Supermassive Black Holes as Detectors for Ultra-light Bosons

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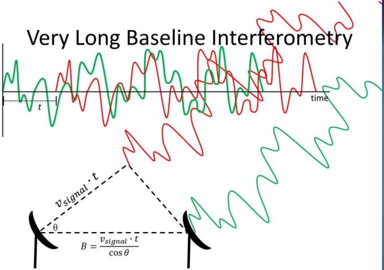
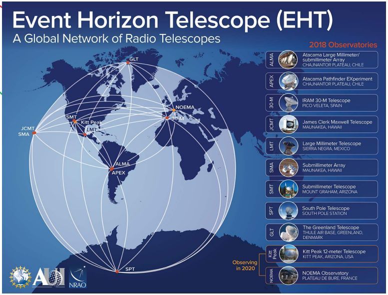
Event Horizon Telescope: an Earth-sized Telescope

- For single telescope with diameter D, the angular resolution for photon of wavelength λ is around $\frac{\lambda}{D}$;
- VLBI: for multiple radio telescopes, the effective D becomes the maximum separation between the telescopes.

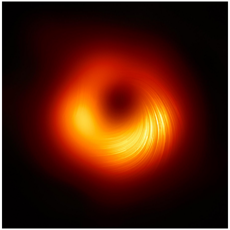




- As good as being able to see  on the moon from the Earth.

Supermassive Black Hole (SMBH) M87* [EHT 19' 21']

Total intensity I



Linear polarization Q, U
EVPA $\chi \equiv \arg(Q + i\ U)/2$

- First time ever: **shadow** and the ring;
- Ring size determines $6.5 \times 10^9 M_\odot$;
- Polarization map reveals magnetic field structure.
- Four days' observations **show slight difference**.

From other observations:

- Nearly extreme Kerr black hole: $a_J > 0.8$;
- Almost face-on disk with a 17° inclination angle;
- Rich information under strong gravity, **what else can we learn?**

Ultralight Bosons: $\Psi = a, B^{\mu}$ and $H^{\mu\nu}$

- Axion: hypothetical pseudoscalar motivated by strong CP problem.

- **Extra dimensions** predict a wide range of ultralight boson mass:

$$-\frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \mathcal{L}_{\mathrm{EH}}(H) - V(\Psi)$$

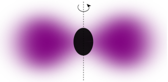
Dimensional reduction from higher form fields:

e.g. $g^{MN}(5D) \to g^{\mu\nu}(4D) + B^{\mu}(4D)$, $\quad B^{M}(5D) \to B^{\mu}(4D) + a(4D)$.

- **Coherent wave** dark matter candidates when $m_{\Psi} < 1$ eV:

$$\Psi(x^{\mu}) \simeq \Psi_0(\mathbf{x})\cos\omega t; \qquad \Psi_0 \simeq \frac{\sqrt{\rho}}{m_{\Psi}}; \qquad \omega \simeq m_{\Psi}.$$

Superradiance and Gravitational Atom



- **Gravitational Atom** between BH and axion cloud:

$$\text{BL coordinate}: \Psi^{\mathrm{GA}}(x^\mu) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r), \qquad \omega \simeq m_\Psi + i\Gamma.$$

- **Superradiance** [Penrose, Zeldovichi, Starobinsky, Damour et al]: bosons' wave-functions are exponentially amplified from extracting BH rotation energy when

$$\text{Compton wavelength } \lambda_c \simeq \text{ gravitational radius } r_g.$$

- **Supermassive black holess as detectors for ultralight bosons**:

$$M_{BH} \sim 10^9 M_\odot \leftrightarrow m_\Psi \sim 10^{-21} eV.$$

- Superradiant cloud can be significantly denser than dark matter profile, e.g., $a^{\mathrm{GA}}_{\max} \simeq f_a$ for axions [Yoshino, Kodama 12' 15', Baryakht et al 20'].

Hunting Axions with Event Horizon Telescope

Polarimetric Measurements

based on
arxiv: 1905.02213, Phys. Rev. Lett. **124** (2020) no.6, 061102,
arxiv: 2105.04572, Nature Astron. **6** (2022) no.5, 592-598,
arxiv: 2208.05724, JCAP **09** (2022), 073.

