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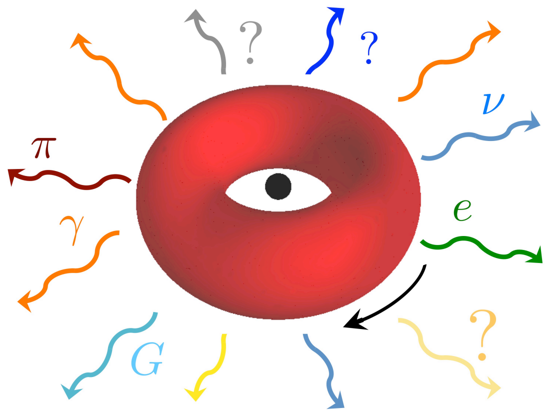
Primordial black hole superradiance



João G. Rosa

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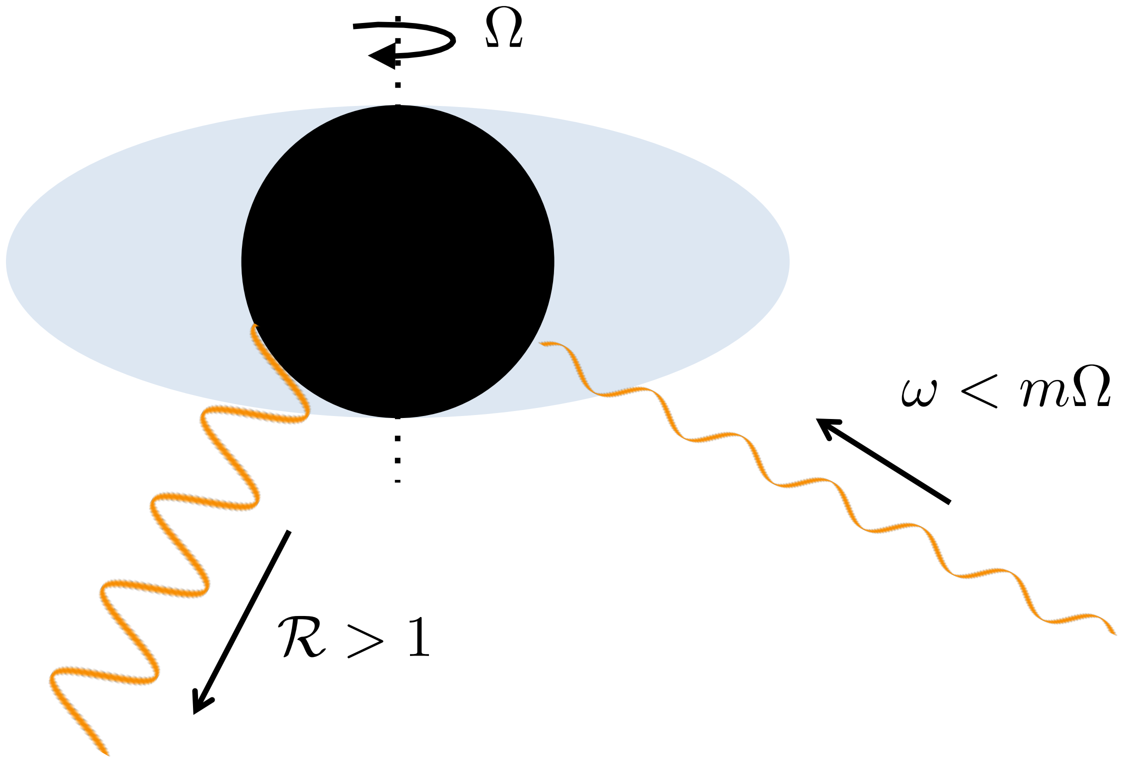
[+ N. Branco, M. Calzà, P. Ferraz, R. Z. Ferreira, T. Kephart, J. March-Russell & F. Serrano]

New Horizons in Primordial Black Hole physics, Naples 21 June 2023

Black hole superradiance

[Zeldovich (1966)]

Low frequency waves are amplified by scattering off a Kerr black hole:



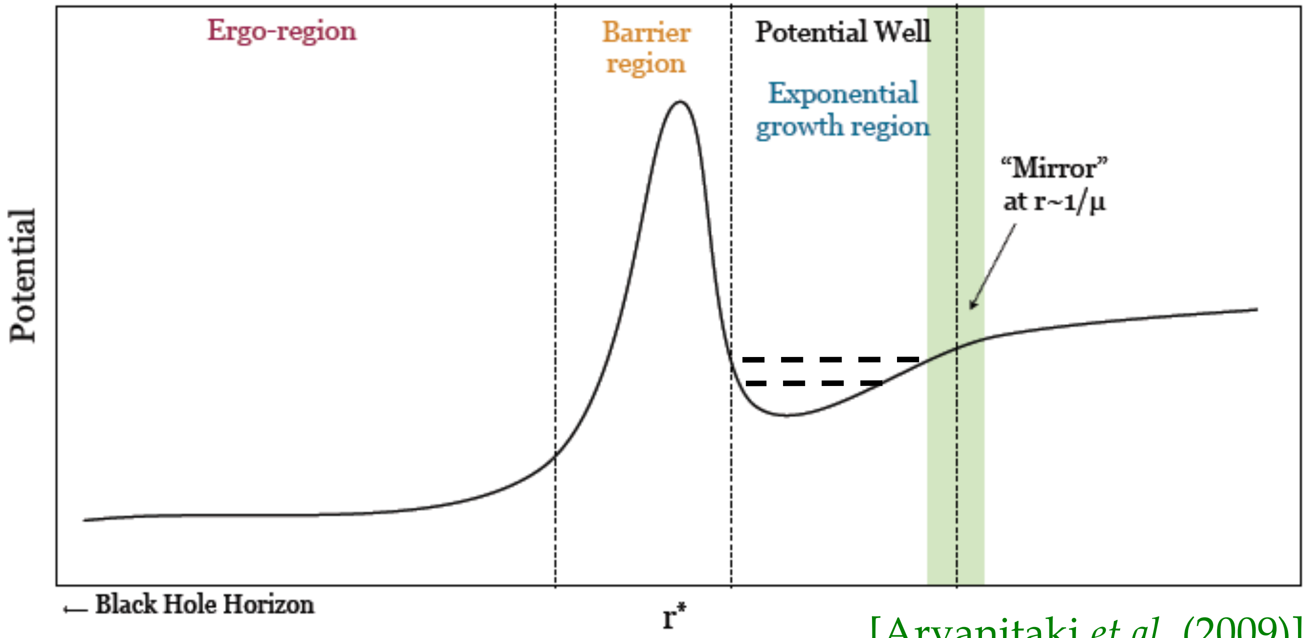
Superradiant instabilities

[Press & Teukolsky (1972); Cardoso, Dias & Lemos (2004)]

If we could surround a BH with a mirror, there would be multiple scatterings, leading to a superradiant instability!

