Medium effects on Lasing of Superradiant Axions

Srimoyee Sen,

Institute for Nuclear Theory,
University of Washington

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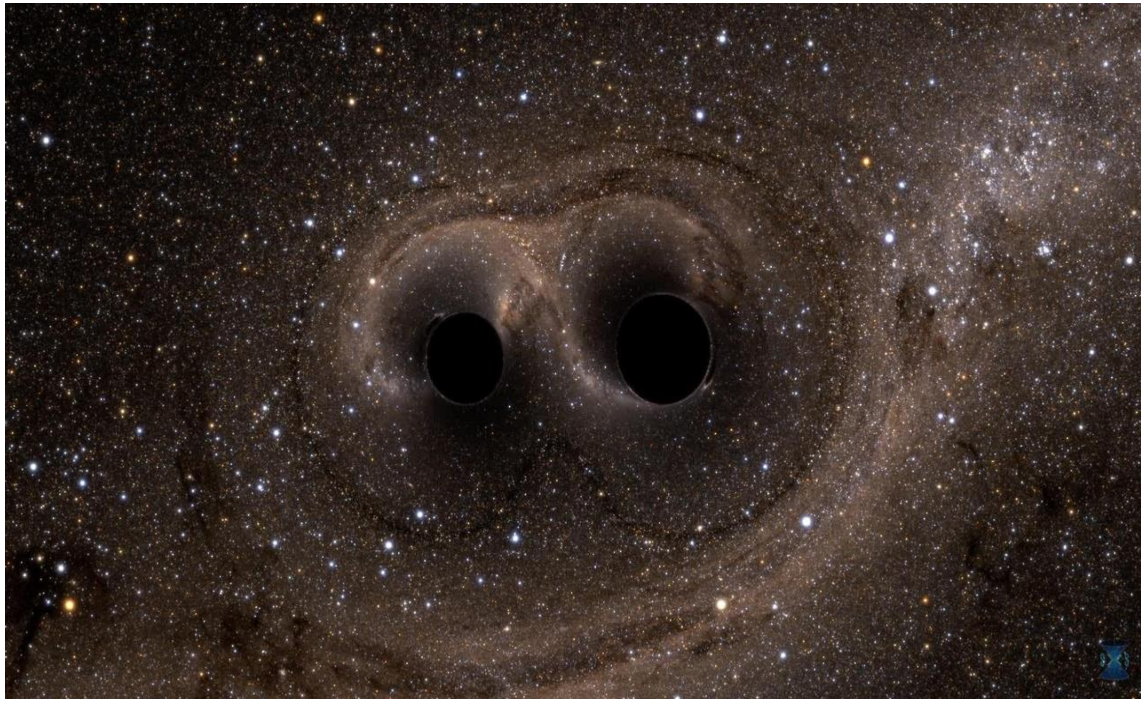
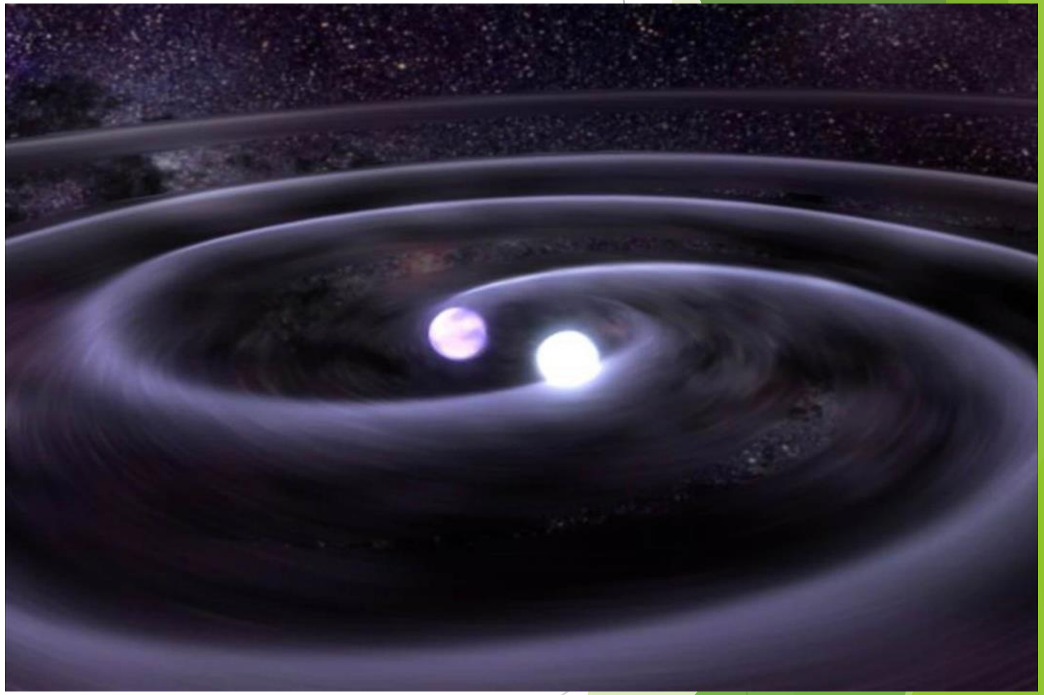
Looking for electromagnetic signatures of BSM physics

