# Black Holes as Transducers for Ultralight Bosons

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# Outlines

Introduction to Ultralight Bosons and Superradiance

Probing Ultralight Bosons with Event Horizon Telescope

Black Holes as Neutrino Factories

# Ultralight Bosons

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

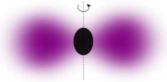
- Axion: hypothetical pseudoscalar motivated by strong CP problem.
- Prediction from fundamental theories with **extra dimensions**:

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

  String axiverse/photiverse: logarithmic mass window, $m_{\Psi}\propto e^{-\mathcal{V}_{6D}}$.
- **Coherent wave** dark matter candidates when $m_{\Psi}<1$ eV:

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

# Superradiant Gravitational Atoms



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

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

- **Superradiance** [Penrose, Zeldovichi, Starobinsky, Damour et al, Brito et al review]: boson cloud exponentially extracting BH rotation energy when

$$\begin{array}{rcl} \text{Compton wavelength } \lambda_c & \simeq & \text{gravitational radius } r_g\,. \\ m_\Psi \sim 10^{-21}\,\text{eV} & \leftrightarrow & M_{\rm BH} \sim 10^9 M_\odot\,. \end{array}$$

- $\Psi^{\rm GA}_{\rm max} \equiv \Psi_0$ **approaches** $M_{\rm pl}$ when $M_{\rm cloud} \lesssim 10\%\, M_{\rm BH}$:

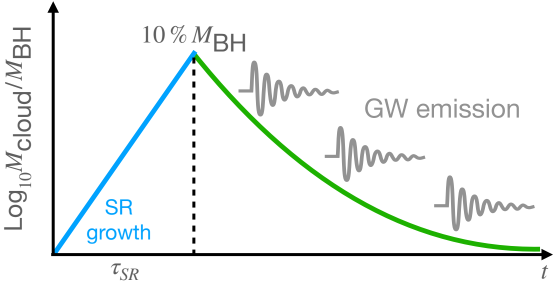
$$\frac{M_{\rm cloud}}{M_{\rm BH}} \approx \begin{cases} 0.5\% \left(\frac{\Psi_0}{10^{16}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for scalar,} \\ 0.8\% \left(\frac{\Psi_0}{10^{17}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for vector,} \end{cases}$$

$\alpha \equiv G_N M_{\rm BH} m_\Psi$ gravitational fine-structure constant

- **Black holes are powerful transducers for ultralight bosons.**

# Superradiance for Boson with Negligible Interaction

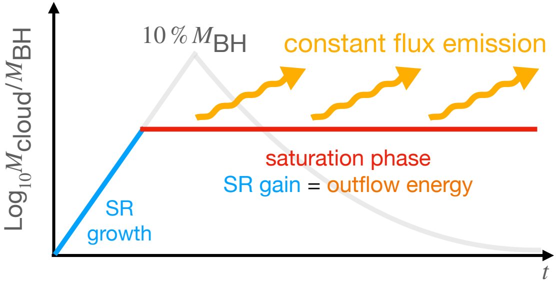
- For bosons with negligible interaction, superradiance stops after BH spins down and $M_{\text{cloud}}$ takes up to $10\% M_{\text{BH}}$.



- **High spin** excludes boson mass in SR range with reasonable $\tau_{\text{BH}}$.
  [Arvanitaki, Brito, Davoudiasl, Denton, Stott, Unal, Saha et al]
- **GW from boson annihilation and transition** slowly decreases $M_{\text{cloud}}$.
  [Yoshino, Brito, Isi, Siemonsen, Sun, Palomba, Zhu, Tsukada, Yuan, LVK et al]

# Superradiant Saturating Cloud

- Self interaction or matter interaction triggers cloud energy leakage, **balancing SR**, invalidating spin constraints.

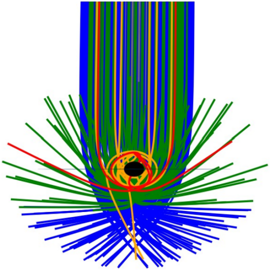


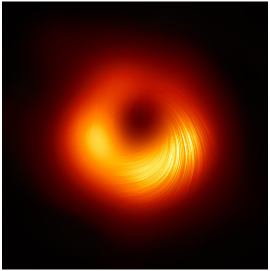
- Two examples for axion:
  - Ionized axion waves for $\Psi_0 \sim f_a < 10^{16}$ GeV [Yoshino et al 12', Baryakht et al 20'].
  - Parametric $\gamma$ production for $g_{a\gamma}\Psi_0 \sim 1$ [Rosa et al 17', Spieksma et al 23'].
- **Particle creation in strong field frontier**.

