Strong Gravity Frontier of Axion Searches

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Axion Dark Matter: Theory and Phenomenology

THE CENTER OF GRAVITY

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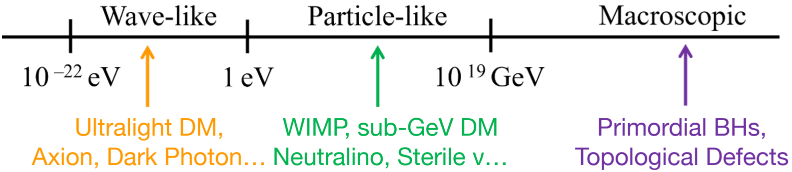
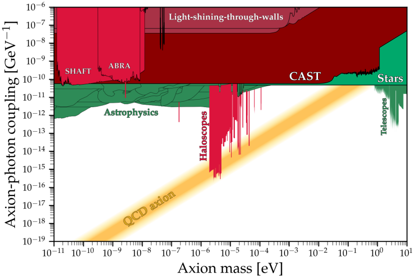
Ultralight Dark Matter

- Landscapes of **dark matter** candidates:



- **QCD Axion**→neutron EDM∼ 0. μeV → **relic abundance**.
- **Extra dimensions**→ **axions** and **dark photons**...
- **Wave-like property** with high occupation number.
- Astro and terrestrial probes.



Superradiant Gravitational Atoms

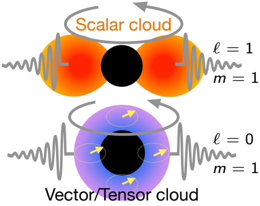
- **Gravitational atom** between BH and boson cloud:

  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 $M_{\rm cloud} \lesssim 10\%\, M_{\rm BH}$:

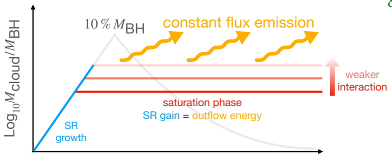
$$\frac{M_{\rm cloud}}{M_{\rm BH}} \approx \begin{cases} 0.5\% \left(\frac{\Psi_0}{10^{16}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for scalar,} \\ 0.8\% \left(\frac{\Psi_0}{10^{17}\,\rm GeV}\right)^2 \left(\frac{0.4}{\alpha}\right)^4 & \text{for vector.} \end{cases}$$

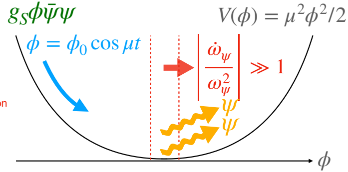
  Local dark matter field: $\Psi_0^\odot \approx 2\,{\rm GeV} \left(\frac{10^{-12}\,\text{eV}}{\mu}\right)$

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

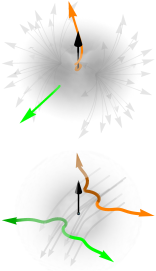
Strong Field Frontier with Saturating Cloud

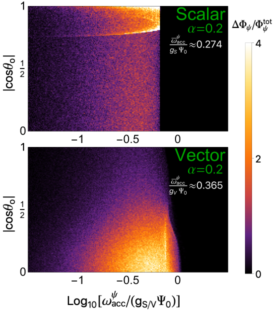
- Up to GUT-scale $\sim 10^{16}$ GeV field values from superradiance or accretion.





- **Strong field frontier**: similar to **preheating** and **strong field QED**.
  - Axion cloud $\rightarrow$ **photon production** [Spieksma et al PRD 23].
  - Boson cloud $\rightarrow$ **fermion production and acceleration** [YC et al JCAP 25].





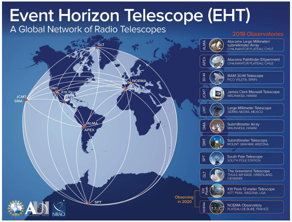
- **Production rate** significantly higher than perturbative decays.

EHT and Future VLBI Arrays for Fundamental Physics

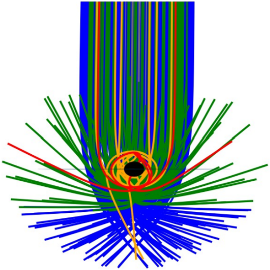
Event Horizon Telescope: best-ever **angular resolution** from VLBI.

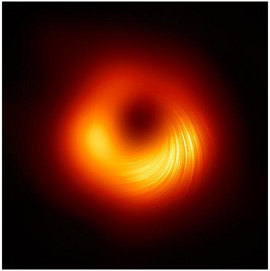
$\theta_{\rm res} \sim \lambda/d$ and $d \to R_E$.

