Exploring Axions through the Photon Ring of a Spherically Symmetric Black Hole

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Abstract

In this study, we examine the phenomenon of photon axion conversion occurring in the spacetime surrounding a black hole.The potential existence of a magnetic field around the supermassive black hole M87*, which could facilitate the conversion of photons into axions in close proximity to the photon sphere. This process leads to a decrease in the intensity of the black hole's photon ring. To explore the possibilities of detecting these hypothetical axion particles, we propose observing the photon sphere using higher resolution telescopes. By doing so, we can gain valuable insights into the conversion mechanism as well as the nature of the spherically symmetric black hole geometry. Moreover, we also investigate how the photon ring luminosities are affected if the black hole possesses a charge parameter. For instance apart from U(1) electric charge, the presence of extra dimension may induce a tidal charge with a characteristic signature. It is important to note that the success of the conversion mechanism relies on the axion-photon coupling and mass. As a result, the modified luminosity of the black hole's photon ring offers a valuable means of constraining the axion's mass and coupling parameter within a certain range. Thus our findings contribute to a better understanding of photon axion conversion in the environment of a black hole spacetime and helps us explore the possible existence of extra spatial dimension.

What is axion ?

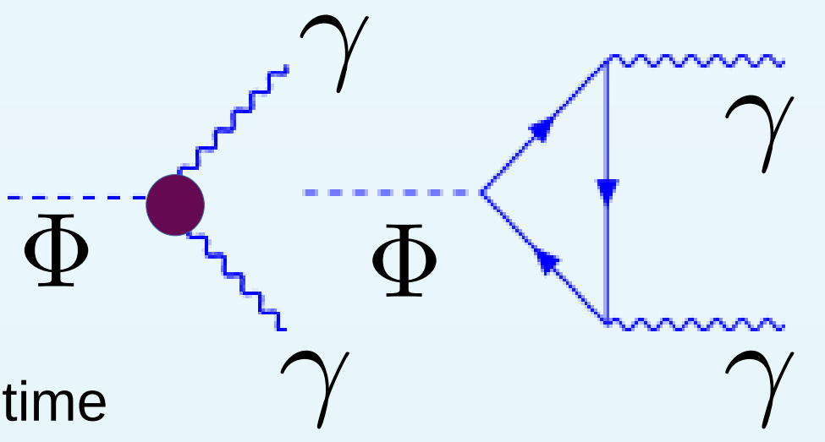
➡ A hypothetical elementary particle.

➡ **QCD Axions** Introduced to solve strong CP problem of QCD. → mass and coupling are proportional

➡ **Axion like particles(ALPs)** Light pseudoscalar fields predicted by many extensions of standard model.

➡ In the presence of magnetic field axions interact with photons through the coupling term,

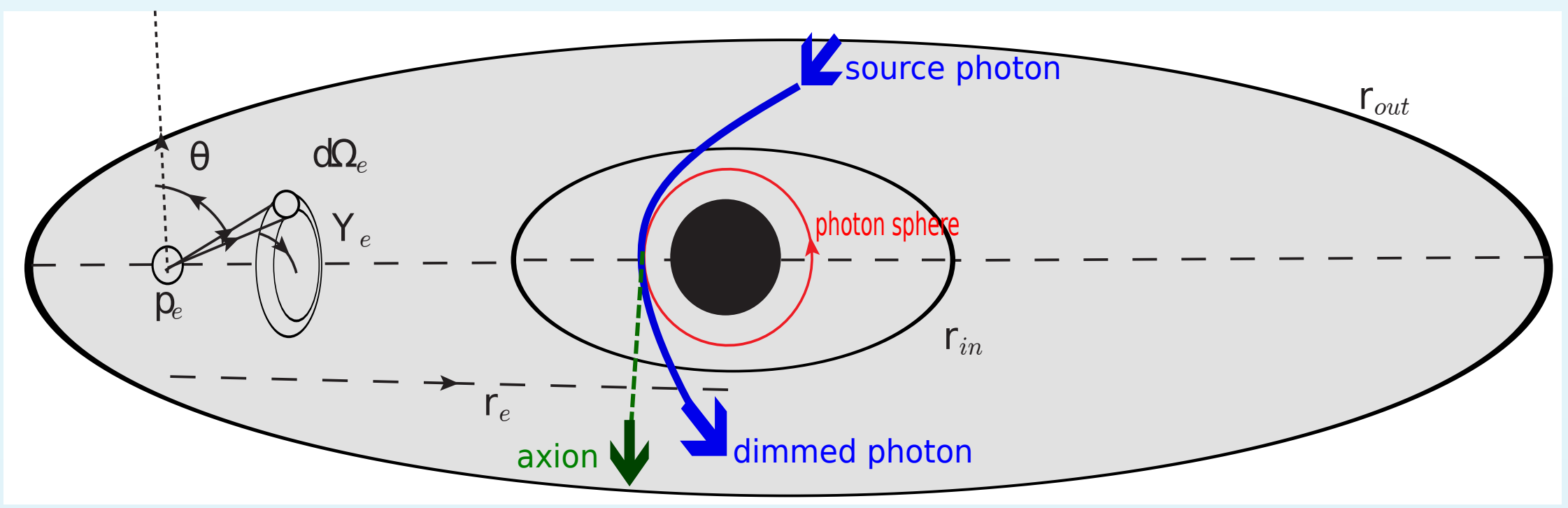
$$\mathcal{L}^{int} = -\tfrac{1}{4} g_{\Phi\gamma}\Phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Objectives:

