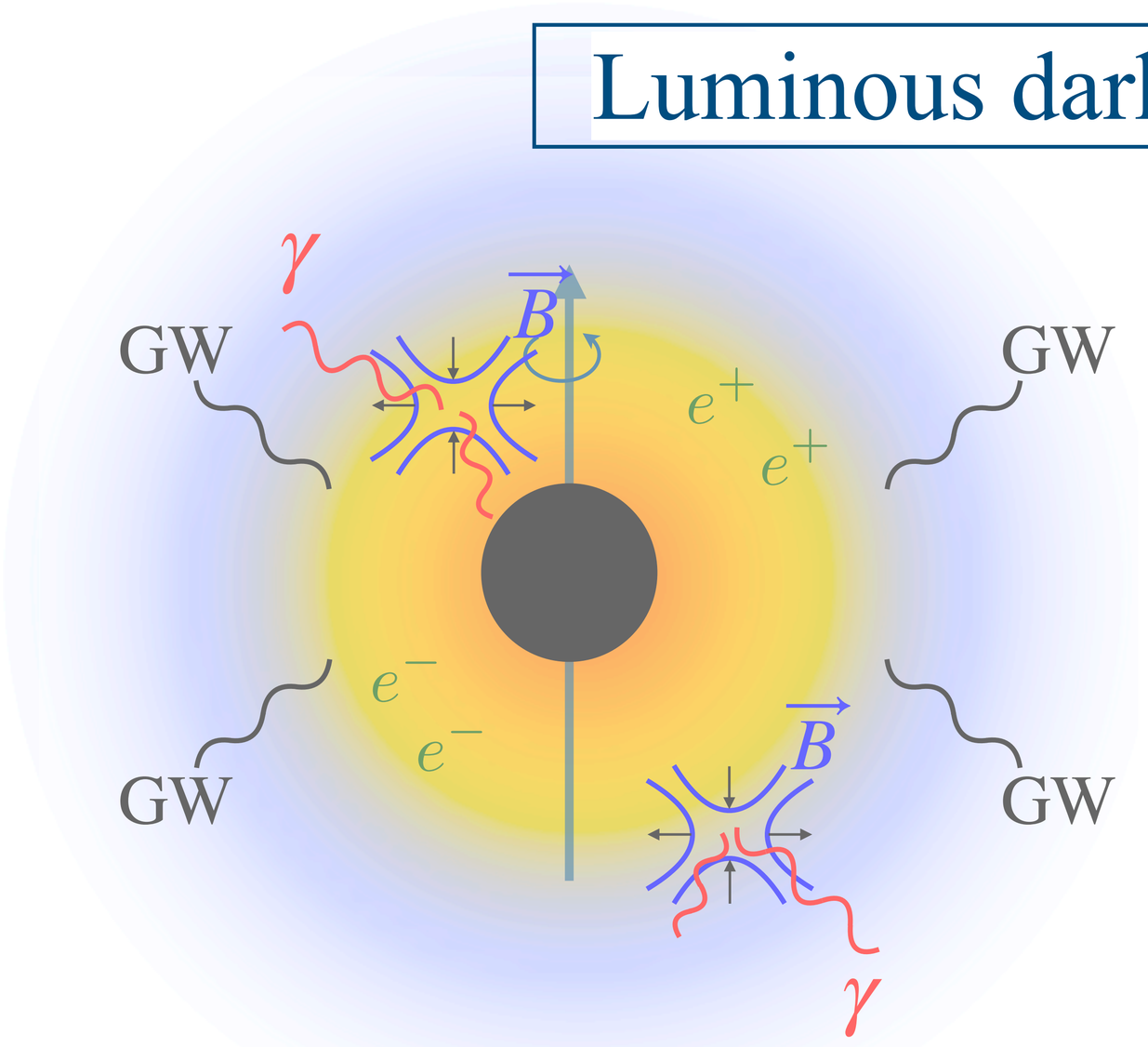
Luminous dark photon clouds



Cristina Mondino

PERIMETER INSTITUTE

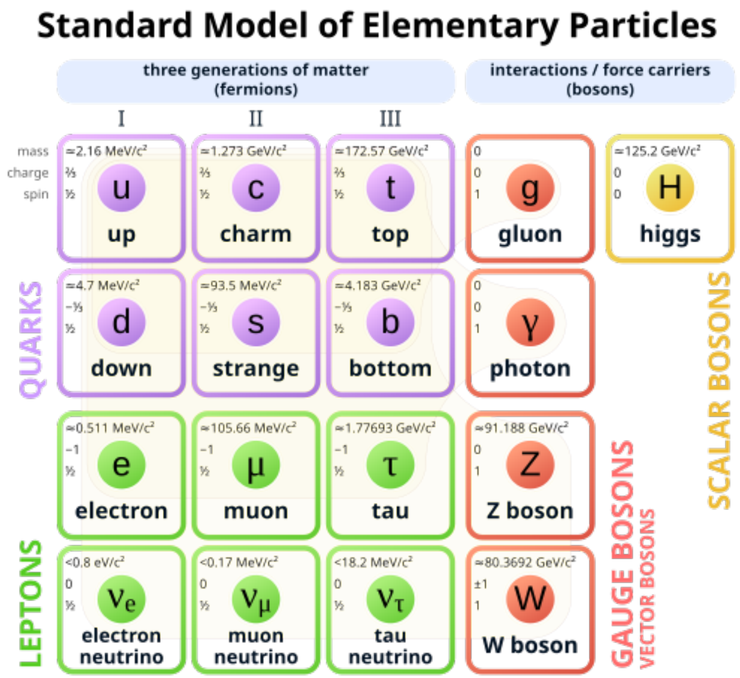
Gravitational Wave Probes of Black Hole Environments

IFPU focus week, 26th of May 2025

Phys. Rev. D 107 (2023) 7, arxiv:2212.09772
Phys. Rev. D 111 (2025) 8, arxiv:2501.02052

With: Nils Siemonsen, Lorenzo Mirasola, Daniel Egaña-Ugrinovic, Junwu Huang, Masha Baryakhtar, William E. East + CW group at INFN Roma/La Sapienza

Model and motivations

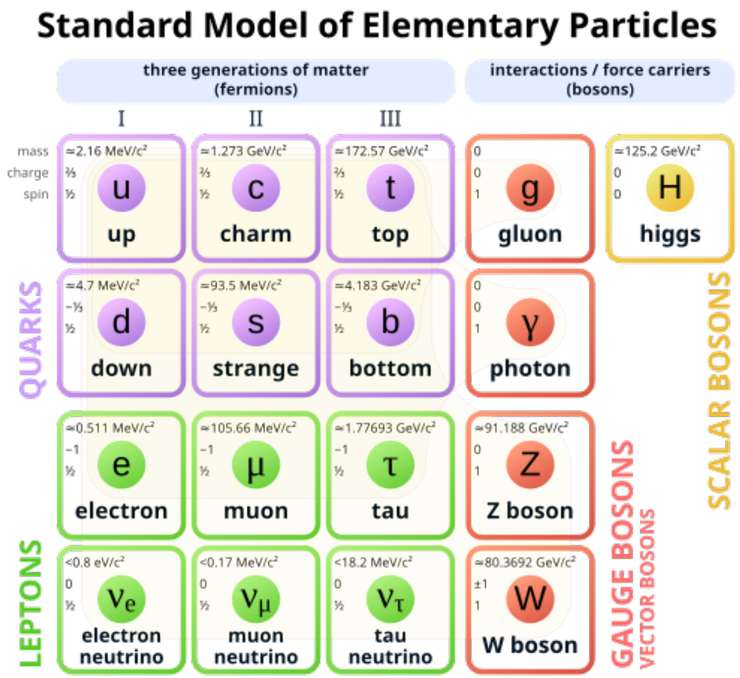


+ $\boxed{\gamma'}$

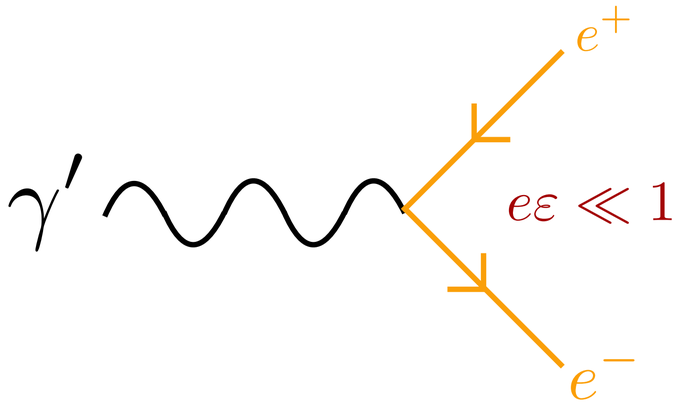
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2 A'^{\mu}A'_{\mu} - \frac{\varepsilon}{2}F^{\mu\nu}F'_{\mu\nu}$$

- New U(1) with massive vector boson gauge field
- Can mix kinetically with the SM photon
- Can be light
- Can be the DM or SM-DM mediator

Model and motivations



$+ \quad \boxed{\gamma'}$



$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2 A'^{\mu}A'_{\mu} + J^{\mu}_{\rm EM}(A_\mu + \varepsilon A'_\mu)$$

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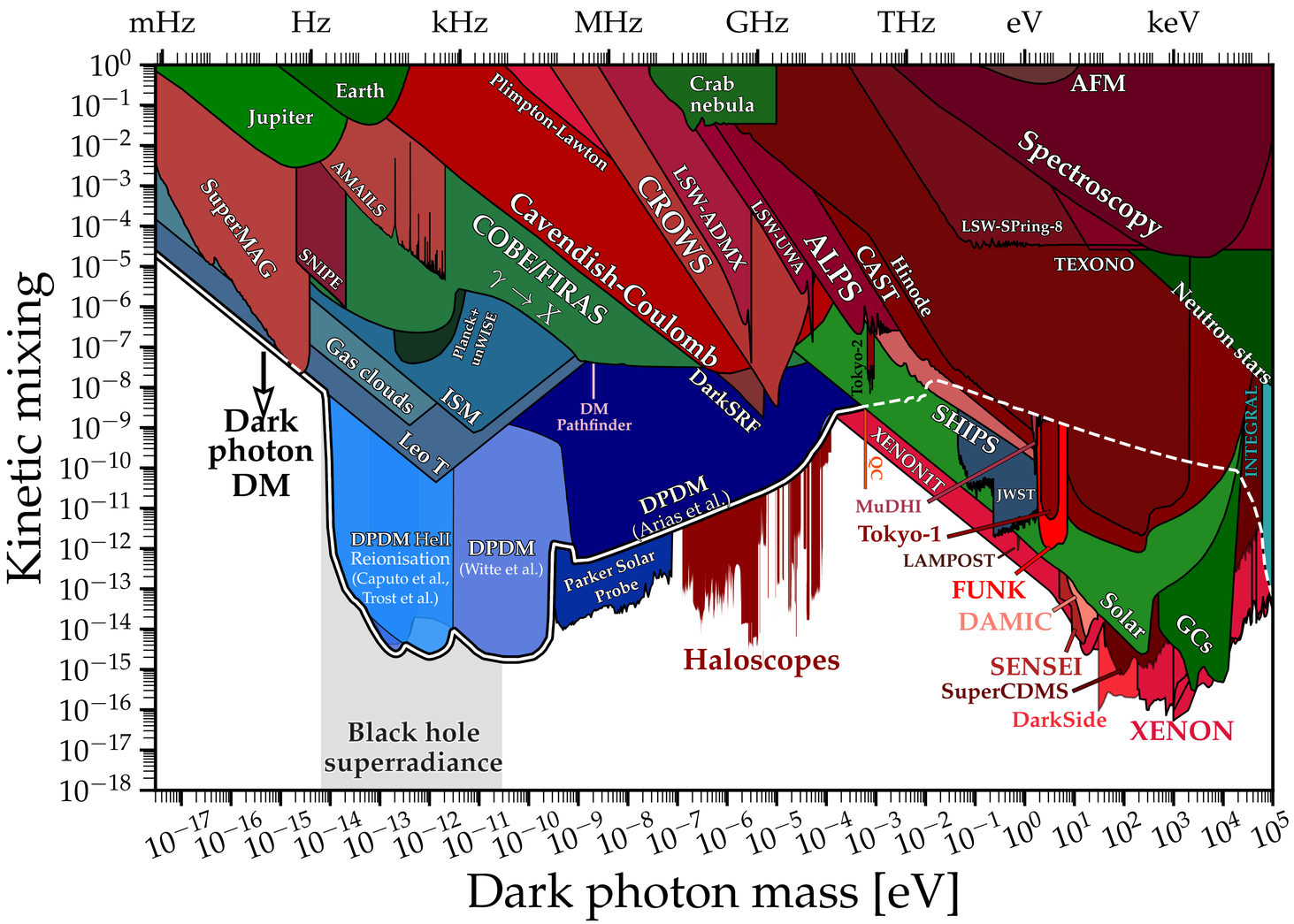
Dark photon parameter space

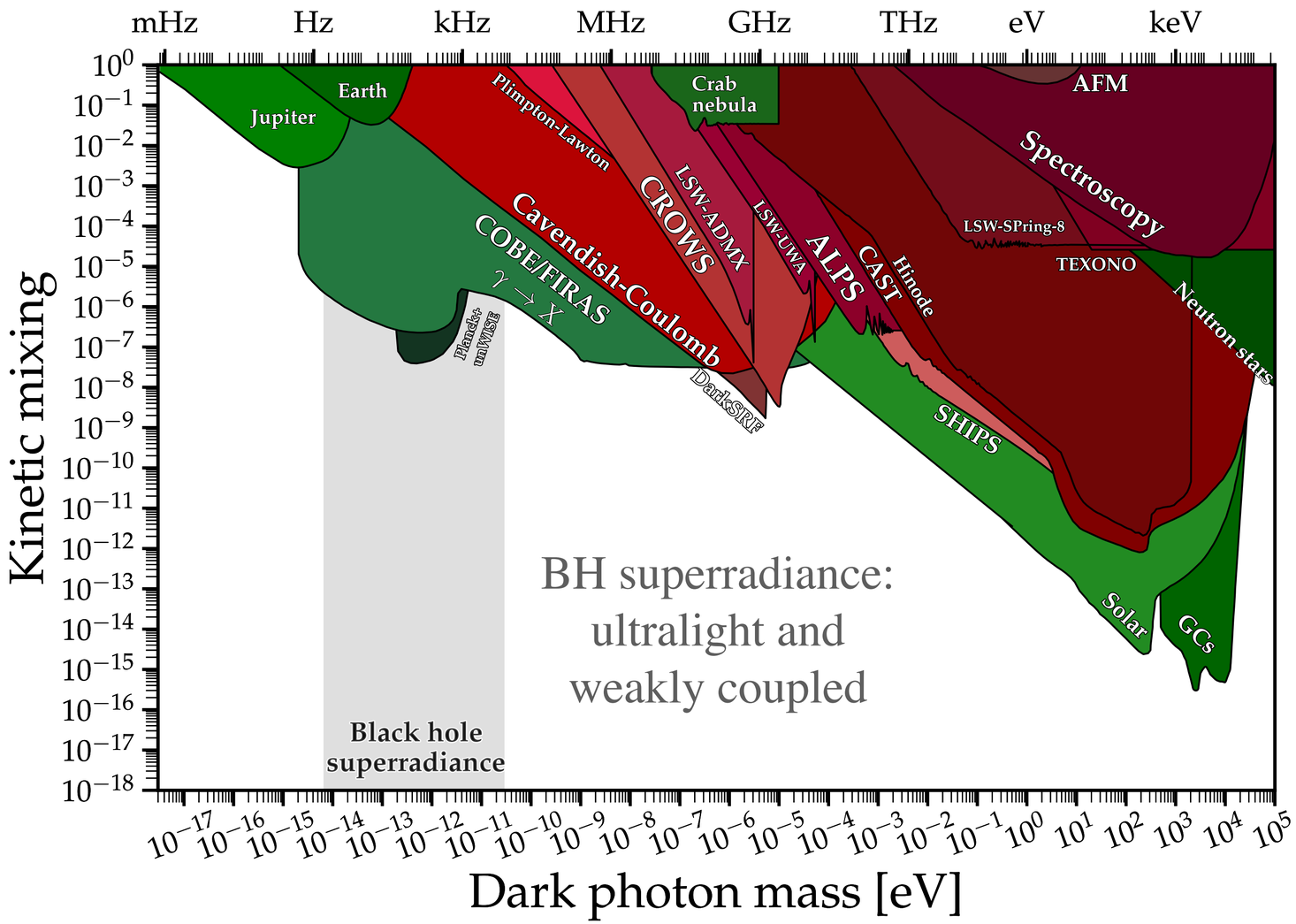


From Ciaran O'Hare (cajohare.github.io/AxionLimits/)

Dark photon parameter space

If

$$\Omega_{A'} \ll \Omega_{\rm DM}$$



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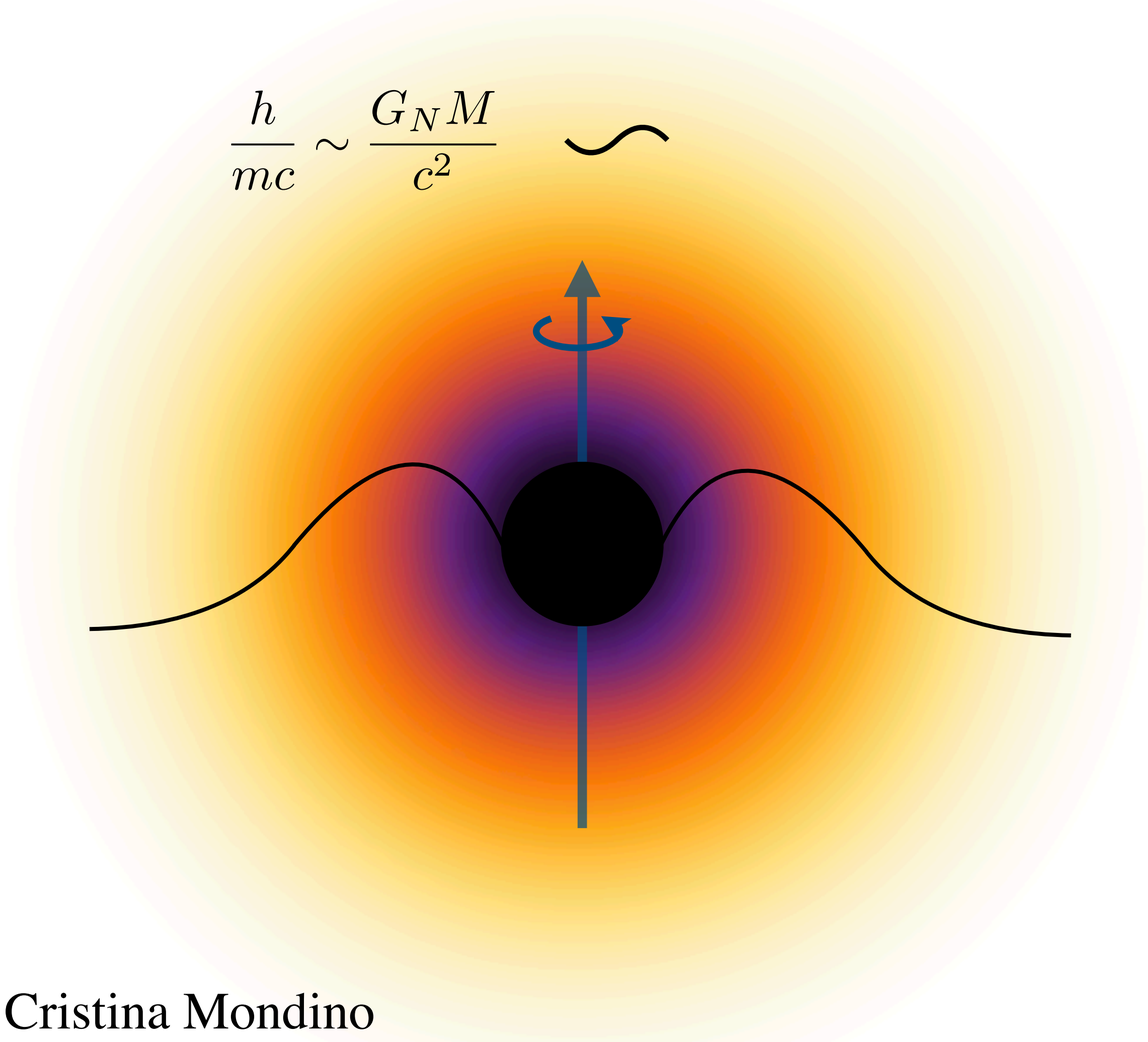
Black hole superradiance - vector field

M. Baryakhtar, R. Lasenby, M. Teo, PRD 2017
D. Bauman, H.S. Chia, J. Stout, L.T. Haar JCAP 2019
...

New massive vector boson

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{1}{2}m^2 A'^{\mu}A'_{\mu}$$

$$\frac{h}{mc} \sim \frac{G_N M}{c^2}$$



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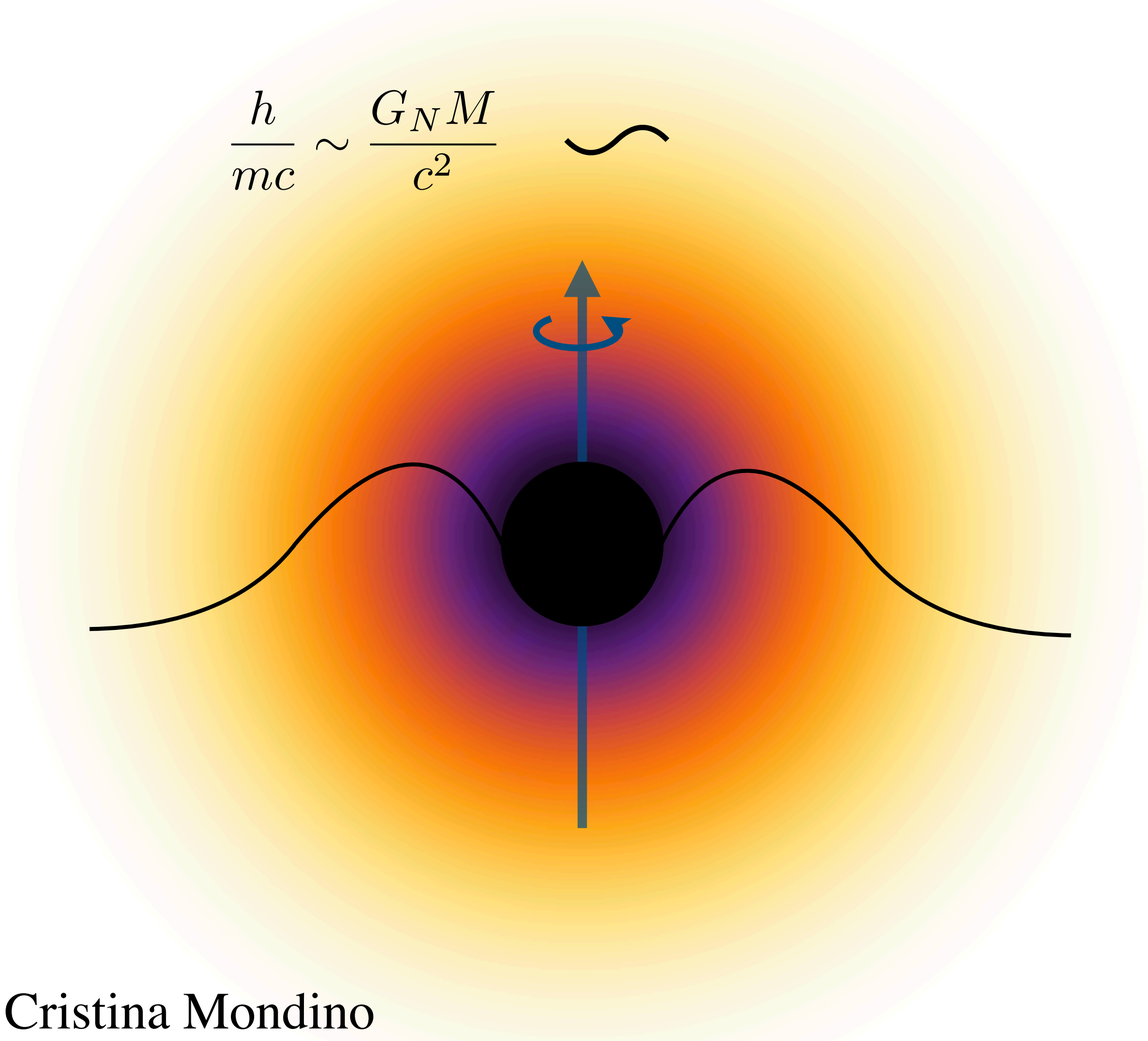

