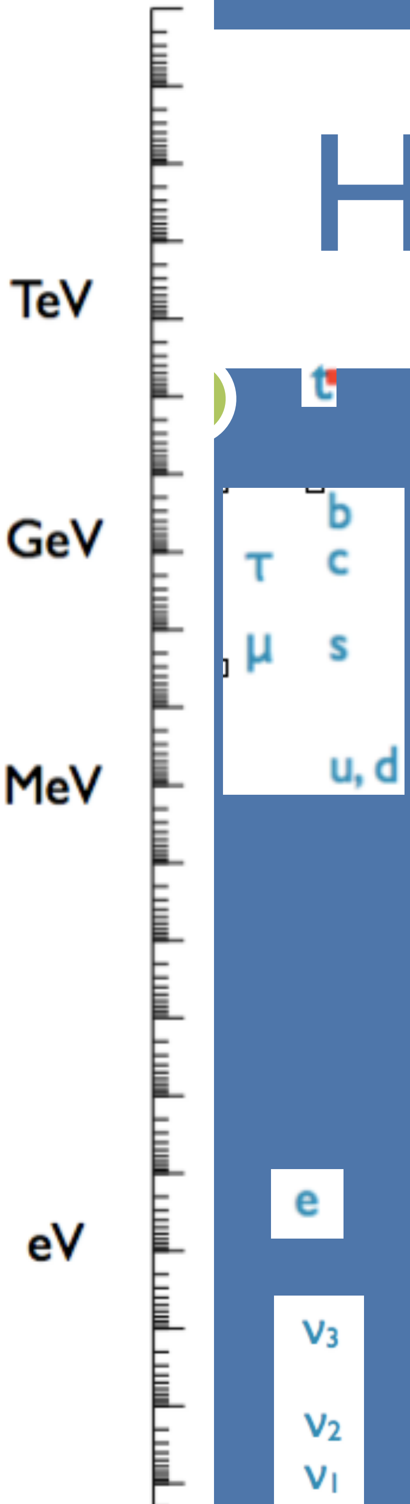
Probing Axions with Event Horizon Telescope Polarimetric Measurements

Y-f. Chen, J. Shu., X. Xiao, Q. Yuan, Y. Zhao, arxiv: 1905.02213

Introduction

- Motivation
- Axion: birefringence effect
- EHT polarmetric measurements
- Super-radiance
- Results
- Summary

High energy physics



W, Z h

2012

p, n

nucleus

12 orders of magnitude

atoms

1895

Open the door of sub-atom physics

Higher and higher energy

Last 122 years

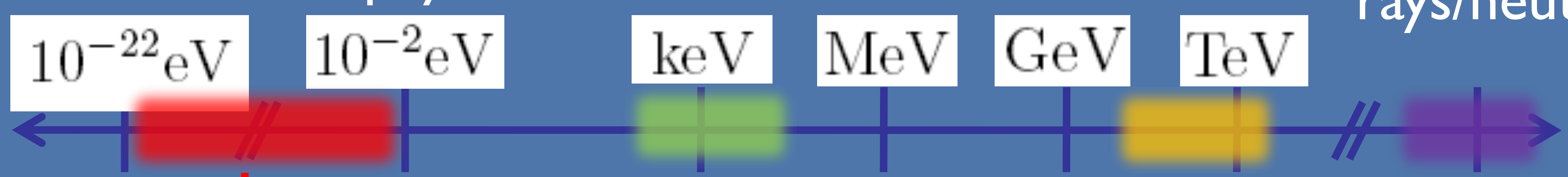
Extremely successful!

Not just higher energy

Besides the higher and higher energies, we may consider other extreme environment to search for NP

neutrino physics

high energy cosmic rays/neutrinos



Flavor physics

LHC colliders

Super light particles (QCD, axion, ALPs, DP, ….)

Table top exp: Cavity, LC circult, quantum sensor, etc.

Astrophysical exp: Radio signal, sun, supernova, etc.

