

10 September 2026
IFPU workshop - Trieste

Indirect searches of Dark Matter in the PeV energy range

Marco Cirelli

(CNRS LPTHE Jussieu Paris)



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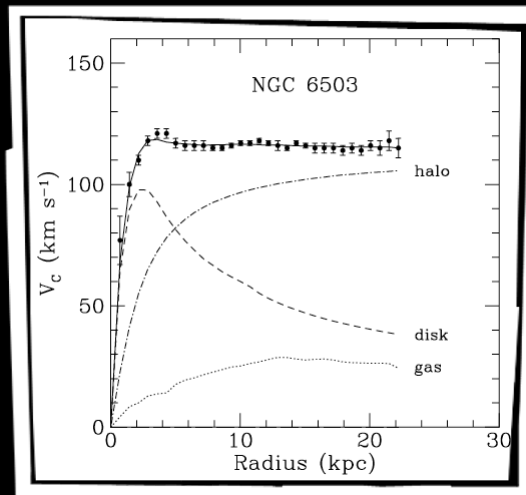
Executive summary

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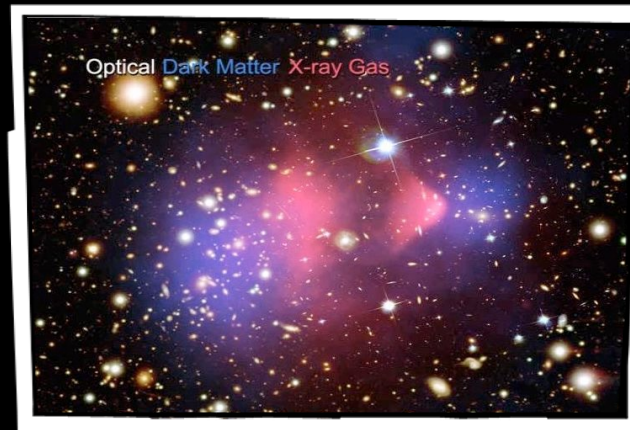
- DM exists

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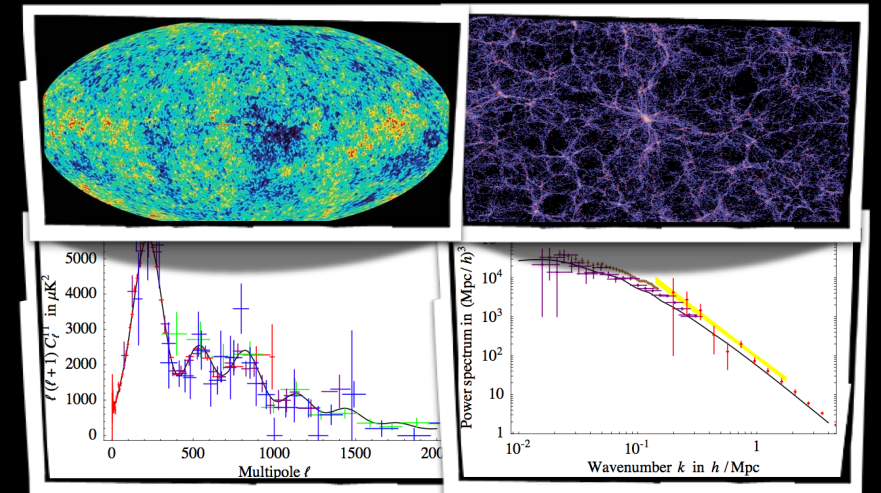
● DM exists



galactic rotation curves



weak lensing (e.g. in clusters)



‘precision cosmology’ (CMB, LSS)

Executive summary

- DM exists

- it's a new, unknown particle

*no SM particle
can fulfill*

*dilutes as $1/a^3$ with
universe expansion*

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- DM exists
- it's a **new, unknown particle**
- makes up **26%** of total energy
84% of total matter

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$$\Omega_{\text{DM}} h^2 = 0.1200 \pm 0.0012$$

(notice error!)

Planck 2015,
1502.01589 (tab.4)

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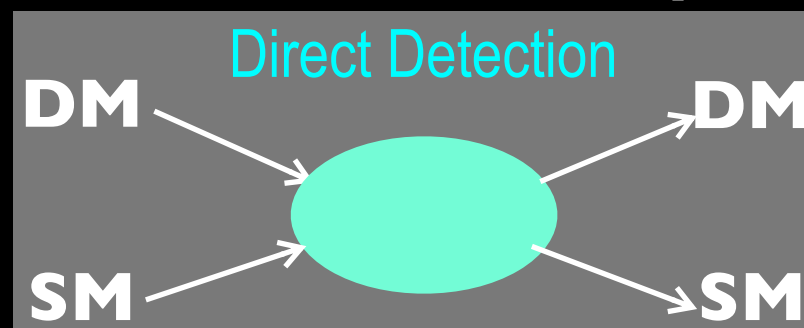
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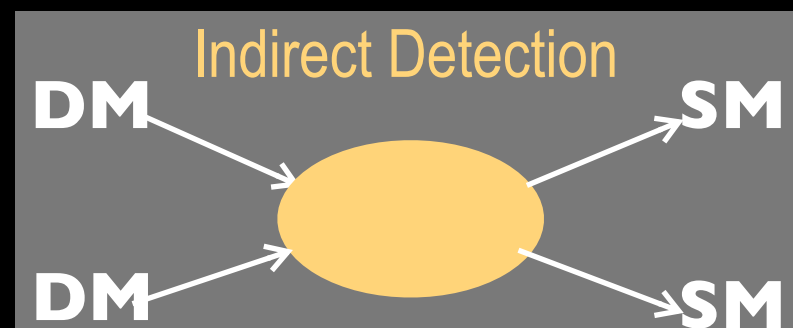
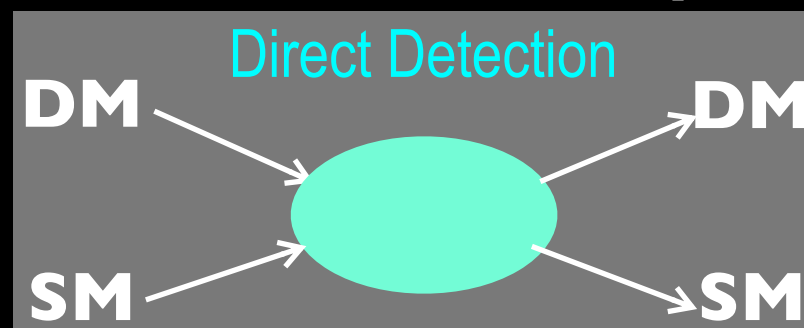
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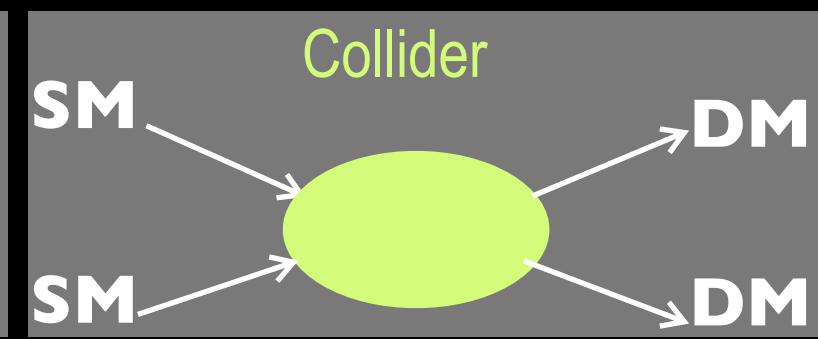
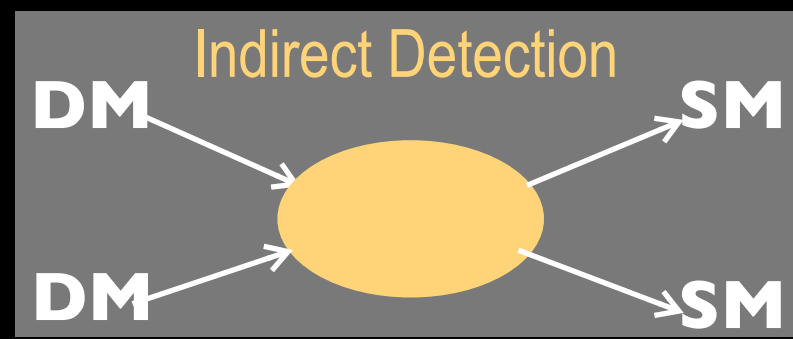
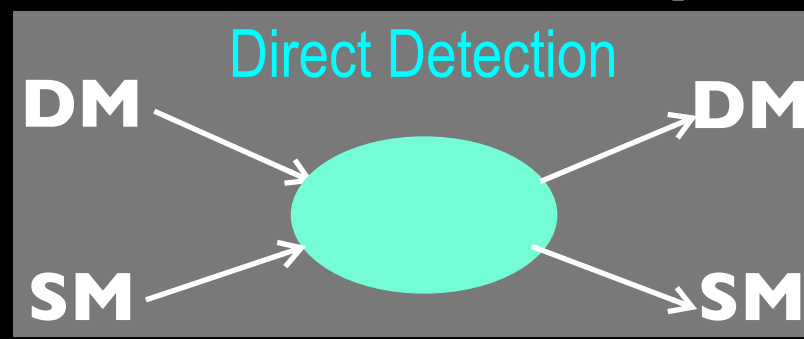
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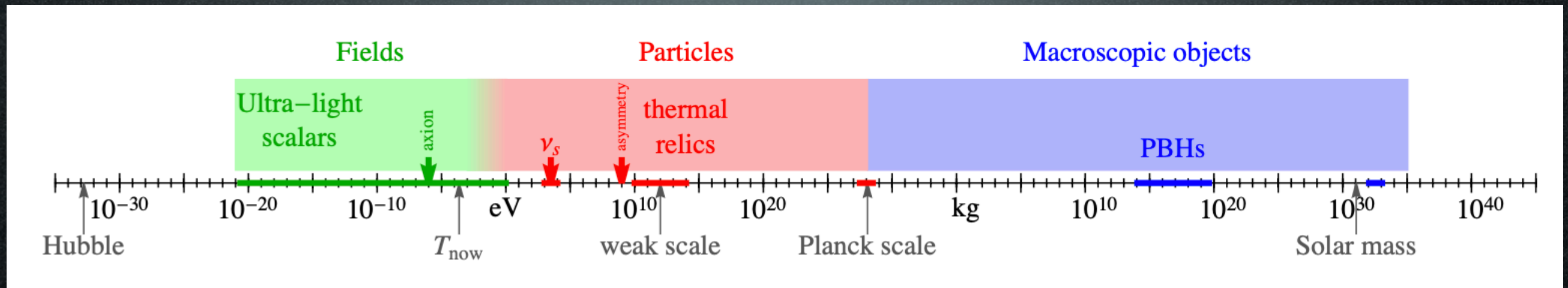
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Mass??

Charge??
Interactions??

Candidates

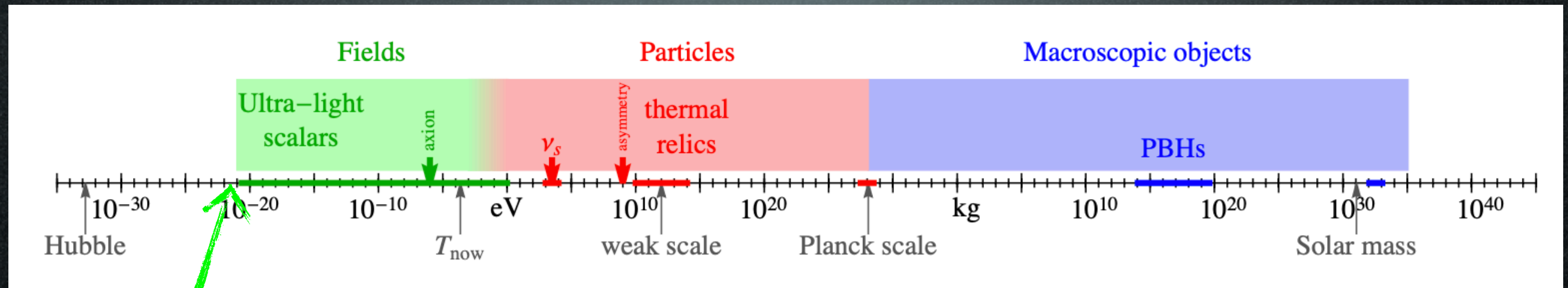
A matter of perspective: plausible mass ranges



90 orders of magnitude!

Candidates

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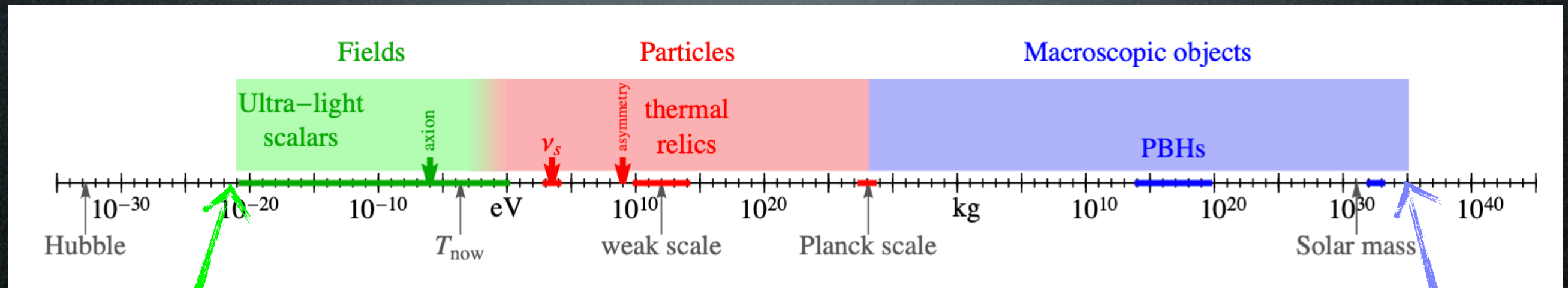
as diffuse as a
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DM de Broglie wavelength

$$\lambda = 2\pi/Mv \lesssim 1 \text{ kpc}$$

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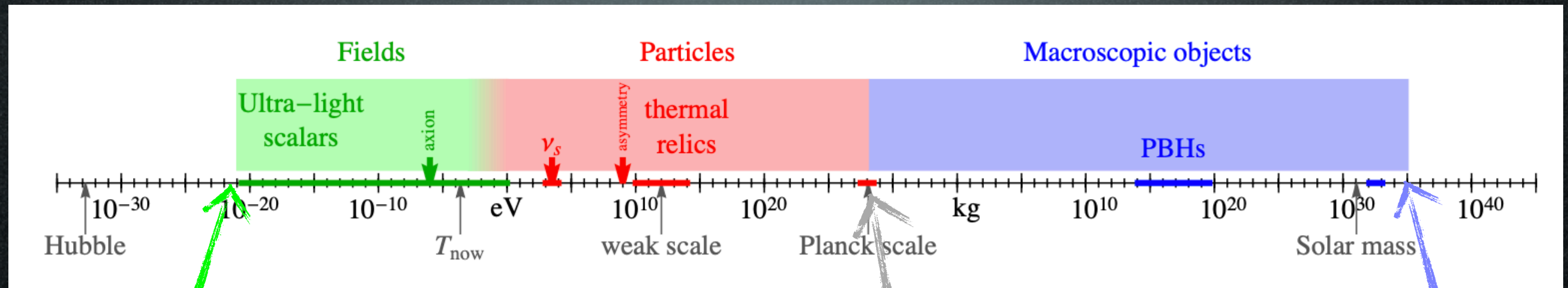
as **big** as a
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DM mass

$$M \lesssim 10^4 M_{\odot}$$

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most likely
elementary | most likely
composite

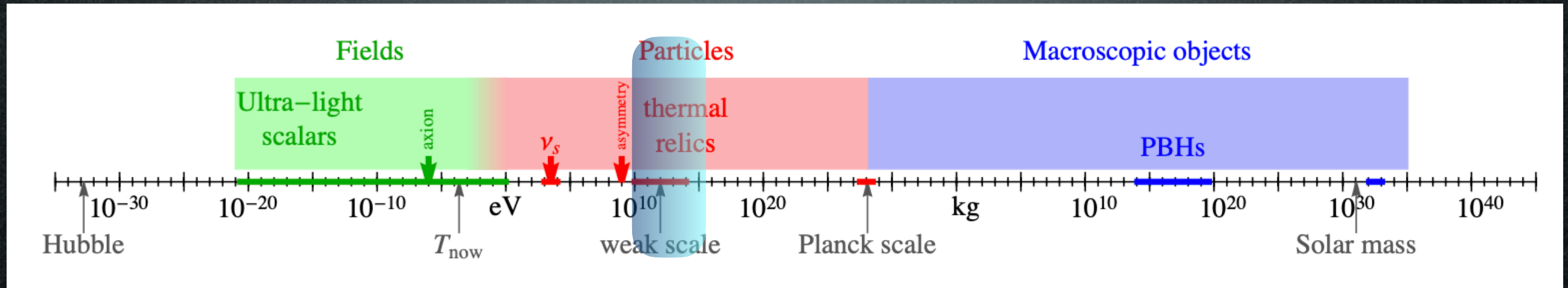
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Candidates

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Candidates

WIMPs

Candidates

new physics at
the TeV scale



thermal
freeze-out



WIMPs

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WIMPs

Collider
Searches

Indirect
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Direct
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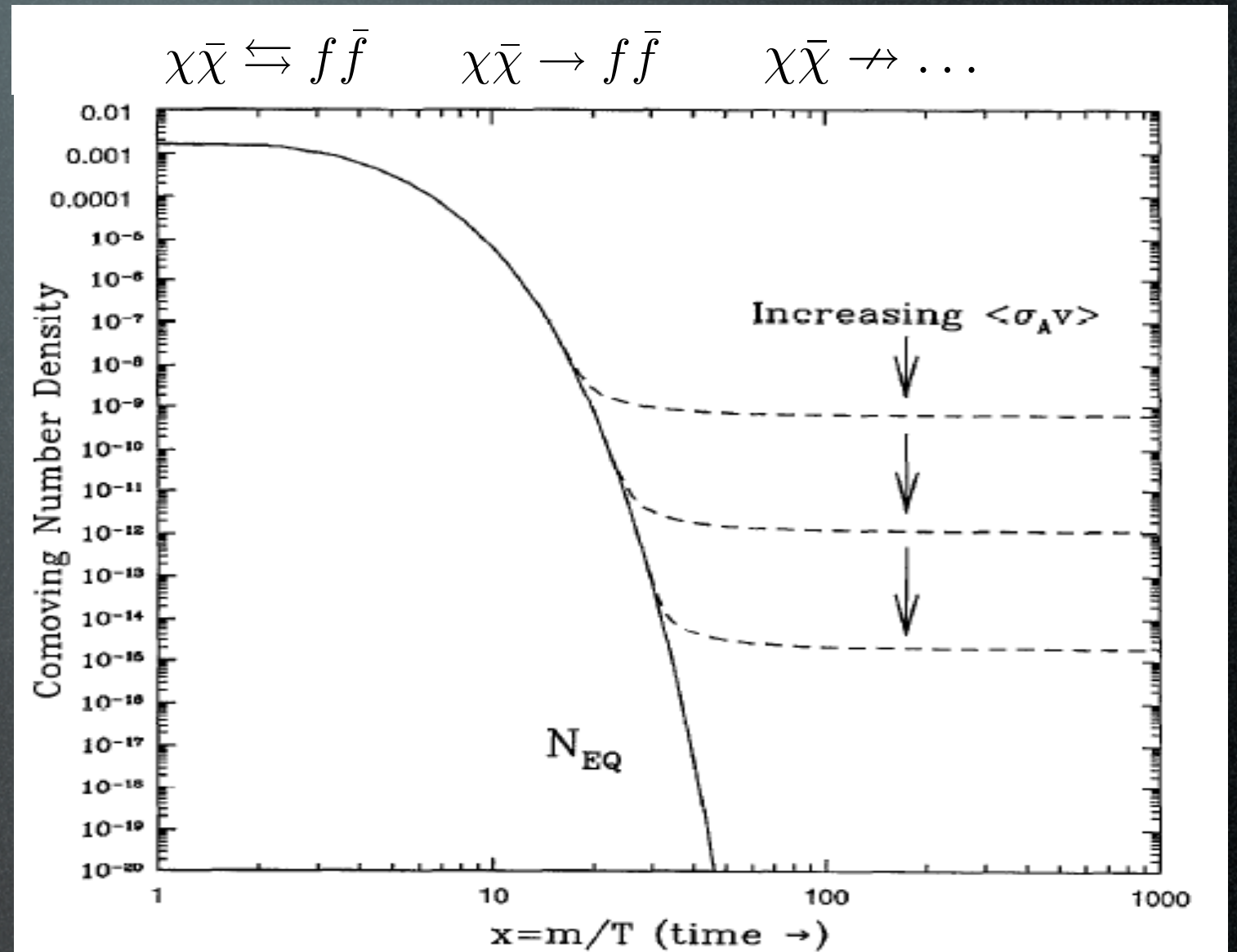
DM as a thermal relic from the Early Universe

Boltzmann equation
in the Early Universe:

$$\Omega_X \approx \frac{6 \cdot 10^{-27} \text{cm}^3 \text{s}^{-1}}{\langle \sigma_{\text{ann}} v \rangle}$$

Relic $\Omega_{\text{DM}} \simeq 0.26$ for

$$\langle \sigma_{\text{ann}} v \rangle = 3 \cdot 10^{-26} \text{cm}^3 / \text{sec}$$



Weak cross section:

$$\langle \sigma_{\text{ann}} v \rangle \approx \frac{\alpha_w^2}{M^2} \approx \frac{\alpha_w^2}{1 \text{TeV}^2} \Rightarrow \Omega_X \sim \mathcal{O}(\text{few } 0.1) \quad (\text{WIMP})$$

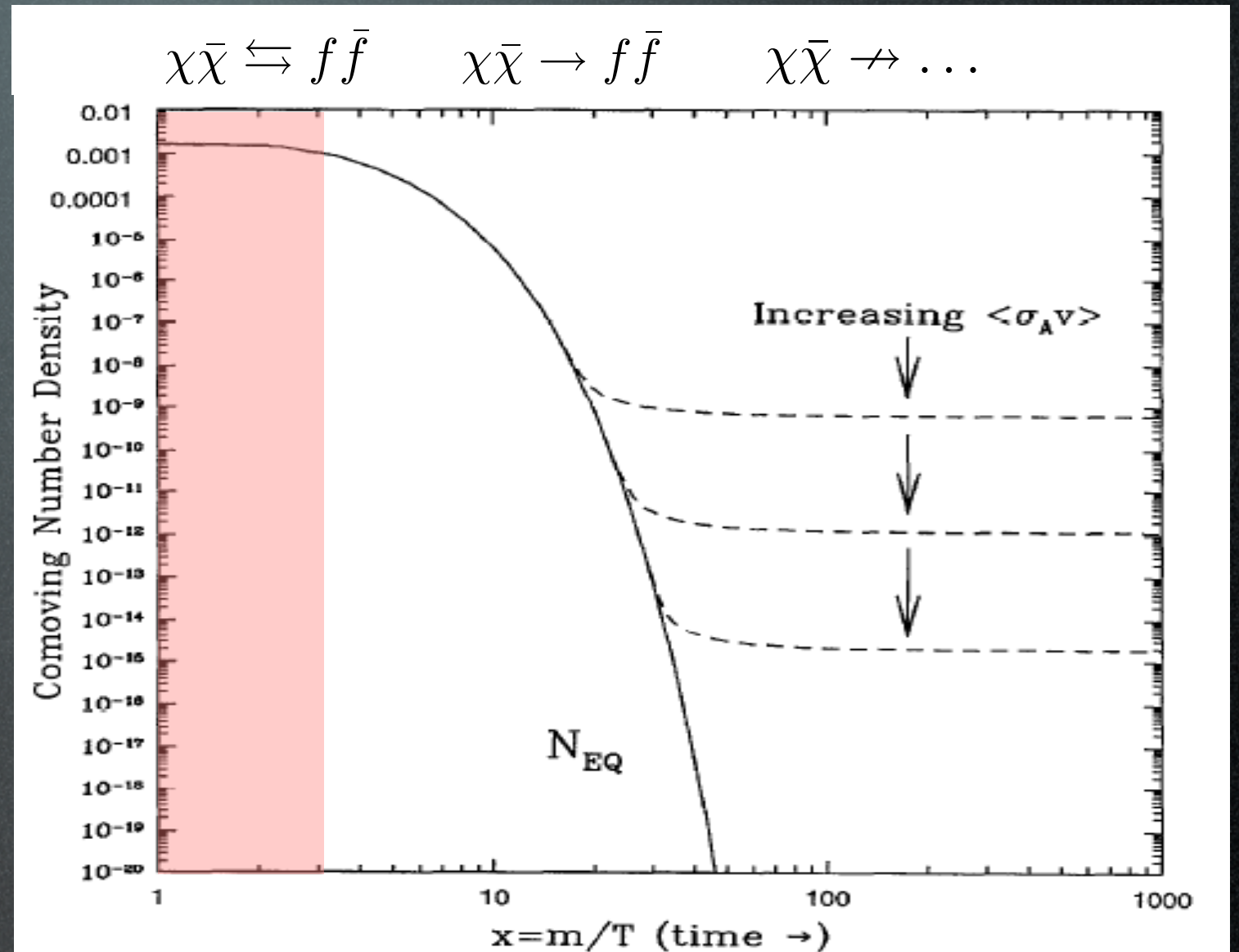
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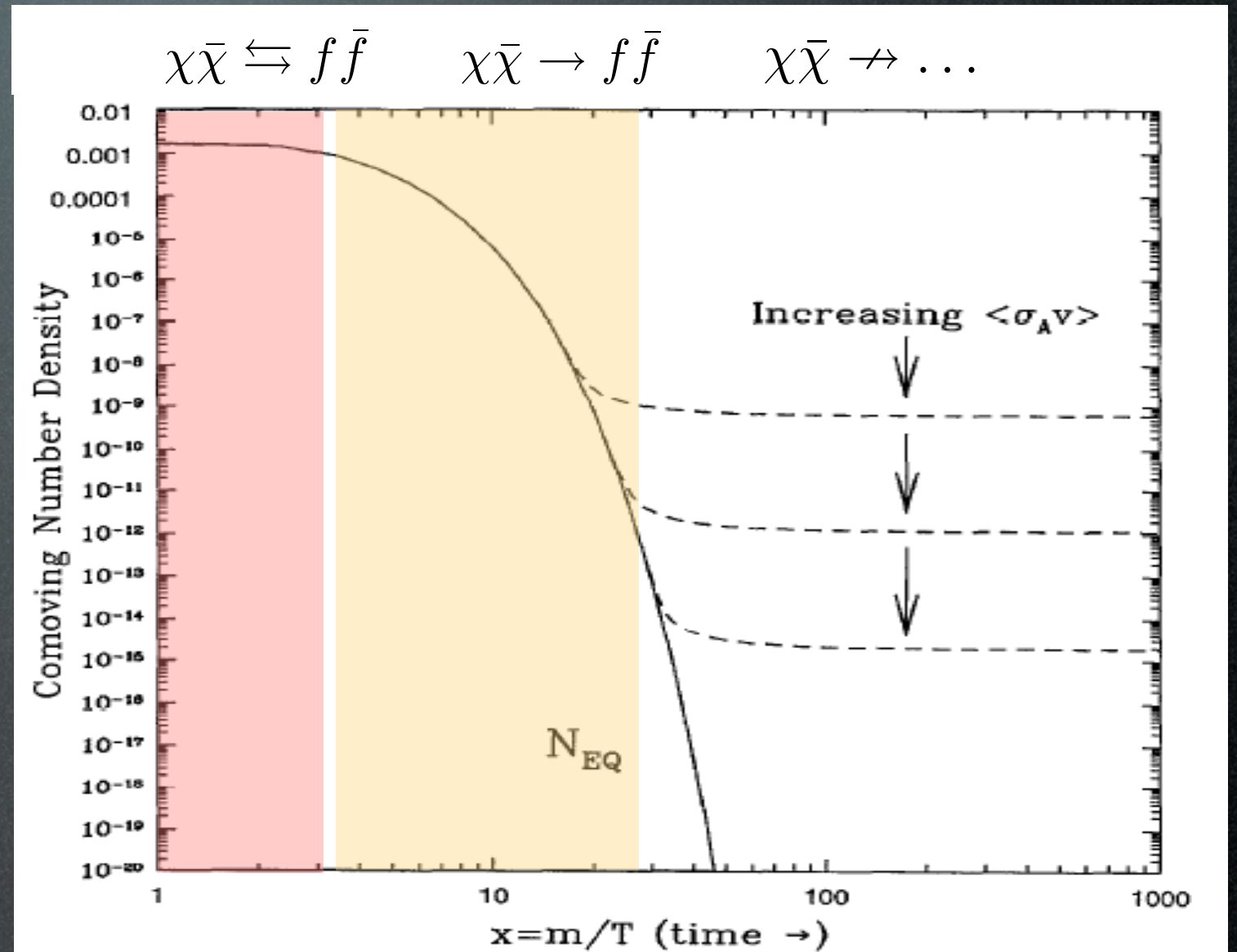
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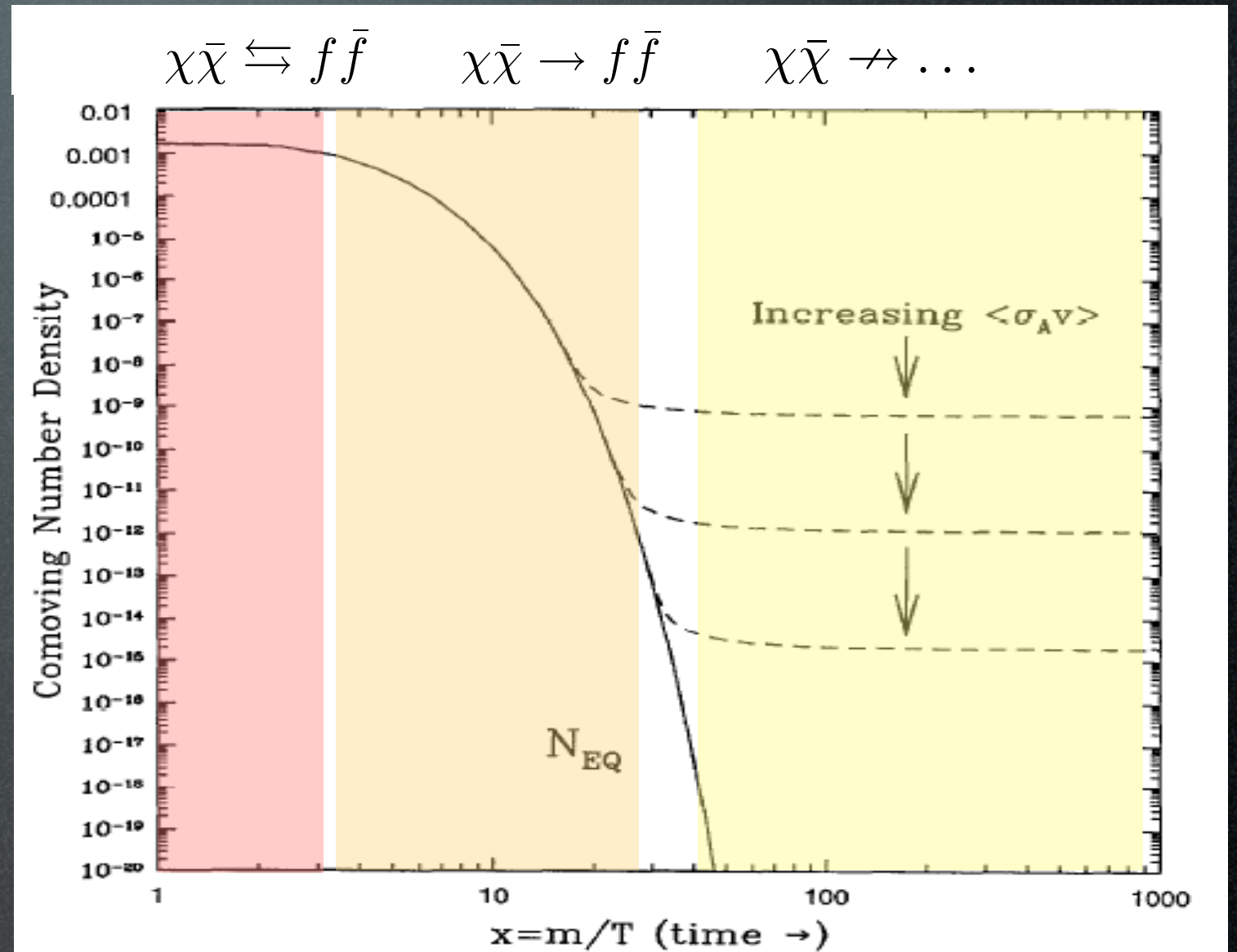
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Candidates

new physics at
the TeV scale

thermal
freeze-out

WIMPs

Collider
Searches

Indirect
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1. even without a larger framework, WIMPs are **still appealing**
- 2.

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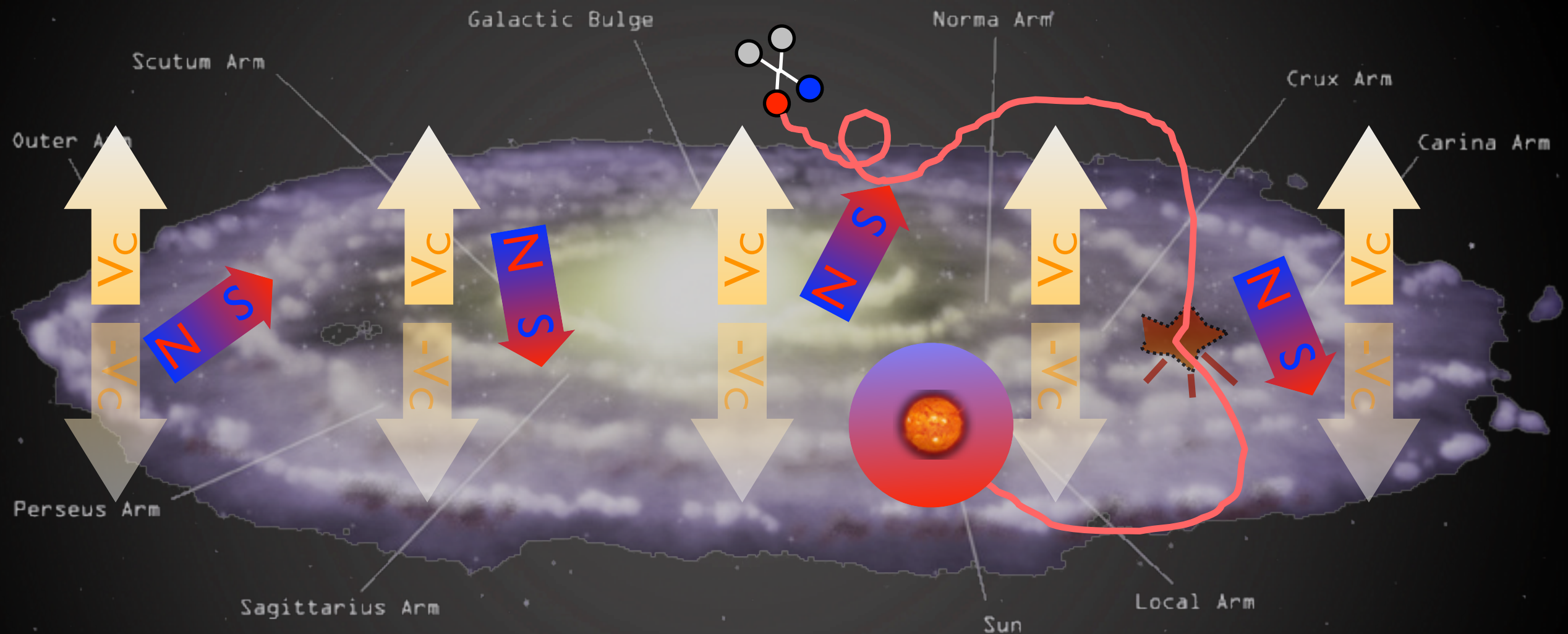
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1. even without a larger framework, WIMPs are **still appealing**
2. the three search strategies are **complementary**

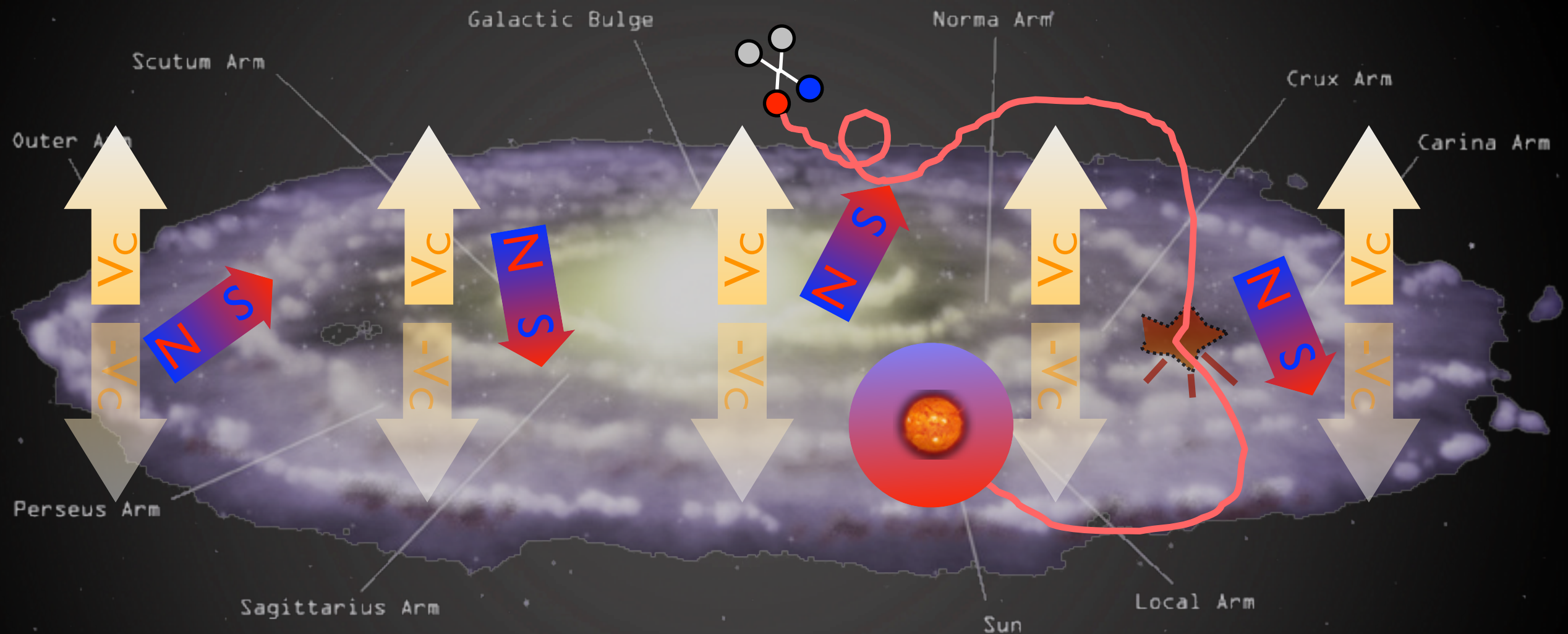
Indirect Detection: charged CRs

$\bar{p}$ and e^+ from DM annihilations/decays in halo



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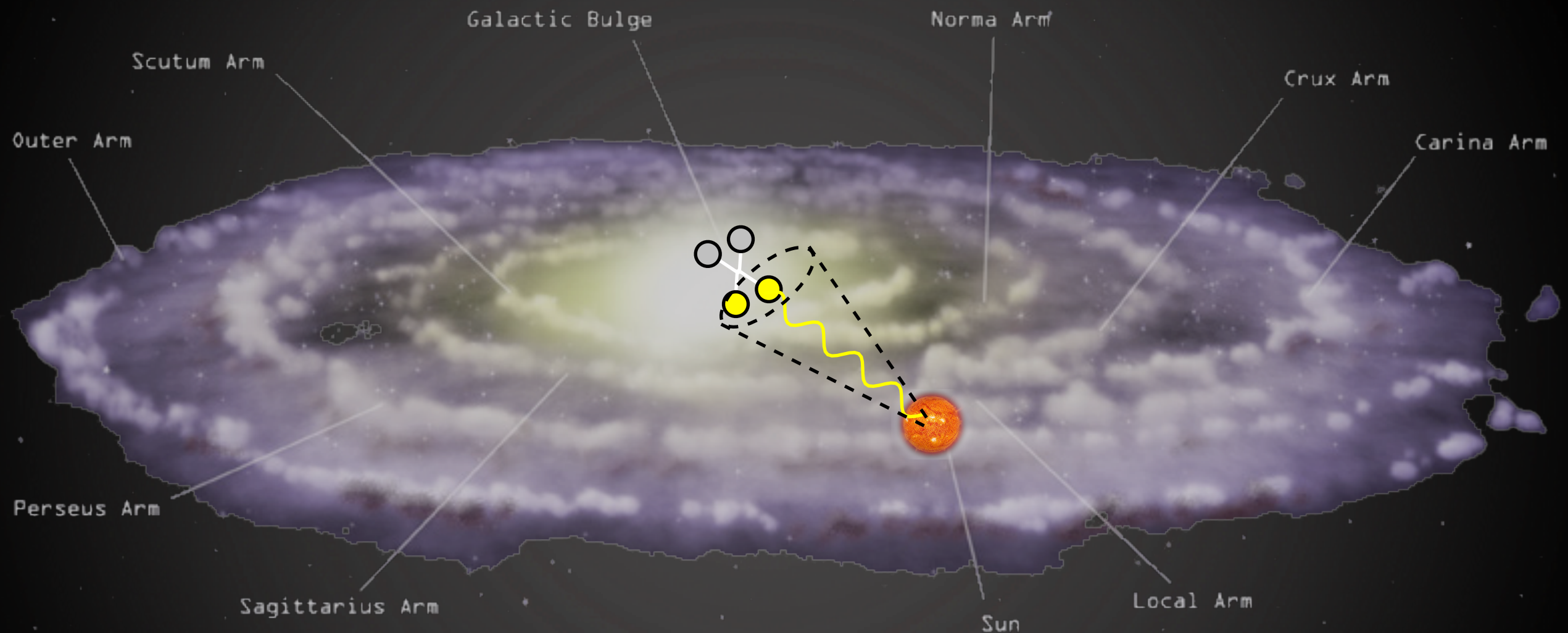
$\bar{p}$ and e^+ from DM annihilations/decays in halo



No signals. Only constraints.

