Strong Gravity Frontier of Particle Physics

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Outlines

Ultralight Bosons

and Superradiance

Ultralight Bosons

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

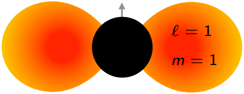
- Axion: hypothetical pseudoscalar motivated by strong CP problem.
- Prediction from fundamental theories with **extra dimensions**:

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

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

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

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: $\alpha \equiv G_N M_{\rm BH} \mu$, Bohr radius: r_g/α^2.

  BH horizon $\to \omega \simeq \mu + i\Gamma$.

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

$$\text{Compton wavelength } \lambda_c \quad \simeq \quad \text{gravitational radius } r_g.$$
$$\mu \sim 10^{-12}\,\text{eV} \quad \leftrightarrow \quad M_{\rm BH} \sim 10\, M_\odot.$$

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

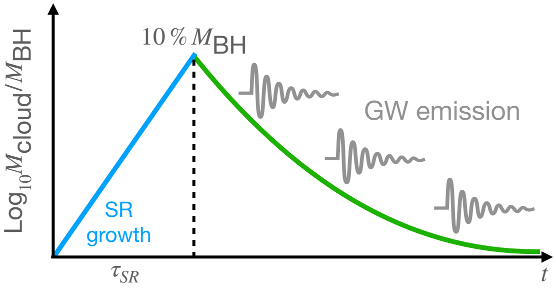
$$\frac{M_{\rm cloud}}{M_{\rm BH}} \approx \begin{cases} 0.5\% \left(\frac{\Psi_0}{10^{16}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for scalar,} \\ 0.8\% \left(\frac{\Psi_0}{10^{17}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for vector.} \end{cases}$$

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

- **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_{cloud} takes up to $10\% M_{\text{BH}}$.

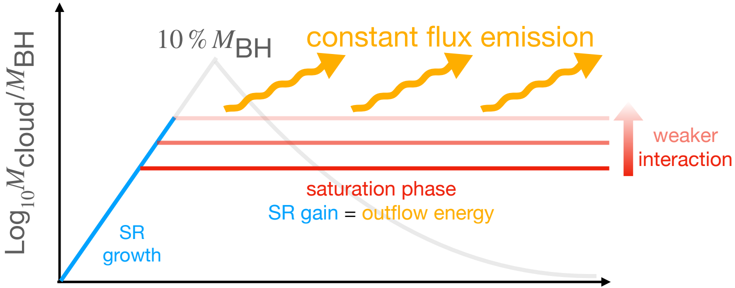


- **High spin** excludes boson mass in SR range with reasonable τ_{BH}.
  [Arvanitaki, Brito, Davoudiasl, Denton, Stott, Unal, Saha et al]

- **GW from boson annihilation and transition** slowly decreases M_{cloud}.
  [Yoshino, Brito, Isi, Siemonsen, Sun, Palomba, Zhu, Tsukada, Yuan, LVK et al]

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'].
- **Saturated** $M_{\rm cloud}$ is determined by interaction strength.

Black Holes as

Neutrino Factories

Particle Production from Boson Background

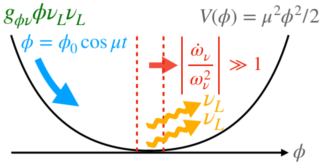
- Neutrino self-interaction mediated by light scalar, majoron: $g_{\phi\nu}\phi\nu_L\nu_L$.

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

- Non-adiabatic production when $|\dot{\omega}_\nu/\omega_\nu^2| \gg 1$:

  A **fermi sphere with** $k_* = \sqrt{g_{\phi\nu}\phi_0\mu}/2$ is pumped when $m_{\text{eff}} \sim 0$ [Greene Kofman 98' 00'].

  Production rate: $\Gamma_{\phi\nu} \approx (g_{\phi\nu}\phi_0)^{3/2}\mu^{5/2}/(48\pi^3)$.



- Schwinger pair production from vector clouds with $g_{V\nu}A'^\mu\nu_L^\dagger\bar{\sigma}^\mu\nu_L$.

  Production rate: $\Gamma_{V\nu} \approx \frac{g_{V\nu}^2 E_{A'}^2}{48\pi}$, where $E_{A'} \sim \mu|\vec{A}'|$.