YC, Chunlong Li, Yuxin Liu, Ru-Sen Lu, Yosuke Mizuno, Jing Shu, Xiao Xue, Qiang Yuan, Yue Zhao, Zihan Zhou.

Axion QED: Achromatic Birefringence [Carroll, Field, Jackiw 90']

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

- Chiral dispersions under axion background:

$$[\partial_t^2 - \nabla^2]A_{L,R} = \mp\, 2g_{a\gamma}n^\mu\partial_\mu a\, k\, A_{L,R}, \qquad \omega_{L,R} \sim k \mp g_{a\gamma}n^\mu\partial_\mu a.$$

n^μ: unit directional vector

- Shift of **electric vector position angle** of linear polarization:

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

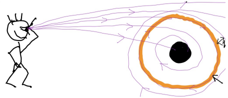
- Topological effect for each photon: only $a(x^\mu_{\mathrm{emit}})$ and $a(x^\mu_{\mathrm{obs}})$ dependent.

Axion Cloud and Birefringence

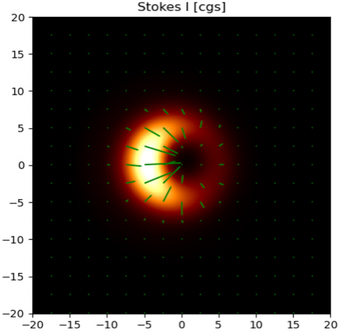
- Extended sources, plasma and curved space-time effects?

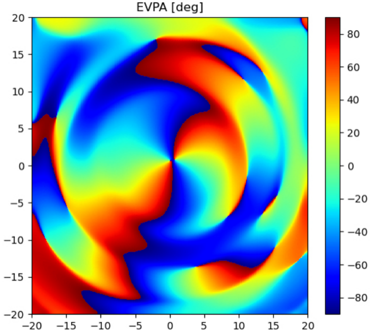
Covariant radiative transfer [IPOLE simulation]

with an accretion flow model outside SMBH:



[Strominger 19']

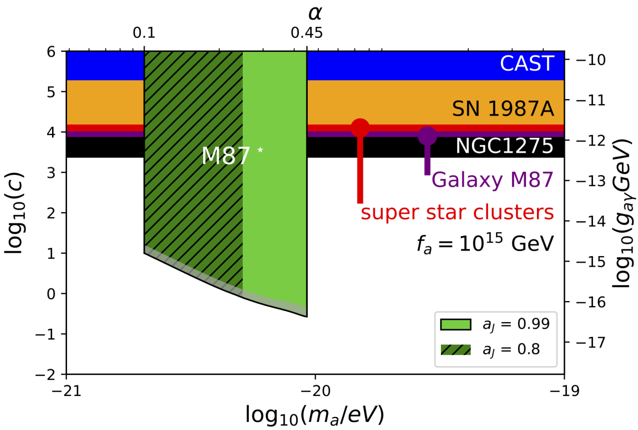




Stringent Constraints on Axion-Photon Coupling

- Uncertainty of EVPA in [EHT 21']:

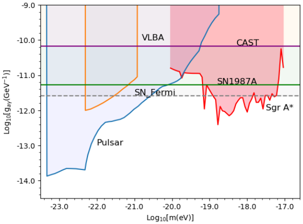
  $\rightarrow$ dimensionless **axion photon coupling** $c \equiv 2\pi g_{a\gamma} f_a$:

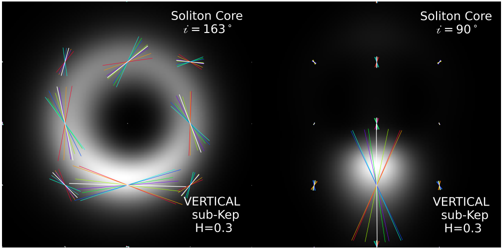


- Next-generation EHT is expected to significantly increase sensitivity.

