Probing Axions with Event Horizon Telescope Polarimetric Measurements

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ITP-CAS

based on arXiv:1905.02213, by:

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Outlines

Oscillating Ultralight Scalar Background

- **Ultralight scalars behave as coherent wave**:

$$\phi(\mathbf{x}, t) \simeq \phi_0(\mathbf{x}) \cos \mu t; \qquad \phi_0 \sim \frac{\sqrt{\rho}}{m_\phi}; \qquad \mu \simeq m_\phi .$$

- **Oscillating field value: physical observables oscillate as well in standard model sector**:
  Dilaton: coupling constant, mass...
  Axion: EDM, **photon birefringence**...

- **The interactions with SM are suppressed by high scale.**

- **Amplifications of the signals:**
  Tabletop experiments on earth: $\rho_{DM} \sim 0.4\ \text{GeV/cm}^3$;

  Astrophysical: **large** ρ, e.g., **near Kerr black hole**.

Axion/Axion-like Particle

- A hypothetical pseudoscalar originally motivated by the strong CP problem:
  Neutron electric dipole $|\bar{\theta}|10^{-16}e.cm$ is smaller than $10^{-26}e.cm$. Why is $\bar{\theta}$ so small?
  Solution: introducing an dynamical field with effective potential

$$V \sim -\Lambda_{QCD}^4 \cos(\bar{\theta} + \frac{a}{f_a}).$$

- String theory predicts a wide range of axion mass.
  Compactified extra dimension is parameterized by complex scalars: moduli fields.
  e.g. $A_4(5D) \to a(4D)$.

- Cold dark matter candidate.
  Coherent wave dark matter, very different from WIMP.

Birefringence from Axion

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial^\mu a\partial_\mu a - V(a),$$

- Equation of motion for photon:

$$[\partial_t^2 - \nabla^2]A_{L,R} = -2g_{a\gamma}n^\mu\partial_\mu a\nabla \times A_{L,R} = \mp\, 2g_{a\gamma}n^\mu\partial_\mu akA_{L,R}.$$

- **Birefringent effect with different dispersion relations**:

$$\omega_{L,R} \sim k\mp g_{a\gamma}n^\mu\partial_\mu a.$$

- For linearly polarized photons, the **polarization angle** is shifted by

$$\begin{aligned}\Delta\Theta_\gamma &= g_{a\gamma}\int_{\rm emit}^{\rm obs} n^\mu\partial_\mu a\, dl \\ &= g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})],\end{aligned}$$

- This only depends on the initial and final background axion field values. **How large?**

Search Strategies

A region with:

- **a concentration of axion field**
  Outside black hole, the density of axion can be large.
- **source for linearly polarized photon**
  The polarization angle, at emission point, should be stable.

Search for:

- **polarization angle oscillates with time**;
  Axion field is an oscillating background field.
- **oscillation amplitude change as a function of spatial distribution.**
  Extended light source

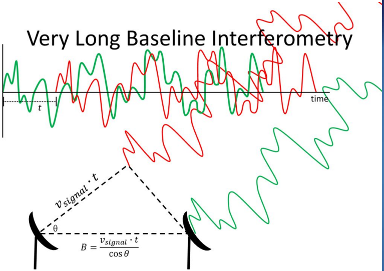
Scenarios: EHT-SMBH

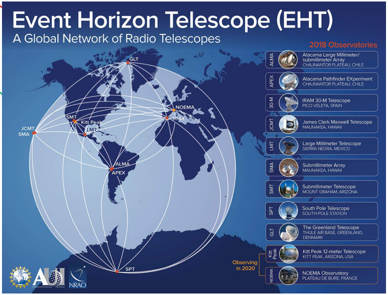
Later we will see to a **radiation ring** instead of a point is necessary for polarimetric probing of axion.

Event Horizon Telescope and $M87^{\star}$

Event Horizon Telescope: an Earth-sized Telescope

- For single telescope with diameter D, the angular resolution for photon of wavelength λ is around $\frac{\lambda}{D}$;
- VLBI: for multiple radio telescopes, the effective D becomes the maximum separation between the telescopes.





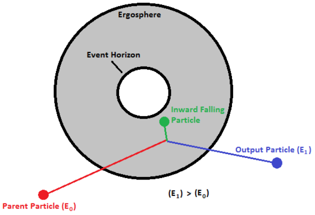
- As good as being able to see  on the moon from the Earth.

