Strong Gravity Frontier of Particle Physics

Yifan Chen
Niels Bohr International Academy
yifan.chen@nbi.ku.dk

25 January 2024
Rencontres de Physique des Particules 2024, Paris

strong. niels bohr institute
KØBENHAVNS UNIVERSITET
Danmarks Grundforskningsfond
Danish National Research Foundation
VILLUM FONDEN
erc European Research Council
Established by the European Commission

Outlines

Ultralight Bosons

and Superradiance

Ultralight Bosons

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

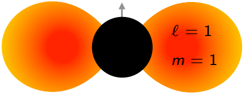
- Axion: hypothetical pseudoscalar motivated by strong CP problem.
- Prediction from fundamental theories with **extra dimensions**:

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

  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 boson cloud:

  BL coordinate: $\Psi^{\rm GA}(x^\mu) = e^{-i\omega t} e^{im\phi} S_{\ell m}(\theta) R_{\ell m}(r)$.

  Fine-structure constant: $\alpha \equiv G_N M_{\rm BH} m_\Psi$, Bohr radius: r_g/α^2.

  BH horizon $\rightarrow \omega \simeq m_\Psi + i\Gamma$.

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

$$\begin{array}{ccc} \text{Compton wavelength } \lambda_c & \simeq & \text{gravitational radius } r_g. \\ m_\Psi \sim 10^{-12}\,\text{eV} & \leftrightarrow & M_{\rm BH} \sim 10\, M_\odot. \end{array}$$

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

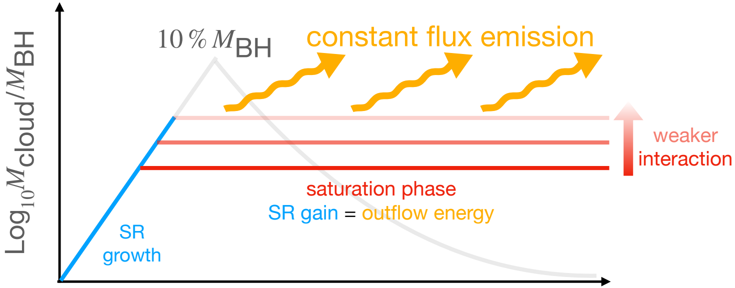
$$\frac{M_{\rm cloud}}{M_{\rm BH}} \approx \begin{cases} 0.5\% \left(\frac{\Psi_0}{10^{16}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for scalar,} \\ 0.8\% \left(\frac{\Psi_0}{10^{17}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for vector.} \end{cases}$$

  Local dark matter field:
  $\Psi_0^\odot \approx 2\,\text{GeV} \left(\frac{10^{-12}\,\text{eV}}{m_\Psi}\right)$

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

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'].
  - γ production for $g_{a\gamma}\Psi_0 \sim 1$ [Rosa et al 17', Ikeda et al 18', Spieksma et al 23'].
- **Strong field frontier**: similar to preheating and strong field QED.
- **Saturated** M_{cloud} is determined by interaction strength.

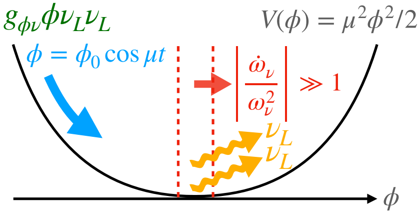
Black Holes as

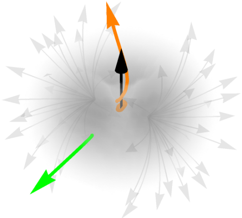
Neutrino Factories

Black Holes as Neutrino Factories [YC, Xue, Cardoso, arXiv:2308.00741]

- Scalar neutrino coupling: $g_{\phi\nu}\phi\nu_L\nu_L$.

$$\omega_\nu^2 = k^2 + m_{\rm eff}^2, \qquad m_{\rm eff} = m_\nu + g_{\phi\nu}\phi_0 \cos\mu t.$$





- Periodic Fermi-sphere generation: $\Gamma_{\phi\nu} \approx (g_{\phi\nu}\phi_0)^{3/2}\mu^{5/2}/(48\pi^3)$.
- Further neutrino acceleration under scalar cloud background:

$$\frac{{\rm d}p_\nu^\alpha}{{\rm d}t} = -\frac{1}{p_\nu^0}\Gamma^\alpha_{\kappa\beta}p_\nu^\kappa\, p_\nu^\beta - \frac{1}{2p_\nu^0}\nabla^\alpha m_{\rm eff}^2. \leftarrow \text{scalar force}$$ [Uzan et al 20']

- Schwinger pair production and acceleration from vector clouds.
- **Multi-messenger observation**:
  - GW and EM searches for BHs.
  - Neutrino and boosted dark matter.

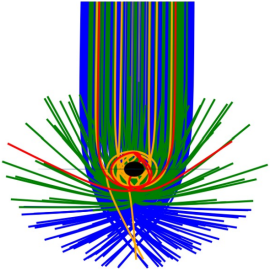
Probing Particle Physics

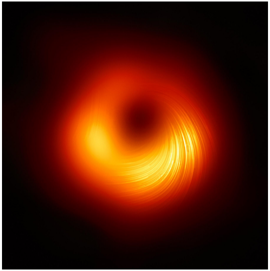
with Event Horizon Telescope

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.

$\rightarrow$ Precise test of general relativity.

- **Astrometry for new physics**?

Linear polarization from synchrotron radiation reveals magnetic field structure.

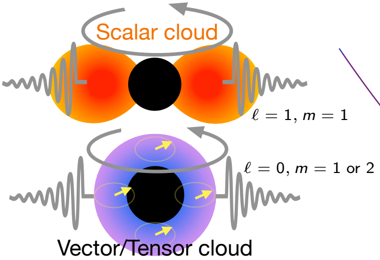
Four days' observations **show slight difference**.

