Probing Axions with Event Horizon Telescope Polarimetric Measurements

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Yifan Chen, Jing Shu, Xiao Xue,
Qiang Yuan, and Y.Z.
arXiv:1905.02213 [hep-ph]
Phys.Rev.Lett. 124 (2020) 6, 061102

Y. Chen, Y. Liu, R. Lu, Y. Mizuno,
J. Shu, X. Xue, Q. Yuan, Y.Z.
arXiv:2105.04572 [hep-ph]
Nature Astron. 6 (2022) 5, 592-598

Y. Chen, et. al.
arXiv:2208.05724 [hep-ph]
JCAP09(2022)073

Yifan Chen, et. al.
On-going work

Left-over problems:

- The identity of dark matter
- Gauge hierarchy problem
- Strong CP problem → QCD axion
- The identity of inflaton field
- Baryogenesis
- Cosmological constant

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Left-over problems:

- The identity of dark matter → misalignment mechanism
- Gauge hierarchy problem → relaxion
- Strong CP problem → QCD axion
- The identity of inflaton field
- Baryogenesis
- Cosmological constant

(The identity of inflaton field, Baryogenesis, Cosmological constant) can be related to axion

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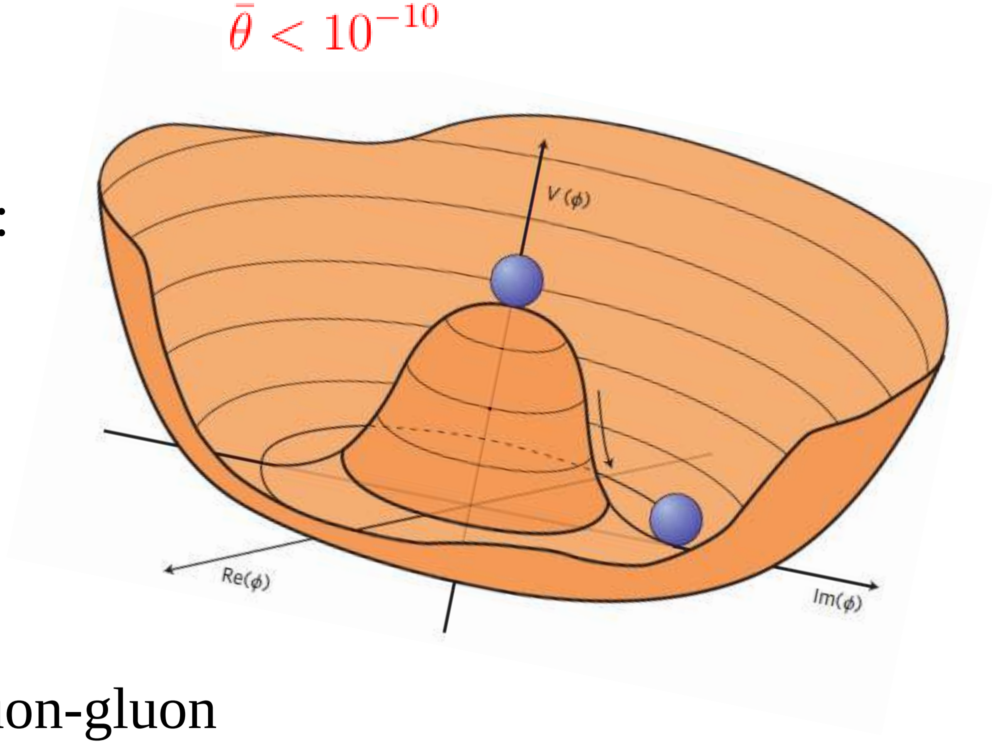
Theory motivations:

Strong CP-problem:

$$\underbrace{(\theta - \arg\det M_q)}_{\bar\theta < 10^{-10}}\frac{\alpha_s}{8\pi}G\tilde{G}$$

Introduce axion field:



Couplings:

axion-gluon-gluon
axion-photon-photon
axion-fermion-fermion

Search strategies:

- axion-gluon-gluon coupling:

  CASPEr (DM)
  axion phase transition inside neutron stars

- axion-photon-photon coupling:

  ADMX (DM)
  CAST
  ALPS
  X-ray (Chandra, IXPE, Polstar)

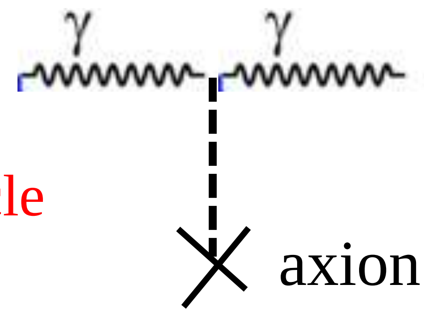
- axion-fermion-fermion coupling:

  stellar cooling
  absorption in superconductor (DM)

Search strategies:

- axion induced birefringent effect (Harari & Sikivie 92)

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



The condensation of a CP-odd particle distinguishes helicities of a photon

$$\Rightarrow \quad \Box A_{\pm} = \pm 2ig_{a\gamma}[\partial_z a\dot{A}_{\pm} - \dot{a}\partial_z A_{\pm}]$$

- Only the derivatives on the axion background can change photon’s EoM.
- The modifications are opposite for different helicity.

Search strategies:

- axion induced birefringent effect

$$\omega_\pm \simeq k \mp 2g_{a\gamma}(\partial a/\partial t + \partial_z a)$$

different phase velocities for +/- helicities

A linearly polarized photon can be decomposed into the super-position of photons with +/- helicities.

⇨ change of position angle

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

Search strategies:

A region with:

a concentration of axion field

axion field is an oscillating background field

+ source for linearly polarized photon

the position angle, at emission, should be stable

Search for:

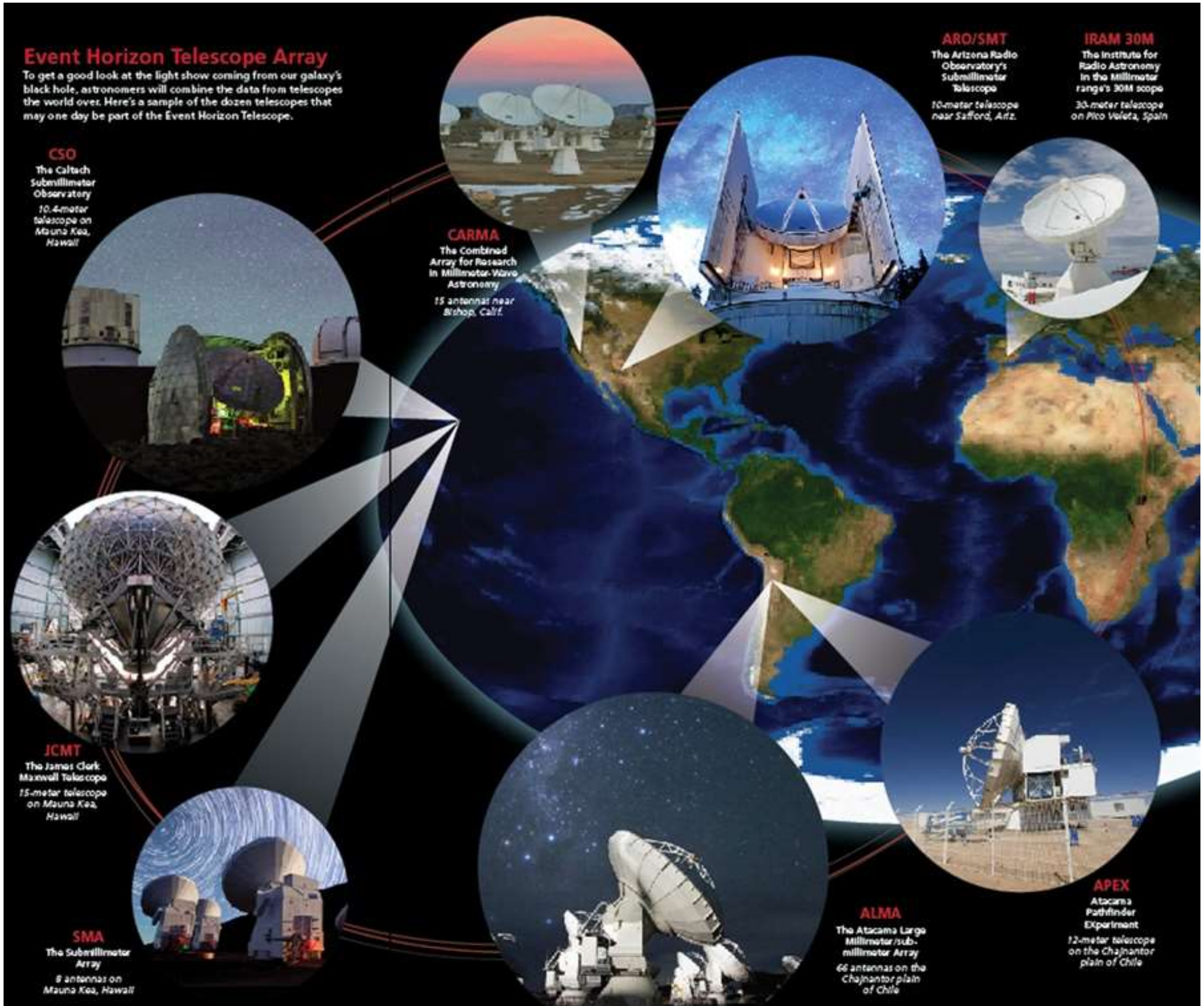
- position angle oscillates with time

- study the axion induced position angle change as a function of spatial distribution. (extended light source)

Scenarios: EHT-SMBH & pulsars measurements

Tao Liu, George Smoot, Y.Z.
arXiv:1901.10981 [astro-ph.CO]
Phys.Rev.D 101 (2020) 6, 063012

Event Horizon Telescope:



telescope array at radio frequency around the Earth

Event Horizon Telescope:

