Axion Weak Leaks: Dark matter driven inspirals

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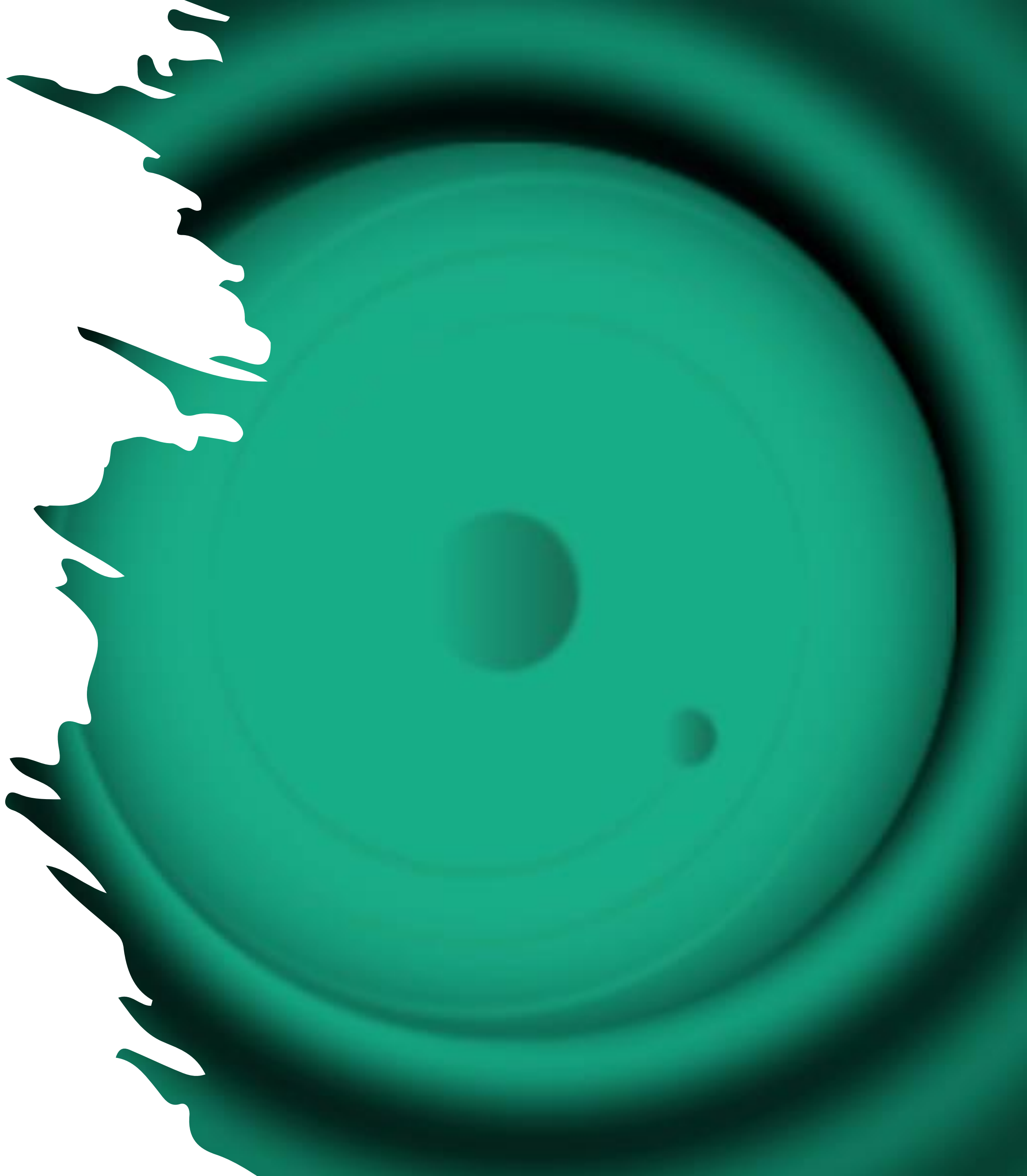
Outline

- **Axions, the string axiverse and black holes**
- **What happens to BHs and their motion?**
- **BH+Fields and Einstein's field equations**
- **Axion weak leaks. The imprints on binaries**
- **Final remarks**



Axions and the string axiverse

(Arvanitaki *et al.* 2009, Ferreira 2021)

- Axions arise as a possible solution for the Strong CP problem in the SM.

- As a consequence we have a ultralight (pseudoscalars) with mass

$$m_a \approx 6 \times 10^{-10} \left(\frac{10^{16}\mathrm{GeV}}{f_a}\right) \mathrm{eV}.$$

- From **KK mechanisms** from string theory, we also expect ultralight bosons down to Hubble scale $\approx 10^{-33}\mathrm{eV}$.

- These particles are good candidates for ***dark matter***.

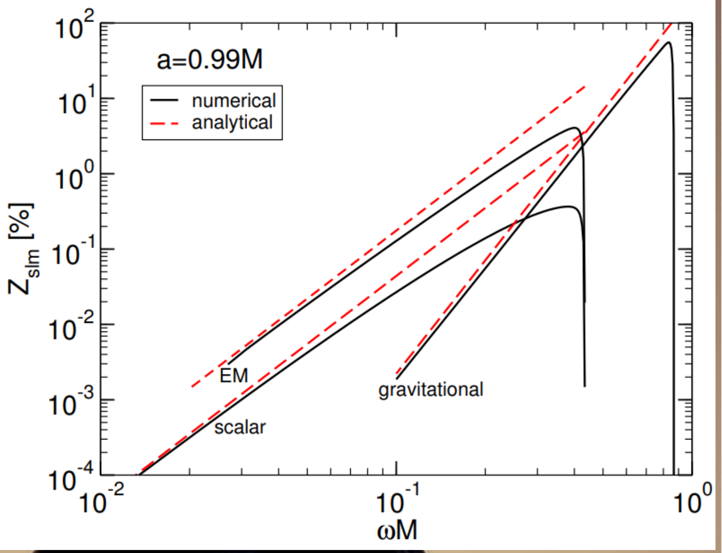
Why is that important for BHs?