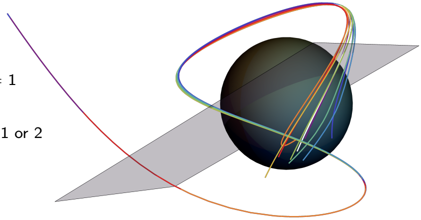
- **New interactions**?

[Fundamental Physics Opportunities with the ngEHT, Ayzenberg et al, 2312.02130]

Photon Ring Astrometry for Gravitational Atoms

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





[YC, Xue, Brito, Cardoso, PRL. **130** (2023) no.11, 111401]

- **Axion/scalar cloud** mainly causes time delay [Khmelnitsky, Rubakov 13'].

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

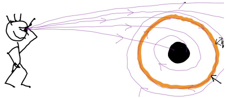
- Photon ring autocorrelations [Hadar et al 20'] **probe** $M_{\rm cloud}/M_{\rm BH}$ **to** 10^{-3} **for vector and** 10^{-7} **for tensor**.

Axion Cloud Induced Birefringence

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

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

- Extended sources, plasma and curved space-time?

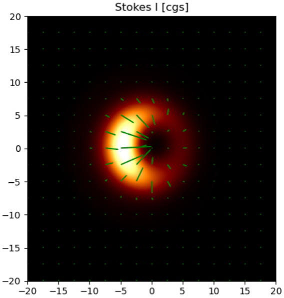


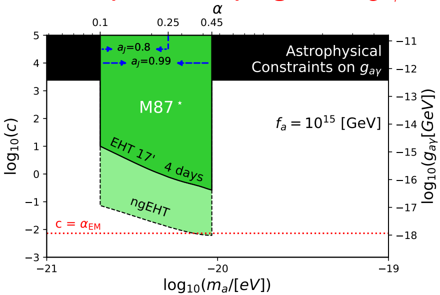
[Strominger 19']

Covariant radiative transfer [IPOLE simulation]

with an accretion flow model outside SMBH:

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

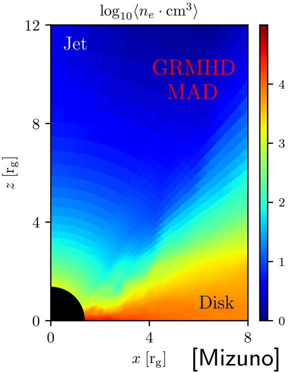




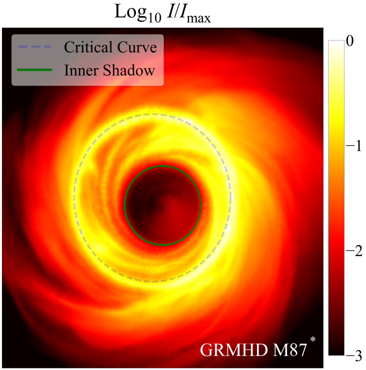
[YC, Li, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Zhou,
PRL **124** (2020) no.6, 061102, Nature Astron. **6** (2022) no.5, 592-598, JCAP **09** (2022), 073]

Black Hole Inner Shadow [Chael, Johnson, Lupsasca 21']

- **Best-fit GRMHD model (MAD)** from EHT observation:
  - Jet region: strong B and low n_e.
  - Geometric thin emissions near equator, **extending to BH horizon**,
  - $\rightarrow$ **Inner shadow**: lensed contour of **equatorial BH horizon**.



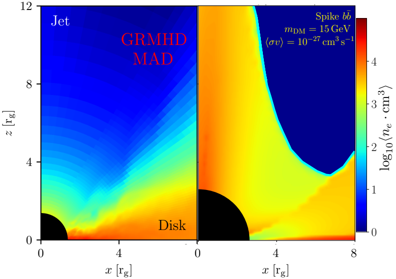
[Mizuno]

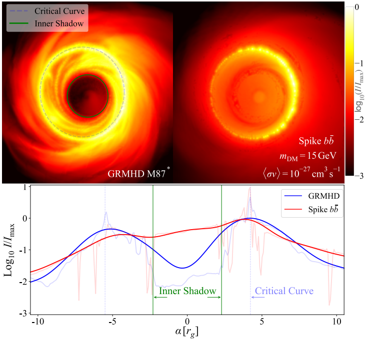


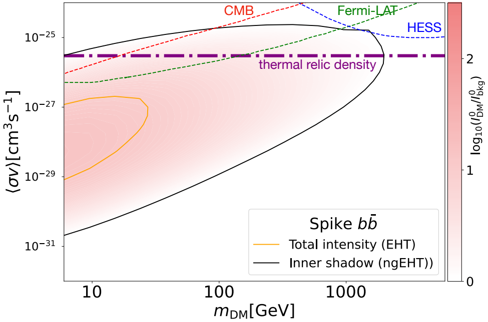
- **ngEHT** with high dynamic range $I/I_{\max} > 10^{-3}$ can see **inner shadow**.

Illuminating Black Hole Shadow with Dark Matter Annihilation

- **Particle DM density** can be significant outside SMBHs [Gondolo, Silk 99'].
- Annihilation into e^+/e^- contribute to synchrotron radiation [Lacroix et al 18'].
- Inner shadow can be illuminated, setting **stringent constraints**:

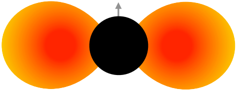




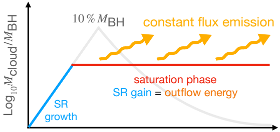


[YC, Ding, Liu, Mizuno, Shu, Yu, Zeng, to appear]

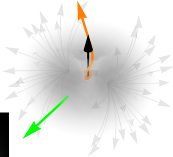
Summary



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

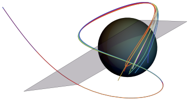


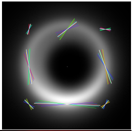
- **Strong field frontier**:
  - Parametric particle production and acceleration.



