Dissecting Axion Around SMBH with EHT/ngEHT

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based on
arxiv: 1905.02213, Phys. Rev. Lett. **124** (2020) no.6, 061102,
arxiv: 2105.04572 and ongoing

YC, Chunlong Li, Yuxin Liu, Ru-Sen Lu, Yosuke Mizuno, Jing Shu, Xiao Xue, Qiang Yuan, Yue Zhao and Zihan Zhou

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Outlines

Motivation and Introduction to Axion

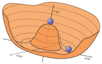
Axion/Axion-like Particle

- Hypothetical pseudoscalar initially motivated by strong CP problem:
  Neutron electric dipole $|\bar{\theta}| 10^{-16}$ **e.cm is smaller than** 10^{-26} **e.cm.**

$$\bar{\theta} = \theta_{\rm QCD} + \arg\, \det M_u M_d, \qquad \text{Fine tuning!}$$

  Why is $\bar{\theta}$ so small? Why  instead of ?
  Solution: introducing an **dynamical** field with effective potential

$$V \sim -m_\Phi^2 f_\Phi^2 \cos(\bar{\theta} + \frac{\Phi}{f_\Phi}).$$



- Extra dimension predicts a wide range of axion mass.
  Dimensional reduction from higher form fields:
  e.g. $A^M(5D) \to A^\mu(4D) + \Phi(4D)$.

- Cold dark matter candidate behaving like **coherent wave**:

$$\Phi(x^\mu) \simeq \Phi_0(\mathbf{x}) \cos \omega t; \qquad \Phi_0 \simeq \frac{\sqrt{\rho}}{m_\Phi}; \qquad \omega \simeq m_\Phi.$$

  Amplifications of the signals:
  Tabletop experiments on earth: $\rho_{\rm DM} \sim 0.4$ GeV/cm^3;
  Astrophysical: **larger** ρ, e.g., galaxy center or near Kerr black hole.

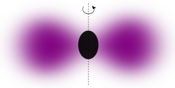
Superradiance and Gravitational Atom

Superradiance and Gravitational Atom

- **Rotational and dissipational medium** can amplify the wave around. [Zeldovichi 72']

- **Superradiance**: the wave-function is exponentially amplified from extracting BH rotation energy when $\lambda_c \simeq r_g$. [Penrose, Starobinsky, Damour et al]

- **Gravitational bound state** between BH and axion cloud:

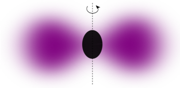


$$\Phi(x^\mu) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r),$$

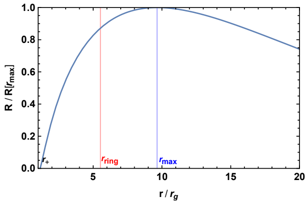
- Most efficient for $(l, m) = (1, 1)$ state, the ground superradiant state.

Axion Field Value

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

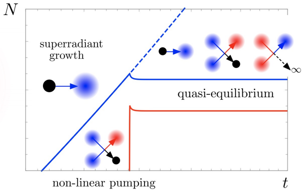


- R_{11} at the **emission point of the ring** can be **near the maximum**, e.g. : whose radius $r_{\rm max}$ moves farther with smaller $\alpha \equiv G_N M_{BH} m_\Phi \equiv r_g/\lambda_c$.



- The wave function **peaks at the equatorial plane of the black hole** since $S_{11} \simeq Y_{11} \propto \sin\theta$.

- **Self interaction saturating phase where $\Phi_{\rm max} \simeq f_\Phi$.** [Yoshino, Kodama 12', Baryakht et al 20']



Birefringence and Radiative Transfer

Axion QED: Birefringence

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

- Equation of motion for photon under axion background:

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

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

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

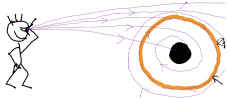
- The **electric vector position angle** of linear polarization is shifted by

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

- This only depends on the initial and final background axion field values. $\Phi(t_{\rm emit},\mathbf{x}_{\rm emit}) \sim f_\Phi$ from superradiant cloud.

Radiative Transfer and Birefringence

$$\mathcal{L} \ni -\frac{1}{2} g_{\Phi\gamma} \Phi F_{\mu\nu} \tilde{F}^{\mu\nu},$$



- $\Delta\chi = g_{\Phi\gamma}[\Phi_f - \Phi_i]$ **only applies to point-like source in vacuum**.

- Extended sources, plasma and general relativity effect?

