“Inferences on particle physics”: Superradiance

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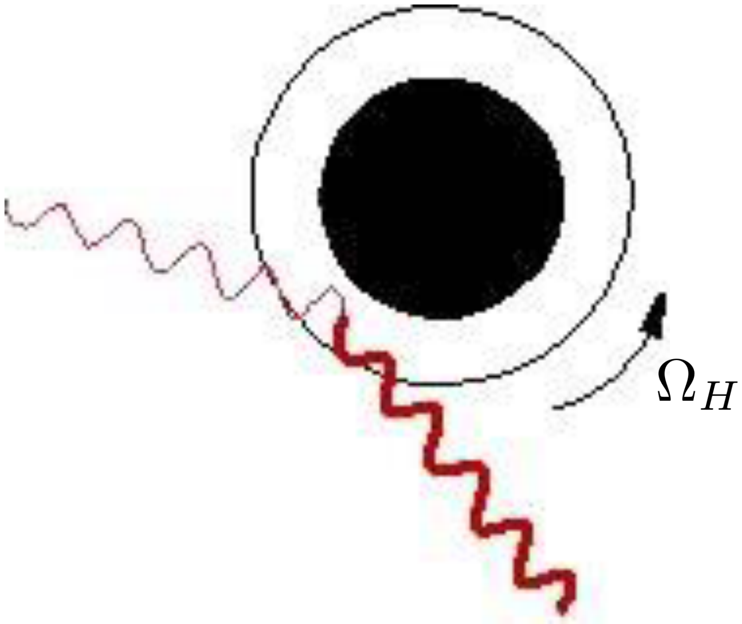
Superradiance

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



$$\Phi(t, r, \theta, \phi) = \Psi(r) e^{-i\omega t + im\phi} P_l(\cos\theta)$$

$$\frac{\omega}{m} < \Omega_H$$

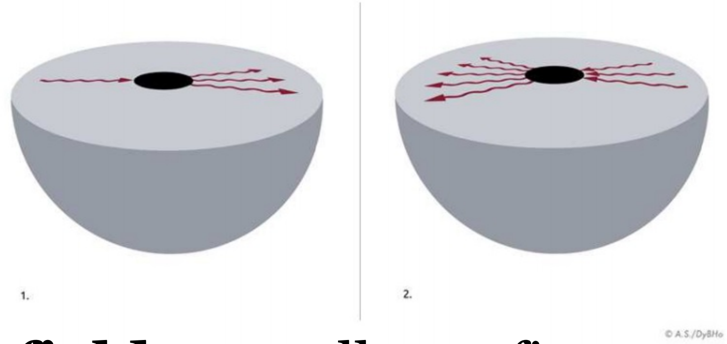
Superradiant scattering of **bosonic** waves ⇒ Extraction of energy and angular momentum from the black hole

Overview on superradiance: R. Brito, V. Cardoso, P. Pani, Springer - arXiv: 1501.06570

Superradiant instability

Press & Teukolsky, ’72; Zouros & Eardley ’79; Detweiler ’80; Dolan ’07; Arvanitaki et al ’09; Pani *et al* ’12; Witek *et al* ’12; RB, Cardoso & Pani ’13; Baryakthar, Lasenby & Teo ’17; East ’17; Cardoso *et al* ’18; Frolov *et al* ’18, Dolan’ 18…

Confinement + Superradiance ⟶ Superradiant instability



The Yukawa potential of a **massive bosonic field** naturally confines low-frequency waves.

Spinning BHs are **unstable** against massive bosons (independently of the boson spin).

Mostly relevant when:

$$0.02\left(\frac{M}{10^6 M_\odot}\right)^{1/9} \lesssim \alpha \equiv \frac{GM}{c^2 \lambda\!\!\!^{-}} \lesssim \frac{\chi M}{2r_+} \lesssim \frac{1}{2}$$

$$\alpha \sim 0.075\left(\frac{M}{10^6 \mathrm{M}_\odot}\right)\left(\frac{m_b c^2}{10^{-17}\mathrm{eV}}\right)$$

“Gravitational atom”

