Lecture 3: Searching for Axions

Francesca Chadha-Day

IPPP, Durham University

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Plan

Axion production

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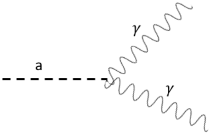
- Gravitational effects

Detecting Axion Dark Matter

Axion decay to two photons:



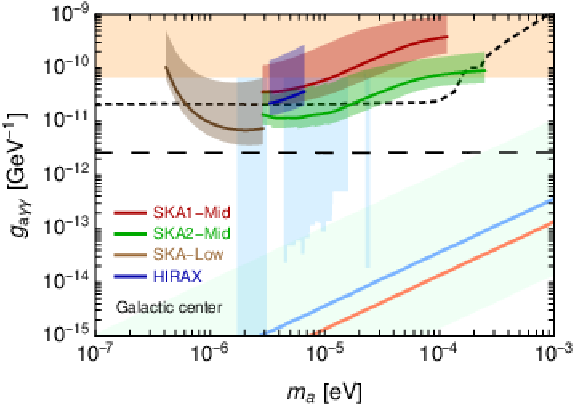
$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$

$$E_\gamma = m_a/2$$

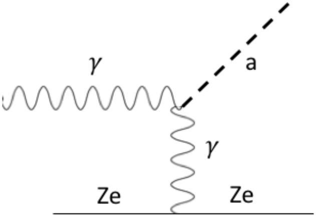
$$\Delta E_\gamma = E_\gamma \frac{\sigma}{c}$$

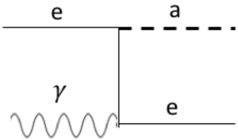
Detecting Axion Dark Matter

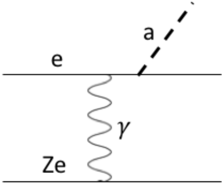
For $m_a \sim 1\,\mu$eV and $g_{a\gamma\gamma} \sim 10^{-10}$ GeV, $\tau \sim 10^{32}$ years. The decay rate could be significantly enhanced by stimulated decay from ambient photons. From Caputo, Regis, Taoso & Witte (1811.08436):



Production in stars







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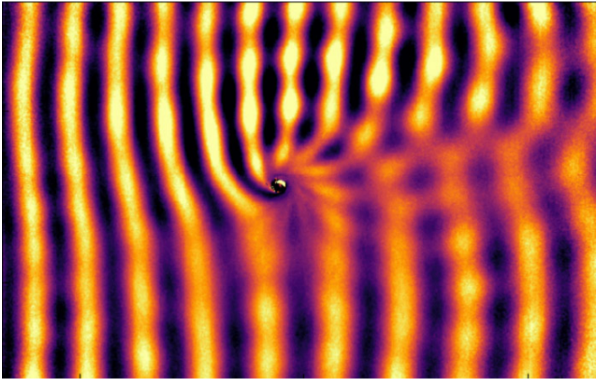
- Bounds on g_{aee} from the brightness of the Red Giant Branch (Viaux *et al*, 1311.1669), and from the luminosity function of white dwarfs (Raffelt 1986 and Blinnikov & Dunina-Barkovskaya, 1994).

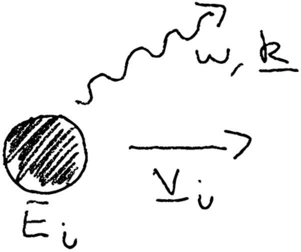
Superradiance

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



Reproduced from Torres *et al*, 1612.06180

Radiation from a moving particle



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

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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- 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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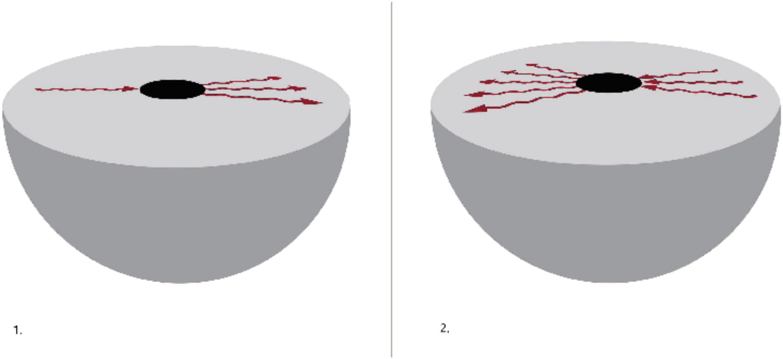
- Black hole superradiance is effective for Beyond the Standard Model bosons such as axions.