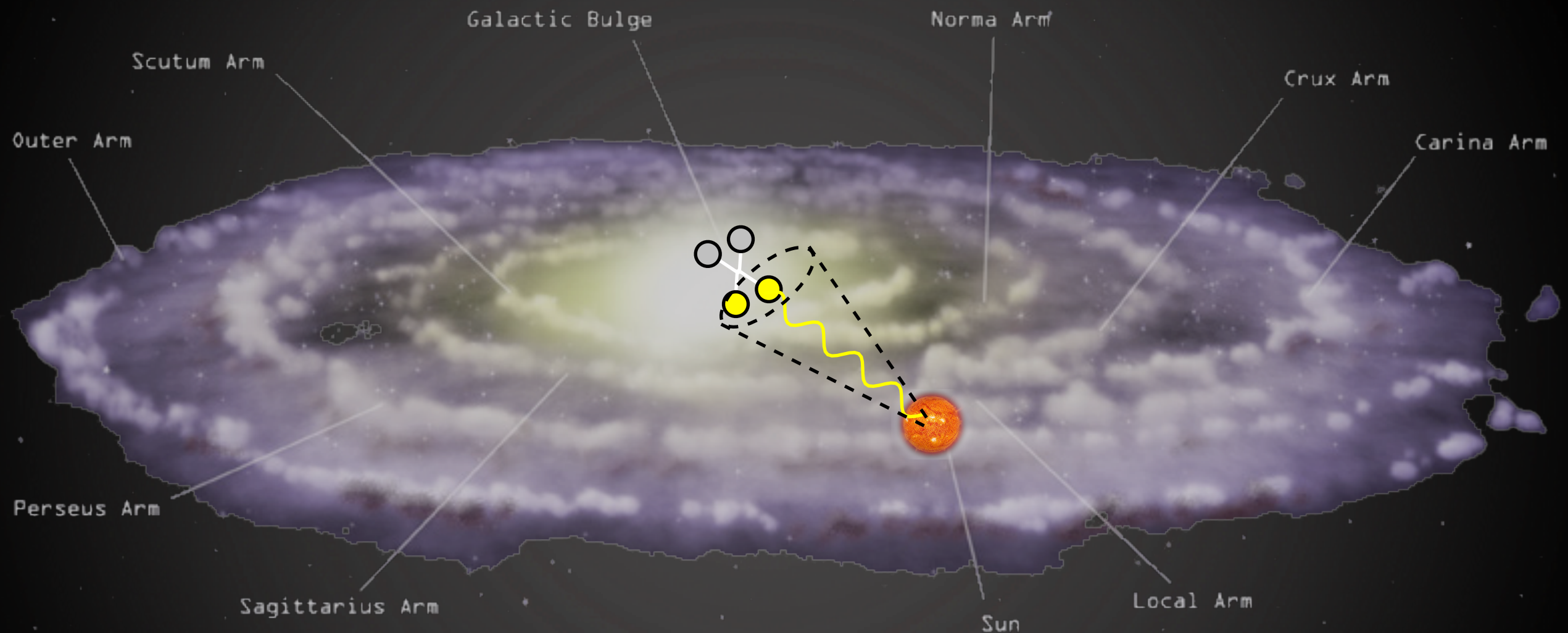
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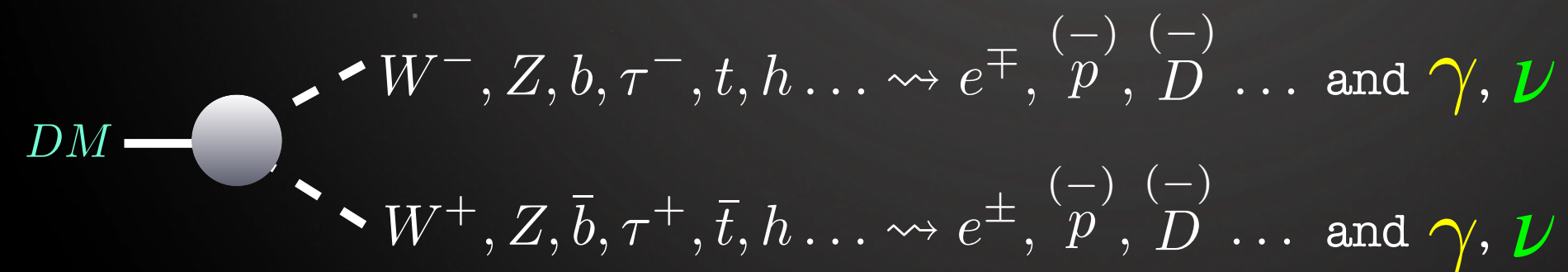
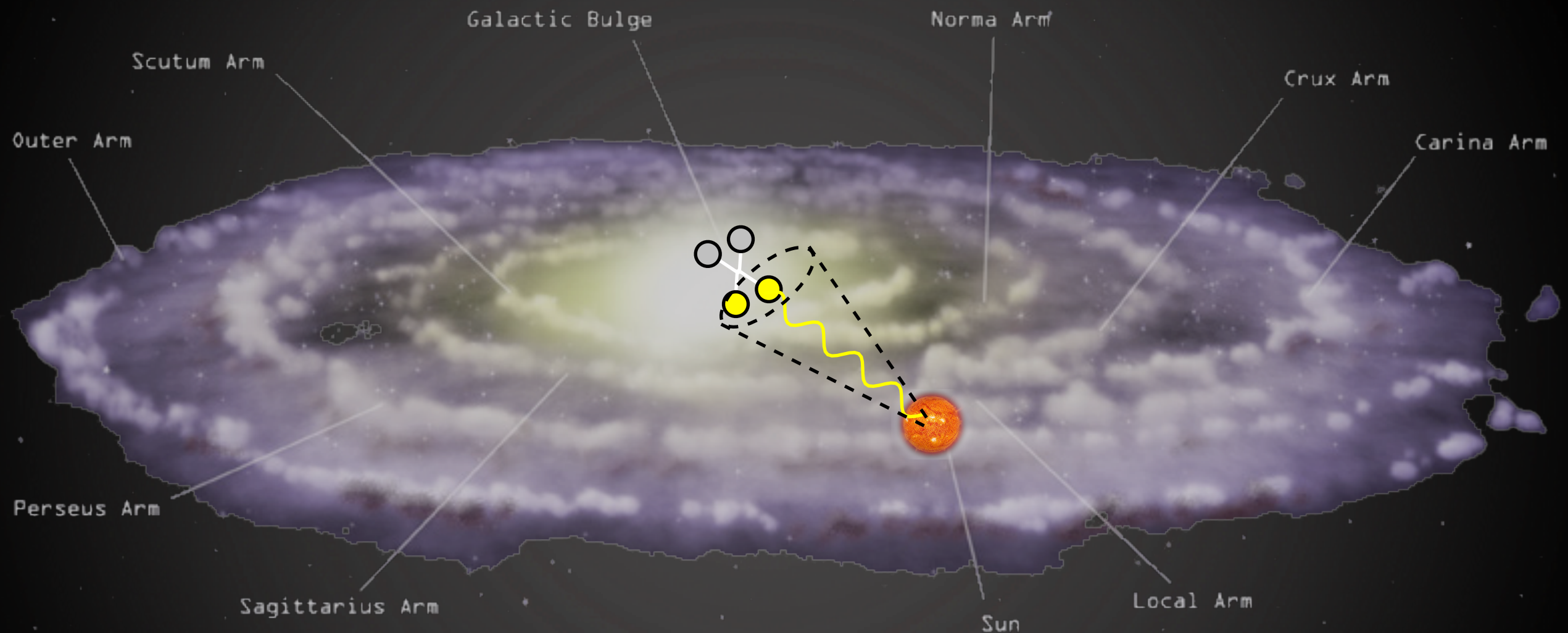
DM DM

$W^-, Z, b, \tau^-, t, h \dots \rightsquigarrow e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \dots$ and γ, ν

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \dots \rightsquigarrow e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \dots$ and γ, ν

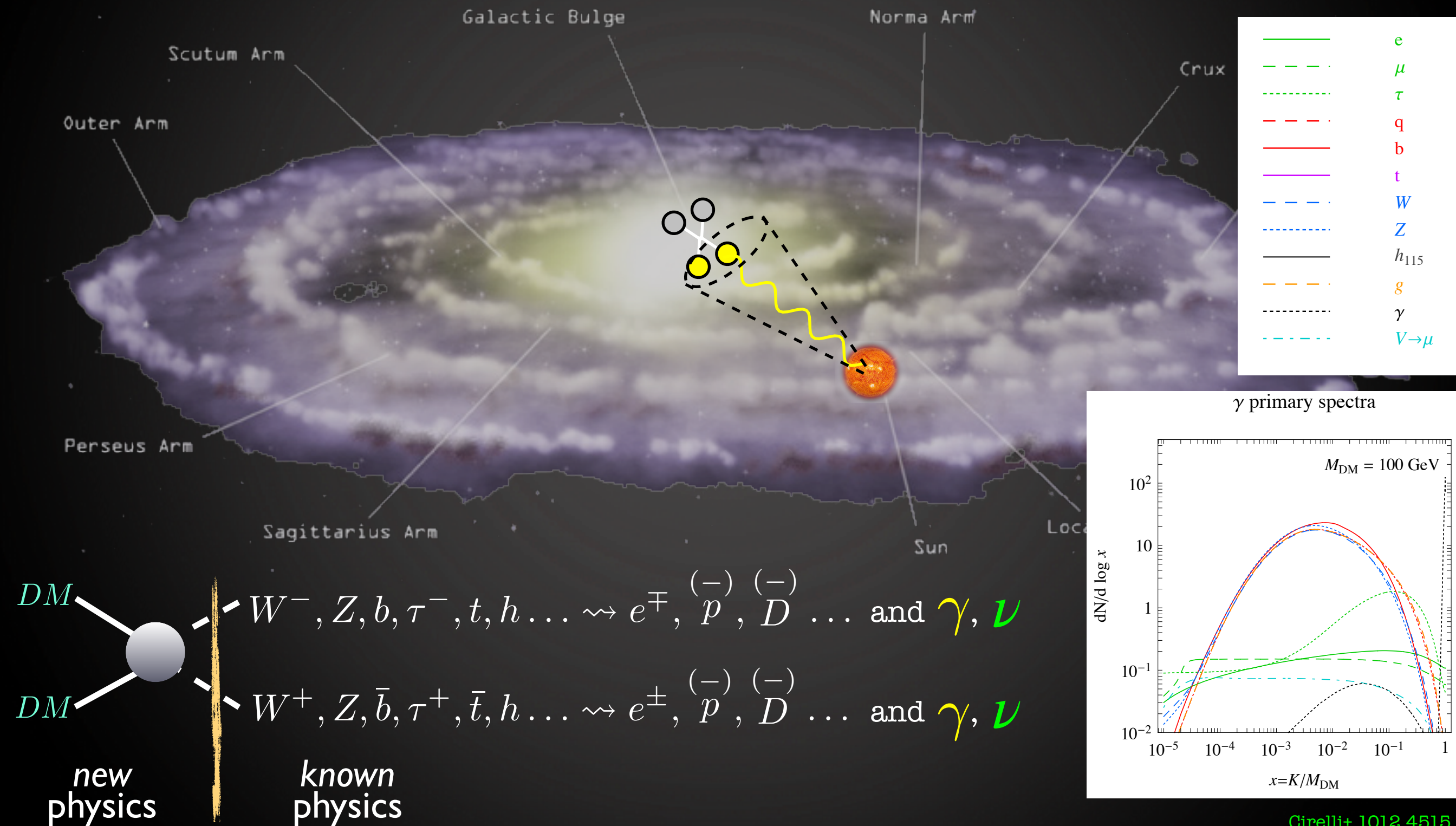
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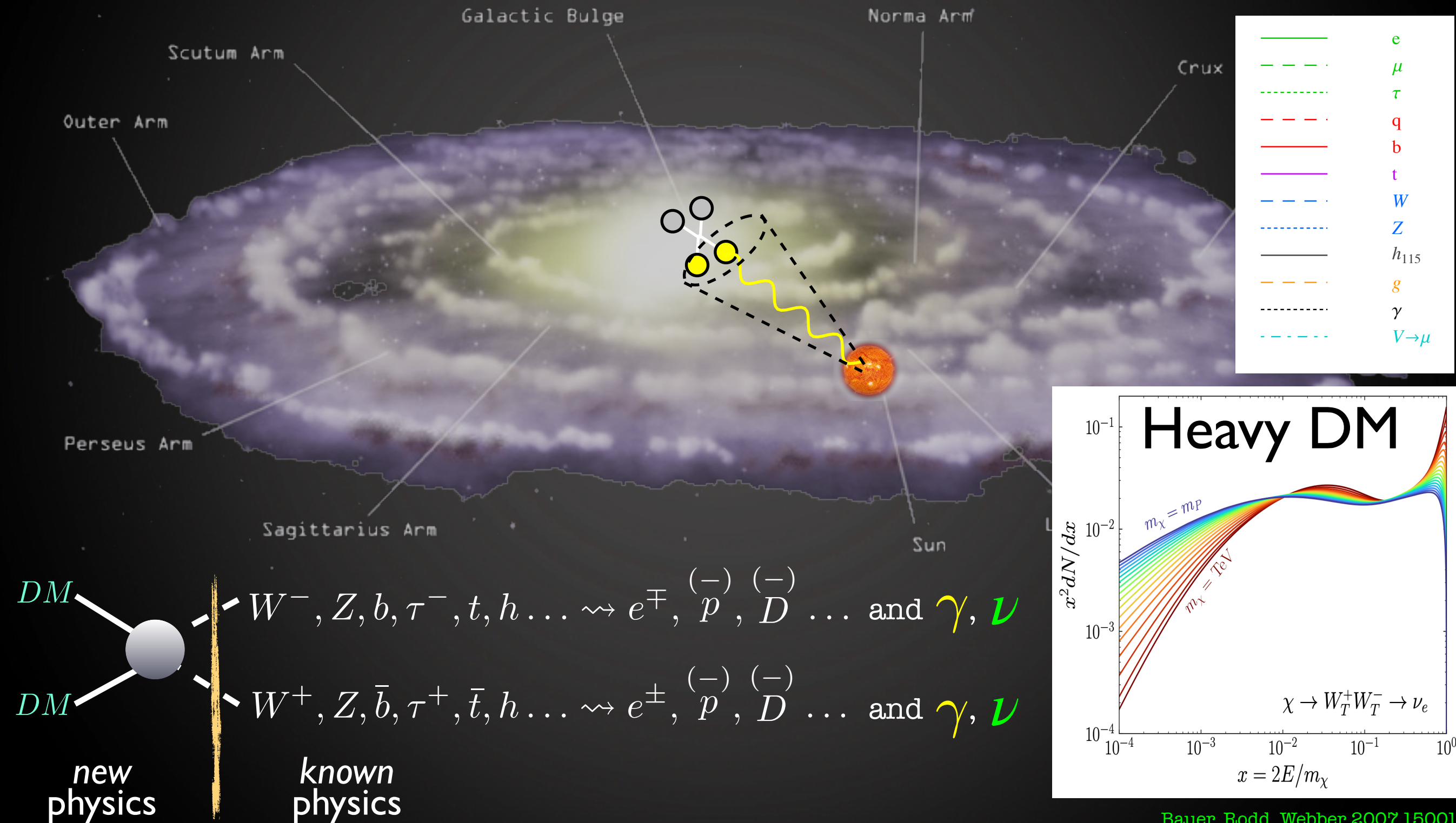
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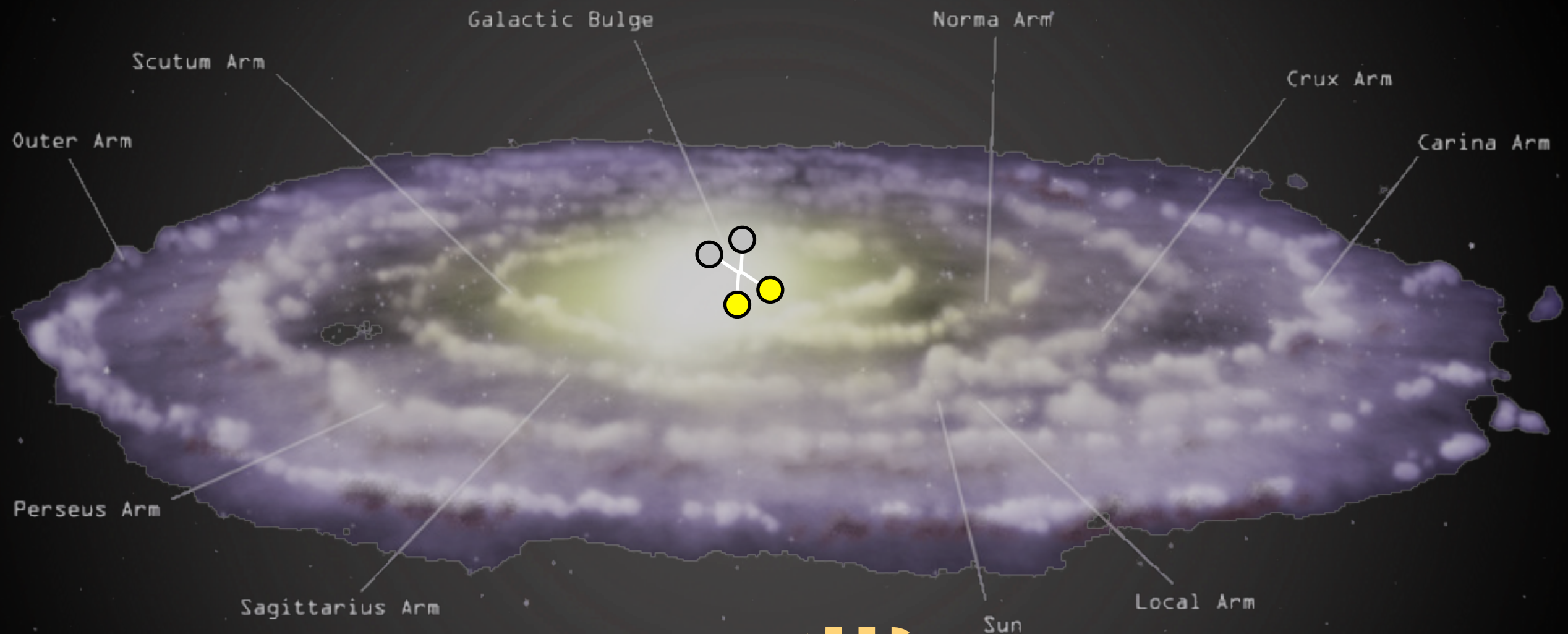
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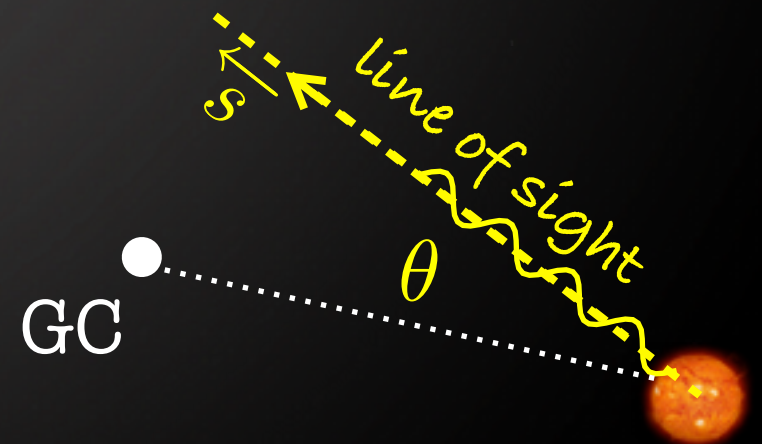
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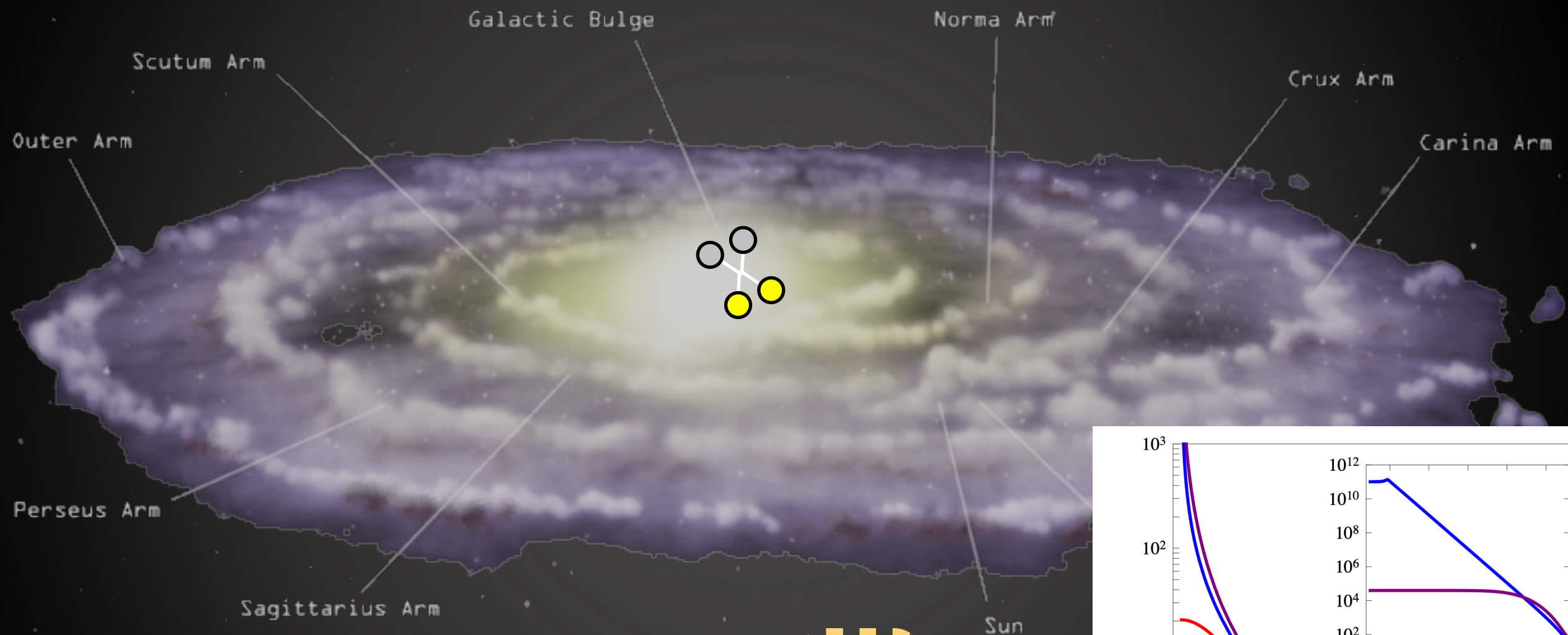
$$\frac{d\Phi_\gamma}{d\Omega dE} = \frac{1}{2} \frac{r_\odot}{4\pi} \left(\frac{\rho_\odot}{M_{\text{DM}}} \right)^2 \boxed{J} \sum_f \langle \sigma v \rangle_f \boxed{\frac{dN_\gamma^f}{dE}}$$

$$\boxed{J} = \int_{\text{l.o.s.}} \frac{ds}{r_\odot} \left(\frac{\rho(r(s, \theta))}{\rho_\odot} \right)^2$$



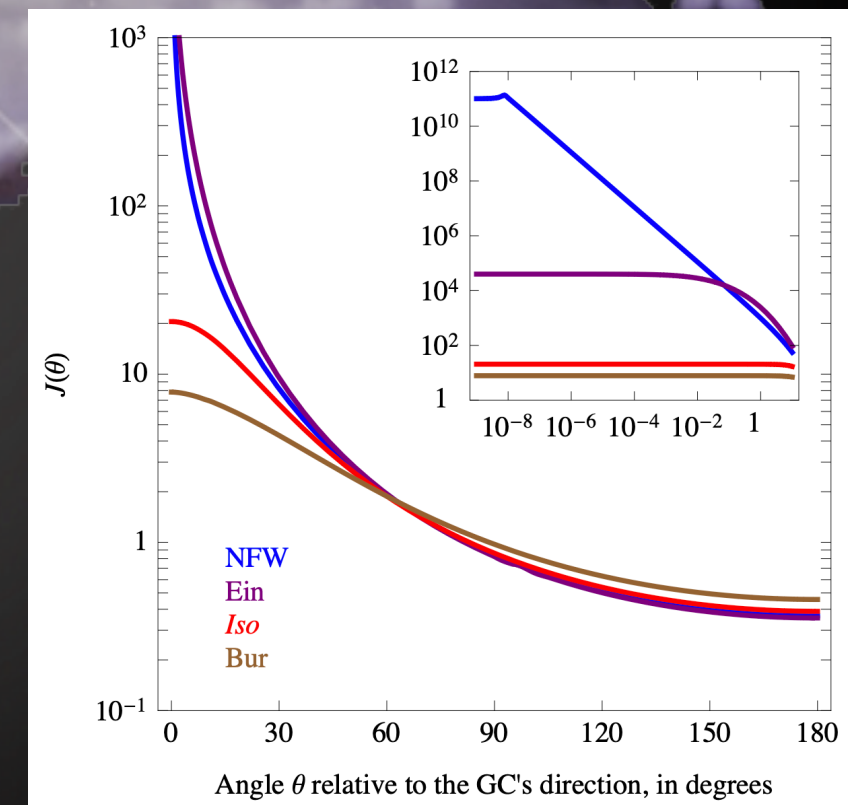
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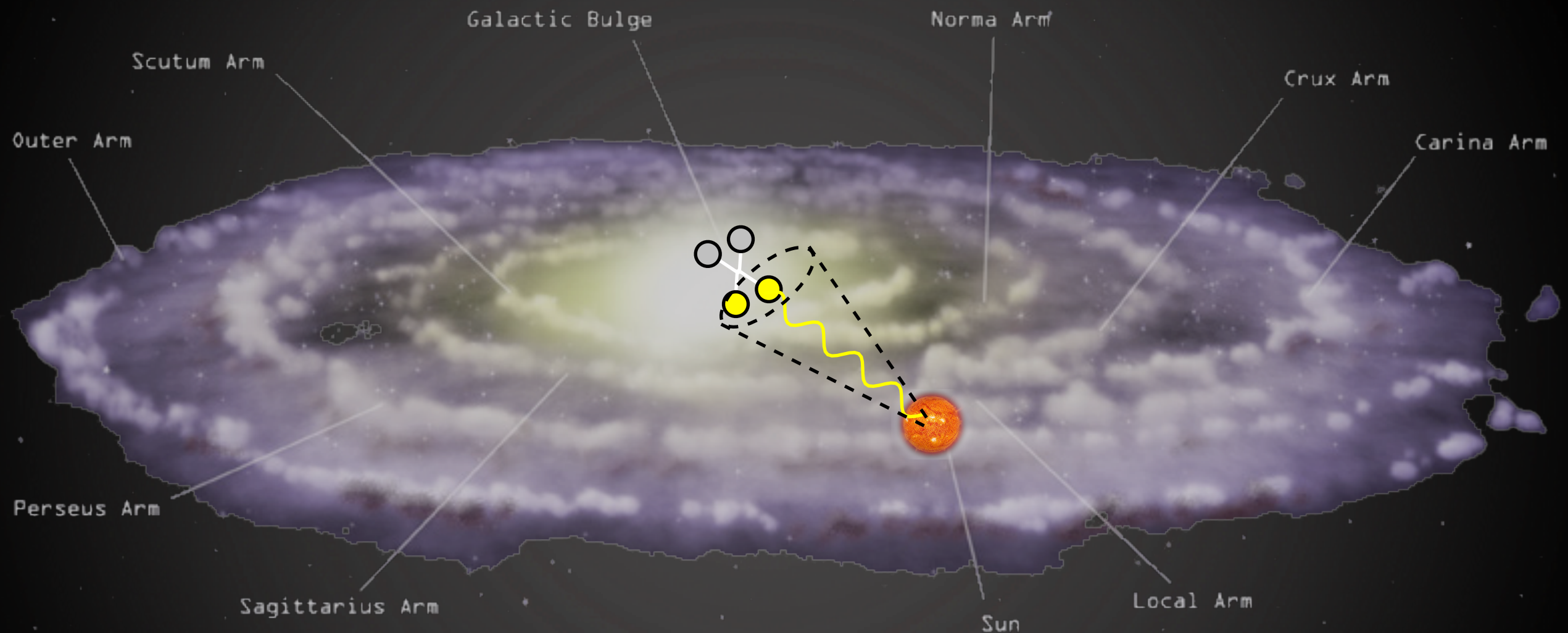
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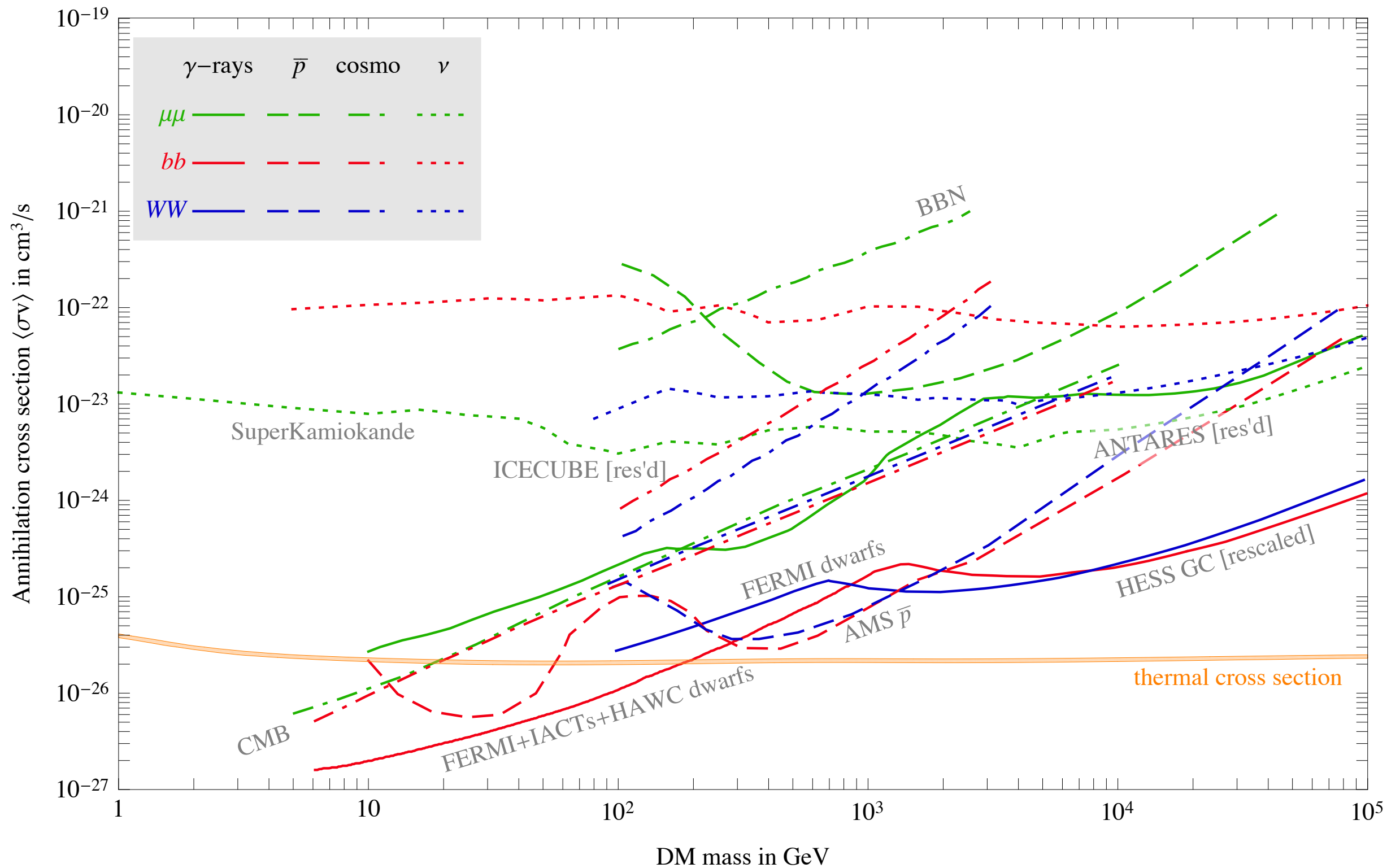
γ (and ν) from DM annihilations/decays (e.g. in the GC)



One long-standing, exciting **signal**.
And many **constraints**.

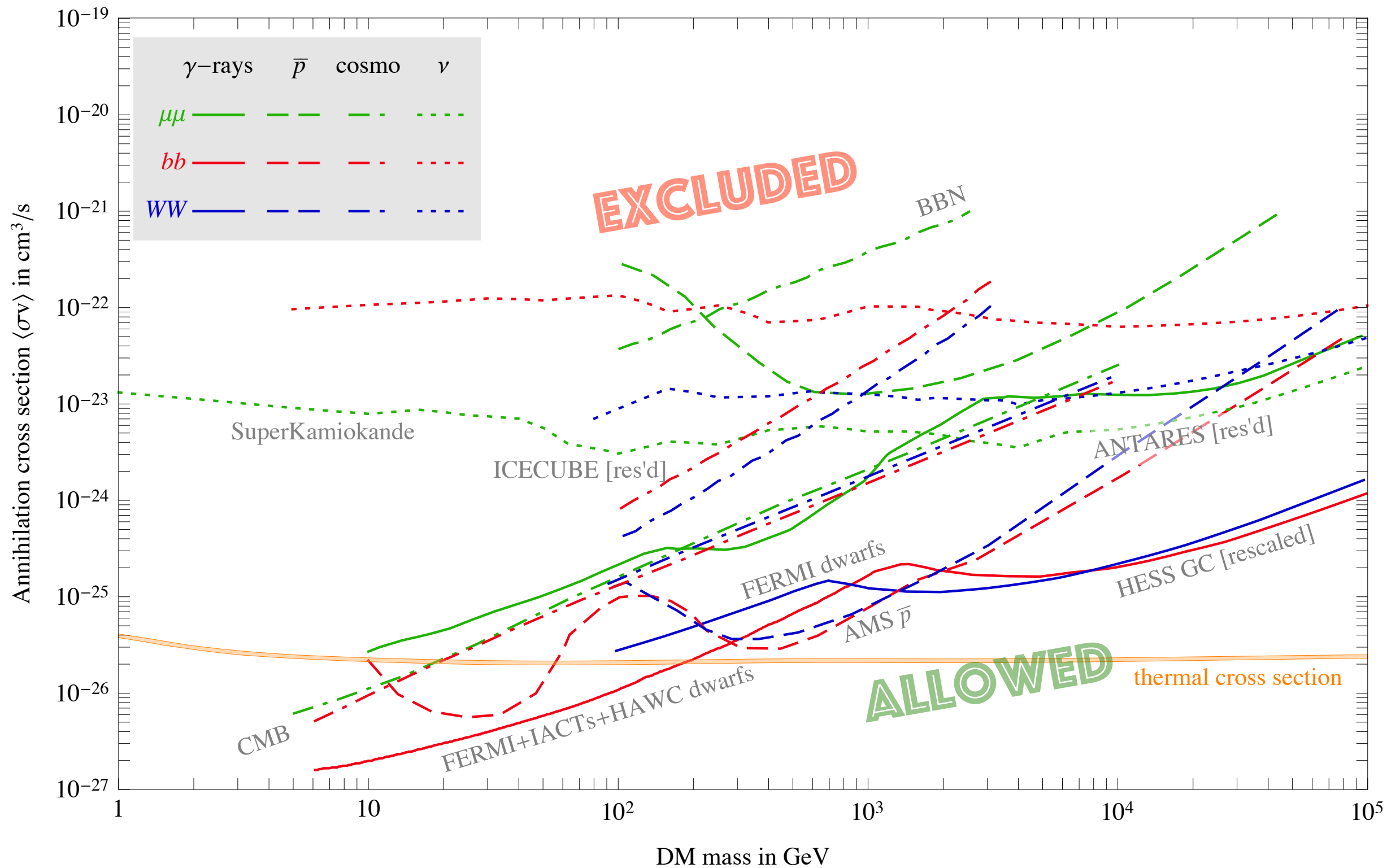
WIMP Indirect Detection

All Indirect Detection constraints



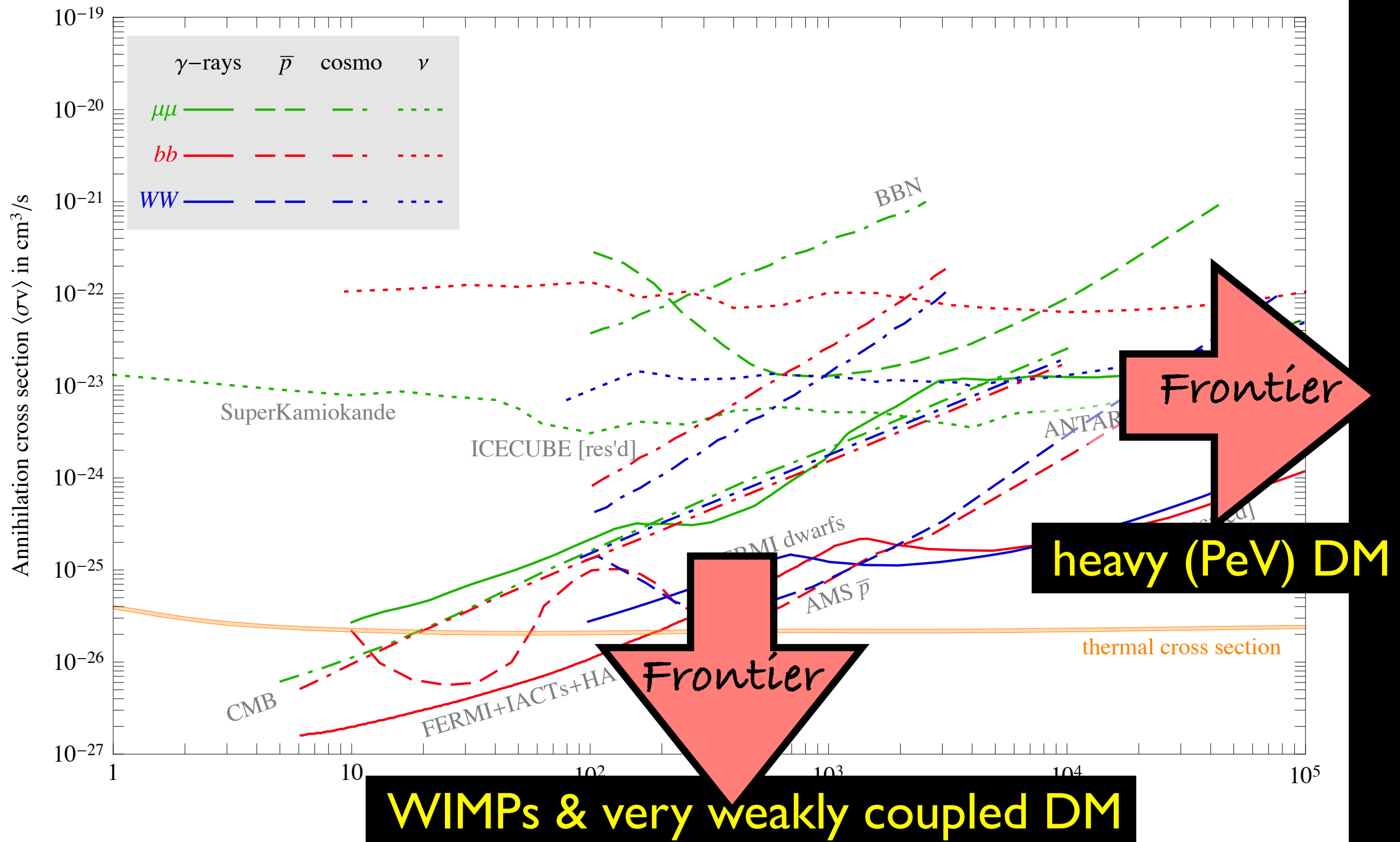
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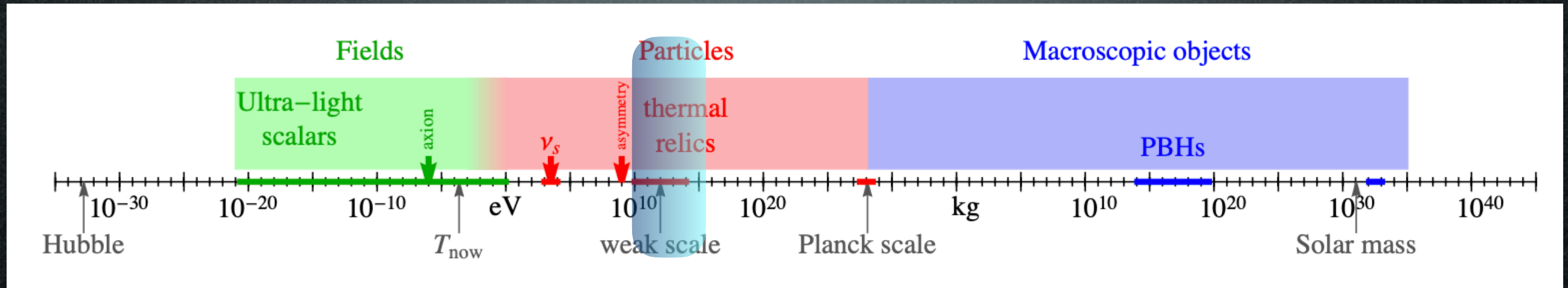
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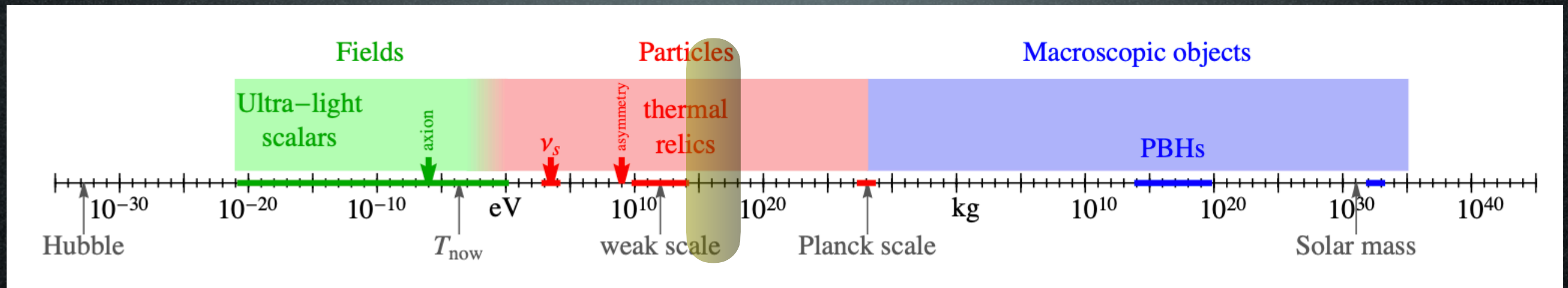
Candidates

A matter of perspective: plausible mass ranges



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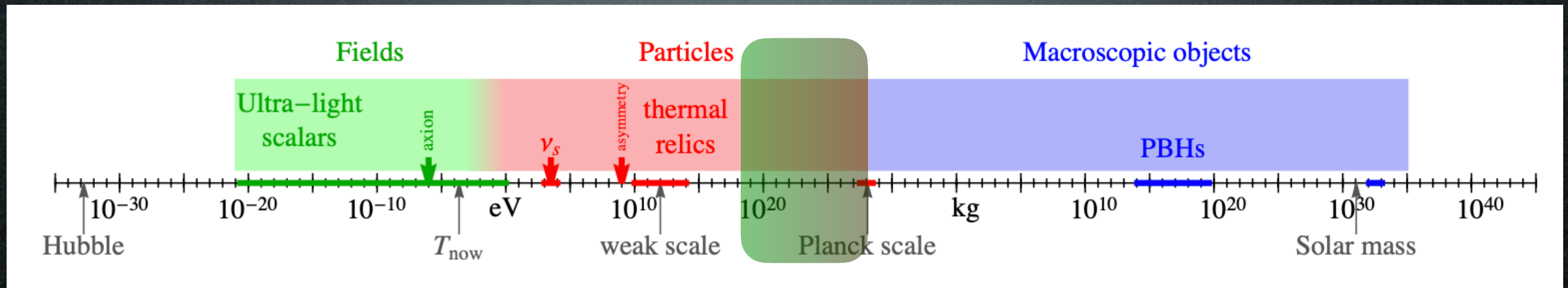


Super-heavy DM?

