TÉCNICO LISBOA

Fundação para a Ciência e a Tecnologia

Extreme-mass-ratio inspirals into black holes surrounded by boson clouds

Richard Brito
CENTRA, Instituto Superior Técnico, Lisboa

RB & Shreya Shah, arXiv:2307.16093 [gr-qc]
Hassan Khalvati+, arXiv:2410.17310 [gr-qc]

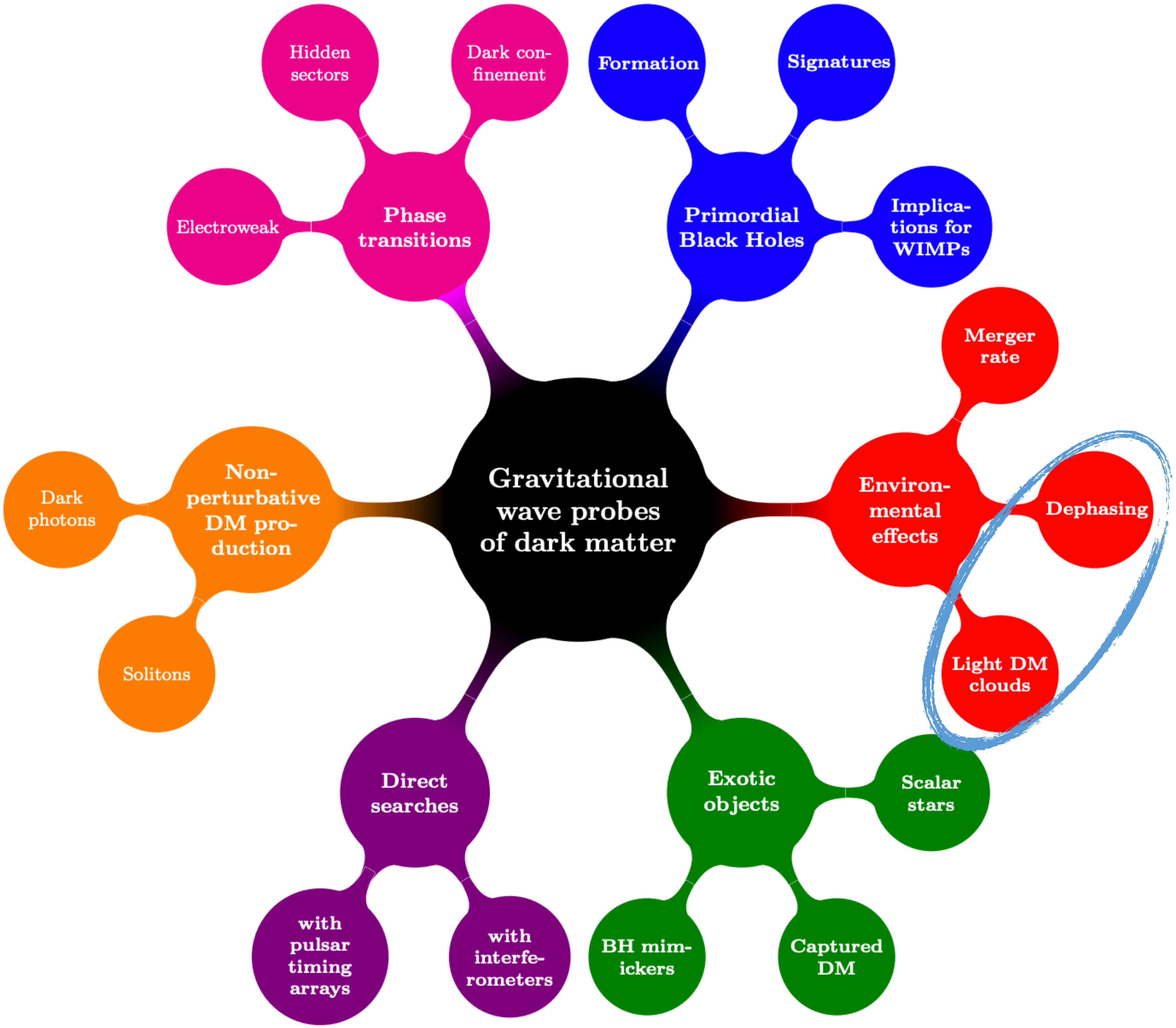
centra
30th Anniversary

grit
gravitation in técnico

Dark matter & Gravitational Waves

From: Bertone *et al*, arXiv:1907.10610

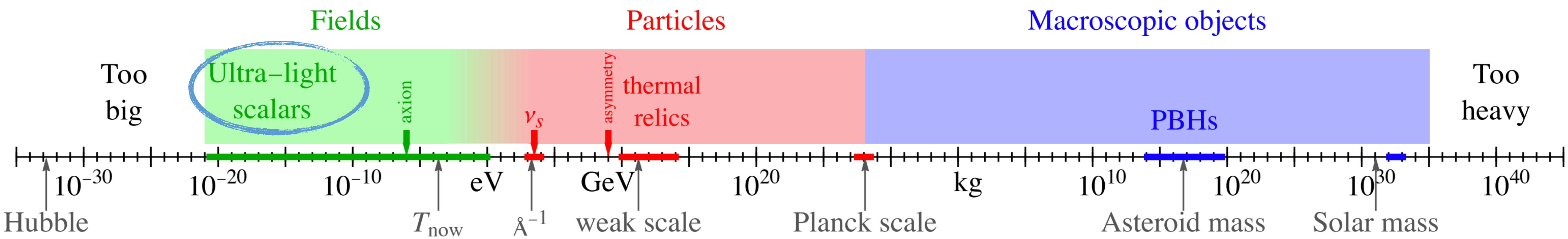
Dark matter & Gravitational Waves



From: Bertone *et al*, arXiv:1907.10610

Dark matter, ultralight bosons & black holes

Dark matter candidates all over the place…



From: Cirelli, Strumia& Zupan, arXiv:2406.01705

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

$$\mathscr{L} = \frac{R}{16\pi} - \frac{1}{2}\nabla^\mu \Phi \nabla_\mu \Phi - \frac{\mu^2}{2}\Phi^2$$

$$\mu = m_b c/\hbar = \lambda_c^{-1} \qquad \alpha := M\mu = R_G/\lambda_C \approx 0.1 \left(\frac{M}{15 M_\odot}\right)\left(\frac{m_b c^2}{10^{-12}\mathrm{eV}}\right)$$