Black Hole Superradiance



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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

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

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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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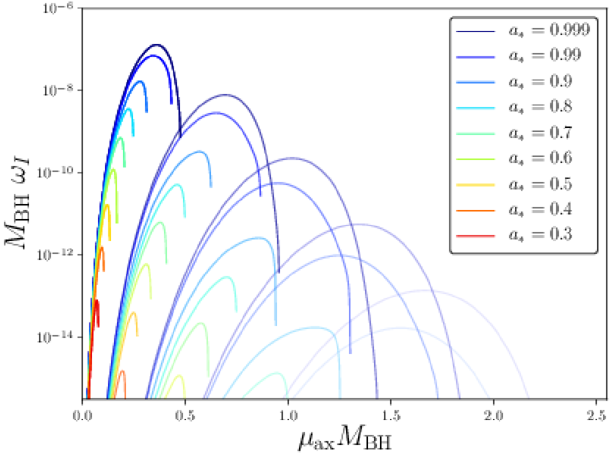

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- The instability is less efficient for higher l and m modes.

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Bosenova

Energy of a cloud of size R with N axions:

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

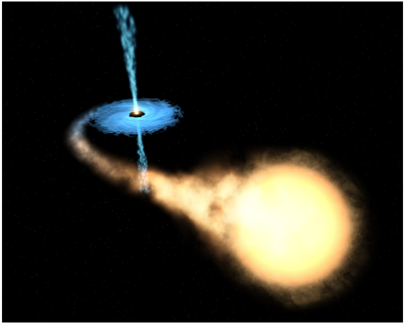
At large N, the gradient energy of the axion field makes the cloud unstable. The collapse may be observed as a gravitational wave and potentially γ-ray burst.

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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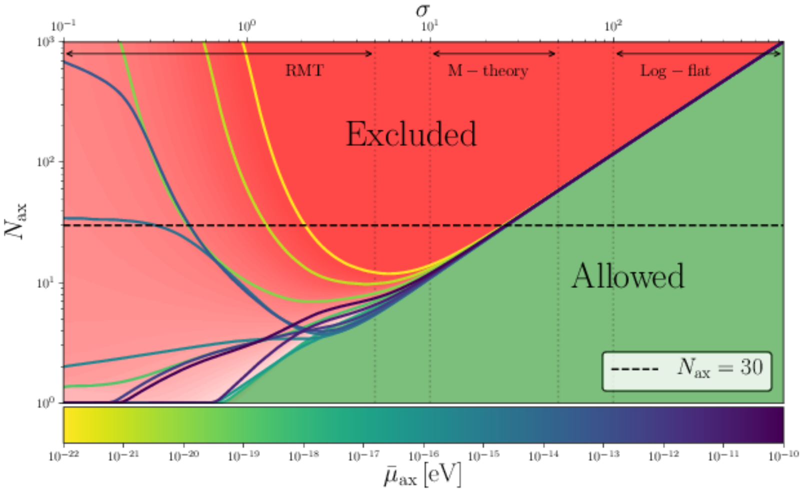

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- Lasing (Ikeda, Brito & Cardos, 1811.04950)
- Orbits in binary systems (Kavic *et al*, 1910.06977)

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- Axion self-interaction can lead to level mixing.
- 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.).

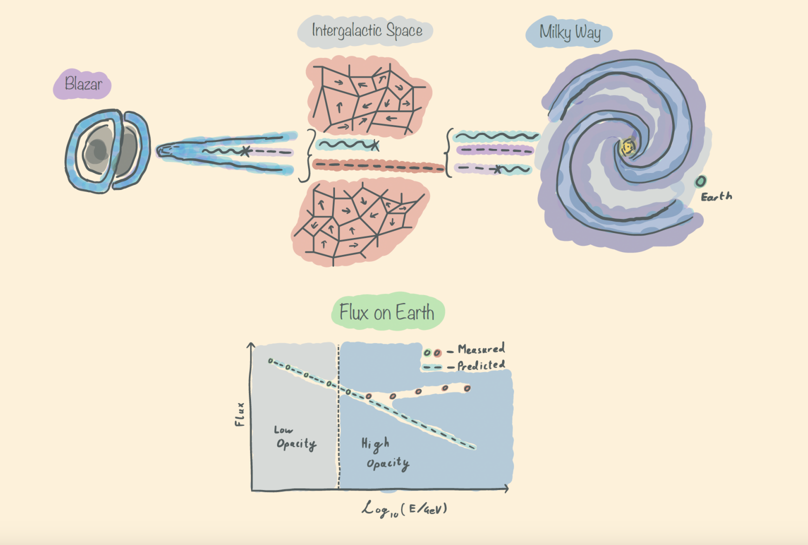
Axion-photon conversion

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right) \begin{pmatrix} |\,\gamma_x\rangle \\ |\,\gamma_y\rangle \\ |\,a\rangle \end{pmatrix} = 0$$

