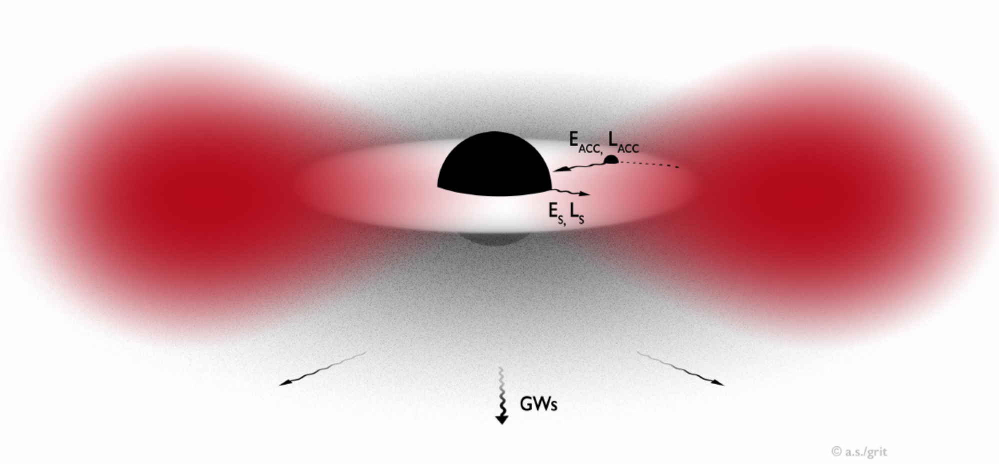
Probing dark matter with black holes and gravitational waves



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[**overview:** R. Brito, V. Cardoso, P. Pani - Springer Lect.Notes Phys. 906 (2015) - **1501.06570**]

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Outline

- Ultralight fields beyond the Standard Model
- Black-hole (BH) superradiant instability
- Adiabatic evolution of bosonic condensates near BHs
- Gravitational-wave (GW) signatures
- Superradiant instabilities triggered by plasma
- Superradiance in stars

Ultralight fields in the dark universe?

- Compelling dark-matter candidates alternative to WIMPs
  - **Fuzzy DM:** mass~10^{-22} eV → may solve sub-kpc problems

    Hui, Ostriker, Tremaine, Witten, PRD95 043541 (2017)
  - **Plethora of sub-eV DM particles:**
    - QCD axion, stringy axion-like particles (ALPs)
    - Dark photons & hidden sectors, massive gravitons …

- **Common properties:**
  - Bosonic fields
  - Small-mass landscape (from sub-eV down to 10^{-33} eV)
  - Weakly coupled to SM (*or not coupled at all!*)

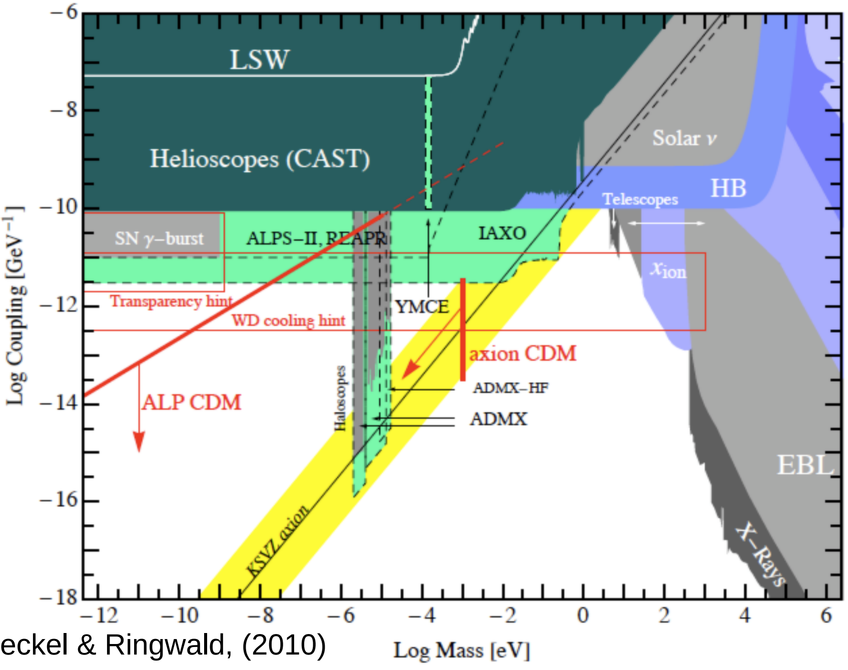
Dark sectors and ultralight particles

Essig+, 1311.0029

$$\mathcal{L} = \frac{R}{16\pi G} - \frac{1}{2}(\nabla_\mu\phi^*)(\nabla^\mu\phi) - \frac{\mu_S^2}{2}|\phi|^2 - V(|\phi|) - \kappa_{\mathrm{axion}}\phi\, F^{(a)}_{\mu\nu}{}^{*}F^{\mu\nu}_{(a)}$$

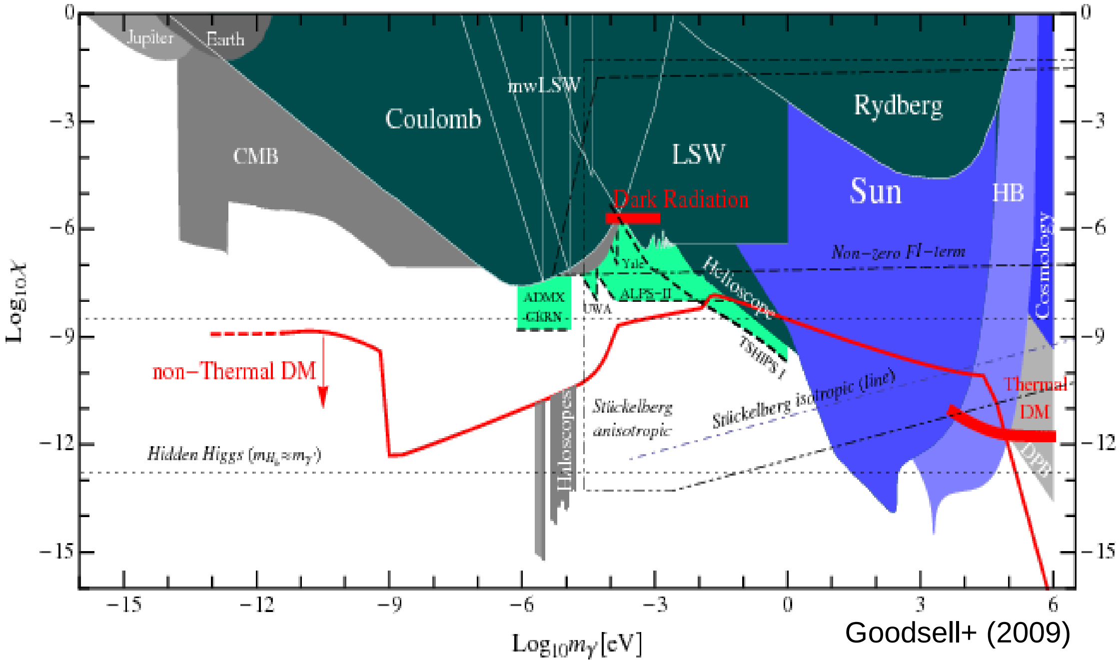
$$- \frac{1}{4g_a^2}F^{(a)}_{\mu\nu}F^{\mu\nu}_{(a)} - \frac{1}{4g_b^2}F^{(b)}_{\mu\nu}F^{\mu\nu}_{(b)} + \frac{\chi_{ab}}{2g_a g_b}F^{(a)}_{\mu\nu}F^{(b)\mu\nu} + \frac{m_{ab}^2}{g_a g_b}A^{(a)}_{\mu}A^{(b)\mu}$$

Axion-like particles (ALPs)



Jaeckel & Ringwald, (2010)

Dark photons

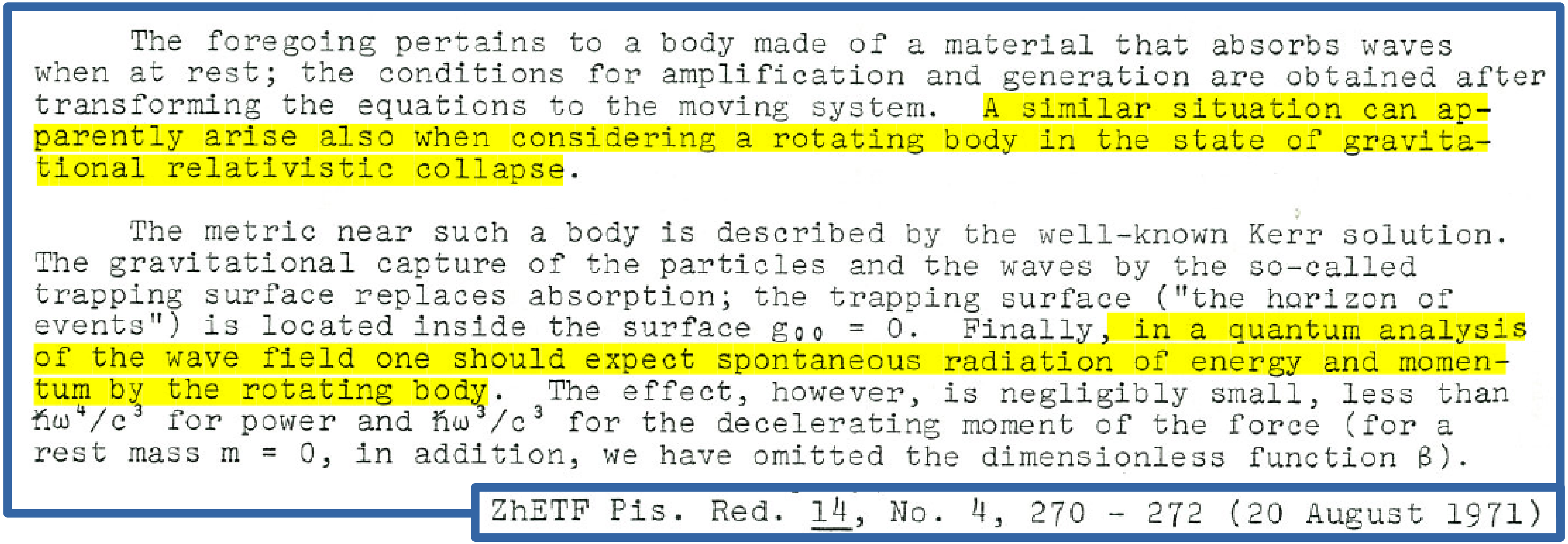


Goodsell+ (2009)

Looking for ultralight fields in strongly-gravitating systems?