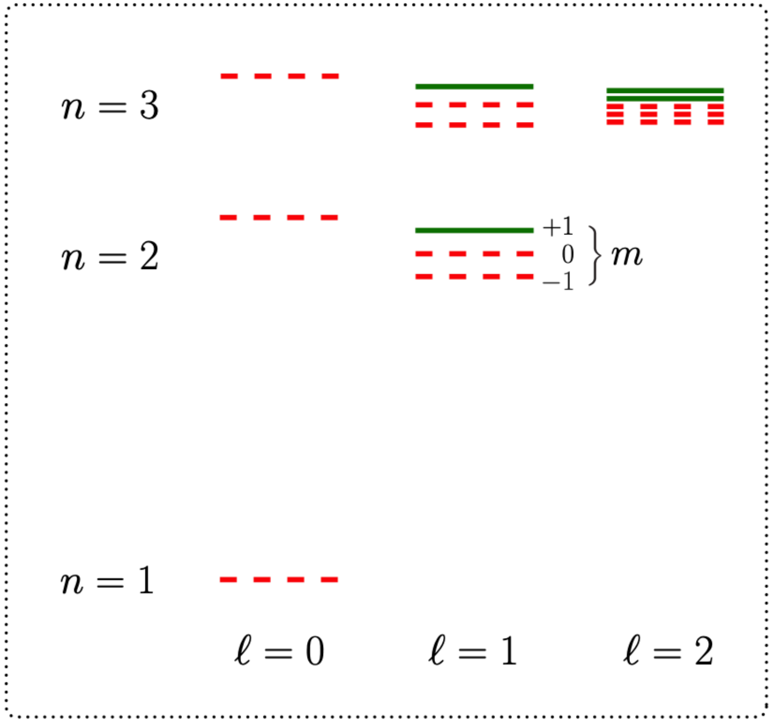
$$\Box\Phi - \mu^2\Phi = 0 \quad \text{with} \quad \mu = \lambda^{-1}$$

$$\Phi(t, r, \theta, \phi) = \Psi(r) e^{-i\omega t + im\phi} P_l(\cos\theta)$$

$$\Big\downarrow \; \alpha \ll \ell$$

$$\omega_{nlm} \simeq \mu \left(1 - \frac{\alpha^2}{2n^2}\right) + \Delta\omega_{nlm}$$

$$\Delta\omega_{n\ell m} = \mu\left(-\frac{\alpha^4}{8n^4} + \frac{(2\ell - 3n + 1)\,\alpha^4}{n^4(\ell + 1/2)} + \frac{2\tilde{a} m \alpha^5}{n^3 \ell(\ell + 1/2)(\ell + 1)}\right)$$



From: Baumann, Chia, Porto ’18

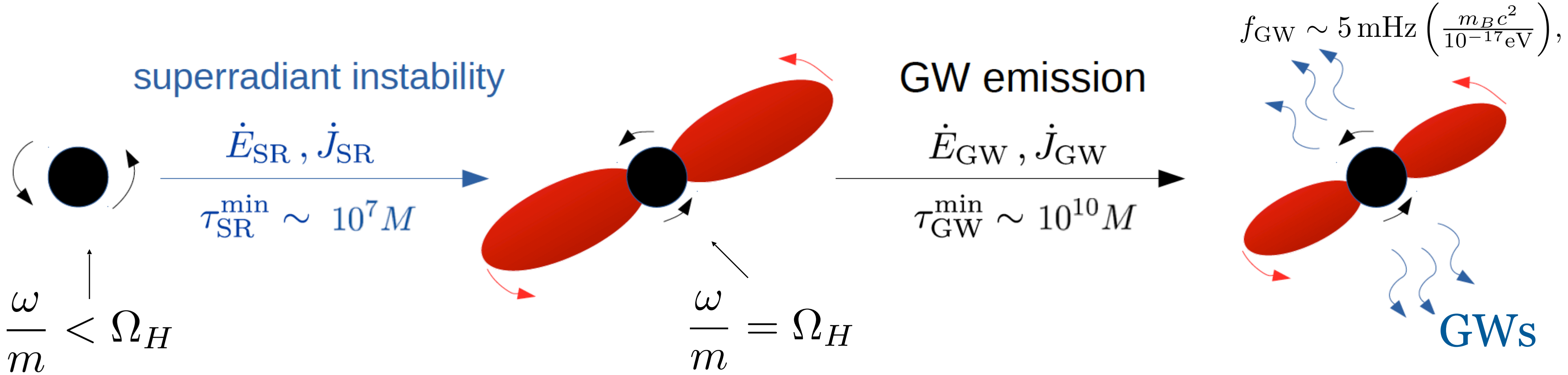
Boundary conditions at the horizon -> problem is non-Hermitian (dissipative):