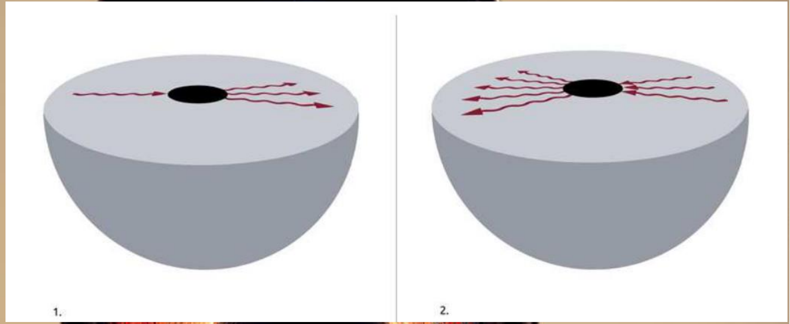
(Teukolsky&Press 1974, Brito, Cardoso & Pani 2020)

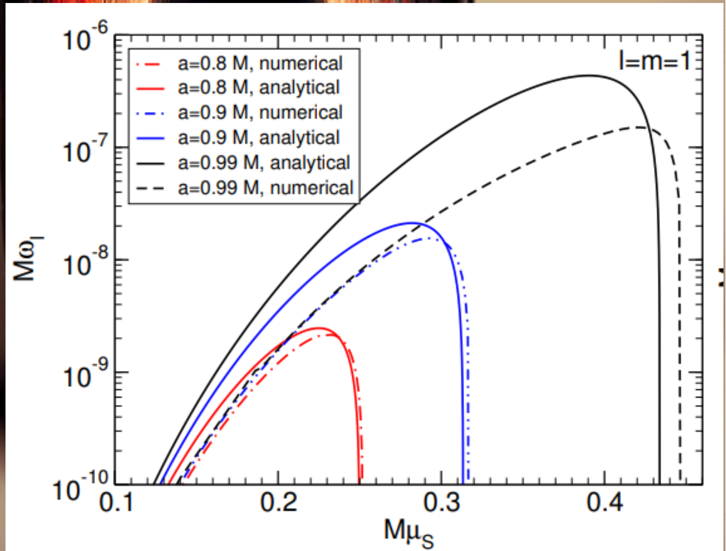
- Rotating BHs and **superradiance**.
- A BH in a bottle: **BH bomb**.
- The natural confinement: **massive fields**.
- A rule of thumb: $r_h \sim \lambda_c$, which leads to

$$m_b \sim 5.6 \times 10^{-11} \left(\frac{M_\odot}{M}\right) \text{eV}.$$

No SM particle has that!

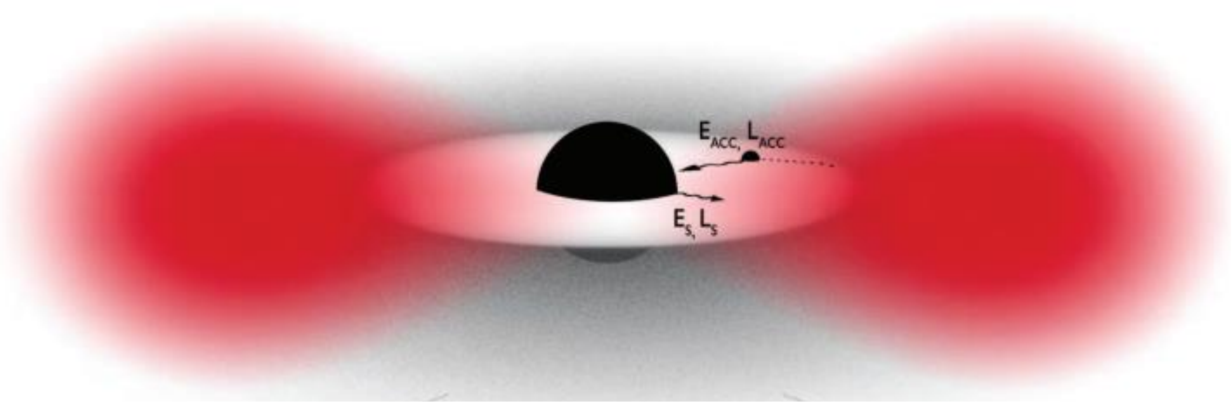


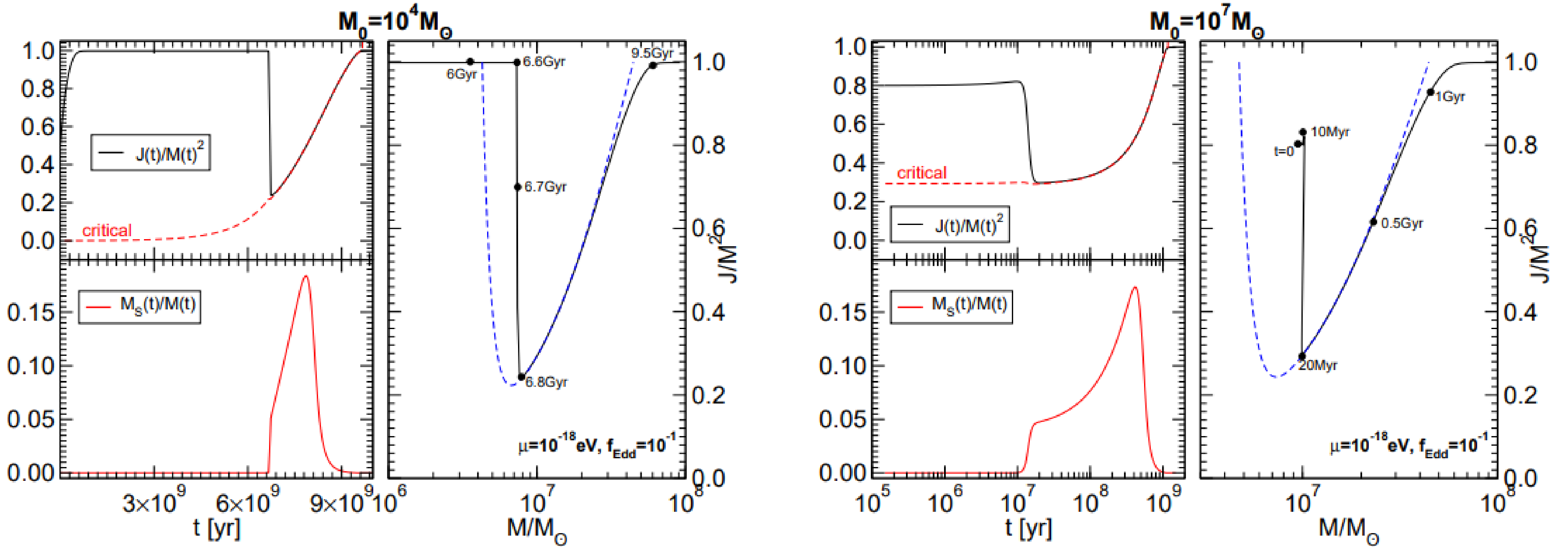




Black holes and revelations (of axions)