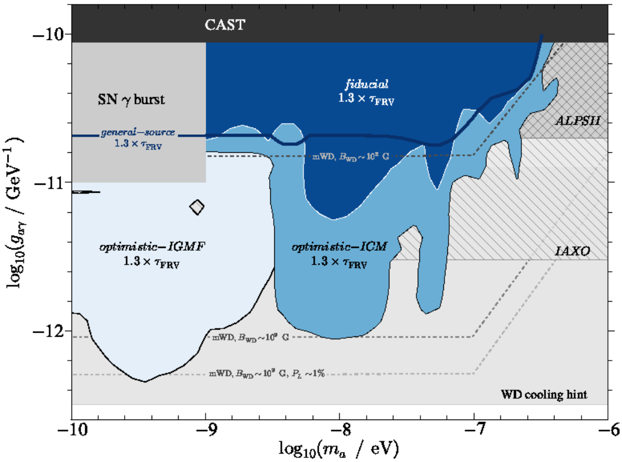
- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- Plasma frequency: $\omega_{pl} = \left(4\pi\alpha \frac{n_e}{m_e}\right)^{\frac{1}{2}}$
- $\Delta_a = \frac{-m_a^2}{\omega}$.
- Mixing: $\Delta_{\gamma ai} = \frac{B_i}{2M}$

$$P_{a\to\gamma}(L) = |\,\langle 1,0,0|f(L)\rangle\,|^2 + |\,\langle 0,1,0|f(L)\rangle\,|^2$$

Transparency of intergalactic space

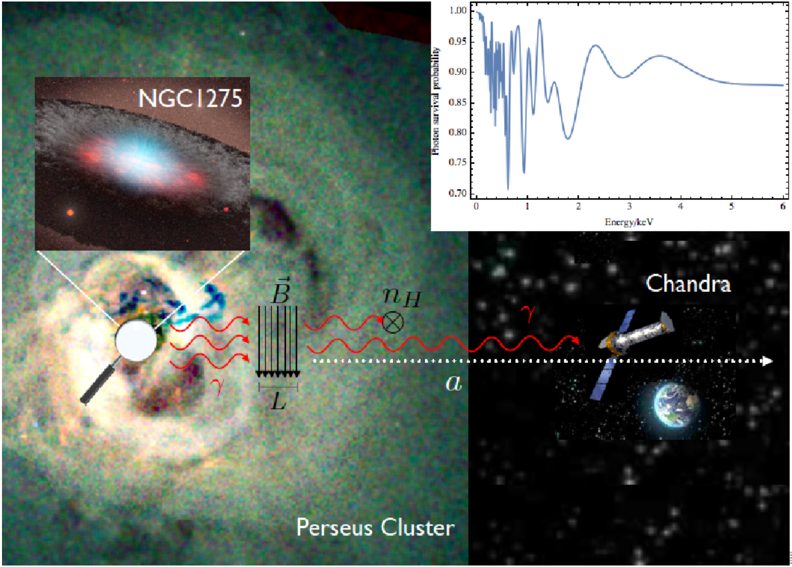


Anomalous Transparency Hint

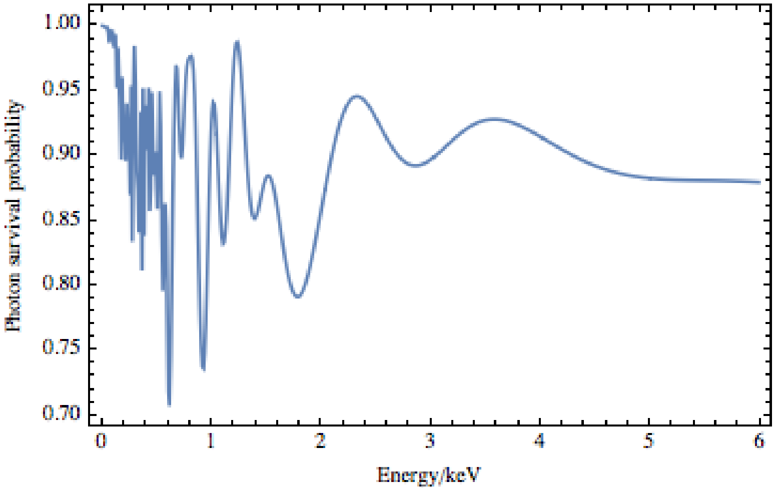


Reproduced from Meyer, Horns & Raue, 1302.1208.

