Probing Axions via Light Circular Polarization
and
Event Horizon Telescope

Fazlollah Hajkarim

University of Oklahoma

Cosmology from Home Conference, Online, July 2023

Overview

- Vacuum solutions of General Relativity results in the presence of Black Holes. BH properties depend on the boundary conditions for the GR solutions.

- Kerr BH predicted in 1963 describes massive spinning objects as one of the realistic solution of GR

- The observation of a BH at galactic centre by Event Horizon Telescope (EHT) was one of the confirmation of GR beyond the solar system and a confirming evidence for the presence of BH especially supermassive BH (SMBH) at the centre of galaxies

- Also, observation of gravitational wave from binary BH mergers by LIGO was another triumph of GR at the galactic/cosmological scale

- These new experiments can also indirectly constrain/observe the physics beyond the standard model

- Axion (like particles) as a BSM physics candidate (for dark matter) due to the interaction with photons or indirect impact on massive objects can be probed with EHT or GW experiments

We studied the impact of axion on light polarisation around a SMBH!

Event Horizon Telescope

The Detection Method of EHT: behaves like virtual Earth-sized telescope using very long baseline interferometry
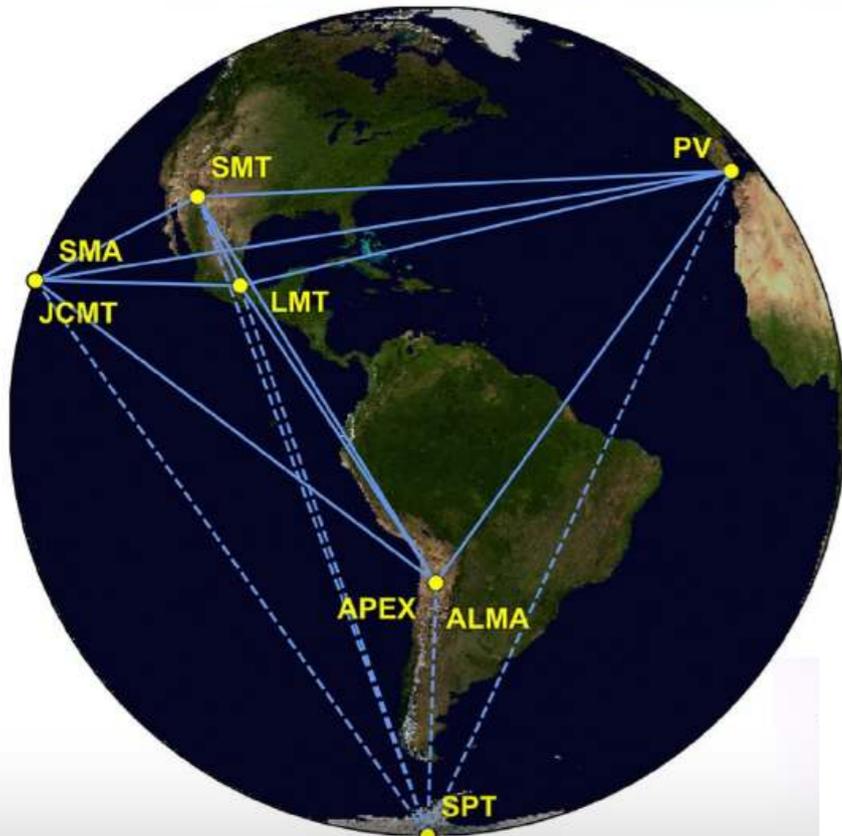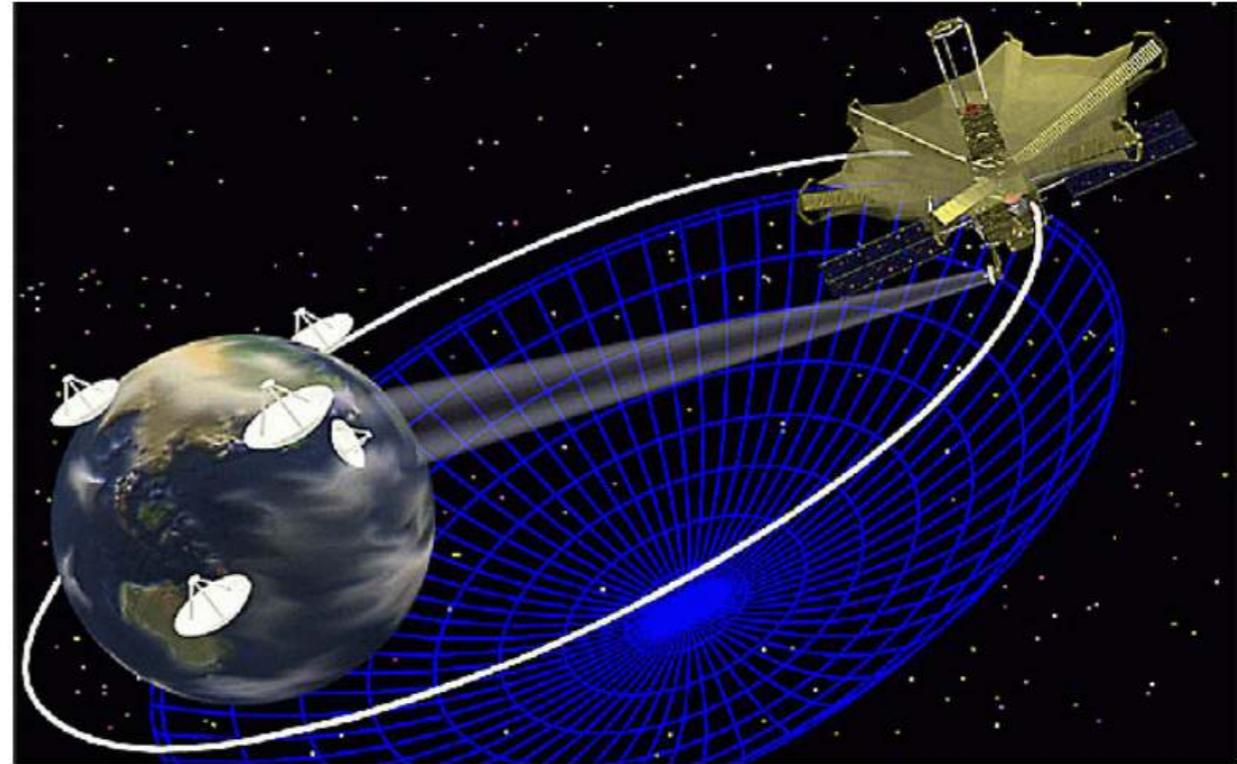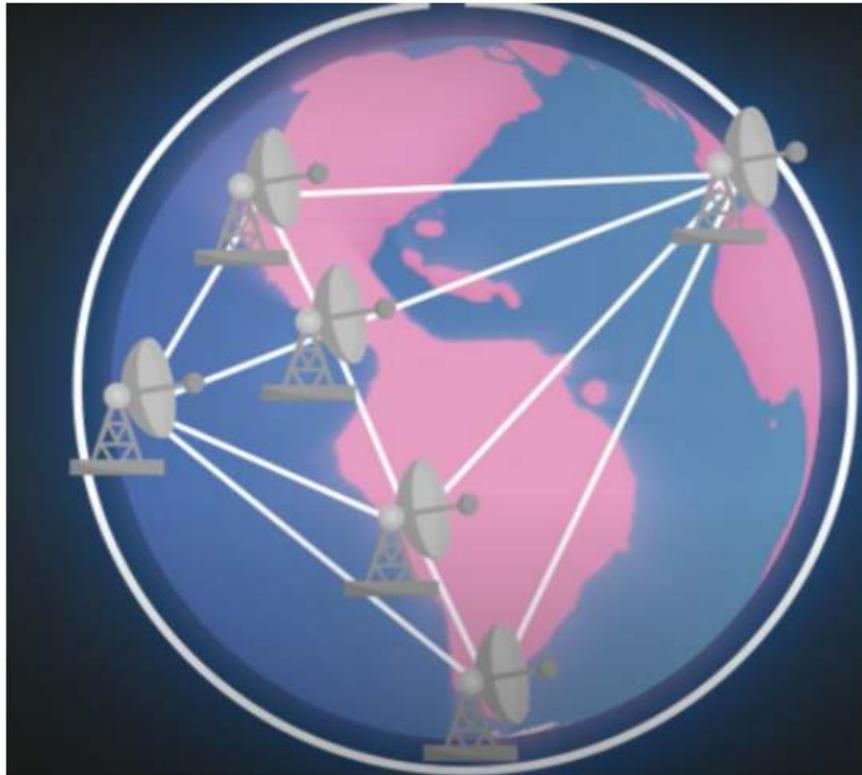
At frequencies of about 230 GHz (wavelength of 1.3 mm), Earth-size baselines can resolve an apple on the Moon.