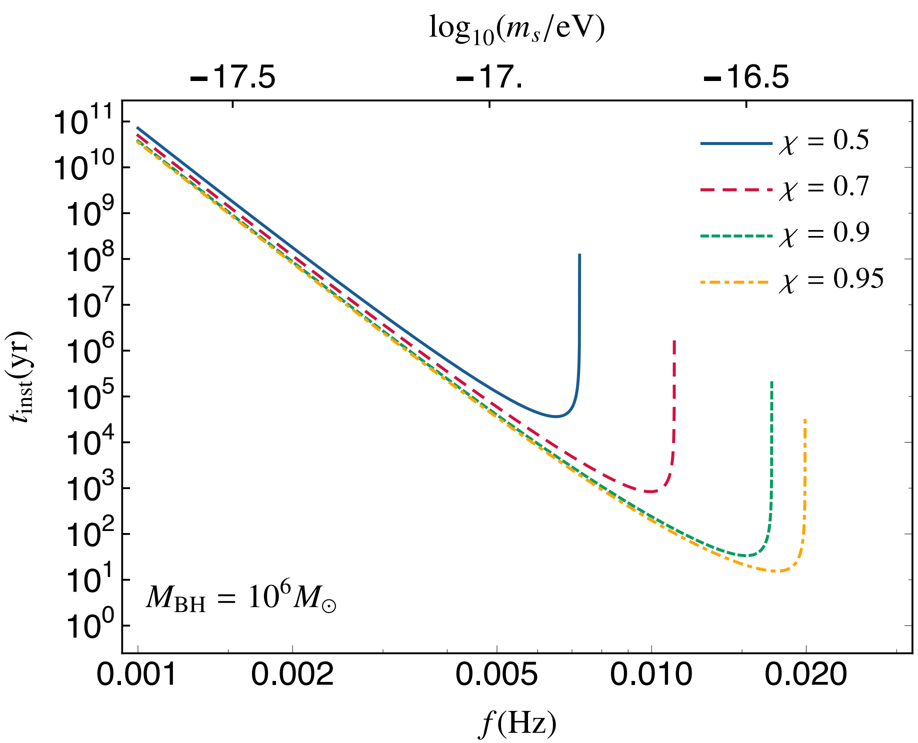
$$\omega_{n\ell m} \rightarrow \omega_{n\ell m} + i\Gamma_{n\ell m} \qquad \Gamma_{n\ell m} = \frac{2r_+}{M} C_{n\ell m}(\alpha)\,(m\Omega_{\rm H} - \omega)\,\alpha^{4\ell+5}$$

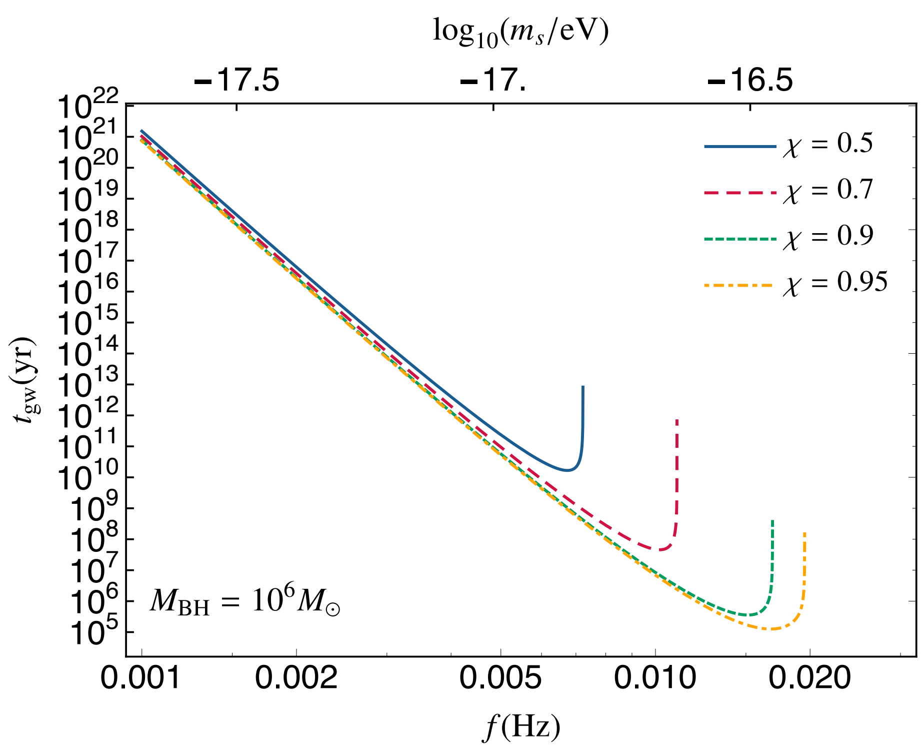
Results agree with numerical results that can be used to obtain the eigenfrequencies for arbitrary α and BH spin.

