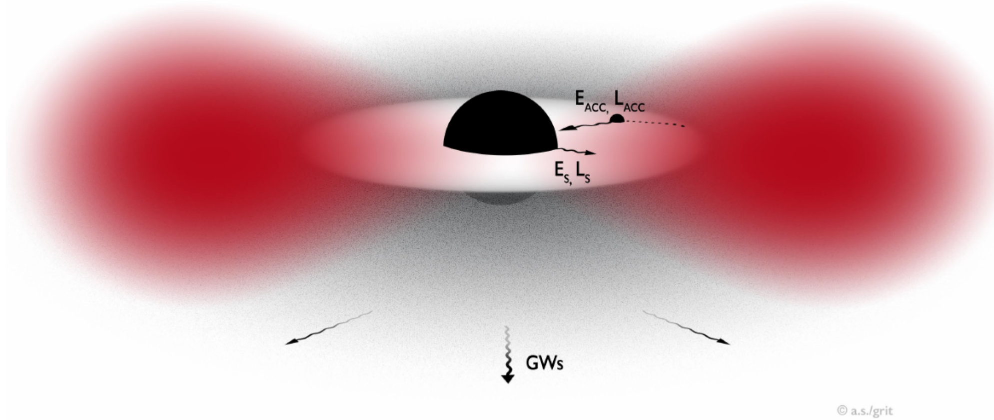
Black-hole superradiance:

probing the dark universe with compact objects and GWs



(Obsolete!) overview: Brito, Cardoso, Pani, “Superradiance” –

Springer Lect. Notes Phys. 906 (2015) - **1501.06570**

Paolo Pani

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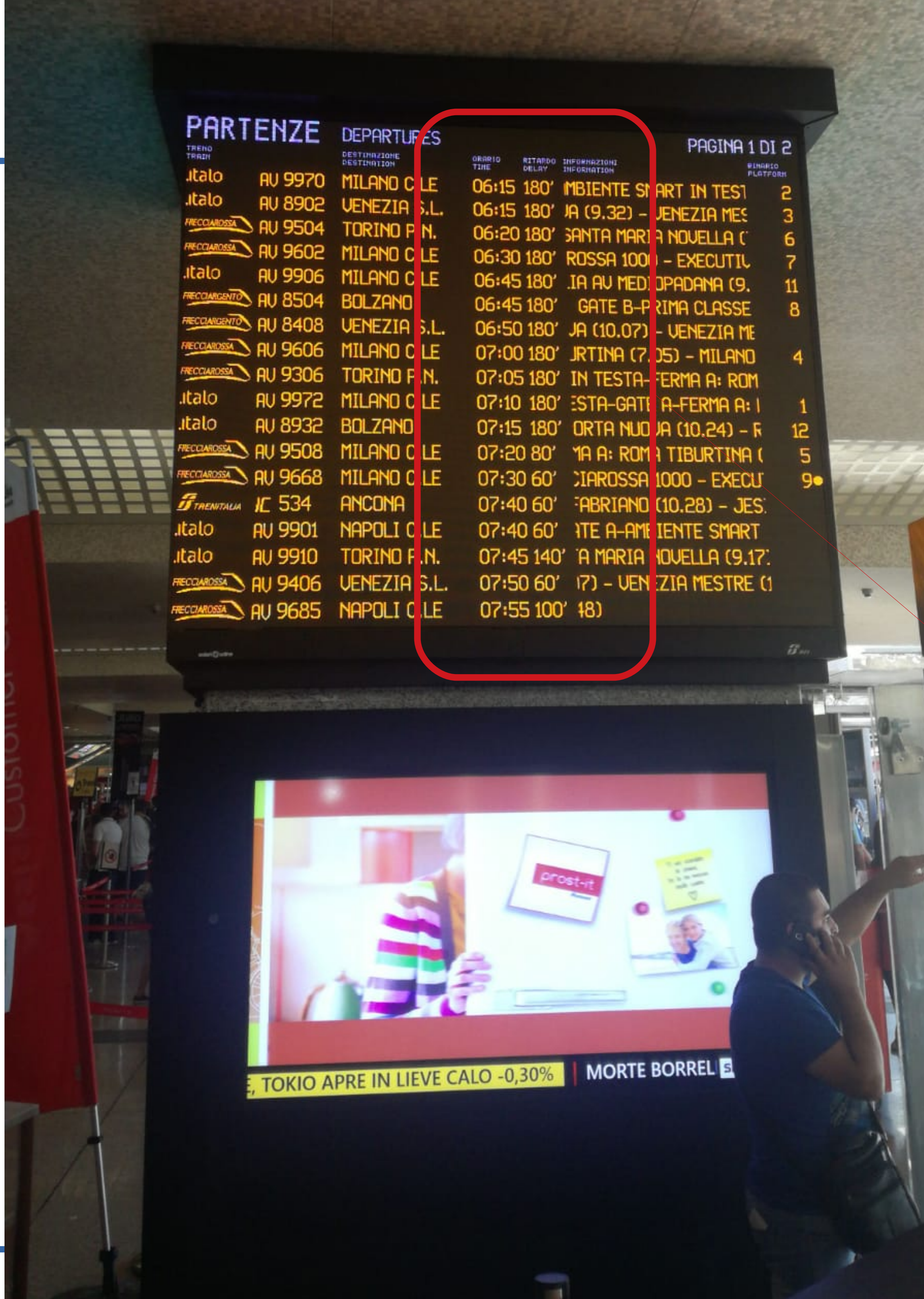


Average train delay yesterday in Italy:

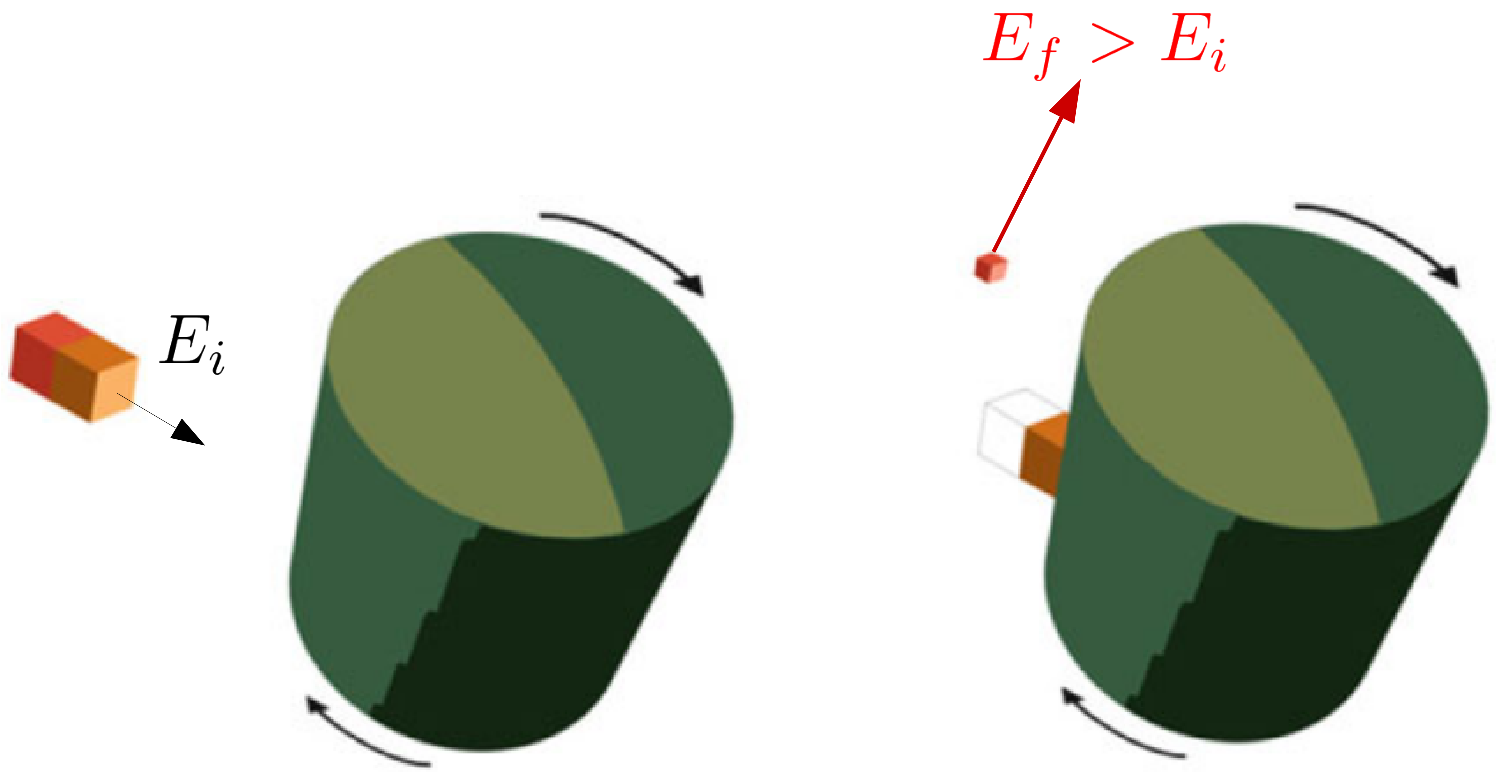
3-4 hr

Outline

- Black-hole (BH) superradiance: a primer
- BH superradiant instability triggered by ultralight bosons & GW signatures
- Superradiance in stars and pulsar-timing constraints on dark photons
- Superradiance triggered by plasma: constraints on spinning primordial BHs

What's superradiance?

In physics, *superradiance* is a **radiation enhancement effect** in several contexts including quantum mechanics, astrophysics and relativity. [cit. Wikipedia]



BH superradiance

Zeldovich, Press, Teukolsky (1970s)

The foregoing pertains to a body made of a material that absorbs waves when at rest; the conditions for amplification and generation are obtained after transforming the equations to the moving system. A similar situation can apparently arise also when considering a rotating body in the state of gravitational relativistic collapse.

The metric near such a body is described by the well-known Kerr solution. The gravitational capture of the particles and the waves by the so-called trapping surface replaces absorption; the trapping surface ("the horizon of events") is located inside the surface $g_{00} = 0$. Finally, in a quantum analysis of the wave field one should expect spontaneous radiation of energy and momentum by the rotating body. The effect, however, is negligibly small, less than $\hbar\omega^4/c^3$ for power and $\hbar\omega^3/c^3$ for the decelerating moment of the force (for a rest mass m = 0, in addition, we have omitted the dimensionless function β).

ZhETF Pis. Red. 14, No. 4, 270 - 272 (20 August 1971)

- Superradiant scattering off a **Kerr BH** when $\omega/m < \Omega_H$
- Requires **dissipation** → event horizon

Thorne, Price, Macdonald's "Membrane Paradigm" (1986)

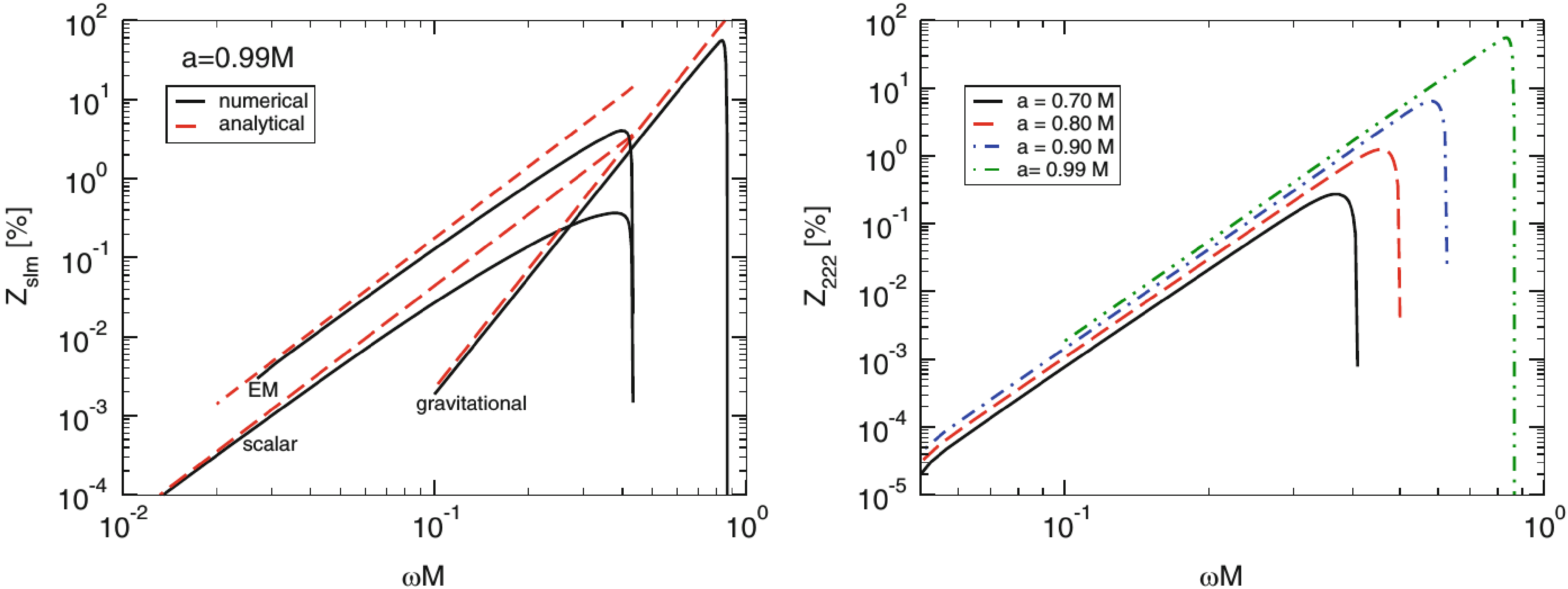
Richartz+, Phys.Rev. D80 (2009) 124016

Brito, Cardoso, PP, "Superradiance" Springer (2015)

