

PBHs from Domain Walls and First-Order Phase Transitions

Yann Gouttenoire

4th November 2025

Miramare (IFPU), Trieste

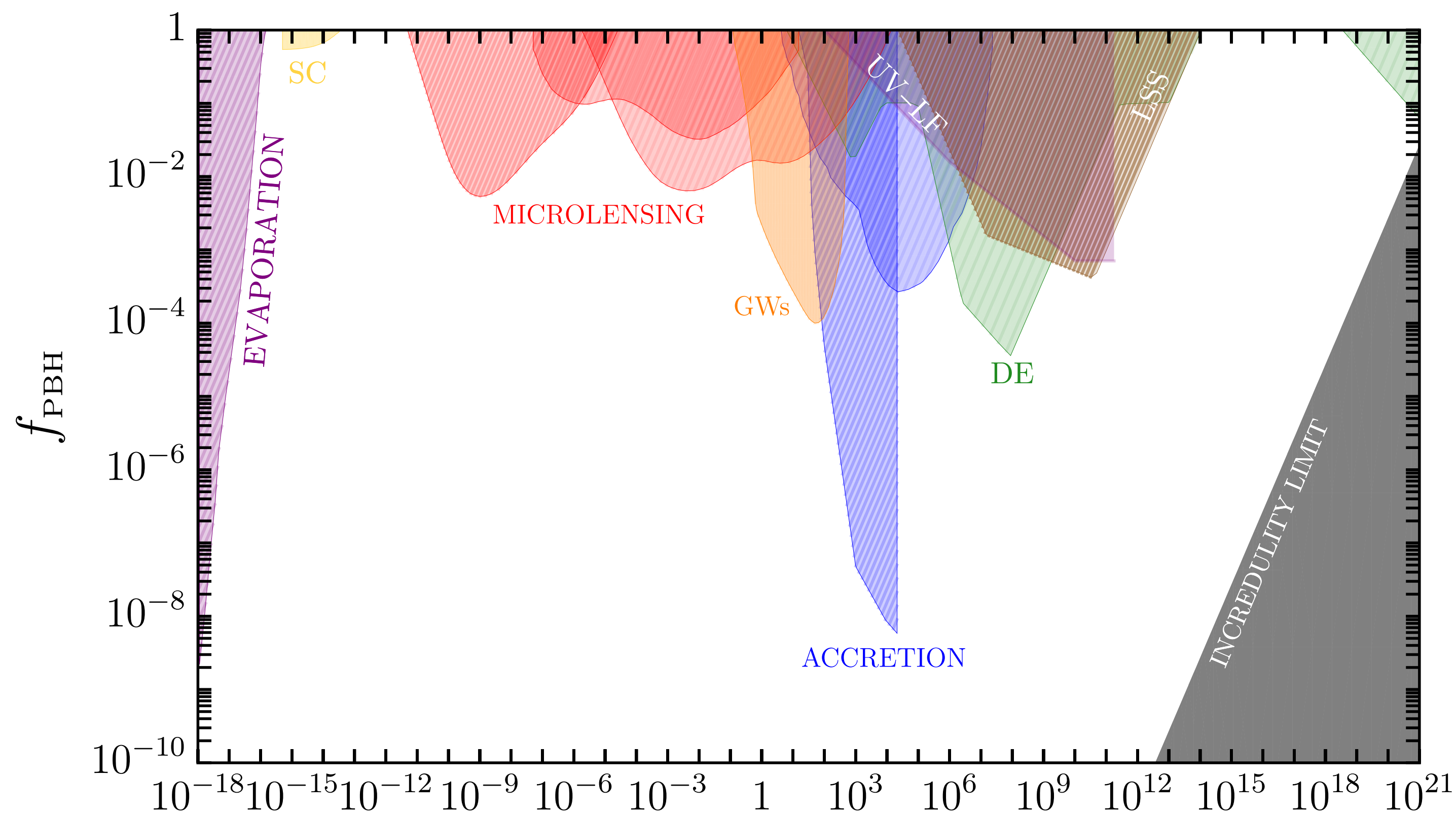


“Primordial Black Holes in the Multi-Messenger Era”

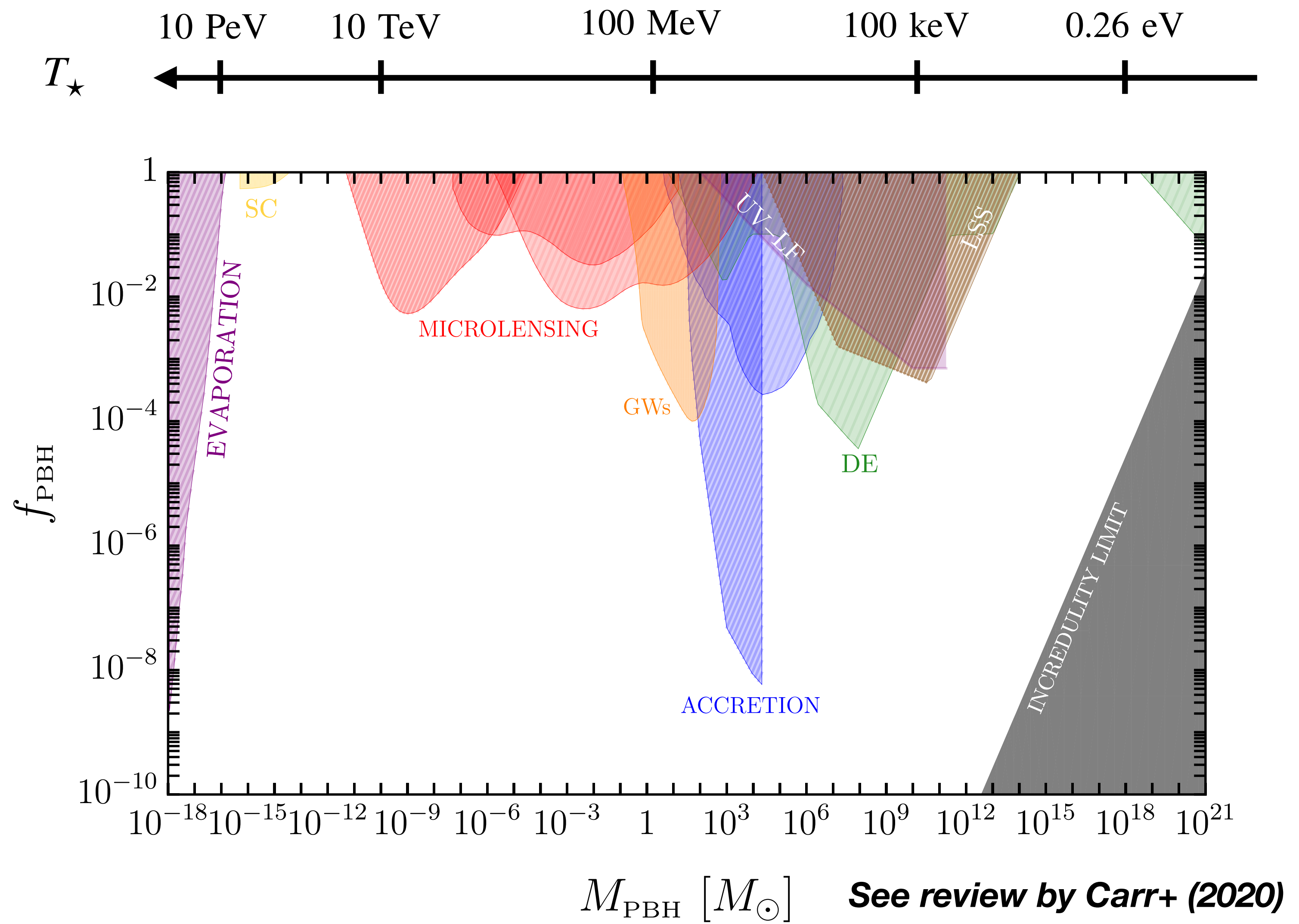


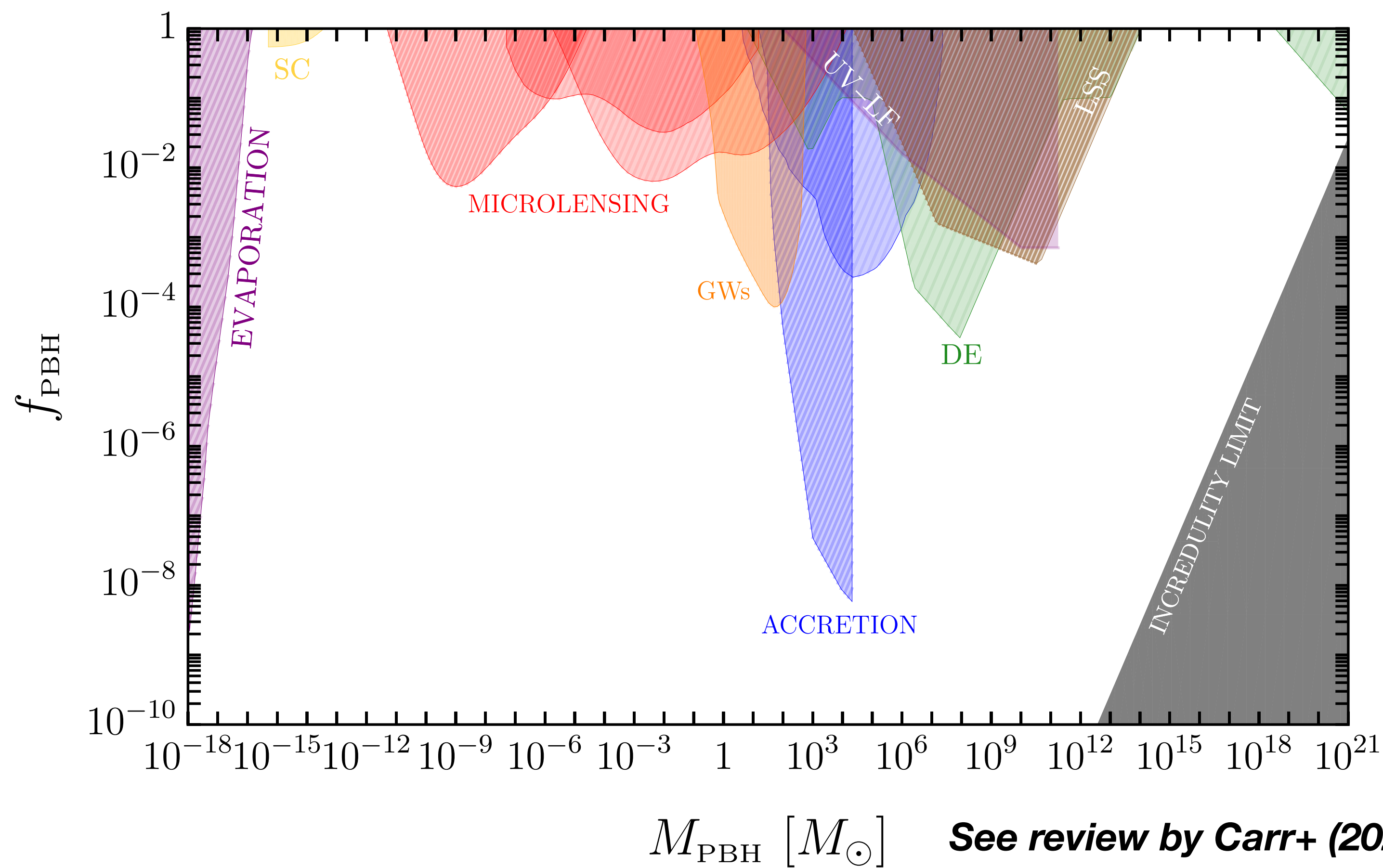
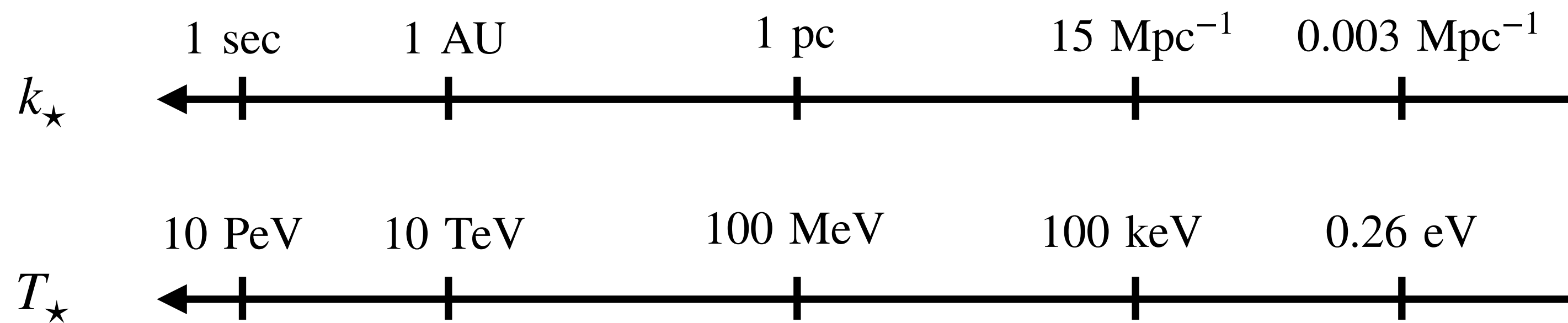
February 2026





$M_{\text{PBH}} [M_{\odot}]$ **See review by Carr+ (2020)**





Lyman α

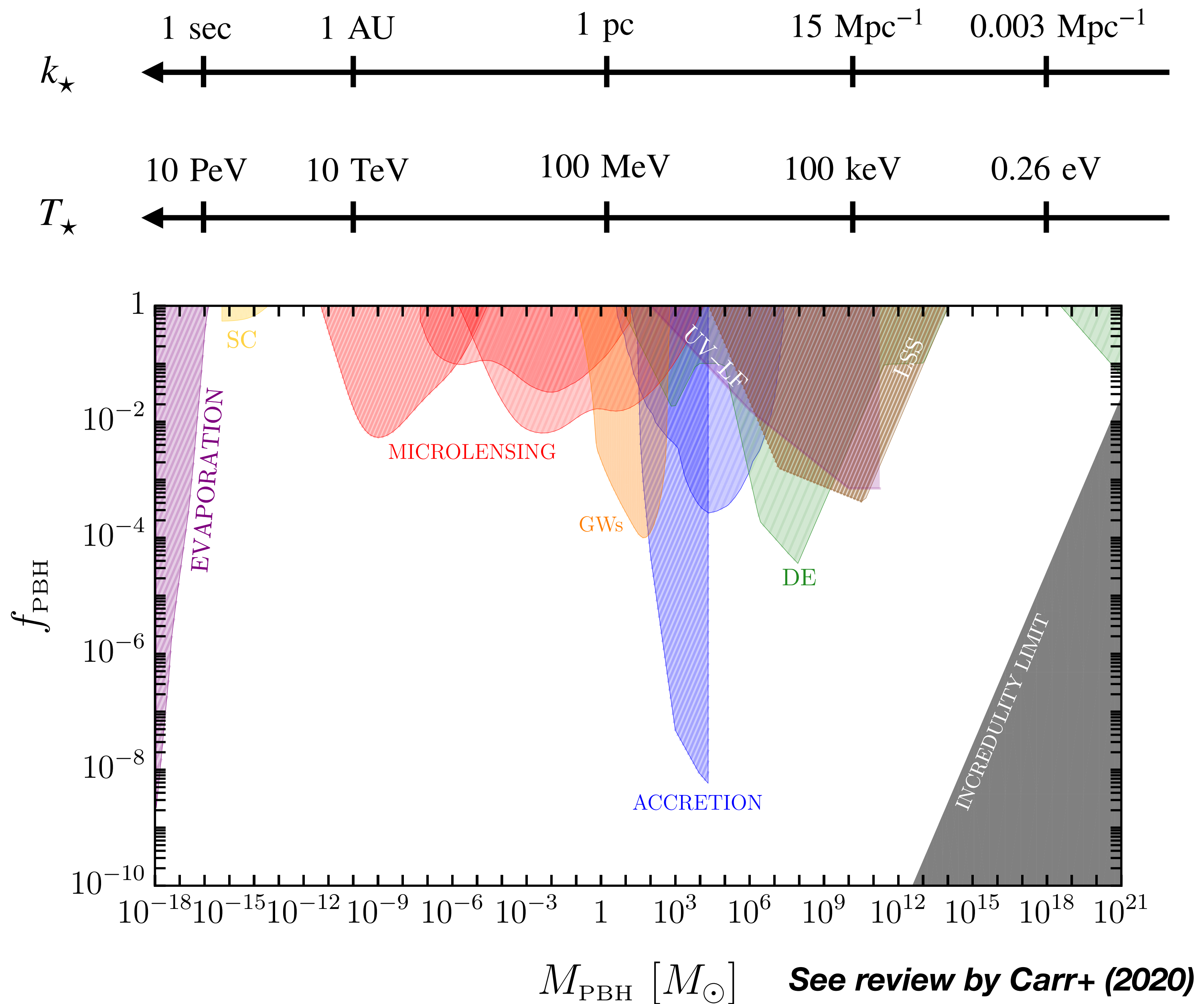
Effective Field Theory Constraints on Primordial Black Holes from the High-Redshift Lyman- α Forest

Mikhail M. Ivanov^{1,*} and Sokratis Trifinopoulos^{1,2,3,†}

¹*Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

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Lyman – α

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CMB + BAO

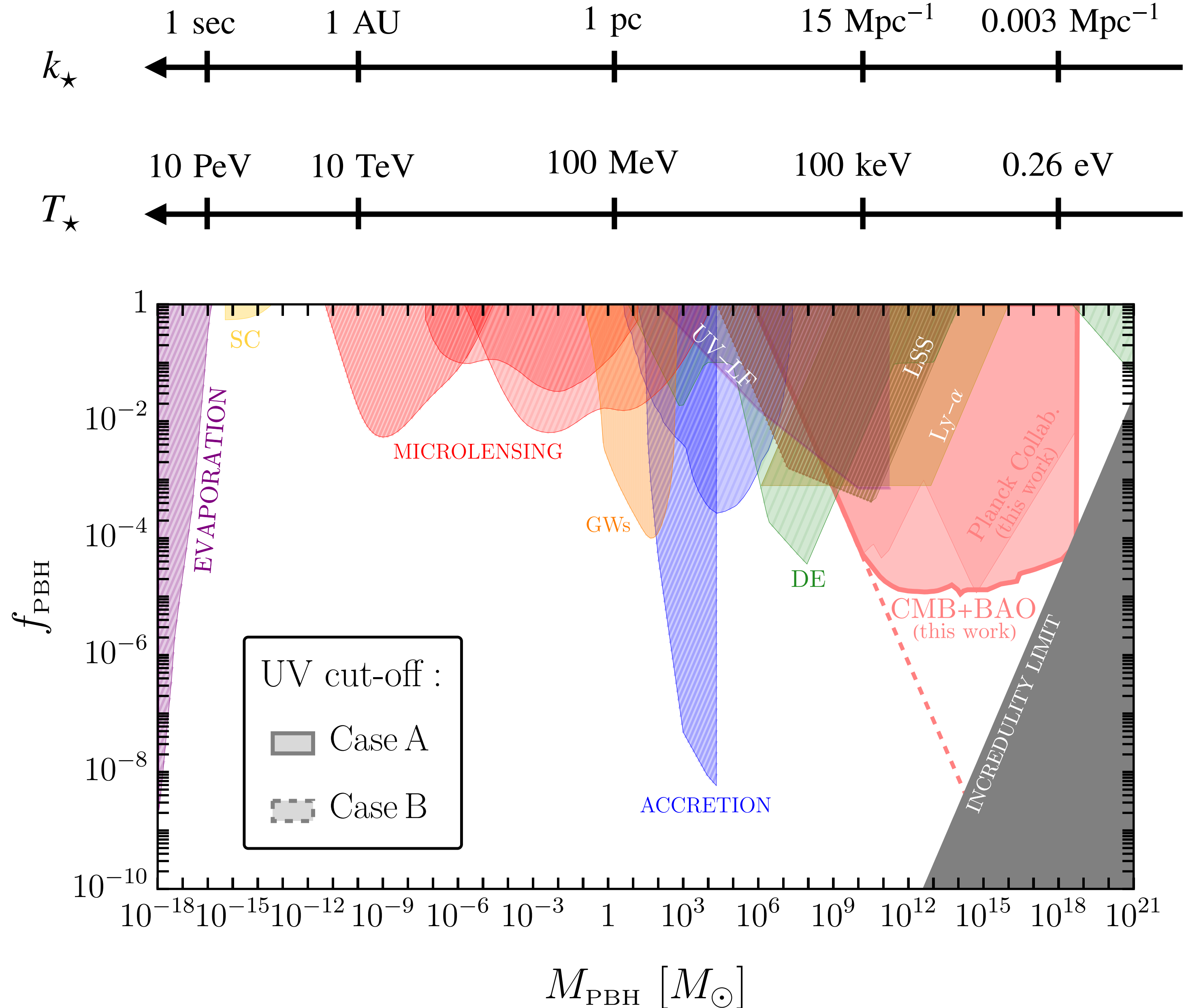
Closing the Mass Window for Stupendously Large Black Holes

Christopher Gerlach^{⊞,1,*} Yann Gouttenoire^{⊞,1,†} Antonio J. Iovino^{⊞,2,3,‡} and Nicholas Leister^{⊞1,§}

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Lyman – α

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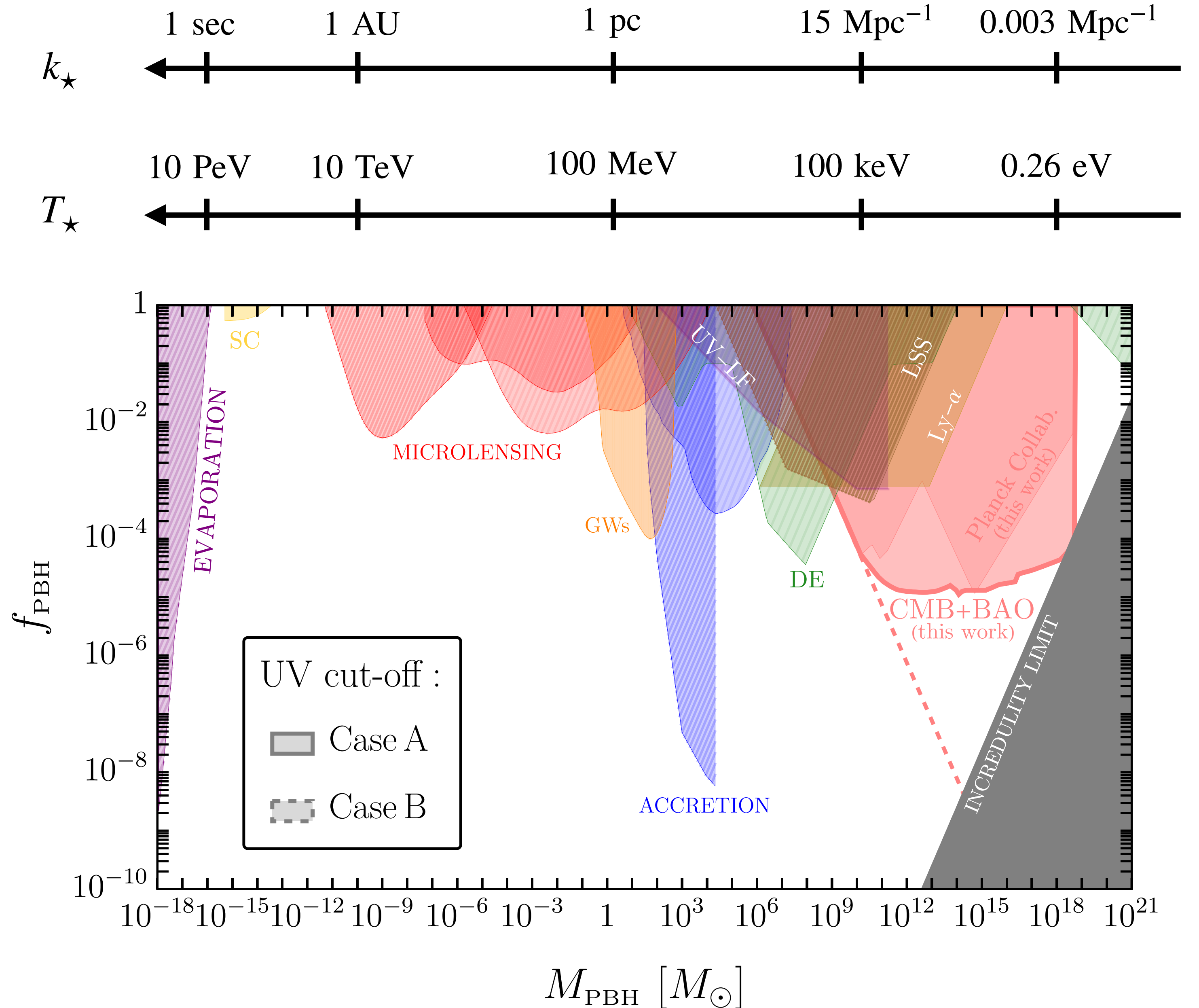
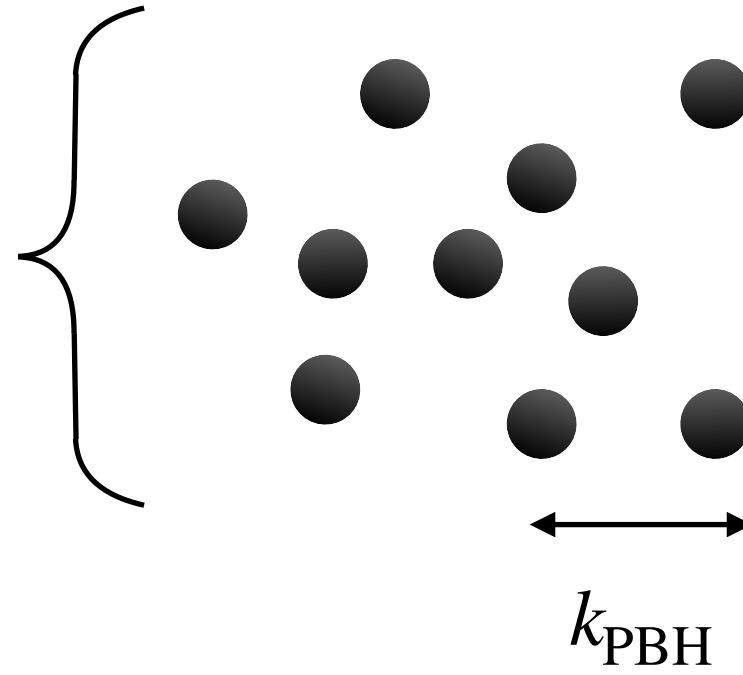
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Gas of PBHs



Lyman – α

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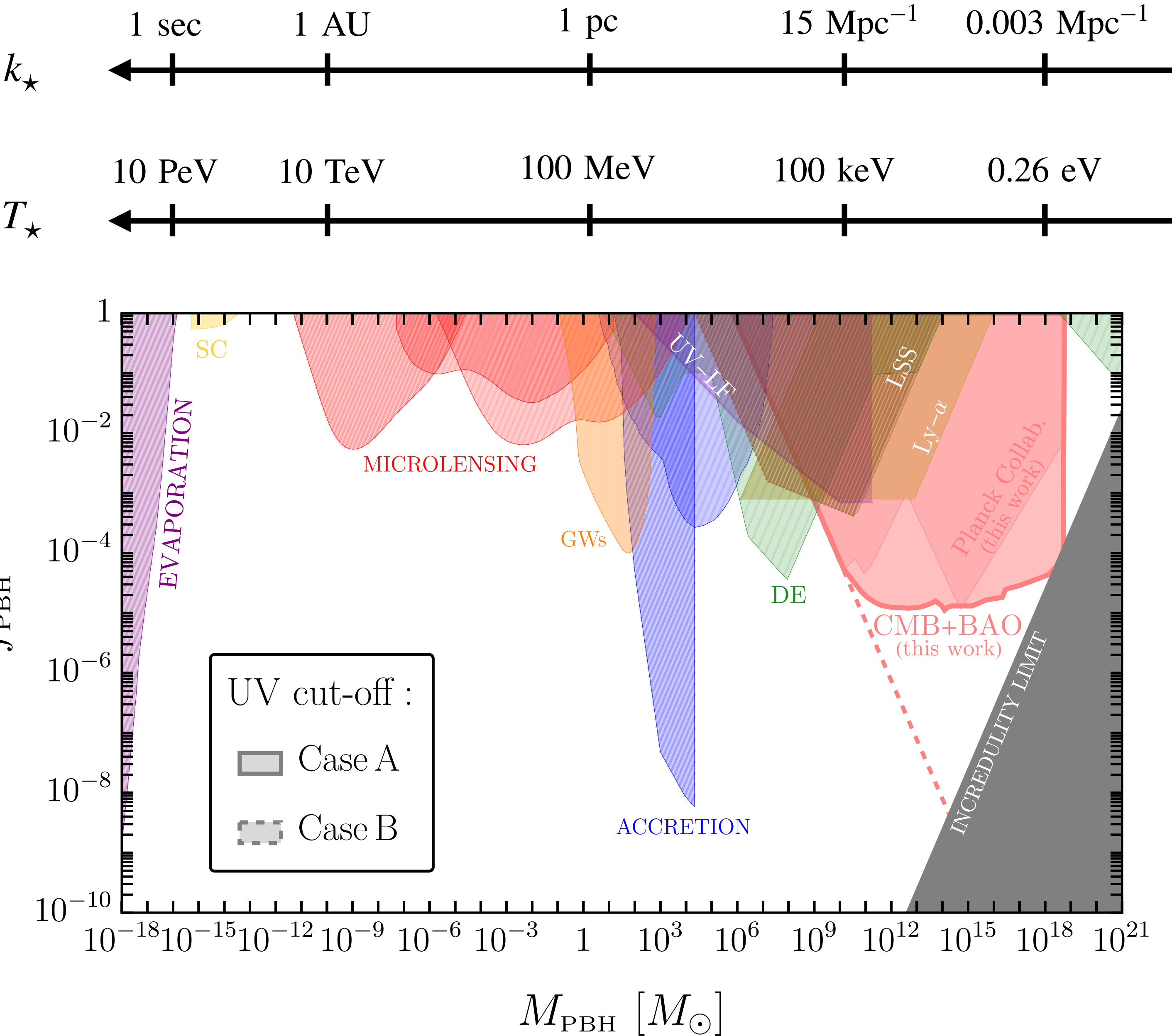
Gas of PBHs

Poisson noise :

$$\mathcal{P}_\delta = f_{\text{PBH}}^2 \left(\frac{k}{k_{\text{PBH}}} \right)^3 \Theta(k_{\text{cut}} - k)$$

Inman, Ali-Haïmoud (1907.08129)

⇒ source isocurvatures



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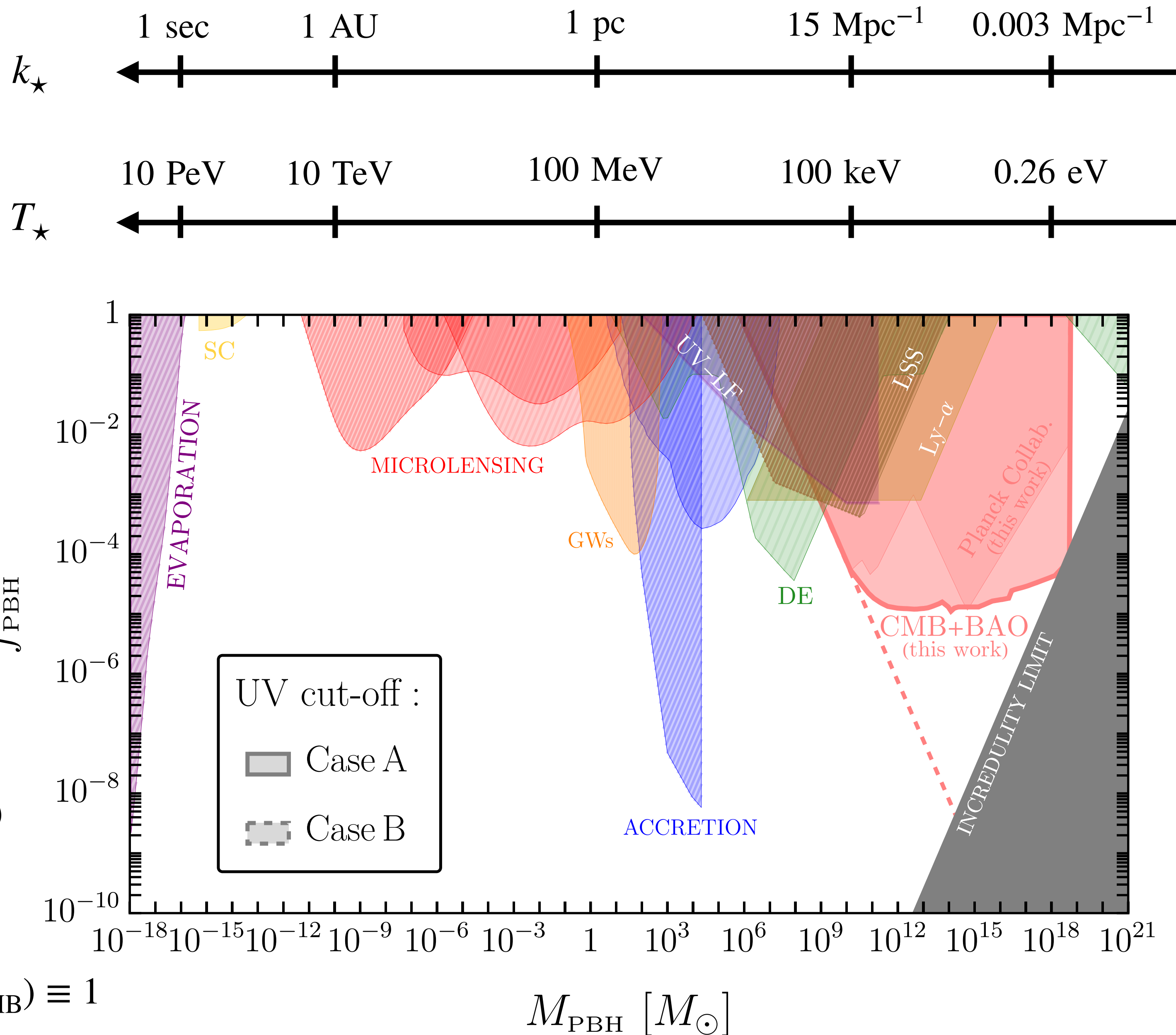
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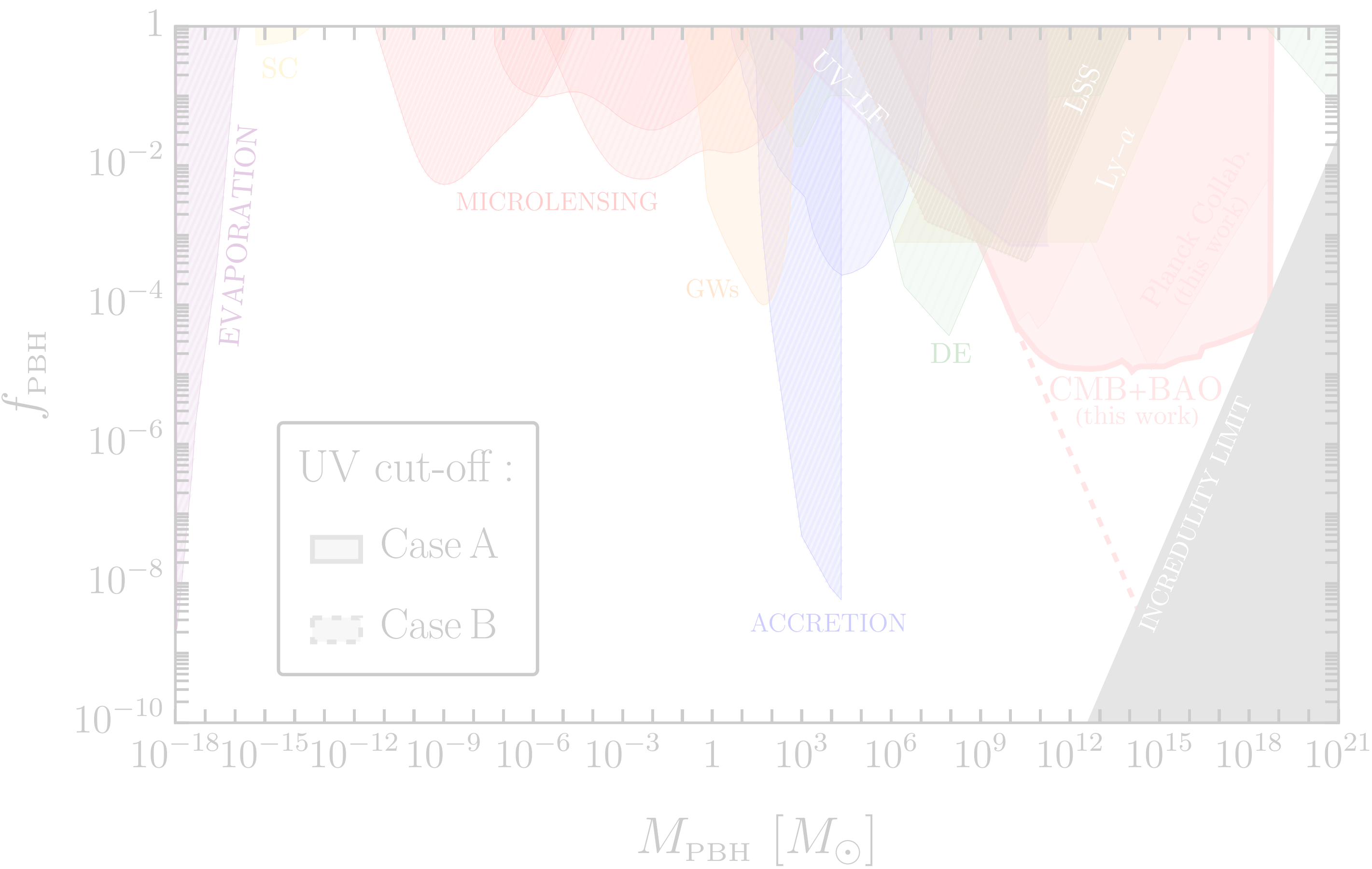
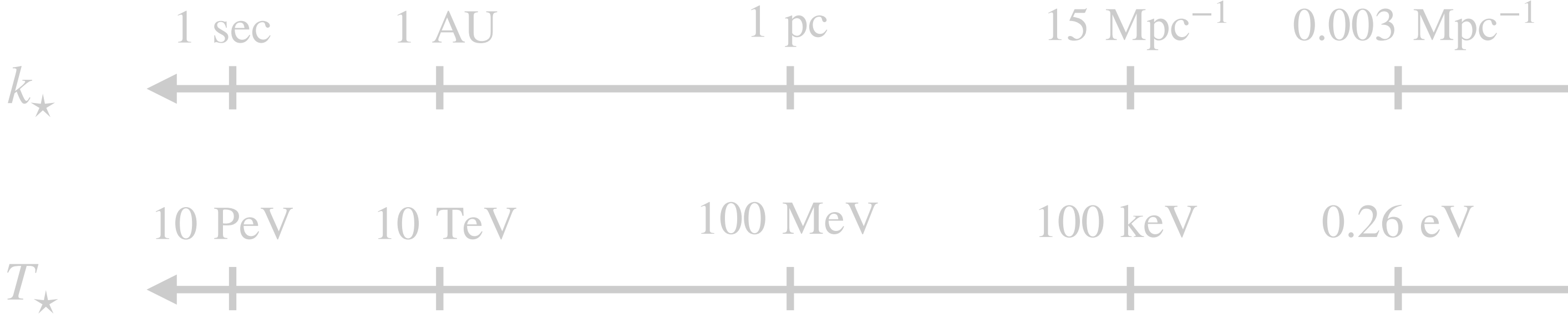
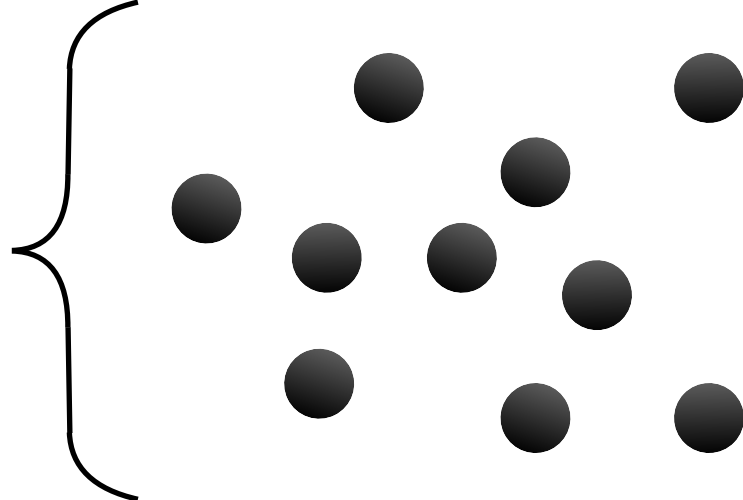
⇒ **source isocurvatures**

$$k_{\text{cut}} = \begin{cases} k_{\text{PBH}}, & \text{(solid line)} \\ k_{\text{NL}}, & \text{(dashed line)} \end{cases} \quad \text{with} \quad \delta_{\text{DM}}(k_{\text{NL}}, t_{\text{CMB}}) \equiv 1$$



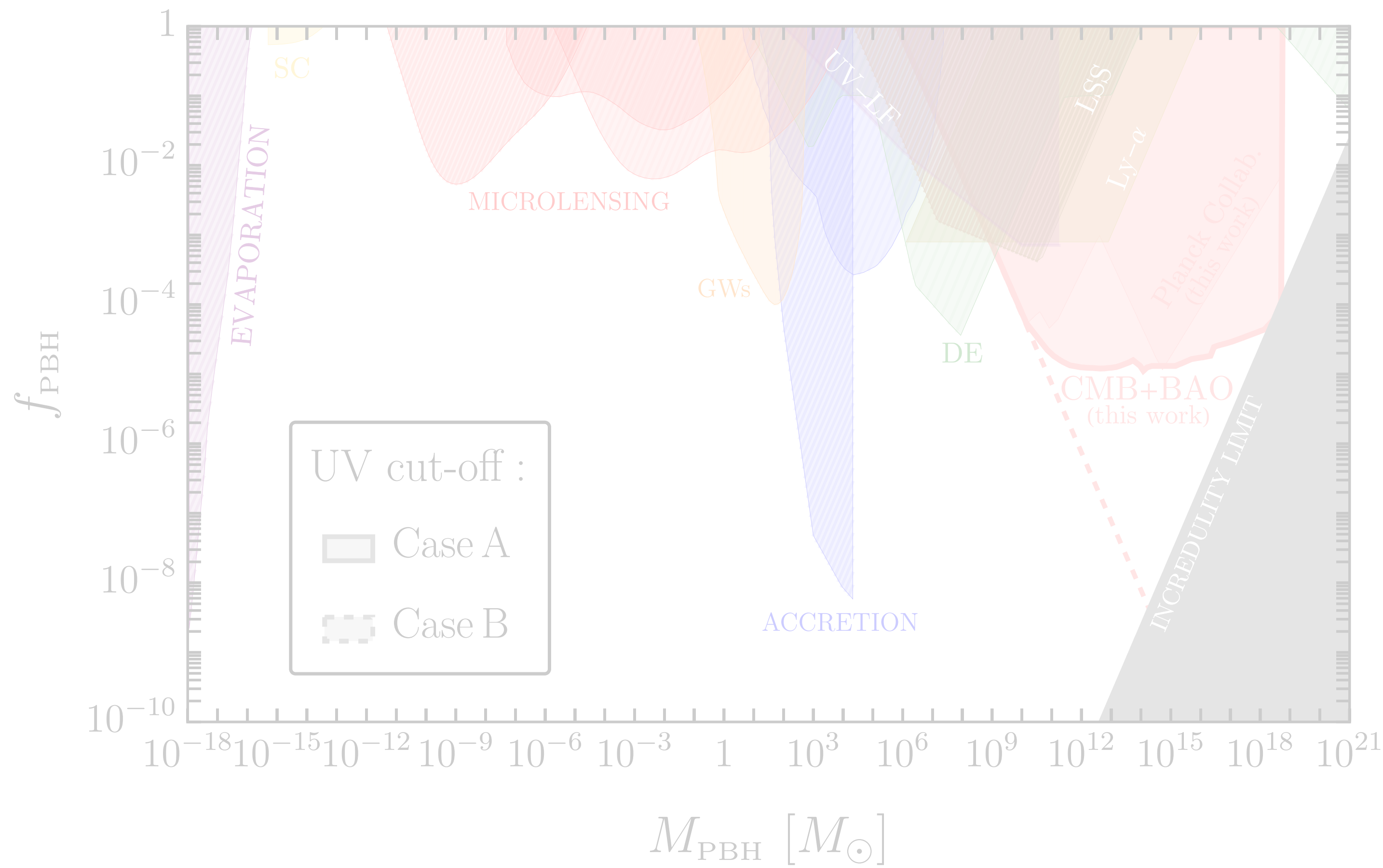
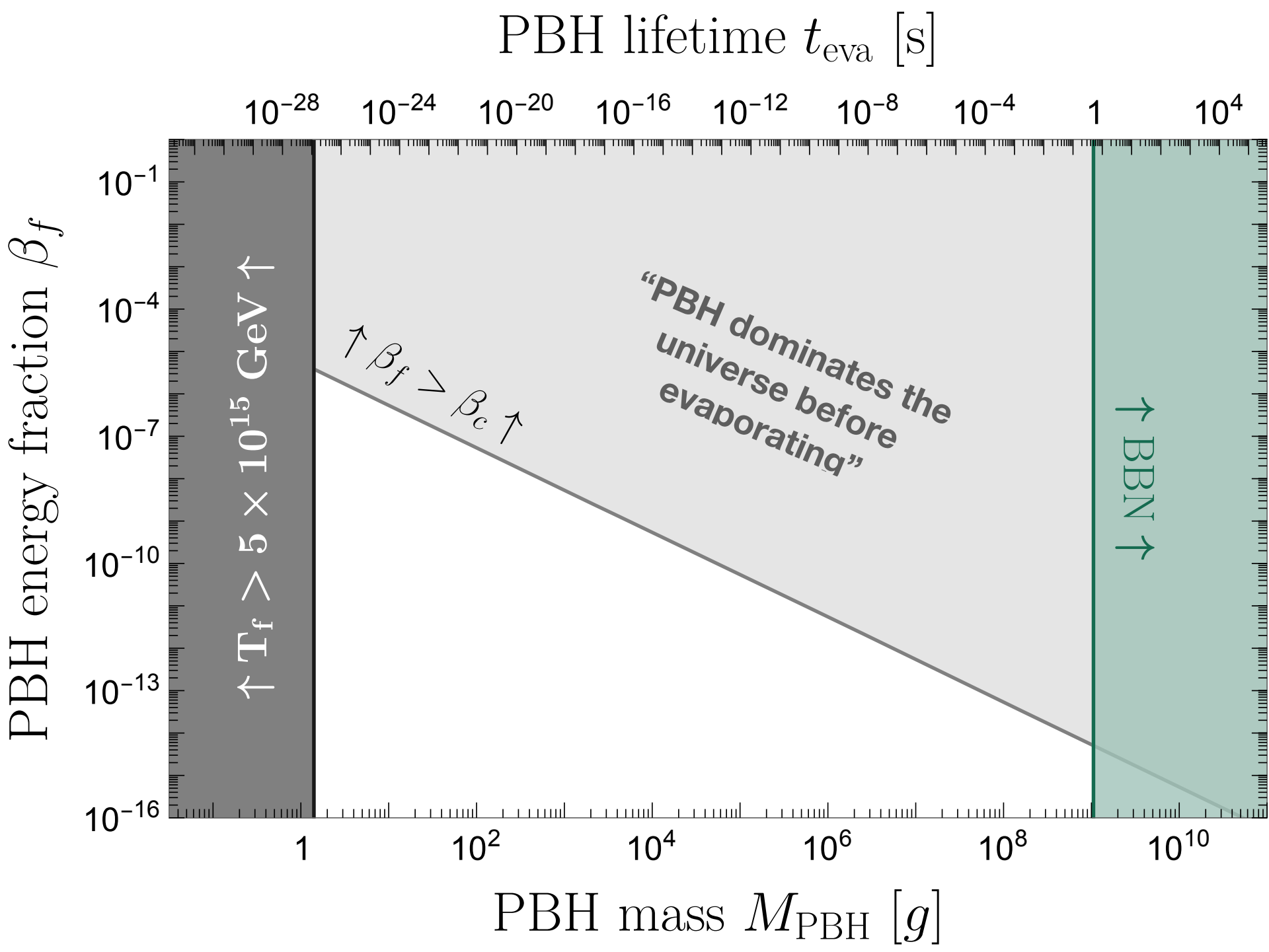
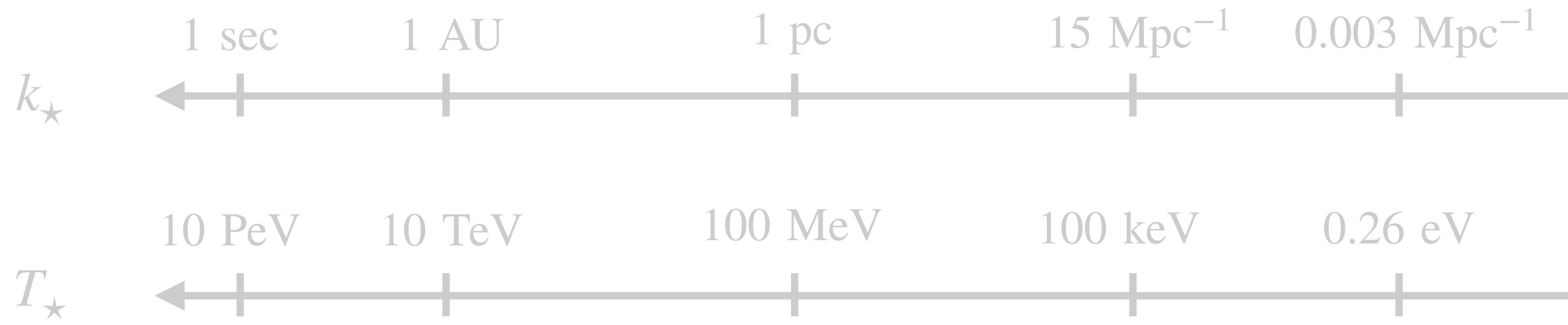
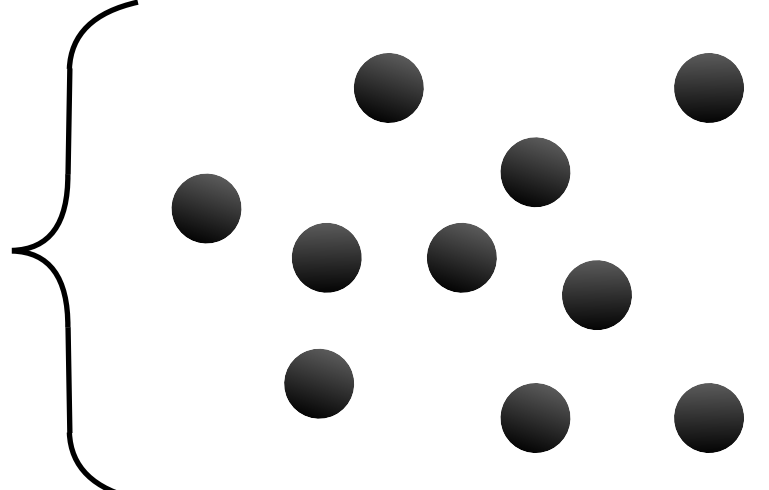
Ultra-light PBHs

Gas of
evaporating PBHs



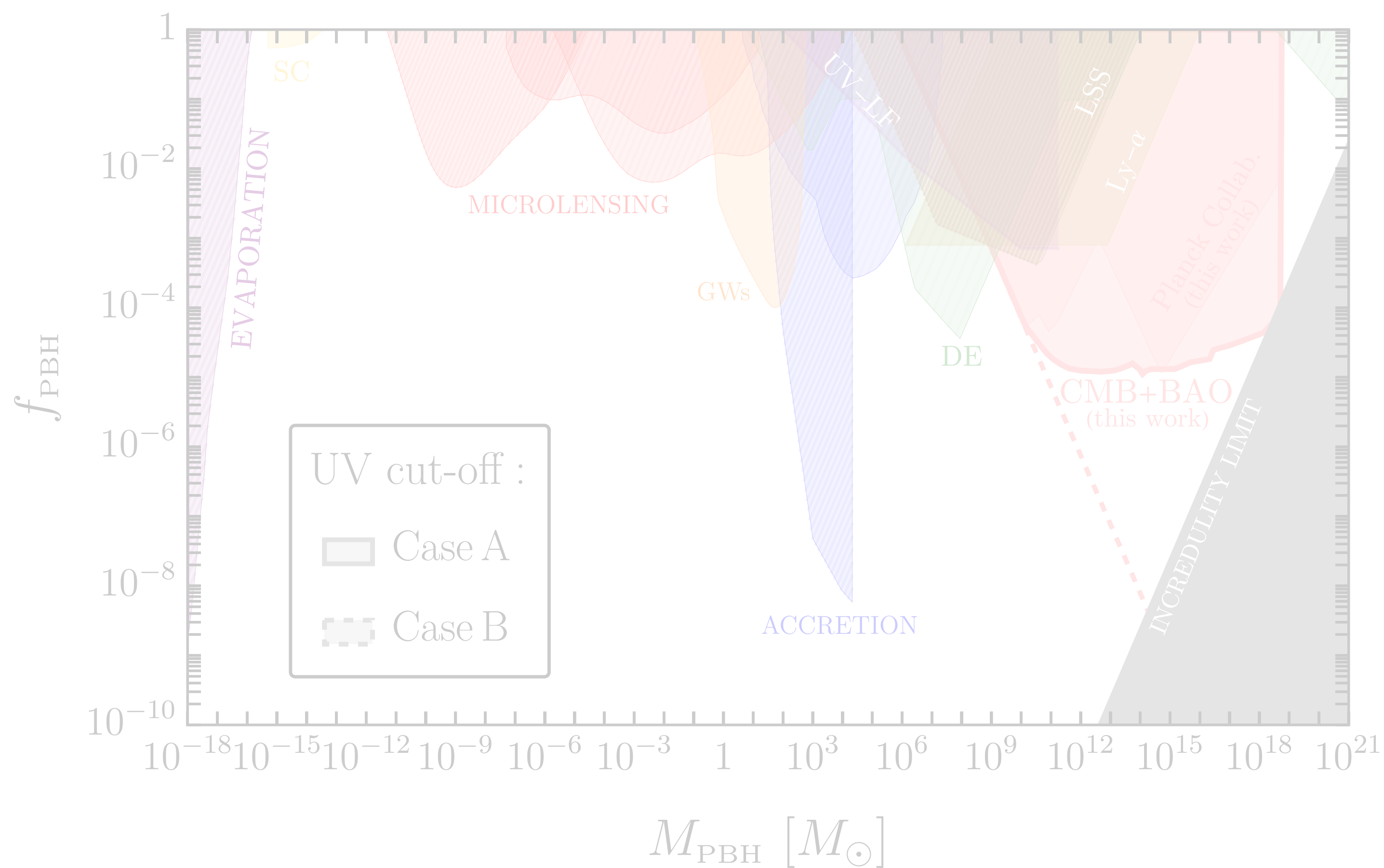
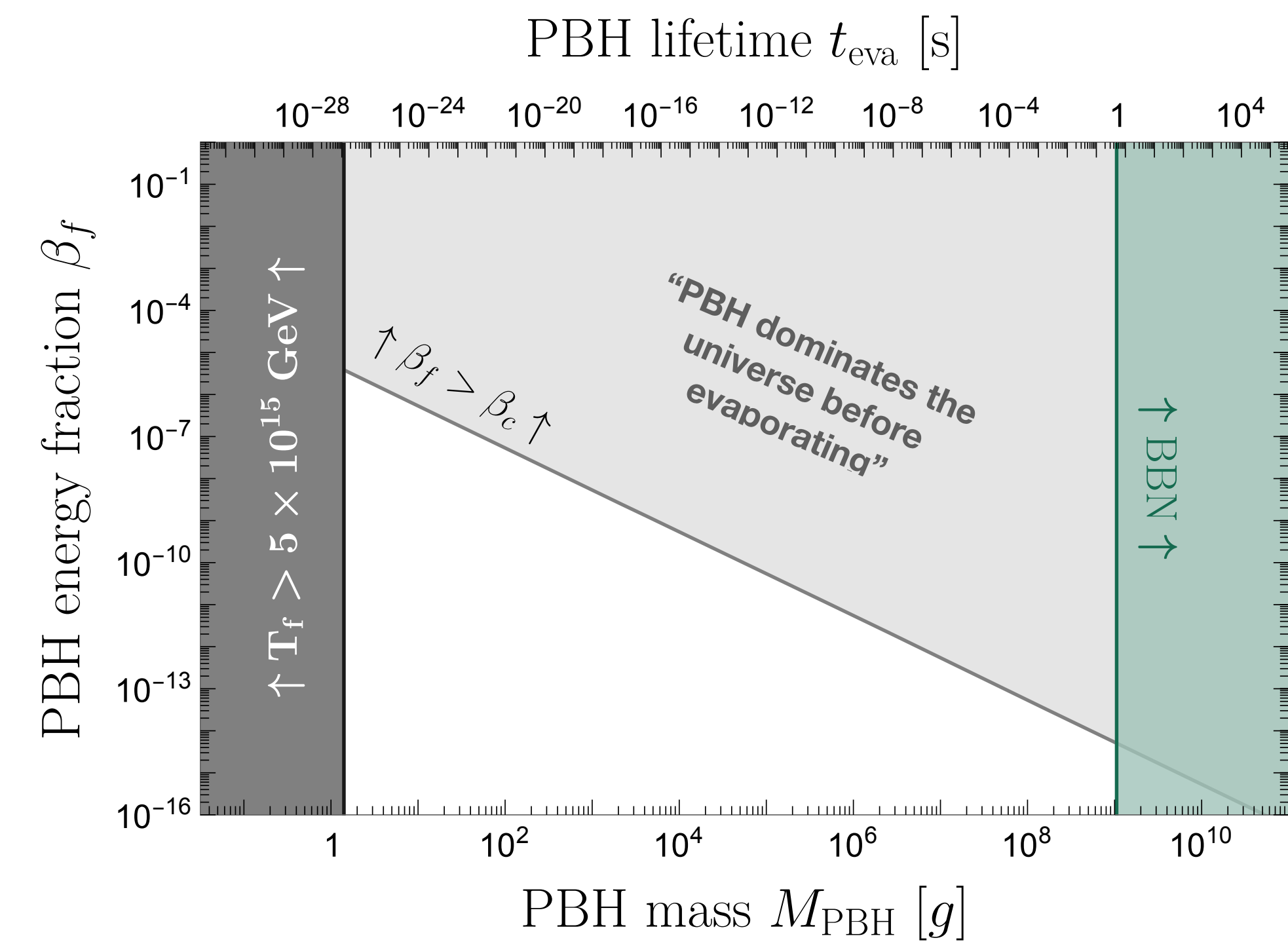
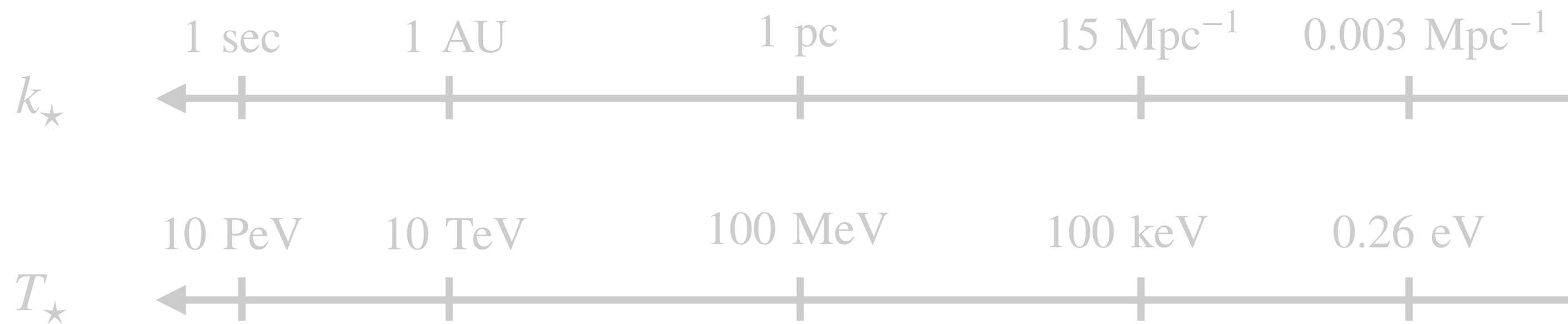
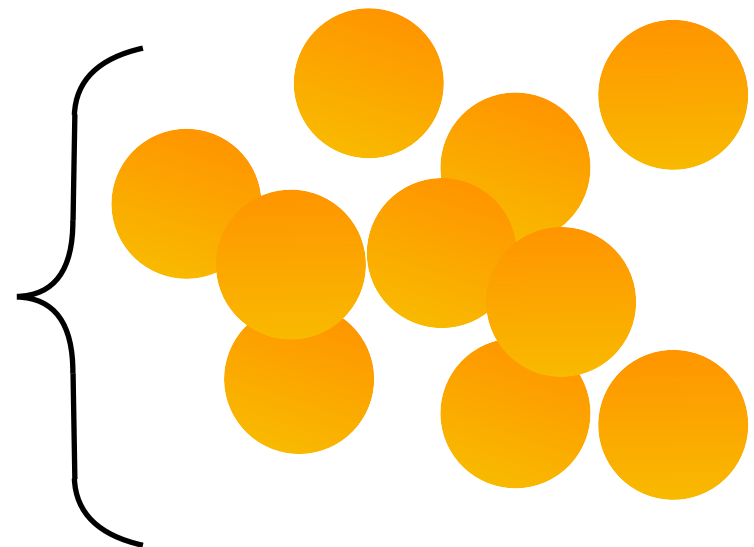
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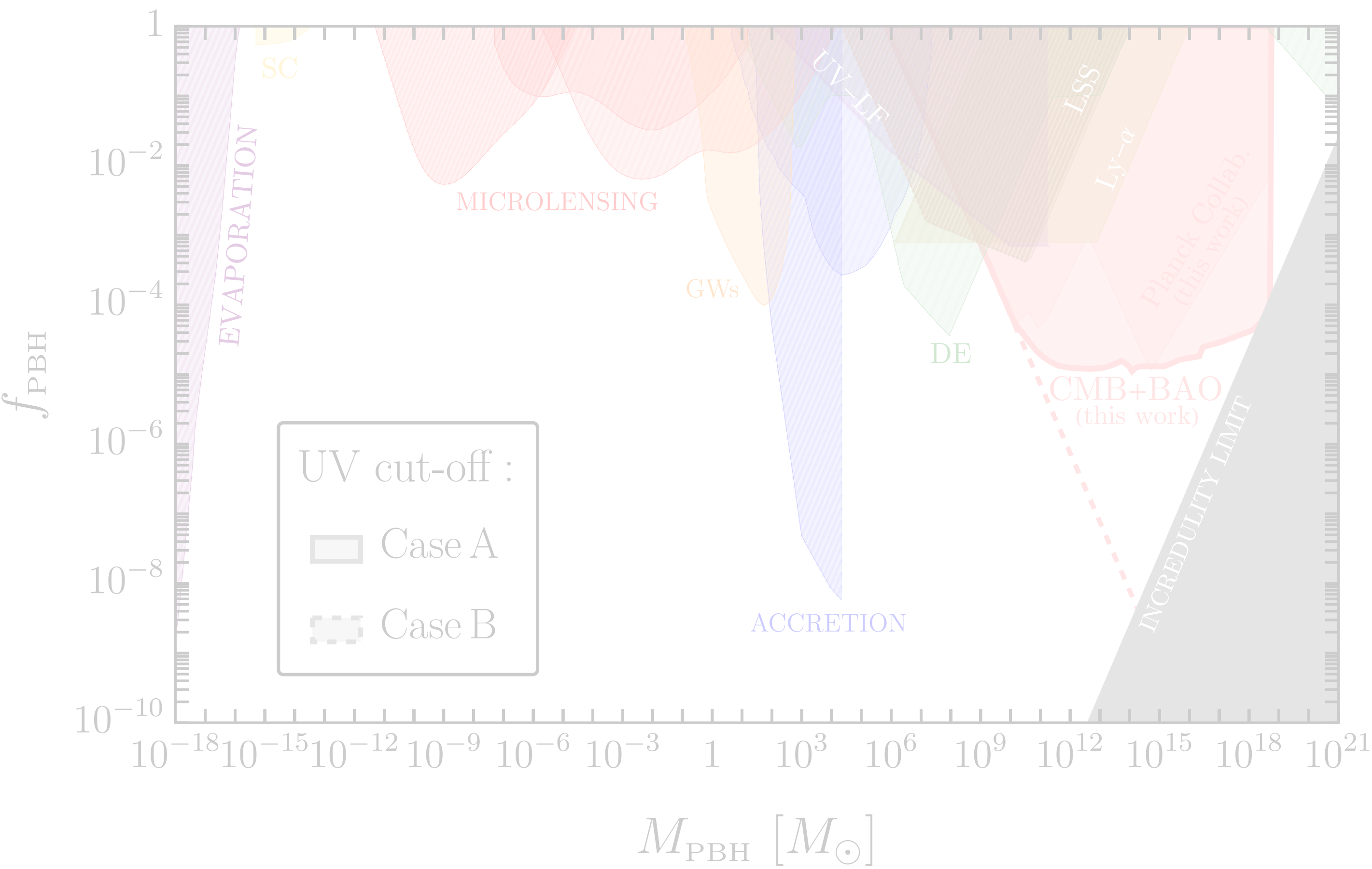
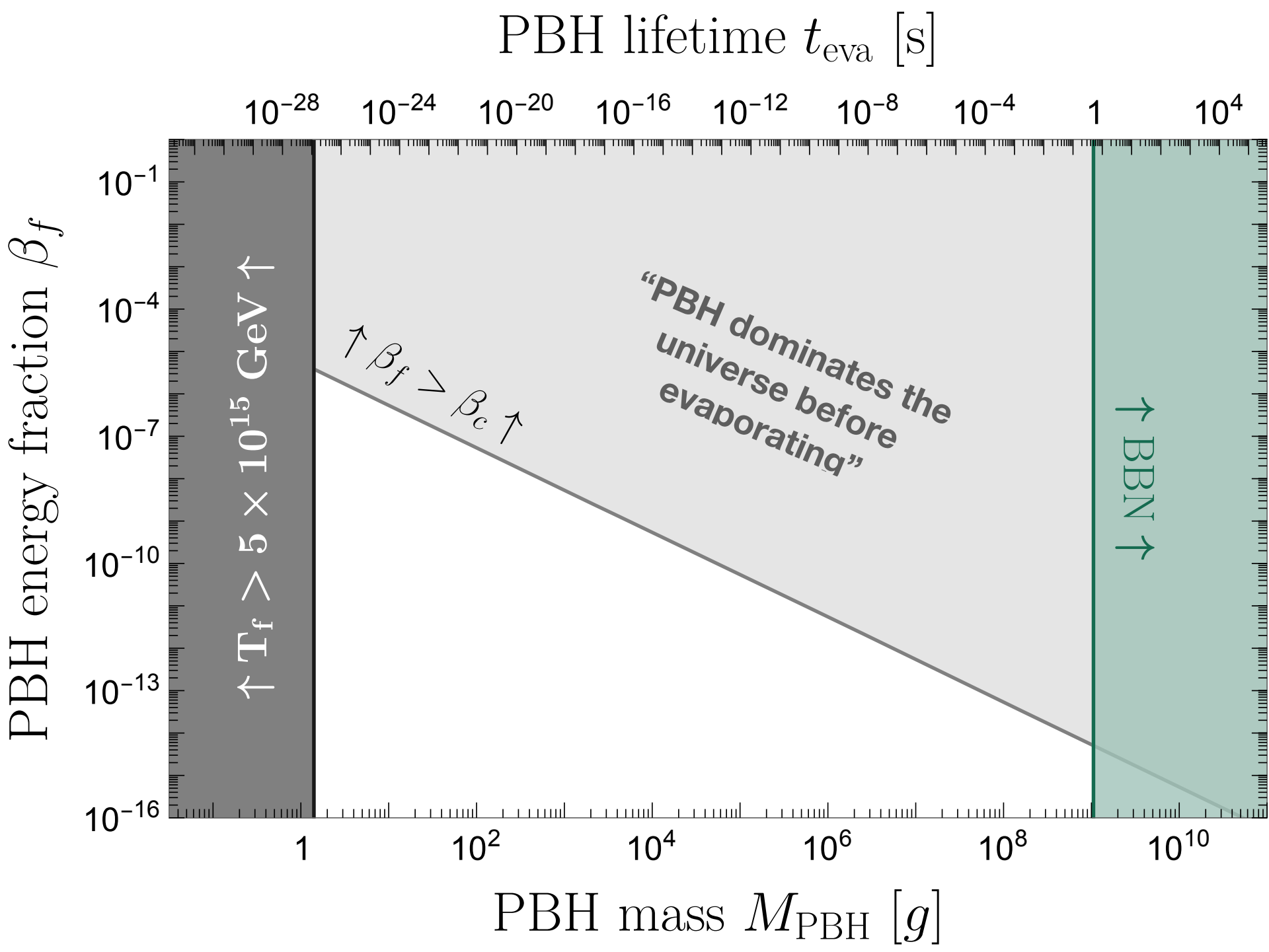
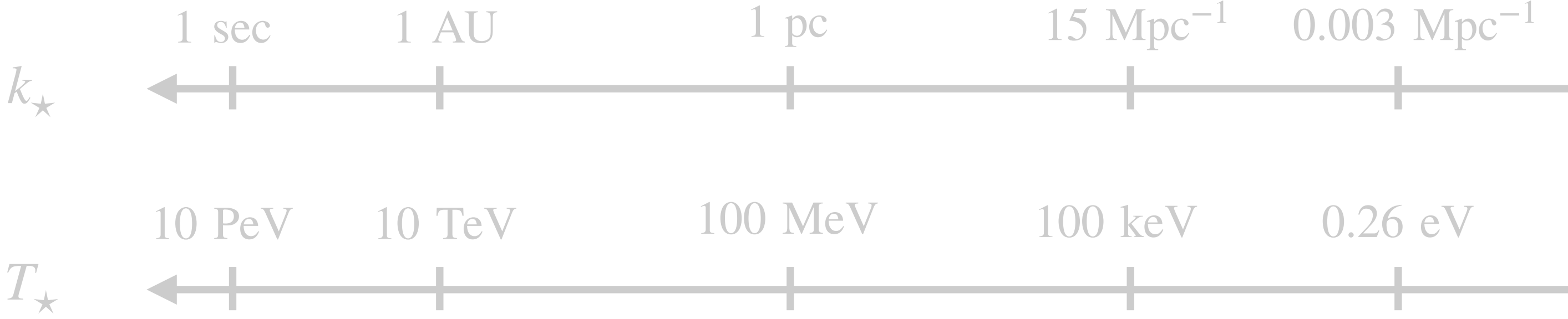
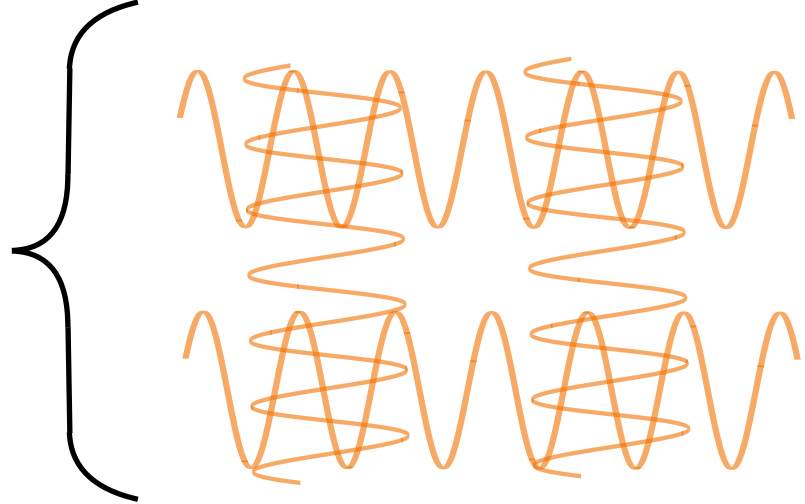
**Gas of
evaporating PBHs**

Evaporation



Evaporation $\Rightarrow$ Sound waves

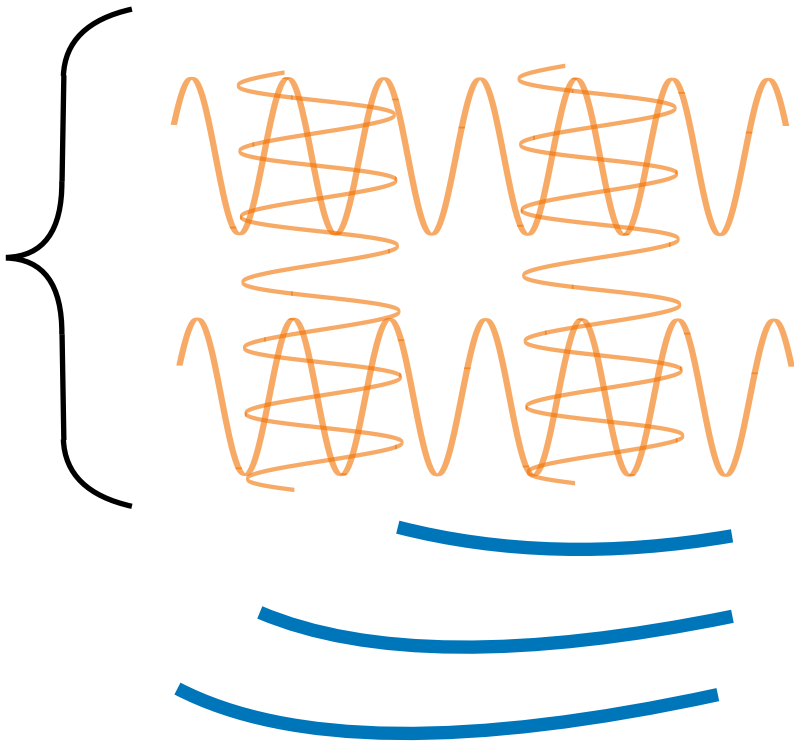
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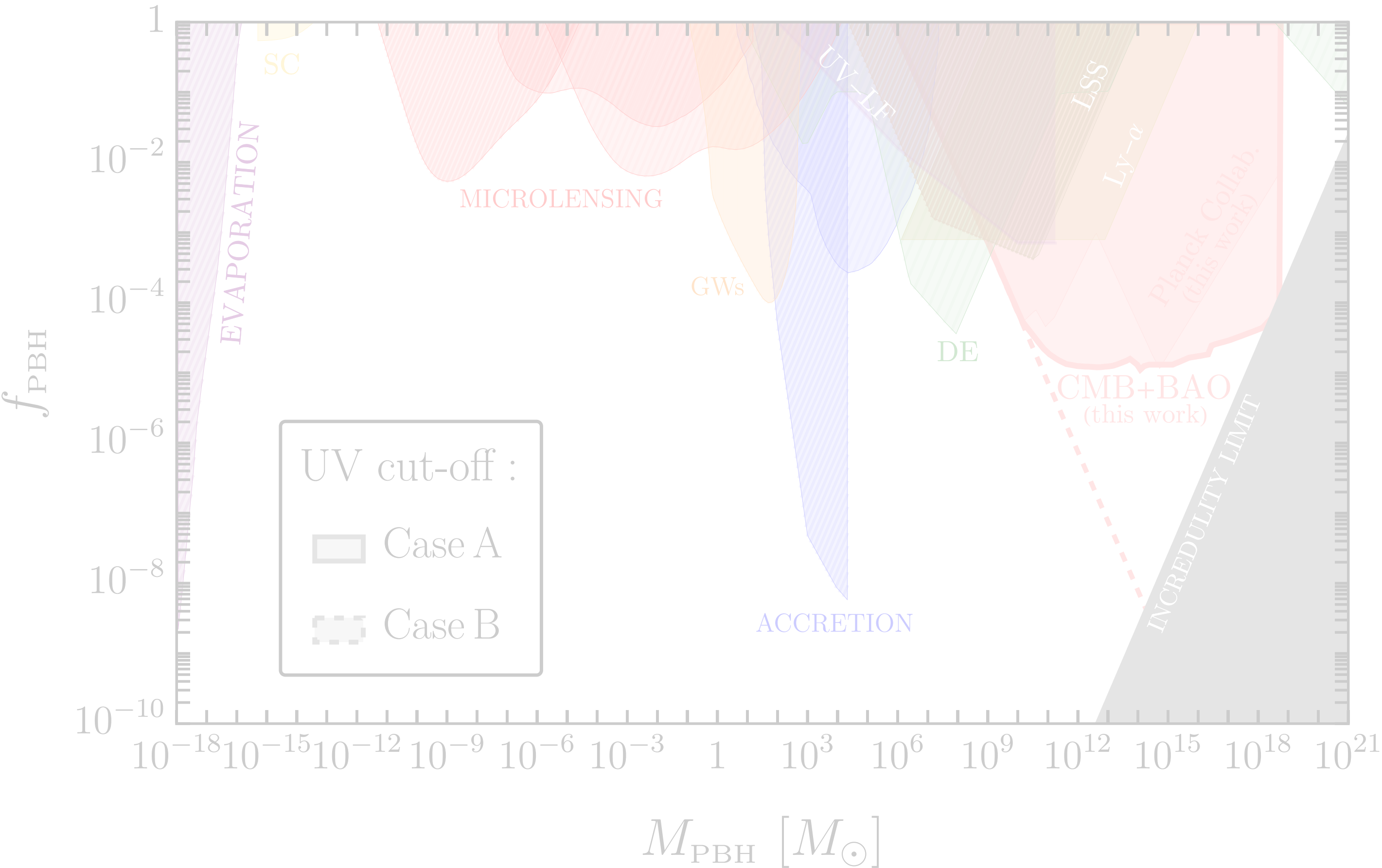
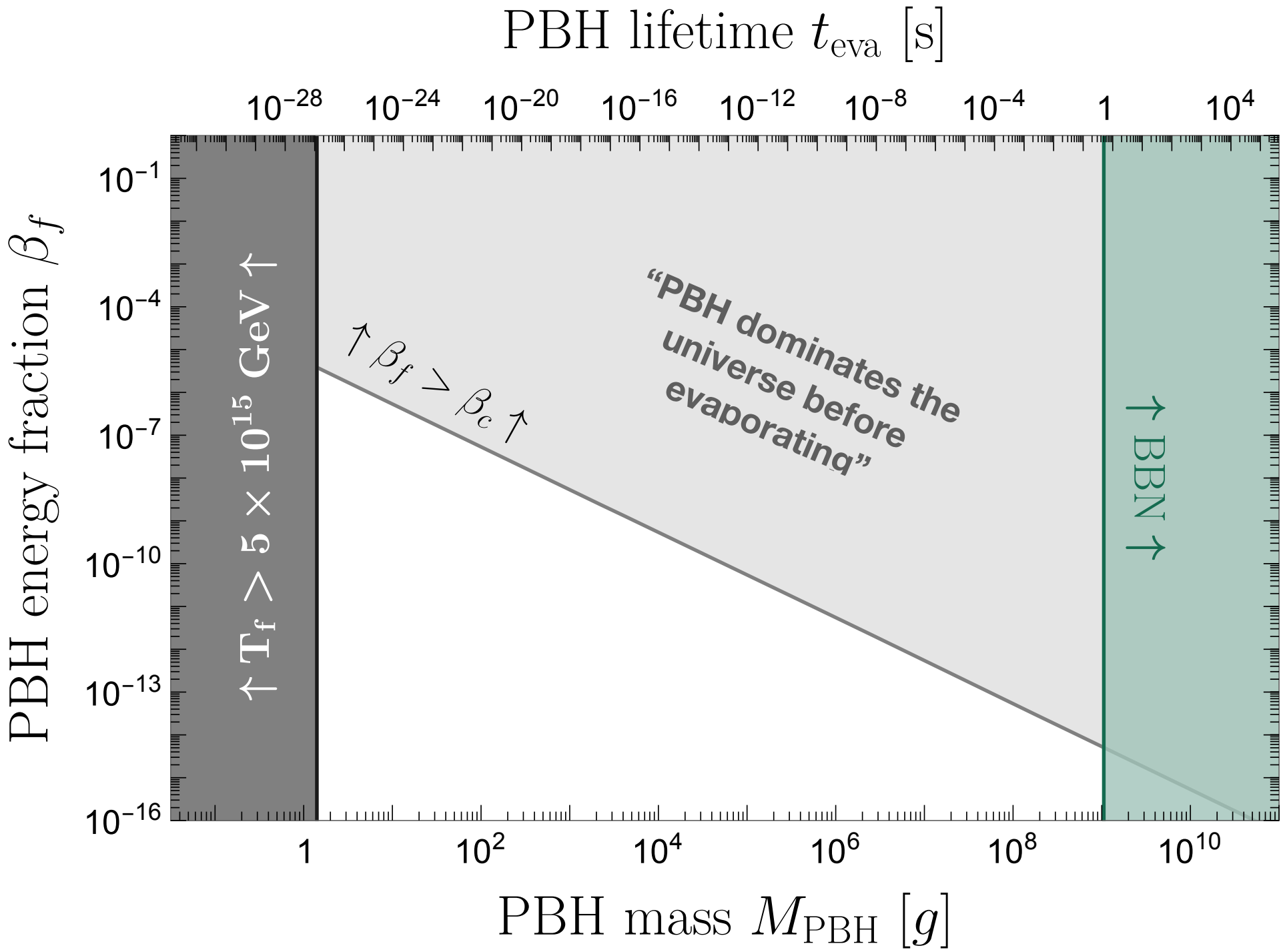
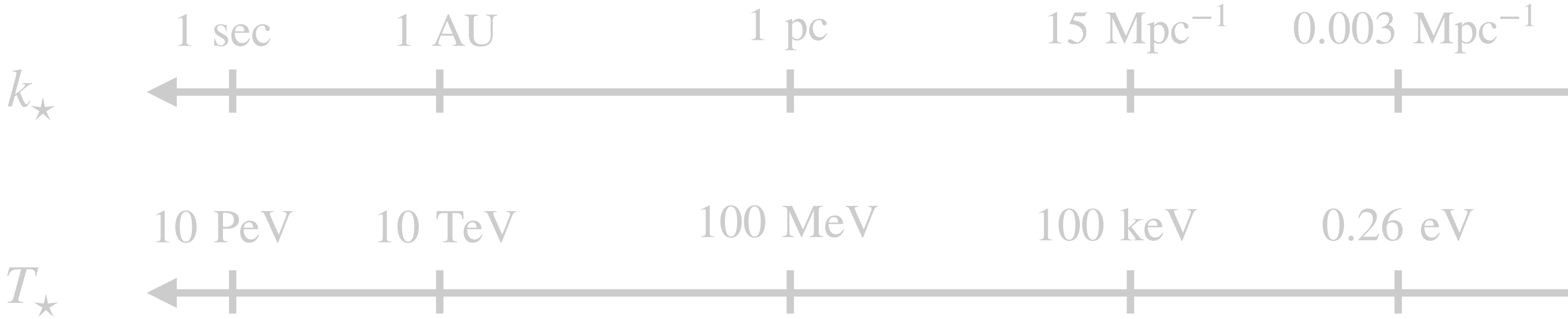
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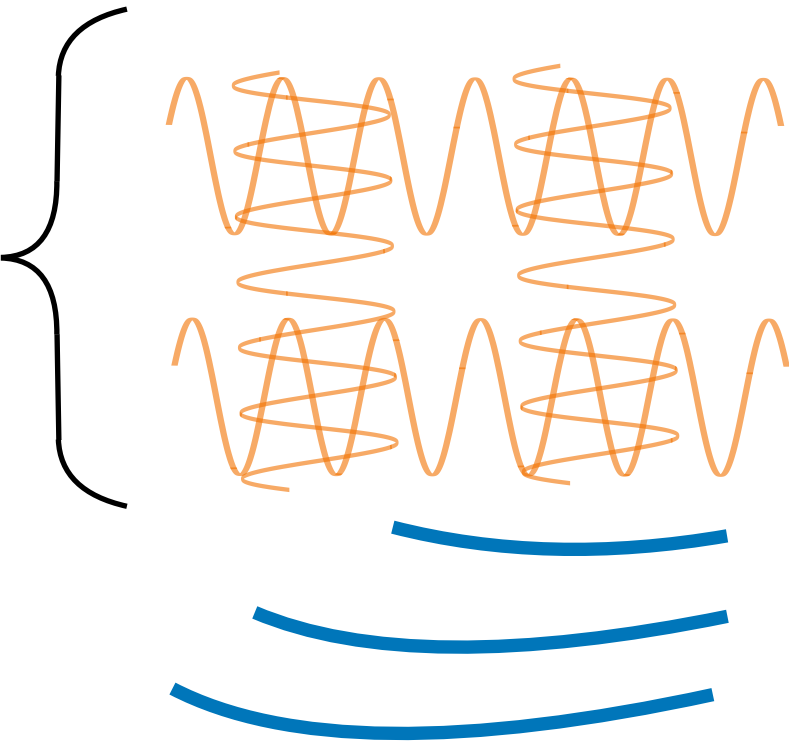
Poltergeist GWs



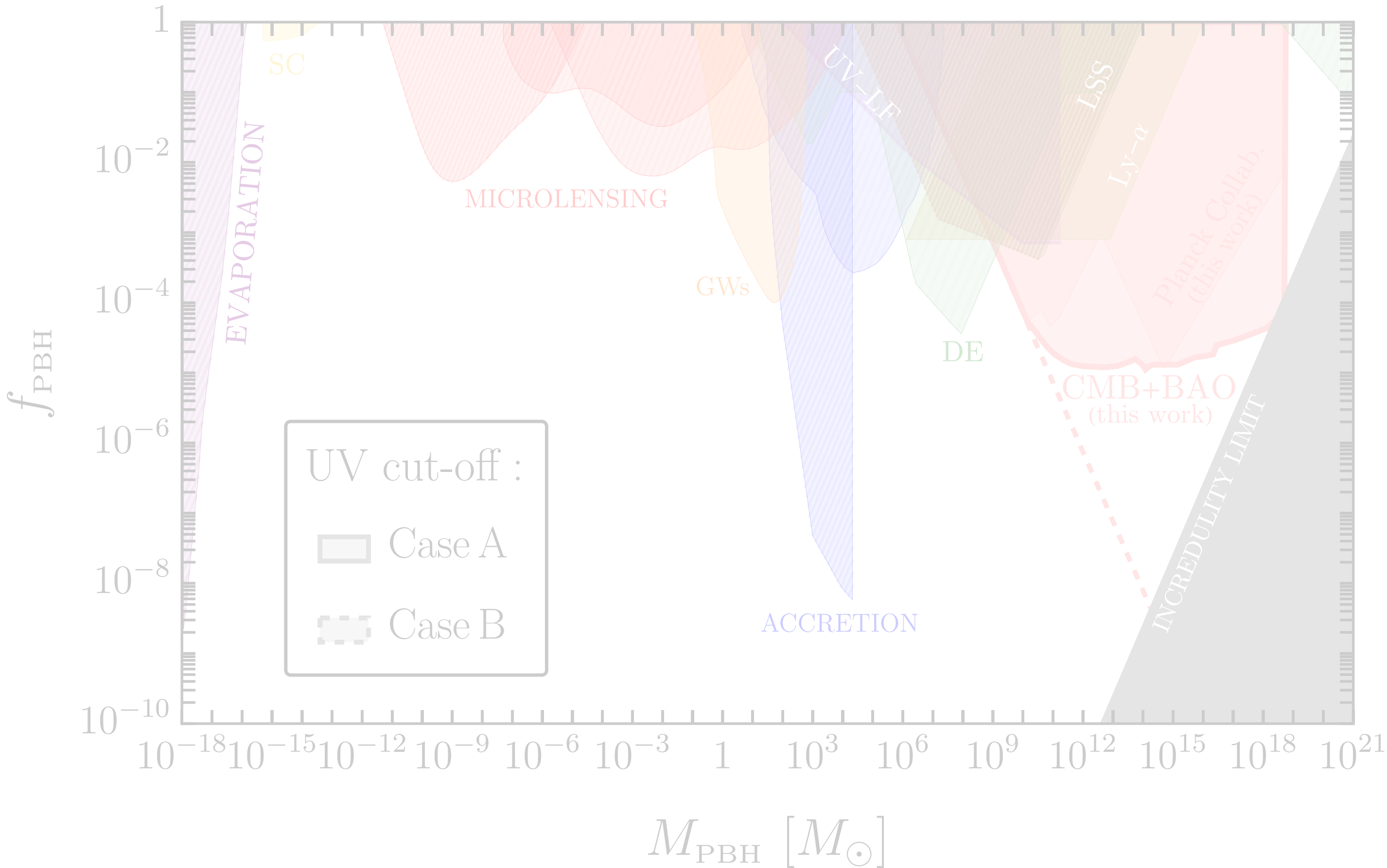
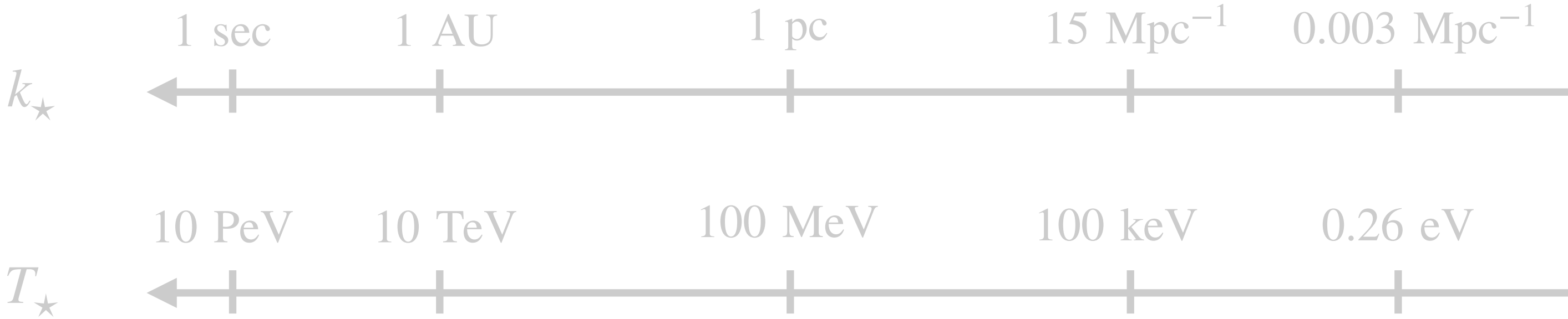
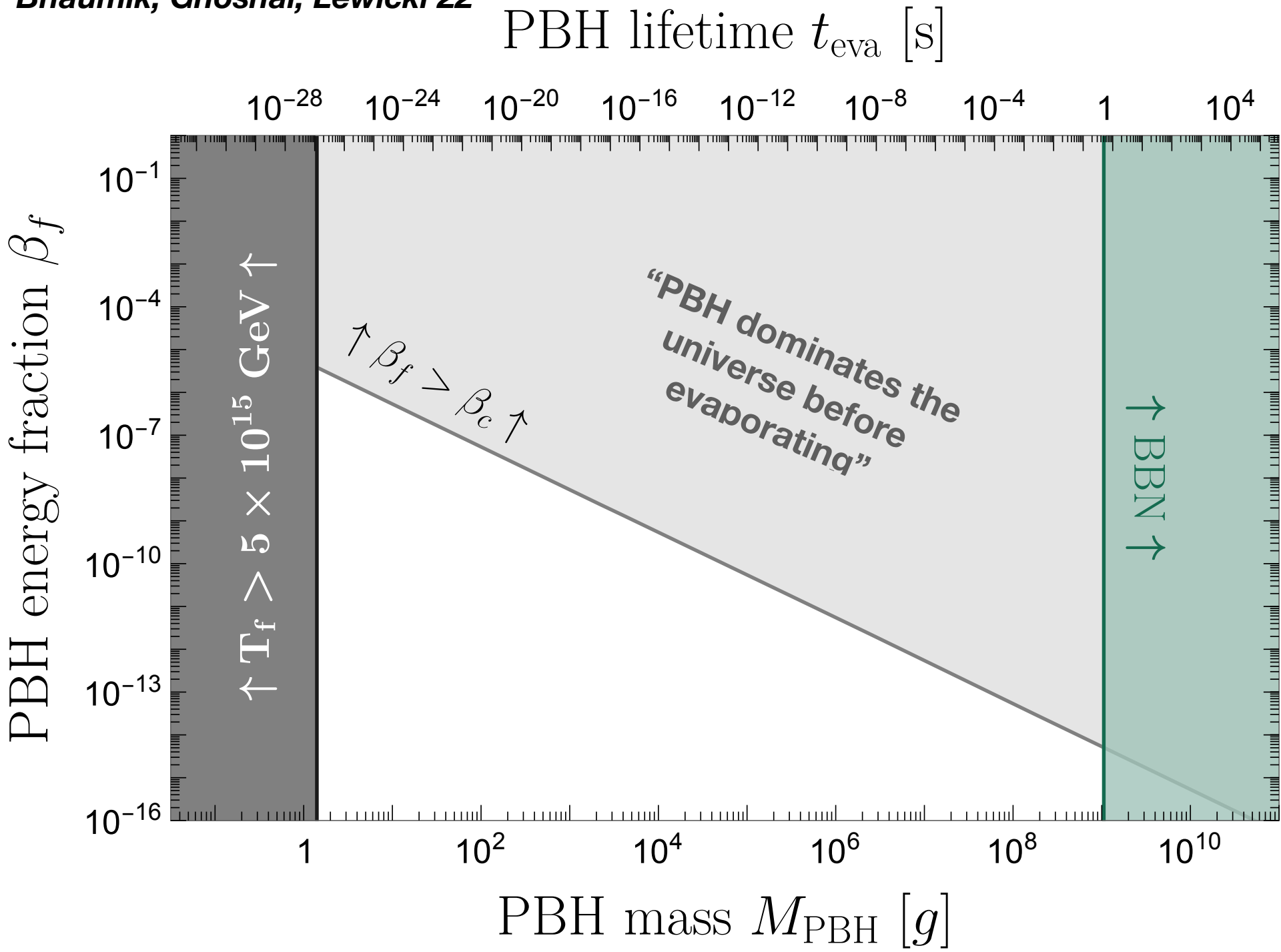
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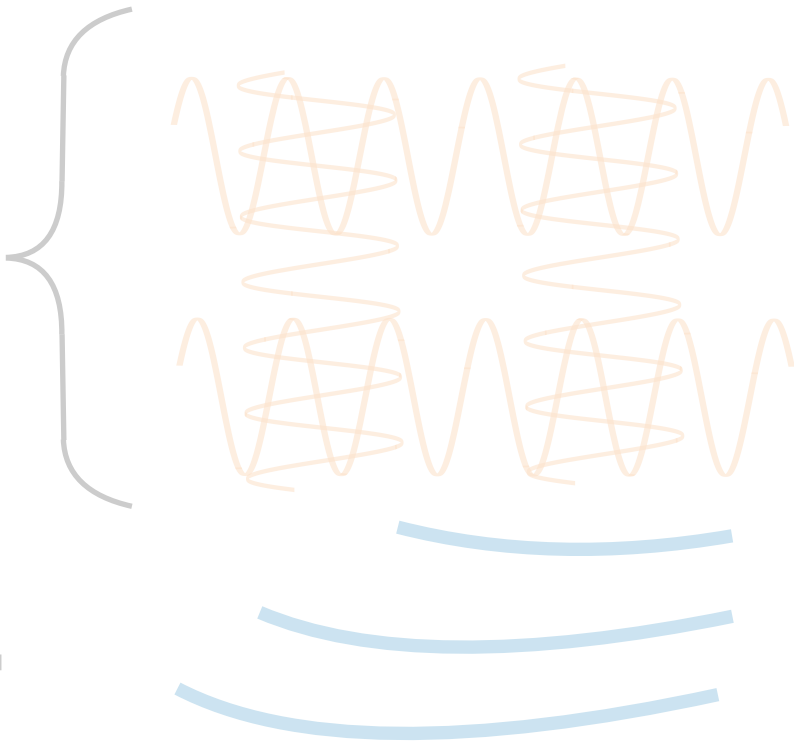


Poltergeist GWs



Evaporation ⇒ Sound waves

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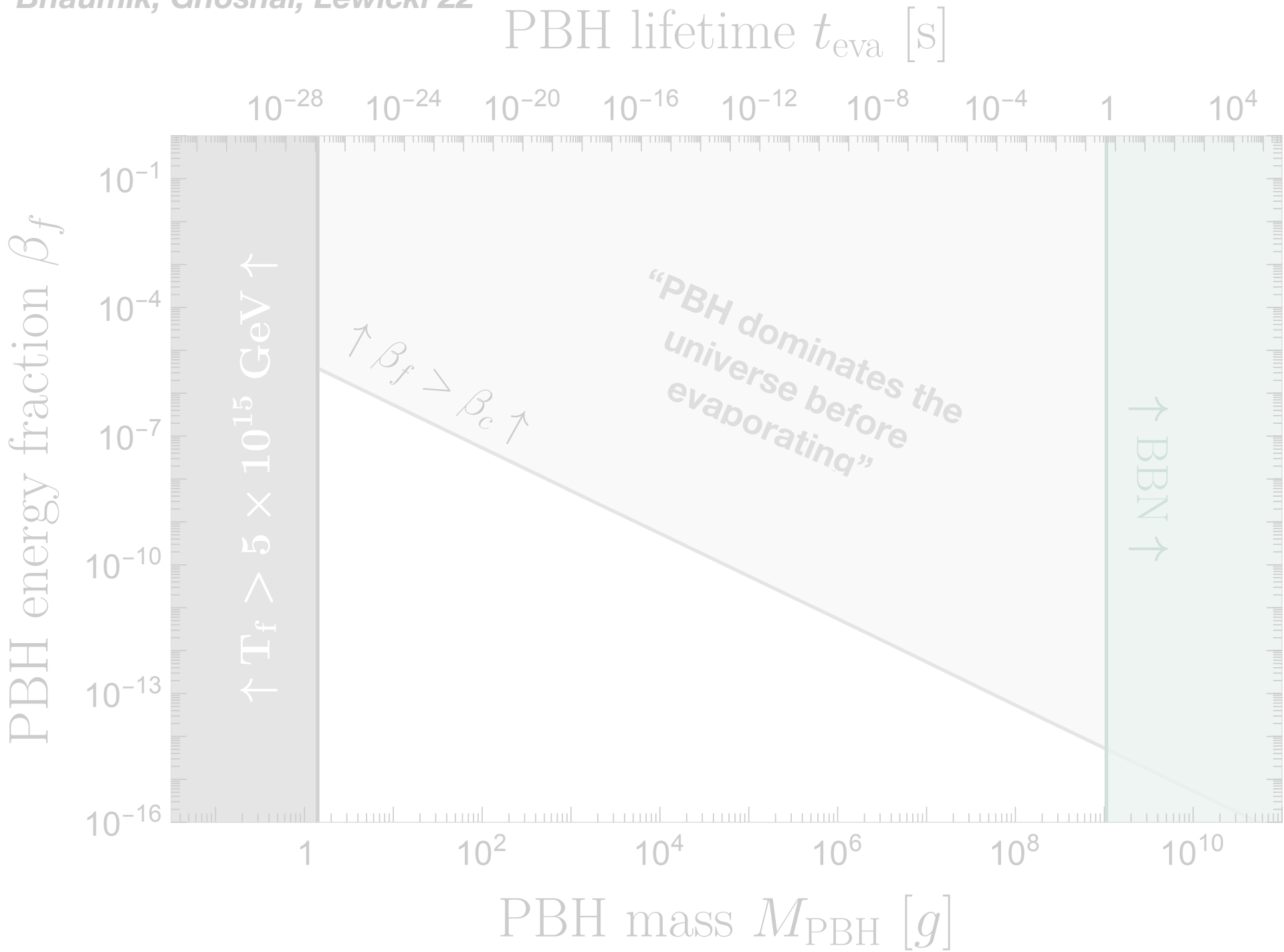
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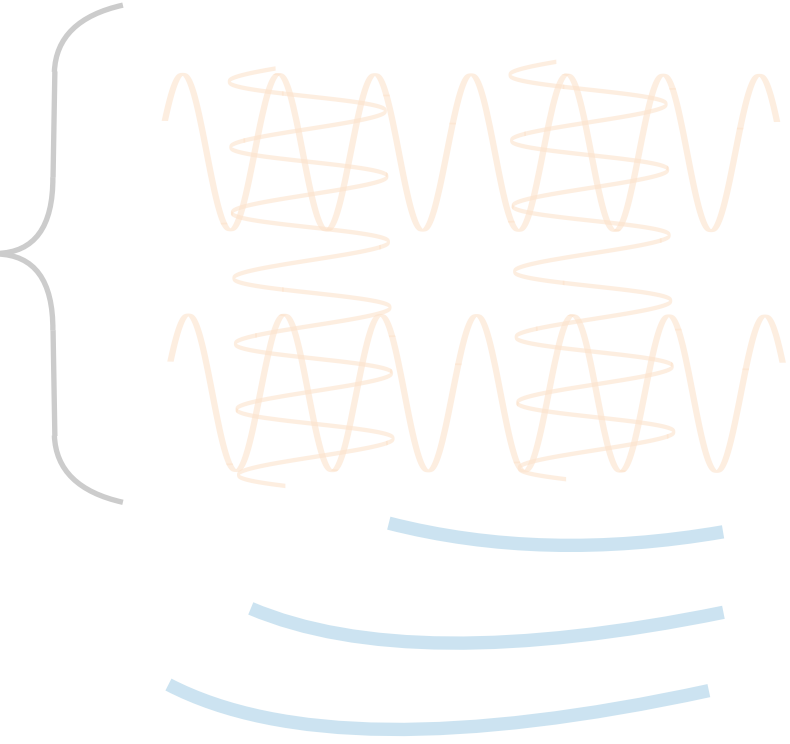
Poltergeist GWs

$$G_{\mu\nu} = \frac{8\pi G}{3} T_{\mu\nu}$$



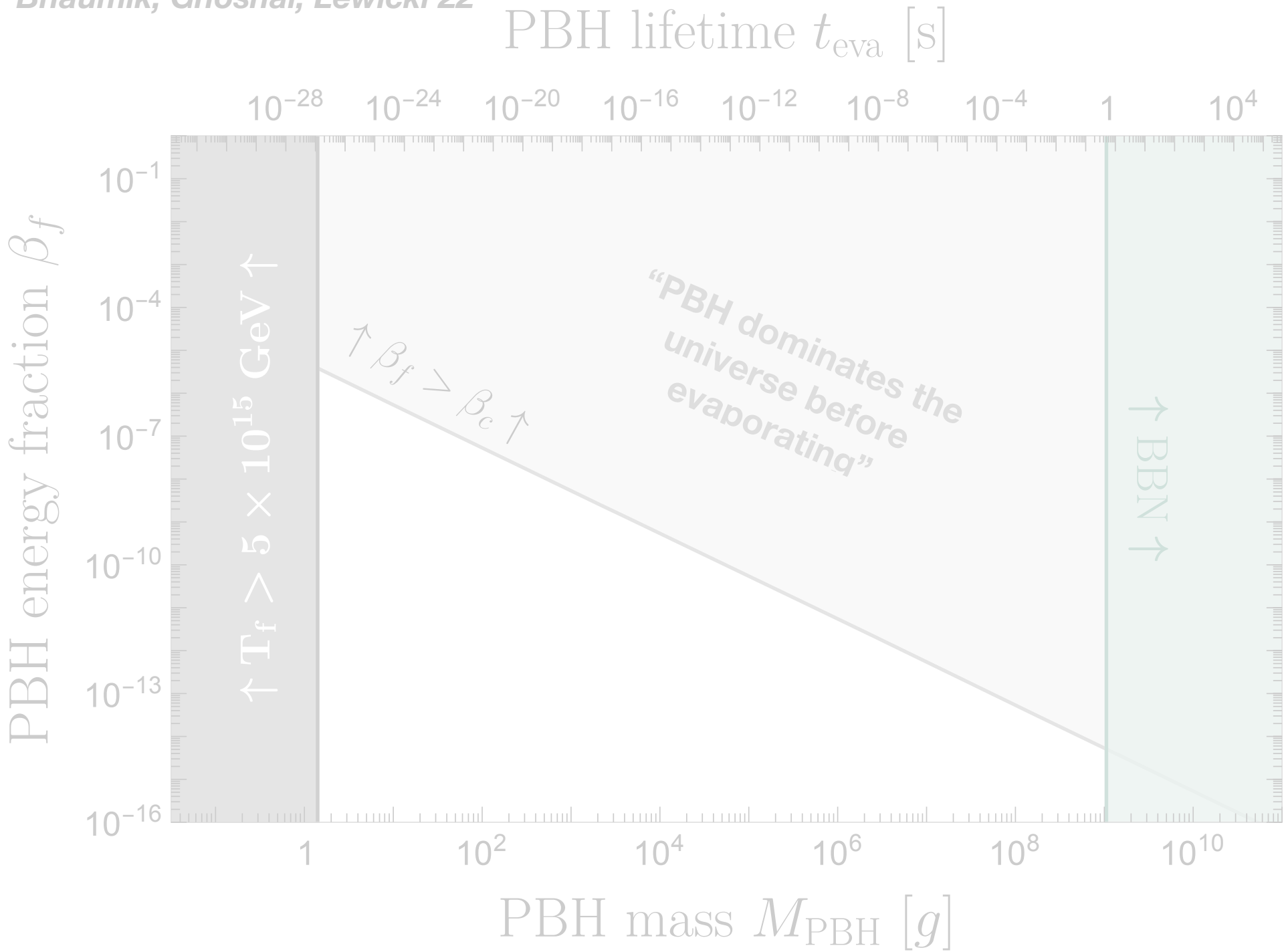
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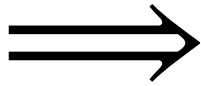


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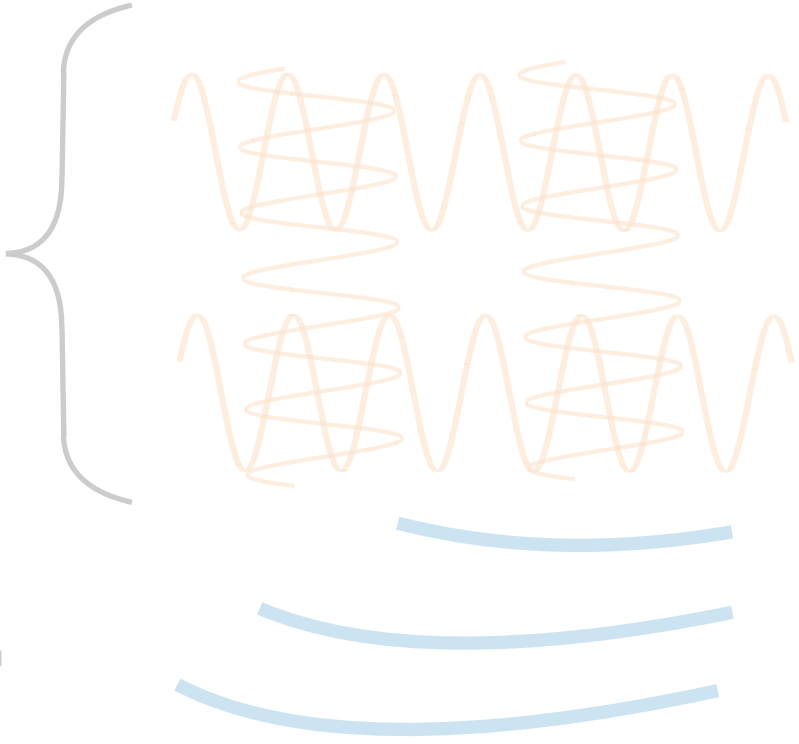
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$$\begin{cases} \nabla^2 \Phi - 3\mathcal{H}(\Phi' + \mathcal{H}\Phi) = \frac{3}{2}\mathcal{H}^2 \delta, \\ (\Phi' + \mathcal{H}\Phi) = -\frac{3}{2}\mathcal{H}^2(1 + \omega) v \\ \Phi'' + 3\mathcal{H}\Phi' - 3\omega\mathcal{H}^2\Phi = \frac{3}{2}\mathcal{H}^2 \frac{\delta p}{\bar{\rho}} \end{cases}$$

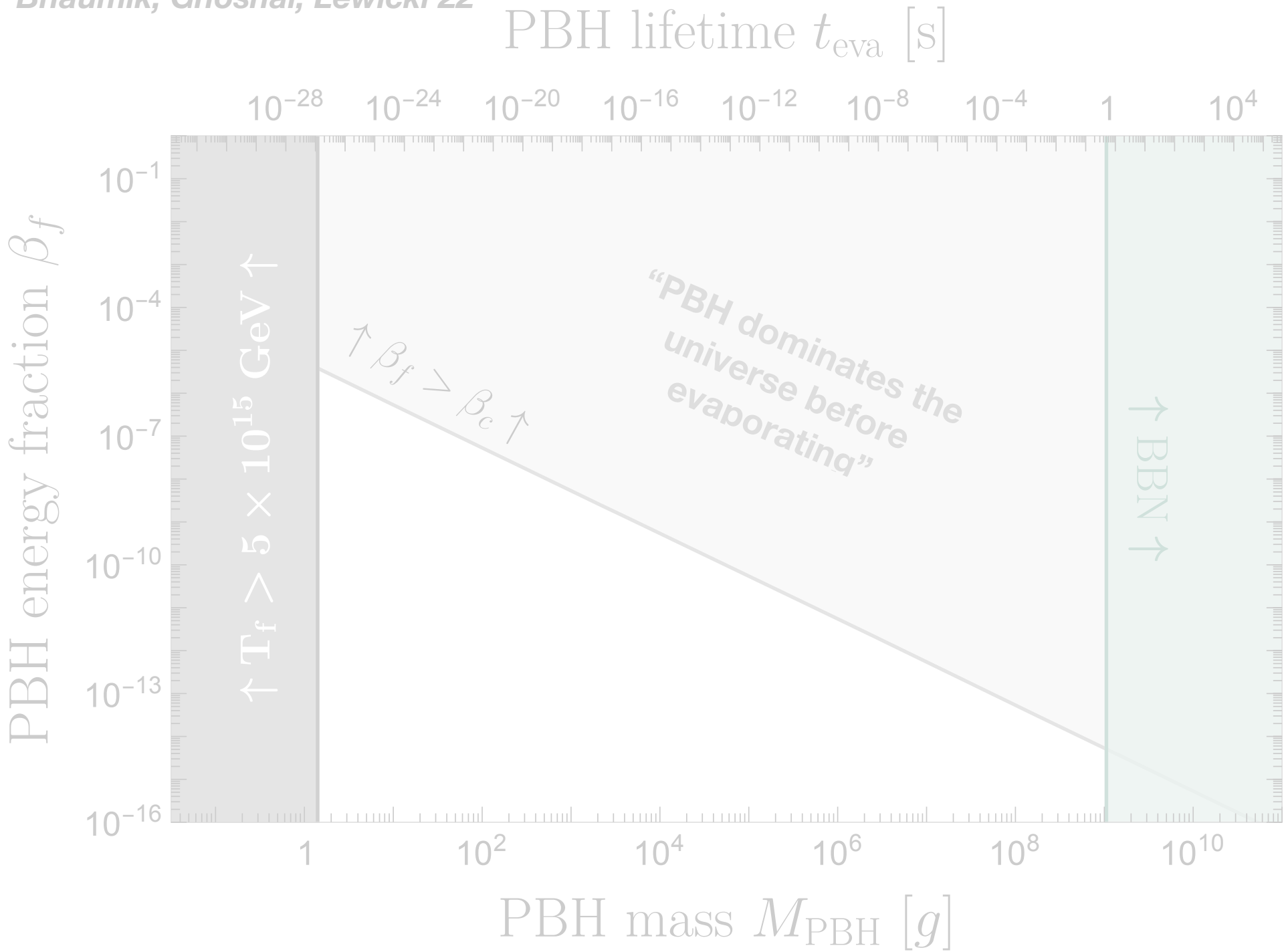
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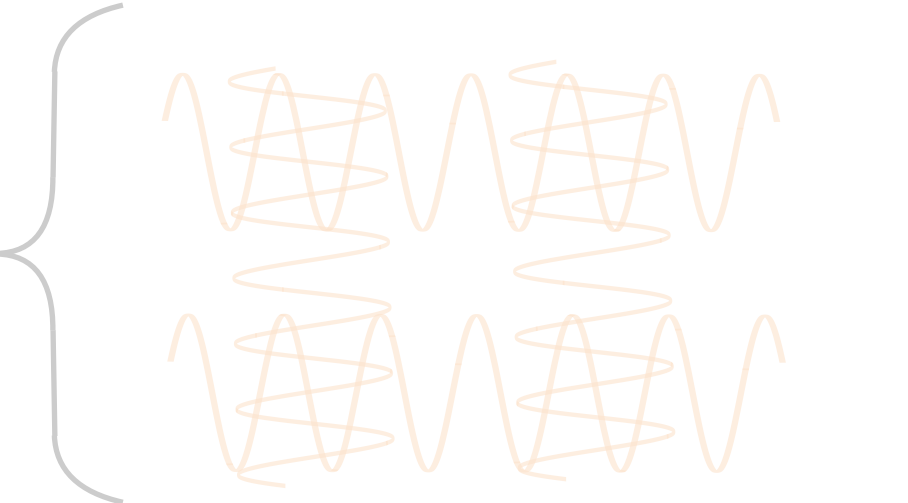


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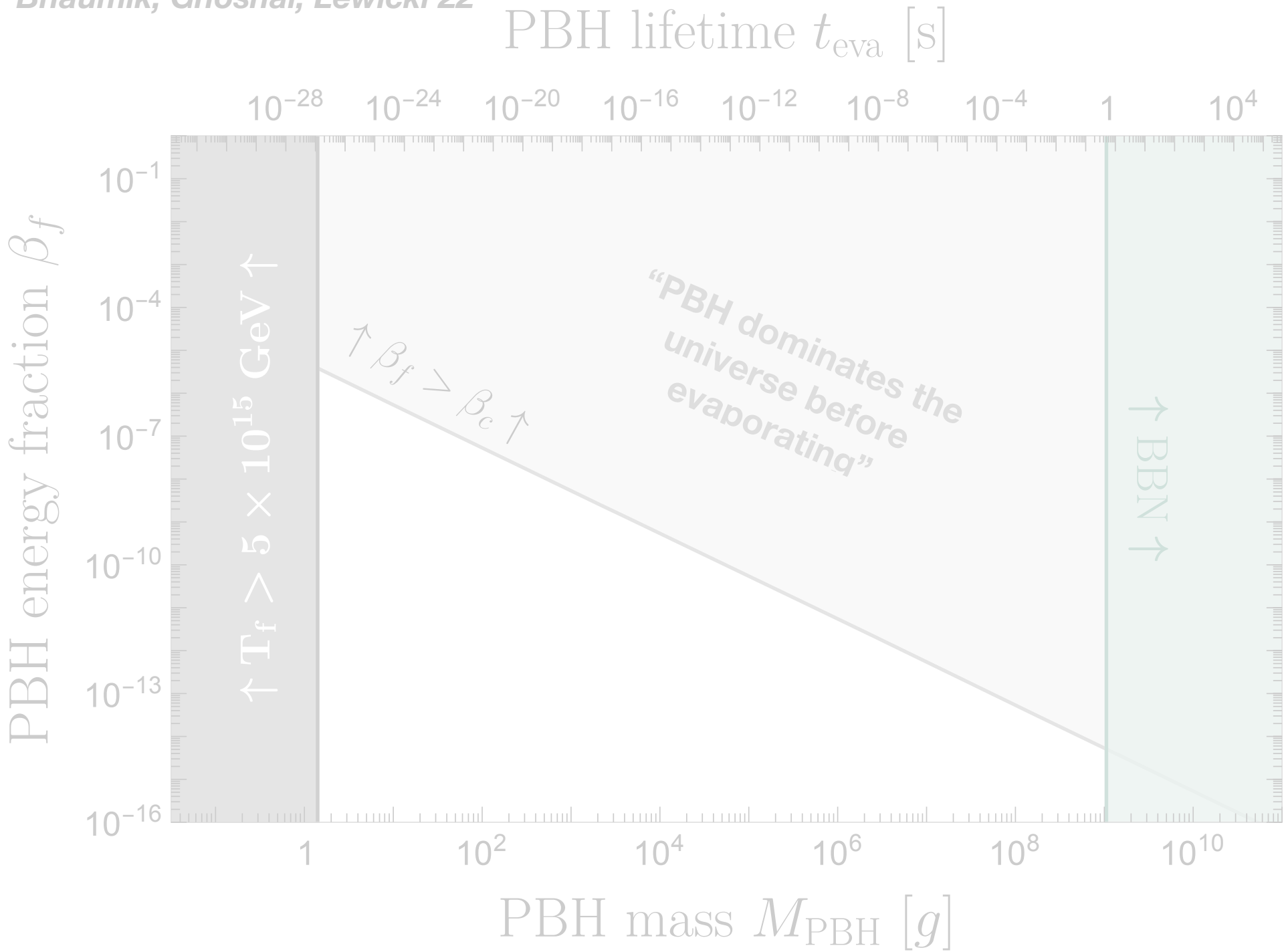
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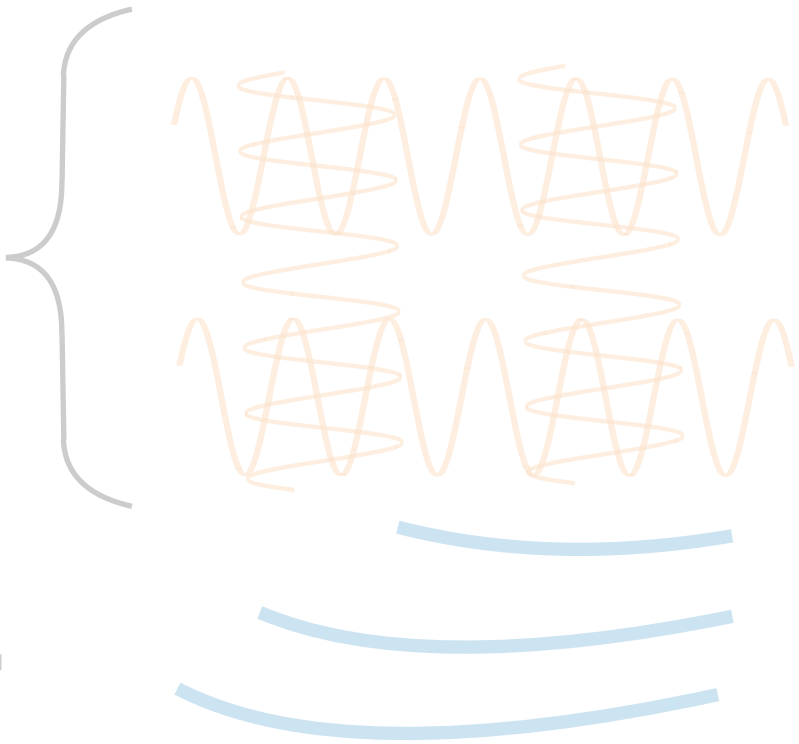
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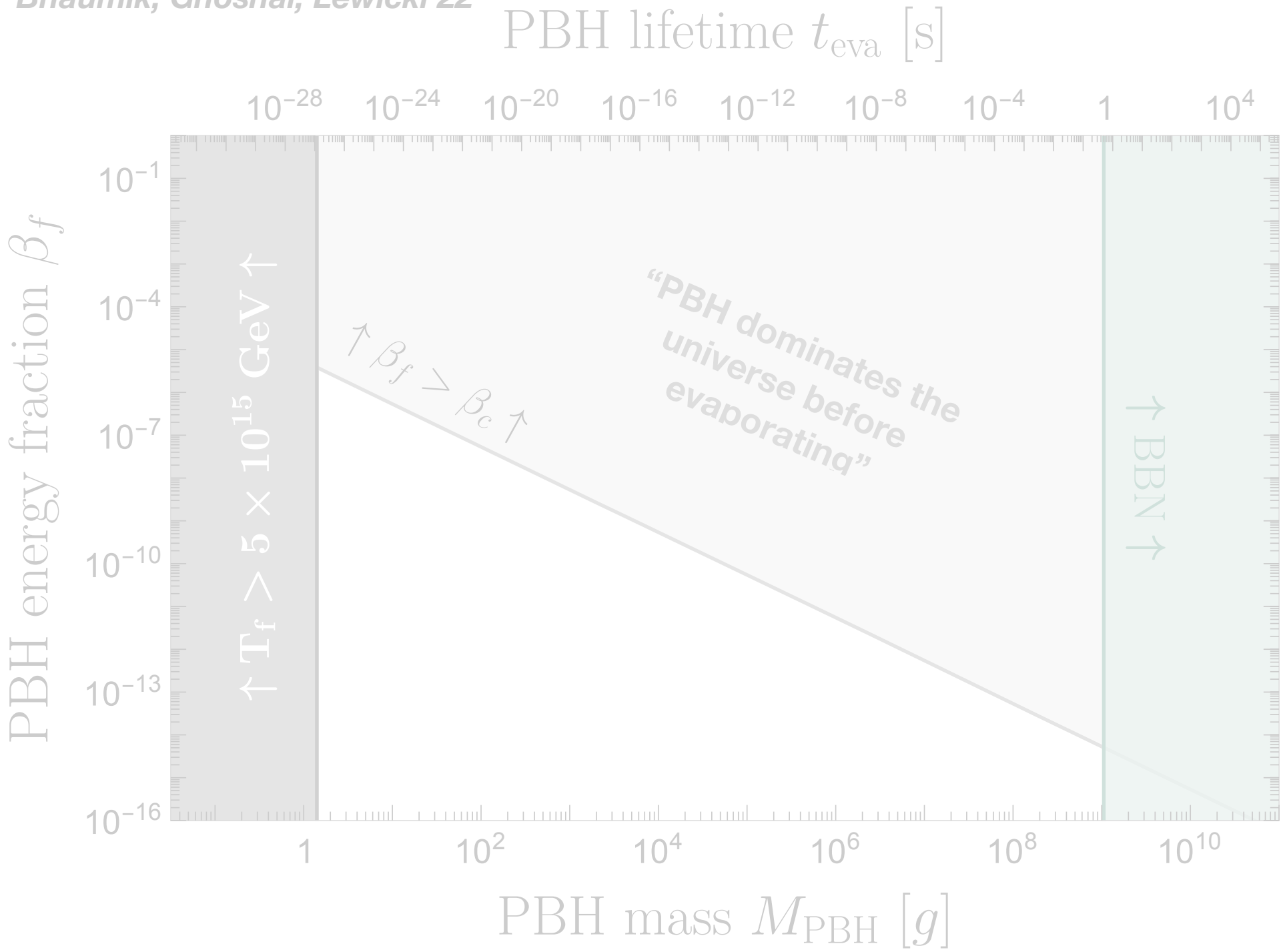
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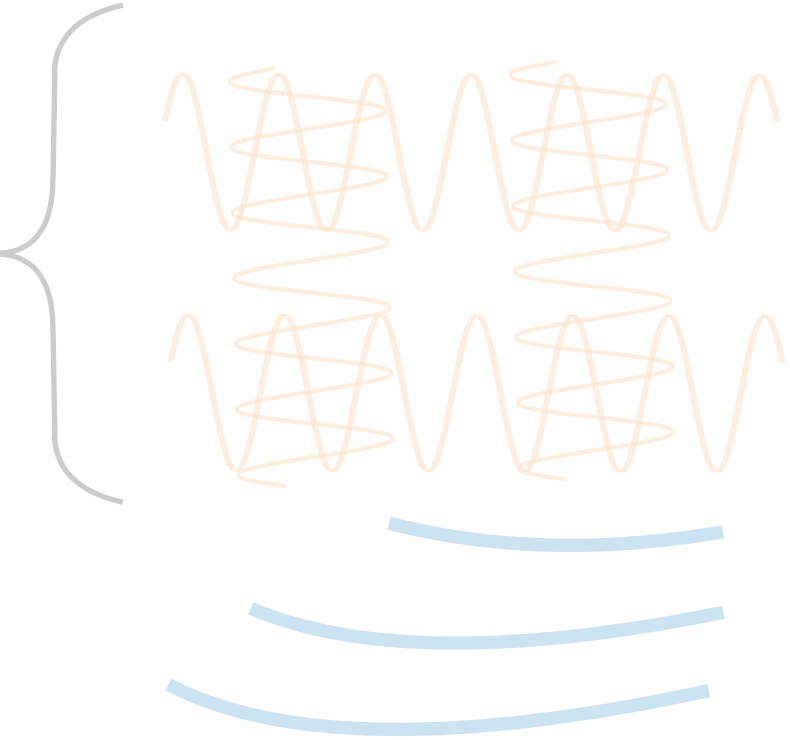


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$$S_{ab} \equiv \frac{\delta_a}{(1 + \omega_a)} - \frac{\delta_b}{(1 + \omega_b)}.$$

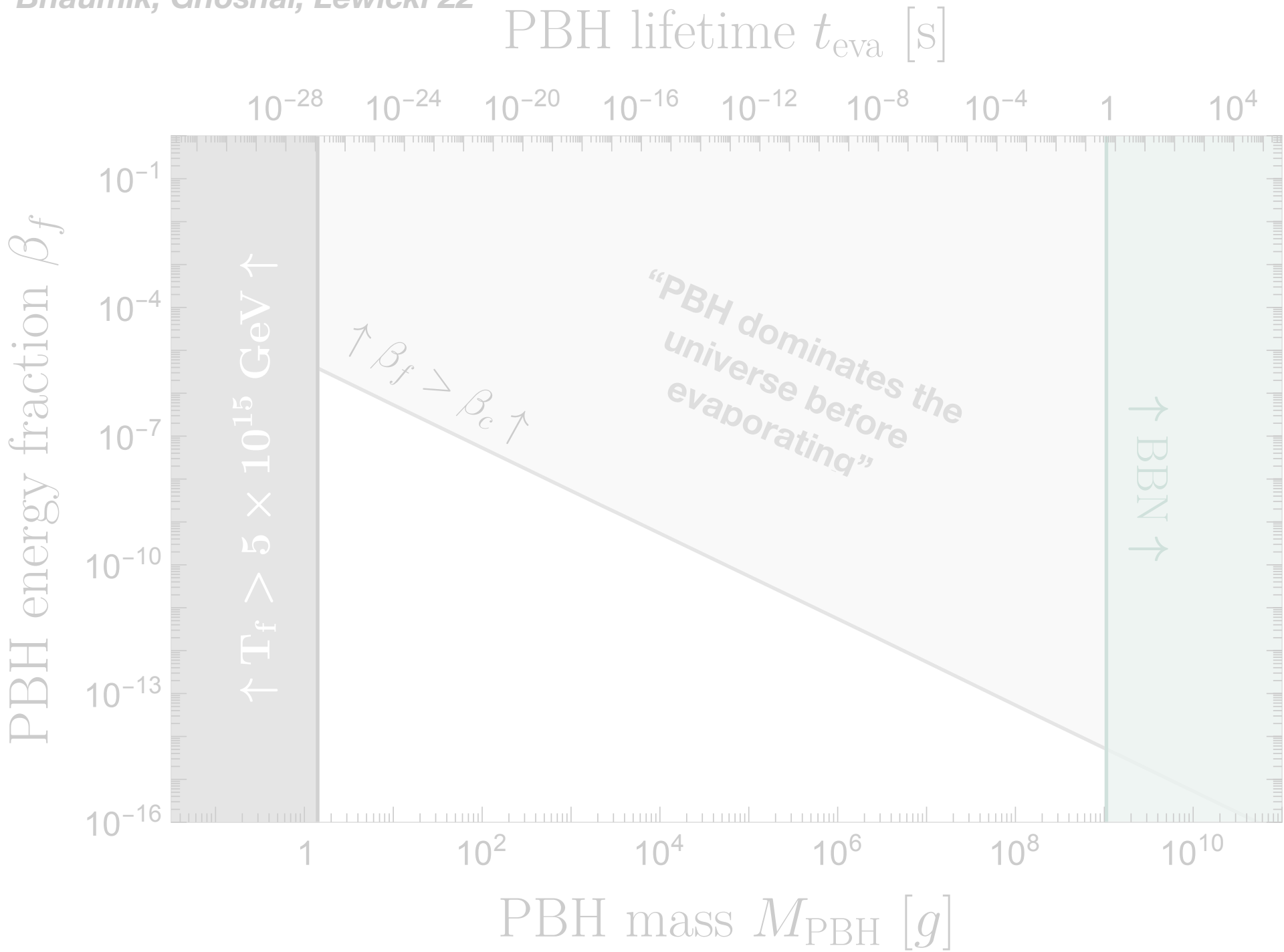
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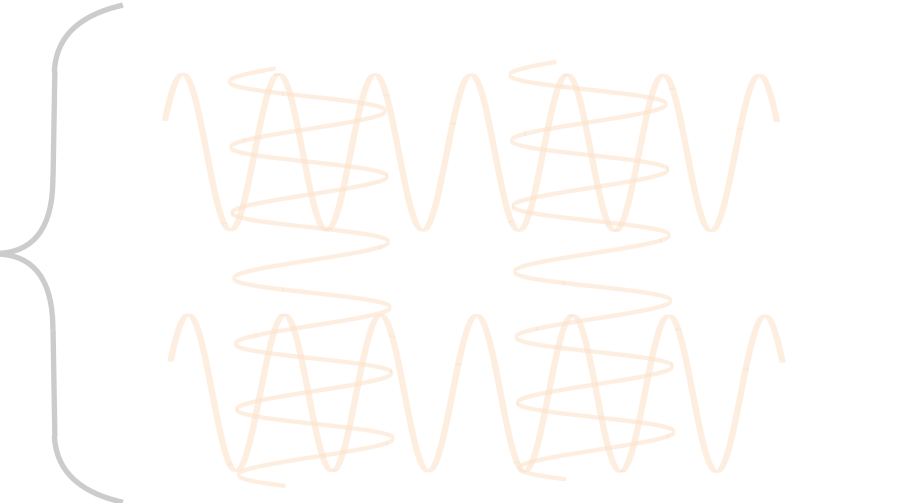


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$$S_{ab} \equiv \delta_{\text{PBH}} - \frac{3}{4}\delta_{\text{R}}$$

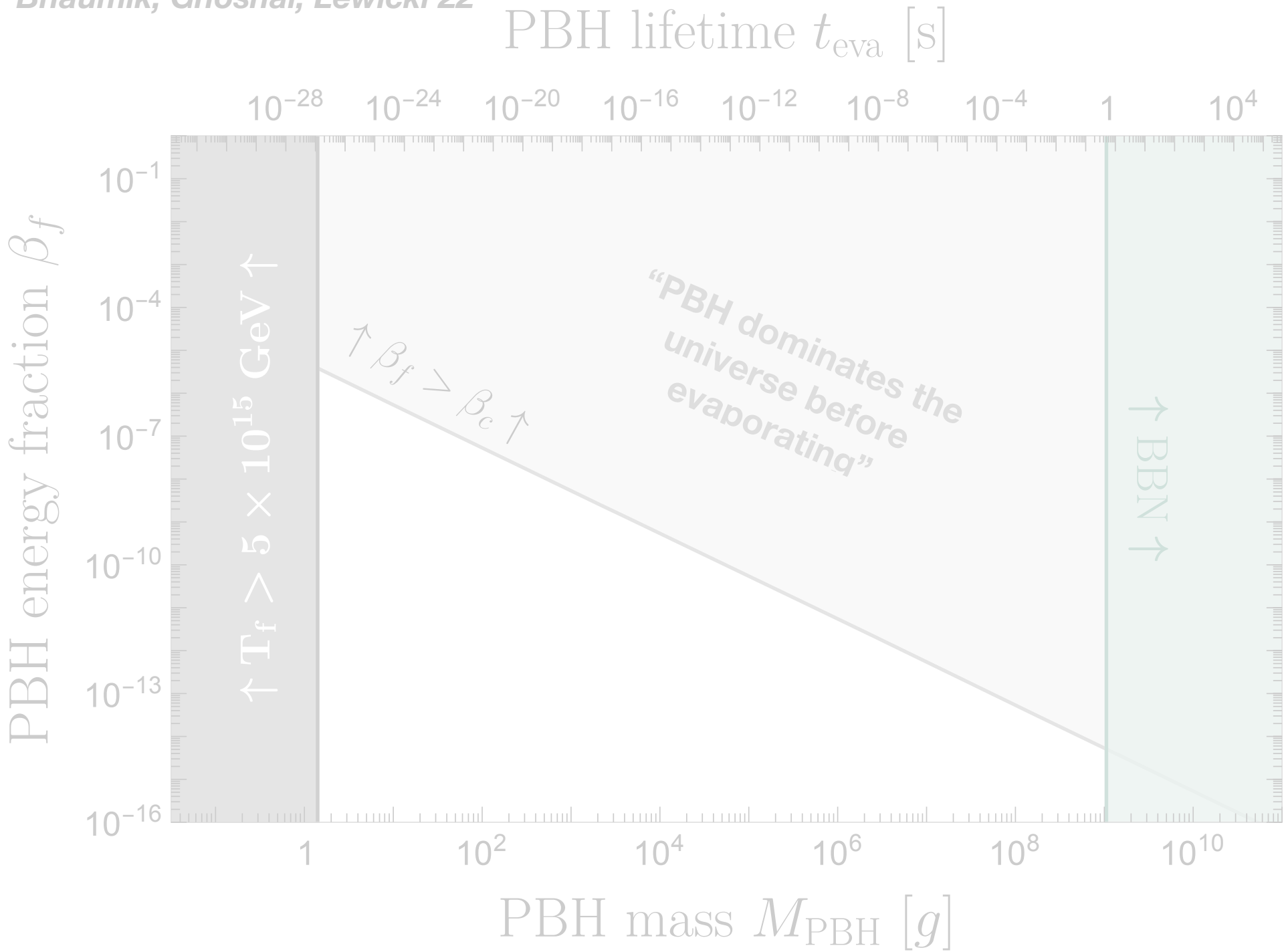
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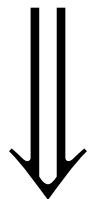
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$$G_{\mu\nu} = \frac{8\pi G}{3} T_{\mu\nu} \quad \Rightarrow \quad \begin{cases} \nabla^2 \Phi - 3\mathcal{H}(\Phi' + \mathcal{H}\Phi) = \frac{3}{2}\mathcal{H}^2 \delta, \\ (\Phi' + \mathcal{H}\Phi) = -\frac{3}{2}\mathcal{H}^2(1 + \omega) v \\ \Phi'' + 3\mathcal{H}\Phi' - 3\omega\mathcal{H}^2\Phi = \frac{3}{2}\mathcal{H}^2 \frac{\delta p}{\bar{\rho}} \end{cases}$$

$$\partial_\mu T^\mu_\nu = 0 \quad \Rightarrow \quad \begin{cases} \delta'_a - (1 + w_a)(-\Delta v_a + 3\Phi') + 3\mathcal{H}(c_a^2 - \omega_a)\delta_a = -3\mathcal{H}\delta_{\text{p,nad,a}} \\ v'_a + \mathcal{H}v_a + \frac{c_a^2}{1 + \omega_a}\delta_a^C + \Phi = -\frac{\delta_{\text{p,nad,a}}}{1 + \omega} \end{cases}$$

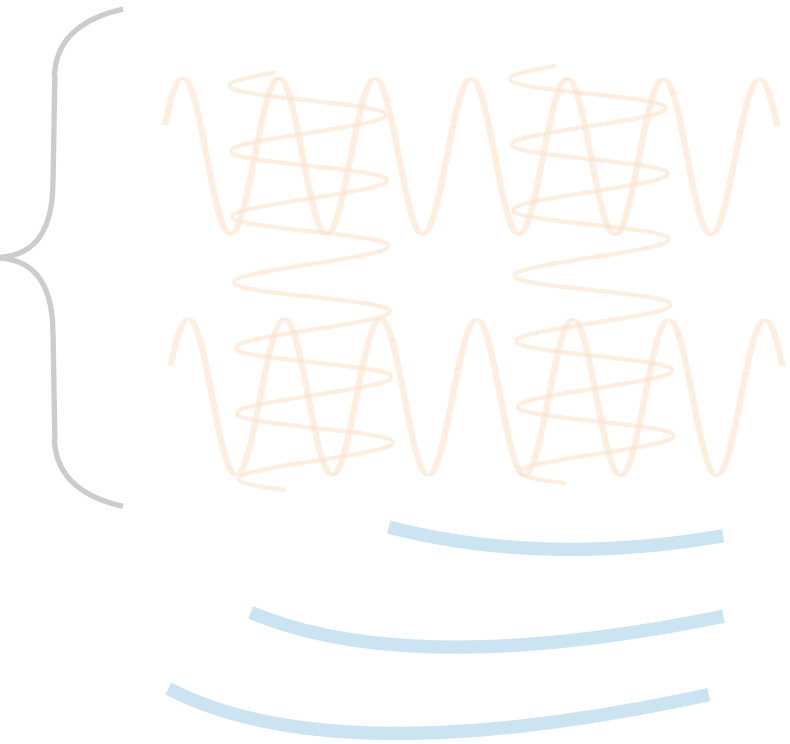
$$S_{ab} \equiv \delta_{\text{PBH}} - \frac{3}{4}\delta_{\text{R}}$$



$$\begin{cases} \Phi'' + 3\mathcal{H}(1 + c_s^2)\Phi' + [3(c_s^2 - \omega)\mathcal{H}^2 - c_s^2\Delta]\Phi = \frac{3}{2}\mathcal{H}^2 c_{ab} S_{ab} & \text{(Domenech, Trankle 24')} \\ S''_{ab} + \mathcal{H}S'_{ab} - \frac{\Omega_a(1 + \omega_a)c_b^2 + \Omega_b(1 + \omega_b)c_a^2}{1 + \omega}\Delta S_{ab} = 2(c_a^2 - c_b^2)\frac{\Delta^2\Phi}{3\mathcal{H}^2(1 + \omega)} \end{cases}$$

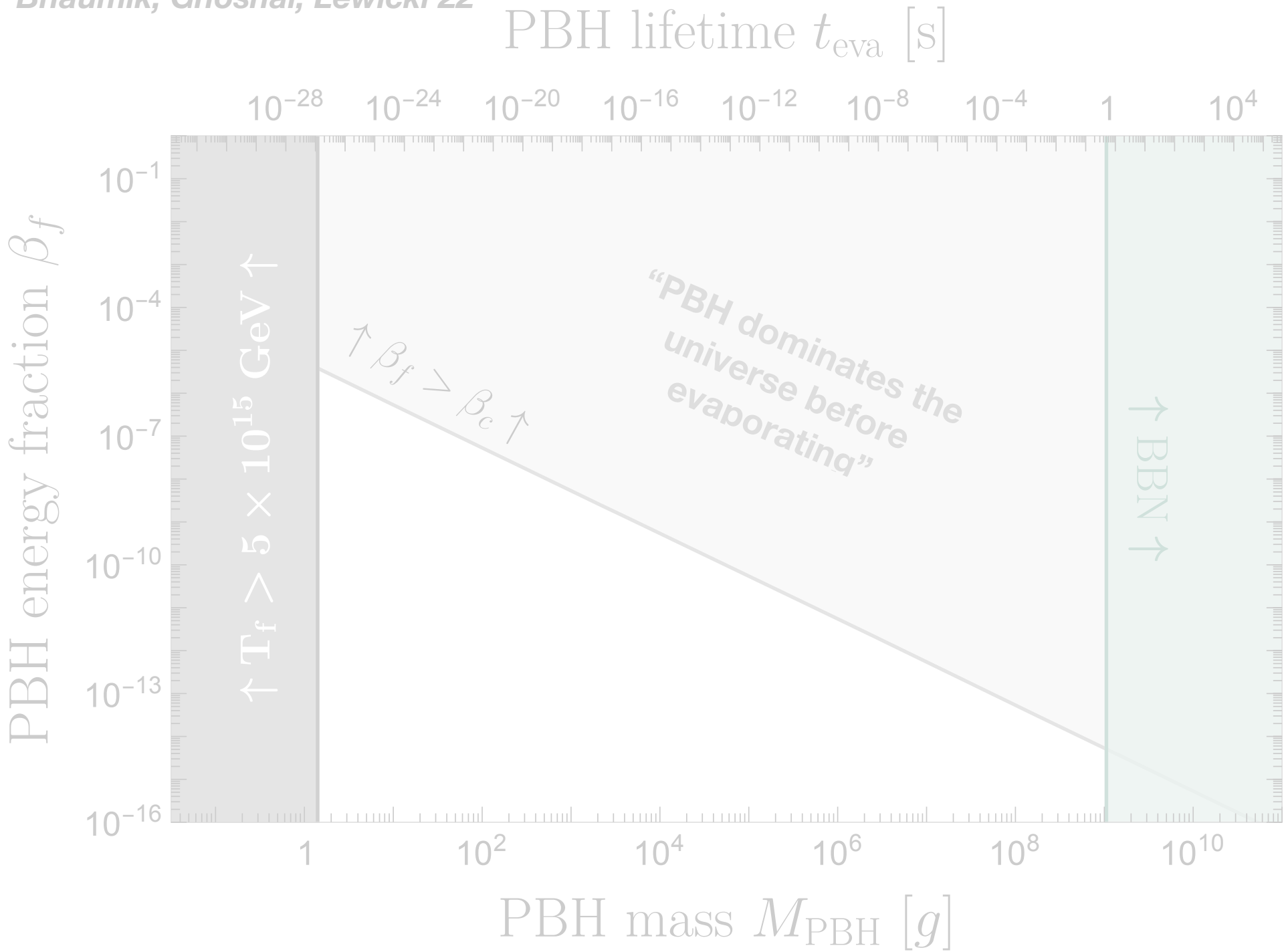
Evaporation $\Rightarrow$ Sound waves

Gas of
evaporating PBHs



Poltergeist GWs

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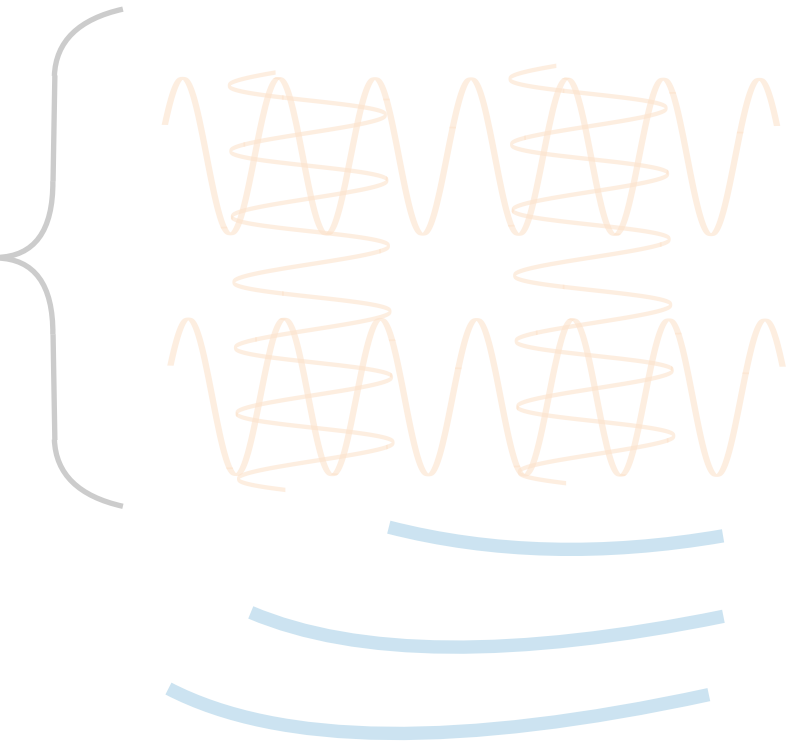
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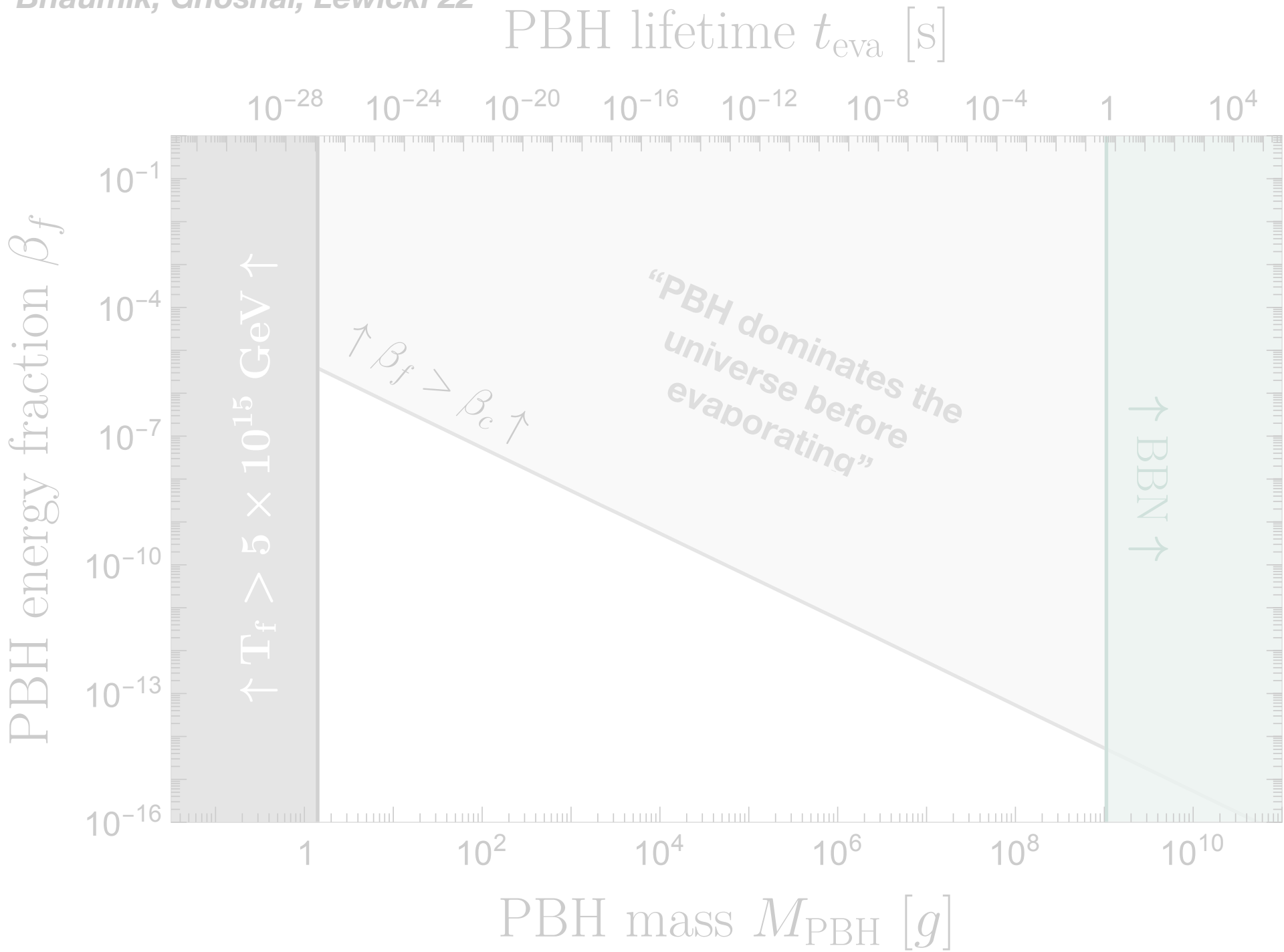
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Poltergeist GWs

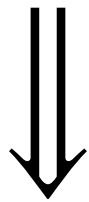
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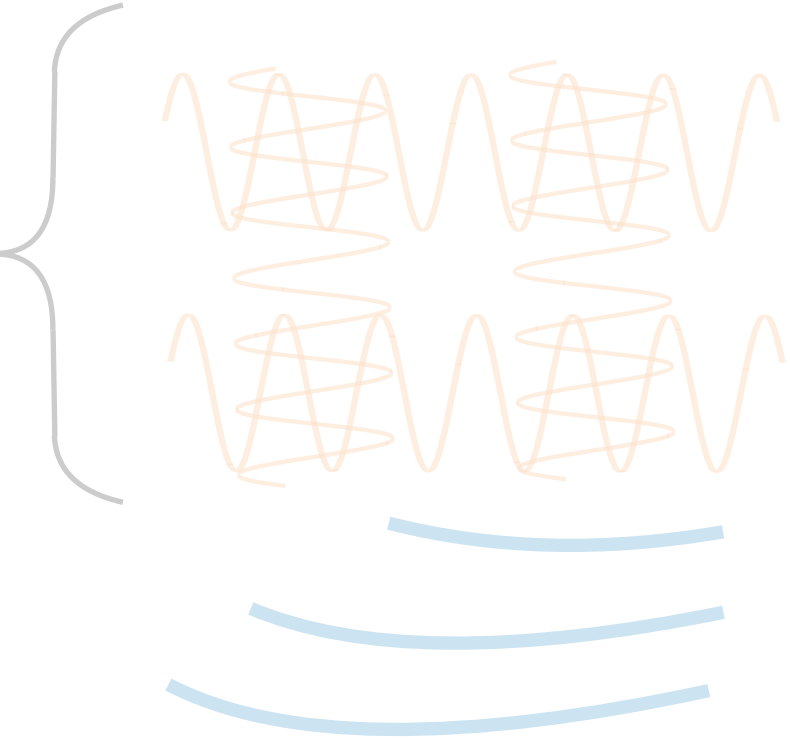
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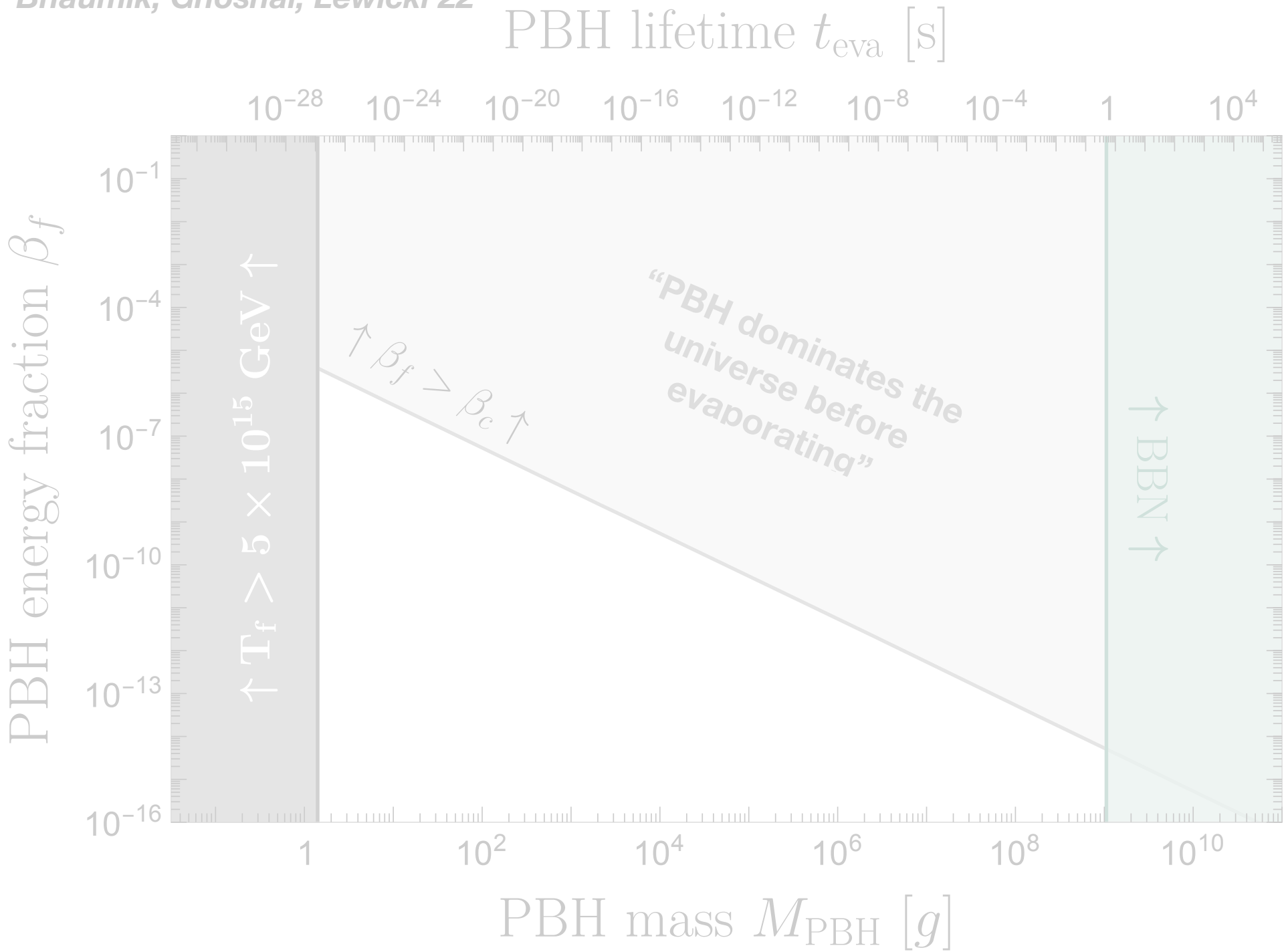
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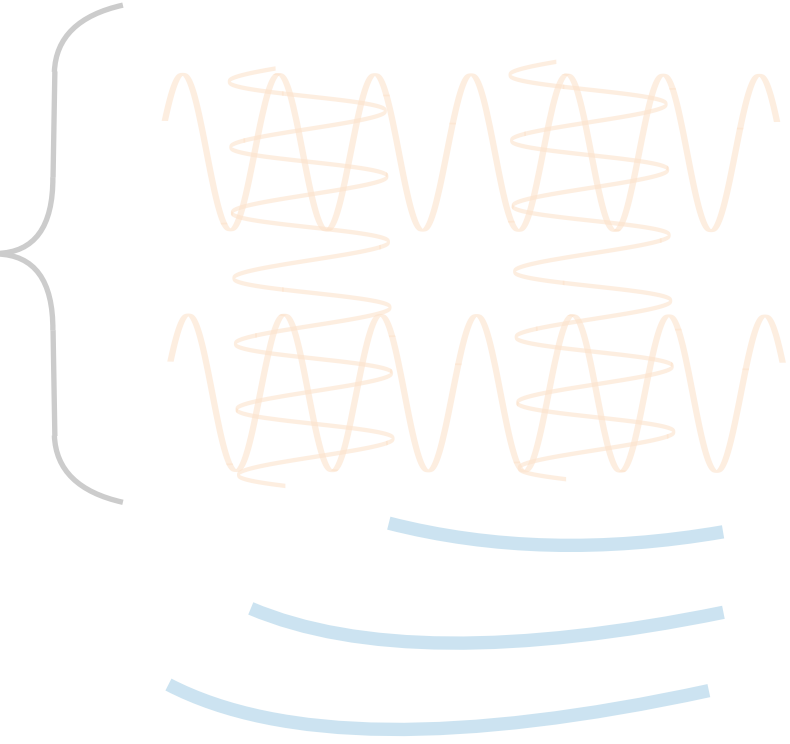


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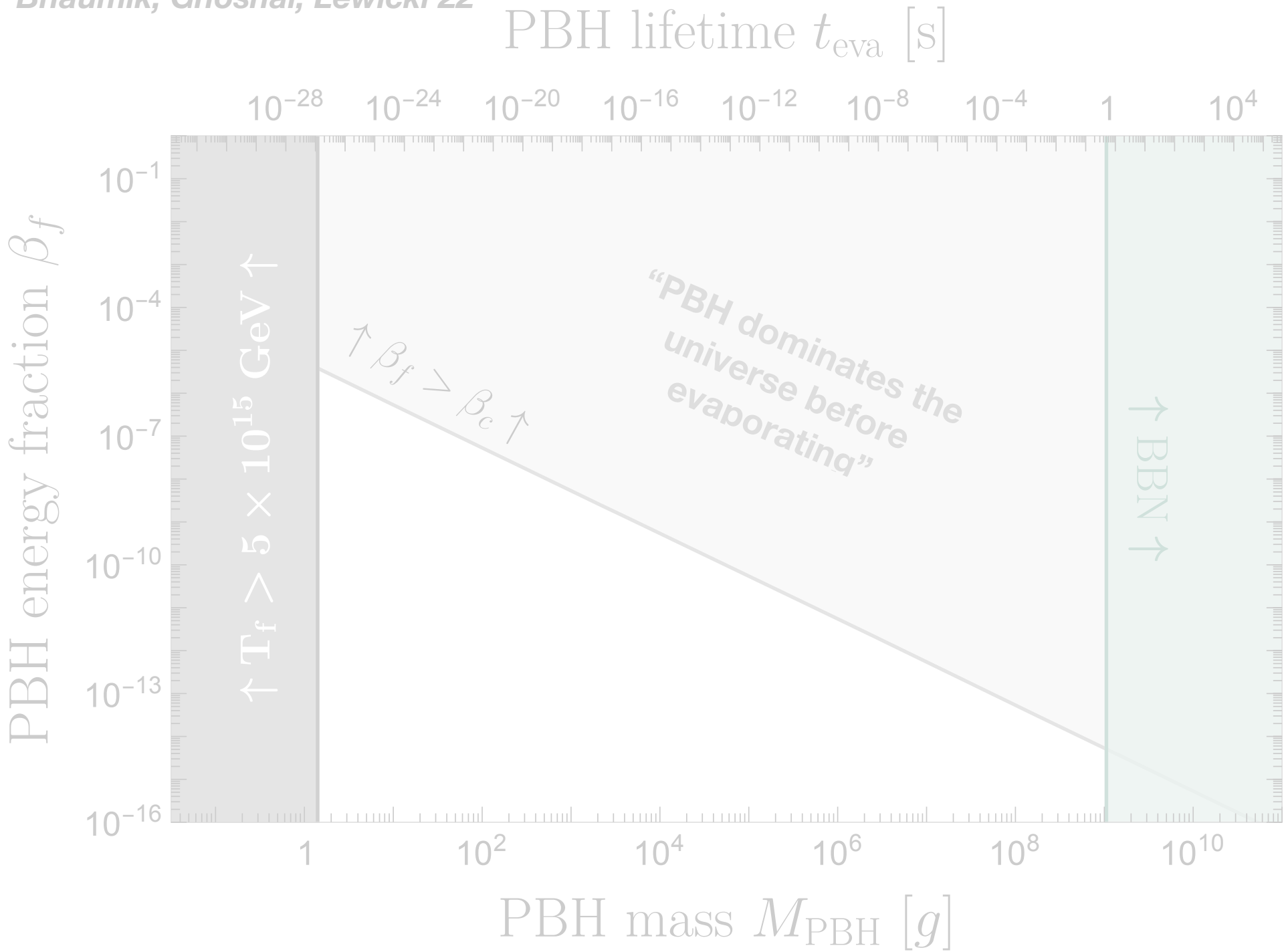
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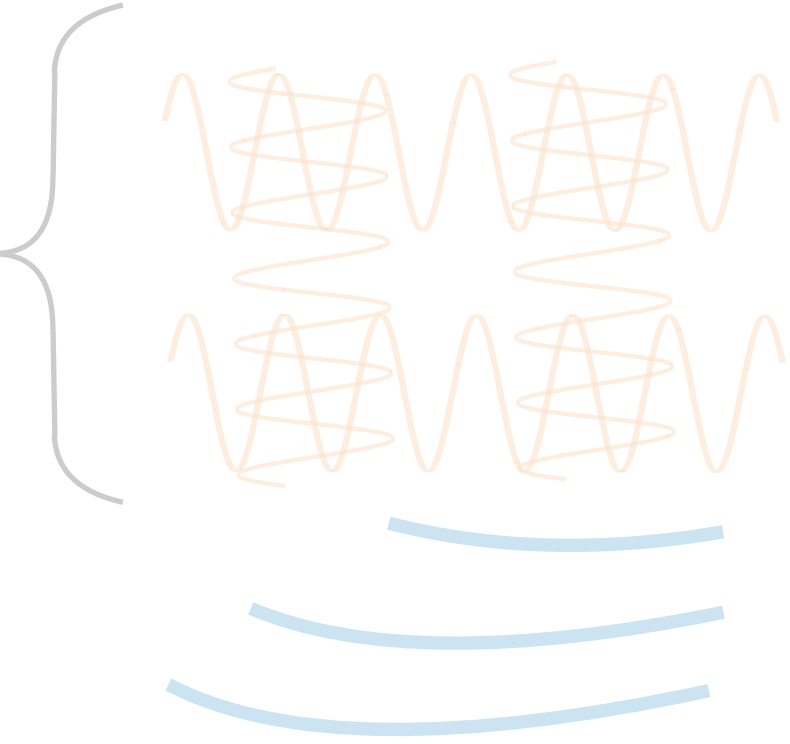
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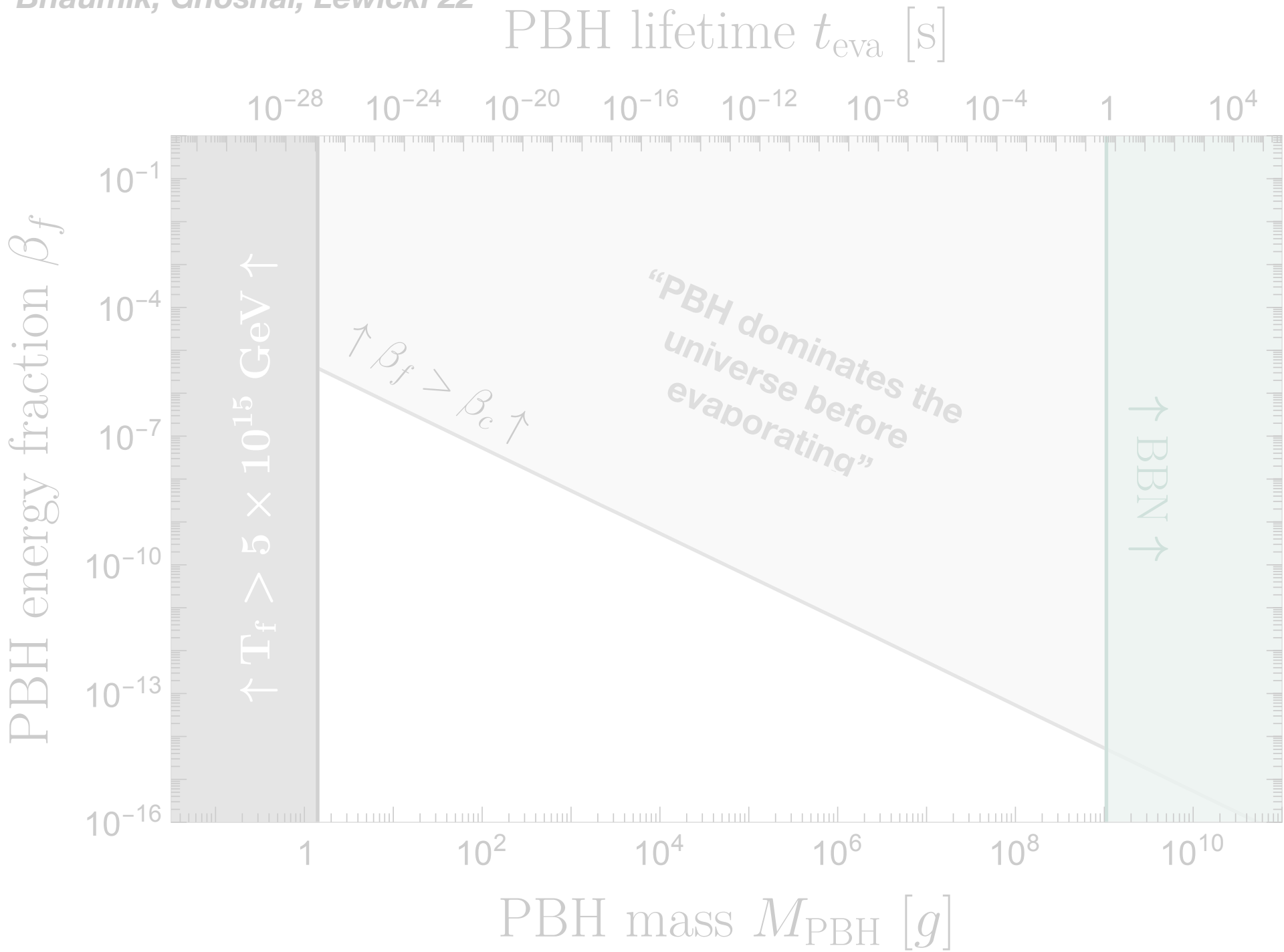
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Poltergeist GWs



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$$\Omega_{\text{GW}}(k, t) = \frac{k^2}{12\mathcal{H}^2} \overline{\mathcal{P}_h(k, t)} \propto \overline{\mathcal{P}_\Phi(k, t)}^2$$

Evaporation ⇒ Sound waves

Gas of evaporating PBHs

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PBH lifetime t_{eva} [s]

PBH mass M_{PBH} [g]

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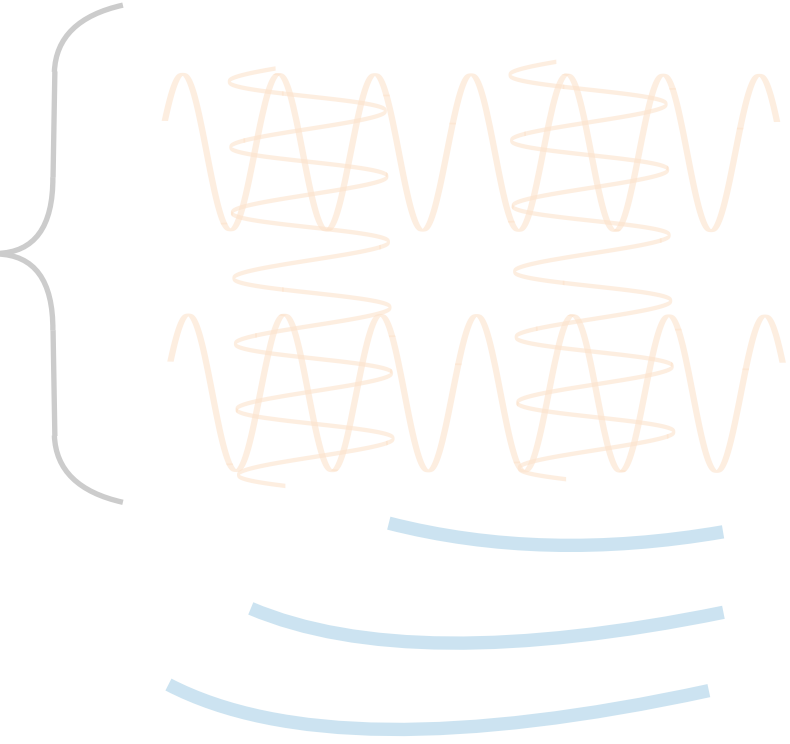
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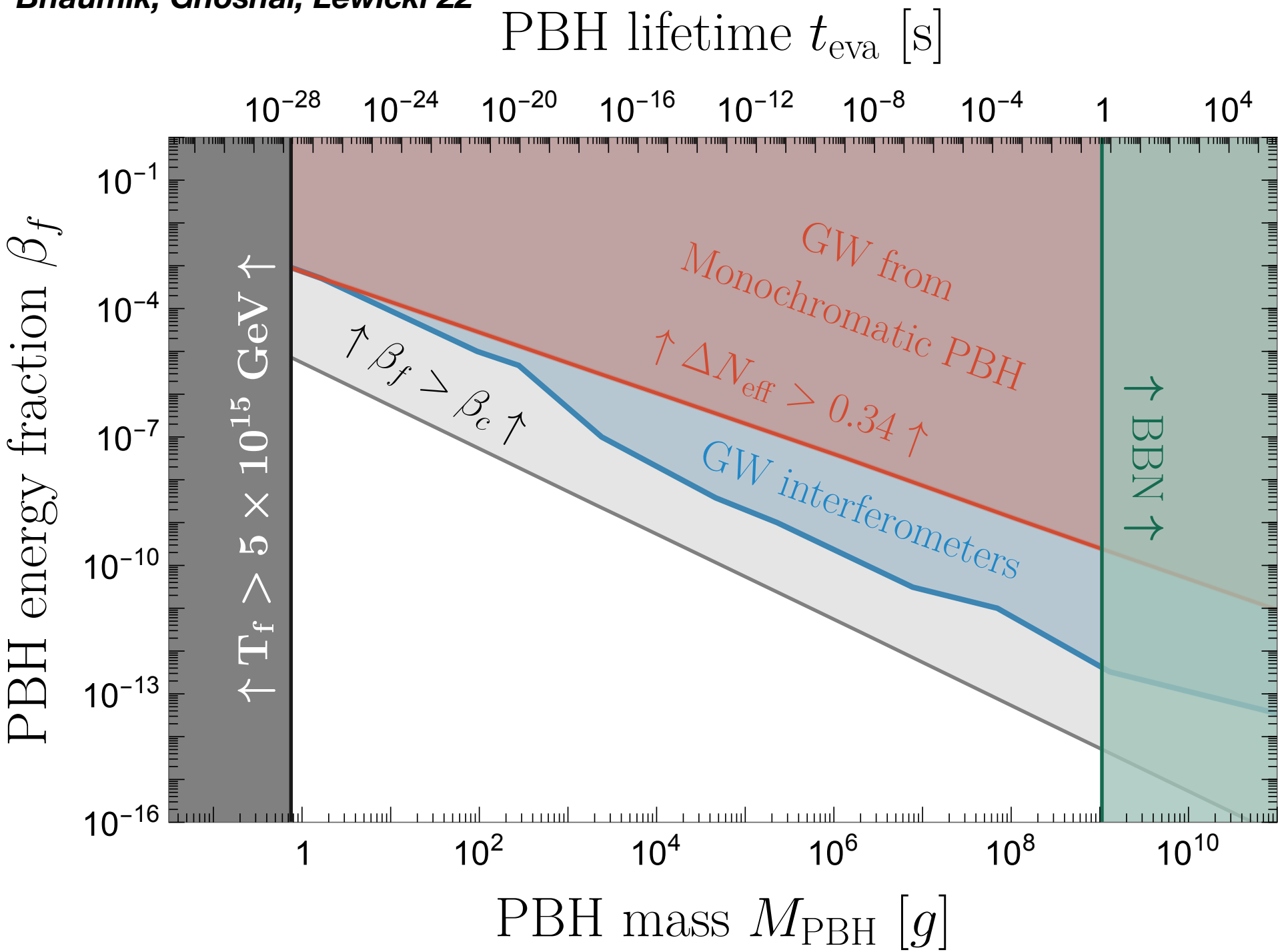
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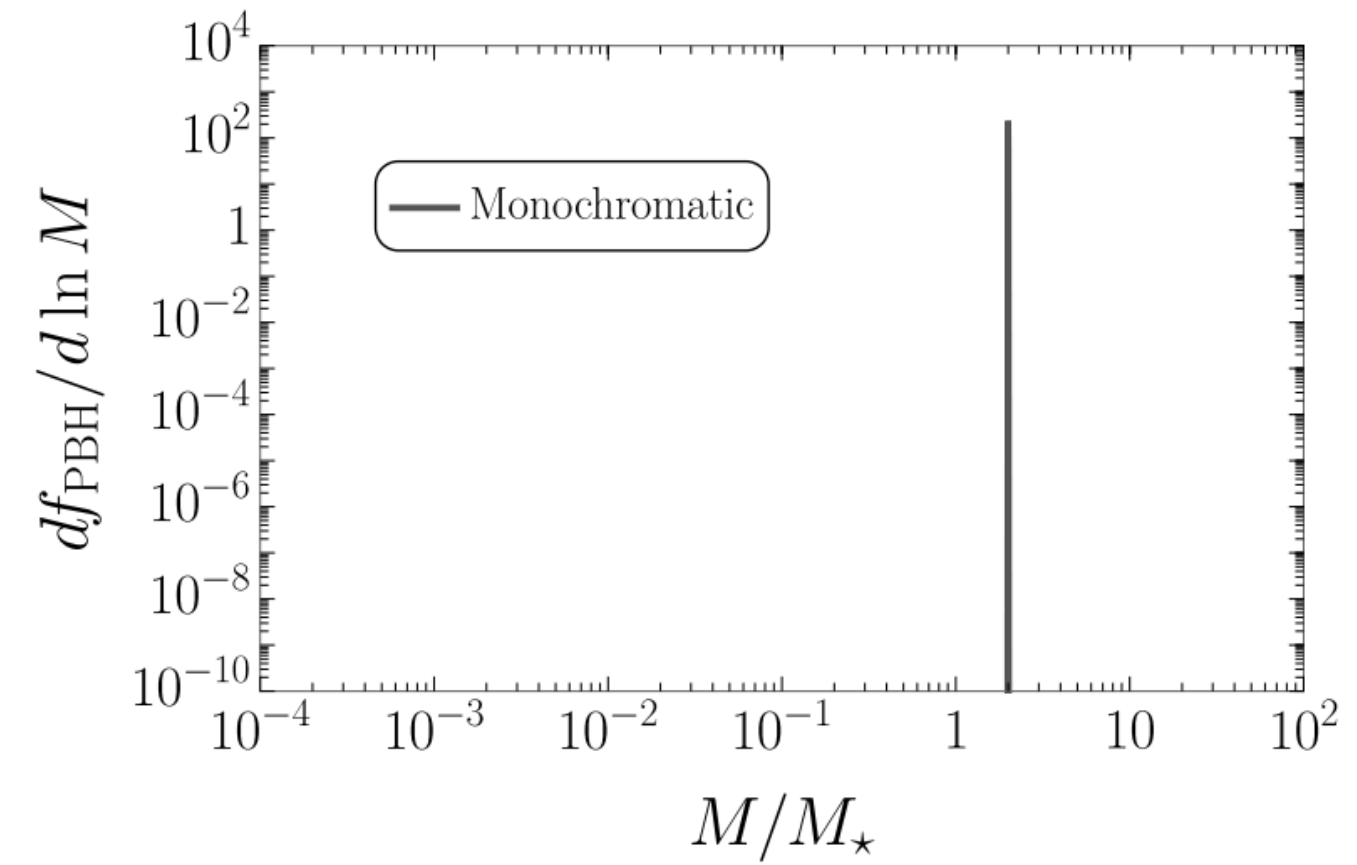


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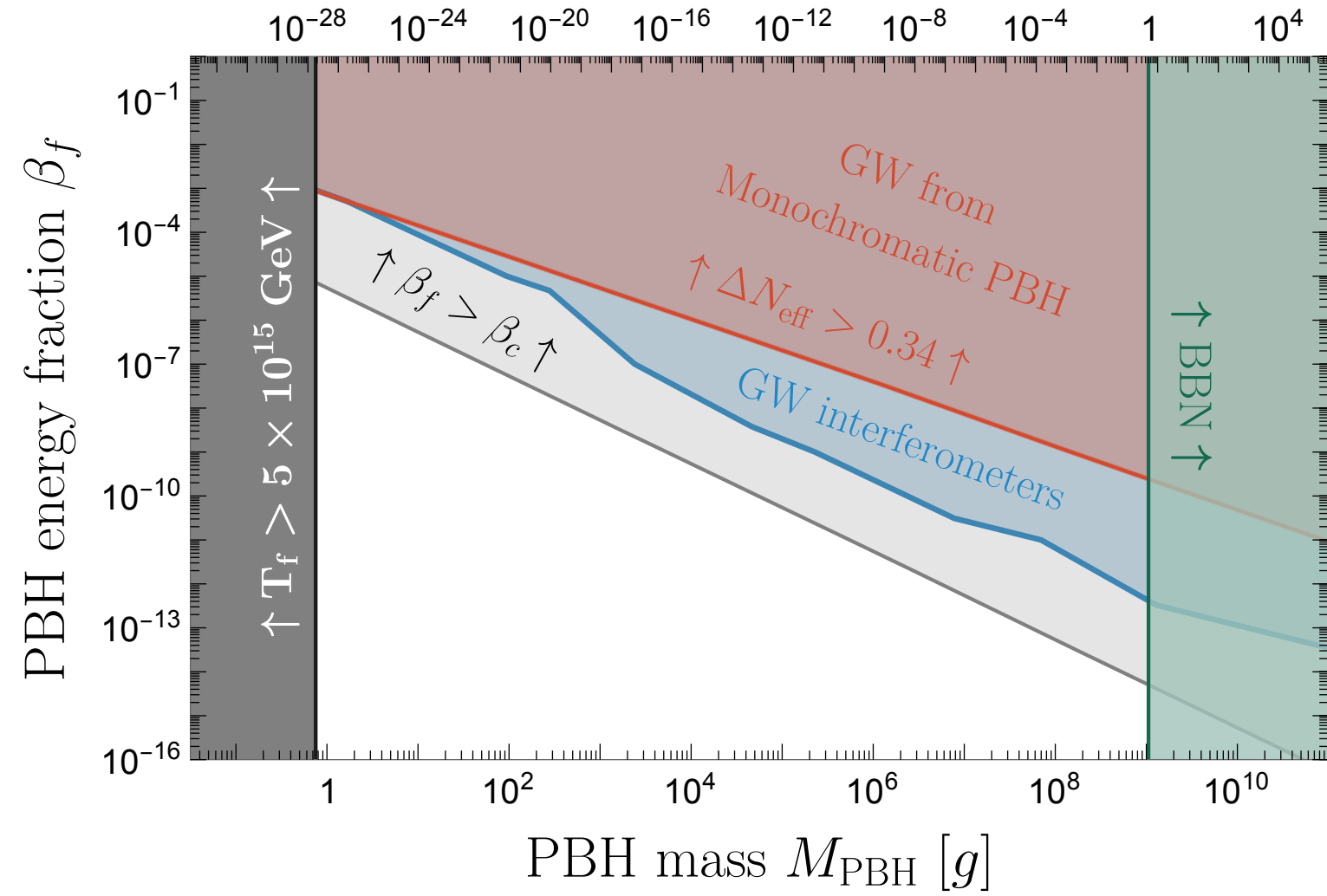
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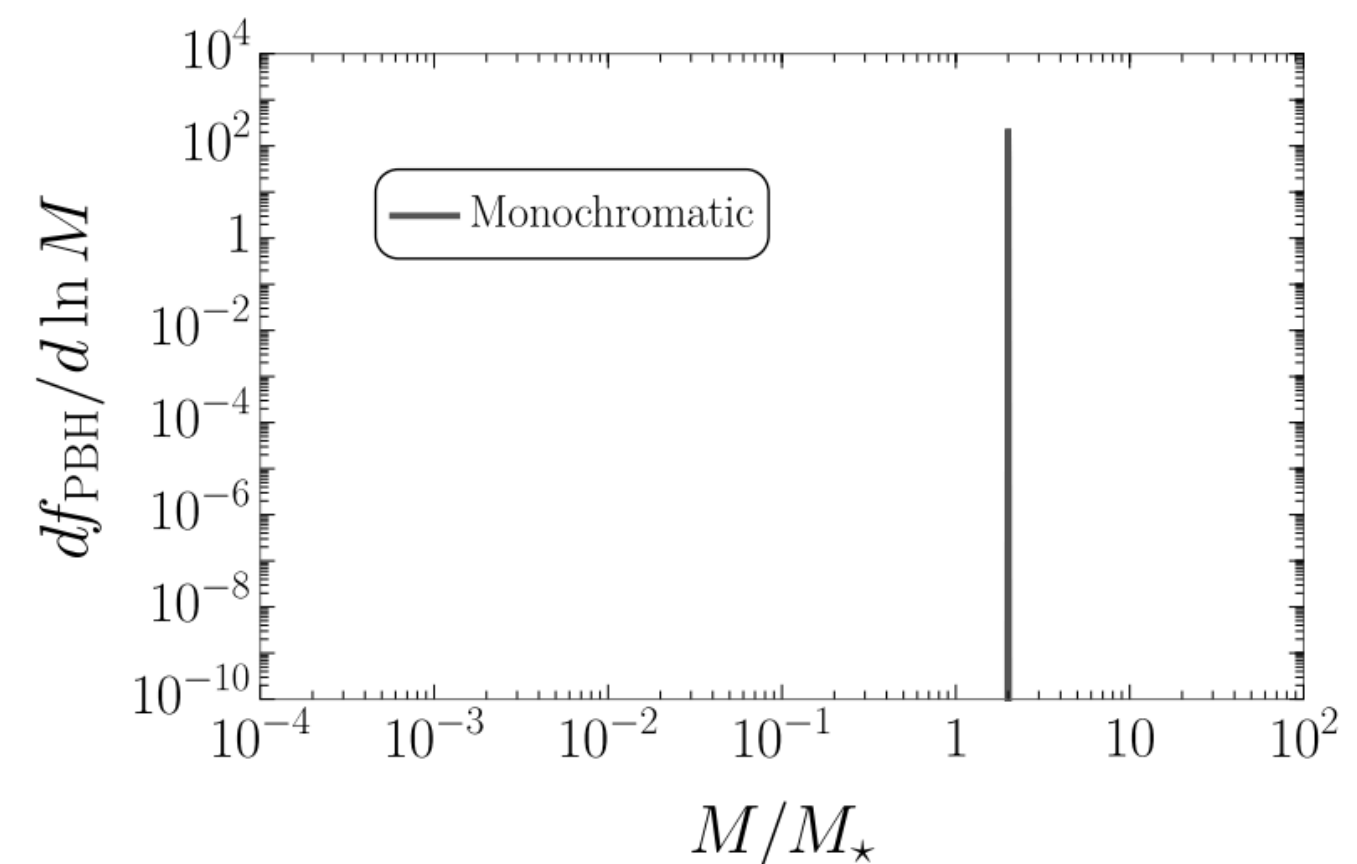
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$$k_{\text{cut}} = k_{\text{NL}} \quad (\text{conservative})$$

PBH lifetime t_{eva} [s]





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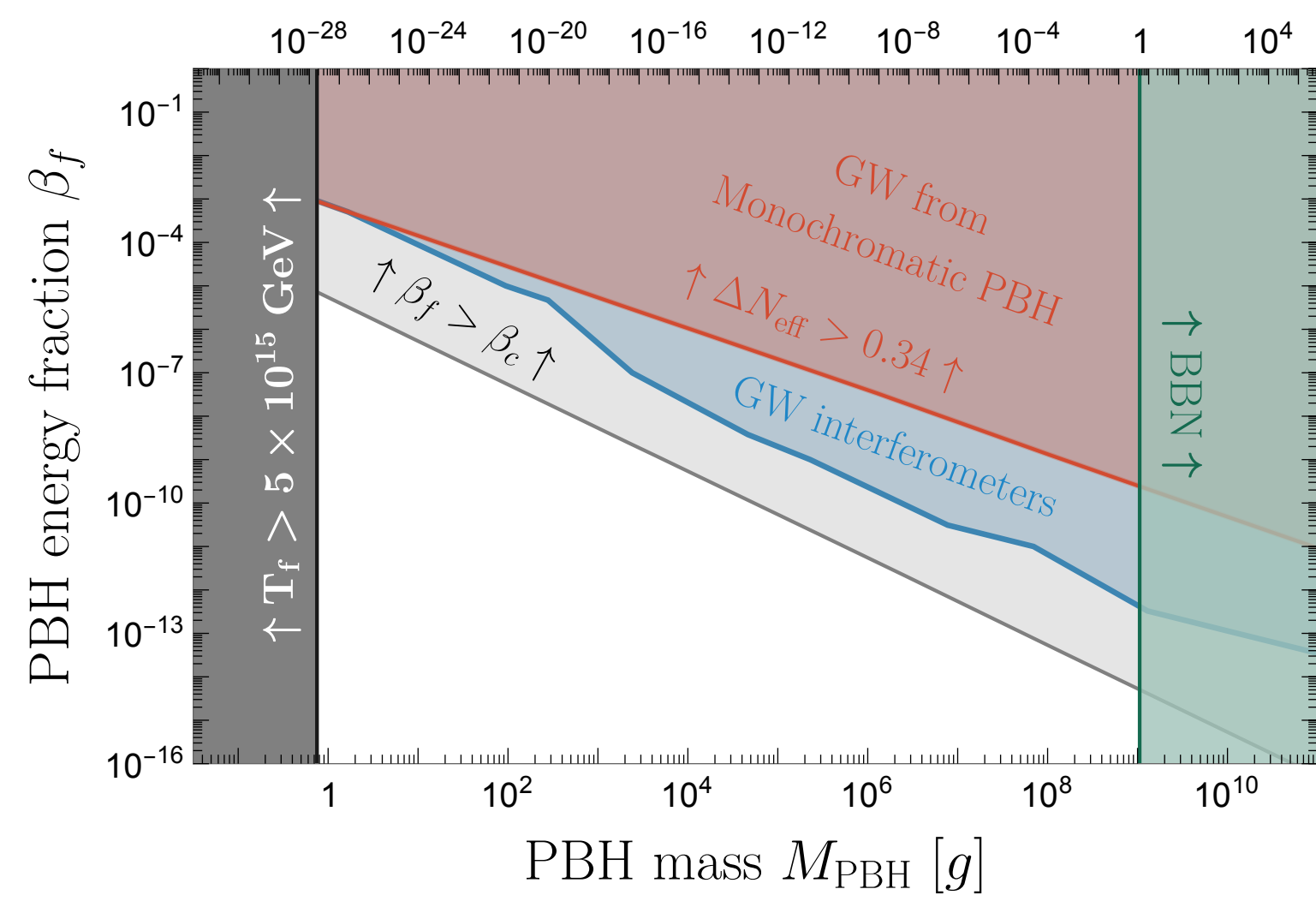
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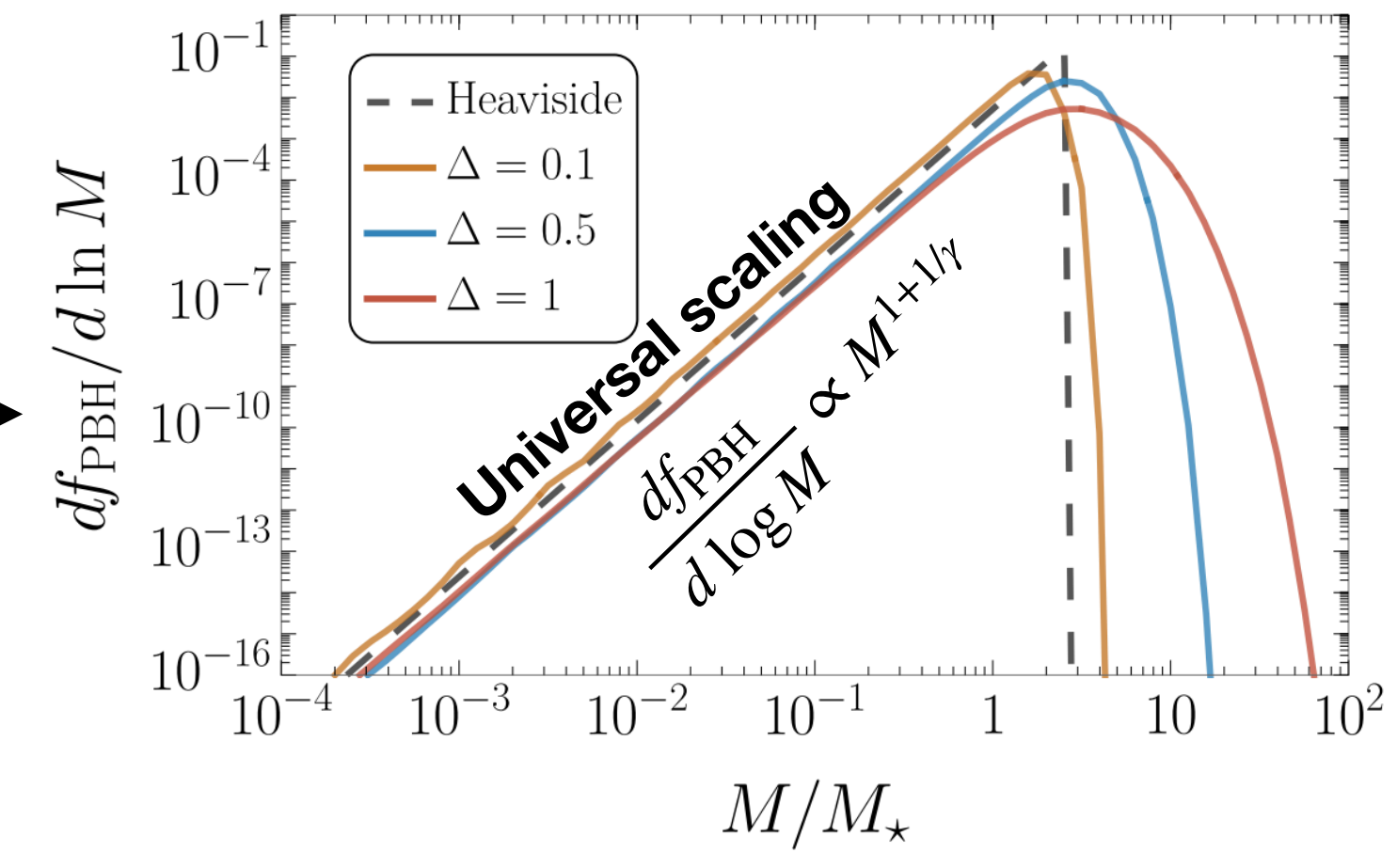
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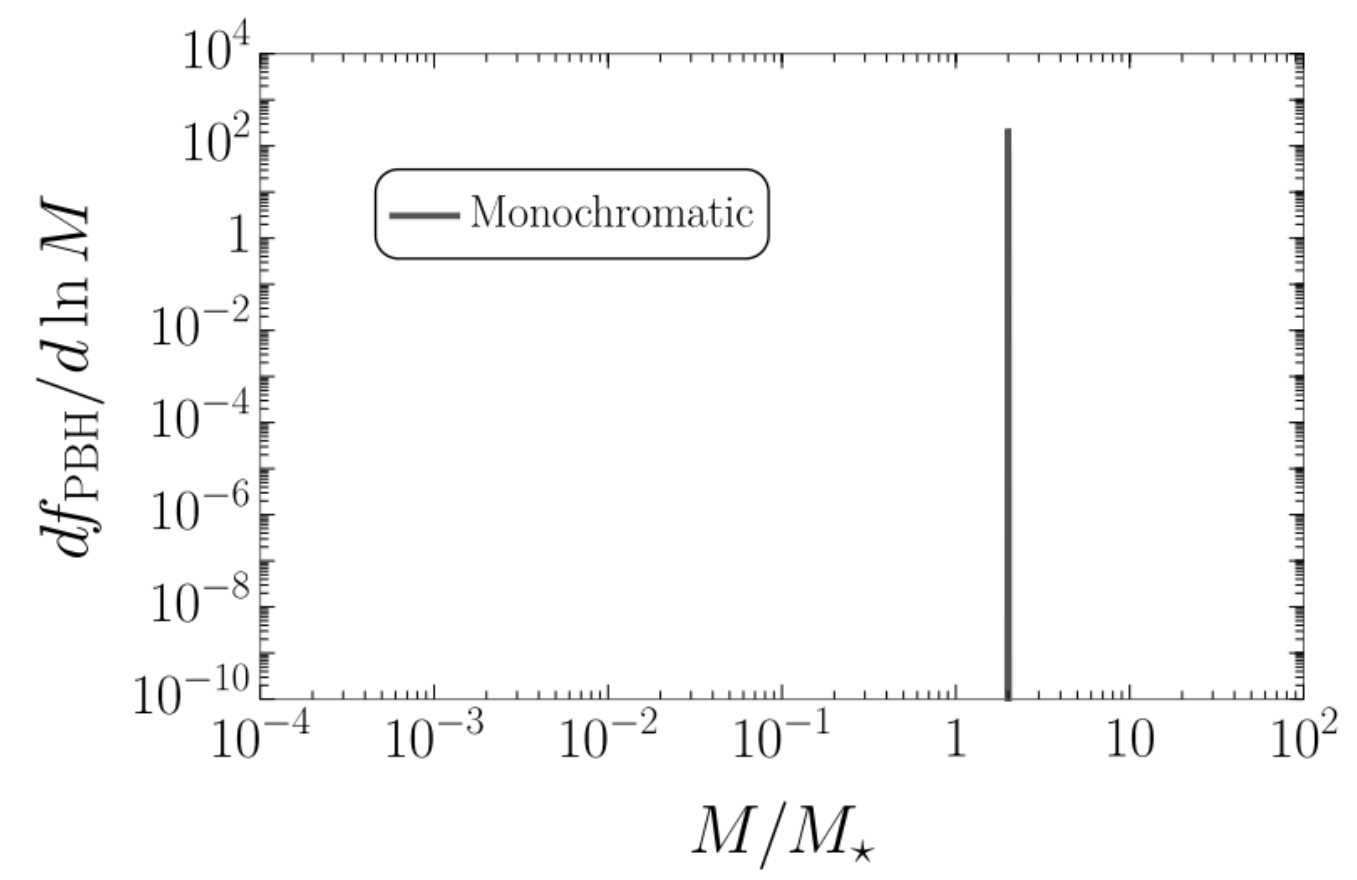


$$\gamma \simeq 0.36$$

$$M_{\text{PBH}} = M_{\text{H}}(\delta - \delta_c)^\gamma$$

Choptuik's law
(Choptuik 93')





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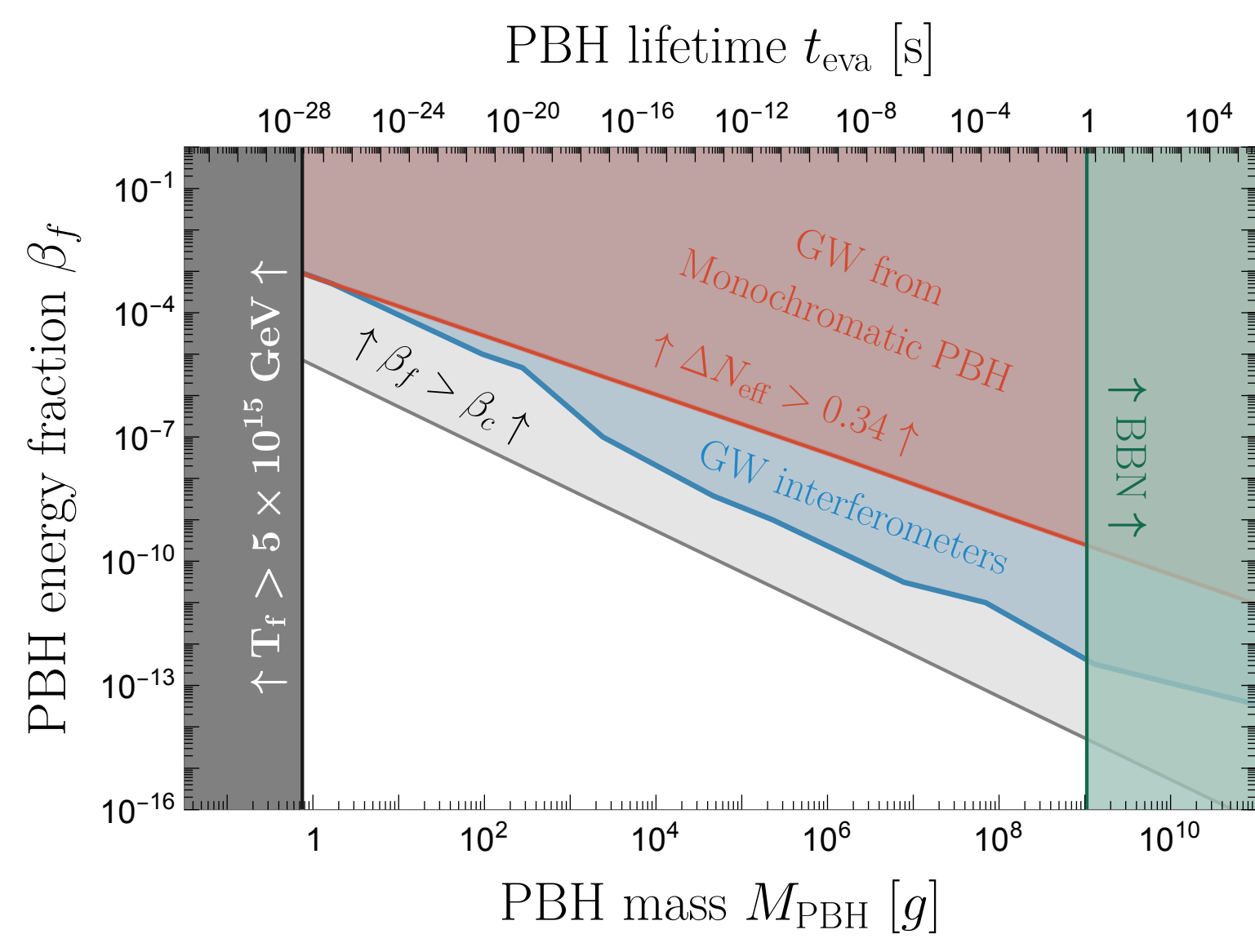
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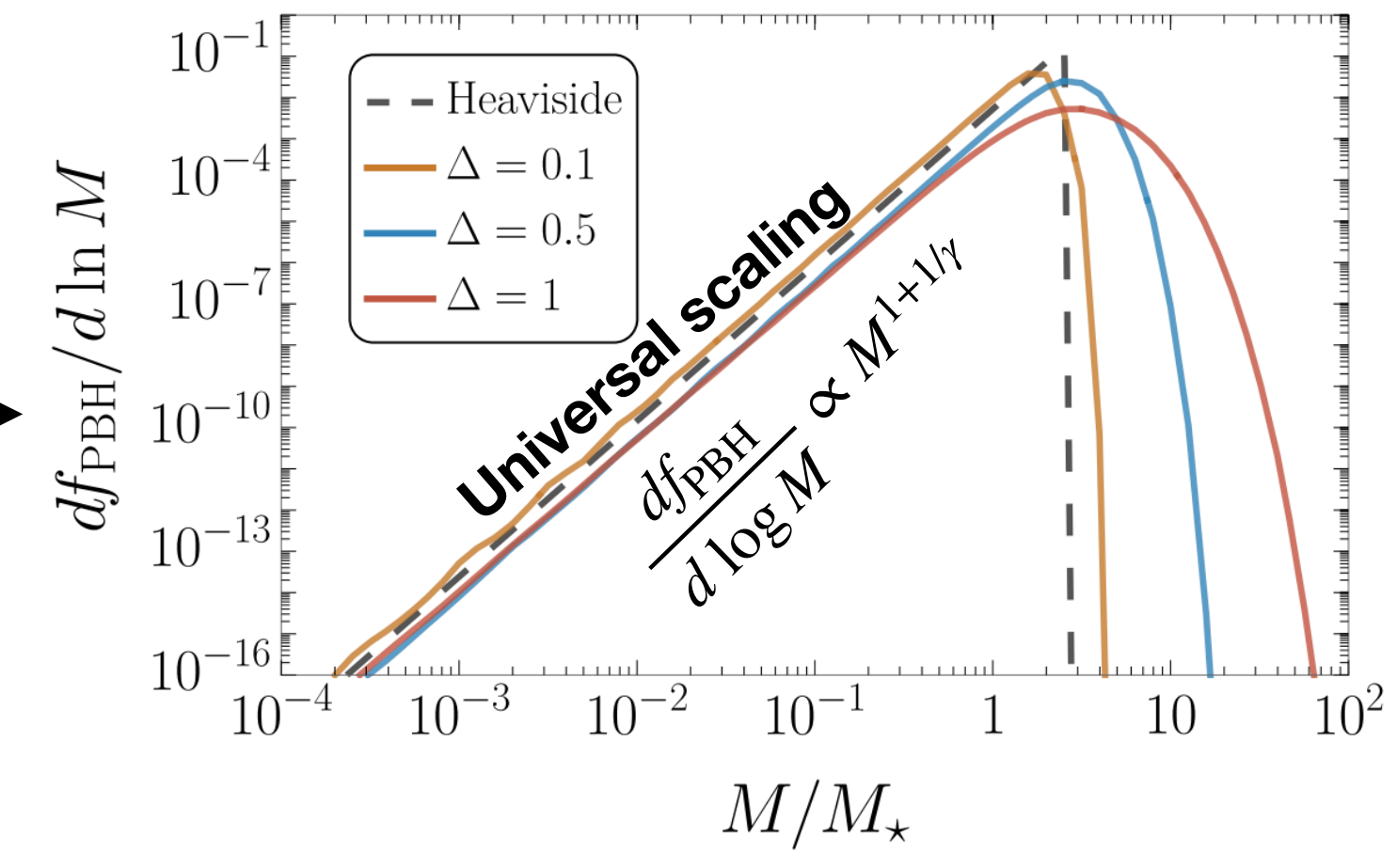
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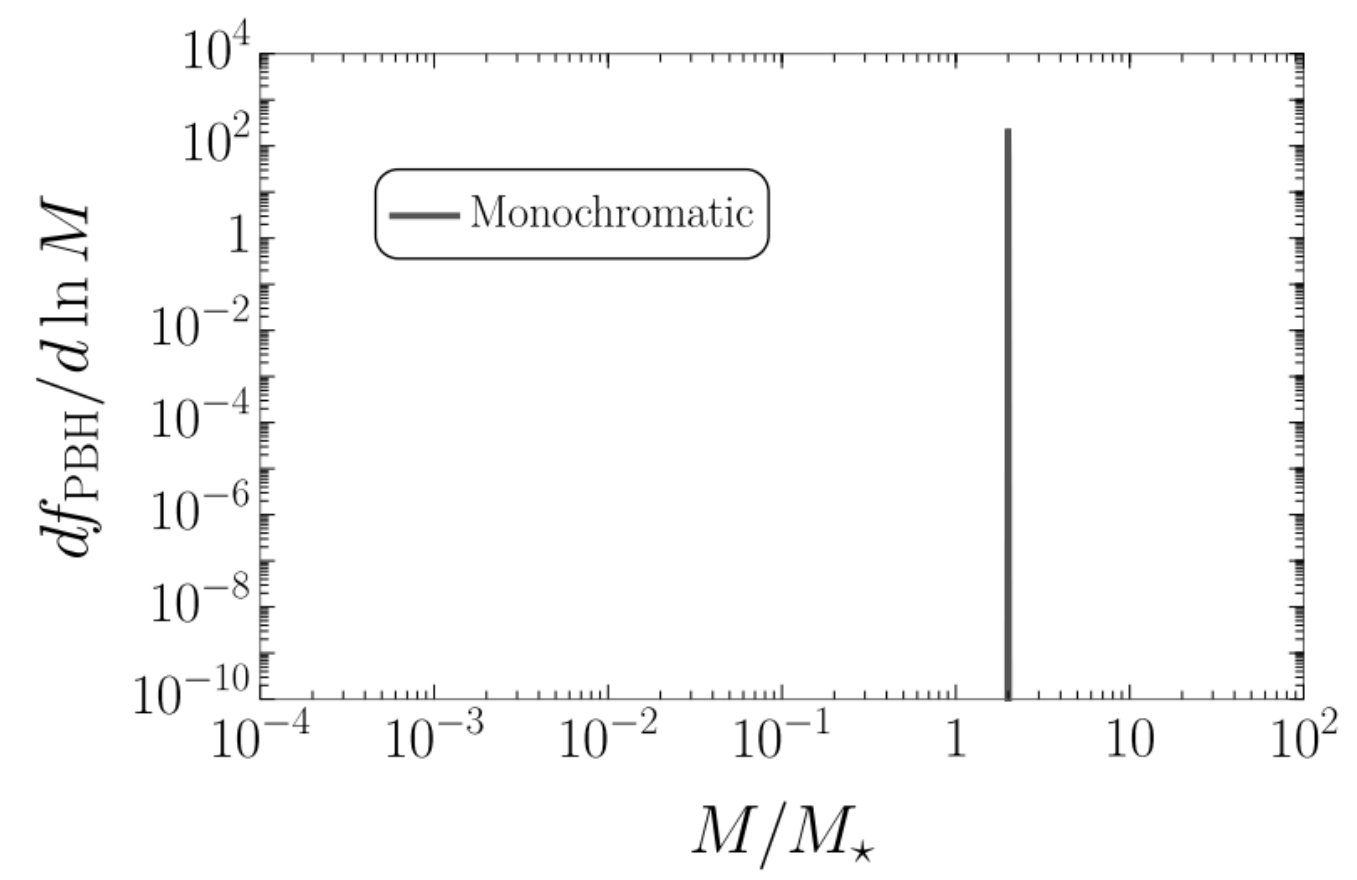
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Opening the Window for Ultra-Light Primordial Black Holes

In preparation (25XX.XXXX)

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany



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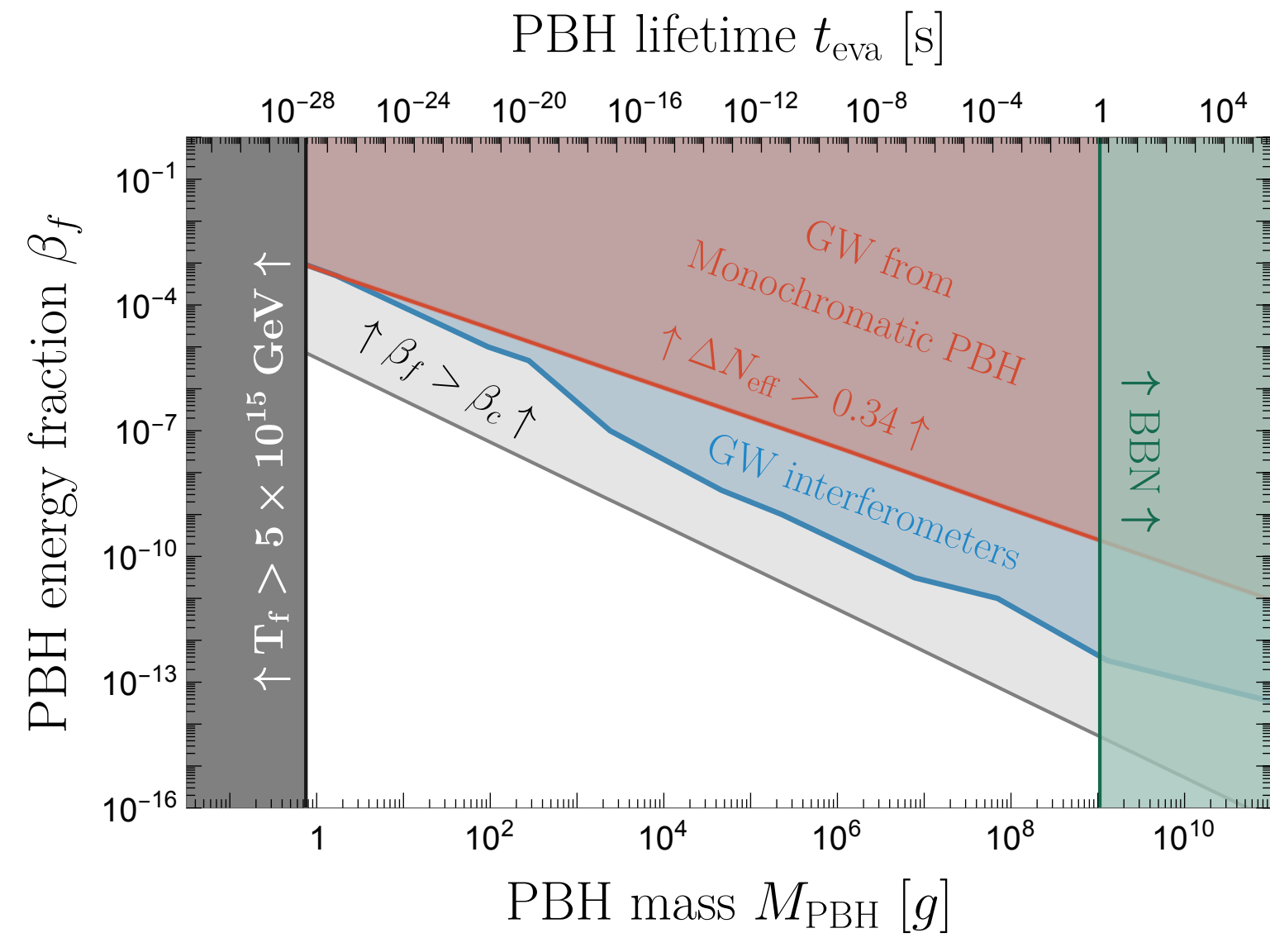
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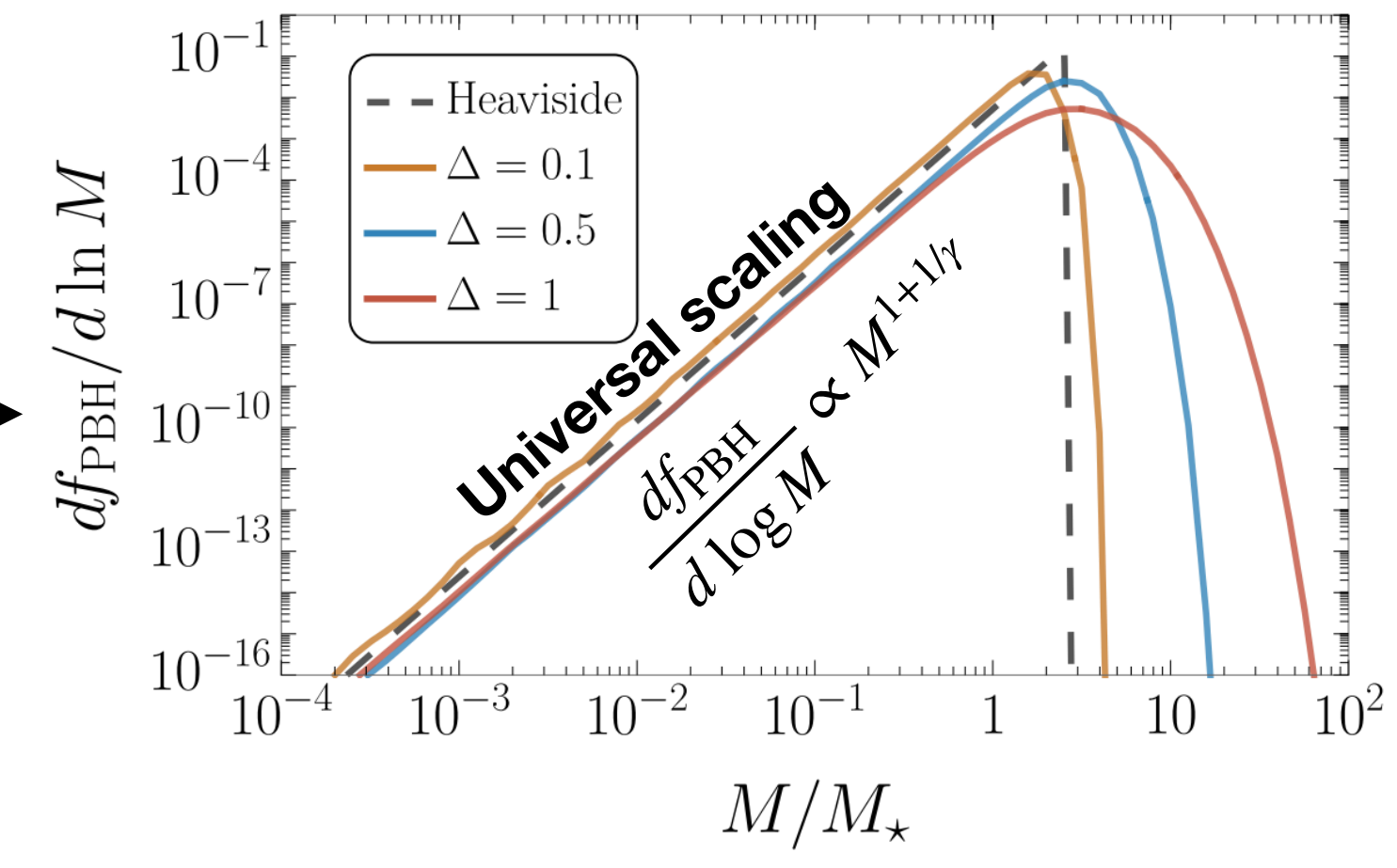
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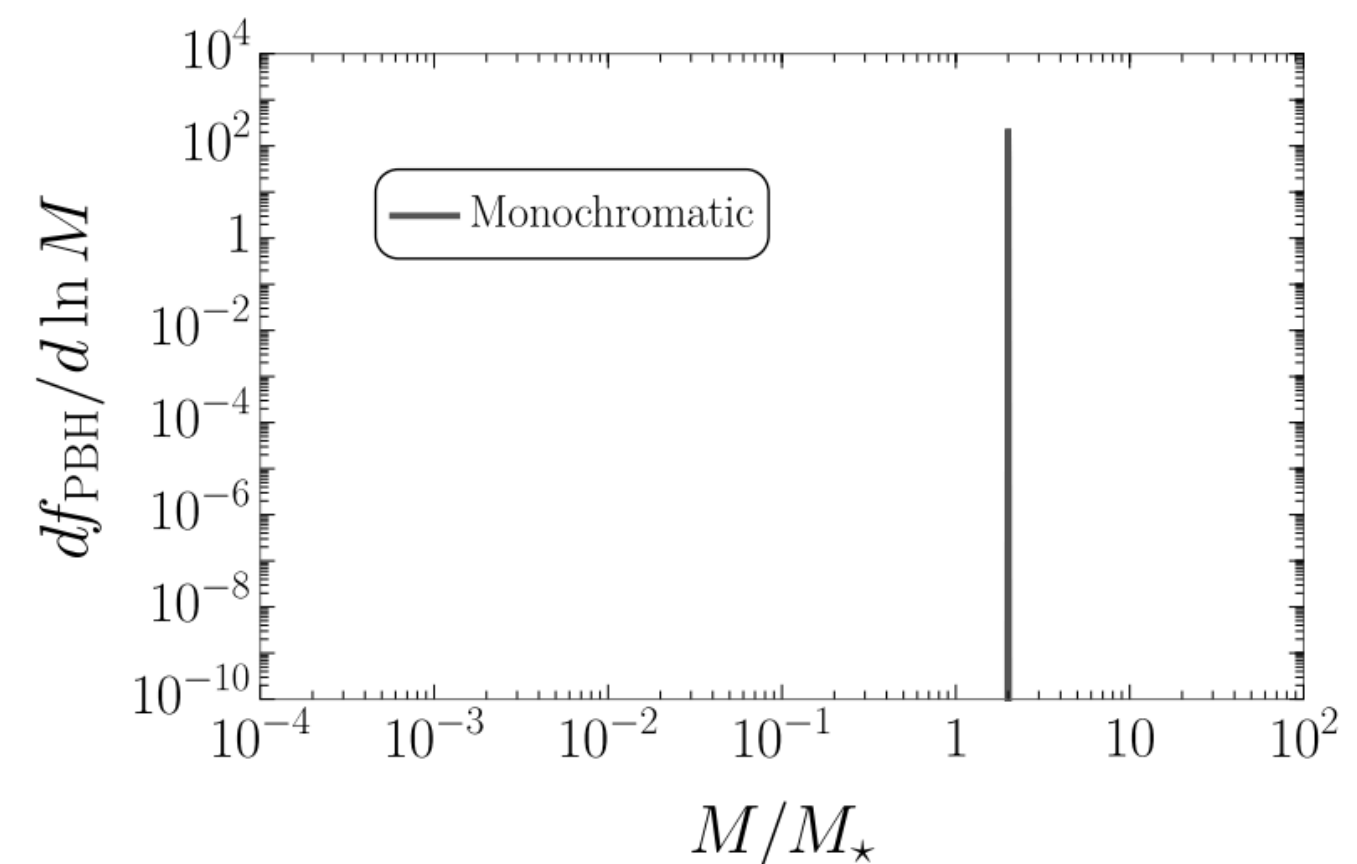
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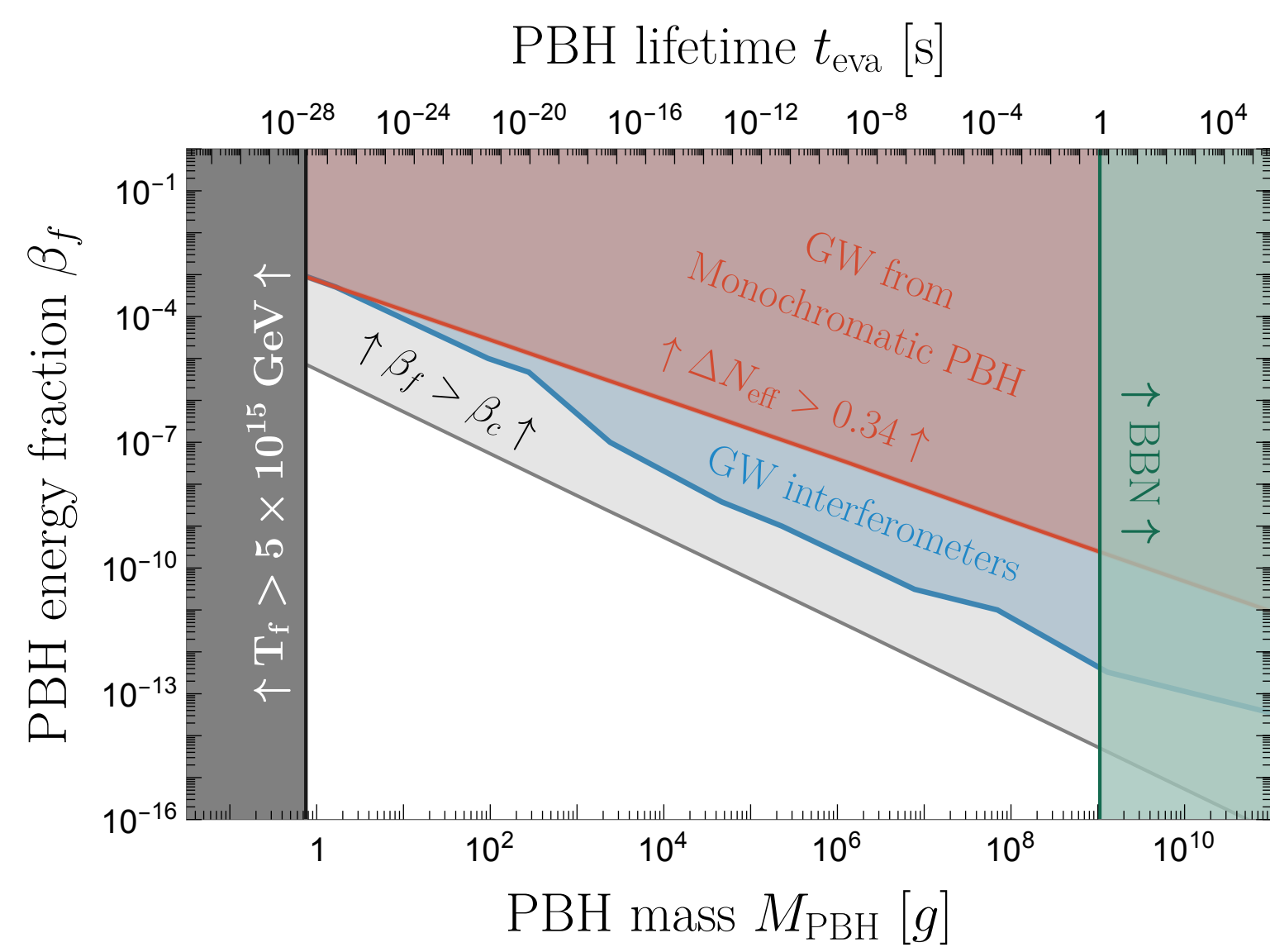
Domenech, Lin, Sasaki 20'

