Searching for Axion Birefringence Signal in Event Horizon Telescope Polarimetric Data

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Collabrators: Yifan Chen, Chunlong Li, Yuxin Liu, Ru-sen Lu, Yosuke Mizuno, Jing Shu, Qiang Yuan, Yue Zhao, Zihan Zhou

6th October | MITP JGU YOUNGST@RS - Shoot for the Stars, Aim for the Axions

Related papers

Probing axions with event horizon telescope polarimetric measurements

Physical Review Letters, 124(6), 061102. 1905.02213

Stringent axion constraints with Event Horizon Telescope polarimetric measurements of M87⋆

Nature Astronomy (2022), 1-7. 2105.04572

Birefringence tomography for axion cloud

JCAP 09 (2022) 073 2208.05724

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Introduction:

QCD Axion and Axion-Like-Particles

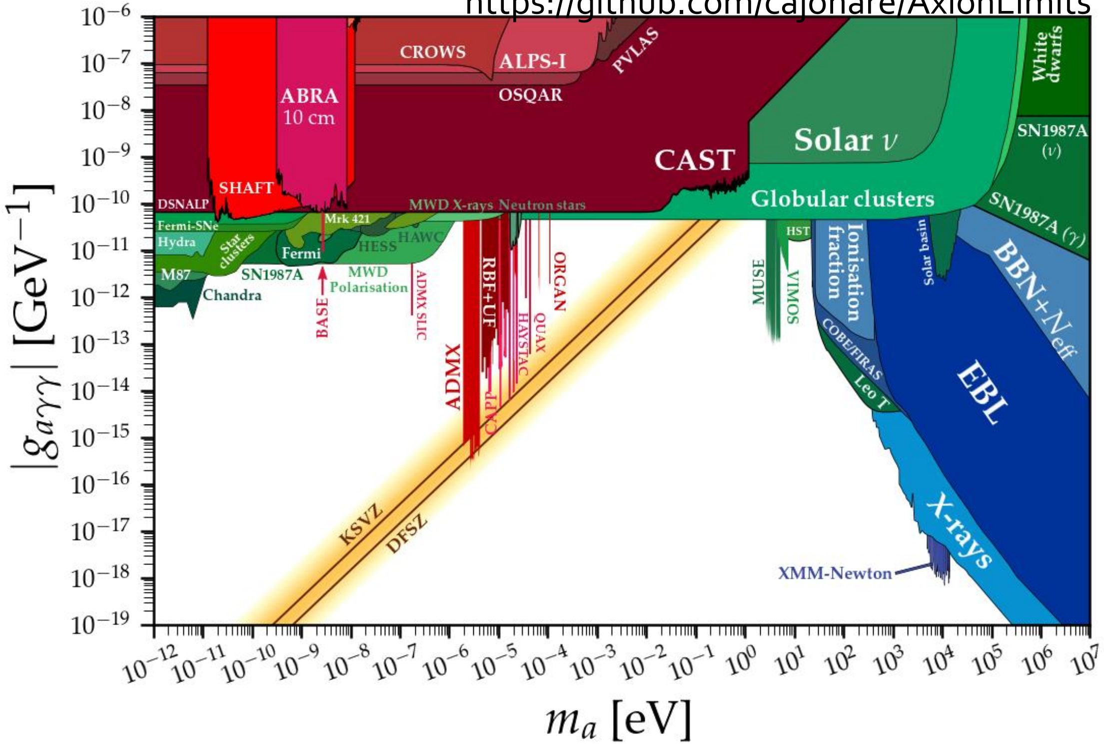
QCD Axion:

Hypothetical particle first proposed in the **Peccei-Quinn theory** (1977). A spontaneously broken Peccei-Quinn symmetry would cancel the CP-violation term of QCD, resulting in a new particle, namely **QCD axion**.

Axion-Like-Particles:

ALPs come from the compactification of massless fields in theories with extra dimensions, such as the string theory.

https://github.com/cajohare/AxionLimits



Theory:

Properties of Axion and ALPs

Effective Potential

$$V(a) = f_a^2 \mu^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$ (mass and self-interactions)

Possible Interactions

$$\mathcal{L}_{\text{in}} \supset g_{aF}\ a\ F^{\mu\nu}\tilde{F}_{\mu\nu}\ / g_{aG}\ a\ G^{\mu\nu}\tilde{G}_{\mu\nu}$$ (with gauge bosons)

$$\mathcal{L}_{\text{in}} \supset\ g_{af}\ a\ \bar{\psi}\gamma^5\psi\ /\ g_{af}\partial_\mu a\ \bar{\psi}\gamma^\mu\gamma^5\psi$$ (with fermions)

