Detecting Axion Dark Matter with Black Hole Polarimetry

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arxiv: 2311.02149 with Xucheng Gan (NYU) and Liantao Wang (Uchicago)

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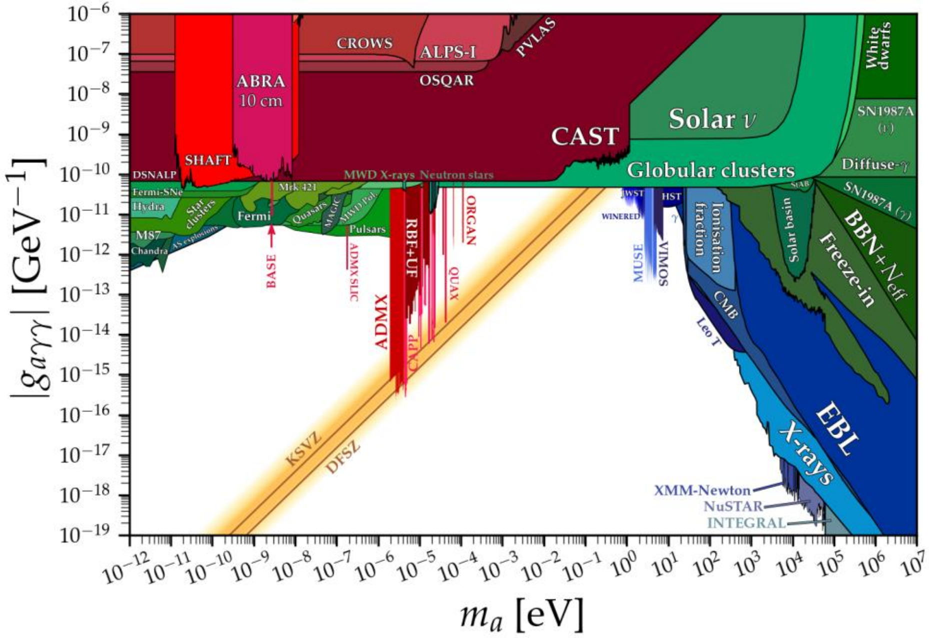
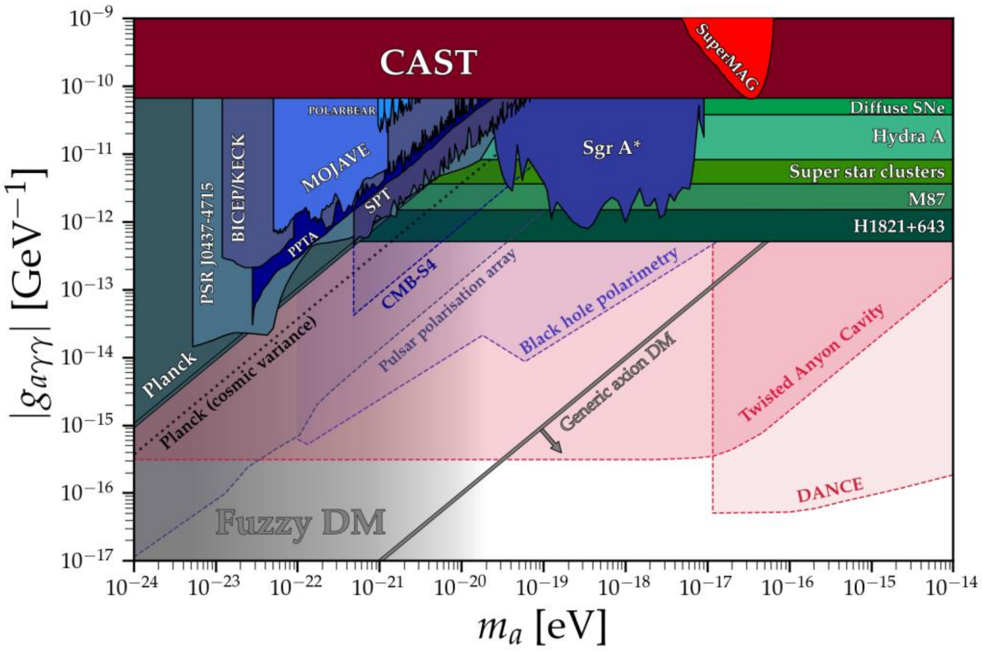
Current Landscape of Axions

Plot taken from axionlimit website. There are ground experiments and astrophysical constraints on axion-photon couplings. Some laboratory searches start to cover the QCD axion line (with some caveats on the local axion dark matter density, especially in the post-inflationary scenario). Some bounds are independent of the dark matter assumption (CAST).