- Photon-axion conversion in black hole(BH) spacetime
- Generalizing to spherically symmetric non rotating BH
- Relevant axion / ALP parameter space.
- Observation prospects .

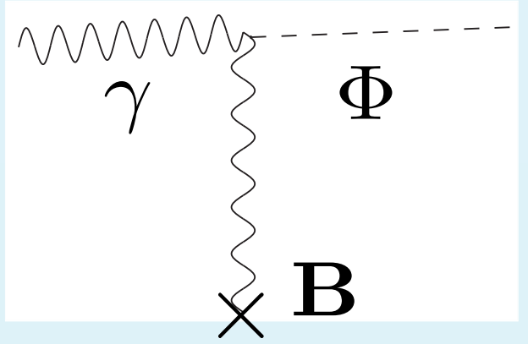
Outline of the problem



I. The Event Horizon Telescope observations of supermassive black hole M87* centered in Messier galaxy discovered the potential existence of magnetic field of the order (1-30) gauss.

Akiyama et al. EHT collaboration Astrophys.J.Lett 875(2019)

II.The Event Horizon Telescope achieved to get an image of the black hole photon sphere through radio observation.



III.Photons can be converted to axion in presence of the magnetic field.

IV.The propagation length of photon-axion conversion is of the order of milli-parsec, comparable to the Schwarzschild radius of a supermassive black hole with a mass of $10^9 M_\odot$

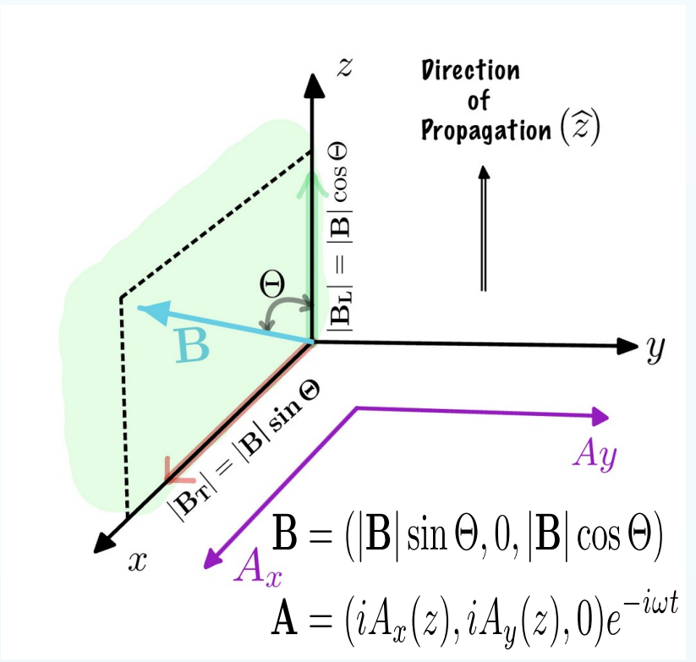
The Photon-axion conversion

We consider the following photon-axion system,

$$\mathcal{S} = \int d^4x \left(-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}\partial_\mu\Phi\partial^\mu\Phi - \frac{1}{2}m_\Phi^2\Phi^2 - \frac{1}{4}g_{\Phi\gamma}\Phi F_{\mu\nu}\widetilde{F}^{\mu\nu}\right)$$

With QED correction term to Maxwell equations,

$$\mathcal{L}_{EH} = \frac{\alpha^2}{90m_e^4}\left[(F_{\mu\nu}F^{\mu\nu})^2 + \frac{7}{4}\left(F_{\mu\nu}\widetilde{F}^{\mu\nu}\right)^2\right],$$



and also taking the effect of plasma as photon acquire effective mass in plasma, the equations of motion are,

$$\Box A_x - \omega_{pl}^2 A_x + 7\omega^2\frac{\alpha e^2}{45\pi m_e^4}|\mathbf{B}|^2\sin^2\Theta A_x + \omega g_{\Phi\gamma}|\mathbf{B}|\sin\Theta\Phi = 0 \quad \checkmark$$

$$\Box A_y + 4\omega^2\xi\sin^2\Theta A_y = 0$$

$$(\Box - m_\Phi^2)\Phi + \omega g_{\Phi\gamma}|\mathbf{B}|\sin\Theta A_x = 0 \quad \checkmark$$