# EHT and ngEHT for new physics

**Event Horizon Telescope**: best-ever spatial resolution from VLBI.

Photon orbits `[KGEO]`





Stokes $Q, U$
**EVPA** $\chi \equiv \arg(Q + i\ U)/2$
[EHT 21']

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

→ Precise test of general relativity.

- **Astrometry for new physics**?

Linear polarization from synchrotron radiation reveals magnetic field structure.

Four days' observations **show slight difference**.

- **New interactions**?

# Photon Ring Astrometry

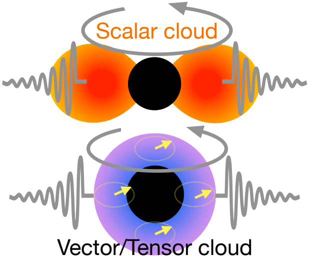
# for Superradiant Clouds

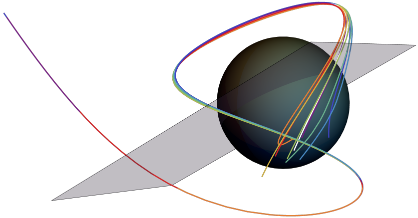
based on
arXiv:2211.03794, Phys. Rev. Lett. **130** (2023) no.11, 111401

YC, Xiao Xue, Richard Brito, Vitor Cardoso.

# Gravitational Atom-induced Geodesics Deflections

- Superradiant clouds generate local oscillatory metric perturbations $g_{\mu\nu} \simeq g^{\mathrm{K}}_{\mu\nu} + \epsilon h_{\mu\nu}$ that **deflect geodesics** $x^\mu \simeq x^\mu_{(0)} + \epsilon x^\mu_{(1)}$:

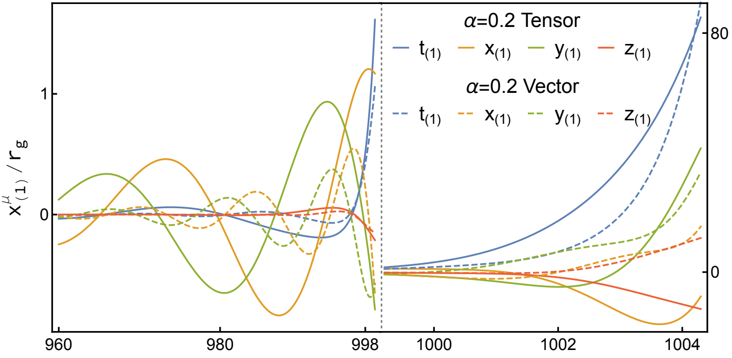


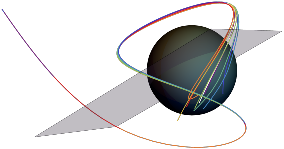


- **Scalar cloud** mainly causes time delay.
- **Polarized vector or tensor cloud** contribute to both time delay and **spatial deflection**.

# Gravitational Atom-induced Geodesics Deflections

**Backward ray-tracing**:

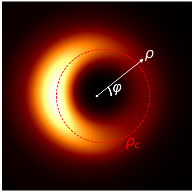




Two phases of evolution:

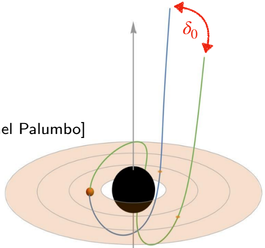
- Perturbative generation of oscillatory deviations;
- Photon ring instability leads to **exponential growth** of the oscillatory deviations between two sequential crossing the equatorial plane.

# Astrometrical Photon Ring Autocorrelations



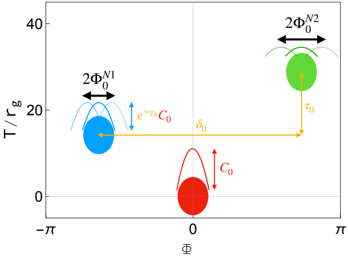
A photon pair executing different half orbits number $N$:

- Intensity fluctuation **correlation**: $\langle \Delta I(t,\varphi)\Delta I\,(t+T,\varphi+\Phi)\rangle$, peaks at $T \approx N\tau_0$ and $\Phi \approx N\delta_0$ [Hadar, Johnson, Lupsasca, Wong 20'] .