Superradiance

Teukolsky, Zeldovich, Press (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)

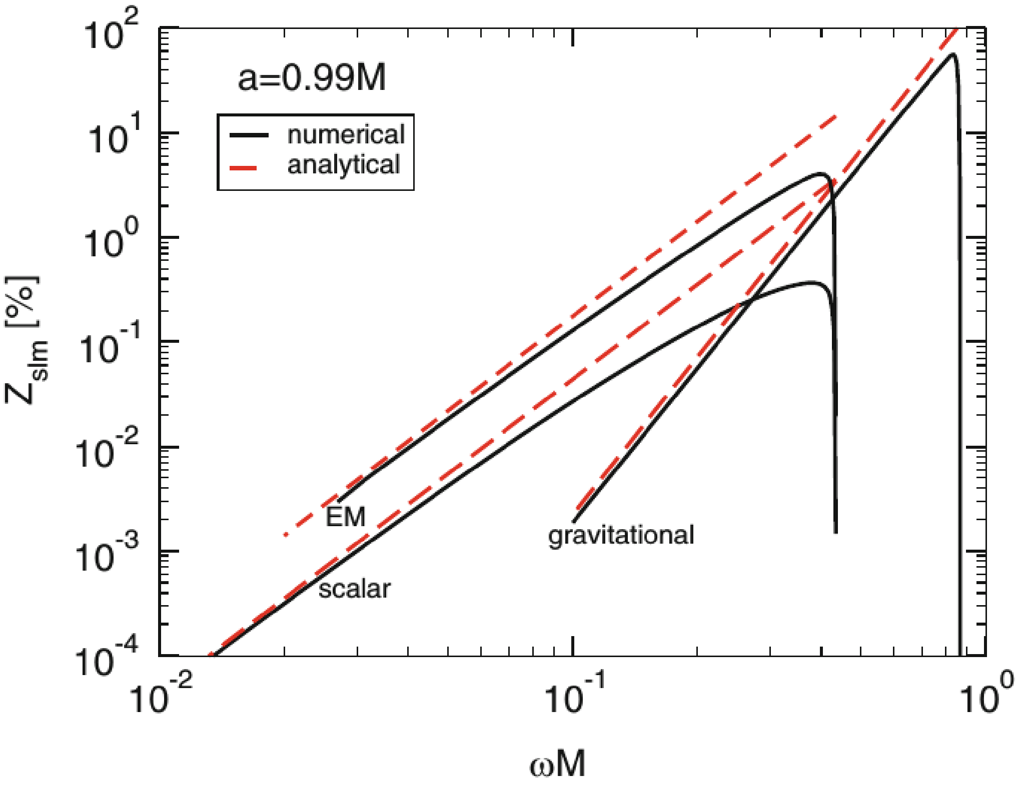
- Superradiant scattering off a Kerr BH when $\omega/m < \Omega_H$
- Requires **dissipation** → event horizon

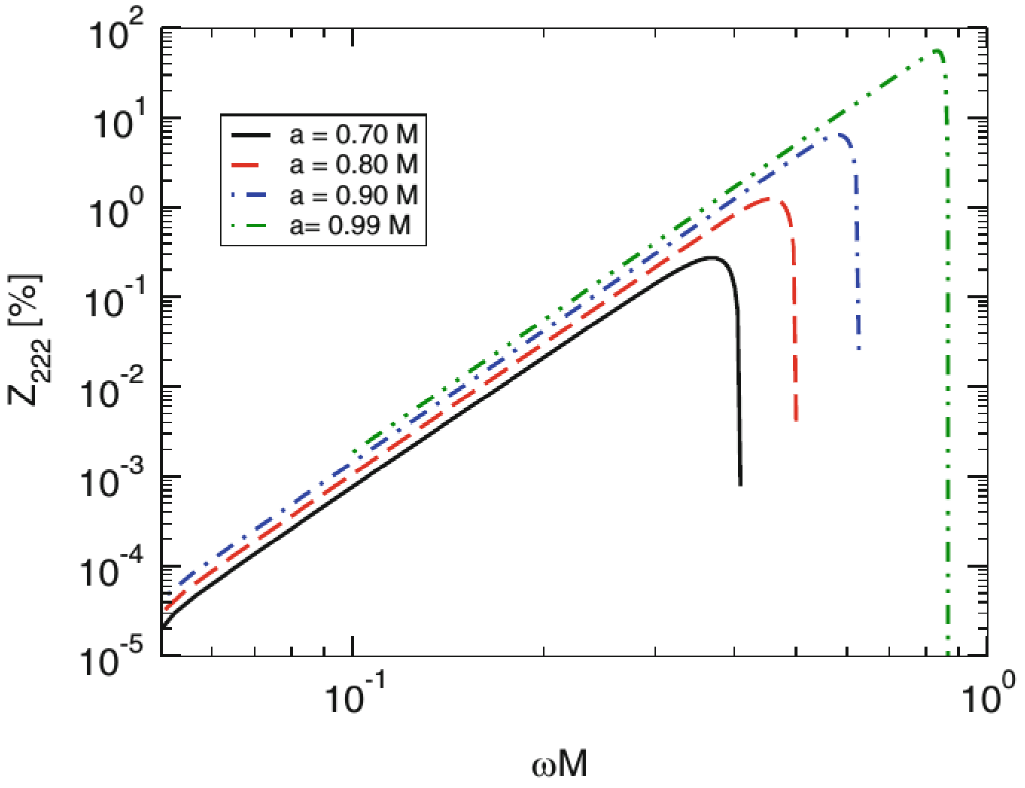
Thorne, Price, Macdonald's “Membrane Paradigm” (1986)
Richartz+, Phys.Rev. D80 (2009) 124016
Brito, Cardoso, PP, “Superradiance” Springer (2015)

- Amplification depends on the **nature of the bosonic field**
- Verified in the lab

Torres+, Nature Phys. 13 (2017) 833-836

Superradiant scattering





- Larger amplification for GWs (spin=2), requires high spin
- Nonlinear effects (slightly) decrease efficiency

East, Ramazanoğlu, Pretorius PRD 89 061503 (2014)

- Luminosity modulation in binary systems

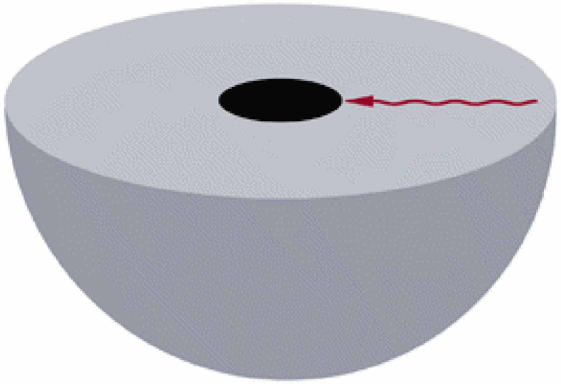
Rosa, PLB 2015 & 1612.01826

Superradiant instability

Damour, Deruelle & Ruffini; Detweiler; Zouros & Eardley 1980s;…, Shlapentokh-Rothman, 2015

- Superradiant scattering + Yukawa effective potential
- Spinning BHs are unstable against massive bosons

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



Press & Teukolsky, Nature 238 (1972) 211-212

- BH energy/spin extraction → condensate

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

Coupling parameter

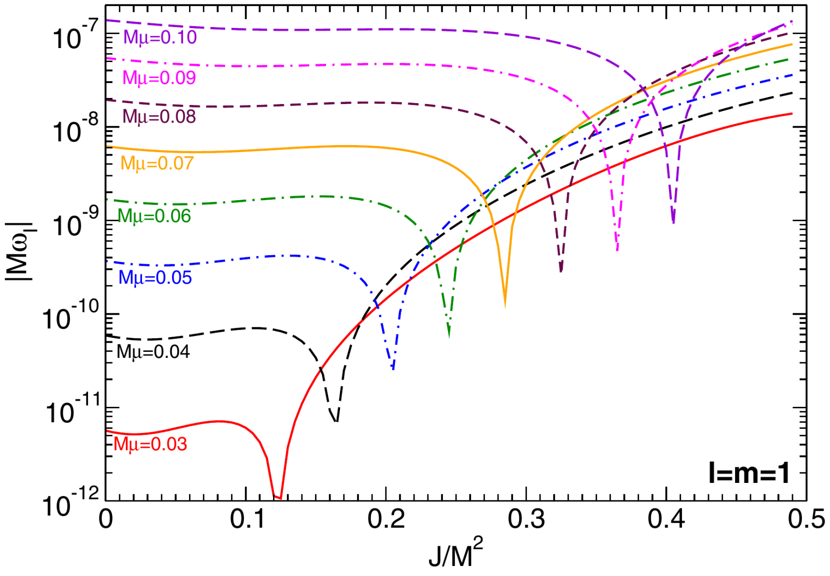
- Can be used to probe ultralight bosonic fields [Arvanitaki+ 2010-2016]
- Effective field theory [Endlich & Penco, 1609.06723]

BH instability for bosonic fields

Proca field (massive spin-1)

Pani+, Phys.Rev.Lett. 109 (2012) 131102

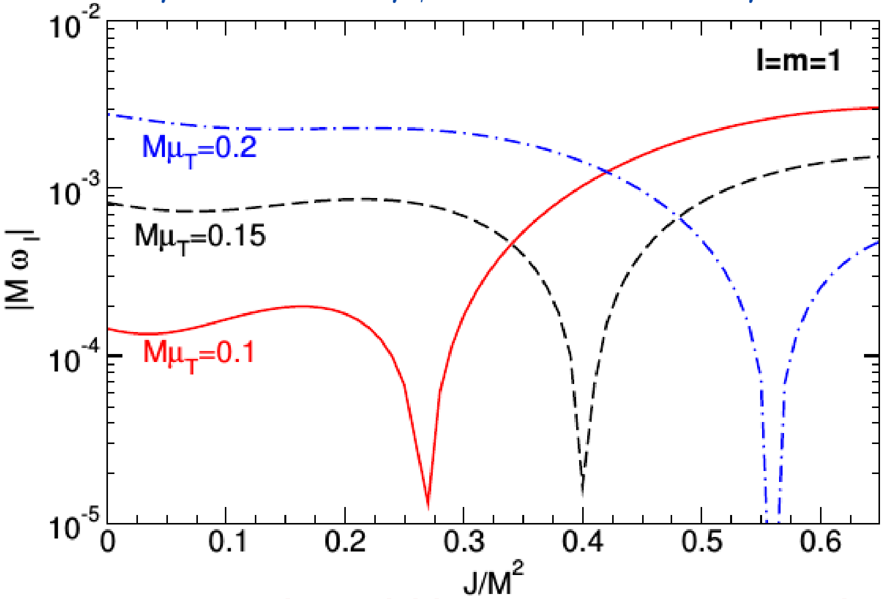
$$\nabla_\sigma F^{\sigma\nu} - \mu^2 A^\nu = 0$$



