TÉCNICO LISBOA

Fundação para a Ciência e a Tecnologia

Ultralight bosons and gravitational waves: Theory

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centra
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grit
gravitation in técnico

Dark matter & Gravitational Waves

From: Bertone *et al*, arXiv:1907.10610

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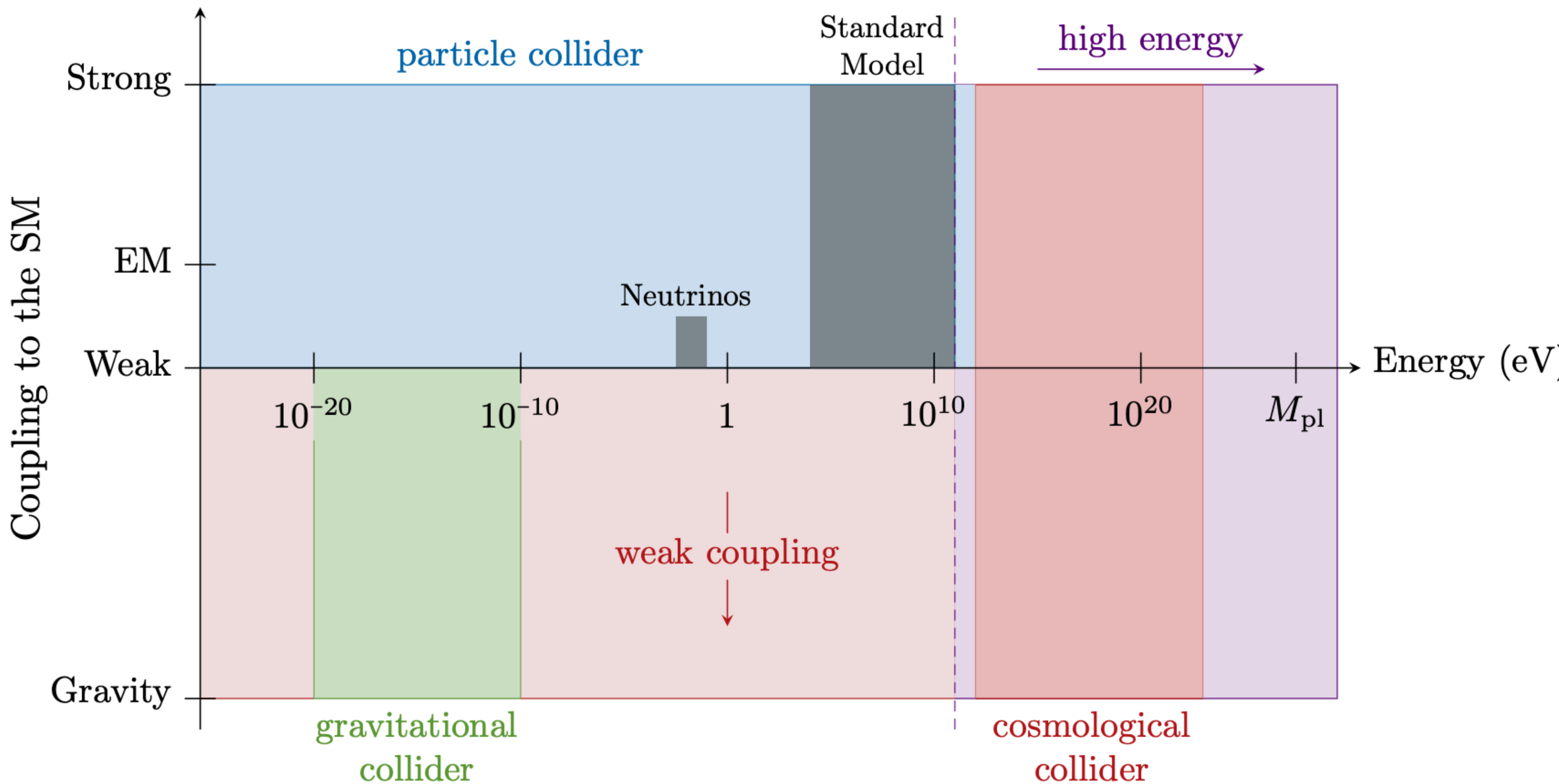
Ultralight bosons & Black holes



From: Baumann et al '20, PRD101, 083019

Particles with masses $\sim 10^{-21}$ eV $- 10^{-11}$ eV have Compton wavelengths as large as the size of **astrophysical black holes** ranging from $\sim 10 M_\odot - 10^{10} M_\odot$.

$$\mathscr{L} = \frac{R}{16\pi} - \frac{1}{2}\nabla^\mu\Phi\,\nabla_\mu\Phi - \frac{\mu_S^2}{2}\Phi^2 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{2}\mu_V^2 A_\nu A^\nu$$

Massive bosonic fields around black holes

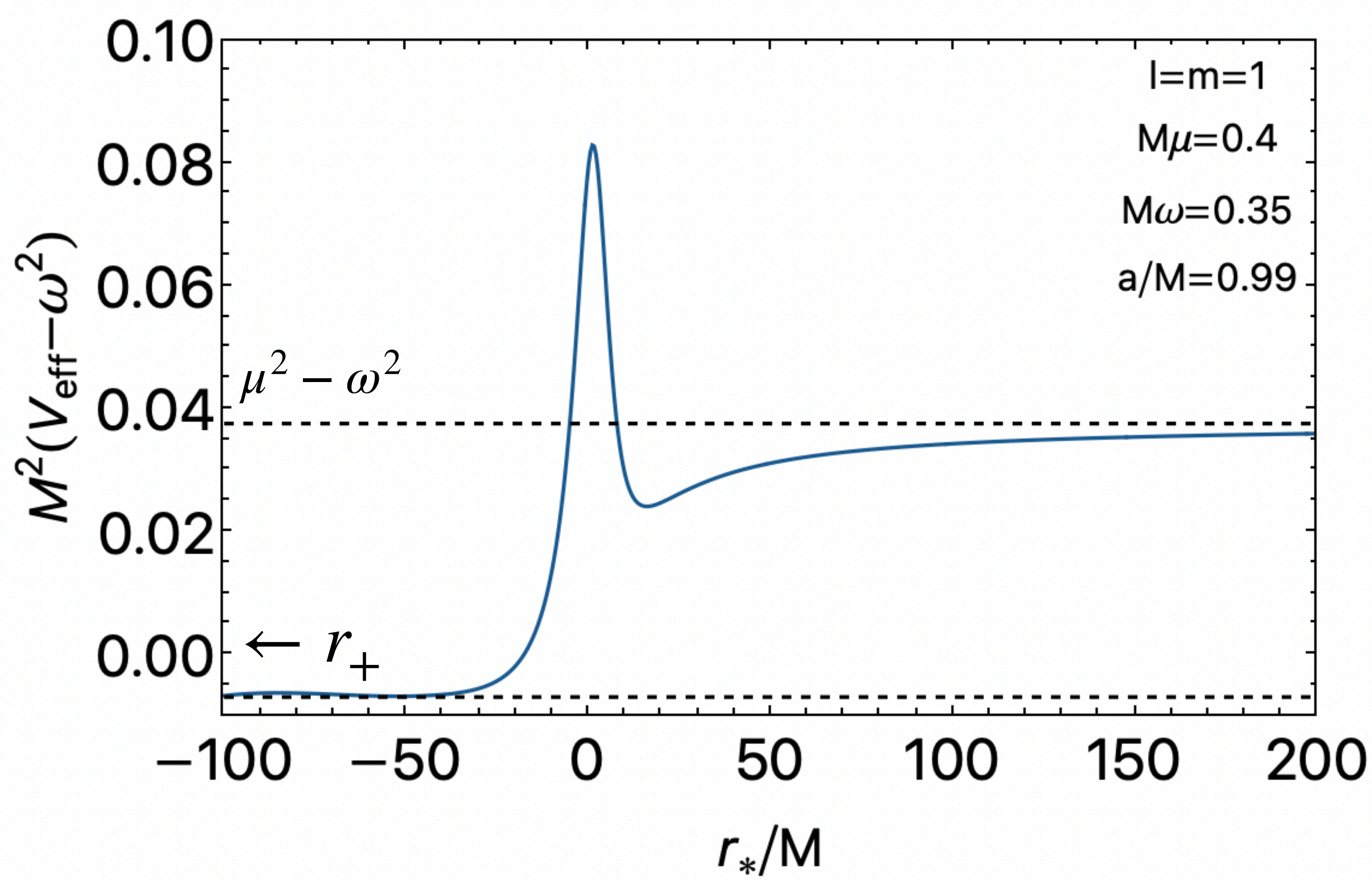
Damour '76; Gaina '78; Zouros & Eardley '79; Detweiler '80; Cardoso&Yoshida, '05; Dolan '07; Rosa & Dolan '12; Pani *et al* '12; RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso *et al* '18; Frolov *et al* '18; Dolan '18; Baumann et al '19; RB, Grillo & Pani '20; Dias, Lingetti, Pani & Santos '23...