- BH looses energy and angular momentum in favor of amplification of boson wave

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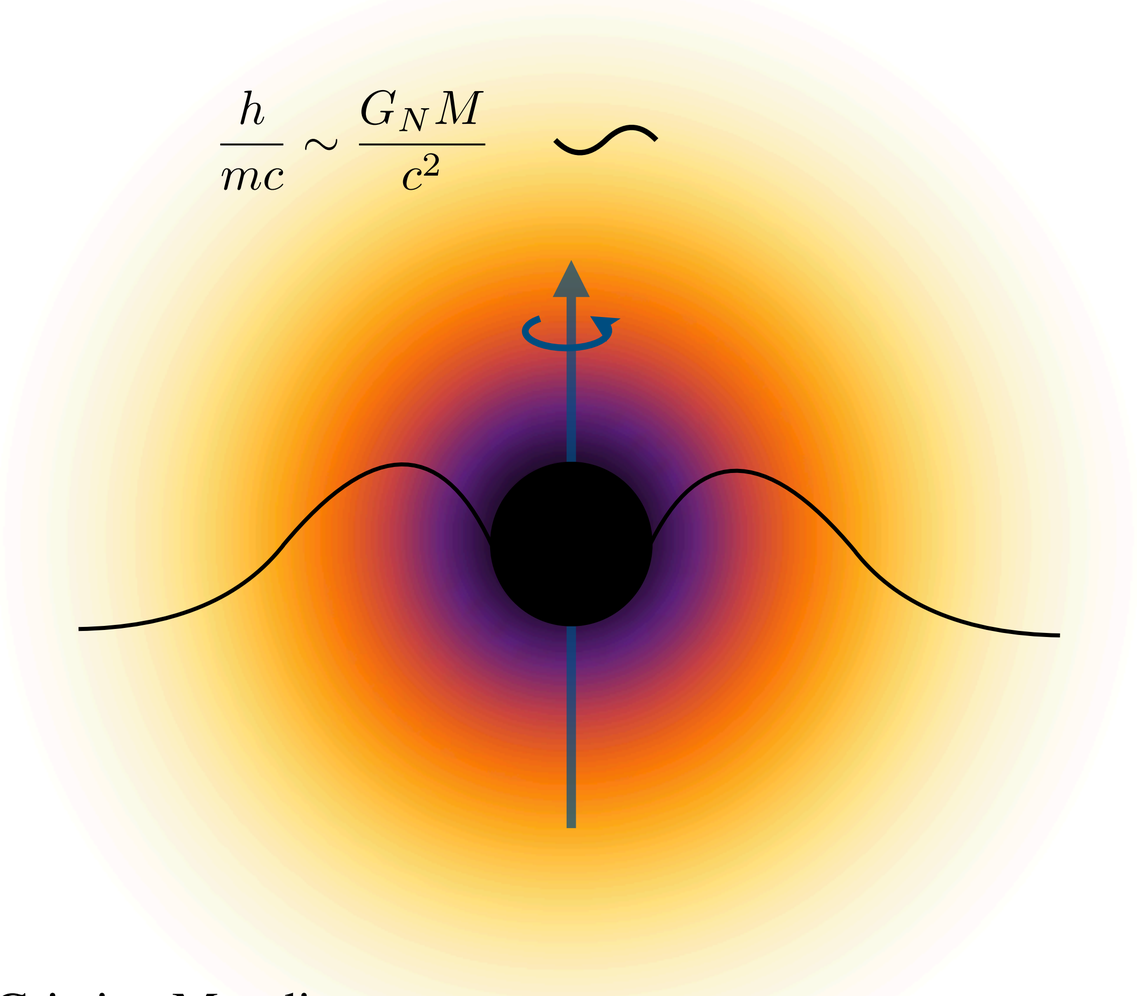

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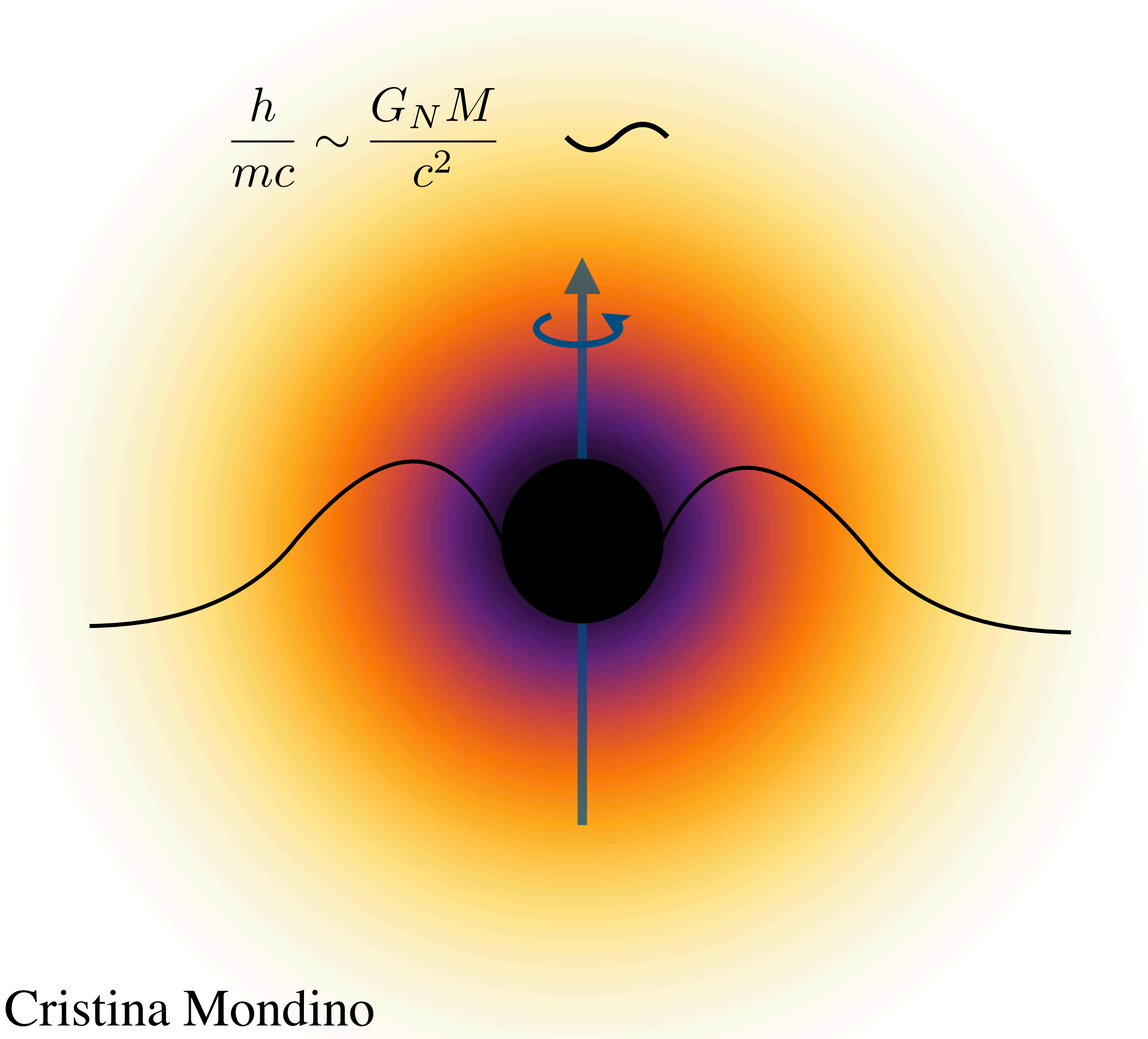

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- Cloud decays through emission of long-duration quasi-monochromatic GWs ($f_{\rm GW} \simeq mc^2/\pi\hbar$)

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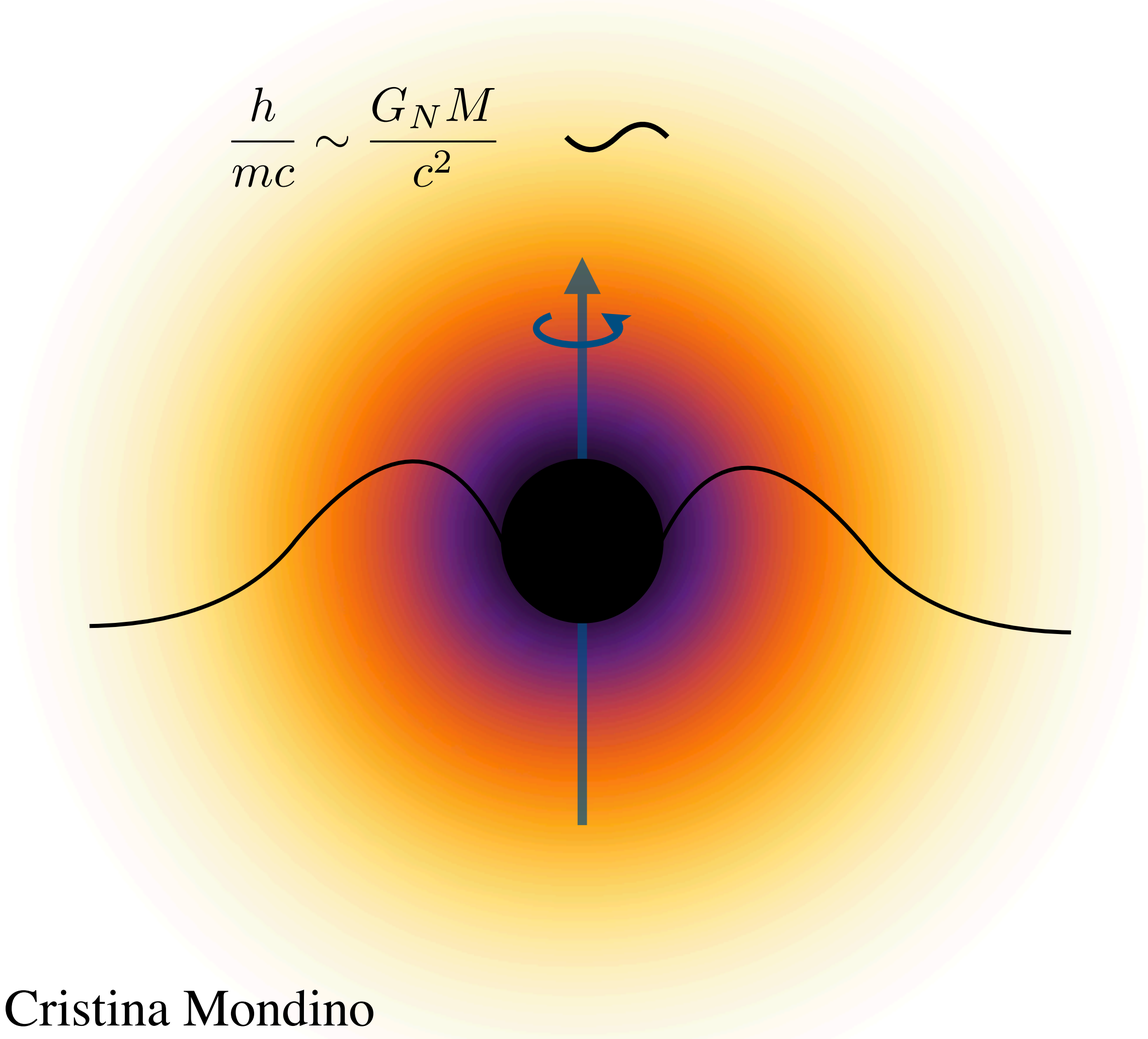


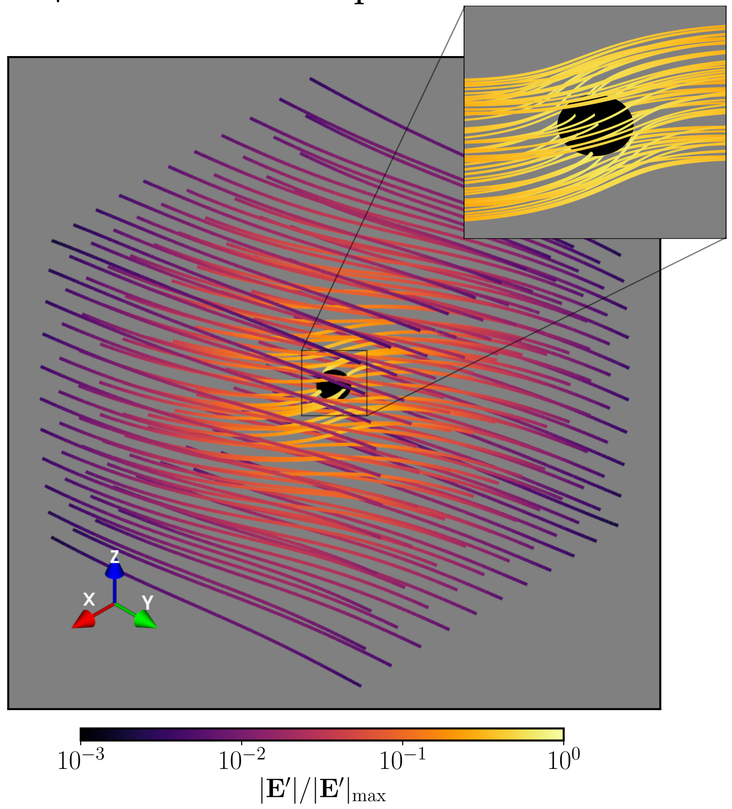
- BH looses energy and angular momentum in favor of amplification of boson wave
- Create large bosonic cloud around spinning BHs
- Cloud decays through emission of long-duration quasi-monochromatic GWs ($f_{\rm GW} \simeq mc^2/\pi\hbar$)

Allows to probe the existence of new ultralight fields, irrespectively of their cosmological production

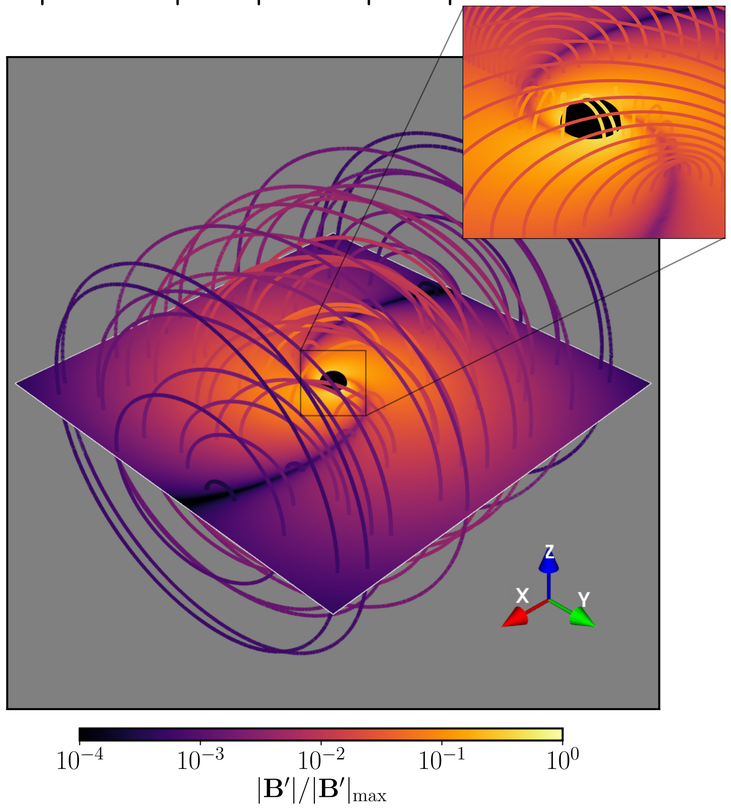
Black hole superradiance - vector field

M. Baryakhtar, R. Lasenby, M. Teo, PRD 2017
D. Bauman, H.S. Chia, J. Stout, L.T. Haar JCAP 2019
…

$|\vec{E}'| \sim \alpha^{5/2} m M_{\rm pl}$



$|\vec{B}'| \sim \alpha |\vec{E}'| \ll |\vec{E}'|$



Credit: Nils Siemonsen

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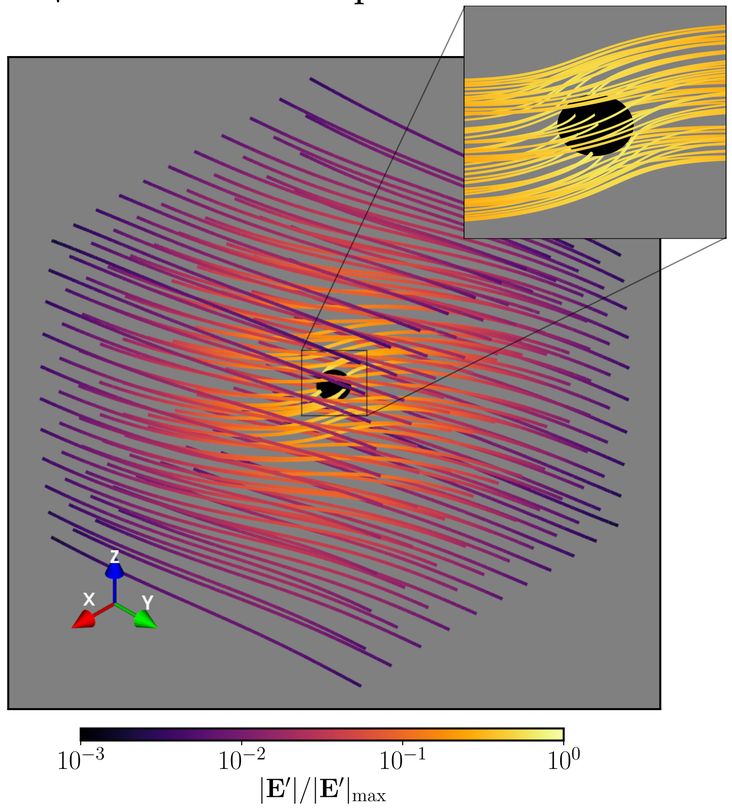

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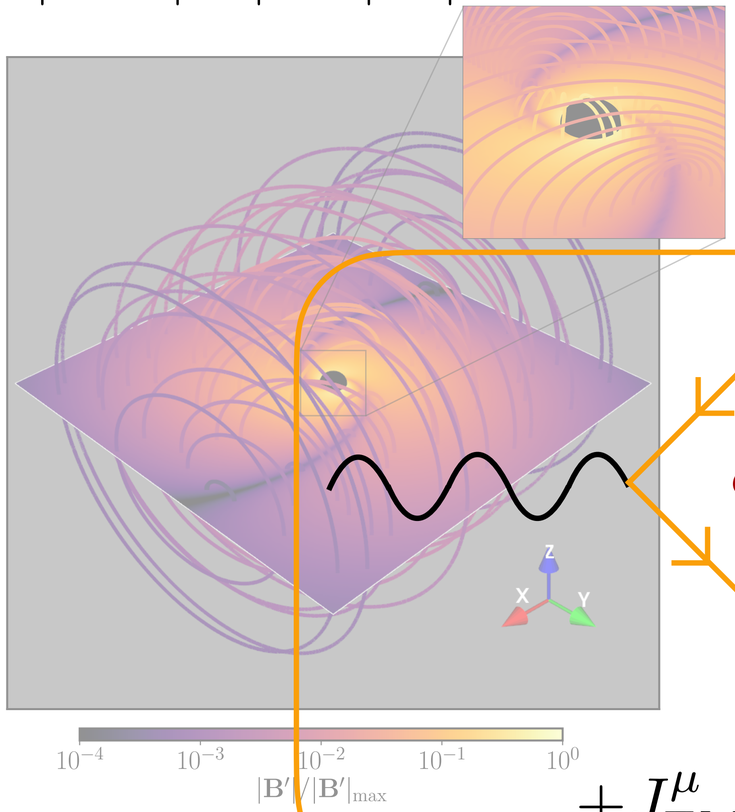