Domenech, Takhistov, Sasaki 21'

Domenech, Trankle 24'

Bhaumik, Ghoshal, Lewicki 22'

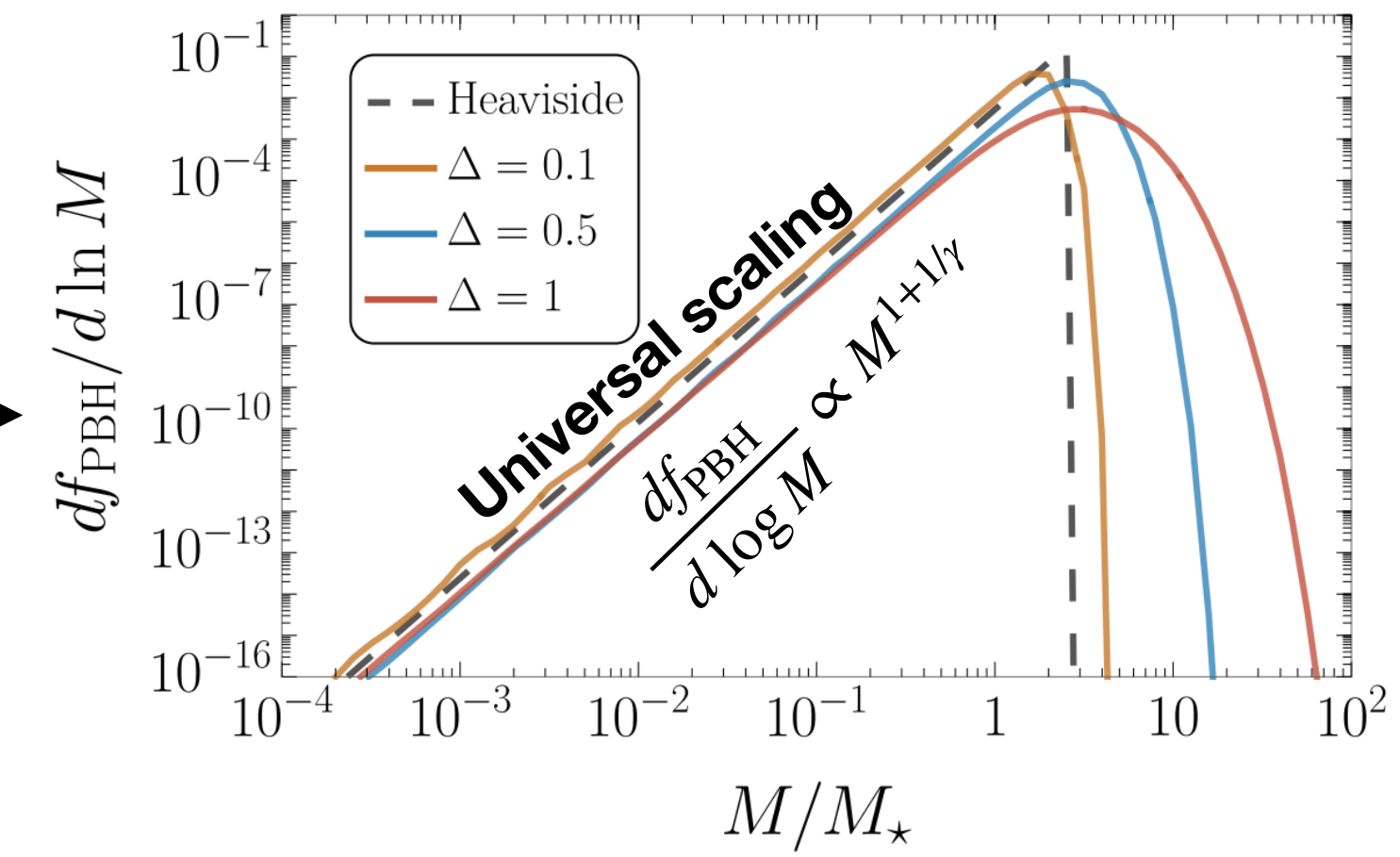
$$k_{\text{cut}} = k_{\text{NL}} \quad (\text{conservative})$$



$$\gamma \simeq 0.36$$

$$M_{\text{PBH}} = M_{\text{H}}(\delta - \delta_c)^\gamma$$

Choptuik's law
(Choptuik 93')

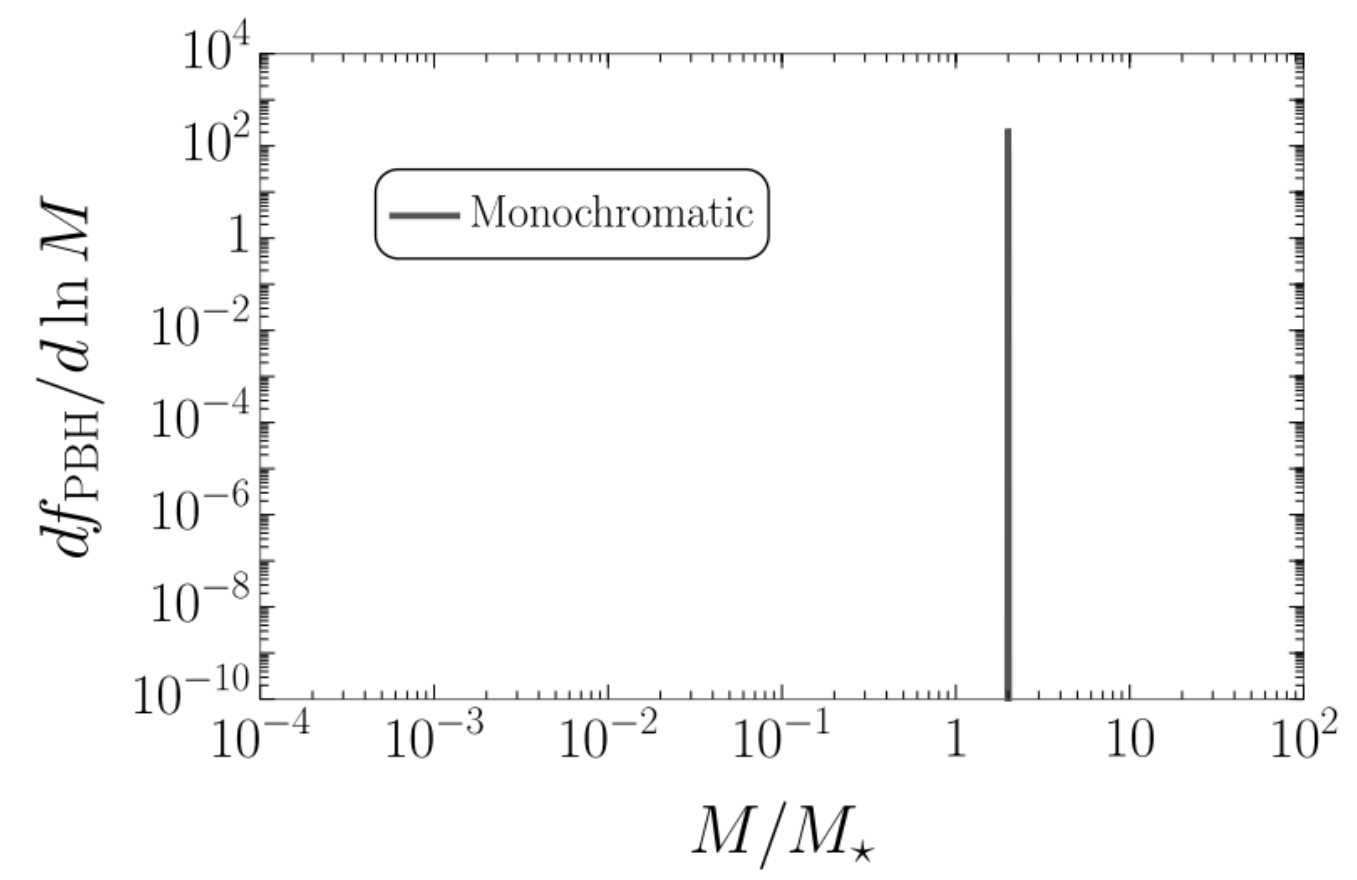


Opening the Window for Ultra-Light Primordial Black Holes

In preparation (25XX.XXXX)

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

$$\int d \ln M \frac{df_{\text{PBH}}}{d \ln M} \left(\text{all the equations leading to } \Phi \text{ and } h_{ij} \right)$$



Inomata, Kawasaki, Mukaida, Terada, Yanagida (2003.10455)

Papanikolaou, Vennin, Langlois 20'

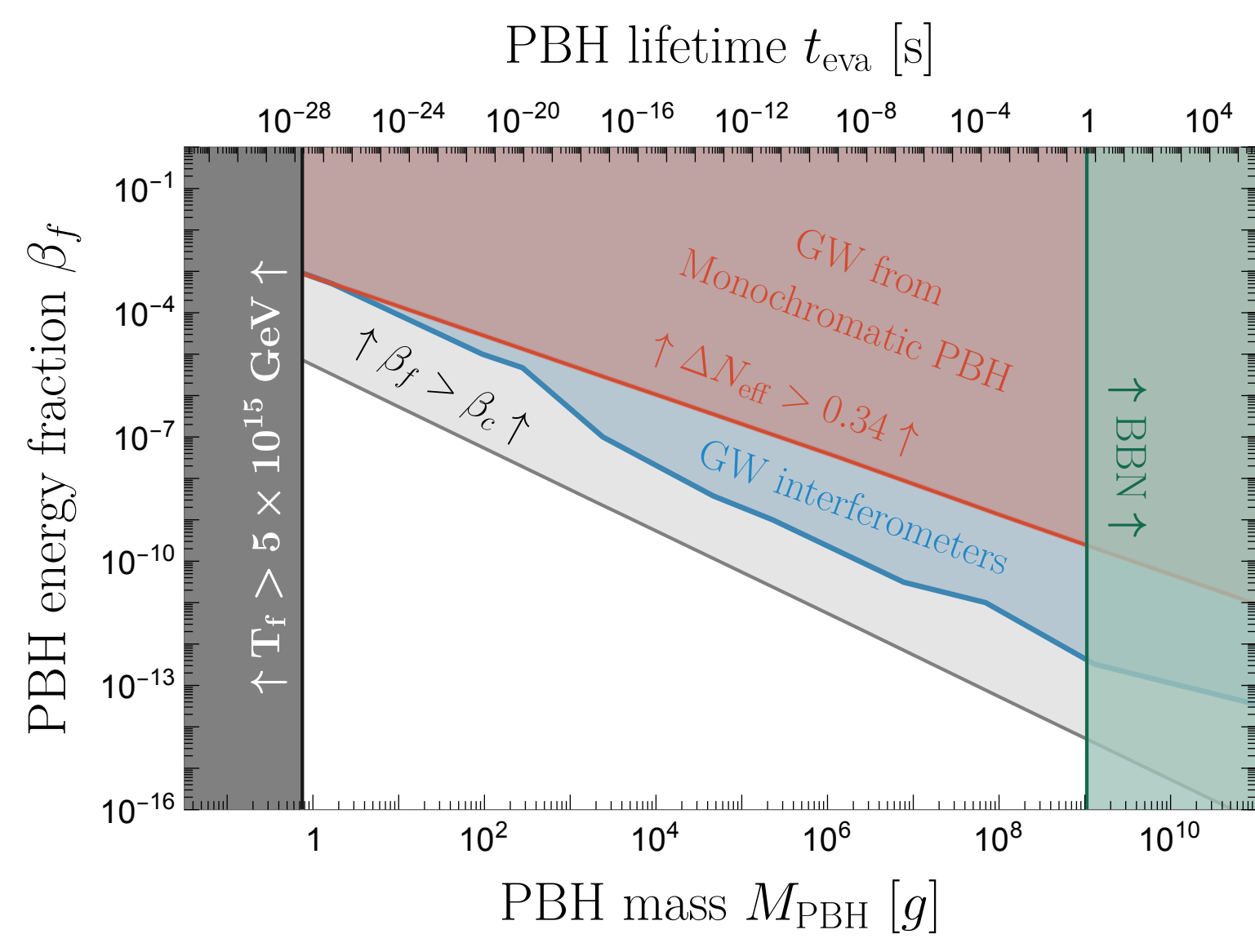
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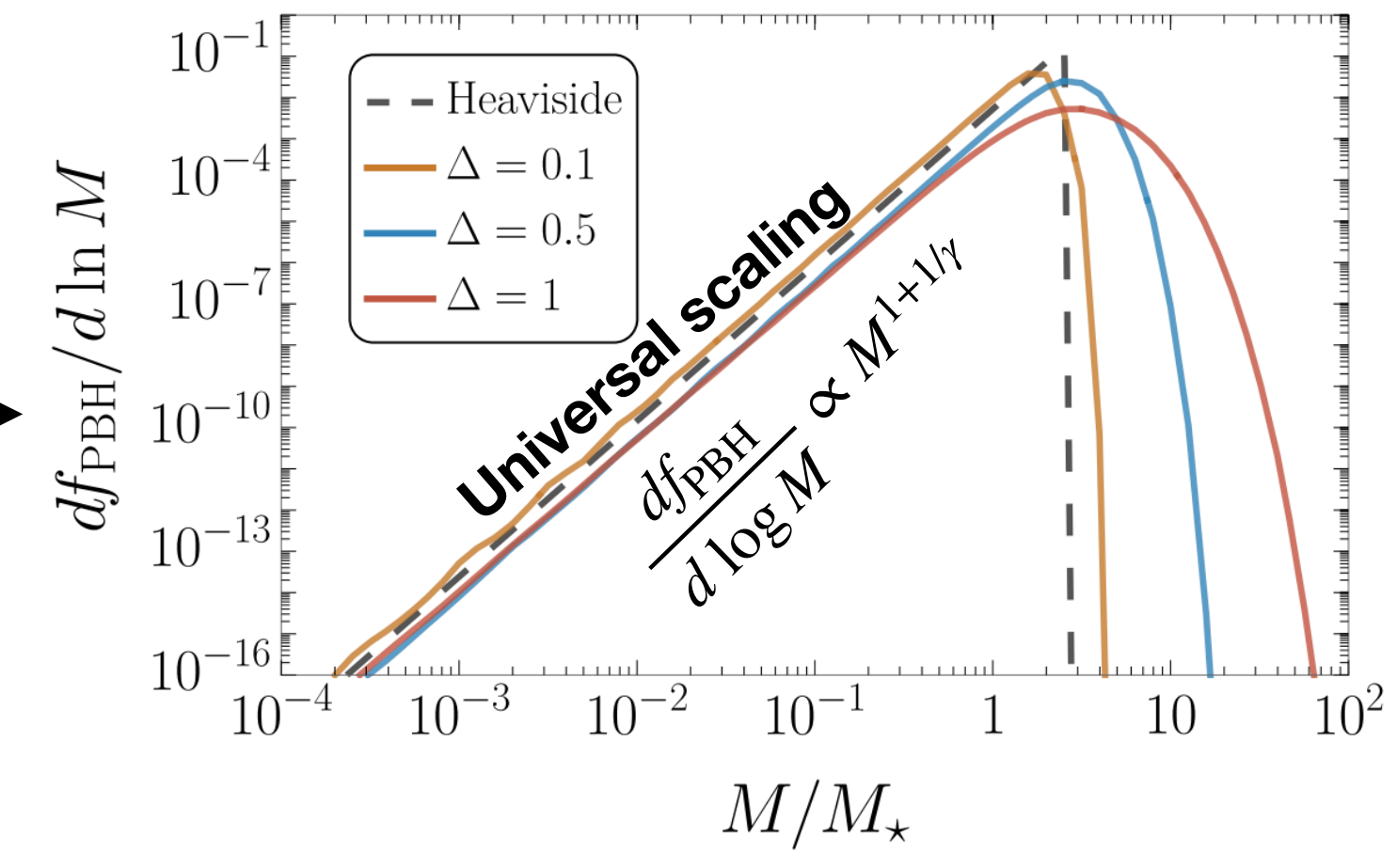
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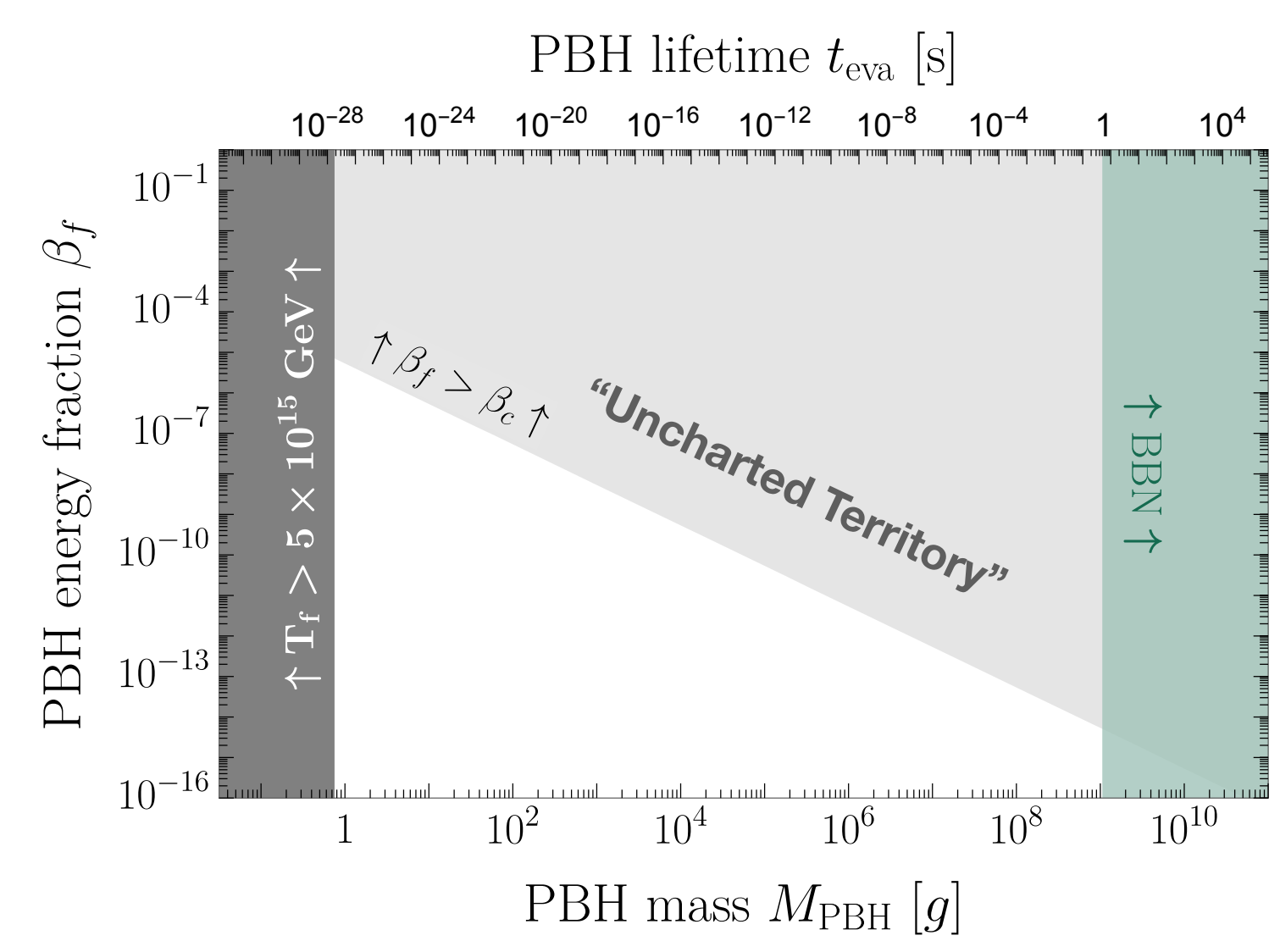


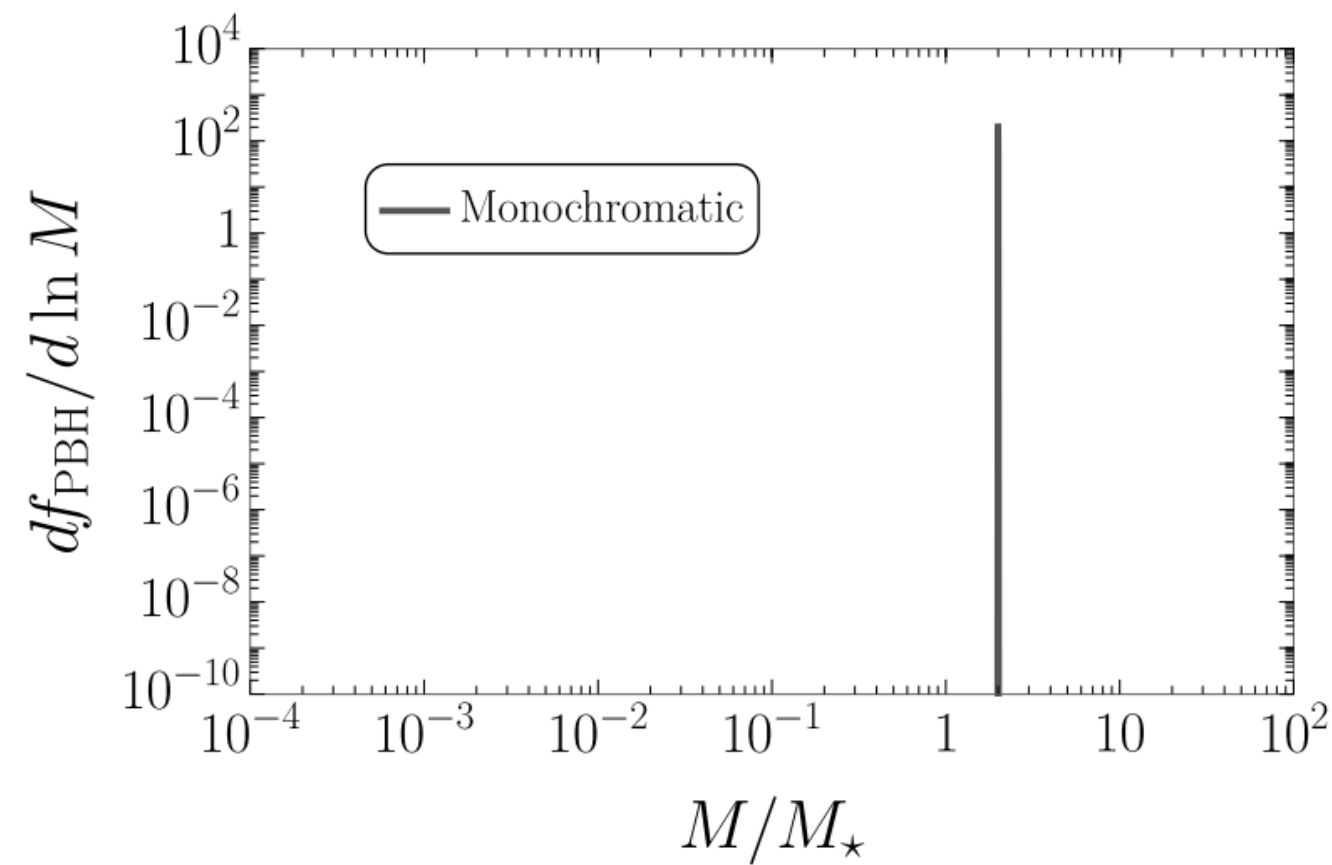
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*Inomata, Kawasaki, Mukaida,
Terada, Yanagida (2003.10455)*

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Domenech, Lin, Sasaki 20'

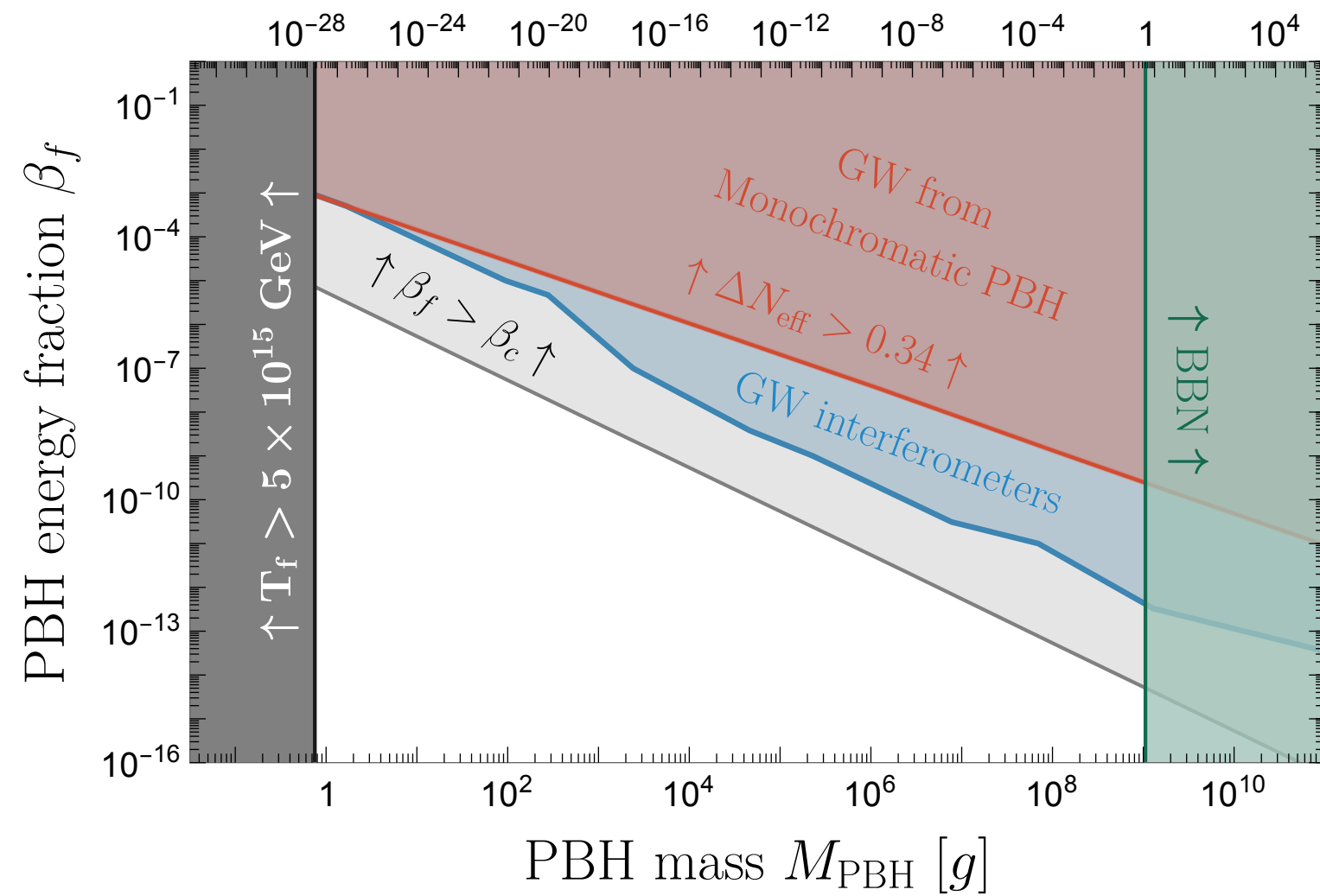
Domenech, Takhistov, Sasaki 21'

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$$k_{\text{cut}} = k_{\text{NL}} \quad (\text{conservative})$$

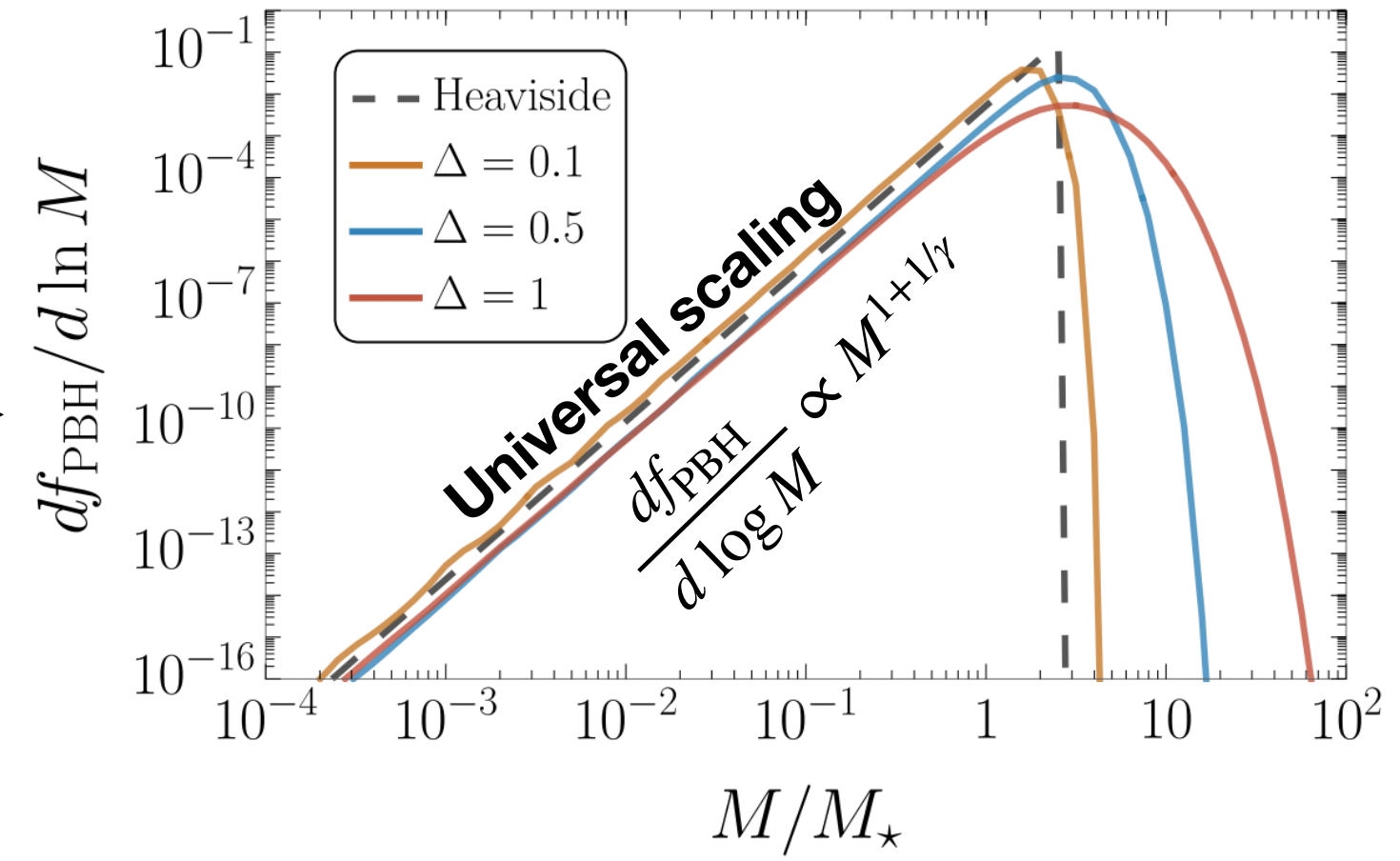
PBH lifetime $t_{\text{eva}} \text{ [s]}$



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Choptuik's law
(Choptuik 93')



**Opening the Window for Ultra-Light Primordial
Black Holes**

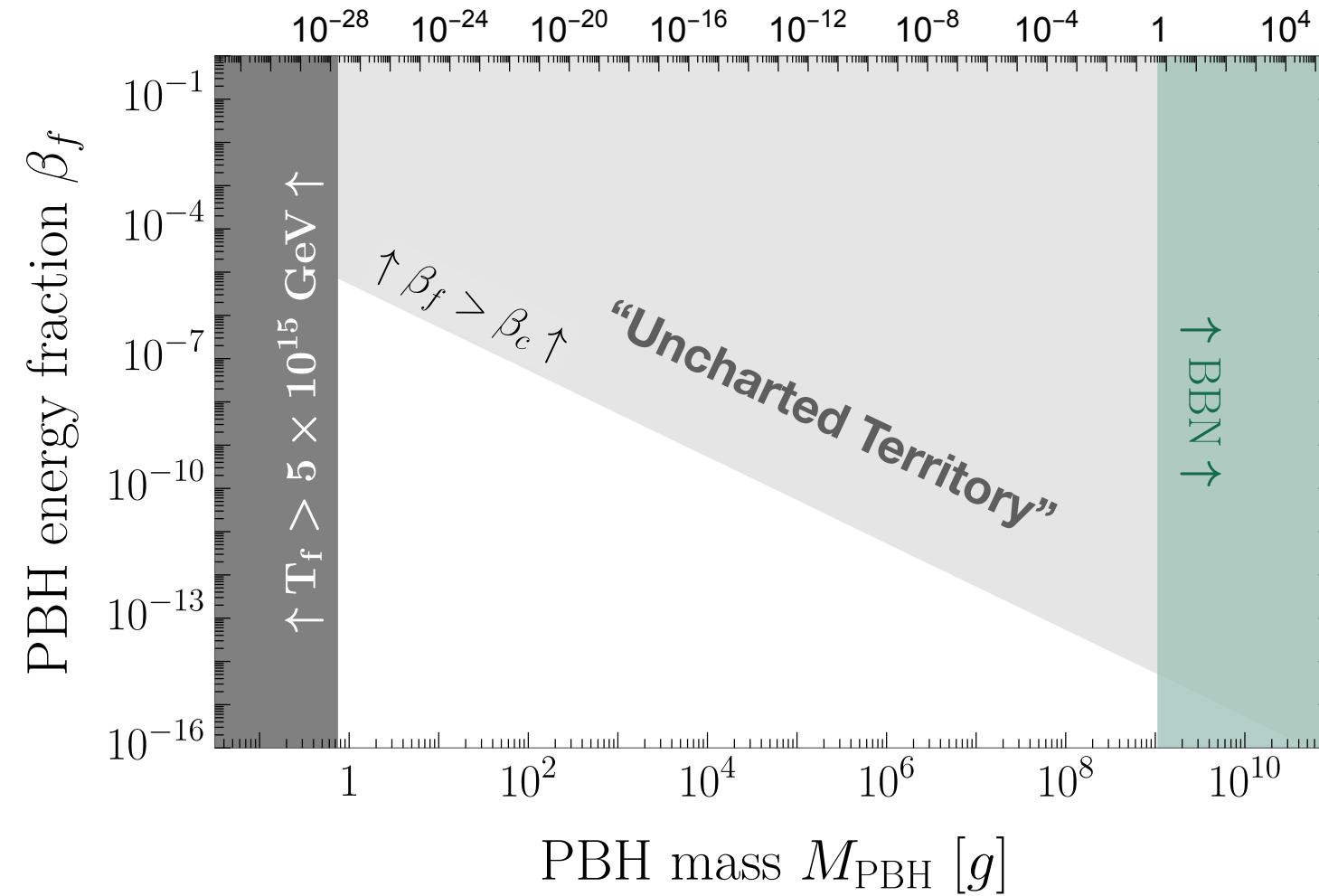
In preparation (25XX.XXXX)

Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

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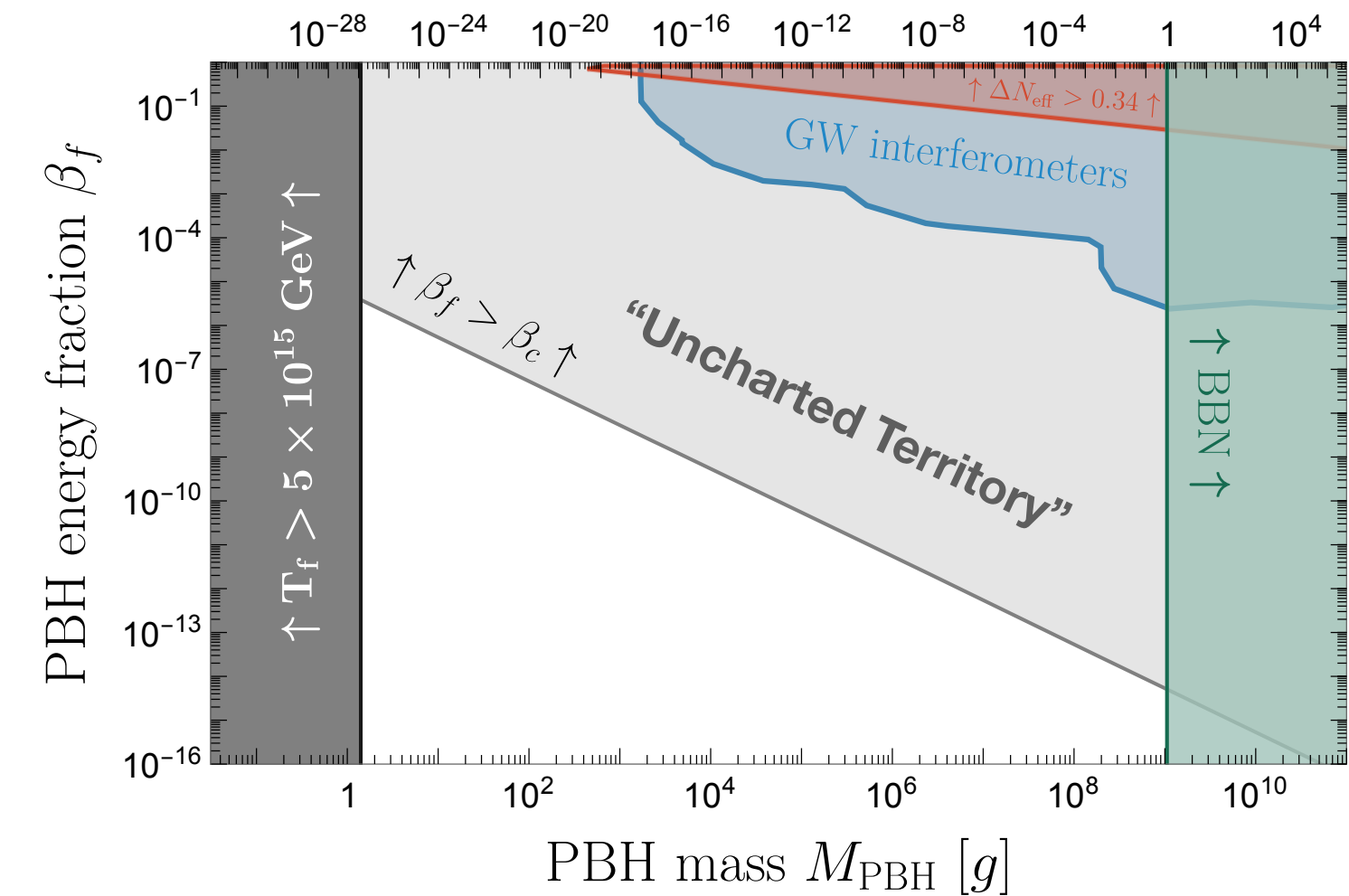
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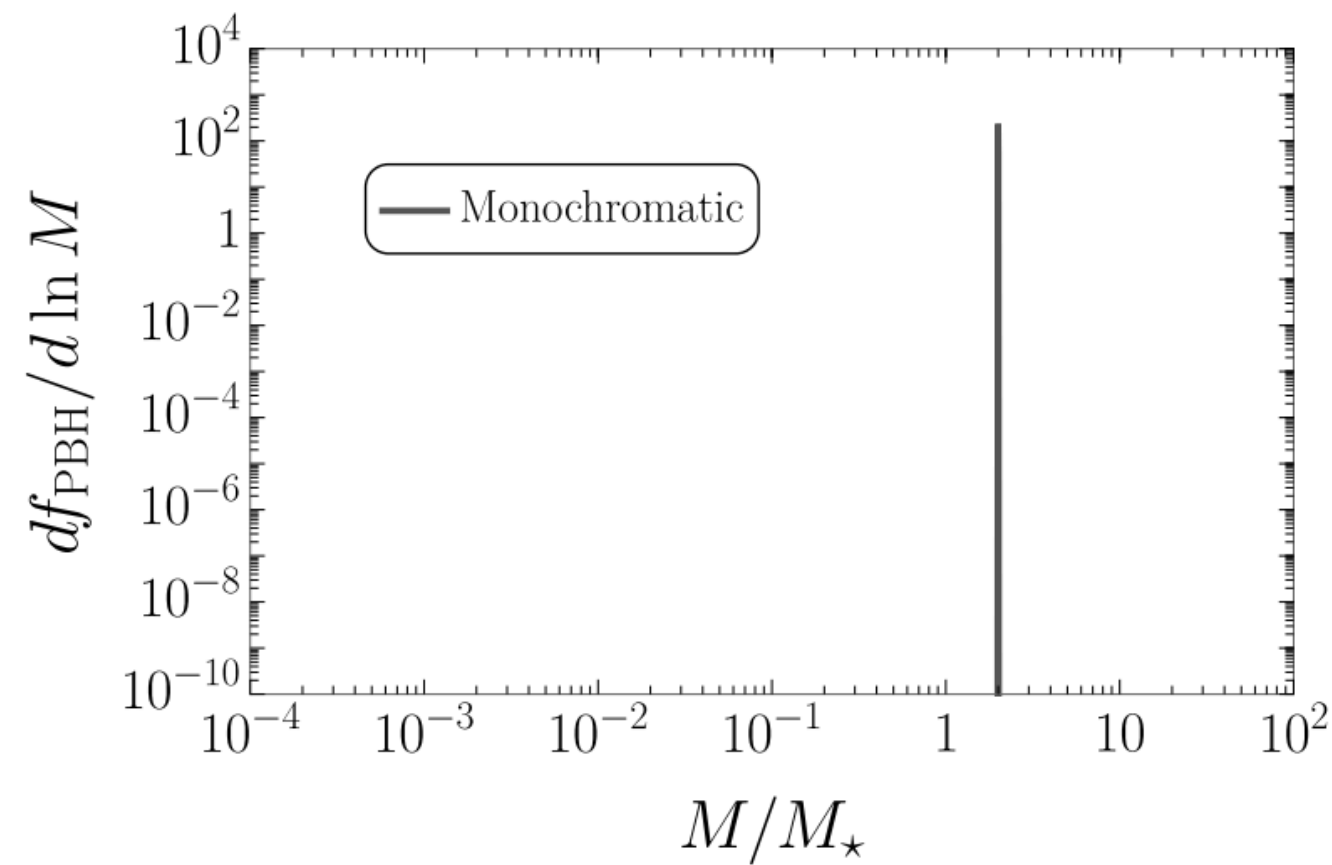
PBH lifetime $t_{\text{eva}} \text{ [s]}$



$$k_{\text{cut}} = k_{\text{PBH}} \quad (\text{aggressive})$$

PBH lifetime $t_{\text{eva}} \text{ [s]}$





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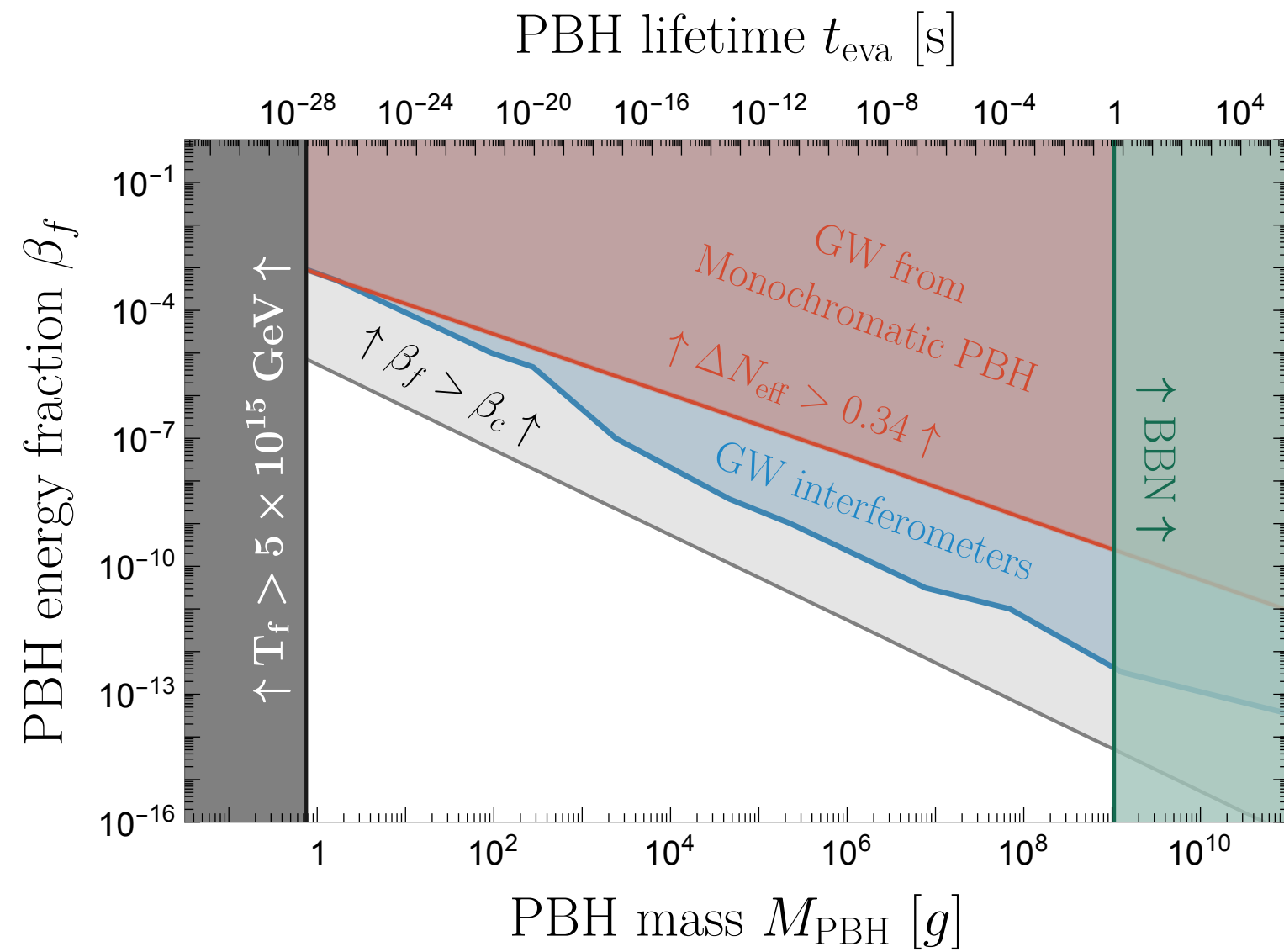
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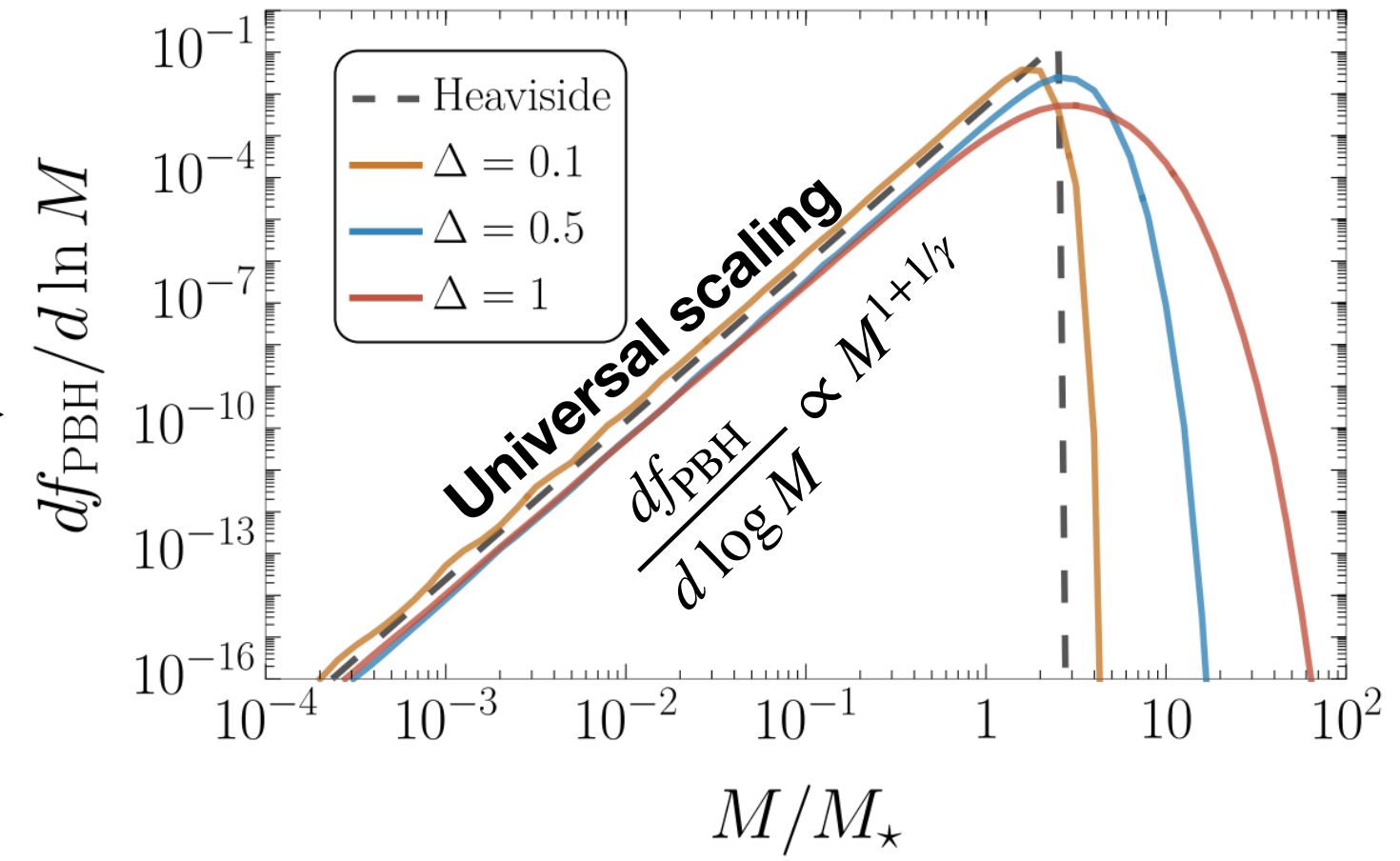
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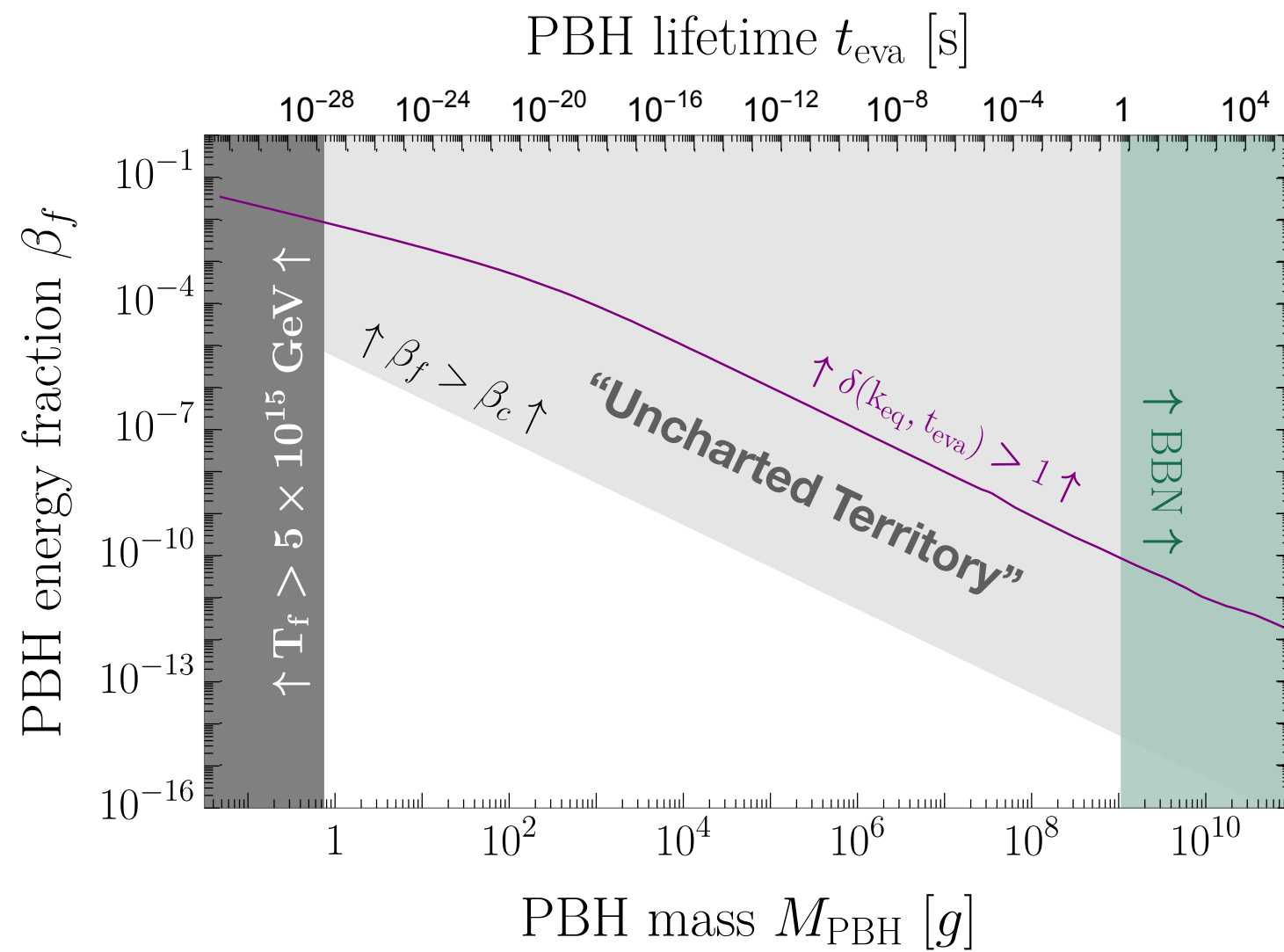
**Opening the Window for Ultra-Light Primordial
Black Holes**

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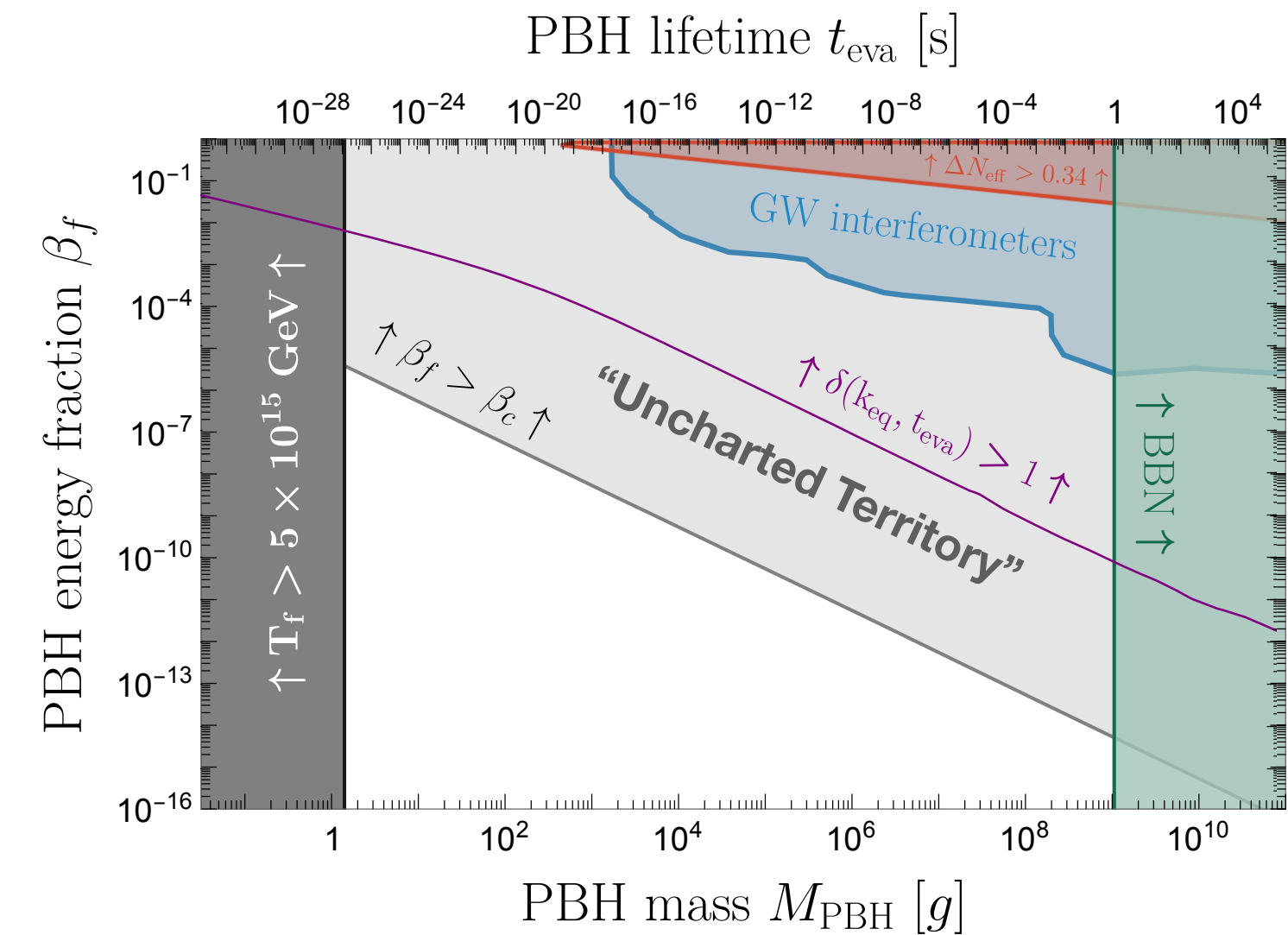
Yann Gouttenoire, Nicholas Leister, Pedro Schwaller

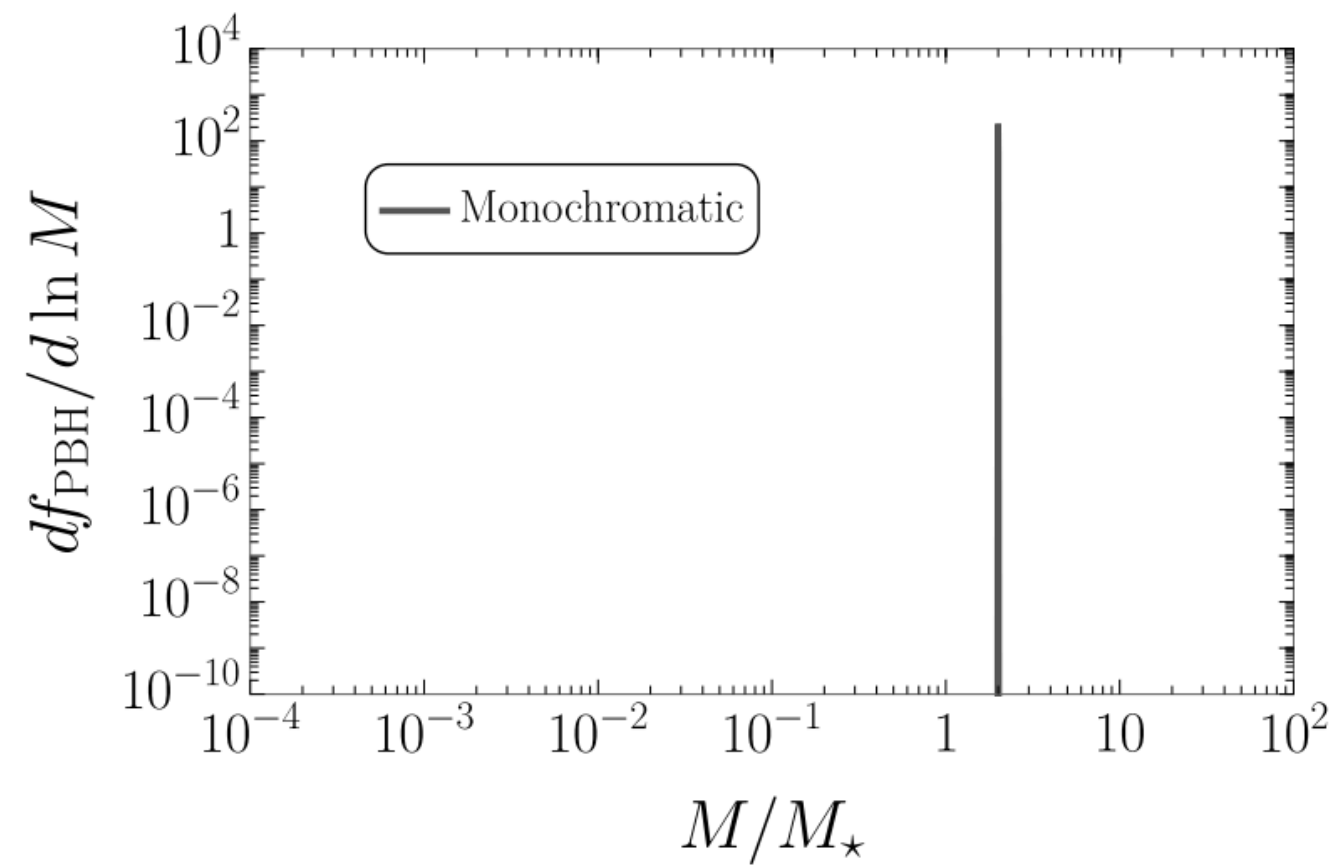
PRISMA+ Cluster of Excellence & MITP, Johannes Gutenberg University, 55099 Mainz, Germany

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$$k_{\text{cut}} = k_{\text{PBH}} \quad (\text{aggressive})$$





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Terada, Yanagida (2003.10455)*

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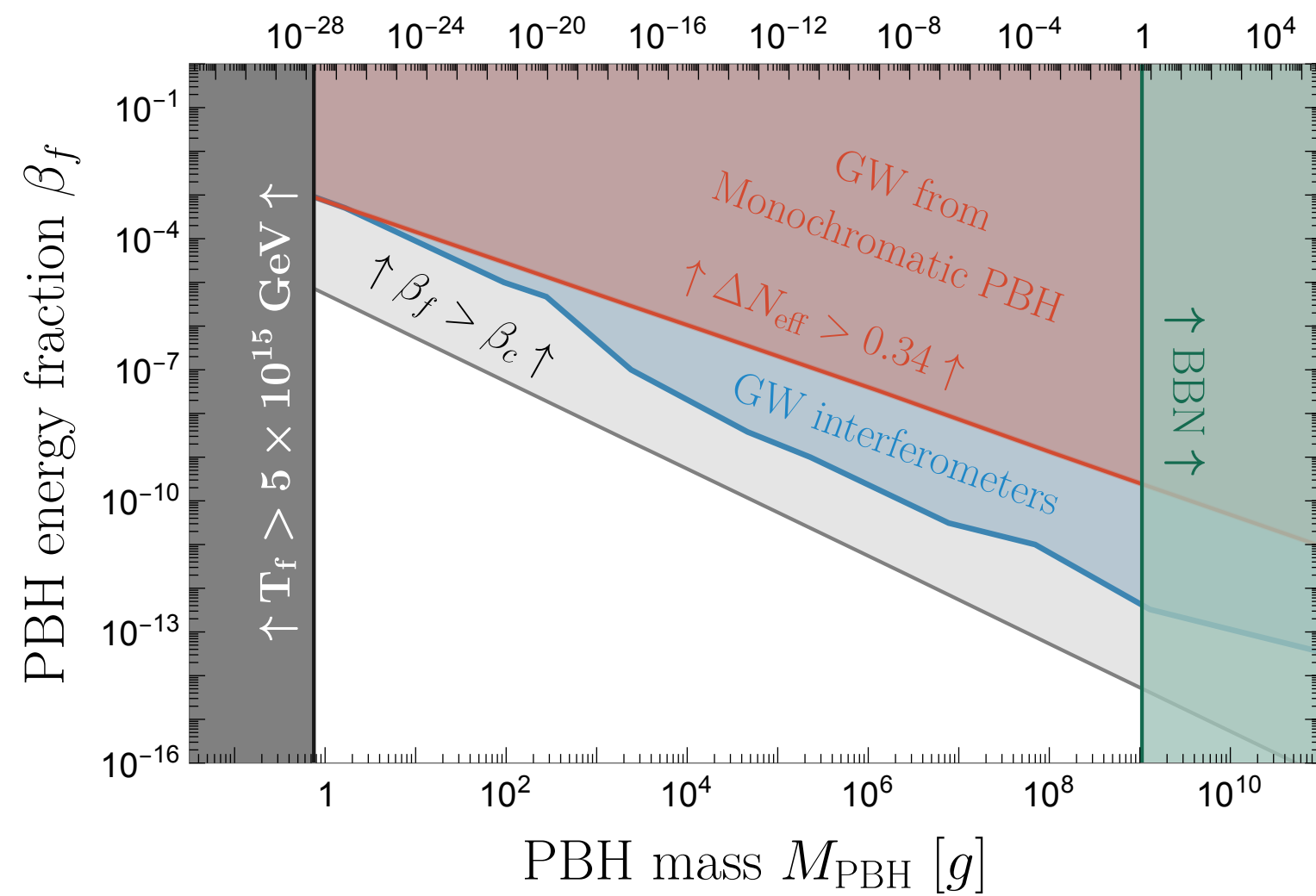
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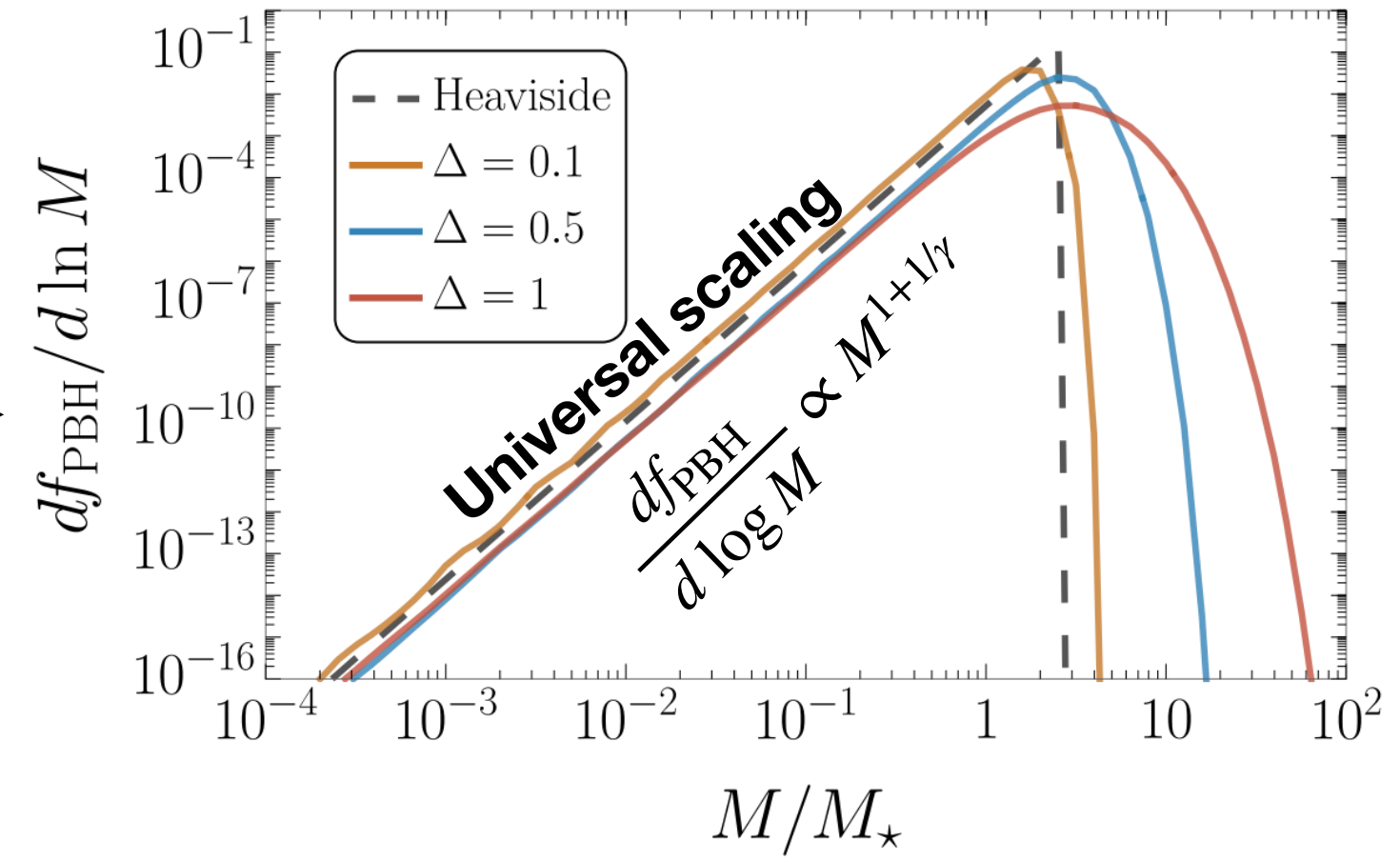
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**Opening the Window for Ultra-Light Primordial
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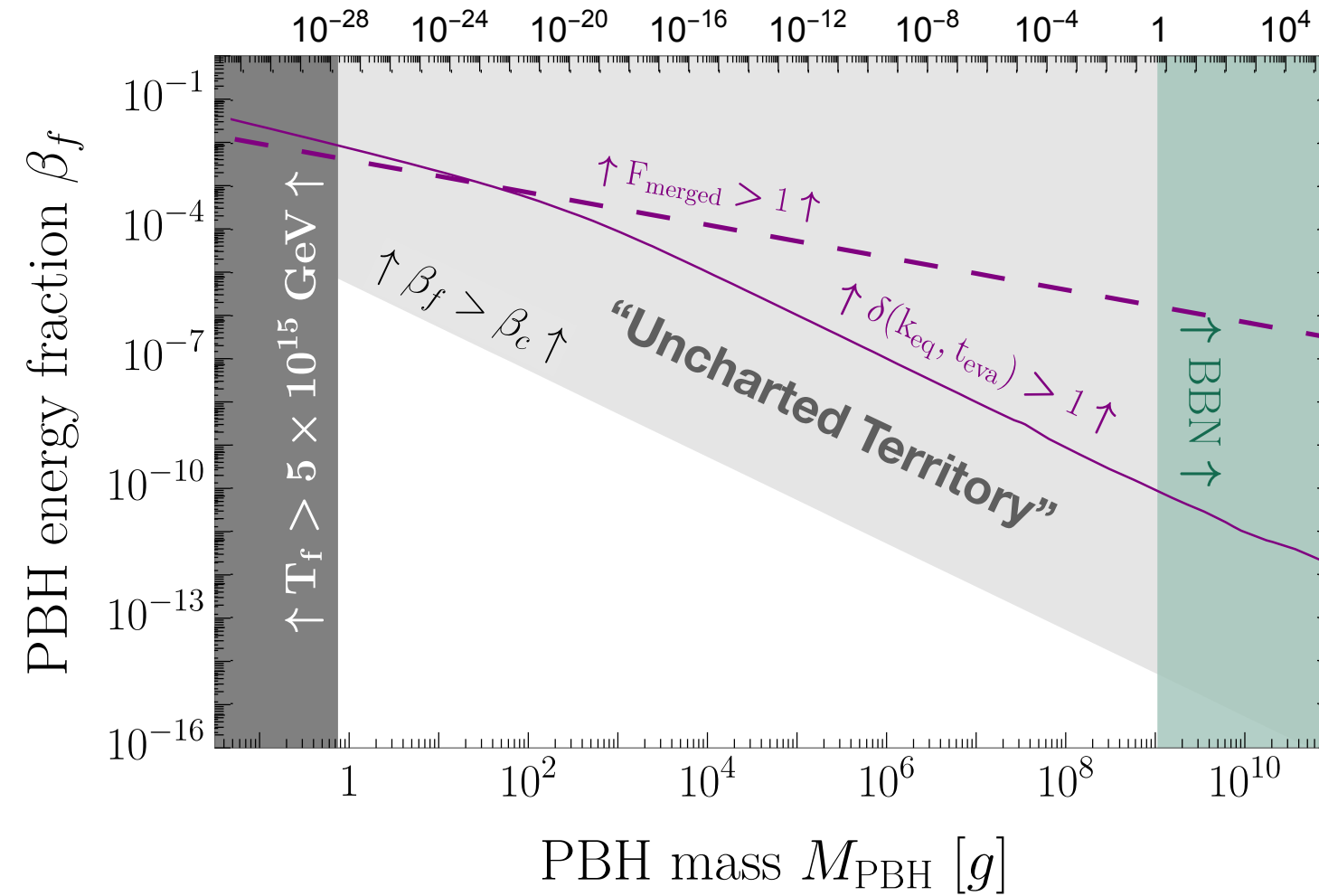
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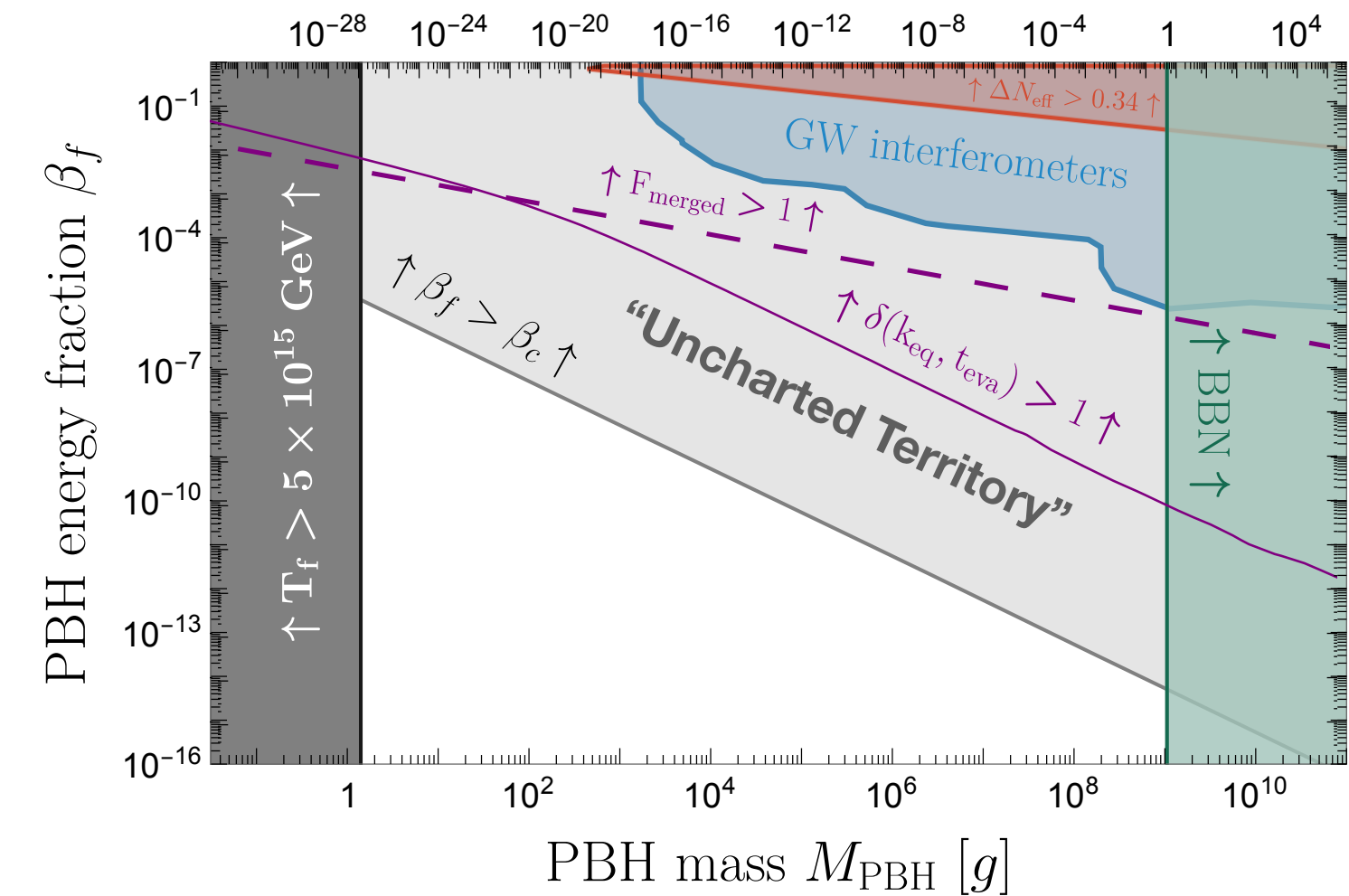
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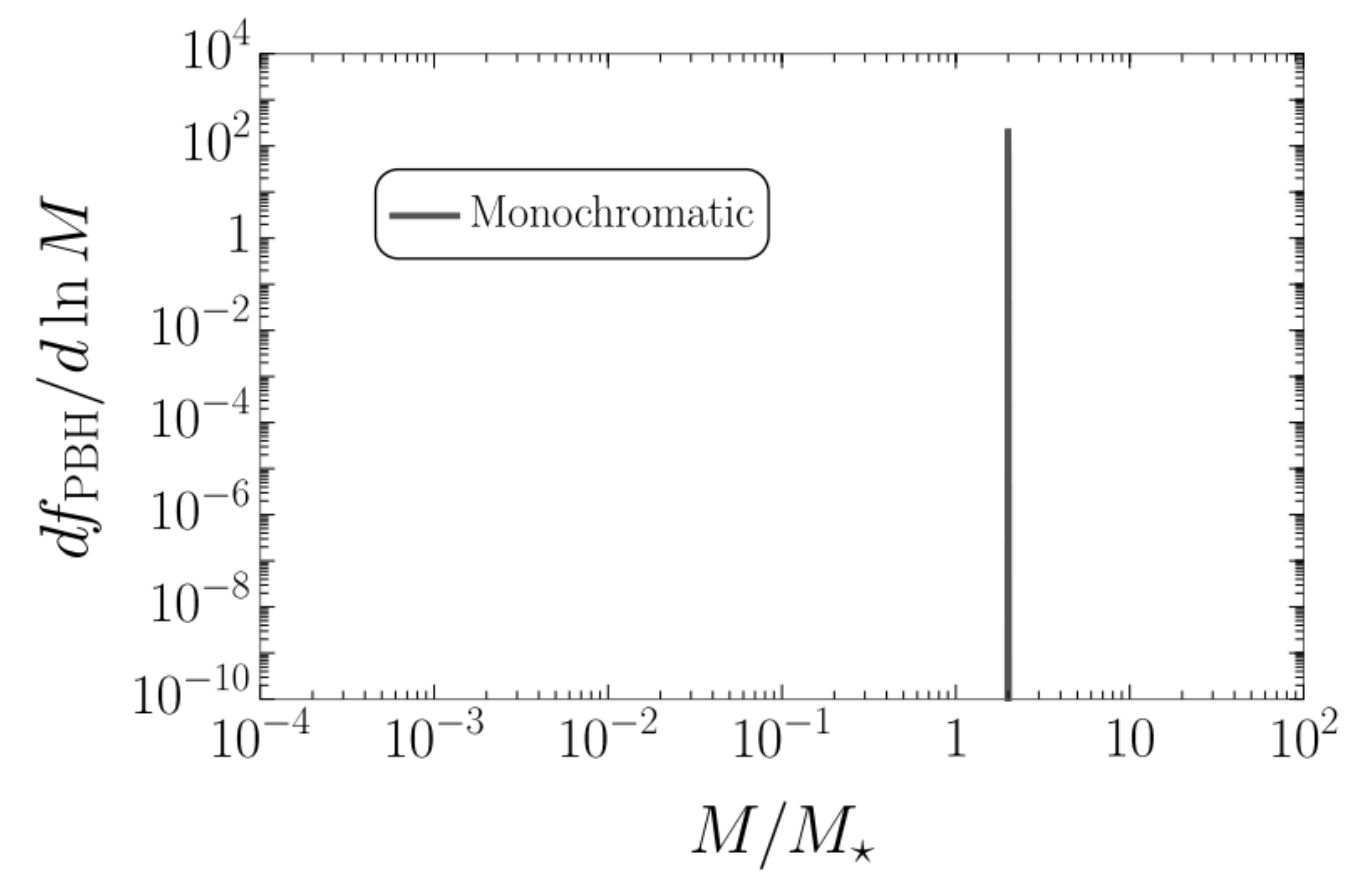
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$$k_{\text{cut}} = k_{\text{PBH}} \quad (\text{aggressive})$$

PBH lifetime $t_{\text{eva}} \text{ [s]}$





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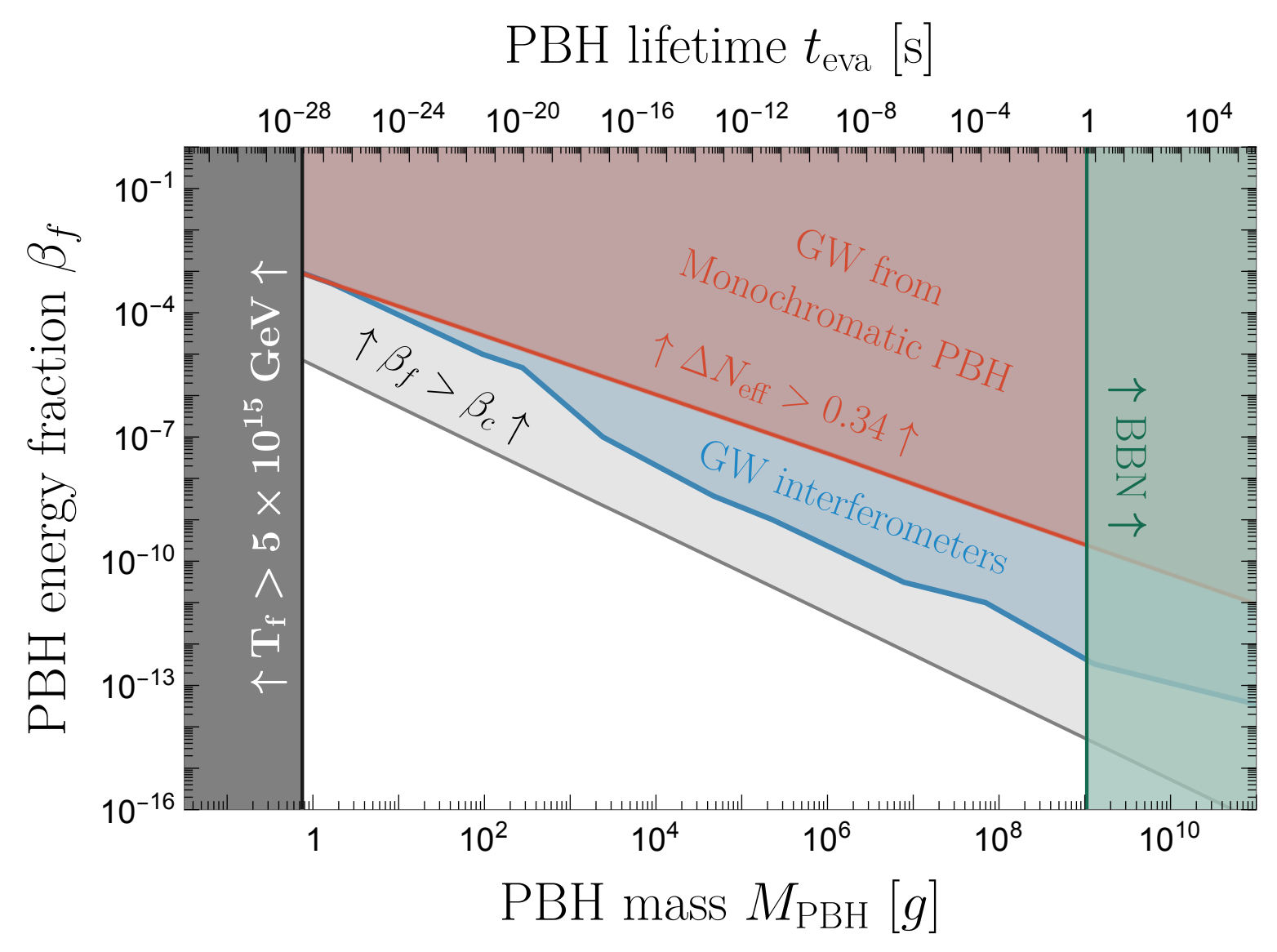
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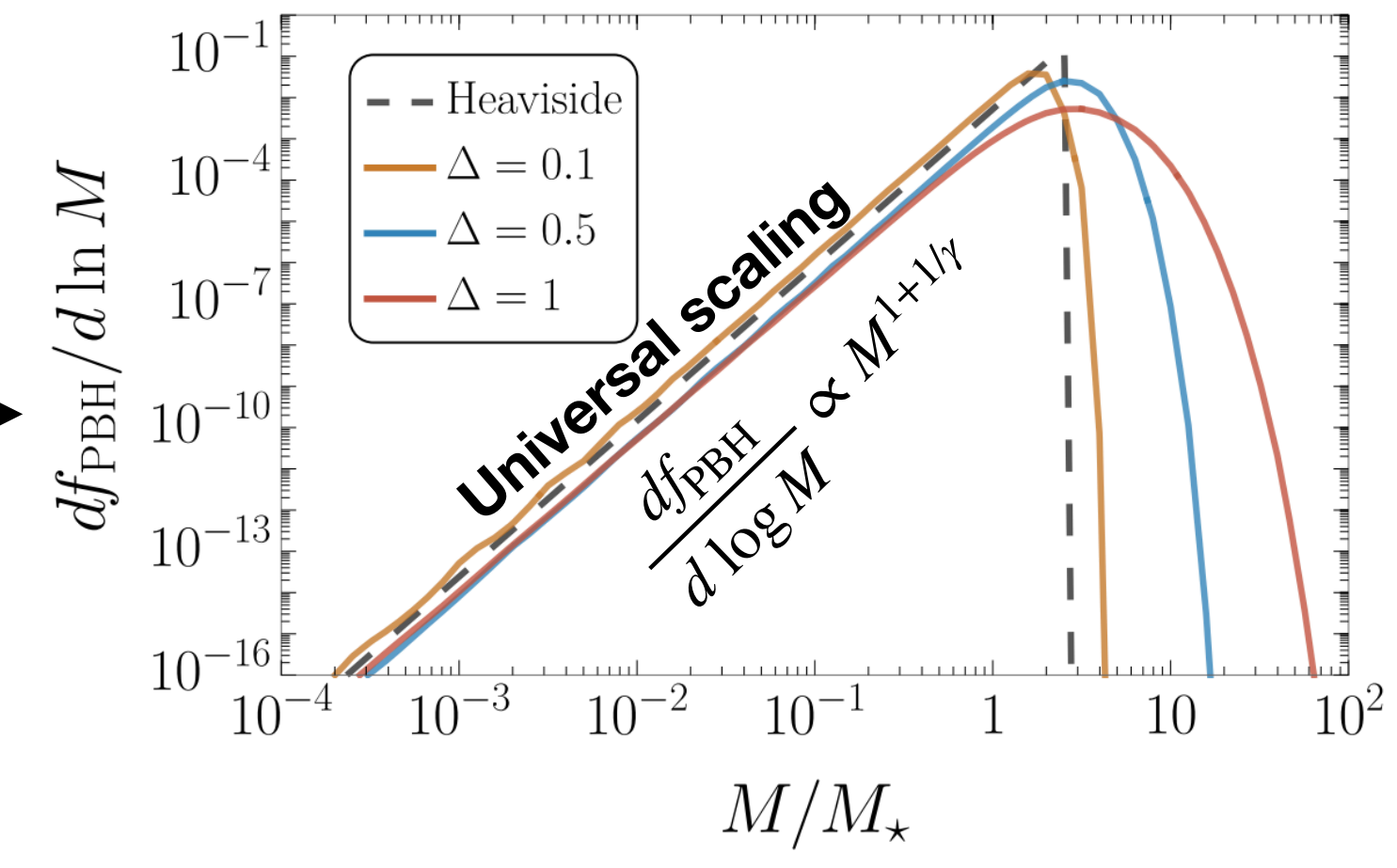
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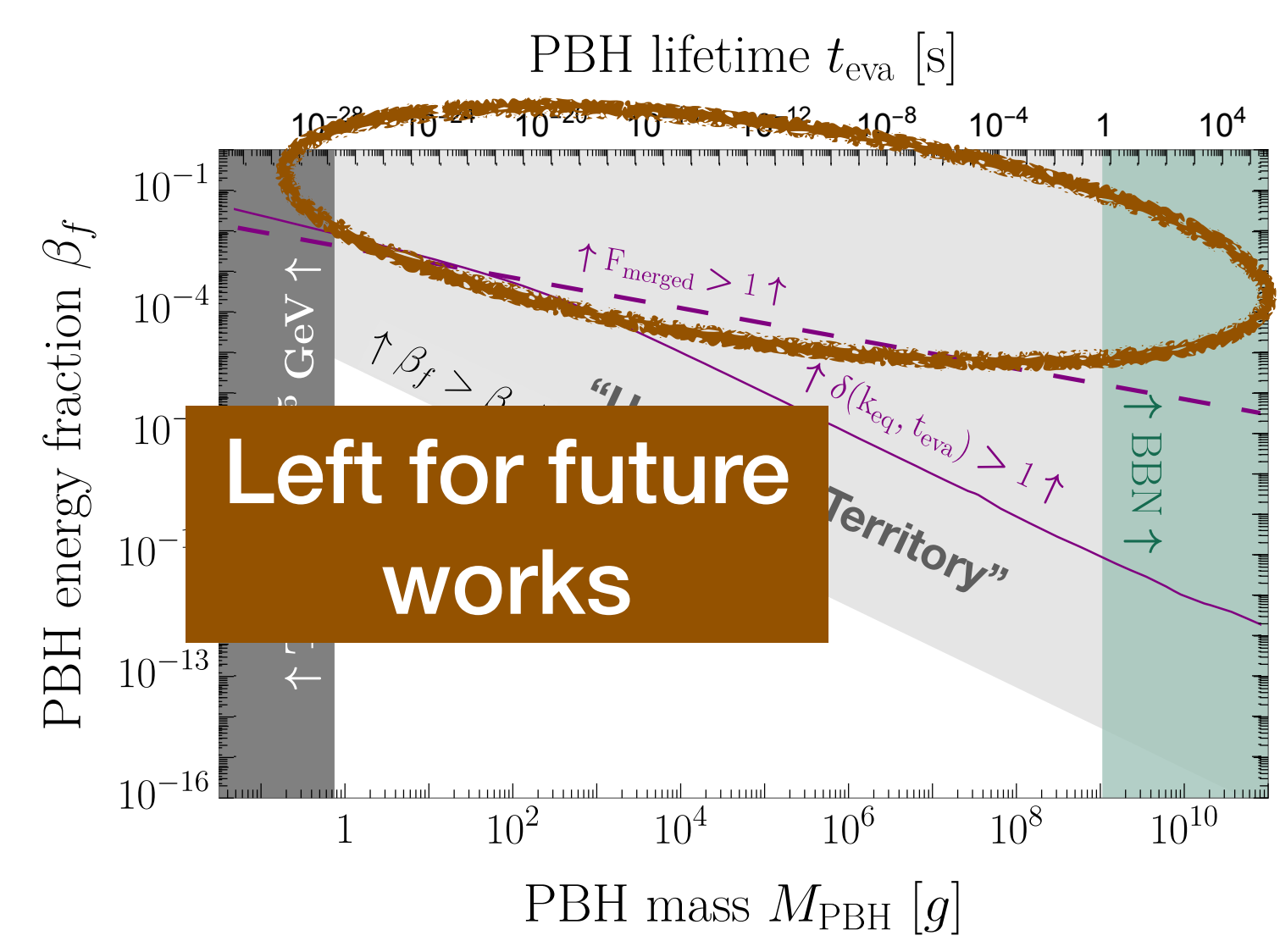


Opening the Window for Ultra-Light Primordial Black Holes

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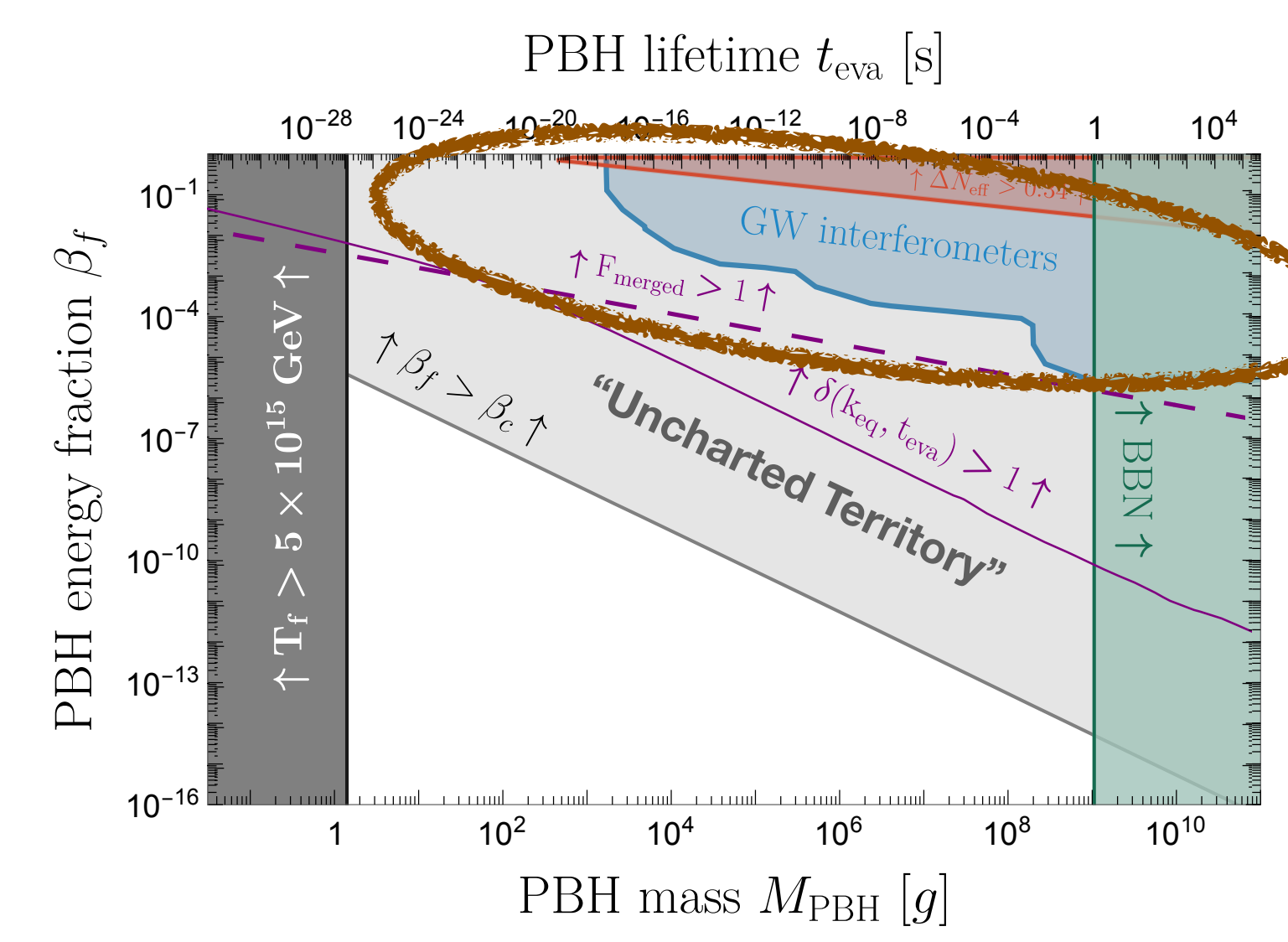
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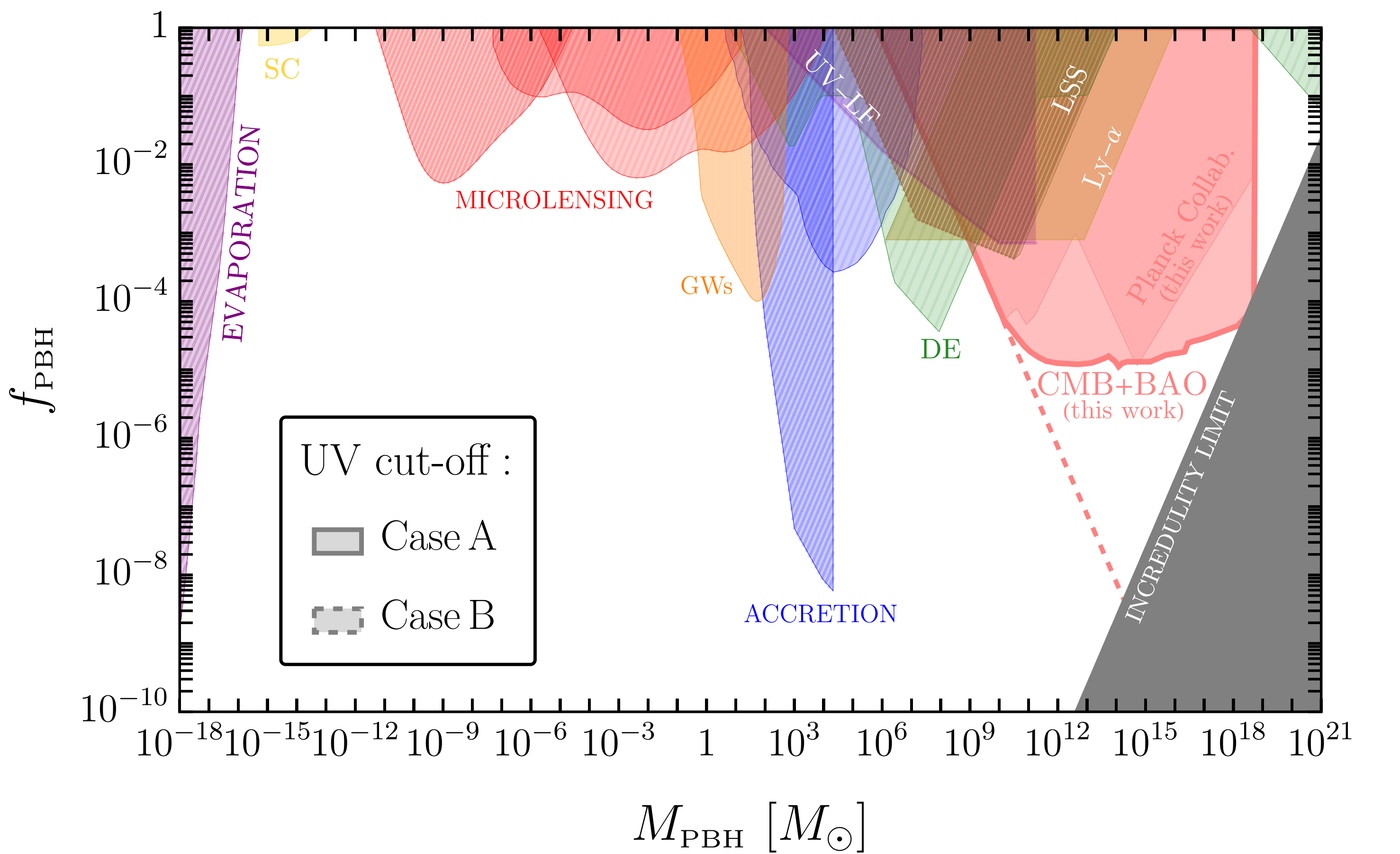
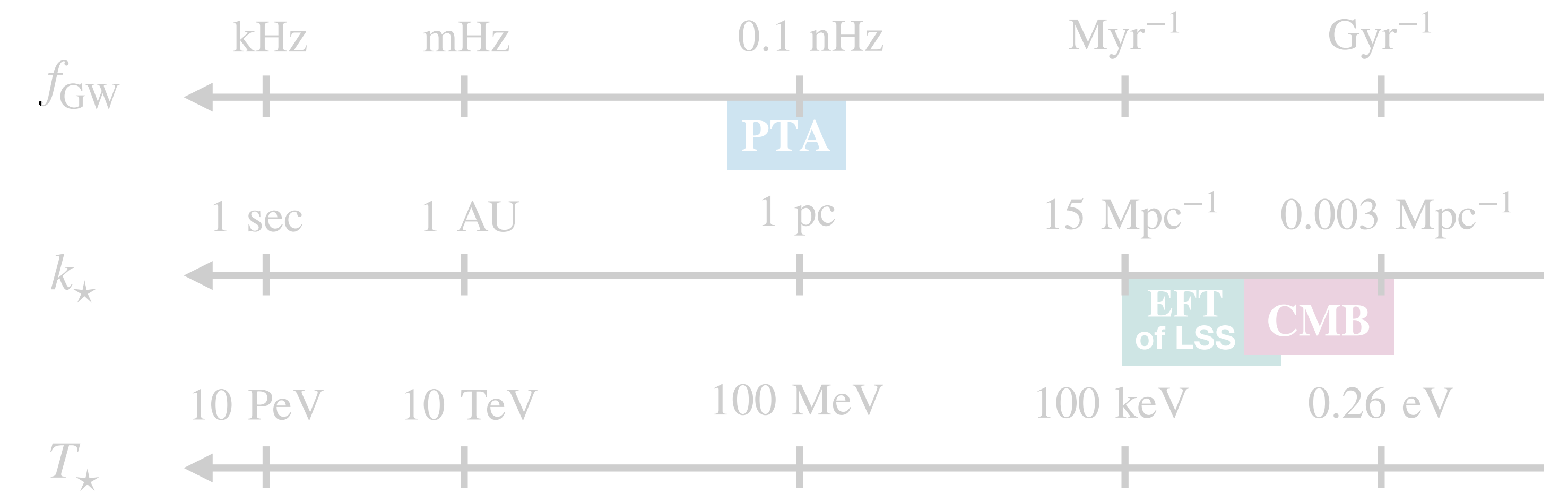
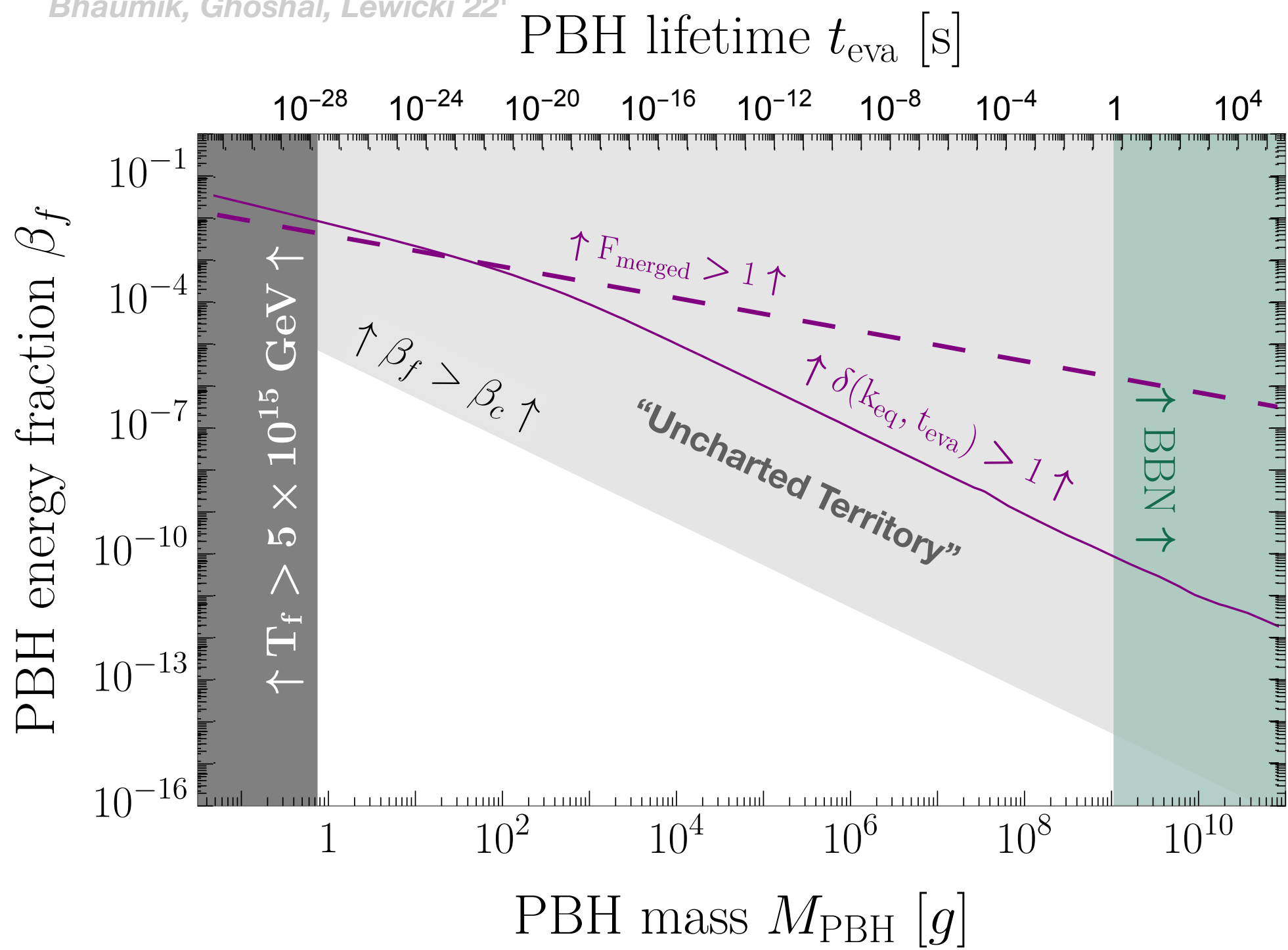
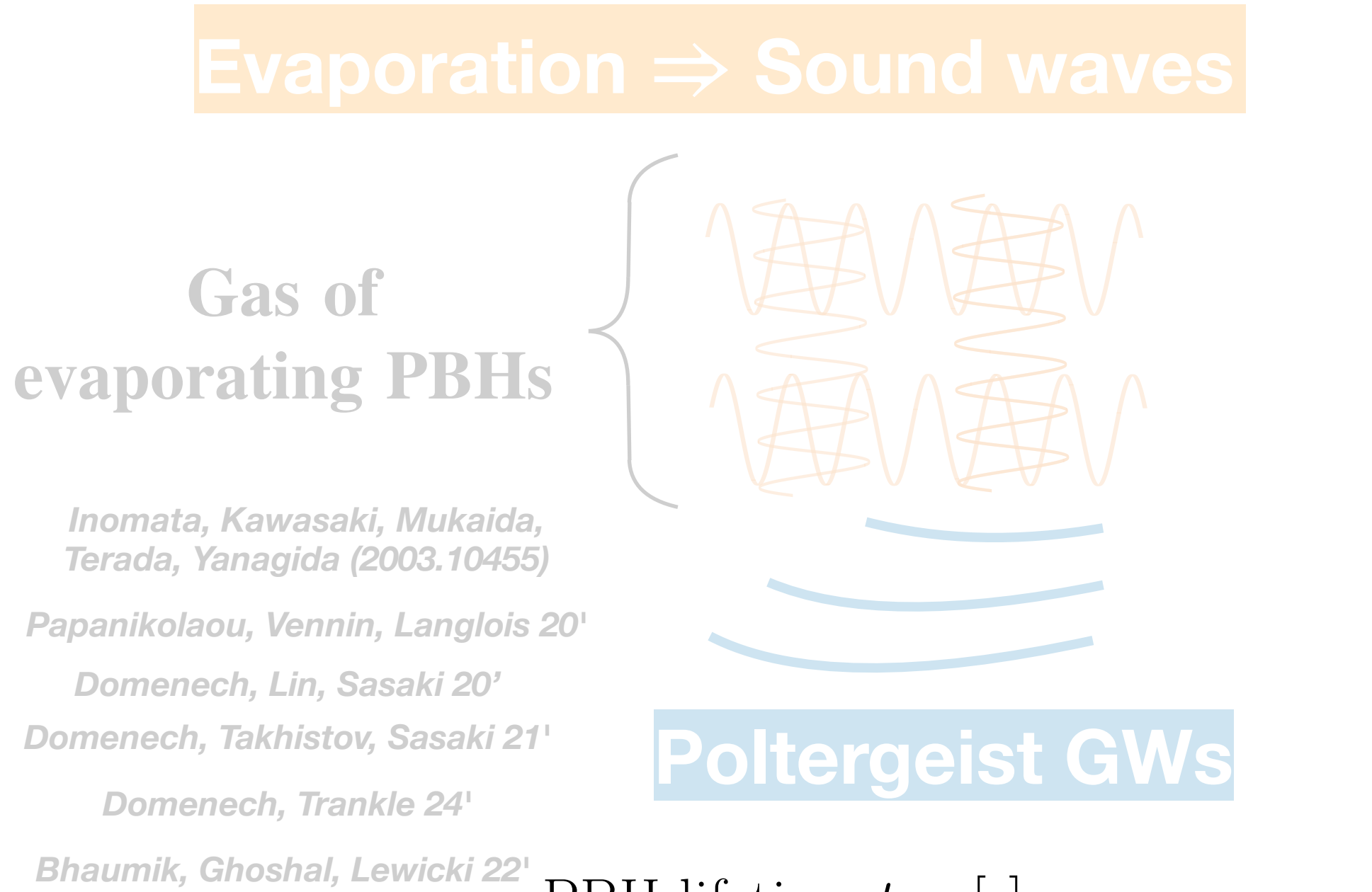
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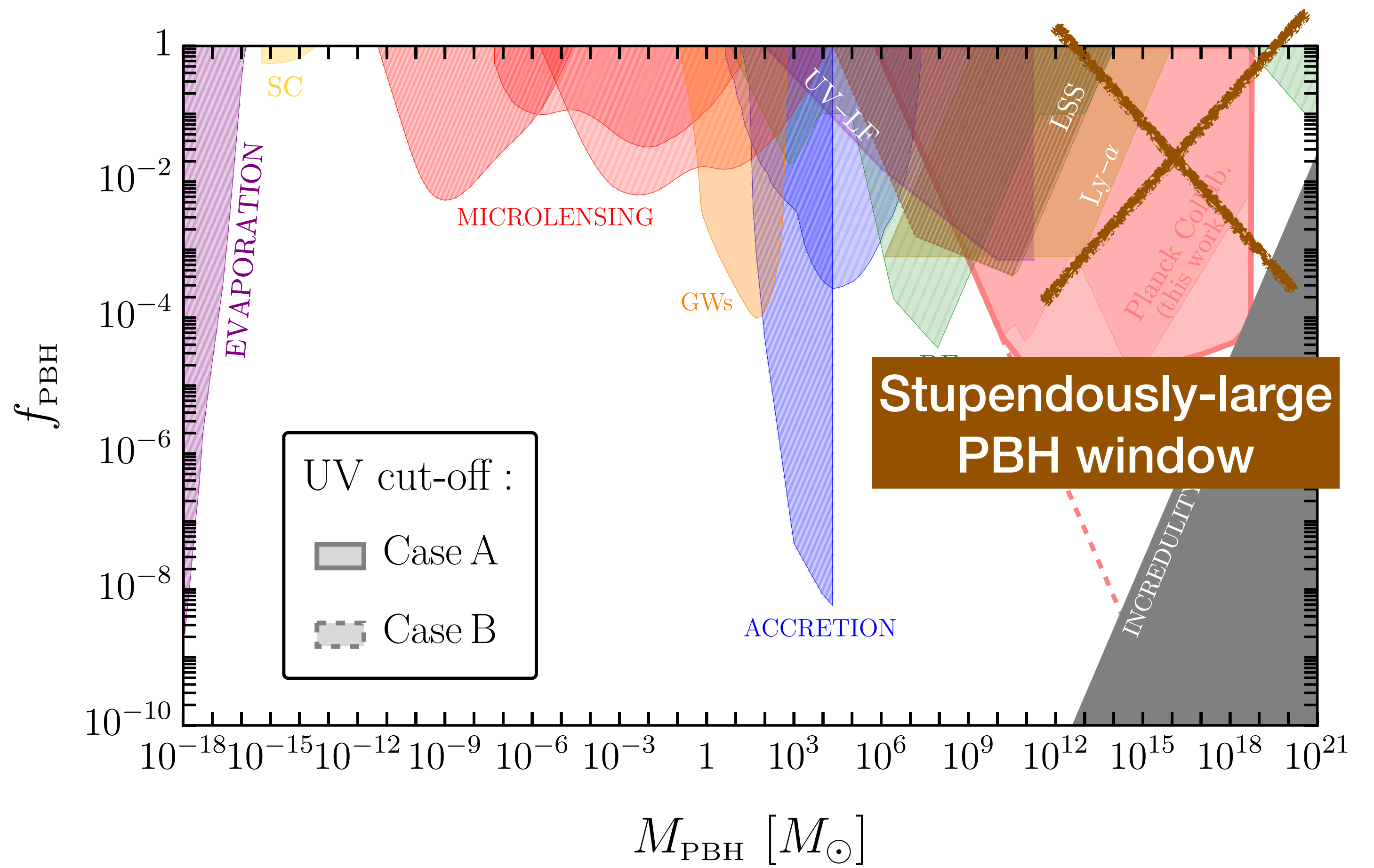
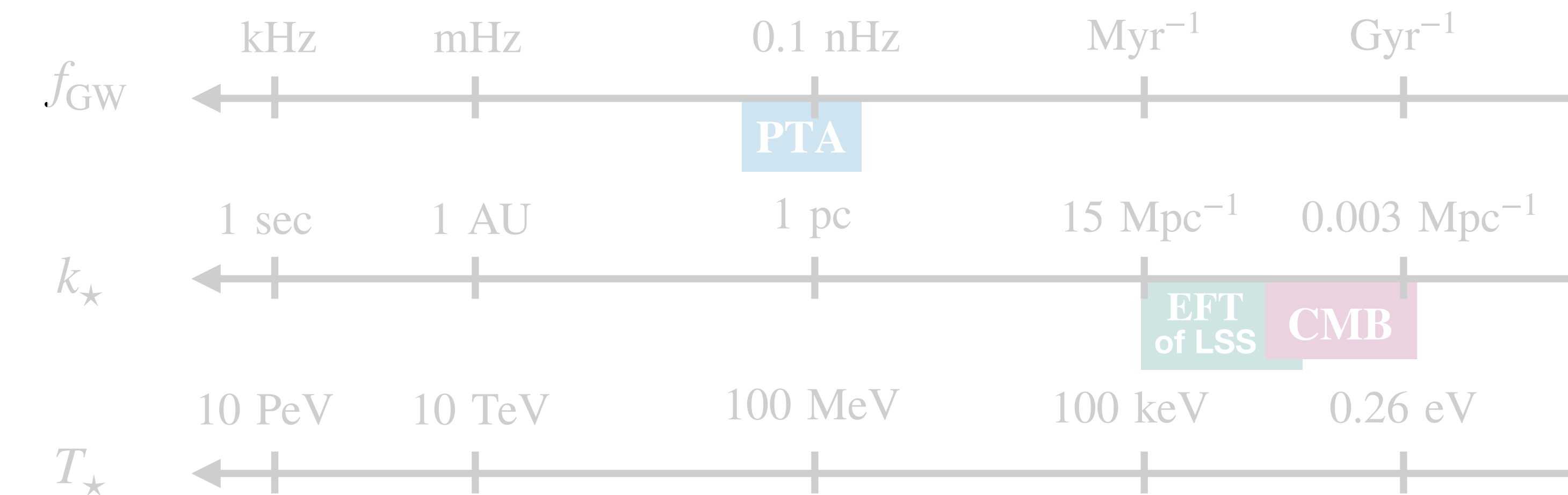
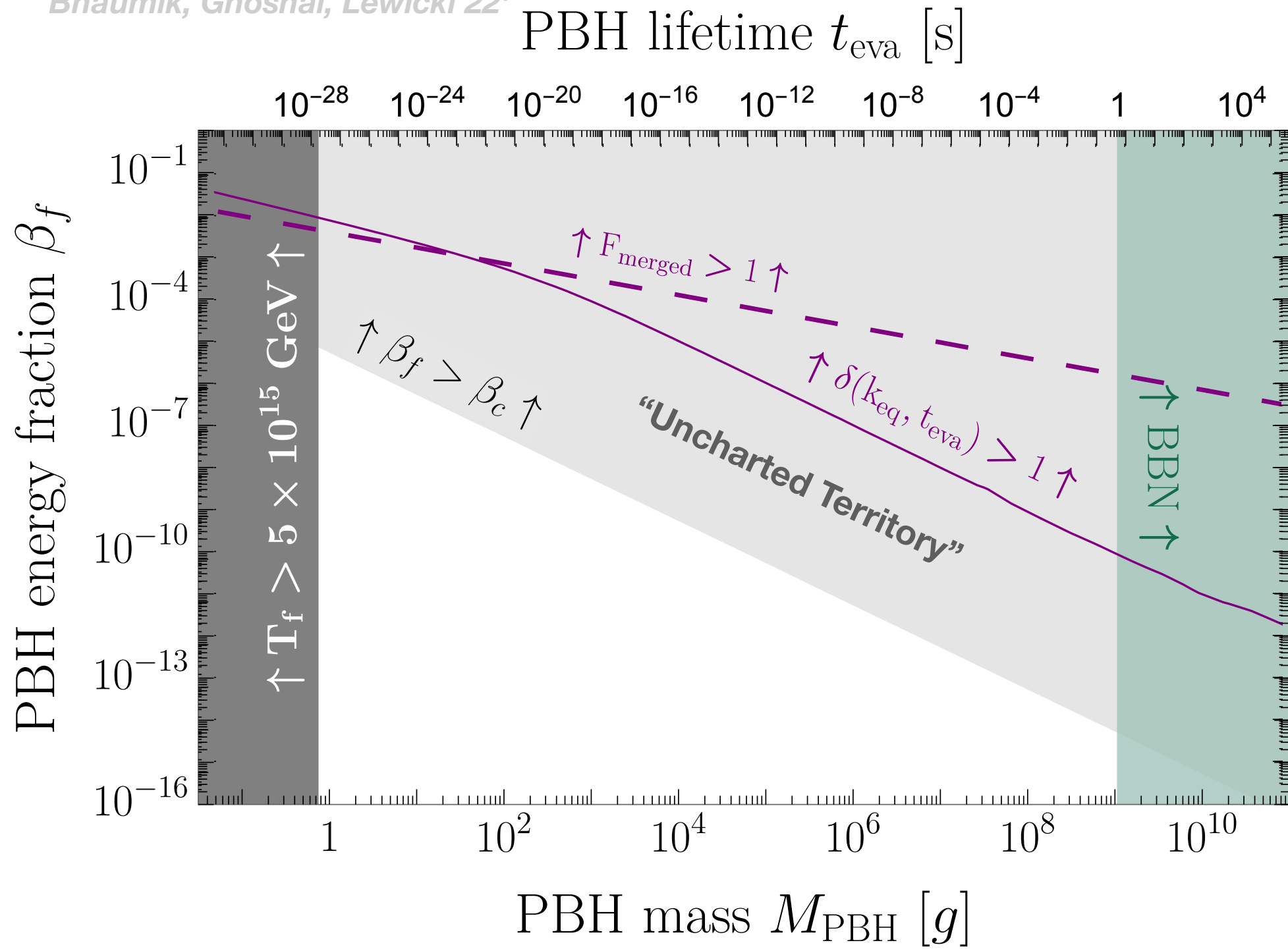
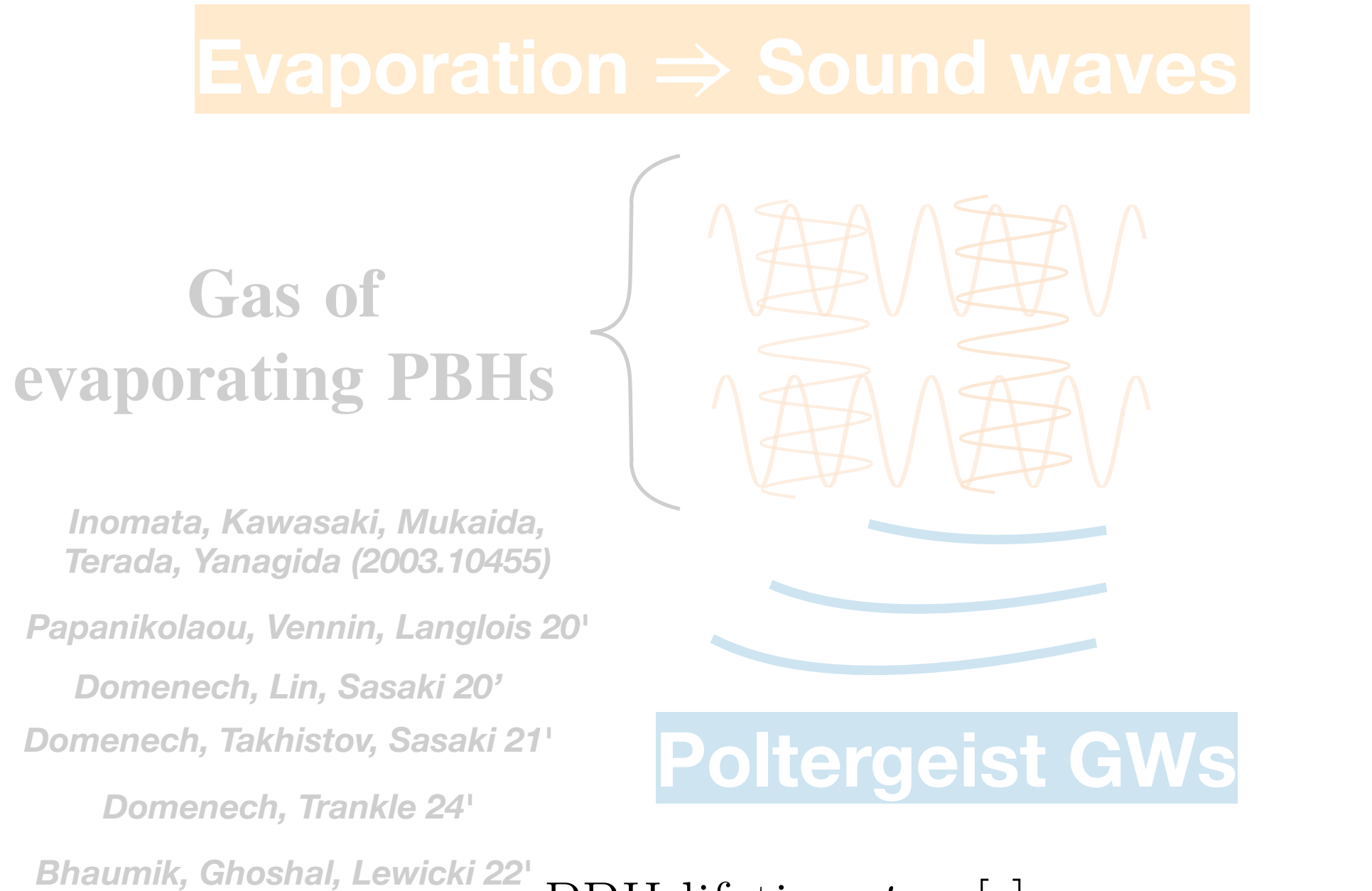


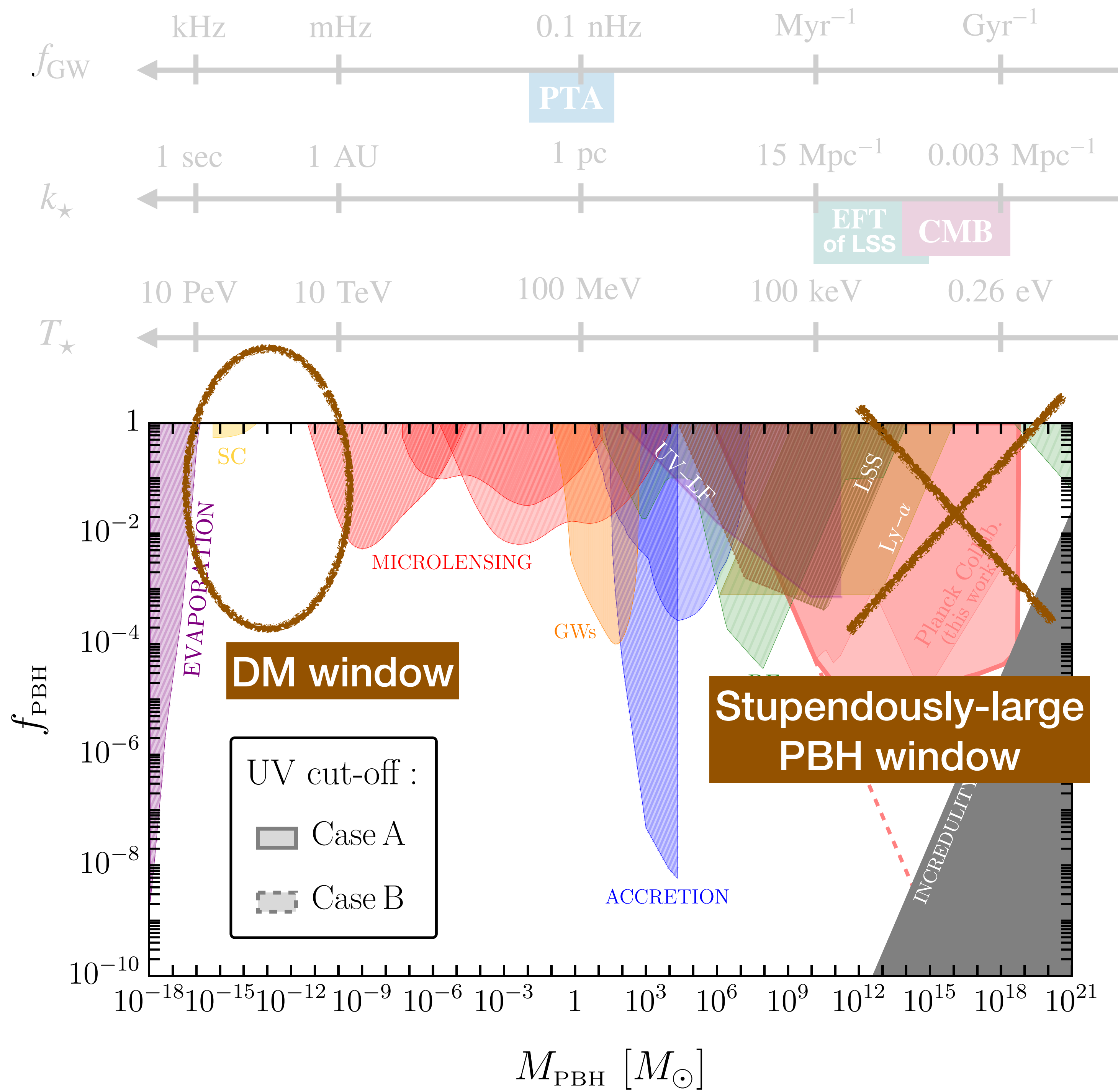
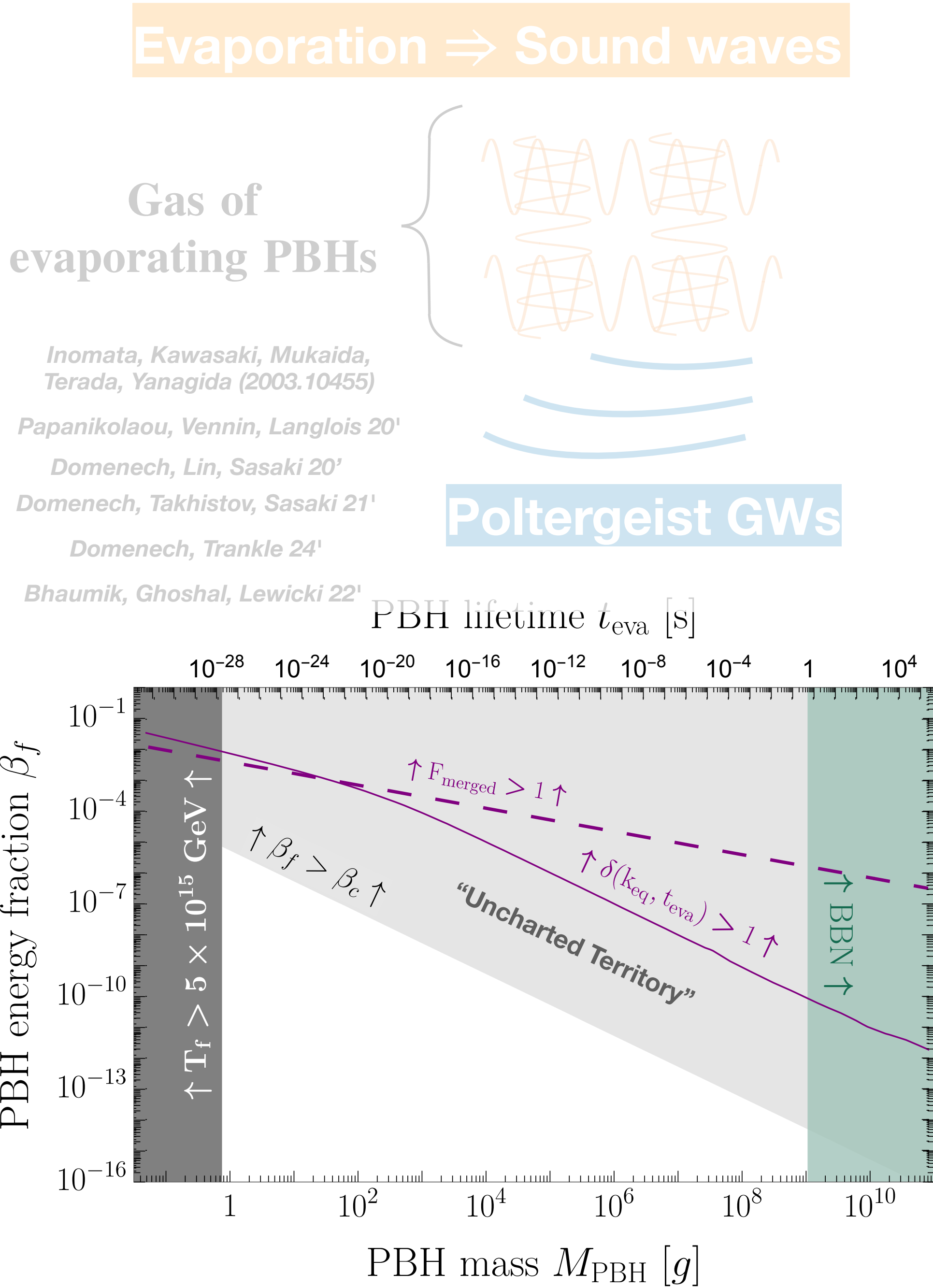
Left for future works

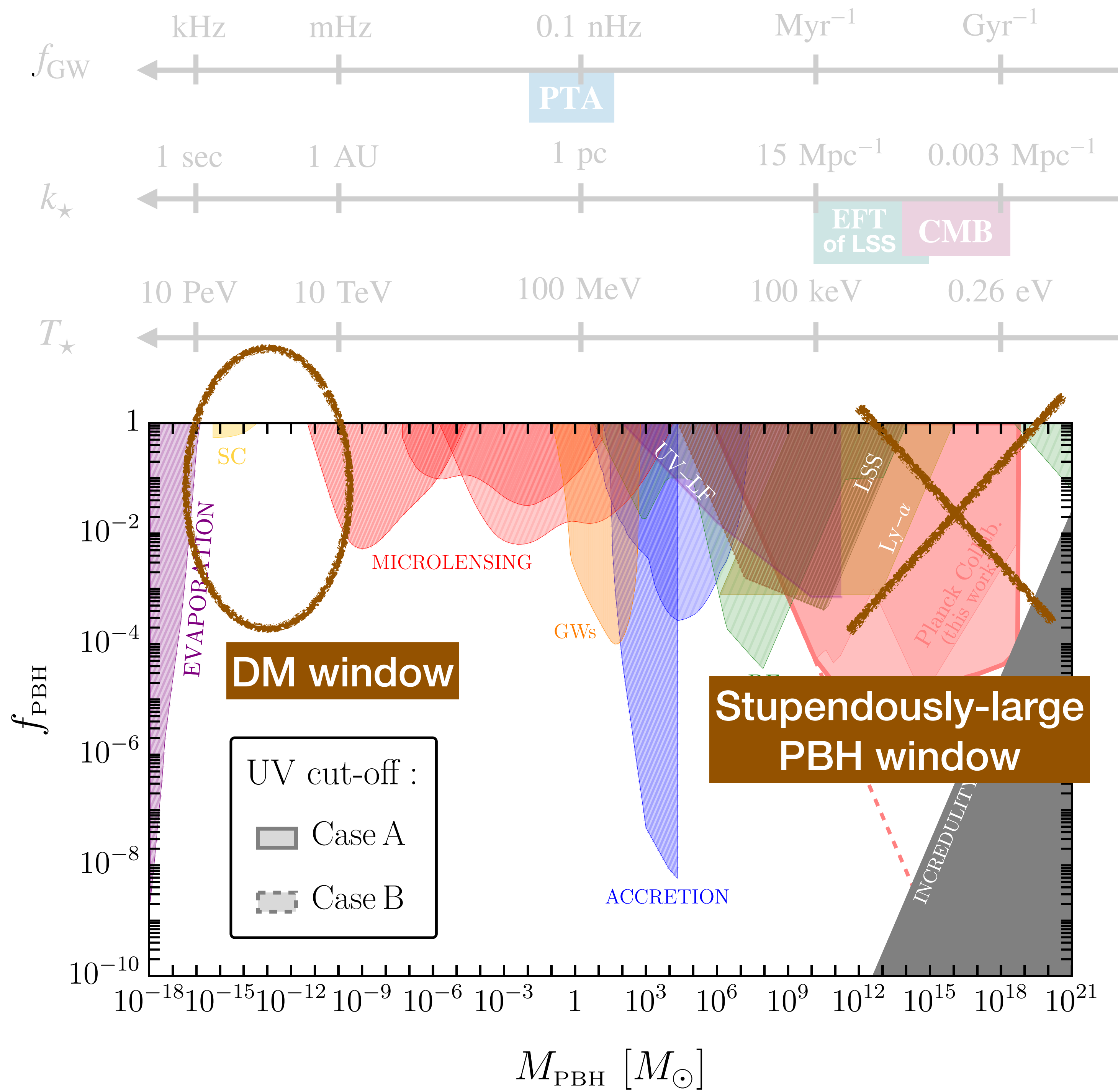
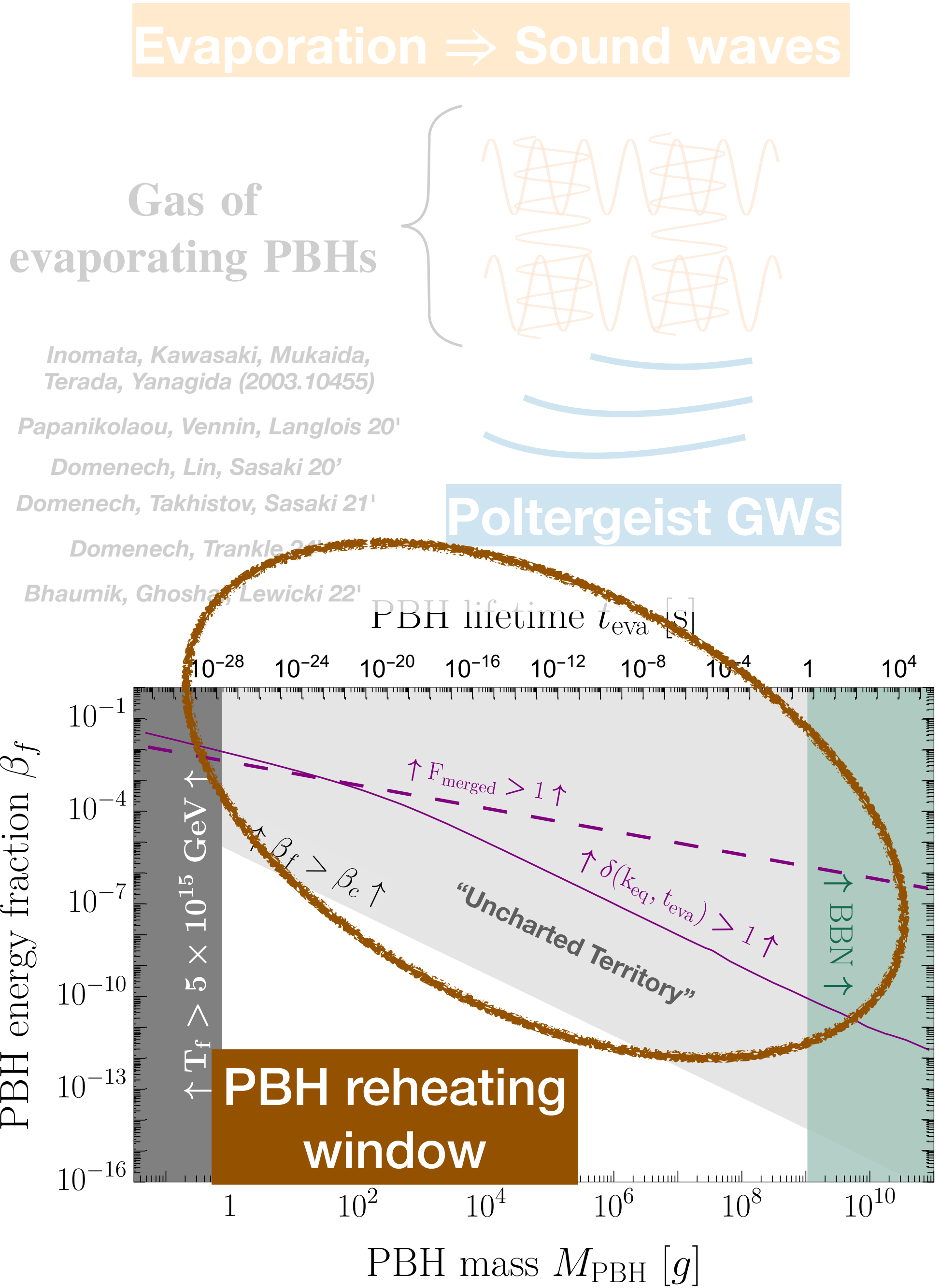
$$k_{\text{cut}} = k_{\text{PBH}} \quad (\text{aggressive})$$











Pulsar Timing Arrays (PTA)

1 M_⊙

10 km

500 rotations/s

Pulses

Pulses

Gravitational
Waves

The New York Times

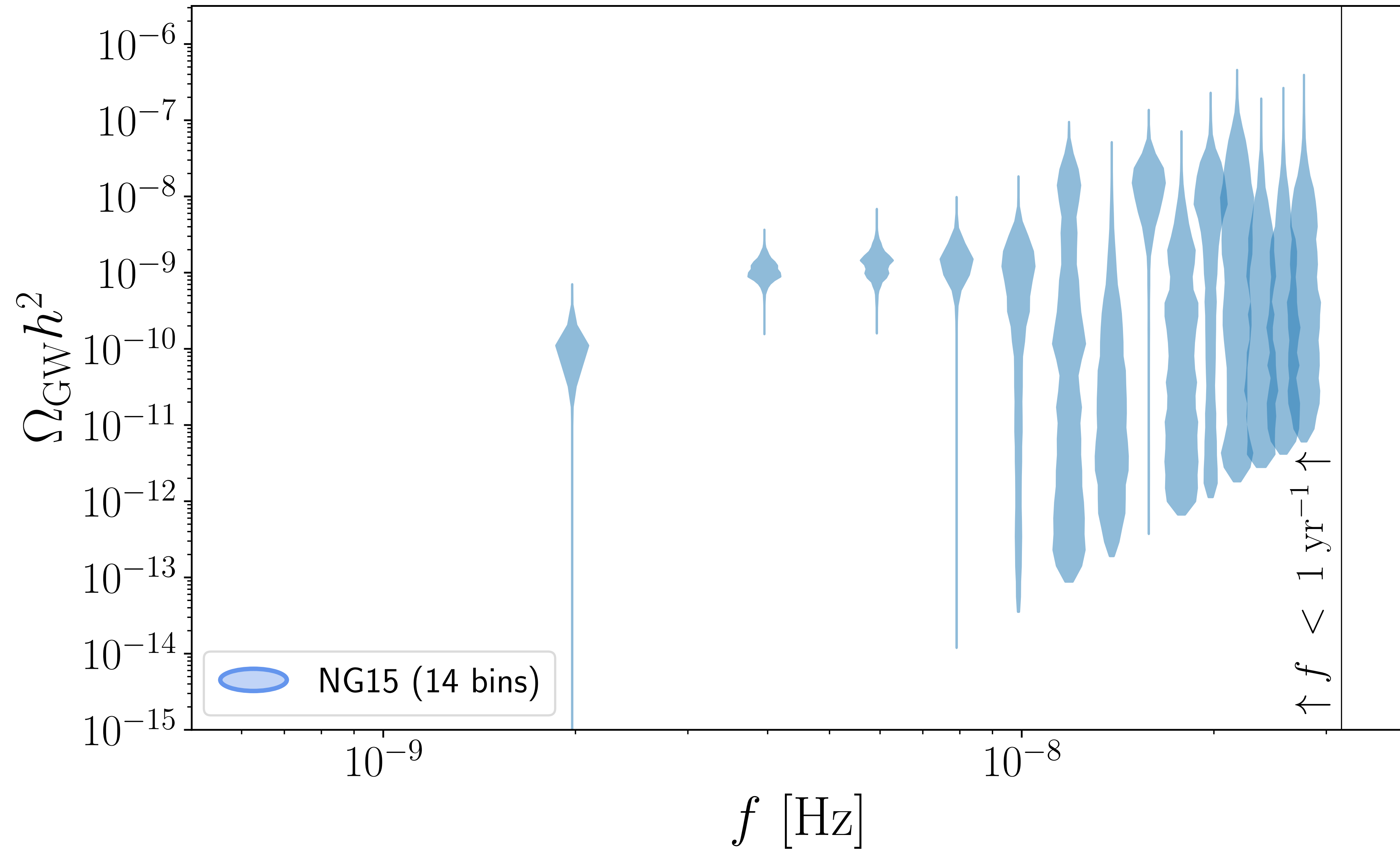
© 2023 The New York Times Company

NEW YORK, THURSDAY, JUNE 29, 2023

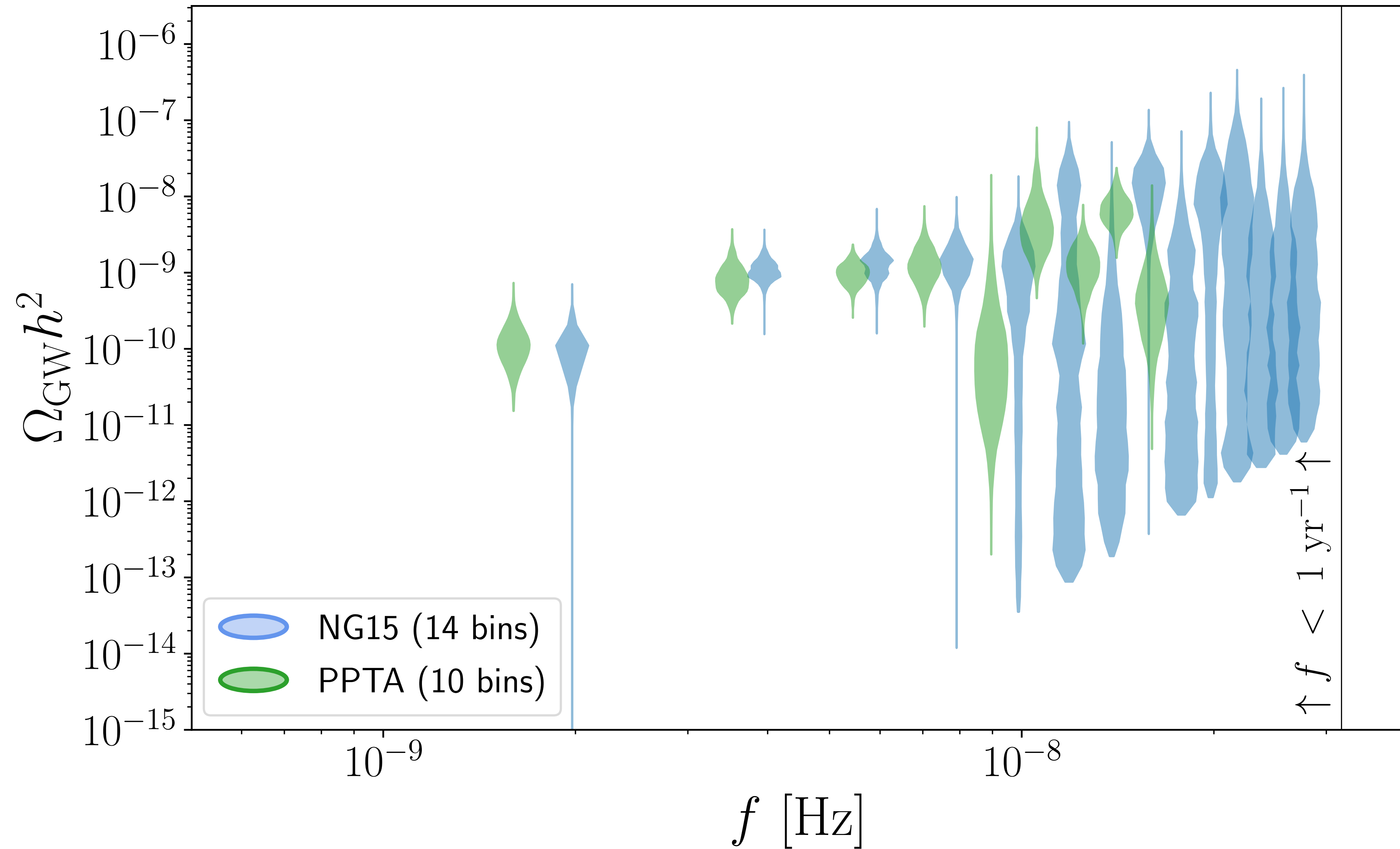
*The Cosmos Is Thrumming With
Gravitational Waves, Astronomers
Find*



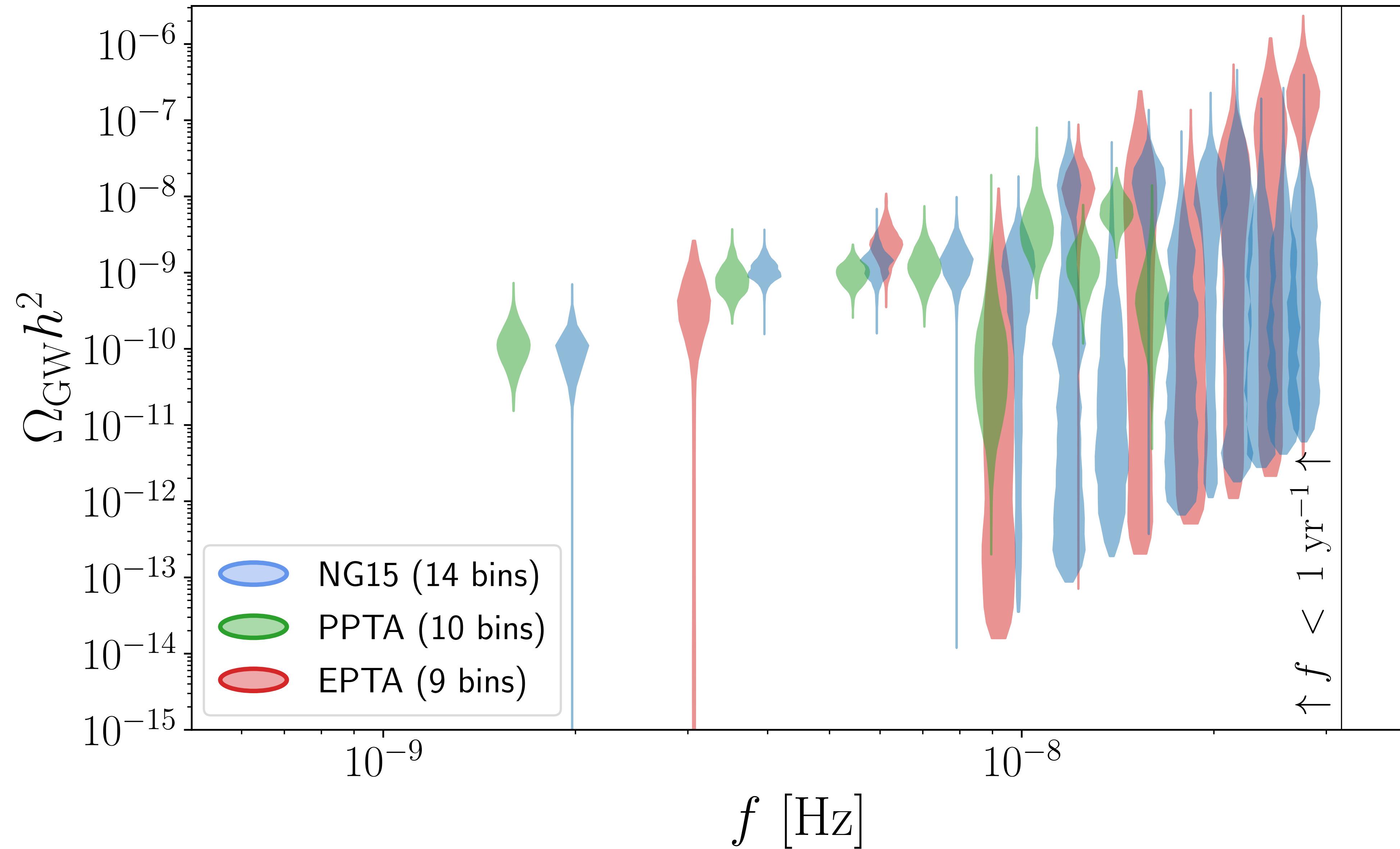
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



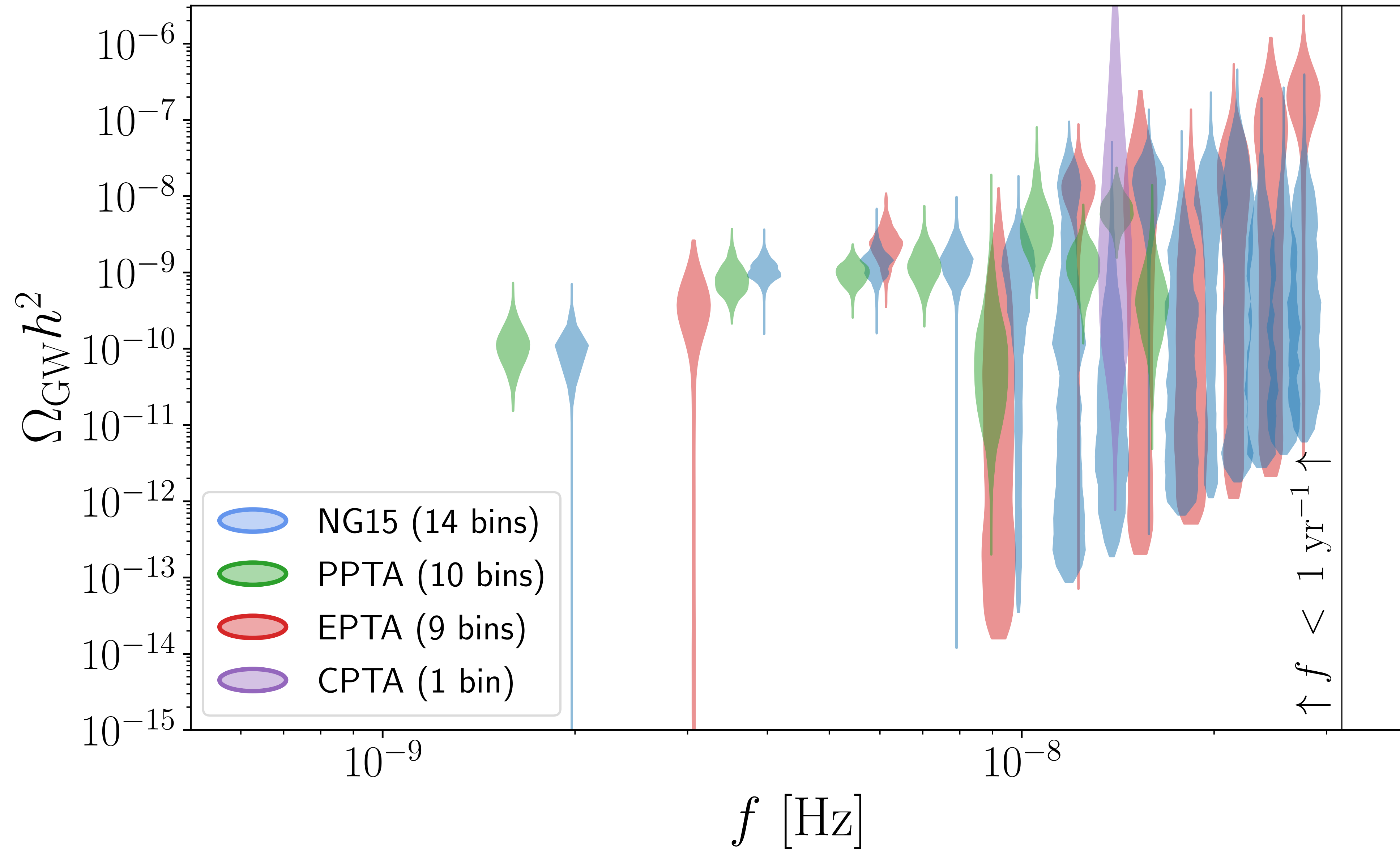
Discovery of the first stochastic GW background by Pulsar Timing Arrays (PTA)



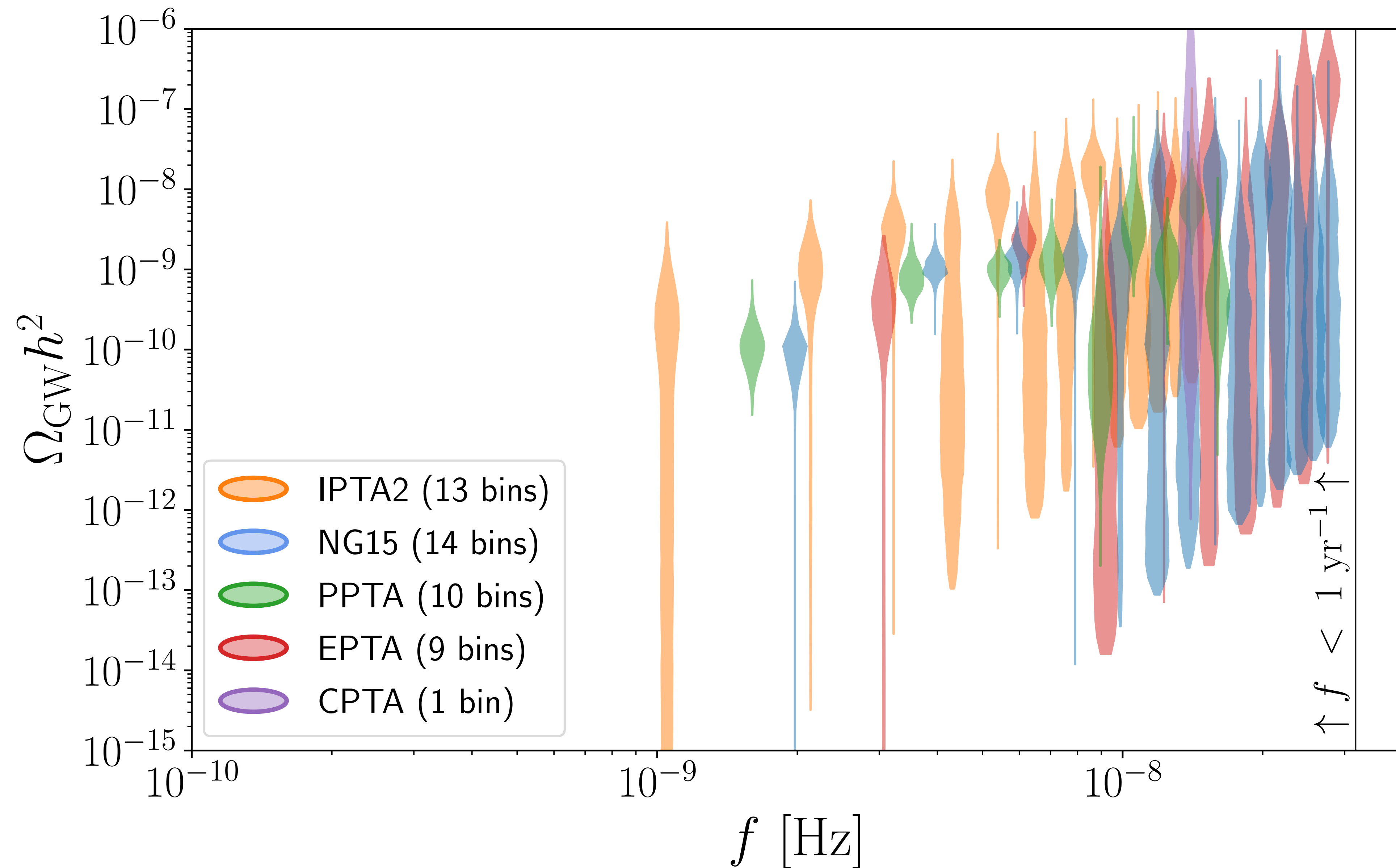
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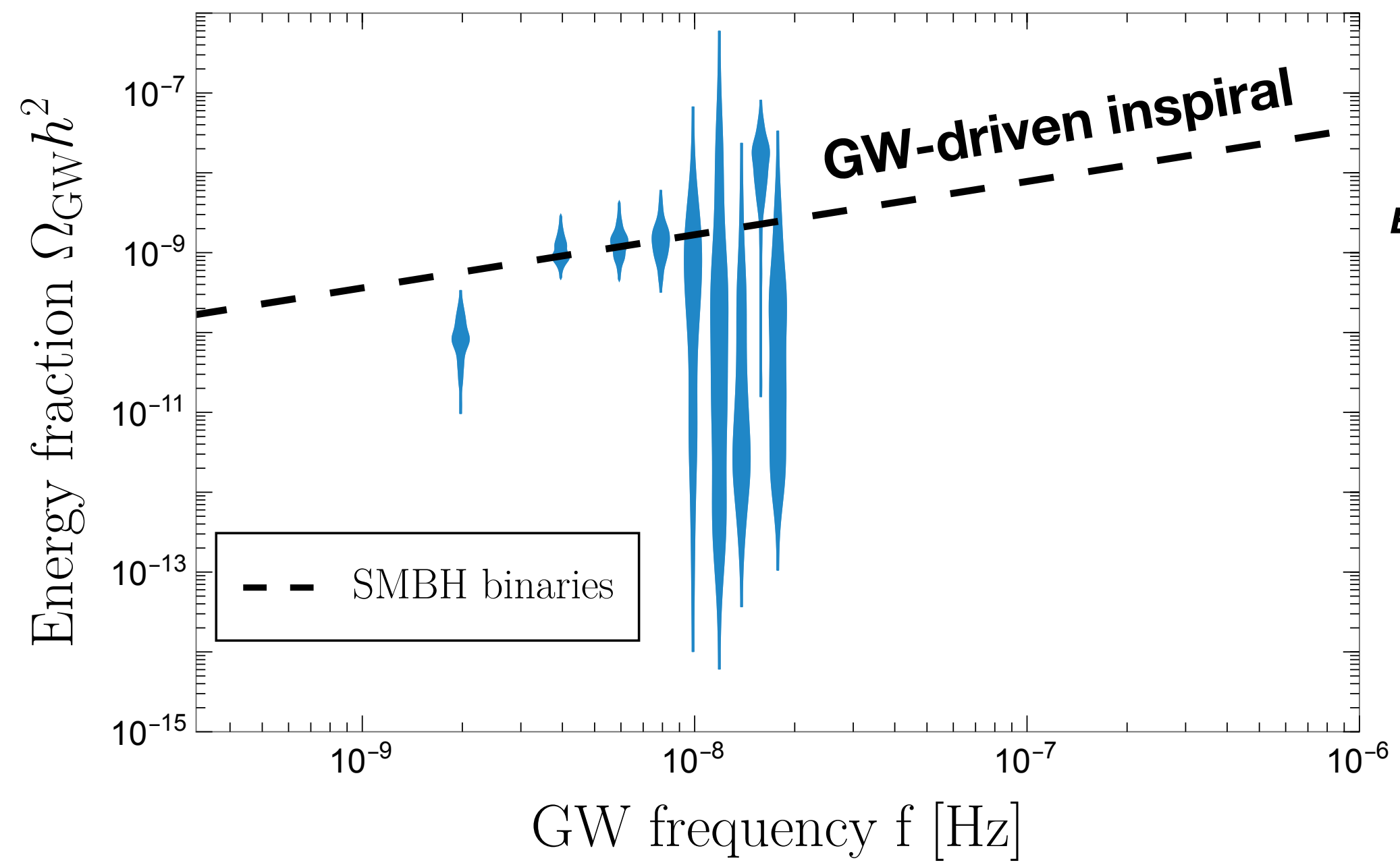
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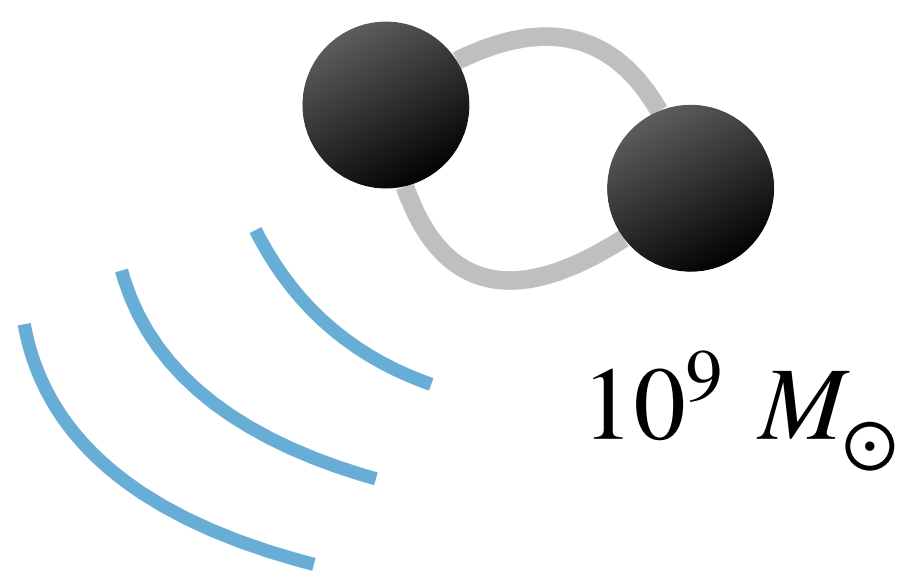


Pulsar Timing Arrays (PTA)



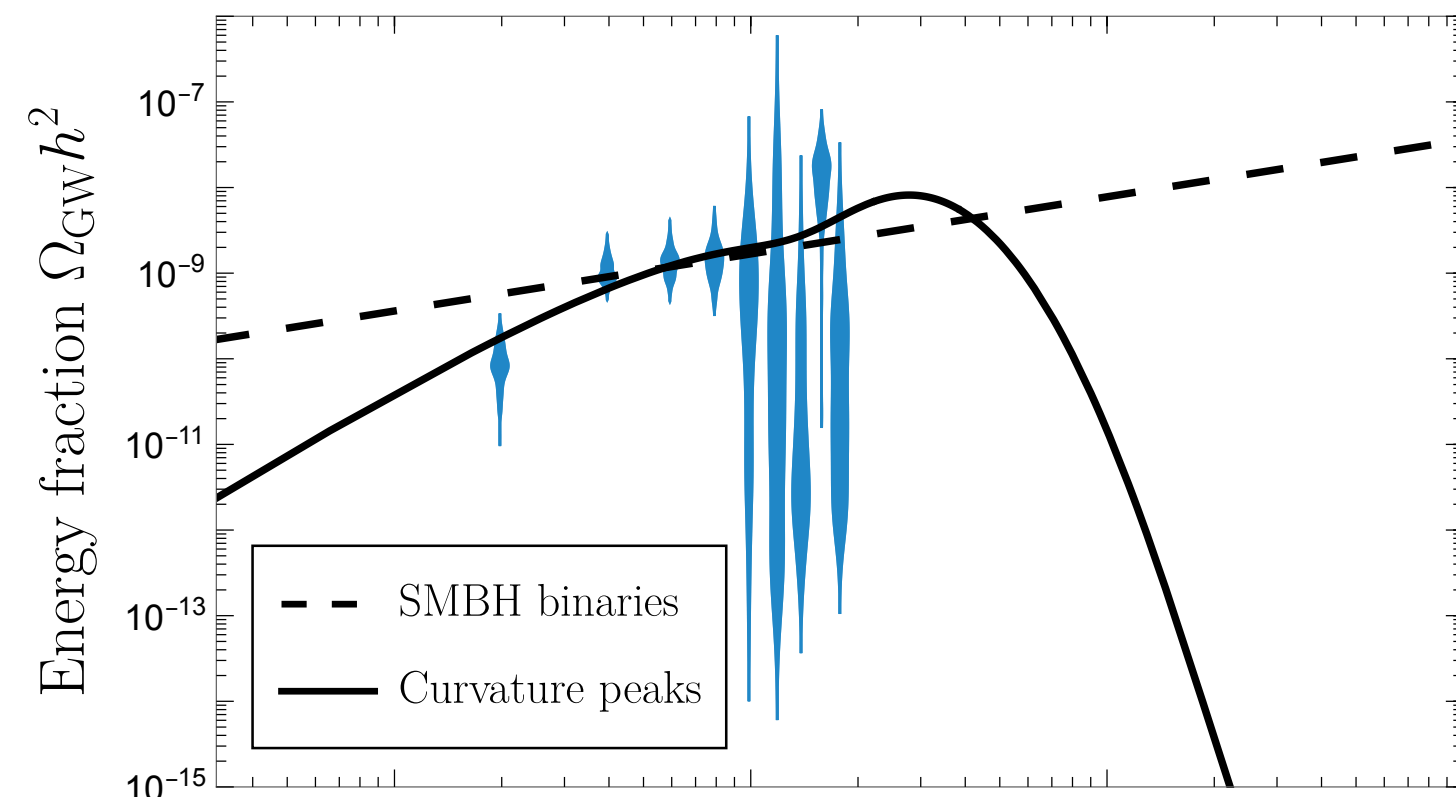
*Ellis, Fairbairn, Hutsi, Raidal, Urrutia,
Vaskonen, Veermäe (23', 24')*

Supermassive
black holes binaries



Gravitational Waves



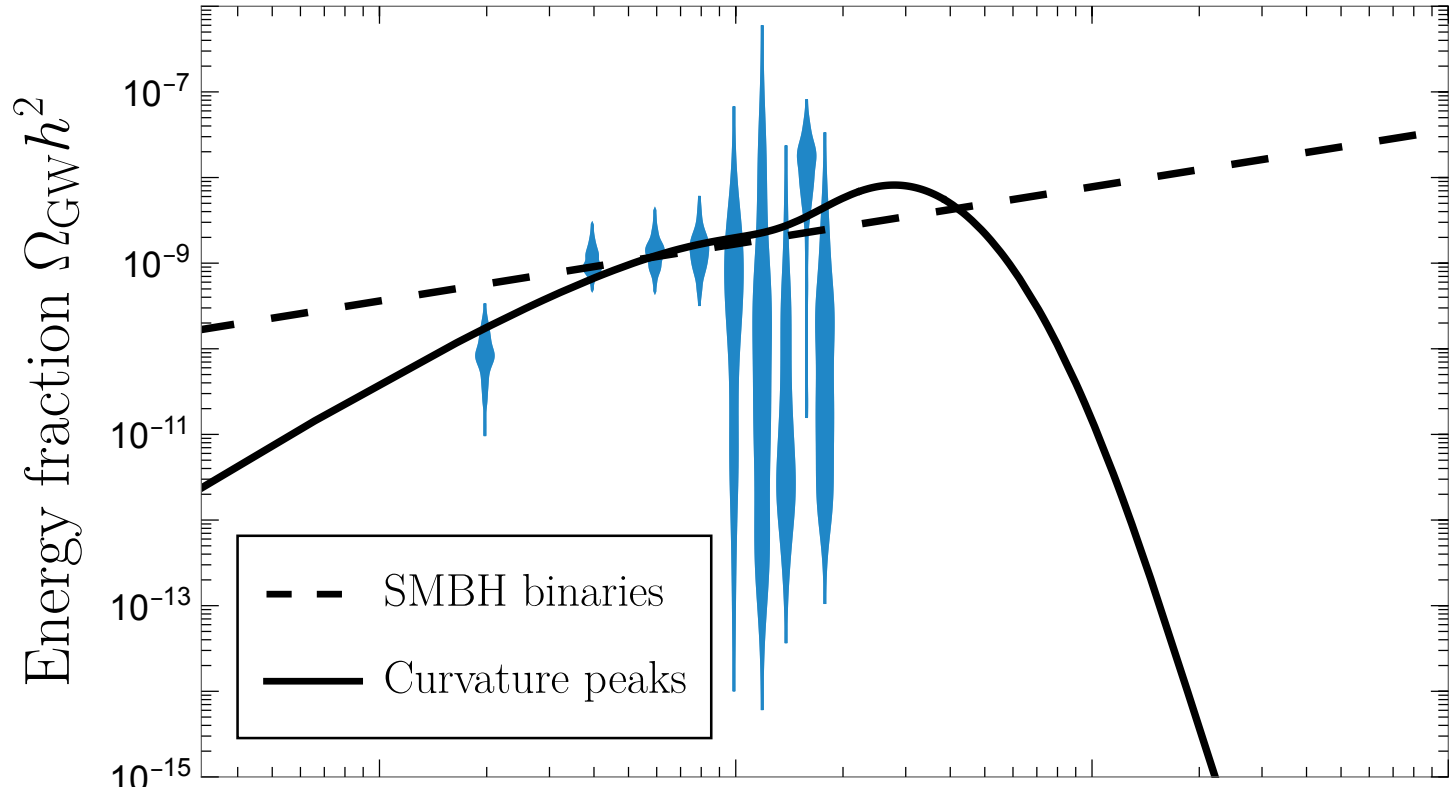


Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermae (2009.07832),
Franciolini, Iovino, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...

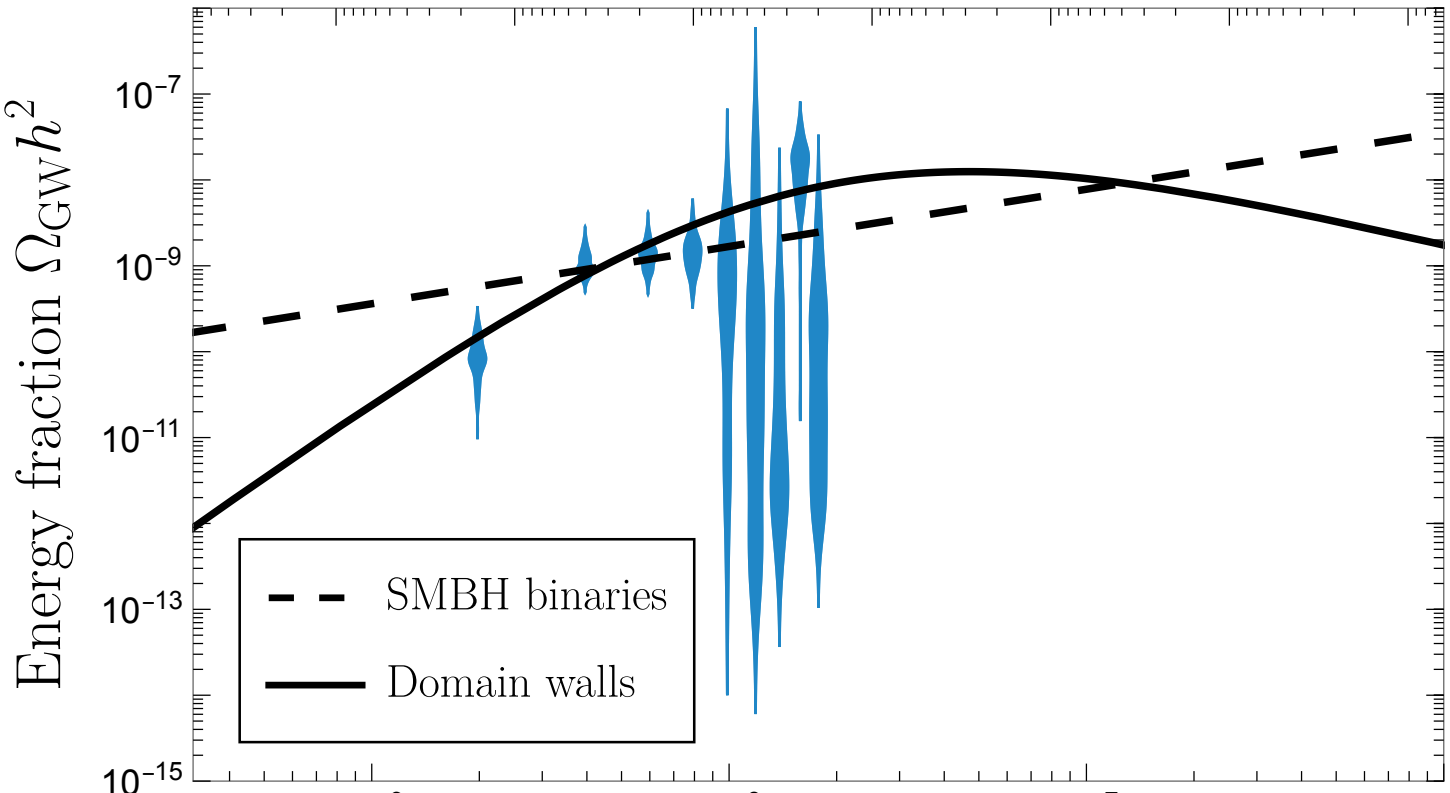


Reviews: Madge et al (2306.14856),
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



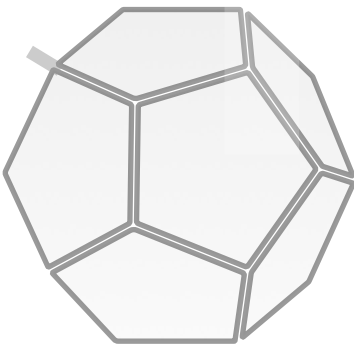
Curvature peaks

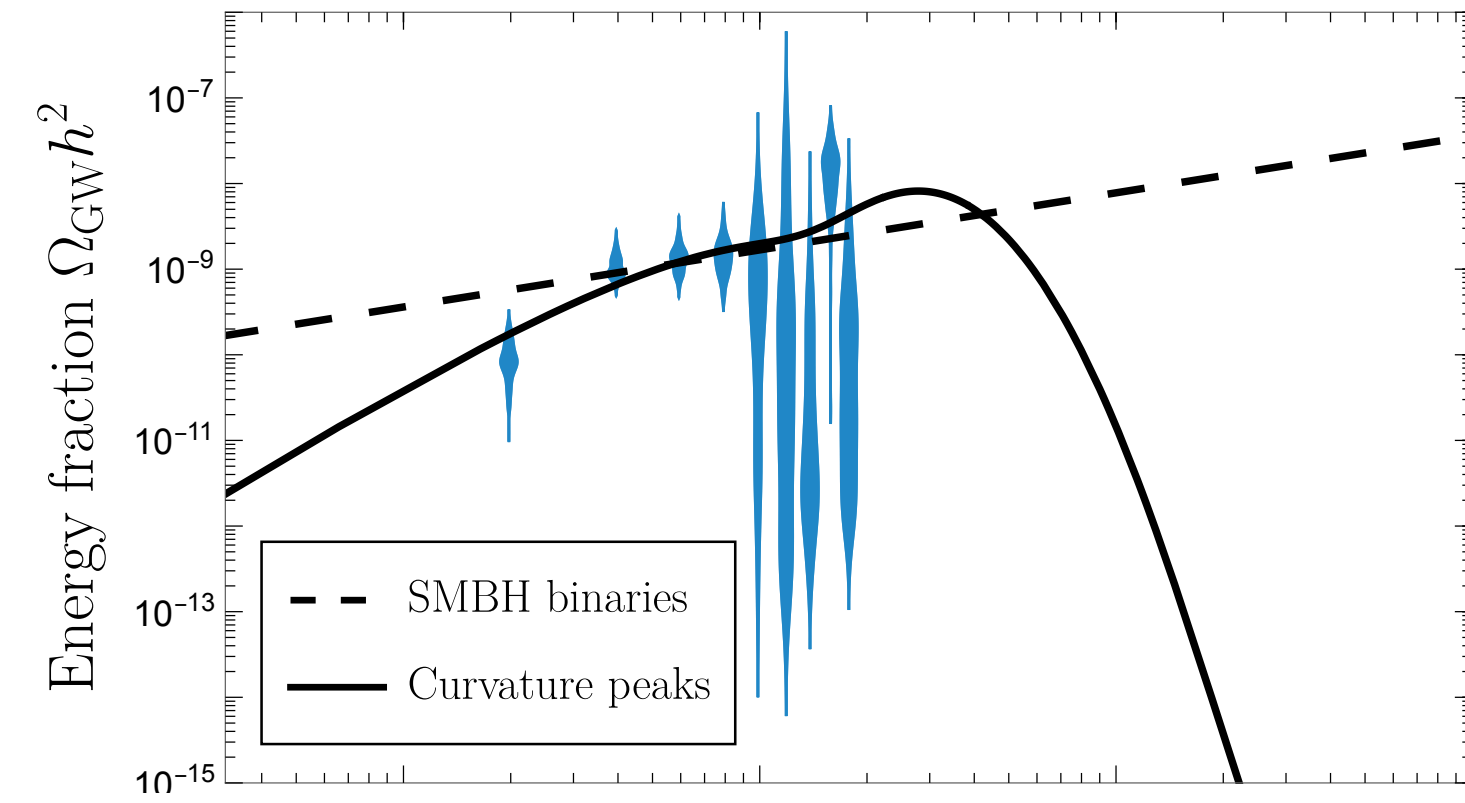
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...



Domain wall networks

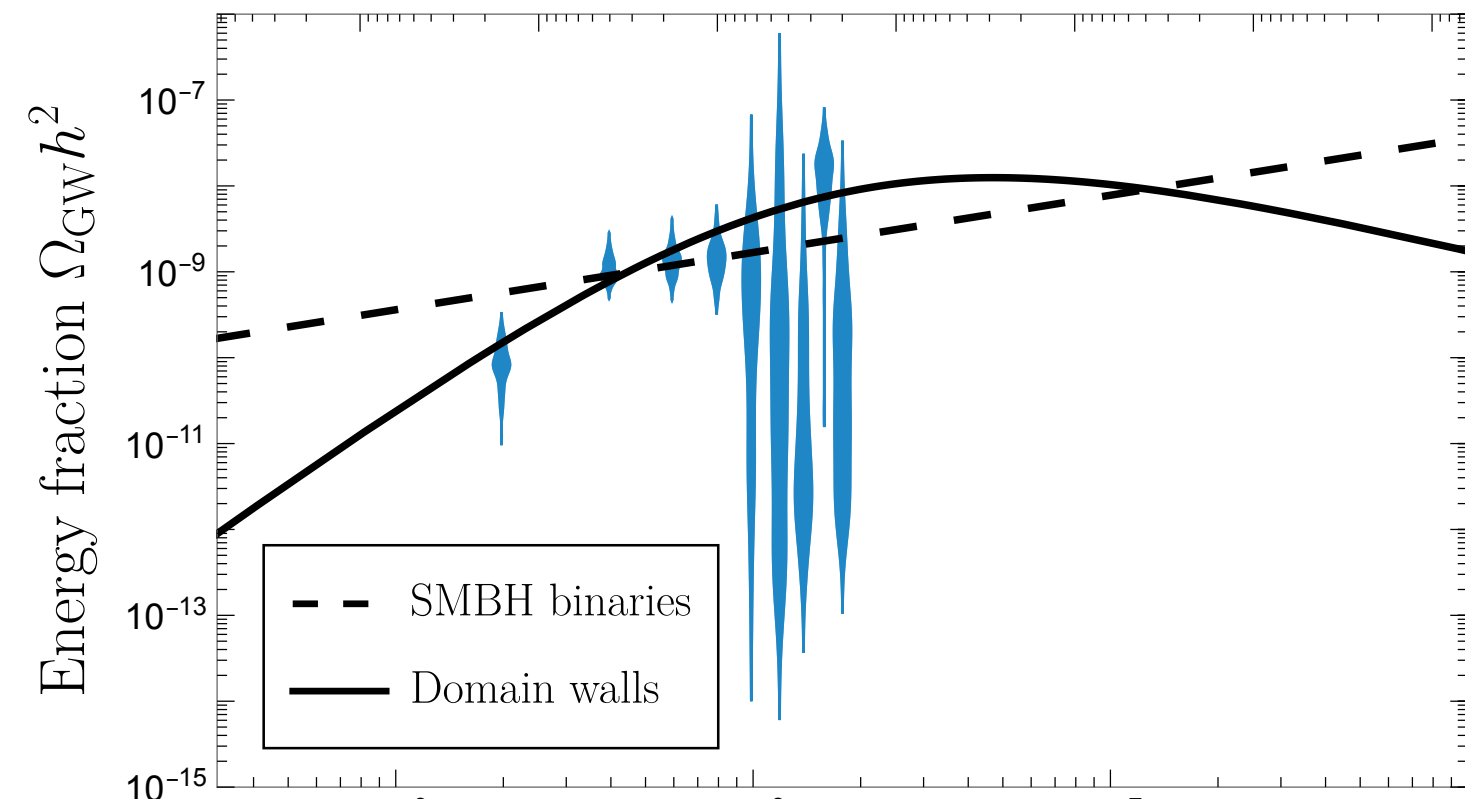
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...