Birefringence from Soliton Core Dark Matter

- Ultralight axion dark matter forms soliton core in the galaxy center. **Quantum pressure balences gravitational interactions** $a \sim 10^{10}$ **GeV.**





- Linearly polarized photon from **pulsar**. [Liu et al 19' Caputo et al 19']

- Polarized radiation from **Sgr A***.[Yuan, Xia, YC, Yuan et al 20']

- Coherent signals at each pixel increase the sensitivity.

Photon Ring Astrometry

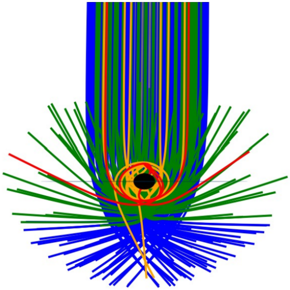
for Superradiant Clouds

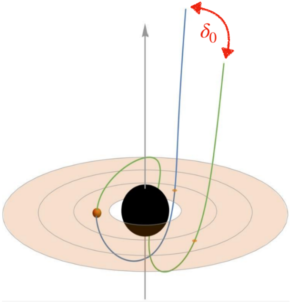
based on
arXiv:2211.03794,

YC, Xiao Xue, Richard Brito, Vitor Cardoso.

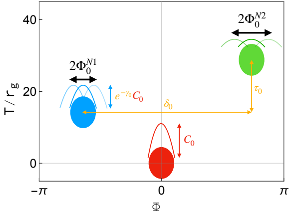
Photon Ring

Bound solutions of Kerr null geodesics: photons propagating multiple times around BH enhance intensity on the image plane:



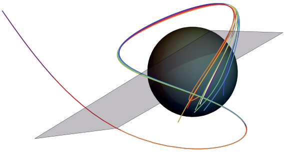


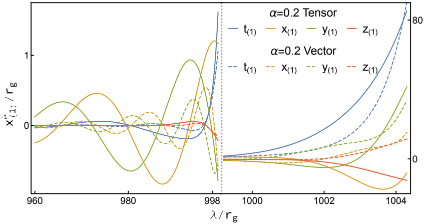
- **Autocorrelation** for intensity fluctuations:
  $\mathcal{C}(T,\Phi) \equiv$
  $\iint d\rho\, d\rho' \rho\, \rho' \left\langle \Delta I(t,\rho,\varphi) \Delta I\,(t+T,\rho',\varphi+\Phi)\right\rangle$,
  peaks at $T = \tau_0$ and $\Phi = \delta_0$.
- Precise test of general relativity
  $\rightarrow$ **astrometry for new physics**?



Gravitational Atom-induced Geodesics Deflections

- Real vector or tensor clouds generate oscillating metric perturbations $g_{\mu\nu} \simeq g^{\mathrm{K}}_{\mu\nu} + \epsilon h_{\mu\nu}$ that **deflect geodesics** $x^{\mu} \simeq x^{\mu}_{(0)} + \epsilon x^{\mu}_{(1)}$:





- Two phases of evolution:

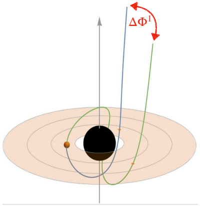
  Perturbative generation of oscillatory deviations;

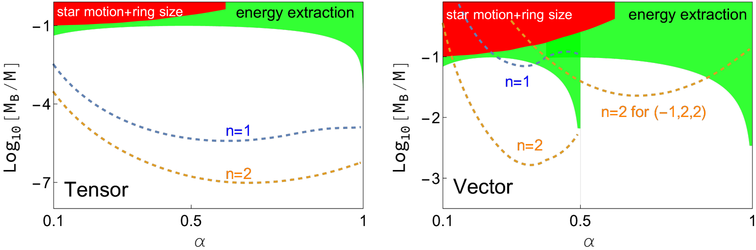
  Photon ring instability leads to **exponential growth** of the deviations.

Photon Ring Autocorrelations as Astrometry

- For lensed photons propagating n half-orbits around BH:

  Oscillating azimuthal lapse $\Delta\Phi^n/\epsilon = x^{\phi}_{(1)}(\lambda_n) - x^{\phi}_{(1)}(\lambda_0)$.





- $n = 2$ photon ring autocorrelation can probe large unexplored parameter space of cloud mass.

