

Black Hole and Stellar Superradiance

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COSMIC WISPers
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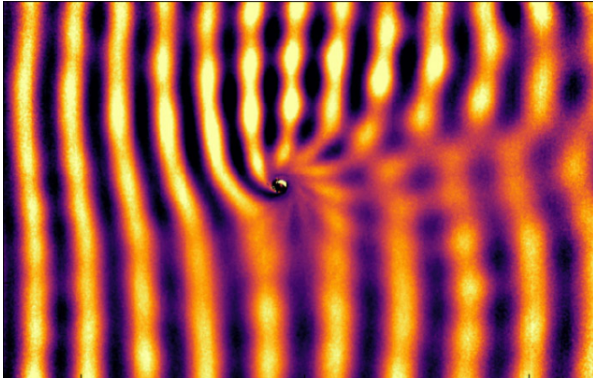


Outline

- 1 Superradiance
- 2 Black hole superradiance
- 3 Stellar superradiance
- 4 Conclusions

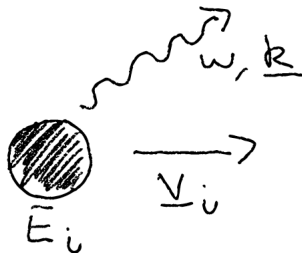
Superradiance

Superradiance is the amplification or enhancement of radiation in a dissipative system.



Reproduced from Torres *et al*, 1612.06180

Radiation from a moving particle



$$E_f = E_i - \omega, \quad \mathbf{p}_f = \mathbf{p}_i - \mathbf{k}$$

Find the particle's rest mass by moving to comoving frame:

$$m_i = \gamma_i(E_i - \mathbf{v}_i \cdot \mathbf{p}_i), \quad m_f = \gamma_f(E_f - \mathbf{v}_f \cdot \mathbf{p}_f)$$

$$\Delta m = -\gamma_i(\omega - \mathbf{v}_i \cdot \mathbf{k}) + \mathcal{O}(\delta \mathbf{v}).$$

Brito, Cardoso & Pani, 1501.06570

Bekenstein & Schiffer, gr-qc/9803033

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- This can occur with tachyons or from medium effects giving $\omega(k) < k$.

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- When $v_{\text{ph}} > v_i$, an absorption effect can become a spontaneous radiation effect, taking energy from the particle's kinetic energy.

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- Superradiance requires that the rotating body be dissipative.

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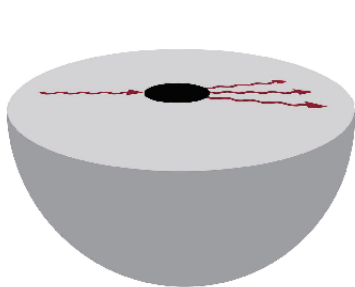
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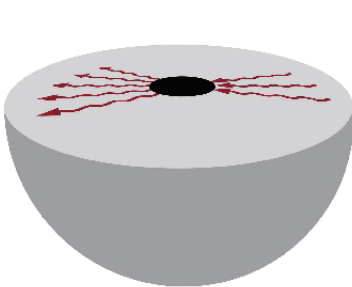
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- The ergoregion of a Kerr black hole can amplify incident radiation.
- Black holes can trap massive radiation.
- Could get exponential amplification of this trapped radiation - a superradiant instability.
- Black hole superradiance is effective for Beyond the Standard Model bosons such as axions.

Black Hole Superradiance



1.



2.

Reproduced from 1501.06570

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- Similar to Hydrogen atom wavefunctions $\psi_{nlm}(r)$.
- The eigen-energies will have an imaginary component, corresponding to the axion being eaten by the black hole, or to superradiant amplification of the axion field.

Black Hole Superradiance

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{2} \nabla_\mu \phi \nabla^\mu \phi - \frac{1}{2} m_a \phi^2 \right)$$

- The equations of motion admit quasi-bound states with $\omega = \omega_R + i\omega_I$.

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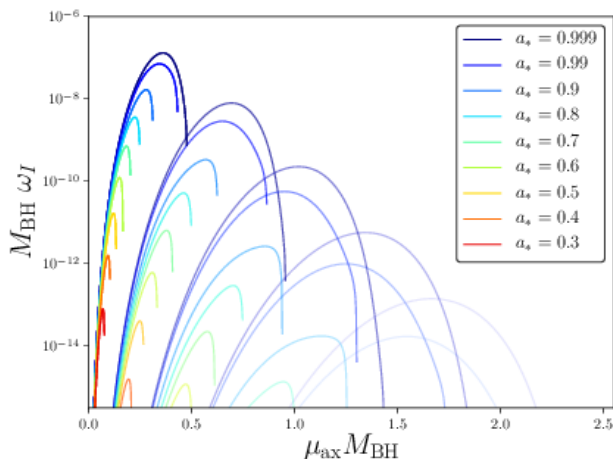
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- We can find ω_I numerically and in some cases analytically.
- $\omega_I > 0$ corresponds to superradiant amplification with timescale $\tau = \frac{1}{\omega_I}$.
- Time domain analysis has also been performed.