Effective mirror:

massive boson fields confined in BH's gravitational potential



[Arvanitaki *et al.* (2009)]

Gravitational atoms

Hydrogen-like spectrum of quasi-bound states: (n, l, m)

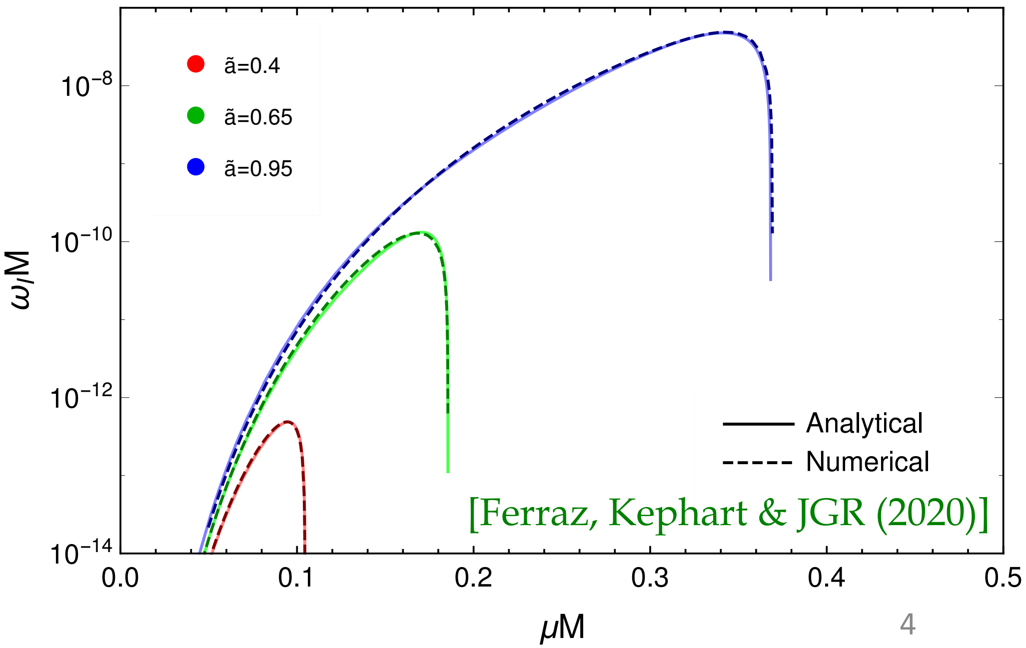
[Detweiler (1980); Furuhashi & Nambu (2004); Dolan (2007)]

$$\omega_n \simeq \mu - \frac{\alpha^2}{2n^2}\mu \qquad \Gamma = -C_{ln}(\omega_n - m\Omega)\alpha^{4l+5}\left(\frac{r_+ - r_-}{r_+ + r_-}\right)^{2l+1}$$

$$\alpha = \frac{\mu M}{M_P^2}$$

Exponential growth of particle number leads to formation of superradiant cloud

$n = 2, l = m = 1$

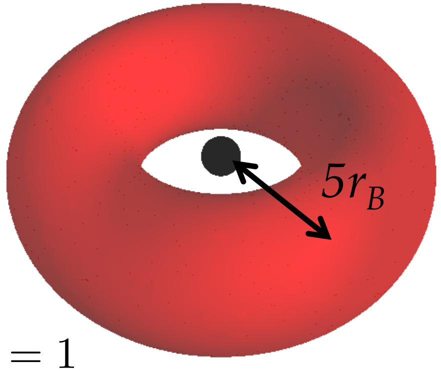


[Ferraz, Kephart & JGR (2020)]

[see review by Brito, Cardoso & Pani (2015)]

Superradiant clouds

Scalar clouds are toroidal:



$n = 2, l = m = 1$

$$r_B = \frac{1}{\alpha\mu} = \frac{r_S}{2\alpha^2} \gg r_S$$

$$\langle v^2 \rangle \simeq \frac{\alpha^2}{4} \ll 1$$

For spin-1 the fastest mode has *j=m=1, l=0,* and has spherical topology.

[JGR & Dolan (2011); Pani *et al.* (2012); East & Pretorius (2017); Cardoso *et al.* (2018); Frolov *et al.* (2018); Dolan (2018)]

$$\Gamma_s \simeq \begin{cases} \frac{1}{24}(\tilde{a} - 4\alpha)\alpha^8\mu\ , & s = 0 \\ 4(\tilde{a} - 4\alpha)\alpha^6\mu\ , & s = 1 \end{cases}$$

Mass and spin extraction from BH:

$$N_{SR} = \tilde{a}\left(\frac{\Delta J}{J}\right)\left(\frac{M}{M_P}\right)^2$$

PBH superradiance

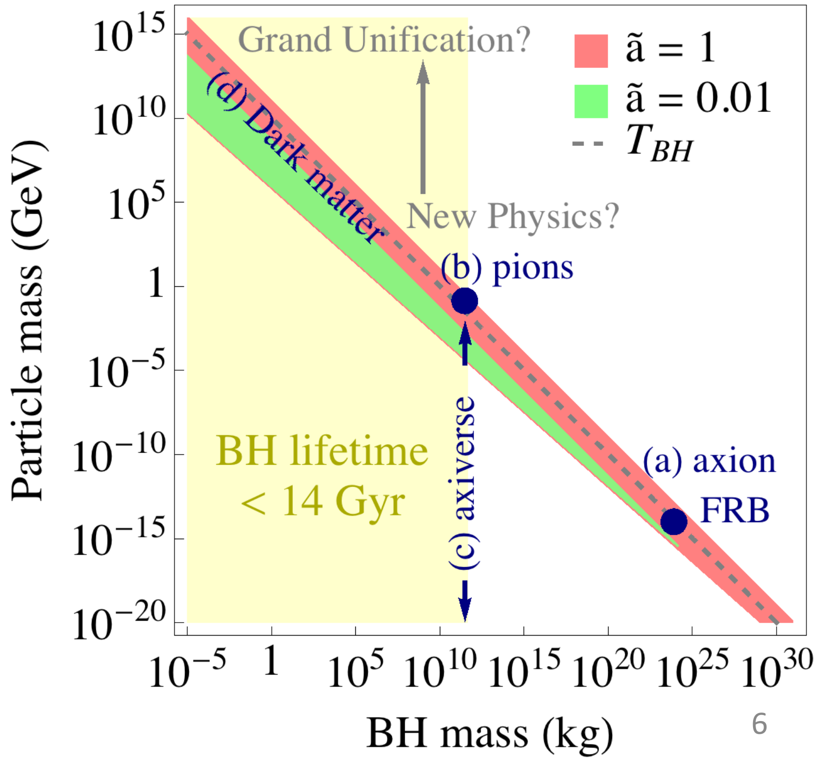
Why Primordial Black Holes?