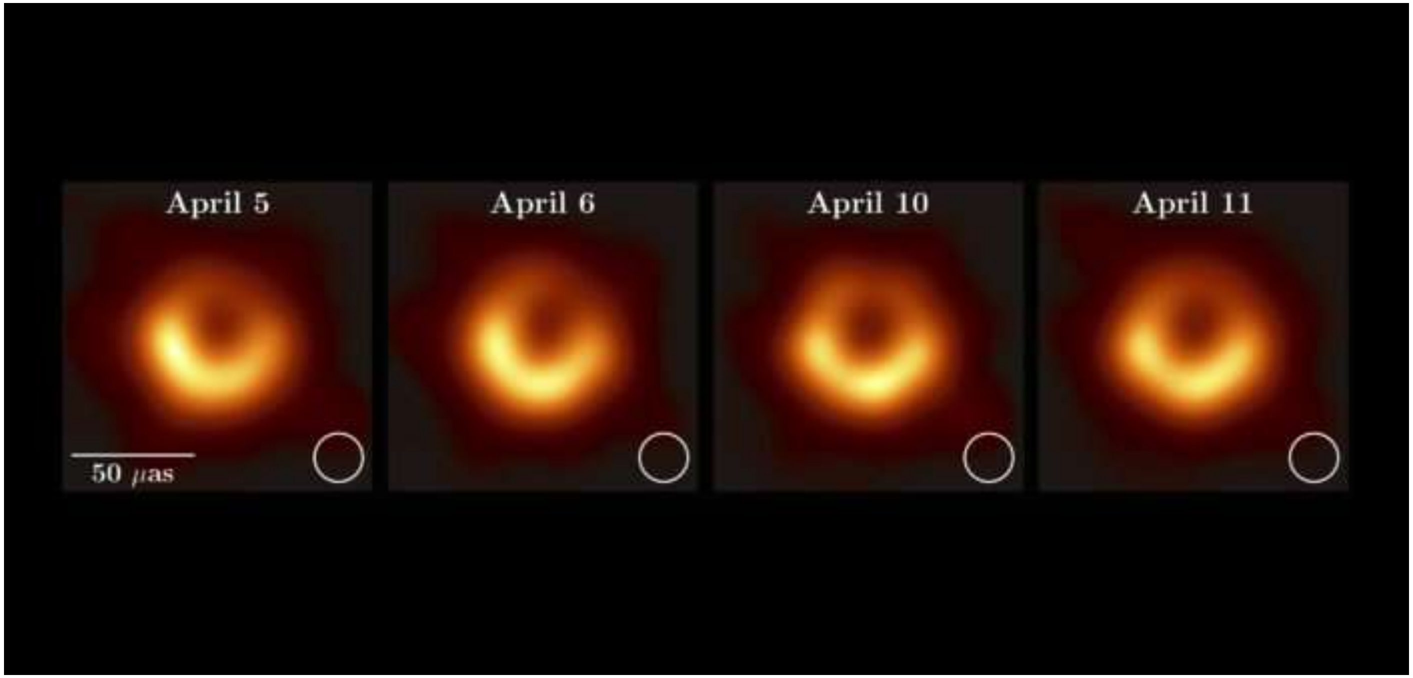
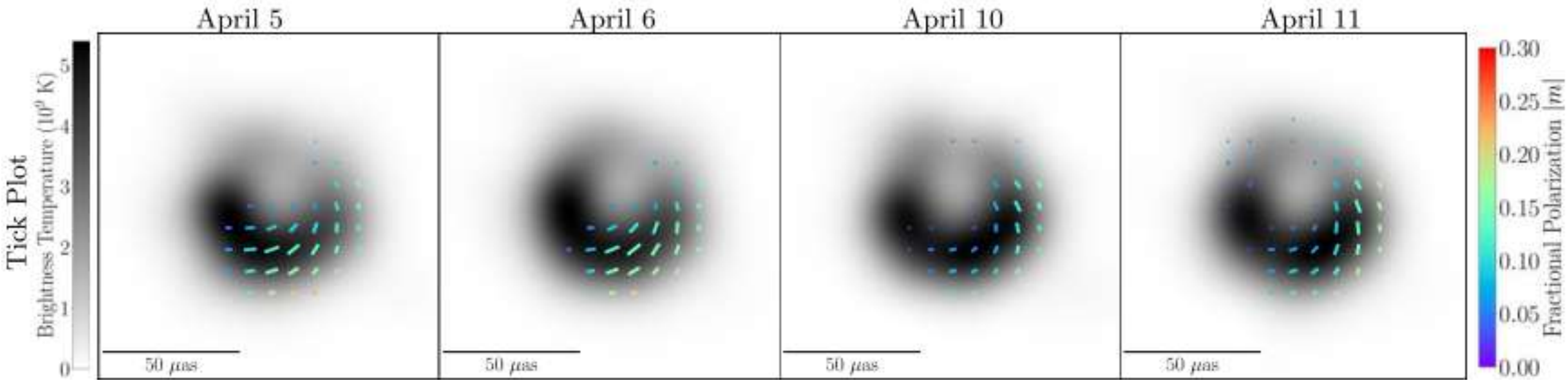
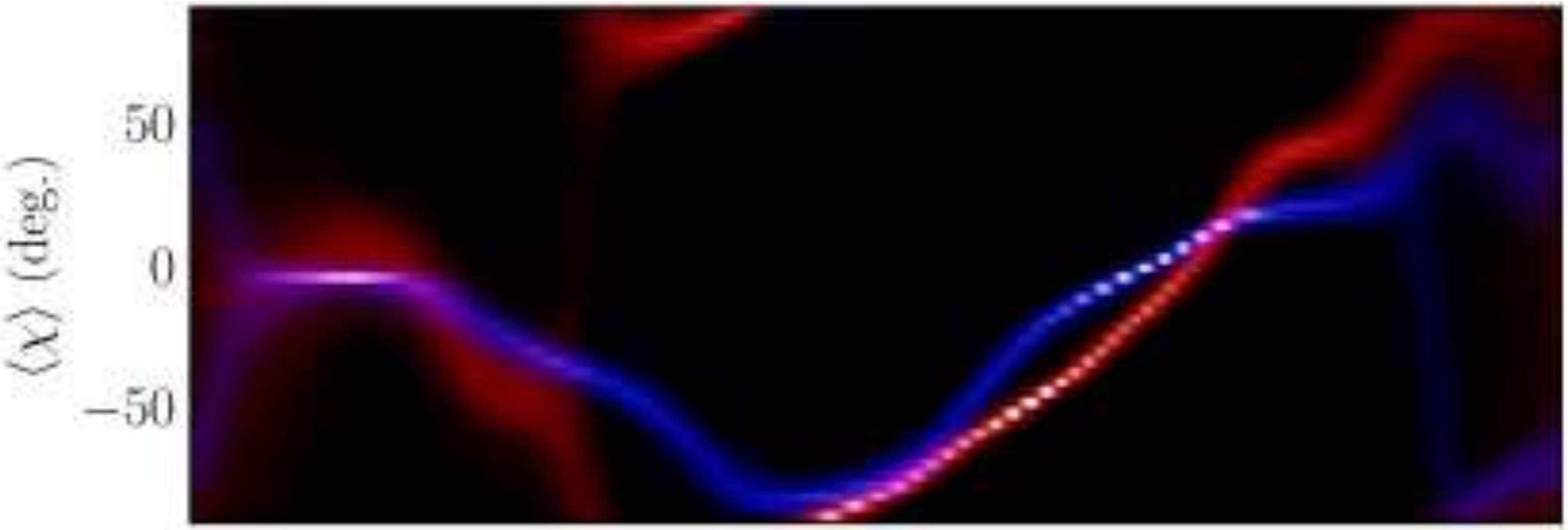


Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.

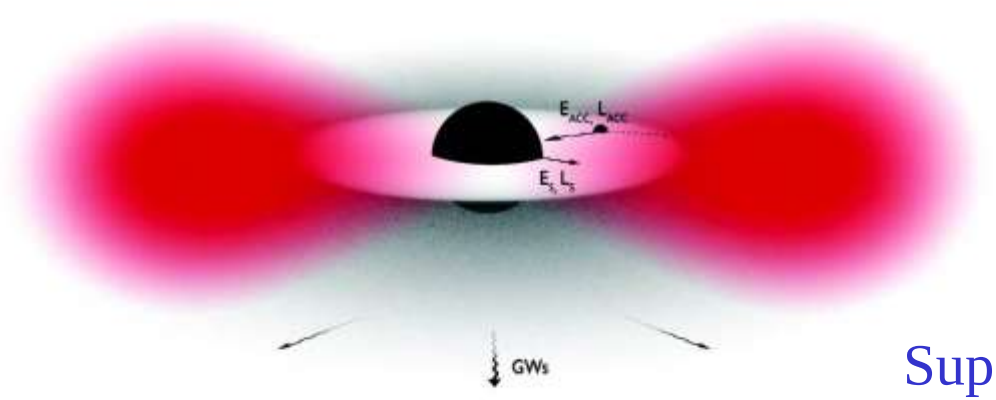
Event Horizon Telescope:

EHT Collaboration (2021)





Black hole superradiance:



Superradiance condition

$$\omega < \omega_c = \frac{a_J m}{2 r_+}$$

When $\lambda_a \sim GM$:

a rapidly rotating black hole loses:

energy + angular momentum

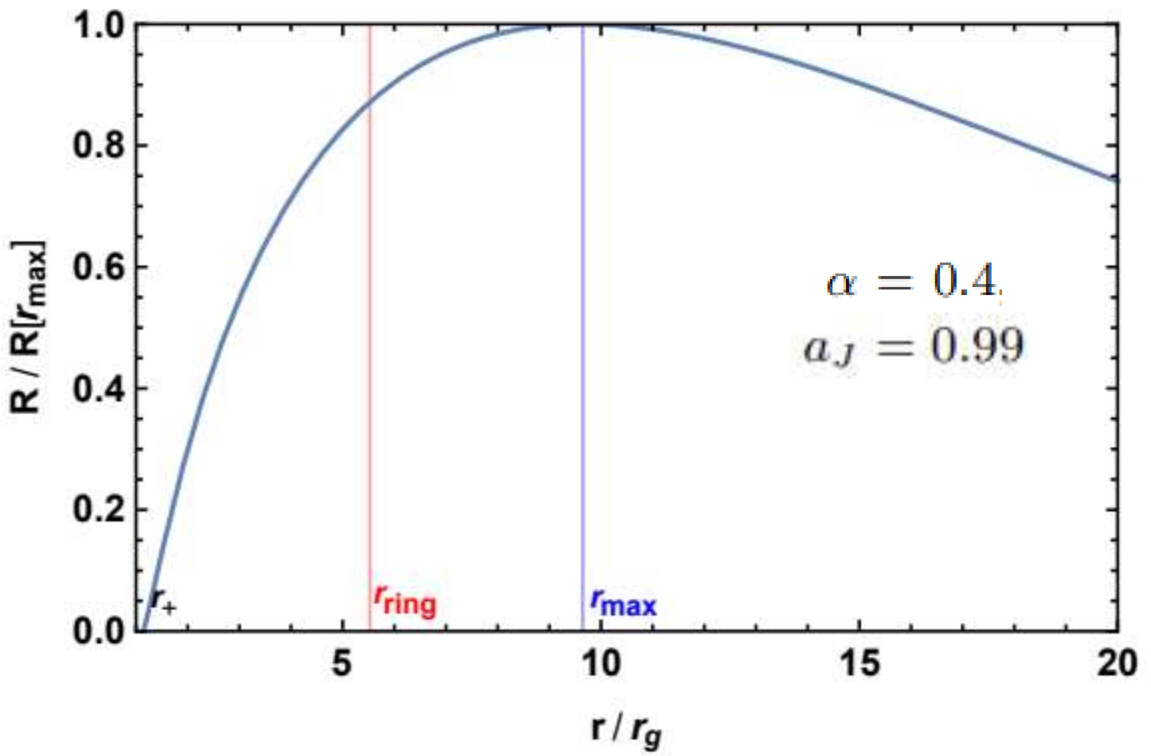
axion cloud will be produced around BH

Energy in axion cloud can be comparable to BH mass!