Ultralight Axion Dark Matter

Astrophysical and cosmological measurements start to take over at the ultralight axion mass range. Such as CMB polarization measurements, pulsar polarization array and **black hole polarimetry.**



Cosmic birefringence and polarization searches for axions

Axion fields will induce a phase shift on the polarization angle that only depends on the boundary term:

$$\delta\phi = \frac{g_{a\gamma}}{2}(a_{\mathrm{source}} - a_{\mathrm{earth}})$$

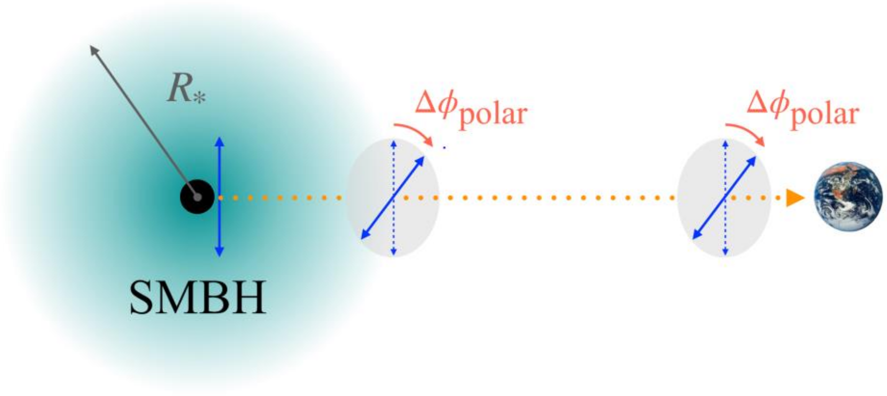
The axion field value is related to the density:

$$a = \sqrt{\frac{2\rho_a}{m_a^2}}\cos(m_a t)$$

Therefore the sensitivity relies on two things: 1) The precision on the polarization measurement; 2) The axion field value on the source (or earth).

Various sources for polarization detection of axions

- CMB photons
- Pulsars
- *Active supermassive black holes*



What is the advantage of observing SMBHs?

- Accurate polarization measurements
- Enhancements on the axion field value due to **axion star formation**

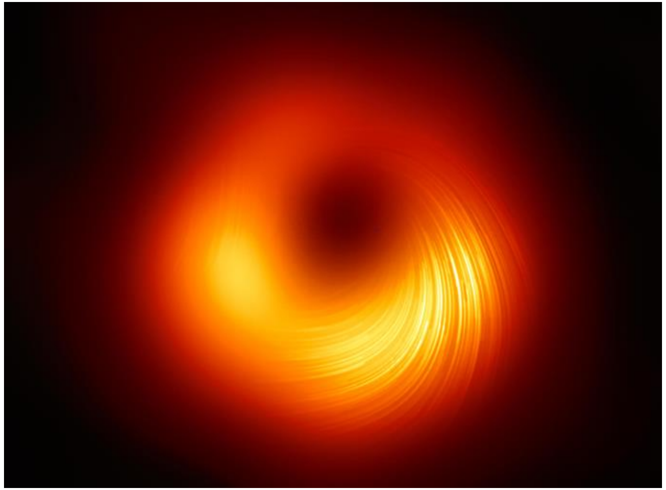


Image: EHT collaboration, M87* in polarized light.

Some estimates on CMB sensitivities

Observations like Planck, SPT, POLARBEAR are actively study the cosmic birefringence effect induced by axions. The dark matter density at last scattering can be estimated as

$$\rho_a(z_{cmb}) \sim (1 + z_{cmb})^3 \rho_0 \sim 10^3 \mathrm{GeV}/\mathrm{cm}^3$$

The axion field value can be estimated as

$a(z_{cmb}) \sim \sqrt{\frac{2\rho_a}{m_a}} \sim 10^8 \mathrm{GeV} \left(\frac{10^{-18}\mathrm{eV}}{m_a}\right)$; Current precision on polarization angle $\sim 1^\circ$

Therefore the sensitivity on axion-photon coupling is $g_{a\gamma} \sim 10^{-10} \mathrm{GeV}^{-1} \left(\frac{m_a}{10^{-18}\mathrm{eV}}\right)$