The kinematic term

$$\frac{1}{2}(\partial_\mu a)(\partial^\mu a)$$

Theory:
Properties of Axion and ALPs

Axion-Photon interacton term:

$$\mathcal{L}_{\text{in}} \supset -\frac{1}{2} g_{a\gamma}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu} = 2\, a\, g_{a\gamma}\, \vec{E}\cdot\vec{B}$$

Dispersion relation of left/right handed photon traveling in axion background

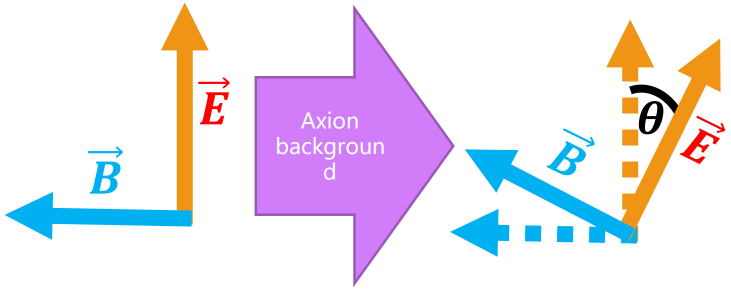
$$\omega^{\pm}(\boldsymbol{k}) \simeq |\boldsymbol{k}| \pm g_{a\gamma}\left(\hat{\boldsymbol{k}}\cdot\boldsymbol{\nabla} a + \dot{a}\right)$$

McDonald, Jamie I., and Luís B. Ventura. "Optical properties of dynamical axion backgrounds." Physical Review D 101.12 (2020): 123503. 1911.10221

Polarization angle
In linear polarization Basis

$$\Delta\theta \equiv \frac{1}{2}\int d\lambda(\omega^{+} - \omega^{-}) = g_{a\gamma}\left(a_f - a_i\right)$$

Axion induced birefringence



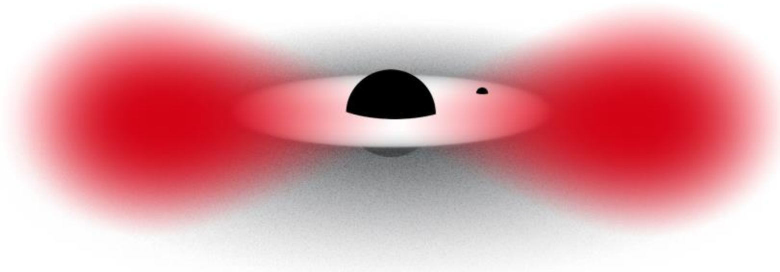
Rotation angle of linearly polarized light:

$$\frac{d\theta}{ds} = g_{a\gamma}\frac{da}{ds}$$

Theory:
Black Hole Superradiance

Superradiance:

Obtained by solving **Klein-Gordon equation** in **Kerr** space-time, with boundary condition of **in-going wave** on the event horizon.



R. Brito, V. Cardoso & P. Pani, "Superradiance", Lect. Notes in Physics 971 (2020)

It can be understood as scalar field subtracting energy from the black hole **ergoregion**, causing an **exponential growth** of the field. The fasted growth happens when (in SI)

$$\alpha \equiv \frac{GM\mu}{\hbar c} = \frac{GM}{c^2}\frac{\mu c}{\hbar} \simeq 0.4$$

For the mode

$$l = 1; m = 1$$

Theory:
Superradiant Axion Cloud

The effective potential:

$$V(a) = f_a^2 \mu^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

the superradiant axion cloud stops growing if

$$a_{max} \simeq f_a$$

when the superradiance is terminated by the axion self-interaction. On the other hand, simulations showed that the axion field can remain saturated as long as the nonlinear regime is ever reached.

See H. Yoshino and H. Kodama, The bosenova and axiverse, Class. Quant. Grav. 32 (2015) 214001