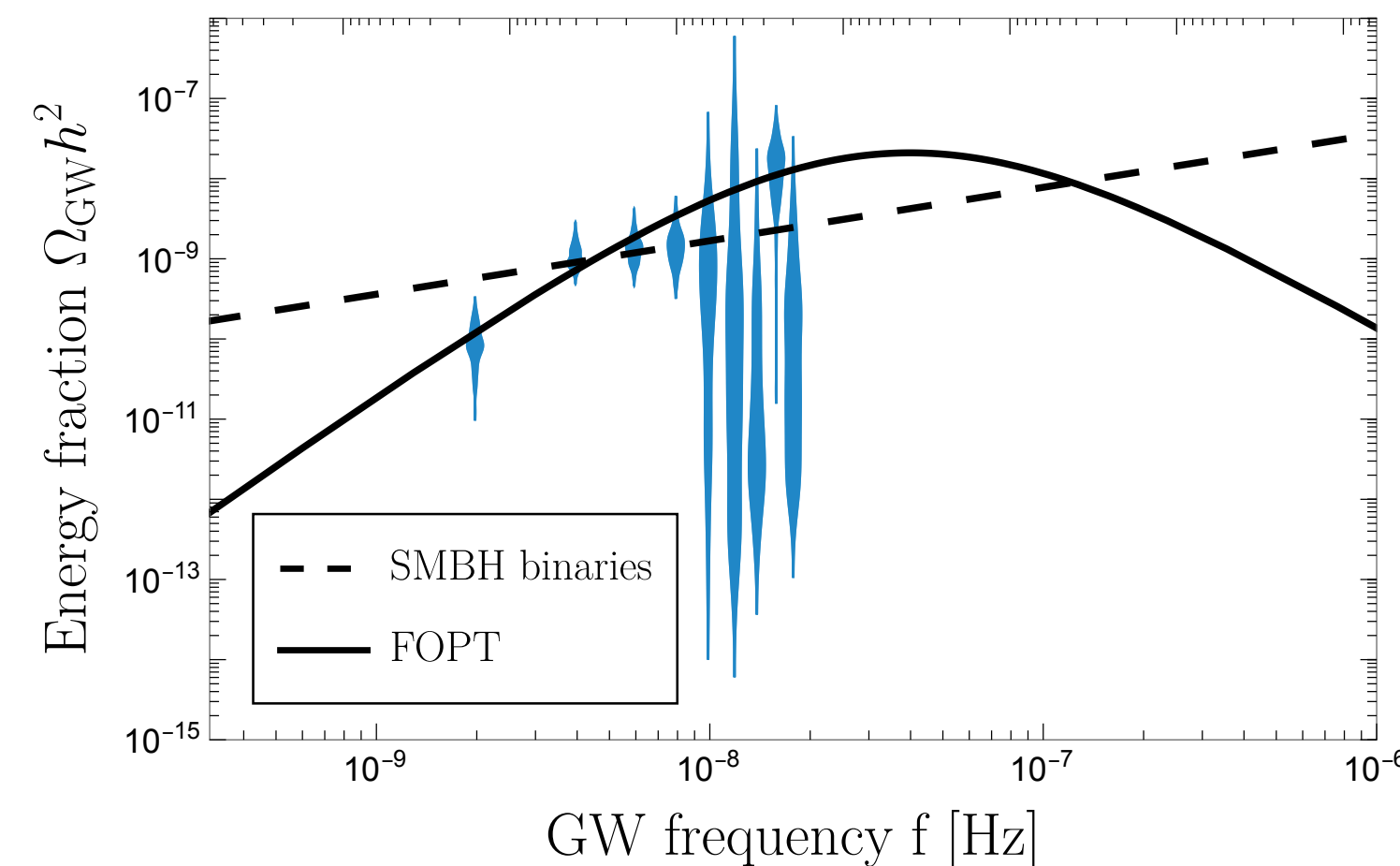
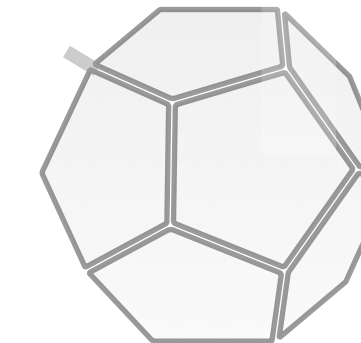
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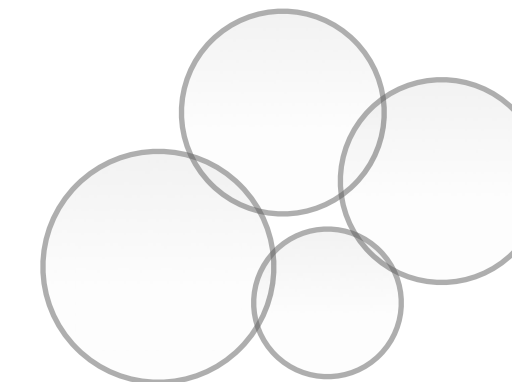
Domain wall networks

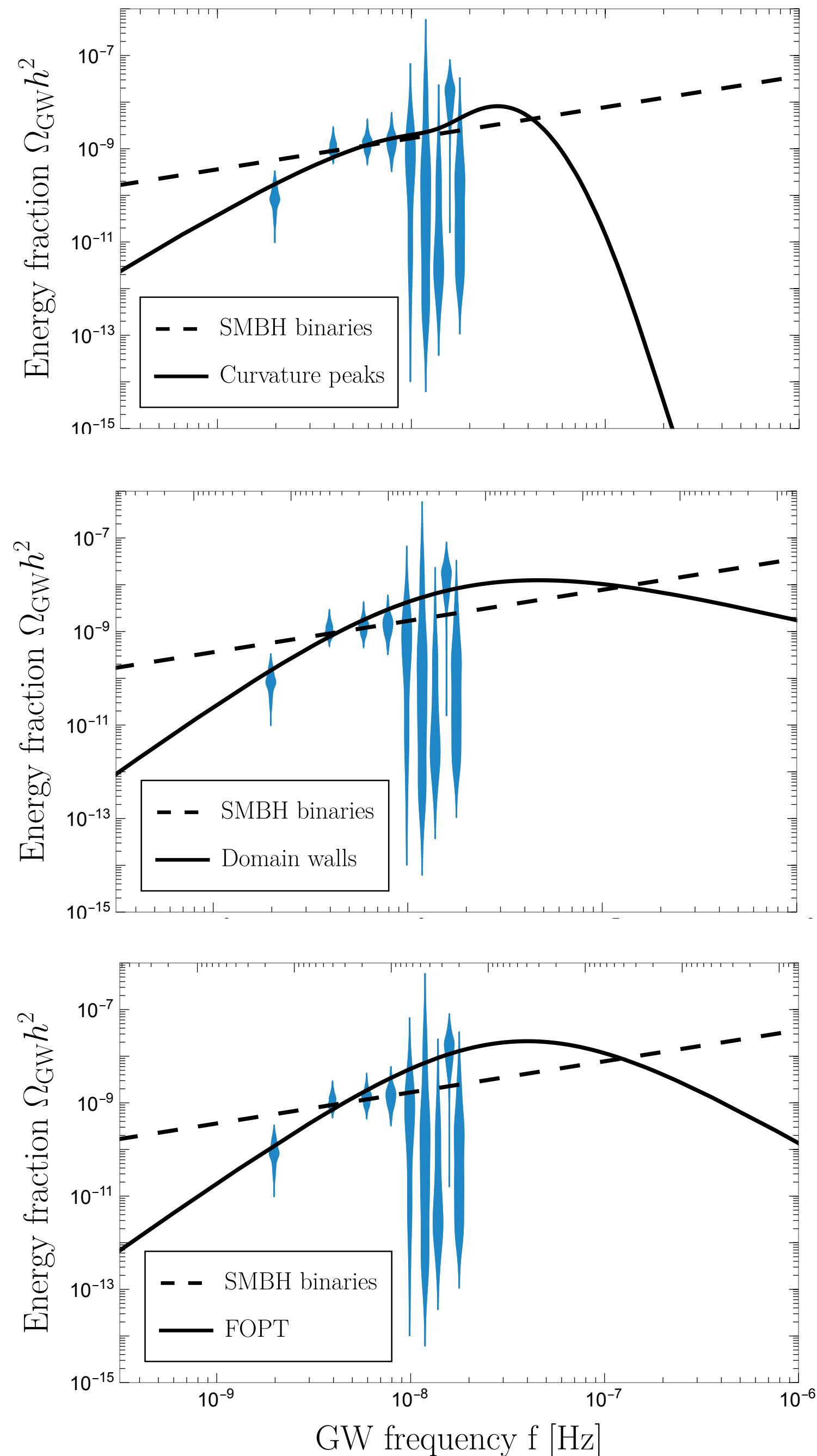
***Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...***



First-order phase transitions

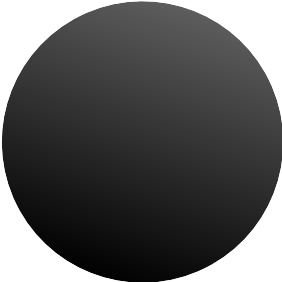
***Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
Hoefken Zink et al. (2501.15649)
...***





Curvature peaks

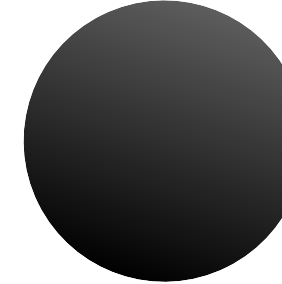
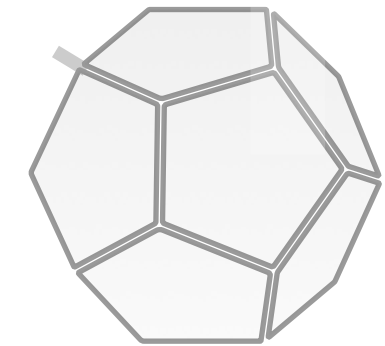
Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Iovino, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



PBH

Domain wall networks

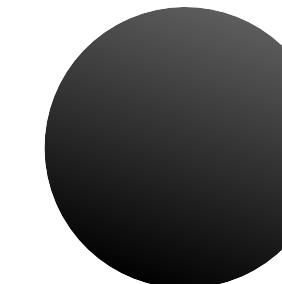
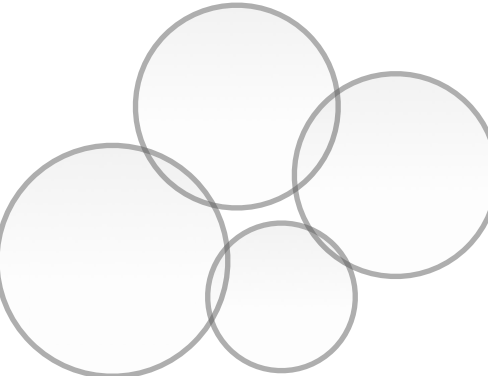
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
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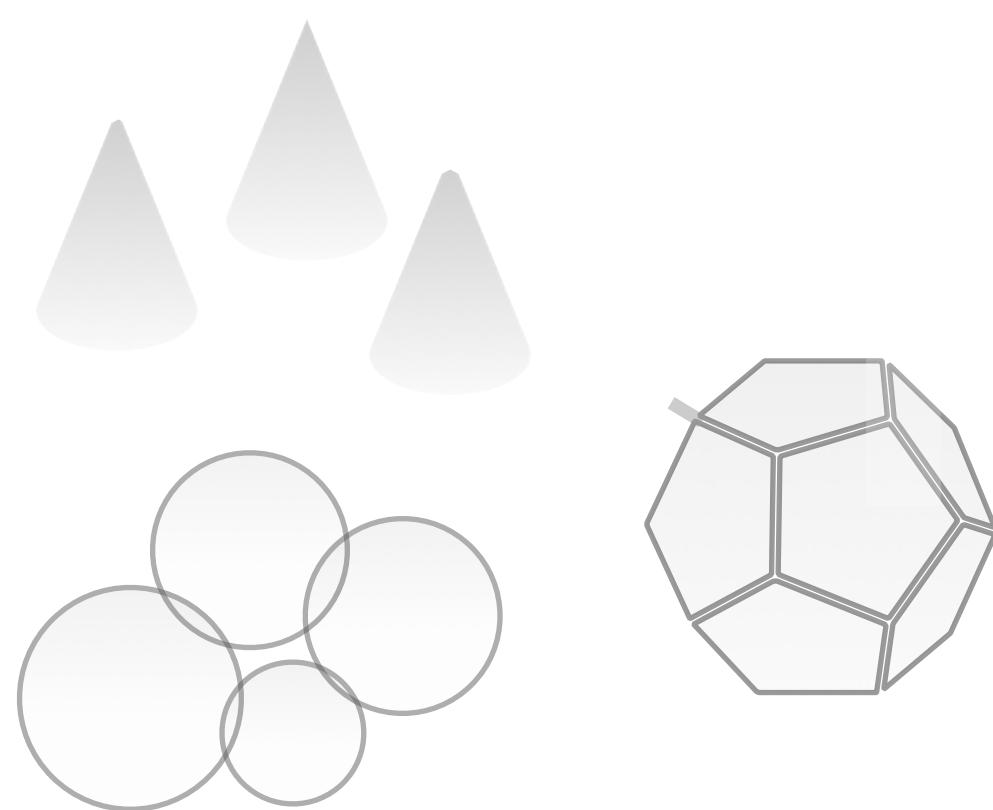
PBH

First-order phase transitions

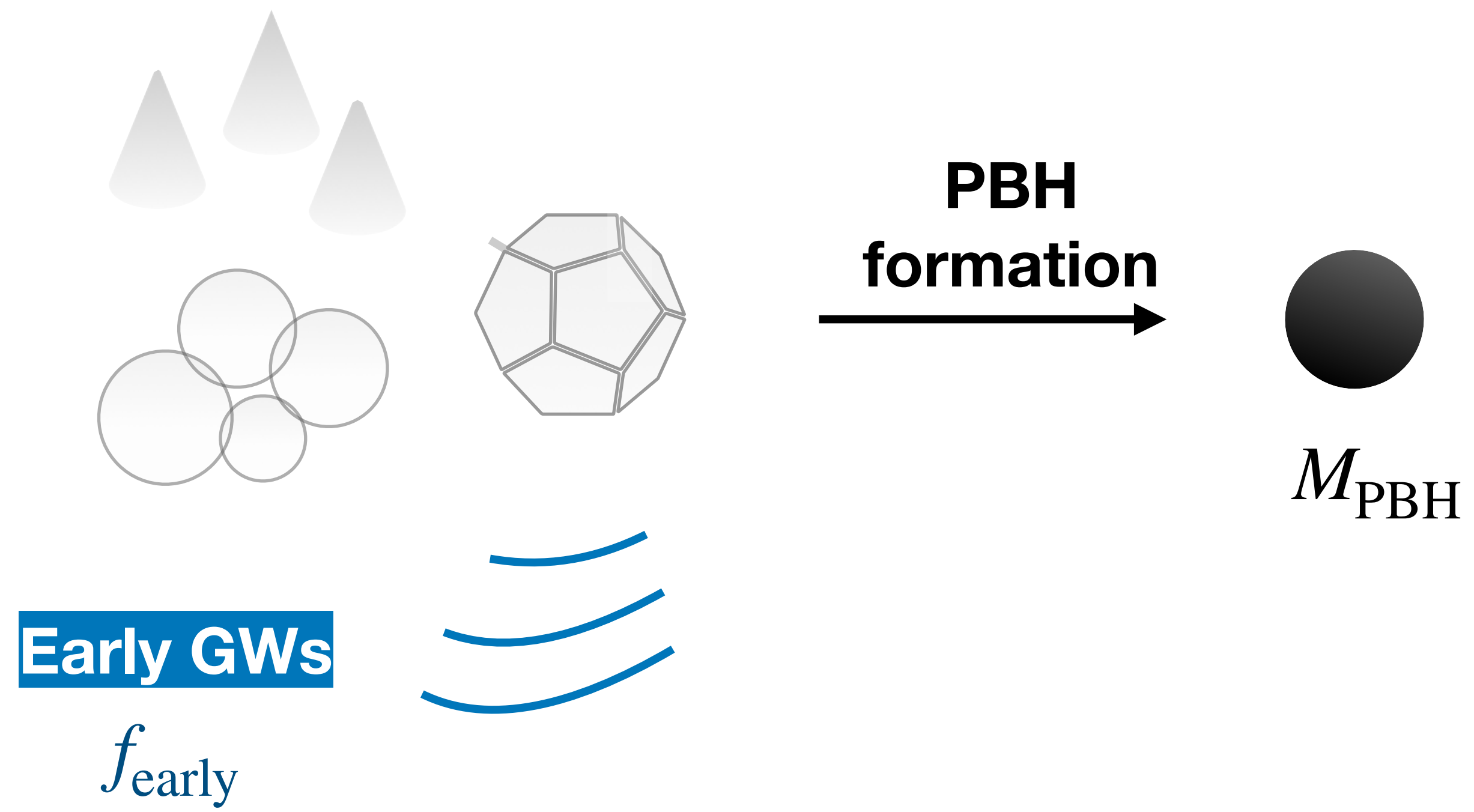
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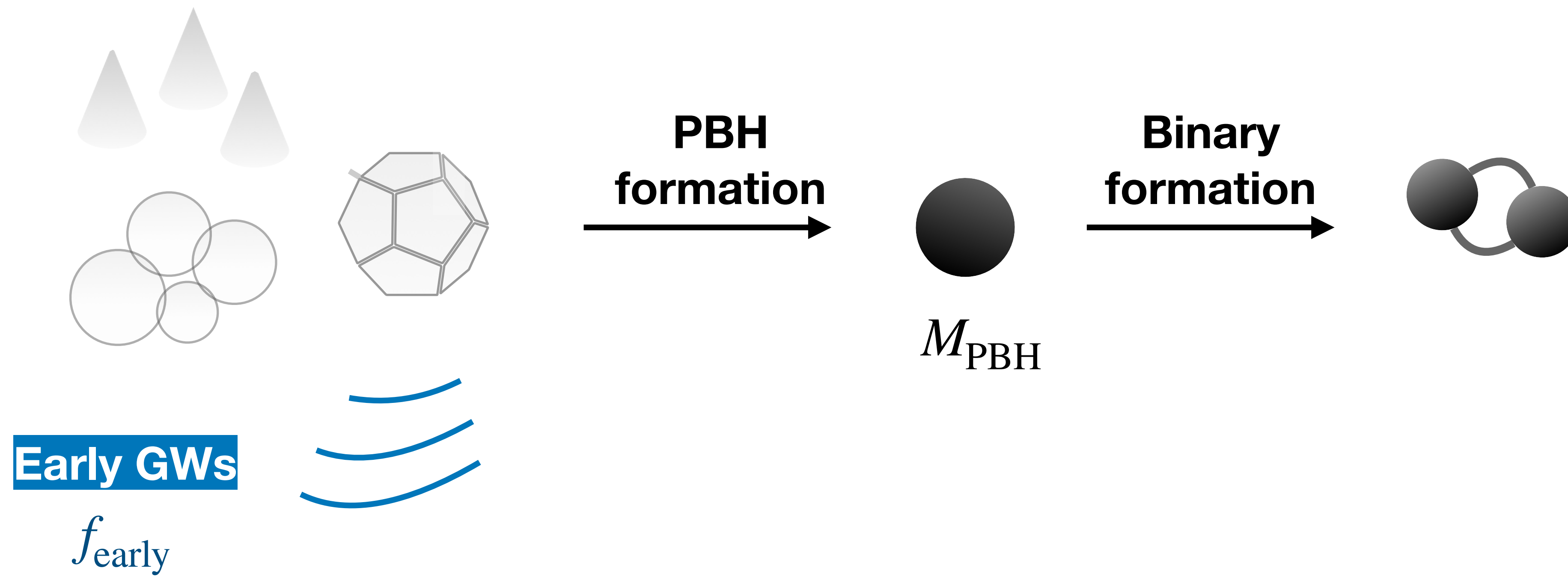


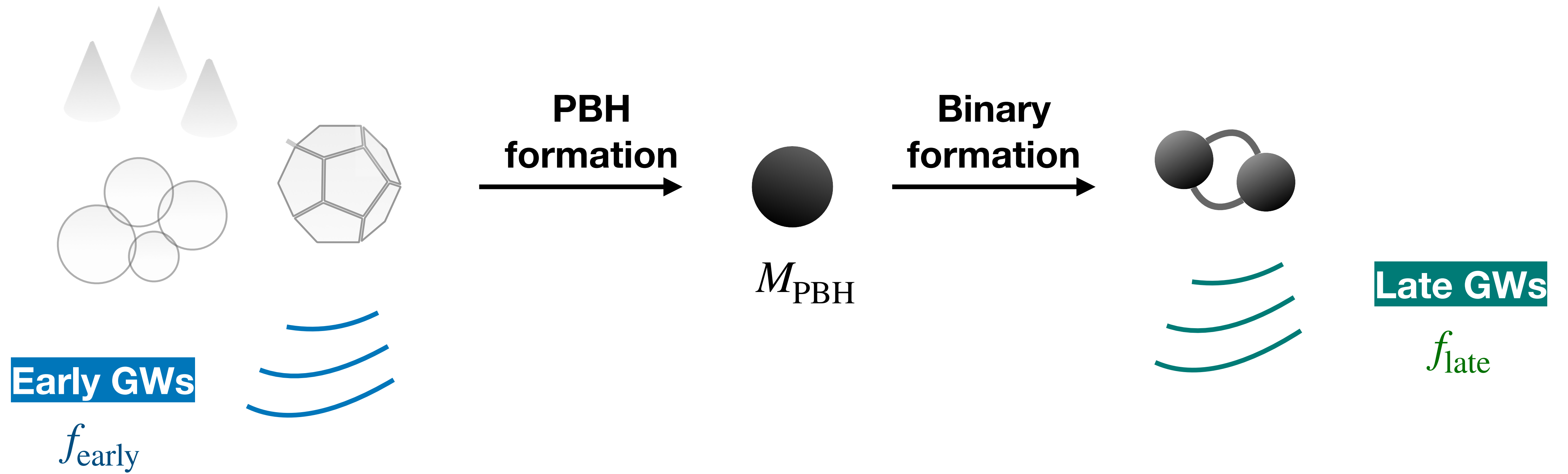
PBH



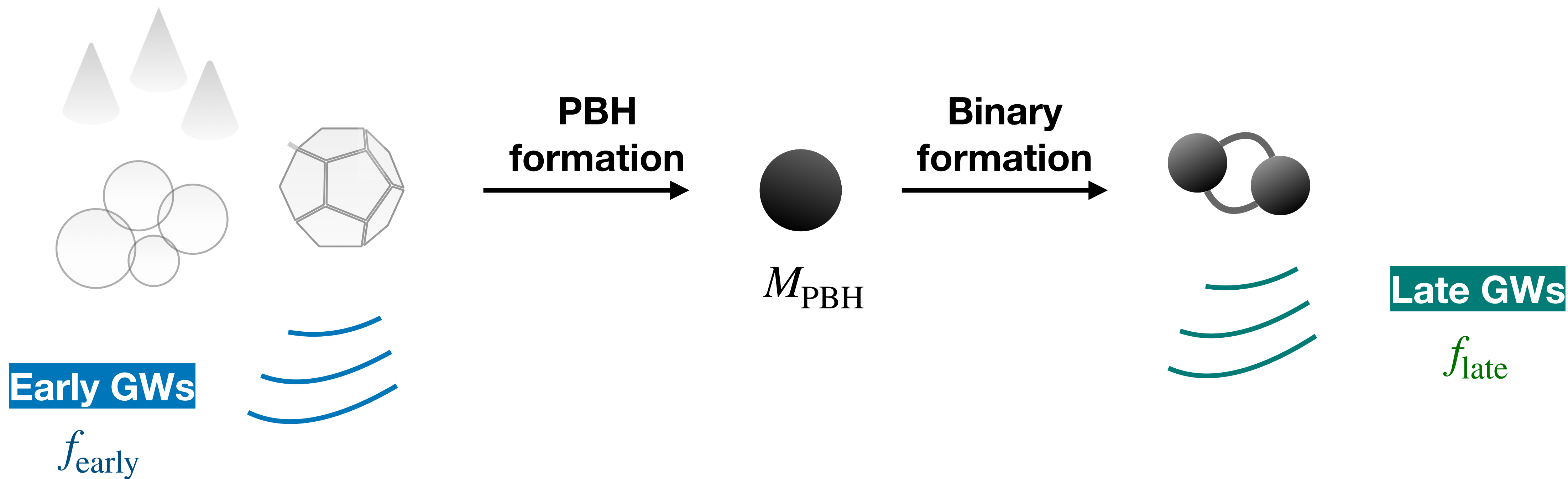








$$\left(\frac{f_{\text{early}}}{3 \text{ nHz}} \right) \simeq \epsilon_{\star} \left(\frac{4 M_{\odot}}{M_{\text{PBH}}} \right)^{1/2} \simeq \epsilon_{\star} \left(\frac{f_{\text{late}}}{1 \text{ kHz}} \right)^{1/2} \quad \left(\epsilon_{\star} \equiv \frac{k_{\star}}{\mathcal{H}_{\star}} \right)$$

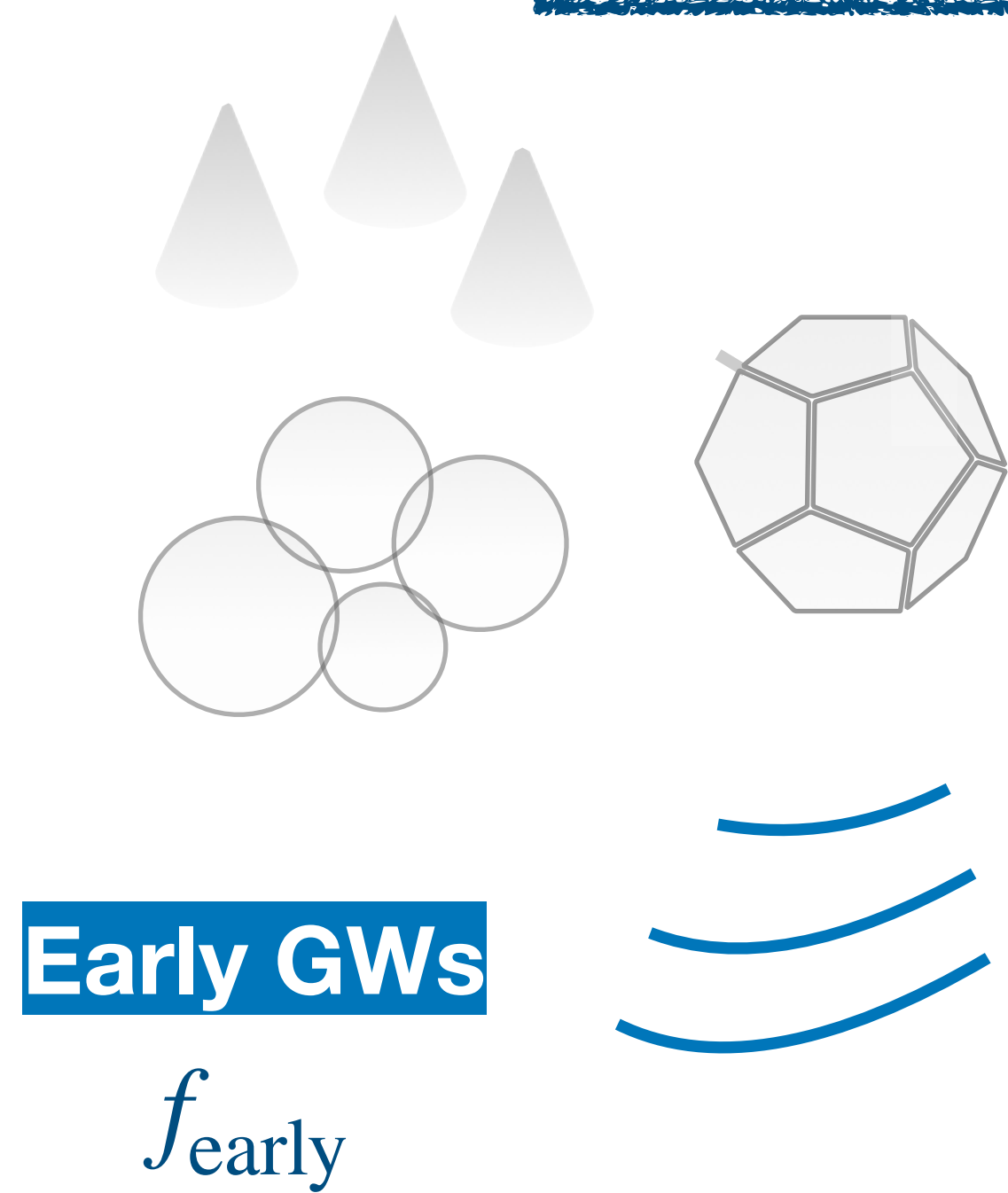


$$\left(\frac{f_{\text{early}}}{3 \text{ nHz}} \right)$$

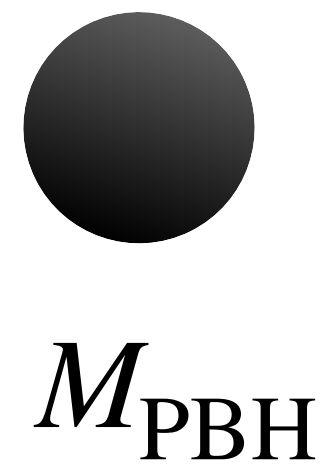
$$\simeq \epsilon_{\star} \left(\frac{4 M_{\odot}}{M_{\text{PBH}}} \right)^{1/2}$$

$$\simeq \epsilon_{\star} \left(\frac{f_{\text{late}}}{1 \text{ kHz}} \right)^{1/2}$$

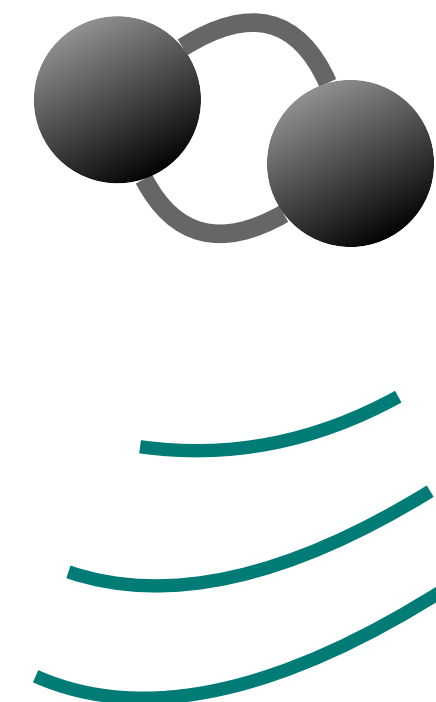
$$\left(\epsilon_{\star} \equiv \frac{k_{\star}}{\mathcal{H}_{\star}} \right)$$



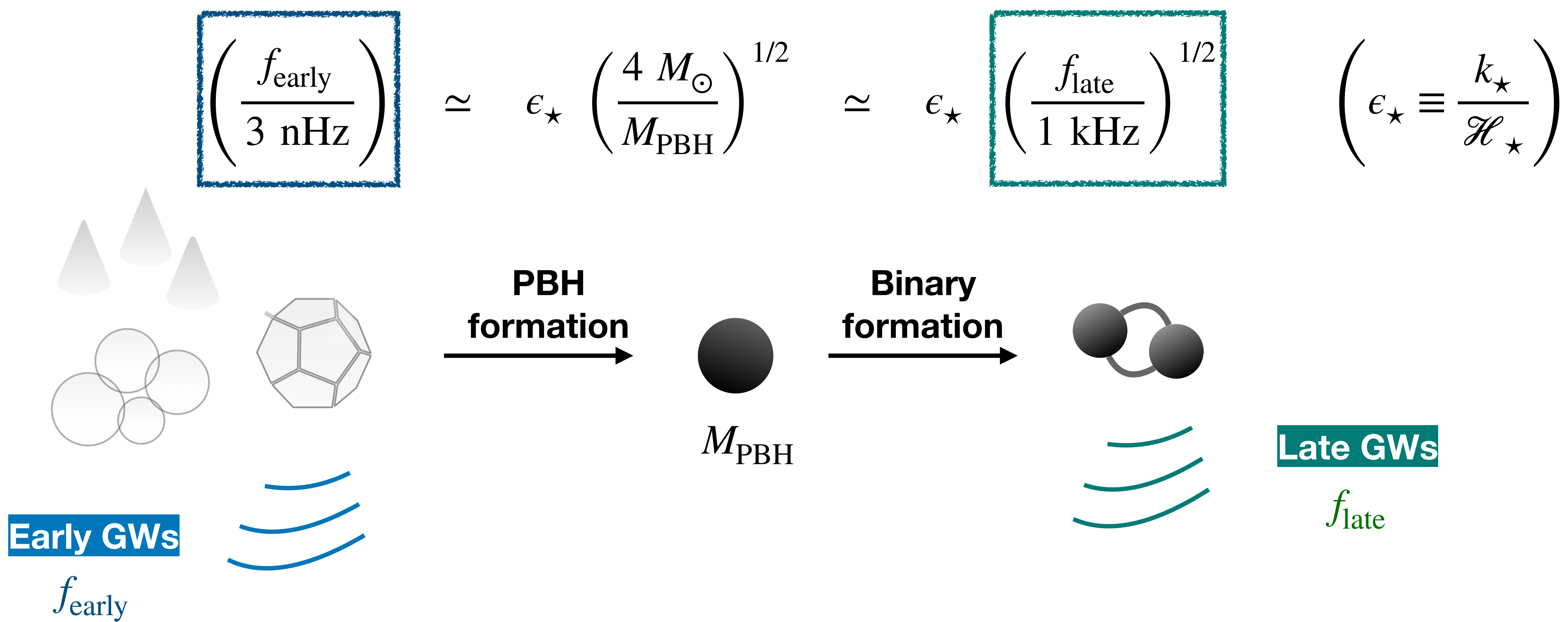
**PBH
formation**
→



**Binary
formation**
→



Late GWs
 f_{late}



$$\left(\frac{f_{\text{early}}}{3 \text{ nHz}} \right)$$

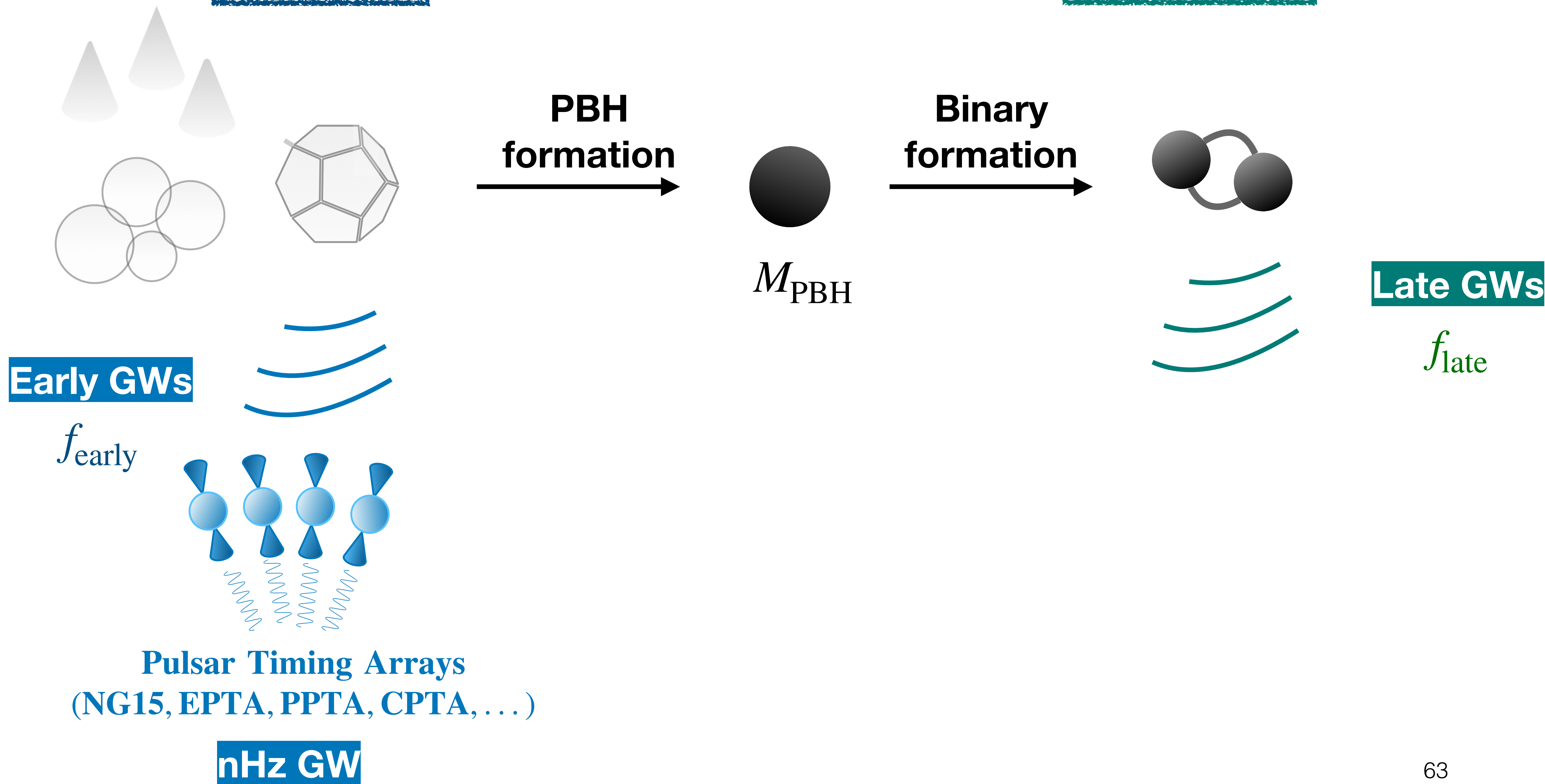
 $\simeq$

$$\epsilon_{\star} \left(\frac{4 M_{\odot}}{M_{\text{PBH}}} \right)^{1/2}$$

 $\simeq$

$$\epsilon_{\star} \left(\frac{f_{\text{late}}}{1 \text{ kHz}} \right)^{1/2}$$

$$\left(\epsilon_{\star} \equiv \frac{k_{\star}}{\mathcal{H}_{\star}} \right)$$



$$\left(\frac{f_{\text{early}}}{3 \text{ nHz}} \right)$$

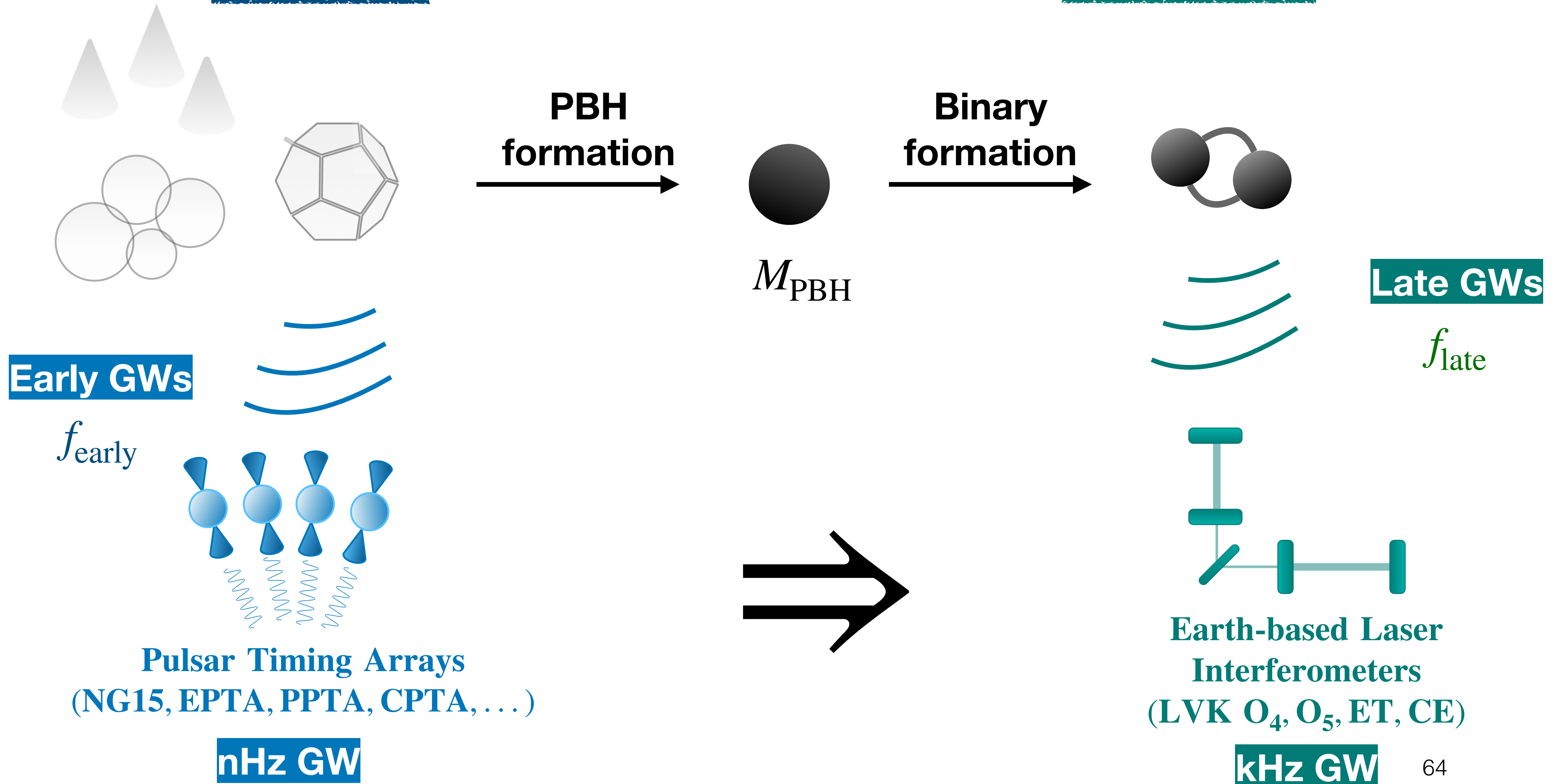
 $\approx$

$$\epsilon_{\star} \left(\frac{4 M_{\odot}}{M_{\text{PBH}}} \right)^{1/2}$$

 $\approx$

$$\epsilon_{\star} \left(\frac{f_{\text{late}}}{1 \text{ kHz}} \right)^{1/2}$$

$$\left(\epsilon_{\star} \equiv \frac{k_{\star}}{\mathcal{H}_{\star}} \right)$$



$$\left(\frac{f_{\text{early}}}{3 \text{ nHz}} \right)$$

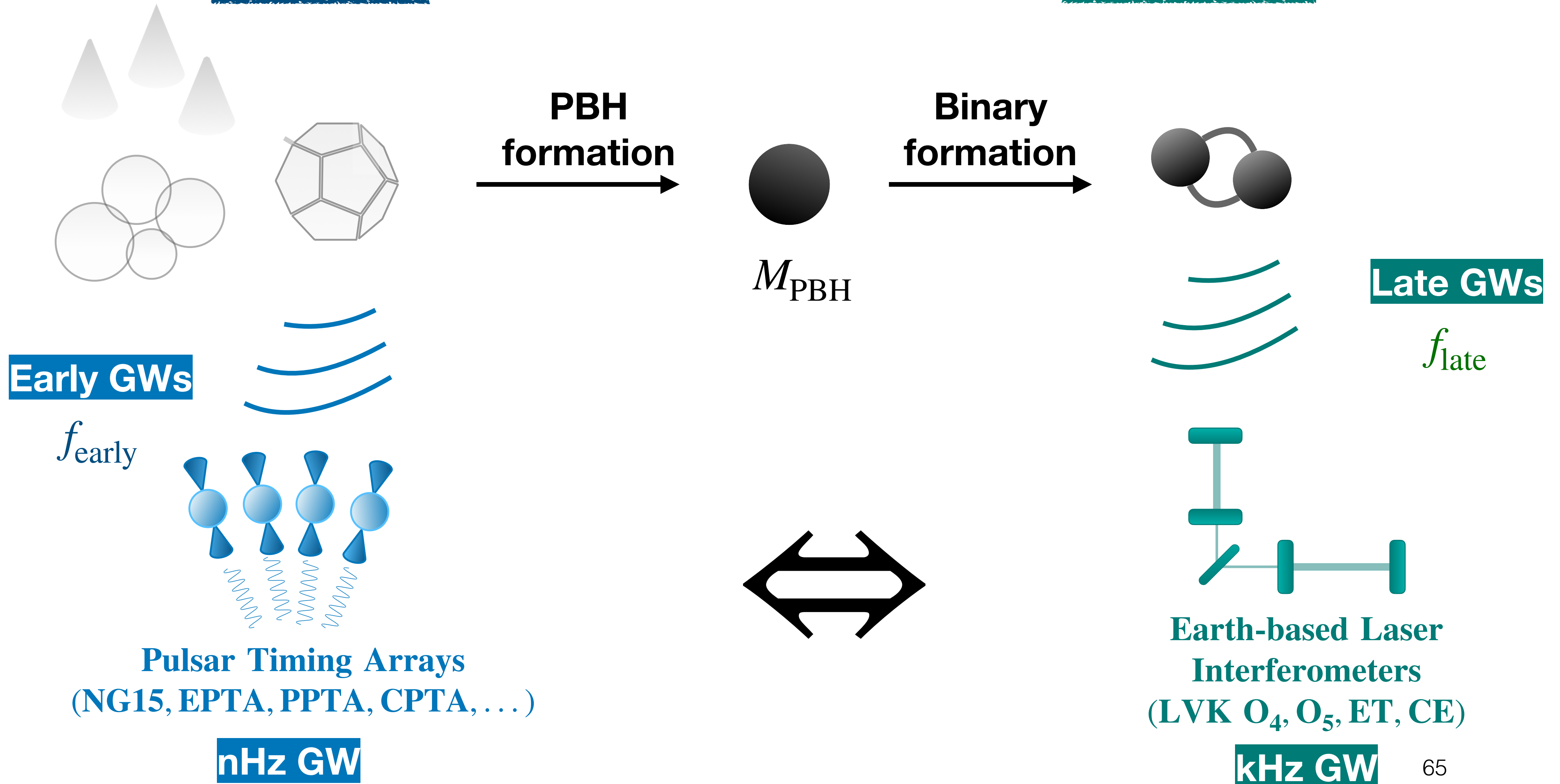
 $\approx$

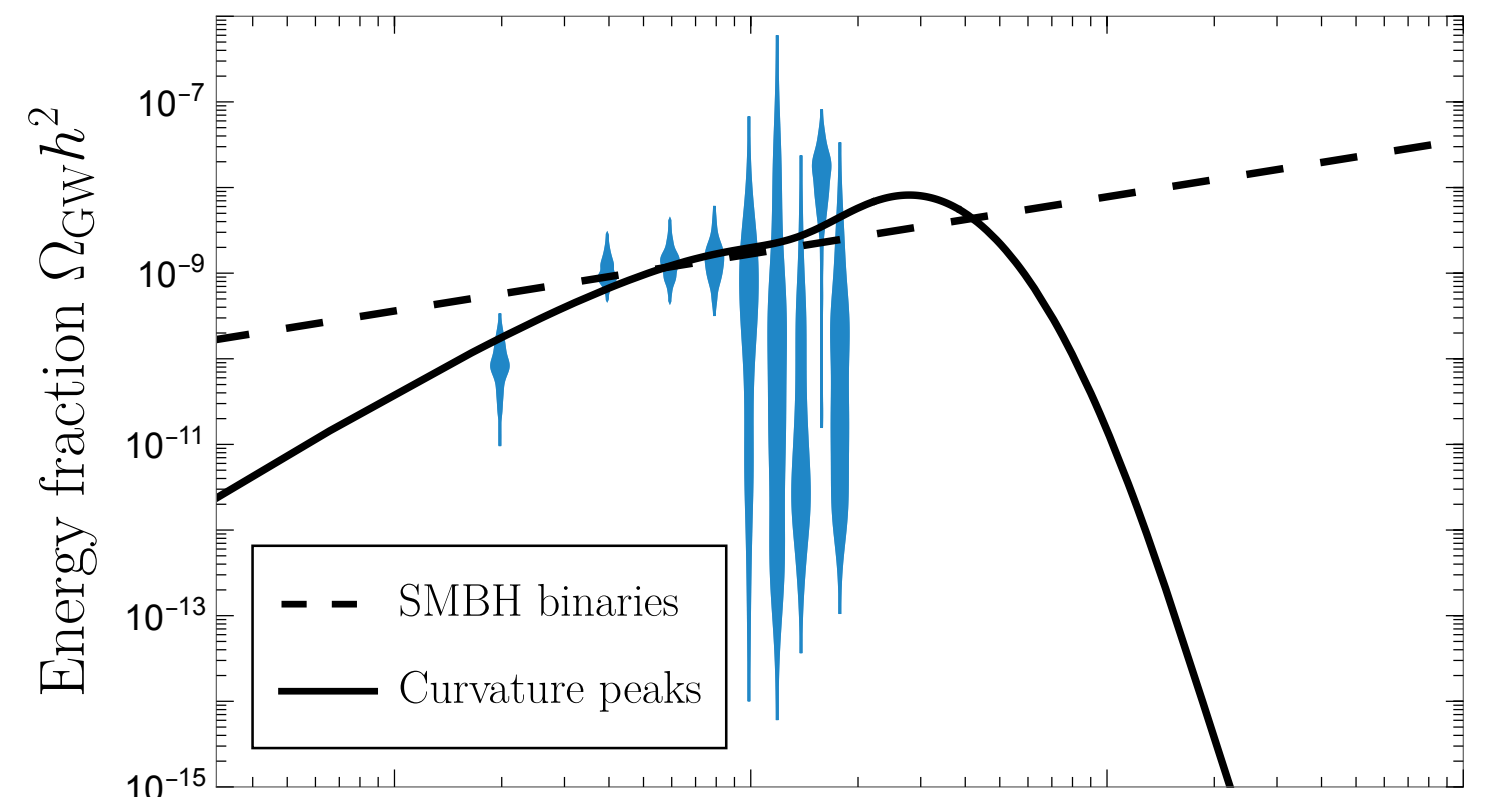
$$\epsilon_{\star} \left(\frac{4 M_{\odot}}{M_{\text{PBH}}} \right)^{1/2}$$

 $\approx$

$$\epsilon_{\star} \left(\frac{f_{\text{late}}}{1 \text{ kHz}} \right)^{1/2}$$

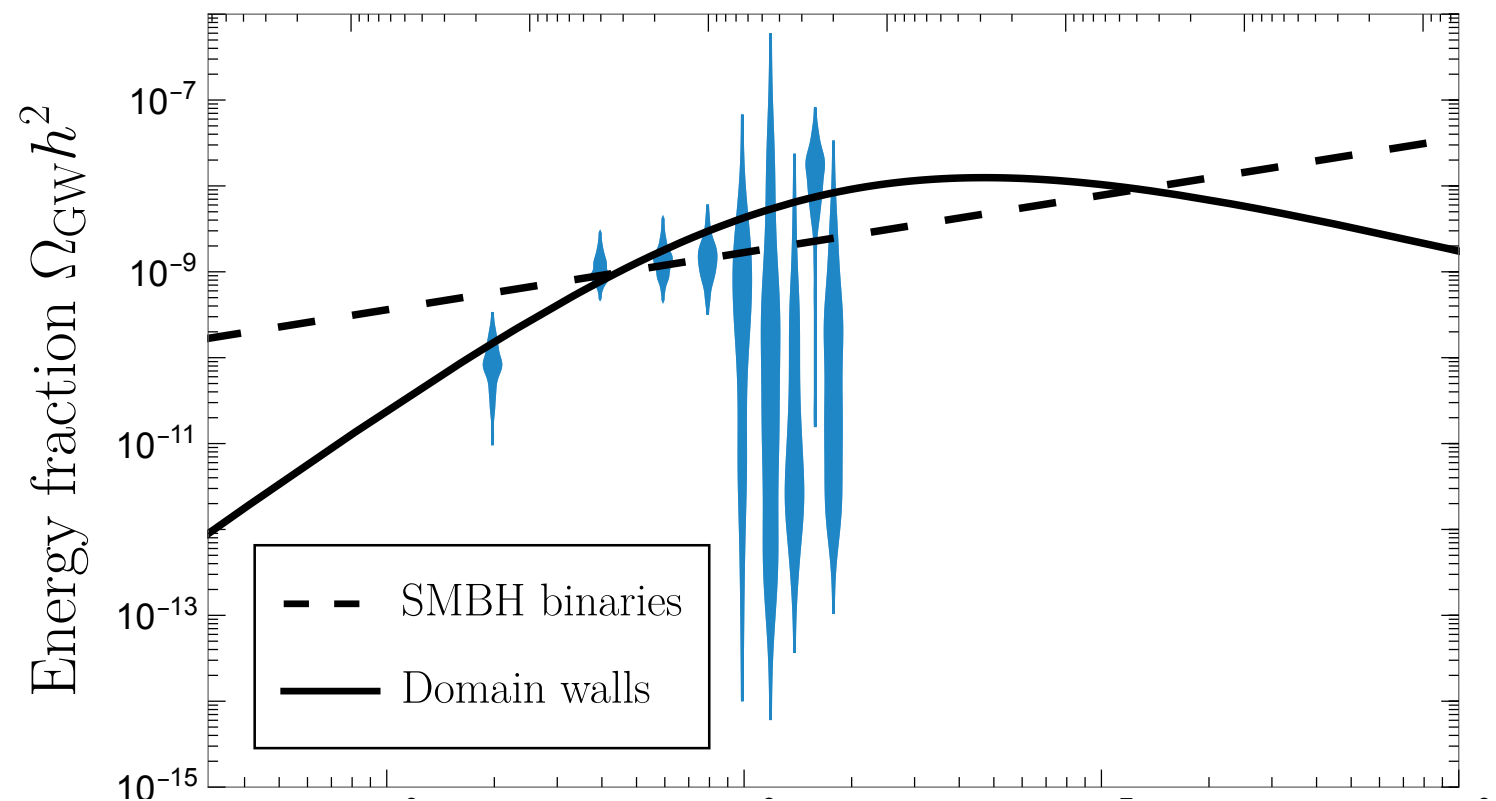
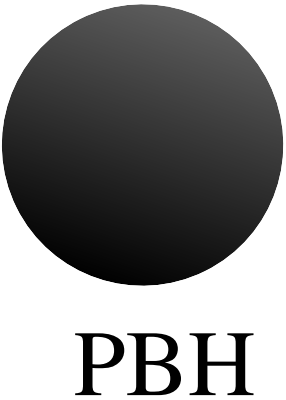
$$\left(\epsilon_{\star} \equiv \frac{k_{\star}}{\mathcal{H}_{\star}} \right)$$





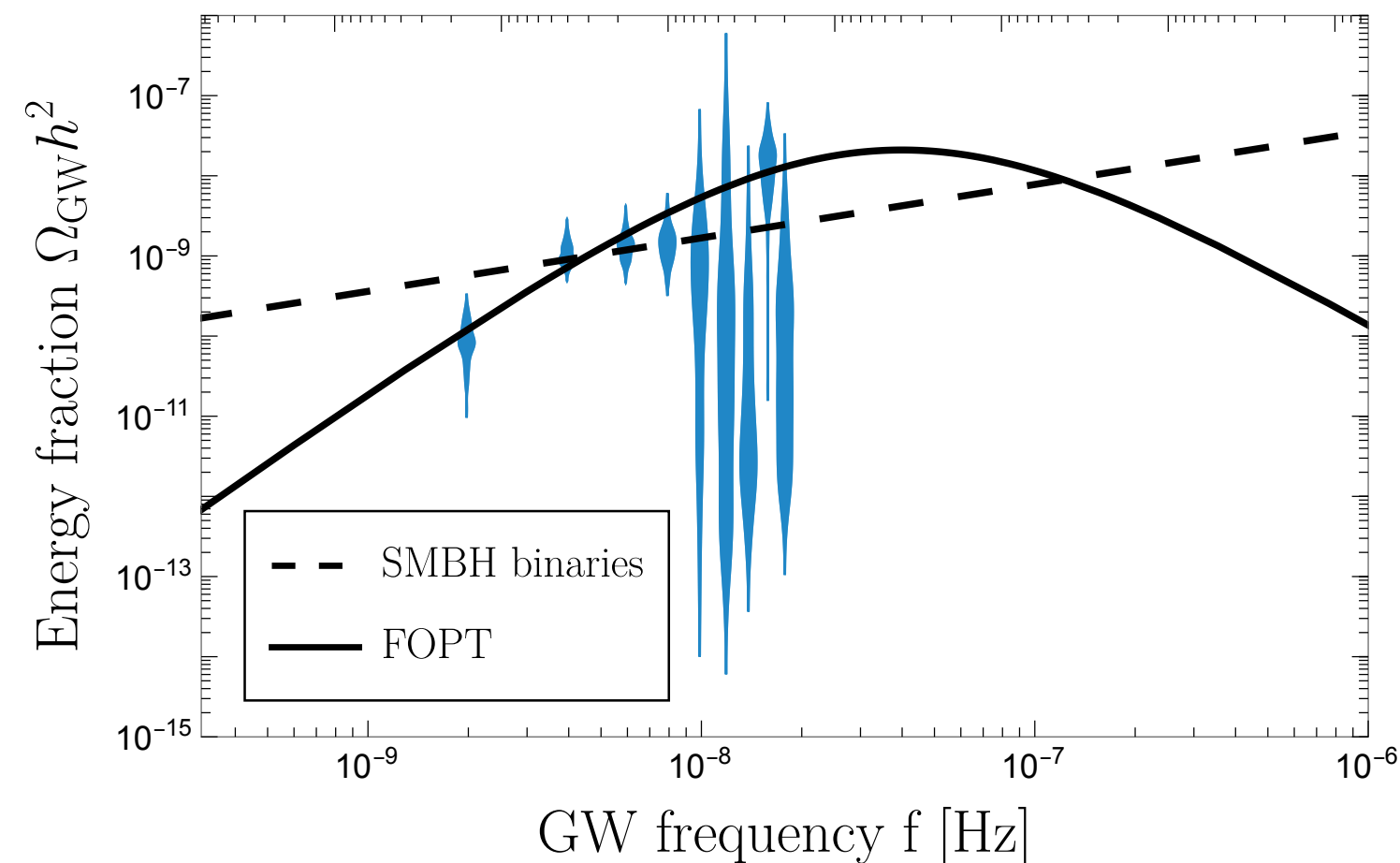
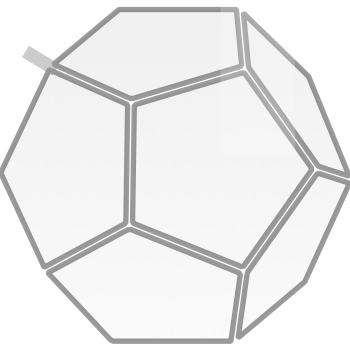
Curvature peaks

Kohri, Terada (2009.11853)
Vaskonen, Veermäe (2009.07832),
Franciolini, Iovino, Vaskonen, Vermae (2306.17143)
Cecchini, Franciolini, Pieroni (2503.10805)
...



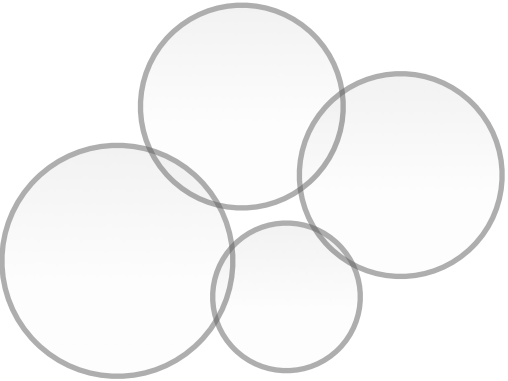
Domain wall networks

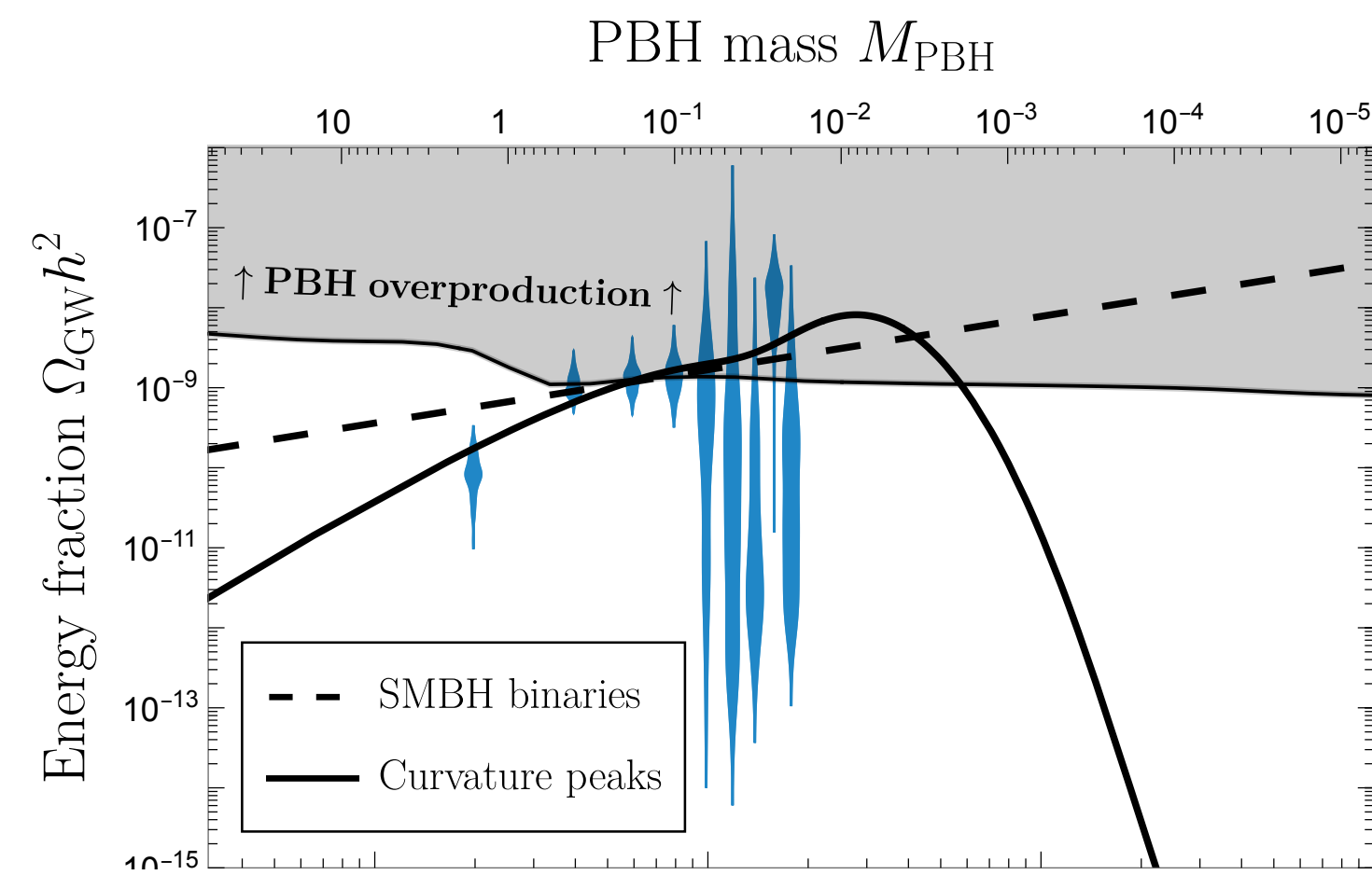
Ferreira, Notari, Pujolas, Rompineve (2204.04228)
Blasi, Mariotti, Rase, Sevrin (2306.17830)
...



First-order phase transitions

Roper Pol et al. (2201.05630)
Ghoshal, White et al. (2307.02259)
YG (2307.04239)
Lewicki, Toczek, Vaskonen (2402.04158)
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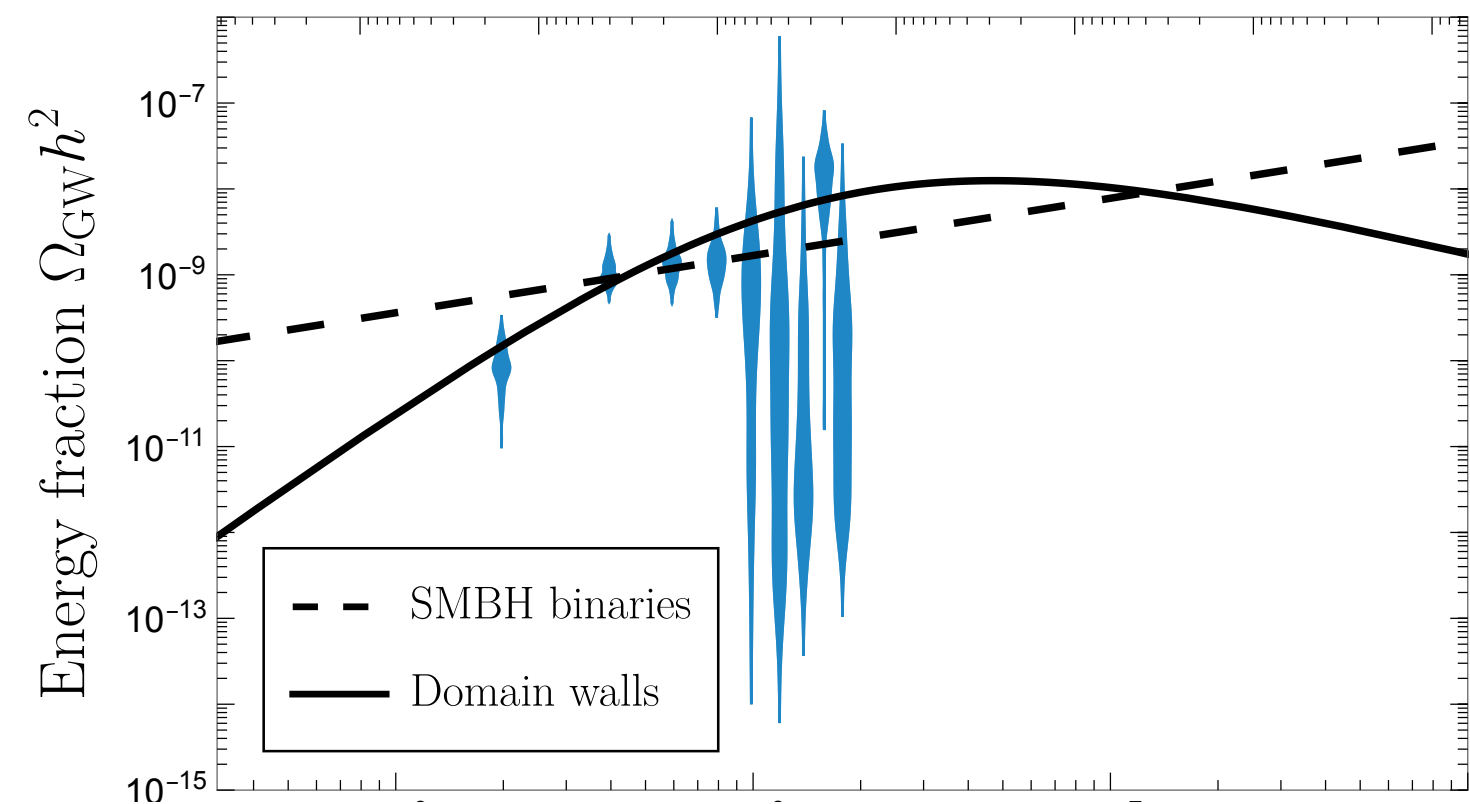
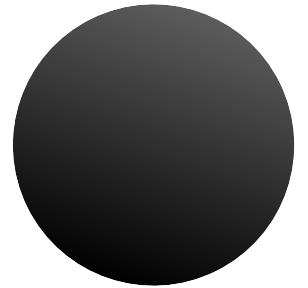
De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

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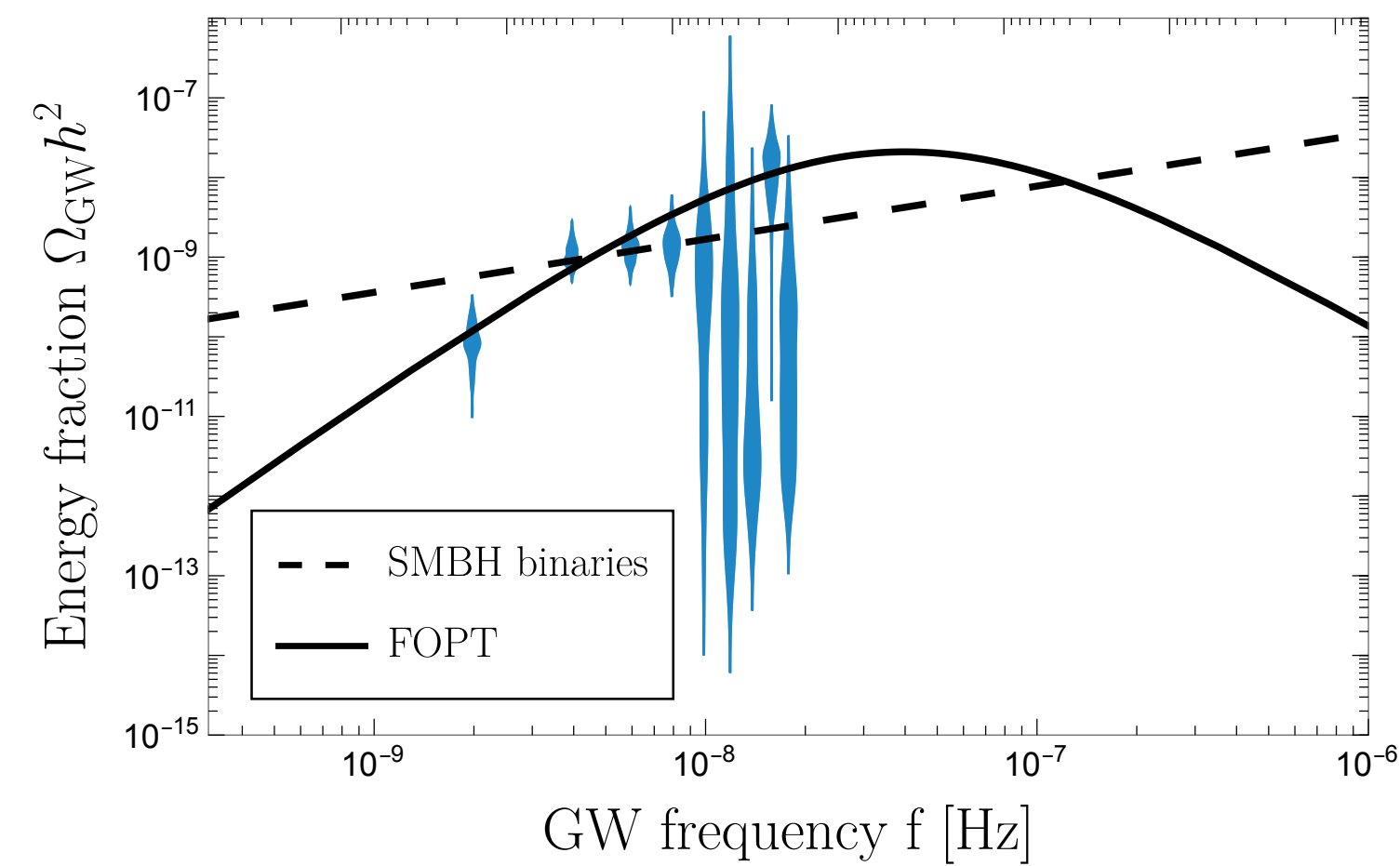
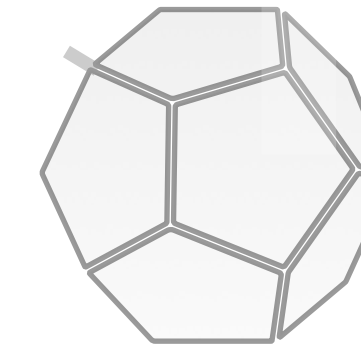


Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

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...



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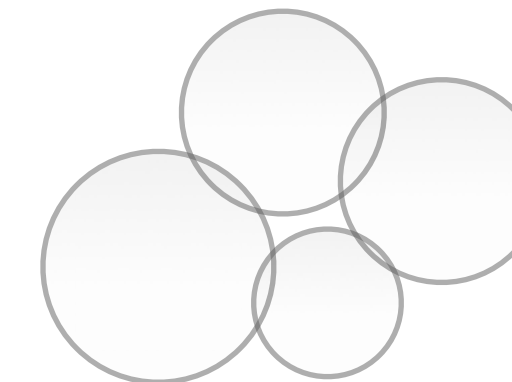
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

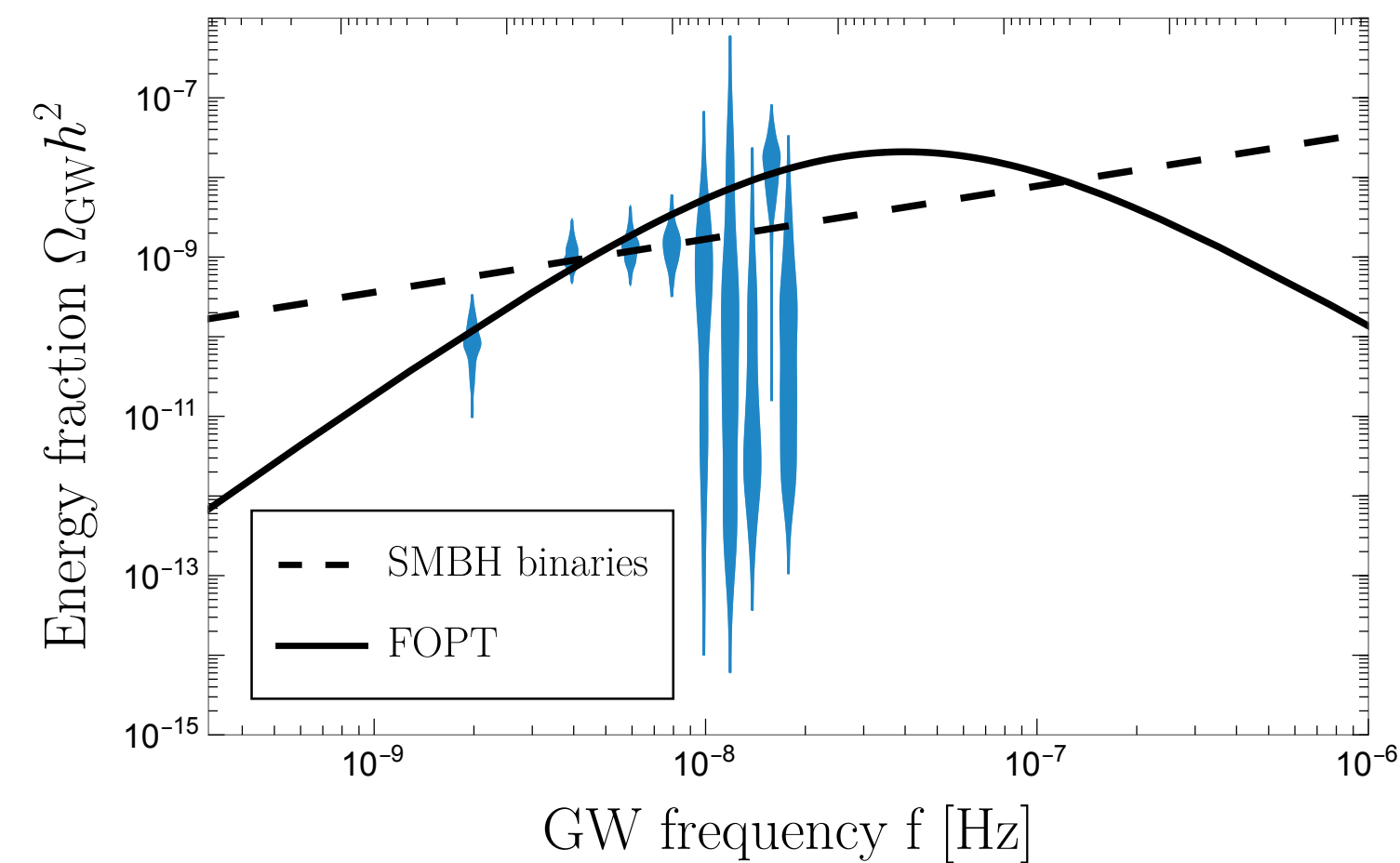
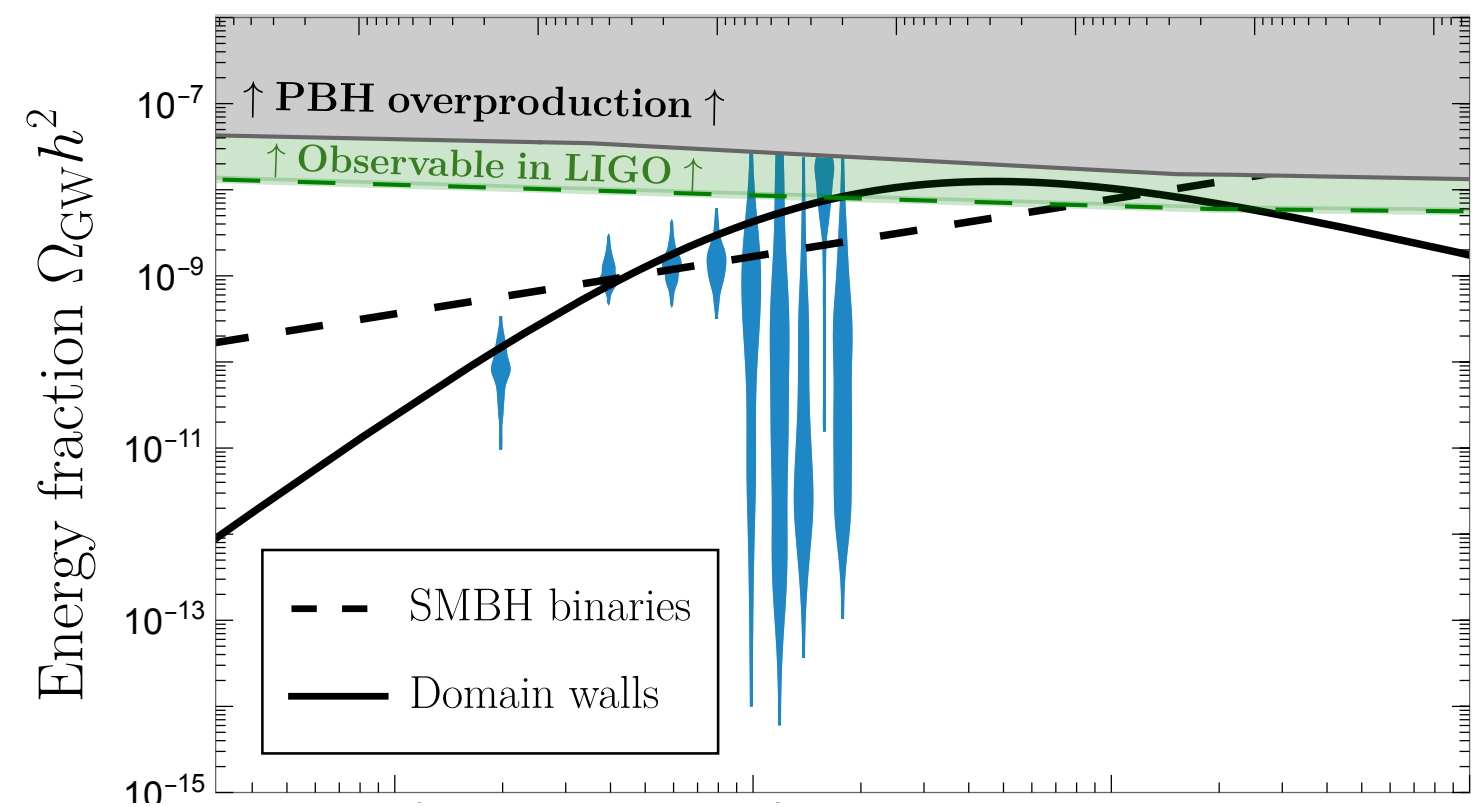
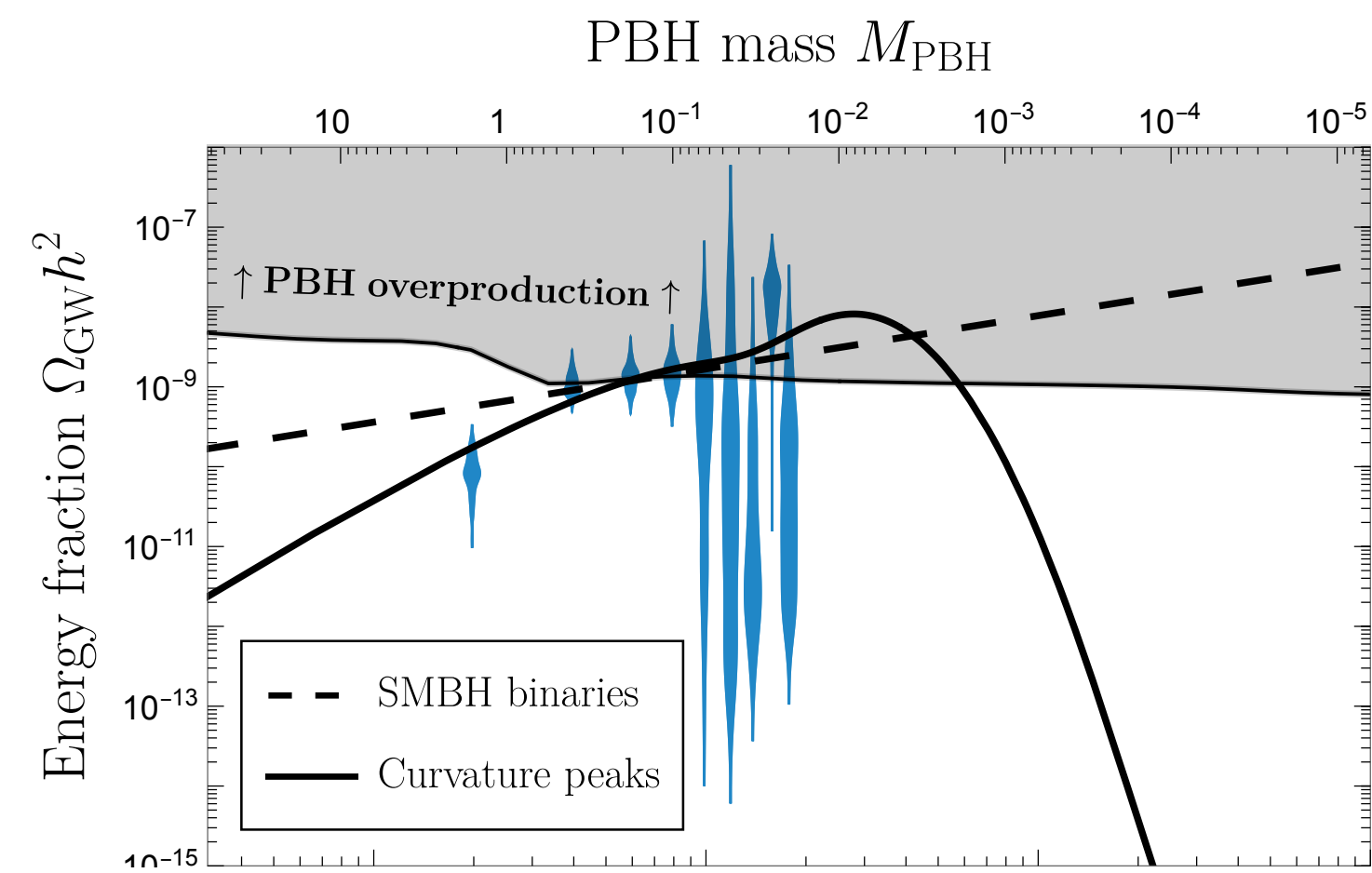
Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

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Reviews: *Madge et al (2306.14856),*
Figueroa et al (2307.02399),
Ellis et al (2308.08546)



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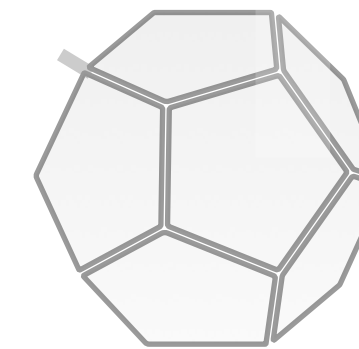
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Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

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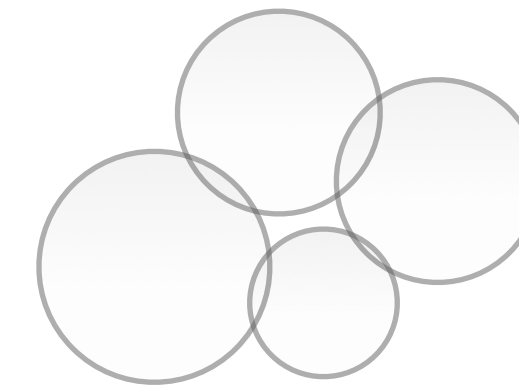
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

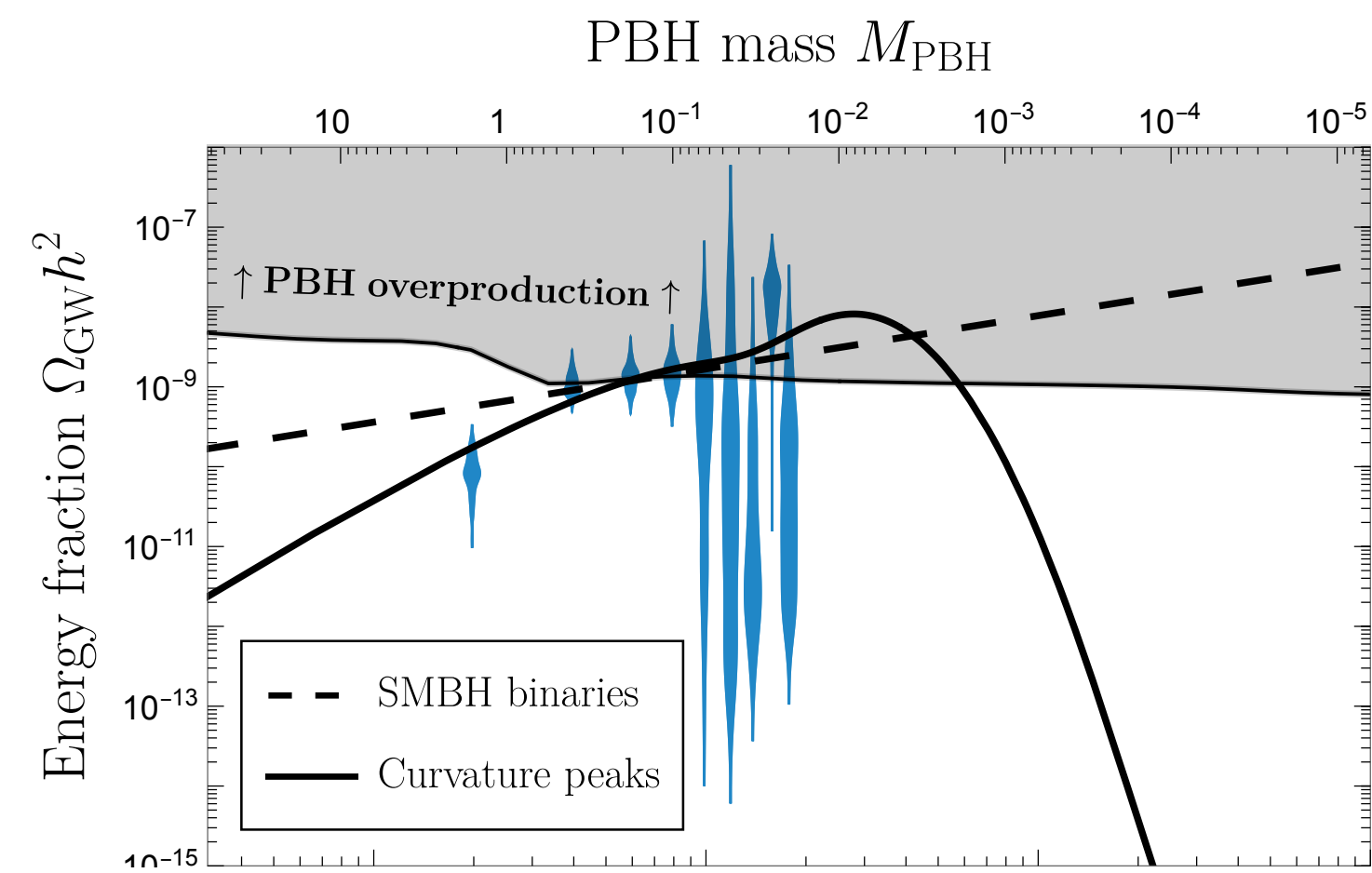
Lewicki, Toczek, Vaskonen (2402.04158)

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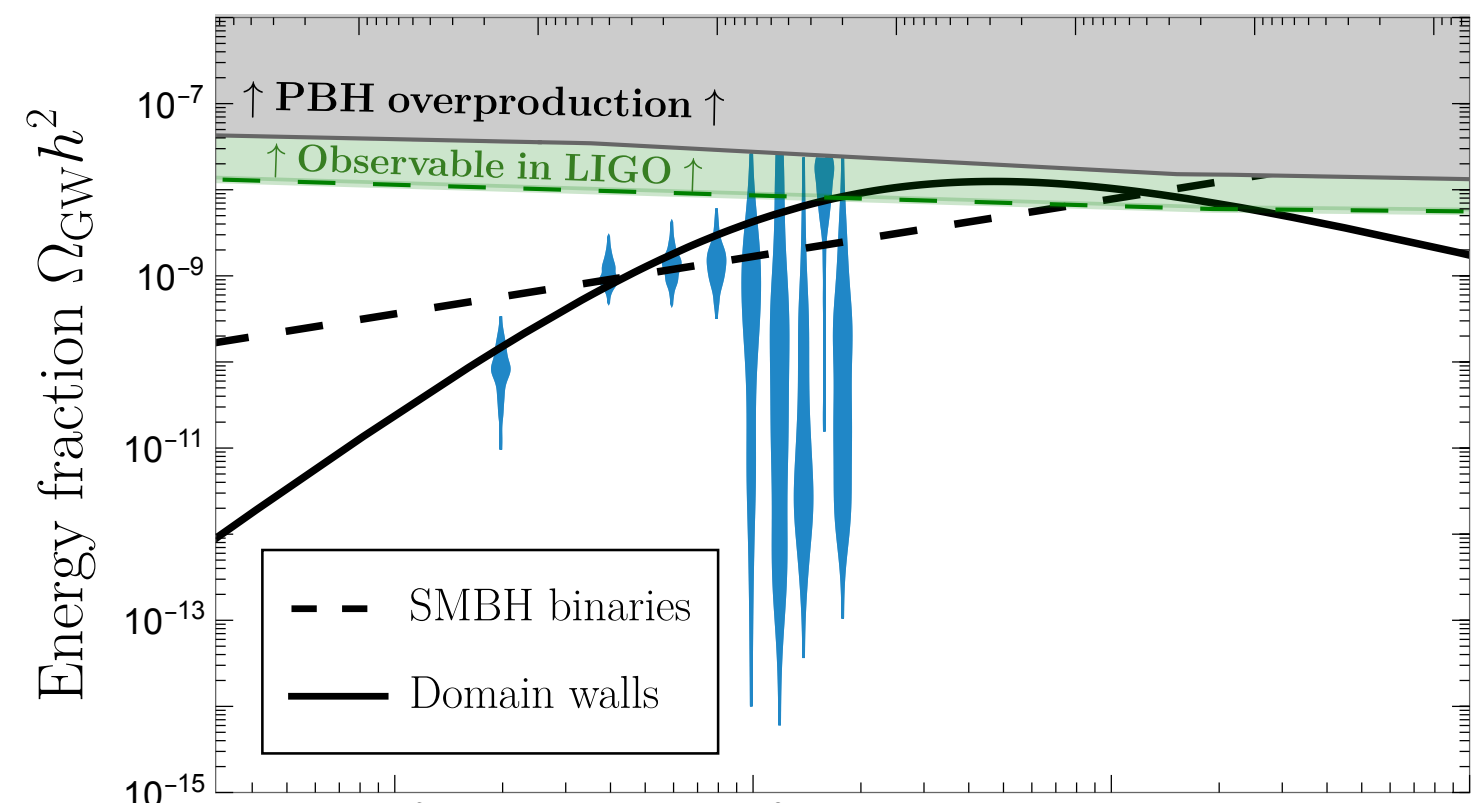
YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Reviews: *Madge et al (2306.14856),*

Figueroa et al (2307.02399),

Ellis et al (2308.08546)



Domain wall networks

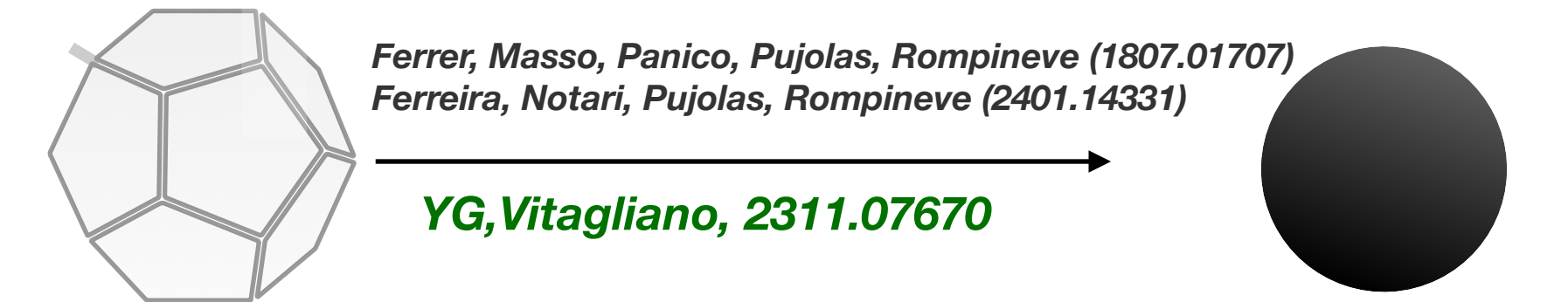
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

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Produce solar-mass PBH

YG, Vitagliano 2306.17841

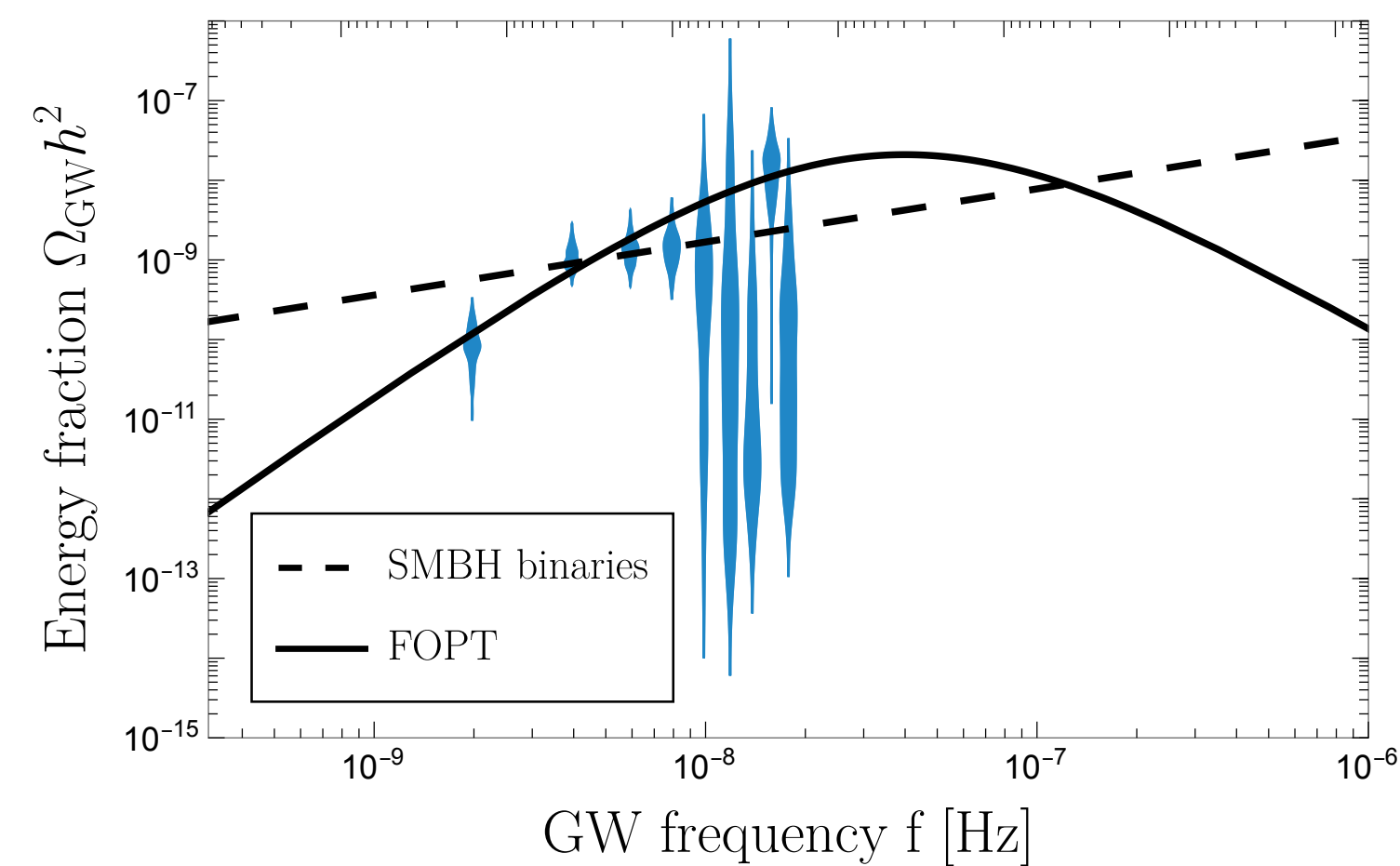


Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670

PBH



First-order phase transitions

Roper Pol et al. (2201.05630)

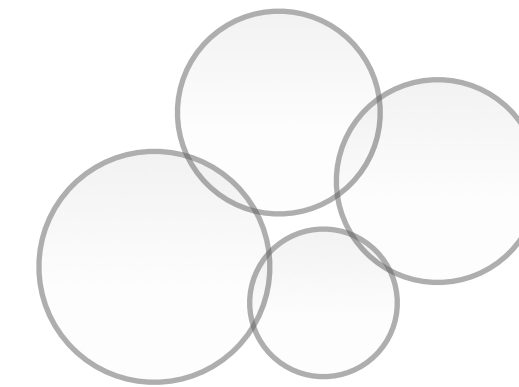
Ghoshal, White et al. (2307.02259)

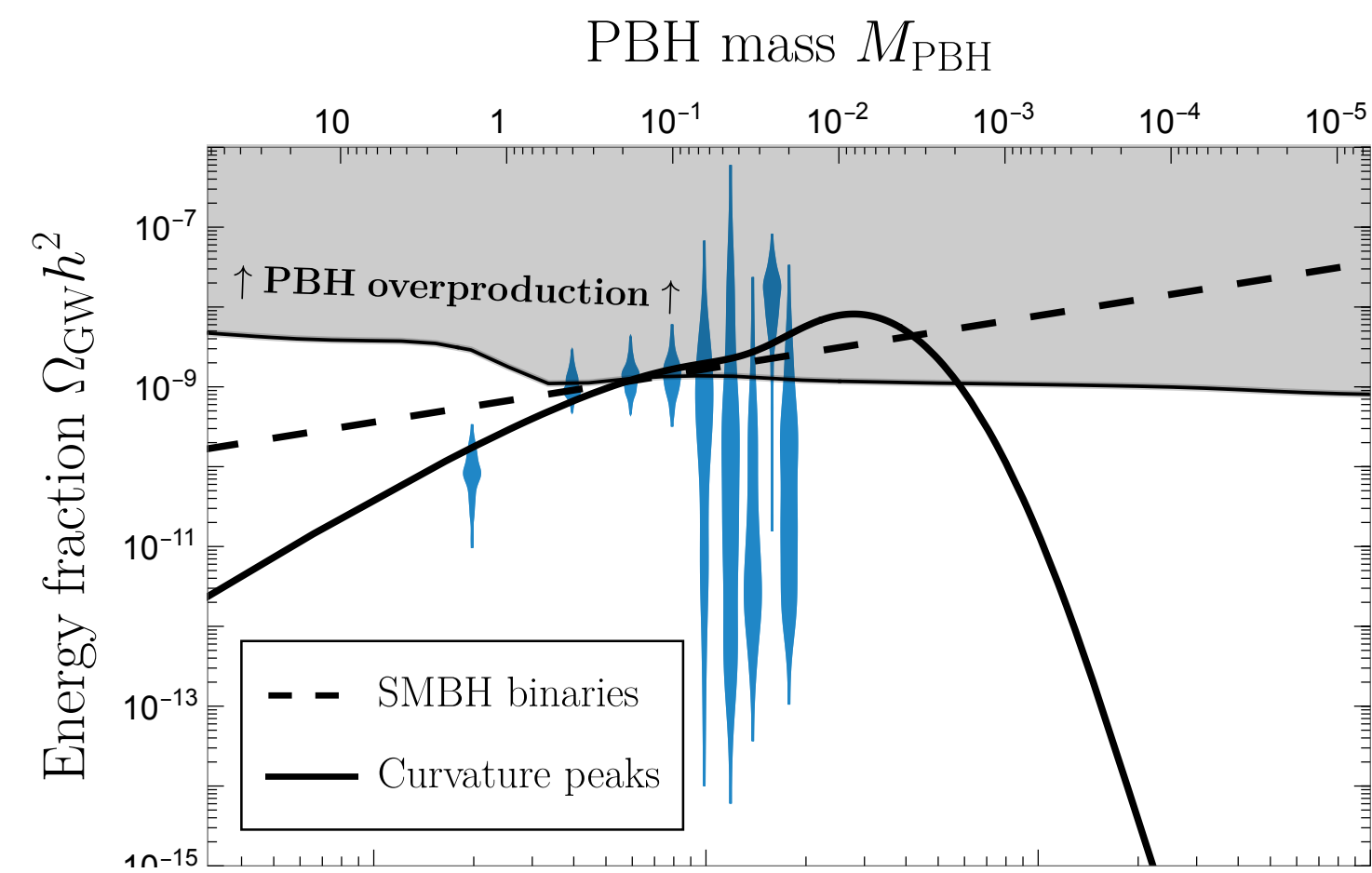
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Hoefken Zink et al. (2501.15649)

...





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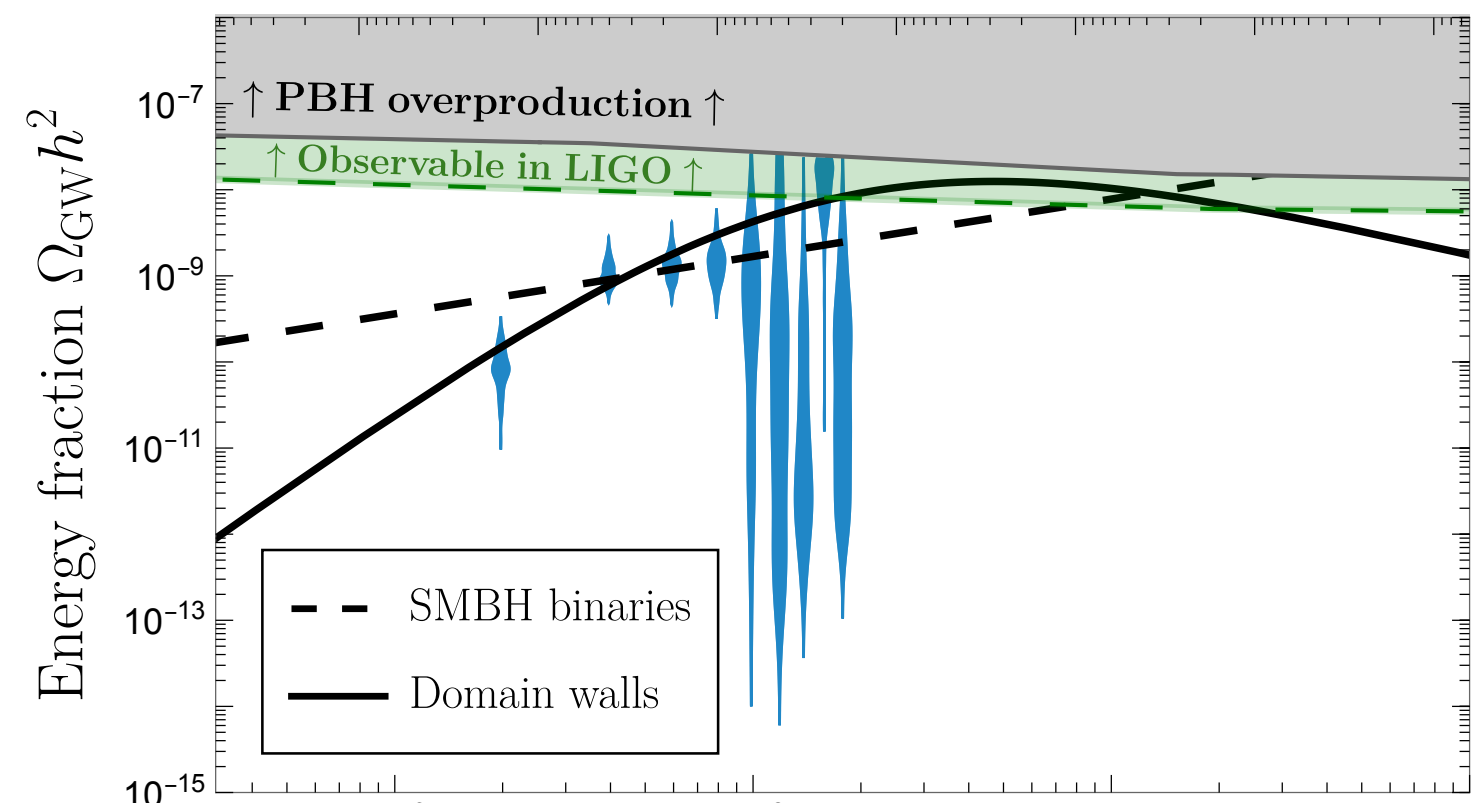
YG, Trifinopoulos, Vanvlasselaer (2508.19328)



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Domain wall networks

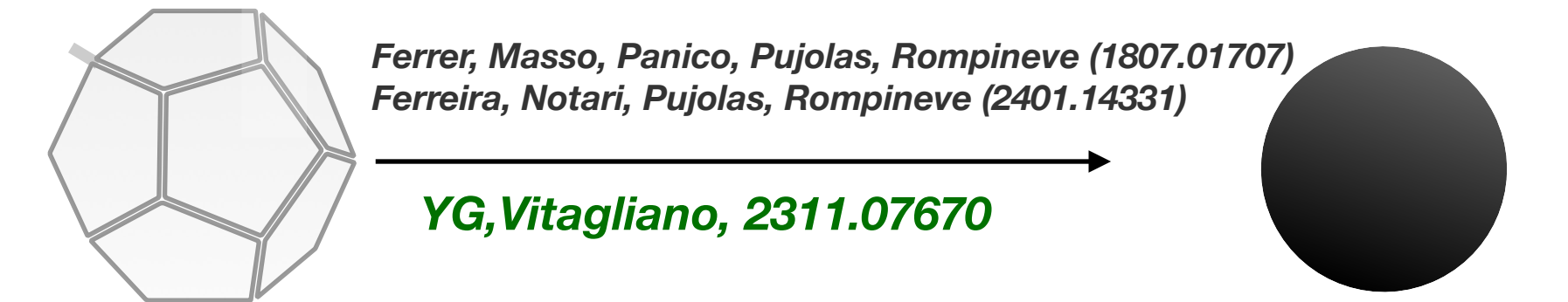
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

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Produce solar-mass PBH

YG, Vitagliano 2306.17841

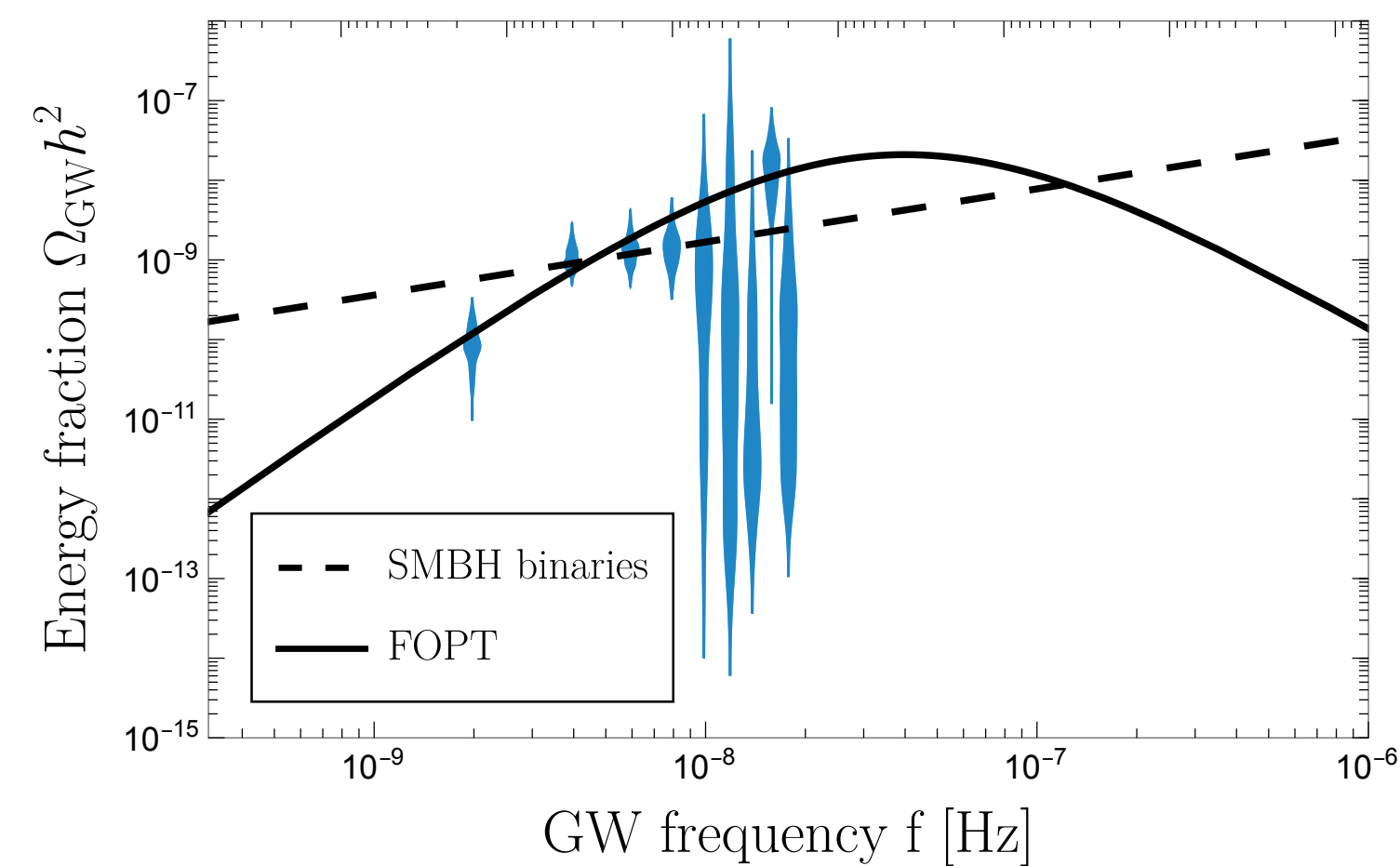


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PBH



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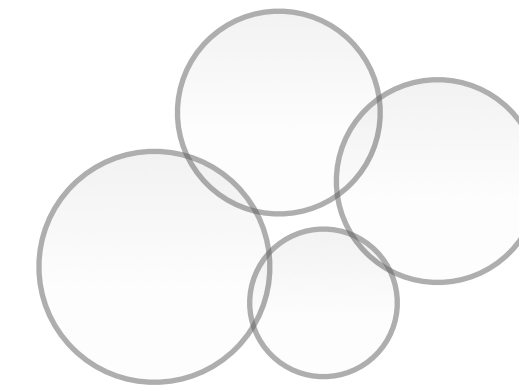
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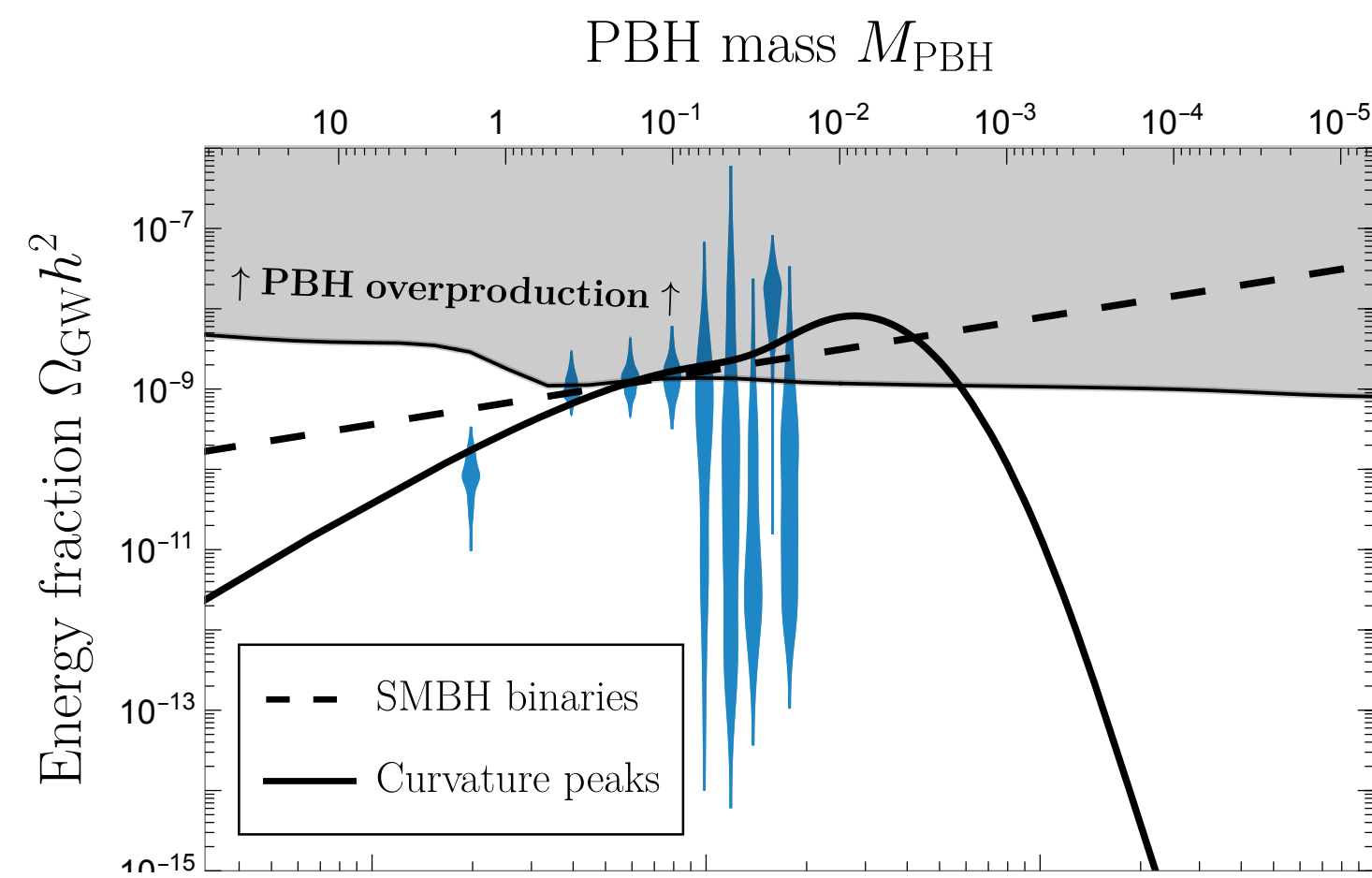
YG (2307.04239)

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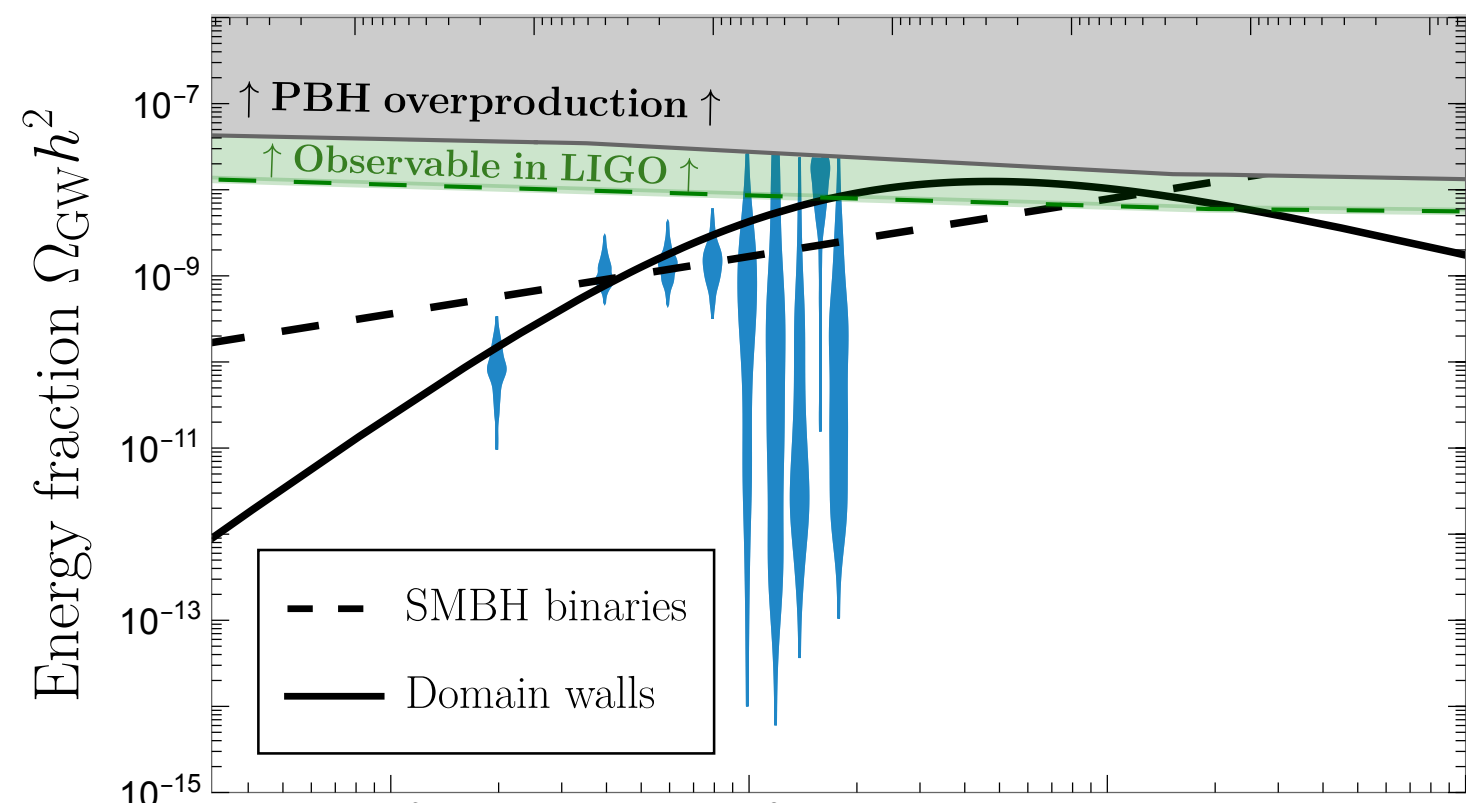
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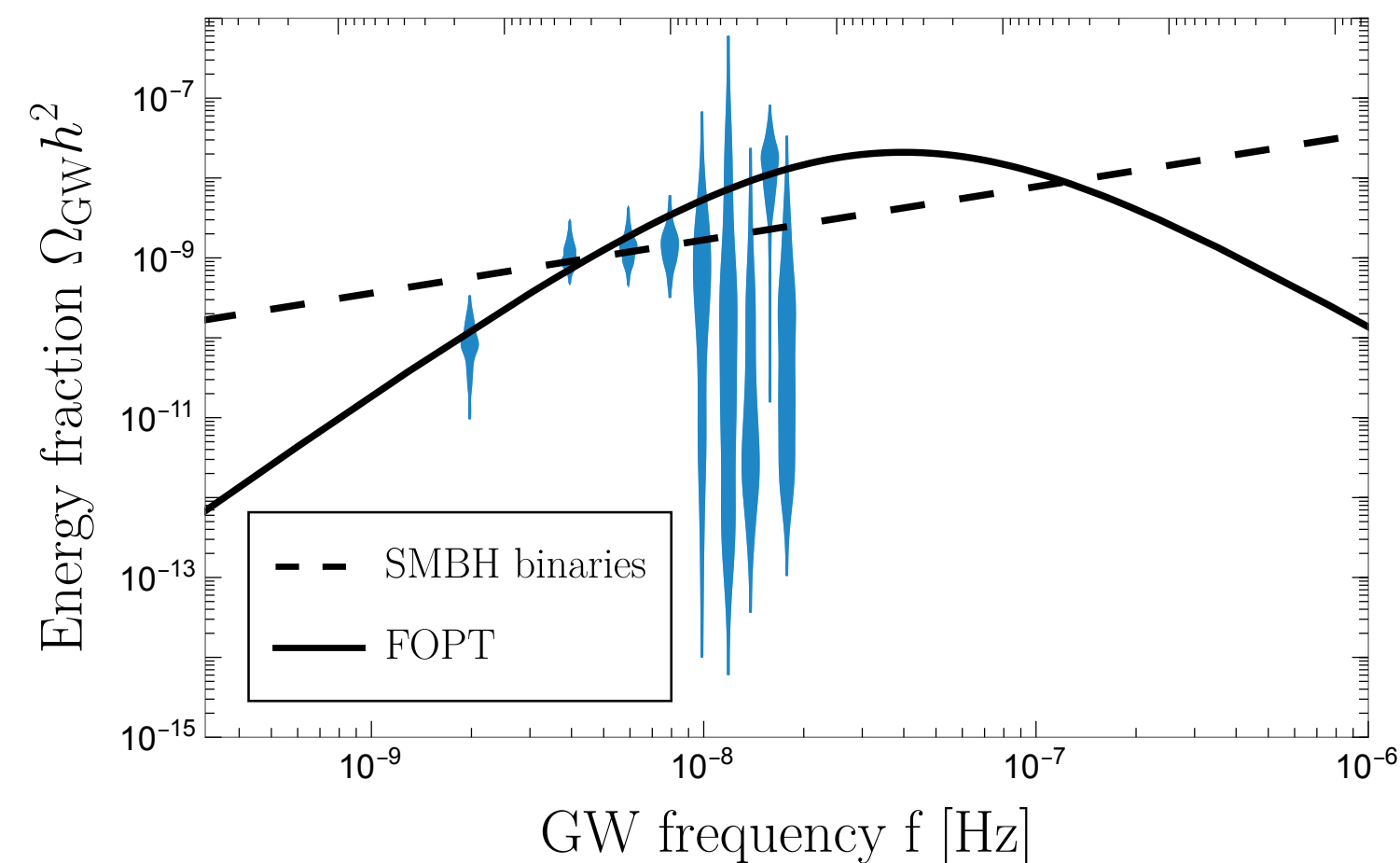
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Produce solar-mass PBH

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Baby-universe

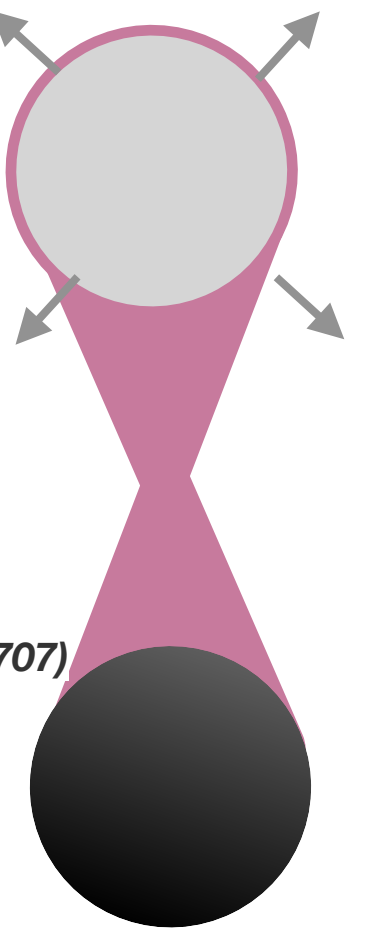
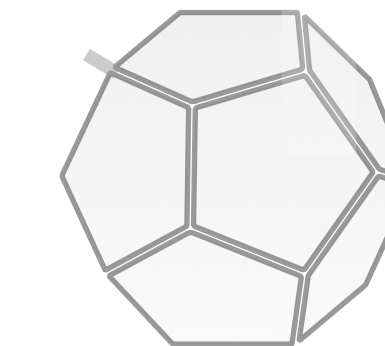
Deng, Garriga, Vilenkin (1612.03753)

Wormhole

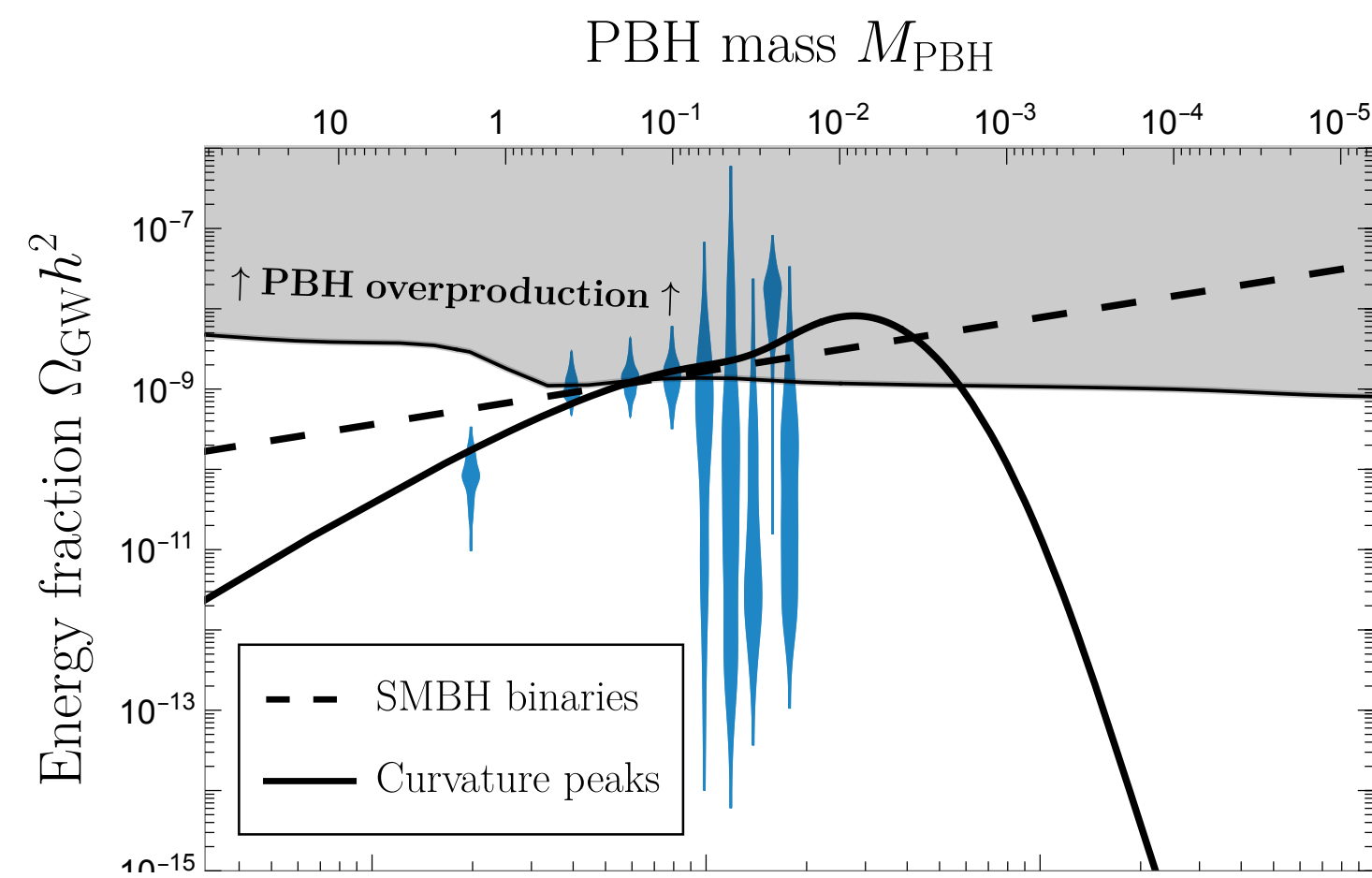
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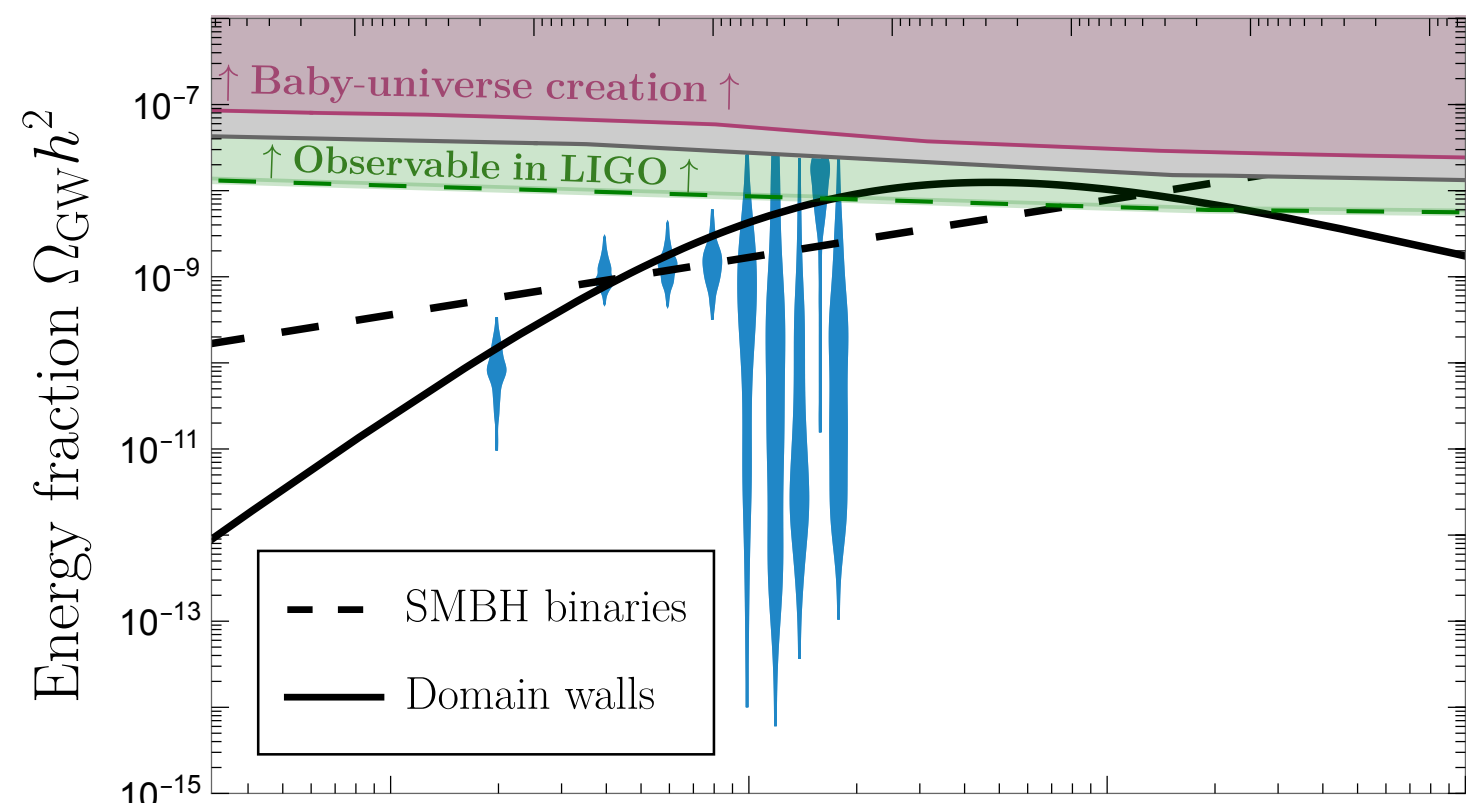
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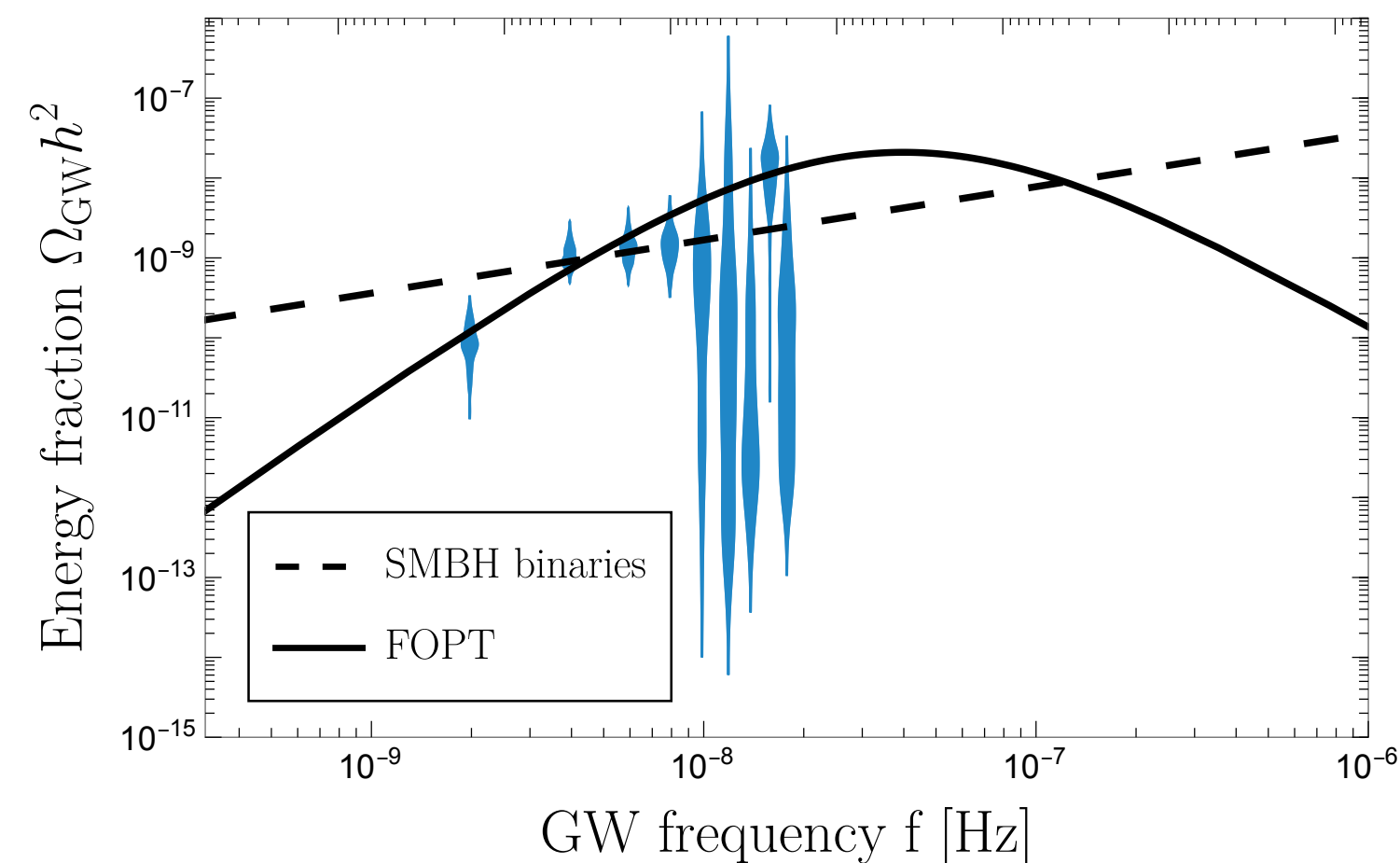
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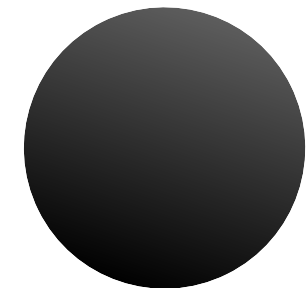
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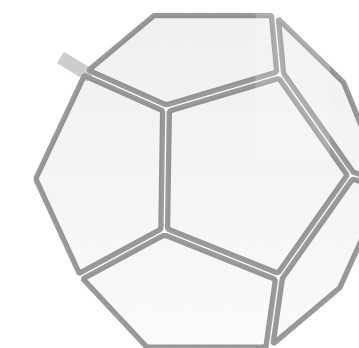
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Baby-universe

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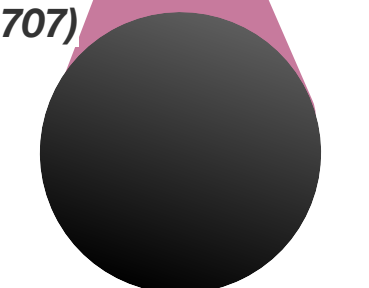
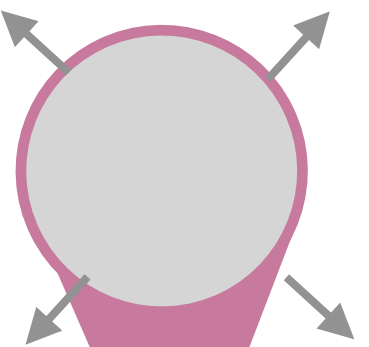
Wormhole



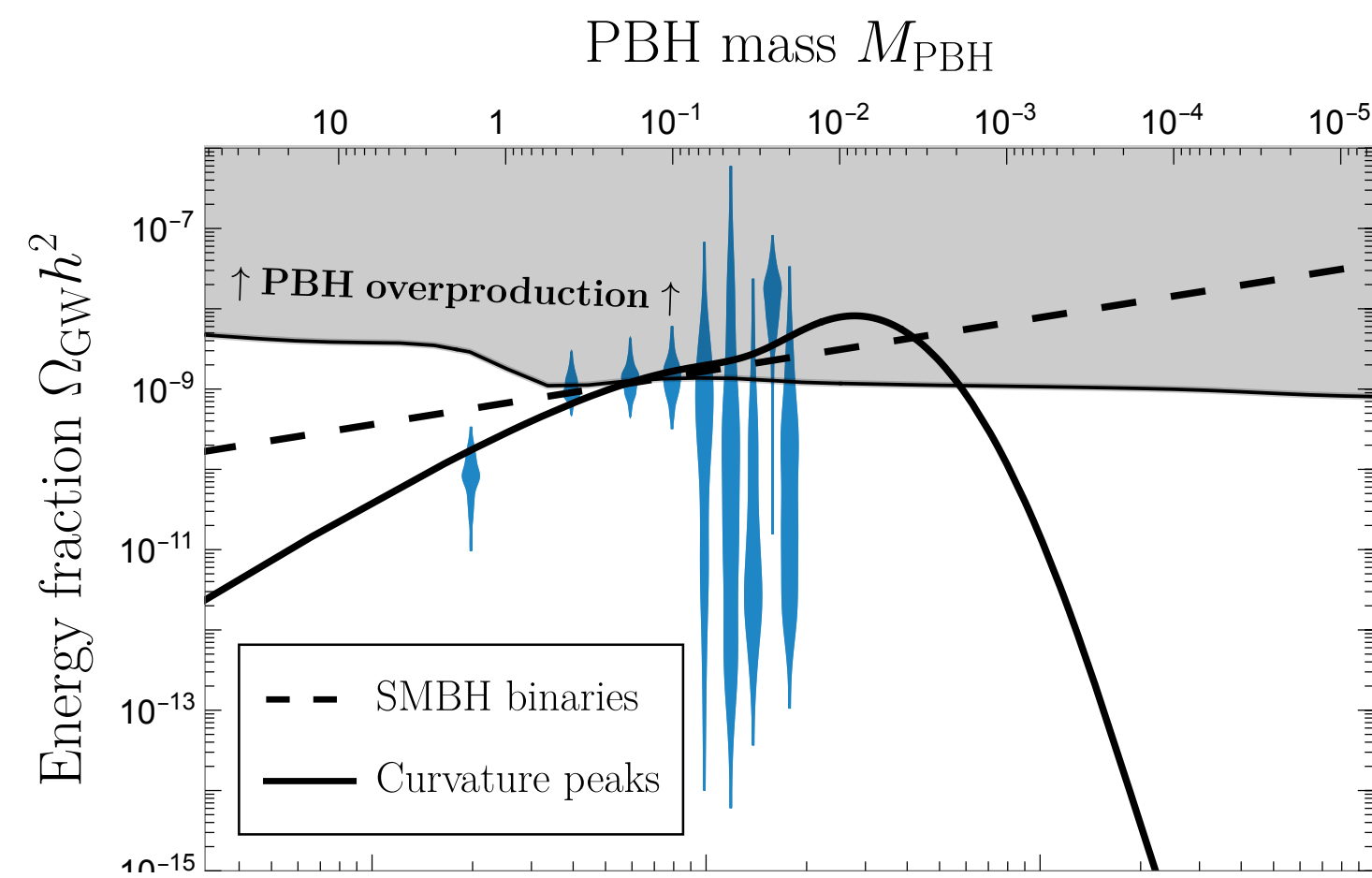
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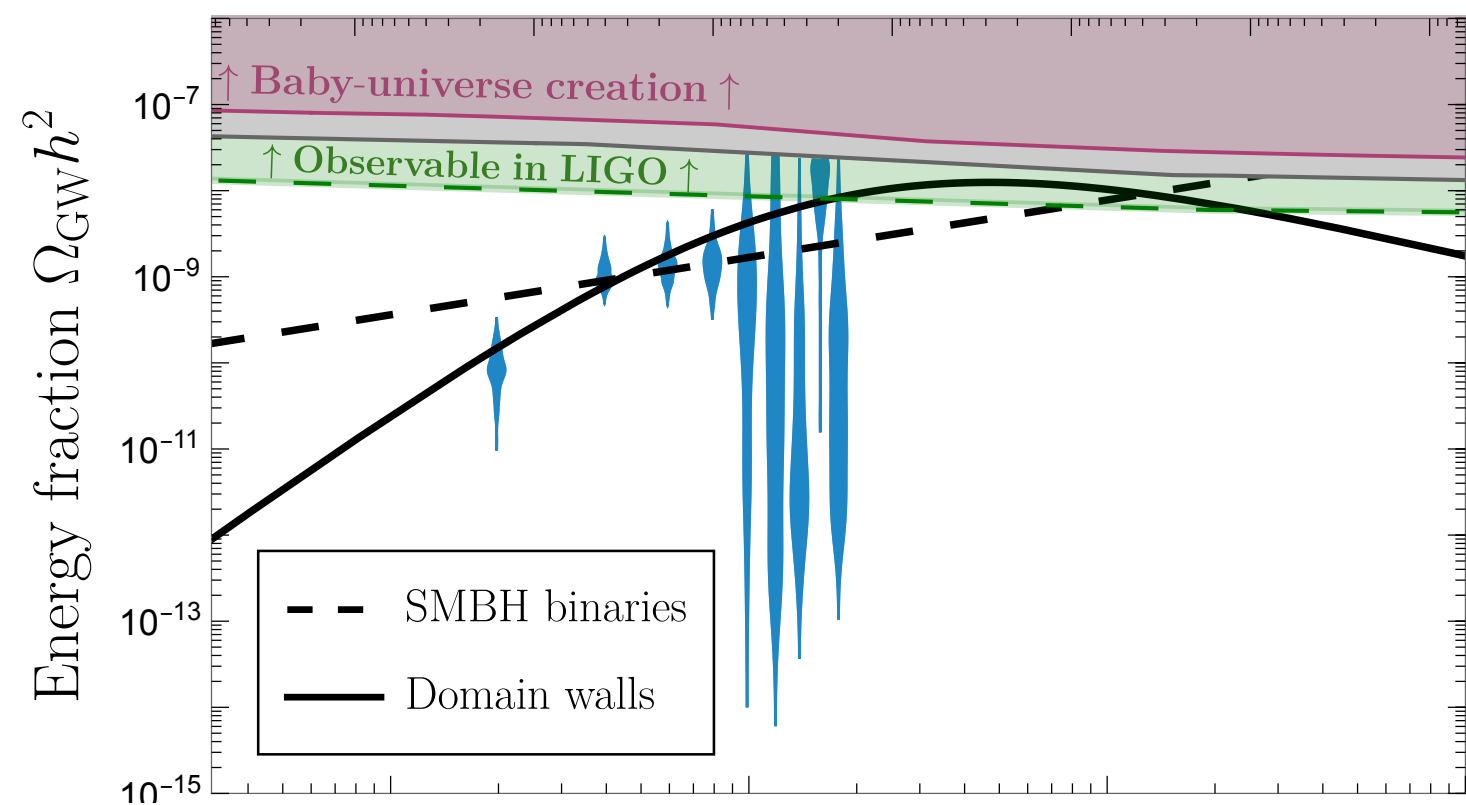
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Domain wall networks

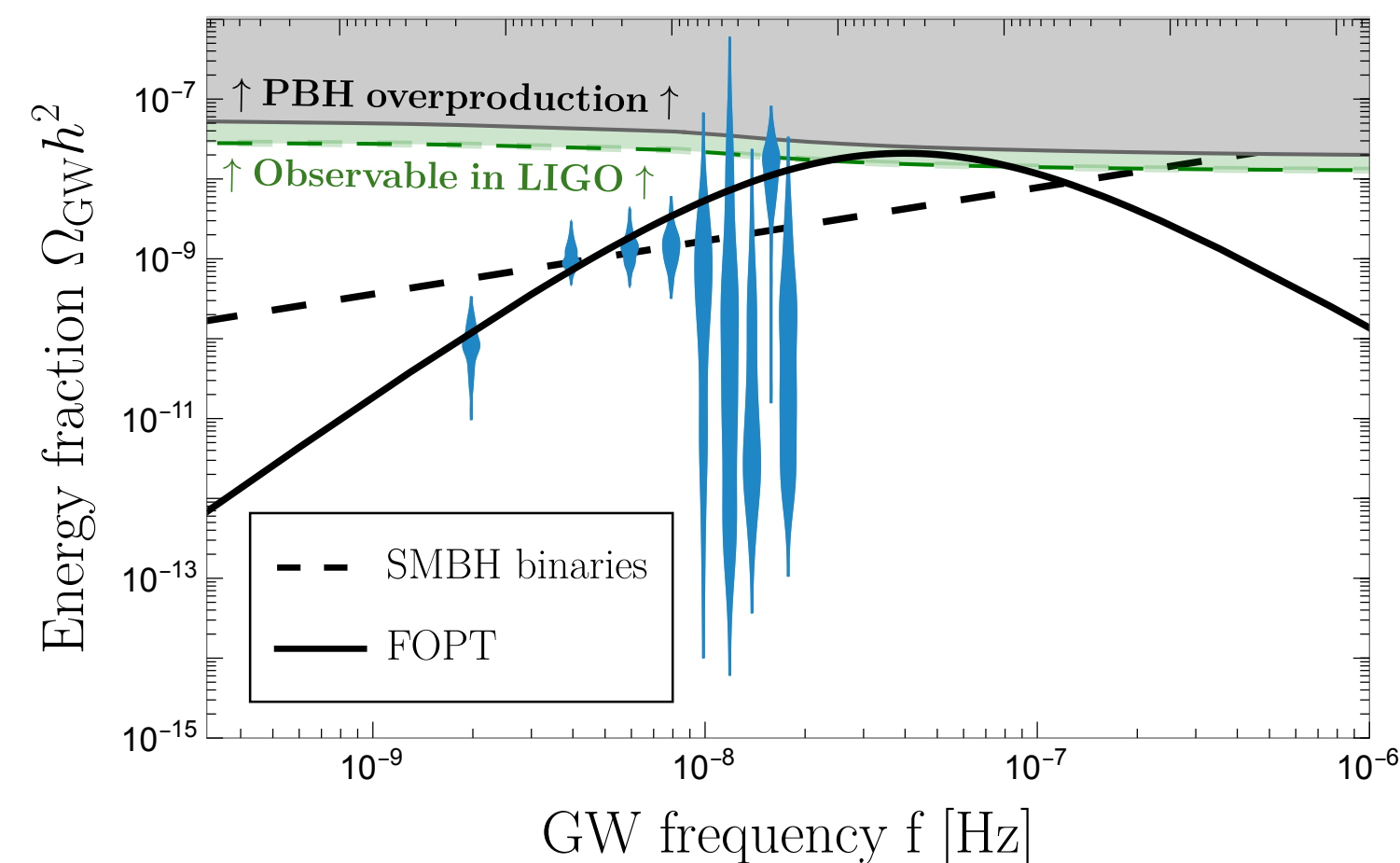
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Produce solar-mass PBH

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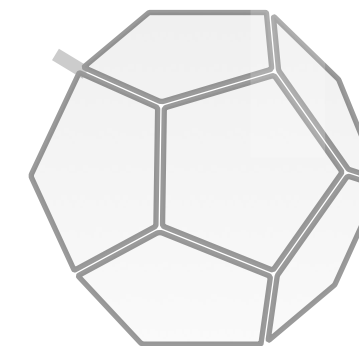
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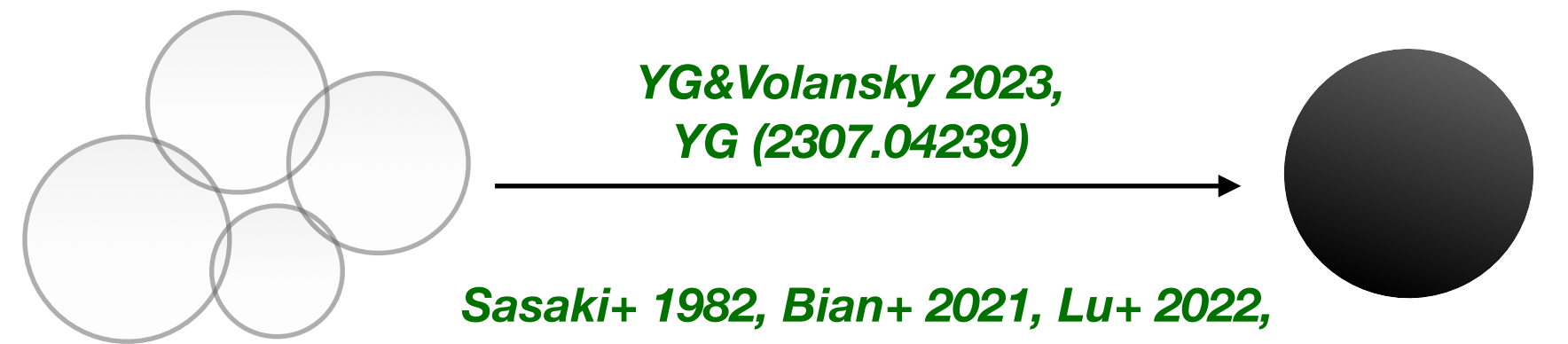
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YG, Vitagliano, 2311.07670



PBH



YG&Volansky 2023,

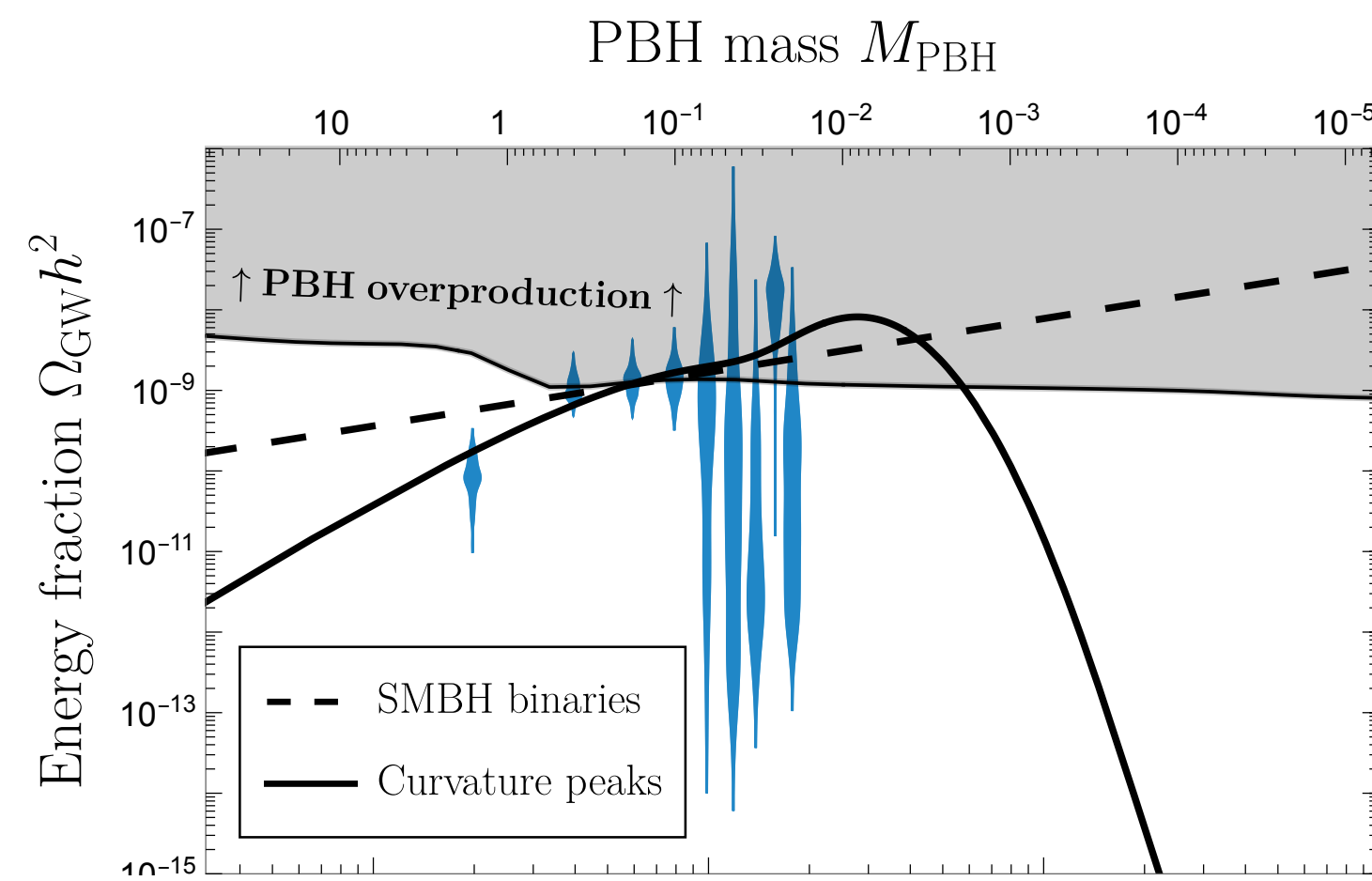
YG (2307.04239)

Sasaki+ 1982, Bian+ 2021, Lu+ 2022,

Lewicki, Toczek, Vaskonen 2023,

Baldes+ 2023,

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Curvature peaks

Overproduce PBH

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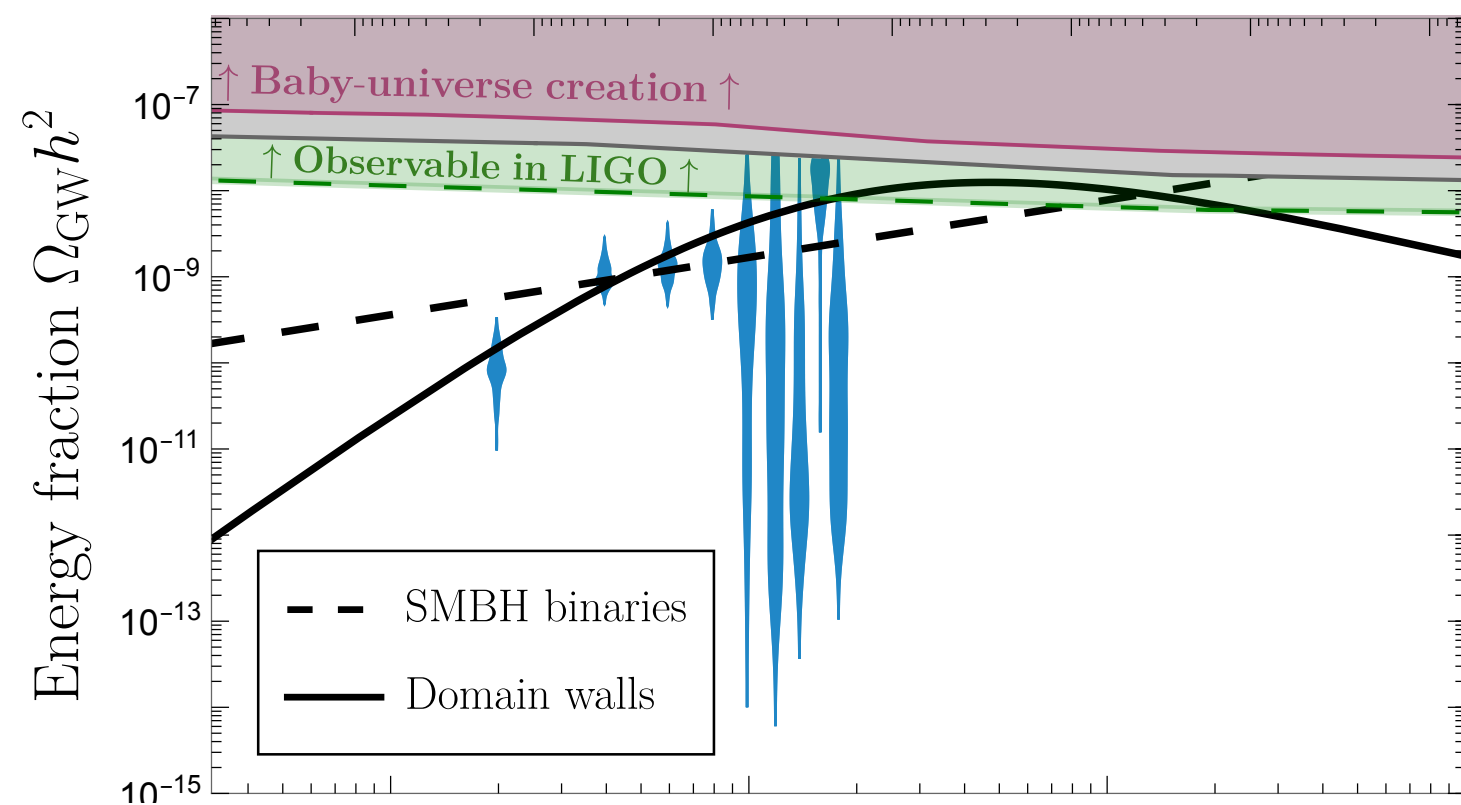
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Domain wall networks

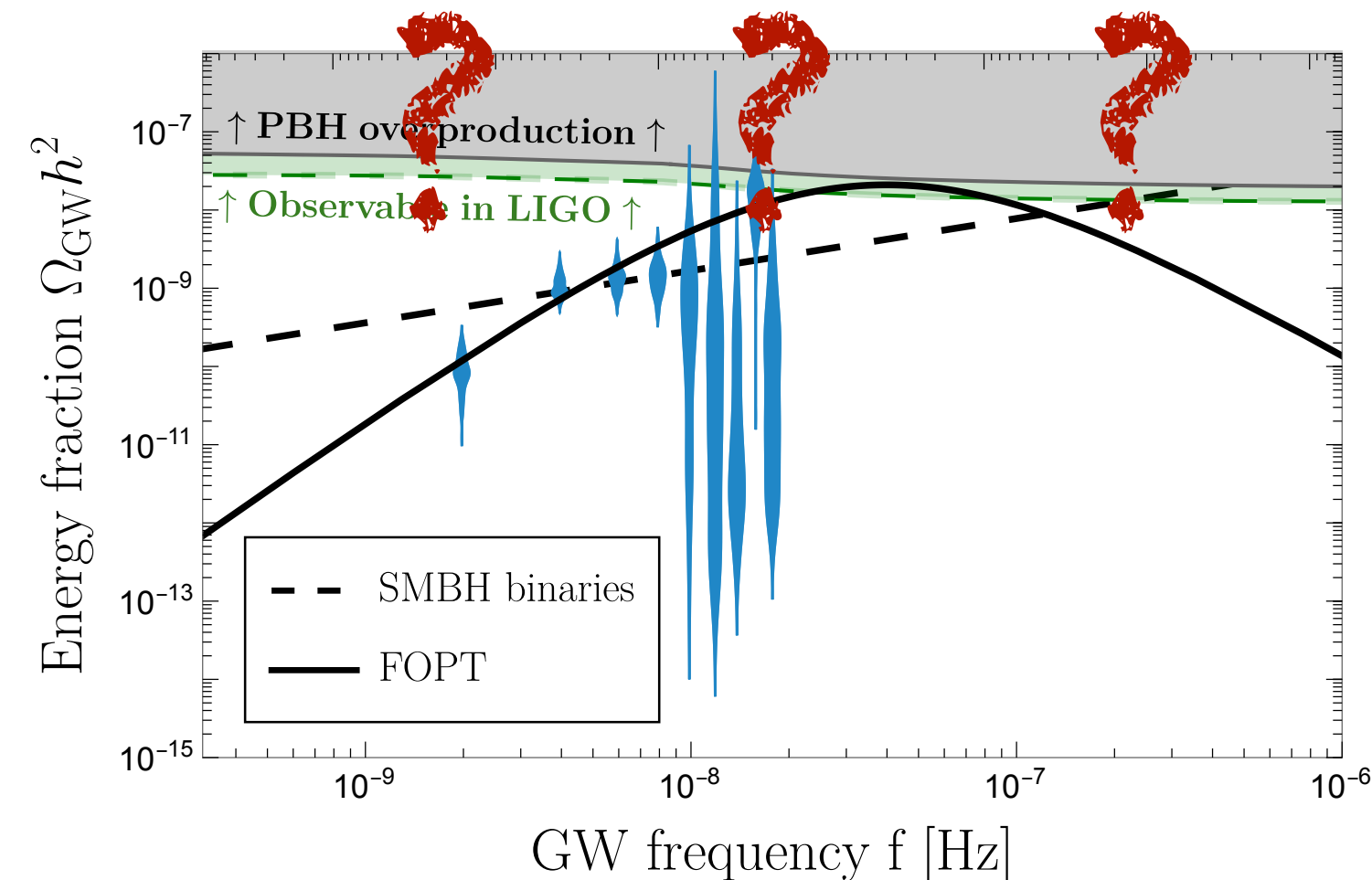
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

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Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

Ghoshal, White et al. (2307.02259)

YG (2307.04239)

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Baby-universe

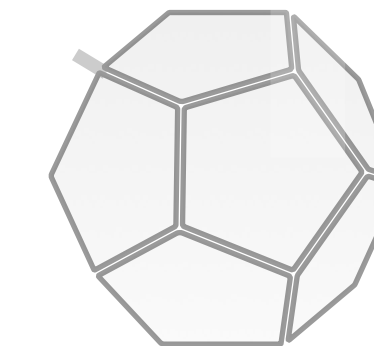
Deng, Garriga, Vilenkin (1612.03753)

Wormhole

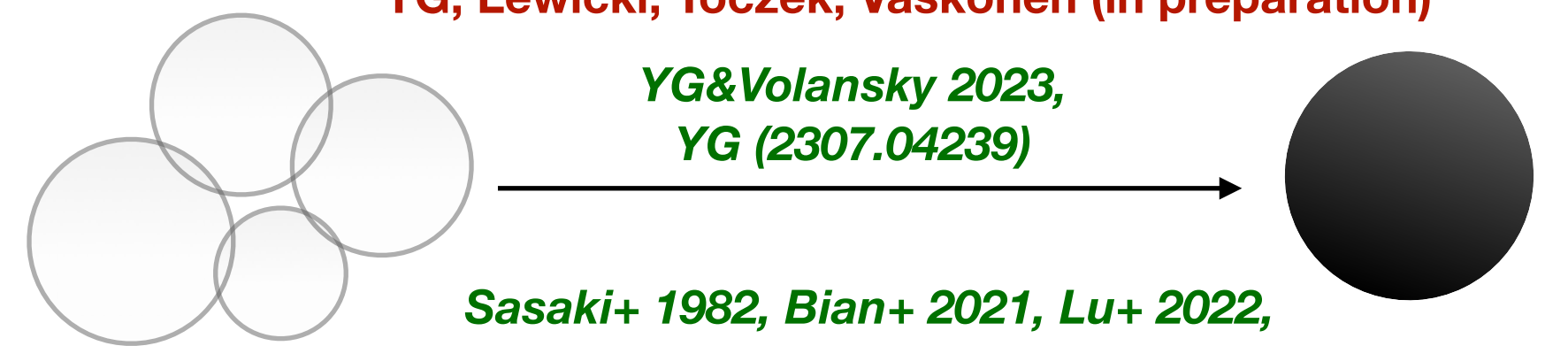
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

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YG, Vitagliano, 2311.07670



PBH



Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

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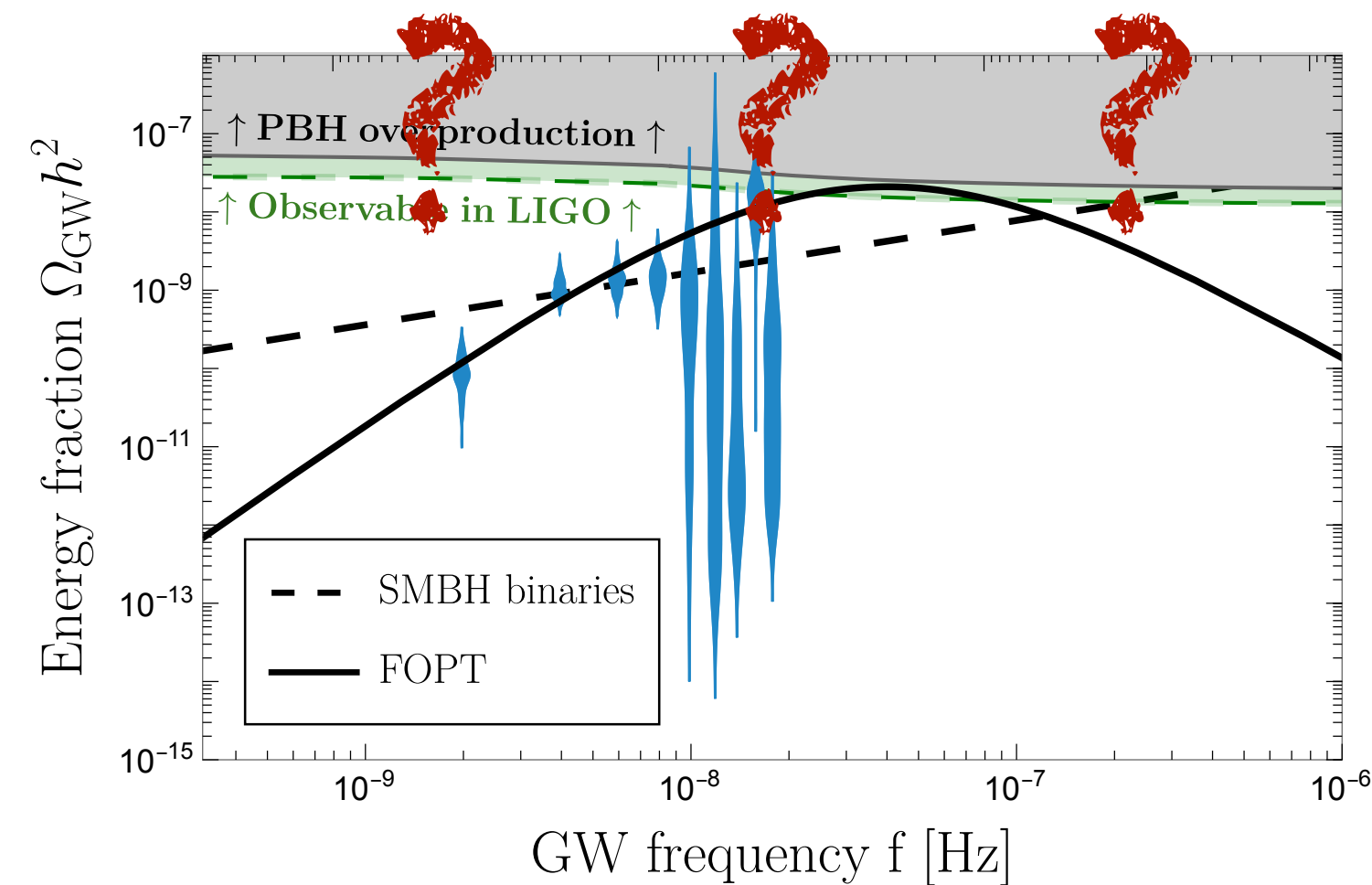
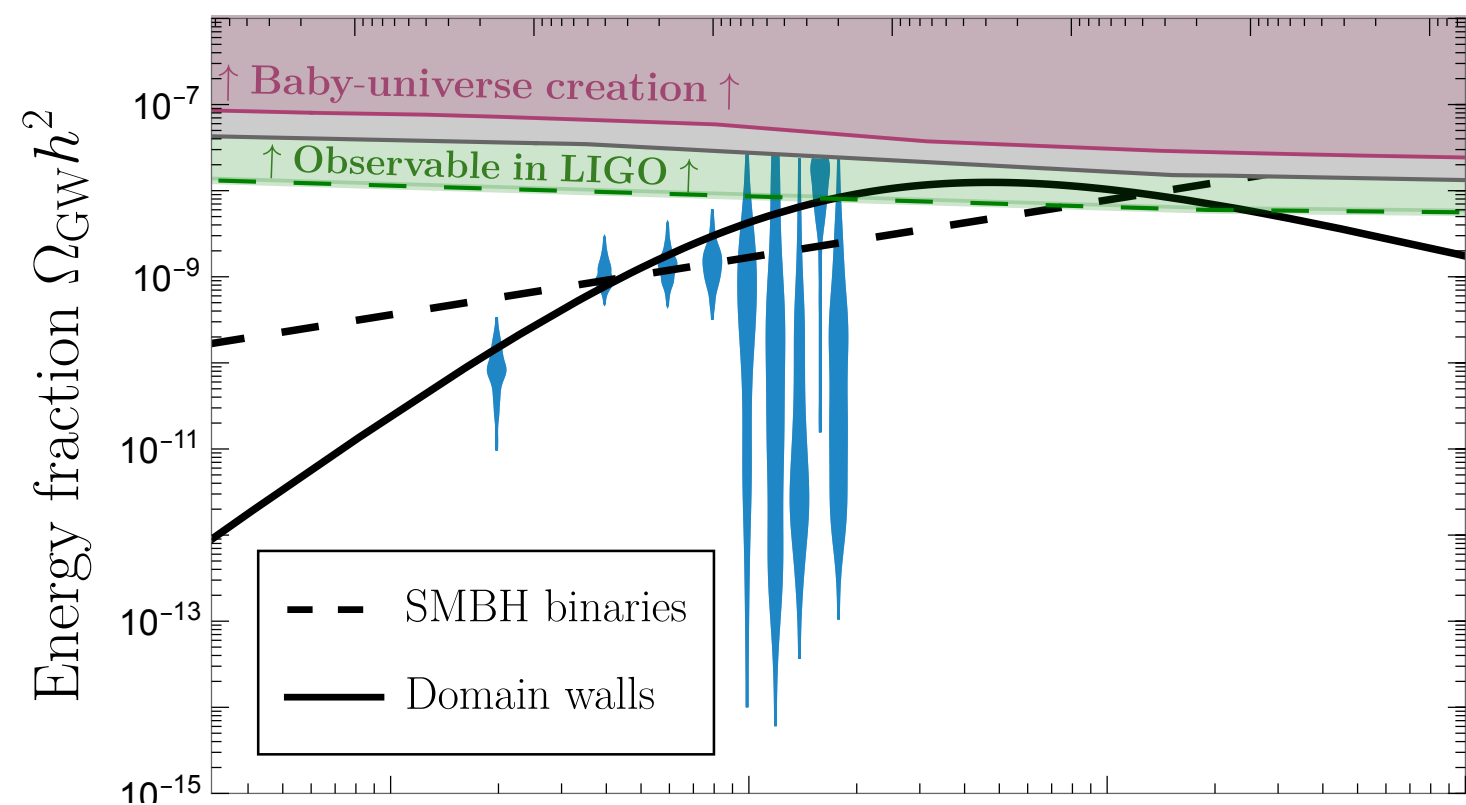
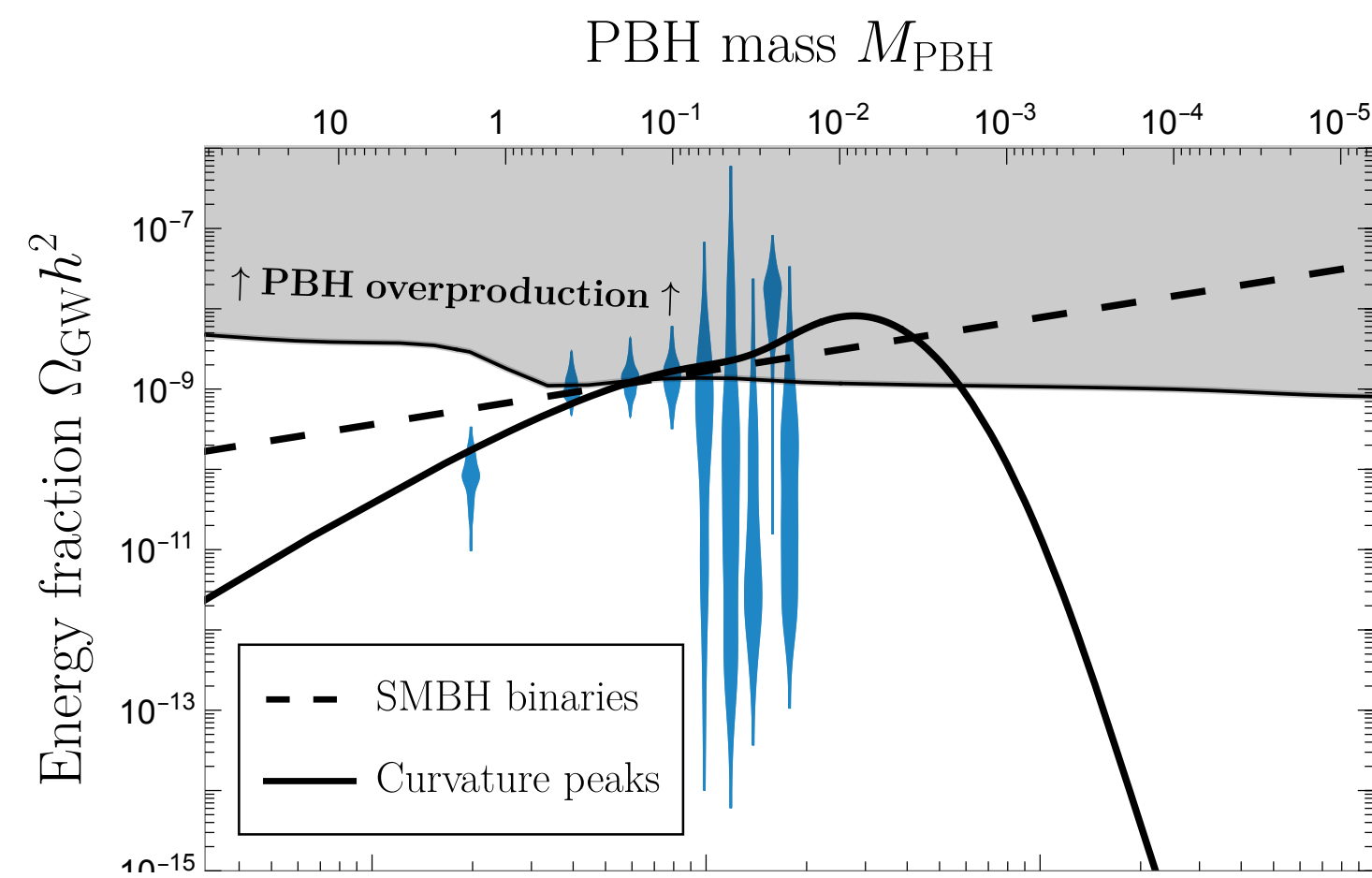
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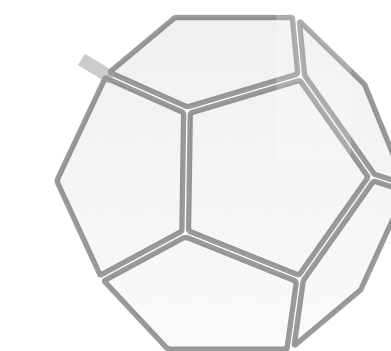
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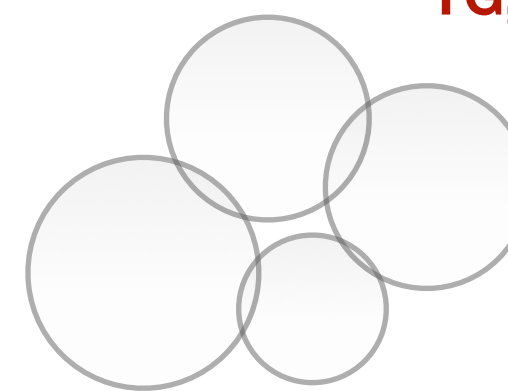


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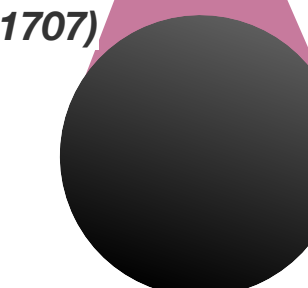
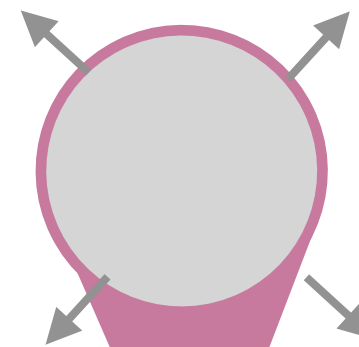
Baldes+ 2023,

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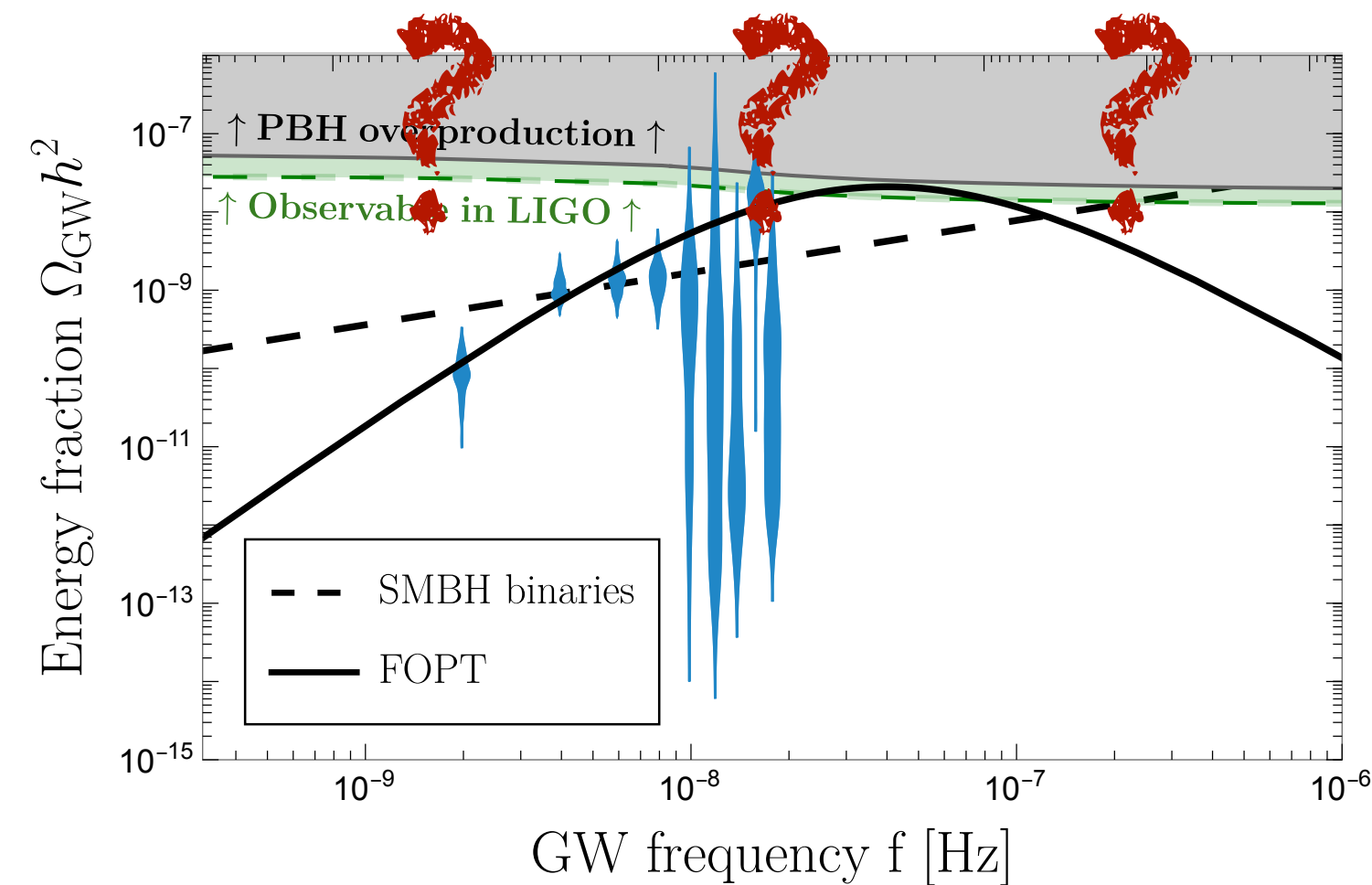
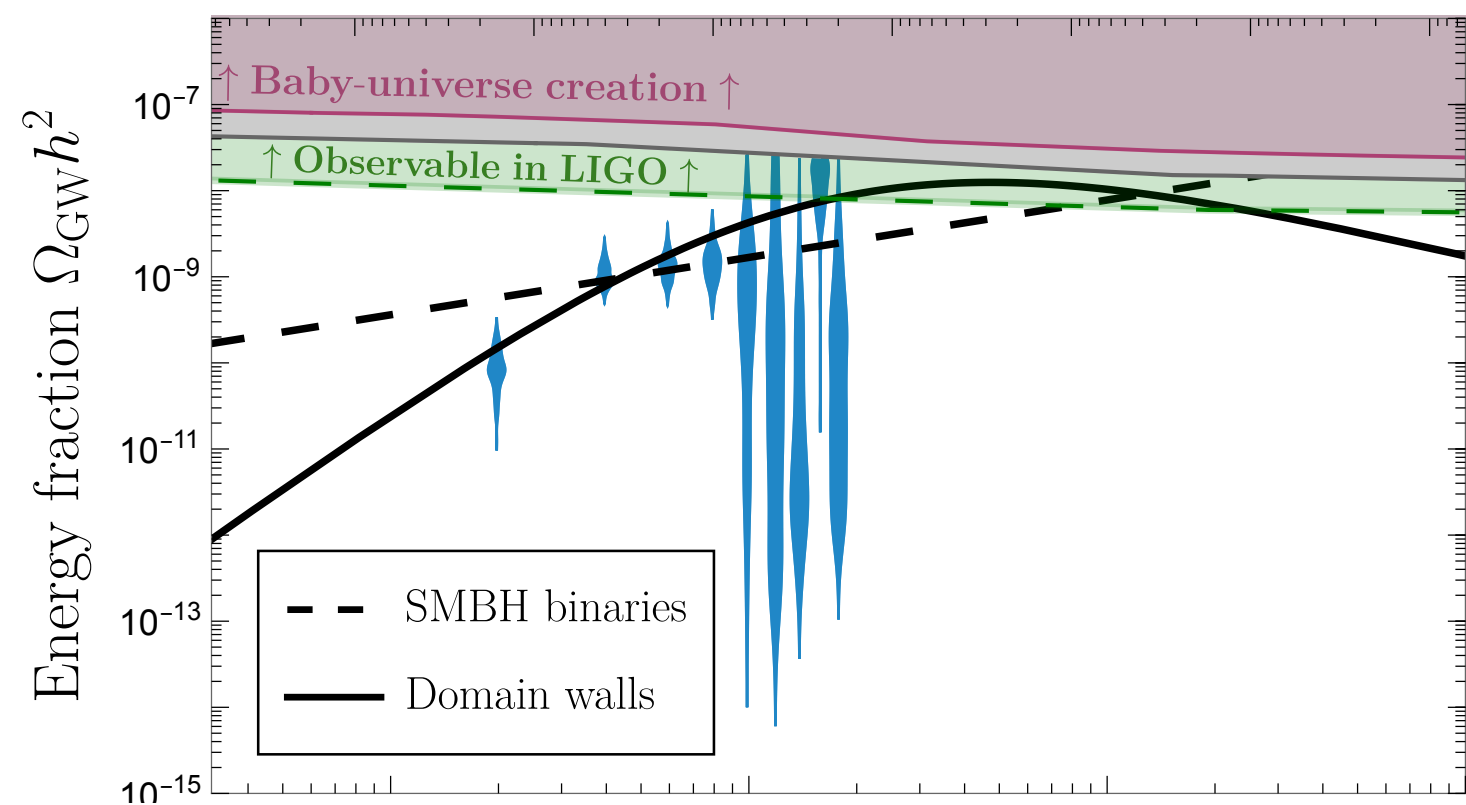
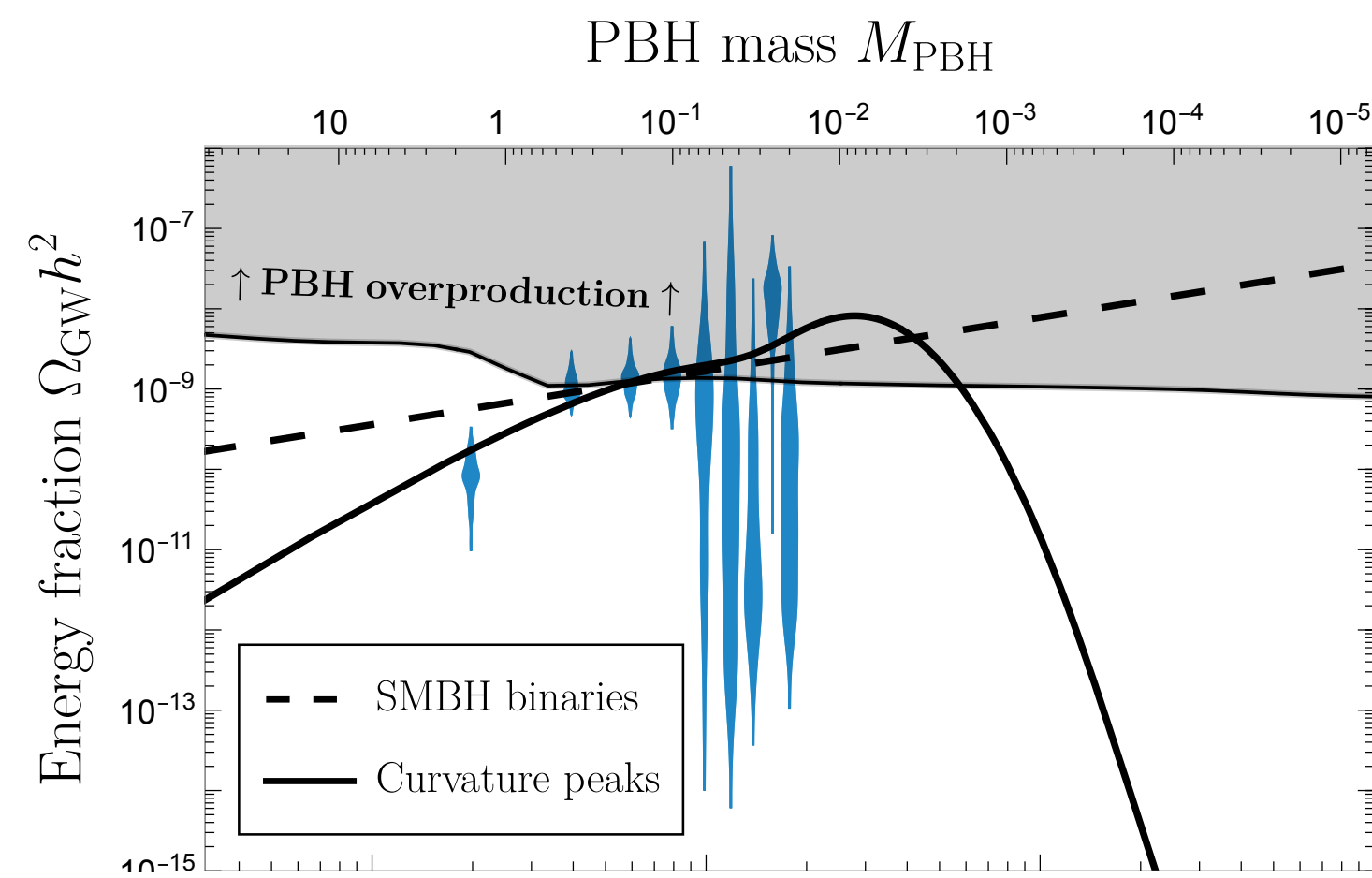
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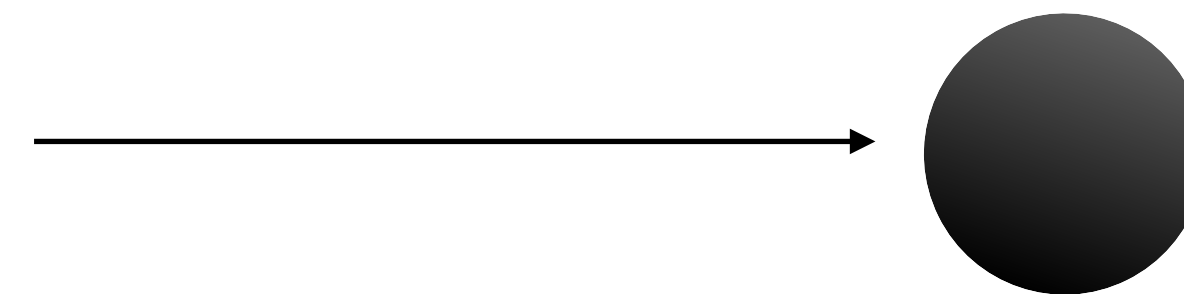
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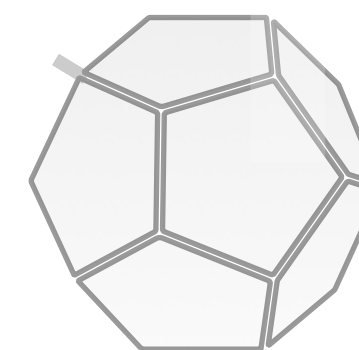
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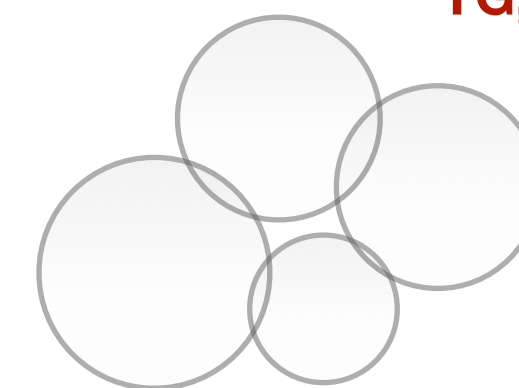
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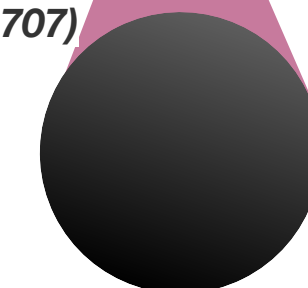
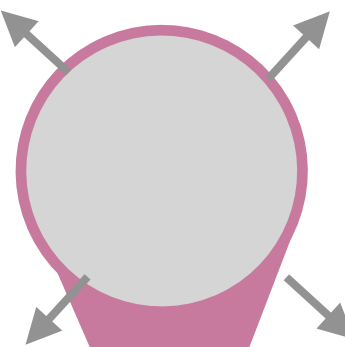
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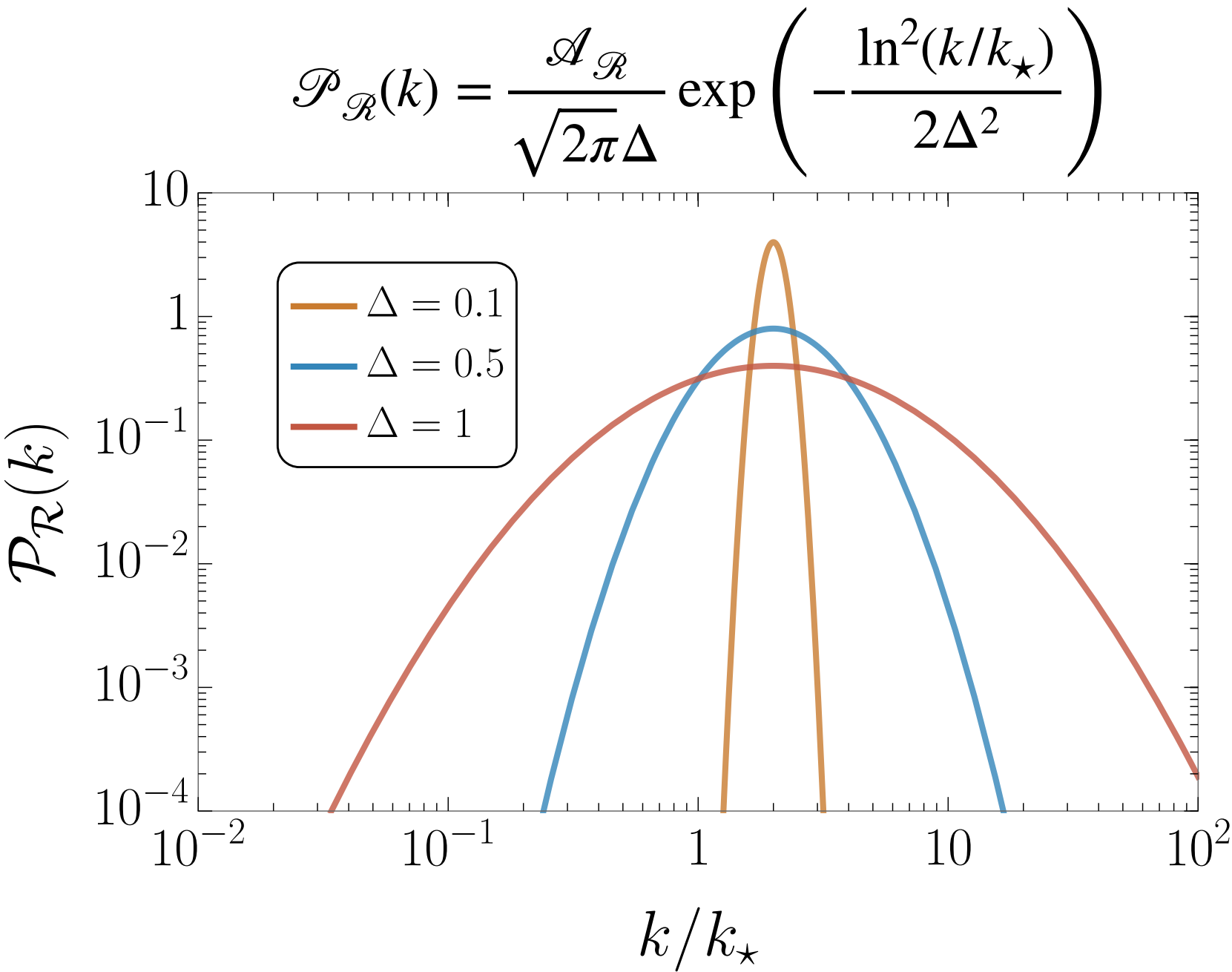
Lewicki, Toczec, Vaskonen 2023,

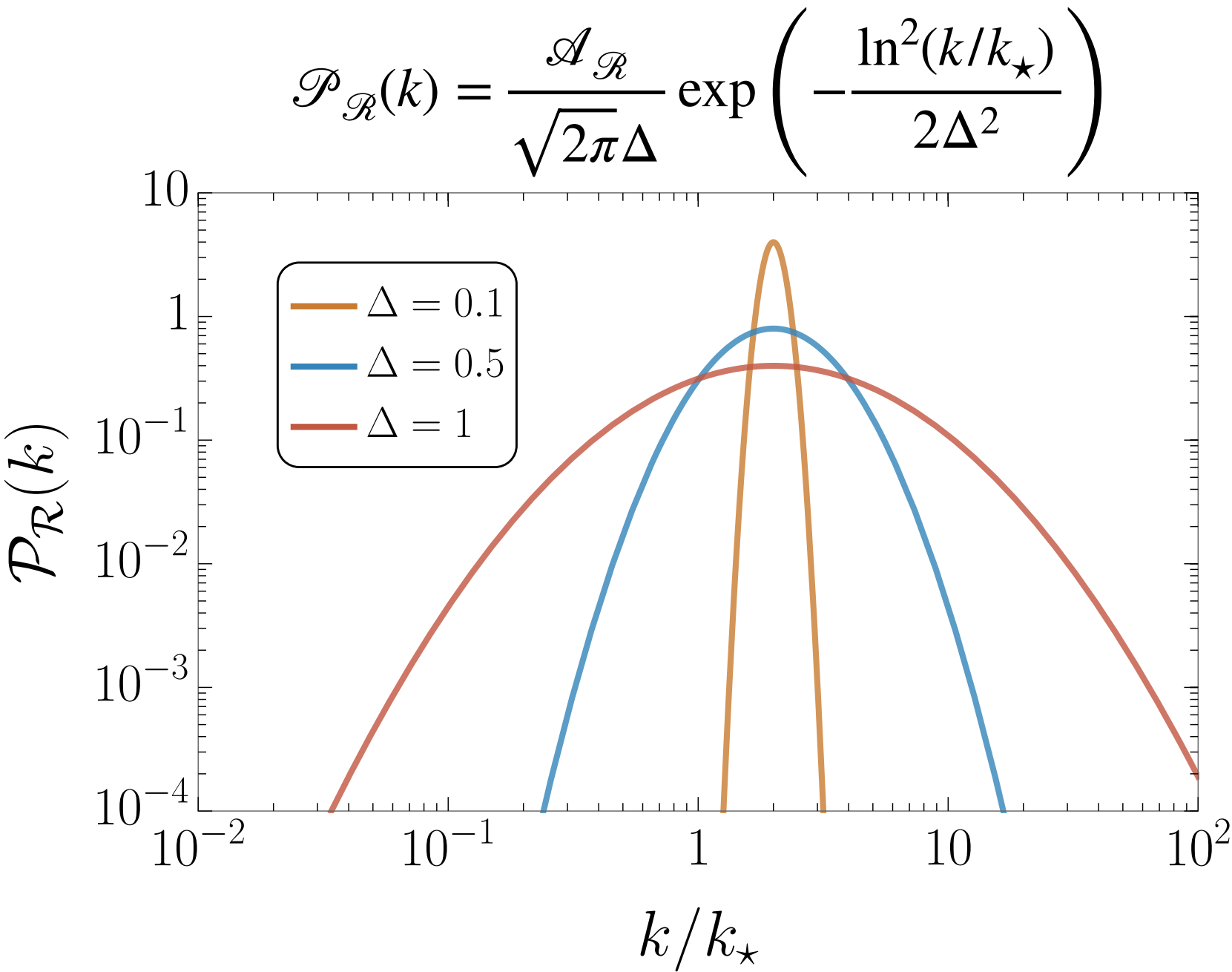
Baldes+ 2023,

Lewicki, Toczec, Vaskonen 2024,



PBH



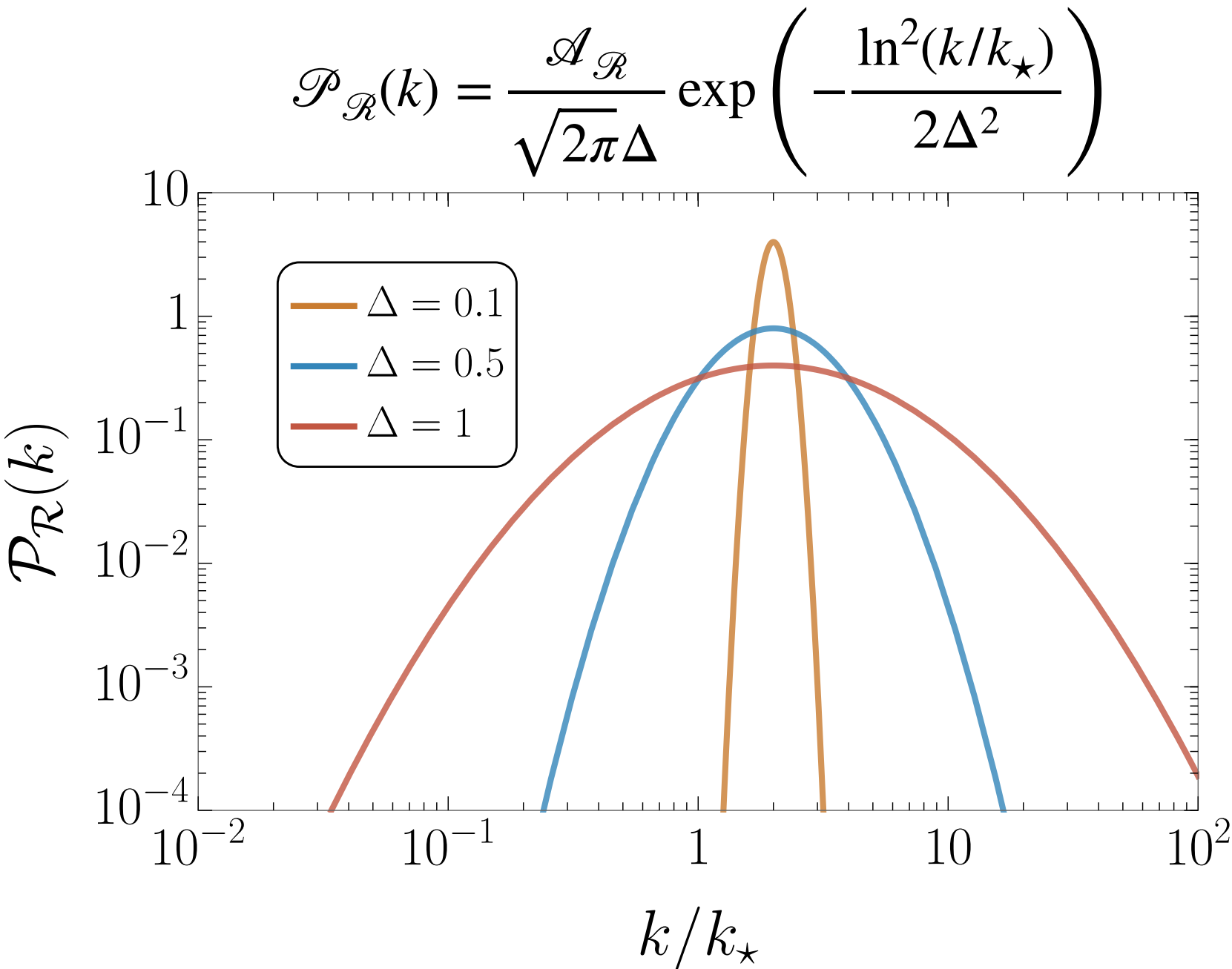


$$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$$

→

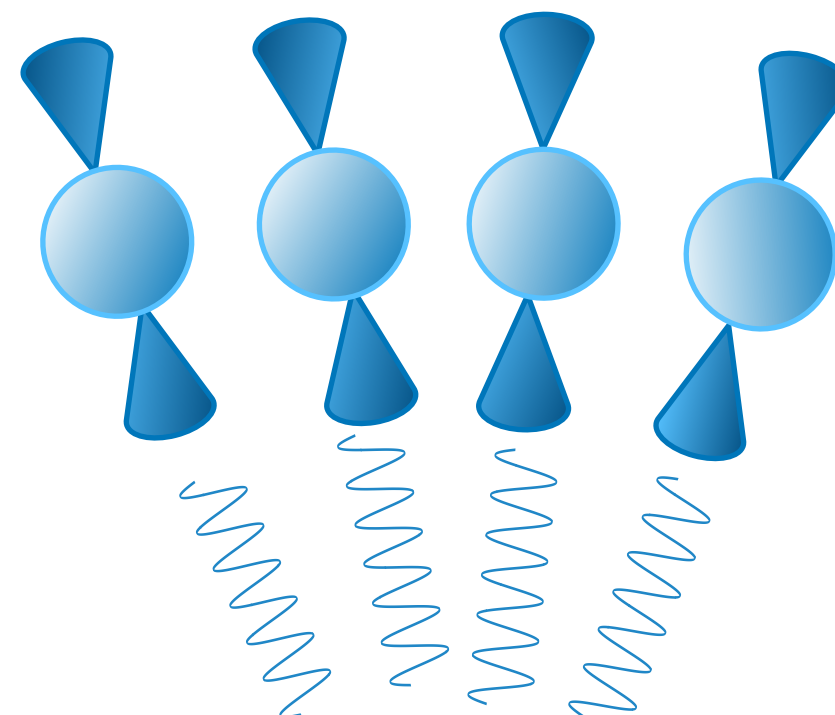
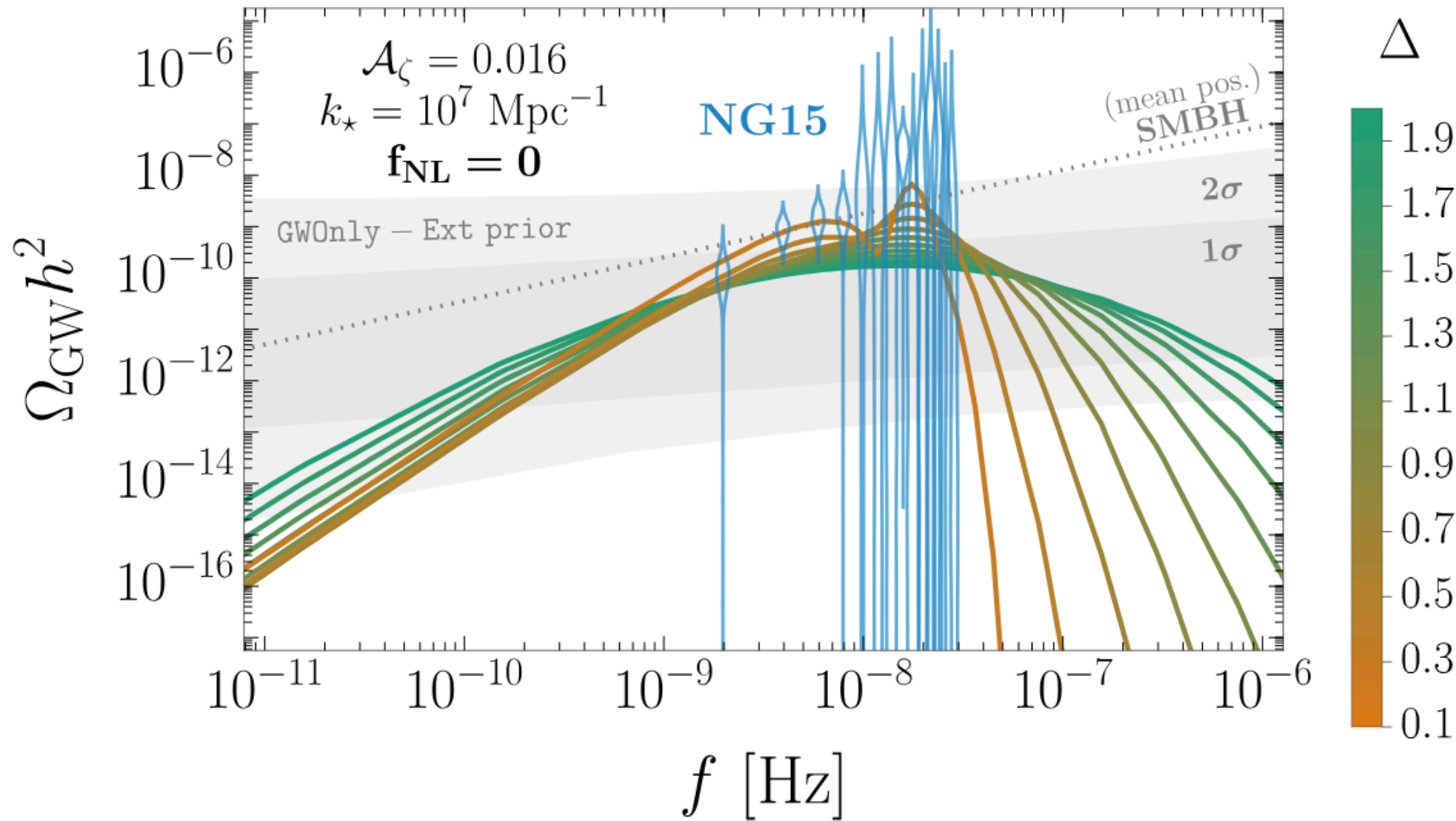
Scalar induced GW

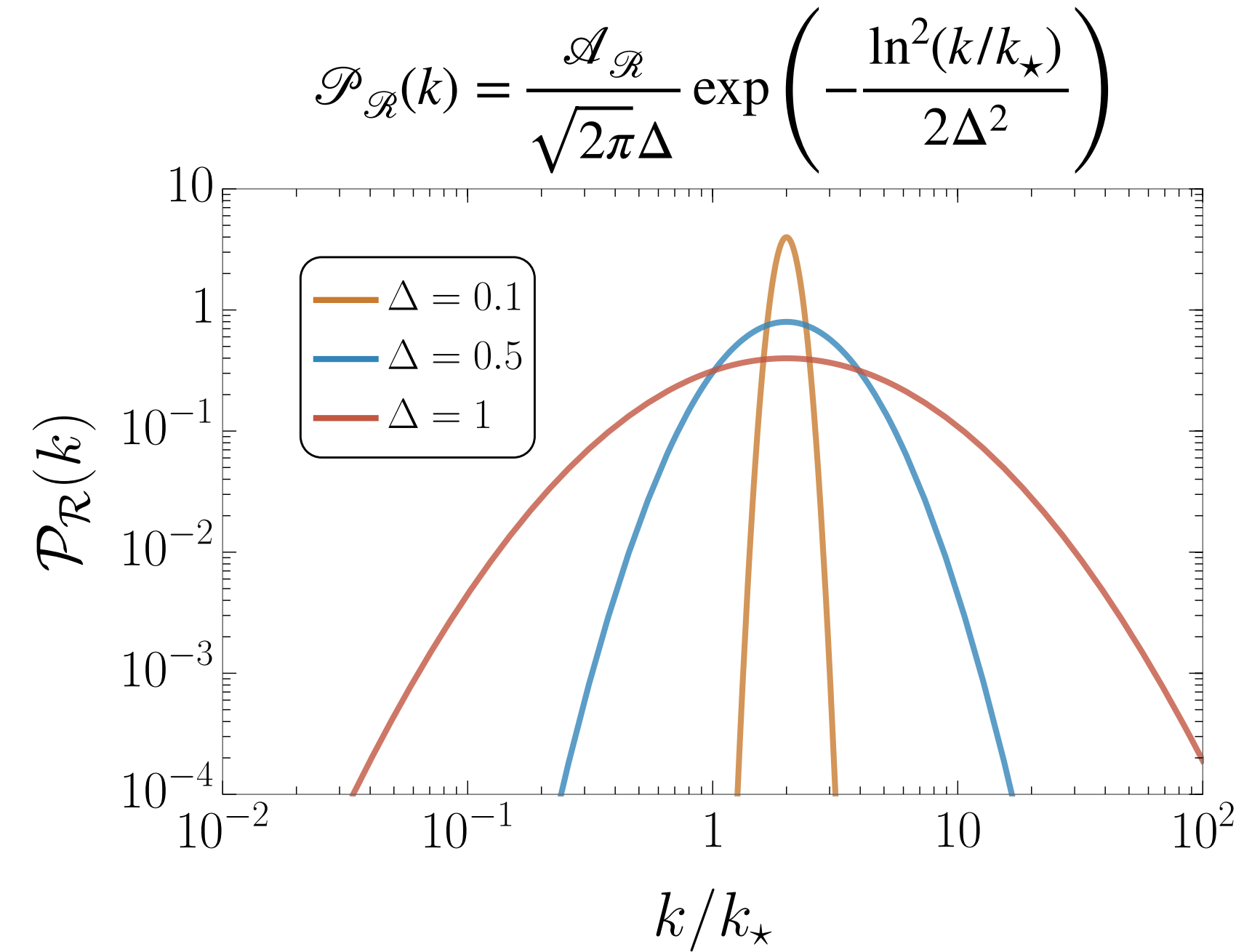




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Scalar induced GW

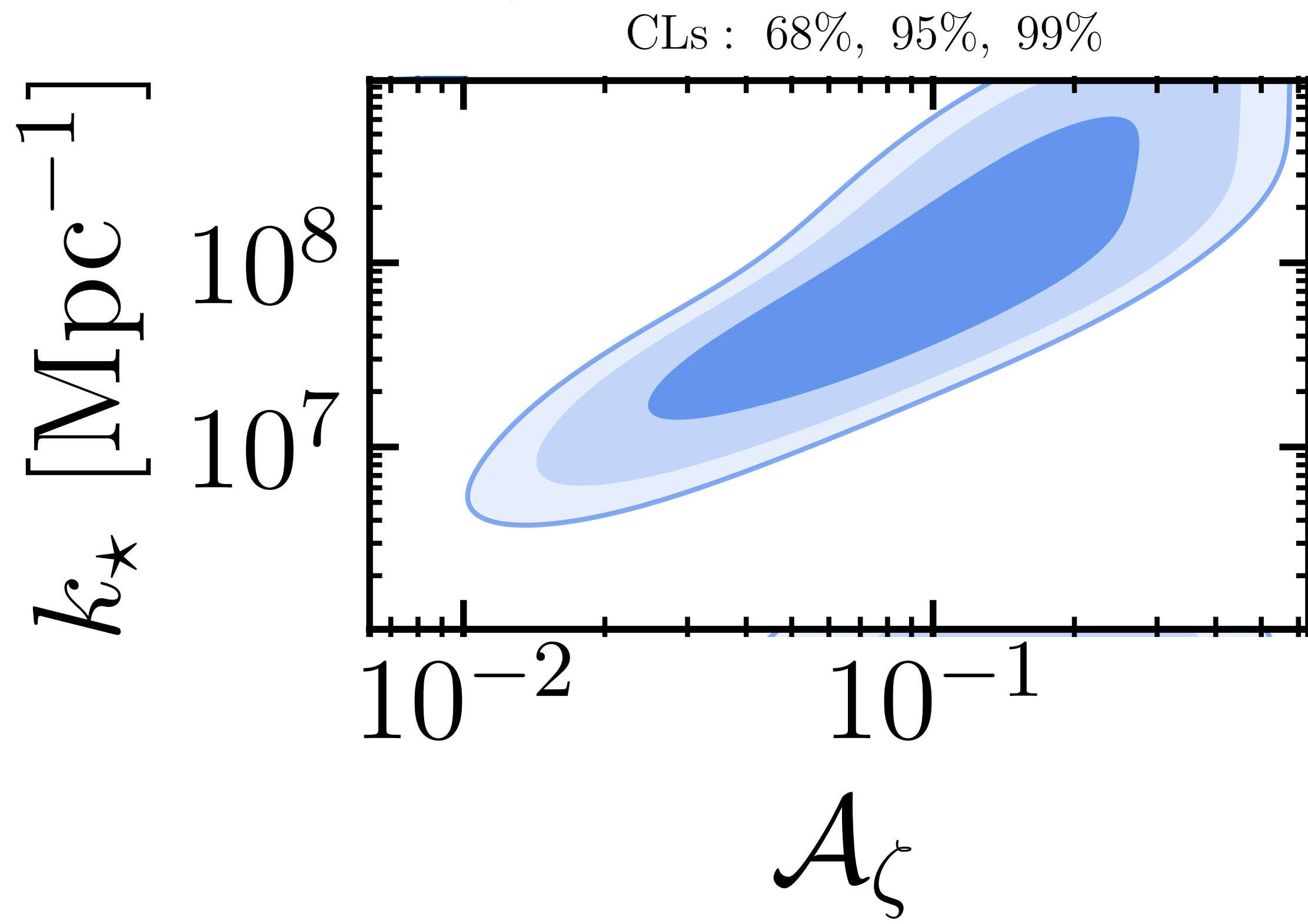
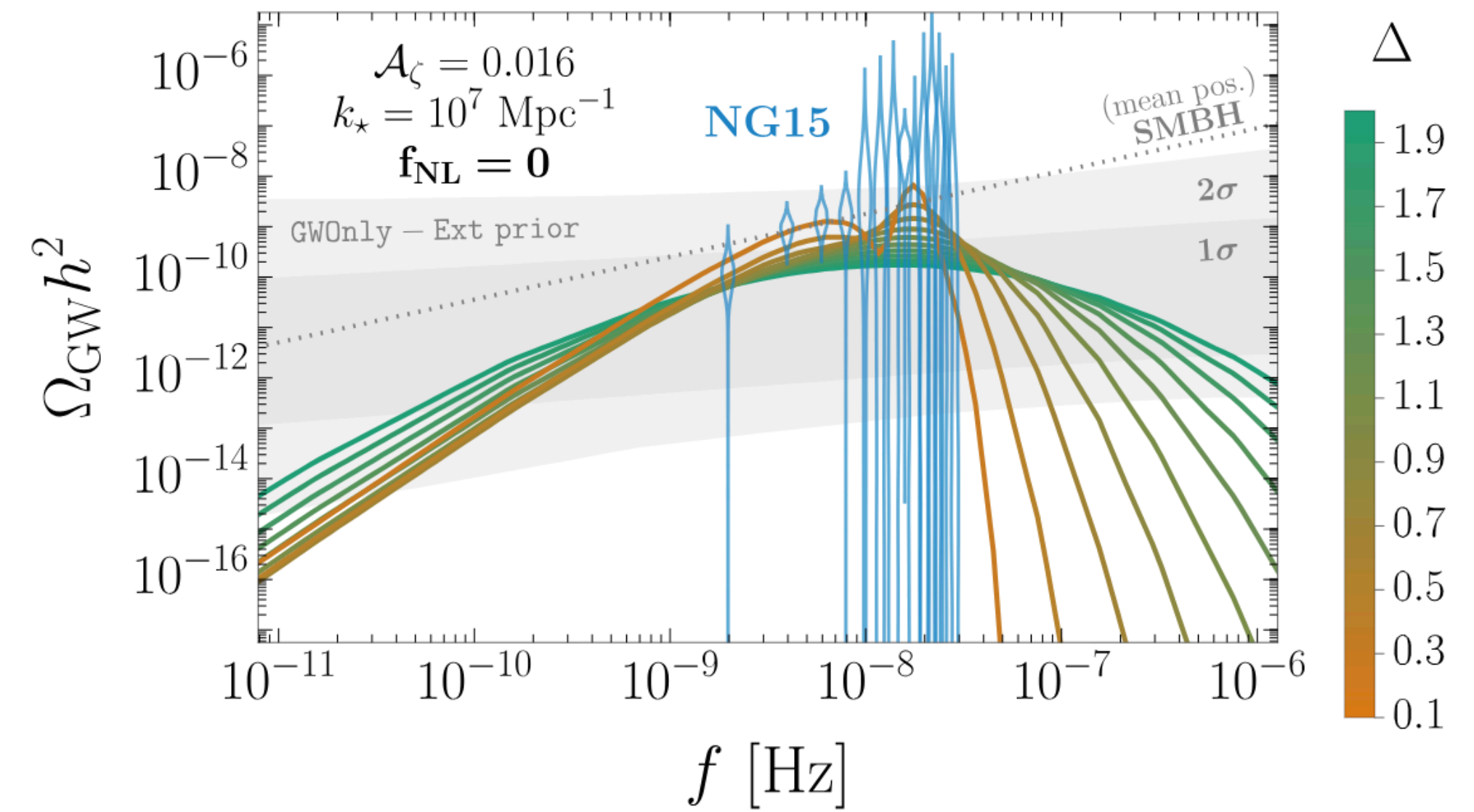




$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

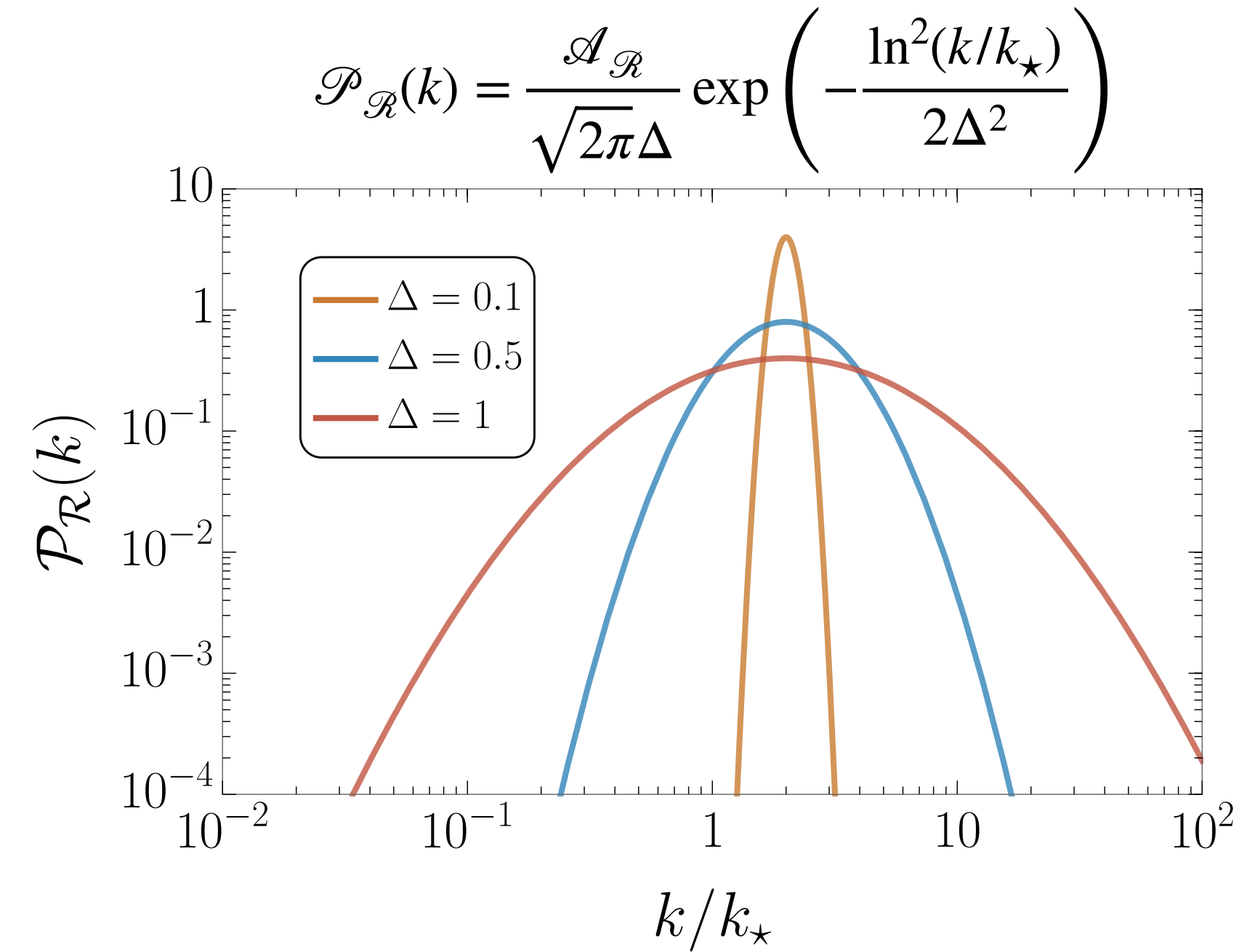
→

Scalar induced GW



○ NG15: SIGW (no PBH prior)

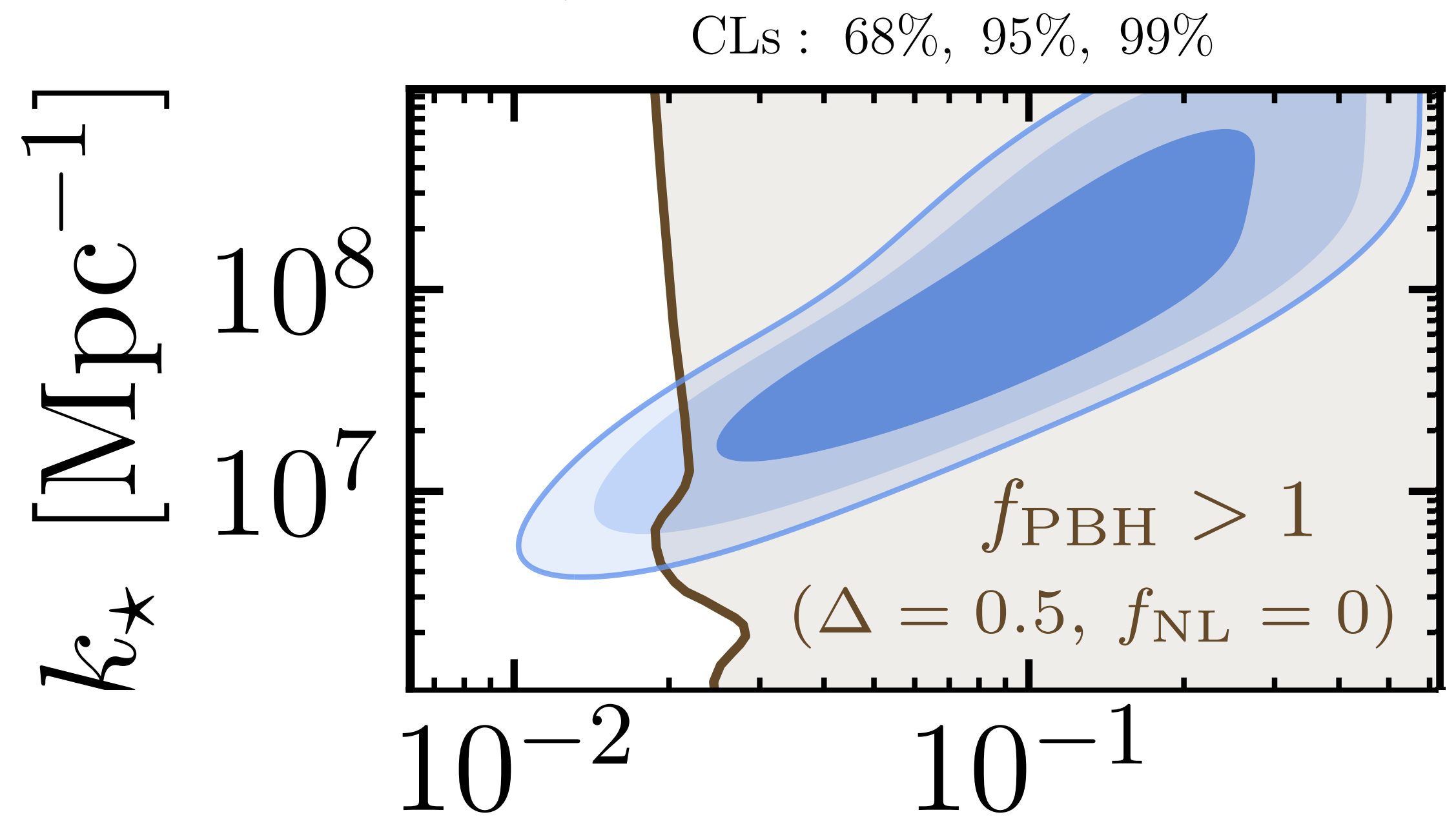
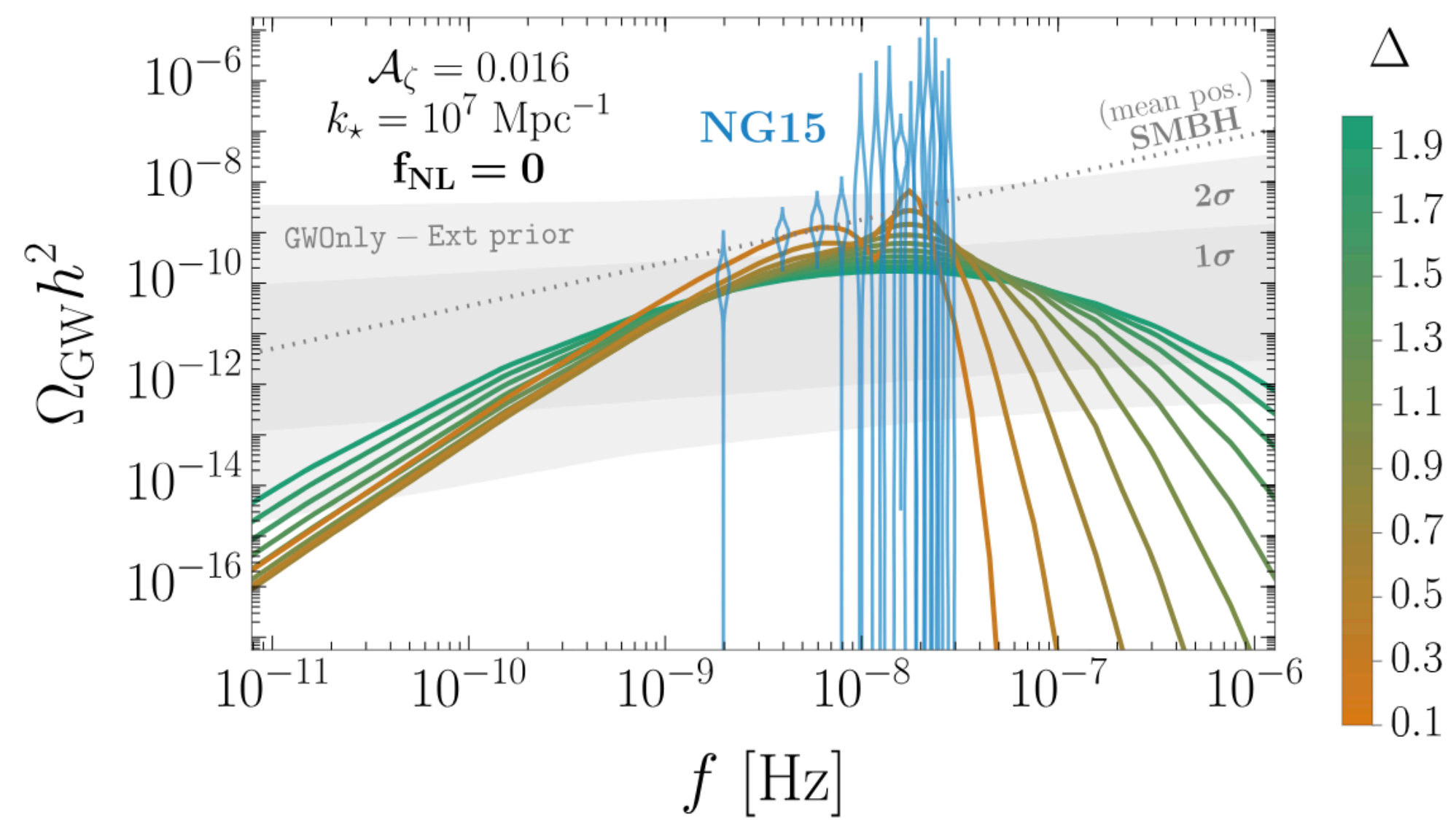
Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

→

Scalar induced GW

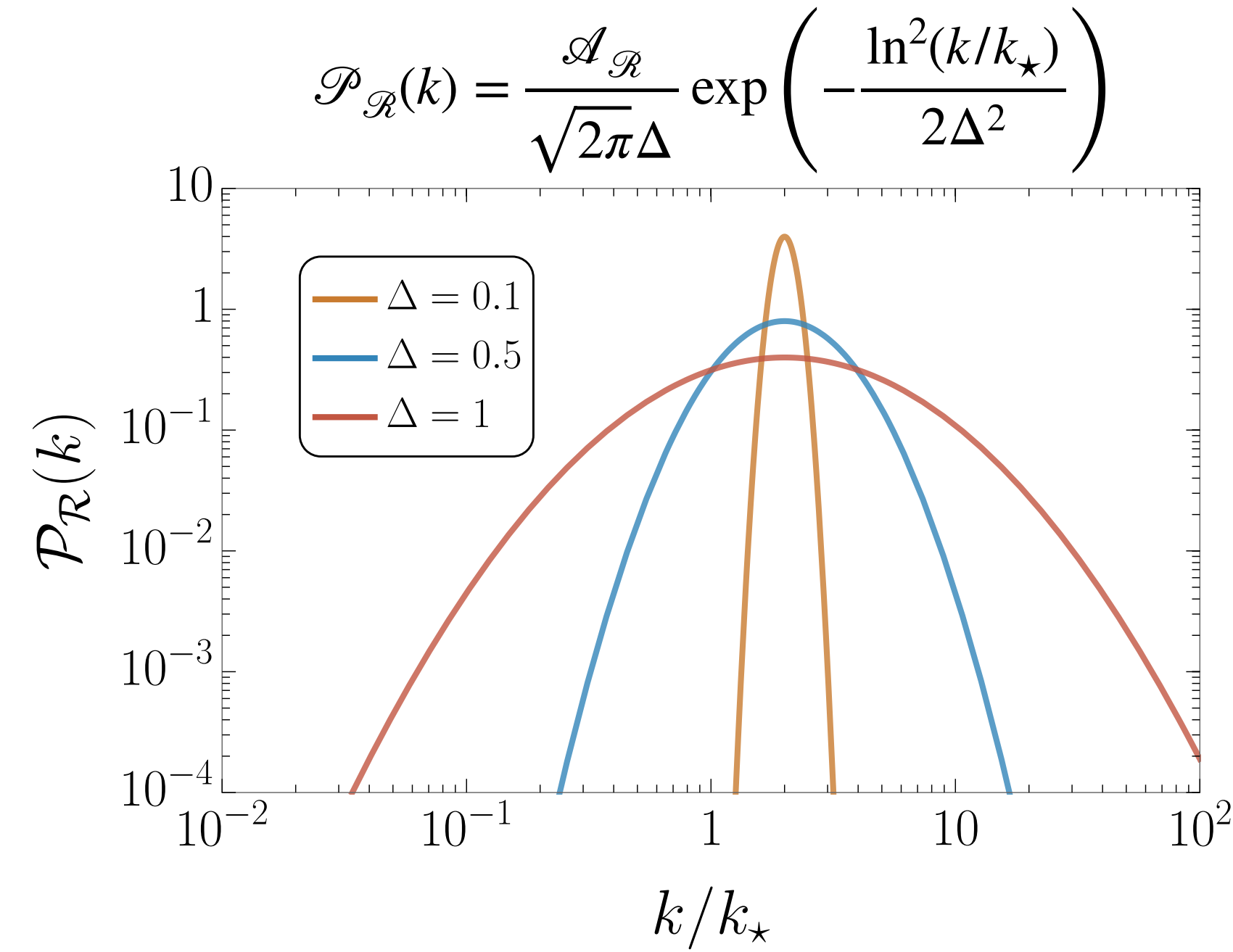


NG15: SIGW (no PBH prior)

Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28

PBH production formalism from:
Ferrante, Franciolini, Iovino,
Urbano (2211.01728)

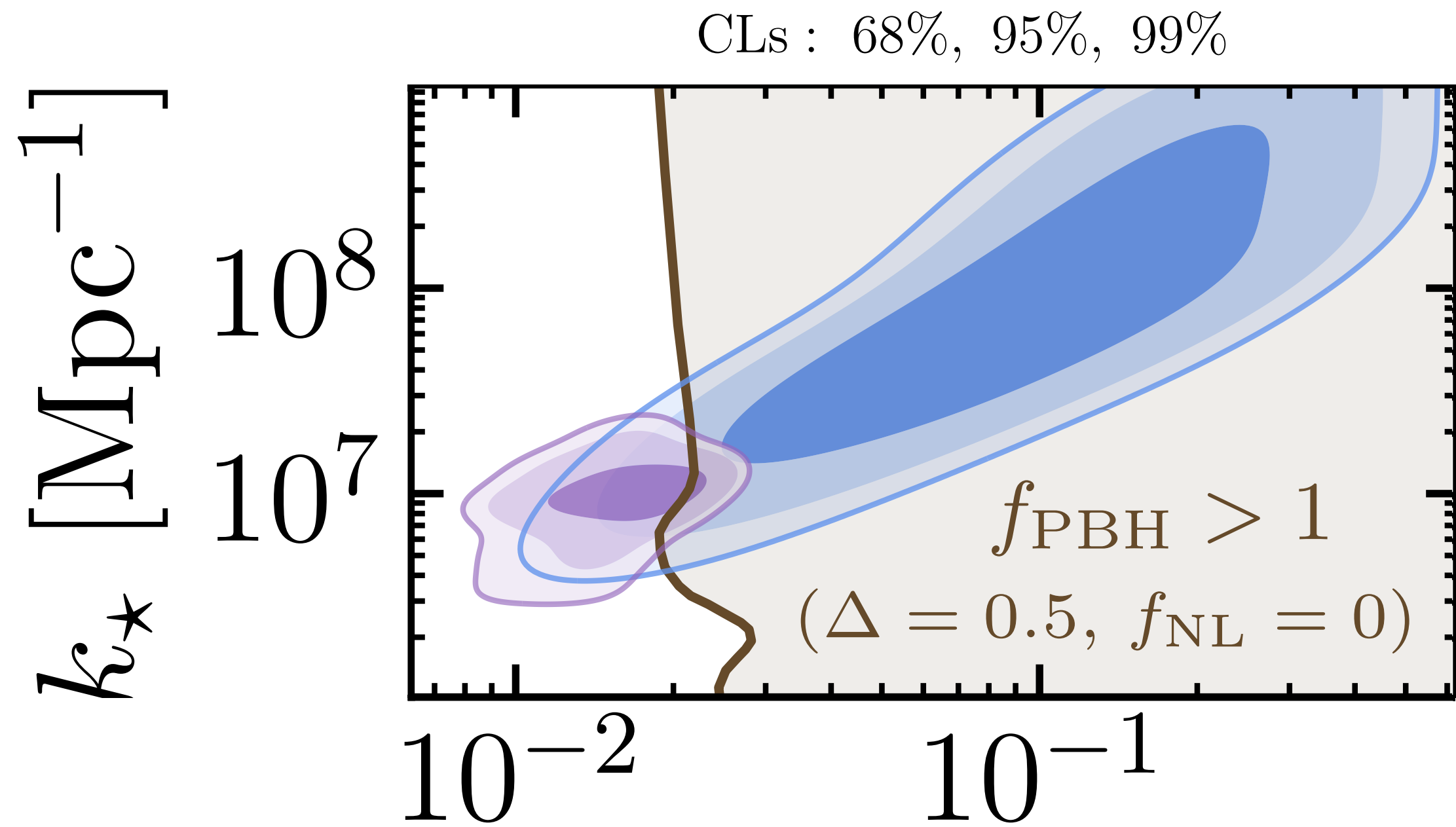
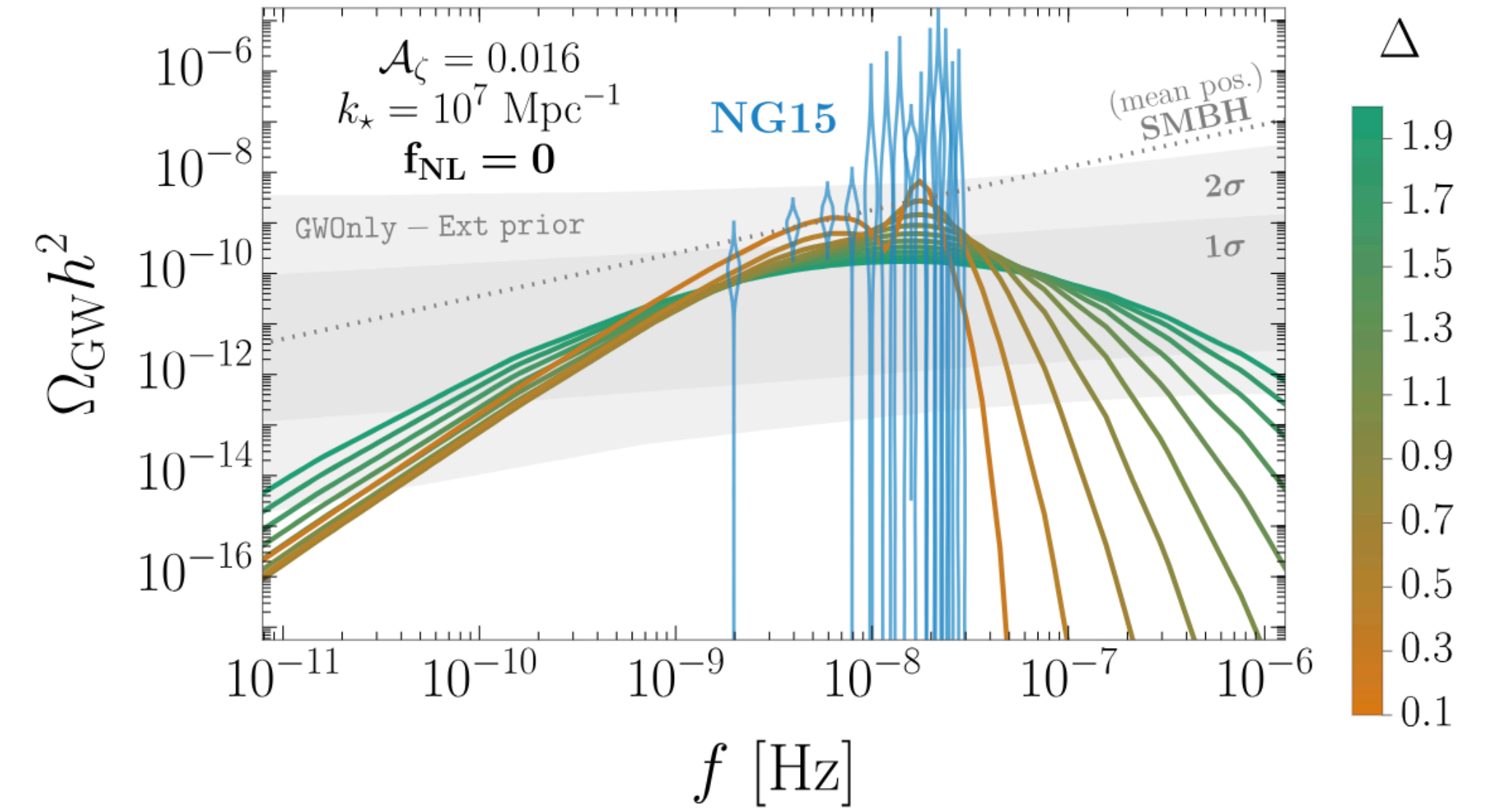
$\mathcal{A}_{\zeta}$