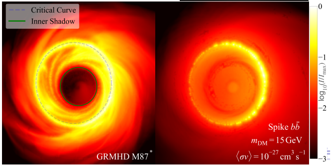
- **Multi-messenger correlation**:

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

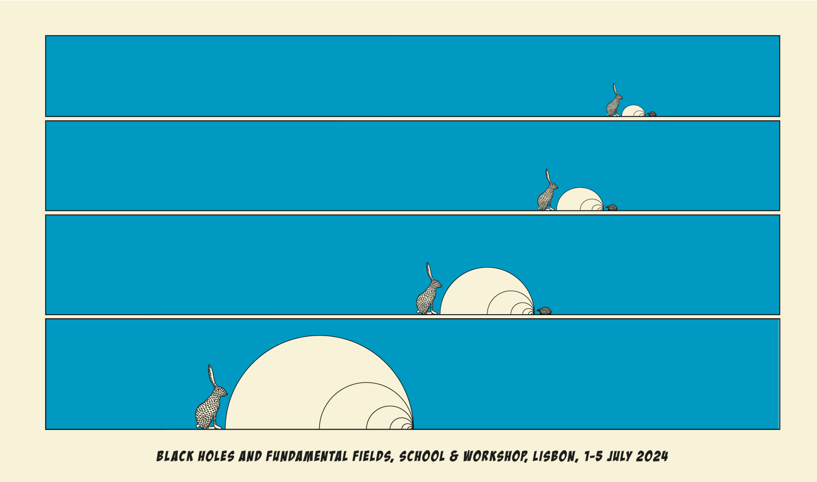




- **Event Horizon Telescope**:
  - **Photon geodesics deflection**.
  - **Linear polarization rotation**.
  - **Dark matter illuminating the inner shadow**.



Thank you!

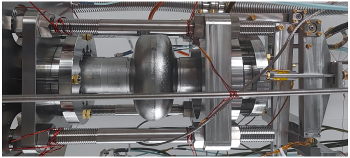

BLACK HOLES AND FUNDAMENTAL FIELDS, SCHOOL & WORKSHOP, LISBON, 1-5 JULY 2024

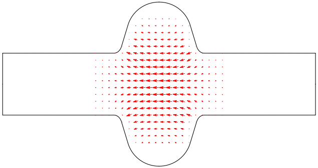
Appendix

Cavity as Indirect Detection for Axion Dark Matter

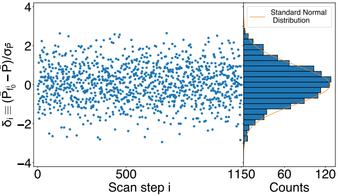
Superconducting Radio-Frequency (SRF) Cavity

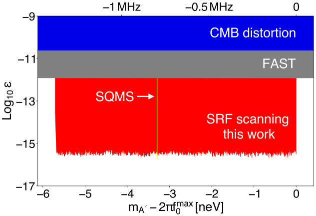
- **SRF cavities** with significant $Q_0 > 10^{10}$ are widely used for accelerators.
- 1-cell niobium elliptical cavity and TM_{010} mode at 1.3 GHz:





- **First scan search for dark photon dark matter with SRF using a mechanical turner**.





[Tang et al, 2305.09711]

Galactic Dark Photon from Axion Dark Matter

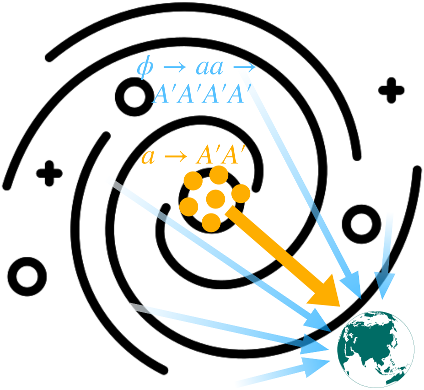
Indirect detection of axion dark matter?

Two-body decay (e.g., $a \to \gamma\gamma$) will typically either exponentially deplete axion due to Bose-enhancement, or render too small fluxes.

Alternative production mechanisms:

- Four-body cascade decay from **standard halo**.
  [ADMX Dror et al 23']

- Two-body parametric decay from **axion clump** surrounded by miniclusters.



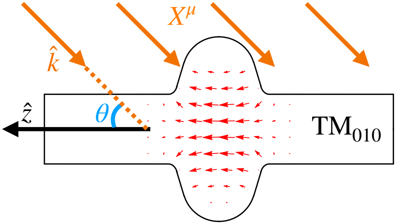
Polarization-dependent production:

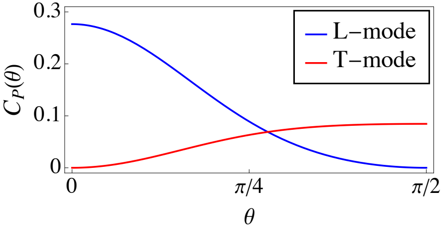
- Longitudinal mode from a dark higgs.

- Transverse mode from axion-photon-type coupling.

Diurnal Modulation from Earth Rotation

- **Angular-dependent response** to relativistic dark photon characterized by **overlapping form factor** $C_P(\theta)$. [ADMX Dror et al 23' for galactic axion]
- Detector is rest at Earth frame while Earth is **rotating in galactic frame**.
- **Diurnal modulation** of the signals in cavity.
- Longitudinal and transverse modes show opposite variation.

