Axions and superradiance

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Shoot for the Stars, Aim for the Axions
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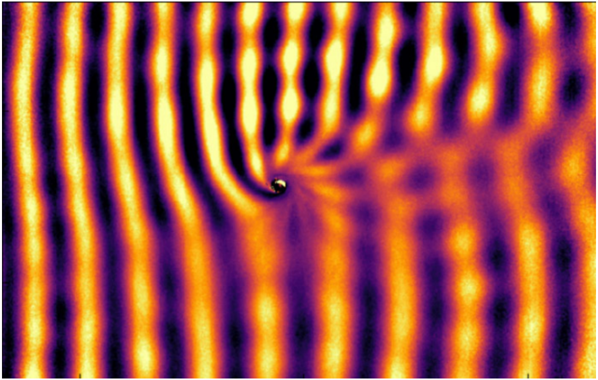
Outline

Superradiance

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



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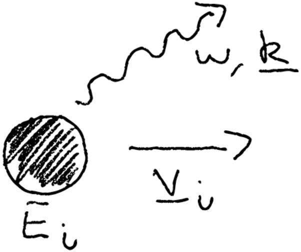
Radiation from a moving particle



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

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

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

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

Brito, Cardosa & 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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- If the particle can *absorb* photons, we can also have spontaneous radiation with $m_i < m_f$.
- When $v_{\rm ph} > v_i$, 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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- Black holes can trap massive radiation, such as axions.
- Could get exponential amplification of this trapped radiation - a superradiant instability.

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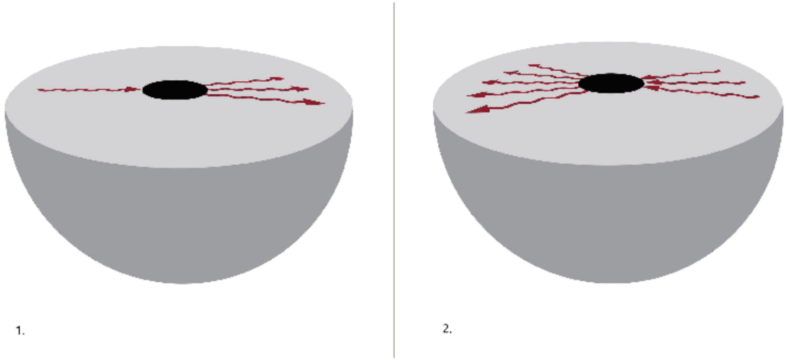

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- The eigen-energies will have an imaginary component, corresponding to the axion being eaten by the black hole, or to superradiant amplification of the axion field.

Black Hole Superradiance

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

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- Time domain analysis has also been performed.

Zouros & Eardley, Annals of Physics, 1979
Detweiler, Phys Rev D, 1980
Dolan, 0705.2880 & 1212.1477

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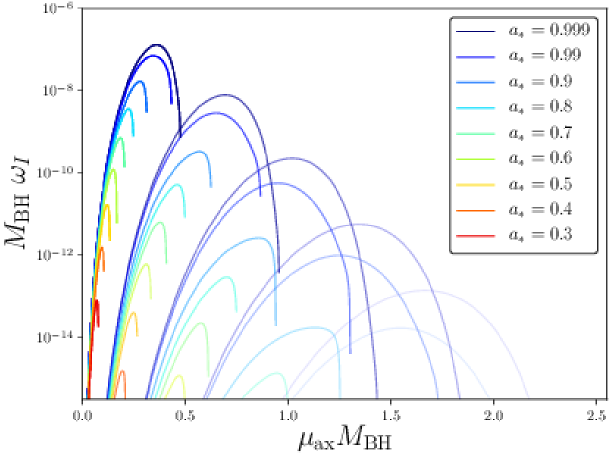

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- The instability is most efficient when the black hole's gravitational radius is similar to the axion's compton radius: $GMm_a \sim 1$.
- The instability is less efficient for higher l and m modes.

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Bosenova

Energy of a cloud of size R with N axions:

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

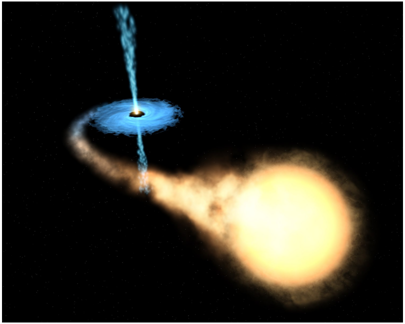
At large N, the gradient energy of the axion field makes the cloud unstable. The collapse may be observed as a gravitational wave and potentially γ-ray burst.