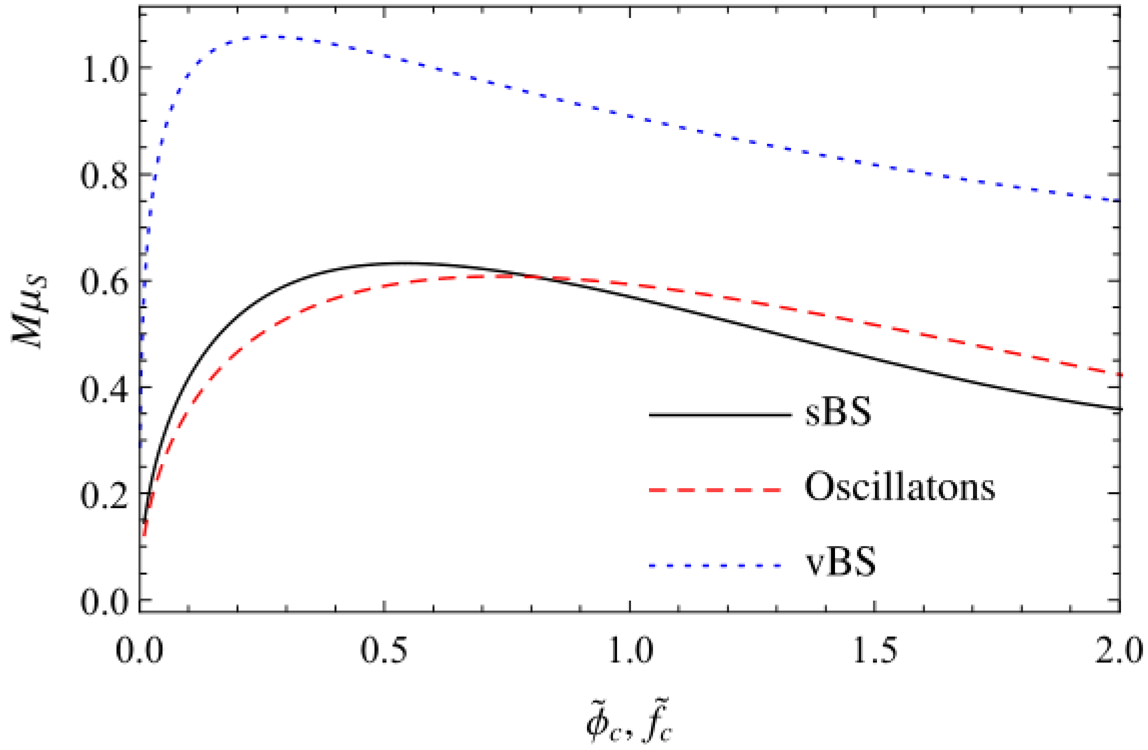
(Brito, Cardoso & Pani 2014, Arvanitaki, Baryakhtar and Baryakhtar 2015, East 2018,...)

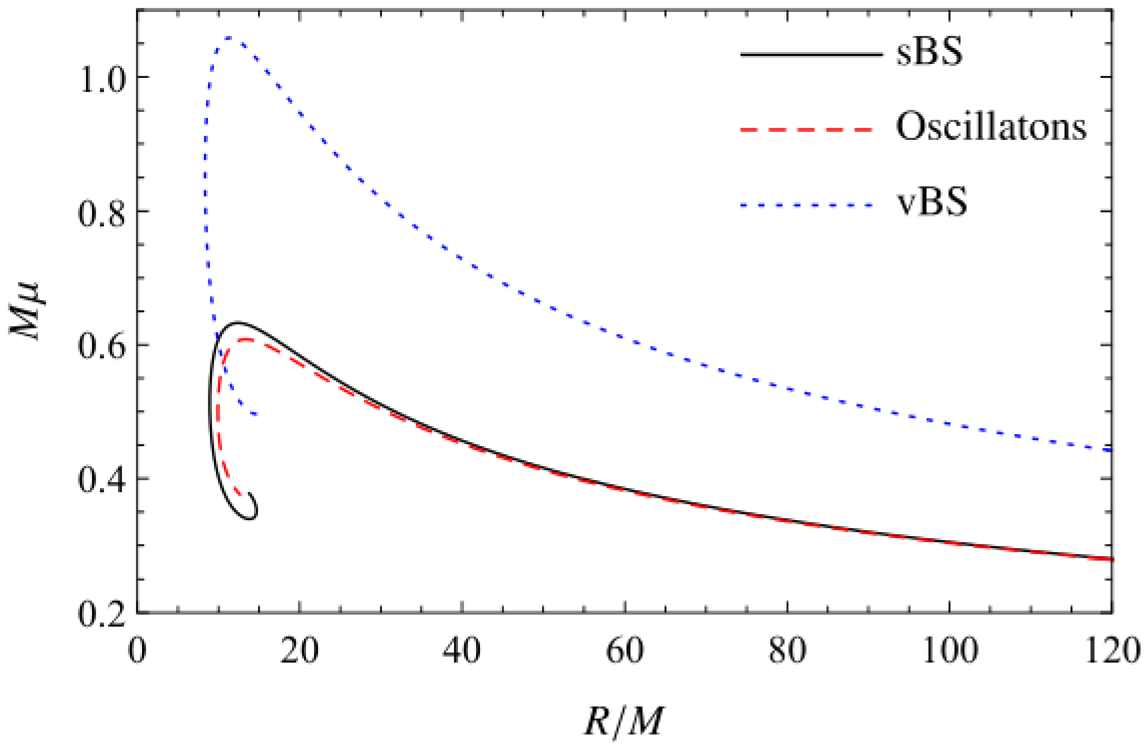




Condensation of axions: Boson stars

(Palenzuela 2023 for a review, ...)