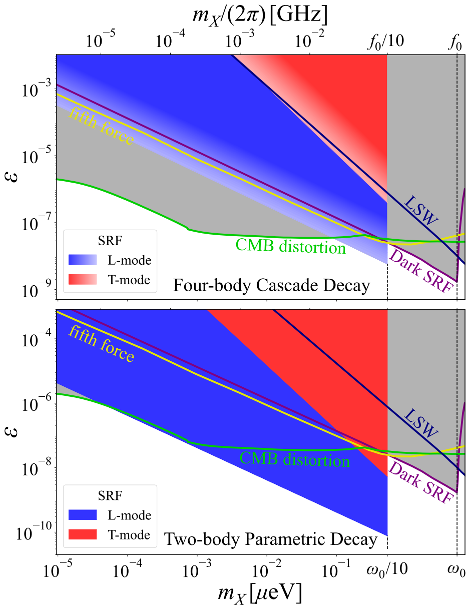




SRF Constraints for Galactic Dark Photons

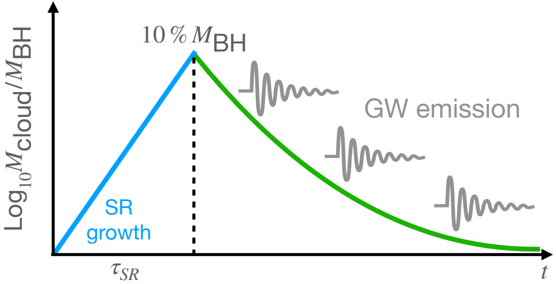
Same dataset as dark photon dark matter searches:

- Total scan range of $\sim 1\,\text{MHz}$: within bandwidth of galactic dark photon.
- Total experimental time of $\sim 100\,\text{hours}$: diurnal modulation tests.
- Decay rate constraint requires $\rho_{A'} \lesssim 1000\,\rho_\gamma$ on Earth.
- Constraints for longitudinal modes are more stringent due to its $|\vec{A}'_L| = \omega_{A'}/m_{A'} \gg 1$.



Superradiance for Boson with Negligible Interaction

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



- **High spin** excludes boson mass in SR range with reasonable τ_{BH}.

  [Arvanitaki, Brito, Davoudiasl, Denton, Stott, Unal, Saha et al]

- **GW from boson annihilation and transition** slowly decreases M_{cloud}.

  [Yoshino, Brito, Isi, Siemonsen, Sun, Palomba, Zhu, Tsukada, Yuan, LVK et al]

Neutrino Acceleration

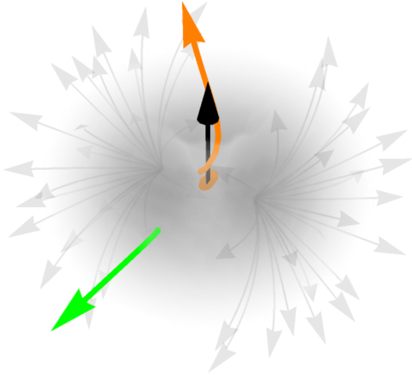
- Neutrino propagation under majoron cloud background:

$$\frac{\mathrm{d}p_\nu^\alpha}{\mathrm{d}t} = -\frac{1}{p_\nu^0}\Gamma^\alpha_{\kappa\beta}p_\nu^\kappa\, p_\nu^\beta - \frac{1}{2p_\nu^0}\nabla^\alpha m_{\mathrm{eff}}^2 . \leftarrow \text{scalar force}$$ [Uzan et al 20']

- Two parts of scalar force:

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

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



- Both spatial and temporal variation are necessary for acceleration.

Cosmic Ray and Neutrino Fluxes

- ν decay to charged leptons and $\pi^{\pm}$ once m_{eff} reaches 0.1 GeV.

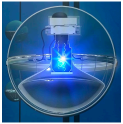
  ν and $e^{\pm}$ expected at $\sim 0.1\,$**GeV**.

- ν pair production and acceleration from a vector cloud.

  Point-like sources surpass atmospheric neutrino background at $\sim$ **TeV**.

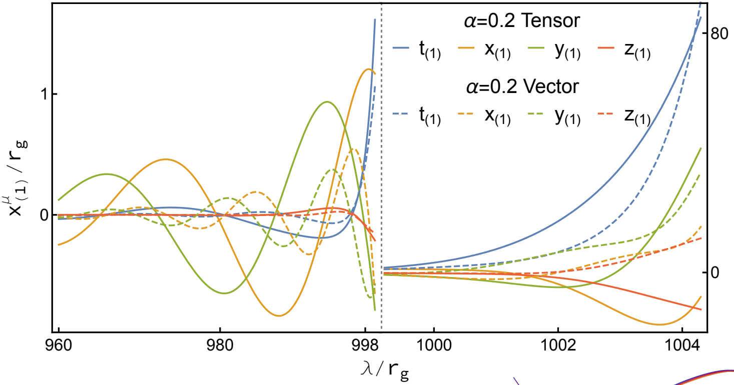
- Boosted dark matter from boson clouds.

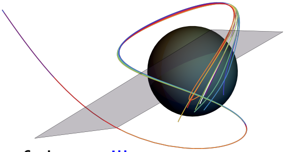
- **Multi-messenger observation**:
  - GW and EM searches for BHs.
  - Neutrinos, cosmic rays and BDM.



Gravitational Atom-induced Geodesics Deflections

Backward ray-tracing:

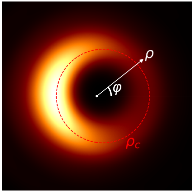




Two phases of evolution:

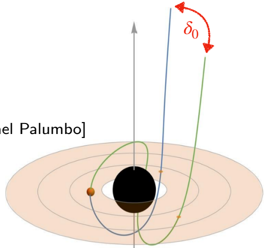
- Perturbative generation of oscillatory deviations;
- Photon ring instability leads to **exponential growth** of the oscillatory deviations between two sequential crossing the equatorial plane.

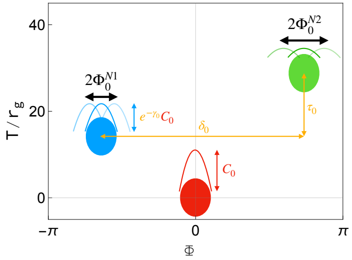
Astrometrical Photon Ring Autocorrelations



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'] .