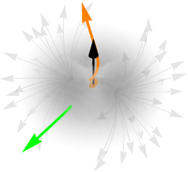
- **Strong field frontier**: similar to preheating and strong field QED.

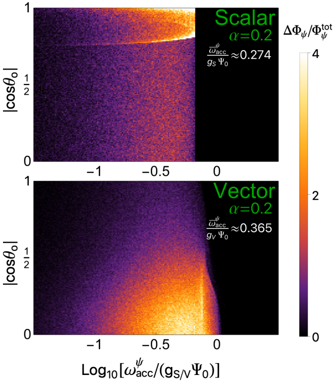
Neutrino Acceleration from Boson Cloud

- Neutrino propagation under boson background:

$$\frac{\mathrm{d}p_\nu^\alpha}{\mathrm{d}t} = -\frac{1}{p_\nu^0}\Gamma^\alpha_{\kappa\beta}\, p_\nu^\kappa\, p_\nu^\beta + \begin{cases} -\nabla^\alpha m_{\mathrm{eff}}^2/(2p_\nu^0) \leftarrow \textbf{scalar force} \text{ [Uzan et al 20']}. \\ \pm g_{A'\nu}(\vec{E}_{A'} + \vec{v}_\nu \times \vec{B}_{A'}). \end{cases}$$

- Final average momentum: $\bar{\omega}^\nu_{\mathrm{acc}} \sim g_{\Psi\nu}\Psi_0$.
- Flux from scalar cloud prefers **face-on** observer while vector cloud prefers **edge-on** one.
- Both spatial and temporal variation are necessary for acceleration in scalar cloud.





- ν decays to charged leptons and $\pi^\pm$ once $m_{\mathrm{eff}} > m_\pi$.

Spin Measurement and Neutrino Flux

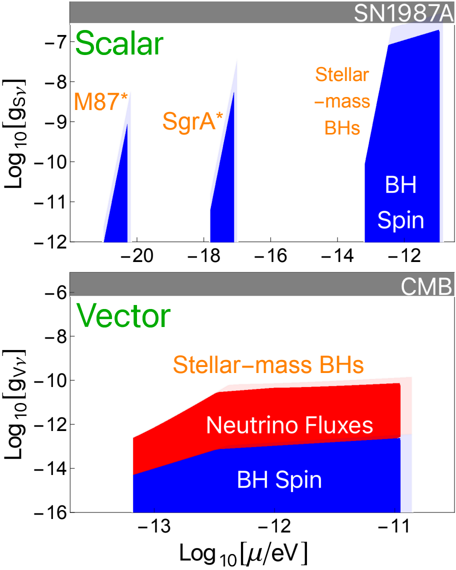
- **Neutrino emission** from saturation phase $\Gamma_{\Psi\nu} = \Gamma_{SR}$.

  $\rightarrow$ saturated field value Ψ_0^c.

- **High spin** excludes region:
  - Scalar: $g_{\phi\nu}\Psi_0^c \geq m_\pi$.
  - Vector: $\Gamma_{V\nu} \ll \Gamma_{SR}$.

- TeV-point sources surpass diffusive atmospheric ν.

- **Multi-messenger observation**:
  - GW and EM searches for BHs.
  - Neutrino and boosted dark matter.



[YC, Xue, Cardoso, arXiv:2308.00741]

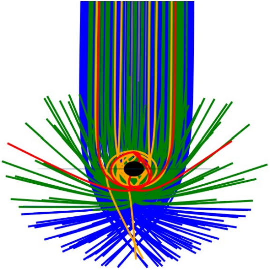
Probing Ultralight Bosons

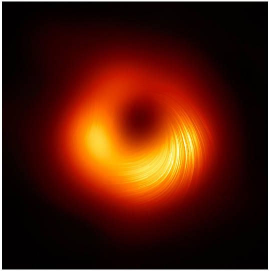
with Event Horizon Telescope

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']

Photon bound orbits outside BHs:

Photon ring with enhanced intensity.

$\rightarrow$ Precise test of general relativity.

- **Astrometry for new physics**?

Synchrotronic Linear polarization reveals magnetic field structure.