Massive bosonic fields around black holes

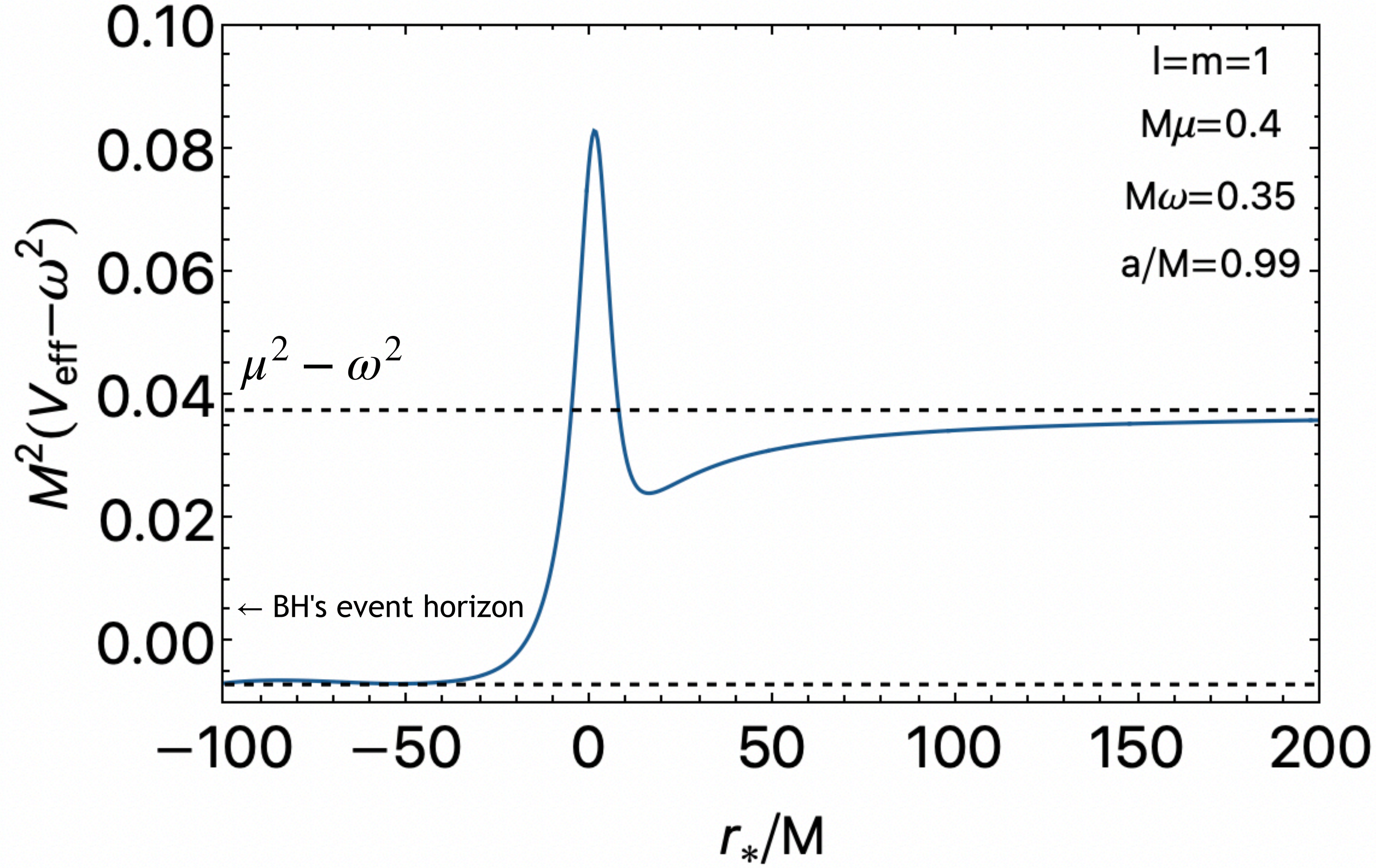
Damour+ '76; Zouros & Eardley '79; Detweiler '80; Cardoso & Yoshida, '05; Dolan '07; Rosa & Dolan '12; Pani+'12; Witek+ '12; RB, Cardoso & Pani '13; Baryakthar, Lasenby & Teo '17; East '17; Cardoso+ '18; Frolov+ '18; Dolan '18; Baumann+ '19; RB, Grillo & Pani '20; Dias+ '23...

Massive bosonic fields can form bound states around black holes.

$$\Box_{g^{\mathrm{Kerr}}} \Phi - \mu^2 \Phi = 0$$

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

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



$$\Re(\omega_{nlm}) \approx \mu \left(1 - \frac{\alpha^2}{2n^2} + \cdots\right)$$

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

$\alpha \equiv M\mu, \quad \Omega$ – "BH's angular velocity"

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

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

Most unstable mode $l = m = 1$ **maximized** when $\alpha \sim 0.5$.