We have a lot of BS in the Symposium. ☺

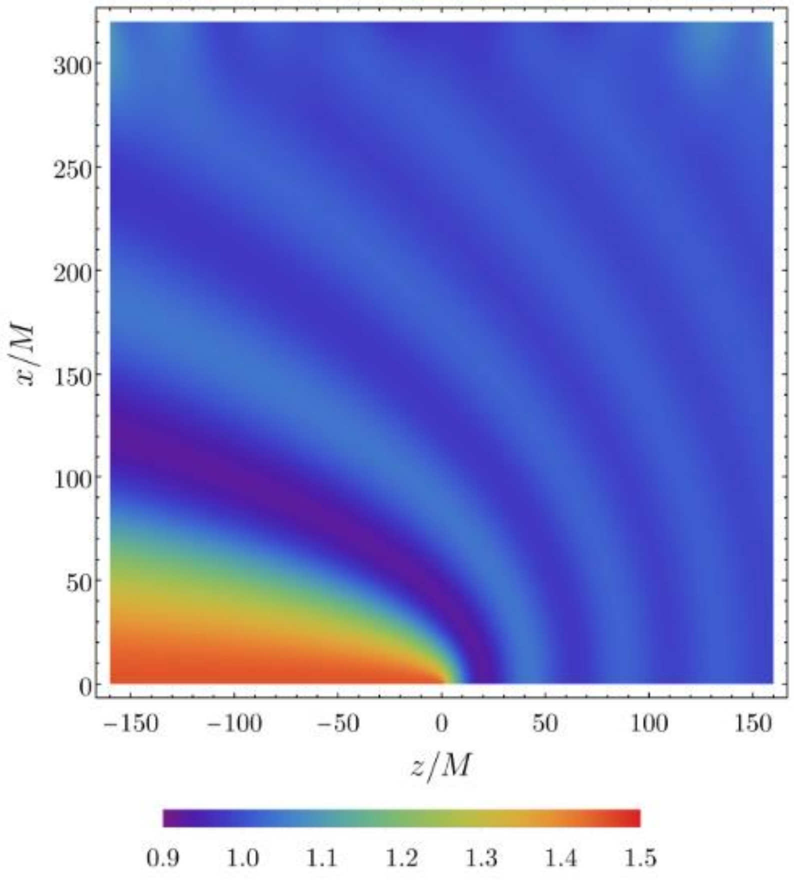
What to expect when moving through

Traykova *et al.* 2021, Vicente and Cardoso 2022, Traykova *et al.* 2023

$$\dot{E}_{\rm BH} = \frac{\pi\hbar\omega n}{\mu k_\infty}\sum_{\ell,m}(2\ell+1)\frac{(\ell-m)!}{(\ell+m)!}({\rm Ps}_\ell^m)^2\left(1-\left|\frac{R}{I}\right|^2\right).$$

$$P_S^i(t') = \int_{S_{t'}} dV_3 T^{\alpha i} N_\alpha.$$

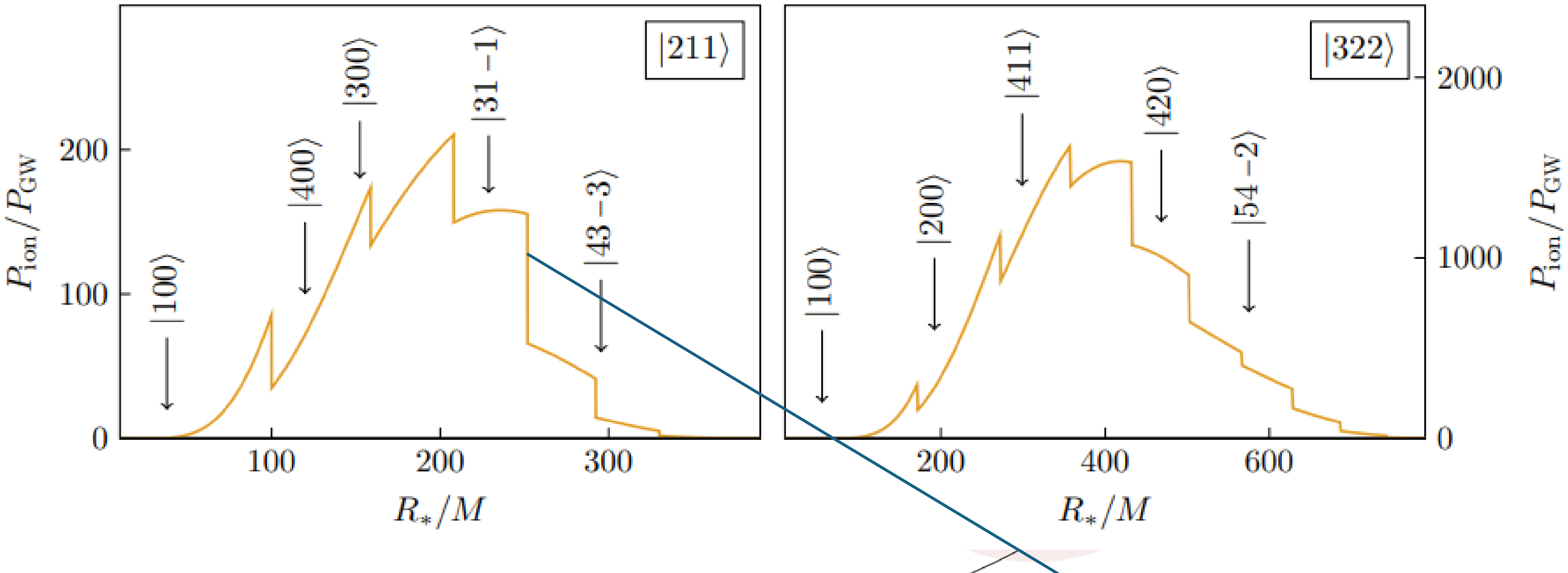
$$\boldsymbol{F}' = -\frac{4\pi M^2\rho\boldsymbol{v}}{v^3}\log\left(\sqrt{1+\frac{b_{\rm max}^2}{(M/v^2)^2}}\right)$$



Note that the Chandrasekhar case is recovered

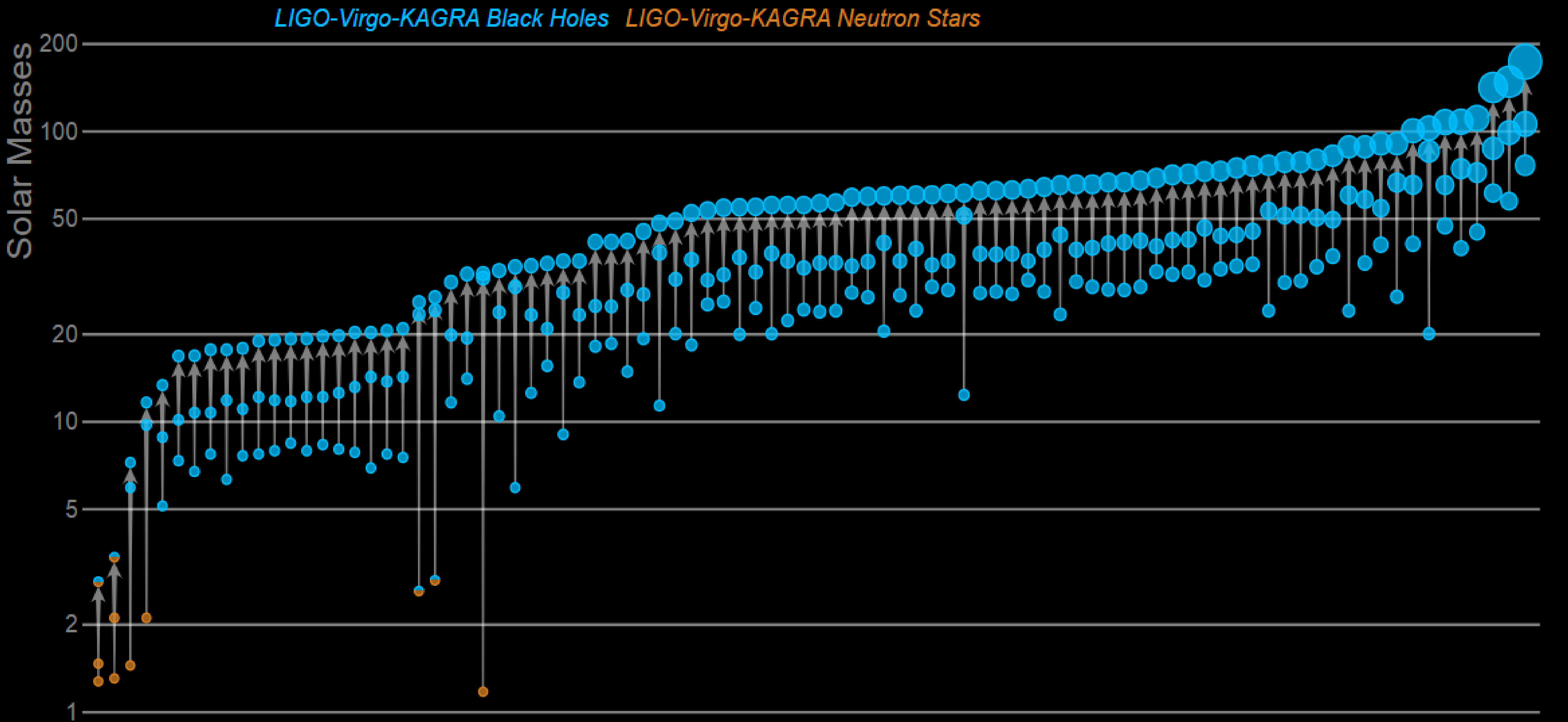
What to expect when binaries move through