Zouros & Eardley, Annals of Physics, 1979

Detweiler, Phys Rev D, 1980

Dolan, 0705.2880 & 1212.1477

Black Hole Superradiance



Reproduced from Stott & Marsh, 1805.02016

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- The instability is most efficient when the black hole's gravitational radius is similar to the axion's compton radius:
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- The instability is less efficient for higher l and m modes.

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Bosenova

Energy of a cloud of size R with N axions:

$$V(R) \sim N \frac{l(l+1) + 1}{2m_a R^2} - N \frac{GMm_a}{R} + \frac{N^2}{32\pi f_a^2 R^3}$$

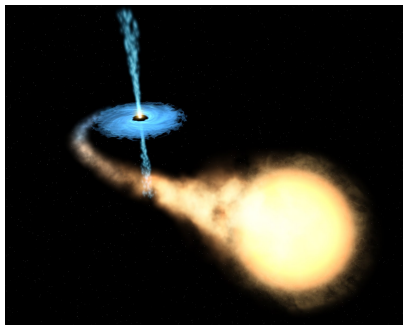
At large N , the gradient energy of the axion field makes the cloud unstable. The collapse may be observed as a gravitational wave and potentially γ -ray burst.

Arvanitaki & Dubovsky, 1004.3558

Black hole spin depletion

We can measure black hole spins:

- X-ray spectra of black hole X-ray binaries
- Gravitational wave emission from mergers



Black hole spin depletion

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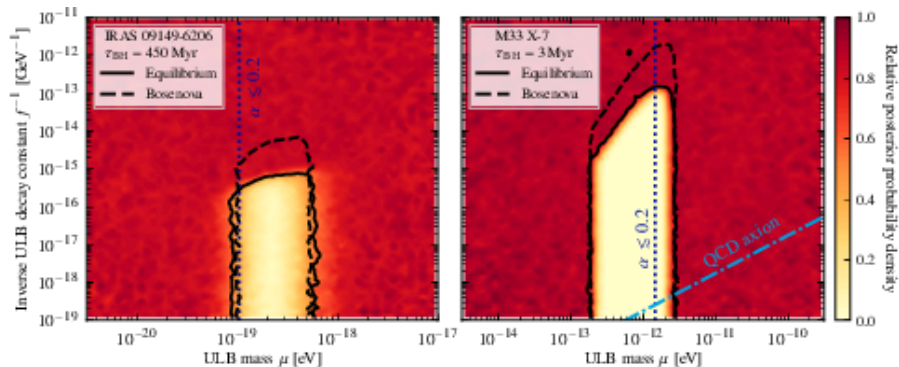
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- Stellar mass BH spin measurements exclude
 $6 \times 10^{-13} \text{ eV} < m_a < 2 \times 10^{-11} \text{ eV}$ for $f_a \gtrsim 10^{13} \text{ GeV}$.
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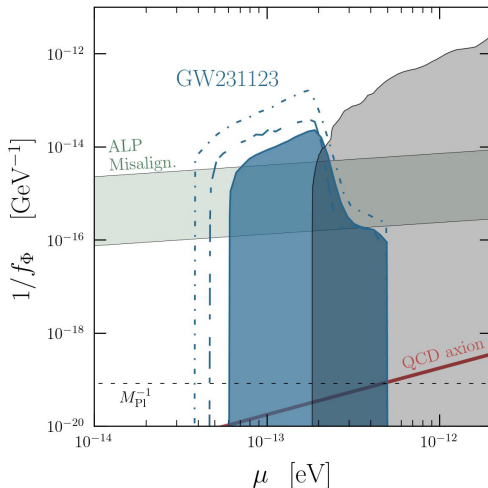
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- Advanced Ligo will be sensitive to $m_a \lesssim 10^{-10} \text{ eV}$. (Arvanitaki *et al*, 1604.03958).

Black hole spin depletion



Reproduced from Hoof *et al*, 2406.10337

Black hole spin depletion



Reproduced from Caputo, Franciolini & Witte, 2507.21788

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- Orbits in binary systems (Kavic *et al*, 1910.06977)

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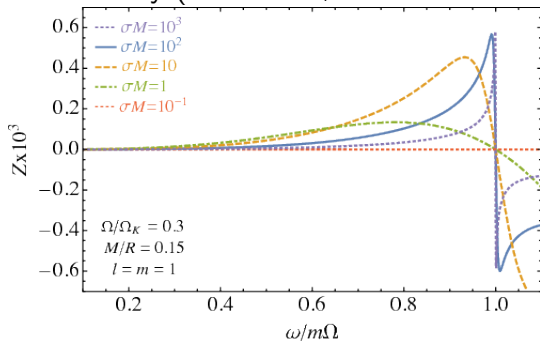
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- For large initial seeds, if both superradiant and non-superradiant modes are populated, the instability may not occur (Ficarra, Pani & Witek, 1812.02758.).
- We should include the effect of the accretion disk (Sarmah, Verma, Cheung & Silk, 2404.09955).