For definiteness / convention:
 $100 \text{ TeV} \lesssim M_{\text{DM}} \lesssim 1 \text{ EeV}$

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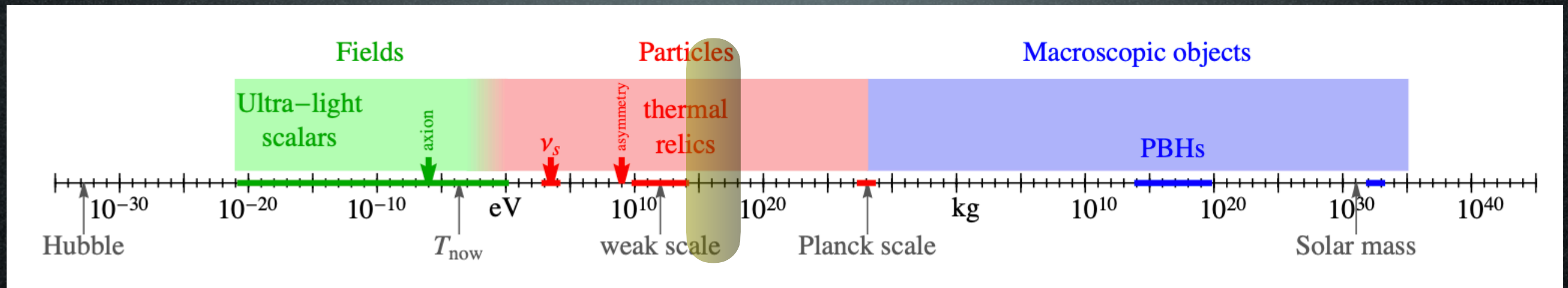
Ultra-heavy DM

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$$M_{\text{DM}} \gtrsim 1 \text{ EeV}$$

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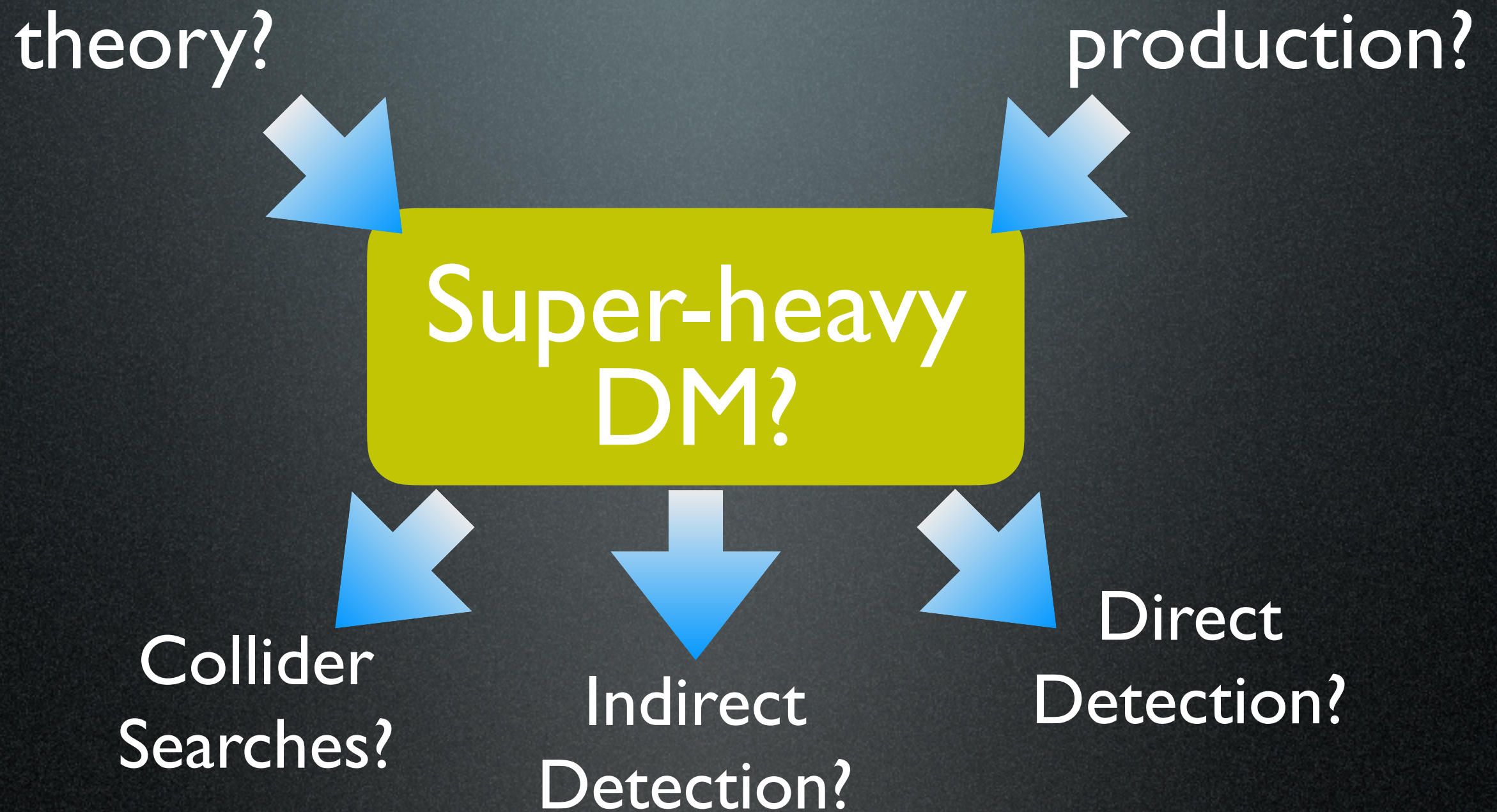
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Candidates



Theory

The unitarity bound

(super simplified)

Griest,
Kamionkowski
1990

$$\langle \sigma_{\text{ann}} v \rangle \approx \frac{4\pi \alpha^2}{M^2} \quad \alpha = \frac{g^2}{4\pi}$$

M too large $\Rightarrow \langle \sigma v \rangle$ too small $\Rightarrow$ too much DM

$$\Omega_{\text{DM}} = 0.26 \Rightarrow$$

$$M \lesssim 100 \text{ TeV}$$

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Under which conditions?

DM is an elementary particle
thermally produced
via $2 \rightarrow 2$ annihilations
in standard cosmology

Theory

Unitarity bound:

DM is an elementary particle
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~~in standard cosmology~~

Theory

Unitarity bound:

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~~in standard cosmology~~

Dilution: Homeopathic DM

Berlin, Hooper, Krnjaic
1602.08490, 1609.02555
Cirelli+ 1811.03608

Theory

Unitarity bound:

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~~in standard cosmology~~

Dilution: Homeopathic DM

Setup: DM charged under a new dark force (dark photon)
mixed with the photon

$$\mathcal{L} = \bar{X}(i\not{D} - M_{\text{DM}})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

parameters are: $\alpha, \epsilon, m_{V_D}, M_{\text{DM}}$

Berlin, Hooper, Krnjaic
1602.08490, 1609.02555
Cirelli+ 1811.03608

Theory

Unitarity bound:

DM is an elementary particle
thermally produced
via $2 \rightarrow 2$ annihilations
~~in standard cosmology~~

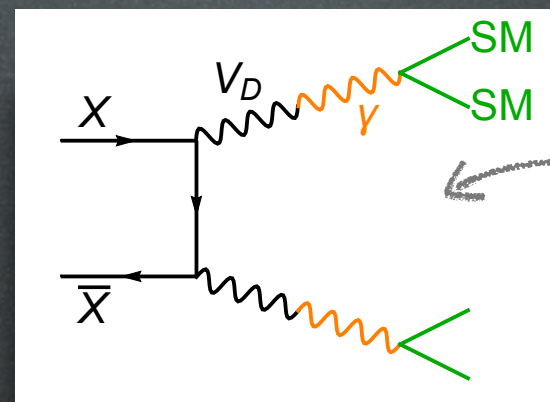
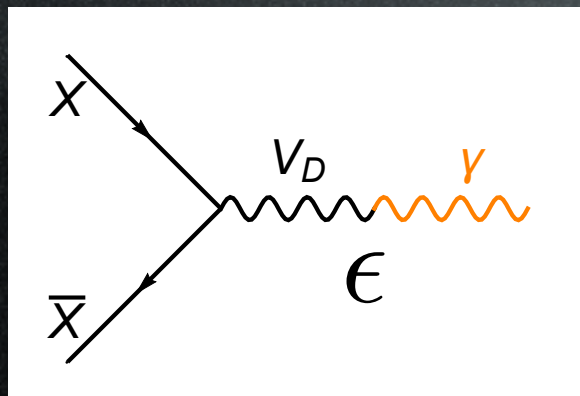
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These annihilations determine
the relic abundance

ϵ very small, V_D very long-lived (a few seconds)

Theory

Unitarity bound:

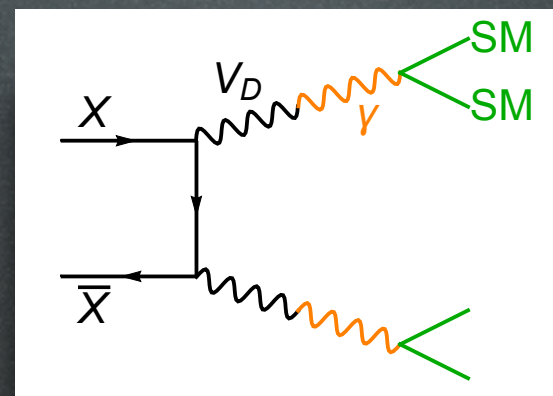
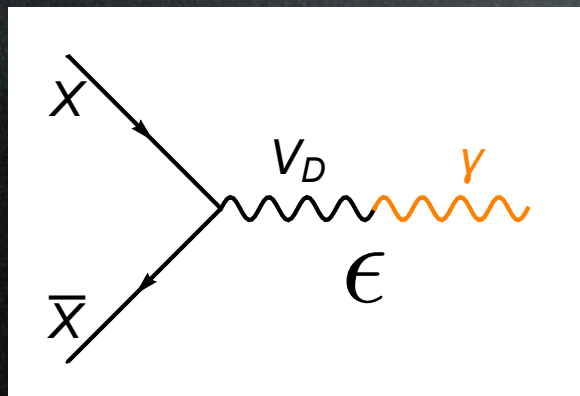
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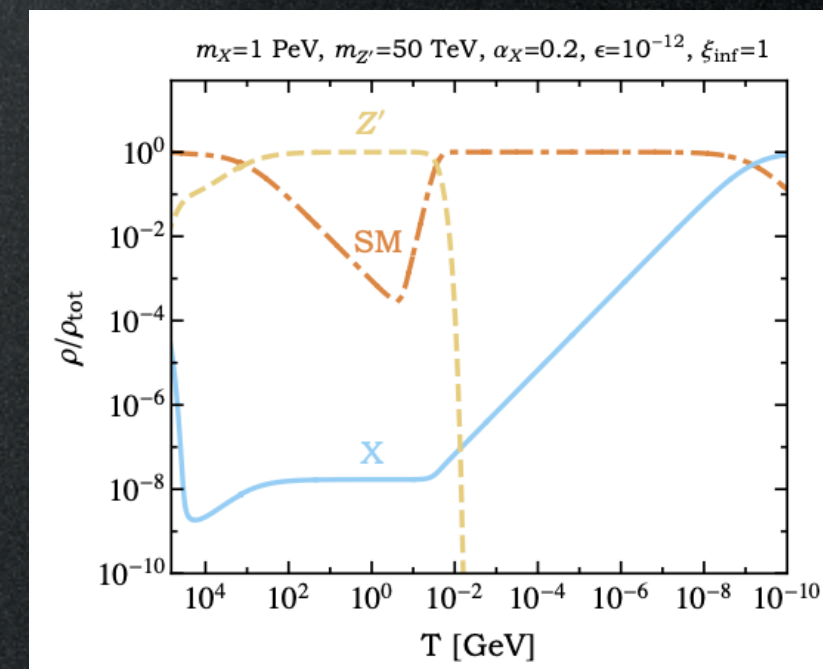
$$\mathcal{L} = \bar{X}(i\not{D} - M_{\text{DM}})X - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{D\mu\nu}F_Y^{\mu\nu}$$

parameters are: $\alpha, \epsilon, m_{V_D}, M_{\text{DM}}$



ϵ very small, V_D very long-lived (a few seconds)

Basic idea: DM super heavy hence super abundant,
but then V_D decays and dilutes,
bringing DM abundance back to needed



Berlin, Hooper, Krnjaic 1602.08490

Theory

Unitarity bound:

DM is an elementary particle
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via $2 \rightarrow 2$ annihilations
~~in standard cosmology~~

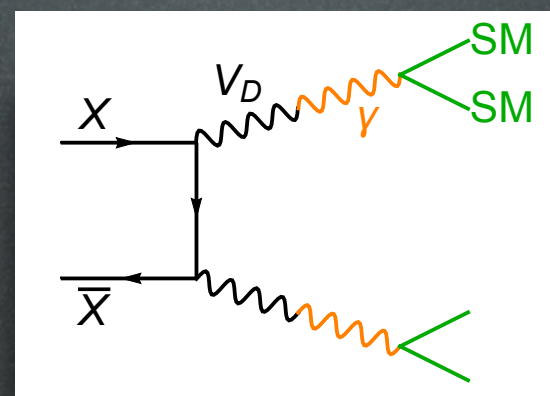
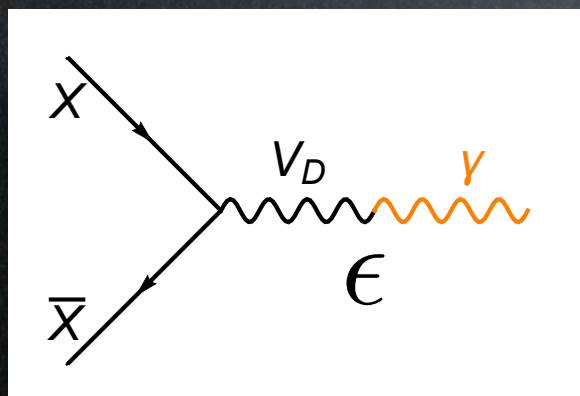
Dilution: Homeopathic DM

Berlin, Hooper, Krnjaic
1602.08490, 1609.02555
Cirelli+ 1811.03608

Setup: DM charged under a new dark force (dark photon)
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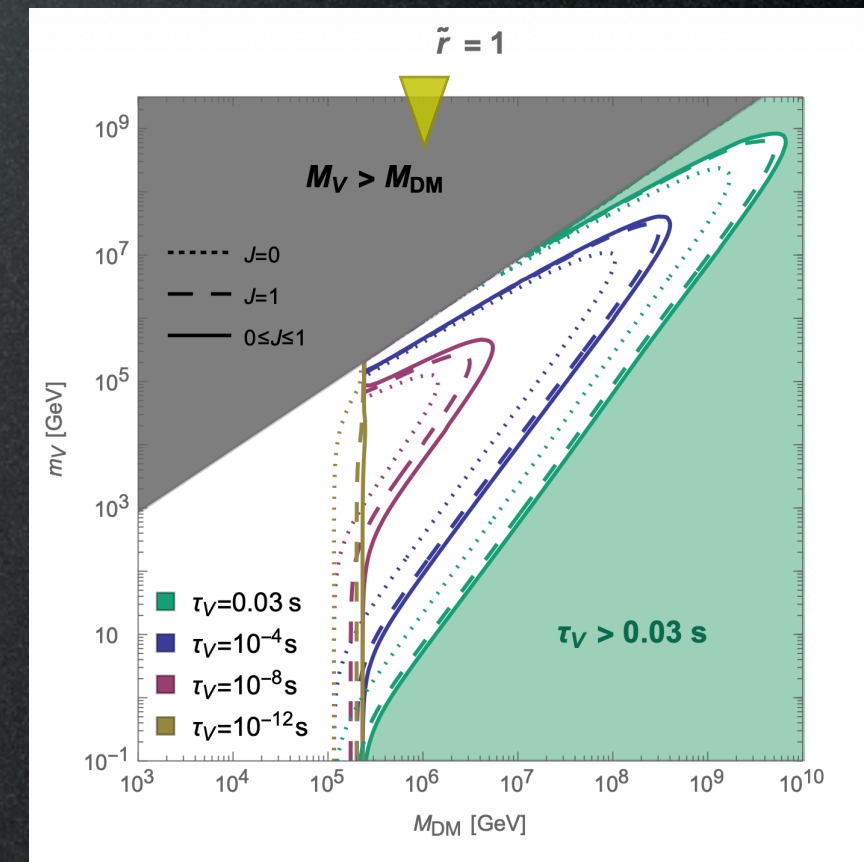
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Theory

Unitarity bound:

DM is an elementary particle
thermally produced

via $2 \rightarrow 2$ annihilations
in standard cosmology

Theory

Unitarity bound:

DM is an elementary particle thermally produced

via $2 \rightarrow 2$ annihilations
in standard cosmology

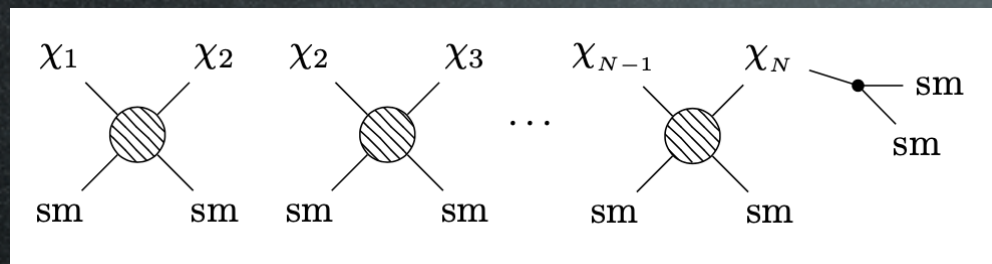
👁️ ‘Domino DM’

Kim, Kuflik 1906.00981

Basic idea: DM χ_1 has $N \sim$ degenerate friends, of which only χ_N decays.

SM shocks **knock-up** χ_1 for a long time, hence efficiently depleted.

Can be super-heavy



can reach

$$m_{\chi_1} \simeq 10^8 \text{ PeV}$$

Theory

Unitarity bound:

DM is an elementary particle thermally produced
via $2 \rightarrow 2$ annihilations
in standard cosmology

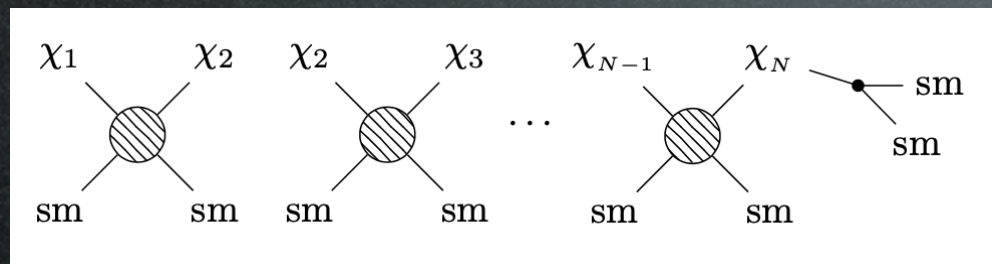
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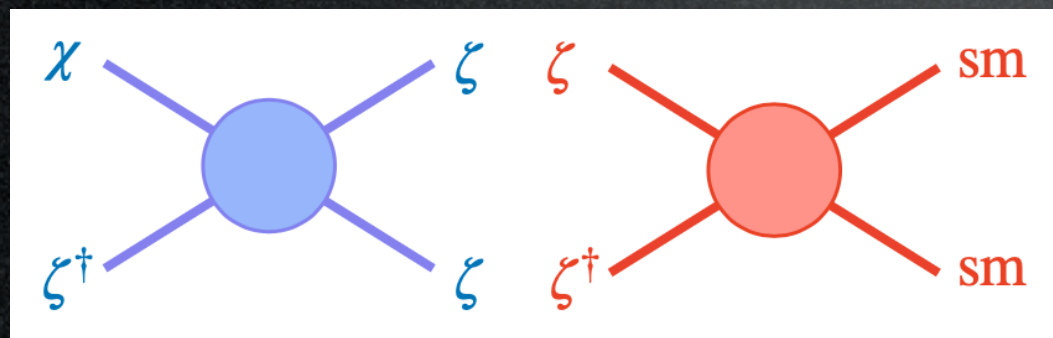
👁️ Zombie DM

Kramer, Kuflik, Ruderman 2003.04900
Generalizations in Kuflik+ 2207.01635

Basic idea: DM χ co-annihilates with a (much more abundant) **zombie** ζ ,

keeps annihilating for a long time hence efficiently depleted.

Can be super-heavy



$m_\chi > m_\zeta$ so that the zombie infection proceeds,
and $m_\chi < 3m_\zeta$ so that $\chi \nrightarrow \zeta\zeta\zeta$ (DM stability)

can reach

$$m_\chi \simeq 10^6 \text{ PeV}$$

Phenomenology?
ID via annihilations or
decays of the zombies

Theory

Unitarity bound:

DM is an elementary particle

~~thermally-produced~~

via $2 \rightarrow 2$ annihilations

in standard cosmology

• **Non-thermal production / Phase Trans.**

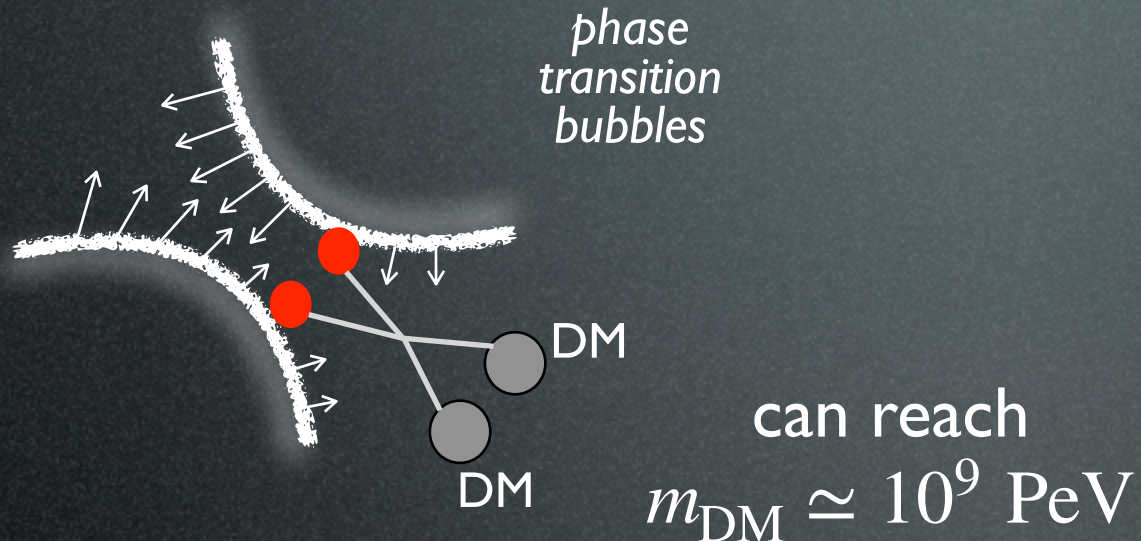
Theory

Unitarity bound:

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Non-thermal production

Bubble collisions



Basic idea: ultrarelativistic bubble walls push SM particles that collide at super-high energy, produce super-heavy DM

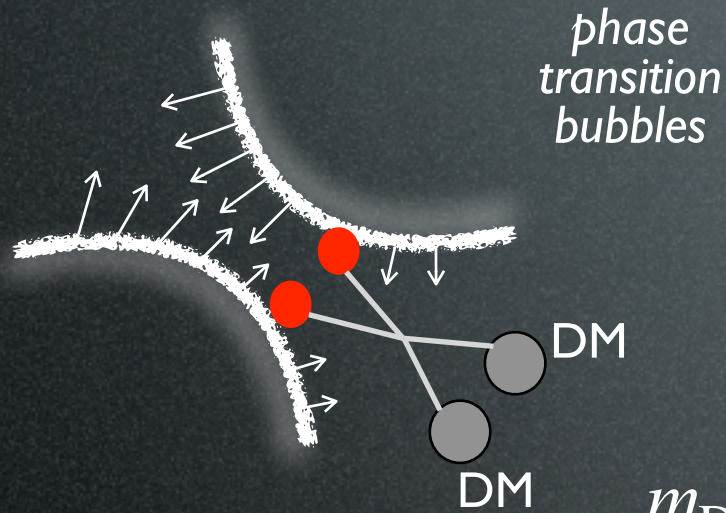
Falkowski, No 1211.5615
Baldes, Sala, Gouttenoire+
2306.16555, 2207.08096...

Theory

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Non-thermal production

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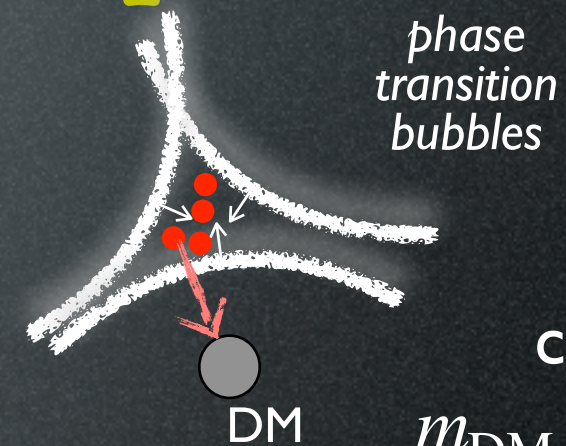


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Baldes, Sala, Gouttenoire+
2306.16555, 2207.08096...

Filtered DM - Compressed DM



can reach
 $m_{\text{DM}} \simeq 10^{12} \text{ PeV}$

Basic idea: ultrarelativistic bubble walls compress DM particles; super-heavy ones cross the wall and survive

Baker, Kopp 1912.02830
Chway+ 1912.04238
Azatov+ 2101.05721

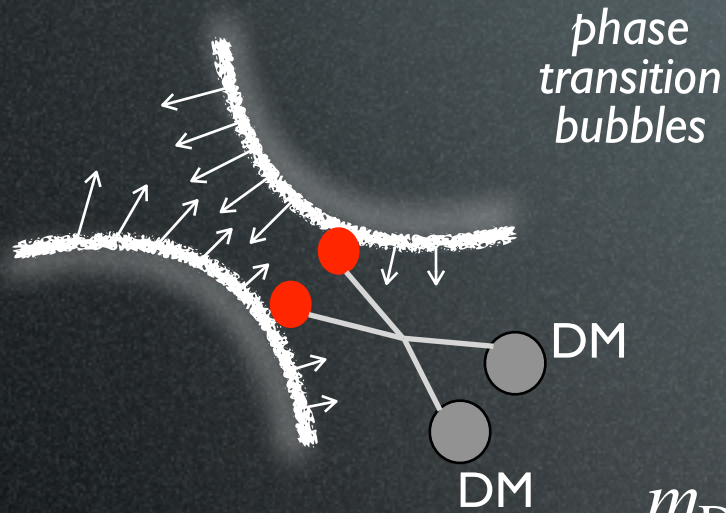
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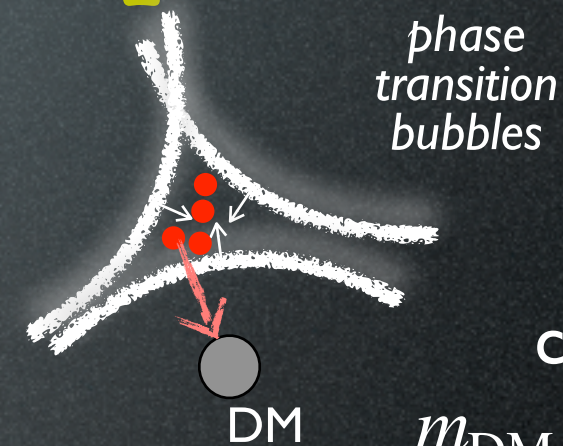


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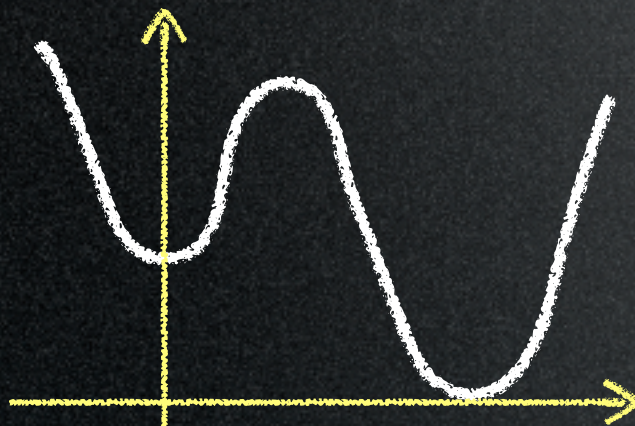


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Supercooling



Basic idea: in the EU, DM is trapped in a false vacuum, and light, hence abundantly produced; After PT, DM becomes (super-)heavy and the reheating (from the PT) dilutes the abundance

Hambye, Strumia, Teresi 1806.01473
Baldes, Gouttenoire, Sala, Servant 2110.13926
Wagner, Medina+ 2602.16822

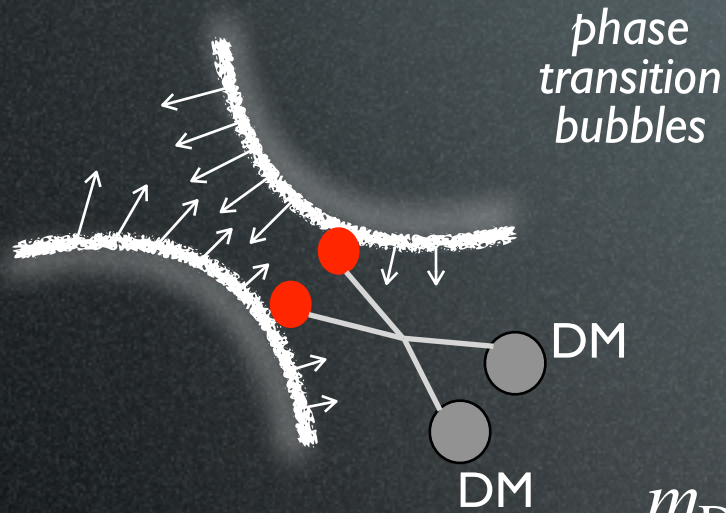
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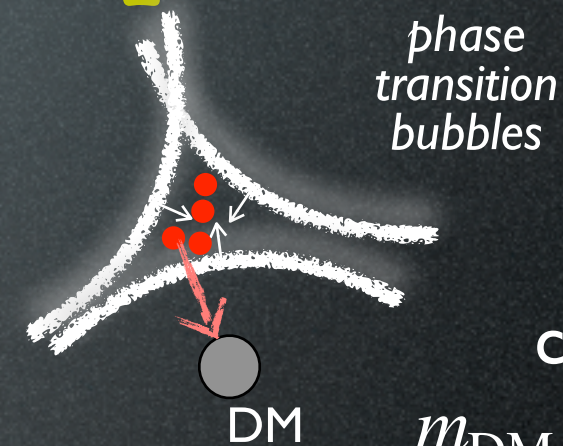


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2306.15555, 2207.05096...

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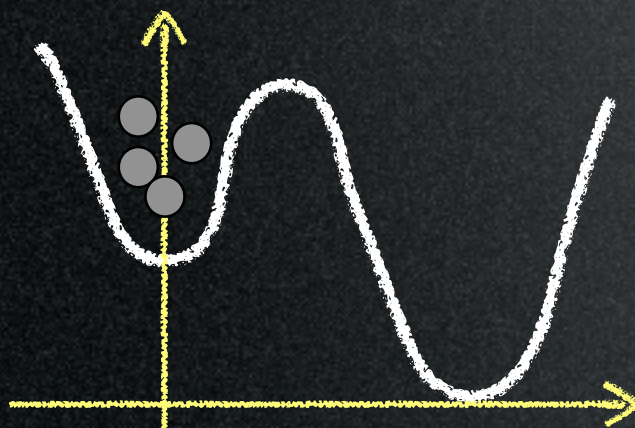


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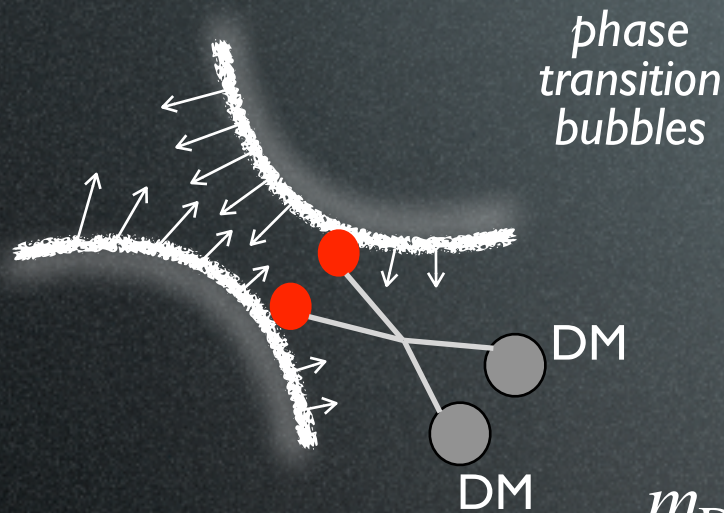
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Non-thermal production

Bubble collisions

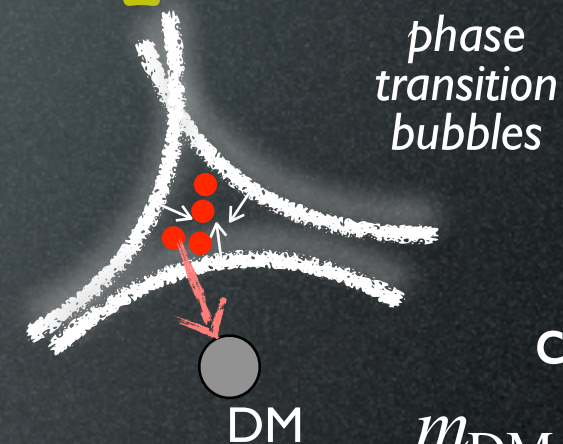


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2306.15555, 2207.05096...