[Chael Palumbo]

**Equatorial plane emissions**



Observables: $\Delta\Phi^N = \Phi_0^N \cos\left(\omega t + \delta\right)$ for $N = 1$ and 2.

- **Probe $M_{\text{cloud}}/M_{\text{BH}}$ to $10^{-3}$ for vector and $10^{-7}$ for tensor.**

# 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 Cloud Induced Birefringence

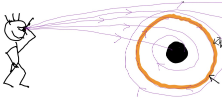
- Axion-induced Birefringence: rotation of **linear polarization**:

$$\mathbf{g}_{a\gamma}\mathbf{a}\mathbf{F}_{\mu\nu}\tilde{\mathbf{F}}^{\mu\nu}/2 \rightarrow \Delta\chi = g_{a\gamma}[a(t_{\rm obs},\mathbf{x}_{\rm obs}) - a(t_{\rm emit},\mathbf{x}_{\rm emit})].$$

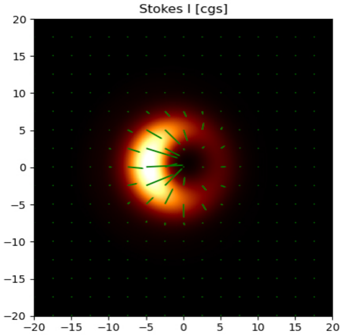
- Extended sources, plasma and curved space-time effects?

**Covariant radiative transfer** [`IPOLE` simulation]

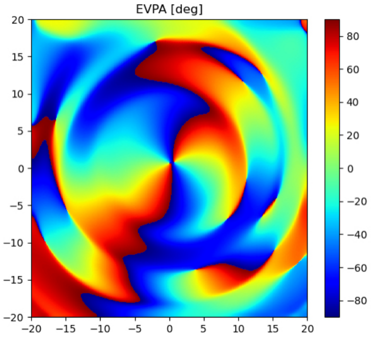
with an accretion flow model outside SMBH:



[Strominger 19']



Stokes I [cgs]

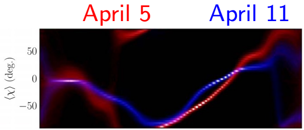


EVPA [deg]

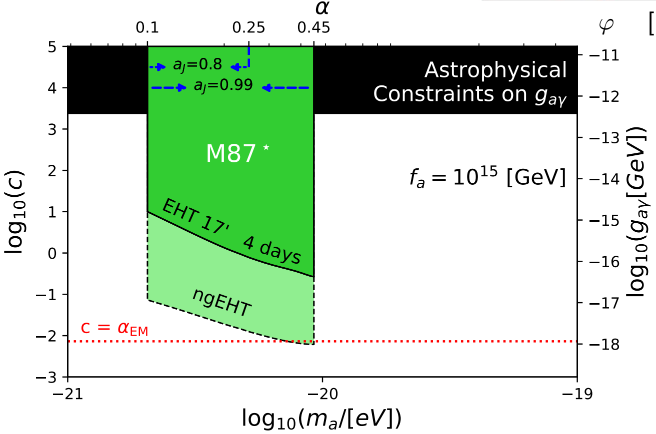
# Stringent Constraints on Axion-Photon Coupling

- Uncertainty of azimuthal EVPA in [EHT 21']:

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



[EHT 21']



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

# Black Holes as

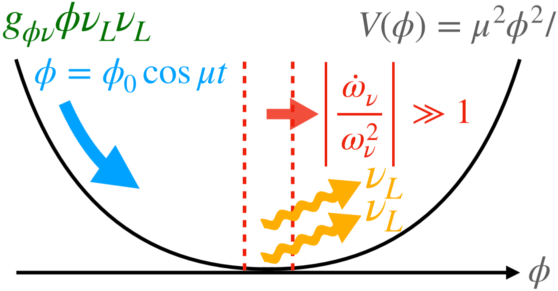
# Neutrino Factories

based on
arXiv:2308.00741

YC, Xiao Xue, Vitor Cardoso.

# Particle Production from Oscillating Background

- Neutrino coupled to majoron: $\omega_\nu^2 = k^2 + m_{\text{eff}}^2$, $m_{\text{eff}} = m_\nu + g_{\phi\nu}\phi_0 \cos\mu t$.



- Non-adiabatic condition $|\dot\omega_\nu/\omega_\nu^2| \gg 1$ is satisfied for $k < k_* = \sqrt{g_{\phi\nu}\phi_0\mu}/2$ when $m_{\text{eff}}$ crosses zero.