Evolution of the superradiant instability

Arvanitaki & Dubovsky, ’10; RB, Pani & Cardoso ’15; East & Pretorius, ’17; East ’18



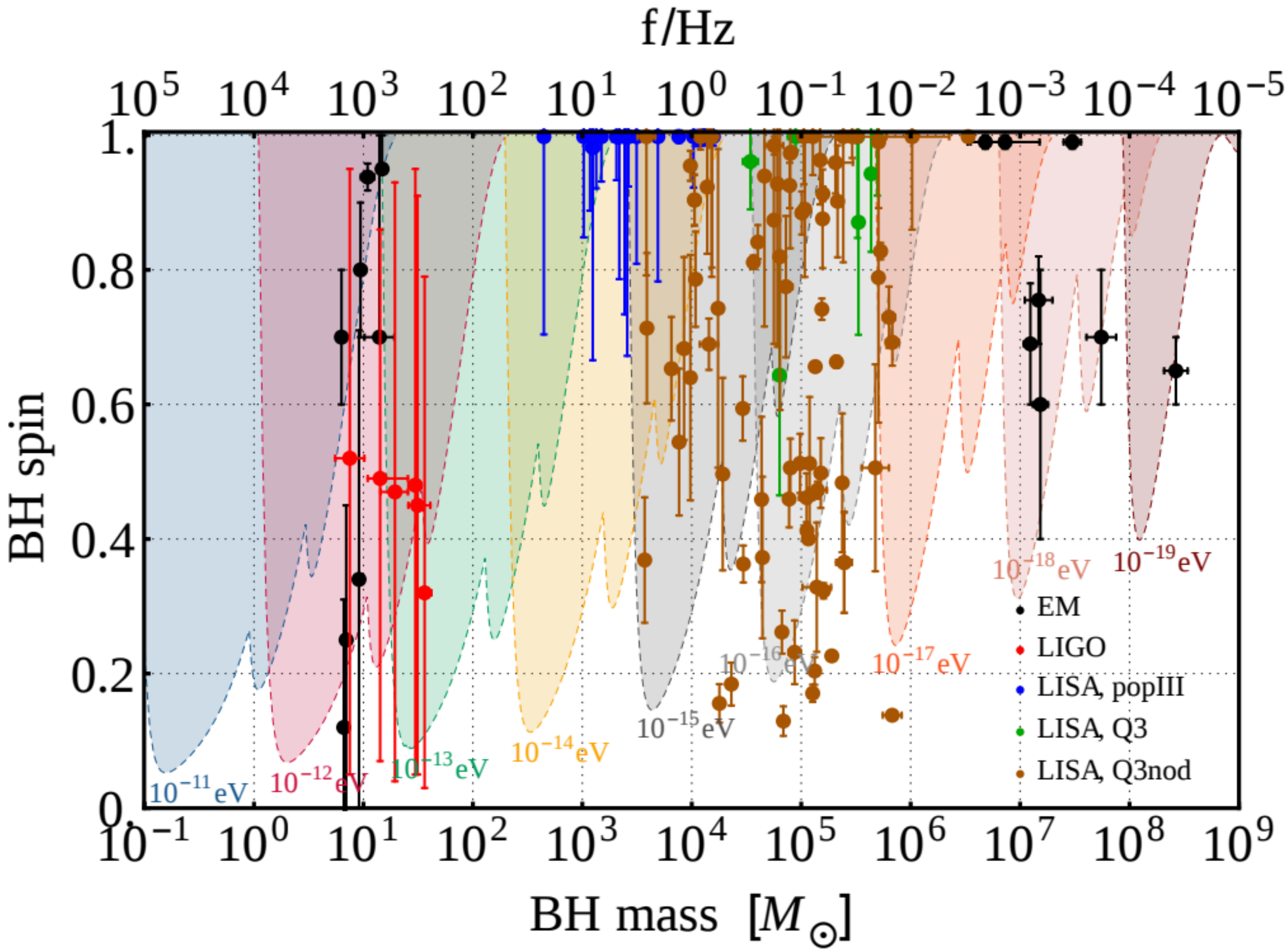




Signatures

Gaps in the BH mass vs spin plane