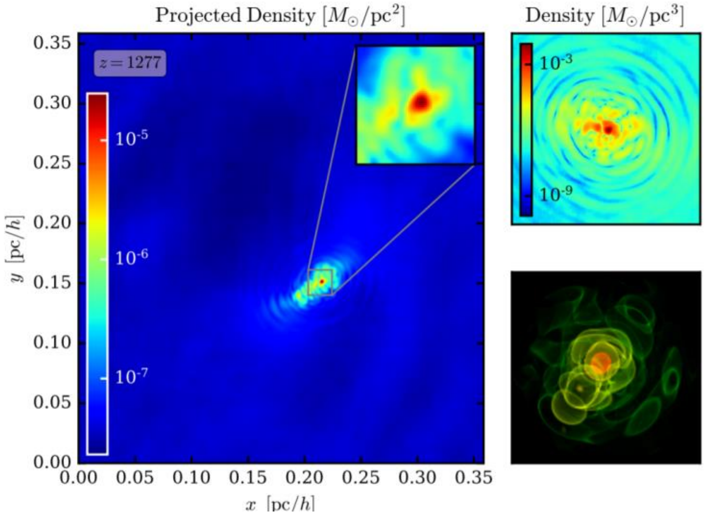
This estimate should not be considered as accurate because there will be washout effects

We will see BH polarimetry can reach a better sensitivity.

Why axions form a star in the galaxy?

Axion star, by definition, is the ground state of axion field configuration. Therefore, given enough time, axions always condensate to axion stars.

Axions go through **Bose-Einstein condensation** and form axion stars (though they do not emit light).



Eggemeier and Niemeyer, 2019

Adding a BH to the axion system

The axion potential is $V(a) = \frac{1}{2} m_a^2 a^2 - \frac{\lambda}{4!} a^4$;
The profile of axion field can be written as $a(r,t) = f_a \Theta(r) \cos(\omega t)$

Equation of motion in the Newtonian limit: $\nabla^2 \Theta = 2\left(m_a^2 \Phi + \frac{m_a^2 - \omega^2}{2}\right)\Theta$;

Where we assume BH dominate the gravitational potential $\Phi = -\frac{GM_{BH}}{r}$;
This leads to hydrogen atom like solution:

$$\Theta = \Theta_0 e^{-GM_{BH} m_a^2 r}$$

And the axion star radius is $R_* \sim \frac{1}{GM_{BH} m_a^2} \sim 10^{-3} \mathrm{pc} \left(\frac{10^{-20} \mathrm{eV}}{m_a}\right)^2$ for $M_{BH} = 7 \times 10^9 M_\odot$

Axion stars as gravitational atoms

- The normalization amplitude is unknown from solving the equation of motion. Remains to be determined from the accretion history of axion stars.
- The radius is larger than the Schwarzschild radius as long as $GM_{BH}m_a < 1$. Therefore we can scan a broad range of axion masses.
- The axion star solution in the SMBH background has a density much greater than the self-gravitating axions.

Determining the mass of axion stars

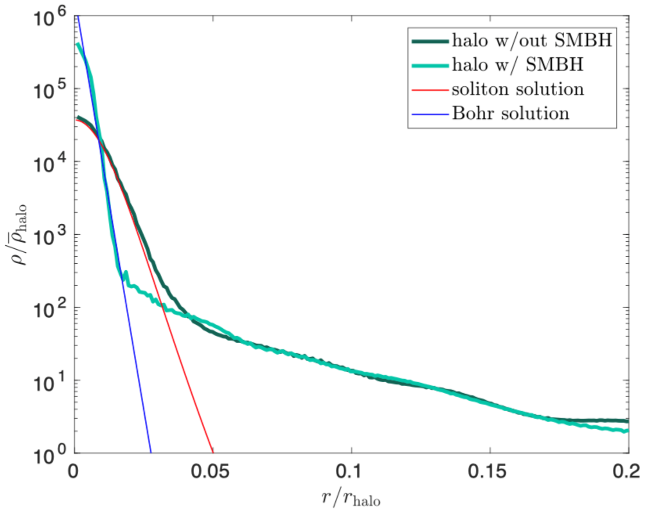
The axion star formation rate is peaked at the densest environment in dark matter halos. There are simulation evidences for dark matter peaks around supermassive black holes.

Therefore, we expect axion stars to form near SMBHs and then be absorbed, further forming gravitational atoms.

Numerical evidences

It was found SMBH will squeeze the existing solitons and reach gravitational atom solution (Davies and Mocz 2020)

Therefore, the soliton formed near halo center will greatly enhance the axion field density.



Determining the mass of axion stars

We have not considered the further enhancements on the formation rate by adding the SMBH, which requires more numerical studies in the future. Instead, we use the well-established formation rate for axion stars at the halo center and the corresponding axion star mass to determine the amplitude of the gravitational atom solution. We use the central density of the NFW halo (roughly at 0.1 scale radius) to compute τ, which is conservative since the BH may further enhance the rate.