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

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

Axion Cloud Induced Birefringence

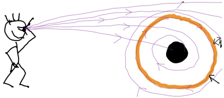
- Axion-induced Birefringence: rotation of **linear polarization**:

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

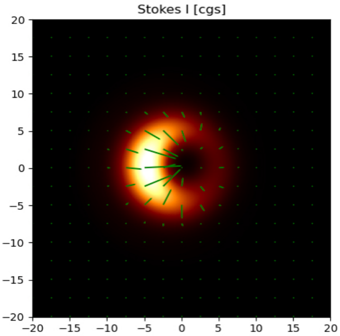
- Extended sources, plasma and curved space-time effects?

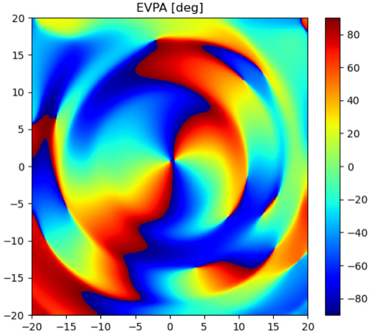
Covariant radiative transfer [IPOLE simulation]

with an accretion flow model outside SMBH:



[Strominger 19']

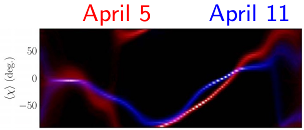




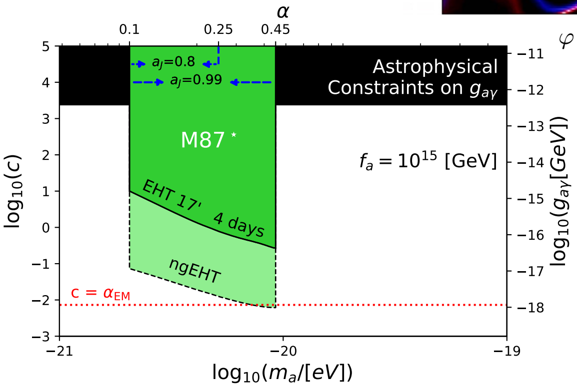
Stringent Constraints on Axion-Photon Coupling

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

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



[EHT 21']

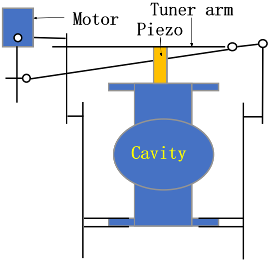


- Next-generation EHT is expected to significantly increase sensitivity.

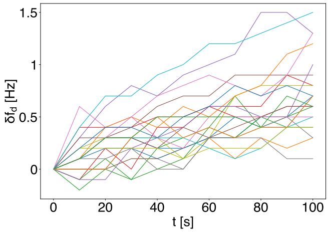
[YC, Li, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Zhou,
PRL **124** (2020) no.6, 061102, Nature Astron. **6** (2022) no.5, 592-598, JCAP **09** (2022), 073]

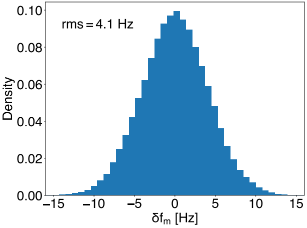
Scan Search with Mechanical Tuning

- The cavity and amplifier line are positioned in **liquid helium at $T \simeq 2\,\mathrm{K}$**.



- **Mechanical turner** scans resonant frequency f_0.
- Each scan is followed by calibration of f_0 and its stability range Δf_0.
- Frequency drift $\delta f_d \lesssim 1.5\,\mathrm{Hz}$ and microphonics effect $\sigma_{f_0} \approx 4\,\mathrm{Hz}$.

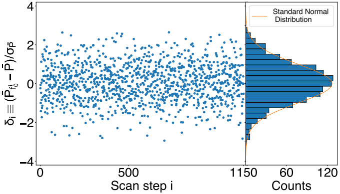


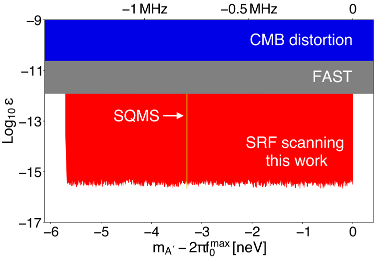


- Conservative choice $\Delta f_0 \approx 10\,\mathrm{Hz}$.

Data Analysis and Constraints

- Total 1150 scan steps with each 100 s integration time.
- **Group every** 50 **adjacent bins** and perform a constant fit to address small helium pressure fluctuation.
- Normal power excess shows **Gaussian distribution**:





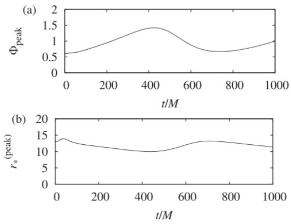
- **First scan search with SRF and most stringent constraints in most exclusion space**.

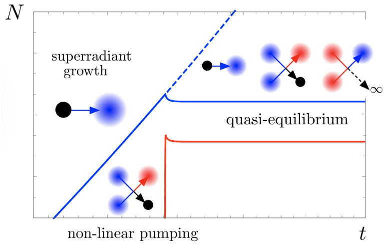
Weakly Saturating Axion Cloud

- Strong self-interaction region $a^{\rm GA} \simeq f_a$ 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 $a^{\rm GA}_{\rm max} \simeq \mathcal{O}(1)\, f_a$.