Summary

- **Rotating supermassive black holes** are powerful detectors for **ultralight bosons** due to superradiance.

- **Linearly polarized radiation from dense axion field saturating $a \simeq f_a$:**

  Oscillating axion background $\rightarrow$ **EVPA oscillates**.

  $c \equiv 2\pi g_{a\gamma} f_a$ constraints from EHT polarimetric measurements.

  Next-generation EHT can significantly improve the constraints.

- Gravitational atoms induce oscillatory metric perturbations that **deflect photon ring geodesics**.

  Exponential growth of geodesics deviation in nearly bound orbit due to photon ring instability.

  EHT photon ring autocorrelation constrains large unexplored parameter space of cloud mass.

Thank you!

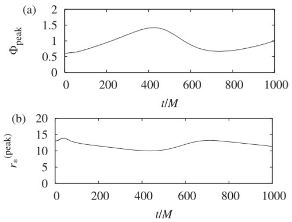
Appendix

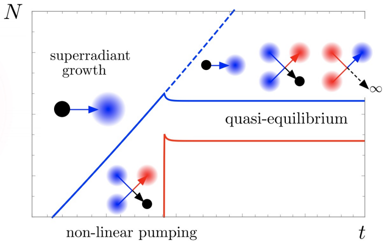
Weakly Saturating Axion Cloud

- Strong self-interaction region $a^{\mathrm{GA}} \simeq f_a$ happens when $f_a < 10^{16}$ GeV:

$$V(a) = m_a^2 f_a^2 \left(1 - \cos\frac{a}{f_a}\right) = \frac{m_a^2 a^2}{2} - \frac{m_a^2 a^4}{24 f_a^2} + \ldots;$$

- A quasi-equilibruim phase where **superradiance and non-linear interaction induced emission balance each other** with $a^{\mathrm{GA}}_{\mathrm{max}} \simeq \mathcal{O}(1)\, f_a$.





[Yoshino, Kodama 12' 15', Baryakht et al 20']

Axion Cloud and Birefringence

- **Axion cloud** saturates f_a due to self-interactions:

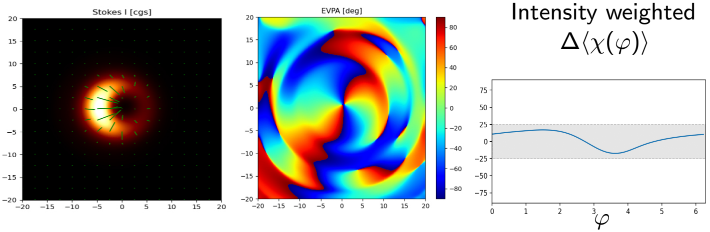
$r_g m_a \approx \mathcal{O}(1)$

$$a^{\rm GA}(x^\mu) \simeq R_{11}(\mathbf{x}) \cos\left[m_a t - \phi\right] \sin\theta; \qquad a^{\rm GA}_{\max} \simeq \mathcal{O}(1)\, f_a; \qquad \omega \simeq m_a.$$

- $g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \rightarrow$ achromatic birefringence to EVPA $\chi \equiv \arg(Q + i\ U)/2$:

$$\text{Local frame}: \quad \frac{d(Q + i\ U)}{ds} = j_Q + i\, j_U + i\left(\rho_V^{\rm FR} - 2 g_{a\gamma} \frac{da^{\rm GA}}{ds}\right)(Q + i\ U).$$

EVPA shift for each photon: $\Delta\chi \approx g_{a\gamma} \times a^{\rm GA}(x^\mu_{\rm emit})$



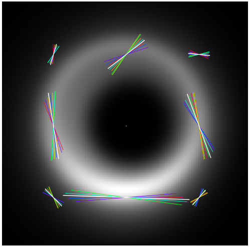
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along** φ on the sky plane

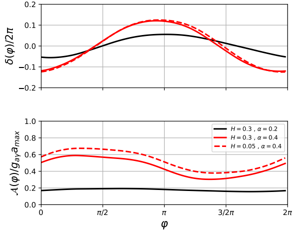
BL coordinate: $a^{\rm GA} \propto \cos\left[m_a t - \phi\right] \rightarrow \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi) \cos\left[m_a t + \varphi + \delta(\varphi)\right].$

Axion Birefringence for RIAF around M87* (IPOLE simulation)

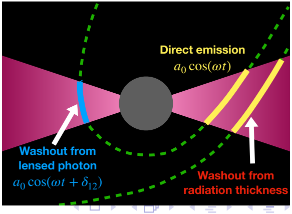
$$\Delta\langle\chi(\varphi)\rangle = \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$$

- Scan axion mass: $\alpha \equiv r_g m_a \in [0.10, 0.44]$ with **period [5, 20] days**.