Evolution of the superradiant instability

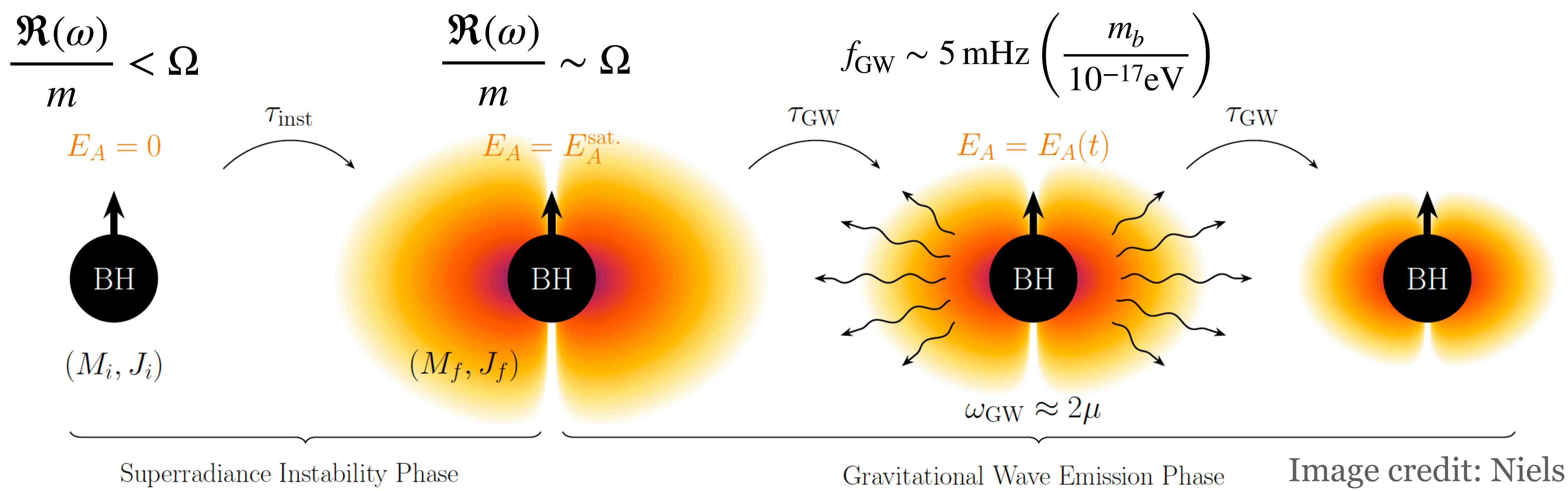
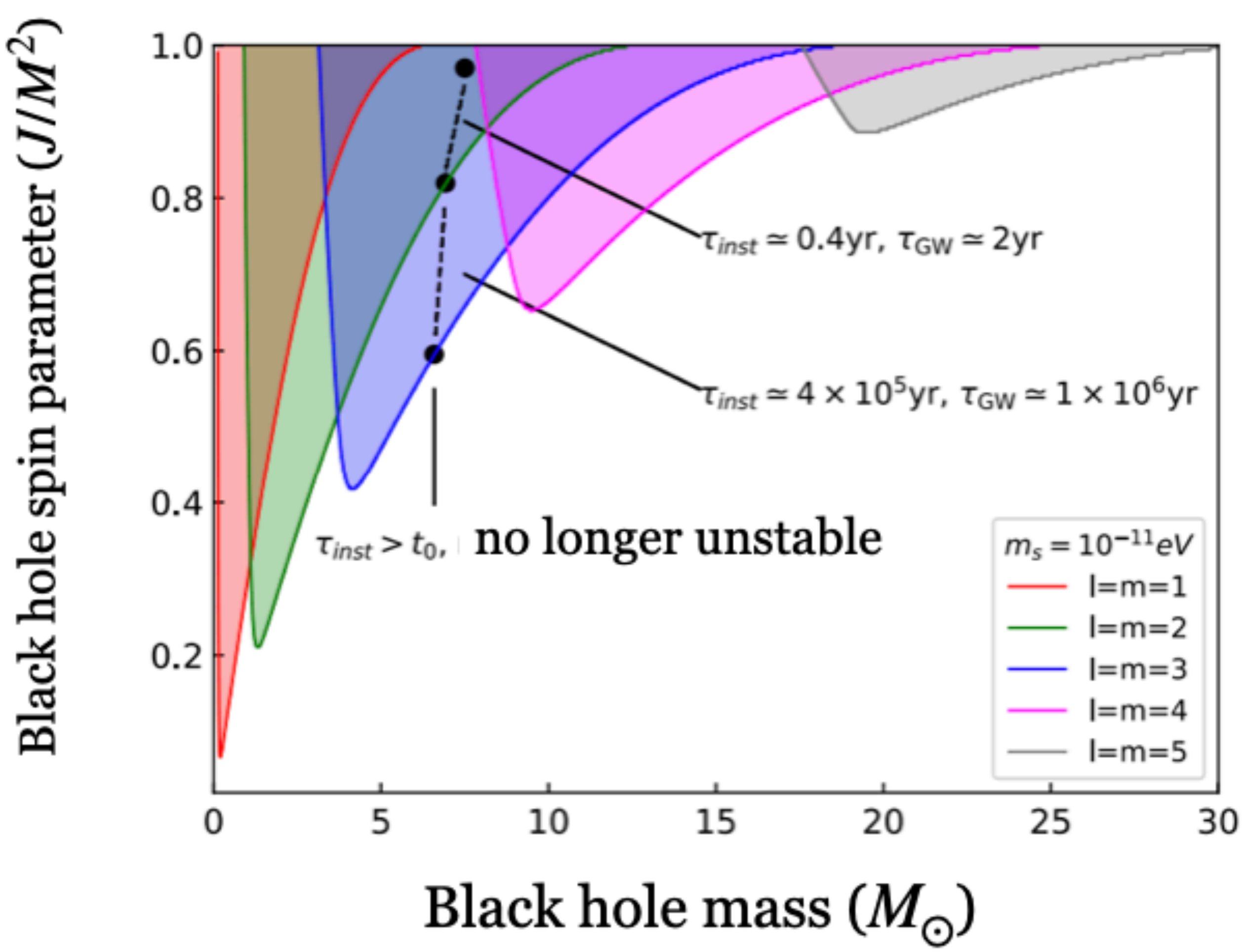


Image credit: Niels Siemonsen



From: Yuan, RB, Cardoso, PRD104, 044011 (2021)

For most unstable mode:

$$\tau_{\rm inst}^{\rm scalar} \approx 10^3\,\mathrm{yrs}\left(\frac{M}{10^5\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^9\left(\frac{0.9}{J/M^2}\right)$$

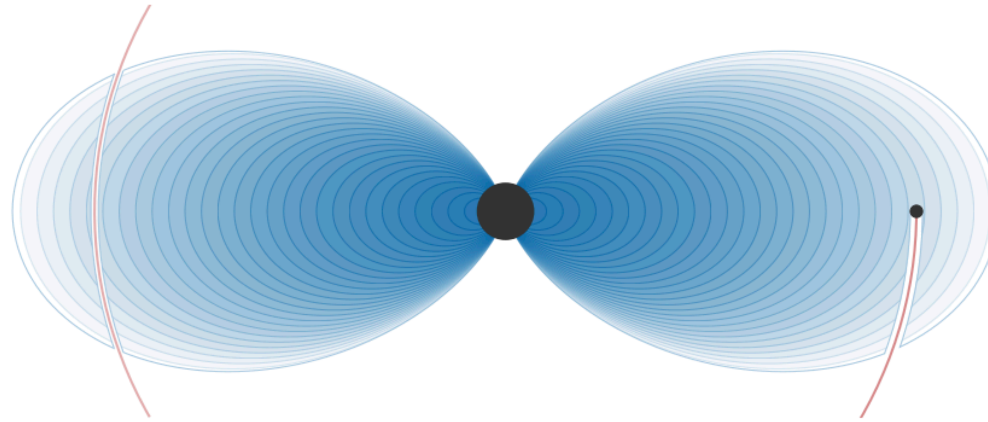
[Detweiler '80; Dolan '07]

$$\tau_{\rm GW}^{\rm scalar} \approx 10^9\,\mathrm{yr}\left(\frac{M}{10^5\,M_\odot}\right)\left(\frac{0.1}{M\mu}\right)^{15}\left(\frac{0.5}{\Delta(J/M^2)}\right)$$

[Yoshino & Kodama '14; Arvanitaki+ '14; RB+ '17]

Note: formulas above only valid for $M\mu \ll 1$

Probing boson clouds with binary systems



From: Baumann+, PRD105, 115036 (2022)

- Some effects induced by the presence of a boson cloud studied using **Newtonian approximations**:
  - **"Ionization"** (dynamical friction) and **accretion** [Baumann+'21; Tomaselli+'23, '24]
  - **Floating/Sicking orbits** at specific orbital frequencies due to excitation of **resonances** [Baumann+'18, '19; Zhang&Yang '18; Tomaselli+'24]
  - Non-vanishing **tidal Love numbers**: $k_l \propto r_{\rm cloud}^{2l+1} \propto 1/\alpha^{4l+2}$ [Baumann+ '18; de Luca+ '21, '22; Arana, RB & Castro '24]