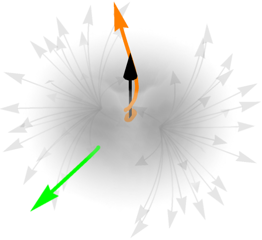
- **Fermi sphere** $\sim k_*$ is pumped for every $t = \pi/\mu$ [Greene Kofman 98' 00'].
  Production rate: $\Gamma_{\phi\nu} \approx (g_{\phi\nu}\phi_0)^{3/2}\mu^{5/2}/(48\pi^3)$.

- **Strong field frontier**: similar to preheating and strong field QED.

# Neutrino Acceleration from Boson Cloud

- Neutrino propagation under majoron cloud background:

$$\frac{\mathrm{d}p_\nu^\alpha}{\mathrm{d}t} = -\frac{1}{p_\nu^0}\Gamma^\alpha_{\kappa\beta}\, p_\nu^\kappa\, p_\nu^\beta - \frac{1}{2p_\nu^0}\nabla^\alpha m_{\rm eff}^2 . \leftarrow \textbf{scalar force}$$



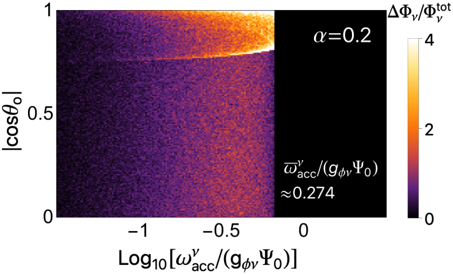
- Two parts of **scalar force**:

$$-\vec{\nabla} m_{\rm eff}^2 \propto \alpha^2\, \hat{r} - \frac{2\, r_g}{r\cos(\alpha t - \phi)\sin\theta}\, \hat{n}_\perp + \cdots$$

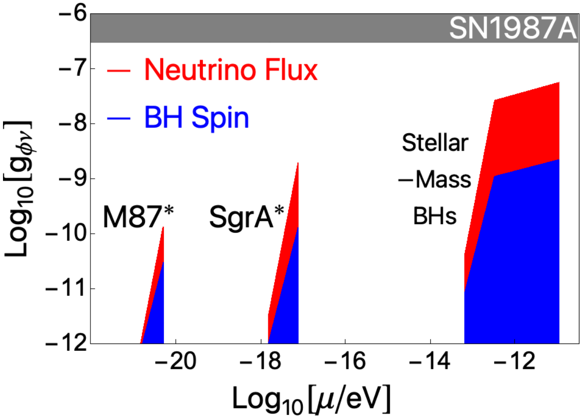
  - Outer region: pure radial acceleration.
  - Inner region: polar trapping.

- Final momentum: $\bar{\omega}_{\rm acc}^\nu \sim g_{\phi\nu}\Psi_0$.

- Both spatial and temporal variation are necessary for acceleration.



# Spin Measurement and Neutrino Flux



- High spin excludes region $\Gamma_{\phi\nu} \ll \Gamma_{\mathrm{SR}}$.
- Neutrino emission from saturation phase $\Gamma_{\phi\nu} = \Gamma_{\mathrm{SR}}$.
  Point-like sources surpass atmospheric neutrino background.
- $M_{\mathrm{BH}}$ from $M_\odot$ to $10^{10}\, M_\odot$ can all be probed.

# Other Interactions

- Neutrino pair production and acceleration from a vector cloud?

  Strict constraints on the coupling.

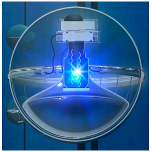
- Boosted dark matter from superradiant clouds.

- **Multi-messenger observation**:

LIGO
VIRGO
KAGRA

KM3NeT

ICECUBE



- GW and EM searches for BHs.
- Neutrino and boosted dark matter.

XLZD

# Summary

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

- **Event Horizon Telescope**:
  - **Photon geodesics deflection** from gravitational atoms.
  - **Linear polarization rotation** from axion cloud.

- **Strong field frontier**:
  - Parametric particle production and acceleration.

- **Multi-messenger correlation**:

  neutrino/dark matter detection $\leftrightarrow$ GW/EM observation.

*Thank you!*

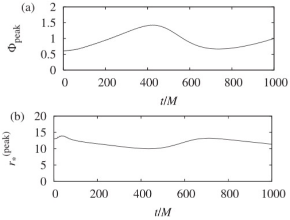
# Appendix

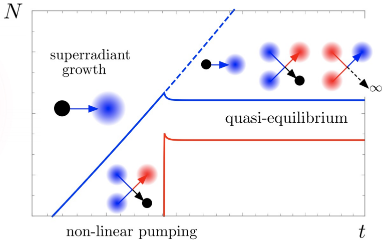
# Weakly Saturating Axion Cloud

- 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 $a^{\mathrm{GA}}_{\mathrm{max}} \simeq \mathcal{O}(1)\, f_a$.