Massive bosonic fields can form (quasi-)bound states around black holes.

$$\nabla_\mu \nabla^\mu \Phi = \mu^2 \Phi \qquad (\mu \equiv m_b/\hbar)$$

$$\Phi = \frac{\Psi(r)}{\sqrt{r^2+a^2}} S_{\ell m}(\theta) e^{im\phi} e^{-i\omega t}$$

$$\frac{d^2}{dr_*^2}\Psi(r) + \left(\omega^2 - V_{\rm eff}\right)\Psi(r) = 0$$



A (macroscopic) **"gravitational atom"** but with some important differences when compared to the hydrogen atom:
i) **boundary conditions** at the horizon: horizon acts as a dissipative membrane
ii) **no Pauli exclusion principle** for bosons

Instability of spinning black holes

Review: RB, Cardoso & Pani "Superradiance" Lect. Notes Phys. 971 (2020), 2nd ed.

- System is ***unstable*** for some values of $M\mu$.

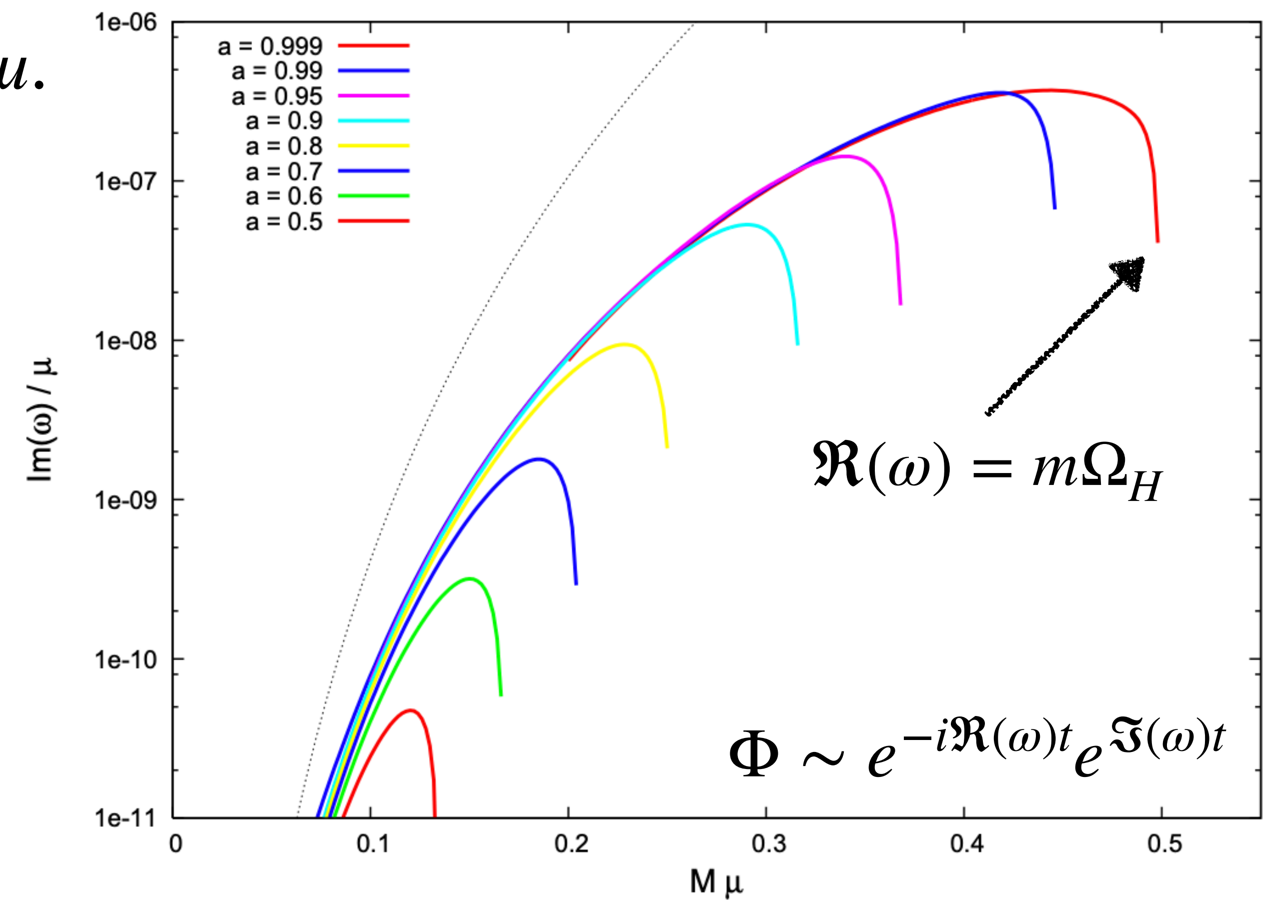
$$\Re(\omega_{nlm}) \approx \mu \left[1 - \frac{\alpha^2}{2n^2} + \mathcal{O}\left(\alpha^4\right)\right]$$

$$\Im(\omega_{nlm}) \propto \left(m\Omega_H - \Re(\omega_{nlm})\right) \alpha^{4l+5}$$

$$\Re(\omega_{nlm}) < m\Omega_H \implies \Im(\omega_{nlm}) > 0$$

Ω_H - BH's angular velocity

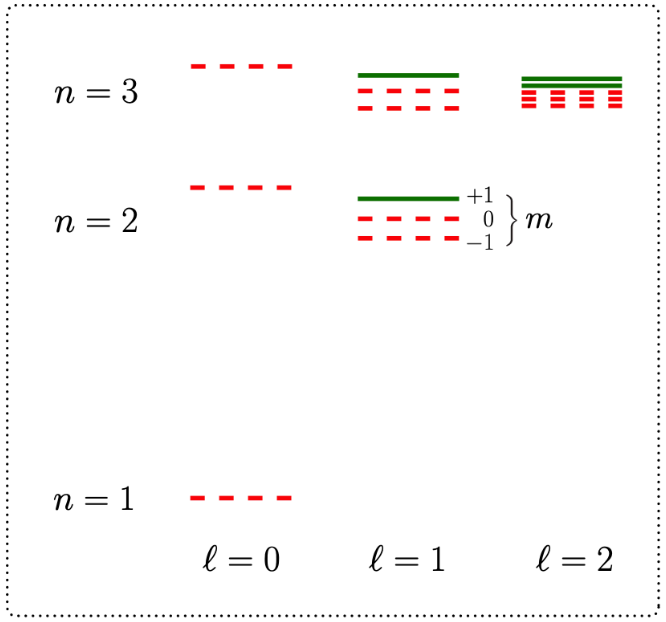
$$\alpha := M\mu = R_G/\lambda_C$$



From: Dolan, arXiv:0705.2880

Superradiant (rotational) ***energy extraction*** drives instability.