  Radiative transfer in terms of linearly polarized Stokes parameters:

  $$\frac{d(Q + i\ U)}{ds} = j_Q + i\ j_U + i\left(\rho_V^{\mathrm{FR}} - 2 g_{\Phi\gamma}\frac{d\Phi}{ds}\right)(Q + i\ U).$$

  ρ_V^{FR}: astrophysical faraday rotation, frequency dependent.

  $2g_{\Phi\gamma}\frac{d\Phi}{ds}$: **gradient of axion field along geodesics**, achromatic.

  Observable on the sky plane: EVPA $\chi \equiv \arg(Q + i\ U)/2$.

- Since $\Phi \propto \cos\omega t$, **source size** $> \lambda_c \equiv 1/m_\Phi$ can wash out the EVPA oscillation.

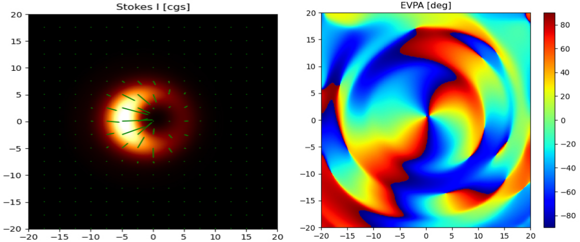
Hunting Axions with

EHT Polarimetric Measurements

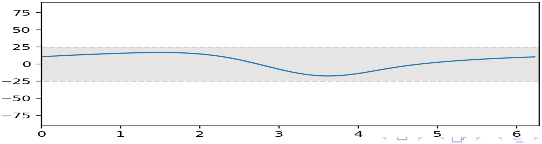
Axion Cloud Induced Birefringence (IPOLE simulation)

- An almost face-on disk (17° for $M87^\star$):

$$\Phi \propto \cos\left[\omega t - \phi\right] \sin\theta \rightarrow \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi)\cos\left[\omega t + \varphi + \delta(\varphi)\right].$$



- **Temporal oscillation** for a fixed position;
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along azimuthal angle** φ due to the angular momentum:

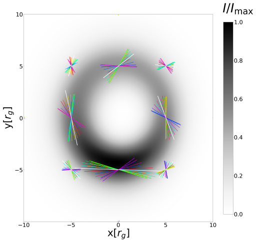


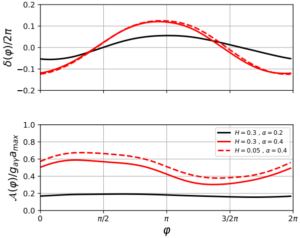
Axion Birefringence Around RIAF (IPOLE simulation)

$$\Delta\langle\chi(\varphi)\rangle = -\mathcal{A}(\varphi)\cos\left[\omega t + \varphi + \delta(\varphi)\right].$$

- Benchmark: **sub-Keplerian RIAF with vertical $\vec{B}$**.

  Axion mass: $\alpha \equiv G_N M_{BH} m_\Phi \in [0.10, 0.44]$ with **period [5, 20] days**.

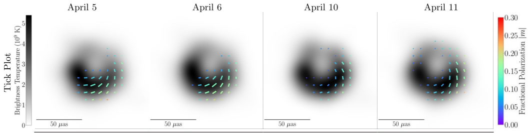




- Phase delay is well fit by $\delta(\varphi) \approx -5\ \alpha\ \sin 17^\circ \cos\varphi$.
- The dominant washout/asymmetry of $\mathcal{A}(\varphi) = \mathcal{O}(1) g_{\Phi\gamma} f_\Phi$ comes from the **lensed photon due to the incoherent phase**!
- For smaller m_Φ, washout is negligible due to longer $\lambda_c \equiv 1/m_\Phi$.

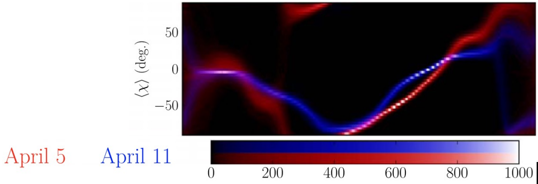
EHT Polarization Data Characterization

- Four days' polarization map with slight difference on sequential days:



[EHT 2021]

- Uncertainty of the azimuthal bin EVPA from `polsolve`:



[EHT 2021]

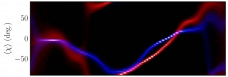
ranging from $\pm 3°$ to $\pm 15°$ for the bins used.