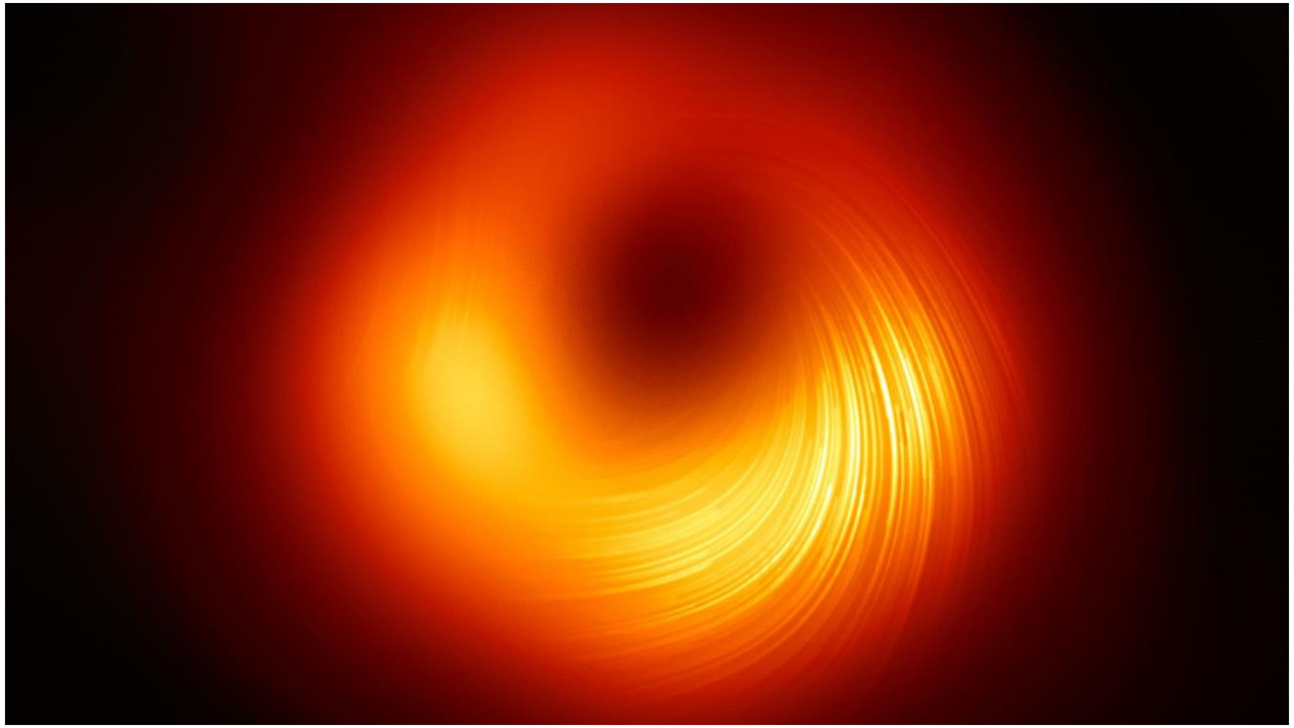
An estimation: $f_a = 10^{15}\mathrm{GeV}$; $g_{a\gamma} = 10^{-15}\mathrm{GeV}^{-1}$, we have $\Delta\theta_{max} \simeq 1\ \mathrm{rad}$. The signal also oscillates with time with frequency $f = \frac{\mu c^2}{h}$.

Experiment:

Event Horizon Telescope

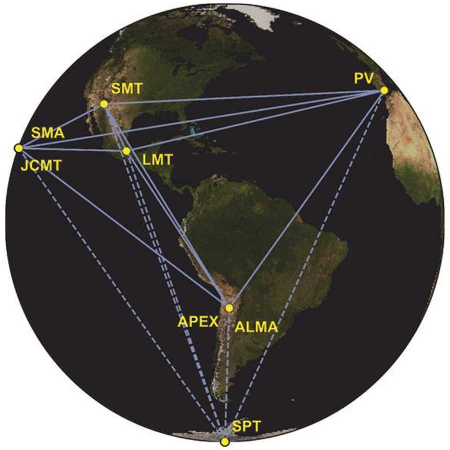
The 4 snapshots of the black hole M87* were taken in 2017 on 5/6 April and 10/11 April.

The Uncertainty at each pixel is ~10 deg.



Event Horizon Telescope Collaboration, APJL, 910(2021) L12

The **Event Horizon Telescope** adopts the technology of Very Long Baseline Interferometry (VLBI) to capture the first image of back hole in 2019.
The Polarimetric data is released in 2021