Massive spin-2

Brito, Cardoso, Pani, Phys.Rev. D88 (2013) 023514

$$\bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu}h^{\alpha\beta} - \mu_T^2 h_{\mu\nu} = 0$$



Strongest instability of a Kerr BH to date

- Instability depends on BH & particle spin:

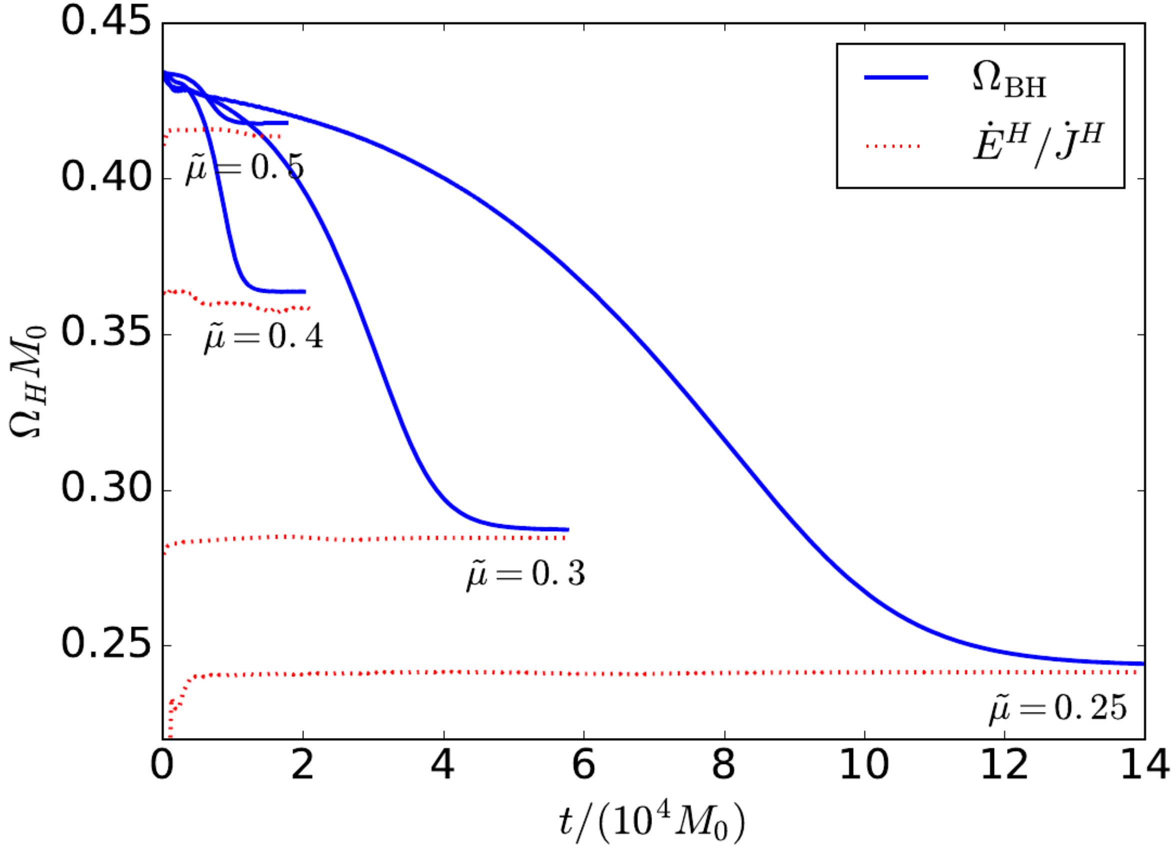
$$\omega_R \sim \mu - \frac{\mu(M\mu)^2}{2(\ell+n+S+1)^2} \qquad \omega_I \sim -\left(\omega_R - m\Omega_H\right)\left(M\mu\right)^{4\ell+4+2S}$$

Dolan 2007; Rosa & Dolan, 2012; Pani+, Phys.Rev.Lett. 109 (2012) 131102; Witek+, Phys.Rev. D87 (2013) 043513; …
Brito, Cardoso, Pani, Phys.Rev. D88 (2013) 023514; Endlich & Penco, JHEP 1705 (2017) 052; Baryakhtar+ 2017

Evolution of superradiant instability

East & Pretorius, PRL (2017)

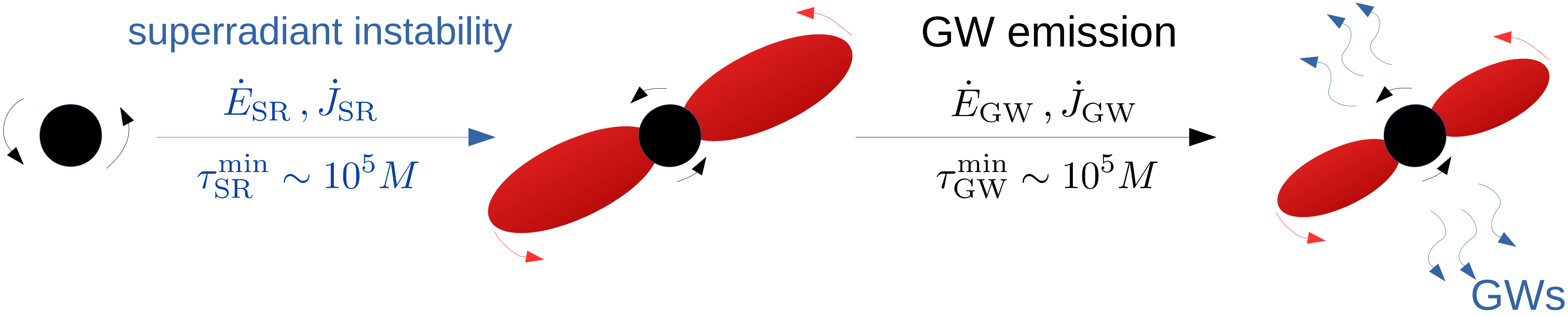
$$\omega_R \to m\Omega_H$$



- Confirms linear analysis
- Similar results charged BHs in AdS

Sanchis-Gual+, PRL116 141101 (2016)
Bosh+, PRL2016 141102 (2016)

Adiabatic approximation



- Separation of scales → adiabatic approx
- Extended cloud → linearized analysis
- GW emission → quadrupole fails
- Accretion of gas → Eddington accretion

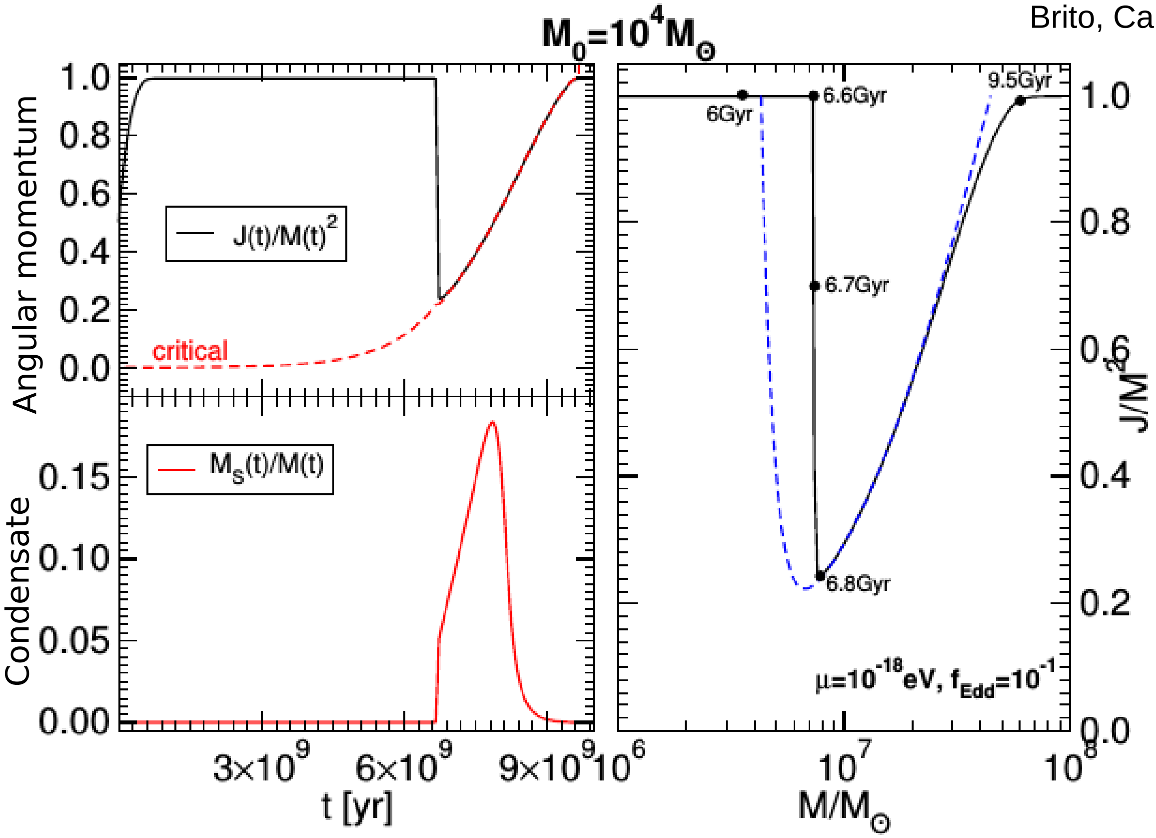
$$\begin{cases} \dot{M}+\dot{M}_{\rm SR}=-\dot{E}_{\rm GW}+\dot{M}_{\rm accr} \\ \dot{J}+\dot{J}_{\rm SR}=-\dfrac{1}{\mu}\dot{E}_{\rm GW}+\dot{J}_{\rm accr} \\ \dot{M}=-\dot{E}_{\rm SR}+\dot{M}_{\rm accr} \\ \dot{J}=-\dfrac{1}{\mu}\dot{E}_{\rm SR}+\dot{J}_{\rm accr} \end{cases}$$