Superradiance in Stars

No horizon - superradiance in stars relies on non-gravitational dissipative dynamics, which become amplifying due to the star's rotation (Zel'dovich, 1971).

Example: Dark photons in neutron stars

Massive dark photons with dissipation from a hidden sector conductivity (V Cardoso, P Pani and T Yu, 1704.06151).



$$Z := \frac{|A_{\text{out}}|^2}{|A_{\text{in}}|^2} - 1.$$

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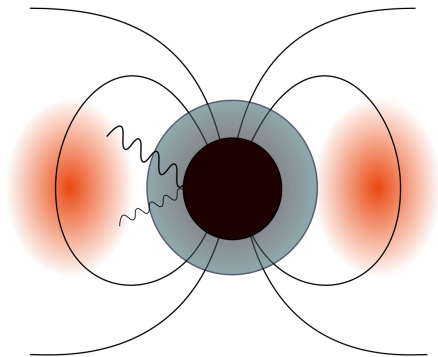
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- This gives the required dissipative interaction.

Kaplan & Rajendran, 1908.10440

Example: Axion-photon superradiance



The axion boundstate (orange) mixes with a photon mode which is then amplified by scattering off the rotating neutron star magnetosphere (grey). The photon energy is then deposited back into the axion sector. (FCD & McDonald, 1904.08341)

Example: Axion-photon superradiance

- We typically find superradiant timescales a few orders of magnitude higher than the neutron star spin down time.
- Therefore, we do not expect this process to be observable.
- Our result is an example of a more general phenomenon which can arise when there is an instability in the plasma sector.
- Sirkia, Heikinheimo & Tuominen (2504.04209) improve this result using a more realistic magnetic field.
- Spieksma & Cannizzaro (2503.19978) show superradiance can be further suppressed by plasma effects.

Stellar superradiance: A general approach

- Many different Beyond the Standard Model interactions could lead to stellar superradiance.
- Stellar environments are complex, with many more degrees of freedom than black holes.
- Spin down from stellar superradiance can be observed directly.
- Can we find a general method for computing stellar superradiance rates from a BSM Lagrangian?

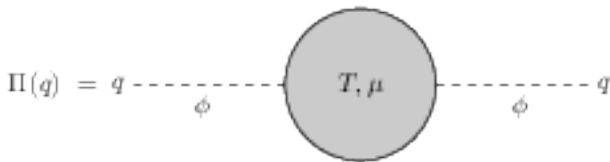
See FCD, Garbrecht & McDonald, 2207.07662.

Stellar superradiance: Damping

Stellar superradiance depends on the **damping rate** of the field into the star. We can find this with thermal field theory.

$$\partial^2 \phi + \mu^2 \phi + \Gamma_\phi \dot{\phi} = 0,$$

$$\Gamma_\phi = - \lim_{p \rightarrow 0} \text{Im} \Pi(p) / p^0.$$



Stellar superradiance: Worldline Effective Field Theory

- Describe interaction of a field ϕ and the star by expanding in $\frac{R}{\lambda}$.
- The extended nature of the star is described by an infinite series of interactions between ϕ and a point-like object.

$$H_{\text{int}}(t, \mathbf{x}) = \partial^I \phi(x) \mathcal{O}_I^{(1)}(x) \delta^{(3)}(\mathbf{x} - \mathbf{y}(t)) + \\ \partial^I \partial^J \phi(x) \mathcal{O}_{IJ}^{(2)}(x) \delta^{(3)}(\mathbf{x} - \mathbf{y}(t)) + \dots$$

Stellar superradiance: Worldline Effective Field Theory

If the star is rotating:

$$H_{\text{int}}(t) = \partial^I \phi(t) R_I^J(t) \mathcal{O}_J^{(1)}(t) \\ + \partial^I \partial^J \phi(t) R_I^K(t) R_J^L(t) \mathcal{O}_{KL}^{(2)}(t) + \dots$$

See S. Endlich and R. Penco, 1609.06723

Superradiant scattering in the worldline EFT

Superradiant scattering from a rotating star:

$$P_{\text{abs}} = \sum_{X_f} \frac{|\langle X_f; 0 | S | X_i; \omega, \ell, m \rangle|^2}{\langle \omega, \ell, m | \omega, \ell, m \rangle}.$$

Amplification factor:

$$Z_{\ell m} = \frac{\Phi_{\text{out}} - \Phi_{\text{in}}}{\Phi_{\text{in}}} = \frac{\ell! q^{2\ell+2}}{4\pi(2\ell+1)!! v\omega} \rho_{\ell}(m\Omega - \omega),$$

$\rho_{\ell}(m\Omega - \omega)$ is related to the worldline EFT operators and must be found with a matching calculation.