- $\delta(\varphi) \approx -5\ \alpha\ \sin 17^\circ \cos\varphi$: phase delay at different φ.
- Asymmetry of $\mathcal{A}(\varphi) = \mathcal{O}(1) g_{a\gamma} f_a$: **washout from lensed photon with** $\delta_{12} = \omega\delta t - \delta\phi$!



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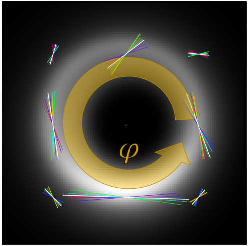

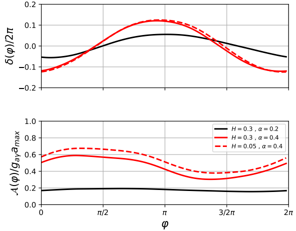

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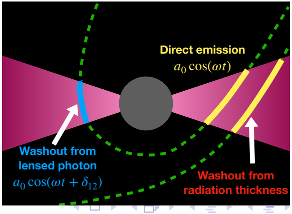
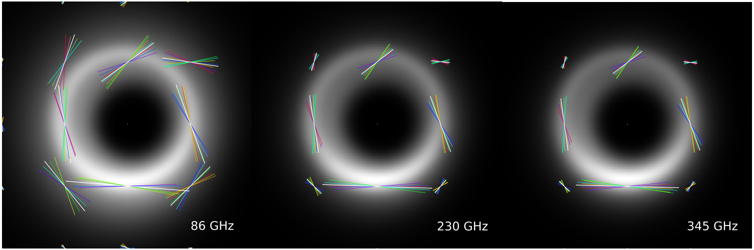


Prospect for next-generation EHT

- Correlation between $\Delta\chi$ at **different radius** and frequency.

  At 86 GHz, lensed photon is suppressed due to higher optical thickness.



- Longer and sequential observations.
- Better resolution of EVPA.
- Better understanding of accretion flow and jet.
  Intrinsic variations of EVPA from GRMHD simulation?

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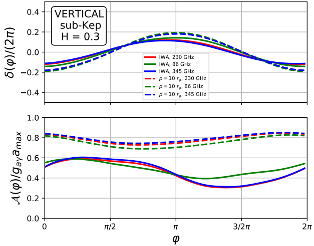

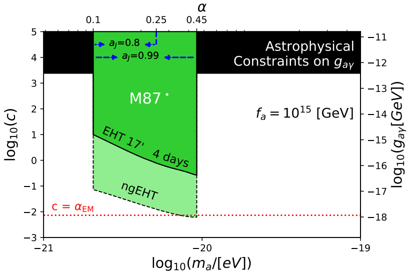

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Superradiant evolution of

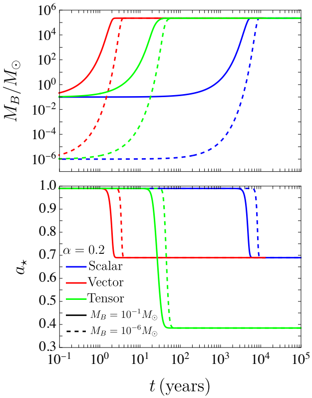
the shadow and photon ring of Sgr A*

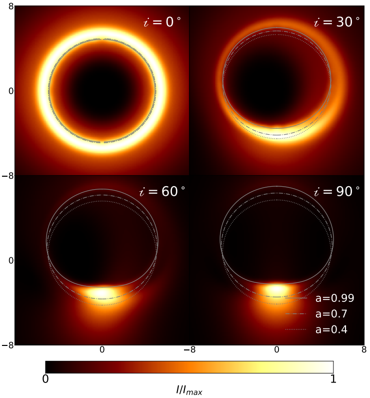
based on
arxiv: 2205.06238, Phys. Rev. D **106** (2022) no.4, 043021.