Future: **ngEHT** and space-VLBI **BHEX**.



Photon orbits [KGEO]





Photon ring: bound orbits.
Precision test of GR and BH.

Synchrotronic linear polarization reveals magnetic field structures.

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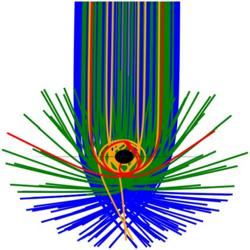
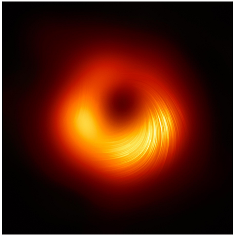
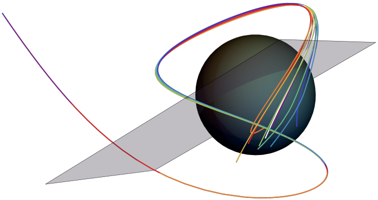


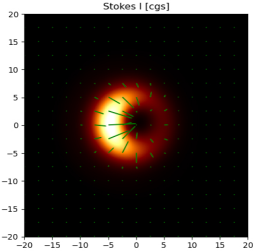


Stokes Q, U
EVPA $\chi \equiv \arg(Q + i\ U)/2$
[EHT 21]

Photon ring: bound orbits.

Synchrotronic linear polarization.





[Fundamental Physics Opportunities with Future Ground-Based mm/sub-mm VLBI Arrays, Living Rev. Rel. 25]

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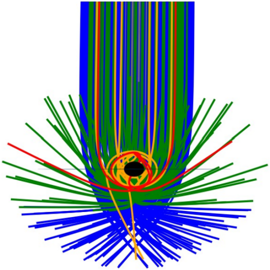

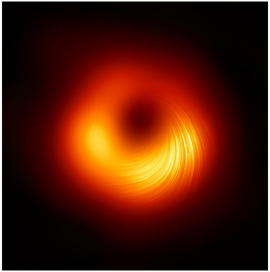

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Photon ring: bound orbits.

- **Astrometry for boson clouds.**
  [YC, Xue, Brito, Cardoso, PRL 23]
- **Ringdown tomography.**
  [Zhong, Cardoso, YC, PRL 25]
- **Forward ray tracing.**
  [Zhou, Zhong, YC, Cardoso, PRD 25]

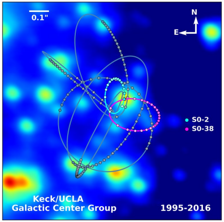
Synchrotronic linear polarization reveals magnetic field structures.

- **Axion cloud birefringence.**
  [YC, Li, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Zhou,
  PRL 20, Nature Astron. 22, JCAP 22]
- **Axion dark matter.**
  [Yuan, Xia, YC et al, JCAP 21]

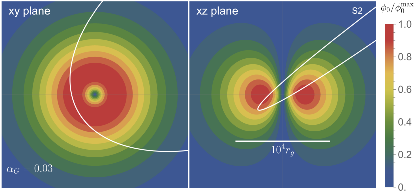
[Fundamental Physics Opportunities with Future Ground-Based mm/sub-mm VLBI Arrays, Living Rev.Rel. 25]

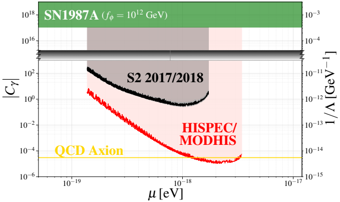
Fine-structure Constant Variation from Axion

$$\frac{g_s^2}{32\pi^2}\frac{\phi}{f_\phi}G_{\mu\nu}\widetilde{G}^{\mu\nu} \rightarrow \frac{C_\gamma}{4}\frac{\phi^2}{f_\phi^2}F_{\mu\nu}F^{\mu\nu}.$$



- Axion can induce **deviation** of $\alpha_{\rm EM}$ at **loop levels**.
- $|C_\gamma| \sim 10^{-5}$ for QCD axions, and free for ALPs.
- **Galactic-center spectroscopy** for S-stars:

