Electromagnetic Signatures of (Dark) Photon Superradiance

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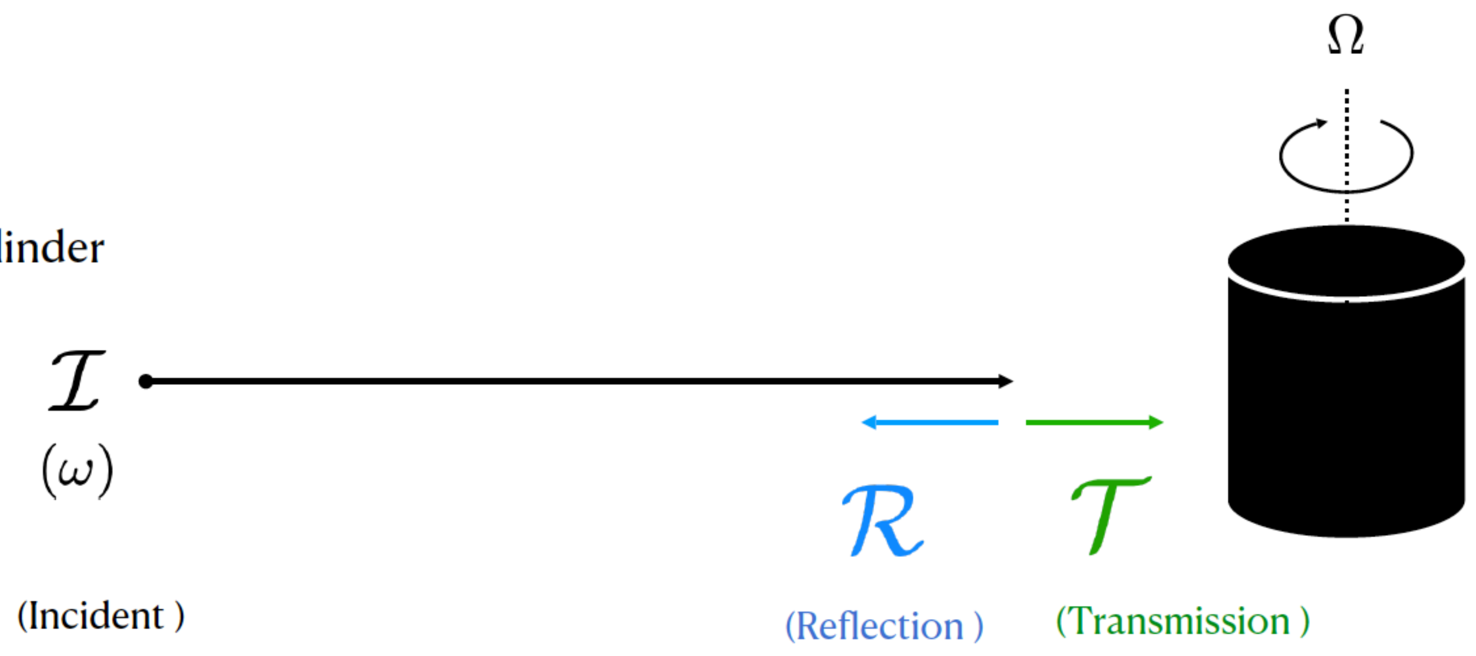
Rotational Superradiance

Thought experiment:

Scatter low-energy radiation off rotating cylinder

Zel'dovich (1971)



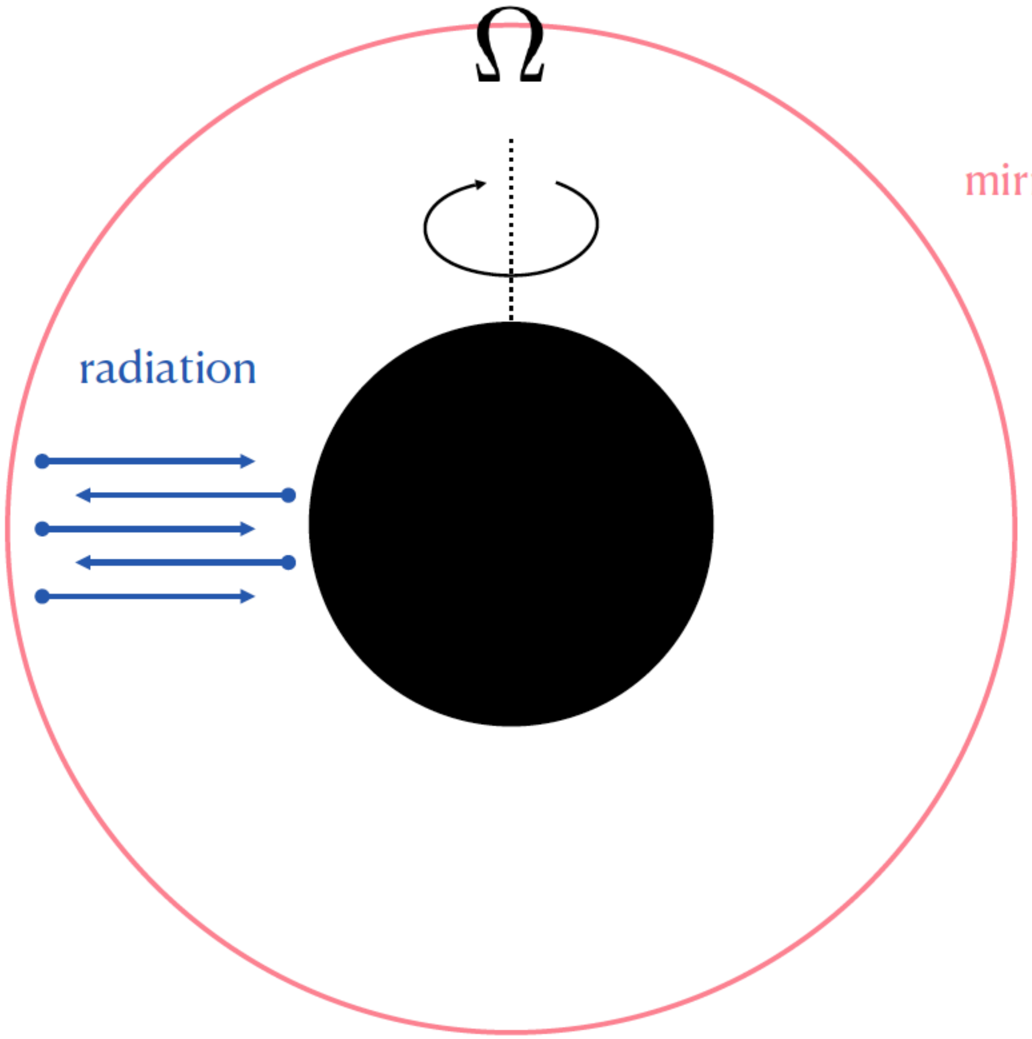
$|\mathcal{R}|^2 > |\mathcal{I}|^2 \quad (|\mathcal{T}|^2 < 0)$ *If* $\boxed{\omega < m\Omega}$

(**m azimuthal number)

Incremental extraction of rotational energy

Black Hole Bombs

Imagine to have a black hole inside a reflecting mirror, with some radiation which comes back and forth



Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74

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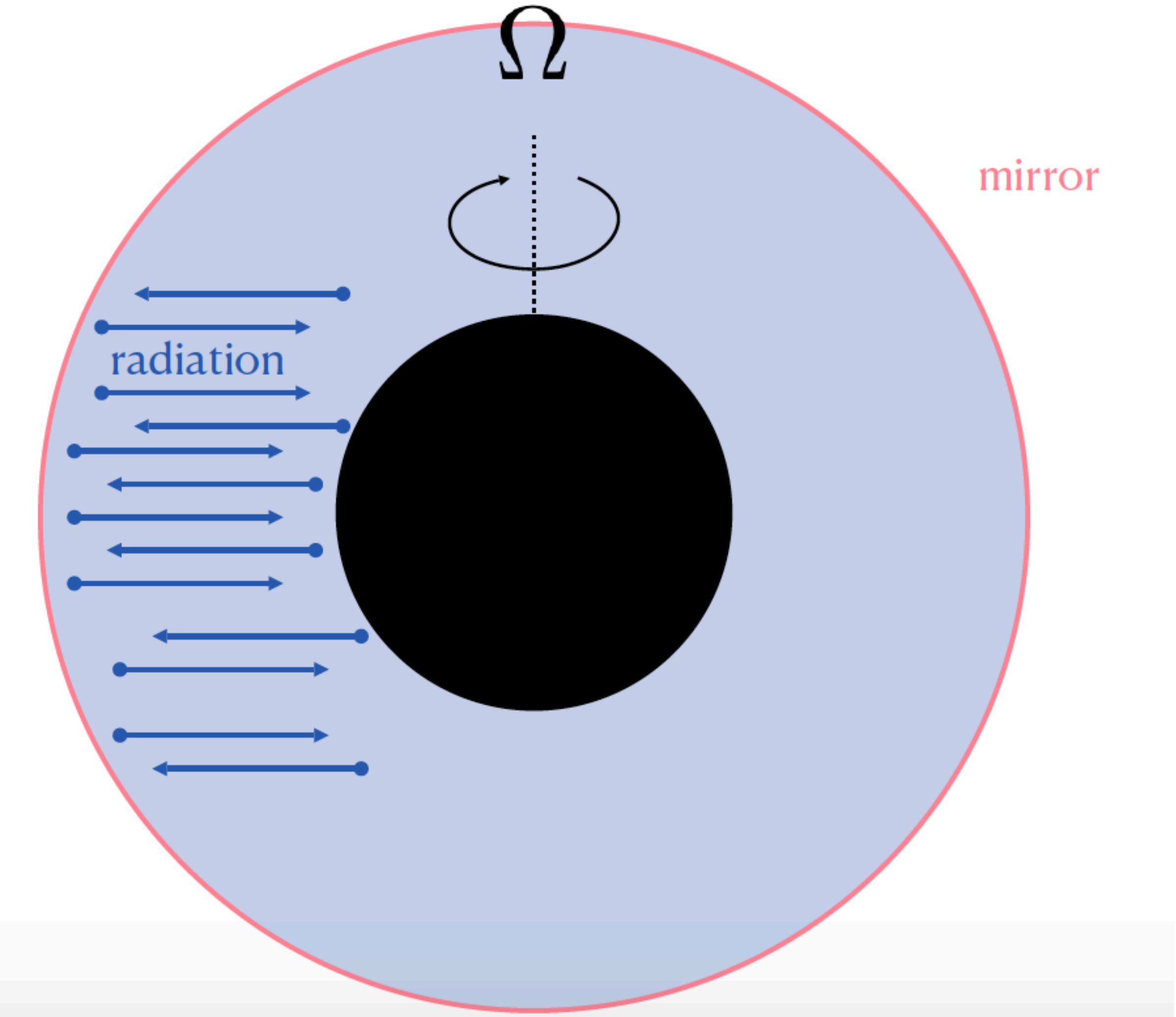