Black hole superradiance:

The ring from EHT has a radius comparable to the peaking radius of the axion cloud

$$r_\pm = r_g \left(1 \pm \sqrt{1 - a_J^2}\right)$$



Axion cloud in non-linear region:

axion Lagrangian including self-interaction:

$$S = \int d^4x\sqrt{-g}[-\frac{1}{2}(\nabla a)^2 - \mu^2 f_a^2(1-\cos\frac{a}{f_a})]$$

take

$$a = \frac{1}{\sqrt{2\mu}}(e^{-i\mu t}\psi + e^{i\mu t}\psi^*)$$

ψ^*: slowly varying function

non-relativistic limit:

$$S_{\rm NR} = \int d^4x\left(i\psi^*\partial_t\psi - \frac{1}{2\mu}\partial_i\psi\partial_i\psi^* - \frac{\alpha}{r}\psi^*\psi + \frac{(\psi^*\psi)^2}{16f_a^2}\right)$$

$\frac{\alpha}{r}\psi^*\psi$: gravitational potential

$\frac{(\psi^*\psi)^2}{16f_a^2}$: leading self-potential term

Hidetoshi Omiya's talk

Axion cloud in non-linear region:

axion self-interaction becomes important when

gravitational potential ~ self-interaction potential

$$\frac{\alpha}{r} \simeq \frac{\mu a_0^2}{4 f_a^2}$$

two possible consequences:

bosenova: a drastic process which explodes away axion cloud

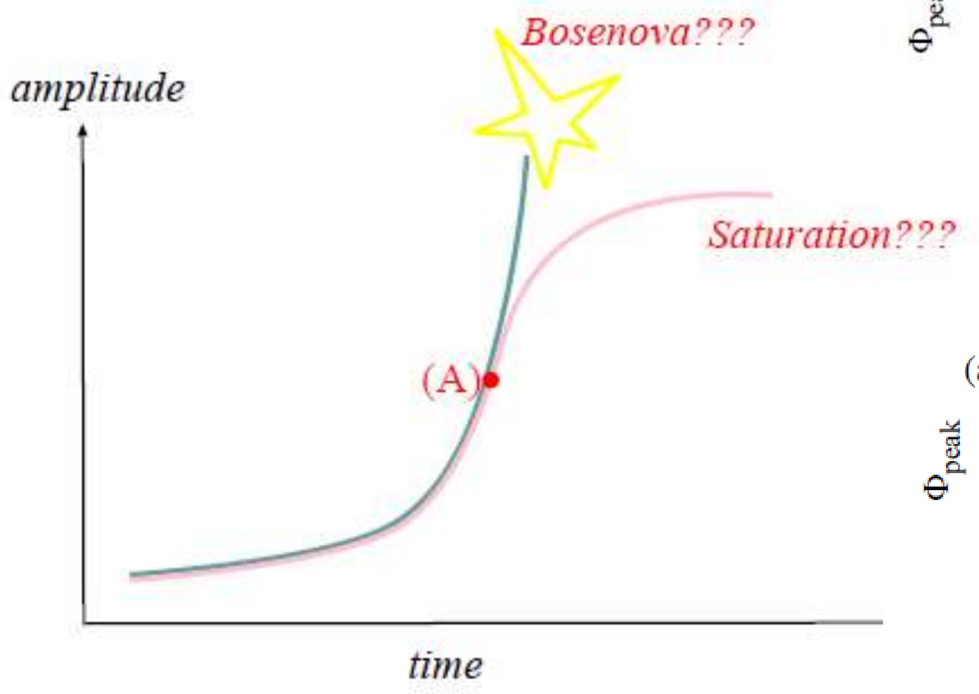
steady axion outflow to infinity

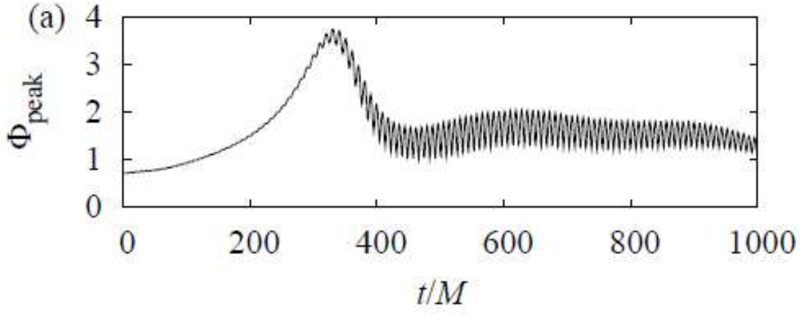
numerical simulation has been performed:

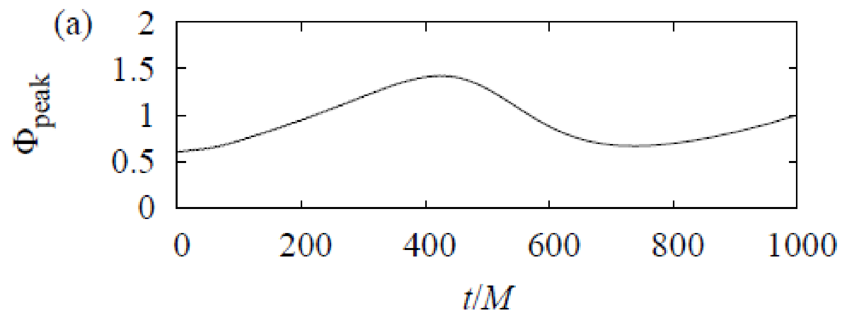
H. Yoshino and H. Kodama, Prog. Theor. Phys. 128, 153 (2012), etc

Hidetoshi Omiya’s talk

Axion cloud in non-linear region:







In either scenario, the amplitude of the axion cloud remains O(1) of its maximal value for most of the time

$$\frac{a}{f_a} \sim O(1)$$

Axion cloud induced position angle change:

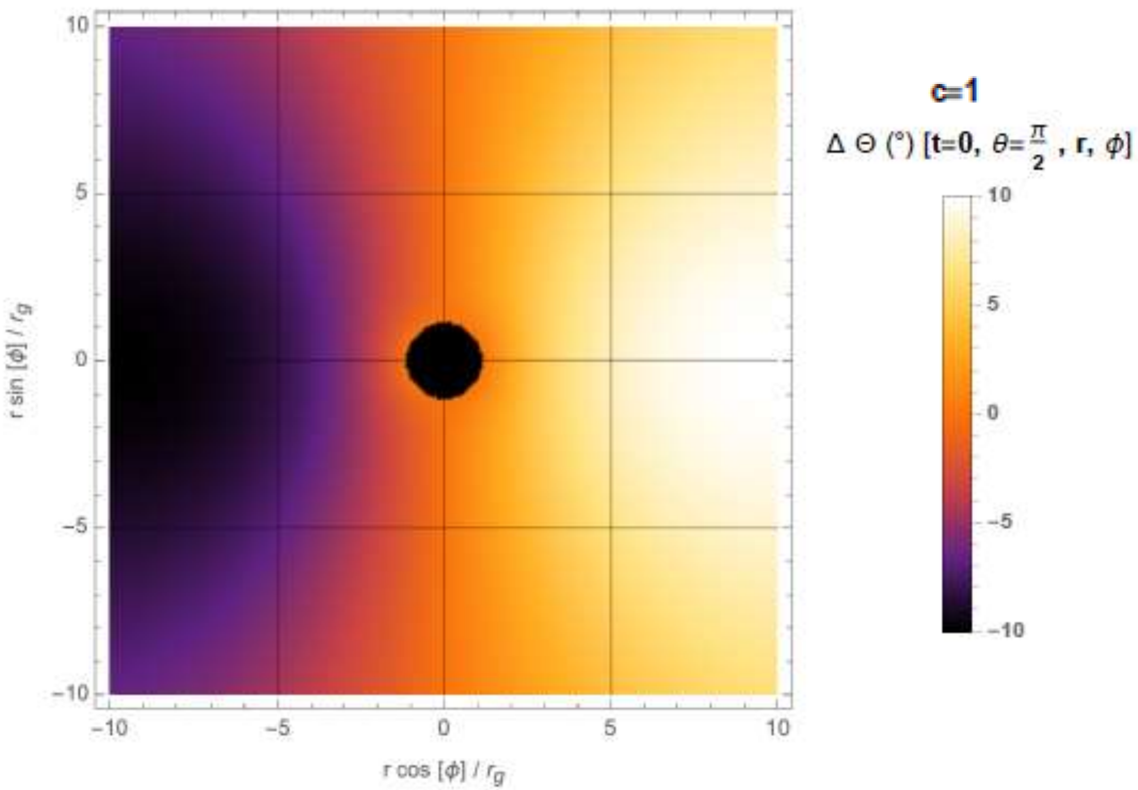
$$b \equiv a_{max}/f_a$$

$$g_{a\gamma} = \frac{\alpha_{em} N}{4\pi f_a} = \frac{c}{2\pi f_a}$$

additional loop suppression to
translate f_a to axion-photon coupling

$$\Delta\Theta(r_{max}) \simeq -\frac{bc}{2\pi} \cos\left[\mu\, t_{emit} + \beta(|\mathbf{x}_{emit}| = r_{max})\right]$$

Axion cloud induced position angle change:

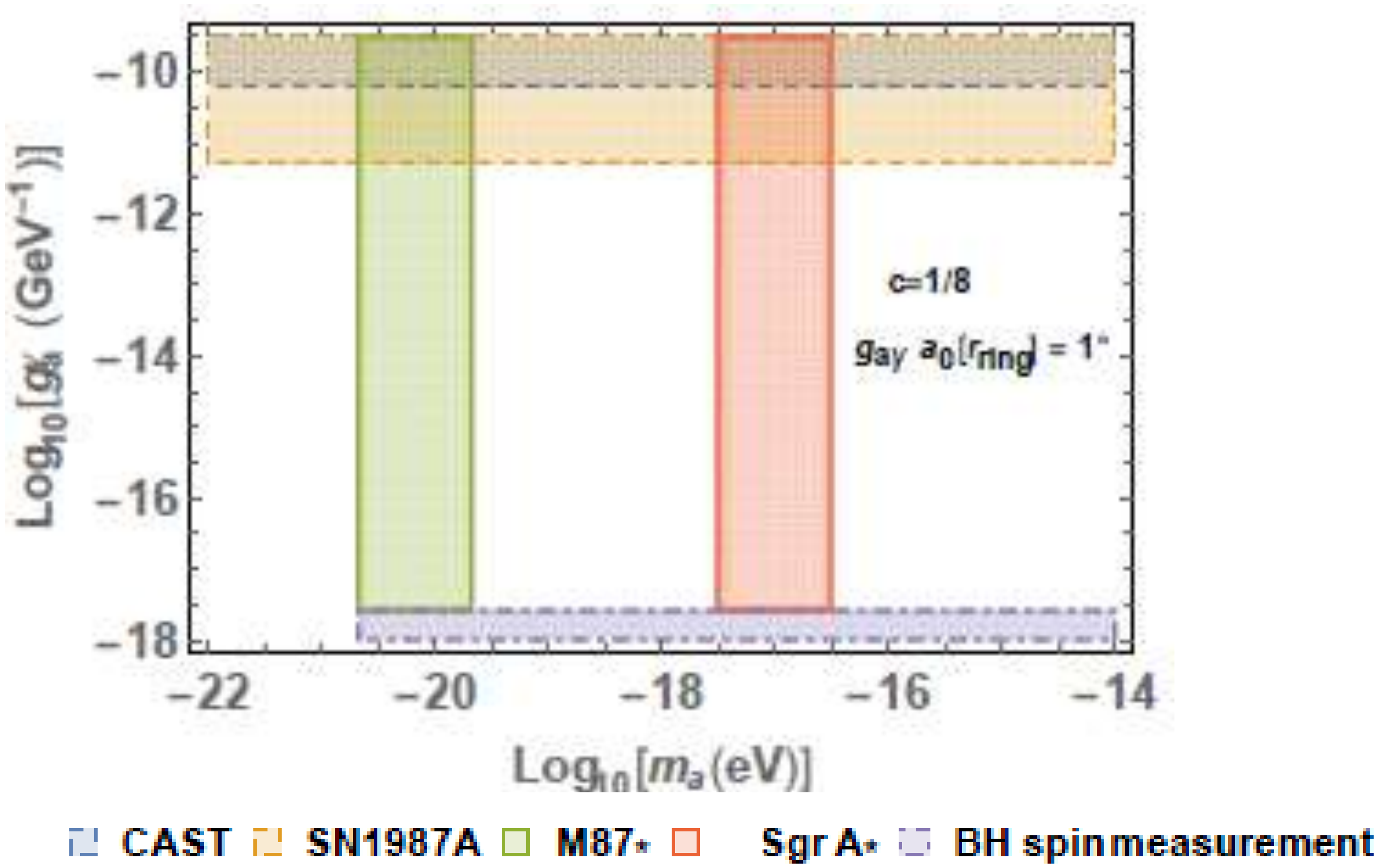


- temporal dependence for a fixed position
- spatial dependence for a fixed time

FIG. 2: $\Delta\Theta(t = 0, \theta = \frac{\pi}{2}, r, \phi)$ assuming the rotation axis is towards the observer. The amplitude of oscillation is around 8° at r_{ring} with $l = 1, m = 1$ state, $\alpha = 0.4$, $a_J = 0.99$, excluding the region for $r < r_+$. The time evolution is equivalent to the rotation around ϕ.

EHT expected sensitivity:

Yifan Chen, Jing Shu, Xiao Xue,
Qiang Yuan, and Y.Z.
Phys.Rev.Lett. 124 (2020) 6, 061102



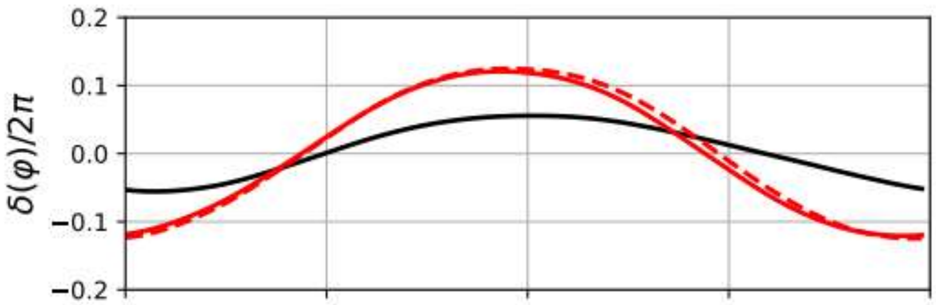
Improved Search Strategy

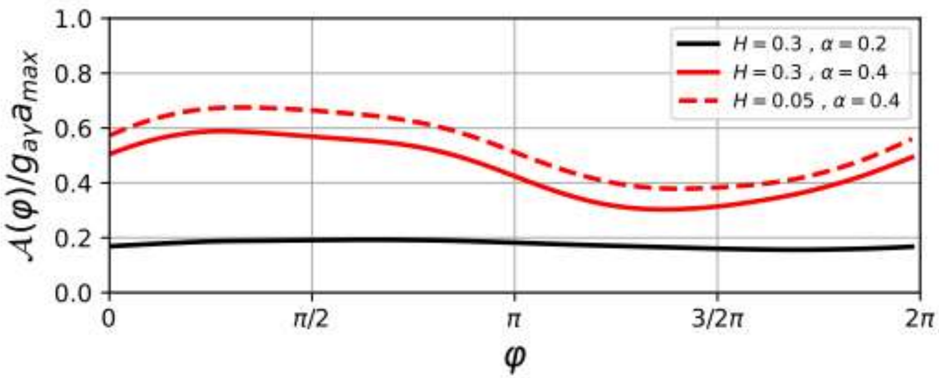
Group 4-day data into two pairs (4/5,4/6) and (4/10,4/11).

Calculate the change of position angle, $\Delta\chi(\phi)$, for each pair.

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

The $\Delta\chi(\phi)$ calculated for each pair is related by a simple phase shift.

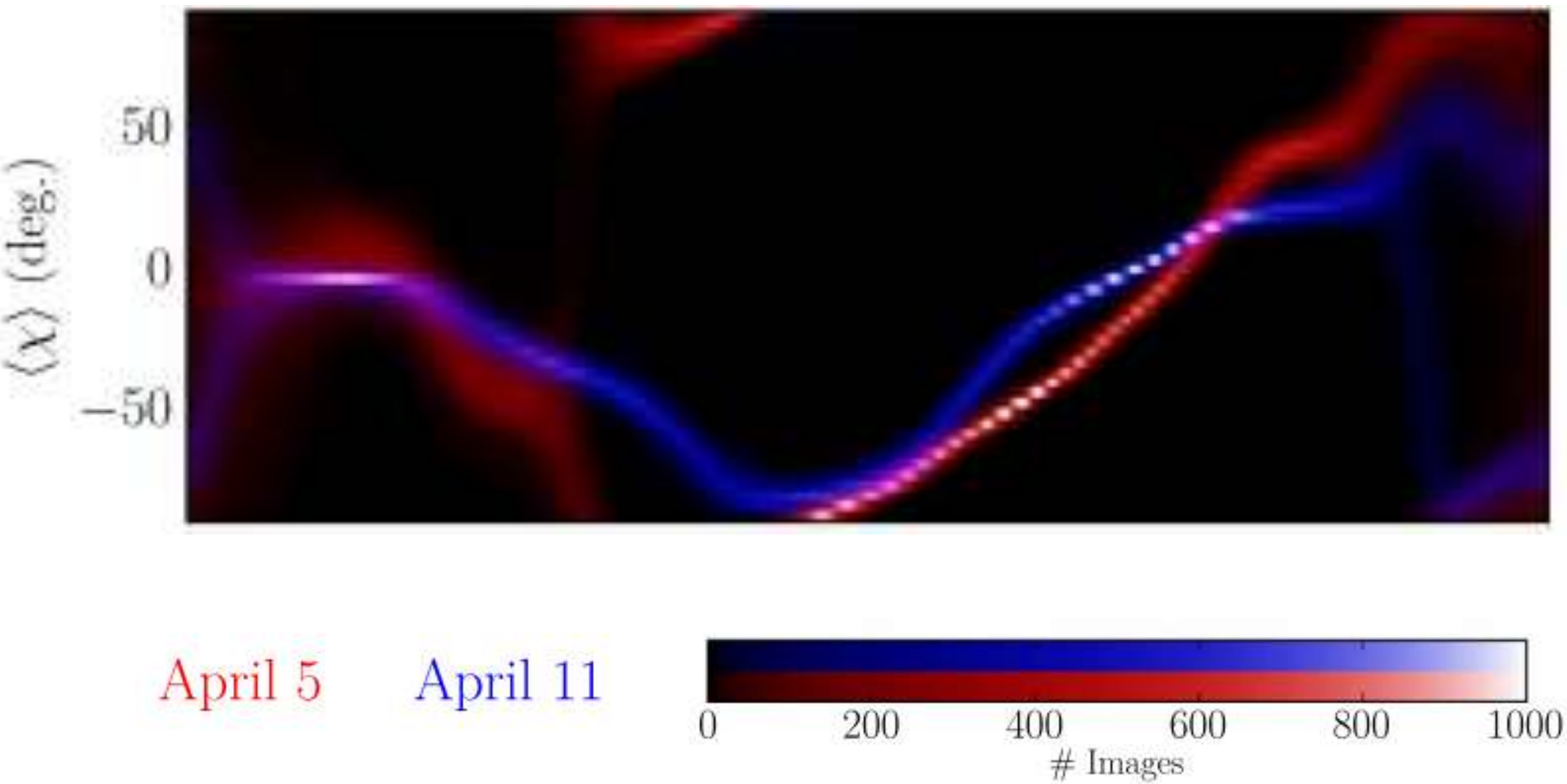




BH spin = 0.99
analytic RIAF using IPOLE,
the vertical magnetic field and sub-Keplerian velocity distribution

Event Horizon Telescope Results:

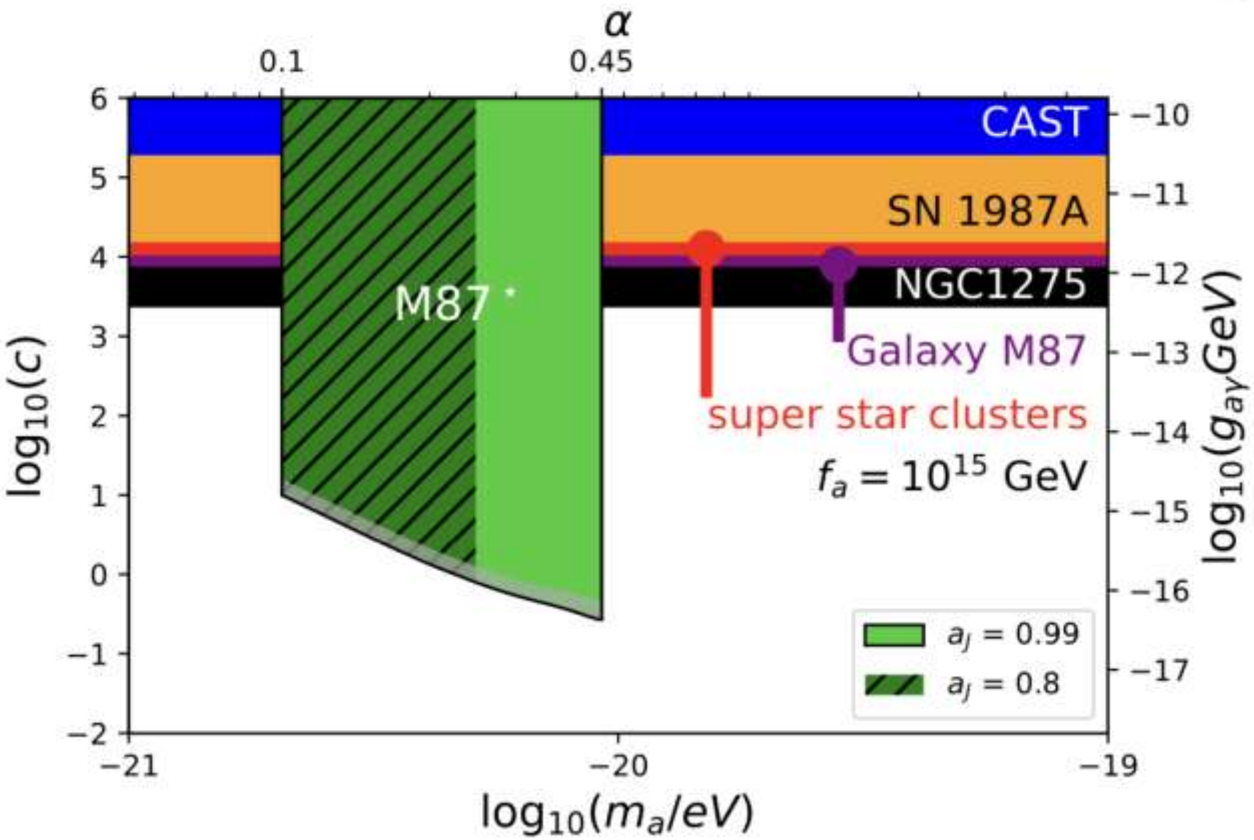
Polsolve method:



Intensity-weighted averages within an angular section of a width of 10°

Results

$$g_{a\gamma} = \frac{c}{2\pi f_a}$$



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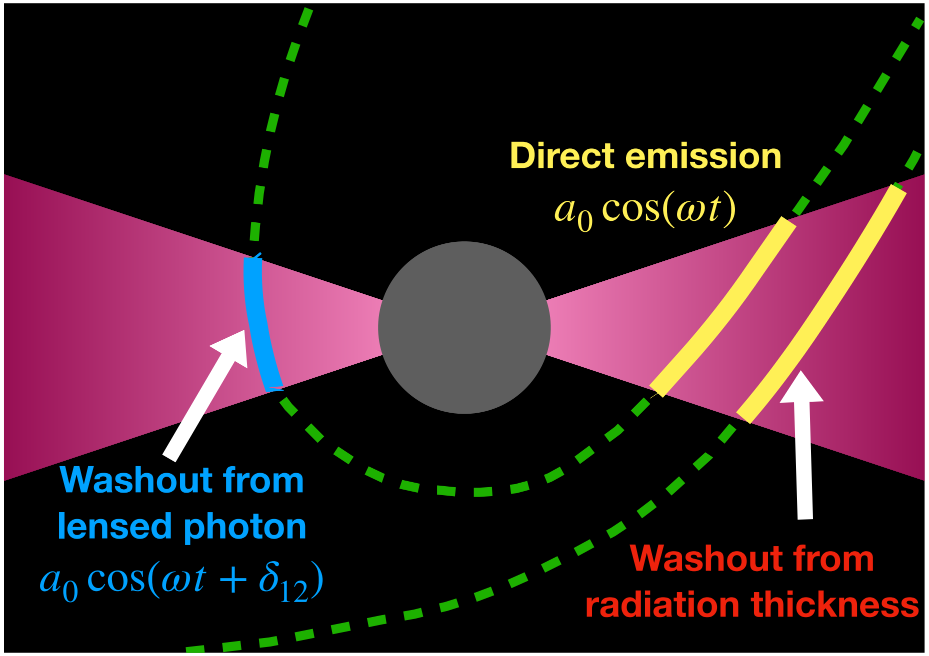
Nature Astron. 6 (2022) 5, 592-598

Wash-out effect

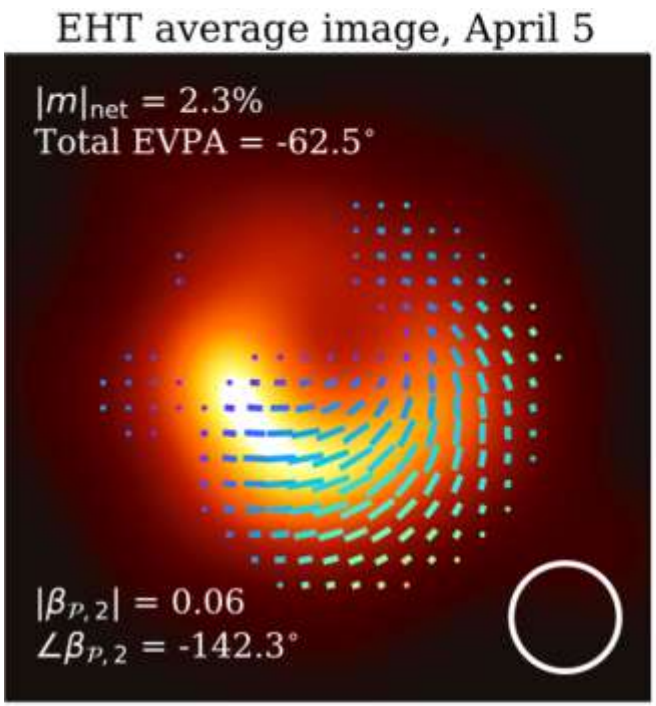
- Incoherent photons average out some of the axion effect
- Lensed photon travels through the accretion flow for more times. Thus, it gains more wash out.

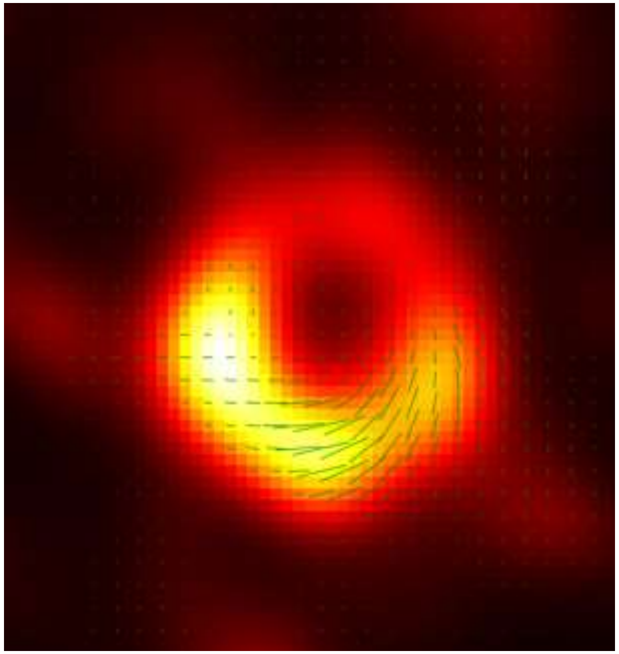


EVPA after intensity-weighted averages:
a mixture of best signal region and the worst noise region

Optimization: breaking into smaller pixels

Reconstructing the polarization map:



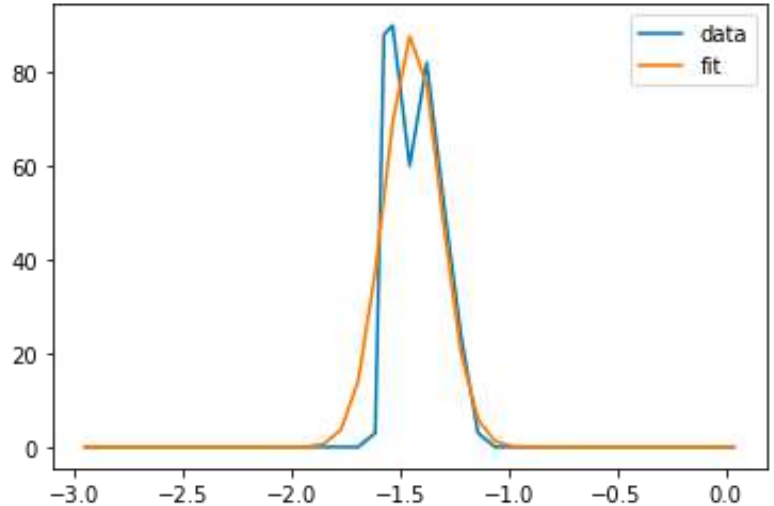


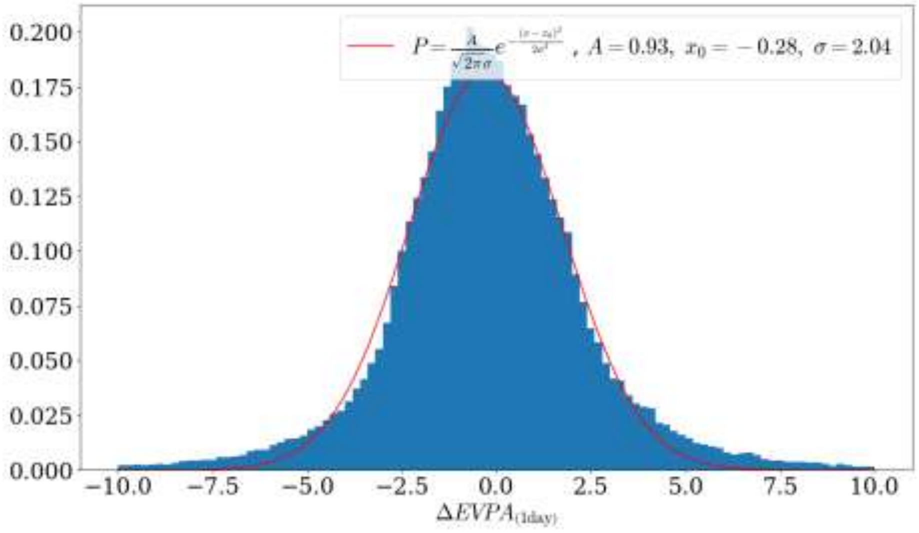
Optimization: breaking into smaller pixels

Understanding the uncertainties:

Reconstruct EVPA for each pixel.
(ensembled within the top set)

Differential EVPA predicted by GRMHD averaged over pixels and top set.