EHT Resolution

EHT observations to date have achieved a resolution of **better than 60 microarcseconds**

Size of the Supermassive Black Hole (SMBH) and its Image

M87*
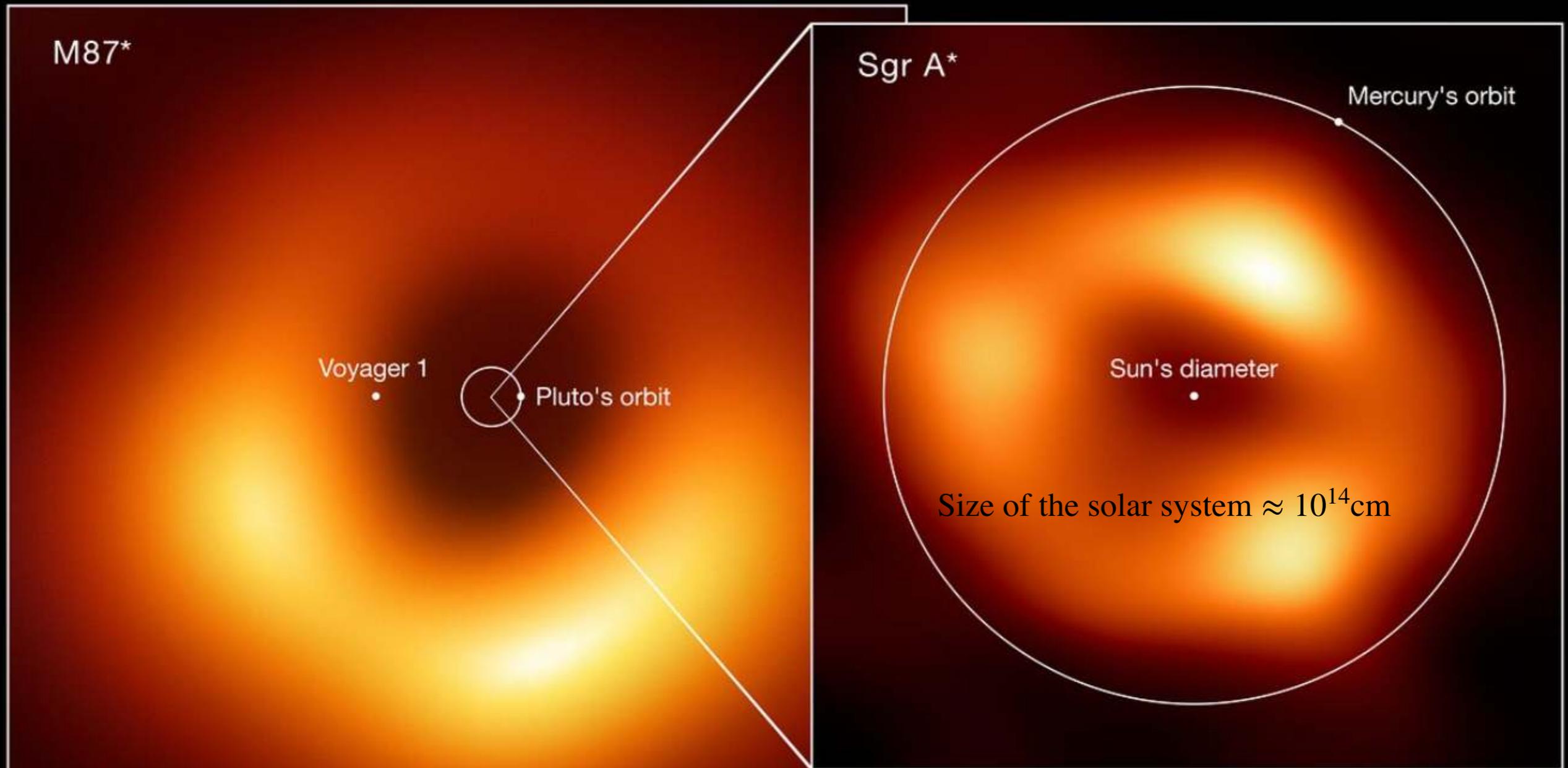
Voyager 1

Pluto's orbit

Sgr A*

Mercury's orbit

Sun's diameter

Size of the solar system $\approx 10^{14}$ cm

$$r_g \equiv GM_{BH} = 2.97 \times 10^{-4} \text{pc} \left(\frac{M_{BH}}{6.2 \times 10^9 M_\odot} \right)$$

$1\text{pc} = 3.086 \times 10^{18} \text{cm}$

The emission region $\sim 5r_g$

The Magnetic Field at the emission region $4.9 \, G$

$M_{BH} \approx 6.2 \times 10^9 M_\odot$

The electron density $n_e \sim 10^4 \text{ cm}^{-3}$

EVENT HORIZON TELESCOPE collaboration, *First M87 Event Horizon Telescope Results. V. Physical Origin of the Asymmetric Ring*, *Astrophys. J.* **875** (2019) L5 [1906.11242].

C. G. et al., *Polarimetric properties of event horizon telescope targets from alma*, ApJL **910** (2021) 54.

E. C. et al., *First m87 event horizon telescope results. vii. polarization of the ring*, ApJL **910** (2021) 48.

E. C. et al., *First m87 event horizon telescope results. viii. magnetic field structure near the event horizon*, ApJL **910** (2021) 43.

Kerr Geometry

In reality black holes are spinning objects. They can be well described by Kerr metric.
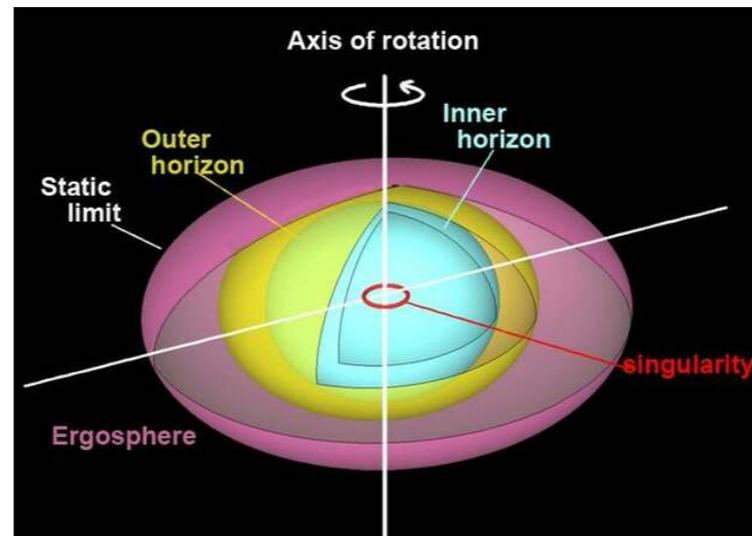
$$ds^2 = -\left(1 - \frac{2M_{BH}r}{\Sigma}\right)dt^2 - \frac{4aM_{BH}r\sin^2\theta}{\Sigma}dtd\phi + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \left(r^2 + a^2 + \frac{2a^2 M_{BH}r\sin^2\theta}{\Sigma}\right)\sin^2\theta d\phi^2$$

$$\Sigma = r^2 + a^2\cos^2\theta \qquad \Delta = (r - r_+)(r - r_-) \qquad r_\pm = M_{BH} \pm \sqrt{M_{BH}^2 - a^2}$$

$a = J/M$ is the angular momentum per unit mass of the black hole.

The ergosphere is a region located outside a rotating black hole's outer event horizon (proposed by Remo Ruffini and John Archibald Wheeler in 1971). "ergon" means "work". It received this name because it is theoretically possible to extract energy and mass from this region.

Superradiance

Superradiance conditions are discovered under which waves incident on a rotating black hole can extract energy and angular momentum from the black hole, leading to amplification and scattering of the waves - Zeldovich, Press, Teukolsky (1970s).

Superradiance is a phenomenon where rotating black holes can extract rotational energy and amplify waves or particles near their event horizons. This occurs when the energy and angular momentum of the incident particles satisfy certain conditions. Axions as dark matter candidates can interact with black holes. Axions can be produced in the intense environment of a black hole's accretion disk and affect its properties. They can also interact with electromagnetic fields, leading to the conversion of photons into axions and vice versa.

The condition for superradiance around a rotating black hole is: $\omega < m\Omega$

- ω: The frequency of the incident wave or particle.
- m: An integer representing the azimuthal mode number.
- Ω: The angular velocity of the rotating black hole.

The condition $\omega < m\Omega$ states that the frequency of the incident wave or particle must be lower than the product of the azimuthal mode number and the angular velocity of the black hole. This condition ensures that the energy and angular momentum of the wave can be extracted by the black hole, leading to superradiant amplification.