- Born in early universe: superradiance on cosmological timescales
- Sub-solar masses: superradiance with heavy particles

$$\alpha = \frac{\mu M}{M_P^2} \simeq 0.4 \left(\frac{M}{10^{17}\ \text{kg}} \right) \left(\frac{\mu}{1\ \text{keV}} \right)$$

PBH superradiance [JGR+]:

- Pions [+Ferraz&Kephart (2022)]
- Dark matter [+March-Russell (2022)]
- Axions (μeV - GeV) [+Kephart (2018); +Branco & Ferreira (2023); +Calzà & Serrano (2023)]



Superradiant dark matter production

[March-Russell & JGR, arXiv:2205.15277]

PBH evaporation can produce all dark matter (DM)

[Khlopov, Barrau & Grain (2006); Fujita et al (2014); Allahverdi, Dent & Osinski (2018); Lennon *et al.* (2018); Hooper, Krnjaic & McDermott (2019); Hooper et al (2020); …]

Can PBH superradiance contribute to dark matter production as well?

[see also Bernal, Perez-Gonzalez & Xu (2022)]

- Bosonic dark matter (spin-0 & spin-1)
- PBHs evaporate before BBN ($M<10^6$ kg, never dominant)
- Coupled PBH evaporation + superradiance dynamics
- Fate of superradiant DM clouds?

Superradiant dark matter production

[March-Russell & JGR, arXiv:2205.15277]

Maximum number of DM particles in superradiant cloud:

$$N_{SR} \simeq 2.1 \times 10^{27} \tilde{a}_0 \left(\frac{\Delta J}{J_0}\right) \left(\frac{M_0}{10^6\mathrm{kg}}\right)^2 .$$

Number of DM particles emitted by Hawking evaporation:

$$N_{HE} \simeq \begin{cases} 3.2 \times 10^{26} \left(\frac{M_0}{10^6\mathrm{kg}}\right)^2 , & s = 0 \\ 5.3 \times 10^{25} \left(\frac{M_0}{10^6\mathrm{kg}}\right)^2 , & s = 1 \end{cases}$$

$$\frac{Y_{SR}}{Y_{HE}} = \epsilon_{SR} \frac{N_{SR}}{N_{HE}} \simeq \epsilon_{SR} \frac{\Delta J}{J_0} \times \begin{cases} \frac{\tilde{a}_0}{0.15} , & s = 0 \\ \frac{\tilde{a}_0}{0.025} , & s = 1 \end{cases}$$

Evaporation spins down the PBH and makes SR less efficient

Superradiant dark matter production

[March-Russell & JGR, arXiv:2205.15277]

Dynamics of superradiance + evaporation:

$$\frac{dM}{dt} = -e_T \frac{M_P^4}{M^2} - \mu \Gamma_s N, \qquad \frac{dJ}{dt} = -e_J \frac{J M_P^4}{M^3} - \Gamma_s N \;, \qquad \frac{dN}{dt} = \Gamma_s N$$

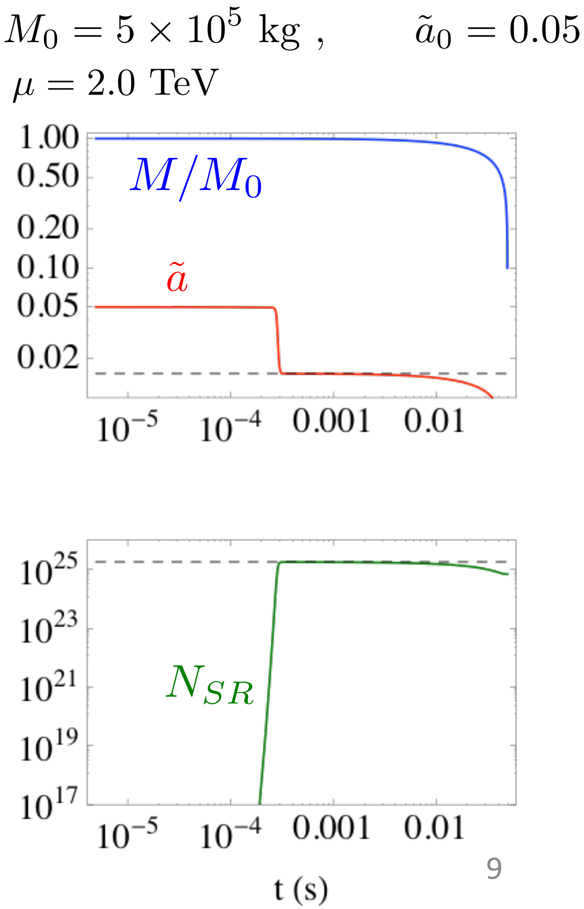
Efficient build-up of superradiant DM cloud:

$$\Gamma_s t_{ev} \gtrsim (e_J/e_T - 2) \ln N_{SR} \sim \text{few} \times 100$$

Superradiant DM cloud re-absorption (quasi-stationary regime):