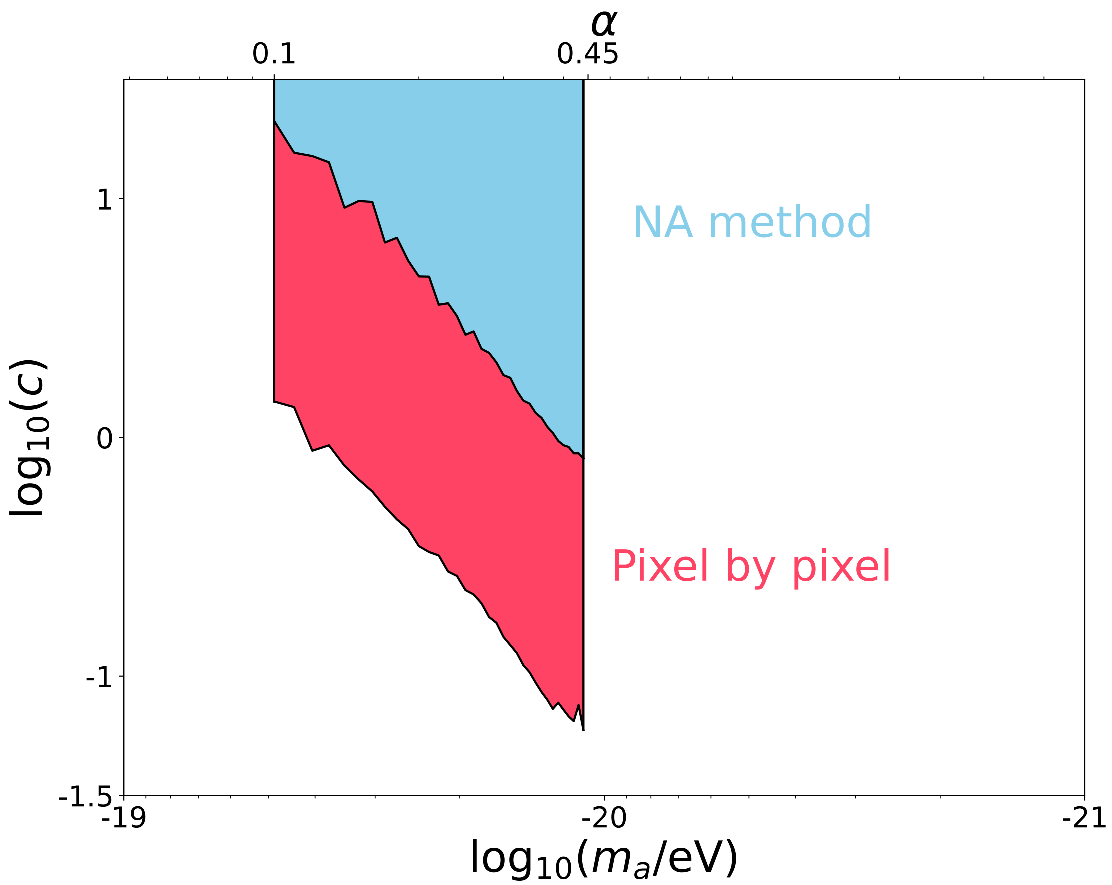




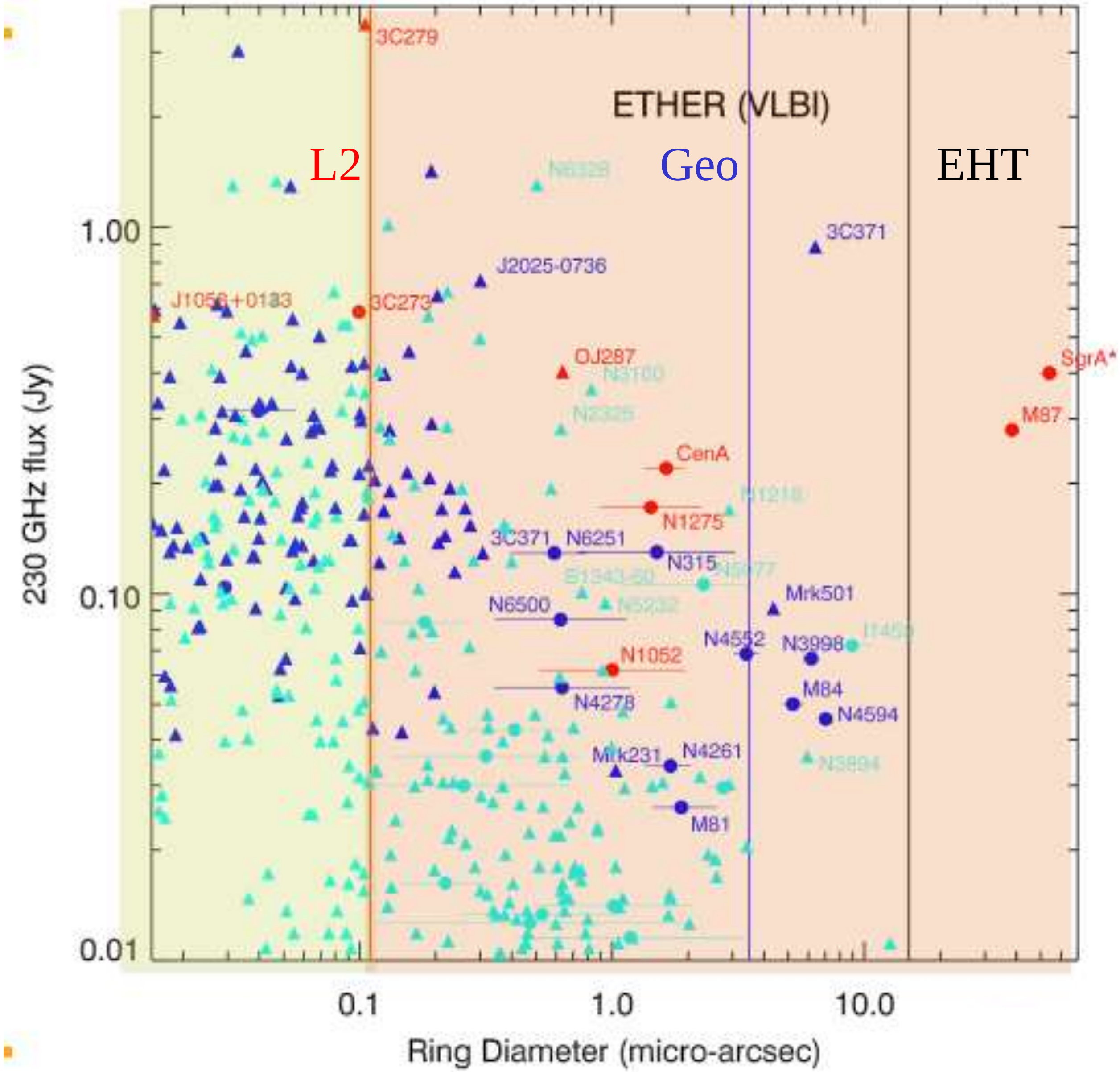
We only keep the pixels which can fit well as a Gaussian function.

Pixels are not independent:
We include the off-diagonal elements when we calculate the chi-square.

Optimization: breaking into smaller pixels!



Future


ETHER (VLBI)
L2
Geo
EHT
3C279
3C371
J2025-0736
J1058+0133
3C273
OJ287
SgrA*
M87
CenA
N1275
3C371
N6251
N315
Mrk501
N6500
N4552
N3998
N1052
M84
N4278
N4594
Mrk231
N4261
M81
1.00
0.10
0.01
0.1
1.0
10.0
230 GHz flux (Jy)
Ring Diameter (micro-arcsec)

Conclusion

Astrophysics provides excellent probes to search for axion!

Supermassive Black holes:

A dense axion cloud can build up near by SMBHs.

Accretion disk emits linearly polarized photons.

EHT resolves the fine features near SMBHs.

EHT can provide measurements on position angles.

⇨ Probe the existence of axion clouds by EHT.

Many potential improvements in the future:

Refined analysis, without the radial average.

Frequency dependence.

More SMBHs with ngEHT.

Axion dark matter:

Axion is an excellent DM candidate!

Can be produced by misalignment mechanism.

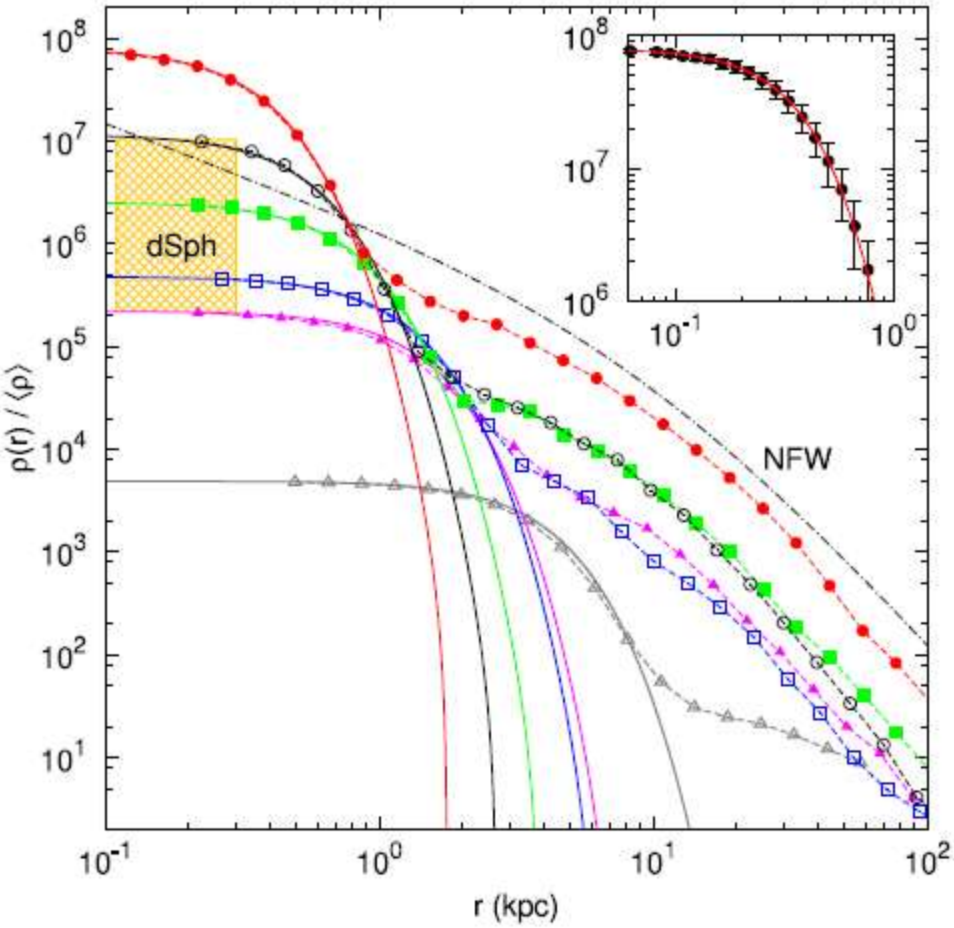
Ultralight axion DM is expected to have a soliton core.