e^+

$e\varepsilon \ll 1$

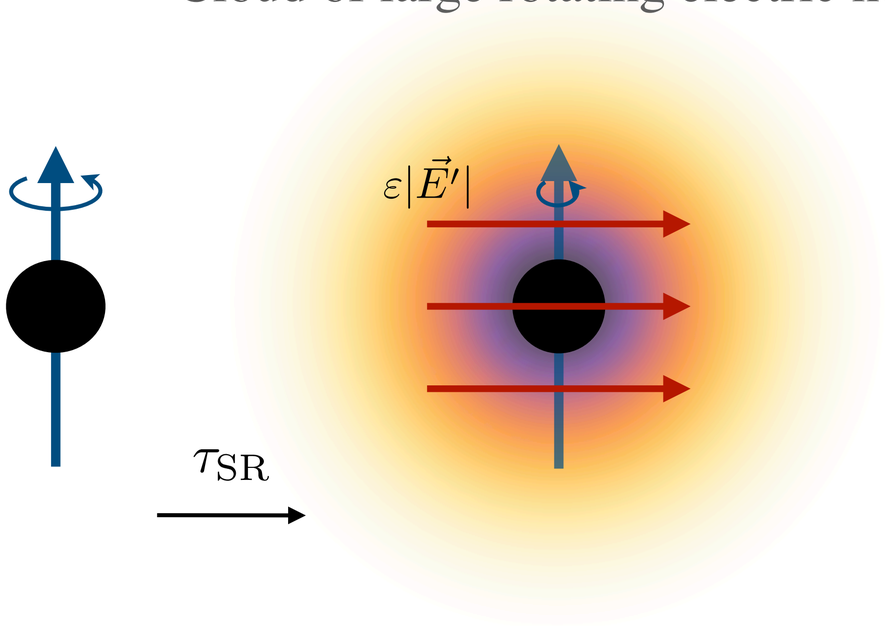
e^-

$+ J^\mu_{\rm EM}(A_\mu + \varepsilon A'_\mu)$

Kinetically-mixed dark photon cloud

N. Siemonsen, **CM**, D. Egaña-Ugrinovic, J. Huang, M. Baryakhtar, W. E. East
Phys. Rev. D (2023), arxiv:2212.09772

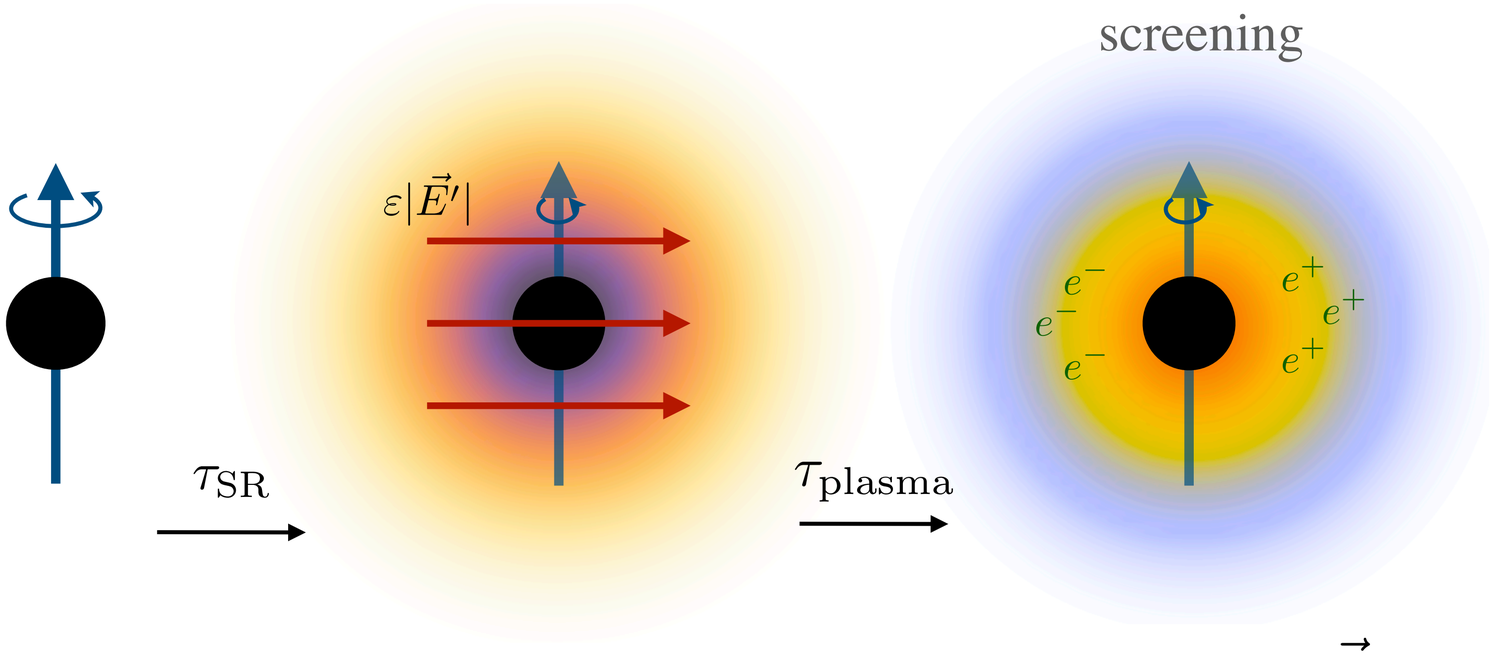
Cloud of large rotating electric field



Kinetically-mixed dark photon cloud

N. Siemonsen, **CM**, D. Egaña-Ugrinovic, J. Huang, M. Baryakhtar, W. E. East
Phys. Rev. D (2023), arxiv:2212.09772

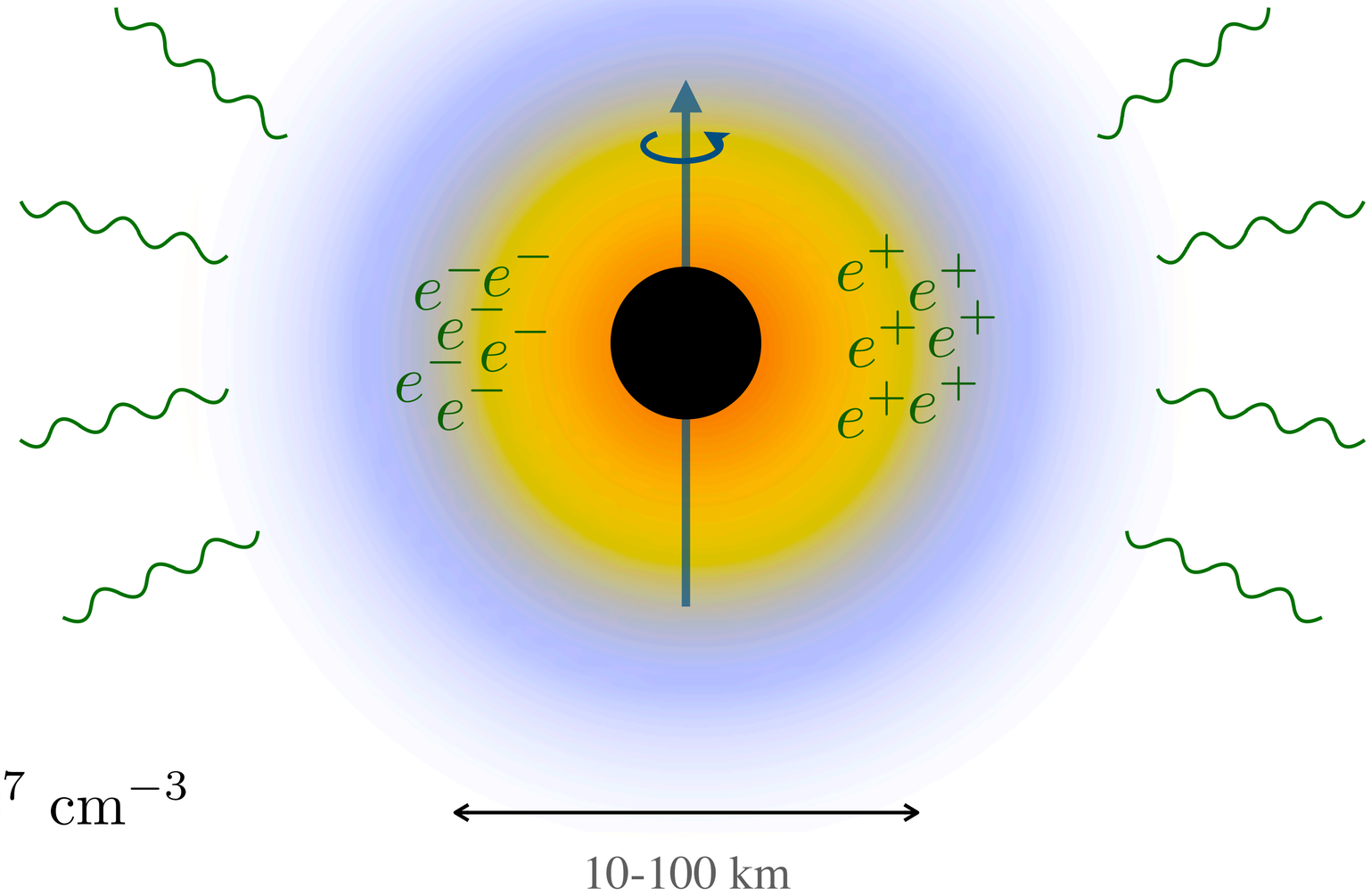
Production of charged particles:
screening



$$e n_e \simeq \varepsilon \nabla \cdot \vec{E}'$$

Rotating dipole

N. Siemonsen, **CM**, D. Egaña-Ugrinovic, J. Huang, M. Baryakhtar, W. E. East
Phys. Rev. D (2023), arxiv:2212.09772



Large amount of EM radiation!

$$en_e \simeq 10^7 \text{ cm}^{-3}$$

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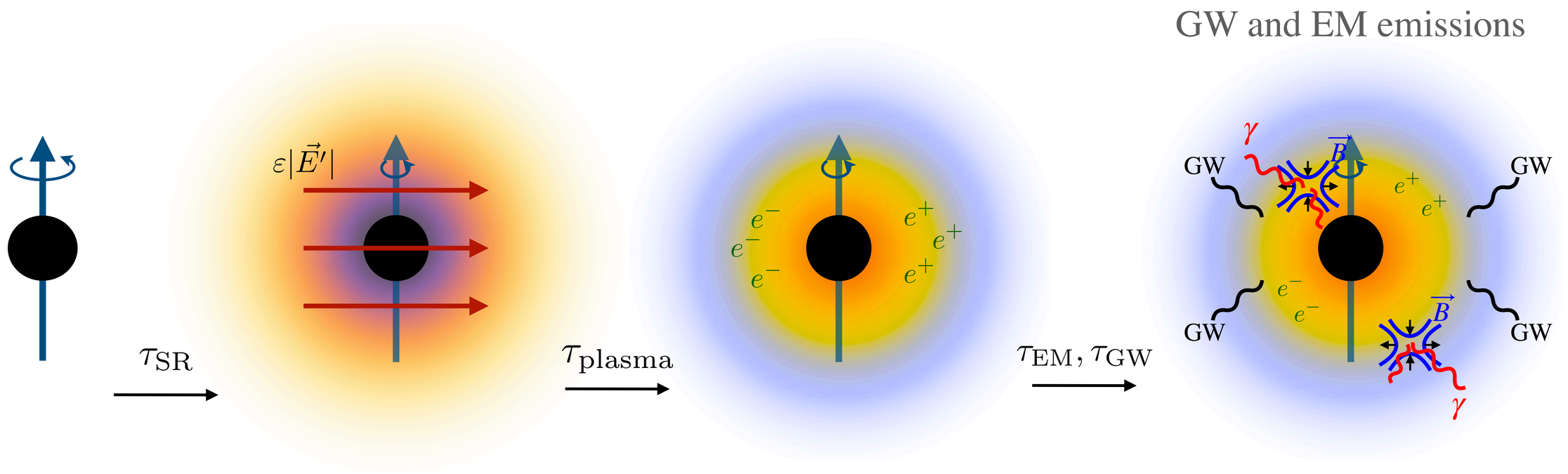
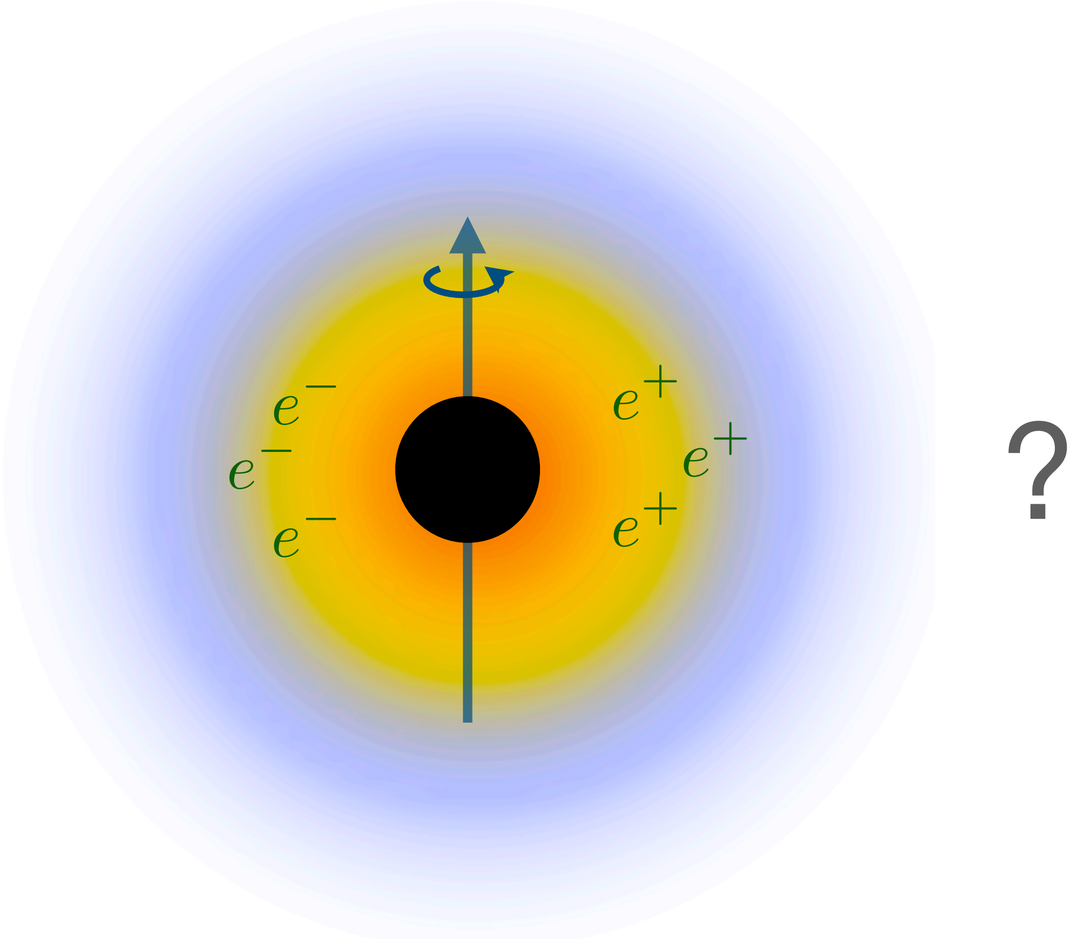


For the case with accretion disk, see:
S. Xin and E. R. Most, Phys.Rev.D 111 (2025), arxiv:2406.02992

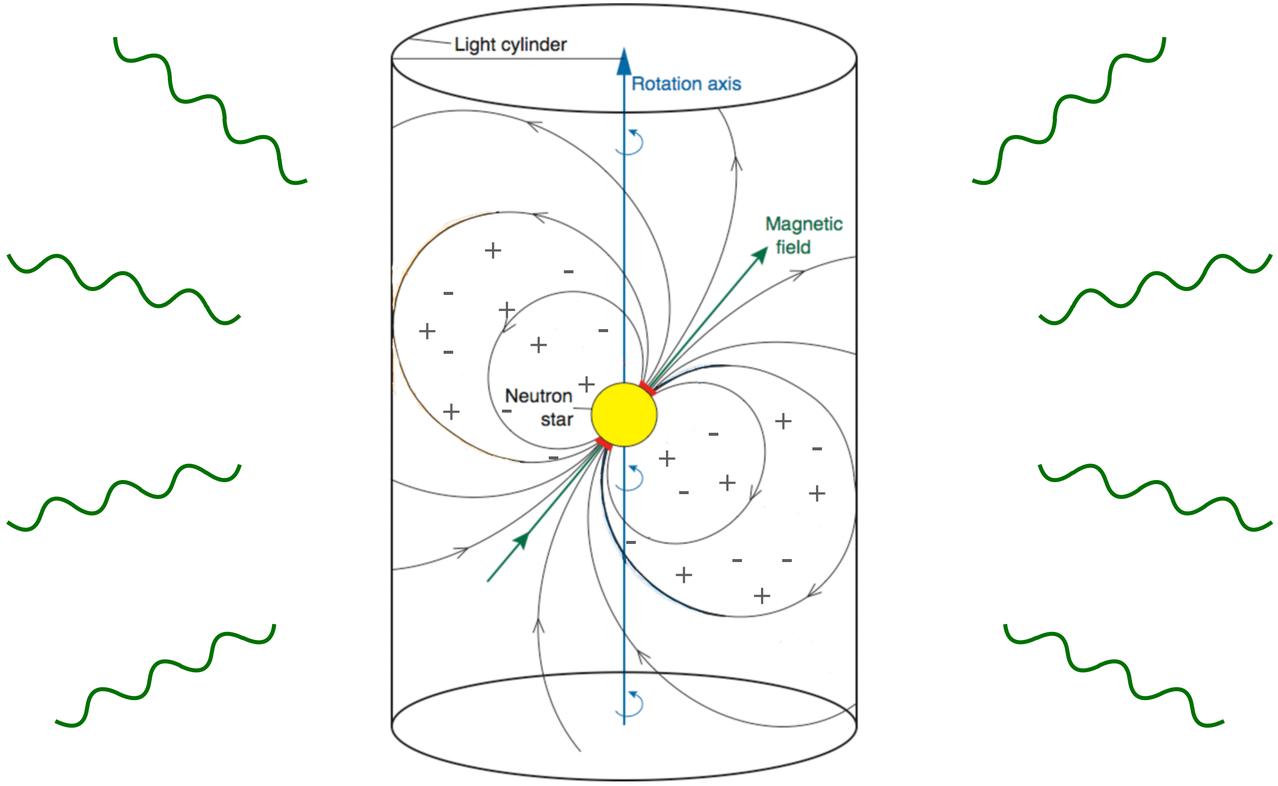
Superradiance cloud + plasma



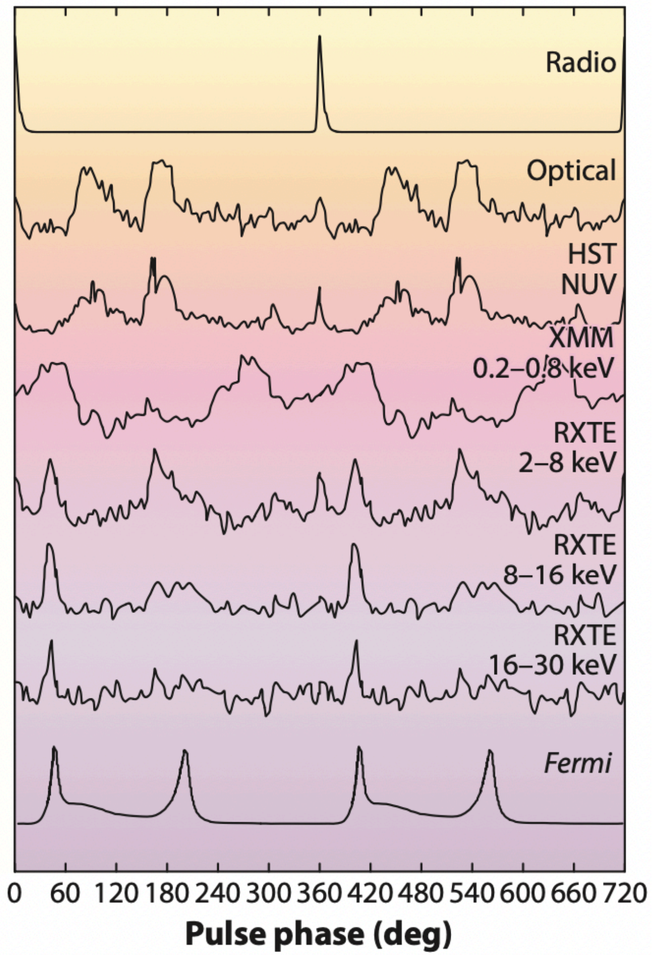
?

Neutron star pulsar

Magnetosphere of neutron star pulsar

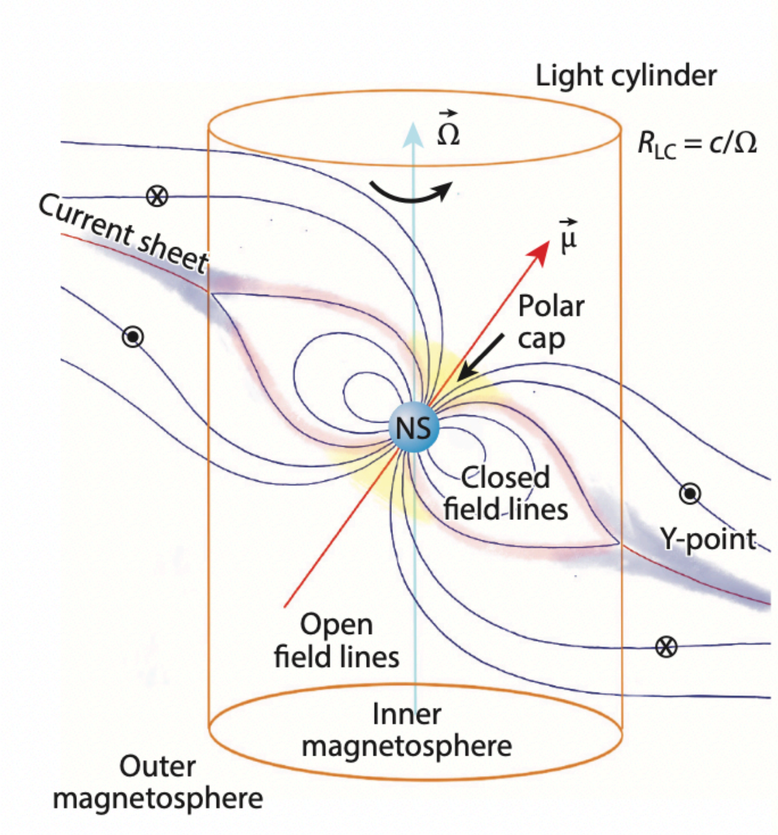


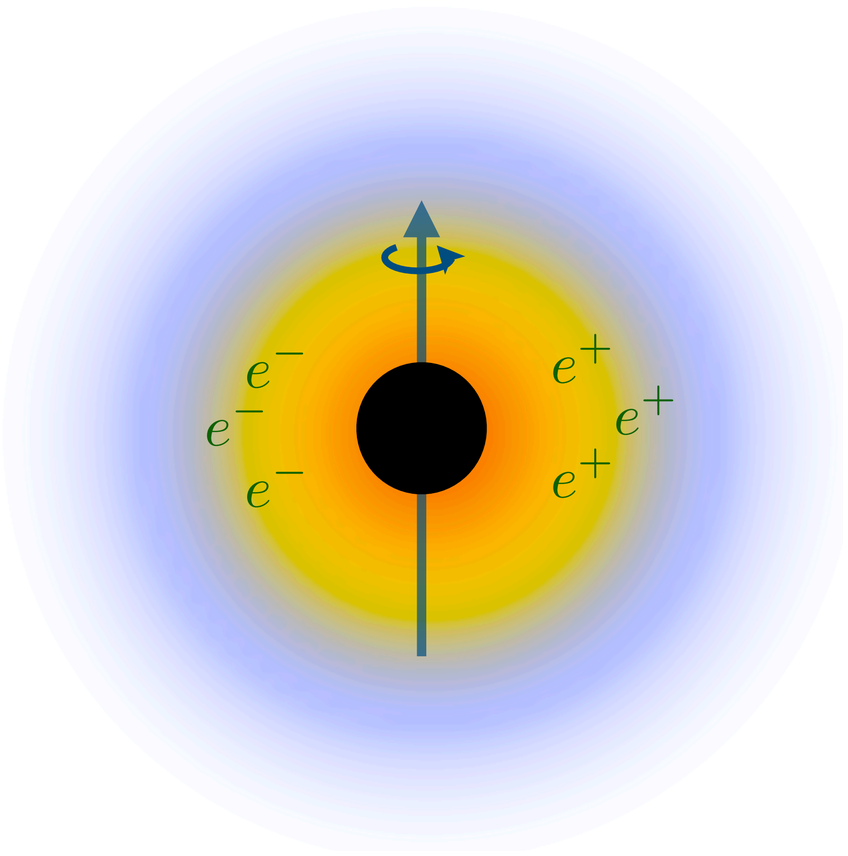
Emission spectra of the Vela pulsar



From *Pulsar Magnetospheres and Their Radiation*
A. Philippov and M. Kramer, Annu. Rev. Astron. Astrophys. 2022