$\mathcal{P}_h(k) \sim \mathcal{P}_{\mathcal{R}}^2(k)$

→

Scalar induced GW

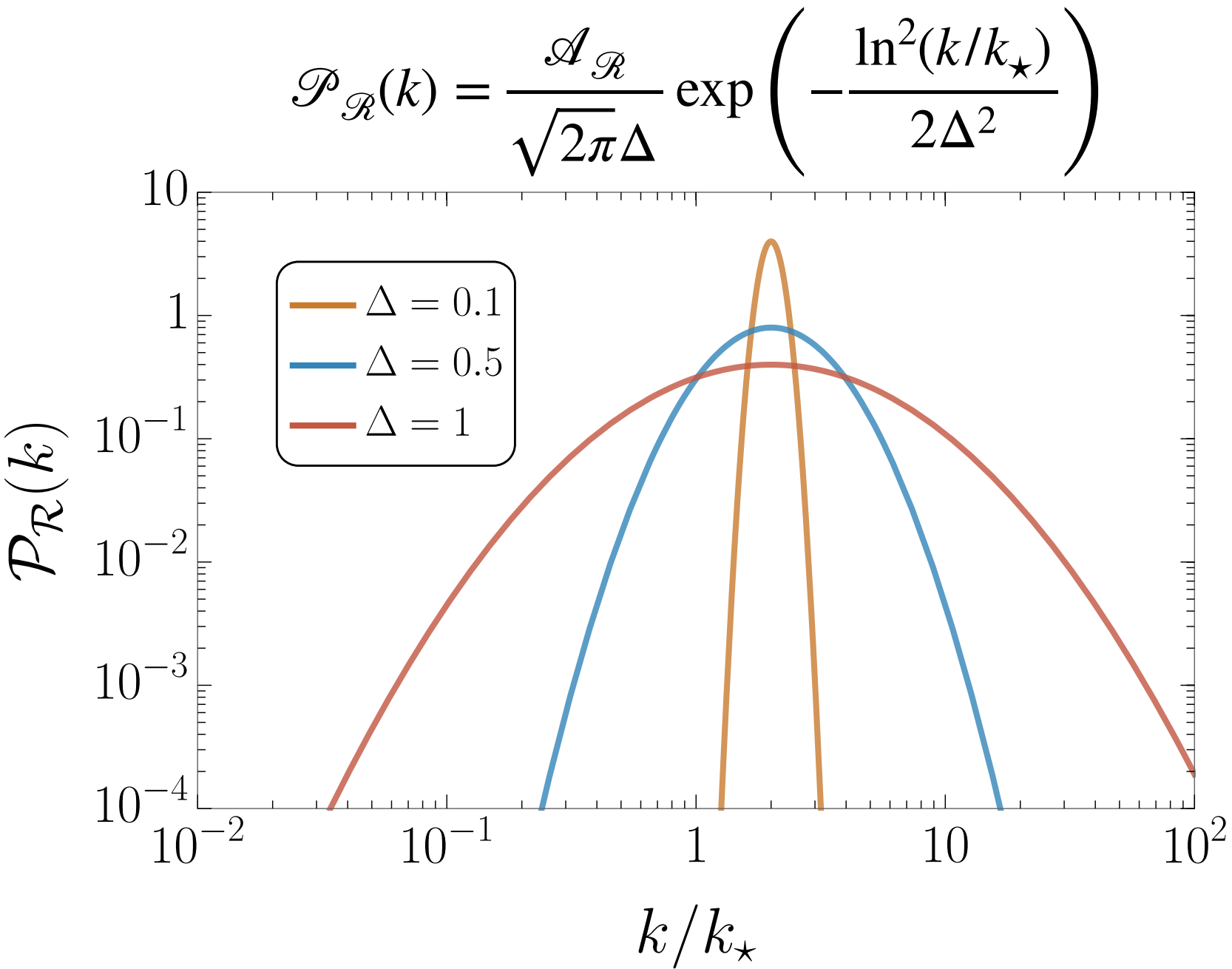


- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)

Prior on PBHs	SIGW / SMBH	
	$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior	2.17	2.28
Astrophysical	-0.90	-0.14

PBH production formalism from:
Ferrante, Franciolini, Iovino,
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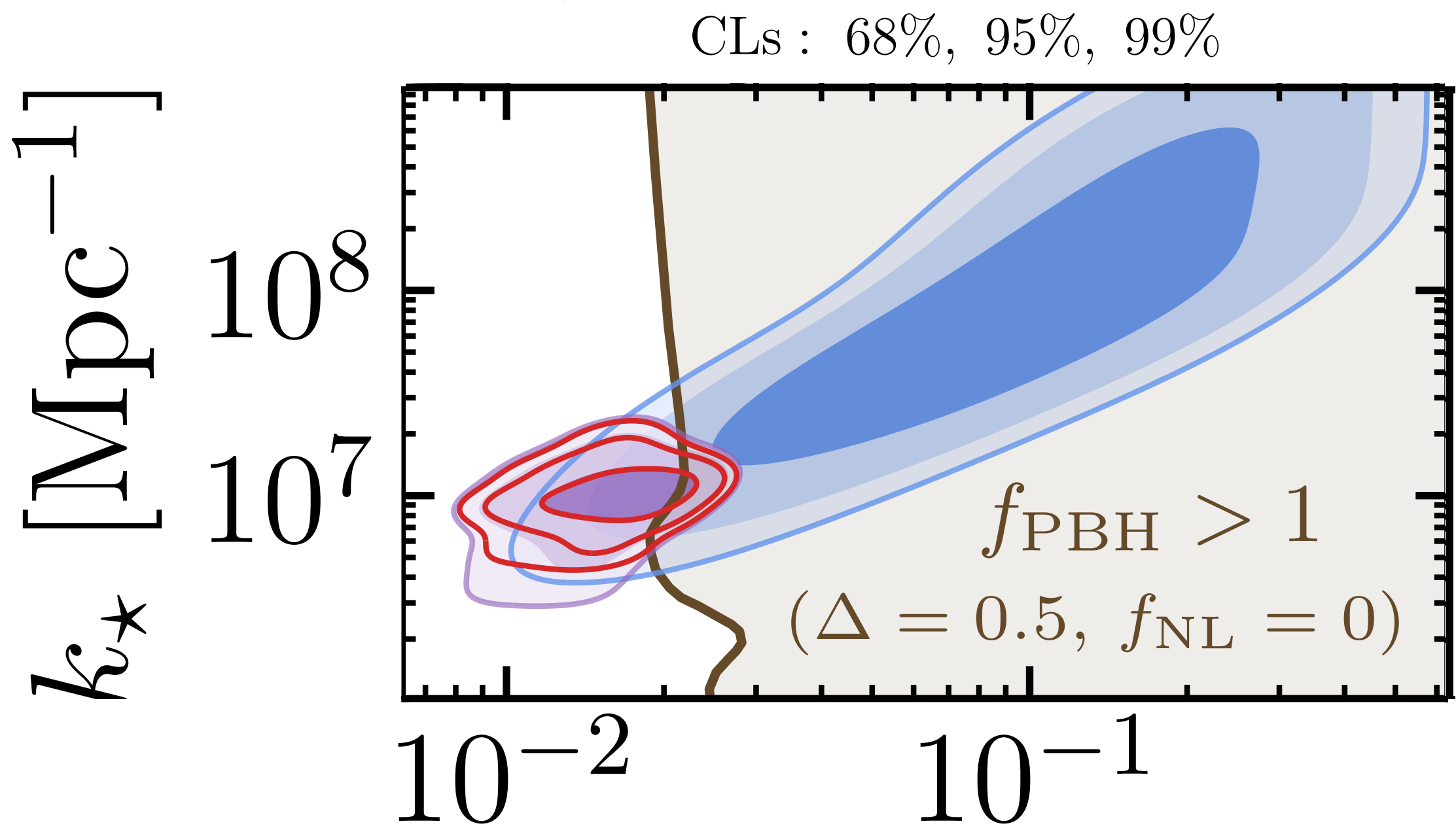
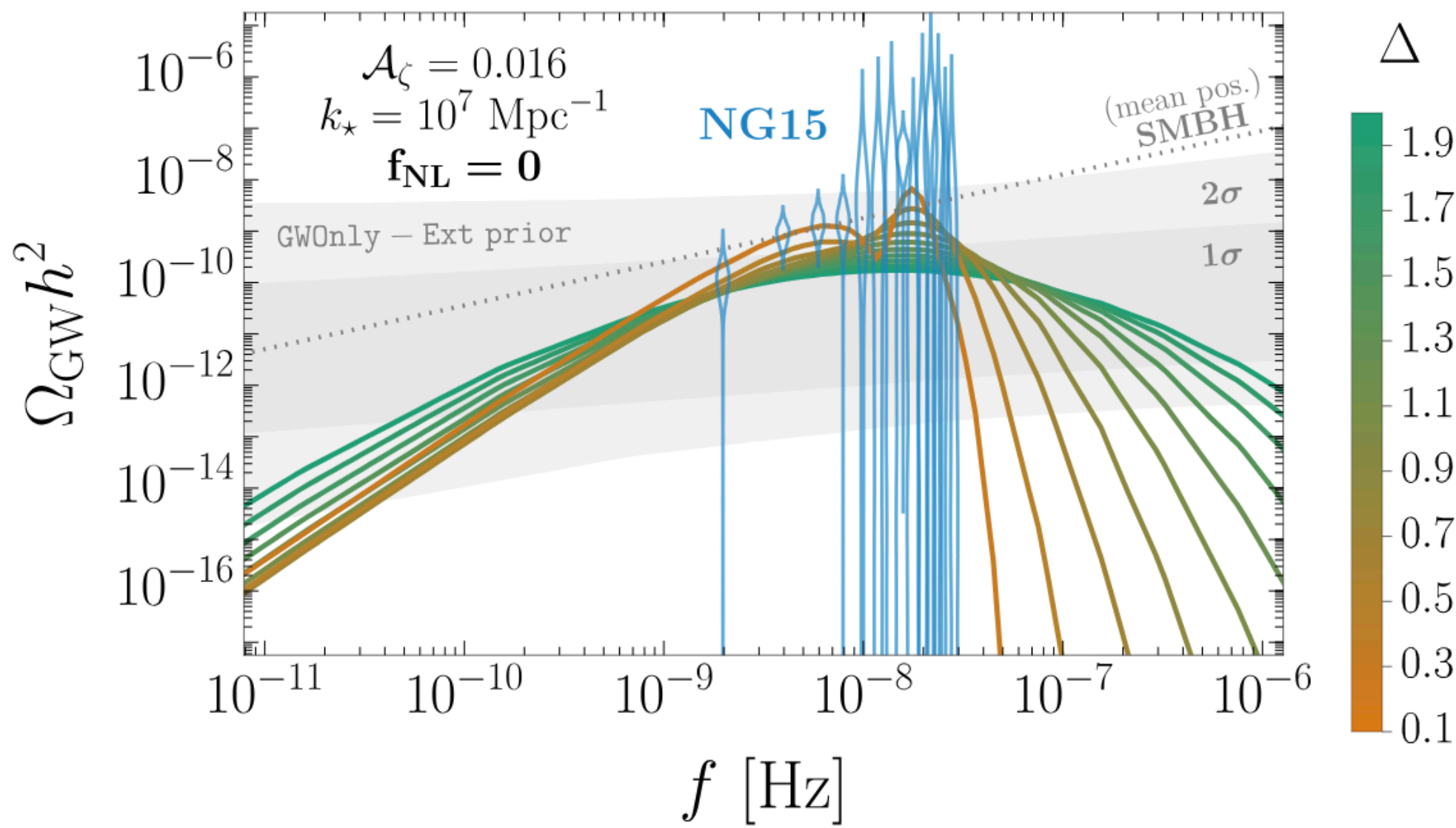
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Scalar induced GW

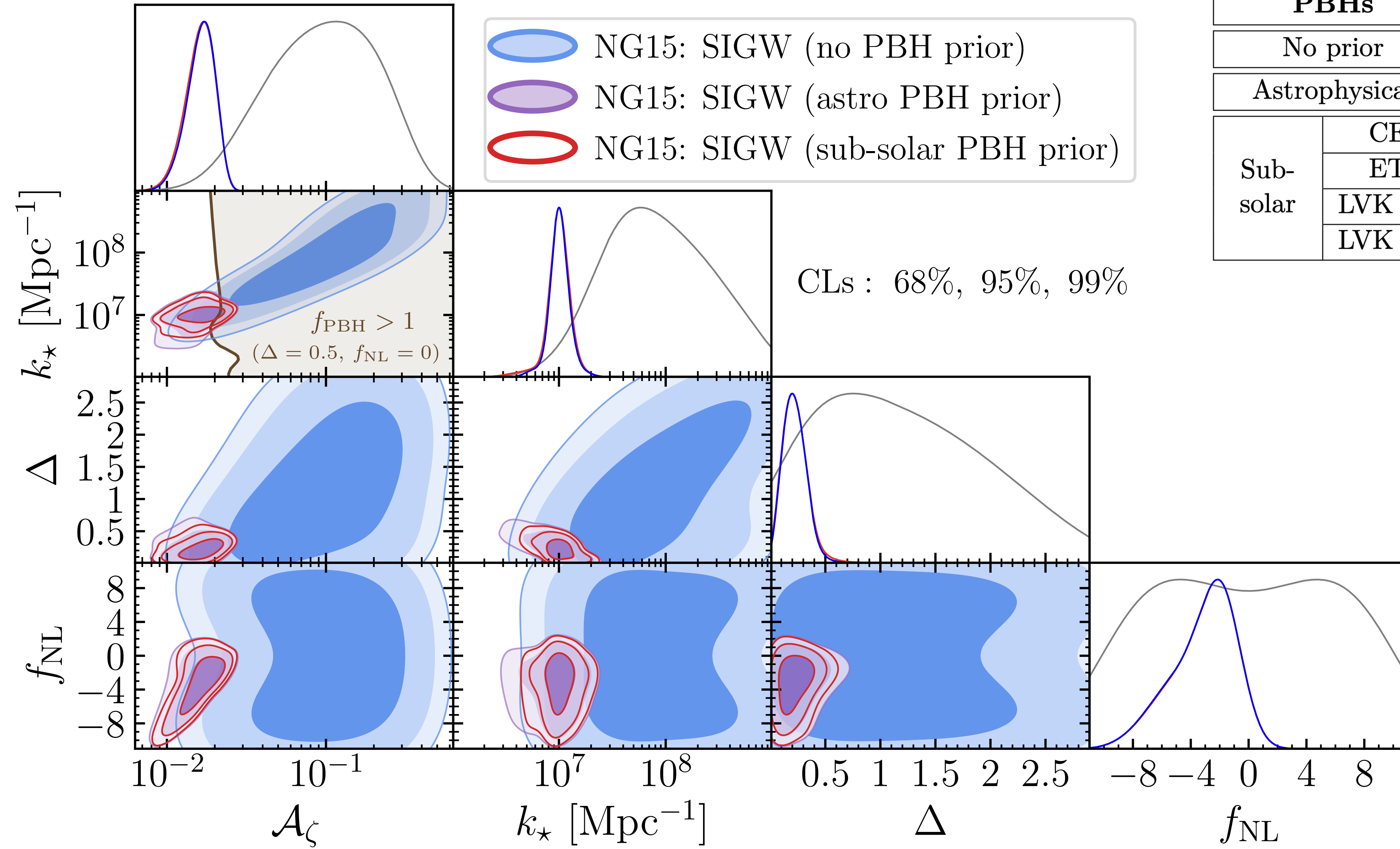


- NG15: SIGW (no PBH prior)
- NG15: SIGW (astro PBH prior)
- NG15: SIGW (sub-solar PBH prior)

Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		-0.90	-0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15

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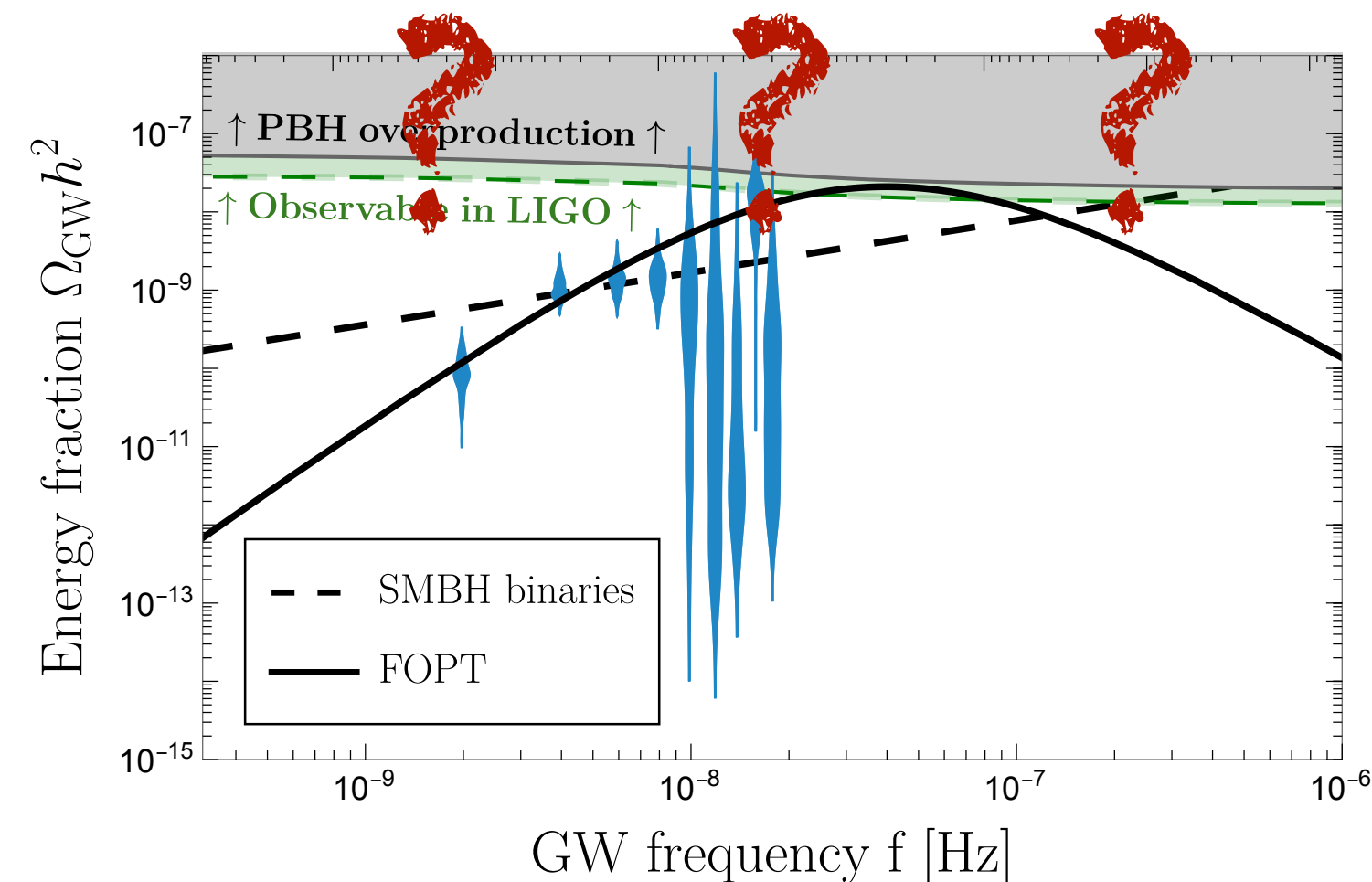
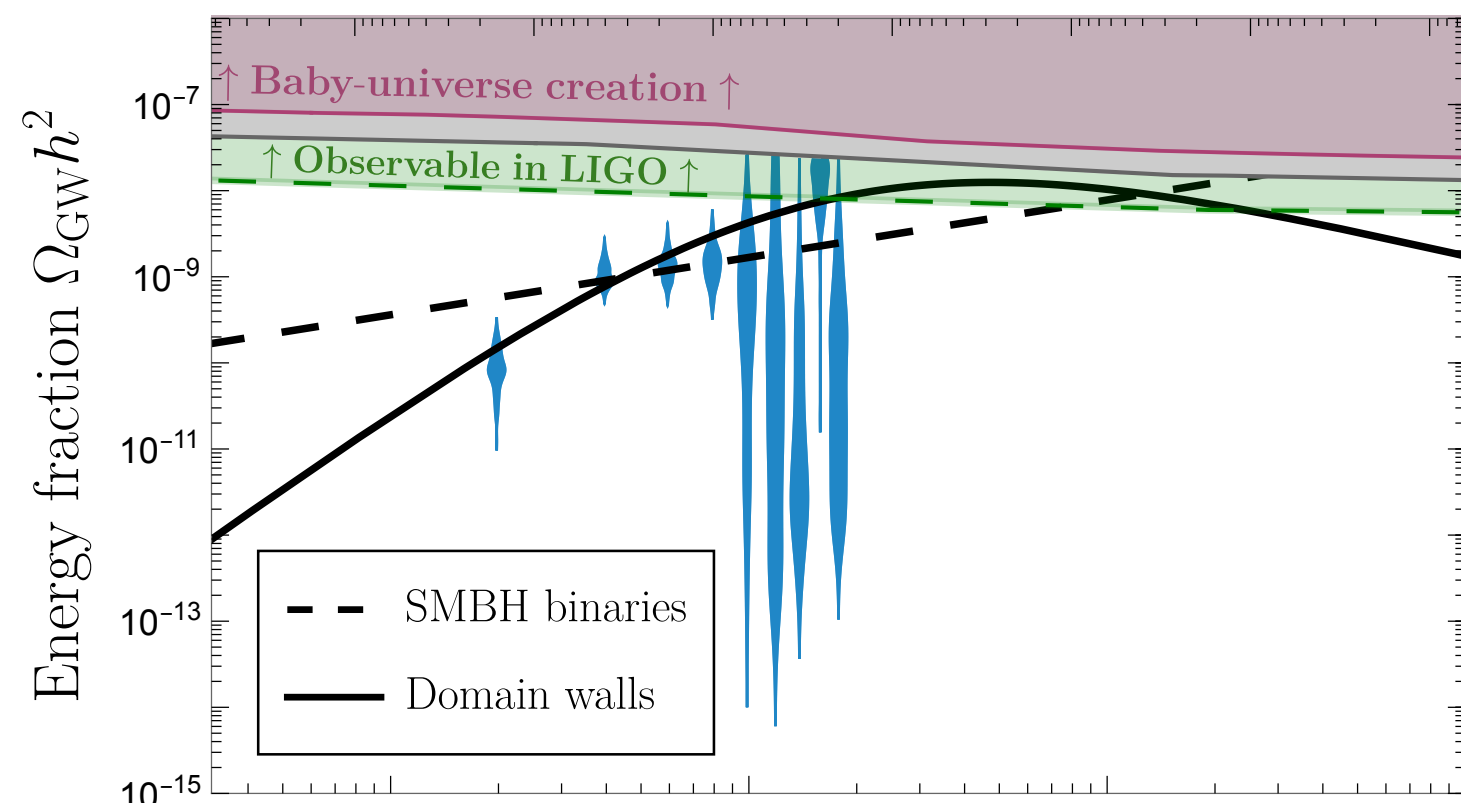
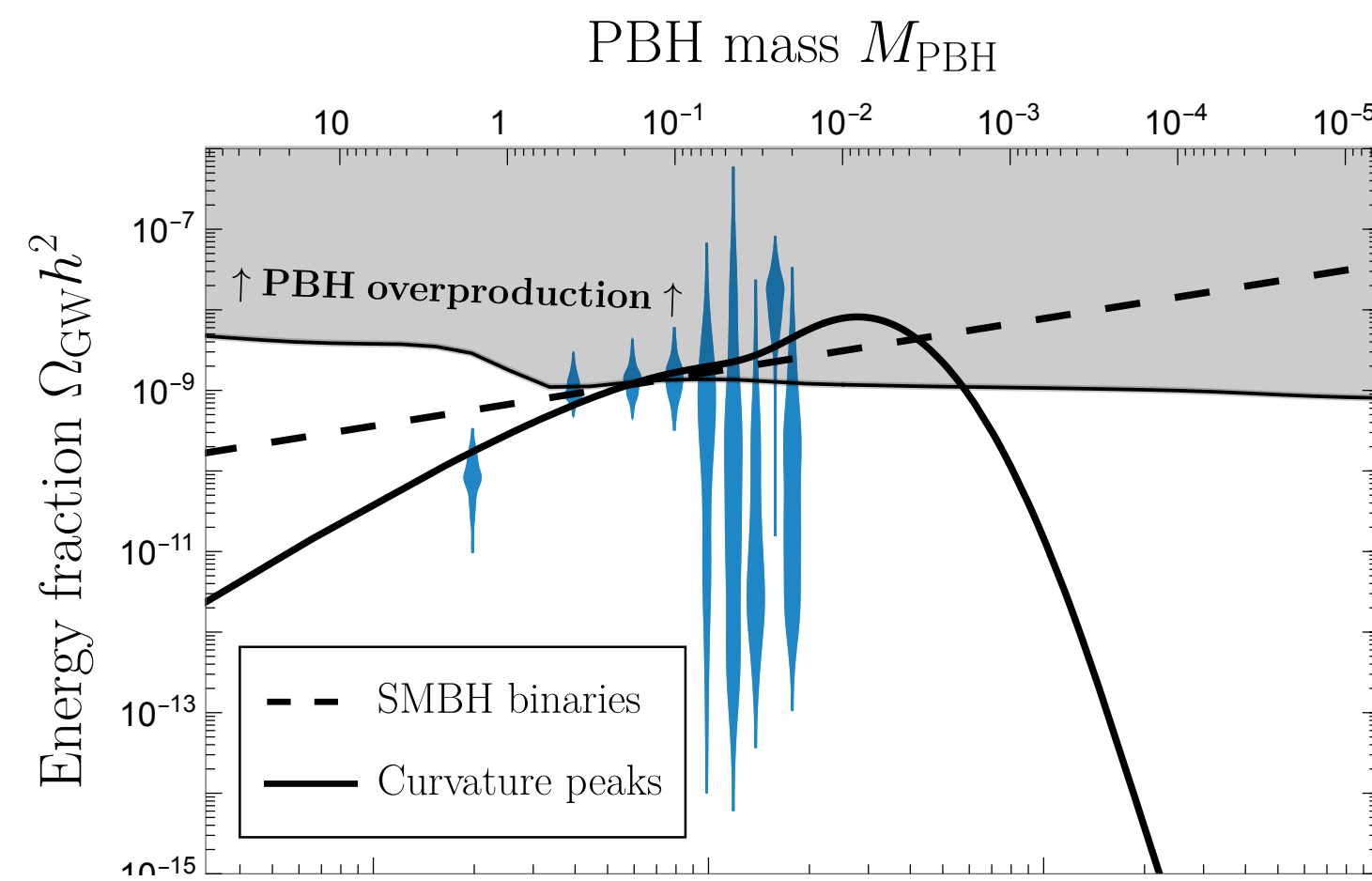
YG, Trifinopoulos, Vanvlasselaer 2508.19328



Prior on PBHs		SIGW / SMBH	
		$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$
No prior		2.17	2.28
Astrophysical		-0.90	-0.14
Sub-solar	CE	0.55	1.33
	ET	0.72	1.51
	LVK O5	1.18	1.96
	LVK O4	1.22	2.15

Prior on PBHs		Model X = SMBH only	Model Y	$\text{Log}_{10} \mathcal{B}_{Y,X} (\pm 0.10)$			
				Threshold statistics			Peak theory
				$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$	$ f_{\text{NL}} < 10$	
No prior		free amplitude	SIGW	1.67	1.74	1.74	1.67
			SIGW+SMBH	1.57	1.64	1.64	1.57
		GWOnly-Ext	SIGW	2.17	2.28	2.33	2.17
			SIGW+SMBH	2.05	2.16	2.22	2.05
Astrophysical		free amplitude	SIGW	−1.46	−0.70	−1.33	−3.34
			SIGW+SMBH	−0.08	−0.01	−0.11	−0.10
		GWOnly-Ext	SIGW	−0.90	−0.14	−0.75	−2.78
			SIGW+SMBH	0.05	0.20	0.06	−0.01
Sub-solar	CE	free amplitude	SIGW	−0.01	0.77	0.07	−2.20
			SIGW+SMBH	0.34	0.81	0.32	0.05
		GWOnly-Ext	SIGW	0.55	1.33	0.66	−1.64
			SIGW+SMBH	0.72	1.31	0.74	0.17
	ET	free amplitude	SIGW	0.16	0.95	0.23	−2.05
			SIGW+SMBH	0.45	0.96	0.42	0.09
		GWOnly-Ext	SIGW	0.72	1.51	0.82	−1.49
			SIGW+SMBH	0.86	1.48	0.87	0.23
	LVK O5	free amplitude	SIGW	0.62	1.40	0.69	−1.50
			SIGW+SMBH	0.74	1.36	0.72	0.20
		GWOnly-Ext	SIGW	1.18	1.96	1.28	−0.94
			SIGW+SMBH	1.21	1.90	1.25	0.37
	LVK O4	free amplitude	SIGW	0.66	1.59	0.79	−1.24
			SIGW+SMBH	0.77	1.52	0.79	0.24
		GWOnly-Ext	SIGW	1.22	2.15	1.37	−0.68
			SIGW+SMBH	1.27	2.06	1.33	0.40

Prior on PBHs		Model X = SMBH only	Model Y	Log ₁₀ $\mathcal{B}_{Y,X}$ (± 0.10)			
				Threshold statistics			Peak theory
				$f_{\text{NL}} = 0$	$f_{\text{NL}} = -2$	$ f_{\text{NL}} < 10$	
No prior		free amplitude	SIGW	1.67	1.74	1.74	1.67
			SIGW+SMBH	1.57	1.64	1.64	1.57
		GWOnly-Ext	SIGW	2.17	2.28	2.33	2.17
			SIGW+SMBH	2.05	2.16	2.22	2.05
Astrophysical		free amplitude	SIGW	-1.46	-0.70	-1.33	-3.34
			SIGW+SMBH	-0.08	-0.01	-0.11	-0.10
		GWOnly-Ext	SIGW	-0.90	-0.14	-0.75	-2.78
			SIGW+SMBH	0.05	0.20	0.06	-0.01
Sub-solar	CE	free amplitude	SIGW	-0.01	0.77	0.07	-2.20
			SIGW+SMBH	0.34	0.81	0.32	0.05
		GWOnly-Ext	SIGW	0.55	1.33	0.66	-1.64
			SIGW+SMBH	0.72	1.31	0.74	0.17
	ET	free amplitude	SIGW	0.16	0.95	0.23	-2.05
			SIGW+SMBH	0.45	0.96	0.42	0.09
		GWOnly-Ext	SIGW	0.72	1.51	0.82	-1.49
			SIGW+SMBH	0.86	1.48	0.87	0.23
	LVK O5	free amplitude	SIGW	0.62	1.40	0.69	-1.50
			SIGW+SMBH	0.74	1.36	0.72	0.20
		GWOnly-Ext	SIGW	1.18	1.96	1.28	-0.94
			SIGW+SMBH	1.21	1.90	1.25	0.37
	LVK O4	free amplitude	SIGW	0.66	1.59	0.79	-1.24
			SIGW+SMBH	0.77	1.52	0.79	0.24
		GWOnly-Ext	SIGW	1.22	2.15	1.37	-0.68
			SIGW+SMBH	1.27	2.06	1.33	0.40



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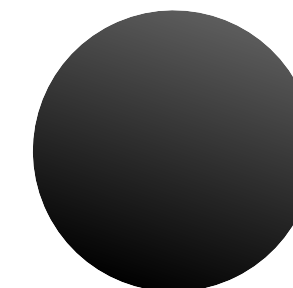
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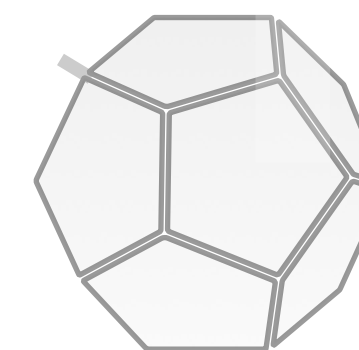
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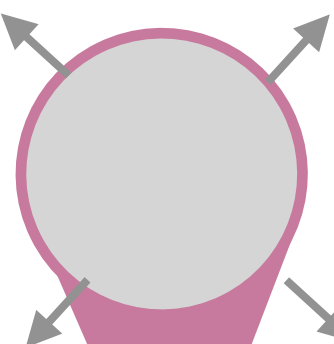
Wormhole



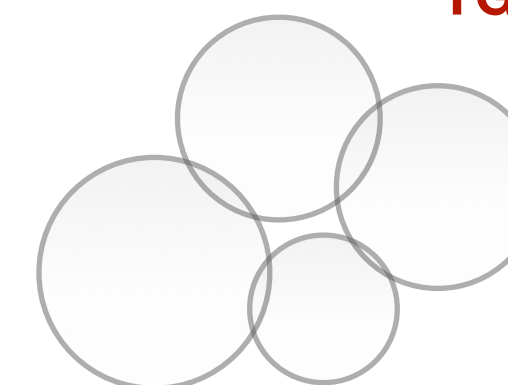
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670



PBH

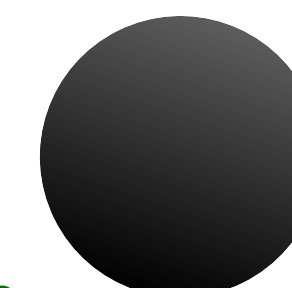


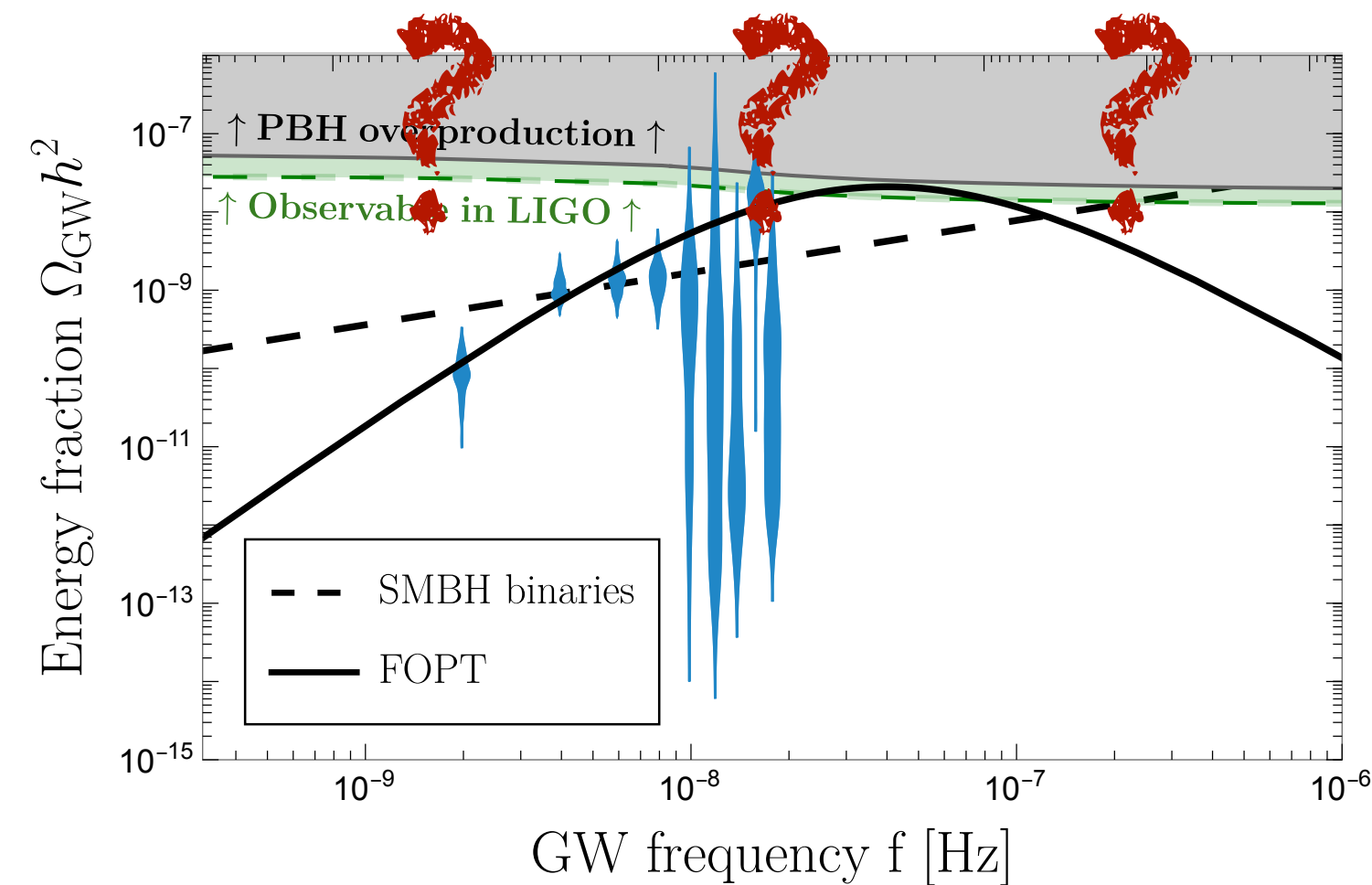
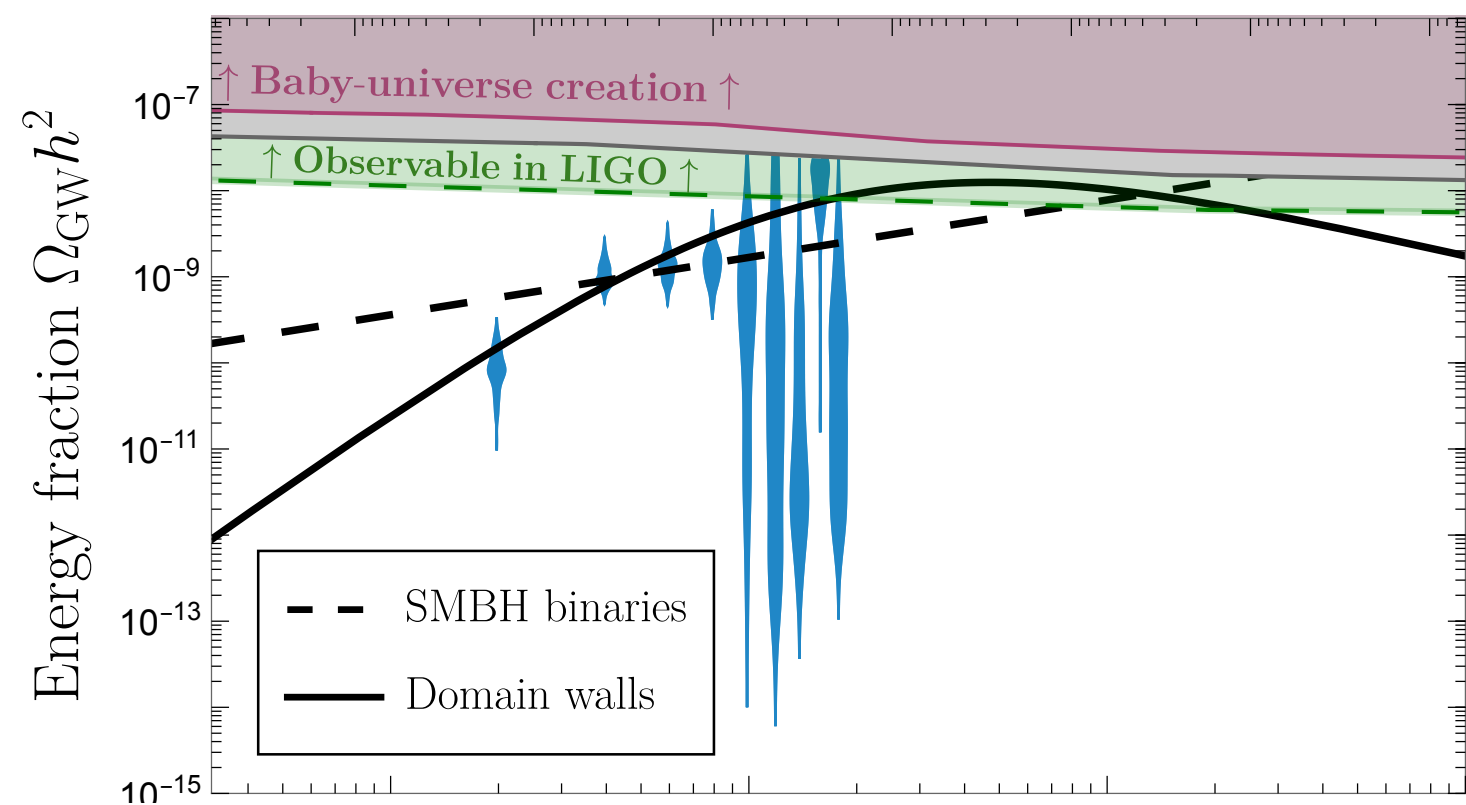
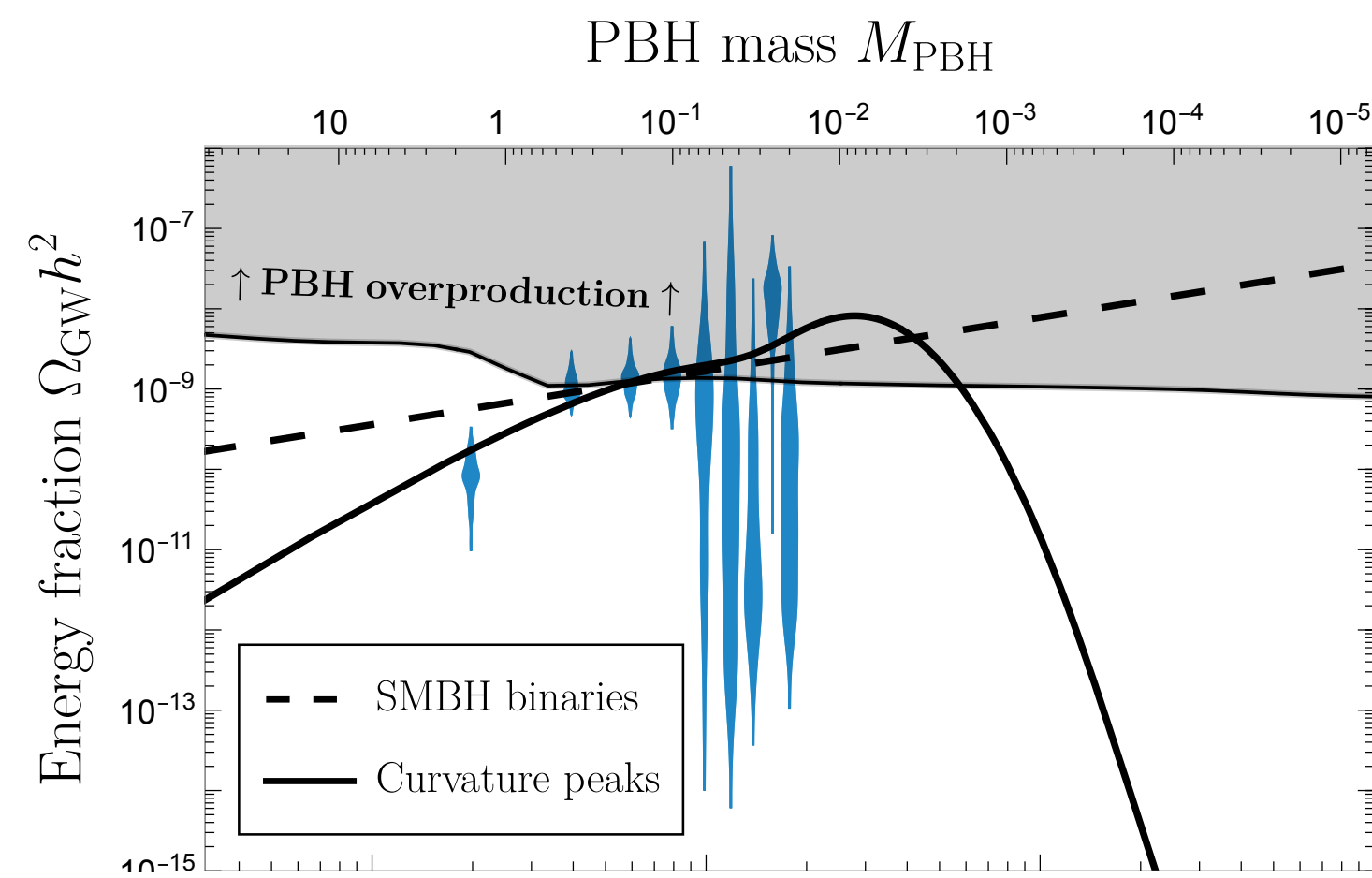
Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

YG&Volansky 2023,
YG (2307.04239)

Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
Lewicki, Toczec, Vaskonen 2023,
Baldes+ 2023,
Lewicki, Toczec, Vaskonen 2024,





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841

First-order phase transitions

Roper Pol et al. (2201.05630)

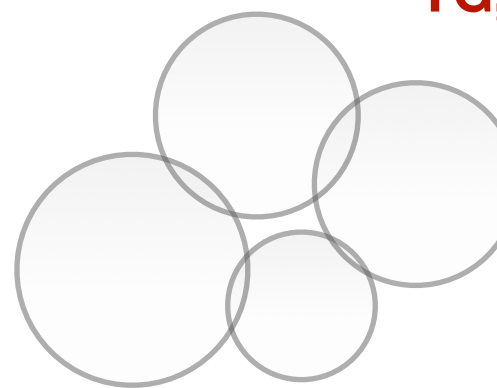
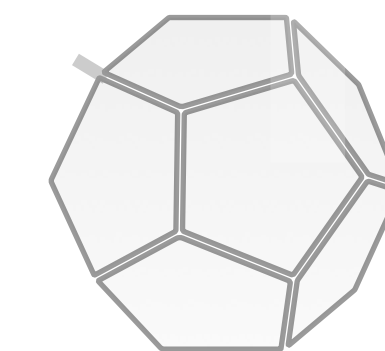
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczec, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...



*Reviews: Madge et al (2306.14856),
Figueroa et al (2307.02399),
Ellis et al (2308.08546)*

Baby-universe

Deng, Garriga, Vilenkin (1612.03753)

Wormhole

Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

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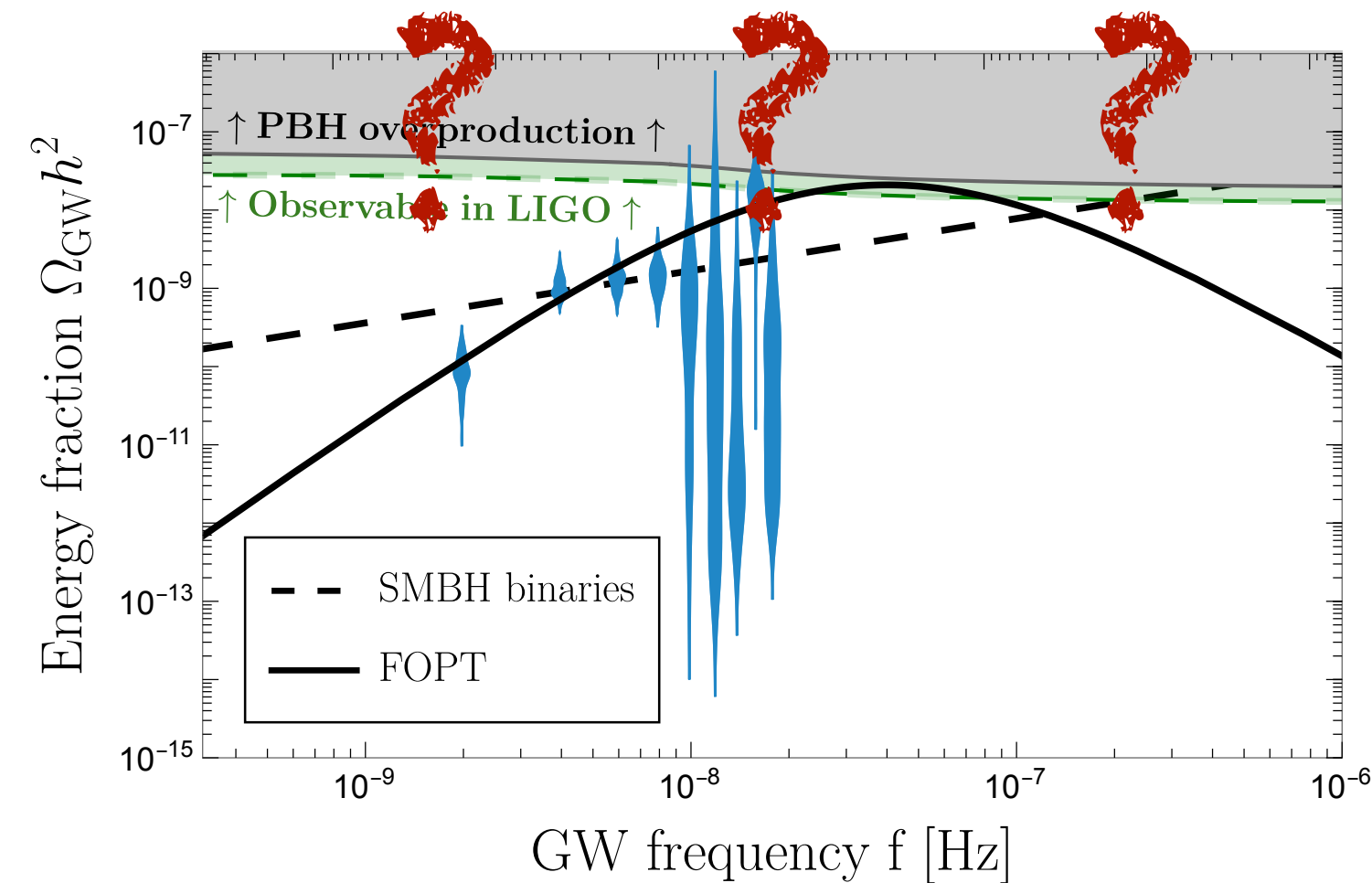
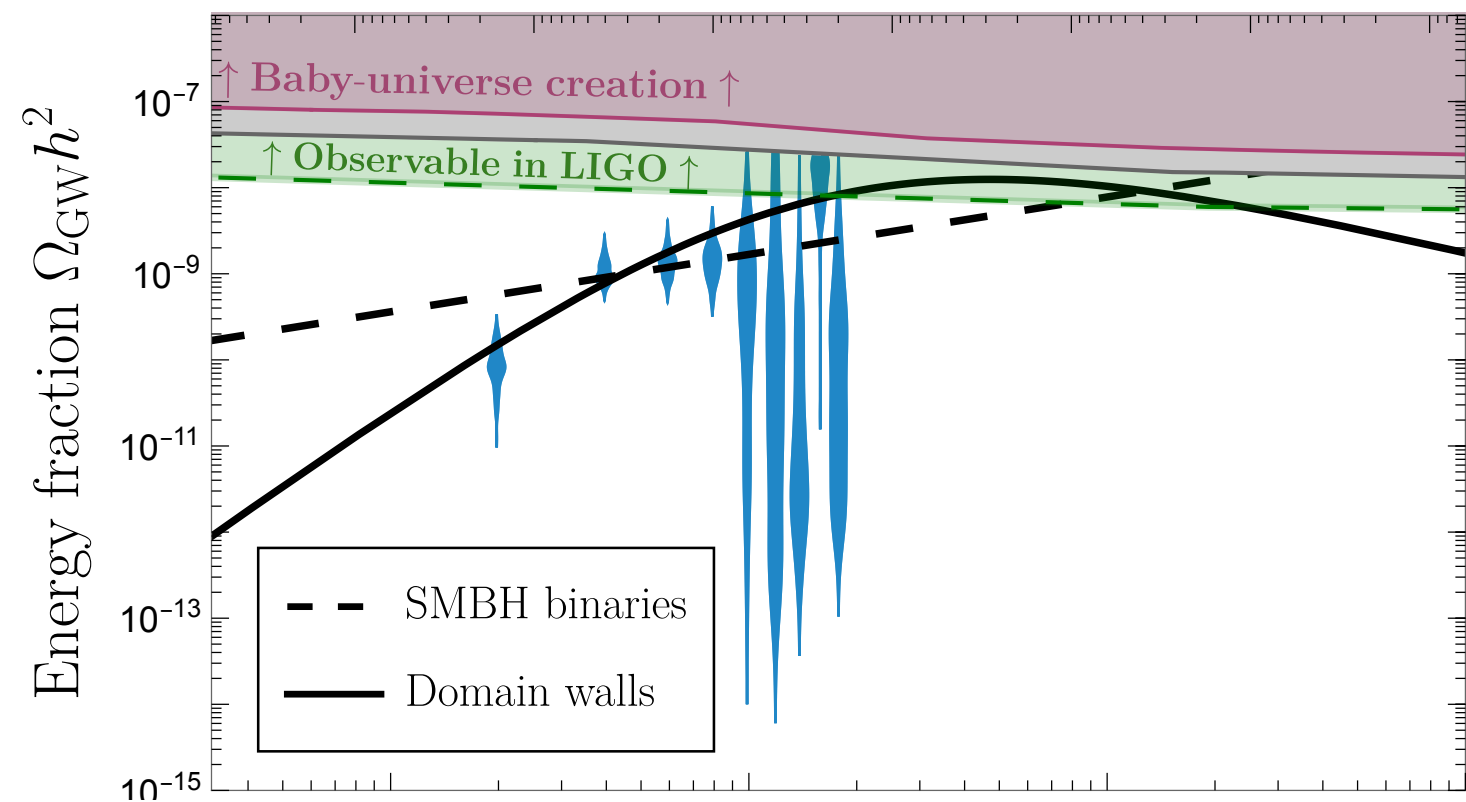
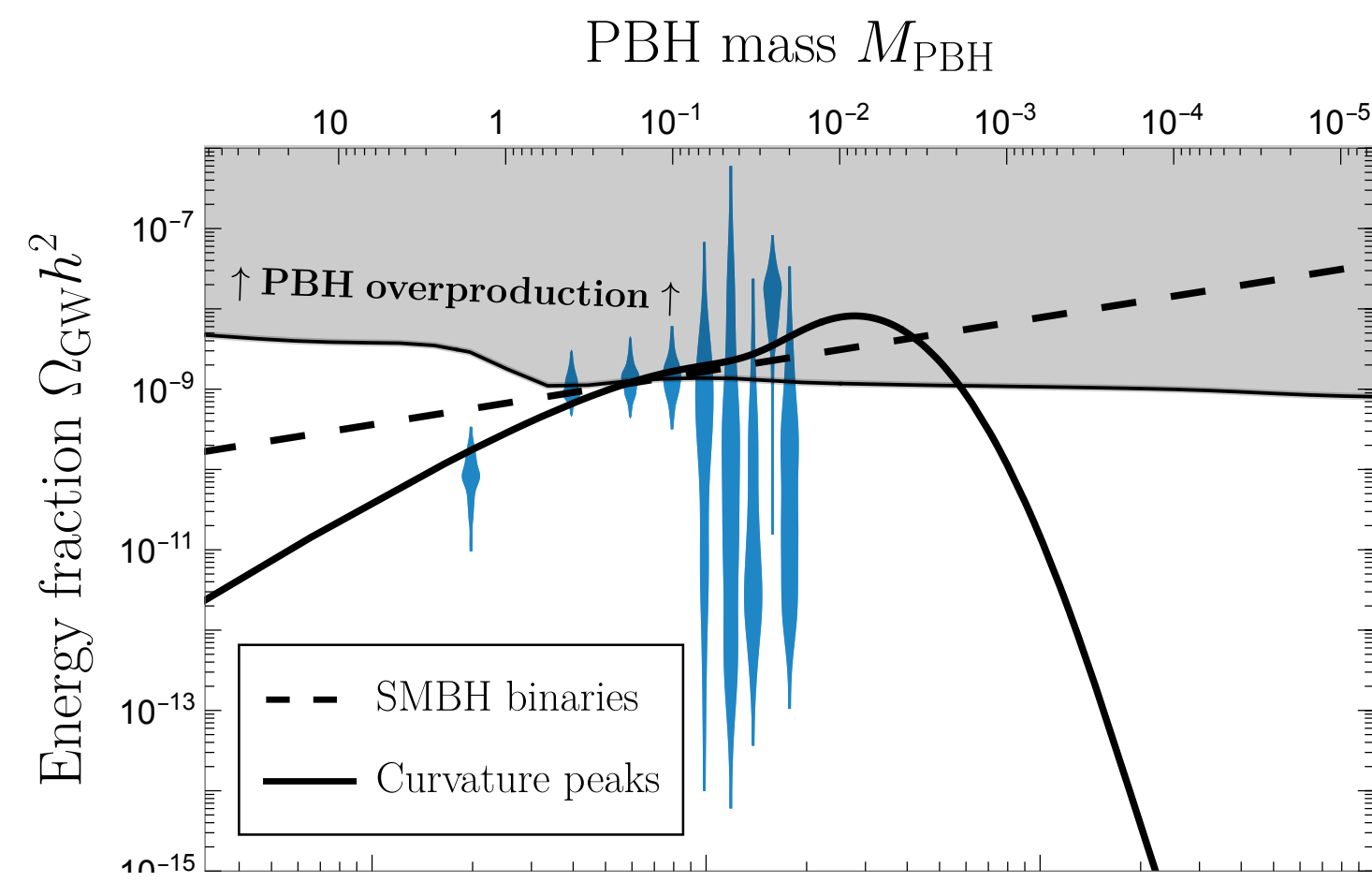
PBH

Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

*YG&Volansky 2023,
YG (2307.04239)*

*Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
Lewicki, Toczec, Vaskonen 2023,
Baldes+ 2023,
Lewicki, Toczec, Vaskonen 2024,*



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...



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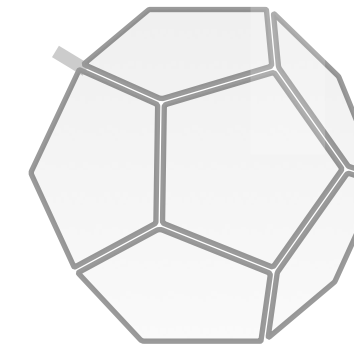
Deng, Garriga, Vilenkin (1612.03753)

Wormhole

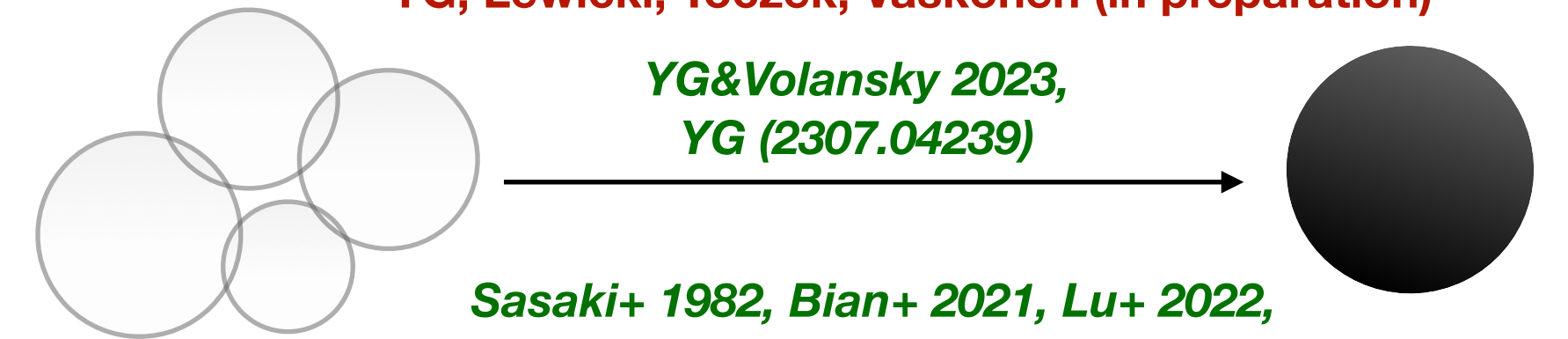
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

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YG, Vitagliano, 2311.07670



PBH



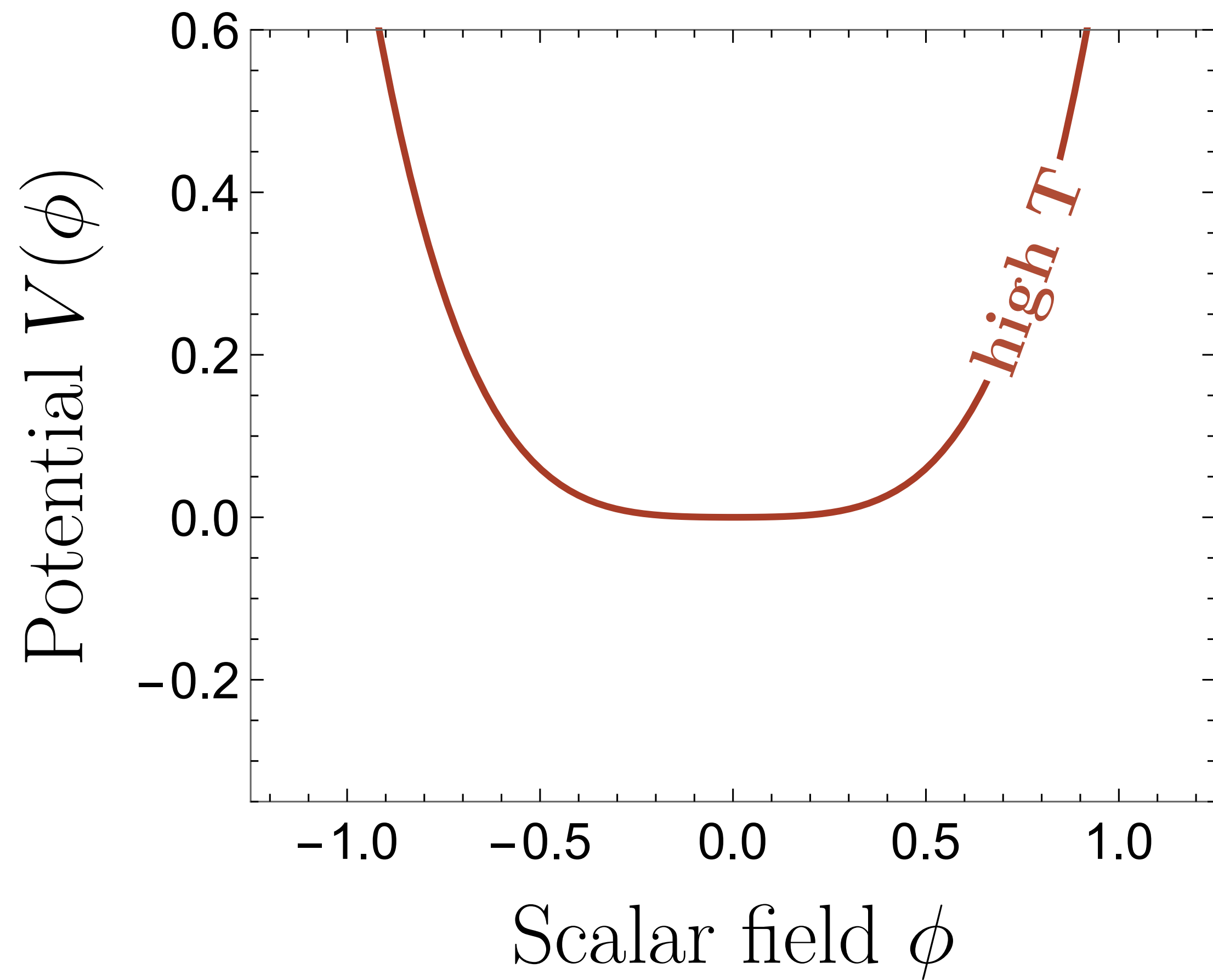
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YG, Lewicki, Toczec, Vaskonen (in preparation)

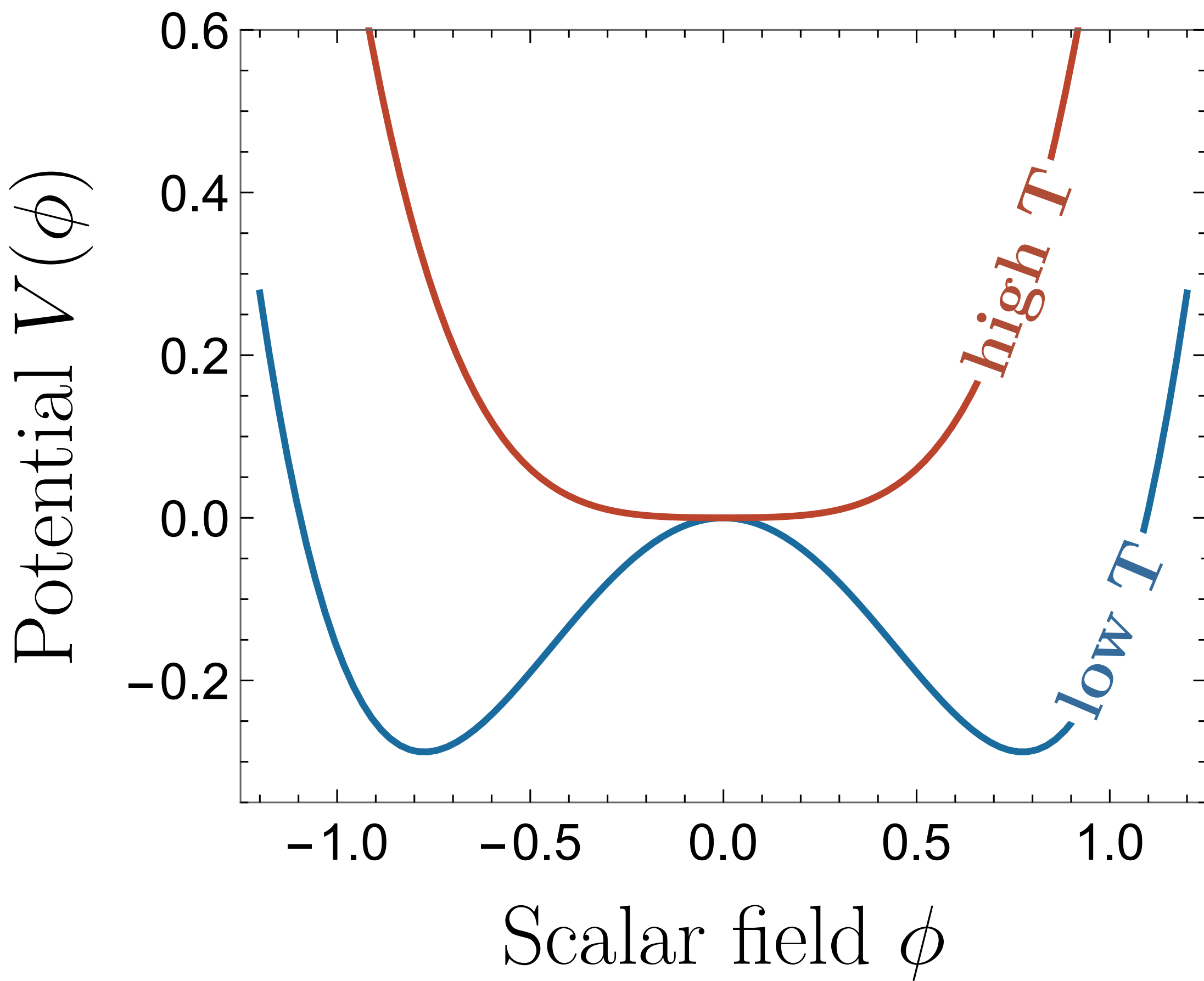
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Sasaki+ 1982, Bian+ 2021, Lu+ 2022,
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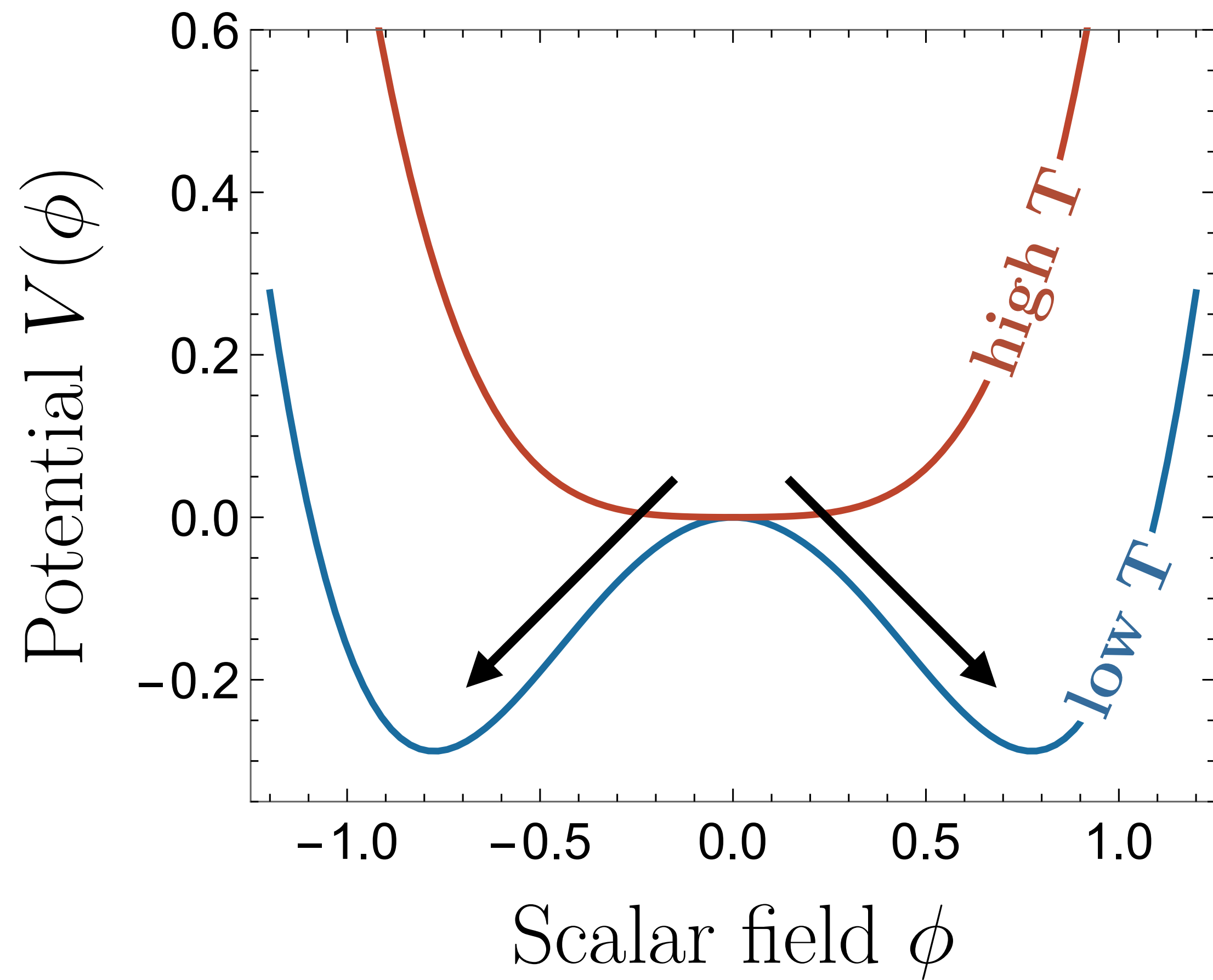
Formation of Domain Wall



Formation of Domain Wall

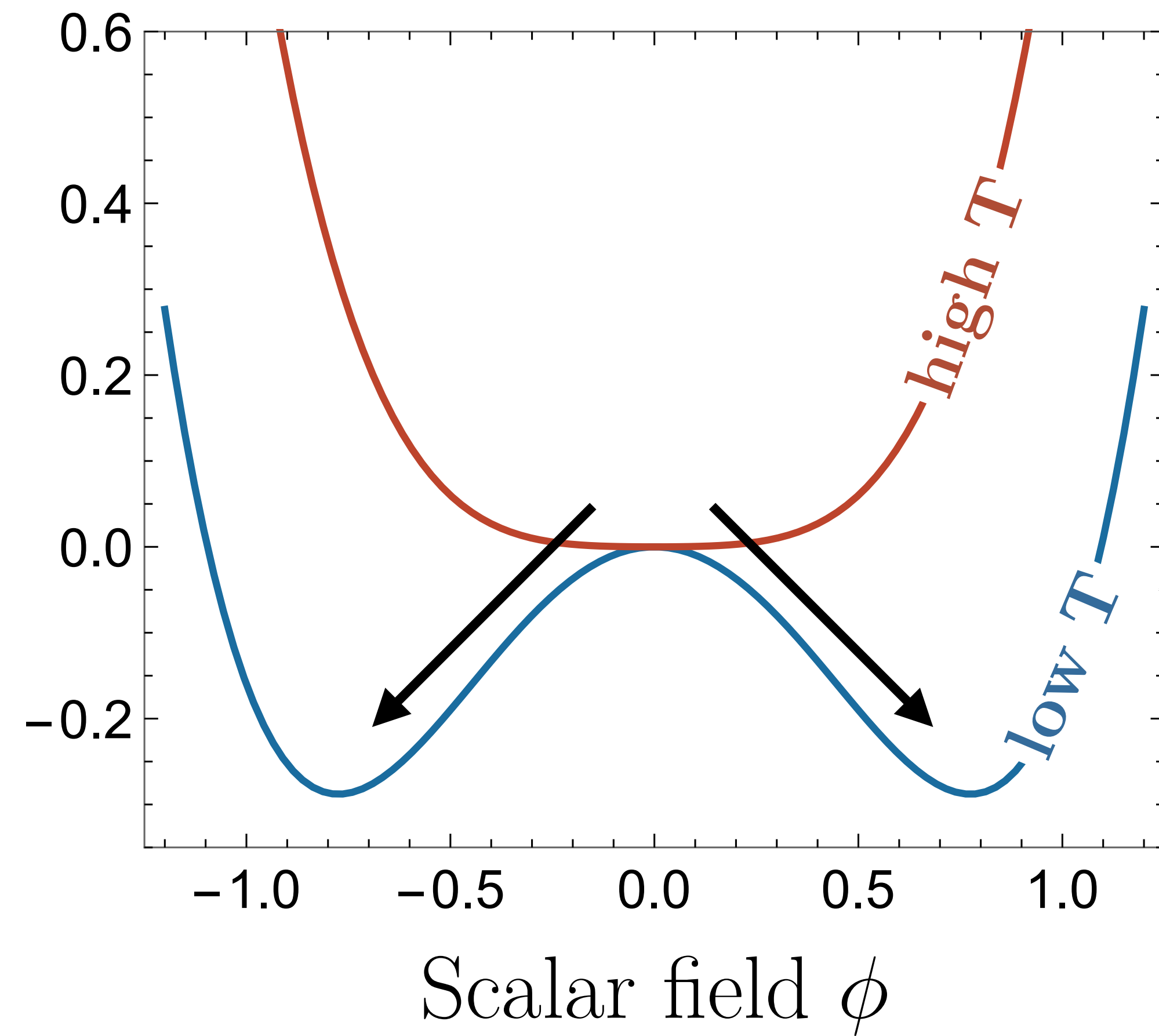


Formation of Domain Wall

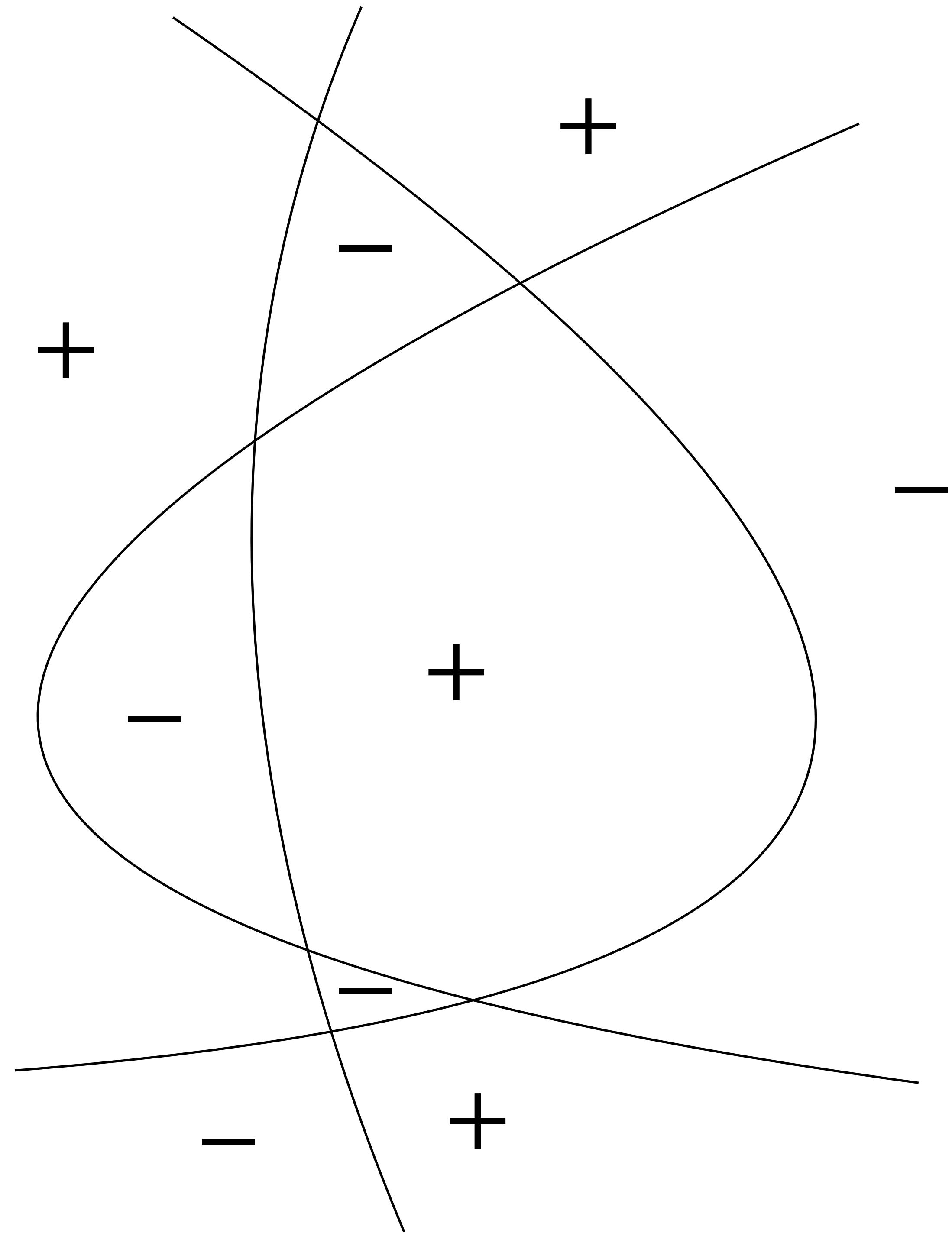


Spontaneous breaking of $\mathbb{Z}_2$

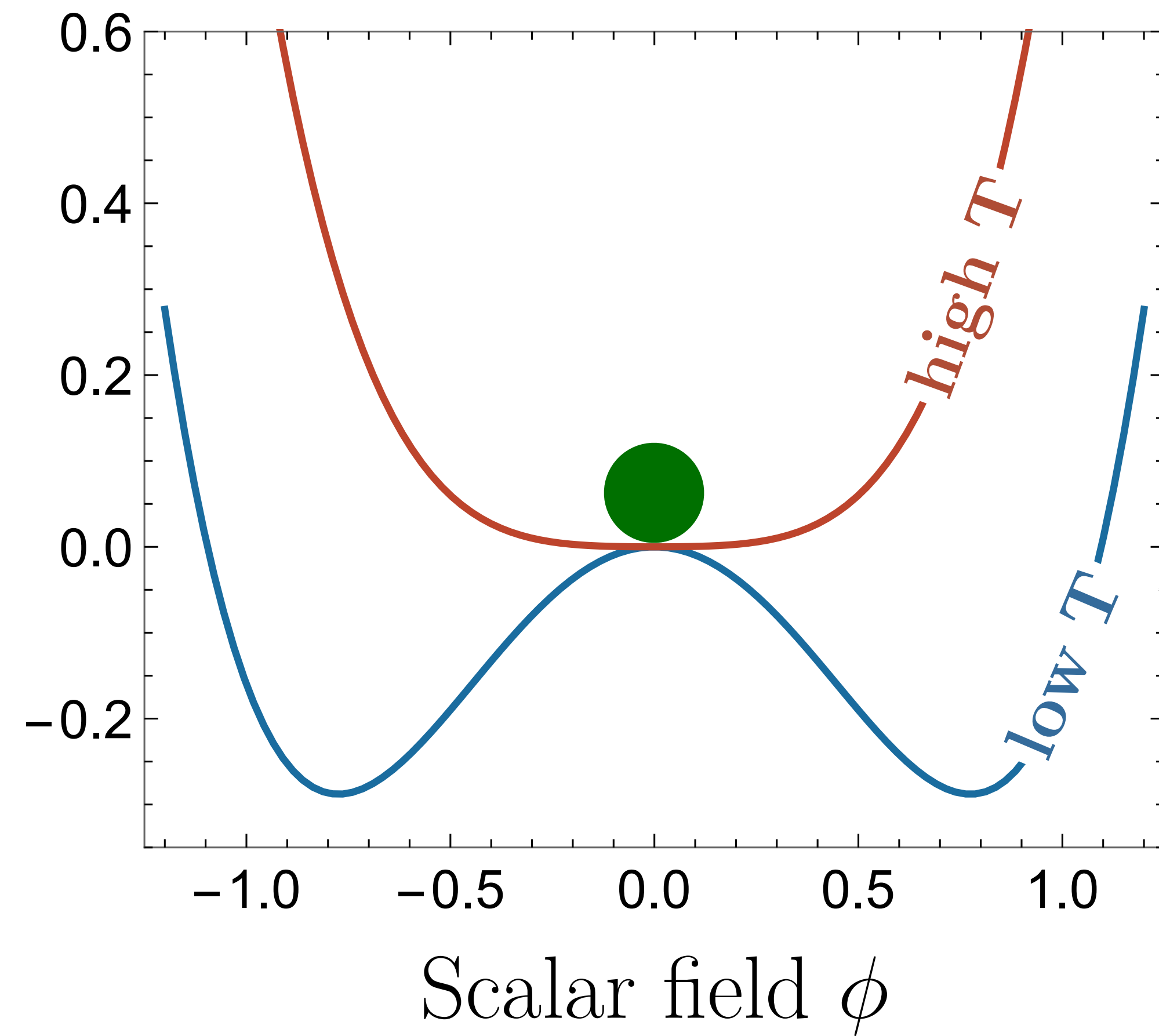
Formation of Domain Wall



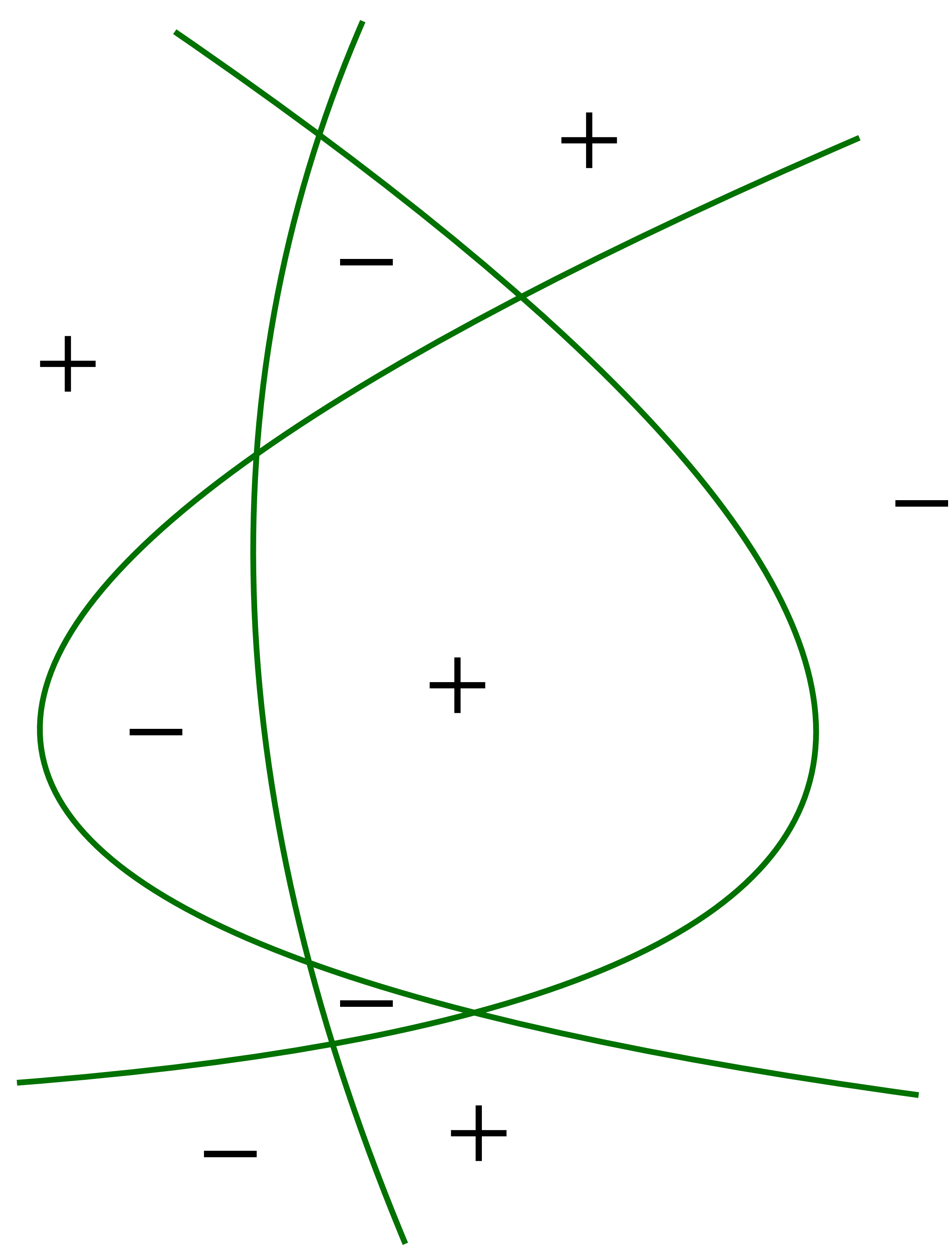
Spontaneous breaking of $\mathbb{Z}_2$



Formation of Domain Wall

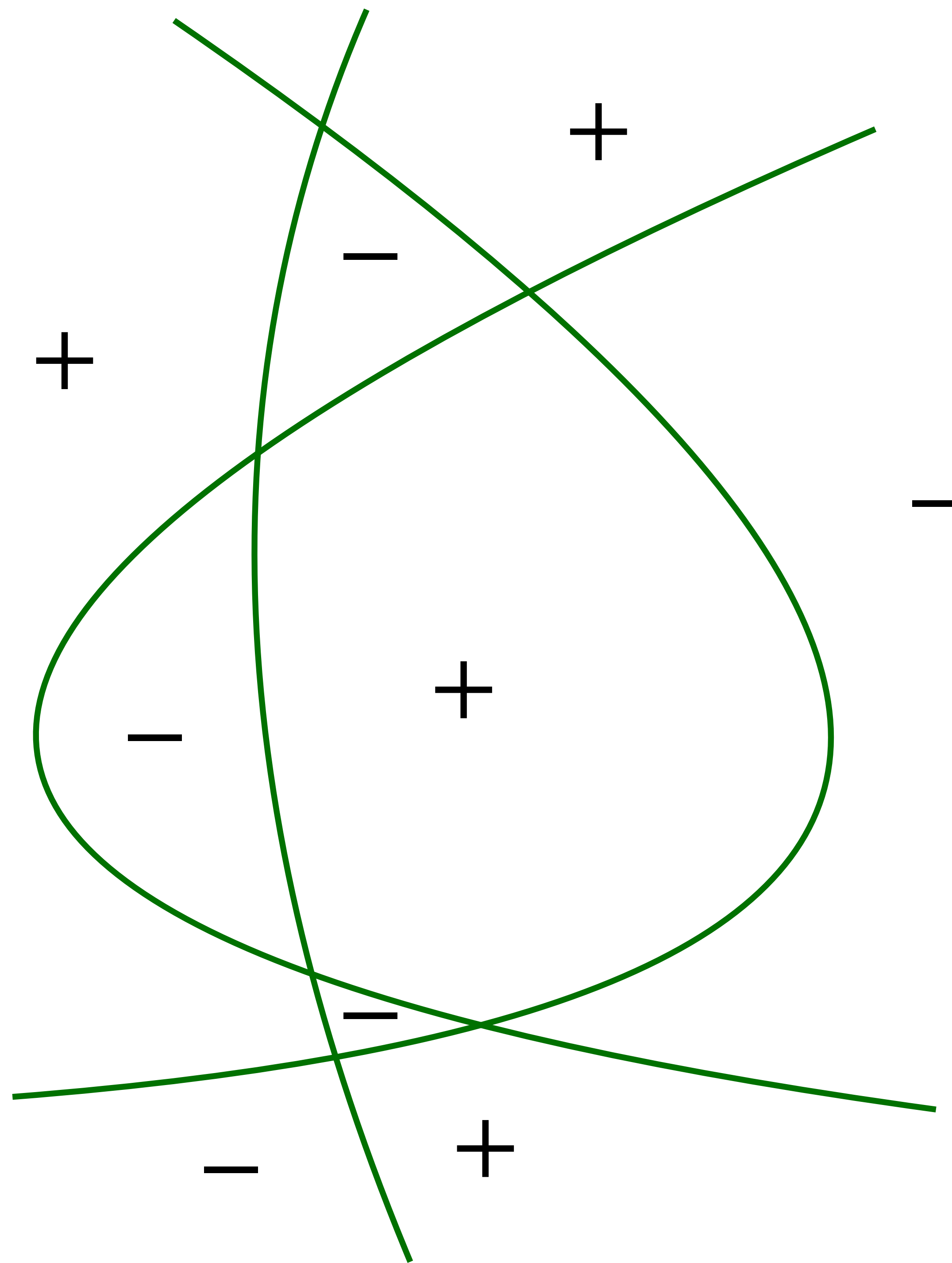


Spontaneous breaking of $\mathbb{Z}_2$



Formation of Domain Wall

$$\rho_{\text{DW}} \simeq \frac{\sigma}{R}$$

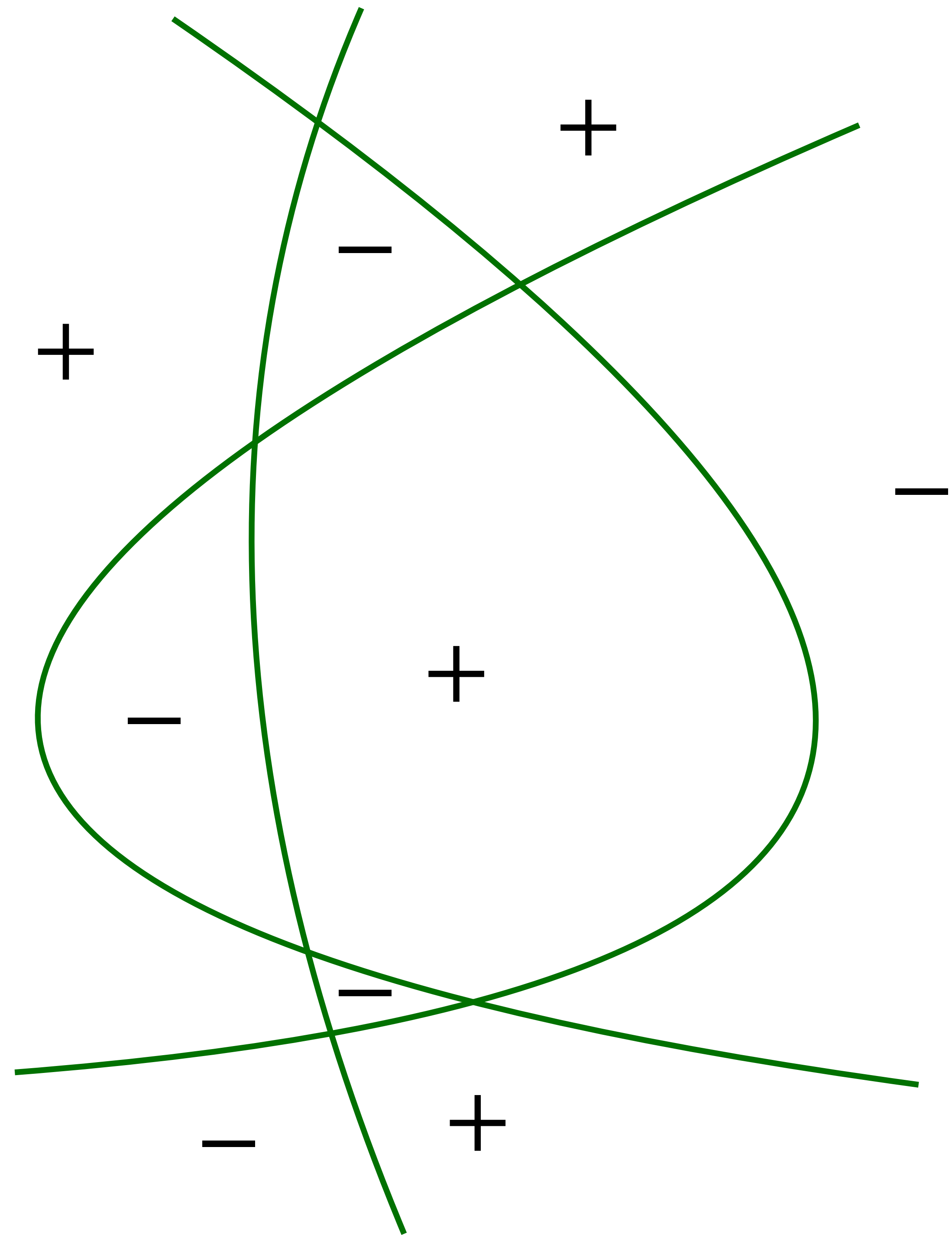


Formation of Domain Wall

Press, Ryden, Spergel 1989 (3D simulation)

Scaling regime : $\langle R \rangle \simeq t$

$$\rho_{\text{DW}} \simeq \frac{\sigma}{R}$$

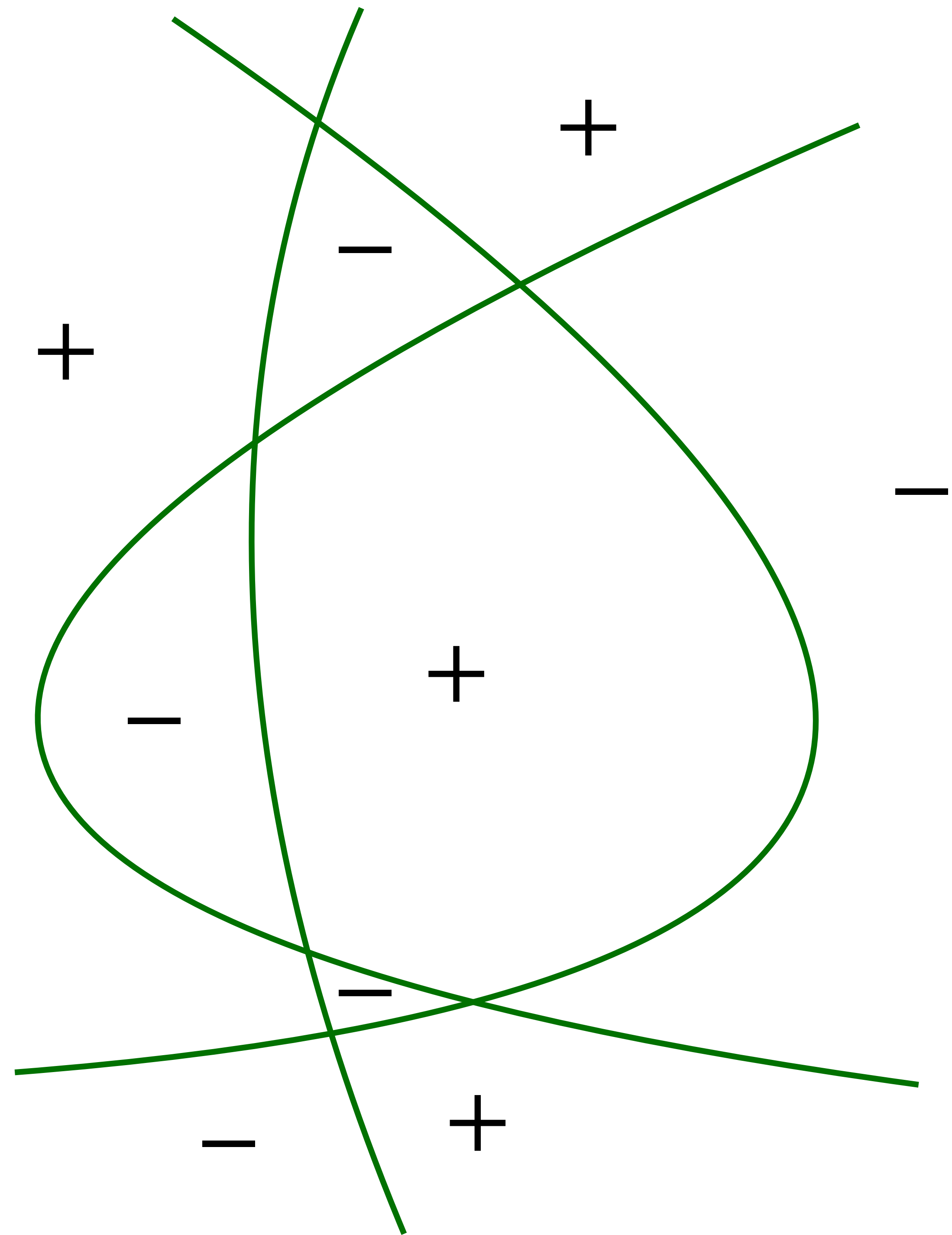


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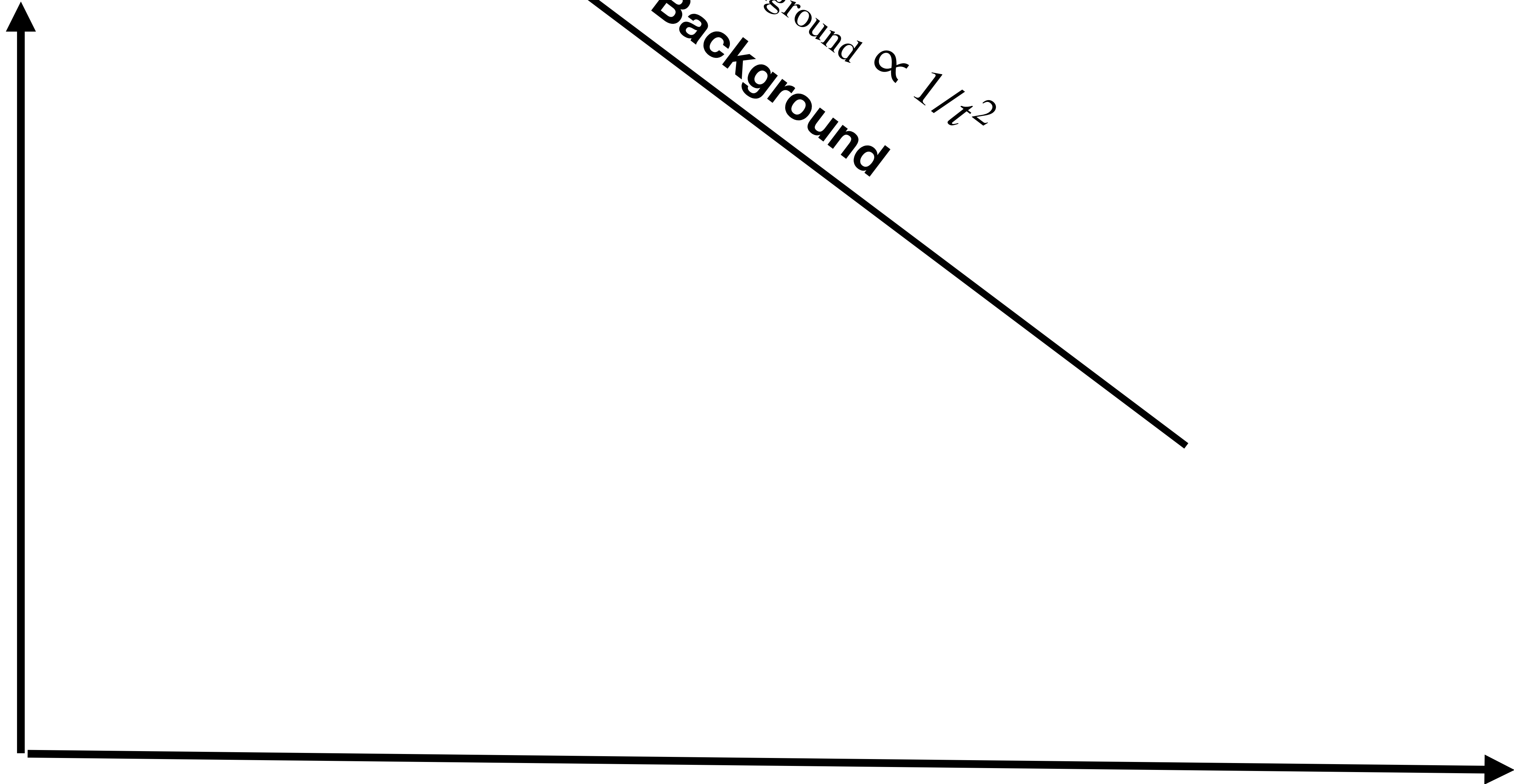
$$\rho_{\text{DW}} \simeq \frac{\sigma}{R} \simeq \frac{\sigma}{t}$$



Energy density

$\rho_{\text{background}} \propto 1/t^2$
Background

t



Energy density

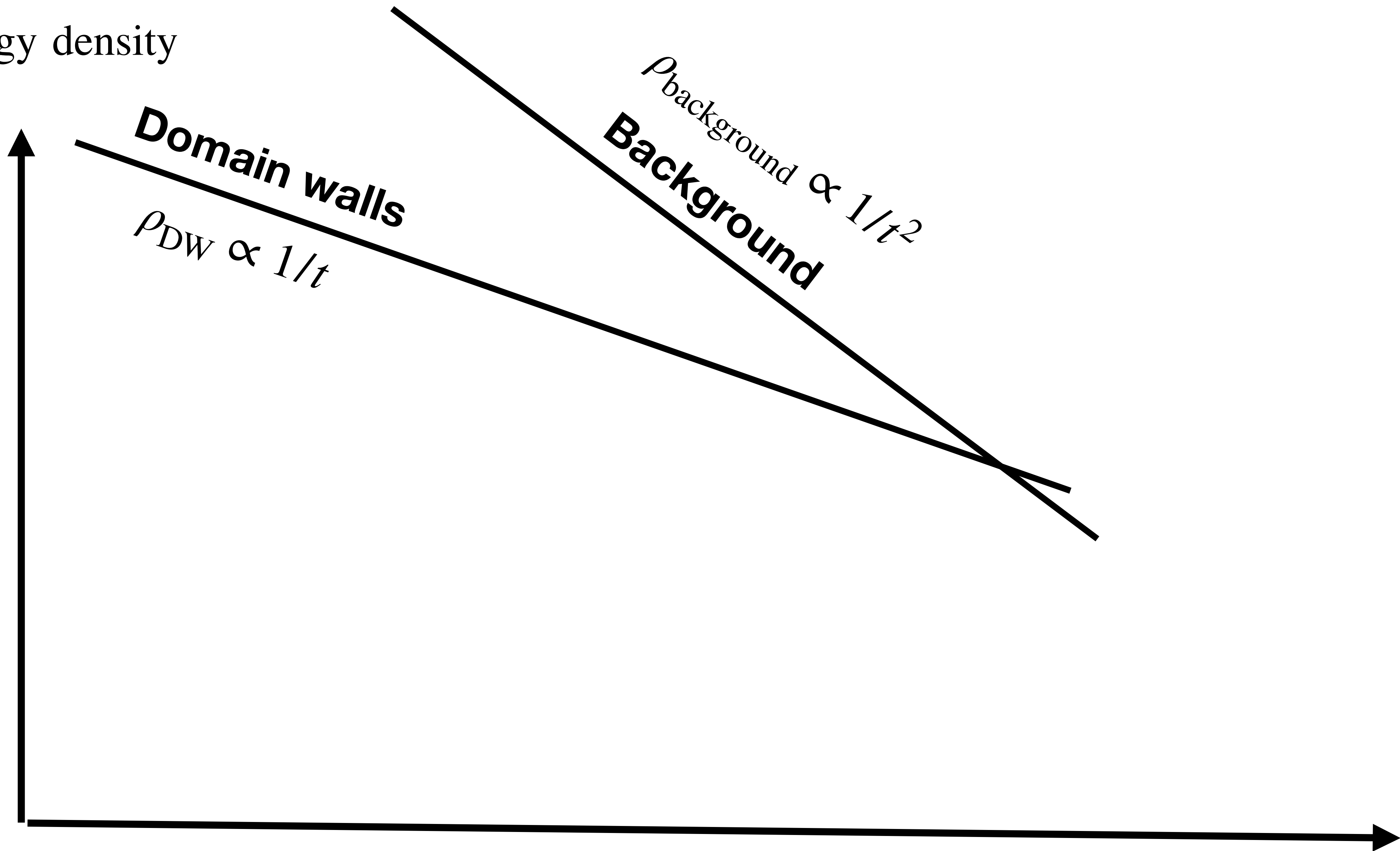
Domain walls

$\rho_{DW} \propto 1/t$

Background

$\rho_{\text{background}} \propto 1/t^2$

t



Energy density

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

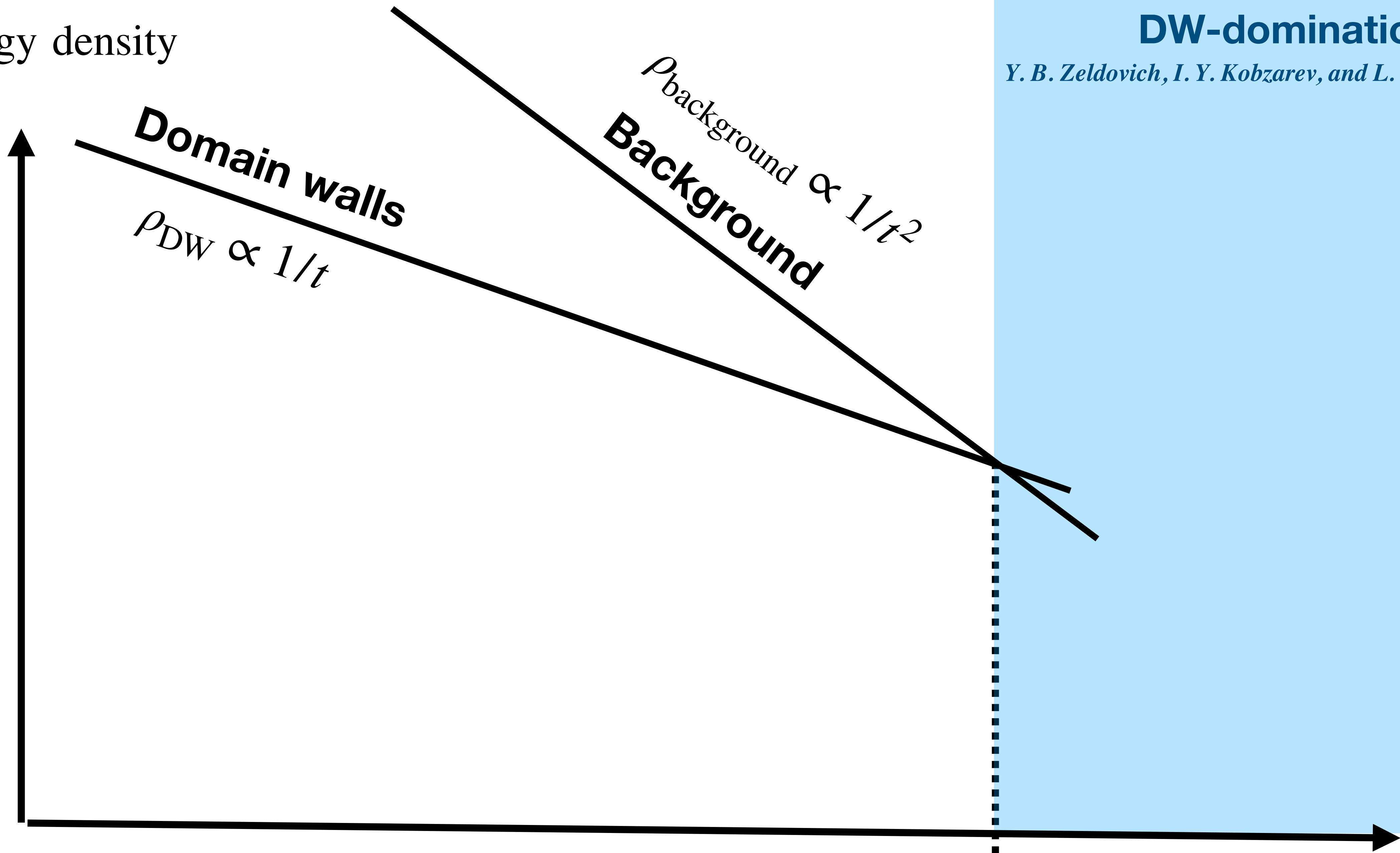
Domain walls

$$\rho_{\text{DW}} \propto 1/t$$

$\rho_{\text{background}} \propto 1/t^2$
Background

t_{dom}

t



Energy density

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$$\rightarrow 1) \delta\rho/\rho \sim 1$$

Domain walls

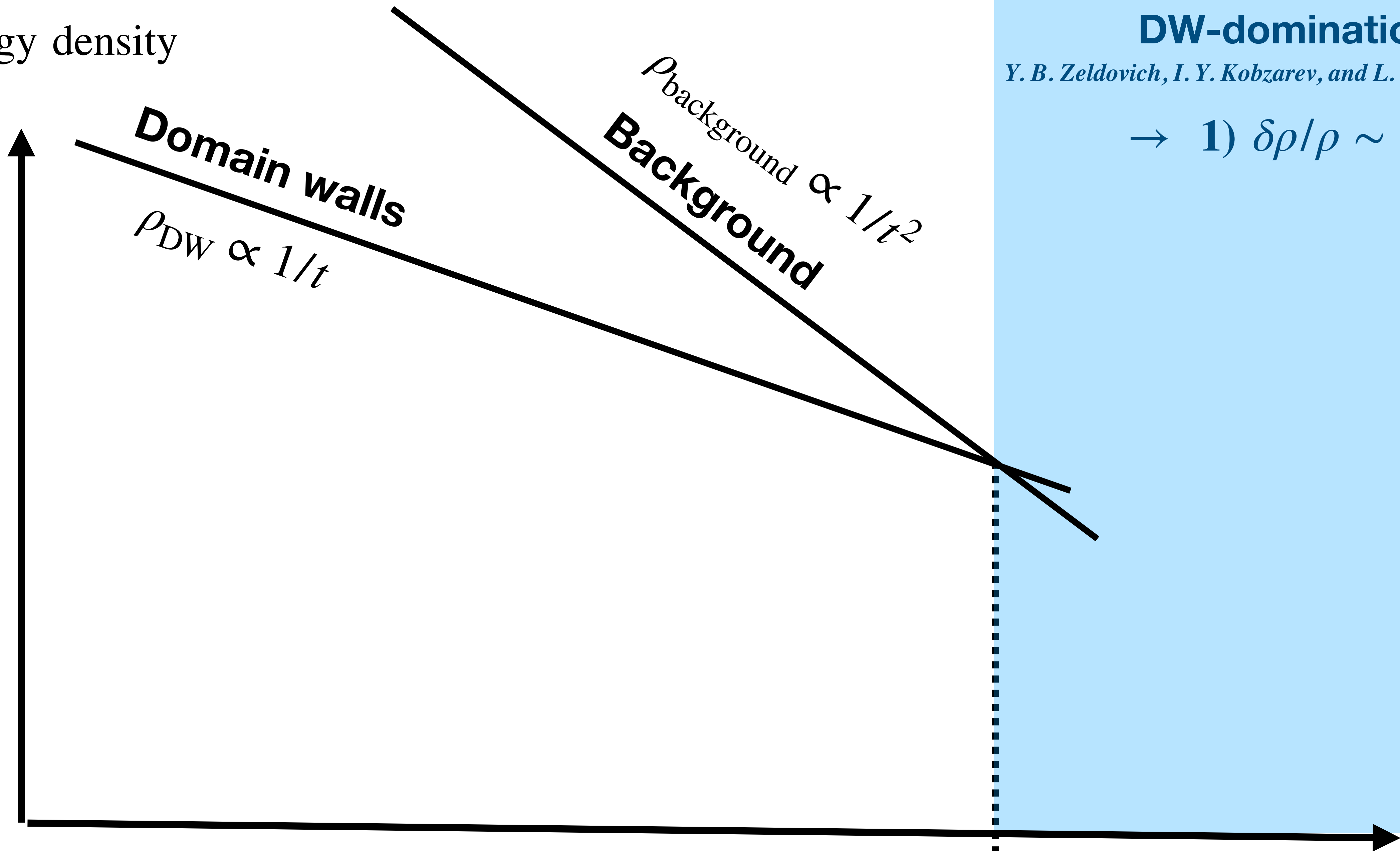
$$\rho_{DW} \propto 1/t$$

Background

$$\rho_{\text{background}} \propto 1/t^2$$

t_{dom}

t



Energy density

Domain walls

$$\rho_{\text{DW}} \propto 1/t$$

Background

$$\rho_{\text{background}} \propto 1/t^2$$

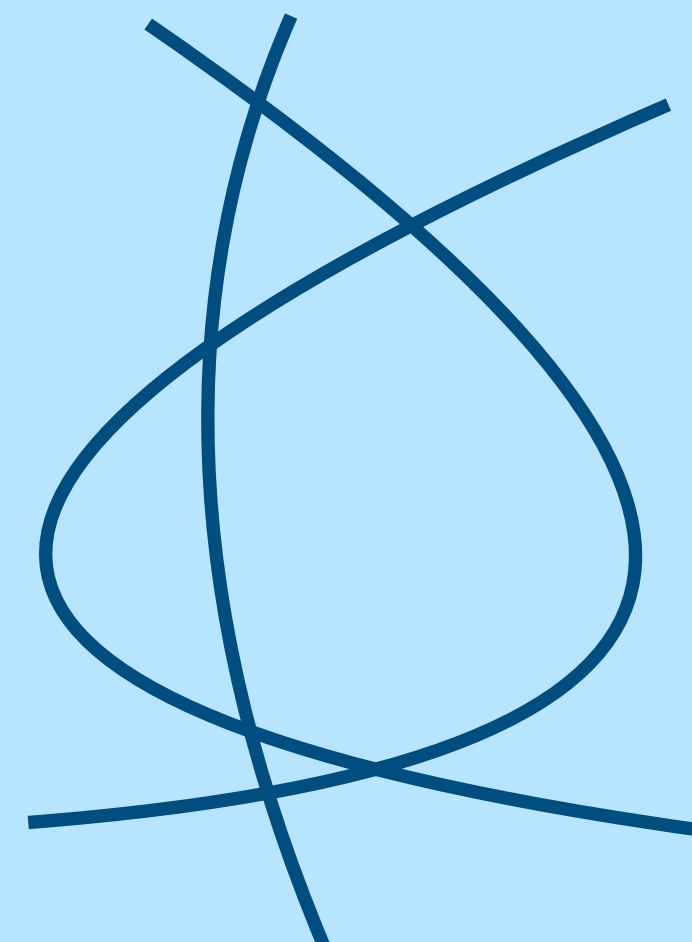
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(scaling regime)



t_{dom}

t

Energy density

Domain walls

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t_{dom}

t

DW-domination

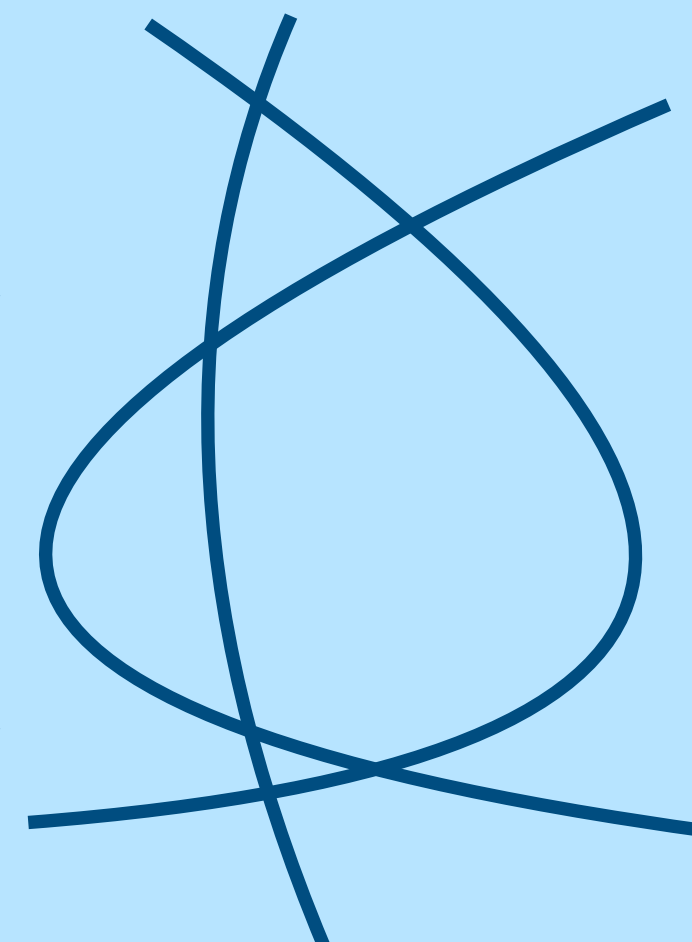
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$$\langle R \rangle \simeq t$$

(scaling regime)

$$\rightarrow 2) \text{ horizon size}$$



Energy density

Domain walls

$$\rho_{DW} \propto 1/t$$

Background

$$\rho_{\text{background}} \propto 1/t^2$$

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$$\langle R \rangle \simeq t$$

(scaling regime)

$$\rightarrow 2) \text{ horizon size}$$

$\Rightarrow$ **Efficient PBH formation**

t_{dom}

t

Energy density

Domain walls

$$\rho_{DW} \propto 1/t$$

Background

$$\rho_{\text{background}} \propto 1/t^2$$

t_{dom}

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$$\rightarrow 1) \delta\rho/\rho \sim 1$$

$$\langle R \rangle \simeq t$$

(scaling regime)

$$\rightarrow 2) \text{ horizon size}$$

$\Rightarrow$ Efficient PBH formation

Vilenkin and Shellard's textbook, 2000

Ferrer, Masso, Panico, Pujolas, Rompineve,
Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707

t

Energy density

Domain walls

$$\rho_{\text{DW}} \simeq \sigma/t$$

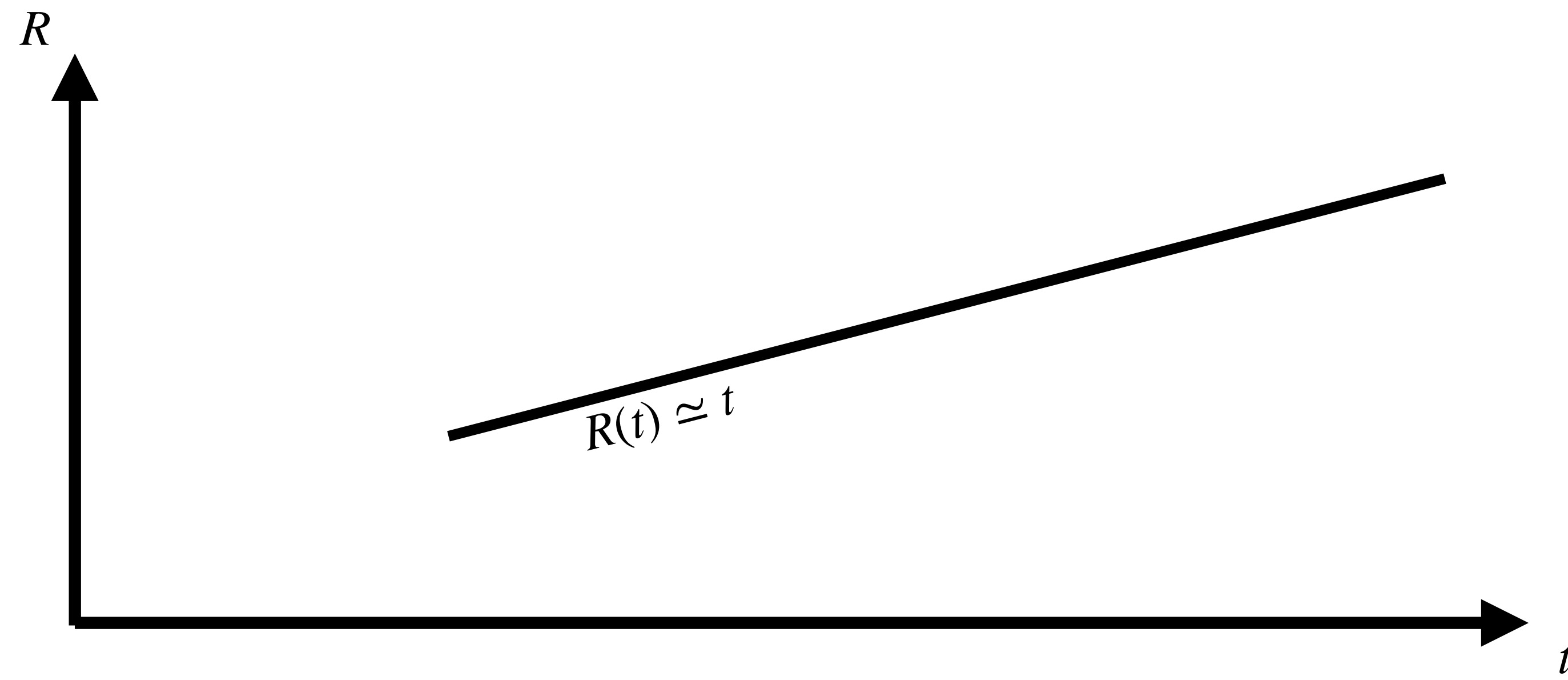
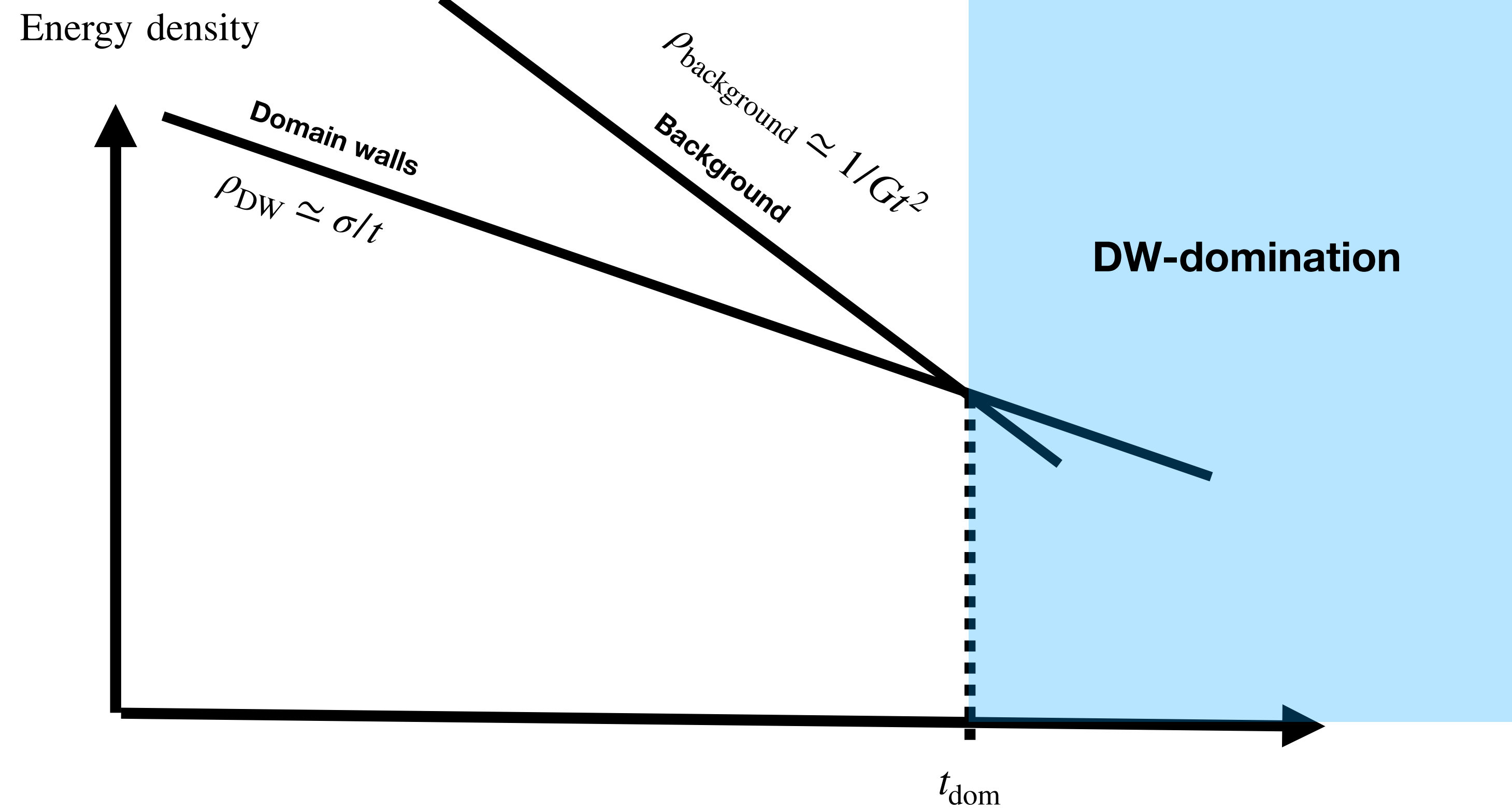
Background

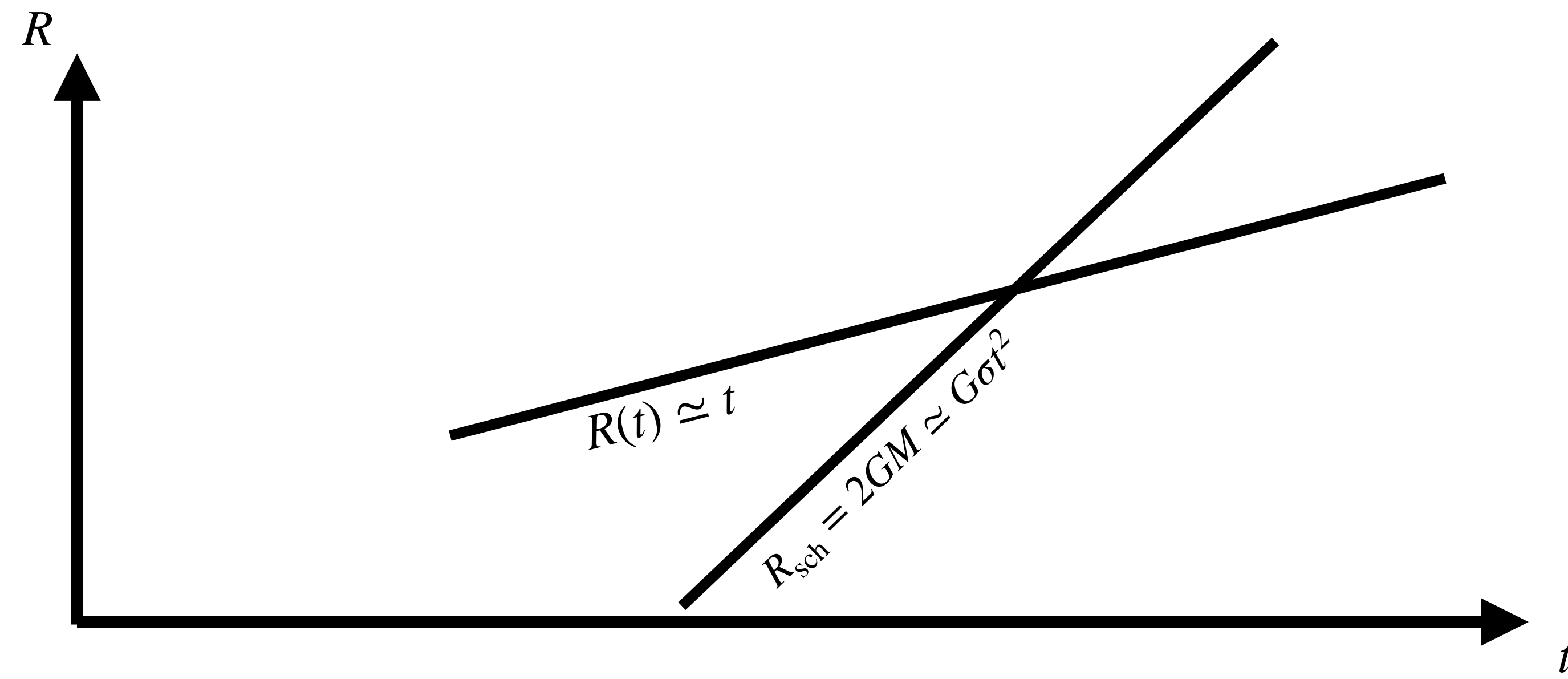
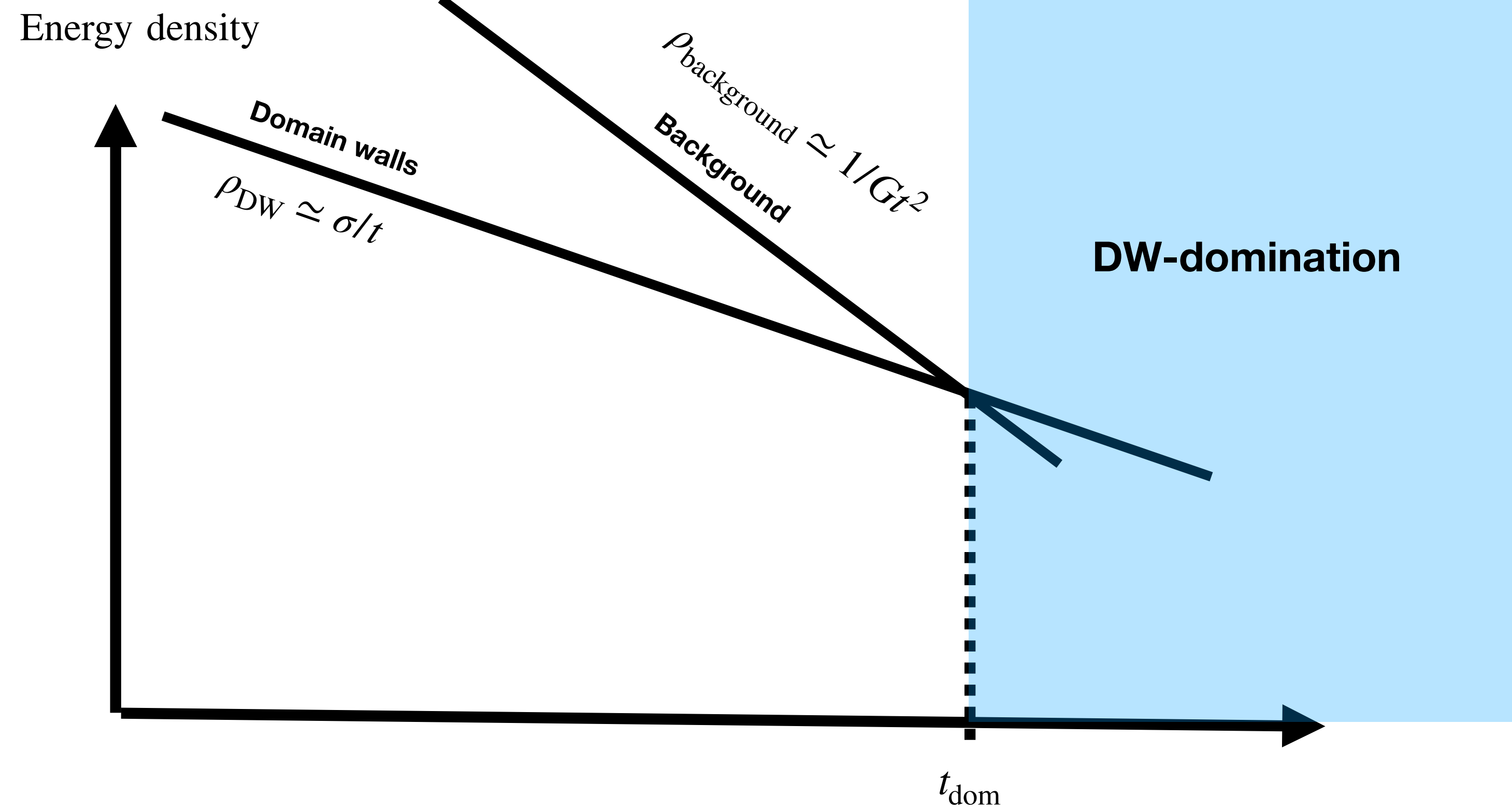
$$\rho_{\text{background}} \simeq 1/Gt^2$$

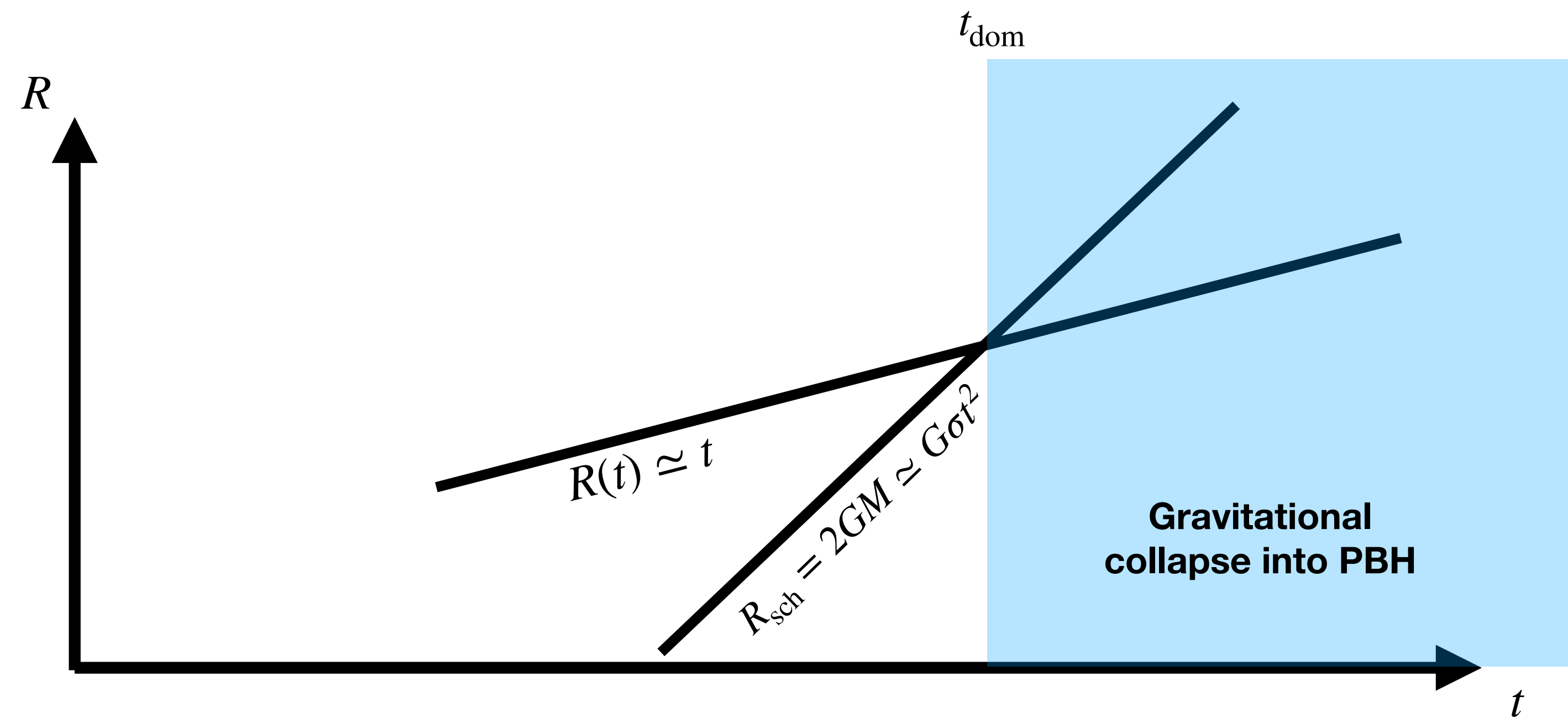
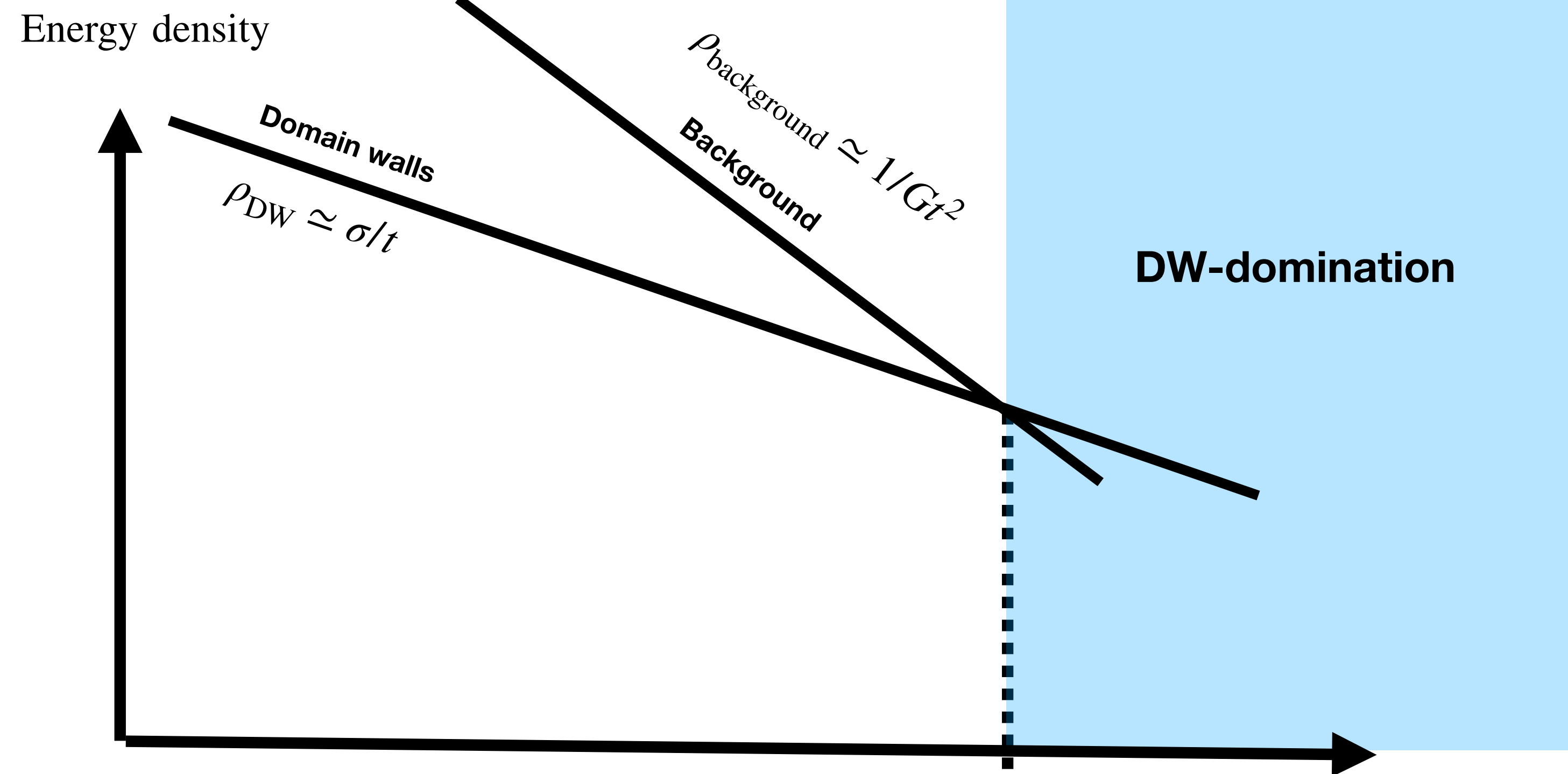
DW-domination

t_{dom}

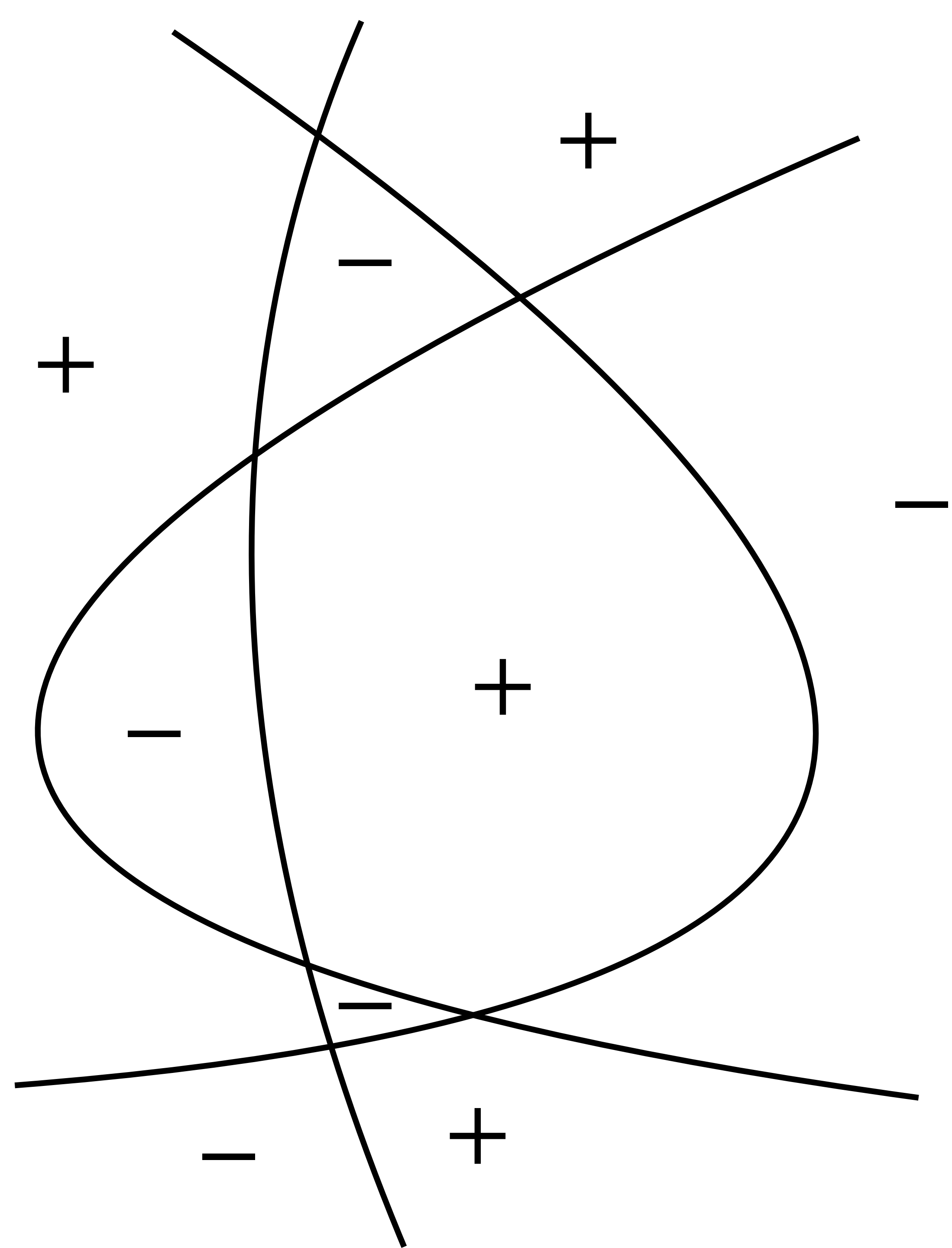
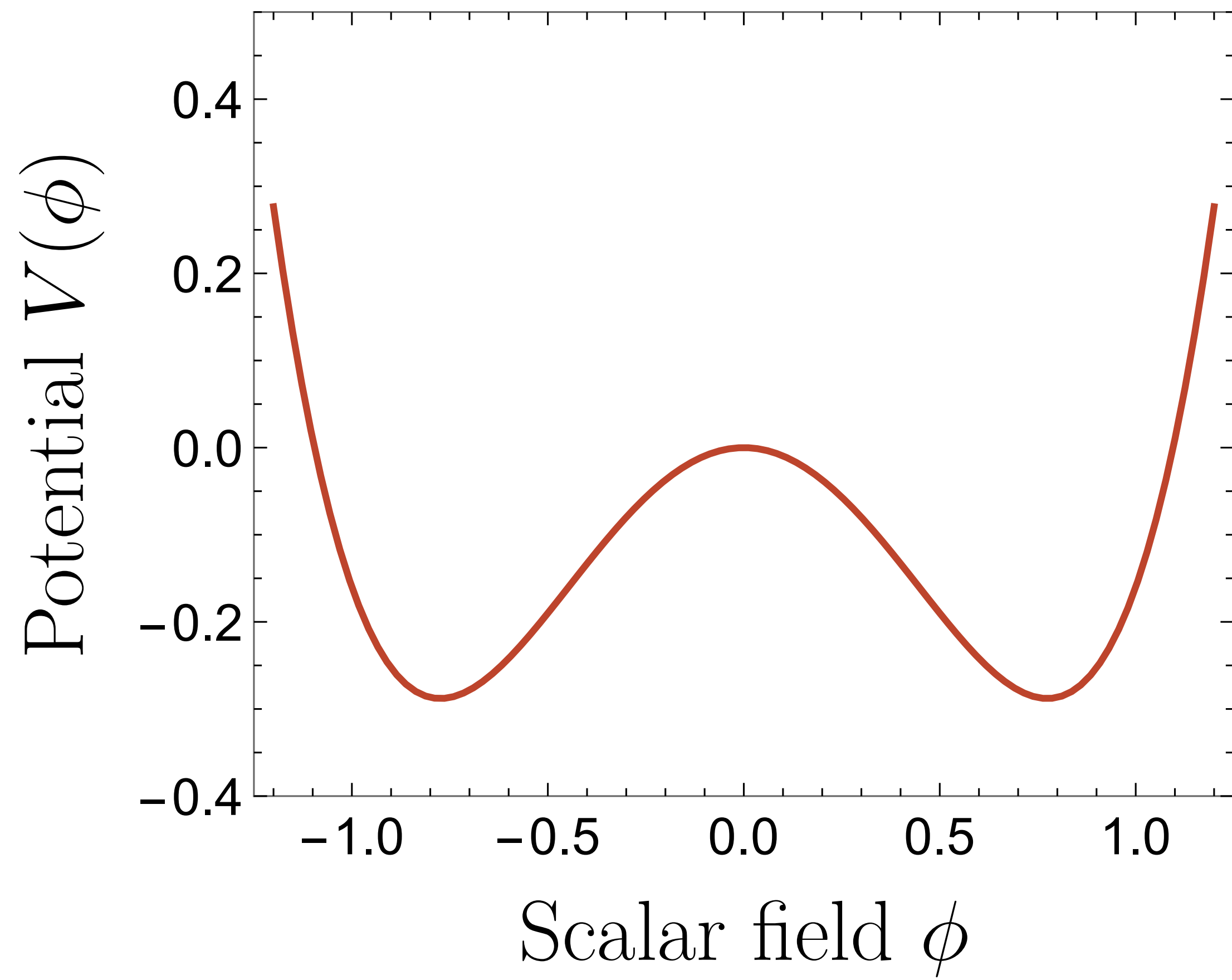
The diagram is a plot of Energy density on the vertical axis against time on the horizontal axis. Two solid black lines originate from the left: a steeper line labeled 'Background' with the equation $\rho_{\text{background}} \simeq 1/Gt^2$, and a less steep line labeled 'Domain walls' with the equation $\rho_{\text{DW}} \simeq \sigma/t$. These two lines intersect at a point. A vertical dashed line extends from this intersection point down to the horizontal axis, where it is labeled t_{dom} . To the right of this dashed line, the plot area is filled with a light blue color, and the text 'DW-domination' is placed within this region. Two short, dark blue line segments branch off from the intersection point into the blue-shaded region.



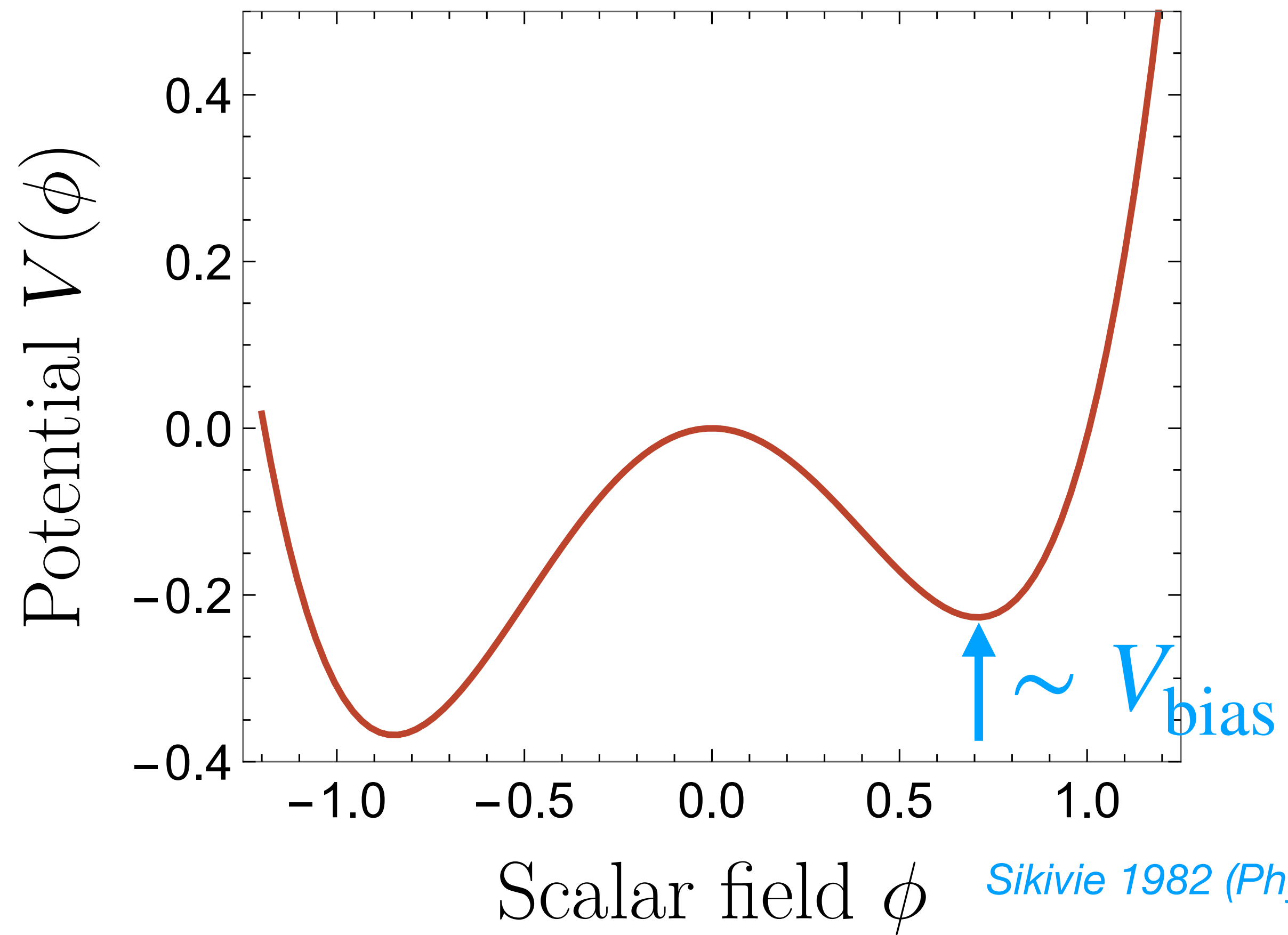




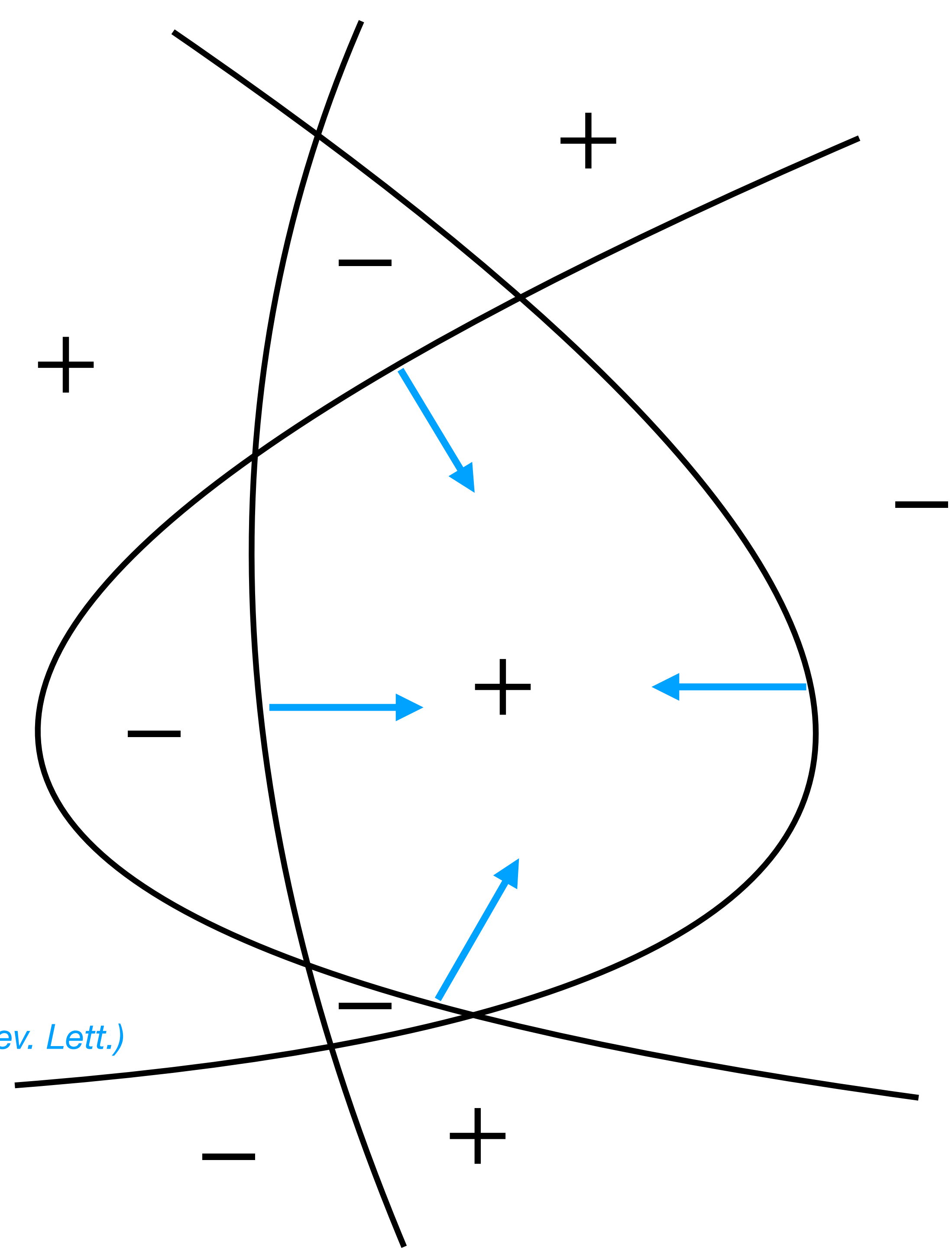
Vacuum energy bias



Vacuum energy bias



Sikivie 1982 (Phys. Rev. Lett.)



Energy density

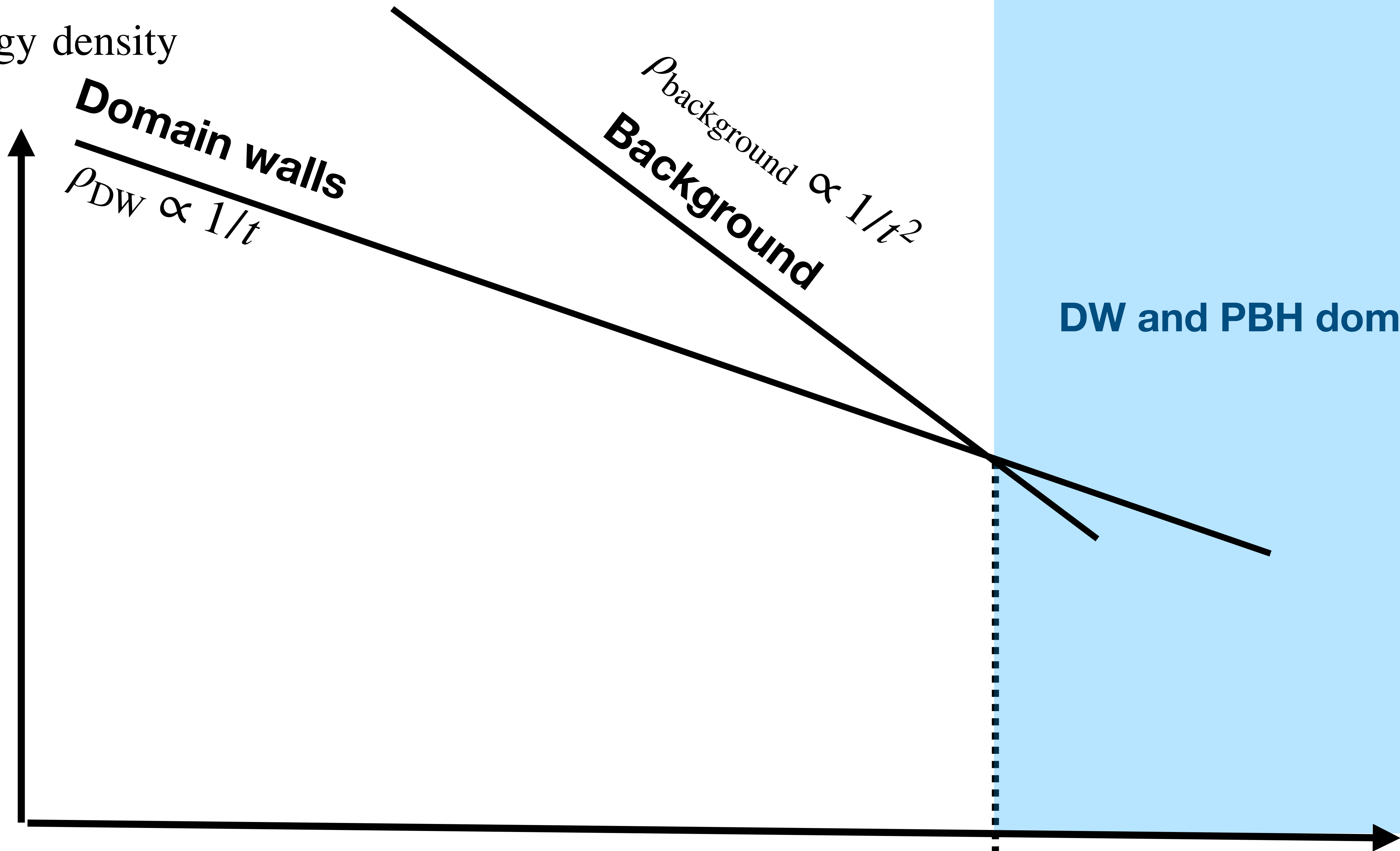
Domain walls

$$\rho_{DW} \propto 1/t$$

$\rho_{\text{background}} \propto 1/t^2$
Background

DW and PBH domination

t_{dom}



Energy density

Domain walls

$$\rho_{DW} \propto 1/t$$

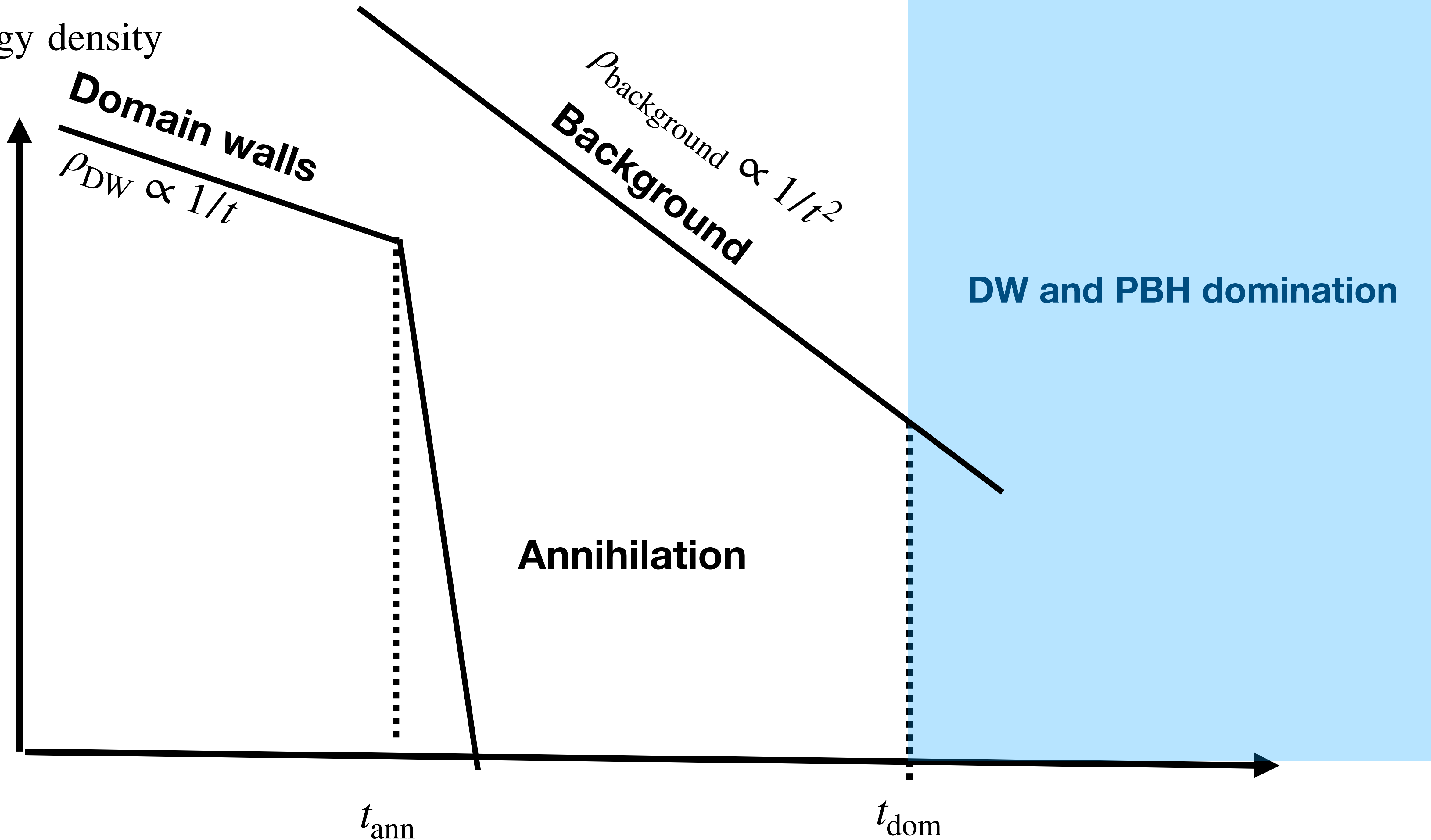
$\rho_{\text{background}} \propto 1/t^2$
Background

DW and PBH domination

Annihilation

t_{ann}

t_{dom}



Energy density

Domain walls

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$\rho_{\text{background}} \propto 1/t^2$
Background

Vilenkin (1982)

Gravitational waves

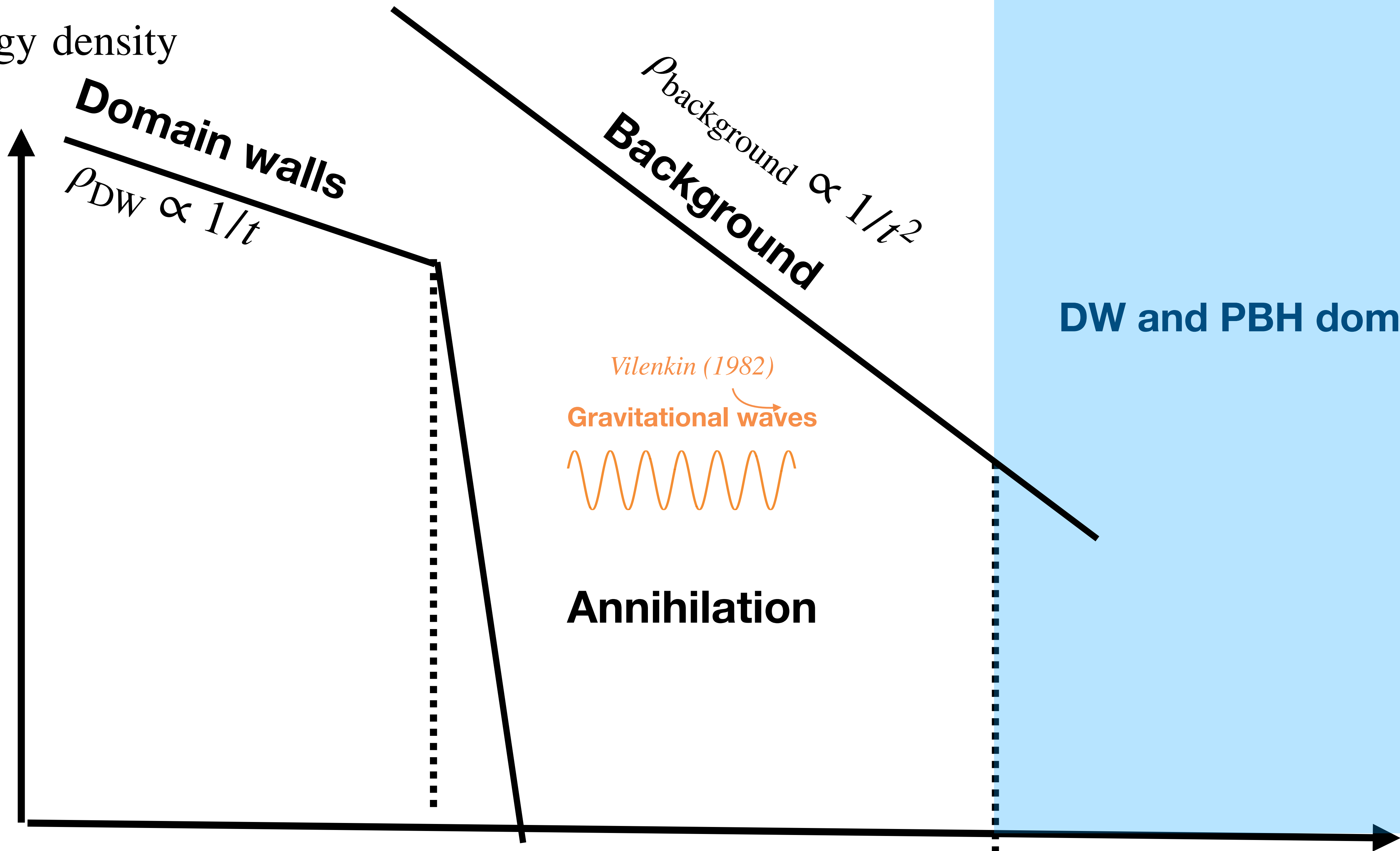


Annihilation

DW and PBH domination

t_{ann}

t_{dom}



Energy density

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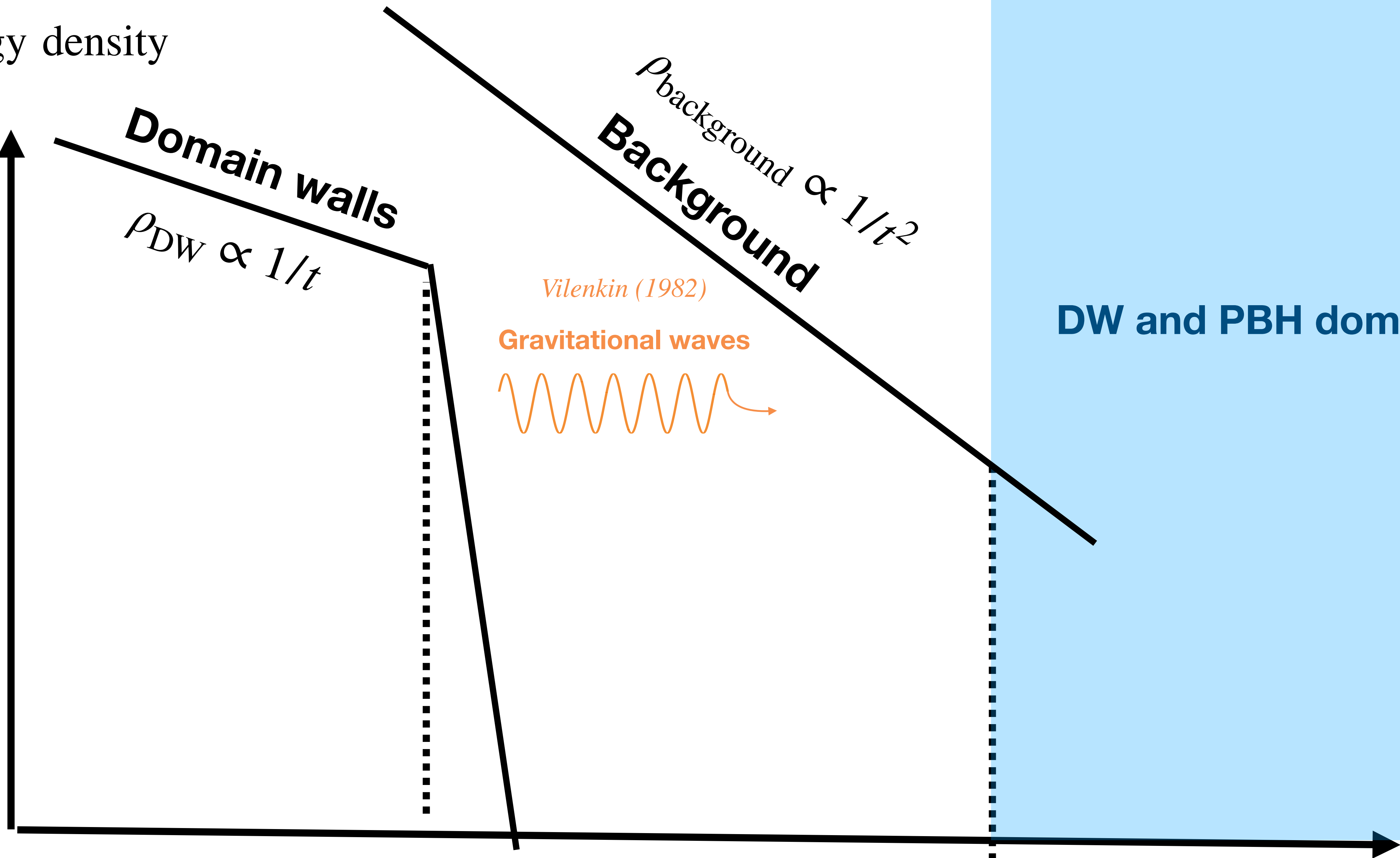
Gravitational waves



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t_{ann}

t_{dom}



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PTA SIGNAL

Vilenkin (1982)

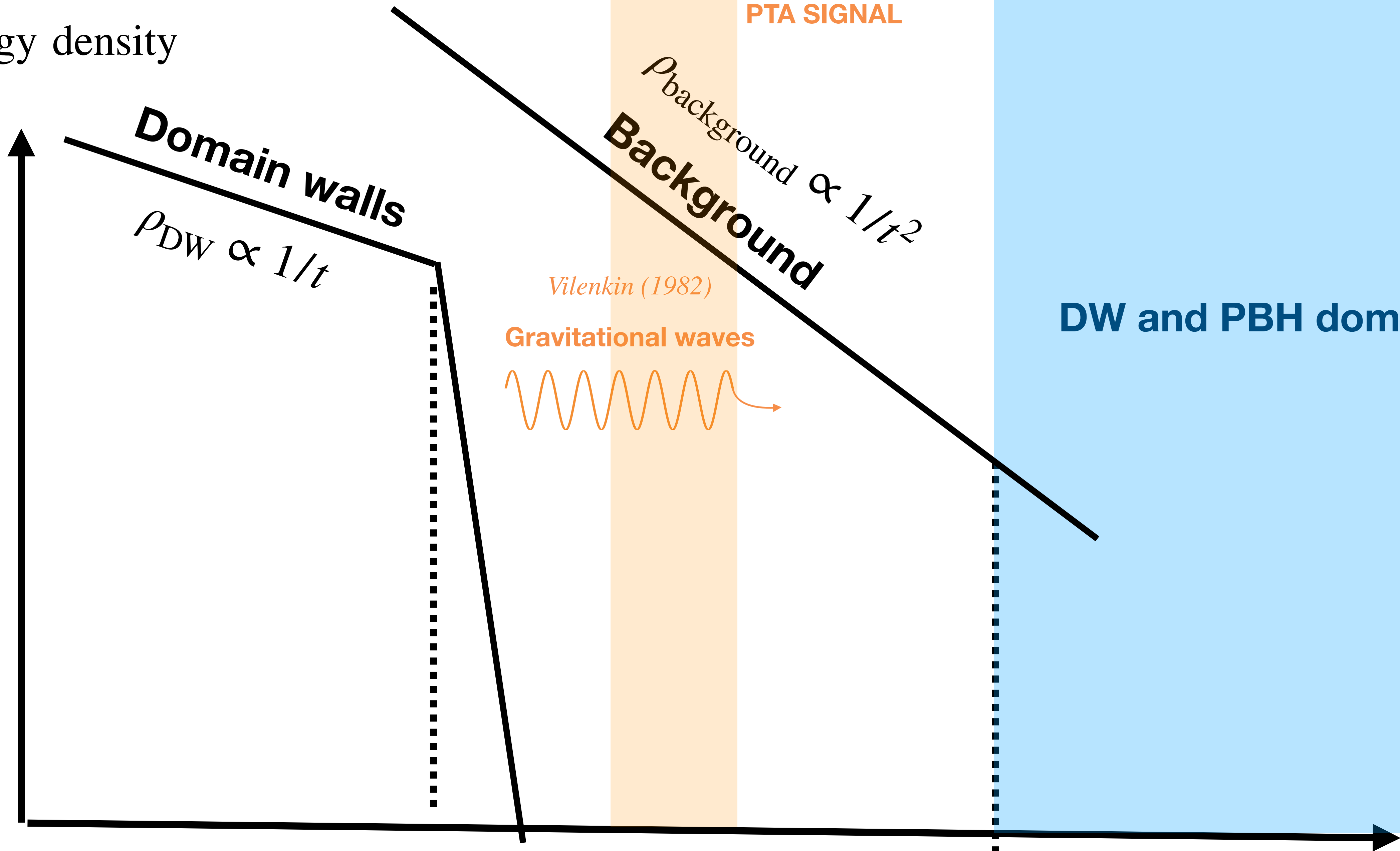
Gravitational waves



DW and PBH domination

t_{ann}

t_{dom}



Energy density

PTA SIGNAL

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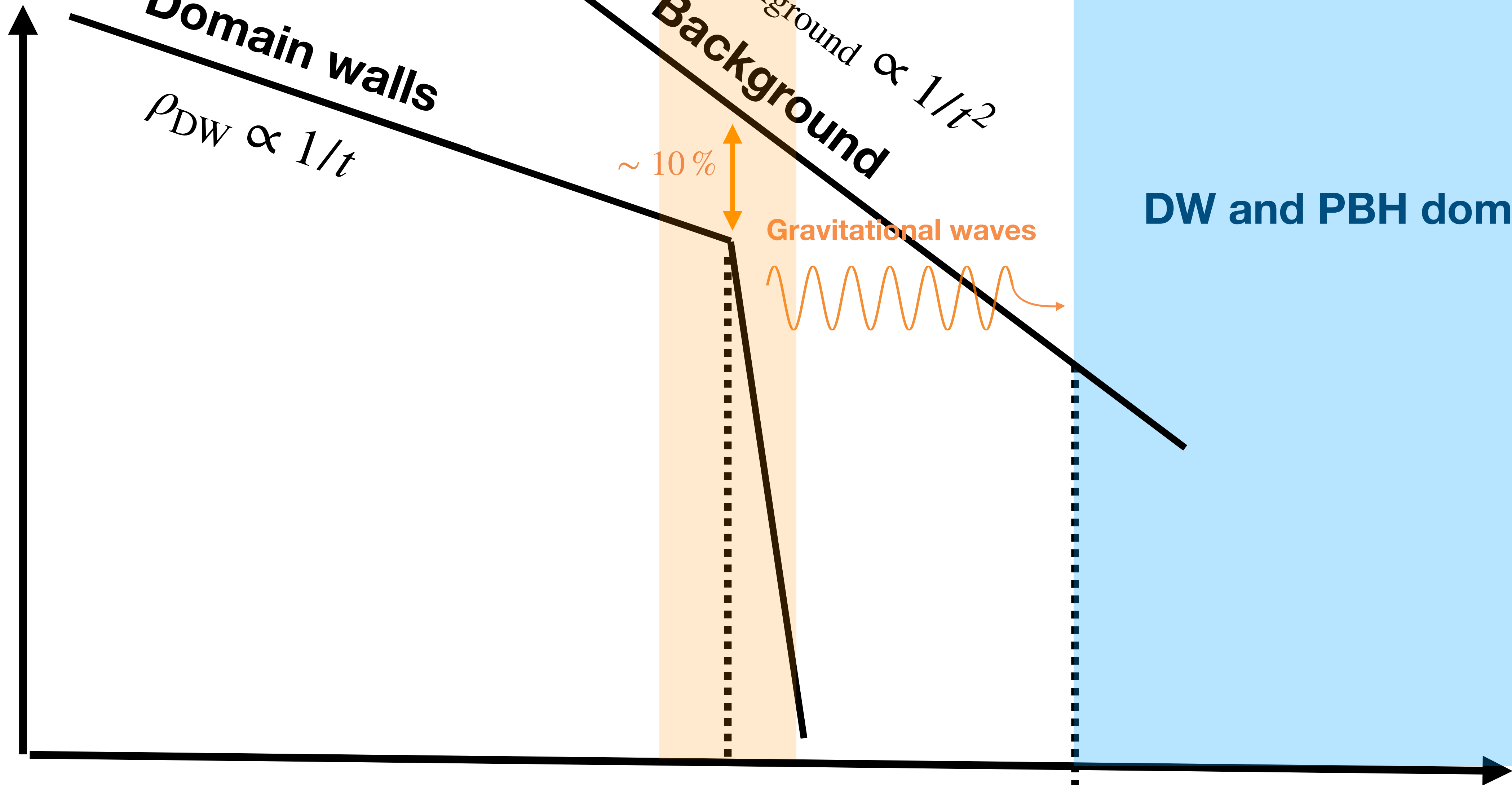
$\sim 10\%$

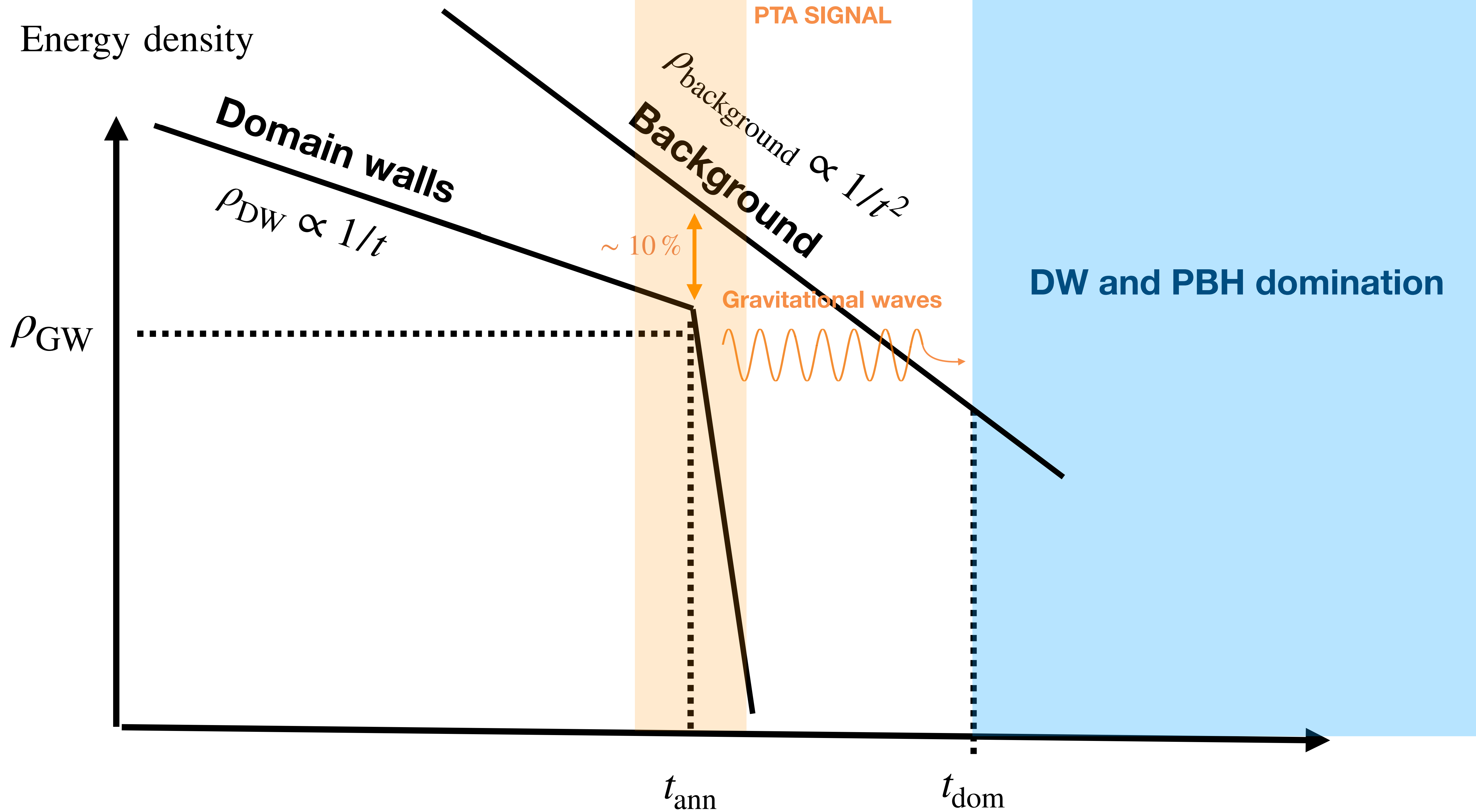
Gravitational waves

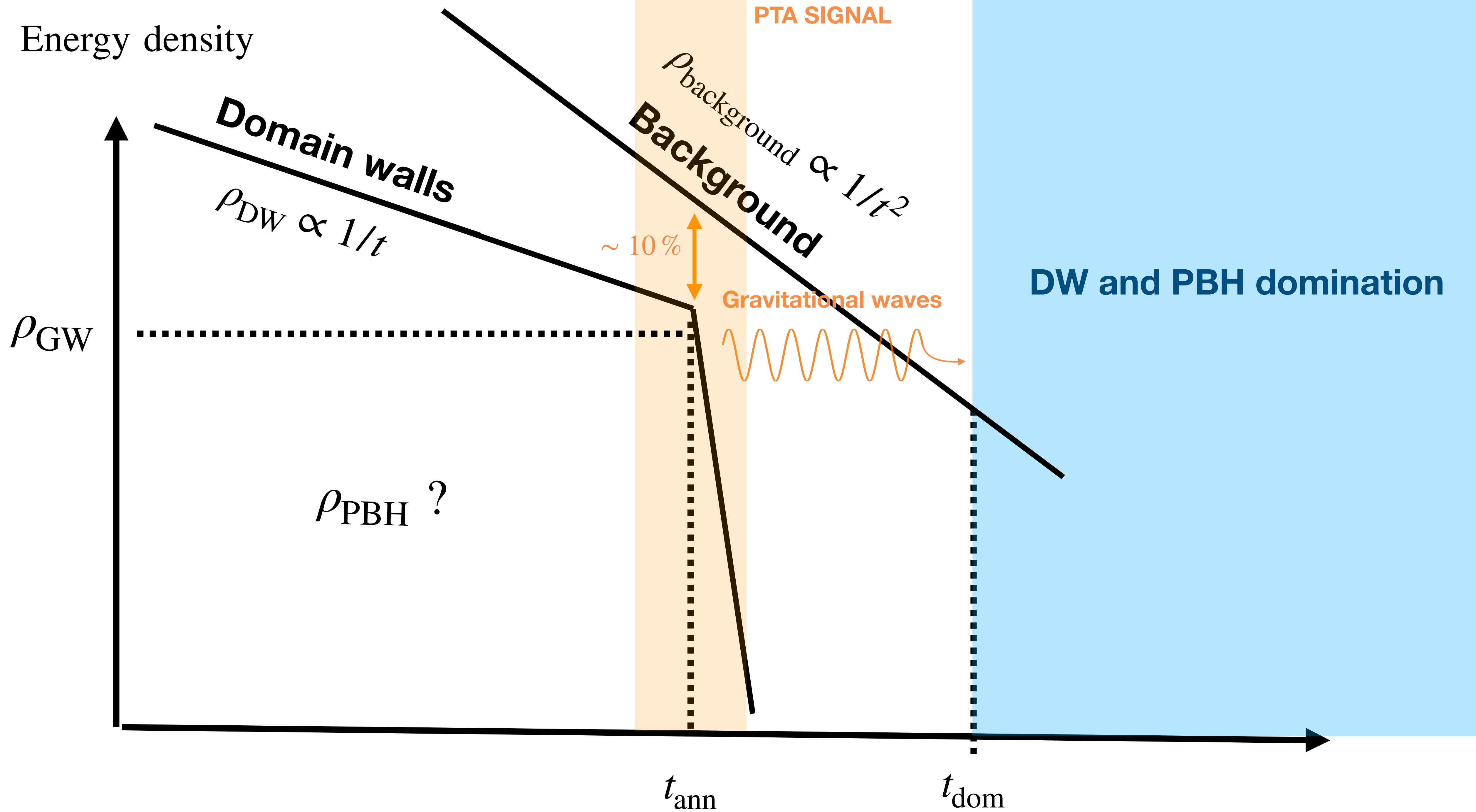
DW and PBH domination

t_{ann}

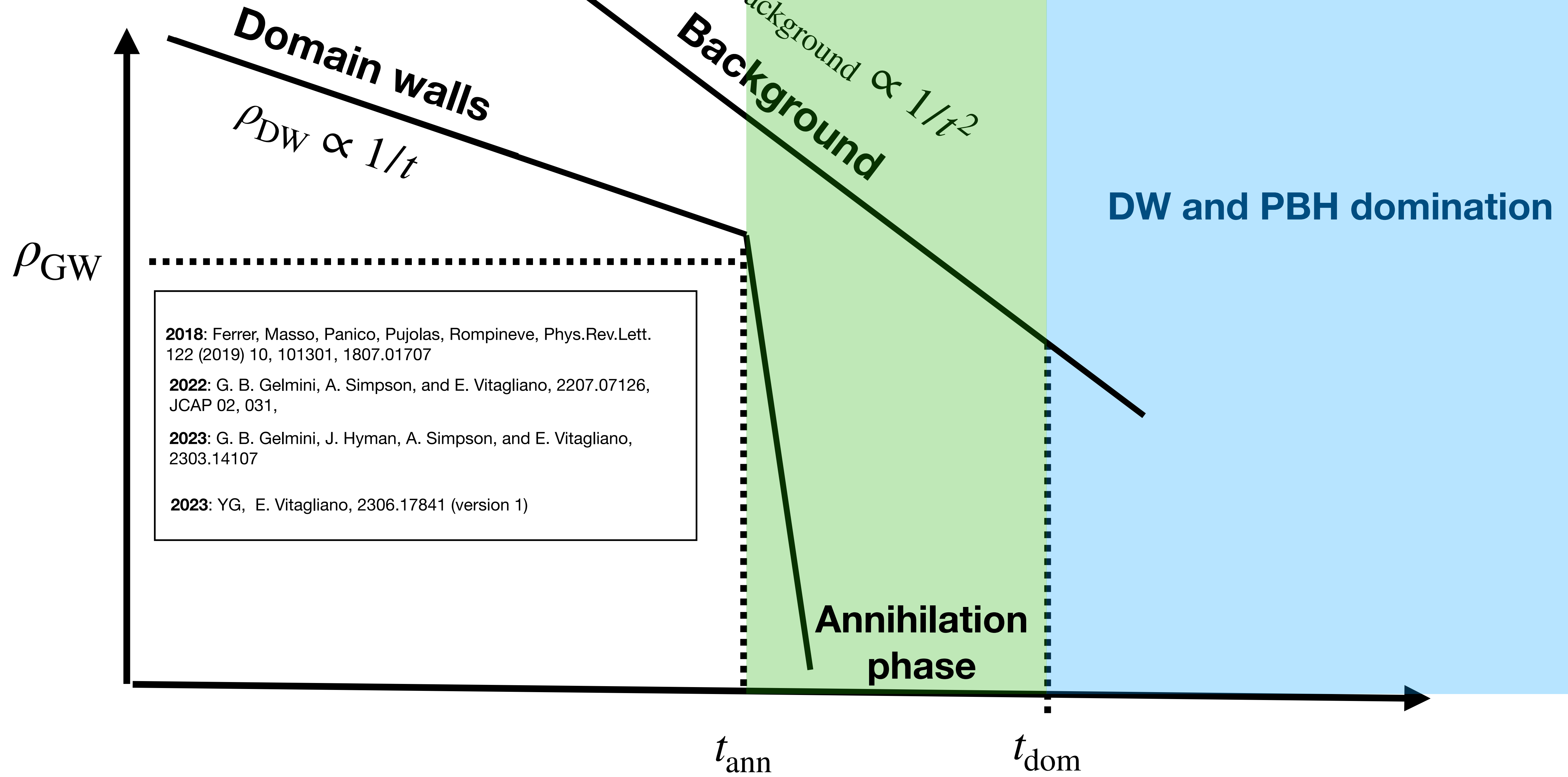
t_{dom}





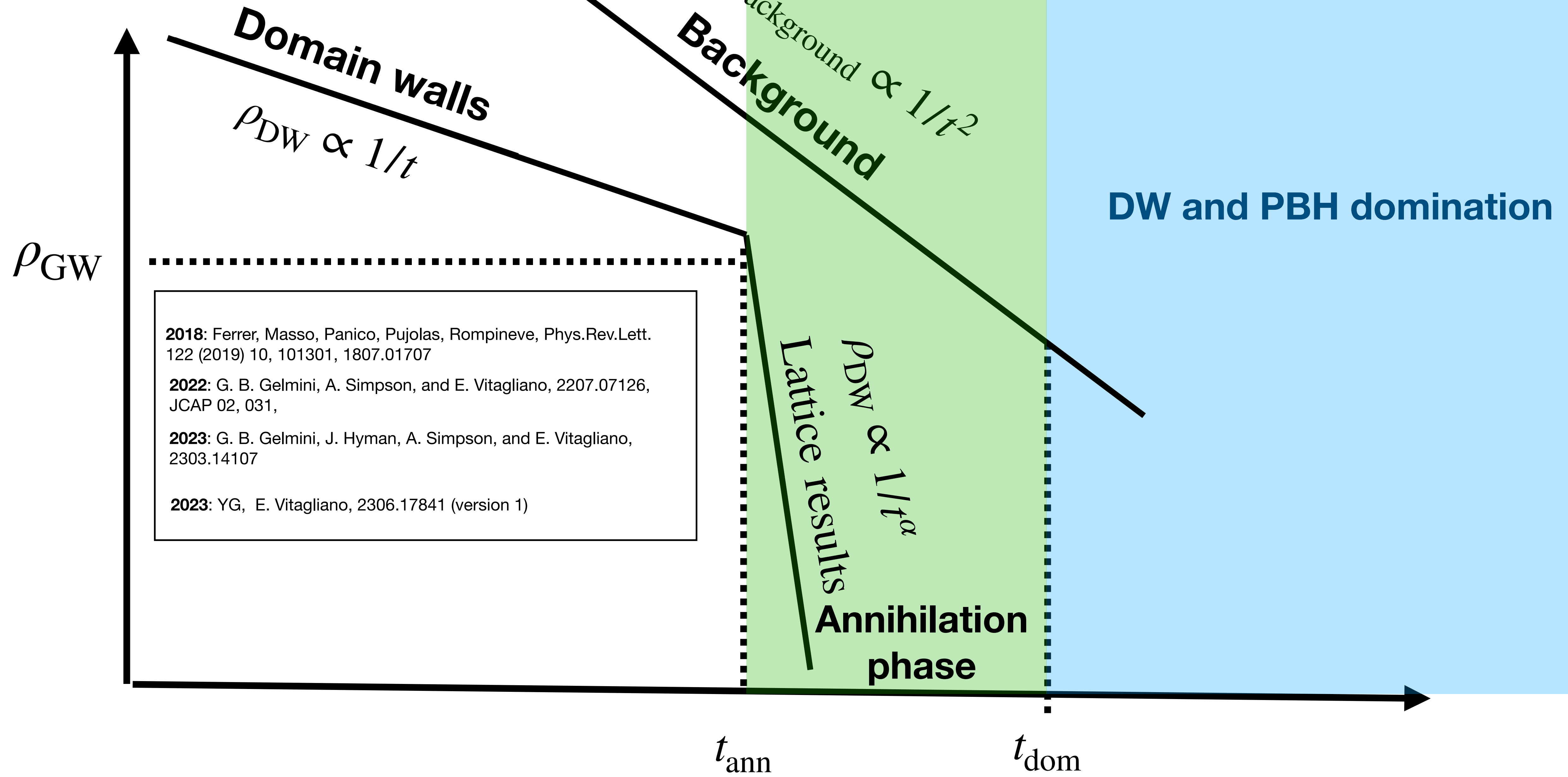


Energy density

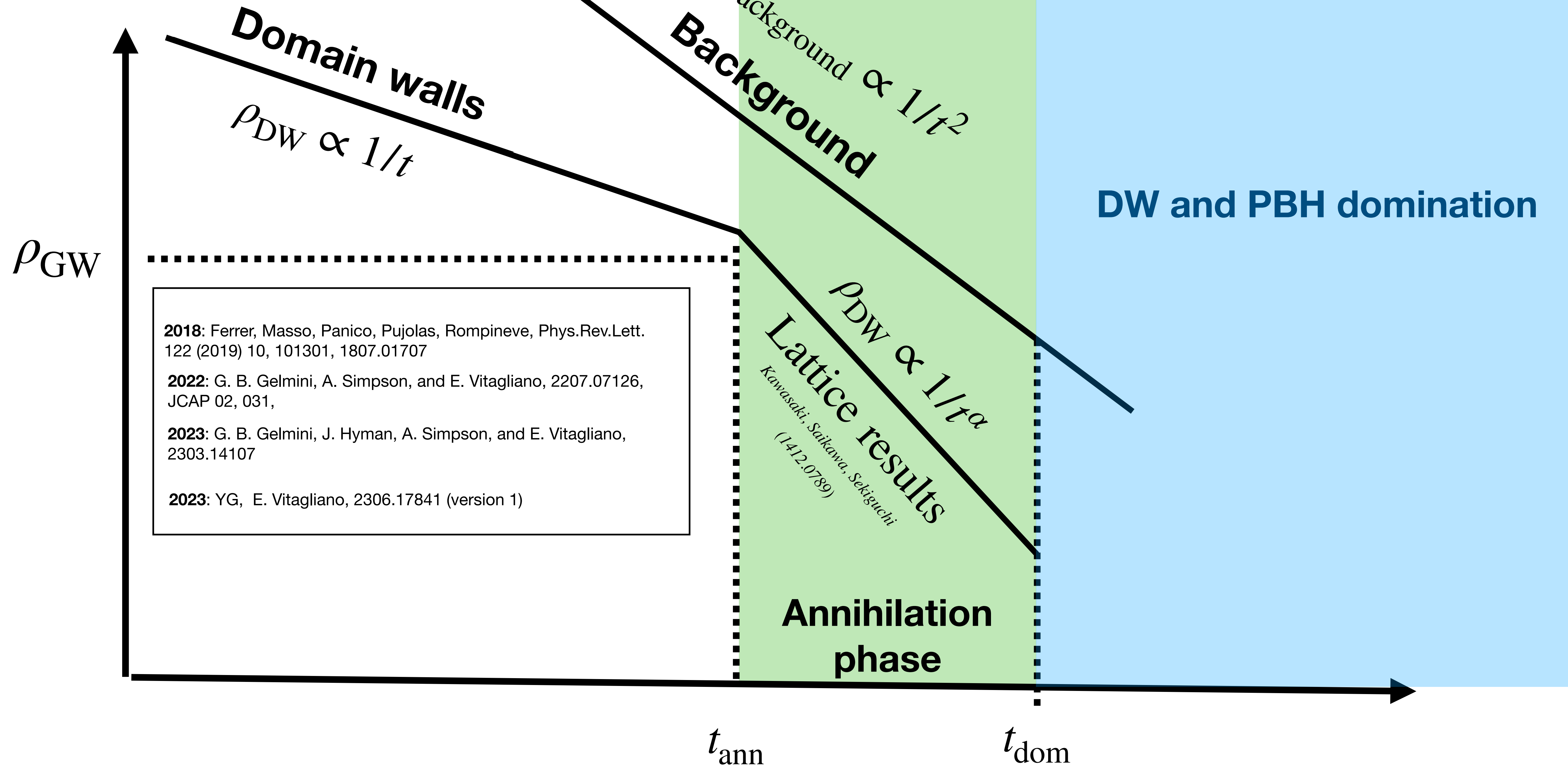


2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
2022: G. B. Gelmini, A. Simpson, and E. Vitagliano, 2207.07126, JCAP 02, 031,
2023: G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107
2023: YG, E. Vitagliano, 2306.17841 (version 1)

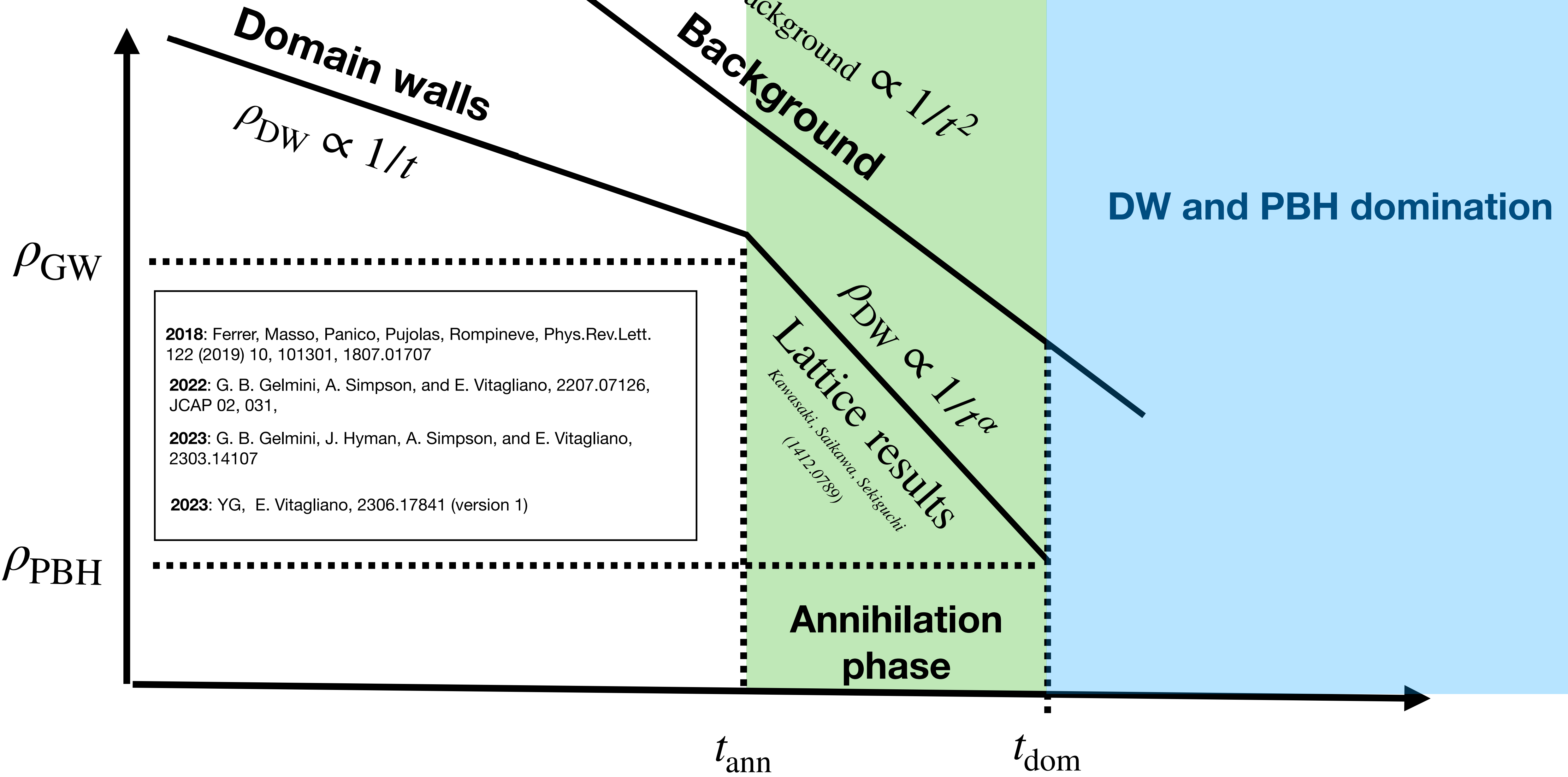
Energy density



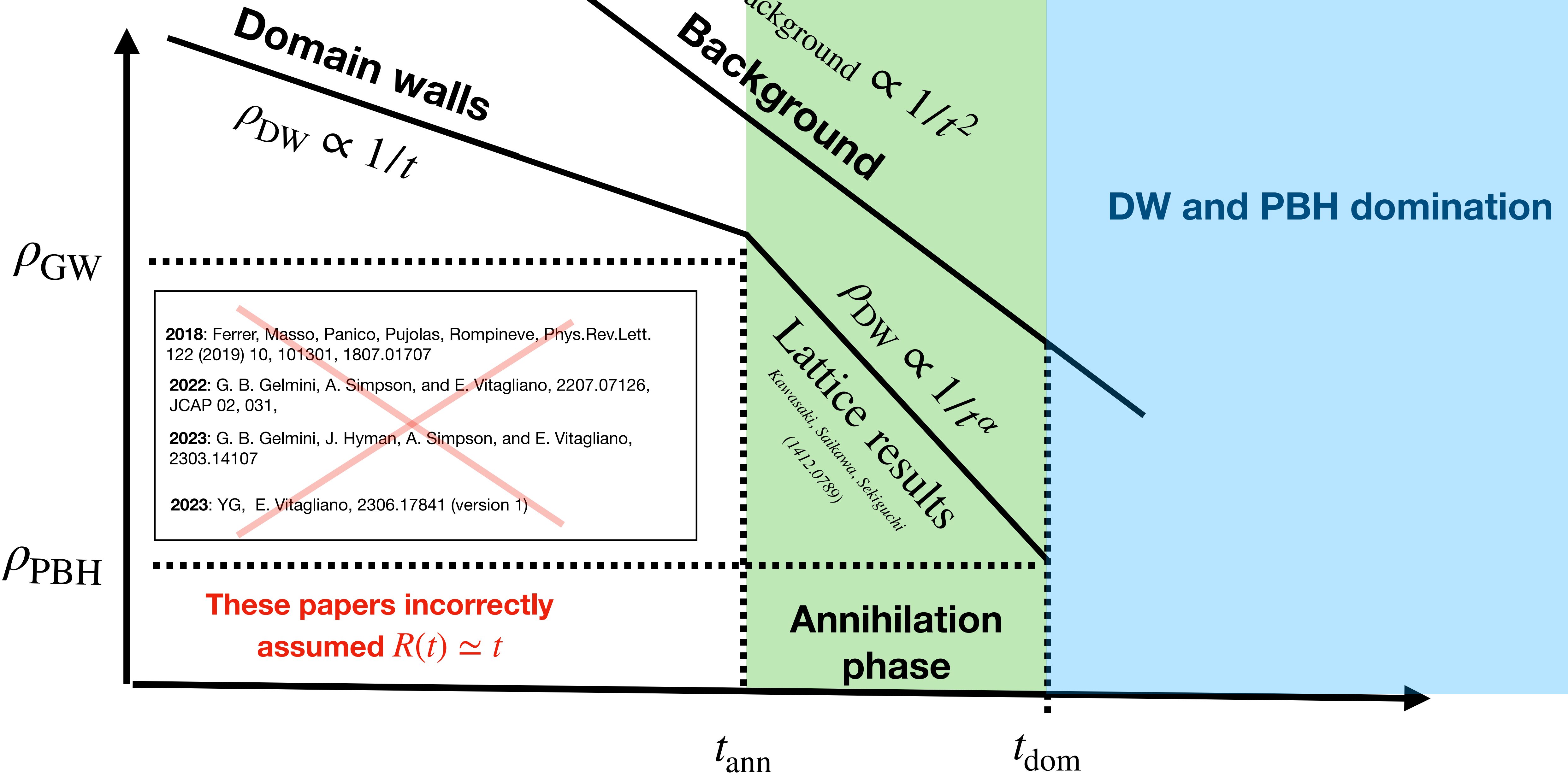
Energy density



Energy density



Energy density



Go back to basics:

$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = - \left(\frac{V_{\text{bias}}}{\sigma} + 6\pi\sigma \right) \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

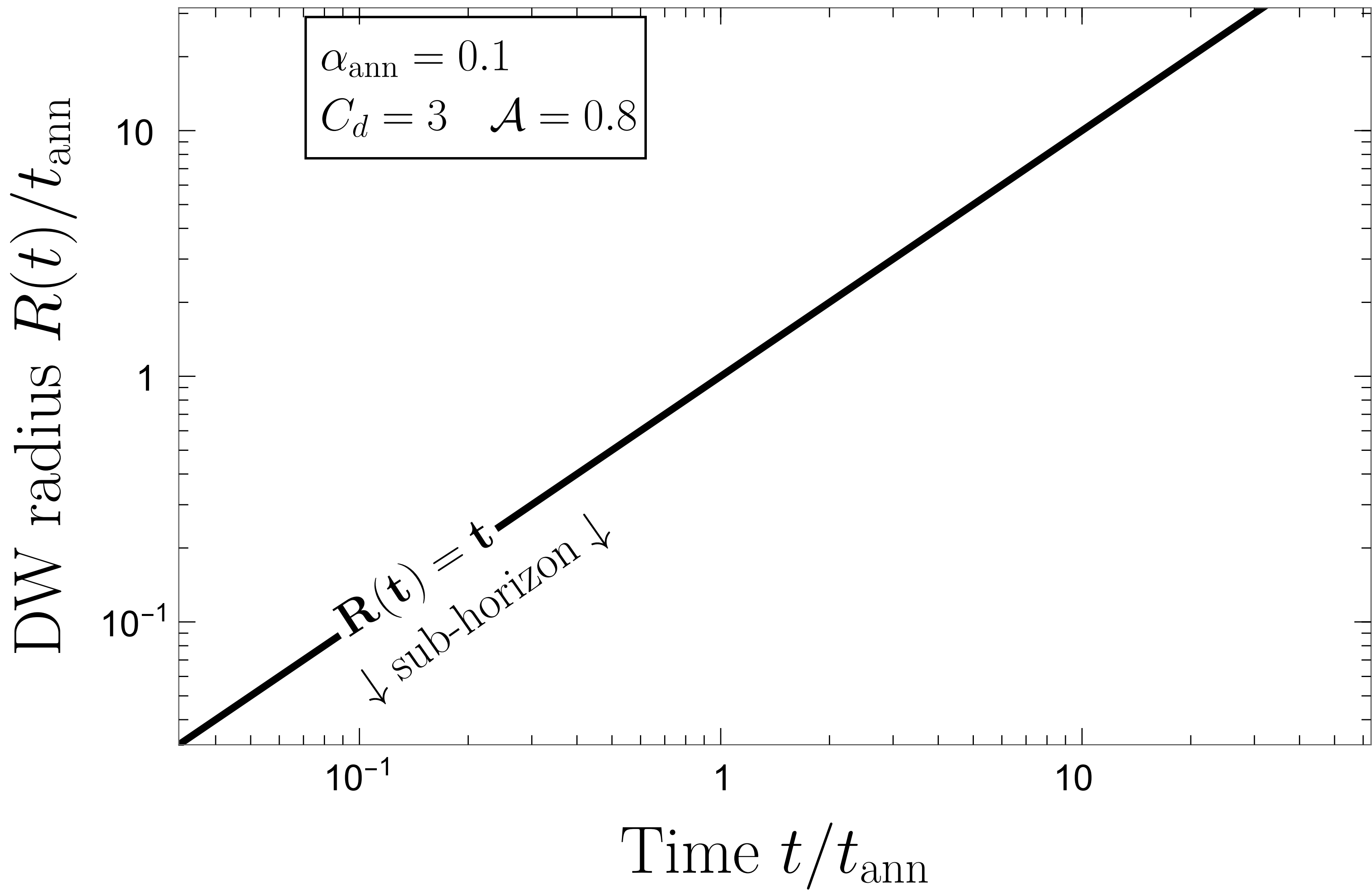
$$R(t) = a(t)\chi(t)$$

Berezin, Kuzmin, and Tkachev, (1983) *Deng, Vilenkin, (2016)*

Go back to basics:
$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = - \left(\frac{V_{\text{bias}}}{\sigma} + 6\pi\sigma \right) \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

$$R(t) = a(t)\chi(t)$$

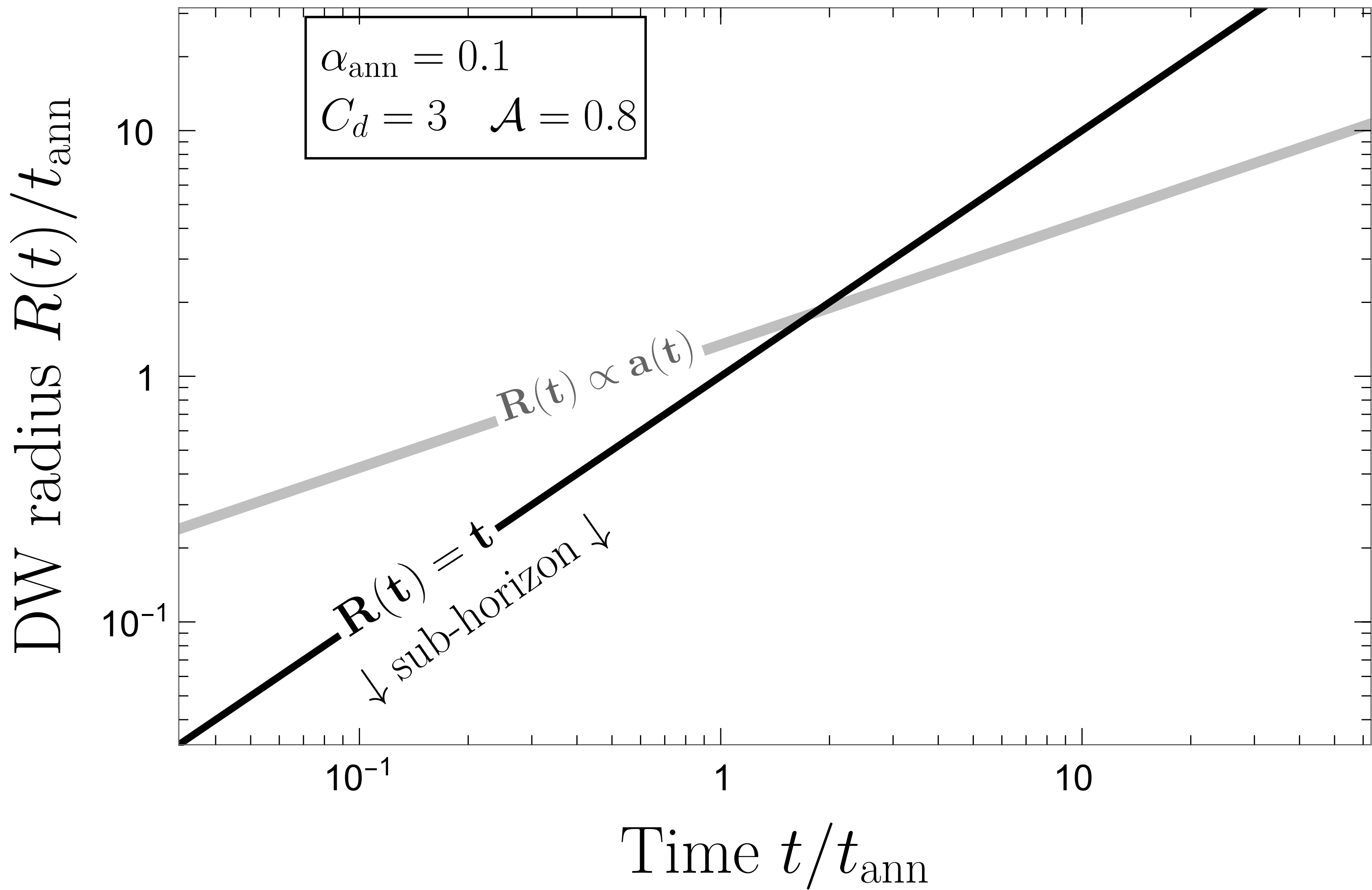
Berezin, Kuzmin, and Tkachev, (1983)
Deng, Vilenkin, (2016)
Gouttenoire, Vitagliano, 2311.07670