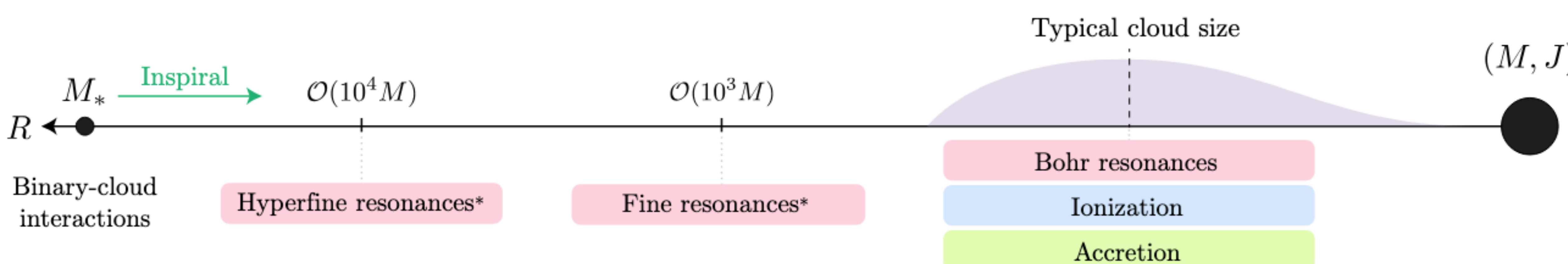


Image credit: Riccardo della Monica

Modelling EMRIs in boson clouds

RB & Shah '23; C. Dyson, T. Spieksma+ *in preparation*
(see also Duque+ '23)

$$S = \int d^4x \sqrt{-\mathbf{g}} \left(\frac{\mathbf{R}}{16\pi} - \nabla_\mu \mathbf{\Phi}^* \nabla^\mu \mathbf{\Phi} - \mu^2 |\mathbf{\Phi}|^2 \right) - m_p \int_\gamma \sqrt{\mathbf{g}_{ab} u^a u^b} d\tau$$

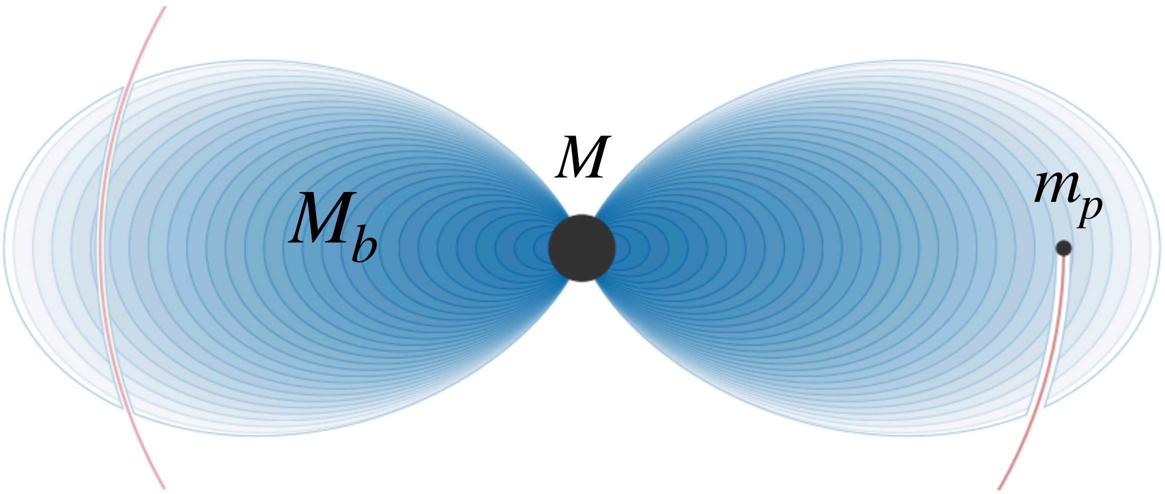
Scalar field "environment"

Secondary object modelled as point-particle

M = Primary BH mass

m_p = Secondary object mass

M_b = total cloud's mass



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*EMRIs = Extreme-Mass-Ratio Inspirals

[see C. Berry's talk]

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$$\mathbf{g}_{\mu\nu} = g^{\rm Kerr}_{\mu\nu} + q h^{(1,0)}_{\mu\nu} + \epsilon^2 h^{(0,2)}_{\mu\nu} + \epsilon^2 q h^{(1,2)}_{\mu\nu} + \ldots \,, \qquad \mathbf{\Phi} = \epsilon \Phi^{(0,1)} + q\epsilon \Phi^{(1,1)} + \ldots$$

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$$\mathcal{O}(q^0, \epsilon^1): \ \left(\Box_{g^{\mathrm{Kerr}}} - \mu^2 \right) \Phi^{(0,1)} = 0 \longrightarrow \Phi_{\ell_b m_b} = R_{\ell_b m_b}(r) S_{\ell_b m_b}(\theta) e^{-i(\omega t - m_b \varphi)}$$

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•••

Scalar energy fluxes

RB & Shah, PRD108, 084019 (2023)

$$\dot{E}_{\rm orb} + \dot{M}_{\rm b} = -\dot{E}^{g,\infty} - \dot{E}^{g,H} - \dot{E}^{\Phi,\infty} - \dot{E}^{\Phi,H}$$

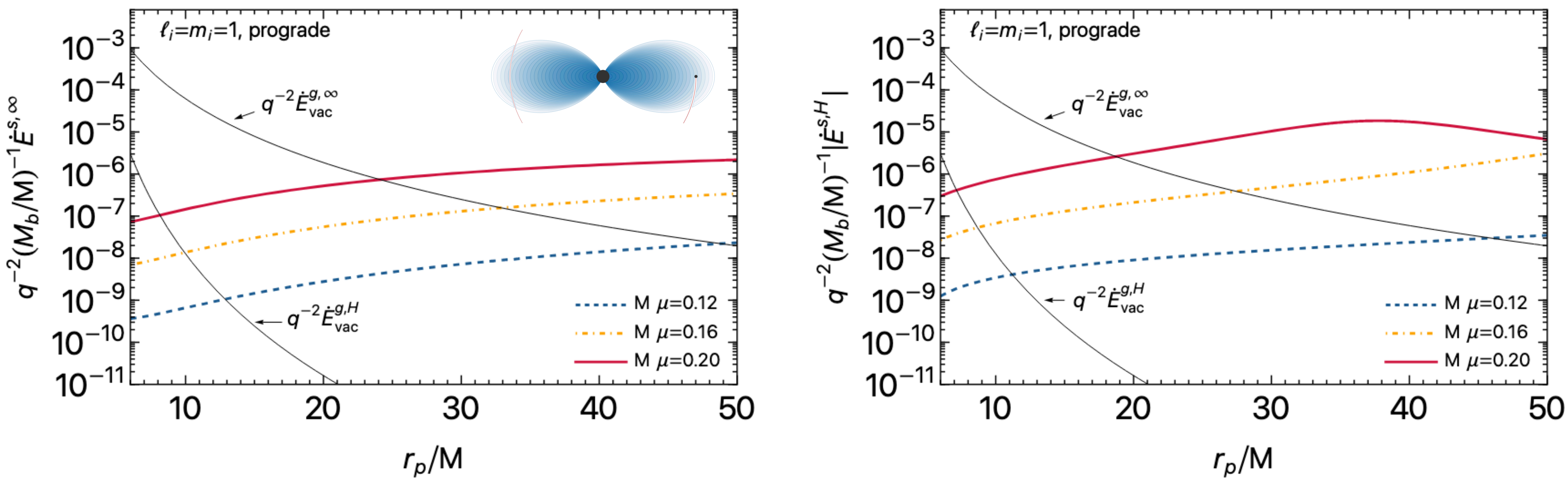
GW fluxes — scalar radiation fluxes

$\dot{M}_b = \omega \dot{Q}\,,\quad Q$ - Noether charge

Convenient to define:

$$\dot{E}^{s,\infty/H} = \dot{E}^{\Phi,\infty/H} + \dot{M}_b^{\,\infty/H}$$

Note: Results for circular, equatorial orbits, **neglecting BH spin.**
Kerr BH case is ongoing work (C. Dyson+, *in prep.*)