- Amplification depends on the **nature of the bosonic field**

Superradiant scattering off a BH

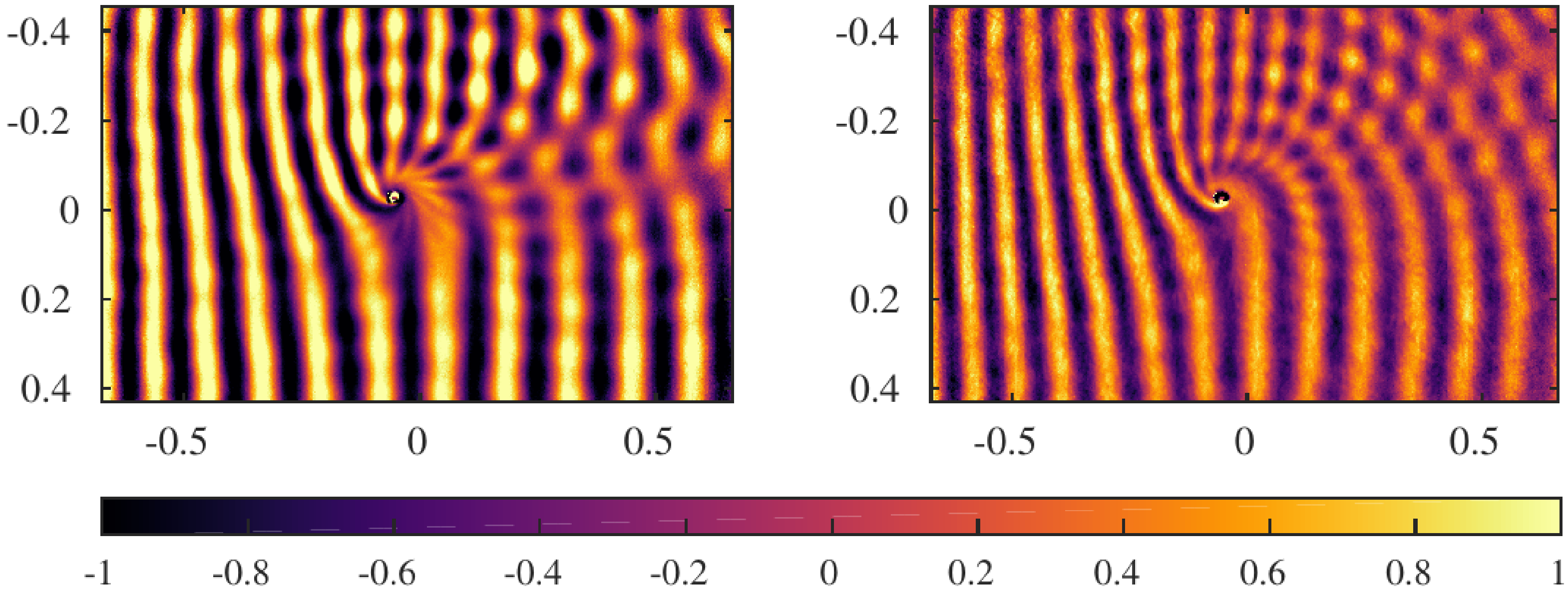
scattering amplification factors

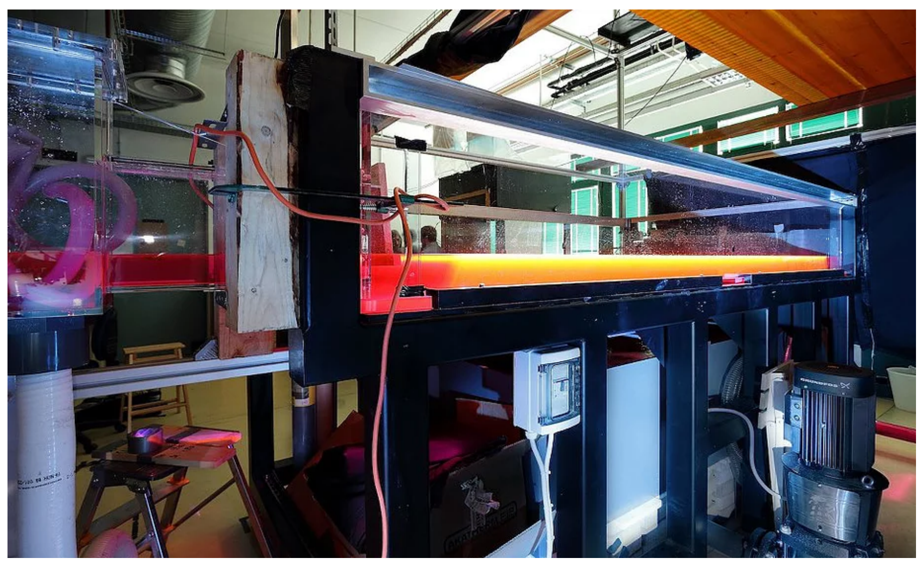


- Larger amplification for GWs (S=2) and at high spin
- Nonlinear effects (slightly) decrease efficiency [East, Ramazanoğlu, Pretorius PRD 89 061503 (2014)]
- Small effect, e.g. luminosity modulation in binary pulsars [Rosa, PLB 2015 & PRD (2017)]

Superradiance in the lab

Torres+, Nature Physics 13, 833-836 (2017), see **Silke Weinfurtner's talk**



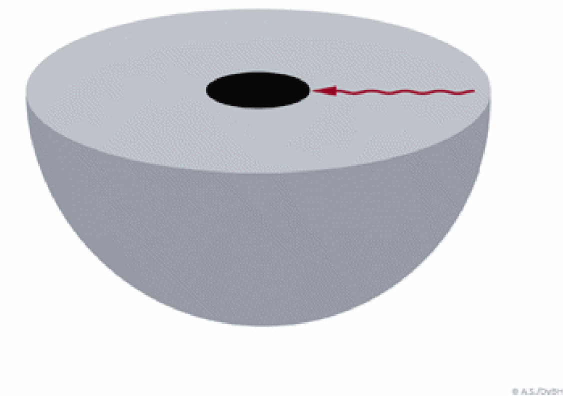


www.gravitylaboratory.com

BH superradiant instability

Damour, Deruelle & Ruffini; Press-Teukolsky, Detweiler; Zouros & Eardley 1980s;..., Shlapentokh-Rothman, 2015

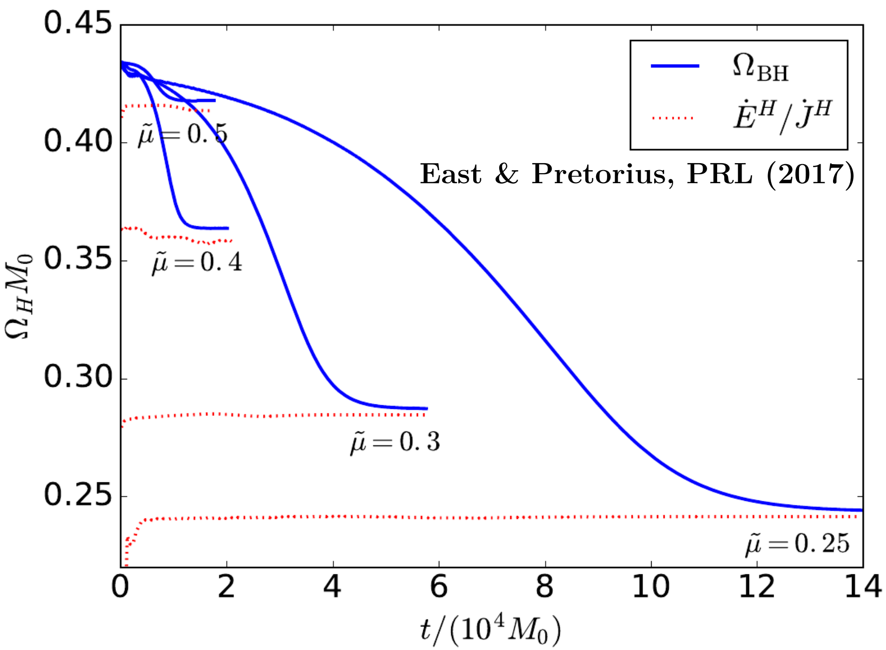
- Superradiant scattering + Yukawa effective potential



- Spinning BHs are unstable against massive bosons

$$\Box\phi - \frac{\mu^2 c^2}{\hbar^2}\phi = 0 \quad \Rightarrow \quad \phi \sim e^{t/\tau}$$

- BH energy/spin extraction → condensate



$$\frac{G}{\hbar c}M\mu \sim \left(\frac{M}{10M_\odot}\right)\left(\frac{\mu c^2}{10^{-11}\,\mathrm{eV}}\right) \sim \mathcal{O}(1)$$

Coupling parameter

Ultralight fields in the dark universe?

- Compelling dark-matter candidates alternative to WIMPs
  - Fuzzy DM: mass ~ 10^{-22} eV → no problems at sub-kpc scale

    Hui, Ostriker, Tremaine, Witten, PRD95 043541 (2017)
  - Plethora of sub-eV DM particles:
    - QCD axion, stringy axion-like particles (ALPs), axiverse

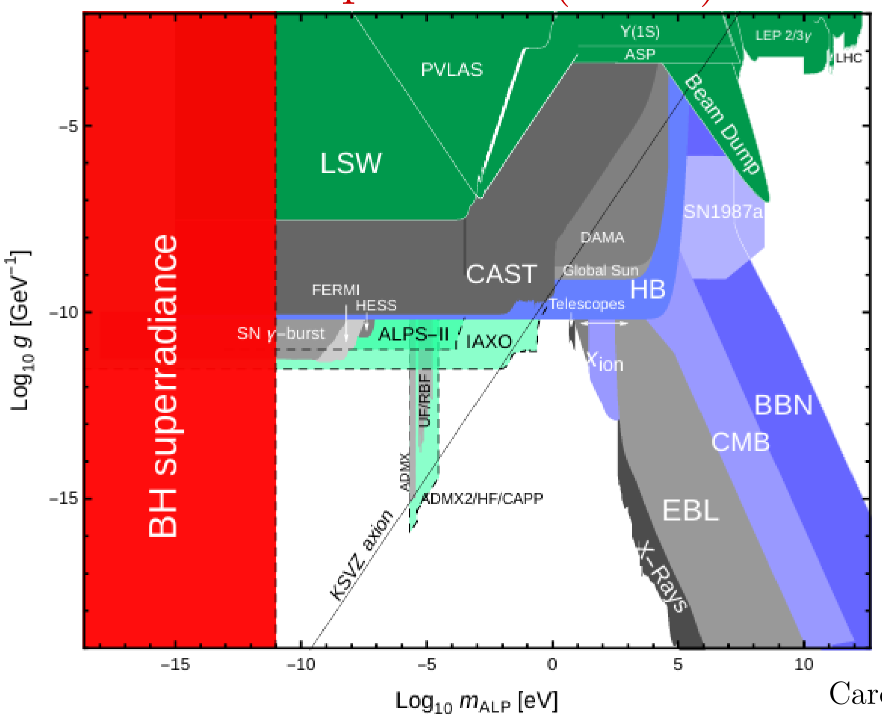
      Arvanitaki+, PRD81 123530 (2010)
    - Dark photons & hidden sectors, massive gravitons ...
- Common properties:
  - Bosonic fields
  - Small mass (from sub-eV down to 10^{-33} eV)
  - Weakly coupled to SM (or not coupled at all!)