Baumann, Chia, and Porto 2019, Berti et al. 2019, Tomaselli et al. 2024, Bošković et al. 2024,…



It is leaking!

Masses in the Stellar Graveyard



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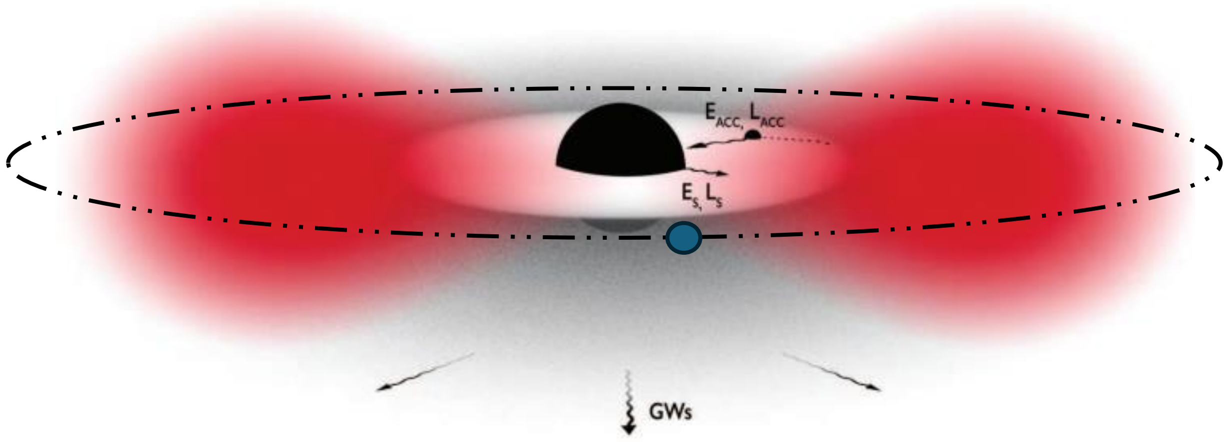
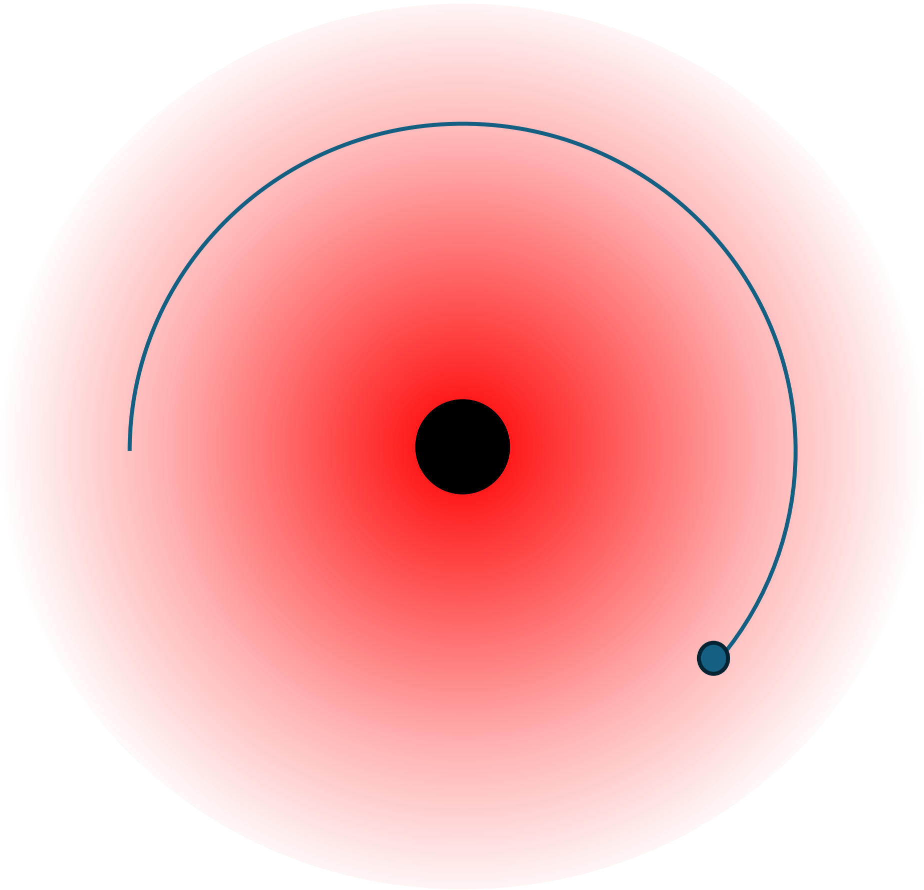
What do we aim to solve: Axion weak leaks



Black hole + cloud with a companion



Parasitic BH in a BS with a companion

Einstein's field equations

$$G_{\mu\nu} = 8\pi T_{\mu\nu}, \qquad \Box_g \Phi = \frac{\partial V}{\partial \Phi^*}$$

$$T_{\mu\nu} \equiv T^{\Phi}_{\mu\nu} + T^{\mathrm{m}}_{\mu\nu}$$

$$\mathrm{d}\hat{s}^2 \equiv \hat{g}_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu \approx -A(r)\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{B(r)} + r^2\mathrm{d}\Omega^2,$$

$$\hat{\Phi} \approx \phi_0(r)e^{-i\omega t}$$

$$g_{\mu\nu} \approx \hat{g}_{\mu\nu} + q\,\delta g_{\mu\nu}, \qquad \Phi \approx \hat{\Phi} + q\,\delta\Phi$$

Waves, disturbances,...