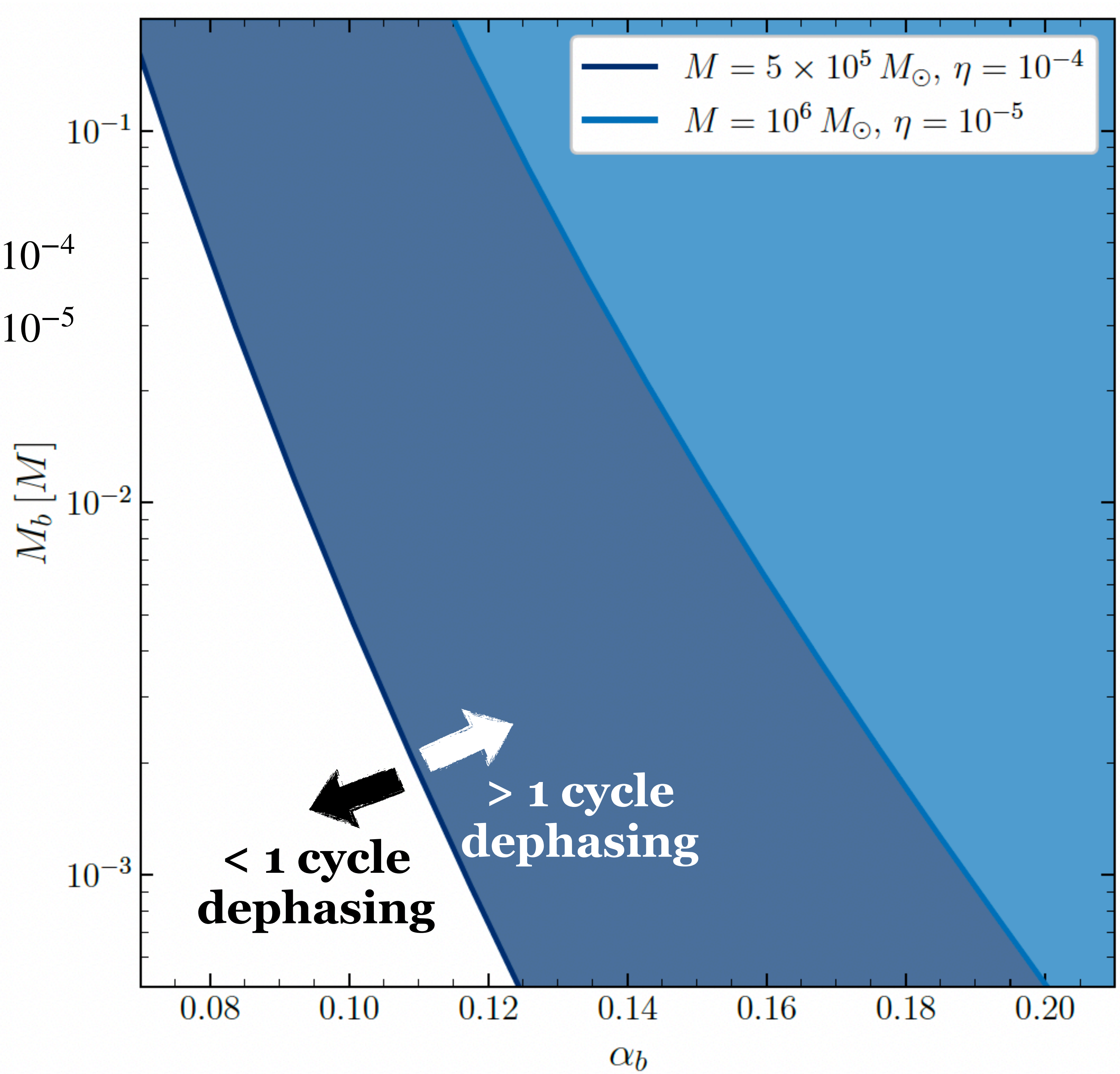
Power lost due to the presence of the boson cloud can **dominate** over GW emission at large orbital separations.

Orbital dephasing due to scalar clouds

H. Khalvati+, 2410.17310

$p_0 \sim 22M$ for $\eta = 10^{-4}$

$p_0 \sim 11M$ for $\eta = 10^{-5}$



Orbit evolved **adiabatically**.

η – mass ratio

$\alpha_b \equiv M\mu$

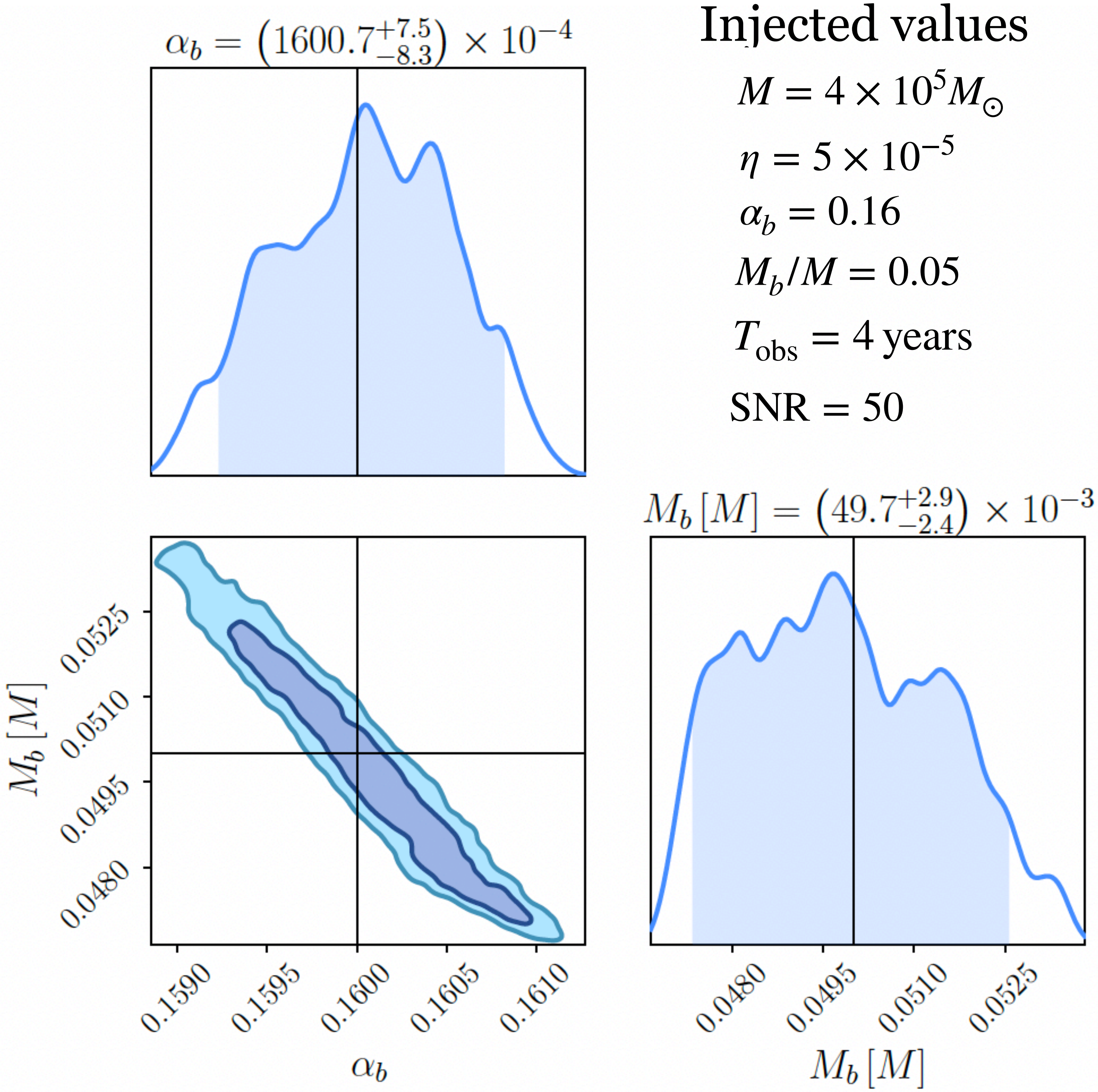
$T_{\rm obs} = 4$ yrs (until plunge)