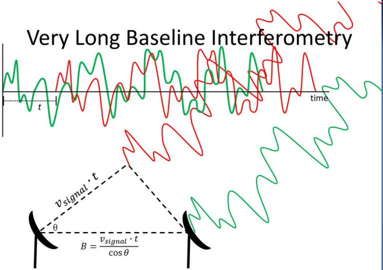


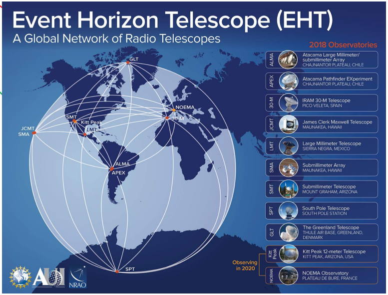


[Yoshino, Kodama 12' 15', Baryakht et al 20']

Event Horizon Telescope: an Earth-sized Telescope

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



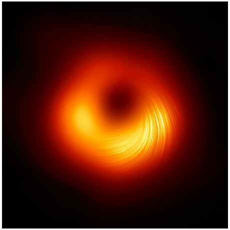


- As good as being able to see  on the moon from the Earth.

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

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

Total intensity I

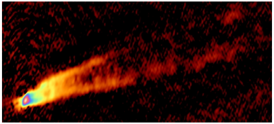


Linear polarization Q, U
EVPA $\chi \equiv \mathbf{arg}(Q + i\ U)/2$

- 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:

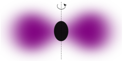
- Nearly extreme Kerr black hole: $a_J > 0.8$;
- Almost face-on disk with a 17° inclination angle;



- Rich information under strong gravity, **what else can we learn?**

Axion Cloud and Birefringence

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



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

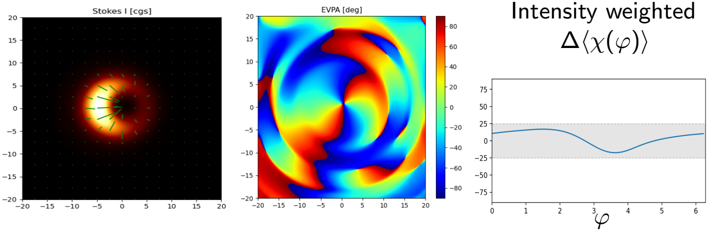
$$a^{\rm GA}(x^\mu) \simeq R_{11}(\mathbf{x}) \cos\left[m_a t - \phi\right] \sin\theta; \qquad a^{\rm GA}_{\rm max} \simeq \mathcal{O}(1)\, f_a; \qquad \omega \simeq m_a.$$

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

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

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

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



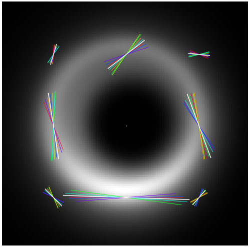
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along** φ on the sky plane

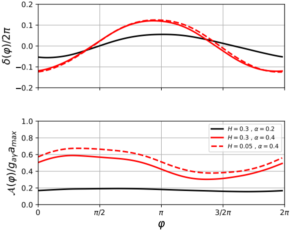
BL coordinate: $a^{\rm GA} \propto \cos\left[m_a t - \phi\right] \to \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$

Axion Birefringence for RIAF around M87* (IPOLE simulation)

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

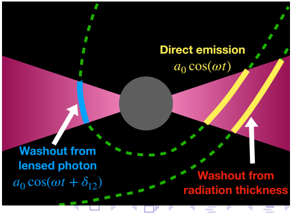
- Scan axion mass: $\alpha \equiv r_g m_a \in [0.10, 0.44]$ with **period [5, 20] days**.





- $\delta(\varphi) \approx -5\ \alpha\ \sin 17^\circ \cos\varphi$: phase delay at different φ.

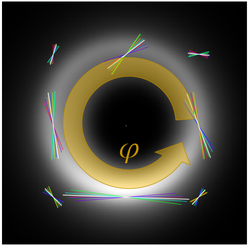
- Asymmetry of $\mathcal{A}(\varphi) = \mathcal{O}(1) g_{a\gamma} f_a$: **washout from lensed photon with** $\delta_{12} = \omega\delta t - \delta\phi$!

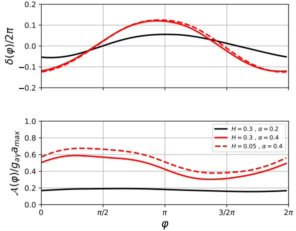


Axion Birefringence for RIAF around M87* (IPOLE simulation)

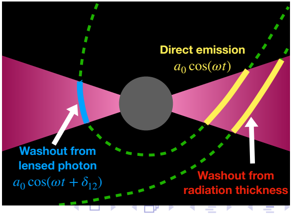
$$\Delta\langle\chi(\varphi)\rangle = \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$$

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



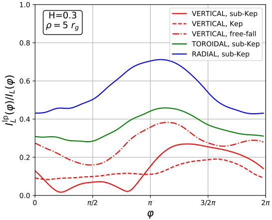


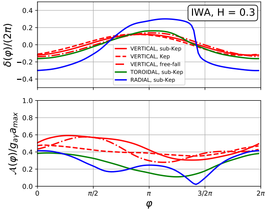
- $\delta(\varphi) \approx -5\ \alpha\ \sin 17^\circ\ \cos\varphi$: phase delay at different φ.
- Asymmetry of $\mathcal{A}(\varphi) = \mathcal{O}(1) g_{a\gamma} f_a$: **washout from lensed photon with** $\delta_{12} = \omega\delta t - \delta\phi$!