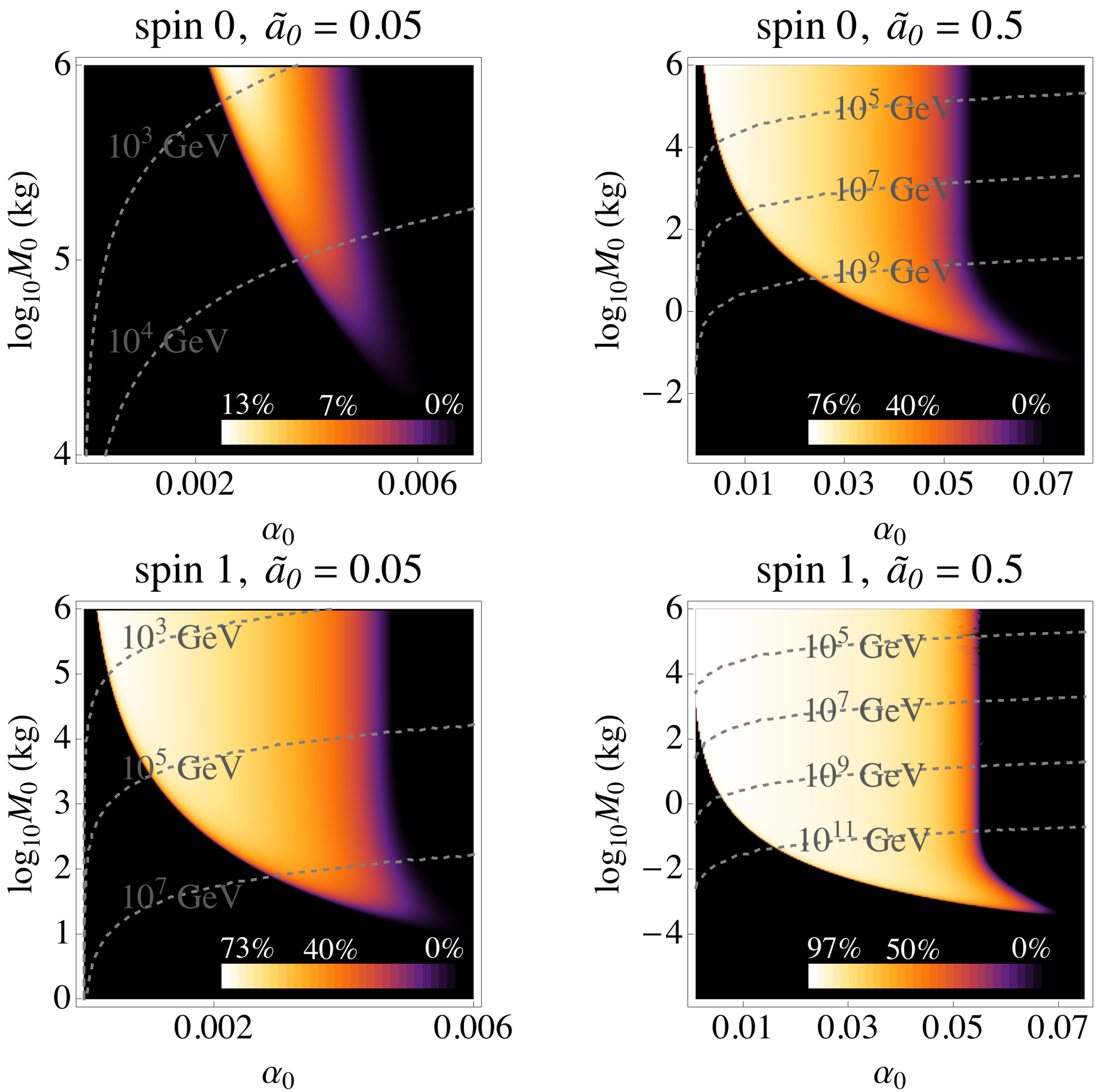
$$\frac{d\tilde{a}}{dt} = \tilde{a}(-eJ + 2e_T)\frac{M_P^4}{M^3} - \Gamma_s N \frac{M_P^2}{M^2}(1 - 2\tilde{a}\alpha) \simeq 0$$

<0 (non-SR)



Superradiant dark matter production

[March-Russell & JGR, arXiv:2205.15277]



Superradiant dark matter production

[March-Russell & JGR, arXiv:2205.15277]

DM cloud starts expanding adiabatically as PBH evaporates: $r_c \simeq \frac{5}{\mu\alpha}$

Evaporation becomes non-adiabatic at ("quantum quench"):

$$\frac{M_*}{M_c} \simeq \frac{0.44}{\epsilon_{SR}} \left(\frac{\Delta J}{J_0}\right)^{-1} \left(\frac{0.003}{\alpha}\right)^{8/5} \left(\frac{0.05}{\tilde{a}_0}\right) \left(\frac{10^6\ \mathrm{kg}}{M_0}\right)^{2/5}$$

DM cloud may become self-gravitating: DM micro-boson star!

$$R_{BS} \simeq \frac{5.5}{\epsilon_{SR} f_{BS}} \left(\frac{0.003}{\alpha}\right)^3 \left(\frac{0.05}{\tilde{a}_0}\right) \left(\frac{M_0}{10^6\ \mathrm{kg}}\right) \left(\frac{\Delta J_0}{J_0}\right)^{-1} \mathrm{pm}$$

$$M_{BS} \simeq 150 \epsilon_{SR} f_{BS} \left(\frac{\alpha}{0.003}\right) \left(\frac{\tilde{a}_0}{0.05}\right) \left(\frac{M_0}{10^6\ \mathrm{kg}}\right) \left(\frac{\Delta J}{J_0}\right) \mathrm{kg}$$

DM micro-boson stars are rare but have potentially spectacular signatures
(e.g. coherent scattering off nuclei [Hardy *et al.* (2015)])

$$\Phi \simeq 5 \times 10^{-4} f_{SR} f_{BS} \left(10\ \mathrm{kg}/M_{BS}\right)\ \mathrm{km}^{-2}\mathrm{yr}^{-1}$$

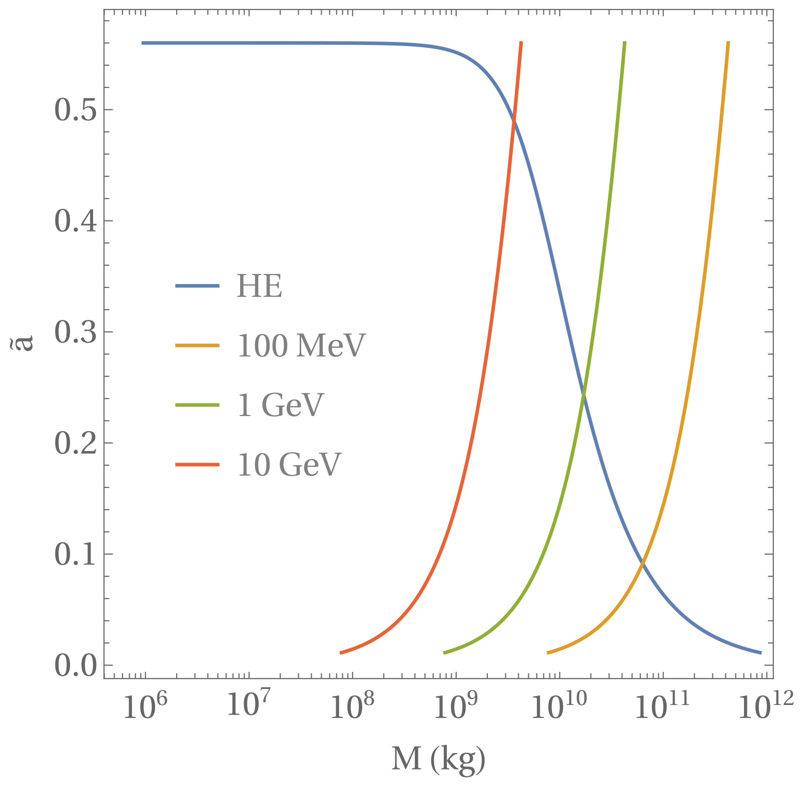
PBH superradiance in the string axiverse