Stringent Constraints on Axion-Photon Coupling

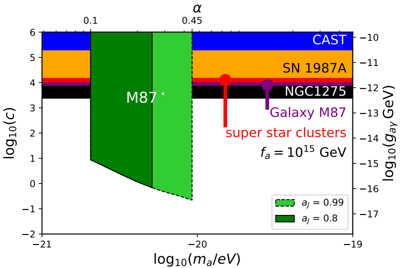
- **Differential EVPA in the time domain**:

$$\langle \chi(\varphi, t_j) \rangle - \langle \chi(\varphi, t_i) \rangle \simeq 2 \sin [\omega t_{\rm int}/2] \Delta \langle \chi(\varphi) \rangle$$

where $t_{\rm int} \equiv t_j - t_i = 1$ day.

- Uncertainty of azimuthal bin EVPA in EHT data 

$\rightarrow$ dimensionless **axion photon coupling** $c \equiv 2\pi g_{\Phi\gamma} f_\Phi$.



[YC, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao 21']

- Weaker bound at small α is due to $R_{11}/R_{\rm max}$ and $\sin[\omega t_{\rm int}/2]$.

Summary

- **Linearly polarized radiation from dense axion field**:

  Oscillating axion background $\rightarrow$ **EVPA oscillates**.

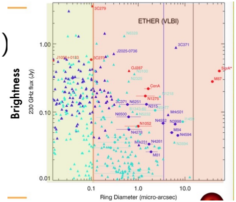
- **Dissectinng superradiant axion cloud**:

  Superradince brings **large density of axion cloud** carrying angular momentum. $\rightarrow \Delta\mathrm{EVPA}(\varphi)$ is like **a propagating wave along** φ.

- **Stringent Constraints from EHT polarimetric measurements**:

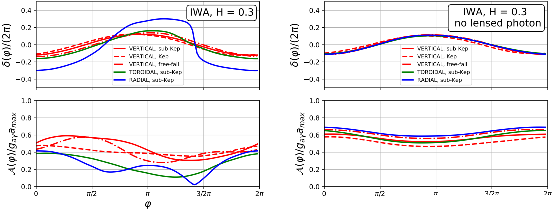
  Using **differential EVPA in time domain**, the uncertainty of azimuthal bin EVPA data on 4 days (2 pairs) can already constrain **axion-photon coupling** to previously unexplored region.

Prospect for ngEHT

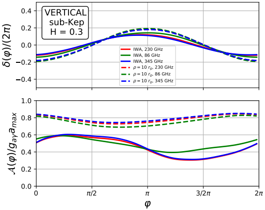


- **Horizon scale SMBH landscape** with ngEHT (space, L2)
  Broader range of axion mass: 10^{-22} eV to 10^{-17} eV.

- **Universal birefringence signals** for direct emission only:



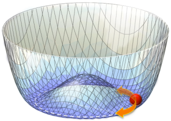
- **Future improvements**:
  Correlation between ΔEVPA at **radius without lensed photon** and different frequency;
  Longer observations;
  Better resolution of EVPA;
  Better understanding of accretion flow and jet.



Thank you

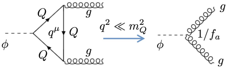
Appendix

Axion Coupling to the Standard Model



- **Axion Fermion coupling**: $\partial_\mu \Phi \bar{\psi}\gamma^\mu\gamma_5\psi/f_\Phi$,
  non-linearization of a chiral global symmetry $\sim \partial_\mu \Phi J_5^\mu/f_\Phi$.
  Stellar cooling, DM wind/gradient.

- **Axion Gluon coupling**: $\Phi \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}/f_\Phi$,
  generated from anomaly/triangle loop diagram.
  Oscillating EDM.

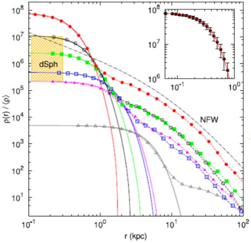


- **Axion Photon coupling**: $\Phi F_{\mu\nu}\tilde{F}^{\mu\nu}/f_\Phi$,
  from mixing with neutral π_0.
  Photon conversion to axion, inverse Primakoff, birefringence.

Astrophysical Birefringence from Soliton Core

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

- Large initial axion field values in galaxy center: soliton core.
  Fuzzy dark matter [Hu et al 00'], with de Broglie wavelength $\sim$ kpc scale suppressing small scale structures and **a soliton core formed inside GC**.



soliton solution

$$\rho(x) = \begin{cases} 0.019\left(\frac{m_a}{m_{a,0}}\right)^{-2}\left(\frac{l_c}{1\mathrm{kpc}}\right)^{-4} M_\odot \mathrm{pc}^{-3}, & \text{for } r < l_c \\ \frac{\rho_0}{r/R_H(1+r/R_H)^2}, & \text{for } r > l_c \end{cases}$$

NFW profile

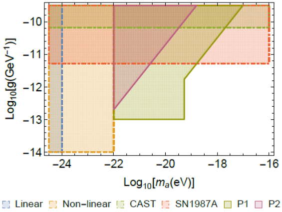
[Schive et al 14']

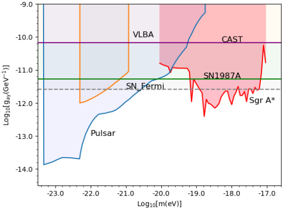
Balance between quantum pressure and gravitational self interaction.