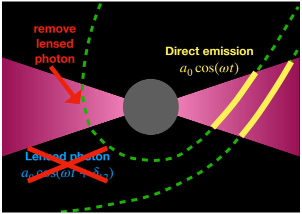
Lensed Photon Washout

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

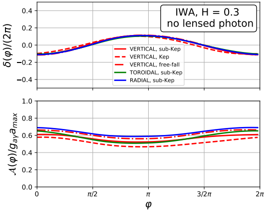




- **Universal birefringence signals** for direct emission only:

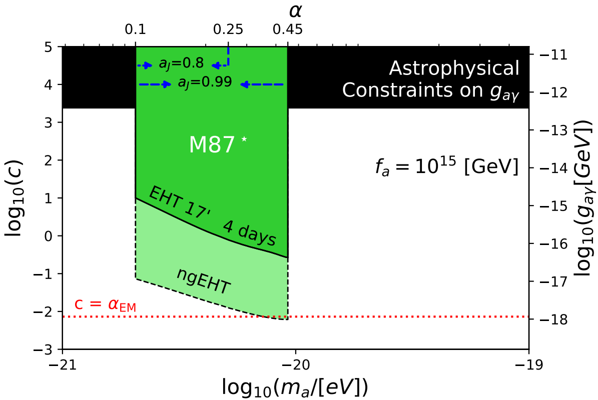


remove lensed photon →



Prospect for next-generation EHT

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



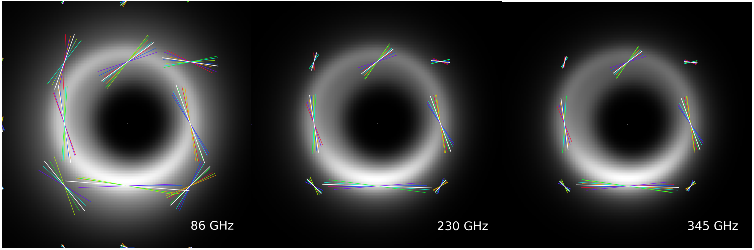
Recent updates:

- 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.

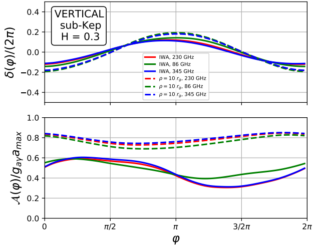


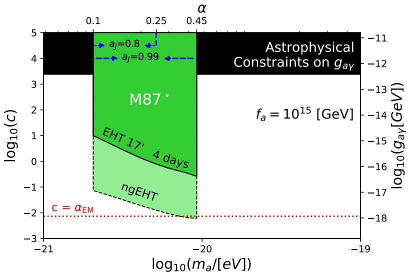
- Longer and sequential observations.
- Better resolution of EVPA.
- Better understanding of accretion flow and jet.
  Intrinsic variations of EVPA from GRMHD simulation?

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.





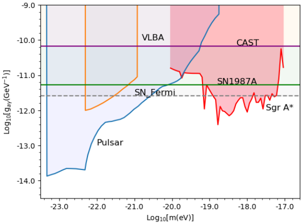
- Longer and sequential observations.

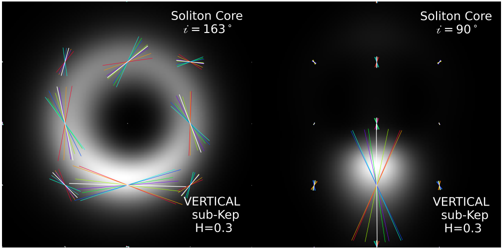
- Better resolution of EVPA.

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

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.

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^{μ}: unit directional vector

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

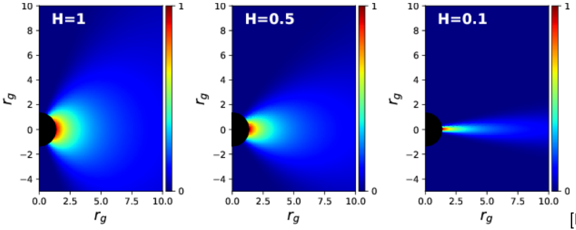
$$\begin{aligned}\Delta\chi &= g_{a\gamma}\int_{\mathrm{emit}}^{\mathrm{obs}} n^{\mu}\partial_{\mu}a\; dl \\ &= g_{a\gamma}[a(t_{\mathrm{obs}}, \mathbf{x}_{\mathrm{obs}}) - a(t_{\mathrm{emit}}, \mathbf{x}_{\mathrm{emit}})].\end{aligned}$$

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

Accretion Flow around M87*

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

n_e:

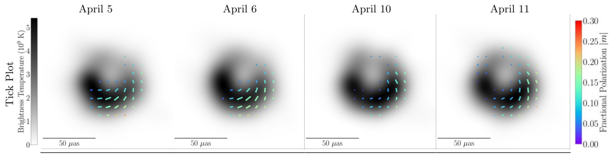


[Pu,Broderick 18']

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

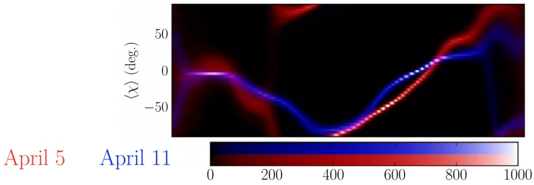
EHT Polarization Data Characterization

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



[EHT 21']

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



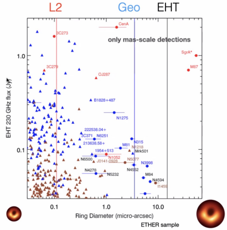
[EHT 21']

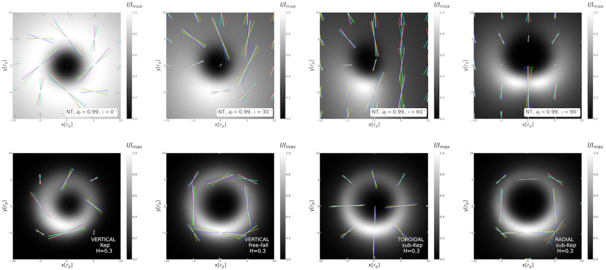
ranging from $\pm 3^\circ$ to $\pm 15^\circ$ for the bins used.