The solutions of the fields are expressed as,

$$A_x(t,z) = \widetilde{A}(z)e^{-i(\omega t - kz)} + \mathrm{h.c}$$
$$\Phi(t,z) = \widetilde{\Phi}(z)e^{-i(\omega t - kz)} + \mathrm{h.c}$$

After few simplifications the equations of motion reduces to,

$$i\frac{d}{dz}\widetilde{A}(z) = \left(\frac{\omega_{\rm pl}^2}{2w} - \frac{28\alpha^2\omega}{90m_e^4}(|\mathbf{B}|\sin\Theta)^2\right)\widetilde{A}(z) - \frac{1}{2}g_{\Phi\gamma}|\mathbf{B}|\sin\Theta\widetilde{\Phi}(z)$$

$$i\frac{d}{dz}\widetilde{\Phi}(z) = \left(-\frac{1}{2}g_{\Phi\gamma}|\mathbf{B}|\sin\Theta\right)\widetilde{A}(z) + \frac{m_\Phi^2}{2\omega}\widetilde{\Phi}(z)$$

Standard form:

$$i\frac{d}{dz}\begin{bmatrix}\widetilde{A}(z)\\ \widetilde{\phi}(z)\end{bmatrix} = \mathfrak{M}\begin{bmatrix}\widetilde{A}(z)\\ \widetilde{\phi}(z)\end{bmatrix}$$

Where,

$$\mathfrak{M} = \begin{bmatrix}\Delta_{\rm pl} - \Delta_{\rm vac} & -\Delta_{\rm M}\\ -\Delta_{\rm M} & \Delta_\Phi\end{bmatrix}$$

Contributions related to M87*

$$\Delta_{\rm pl} \equiv \frac{\omega_{\rm pl}^2}{2\omega} = 6.9\times10^{-25}{\rm eV}\left(\frac{n_e}{{\rm cm}^{-3}}\right)\left(\frac{\rm keV}{\omega}\right)$$

$$\Delta_{\rm vac} \equiv \frac{28\alpha^2\omega}{90m_e^4}(|\mathbf{B}|\sin\Theta)^2 = 9.3\times10^{-29}{\rm eV}\left(\frac{\omega}{\rm keV}\right)\left(\frac{|\mathbf{B}|}{\rm Gauss}\right)^2\sin^2\Theta$$

$$\Delta_{\rm M} \equiv \frac{1}{2}g_{\Phi\gamma}|\mathbf{B}|\sin\Theta = 9.8\times10^{-23}{\rm eV}\left(\frac{g_{\Phi\gamma}}{10^{-11}{\rm GeV}^{-1}}\right)\left(\frac{|\mathbf{B}|}{\rm Gauss}\right)\sin\Theta$$

$$\Delta_\Phi \equiv \frac{m_\Phi^2}{2\omega} = 5\times10^{-22}{\rm eV}\left(\frac{m_\Phi}{\rm neV}\right)^2\left(\frac{\rm keV}{\omega}\right)$$

Assuming initial axion density is negligibly small with respect to that of photons, the probability of conversion of photon into axion as a function of distance z as

$$P_{\gamma\to\Phi}(z) = \left|\widetilde{\Phi}(z)\right|^2 = \left(\frac{\Delta_{\rm M}}{\Delta_{\rm osc}/2}\right)^2\sin^2\left(\frac{\Delta_{\rm osc}}{2}\mathbf{Z}\right)$$

$$\Delta_{\rm osc} = \sqrt{(\Delta_\Phi - \Delta_{\rm pl} + \Delta_{\rm vac})^2 + (2\Delta_{\rm M})^2}\,.$$