Credit: 4wardleaning.wordpress.com

What about the coupling to gravity ?

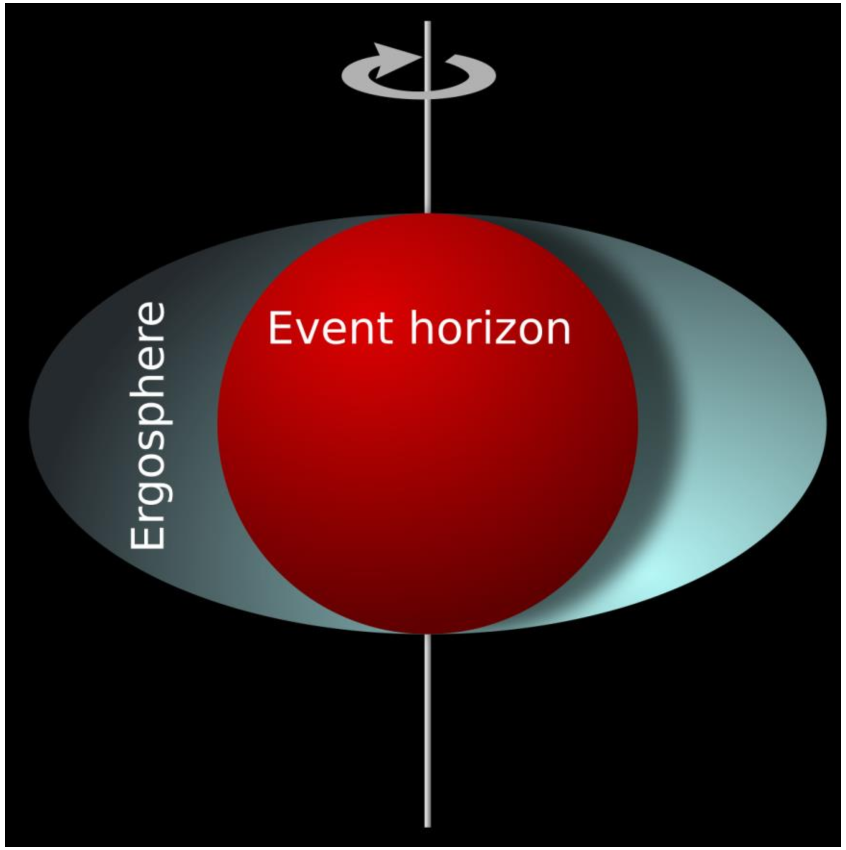


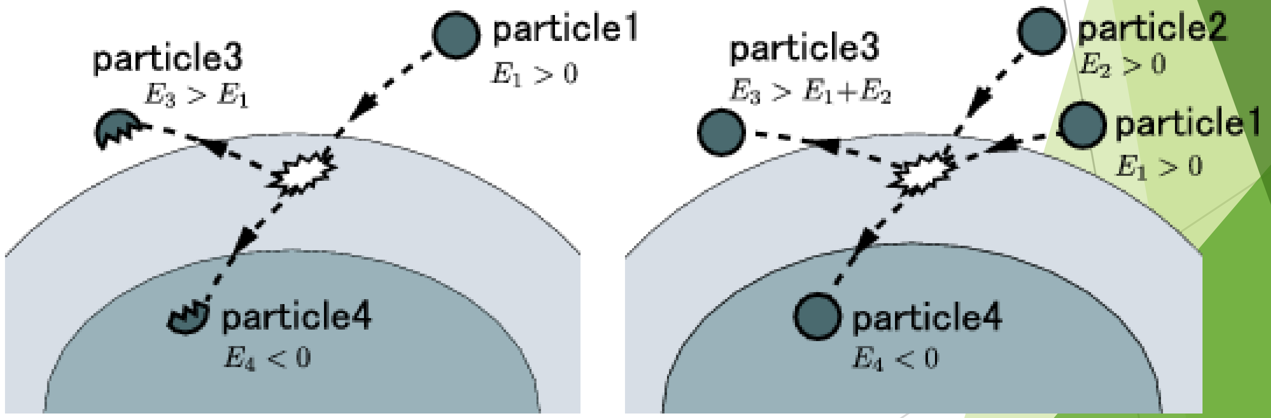
Credit : cornell.edu



Credit: Quanta Magazine

Black hole mining





Superradiance : Penrose process for particles to amplification of waves scattering off of Kerr black holes.

Credit : Wikipedia, ccn.com, arXiv:1409.7502

Superradiant axions :

- The process does not discriminate between fermions and bosons.

- However, it is only massive bosons of Compton wavelengths of the size of the black hole can form bound states eventually producing condensates around the black hole → superradiant axion condensate.

- This condensate can produce detectable gravitational wave signatures from axion annihilation to gravitons, level transitions and finite size effects.

Electromagnetic coupling of axions :

- Axions can potentially decay to two photons via lasing.
- Jeopardizes the possibility of direct detection of gravitational signatures from axion condensate.
- The photons are not detectable either due to their long wavelengths.
- In short, superradiant axion condensate can disappear leaving no trace electromagnetically or gravitationally.

A way around

- Medium effects can affect lasing and hinder growth -> Need to check if this is indeed the case.

Long story short : Lasing is kinematically blocked for most of the parameter space unless the medium around is exceptionally dilute.

However, there is a region in the parameter space, which corresponds to most stellar mass black holes, where details matter.

How to describe laser growth (without matter coupling)

- Short answer : Solve Maxwell’s equations and find exponentially growing modes.
- Long answer : Write down equations of motion from axion photon Lagrangian :

$$\nabla \times \vec{B} - \frac{d\,\vec{E}}{dt} = -\frac{C\,\alpha}{\pi\, f_a}\frac{d\phi}{dt}\,\vec{B}$$