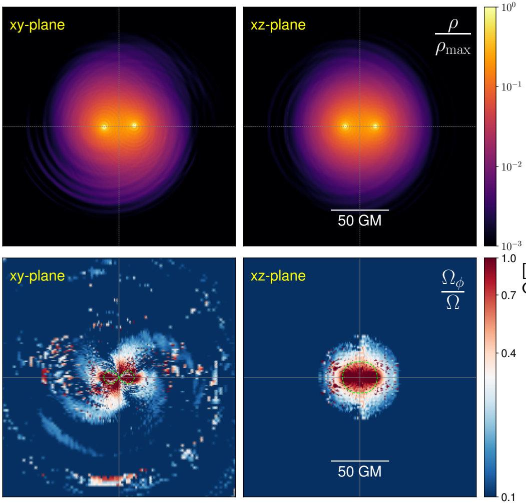




[Bai, Cardoso, YC, Do, Hees, Xiao, Xue to appear]

- Benefit from $\phi \sim f_\phi$ **field value**.
- **Future spectroscopy** can probe QCD axions.

Ultralight Bosons Around Inspiraling Binaries

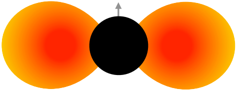


[Guo, Zhong, YC, Zhou, Cardoso, Ikeda, ongoing]

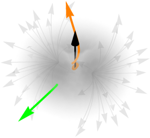
- **Co-rotating** gravitational **molecules**: rapid **circularization**.
- Distinct **ionization** emissions compared to extreme-mass-ratio binaries.
- Difference with signatures of stars or particle dark matter?
  [YC, Xue, NANOGrav Collaboration 2411.05906].

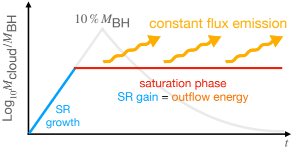
Summary

- **Black holes** are powerful concentrators for **ultralight bosons** with up to **GUT-scale** Ψ_0; $> 10^{10-20}$ **denser** than dark matter on Earth.



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





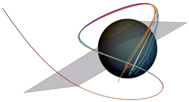
- Black hole observations:

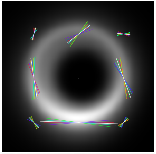
  EHT imaging.

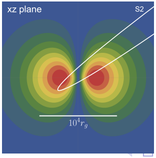
  KECK/GRAVITY spectroscopy.

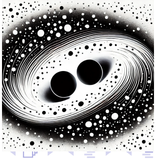
  PTA supermassive binary GW.

  - **Photon geodesics deflection**.
  - **Linear polarization rotation**.
  - **Spectral oscillation**.
  - **Galaxy tomography**.









Thank you!

Appendix

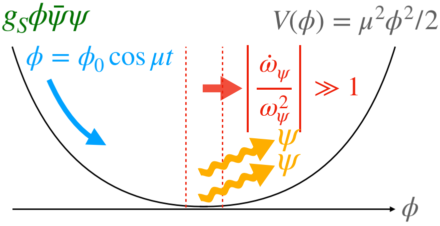
Black Holes as

Fermion Factories

Fermion Production from Boson Background

- **Ultralight bosons** coupled to fermions: $g_S \phi \bar{\psi}\psi$ and $g_V A'_\mu \bar{\psi}\gamma^\mu \psi$.

- **Scalar**: fermi sphere excitation
  when $|\dot{\omega}_\psi/\omega_\psi^2| \gg 1$ ($m_{\rm eff} \sim 0$),
  where $\omega_\psi^2 = k^2 + m_{\rm eff}^2$ and
  $m_{\rm eff} = m_\psi + g_S \phi_0 \cos \mu t$.
  [Greene Kofman 98 00]



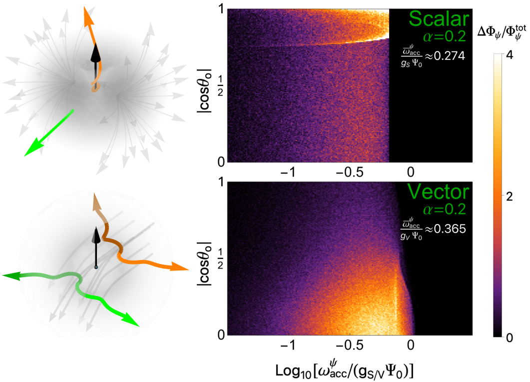
- **Vector**: Schwinger pair production with $\Gamma_{V\psi} \approx \frac{g_V^2 E_{A'}^2}{48\pi}$, where $E_{A'} \sim \mu |\vec{A}'|$.

- **Fermion propagation** under non-uniform boson background:

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

Fermion Fluxes from Boson Cloud

- **Fermion acceleration** under non-uniform boson clumps [YC et al JCAP 2308.00741].