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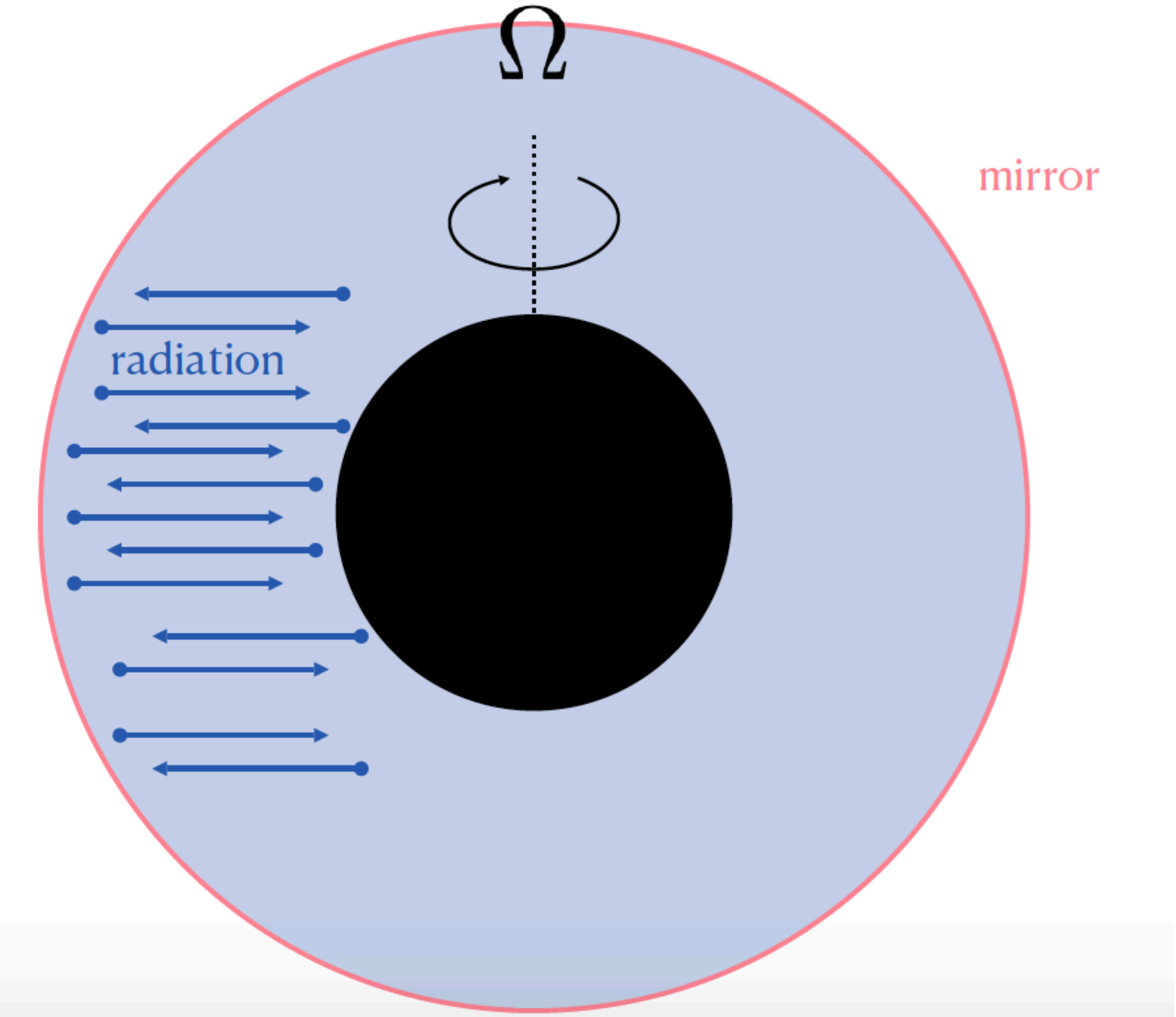
Extraction of energy and angular momentum from the black hole



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Massive bosonic fields around Kerr BHs

- The mass provides a natural mirror;
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$$\Phi = \frac{\Psi(r)}{r} S_{\ell m \omega}(\theta) e^{-i\omega t + im\varphi}$$

$$\frac{d\Psi}{dr_*^2} + (\omega^2 - V_{\rm eff})\Psi = 0\,, \qquad V_{\rm eff}(r \to \infty) = \mu_S^2$$

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Hydrogenic-like solution

$$\boxed{\omega \sim \mu_S - \frac{\mu_S}{2}\left(\frac{M\mu_S}{l+n+1}\right)^2 + \frac{i}{\gamma_{nlm}}\left(\frac{am}{M} - 2\mu_S r_+\right)(M\mu_S)^{4l+5} \,, \qquad M\mu_S \ll 1}$$

Arvanitaki & Dubovsky ’10

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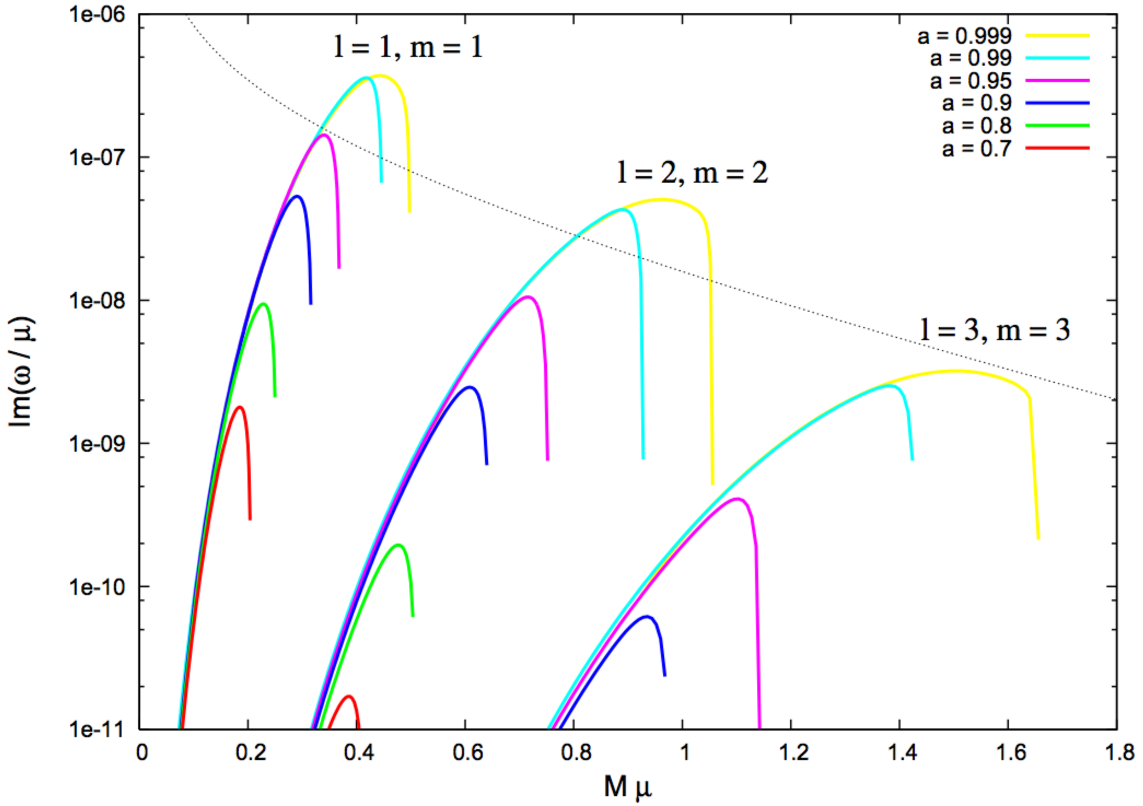

S.Dolan, Phys.Rev.D76:084001,2007

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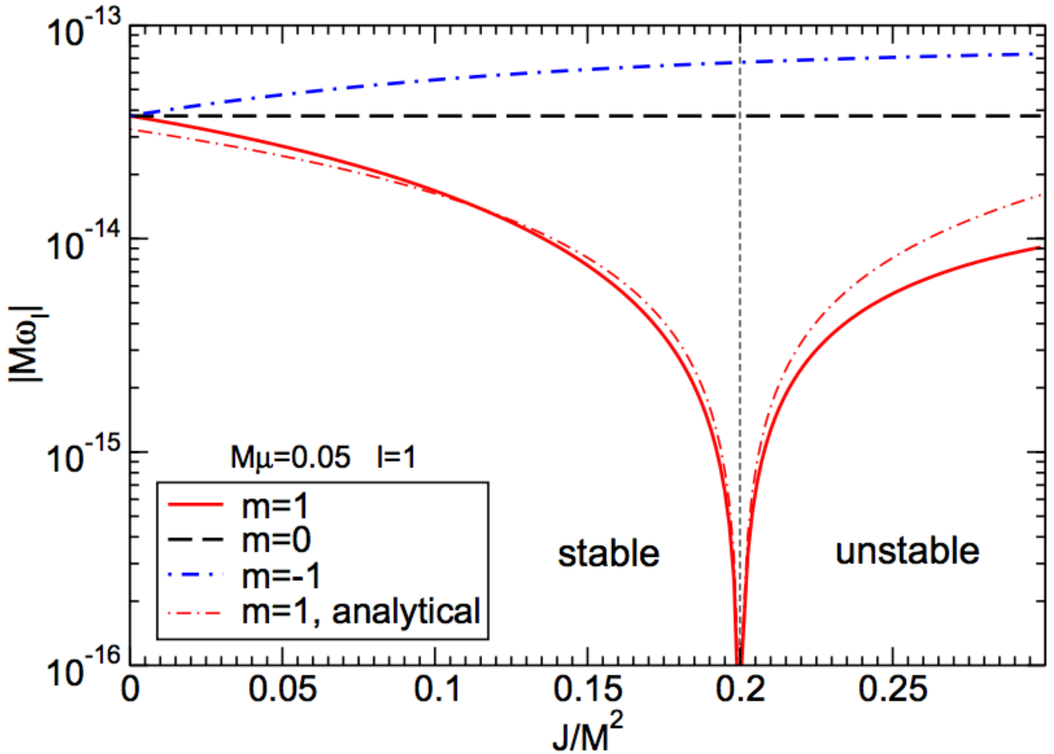
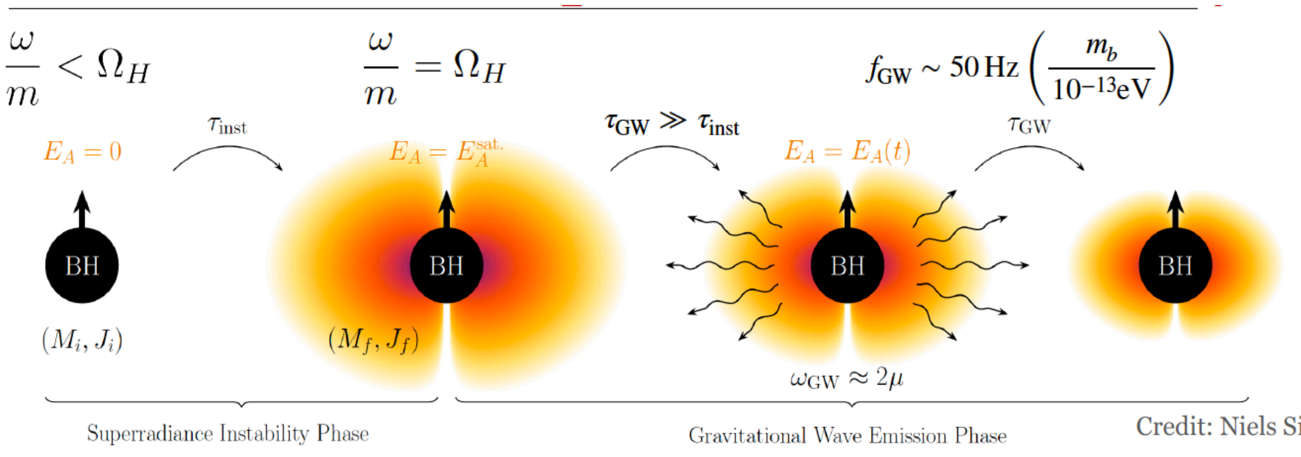


Some rough numbers

Lets take some characteristic *(somewhat maximal)* parameters to get intuitive feel...