YC, Rittick Roy, Sunny Vagnozzi, and Luca Visinelli.

Superradiant Evolution for Bosons

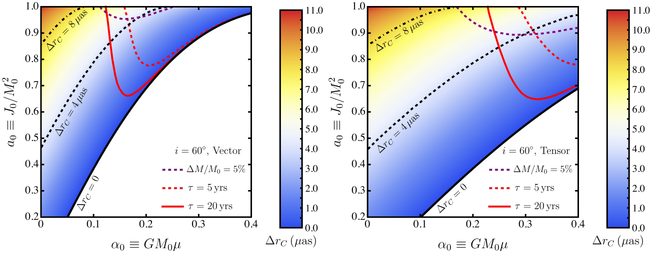
- **Superradiant evolution** for scalar, vector or tensor $\rightarrow$ spin decreases:





- Superradiant timescale $\propto M_{BH}$, and is shorter for vector or tensor due to $l = 0$ and $j = m = 1$ or 2 from **intrinsic spin**.
  $\sim \mathcal{O}(10)$ yrs for vector or tensor outside SgrA*.

Large Inclination Angle: Shadow Drift

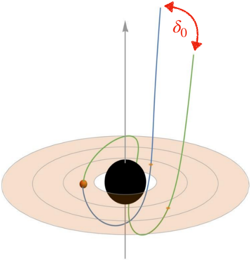


- Center of the shadow contour **drifts** $\sim \mathcal{O}(1) r_g$ once the spin decreases. The drift is more manifest at large inclination angles.

- Resolution to the shadow center benefits from long observation time $\sim \mathcal{O}(1)$ yr.

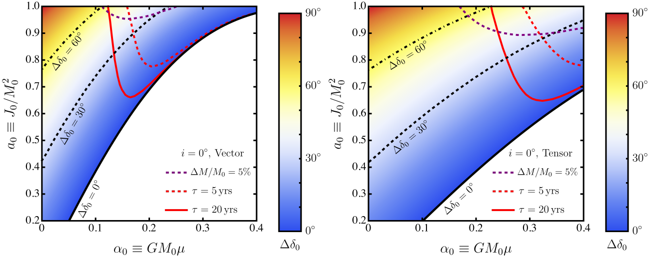
Low Inclination Angle: Azimuthal Lapse

- At low inclination angles,
  photon ring autocorrelation for intensity fluctuations:
  $\mathcal{C}(T,\varphi) \equiv \iint \mathrm{d}r \mathrm{d}r' r\, r' \, \langle \Delta I(t,r,\phi) \Delta I\,(t+T, r', \phi+\varphi)\rangle$
  peaks at $T = \tau_0$ and $\varphi = \delta_0$,
  where δ_0 is the azimuthal lapse.



[Chael Palumbo]

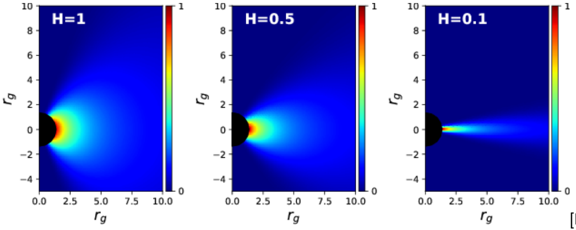
- δ_0 is sensitive to **spin evolution** due to frame dragging.



Accretion Flow around M87*

- EHT polarimetric measurements prefer Magnetically Arrested Disk with **vertical** $\vec{B}$ around M87*.
- Analytic model: **sub-Kep radiatively inefficient accretion flow**:

n_e:

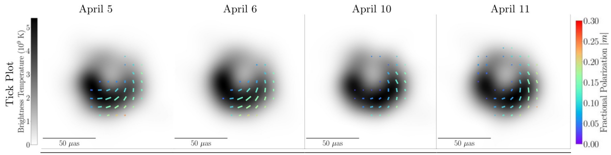


[Pu,Broderick 18']

- Dimensionless thickness parameter $H = 0.05$ and 0.3 as benchmark.