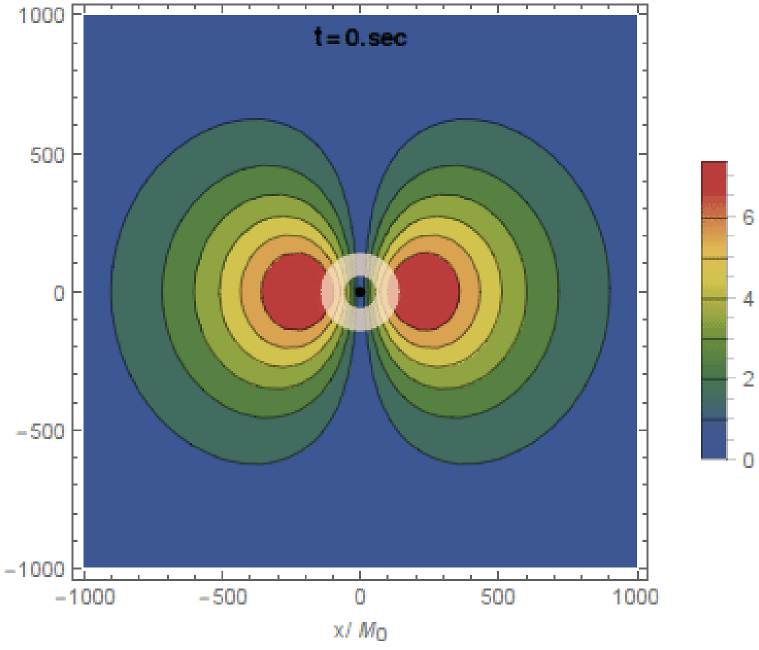
- Can be also studied in terms of transition probabilities & occupation numbers

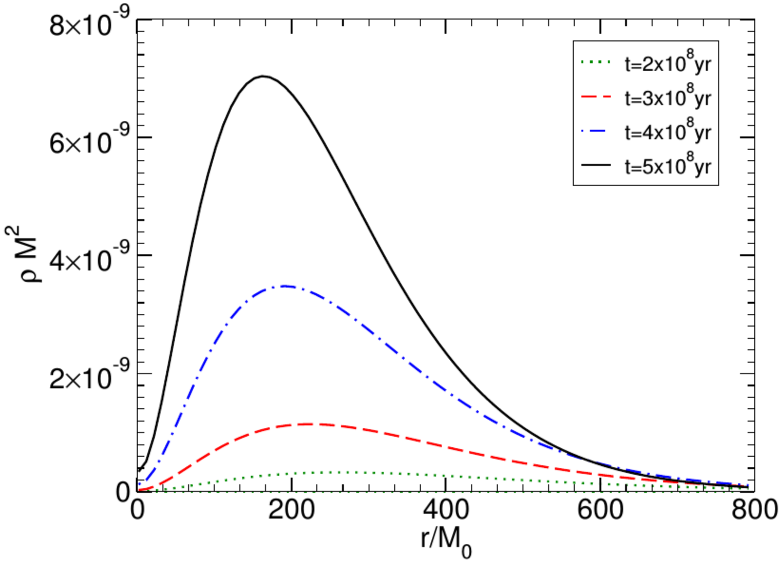
Arvanitaki+ 2014-2016

Evolution of superradiant instability

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







- Complex fields → stationary hairy BHs

Herdeiro-Radu PRL (2014)

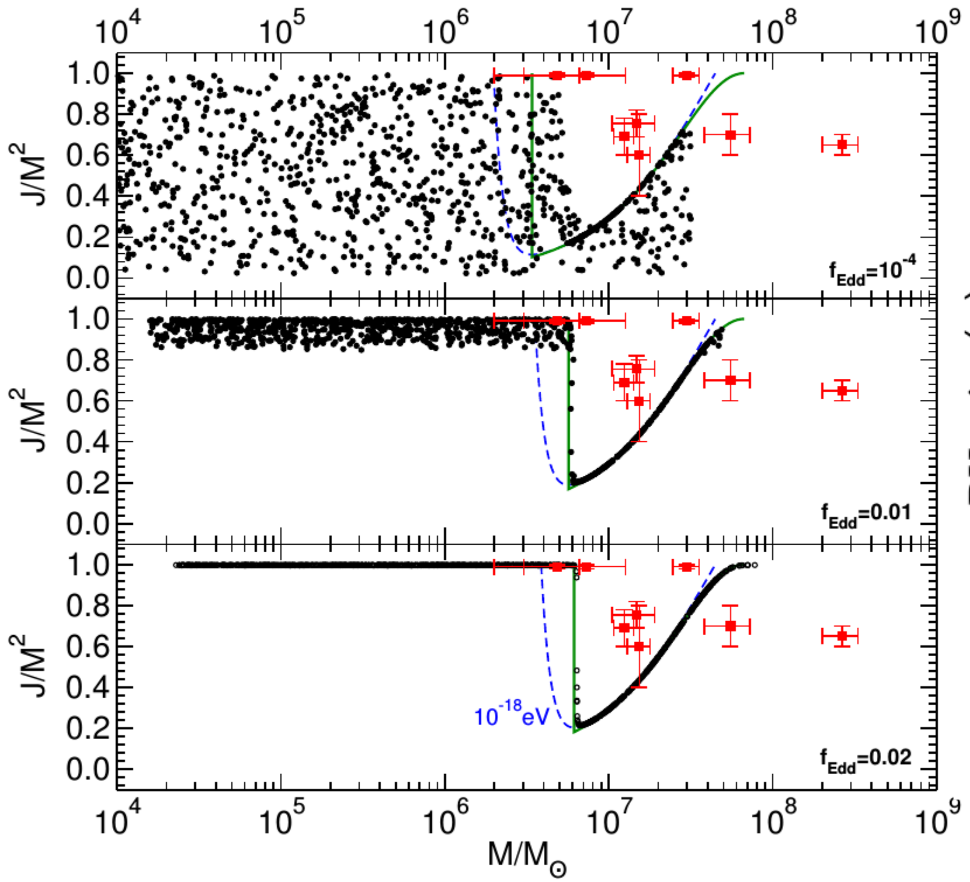
- Real fields → ultralong-lived states

- Backreaction is negligible → Kerr metric
  - No geodesic signature, but GW smoking gun

Arvanitaki, Baryakhtar, Huang, 2015, Kodama & Yoshino 2015, Brito+ 2017

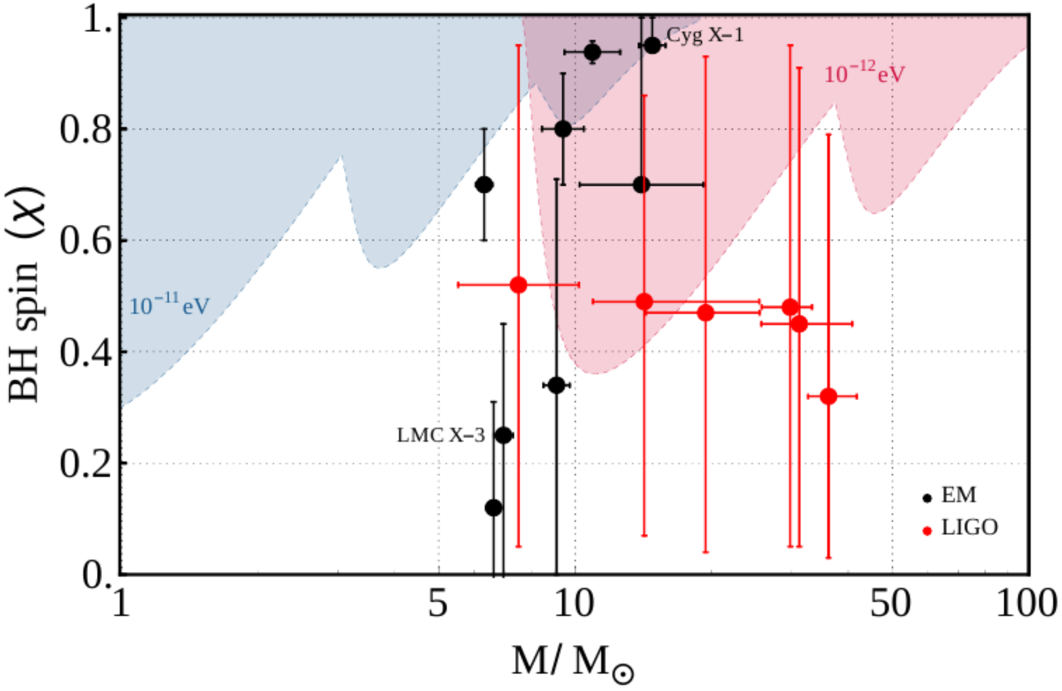
Gaps in the BH “Regge plane”