- Proca Field (s=1)
- $m_b \sim 10^{-11}\,\mathrm{eV}$
- $\mu = 0.4 \;\rightarrow M \sim 10 M_\odot$
- $\tilde{a} \sim 0.99$
- S = -1, l = 1 (fastest growing mode)



Credit: Niels Siemonsen

Superradiant Timescale: $\tau_{sr} \sim 10^{-3}\, s$

Superradiant Cloud Radius: $r_{\rm cloud} \sim 10^{7}\,\mathrm{cm}$

Energy extracted: $\sim 10^{66}\,\mathrm{eV}$ (Over timescale of ~ 1 second)

Millions times more luminous than CC supernova

Final particle number density: $\sim 10^{55}\,\mathrm{cm}^{-3}$

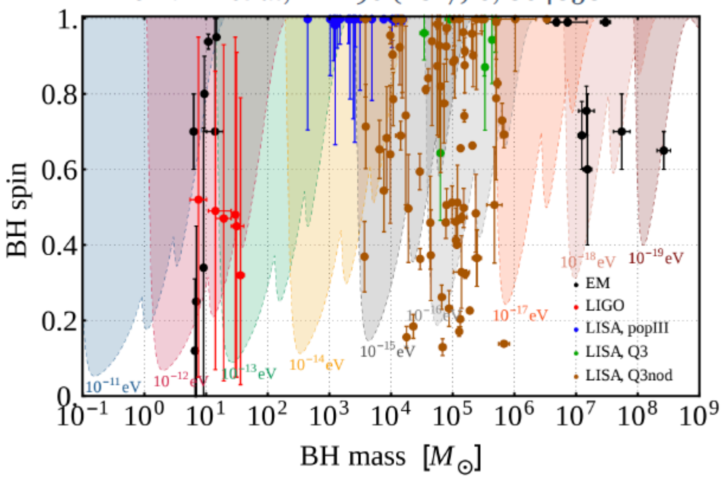
10^{16} times higher than core of neutron star

Final particle energy density: $\sim 10^{44}\,\mathrm{eV/cm^{-3}}$

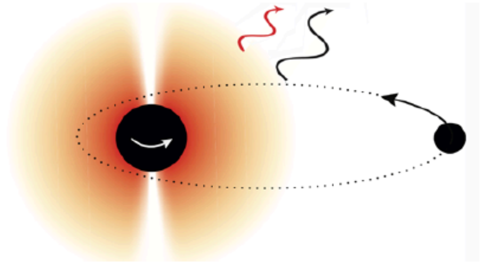
Observables

- "Gaps" in the BH mass-spin astrophysical distribution
  Arvanitaki *et al* '09; Arvanitaki & Dubovsky '10; Arvanitaki, Baryakthar & Huan '15; Pani *et al* '12; Baryakthar, Lasenby & Teo '17; RB *et al* '17; Cardoso et al '18; RB, Grillo & Pani '20; Stott '20; K. Ng *et al* '21,...

From: RB *et al*, PRD96 (2017) 6, 064050

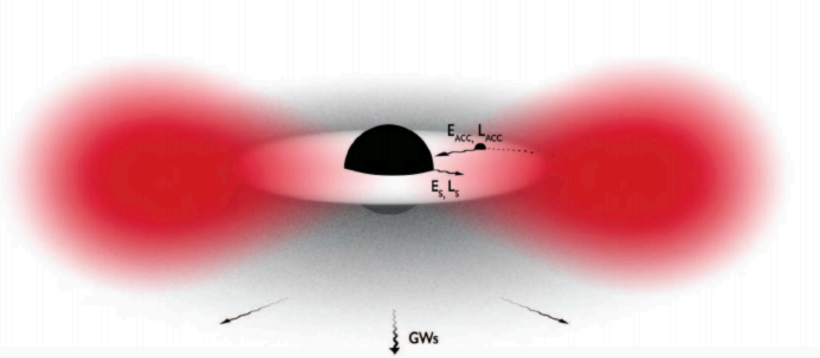


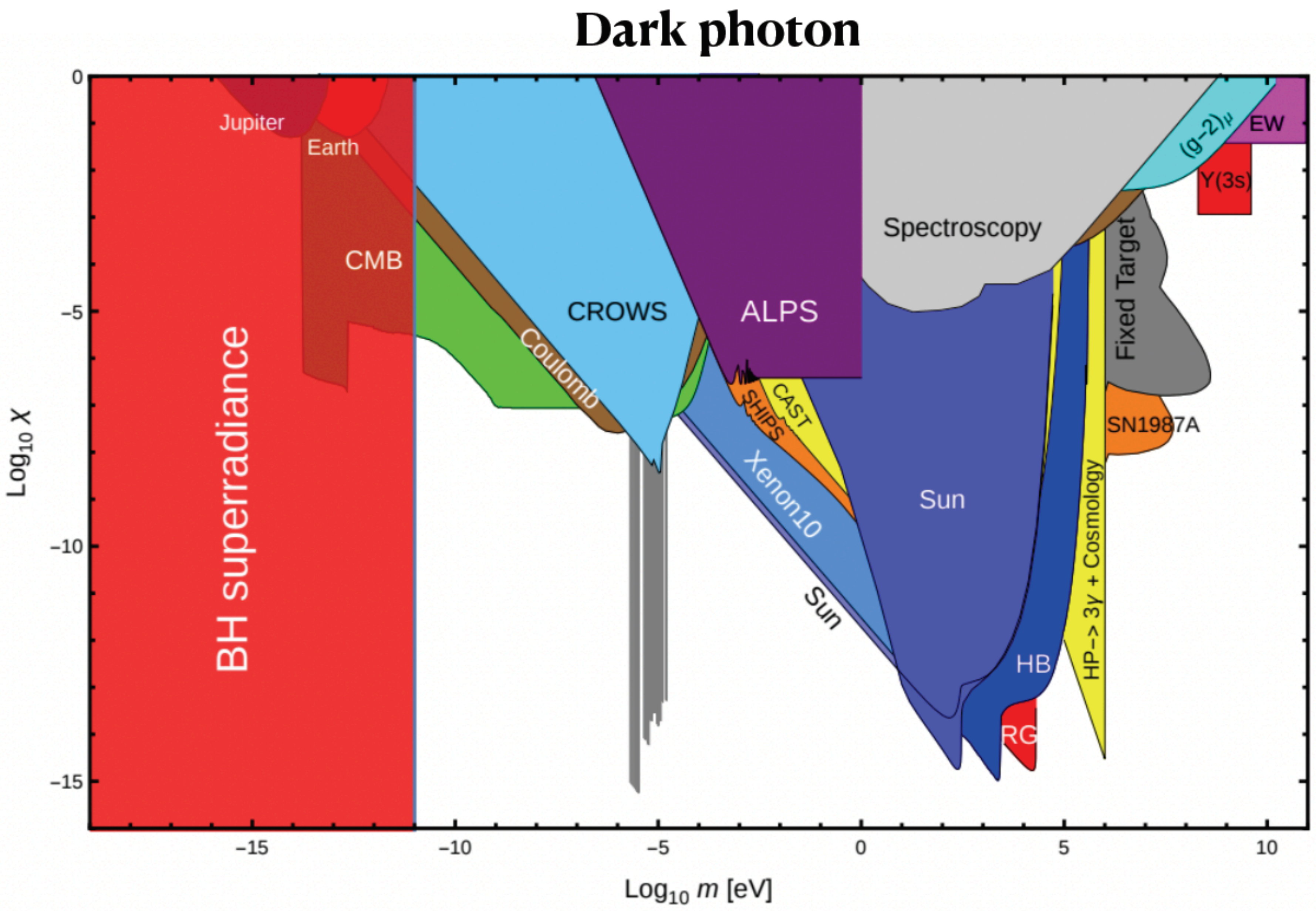
- Signatures in binary systems: dynamical friction, resonances, tidal effects, floating orbits for EMRIs...
  Baumann *et al* '19,'20, Hannuksela *et al* '19; Zhang & Yang '19; Berti *et al* '19; Cardoso, Duque & Ikeda '20...



Credit: D. Baumann/University of Amsterdam

- Emission of continuous GWs (either as individual sources or as stochastic background)
  Arvanitaki *et al*'09; Yoshino & Kodama '14; Arvanitaki, Baryakhtar & Huang, '15; RB *et al '17;* Baryakhtar, Lasenby & Teo '17; Siemonsen & East '20; RB, Grillo & Pani '20, Zhu *et al* '20...





Cardoso et al (2018)

From observation of BH spins

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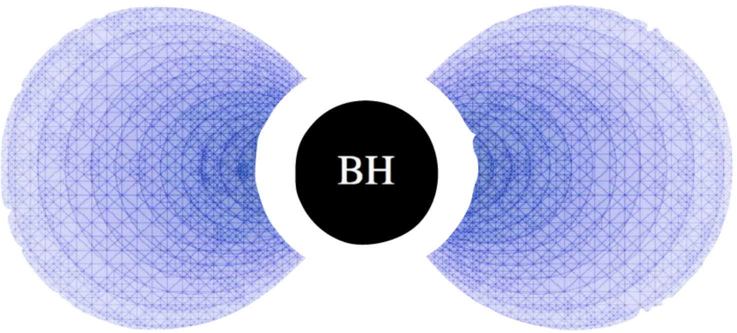
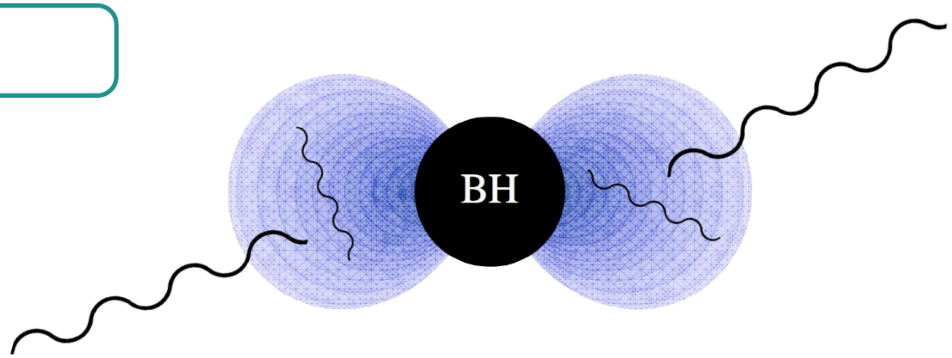
Possible origins for quenching:

1. Alter quasi-bound states



Superradiance becomes inefficient

2. Depopulate cloud



$$E_{\text{dissipated}} \gtrsim E_{sr}$$

Kinetically mixed dark photon

$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\,\mu\nu} + m^2_{\gamma'} A'_\mu A'^{\,\mu} - e \sin\chi_0 J^\mu A'_\mu$$