The photon pathlength

The metric,

$$ds^2 = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

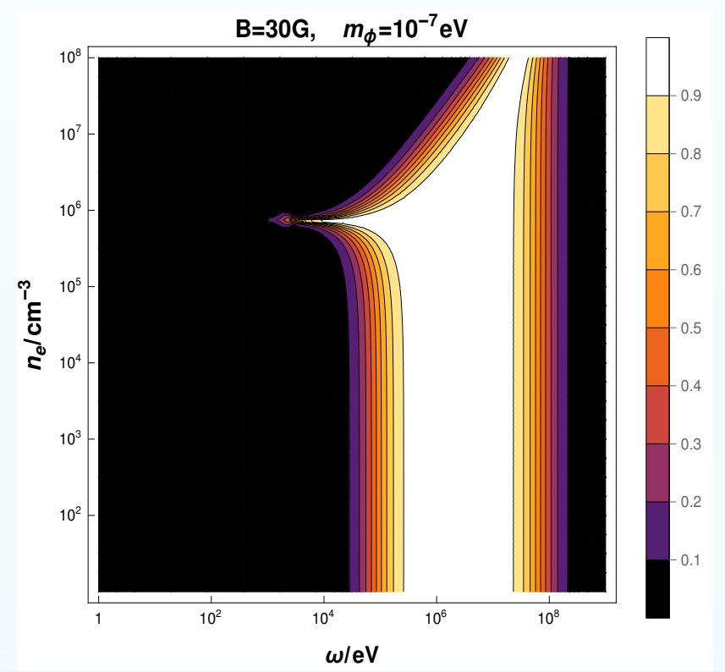
Null geodesic equation,

$$\frac{dr}{dZ} = \pm\sqrt{\frac{b^2}{r^2}f(r)} = \pm\sqrt{\mathfrak{p}\delta r^2 - 2\delta b} \qquad b = b_c\left[1 + \left(\frac{1}{2} - \frac{1}{4}b_c^2 f''(r_{ph})\right)\delta r^2 + \mathcal{O}(\delta r^3)\right]$$

The pathlength of photon around the photon sphere,

$$\mathbf{Z} = -\frac{\mathbf{r_{ph}}}{\sqrt{\mathfrak{p}}}\ln\left[\frac{\mathbf{2(b-b_c)}}{\mathfrak{p}\mathbf{b_c}} \times \frac{\mathbf{r_{ph}^2}}{\epsilon^2\mathbf{M^2}}\right]$$

$$\mathfrak{p} \equiv 1 - \frac{1}{2}r_{ph}^2\frac{f''(r_{ph})}{f(r_{ph})}, \qquad \mathfrak{a} \equiv \left[\frac{1}{2} - \frac{1}{4}b_c^2 f''(r_{ph})\right]\left(\frac{M}{r_{ph}}\right)^2$$



The relevant parameter values:

$$n_{e,c} = 10^4 cm^{-3}, M = 6.2\times10^9 M_\odot$$

$$T_{e,c} = 10^{11}K \qquad \omega_{pl} = 3.7\times10^{-9}eV$$

For finite conversion $m_\Phi \approx$ (1-100) neV

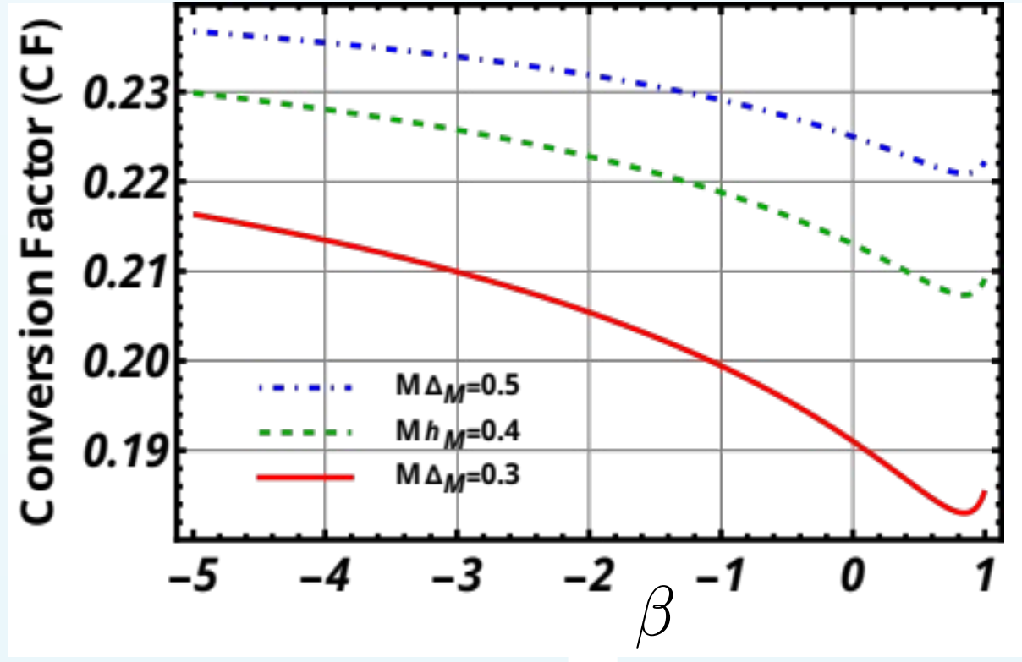
The maximal photon-axion dimming rate

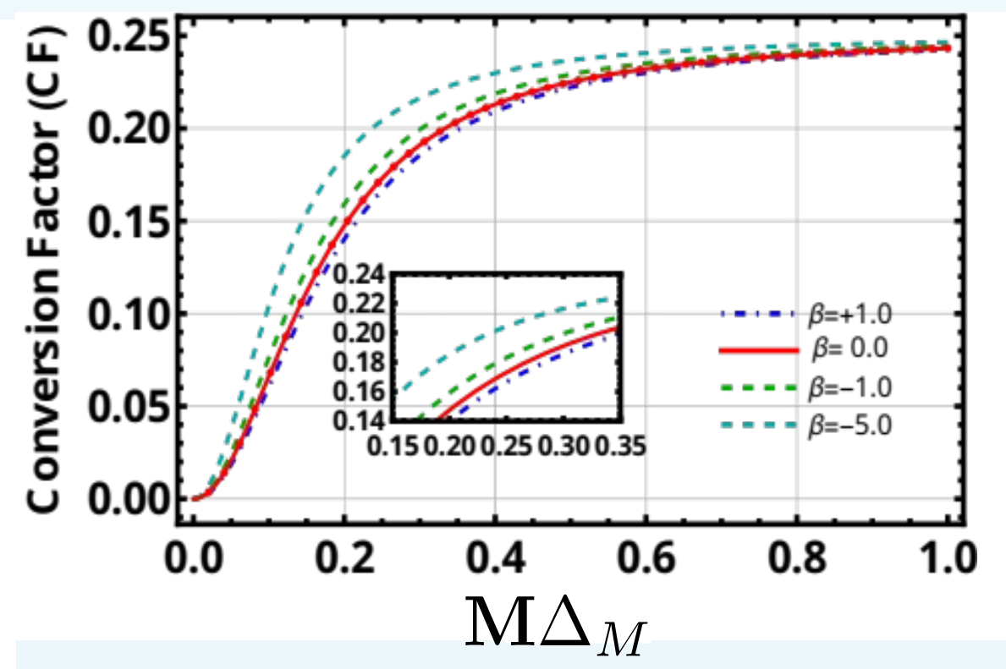
For the efficient conversion, we have $\Delta_{\rm osc} \simeq 2\Delta_{\rm M}$. For such a scenario, the conversion factor (CF) can be given by,

$$CF \simeq \frac{1}{4}\left[\frac{\left(\frac{r_{ph}}{M}\right)^2(2M\Delta_{\rm M})^2}{\left(\frac{r_{ph}}{M}\right)^2(2M\Delta_{\rm M})^2 + f(r_{ph})}\right]$$

$M\Delta_M$ of M87* = 0.13

$$f(r) = \left(1 - \frac{2M}{r} + \frac{\beta M^2}{r^2}\right)$$





Photon number calculation

The number of photons reaching the photon sphere per unit time t and unit frequency ω_c with impact parameter $(b, b+db)$ is given by

$$\left(\frac{d^3N}{dtd\omega_c db}\right) = 4\pi^2\int_{r_{\rm in}}^{r_{\rm out}} dr_e J_e\left(\frac{\sqrt{f(r_{ph})}\omega_c}{\sqrt{f(r_e)}}, r_e\right) \times \frac{br_e\sqrt{f(r_e)}}{\sqrt{(r_e^2/f(r_e)) - b^2}}$$

Source photon number distribution generated through thermal bremmstrahlung process

$$J_e^{(N)}(\omega_e, r_e) = \frac{1}{4\pi\omega_e}\left(\frac{2^4\alpha^3}{3m_e}\right)\left(\frac{2\pi}{3m_e}\right)^{1/2} T_e^{-1/2} n_e^2 e^{-\omega_e/T_e}\bar{g}_{ff}$$

$$n_e = n_{e,c}\left(\frac{r_e}{r_{ph}}\right)^{-3/2} \qquad T_e = T_{e,c}\left(\frac{r_e}{r_{ph}}\right)^{-1}$$

$$T_{e,c} = 10^{11}K$$
$$n_{e,c} = 10^4 cm^{-3}$$

To calculate the number of photons that transform to axions, near the photon sphere, per unit time t and unit frequency ω_c, the following equation can be used