Event Horizon Telescope Collaboration, APJL, 875(2019) L1

Experiment:
Event Horizon Telescope

Mass of the black hole M87*

Event Horizon Telescope Collaboration, APJL, 875(2019) L1

$$M \simeq 6.5 \times 10^9 M_\odot$$

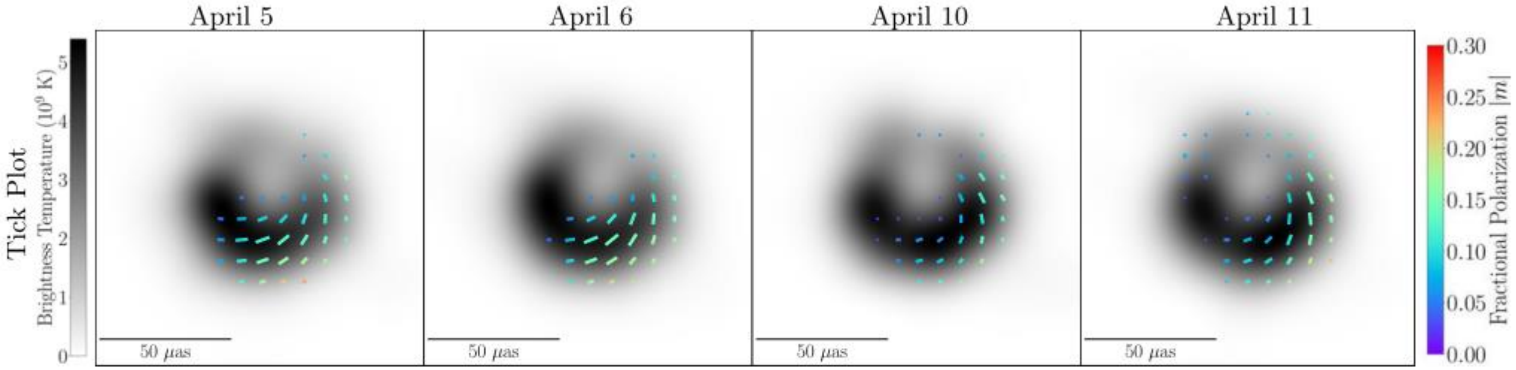
To satisfy the superradiant condition ($\alpha = 0.4$), we have

$$\mu = 8.2 \times 10^{-21}\mathrm{eV}$$

The signal period would be

$$T_{osc} = 5.82 \text{ days}$$

Approximately the total observation time!



Event Horizon Telescope Collaboration, APJL, 910(2021) L12

Signal modeling:
Differential EVPA

EVPA χ : Electric vector polarization angle

$$\Delta\chi_{\mathrm{model}} \simeq 2\,A(\varphi)\sin\left[\frac{\omega t_{\mathrm{int}}}{2}\right]\sin\left[\omega\left(t_i+\frac{\mathrm{t_{int}}}{2}\right)+\varphi+\delta(\varphi)\right]$$

φ: azimuthal angle
t_{int}: integration time
t_i: the initial observation time
ω: angular frequency of the signal

$A(\varphi)$: Amplitude of the signal, fixed by simulation
(caused by washing out effect)

$\delta(\varphi)$: Advance phase, fixed by simulation
(caused by the non-zero inclination angle)

The new dataset is:

$$\Delta\chi_{\mathrm{obs}} = \{\chi_6 - \chi_5, \chi_{11} - \chi_{10}\}$$

Signal Modeling:

Simulation

Radiative Transfer:

IPOLE

Mościbrodzka, M. and Charles F. Gammie. MNRAS (2018)

Accretion Model:

RIAF accretion flow

Yuan, F., Quataert, E. and Narayan, R. APJ (2003)
Pu, Hung-Yi, and Avery E. Broderick. APJ (2018)

Inclination Angle / Magnetic Field / Orbit:

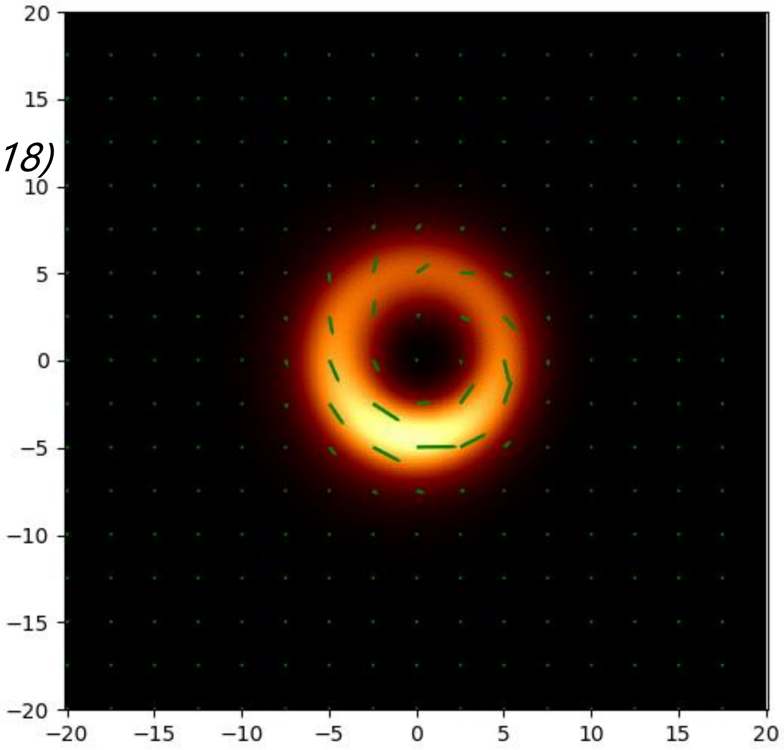
$\iota=17^\circ$, Vertical Magnetic Field
sub-Keplerian flow