supermassive BHs



Brito, Cardoso, PP, 2015 CQG. 32 134001

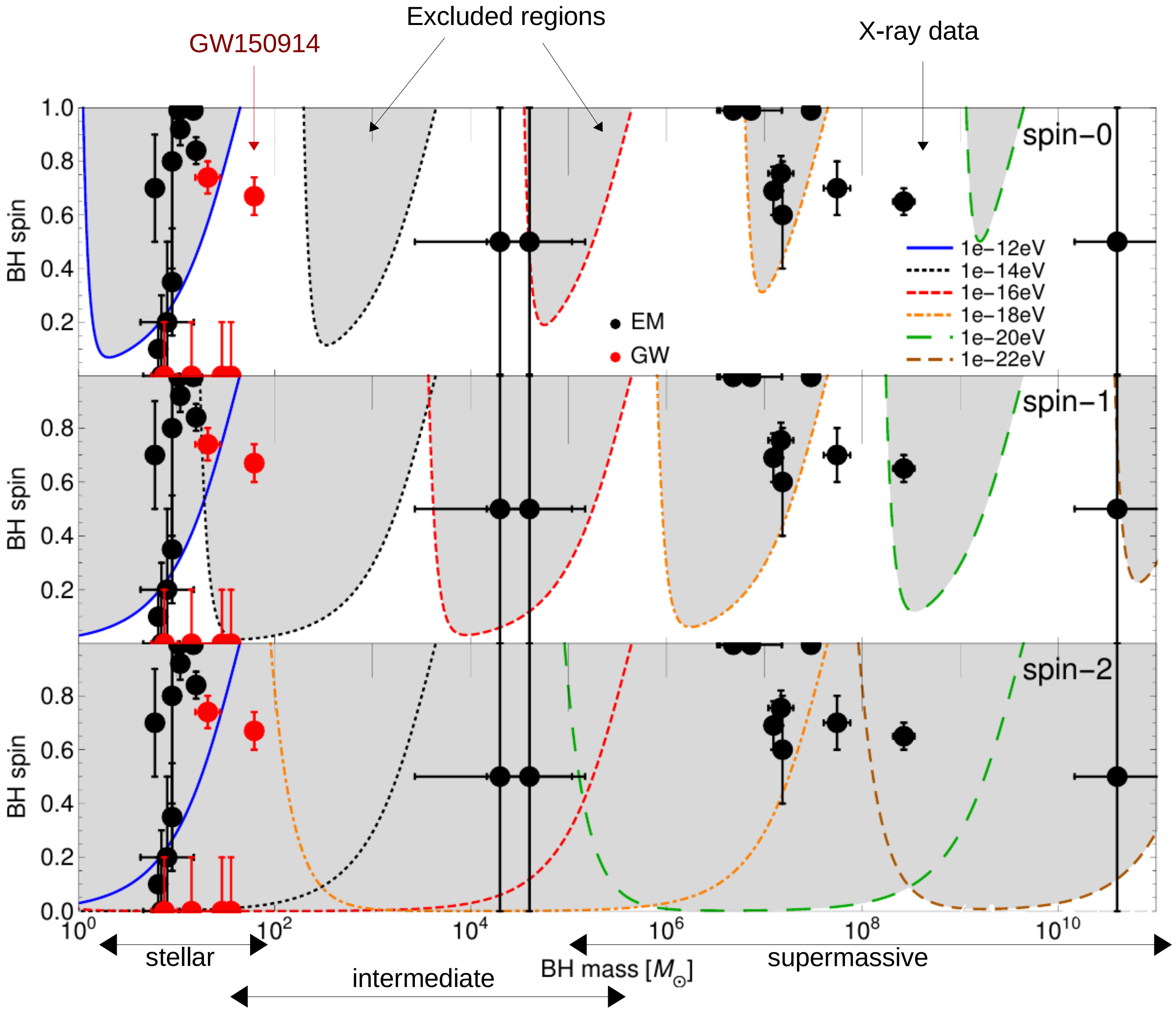
solar-mass BHs



Generic prediction: “gaps” in the BH “Regge plane”

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

Bounds on light bosons



QCD axion
Axion-like particles
String axiverse

Dark photons
Mirror DM
Massive photon

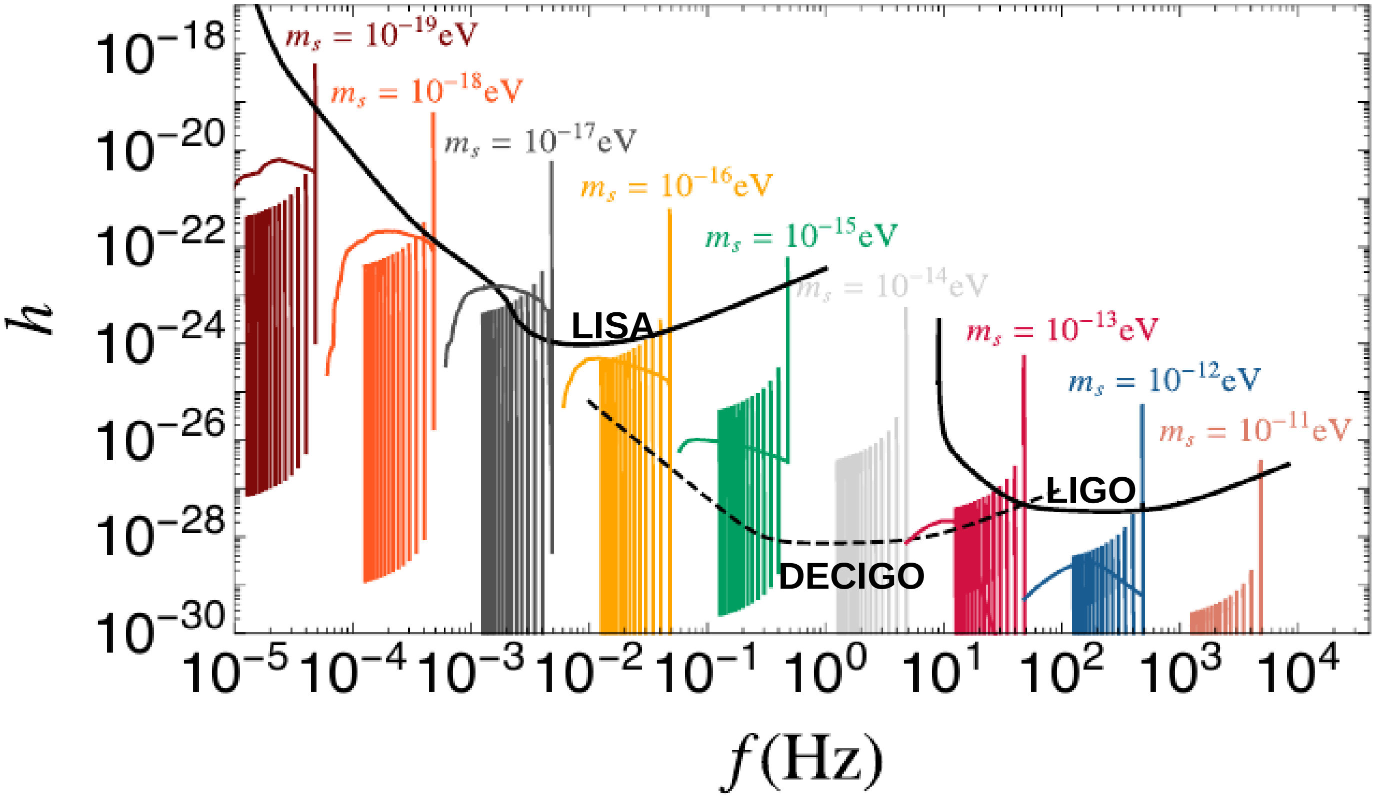
Massive spin-2
Massive graviton

Observations of highly-spinning BHs → bounds on ultralight DM

GW signatures

Arvanitaki+ 2014-2016
Baryakhtar+ 2017
Brito+ 2017

- Monochromatic signal → $\text{SNR} \approx \dfrac{h\sqrt{T_{\rm obs}}}{\sqrt{S_h(f_0)}}$ → Continuous GW source