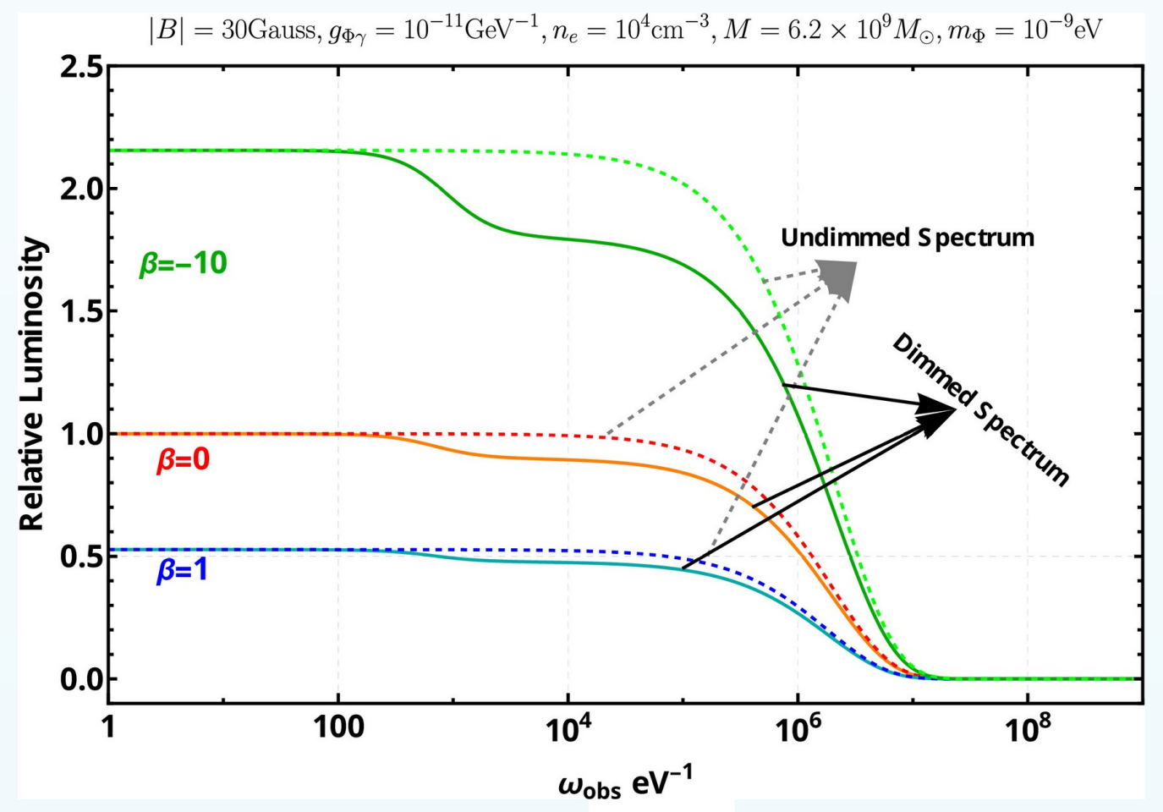
$$\frac{d^2N_{\gamma\to\Phi}}{dtd\omega_c} = \int_{b_c}^{b_c(1+\mathfrak{a}\epsilon^2)} db\,\frac{1}{2}\left(\frac{d^3N}{dtd\omega_c db}\right)P_{\gamma\to\Phi}\left(\sqrt{f(r_{ph})}z(b)\right)$$

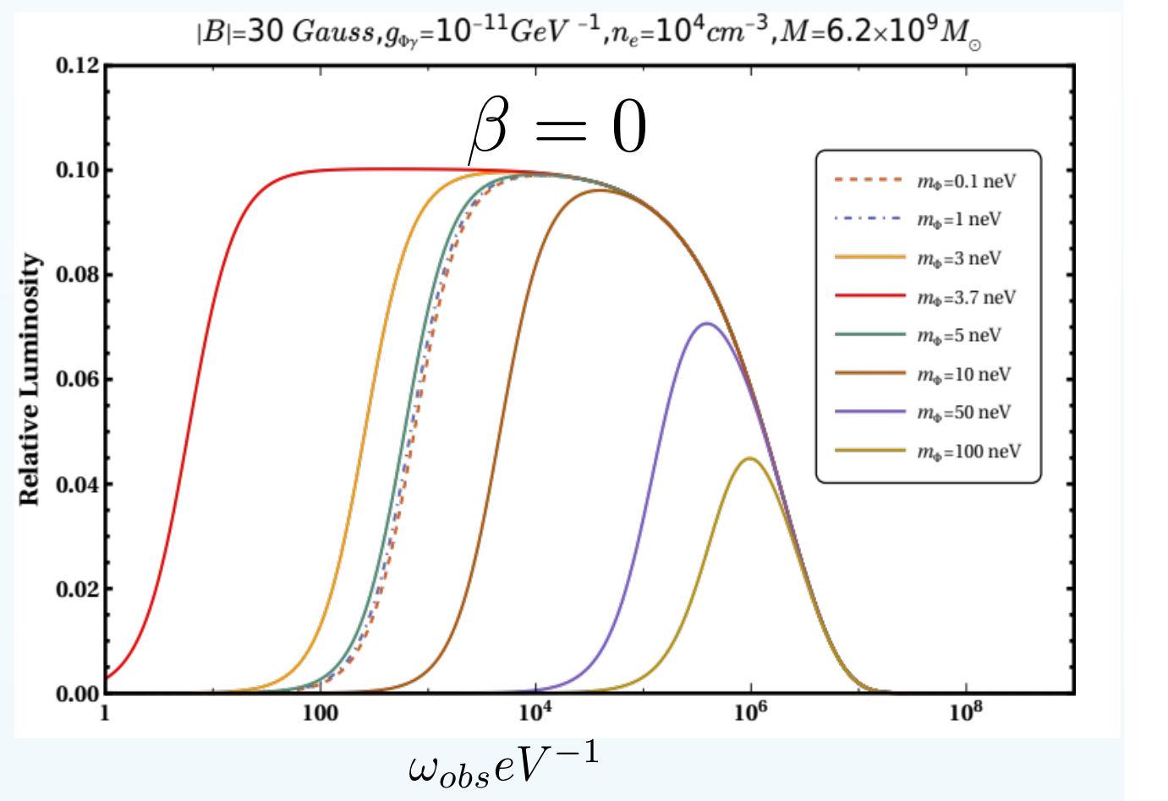
Probability expression for a spherically symmetric BH having general f(r) :