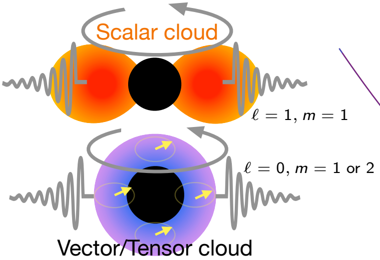
Four days' observations **show slight difference**.

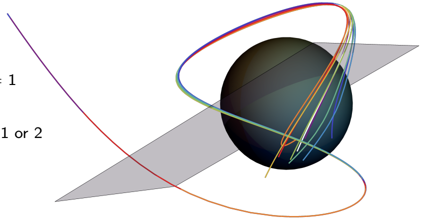
- **New interactions**?

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

Photon Ring Astrometry for Gravitational Atoms

- Superradiant clouds generate local oscillatory metric perturbations $g_{\mu\nu} \simeq g^{\mathrm{K}}_{\mu\nu} + \epsilon h_{\mu\nu}$ 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** $M_{\text{cloud}}/M_{\text{BH}}$ **to** 10^{-3} **for vector and** 10^{-7} **for tensor**.

Axion Cloud Induced Birefringence

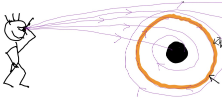
- Axion-induced Birefringence: rotation of **linear polarization**:

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

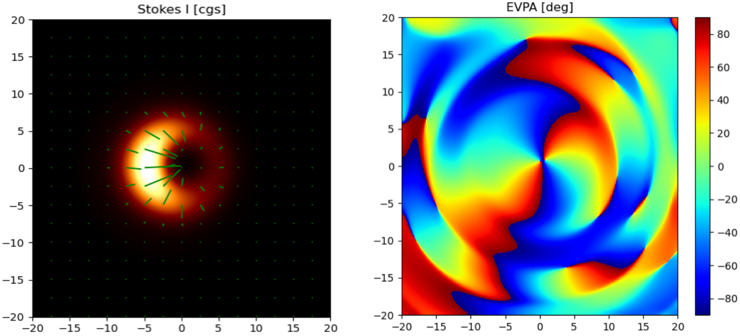
- Extended sources, plasma and curved space-time effects?

Covariant radiative transfer [IPOLE simulation]

with an accretion flow model outside SMBH:



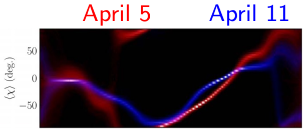
[Strominger 19']

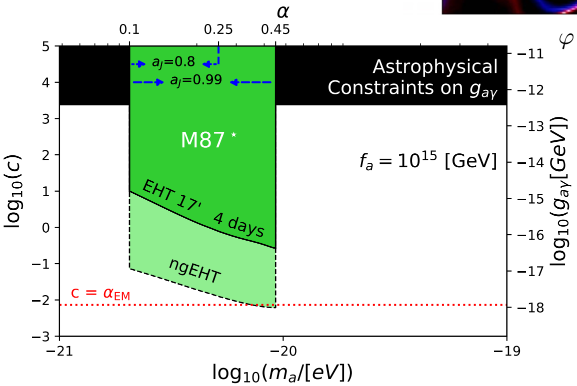


Stringent Constraints on Axion-Photon Coupling

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

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





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

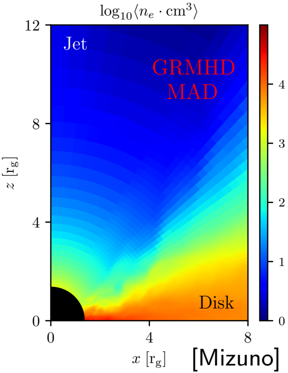
[YC, Li, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Zhou,
PRL **124** (2020) no.6, 061102, Nature Astron. **6** (2022) no.5, 592-598, JCAP **09** (2022), 073]

Illuminating Black Hole Shadow

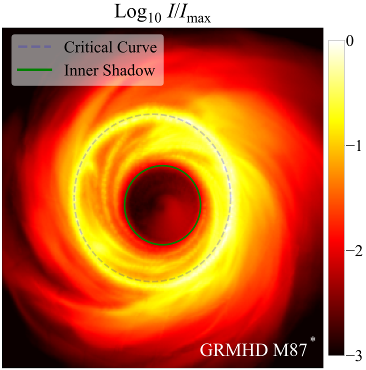
with Dark Matter Annihilation

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**.