Bekenstein, J. D. (1973)   Press, W. H., & Teukolsky, S. A. (1972)   Thorne, Price, Macdonald (1986)   Brito, Cardoso, Paolo Pani (2020)

Axion Density Around a SMBH
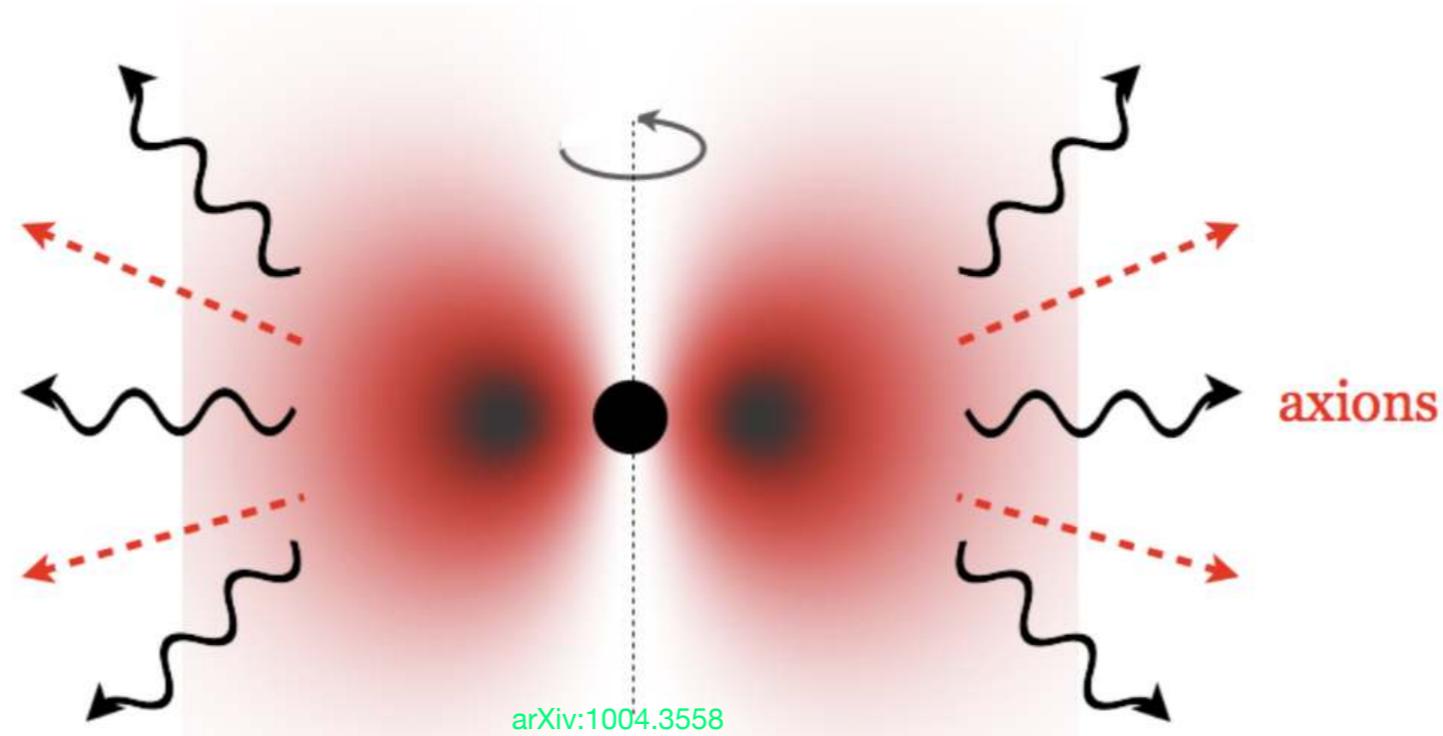
arXiv:1004.3558

$$\rho_a|_{\max} = \frac{1}{2}m_a^2 a^2|_{\max} = \frac{1}{2}m_a^2 f_a^2 \approx 3.83 \times 10^{11} \left(\frac{m_a}{10^{-20}\mathrm{eV}}\right)^2 \left(\frac{f_a}{10^{16}\mathrm{GeV}}\right)^2 \left[\frac{\mathrm{GeV}}{\mathrm{cm}^3}\right]$$

✴ The superradiant instability depends on the dimensionless product of the BH mass and axion mass as

$$M_{\mathrm{BH}}m_a = 4.65 \times 10^{-1} \left(\frac{M_{\mathrm{BH}}}{6.2 \times 10^9 M_\odot}\right)\left(\frac{m_a}{10^{-20}eV}\right)$$

Dark Matter Local Density in Halo:

Outer halo

Inner halo

Thin disk

$$\rho_{\mathrm{DM}} \sim 0.4\frac{GeV}{cm^3}$$
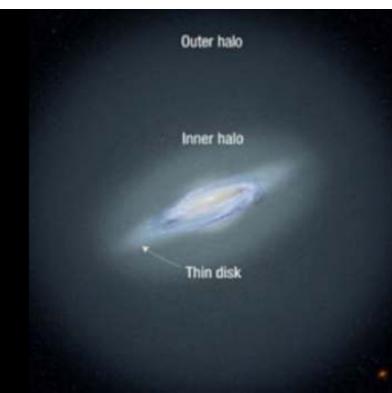
arXiv:2209.13572

Light Polarisation

Linear Polarisation:

- Intrinsic to the emission process: The Synchrotron emission, Bremsstrahlung, curvature radiation, etc.
- Due to the propagation effect: The Compton scattering, plasma effect, etc.

But usual scattering process (like Compton scattering)
can not produce circular polarization!

Circular polarization:

- Parity violating interactions
- Intrinsic asymmetric distribution of left- and right-handed components in target beams
- The presence of an anisotropic background in the medium

Light Polarisation

Stokes parameters: I (the total intensity), Q and U (linear polarization), and V (the circular polarization):

$$I = \rho_{11} + \rho_{22} \equiv \langle \dot{A}_x^2 \rangle + \langle \dot{A}_y^2 \rangle, \quad Q = \rho_{11} - \rho_{22} \equiv \langle \dot{A}_x^2 \rangle - \langle \dot{A}_y^2 \rangle, \quad U = \rho_{12} + \rho_{21} \equiv \langle 2\dot{A}_x \dot{A}_y \cos(\phi_x - \phi_y) \rangle, \quad V = i(\rho_{12} - \rho_{21}), \equiv \langle 2\dot{A}_x \dot{A}_y \sin(\phi_x - \phi_y) \rangle$$

$$\rho = \frac{1}{2} \begin{pmatrix} I + Q & U - iV \\ U + iV & I - Q \end{pmatrix}$$

$$\hat{\mathcal{D}}_{ij}(\mathbf{k}) = \hat{a}_i^\dagger(\mathbf{k}) \hat{a}_j(\mathbf{k})$$

$$(2\pi)^3 2k^0 \delta^{(3)}(0) \frac{d}{dt} \rho_{ij}(\mathbf{k}) = i\langle [\hat{\mathcal{H}}_{int}(t), \hat{\mathcal{D}}_{ij}(\mathbf{k})] \rangle - \frac{1}{2} \int_{-\infty}^{+\infty} dt \left\langle \left[\hat{\mathcal{H}}_{int}(t), [\hat{\mathcal{H}}_{int}(0), \hat{\mathcal{D}}_{ij}(\mathbf{k})] \right] \right\rangle$$

$$A_\mu(x) \equiv A_\mu^+(x) + A_\mu^-(x) = \int \frac{d^3\mathbf{k}}{(2\pi)^3 2\omega_\gamma} \left[\hat{\mathbf{a}}_i(\mathbf{k}) \epsilon_{i\mu}(\mathbf{k}) e^{-ik \cdot x} + \hat{\mathbf{a}}_i^\dagger(\mathbf{k}) \epsilon_{i\mu}^*(\mathbf{k}) e^{ik \cdot x} \right]$$

Coherently Oscillating Axion Field

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a^2\right) + \frac{1}{4}\mathsf{g}_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\mathsf{g}_{a\gamma} \equiv \frac{c_{a\gamma}}{2\pi f_a} \qquad c_{a\gamma} \equiv \alpha_{\text{em}}\left(\frac{E}{N} - 1.92\right)$$

$$a(\vec{r}, t) \equiv \mathfrak{Re}\left(a_0(r)\, e^{i(\mathbf{p}\cdot\mathbf{r} - \omega t)}\right) \equiv a_0(r)\cos\left[m_a t + \delta(r)\right]$$

$$T \simeq \frac{2\pi}{m_a} \simeq 4.2 \times 10^{-9}\left(\frac{10^{-6}\text{eV}}{m_a}\right)s$$

$$r_g \equiv GM_{BH} = 2.97 \times 10^{-4}\text{pc}\left(\frac{M_{BH}}{6.2 \times 10^9 M_\odot}\right)$$

arXiv:2209.13572

Axion-Photon Interaction is Parity Violating!

$$\mathscr{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} a(x) F_{\mu\nu} \tilde{F}^{\mu\nu} = - g_{a\gamma} a(x) \overrightarrow{E} \cdot \overrightarrow{B}$$

$$\vec{E} \xrightarrow{P} -\vec{E} \text{ and } \vec{B} \xrightarrow{P} \vec{B}$$
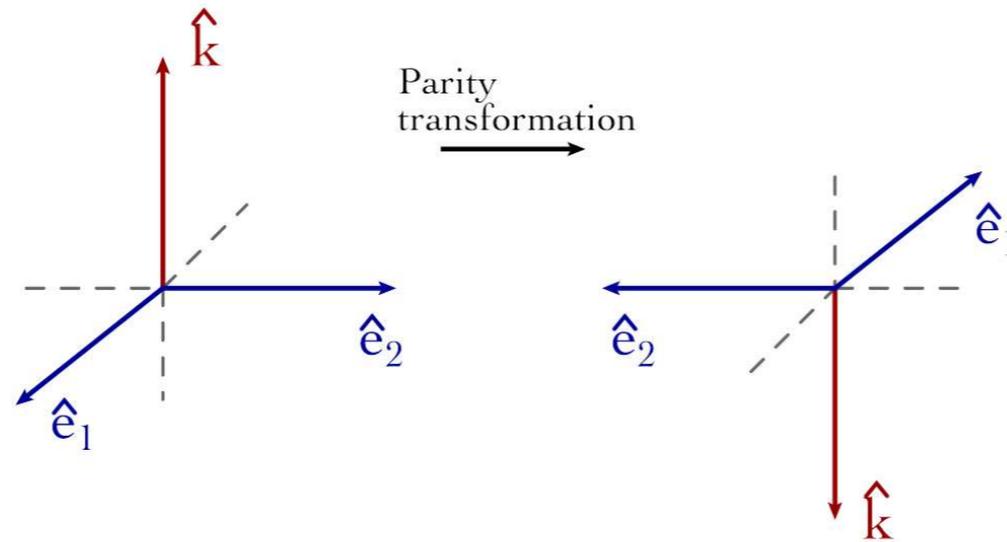
The photon dispersion relation in an axion background can be identified as