Supermassive Black Hole (SMBH) $M87^{\star}$

- To see the **shadow** and the ring, an excellent spatial resolution is necessary.
- One of the most massive black hole ever known: $6.5 \times 10^9 M_{\odot}$;
- Nearly extreme Kerr black hole: $a_J > 0.8$;
- Almost face-on disk with a 17° inclination angle;
- Rich astrophysical information under extremal condition;
- **What else can we learn?**

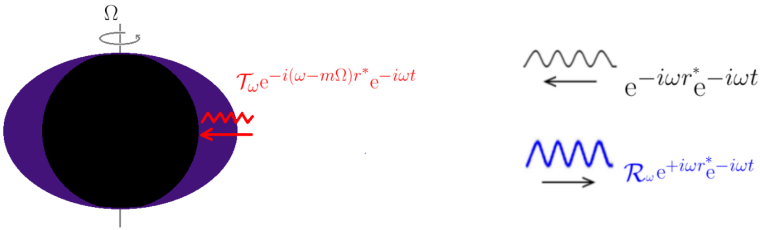
Axion-induced Superradiance

Penrose Process



- For Kerr black hole, there exists a region near the event horizon called Ergosphere where g_{tt} is different sign from the outside.
- For a particle scattering into this region, the outgoing one carries **more energy** since there is another particle with negative energy falling into the black hole.
- The net energy increase comes from **rotation energy**.

Black hole Superradiance: wave analogue of the Penrose Process

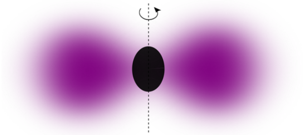


$$|\mathcal{R}_\omega|^2 = 1 - \frac{\omega - m\Omega}{\omega} * (\text{positive quantity})$$

- For $\omega < m\ \Omega$ where m is the the azimuthal number and Ω is the black hole angular velocity, reflected waves are amplified.

Gravitational Atom

- For a ultralight boson whose $\lambda_C \simeq r_g$, i.e., $\mu M \sim \mathcal{O}(1)$ in Planck unit, the wave-function is exponentially amplified from extracting rotation energy.
- A gravitational bound state between BH and axion cloud, very similar to the hydrogen solution with fine structure constant $\alpha_G = \mu M$:



- KG equation under Kerr background has general solution

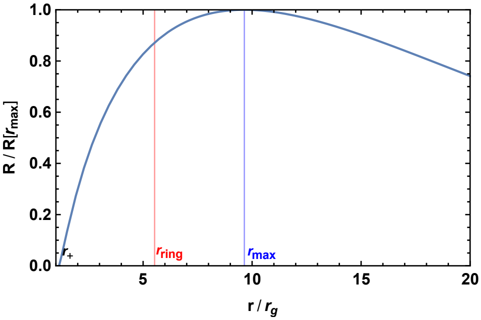
$$a(x^{\mu}) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r),$$

with $S_{lm}(\theta)$ a deformed version of $Y_{lm}(\theta)$ with zenith angle θ.

- Axion cloud populates more efficiently at lower l-mode. m=l mode is more efficient than other m-levels.

Radial Distribution

e.g., $R_{11}(r)$ is:



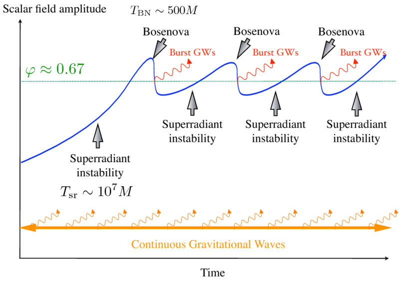
- The **ring EHT observed** has a radius comparable to the **peaking radius of the axion cloud**.

Bosenova

- When the peak field value is large enough $\varphi = a_0/f \sim 1$, one should take into account the non-perturbative axion potential:

$$V = \mu^2 f^2 \left(1 - \cos\frac{a}{f}\right) = \frac{\mu^2 a^2}{2} - \frac{\mu^2 a^4}{24 f^2} + \ldots;$$

- The eom is Sine Gordon equation under Kerr background. The leading order is the mass term, while the subleading order is the quadratic self-interaction that makes the axion cloud collapse.



Axion Density

$$\Delta\Theta_\gamma \simeq -g_{a\gamma} a(t_{\rm emit}, \mathbf{x}_{\rm emit})$$

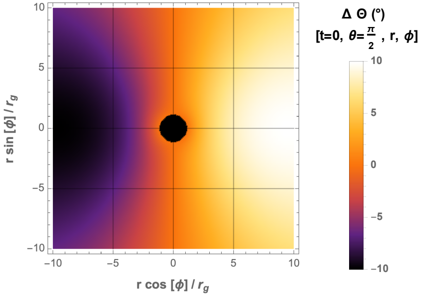
- We focus on the photon emitted from the ring where a_0 is near the peak value of axion cloud.
- During periodic bosenova/superradiance phase, $a_0/f \sim 1$.
- The main model dependent parameter is c in $g_{a\gamma} = \frac{c}{2\pi f}$.