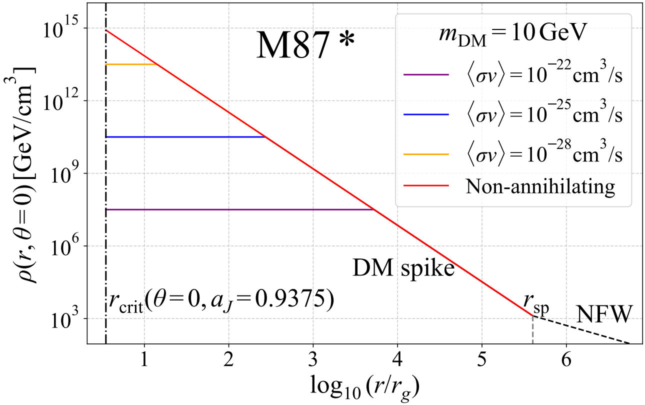
[Mizuno]



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

Dark Matter Spike

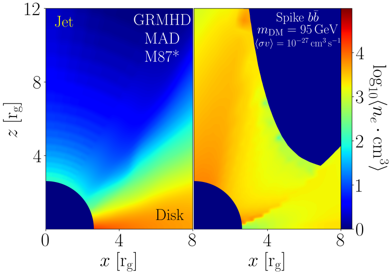
- **Particle DM density** can be significant outside SMBHs assuming adiabatic accretion [Gondolo, Silk 99'].

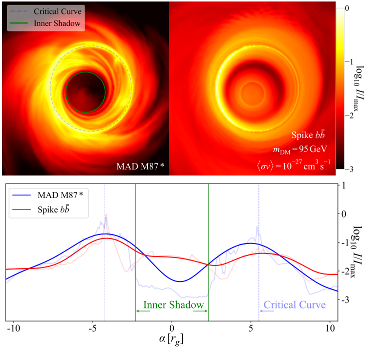


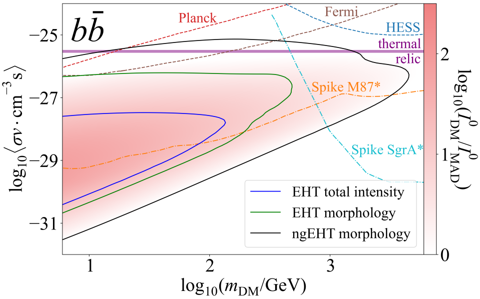
- Annihilation into e^+/e^- contribute to synchrotron radiation [Lacroix et al 18'].

Illuminating Black Hole Shadow with Dark Matter Annihilation

- n_e after propagation under **GRMHD and BH potential**:
- Inner shadow can be illuminated, setting **stringent constraints**:







[YC, Ding, Liu, Mizuno, Shu, Yu, Zeng, arxiv: 2404.16673]

Illuminating Black Hole Shadow with Dark Matter Annihilation

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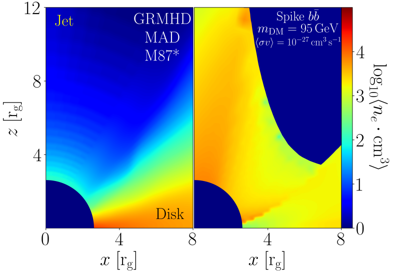
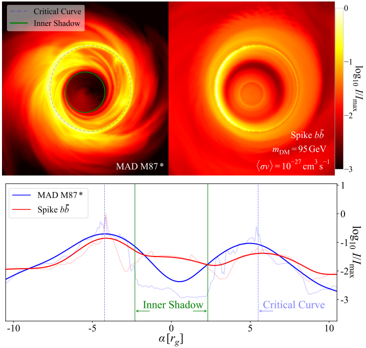
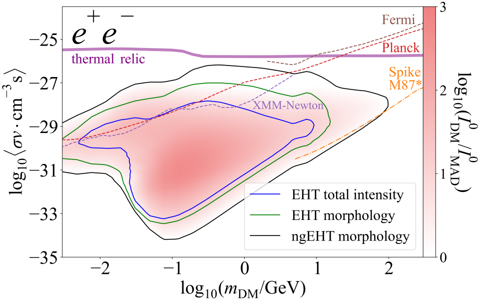


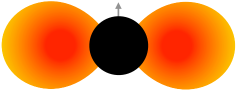


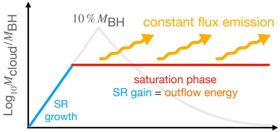


[YC, Ding, Liu, Mizuno, Shu, Yu, Zeng, arxiv: 2404.16673]

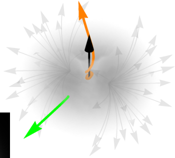
Summary

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



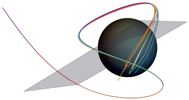


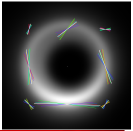
- **Strong field frontier**:
  - Parametric particle production and acceleration.