(We will assume mass arises from Stuckelberg mechanism)

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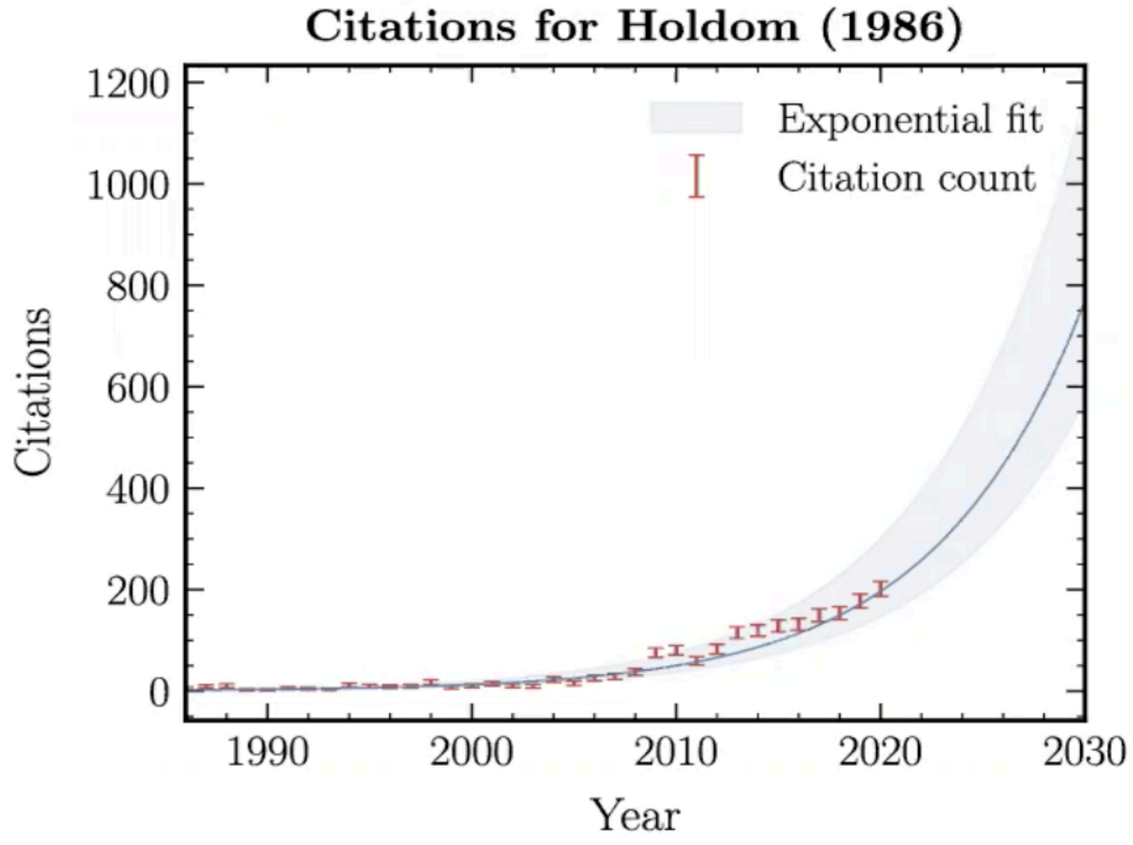
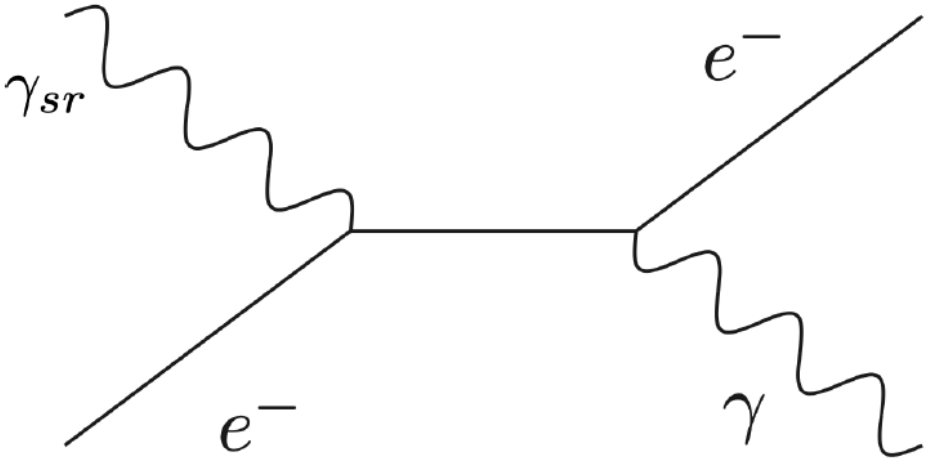


Kinetic mixing

- How do we really quench supperadiance in this case?

Superradiance gives us: $$\frac{dn_{\gamma'}}{dt} \propto n_{\gamma'}$$

Looking for: $$\frac{dn_{\gamma'}}{dt} \propto -n_{\gamma'}^2,$$ (Or faster)



$$\frac{dE_{\mathrm{sC}}}{dt} = \frac{4}{3}(\gamma^2 - 1)\sin^2\chi\,\sigma_T \rho_{\gamma'}\, n_e \overset{\gamma \gg 1}{\simeq} \frac{4}{3}\sin^4\chi \frac{n_{\gamma'}^2}{m_e^2}\sigma_T n_e\,.$$

Effect of large plasma mass

$$0 = \left[-\omega^2 + \begin{pmatrix} \frac{\omega_p^2}{\gamma} & \frac{\sin\chi_0\omega_p^2}{\gamma} \\ \frac{\sin\chi_0\omega_p^2}{\gamma} & \frac{\sin^2\chi_0\omega_p^2}{\gamma} + m^2 \end{pmatrix} \right] \begin{pmatrix} A_T \\ A'_T \end{pmatrix}$$

Dark photon linear combination of A and A'

$$A_{\text{obs}} = A + \sin\chi_0 A' \sim \sin\chi A_{dp}$$

Propagating field

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Net effect is in-medium mixing suppression

Vacuum regime: $m_{\gamma'} \gg \omega_p \to \sin\chi \sim \sin\chi_0$

Medium-Response: $\omega_p \gg m_{\gamma'}\,,\ E \ll m_e m_\gamma \to \sin\chi \sim \sin\chi_0 \frac{m_{\gamma'}^2}{\omega_p^2}$

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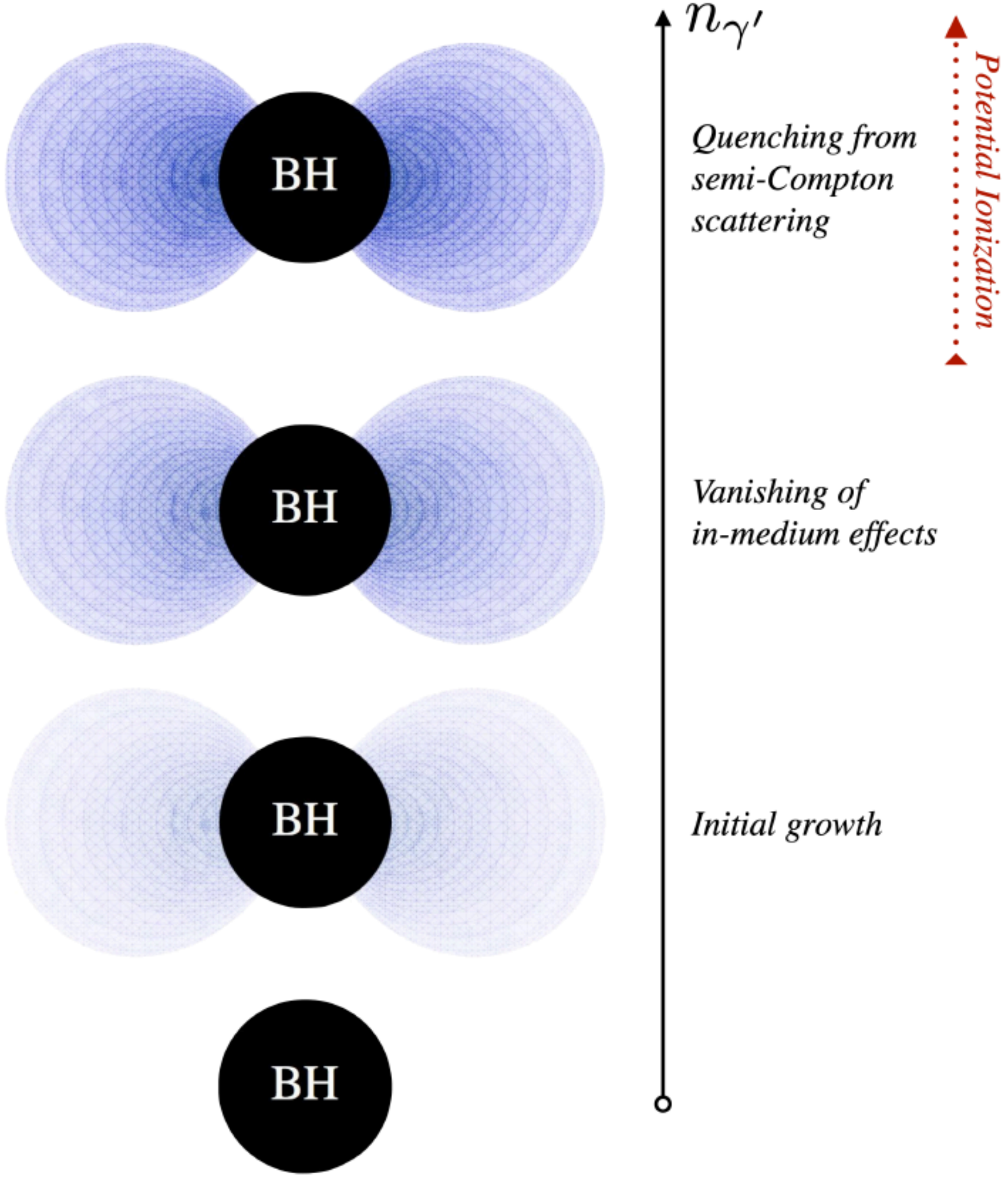
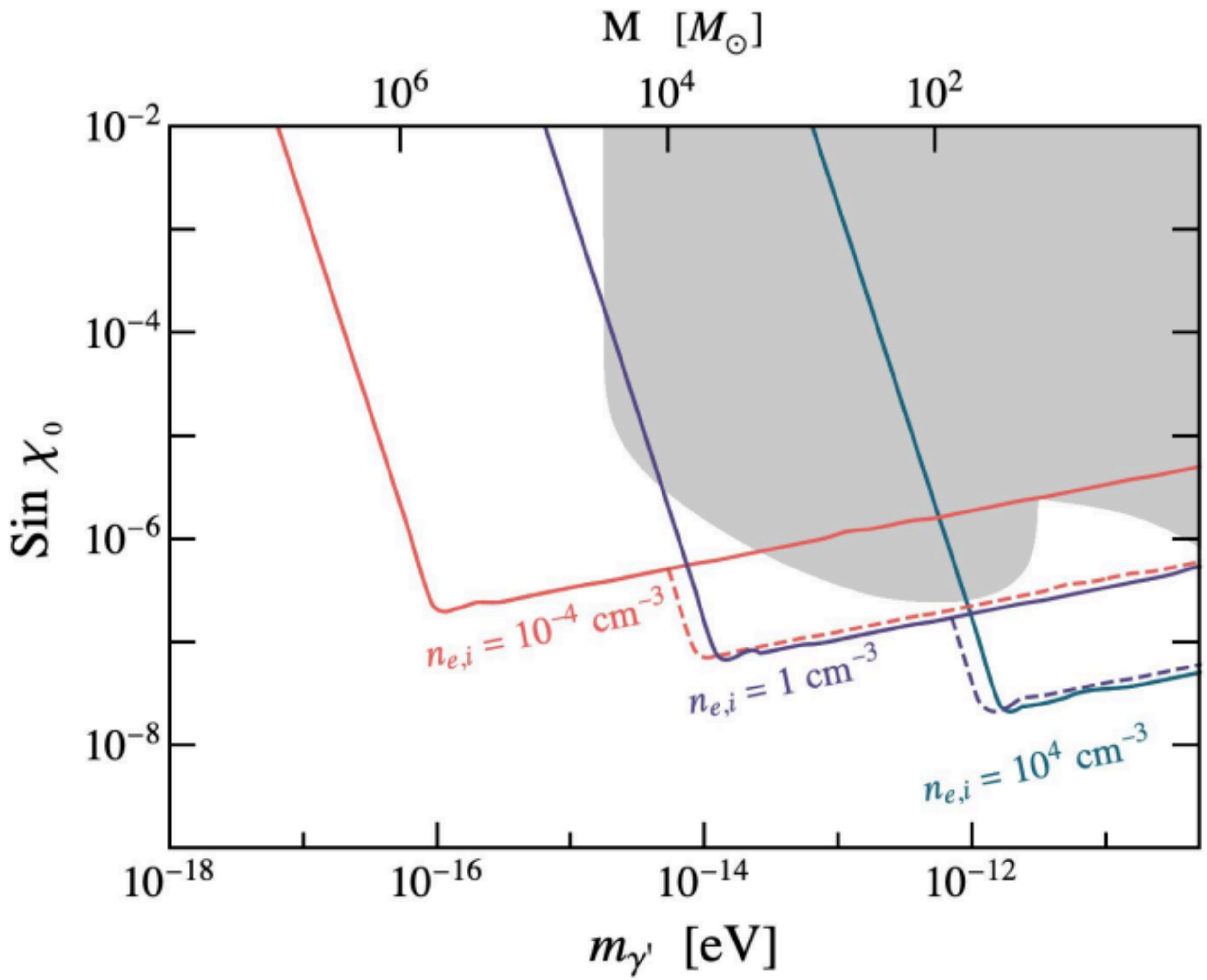
A.C, S. Witte, D.Blas, P.Pani, *Phys.Rev.D* 104 (2021) 4, 043006