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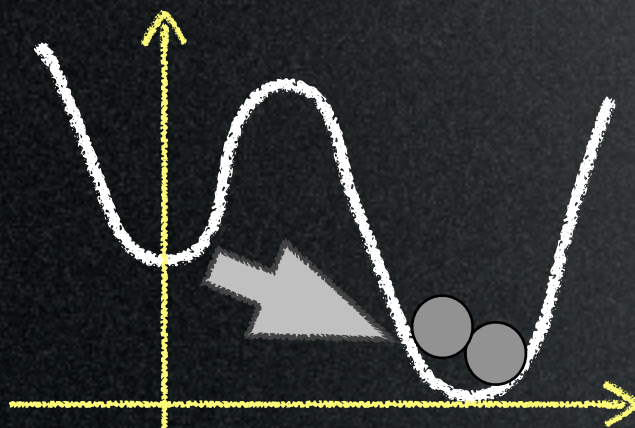


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Basic idea: ultrarelativistic bubble walls compress DM particles; super-heavy ones cross the wall and survive

Baker, Kopp 1912.02830
Chway+ 1912.04238
Azatov+ 2101.05721

Supercooling



Basic idea: in the EU, DM is trapped in a false vacuum, and light, hence abundantly produced; After PT, DM becomes (super-)heavy and the reheating (from the PT) dilutes the abundance

can reach
 $m_{\text{DM}} \simeq 10^3 \text{ PeV}$

Hambye, Strumia, Teresi 1805.01473
Baldes, Gouttenoire, Sala, Servant 2110.13926
Wagner, Medina+ 2602.16822

Theory

Unitarity bound:

DM is ~~an elementary particle~~
thermally produced
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in standard cosmology

Compositeness

Harigaya+ 1606.00159
Also: Contino+ 1811.06975

Theory

Unitarity bound:

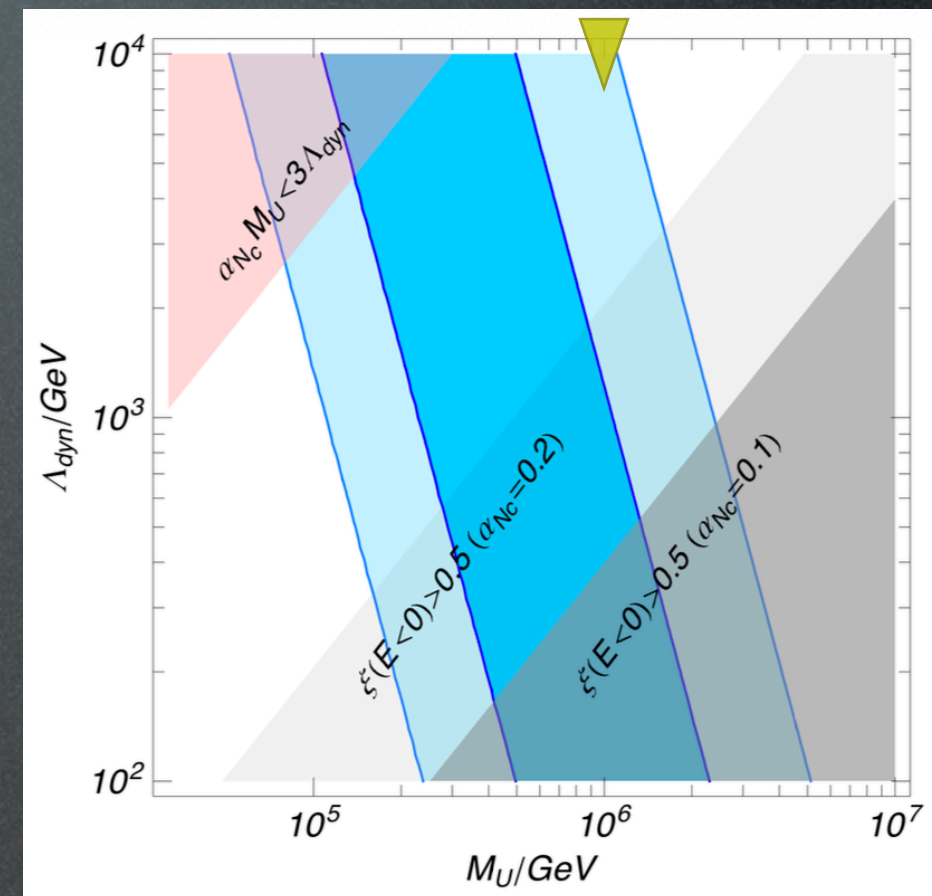
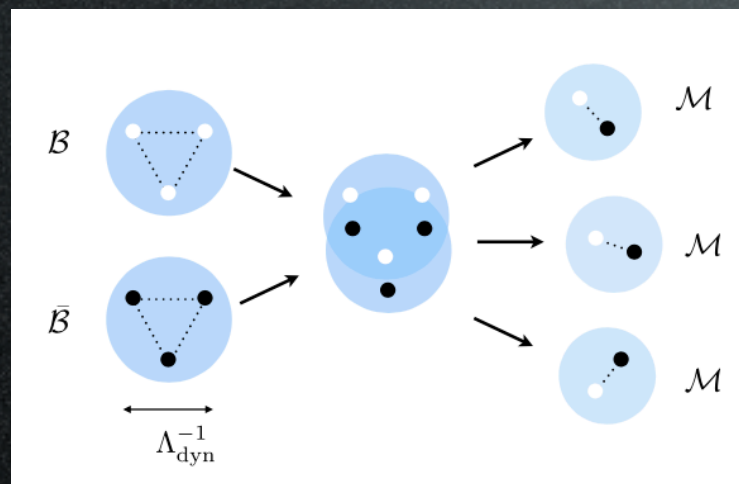
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Compositeness

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If DM is a bound state of N (heavy) constituents

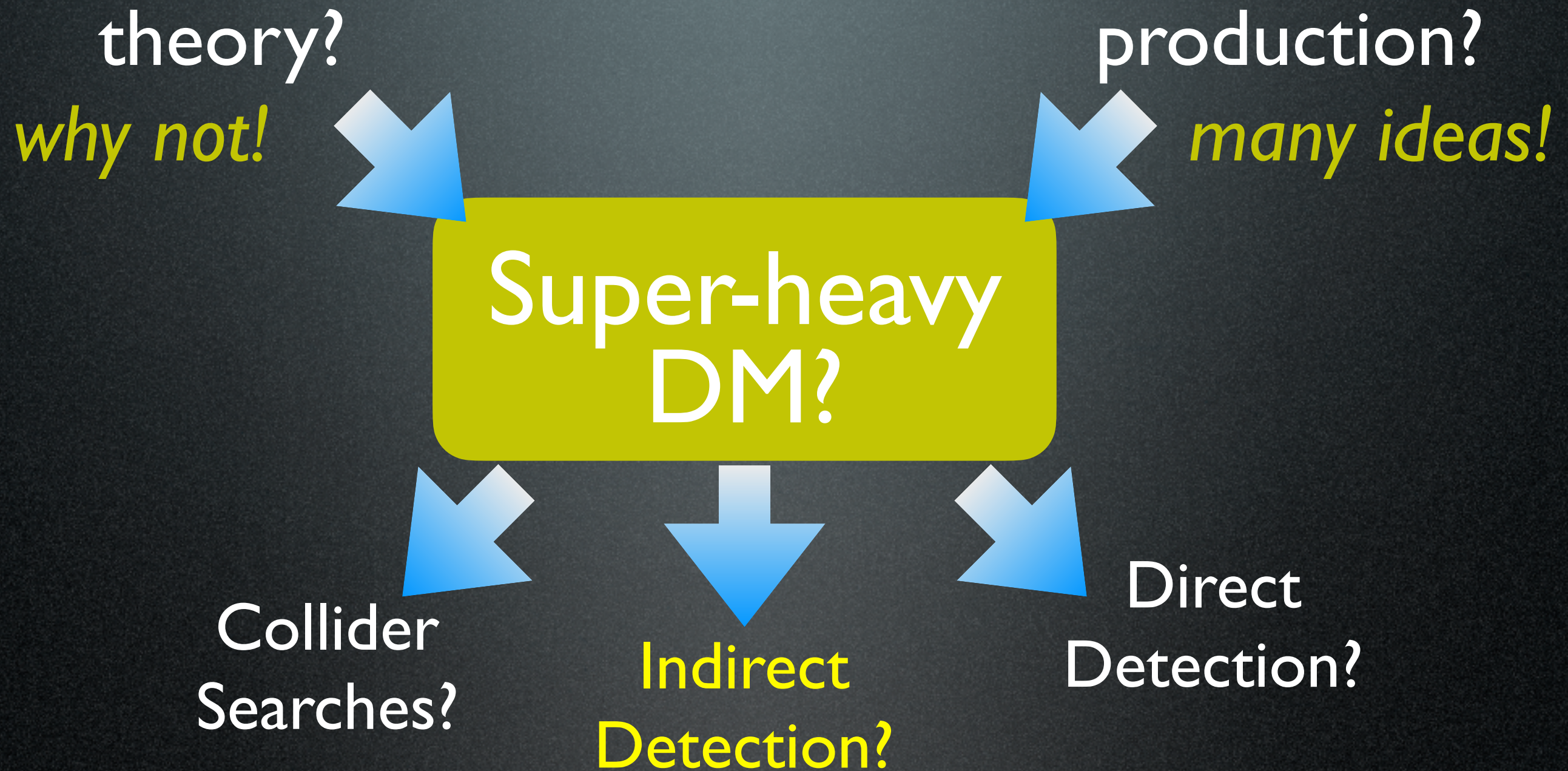
$$\sigma \simeq 4\pi R^2$$



Harigaya+ 1606.00159

Basic idea: DM freezes-out, but the crucial parameter is no more M_{DM} ,
rather it's R , in turn connected to some scale of 'confinement'.
DM can be super-heavy; as long as it is also large, it annihilates efficiently

Candidates



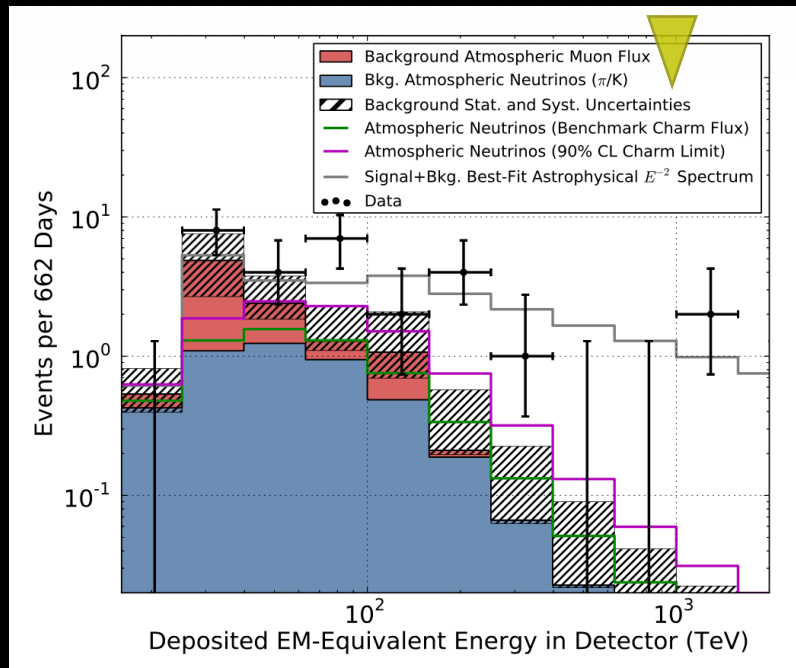
Super-heavy DM ID

NB: ▼ = 1 PeV

Super-heavy DM ID

Turning point: the IceCube HE data

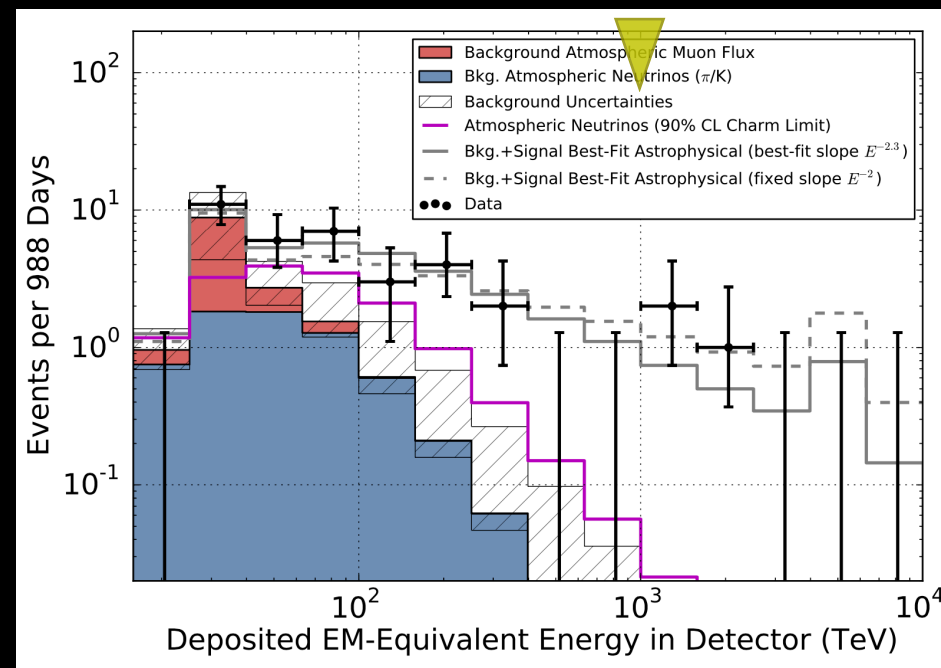
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector



[IceCube 1311.5238](#)

28 events (incl. Bert & Ernie),
of which 2 already in [1304.5356](#),
the first ones above PeV

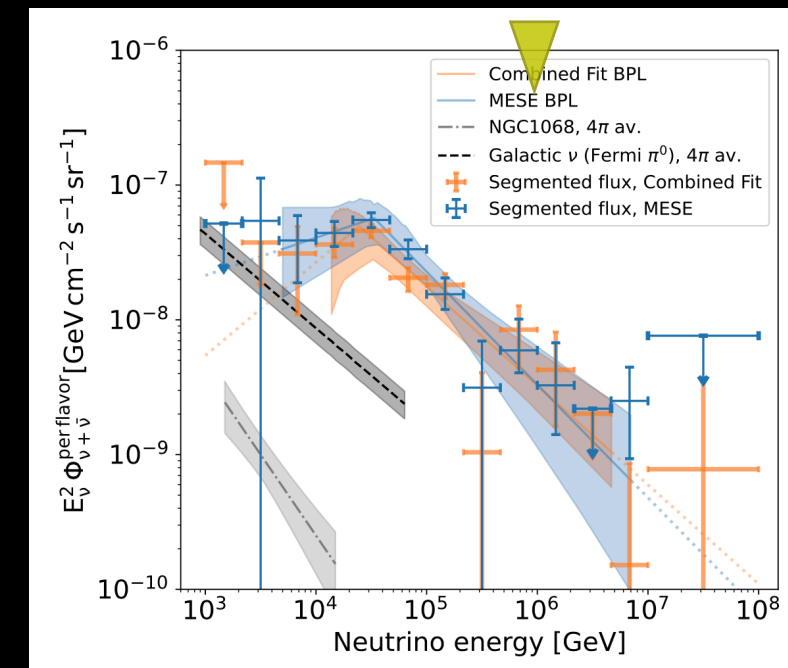
Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data



[IceCube 1405.5303](#)

Total of 37 events

Evidence for a Spectral Break or Curvature in the Spectrum of Astrophysical Neutrinos from 5 TeV to 10 PeV



[IceCube 2507.22233](#)

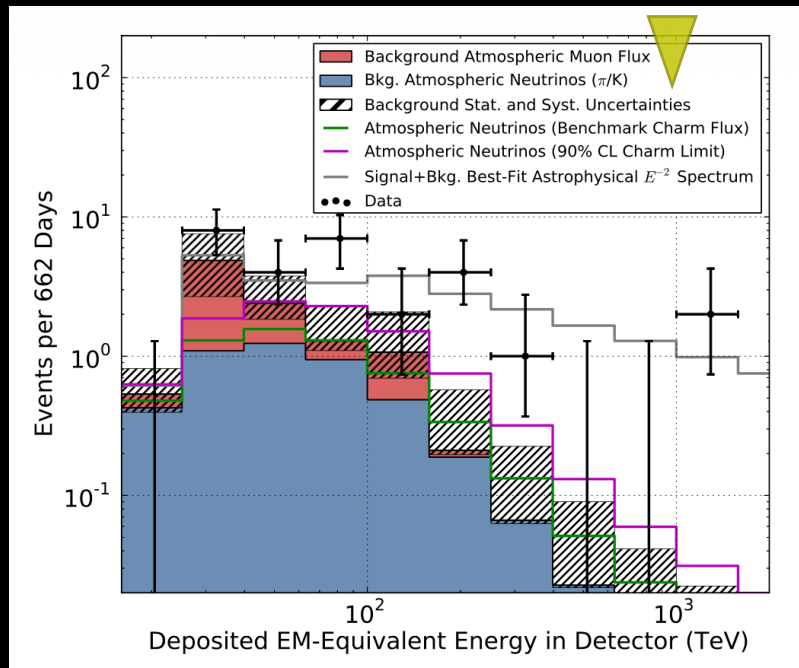
See also [2507.22234](#)

[2502.19776](#)

Super-heavy DM ID

Turning point: the IceCube HE data

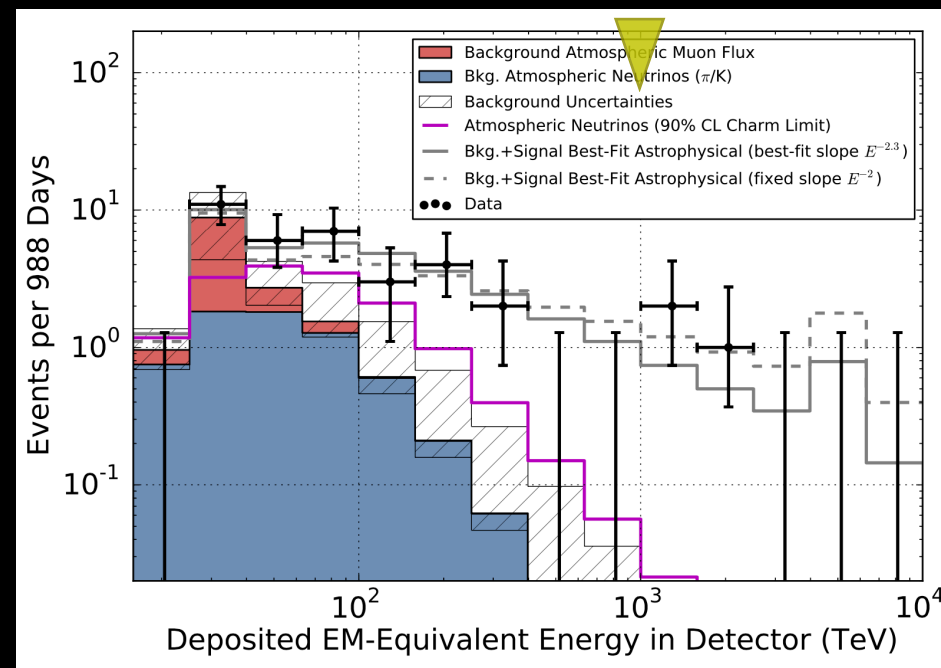
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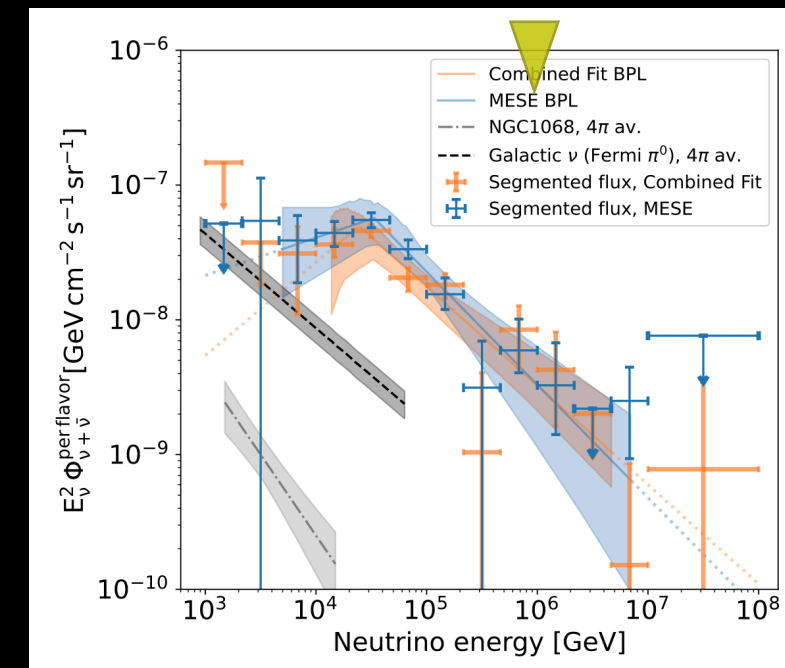
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See also 2507.22234

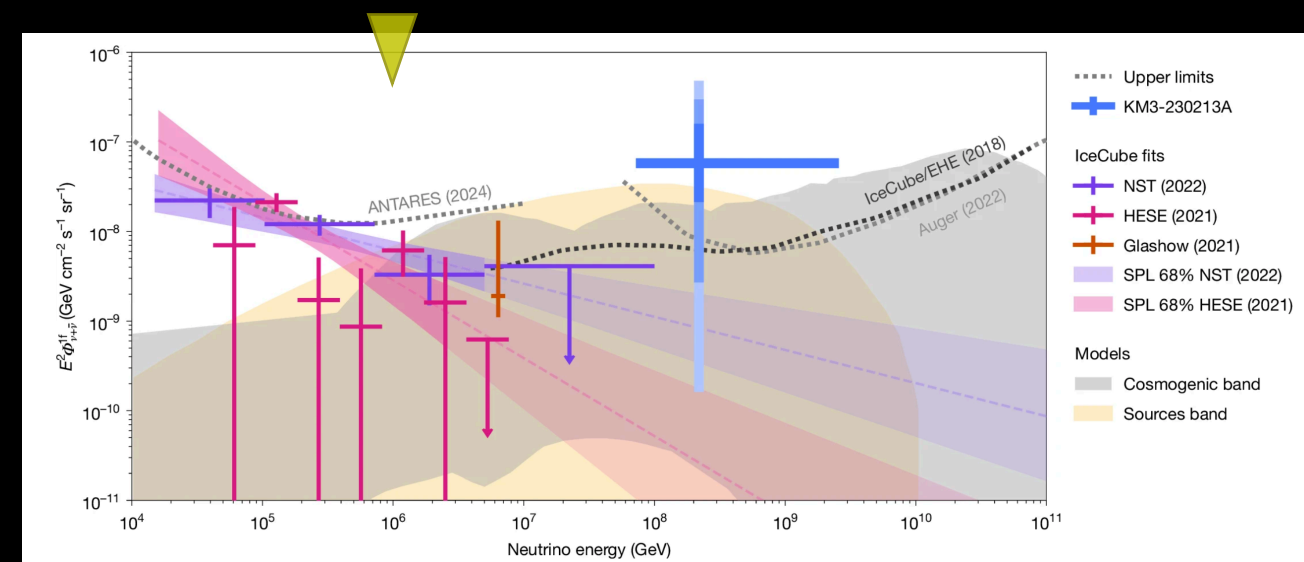
2502.19776

Then Amaterasu event: $2.4 \cdot 10^5$ PeV

Telescope Array coll. 2311.14231

Then KM3NeT: ~ 220 PeV
(110-790 PeV @68%CL,
muon energy 120^{+110}_{-60} PeV)

KM3NeT coll. Nature 638 (2025)

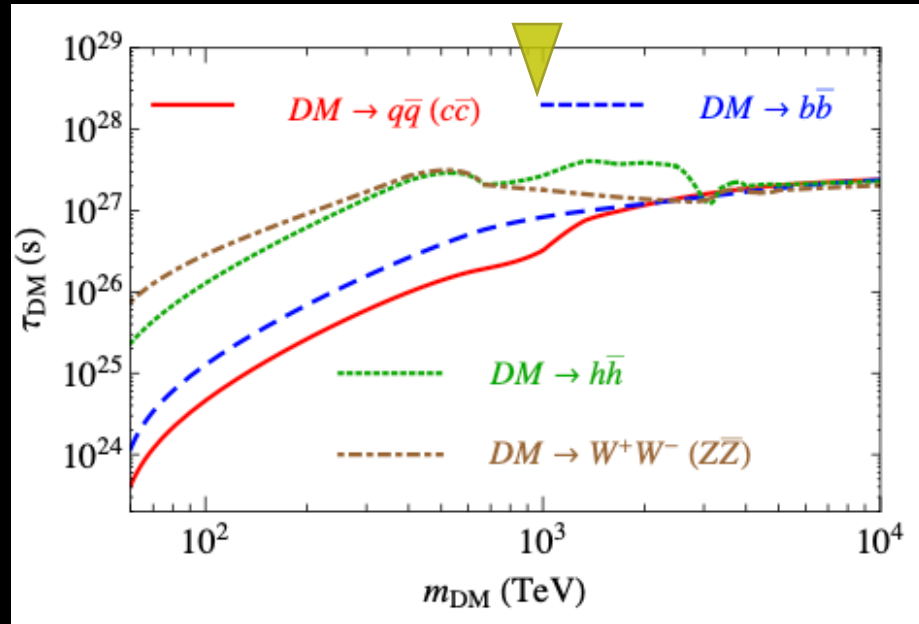


Super-heavy DM ID

Decaying DM - neutrinos

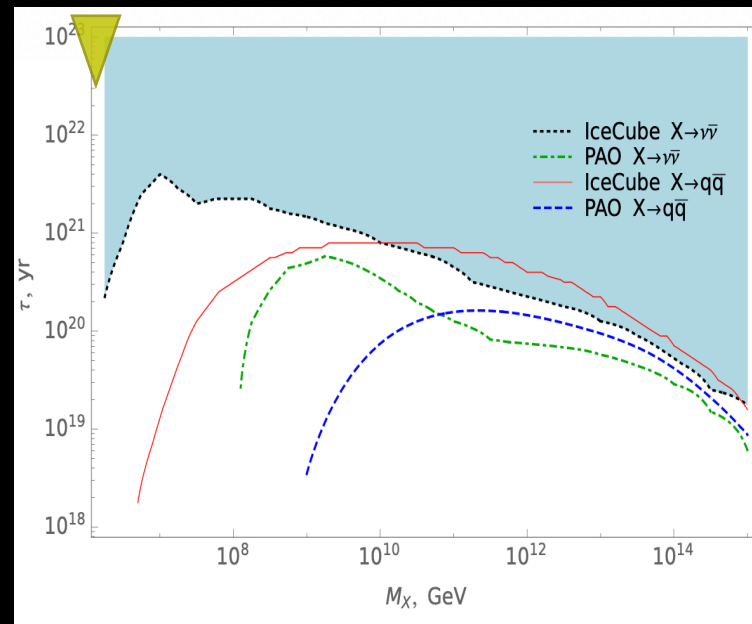
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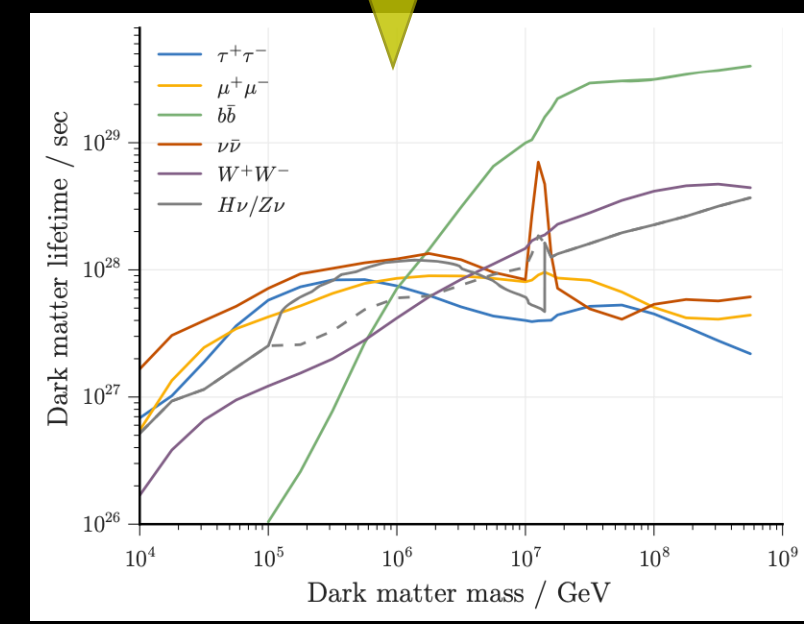
2014 IceCube data

Esmaili Kang Serpico 1410.5979

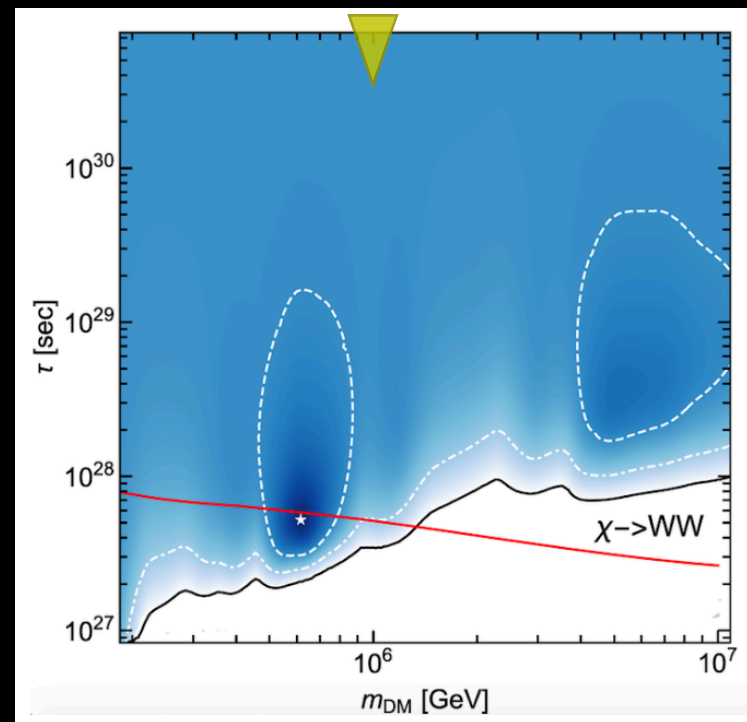


PAO,
IceCube

Kachelriess, Kalashev, Kuznetsov
1805.04500

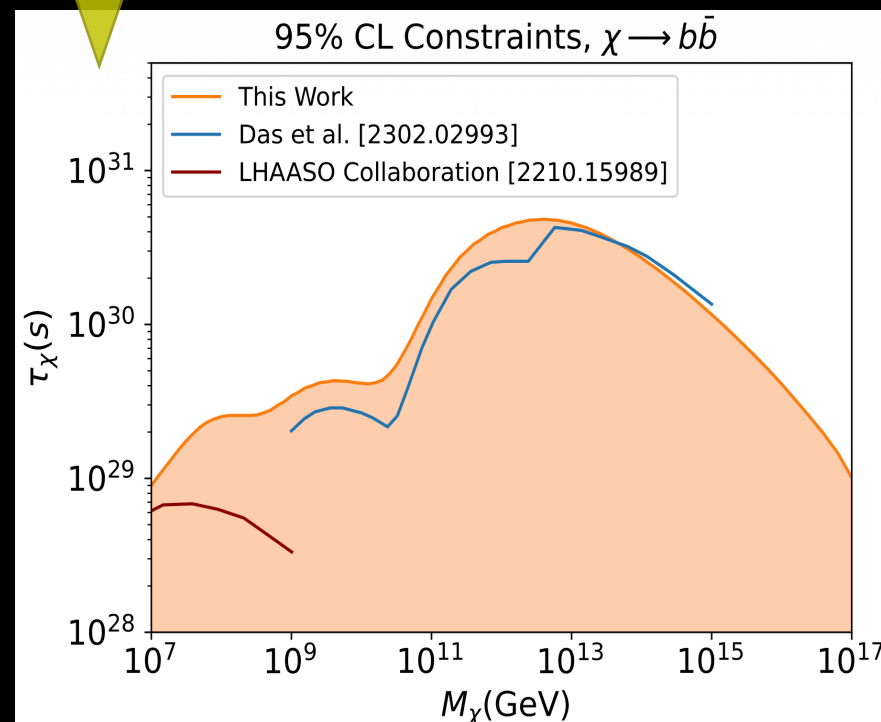


IceCube 1804.03848



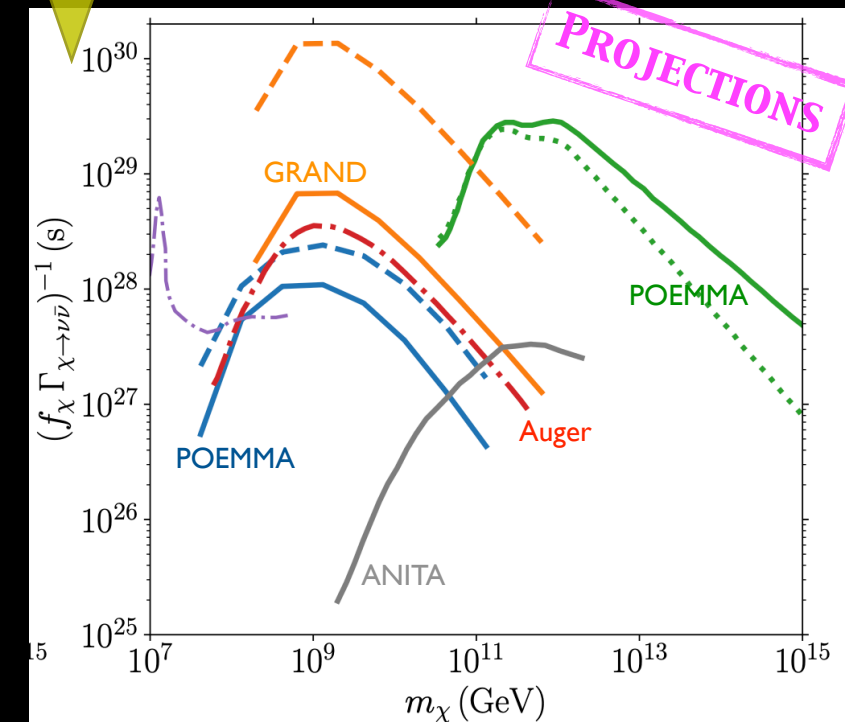
IceCube fit
(w astro component)

Chianese+ 1907.11222
Also: Sui Dev 1804.04919



KM3NeT event

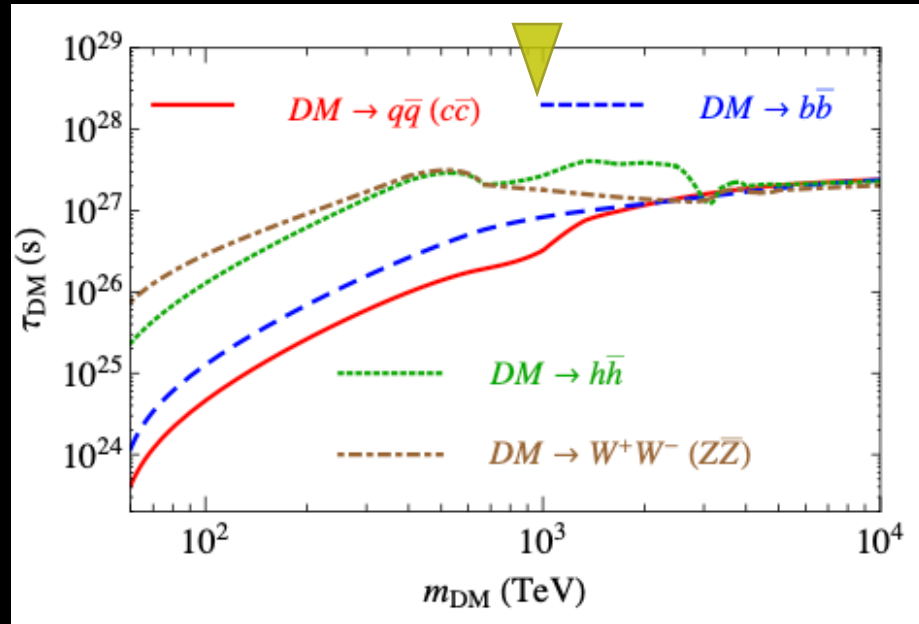
Aloisio, Evoli+ 2508.08779



Guépin+ 2106.04446

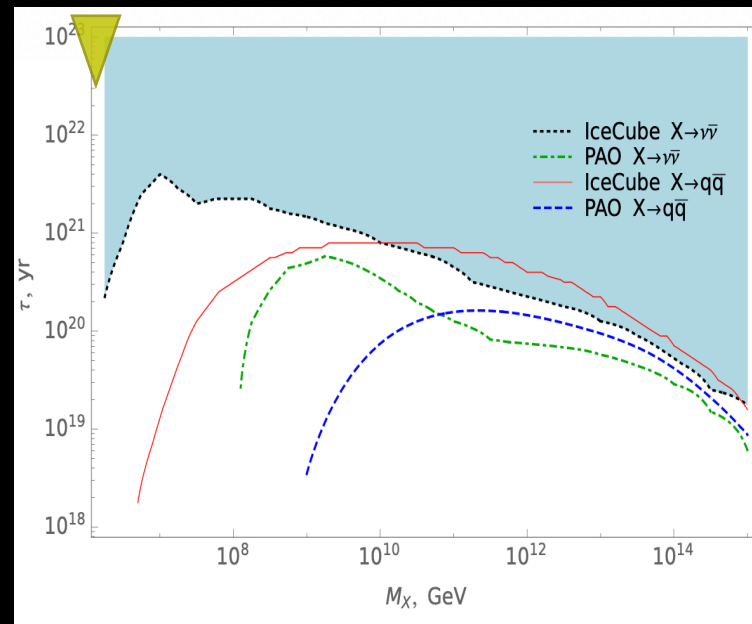
Super-heavy DM ID

Decaying DM - neutrinos



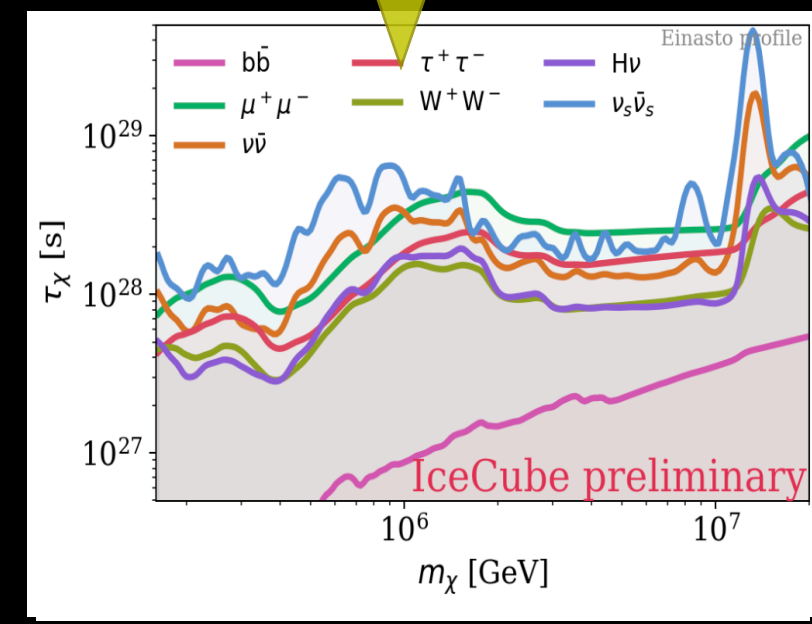
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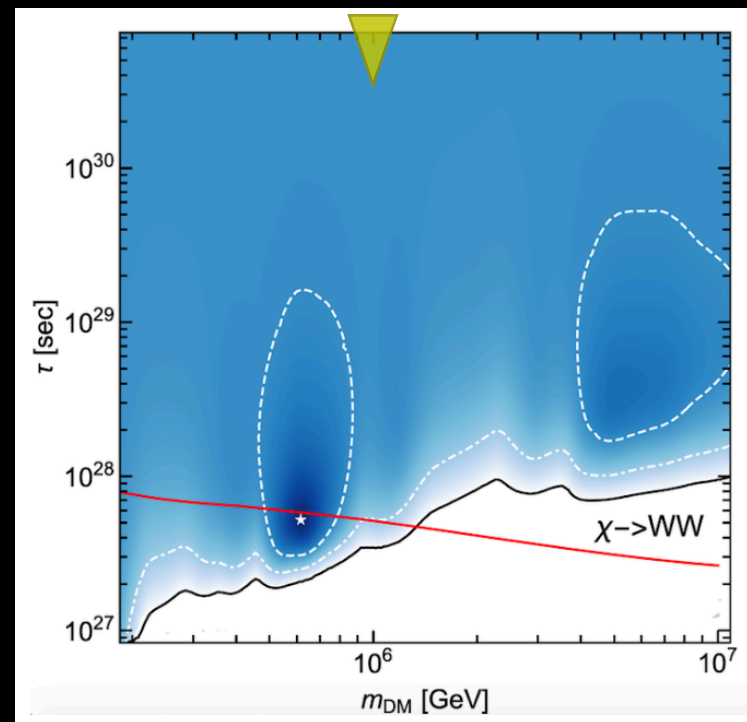


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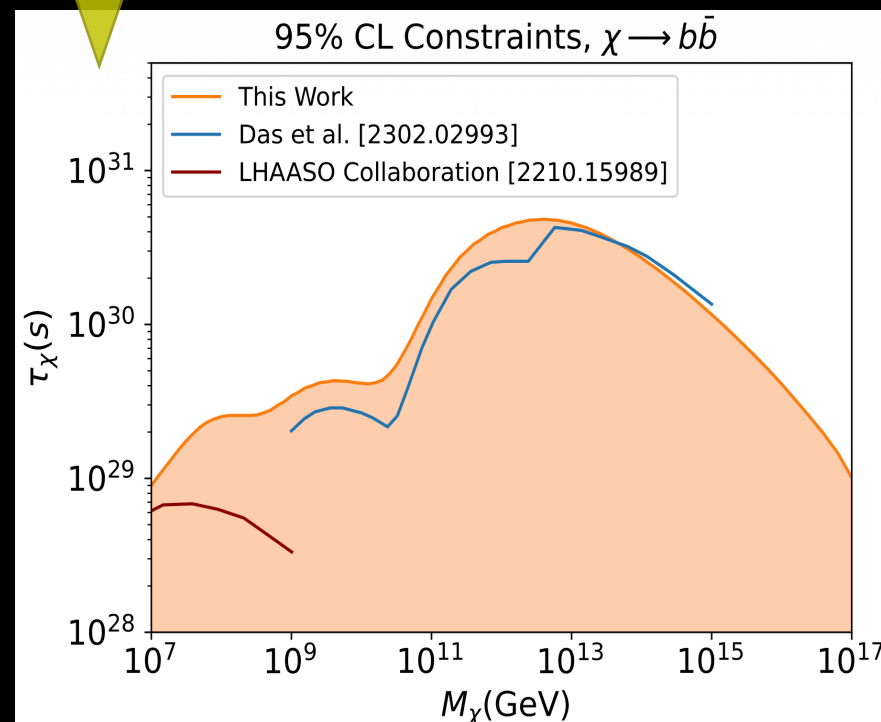