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



Dashed: stable

Solid: unstable

From: Baumann+, arXiv:1804.03208

Evolution of the superradiant instability

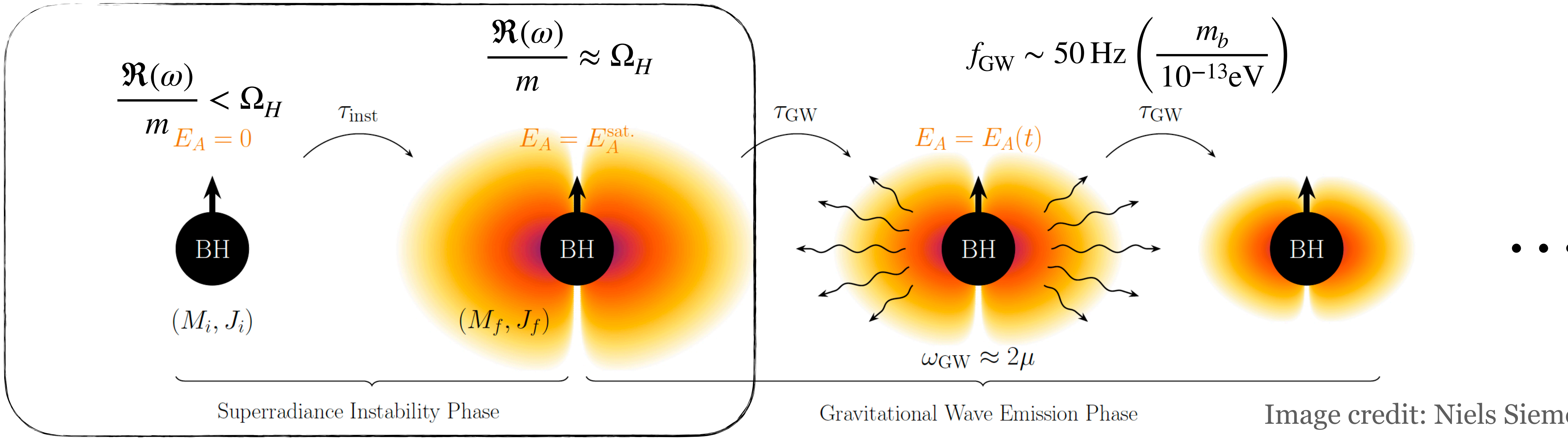
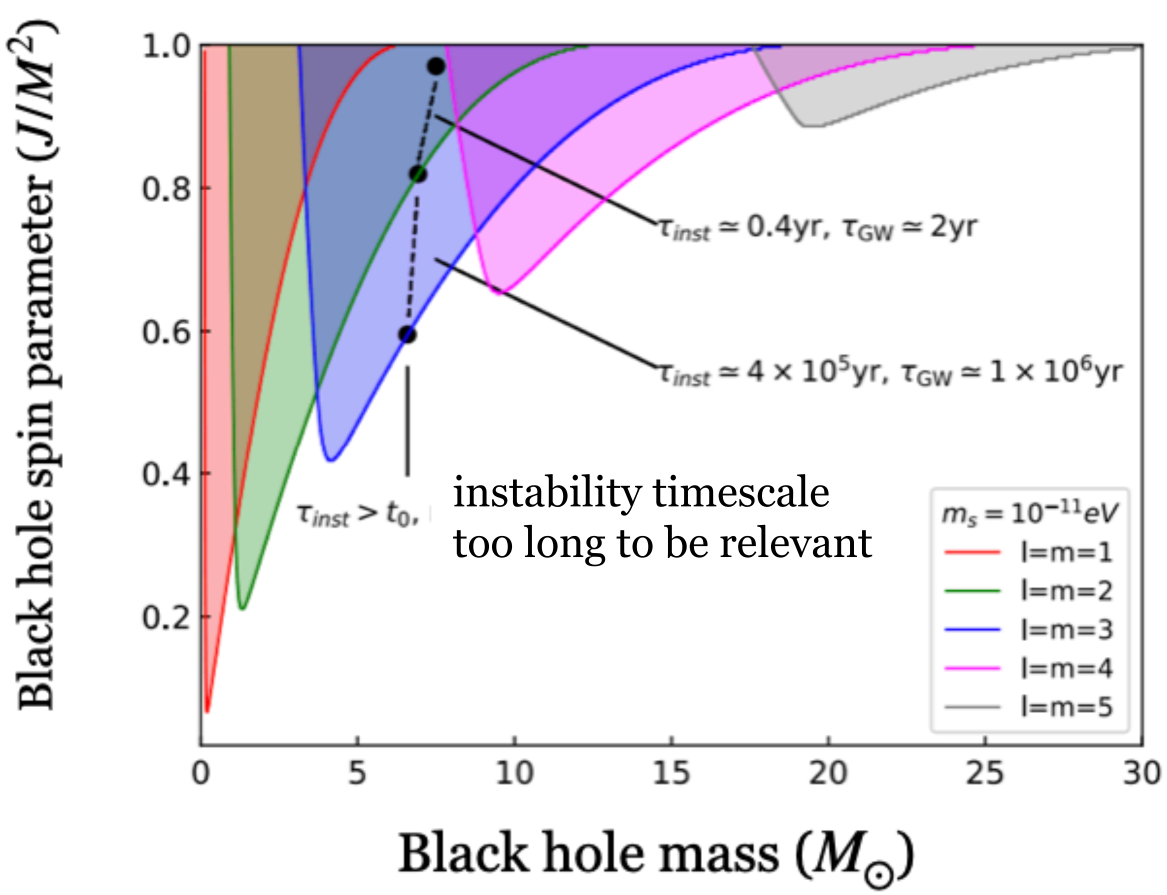


Image credit: Niels Siemonsen



Adapted from: Chen, RB, Cardoso, arXiv:2106.00021

For most unstable mode:

$$\tau_{\rm inst}^{\rm scalar} \approx 30\,{\rm days} \left(\frac{M}{10\,M_\odot}\right) \left(\frac{0.1}{M\mu}\right)^9 \left(\frac{0.9}{J/M^2}\right)$$

$$\tau_{\rm inst}^{\rm vector} \approx 280\,{\rm s} \left(\frac{M}{10\,M_\odot}\right) \left(\frac{0.1}{M\mu}\right)^7 \left(\frac{0.9}{J/M^2}\right)$$

(even smaller instability timescales for massive spin-2 case, Dias+ '23)

$$M\mu \approx 0.1 \left(\frac{M}{15 M_\odot}\right) \left(\frac{m_b c^2}{10^{-12}{\rm eV}}\right)$$

Evolution of the superradiant instability

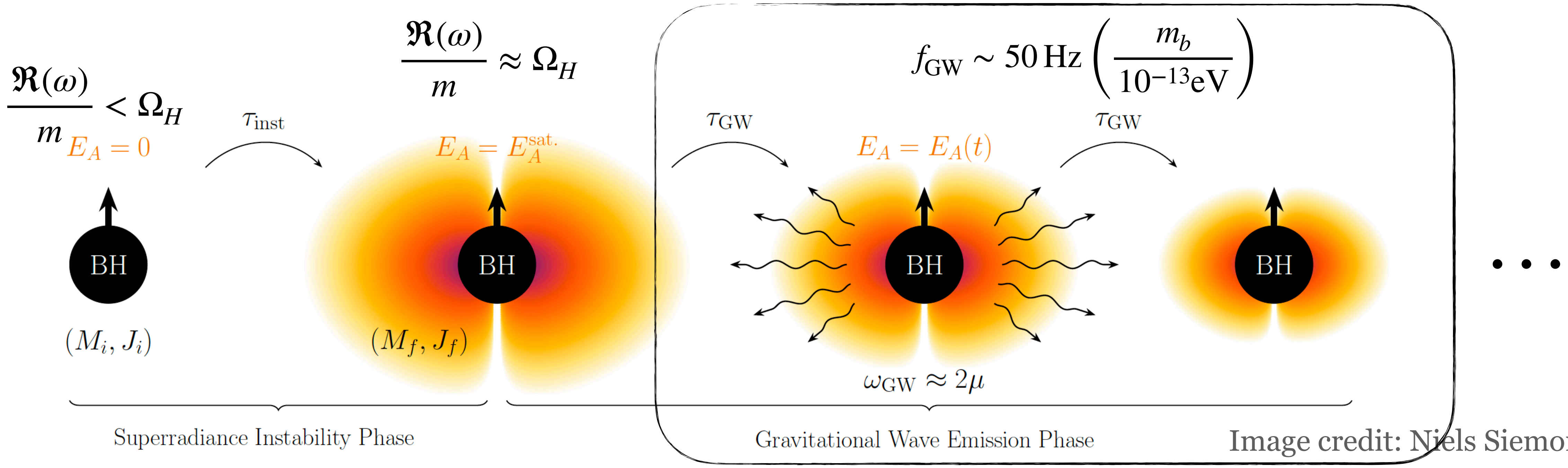
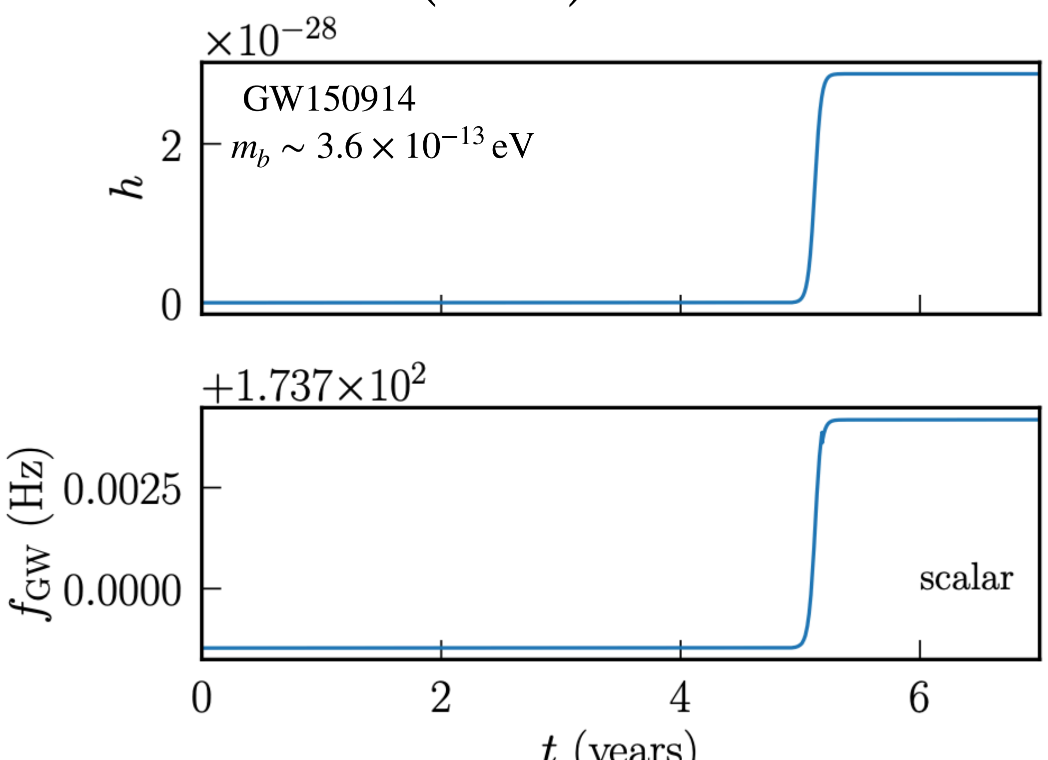