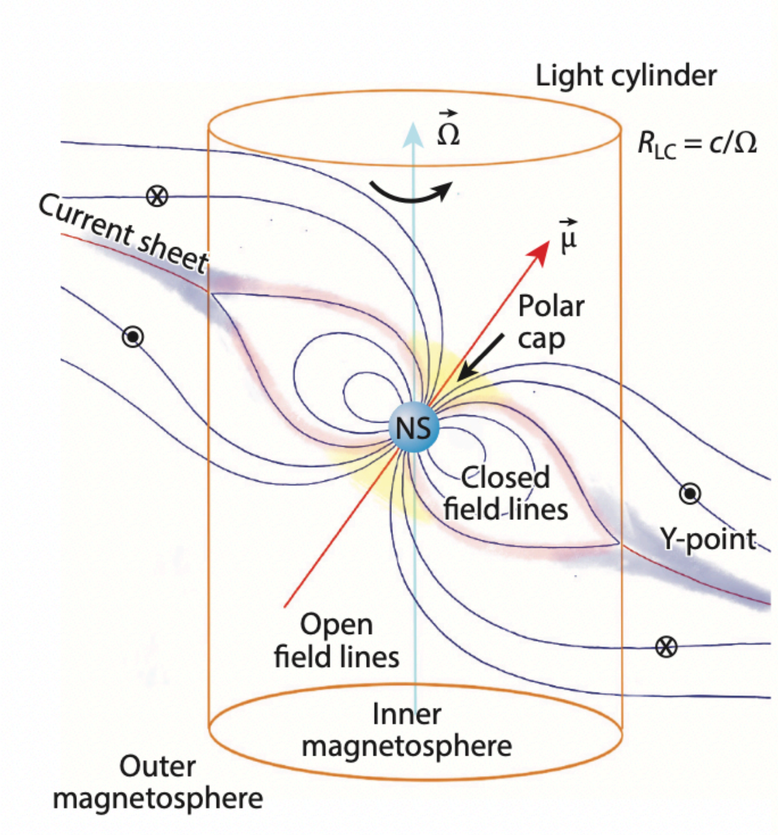
Dark photon cloud-pulsar analogies





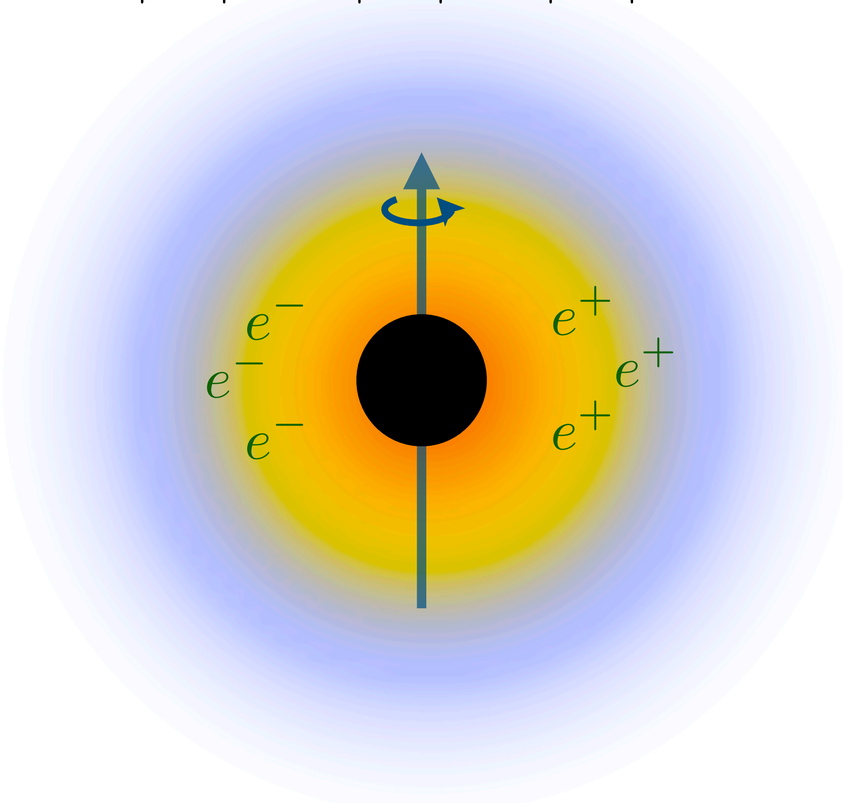
- Large EM fields
- Rotating objects (~ ms periods)

Dark photon cloud-pulsar differences



Magnetically dominated

$$|\vec{B}'| \sim \alpha |\vec{E}'| \ll |\vec{E}'|$$

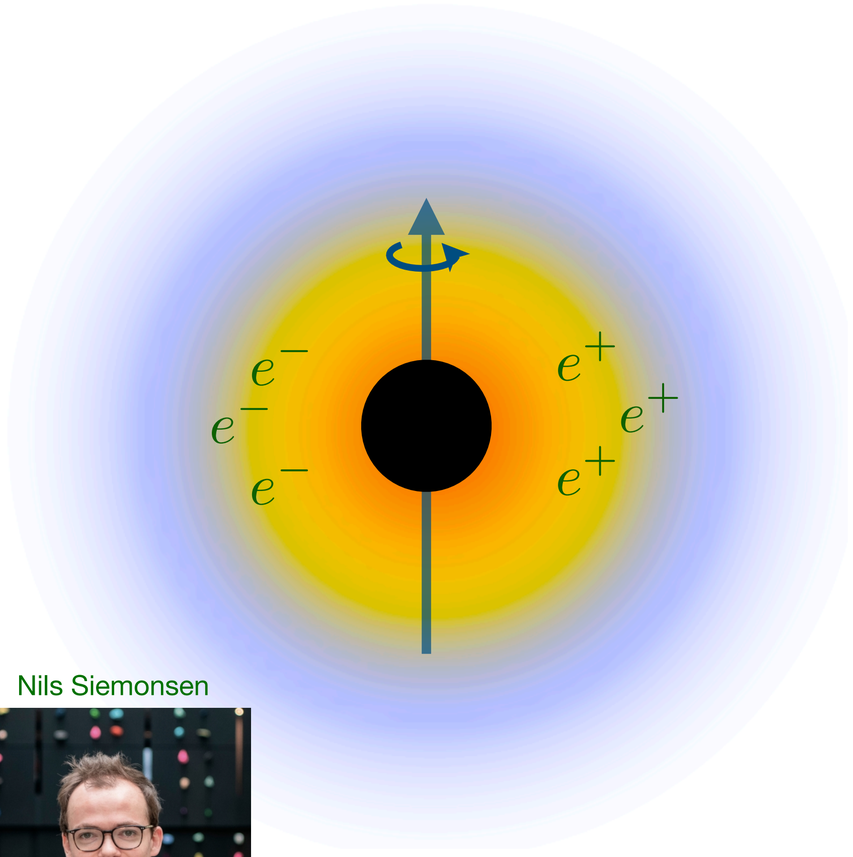


Electrically dominated

↓

Dissipation is important

Superradiance cloud + plasma modeling



Superradiance field (source)

$$\partial_t \vec{B} = -\nabla \times \vec{E}$$

$$\partial_t \vec{E} = \nabla \times \vec{B} - \vec{J} - \epsilon m^2 \vec{A}'$$

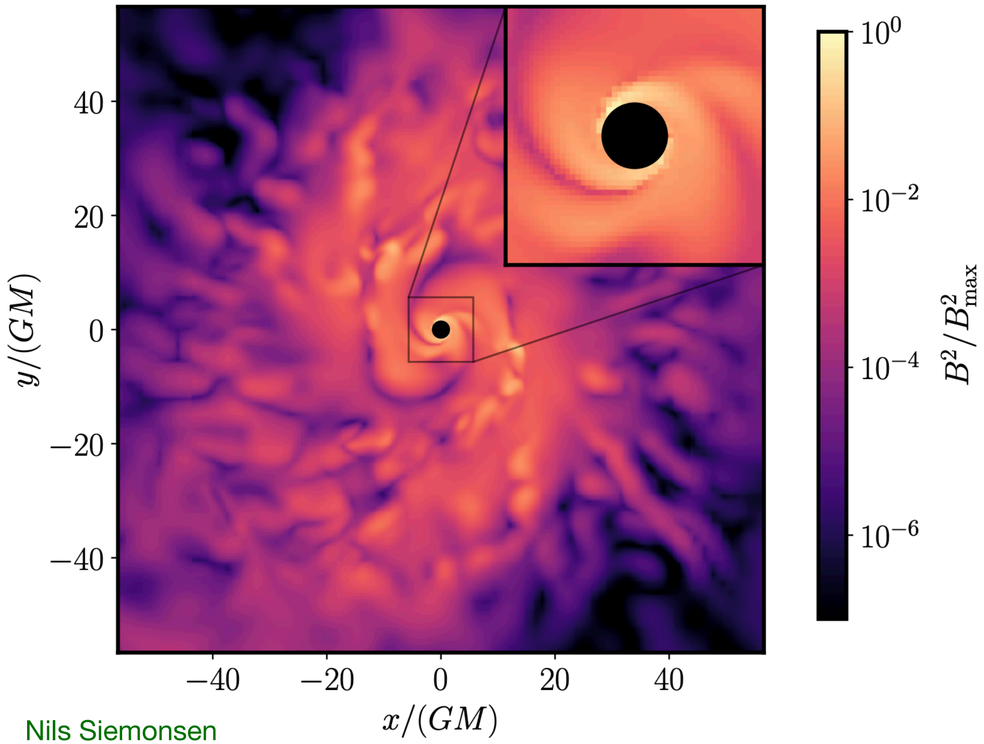
Ohm's law $\quad \vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B})$

- Solve equations for the E, B fields
- Compute EM energy emitted for $\sigma \to \infty$ $(\sigma \gg m)$

Nils Siemonsen

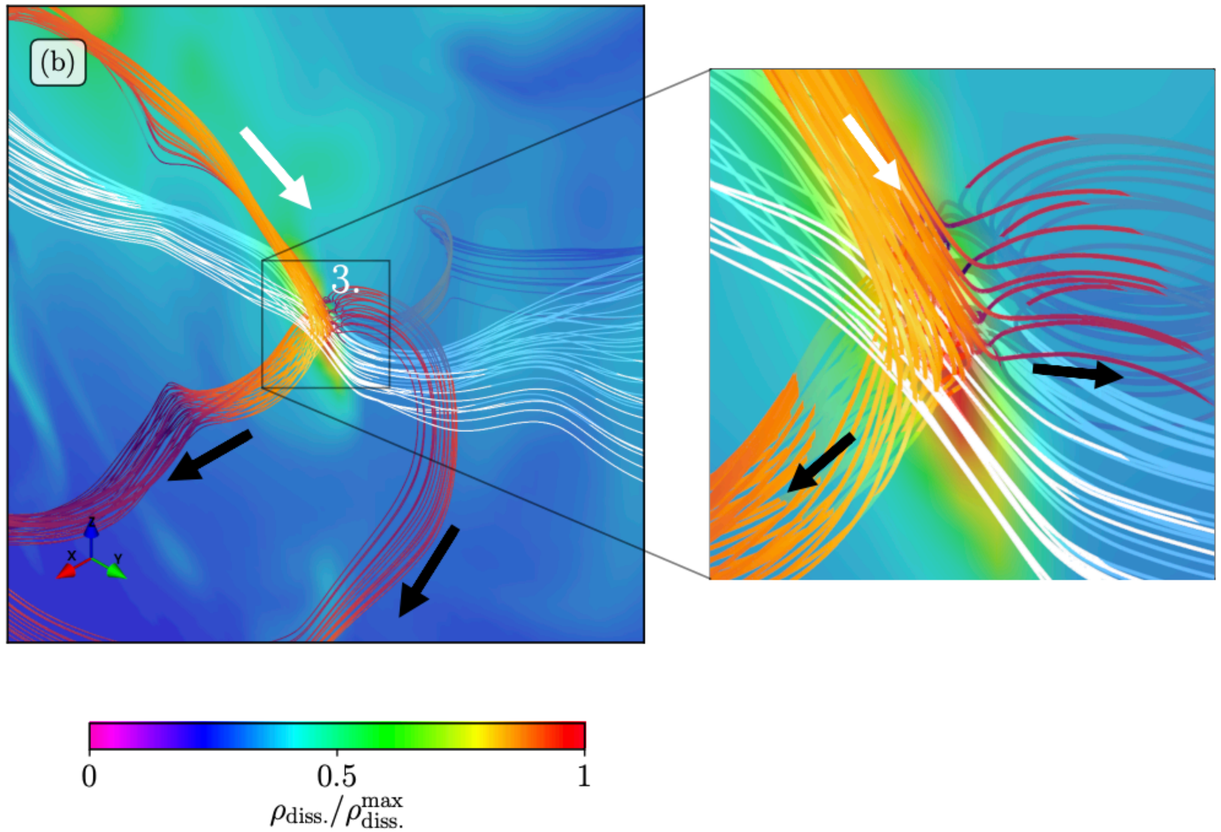
Full GR numerical MHD simulations

Simulations: B field & energy dissipation



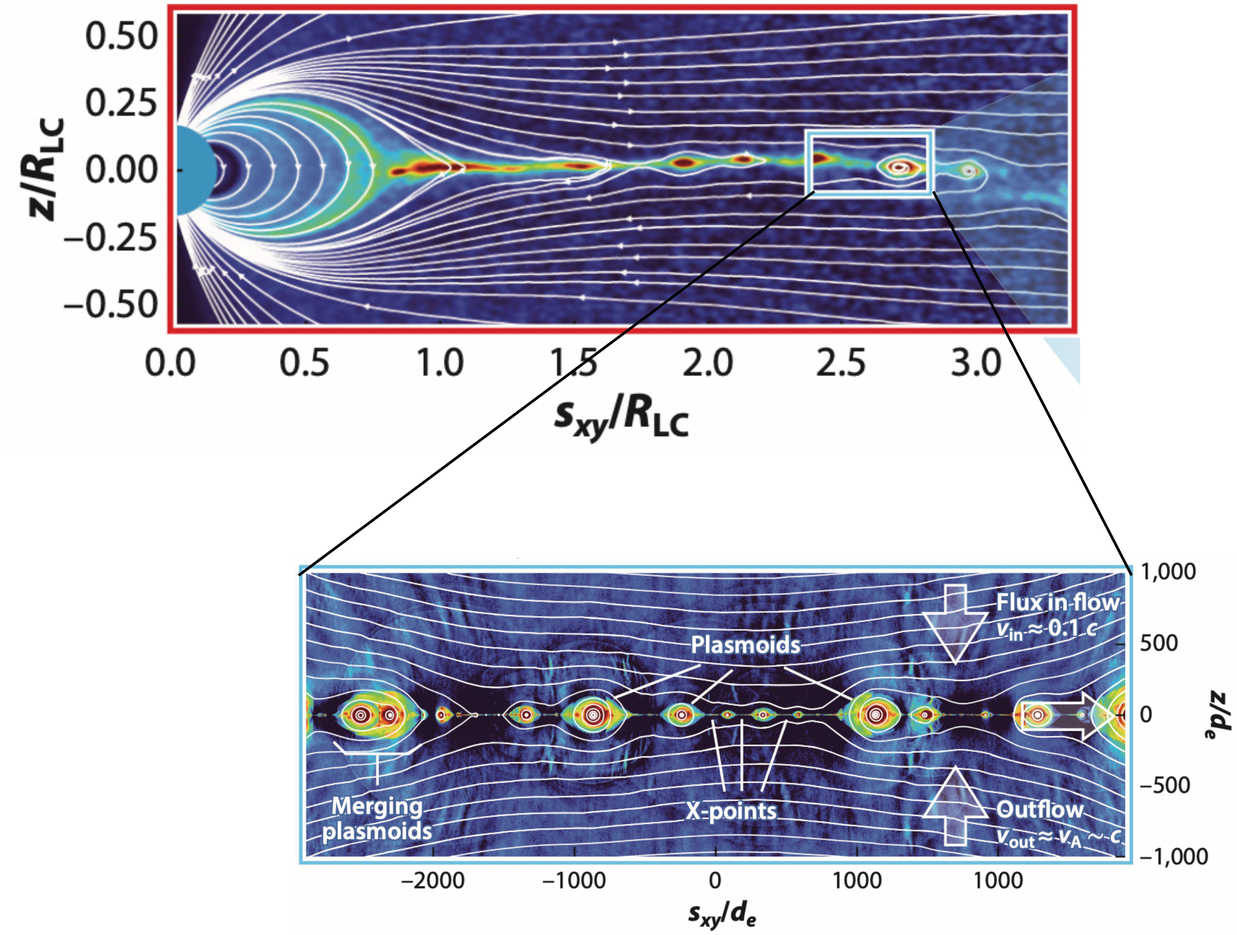
Nils Siemonsen

The dissipative energy density is maximal in the regions of magnetic field lines reconnection.

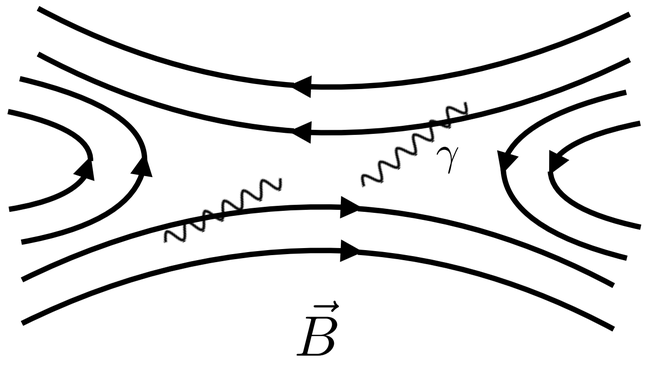


Magnetic reconnection

Plasma density



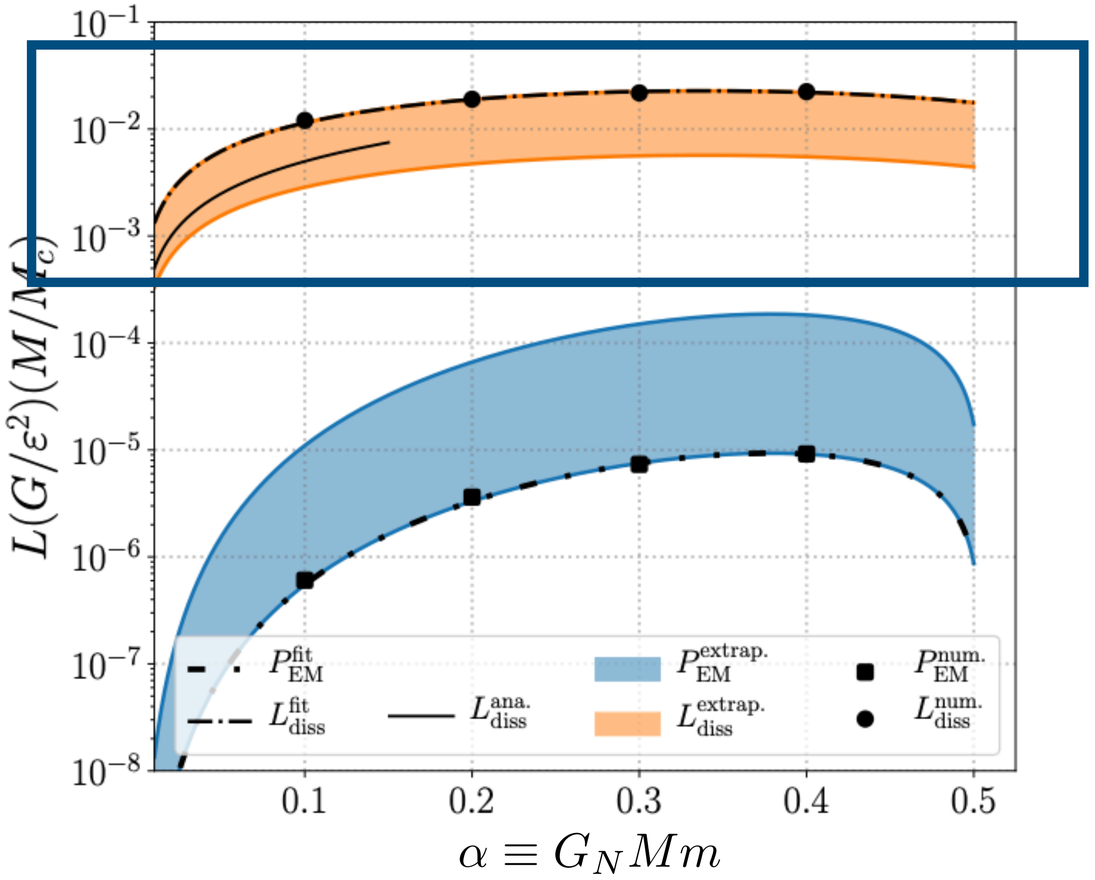
- Discontinuity in the magnetic field lines
- In a **neutron star pulsars** it happens on the equatorial plane (2d structures "current sheets")



Field energy dissipated into particle acceleration and high energy emissions

Dark photon cloud's luminosity

Numerical solutions and fit

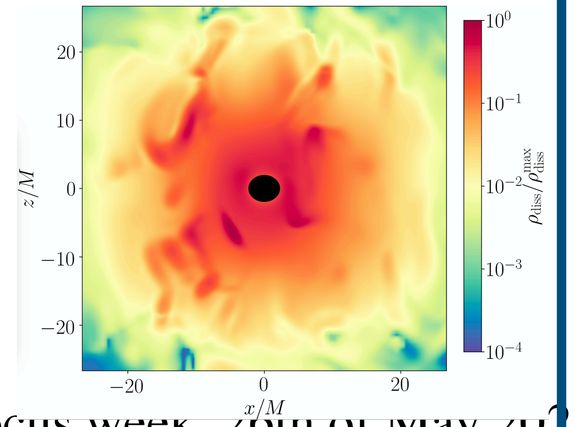


- Poynting flux

$$P_{\rm EM} = \oint dS\, \vec{r} \cdot (\vec{E} \times \vec{B})$$

- Dissipative losses

$$L_{\rm diss} = \int dV \vec{E} \cdot \vec{J}$$



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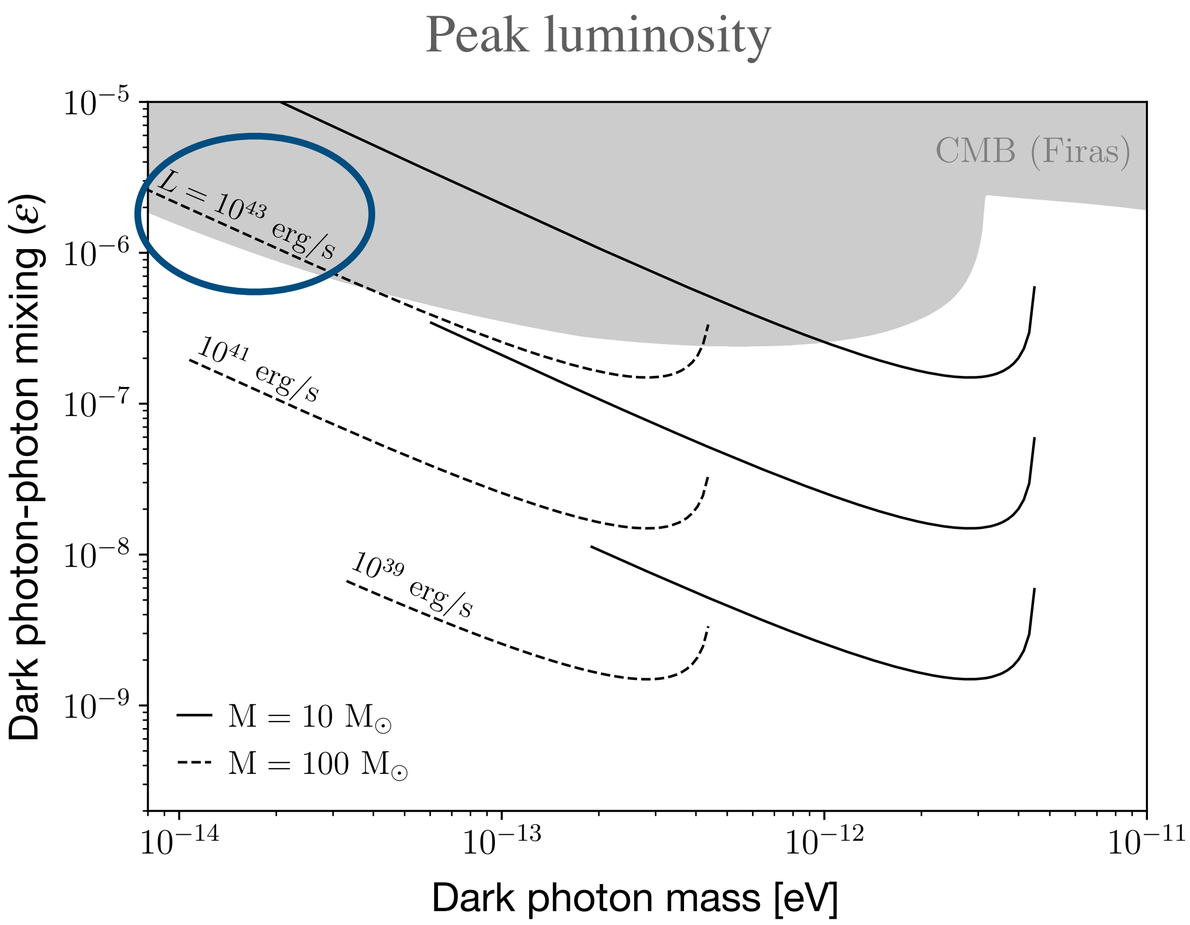
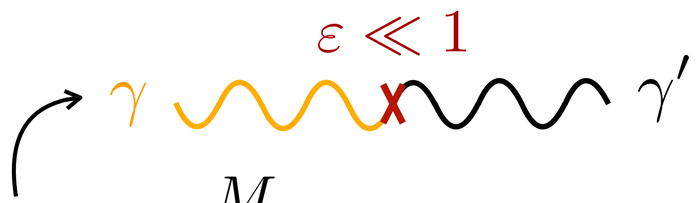