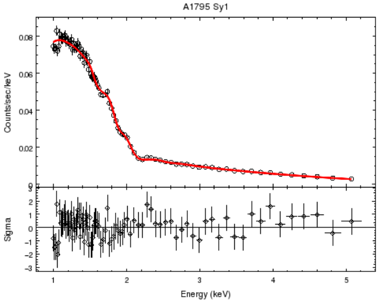
Photon-axion conversion in Galaxy Clusters

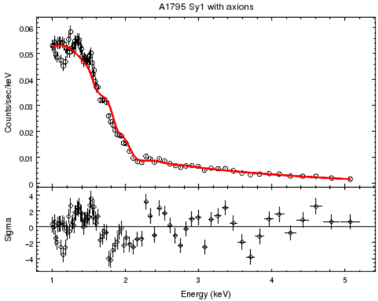


Photon survival probability



Spectra with axions

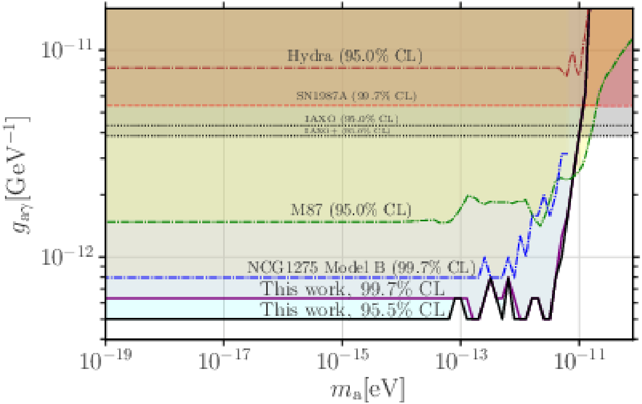




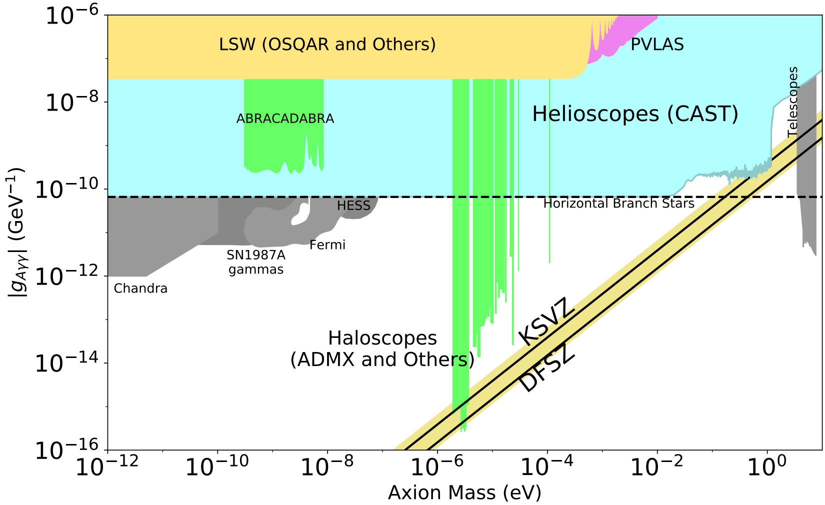
Left: the observed spectrum of the Seyfert galaxy 2E3140 in the galaxy cluster A1795 fitted with an absorbed power law. Right: the same spectrum multiplied by the photon survival probability for a realisation of the A1795 magnetic field and assuming the existence of axions with $g_{a\gamma} = 5 \times 10^{-12}\,\mathrm{GeV}^{-1}$.

Bounds

The leading bounds are from *Chandra* transmission grating spectroscopy of quasar H1821+643 (J Sisk-Reynés *et al*, 2109.03261):



Axion bounds



From the Particle Data Group