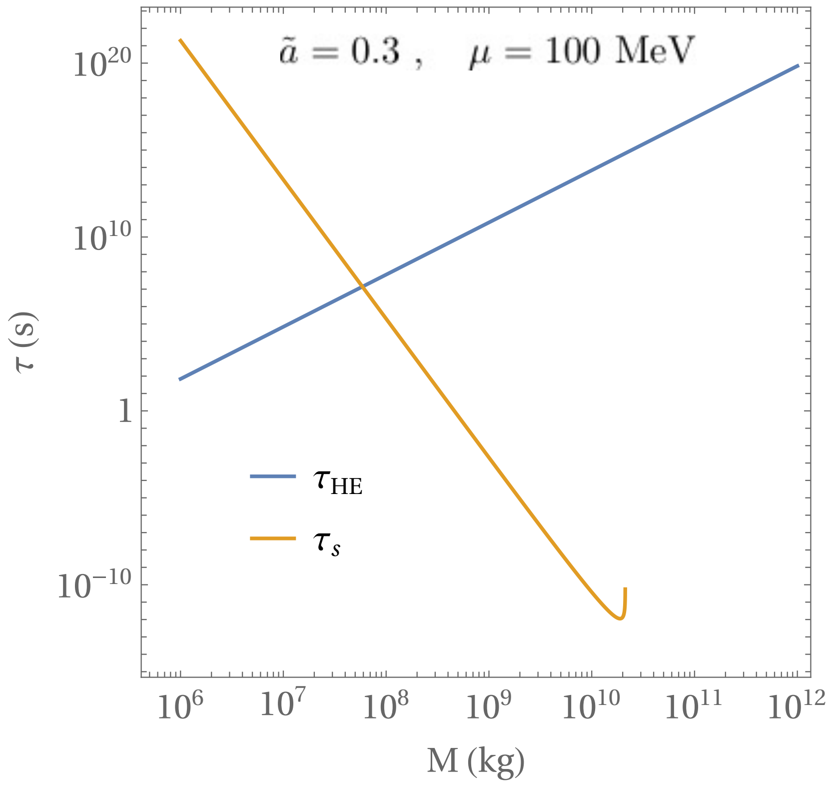
[Calzà, JGR & Serrano, arXiv:2306.XXXXX]

PBHs spin up if they emit N_a>O(100) light axions (sub-MeV).
[Calzà, March-Russell & JGR (2021)]

Marco Calzà's talk

Can this trigger superradiant instabilities (with a heavy axion >MeV)?





PBH superradiance in the string axiverse

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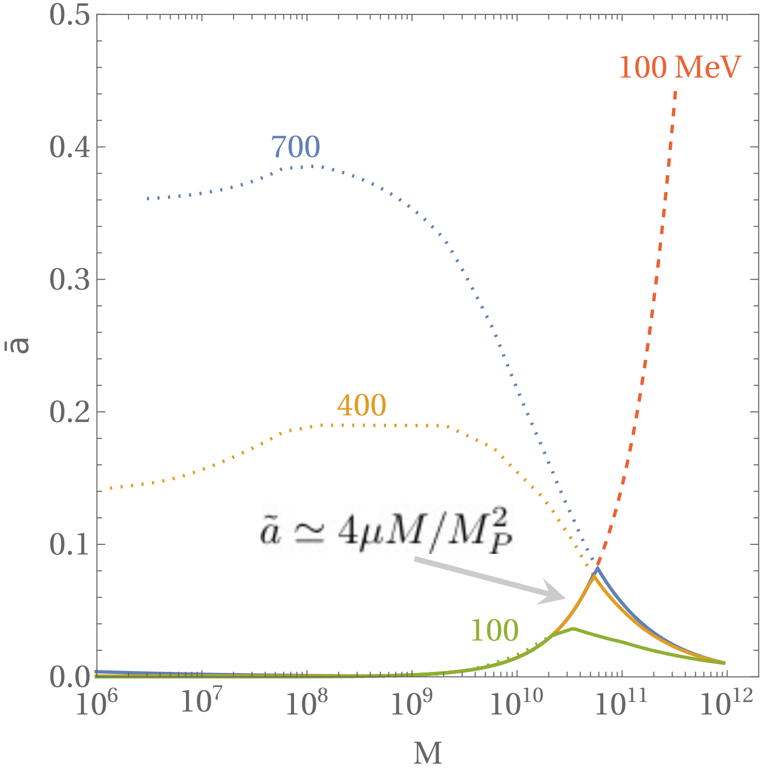
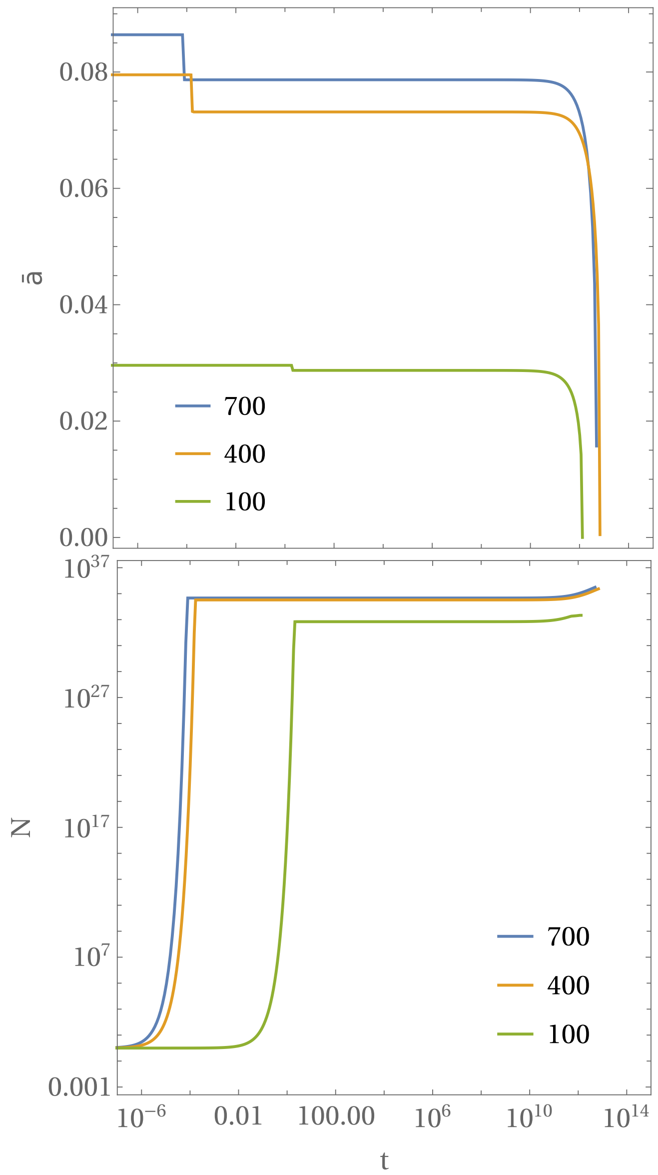