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



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- Advanced Ligo will be sensitive to $m_a \lesssim 10^{-10}\,\mathrm{eV}$. (Arvanitaki *et al*, 1604.03958).

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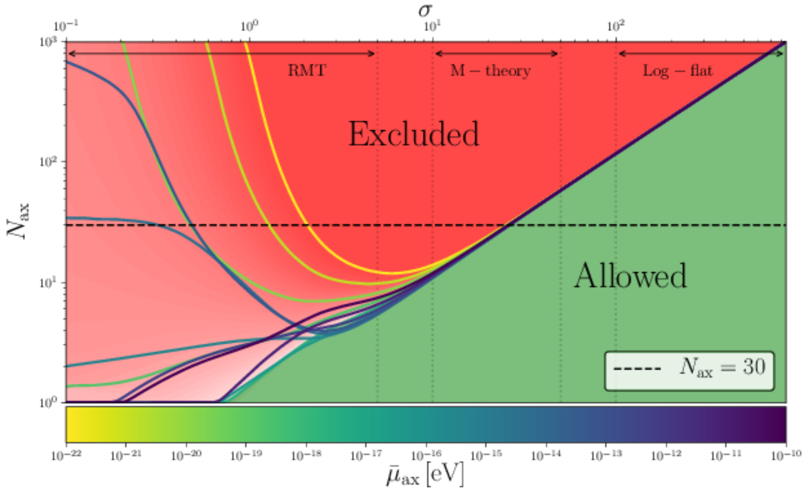

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- Birefringence (Plascencia & Urbano, 1711.08298)
- Lasing (Ikeda, Brito & Cardos, 1811.04950)
- Orbits in binary systems (Kavic *et al*, 1910.06977)

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- Axion annihilations could decrease the superradiance rate.
- For large initial seeds, if both superradiant and non-superradiant modes are populated, the instability may not occur (Ficarra, Pani & Witek, 1812.02758.).

Superradiance in Stars

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

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- This gives the required dissipative interaction.

Kaplan & Rajendran, 1908.10440

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- Bound states - i.e. massive particle for gravitational bound state

Can the massive particle and the dissipation be in different sectors that talk to eachother?

FCD & McDonald, 1904.08341

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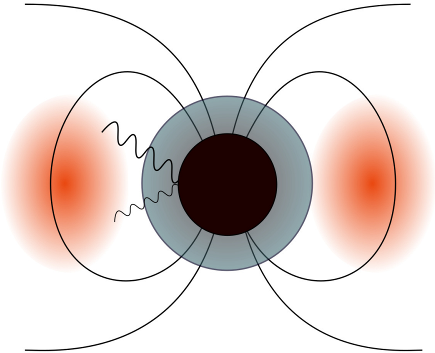
- *Photons* dissipate energy into the neutron star magnetosphere via the magnetosphere's bulk conductivity.
- Axions and photons mix, so these effects together lead to a superradiant instability in the neutron star magnetosphere.

Axion-photon superradiance in neutron stars



Schematic illustration of the instability. The axion boundstate (orange) mixes with a photon mode which is then amplified by scattering off the rotating magnetosphere (grey). The photon energy is then deposited back into the axion sector.

Axion-photon superradiance in neutron stars

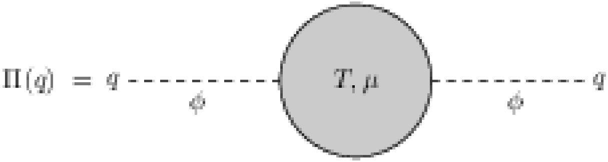
- We typically find superradiant timescales $\tau = \frac{1}{\text{Im}[\omega_{\ell mn}]}$ a few orders of magnitude higher than the neutron star spin down time.
- Therefore, we do not expect this process to be observable.
- Our result is an example of a more general phenomenon which can arise when there is an instability in the plasma sector.
- For axion modes which couple to an unstable mode of the neutron star, one could in principle find similar instabilities.

Stellar superradiance: A general approach

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

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

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



See FCD, Garbrecht & McDonald, 2207.07662.

Stellar superradiance: A general approach

- We find the superradiant instability rate from the damping rate using **worldline effective field theory** (S Endlich $ R Penco, 1609.06723).
- Expand the interaction between the field at the star in R/λ.
- Match calculations at low energy to obtain the superradiant instability rate:

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

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.