$$k^2 = \omega_\gamma^2 - |\overrightarrow{k}|^2 \approx \pm g_{a\gamma} \left[\omega_\gamma \dot{a} - \overrightarrow{k} \cdot \overrightarrow{\nabla} a \right]$$

scalar cloud
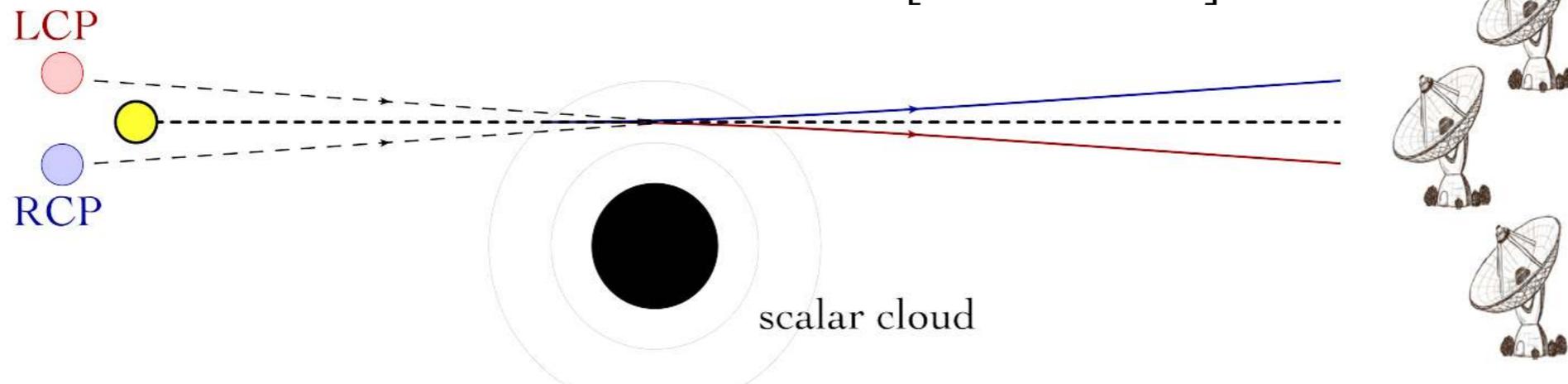
Axion Field Around the Black Hole
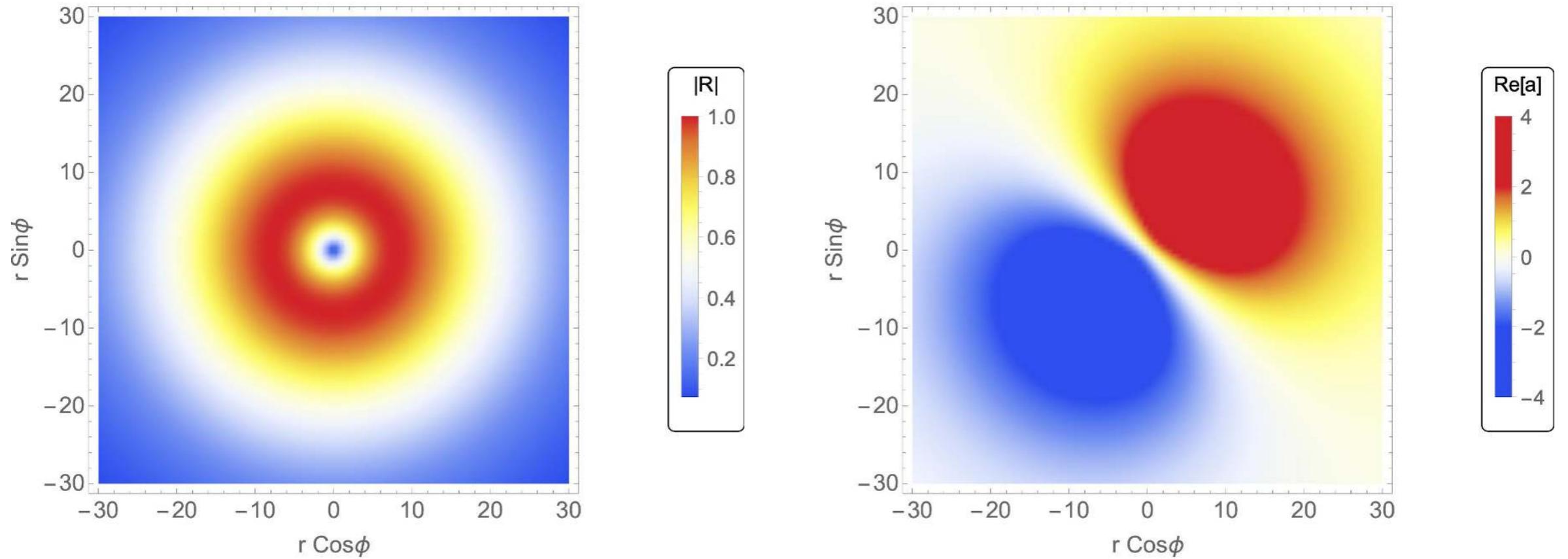
Axion field around the black hole is shown. The left and right panels are for the radial part of axion field $|R|$ (scaled to its maximum) and its real part $\mathrm{Re}[a]$ scaled to its numerical factor at $\theta = \pi/2$ from following equations with $l = 1$, respectively. The radial distance has been scaled to $r_{cloud} \sim 8$ which means that $M_{BH} m_a^2 = 0.25$.

$$\Box\, a = m_a^2 a \;\rightarrow\; a(t, r, \theta, \phi) = e^{im\phi} S_{lm}(\theta) e^{-i\omega t} R_{nl}(r) \;\rightarrow\; R_{nl}(r) = A_{nl} g(\tilde{r}), \quad g(\tilde{r}) = \tilde{r}^l e^{-\tilde{r}/2} L_n^{2l+1}(\tilde{r}), \quad \tilde{r} = \frac{2r M_{\mathrm{BH}} m_a^2}{l + n + 1}$$

$$a(t, r, \theta, \phi) = \sqrt{\frac{3M_{\mathrm{S}}}{4\pi \times 24 M_{\mathrm{BH}}}} (M_{\mathrm{BH}} m_a)^2 g(\tilde{r})^{n=0,\, l=1} \cos(\phi - \omega_R t) \sin\theta$$

arXiv:1711.08298   arXiv:2209.13572

Polarisation Angle of Linearly Polarized Emission

Polarization Angle $\Delta\psi$ of Linearly Polarized Emission	
Physical Process	**The Axion Polarization Angle**
Propagation of Photons in an Axion Background	$\Delta\psi = g_{a\gamma}\Delta a\left(\vec{r}, t\right)$
Axion-photon Conversion in a Magnetic Field	$\Delta\psi = \frac{1}{4}P_{\gamma\to a}\sin 2\alpha$
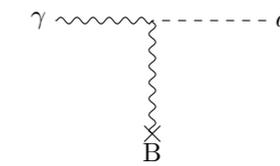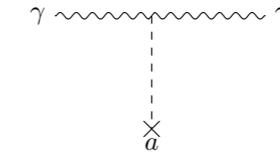
Sources of Circular Polarization

Sources of Circular Polarization	
Physical Process	**Form of the Axion Polarization Term**
Axion Induced Propagation Effect	$\Pi_V = \frac{2\pi g_{a\gamma}\dot{a}}{\omega_\gamma} + \mathcal{O}(g_{a\gamma}^2)$
Scattering of Photon from Axion	$\Pi_V = 8g_{a\gamma}^2 a_0^2 \frac{\omega_\gamma}{m_a^2 - 4\omega_\gamma^2}\left(\mathbf{p}_x^2 + \mathbf{p}_y^2\right)r$
Photon Scattering from a Magnetic Field	$\Pi_V = \frac{\omega_\gamma g_{a\gamma}^2}{m_a^2}\left(B_x^2 + B_y^2\right)r$
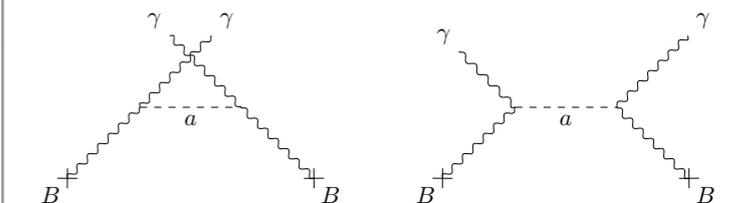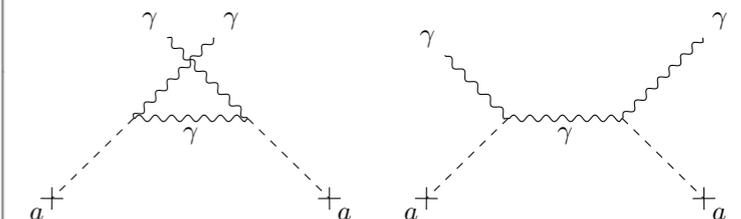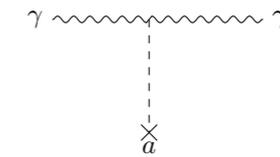
Contribution of Different Axion Channels on Light Polarisation around SMBH