Express gauge and axion fields in their second quantized form. Evaluate the above equation to solve for the expectation values of the creation and annihilation operators in coherent states which should exhibit exponential growth as a signature of laser.

Laser growth with matter coupling :

- Supplement Maxwell's equations with appropriate medium dependent linear response.
- This problem in its full generality is complicated and beyond the scope of this talk.
- I will instead use toy models that neatly capture the physics in question.

Toy model without matter coupling :

- Spatially uniform, time independent axion condensate.
- Ignore the effect of the metric.
- Ignore axion self-interaction.

Laser growth rate (no matter coupling)

- Maxwell's equations produce a laser growth rate of $\lambda = \frac{C\,\alpha\, m_a|\phi|}{2\pi f_a}$ in the absence of any matter coupling to electromagnetism.
- The corresponding depletion time scale for a QCD axion condensate is less than a second as mentioned earlier.
- No hope of detecting any gravitational signatures.
- No detectable photons due to their extremely long wavelengths.

Toy model with matter coupling :

- Supplement the Maxwell’s equations with a nonzero conductivity.

- Medium polarization of interest to this work is well described by the Drude model

$$\sigma(\omega) = \frac{4\pi\, n_e e^2 \tau_{coll}}{m_e(1 - i\, \tau_{coll}\omega)}$$

The details :

- Black hole environment can consist of an accretion disc and dilute interstellar medium outside of the disc for a thin disc.

- Transport properties in the accretion disc is dominated by Inside the accretion disk $\omega\tau_{coll} \ll 1$. The conductivity is given by

$$\sigma(\omega) = \frac{4\pi\, n_e e^2 \tau_{coll}}{m_e} \gg m_a$$ → No lasing. (m_a = axion mass, σ = electrical conductivity of the medium).

- Outside of the disc, interstellar medium is a collision-less plasma. $\sigma(\omega) = i\,\frac{4\pi\, n_e e^2}{m_e\, \omega}$. Here, no lasing for $m_a \ll \omega_P$ where ω_P is the plasma frequency given by $\omega_P = \omega\, \mathrm{Im}[\sigma] = \frac{4\pi\, n_e e^2}{m_e}$.

