Testing ultralight bosons through black hole superradiance

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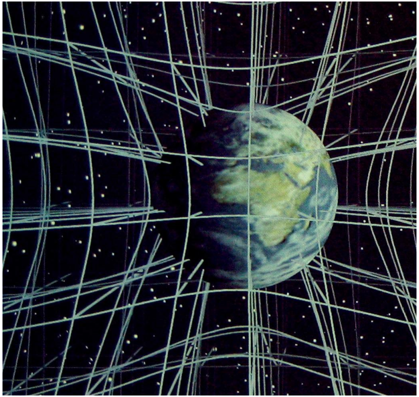
General Relativity: a brief introduction

"Space-time tells matter how to move; matter tells space-time how to curve."
(John Archibald Wheeler)



- Energy/matter dynamics in curved space-time:

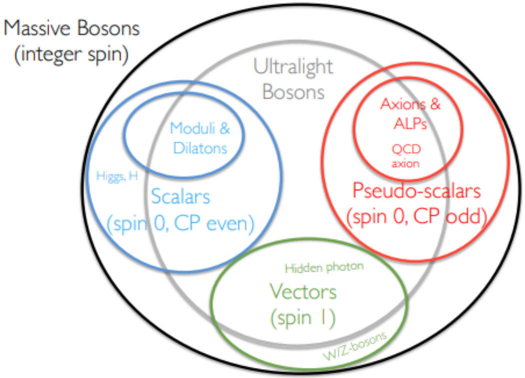
$$\frac{d^2x^\sigma}{d\tau^2} + \Gamma^\sigma{}_{\mu\nu}\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau} = 0$$

$$\left(g^{\mu\nu}\nabla_\mu\nabla_\nu + \frac{\mu^2c^2}{\hbar^2}\right)\Phi = 0$$

- space-time dynamics

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

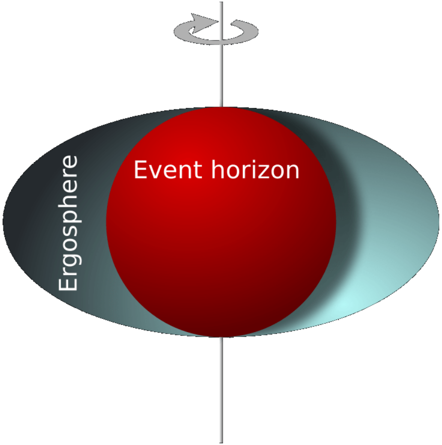
What are ultralight bosons?



(F. Chadha-Day, J. Ellis, D. J. E. Marsh, *arXiv:2105.01406*)

- Hypothetical particles having masses < 1 eV
- Extensions of Standard Model and General Relativity
- Weak coupling to Standard Model particles
- Dark Matter candidates
- Examples: axions, dark photons, massive gravitons
- Gravity can be used for detection
- Black holes as particle physics labs

Some properties of spinning black holes



(credits: MesserWoland, via Wikimedia Commons)

- Event horizon having radius
  $$r_+ = \frac{GM}{c^2}\left(1 + \sqrt{1 - a^{*2}}\right)$$
- Event horizon = one-way surface
- Adimensional spin parameter:
  $$0 < a^* = \frac{cJ}{GM^2} < 1$$
- Ergosphere:
  $$r(\theta) = \frac{GM}{c^2}\left(1 + \sqrt{1 - a^{*2}\cos^2\theta}\right)$$
- Ergoregion: $r_+ < r < r(\theta)$
- Ergoregion allows negative energy

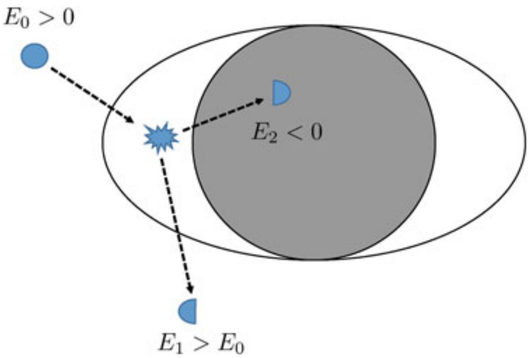
What is black hole superradiance?