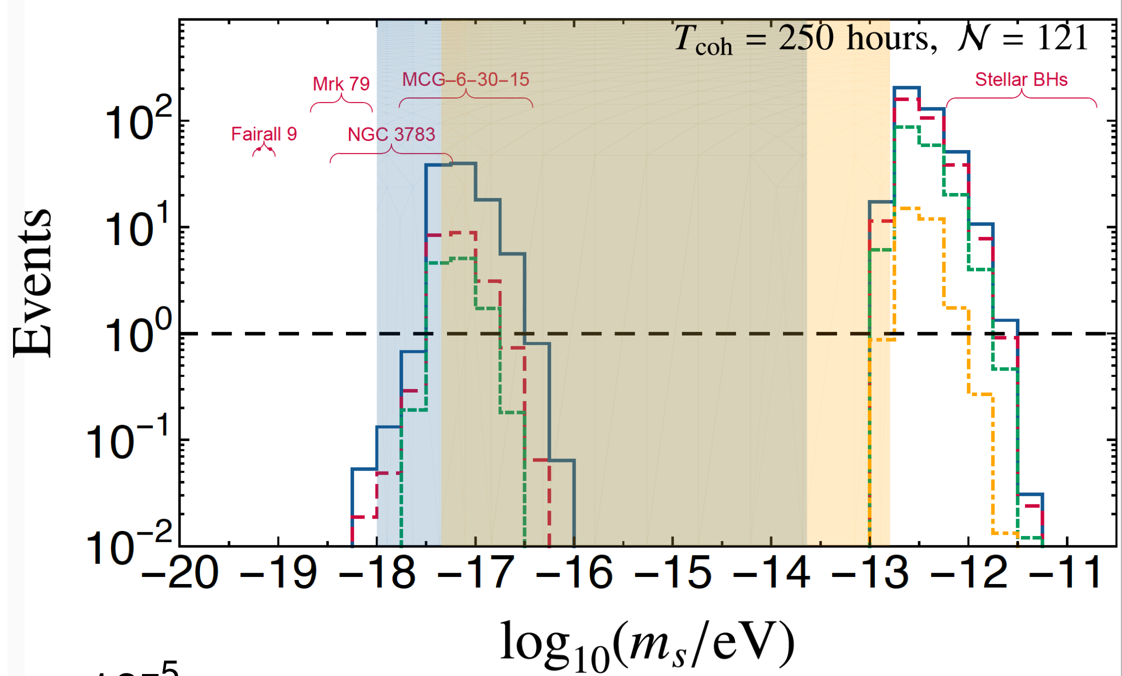
Arvanitaki & Dubovsky, '10; RB, Cardoso, Pani, '14; Arvanitaki *et al* '15; Baryakthar, Lasenby & Teo '17; RB *et al* '17; Cardoso et al '18; Stott & Marsh '18