Compatible with EHT et al. APJL, 875, L1 (2019)

Black Hole Spin:

$a_J = 0.99$

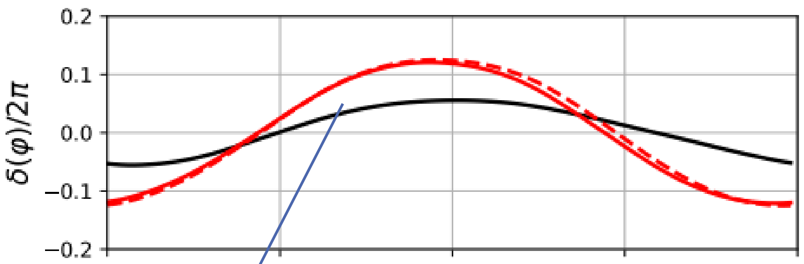
Note that the signal is not sensitivity to aJ as long as it is larger 0.5.

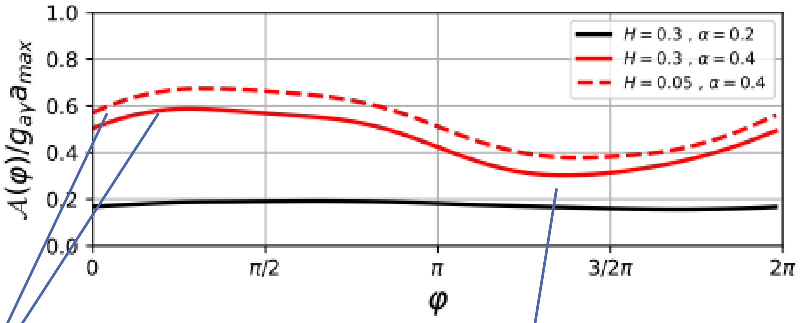


We add **axion field** in the **radiative transfer** equation.
With the presence of the dense superradiant axion cloud, the polarization angle **oscillates with time**. The signal also **propagates along the azimuthal angle.**

Signal Modeling: Simulation

The Simulation Results:





Chen, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Nat. Astron.

The nonzero δ is due to the non-zero inclination angle

The signal amplitude is smaller than the most optimal value (=1)

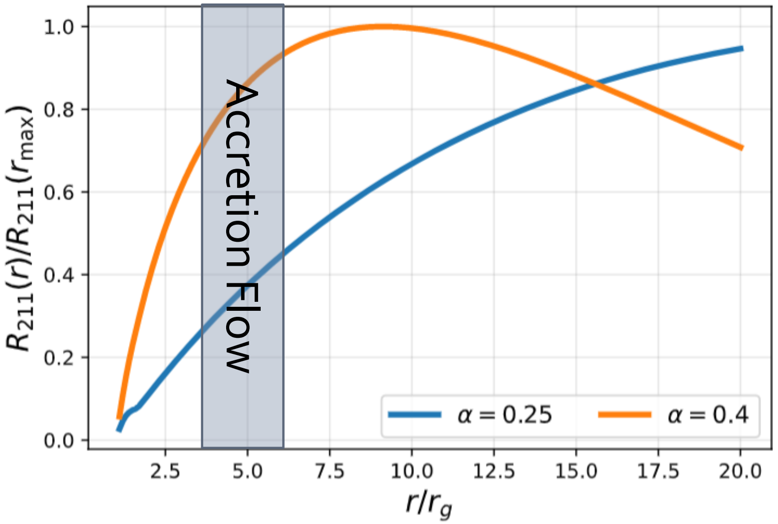
The signal is “washed out” the most at the **brightest”** point

$$\Delta\chi_{\text{model}} \simeq 2\, A(\varphi) \sin\left[\frac{\omega t_{\text{int}}}{2}\right] \sin\left[\omega\left(t_i + \frac{\text{t}_{\text{int}}}{2}\right) + \varphi + \delta(\varphi)\right]$$