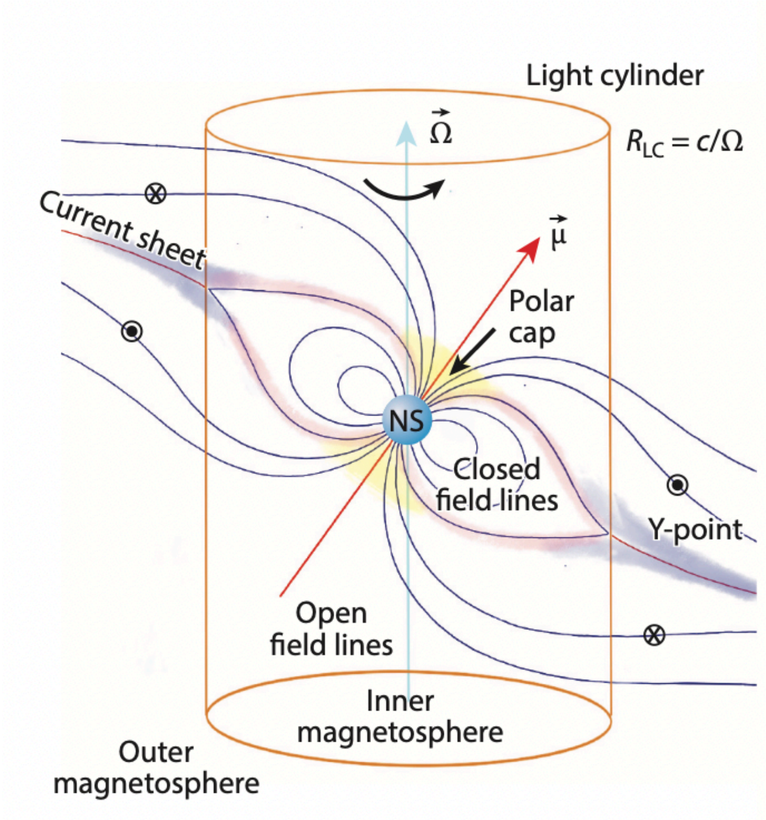
$$L_{\rm fit} = \varepsilon^2 F(\alpha) \frac{M_c}{GM} \simeq 10^{43}\ {\rm erg/s}$$

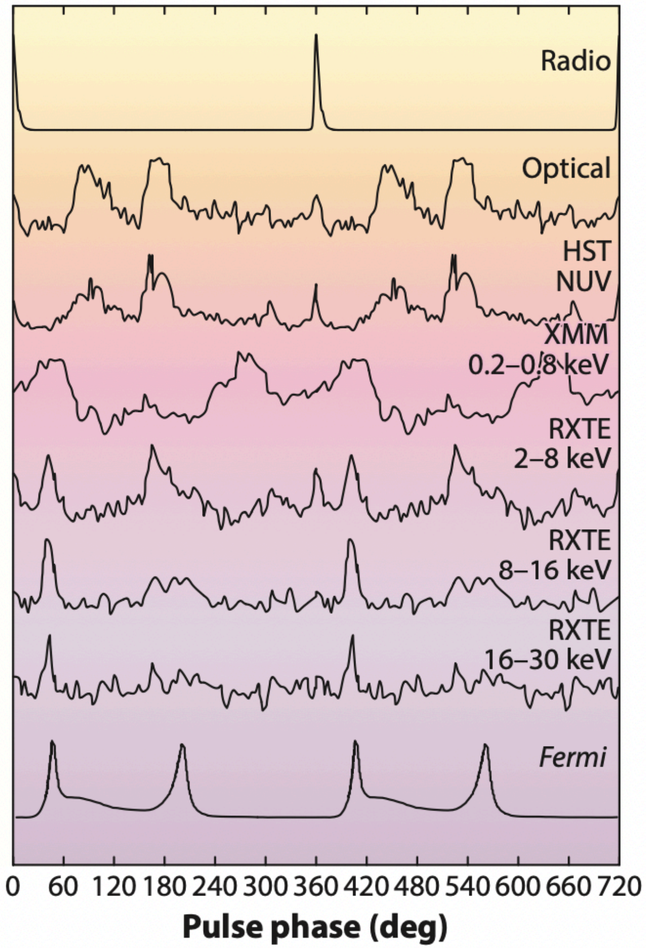
Crab pulsar $\quad L_{\rm crab} \simeq 10^{38}\ {\rm erg/s}$

Supernova $\quad L_{\rm SN} \simeq 10^{43} - 10^{45}\ {\rm erg/s}$

“New pulsar”: periodicity and spectrum

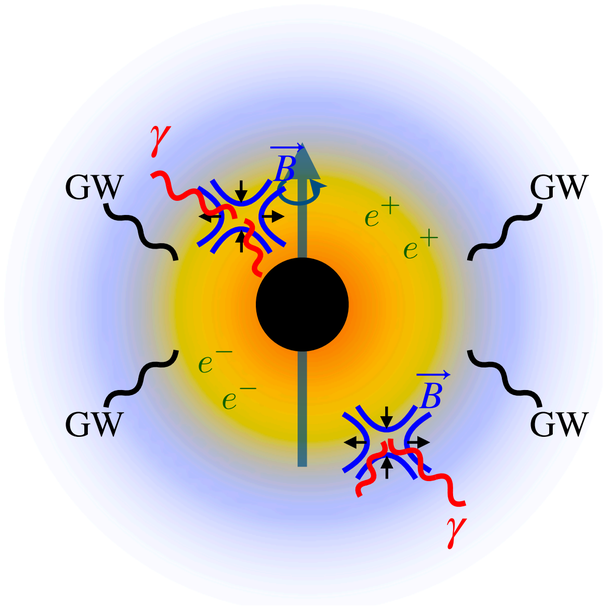
- Cannot be robustly inferred from current simulations
- Pulsar analogy: low energy periodic component + X-ray/γ-ray emissions





Multimessenger searches

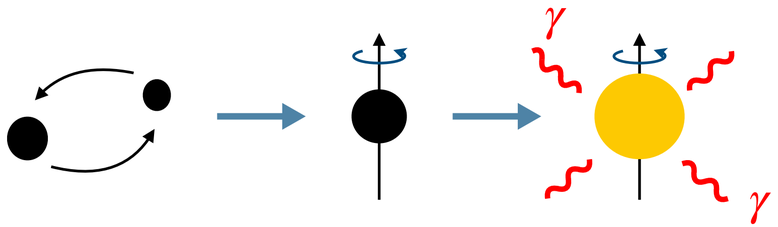
“New pulsar” signals



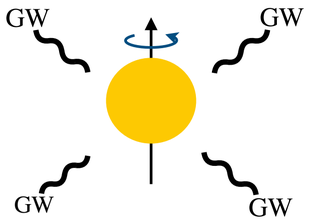
- GW emissions with frequency $mc^2/\pi\hbar \sim$ few x 100 Hz
- Low and high energy EM emissions with periodicity $2\pi\hbar/mc^2 \sim$ ms
- Decays over time with timescales from ~ days to ~ thousands of years

Multimessenger signatures

1. EM follow-ups of compact binary mergers
   (large $\alpha \equiv G_N M m$, young system)

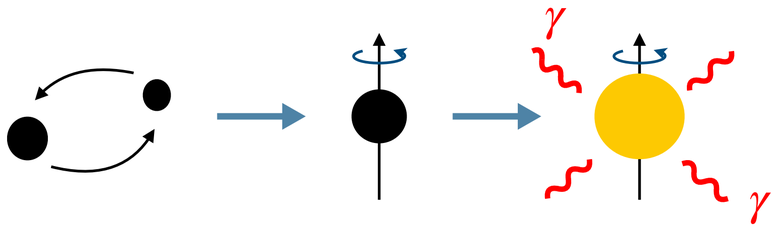


2. GW follow-ups of anomalous pulsars
   (small $\alpha \equiv G_N M m$, old system)

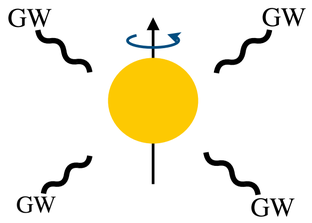


Multimessenger signatures

1. EM follow-ups of compact binary mergers
   (large $\alpha \equiv G_N M m$, young system)



2. GW follow-ups of anomalous pulsars
   (small $\alpha \equiv G_N M m$, old system)



Source selection

3 classes of selected sources:

- Spinning-up $\dot{f}_{\rm rot} > 0$
- Frequency doublets: 2 pulsars with $\frac{|f_i - f_j|}{f_i} < \frac{v_{\rm rad}}{c} \simeq 10^{-3}$
- Frequency triplets: 3 pulsars with $\frac{|f_i - f_j|}{f_i} < \frac{v_{\rm rad}}{c} \simeq 10^{-3}$

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$\Longrightarrow$ 59 sources selected
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- 44 sources
  - 4 sources already targeted LVK O2-O3
    R. Abbott et al., Astrophys.J. 935, 1 (2022), arxiv:2111.13106
  - 6 w/ bad sky position measurements -> using LVK O3 all-sky search
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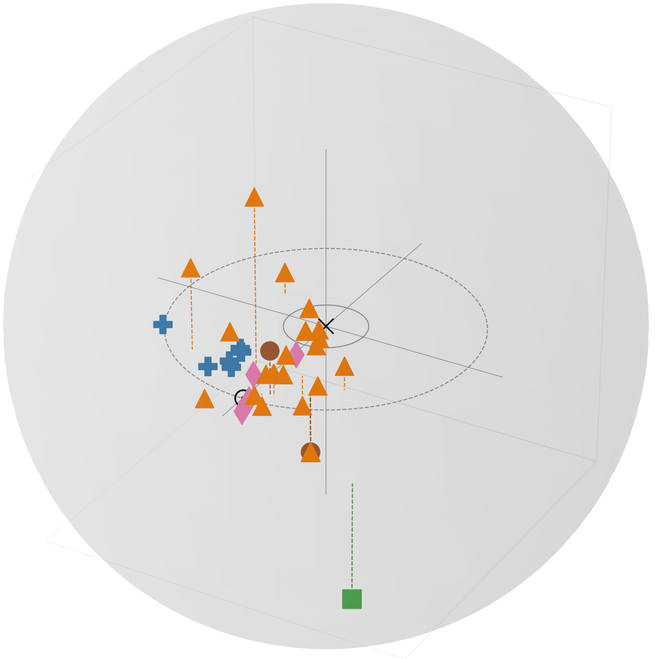
Narrow-band
Targeted
Semi-coherent
All-sky
Binary
Galactic Center
Sun

Milky Way



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Methods for the analysis

Lorenzo Mirasola, Francesco Amicucci, Sabrina D'Antonio, Cristiano Palomba, Paola Leaci, Luca D'Onofrio, Pia Astone

Isolated sources

Maximum coherence time insensitive to **sky position uncertainty**:

$$T_{\mathrm{FFT}}^{\mathrm{sky}}(\delta\beta) \approx \frac{10^4}{f_0\,\delta\beta\,\sin\beta}$$

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Singhal+ CQG (2019)

Semi-coherent for sources in a binary system
Mirasola+ (2024)

False alarm probability for outliers at 1%

Results analysis with O3 data

Credits: Lorenzo Mirasola

No outliers identified

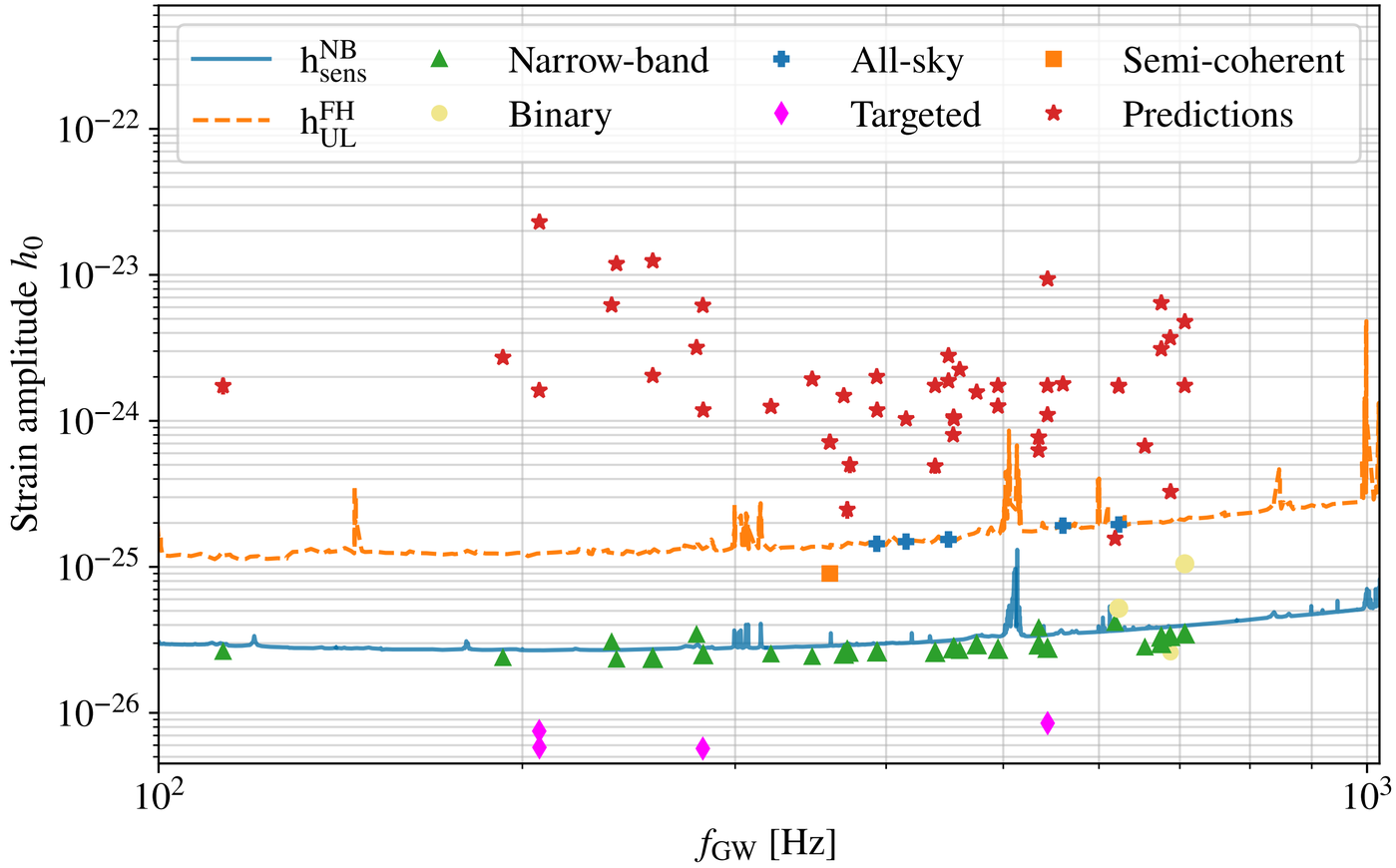
↓

Upper limits at the 95% confidence level

↓

ULs below the maximum predicted strain

L. Mirasola, **CM**, et al.
Phys. Rev. D 11 (2025), arxiv:2501.02052



Interpretation of CW strain ULs

CW strain at the detector:

$$h_0(M, \chi, \tau_{\rm obs}, d|m) = \frac{h_0^s(M, \chi|m)}{1 + \tau_{\rm obs}/\tau_{\rm GW}(M, \chi|m)} \frac{1}{d},$$

Dark photon
m

→ Fixed by the radio observation
$f_{\rm GW} = 2 f_{\rm rot} = mc^2/\pi\hbar$

BH properties
$M, \chi, \tau, d,$
# of BHs

→ Integrate over,
Given a BH population

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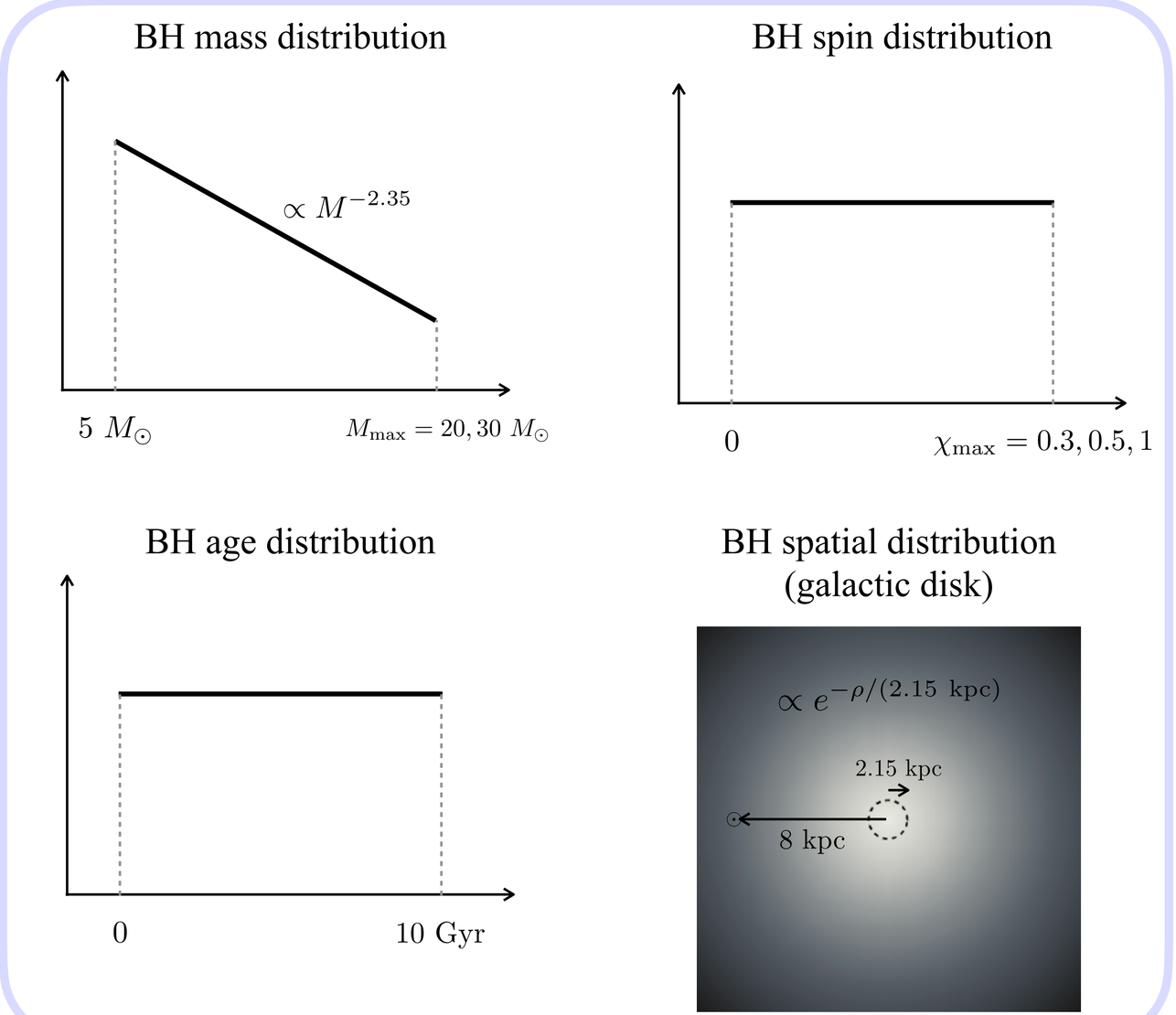
BH properties $M, \chi, \tau, d,$ # of BHs → Integrate over, Given a BH population

BH in the Galactic disk



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→ Fixed by the radio observation
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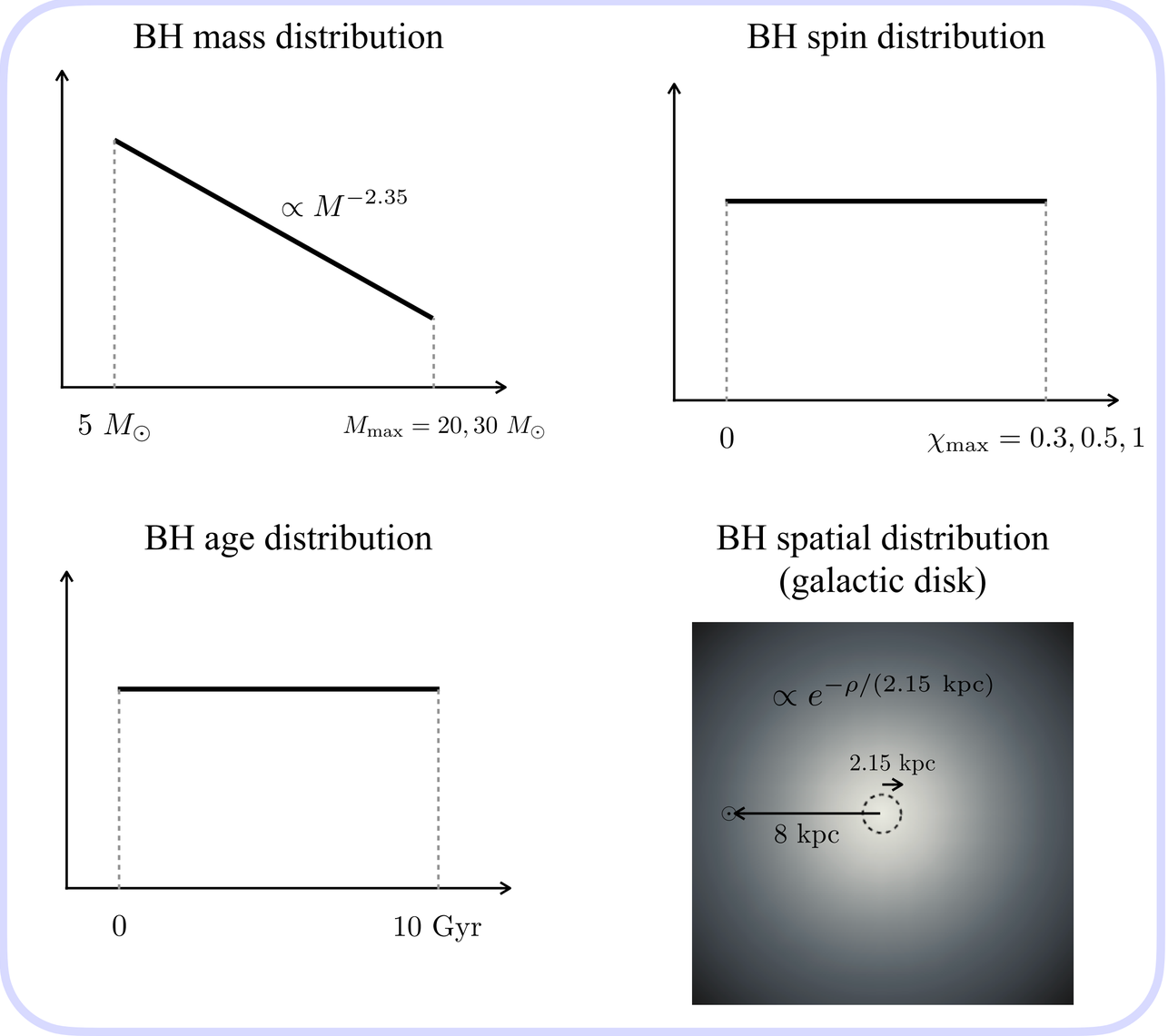
BH properties
$M, \chi, \tau, d,$
# of BHs

→ Targeted search also depends on EM dark photon coupling!