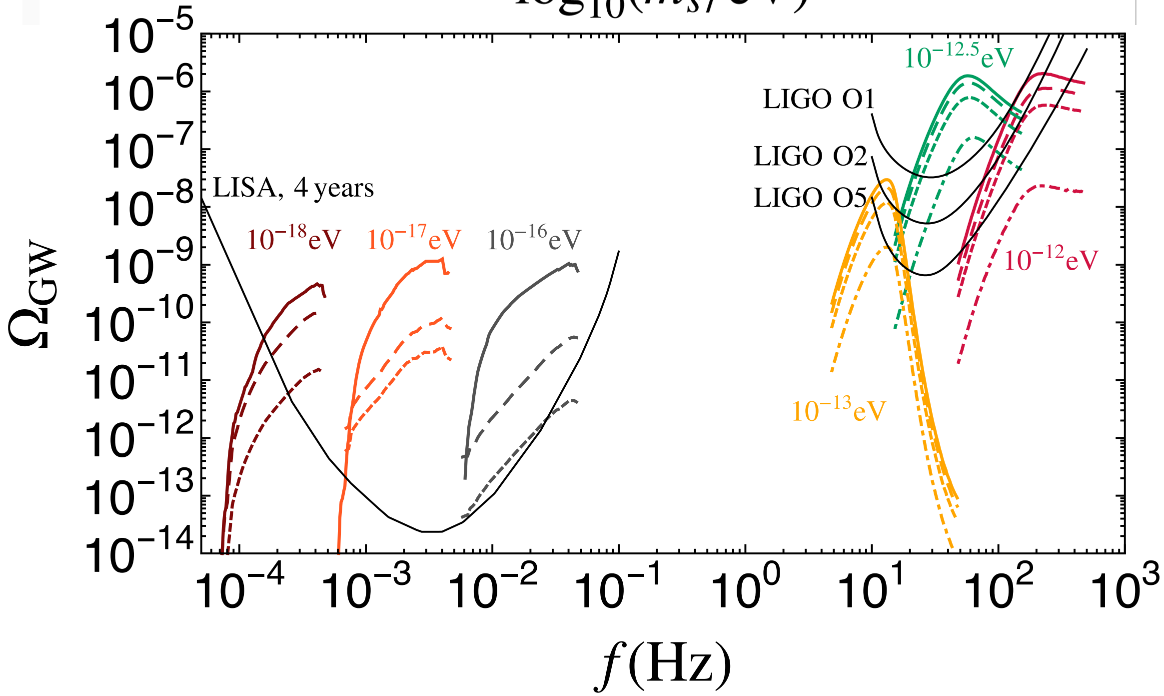
GW sources

Arvanitaki, Baryakhtar & Huang ’15; Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky & Lasenby ’15; Baryakthar, Lasenby & Teo ’17; RB *et al* ‘17

- ❖ Invidividual resolved events.



- ❖ Stochastic background of undersolved sources.



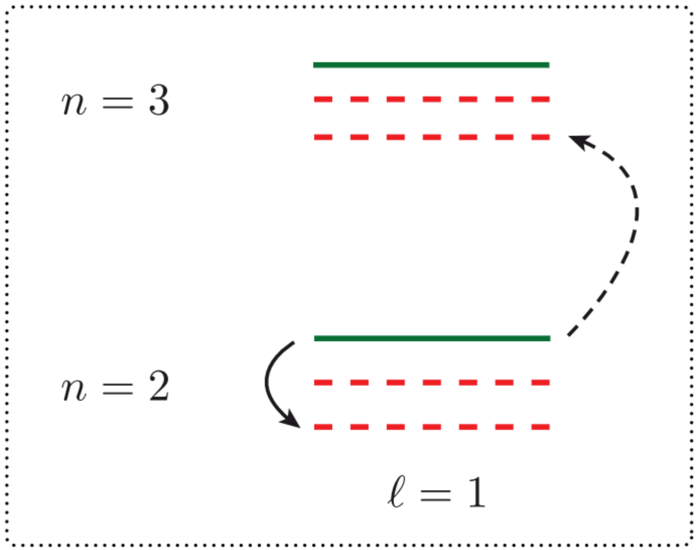
Clouds in a binary system: level-mixing

Baumann, Chia, Porto '18

- When the BH carrying the cloud is part of a binary system, the companion induces a small perturbation on the gravitational potential felt by the cloud.

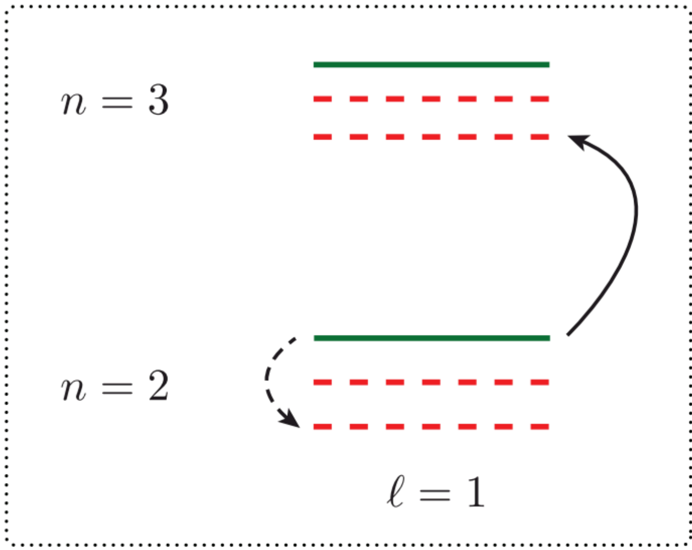
- Can induce transitions between modes at orbital frequencies that match the energy split between those modes. Transitions to a decaying mode can lead to a partial or total depletion of the cloud

co-rotating orbits



"Hyperfine resonance"