Axion: birefringence effect

Theory motivation

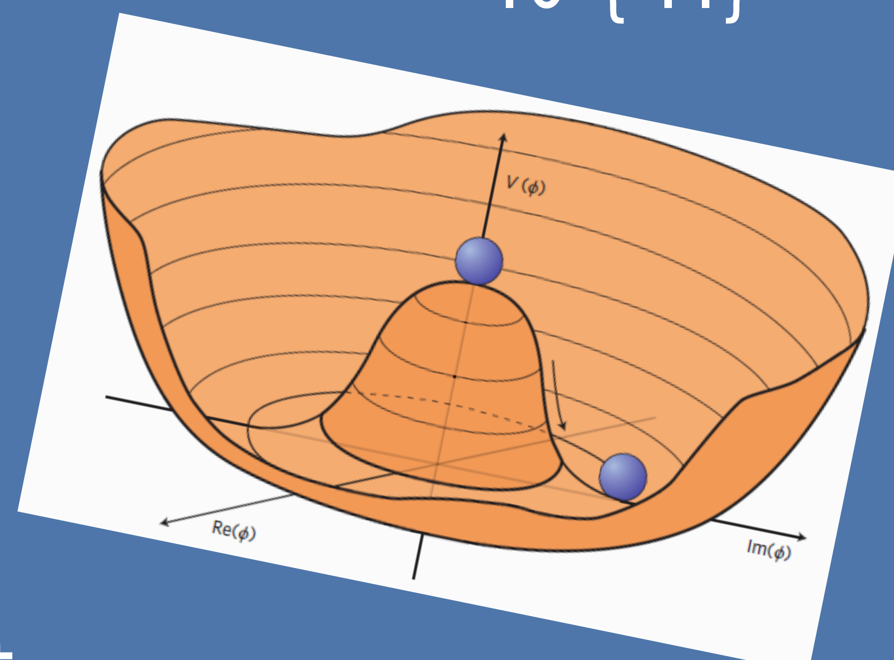
Strong CP problem

$$\underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi \le \bar{\Theta} \le +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

<10^{-11}

Induced axion fields

misalignment



PQ symmetry soft explicit
broken at high scale f

pNGB naturally very light

Why axion?

Big problems of particle physics & Comoslogy

- Strong CP problem
- The identity of dark matter — misalignment mechanism, non-thermal DM
- Gauge hierarchy problem, the origin of EWSB — relaxion
- Baryogenesis
- Inflation
- Cosmological Constant Problem

Search of axion

How to search axion?

Axion-couplings:

- Axion-photon

ADMX

CAST

LIGO, polsar, etc

- Axion-gluon

QCD phase transition

CASPEr

Axion like particle

Axion induce birefringent effect:

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

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

$$\nabla\cdot\boldsymbol{E} = g\nabla\varphi\cdot\boldsymbol{B}\,, \quad \nabla\times\boldsymbol{E} + \frac{\partial\boldsymbol{B}}{\partial t} = 0\,,$$

$$\nabla\times\boldsymbol{B} - \frac{\partial\boldsymbol{E}}{\partial t} = g\left(\boldsymbol{E}\times\nabla\varphi - \boldsymbol{B}\frac{\partial\varphi}{\partial t}\right),$$

$$\nabla\cdot\boldsymbol{B} = 0\,,$$

$$\Box\varphi = \frac{\partial^2\varphi}{\partial t^2} - \nabla^2\varphi = -g\boldsymbol{E}\cdot\boldsymbol{B}\,.$$

Maxell equation
with axion source

Birefringent effect

Axion induced birefringent effect

$$\Box A_{\pm} = \pm 2 i g_{a\gamma} [\partial_z a \dot{A}_{\pm} - \dot{a} \partial_z A_{\pm}],$$

$$\omega_{\pm} \approx k \pm \tfrac{1}{2} g \left(\frac{\partial \varphi}{\partial t} + \nabla \varphi \cdot \frac{\boldsymbol{k}}{k} \right)$$