Zel'dovich (1971); Misner (1972); Press and Teukolsky (1972-1974)

$$\Phi_i \sim A_i e^{-i\omega(t+r)} e^{im\phi} S(\theta) \qquad \Phi_f \sim A_f e^{-i\omega(t-r)} e^{im\phi} S(\theta)$$

- $|\omega| < m\Omega \implies |A_f| > |A_i|$ (superradiance)
- Wave amplification through scattering on black hole
- Extraction of energy and angular momentum from black hole
- Happens with all bosonic waves (any type, i.e. scalar, vector, tensor...)

The Penrose process

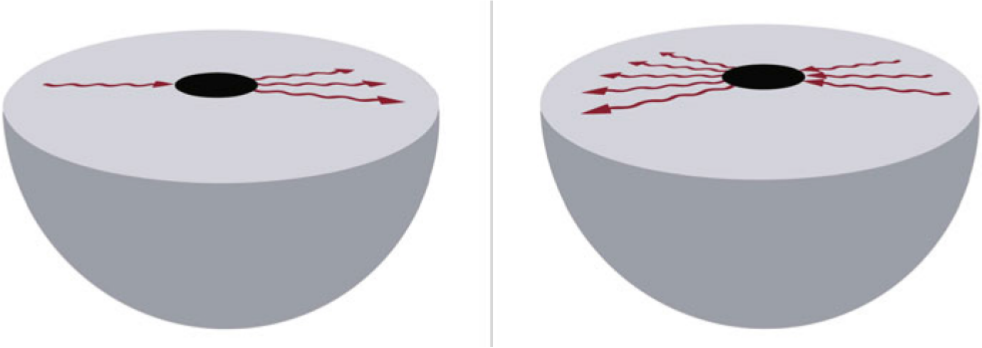


(R.Brito, V.Cardoso, P.Pani, *"Superradiance: New Frontiers in Black Hole Physics"*, ISBN: 978-3-030-46622-0)

- Ergoregion + Event Horizon = dissipative mechanism
- Superradiance = wave equivalent of Penrose process

Superradiant instability: the black hole bomb

Spinning black hole in a closed mirror (Press and Teukolsky, 1972):

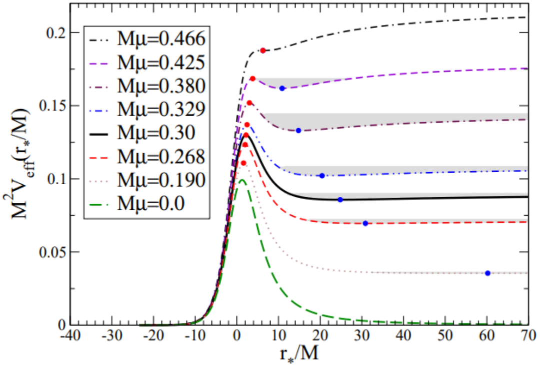


(R.Brito, V.Cardoso, P.Pani, *"Superradiance: New Frontiers in Black Hole Physics"*, ISBN: 978-3-030-46622-0)

- Waves are continuously scattered, as long as $|\omega| < m\Omega$
- The system is unstable under bosonic perturbations
- Black hole spin-down

Superradiant instability: massive bosons

Damour (1976); Zouros and Eardley (1979); Detweiler (1980); Dolan (2007); Rosa and Dolan (2012); Pani et al (2012); Baryakthar et al (2017); East (2017); Cardoso et al (2018); Frolov et al (2018); Dolan (2018); Baumann et al (2019); Brito et al (2020)



(J. Barranco et al, *Phys. Rev. D 84, 083008 (2011)*)

BH perturbed by massive boson field:

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

- Mass introduces potential well
- Mass term works as confinement
- Quasi-bound states for $|\omega| < \frac{\mu c}{\hbar}$
- Superradiant instability
- Expected for any boson spin

Bosonic quasi-bound states: the gravitational atom

Damour (1976); Zouros and Eardley (1979); Detweiler (1980); Dolan (2007); Rosa and Dolan (2012); Pani et al (2012); Baryakthar et al (2017); East (2017); Cardoso et al (2018); Frolov et al (2018); Dolan (2018); Baumann et al (2019); Brito et al (2020)