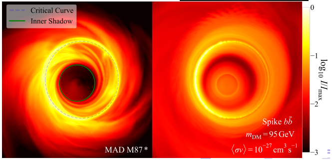
- **Multi-messenger correlation**:

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

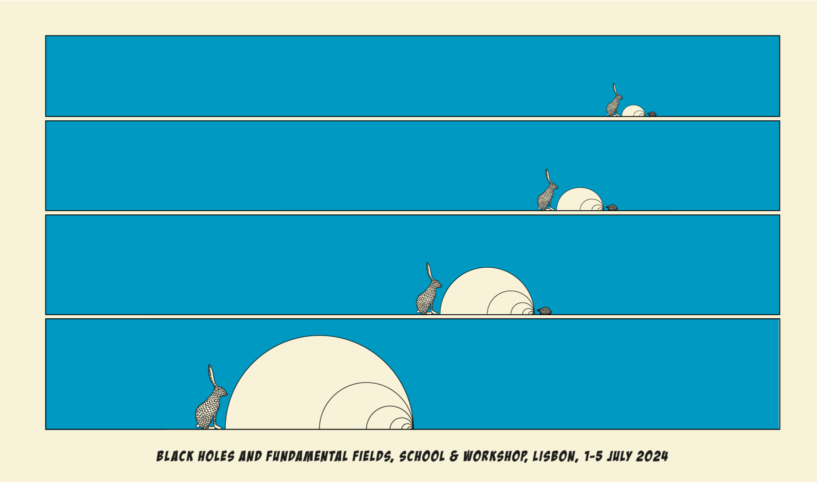




- **Event Horizon Telescope**:
  - **Photon geodesics deflection**.
  - **Linear polarization rotation**.
  - **Dark matter illuminating the inner shadow**.



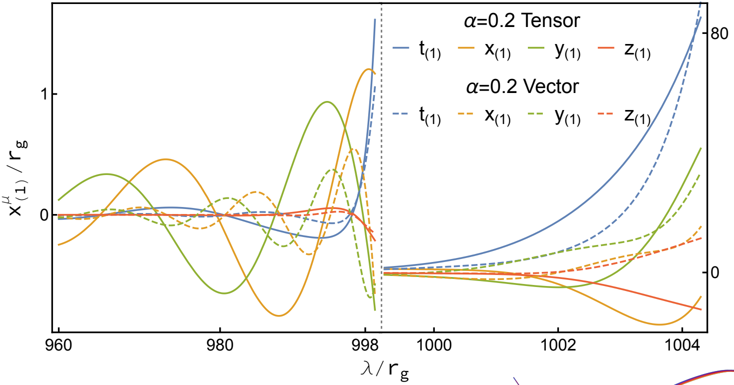
Thank you!

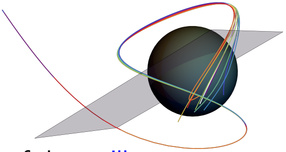

BLACK HOLES AND FUNDAMENTAL FIELDS, SCHOOL & WORKSHOP, LISBON, 1-5 JULY 2024

Appendix

Gravitational Atom-induced Geodesics Deflections

Backward ray-tracing:

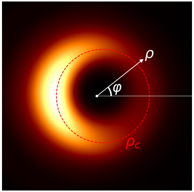




Two phases of evolution:

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

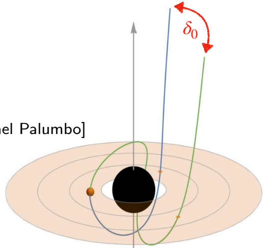
Astrometrical Photon Ring Autocorrelations