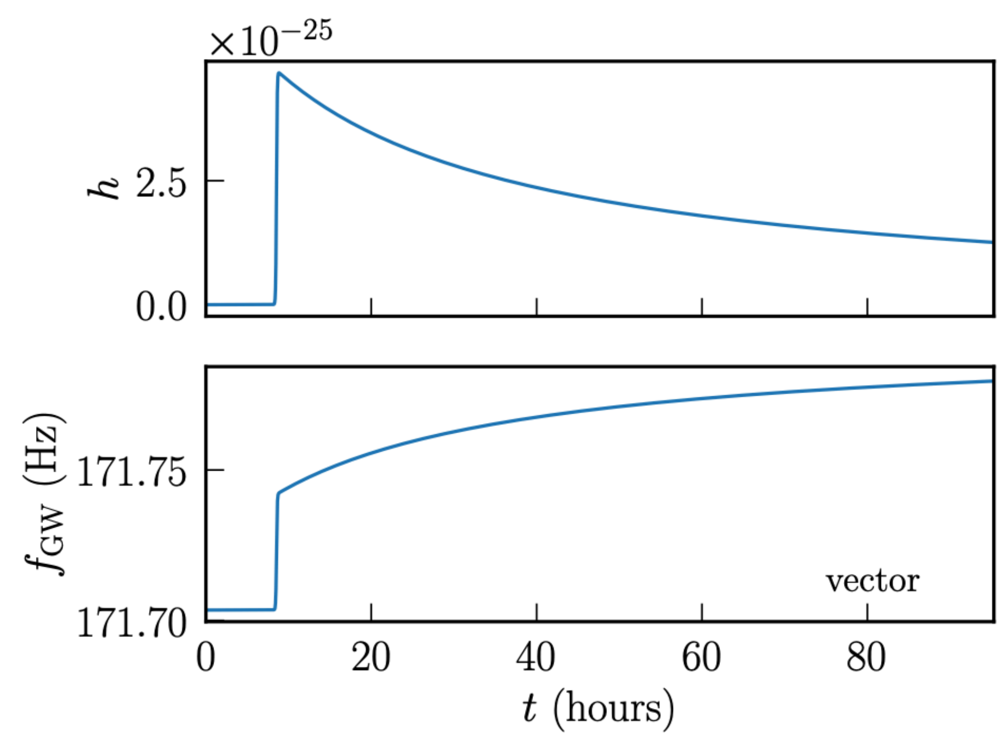
Image credit: Niels Siemonsen

For most unstable mode:

$$\tau_{\rm GW}^{\rm scalar} \approx 10^5\,{\rm yr}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\Delta(J/M^2)}\right)$$

$$\tau_{\rm GW}^{\rm vector} \approx 2\,{\rm days}\left(\frac{M}{10\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{11}\left(\frac{0.5}{\Delta(J/M^2)}\right)$$





scalar: Yoshino & Kodama '14; RB *et al* '17
vector: Baryakhtar *et al* '17; Siemonsen & East '20

From: Siemonsen, May & East, arXiv:2211.03845

Gravitational-wave signatures

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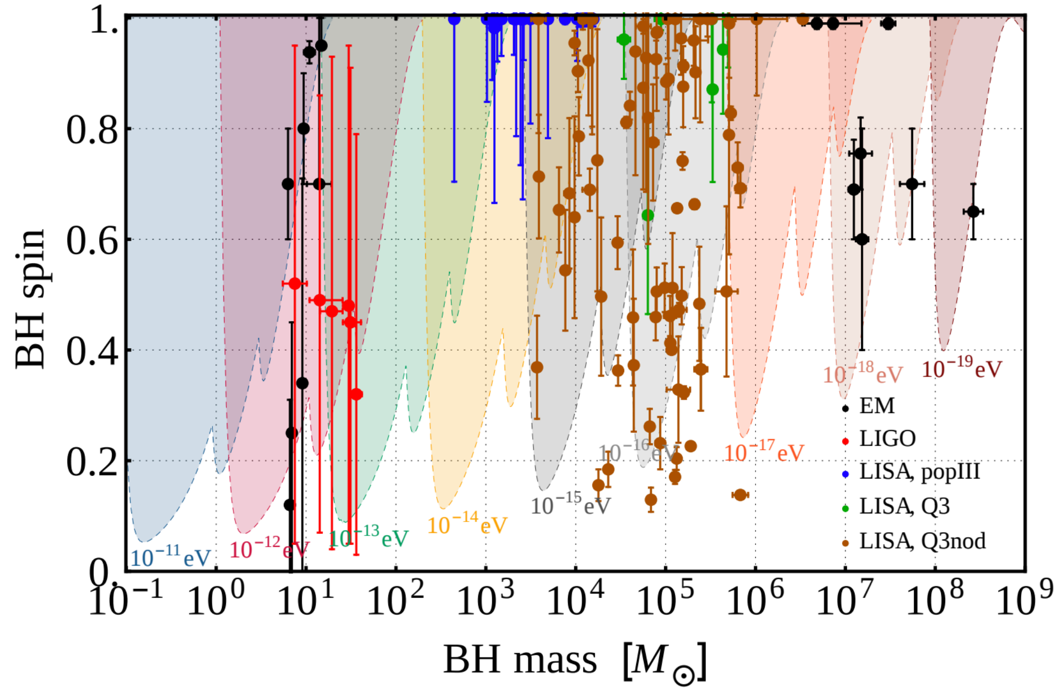
From: RB+, PRD96 6, 064050, '17

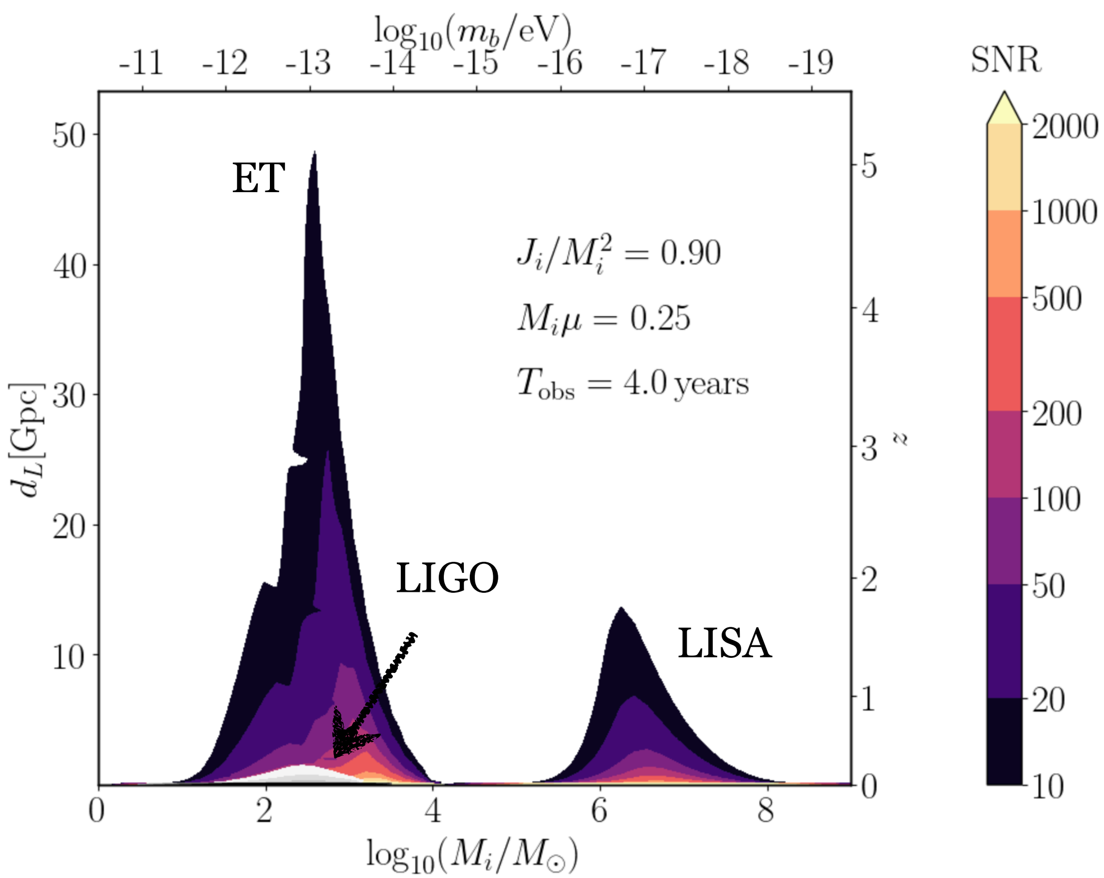


- Indirect constraints through **black hole mass & spin measurements**

  Arvanitaki+ '09; Pani+'12; Arvanitaki+ '16; RB+ '17; Cardoso+'18; Ng+ '21...