Go back to basics:
$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = - \left(\frac{V_{\text{bias}}}{\sigma} + 6\pi\sigma \right) \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

$$R(t) = a(t)\chi(t)$$

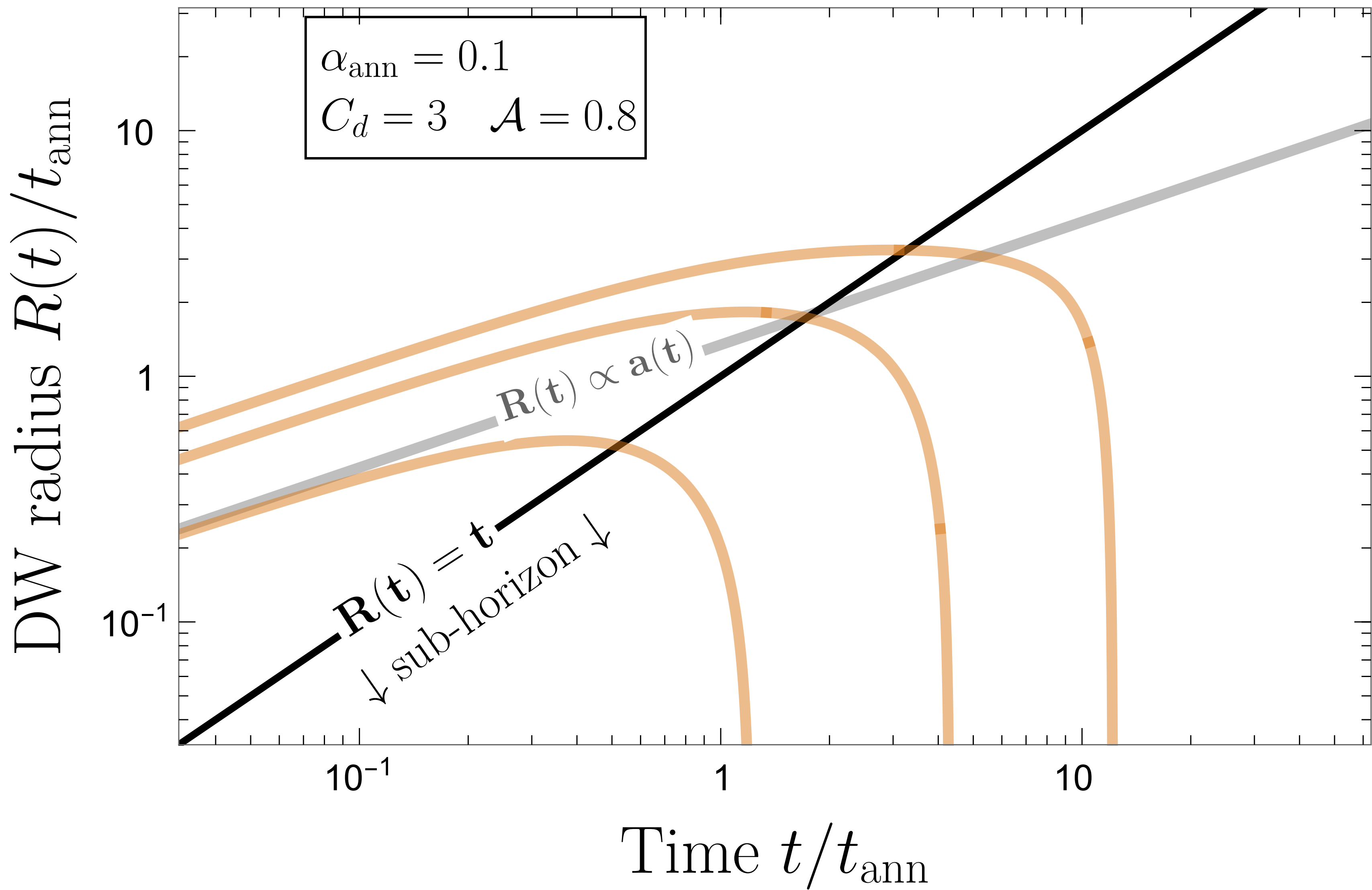
Berezin, Kuzmin, and Tkachev, (1983)
Deng, Vilenkin, (2016)
Gouttenoire, Vitagliano, 2311.07670



Go back to basics:
$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = - \left(\frac{V_{\text{bias}}}{\sigma} + 6\pi\sigma \right) \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

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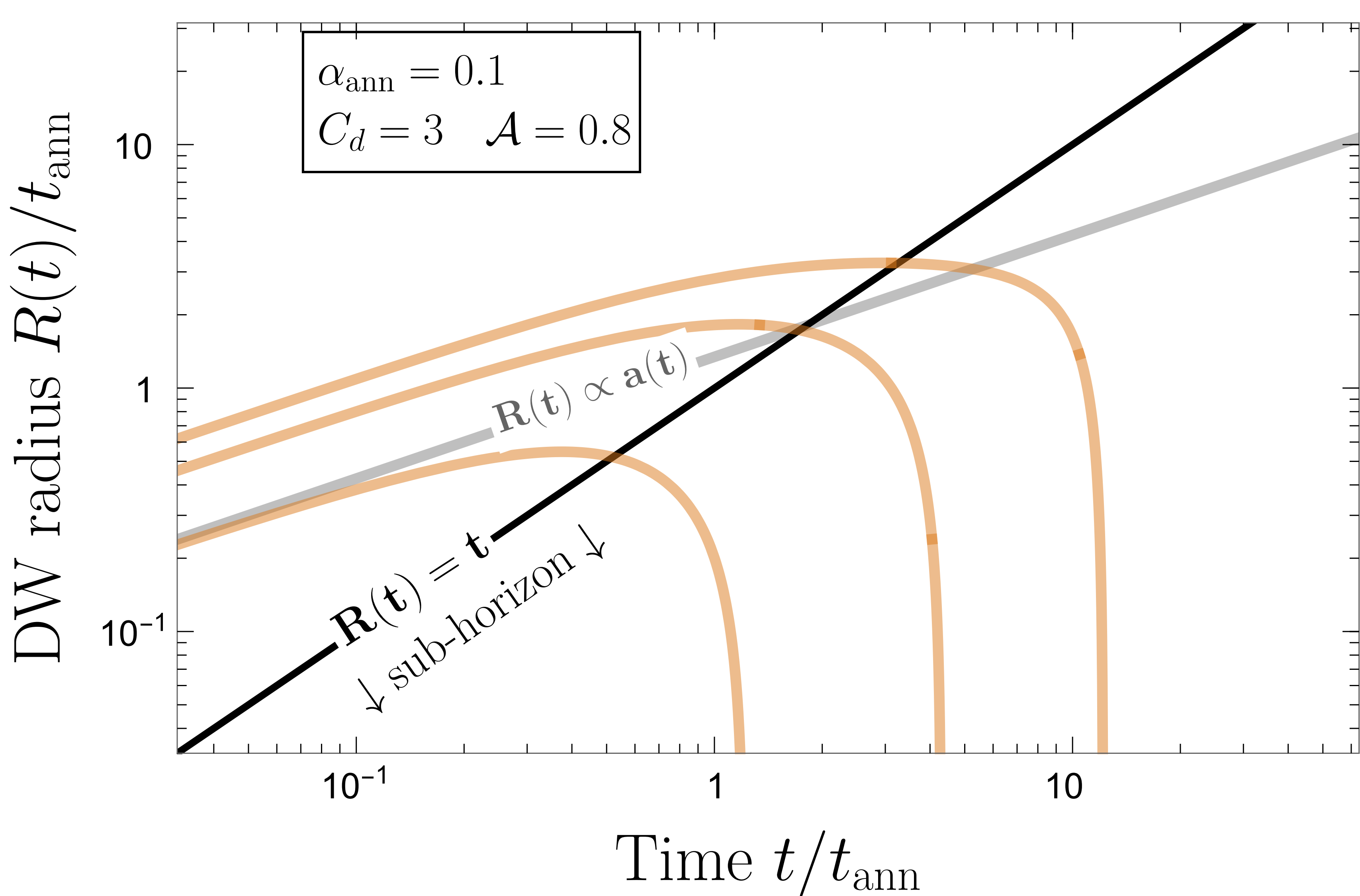


$$R(t) \propto \begin{cases} a(t), & \text{if } R > t, \\ e^{-\Gamma t}, & \text{if } R < t. \end{cases}$$

Go back to basics:
$$\ddot{\chi} + (4 - 3a^2\dot{\chi}^2)H\dot{\chi} + \frac{2}{a^2\chi}(1 - a^2\dot{\chi}^2) = - \left(\frac{V_{\text{bias}}}{\sigma} + 6\pi\sigma \right) \frac{(1 - a^2\dot{\chi}^2)^{3/2}}{a}$$

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Result:

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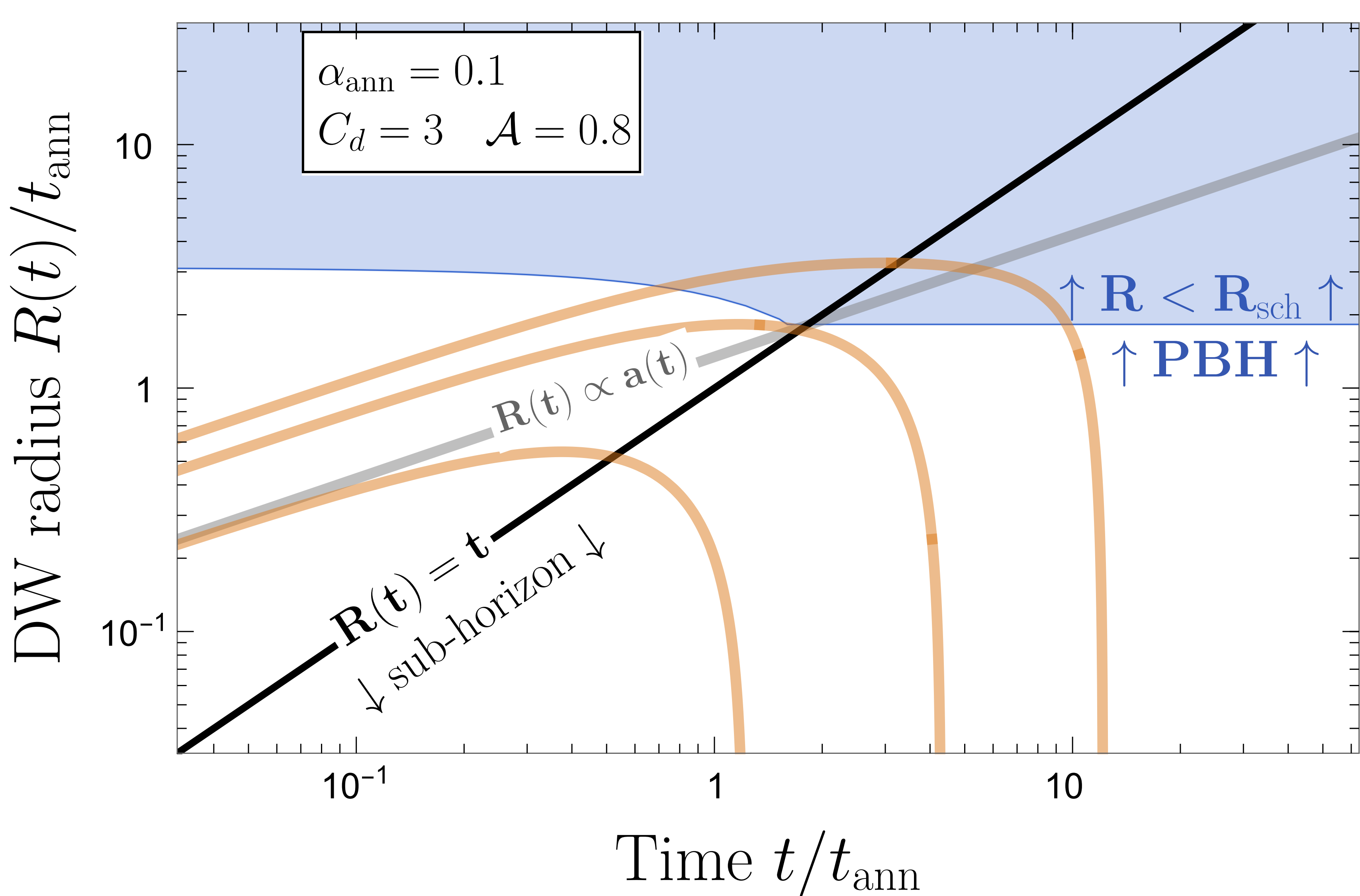
~~Assumption: $R(t) \simeq t$~~

2018: Ferrer, Masso, Panico, Pujolas, Rompineve, Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707
2022: G. B. Gelmini, A. Simpson, and E. Vitagliano, 2207.07126, JCAP 02, 03,
2023: G. B. Gelmini, J. Hyman, A. Simpson, and E. Vitagliano, 2303.14107
2023: YG, E. Vitagliano, 2306.17841 (version 1)

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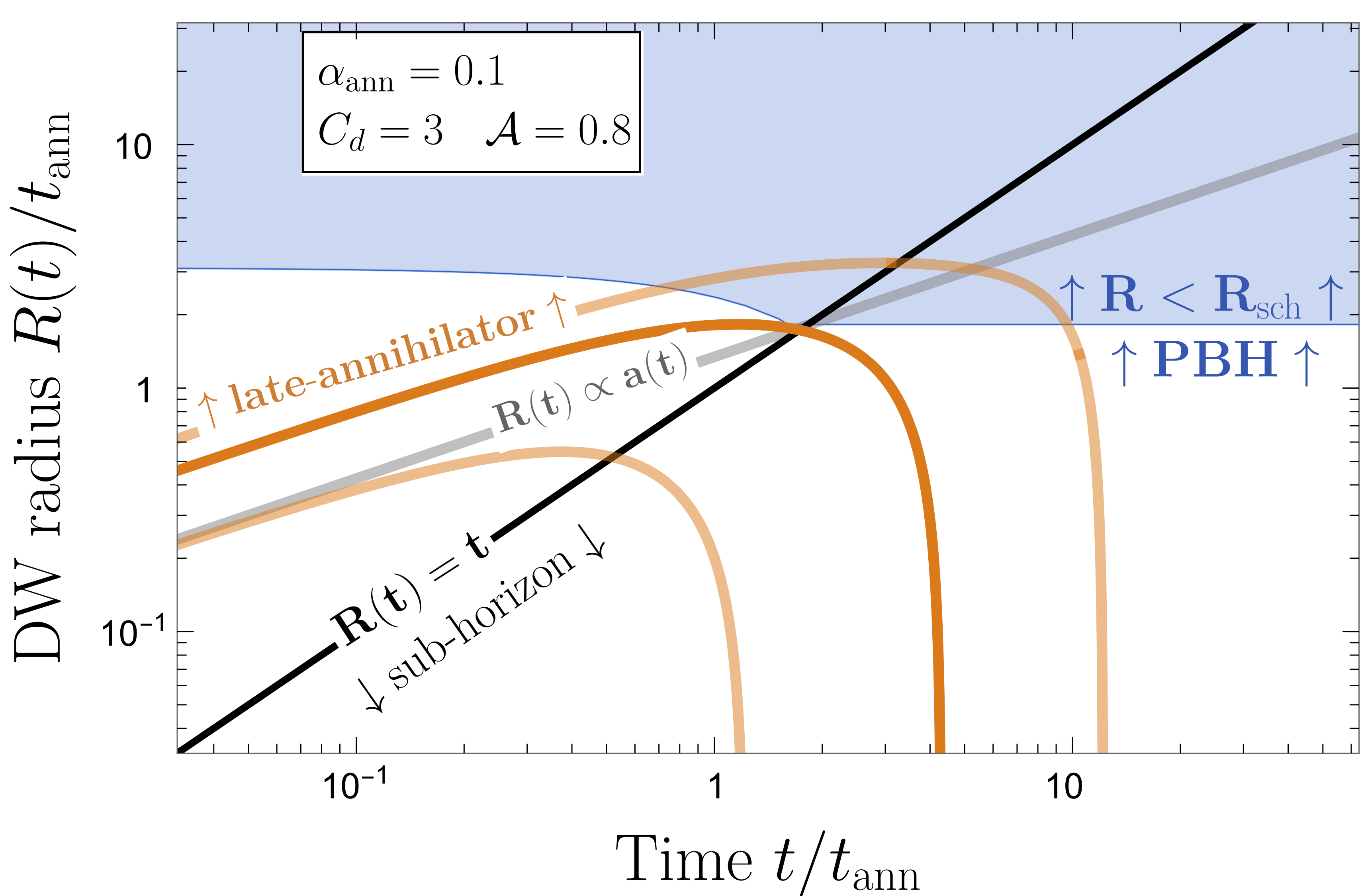
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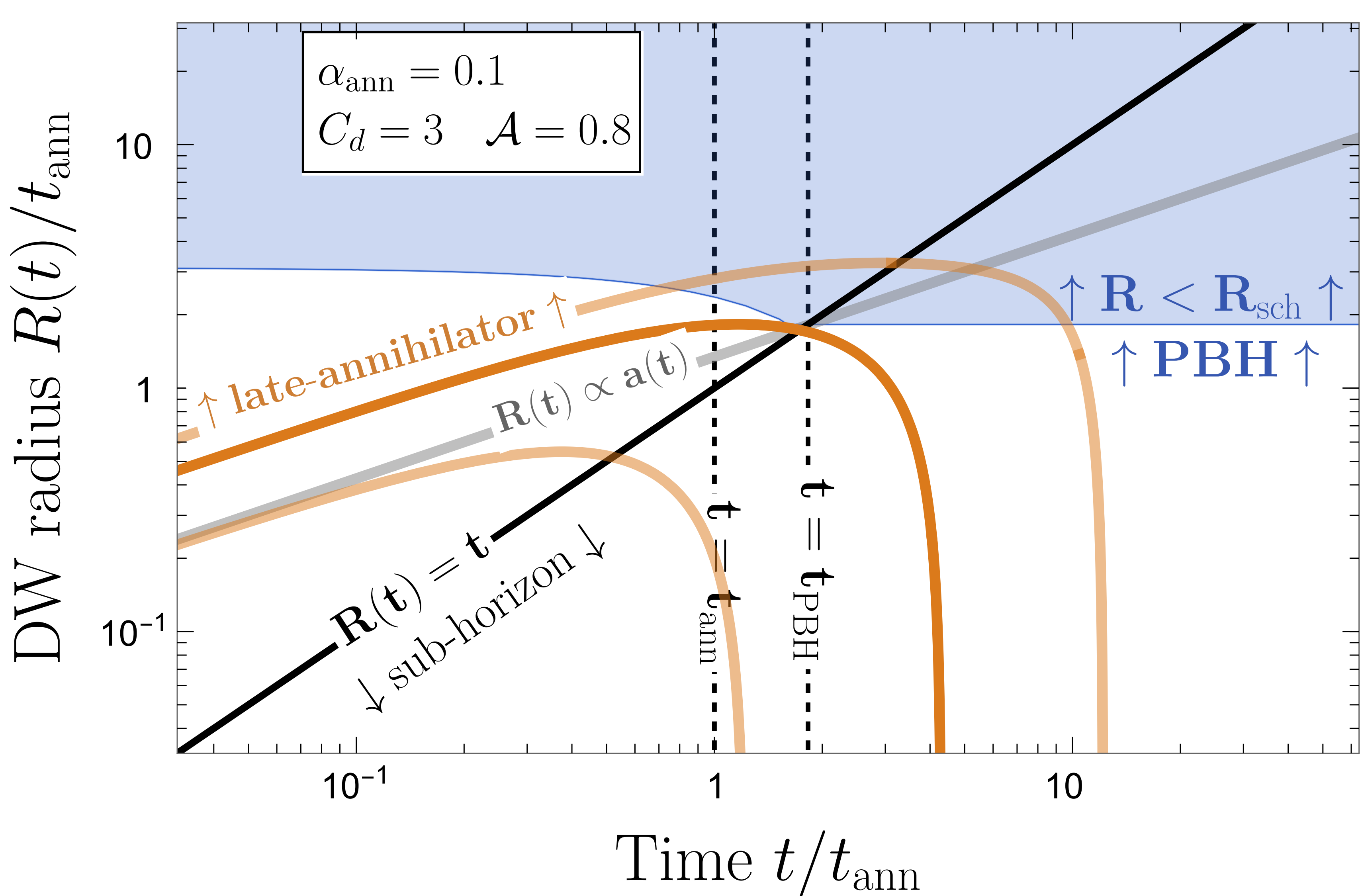
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DW radius R



t

$\uparrow$ super-horizon $\uparrow$
 $R(t) = t$

DW radius R



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$R(t) \simeq t$

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101301, 1807.01707

2022: G. B. Gelmini, A. Simpson, and E.
Vitagliano, 2207.07126, JCAP 02, 031,

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t

DW radius R

Gouttenoire, Vitagliano, [2311.07670](#)
→ Solve thin DW in full General Relativity

↑ super-horizon ↑
 $R(t) = t$

~~$R(t) \simeq t$~~

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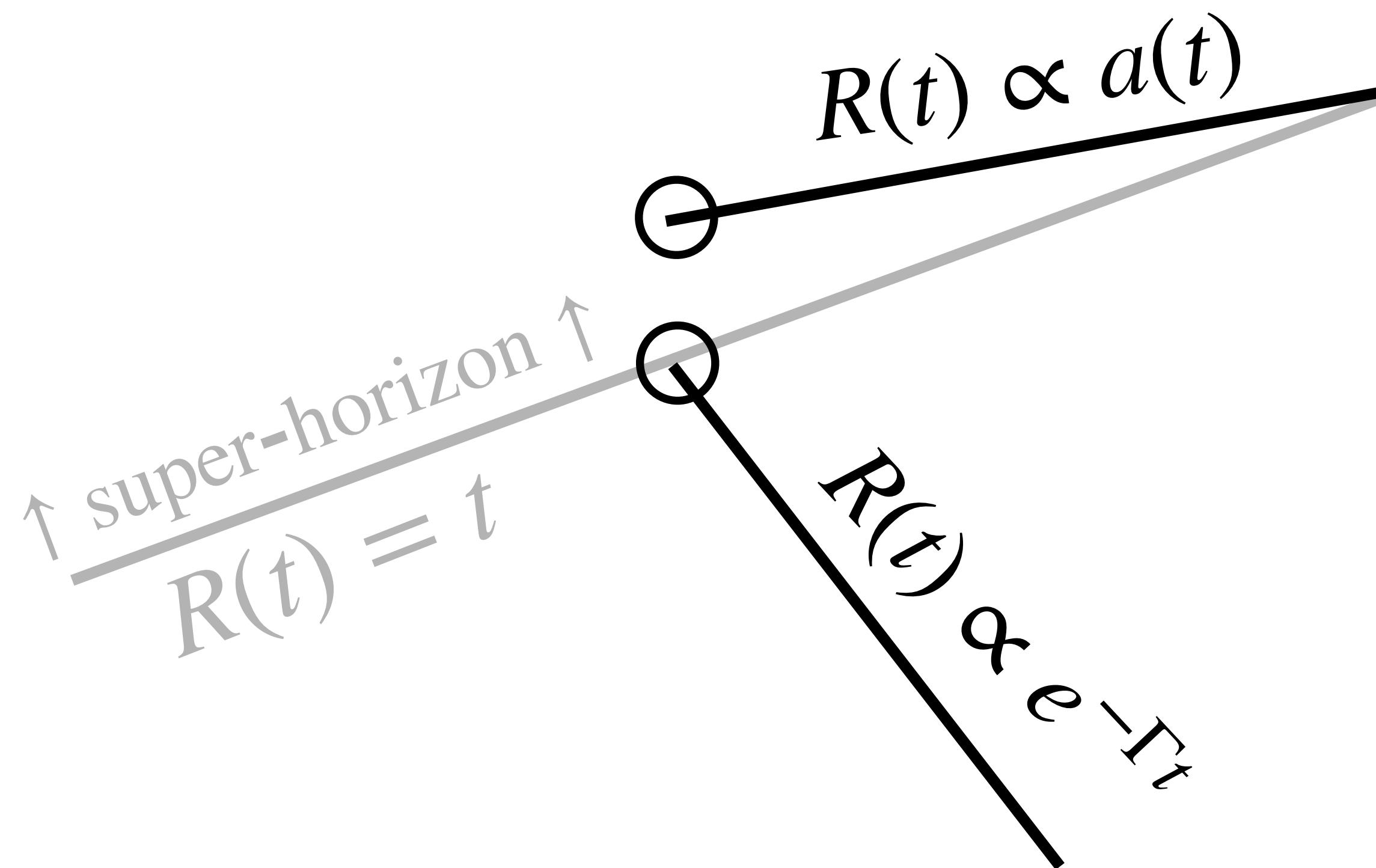
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t

DW radius R

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity



DW radius R

Gouttenoire, Vitagliano, [2311.07670](#)

→ Solve thin DW in full General Relativity

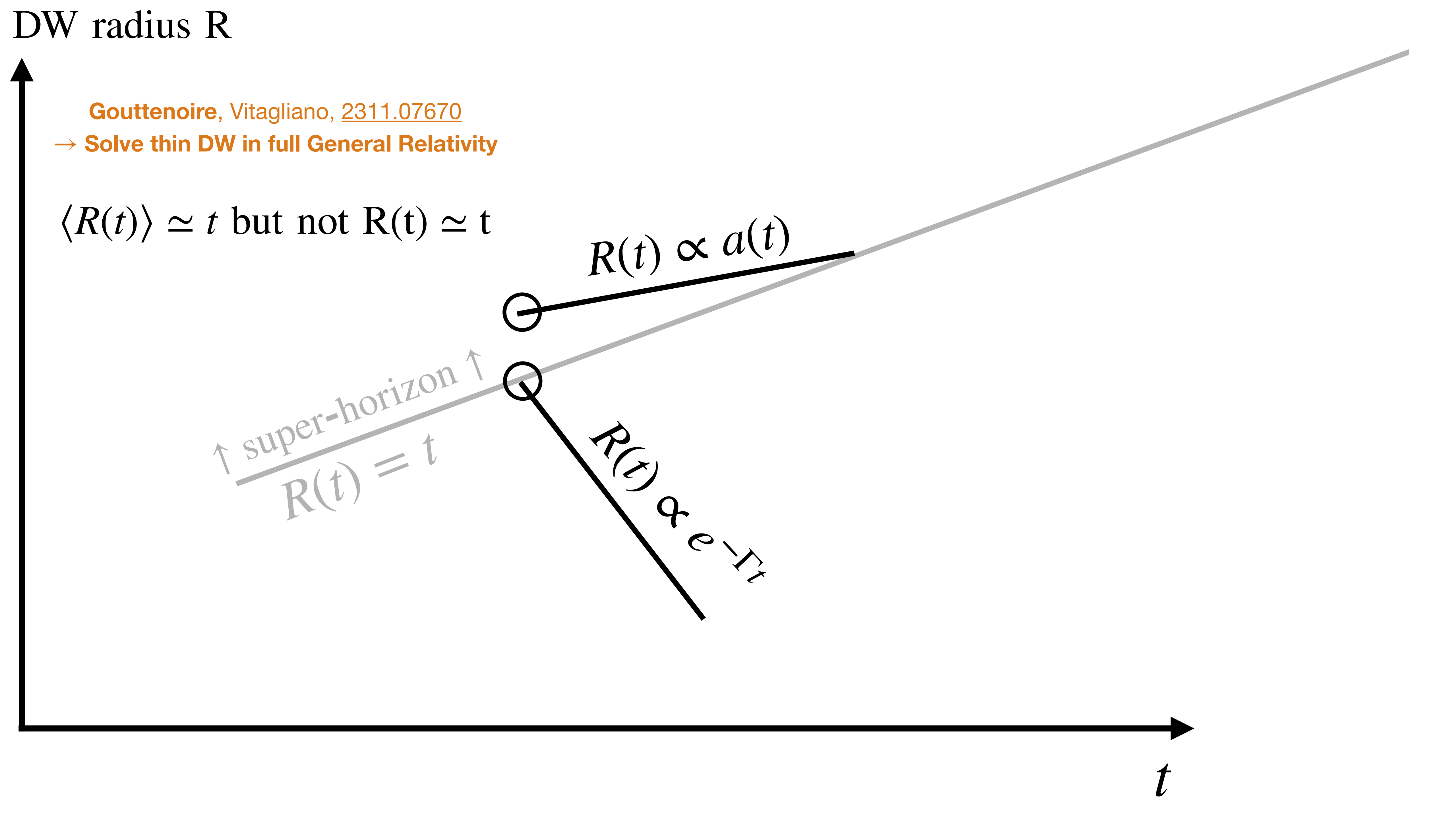
$\langle R(t) \rangle \simeq t$ but not $R(t) \simeq t$

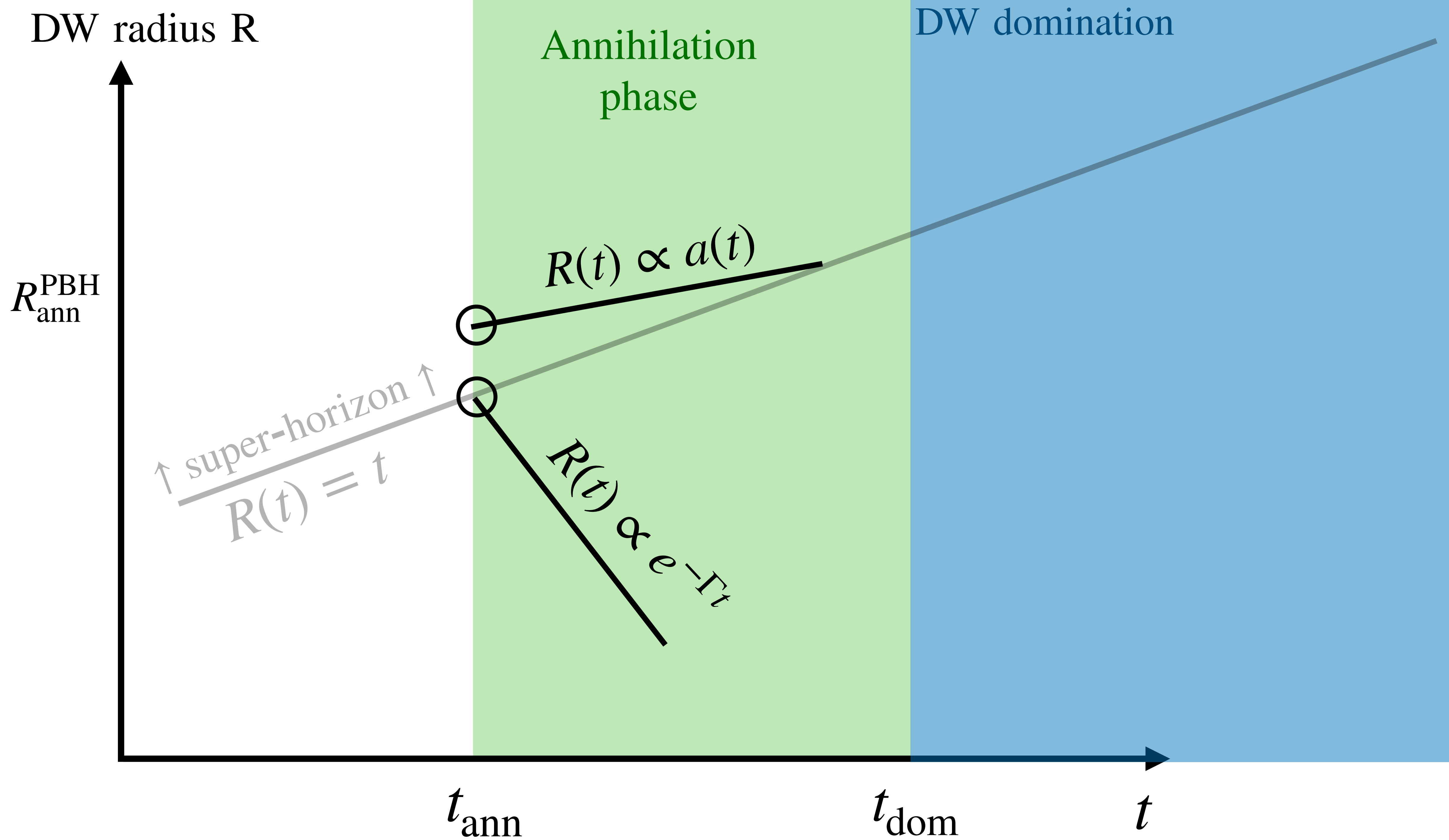
↑ super-horizon ↑
 $R(t) = t$

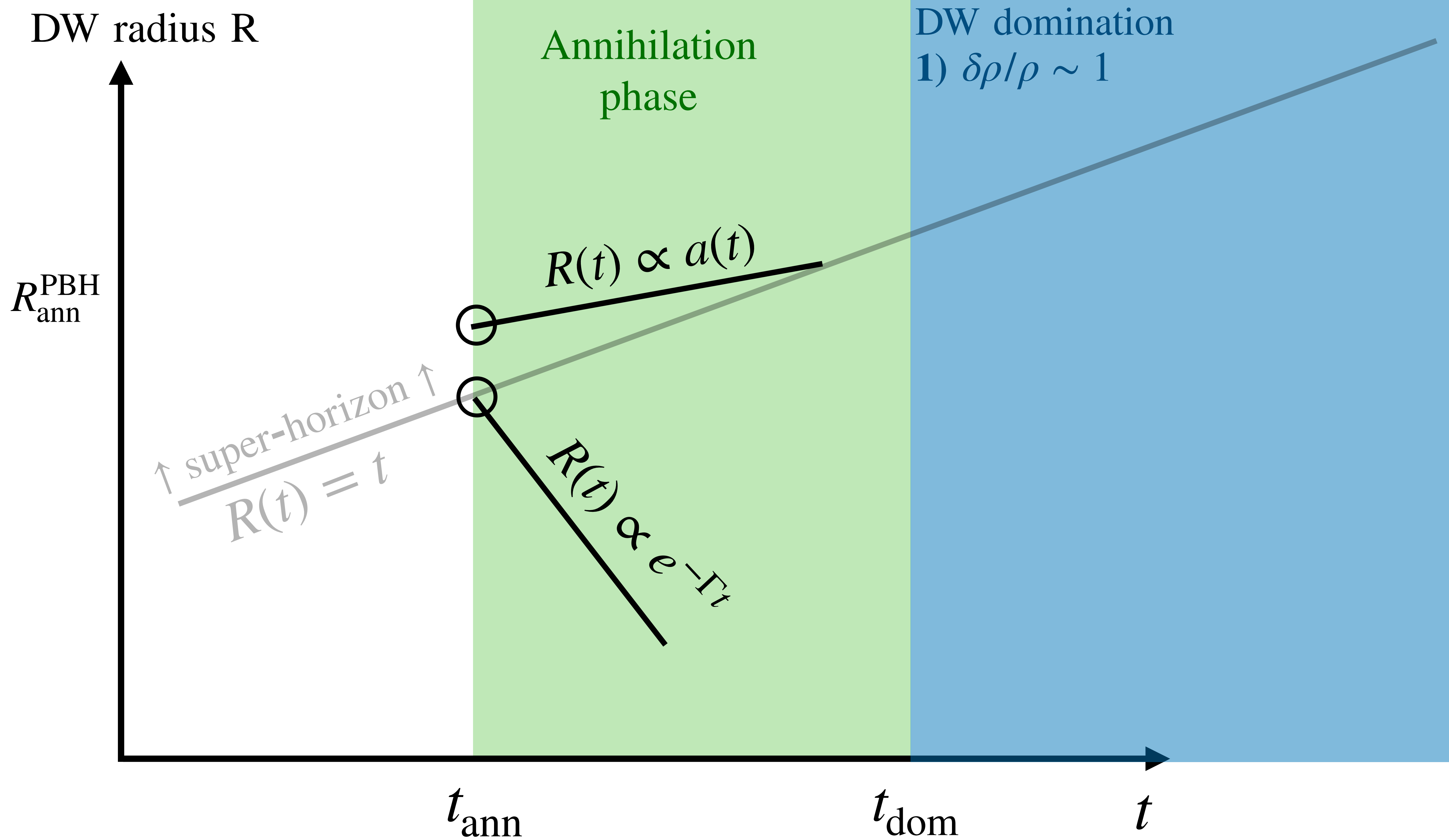
$R(t) \propto a(t)$

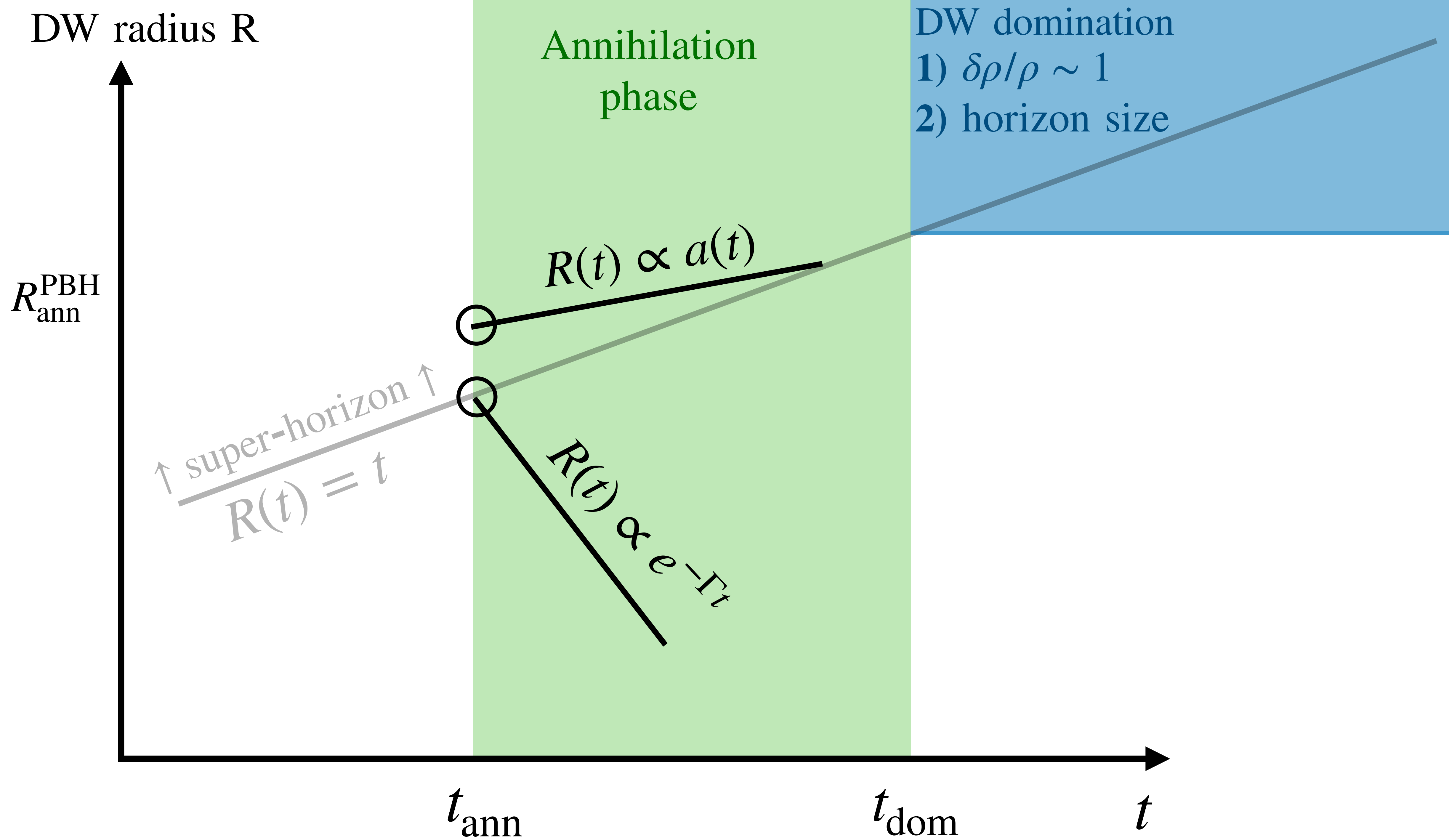
$R(t) \propto e^{-\Gamma t}$

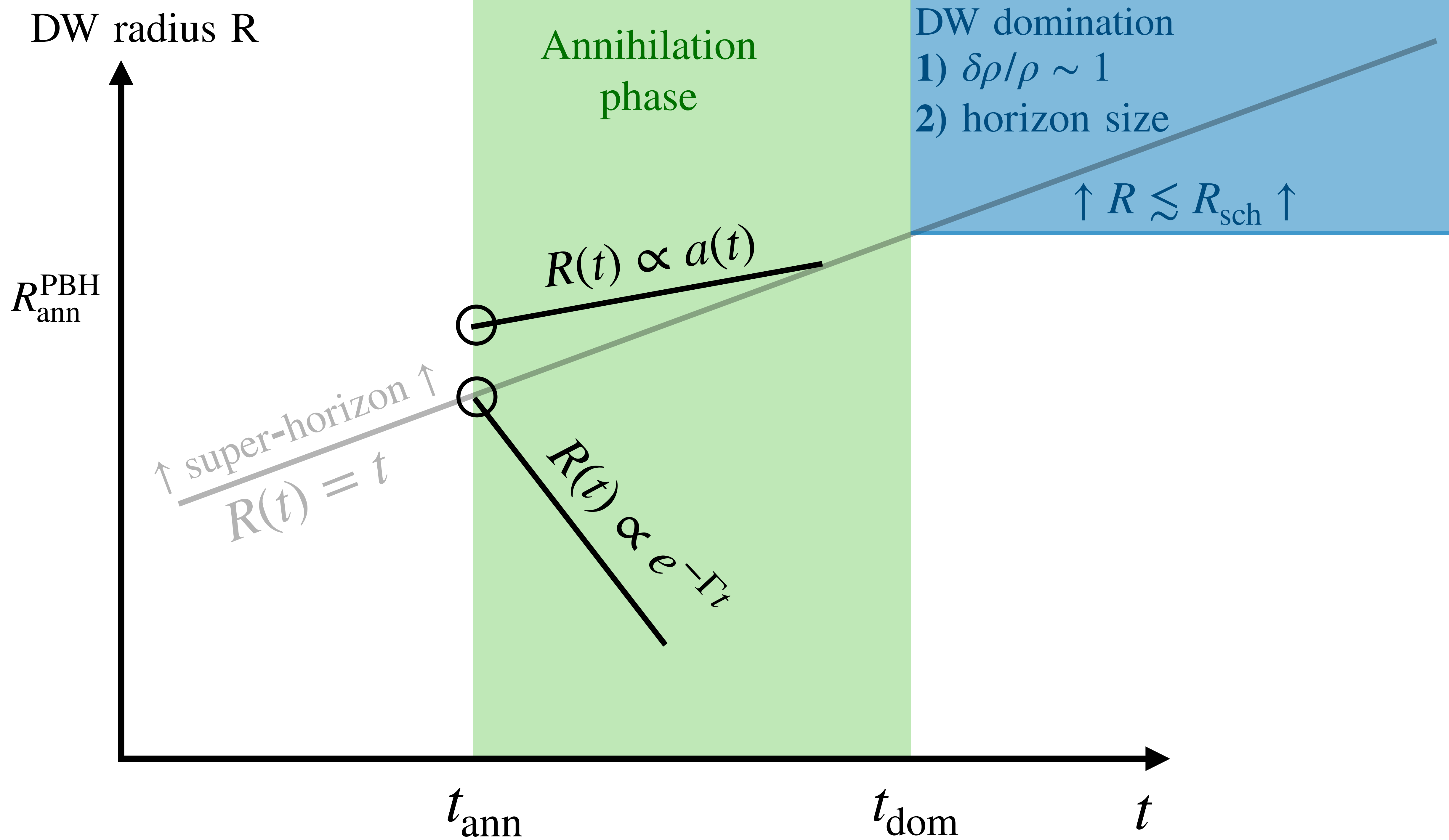
t

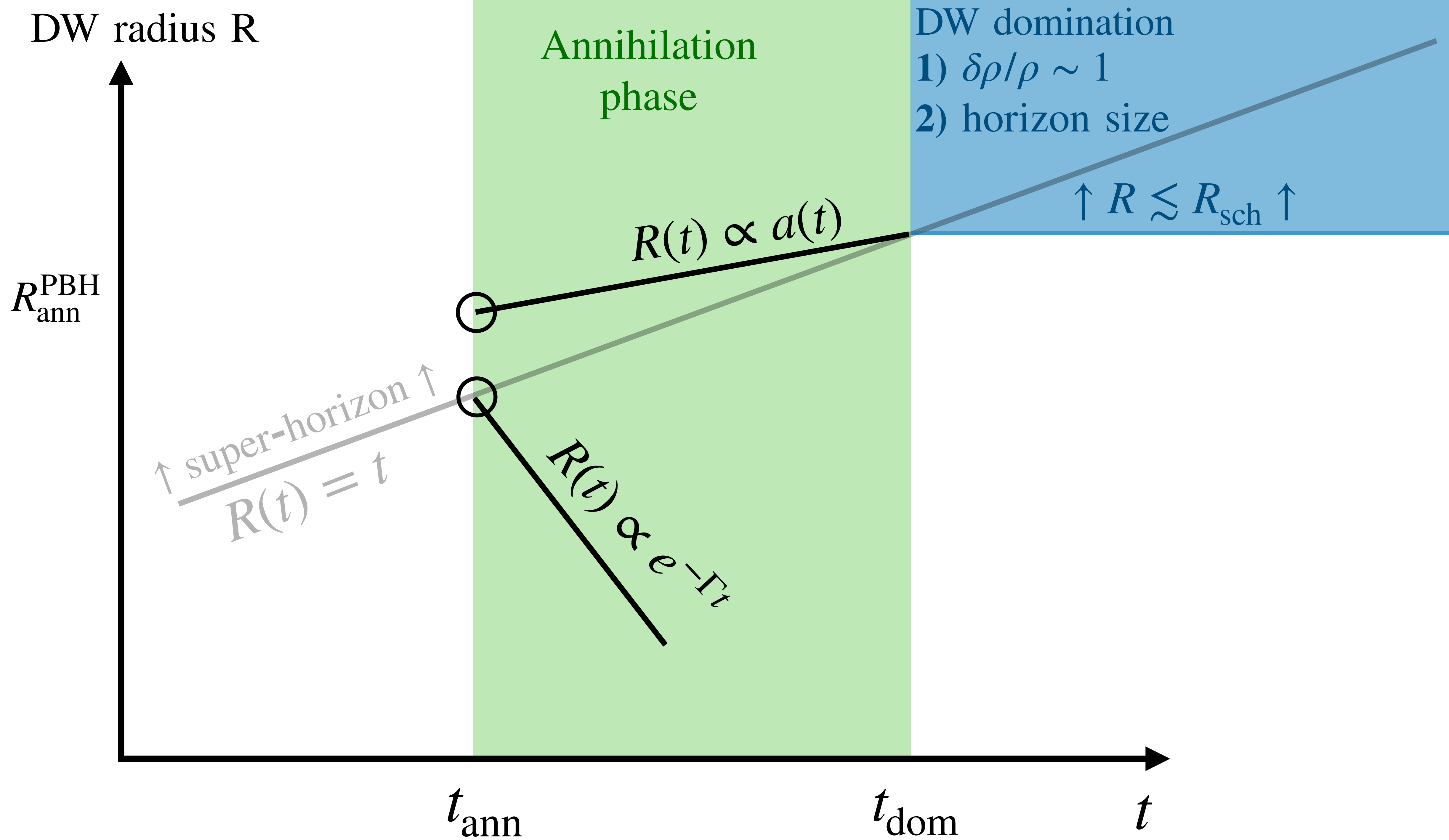


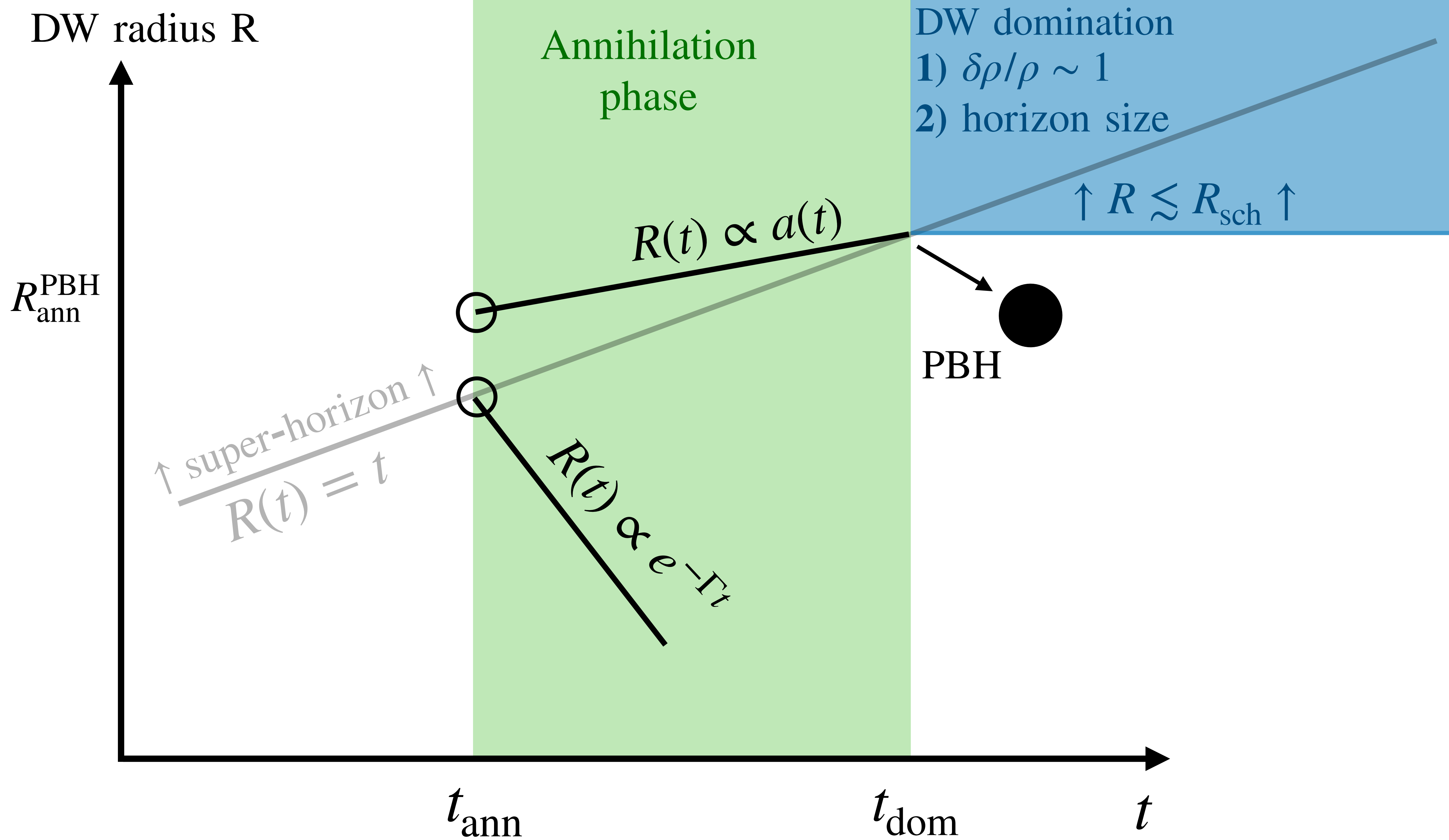


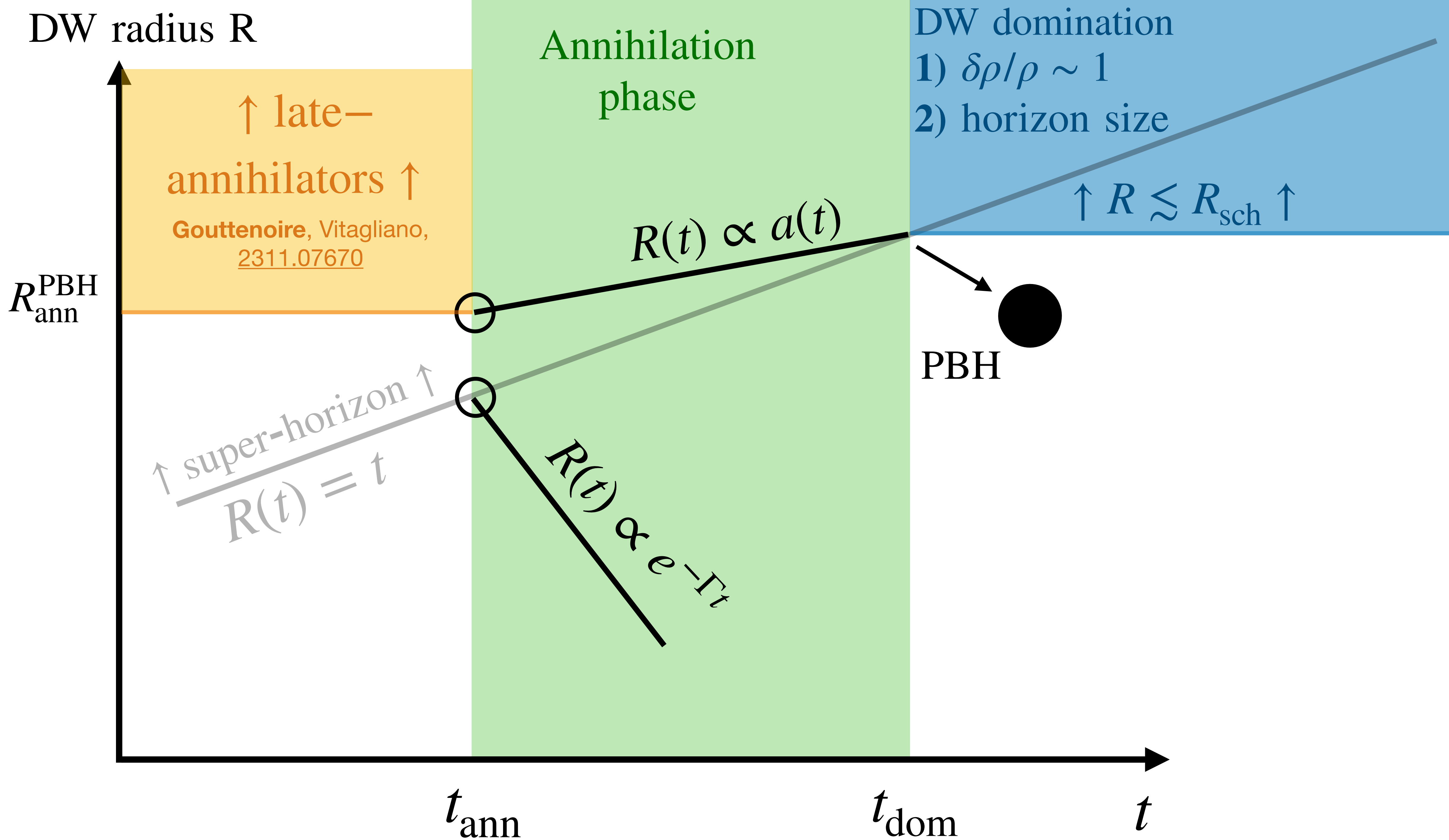


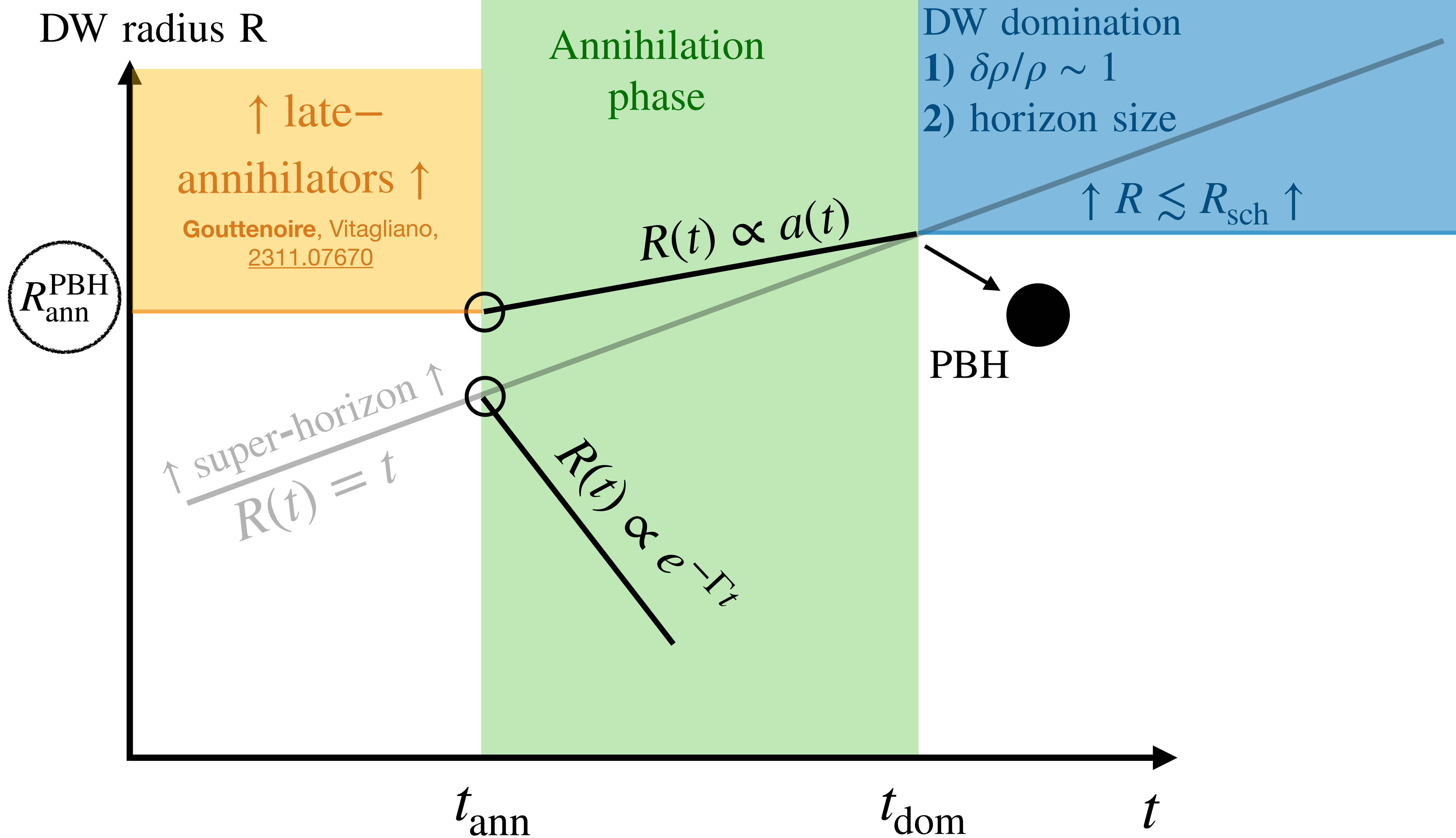




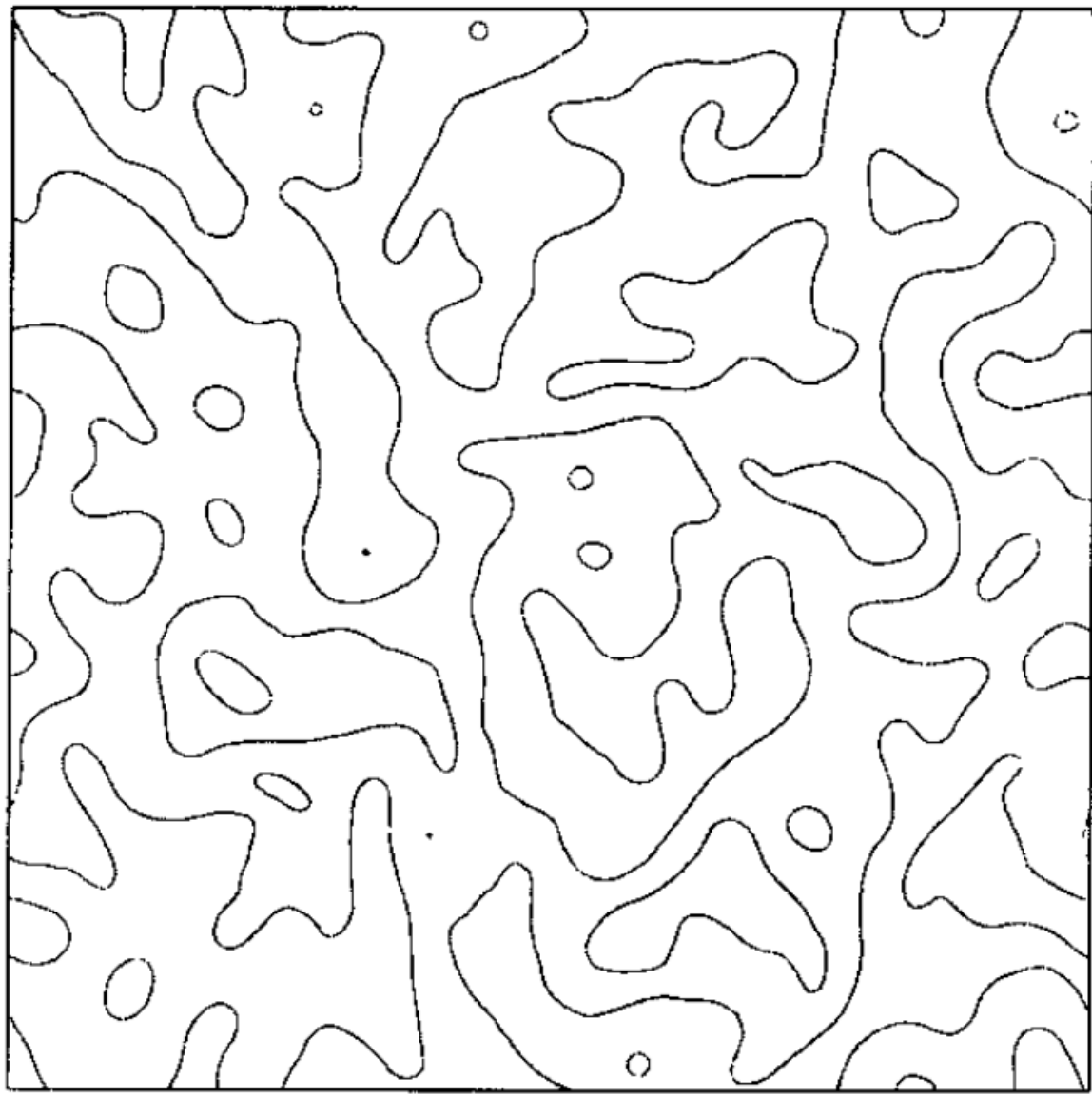








Abundance of late-annihilators $\mathcal{F}$



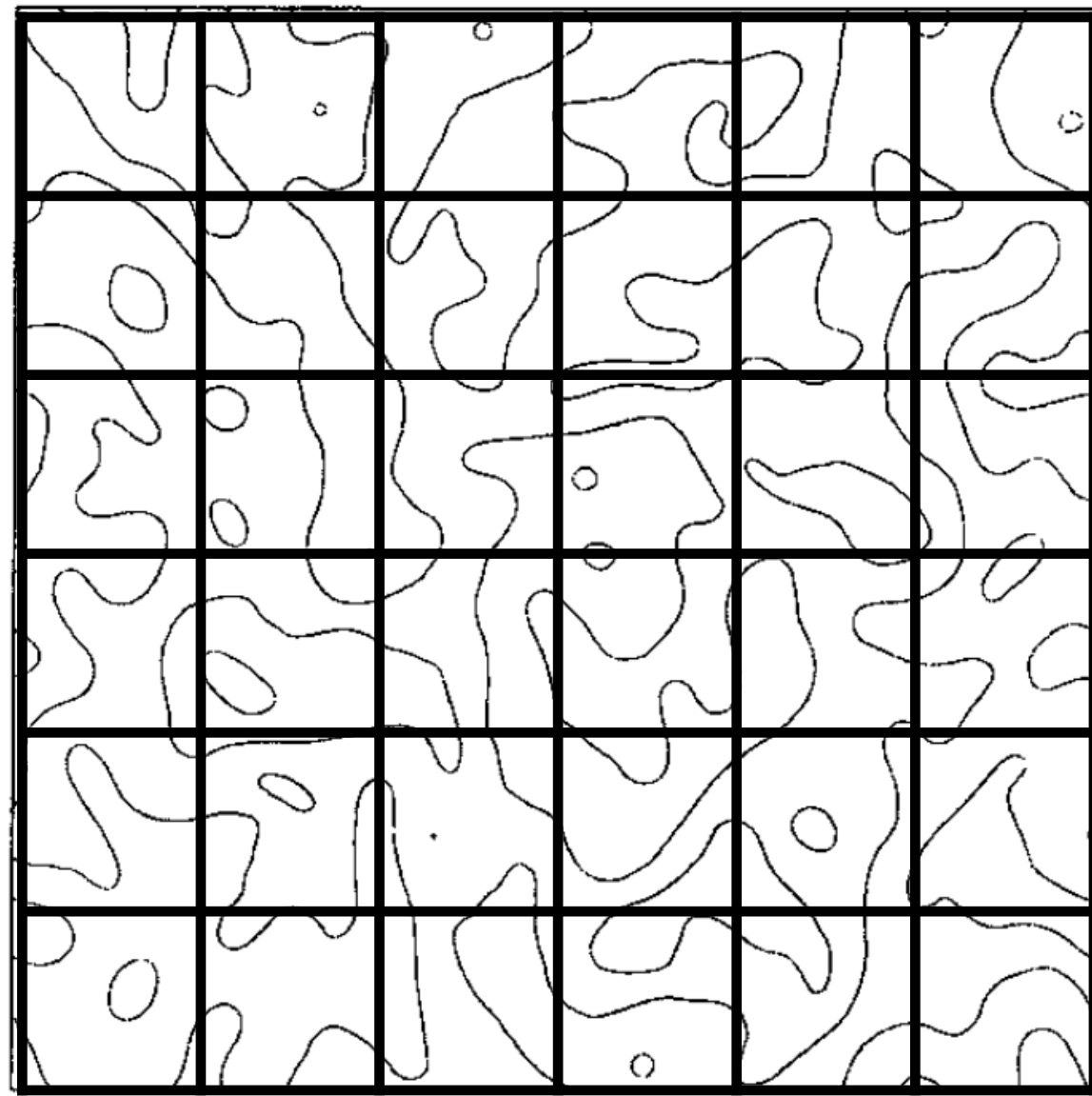
Vilenkin&Shellard 2000

Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

Stauffer (1979)

Coulson, Lalak, Ovrut (1995)



Vilenkin&Shellard 2000



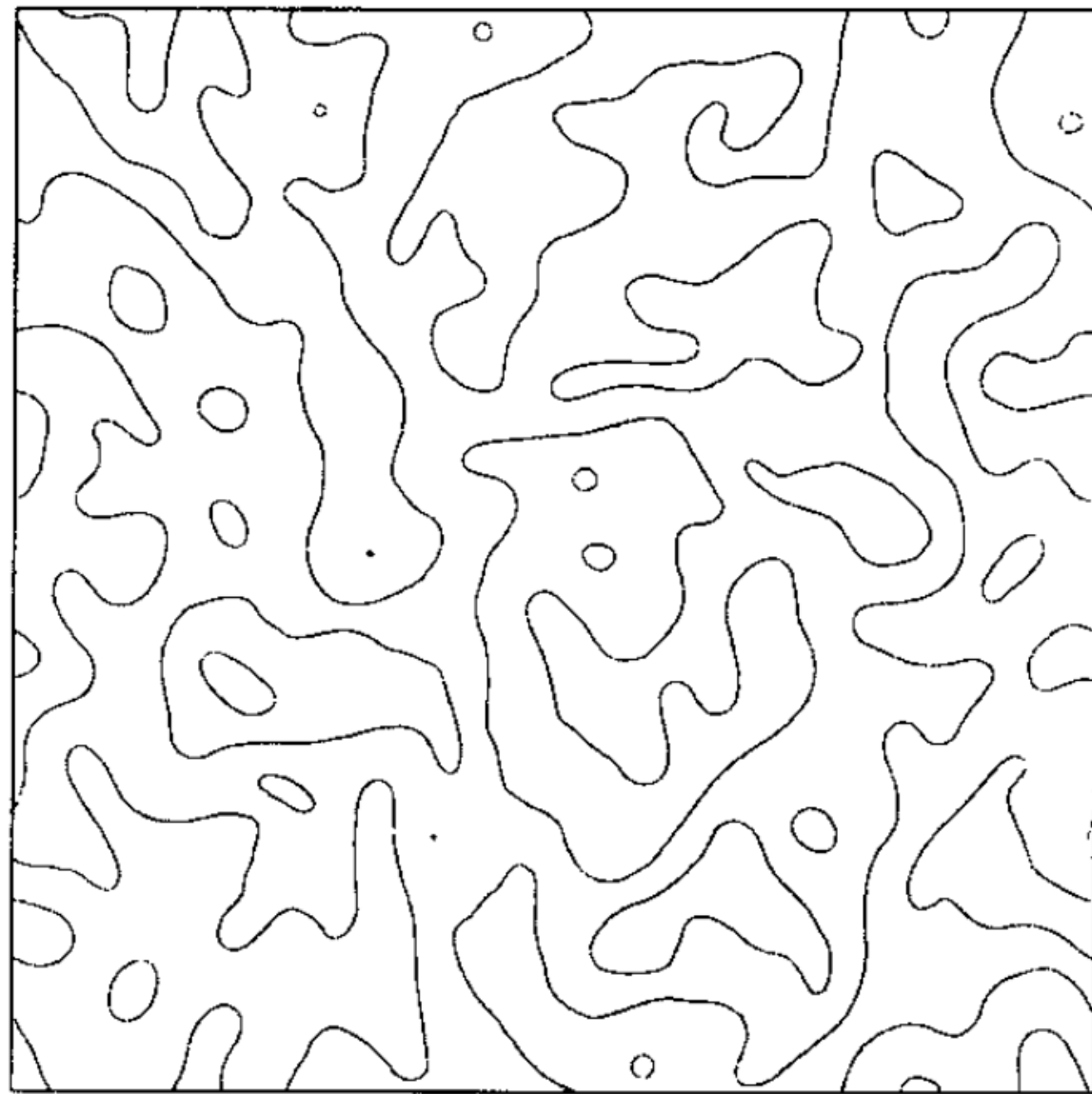
$$L \sim t$$

Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

Stauffer (1979)

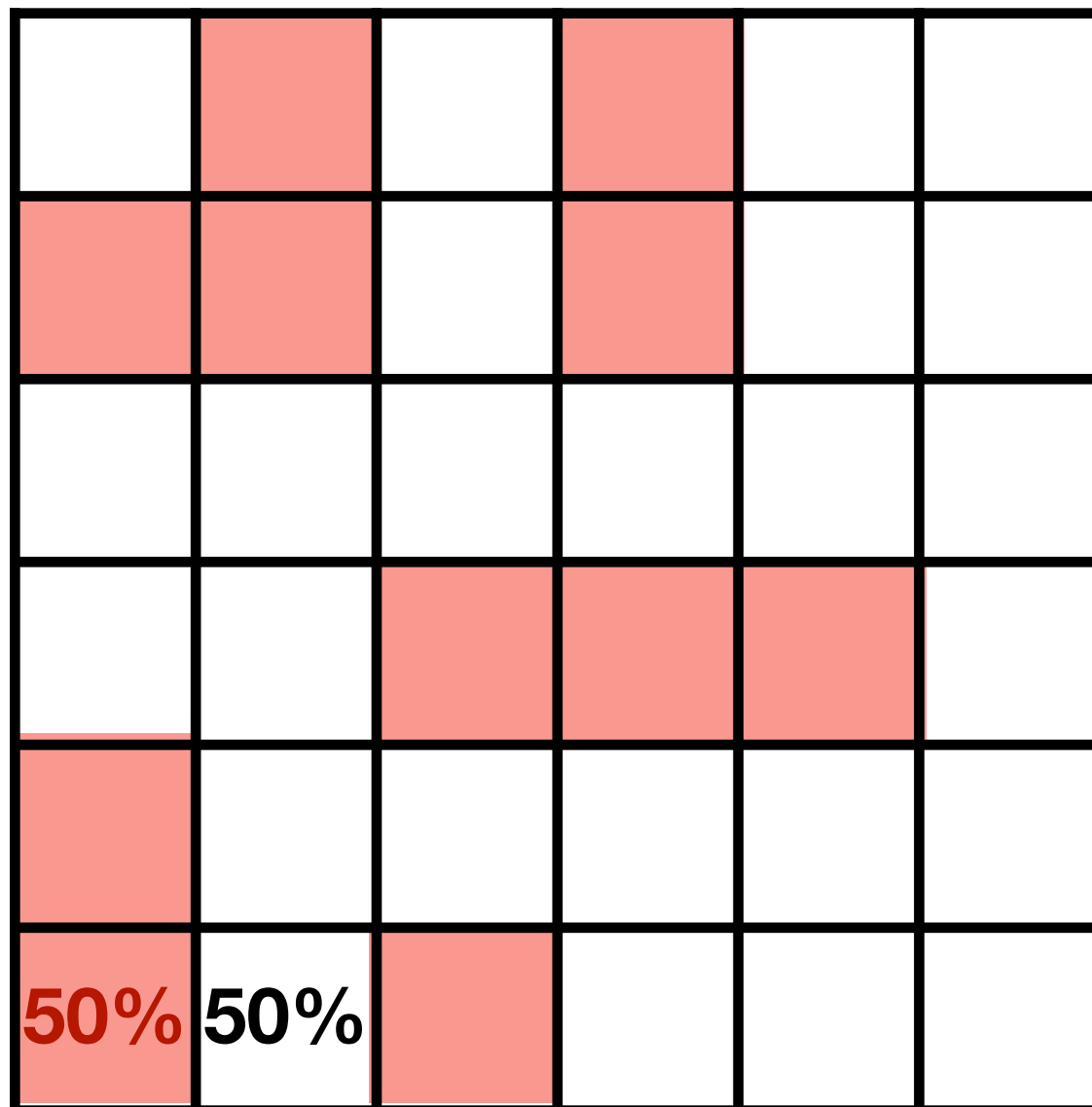
Coulson, Lalak, Ovrut (1995)



Vilenkin&Shellard 2000

$L \sim t$

Discretization

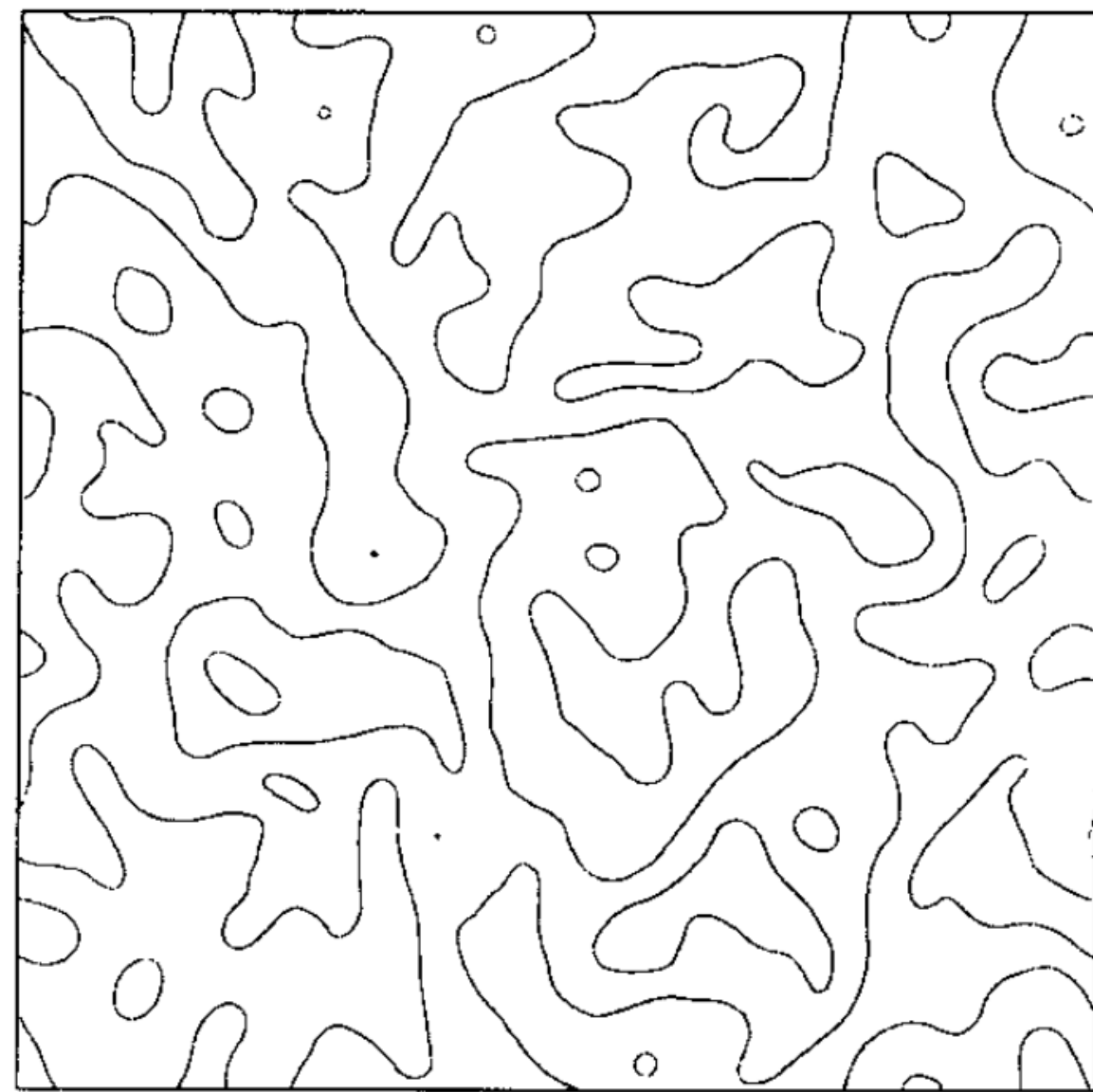


Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

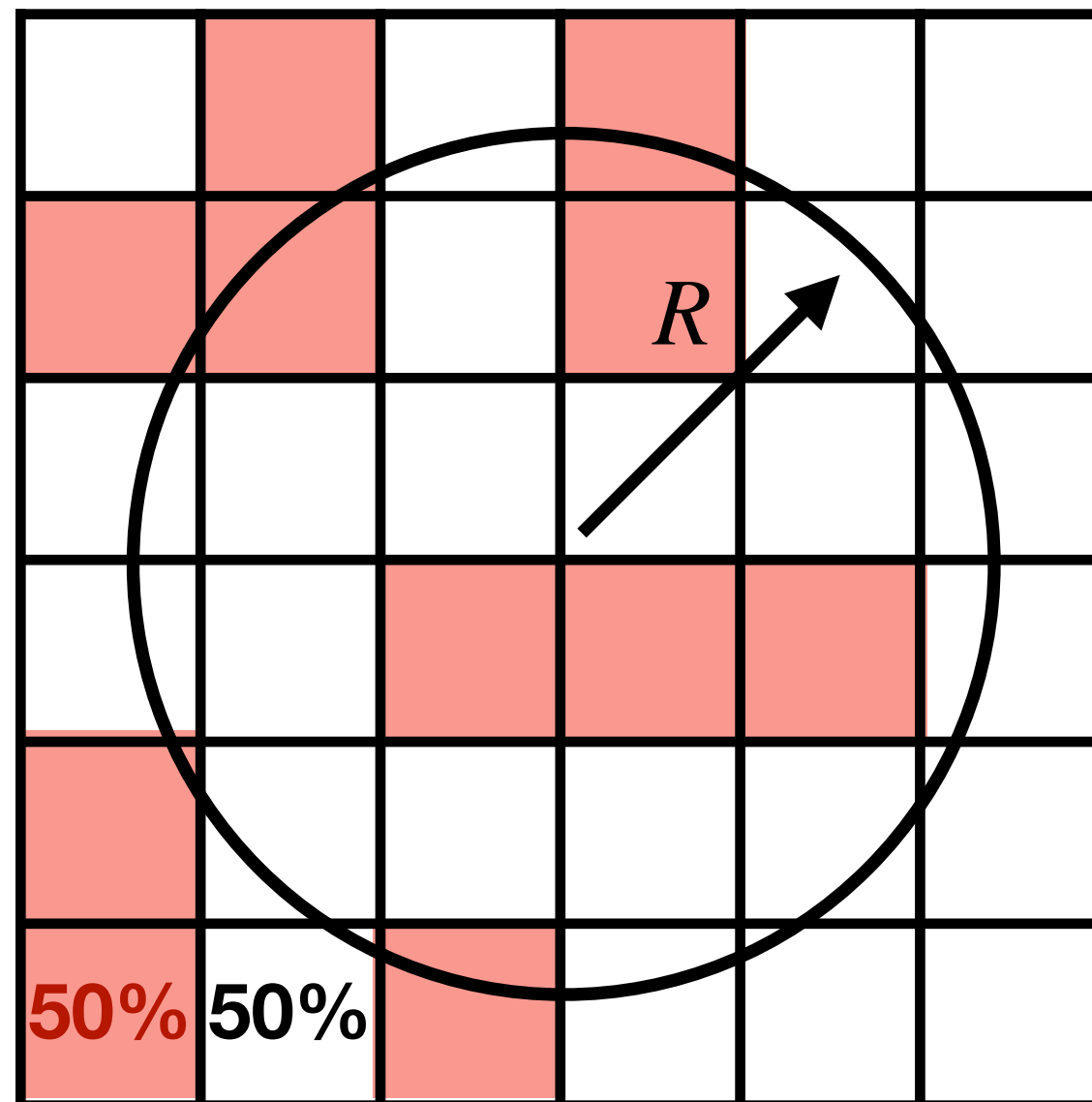
Stauffer (1979) Coulson, Lalak, Ovrut (1995)

Probability of a spherical false vacuum domain of size R :



Vilenkin&Shellard 2000

$L \sim t$
Discretization



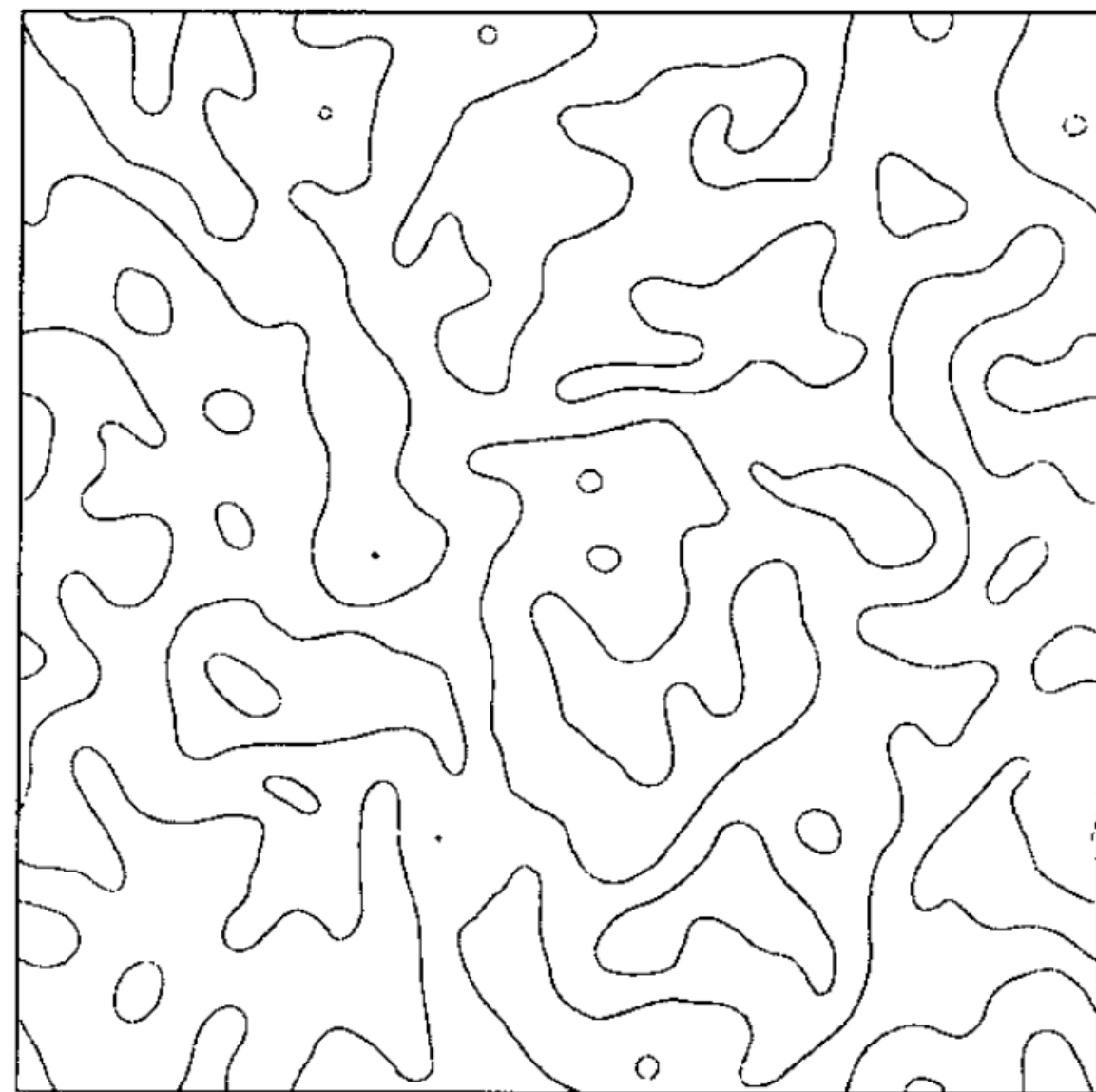
Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

Stauffer (1979)

Coulson, Lalak, Ovrut (1995)

Probability of a spherical false vacuum domain of size R :

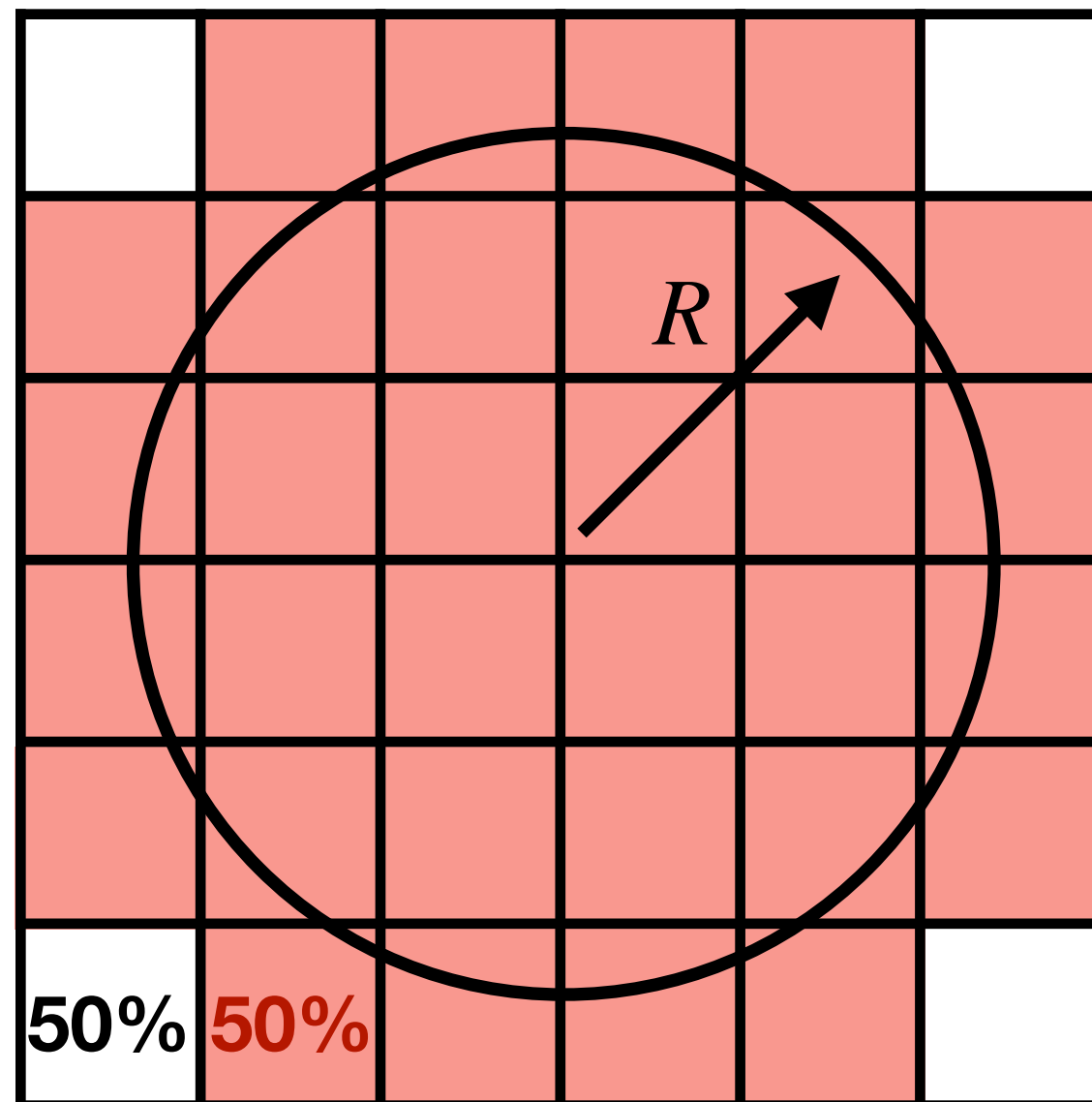


Vilenkin&Shellard 2000

$L \sim t$



Discretization



Abundance of late-annihilators $\mathcal{F}$

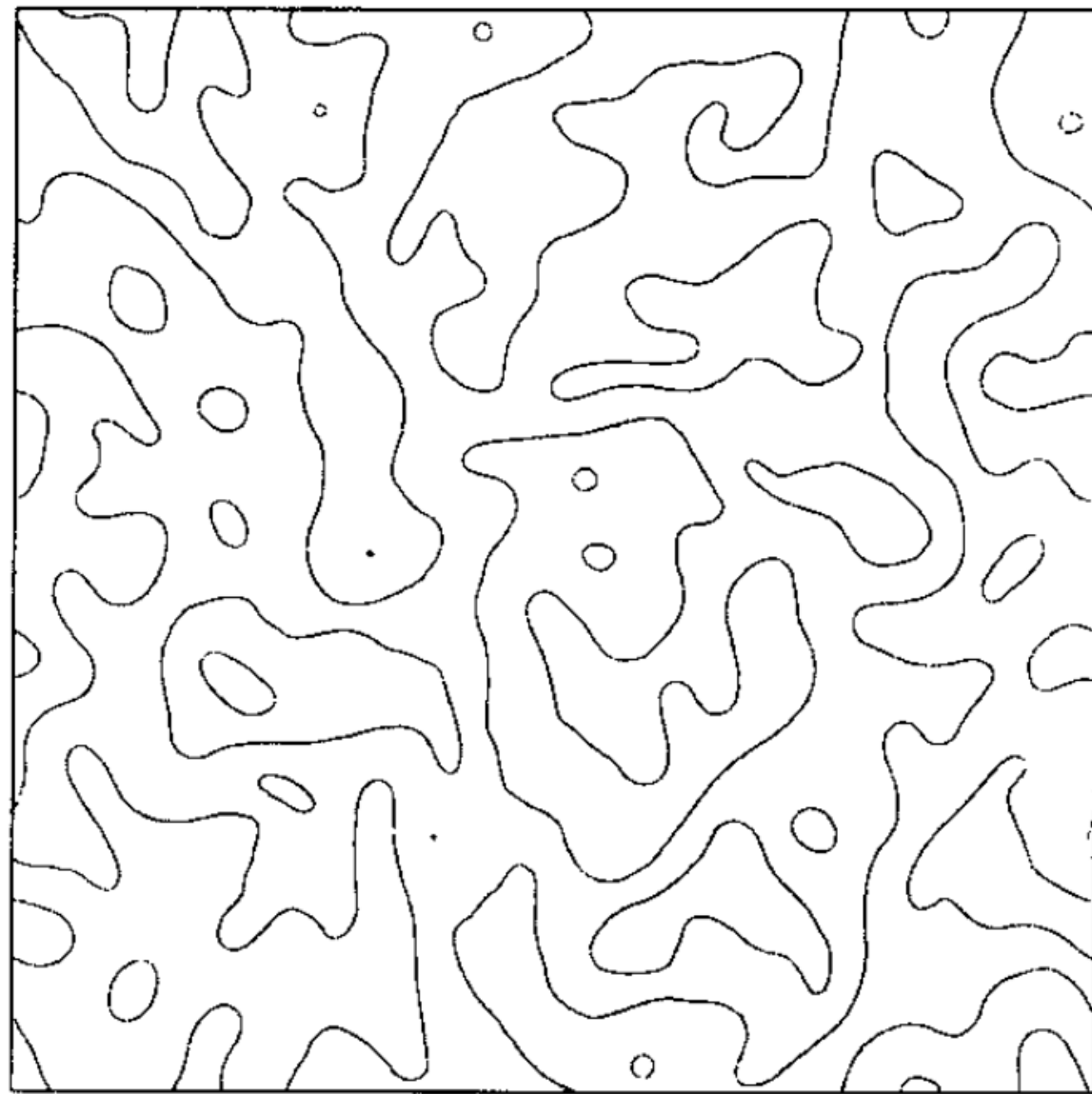
Percolation theory on a lattice

Stauffer (1979)

Coulson, Lalak, Ovrut (1995)

Probability of a spherical false vacuum domain of size R :

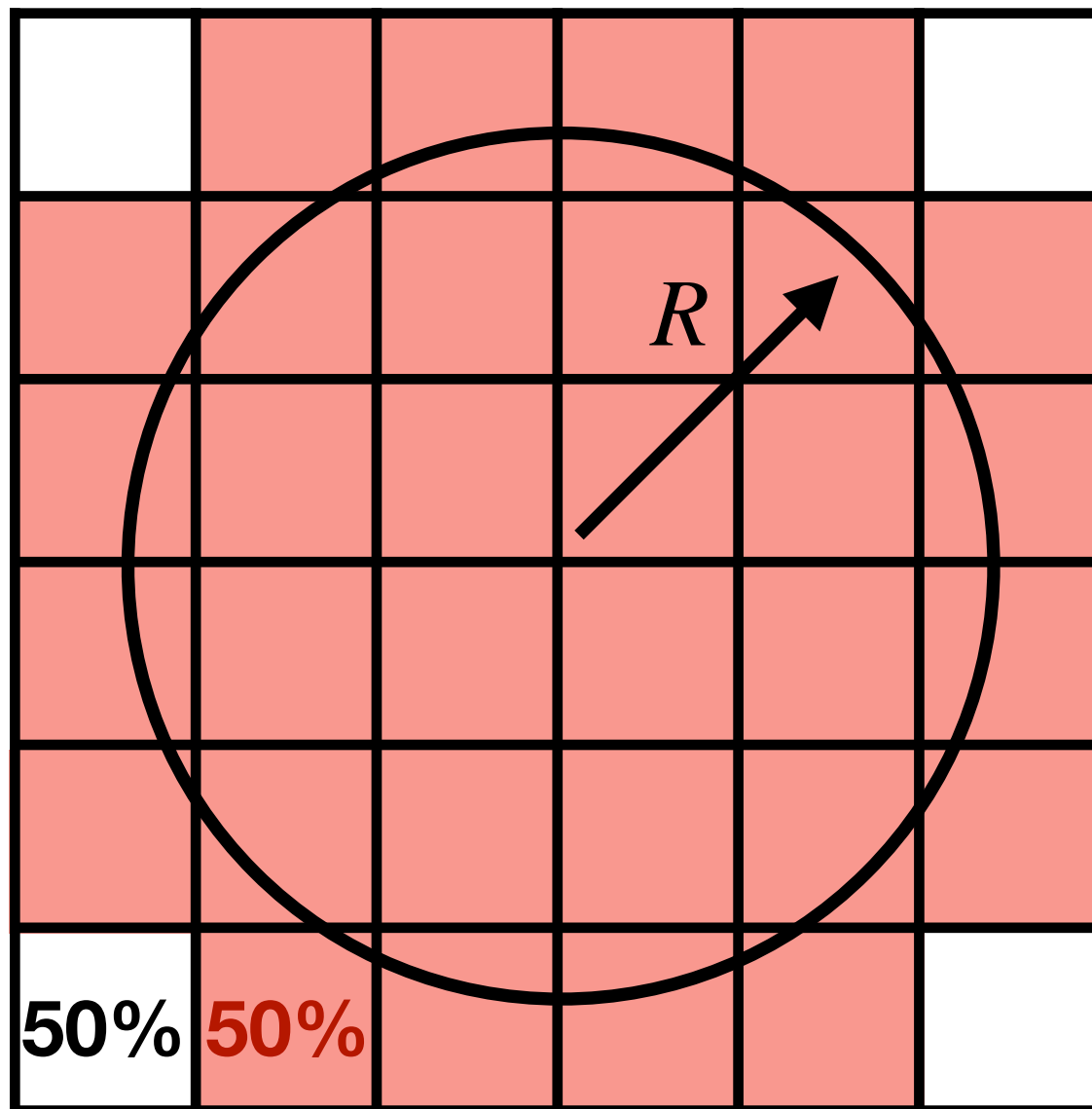
$$\mathcal{F}(R) \simeq (50\%)^{\text{number of sites}}$$



Vilenkin&Shellard 2000

$L \sim t$

Discretization



Abundance of late-annihilators $\mathcal{F}$

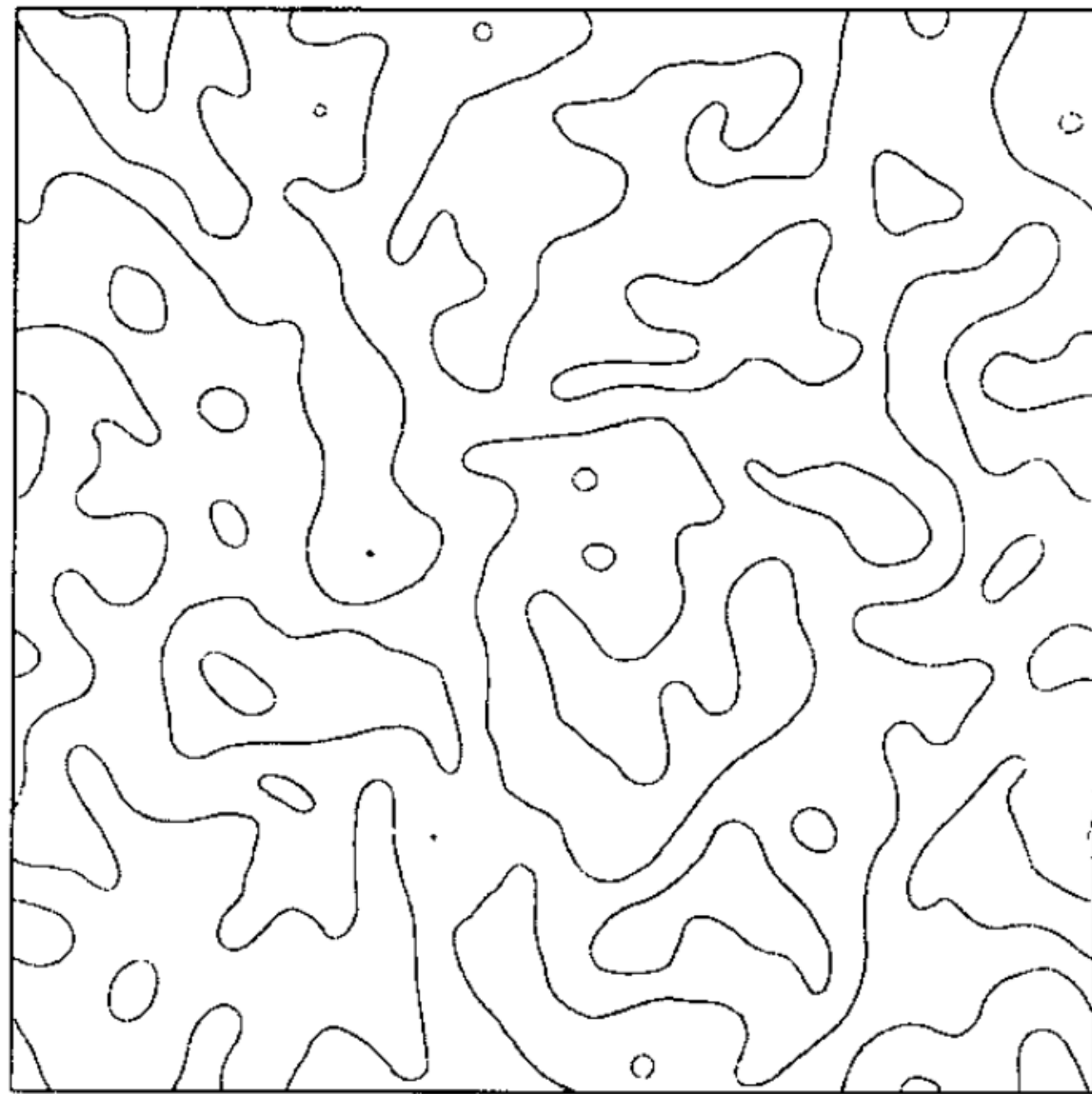
Percolation theory on a lattice

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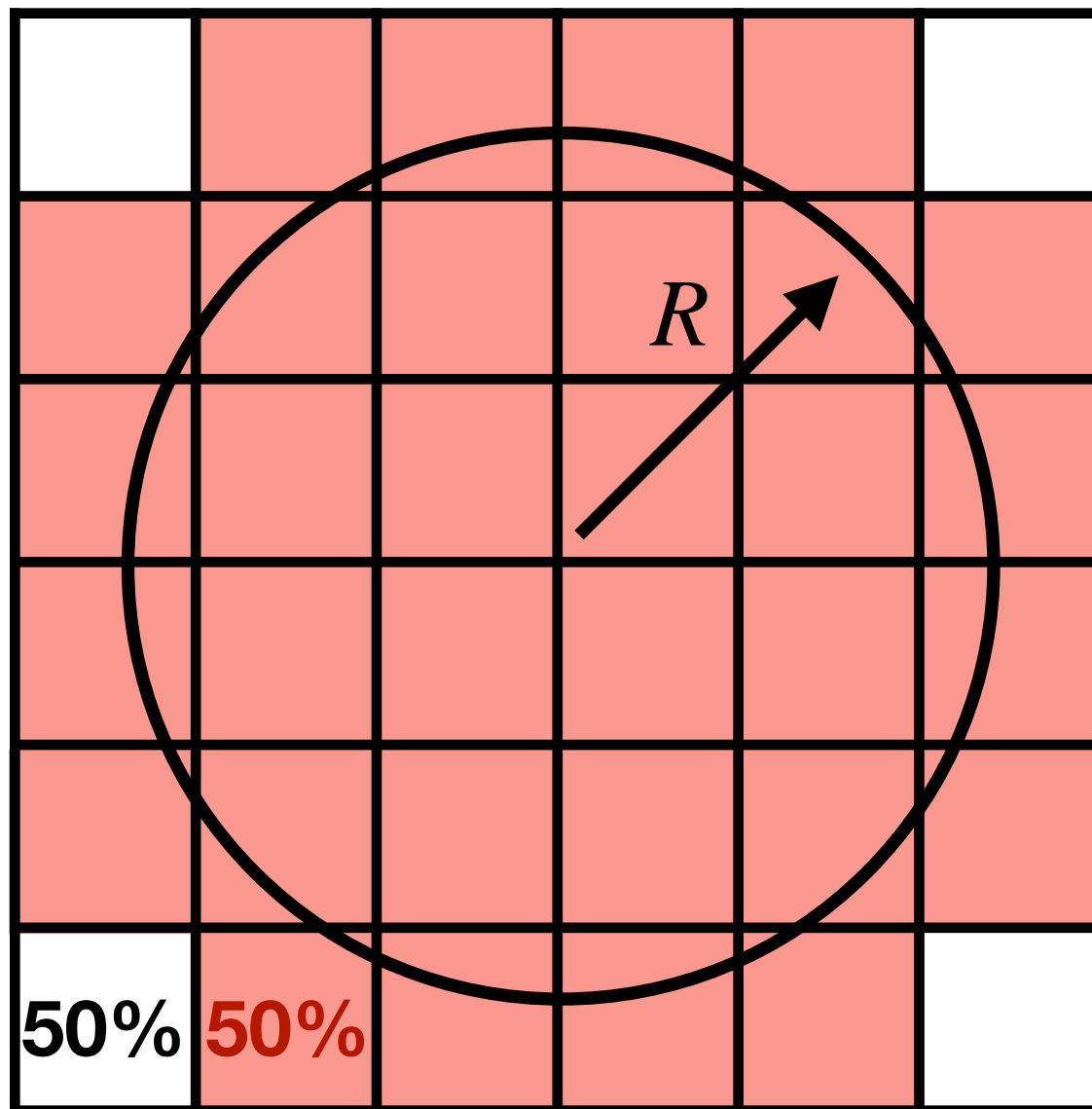
$$\mathcal{F}(R) \simeq (50\%)^{\text{number of sites}} \simeq 0.5^{\frac{4\pi}{3} \left(\frac{R}{L}\right)^3}$$



Vilenkin&Shellard 2000

$L \sim t$

Discretization



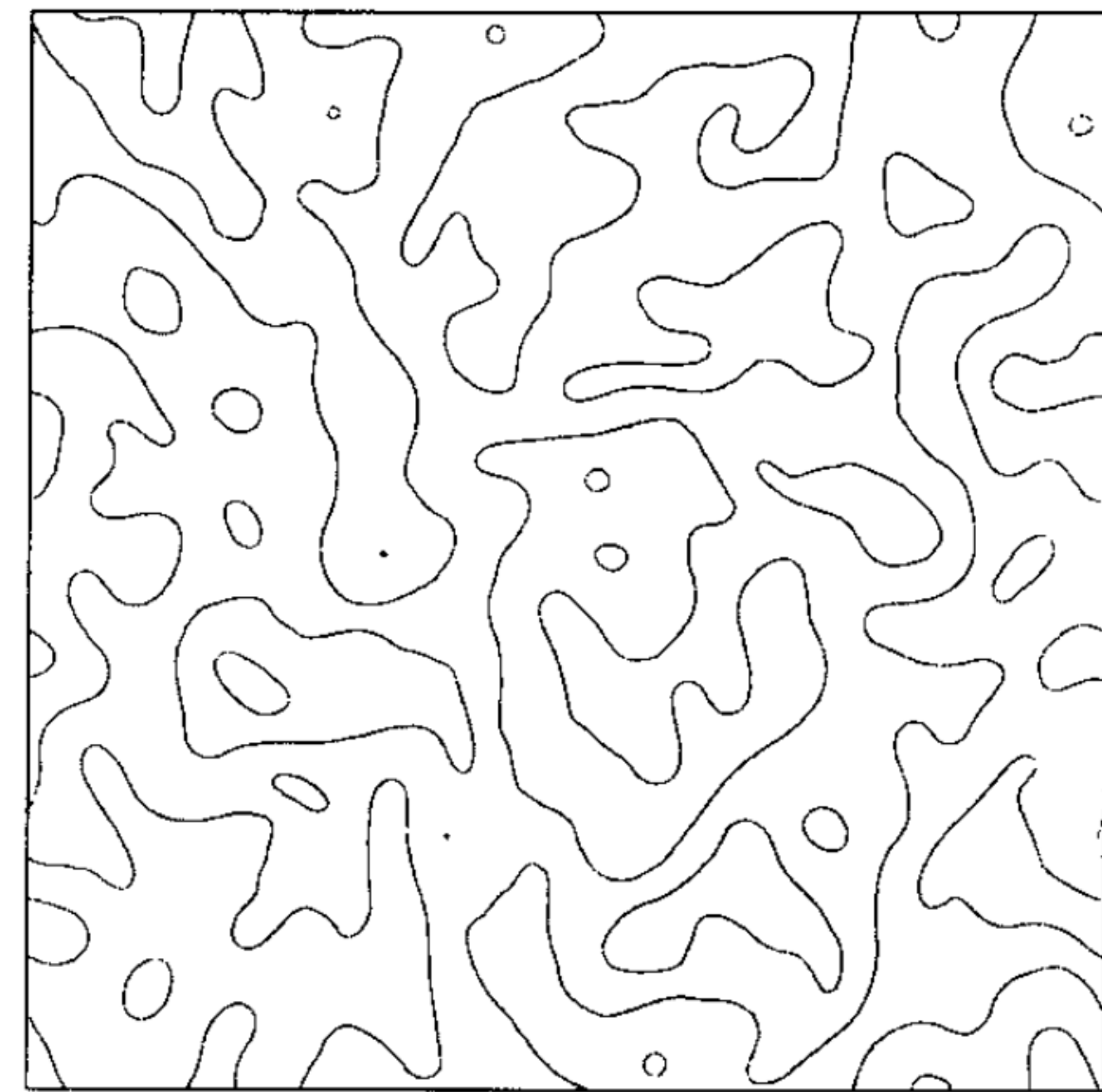
Abundance of late-annihilators $\mathcal{F}$

Percolation theory on a lattice

Stauffer (1979) Coulson, Lalak, Ovrut (1995)

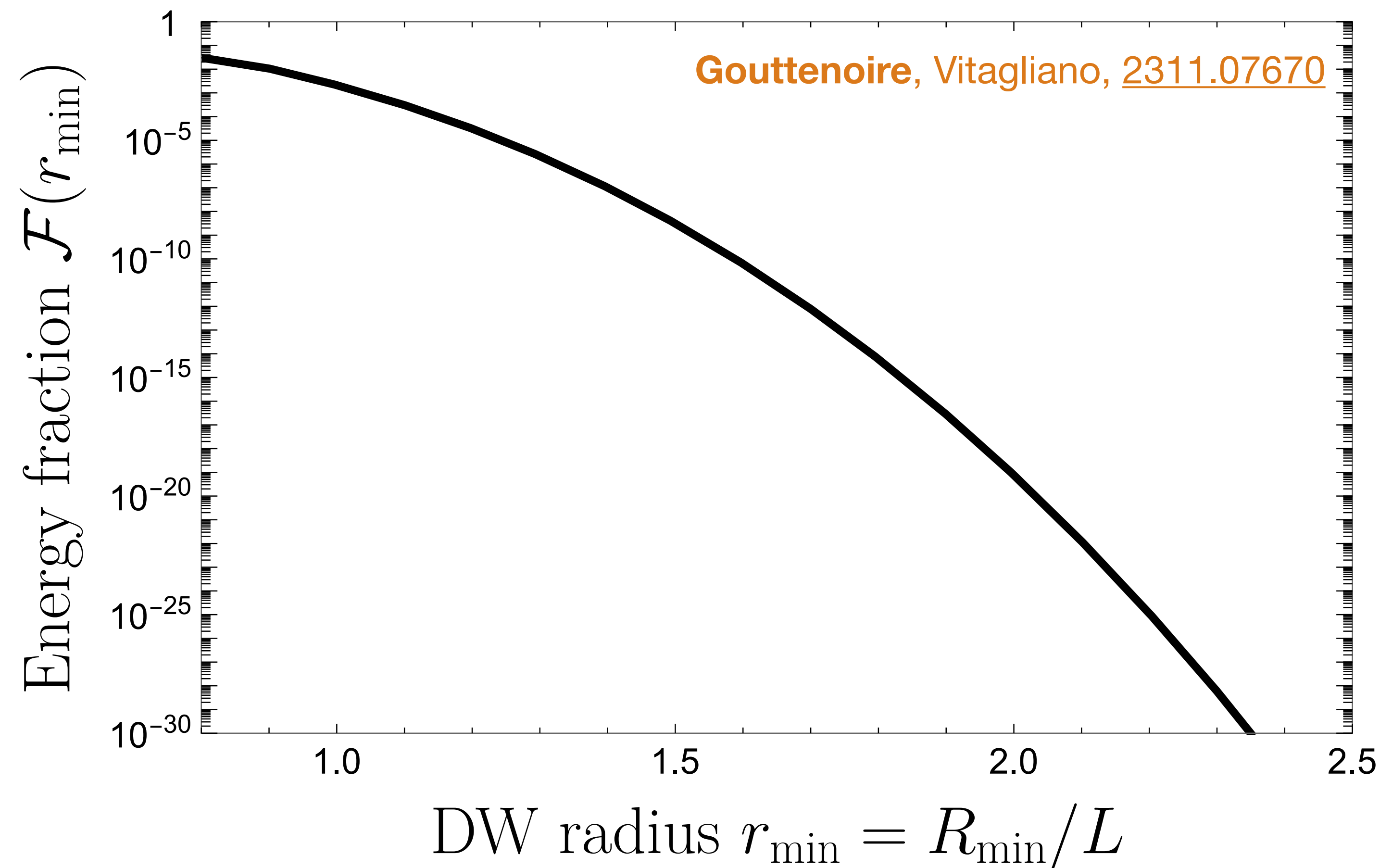
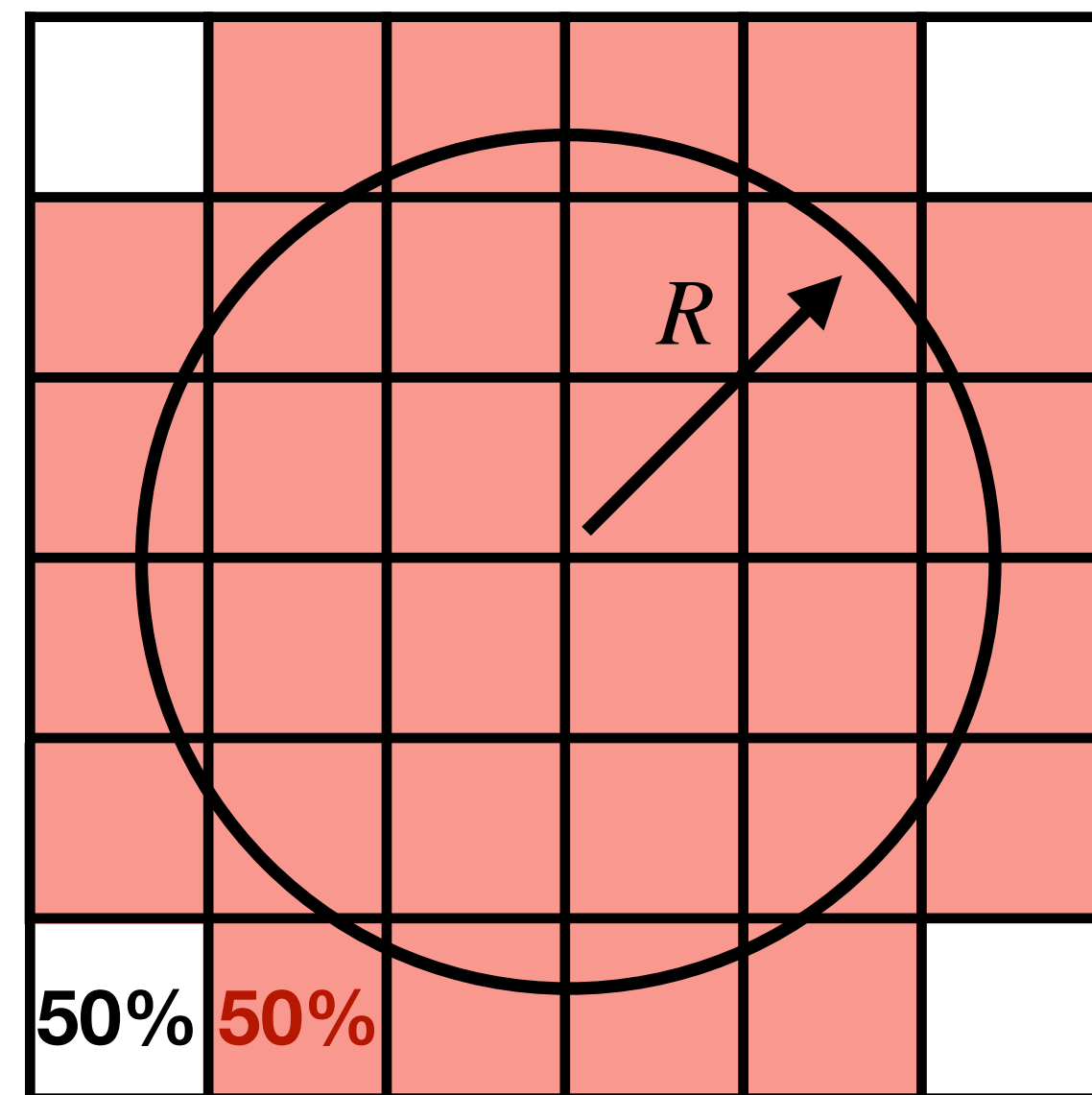
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Vilenkin&Shellard 2000

$L \sim t$
Discretization



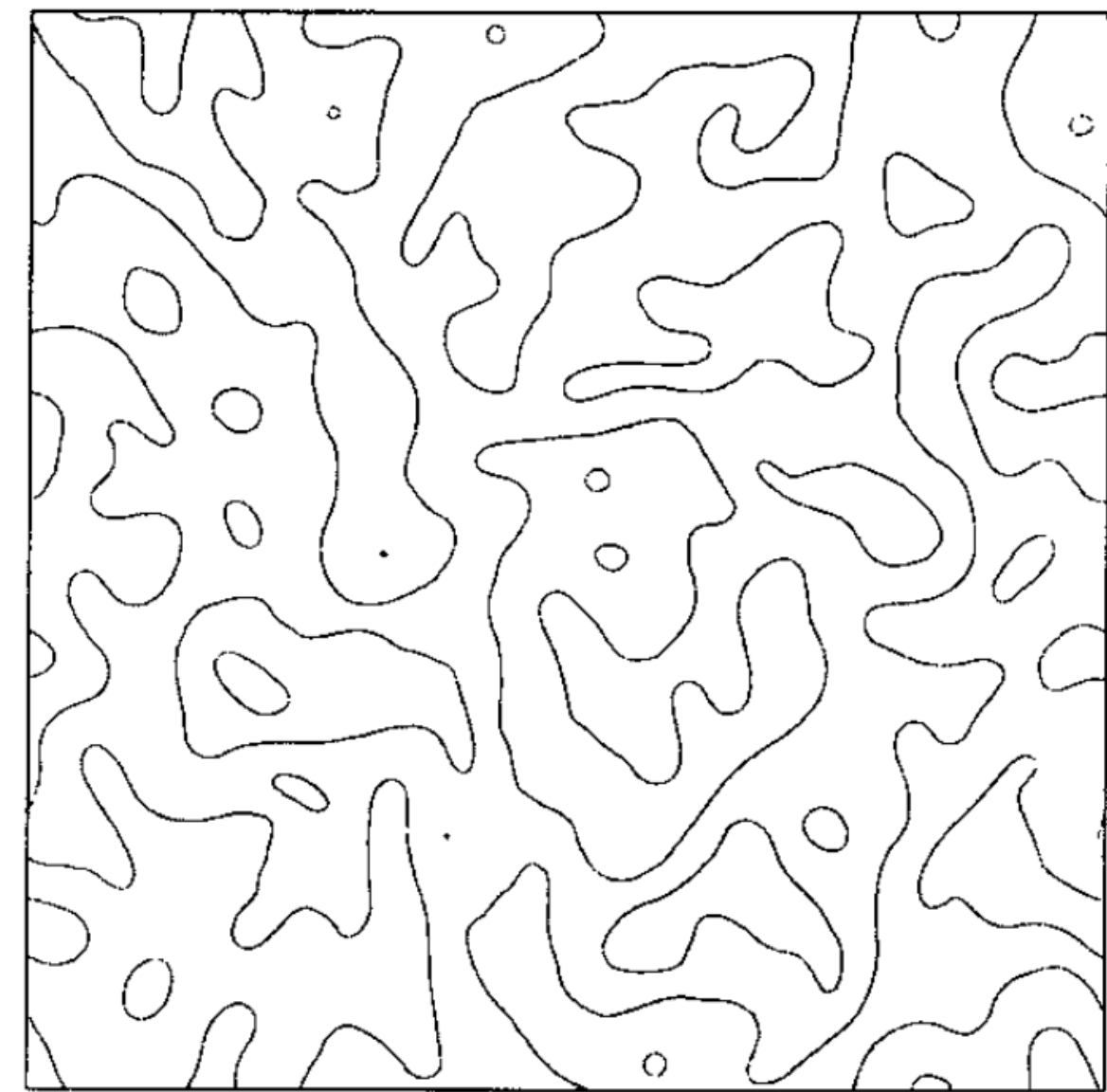
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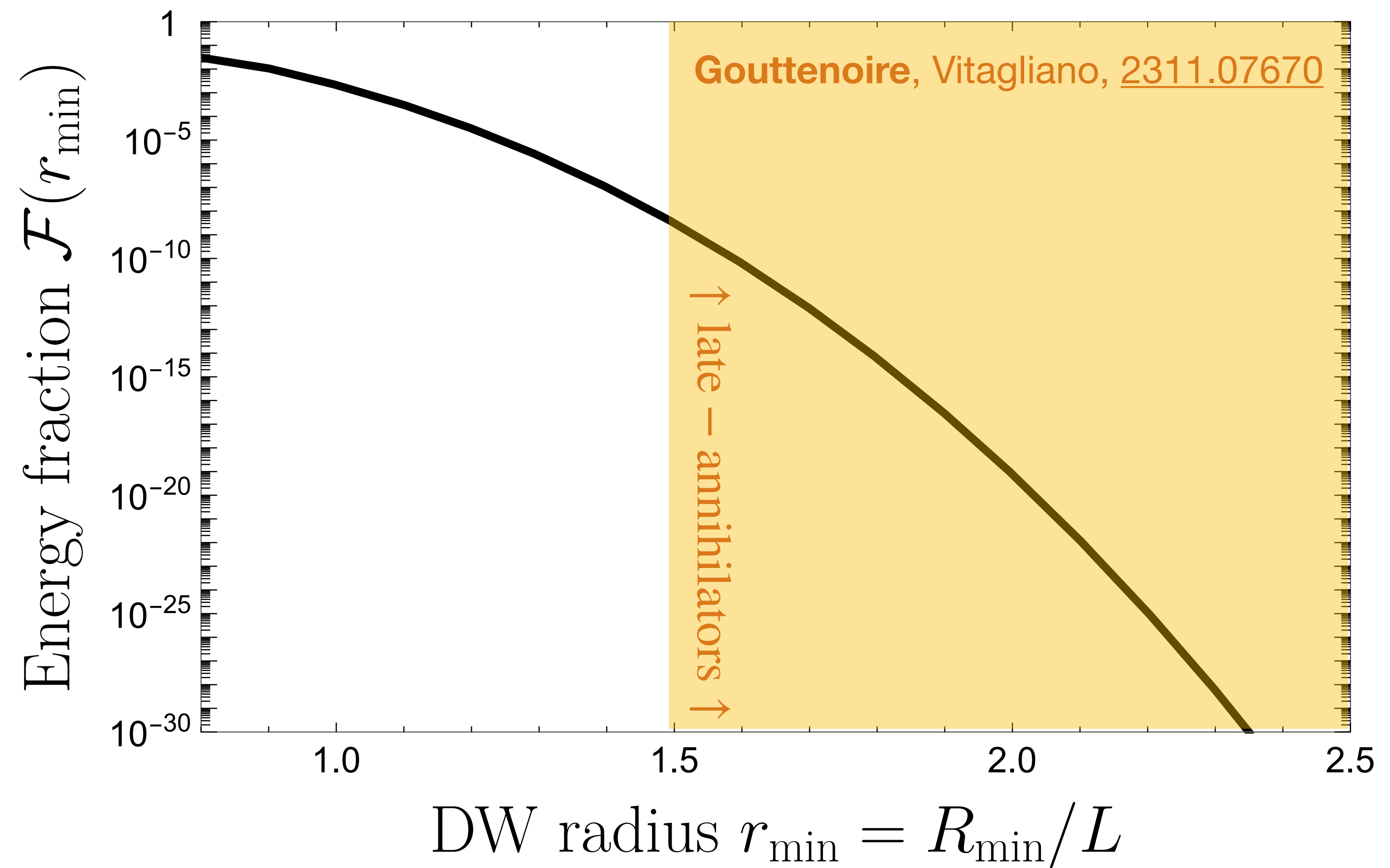
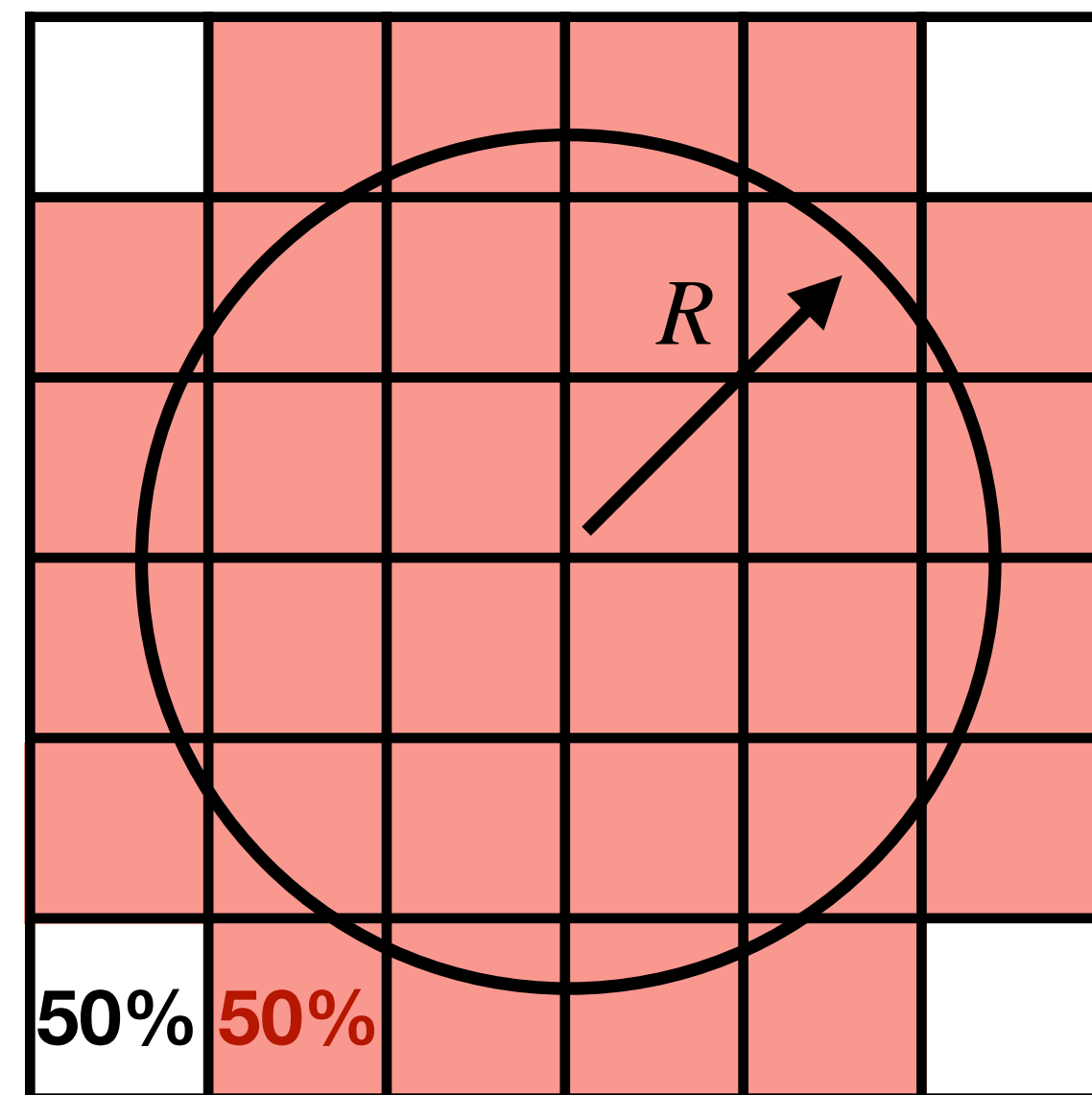
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Vilenkin&Shellard 2000

$L \sim t$
Discretization



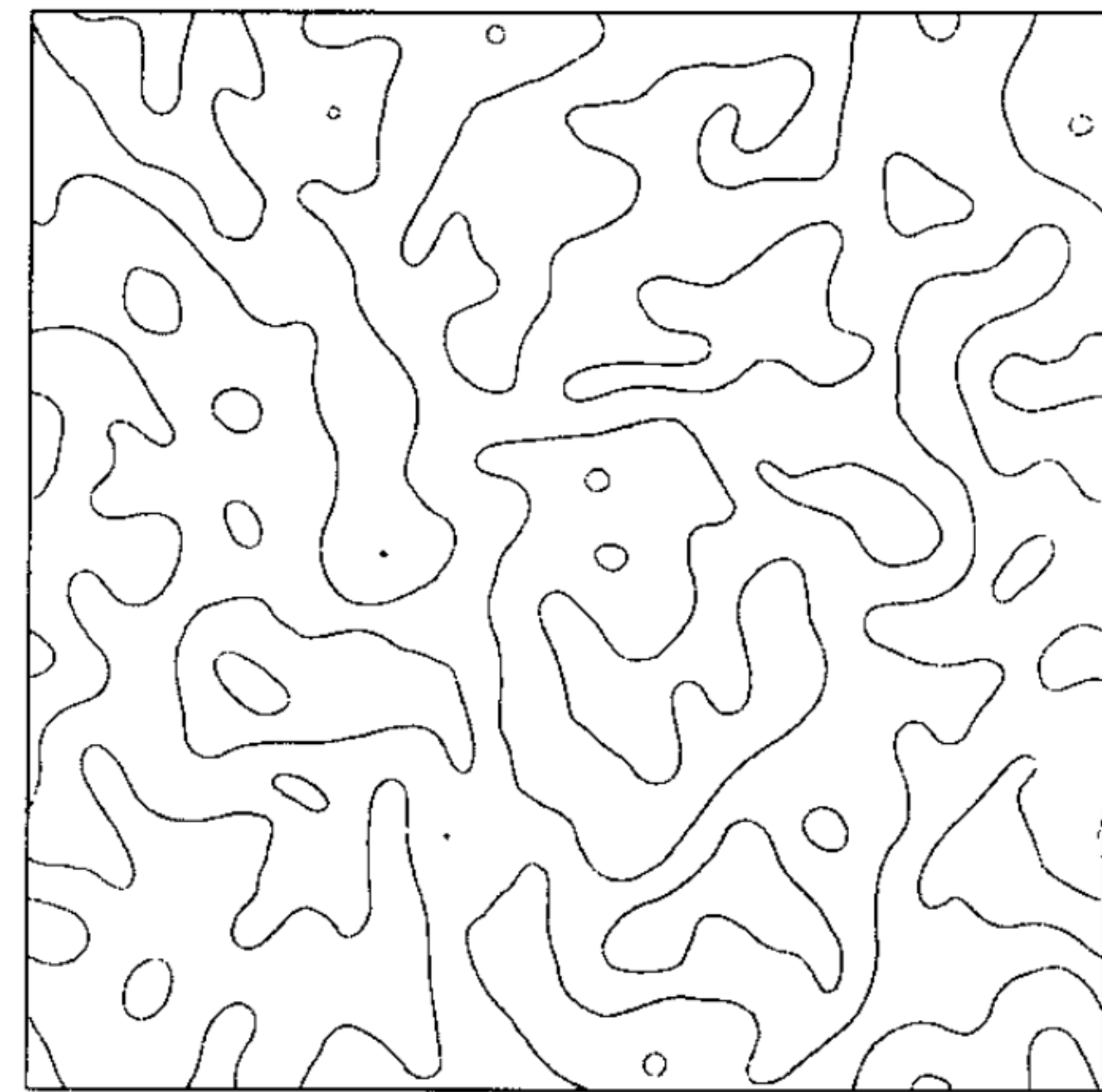
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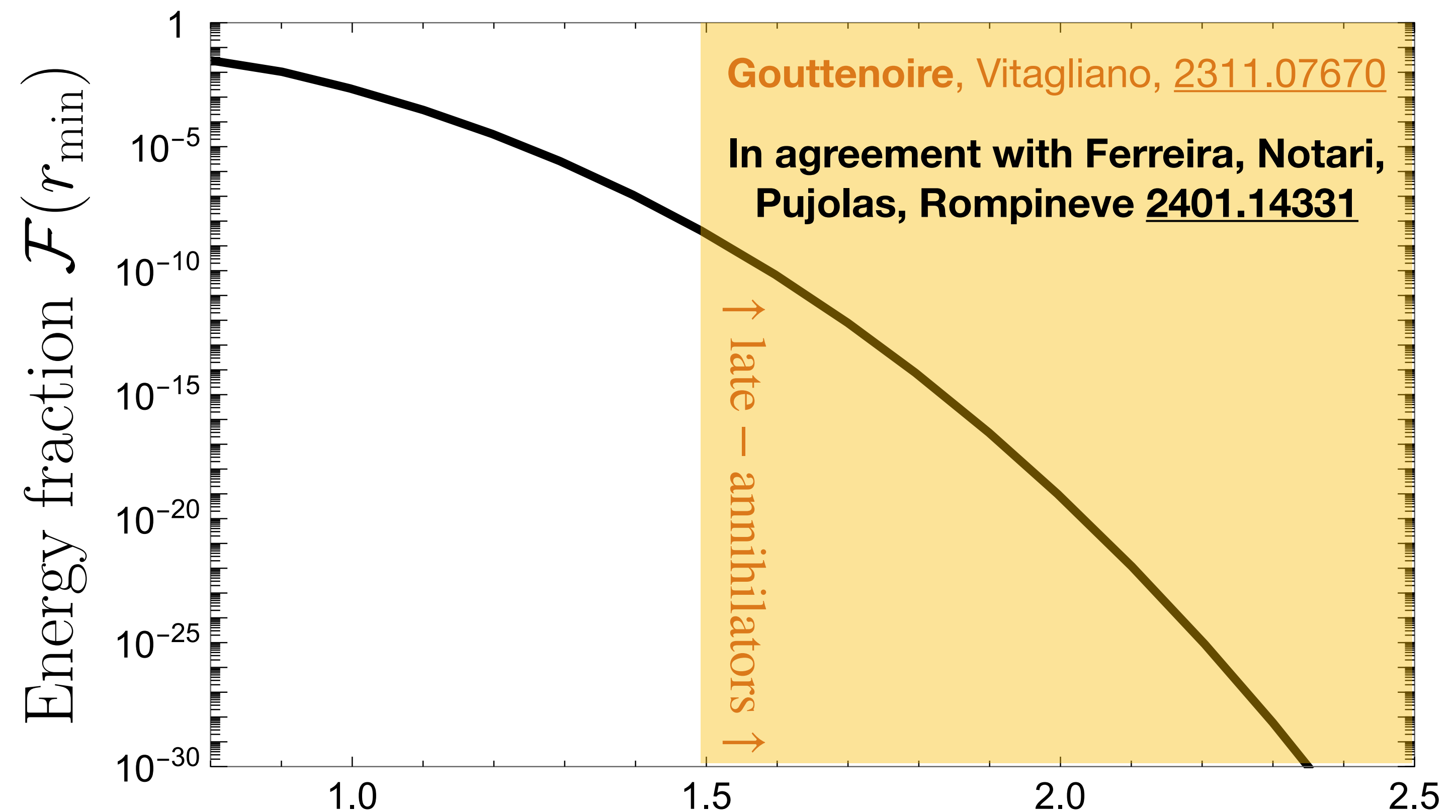
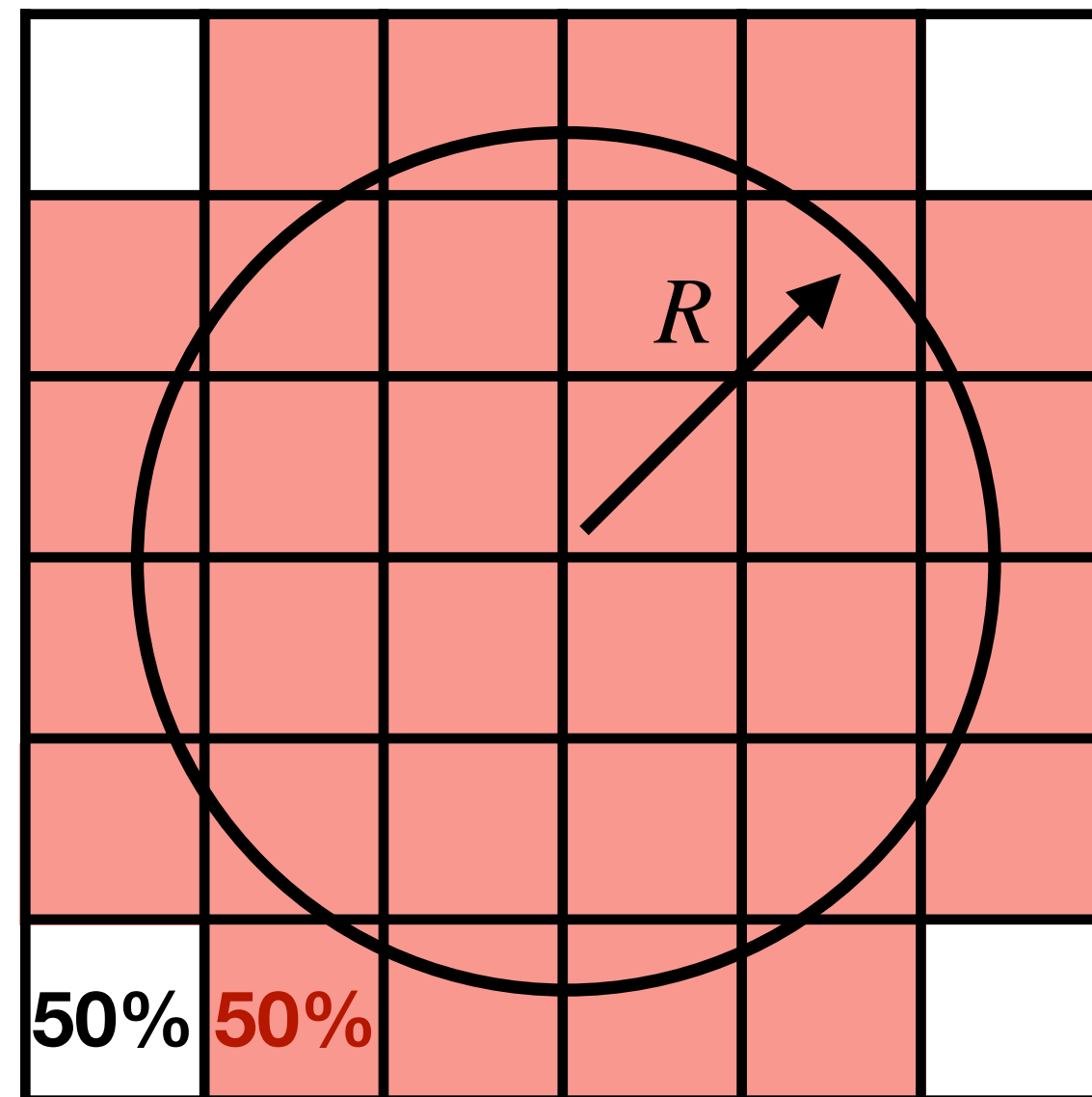
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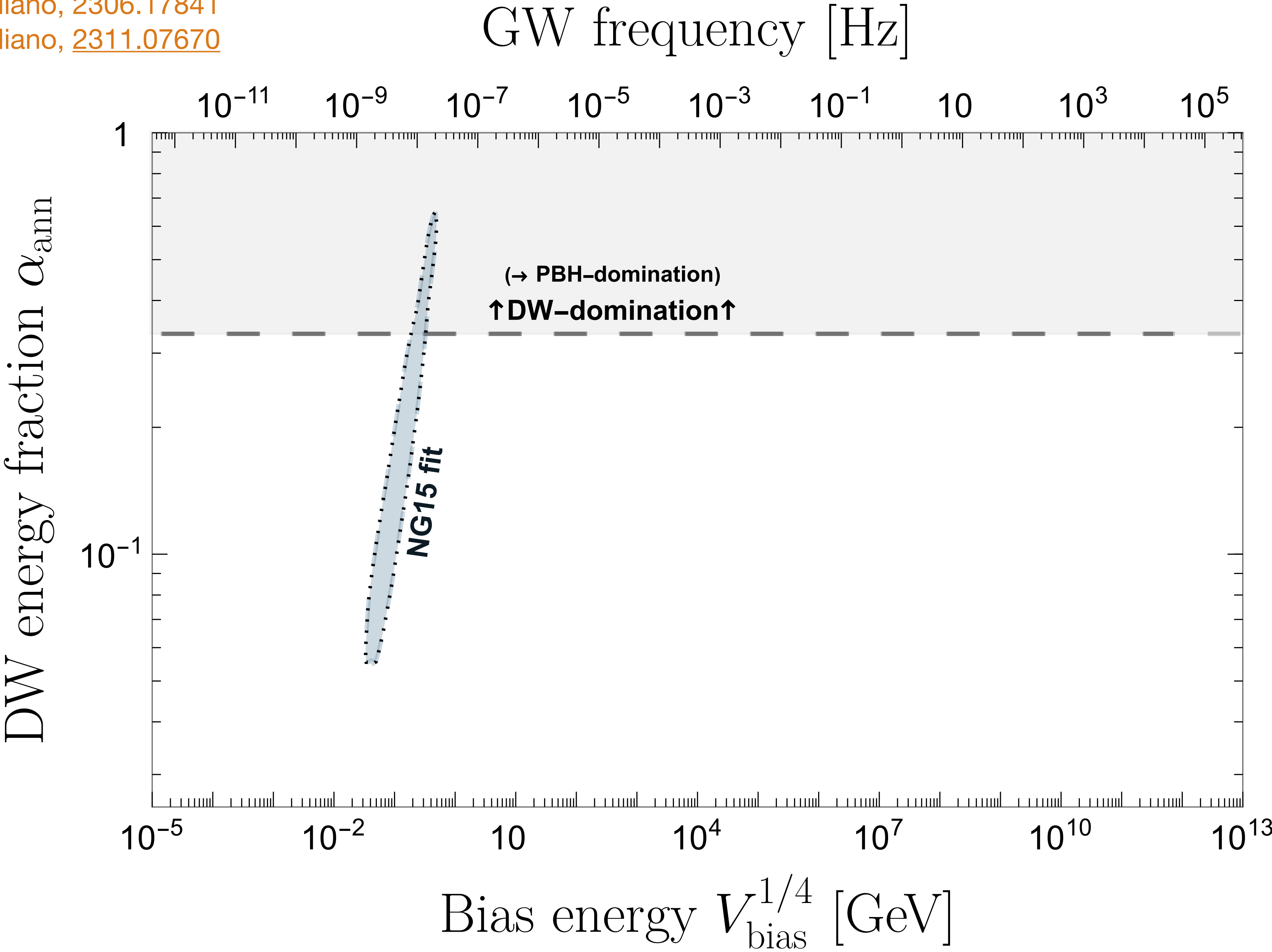


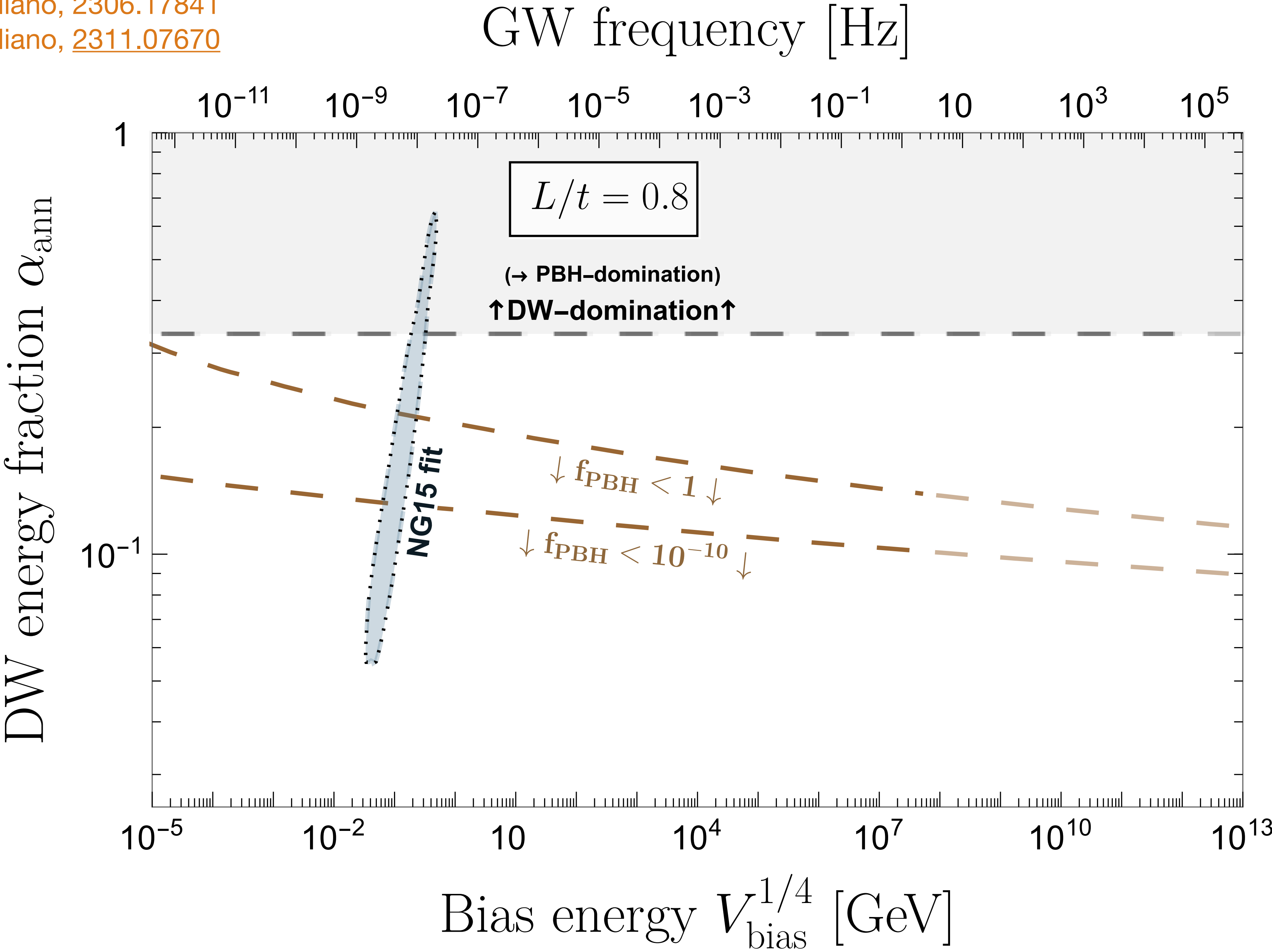
Vilenkin&Shellard 2000

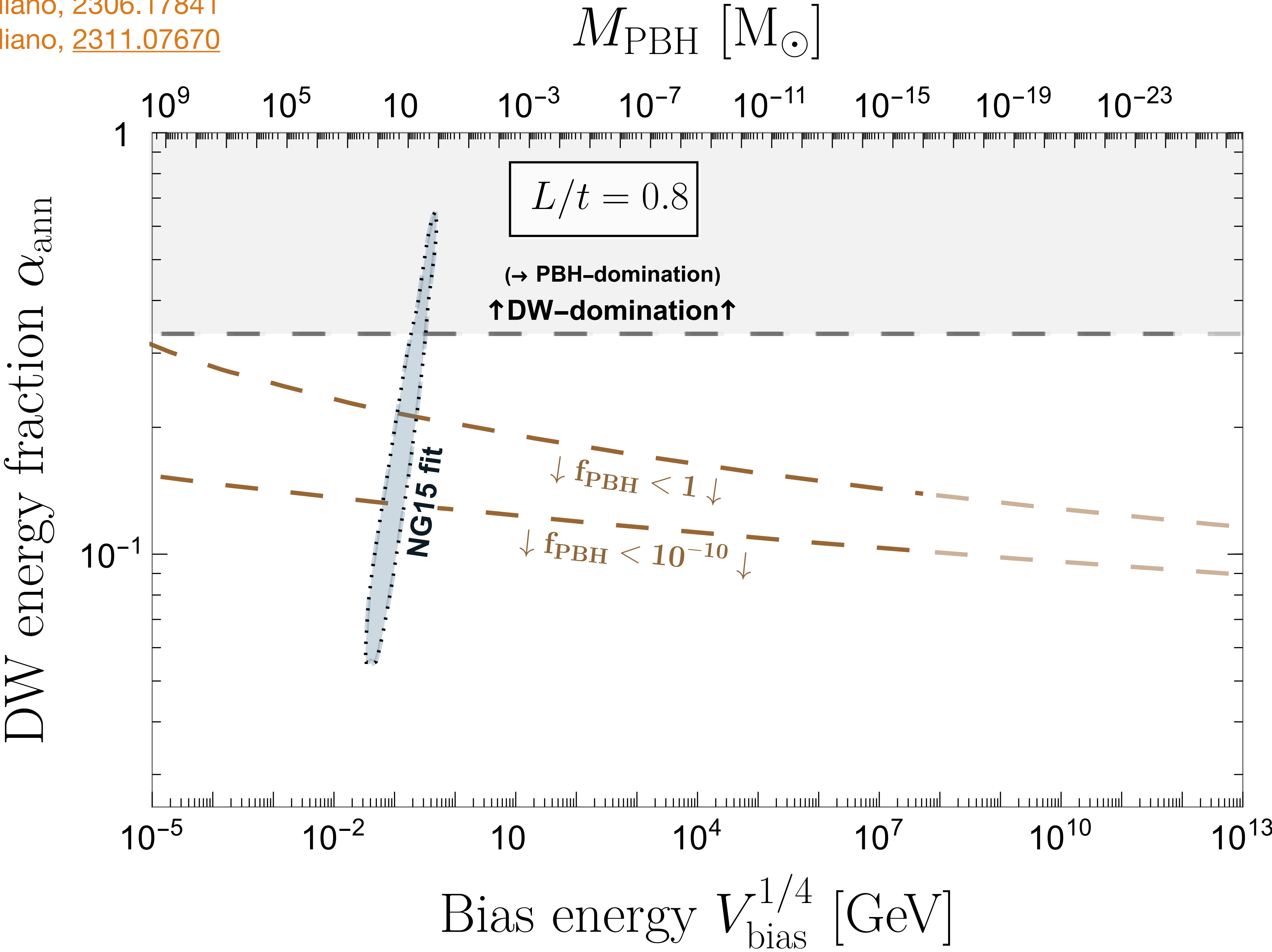
$L \sim t$
Discretization

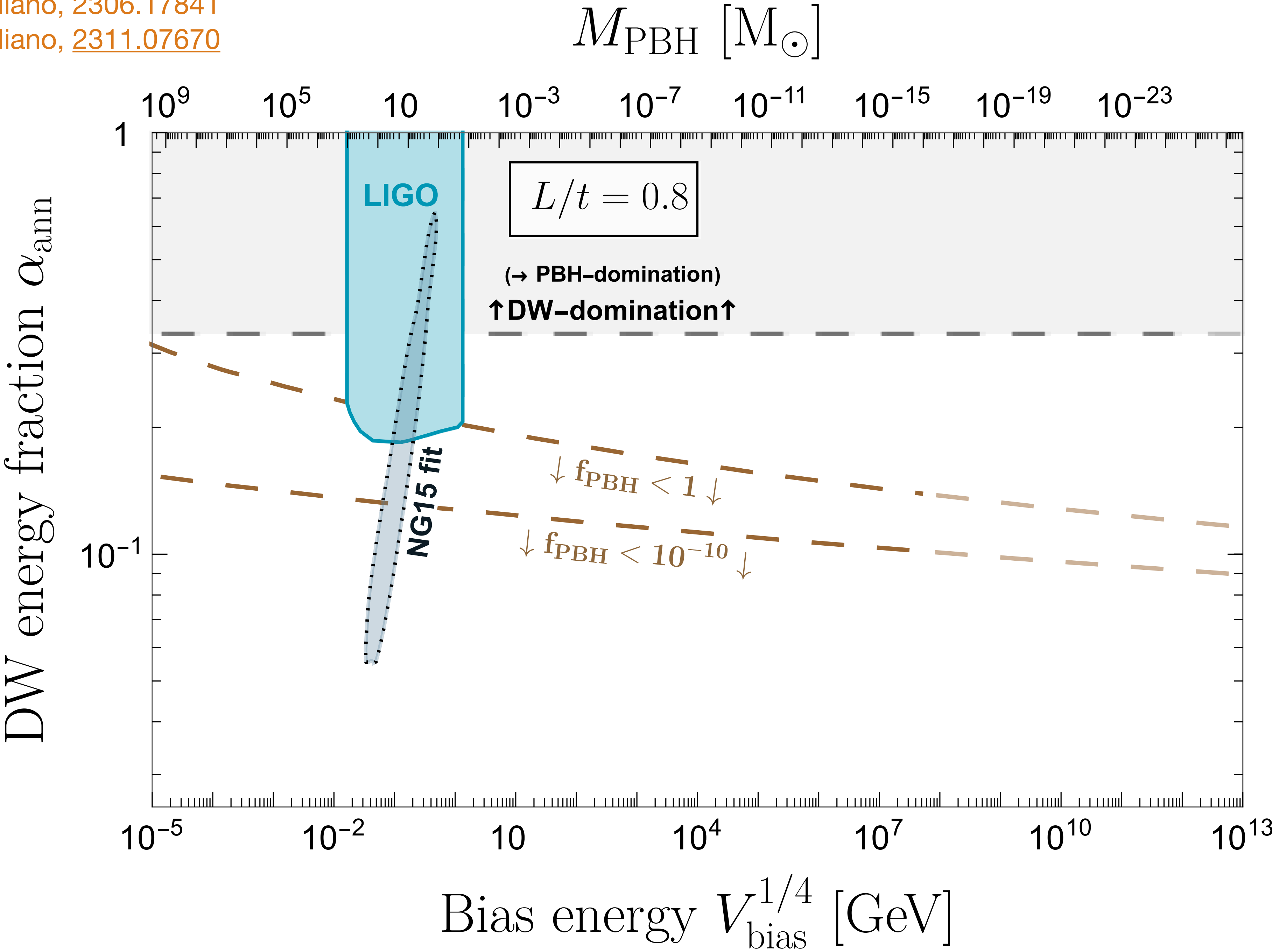


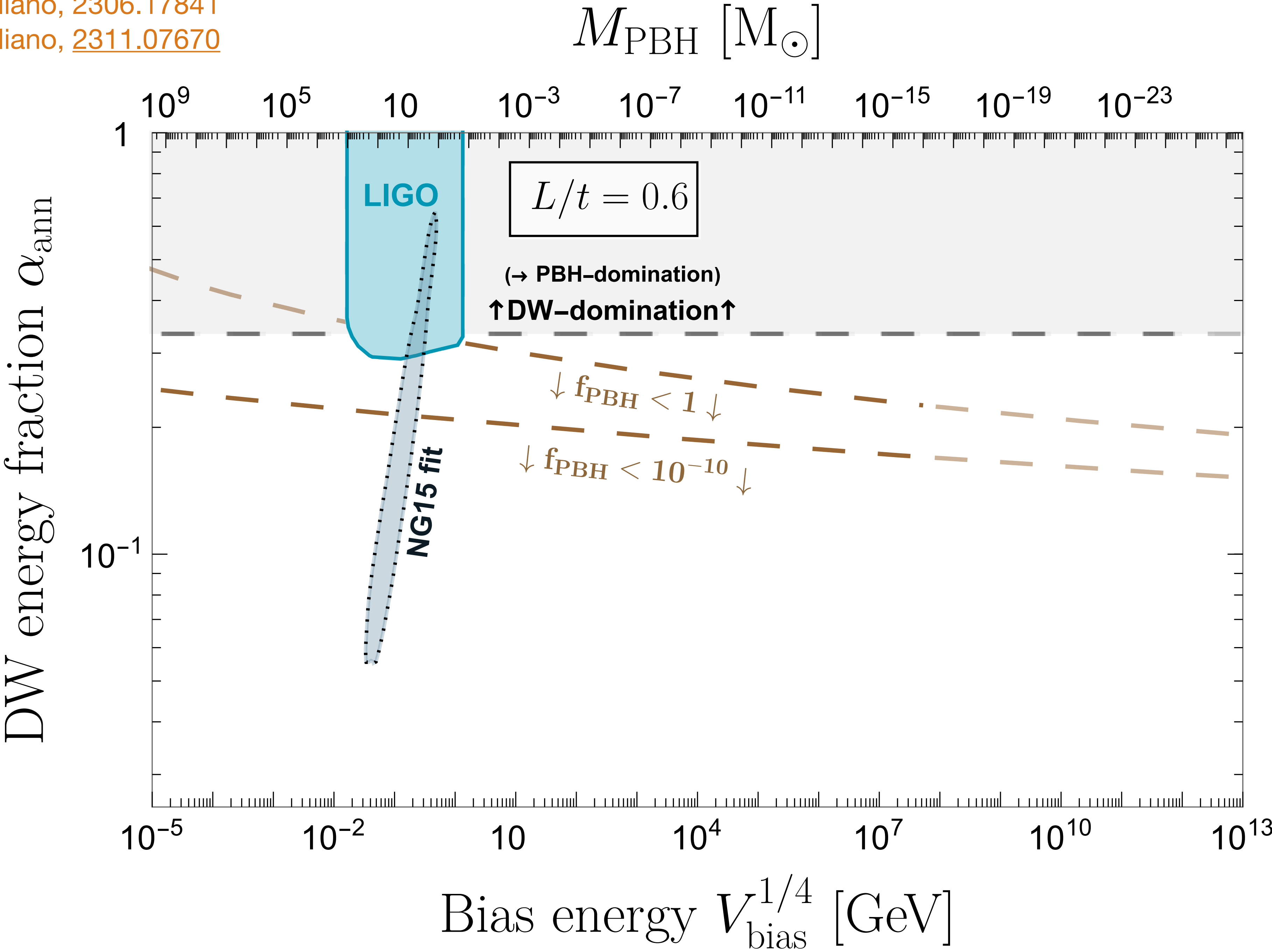
DW radius $r_{\min} = R_{\min}/L$

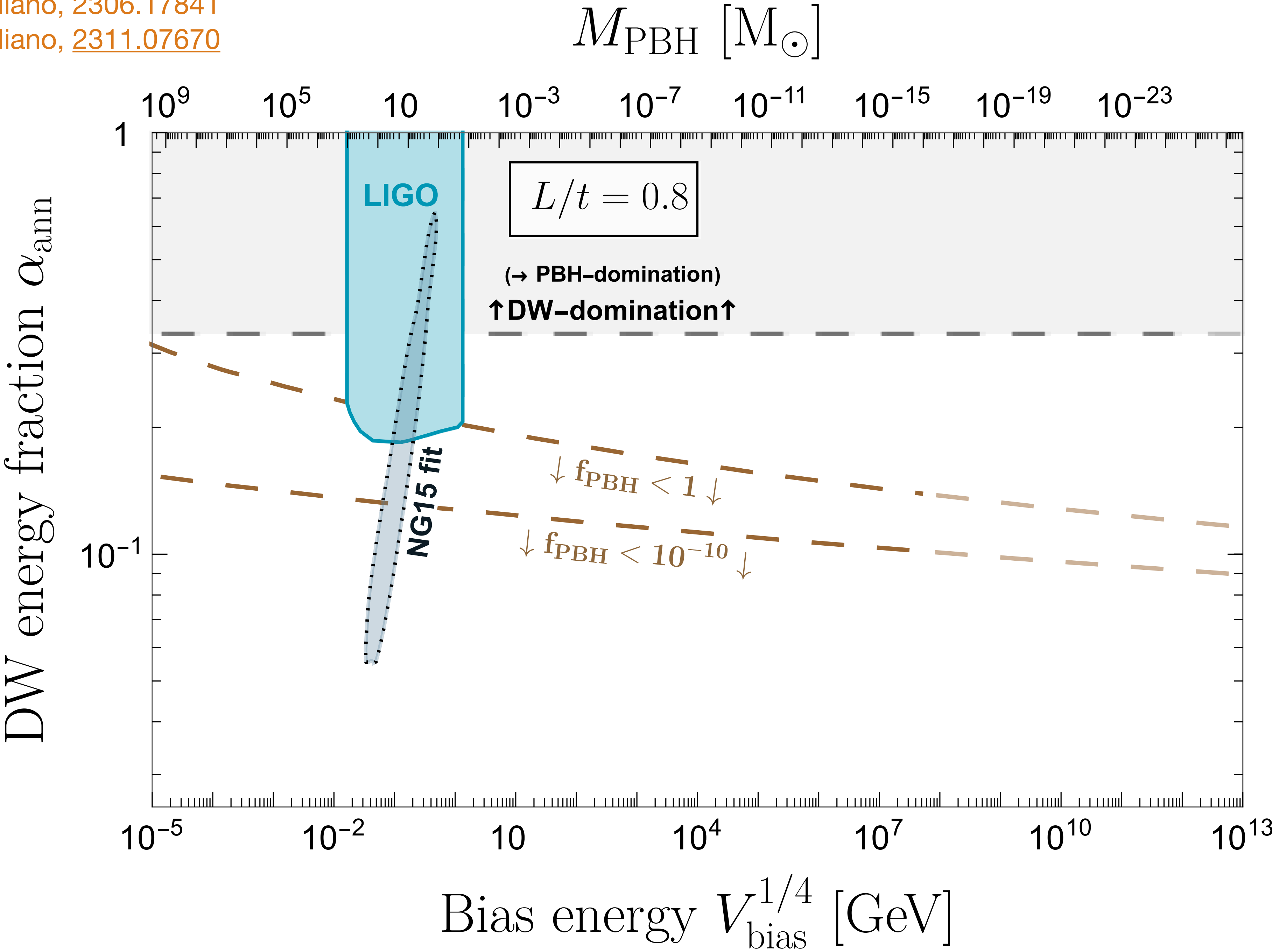


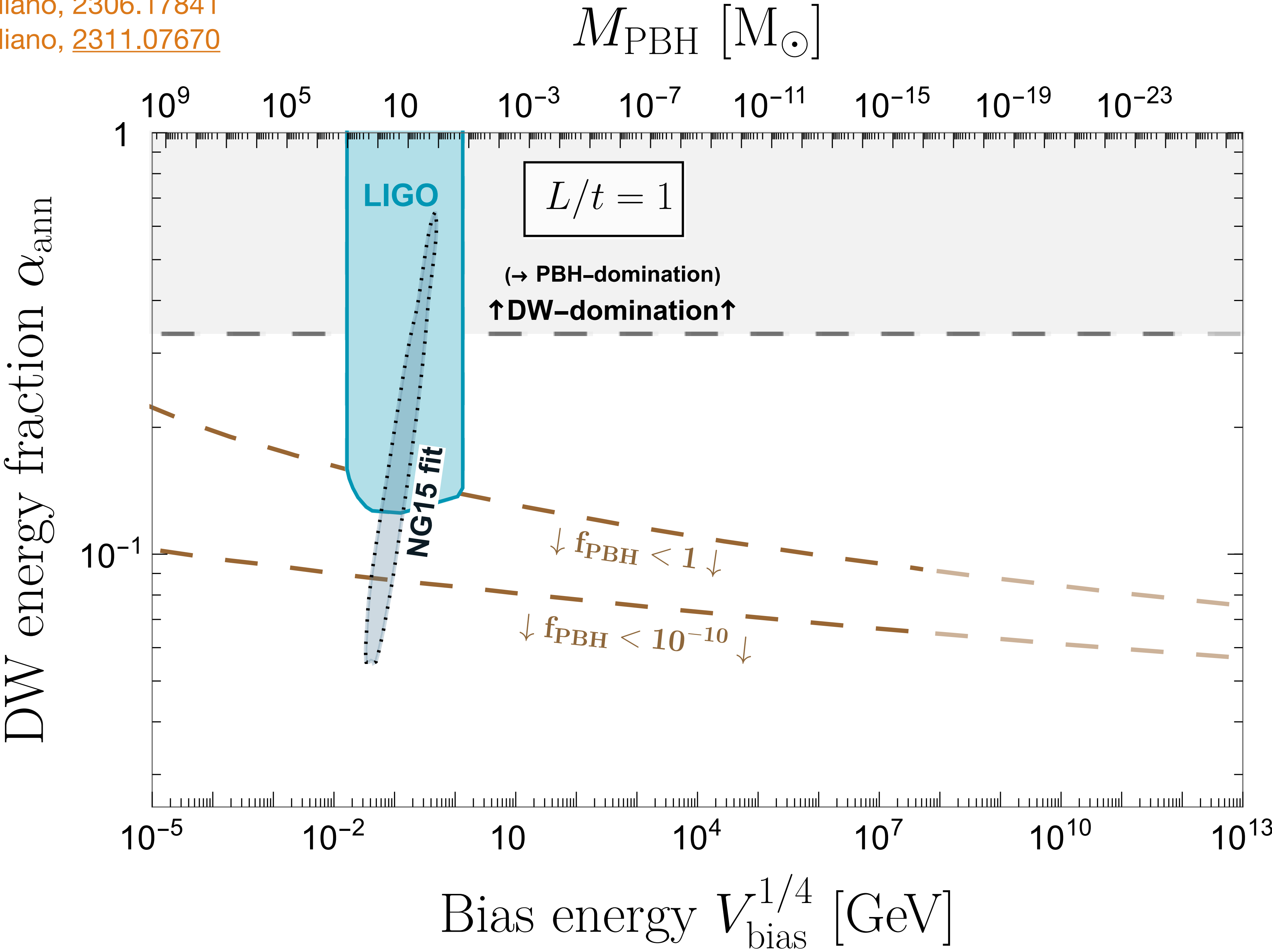


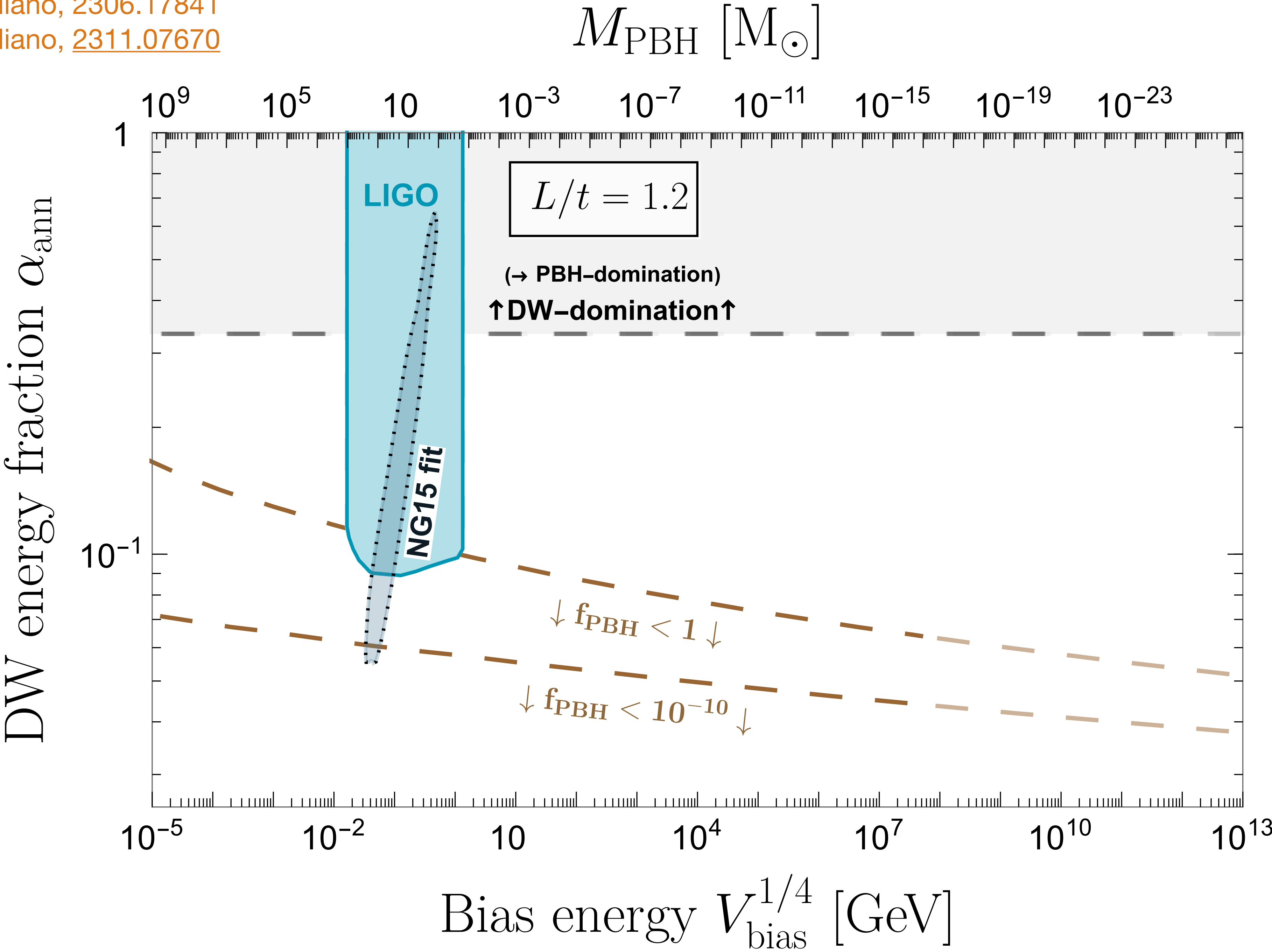


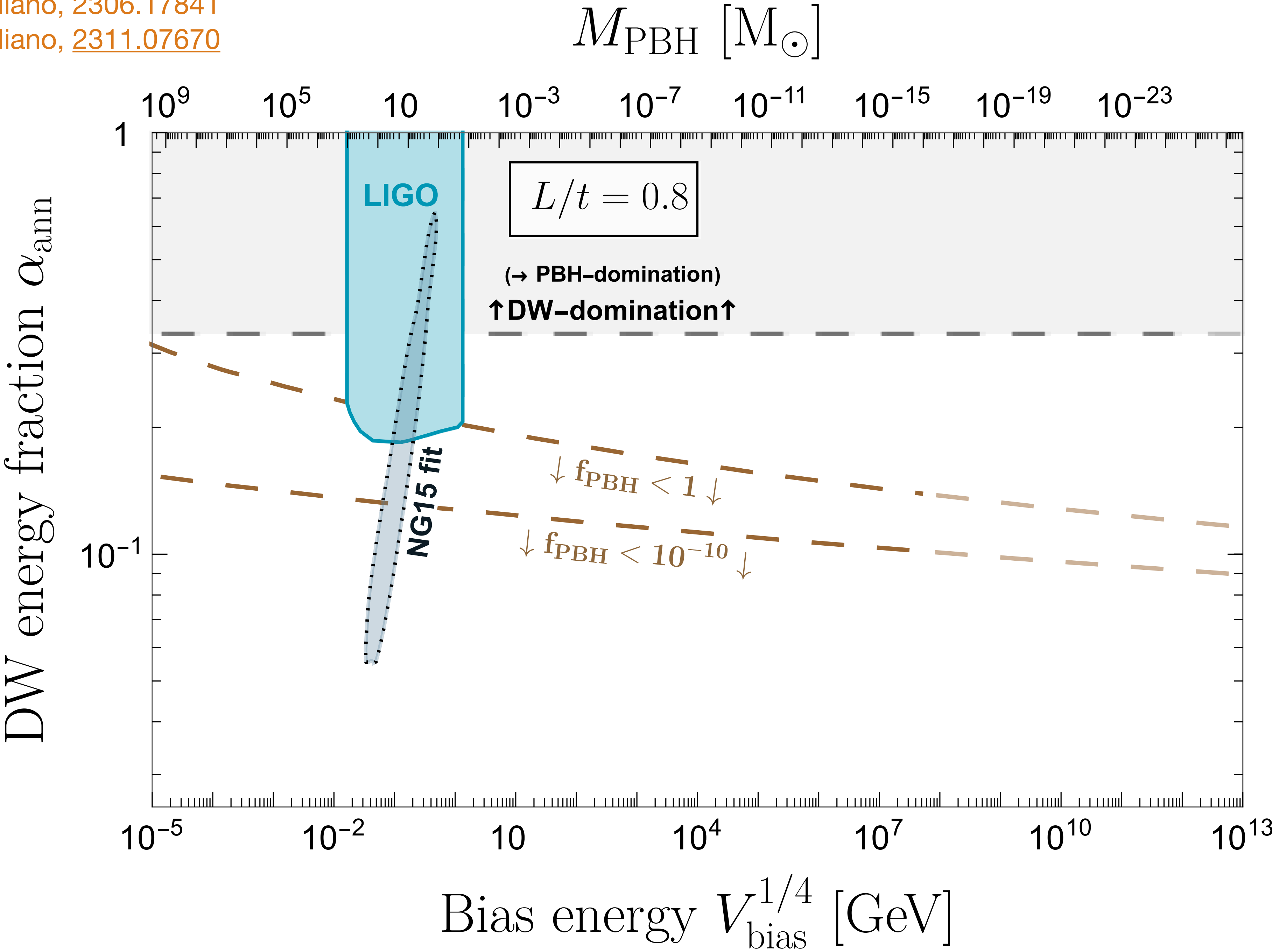


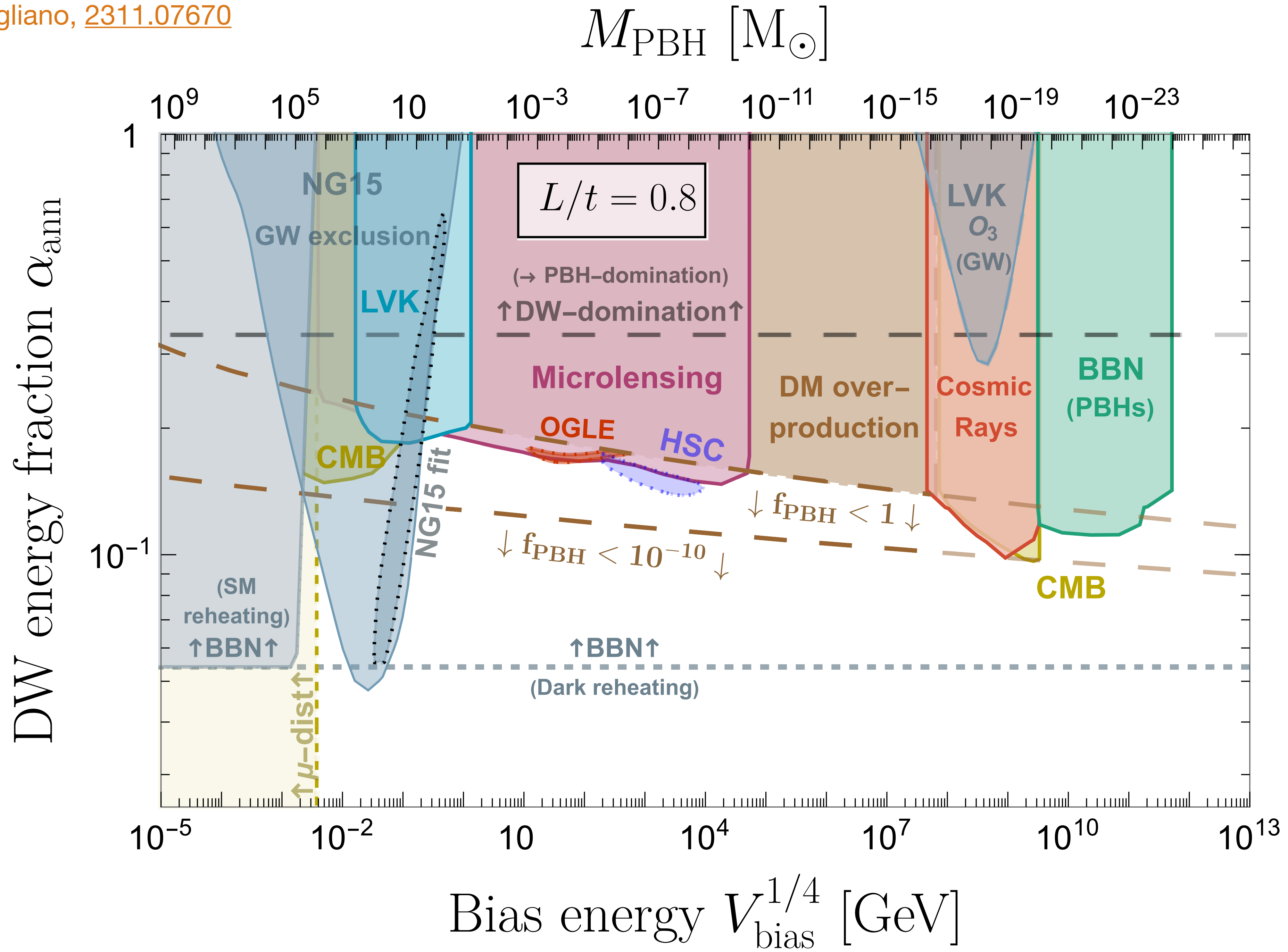


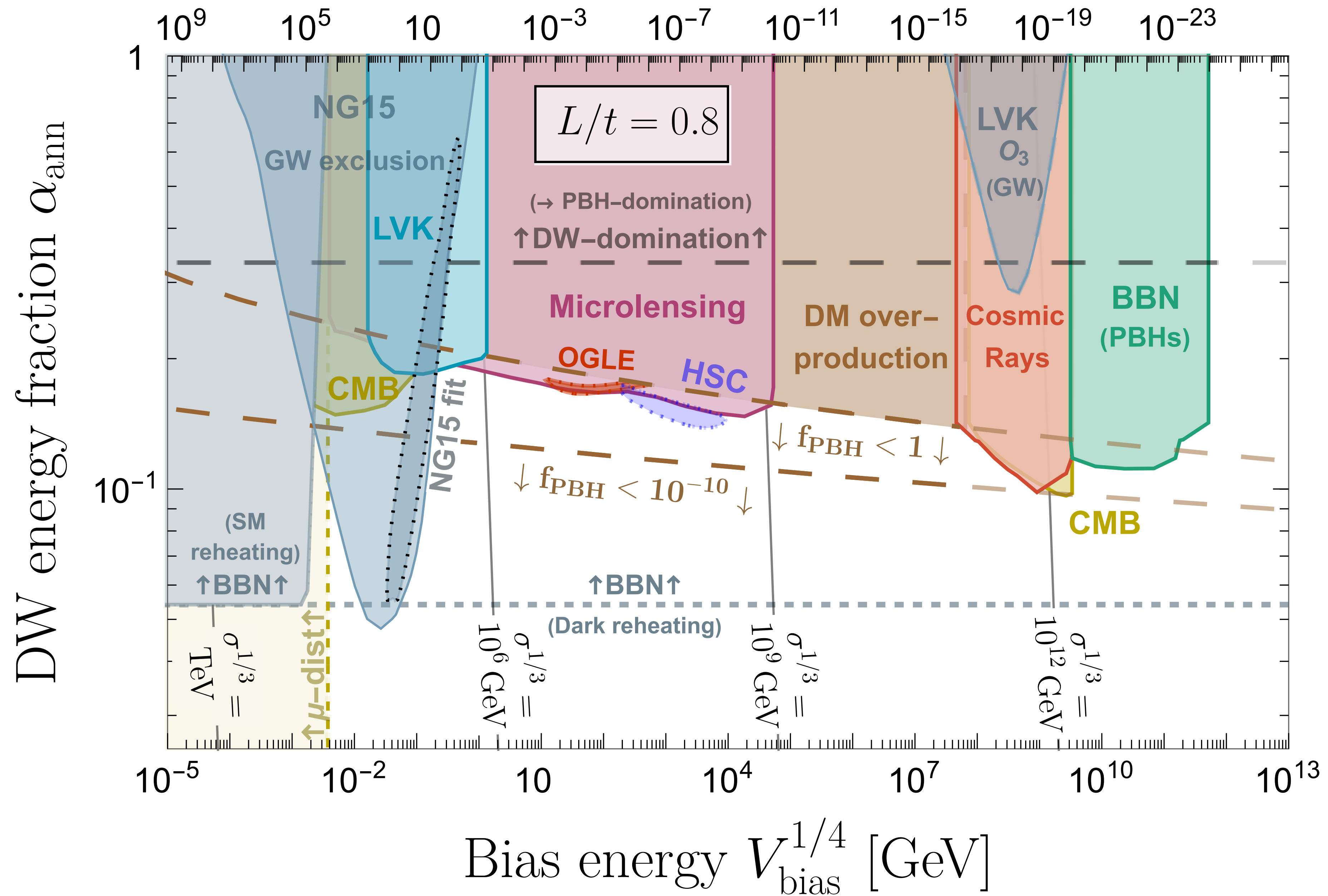


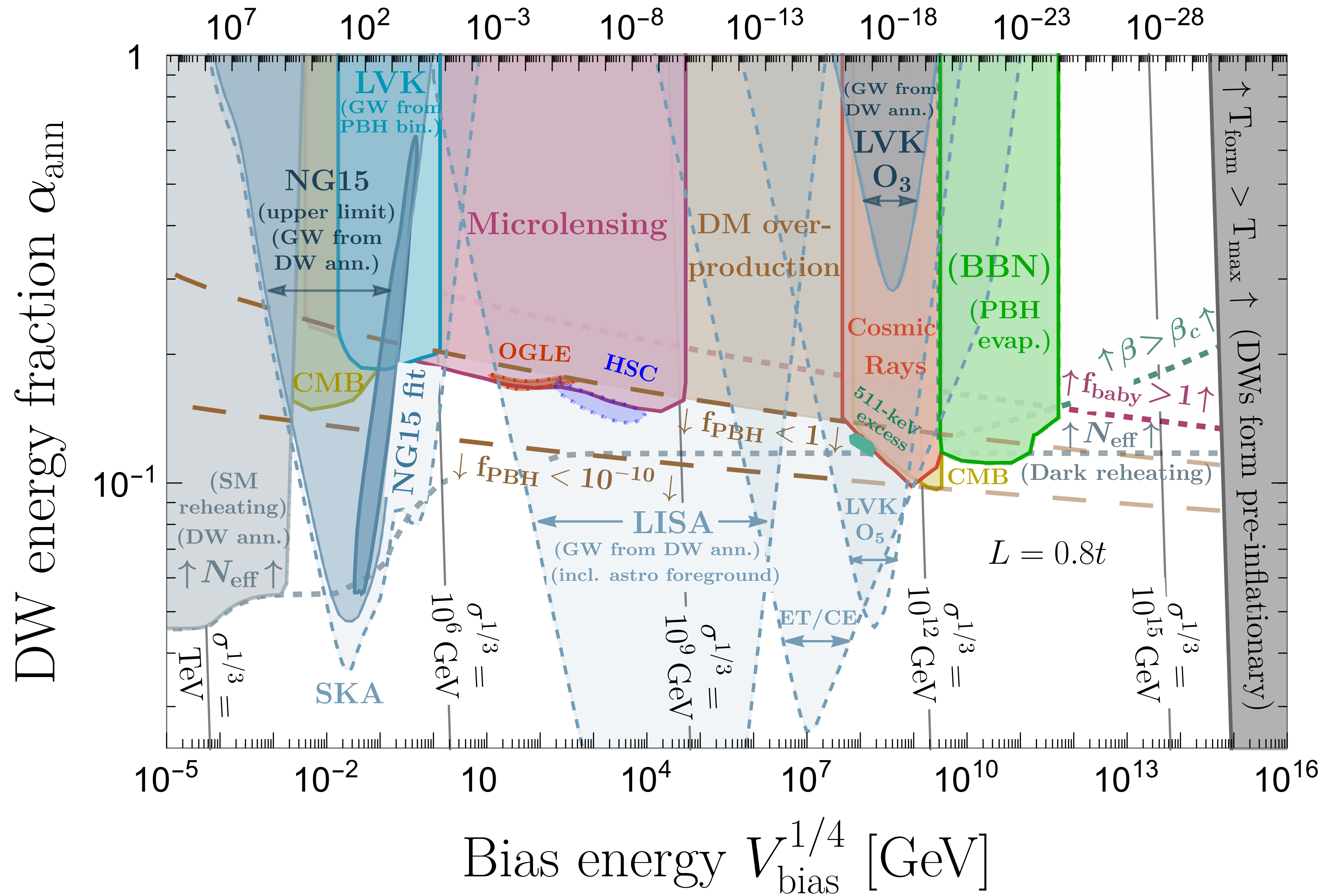






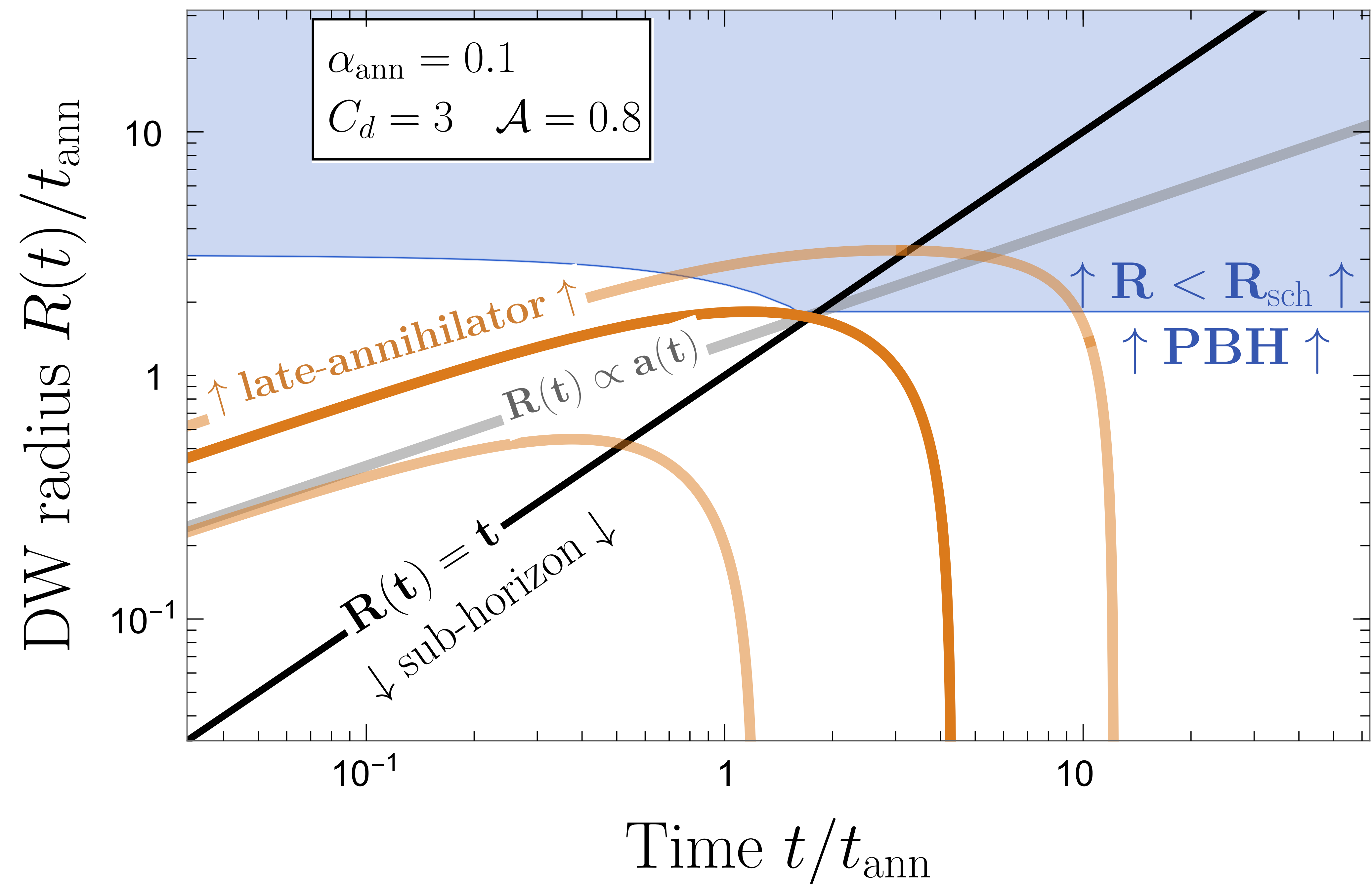


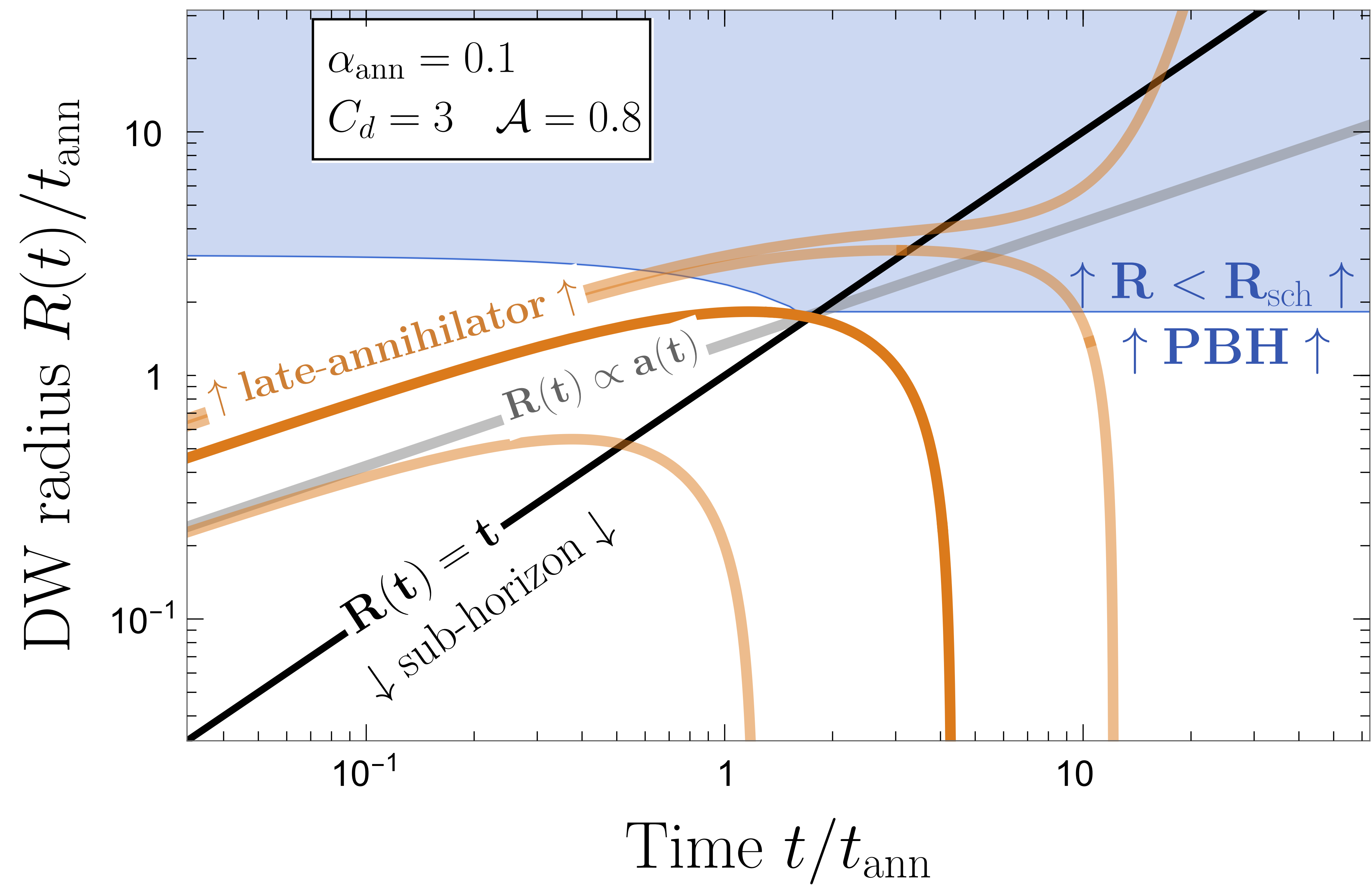


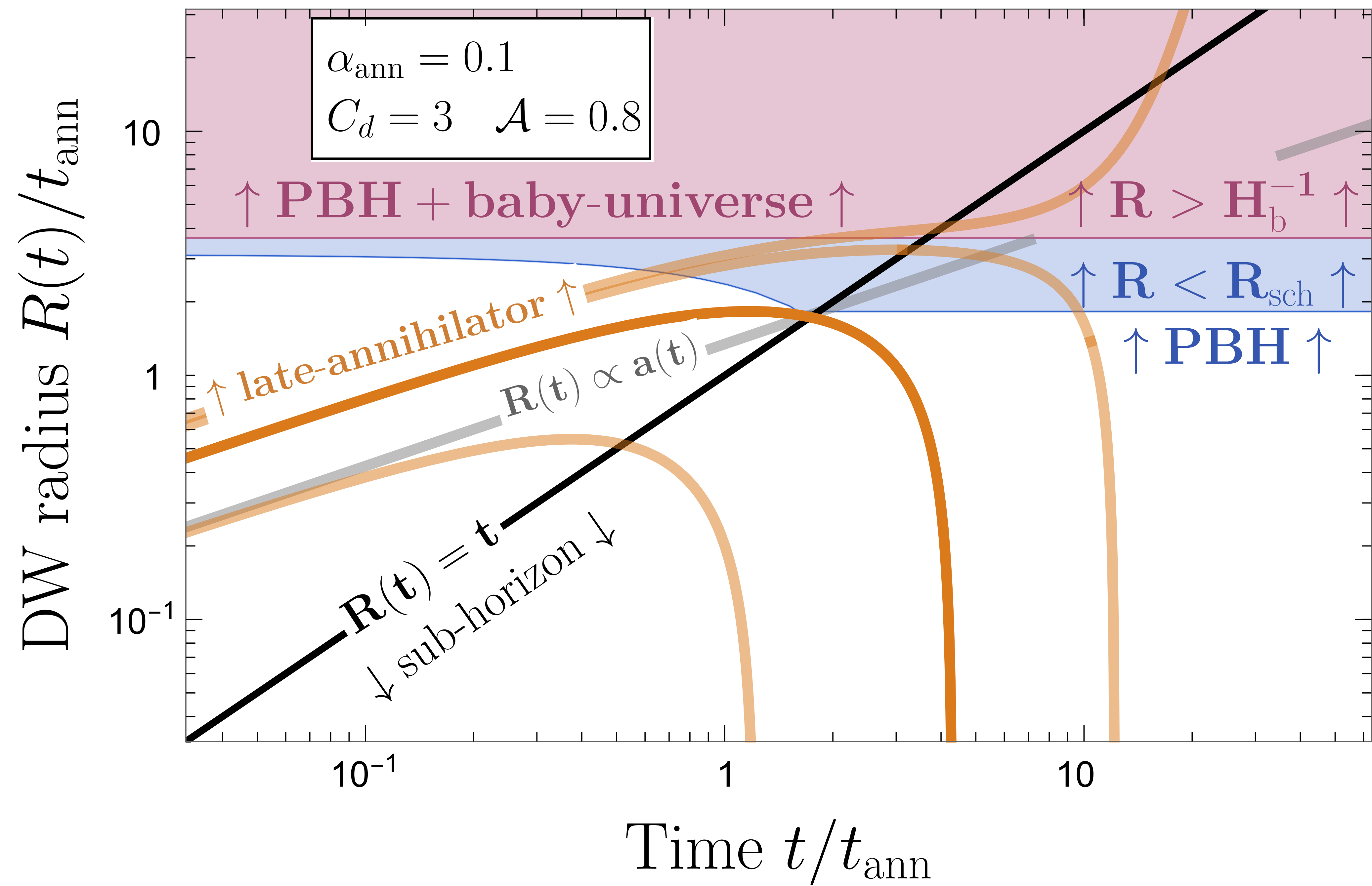


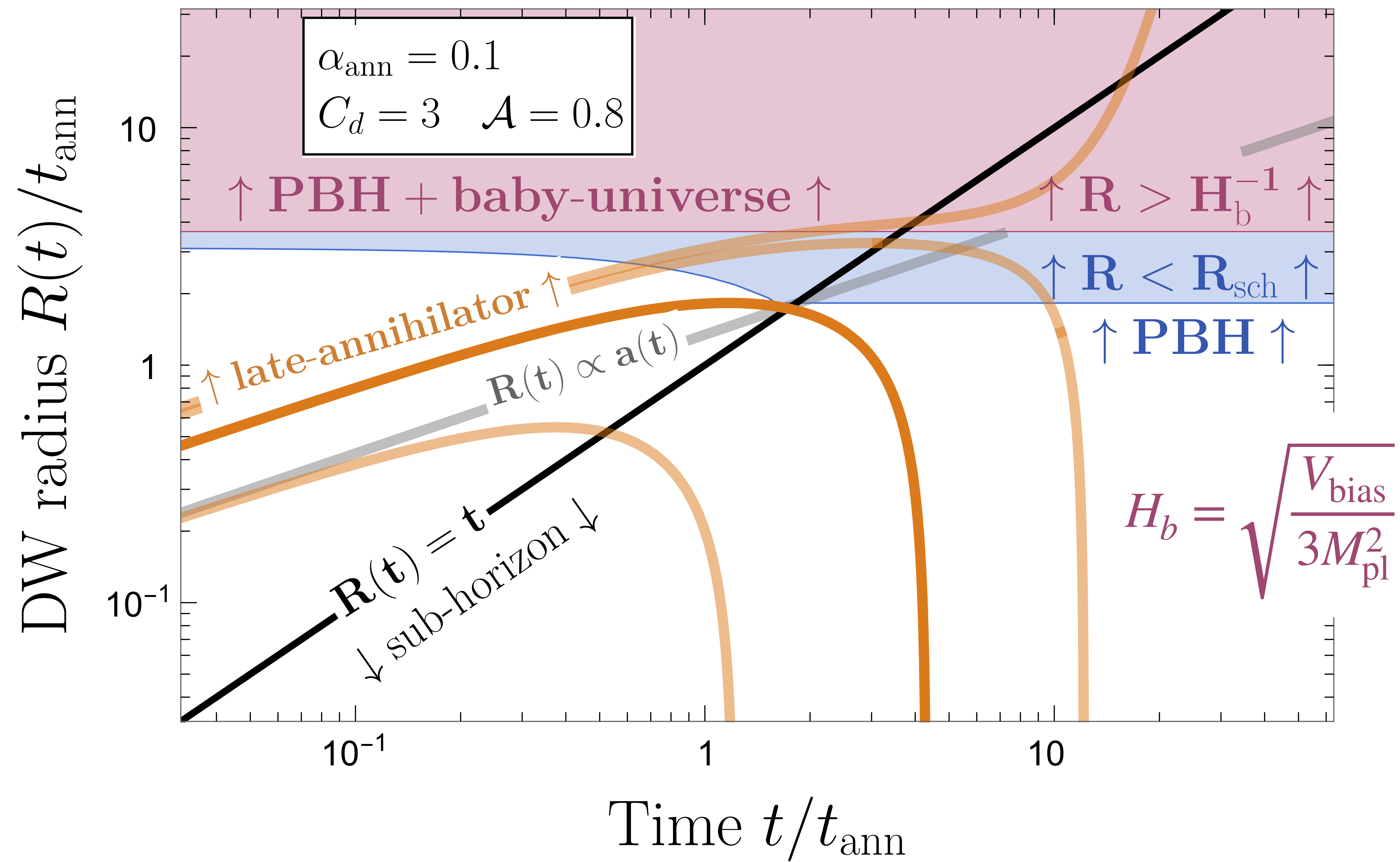
Wormholes to baby-universe

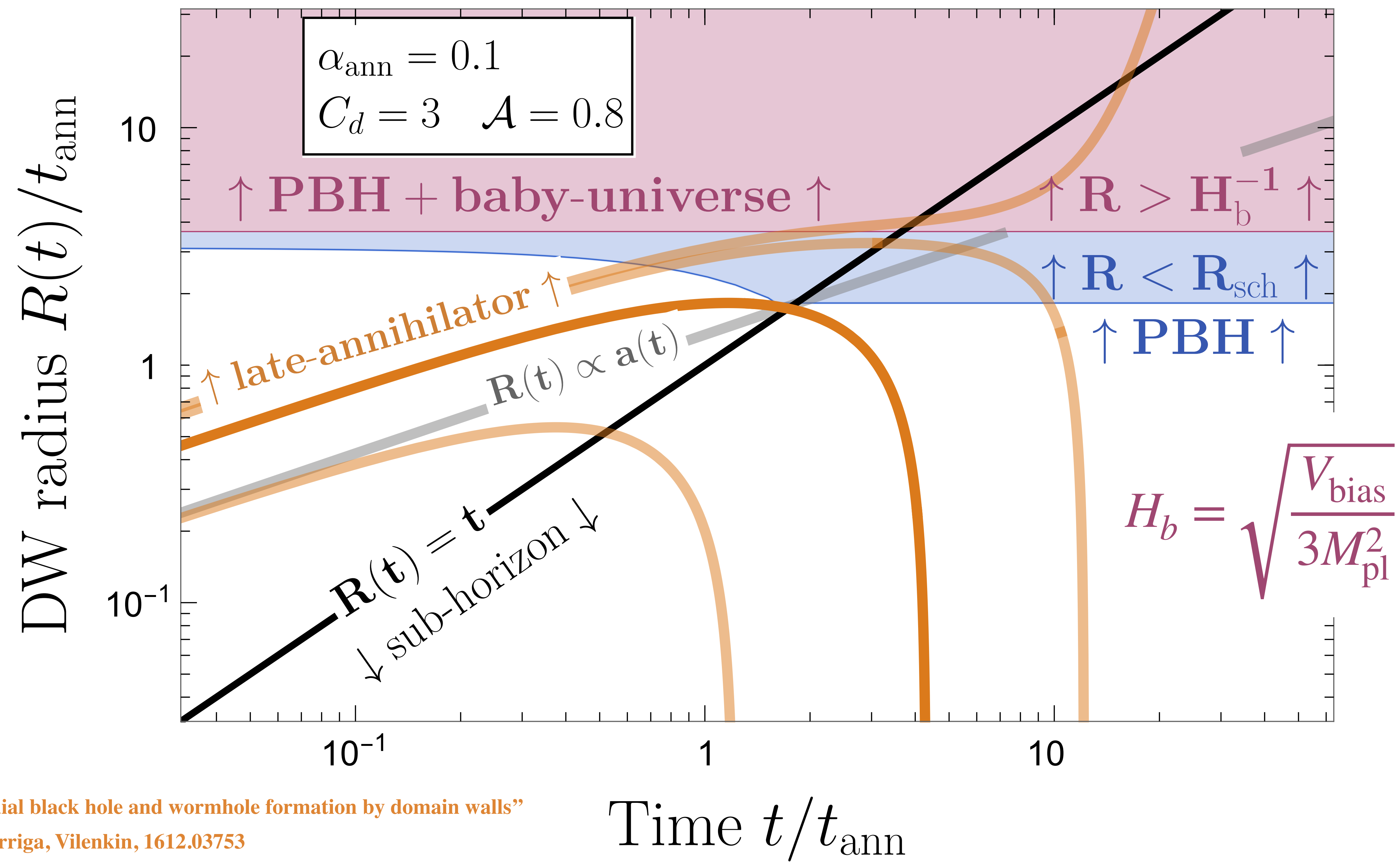








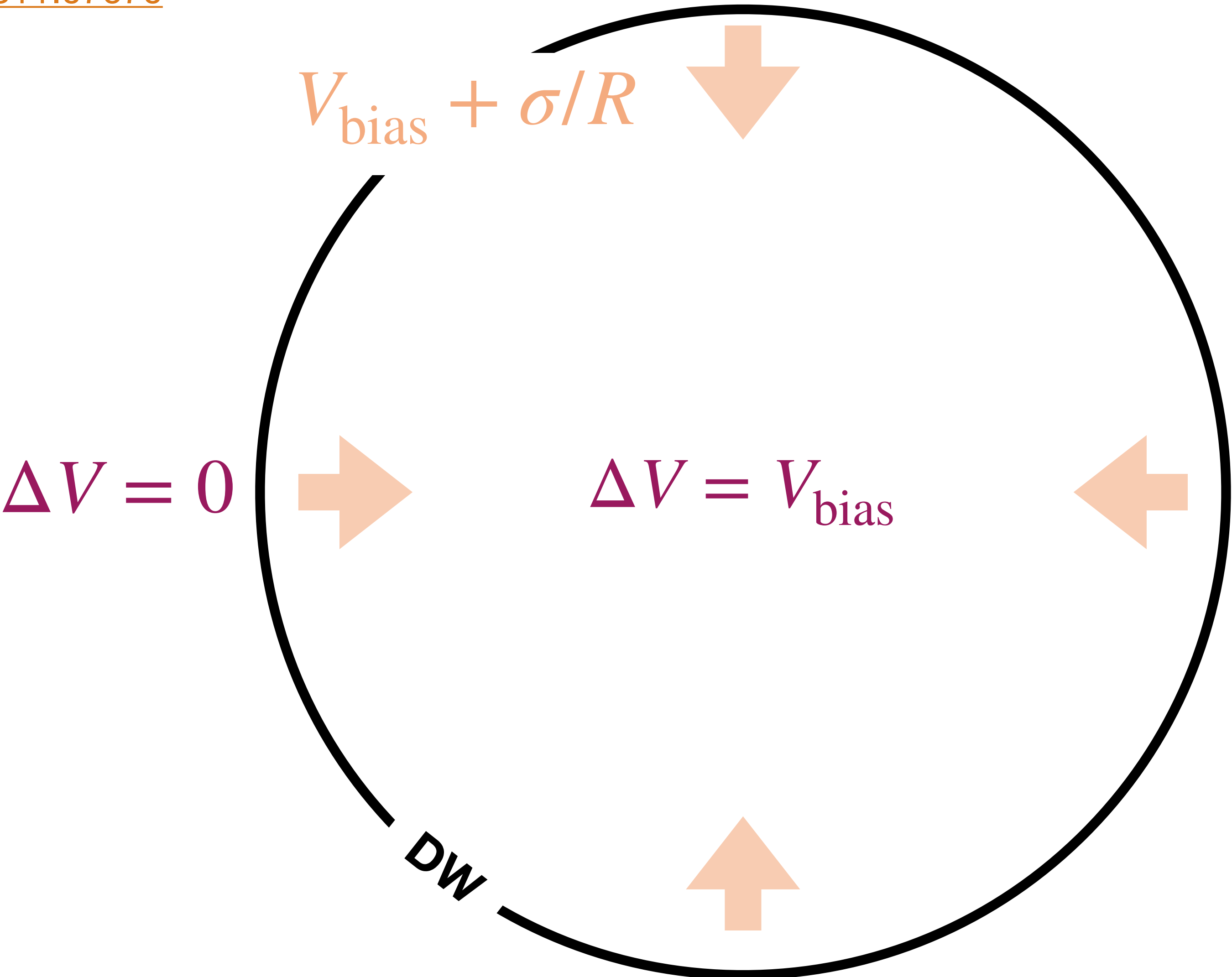


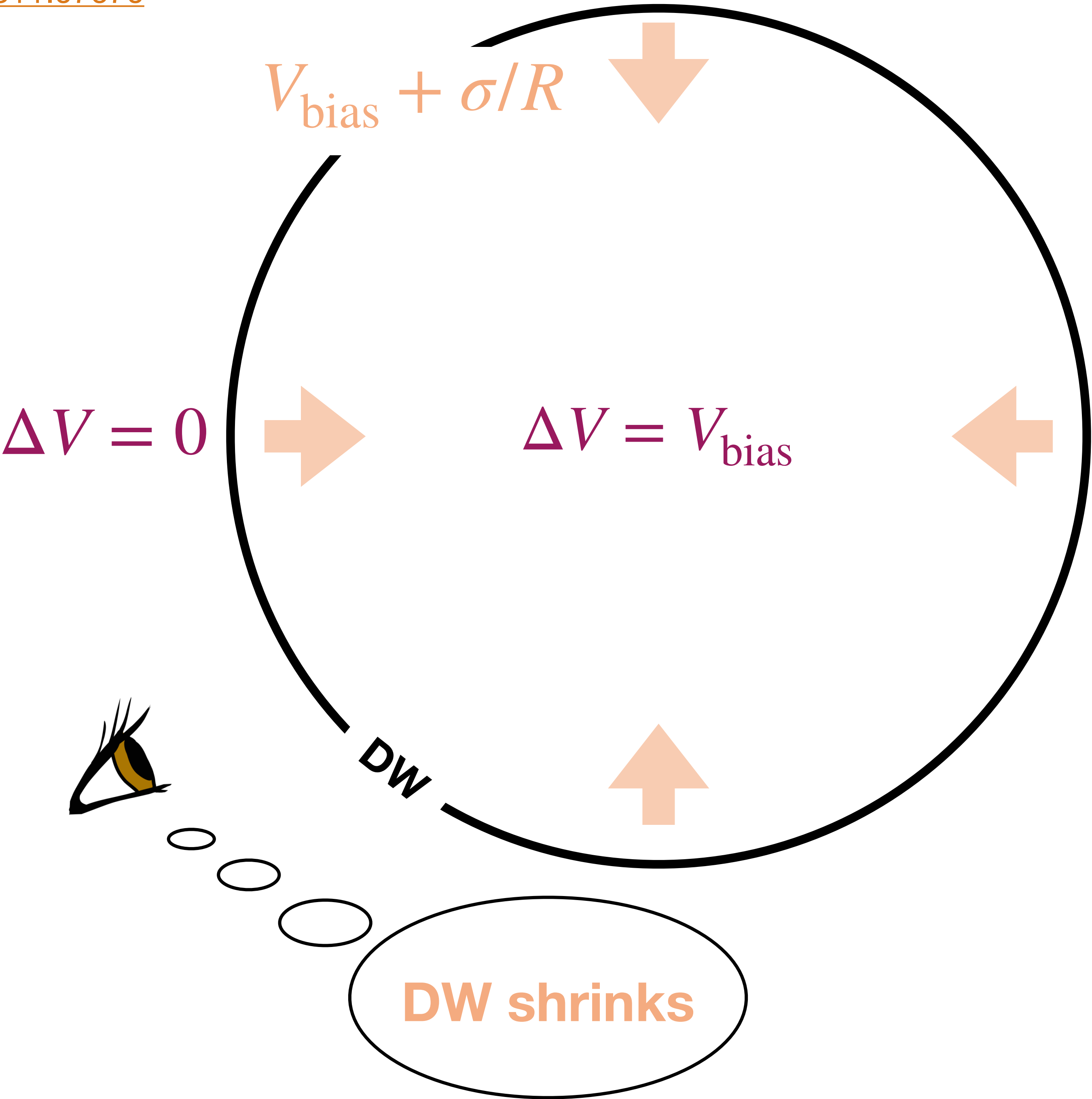


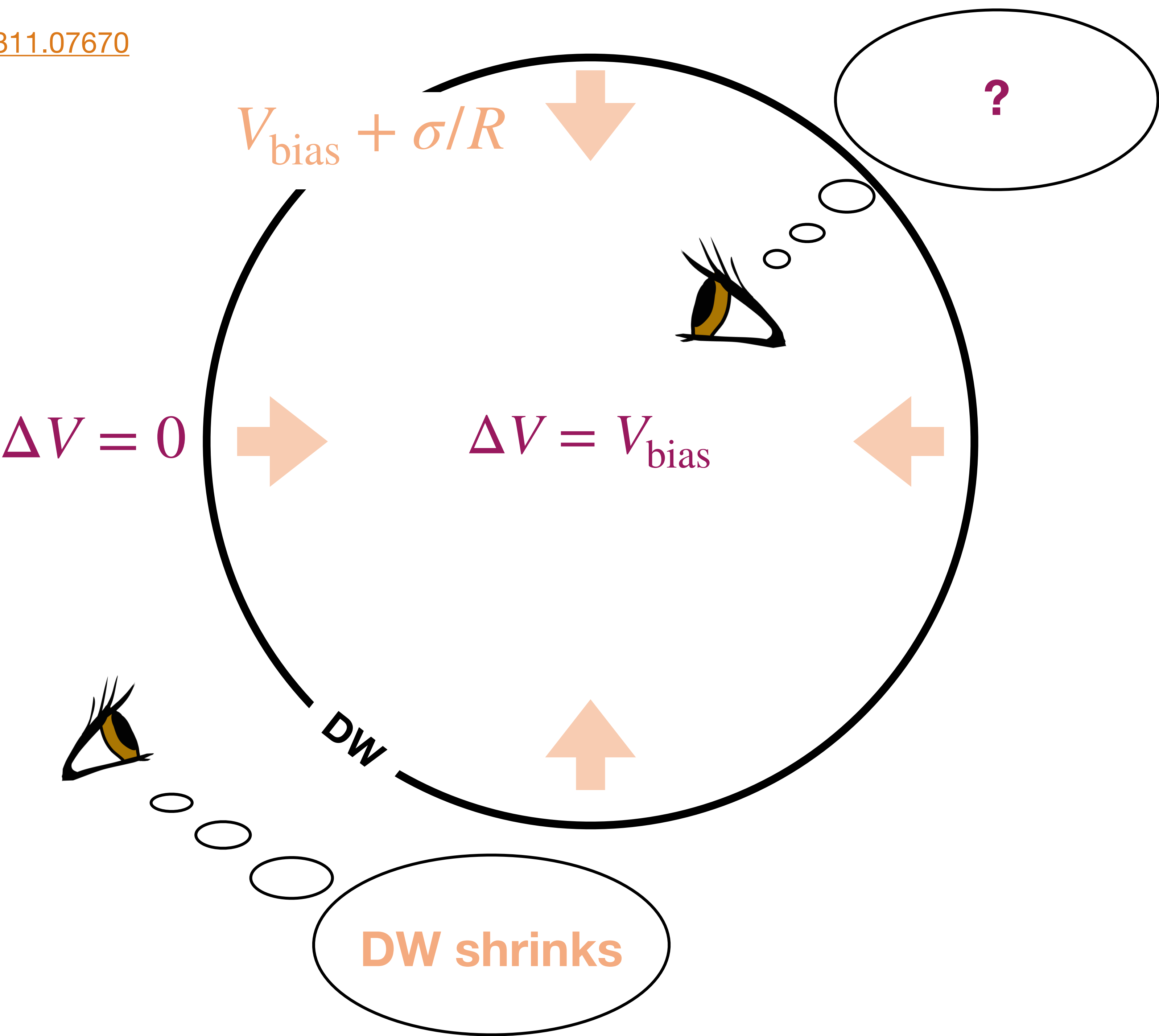
$\Delta V = 0$

$\Delta V = V_{\text{bias}}$

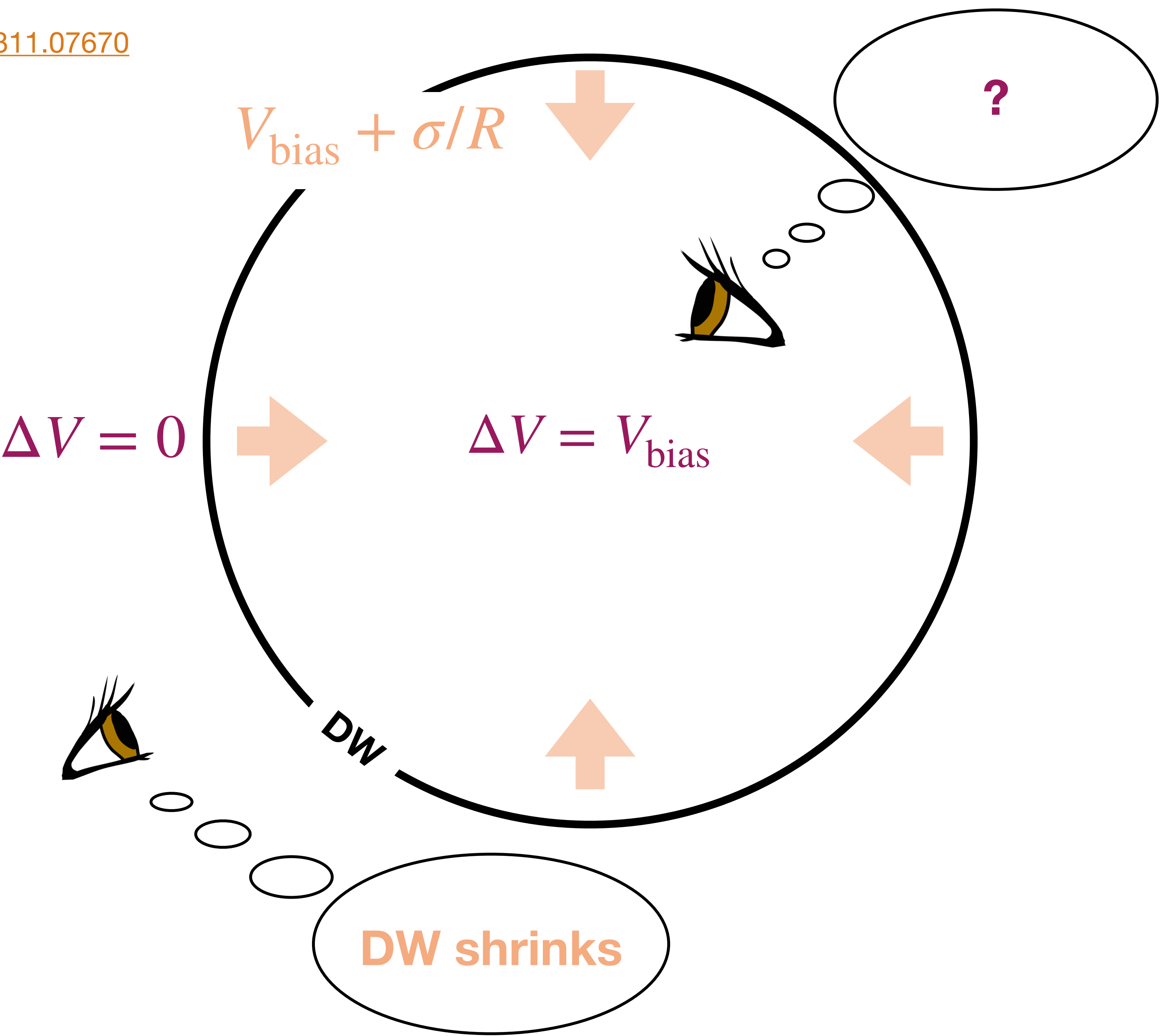
DW

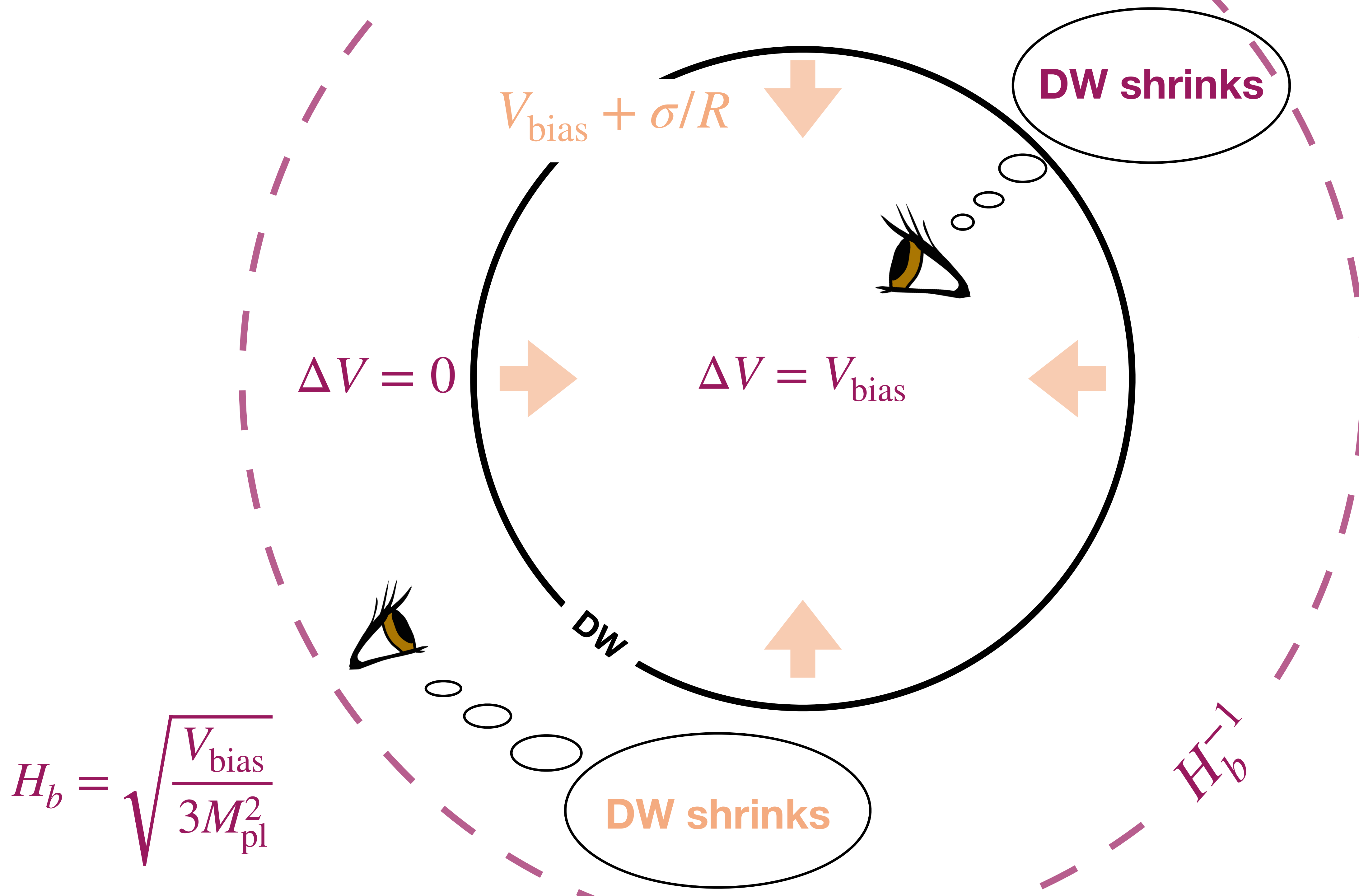


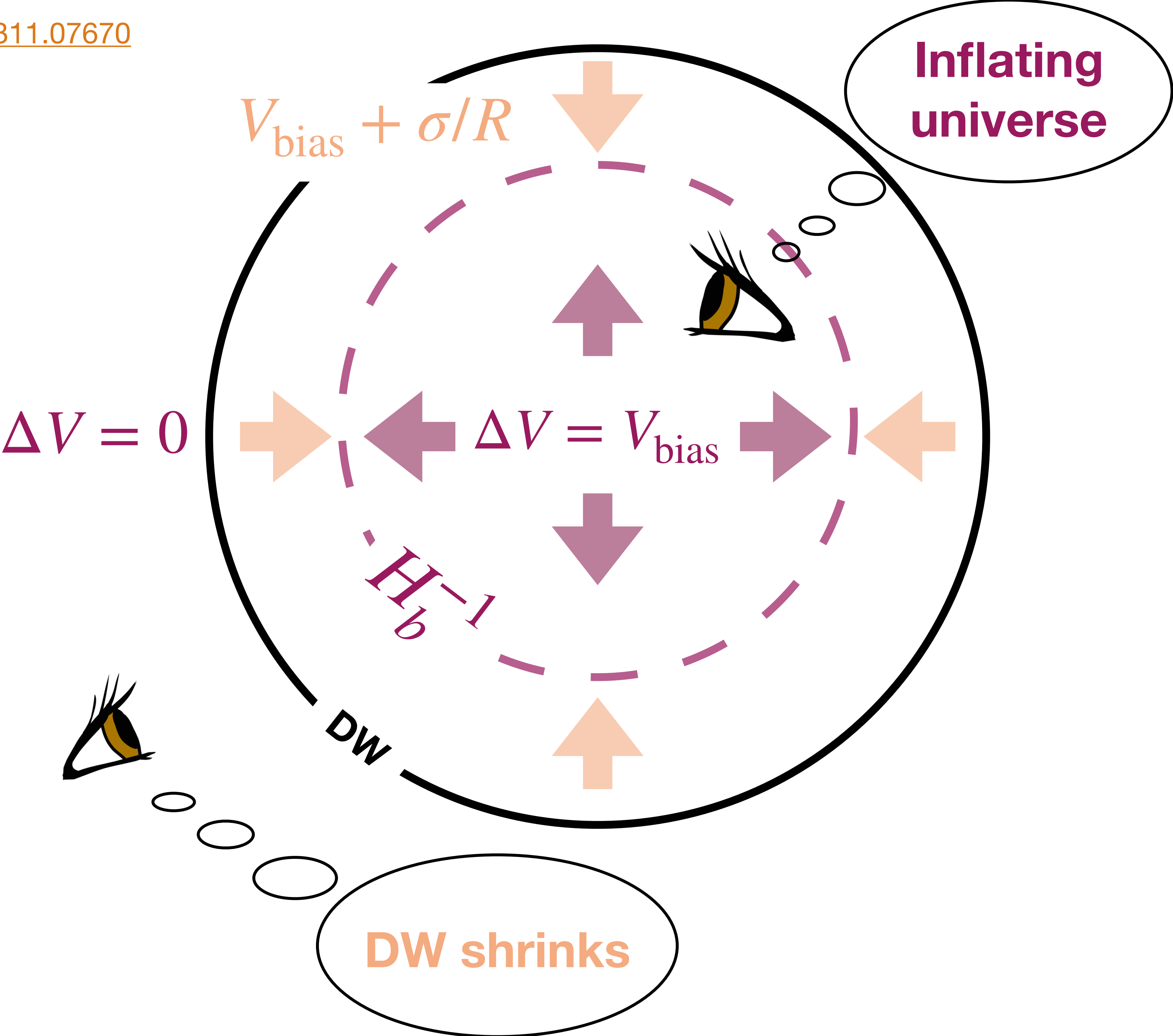


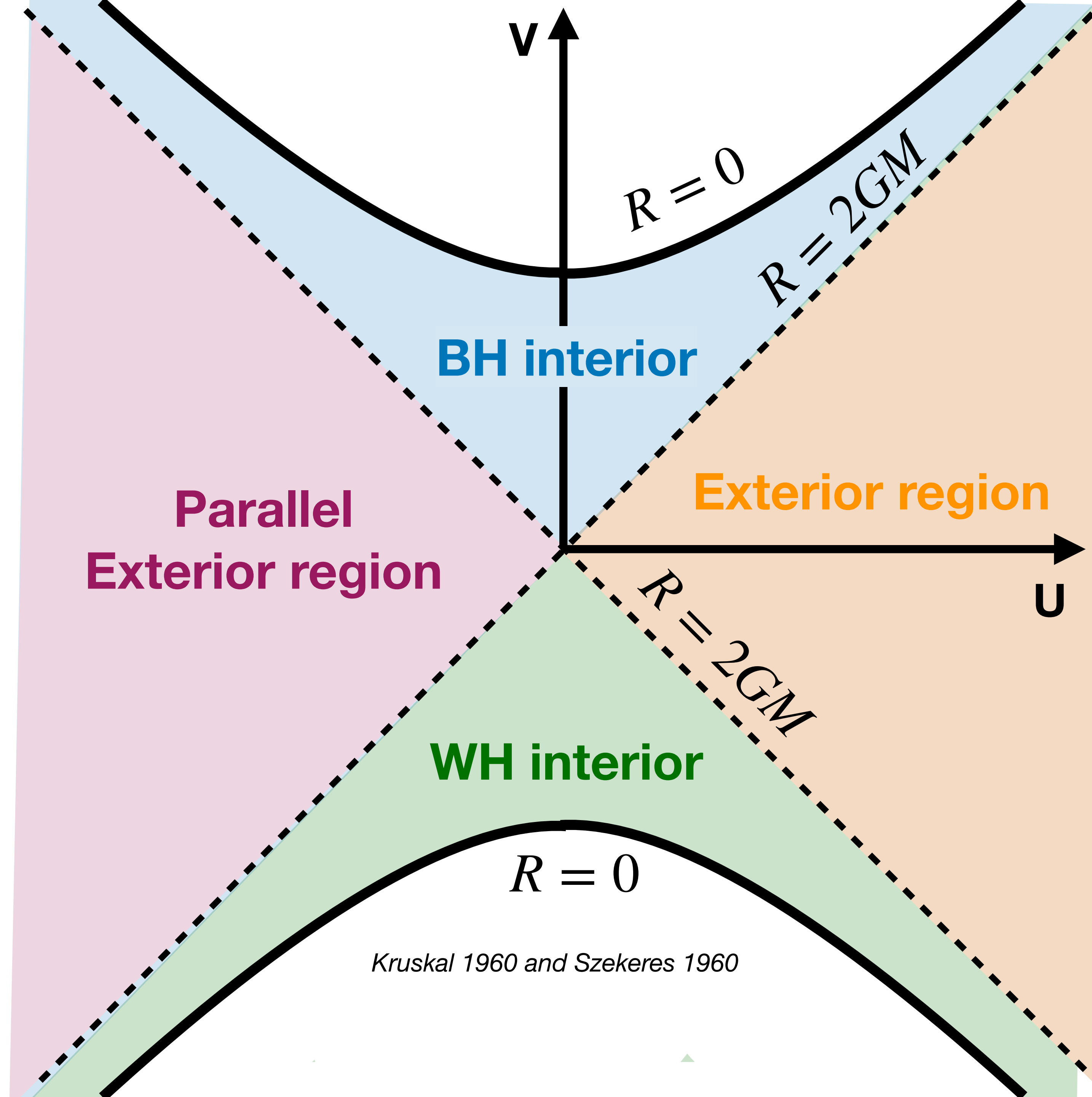


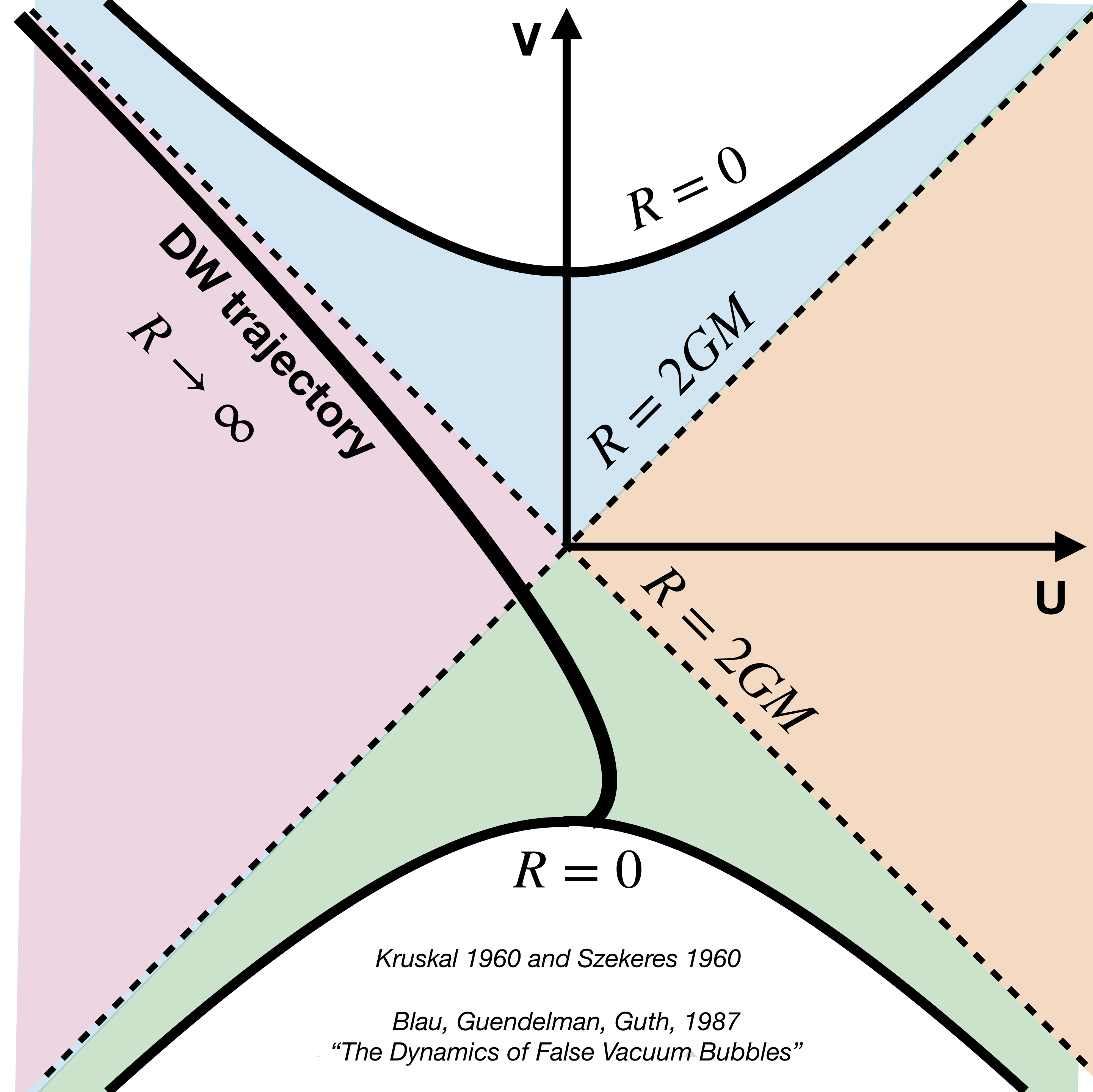
$$H_b = \sqrt{\frac{V_{\text{bias}}}{3M_{\text{pl}}^2}}$$