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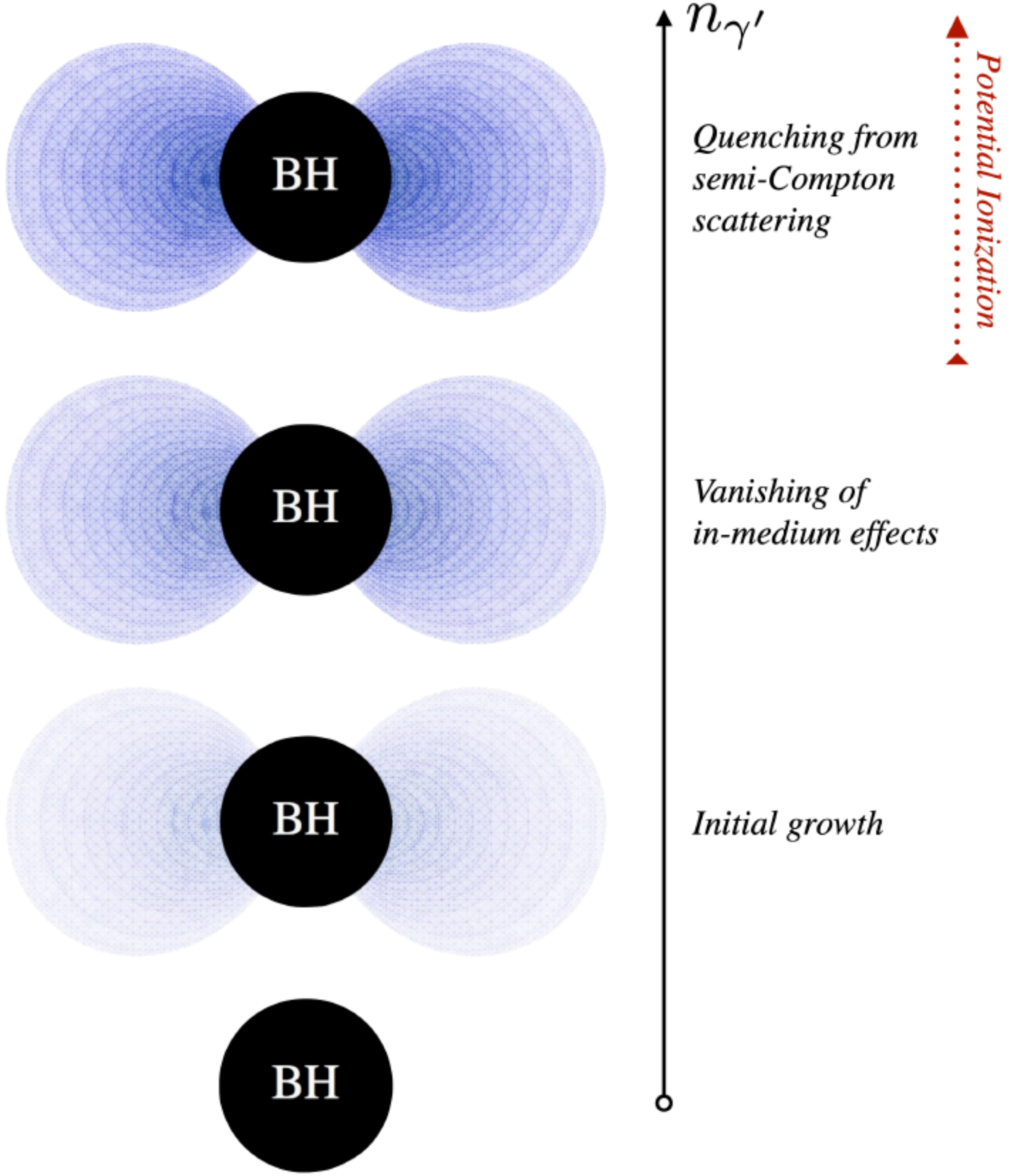
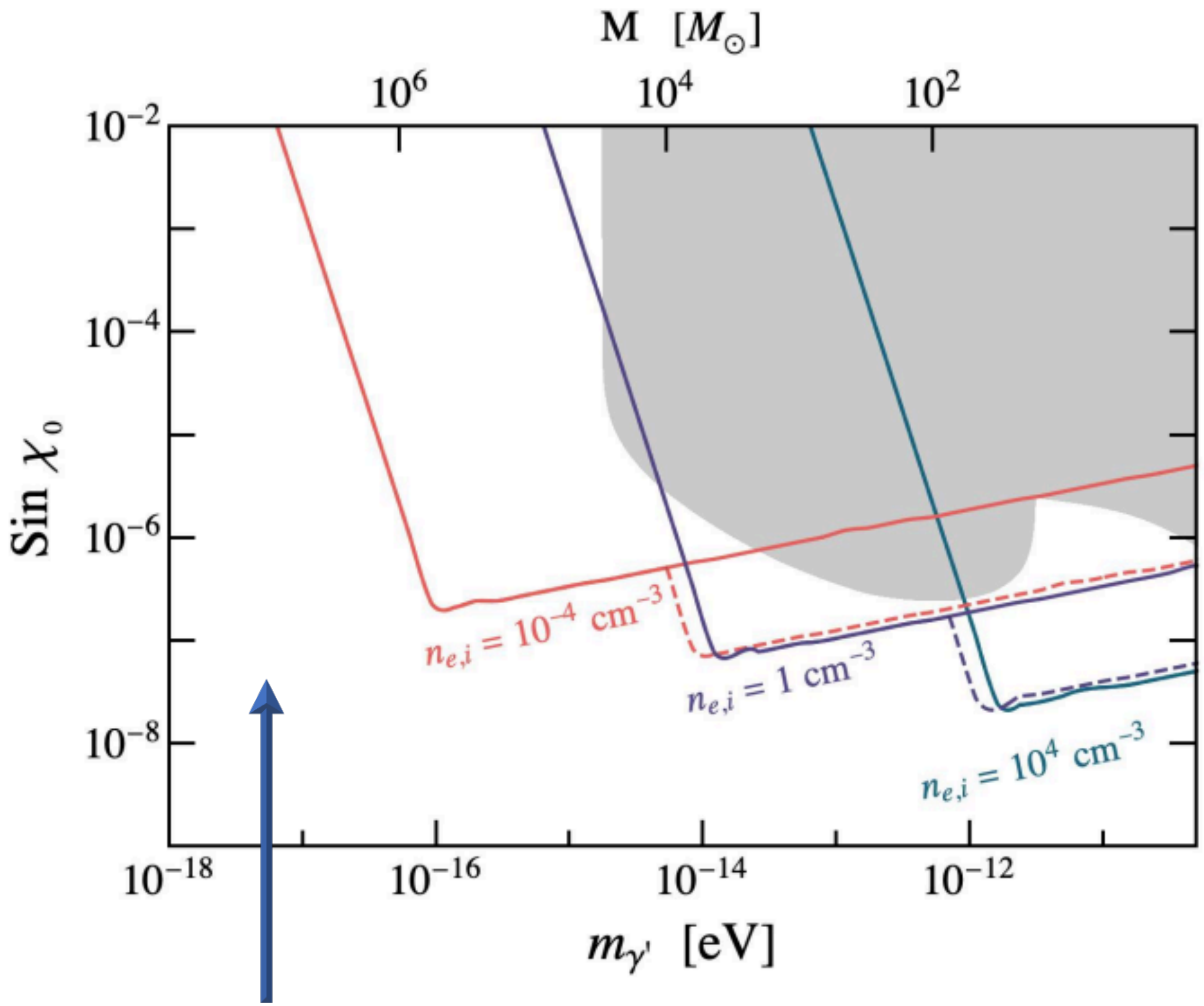
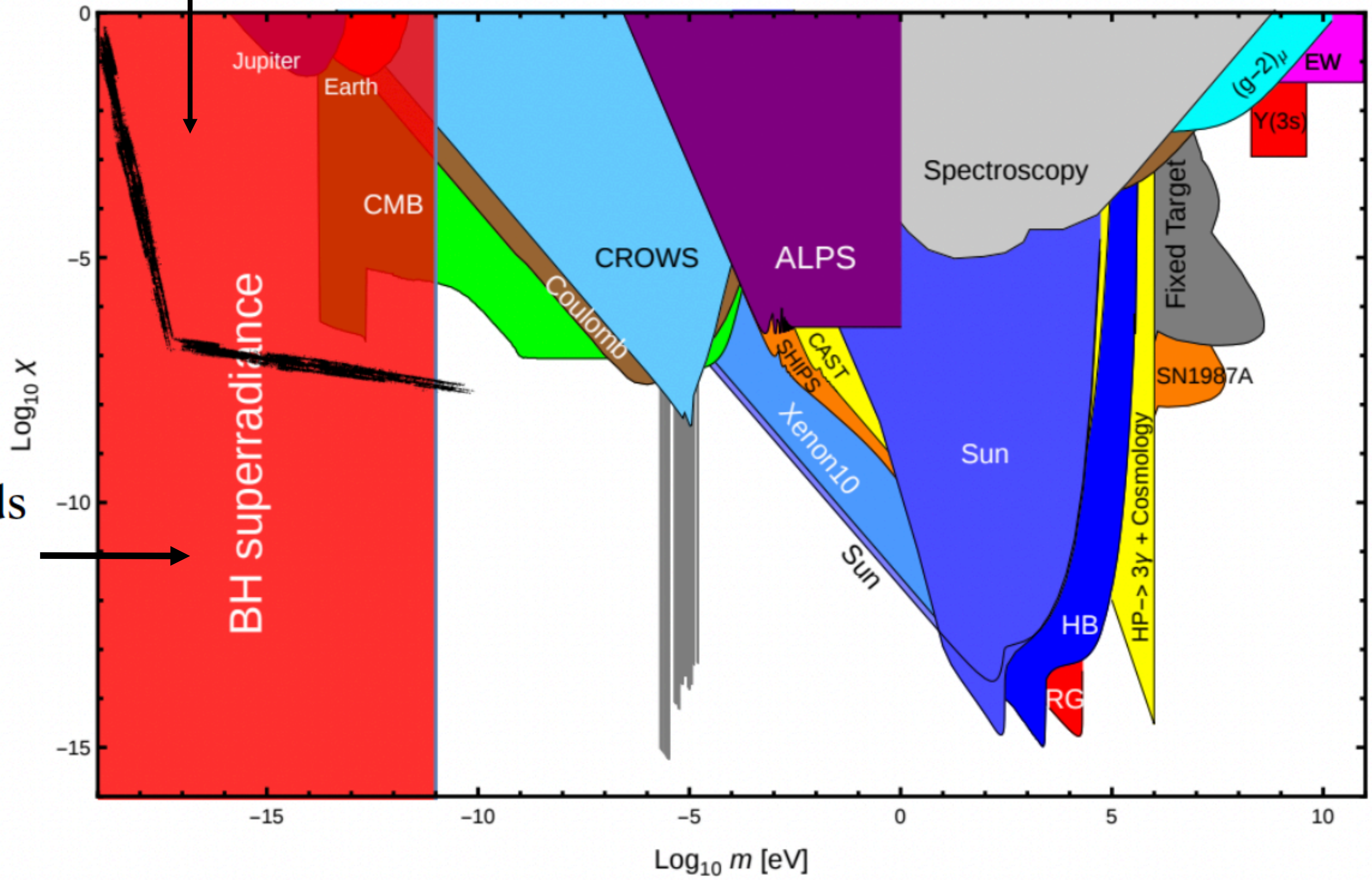