Gravitational-wave signatures

❖ Indirect constraints through **black hole mass & spin measurements**



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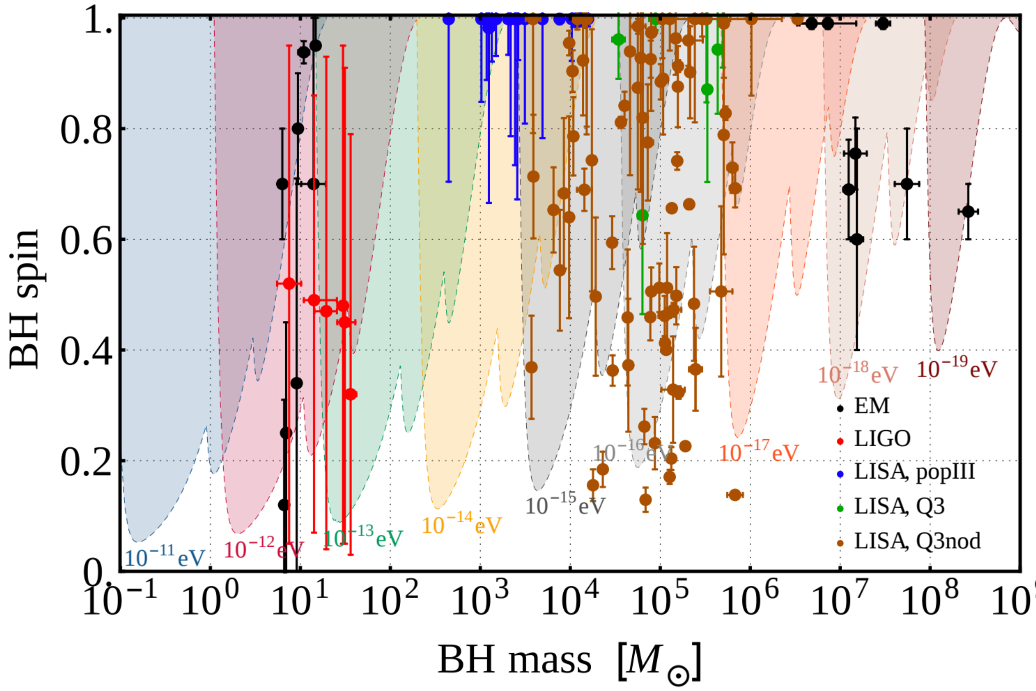

❖ **Continuous gravitational waves** from the boson cloud (also in the form of a stochastic background) [see Palomba's talk]

Arvanitaki+'14; Yoshino&Kodama '14; RB+ '17; Baryakhtar+'17; Siemonsen&East '20; ...

Gravitational-wave signatures

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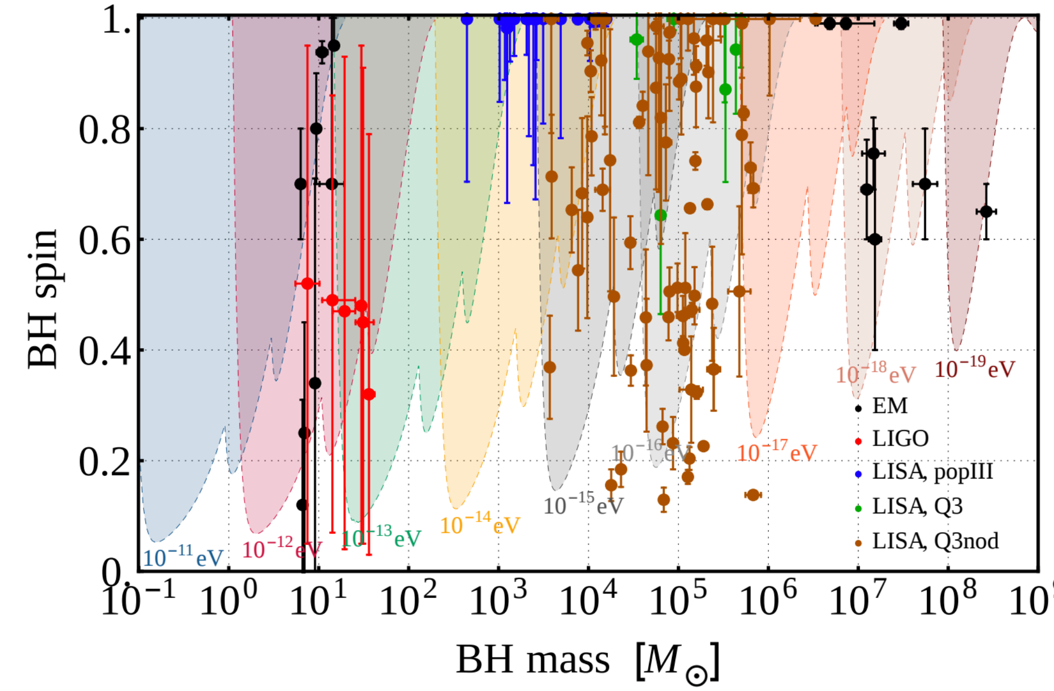
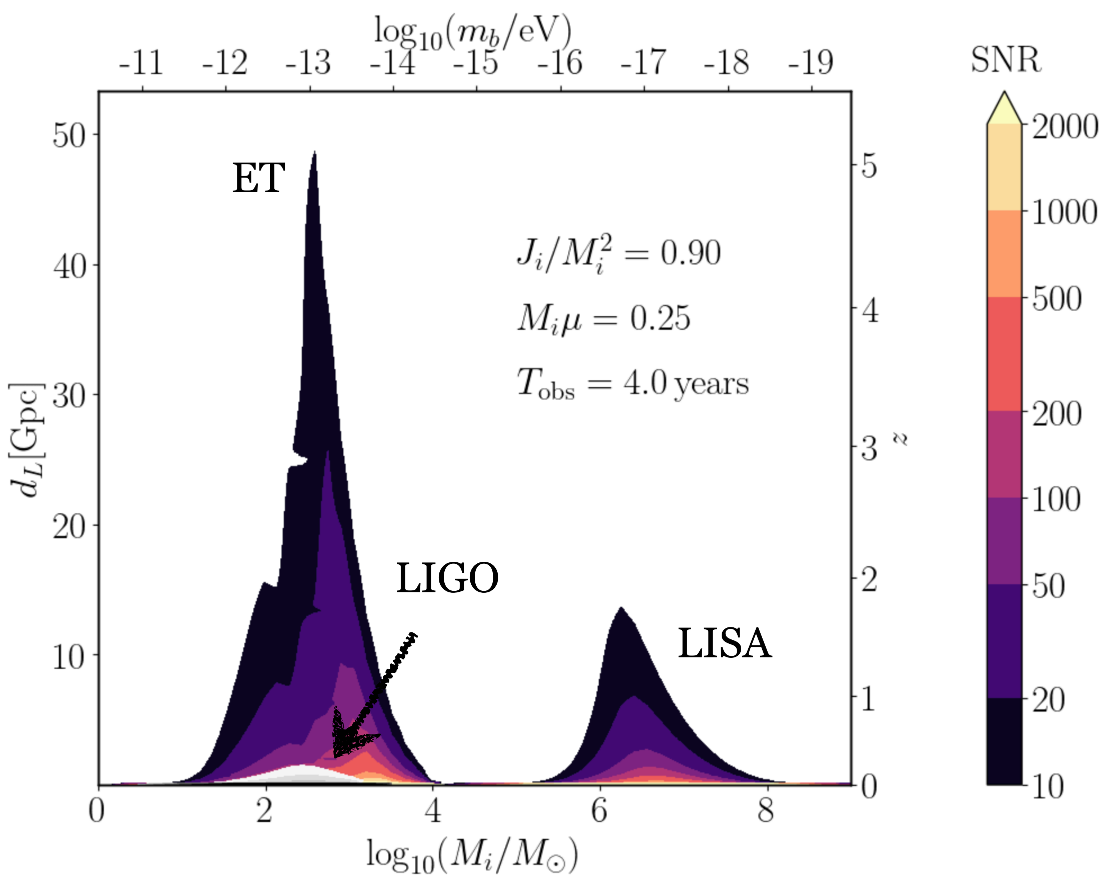