different phase velocities for +/- helicities

For linearly polarized photons

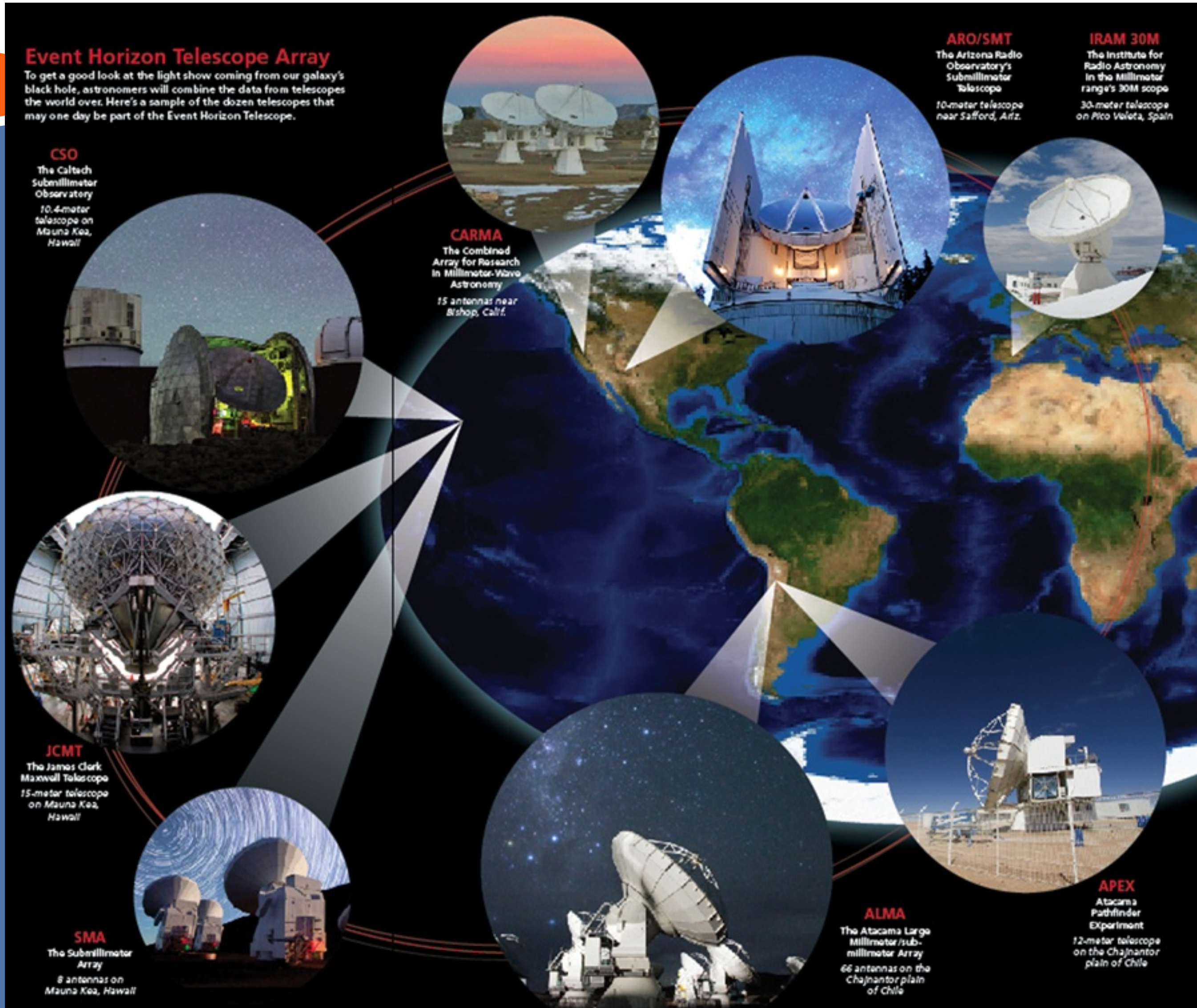
$$\begin{aligned} \Delta\Theta &= g_{a\gamma} \Delta a(t_{\rm obs}, \mathbf{x}_{\rm obs}; t_{\rm emit}, \mathbf{x}_{\rm emit}) \\ &= g_{a\gamma} \int_{\rm emit}^{\rm obs} ds\; n^{\mu}\; \partial_{\mu} a \\ &= g_{a\gamma} [a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})],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

Measure the change of the position angle:

Requires polarimetric measurements

EHT polarmetric measurements

Event Horizon Telescope



mm telescope array at radio frequency around the Earth

mm wavelength radio telescope particularly good for astro-astro-polarimetric measurements

Farady rotation: position angle around O(1)

Imagine of M87*

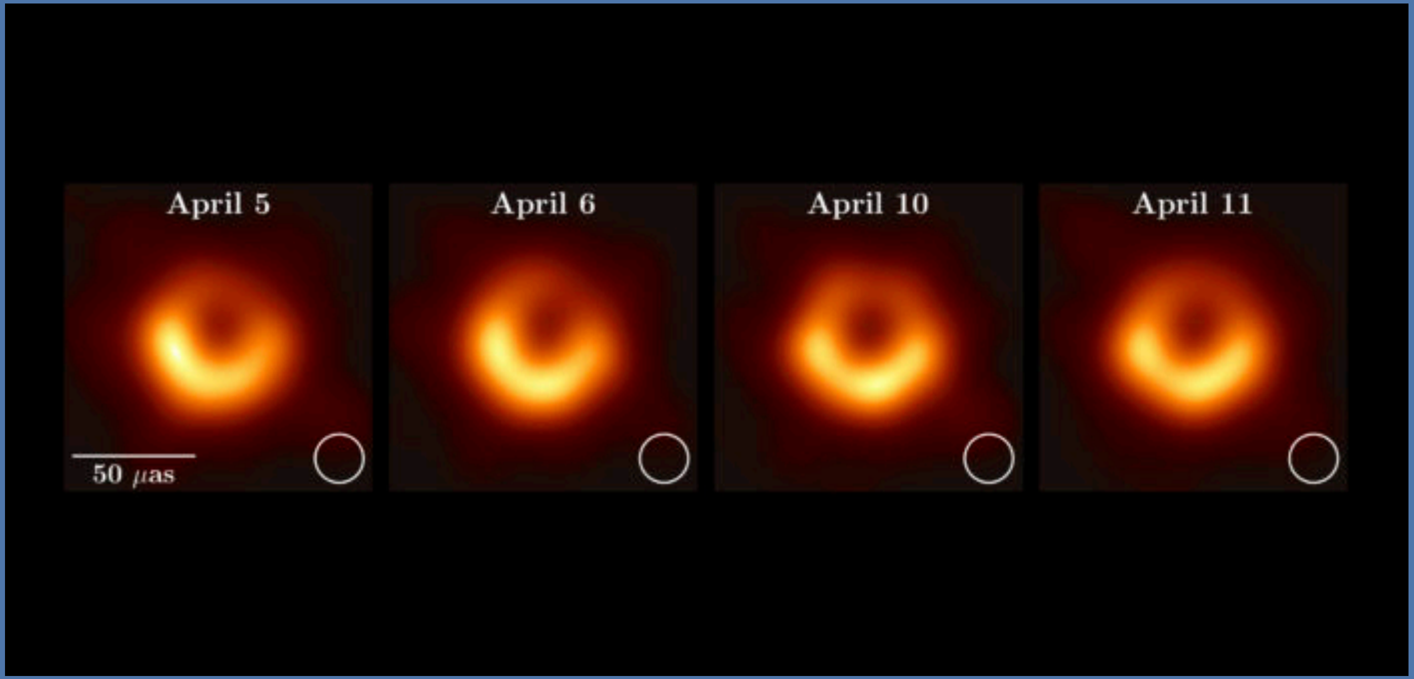


Image of the supermassive black hole at the center of the elliptical galaxy M87, for four different days.