Pulsars are commonly producing stable linearly polarized photons.

(Milli)-second pulsars may be largely populated near the galactic center.

⇨ Measurements on pulsar radiation provides an excellent tool to study axion DM.

Axion dark matter:



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

soliton solution

NFW profile

Pulsar measurements:

Most measurements are in radio-wave band.

Excellent on polarization measurements.

The properties of each pulse are not completely the same.

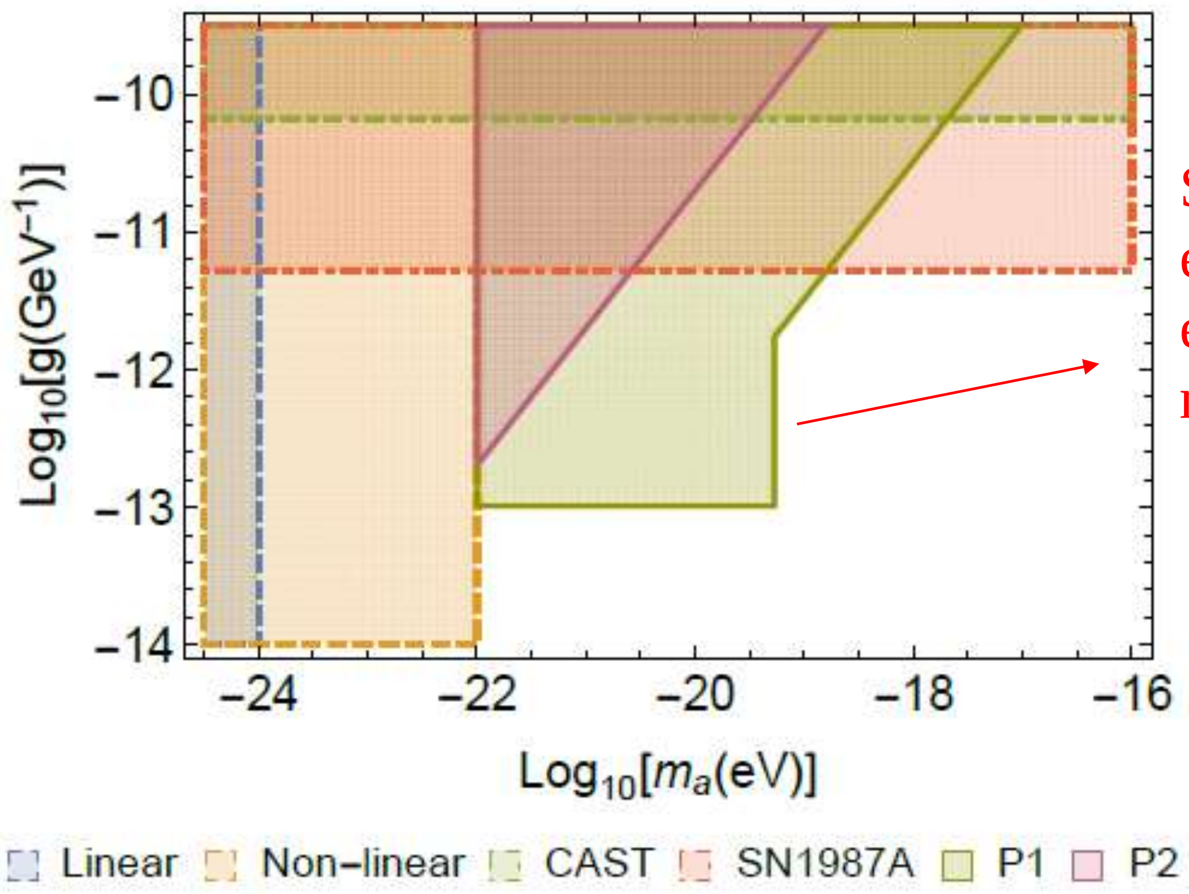
After averaging O(100) pulses, properties become stable.

Only a few pulsars are found near our galactic center.

VLA is expected to find many more.

Position angle accuracy ~ O(1) degree.

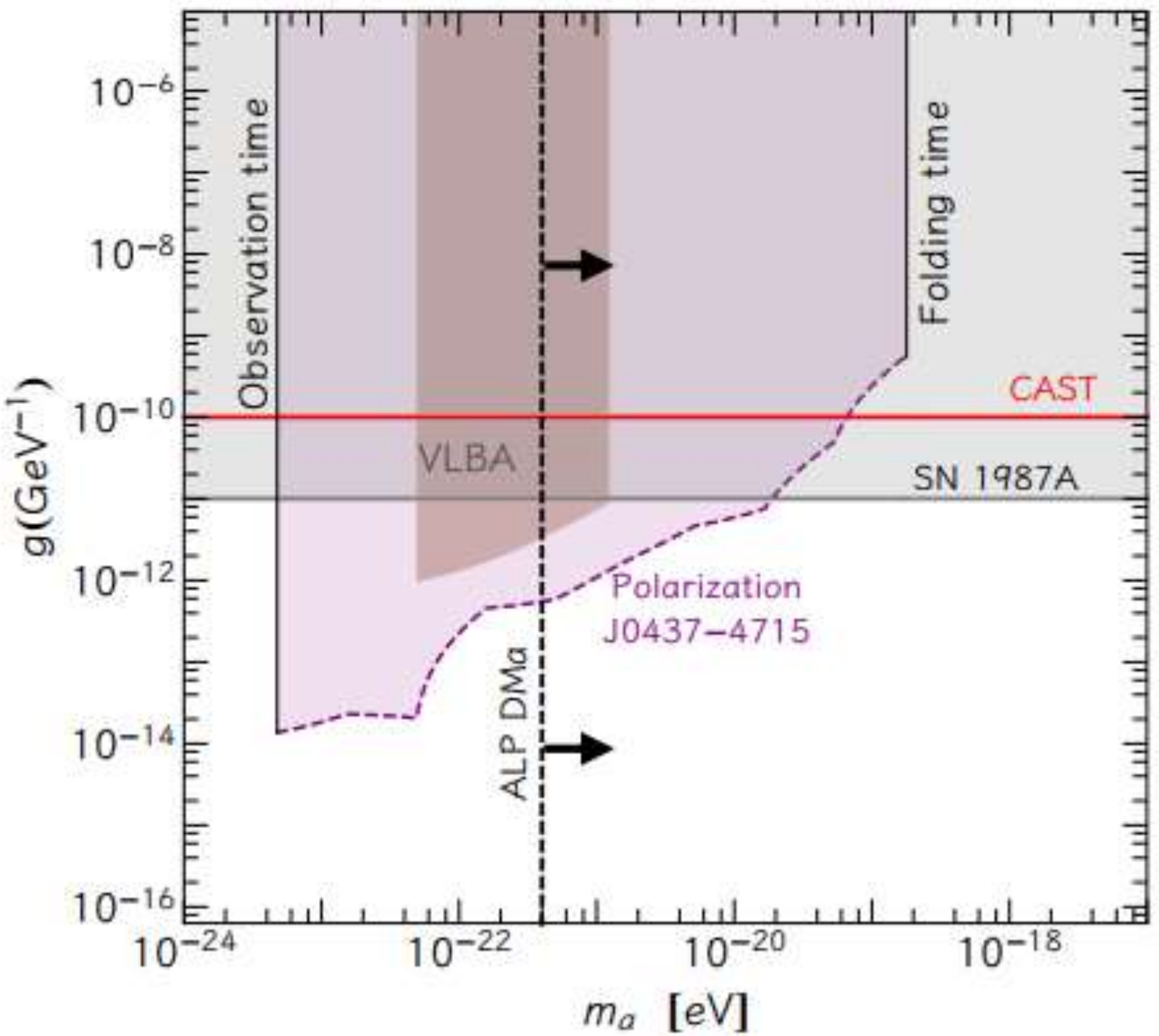
Sensitivity by pulsar measurements:



Significant enhancement is expected by correlating many pulsars.

	R_j (pc)	d_j (pc)	$m_{a,j}$ (eV)
P_1	1	8000	5.3×10^{-20}
P_2	7000	1000	7.5×10^{-24}

Sensitivity by pulsar measurements:



Conclusion

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Supermassive Black holes:

A dense axion cloud can build up near by SMBHs.

Accretion disk emits linearly polarized photons.

EHT resolves the fine features near SMBHs.

EHT can provide measurements on position angles.

⇨ Probe the existence of axion clouds by EHT.

Pulsars:

Axion DM is concentrated near galactic center.

Pulsars emits linearly polarized photons.