$$P_{\gamma\to\Phi}\left(\sqrt{f(r_{ph})}z(b)\right) = \left(\frac{2\Delta_{\rm M}}{\Delta_{\rm osc}}\right)^2 \times \sin^2\left(-\frac{\Delta_{\rm osc}}{2}\frac{r_{ph}}{\sqrt{\mathfrak{p}}\sqrt{f(r_{ph})}}\ln\left[\frac{2(b-b_c)}{b_c}\frac{r_{ph}^2}{\epsilon^2 M^2}\right]\right)$$

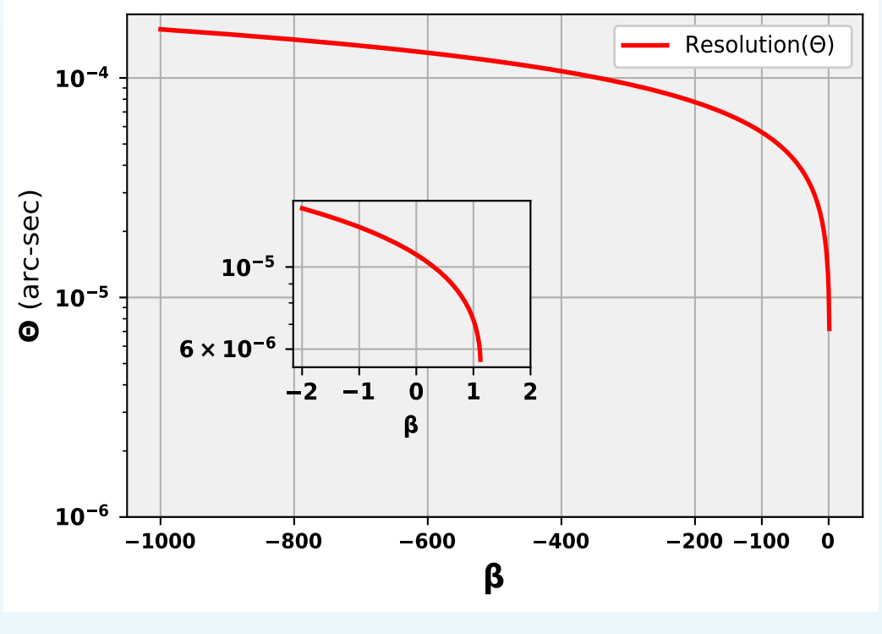
The normalized spectral luminosity and observation window

$$L_\omega^0 = 6.48\times10^{27}{\rm erg\cdot sec^{-1}\cdot KeV^{-1}}\epsilon^2\left(\frac{M}{6.2\times10^9 M_\odot}\right)^3\left(\frac{T_{e,c}}{10^{11}K}\right)^{-1/2}\left(\frac{n_{e,c}}{10^4{\rm cm}^{-3}}\right)^2\bar{g}_{ff}$$