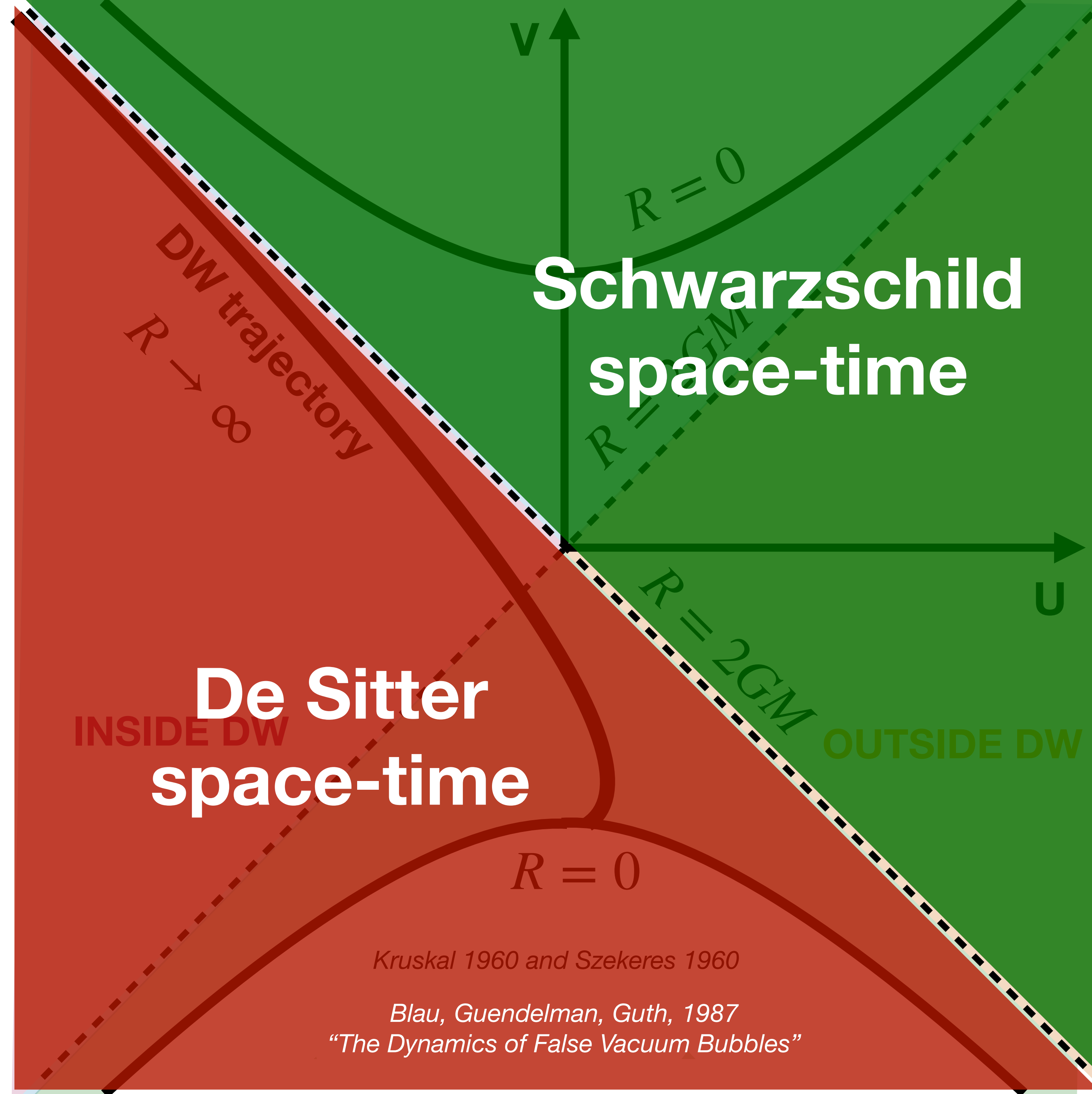


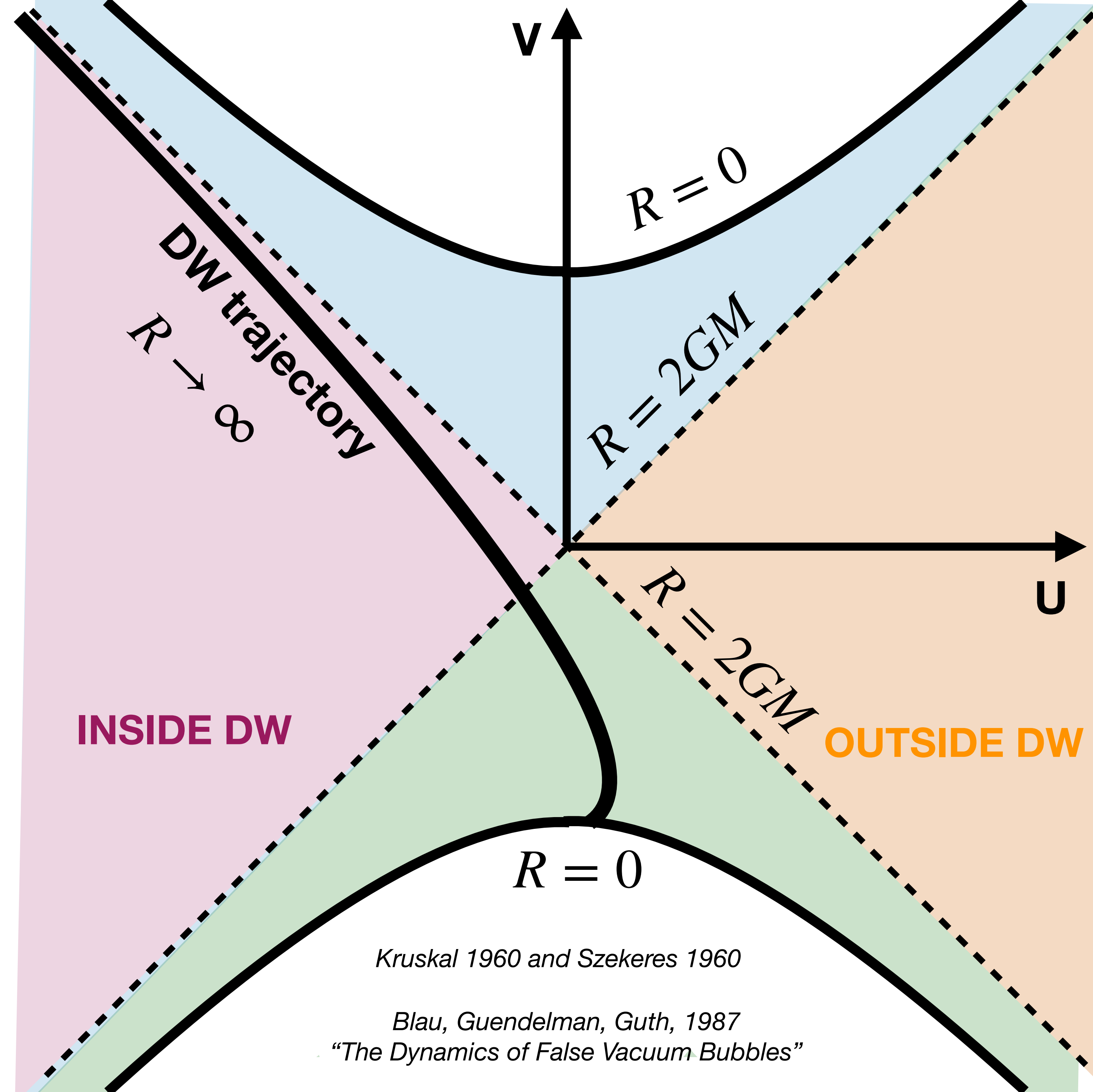




Kruskal 1960 and Szekeres 1960

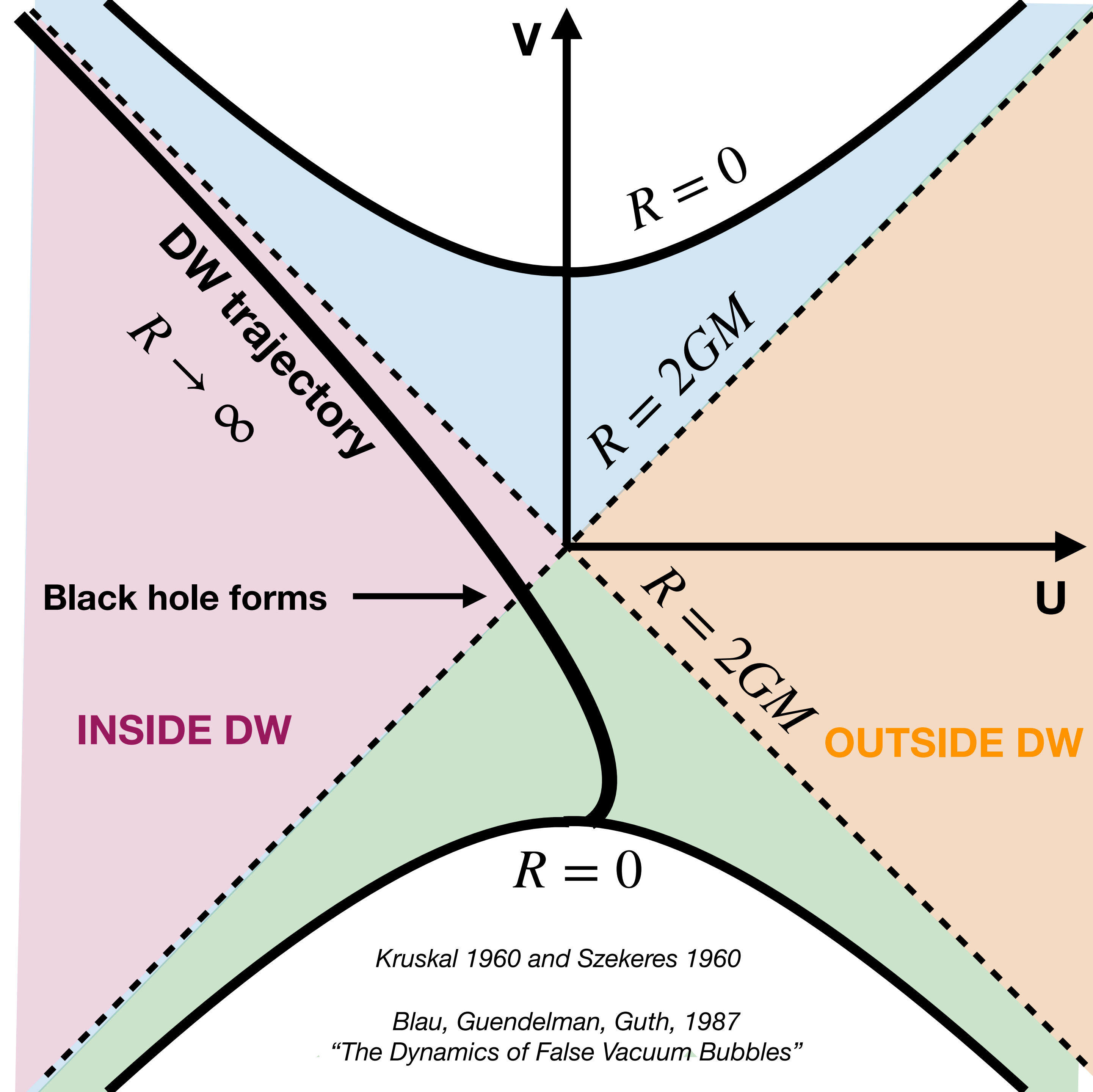
Blau, Guendelman, Guth, 1987
"The Dynamics of False Vacuum Bubbles"





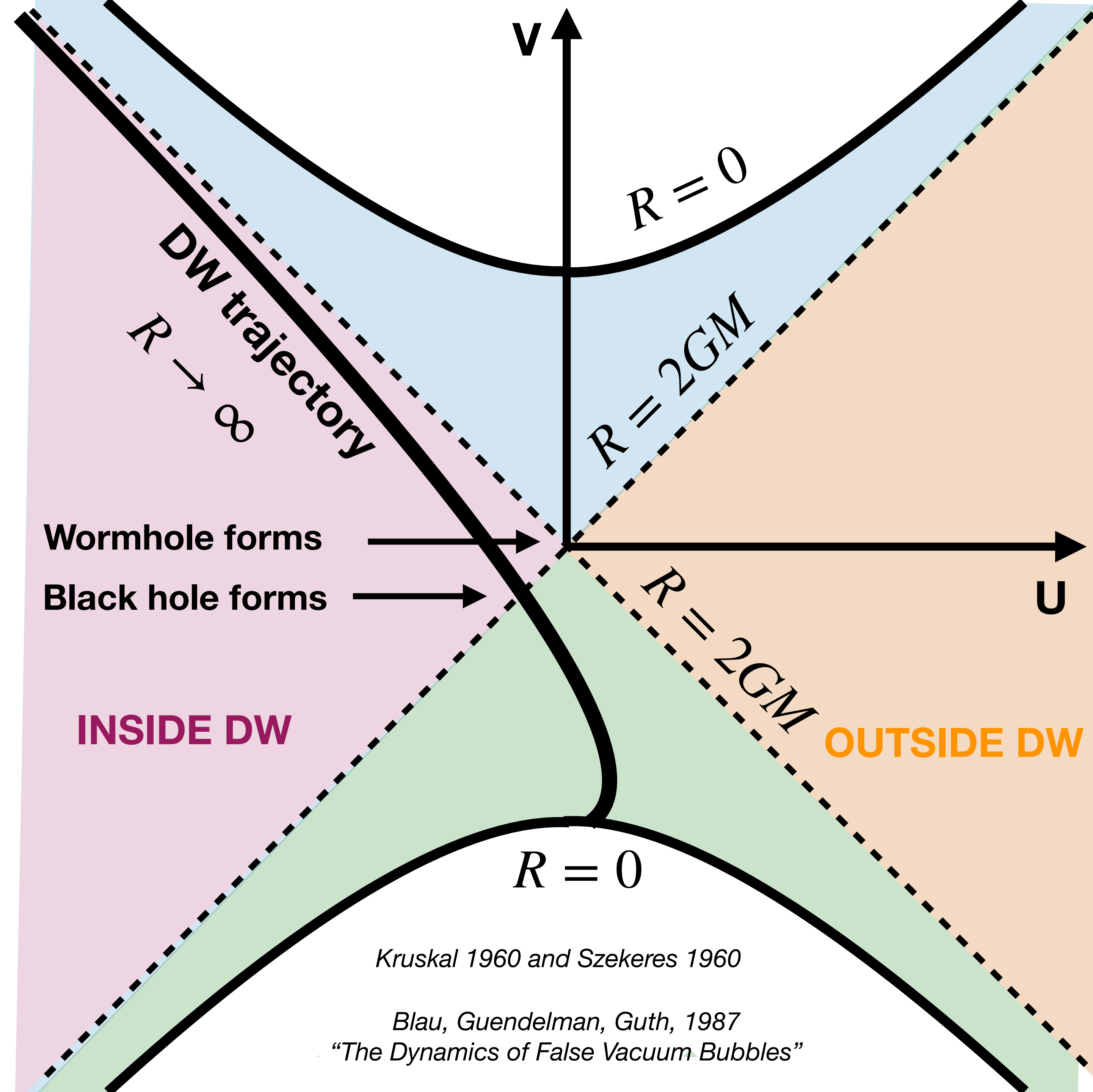
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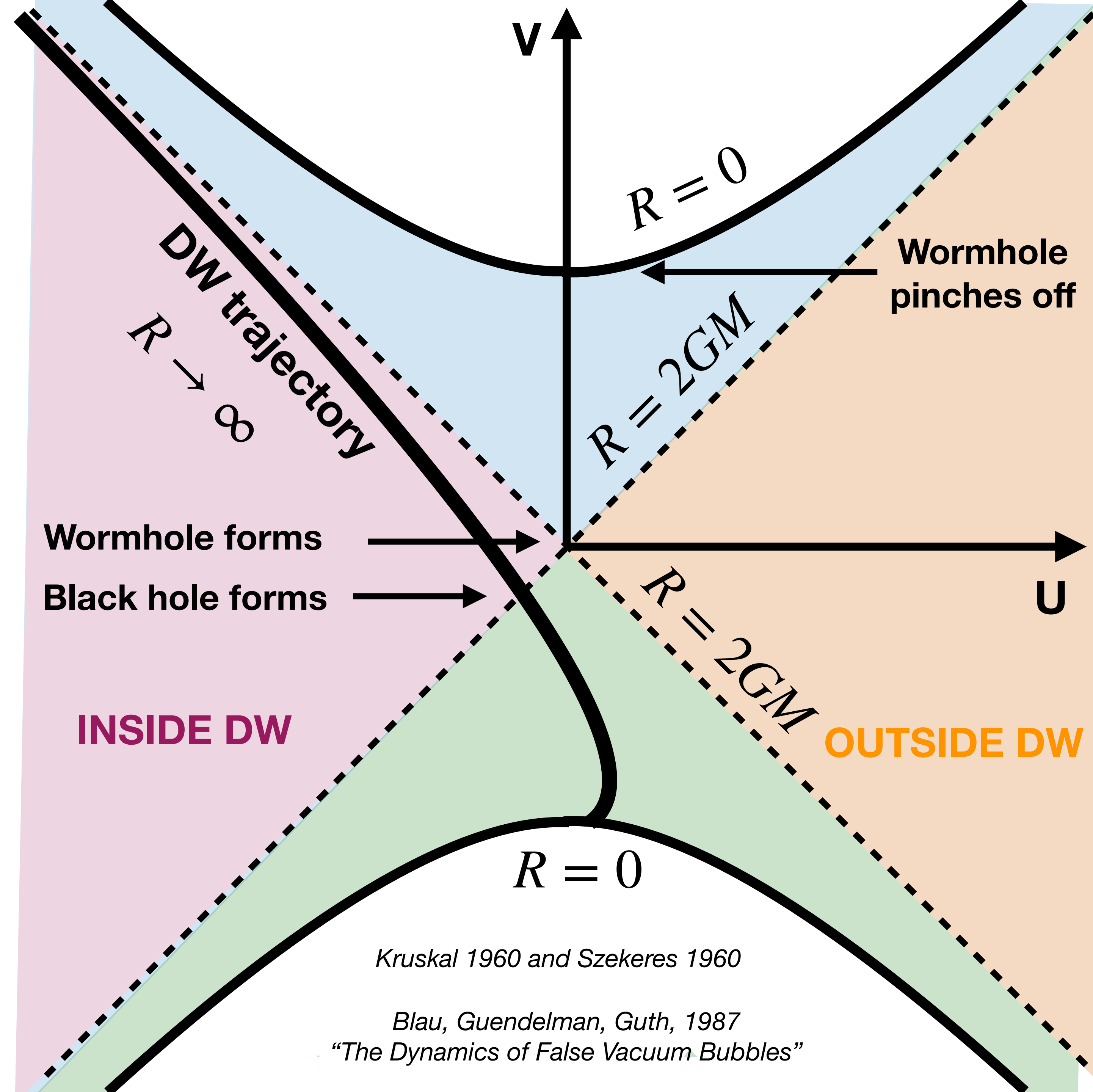
Kruskal 1960 and Szekeres 1960

*Blau, Guendelman, Guth, 1987
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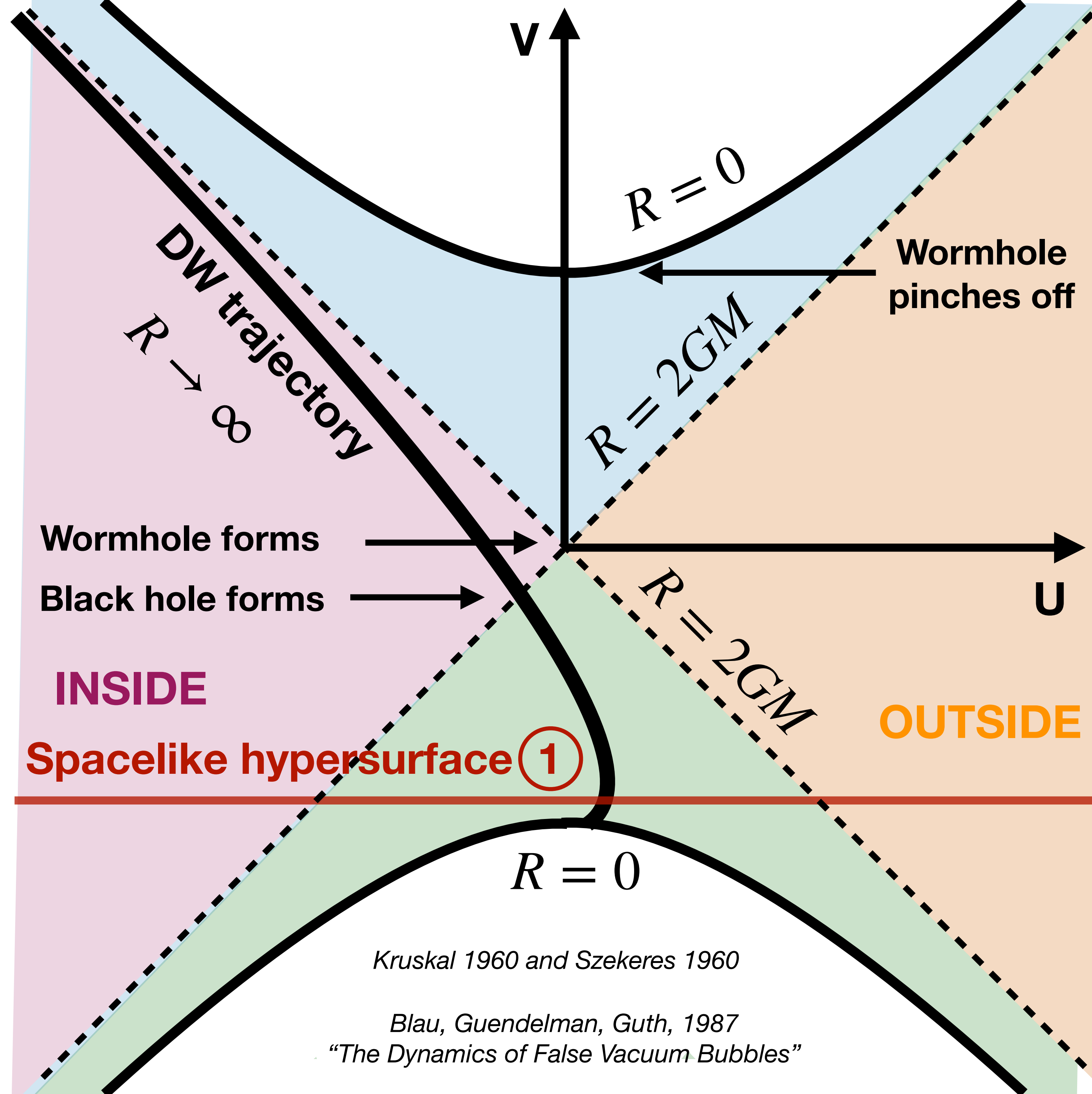
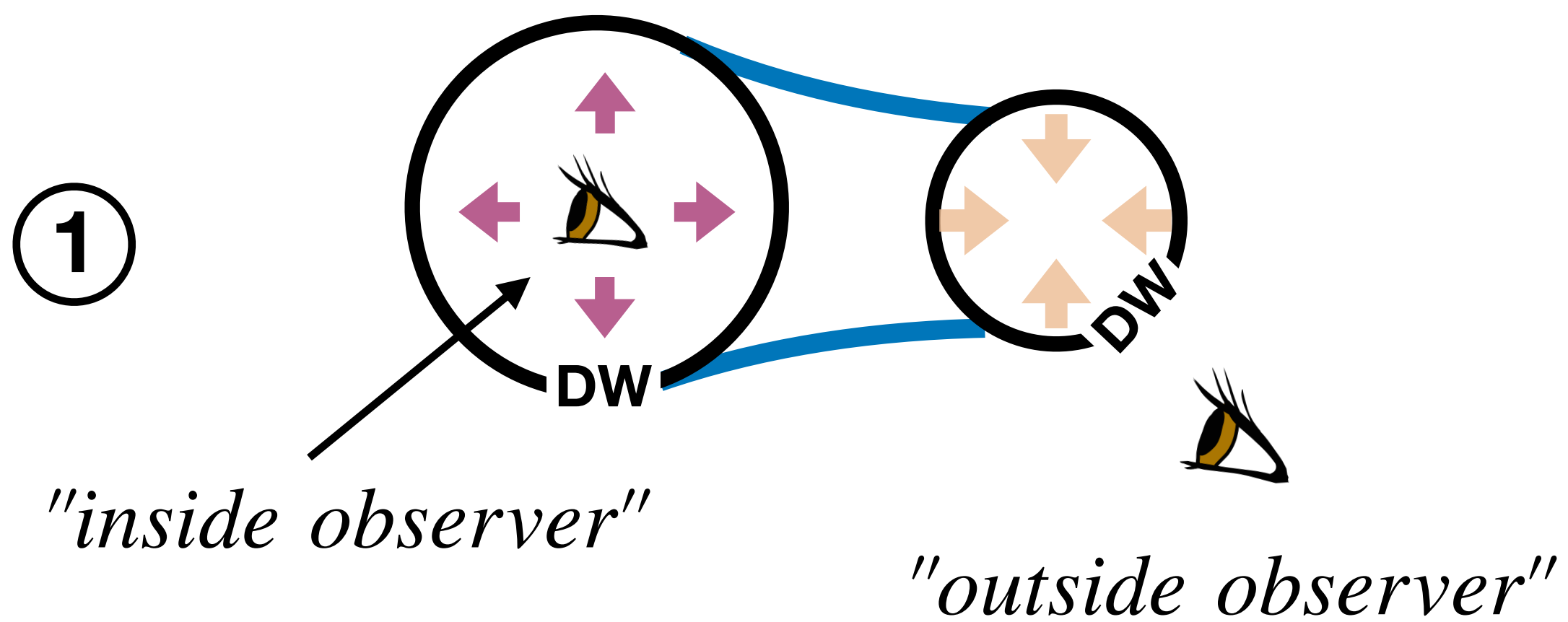
Kruskal 1960 and Szekeres 1960

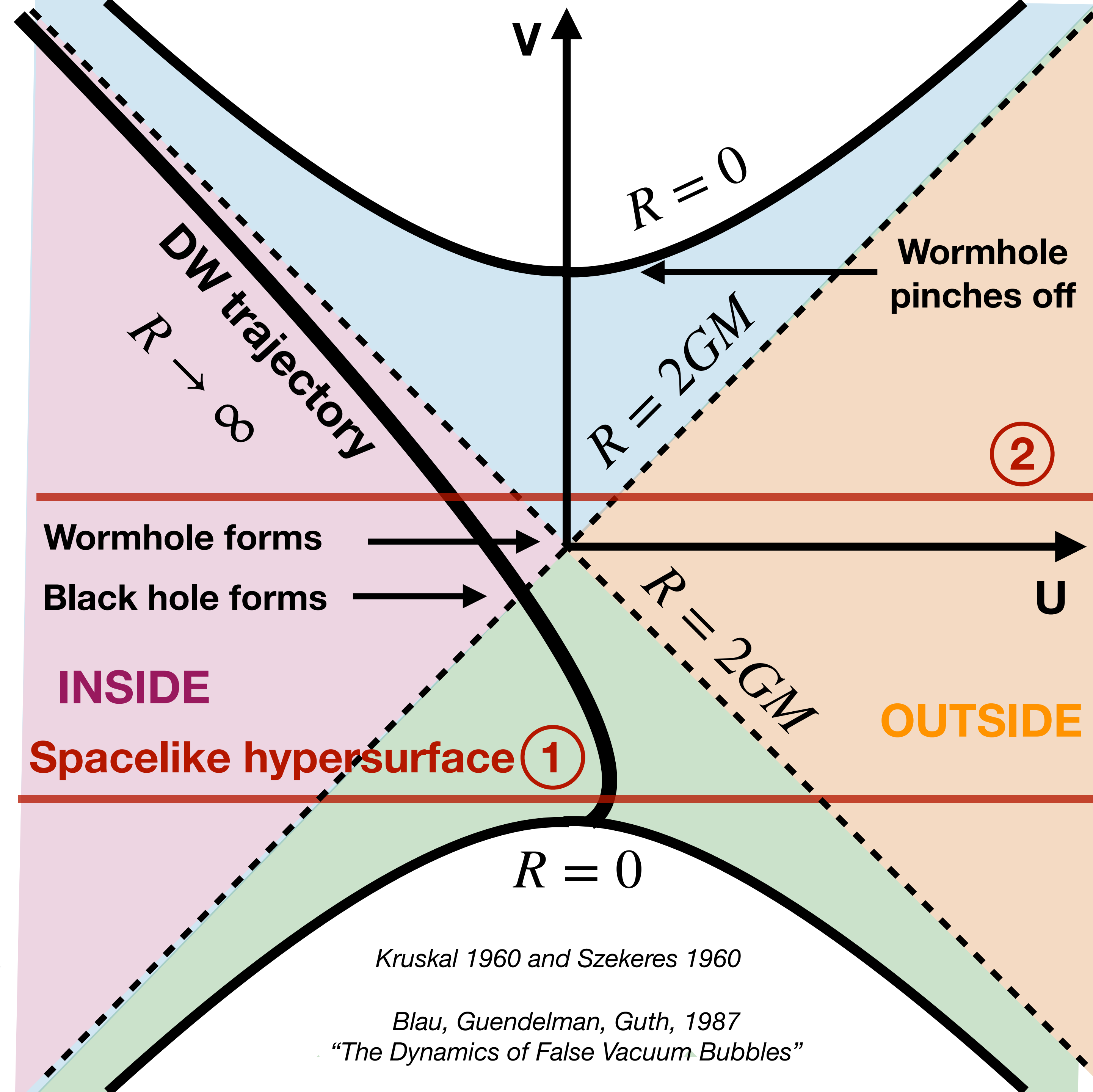
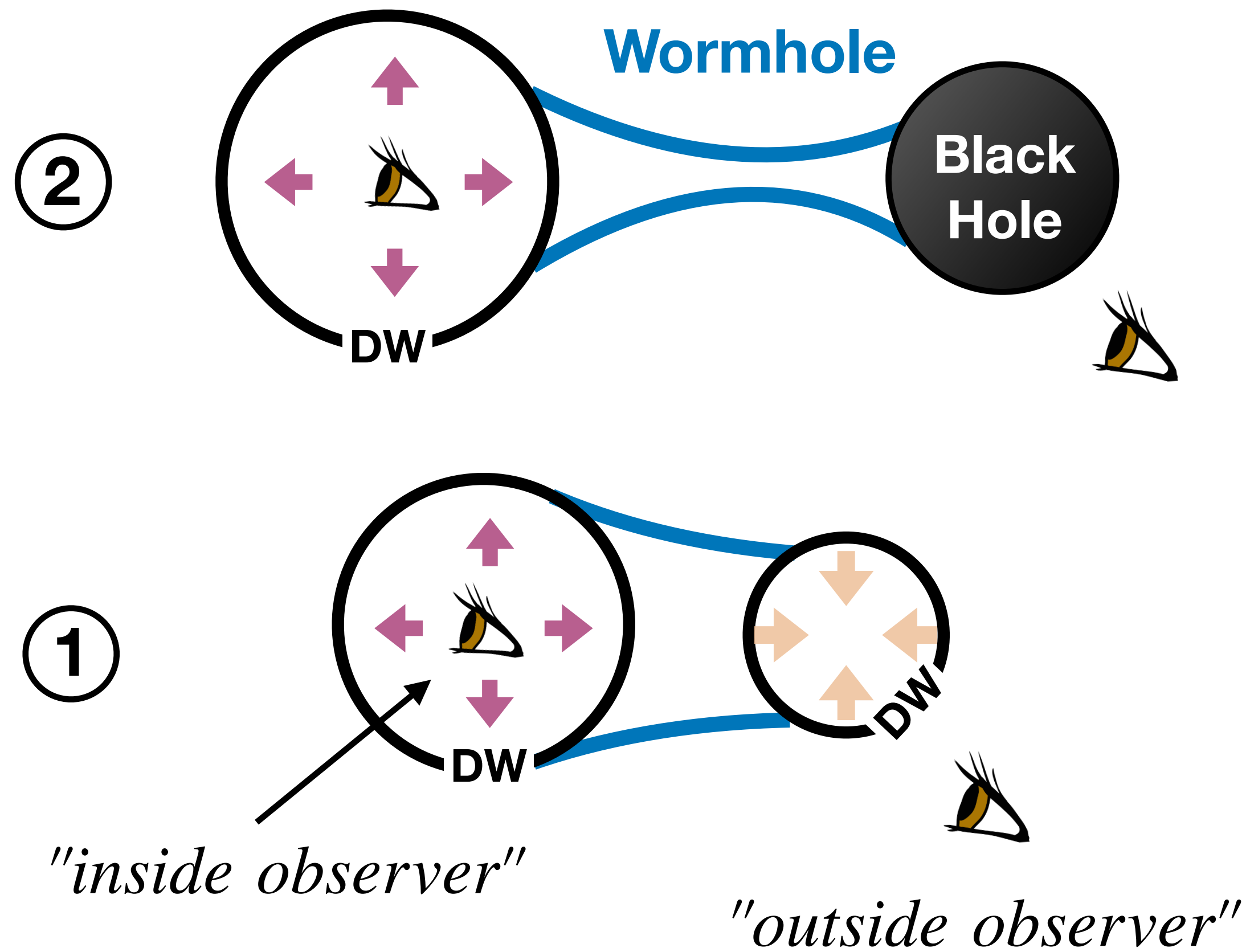
Blau, Guendelman, Guth, 1987
"The Dynamics of False Vacuum Bubbles"



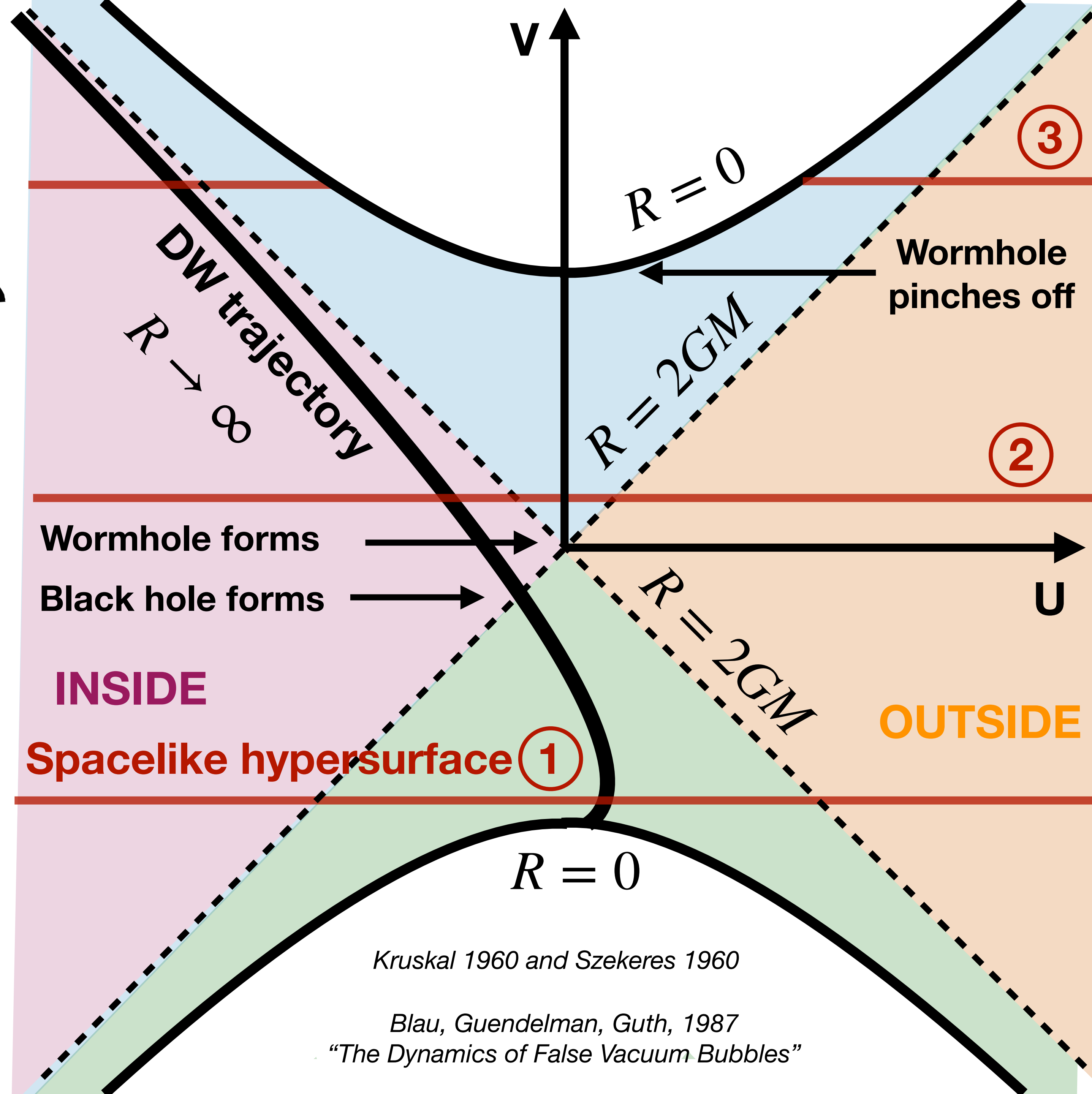
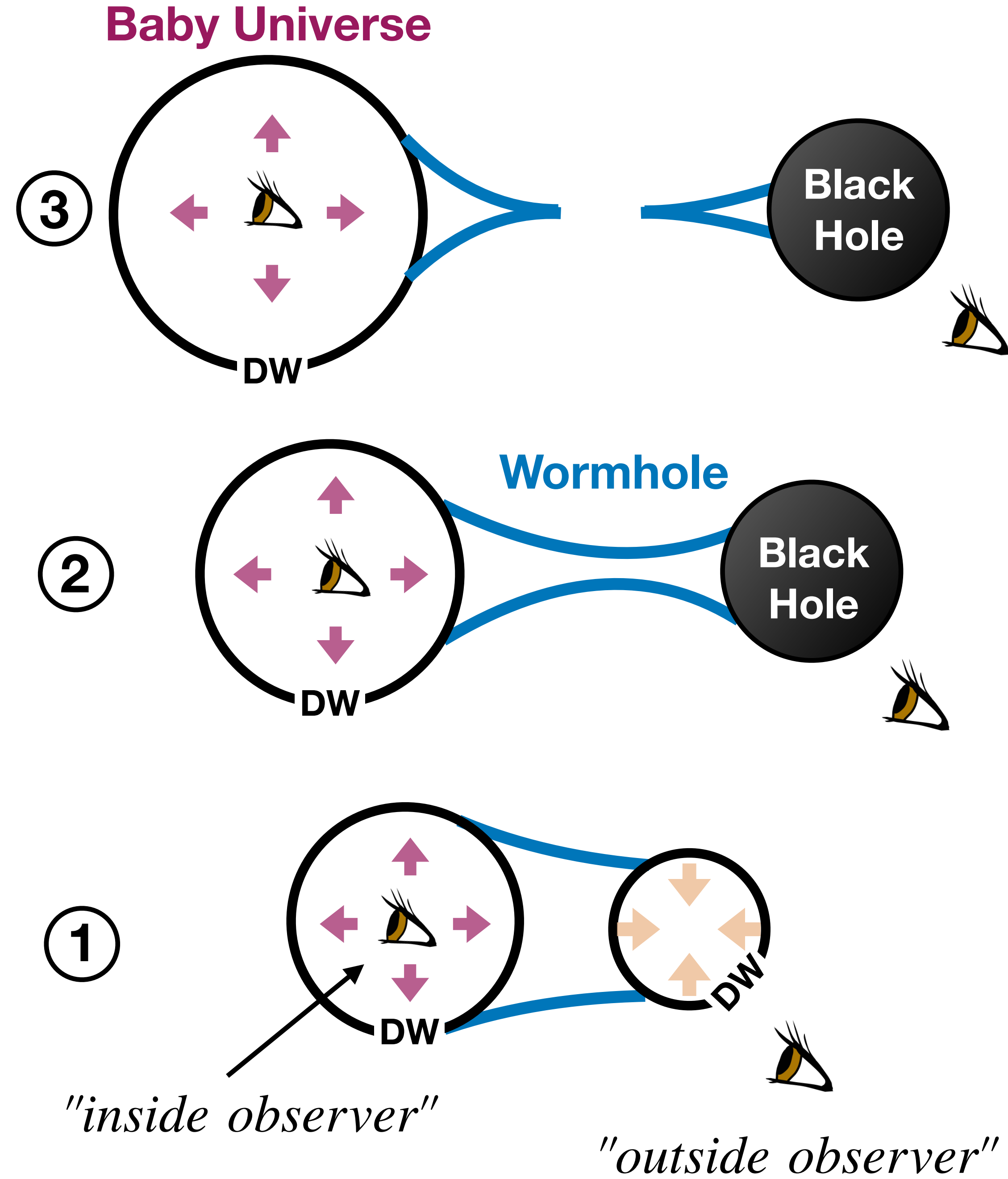
Kruskal 1960 and Szekeres 1960

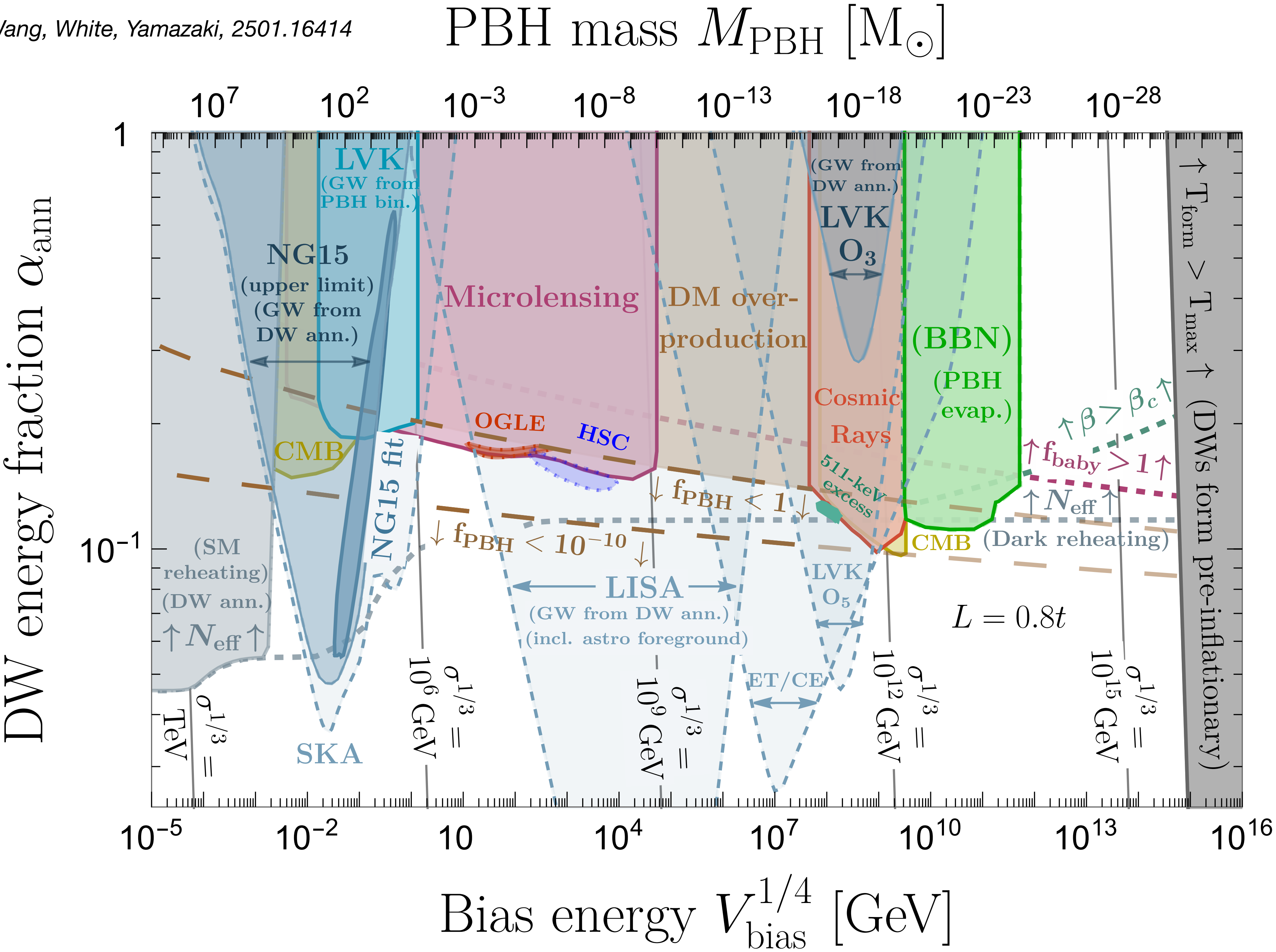
Blau, Guendelman, Guth, 1987
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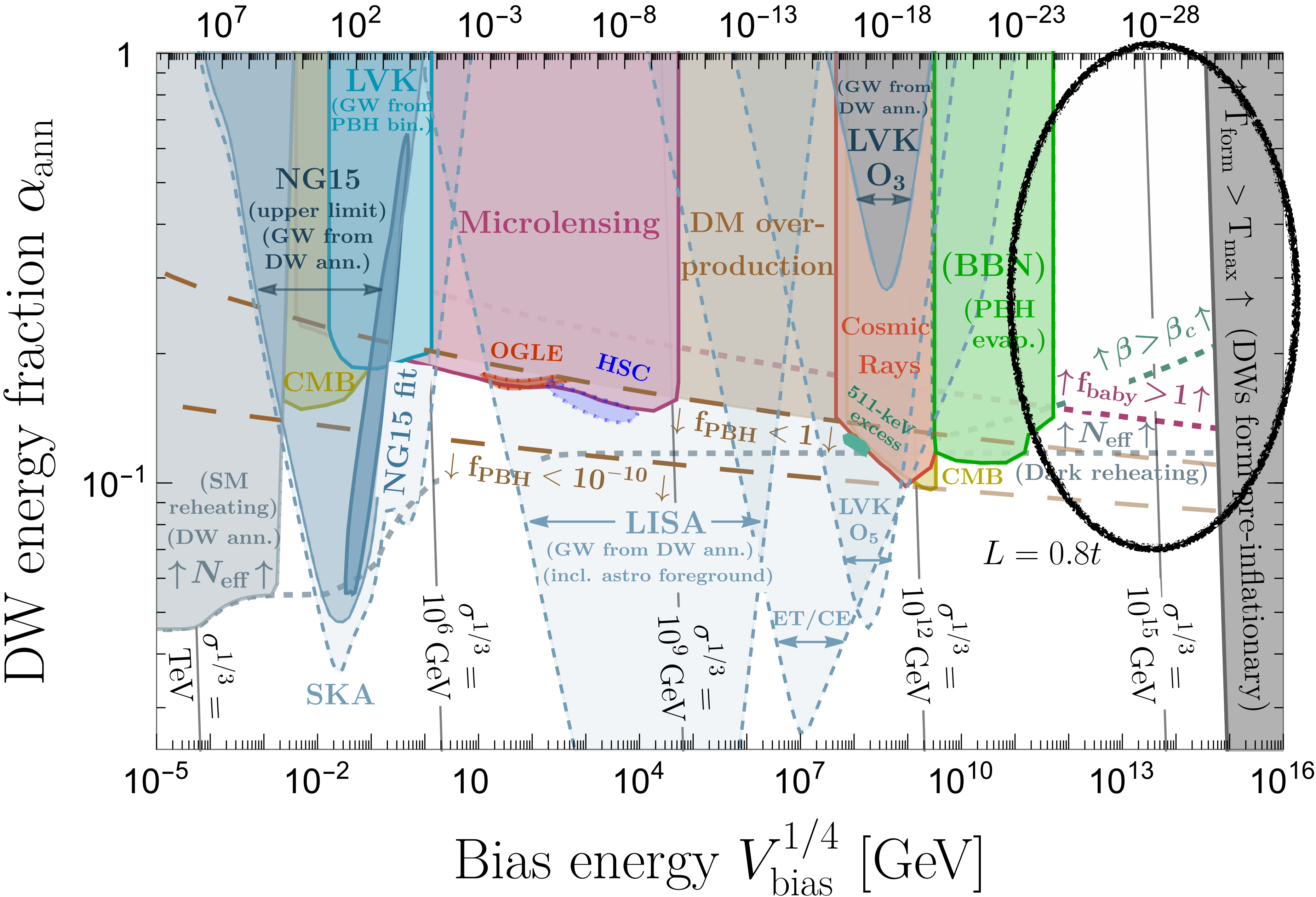


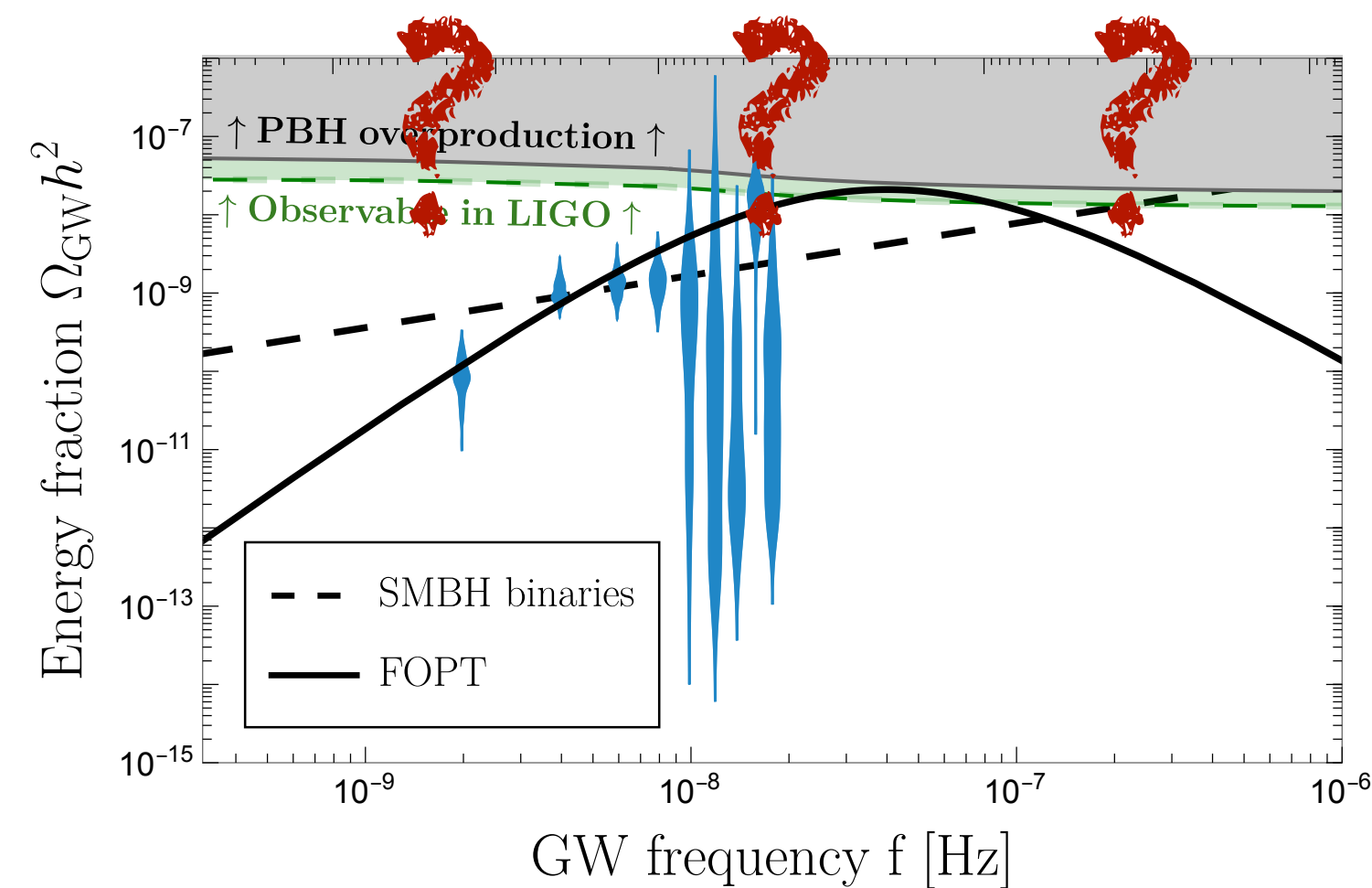
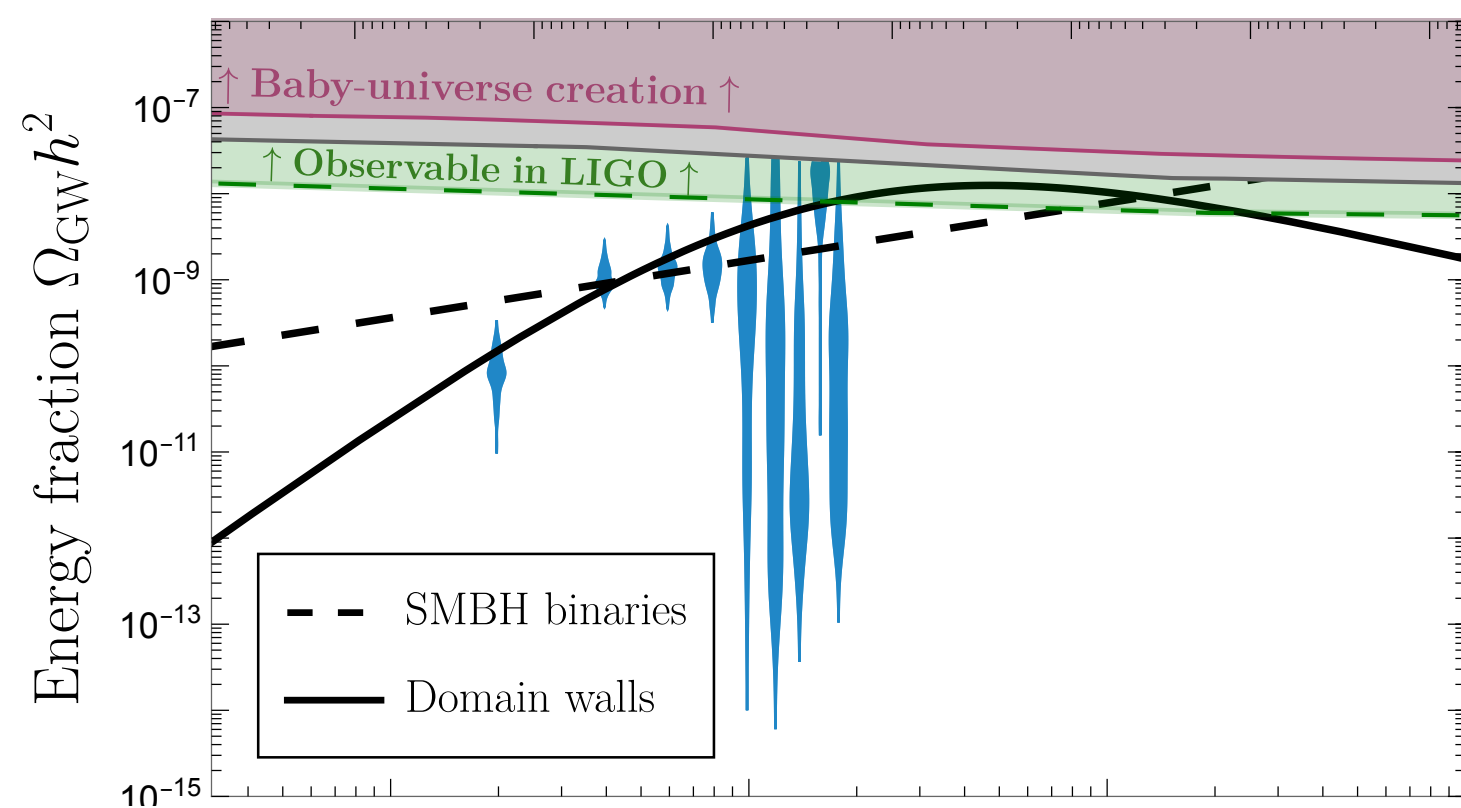
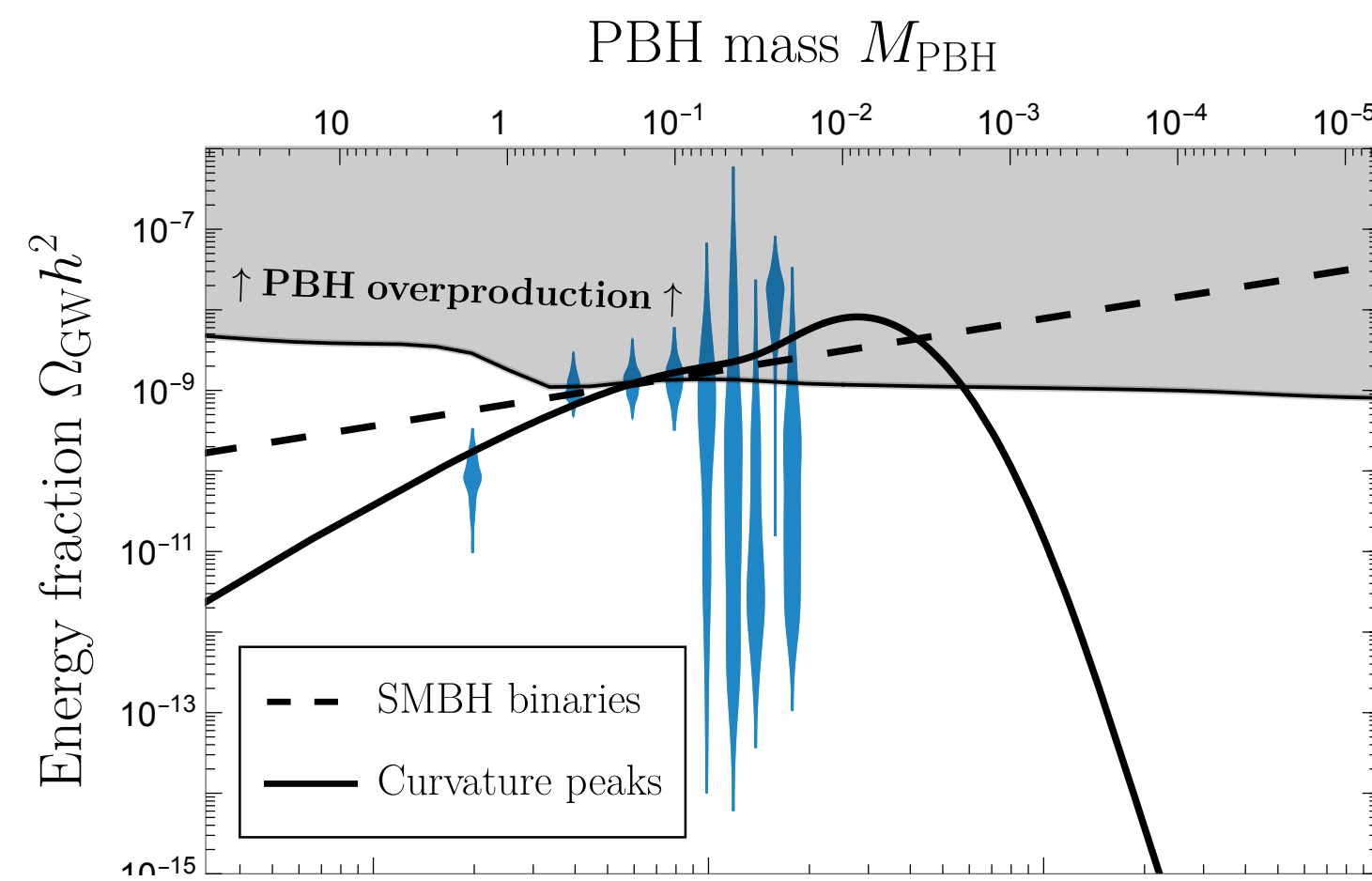


Baby Universe









Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

Domain wall networks

Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841

First-order phase transitions

Roper Pol et al. (2201.05630)

Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczec, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

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Baby-universe

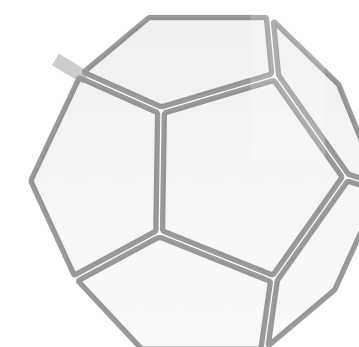
Deng, Garriga, Vilenkin (1612.03753)

Wormhole

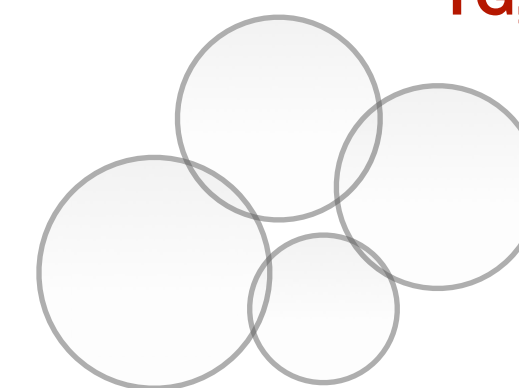
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670



PBH



Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

YG&Volansky 2023,

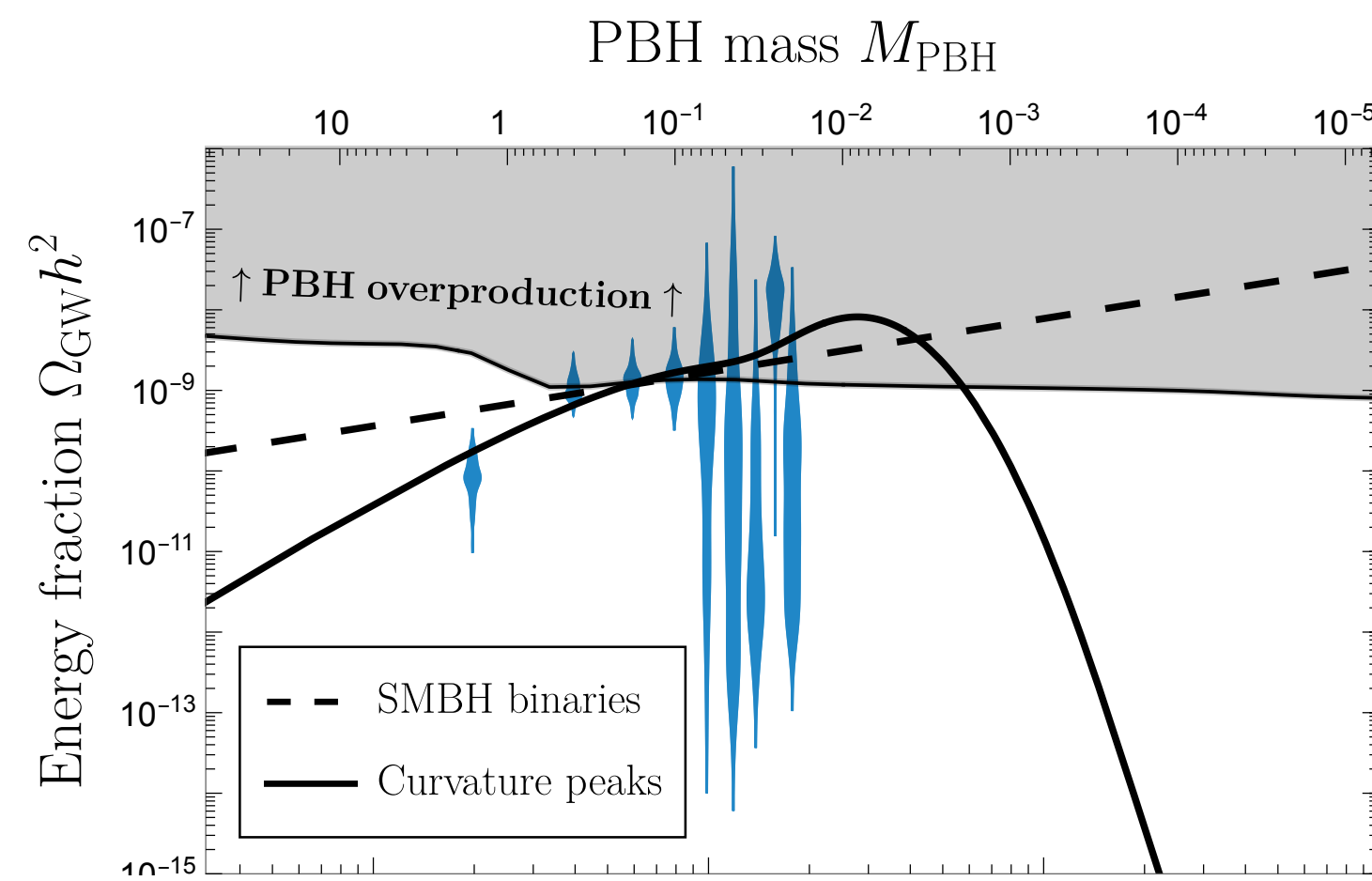
YG (2307.04239)

Sasaki+ 1982, Bian+ 2021, Lu+ 2022,

Lewicki, Toczec, Vaskonen 2023,

Baldes+ 2023,

Lewicki, Toczec, Vaskonen 2024,



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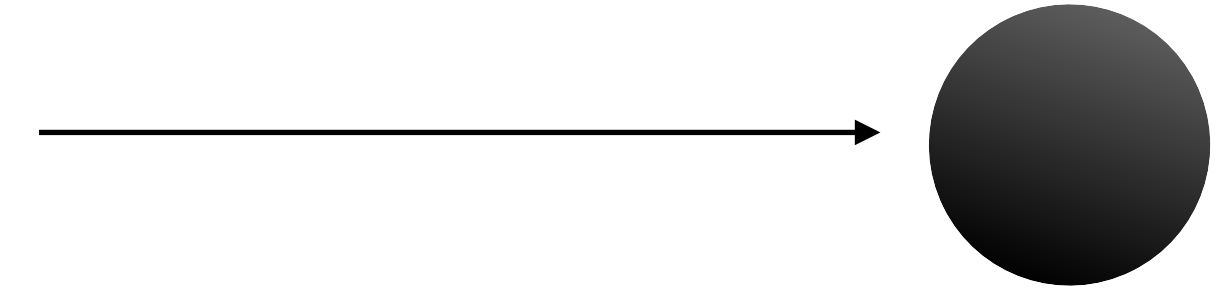
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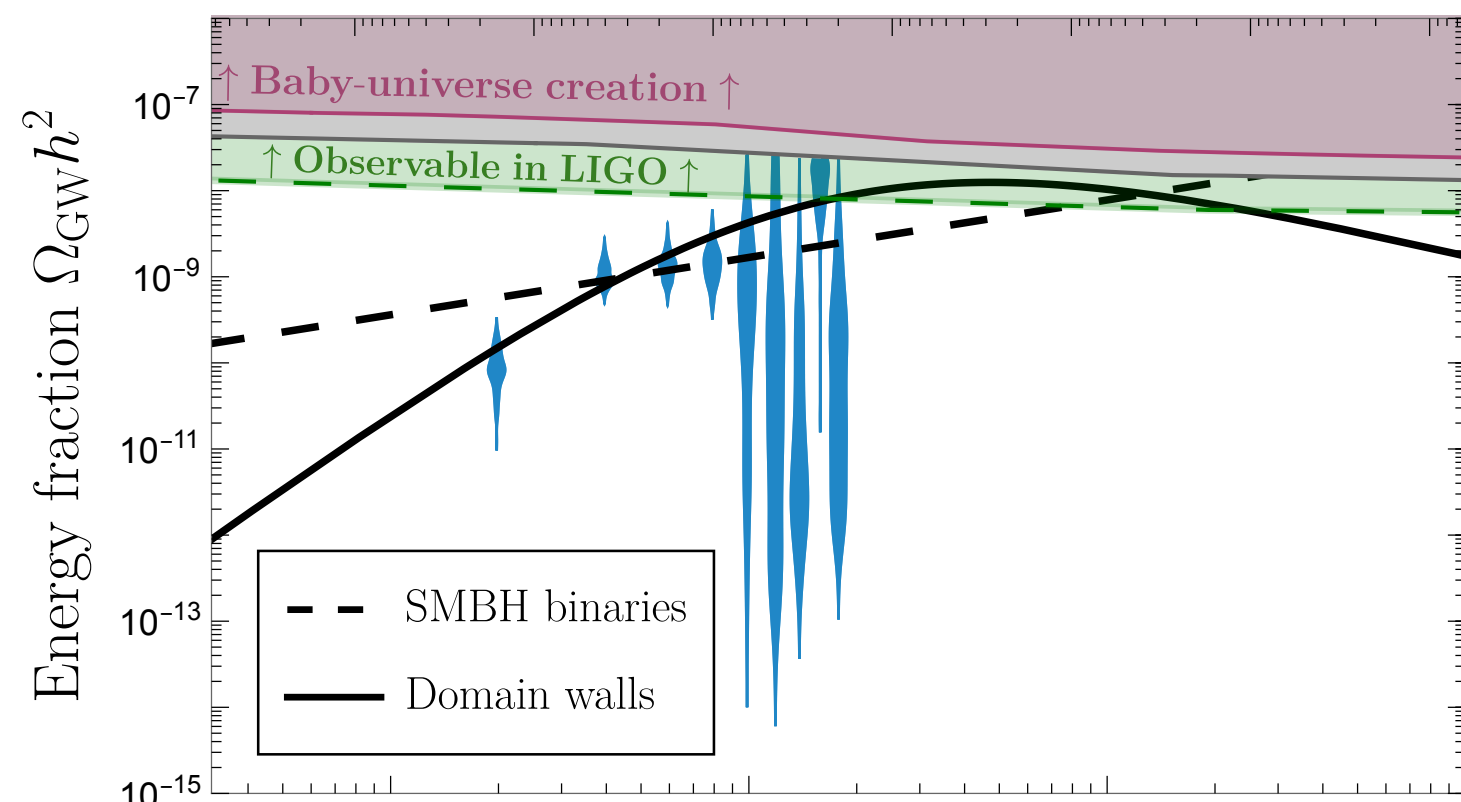
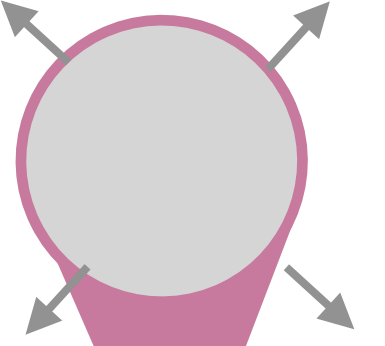
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Baby-universe



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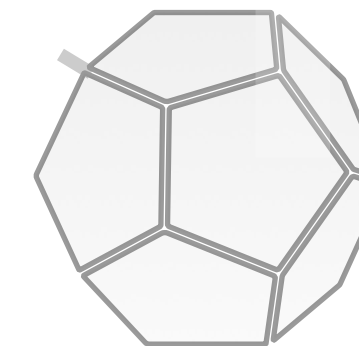
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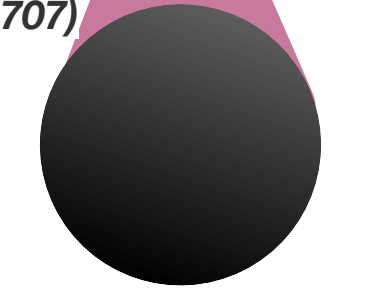
YG, Vitagliano 2306.17841



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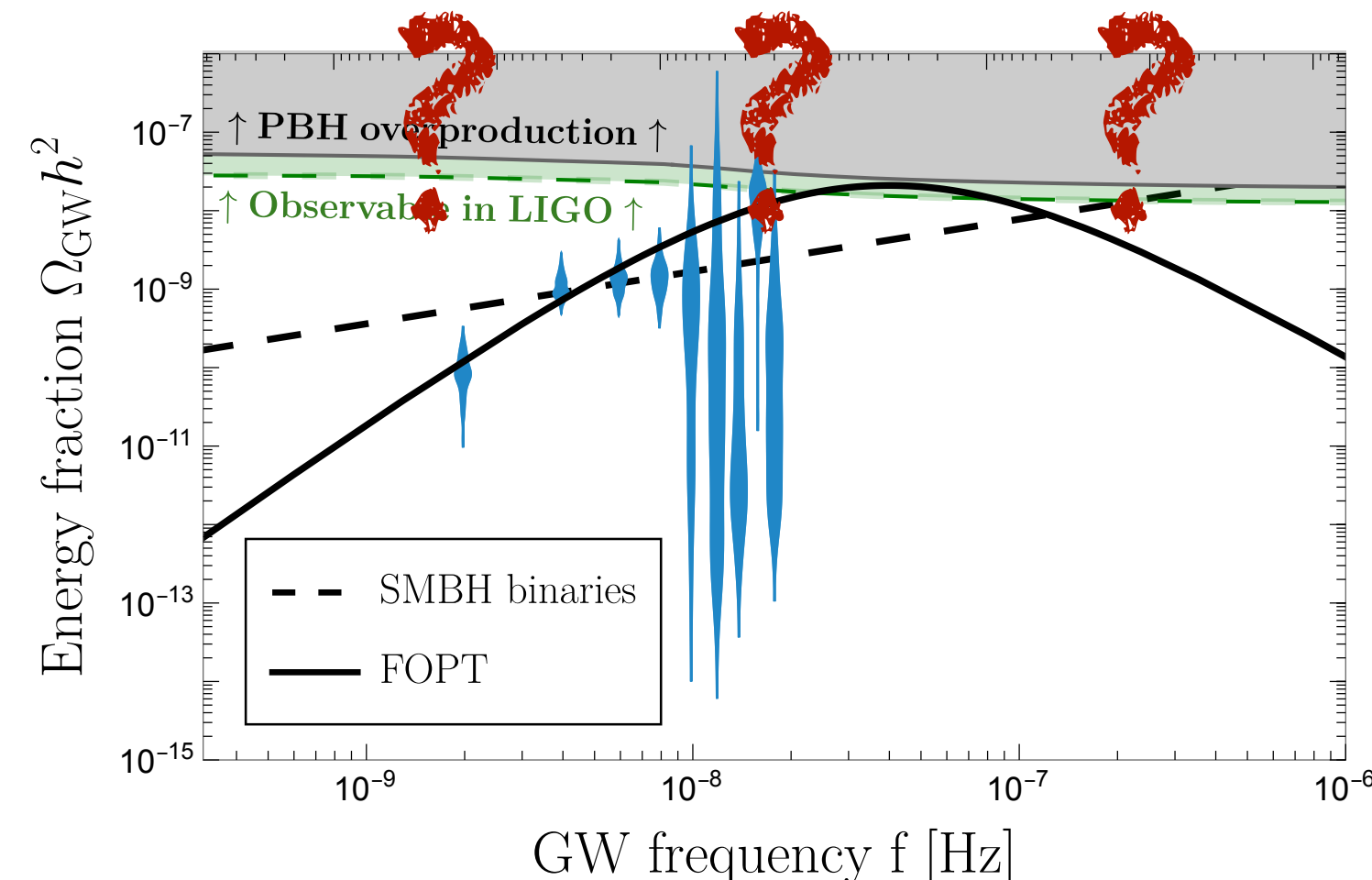
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Roper Pol et al. (2201.05630)

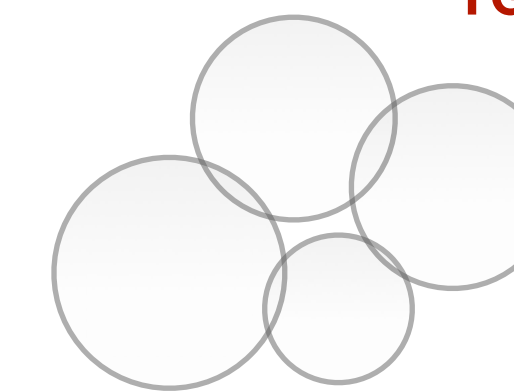
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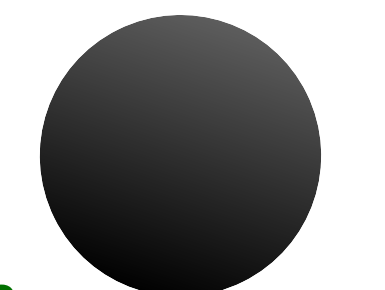
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Sasaki+ 1982, Bian+ 2021, Lu+ 2022,

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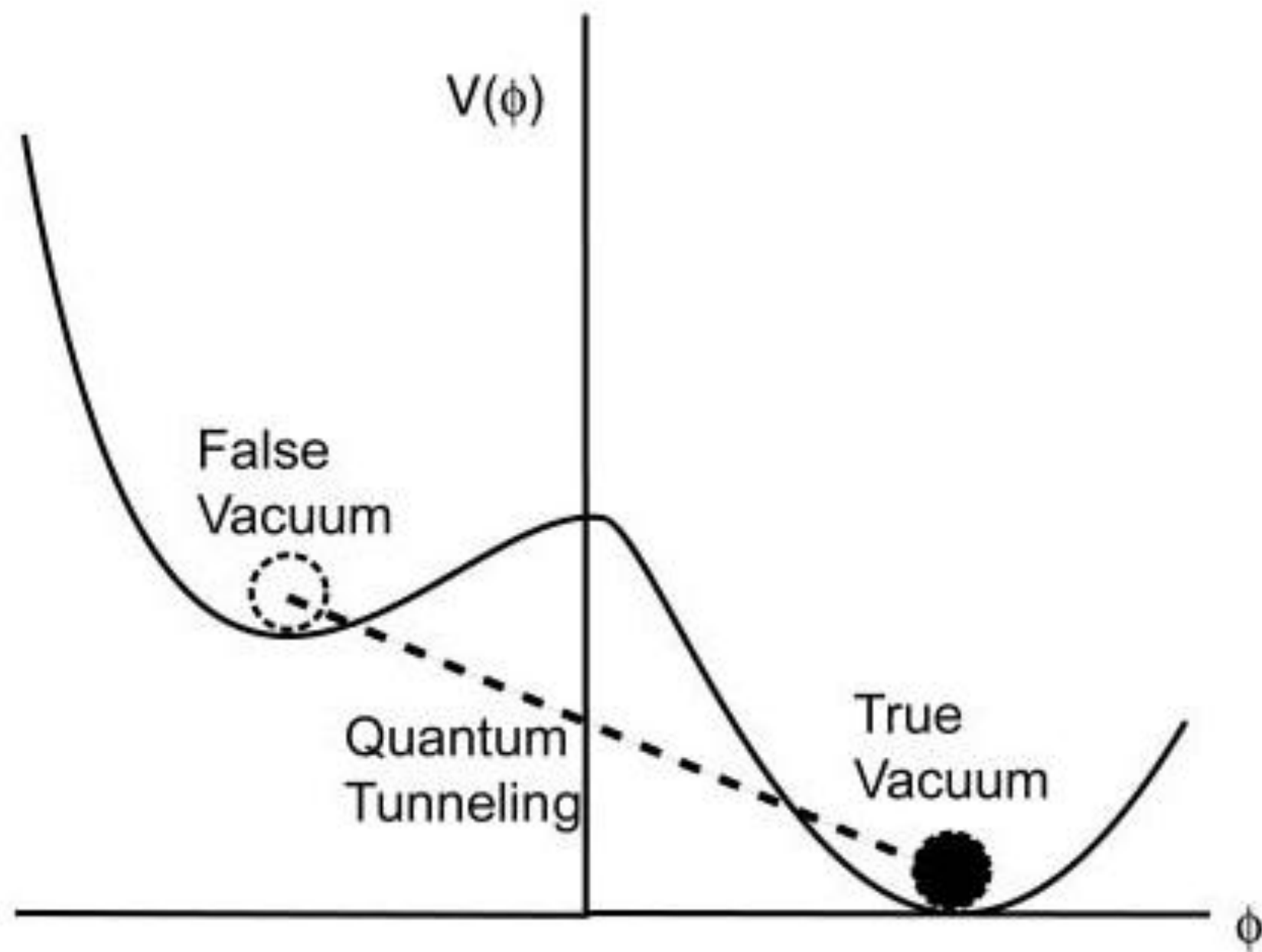
Baldes+ 2023,

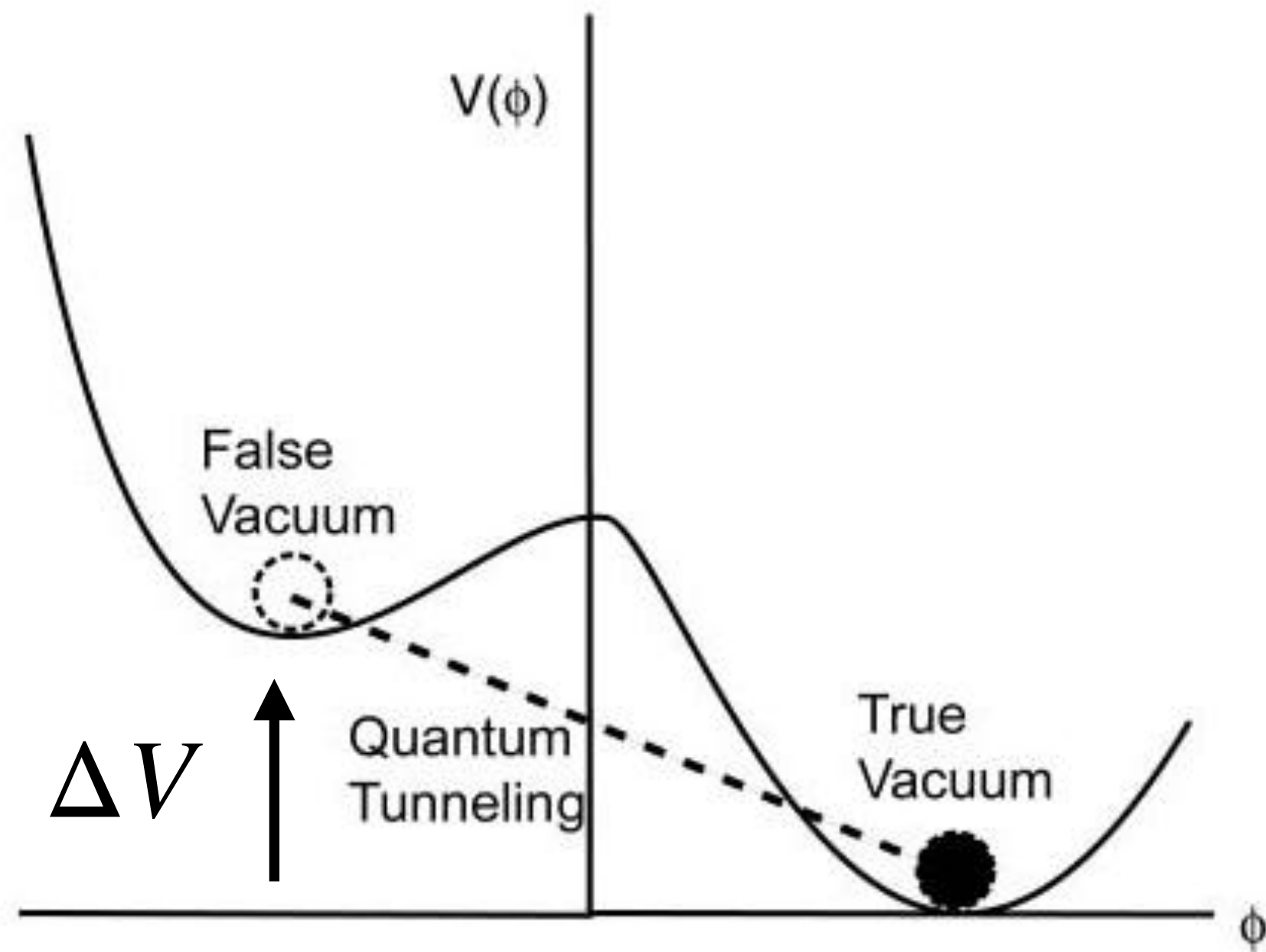
Lewicki, Toczec, Vaskonen 2024,



PBHs from 1stOPT

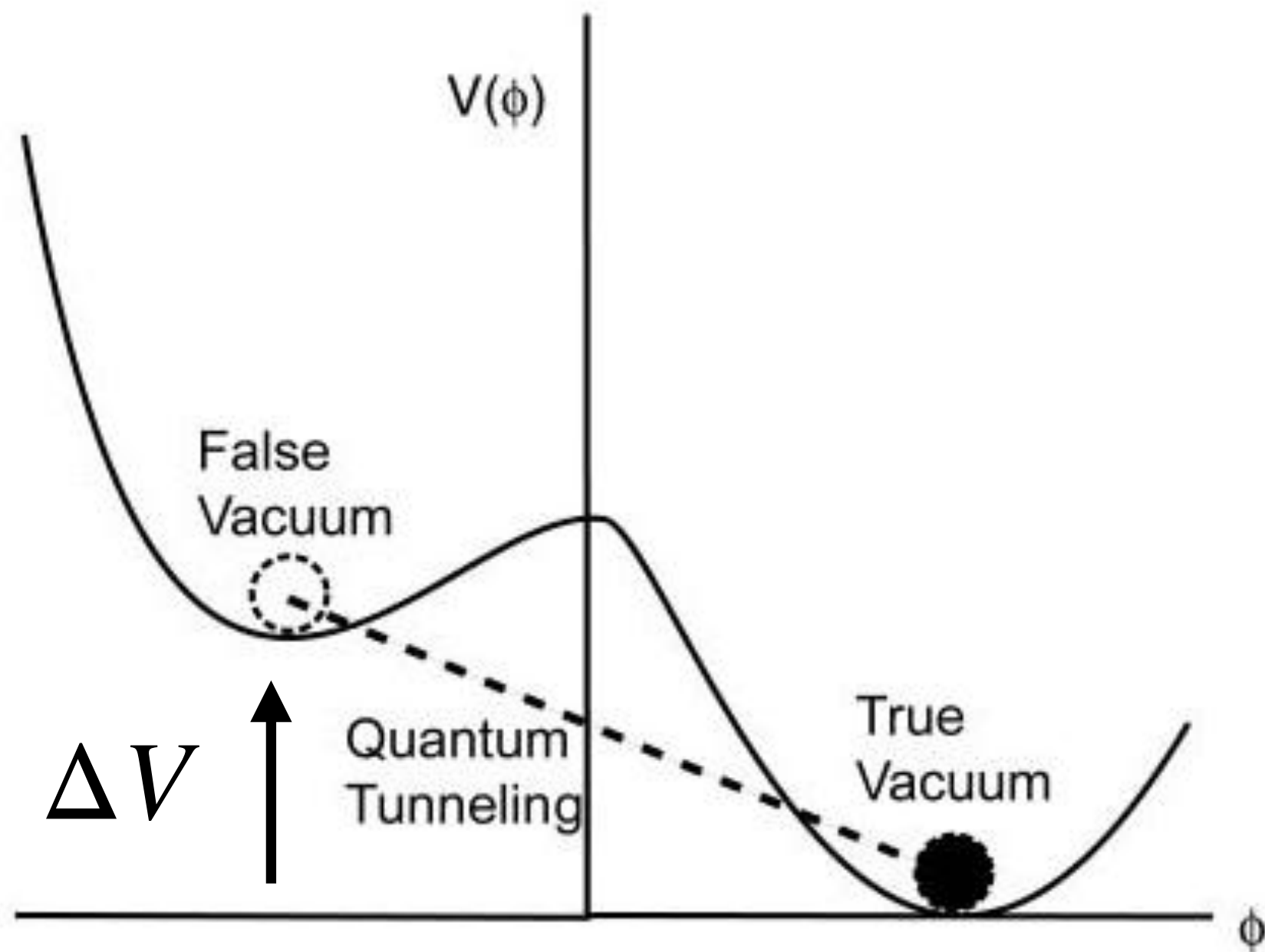
YG, Volansky 2305:04942





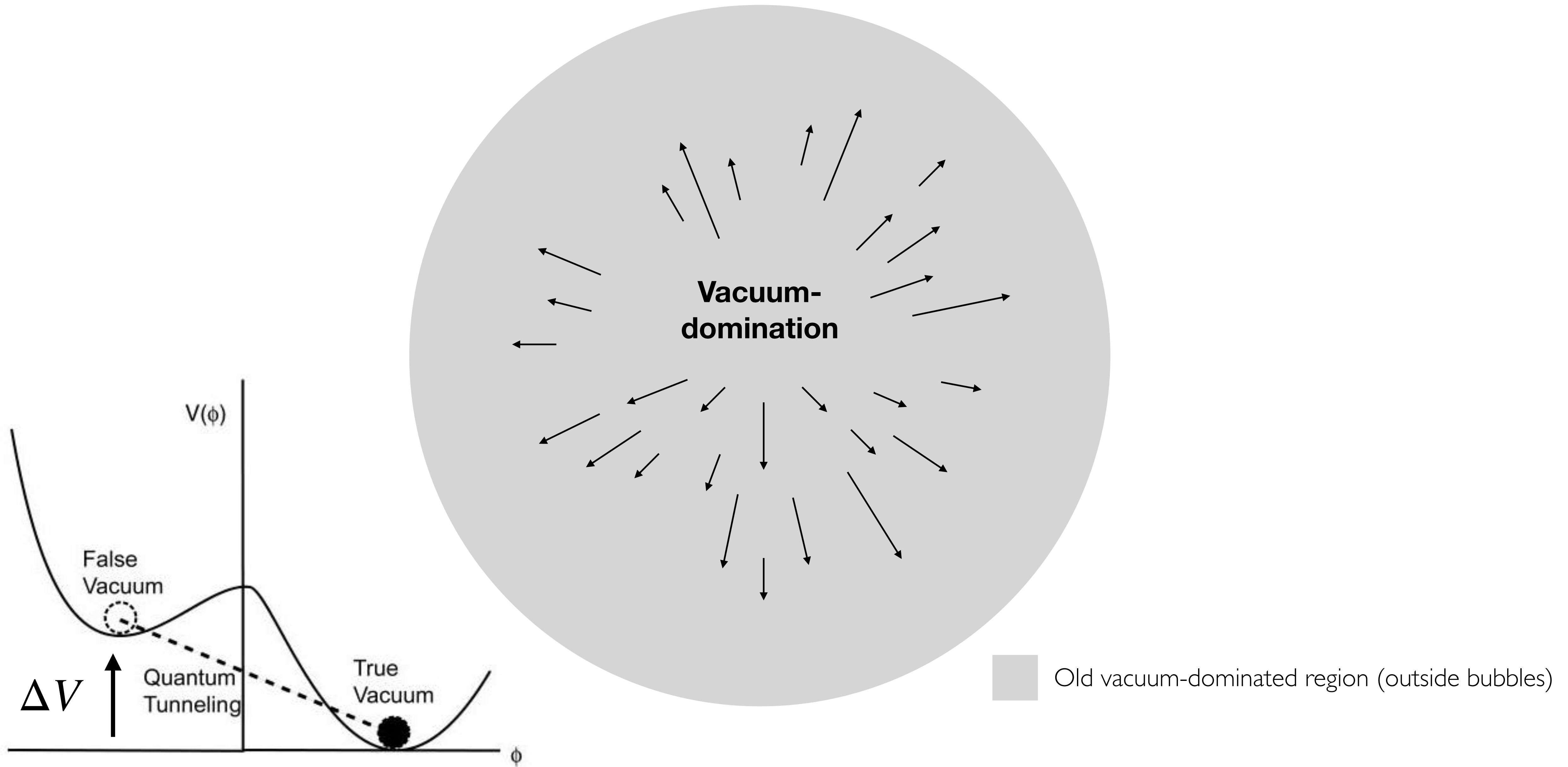
Strong 1st order PT:

$$\Delta V \gg \rho_{\text{rad}}$$



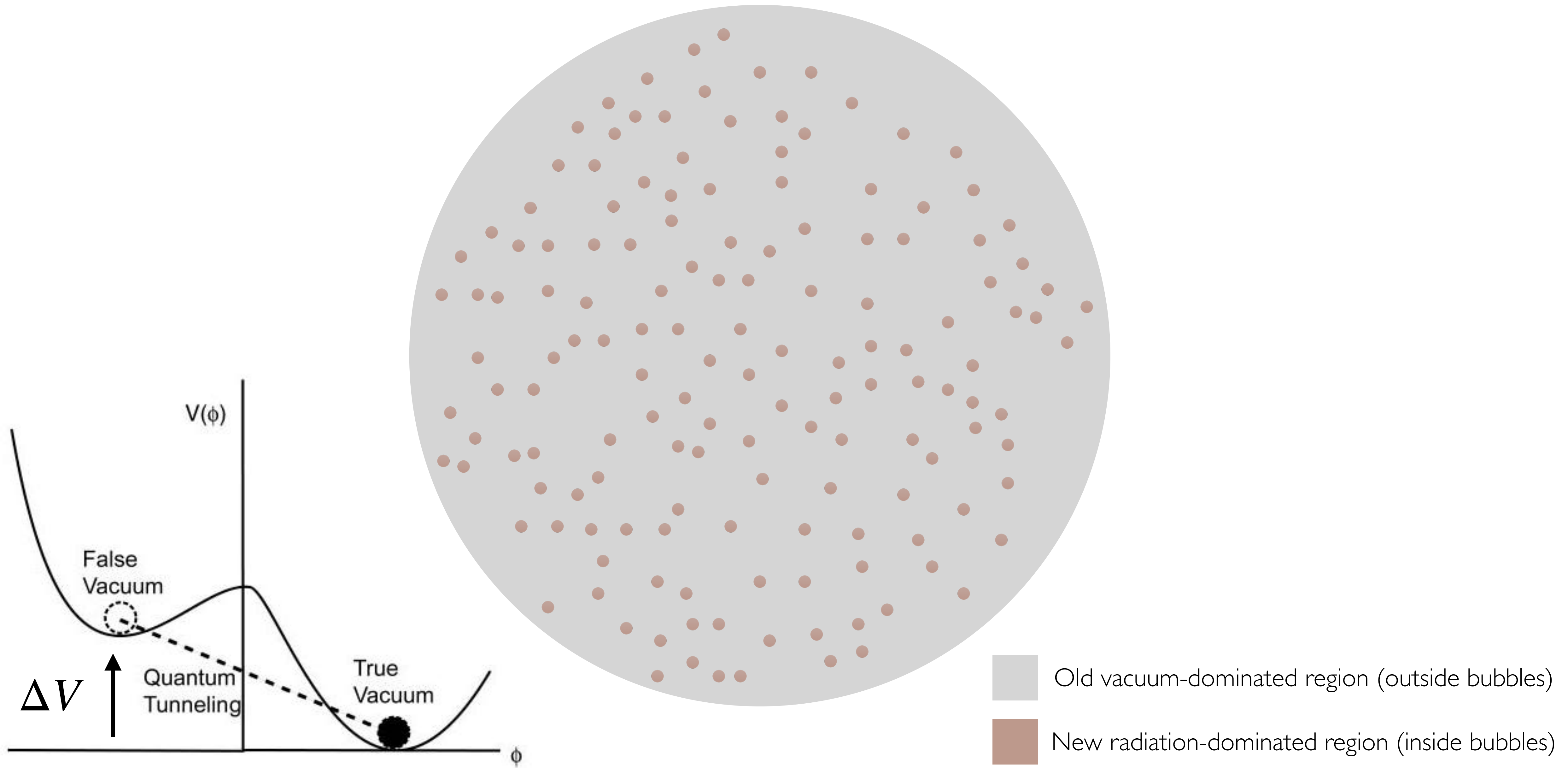
PBHs from 1stOPT

YG, Volansky 2305:04942



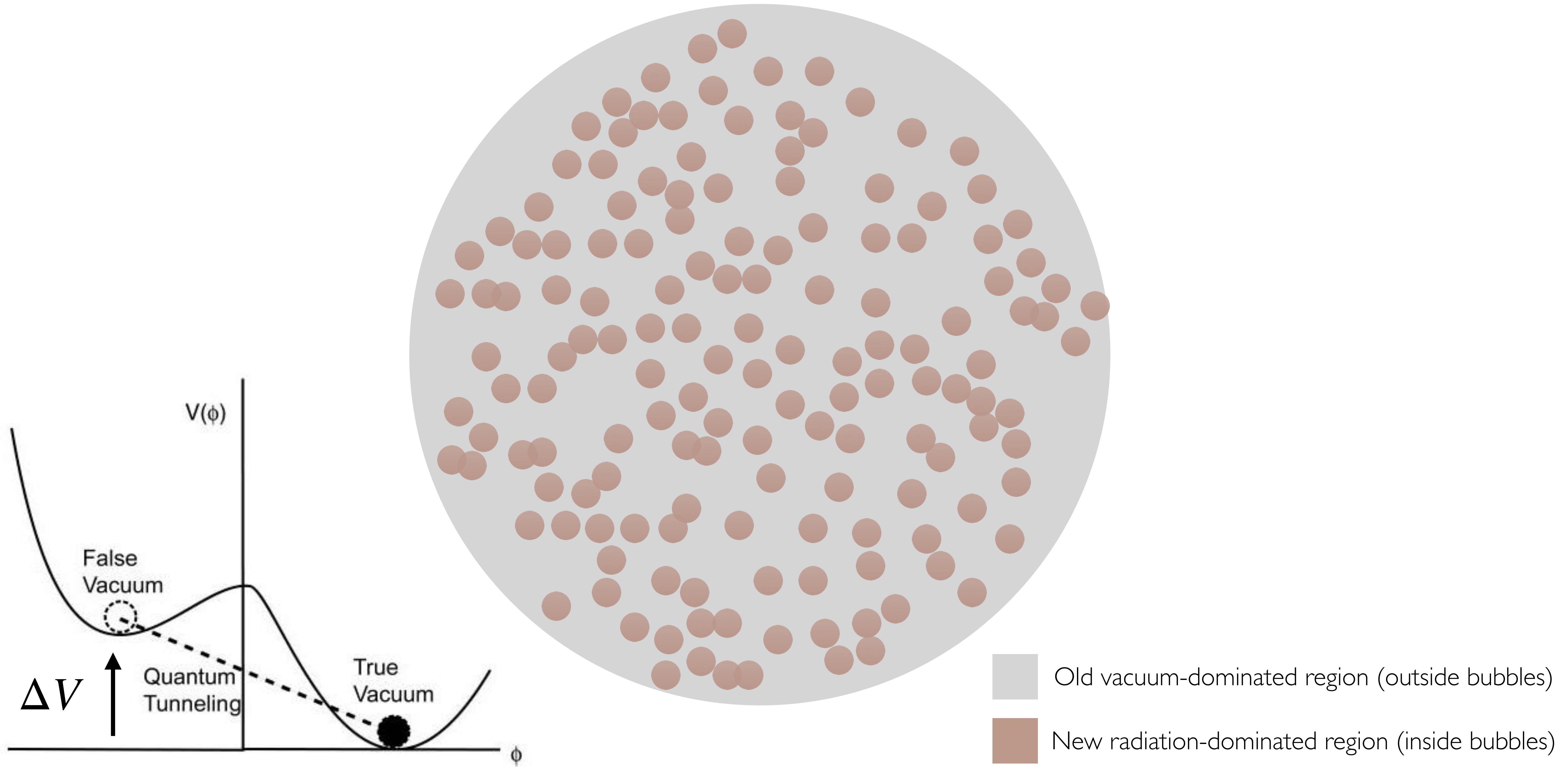
PBHs from 1stOPT

YG, Volansky 2305:04942



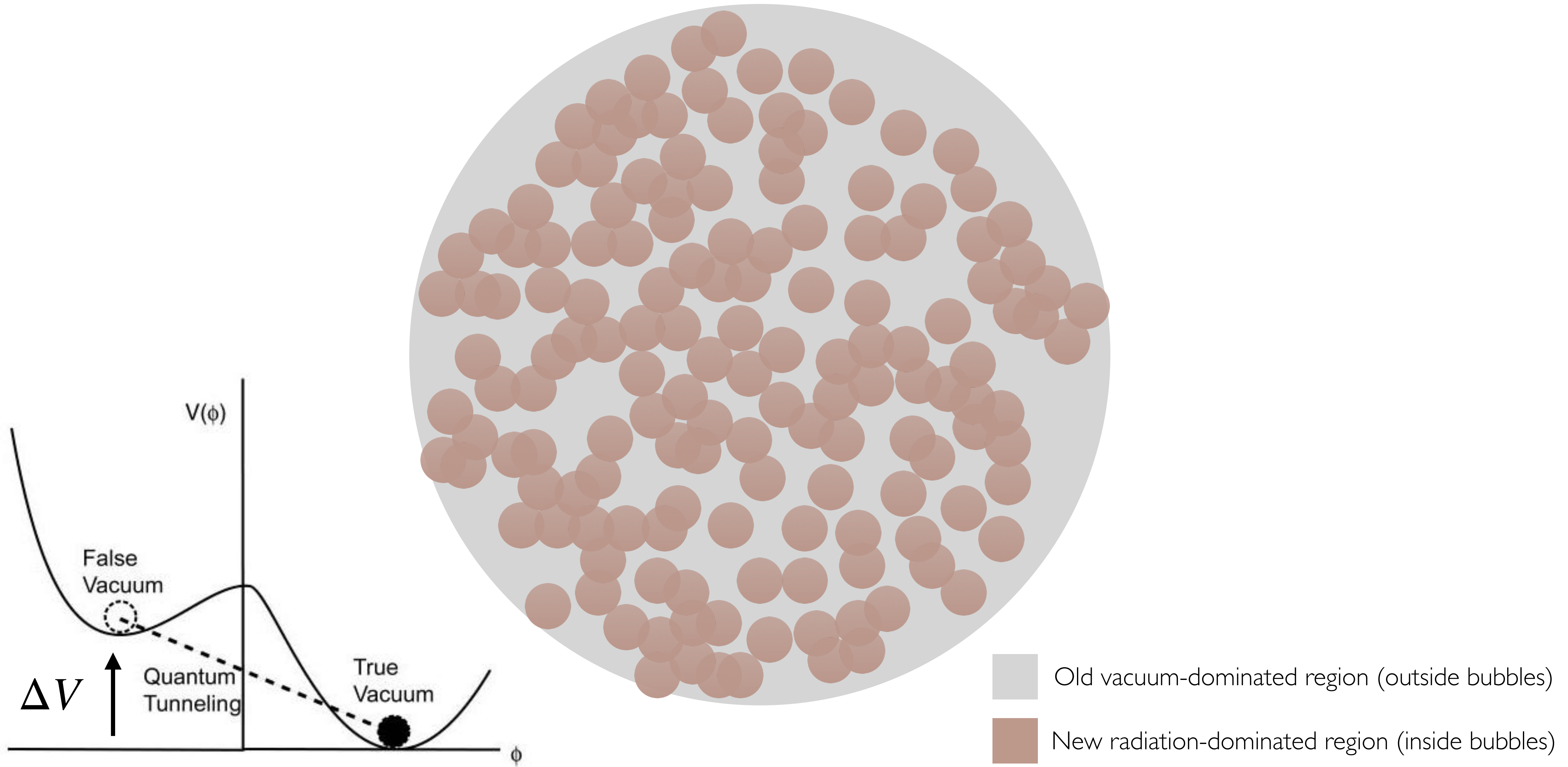
PBHs from 1stOPT

YG, Volansky 2305:04942



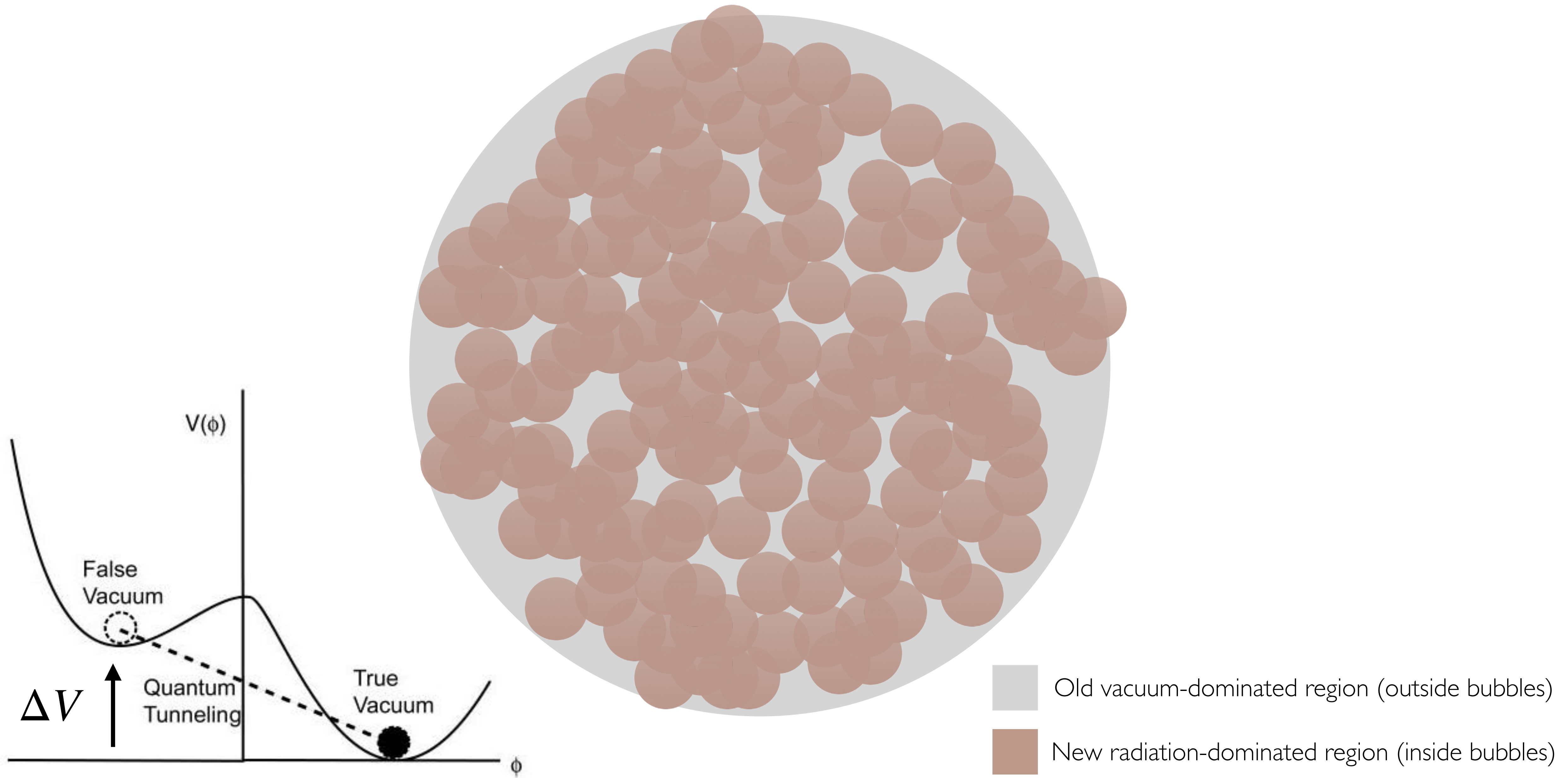
PBHs from 1stOPT

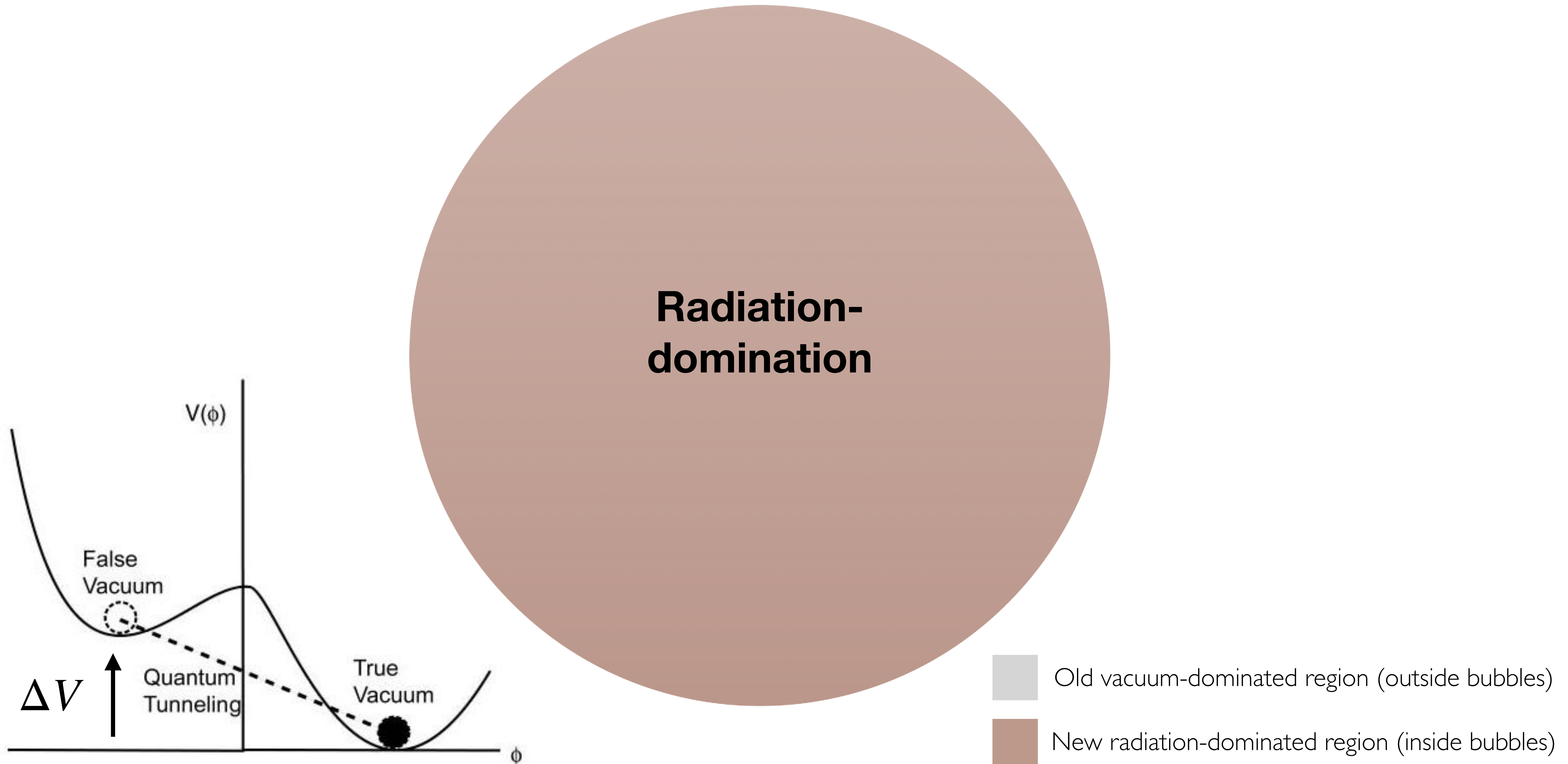
YG, Volansky 2305:04942



PBHs from 1stOPT

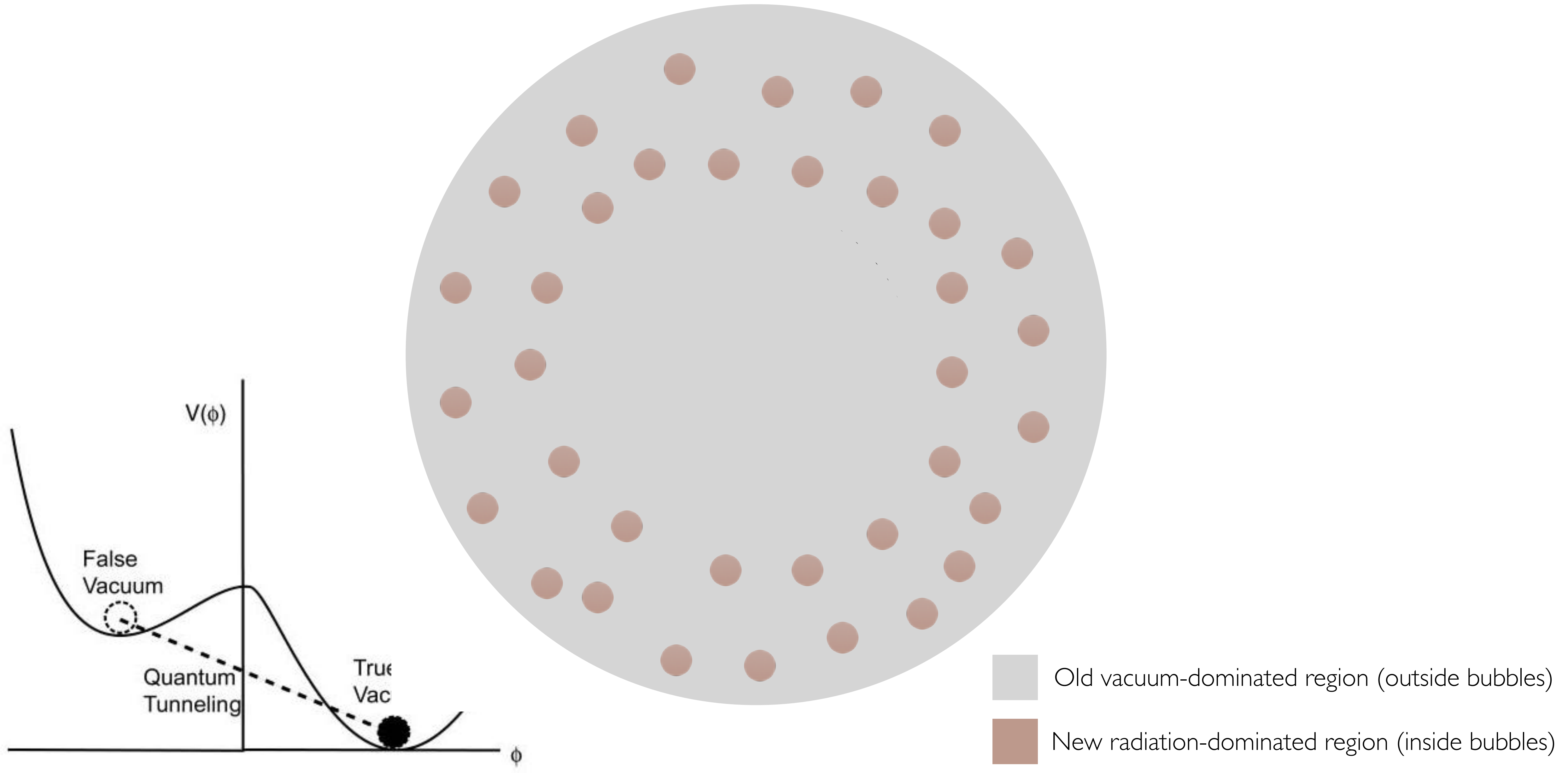
YG, Volansky 2305:04942





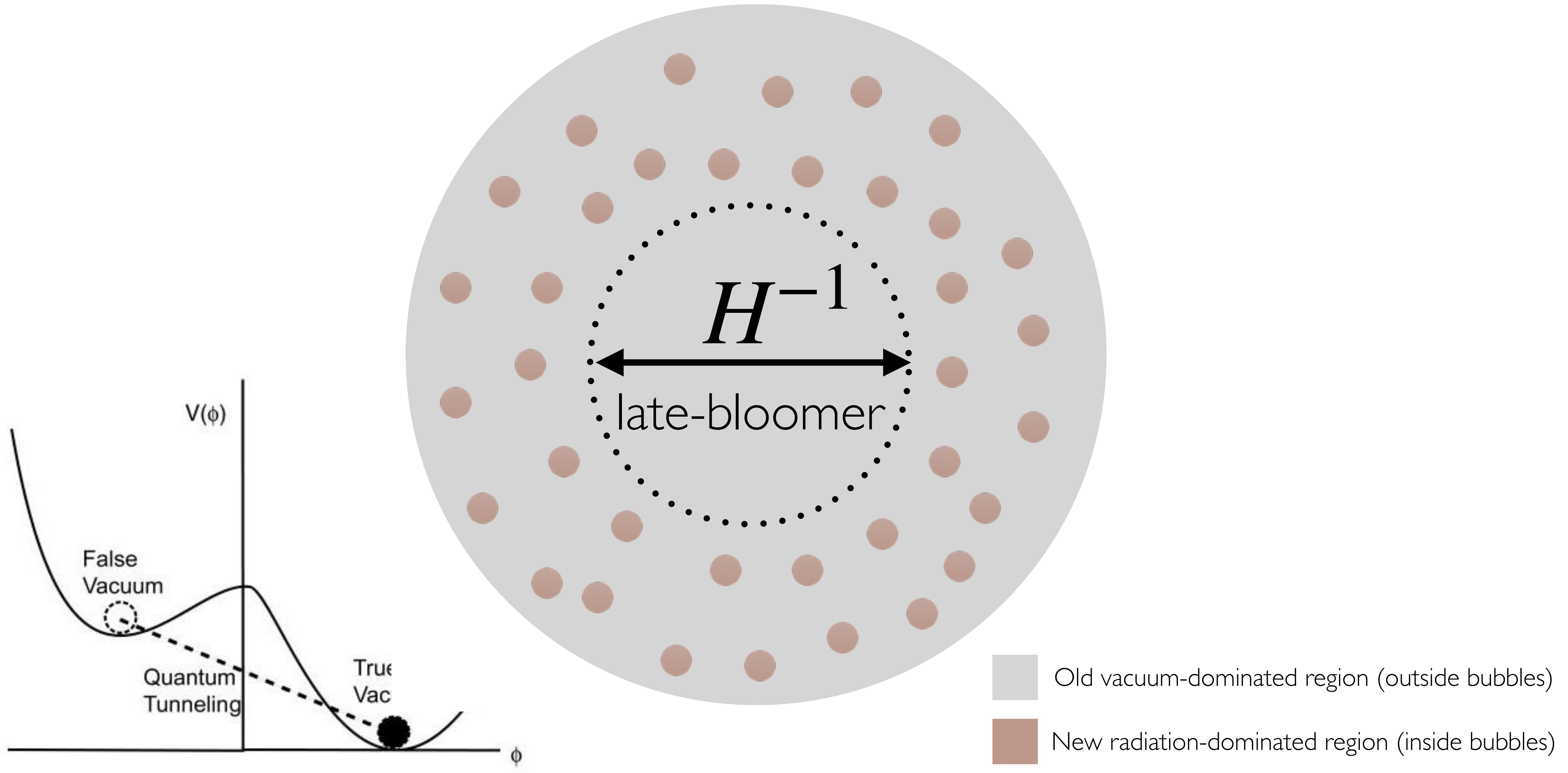
PBHs from 1stOPT

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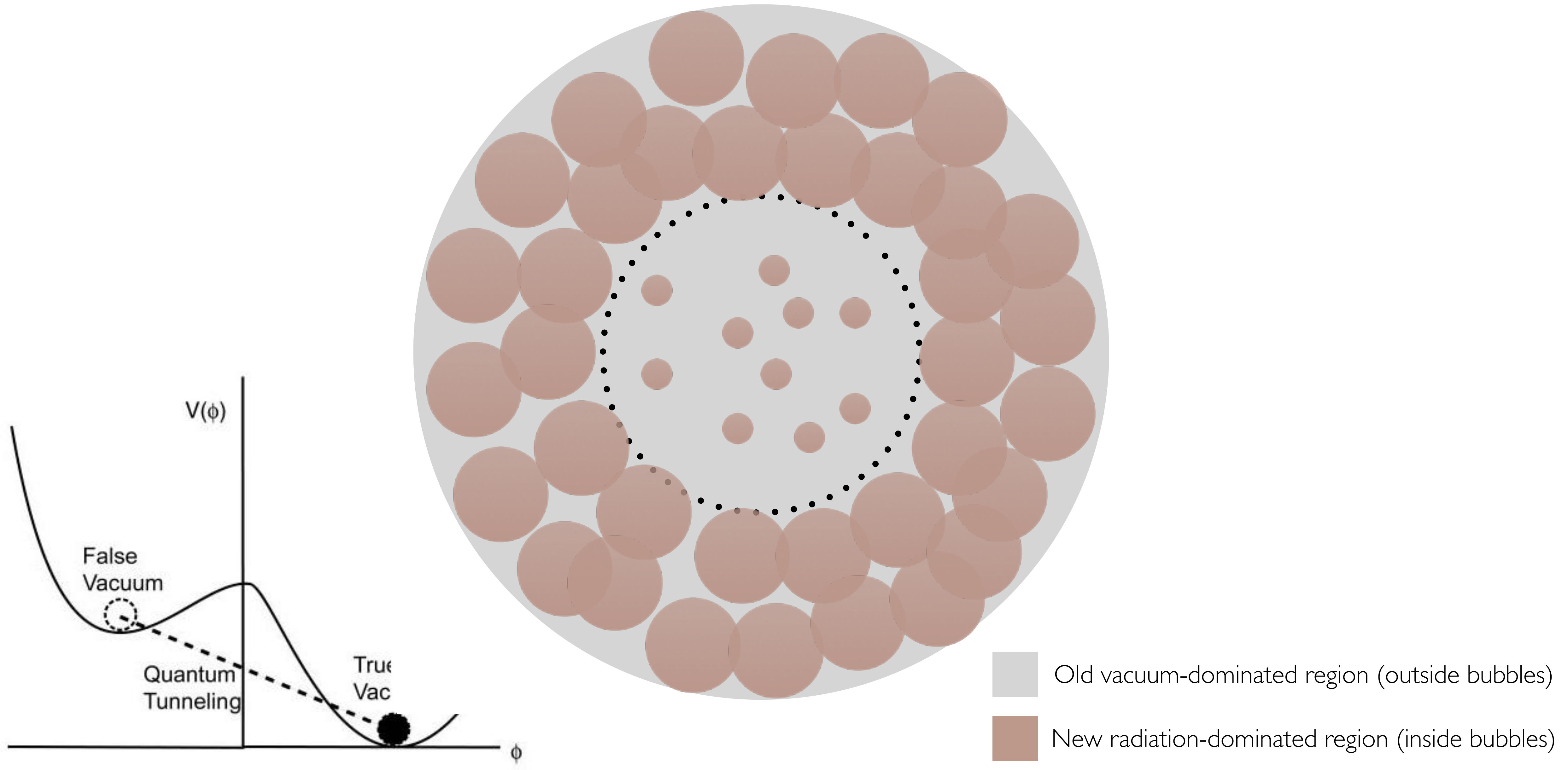
PBHs from 1stOPT

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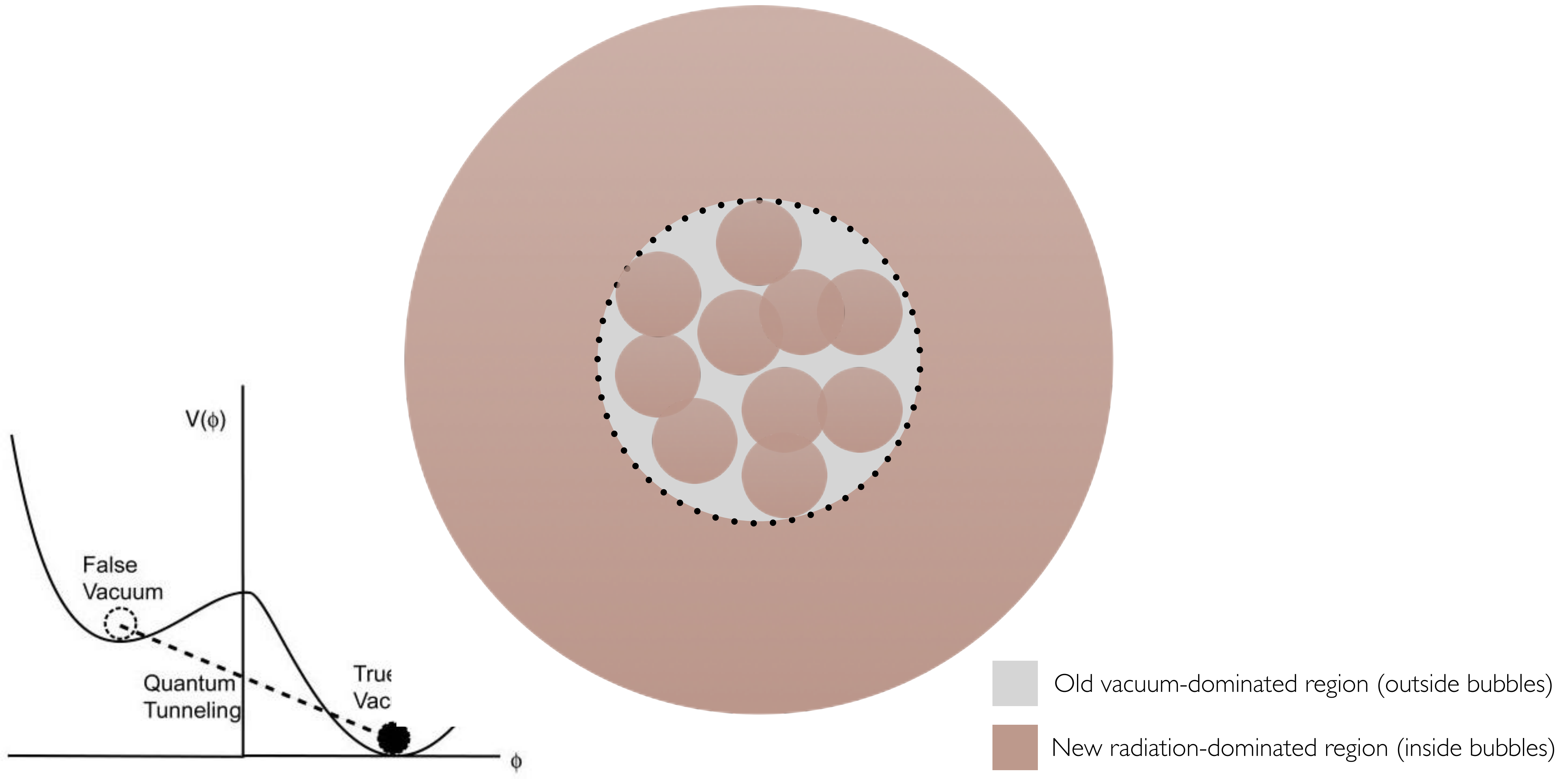
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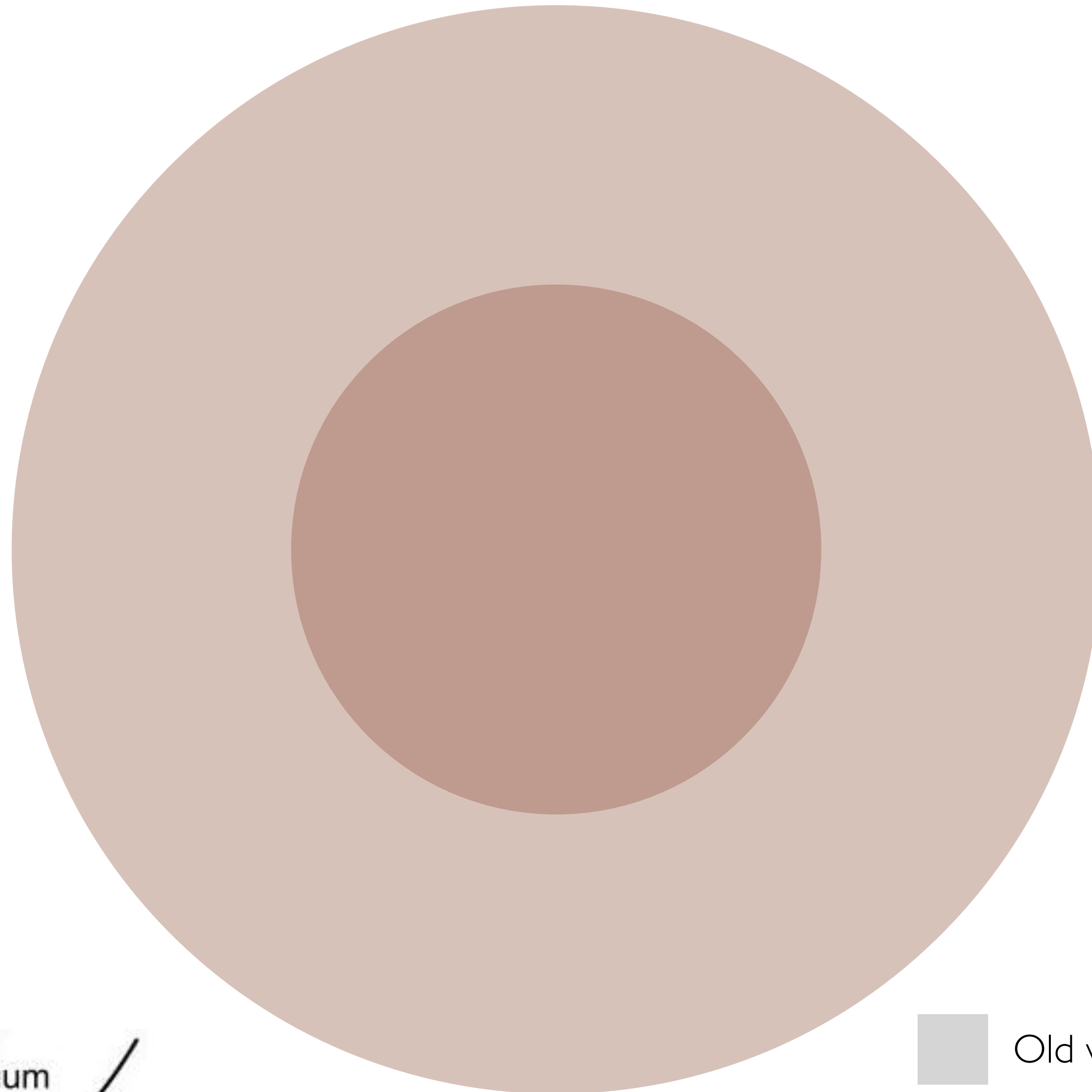
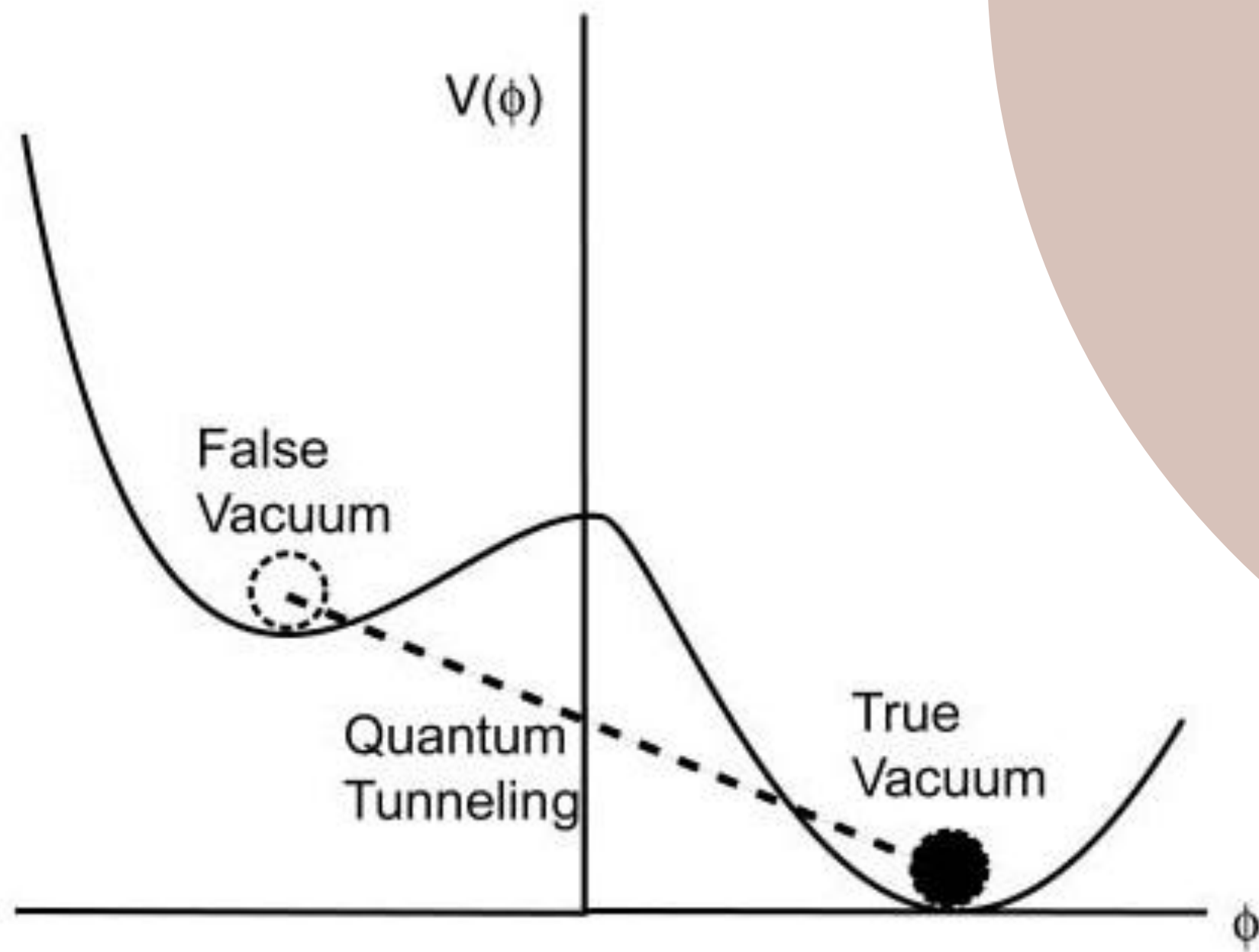
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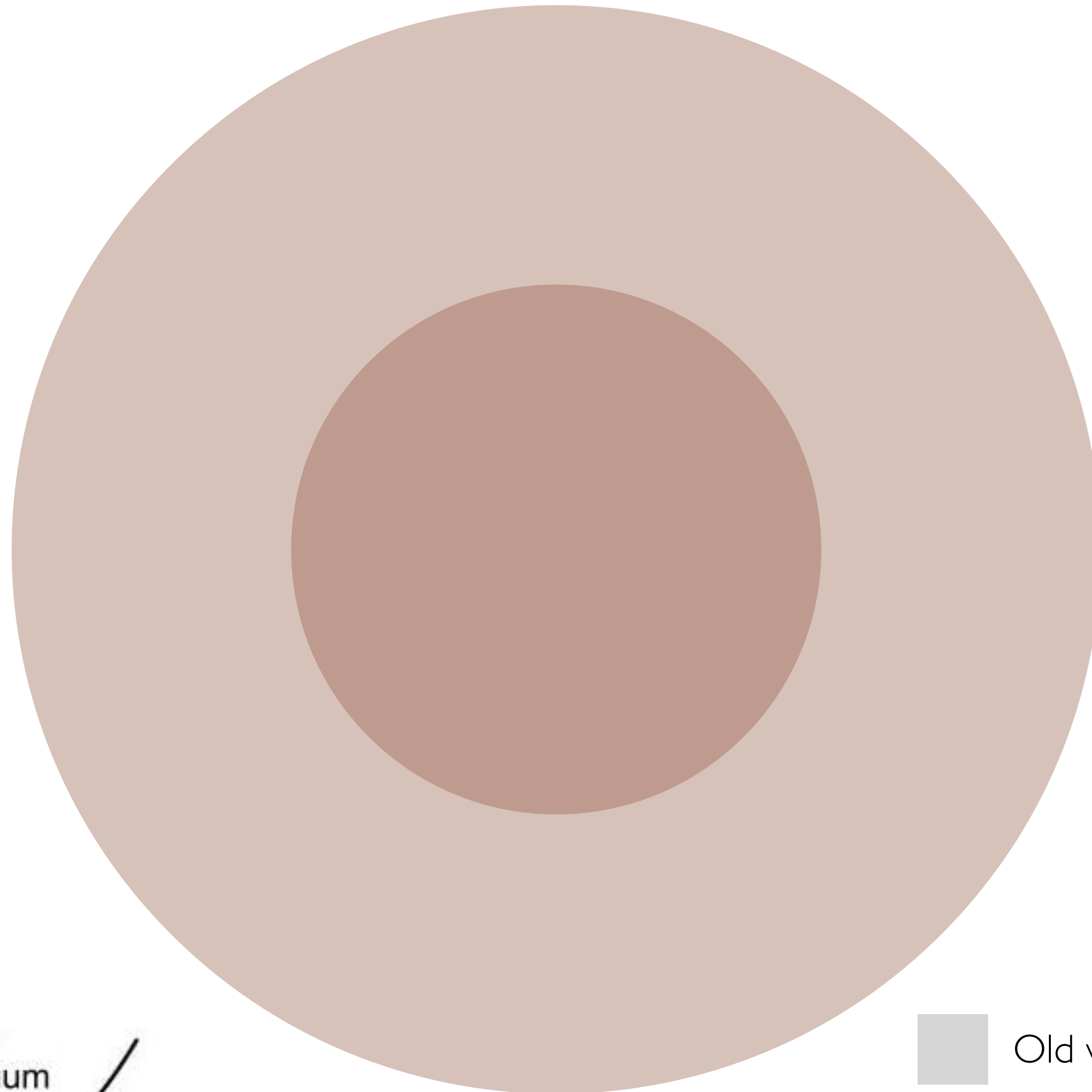
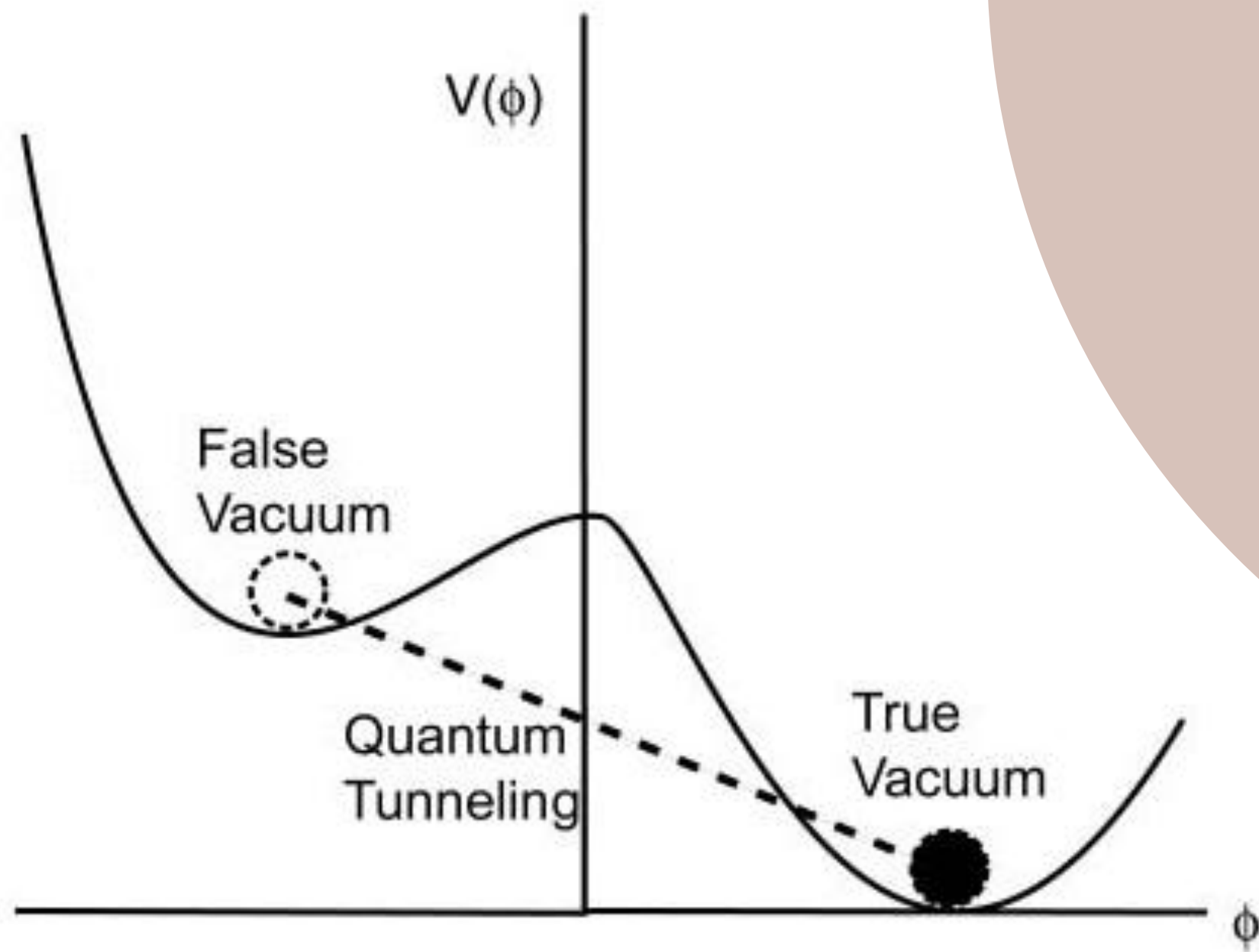
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-  Old vacuum-dominated region (outside bubbles)
-  New radiation-dominated region (inside bubbles)

if

$$\delta\rho/\rho \gtrsim 0.50.$$



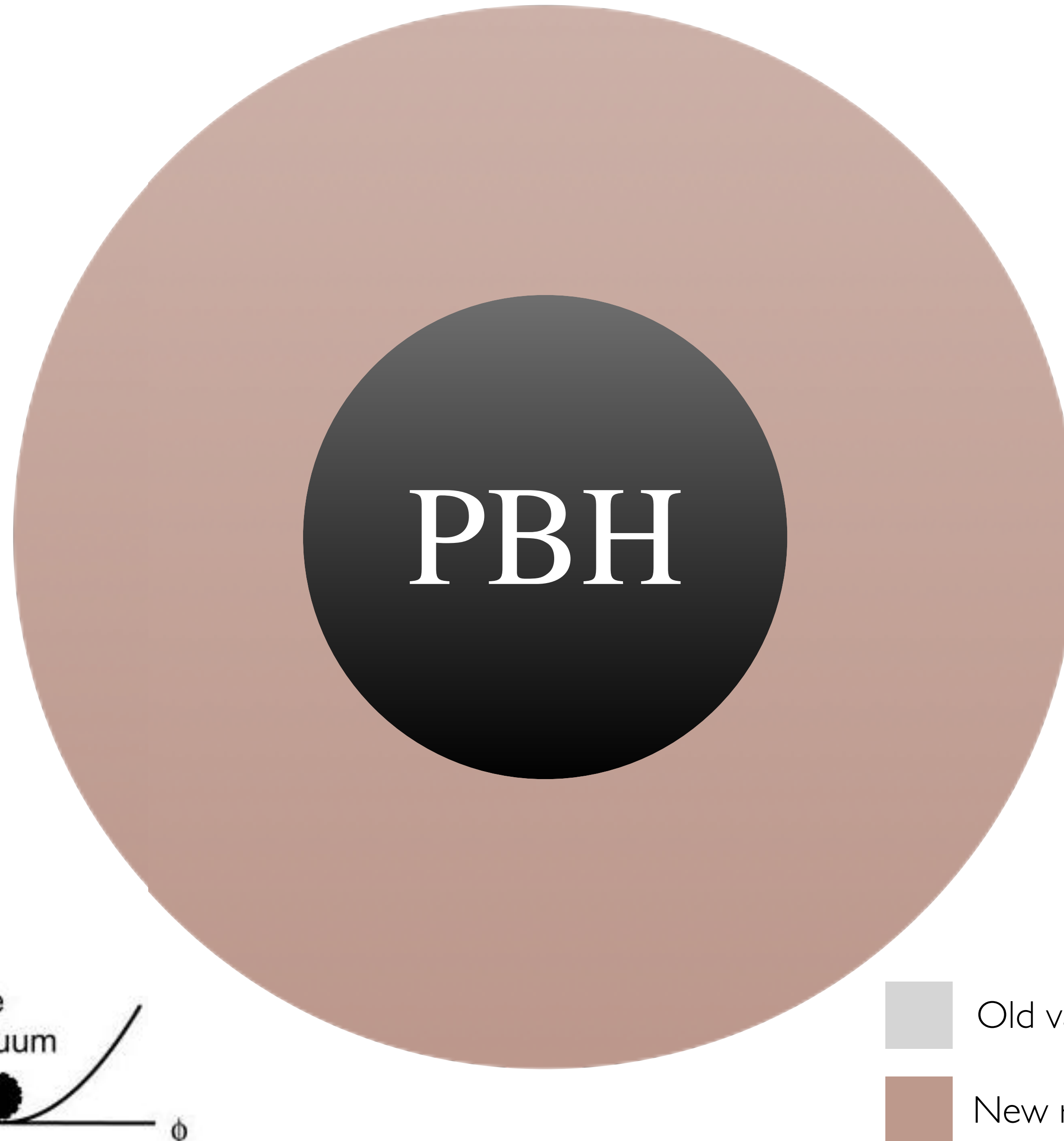
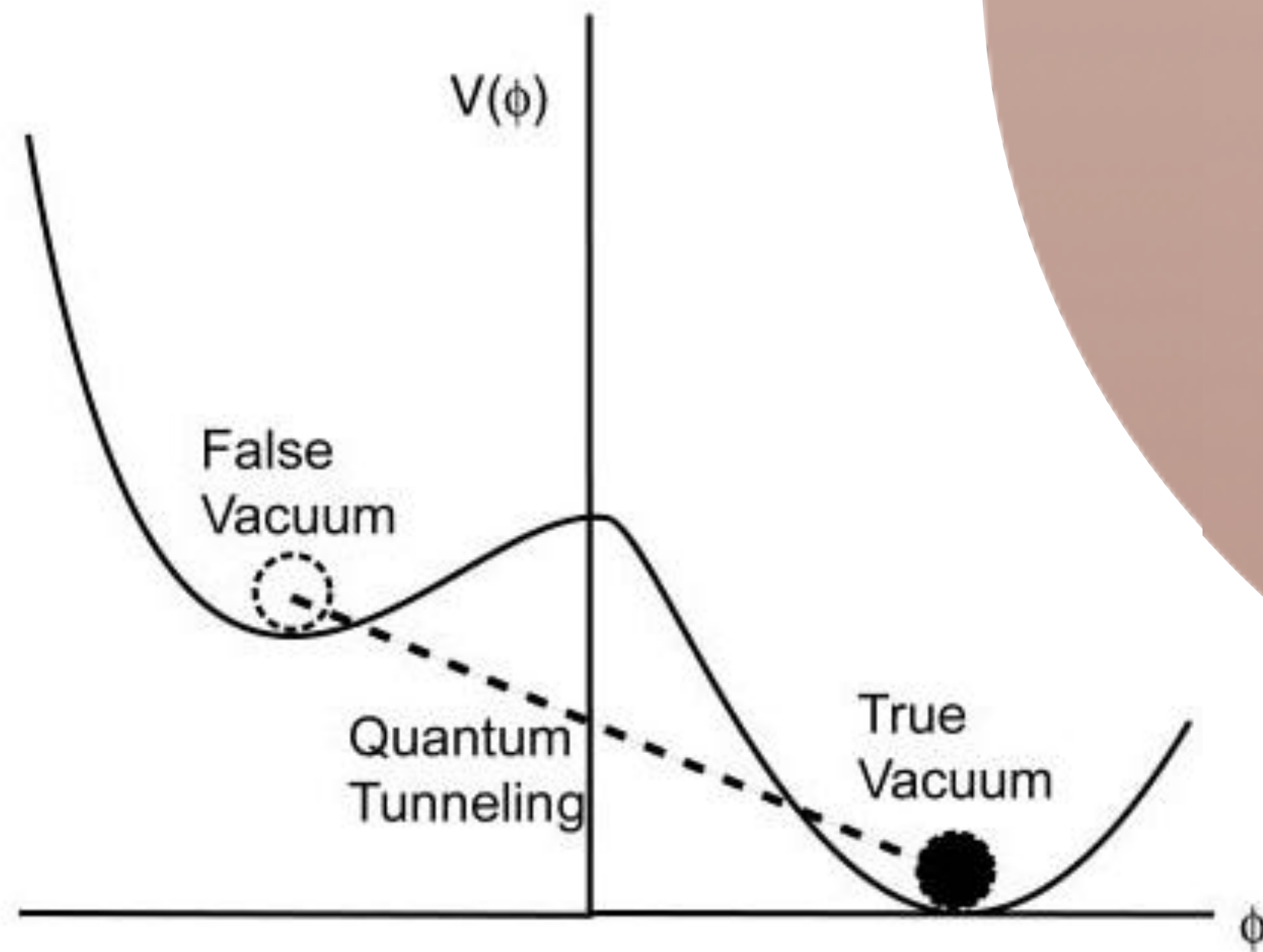
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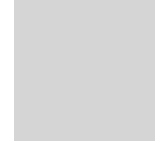
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then

PBH



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How to calculate PBHs from FOPTs ?

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1) calculate $\langle \delta(t) \rangle_{\text{H}} = \left\langle \frac{\delta\rho_R + \delta\rho_V}{\rho} \right\rangle_{\text{H}}$

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2) calculate probability for $\langle \delta(t) \rangle_{\text{H}} \gtrsim 0.5$

$$\rho' + 3\mathcal{H}(1 + \omega)\rho = 0$$

Use $\rho = \rho_R + \rho_V$:

$$\rho' + 3\mathcal{H}(1 + \omega)\rho = 0$$

Use $\rho = \rho_R + \rho_V$: $\rho_R'(t) + 4\mathcal{H}\rho_R(t) = -\rho_V'(t)$

$$\delta\rho_R'(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho_V'(t)$$

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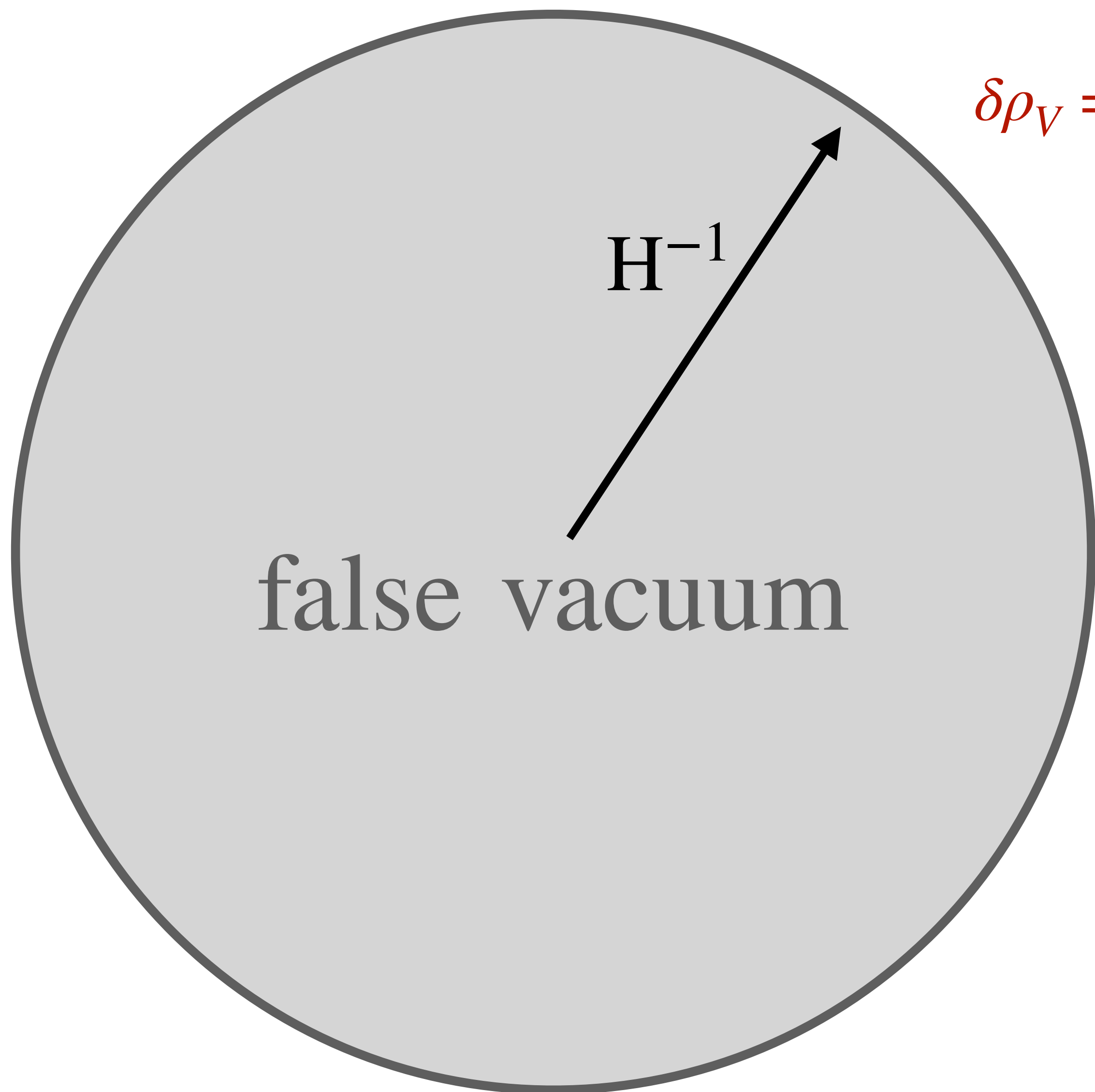


$$\delta(t) = \frac{\delta\rho_R + \delta\rho_V}{\rho}$$

$$\delta\rho'_R(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho'_V(t)$$

$$\delta\rho_V = F_{\text{false}} - \overline{F_{\text{false}}}$$

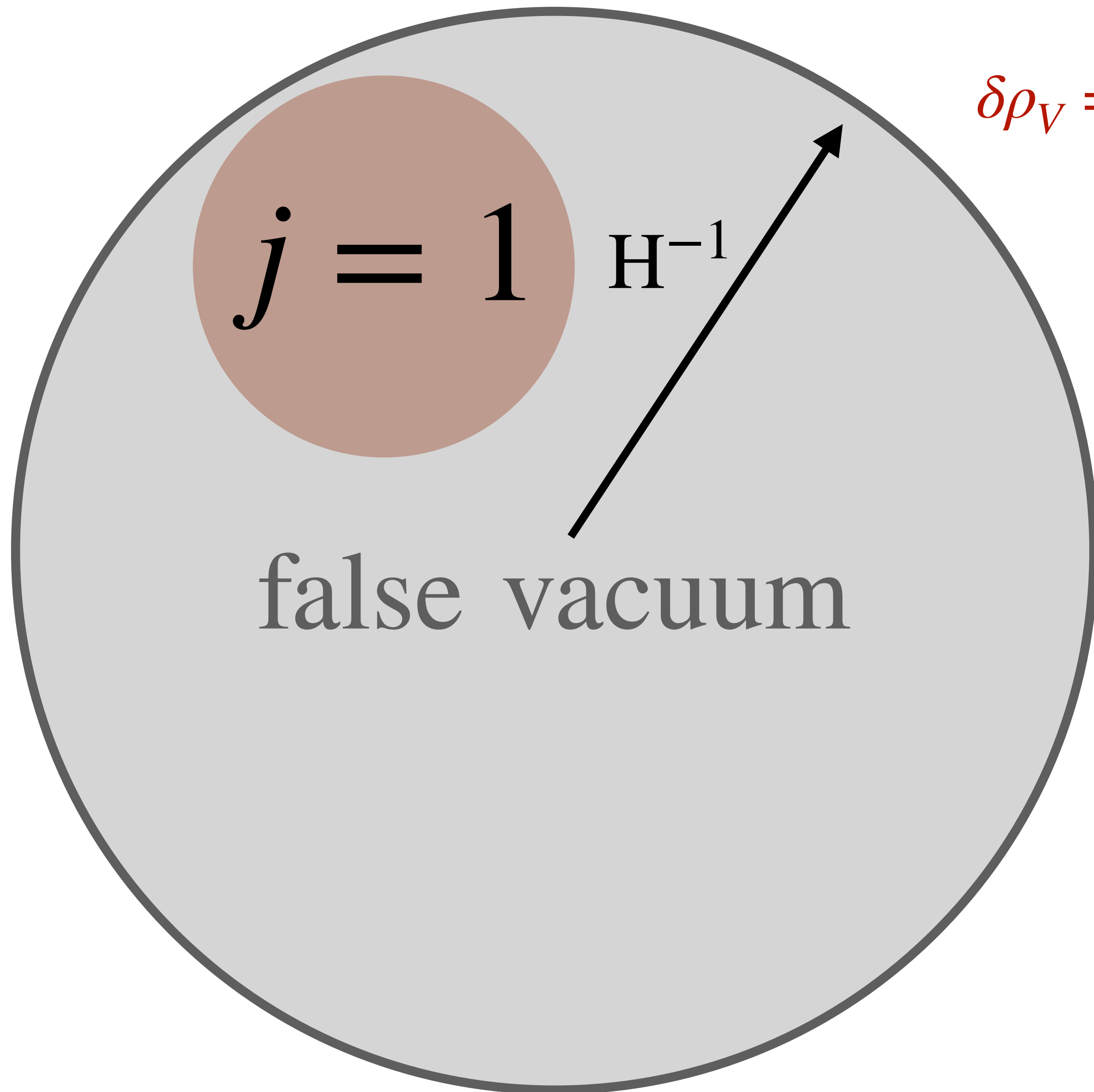
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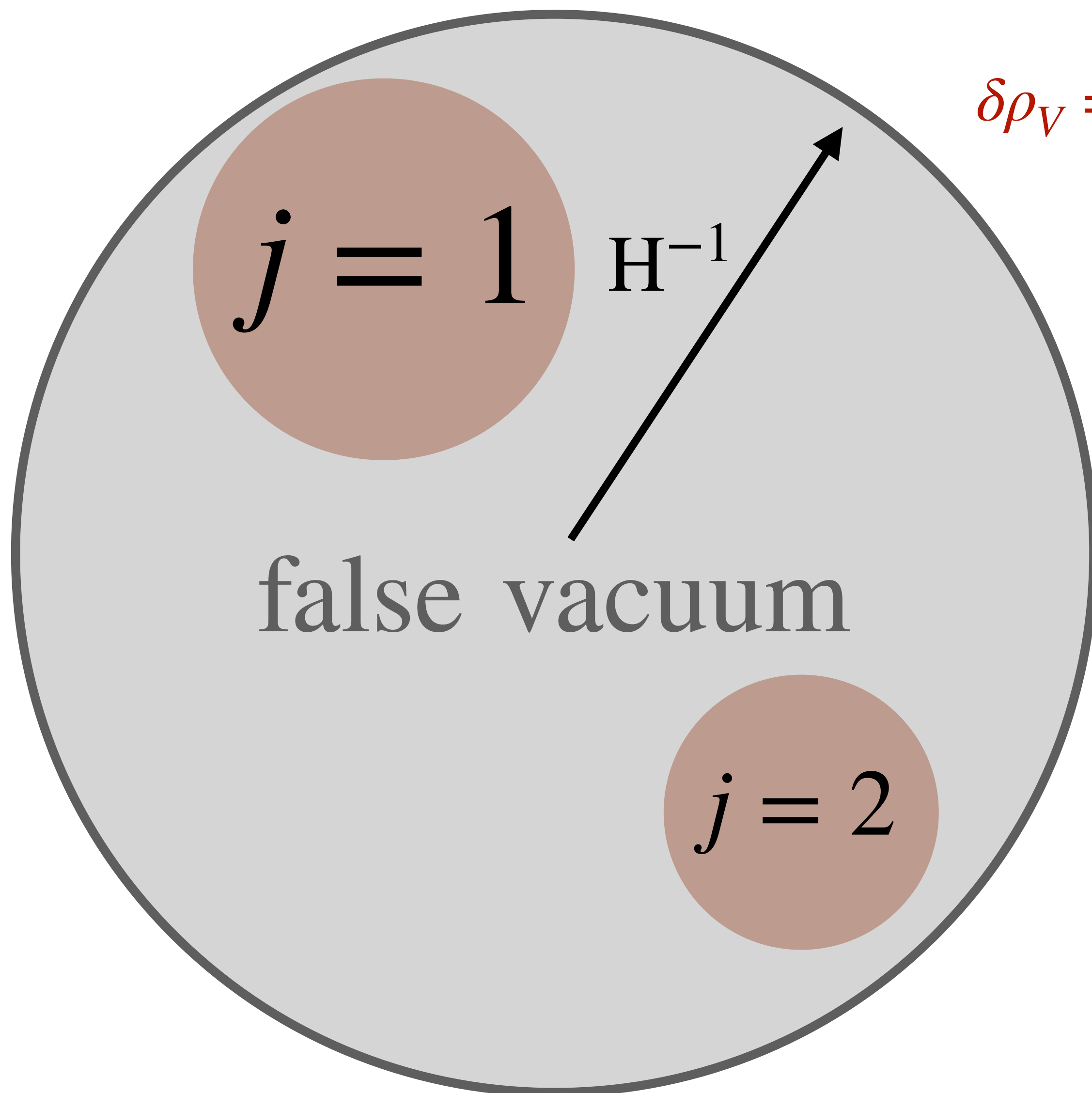


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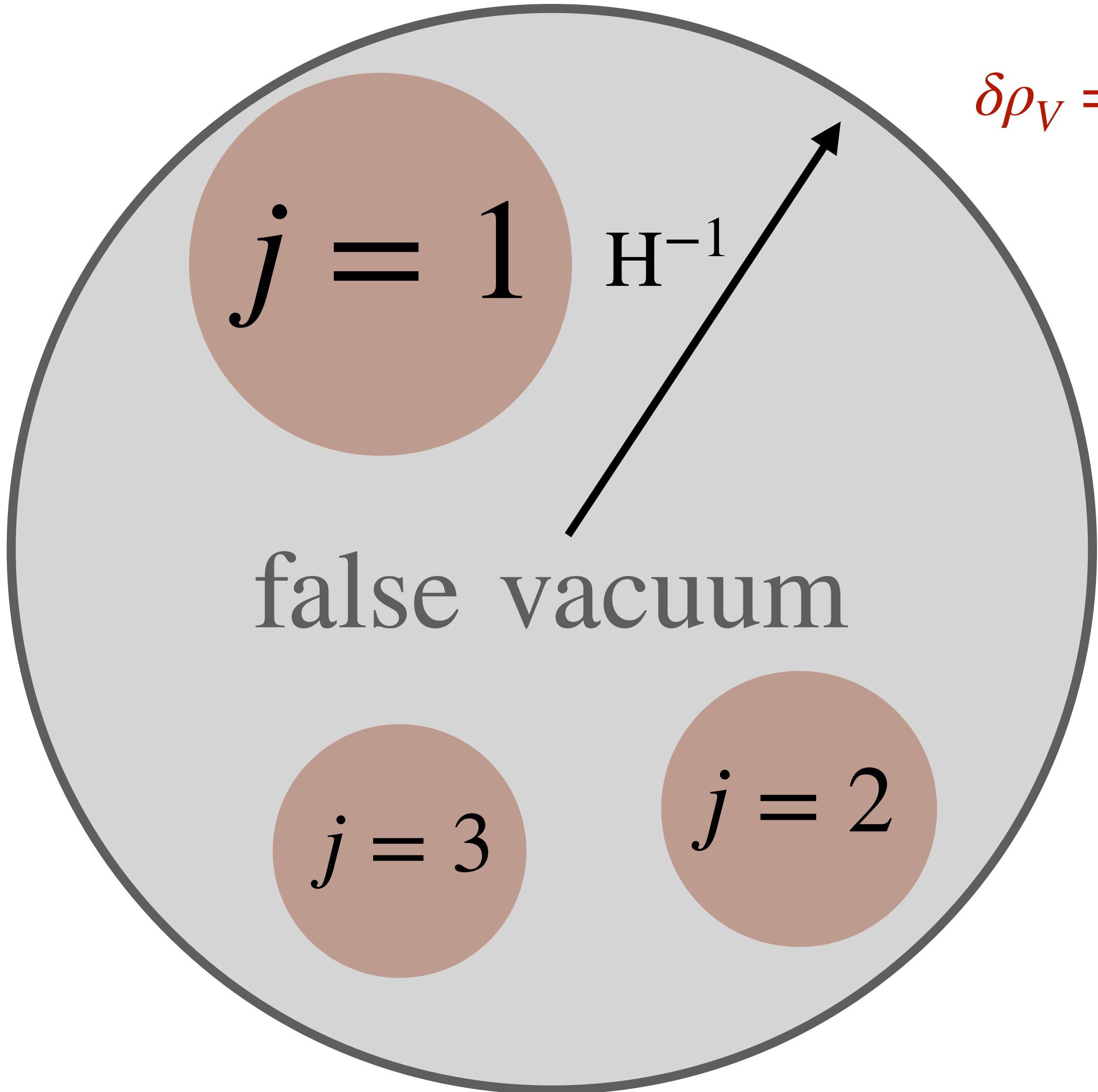
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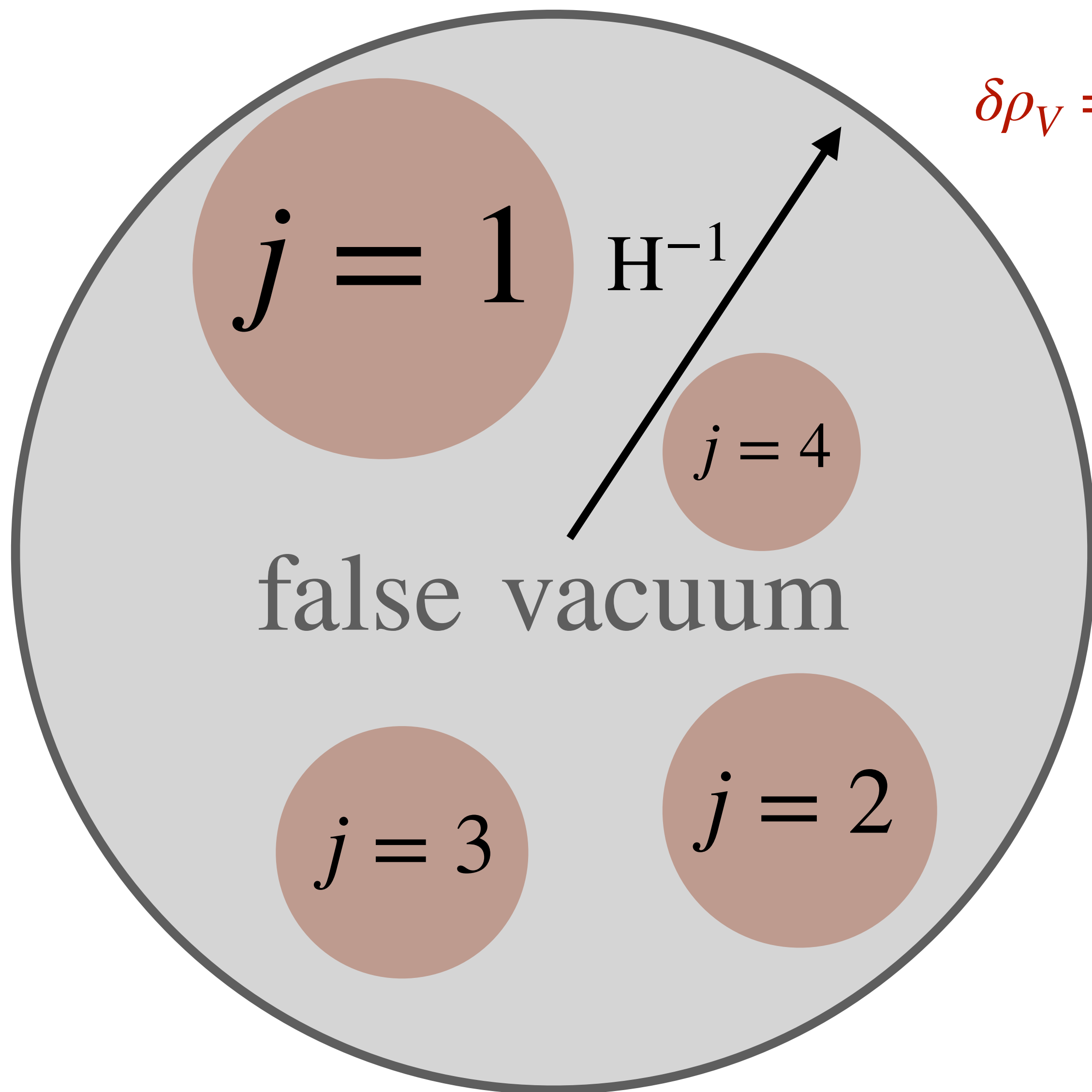
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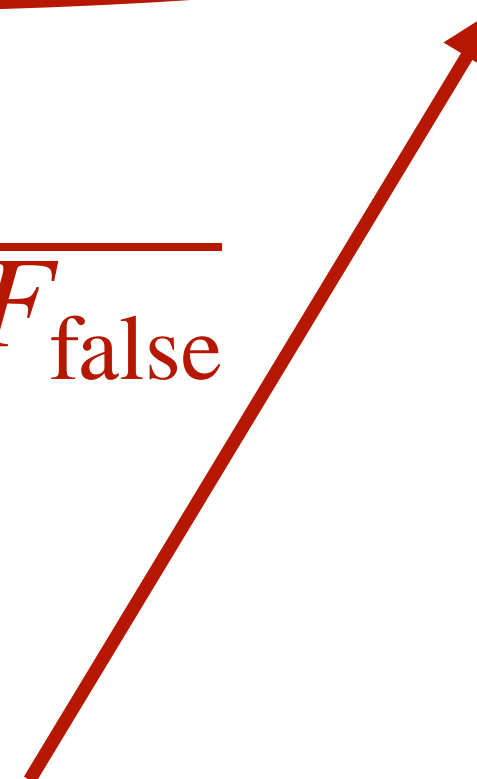
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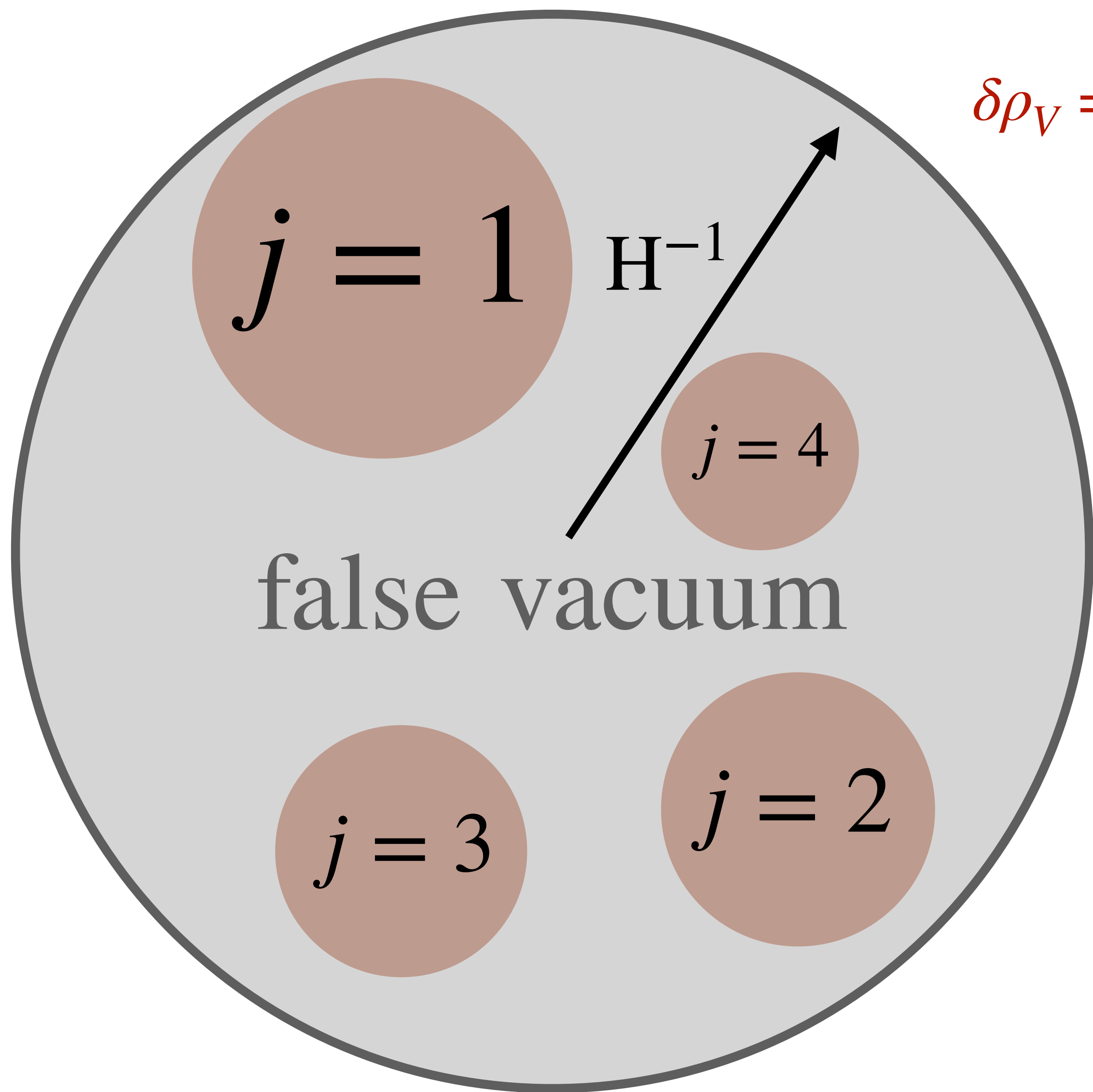
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$$\delta\rho_V = F_{\text{false}} - \overline{F_{\text{false}}}$$

$$\rho_V(t) = F_{\text{false}}$$



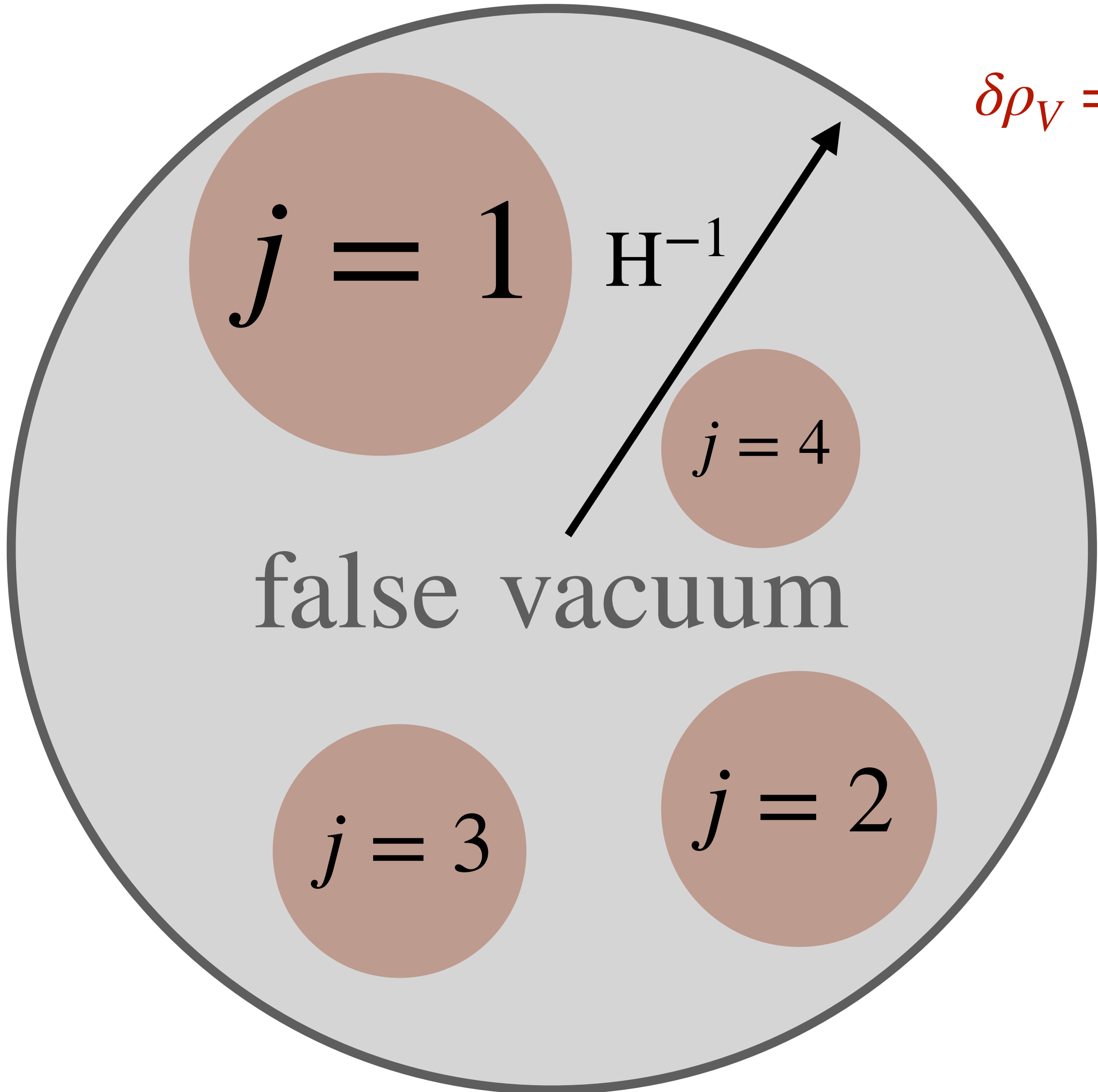


$$\delta\rho_R'(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho_V'(t)$$

$$\delta\rho_V = F_{\text{false}} - \overline{F_{\text{false}}}$$

$$\rho_V(t) = F_{\text{false}}(t_{j=1}, t_{j=2}, t_{j=3}, \cdots t_{J_c})$$

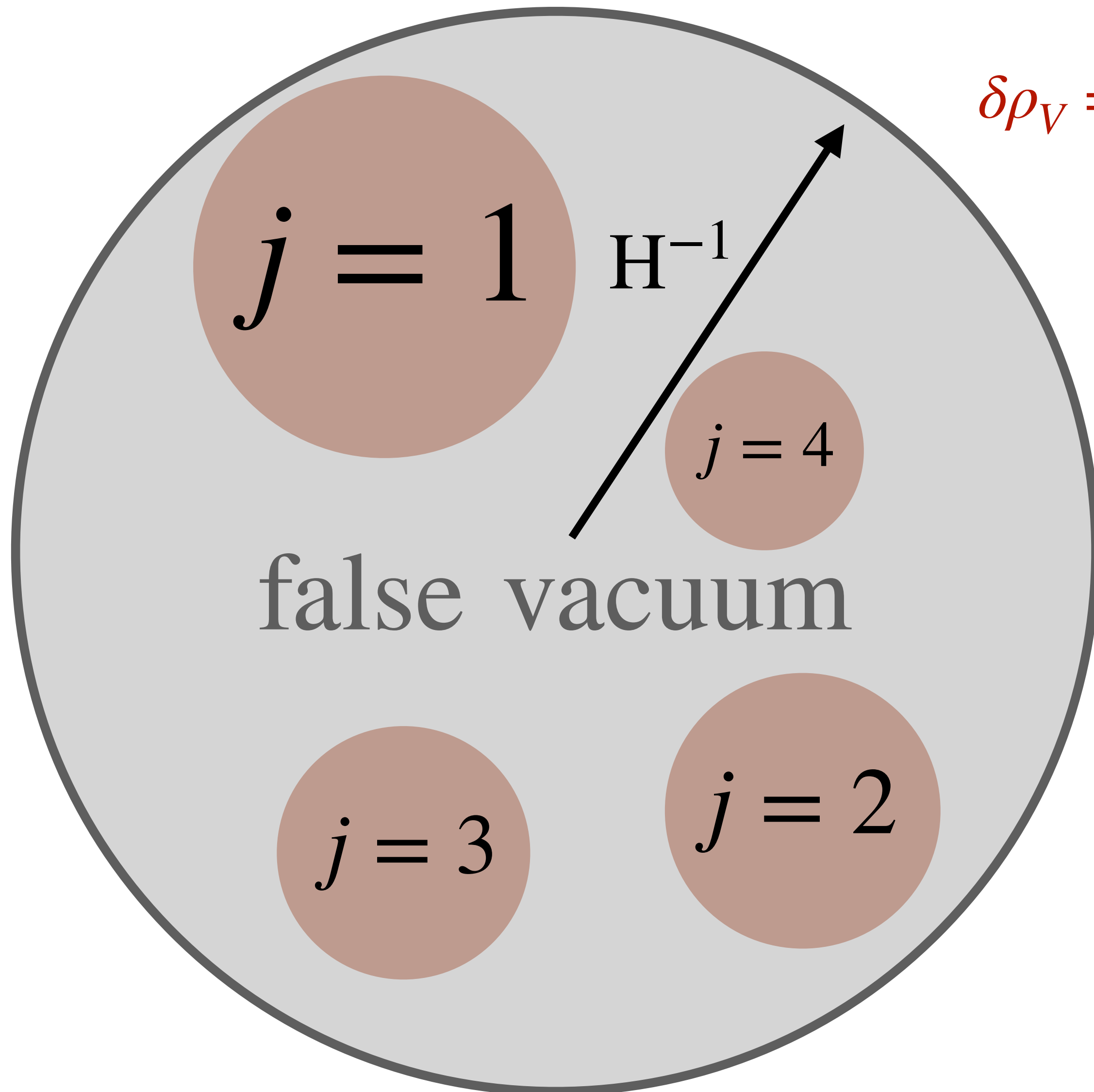
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$$\delta\rho_V = F_{\text{false}} - \overline{F_{\text{false}}}$$

random variables

$$\rho_V(t) = F_{\text{false}}(t_{j=1}, t_{j=2}, t_{j=3}, \cdots t_{J_c})$$



$$\delta\rho'_R(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho'_V(t)$$

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$$J_c = 1$$

Sasaki+ 1982

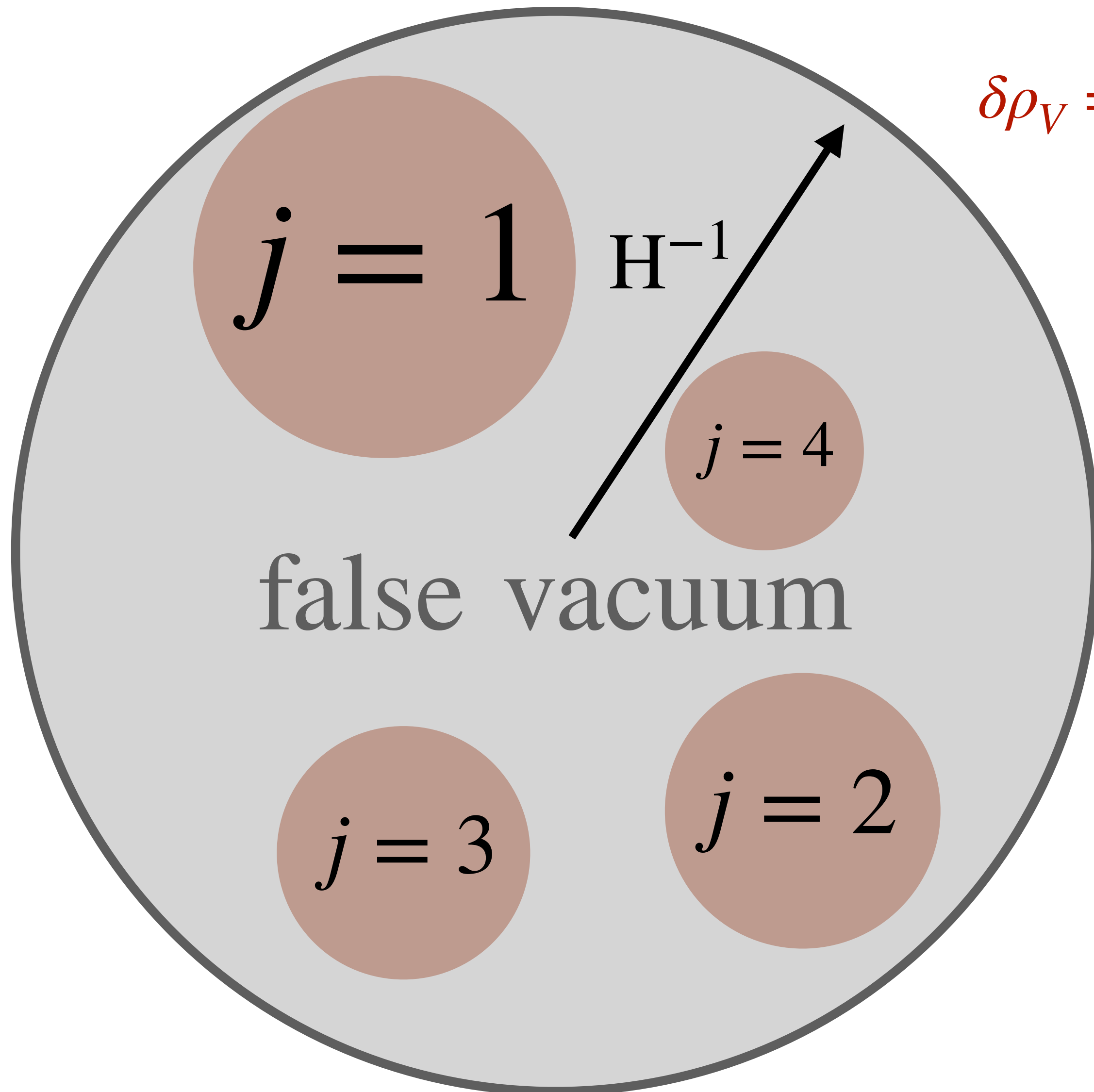
Bian+, 2021

YG, Volansky 2305:04942

Baldes, Olea-Romacho, 2307.11639

YG, PRL, 2307.04239

YG, 2311.13640



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$$J_c \text{ arbitrary}$$

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c++ code: *deltaPT*

$$\delta\rho_R'(t) + 4\mathcal{H}\delta\rho_R(t) = -\delta\rho_V'(t)$$

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

deltaPT

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PRL
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$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

deltaPT



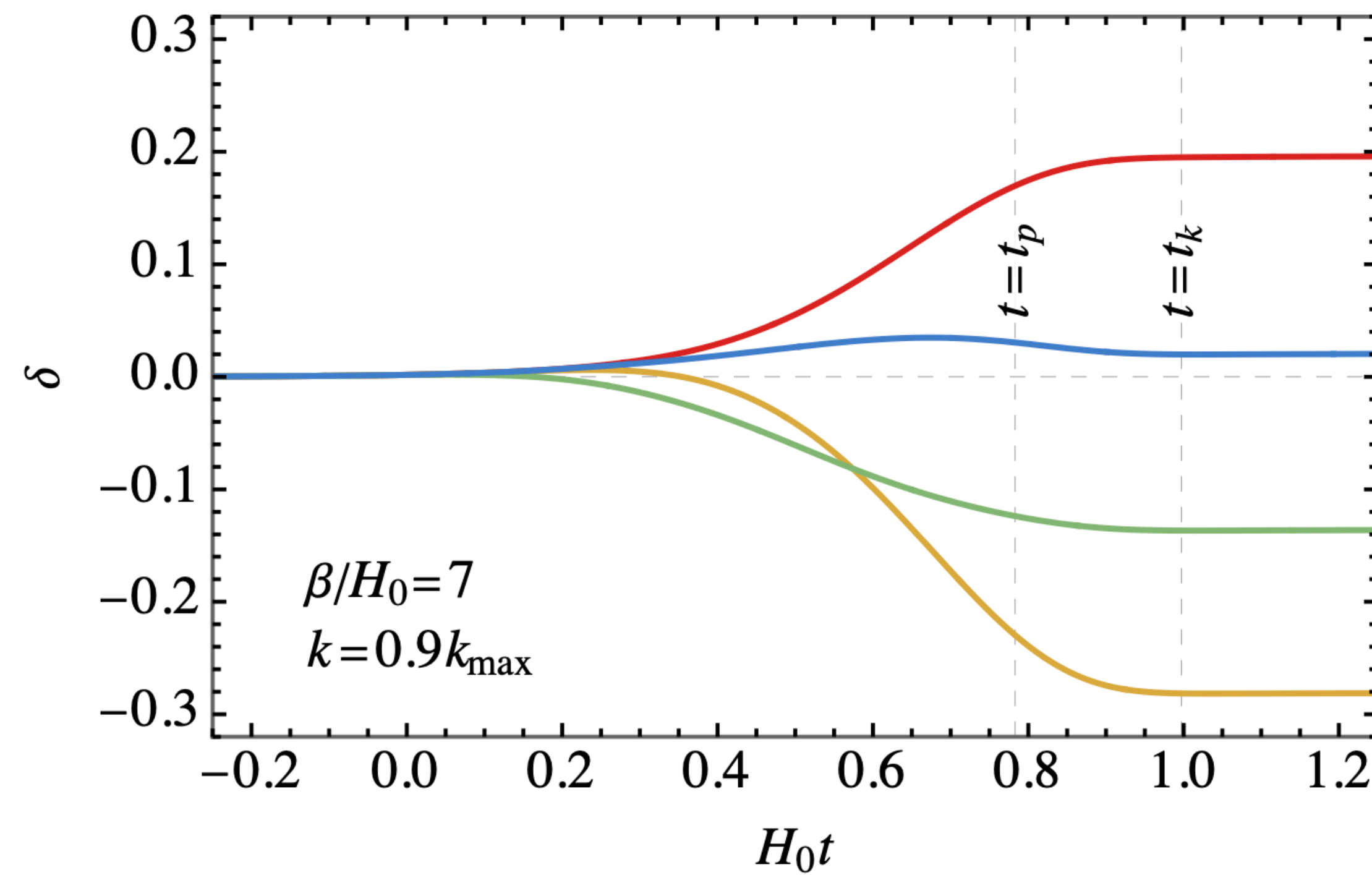
$$\delta(t) = \frac{\delta\rho_R + \delta\rho_V}{\rho}$$

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2402.04158

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

deltaPT

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2402.04158



How to calculate PBHs from FOPTs ?

$$1) \text{ calculate } \langle \delta(t) \rangle_{\text{H}} = \left\langle \frac{\delta\rho_R + \delta\rho_V}{\rho} \right\rangle_{\text{H}}$$

2) calculate probability for $\langle \delta(t) \rangle_{\text{H}} \gtrsim 0.5$

How to calculate PBHs from FOPTs ?