Cannot remove in-medium suppression

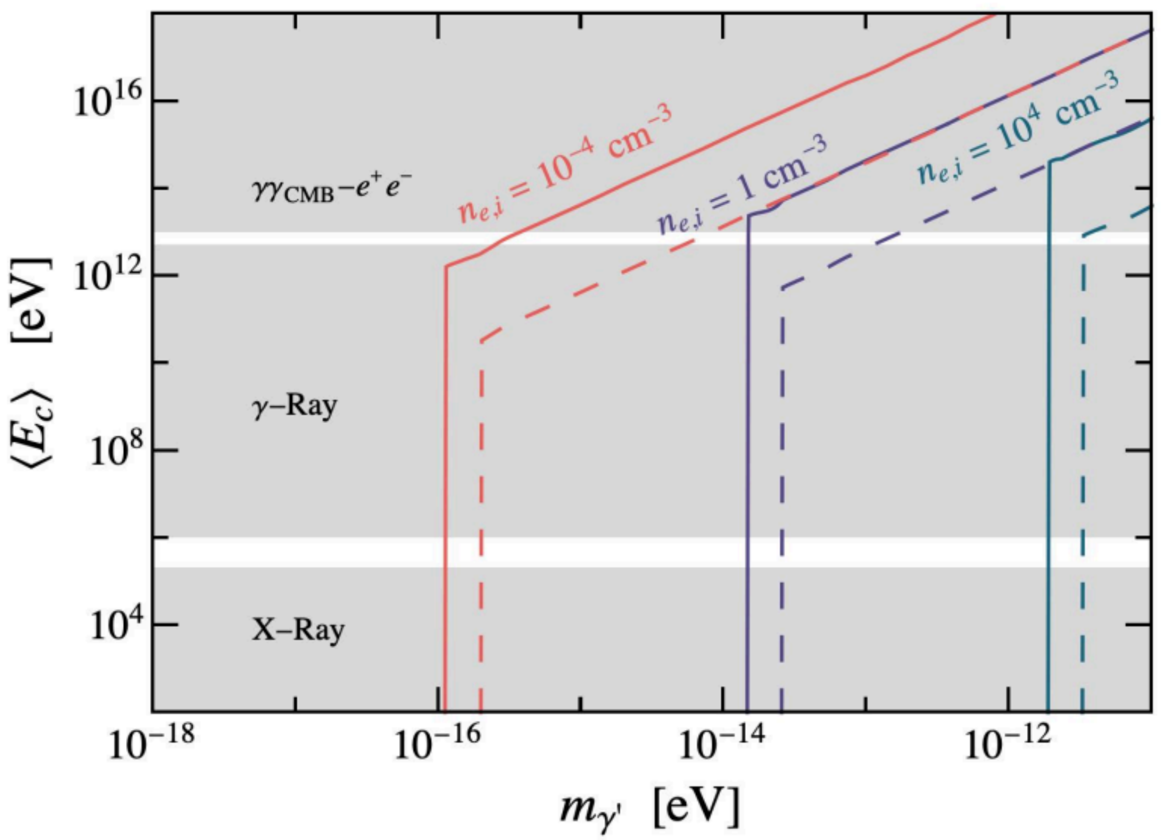
Superradiance bounds
NOT applicable here

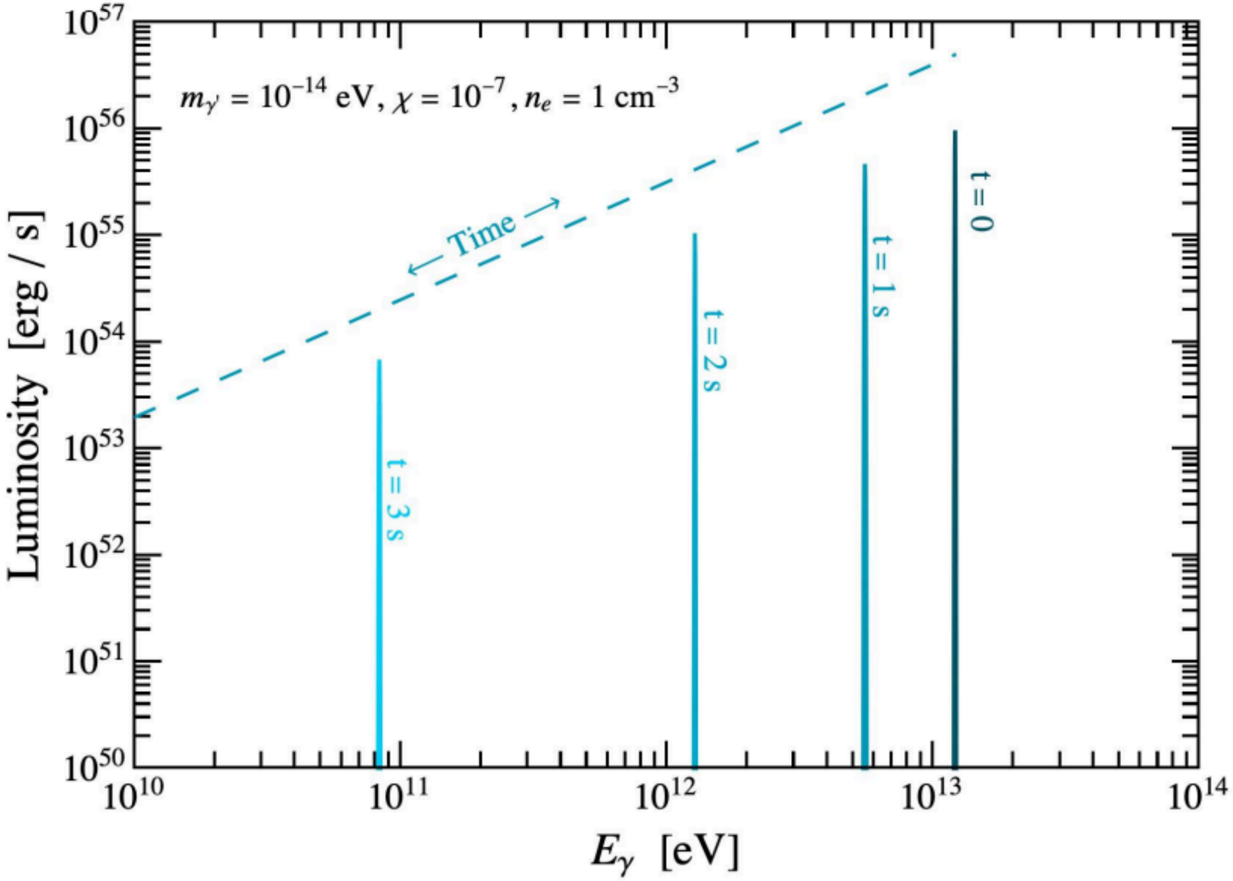
Superradiance bounds
may still apply here



Cardoso et al (2018)

New observables?





The quenching is a consequence of the fact that the accelerated electrons radiate synchrotron emission and semi-Compton scatter off the ambient dark photon. These processes result in the direct emission of very energetic photons.

Bonus: another simple mechanism to quench Dark Photon superradiance

Schwinger pair production rate if dark fermions are present in the spectrum of the theory

$$\mathcal{L}_{Dark} \sqsupset \lambda \bar{\psi}_d \gamma^\mu \psi_d A'_\mu$$

$$m_d \lesssim 7 \times 10^7 \left(\frac{\lambda}{0.1}\right)^{1/4} \left(\frac{m_{\gamma'}}{10^{-12}\,\mathrm{eV}}\right)^{1/2} \left(\frac{\alpha}{0.4}\right)^{5/4} \mathrm{eV} \longrightarrow \text{Particle production saturates growth}$$

Summing up: it is not true that interactions are not relevant and SR bounds always apply. One should be careful because there may be simple ways to avoid SR bounds.

Photon Superradiance?