Credit: Hassan Khalvati, Alessandro Santini & Francisco Duque

EMRIs in clouds: parameter estimation

H. Khalvati+, 2410.17310

FEW: see Chapman-Bird's talk



Injected values

$M = 4 \times 10^5 M_\odot$

$\eta = 5 \times 10^{-5}$

$\alpha_b = 0.16$

$M_b/M = 0.05$

$T_{\rm obs} = 4$ years

SNR = 50

Scalar fluxes included in **FEW**.

Proof-of-principle bayesian analysis in LISA:

$\sigma_{M_b}/M_b \sim 5\,\%$

$\sigma_{\alpha_b}/\alpha_b \sim 0.5\,\%$

Distinguishable from other environments (e.g. disks, dark matter spikes)?

Probably **yes**.

See P.S. Cole+ '23

Credit: Hassan Khalvati, Alessandro Santini & Francisco Duque

Conclusions

Presence of **boson clouds** around black holes could leave imprint in GWs emitted by binary black hole systems.

We proposed a **fully relativistic, perturbative framework** to study EMRIs in the presence of boson clouds.

Proof-of-principle results (neglecting BH spin, circular equatorial orbits) promising. **Extension to equatorial, circular orbits in Kerr** being worked out now.

We considered scalar clouds only, but formalism could be useful for **other environments** as well.

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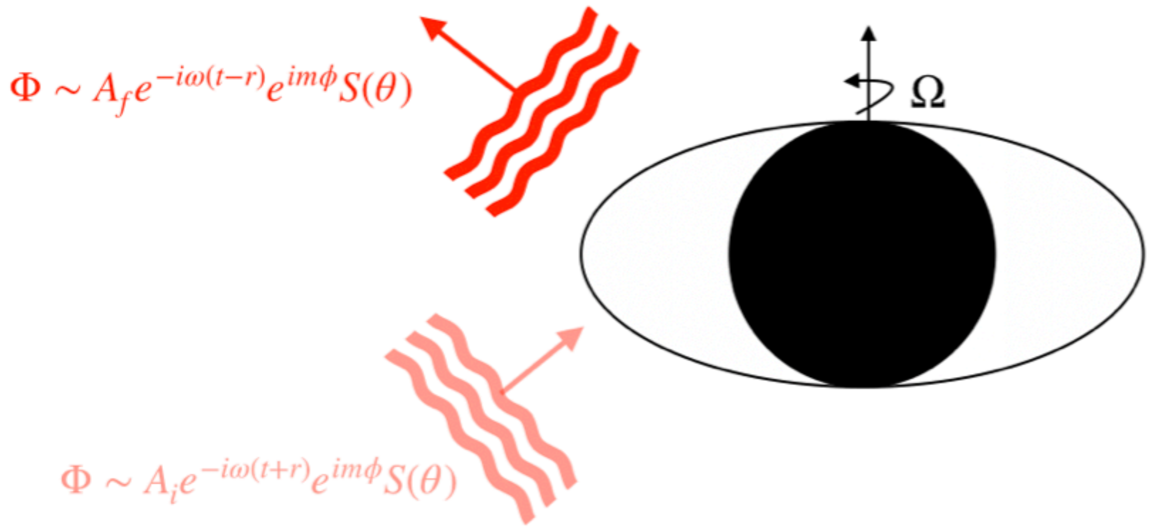
Thank you!

Backup slides

Black hole superradiance

Zel'dovich, '71; Misner '72; Press and Teukolsky ,'72-74;
Review: RB, Cardoso & Pani "Superradiance" Lect. Notes Phys. 971 (2020), 2nd ed.