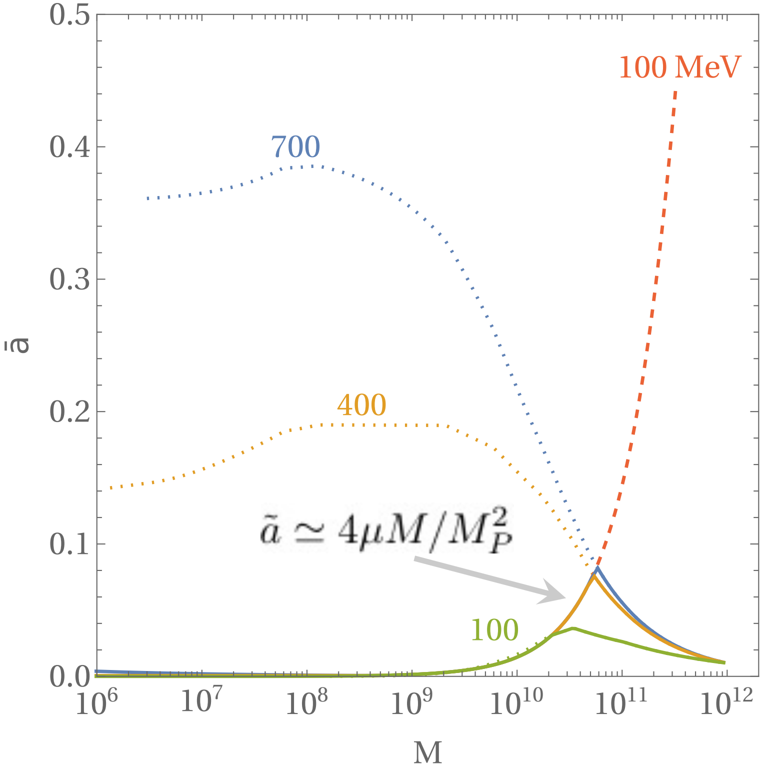


Peak in PBH mass-spin distribution depends on:

- number of light axions (HE)
- heavy axion mass (SR)

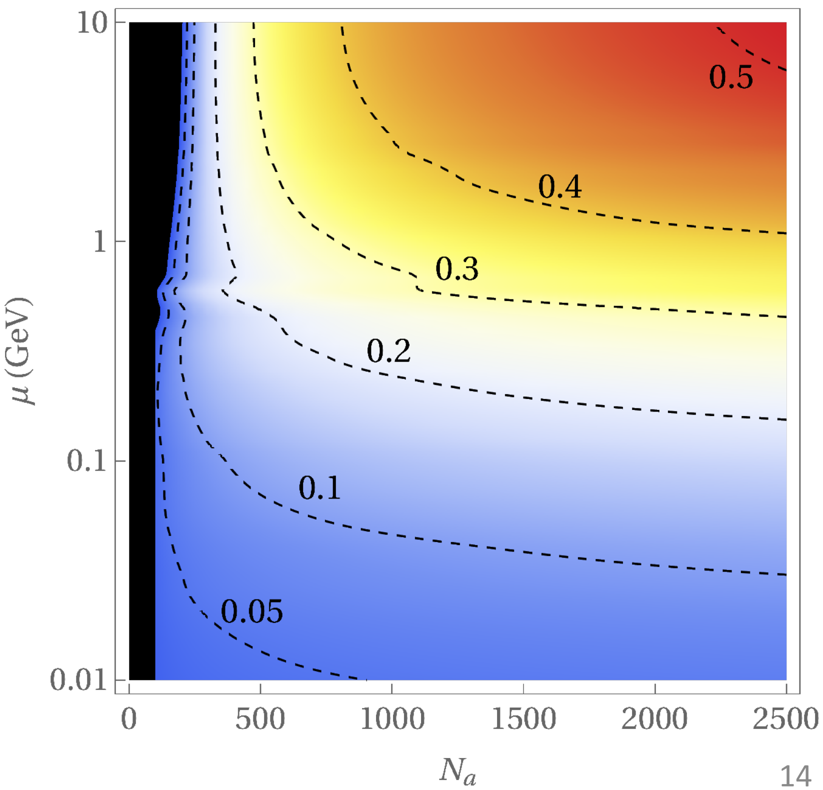
PBH superradiance in the string axiverse

[Calzà, JGR & Serrano, arXiv:2306.XXXXX]



Peaked mass-spin PBH distribution depending on:

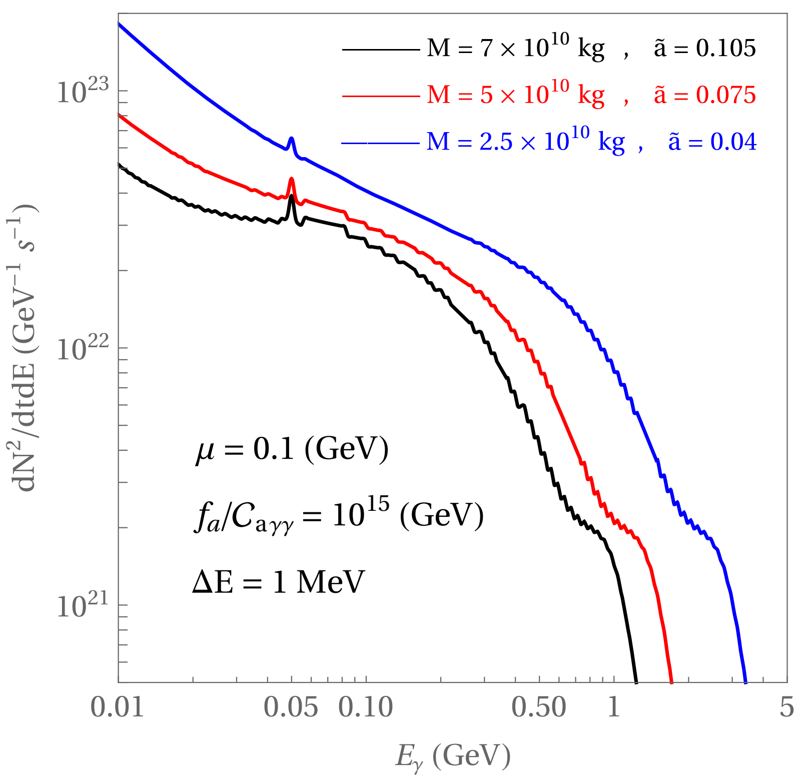
- number of light axions (HE)
- heavy axion mass (SR)

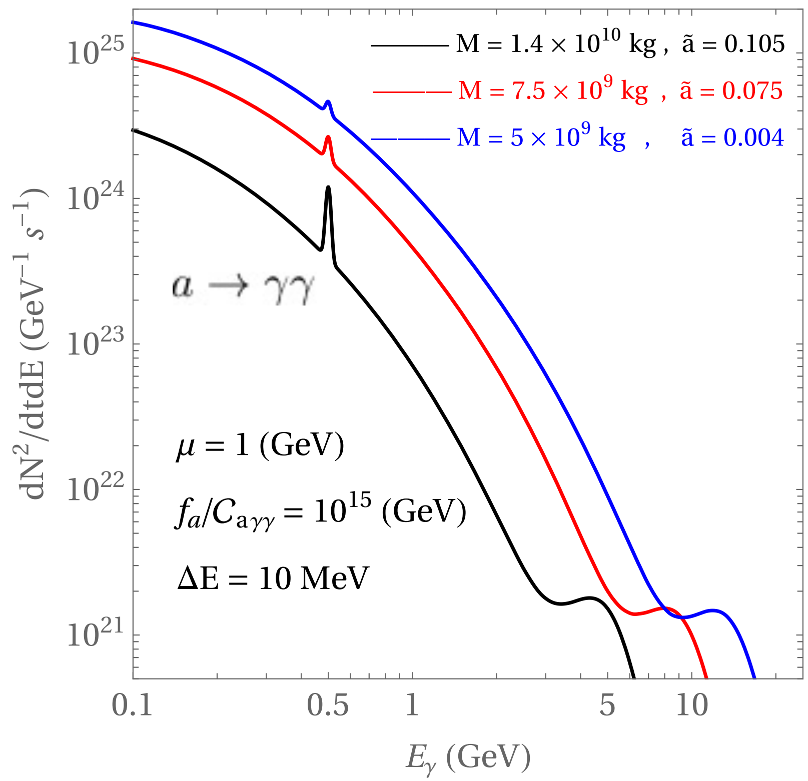


PBH superradiance in the string axiverse

[Calzà, JGR & Serrano, arXiv:2306.XXXXX]

PBH + SR axion cloud have unique photon spectrum:





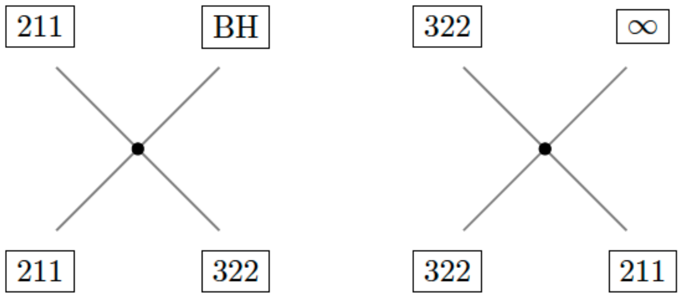
Superradiant clouds may also survive as axion stars after PBHs evaporate
(live for a PBH near you!)

PBH dark matter + superradiant axion clouds

[Branco, Ferreira & JGR, arXiv:2301.01780]

If all DM is made of asteroid-mass PBHs (10^{14} - 10^{18} kg), these can grow axion clouds!

Include dynamical effects of axion self-interactions [Baryakhtar *et al.* (2021)]