Birefringence from Soliton Core Axion

- Ultralight axion dark matter forms soliton core in the galaxy center.

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





- Linearly polarized photon from **pulsar**. [Liu, Smoot, Zhao, 19']

- Polarized radiation from **Sgr A***.[Yuan, Xia, YC, Yuan et al 20']

Search Strategies

A region with:

- **Large axion density**
  Outside black hole?
- **Source for linearly polarized photon**
  Stable initial position angle.

Search for:

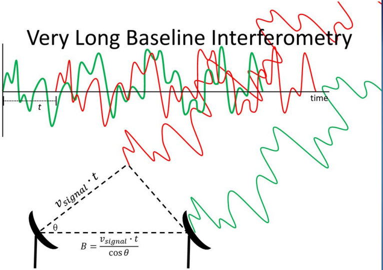
- **Position angle oscillates with time**;
  Axion is an oscillating background field.
- **Oscillation amplitude change as a function of spatial distribution.**
  Extended light source.

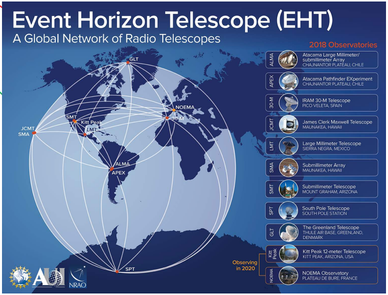
Scenarios: EHT-SMBH

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

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?**

Fate of Superradiance

Axion cloud can't keep growing exponentially. What's **the fate of it**?

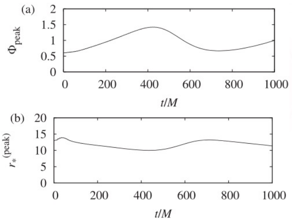
- **Self interaction** of axion becomes important for $f_a < 10^{16}$ GeV. [Yoshino, Kodama 12', Baryakht et al 20']
- Black hole **spins down** until the superradiance condition is violated for $f_a > 10^{16}$ GeV. [Arvanitakia, Dubovsky 10']
- Formation of a **binary system** leads to the decay/transition of the bound state. [Chia et al 18']
- **Electromagnetic blast** for strong (large field value) axion-photon coupling. [Boskovic et al 18']

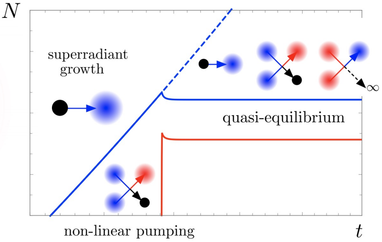
Weakly Saturating Axion Cloud

- When the field value is large enough, one should take into account the non-perturbative axion potential:

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

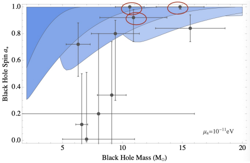
- A quasi periodic phase where **superradiance and non-linear interaction induced emission balance each other** with $\Phi_{\mathbf{peak}} = a_0/f \sim 1$.



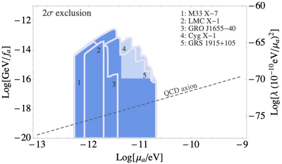


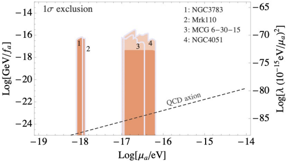
[Yoshino, Kodama 12' 15', Baryakht et al 20']

Black Hole Spin Measurements [Arvanitakia et al 10' 14']

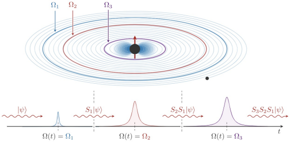


- Comparing **the timescale between the superradiance and BH accretion**, a BH with large spin can typically exclude axion with $f_a > 10^{16}$ GeV.





Gravitational Collider [Chia et al 18']



- Resonant transition from one bound state to another happens when orbital frequency Ω **matches the energy gap**.
- Due to the GW emission of the binary system, $\Omega(t)$ slowly increases and scan the spectrum.
- Orbits could float or shrink dependent on the transition.

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.
- A subset of the EHT configuration previously measured the position angle at precision of $\sim 3^\circ$. It's reasonable to expect better precision.