IceCube 1907.11193
also: IceCube 2107.11527 (clusters)



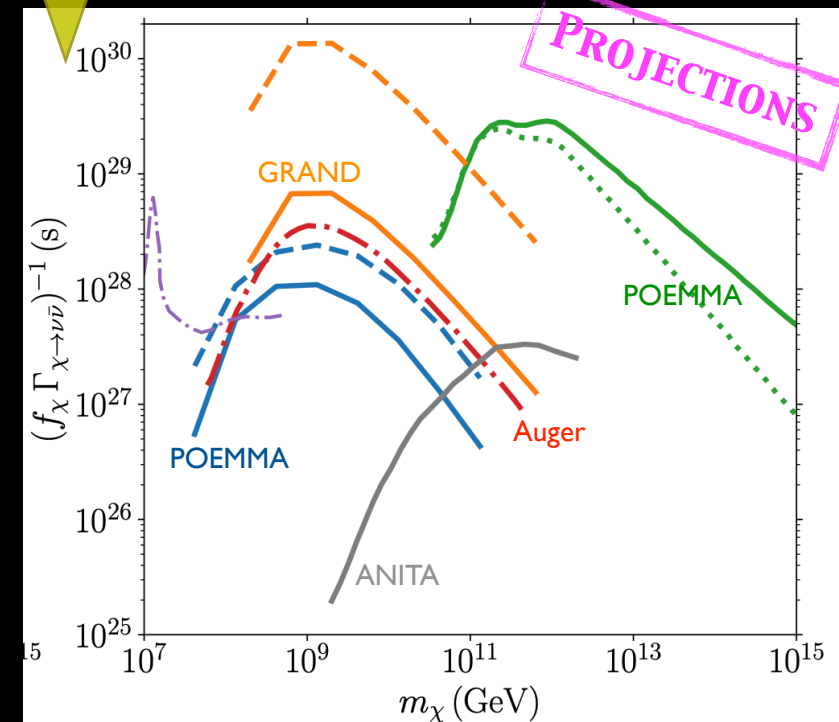
IceCube fit
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KM3NeT event

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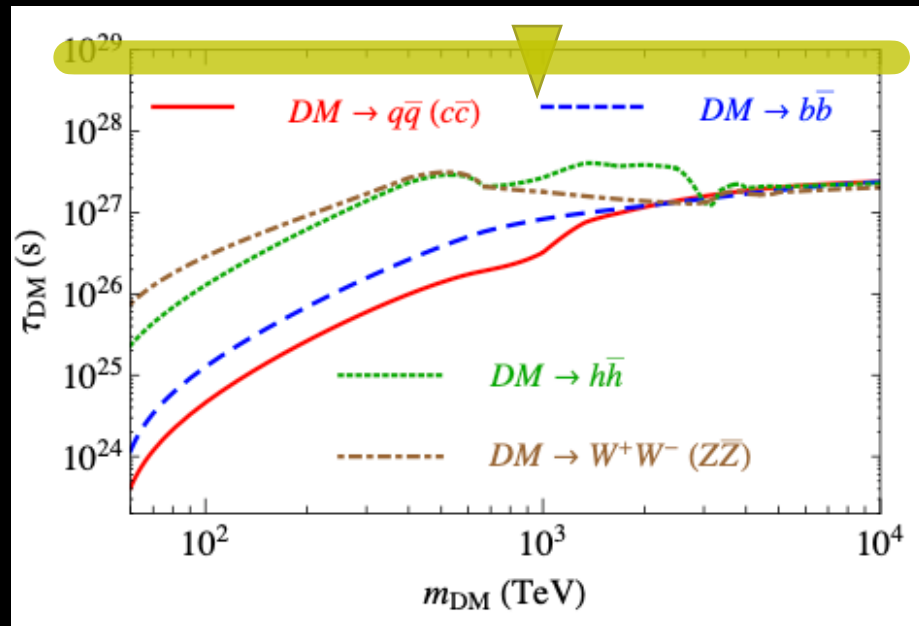


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Super-heavy DM ID

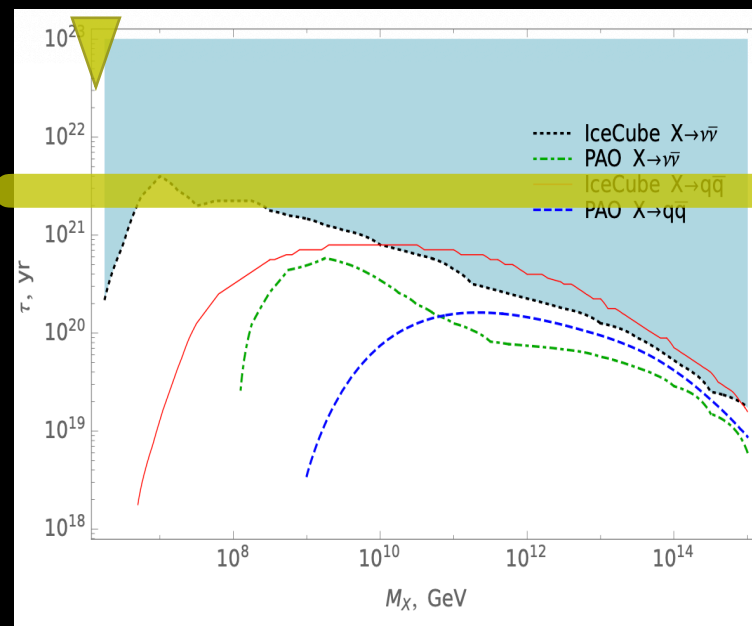
Decaying DM - neutrinos

$$\tau = 10^{29} \text{ sec}$$



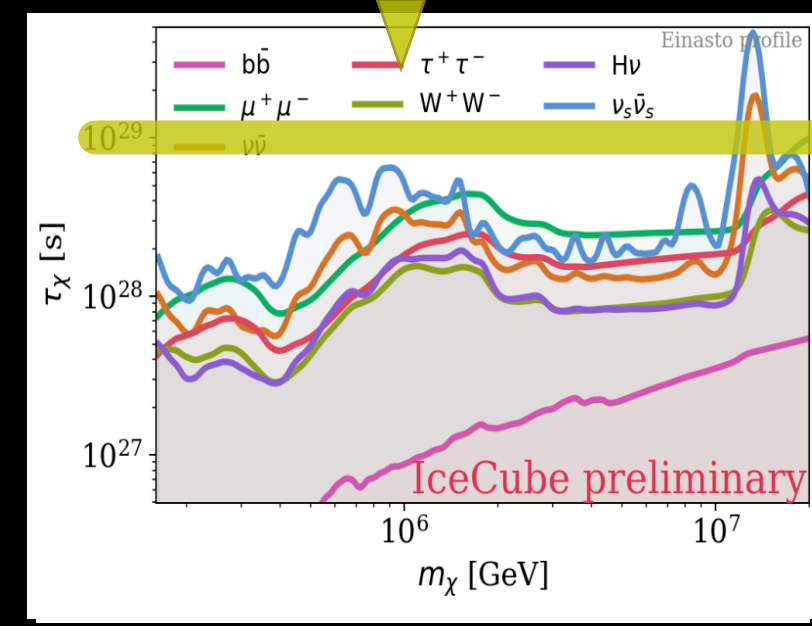
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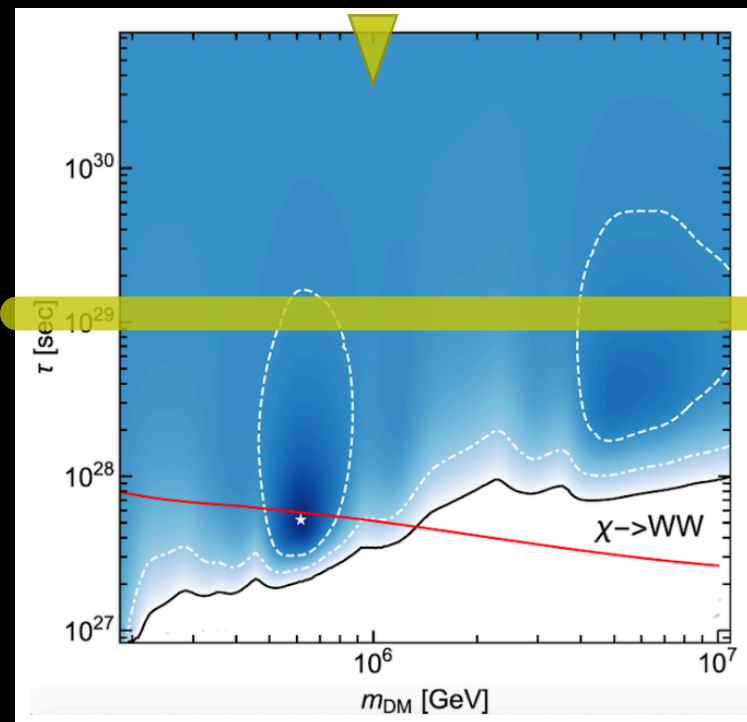


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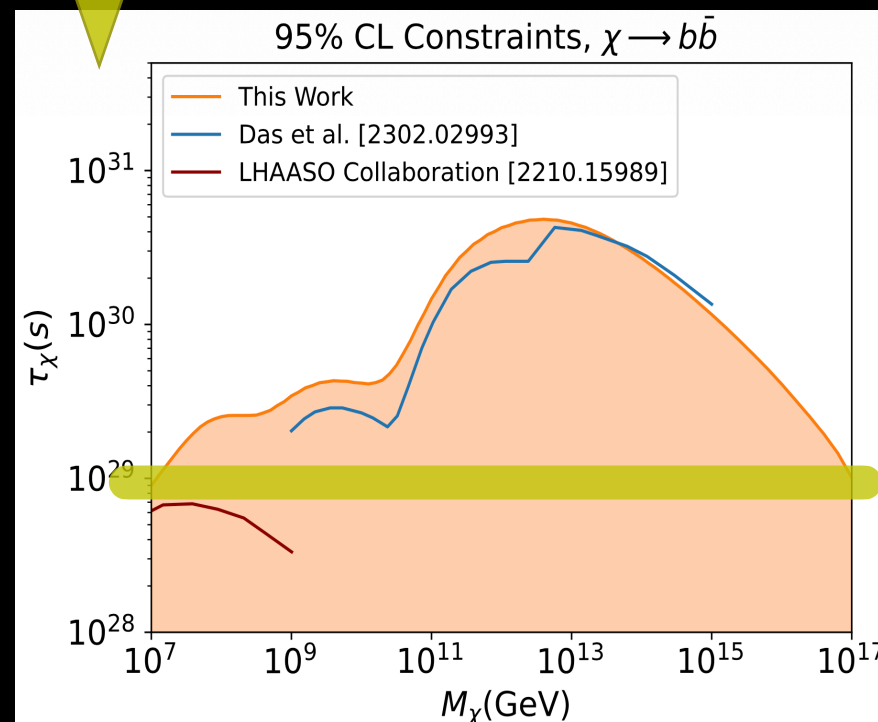


IceCube 1907.11193
also: IceCube 2107.11527 (clusters)



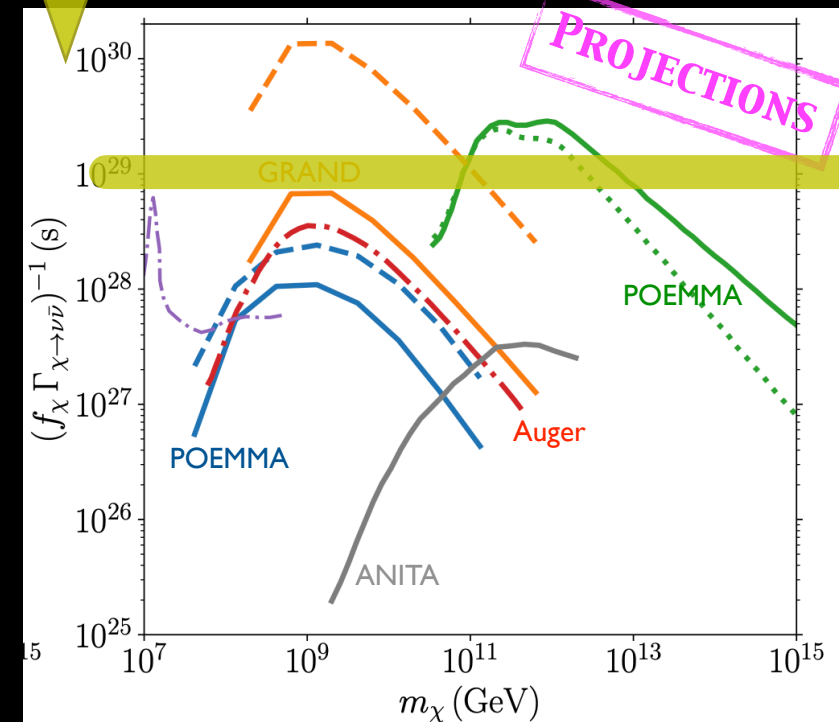
IceCube fit
(w astro component)

Chianese+ 1907.11222
Also: Sui Dev 1804.04919



KM3NeT event

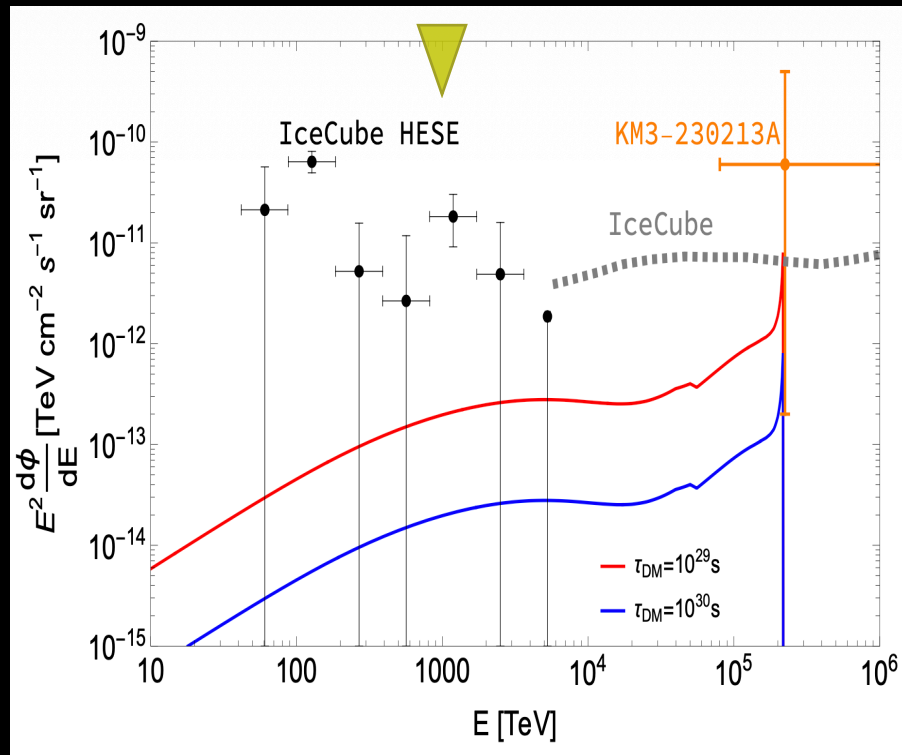
Aloisio, Evoli+ 2508.08779



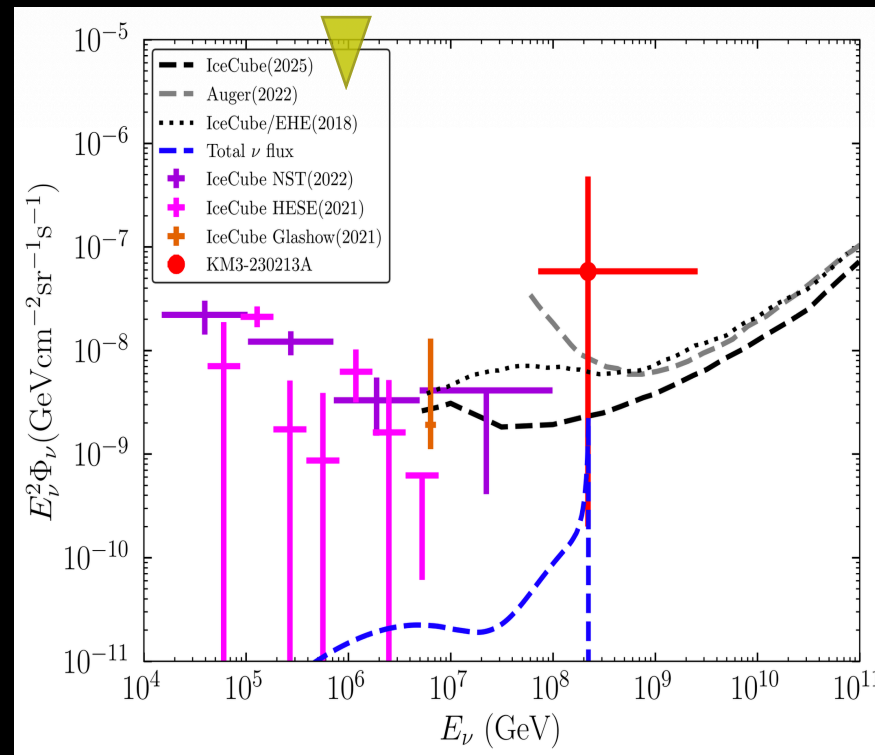
Guépin+ 2106.04446

Super-heavy DM ID

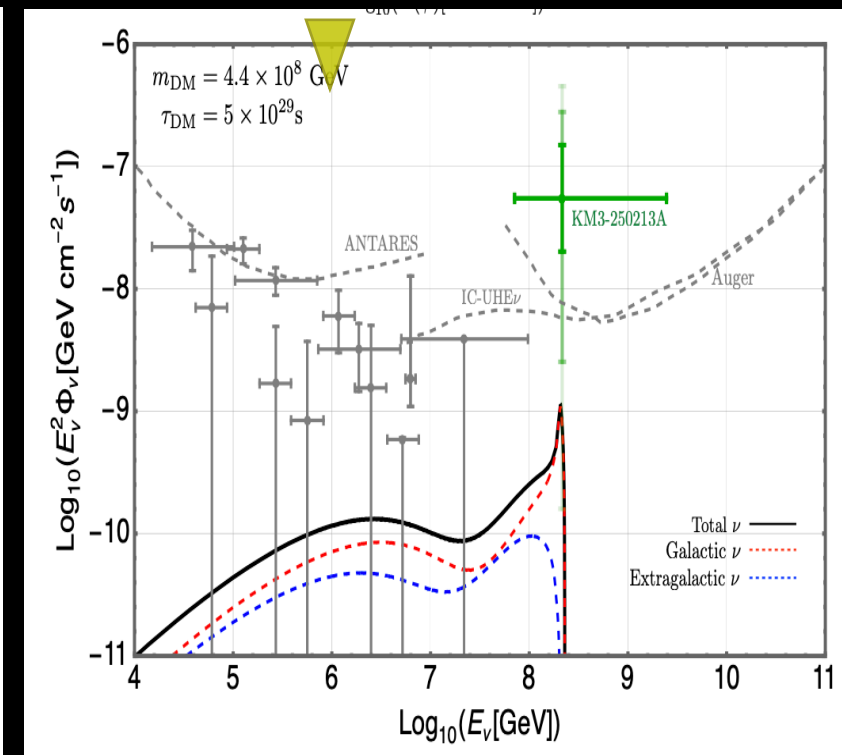
Decaying DM - neutrinos - fit of KM3NeT



Borah+ 2503.00097



Kohri, Paul, Sahu 2503.04464

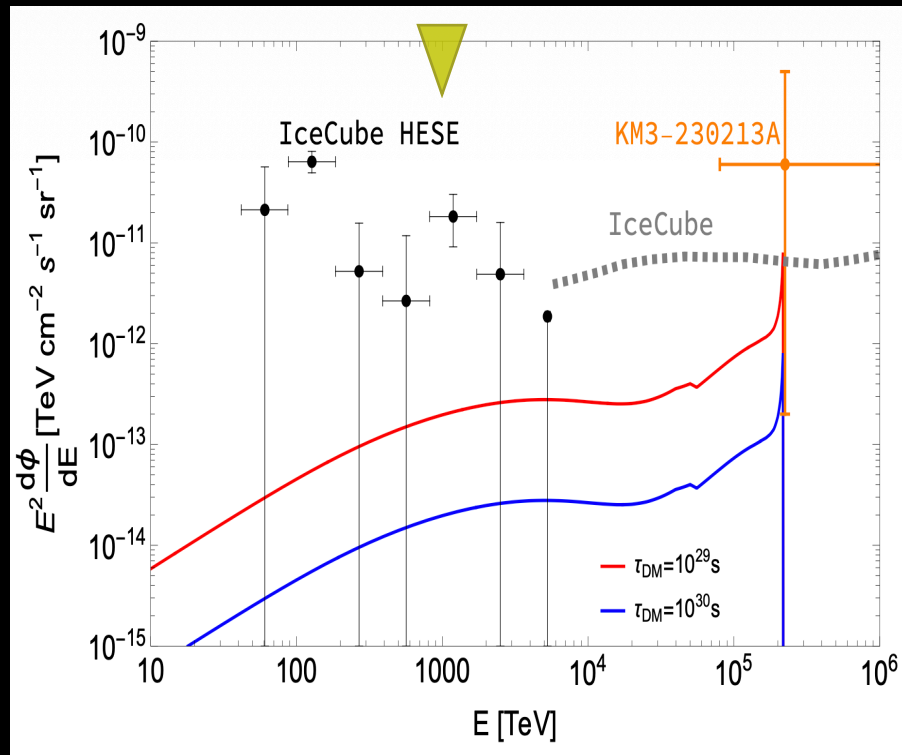


Jho, Park, Shin 2503.18737

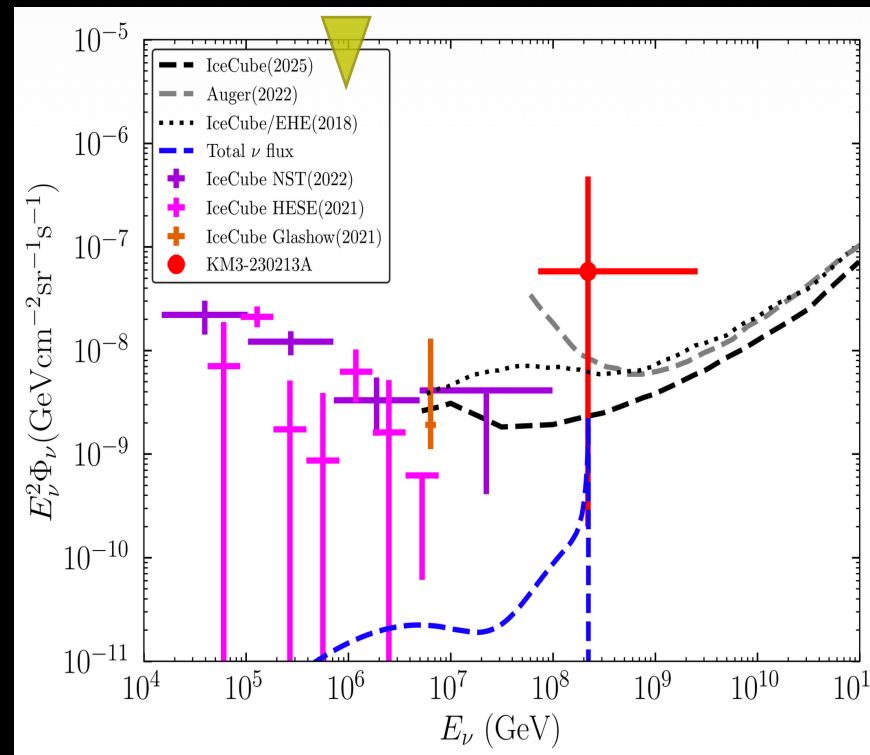
Tension with IceCube limit alleviated by uncertainties and sharp decay spectrum
(or assume matter effects in the Earth (Dev+ 2505.22754))

Super-heavy DM ID

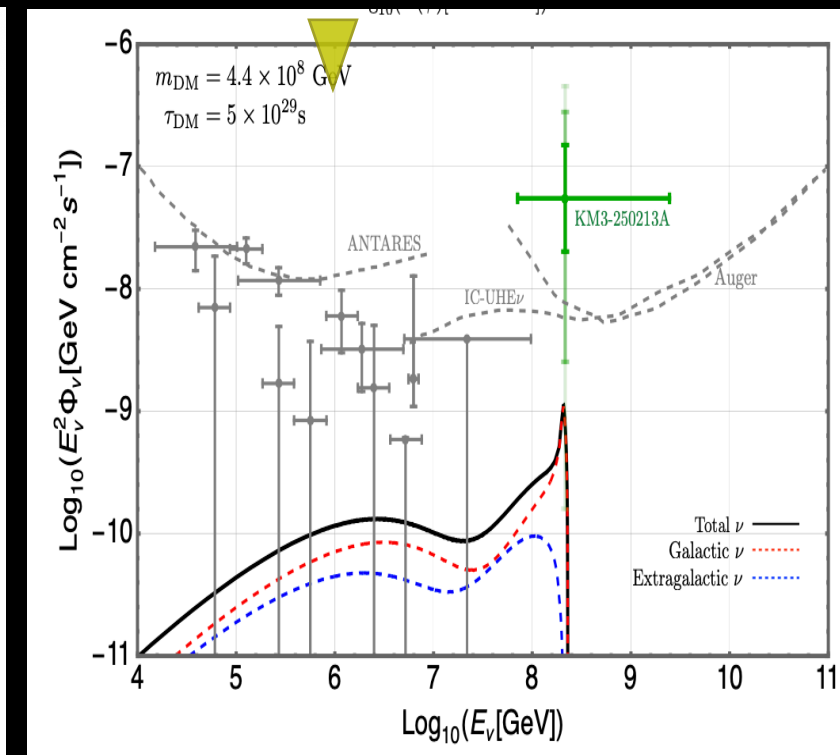
Decaying DM - neutrinos - fit of KM3NeT



Borah+ 2503.00097

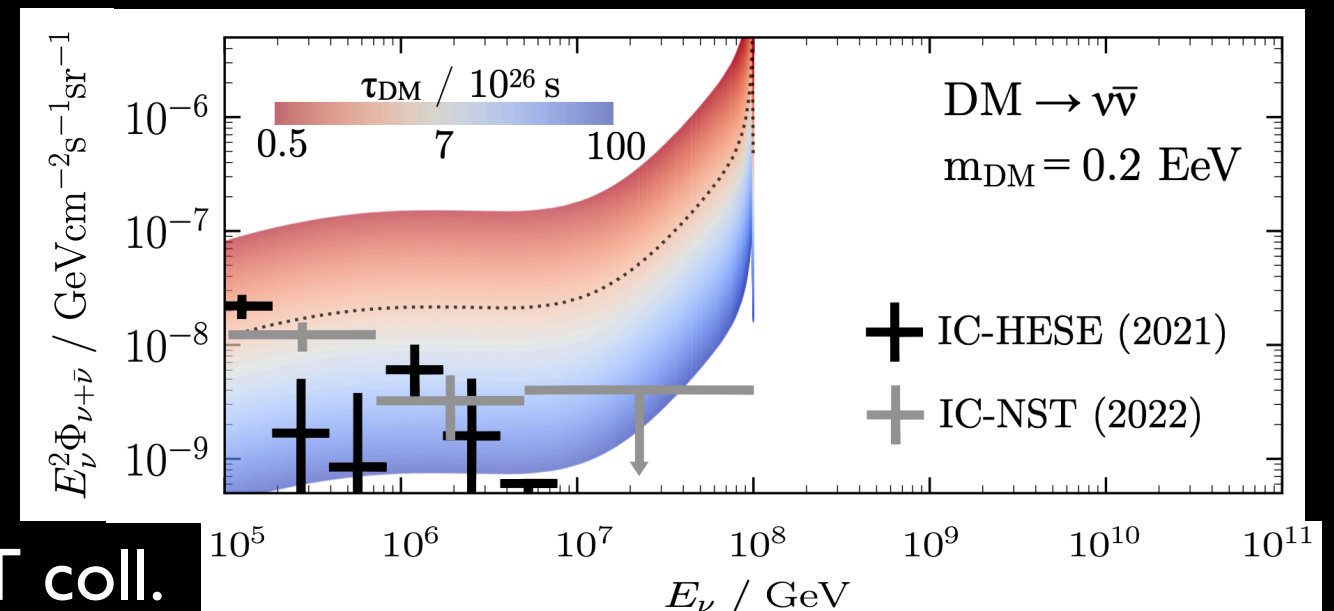


Kohri, Paul, Sahu 2503.04464



Jho, Park, Shin 2503.18737

Tension with IceCube limit alleviated by uncertainties and sharp decay spectrum
(or assume matter effects in the Earth (Dev+ 2505.22754))

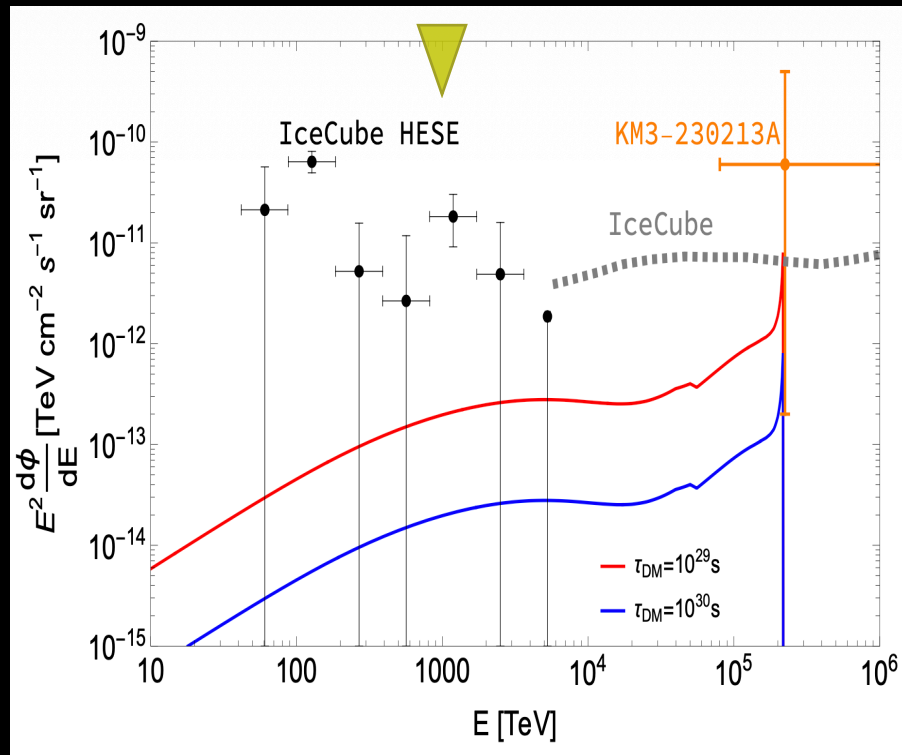


KM3NeT coll.

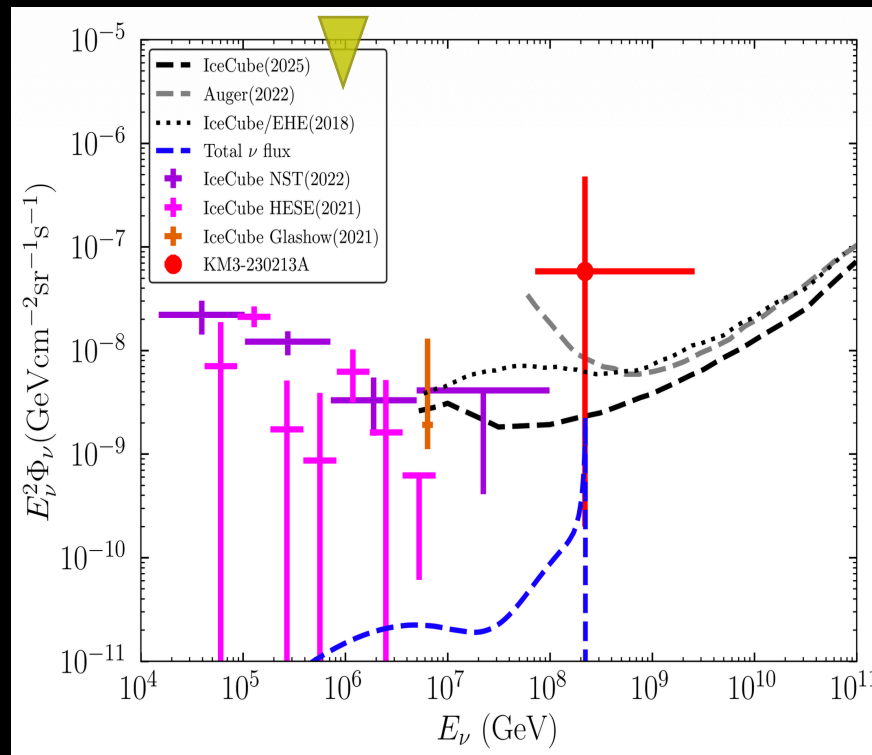
KM3NeT coll. 2606.09986

Super-heavy DM ID

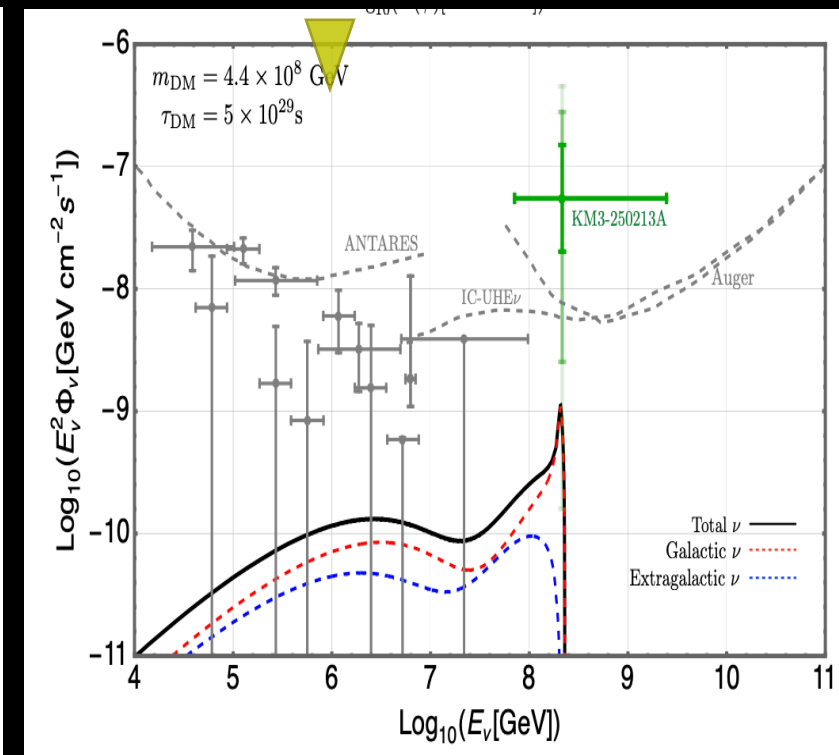
Decaying DM - neutrinos - fit of KM3NeT



Borah+ 2503.00097



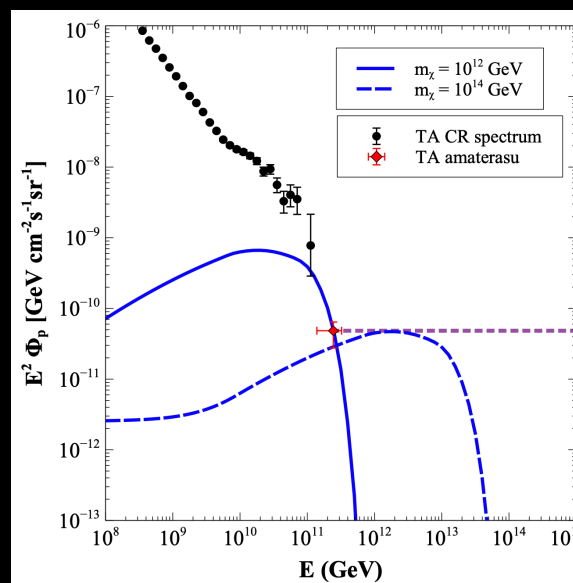
Kohri, Paul, Sahu 2503.04464



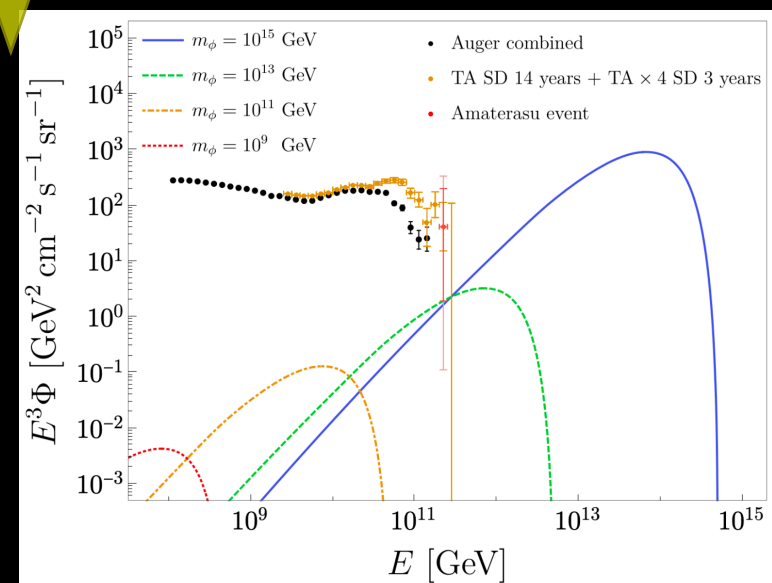
Jho, Park, Shin 2503.18737

Tension with IceCube limit alleviated by uncertainties and sharp decay spectrum
(or assume matter effects in the Earth (Dev+ 2505.22754))