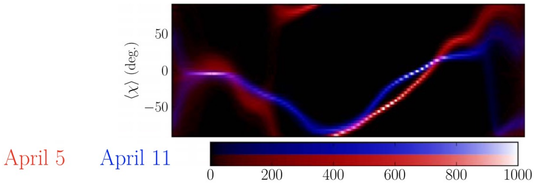
EHT Polarization Data Characterization

- Four days' polarization map with slight difference on sequential days:



[EHT 21']

- Uncertainty of the azimuthal bin EVPA from `polsolve`:



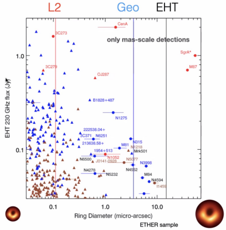
[EHT 21']

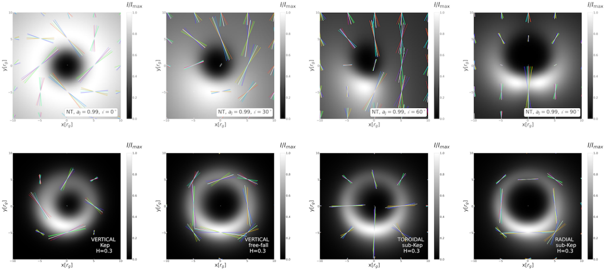
ranging from $\pm 3^\circ$ to $\pm 15^\circ$ for the bins used.

Landscape of SMBH and Accretion Flow (IPOLE simulation)

- **Horizon scale SMBH landscape** with nnngEHT (space, L2):

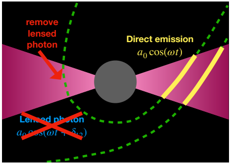
[Nagar ngEHT21]

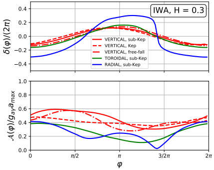




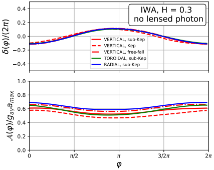
Broader range of axion mass: 10^{-22} eV to 10^{-17} eV.

- **Universal birefringence signals** for direct emission only:





remove
lensed
photon
→

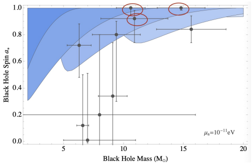


Fate of Superradiance

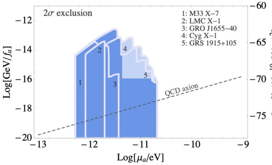
Axion cloud can't keep growing exponentially. What's **the fate of it**?

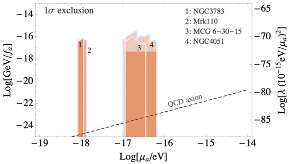
- **Self interaction** of axion becomes important for $f_a < 10^{16}$ GeV. [Yoshino, Kodama 12', Baryakht et al 20']
- Black hole **spins down** until the superradiance condition is violated for $f_a > 10^{16}$ GeV. [Arvanitakia, Dubovsky 10']
- Formation of a **binary system** leads to the decay/transition of the bound state. [Chia et al 18']
- **Electromagnetic blast** for strong (large field value) axion-photon coupling. [Boskovic et al 18']

Black Hole Spin Measurements [Arvanitakia et al 10' 14']

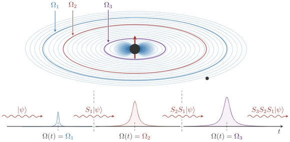


- Comparing **the timescale between the superradiance and BH accretion**, a BH with large spin can typically exclude axion with $f_a > 10^{16}$ GeV.





Gravitational Collider [Chia et al 18']



- Resonant transition from one bound state to another happens when orbital frequency Ω **matches the energy gap**.
- Due to the GW emission of the binary system, $\Omega(t)$ slowly increases and scan the spectrum.
- Orbits could float or shrink dependent on the transition.