Superradiant instabilities in the worldline EFT

Superradiant instabilities arise from *bound states*:

$$P_{\text{abs}} = \sum_{X_f} |\langle X_f; 0 | S | X_i; n\ell m \rangle|^2.$$

The superradiance rate is:

$$\Gamma_{n\ell m} = \Gamma_{\text{em}} - \Gamma_{\text{abs}} = \frac{A_{n\ell m}}{2\omega_{\ell n}} \left(\frac{1}{r_{n\ell}} \right)^{2\ell+3} \rho_{\ell}(m\Omega - \omega_{\ell n}),$$

where $r_{n\ell} = (n + \ell + 1)/(2GM\mu^2)$.

Matching the worldline EFT

- We can also find the amplification factor $Z_{\ell m}$ directly from the equation of motion $\partial^2 \phi + \mu^2 \phi + \Gamma_\phi \dot{\phi} = 0$ (see 1505.05509).
- Matching these results we can obtain $\rho_\ell(m\Omega - \omega_{\ell n})$ (or equivalently the EFT coefficients).

This gives a superradiance rate:

$$\Gamma_{n\ell m} = C_{n\ell m} \left(\frac{R}{r_{n\ell}} \right)^{(2\ell+3)} \frac{(m\Omega - \omega)}{\omega} \Gamma_\phi,$$

where the damping Γ_ϕ of the field ϕ into the star can be calculated in thermal field theory.

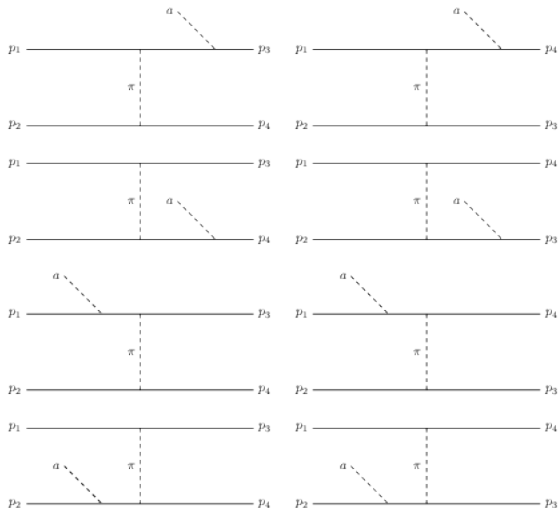
Stellar superradiance: Axion Example

Consider an axion damping into a neutron star via the interactions

$$\mathcal{L}_{aNN} = \frac{g_{an}}{2m} \partial_\mu a \bar{N} \gamma^\mu \gamma_5 N,$$

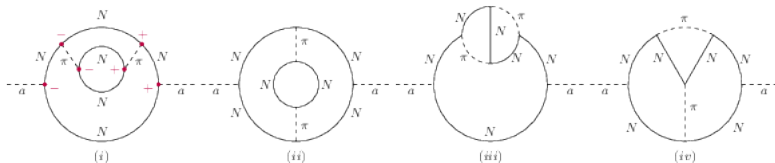
$$\mathcal{L}_{\pi NN} = \frac{2m}{m_\pi} f_{\pi 0} \bar{N} \gamma^5 N,$$

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To find the superradiance rate, we must compute Γ_ϕ from the self-energy:



The self-energy is related to the axion mean free path

$$\lambda^{-1} = \frac{\text{Im}\Pi}{\omega}$$

calculated in e.g. S. Harris, 2005.09618 - we find a superradiance time somewhat larger than the age of the universe!

Stellar superradiance: A general approach

- We find the damping rate from the in-medium self energy.
- We find the superradiant instability rate from the damping rate using **worldline effective field theory** (S Endlich & R Penco, 1609.06723).
- Match calculations at low energy to obtain the superradiant instability rate:

$$\Gamma_{nlm} = C_{nlm} \left(\frac{R}{r_{nl}} \right)^{(2\ell+3)} \frac{(m\Omega - \omega)}{\omega} \Gamma_{\phi}$$

This allows us to calculate the stellar superradiance rate for any interaction between a bosonic field and a star.

See FCD, Garbrecht & McDonald, 2207.07662.

Conclusions

- Black hole superradiance offers a purely gravitational probe of Beyond the Standard Model bosons.
- Stellar superradiance can probe additional interactions between new bosons and the Standard Model.