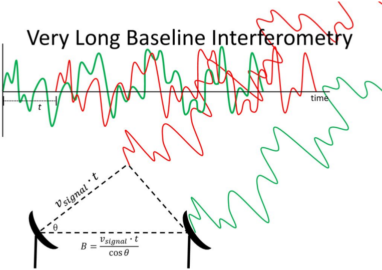


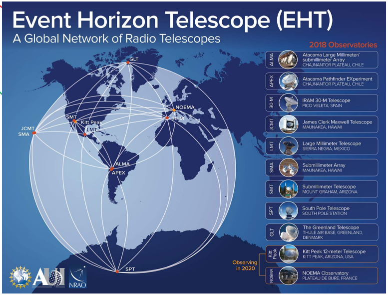


[Yoshino, Kodama 12' 15', Baryakht et al 20']

# Event Horizon Telescope: an Earth-sized Telescope

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



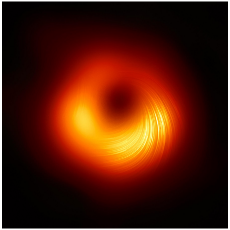


- As good as being able to see  on the moon from the Earth.

# Supermassive Black Hole (SMBH) M87$^\star$ [EHT 19' 21']

**Event Horizon Telescope**: best-ever spatial resolution from VLBI.

Total intensity $I$



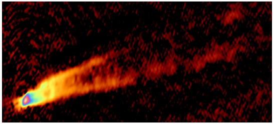
Linear polarization $Q, U$

**EVPA** $\chi \equiv \mathbf{arg}(Q + i\ U)/2$

- First-time: **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?**

# Axion Cloud and Birefringence

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

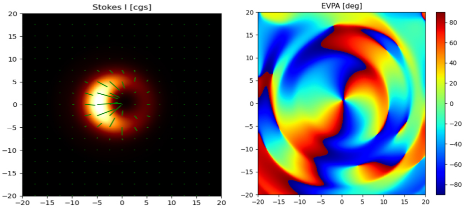
$r_g m_a \approx \mathcal{O}(1)$

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

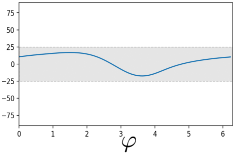
- $g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} \to$ achromatic birefringence to EVPA $\chi \equiv \arg(Q + i\, U)/2$:

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

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



Intensity weighted $\Delta\langle\chi(\varphi)\rangle$



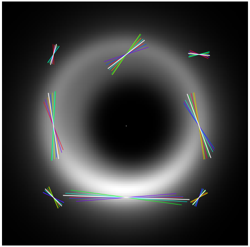
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along** $\varphi$ on the sky plane

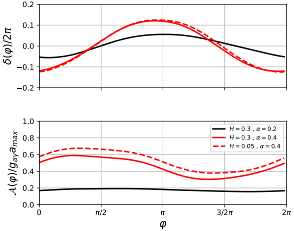
BL coordinate: $a^{\rm GA} \propto \cos[m_a t - \phi] \to \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi)\cos[m_a t + \varphi + \delta(\varphi)]$.

# Axion Birefringence for RIAF around M87$^\star$ (`IPOLE` simulation)

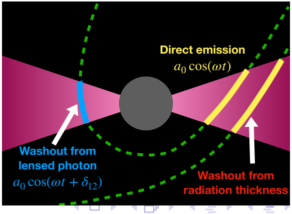
$$\Delta\langle\chi(\varphi)\rangle = \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$$

- 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 $\varphi$.
- Asymmetry of $\mathcal{A}(\varphi) = \mathcal{O}(1) g_{a\gamma} f_a$: **washout from lensed photon with** $\delta_{12} = \omega\delta t - \delta\phi$!