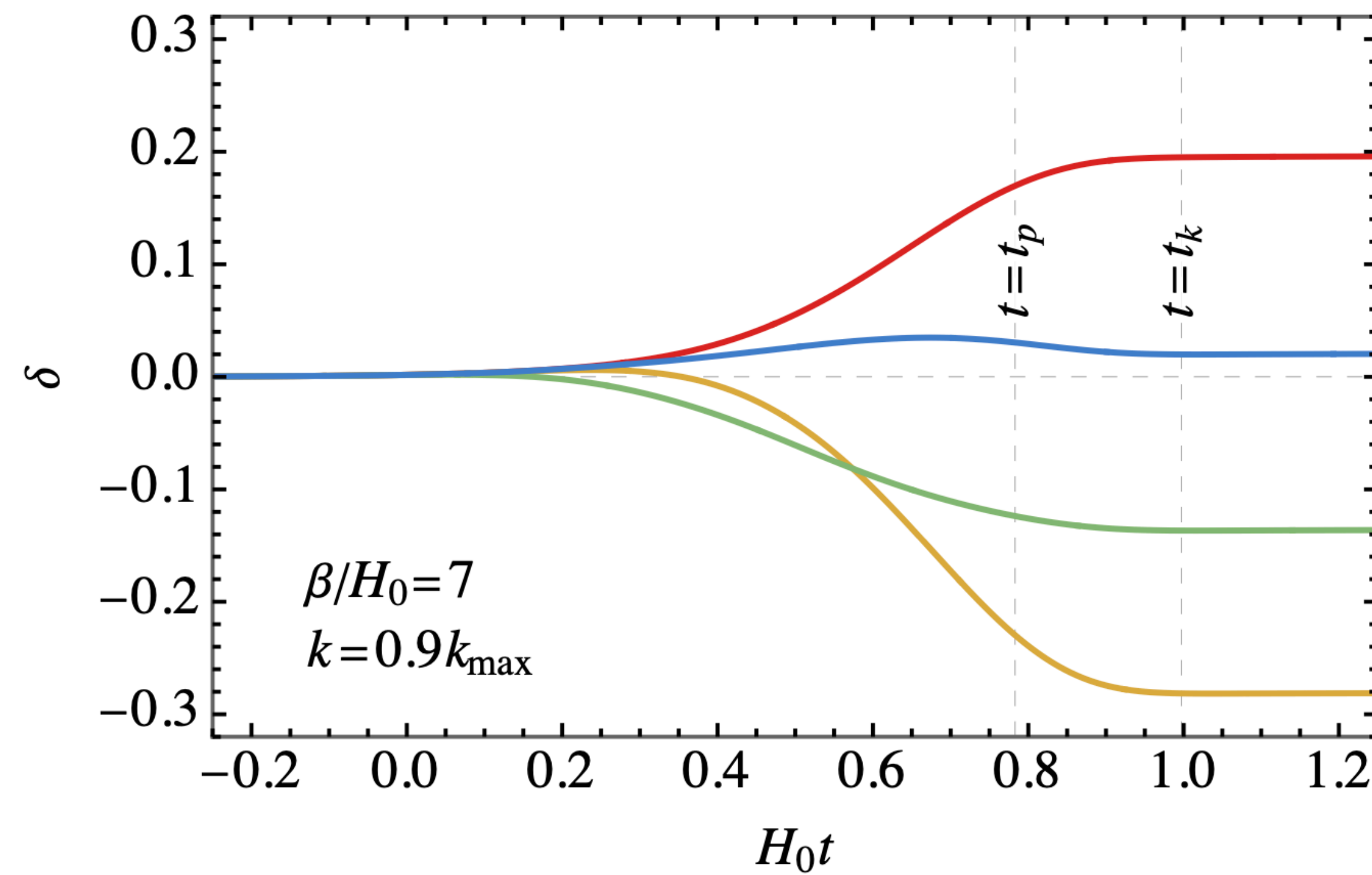
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deltaPT

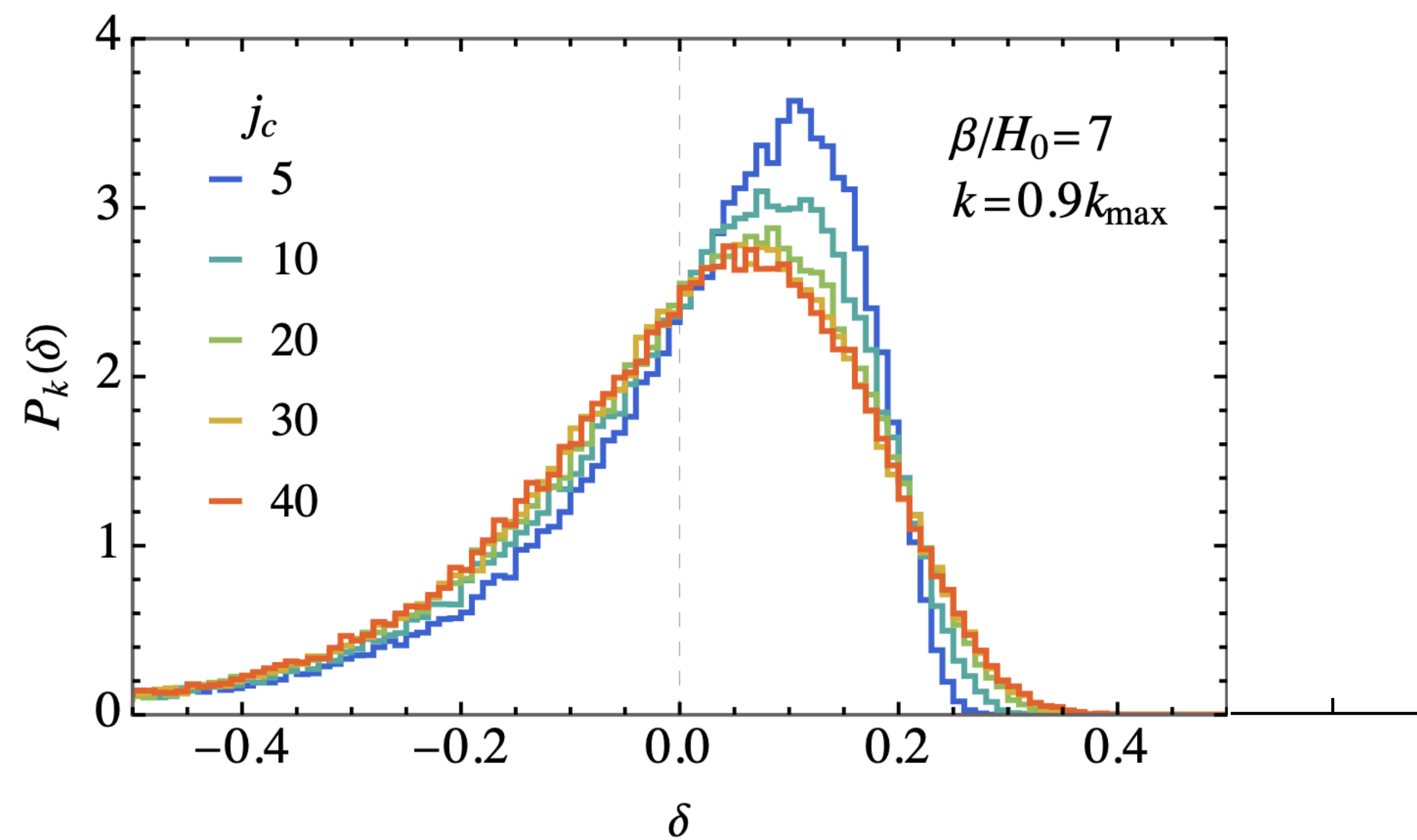
Lewicki, Toczek, Vaskonen
PRL
2402.04158



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deltaPT

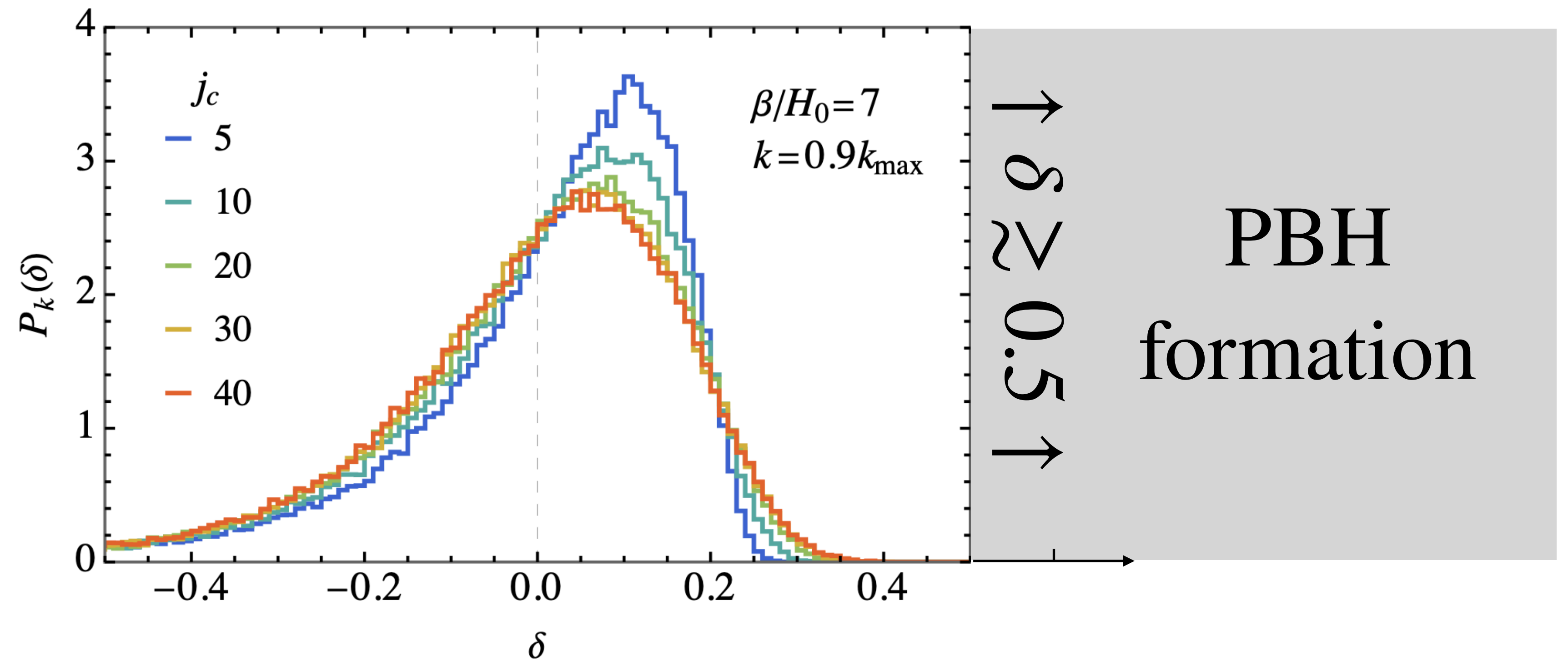
Lewicki, Toczek, Vaskonen
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deltaPT

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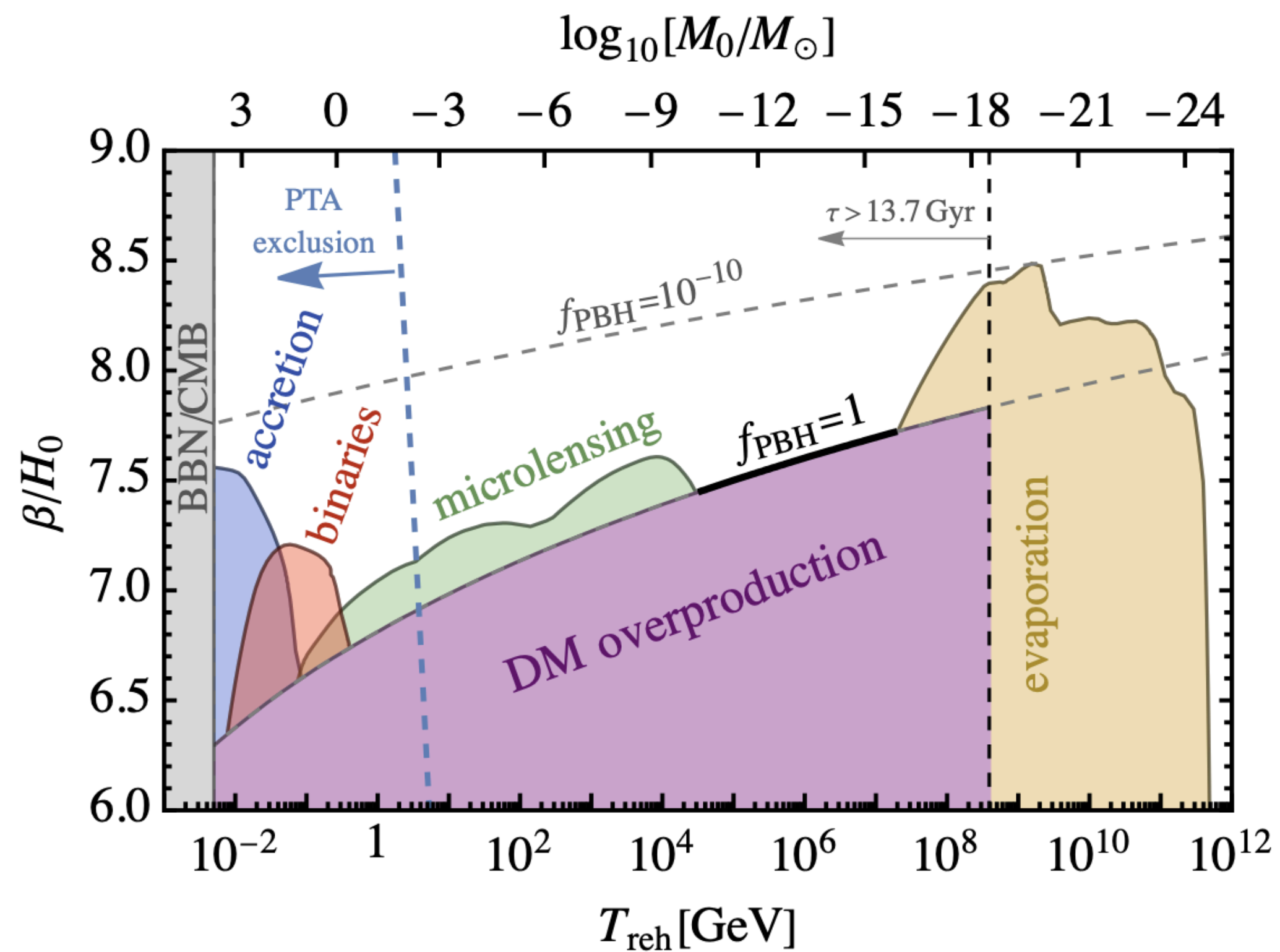


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$$\delta \gtrsim \delta_{\text{th}} \simeq 0.5$$

deltaPT

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Boiling time $\frac{\beta^{-1}}{H^{-1}}$

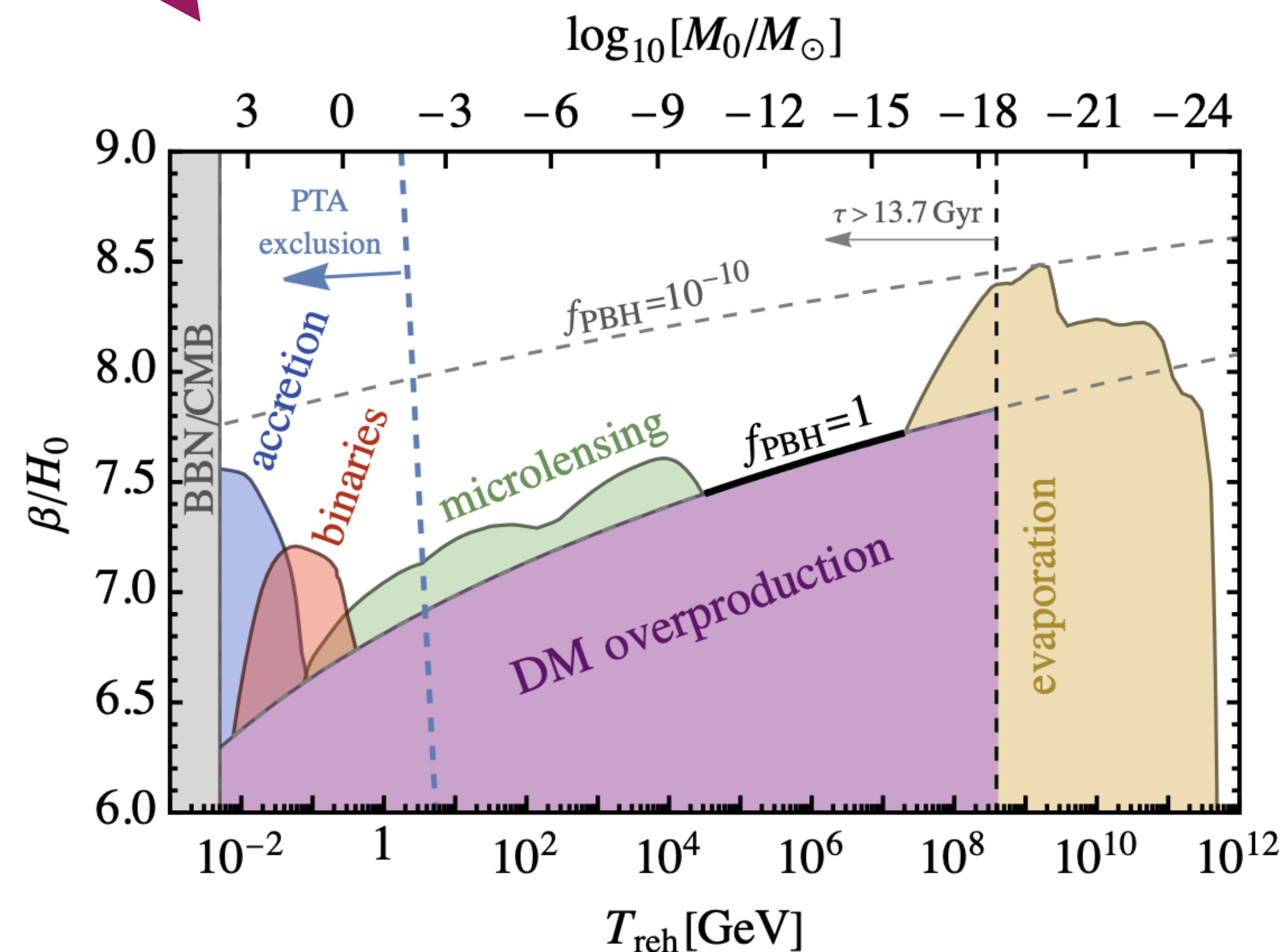
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deltaPT

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$J_c = 50$ random bubbles



Sasaki+ 1982

Bian+, 2021

YG, Volansky 2305:04942

Baldes, Olea-Romacho, 2307.11639

YG, PRL, 2307.04239

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$J_c = 1$ random bubble only

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

deltaPT

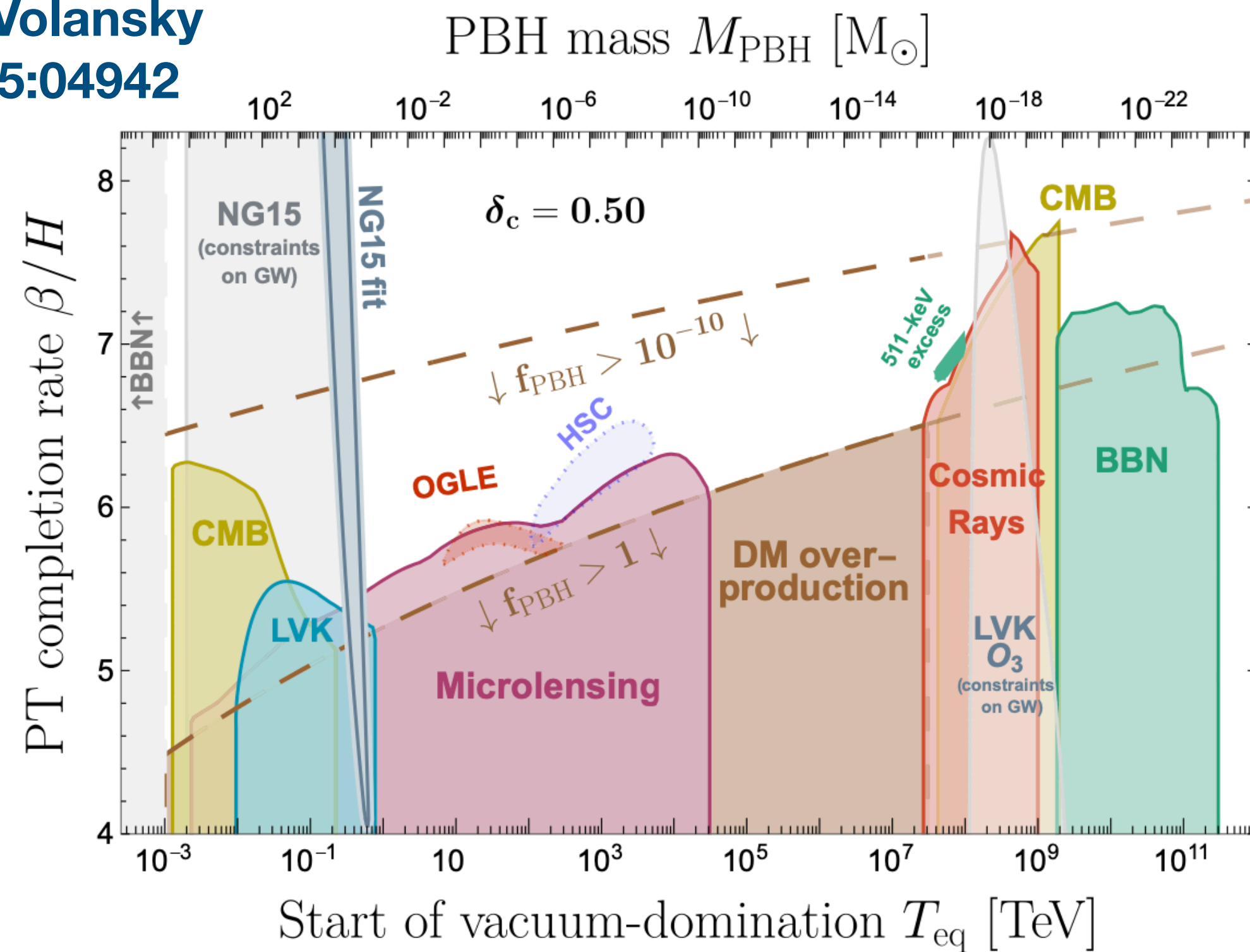
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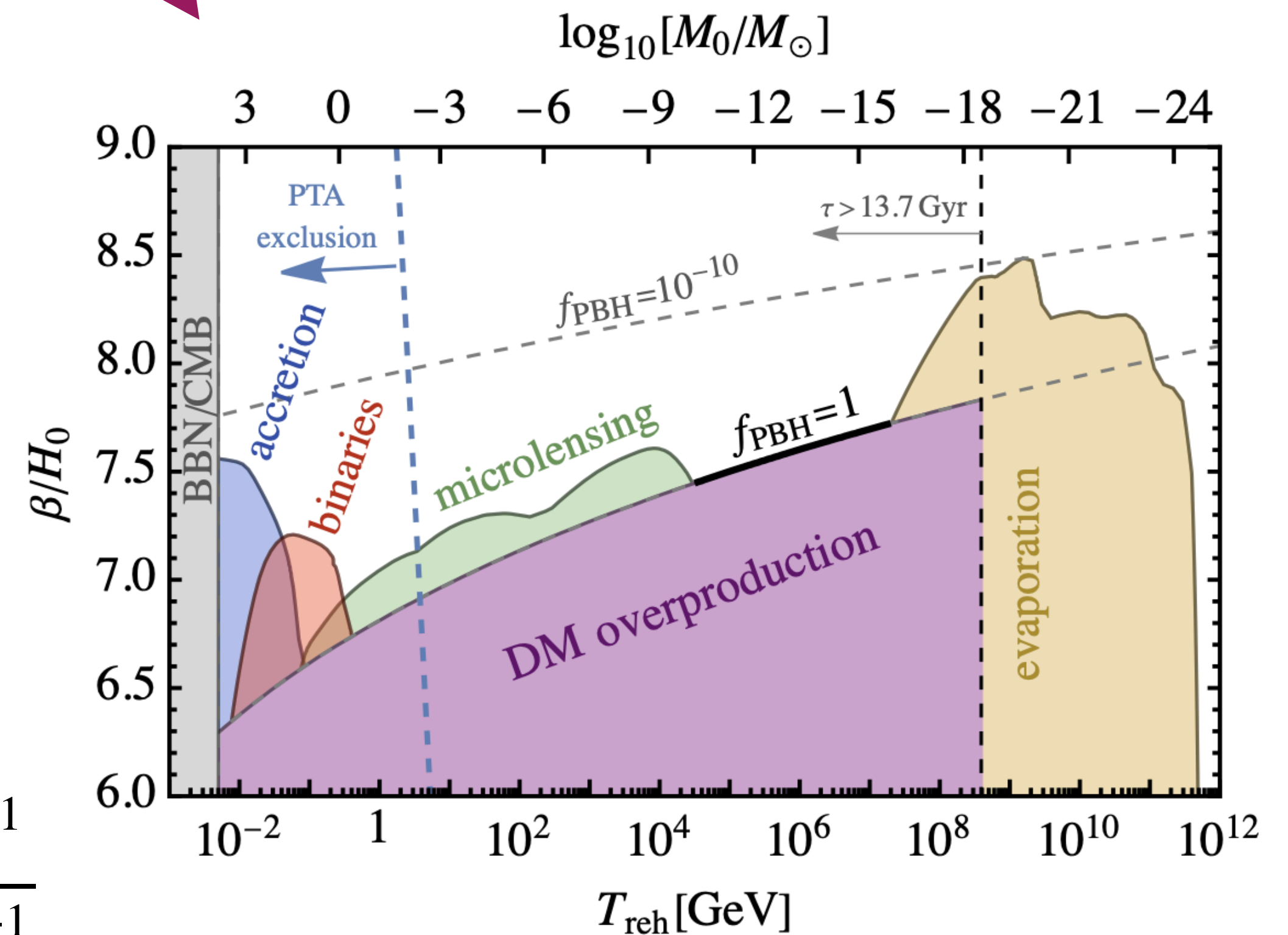
2402.04158

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YG, Volansky
2305:04942



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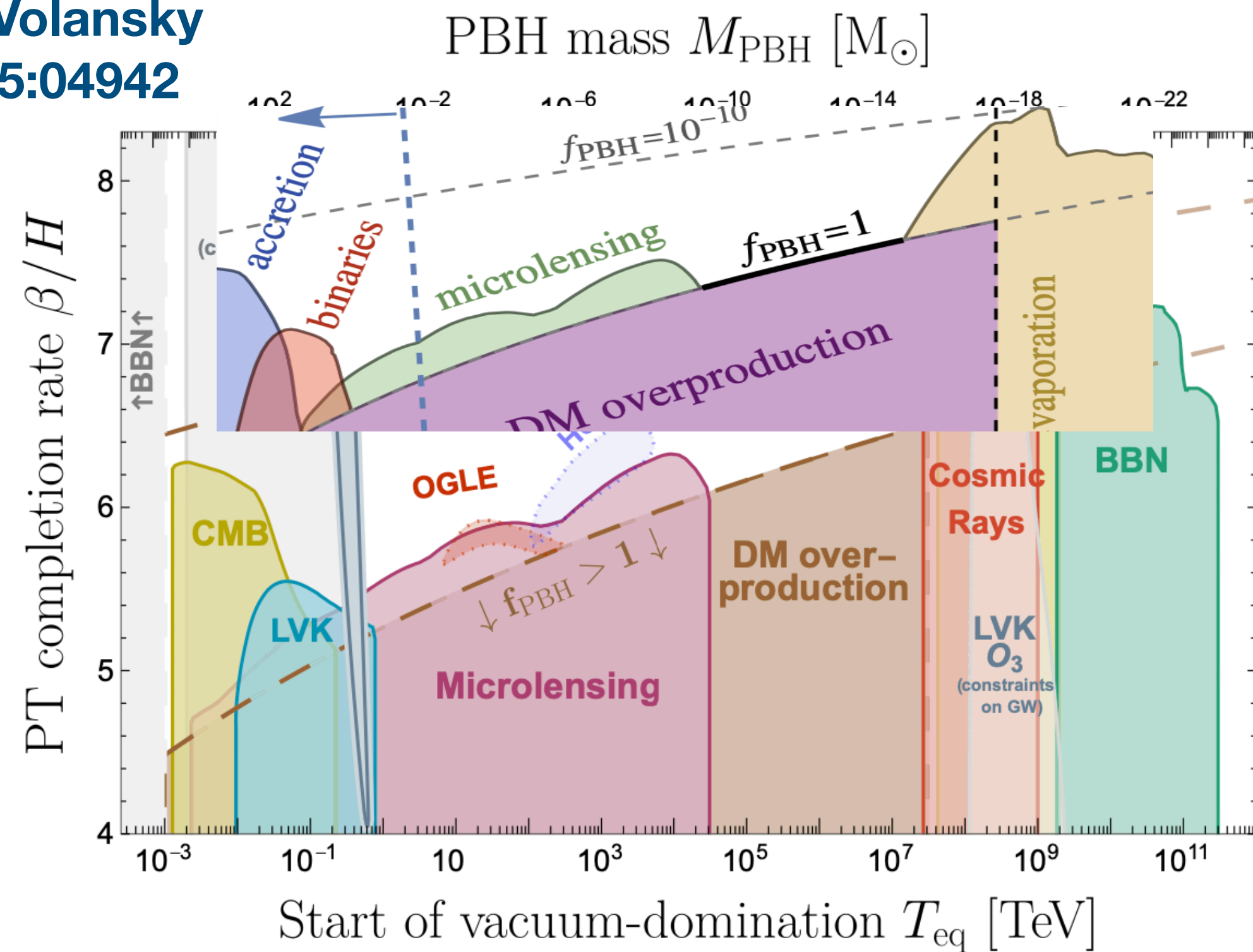
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2305:04942



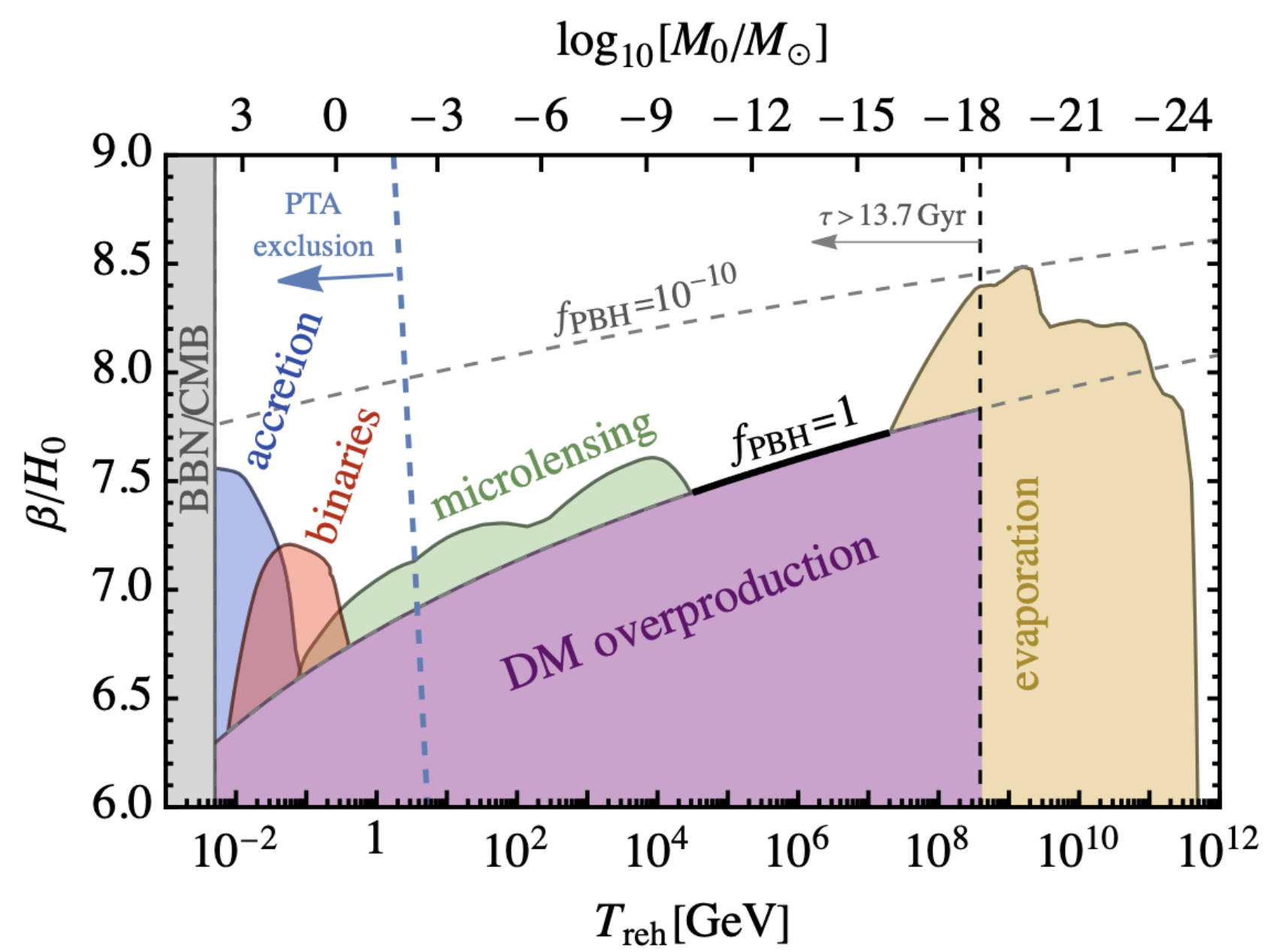
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$$\delta \gtrsim \delta_{\text{th}} \simeq 0.5$$

- Sasaki+ 1982
- Bian+, 2021
- Lewicki+, 2023
- YG&Volansky, 2023
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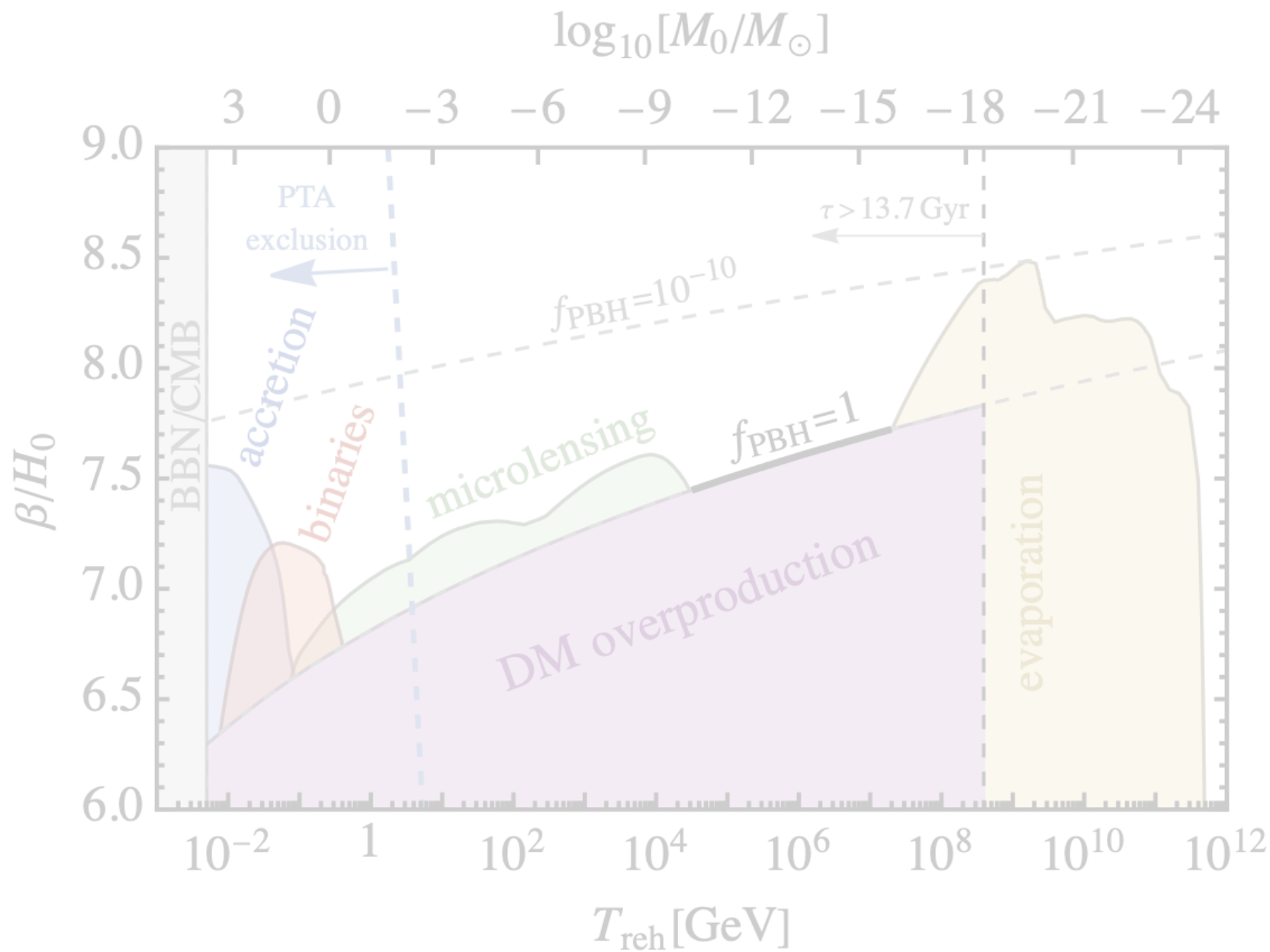
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2402.04158

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

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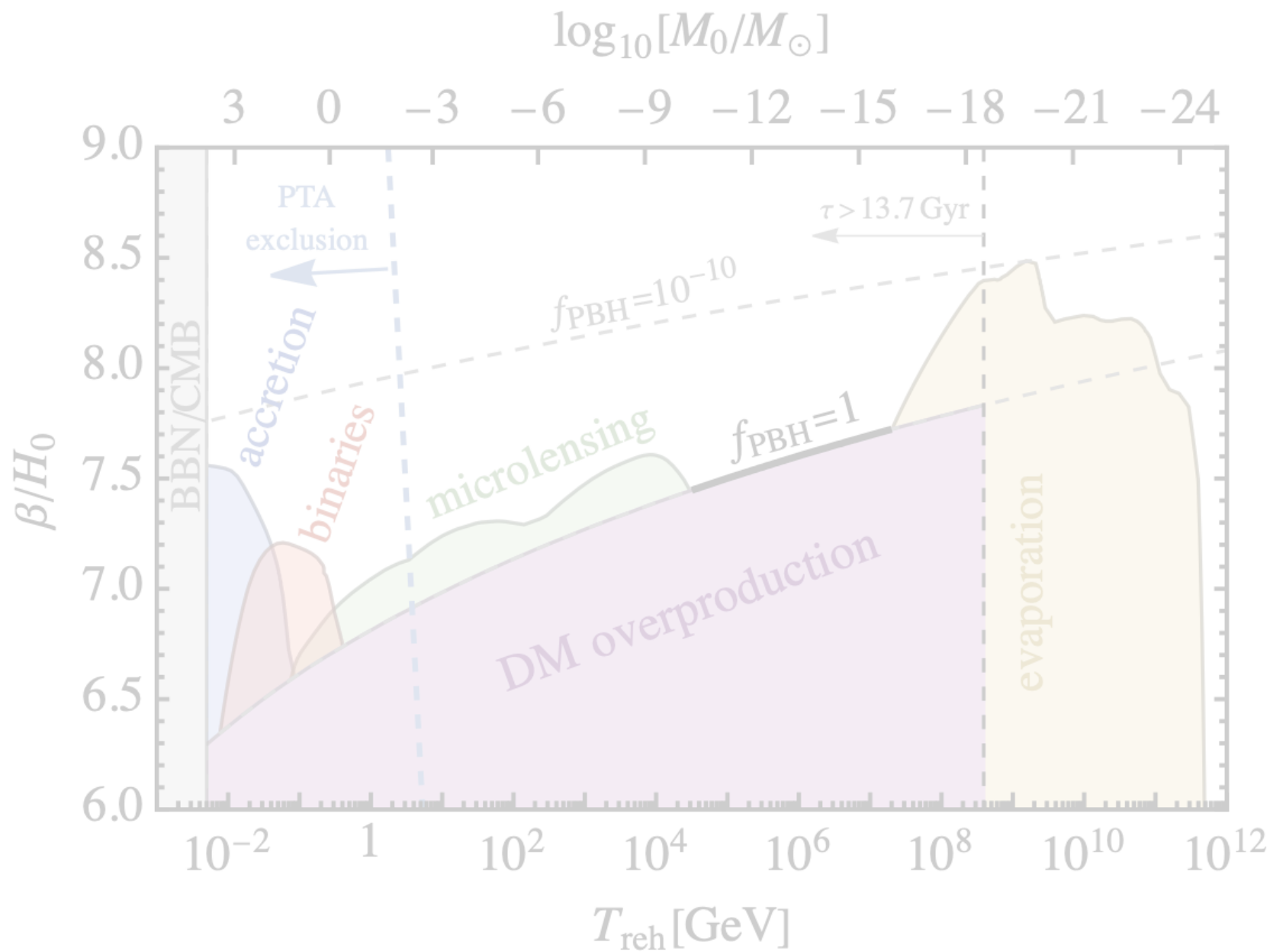
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2nd order GW

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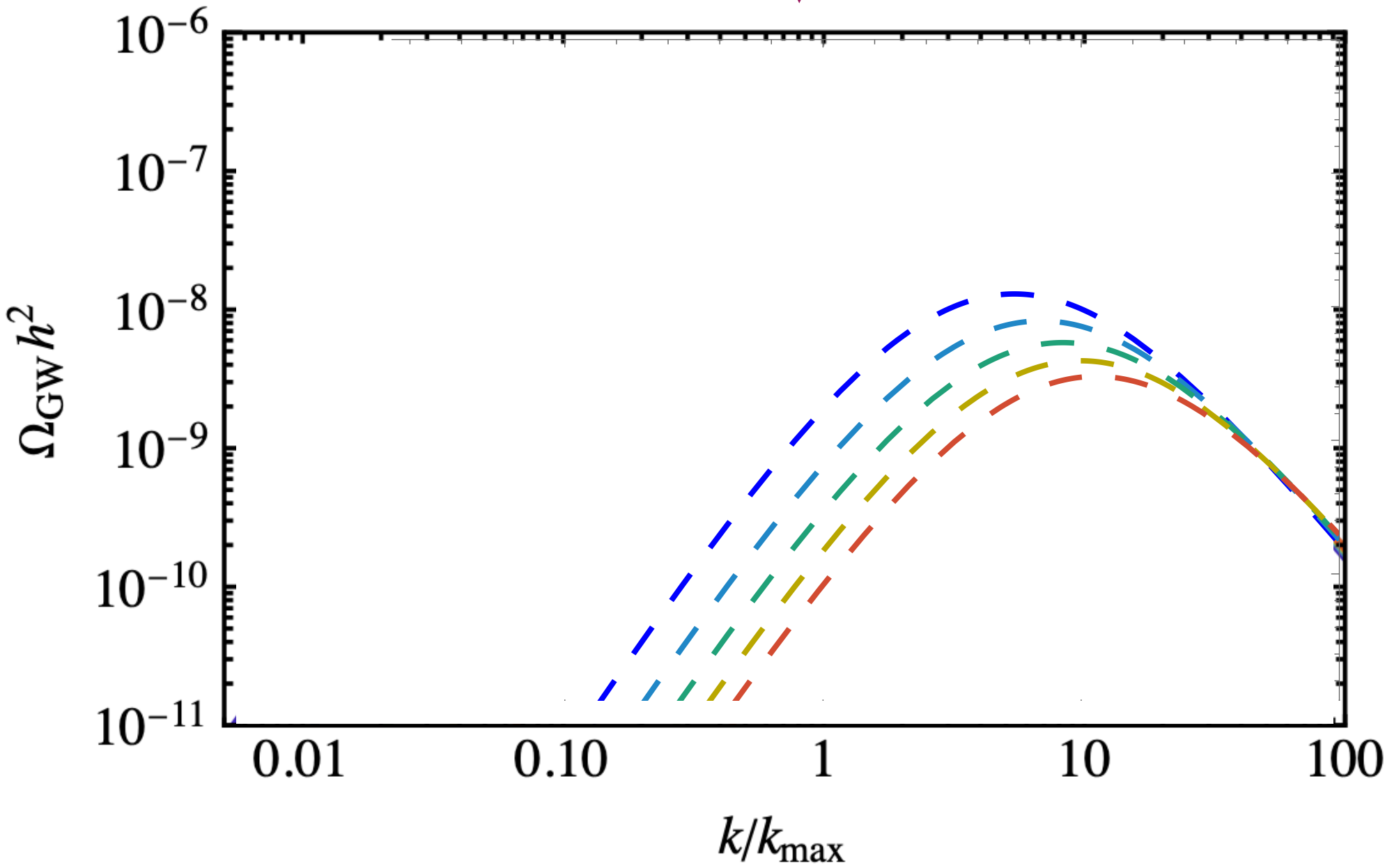
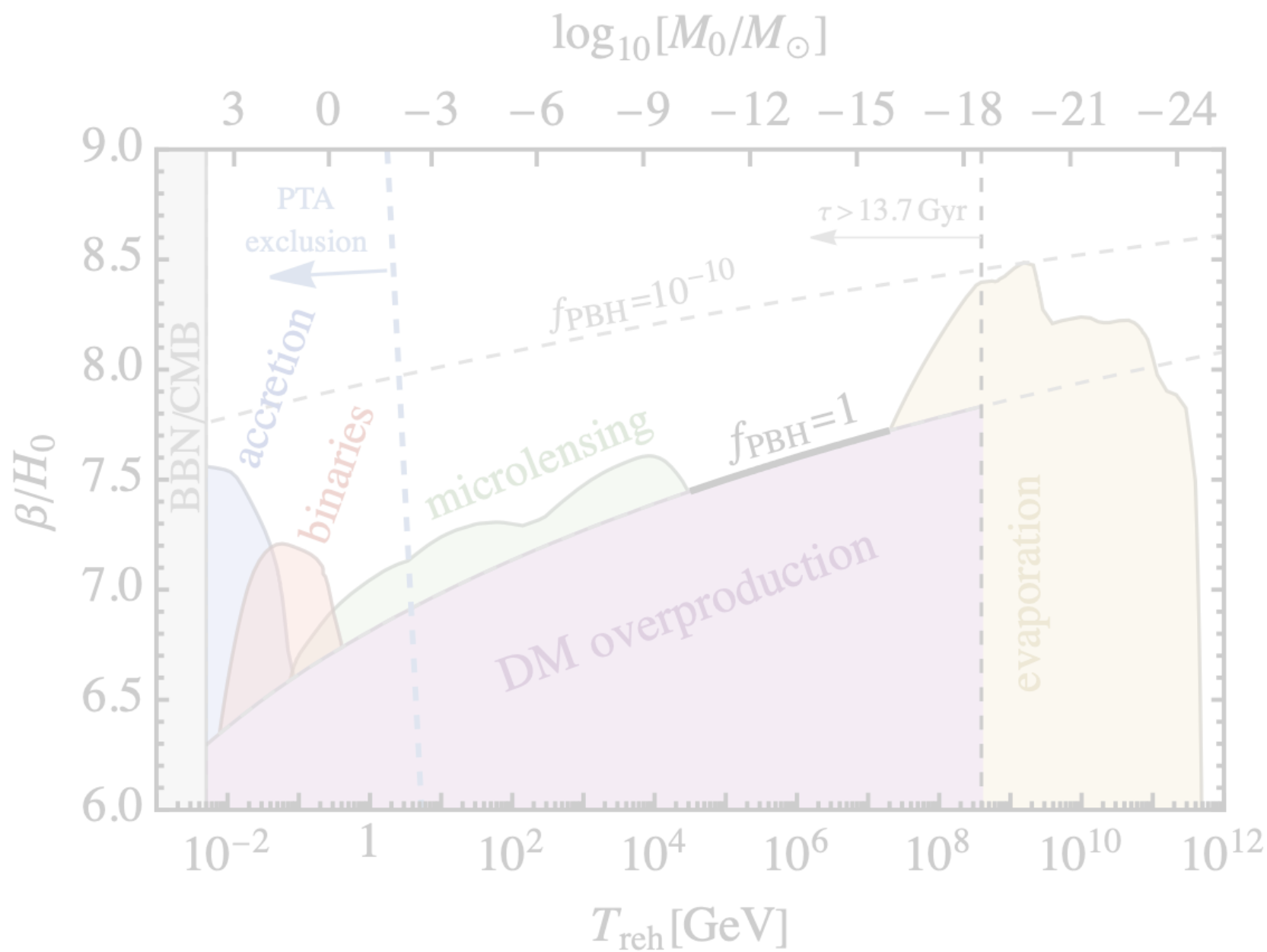
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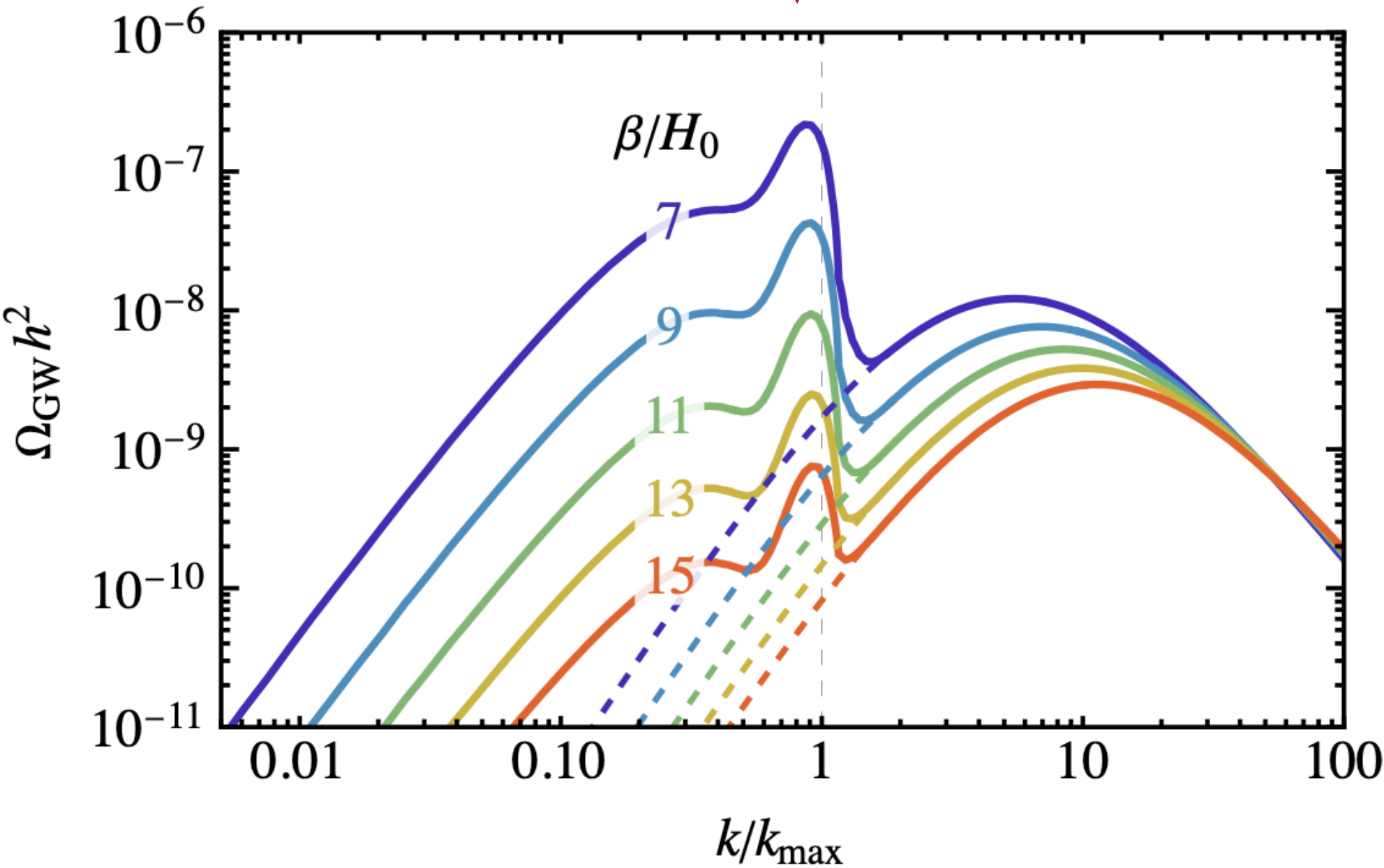
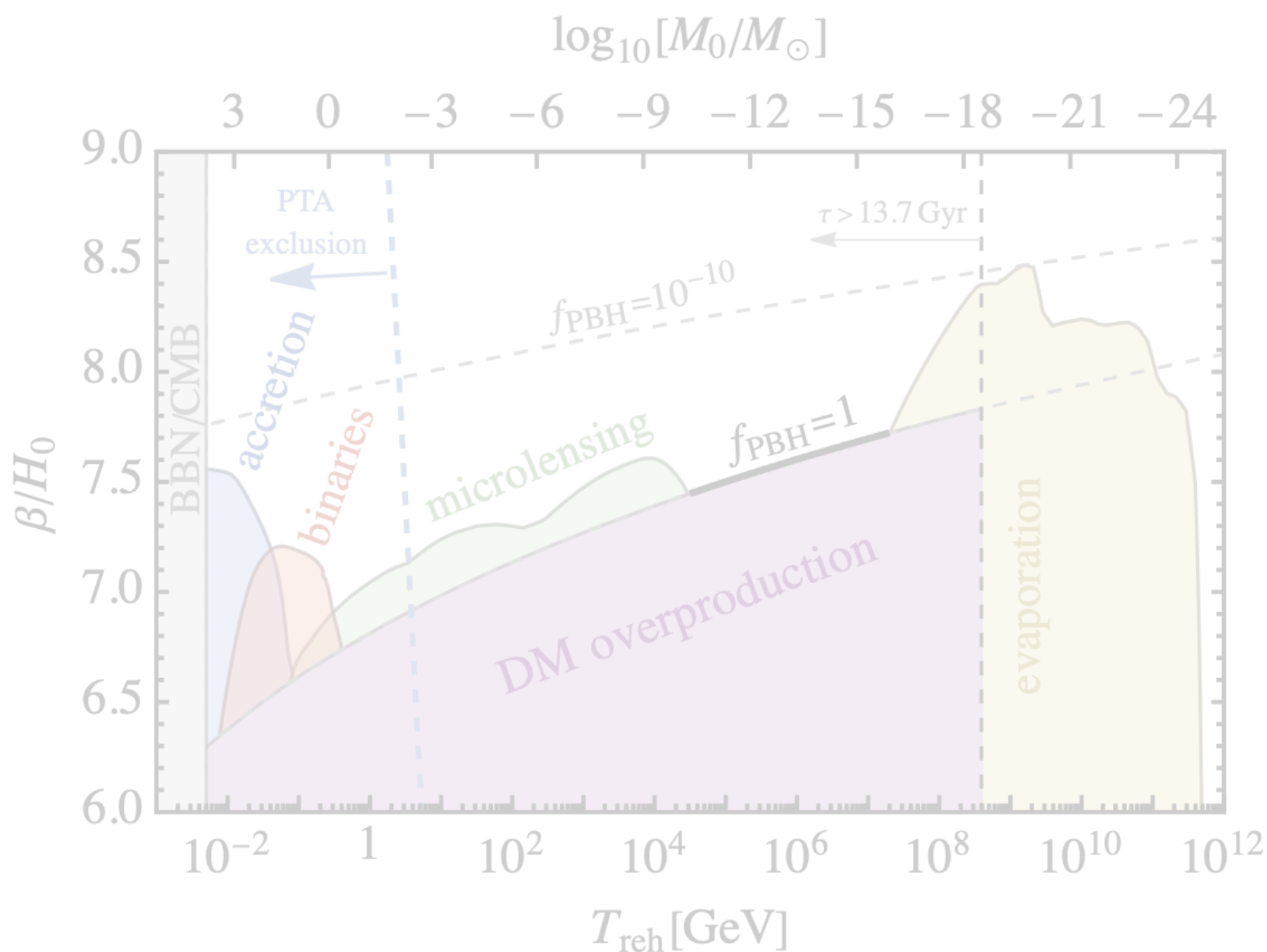
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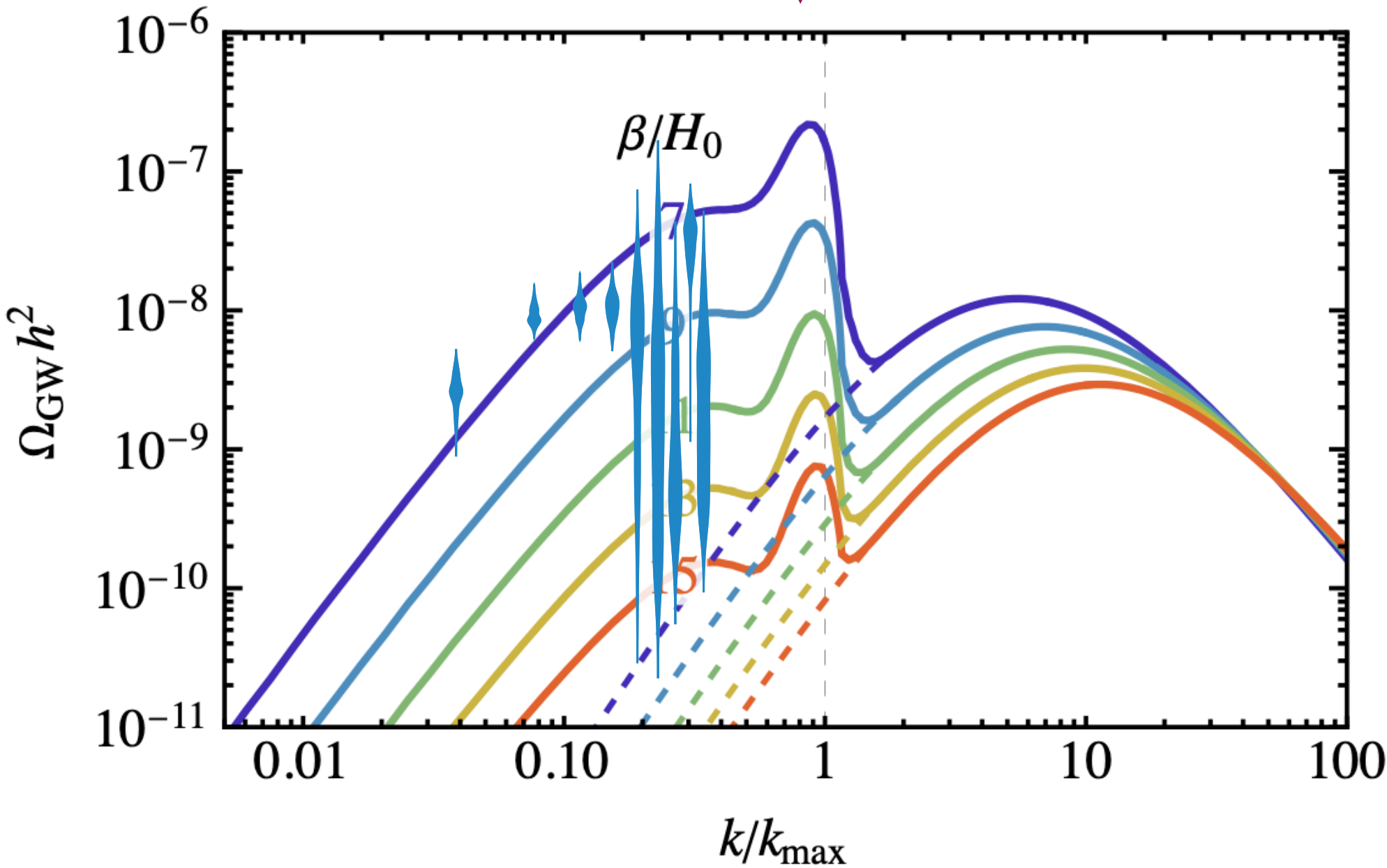
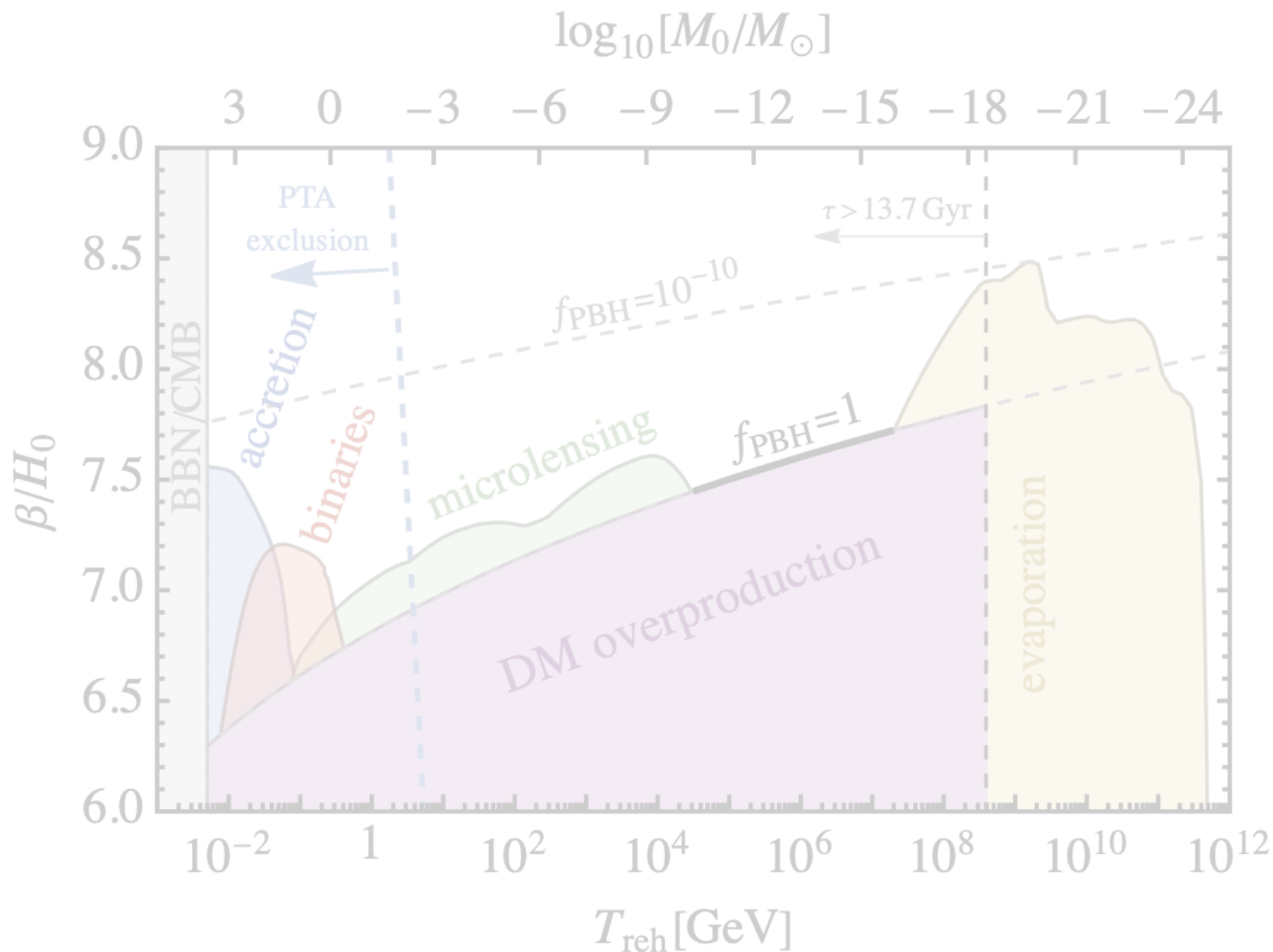
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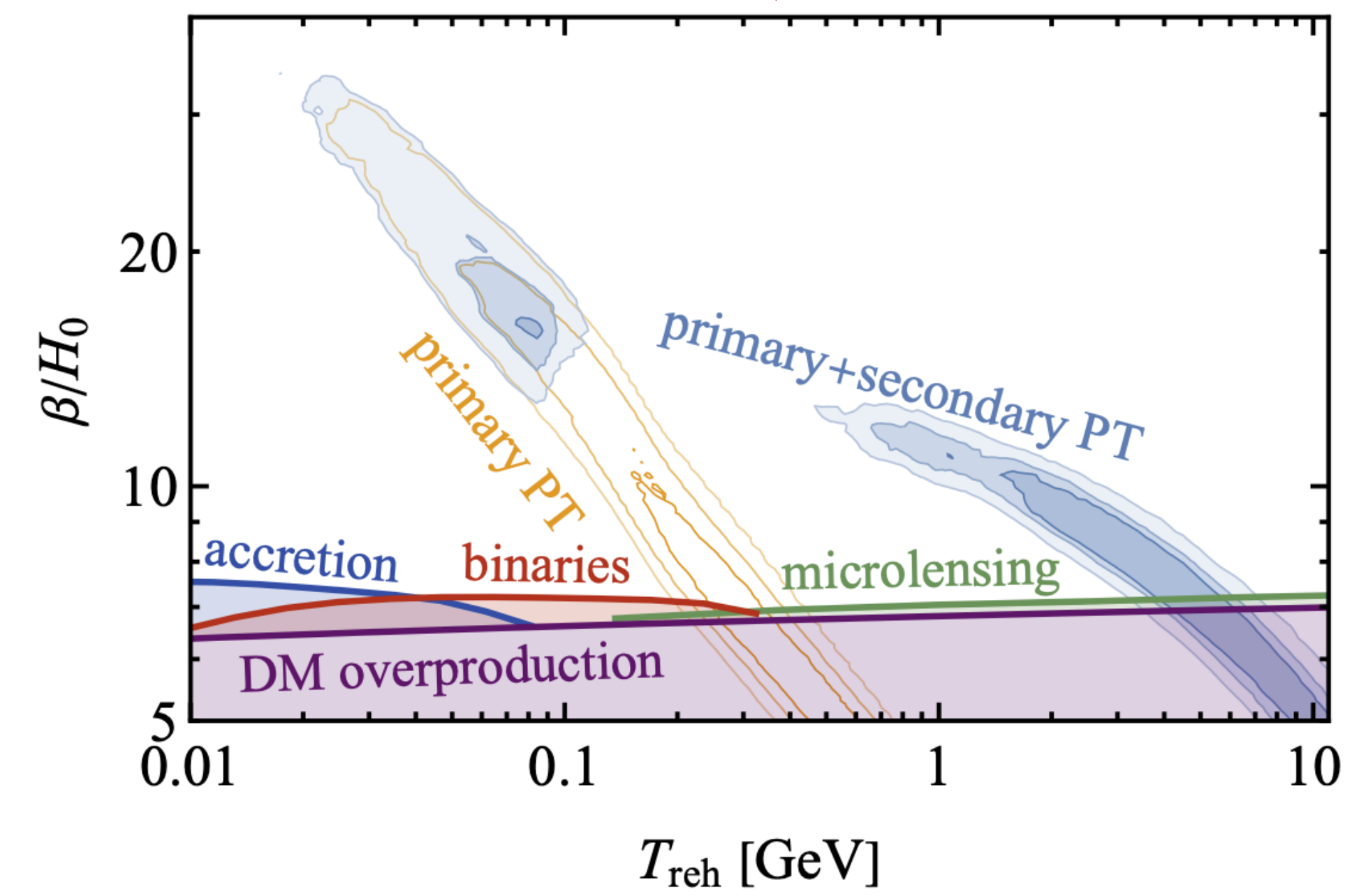
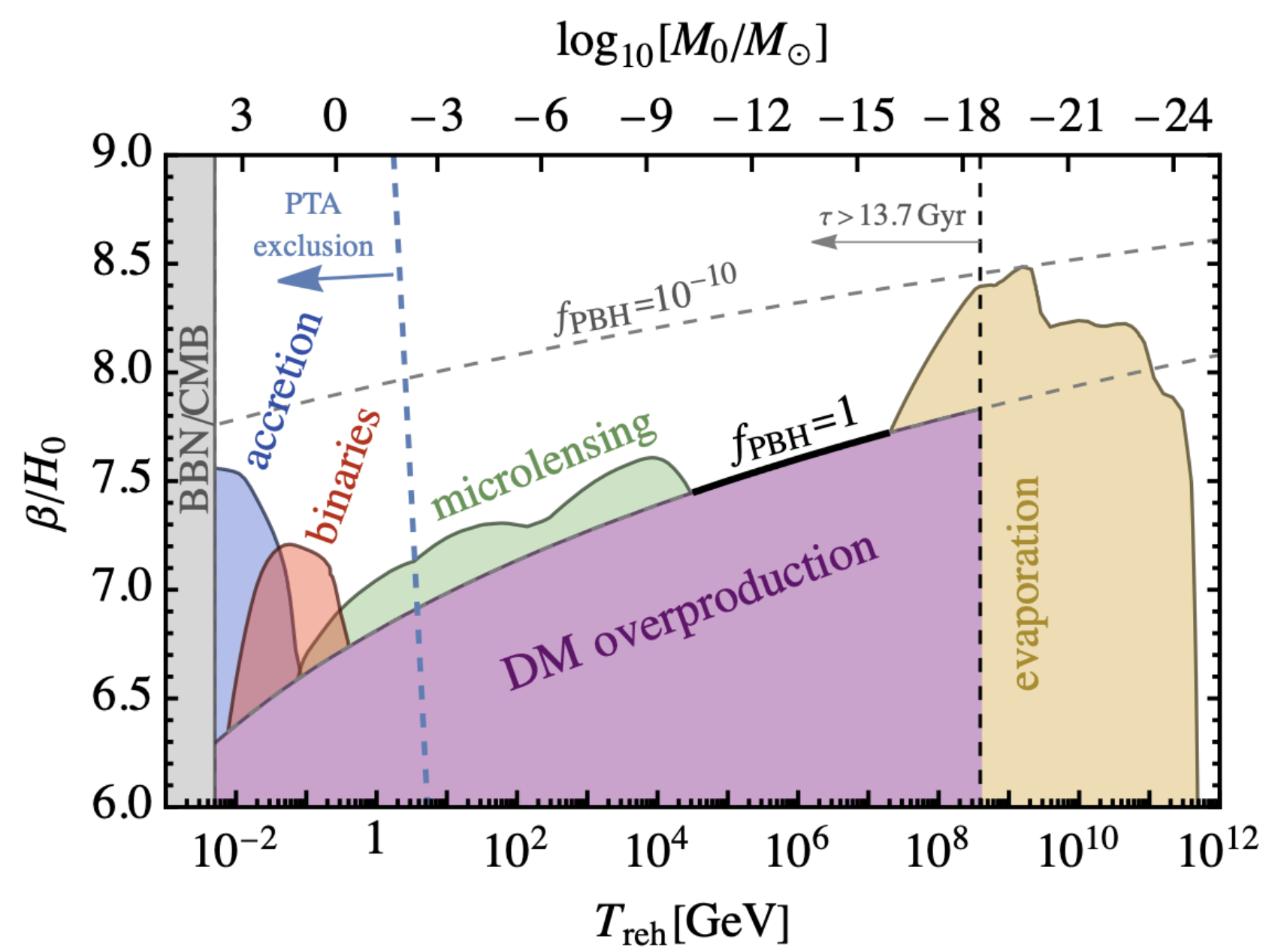
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$$\text{Where is } \mathcal{R}?$$

2402.13341

Revisiting formation of primordial black holes in a supercooled first-order phase transition

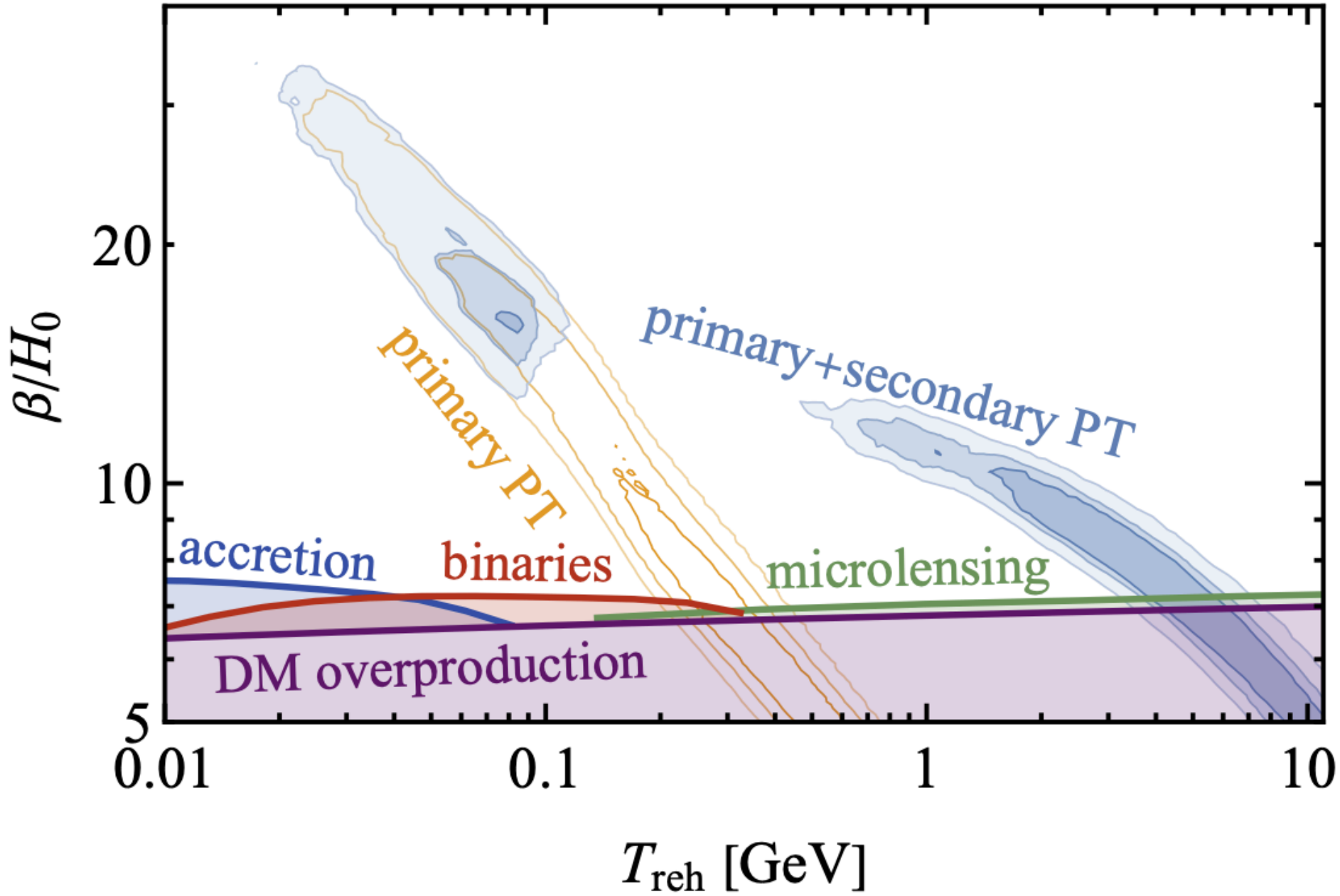
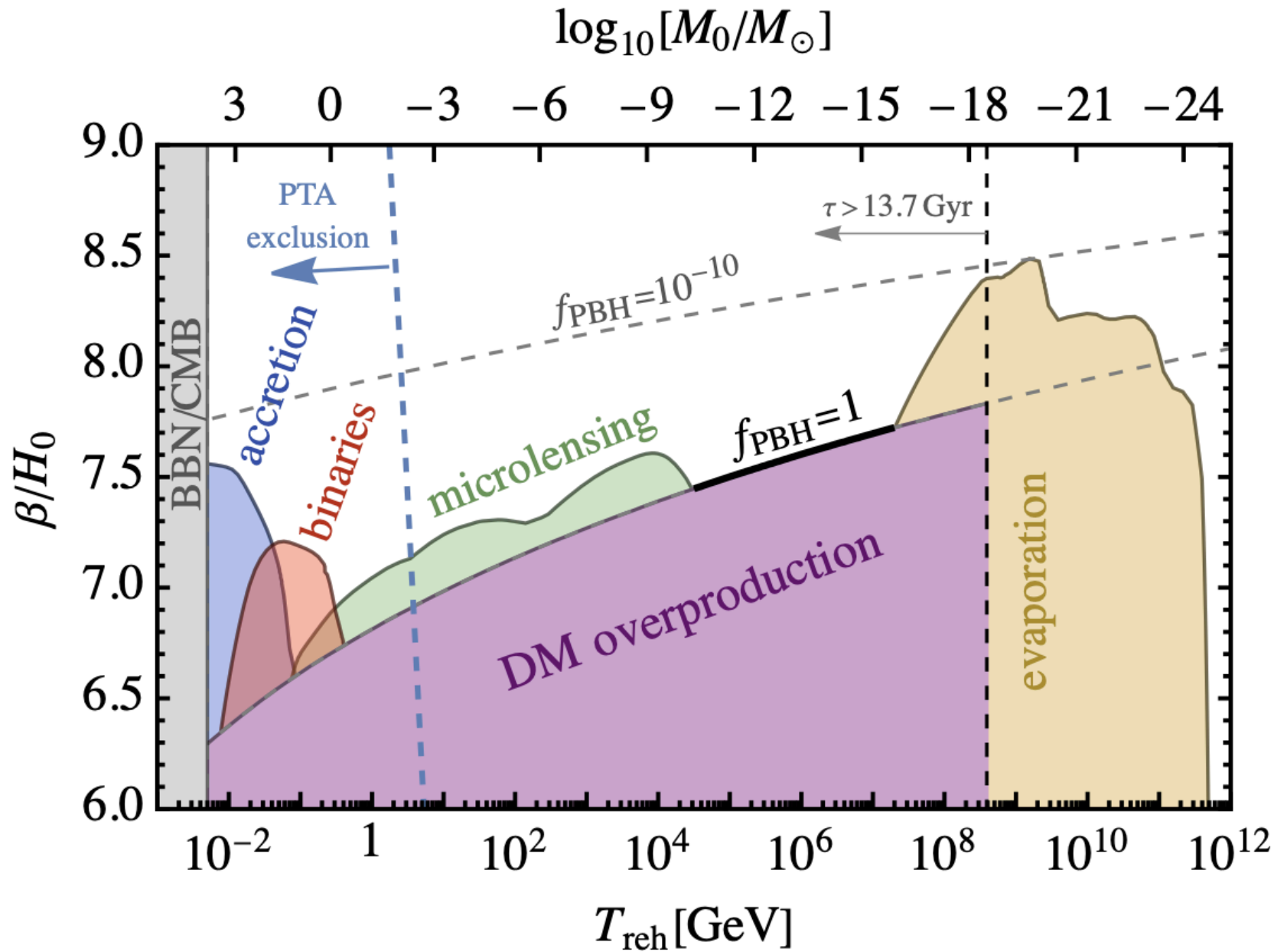
Marcos M. Flores,^{1,2} Alexander Kusenko,^{3,4} and Misao Sasaki^{4,5,6}

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Revisiting formation of primordial black holes in a supercooled first-order phase transition **2402.13341**

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Without a curvature component, the equations of motion describing any Hubble-sized patch containing radiation provide only expansionary solutions



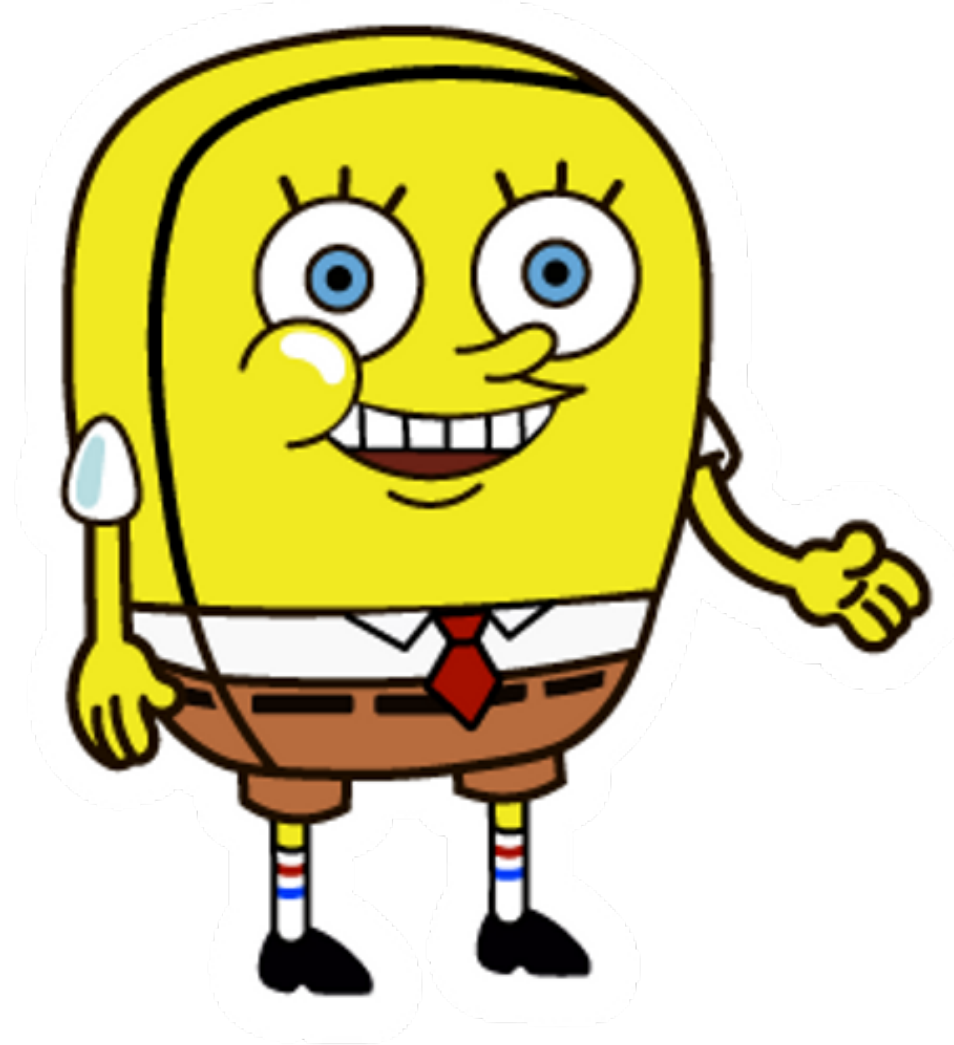
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Hello, I am trying to be a PBH cosmologist



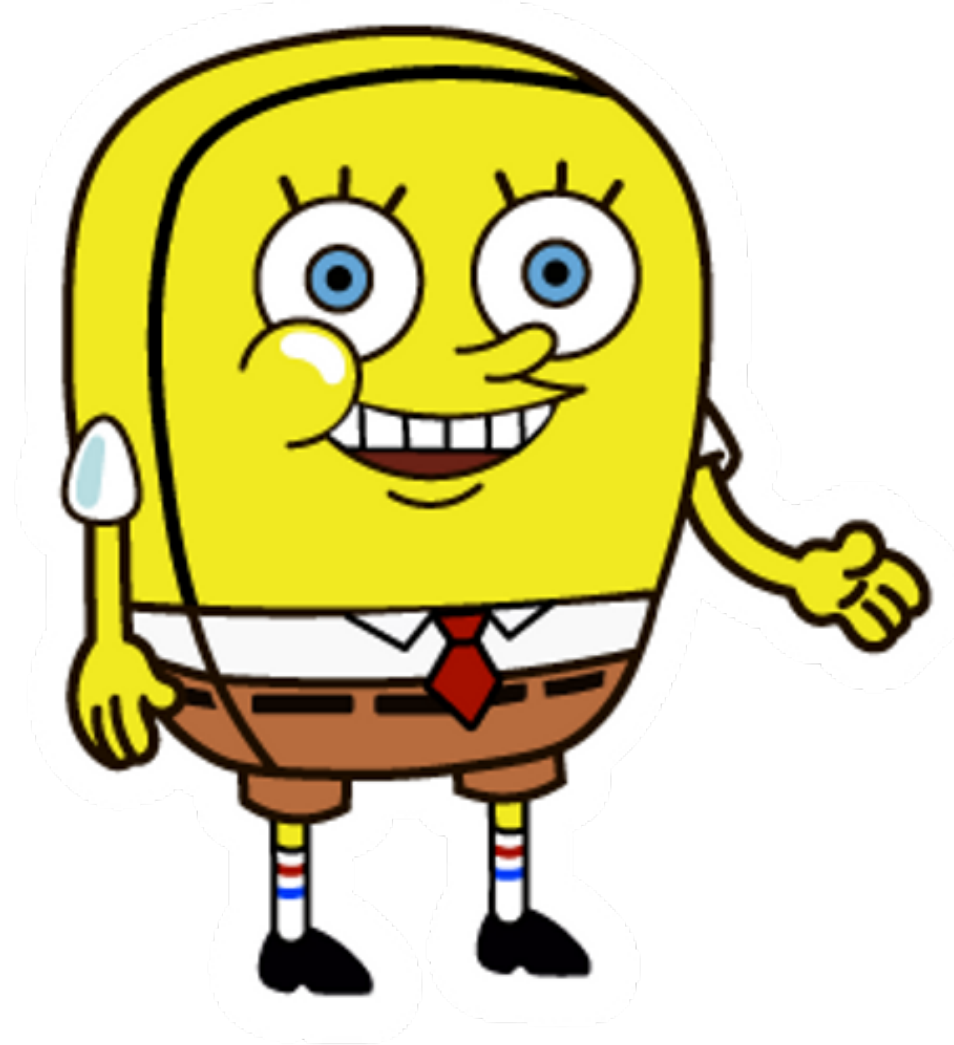
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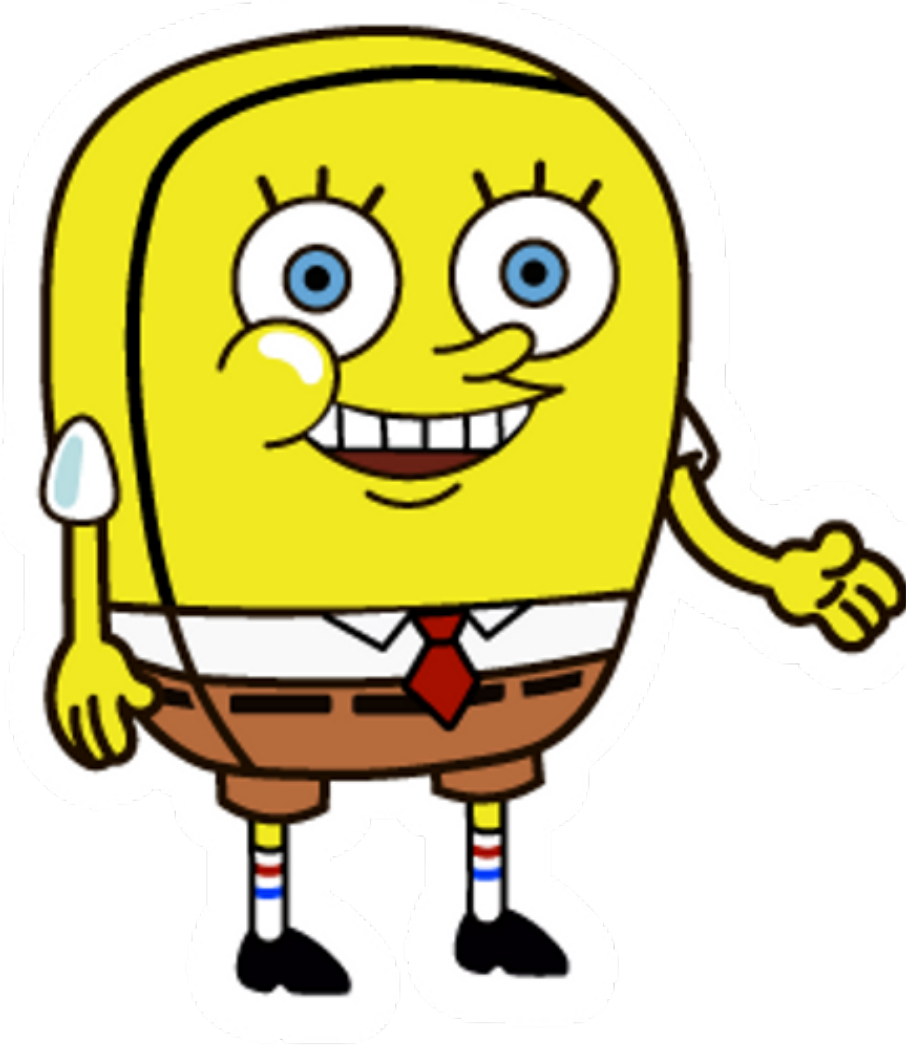
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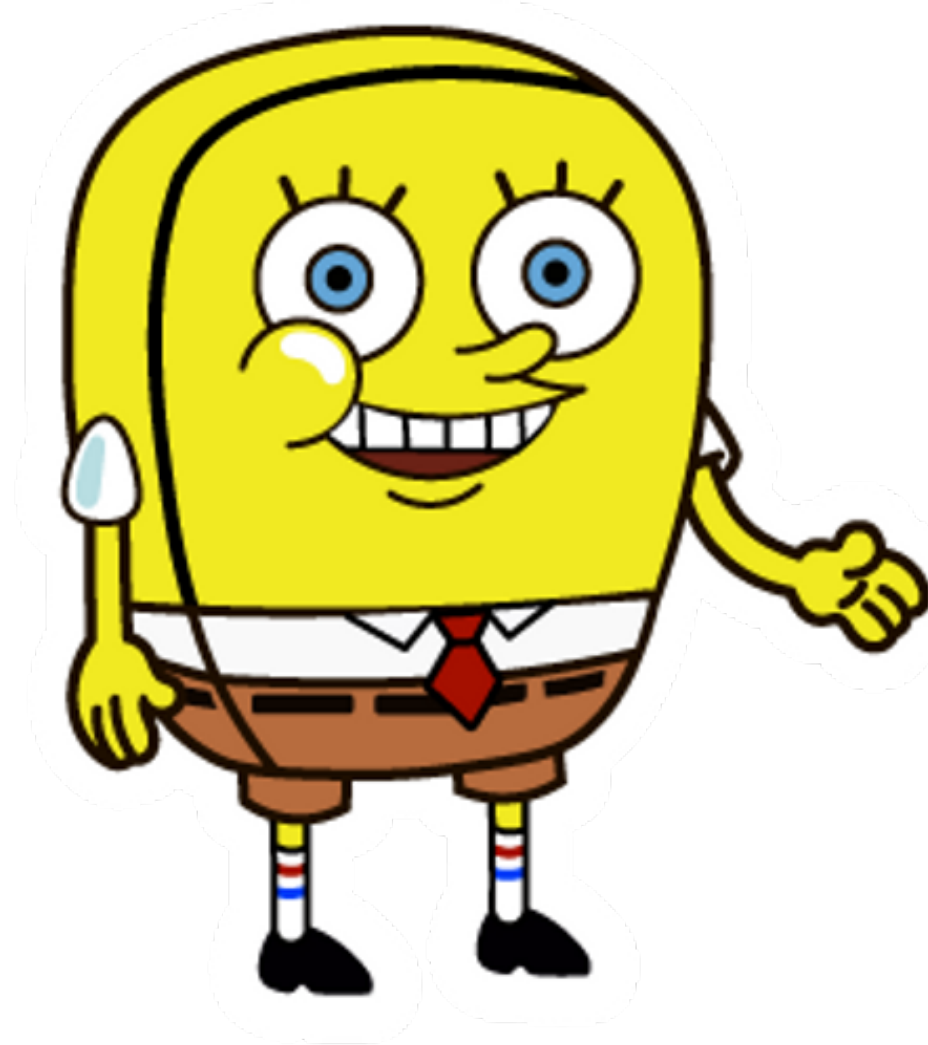
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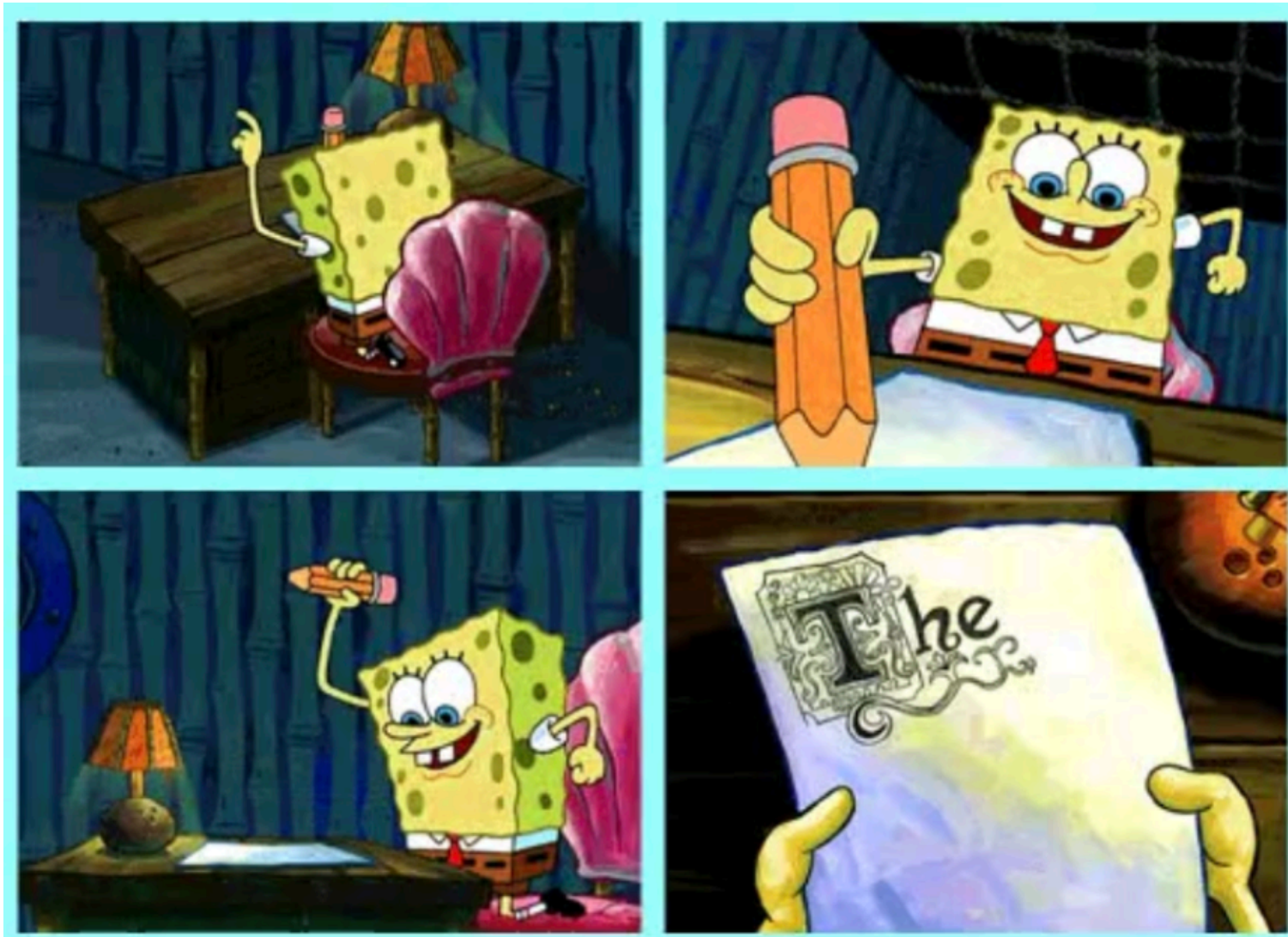
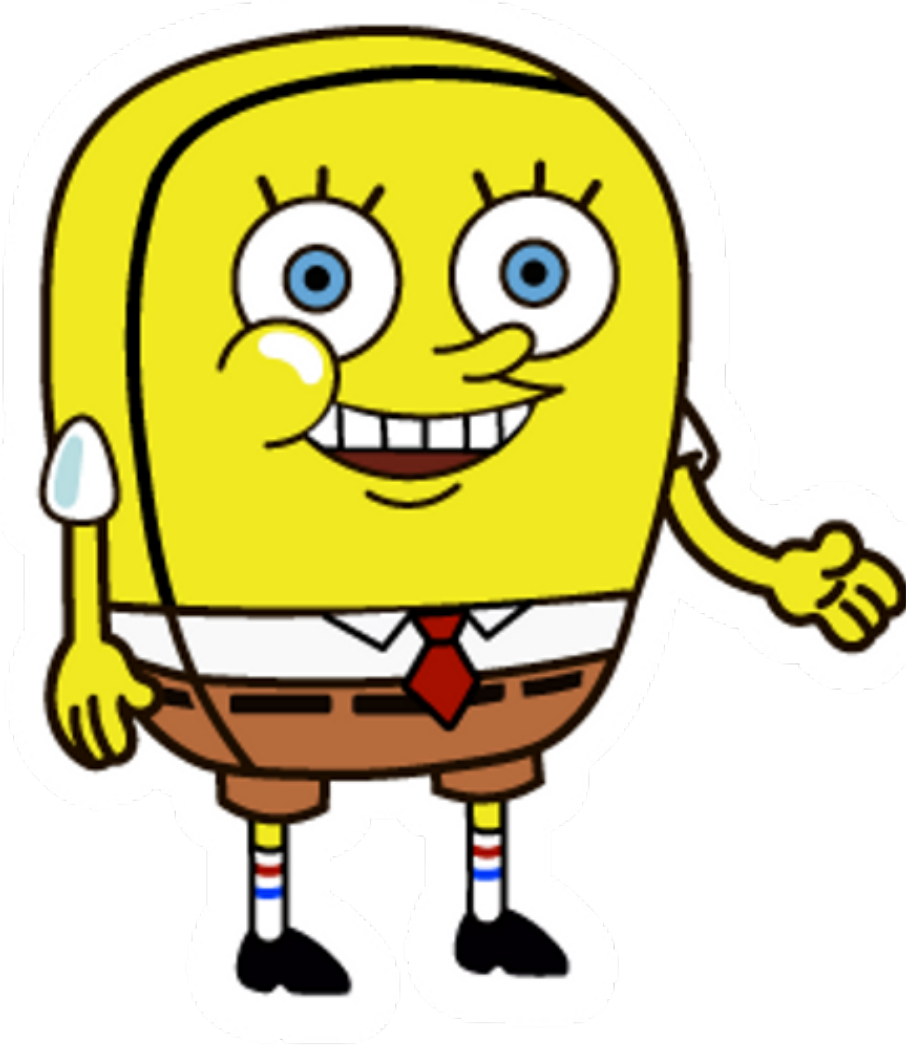
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$$(\delta \equiv \delta\rho/\bar{\rho})$$

Sasaki+ 1982
Bian+, 2021
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$$\text{Where is } \mathcal{R}?$$

2402.13341

Revisiting formation of primordial black holes in a supercooled first-order phase transition

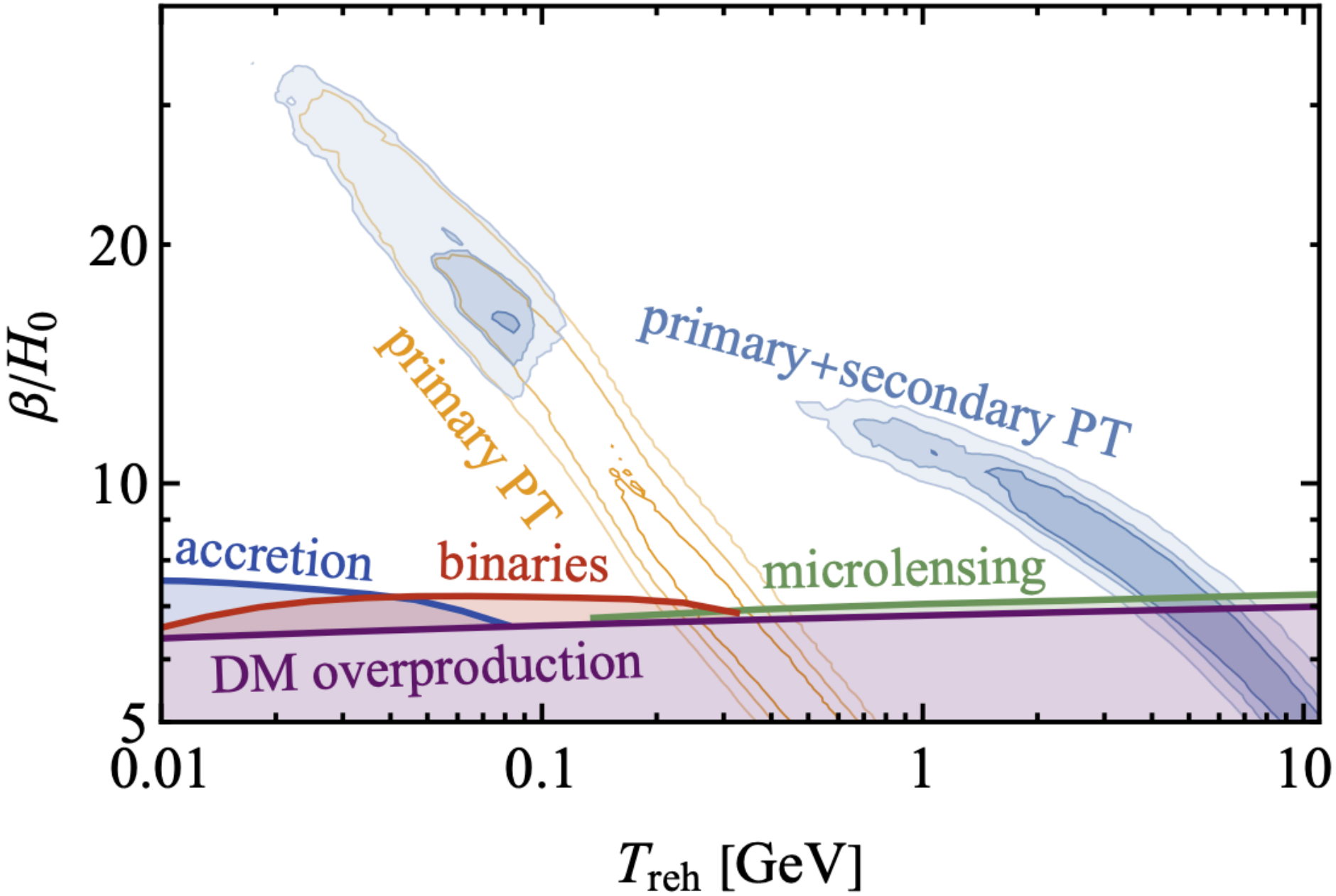
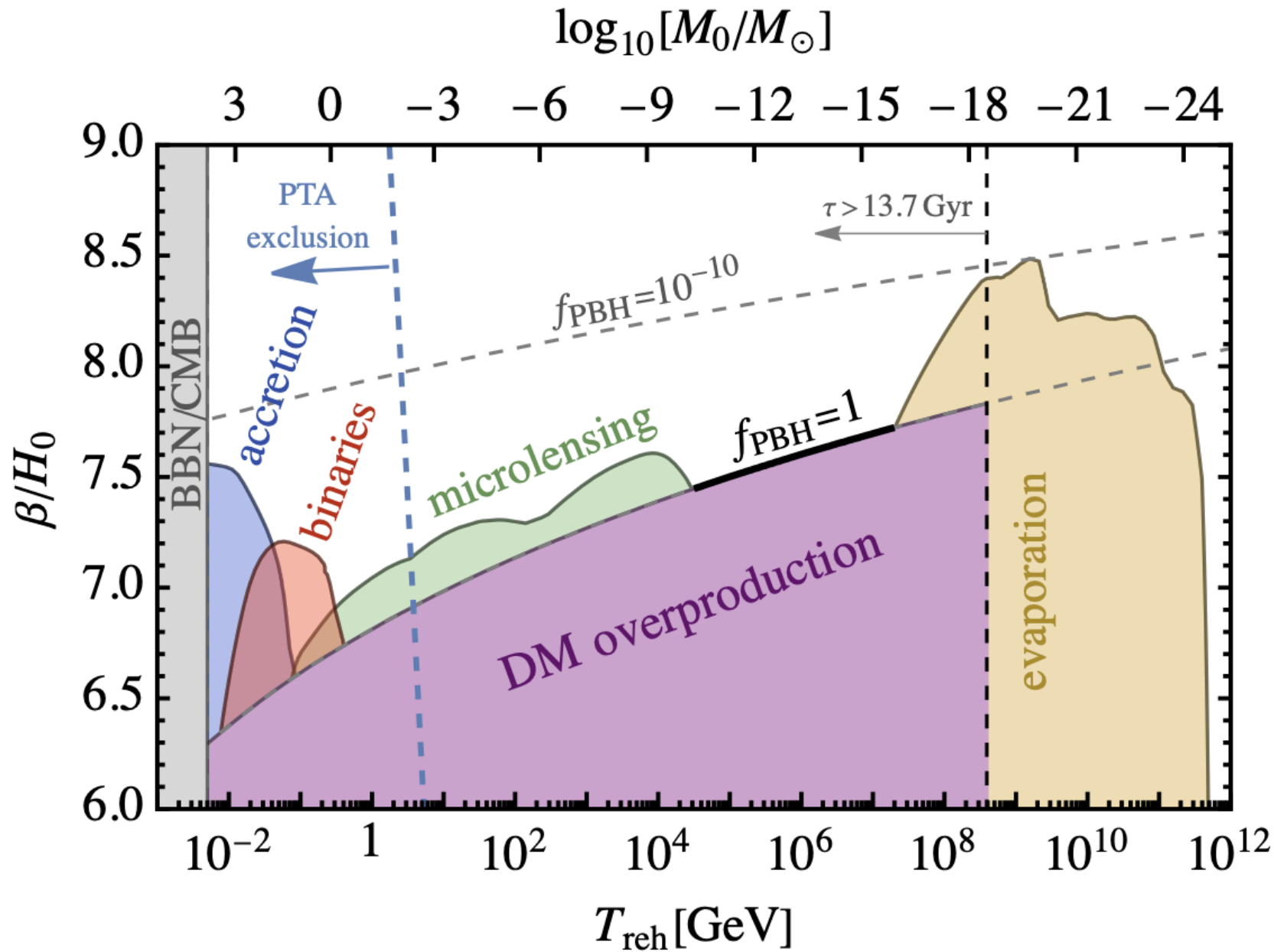
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2nd order GW



Where does this come from ?

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Franciolini, YG, Jinno, 2503.01962



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Go back to basics (GR):

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Friedmann background: $ds^2 = a^2 [d\eta^2 - d\mathbf{x}^2]$

Where does this come from ?

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Go back to basics (GR):

$$ds^2 = a^2[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) d\mathbf{x}^2]$$

Perturbations

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$\Uparrow$?

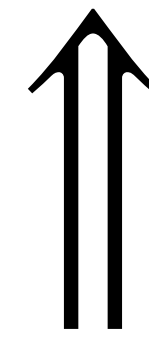
Einstein equation : $G_{\mu\nu} = T_{\mu\nu}$ $ds^2 = a^2[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) d\mathbf{x}^2]$

Perturbations

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Where does this come from ?

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V' + 4\bar{\rho}_R\Phi$$



Newtonian gauge

$$\Phi = \Psi$$

Einstein equation : $G_{\mu\nu} = T_{\mu\nu}$

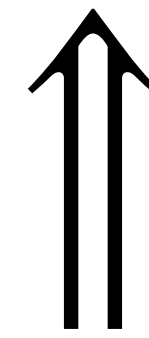
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Perturbations

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Where does this come from ?

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V \quad (\Leftrightarrow \bar{\rho}'_R + 4\mathcal{H}\bar{\rho}_R = -\bar{\rho}'_V)$$



Spatially-flat gauge

$$\Phi = 0$$

Einstein equation : $G_{\mu\nu} = T_{\mu\nu}$ $ds^2 = a^2[(1 + 2\Psi) d\eta^2 - (1 - 2\Phi) d\mathbf{x}^2]$

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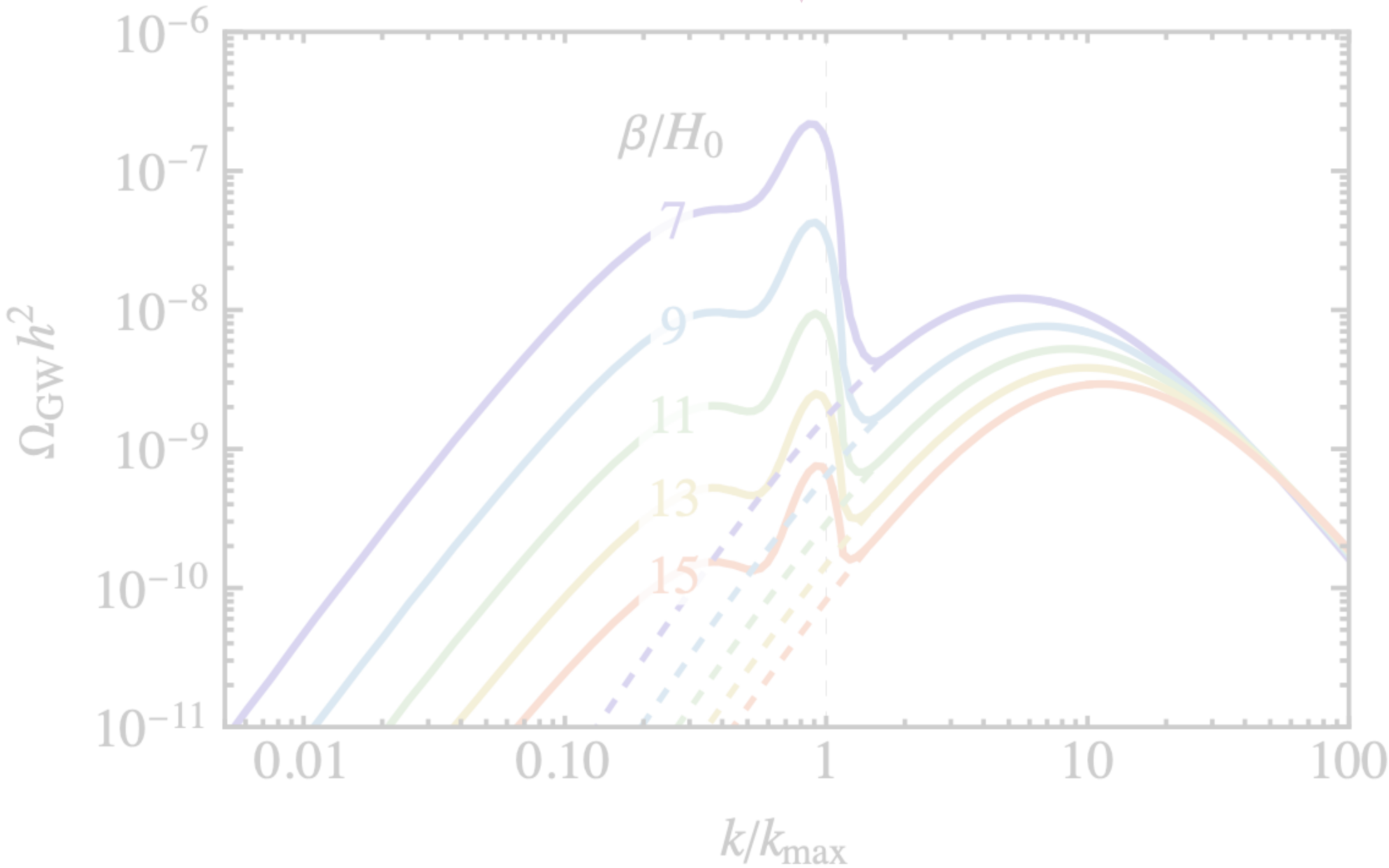
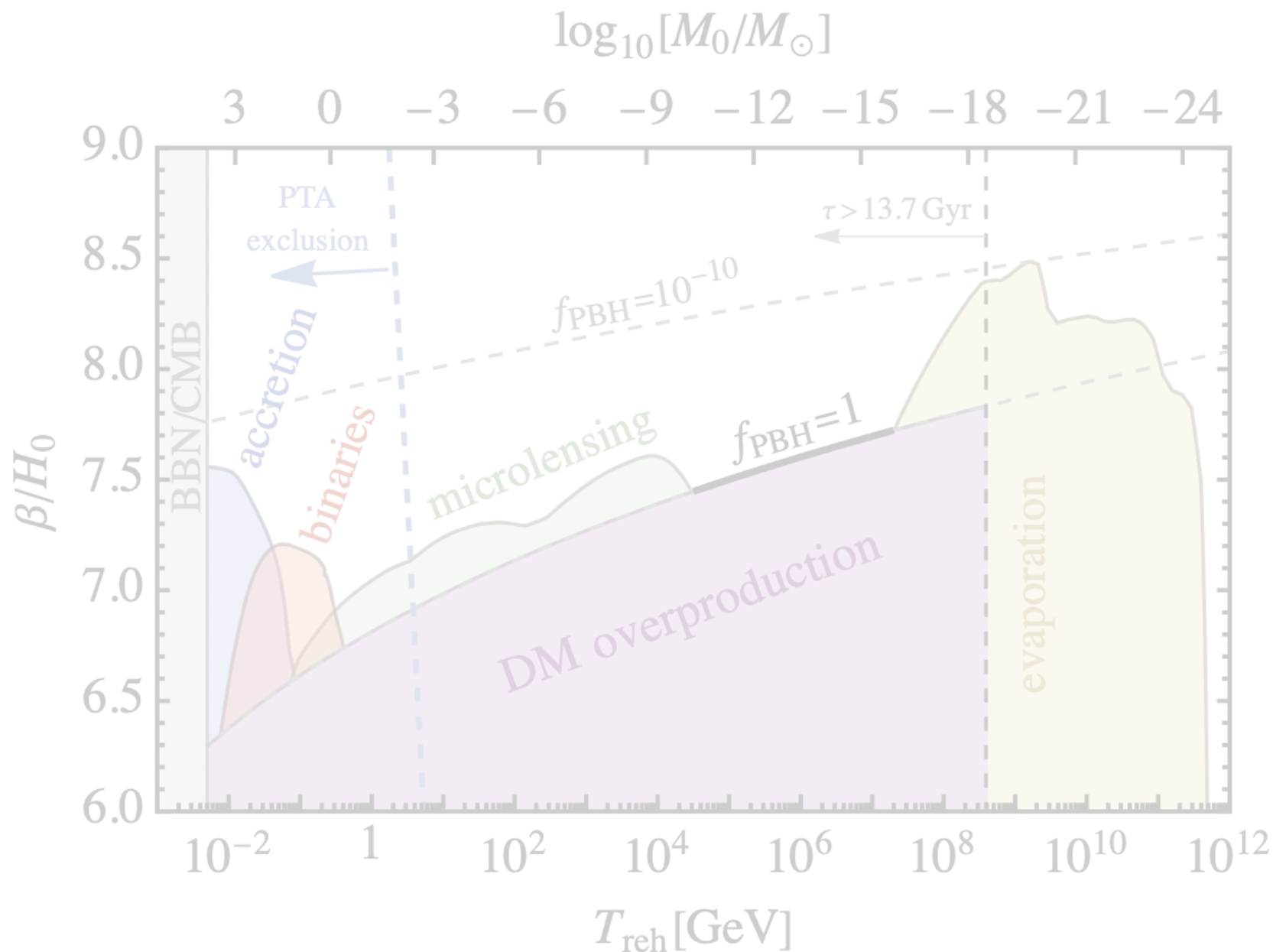
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2402.04158

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$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Comoving gauge

$$\square h \sim k^2 \mathcal{R}^2$$

$$\delta \gtrsim \delta_{\text{th}} \simeq 0.5$$

Musco 1809.02127
Escriva+ 1907.13311
Comoving gauge

Sasaki+ 1982

Bian+, 2021

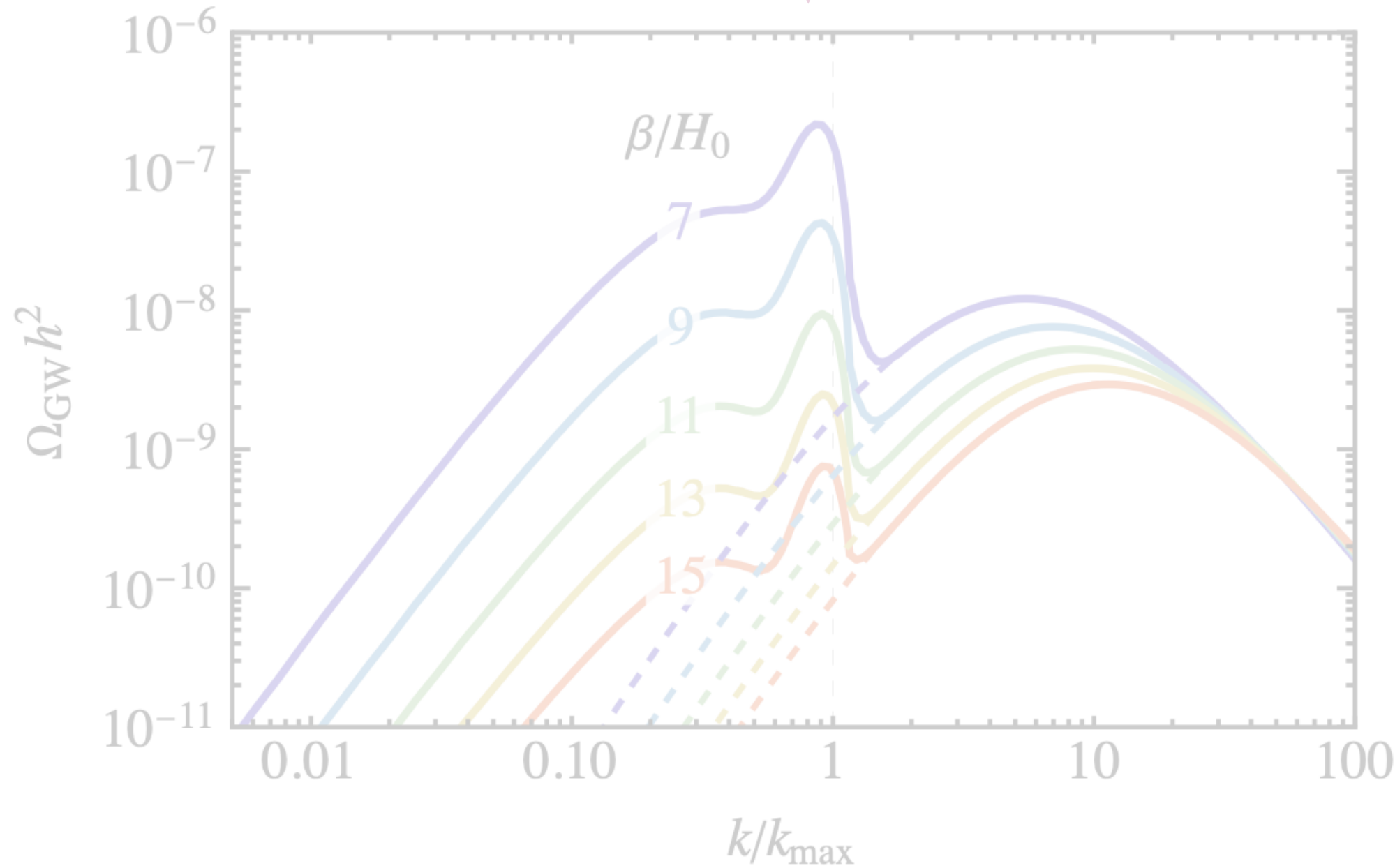
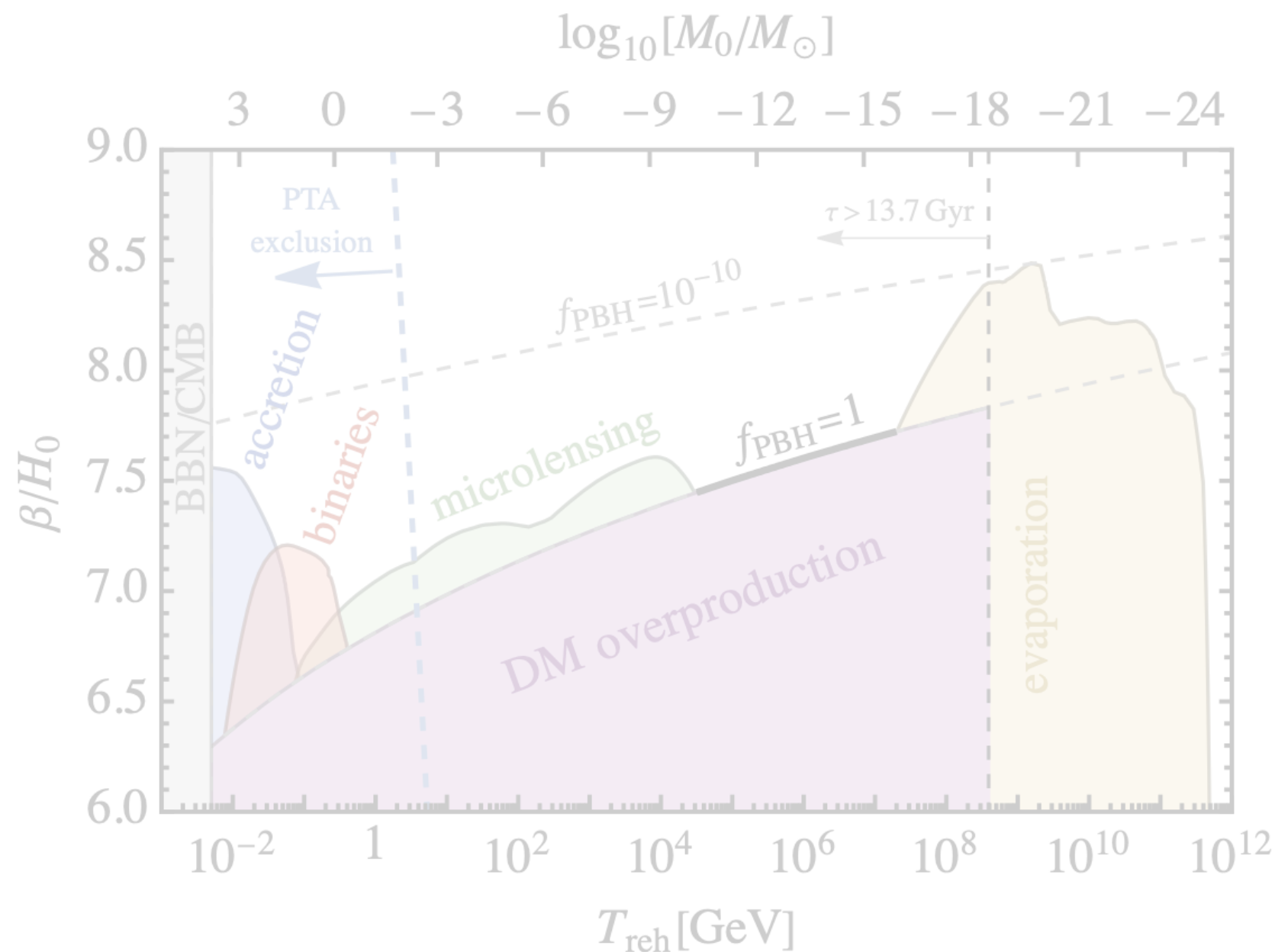
Lewicki+, 2023

YG&Volansky, 2023

YG, PRL, 2023

YG, PLB, 2023

Lewicki+, PRL, 2024



$$(\delta \equiv \delta\rho/\bar{\rho})$$

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

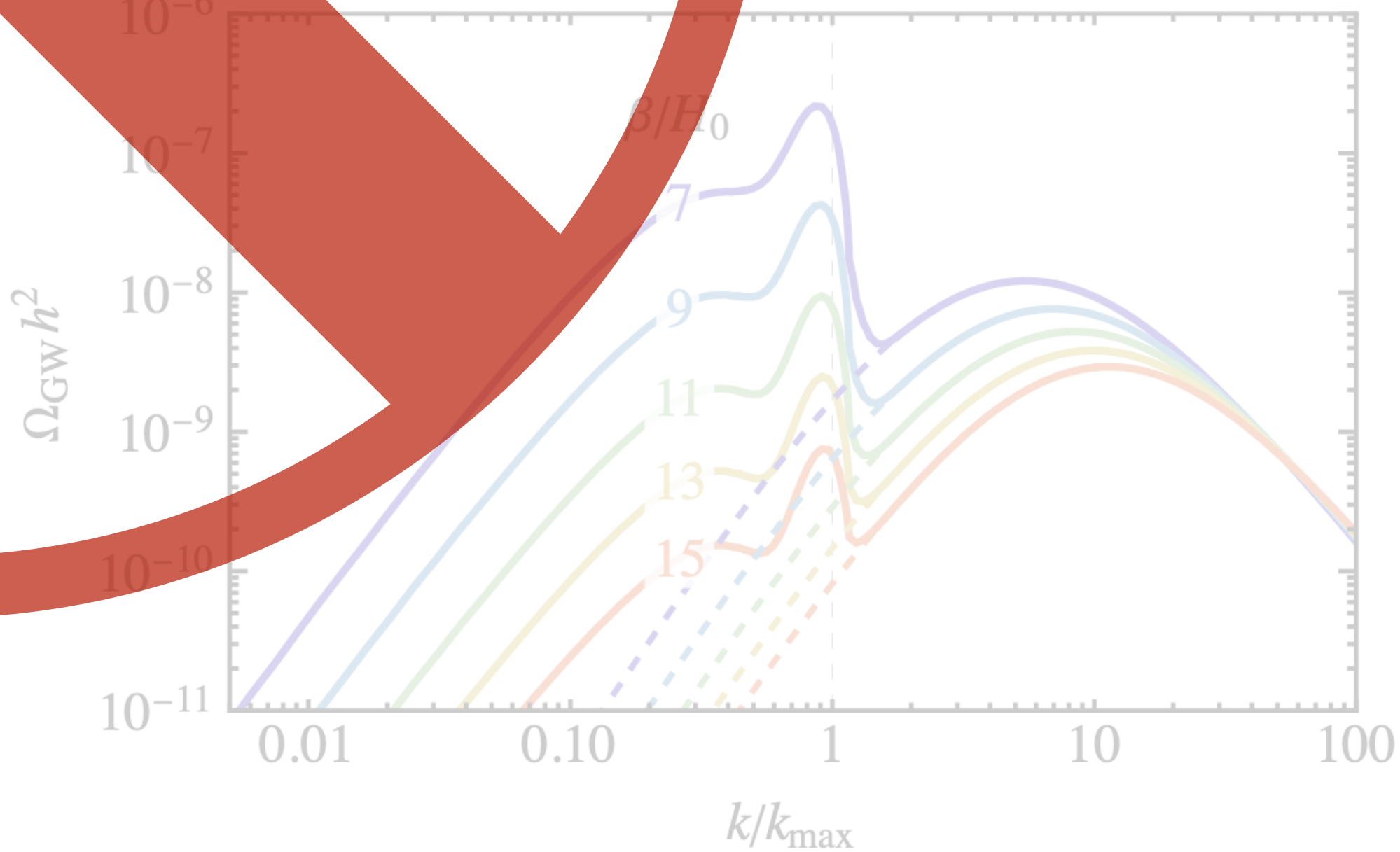
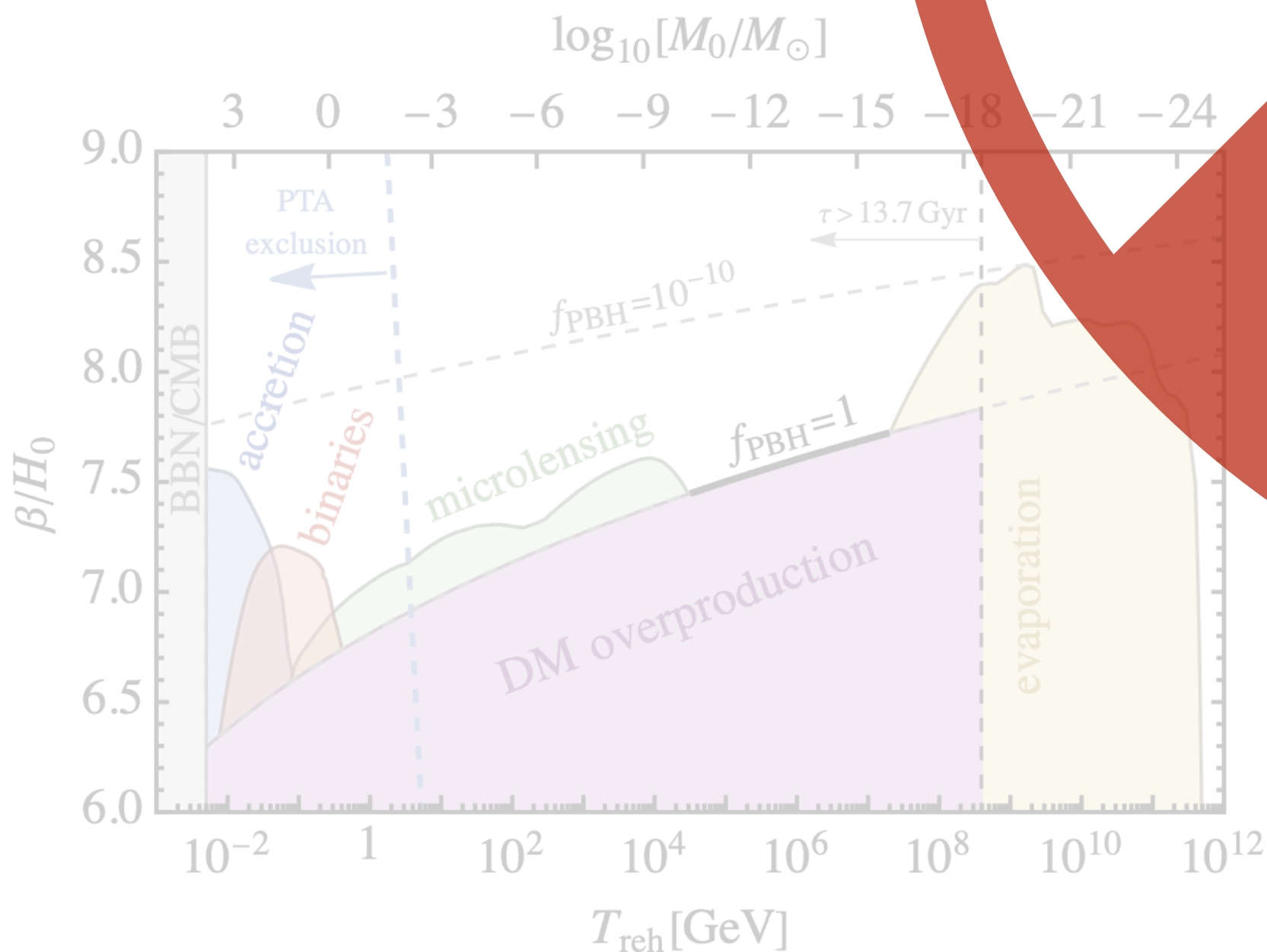
Comoving gauge

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Musco 1809.02127
Escriva+ 1907.13311
Comoving gauge

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Sasaki+ 1982
Bian+, 2021
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YG&Volansky, 2023
YG, PRL, 2023
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Musco 1809.02127
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Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Comoving gauge

$$(\delta \equiv \delta\rho/\bar{\rho})$$

$$\delta\rho'_R + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho'_V$$

Comoving gauge

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Comoving gauge



$$(\delta \equiv \delta\rho/\bar{\rho})$$

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Musco 1809.02127
Escriva+ 1907.13311

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Comoving gauge

Choose B such that: $U_i = 0$

$$ds^2 = a^2 \left[(1 + 2\Phi - \mathcal{H}B - B') d\eta^2 - 2\partial_i B dx^i d\eta - (1 - 2\Phi - 2\mathcal{H}B) d\mathbf{x}^2 \right]$$

$$(\delta \equiv \delta\rho/\bar{\rho})$$

$$\delta\rho'_R + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho'_V$$

Comoving gauge

$$\delta \gtrsim \delta_{\text{th}} \simeq 0.5$$

Musco 1809.02127

Escriva+ 1907.13311

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta$$

Comoving gauge



$$(\delta \equiv \delta\rho/\bar\rho)$$

$$\delta\rho_R' + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho_V'$$

Comoving gauge

$$\delta_{\text{th}}^{(C)} \simeq 0.5$$

Musco 1809.02127
Escriva+ 1907.13311

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta^{(C)}$$

Comoving gauge



$$(\delta \equiv \delta\rho/\bar\rho)$$

$$\delta\rho_R' + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho_V'$$

Comoving gauge

$$\delta_{\text{th}}^{(C)} \simeq 0.5$$

Musco 1809.02127
Escriva+ 1907.13311
Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta^{(C)}$$

Comoving gauge

----- Another alternative -----

deltaPT

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

$$\delta_{\text{th}}^{(F)} = ?$$

PBH threshold

$$\mathcal{R} \simeq ?$$

$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$

$$(\delta \equiv \delta\rho/\bar\rho)$$

$$\delta\rho_R' + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho_V'$$

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta^{(C)}$$

Comoving gauge

$$\delta_{\text{th}}^{(C)} \simeq 0.5$$

Musco 1809.02127
Escriva+ 1907.13311

Comoving gauge

Peter & Uzan's textbook

$$\delta^{(F)} = \delta^{(C)} + 3(1 + \omega)\mathcal{R}$$

$$\mathcal{R} = \frac{9}{4}\left(\frac{\mathcal{H}}{k}\right)^2\delta^{(C)}$$

----- Another alternative -----

deltaPT

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

$$\mathcal{R} \simeq ?$$

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$$\delta_{\text{th}}^{(F)} = ?$$

PBH threshold

$$(\delta \equiv \delta\rho/\bar\rho)$$

$$\delta\rho_R' + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho_V'$$

Comoving gauge

$$\mathcal{R} \simeq \frac{9}{4}\delta^{(C)}$$

Comoving gauge

$$\delta_{\text{th}}^{(C)} \simeq 0.5$$

Musco 1809.02127
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Comoving gauge

Peter & Uzan's textbook

$$\delta^{(F)} = \delta^{(C)} + 3(1 + \omega)\mathcal{R}$$

$$\mathcal{R} = \frac{9}{4}\left(\frac{\mathcal{H}}{k}\right)^2\delta^{(C)}$$

$$\Downarrow \begin{matrix} k = \mathcal{H} \\ \omega = 1/3 \end{matrix}$$

$$\delta^{(F)} = 10\delta^{(C)}$$

----- Another alternative -----

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

Spatially-flat gauge

deltaPT
Lewicki, Toczek, Vaskonen
PRL
2402.04158

$$\mathcal{R} \simeq ?$$

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$$\delta_{\text{th}}^{(F)} = ?$$

PBH threshold

$$(\delta \equiv \delta\rho/\bar\rho)$$

$$\delta\rho_R' + 3\mathcal{H}(\delta\rho_R + \delta\rho_V) = -\delta\rho_V'$$

Comoving gauge

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Comoving gauge

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Musco 1809.02127
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Another alternative

deltaPT

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

$$\mathcal{R} \simeq \frac{9}{40}\delta^{(F)}$$

$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$

$$\delta_{\text{th}}^{(F)} \simeq 5$$

PBH threshold

Peter & Uzan's textbook

$$\delta^{(F)} = \delta^{(C)} + 3(1 + \omega)\mathcal{R}$$

$$\mathcal{R} = \frac{9}{4}\left(\frac{\mathcal{H}}{k}\right)^2\delta^{(C)}$$

$$k = \mathcal{H}$$

$$\omega = 1/3$$

$$\delta^{(F)} = 10\delta^{(C)}$$

deltaPT

Lewicki, Toczek, Vaskonen
PRL
2402.04158

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

Spatially-flat gauge

$$\delta_{\text{th}}^{(F)} \simeq 5$$

PBH threshold

$$\mathcal{R} \simeq \frac{9}{40} \delta^{(F)}$$

$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$

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Lewicki, Toczek, Vaskonen
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$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

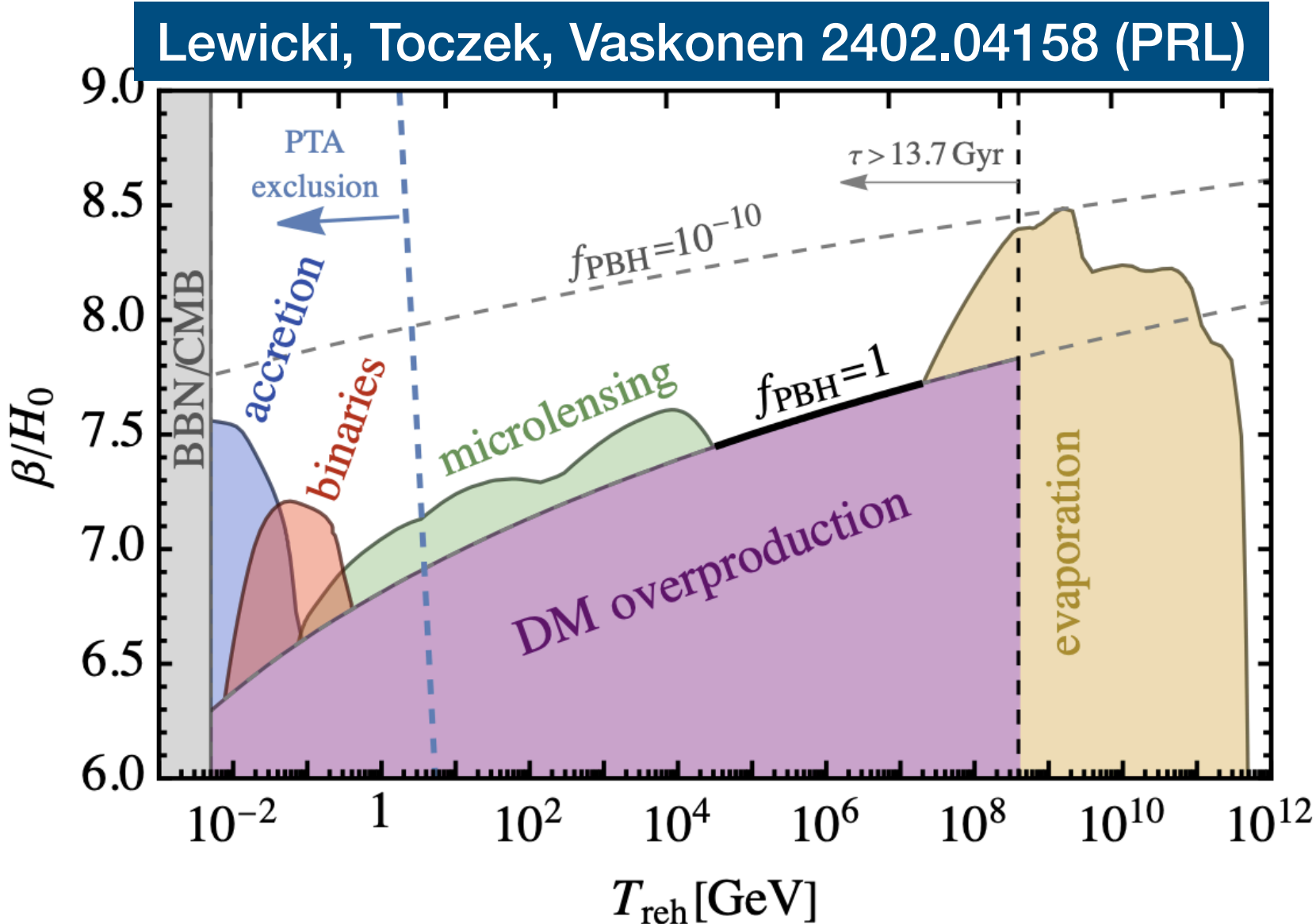
Spatially-flat gauge

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PBH threshold

$$\mathcal{R} \simeq \frac{9}{40}\delta^{(F)}$$

$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$



Sasaki+ 1982

Bian+, 2021

Lewicki+, 2023

YG&Volansky, 2023

YG, PRL, 2023

YG, PLB, 2023

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

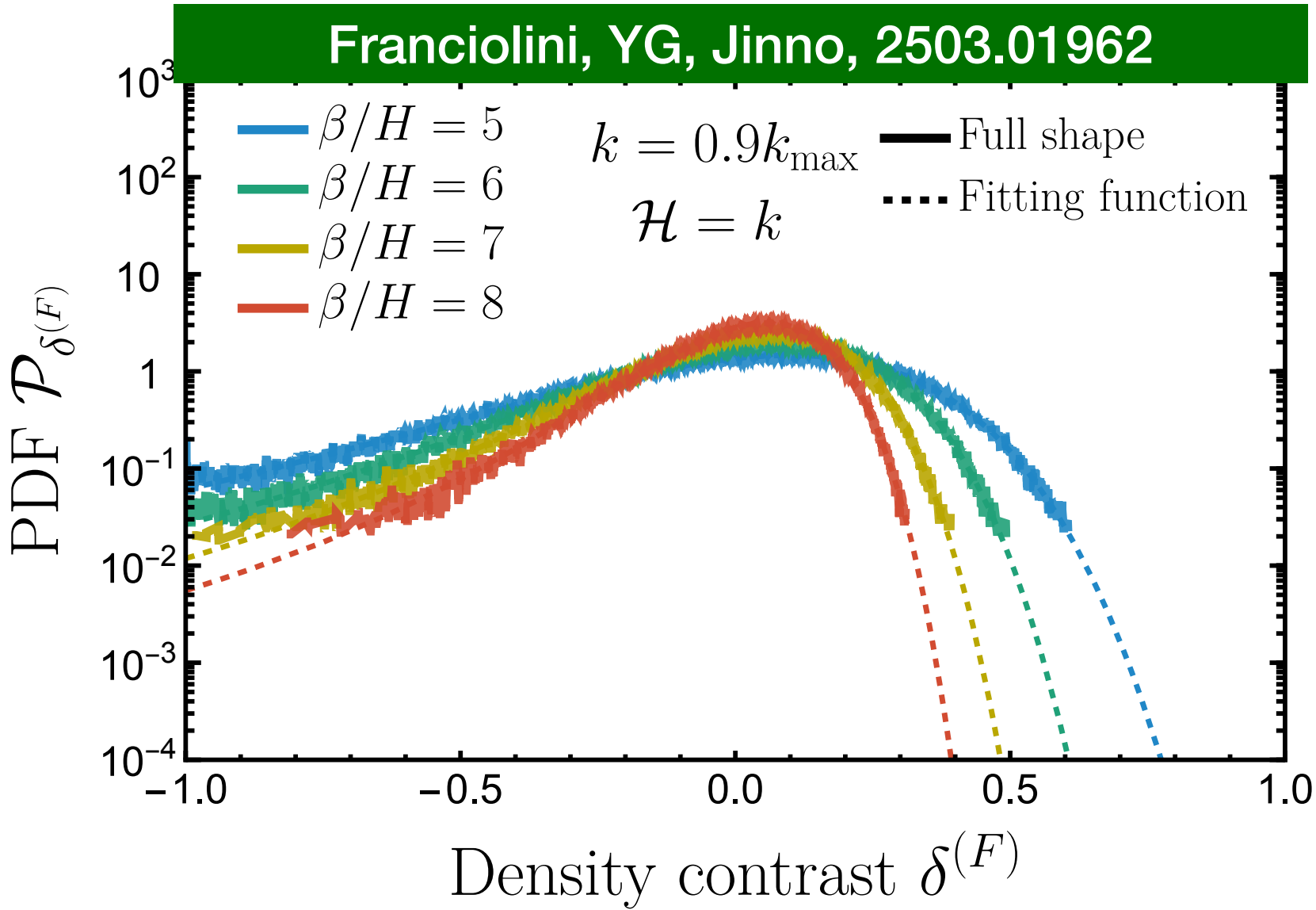
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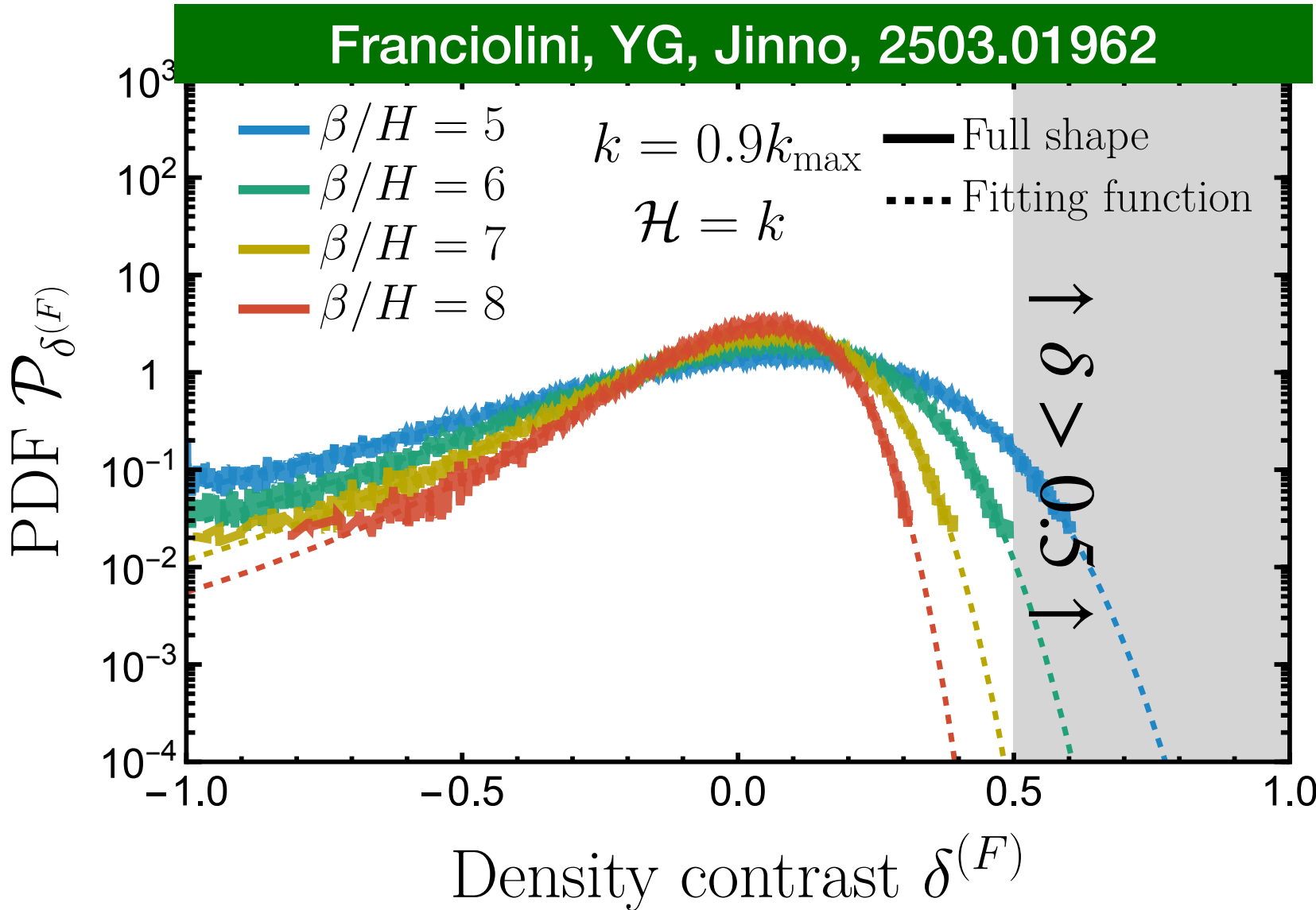
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deltaPT

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Lewicki, Toczek, Vaskonen
PRL
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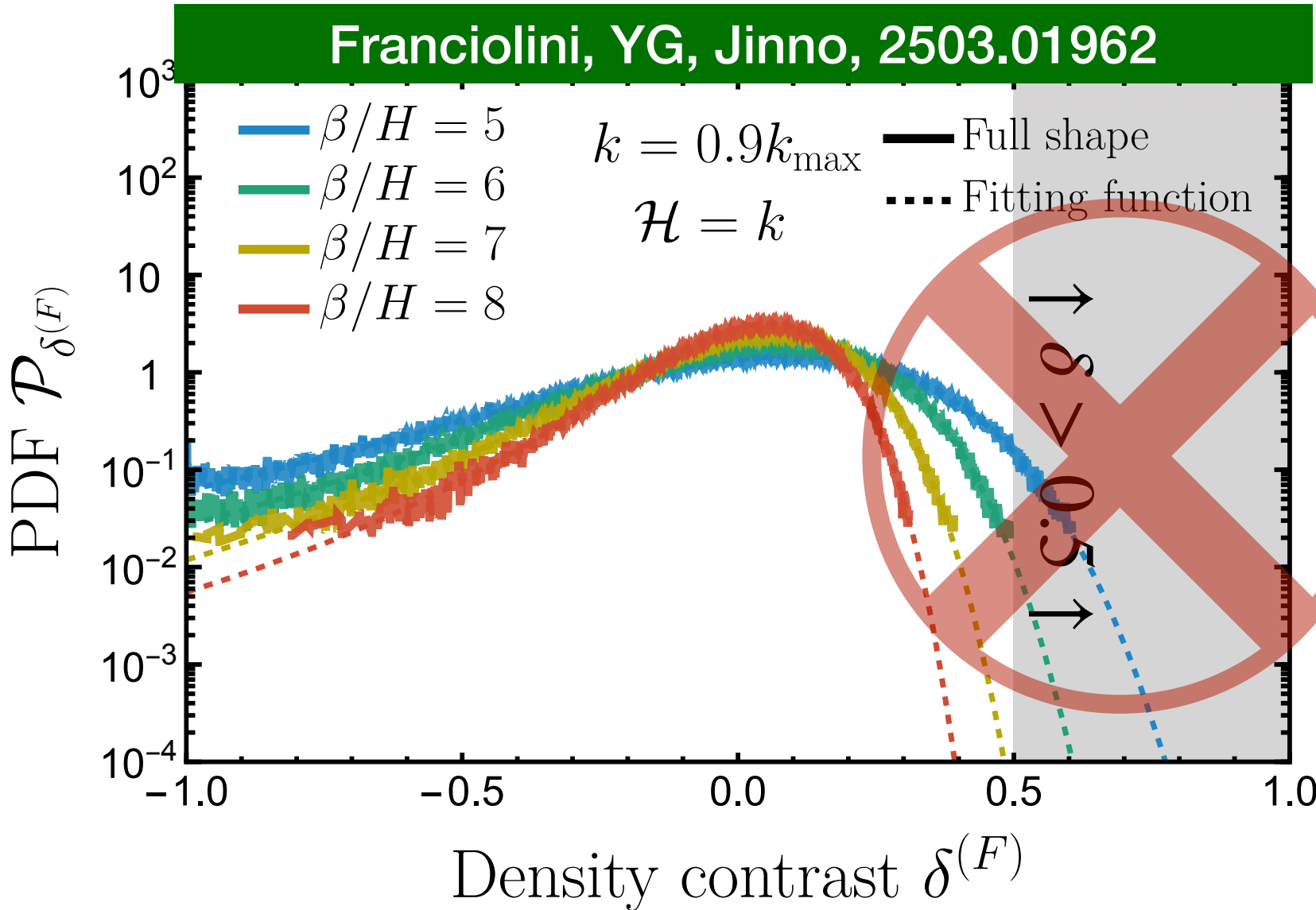
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PRL
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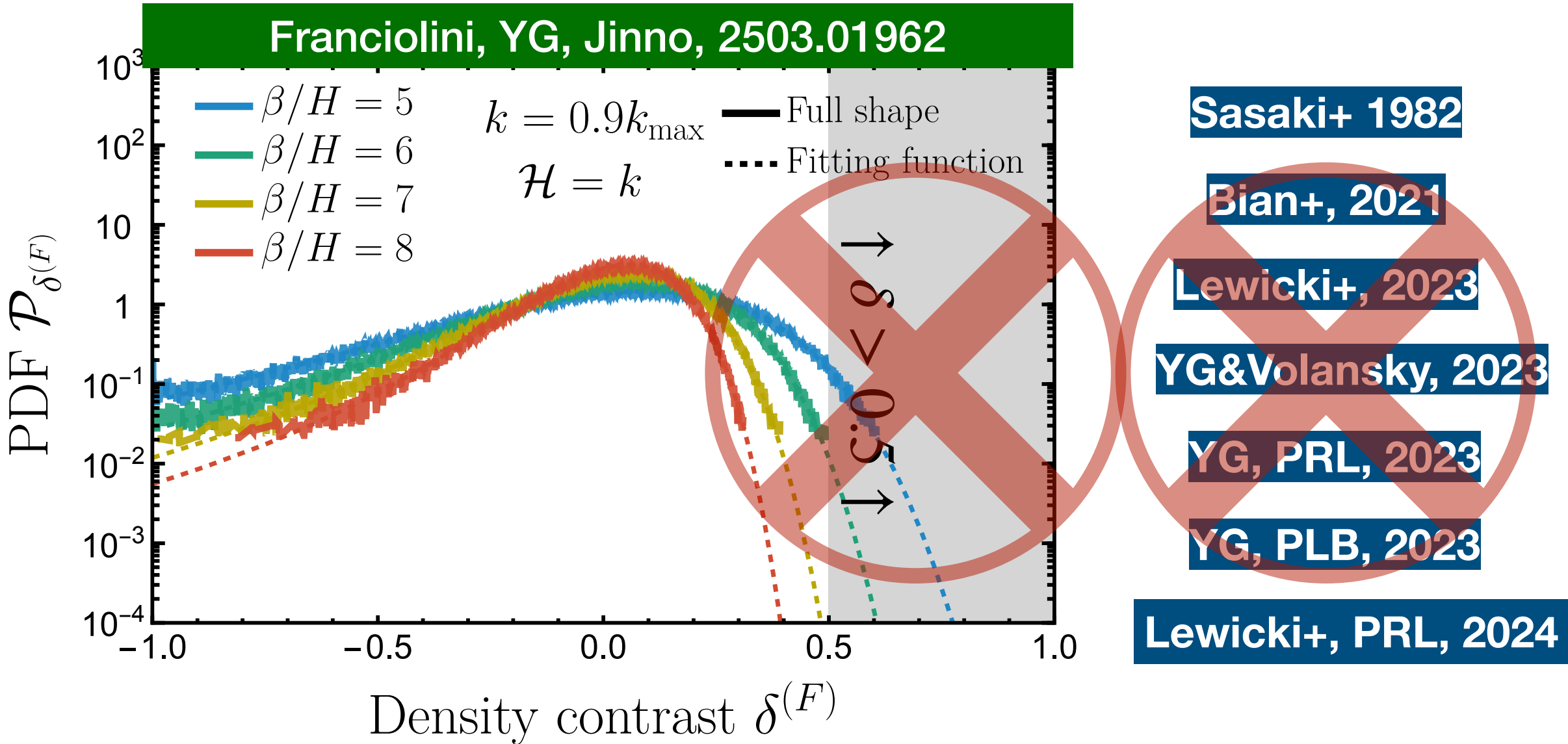
Spatially-flat gauge

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PRL
2402.04158

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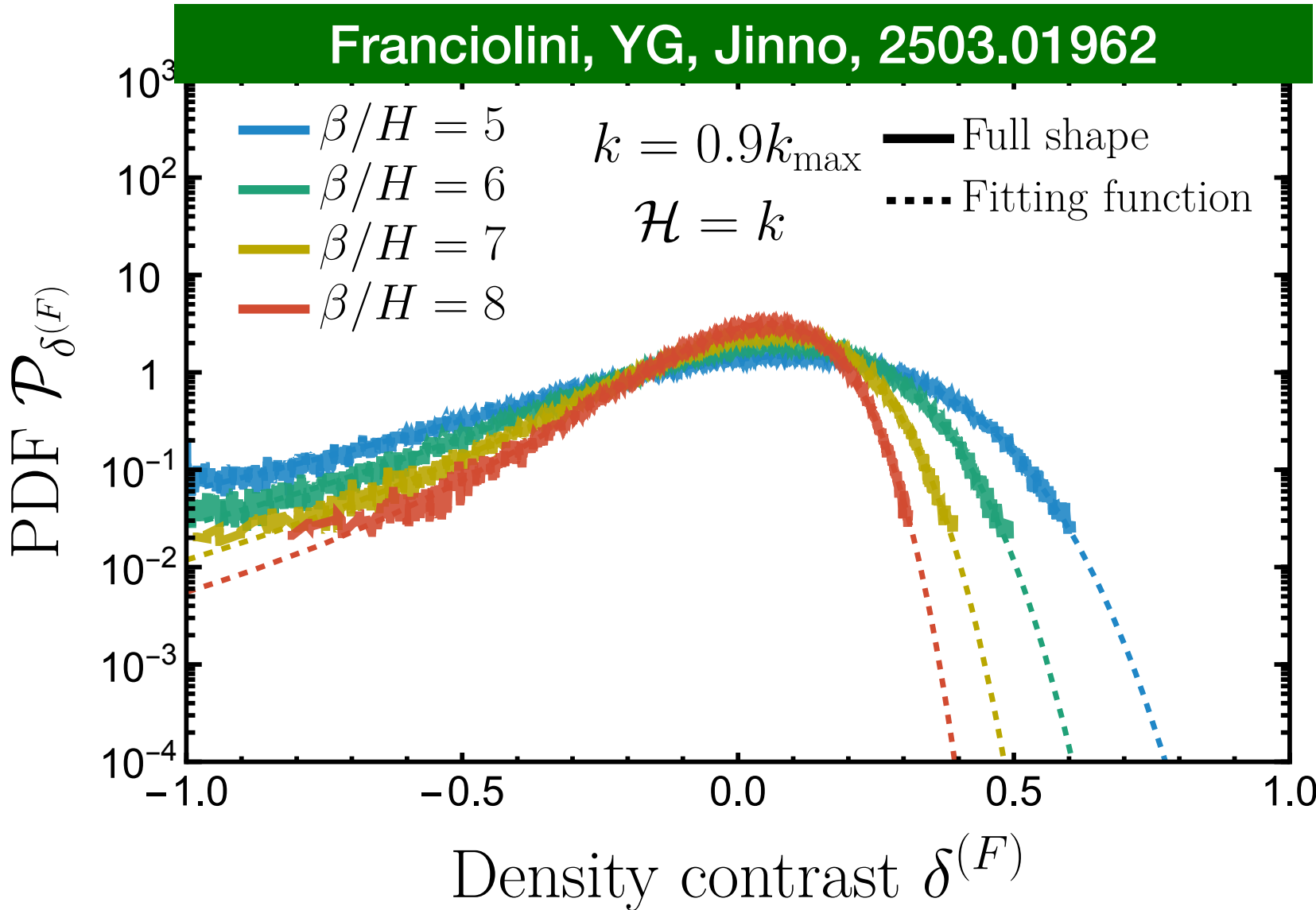
Spatially-flat gauge

$$\delta_{\text{th}}^{(F)} \simeq 5$$

PBH threshold

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$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$



$\uparrow \delta^{(F)} > 5 \uparrow$

$$\delta\rho_R' + 4\mathcal{H}\delta\rho_R = -\delta\rho_V'$$

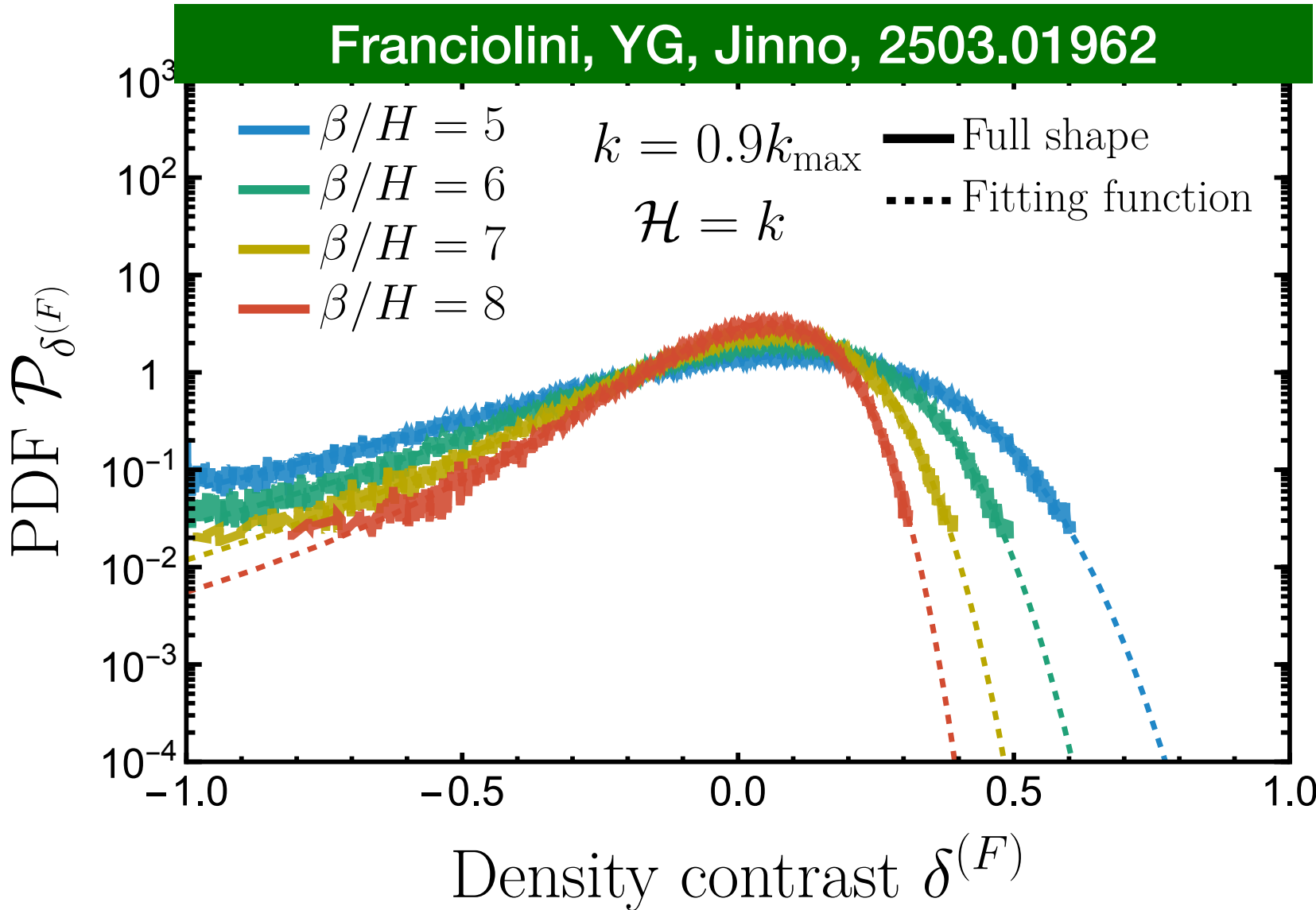
Spatially-flat gauge

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Key conclusion 1:
We find no PBH from FOPT

$\uparrow \delta^{(F)} > 5 \uparrow$

$$\delta\rho'_R + 4\mathcal{H}\delta\rho_R = -\delta\rho'_V$$

Spatially-flat gauge

$$\delta_{\text{th}}^{(F)} \simeq 5$$

PBH threshold



$$\mathcal{R} \simeq \frac{9}{40}\delta^{(F)}$$

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Key conclusion 1:**We find no PBH from FOPT**

deltaPT

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Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

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PBH threshold

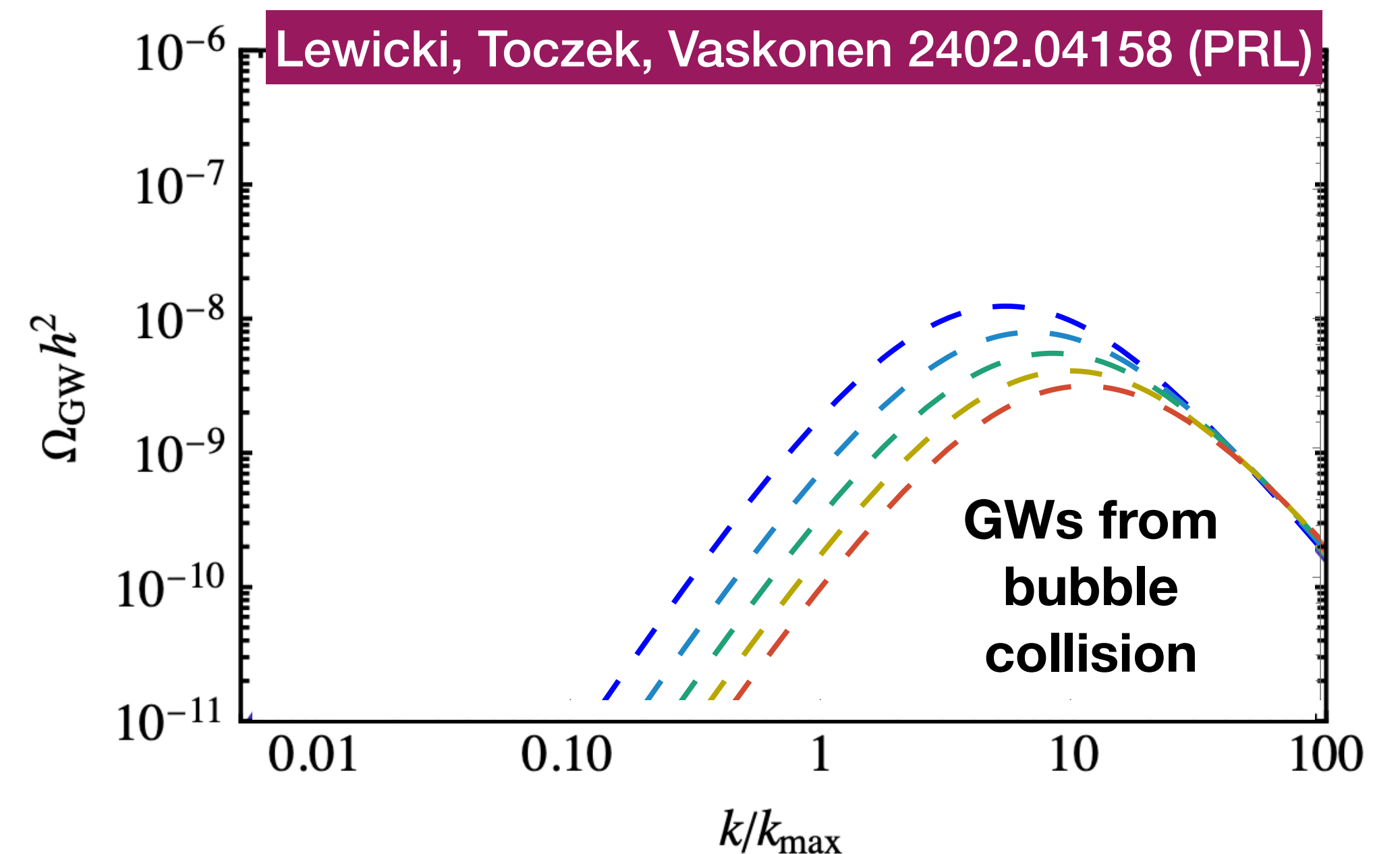
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Key conclusion 1:
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Franciolini, YG, Jinno, 2503.01962



deltaPT

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Lewicki, Toczek, Vaskonen
PRL
2402.04158

Spatially-flat gauge

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PBH threshold

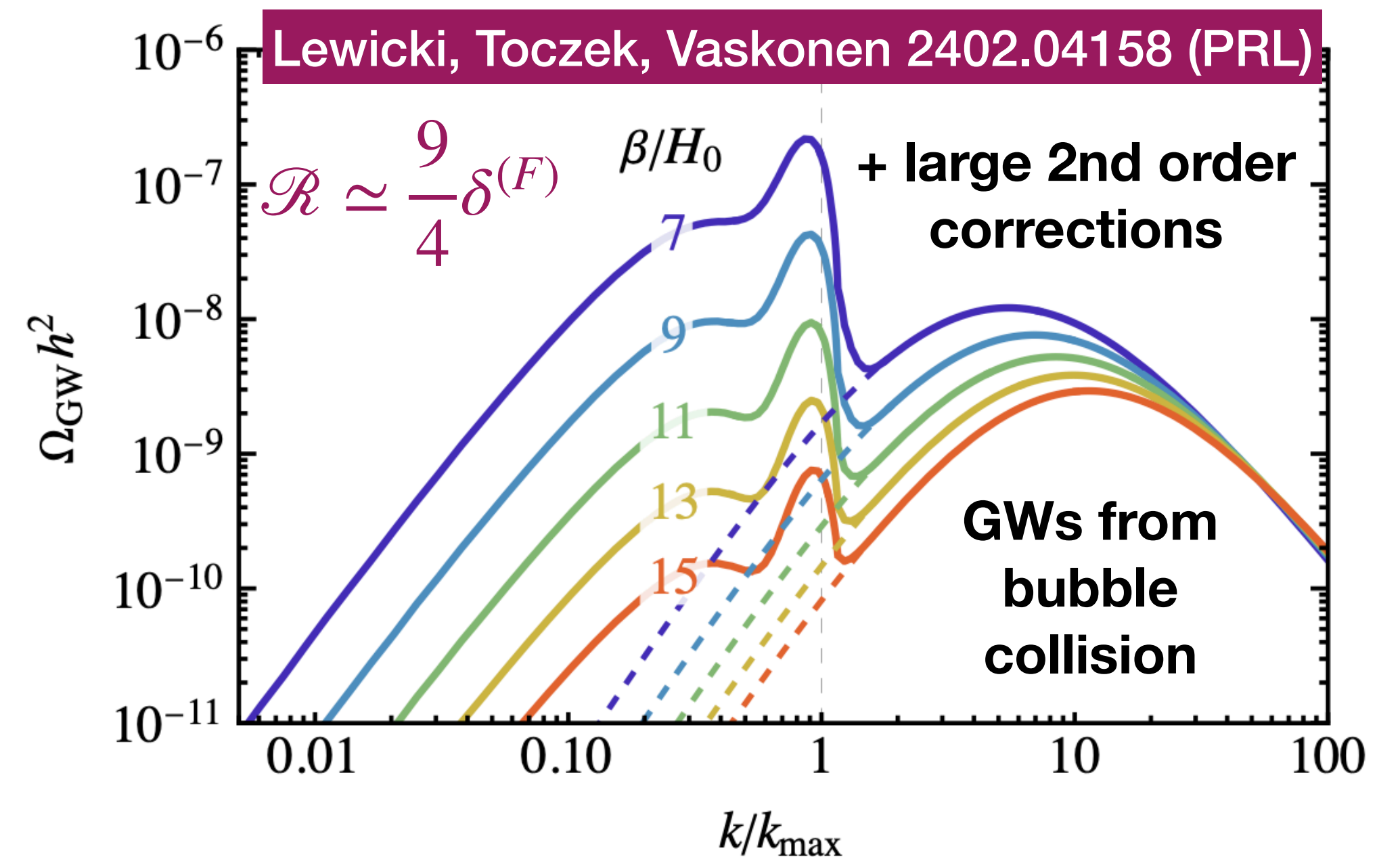
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PRL
2402.04158

Spatially-flat gauge

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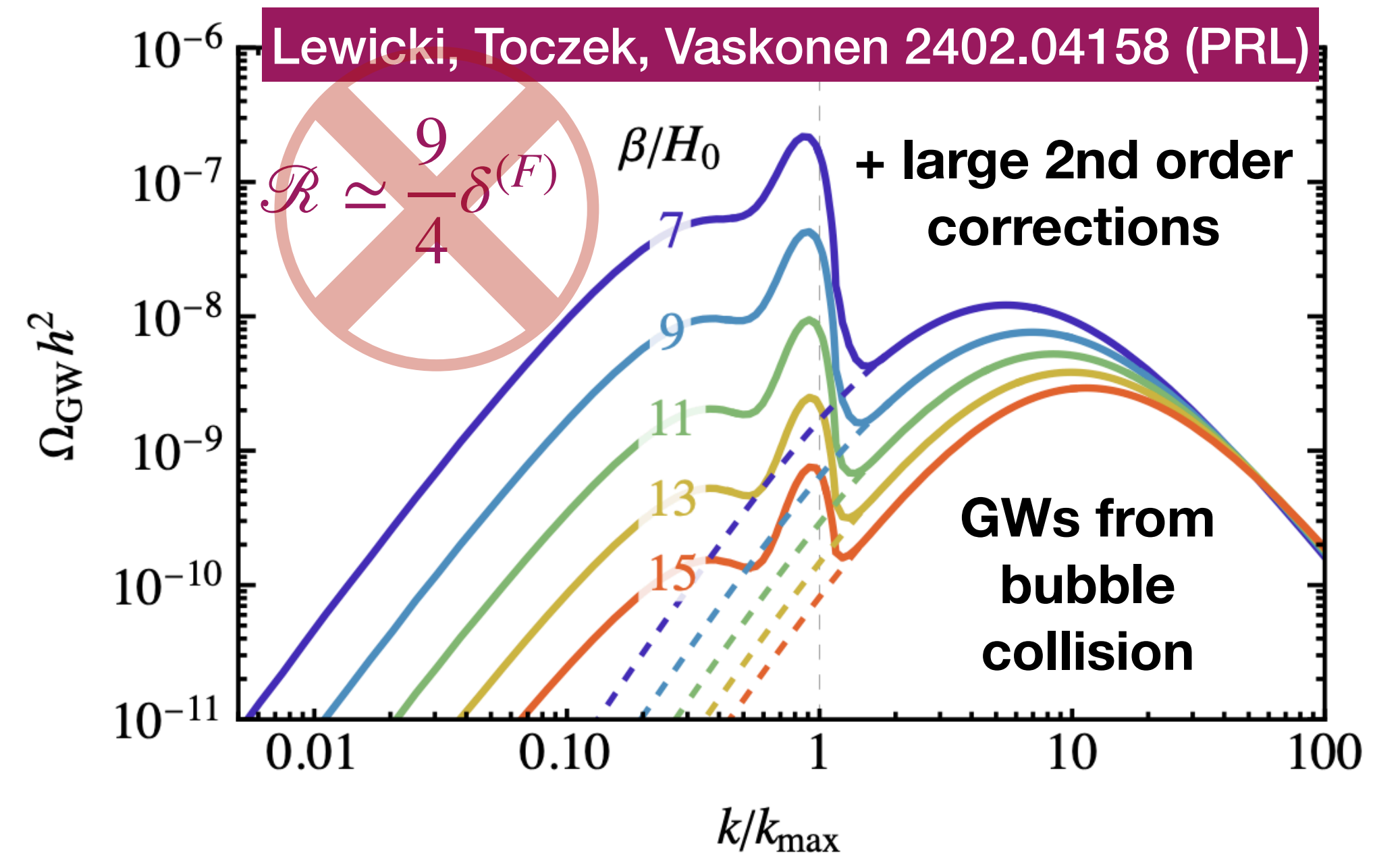
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PRL
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Spatially-flat gauge

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PBH threshold

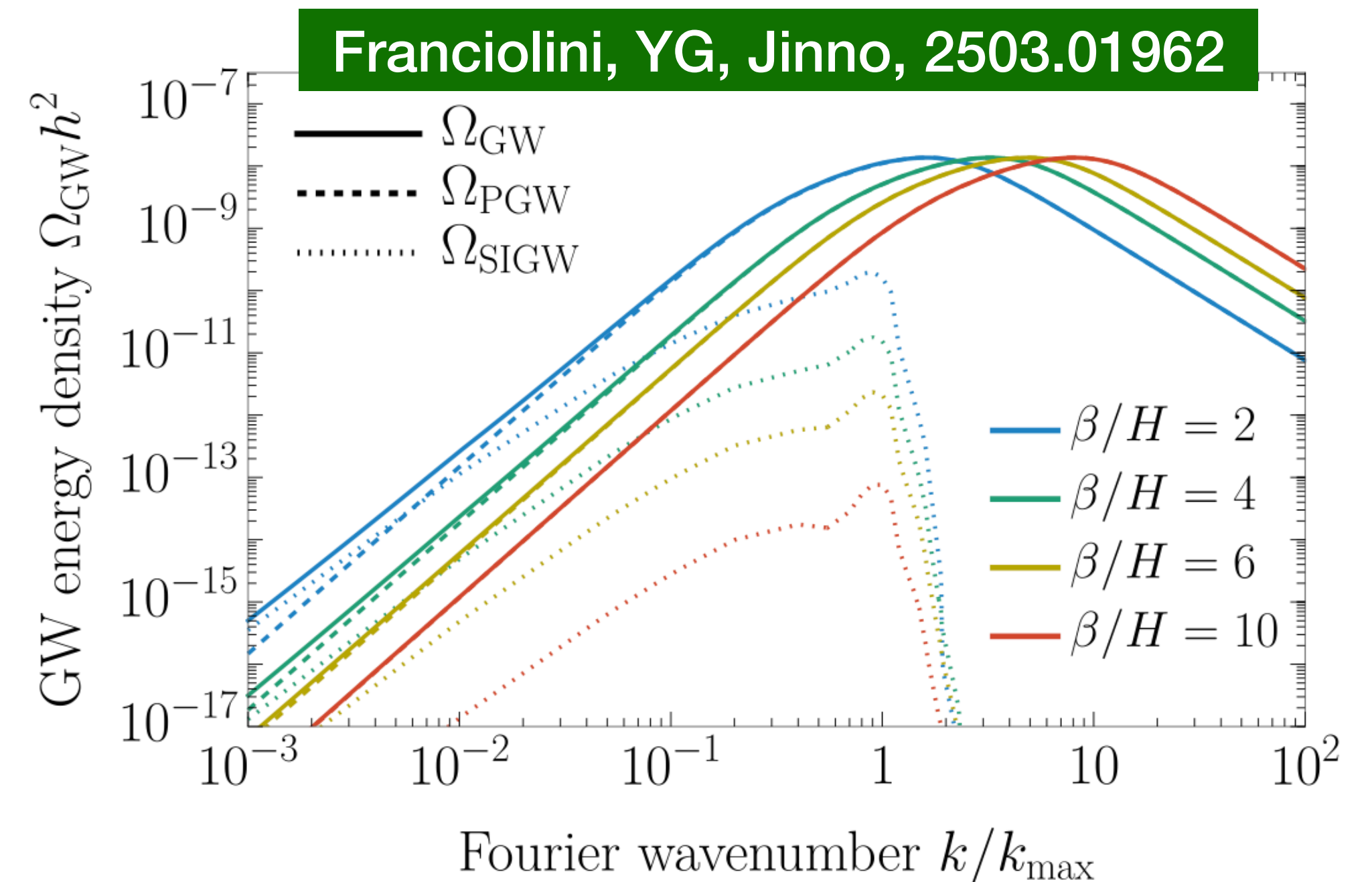
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Franciolini, YG, Jinno, 2503.01962



deltaPT

Lewicki, Toczek, Vaskonen
PRL
2402.04158

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Spatially-flat gauge

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PBH threshold



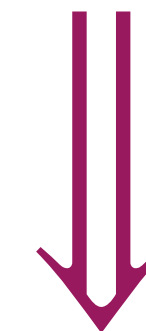
Key conclusion 1:

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Franciolini, YG, Jinno, 2503.01962

$$\mathcal{R} \simeq \frac{9}{40}\delta^{(F)}$$

$$\square h \sim \mathcal{R}^2 \text{ (SIGW)}$$



Key conclusion 2:

We find no SIGW from FOPT

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Key conclusion 1:

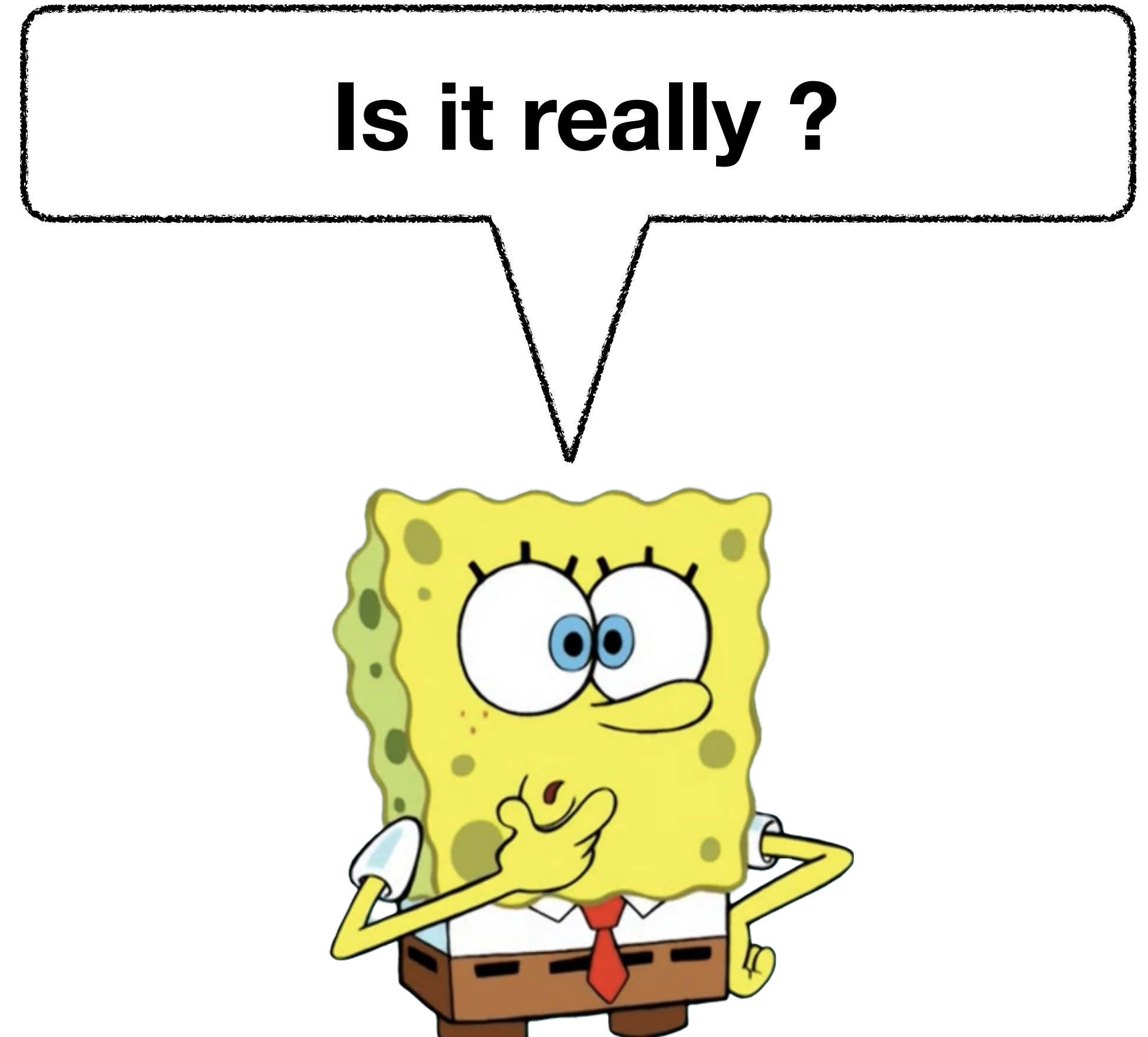
We find no PBH from FOPT

Franciolini, YG, Jinno, 2503.01962

Key conclusion 2:

We find no SIGW from FOPT

Franciolini, YG, Jinno, 2503.01962



Key conclusion 1:

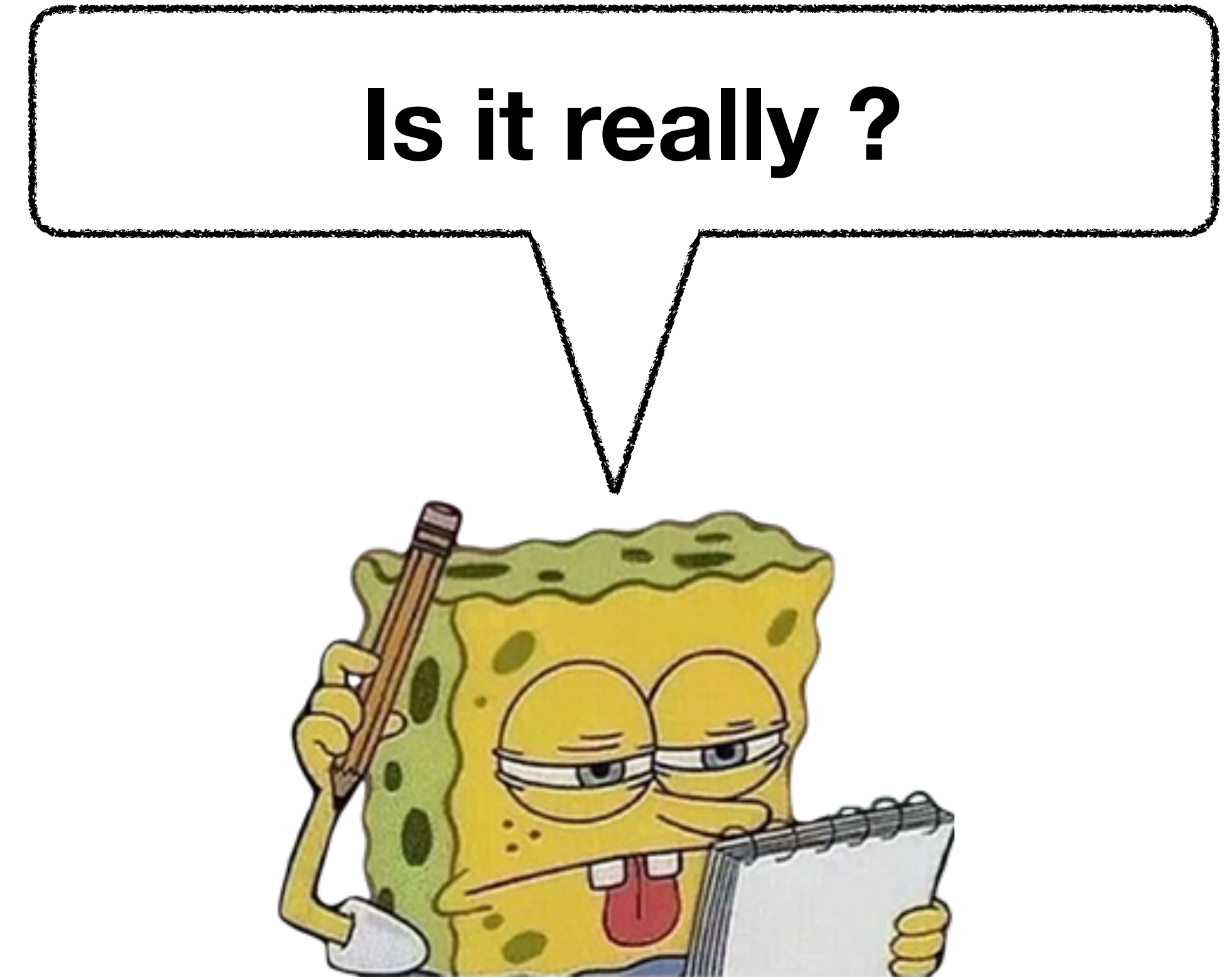
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We find no SIGW from FOPT

Franciolini, YG, Jinno, 2503.01962



Key conclusion 1:

We find no PBH from FOPT

Franciolini, YG, Jinno, 2503.01962

Key conclusion 2:

We find no SIGW from FOPT

Franciolini, YG, Jinno, 2503.01962

Lewicki, Toczek, Vaskonen, 2402.04158, PRL
(deltaPT)

Franciolini, YG, Jinno 2503.01962

Neglect effects from bubble walls

Lewicki, Toczek, Vaskonen, 2402.04158, PRL
(deltaPT)

Franciolini, YG, Jinno 2503.01962

Neglect effects from bubble walls

Lewicki, Toczek, Vaskonen 2305.04924

Flores, Kusenko, Sasaki 2402.13341

**Hashino, Kanemura, Takahashi,
Tanaka, Yoo 2501.11040**

Suggest bubble walls could be important

Lewicki, Toczek, Vaskonen, 2402.04158, PRL
(deltaPT)

Franciolini, YG, Jinno 2503.01962

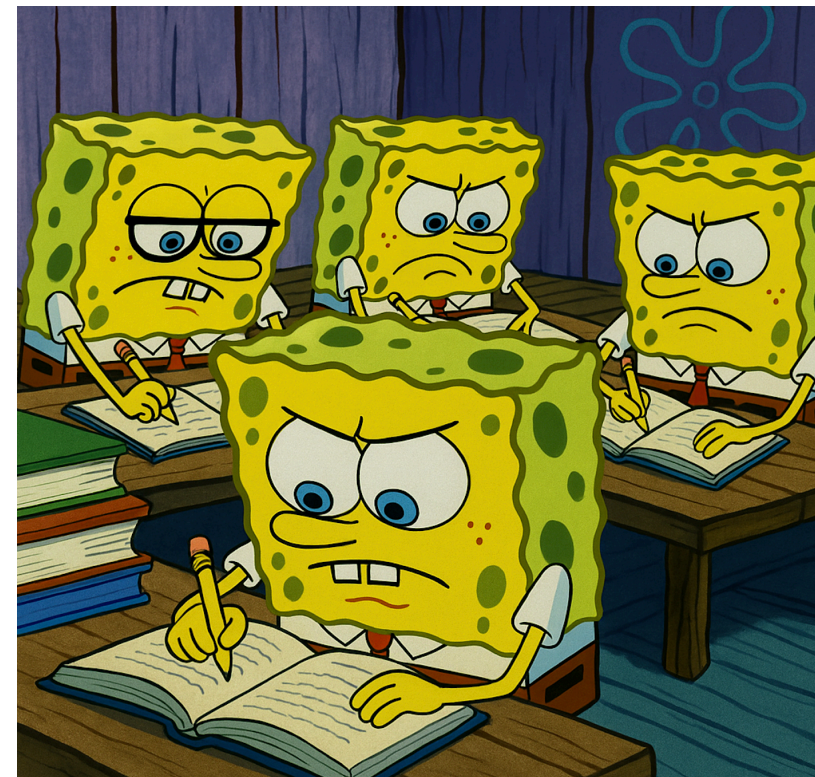
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Suggest bubble walls could be important



YG, Lewicki, Toczek, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls

Lewicki, Toczek, Vaskonen, 2402.04158, PRL
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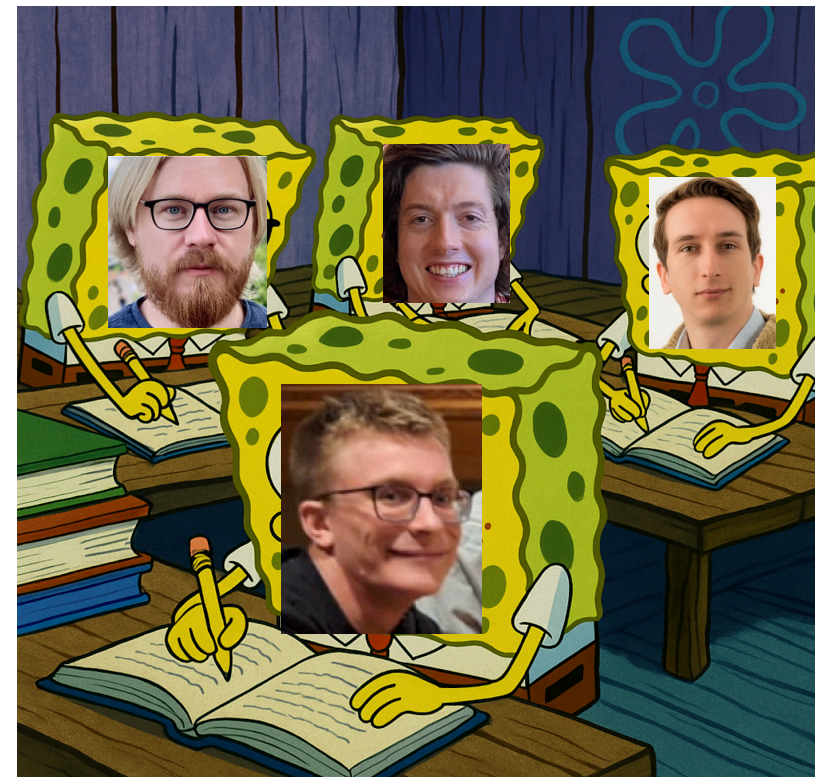
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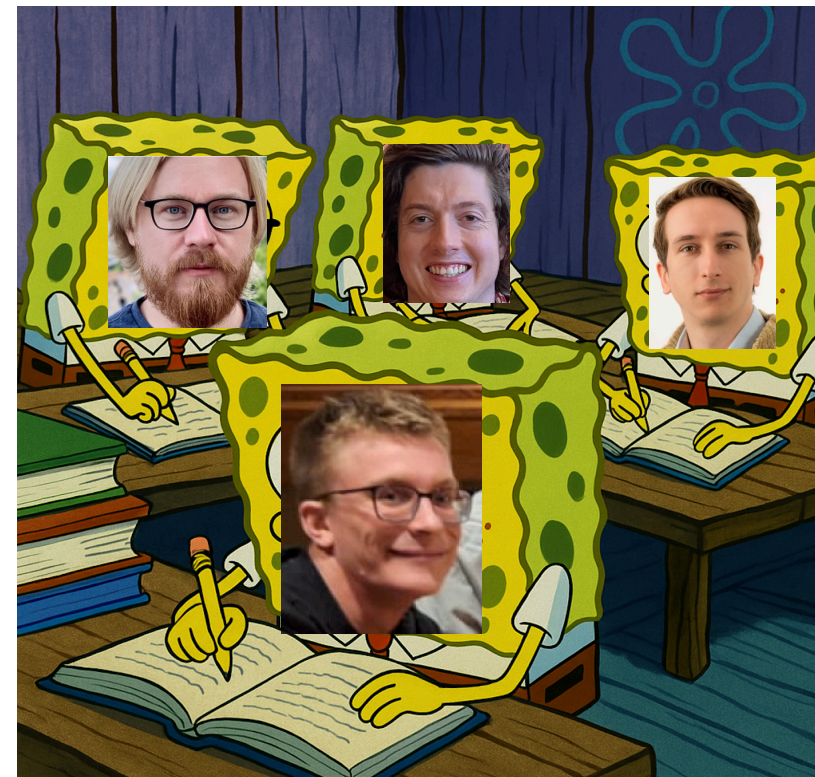
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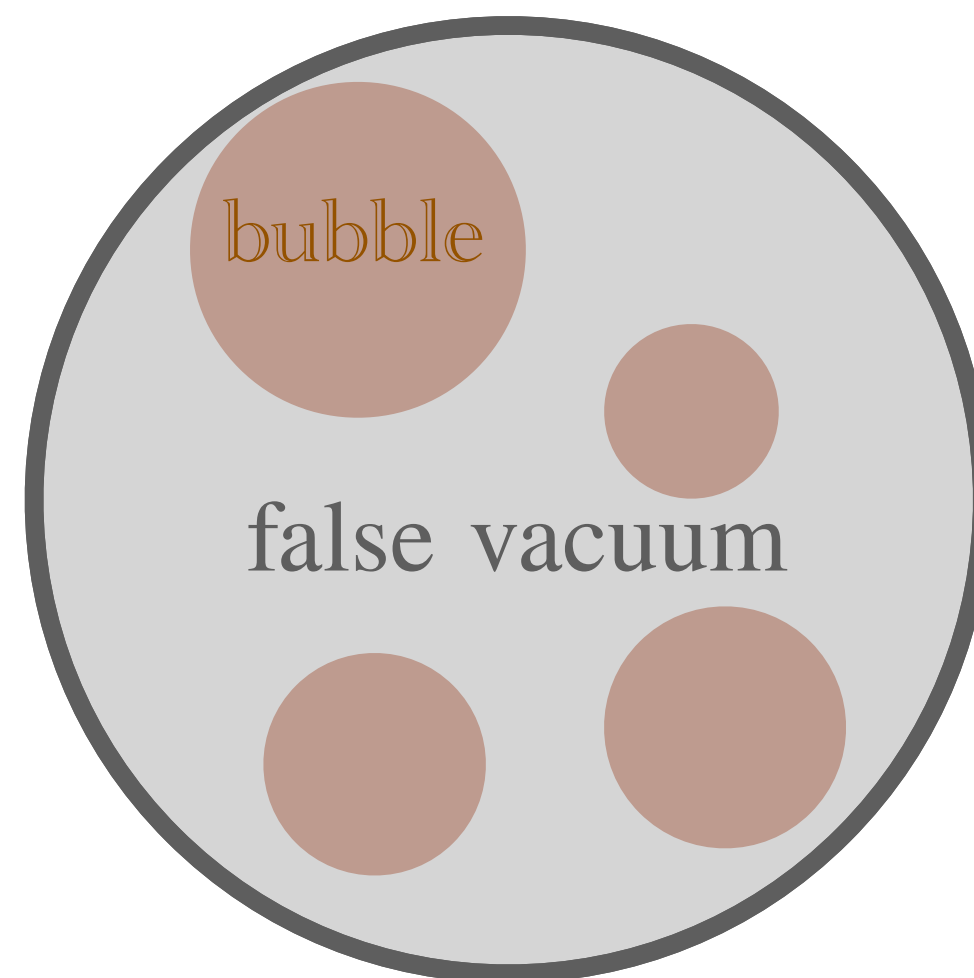
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Account for momentum flux from bubble walls



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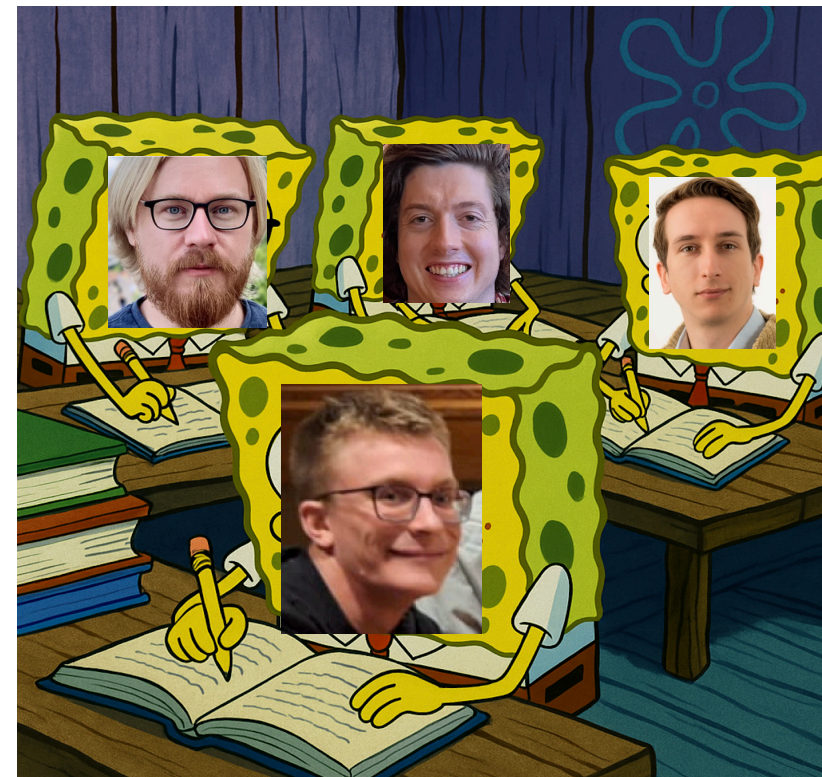
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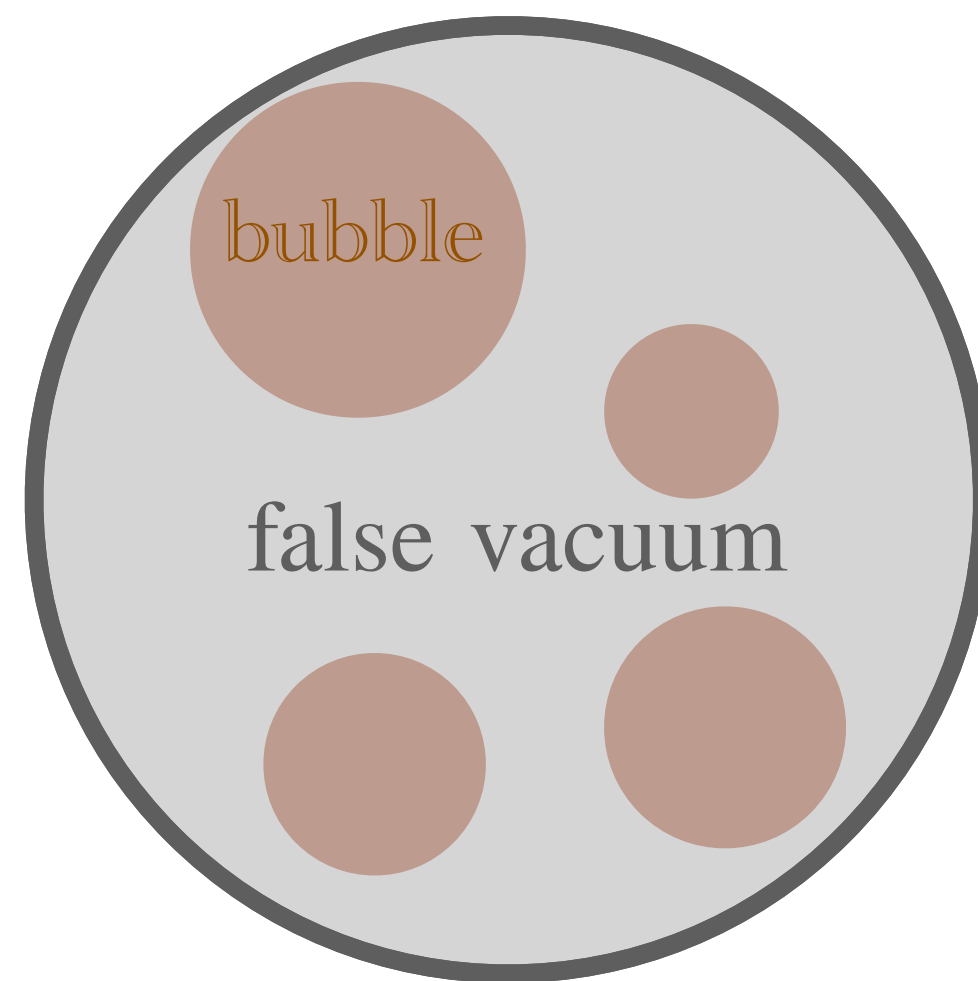
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YG, Lewicki, Toczec, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls



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Lewicki, Toczec, Vaskonen, 2402.04158, PRL
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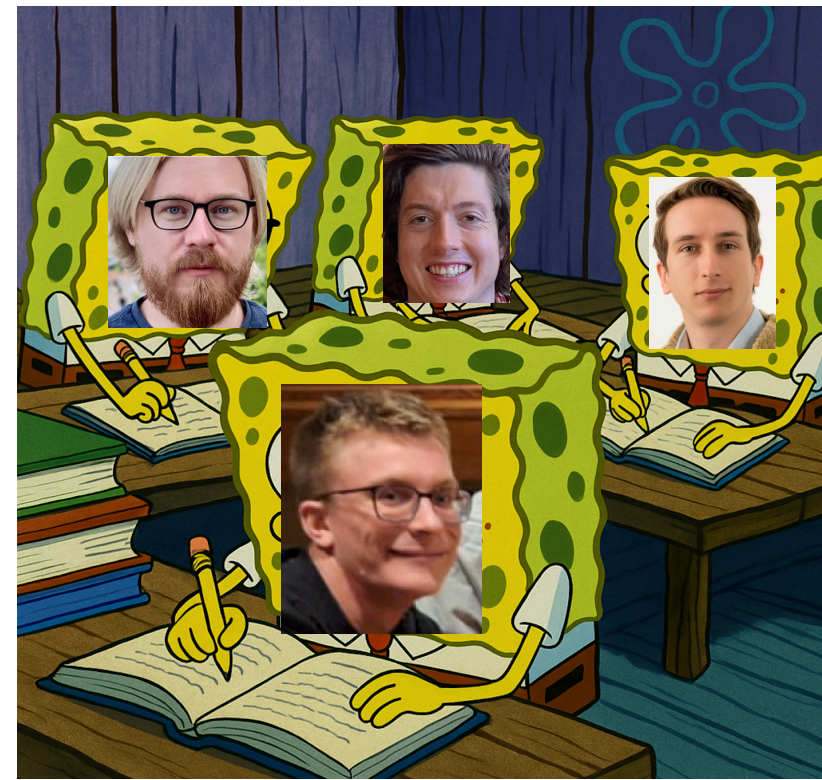
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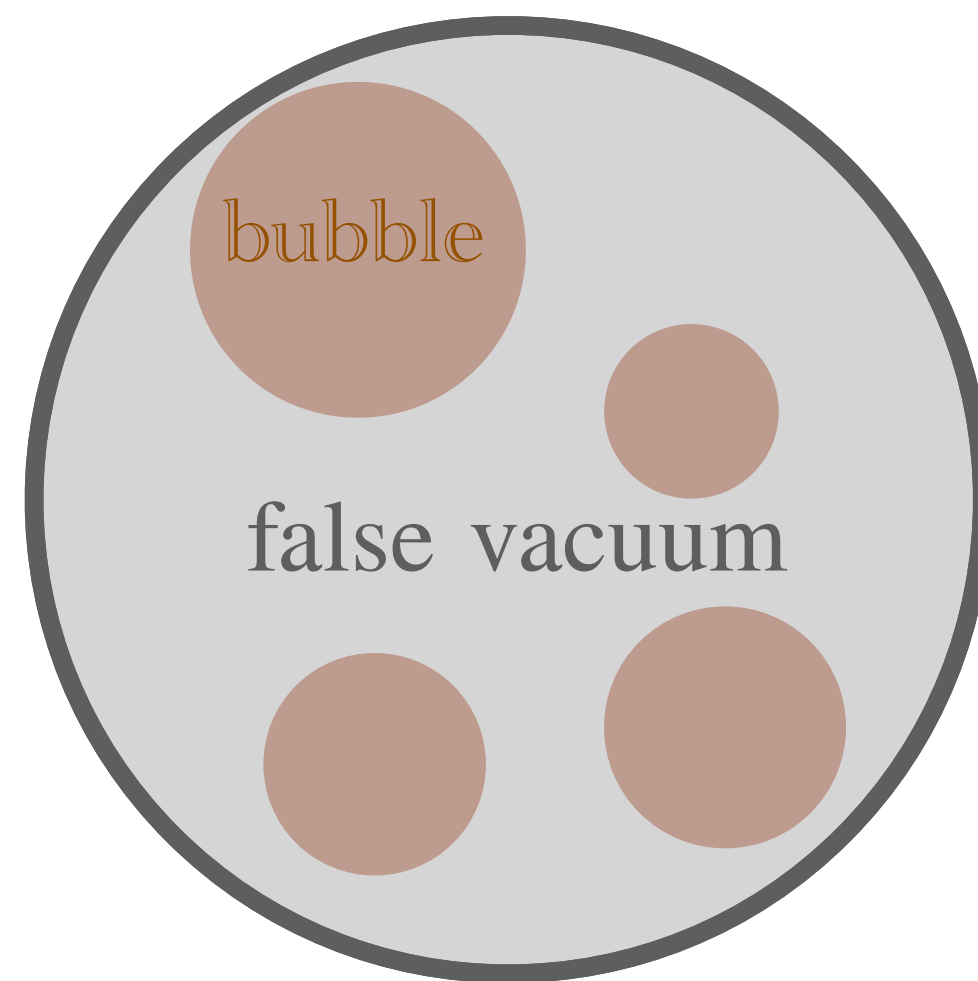
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Suggest bubble walls could be important

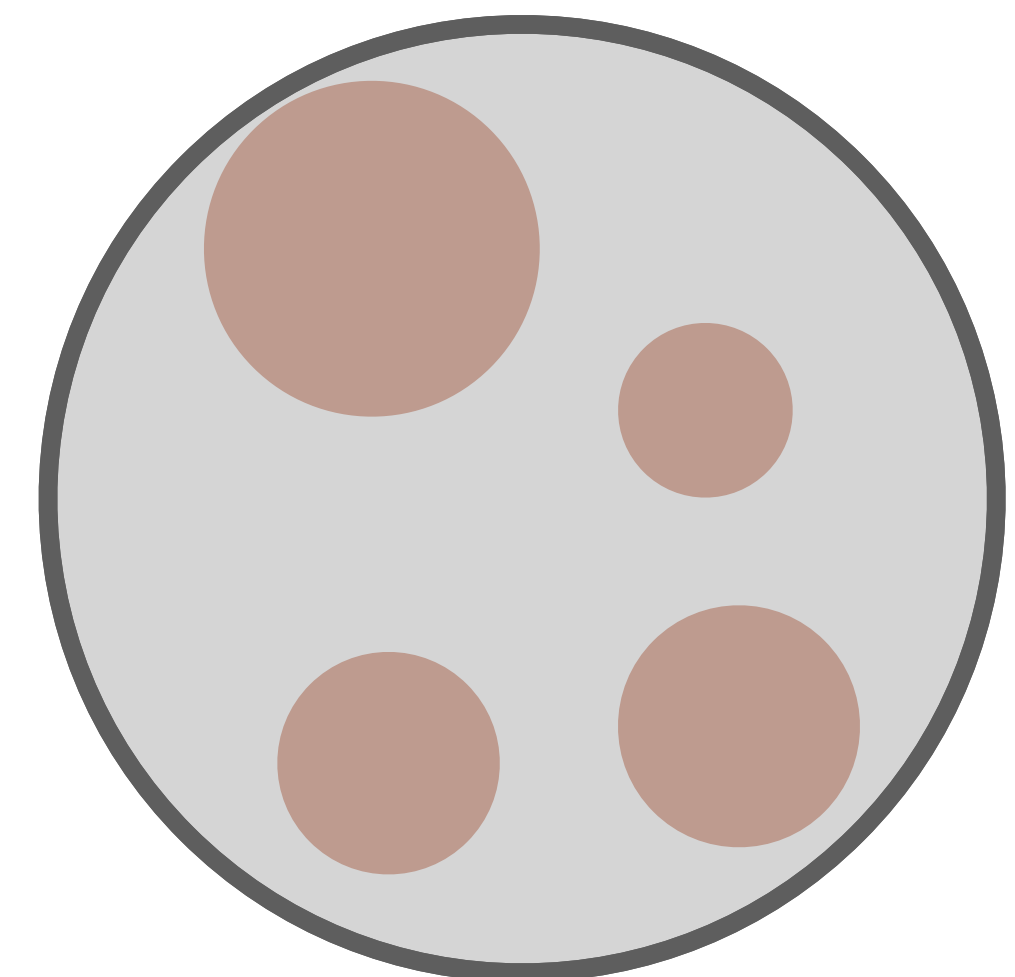


YG, Lewicki, Toczec, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls



deltaPT



Lewicki, Toczek, Vaskonen, 2402.04158, PRL
(deltaPT)

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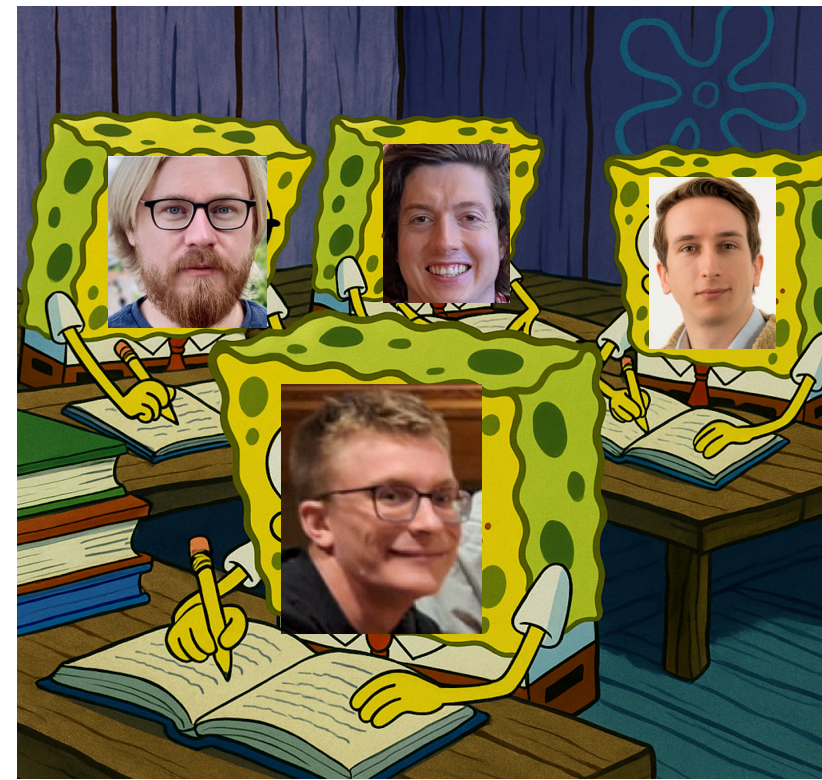
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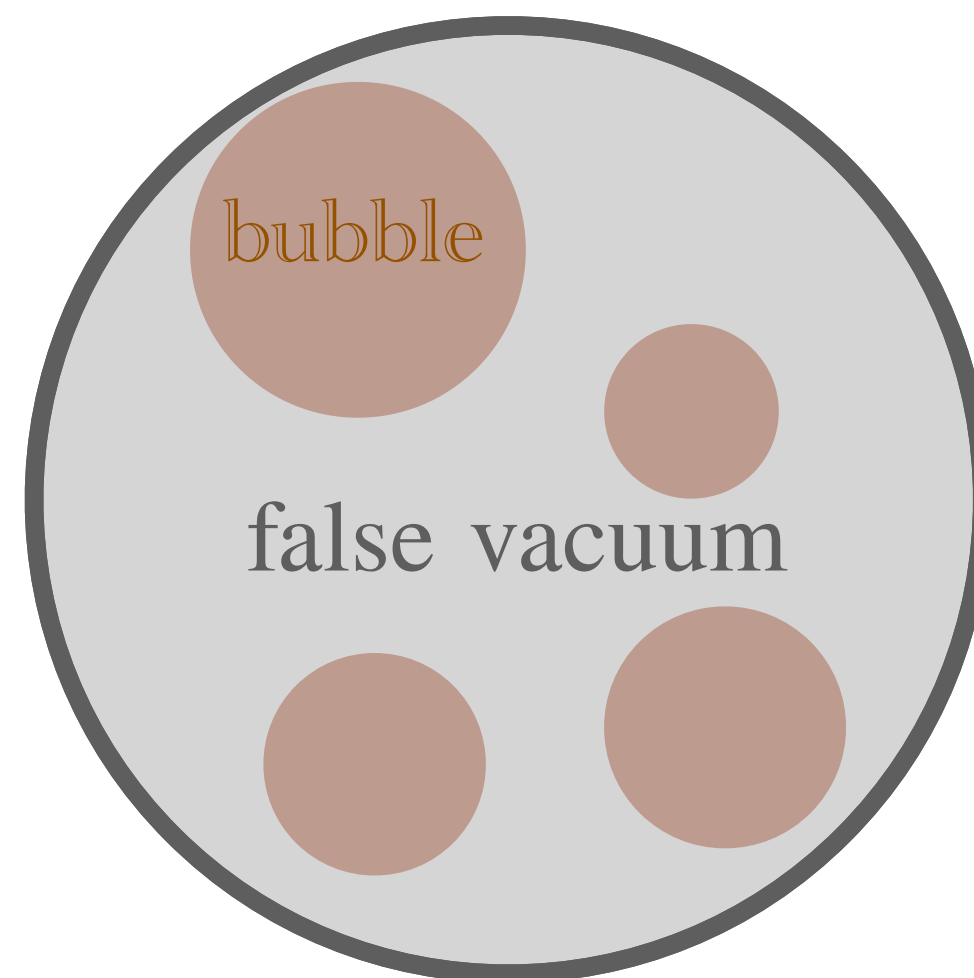
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Tanaka, Yoo 2501.11040

Suggest bubble walls could be important

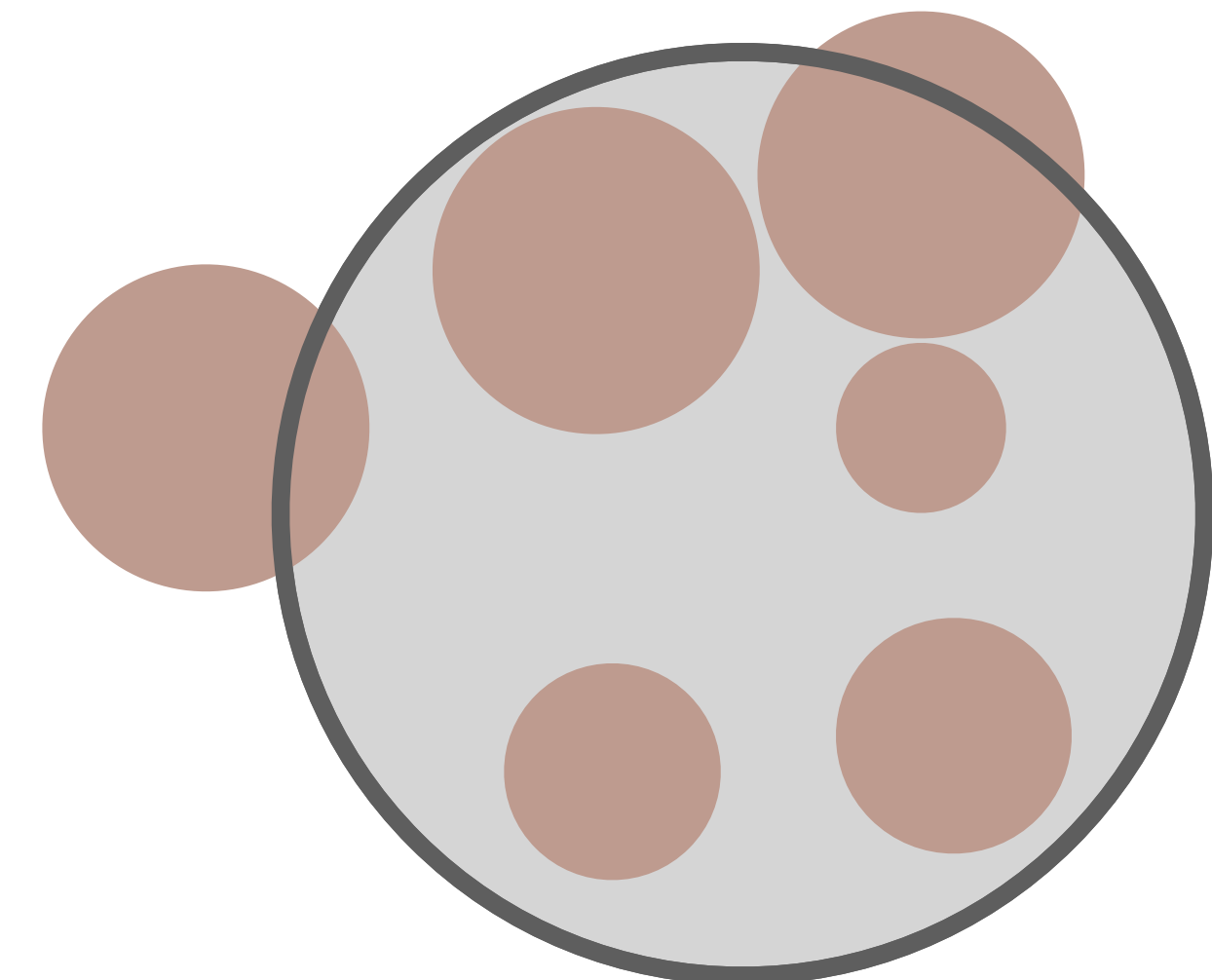


YG, Lewicki, Toczek, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls



deltaPT



Lewicki, Toczec, Vaskonen, 2402.04158, PRL
(deltaPT)