$$\lambda = \frac{\mu^2}{f_a^2}$$

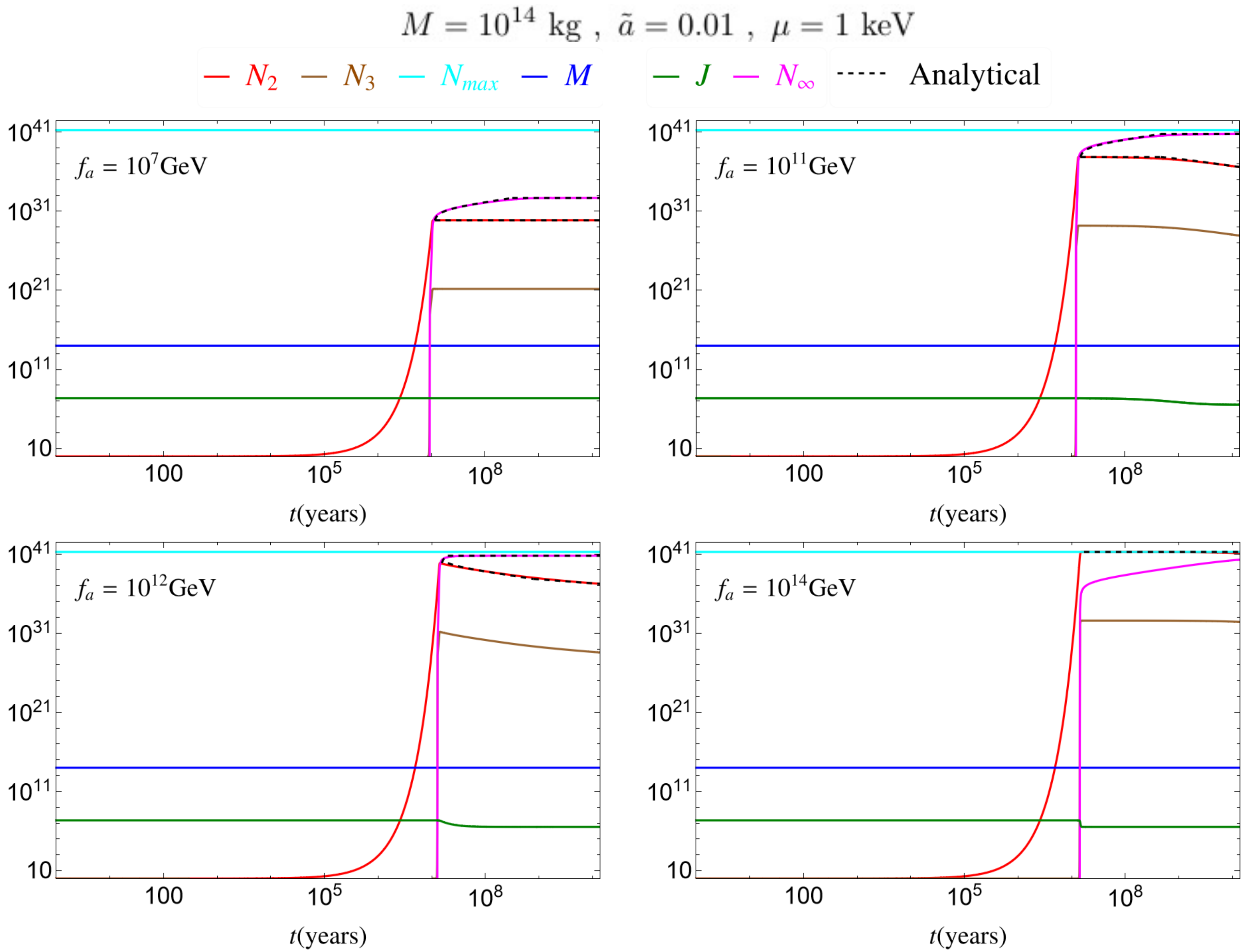
$$\begin{aligned}\frac{dN_2}{dt} &= N_2\left[\Gamma_2 - \Gamma_{a\gamma\gamma} + N_3\left(\Gamma_\mathrm{R} N_3 - 2\Gamma_\mathrm{D} N_2\right)\right] \\ \frac{dN_3}{dt} &= N_3\left[\Gamma_3 - \Gamma_{a\gamma\gamma} + N_2\left(\Gamma_\mathrm{D} N_2 - 2\Gamma_\mathrm{R} N_3\right)\right]\end{aligned}$$

$$\frac{dN_\infty}{dt} = \Gamma_\mathrm{R} N_3^2 N_2 - \Gamma_{a\gamma\gamma} N_\infty$$

$$\frac{dM}{dt} = -\mu\left(\Gamma_2 N_2 + \Gamma_3 N_3 - \Gamma_\mathrm{D} N_2^2 N_3\right) \qquad \frac{dJ}{dt} = -\left(\Gamma_2 N_2 + 2\Gamma_3 N_3\right).$$

PBH dark matter + superradiant axion clouds

[Branco, Ferreira & JGR, arXiv:2301.01780]

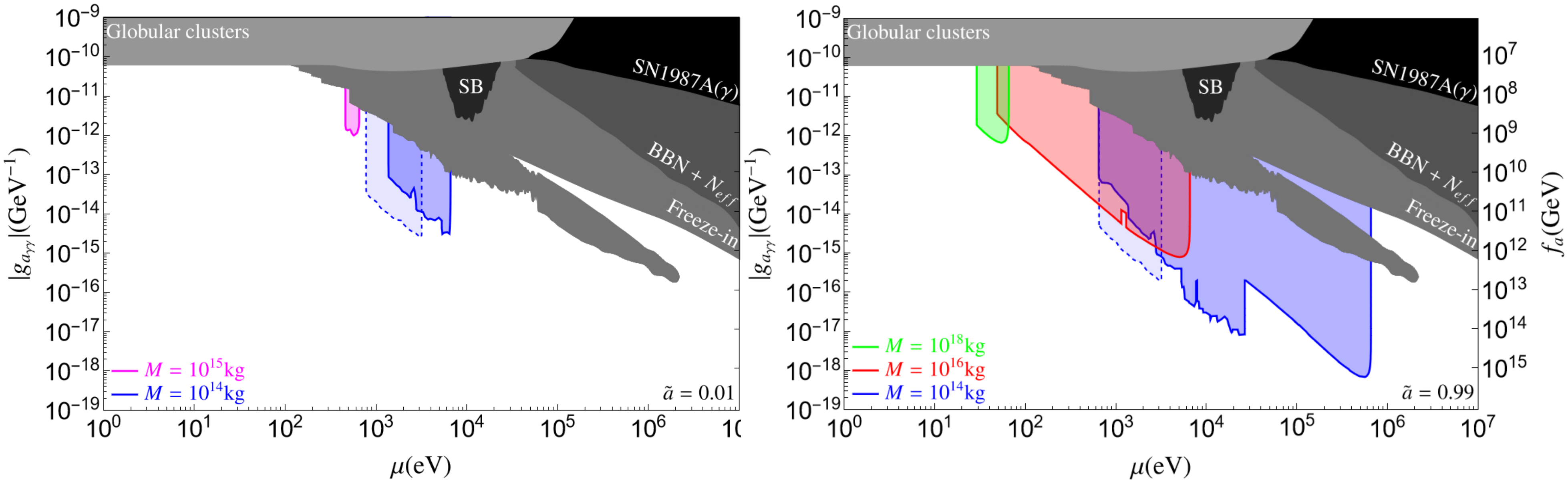


PBH dark matter + superradiant axion clouds

[Branco, Ferreira & JGR, arXiv:2301.01780]

Ionized axions can be non-relativistic and bound to host galaxy or else travel in intergalactic medium.

Axion decay into photons contributes to galactic and extra-galactic EM flux!



$\tilde{a} = 0.01$ $\tilde{a} = 0.99$

Summary

- PBH superradiance can have a significant impact in cosmology and high-energy physics
- Can produce both known particles and new exotic particles
- PBH superradiance relevant for $\tilde{a} \gtrsim 0.01$
- Interesting interplay between Hawking emission and superradiance
- Potential observational impact (multi-messenger?)

Thank you!