**Direct emission**
$a_0\cos(\omega t)$

**Washout from lensed photon**
$a_0\cos(\omega t + \delta_{12})$

**Washout from radiation thickness**

# Axion Birefringence for RIAF around M87$^\star$ (`IPOLE` simulation)

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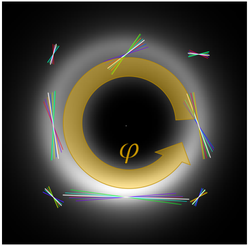

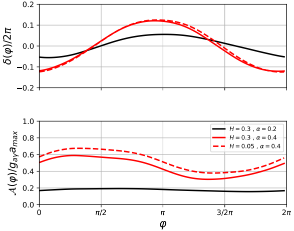

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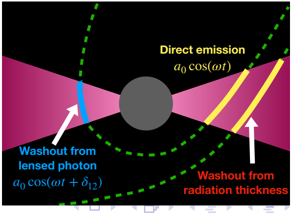
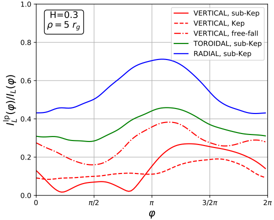
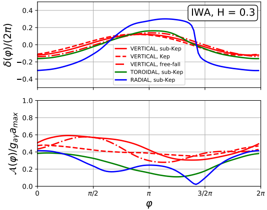


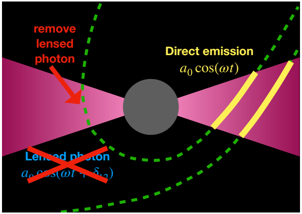
# Lensed Photon Washout

- The ratio between linear polarization from lensed photon and direct emissions vary from RIAF models, giving different washout effects.

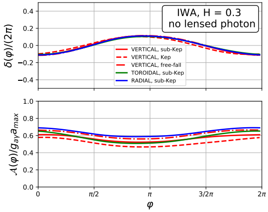




- **Universal birefringence signals** for direct emission only:

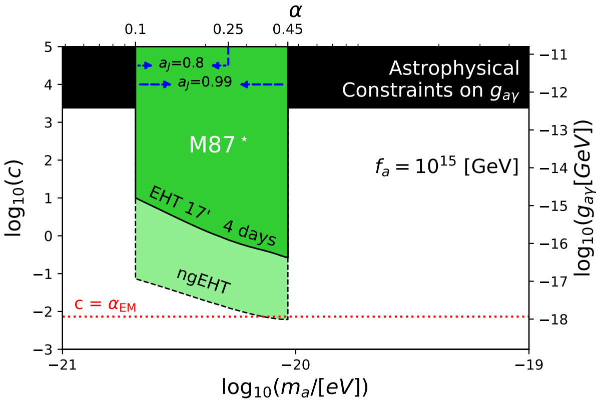


remove lensed photon →



# Prospect for next-generation EHT

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



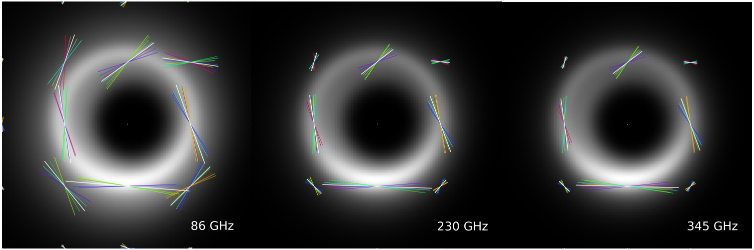
Recent updates:

- Constraints from EVPAs on the whole image.
- Closure traces for EVPA variations with specific patterns [Broderick et al].

# 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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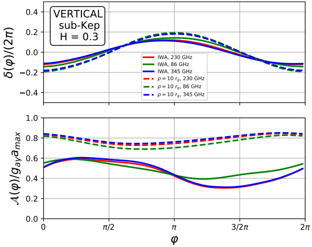

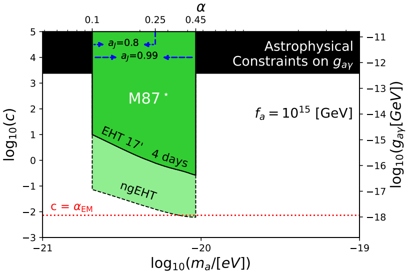

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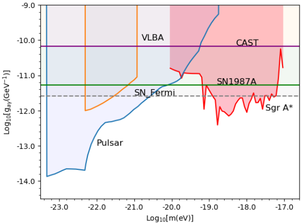
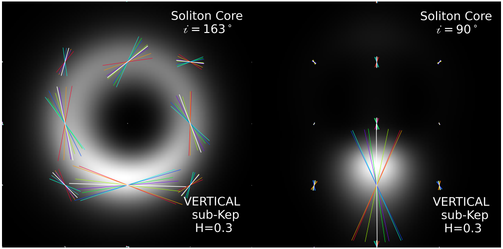
- Better understanding of accretion flow and jet.
  Intrinsic variations of EVPA from GRMHD simulation?