Franciolini, YG, Jinno 2503.01962

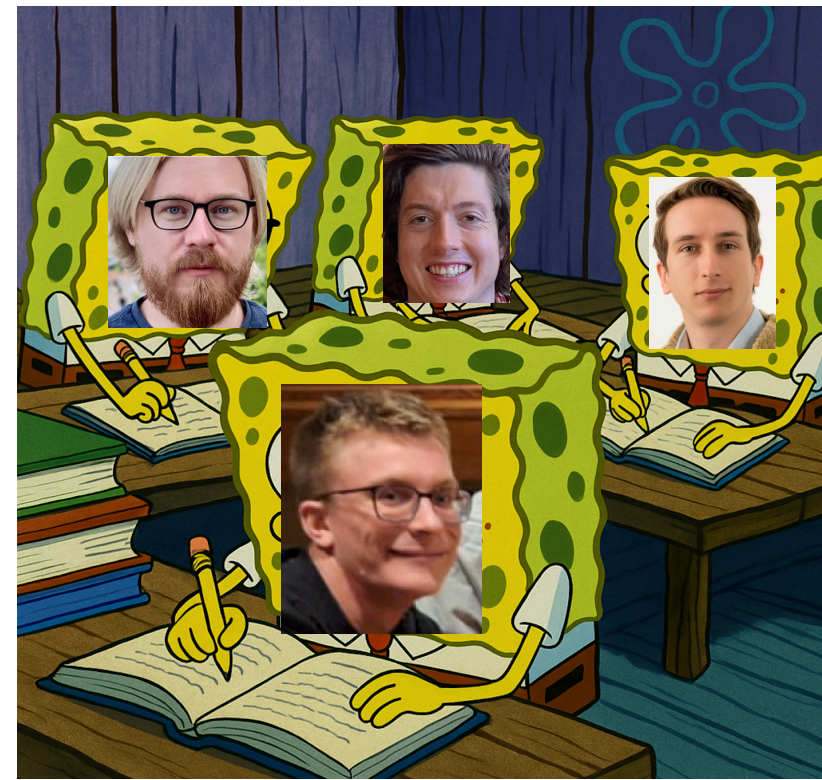
Neglect effects from bubble walls

Lewicki, Toczec, Vaskonen 2305.04924

Flores, Kusenko, Sasaki 2402.13341

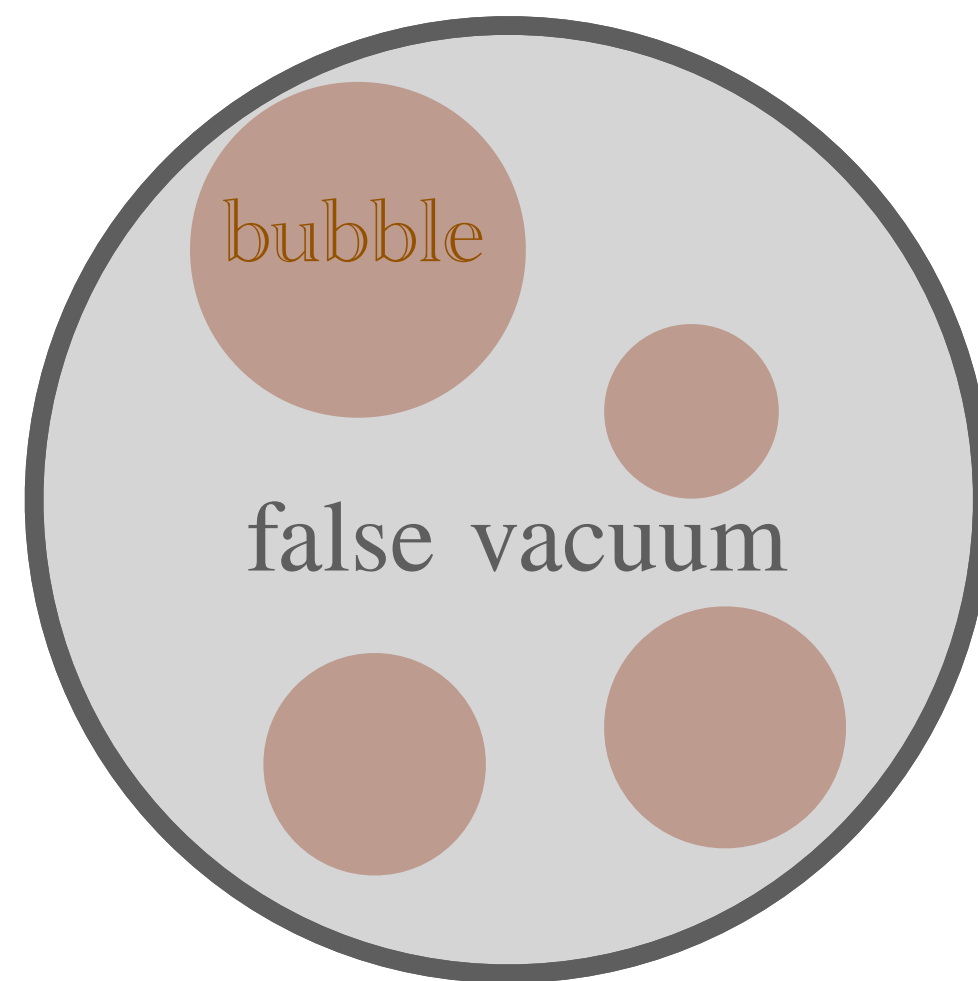
Hashino, Kanemura, Takahashi,
Tanaka, Yoo 2501.11040

Suggest bubble walls could be important

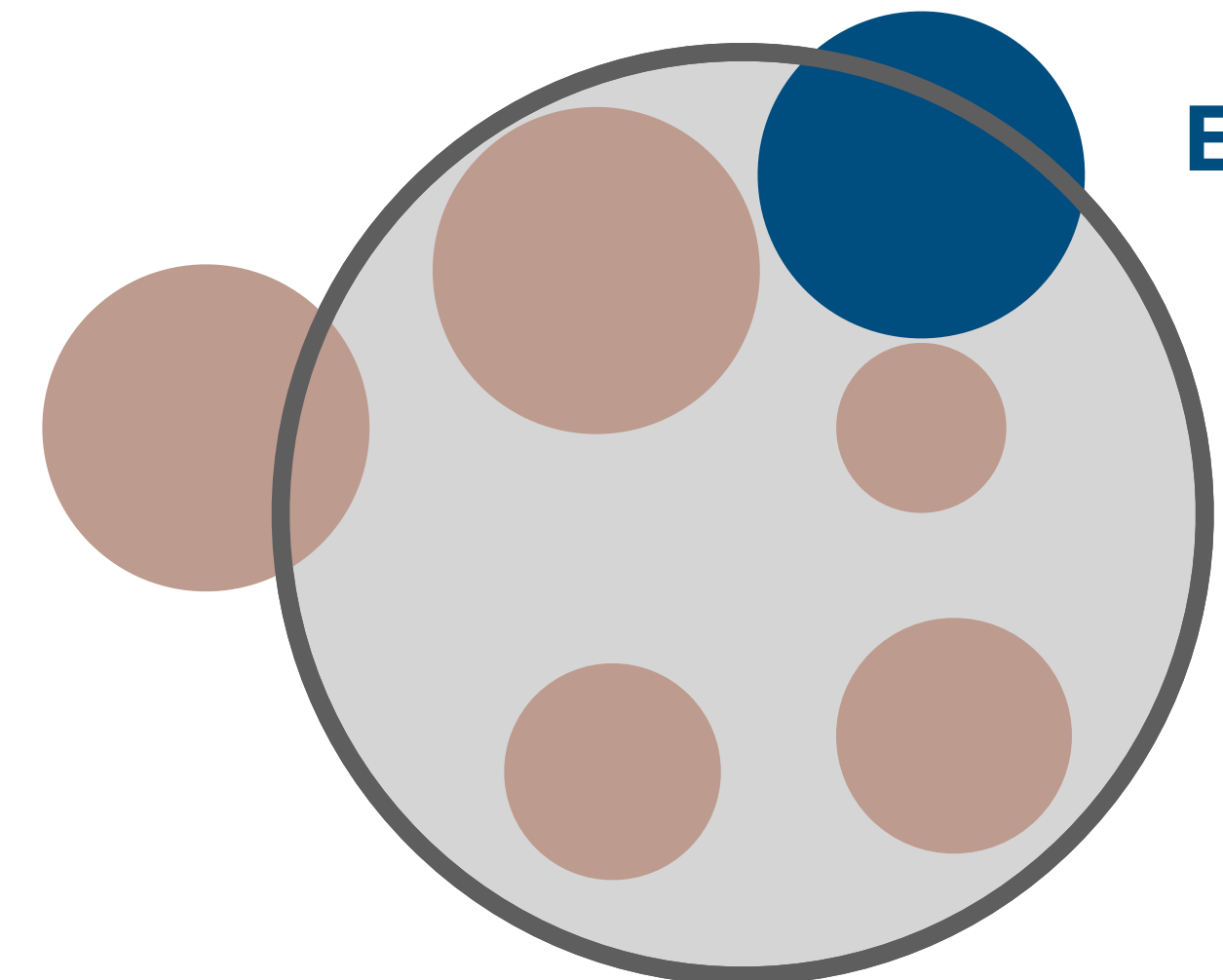


YG, Lewicki, Toczec, Vaskonen, 26XX.XXXXX

Account for momentum flux from bubble walls



deltaPT



Energy loss

Lewicki, Toczec, Vaskonen, 2402.04158, PRL
(deltaPT)

Franciolini, YG, Jinno 2503.01962

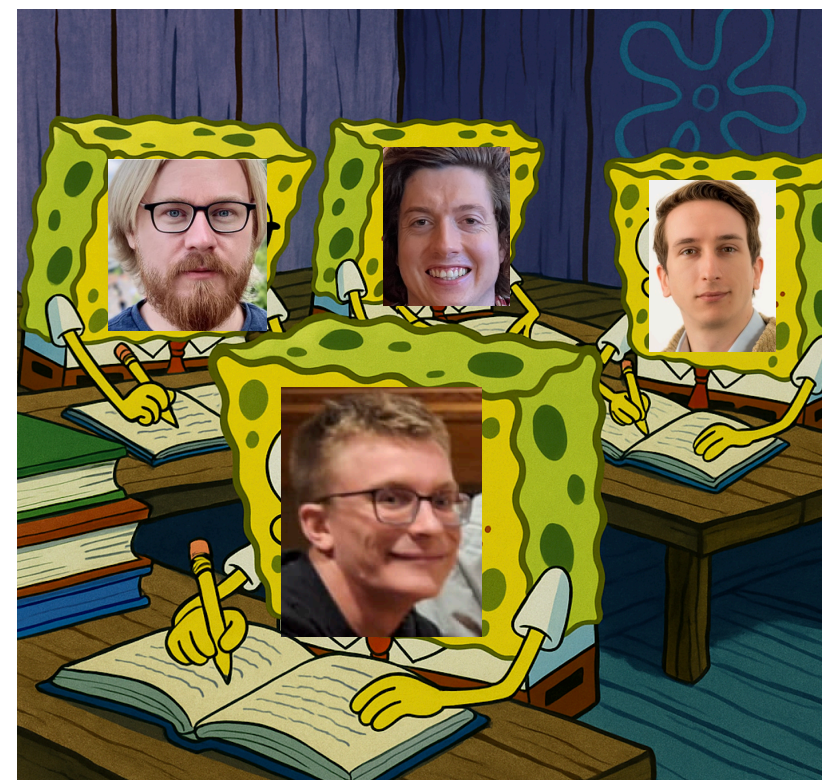
Neglect effects from bubble walls

Lewicki, Toczec, Vaskonen 2305.04924

Flores, Kusenko, Sasaki 2402.13341

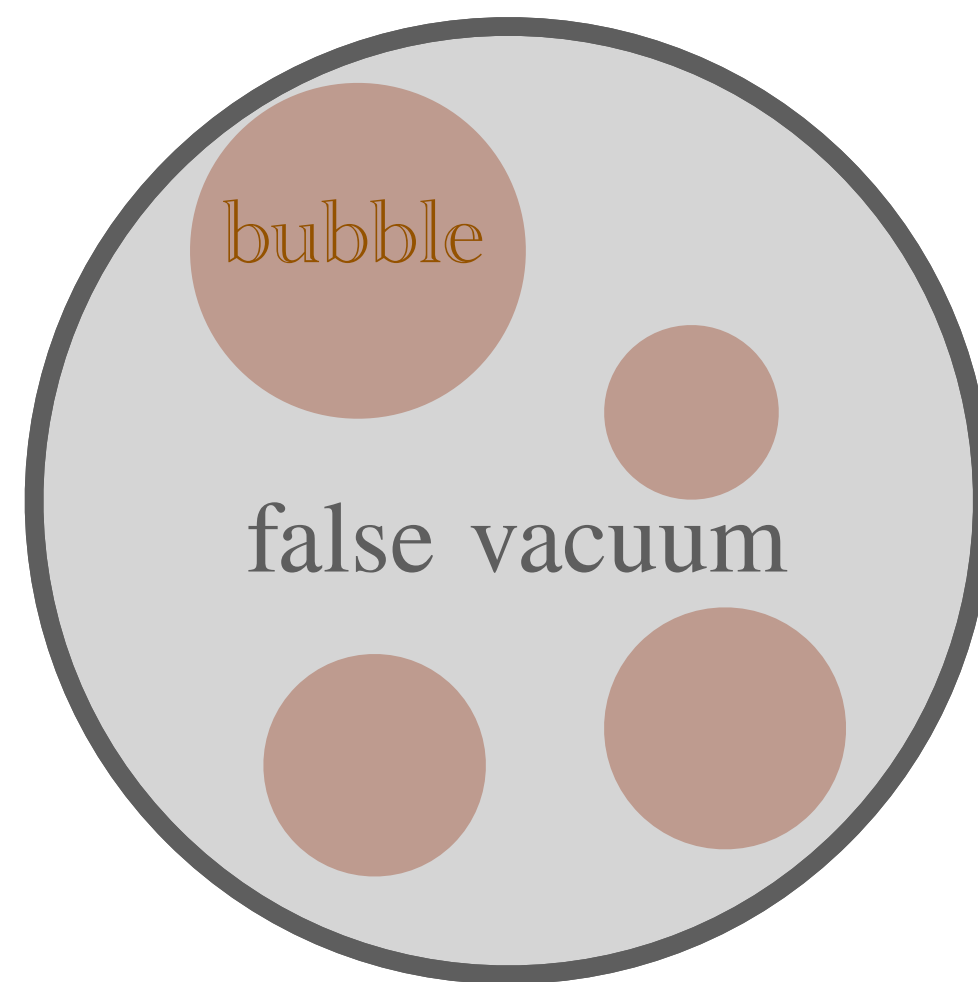
Hashino, Kanemura, Takahashi,
Tanaka, Yoo 2501.11040

Suggest bubble walls could be important



YG, Lewicki, Toczec, Vaskonen, 26XX.XXXXX

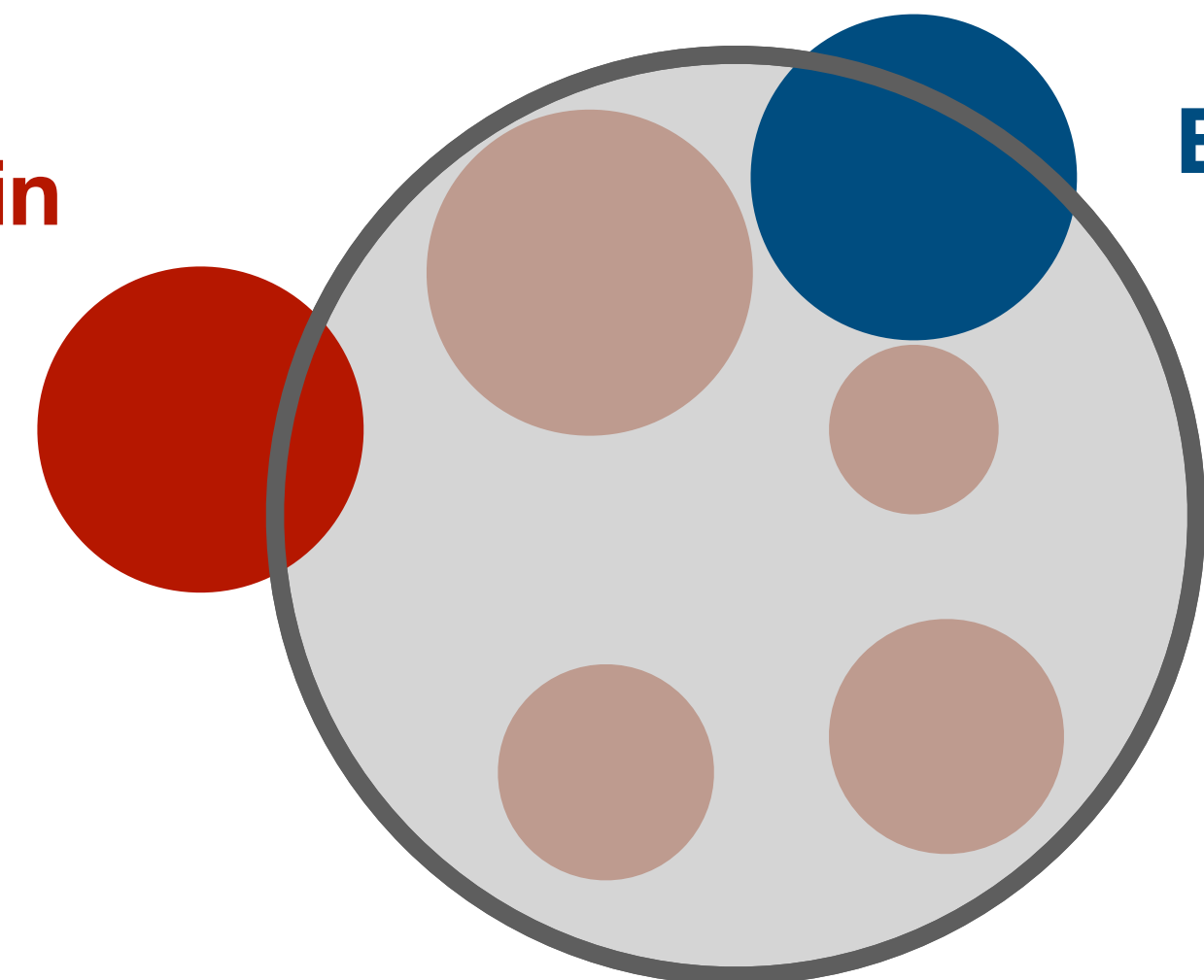
Account for momentum flux from bubble walls



deltaPT

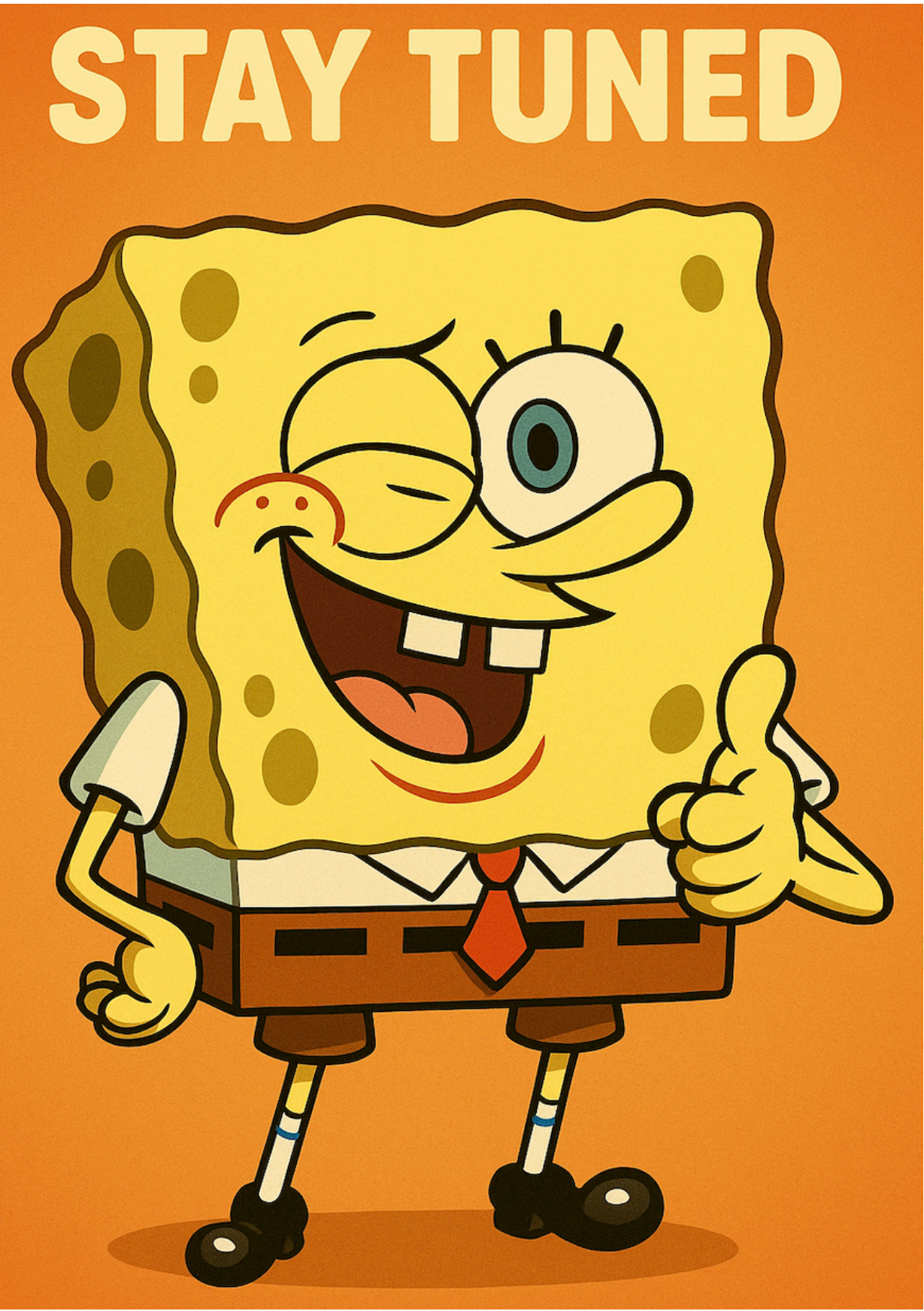


Energy gain



Energy loss

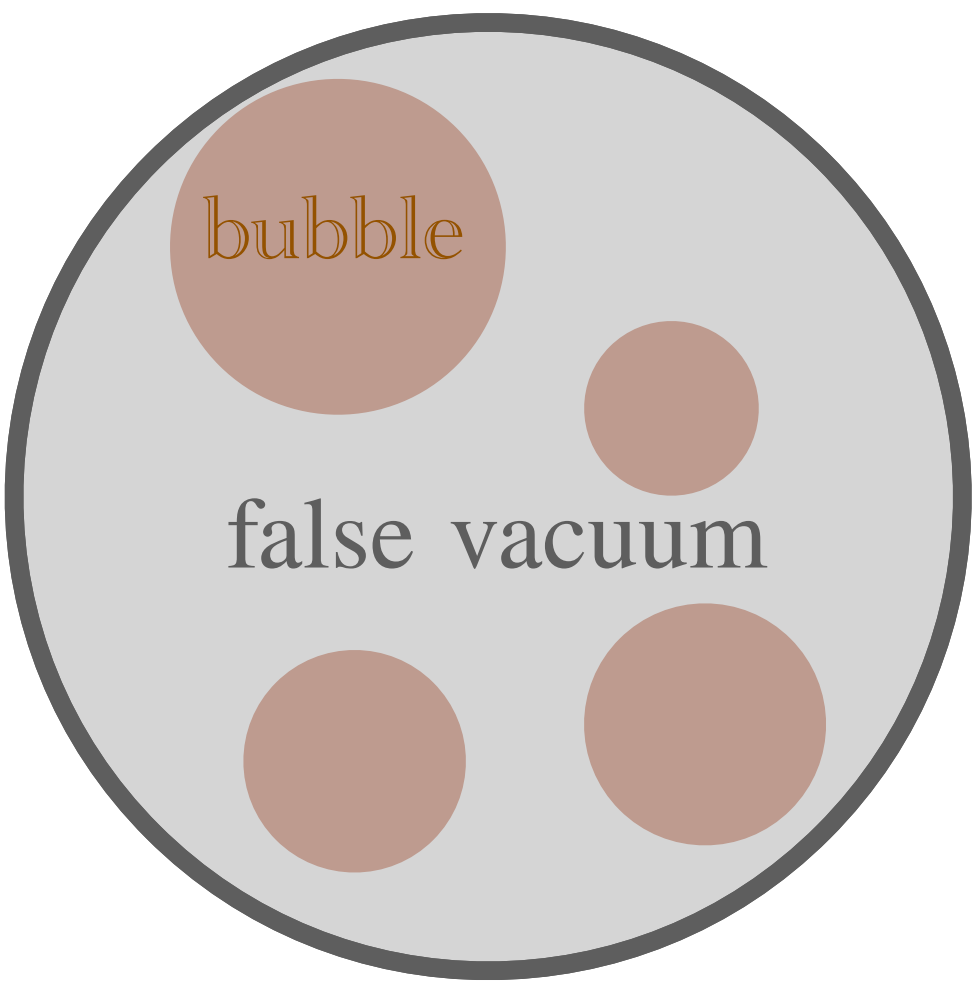
Lewicki, Toczek, Vaskonen, 2402.04158,
(deltaPT)
Franciolini, YG, Jinno 2503.01962



Lewicki, Toczek, Vaskonen 2305.04924
Flores, Kusenko, Sasaki 2402.13341
Hashino, Kanemura, Takahashi,
Tanaka, Yoo 2501.11040

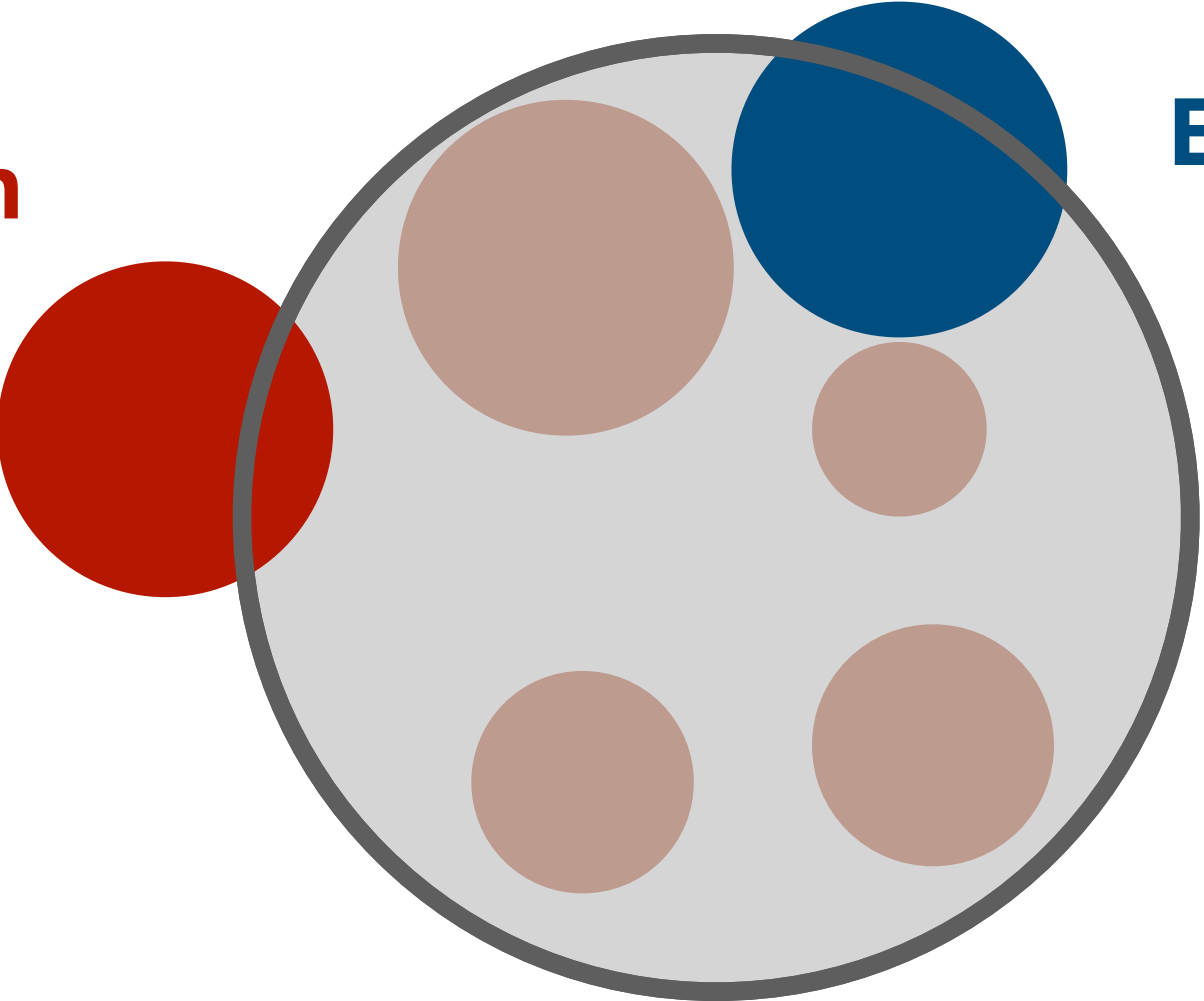
Neglect effects from bubble wa
est bubble walls could be important

YO
XX.XXXXXX
Accou
bubble walls

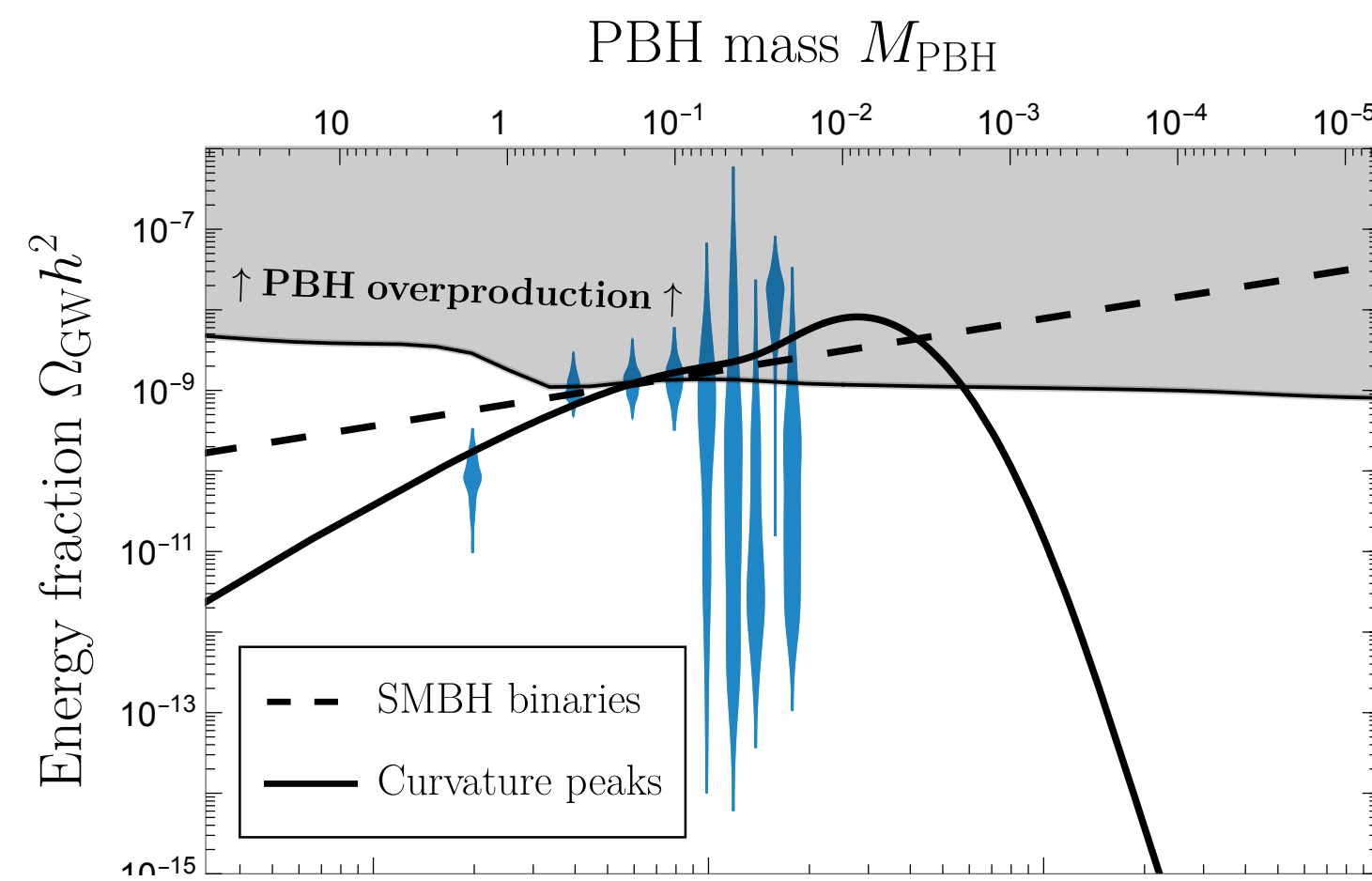


deltaPT

Energy gain



Energy loss



Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermae (2009.07832),

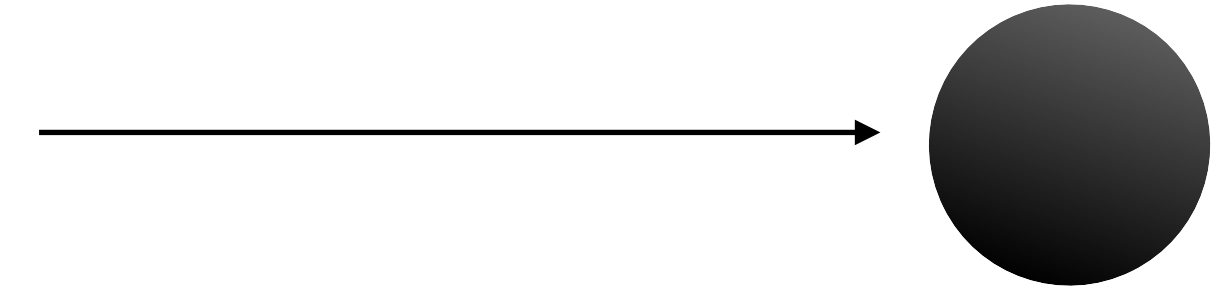
De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

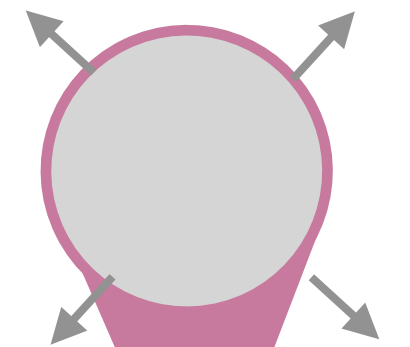
Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)

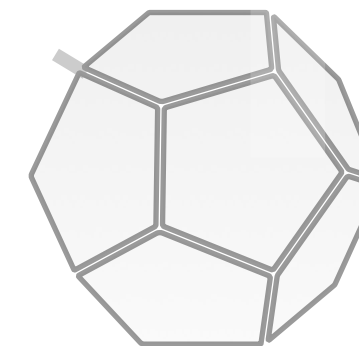


Baby-universe



Deng, Garriga, Vilenkin (1612.03753)

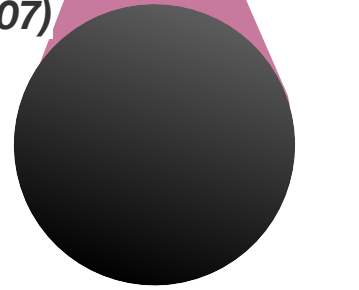
Wormhole



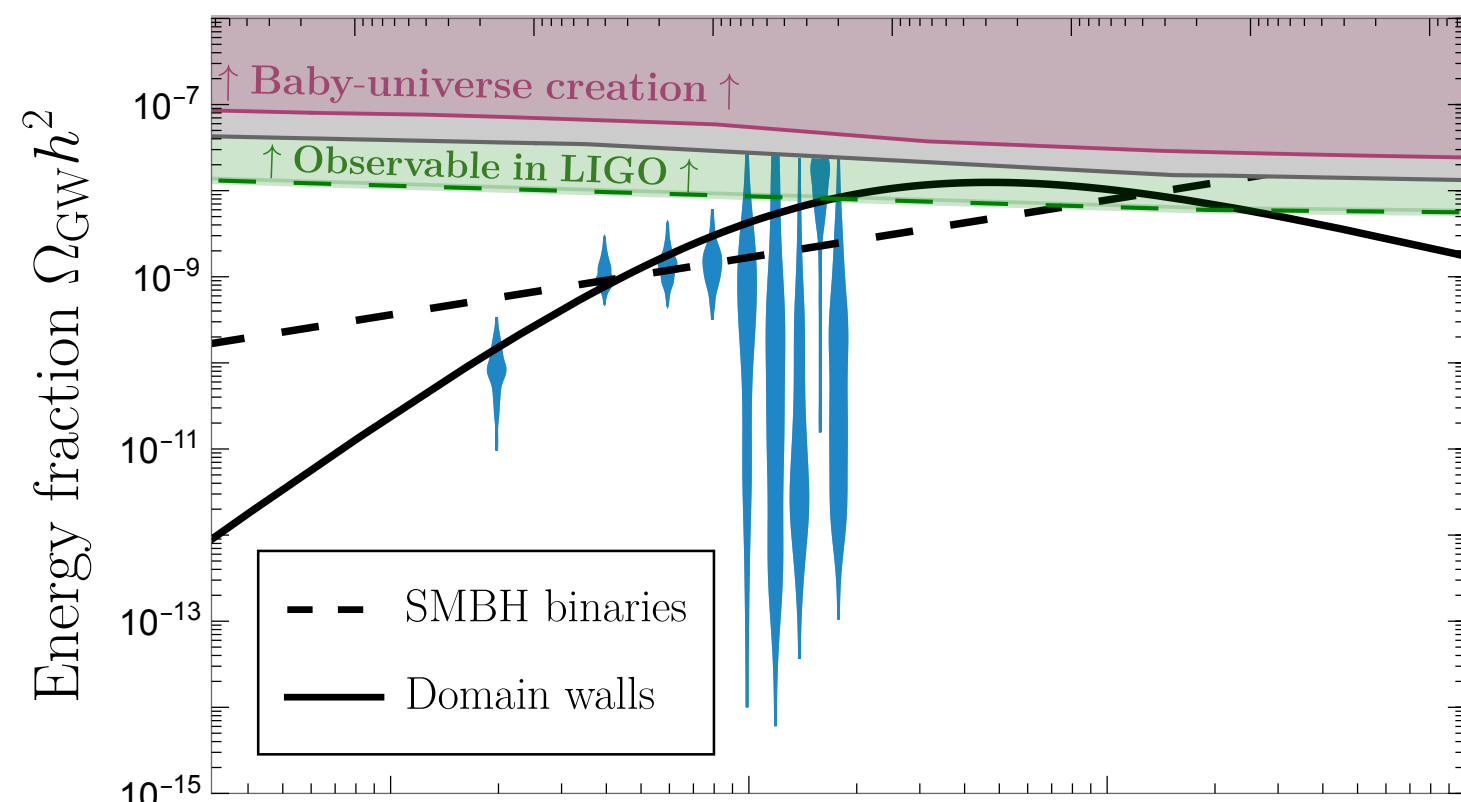
Ferrer, Masso, Panico, Pujolas, Rompineve (1807.01707)

Ferreira, Notari, Pujolas, Rompineve (2401.14331)

YG, Vitagliano, 2311.07670



PBH



Domain wall networks

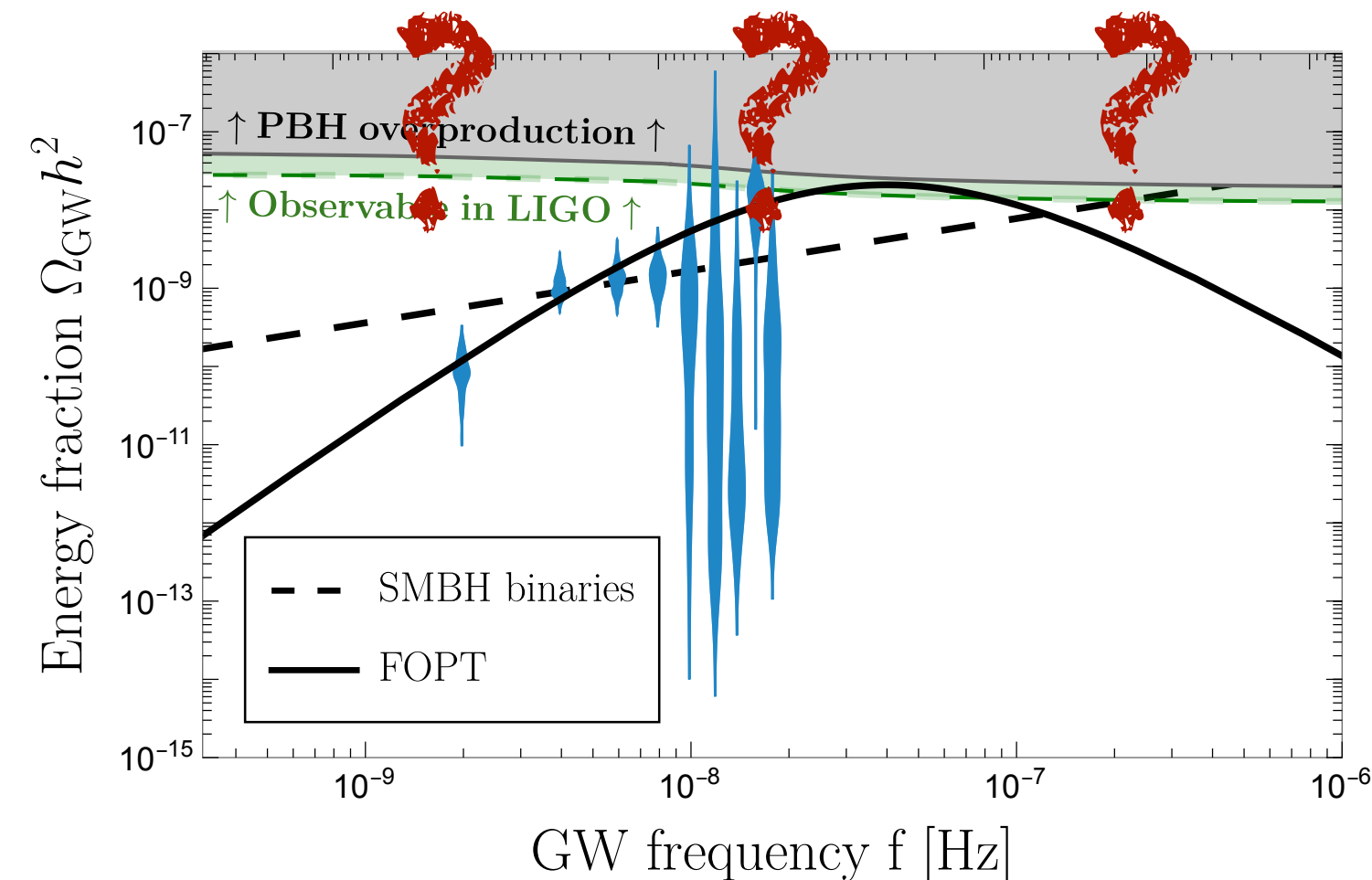
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

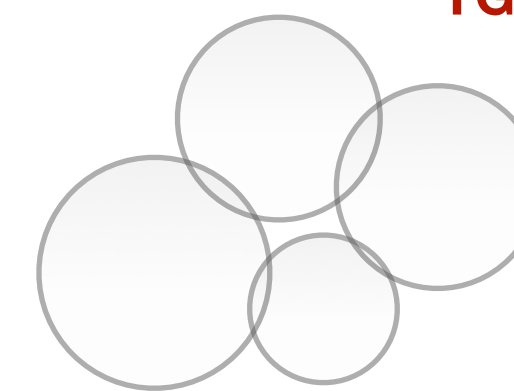
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczec, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...



Franciolini, YG, Jinno, 2503.01962

YG, Lewicki, Toczec, Vaskonen (in preparation)

YG&Volansky 2023,

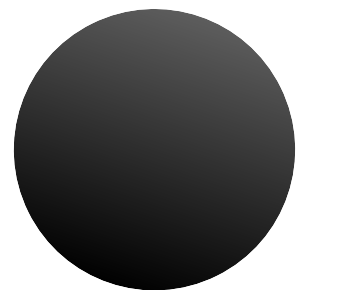
YG (2307.04239)

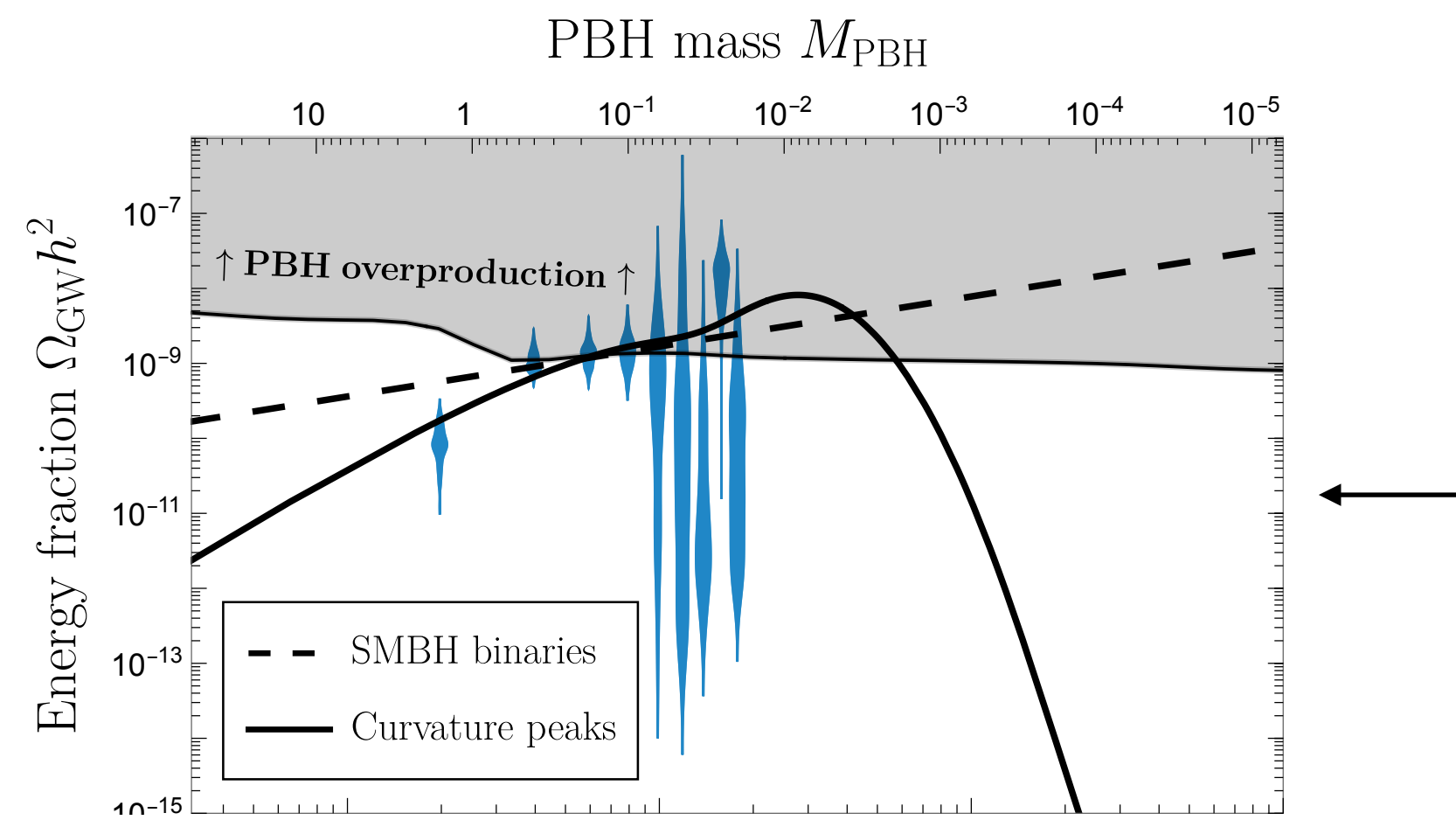
Sasaki+ 1982, Bian+ 2021, Lu+ 2022,

Lewicki, Toczec, Vaskonen 2023,

Baldes+ 2023,

Lewicki, Toczec, Vaskonen 2024,





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermäe (2009.07832),

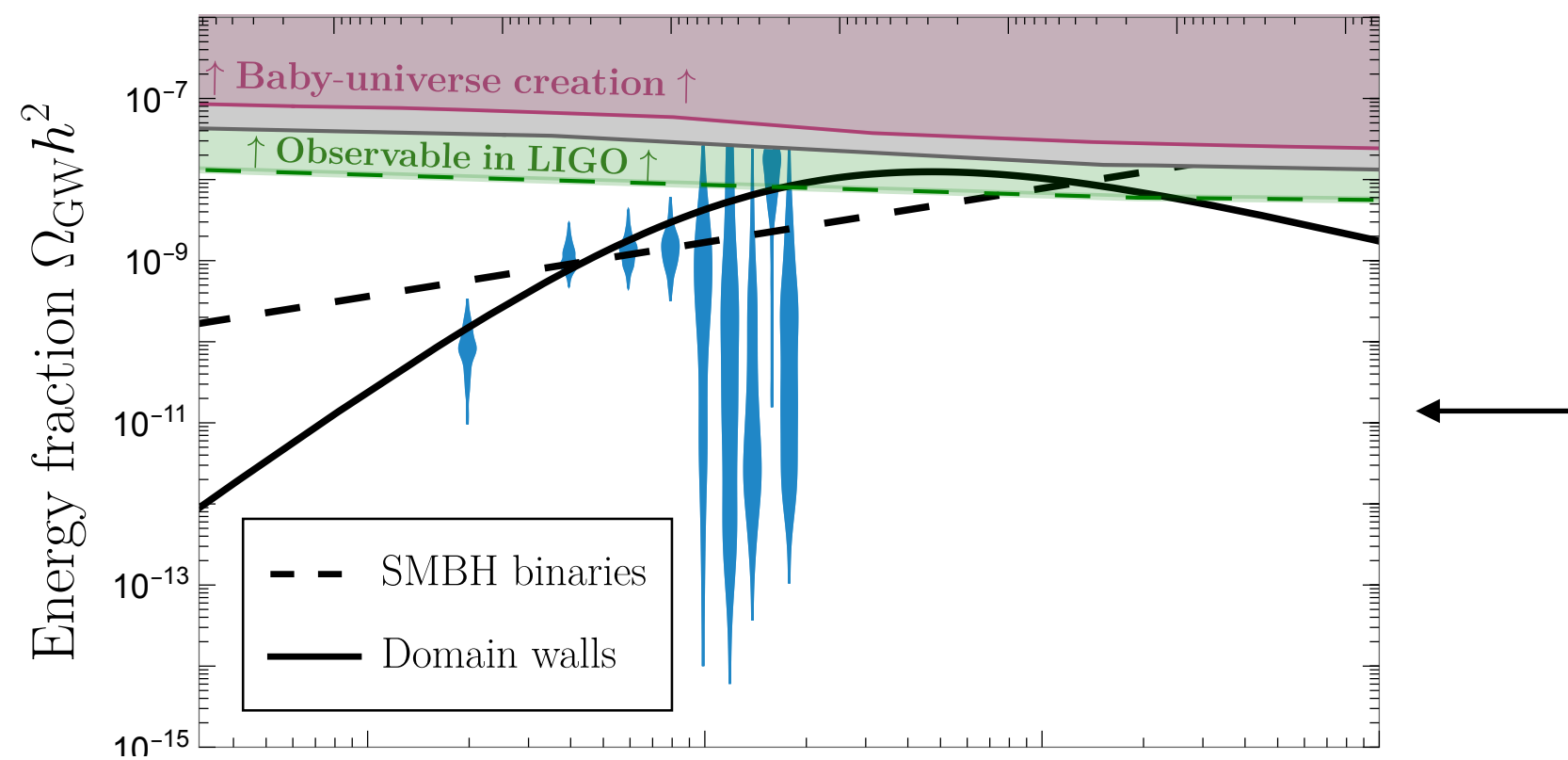
De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermäe (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

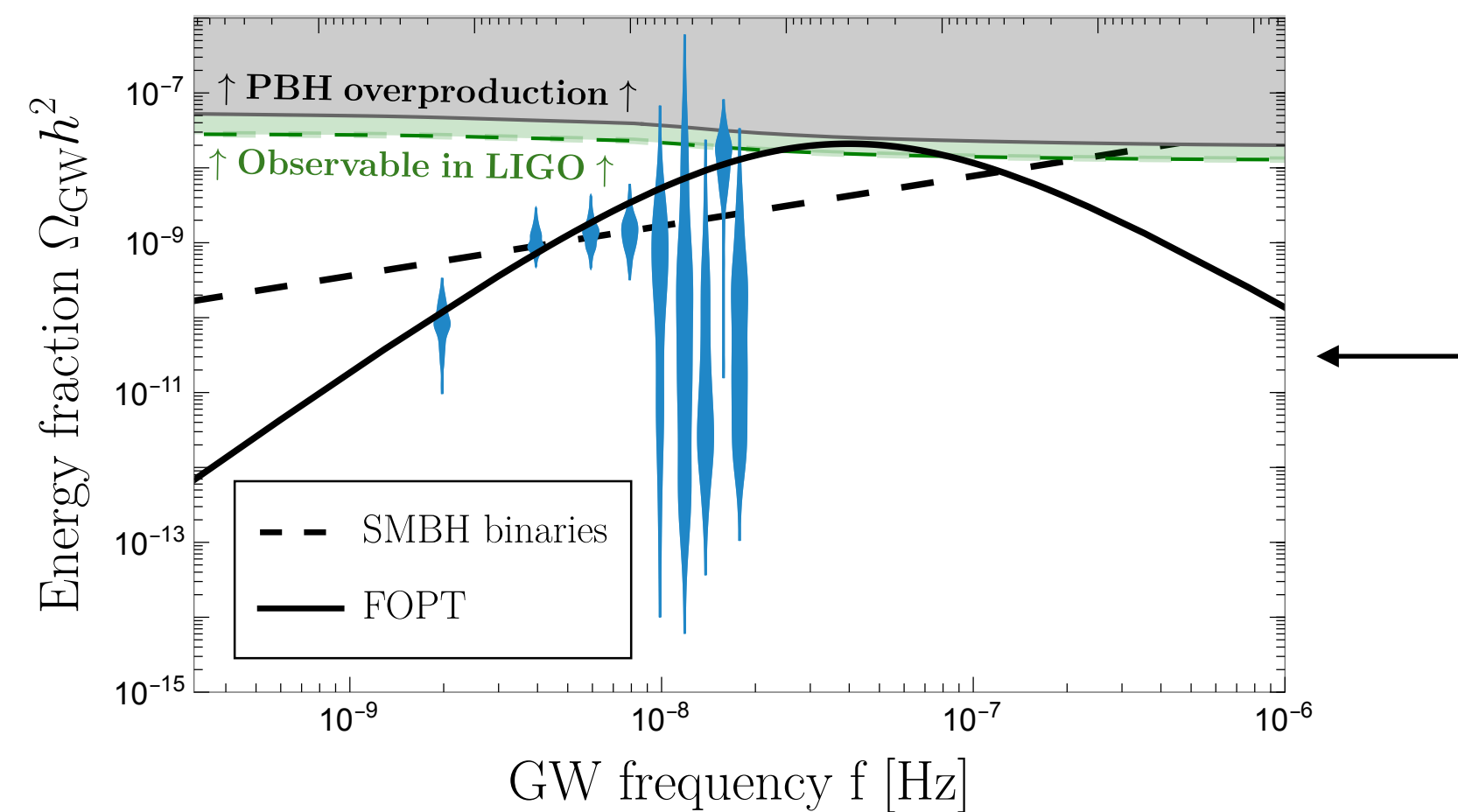
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

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Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...

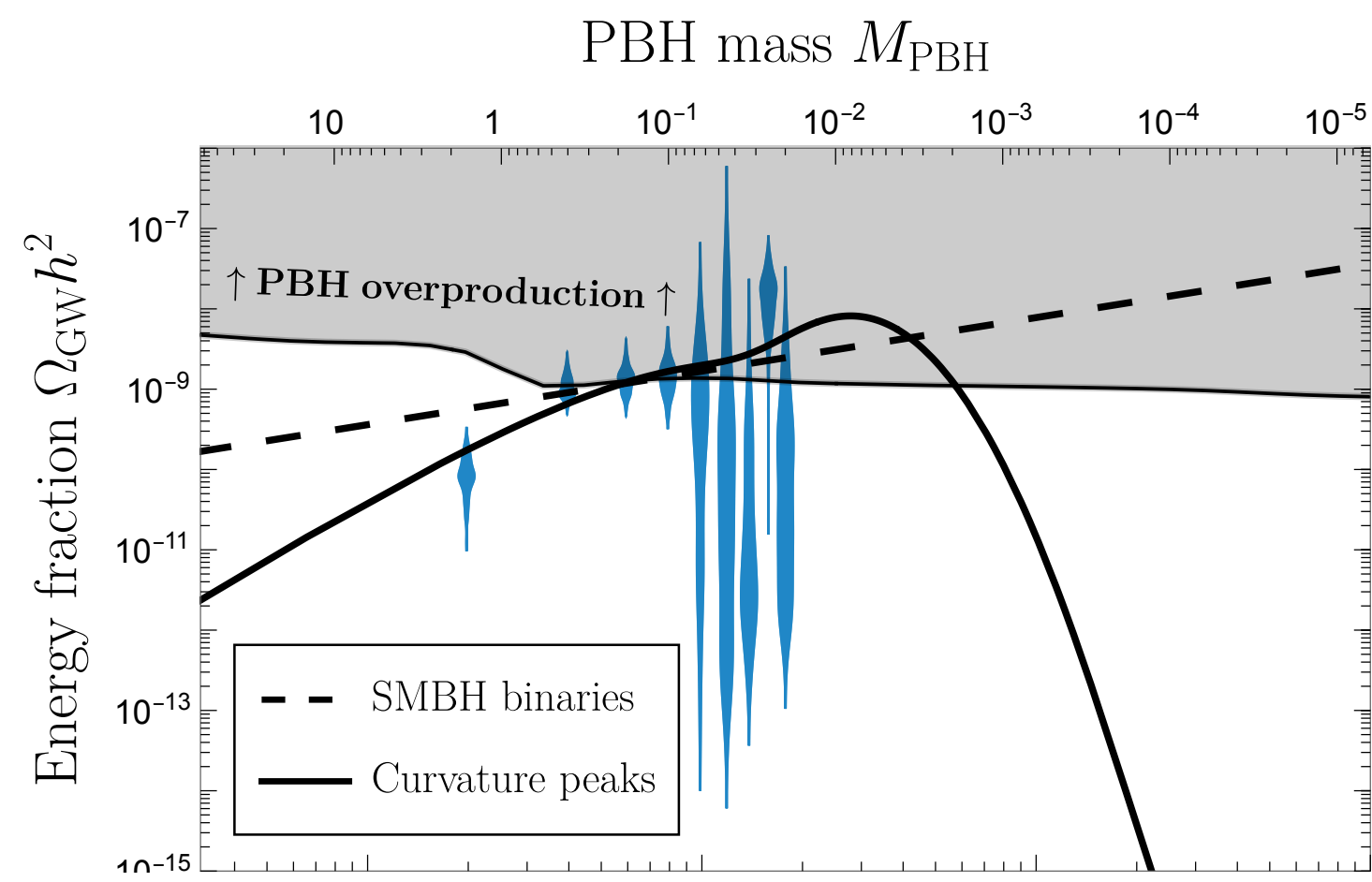
Scalar Curvature

$\mathcal{R}(\vec{x}, t)$

YG 2503.03857

Franciolini, YG, Jinno,

2503.01962



Curvature peaks

Overproduce PBH

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Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermäe (2009.07832),

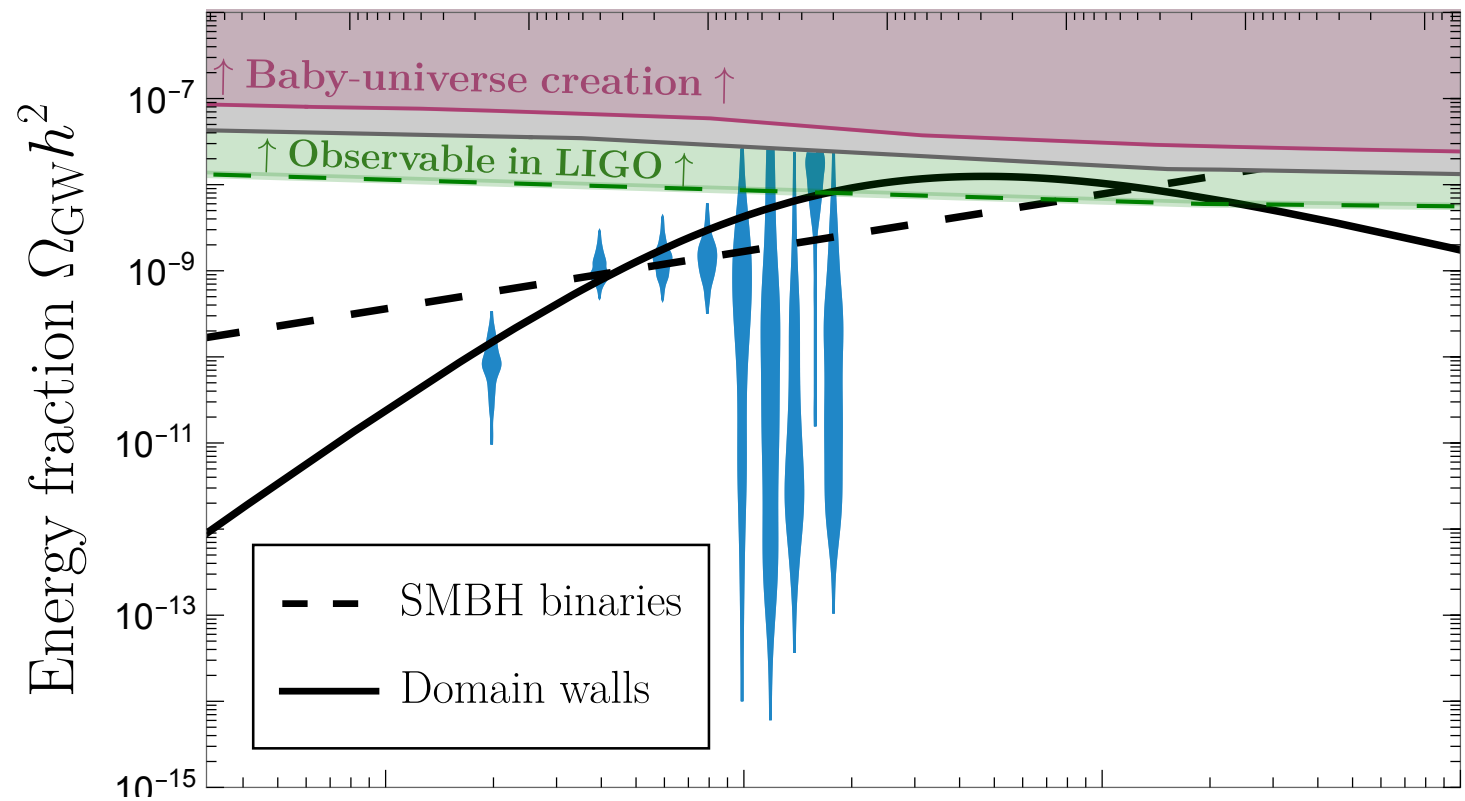
De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermäe (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

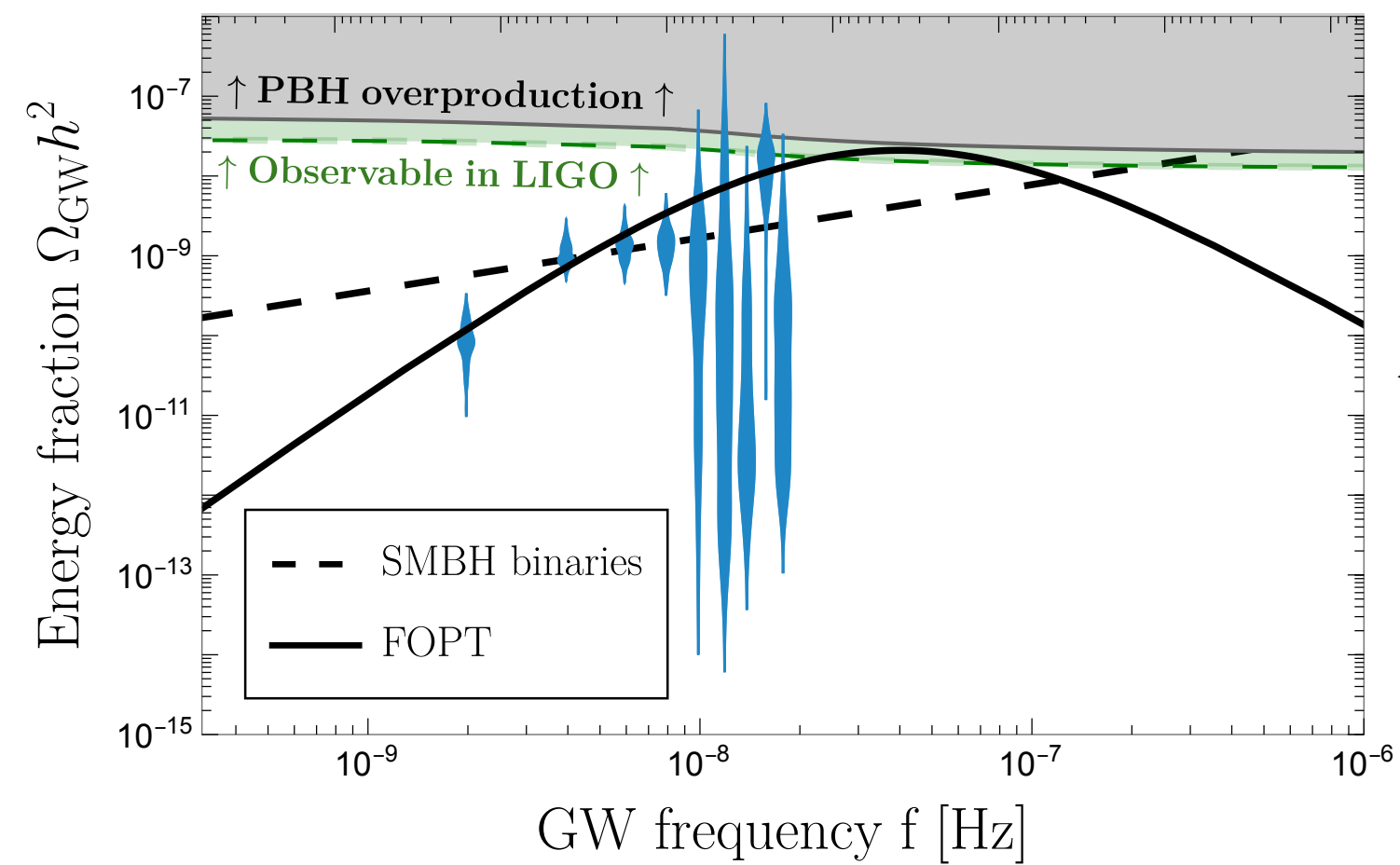
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

Ghoshal, White et al. (2307.02259)

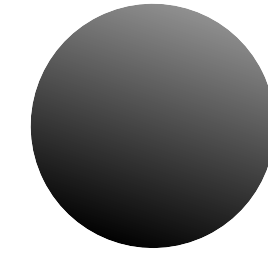
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...

Primordial Black Holes (PBHs)



if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

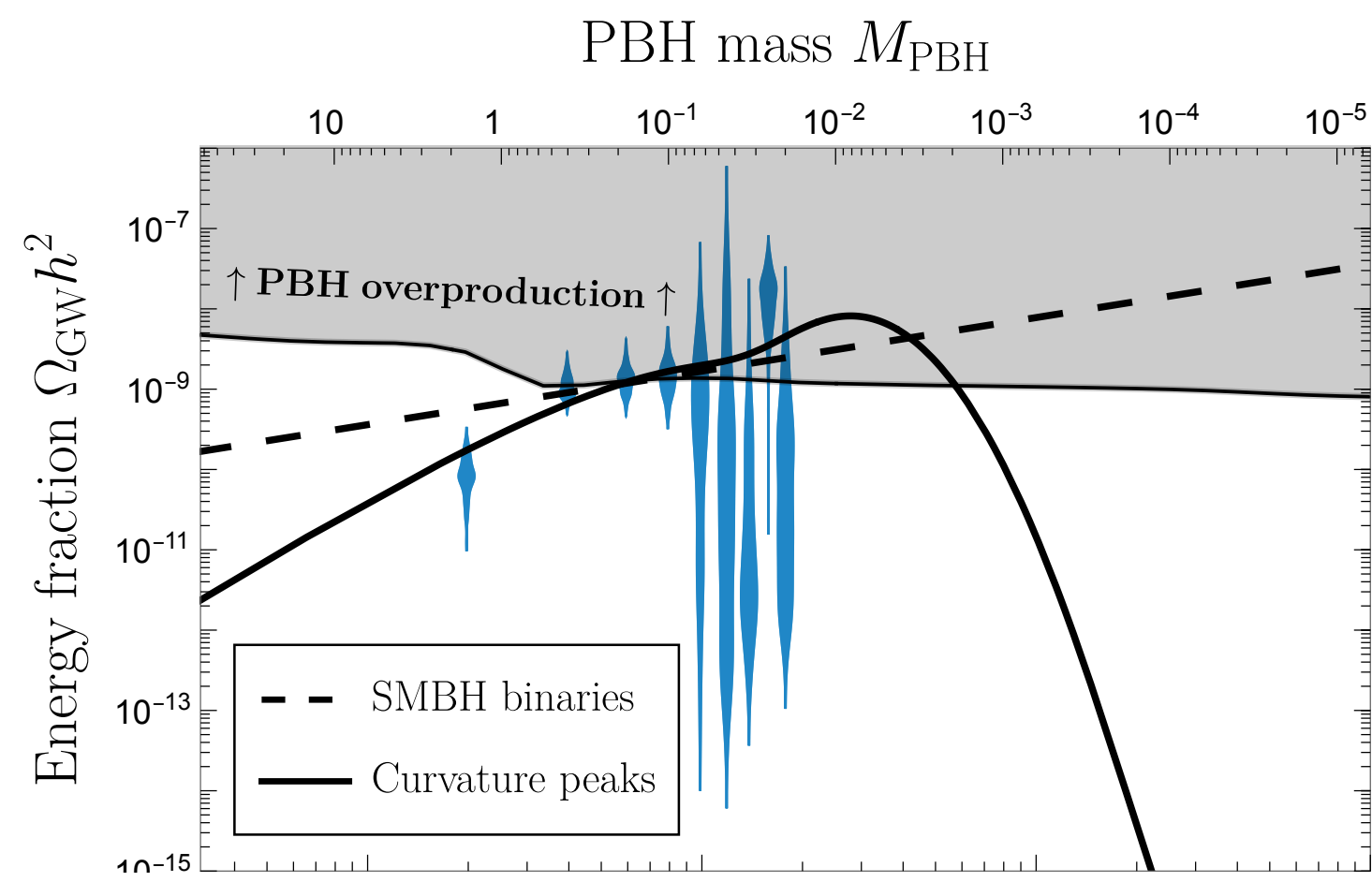
(Shibata & Sasaki 1999)

Scalar Curvature

$\mathcal{R}(\vec{x}, t)$



YG 2503.03857
Franciolini, YG, Jinno, 2503.01962



Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

Vaskonen, Veermäe (2009.07832),

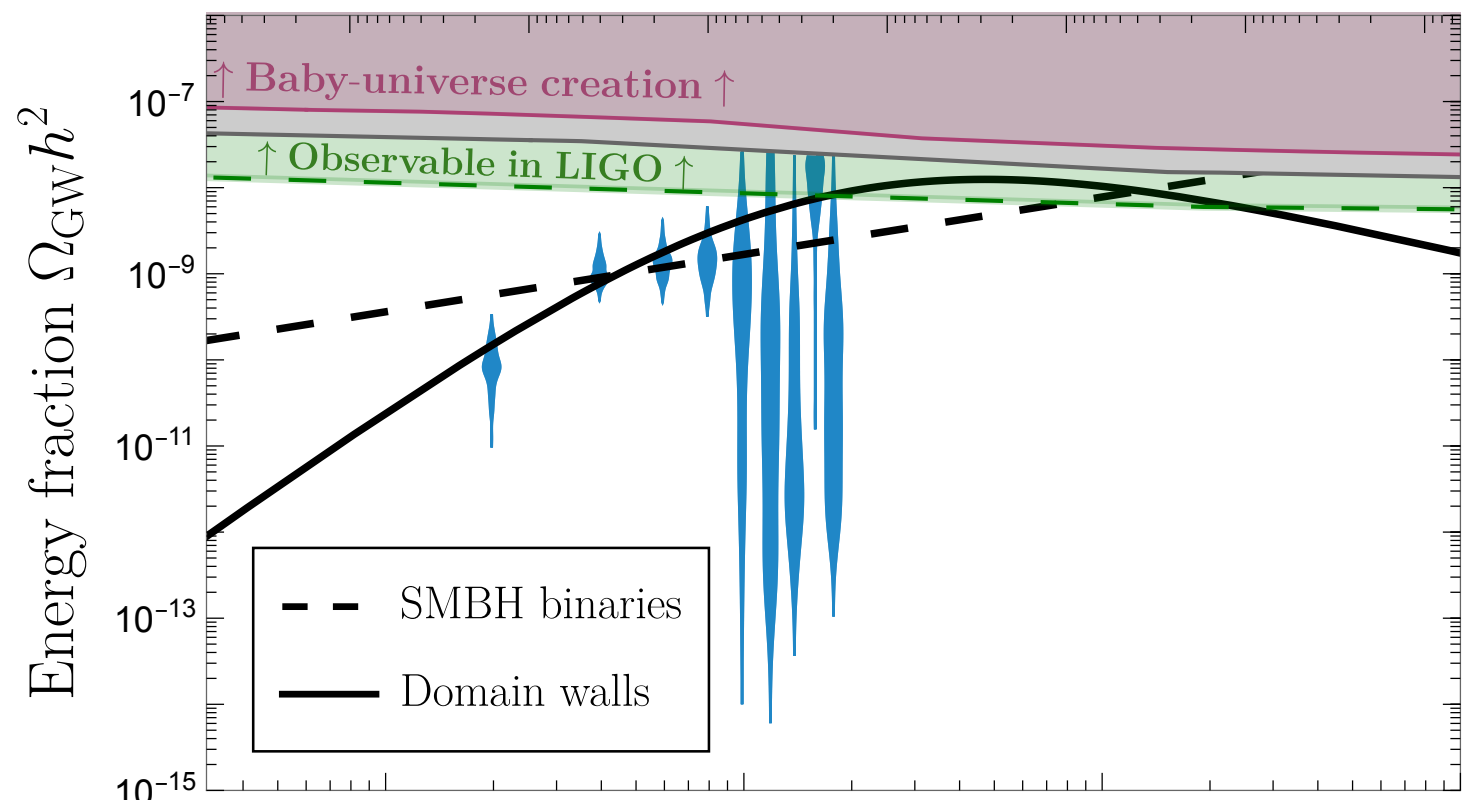
De Luca, Franciolini, Riotto (2009.08268)

Clesse, Dandoy, Verma (2412.15989)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermäe (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

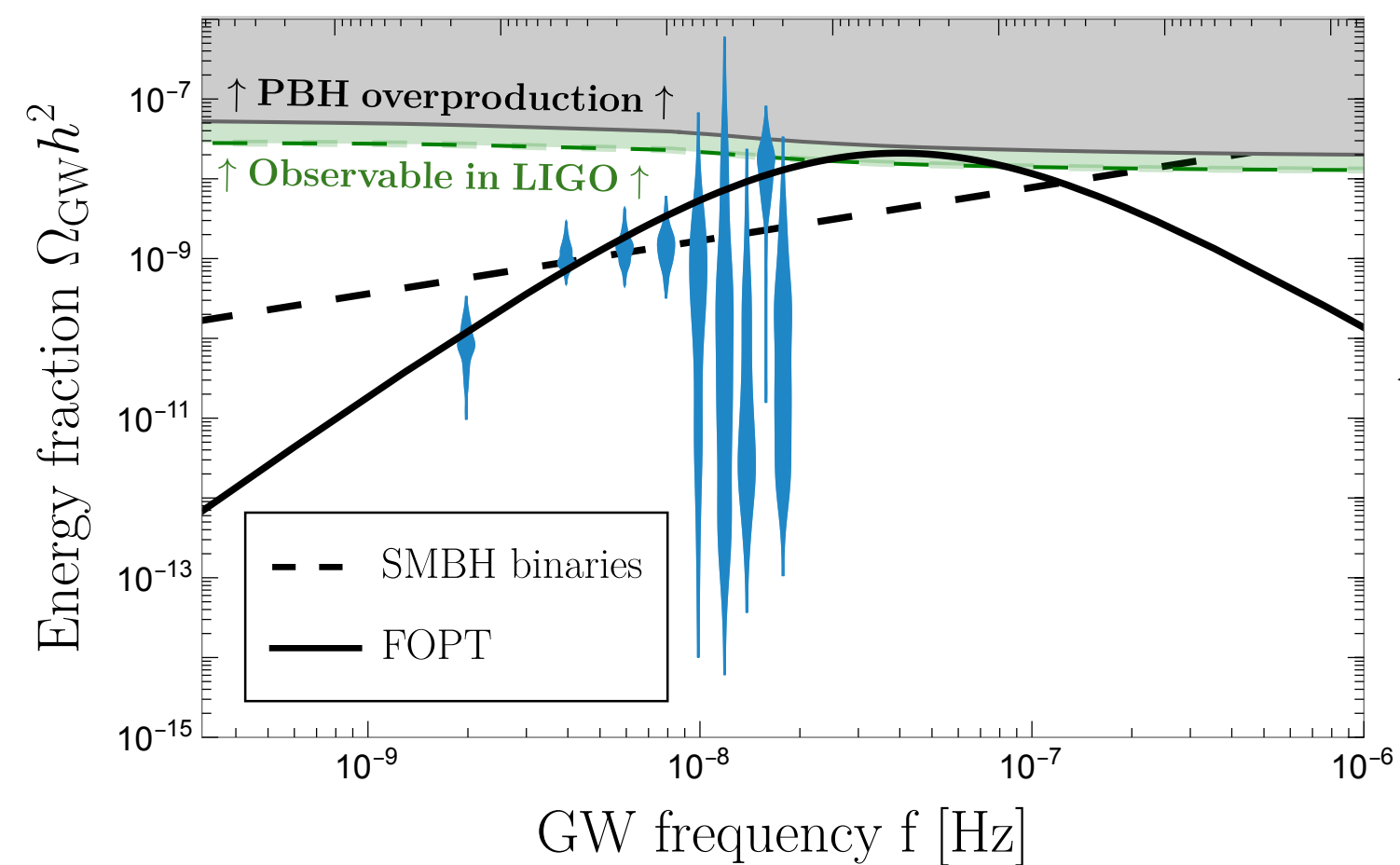
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

Ghoshal, White et al. (2307.02259)

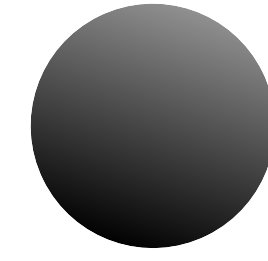
YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...

Primordial Black Holes (PBHs)



if $\langle \mathcal{R} \rangle_H \gtrsim 0.1$

(Shibata & Sasaki 1999)

Scalar Curvature

$\mathcal{R}(\vec{x}, t)$



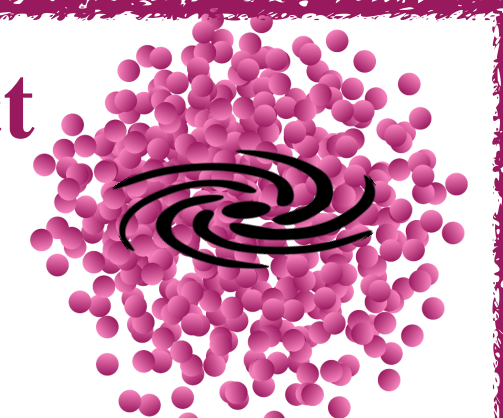
YG 2503.03857

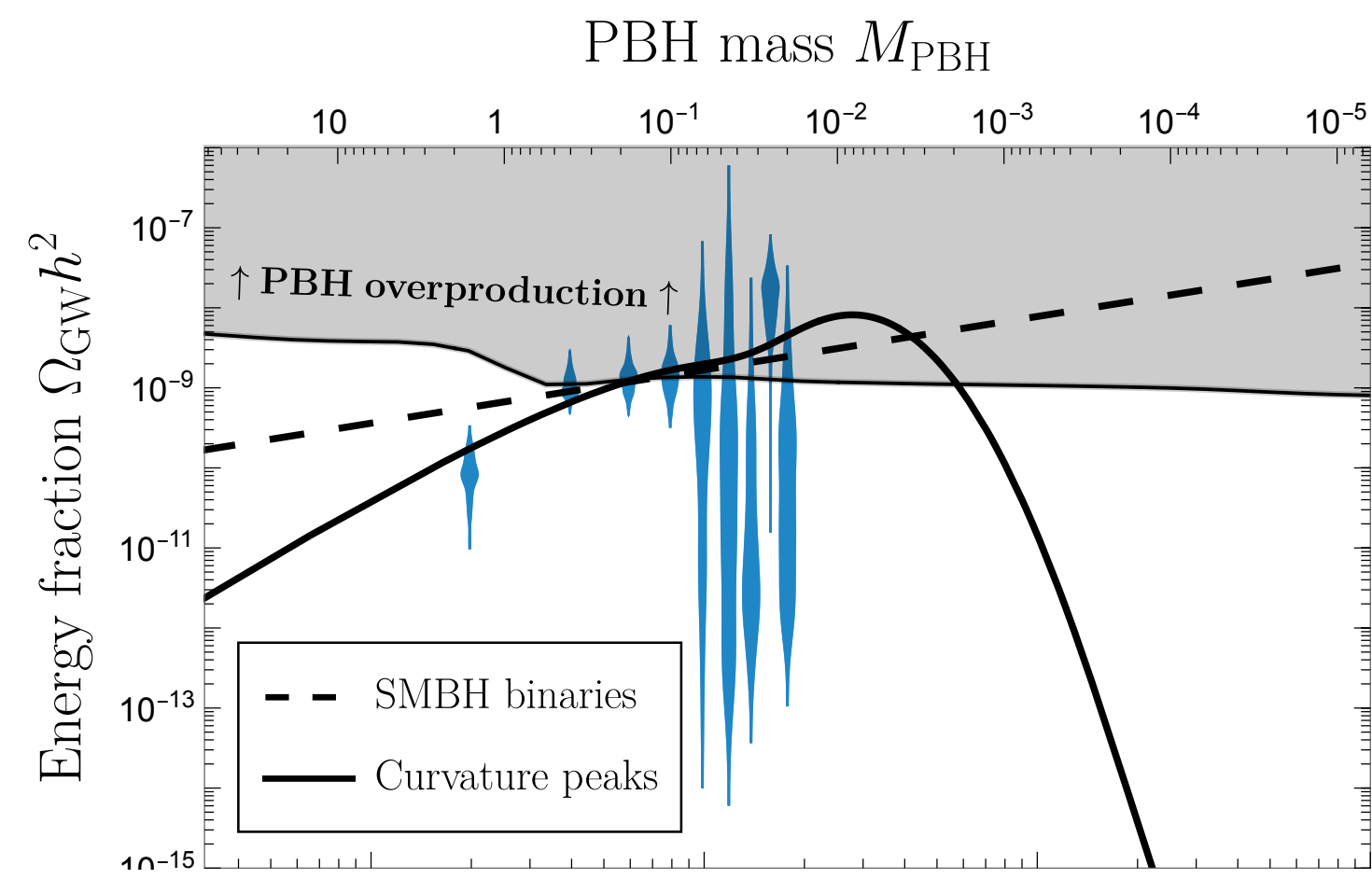
*Franciolini, YG, Jinno,
2503.01962*

if $\langle \mathcal{R} \rangle_H \gtrsim 10^{-3}$

Ricotti, Gould (0908.0735)

DM Ultra Compact Mini Halos (UCMH)





Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

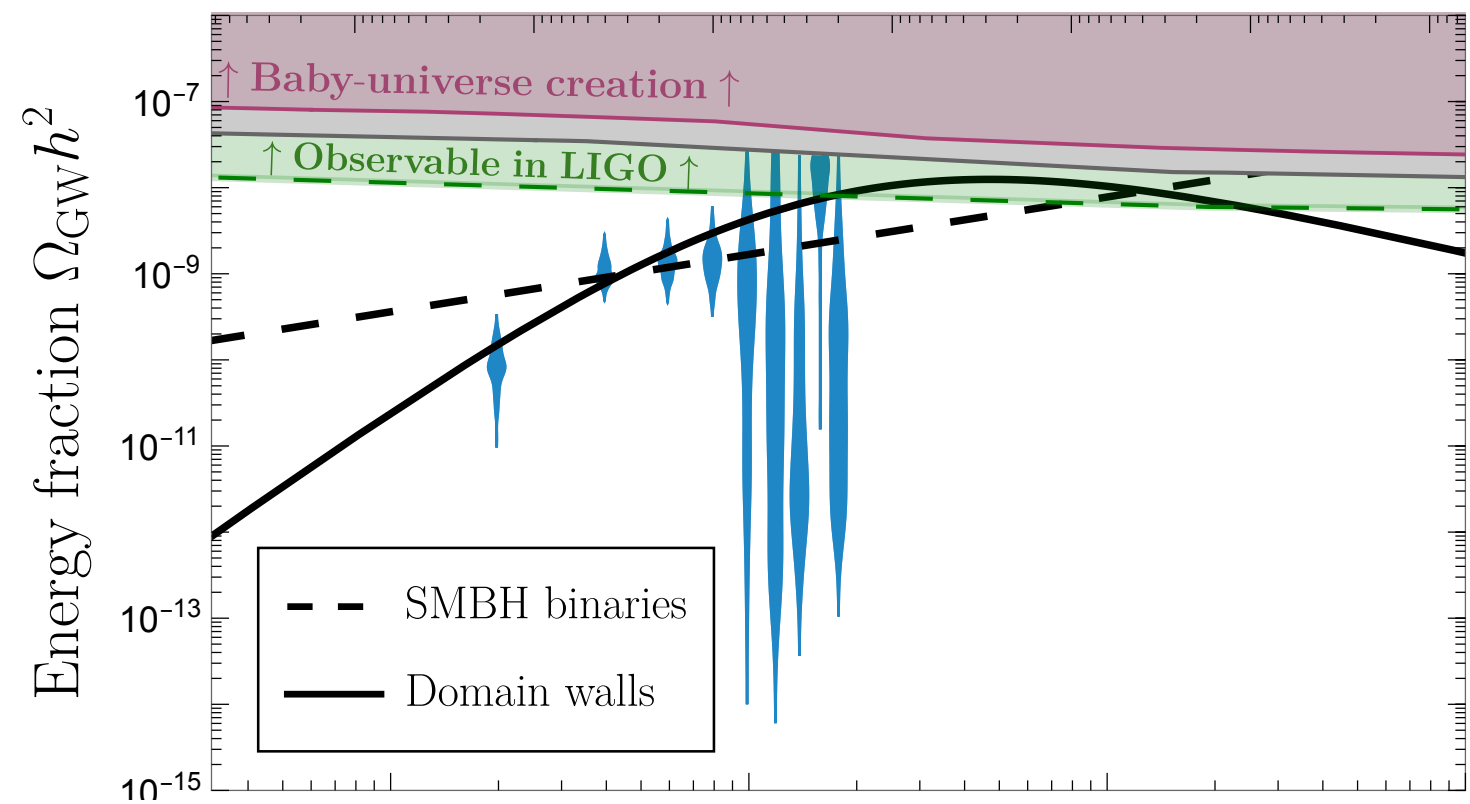
Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

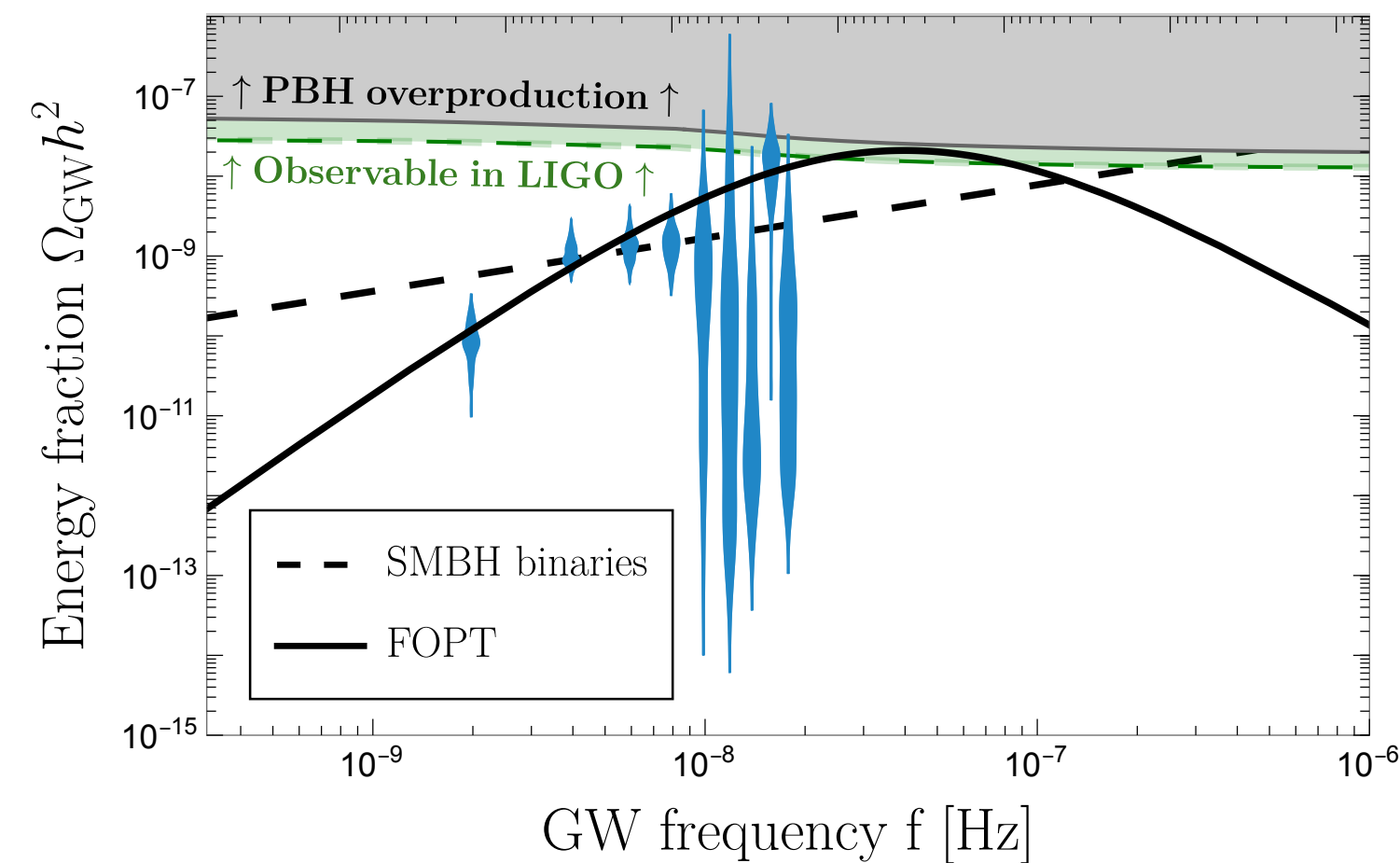
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

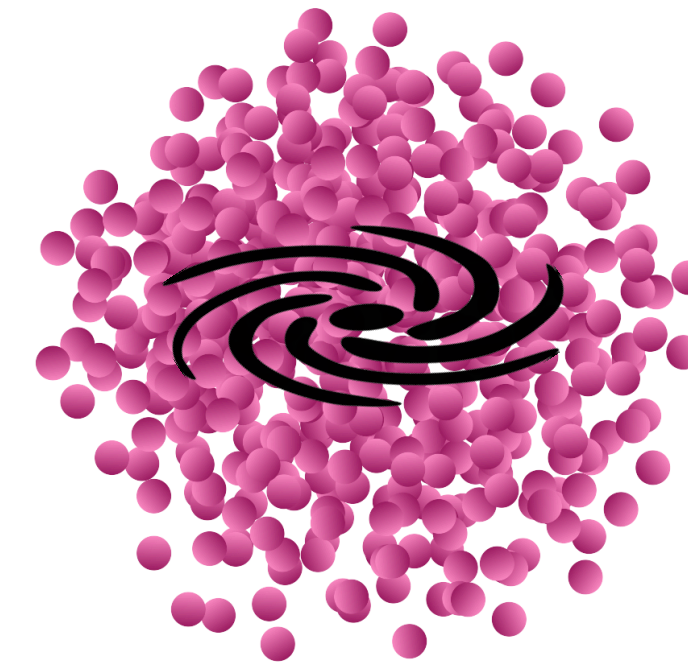
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

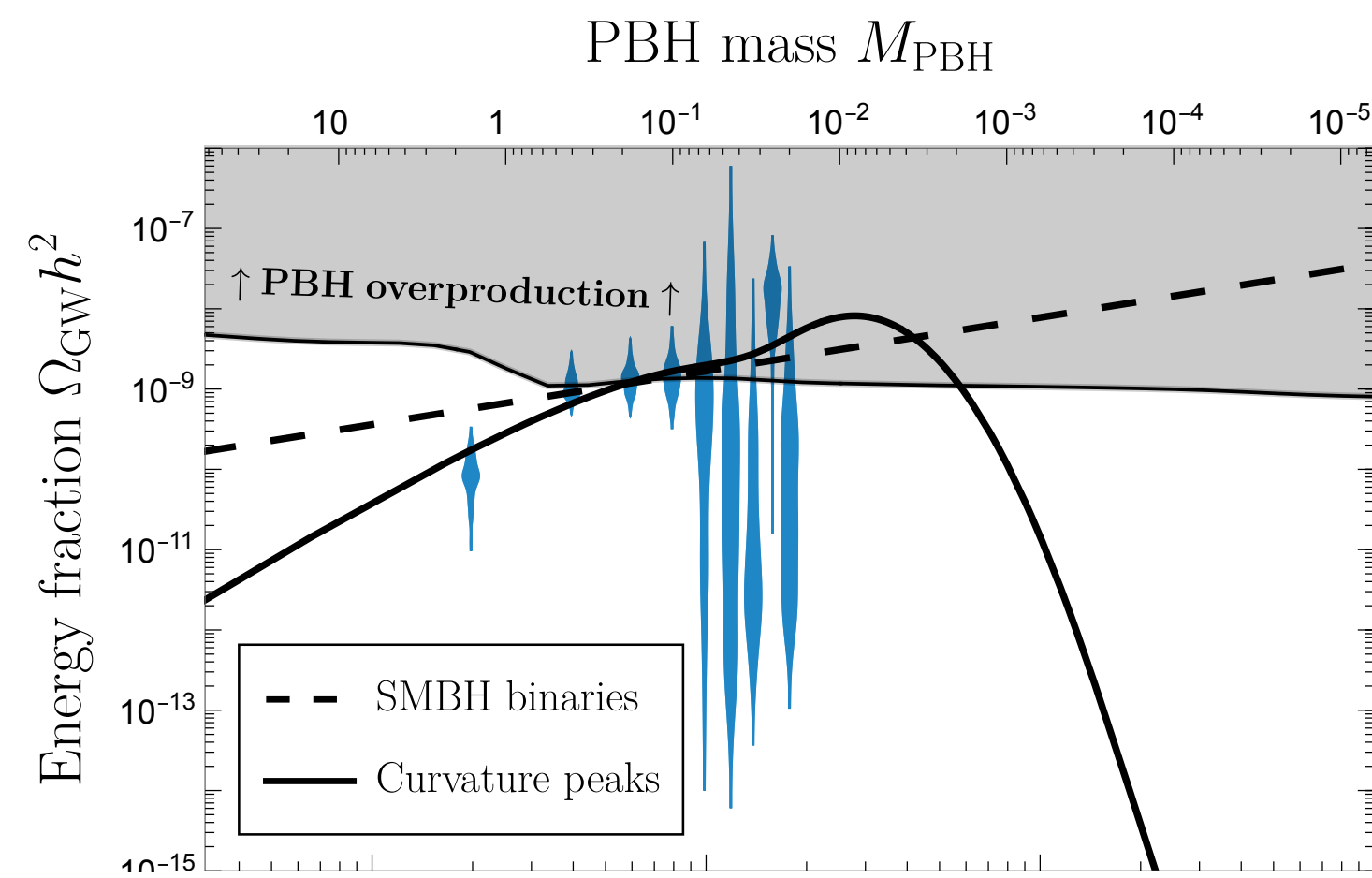
...



DM Ultra Compact Mini Halos

$$R_{\text{UCMH}} \sim 200 \text{ AU} \left(\frac{1000}{z_{\text{collapse}}} \right)$$

$$M_{\text{UCMH}} \sim 10^{-7} M_{\odot}$$



Curvature peaks

Overproduce PBH

Chen, Yuan, Huang (1910.12239)

Kohri, Terada (2009.11853)

Inomata, Kawasaki, Mukaida, Yanagida (2011.01270)

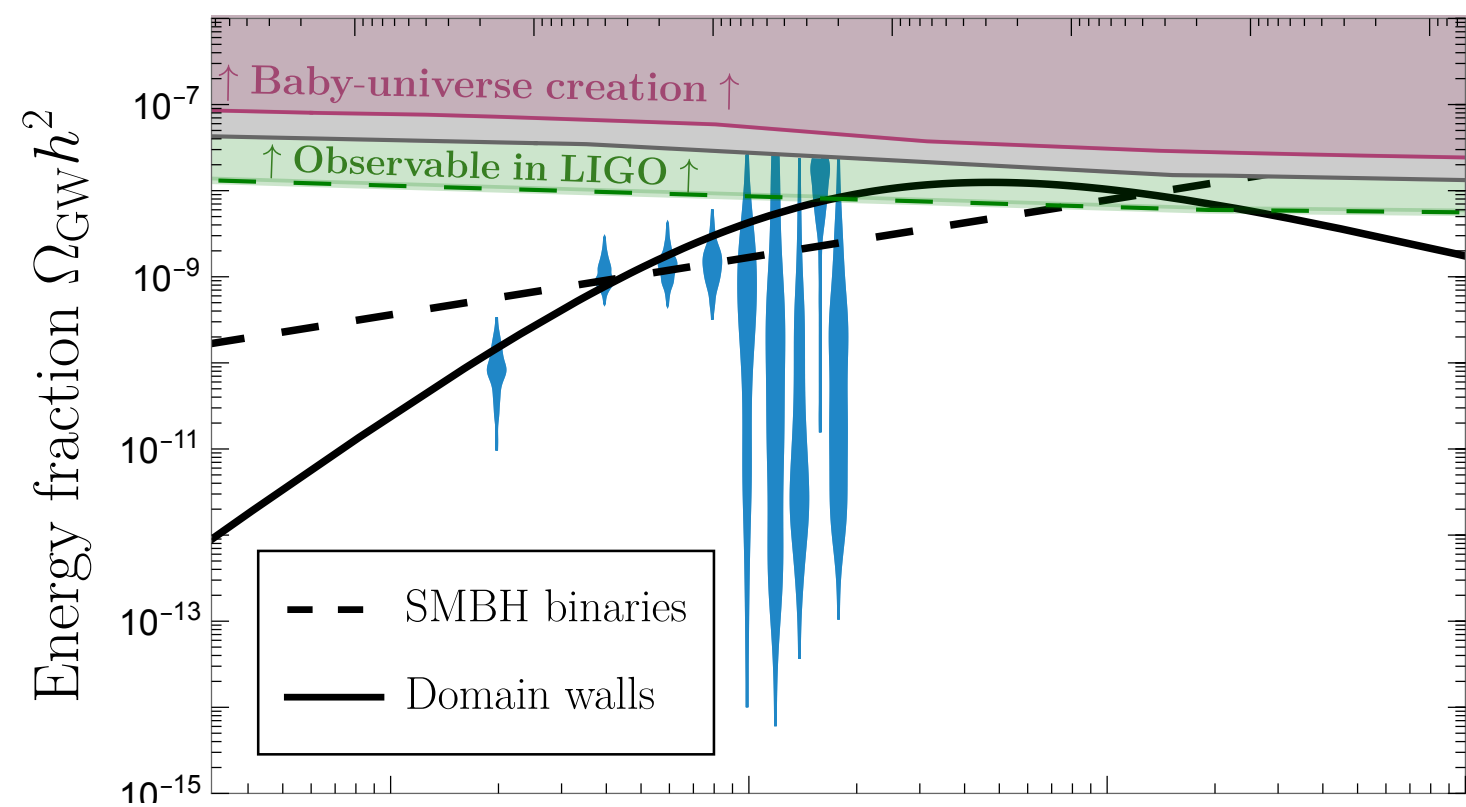
Vaskonen, Veermae (2009.07832),

De Luca, Franciolini, Riotto (2009.08268)

Except if negative non-Gaussianities

Franciolini, Iovino, Vaskonen, Veermae (2306.17143)

YG, Trifinopoulos, Vanvlasselaer (2508.19328)



Domain wall networks

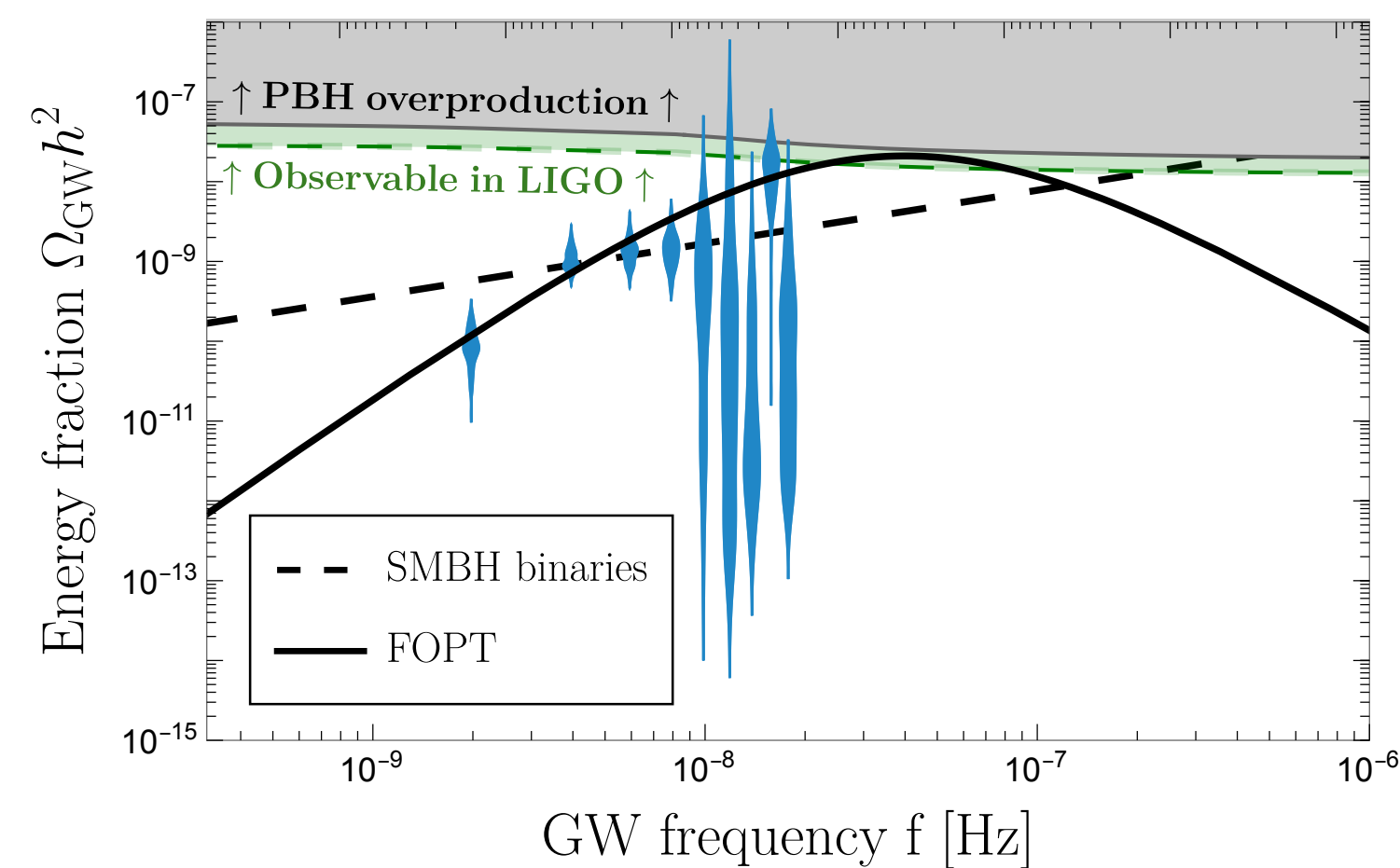
Ferreira, Notari, Pujolas, Rompineve (2204.04228)

Blasi, Mariotti, Rase, Sevrin (2306.17830)

...

Produce solar-mass PBH

YG, Vitagliano 2306.17841



First-order phase transitions

Roper Pol et al. (2201.05630)

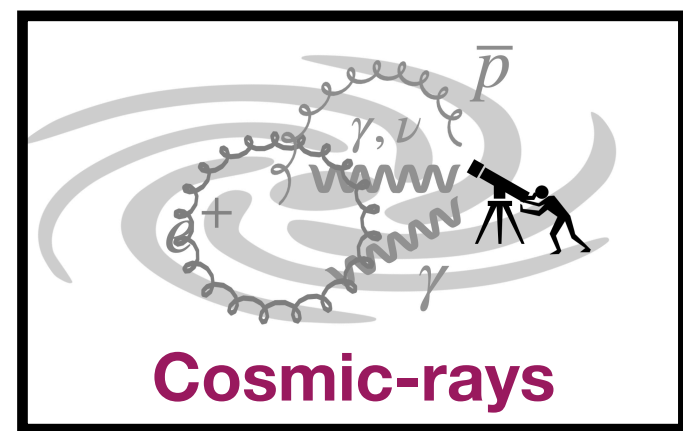
Ghoshal, White et al. (2307.02259)

YG (2307.04239)

Lewicki, Toczek, Vaskonen (2402.04158)

Hoefken Zink et al. (2501.15649)

...



if DM=WIMPs

YG 2503.03857

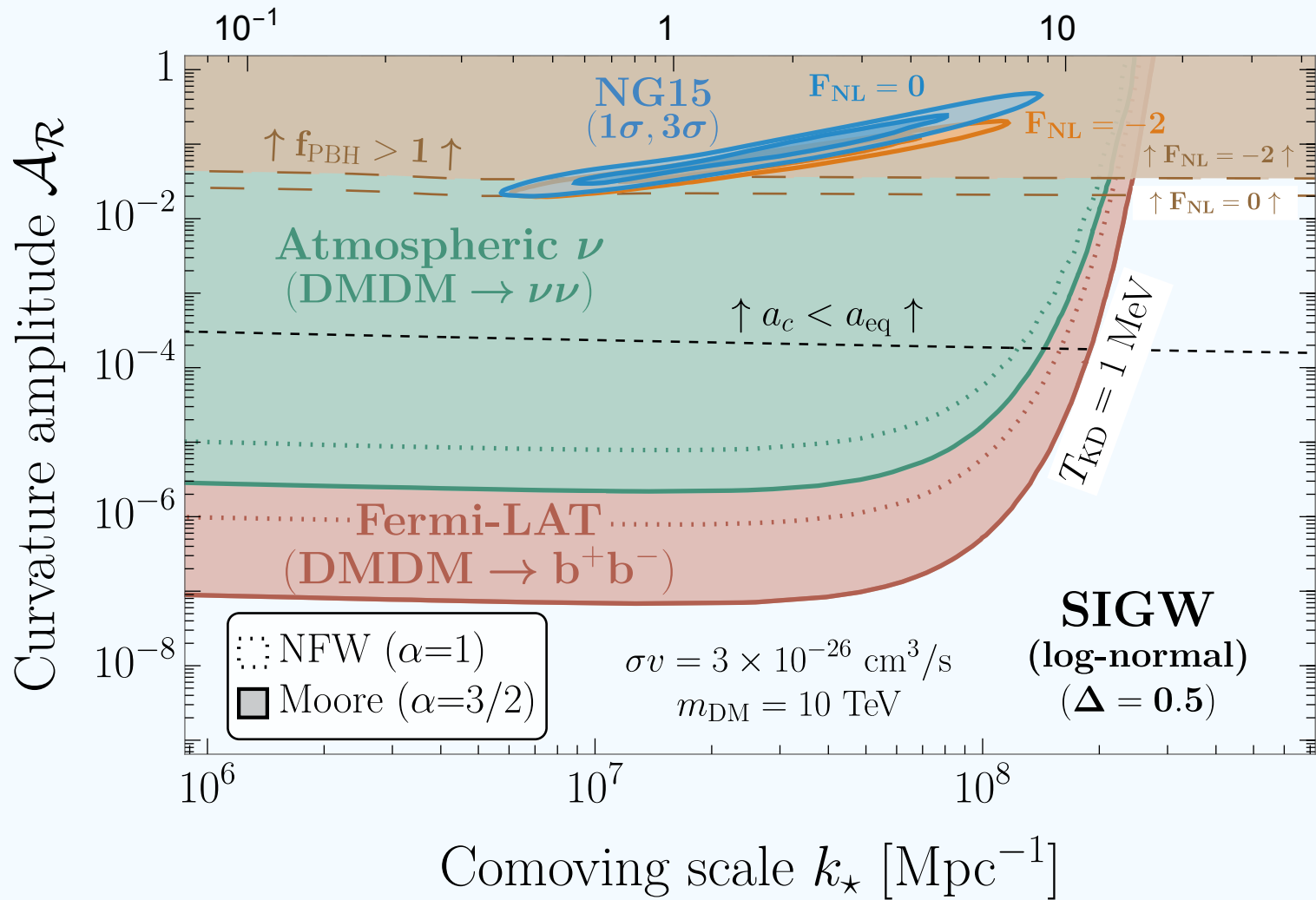


“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Gaussian curvature peaks

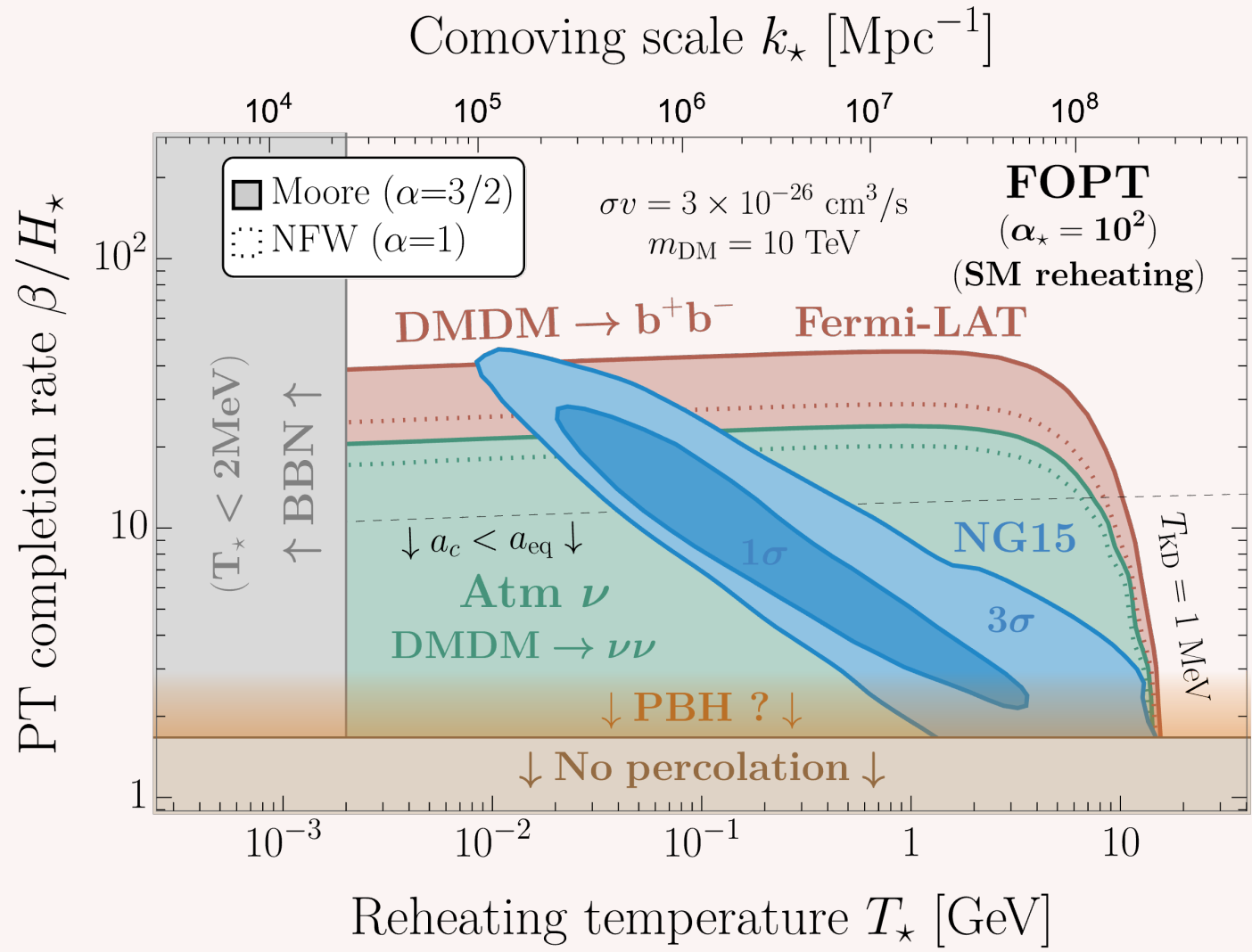
$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_{\star})}{2\Delta^2}\right]$$

Horizon crossing temperature $T_{\star}$ [GeV]



See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)

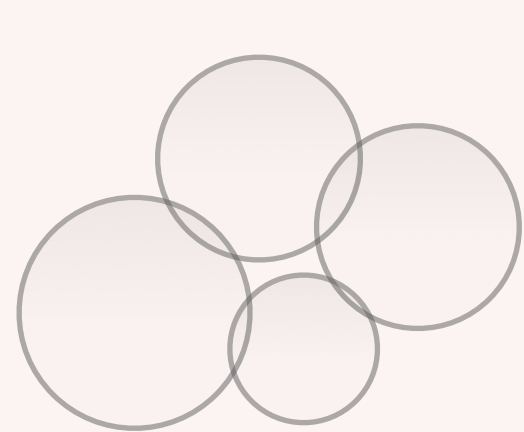
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_{\star}}{1 + \alpha_{\star}} \right)^2 \left(\frac{H_{\star}}{\beta} \right)^2 \frac{a_1 (k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2 \right)^3}$$

Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)



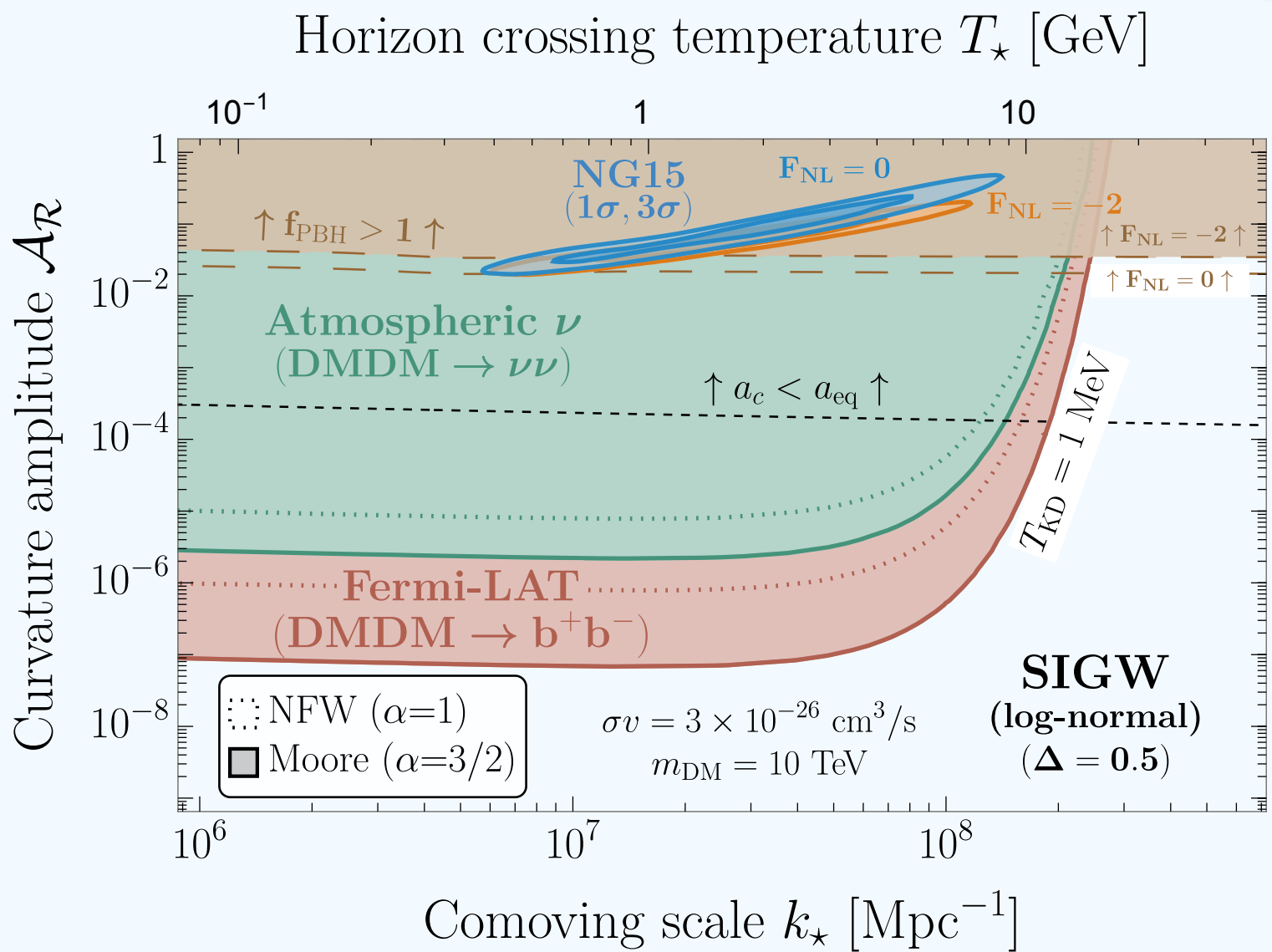
$$k_p = k_{\star}/a_{\star}$$

YG 2503.03857

“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

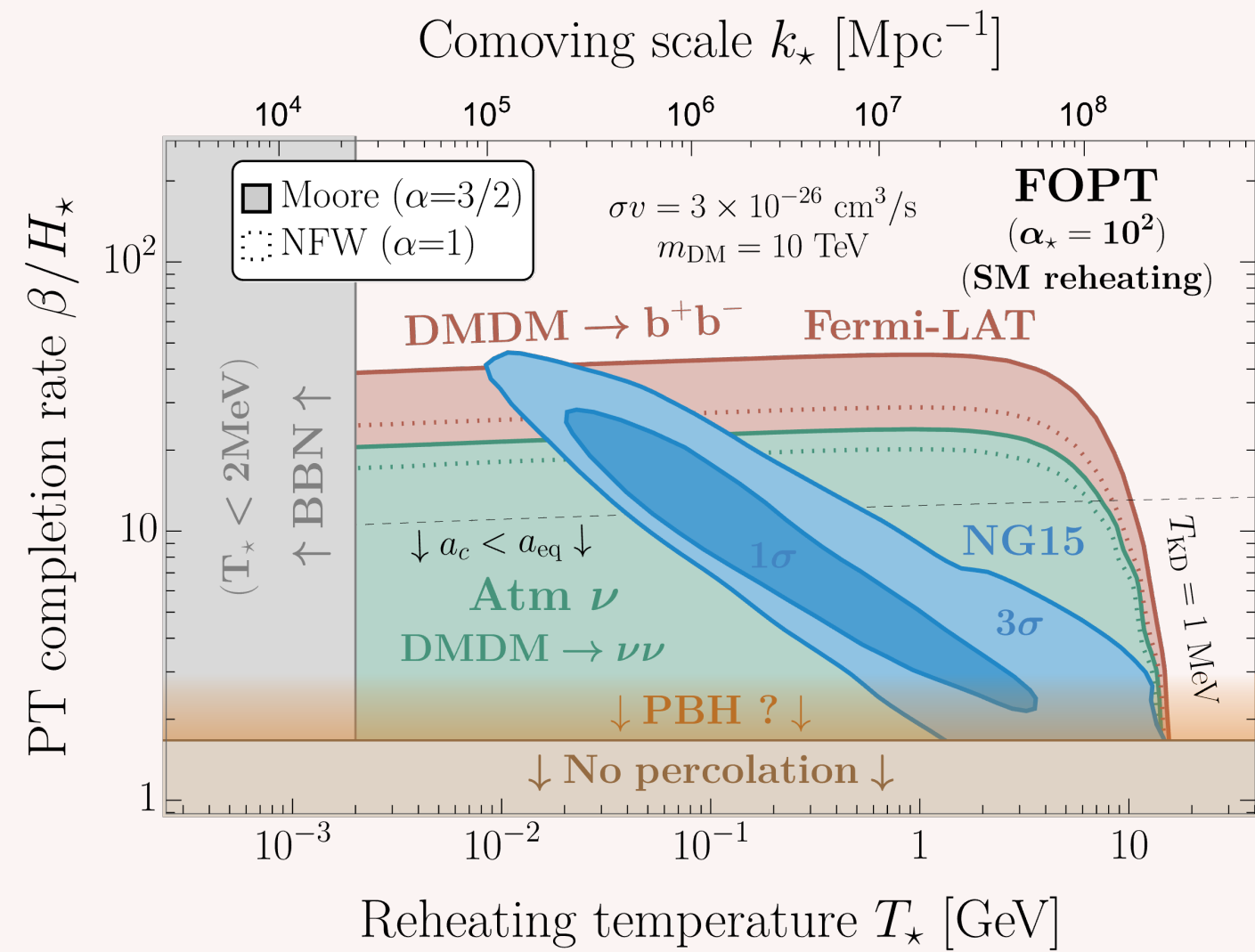
Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp \left[-\frac{\log^2(k/k_{\star})}{2\Delta^2} \right]$$



See also Nakama,
Suyama, Kohri,
Hiroshima (1712.08820)

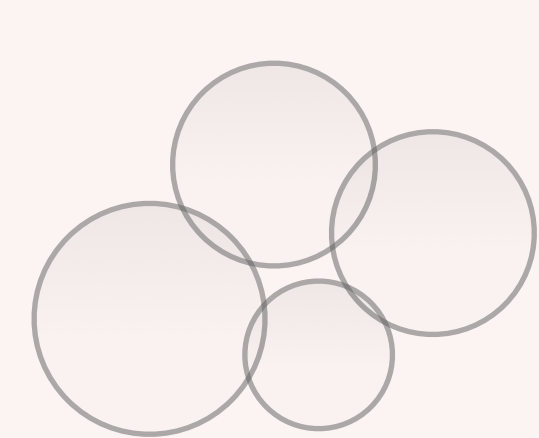
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_\star}{1 + \alpha_\star} \right)^2 \left(\frac{H_\star}{\beta} \right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2 \right)^3}$$

Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)



$$k_p = k_\star/a_\star$$

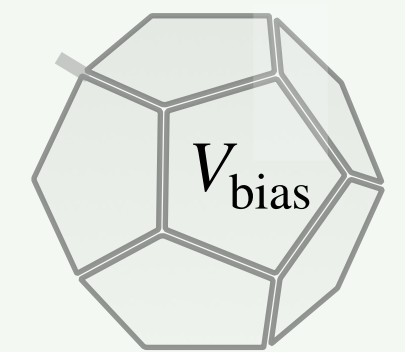
YG 2503.03857

“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2 \right]^2}$$

$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}}$$



$$L_{\text{ann}} \sim t_{\text{ann}}$$

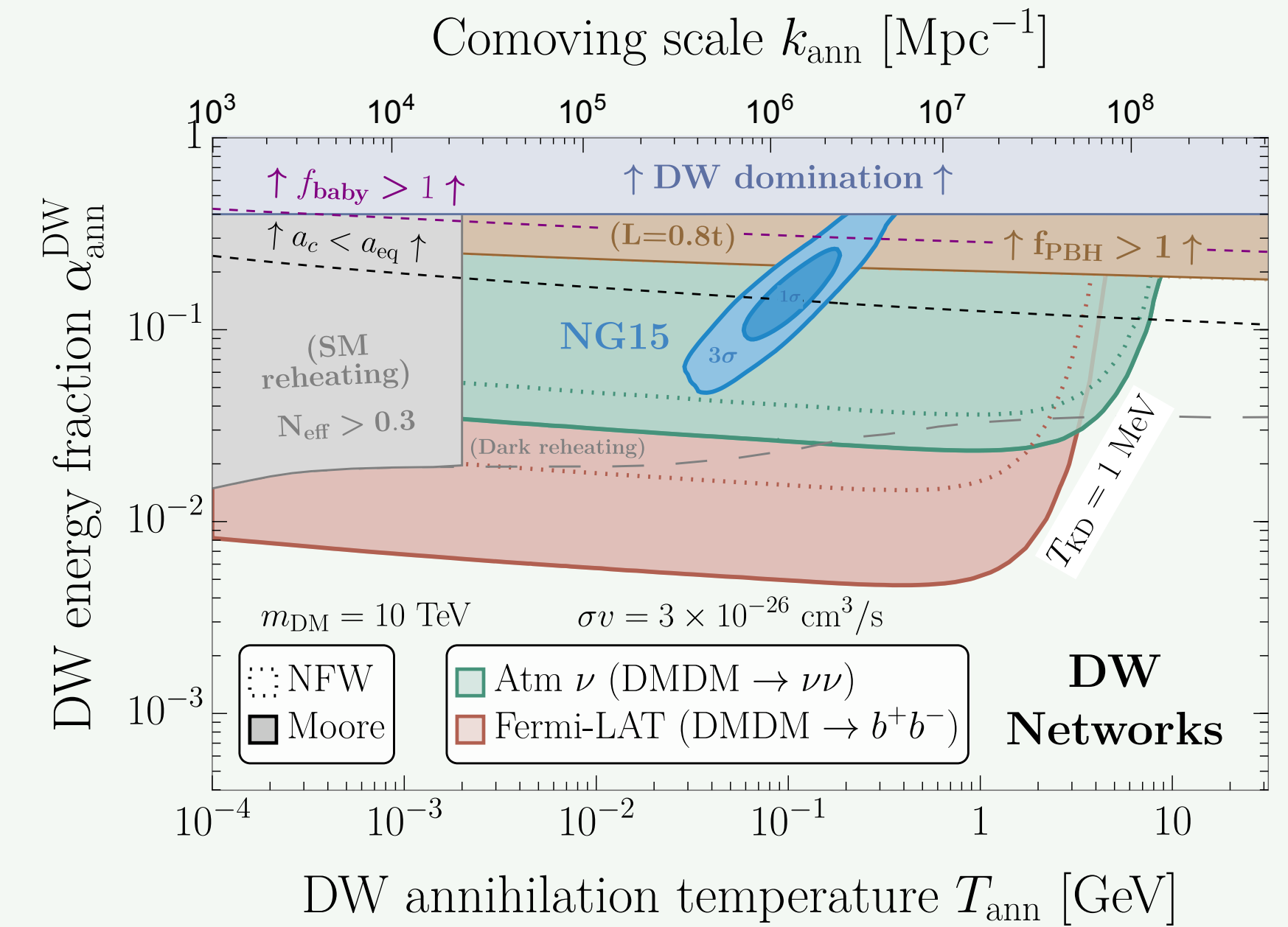
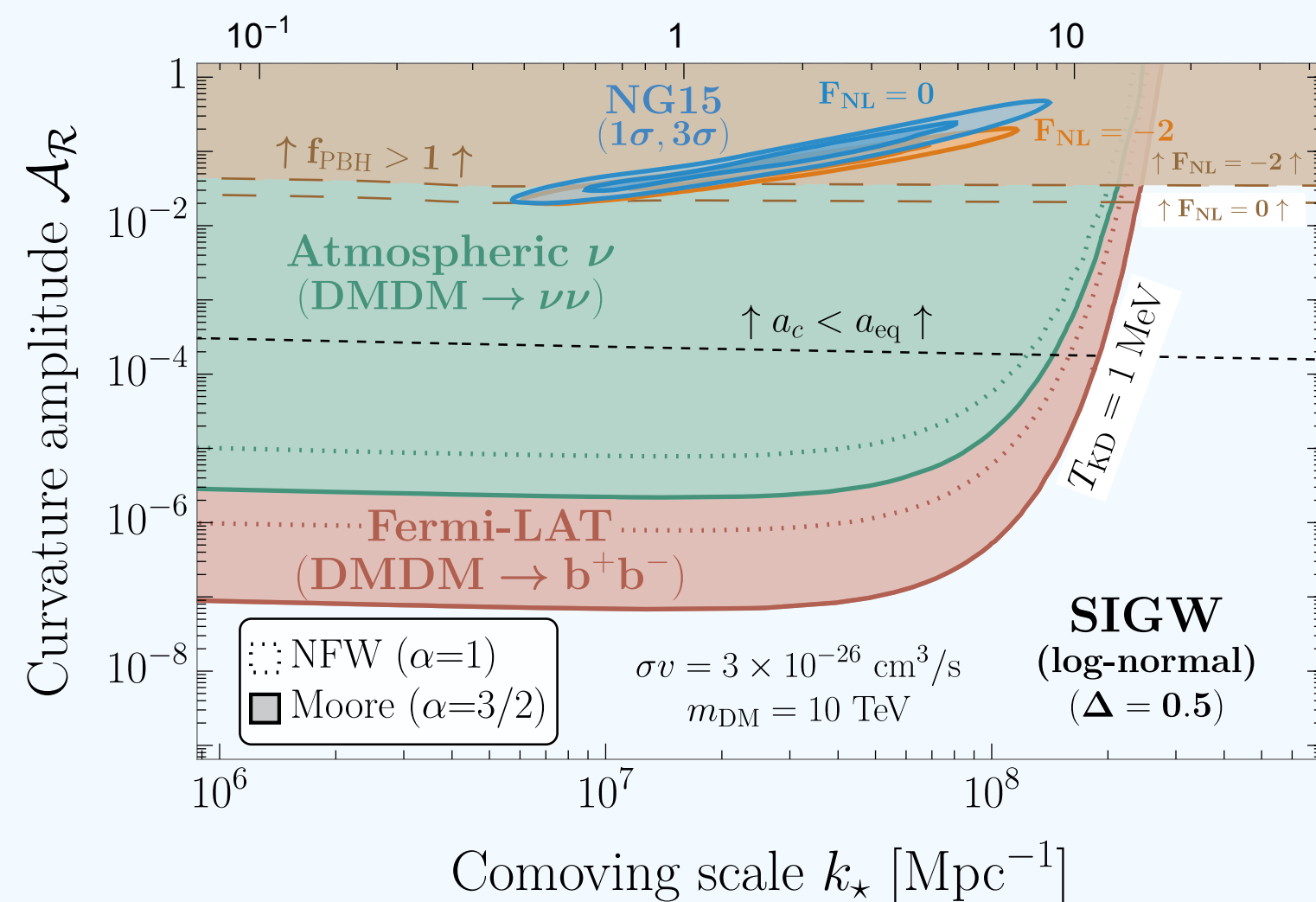
Gaussian curvature peaks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp \left[-\frac{\log^2(k/k_\star)}{2\Delta^2} \right]$$

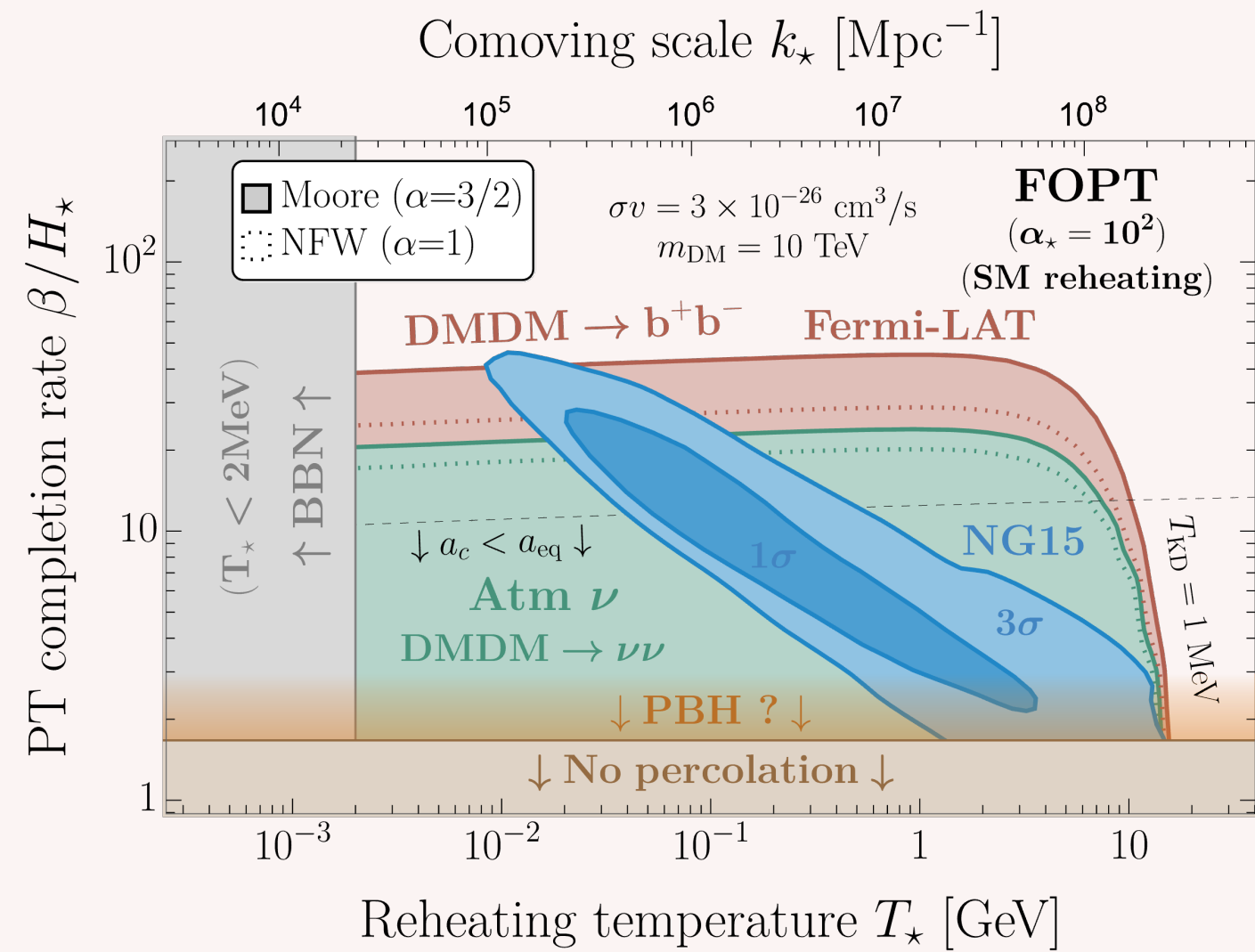
Horizon crossing temperature $T_\star$ [GeV]



See also Nakama,
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Hiroshima (1712.08820)



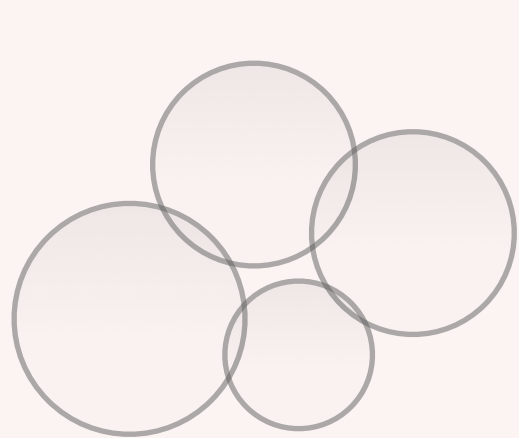
First-order Phase Transition



$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{\alpha_\star}{1 + \alpha_\star}\right)^2 \left(\frac{H_\star}{\beta}\right)^2 \frac{a_1(k_p/\beta)^3}{\left(a_2 + (k_p/\beta)^2\right)^3}$$

Franciolini, YG, Jinno
2503.01962

Elor, Jinno, Kumar,
McGehee, Tsai,
2311.16222 (PRL)



$$k_p = k_\star/a_\star$$

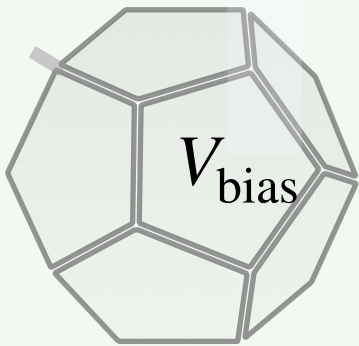
YG 2503.03857

“New Physics Explanations of PTA
signal are incompatible with WIMPs
Dark Matter”

Domain Wall Networks

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\alpha_V^2}{2\pi} \frac{(k_p L_{\text{ann}})^3}{\left[4 + (k_p L_{\text{ann}})^2\right]^2}$$

$$\alpha_V = V_{\text{bias}}/\rho_{\text{rad}} \Big|_{t=t_{\text{ann}}}$$

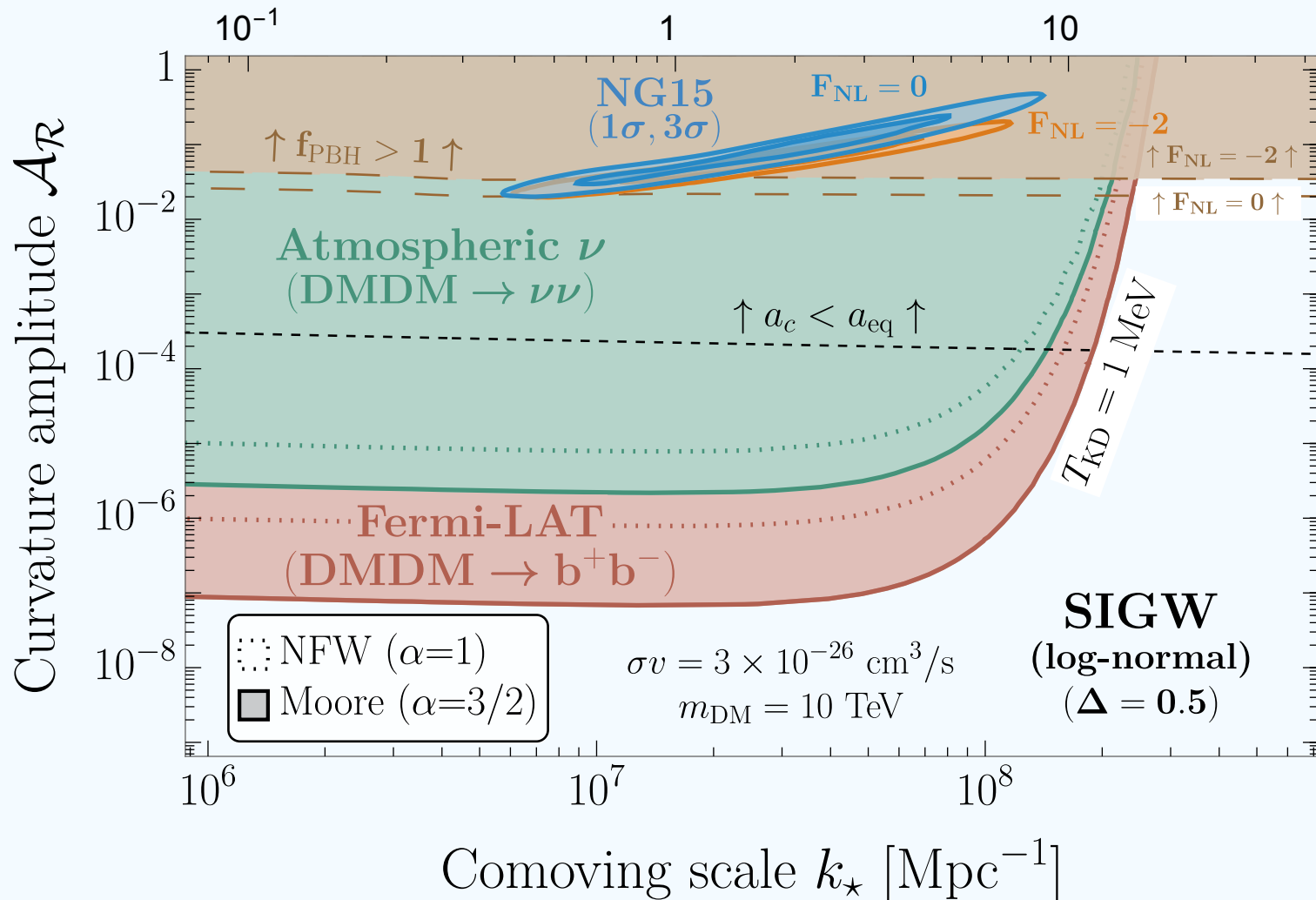


$$L_{\text{ann}} \sim t_{\text{ann}}$$

Gaussian curvature peaks

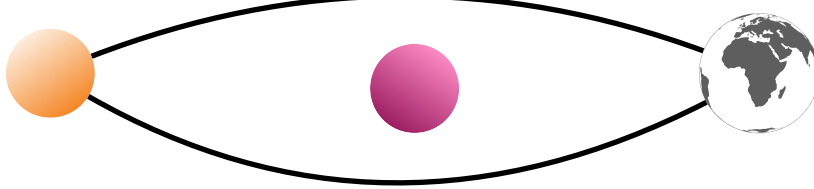
$$\mathcal{P}_{\mathcal{R}}(k) = \frac{\mathcal{A}_{\mathcal{R}}}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\log^2(k/k_\star)}{2\Delta^2}\right]$$

Horizon crossing temperature $T_\star$ [GeV]



Thank you

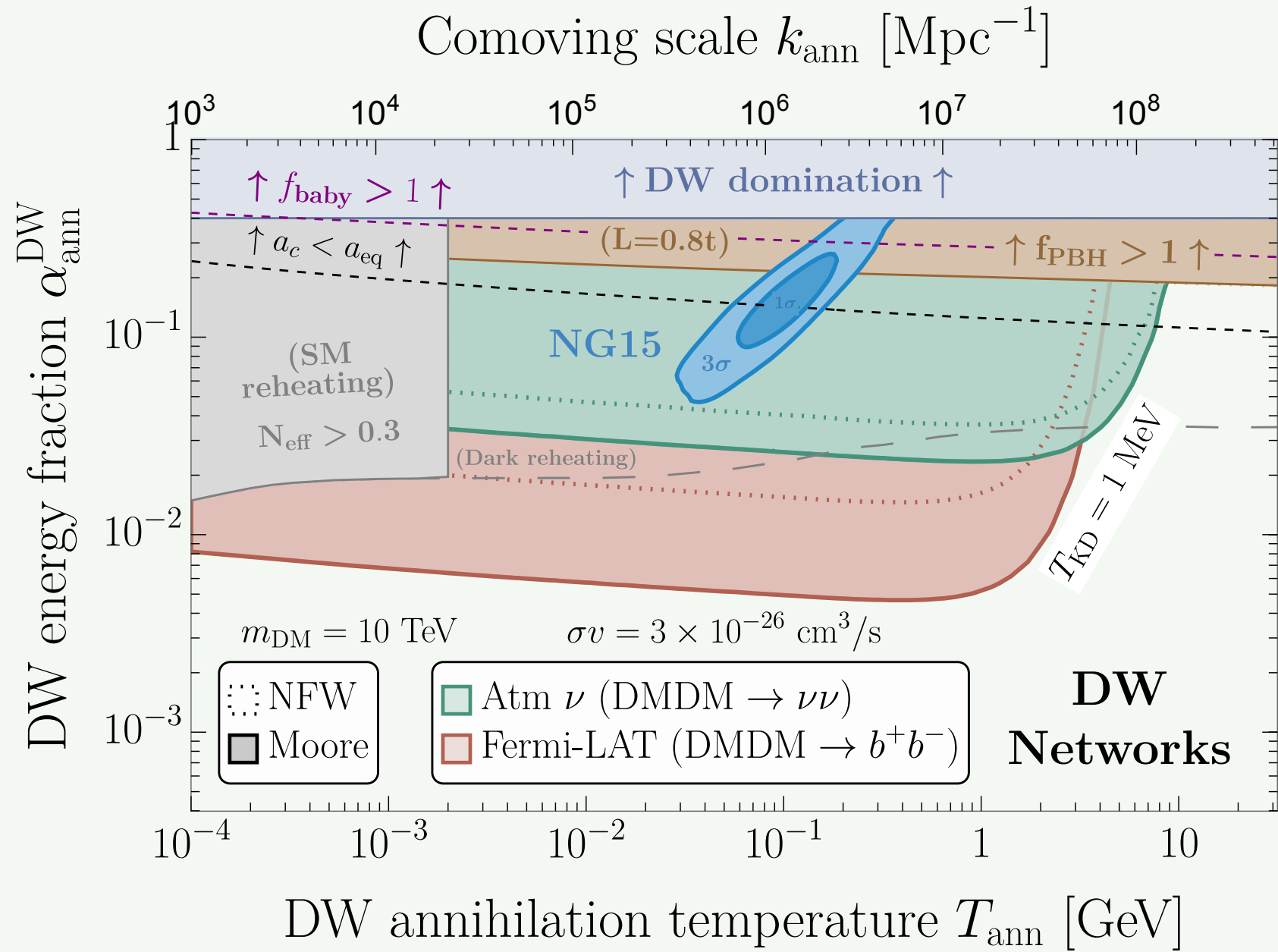
Next step: Get rid of WIMPs
assumption with
Gravitational Lensing



HSC microlensing and
lensed Quasars

(in preparation)

See also Delos, Franciolini 2301.13171



The banner features a red triangle on the left with the text 'MITP SCIENTIFIC PROGRAM'. The background is a stylized illustration of a city at night with a large cathedral and a bridge, under a sky with concentric circles and black holes.

MITP
SCIENTIFIC
PROGRAM

The Phenomenology of Primordial Black Holes



July 20 – 31, 2026

<https://indico.mitp.uni-mainz.de/event/452/>

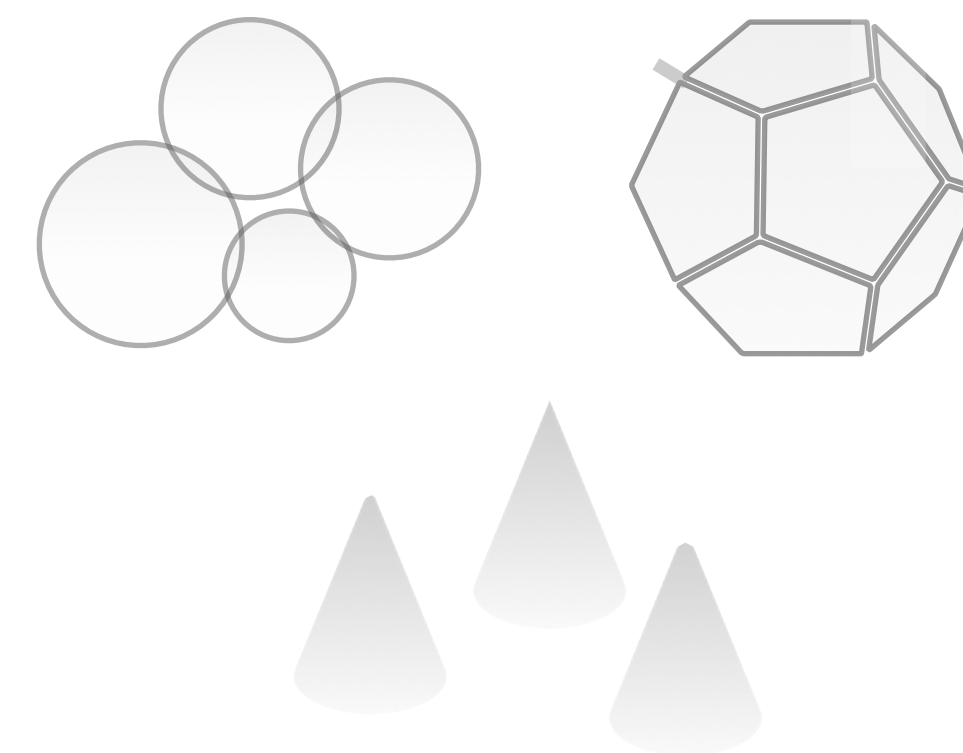
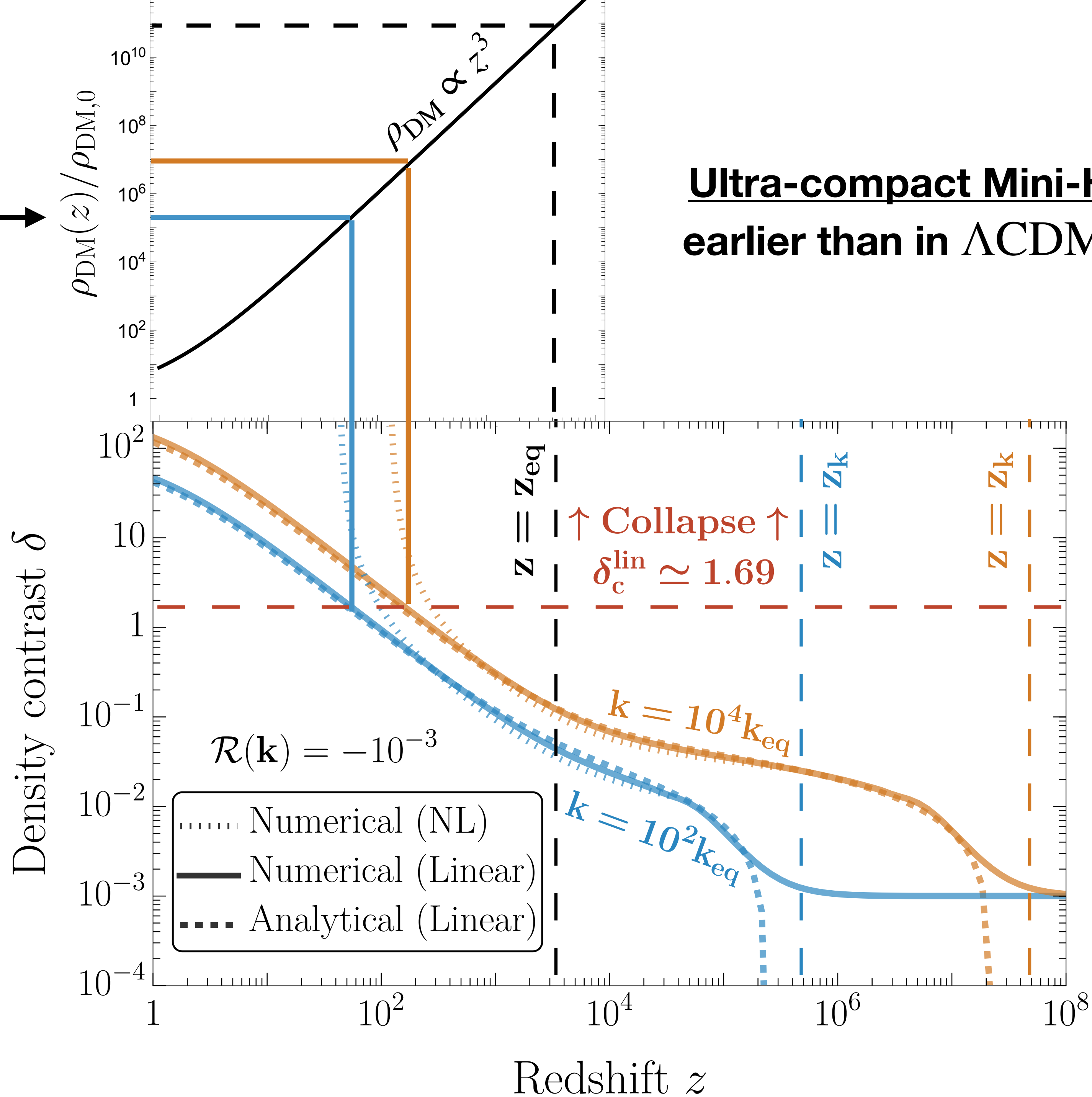
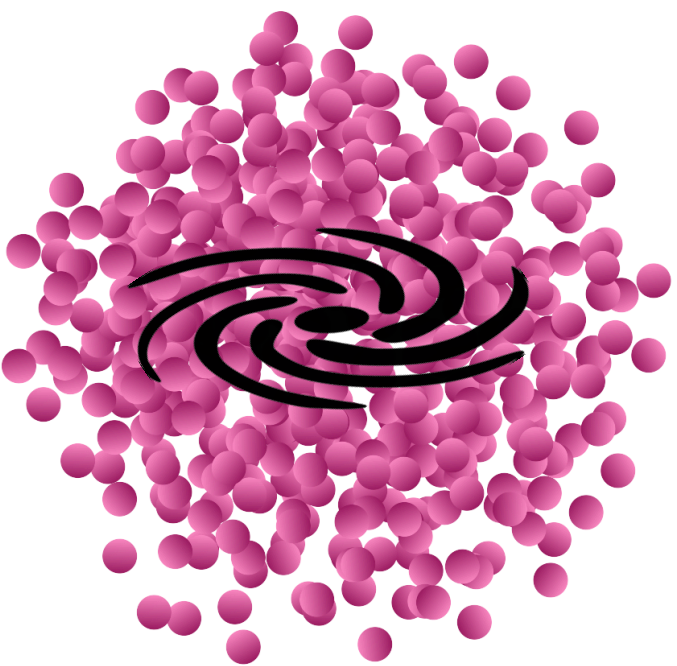
mitp
Mainz Institute for
Theoretical Physics

Organized by Michael Baker, Christian Byrnes, Joaquim Iguaz Juan, Andrea Thamm, and Yann Gouttenoire

Register here until 20 March 2026

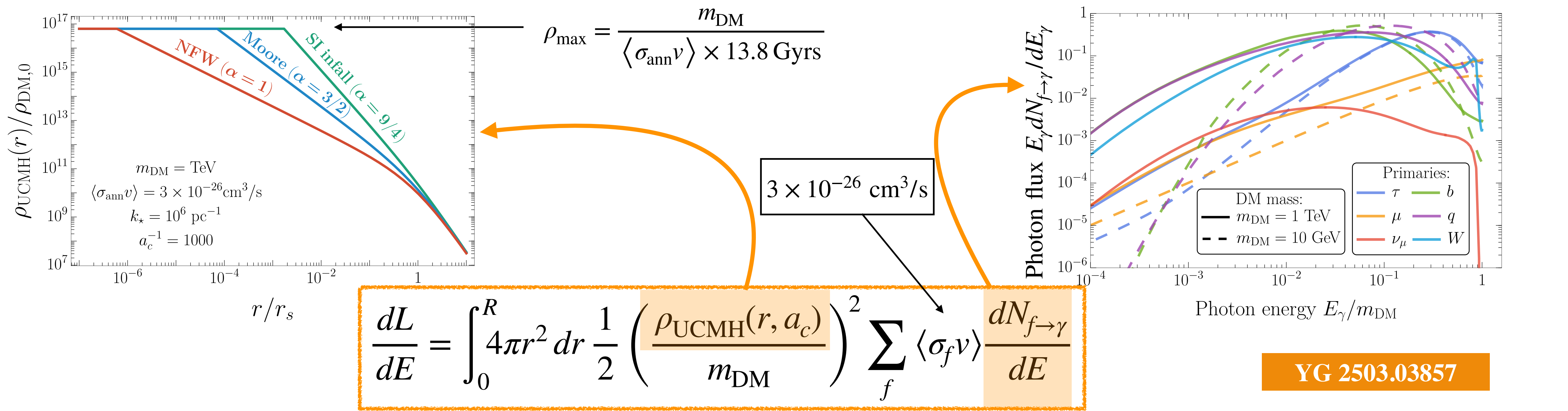
$$\rho_{\odot} \simeq 0.3 \text{ GeV/cm}^3$$

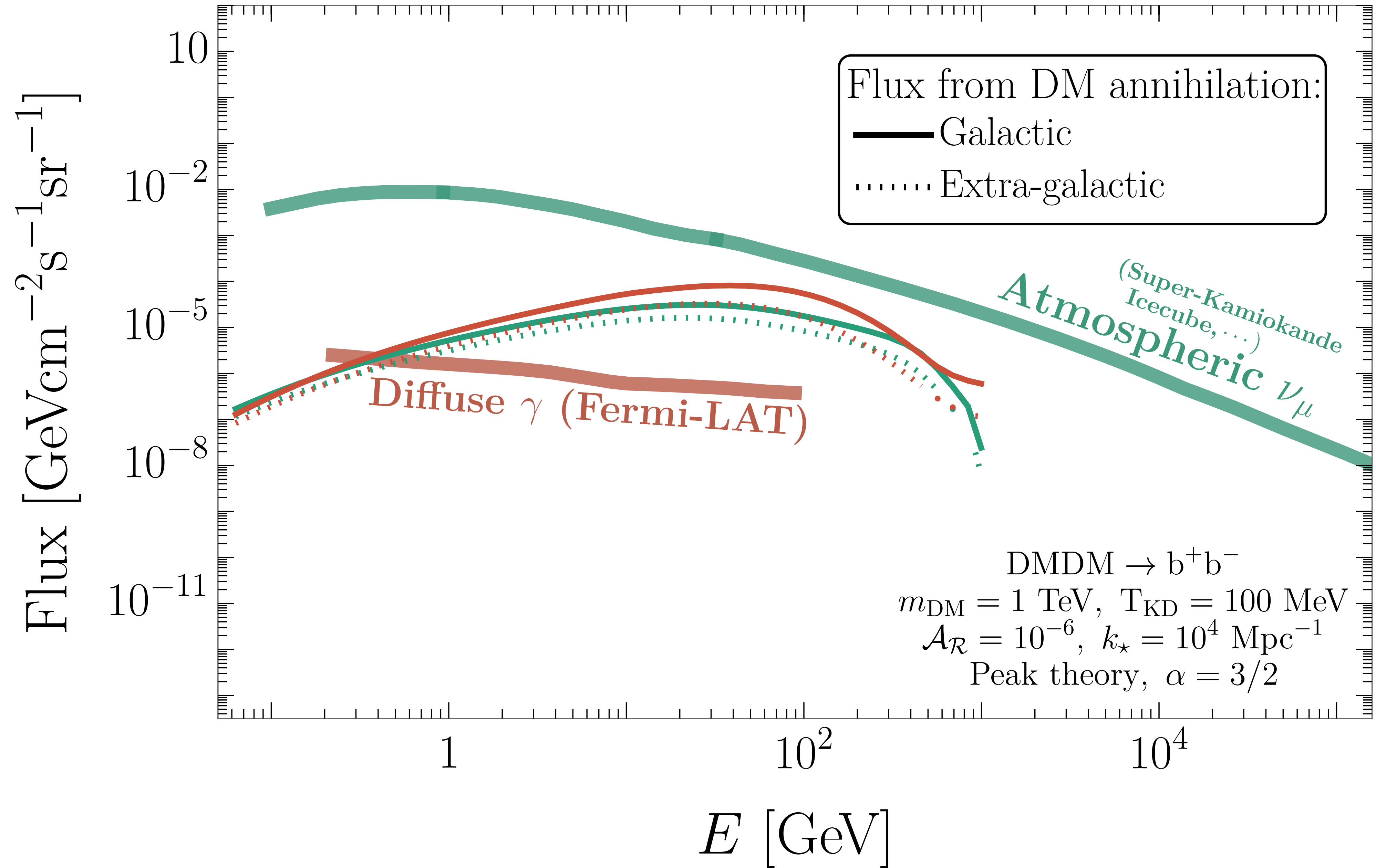
$$\simeq 2 \times 10^5 \rho_{\text{DM},0}$$

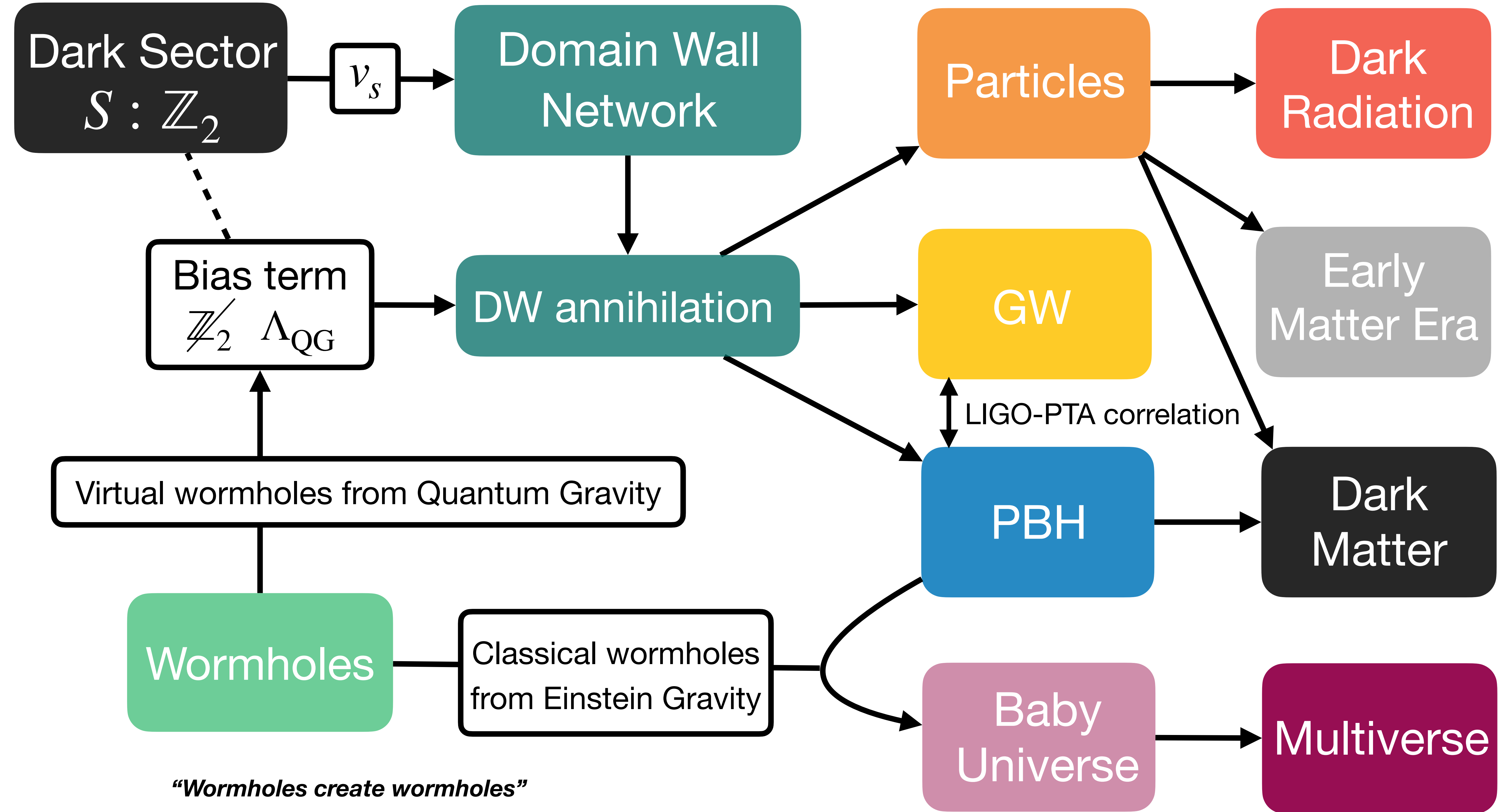


$$\delta(k, t_H) \simeq \frac{4}{9} \mathcal{R}(k)$$

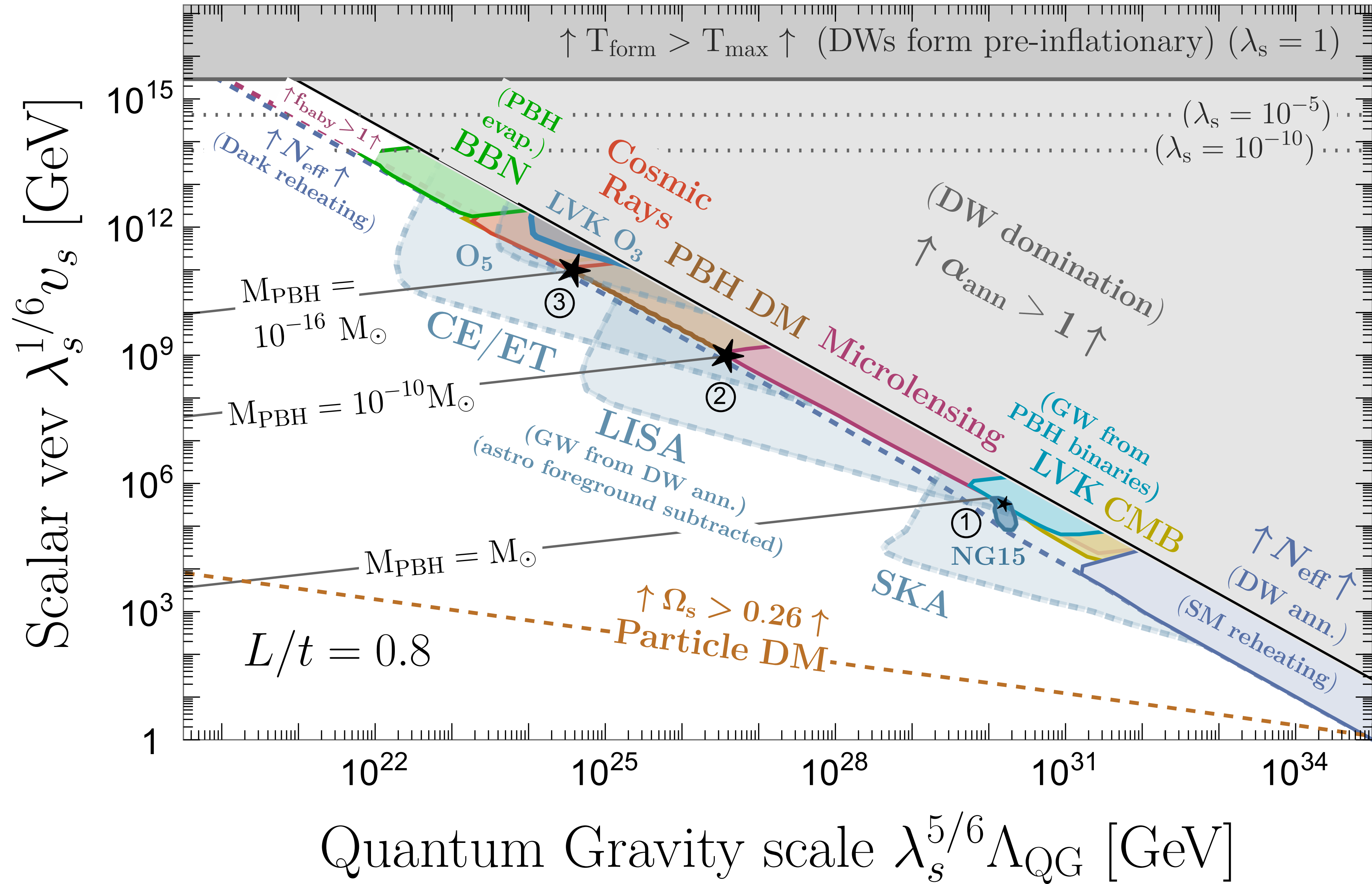
$$\delta_{\Lambda\text{CDM}} \simeq \frac{4}{9} \sqrt{\mathcal{P}_{\mathcal{R}}} \simeq 2 \times 10^{-5}$$







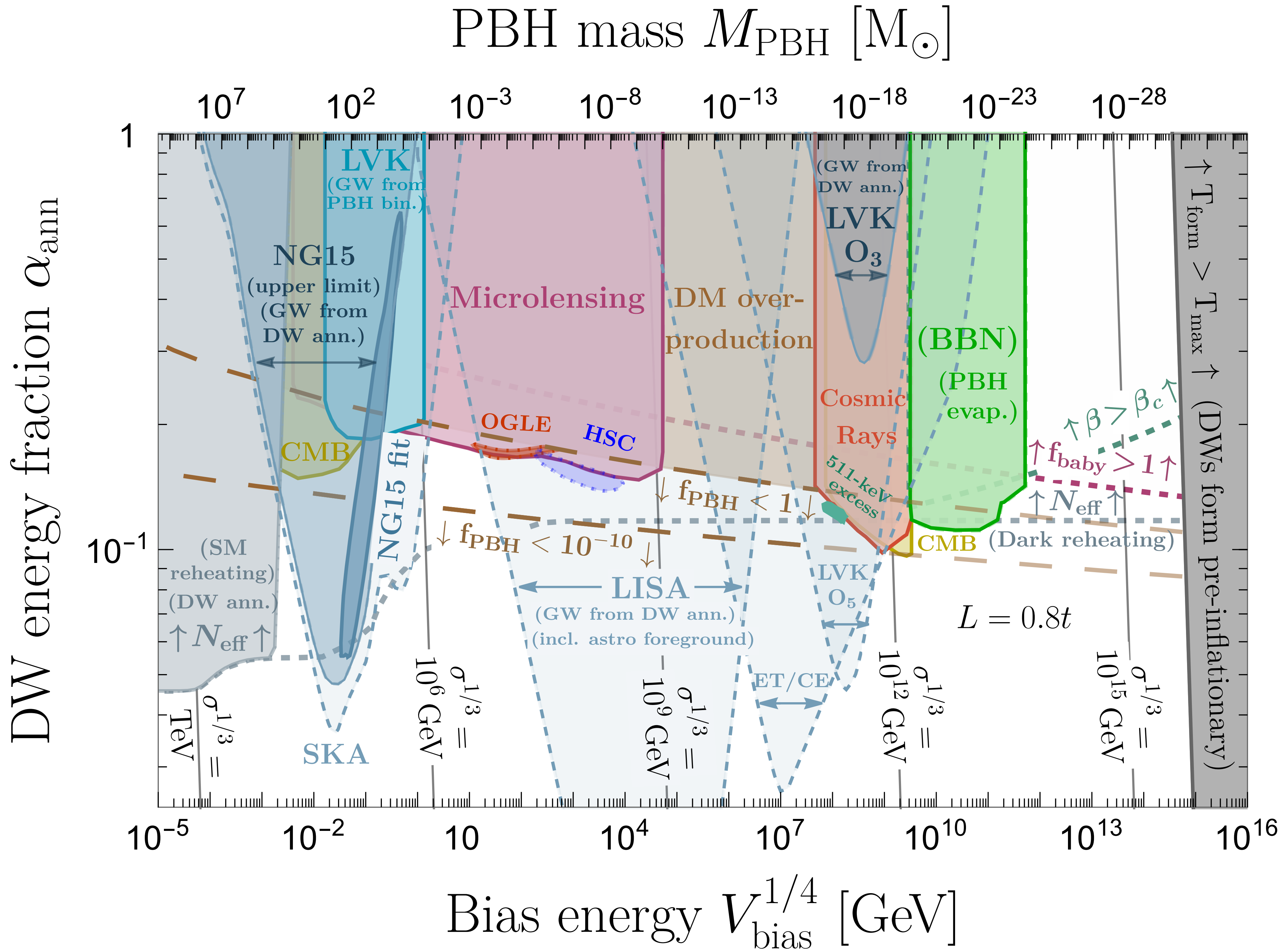
Domain wall networks biased by Quantum Gravity



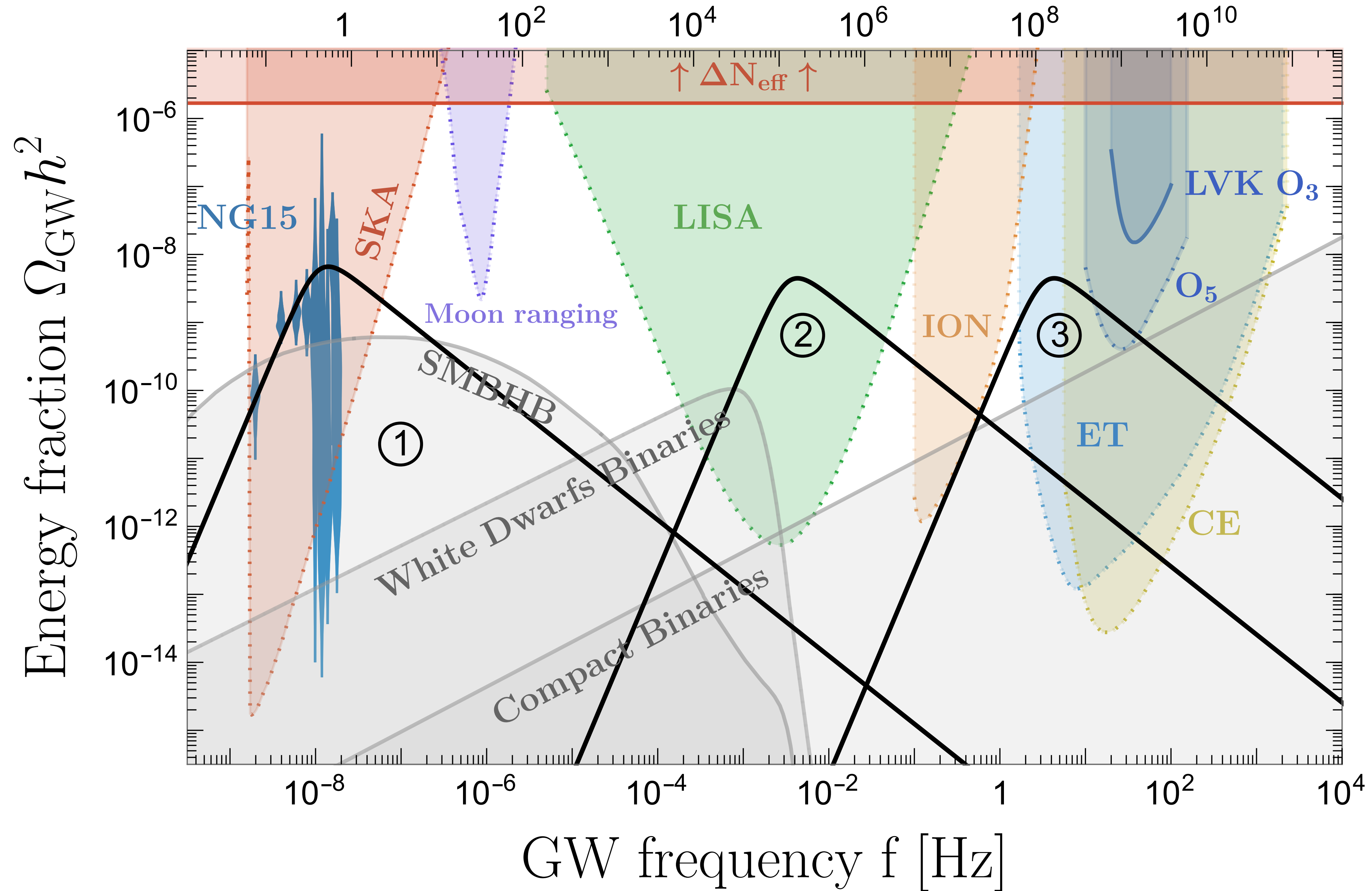
$$\sigma \simeq \frac{4}{3} \sqrt{\frac{\lambda_s}{2}} v_s^3$$

$$V_{\text{bias}} \simeq \frac{v_s^5}{\Lambda_{\text{QG}}}$$

$$\alpha_{\text{ann}} \simeq \lambda_s \frac{v_s \Lambda_{\text{QG}}}{M_{\text{pl}}^2}$$



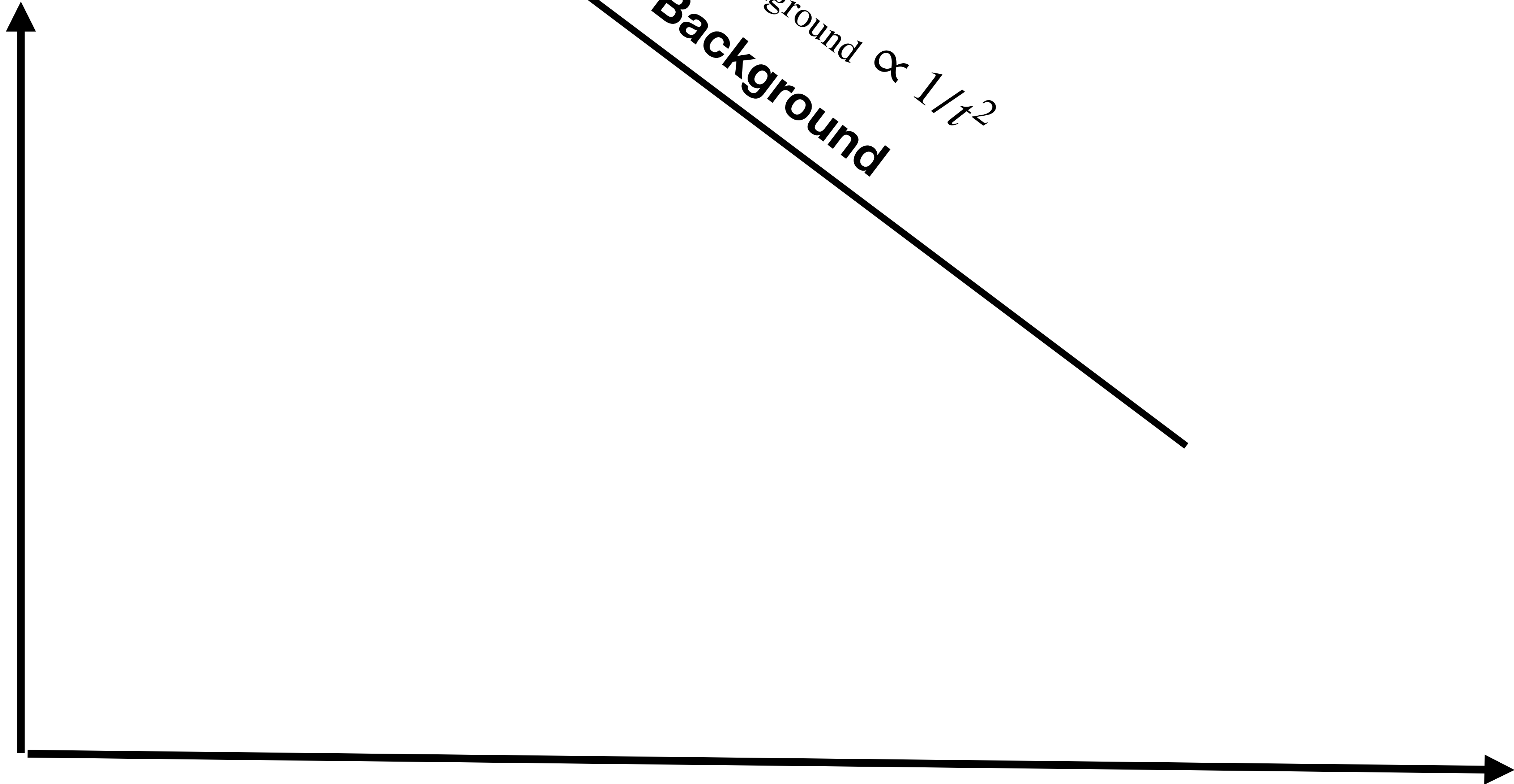
DW annihilation temperature T_{ann} [GeV]



Energy density

$\rho_{\text{background}} \propto 1/t^2$
Background

t



Energy density

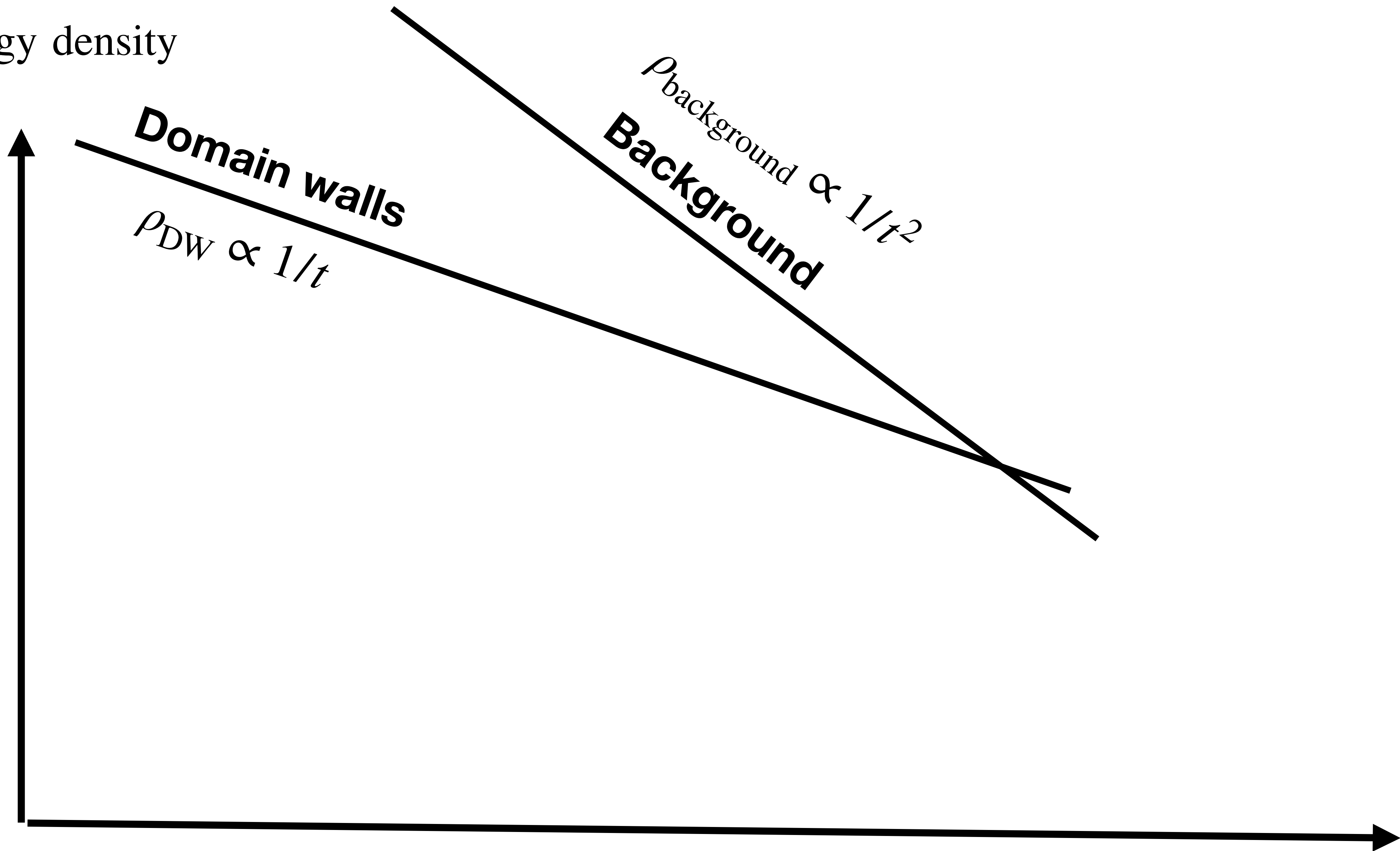
Domain walls

$\rho_{DW} \propto 1/t$

Background

$\rho_{\text{background}} \propto 1/t^2$

t



Energy density

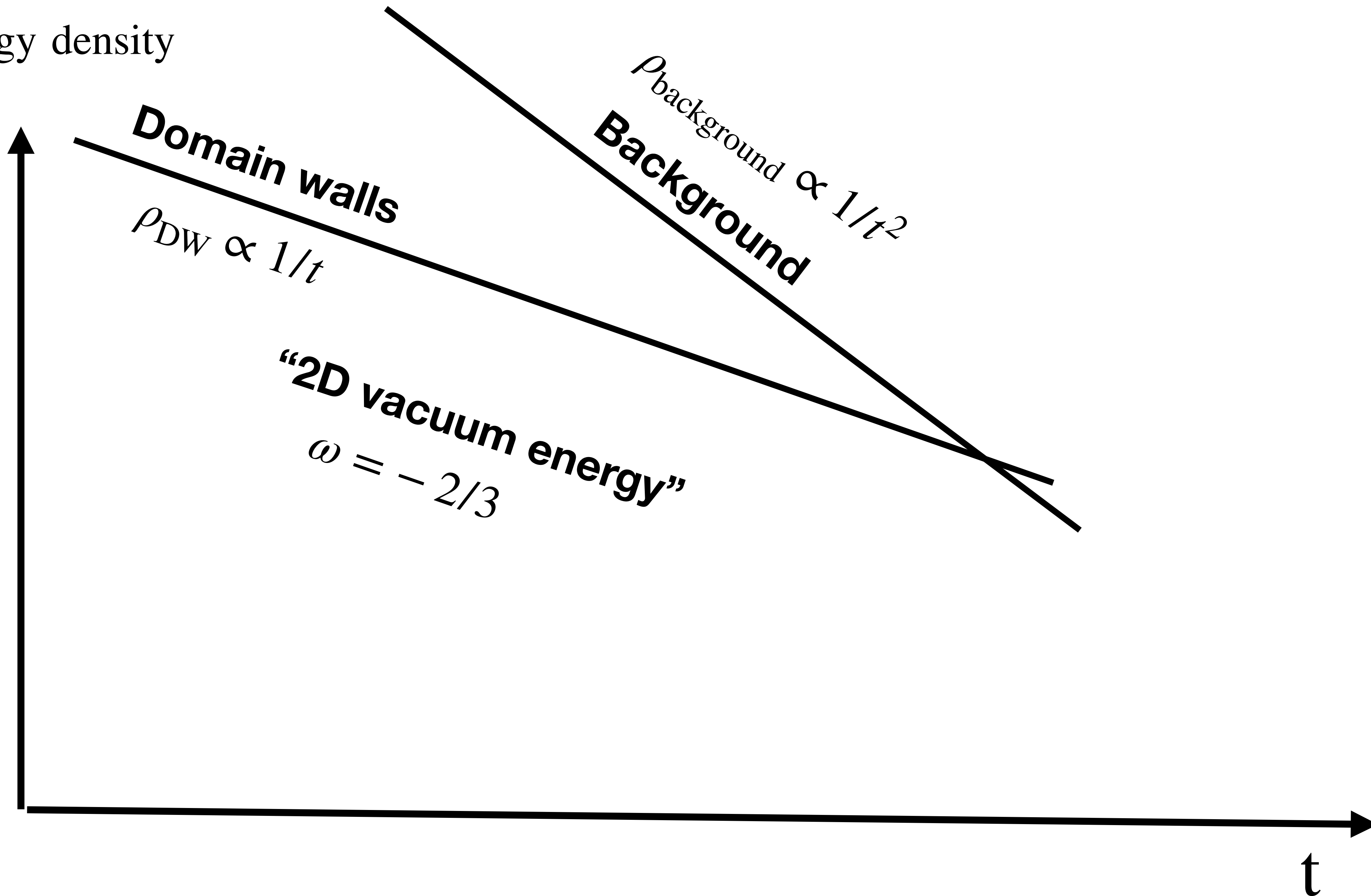
Domain walls

$$\rho_{DW} \propto 1/t$$

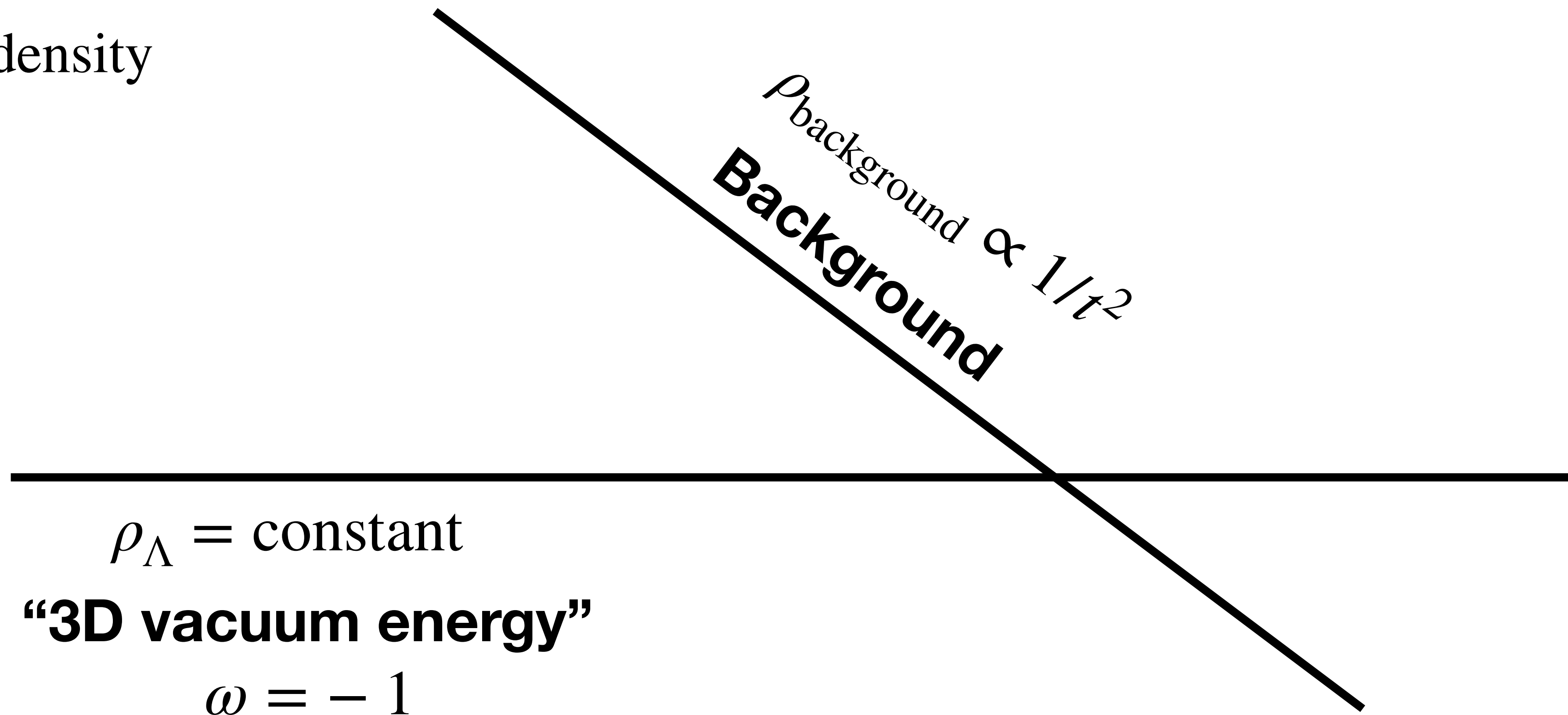
$\rho_{\text{background}} \propto 1/t^2$
Background

“2D vacuum energy”
 $\omega = -2/3$

t



Energy density



t

Energy density

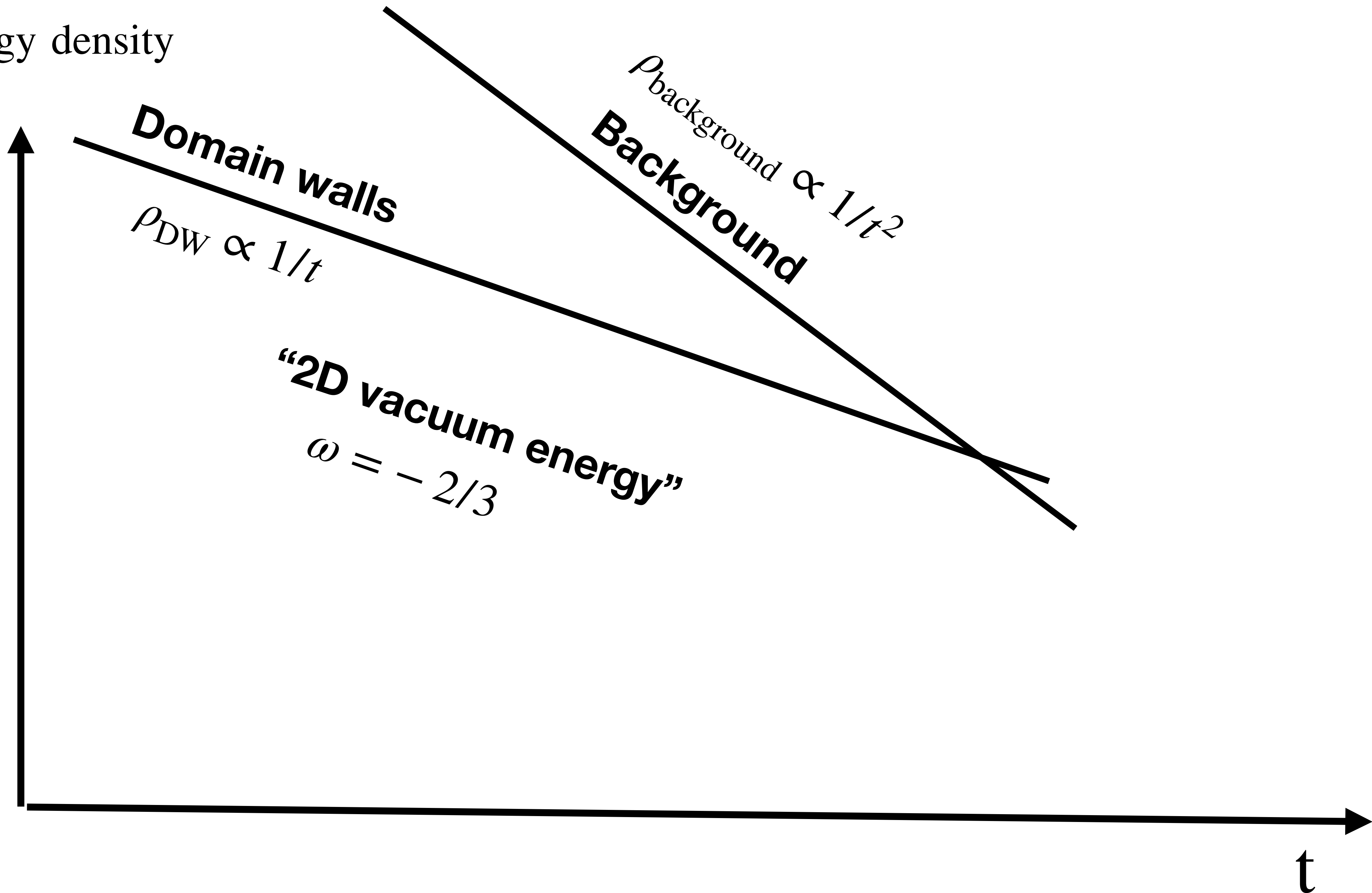
Domain walls

$$\rho_{DW} \propto 1/t$$

$\rho_{\text{background}} \propto 1/t^2$
Background

“2D vacuum energy”
 $\omega = -2/3$

t



Energy density

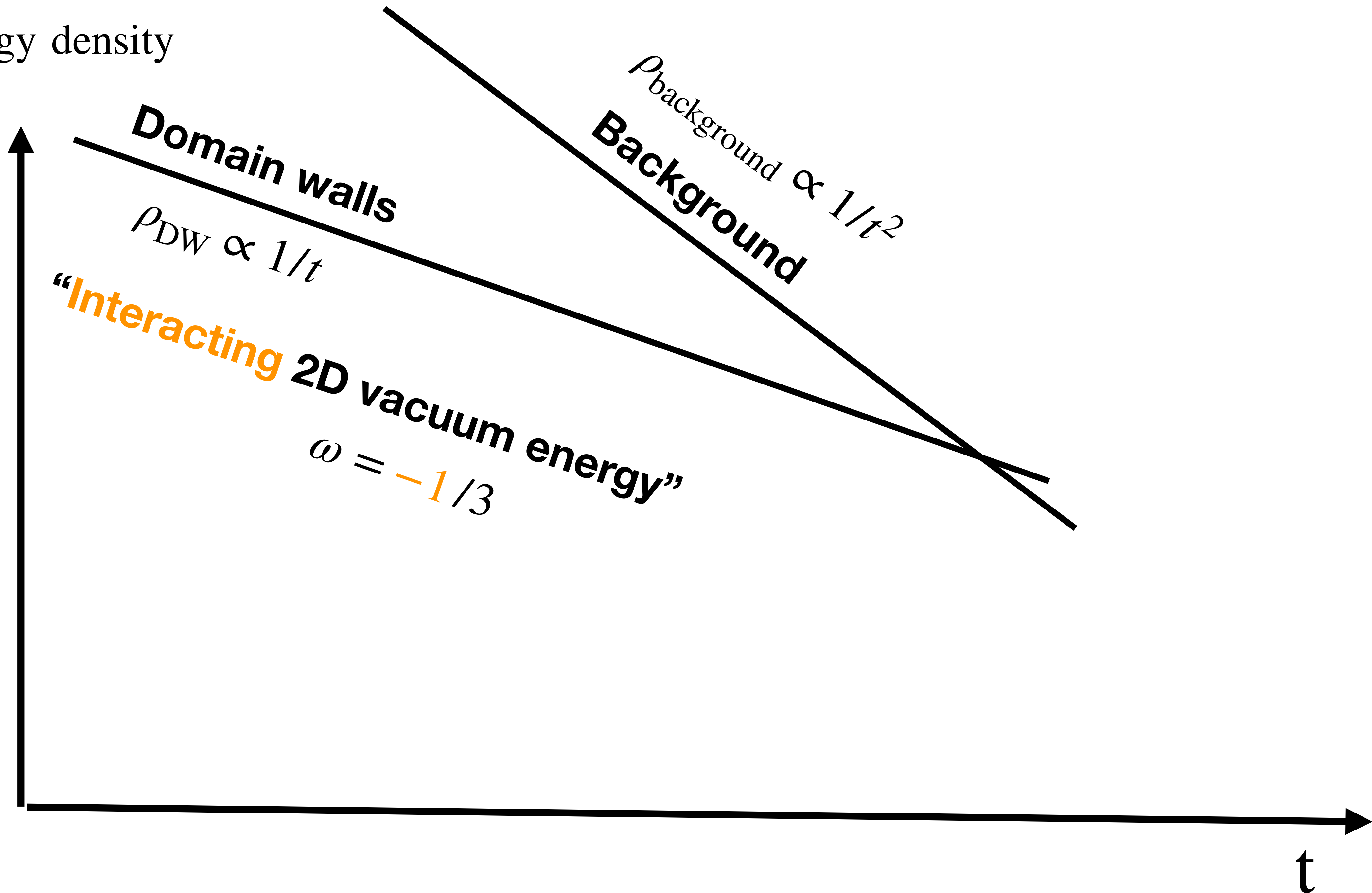
Domain walls

$$\rho_{\text{DW}} \propto 1/t$$

“Interacting 2D vacuum energy”
 $\omega = -1/3$

$\rho_{\text{background}} \propto 1/t^2$
Background

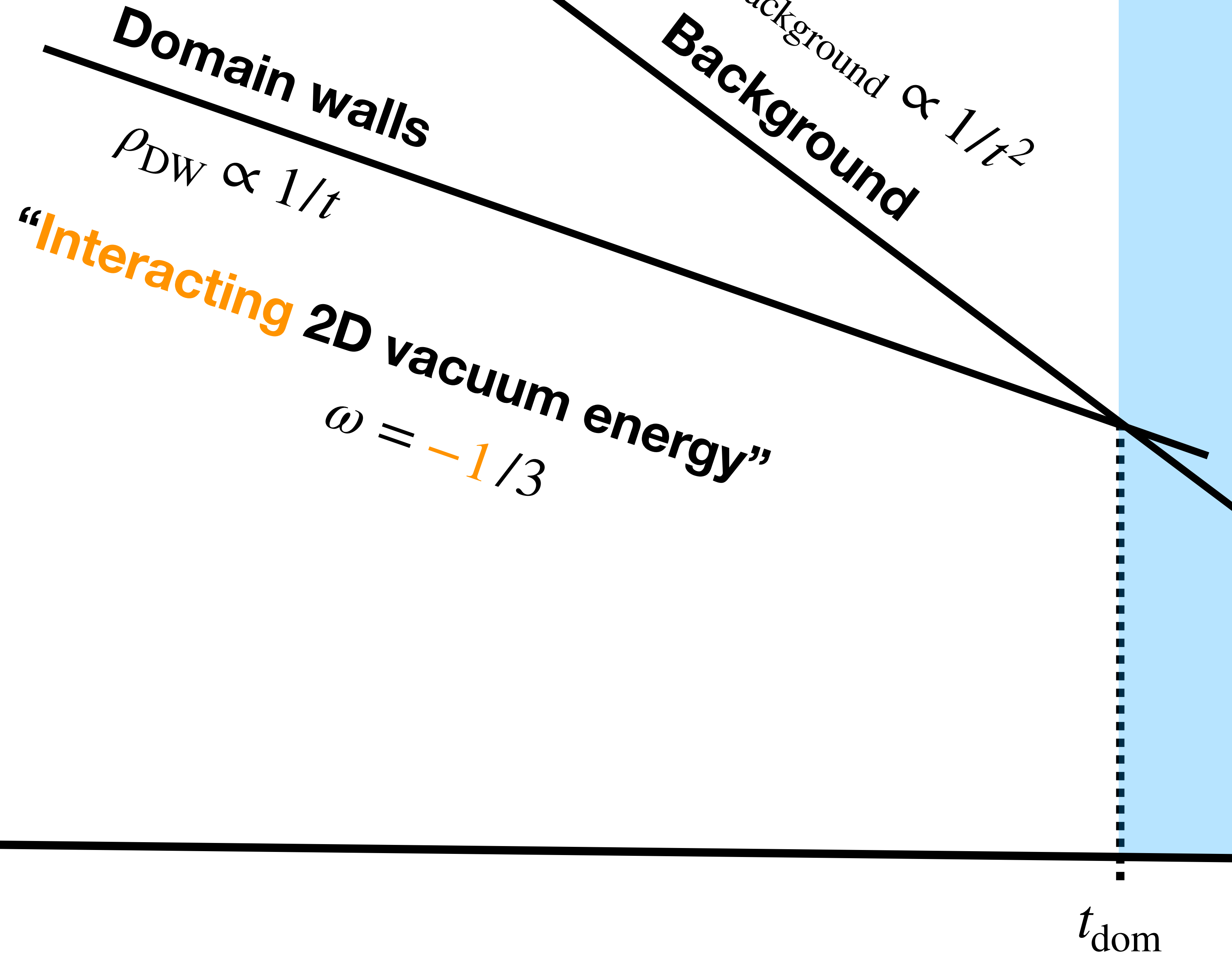
t



Energy density

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

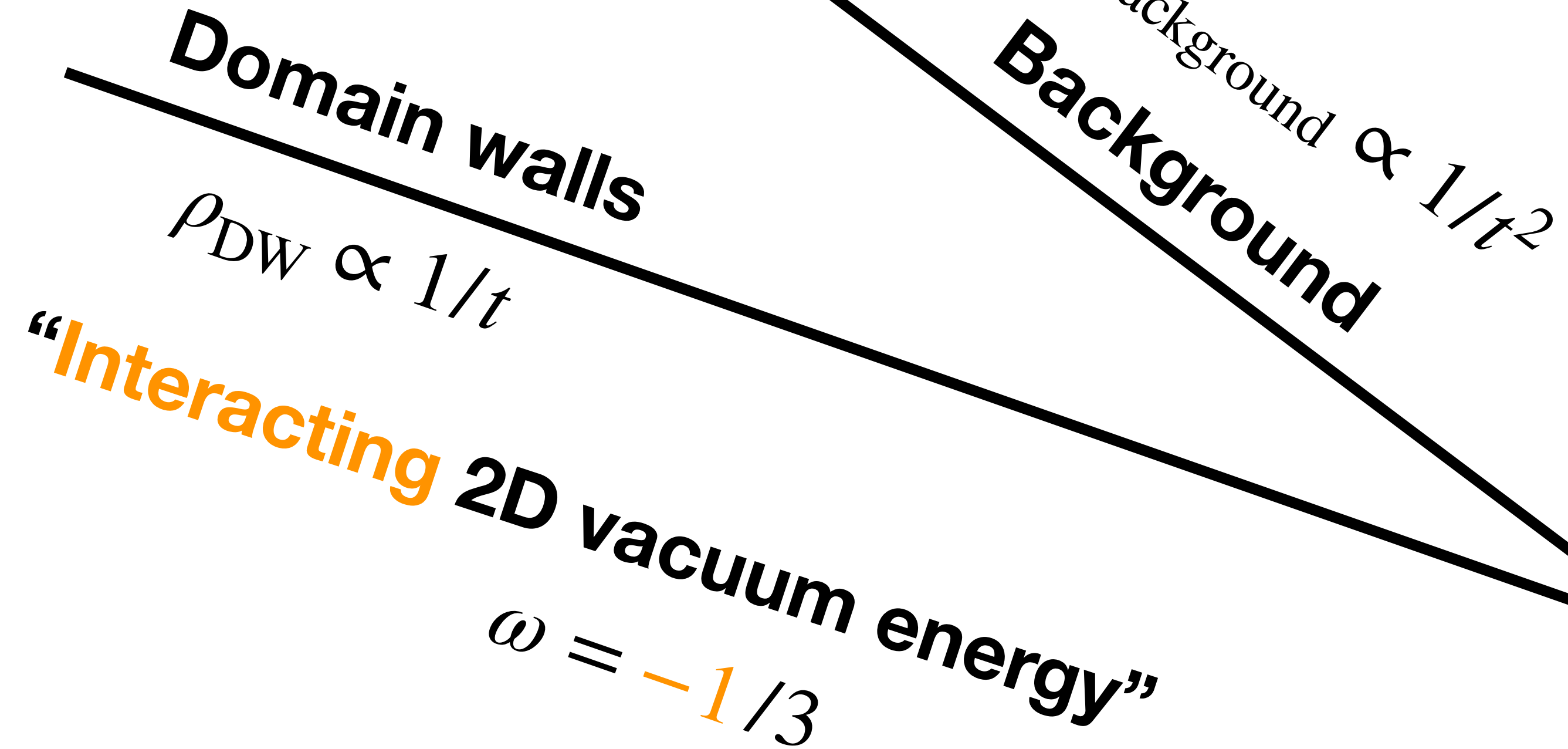


Energy density

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Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$$\rightarrow 1) \delta\rho/\rho \sim 1$$



Energy density

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Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

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Domain walls

$$\rho_{\text{DW}} \propto 1/t$$

“Interacting 2D vacuum energy”

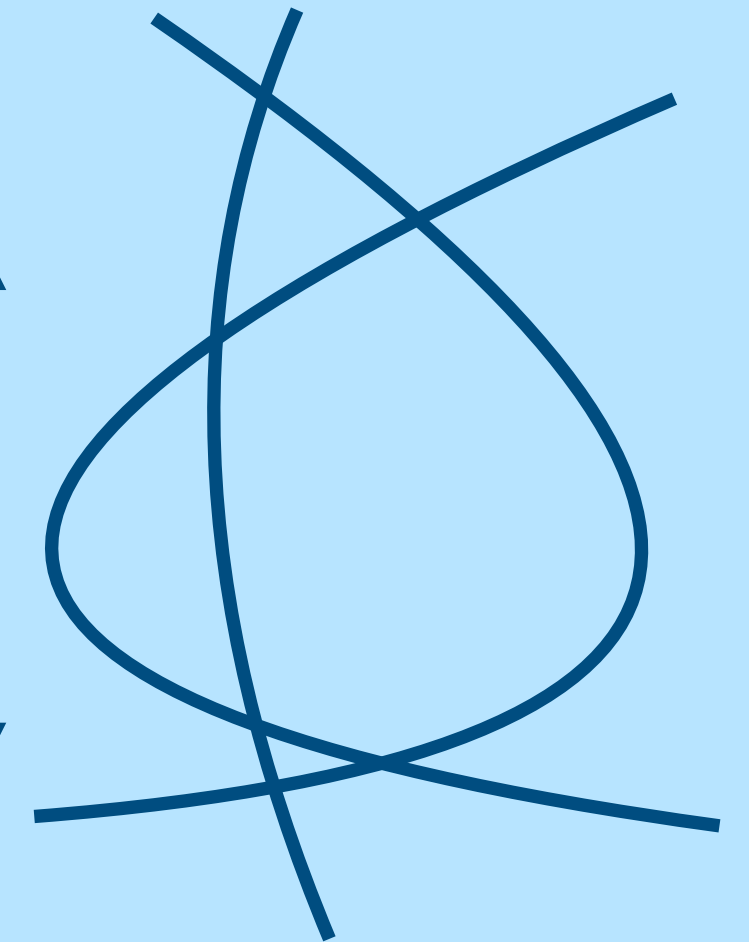
$$\omega = -1/3$$

Background

$$\rho_{\text{background}} \propto 1/t^2$$

$$\langle R \rangle \simeq t$$

(scaling regime)



t_{dom}

t

Energy density

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

$$\rightarrow 1) \delta\rho/\rho \sim 1$$

$$\langle R \rangle \simeq t$$

(scaling regime)

$$\rightarrow 2) \text{horizon size}$$

Domain walls
 $\rho_{\text{DW}} \propto 1/t$
“Interacting 2D vacuum energy”
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(scaling regime)

$$\rightarrow 2) \text{ horizon size}$$

$\Rightarrow$ **Efficient PBH formation**

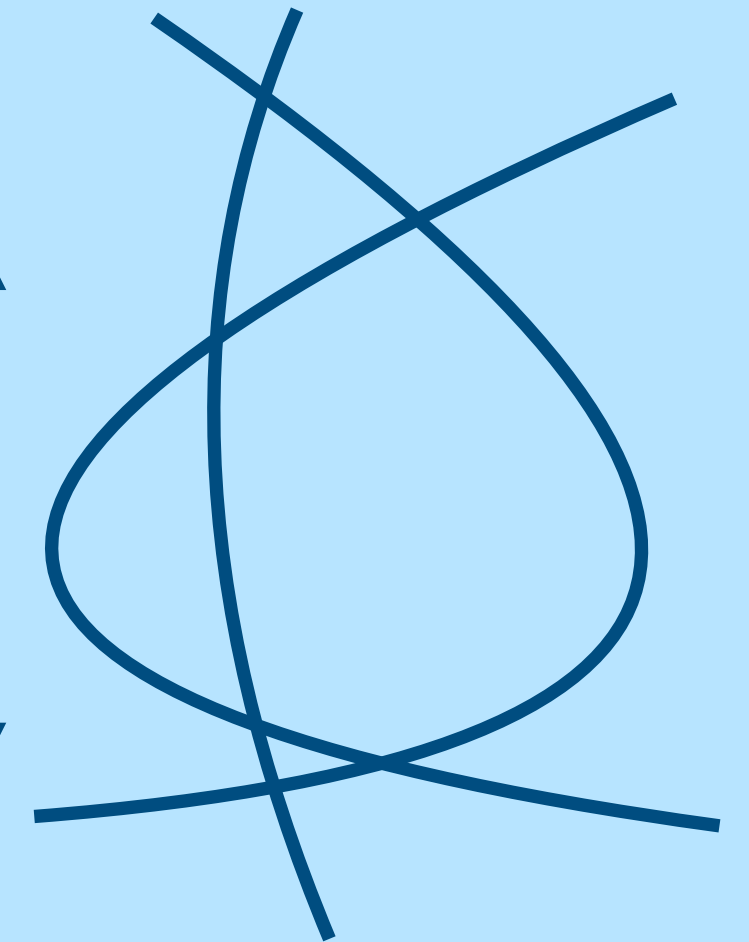
Domain walls
 $\rho_{\text{DW}} \propto 1/t$

Background
 $\rho_{\text{background}} \propto 1/t^2$

“Interacting 2D vacuum energy”
 $\omega = -1/3$

t_{dom}

t



Energy density

Domain walls
 $\rho_{\text{DW}} \propto 1/t$
“Interacting 2D vacuum energy”
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Background

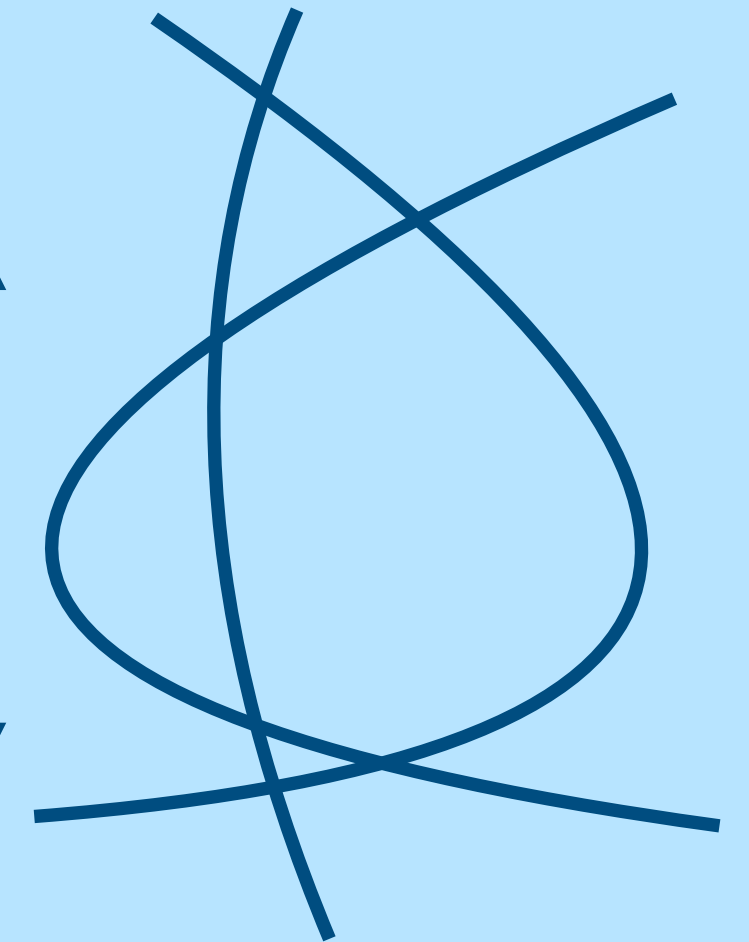
t_{dom}

DW-domination

Y. B. Zeldovich, I. Y. Kobzarev, and L. B. Okun (1974)

→ 1) $\delta\rho/\rho \sim 1$

$\langle R \rangle \simeq t$
(scaling regime)



→ 2) horizon size

⇒ **Efficient PBH formation**

Vilenkin and Shellard's textbook, 2000

Ferrer, Masso, Panico, Pujolas, Rompineve,
Phys.Rev.Lett. 122 (2019) 10, 101301, 1807.01707