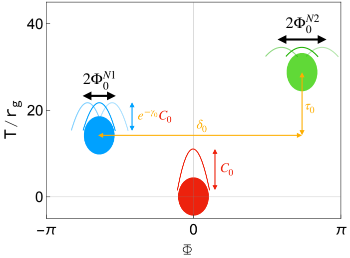
A photon pair executing different half orbits number N:

- 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

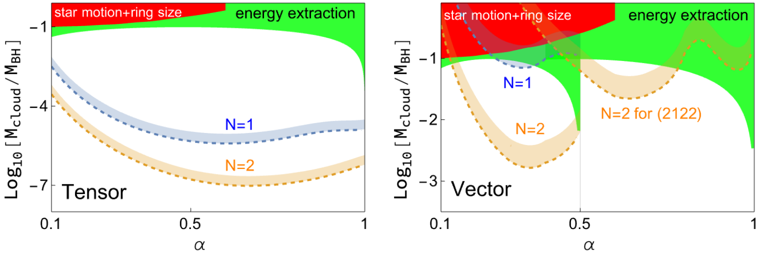


Observables: $\Delta\Phi^N = \Phi_0^N \cos(\omega t + \delta)$ for $N = 1$ and 2.

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

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°.



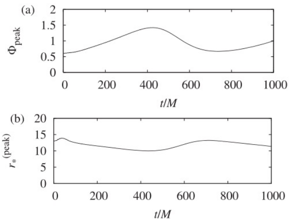
- A tensor with linear coupling to stress tensors is more sensitive than a vector with quadratic couplings.
- $N = 2$ correlation peak can probe large unexplored parameter space of cloud mass.
- Sources with shorter correlation time, e.g., hotspots or pulsars can significantly increase the sensitivity.

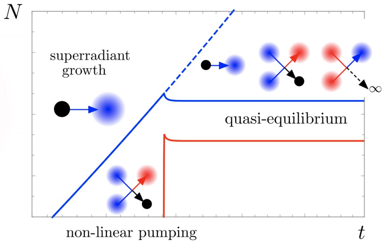
Weakly Saturating Axion Cloud

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

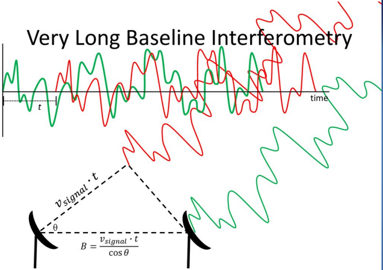


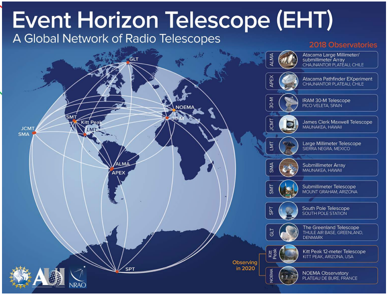


[Yoshino, Kodama 12' 15', Baryakht et al 20']

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.



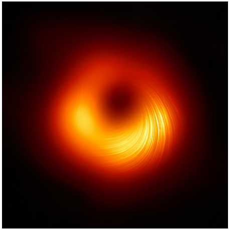


- As good as being able to see  on the moon from the Earth.

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

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

Total intensity I

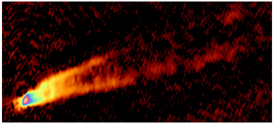


Linear polarization Q, U
EVPA $\chi \equiv \arg(Q + i\ U)/2$

- 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

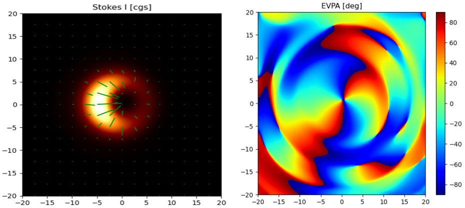
- **Axion cloud** saturates f_a due to self-interactions: $r_g m_a \approx \mathcal{O}(1)$

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

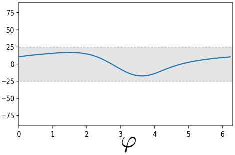
- $g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \to$ achromatic birefringence to EVPA $\chi \equiv \arg(Q + i\ U)/2$:

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

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



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



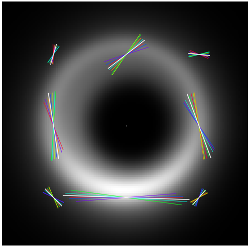
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along** φ on the sky plane

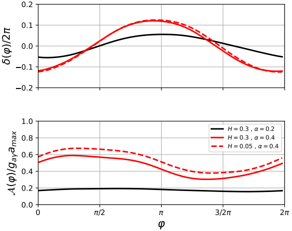
BL coordinate: $\quad a^{\rm GA} \propto \cos\left[m_a t - \phi\right] \to \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$

Axion Birefringence for RIAF around M87* (IPOLE simulation)

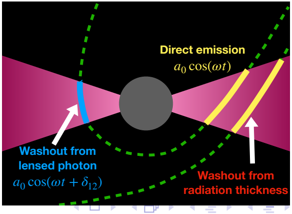
$$\Delta\langle\chi(\varphi)\rangle = \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$$

- 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** $\delta_{12} = \omega\delta t - \delta\phi$!



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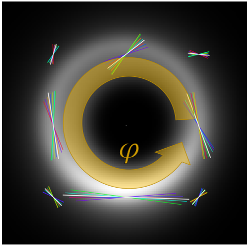

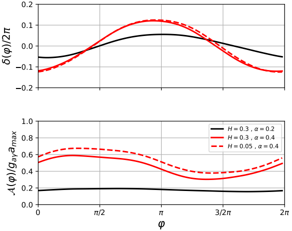

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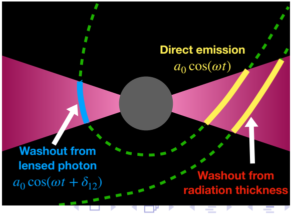
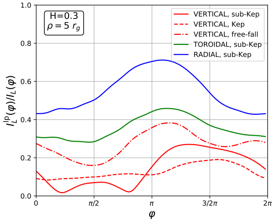
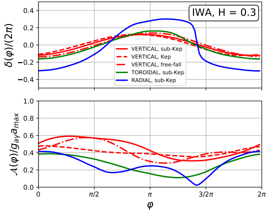


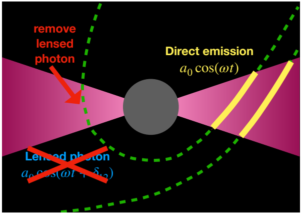
Lensed Photon Washout

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

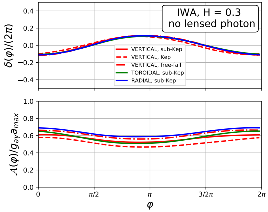




- **Universal birefringence signals** for direct emission only:

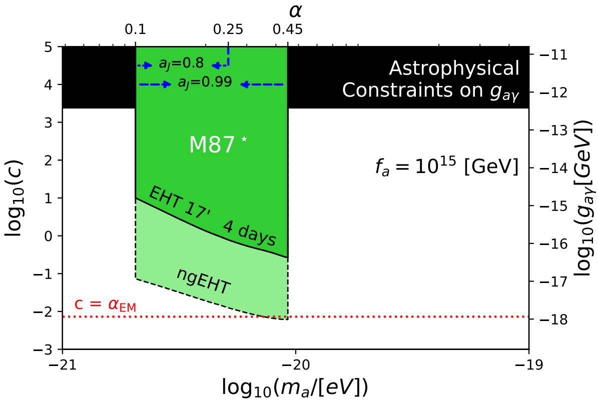


remove lensed photon →



Prospect for next-generation EHT

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



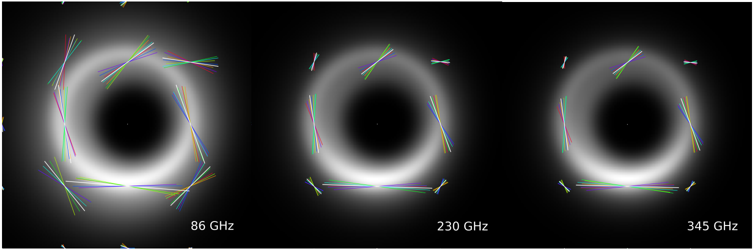
Recent updates:

- 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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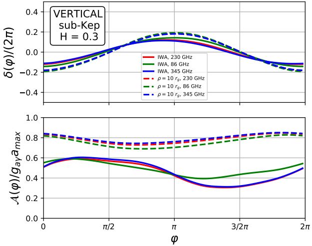

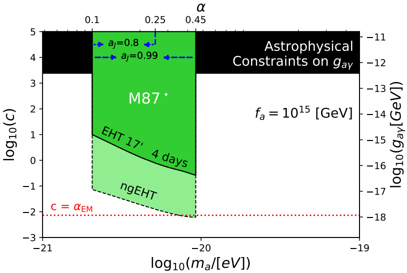

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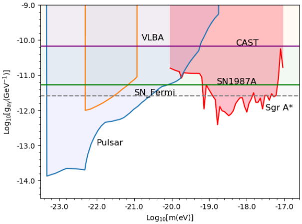
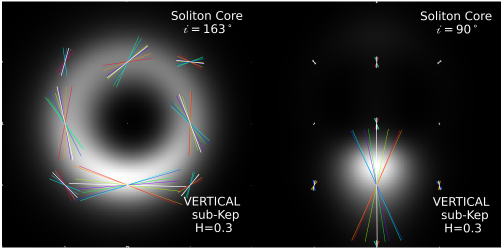
Birefringence from Soliton Core Dark Matter

- 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:

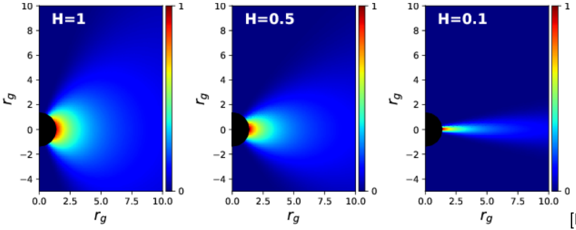
$$\begin{aligned}\Delta\chi &= g_{a\gamma}\int_{\rm emit}^{\rm obs} n^{\mu}\partial_{\mu}a\, dl \\ &= g_{a\gamma}[a(t_{\rm obs}, \mathbf{x}_{\rm obs}) - a(t_{\rm emit}, \mathbf{x}_{\rm emit})].\end{aligned}$$

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

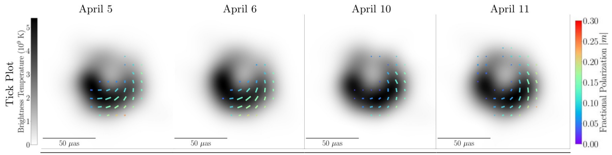


[Pu,Broderick 18']

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

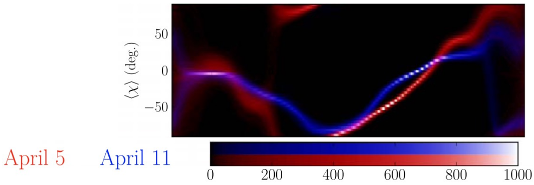
EHT Polarization Data Characterization

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



[EHT 21']

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



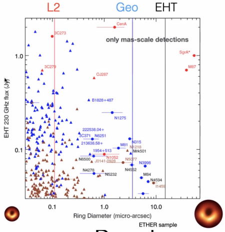
[EHT 21']

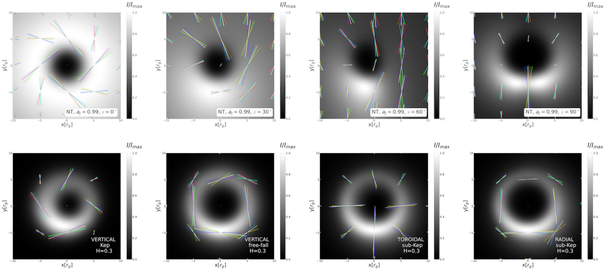
ranging from $\pm 3^\circ$ to $\pm 15^\circ$ for the bins used.

Landscape of SMBH and Accretion Flow (IPOLE simulation)

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

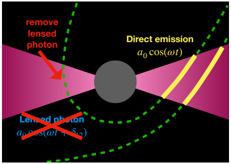
[Nagar ngEHT21]

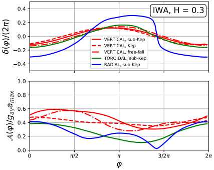




Broader range of axion mass: 10^{-22} eV to 10^{-17} eV.

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





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