Fit of Amaterasu



Sarmah+ 2406.03174



Murase+ 2504.15272

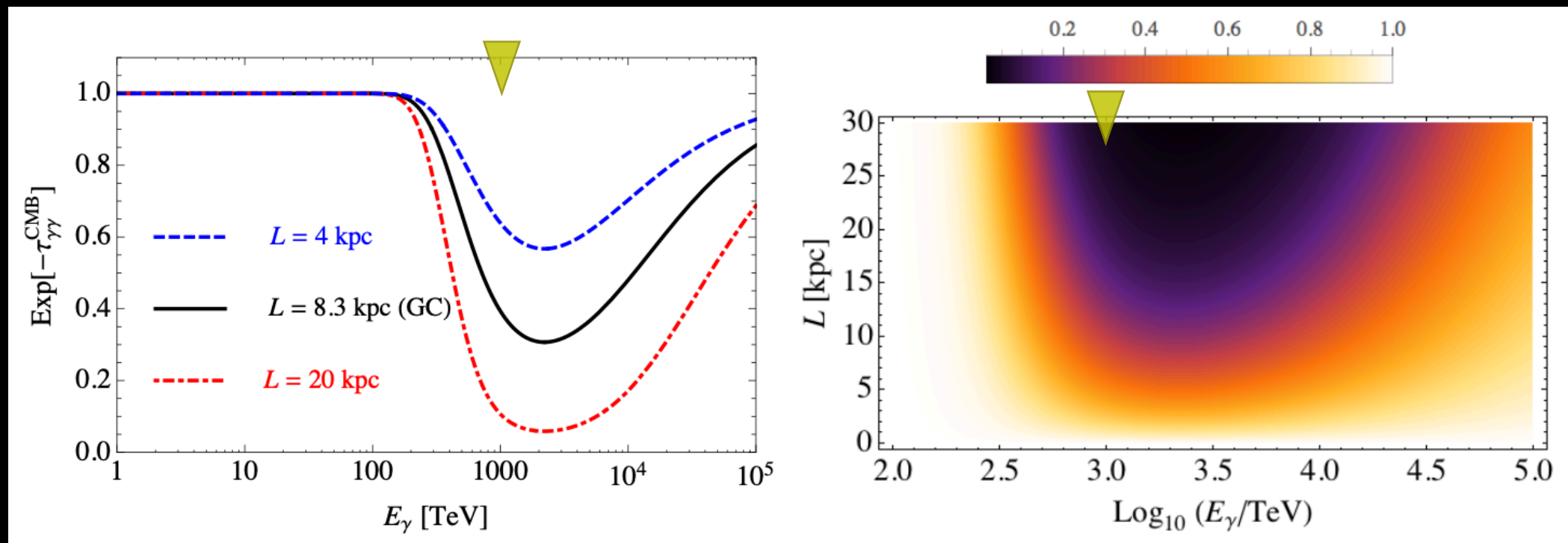
Super-heavy DM ID

Decaying DM - gamma rays

Super-heavy DM ID

Decaying DM - gamma rays

Aside: gamma-ray absorption on CMB photons

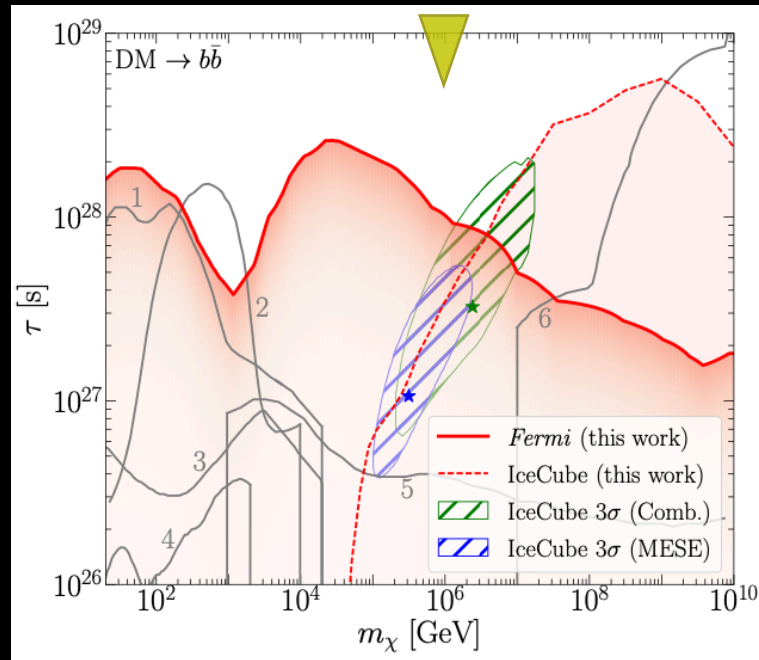


Esmaili Serpico 1505.06486

Vernetto Lipari 1608.01587

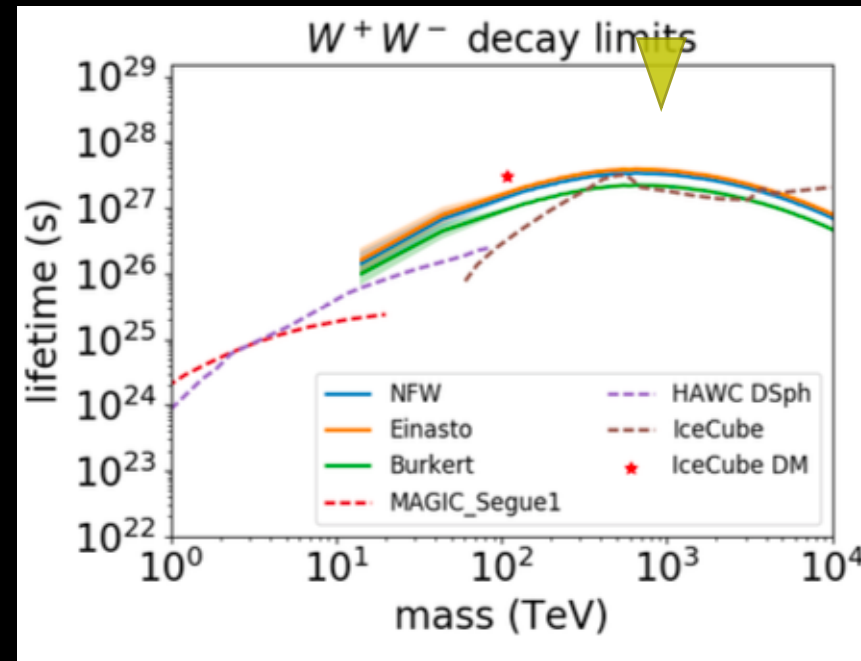
Super-heavy DM ID

Decaying DM - gamma rays



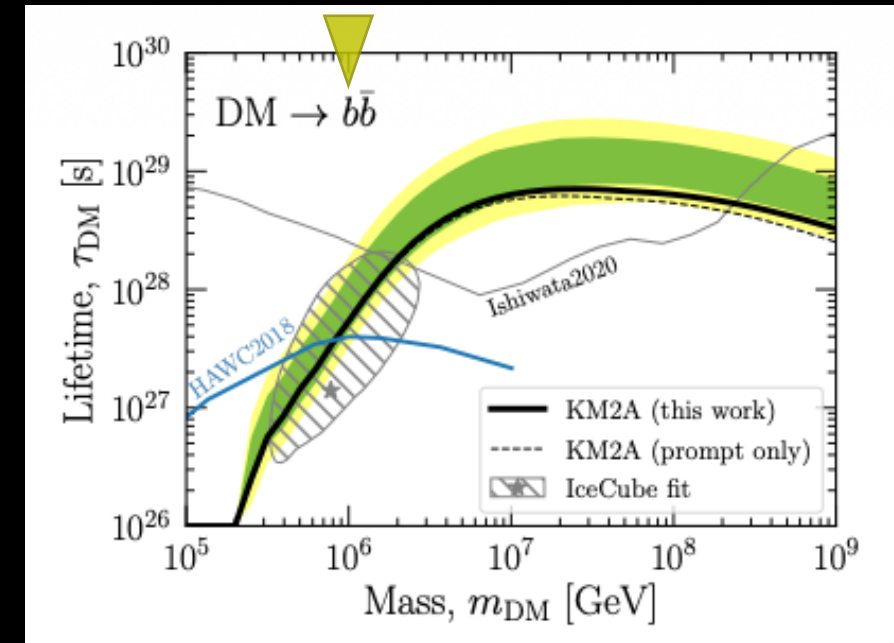
Fermi & IceCube

Cohen+ 1612.05638



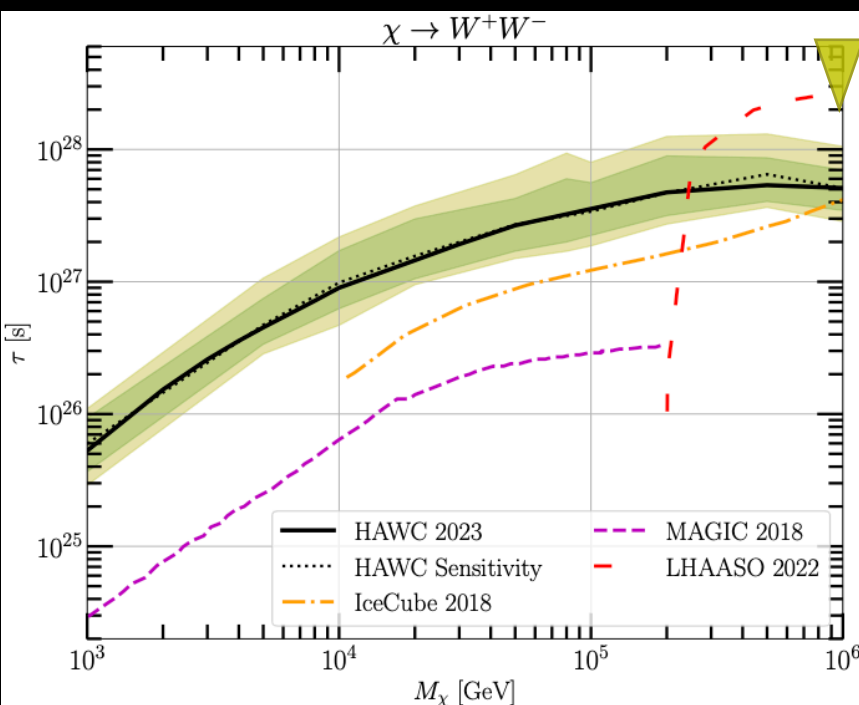
dSphs

HAWC 1710.10288



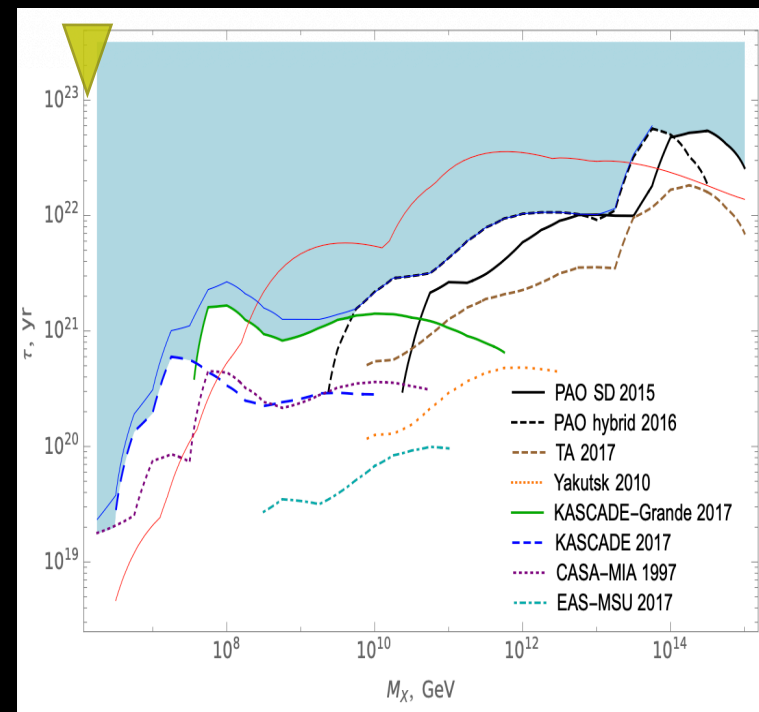
Several Rols

LHAASO 2210.15989



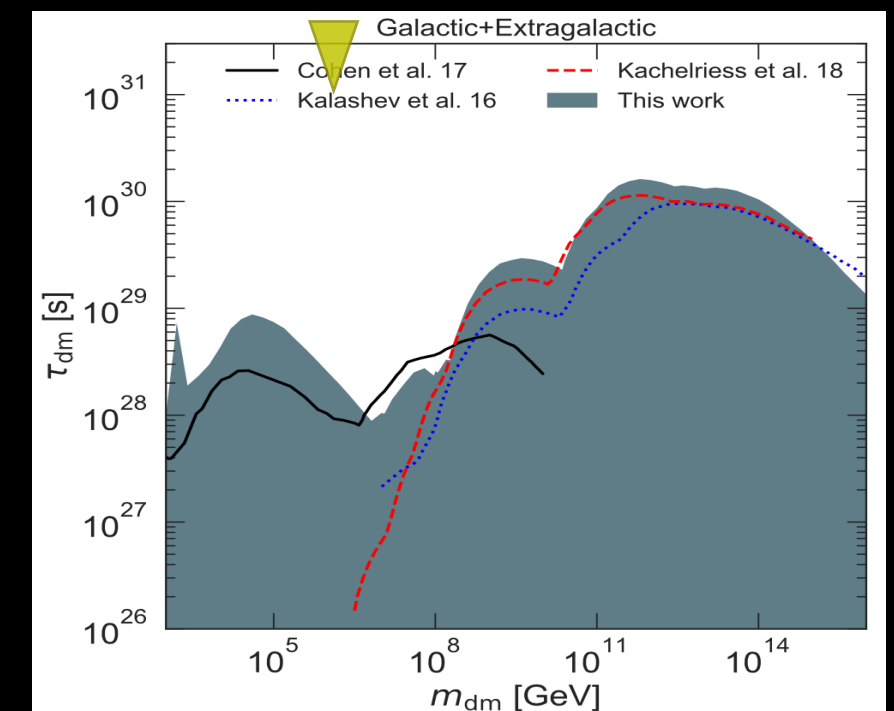
Virgo cluster

HAWC 2309.03973



PAO,
KASCADE,
Casa-Mia

Kachelriess, Kalashev, Kuznetsov
1805.04500 (also 1606.07354)



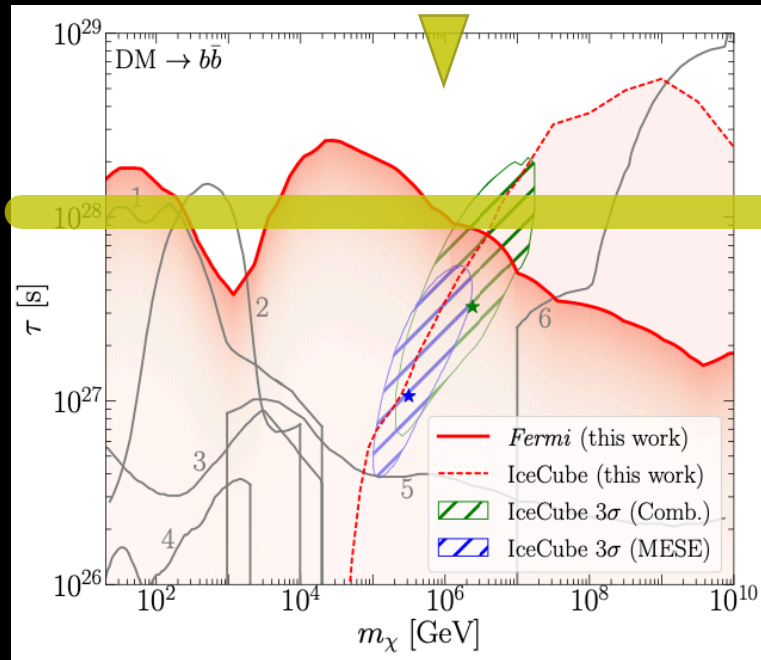
PAO, KASCADE, Casa-Mia, TA,
AMS, Fermi, IceCube

Ishiwata, Macias,
Ando+ 1907.11671

Super-heavy DM ID

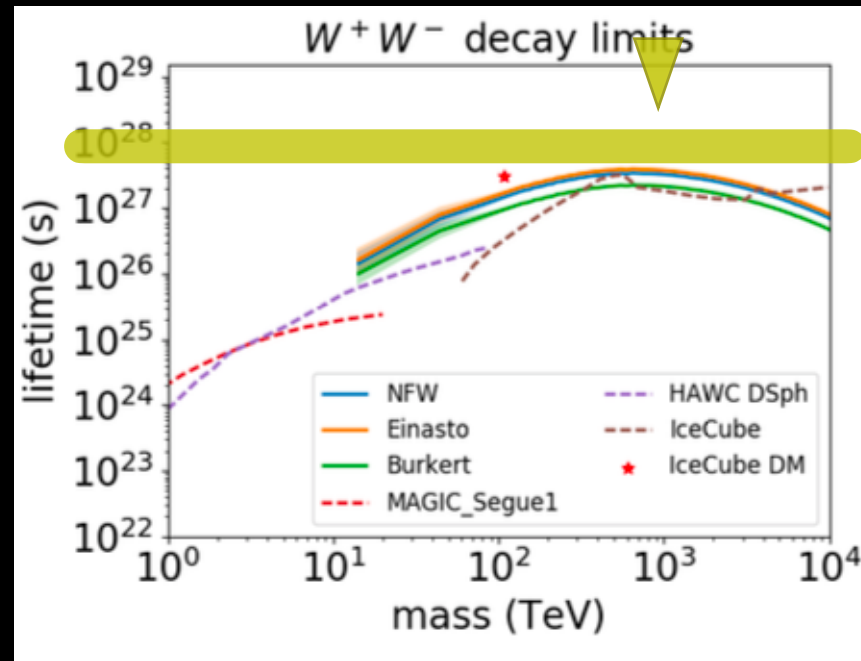
Decaying DM - gamma rays

$$\tau = 10^{28} \text{ sec}$$



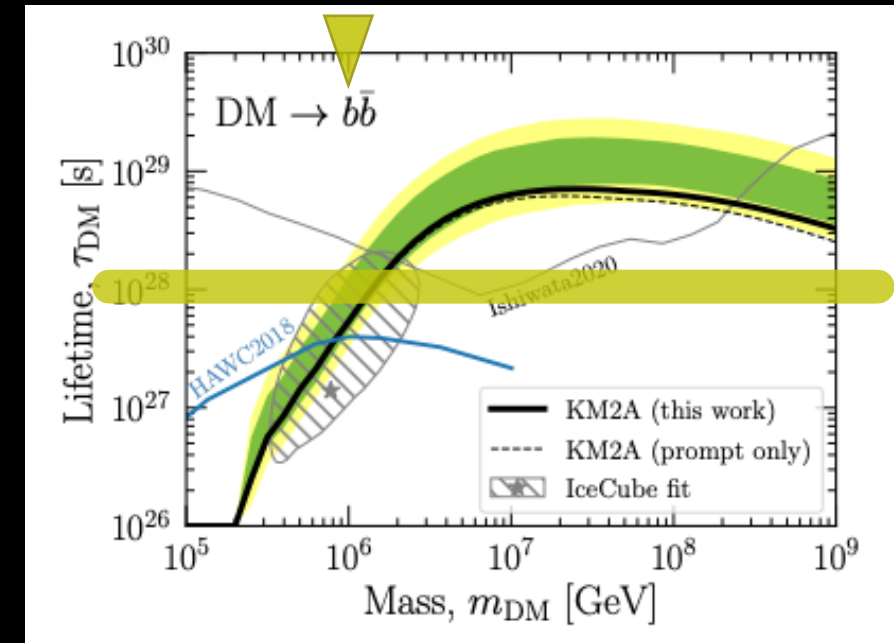
Fermi & IceCube

Cohen+ 1612.05638



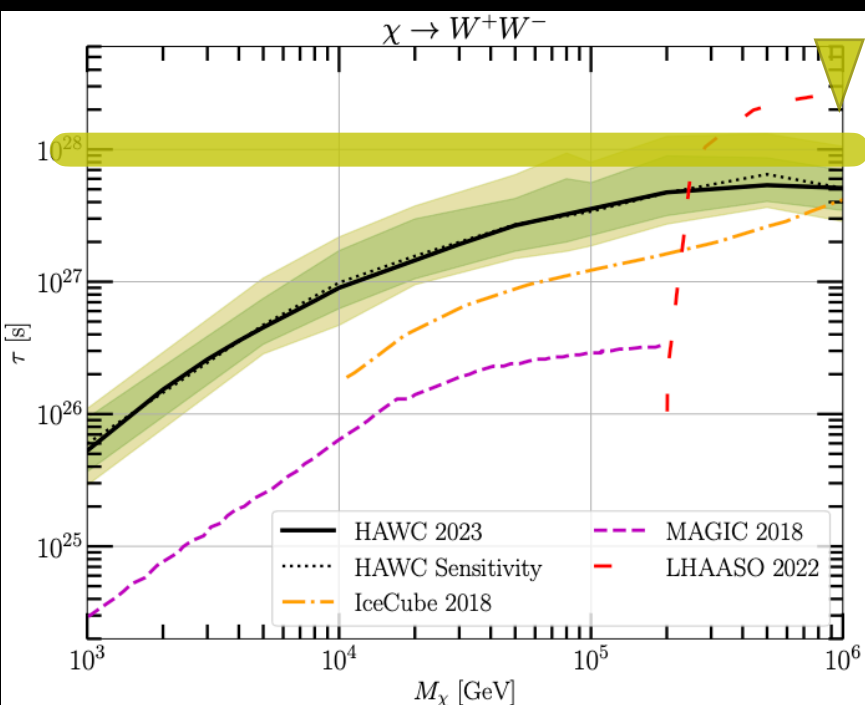
dSphs

HAWC 1710.10288



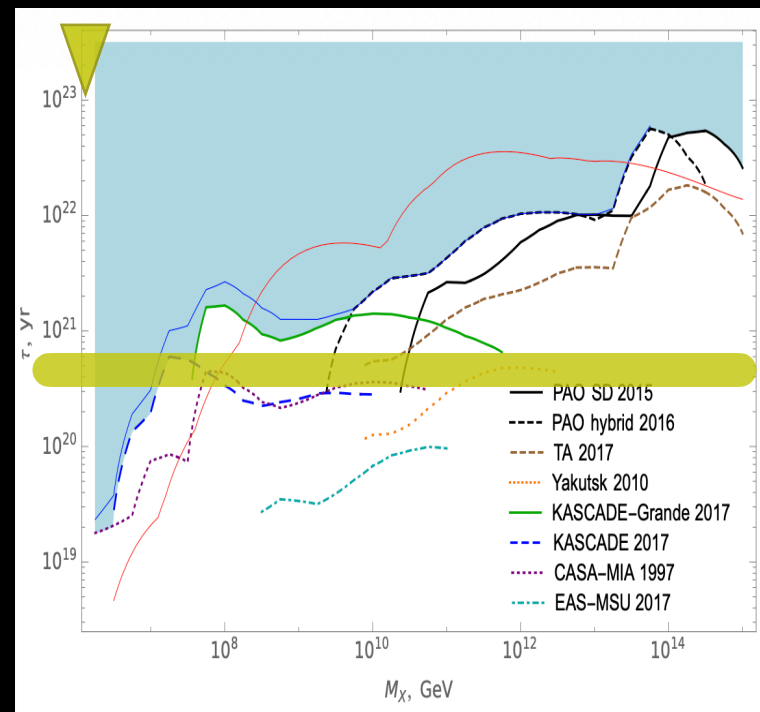
Several Rols

LHAASO 2210.15989



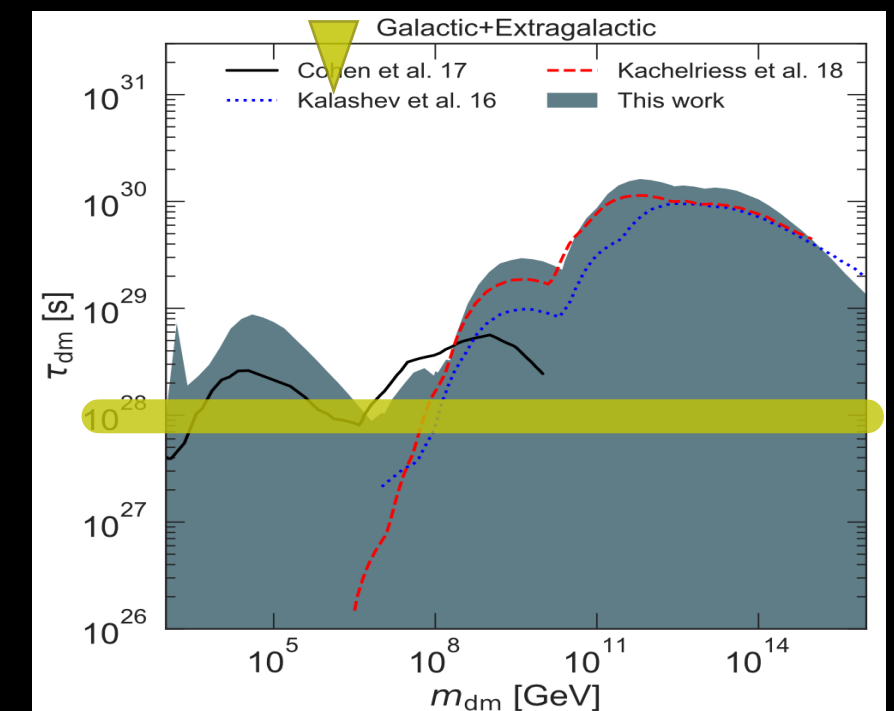
Virgo cluster

HAWC 2309.03973



PAO,
Kascade,
Casa-Mia

Kachelriess, Kalashev, Kuznetsov
1805.04500 (also 1606.07354)