# 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**$^\star$.[Yuan, Xia, YC, Yuan et al 20']
- Coherent signals at each pixel increase the sensitivity.

# 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 for photons propragating under axion background:

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

$n^{\mu}$: unit directional vector

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

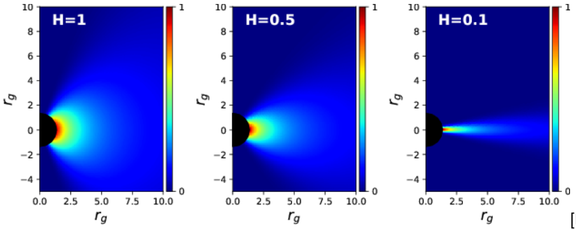
$$\begin{aligned} \Delta\chi &= g_{a\gamma}\int_{\mathrm{emit}}^{\mathrm{obs}} n^{\mu}\partial_{\mu}a\, dl \\ &= g_{a\gamma}[a(t_{\mathrm{obs}}, \mathbf{x}_{\mathrm{obs}}) - a(t_{\mathrm{emit}}, \mathbf{x}_{\mathrm{emit}})]. \end{aligned}$$

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

# Accretion Flow around M87$^\star$

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

$n_e$:

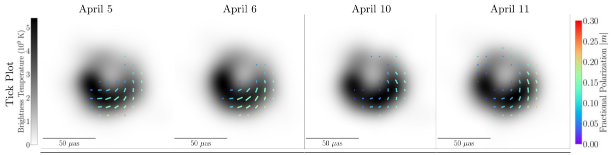


[Pu,Broderick 18']

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

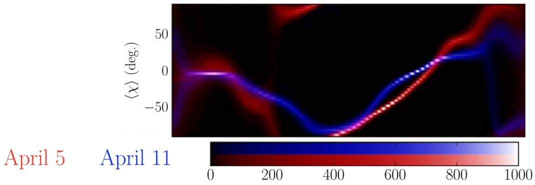
# EHT Polarization Data Characterization

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



[EHT 21']

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



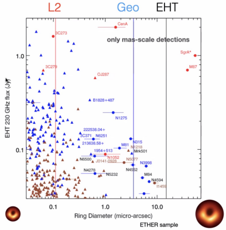
[EHT 21']

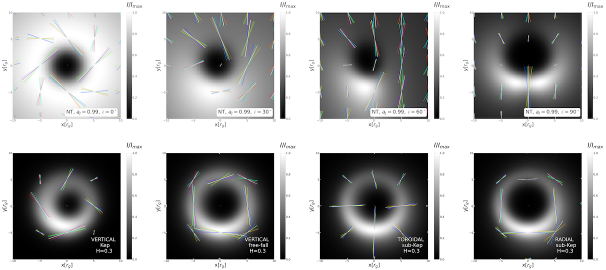
ranging from ±3° to ±15° for the bins used.

# Landscape of SMBH and Accretion Flow (IPOLE simulation)

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

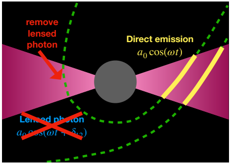
[Nagar ngEHT21]

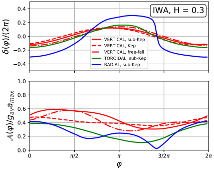




Broader range of axion mass: $10^{-22}$ eV to $10^{-17}$ eV.

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





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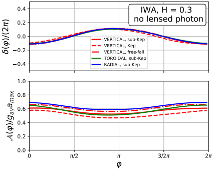
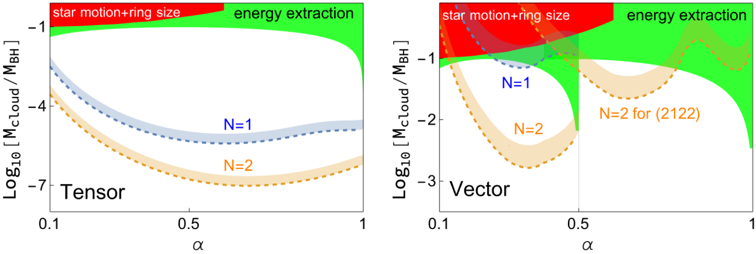


# Photon Ring Autocorrelations as Astrometry

- Photon ring autocorrelation exclusion **criteria**: $\Delta\Phi^N > \ell_\phi \approx 4.3^\circ$ or ngEHT's smearing kernel for $\varphi$: $10^\circ$.