The polarization angle can be defined in terms of Stokes parameters as

$$\psi = \frac{1}{2}\arctan\frac{U}{Q}$$

$$\Delta\psi\,|_{\max} \approx -8.20\times10^{-3}c_{a\gamma}\cos(\phi - m_a t)\sin\theta$$

$$\Delta\psi\,|_{\max} \approx 7.28\times10^{-5}\,{}^{\circ}\,\left(g_{a\gamma}/10^{-12}\mathrm{GeV}^{-1}\right)^2 \to f_a = 10^{15}\mathrm{GeV} \to \Delta\psi\,|_{\max} \approx 1.16\times10^{-8}c_{a\gamma}^2\,{}^{\circ}$$

$$\Pi_{\mathrm{V}} = \frac{2\pi g_{a\gamma}\dot{a}}{\omega_\gamma} = 5.41\times10^{-19}\,c_{a\gamma}\left(\frac{m_a}{10^{-20}\mathrm{eV}}\right)\left(\frac{230\mathrm{GHz}}{\nu_\gamma}\right)\sin(\phi - m_a t)\sin\theta$$

$$\Pi_{\mathrm{V}} \equiv \frac{|V|}{I} = |\sin(\Omega t)| \approx |\Omega|\,t = 4.94\times10^{-25}c_{a\gamma}^2\left(\frac{r}{r_g}\right)$$

$$\bigstar\ \Pi_{\mathrm{V}} \equiv \frac{|V|}{I} = |\sin(\Omega t)| \approx |\Omega|\,t = 0.85\left(\frac{c_{a\gamma}}{0.1}\right)^2\left(\frac{\nu_\gamma}{230\mathrm{GHz}}\right)\left(\frac{10^{-19}\mathrm{eV}}{m_a}\right)^2\left(\frac{B_0}{1\mathrm{G}}\right)^2\left(\frac{r}{r_g}\right)$$

arXiv:2209.13572
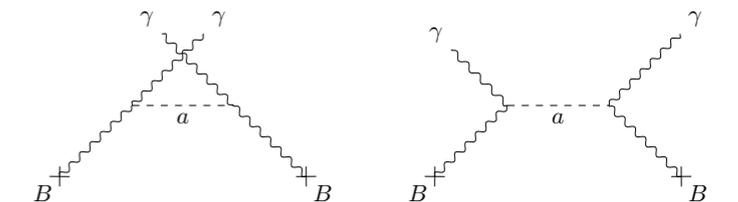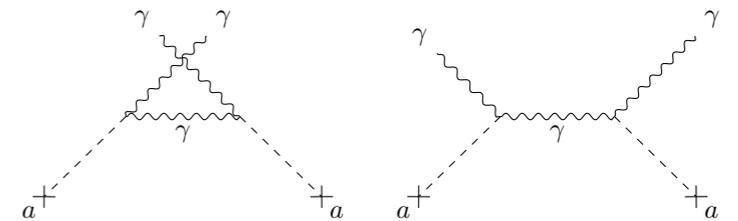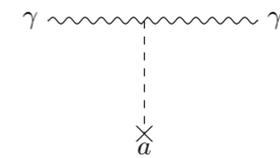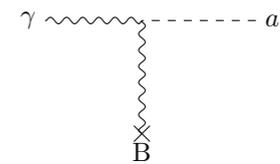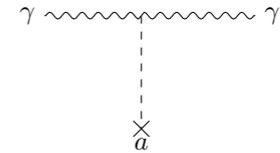
Dominant Contribution of Circular Polarisation

From ALMA (EHT) data we have only a conservative upper bound on the measurement of the circular polarisation of M87* at 230 GHz which is around 0.8 %.

$$\Pi_V \equiv \frac{|V|}{I} = |\sin(\Omega t)| \approx |\Omega| t = 0.85 \left(\frac{c_{a\gamma}}{0.1} \right)^2 \left(\frac{\nu_\gamma}{230\text{GHz}} \right) \left(\frac{10^{-19}\text{eV}}{m_a} \right)^2 \left(\frac{B_0}{1\text{G}} \right)^2 \left(\frac{r}{r_g} \right)$$
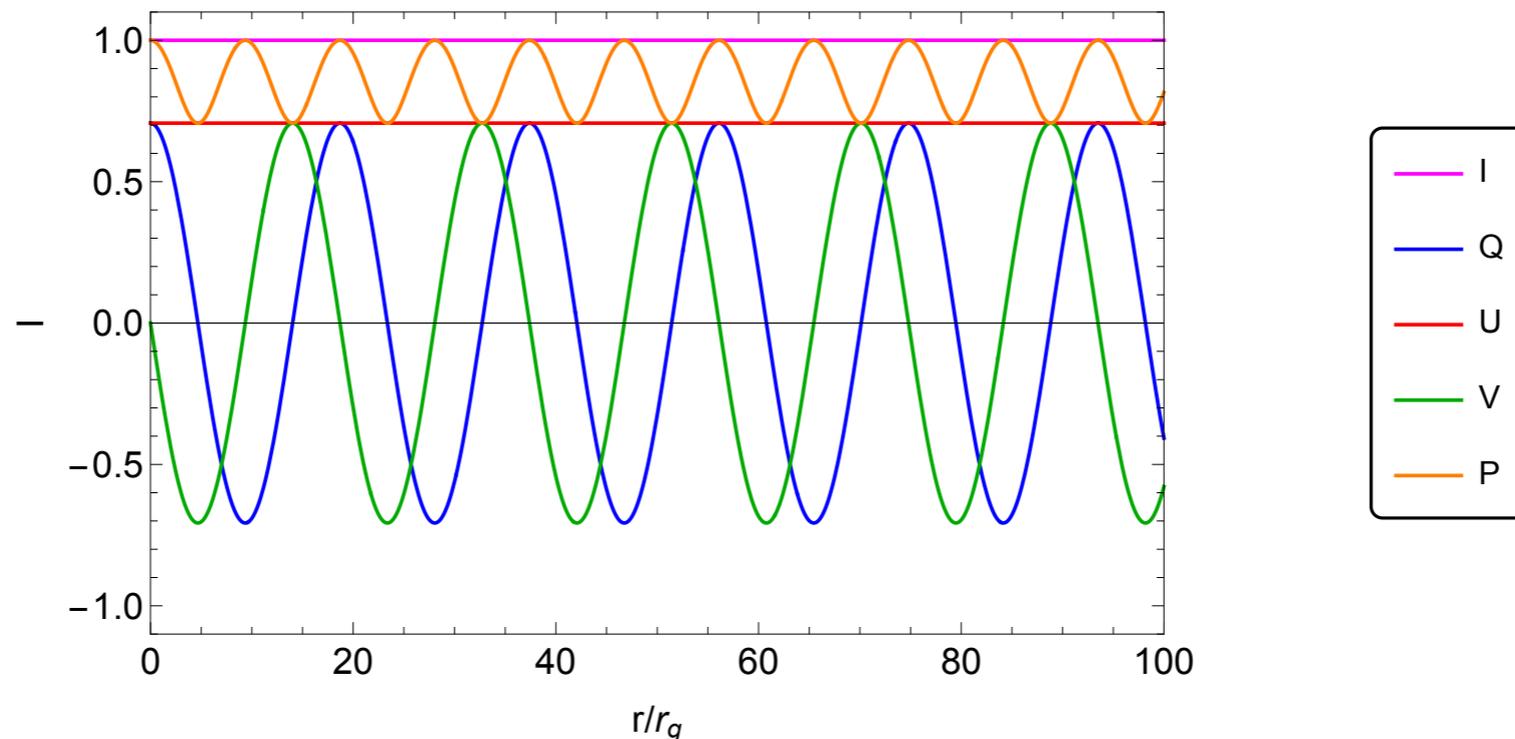
The evolution of Stokes parameters at different distance from the center of black hole are shown in this plot. The initial conditions are $I_0 = 1$, $Q_0 = 1/\sqrt{2}$, $U_0 = 1/\sqrt{2}$ and $V_0 = 0$.