- Large enough for the cloud to be luminous
- Small enough so that the cloud does not decay too fast



Expected signal

$$\frac{\mathrm{d}n_h}{\mathrm{d}\log h_0}(h_0|m,\varepsilon) = \frac{x_{\mathrm{disk}} N_{\mathrm{BH}}}{2\pi\mathcal{N}} \int \mathrm{d}M \frac{M_{\mathrm{min}}^{1.35}}{M^{2.35}} \int \mathrm{d}\chi \, \frac{1}{\chi_{\mathrm{max}}} \frac{h_{r_d}}{h_0} \frac{\tau_{\mathrm{GW}}}{\tau_{\mathrm{max}}} \Theta_{\mathrm{pl}} \int \mathrm{d}\varphi \int \mathrm{d}\tilde{\rho} \frac{\tilde{\rho}\, e^{-\tilde{\rho}}}{\sqrt{\tilde{\rho}^2 + \tilde{r}_{\mathrm{obs}}^2 - 2\tilde{\rho}\, \tilde{r}_{\mathrm{obs}} \cos\varphi}} \Theta_{\dot{f}} \Theta_{\mathrm{EM}} \Theta_{\mathrm{ev}},$$

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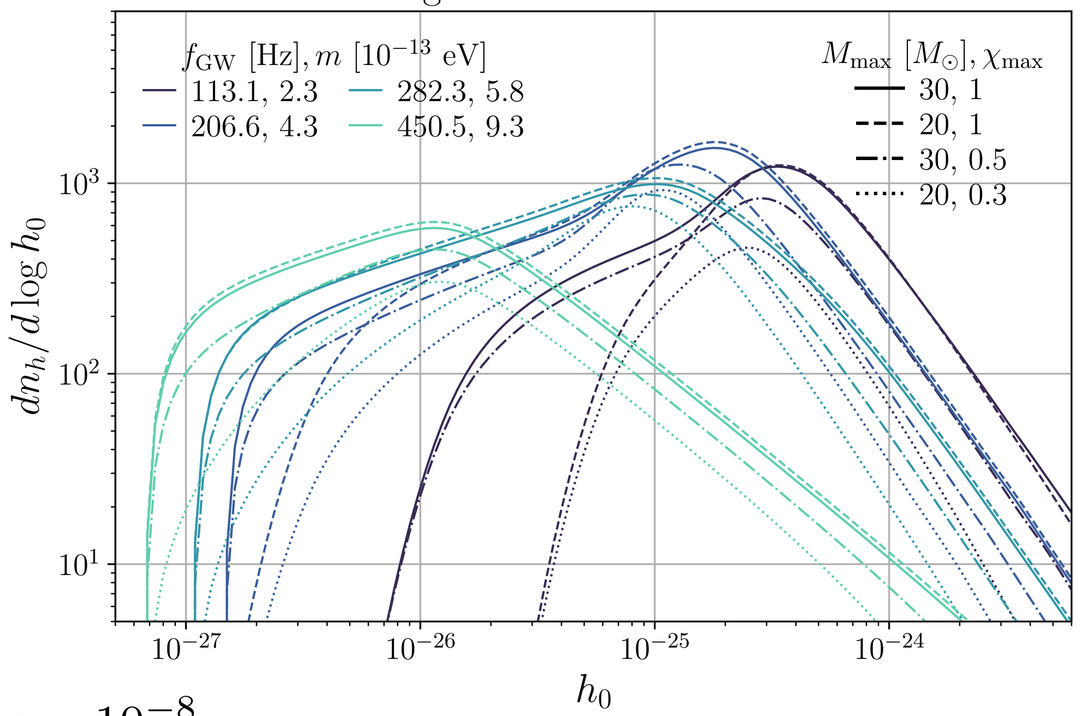
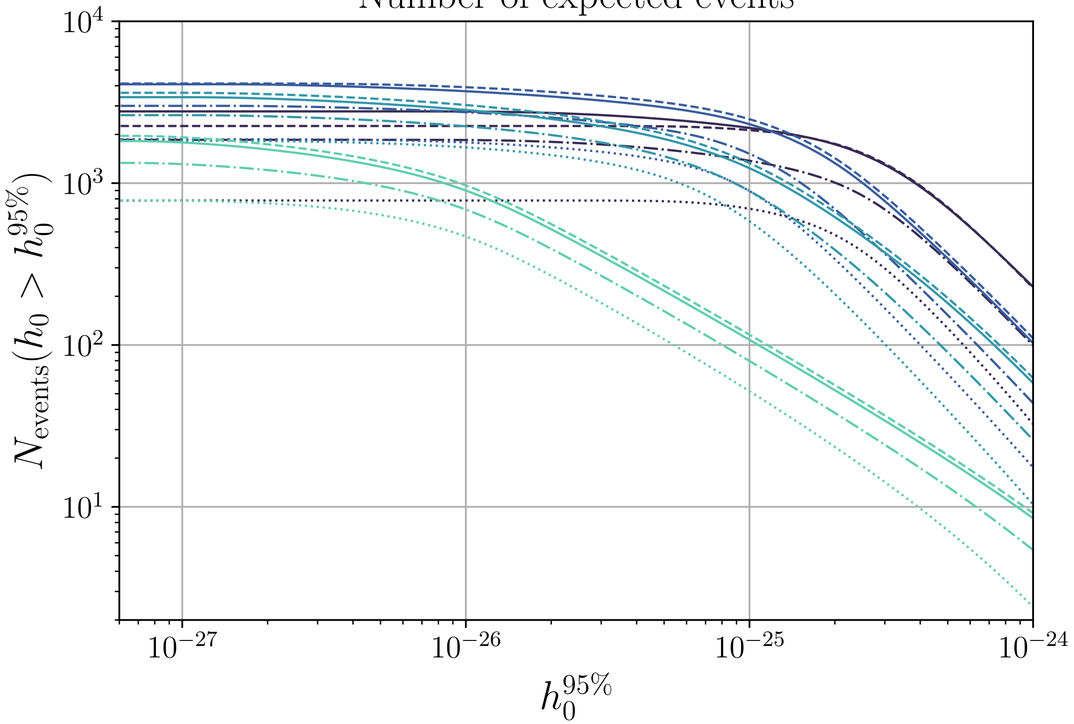
Signal strain distribution



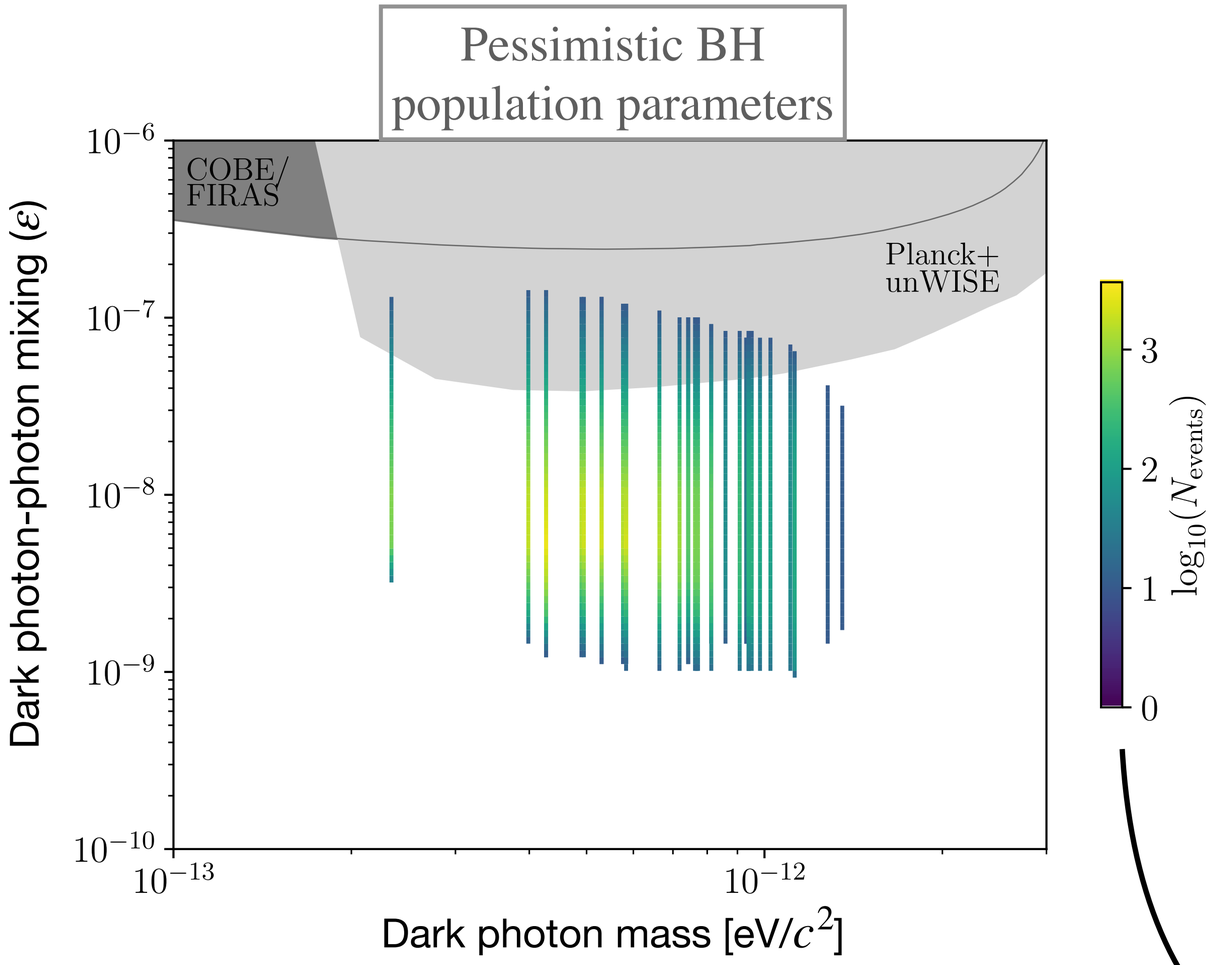
Number of expected events

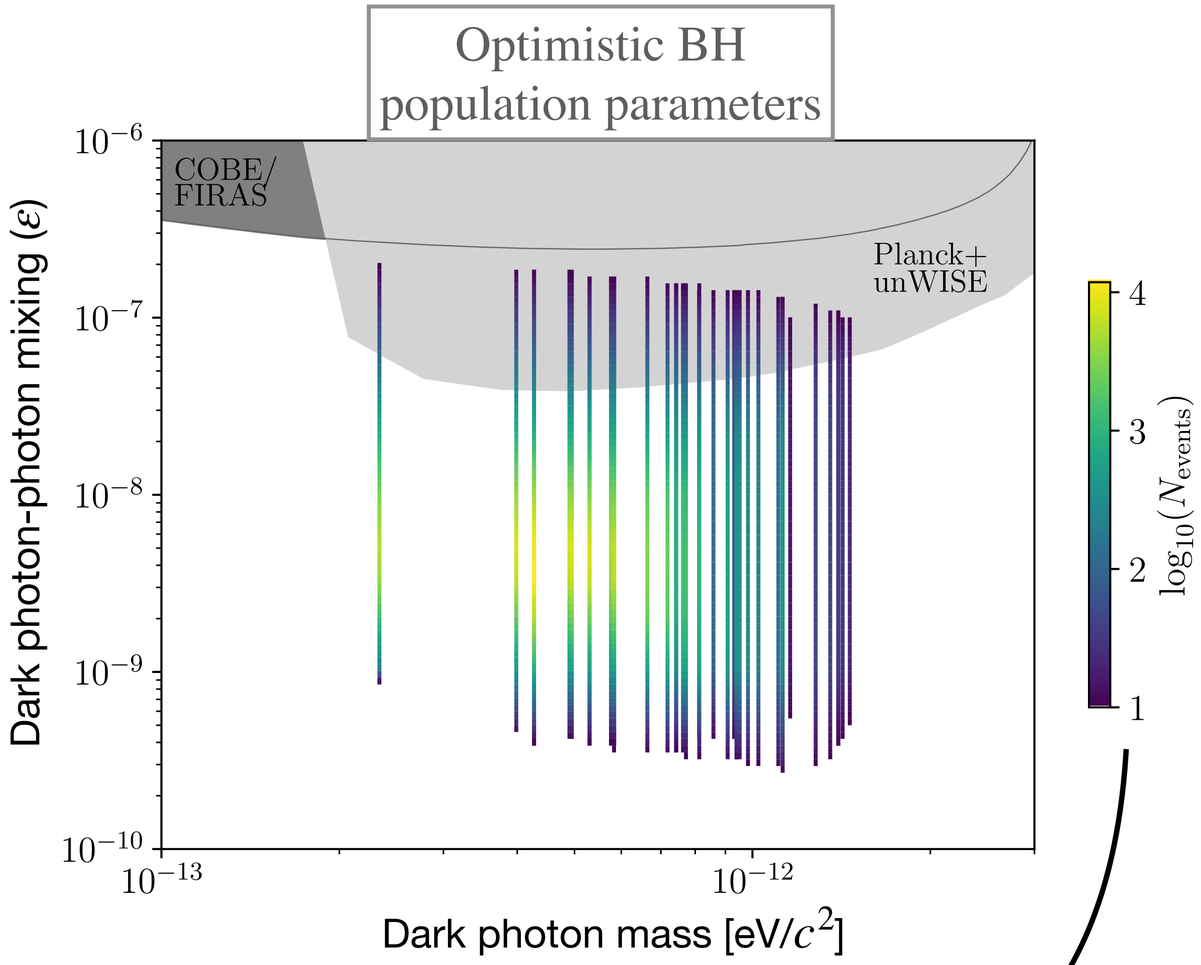


$\varepsilon = 10^{-8}$

Fraction of EM power into radio:

Number of expected events: dark photon parameter space

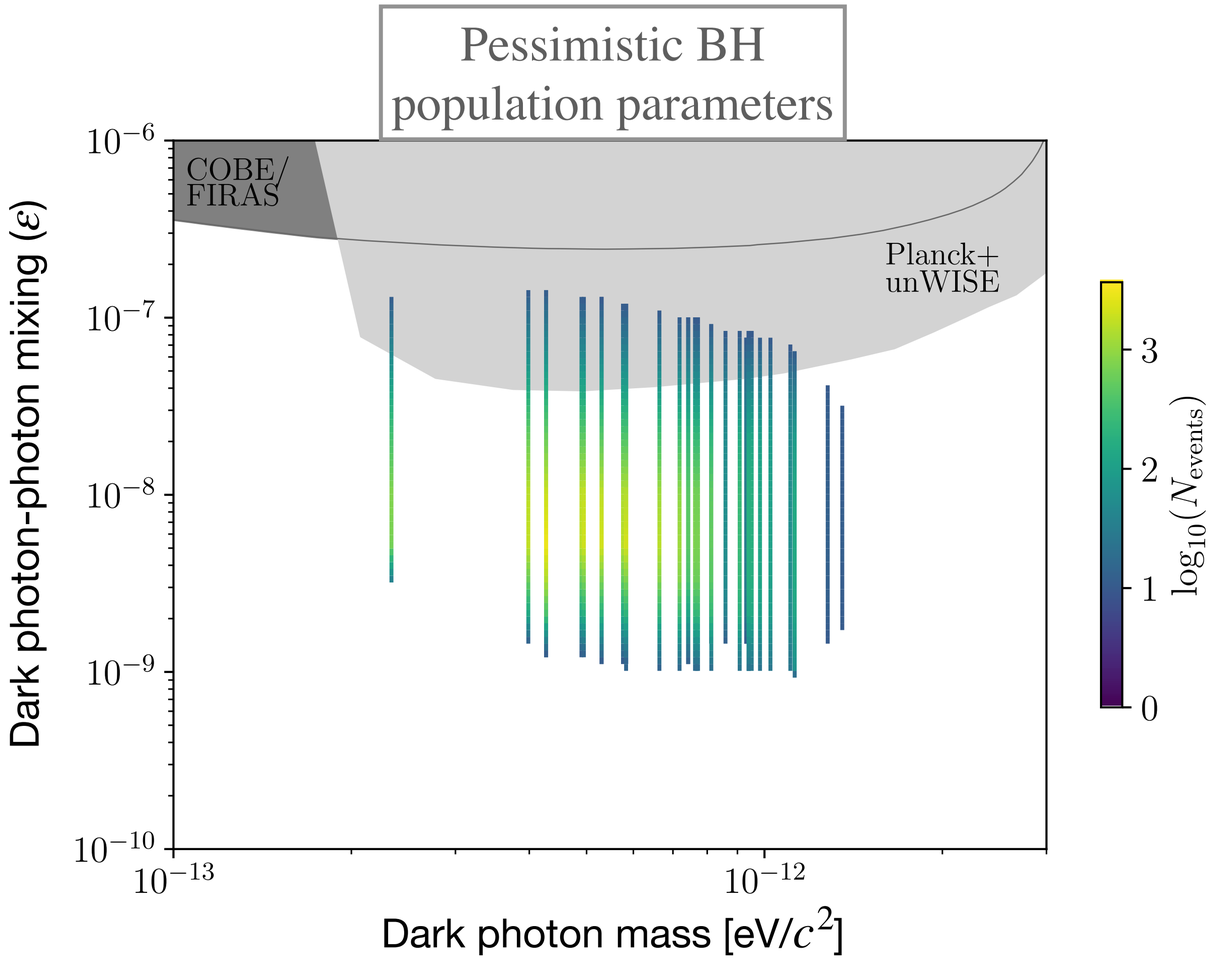




Fraction of EM power into radio: 10^{-5}

Several events expected above detection threshold

Number of expected events: dark photon parameter space



Several events expected above detection threshold

Depend on (not so well known):

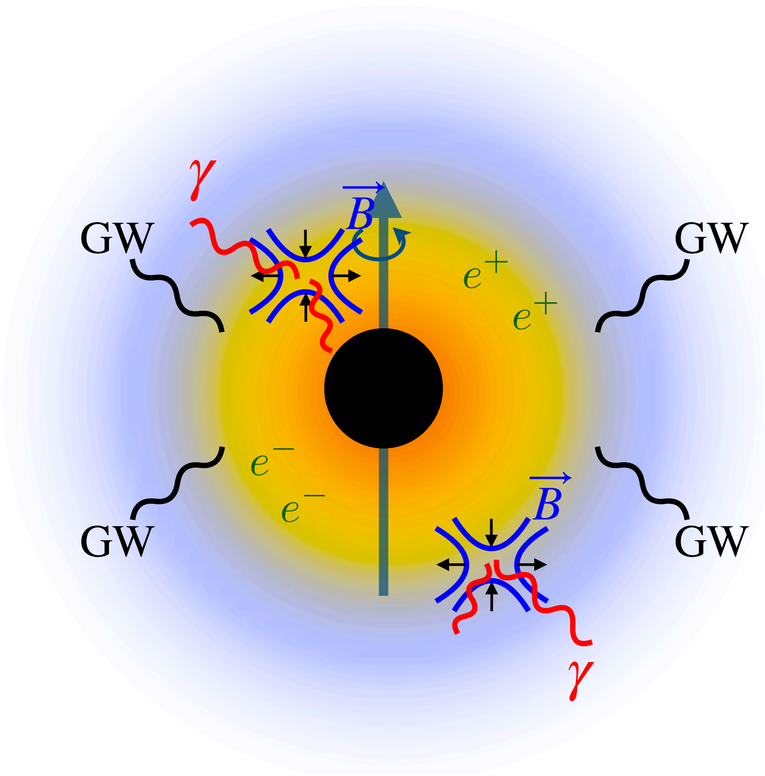
- BH population properties
- Dark photon cloud EM emission properties

Not a robust "exclusion bound", but a signal could have been seen.

Fraction of EM power into radio: 10^{-5}

Summary

- BH superradiance allows to probe the existence of new ultralight vector fields, irrespectively of their cosmological production
- Dark photons with EM coupling can lead to “new pulsars”
- Can be targeted with multimessanger searches



CW emission → **CW+EM**
- CW searches targeting EM sources

EM emission → **CW+EM**

BH merger event → **GW+EM**

EM emission → **GW+EM**
- EM follow-up of merger events

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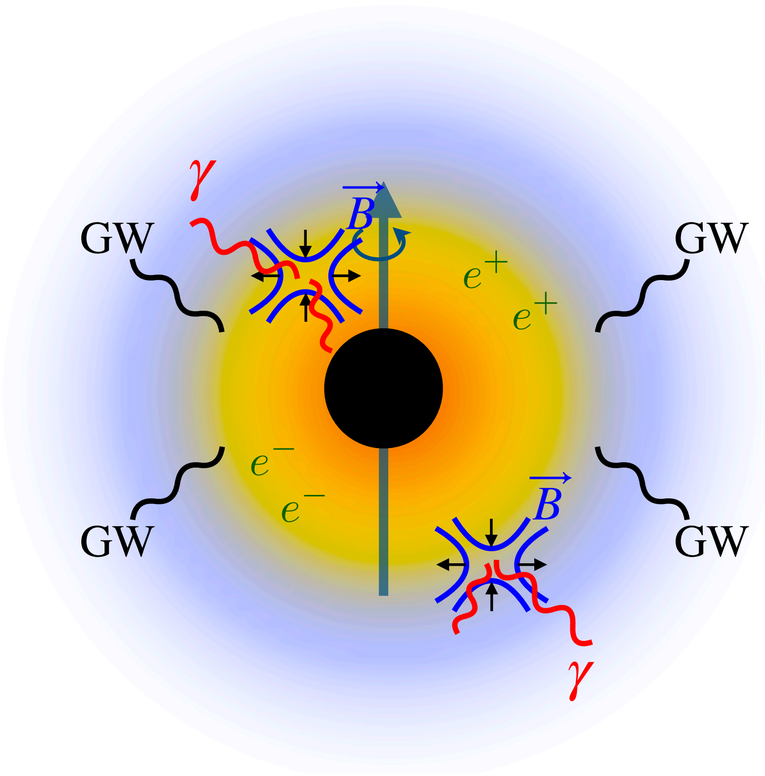

Thank you!