Then, we solve the growth of axion stars, $\frac{dM_*}{dt} = \frac{M_{*0}^2}{M_*}\frac{1}{\tau} - M_*\Gamma_{\text{decay}}$, where the decay rate is determined by the region of the axion wavefunction that is overlapping with the BH horizon. We found the density of axion stars to be (Consider M87)

$$\rho_* \sim \frac{M_*}{R_*^3} \sim 10^8 \text{GeV cm}^{-3} \left(\frac{m_a}{10^{-20}\text{eV}}\right)^{1/2}$$

Huge density enhancements compared to the CMB observation!!!

How to distinguish axion induced signals from background?

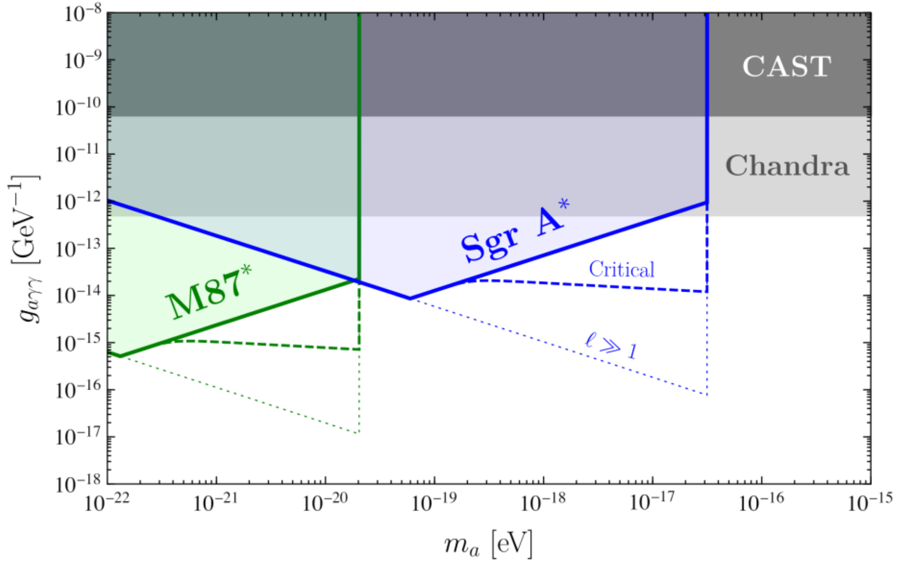
- The axion induced polarization angle is oscillating at the frequency of axion mass (10^{-20} eV is about 1/day.).
- The oscillating polarization angle is correlated because $a(r,t) = f_a \Theta(r) \cos(\omega t)$ and $\Theta = \Theta_0 e^{-GM_{BH} m_a^2 r}$ is nearly a constant for most of the part.
- The modulation of polarization contains information about the axion mass.

New Axion Limits

We obtain the most competitive axion limit at this mass range, assuming axion as the dark matter, conservatively using a polarization measurement precision of 3°.

The dashed curves show a slightly stronger bound with an enhanced formation rate with axion self-interactions.

The dotted curves ignores the decay rate of axion stars, which requires nonzero angular momentum.



A signal for axions?

A rotation on the polarization angle with a period of 70 mins is observed (correspond to axion mass of 10^{-18} eV.

It is interpreted as a hot spot orbiting around the accretion disk with a orbital radius ~ 5 Schwarzschild radii.

Axions can produce similar signals. However, there is a similar periodicity on the gamma ray flux density, which makes the axion interpretation unlikely (axion is a small perturbation to the flux).

A 76 minute γ-ray periodicity in Sagittarius A*

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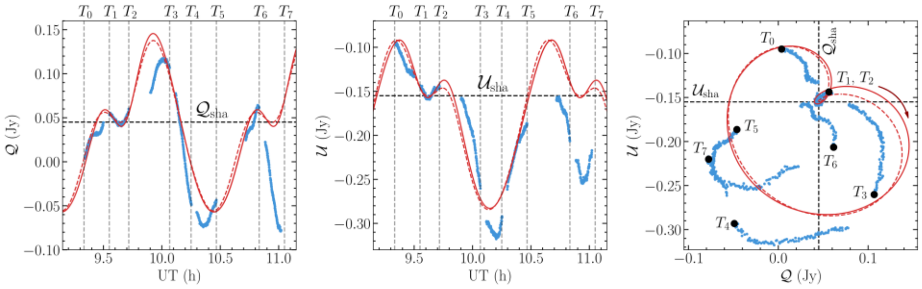
(Dated: November 13, 2023)

Orbital motion near Sagittarius A*

Constraints from polarimetric ALMA observations

M. Wielgus[1,2,3], M. Moscibrodzka[4], J. Vos[4], Z. Gelles[5,3], I. Martí-Vidal[6,7], J. Farah[8,9], N. Marchili[10,1], C. Goddi[11,12], and H. Messias[13]



Possible caveats

- Self-interaction that leads to the collapse of axion stars.
- Alignment between the location of SMBHs and dark matter peak needed?
- Excited states of axion stars may make the bound stronger due to the suppression on the decay rate.