Interstellar medium :

- Numbers are such that for black holes of mass larger than $100M_{\odot}$, $\omega_P \gg m_a$.
- For stellar mass black holes, $\omega_P \sim m_a$.
- For stellar mass black holes the lasing rate is going to depend on both the plasma frequency and the axion mass as well as axion decay constant.

Medium dependence of lasing:

$$\frac{-m_a\xi\phi + \sqrt{|m_a\xi\phi|^2 + m_a^2 - 4\omega_P^2}}{2} < k < \frac{m_a\xi\phi + \sqrt{|m_a\xi\phi|^2 + m_a^2 - 4\omega_P^2}}{2}$$

where $\xi = \frac{C\,\alpha}{\pi f_a}$.

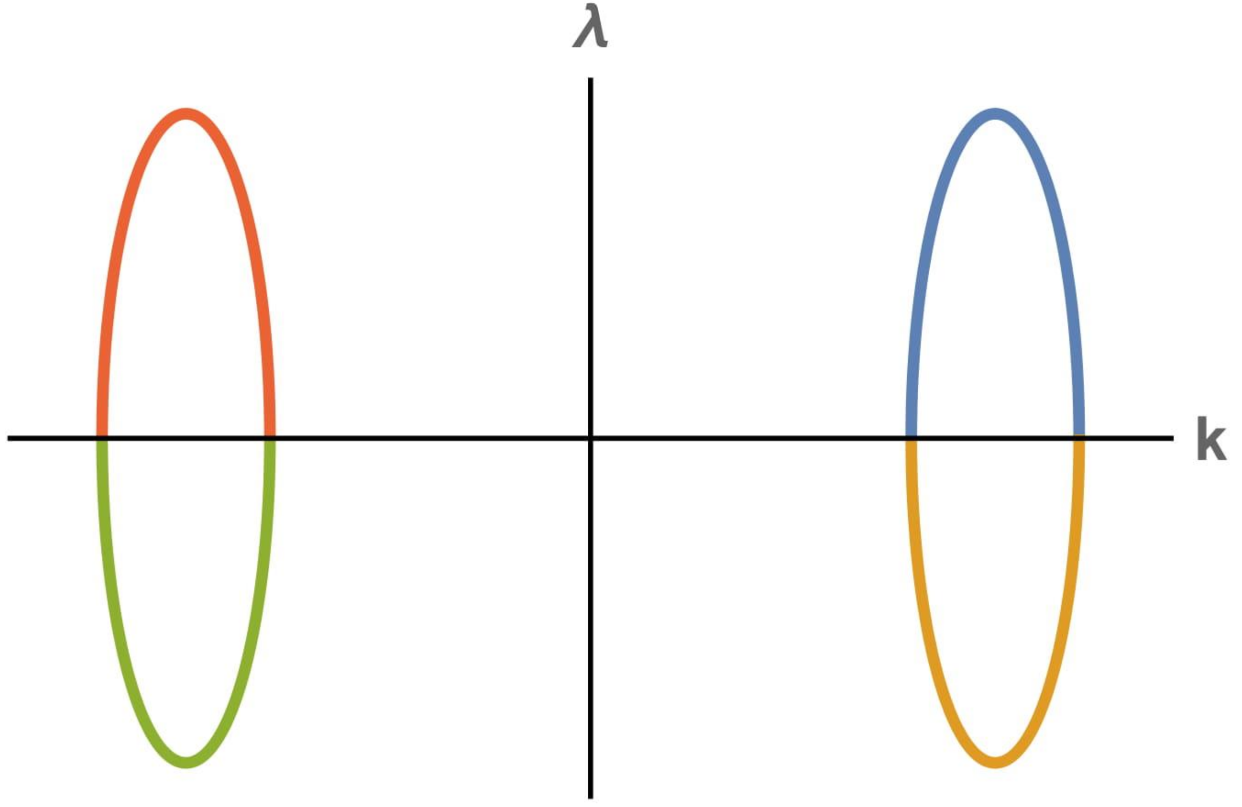
Look at two opposite limits given by $\xi\phi \ll \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$ and $\xi\phi \gg \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$.