The imagine of the ring is around 5 horizon distance

BH measured and EHT

M87*: 16 Mpc, 10^9 solar mass
10^13 m, 10^-20 eV
10^5 s, a=0.99

Blackhole measured:

Sgr A*: 8 kpc, 10^6 solar mass
10^10 m, 10^-17 eV
100 s, a=?

Excellent anglar resolutions:

20 micro as

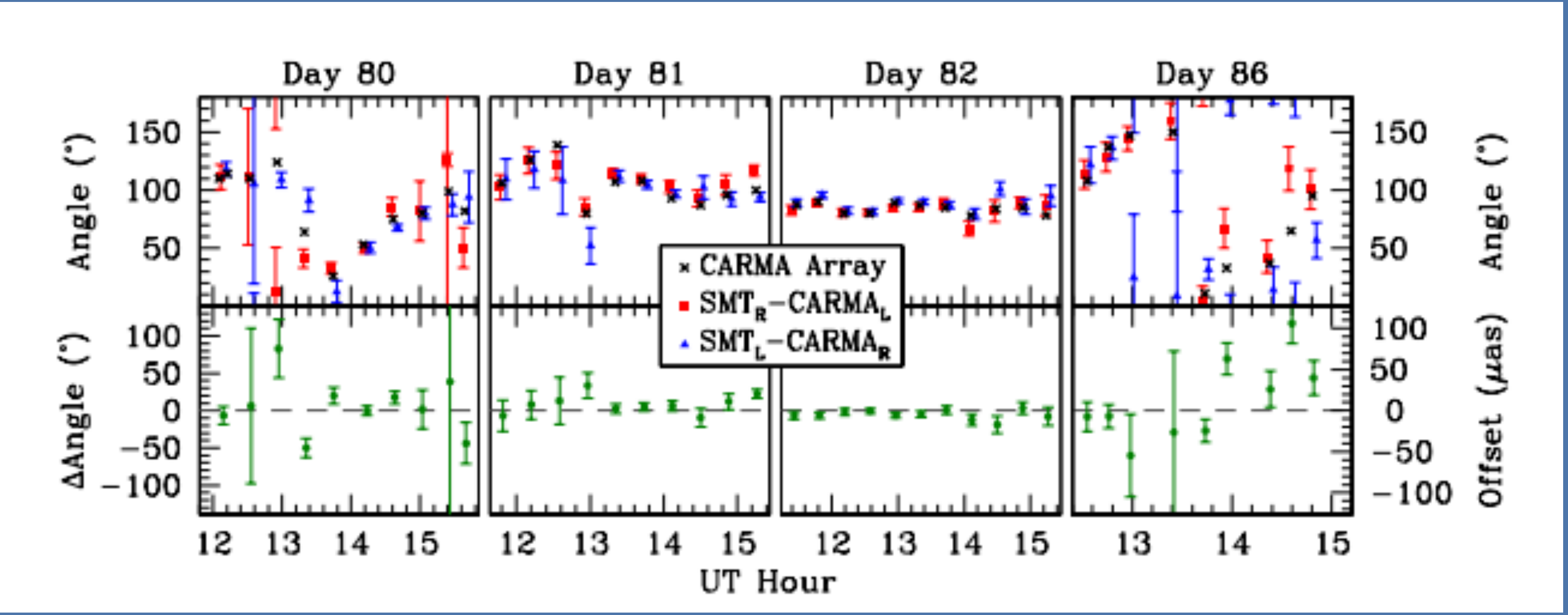
resolve features: smaller than BH size (1/3?)

SMBH	M	a_J	μ range	μ for $\alpha = 0.4$	τ_a	τ_{SR}
M87*	$6.5 \times 10^9 M_\odot$	0.99	$2.1 \times (10^{-21} \sim 10^{-20})$ eV	8.2×10^{-21} eV	5.0×10^5 s	$> 1.5 \times 10^{12}$s
Sgr A*	$4.3 \times 10^6 M_\odot$	—	$3.1 \times (10^{-18} \sim 10^{-17})$ eV	1.2×10^{-17} eV	3.3×10^2 s	$> 1.0 \times 10^9$s

TABLE I: Typical parameters of the axion superradiance of the two SMBHs, M87* and Sgr A*.