Dark sectors and ultralight particles

Essig+, 1311.0029, Hui+, PRD 2017, Irastorza & Redondo+ 2018

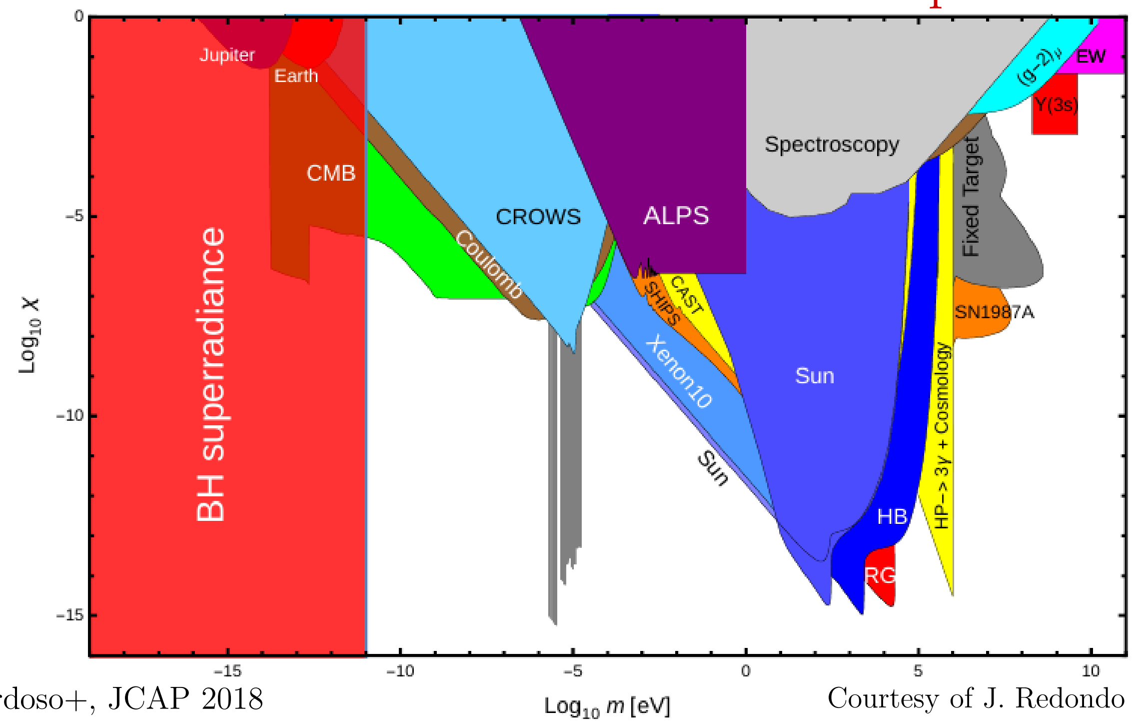
$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}(\nabla_\mu \phi^*)(\nabla^\mu \phi) - \frac{\mu_S^2}{2}|\phi|^2 - V(|\phi|) - \kappa_{\rm axion}\phi\, F^{(a)}_{\mu\nu}{}^* F^{\mu\nu}_{(a)}$$
$$- \frac{1}{4g_a^2} F^{(a)}_{\mu\nu} F^{\mu\nu}_{(a)} - \frac{1}{4g_b^2} F^{(b)}_{\mu\nu} F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2 g_a g_b} F^{(a)}_{\mu\nu} F^{(b)\mu\nu} + \frac{m_{ab}^2}{g_a g_b} A^{(a)}_\mu A^{(b)\mu}$$

Axion-like particles (ALPs)



Cardoso+, JCAP 2018

Dark photons



Courtesy of J. Redondo

Searches for ultralight DM with strong gravity

BH superradiant instability spectrum

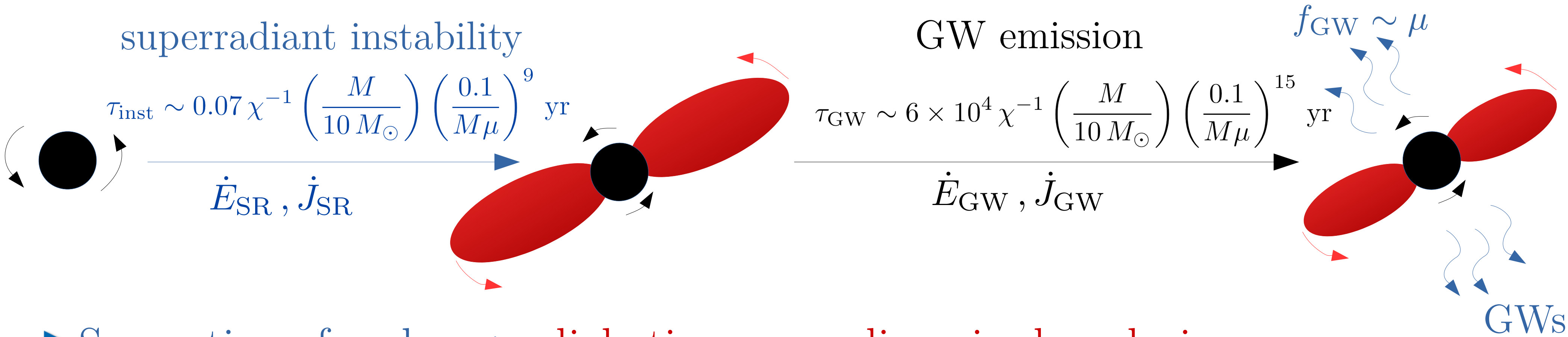
- Instability depends on spin of the BH & particle spin (S):

$$\omega_R \sim \mu - \frac{\mu(M\mu)^2}{2(1+\ell+n+S)^2} \qquad \omega_I \sim -(\omega_R - m\Omega_H)(M\mu)^{4\ell+4+2S}$$

- Incomplete timeline of (relatively) recent developments on the spectrum:
  - Scalar, numerical spectrum [Dolan PRD 2007]
  - Vector, nonspinning case [Rosa & Dolan PRD 2012]
  - Vector, quadratic in spin [Pani+ PRL 2012]
  - Scalar/vector, time-domain, any spin [Witek+ PRD 2013]
  - Tensor, linear in spin [Brito, Cardoso, Pani PRD 2013]
  - EFT approach [Endlich & Penco, JHEP 2017]
  - Vector, Newtonian approximation [Baryakhtar+ PRD 2017]
  - Vector, frequency domain, PDEs, any spin [Cardoso+ JCAP 2018]
  - Vector, separability, any spin [Frolov+ PRL 2018]
  - Vector, numerical spectrum [Dolan PRD 2018]

Evolution of the instability

First nonlinear simulation: East & Pretorius, PRL 2017



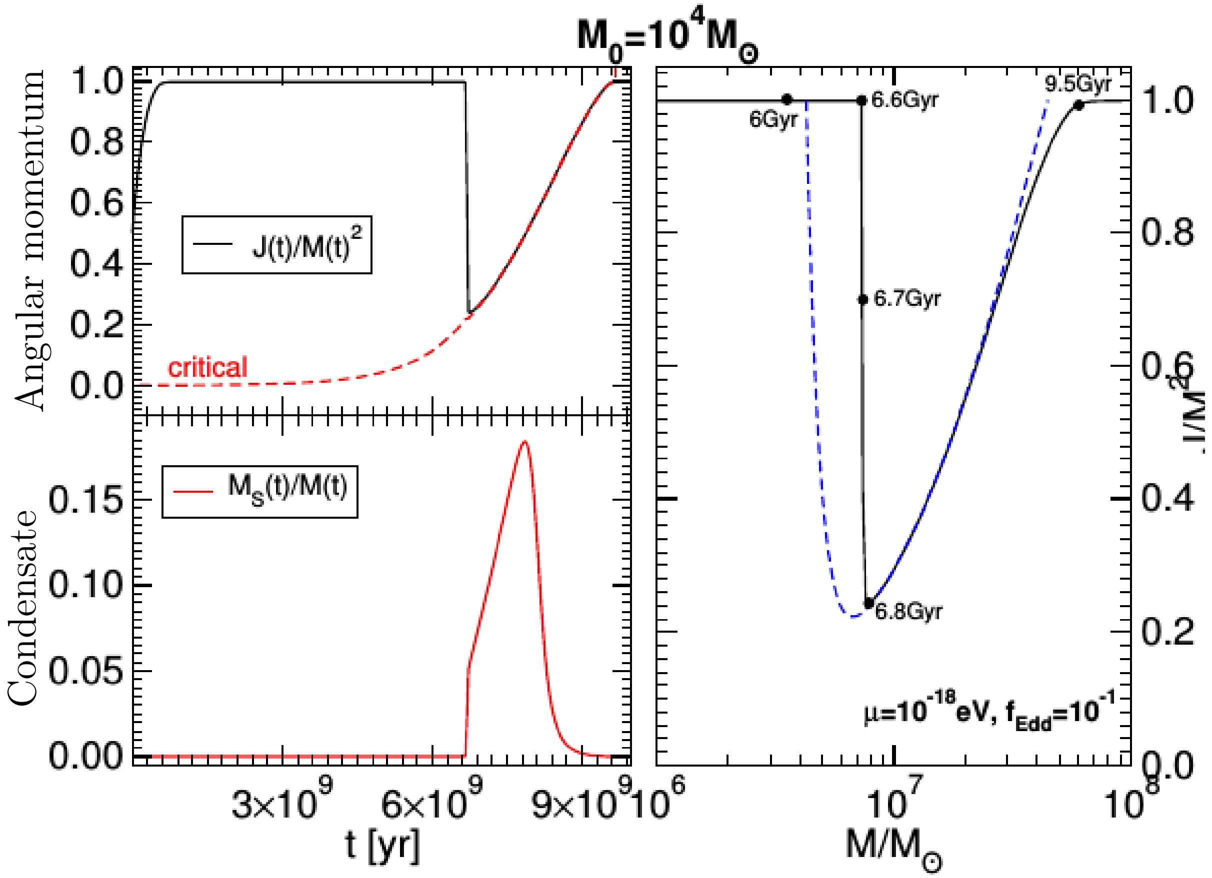
- Separation of scales → adiabatic approx, linearized analysis
- GW emission → quadrupole fails
- Can be also studied in terms of transition probabilities & occupation numbers

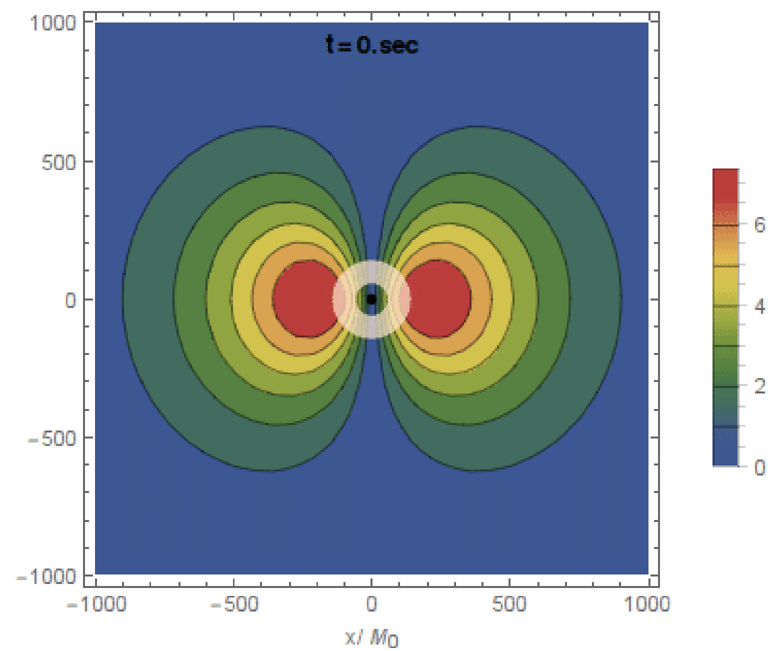
Arvanitaki+ 2014-2016

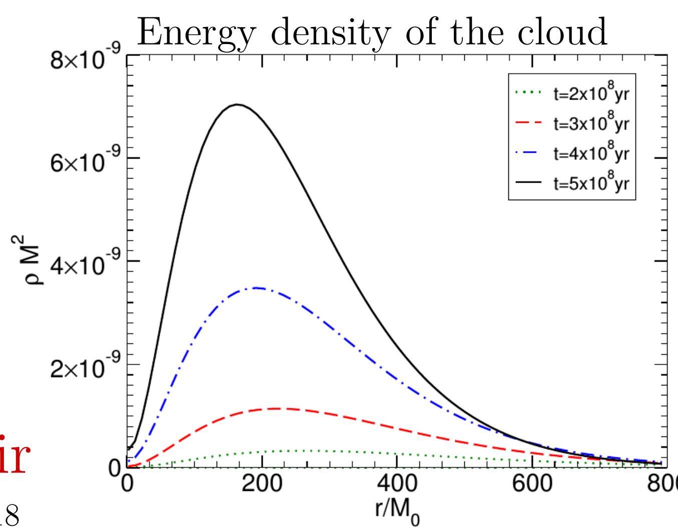
- Two generic predictions:
  - BHs should NOT spin fast in the presence of ultralight bosons
  - Periodic GW signal → continuous sources for LIGO/Virgo/LISA