arXiv:2209.13572

Linear Polarization of Light from EHT and Axion Constraints
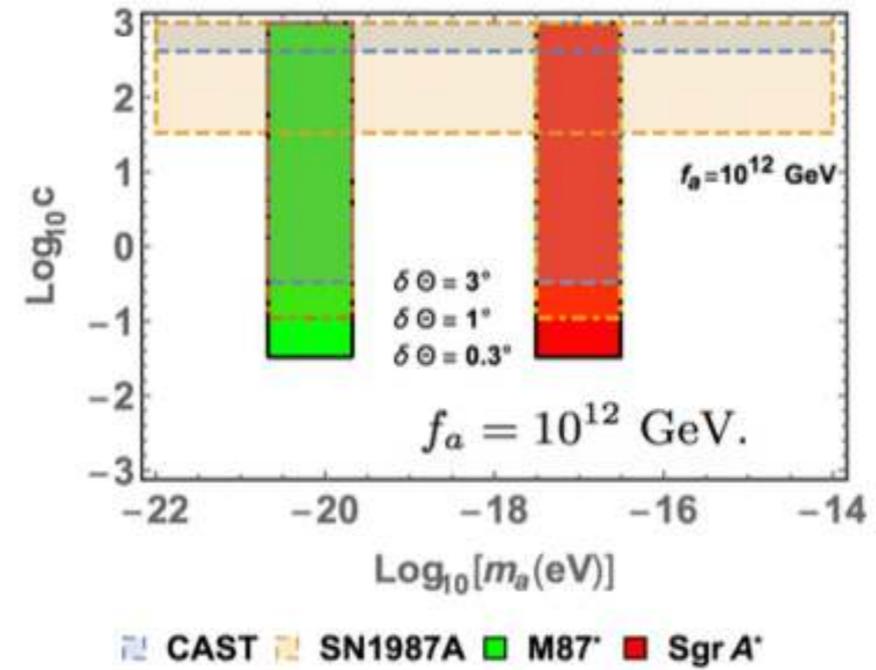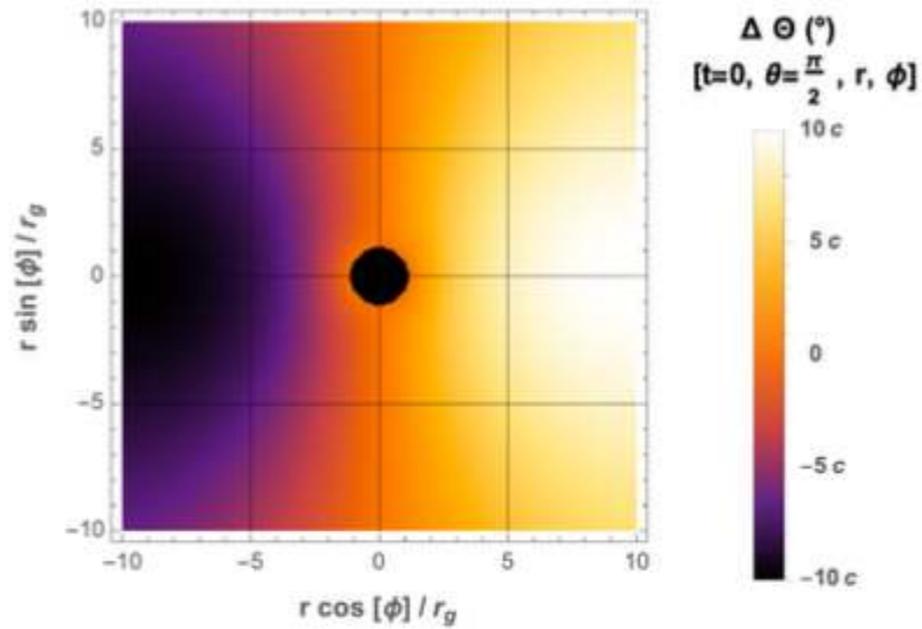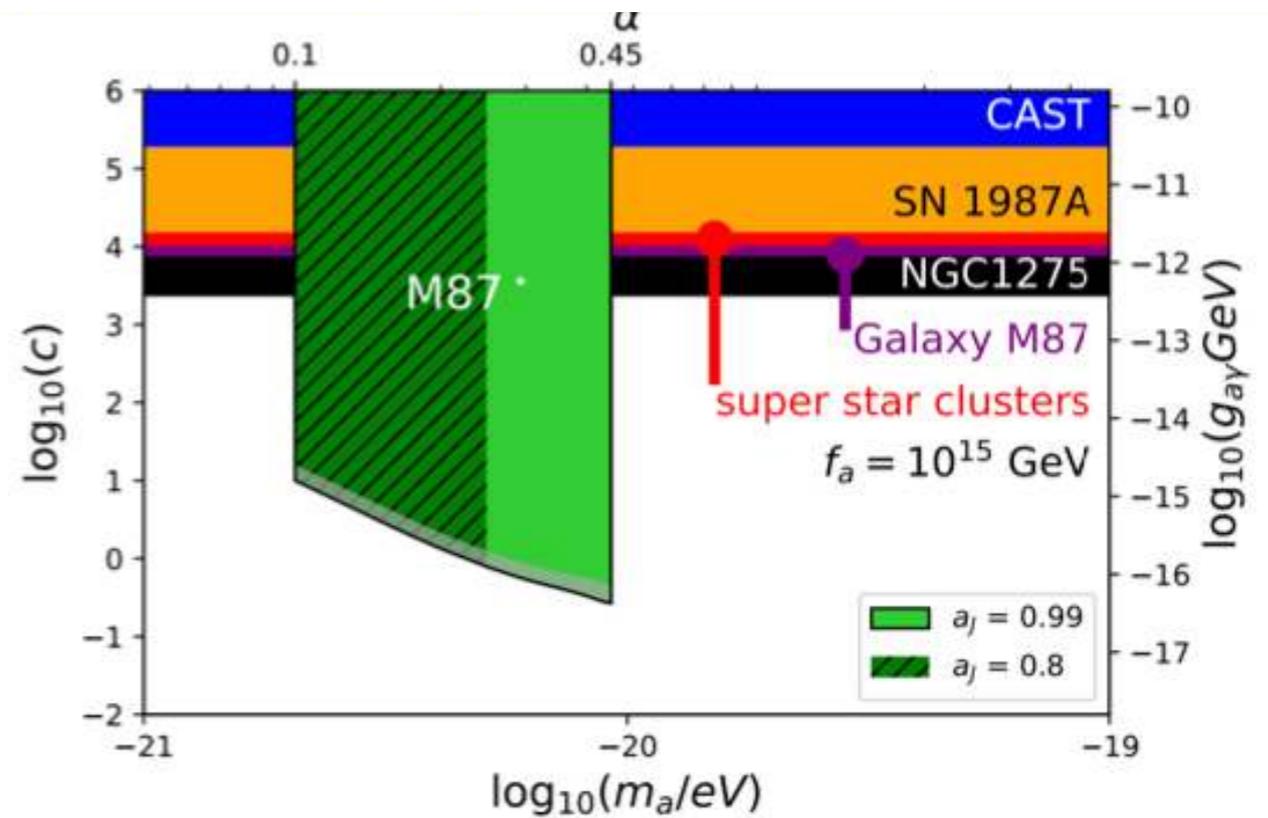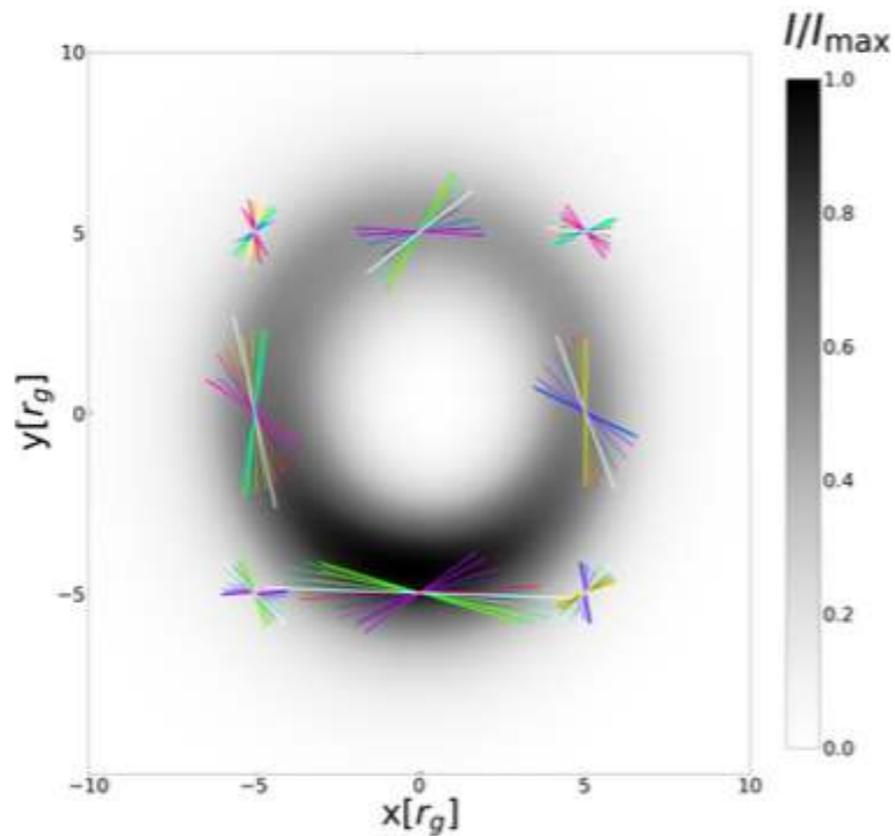
Experimental Constraint from Circular Polarisation of Light from M87
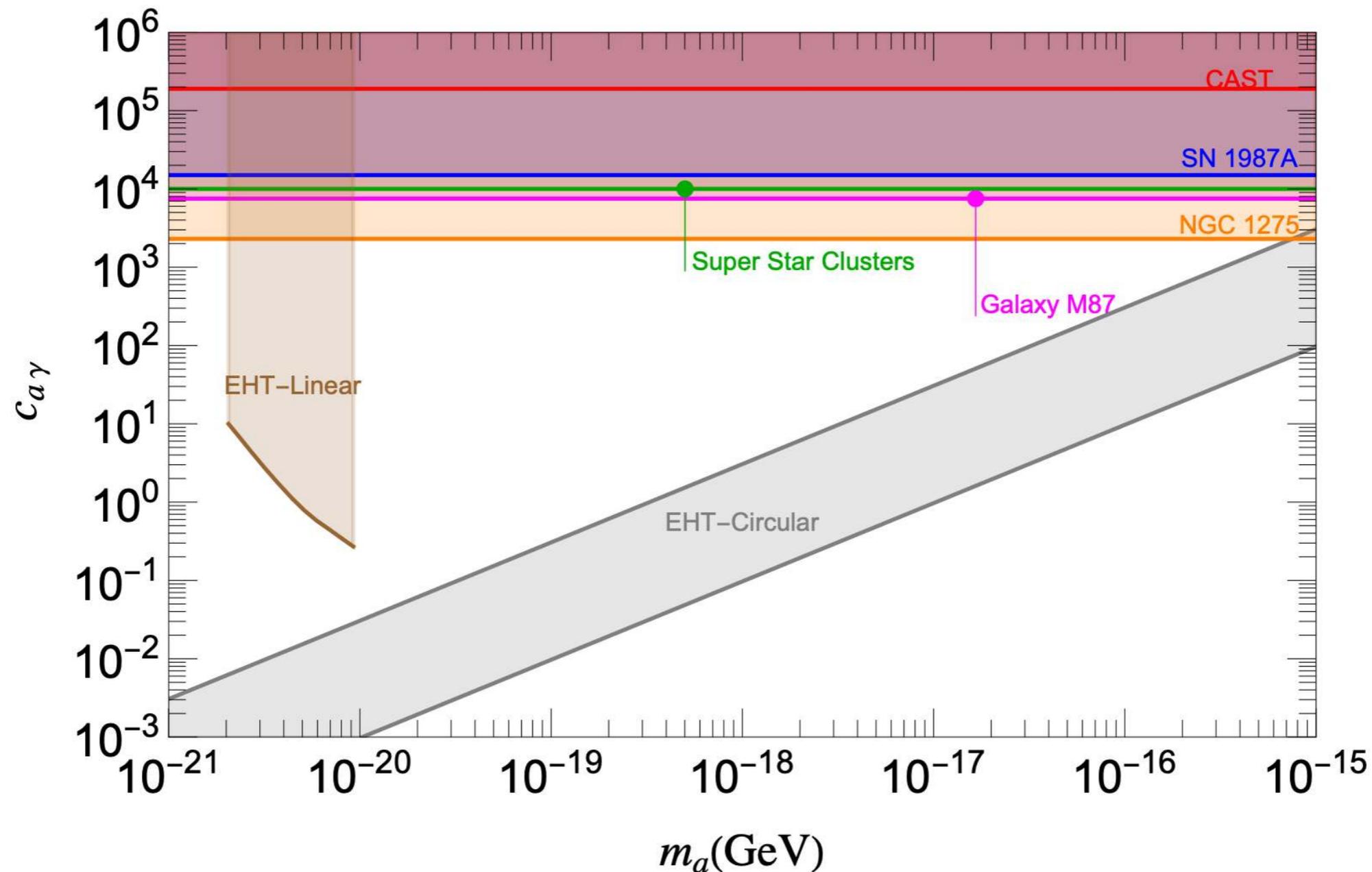
Constraints on axion mass m_a and its coupling to photons $c_{a\gamma} \equiv 2\pi g_{a\gamma} f_a$ where $f_a = 10^{15} \, GeV$ is assumed. The bound from circular polarization of light from EHT is shown by gray color. Linear polarization of light puts a bound from EHT presented by brown color. The experimental bound from CAST is shown by red color. Astrophysical constraints are also shown.