More on EHT measurements

- Accretion disk around SMBH gives linearly polarized radiation
- Millimeter wavelength: optimal for position angle measurements



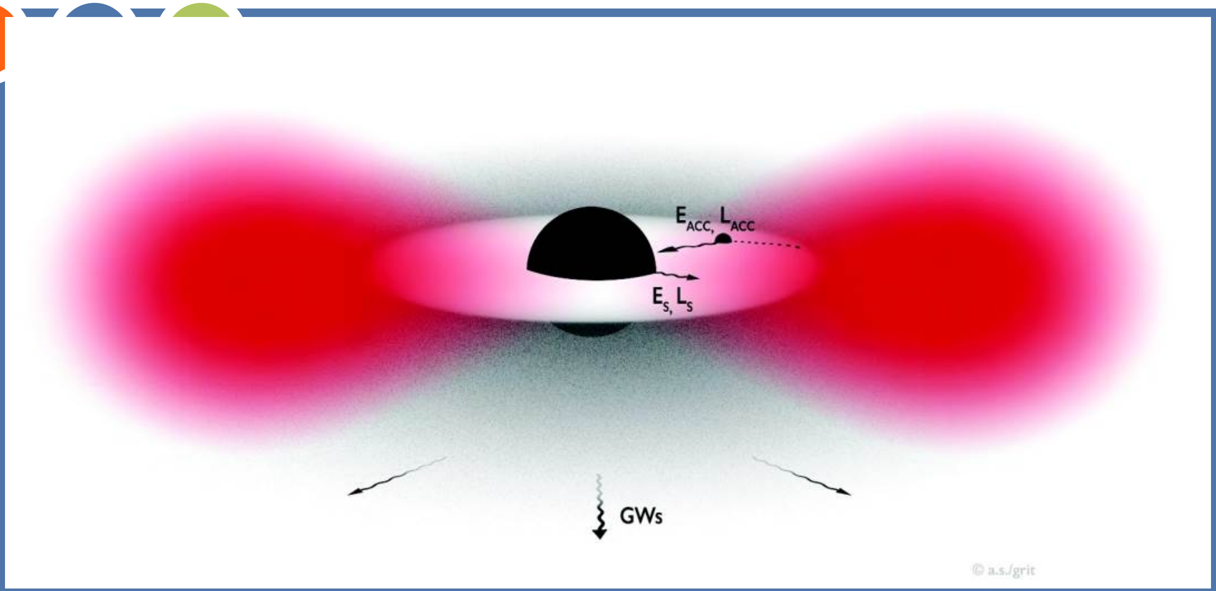
No spatial resolution

- M. D. Johnson et al., Science 350, no. 6265, 1242 (2015)

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

Super-radiance

BH superradiance



Superradiance condition

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

SR takes efficiently for the mass range

$$\frac{r_g}{\lambda_C} = \mu M \equiv \alpha \in (0.1, 1),$$

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!

BH superradiance

Axion cloud: Scalars in the Kerr backgrounds

Very similar to the hydrogen solution (non-relativistic limit):

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

$$\alpha \equiv \mu M$$

reduce to Y_{lm} in spherical
non-relativistic limit

$$\mathrm{Re}(\omega) \simeq \left(1 - \frac{\alpha^2}{2\bar{n}^2}\right) \mu$$

Imaginary part gives you the super-radiation

Axion cloud populates more efficiently at lower ℓ-mode.

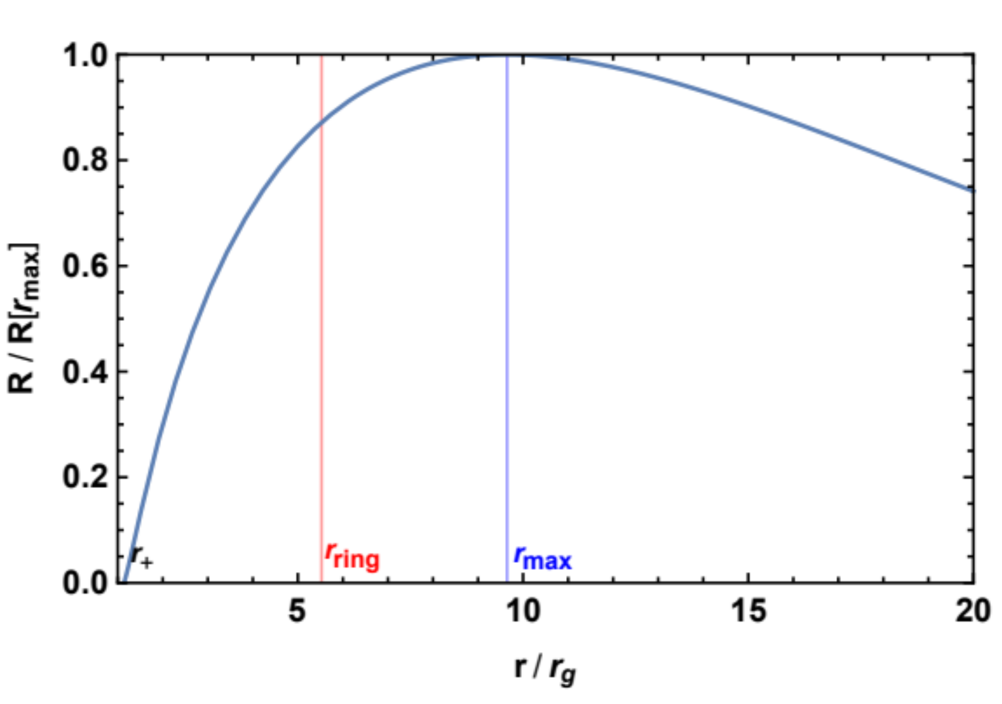
$m=\ell$ mode is more efficient than other m-levels.