Evolution of the instability

Brito, Cardoso, PP, 2015 Class. Quantum Grav. 32 134001



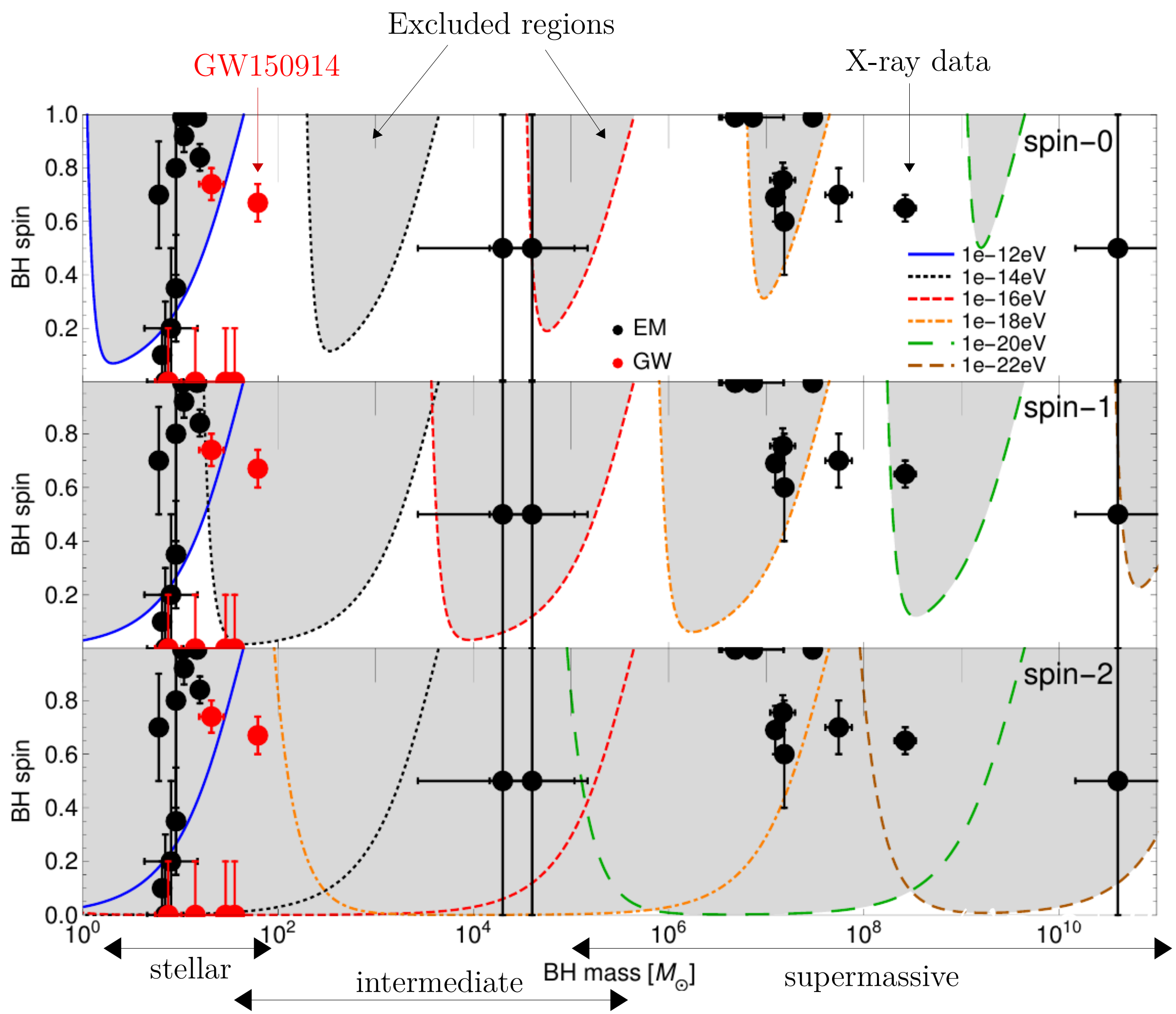




- Backreaction is negligible → Kerr metric
- For real fields → quasi-stationary BHs
- **Note:** for complex field → Kerr BHs with scalar hair

Herdeiro & Radu 2014-2018

Bounds on light bosons



QCD axion

Axion-like particles

String axiverse

Dark photons

Mirror DM

Massive photon

Massive spin-2

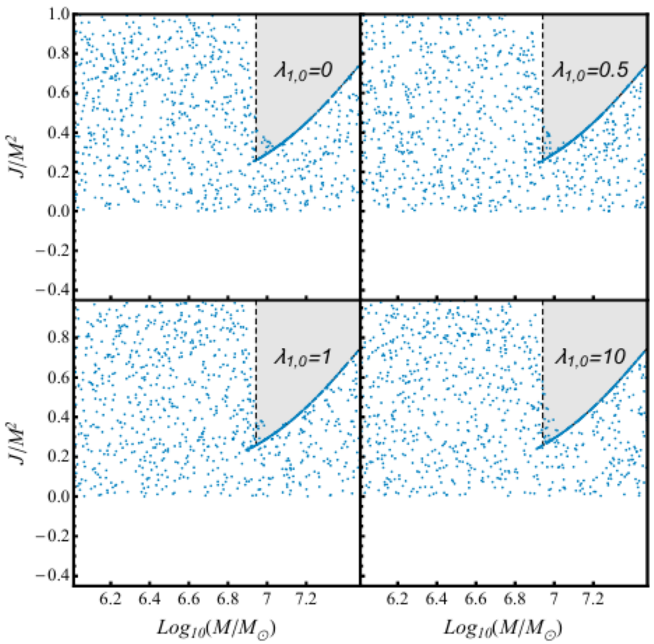
Massive graviton

Generic prediction: "gaps" in the BH "Regge plane"

Arvanitaki+, Phys.Rev. D83 (2011) 044026

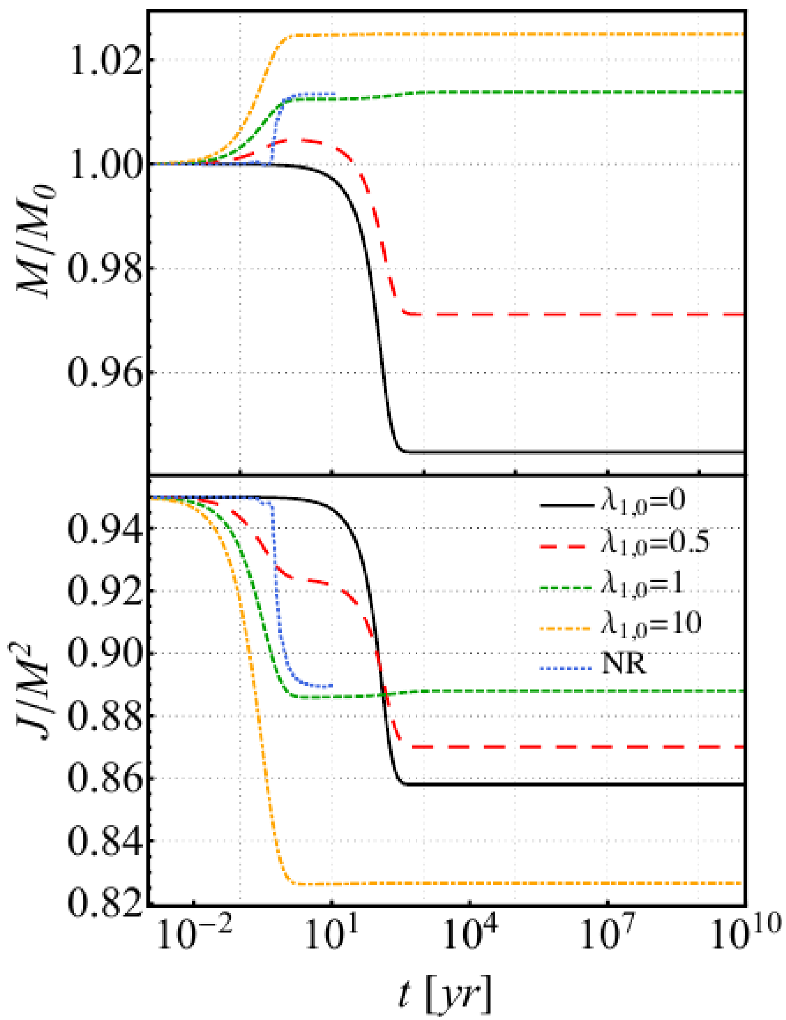
Impact of multiple modes

Small seed

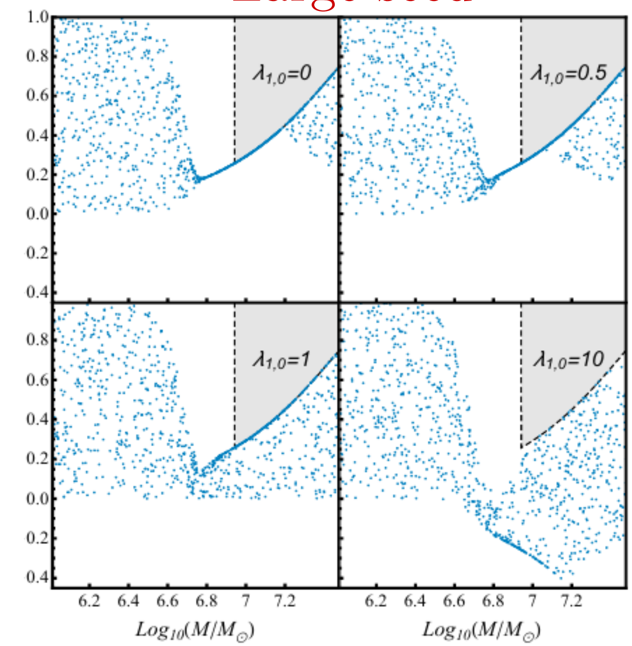


(a) $M_{S0} = 10^{-9} M_0$

Ficarra, Pani, Witek, PRD 2019



Large seed



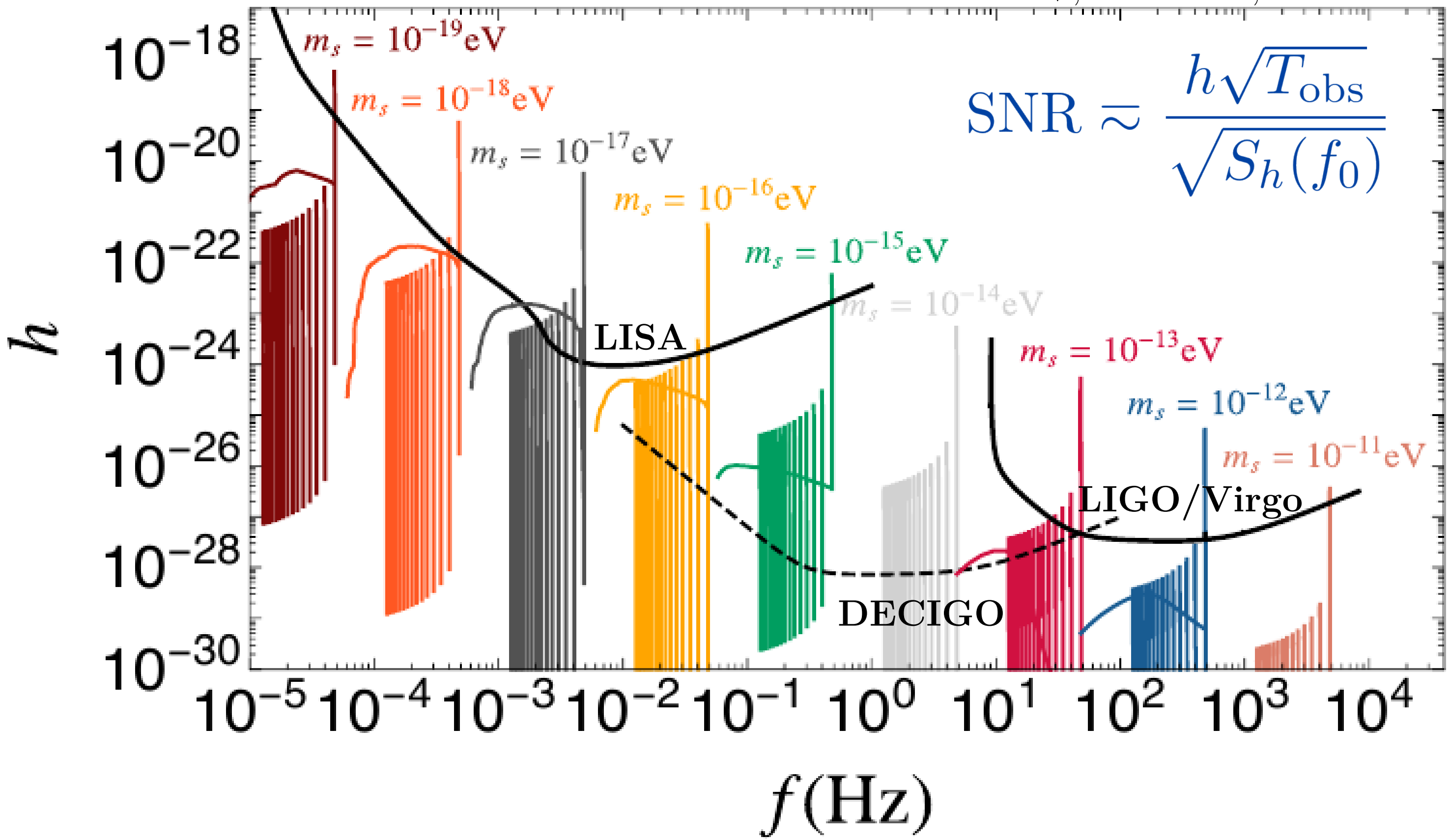
(c) $M_{S0} = 0.05 M_0$

- Evolution depends o
  - Quantum fluctuati
  - Large seed → imp
    - Might be releva
  - Quasi-adiabatic evolution agrees well with numerical simulations [Okawa+ 2018]