$$m_a \gtrsim 3.27 \times 10^{-19} c_{a\gamma} \left(\frac{\nu_\gamma}{230 \text{GHz}} \right)^{1/2} \left(\frac{B_0}{\text{G}} \right) \left(\frac{r}{r_g} \right)^{1/2} \text{eV}$$

arXiv:2209.13572

Thanks for your attention!

Event Horizon Telescope (EHT)
A Global Network of Radio Telescopes

2017 OBSERVATIONS

SMT

JCMT
SMA

LMT

30-M

ALMA
APEX

SPT

ALMA — Atacama Large Millimeter/submillimeter Array
CHAJNANTOR PLATEAU, CHILE

APEX — Atacama Pathfinder EXperiment
CHAJNANTOR PLATEAU, CHILE

30-M — IRAM 30-M Telescope
PICO VELETA, SPAIN

JCMT — James Clerk Maxwell Telescope
MAUNAKEA, HAWAII

LMT — Large Millimeter Telescope
SIERRA NEGRA, MEXICO

SMA — Submillimeter Array
MAUNAKEA, HAWAII

SMT — Submillimeter Telescope
MOUNT GRAHAM, ARIZONA

SPT — South Pole Telescope
SOUTH POLE STATION

NSF

AUI

NRAO

Event Horizon Telescope
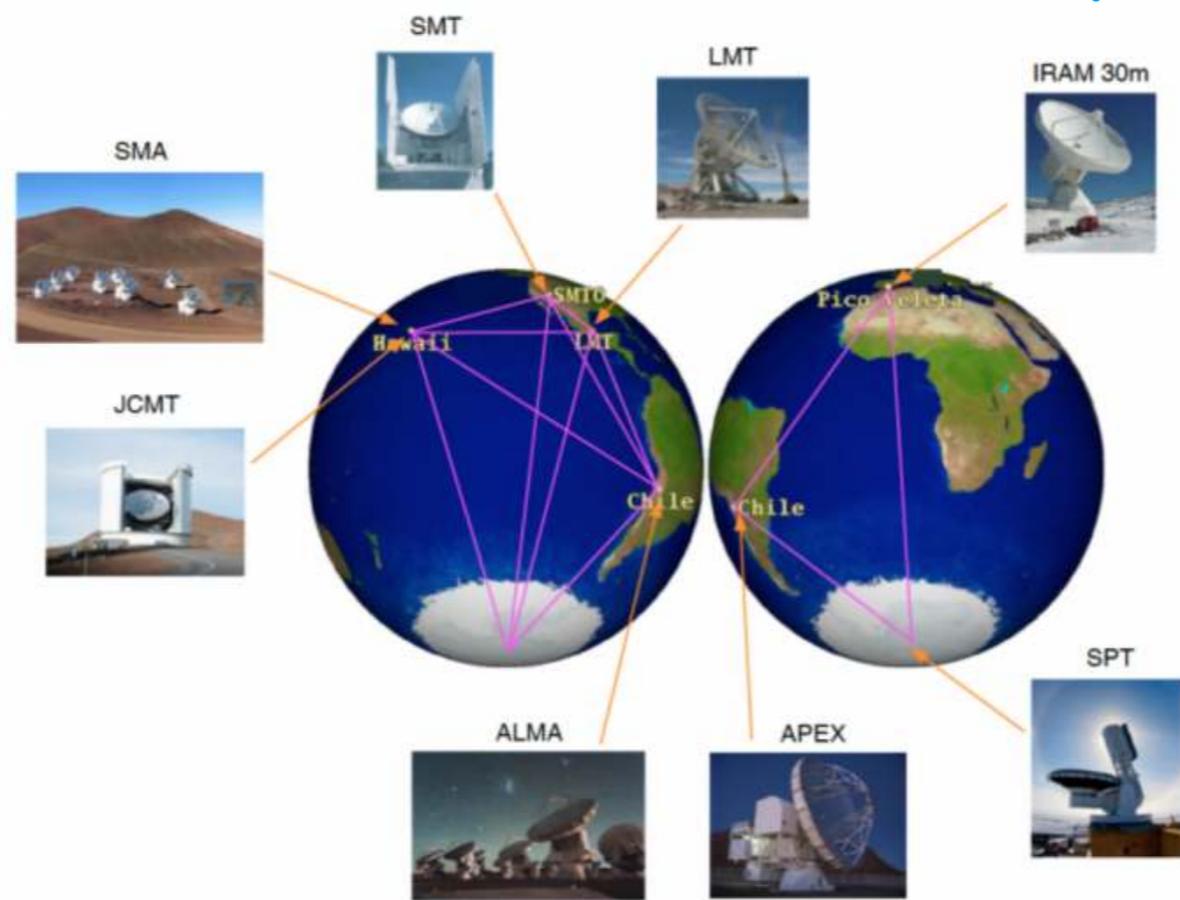
Simulations and Observation

The EHT Collaboration et al.