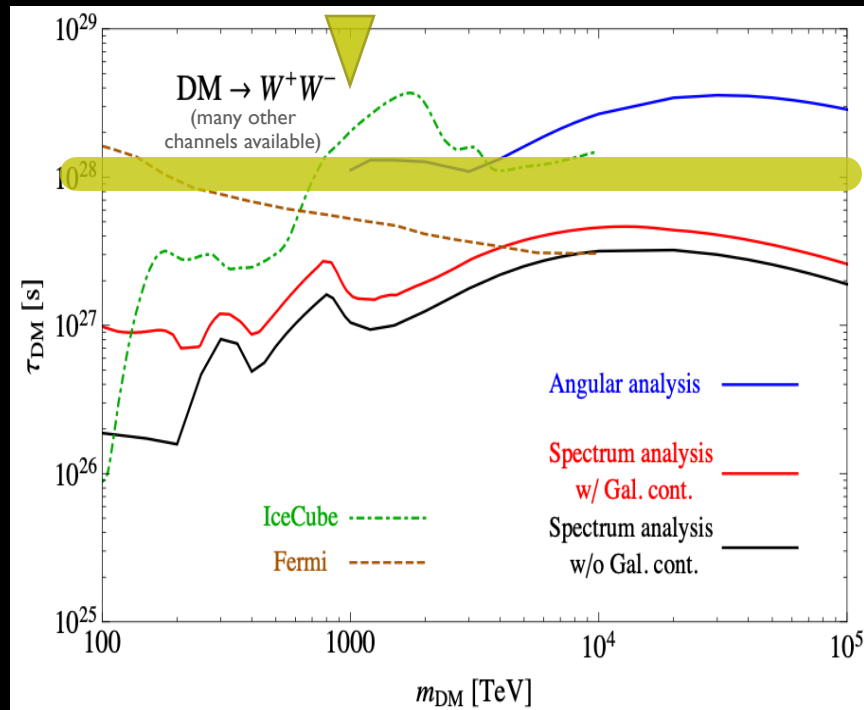


PAO, Kascade, Casa-Mia, TA,
AMS, Fermi, IceCube

Ishiwata, Macias,
Ando+ 1907.11671

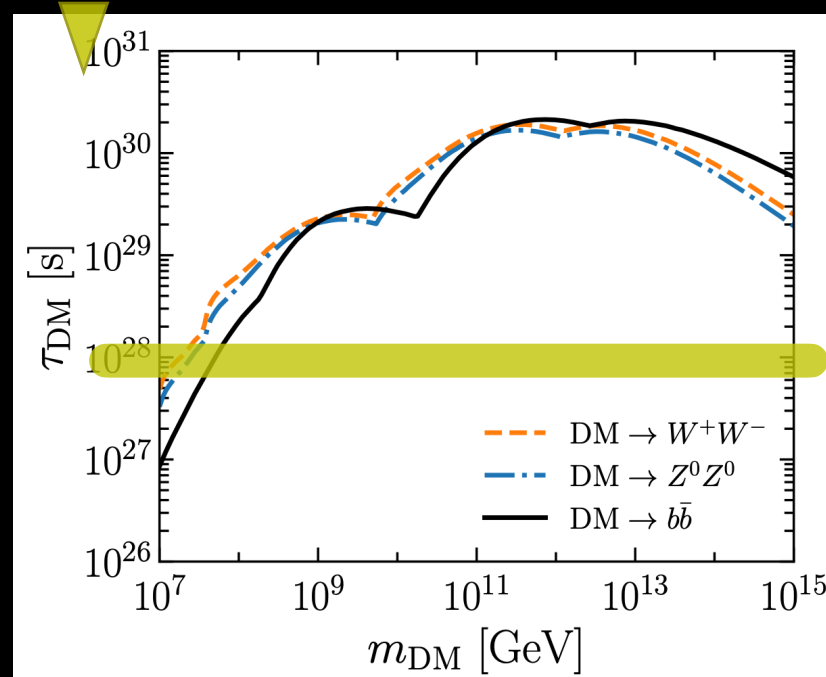
Super-heavy DM ID

Decaying DM - gamma rays



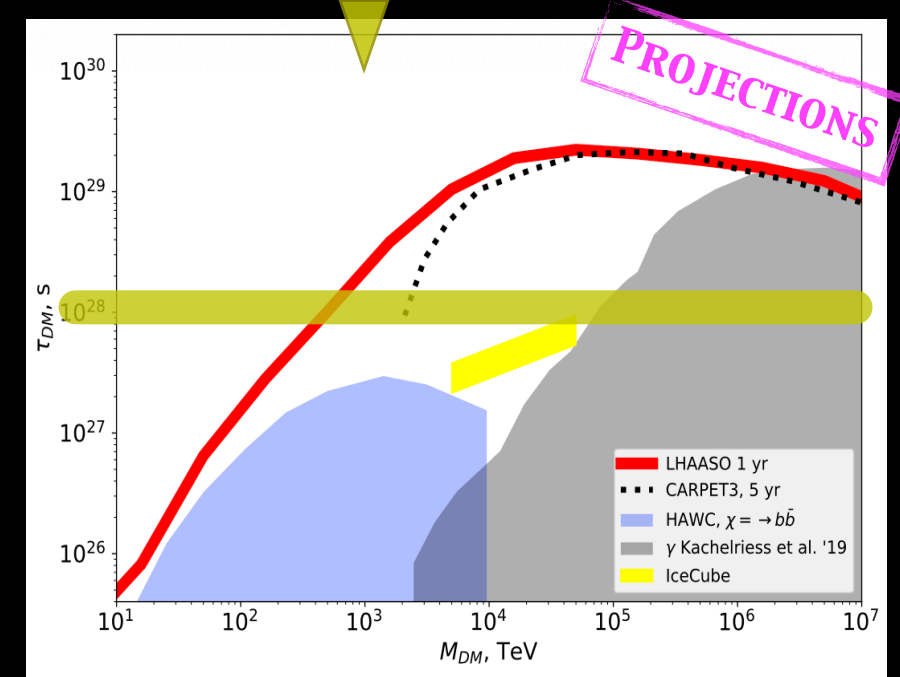
Tibet ASy

Esmaili, Serpico, 2105.01826



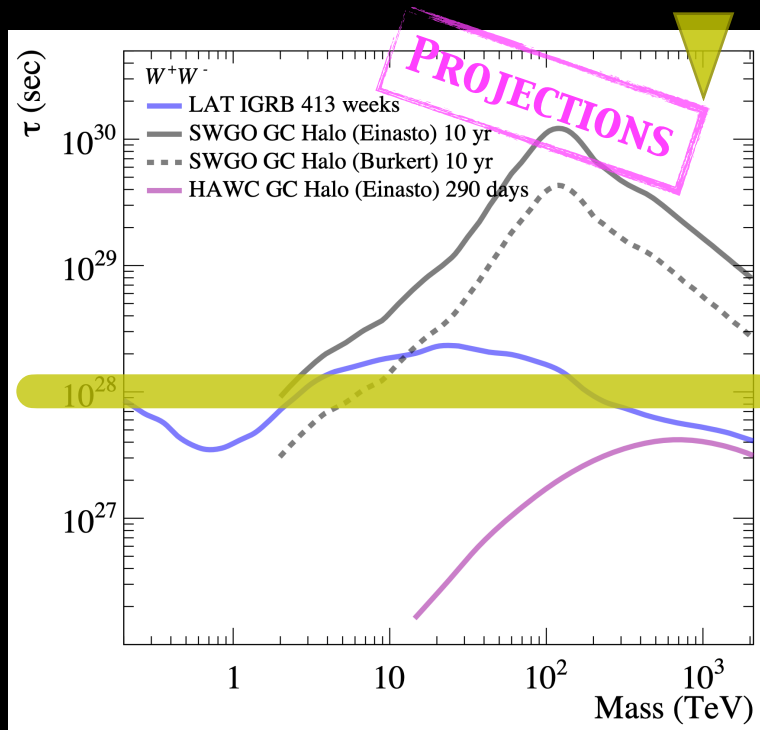
PAO, TA, Cascade, Casa-Mia

Chianese+ 2108.01678



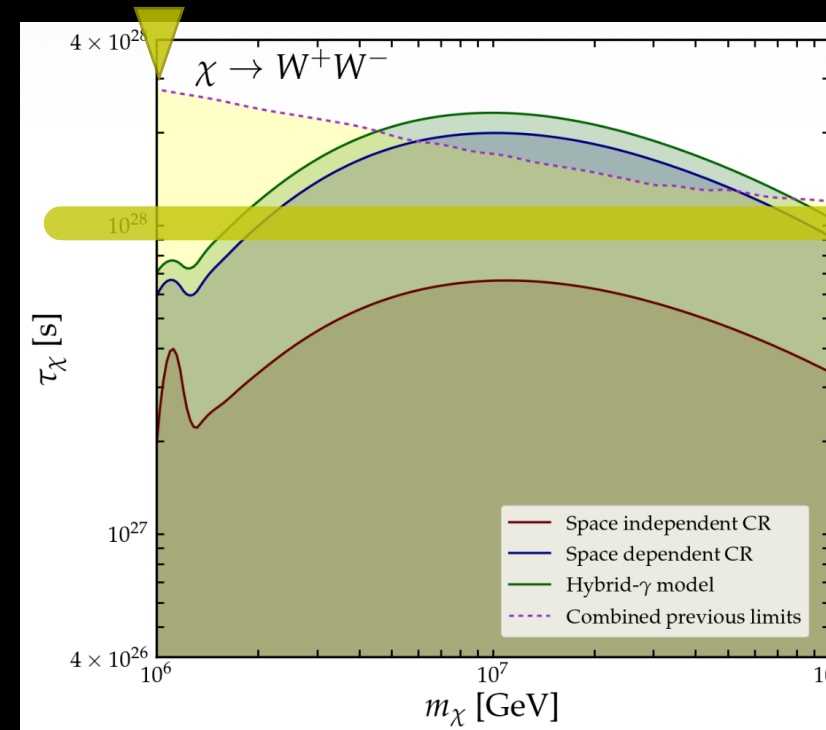
LHAASO projection

Neronov Semikoz 2001.11881



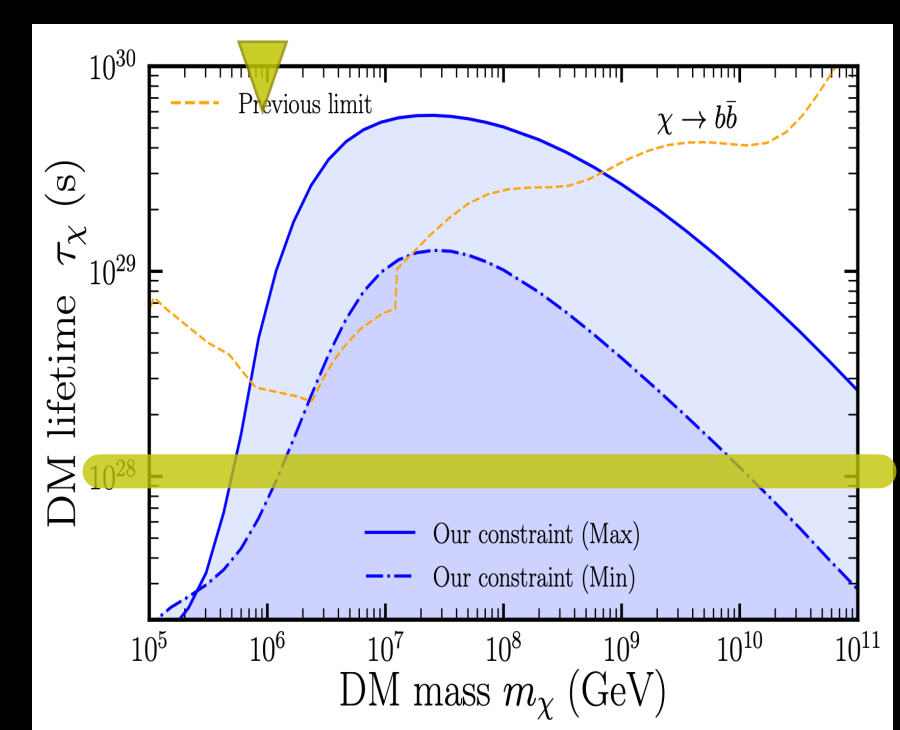
SWGO projections

SWGO 1906.03353



Tibet ASy

Maity, Saha, Dubey, Laha 2105.05680



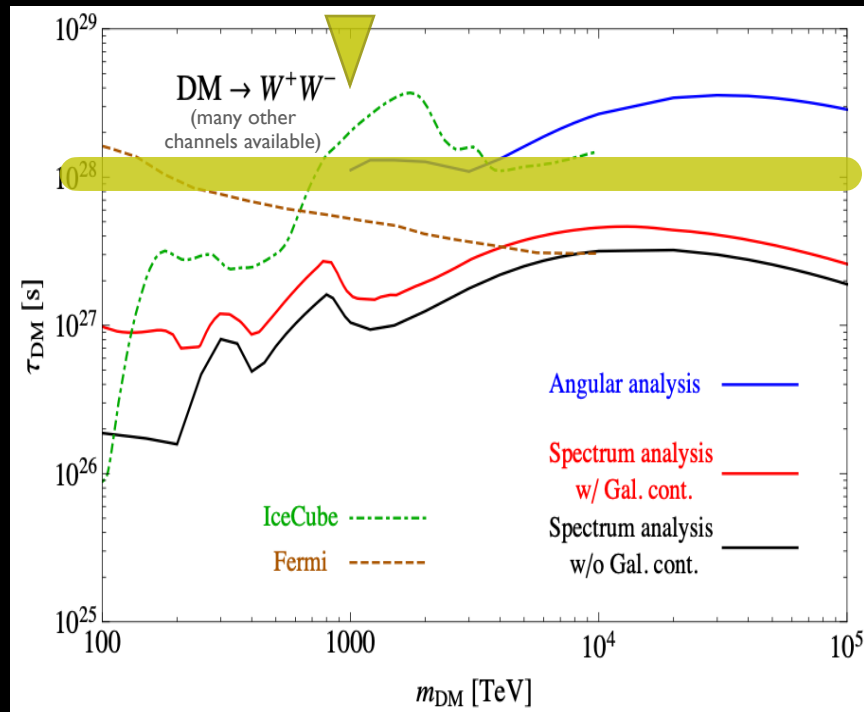
LHAASO

Boehm, Laha, Maity 2509.07982

Super-heavy DM ID

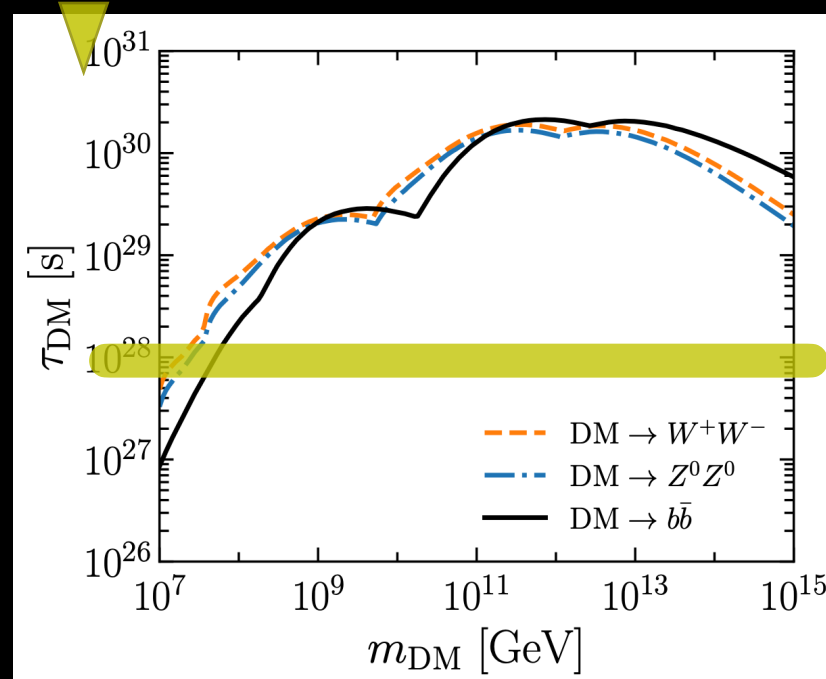
Decaying DM - gamma rays

$\tau = 10^{28}$ sec



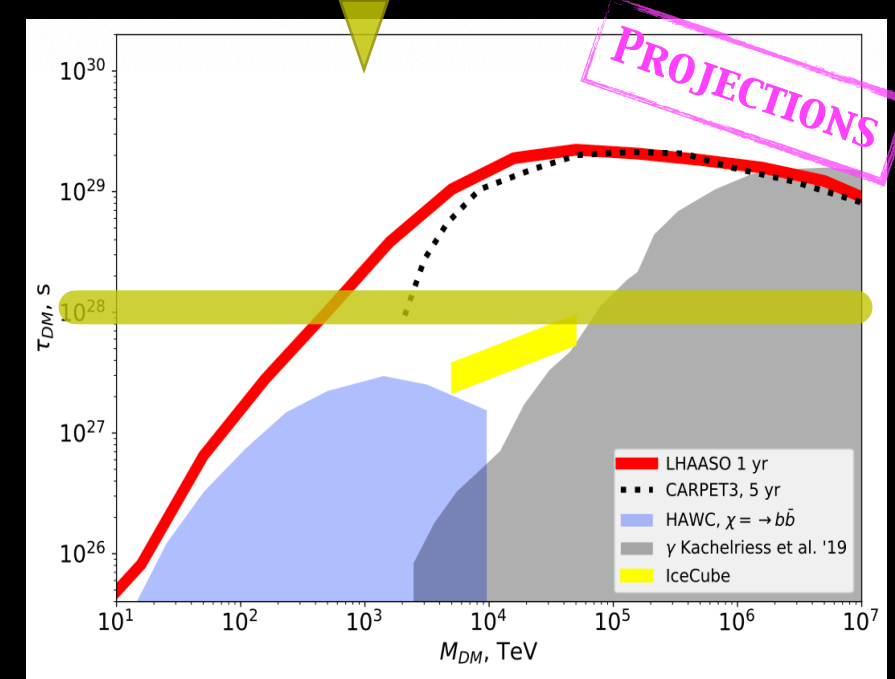
Tibet ASy

Esmaili, Serpico, 2105.01826



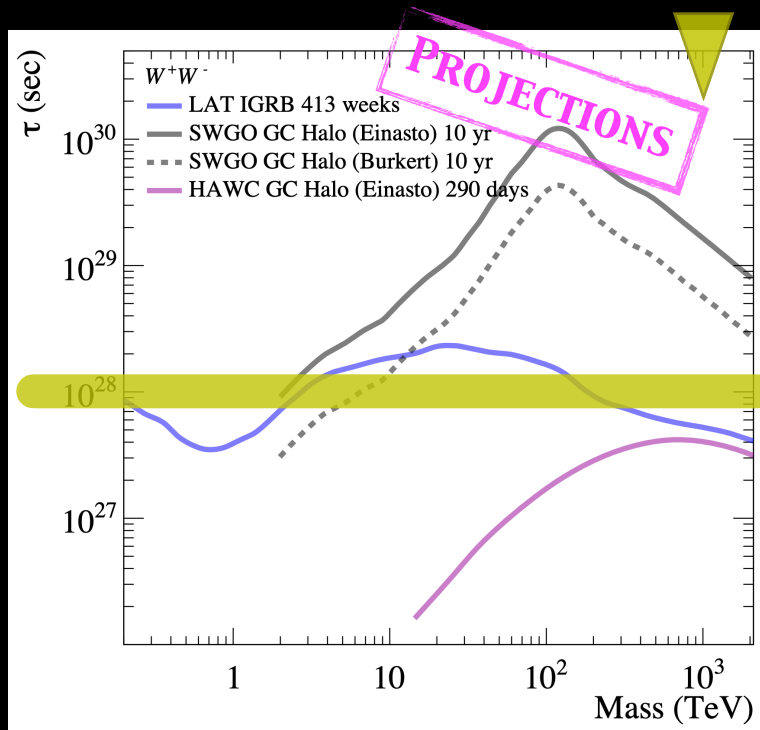
PAO, TA, Cascade, Casa-Mia

Chianese+ 2108.01678



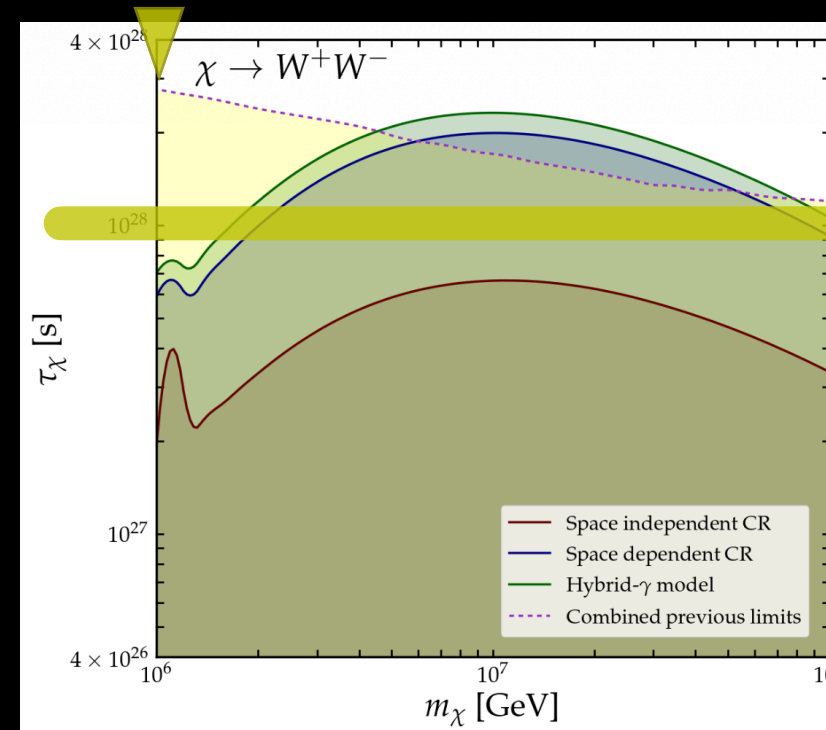
LHAASO projection

Neronov Semikoz 2001.11881



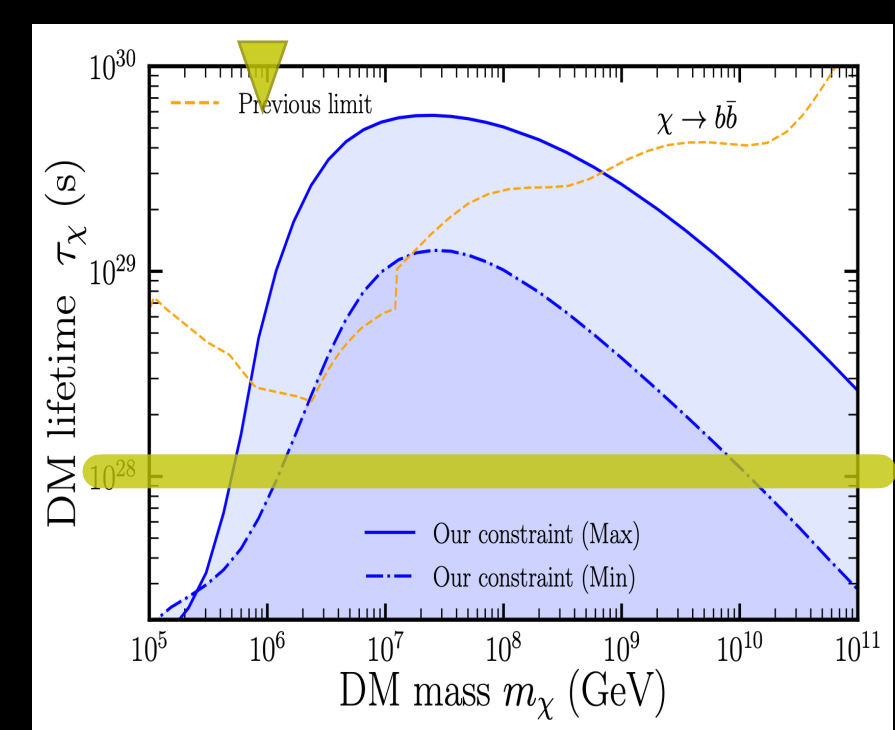
SWGO projections

SWGO 1906.03353



Tibet ASy

Maity, Saha, Dubey, Laha 2105.05680



LHAASO

Boehm, Laha, Maity 2509.07982

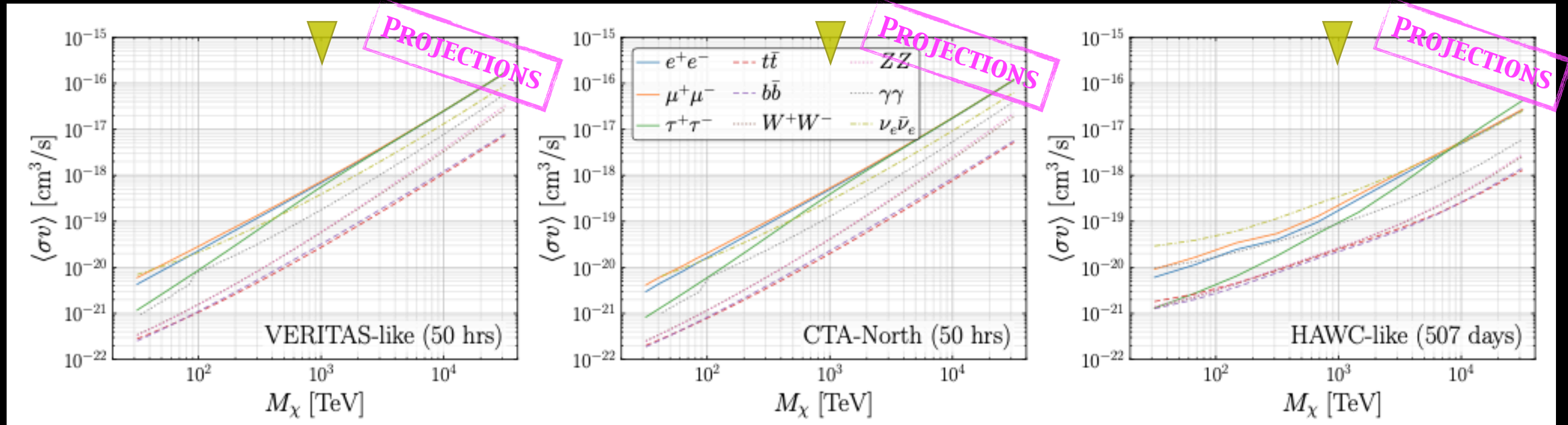
Super-heavy DM ID

Annihilating DM, agnostically

Super-heavy DM ID

Annihilating DM, agnostically - gammas

Projections from Segue I observations with IACTs or EASs

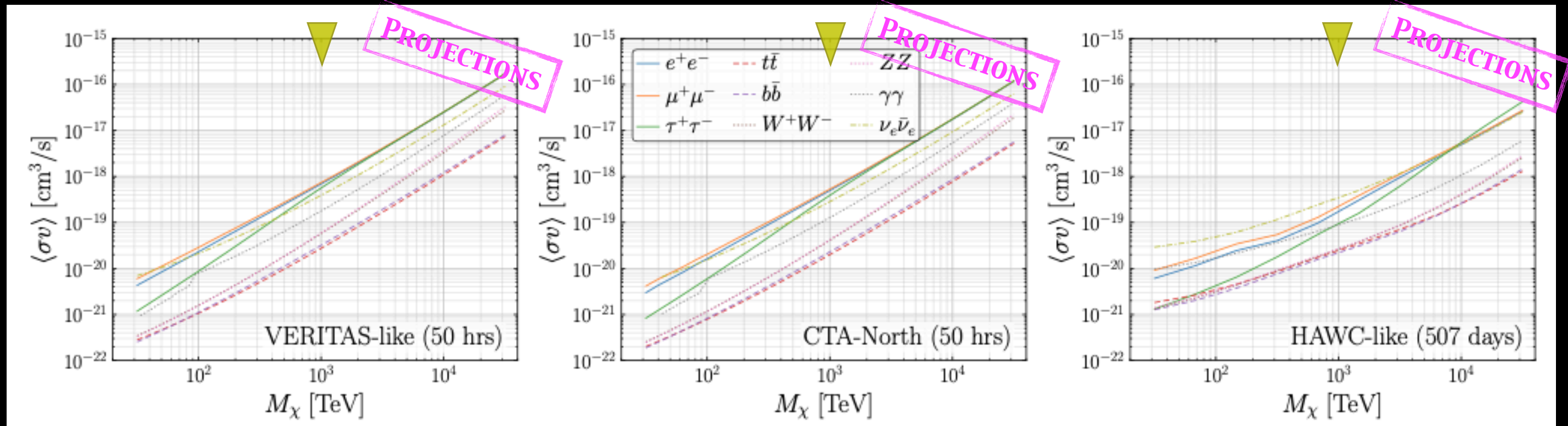


Tak, Baumgart, Rodd, Pueschel 2208.11740

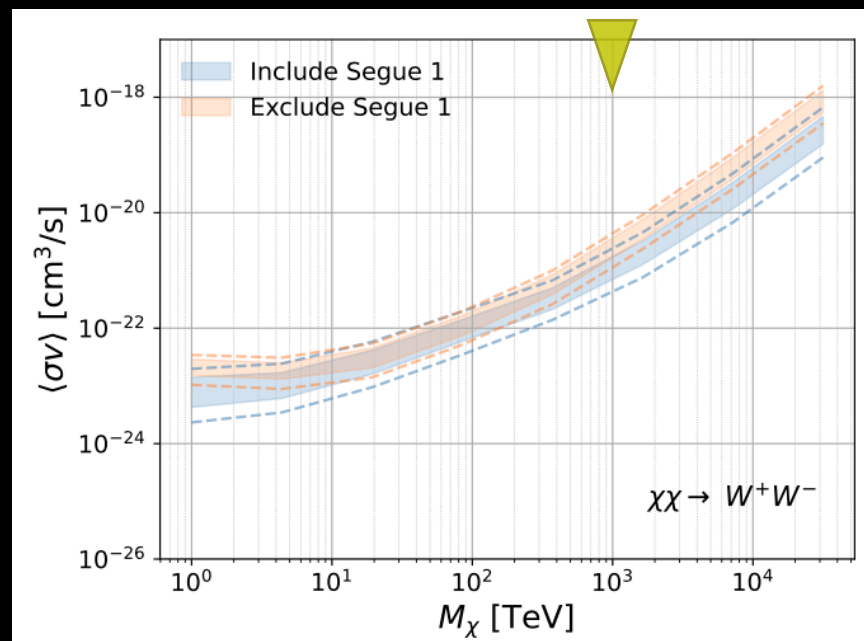
Super-heavy DM ID

Annihilating DM, agnostically - gammas

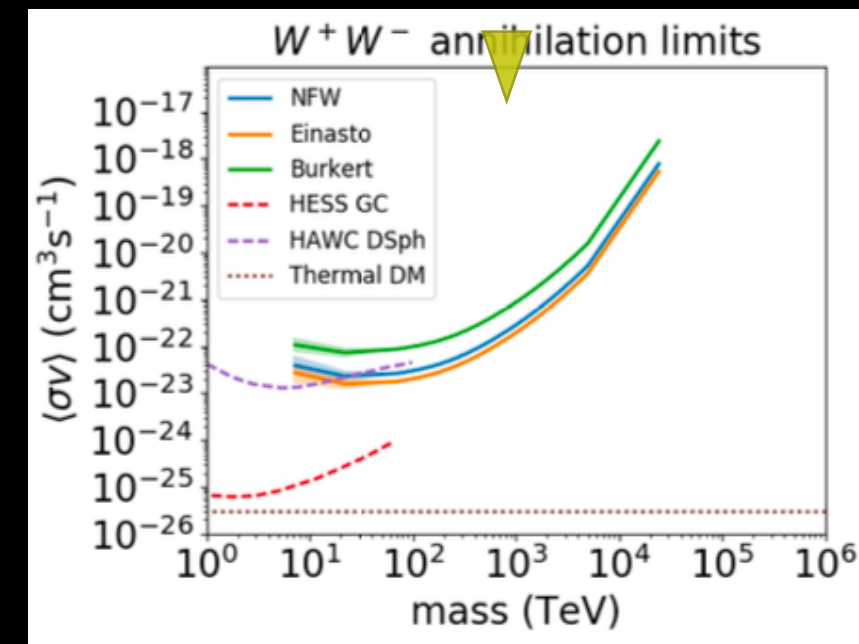
Projections from Segue I observations with IACTs or EASs



Tak, Baumgart, Rodd, Poeschel 2208.11740



VERITAS 2302.08784

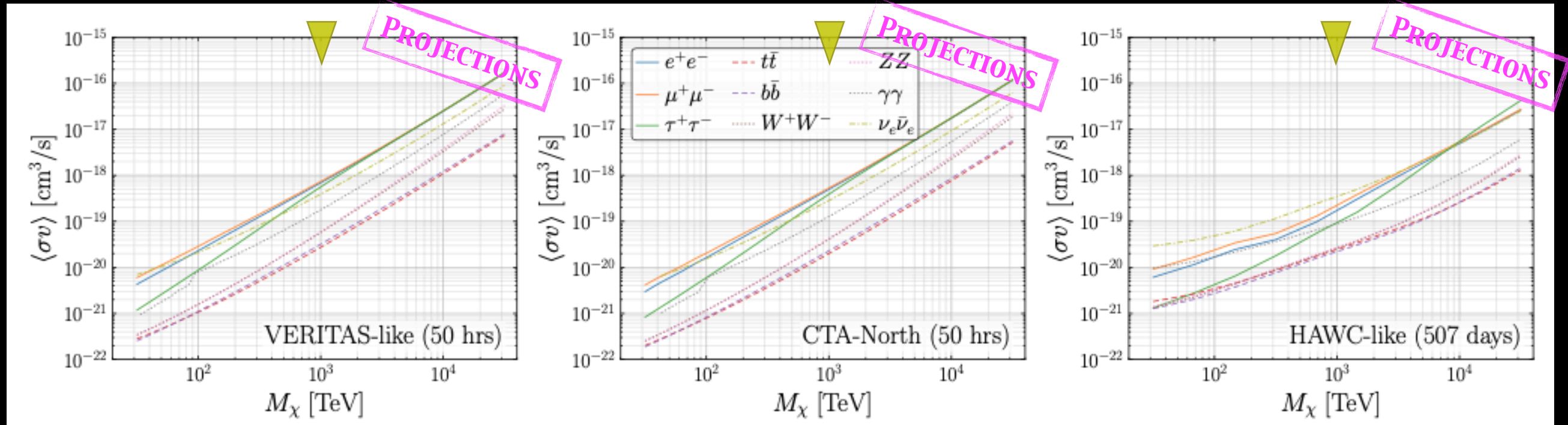


HAWC 1710.10288

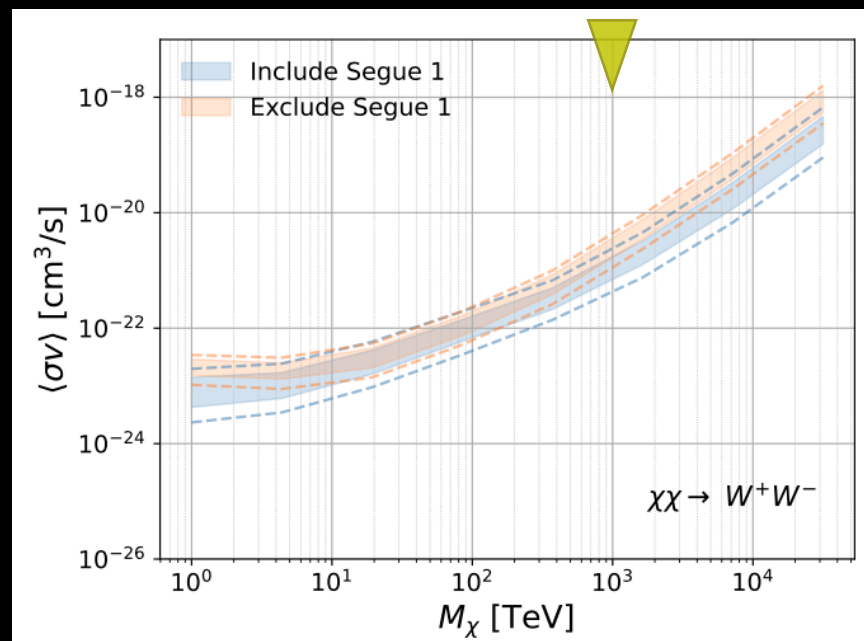
Super-heavy DM ID

Annihilating DM, agnostically - gammas

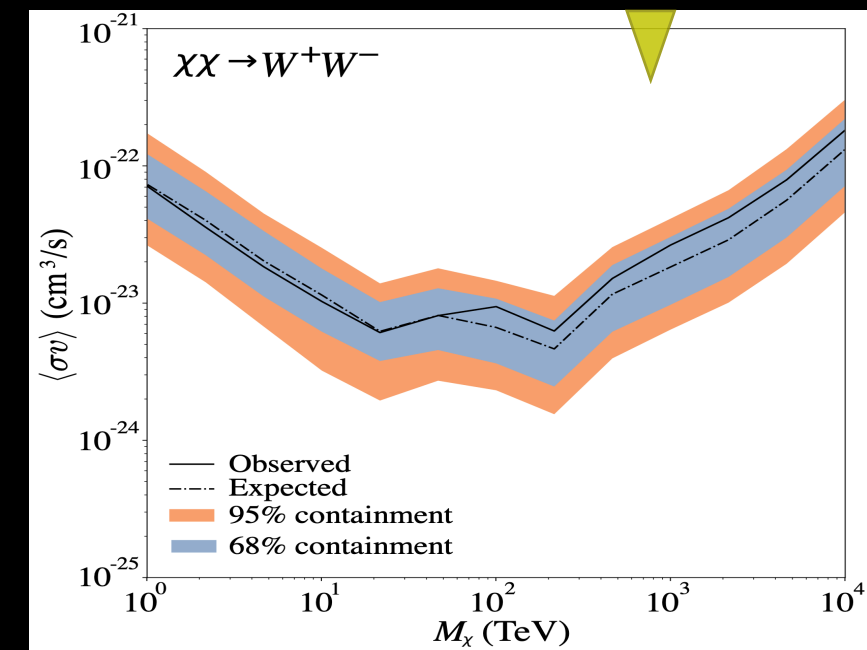
Projections from Segue I observations with IACTs or EASs



Tak, Baumgart, Rodd, Poeschel 2208.11740



VERITAS 2302.08784

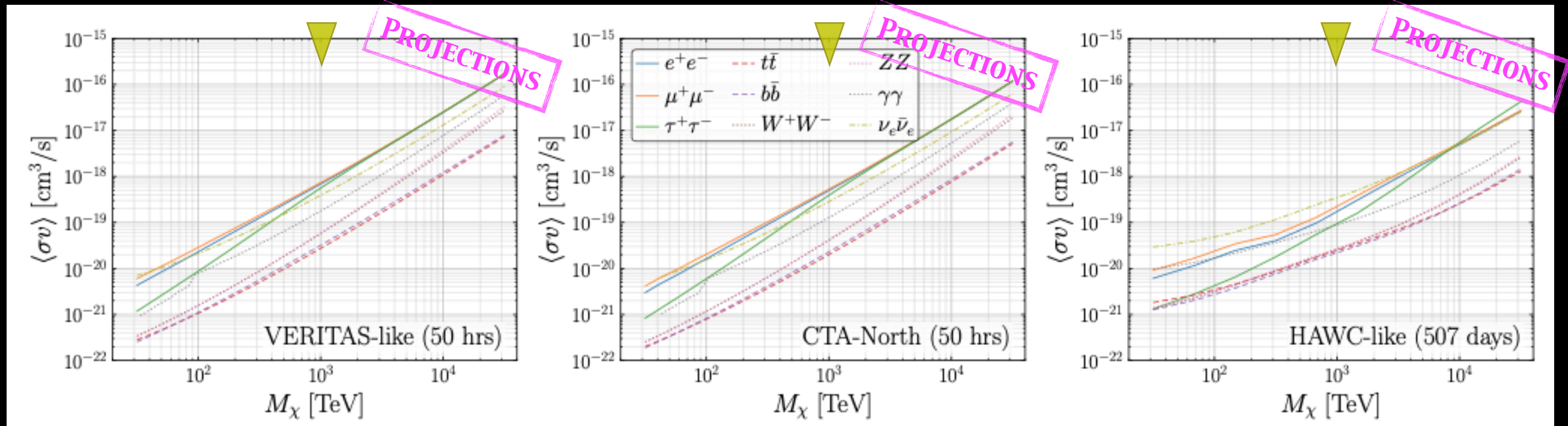


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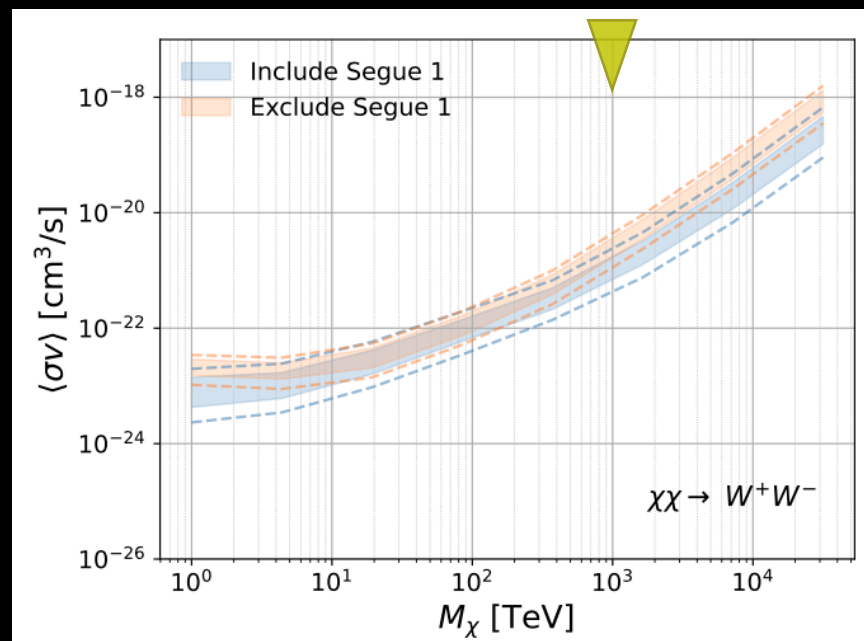
Super-heavy DM ID

Annihilating DM, agnostically - gammas

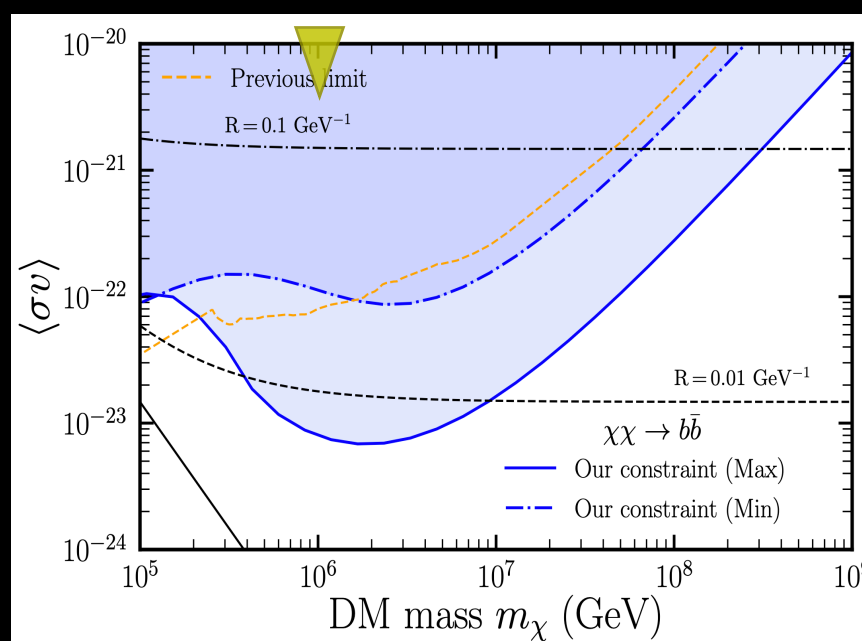
Projections from Segue I observations with IACTs or EASs