GW signatures

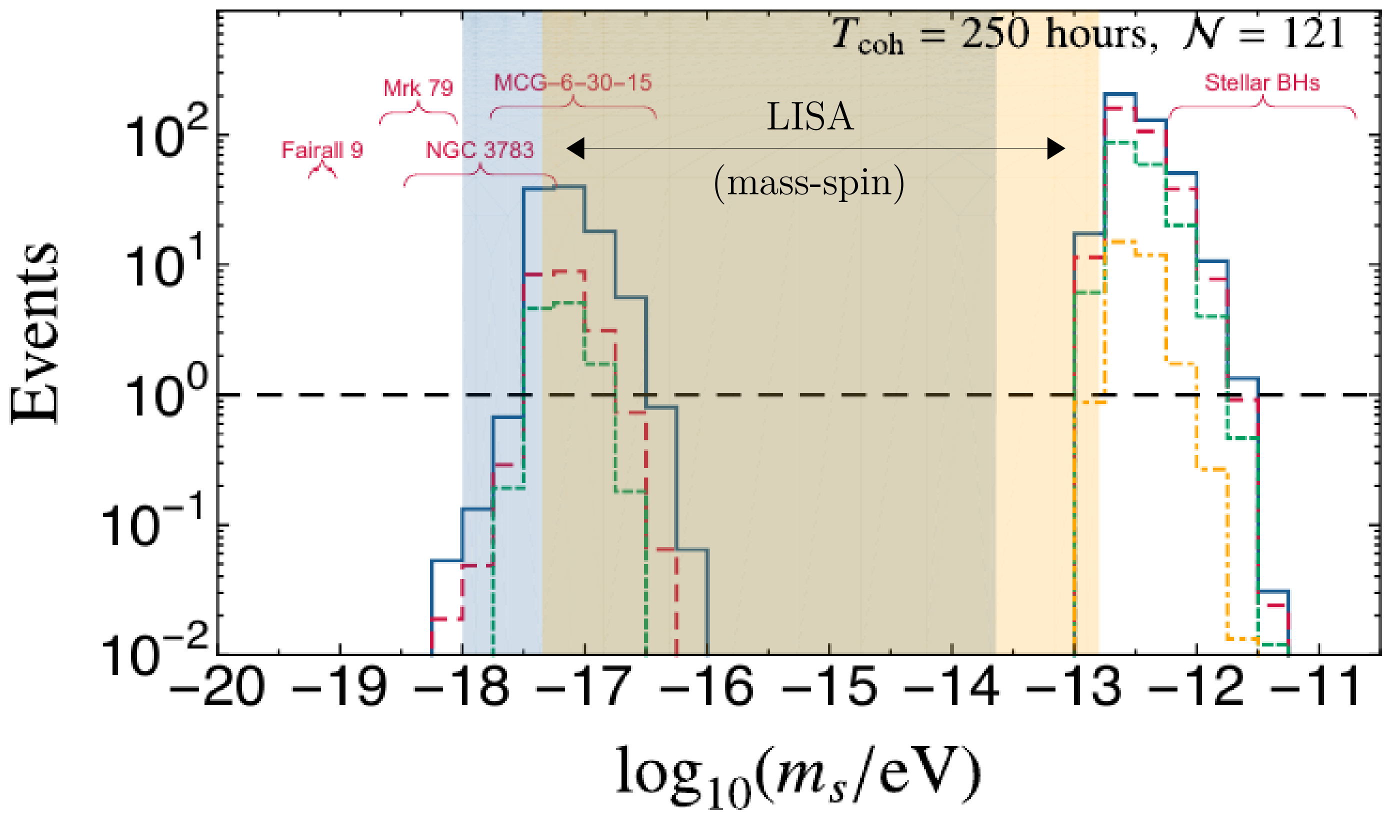
- Continuous GW source at a frequency given by the axion mass

Brito+, PRL 2017, PRD 2017



Towards multiband GW constraints on ultralight fields

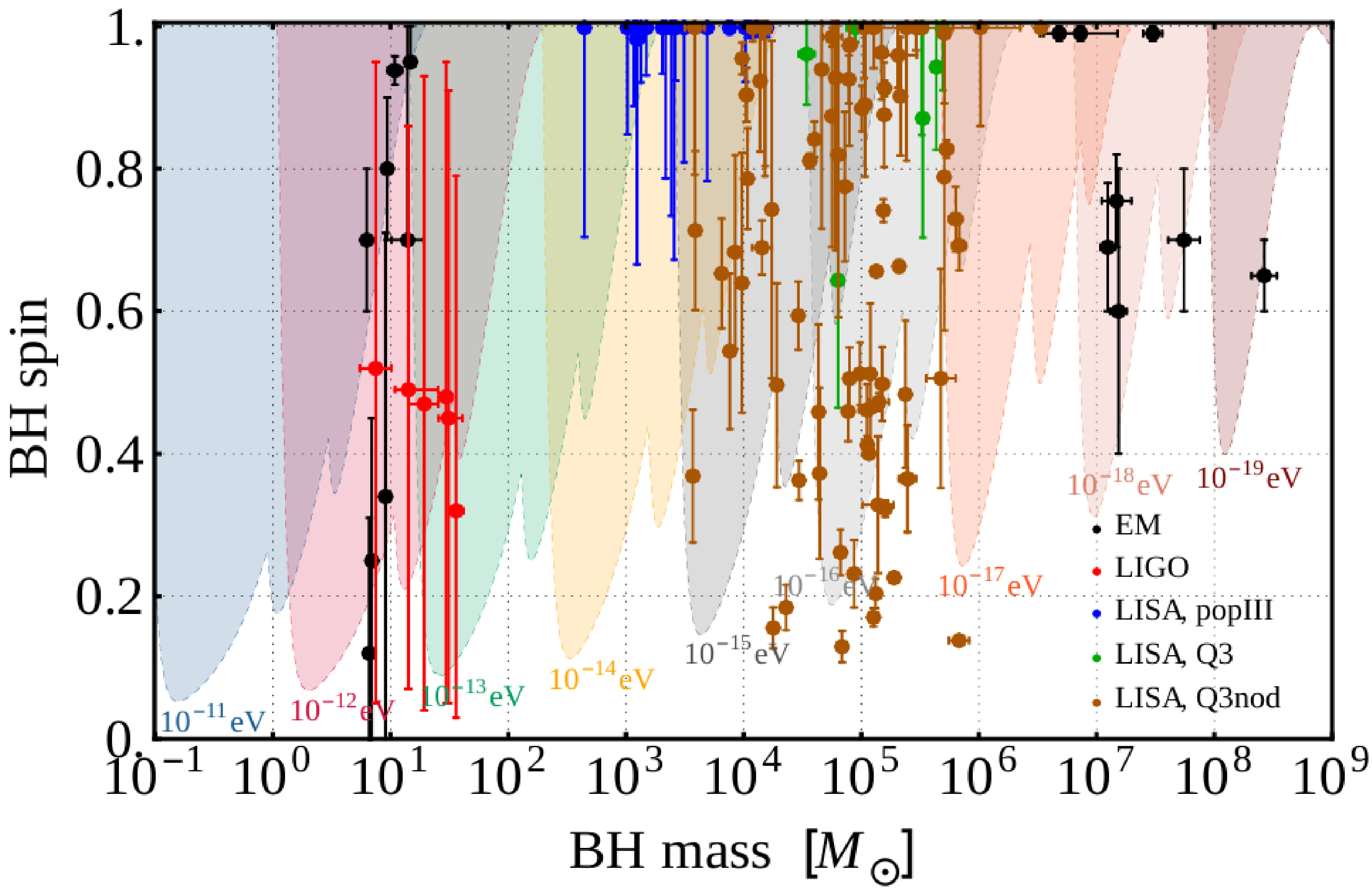
GW direct detection



- Pipeline in LIGO/Virgo [D'Antonio 2018, Isi+ 2018]

BH mass-spin distribution

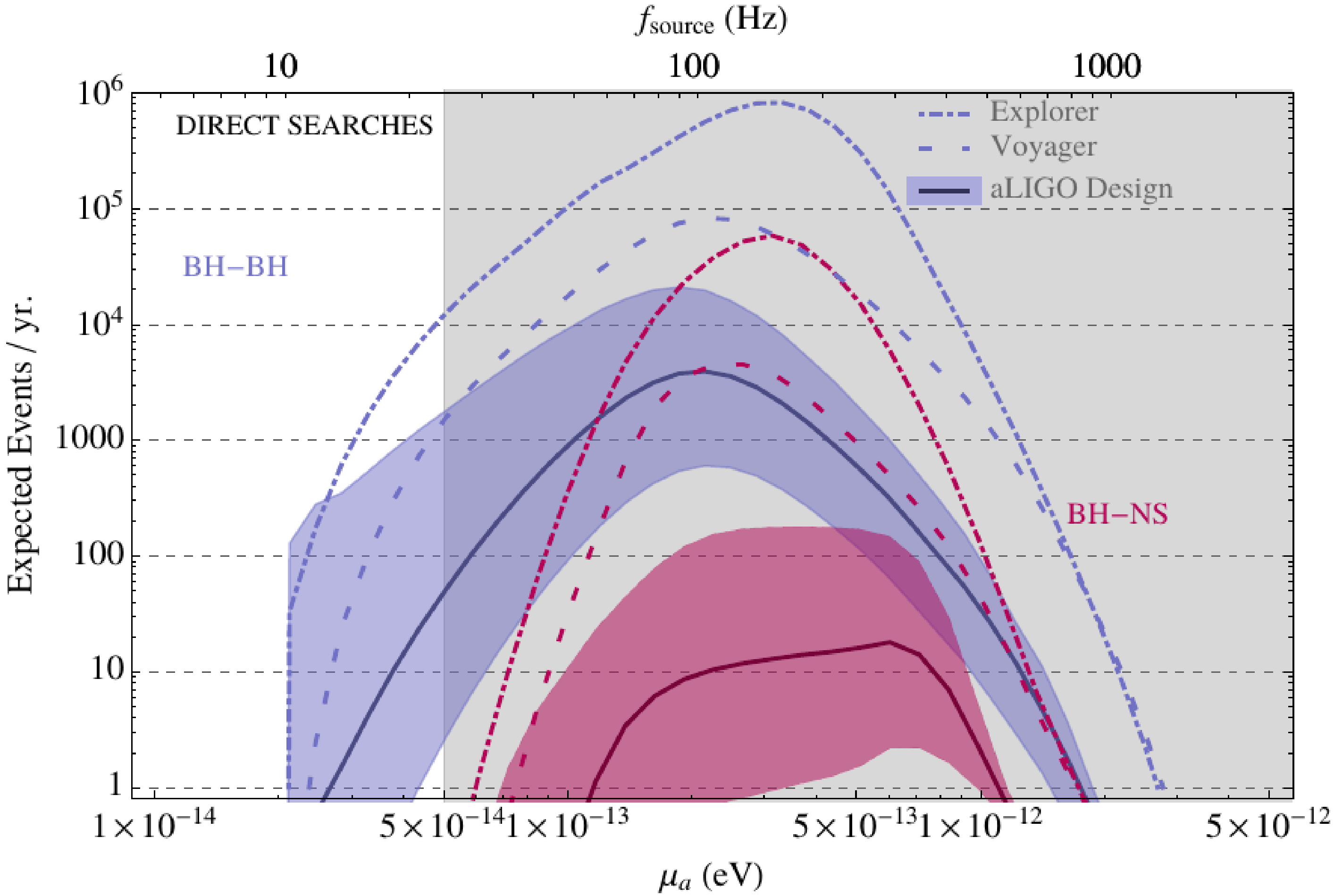
Arvanitaki+ 2014-2016, Baryakhtar+ 2017, Brito+ 2017, Cardoso+ 2018



- LISA will fill the mass gap by detecting intermediate-mass BHs
- Stronger constraints for dark photons and massive spin-2 fields