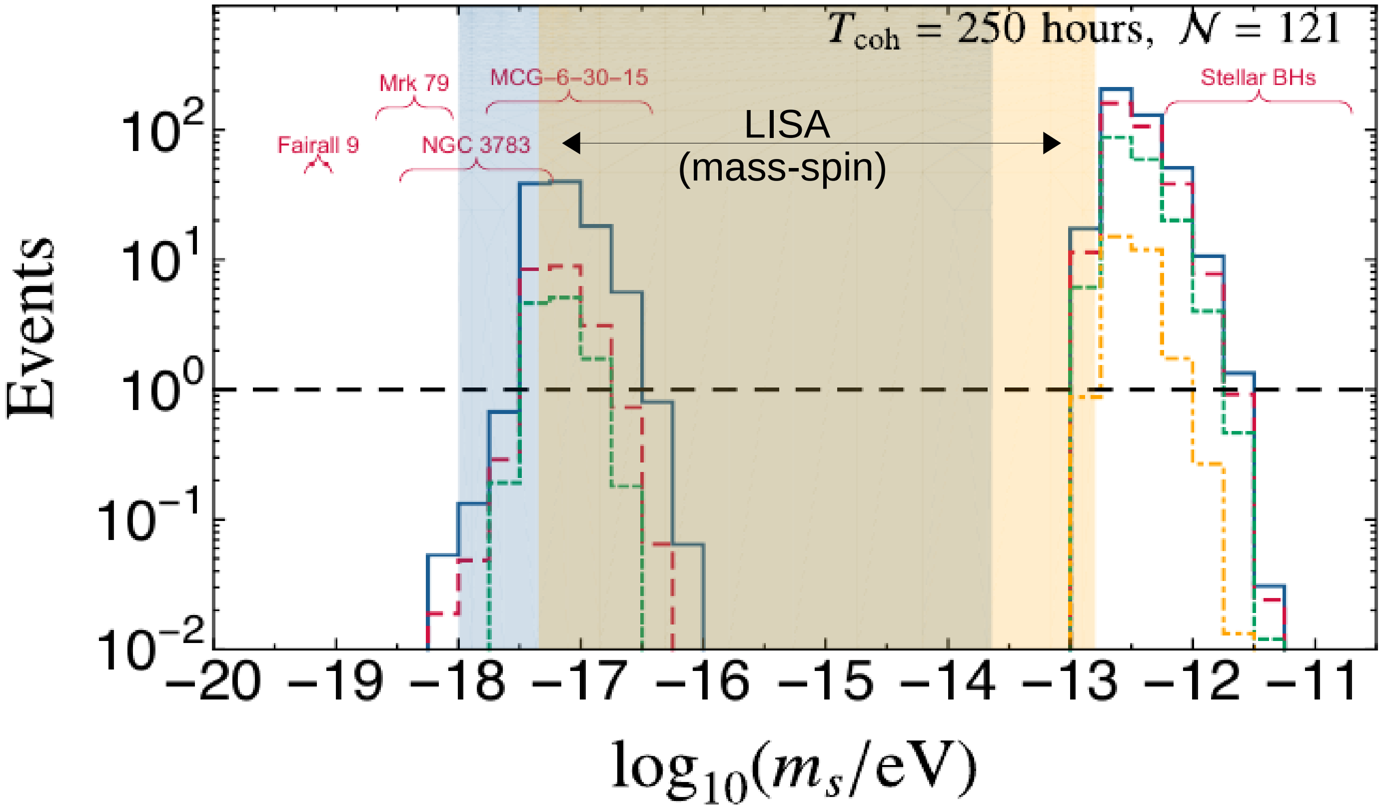


Towards multiband GW constraints on ultralight fields

GW direct detection

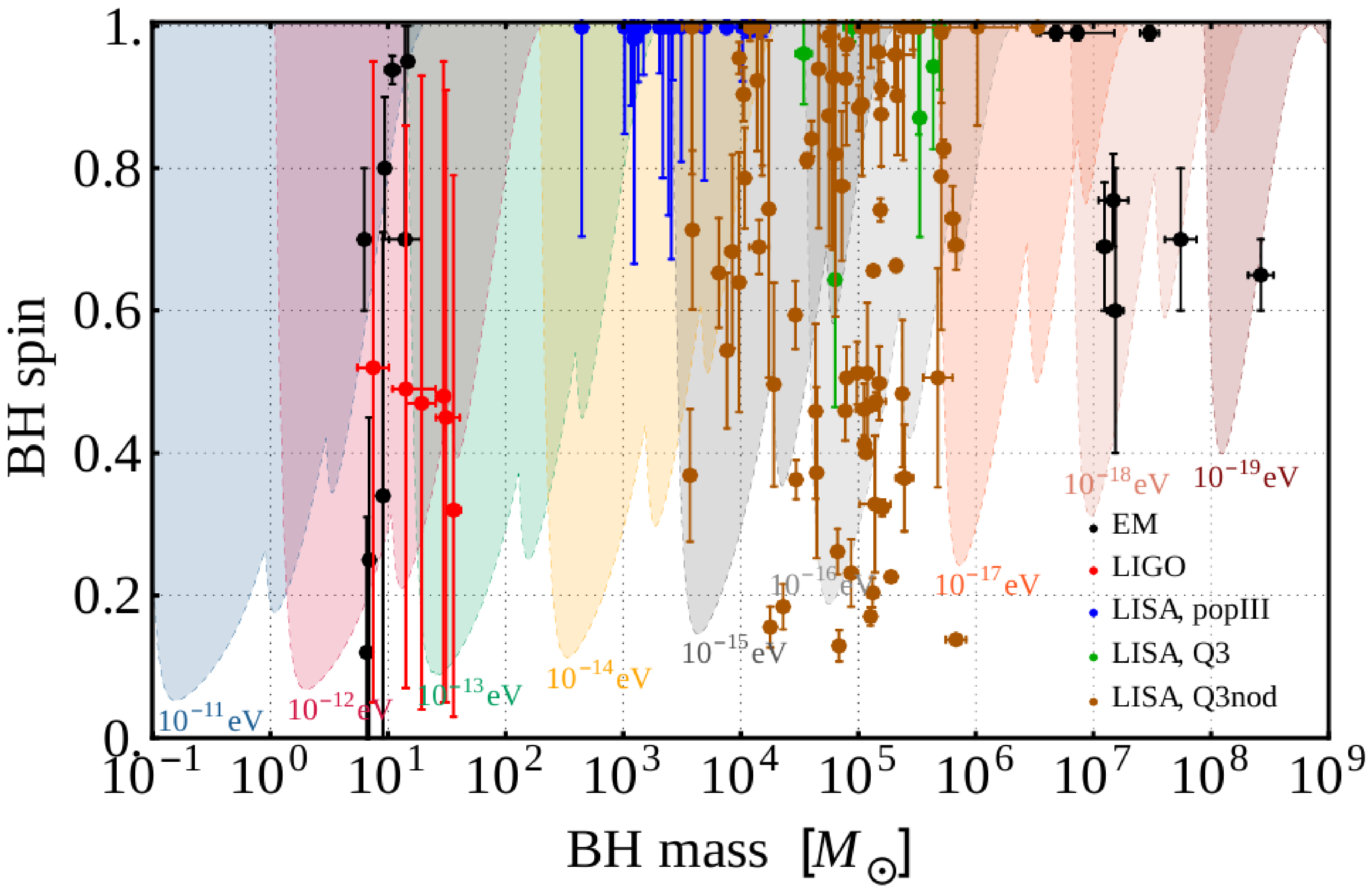
Arvanitaki+ 2014-2016
Baryakhtar+ 2017
Brito+ 2017

- Monochromatic signal → $\mathrm{SNR} \approx \dfrac{h\sqrt{T_{\rm obs}}}{\sqrt{S_h(f_0)}}$ → Continuous GW source



Regge plane

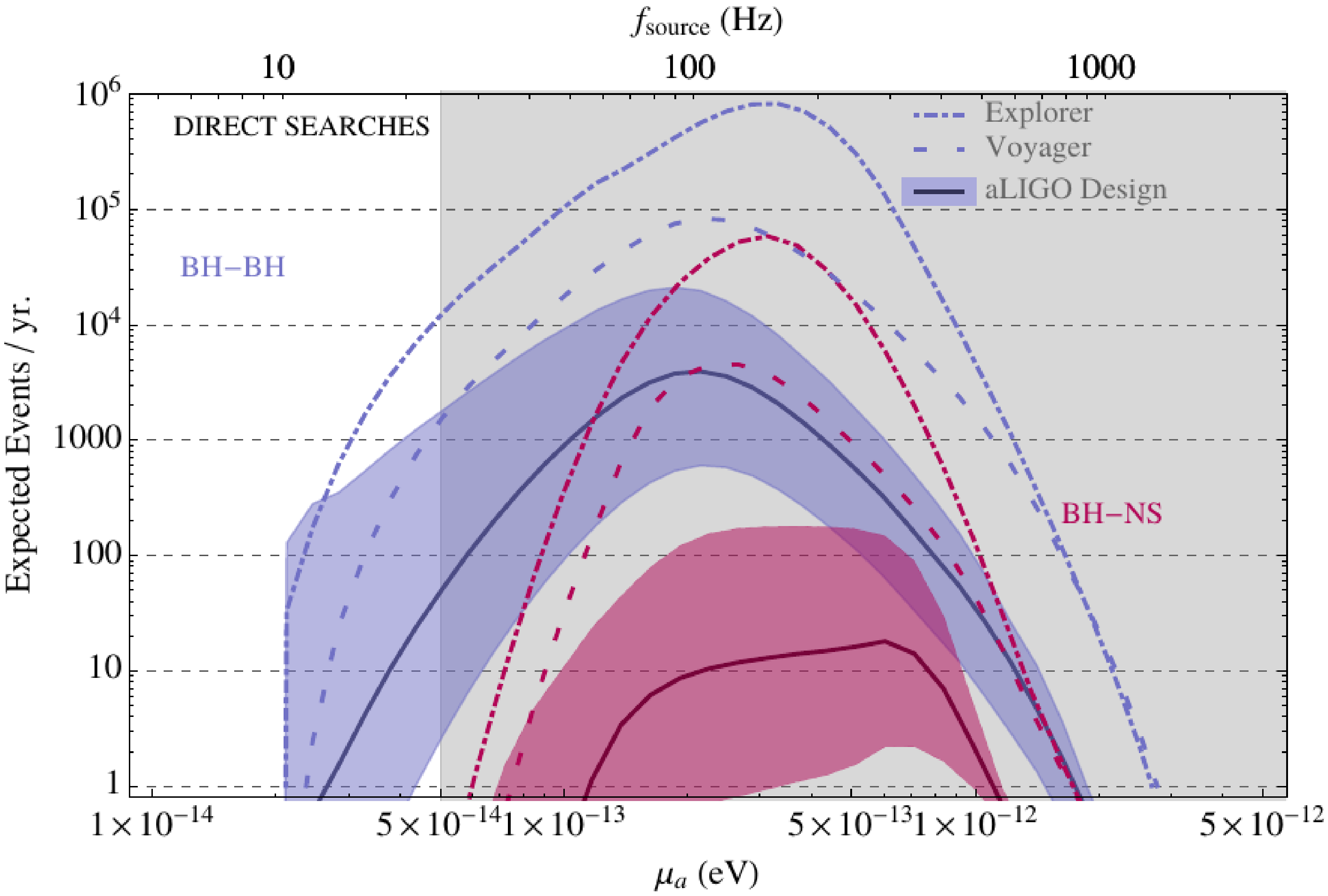
Arvanitaki+ 2014-2016
Baryakhtar+ 2017
Brito+ 2017