Tak, Baumgart, Rodd, Pueschel 2208.11740

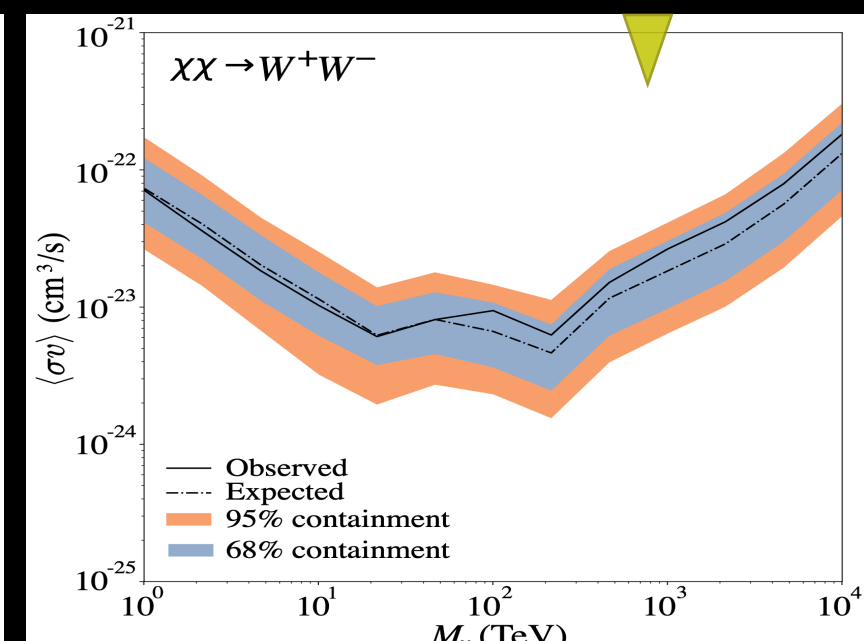


VERITAS 2302.08784



LHAASO

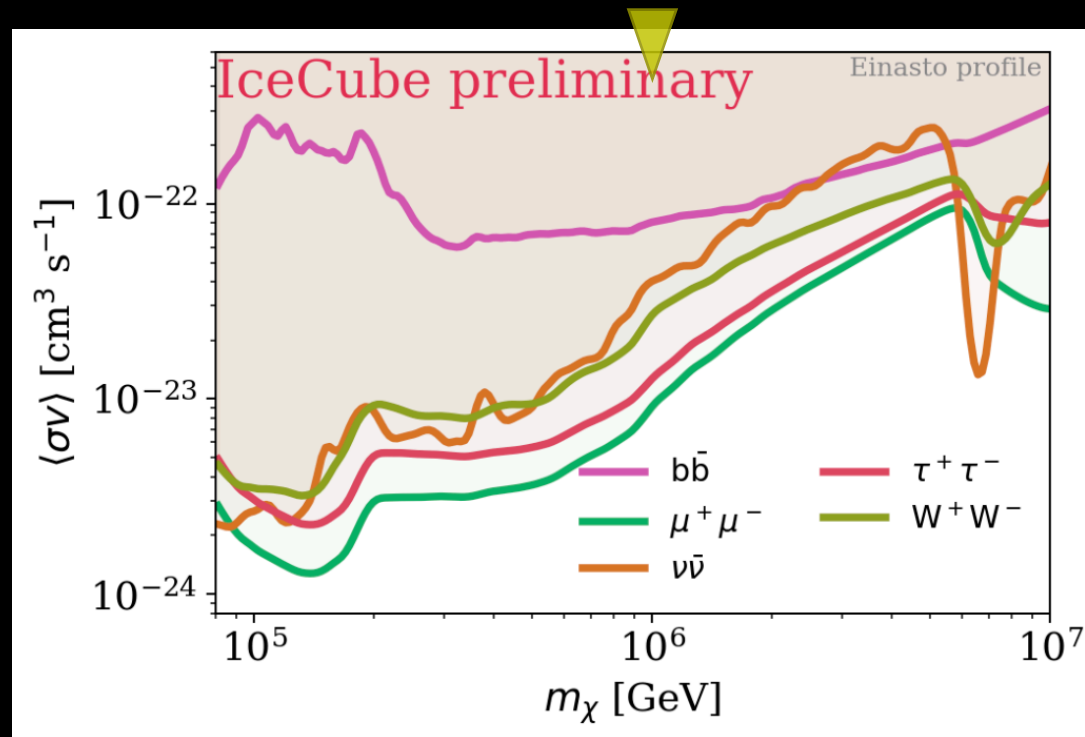
Boehm, Laha, Maity 2509.07982



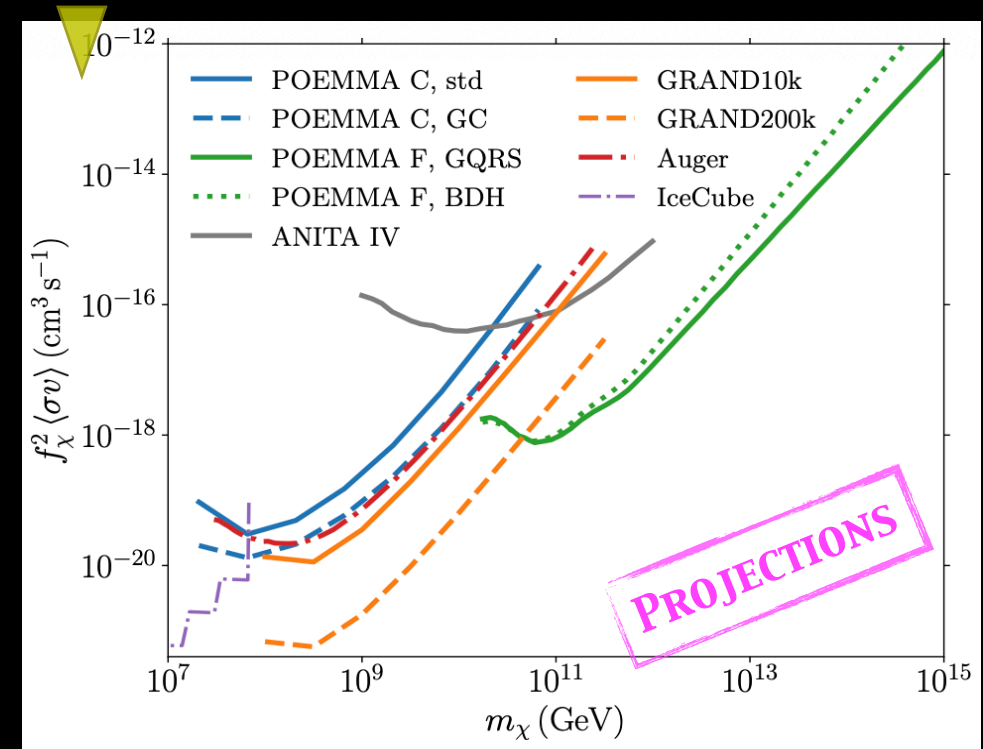
HAWC 2509.06210

Super-heavy DM ID

Annihilating DM, agnostically - neutrinos



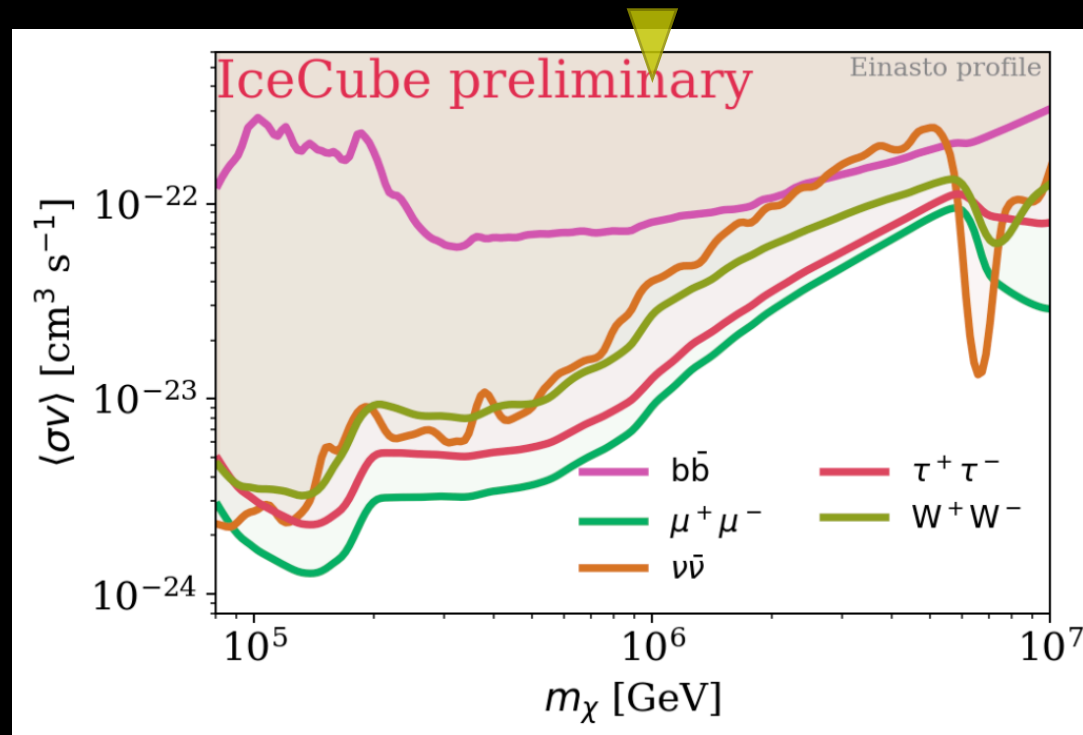
IceCube 1907.11193



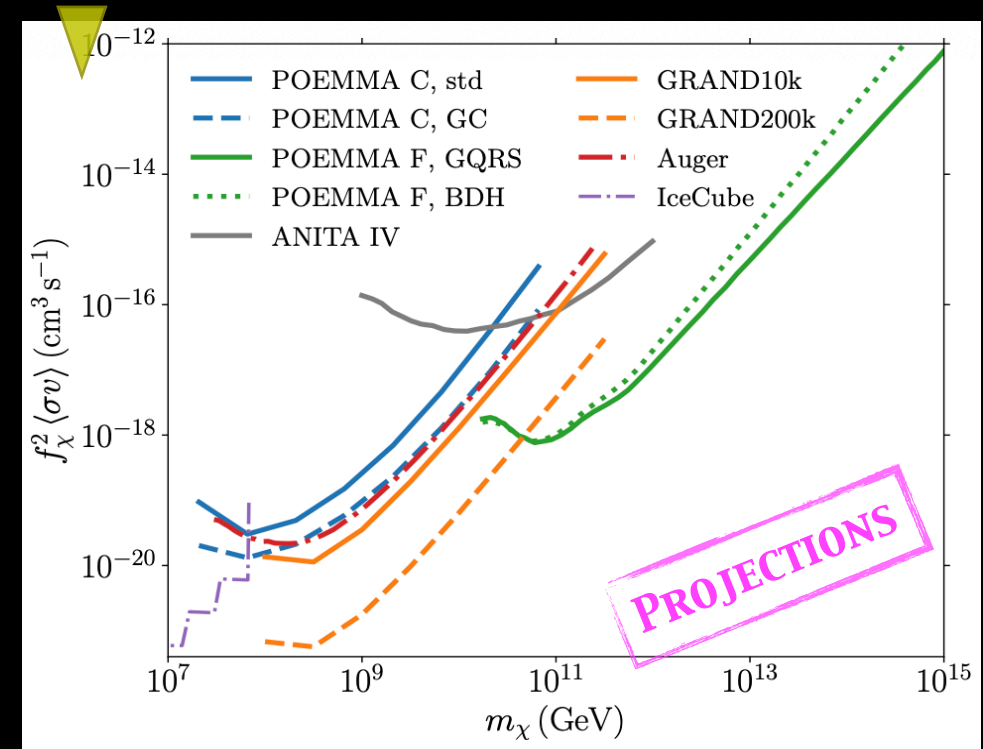
Guépin+ 2106.04446

Super-heavy DM ID

Annihilating DM, agnostically - neutrinos



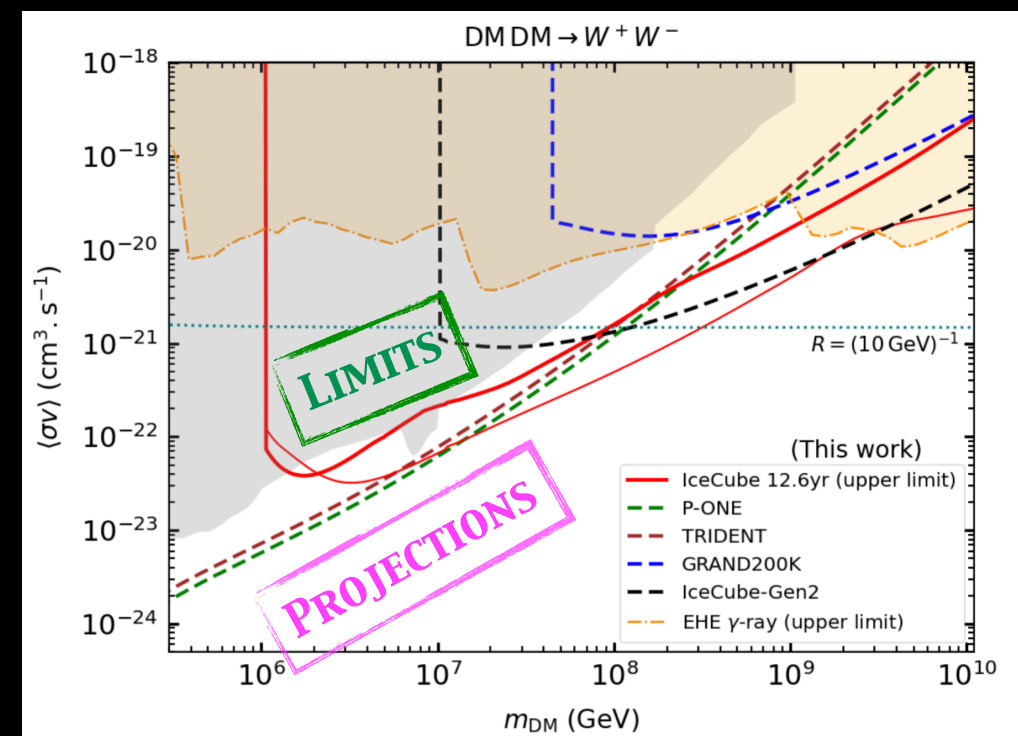
IceCube 1907.11193



Guépin+ 2106.04446

Limits and
projections
for upcoming
telescopes

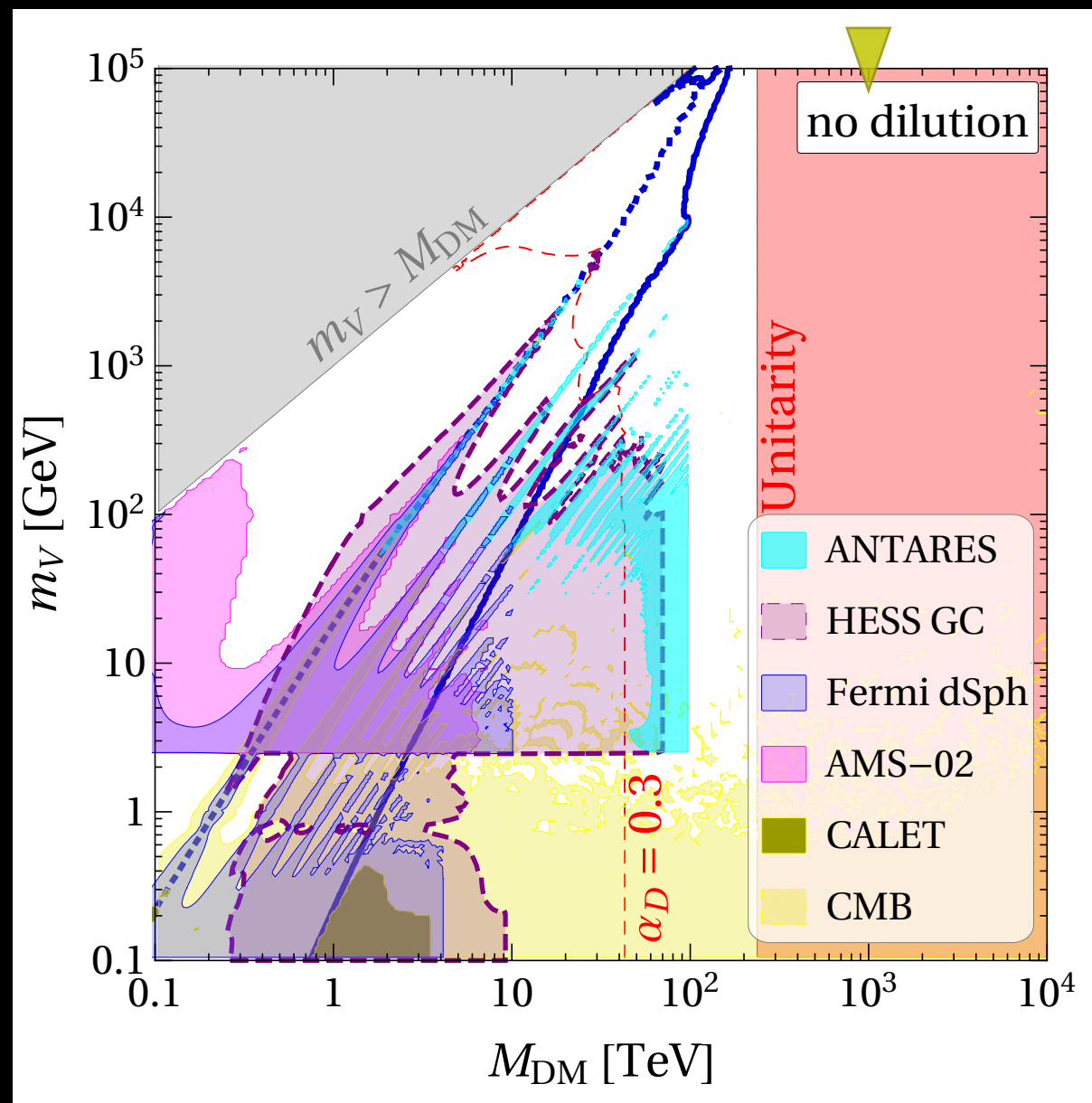
Kar & Cirelli 2609.xxxxx



Super-heavy DM ID

Dilution

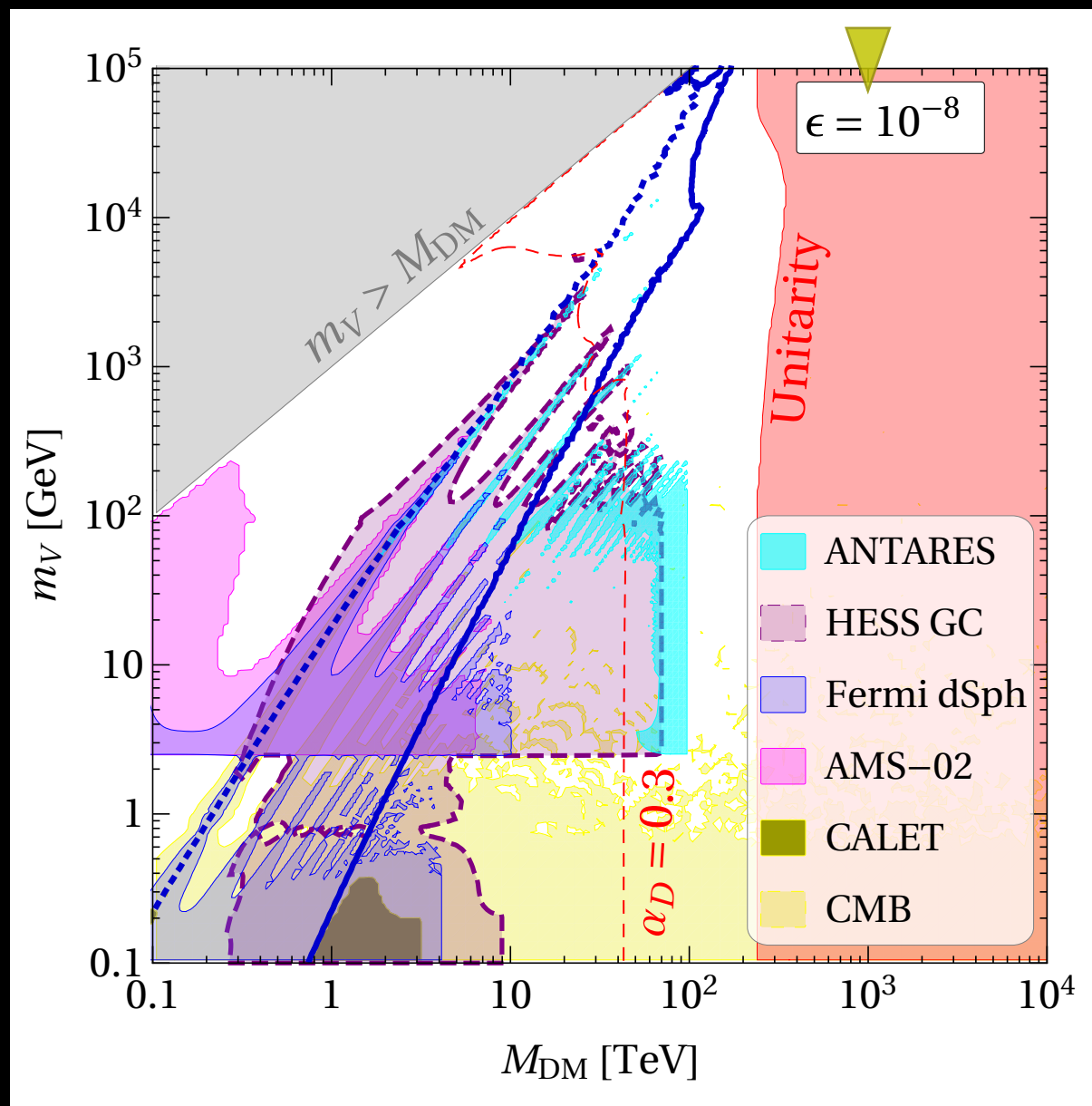
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

Dilution

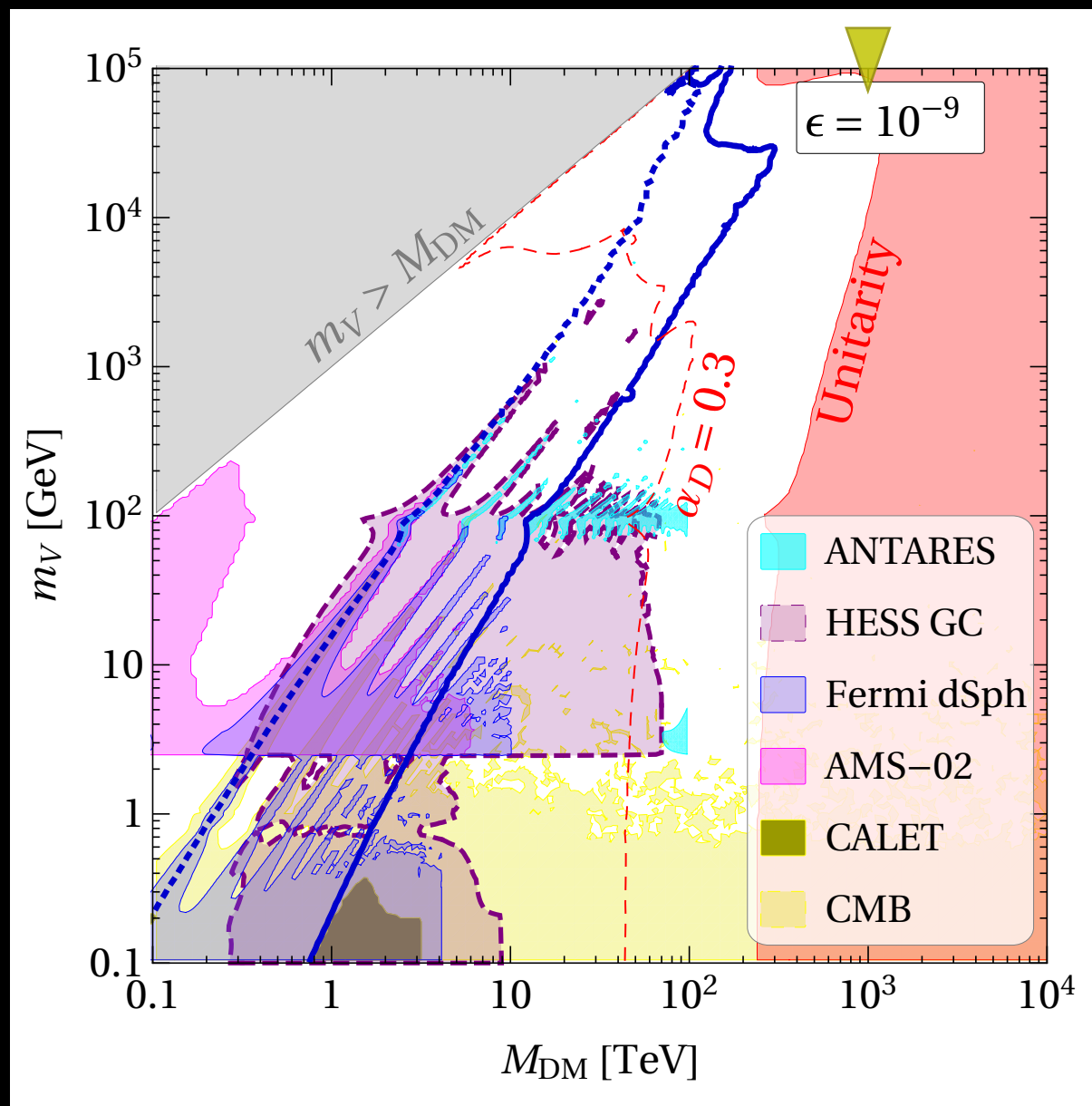
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

Dilution

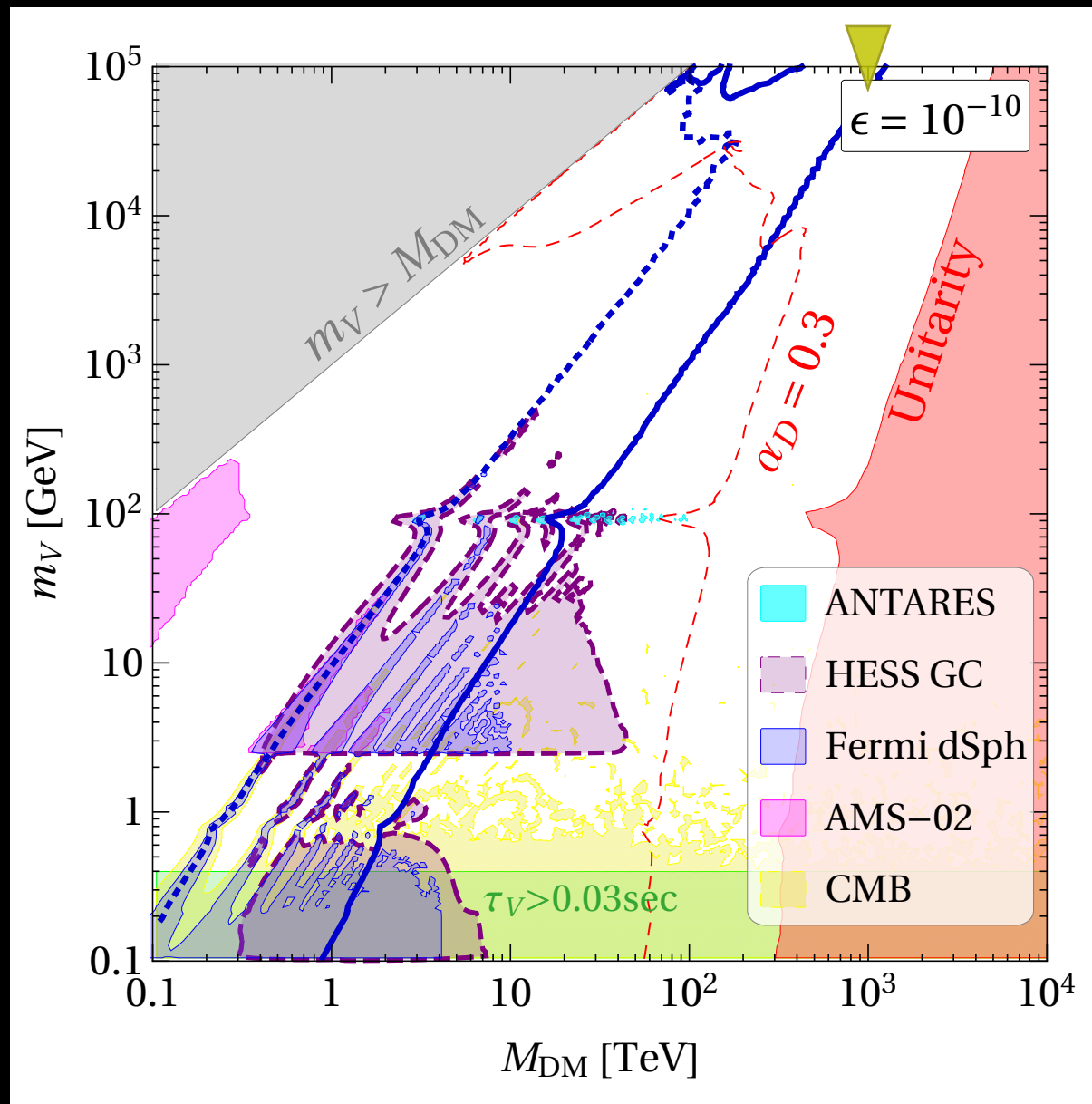
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

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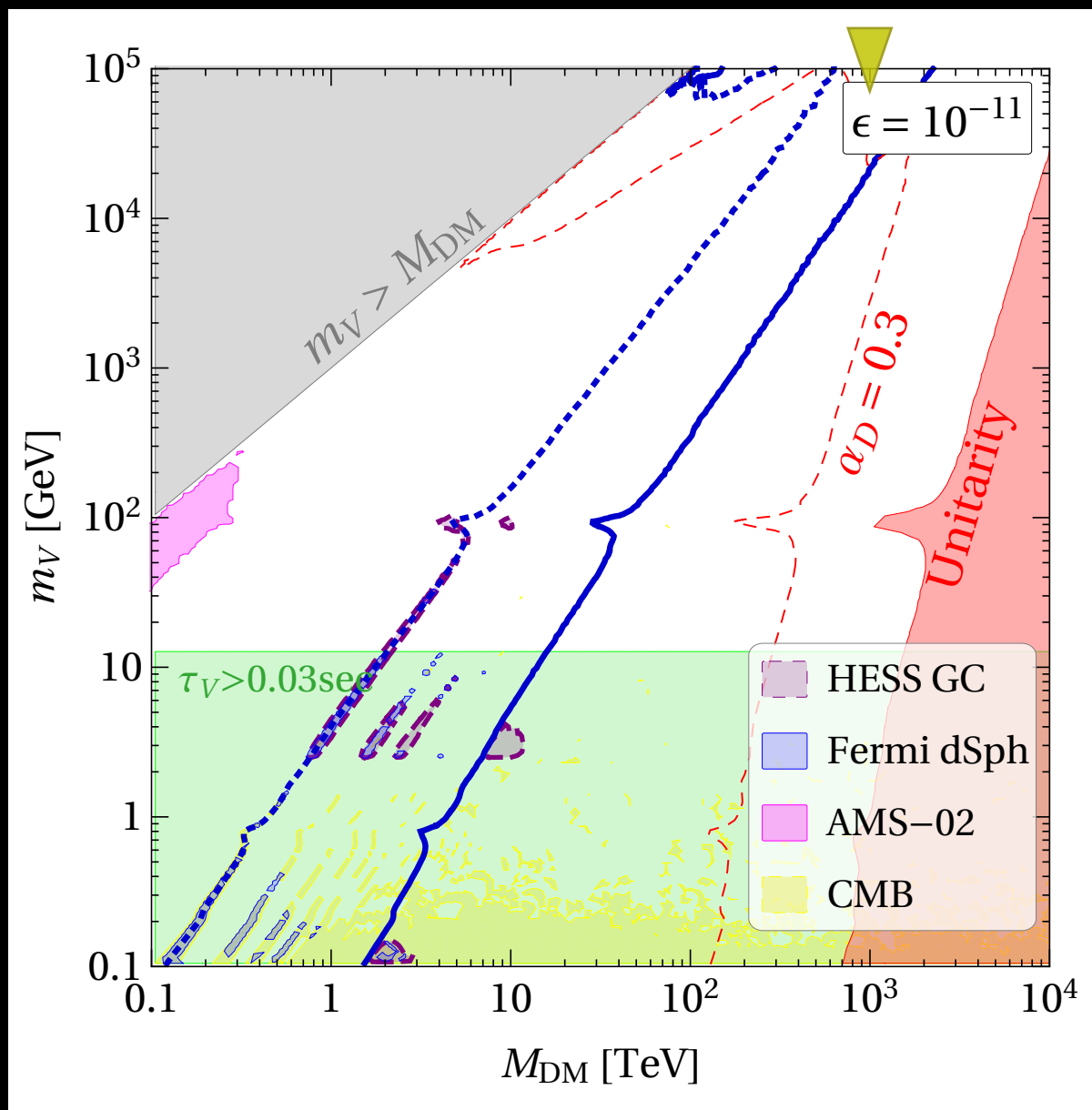
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

Dilution

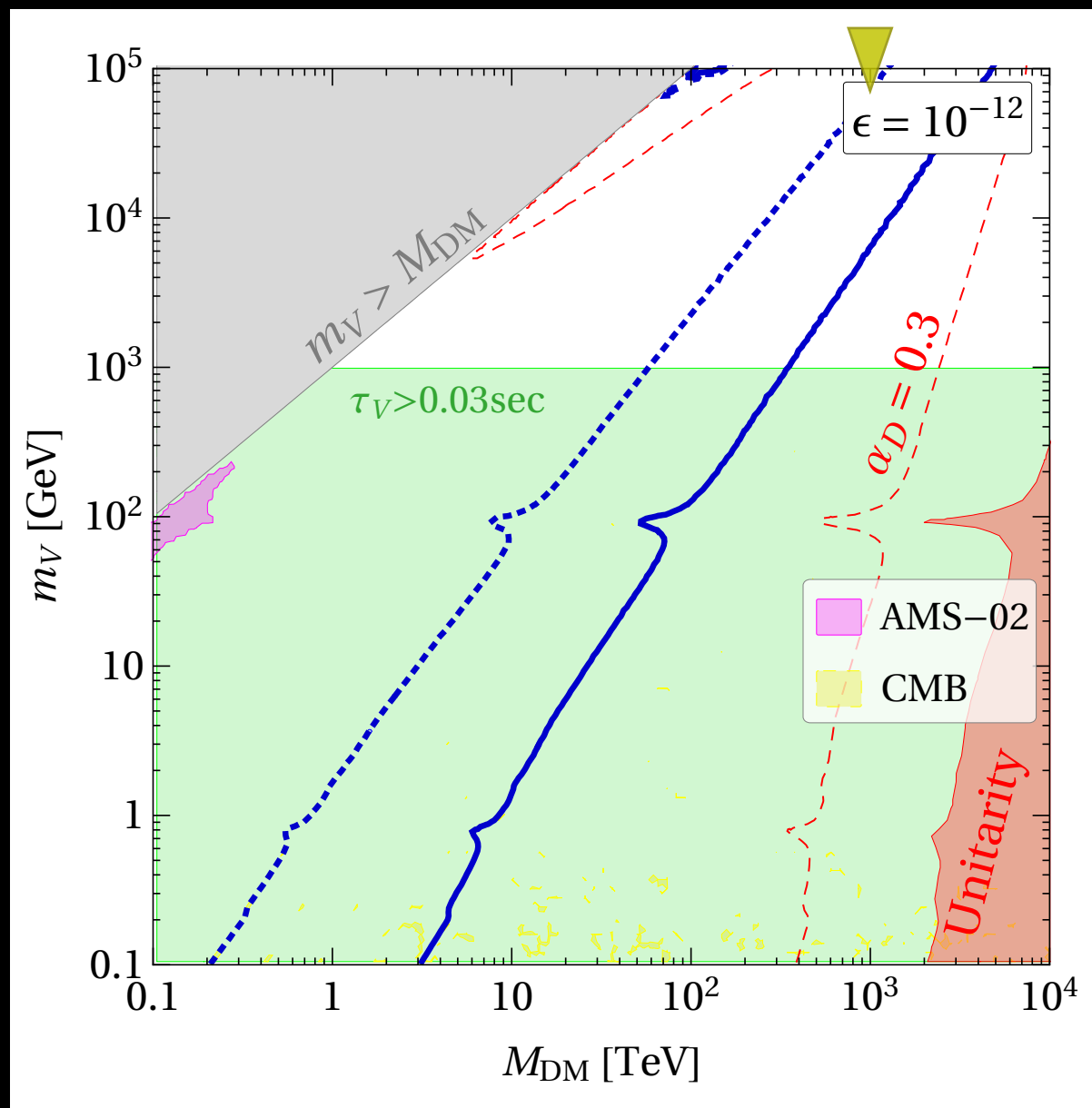
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

Dilution

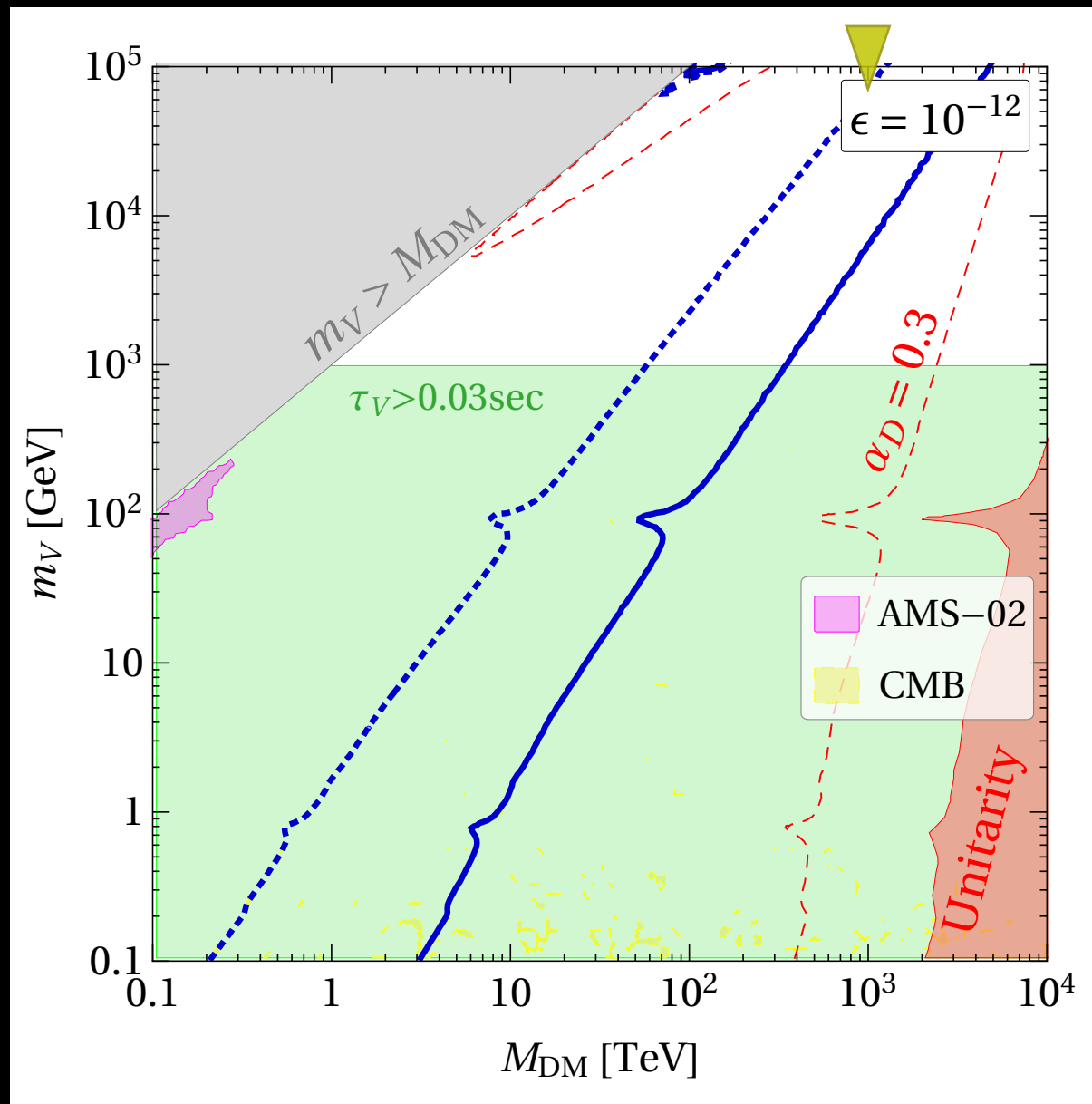
Limits in the parameter space
of homeopathic DM



Super-heavy DM ID

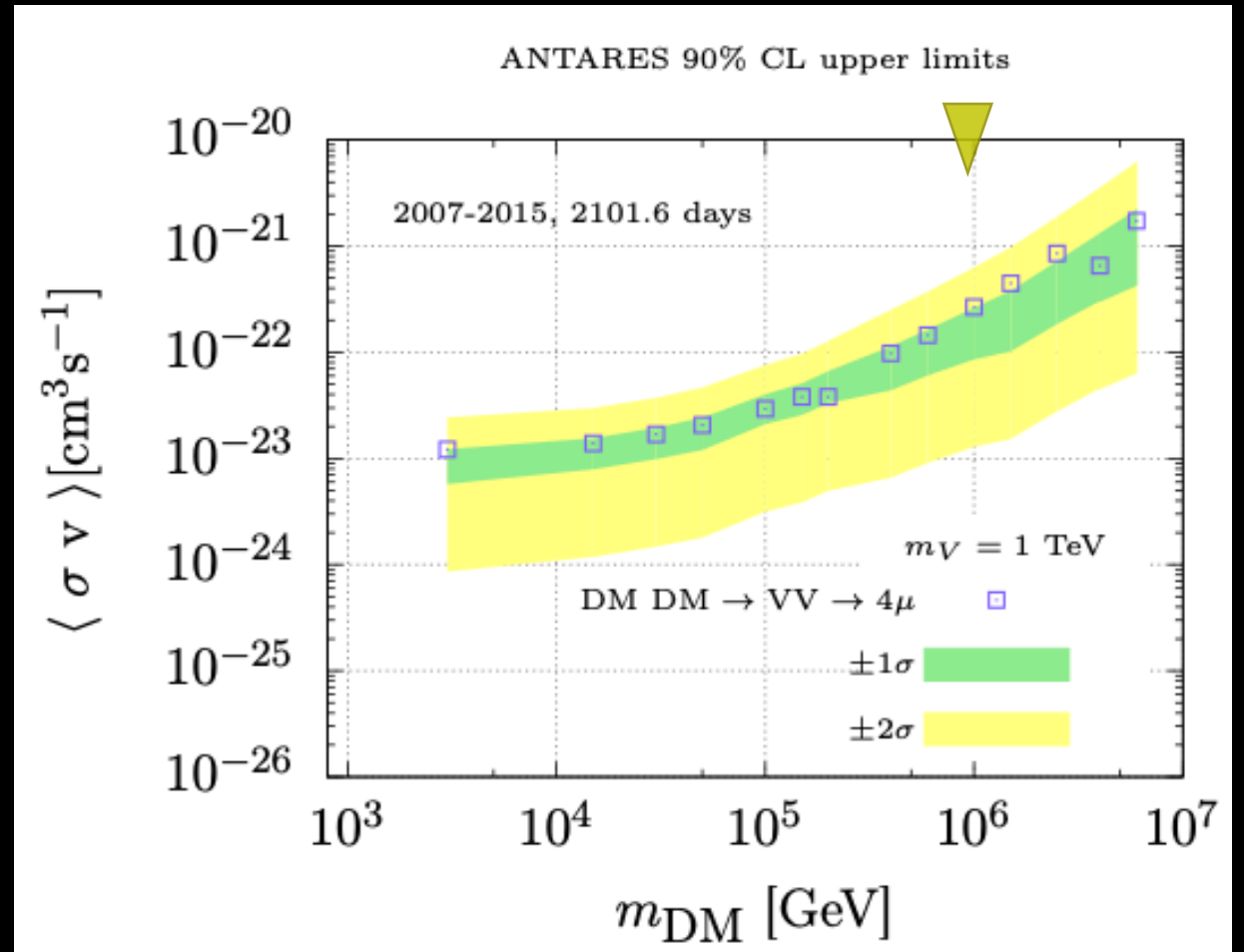
Dilution

Limits in the parameter space of homeopathic DM



Cirelli+ 1811.03608

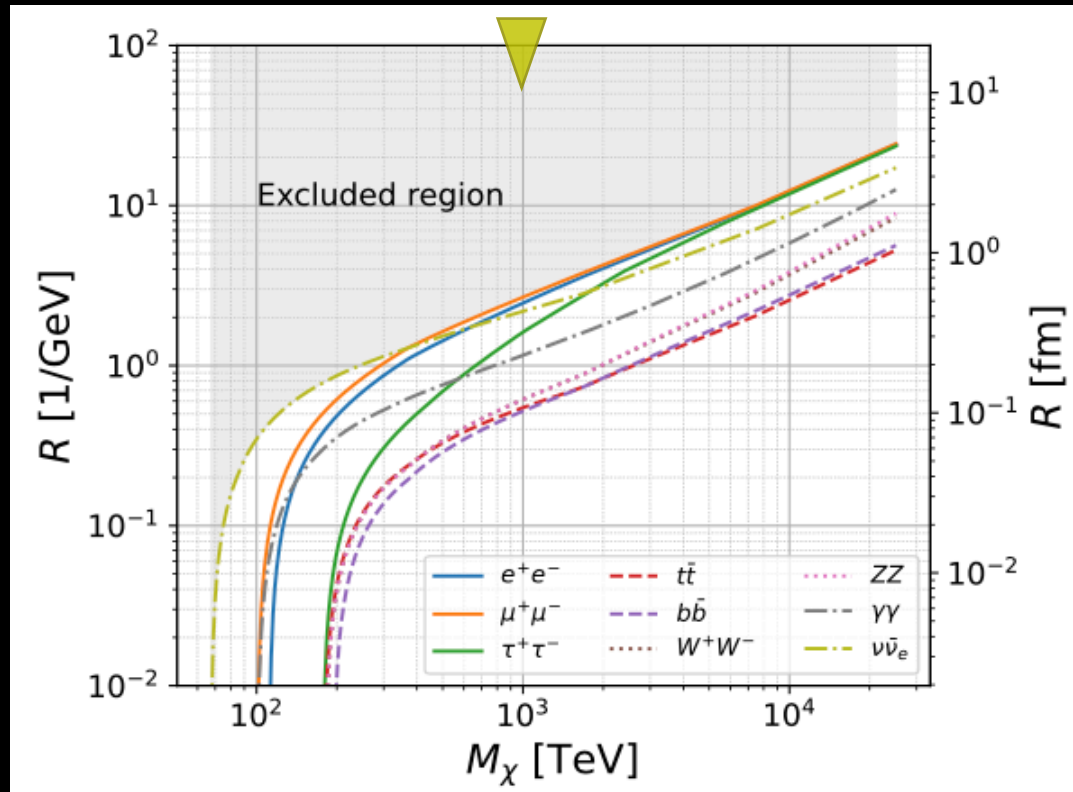
Limits on generic 'secluded' (= dark mediator) DM



ANTARES+Sala 2203.06029

Super-heavy DM ID

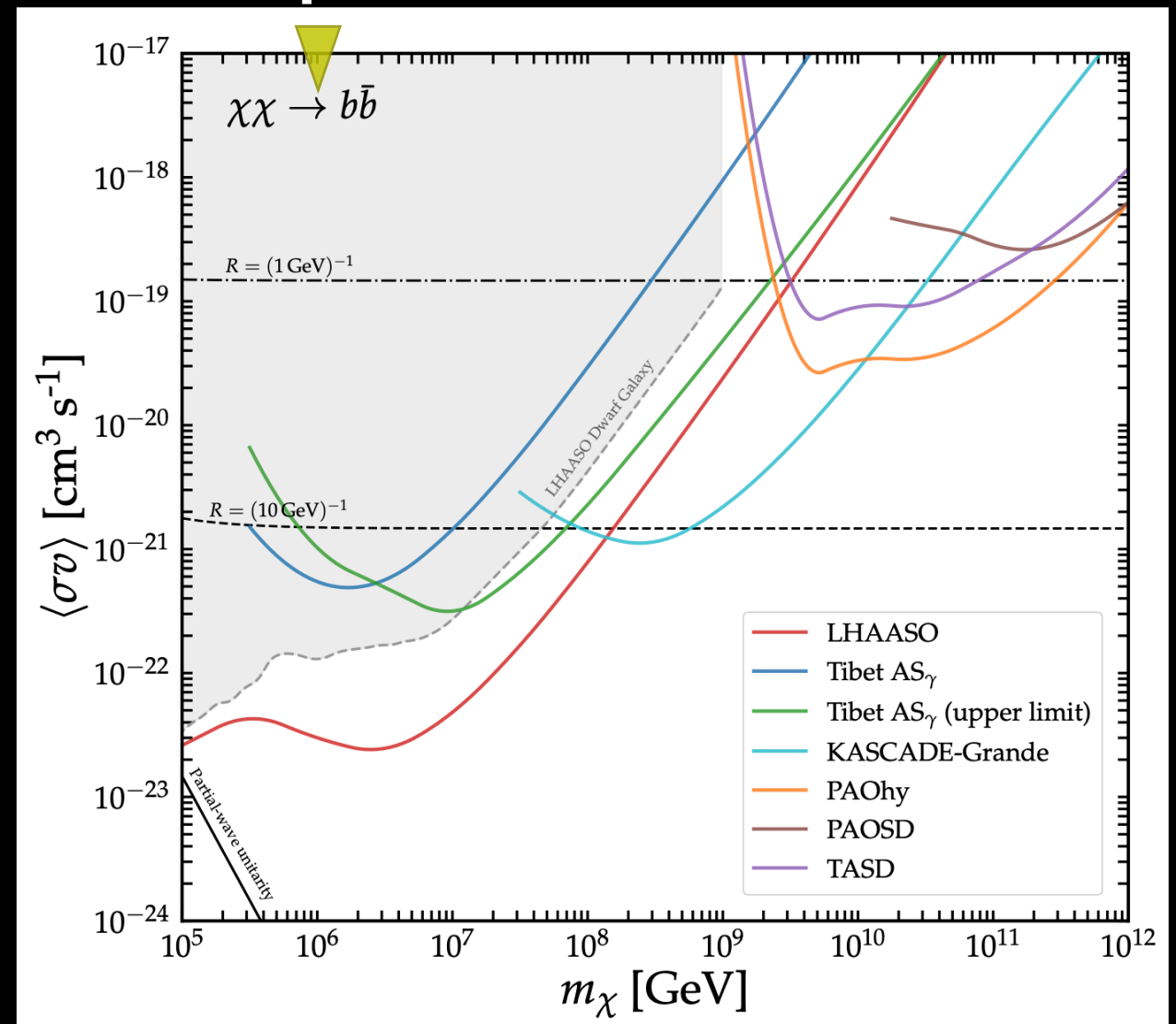
Compositeness



4 or 5 dSphs

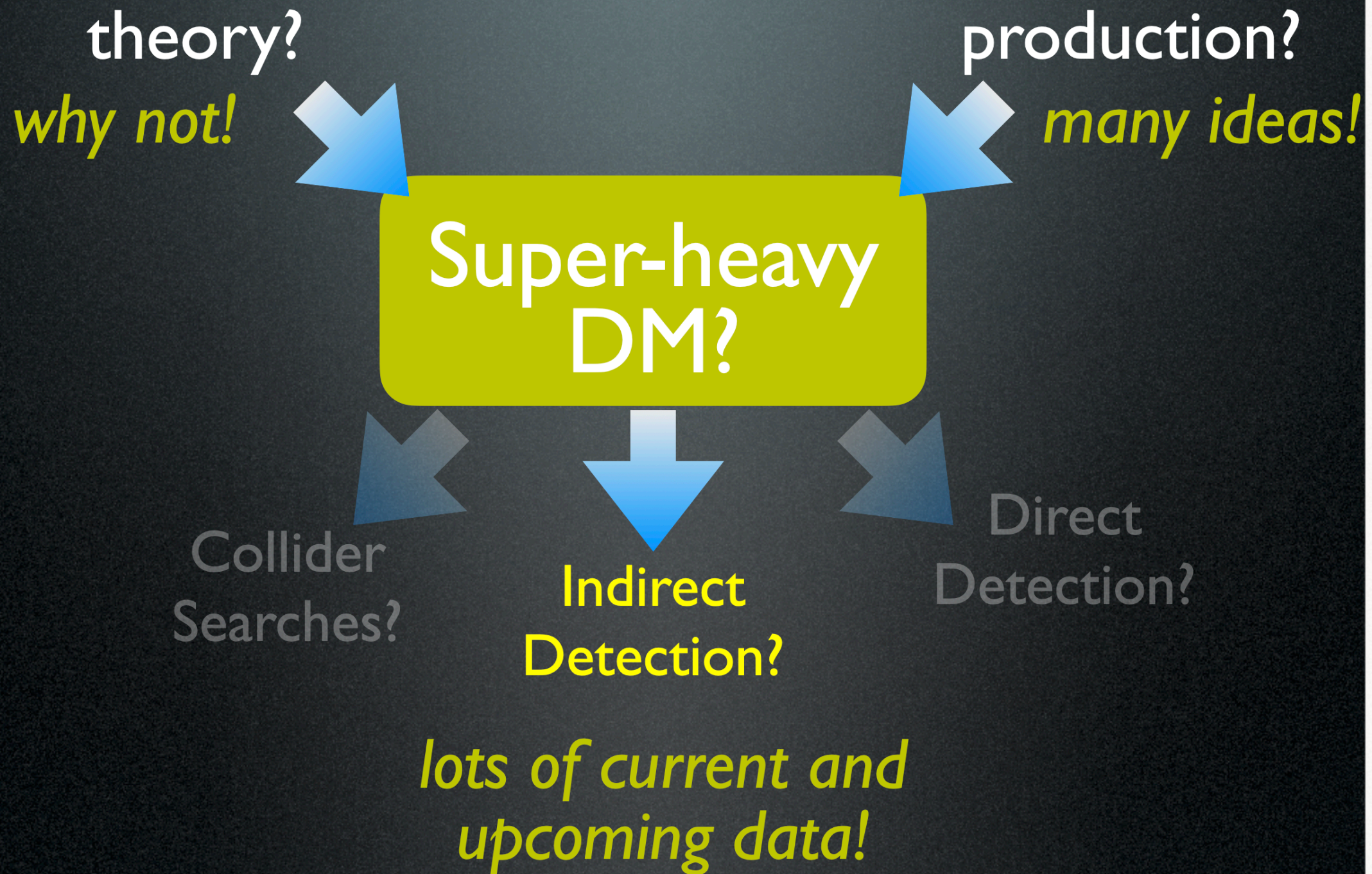
VERITAS 2302.08784

Every $\langle\sigma_{\text{ann}}v\rangle$ limit
maps into an R limit



Dubey, Das, Saha 2606.09976

Conclusions



Backup