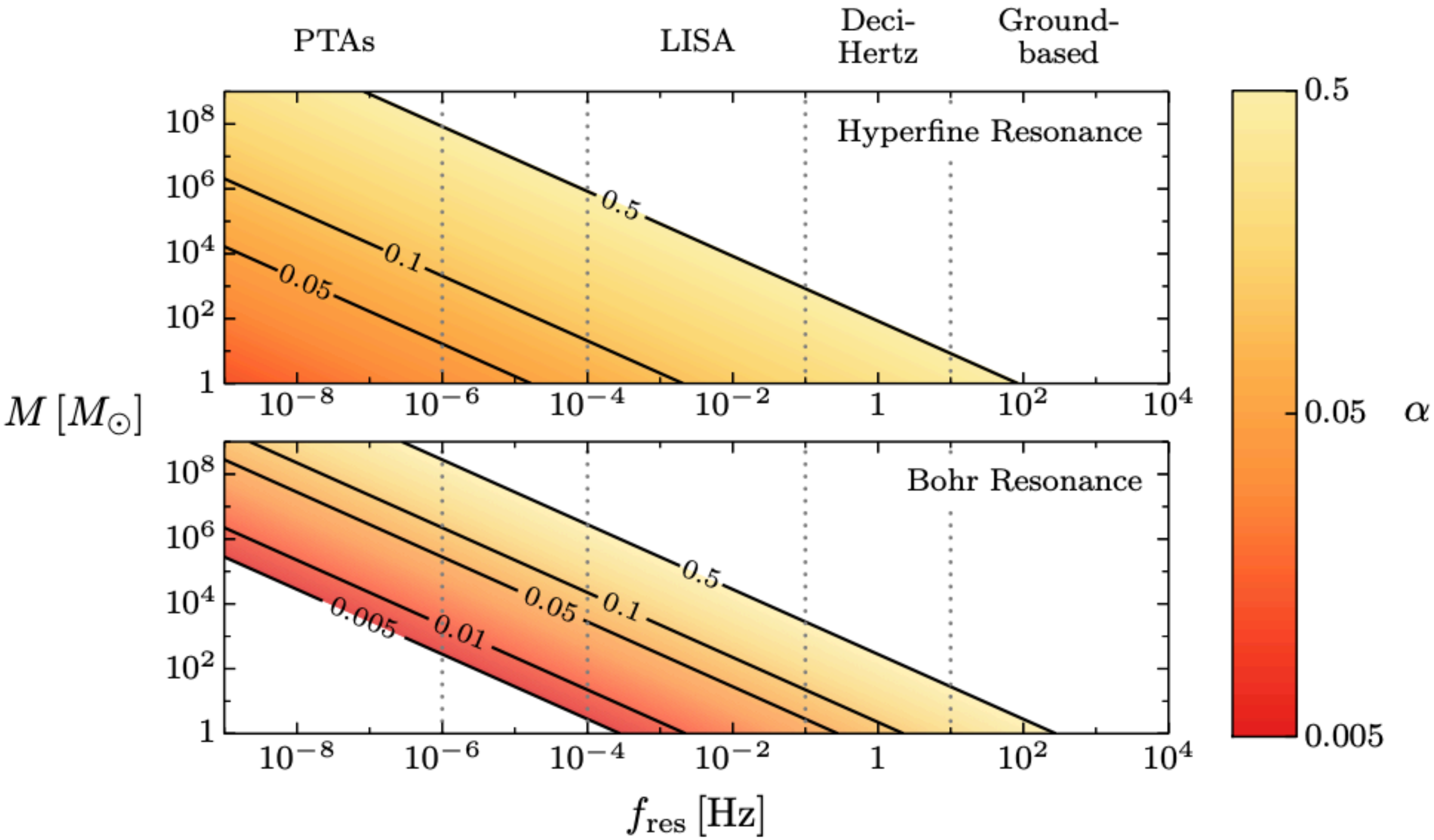
counter-rotating orbits



"Bohr resonance"