- LISA will fill the mass gap by detecting intermediate-mass BHs

Follow-up searches

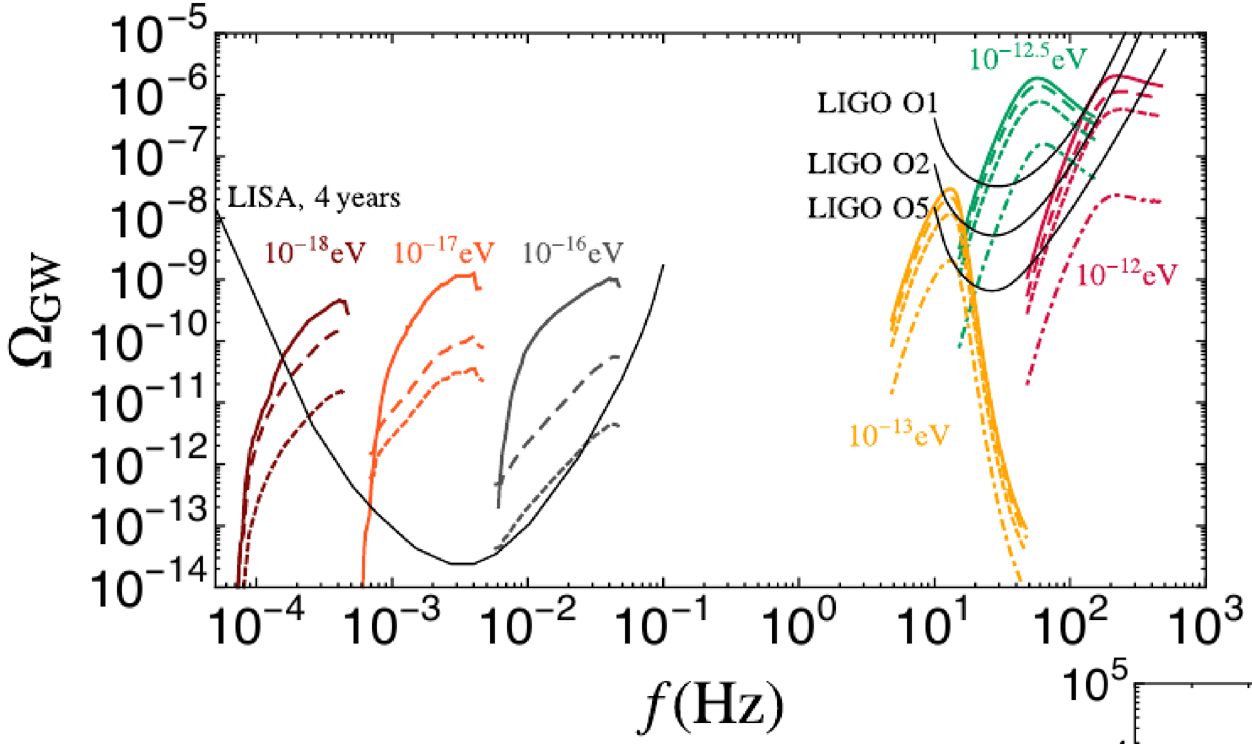
Arvanitaki+ 2016
Baryakhtar+ 2017



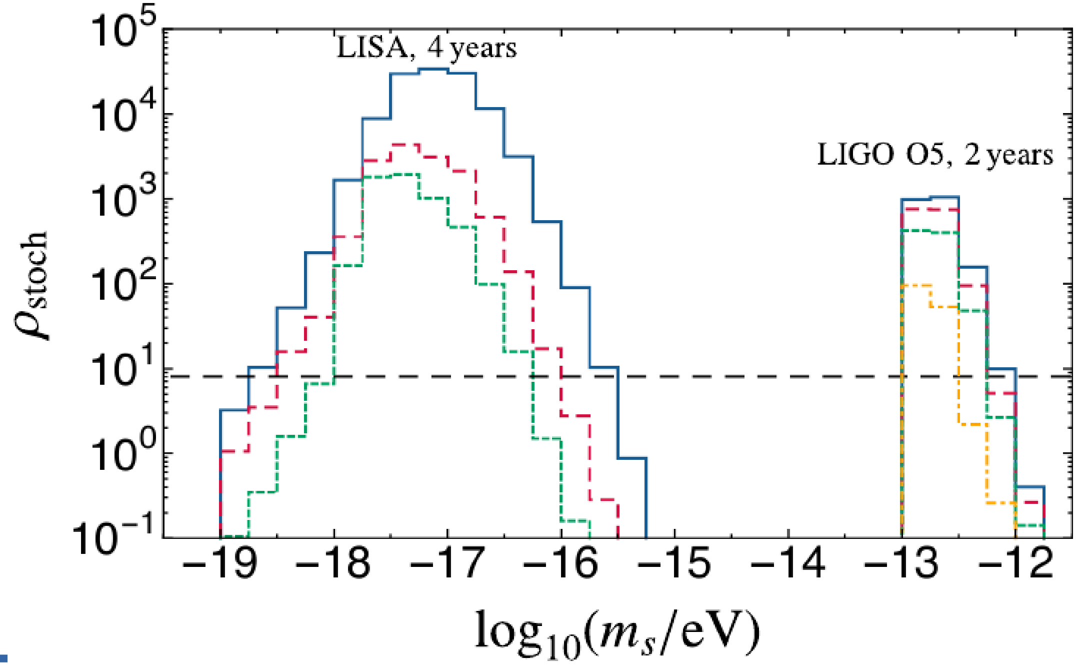
- “Axion” counterpart for LIGO/Virgo

Stochastic background

Brito+ 2017



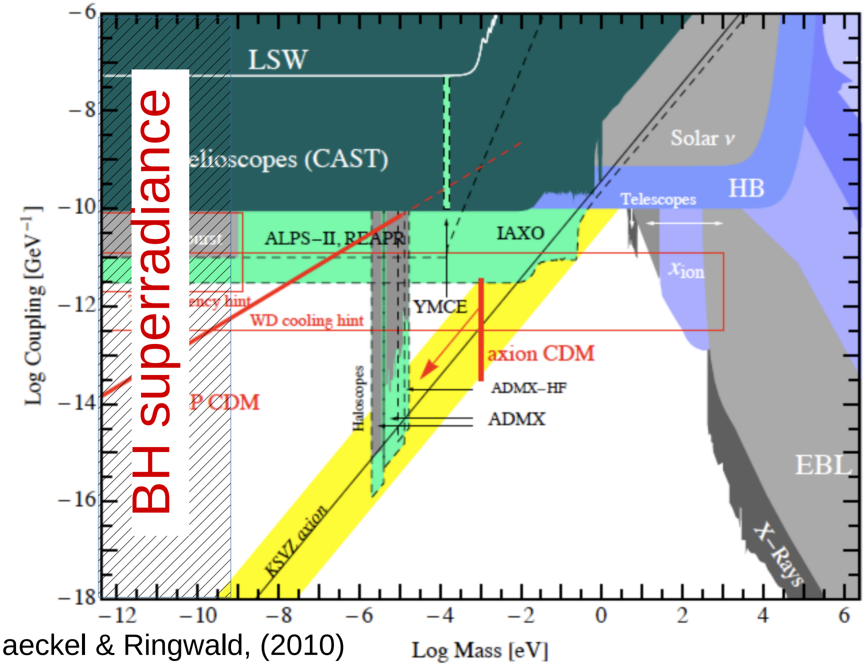
- Direct bounds from LIGO O1
- Can affect direct detection



GW searches for ALPs and dark photons

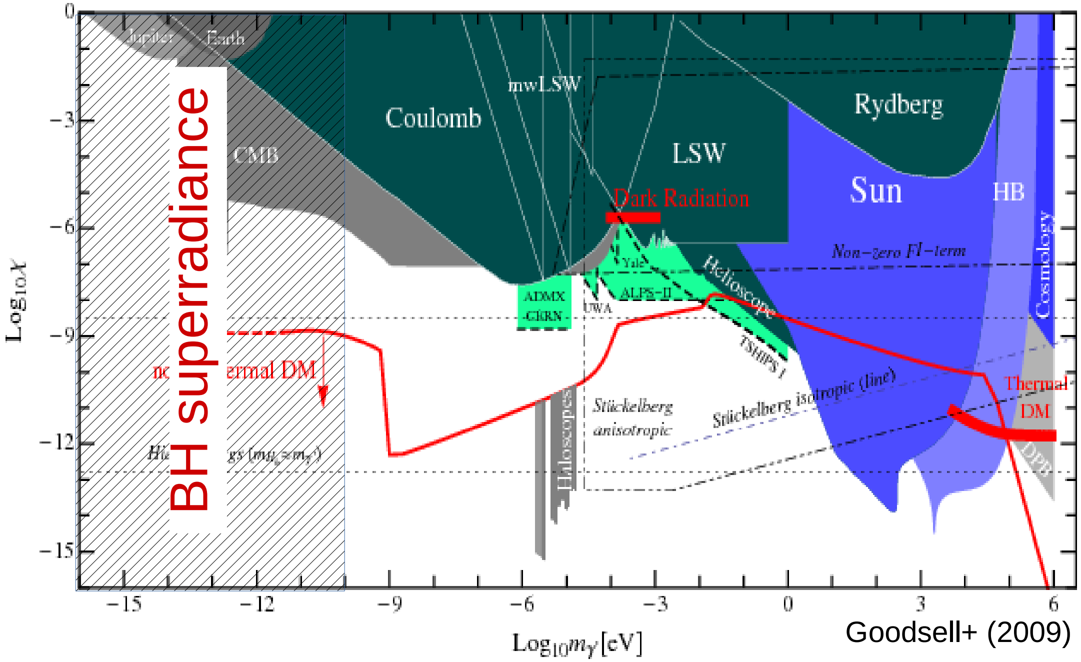
Mass-coupling diagrams:

ALPs



Jaeckel & Ringwald, (2010)

Dark photons



Goodsell+ (2009)

- Independent of the coupling to Standard Model
- Model independent: Axion-like particle (ALP), QCD axion, string axiverse, dark photon, mirror DM,...
- Bounds on massive gravitons comparable to LIGO, but more work is required

Brito, Cardoso, Pani, Phys. Rev. D88 (2013) 023514

BHs and massive gravitons

$$\begin{cases} \bar{\Box} h_{\mu\nu} + 2\bar{R}_{\alpha\mu\beta\nu} h^{\alpha\beta} - \mu^2 h_{\mu\nu} = 0\,, \\ \mu^2 \bar{\nabla}^{\mu} h_{\mu\nu} = 0\,, \\ \left(\mu^2 - 2\Lambda/3\right) h = 0\,, \end{cases}$$

- Healthy extension of the Fierz-Pauli theory in Ricci-flat curved background
- Massive spin-2 field on a GR BH, nonlinear massive gravity, bimetric theories

Hinterbichler, Rev.Mod.Phys. 84 (2012) 671-710; De Rham+, 2011-2014; Hassan+, 2011-2014

- Λ=0 → 5D black string, mass~ KK momentum → Gregory-Laflamme instability

Babichev & Fabbri, Class.Quant.Grav. 30 (2013) 152001

- GR BHs in Partially Massless gravity are stable

Brito, Cardoso, PP; Phys.Rev. D87 (2013) 12, 124024

- Non-bidiagonal BH solutions are stable

Babichev & Fabbri, Phys.Rev. D89 (2014) 081502
Babichev, Brito, PP; Phys.Rev. D93 (2016) 044041

- Constraints on graviton mass better than GW150914

Brito, Cardoso,Pani, Phys. Rev. D88 (2013) 023514

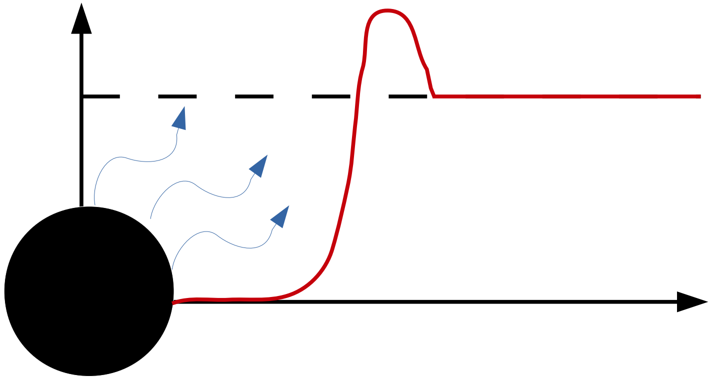
Gravitational collapse in massive (bi)gravity still unknown