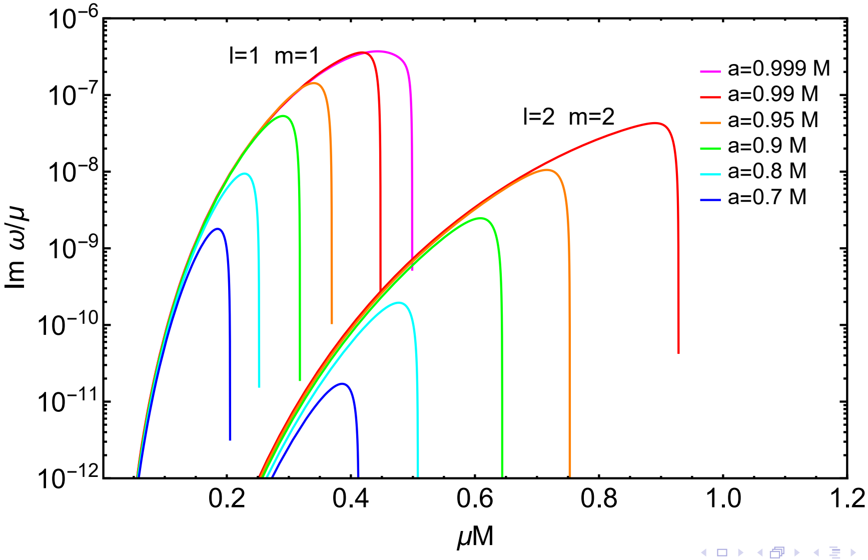
$\alpha := \frac{GM}{c^2}\frac{\mu c}{\hbar}$ gravitational fine structure constant

If $\alpha \ll 1 \implies$ hydrogenic solutions for quasi-bound states (complex frequencies!)

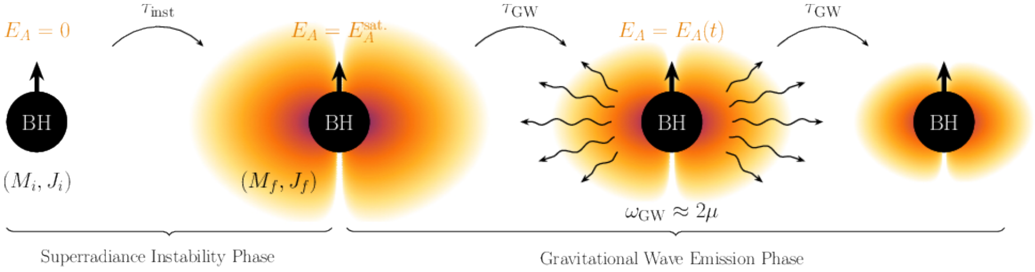
$$\omega_{nlm} \approx \frac{\mu c^2}{\hbar}\left(1 - \frac{\alpha^2}{2n^2}\right) + i\Gamma_{nlm}(\alpha)$$

- there are also hyper-fine (relativistic) corrections
- $|\omega| < m\Omega \implies \Gamma_{nlm}(\alpha) > 0 \implies$ superradiant instability
- similar to hydrogen atom, but classical states (bosonic field, non-stationarity)
- perturbation theory computation, neglecting spacetime back-reaction

Superradiant instability triggered by scalar field



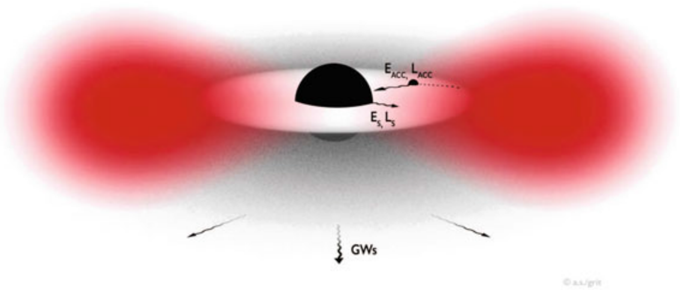
Full evolution of black hole superradiance



(Leo Tsukada, Richard Brito, William E. East, Nils Siemonsen, *Phys. Rev. D 103, 083005 (2021)*)

- Different field spin gives different time scales (scalar $\gg$ vector $>$ tensor)
- Testing through superradiance for $\mu \sim [10^{-20}, 10^{-10}]eV$
- Rich phenomenology observable with gravity:
  emission of continuous GWs, gaps in BH mass-spin distribution, signatures in binaries

Concluding remarks



(R.Brito, V.Cardoso, P.Pani, *"Superradiance: New Frontiers in Black Hole Physics"*, ISBN: 978-3-030-46622-0)

- No ultralight boson detected yet (putting constraints)
- Fully solved perturbation theory computation for scalar and vector bosons
- Tensor perturbations only computed for $\alpha \ll 1$ or $a^* \ll 1$
- Full evolution and binaries are challenging (non-linear dynamics)