Signal Modeling:
Simulation

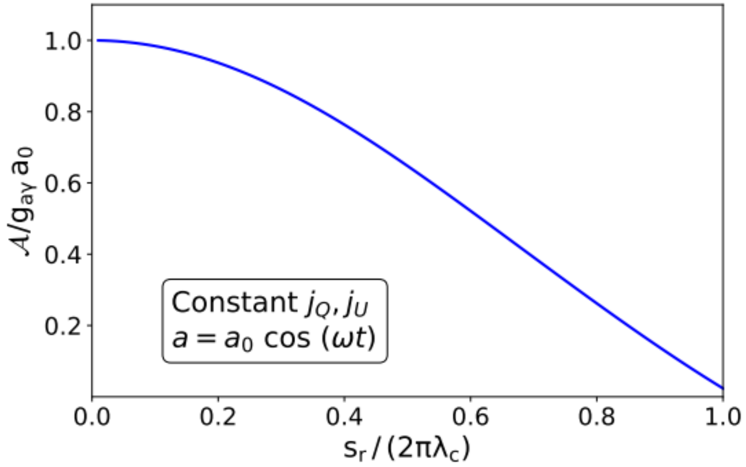
Understanding the Simulation Results:

The **mismatch** between the maximal axion field amplitude and the BH accretion flow



Chen, Li, Mizuno, Shu, Xue, Yuan, Zhao, Zhou, JCAP (2022)

As the **size** (s_r) of the radiation source grows, the washout effect becomes more significant



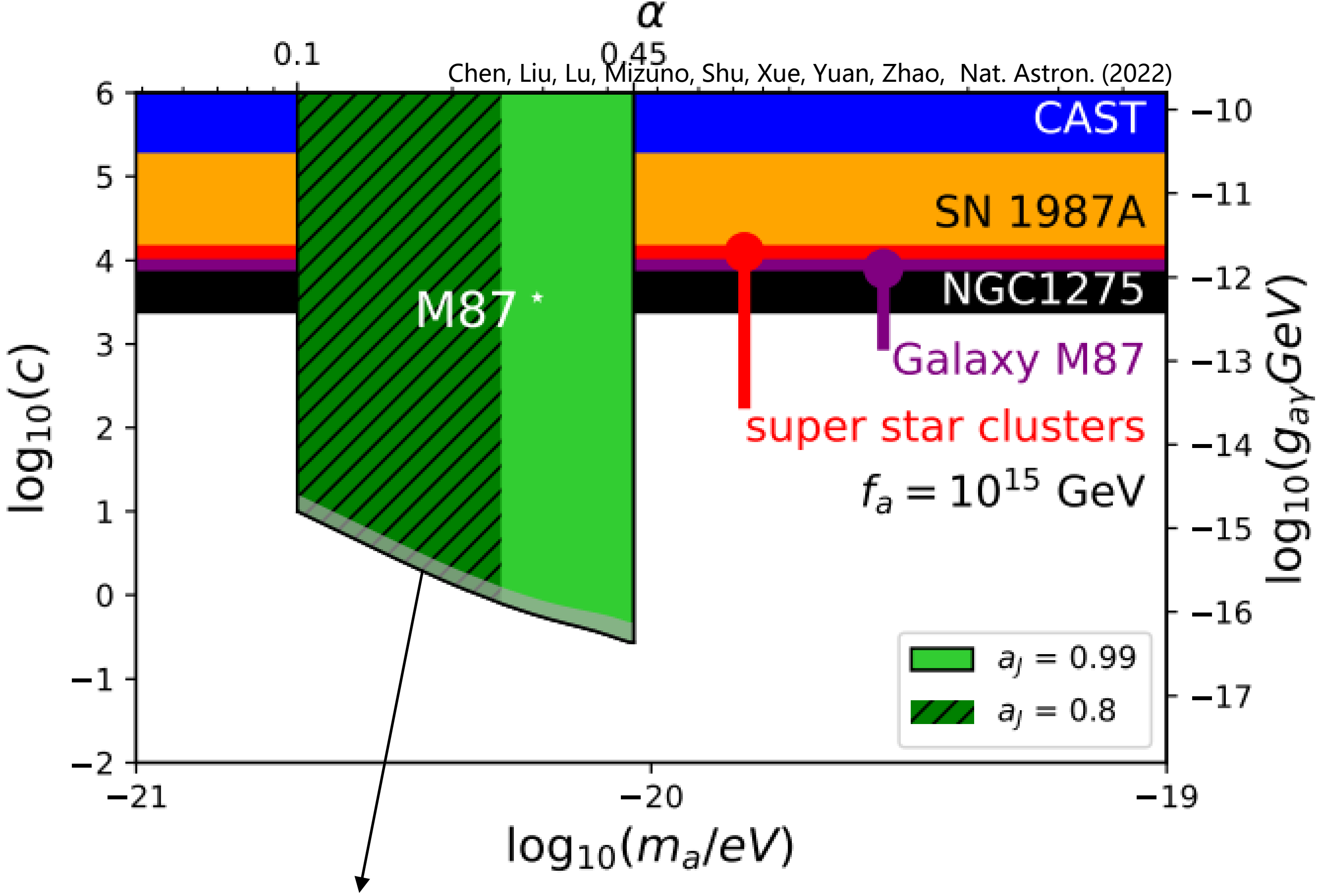
Chen, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Nat. Astron. (2022)