For details, see *Duque, Macedo, Vicente, and Cardoso (2024)* 2312.06767v2

For the background

BH+Clouds

- Background metric is Schwarzschild

$$A = B = 1 - \frac{2M}{r}.$$

- The field around the background is the spherical ground state:

$$\phi_0 \approx C e^{-M\mu^2 r} e^{-2i\mu M \log\left(1 - \frac{2M}{r}\right)}.$$

BH+BS

- We take a PN approach to compute the metric potentials and the field from a known configuration

$$A = \left(1 - \frac{2M_{\rm BH}}{r}\right) e^{2U(r)},$$

$$\phi_0 = \left(1 - \frac{2M_{\rm BH}}{r}\right)^{-2i\mu M_{\rm BH}} \tilde{\phi}_0(r),$$

$$m(r) = M_{\rm BH} + 4\pi\mu^2 \int_{r_i}^{r} dr' r'^2 \left|\phi_0(r')\right|^2$$

In some regimes, the results are consistente with a superposition.

Computing the fluxes

Energy flux

$$\dot{E}^S_L = -\sigma_L \lim_{r\to r_L} r^2 \sqrt{AB} \int \mathrm{d}\Omega\, T^S_{tr}$$

Noether flux

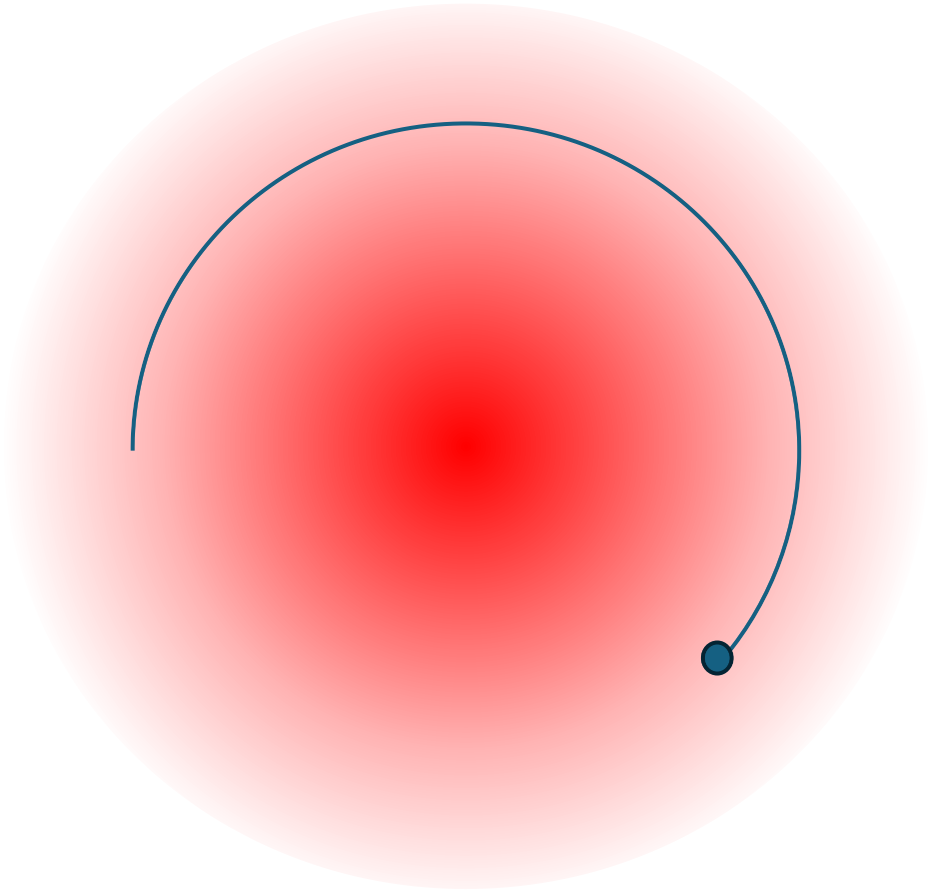
$$\dot{Q}_L = \sigma_L \lim_{r\to r_L} r^2 \sqrt{\frac{A}{B}} \int \mathrm{d}\Omega\, J^r_Q$$

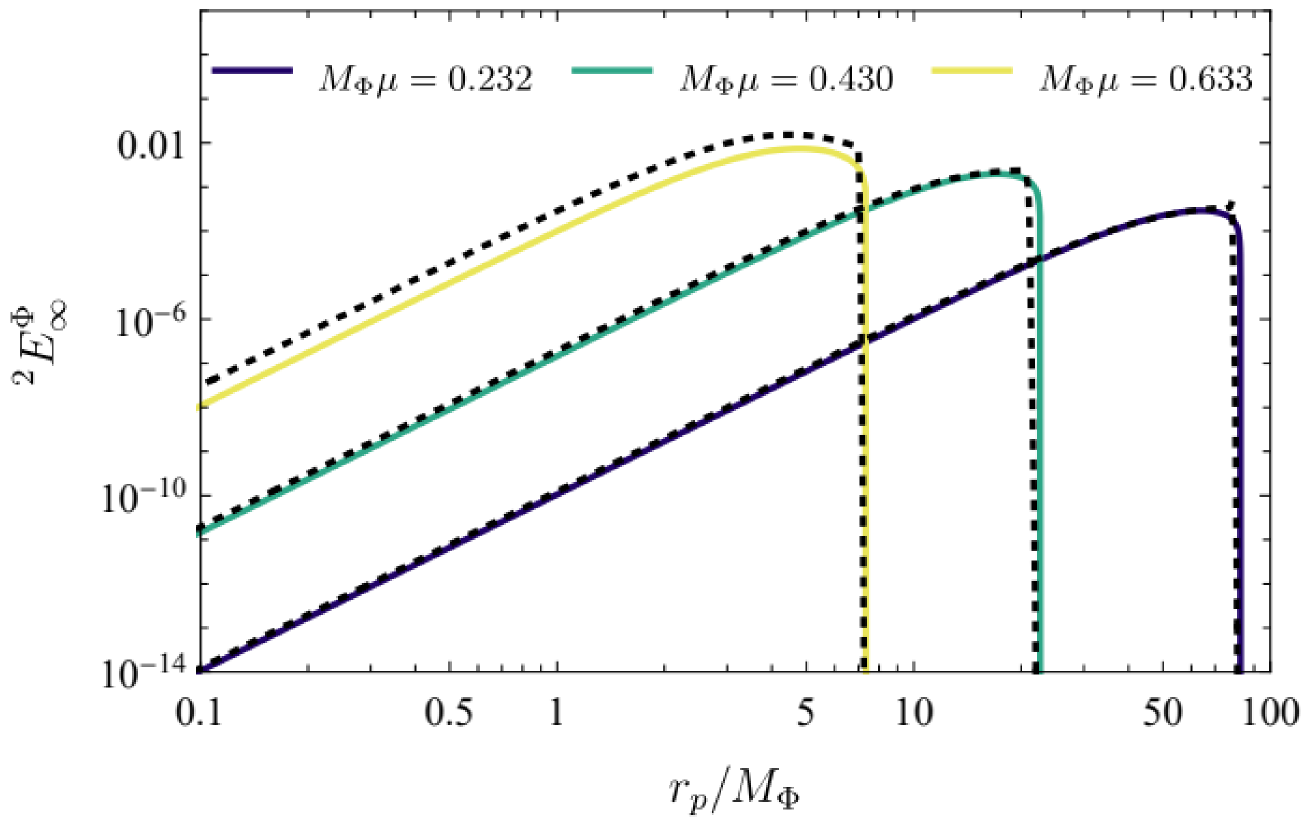
S stands for Φ or g.