Follow-up searches

Arvanitaki+ 2014-2016, Baryakhtar+ 2017, Ghosh+ 2018



- "Axion" counterpart for LIGO/Virgo

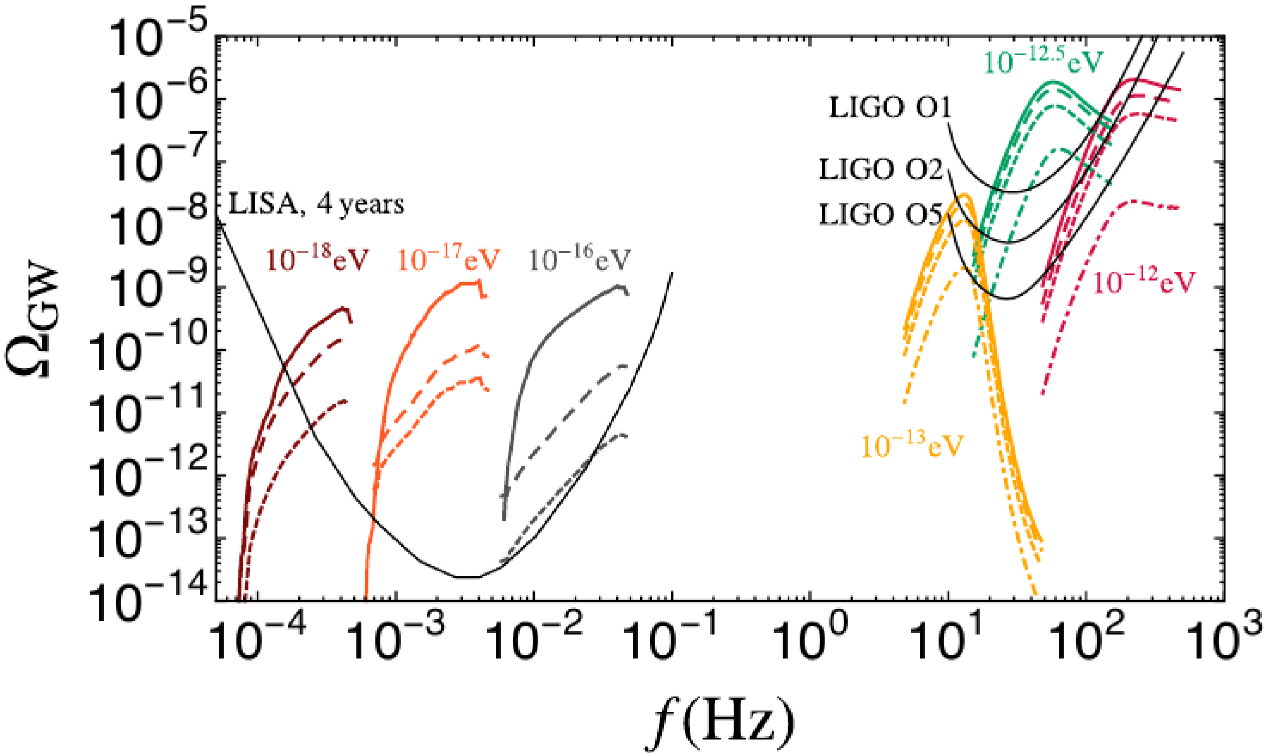
Stochastic background from axions

Brito+ PRL, PRD 2017

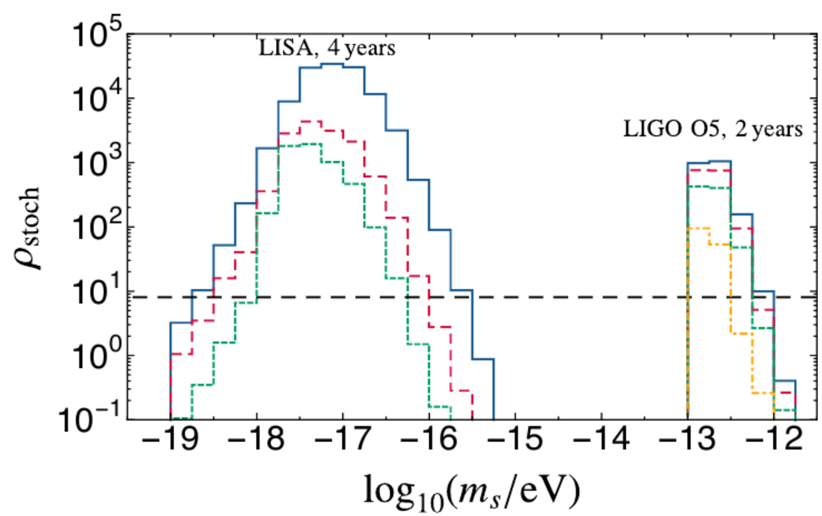
$$\Omega_{\rm GW}(f) = \frac{f}{\rho_{\rm crit}} \int_{\rho<8} dz \frac{dt}{dz} \dot{n}(M,\chi,z) \frac{dE_s}{df_s}$$

Formation rate density per comoving volume

Energy spectrum

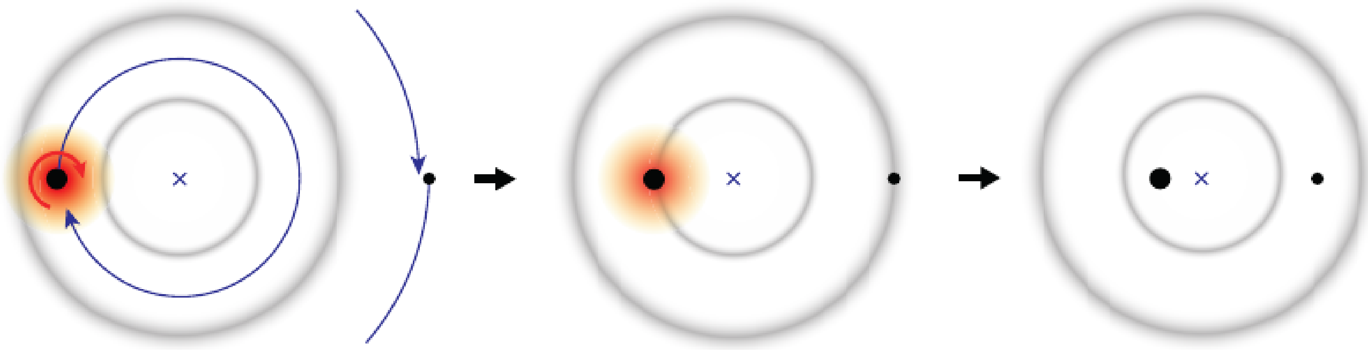


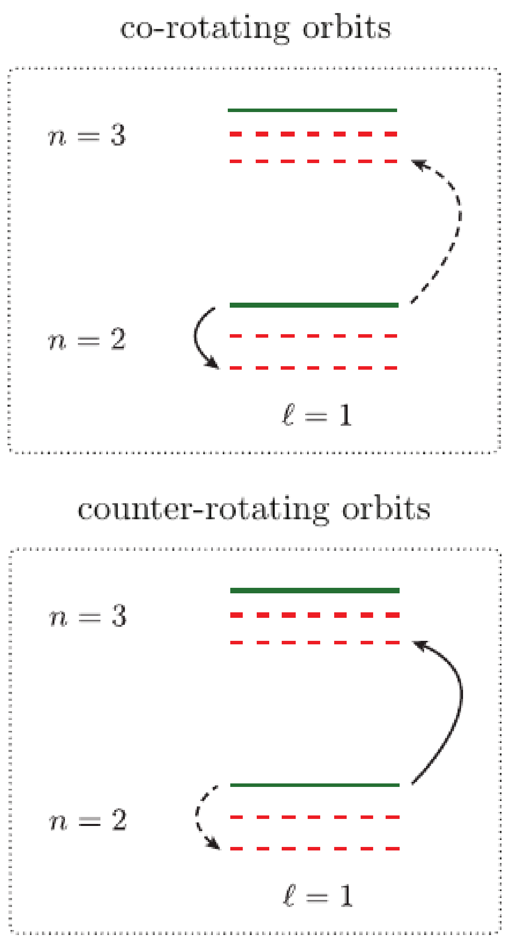
- Can affect direct detection
- Direct bounds from LIGO O1
- Actual searches [Tsukada+, 1812.09622]



Probing superradiance in binaries

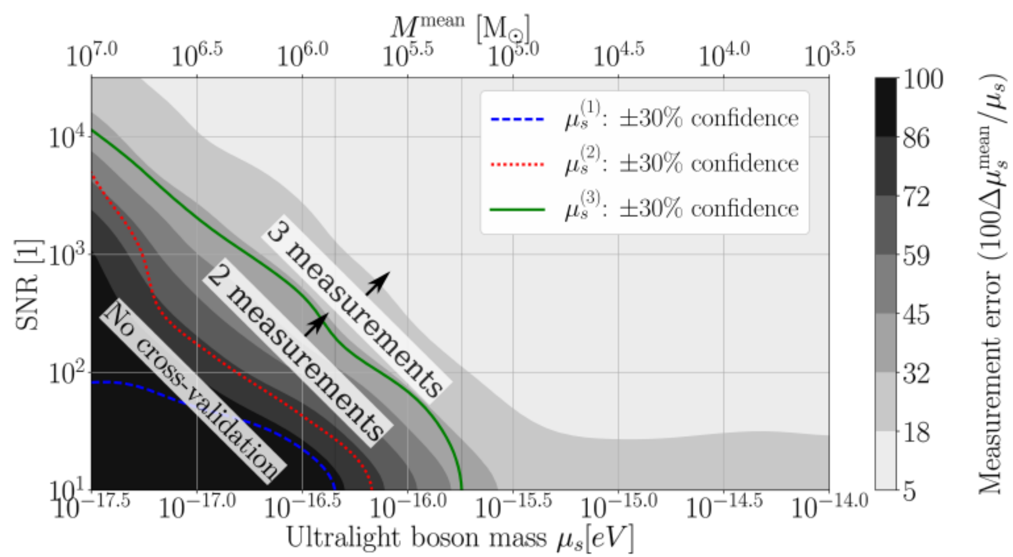
Baumann+ PRD 2019, Hannuksela+ Nature Astron. 2019





- Resonant excitation of levels, depletion of the cloud
- EMRIs can probe the cloud mass function

[Macedo+ ApJ 2013, Hannuksela+ Nat. Astron. 2019]



Coupling to photons

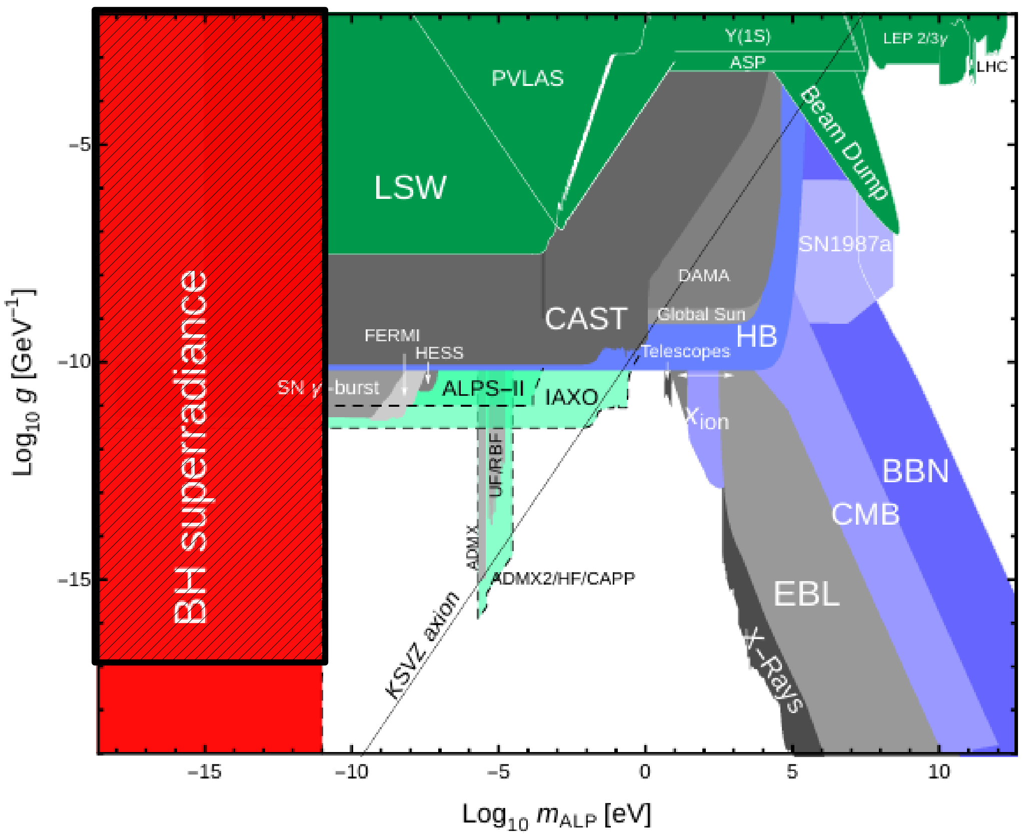
Rosa+ PRL 2018, Ikeda+ PRL 2019, Boskovic+ PRD 2019

$$\mathcal{L} = \frac{R}{k} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - \frac{\mu^2}{2}\Phi^2 - \frac{k_{\rm axion}}{2}\Phi\,{}^*F^{\mu\nu}F_{\mu\nu}$$

- Axion stimulated decay to photon even in flat space
- Blasts of light from Kerr BHs if

$$k_{\rm axion} \gtrsim 2\left(\frac{M}{M_{\rm S}}\right)^{1/2}(\mu M)^{-2}$$

- Millisecond radio burst from axions and primordial BHs [Rosa+ PRL 2018]