For $\xi\phi \ll \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$, the growth rate is $\lambda = m_a^2 \frac{\sqrt{m_a^2 - 4\omega_P^2}}{2m_a^2 - 4\omega_P^2}(\xi\phi)$,

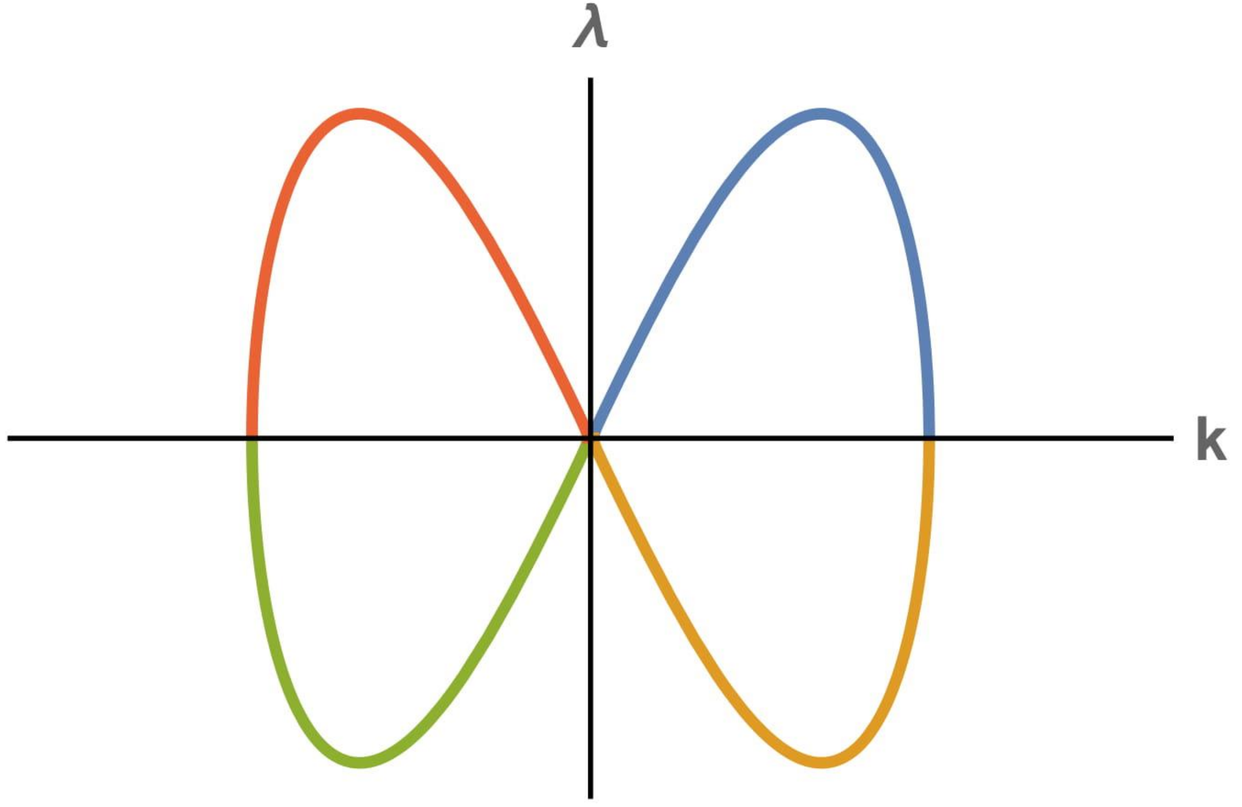
For $\xi\phi \gg \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$, the growth rate is

$$\lambda = m_a\xi^2\phi^2 \frac{\sqrt{2 + 4\xi^2\phi^2} - \sqrt{1 + 4\xi^2\phi^2}}{\sqrt{(1 + 4\xi^2\phi^2)(3 + 8\xi^2\phi^2 - 2\sqrt{2}\sqrt{1 + 6\xi^2\phi^2 + 8\xi^4\phi^4})}}$$

Growth rate schematic : $\xi\phi \ll \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$



Growth rate schematic: $\xi\phi \gg \frac{\sqrt{(m_a^2 - 4\omega_P^2)}}{m_a}$



Future Direction :

- Include the metric dependence in the Maxwell’s equations.
- Use the wave function for the axions in the source term.
- If possible solve for the superradiant instability and the lasing process simultaneously.
- Include self-interaction of axion field.