Results

Exclusion Contour

Exclusion Contour Derived From EHT 17’

$c \equiv 2\pi g_{a\gamma} f_a$

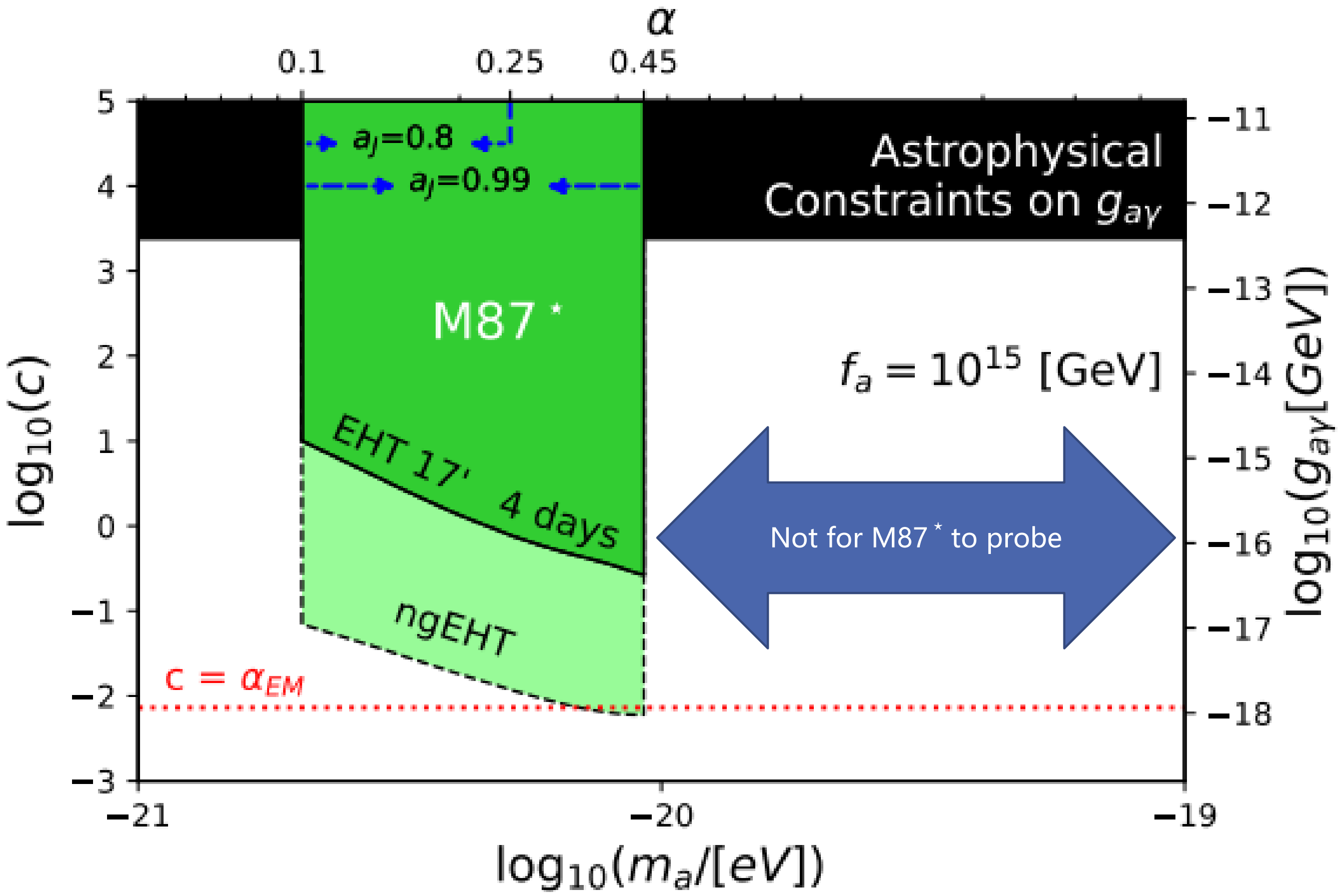


Chen, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Nat. Astron. (2022)