❖ Indirect constraints through **black hole mass & spin measurements**



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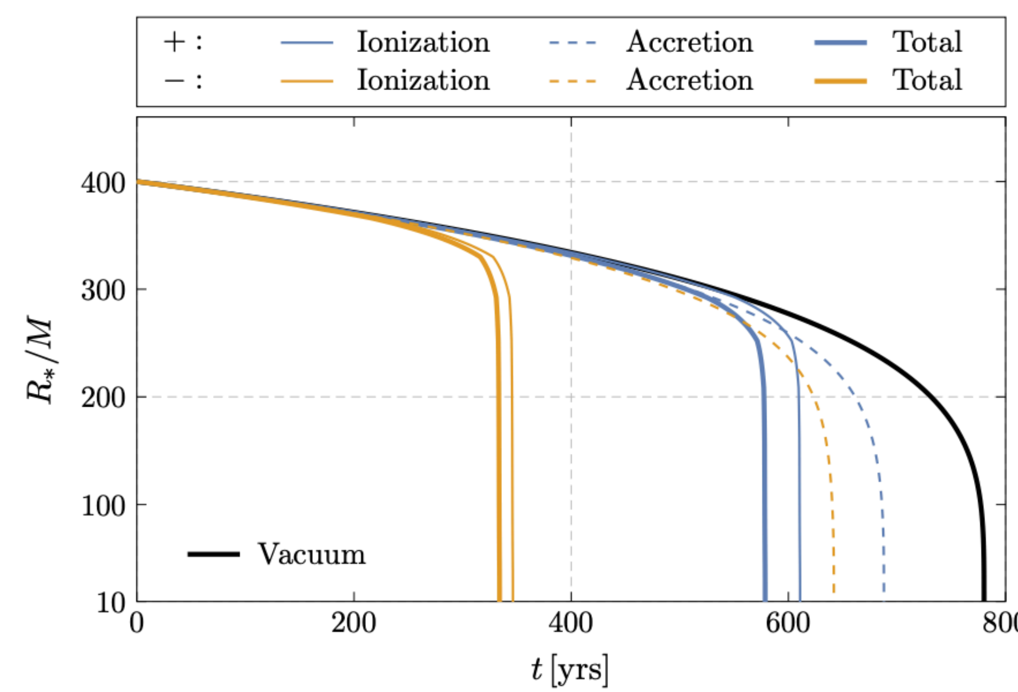


From: Bauman+, PRD105, 115036, '22

❖ Signatures in **binary systems**: resonances, dynamical friction, accretion, tidal Love numbers… [see Cole's talk]

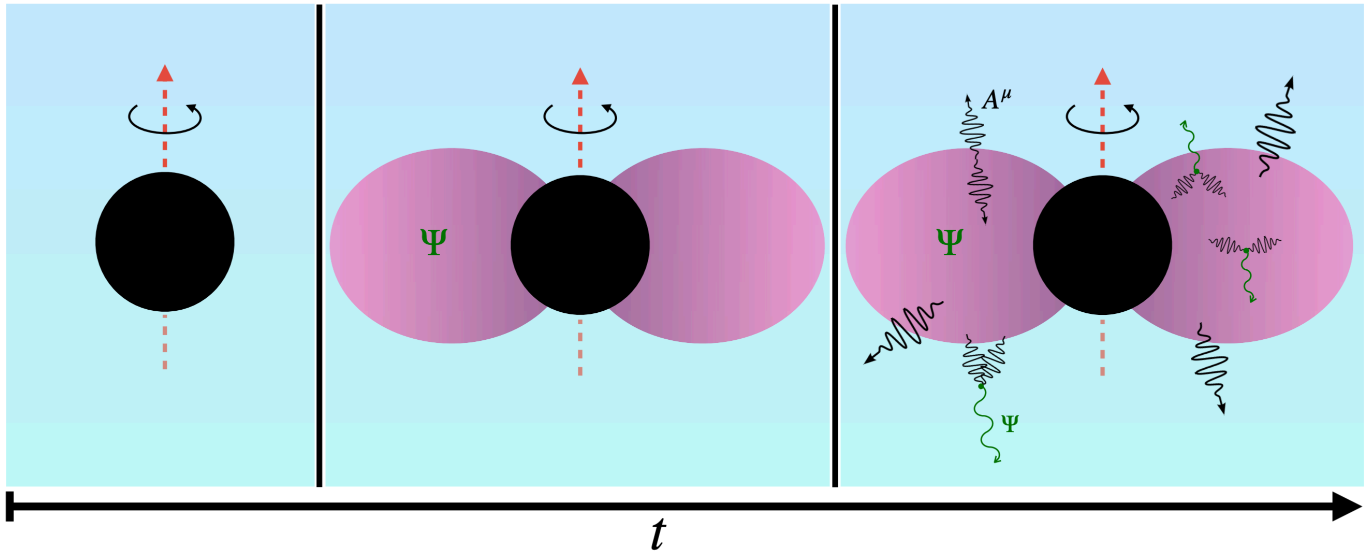
Baumann+'18, '19, '21; Tomaselli+'23;
de Luca & Pani '22; RB & Shah '23; Duque+ '23…

Non-gravitational interactions

❖ Non-gravitational interactions of the ultralight boson e.g. axionic couplings to photons:

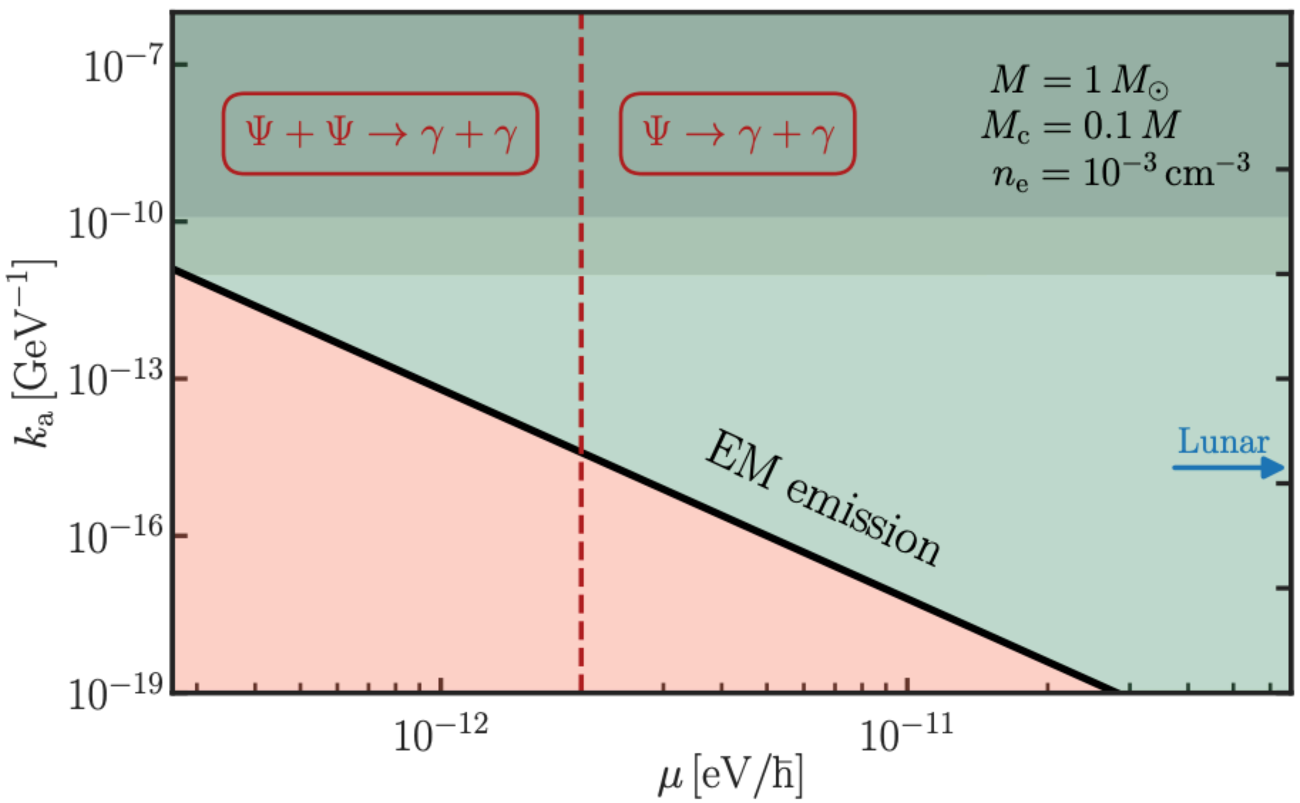
$$(\Box - \mu^2)\Phi = \frac{k_a}{2}\tilde{F}^{\mu\nu}F_{\mu\nu}$$

$$\nabla_\nu F^{\mu\nu} = j^\mu - 2k_a\tilde{F}^{\mu\nu}\nabla^\nu\Phi$$



From: Spieksma *et al*, arXiv:2306.16447

Impact for gravitational-wave signatures?