- A tensor with linear coupling to stress tensors is more sensitive than a vector with quadratic couplings.
- $N = 2$ correlation peak can probe large unexplored parameter space of cloud mass.
- Sources with shorter correlation time, e.g., hotspots or pulsars can significantly increase the sensitivity.

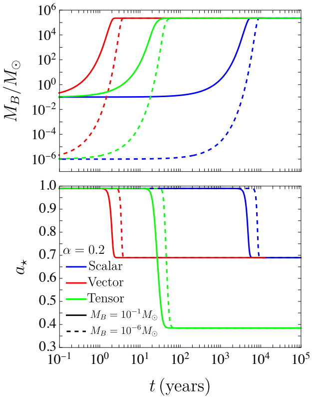
# Superradiant evolution of the shadow and photon ring of Sgr A$^\star$

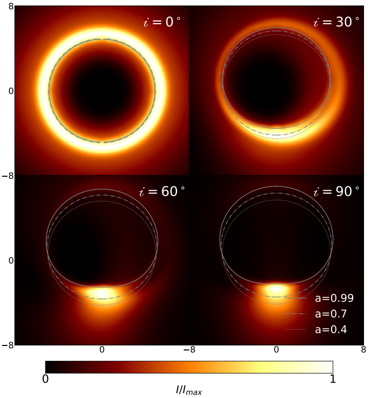
based on
arxiv: 2205.06238, Phys. Rev. D **106** (2022) no.4, 043021.

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

# Superradiant Evolution for Bosons

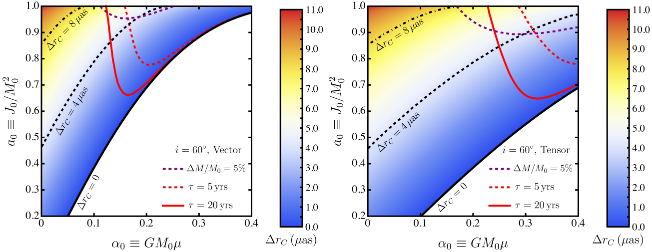
- **Superradiant evolution** for scalar, vector or tensor → spin decreases:





- 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$^\star$.

# 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

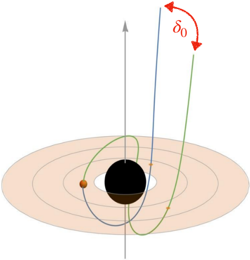
- At low inclination angles,

  **photon ring autocorrelation** for intensity fluctuations:

  $\mathcal{C}(T,\varphi) \equiv \iint \mathrm{d}r\mathrm{d}r' r\, r' \, \langle \Delta I(t,r,\phi) \Delta I\,(t+T,r',\phi+\varphi)\rangle$

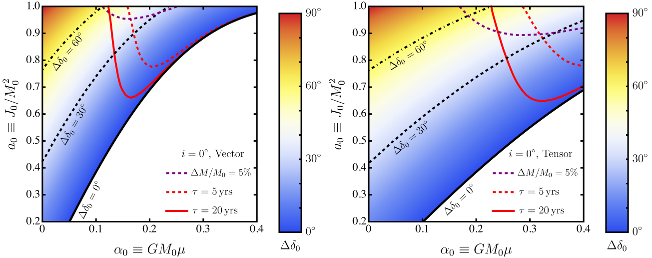
  peaks at $T = \tau_0$ and $\varphi = \delta_0$,

  where $\delta_0$ is the azimuthal lapse.



[Chael Palumbo]

- $\delta_0$ is sensitive to **spin evolution** due to frame dragging.

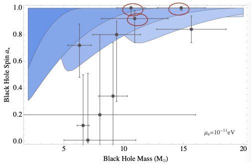


# Fate of Superradiance

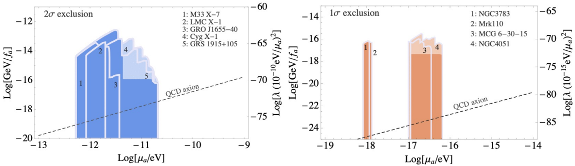
Axion cloud can't keep growing exponentially. What's **the fate of it**?

- **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']

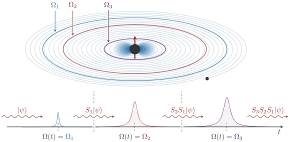
# Black Hole Spin Measurements [Arvanitakia et al 10' 14']



- 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 $\Omega$ **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.