The oscillation period is longer than the total observation time

Results
Exclusion Contour
(future)

Exclusion Contour Derived From the Next Generation EHT (future)



ngEHT fundamental physics white paper, *in preparation*

Prospect improvements in the ng-EHT era

Experimentally

Shorter observing interval and longer observing time (x10) and
More data points on different radii (washout effect) (x5)

Multi-frequency observation (x3, subtract Faraday rotation)

Better angular (azimuthal angle) resolution

Theoretically

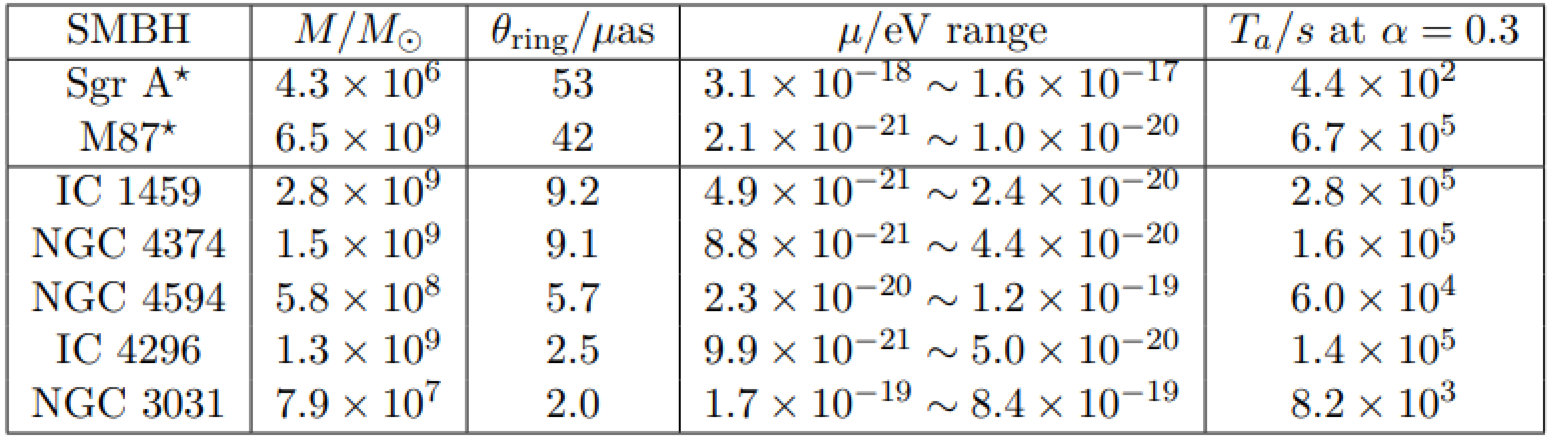
Better understanding of the EVPA uncertainty and to
Use the closure traces to improve detection sensitivity

Building a correct model of the astronomical background through the GRMHD simulation
Broderick, Avery E., and Dominic W. Pesce. Closure traces. APJ (2020)

Prospect

improvements
in the ng-EHT era

Some candidates of SMBHs



SMBH	$M/M_\odot$	$\theta_{\rm ring}/\mu{\rm as}$	$\mu/{\rm eV}$ range	T_a/s at $\alpha = 0.3$
Sgr A*	4.3×10^6	53	$3.1 \times 10^{-18} \sim 1.6 \times 10^{-17}$	4.4×10^2
M87*	6.5×10^9	42	$2.1 \times 10^{-21} \sim 1.0 \times 10^{-20}$	6.7×10^5
IC 1459	2.8×10^9	9.2	$4.9 \times 10^{-21} \sim 2.4 \times 10^{-20}$	2.8×10^5
NGC 4374	1.5×10^9	9.1	$8.8 \times 10^{-21} \sim 4.4 \times 10^{-20}$	1.6×10^5
NGC 4594	5.8×10^8	5.7	$2.3 \times 10^{-20} \sim 1.2 \times 10^{-19}$	6.0×10^4
IC 4296	1.3×10^9	2.5	$9.9 \times 10^{-21} \sim 5.0 \times 10^{-20}$	1.4×10^5
NGC 3031	7.9×10^7	2.0	$1.7 \times 10^{-19} \sim 8.4 \times 10^{-19}$	8.2×10^3

Chen, Li, Mizuno, Shu, Xue, Yuan, Zhao, Zhou, JCAP (2022)

Related papers

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Thank you for listening!