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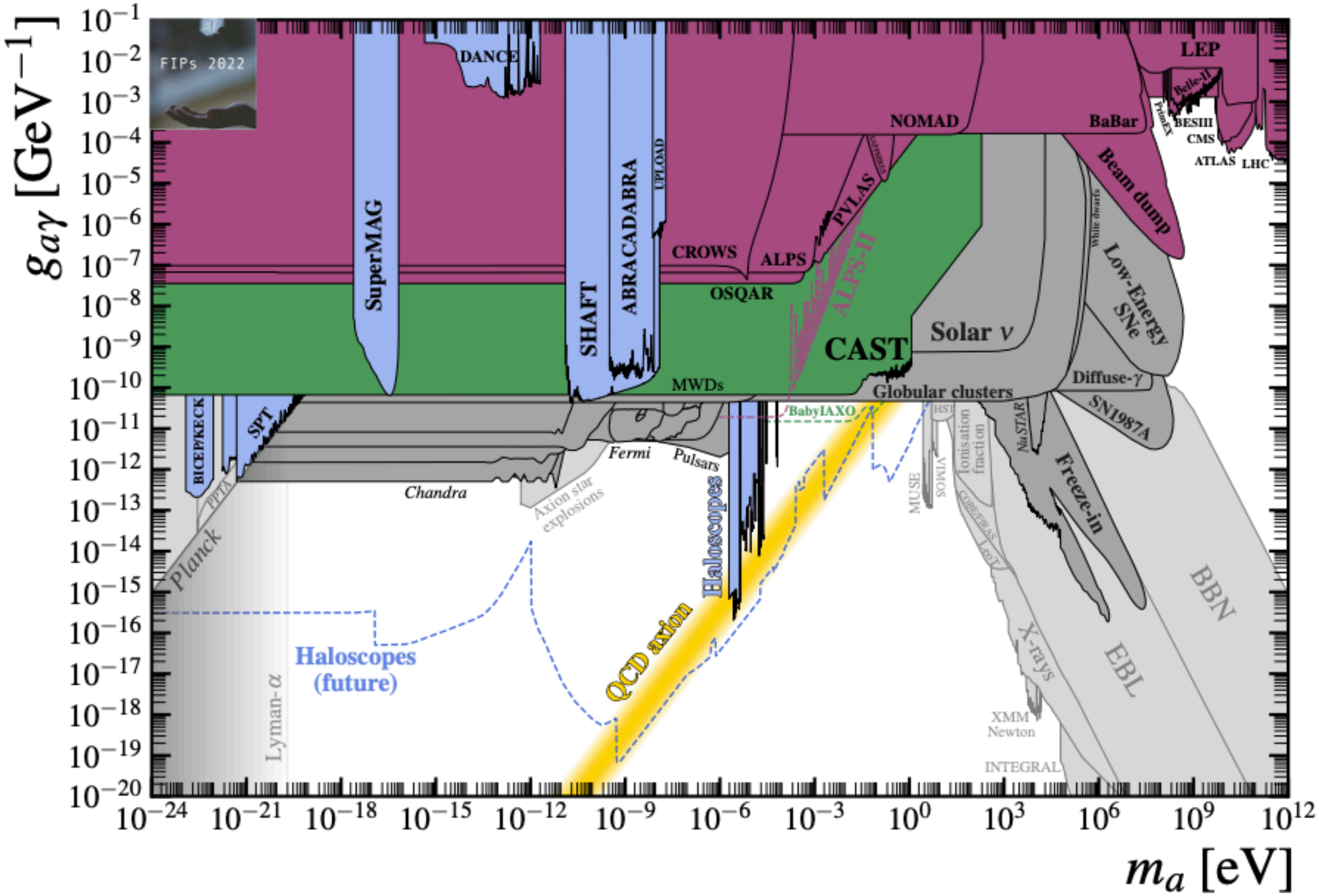
- *Axion coupling to photons:* Rosa & Kephart '18; Ikeda, RB & Cardoso '19; Spieskma+ '23
- *Axion self-interactions:* Baryakthar+ '20; Omiya+ '22
- *Axion coupling to neutrinos:* Chen, Xue & Cardoso '23
- *Dark photon mixing with EM photon:* Caputo+ '21; Siemonsen+'23
- *Dark photon with Higgs mechanism:* East '22

Complementarity with other observations

$$\mathscr{L} = -\frac{1}{2}\partial_\mu a \partial^\mu a - V(a) - \frac{g_{a\gamma}}{4}F_{\mu\nu}\tilde{F}^{\mu\nu} + \dots\,, \quad V(a) \approx \frac{m_a^2 a^2}{2} + \mathcal{O}(a^4/f_a^4)$$



Purple: lab/collider constraints

Green: lack of solar axions

Blue: direct dark matter searches

Light grey: astro/cosmo constraints that assume axions to be dark matter

Dark grey: astro/cosmo constraints that do not assume axions to be dark matter

From: Antel+, arXiv:2305.01715;
see also https://cajohare.github.io/AxionLimits/

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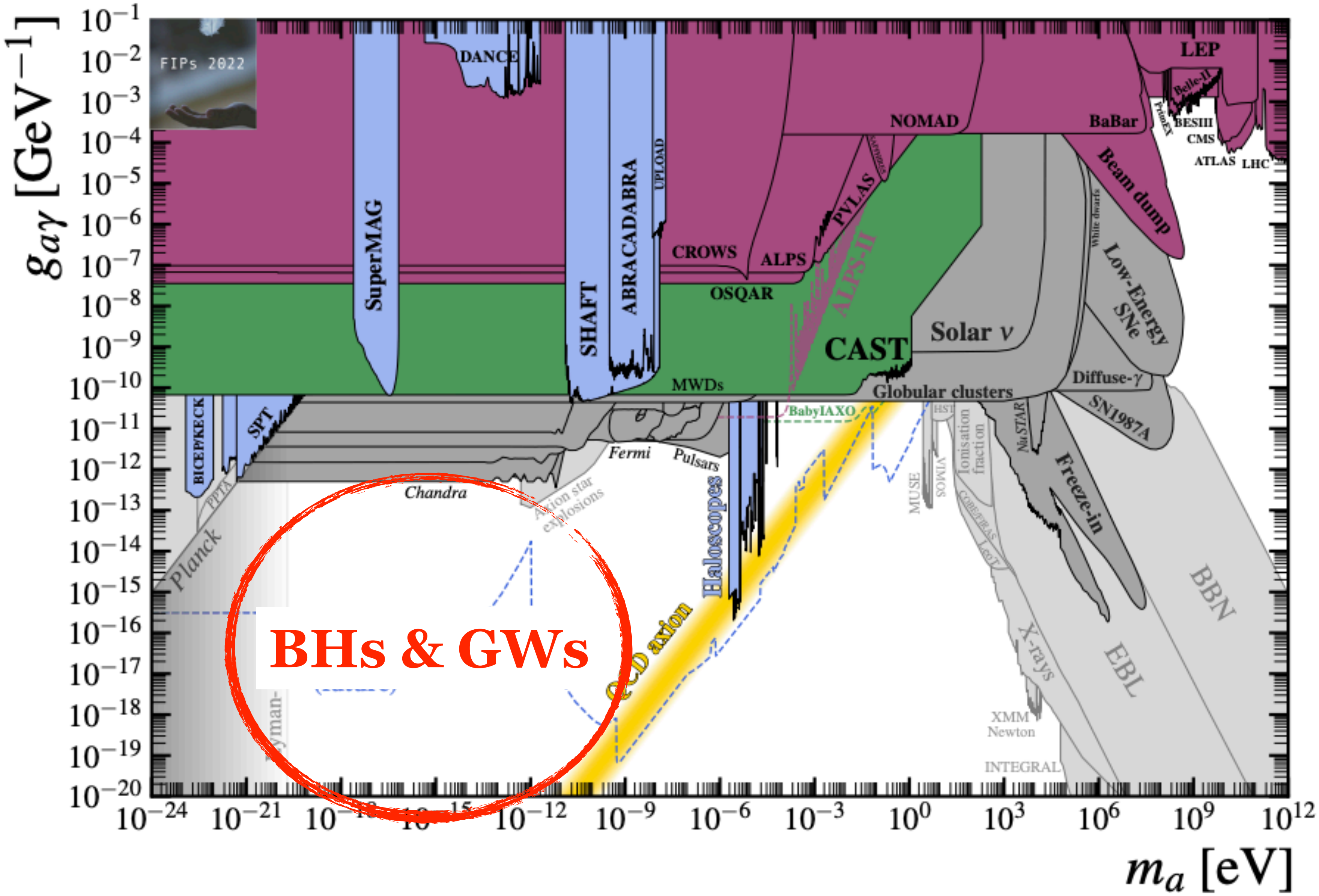