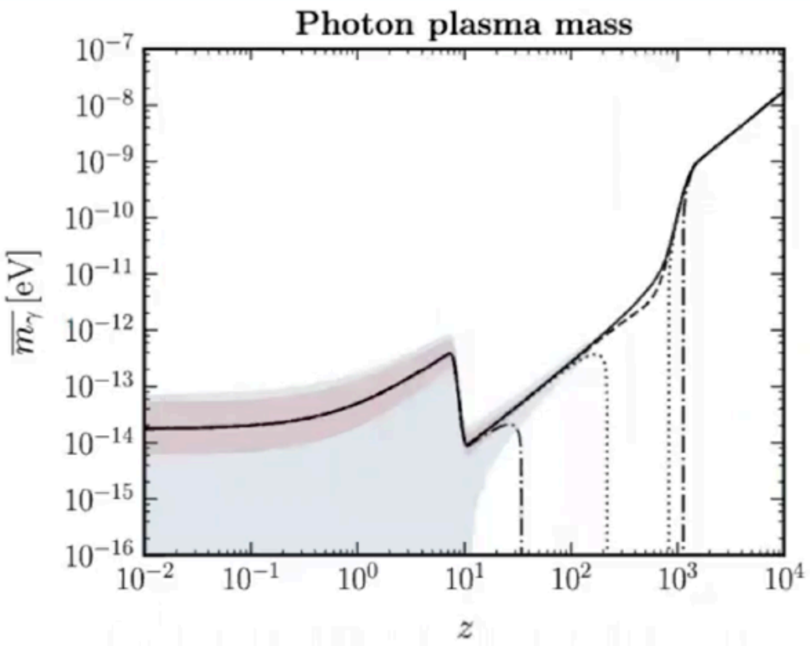
- Recall that one needs a “mass” acting as a mirror for the bound states

Photon Superradiance?

Problem: photons are massless

However, sometimes, nature provides its own mirrors: plasma

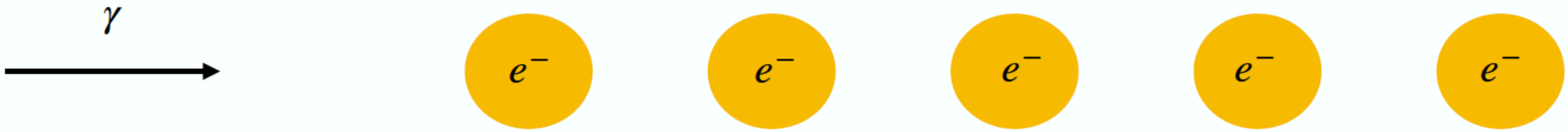
"Effective Mass": $\omega_p = \sqrt{\dfrac{4\pi n_e e^2}{m_e}}$



$$\omega^2 = k^2 + \omega_p^2$$

If $\omega < \omega_p$ the wave is confined by plasma

A.C, H.Liu, S. Mishra-Sharma, J.Ruderman, *Phys.Rev.Lett.* 125 (2020) 22, 221303



Many authors studied the problem, assuming simply a Proca equation

- Conlon et al (2018), Photon superradiance as mechanism for fast radio bursts
- Pani et al (2013), Photon superradiance as probe of PBHs
- Dima et al (2020), Role of plasma inhomogeneities on photon superradiance
- Cardoso et al (2020), Photon superradiance at strong E fields
- Pani et al (2012), Constraining bare photon mass

However the situation is more complicated, because the plasma frequency is NOT a gravitational mass. It is just a gap in the dispersion relation

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$$
\begin{aligned}
\nabla_\nu F^{\mu\nu} &= enu^\mu + J^\mu, \\
u^\mu \nabla_\mu u^\nu &= e/m_e F^\nu{}_\mu u^\mu, \\
u^\mu u_\mu &= -1, \\
\nabla_\mu (nu^\mu) &= 0.
\end{aligned}
$$

These are Maxwell's equations together with the momentum and particle conservation equations, in covariant form.

Theoretical framework

$$h^{\alpha}_{\beta}u^{\delta}\nabla_{\delta}\nabla_{\gamma}\widetilde{F}^{\beta\gamma} + (\omega^{\alpha}_{\beta} + \omega_{L}{}^{\alpha}_{\beta} + \theta^{\alpha}_{\beta} + \theta h^{\alpha}_{\beta} + \frac{e}{m}E^{\alpha}u_{\beta})\nabla_{\gamma}\widetilde{F}^{\beta\gamma} - \omega_p^2\widetilde{F}^{\alpha\beta}u_{\beta} = 0$$

Breuer R. A. , Ehlers J. 1981
E. Cannizzaro, **A.C**, L. Sberna, P. Pani, *Phys.Rev.D* 103 (2021) 124018
E. Cannizzaro, **A.C**, L. Sberna, P. Pani, *Phys.Rev.D* 104 (2021) 10, 104048

Theoretical framework

$$h^{\alpha}_{\beta}u^{\delta}\nabla_{\delta}\nabla_{\gamma}\widetilde{F}^{\beta\gamma}+(\omega^{\alpha}_{\beta}+\omega_{L\beta}^{\ \alpha}+\theta^{\alpha}_{\beta}+\theta h^{\alpha}_{\beta}+\frac{e}{m}E^{\alpha}u_{\beta})\nabla_{\gamma}\widetilde{F}^{\beta\gamma}-\omega_p^2\widetilde{F}^{\alpha\beta}u_{\beta}=0$$

$$\widetilde{A}_{\mu}(r,t,\theta,\varphi)=\frac{1}{r}\sum_{i=1}^{4}\sum_{l,m}c_i u^{lm}_{(i)}(r)e^{-i\omega t}Z^{(i)lm}_{\mu}(\theta,\varphi)$$

i=1,2,3 polar
i=4 axial

Make an Ansatz. EOM assume Schrödinger-like form and can be solved numerically via a direct shooting integration method.

Breuer R. A. , Ehlers J. 1981
E. Cannizzaro, **A.C**, L. Sberna, P. Pani, *Phys.Rev.D* 103 (2021) 124018
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Numerical Results: **Schwarzschild** spacetime

- The equations admit a stable, quasi-bound spectrum around a Schwarzschild BH;
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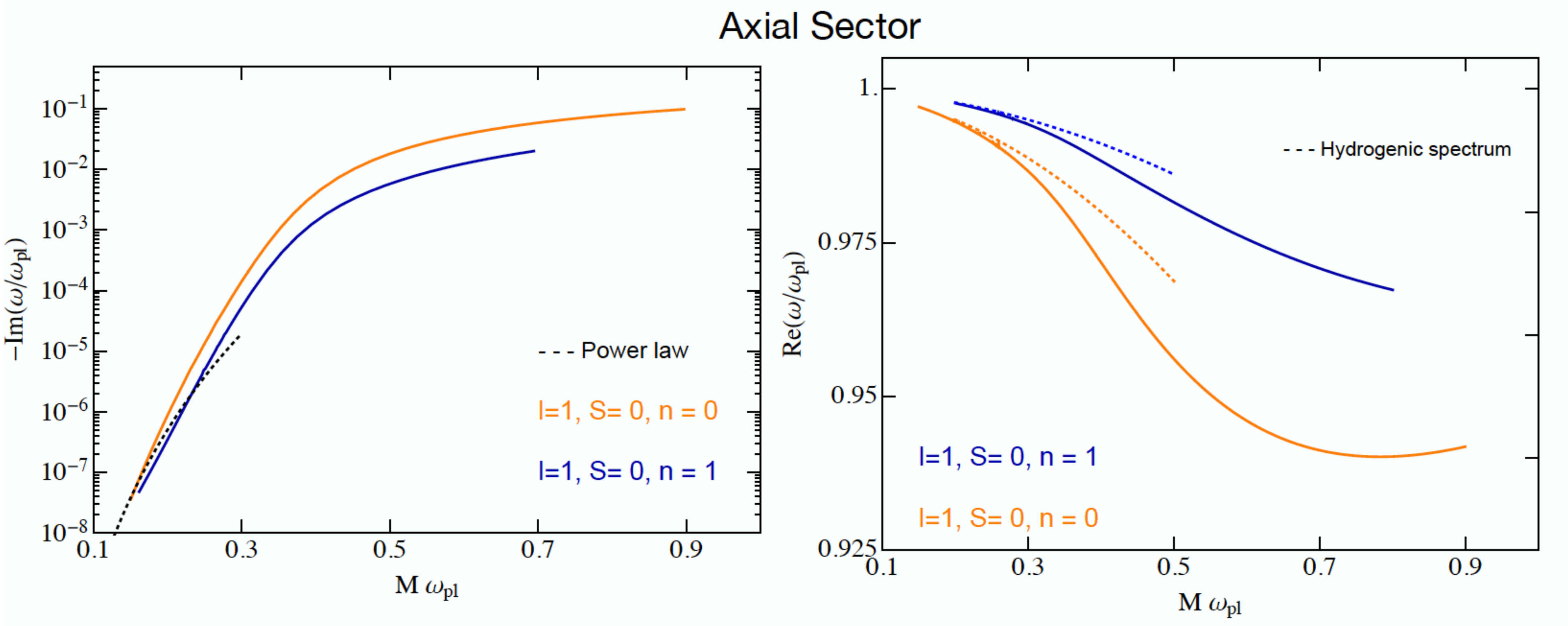
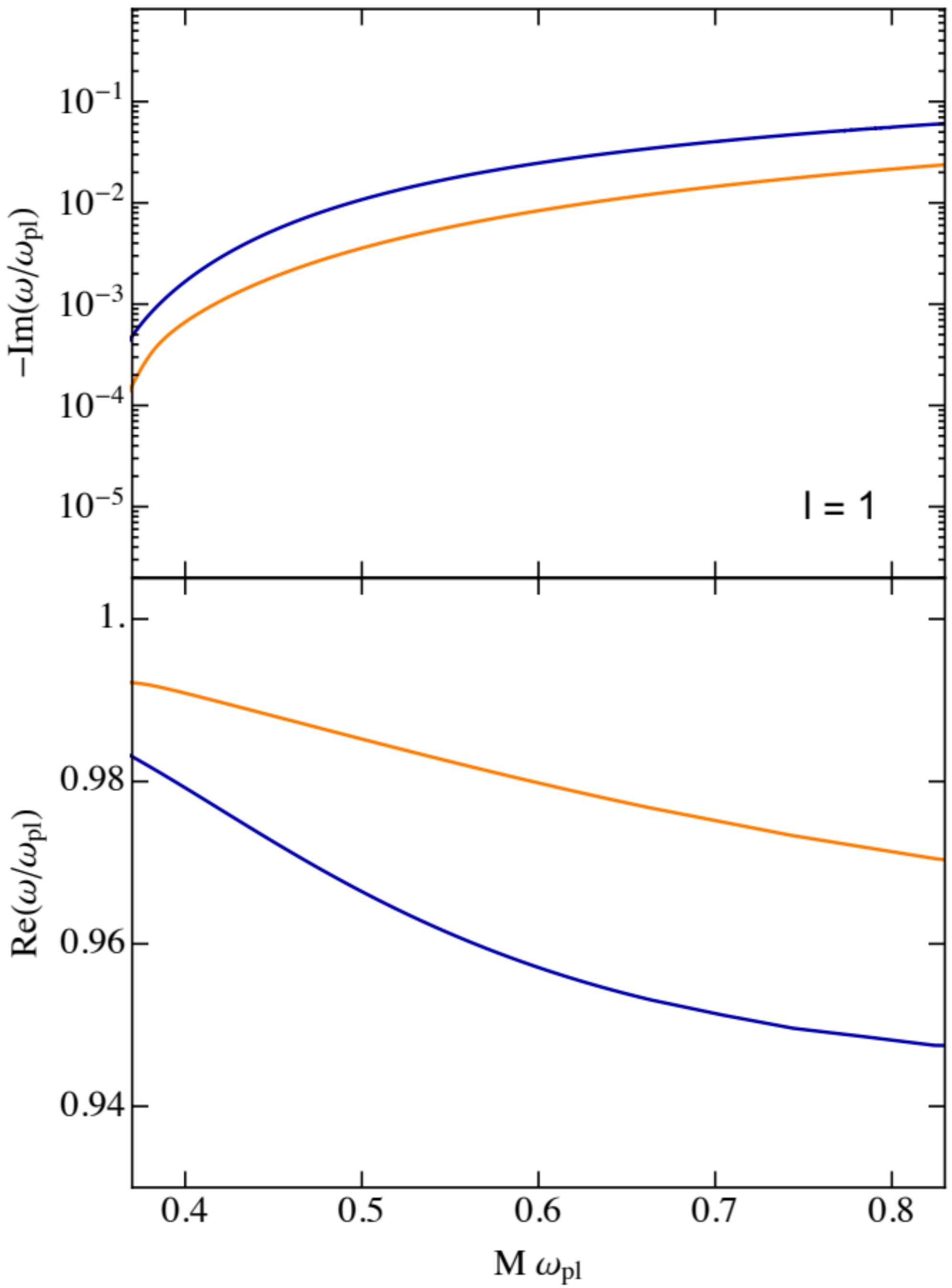