Superradiant instabilities in stars

Cardoso, Pani, Yu, PRD 2017

- Electrical conductivity replaces the horizon

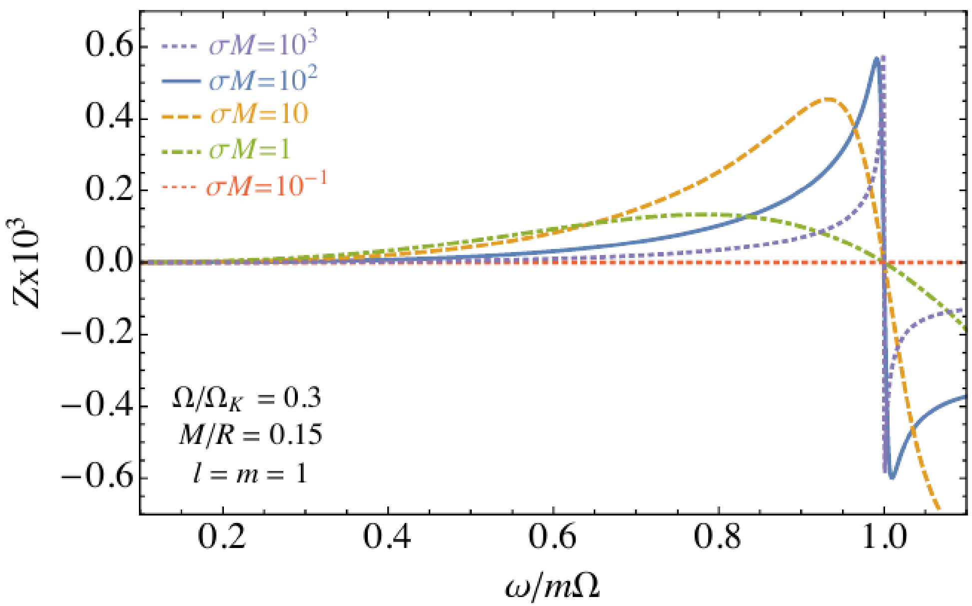
$$\mathcal{L} = \frac{R}{16\pi} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} + 4\pi j^\mu A_\mu - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{m_V^2}{2}X_\nu X^\nu$$

$$\vec{j} = \sigma \vec{E}$$

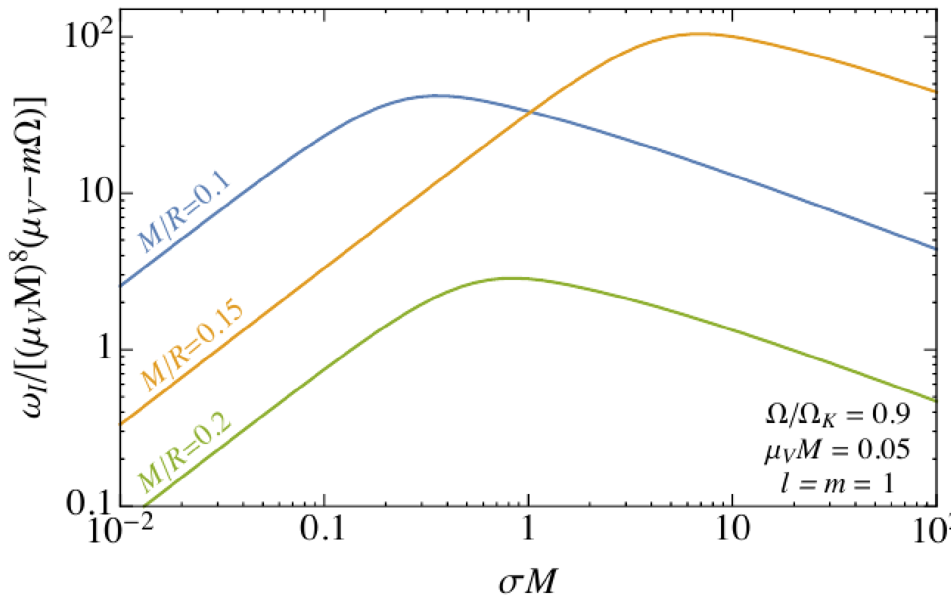
conductivity

$$\sigma \sim nq^2\tau/m$$

Superradiant scattering of EM waves



Instability for dark photons



$$\omega_I \sim -\alpha_1 \frac{M\sigma}{\alpha_2 + (M\sigma)^{3/2}}(Mm_V)^{4l+4+2S}(m_V - m\Omega)$$

Superradiant instabilities in stars

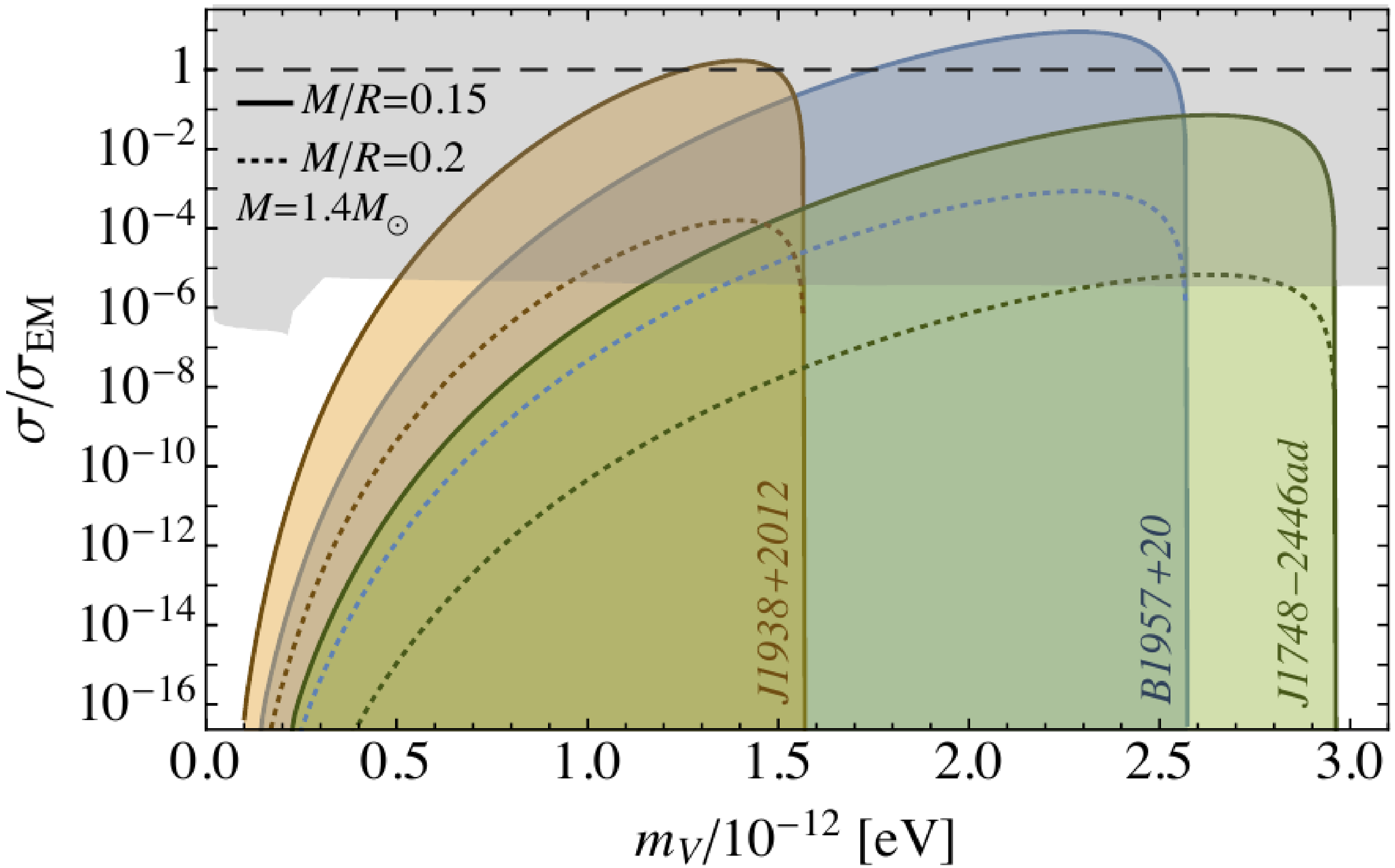
Cardoso, Pani, Yu, PRD 2017

$\tau_{\rm instab}(\sigma, M, R, \Omega, m_V) \sim 10^8\,\text{yr}$

Superradiant-instability time scale

$\tau_{\rm spindown} \sim 10^{10}\,\text{yr}$

Measured for several pulsars



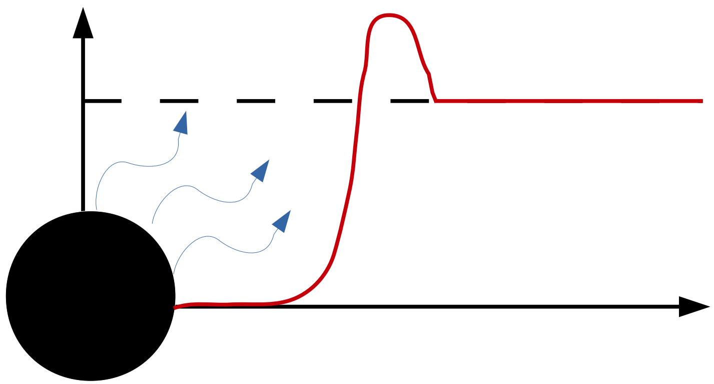
Pulsar-timing measurements of spin and spin-down rates put direct constraint on dark-photon models

Primordial BH bombs

PP & Loeb, Phys.Rev. D88 (2013) 041301

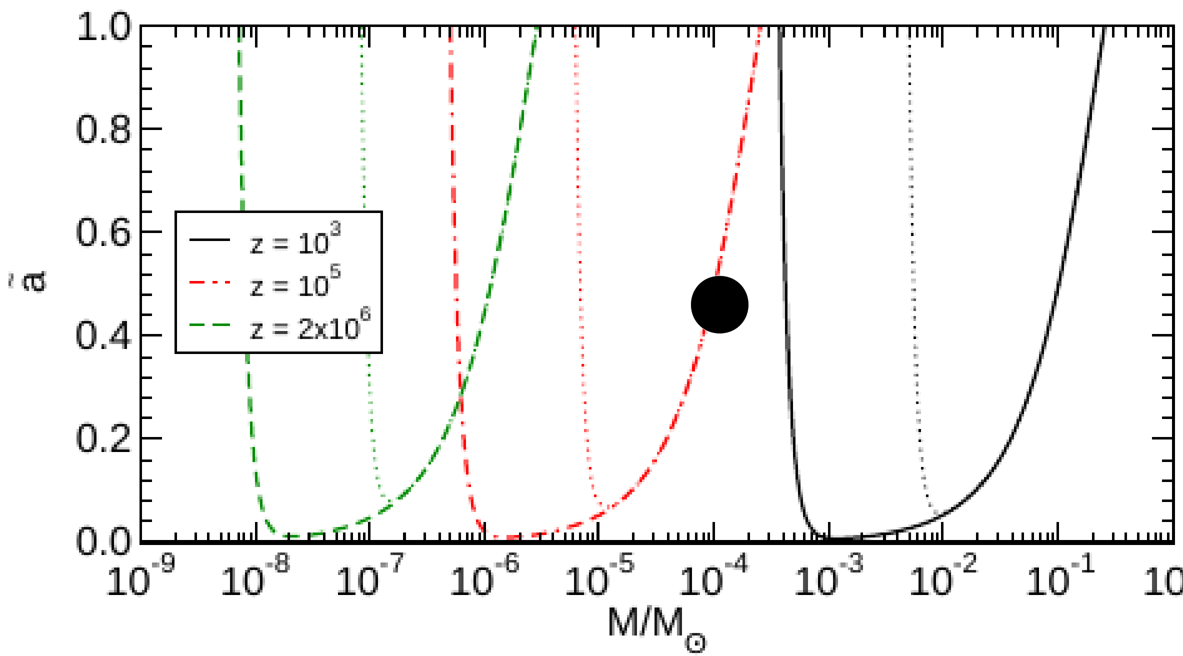
$$\nabla_\sigma F^{\sigma\nu} = \omega_p^2 A^\nu \qquad \omega_p = \sqrt{4\pi e^2 n/m_e}$$