M87 April 6

GRMHD

Blurred GRMHD

40 μas

Brightness Temperature (10^9 K)
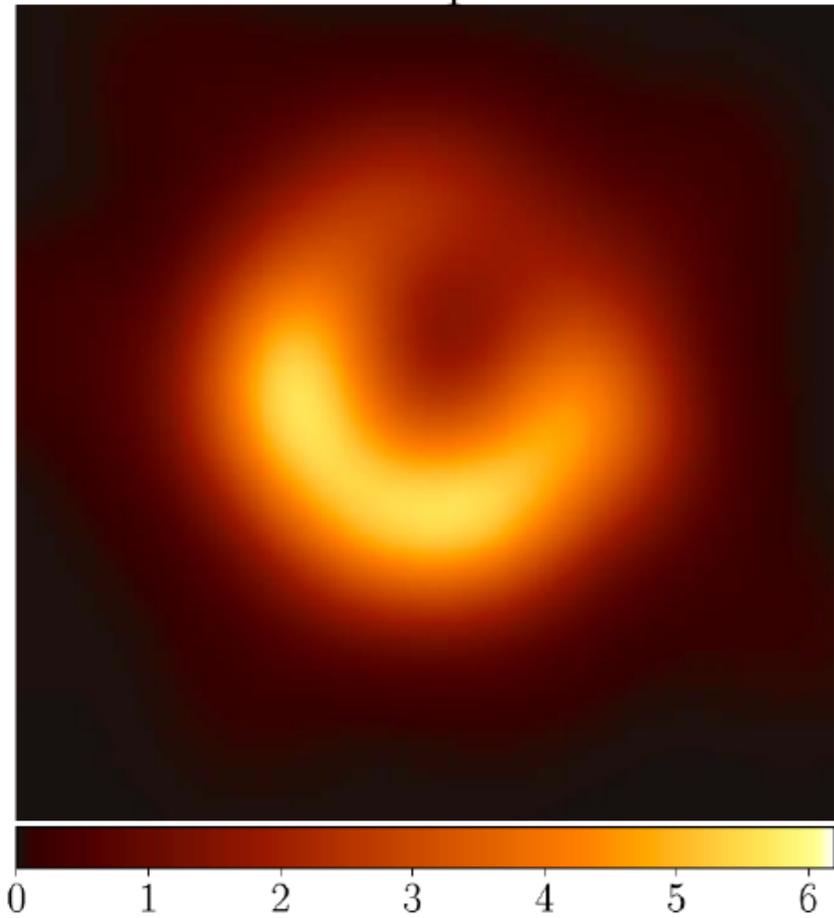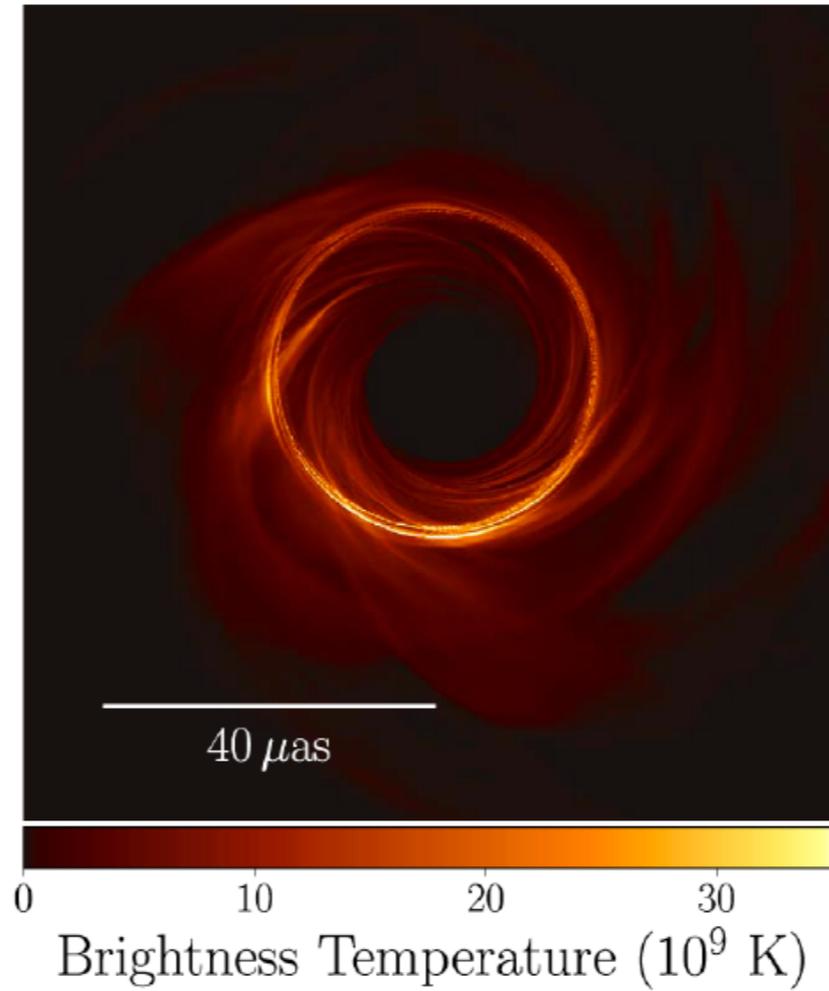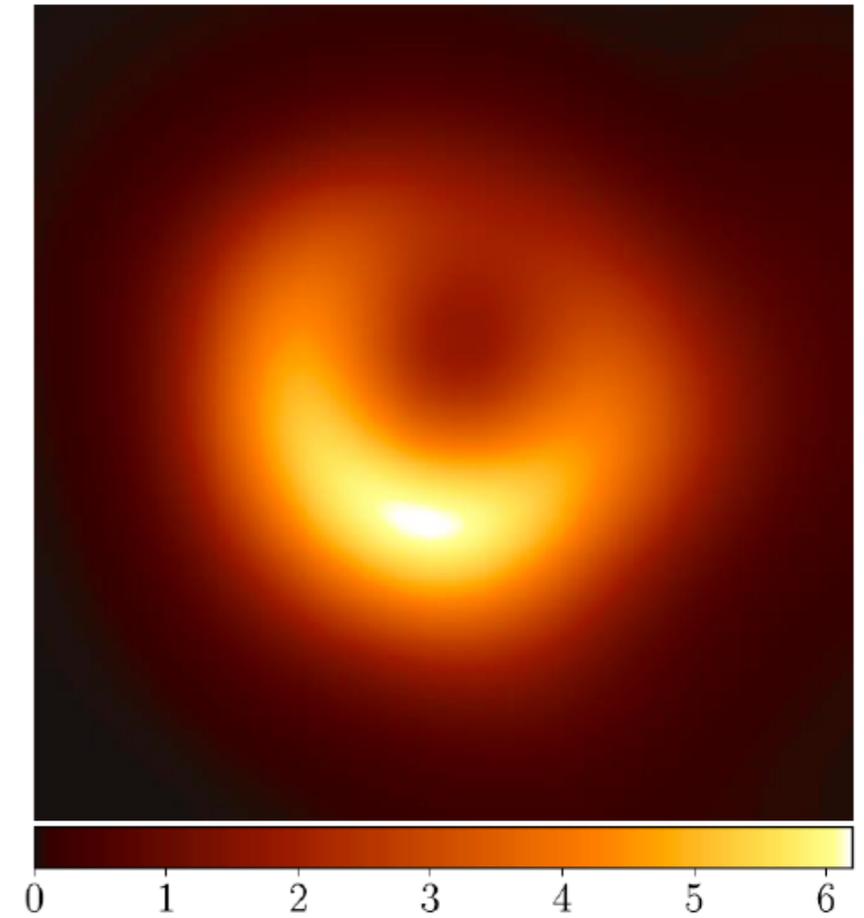
MHD Simulations and Ray Tracing Methods
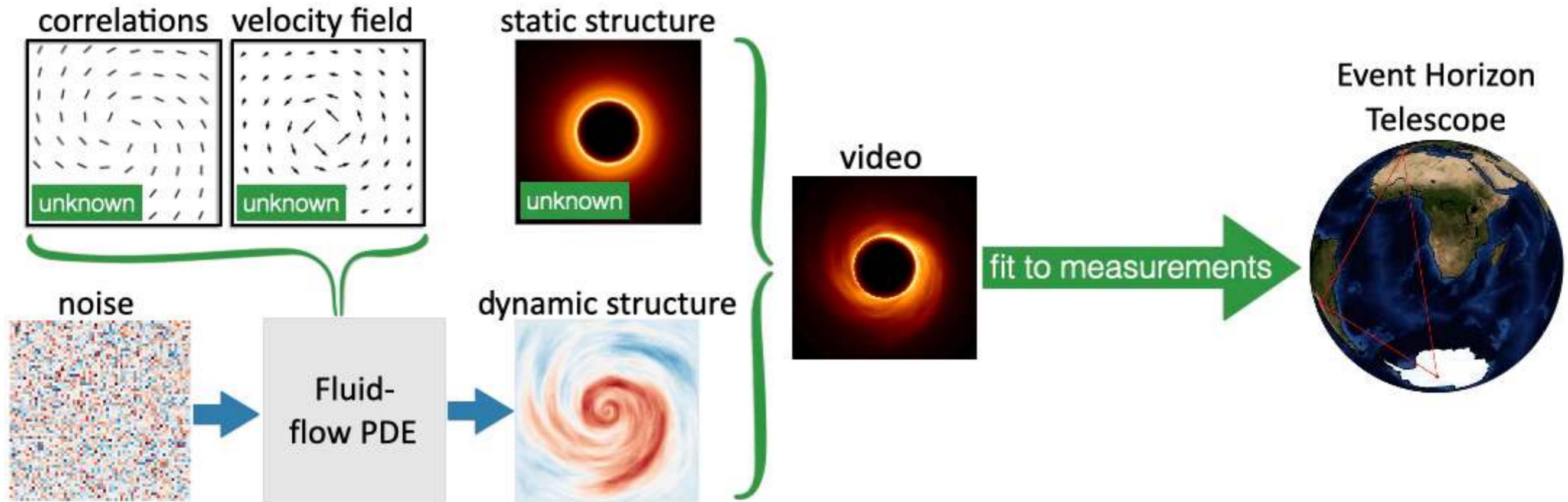
The source is modeled as a composition of static and dynamic structures. The dynamic component is a random field generated as a solution to a partial differential equation (PDE). The unknown PDE coefficients are the spatial correlations and velocity field, which, along with the static structure, are estimated in the inverse problem.

http://imaging.cms.caltech.edu/stochastic_inference/