Landscape of SMBH and Accretion Flow (IPOLE simulation)

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

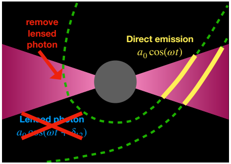
[Nagar ngEHT21]

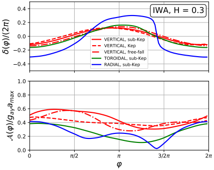




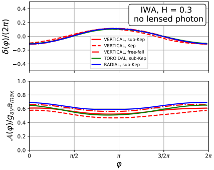
Broader range of axion mass: 10^{-22} eV to 10^{-17} eV.

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



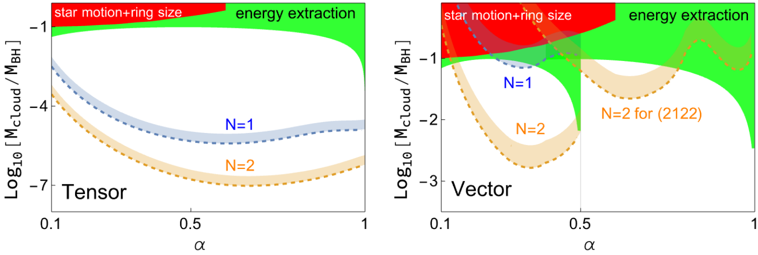


remove lensed photon →



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 φ: 10°.



- 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

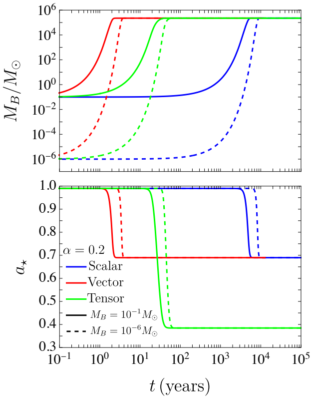
the shadow and photon ring of Sgr $A^{\star}$

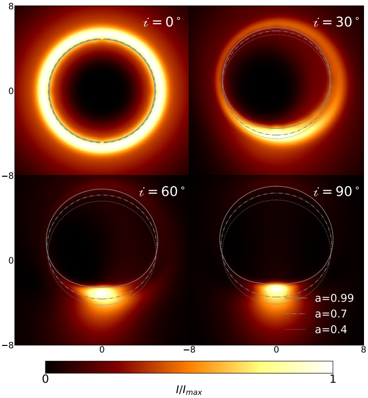
based on
arxiv: 2205.06238, Phys. Rev. D **106** (2022) no.4, 043021.

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

Superradiant Evolution for Bosons

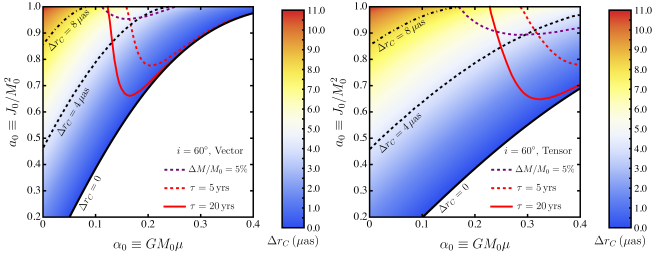
- **Superradiant evolution** for scalar, vector or tensor $\rightarrow$ spin decreases:





- 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*.

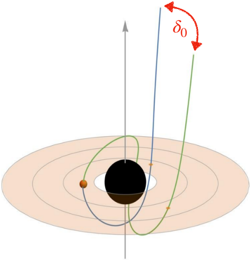
Large Inclination Angle: Shadow Drift



- 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.

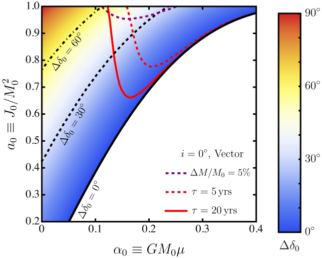
Low Inclination Angle: Azimuthal Lapse

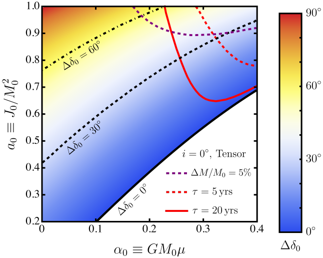
- At low inclination angles,
  photon ring autocorrelation for intensity fluctuations:
  $\mathcal{C}(T,\varphi) \equiv \iint \mathrm{d}r\mathrm{d}r'\, r\, r' \, \langle \Delta I(t,r,\phi)\Delta I\,(t+T,r',\phi+\varphi)\rangle$
  peaks at $T = \tau_0$ and $\varphi = \delta_0$,
  where δ_0 is the azimuthal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



[Chael Palumbo]

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



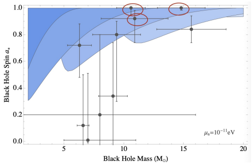


Fate of Superradiance

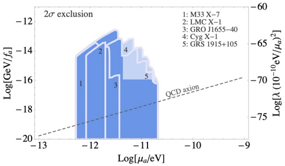
Axion cloud can't keep growing exponentially. What's **the fate of it**?

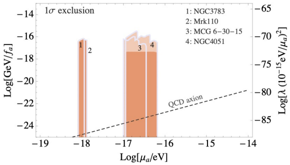
- **Self interaction** of axion becomes important for $f_a < 10^{16}$ GeV. [Yoshino, Kodama 12', Baryakht et al 20']
- Black hole **spins down** until the superradiance condition is violated for $f_a > 10^{16}$ GeV. [Arvanitakia, Dubovsky 10']
- Formation of a **binary system** leads to the decay/transition 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']

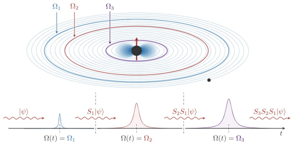


- Comparing **the timescale between the superradiance and BH accretion**, a BH with large spin can typically exclude axion with $f_a > 10^{16}$ GeV.





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.