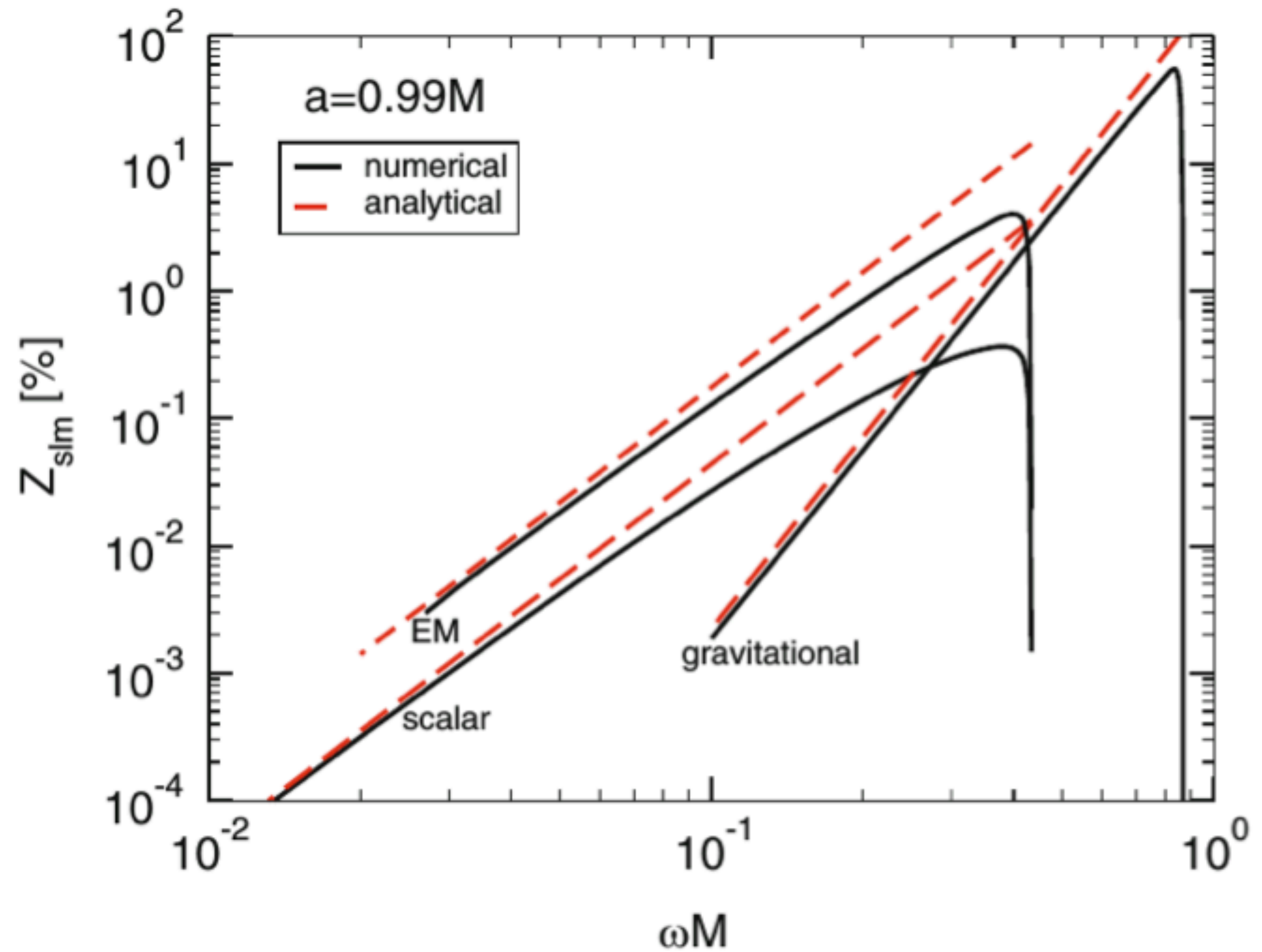


$$Z_{slm} = \frac{dE_{\rm out}/dt}{dE_{\rm in}/dt} - 1$$

$$\omega/m < \Omega \implies Z_{slm} > 1$$

⇓

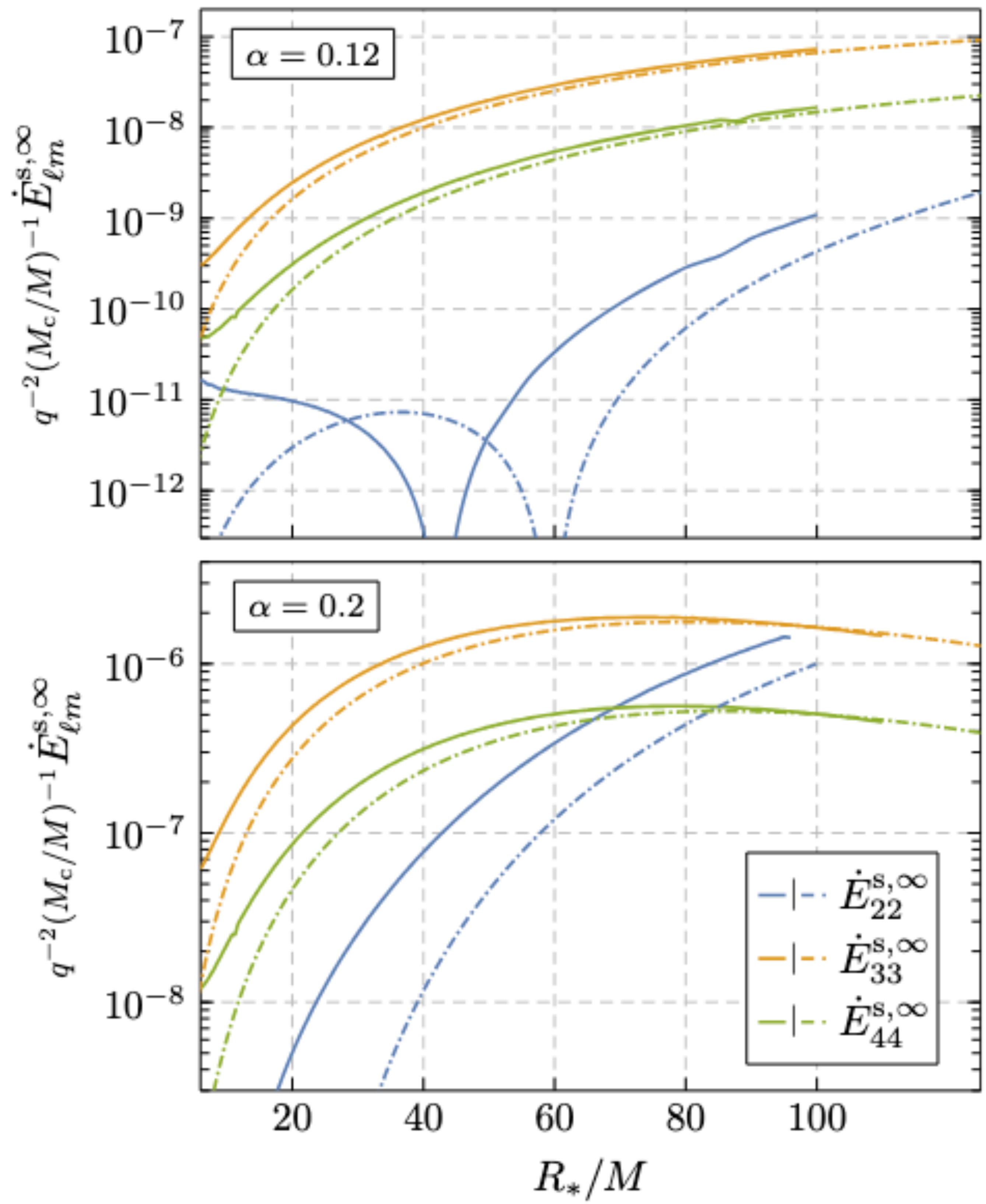
Extraction of energy and angular momentum from the black hole