Axion cloud induced position angle change:

- $\Delta\Theta_\gamma$ is dominated by the emission point density:

$$\begin{aligned}\Delta\Theta_\gamma &\simeq -g_{a\gamma}\, a(t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= -g_{a\gamma}\, a_0(\mathbf{x}_{\rm emit}) \cos\left[\omega t_{\rm emit} + \beta(\mathbf{x}_{\rm emit})\right].\end{aligned}$$

  where $\beta(\mathbf{x}_{\rm emit}) \simeq m\phi$.
- For a face-on disk (17° for $M87^\star$):



- Temporal dependence for a fixed position;
- Spatial dependence for a fixed time.

Detectability of EHT

- Average effect due to the limited resolution and angular dependent phase:

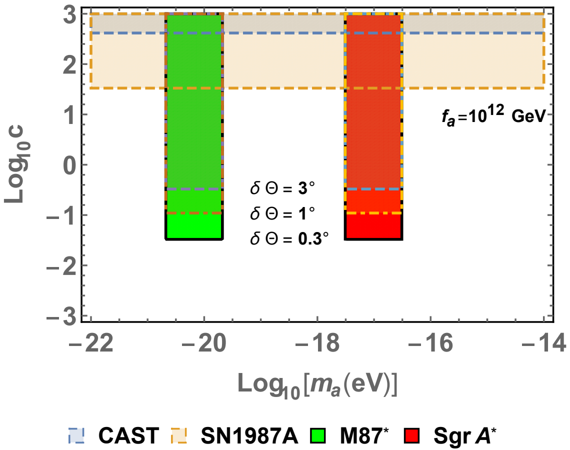
$$\int_0^{\Delta\phi} \cos(\mu t + m\phi) d\phi = \frac{\sin(m\Delta\phi/2)}{m\Delta\phi/2} \cos(\mu t + m\Delta\phi/2).$$

- In the past, we only saw a point instead of a **ring**, $\boldsymbol{\Delta}\phi = \mathbf{2}\pi$, no birefringent effect.

- EHT hasn't published results of polarimetric measurement. However, a subset of the EHT configuration measures the position angle at precision of $\sim 3^{\circ}$. It's reasonable to expect better precision.

Prospect of Constraints on Axions

SMBH	M	a_J	μ range	μ for $\alpha = 0.4$	τ_a	τ_{SR}
$M87^\star$	$6.5 \times 10^9 M_\odot$	0.99	$2.1 \times (10^{-21} \sim 10^{-20})$ eV	8.2×10^{-21} eV	5.0×10^5 s	$> 1.5 \times 10^{12}$s
Sgr $A^\star$	$4.3 \times 10^6 M_\odot$	—	$3.1 \times (10^{-18} \sim 10^{-17})$ eV	1.2×10^{-17} eV	3.3×10^2 s	$> 1.0 \times 10^9$s



Prospect of Constraints on Axions

SMBH	M	a_J	μ range	μ for $\alpha = 0.4$	τ_a	τ_{SR}
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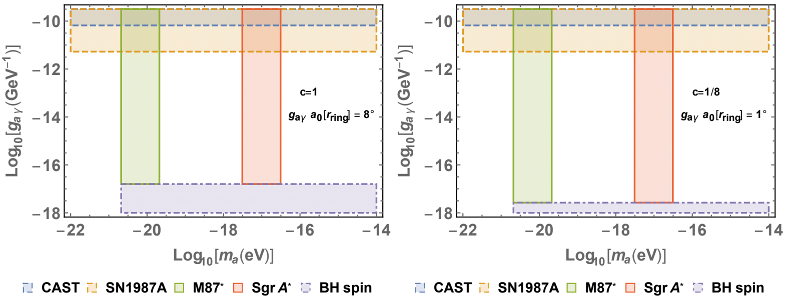

Figure: Here we show the parameter space testable by polarimetric observations of M87* and Sgr A* with two different choices of c.

Summary

- Depending on its excellent spatial resolution, EHT has seen clearly the **ring** and the **shadow** of SMBH $M87^{\star}$, which is the most direct evidence of black hole.

- Outside Kerr black hole, ultralight bosons with Compton wavelength close to horizon radius can build up a bound state with large energy density.

- Axions, with initial motivation to solve strong CP problem, are also generic prediction of string theory/extra dimension.

- Photon emitted from a dense axion cloud has birefringent effect making polarization angle oscillate. The amplitude of the oscillation is dependent on the axion density of the emission position.

- Axion cloud collapses once the self-interaction becomes dominant over gravitational force and builds up again.

- Near Kerr black hole, axions can be most dense in the universe, thus making EHT polarimetric measurement an optimal way to look for axions.

Thank you!

Probing Axions with EHT Polarimetric Measurements

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a - V(a),$$

- Axion-induced birefringence:

$$\Delta\Theta_{\gamma} = g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})],$$

- Near Kerr black hole, a/f can reach $\mathcal{O}(1)$.
- EHT polarimetric measurement can test axions!