- Application to **boosted dark matter** or ν:

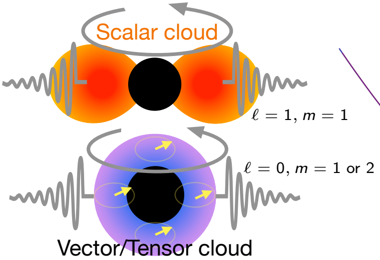
  Vector: TeV-fluxes expected to surpass diffusive atmospheric ν.

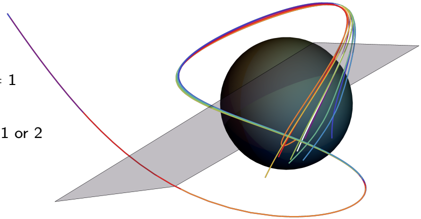
- **Multi-messenger observation**:

  - GW and EM searches for BHs.
  - ν and dark matter detectors.

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

Axion Cloud Induced Birefringence

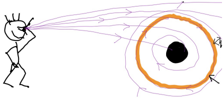
- Axion-induced Birefringence: rotation of **linear polarization**:

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

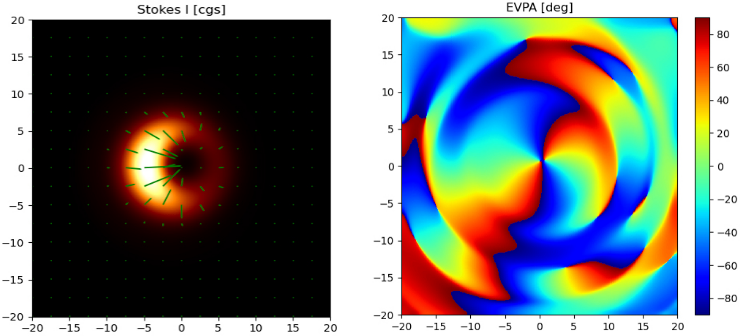
- Extended sources, plasma and curved space-time effects?

Covariant radiative transfer [IPOLE simulation]

with an accretion flow model outside SMBH:



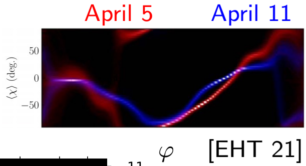
[Strominger 19]

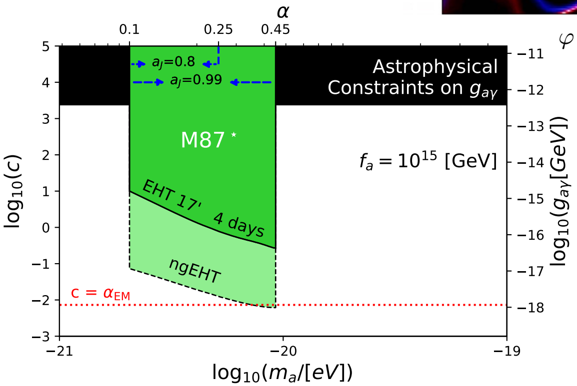


Stringent Constraints on Axion-Photon Coupling

- Uncertainty of azimuthal EVPA in [EHT 21]:

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



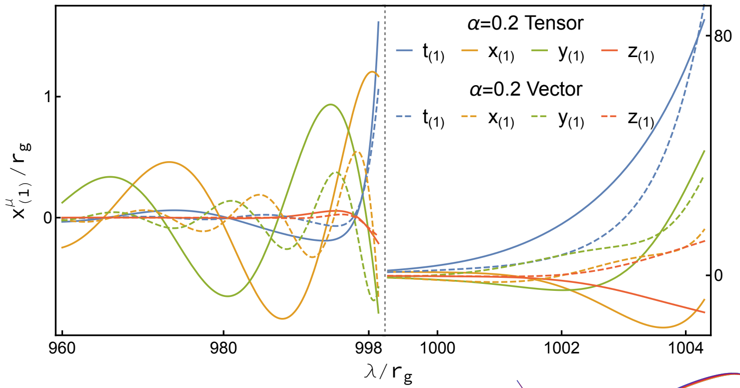


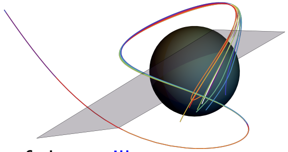
- Next-generation EHT is expected to significantly increase sensitivity.