Primordial BH bombs

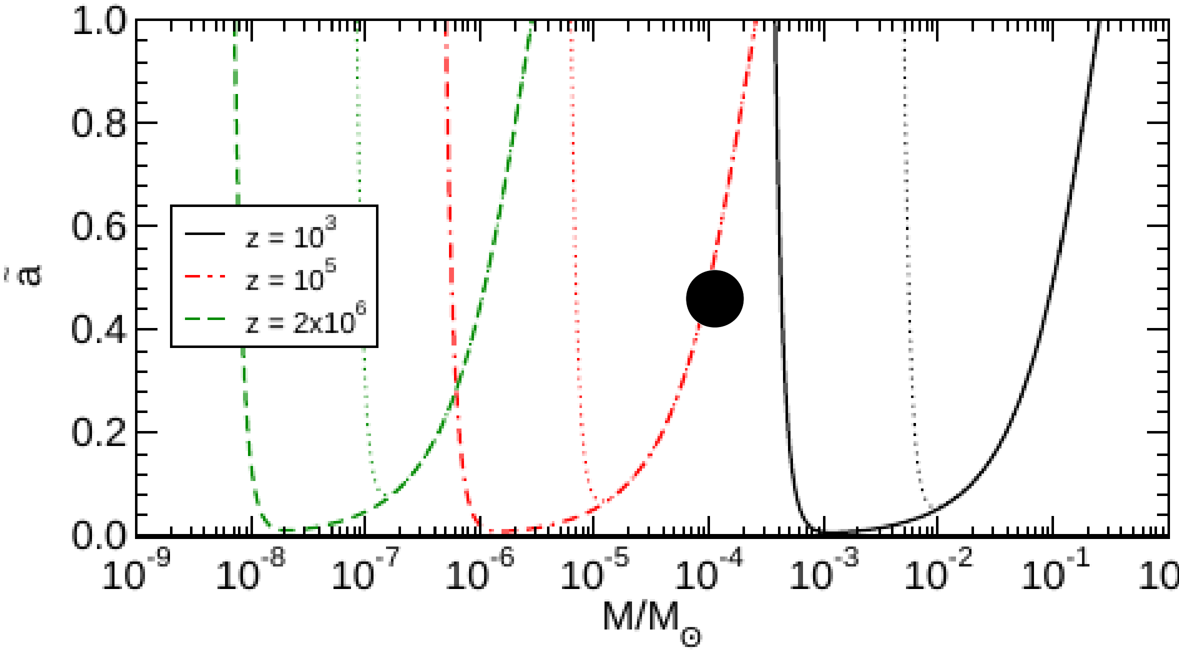
PP & Loeb, Phys.Rev. D88 (2013) 041301

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

Plasma frequency



Superradiant Instability
at different redshift



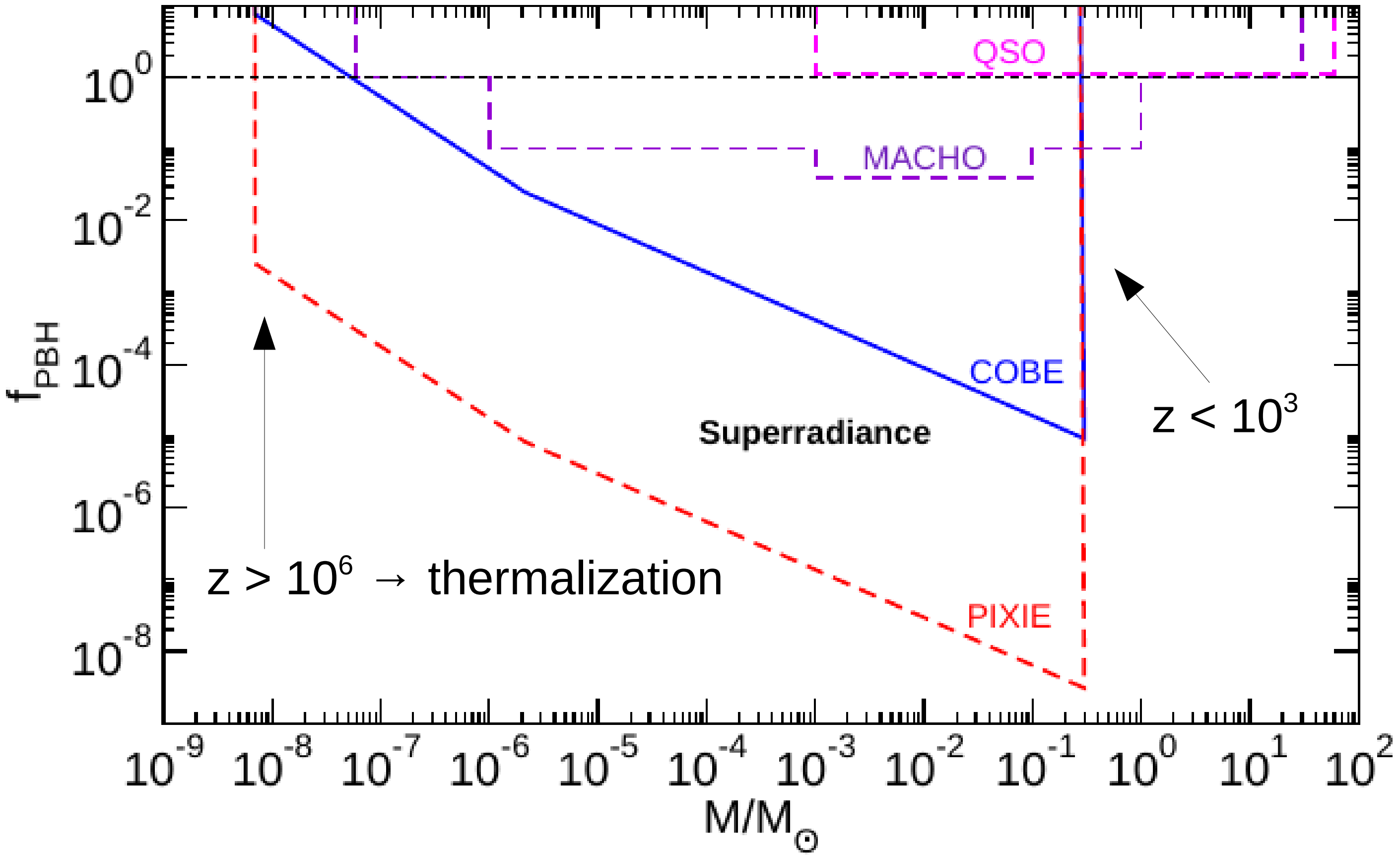
$$\frac{\Delta M}{M} \approx \frac{\tilde{a} M \omega_R}{1 - 2\tilde{a} M \omega_R} \approx 10^{-3} \left(\frac{1+z}{10^3}\right)^{3/2} \left(\frac{\tilde{a} M}{10^{-3} M_\odot}\right)$$

- Recently investigated in the context of Fast Radio Bursts Conlon & Herdeiro, 1701.02034
- Similar effect in modified gravity with nonminimal matter couplings Cardoso+, 2013

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

Stellar SR & bounds on dark photons

Cardoso, Pani, Yu, PRD95 124056 (2017)

Electrical conductivity of stars replaces the horizon

$$\mathcal{L}_{eff} \supset \frac{R}{16\pi} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$$

$$\vec{j} = \sigma\vec{E} \qquad \sigma \sim nq^2\tau/m$$

EM conductivity induces hidden conductivity

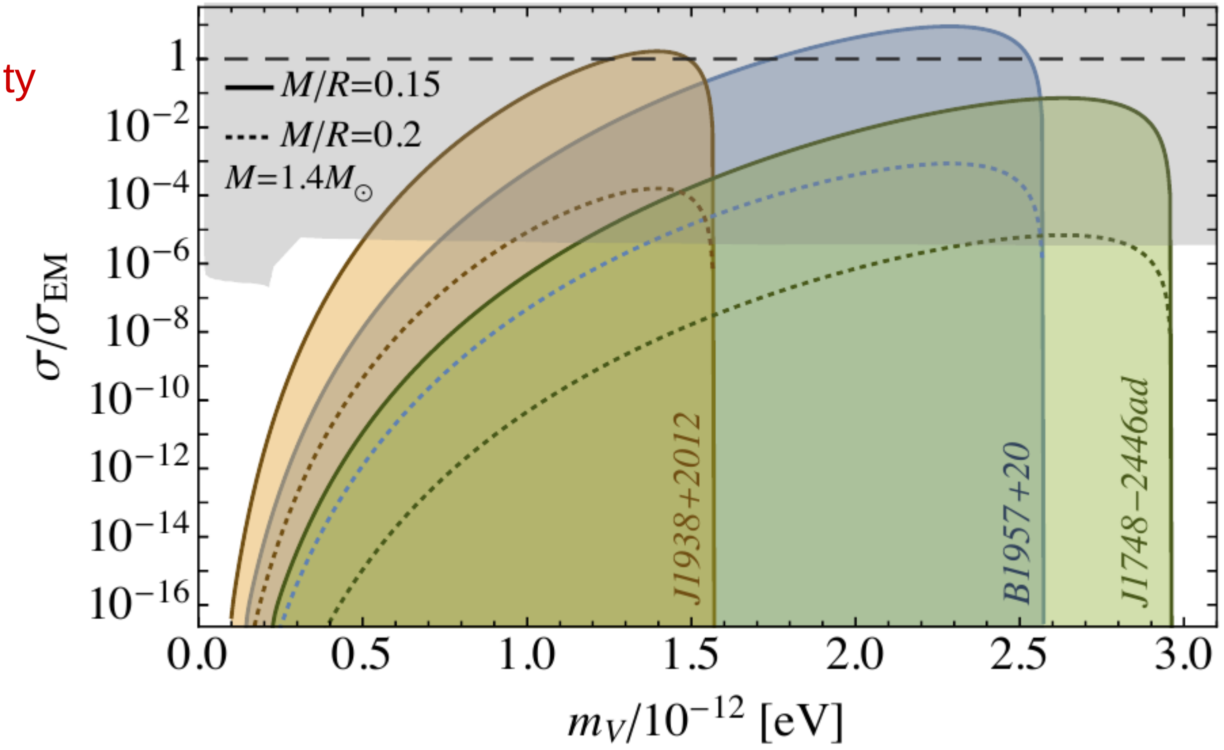
$$\sigma_{\rm hidden} = \epsilon\sigma_{\rm EM}$$

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

Superradiant-instability time scale

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

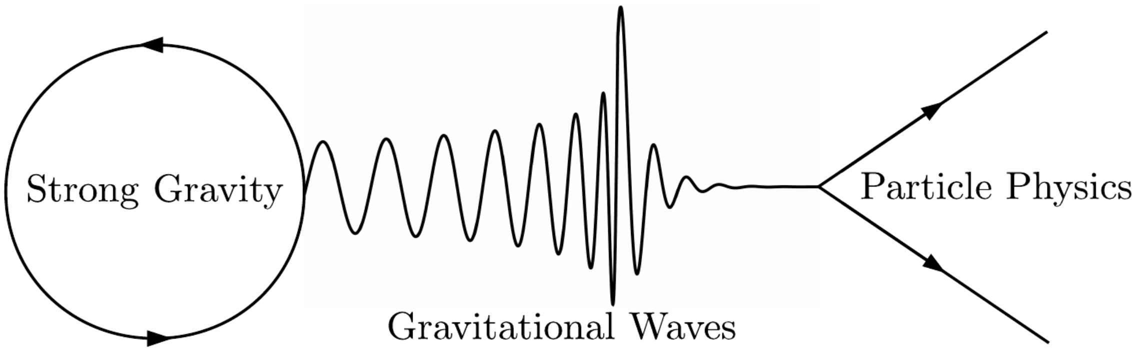
Measured for several pulsars



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

Conclusion & Prospects

- Ultralight bosons leave smoking gun in strongly-gravitating systems
  - Gaps in the BH Regge plane
  - Periodic GW sources (sources for aLIGO/aVirgo, DECIGO, LISA)
  - Superradiant instabilities in primordial BHs and neutron stars
- Open problems:
  - Evolution & end-state (long timescale)
  - High spin (beyond SlowRot approximation)
  - Plasma, nonlinear couplings
  - Spin-2 fields
  - Effects in pulsar binaries?
- Looking for GW signatures of ultralight bosonic DM in LIGO/Virgo data



Cardoso, Pani - CERN Courier, Jan 2017

GW astronomy: expect the unexpected?