BH superradiance

Spatial distribution:

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

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



Axion cloud solution

Axion Lagrangian including self-interaction:

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

K-G equation in the Kerr backgrounds

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

gravitational potential

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

self-interacting potential

Non-linear region

axion self-interaction becomes important when

gravitational potential ~ self-interacting potential

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

Two possible consequences:

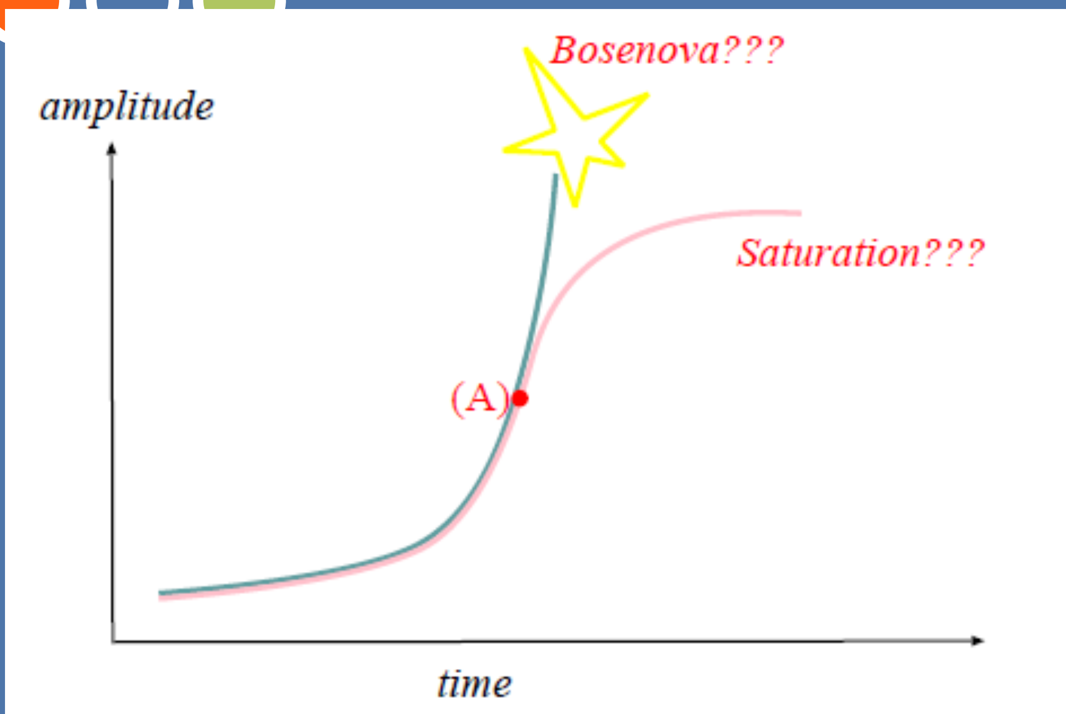
bosenova: a drastic process which explodes away axion cloud

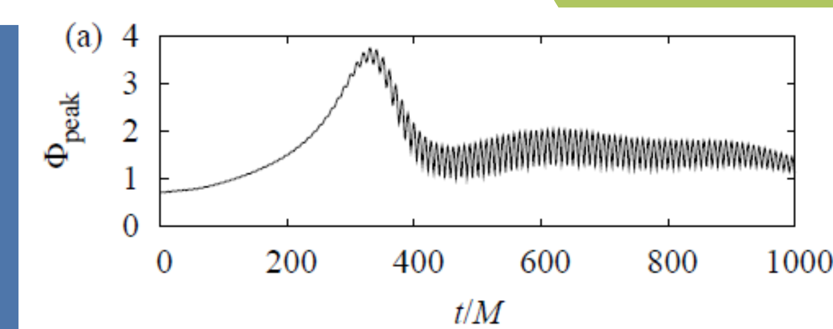
steady axion outflow to infinity

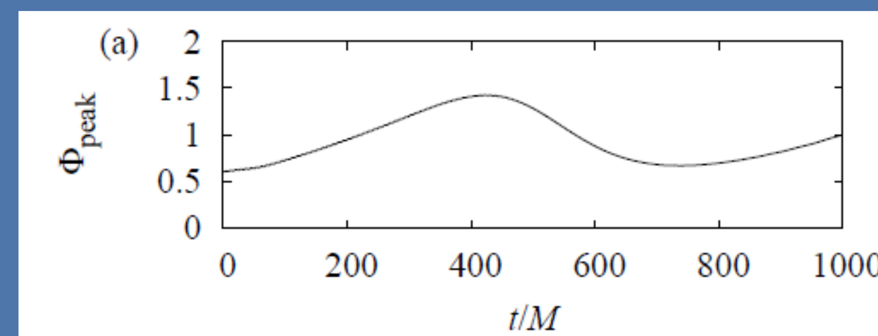
numerical simulation has been performed:

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

Bosenova







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

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

The axion cloud stays after bosenova

Position angle change

Using $a_0 \approx f_a$ and $\omega \approx \mu$ 	Ignore axion density at earth

$$\Delta\Theta_{\rm max} \simeq -b g_{a\gamma} f_a \cos\left[\mu t_{\rm emit} + \beta(|\mathbf{x}_{\rm emit}| = r_{\rm max})\right],$$

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

$$\Delta\Theta(t,r,\theta,\phi) \approx -\frac{b g_{a\gamma} f_a R_{11}(r)}{R_{11}(r_{\rm max})} \sin\theta \boxed{\cos\left[\omega t - m\phi\right].} \quad (17)$$

Require both time and spatial resolution

additional loop suppression to translate fa to axion-photon coupling

$$g_{a\gamma} \equiv \frac{c}{2\pi f_a} \equiv \frac{c_\gamma \alpha_{em}}{4\pi f_a},$$

fermion loop $c_\gamma \sim NQ^2.$

clockwork $c_\gamma \sim 2Q^2 q^{N-M}.$ Large

Polarmetric measurements

Requirements:

Concentration of axion: oscillating background fields

Stable (position angle) polarized source

Search for:

Position angle oscillate with time

Position angle oscillate with spatial distributions (extended source)

Polarmetric measurements at EHT from the axion cloud!