What’s next?

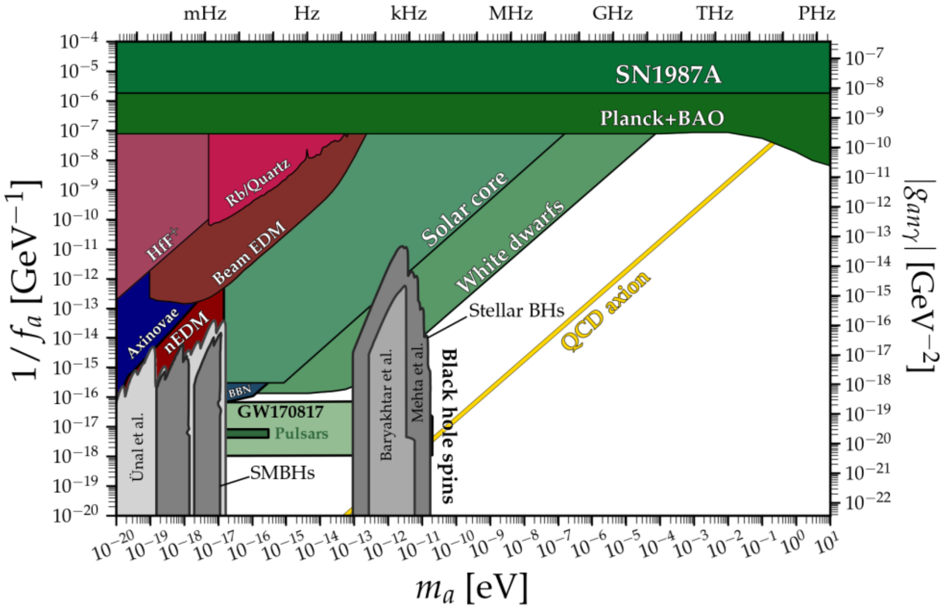
- On the theoretical side, dedicated numerical simulations will be useful to accurately calculate the rate of axion star formation and obtain a more realistic profile of axion stars.
- On the observational side, data analysis with time-varying cross-correlation on the polarization pattern near SMBHs will further enhance the sensitivity and lead to more stringent limit. Combine both the accretion disk and jet may give us more information.
- The observation of SMBHs, from polarimetry and potentially from gravitational waves will be complementary to each other and enable more discovery opportunities.

Conclusions

- Polarization measurements have been commonly used to constrain axion-photon couplings
- Black hole polarimetry will be power tools with current and upcoming observations of EHT targets.
- The formation of axion stars further enchances the sensivitiy of black hole polarimetry because a large field value is developed near supermassive blackholes.
- There are a lot of future theory and experimental opportunities in this direction for axion detection.

New axion limits from axion star collapse

Without considering supermassive black holes, the axion star collapse already lead to interesting constraints on axion parameters.



The condensation timescale of axion stars

Numerical studies found that the timescale of axion star formation can be well approximated by the relaxation timescale

$$\tau \sim (f_{BE} n \sigma v)^{-1}$$

The phase space density is $f_{BE} = 6\pi^2 n\,(m_a v)^{-3}$

The timescale is $\tau_{gr} \approx \frac{1}{48\pi^3} \frac{m_a v^6}{G^2 n^2 \ln(m_a v\, R)}$

Therefore, it is crucial to determine the characteristic velocity and density of the dark matter environments. It is surprising that the analytic prediction works so well. It suggests that the average "collision" timescale is comparable to the formation timescale of axion stars.

The mass growth

Numerical studies found the initial mass of axion stars is well approximated by a characteristic mass where the star virial velocity is equal to the halo virial velocity

$$M_{*0} \approx 3\rho_a^{1/6} G^{-1/2} m_a^{-1} M_h^{1/3}$$

The growth rate of axion stars can be write as

$$\frac{dM_*}{dt} = \frac{M_{*0}^2}{M_*}\frac{1}{\tau} - M_*\Gamma_{\mathrm{decay}}$$

This formula is still subject to numerical uncertainties and it is an active area of research now in axion simulations. The decay term is owing to the SMBH but not present for self-gravitating axion stars.