Plasma frequency



Superradiant instability

at different redshift



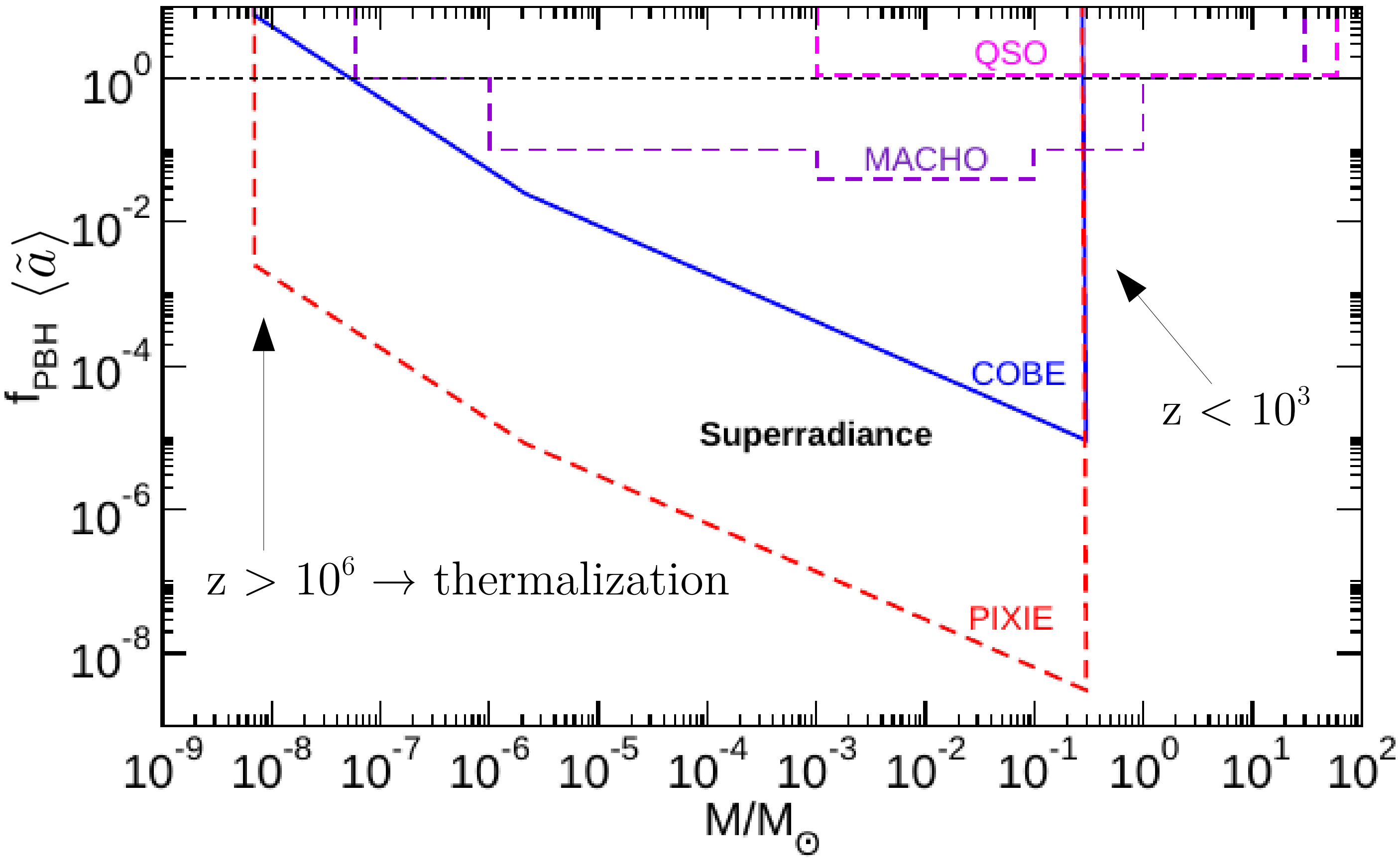
$$\frac{\Delta M}{M} \approx \frac{\tilde{a}M\omega_R}{1-2\tilde{a}M\omega_R} \approx 10^{-3}\left(\frac{1+z}{10^3}\right)^{3/2}\left(\frac{\tilde{a}M}{10^{-3}M_\odot}\right)$$

- Also investigated in the context of Fast Radio Bursts Conlon & Herdeiro, PLB (2018)

Primordial BH bombs

PP & Loeb, Phys.Rev. D88 (2013) 041301

$$\frac{\Delta U}{U} = \langle \tilde{a} \rangle f_{\rm PBH} M \frac{\rho^0_{\rm crit}\Omega_{\rm DM}}{\sigma T_0^4}\sqrt{\frac{4\pi e^2 n_0}{m_e}}(1+z)^{1/2}$$



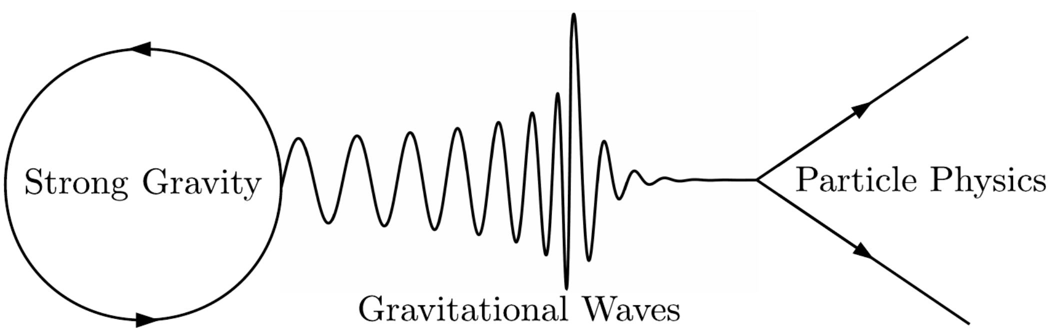
- 95% confidence-level bounds due to μ and y CMB distortions

Bounds depend linearly on the PBH spin (should be small [Harada+ 2017, Mirbabayi+ 2019, De Luca+ 2019])

Conclusion & Open Issues

Smoking guns from BH superradiant instabilities

- Gaps in the BH Regge plane → highly-spinning BHs disfavored
- Periodic GW sources → detecting ultralight bosonic DM with LIGO/Virgo?
- Pulsar-timing constraints on superradiant instabilities in neutron stars
- Bounds on spinning PBHs



Cardoso-Pani, CERN Courier 2017

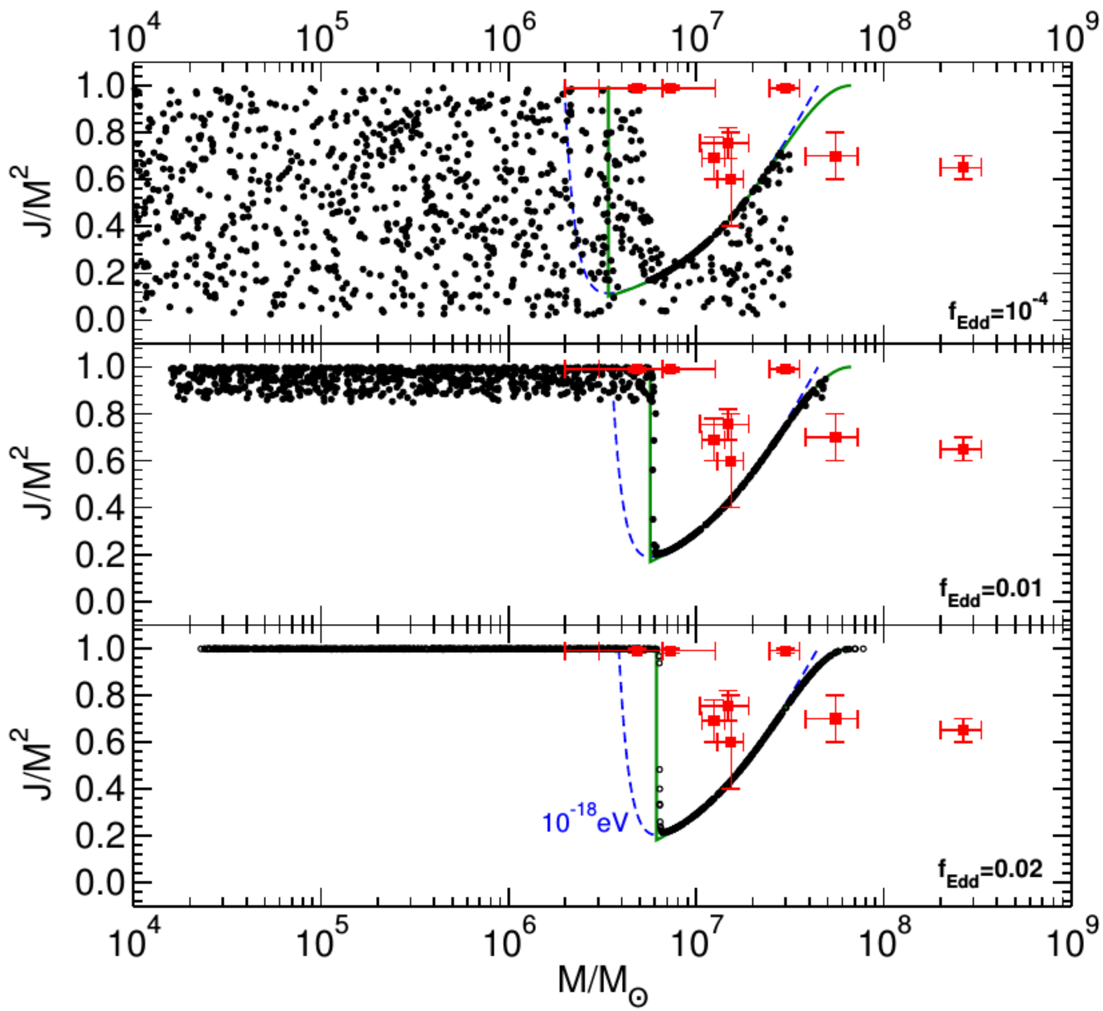
Open problems:

- Massive spin-2, plasma, nonlinear coupling, effects in binaries, ...

Backup slides

“Nothing is More Necessary than the Unnecessary” [cit.]

Gaps in the BH "Regge plane"



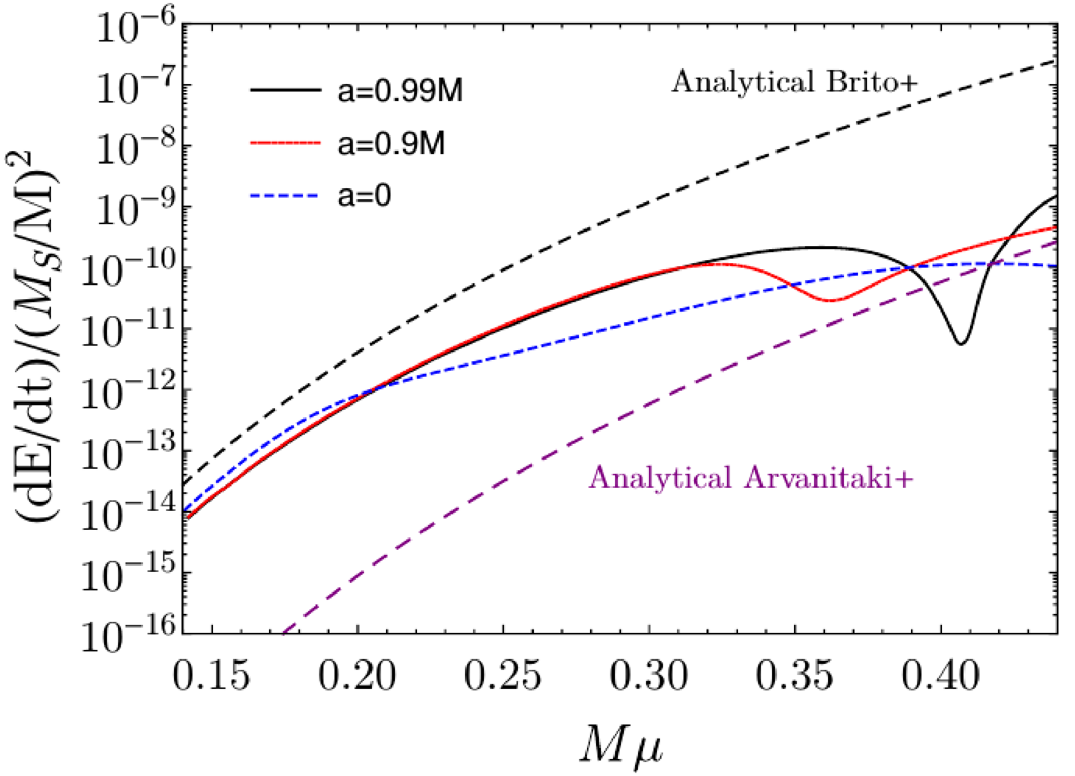
Generic prediction: "gaps" in the BH "Regge plane"

Arvanitaki+, Phys.Rev. D83 (2011) 044026

Evolution of BH-axion condensates

Brito, Cardoso, PP, 2015 Class. Quantum Grav. 32 134001

$$S = \int d^4x\sqrt{-g}\left(\frac{R}{16\pi} - \frac{1}{2}g^{\mu\nu}\Psi^*_{,\mu}\Psi_{,\nu} - \frac{\mu^2}{2}\Psi^*\Psi\right)$$



$$\dot{E}_{\rm GW} \sim (M\mu)^{14}\left[M_{\rm S}/M\right]^2$$

Yoshino & Kodama, PTEP 2014 (2014) 043E02

$$\dot{M}_{\rm accr} \sim 0.02 f_{\rm Edd}\frac{M}{10^6 M_\odot} M_\odot {\rm yr}^{-1}$$

Barausse, Cardoso, PP, Phys.Rev. D89 (2014) 104059

Hidden conductivity

$$\mathcal{L}_{eff} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$$

Mass basis

$$A_\mu \to A_\mu + \epsilon X_\mu \quad \Longrightarrow \quad \mathcal{L}_{\text{eff}} \supset \epsilon j_\mu X^\mu$$

$$j^\mu = \sigma F^{\mu\nu} u_\nu \to \sigma F^{\mu\nu} u_\nu + \epsilon\sigma X^{\mu\nu} u_\nu + \mathcal{O}(\epsilon^2)$$

Hidden conductivity

Evolution of the SR instability