Ionization: Newtonian vs Relativistic

Dashed - Newtonian approximation
Baumann+'21; Tomaselli+'23, '24

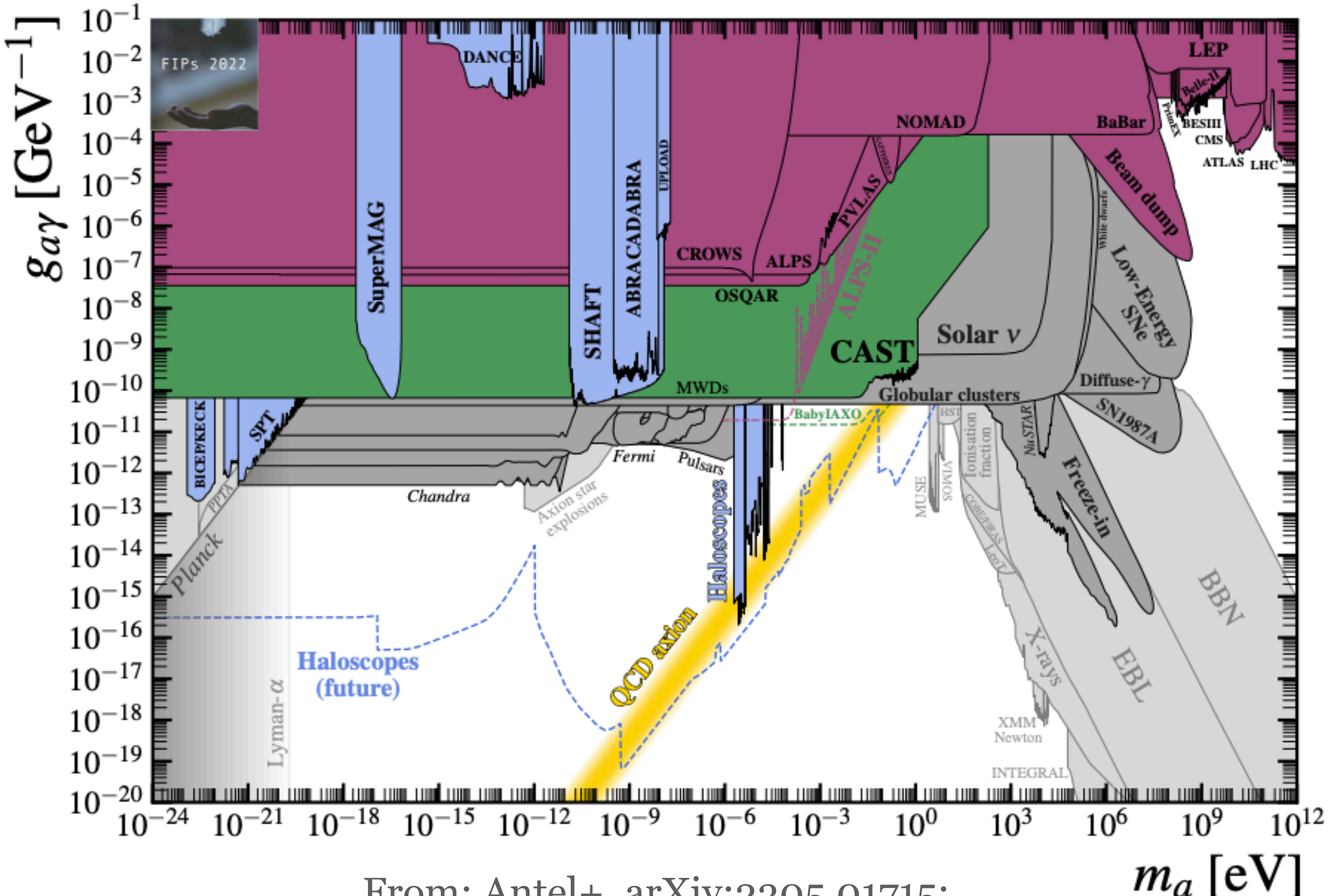
Solid - Relativistic (neglecting BH spin, data only up to $R_* = 100M$)



Credit: Thomas Spieksma

Specific application: axion-like particles

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



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

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

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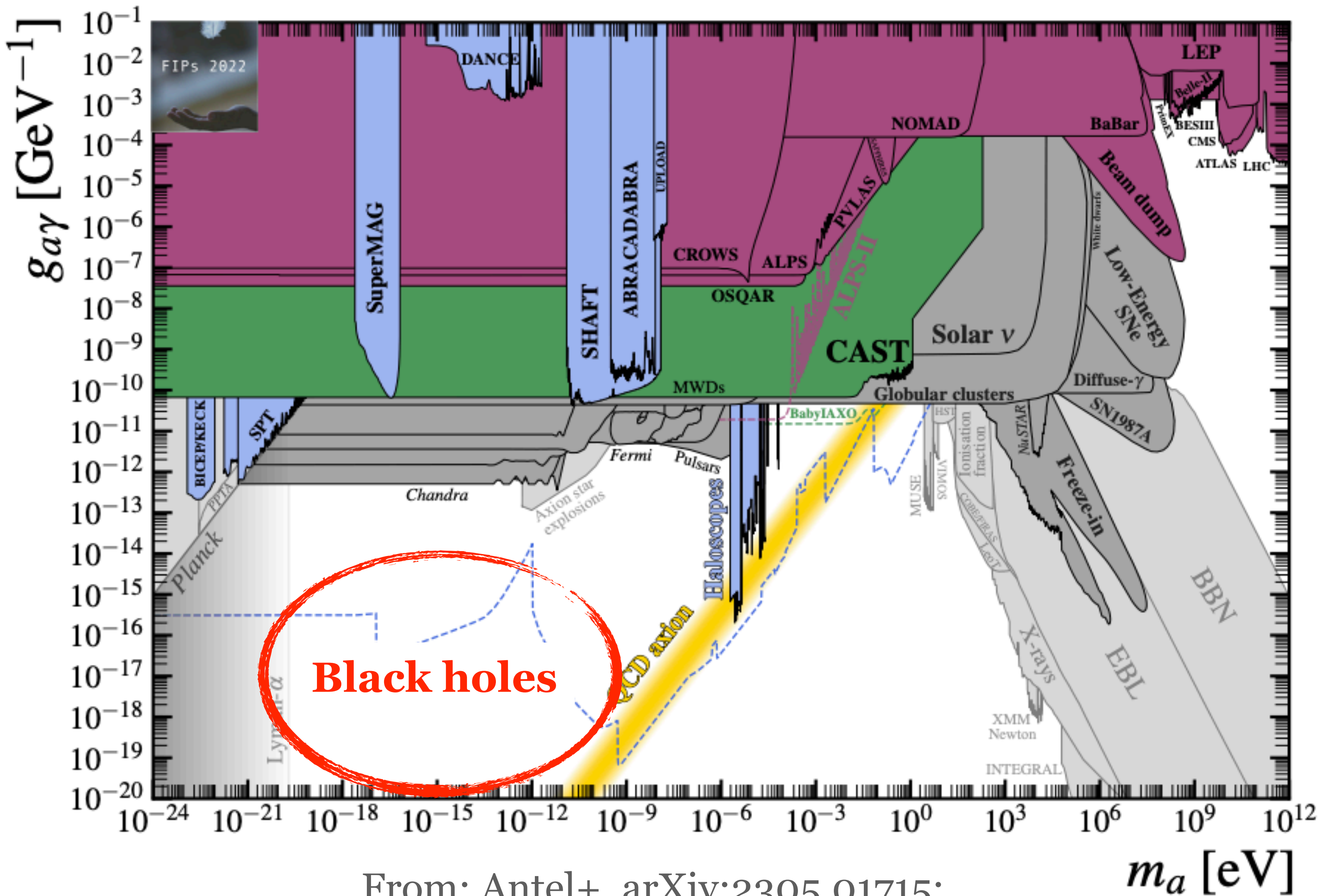

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First proposed in Arvanitaki+, "String axiverse", PRD81, 123530 (2010)