Resolution of observation



Resolution for non zero β parameter

In case of Schwarzchild black hole, the resolution will be

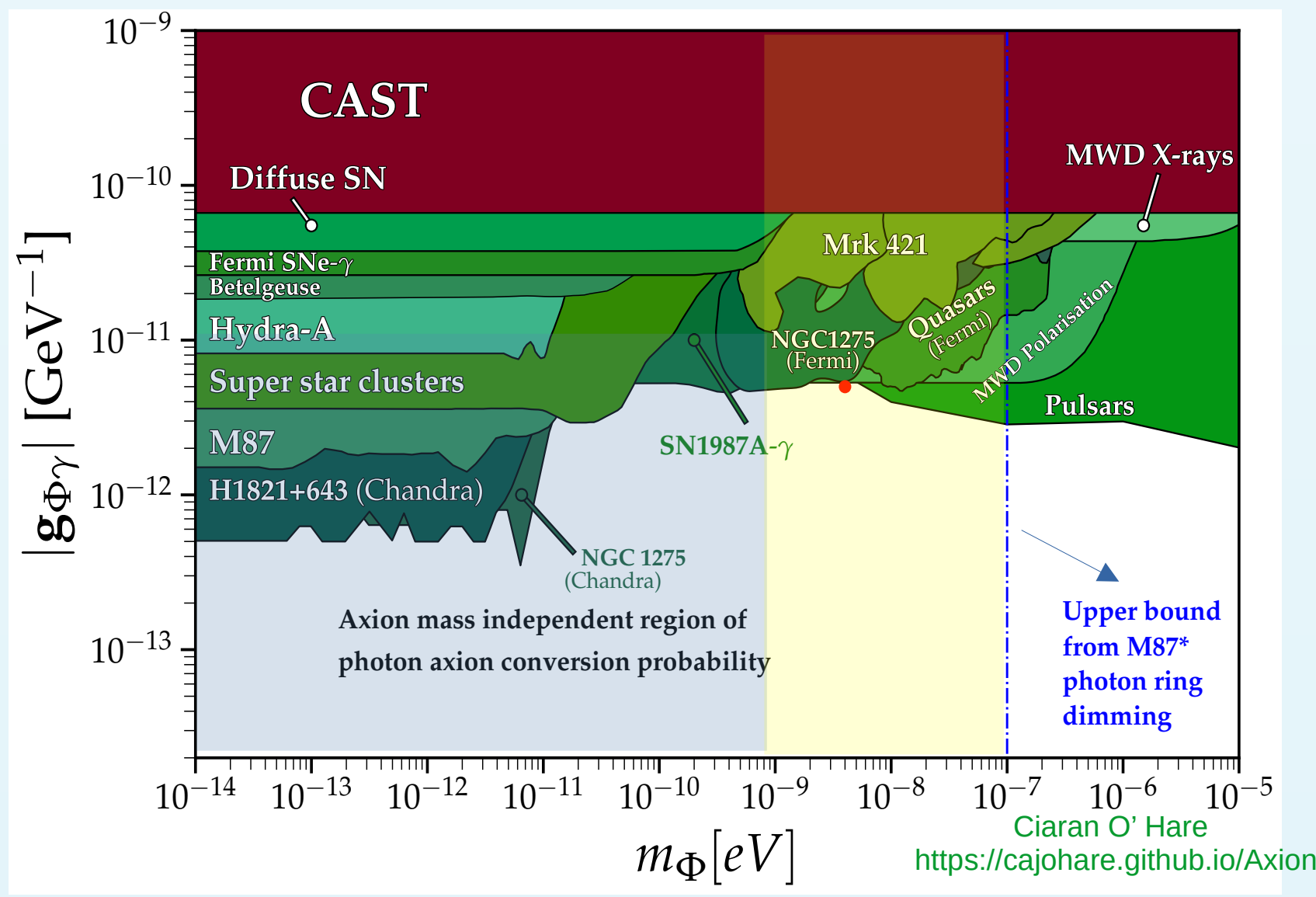
$$\theta = \left.\frac{\mathfrak{R}}{D}\right|_{\beta=0} \lesssim 1.09\times10^{-5}\ \text{arc-sec}\left(\frac{M}{6.2\times10^9 M_\odot}\right)\left(\frac{16.8\ {\rm Mpc}}{D}\right)$$

$\mathfrak{R}$ denoting the size of photon sphere

Why interested with negative β ?

- Greater dimming
- Lower the resolution
- Signature of extra dimension

The axion mass window of expected photon-ring dimming:



Ciaran O' Hare
https://cajohare.github.io/AxionLimits/

Conclusion

➢Photon-ring dimming is possible due to photon-axion oscillation with axion mass $\lesssim$ 100 neV and coupling $\sim 10^{-11}GeV^{-1}$
➢The dimming is expected to be observed in X-ray - Gamma ray band $\approx (10^2 - 10^6)eV$
➢The maximum possible dimming from our analysis of spherically symmetric black hole is about 25%.
➢The expected resolution required for M87* to be a Schwarzchild BH $\lesssim 1.09\times10^{-5}arcsec$
➢The extra dimensional signature can also be explored if the dimming rate and required resolution matches with the predicted result.
➢The dimming rate increases with the black hole mass, axion-photon coupling and nearby magnetic field strength and therefore higher amount of flux can be achievable with moremassive BHs with the same mechanism.

References

Exploring Axions through the Photon Ring of a Spherically Symmetric Black Hole:
Roy, Sarkar,Sau and SenGupta JCAP11(2023)099, Arxiv 2210.05908

Contacts

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