Cloud depletion: detection

Baumann, Chia, Porto '18

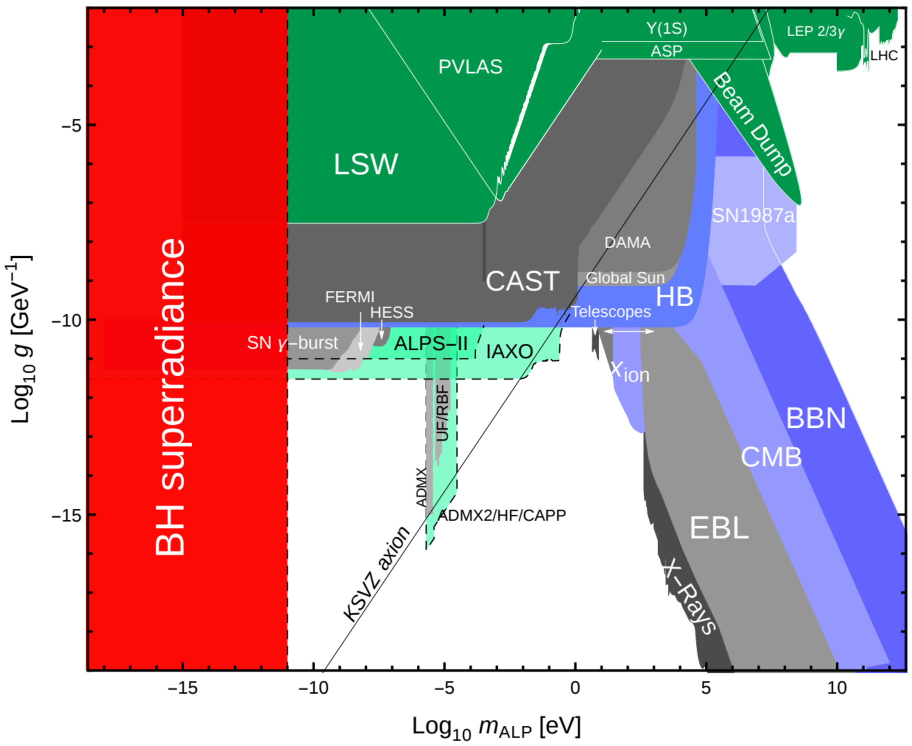


- Sudden changes or time dependence in the parameters of the binary (e.g. tidal Love number or mass quadrupole moment). (Baumann, Chia, Porto '18)

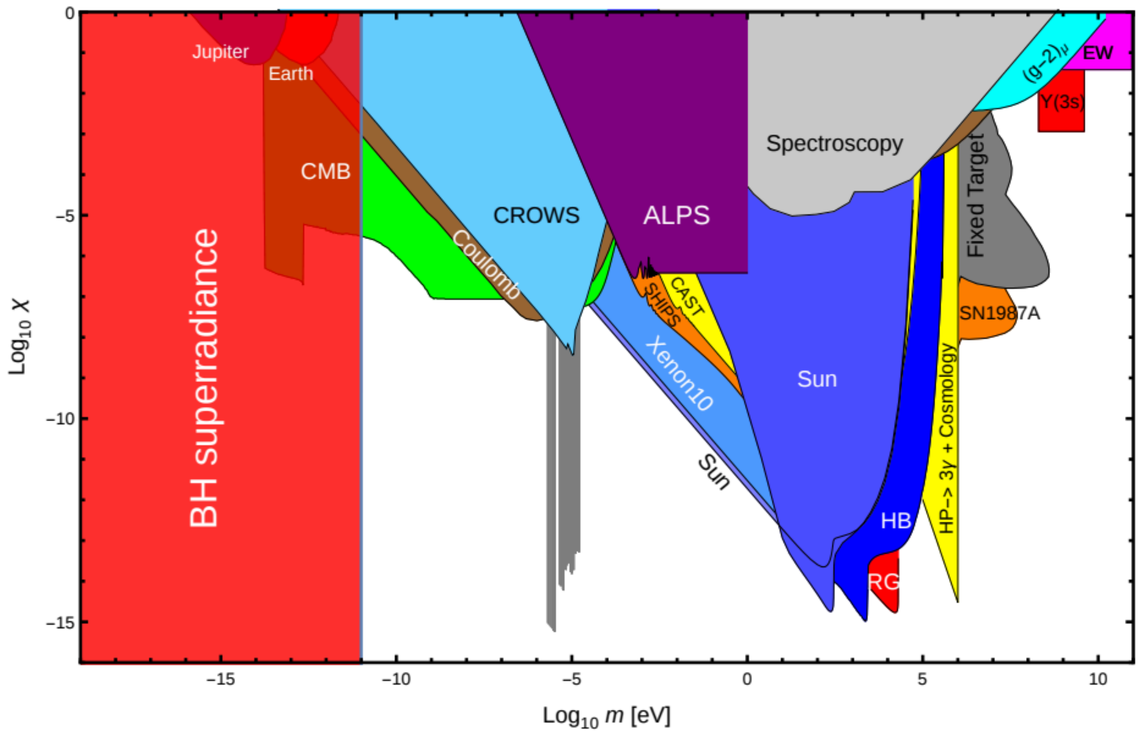
- Backreaction on the companion's orbit could lead to a delayed merger (or even floating orbits). (Zhang & Yang '18)

Complementarity with other experiments

Axion-like particles



Ultralight vector fields



From: Cardoso et al '18, JCAP1803 043

- Black-hole superradiance can fill an important gap in the parameter space.
- Roughly independent on the coupling to SM particles (CAUTION: if couplings or self-interactions are large enough superradiant growth can be quenched, but also other potentially interesting phenomena could happen, e.g. bosenovae).