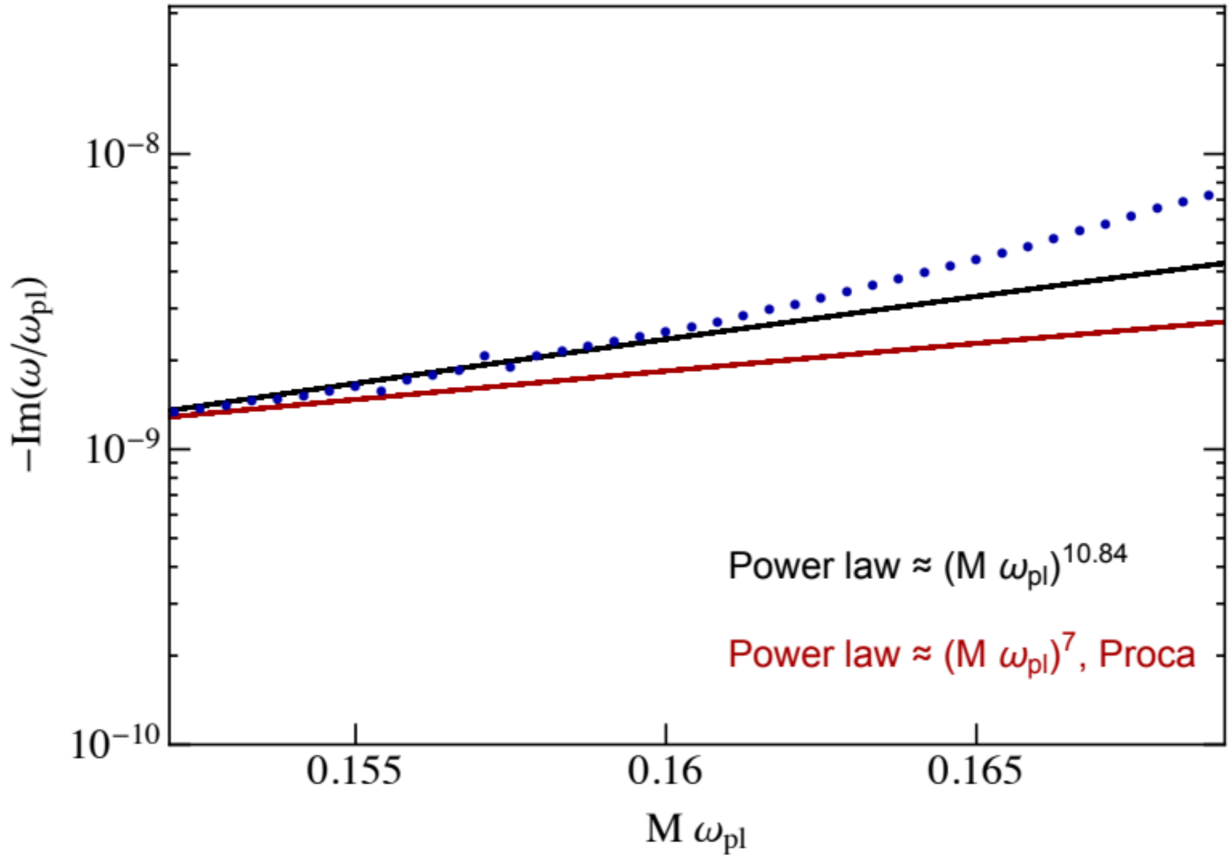
$$Re(\omega) < \omega_{pl}$$

$$Im(\omega) < 0$$

Polar sector



The modes do **not** reduce to the hydrogenic Proca spectrum



Numerical Results: **Kerr** spacetime

EOM solved in the slowly rotating framework

Axial equation

$$\left(\omega^2 + \frac{\partial^2}{\partial r^{*2}} - f[\frac{l(l+1)}{r^2} + \omega_p^2]\right)u_4(r) - \frac{4amM\omega}{r^3}u_{(4)}(r) = \frac{4mMa\omega_p^2 f}{l(l+1)r^3\omega}u_{(4)}(r)$$

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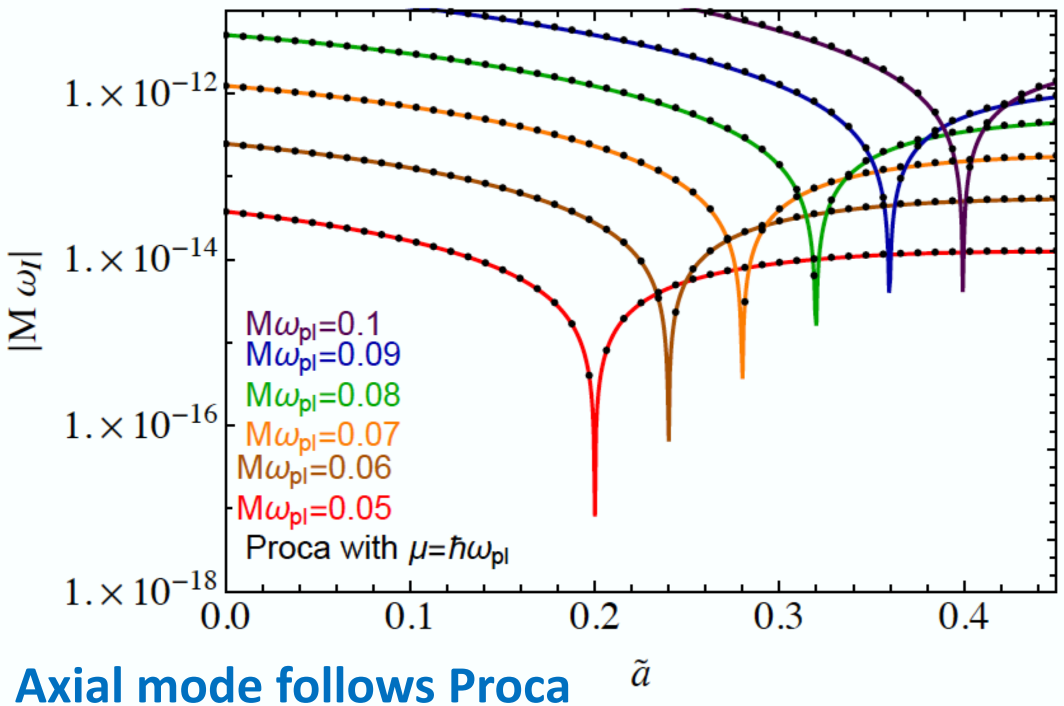
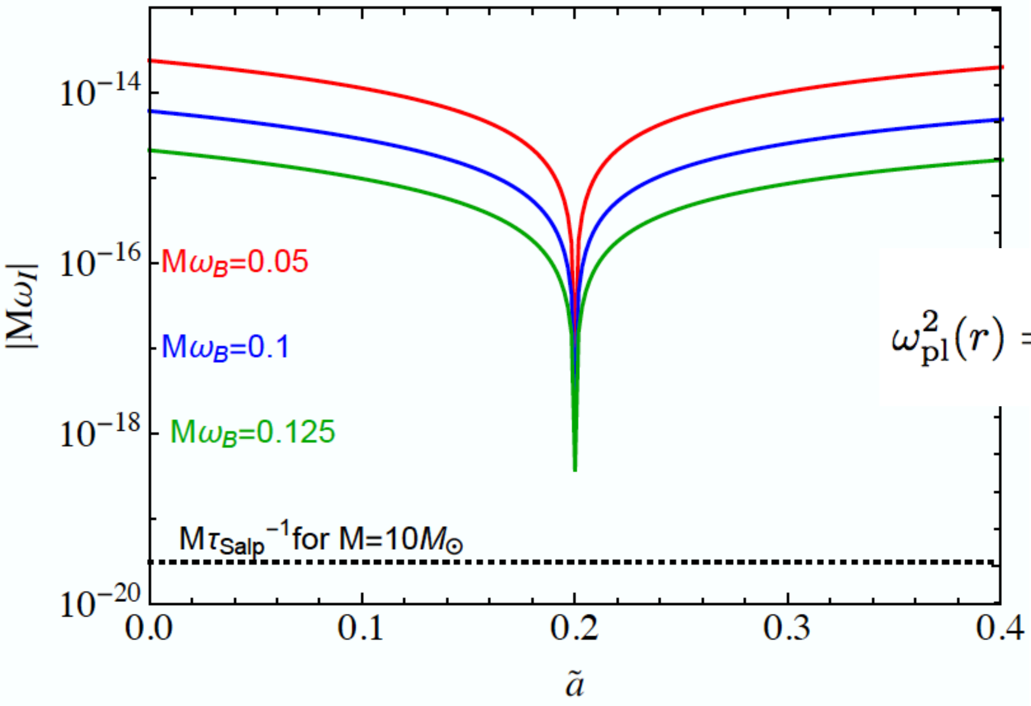
Constant density



Bondi accretion profile



$$\omega_{pl}^2(r)=\omega_B^2\left(\frac{2M}{r}\right)^\lambda+\omega_\infty^2$$

Axial mode follows Proca

What about the polar mode?

Nonlinear effects in the relevant superradiant regime are large. A nonlinear analysis of the polar sector in a Kerr spacetime is necessary to investigate its spectrum and we are doing it at the moment.

Indeed the question is: does the instability really arise?

Non-linear correction of the effective mass

$$(\omega_p^{nl})^2 = \frac{4\pi e^2 n}{m_e\sqrt{1+\frac{e^2E^2}{m_e^2\omega^2}}}$$

Quenching Mechanism: Electrons are accelerated by electric field and become relativistic. The electric field acceleration prevails on the coherent oscillation, quenching the effective mass before the instability becomes efficient.

V. Cardoso, W. d. Guo, C. F. B. Macedo and P. Pani (2021)
E. Cannizzaro, **A.C**, L. Sberna, P. Pani (in preparation)

Conclusions

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- For photon superradiance Proca-like approach too naive.

Thanks for the attention!