The rate of change in the orbital energy is

$$^\ell\dot{\varepsilon}^{\,\Phi}_{\mathrm{p,L}} \approx -\frac{^\ell\dot{E}^\Phi_L - {}^\ell\dot{Q}_L\omega}{m_p}, \quad {}^\ell\dot{\varepsilon}^{\,g}_{\mathrm{p,L}} = -\frac{^\ell\dot{E}^g_L}{m_p}.$$

Let's test first with a supermassive BS

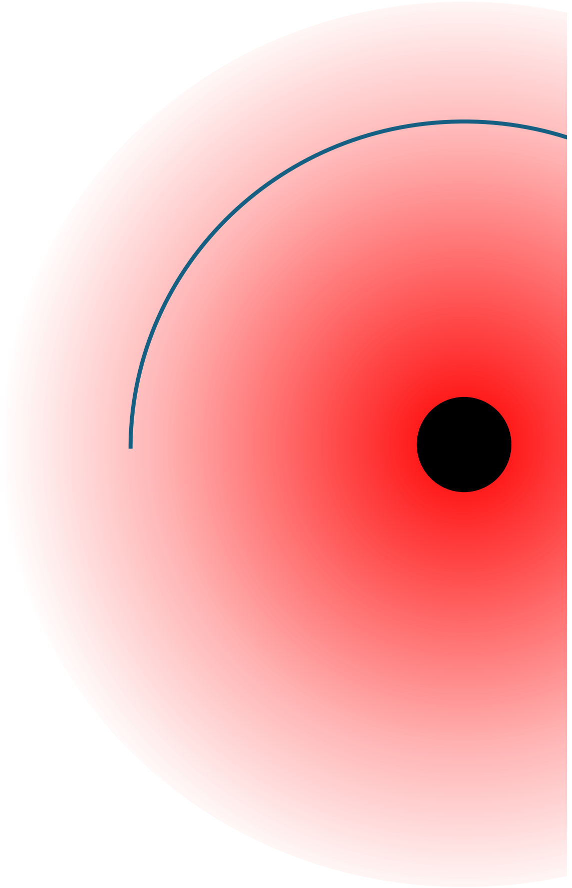


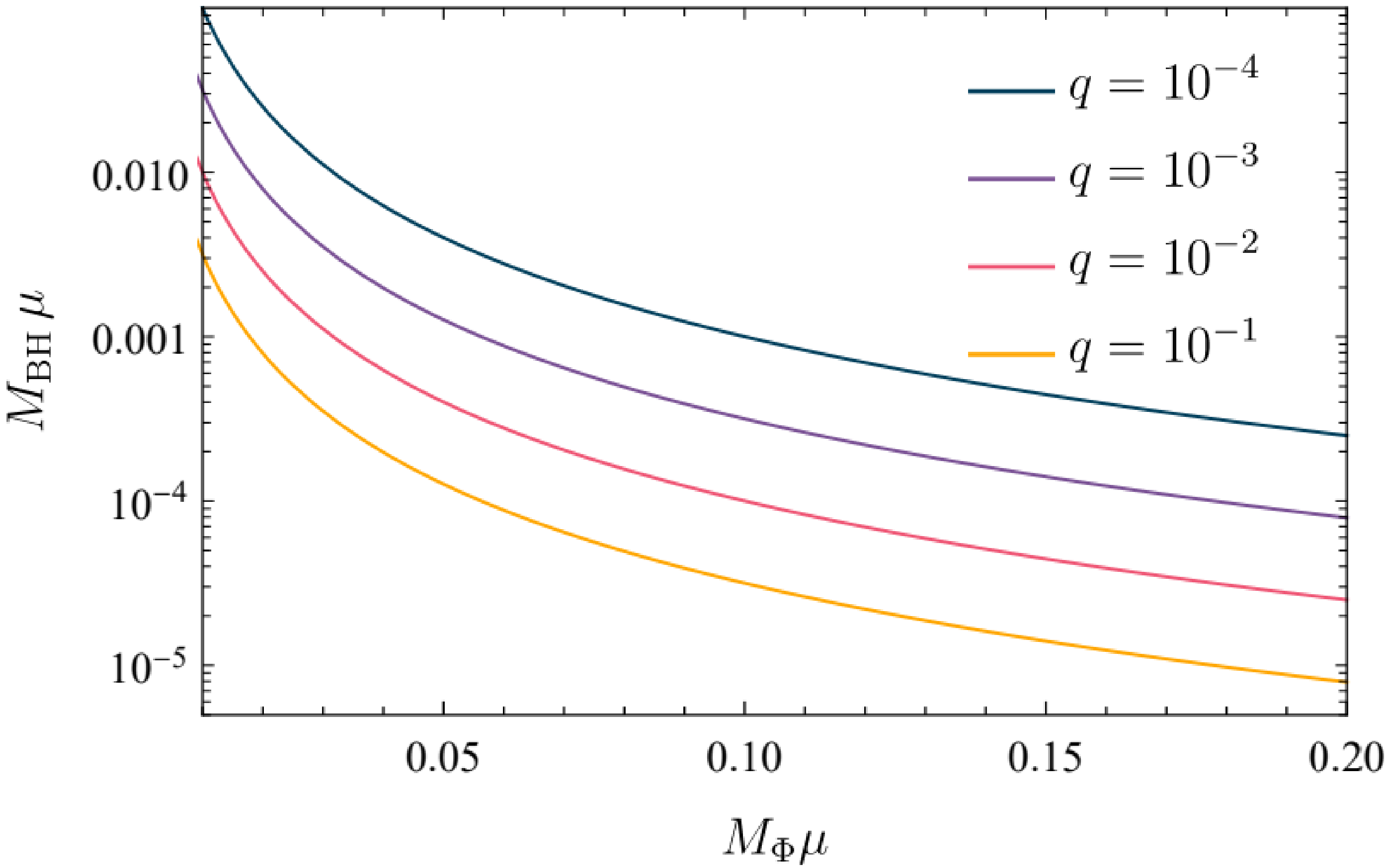


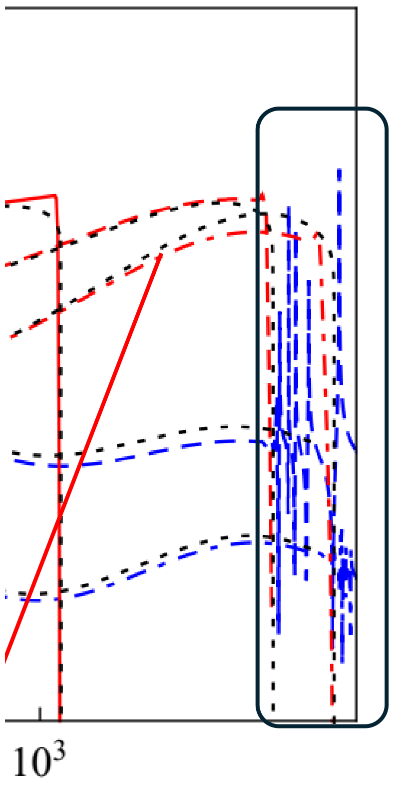
Consistent with an analytical description of the configuration.