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Backup slides

Boson clouds and EMRIs

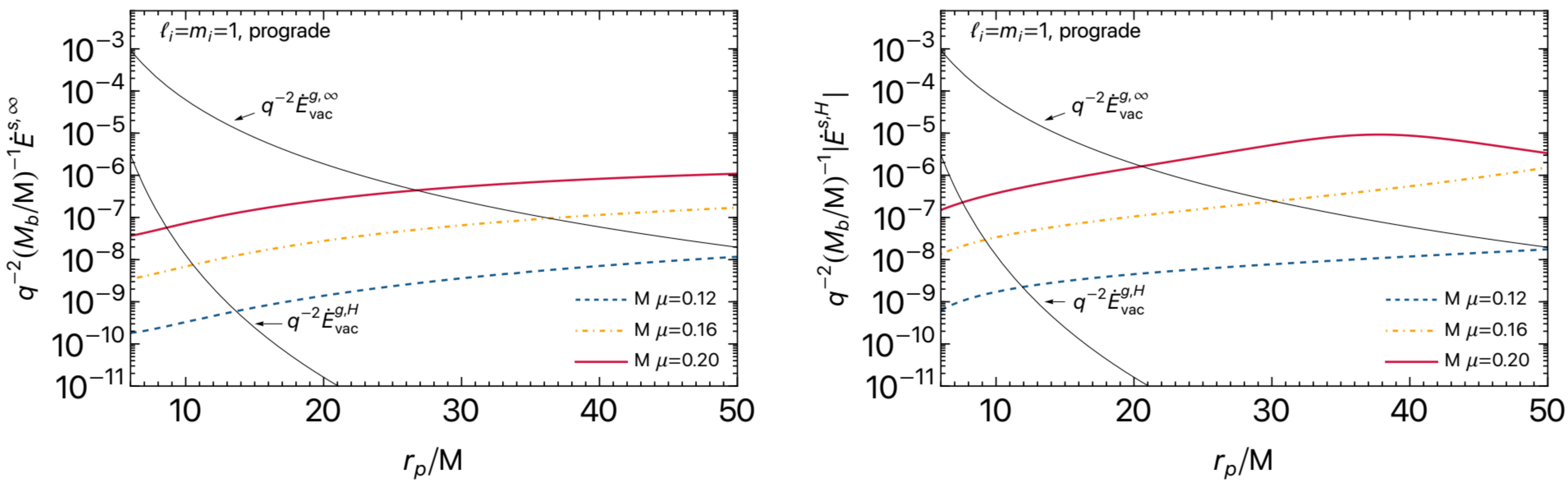
- First steps towards modelling fully-relativistic EMRIs in non-vacuum spacetimes: [Cardoso+ '21-22; Figueiredo+ '23 ;Duque+ '23]
- ***(Non-spherical) boson clouds around BHs*** [RB & Shah '23]

$$G_{\mu\nu} = 8\pi(T^{\Phi}_{\mu\nu} + T^{pp}_{\mu\nu}) \qquad \Box\Phi - \mu^2\Phi = 0$$

$$g_{\mu\nu} = g^{(0,0)}_{\mu\nu} + q g^{(0,1)}_{\mu\nu} + \epsilon^2 g^{(2,0)}_{\mu\nu} + \ldots \qquad \Phi = \epsilon(\Phi^{(1,0)} + q\Phi^{(1,1)}) + \ldots \qquad q \equiv m_p/M \ll 1$$

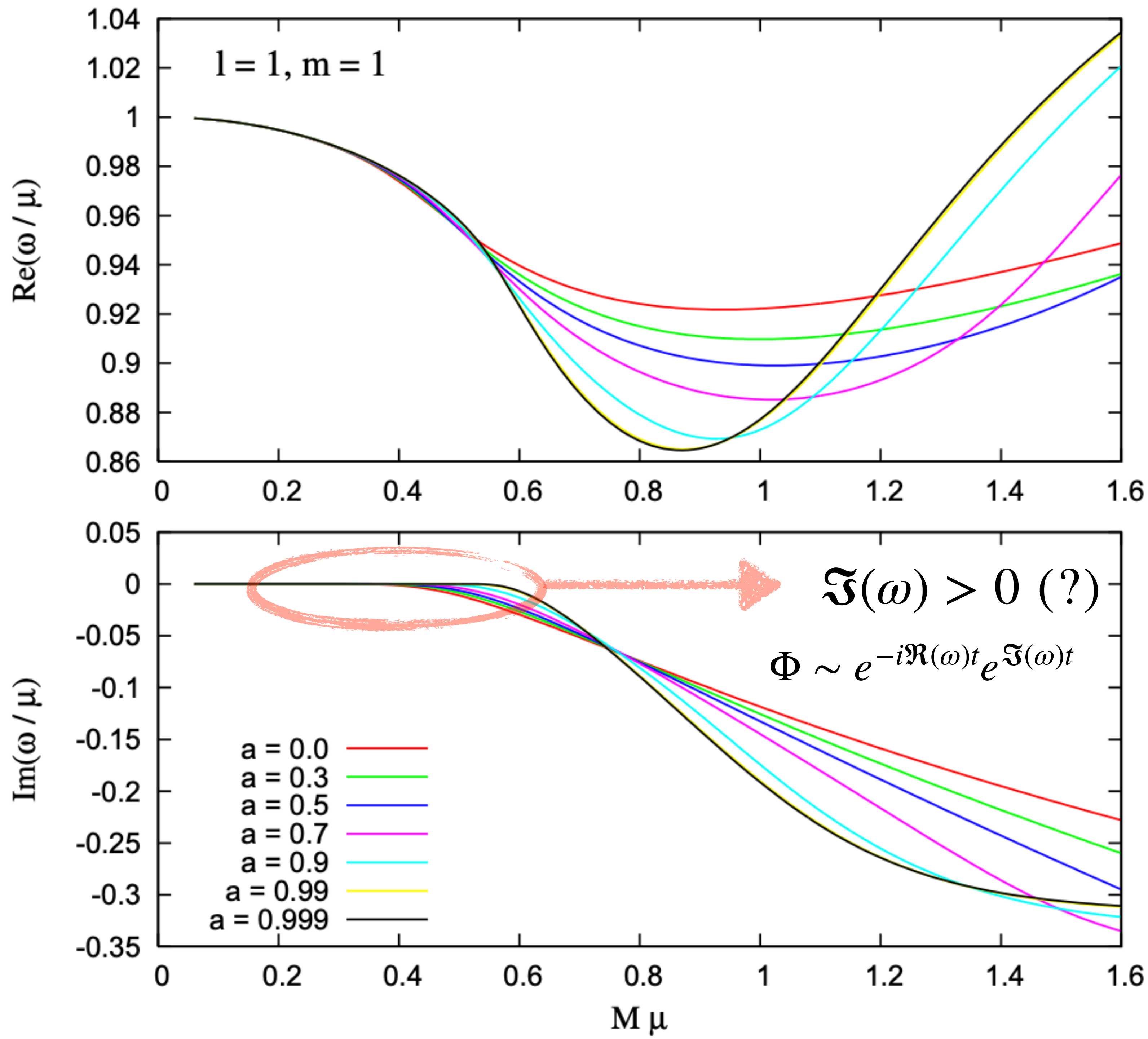
$$\epsilon \ll 1$$

$$\dot{E}_{\rm orb} = -\dot{E}^{{\rm GW},\infty} - \dot{E}^{{\rm GW},H} - \dot{E}^{S,\infty} - \dot{E}^{S,H}$$



[From: RB & S. Shah, 2307.16093]

Spectrum of quasi-bound states



$$M\mu \equiv \frac{M m_b}{M_{\rm Pl}^2} = R_G/\lambda_C$$

From: Dolan, arXiv:0705.2880