Results

Position angle change

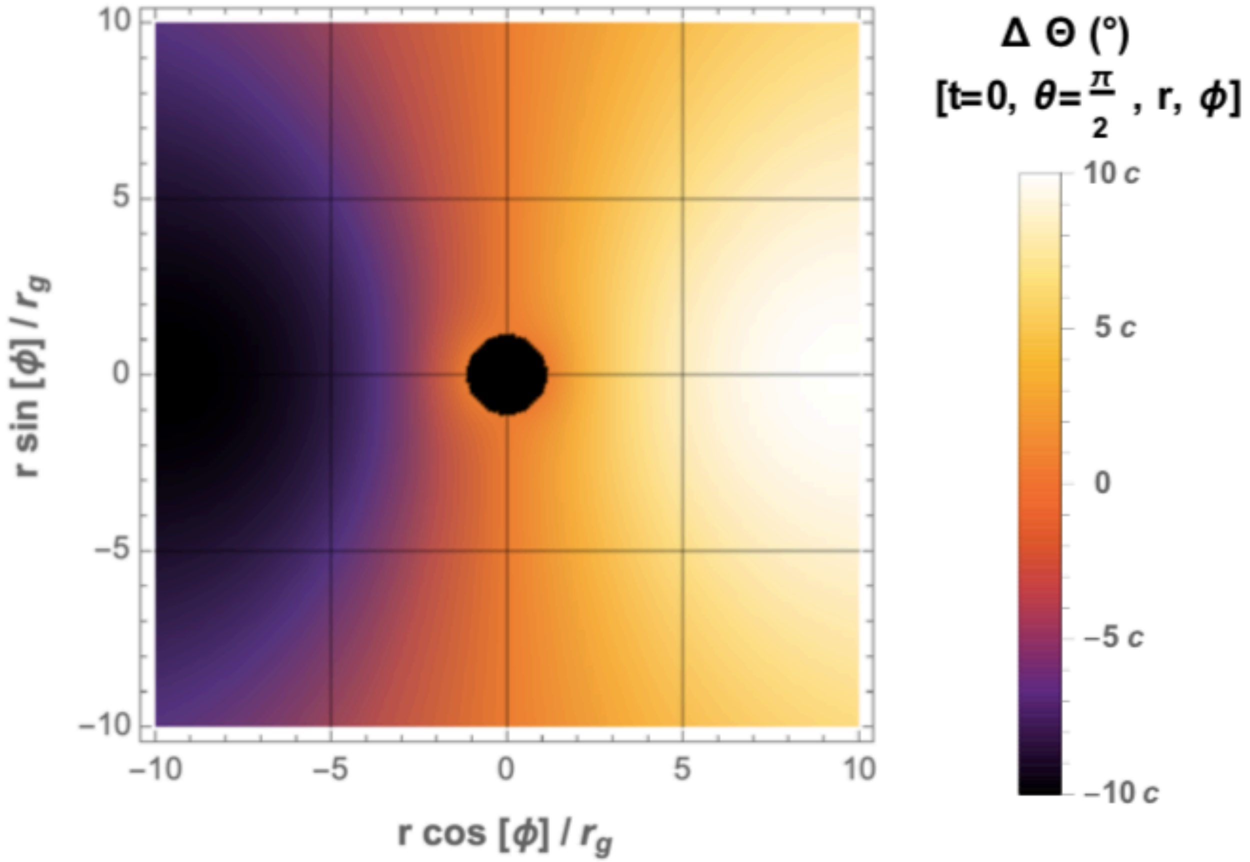
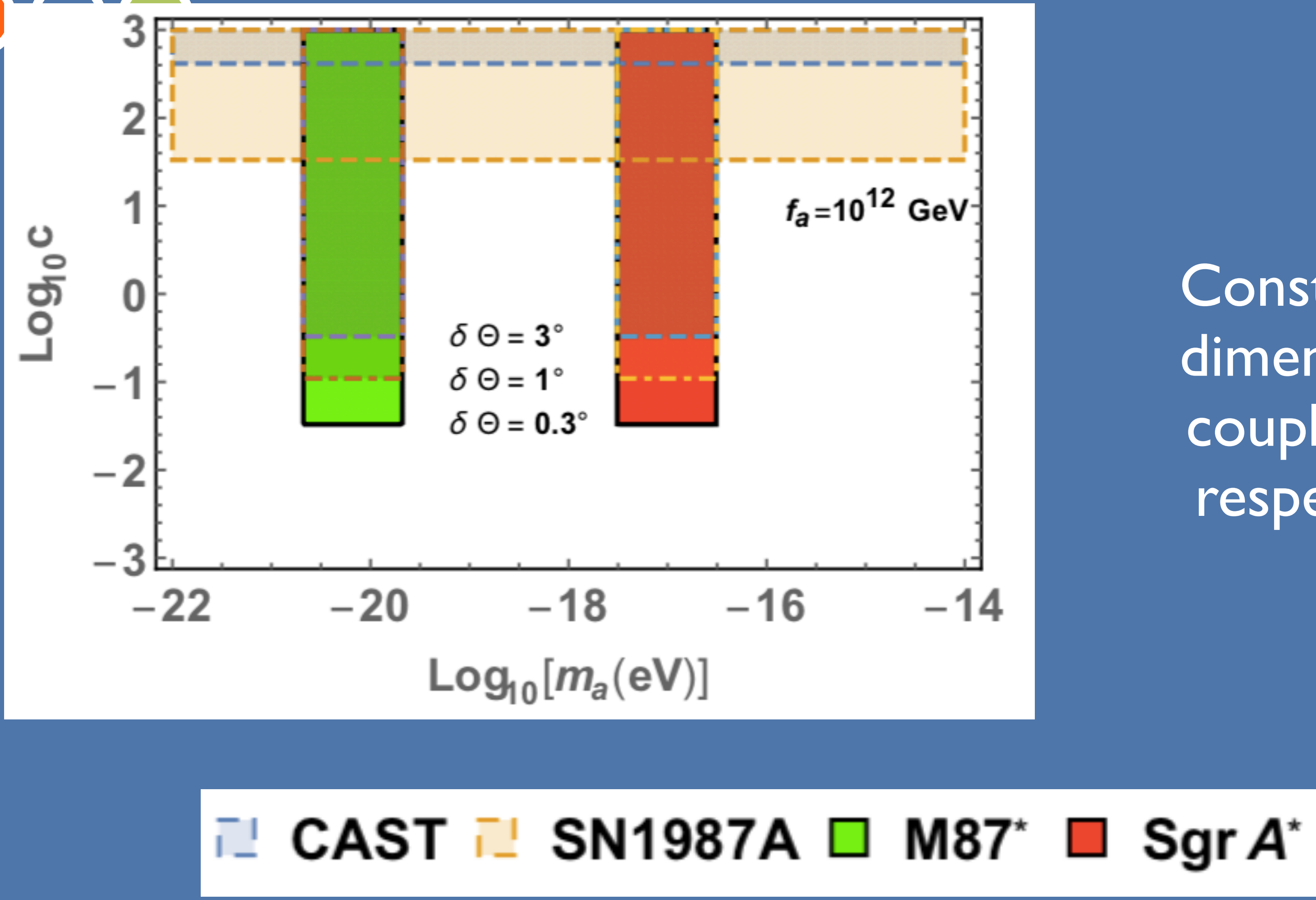


FIG. 2: $\Delta\Theta(t=0, \theta=\pi/2, r, \phi)$ viewed along the rotating axis of the black hole. The amplitude of oscillation is around $8c^\circ$ at $r_{\rm ring}$ for $l=1$, $m=1$, $\alpha=0.4$, and $a_J=0.99$. The region of $r<r_+$ is masked.

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

Expected Limit



Constrain the dimensionless coupling with respect to fa

Summary

Supermassive Black holes provides excellent probes to search for axion!

A dense axion cloud can build up near by SMBHs.

Accretion disk emits linearly polarized photons.

Position angles varies when traveling through the axion cloud

EHT can provide measurements on position angles.

Probe the existence of axion clouds by EHT.

Different than BH spin measurement. (Nonlinear region)

Different than other experiment. (dimensionless coupling)