$$\phi_+(r \to \infty) \approx -\frac{8\pi^{\frac{3}{2}} m_p\, \phi_0(r_p) m^{\frac{m}{2}-1} Y_m^m\left(\frac{\pi}{2}, 0\right) (r_p\Omega)^m}{2^{\frac{m}{2}+2} (\Omega/\mu)^{\frac{m}{2}+1} \Gamma\left(m + \frac{3}{2}\right)}.$$

Parasitic black holes





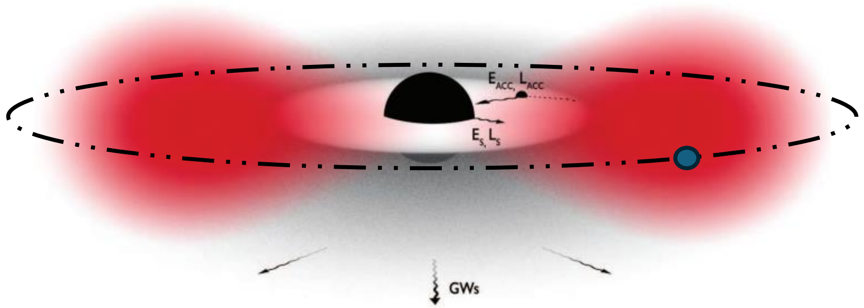


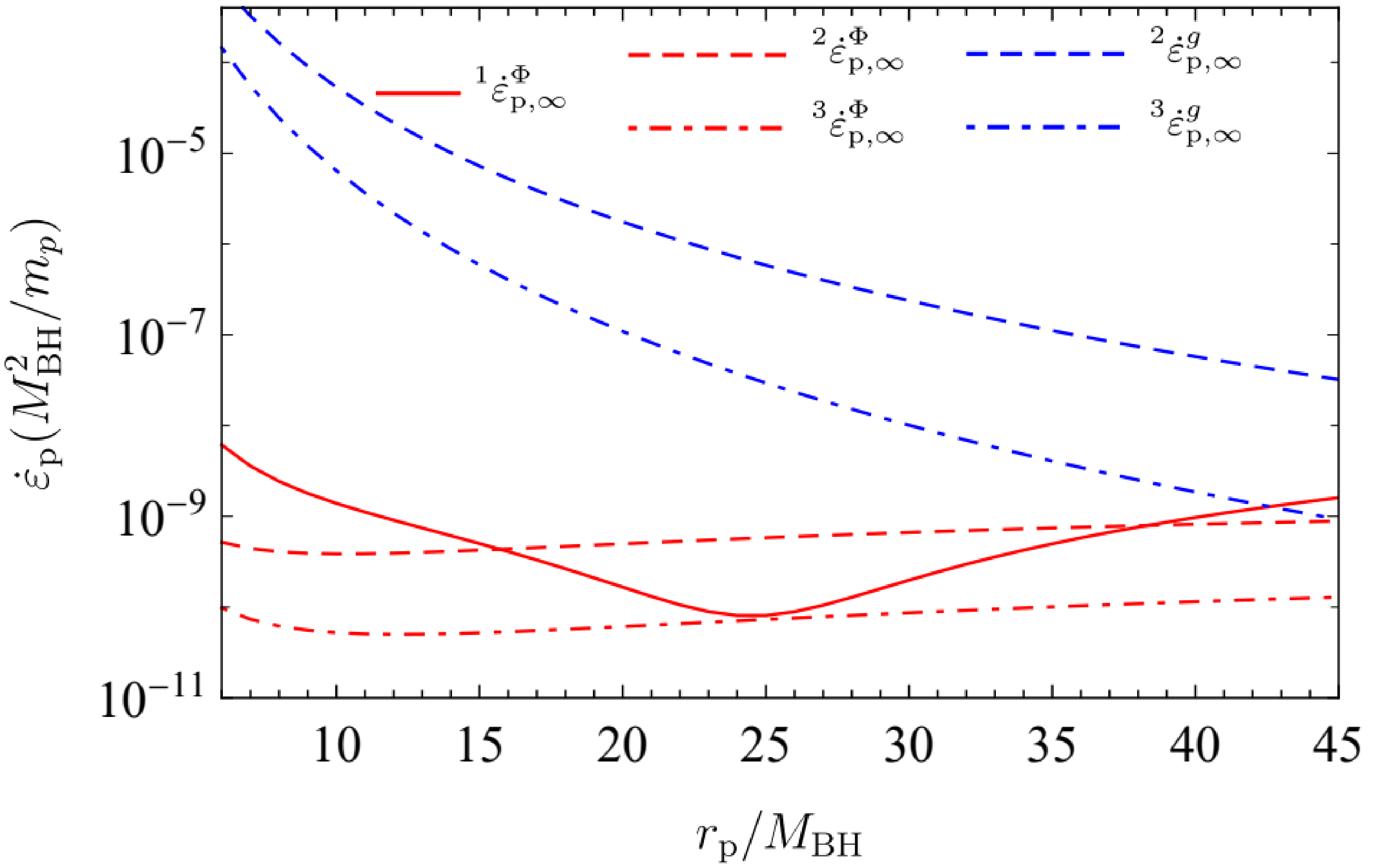
Resonant behavior

In LISA frequecy band, above the line we see >1 cycle of difference

Axion dominating the flux

Black hole + spherical bosonic cloud





We can have observation of ~1cycle dephasing for $M_\Phi/M_{BH} \gtrsim 0.01$, $M_\Phi \mu \gtrsim 0.08$, and q $\gtrsim 5 \times 10^{-5}$.

Final remarks

- Ultralight fields are found everywhere **beyond the SM physics**.

- Due to superadiance, they have a **profound impact in astrophysical BHs and the formation of structures**.

- The Evolution of binaries in these environments can be **potentially tested in future GW observatories**.

- A large fraction of the energy is due to axions... It ***really leaks***.

Thank you!

Fapespa CAPES CNPq

I GRAVITAS SCHOOL

ON GRAVITY AND FIELDS

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