CW emission → **CW+EM**
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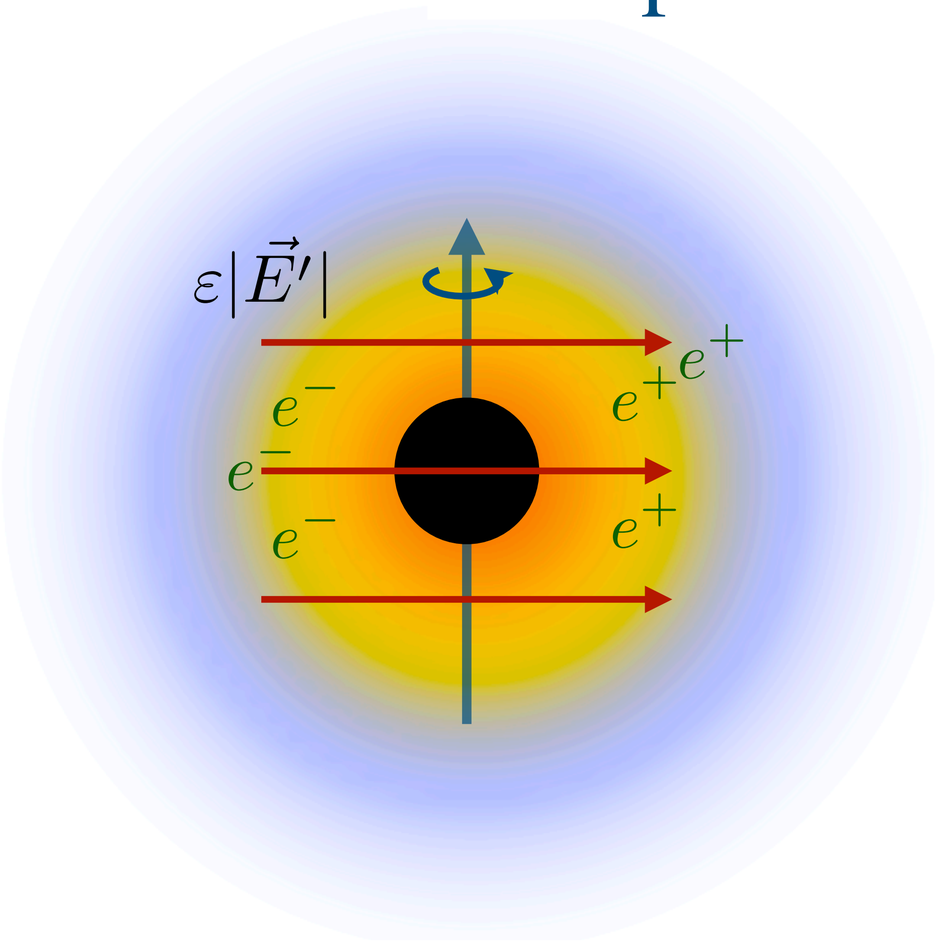
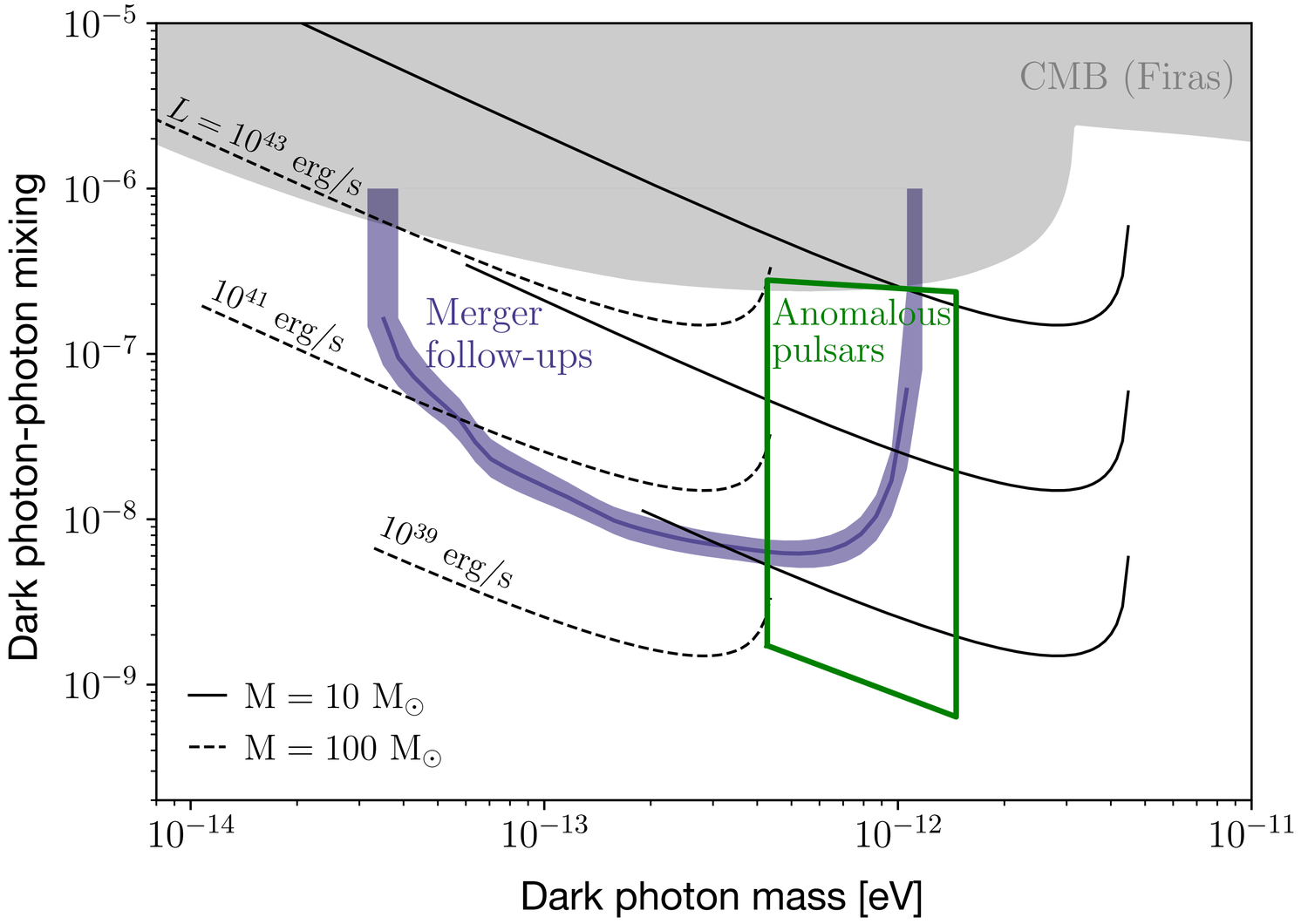
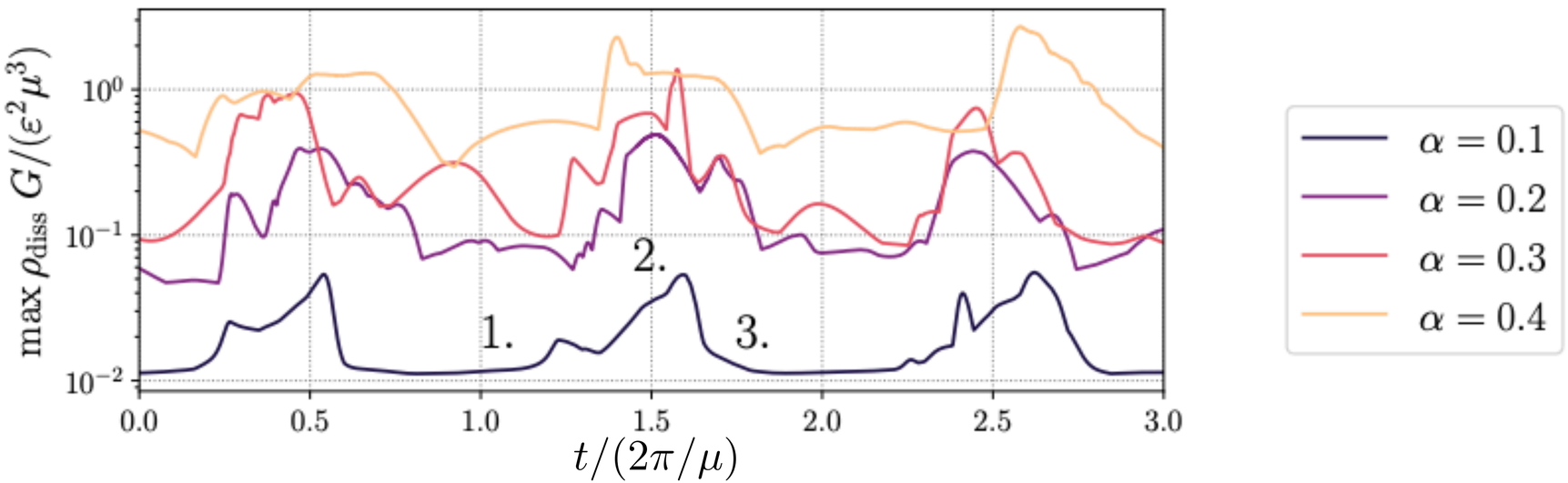
Back-up

Dark photon superradiance parameter space





Simulation: periodicity?



- Fundamental time scale of the system $2\pi/\mu$
- Weak evidence of periodicity from our simulation
- Pulsar analogy

Simulation: spectrum?

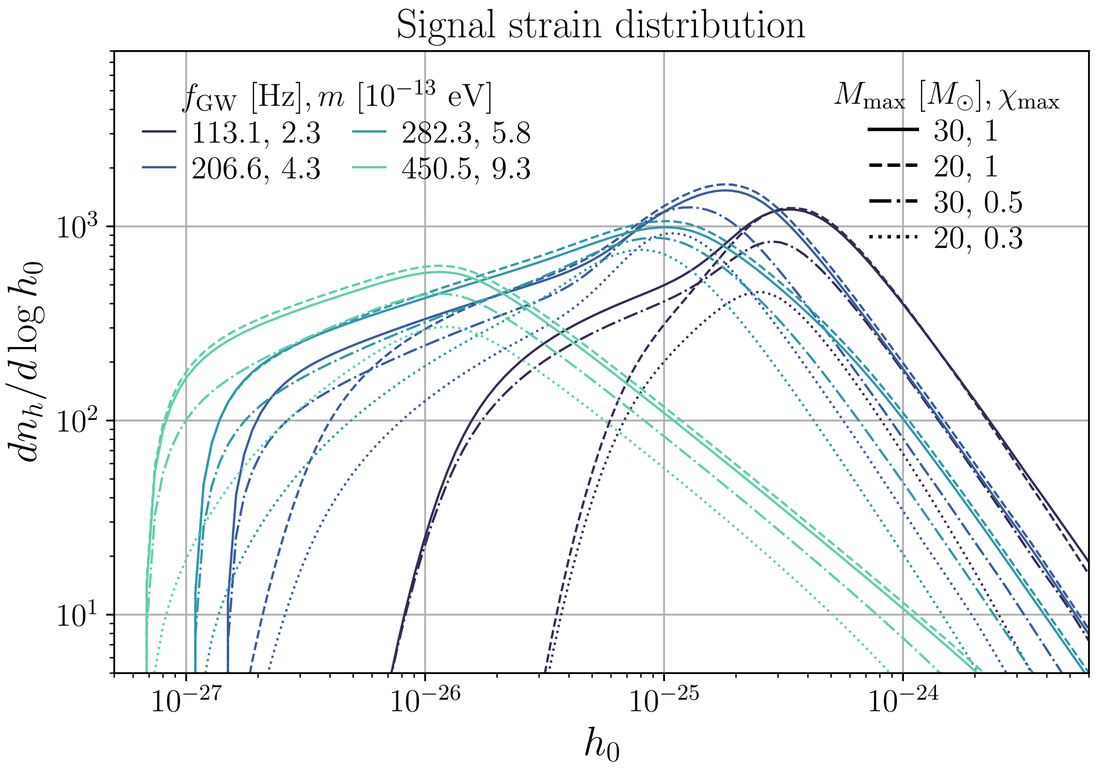
- Synchrotron emission of highly boosted particles

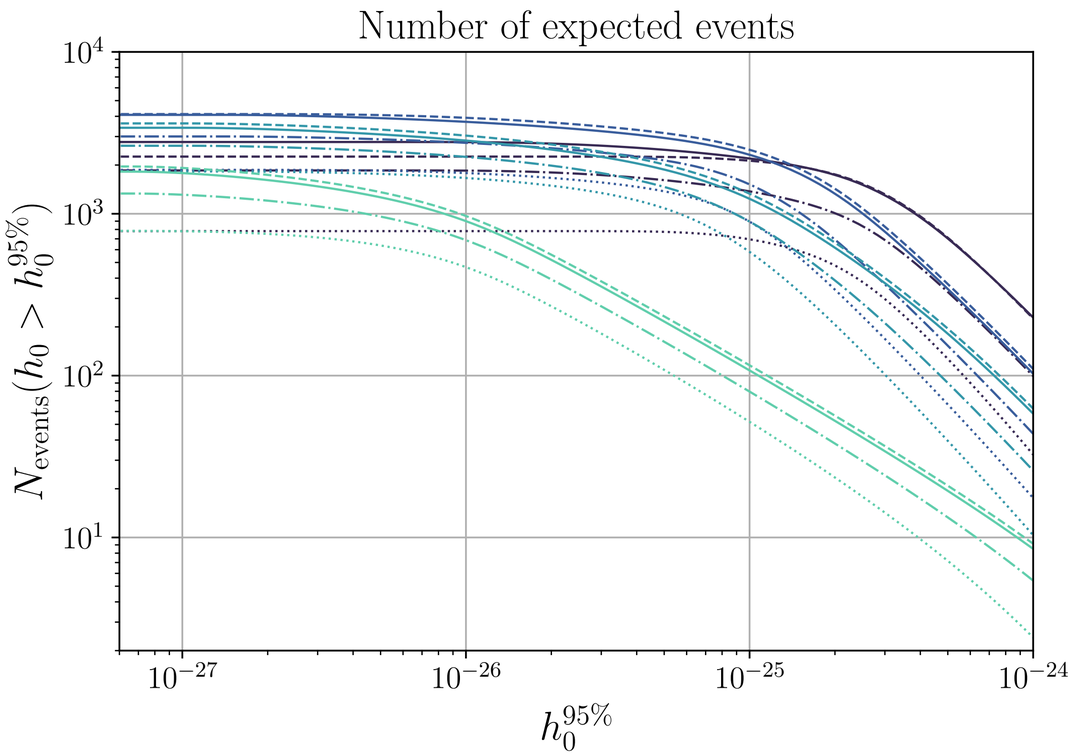
  $e^{\pm}$ boosted to $\gamma \sim \mathcal{O}(10^3)$

  synchrotron photons ~ few keV to MeV

- Coherent low-energy radio emission (continuous + periodic) ?

Expected signals

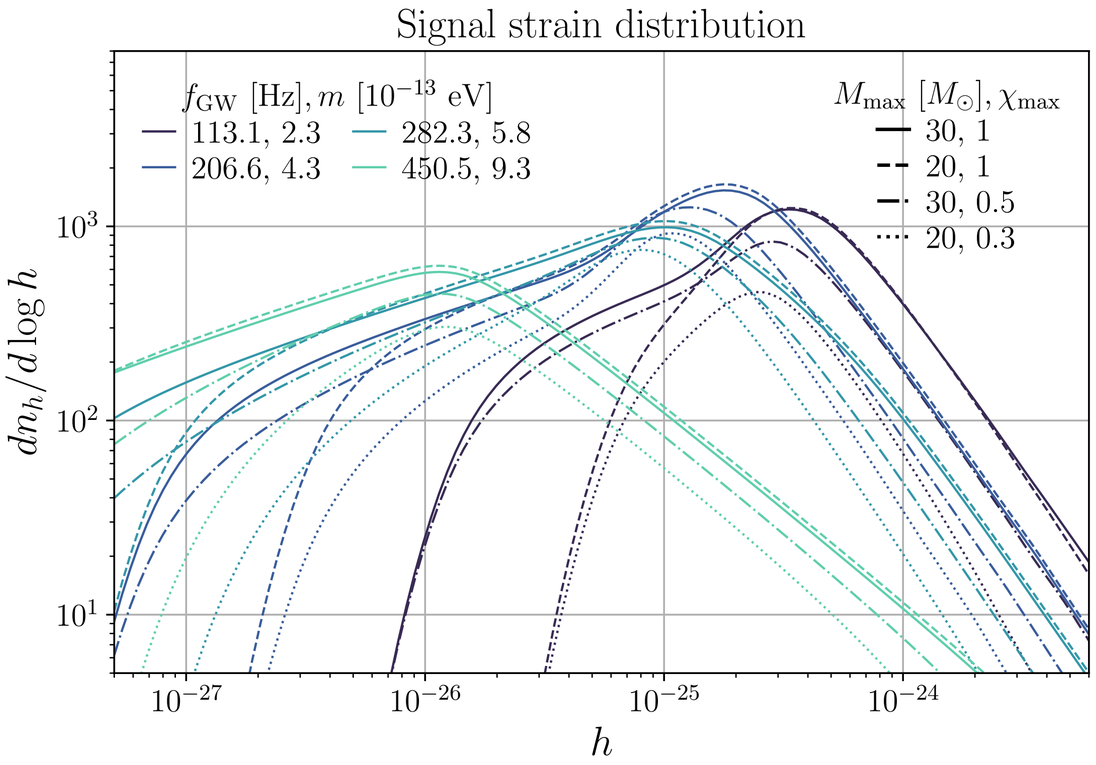


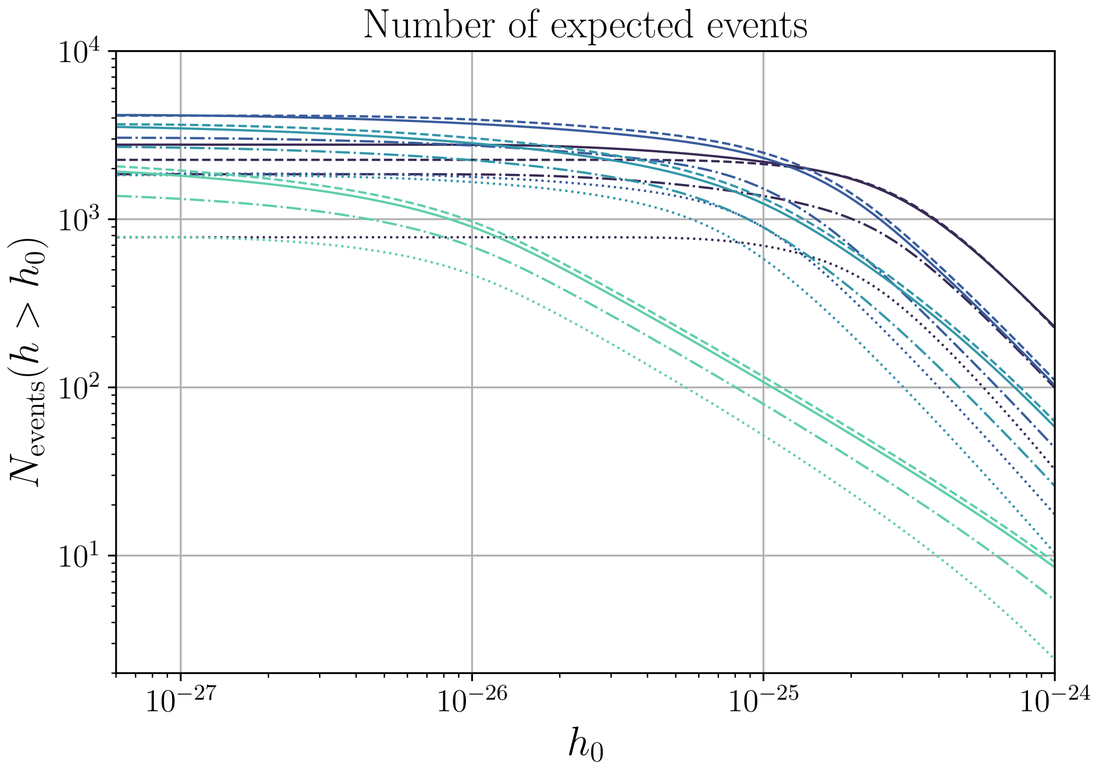


$\varepsilon = 10^{-8}$

Fraction of EM power into radio: 10^{-5}

Expected signals





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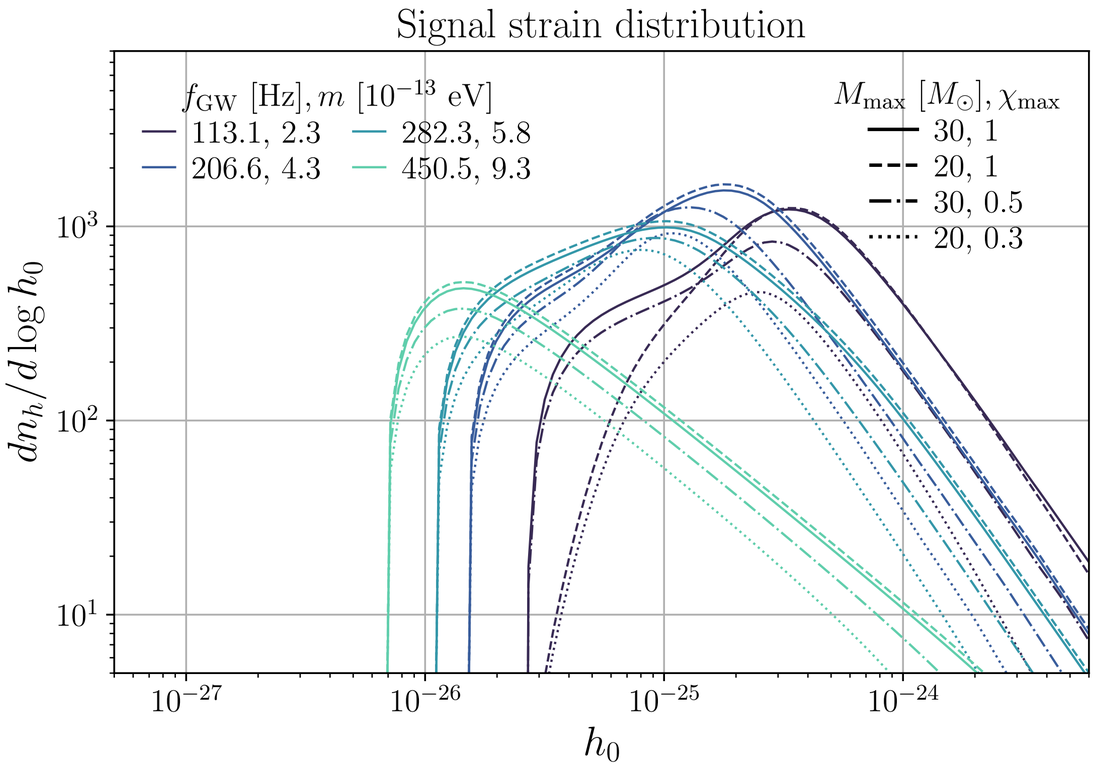
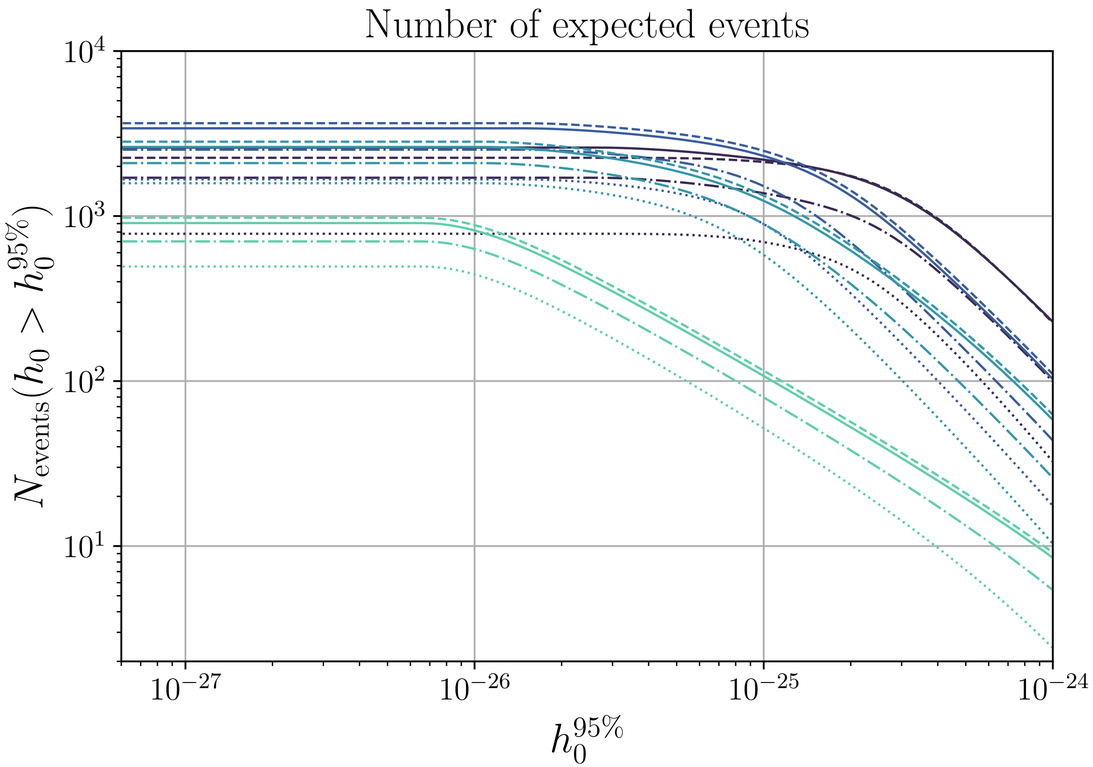
Fraction of EM power into radio: 10^{-3}