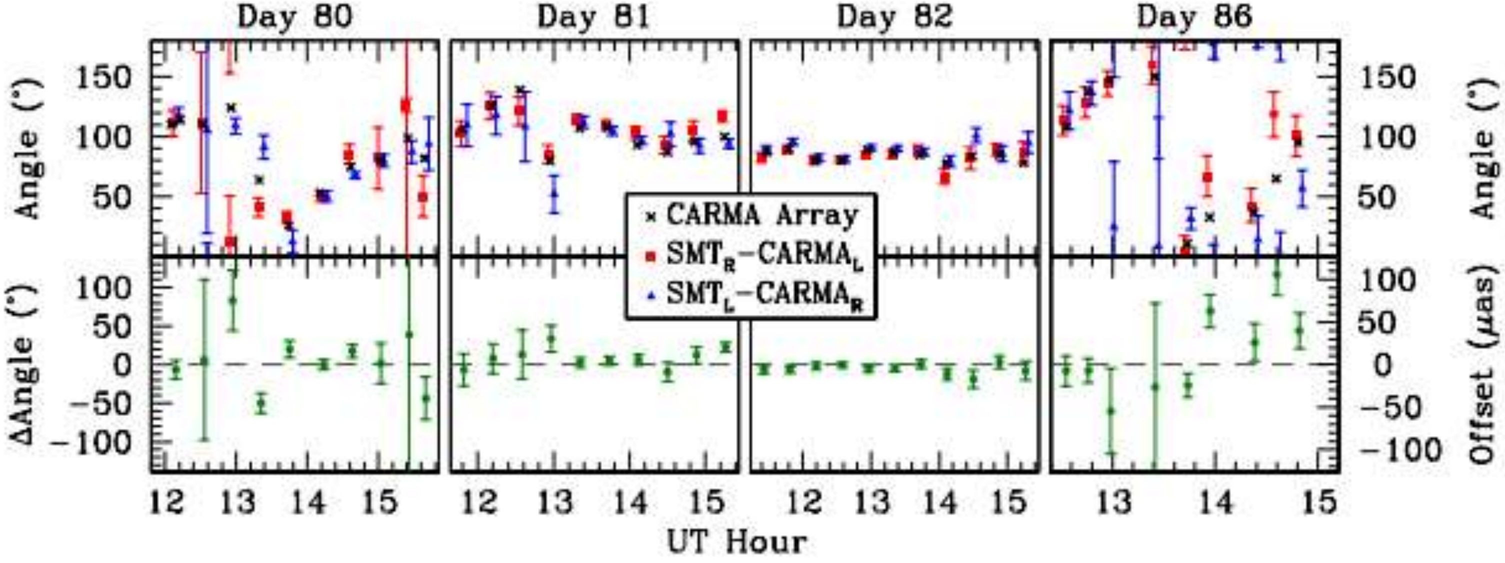
⇨ Probe axion DM by pulsar measurements.

Event Horizon Telescope:

Accretion disk around SMBH gives linearly polarized radiation.

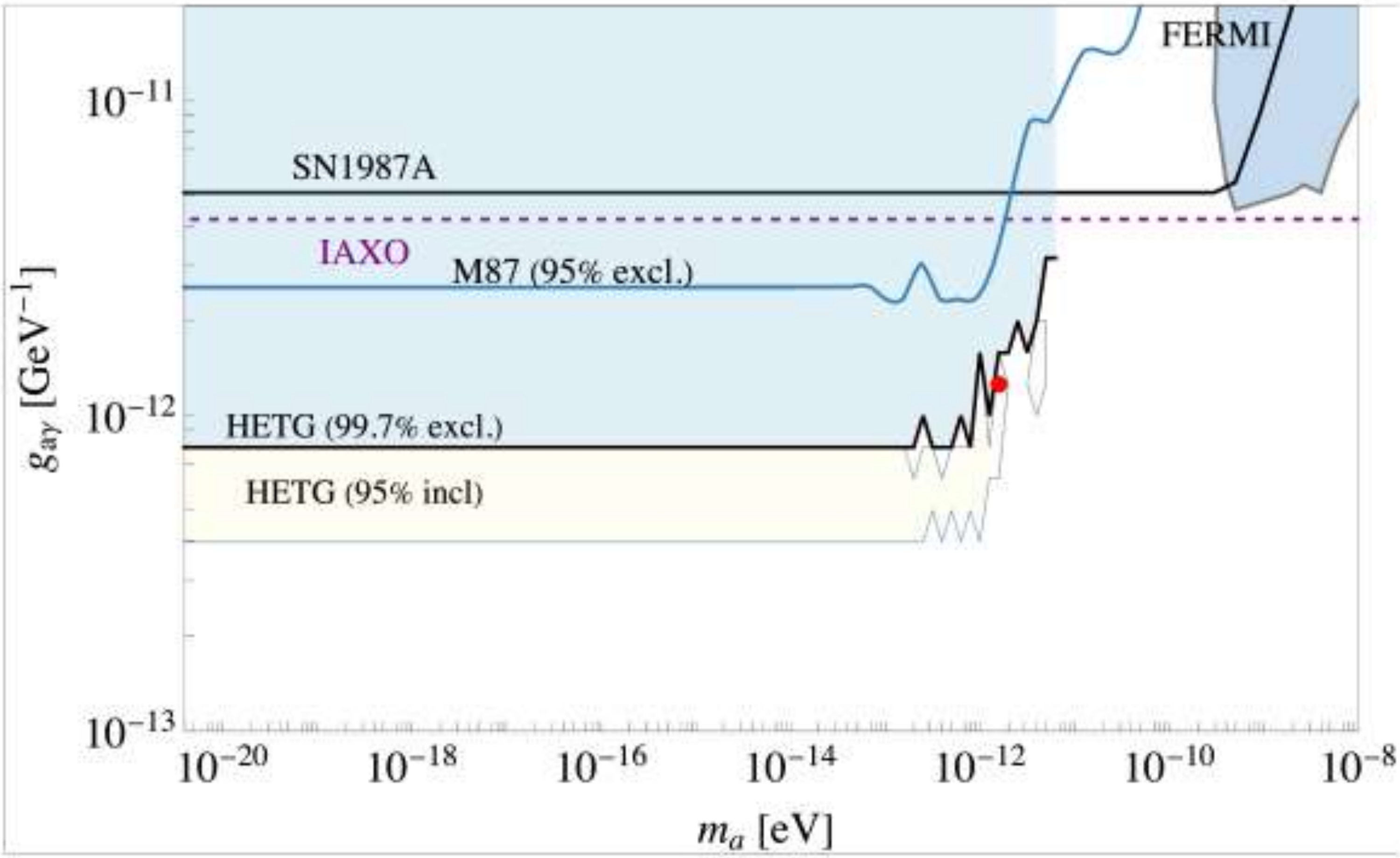
Millimeter wavelength: optimal for the position angle measurement!

measure Sgr A*



A subset of EHT has achieved a precision at 3 degrees!

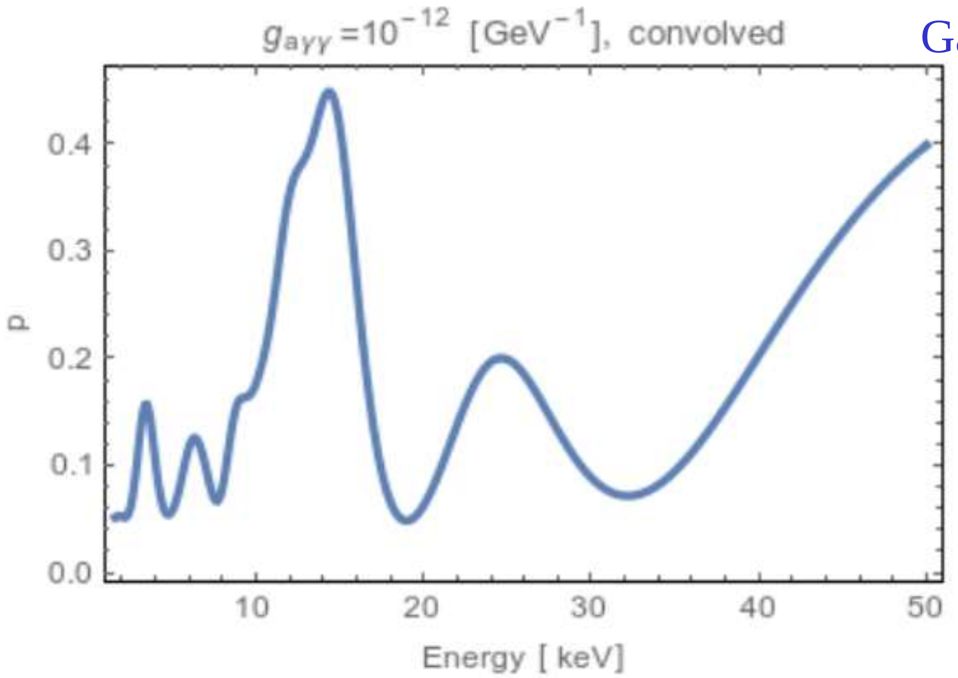
Photon-Axion Mixing



Photon-Axion Mixing

Photons can also gain polarization
when they propagate through a magnetic field:

NGC 1275 (IXPE, Polstar)
Galaxies 6 (2018) 2, 45



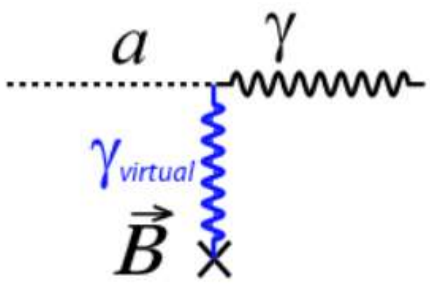
Linear polarization degree

One can use the amount of polarization to search for the existence of axion.

Photon-Axion Mixing

I n the presence of an external magnetic field,
photons and axions can mix with each other

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



plasma mass

Faraday rotation

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

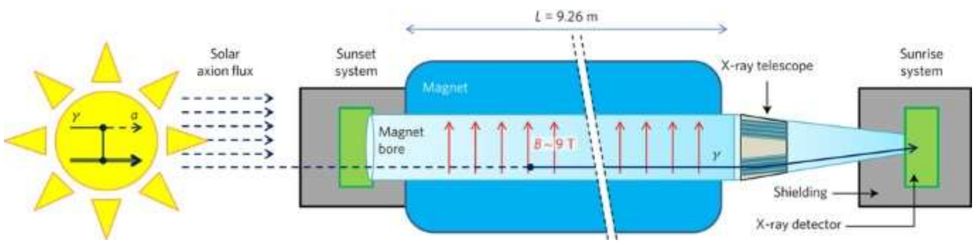
axion-photon mixing
magnetic field dependent

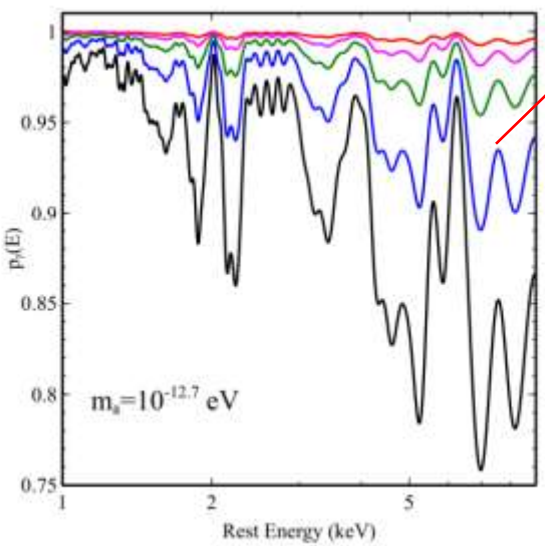
axion mass

Photon-Axion Mixing

Photon survival probability, as a function of photon energy:

Different values of the axion-photon coupling





NGC 1275 (Chandra)
ApJ 2020, 890, 59

Search for axion by measuring the axions produced by the Sun.

Search for axion by measuring the x-ray spectrum.