Expected signals

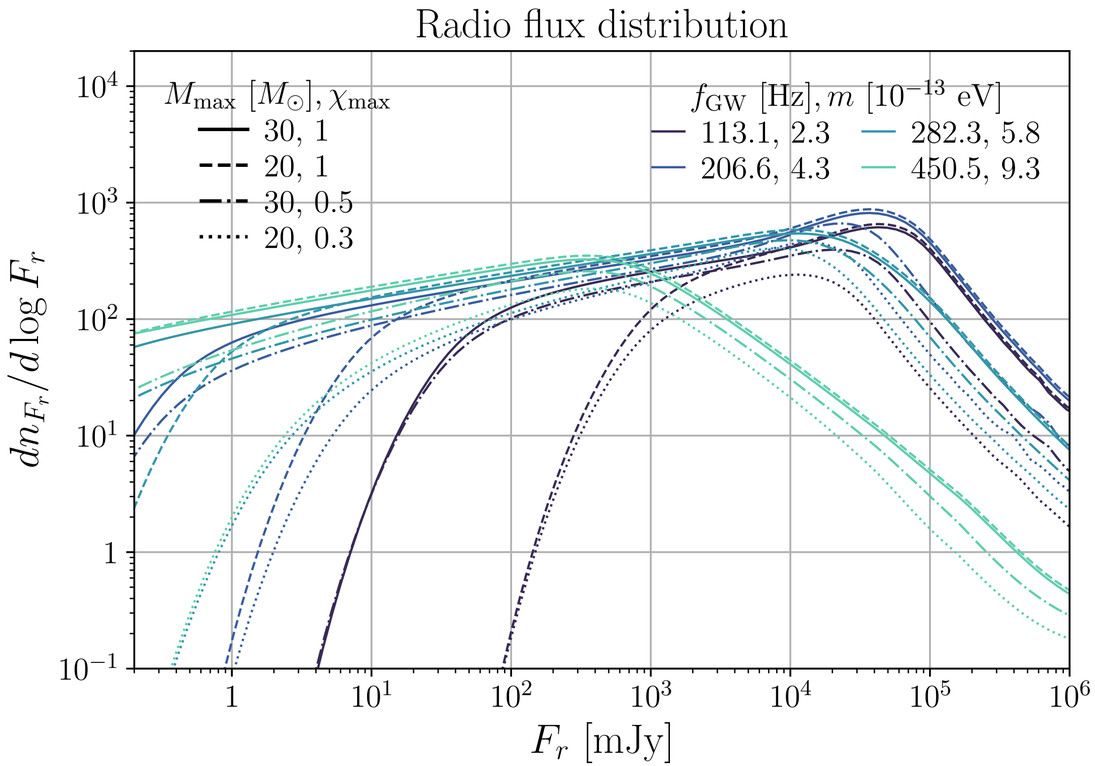


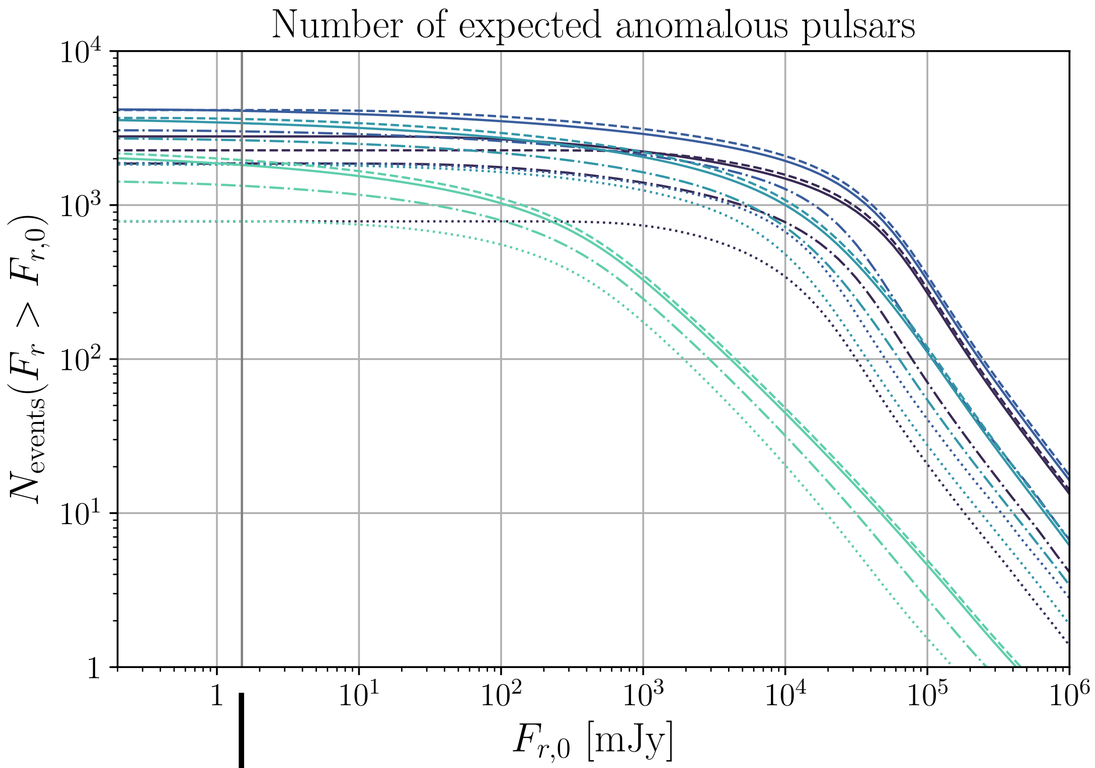


$\varepsilon = 10^{-8}$

Fraction of EM power into radio: 10^{-7}

Expected radio signals





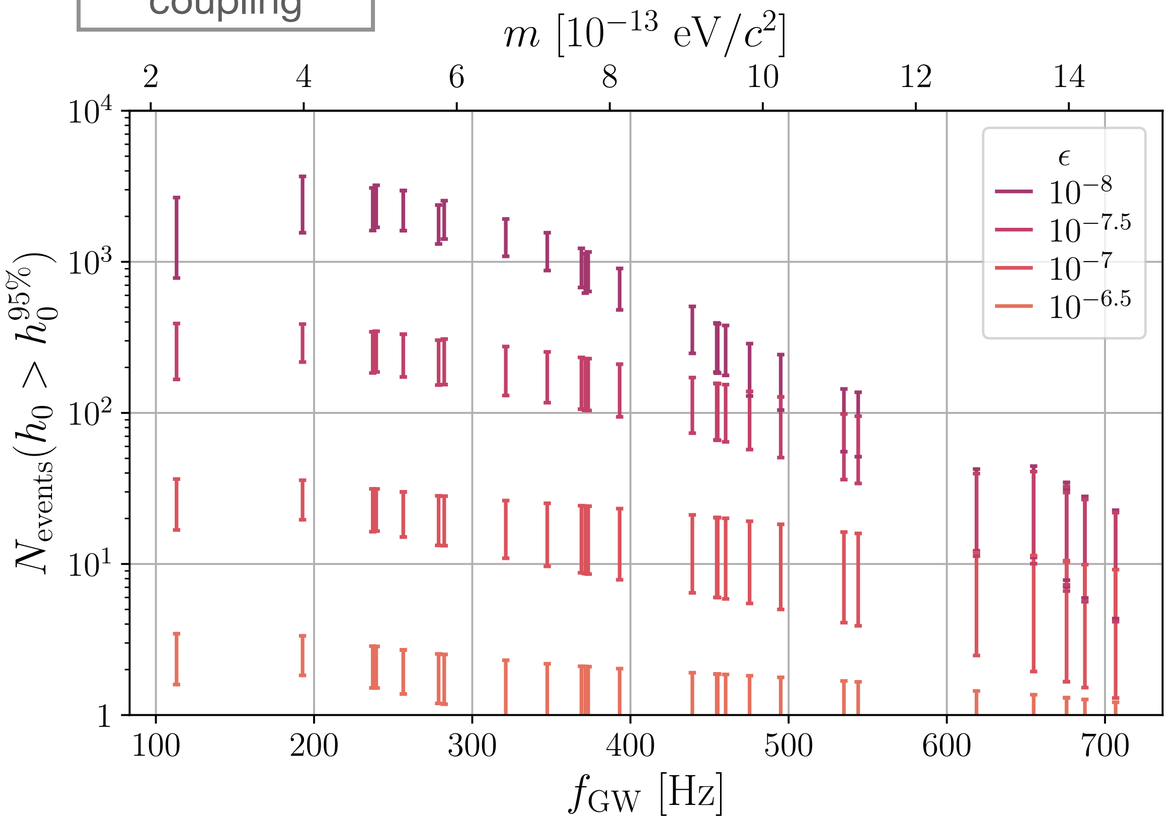
$\varepsilon = 10^{-8}$

Fraction of EM power into radio: 10^{-5}

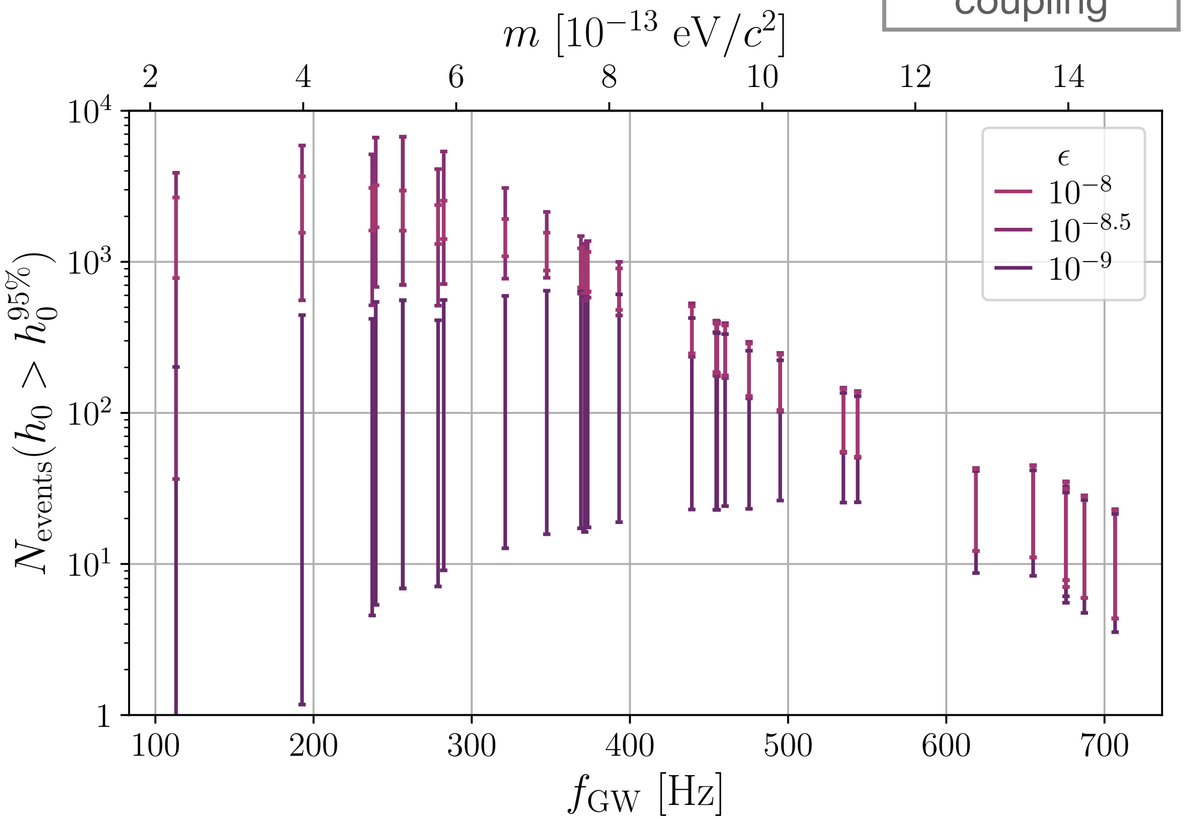
Detection threshold for large-scale radio pulsar surveys

Number of expected events

Increasing EM coupling



Decreasing EM coupling



Fraction of EM power into radio: 10^{-5}

Observational signatures

BH superradiance can be used to probe the existence of ultralight bosons

0905.4720, String Axiverse
A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, J. March-Russell

1004.3558, Exploring the String Axiverse with Precision Black Hole Physics
A. Arvanitaki, S. Dubovsky

1411.2263, Discovering the QCD Axion with Black Holes and Gravitational Waves
A. Arvanitaki, M. Baryakhtar, X. Huang

1704.04791, Superradiant Instability and Backreaction of Massive Vector Fields around Kerr Black Holes
W. E. East, F. Pretorius

1801.01420, Constraining the mass of dark photons and axion-like particles through black-hole superradiance
V. Cardoso, O. J. C. Dias, G. S. Hartnett, M. Middleton, P. Pani, J. E. Santos

....

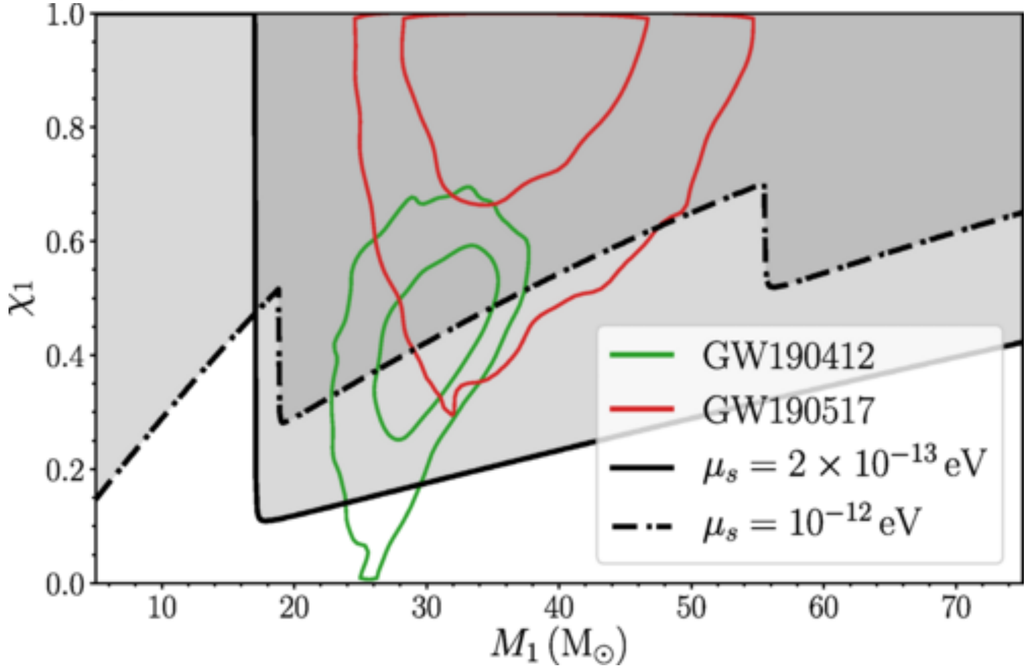
1. Spin distribution of BH population
2. Continuous gravitational wave signal

Observational signatures: spin distribution

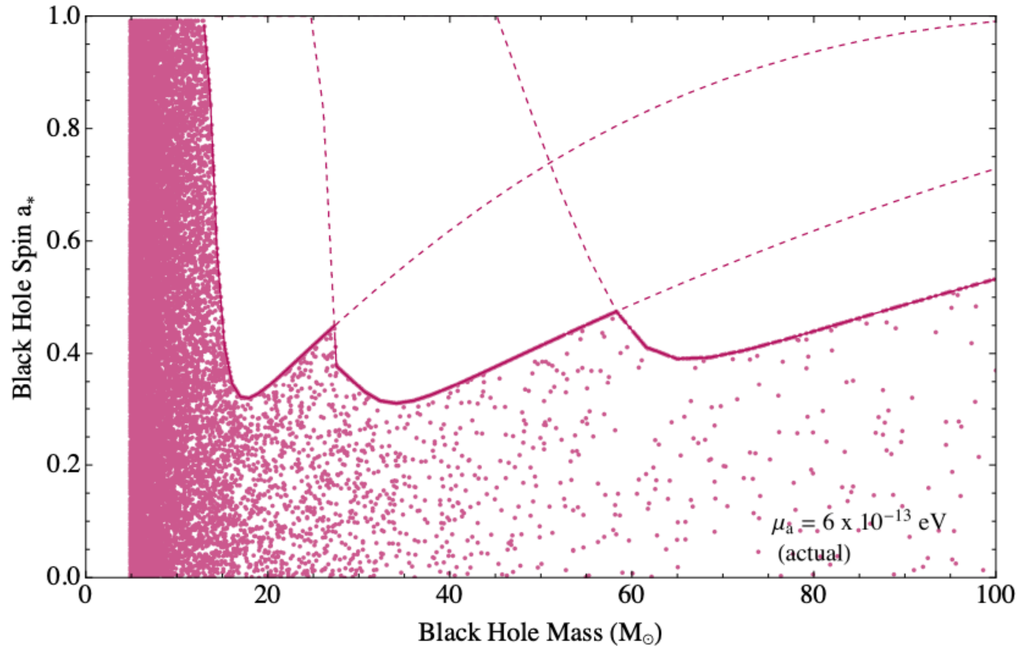
BH superradiance can be used to probe the existence of ultralight bosons

Axion masses around 10^{-13} eV already disfavored!

Ng, Vitale, Hannuksela, and Li PRL 2021



Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky, Lasenby PRD 2017

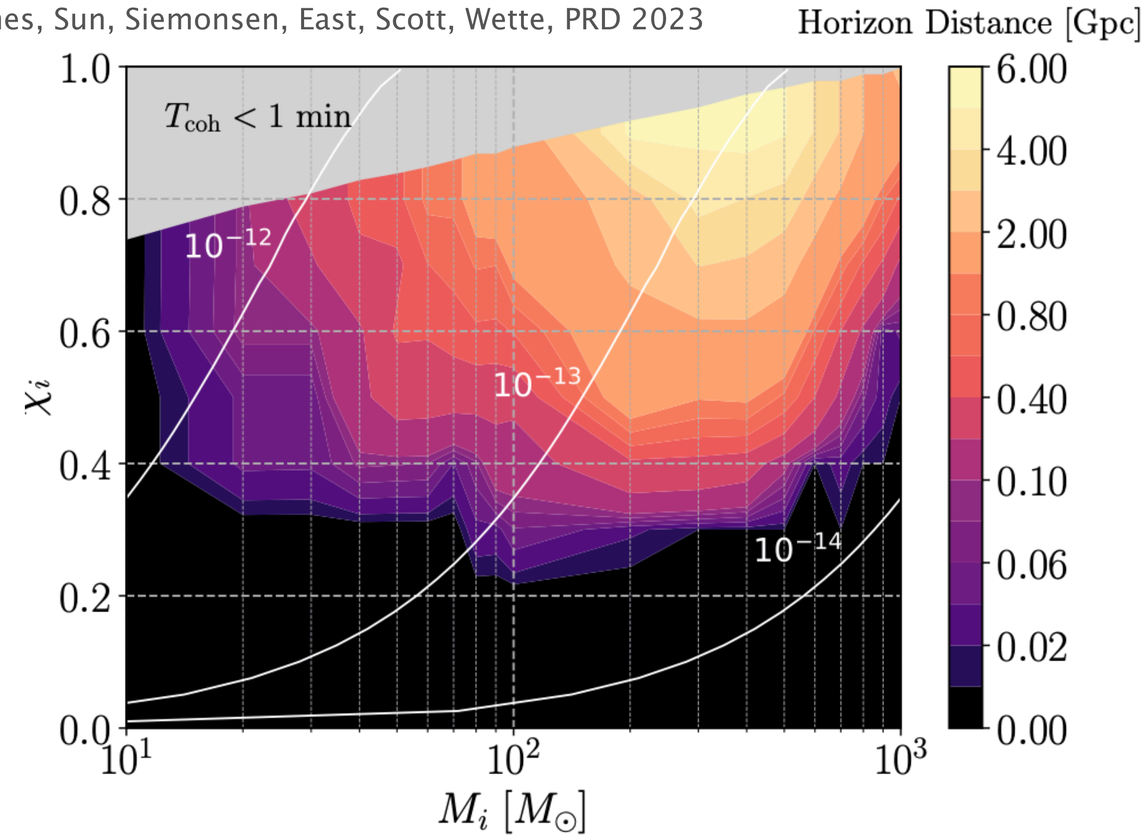


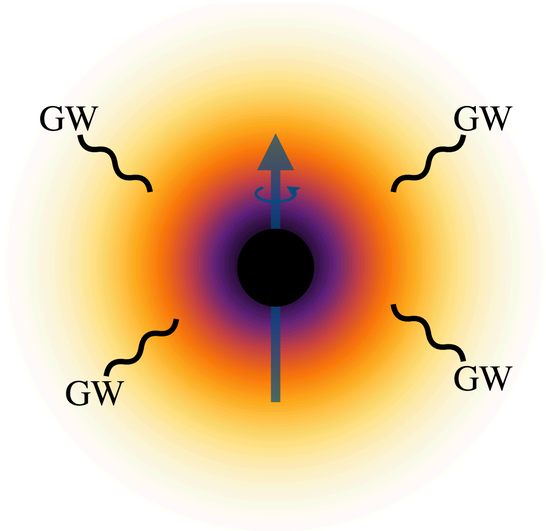
* depends on the time between BH formation and the merger (longer merger time, longer time for SR to grow)

Observational signatures: continuos GW

BH superradiance can be used to probe the existence of ultralight bosons

Jones, Sun, Siemonsen, East, Scott, Wette, PRD 2023





Vector boson clouds could be seen with targeted CW searches of BH merger remnants in future LVK observing runs!

* needs good sky localization