[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]

Gravitational Atom-induced Geodesics Deflections

Backward ray-tracing:

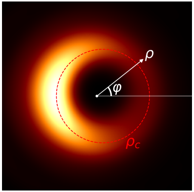




Two phases of evolution:

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

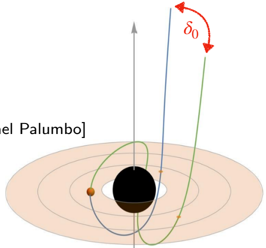
Astrometrical Photon Ring Autocorrelations



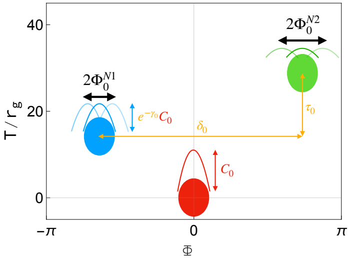
A photon pair executing different half orbits number N:

- 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

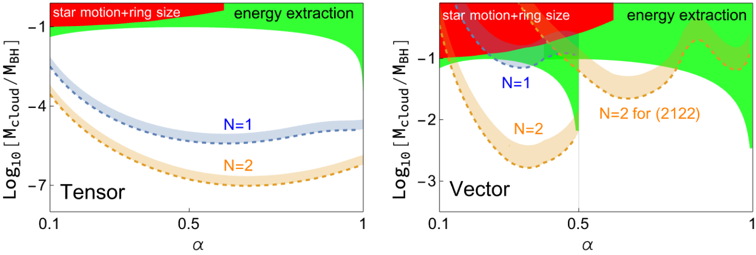


Observables: $\Delta\Phi^N = \Phi_0^N \cos\left(\omega t + \delta\right)$ for $N = 1$ and 2.

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

Photon Ring Autocorrelations as Astrometry

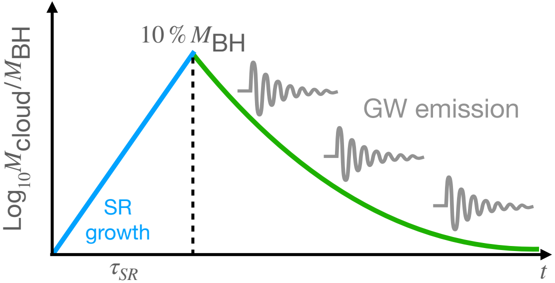
- Photon ring autocorrelation exclusion **criteria**: $\Delta\Phi^N > \ell_\phi \approx 4.3^\circ$ or ngEHT's smearing kernel for φ: 10°.



- 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.

Superradiance for Boson with Negligible Interaction

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



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

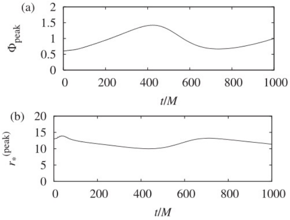
- **GW from boson annihilation and transition** slowly decreases $M_{\rm cloud}$.
  [Yoshino, Brito, Isi, Siemonsen, Sun, Palomba, Zhu, Tsukada, Yuan, LVK et al]

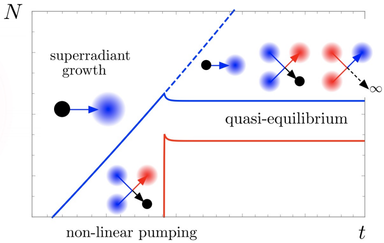
Weakly Saturating Axion Cloud

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

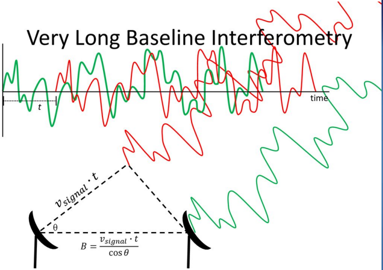


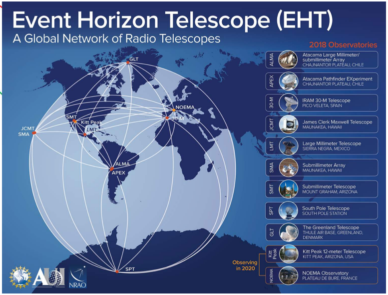


[Yoshino, Kodama 12 15, Baryakht et al 20]

Event Horizon Telescope: an Earth-sized Telescope

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



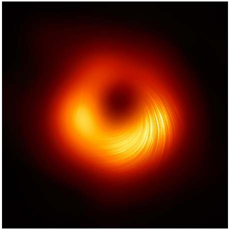


- As good as being able to see  on the moon from the Earth.

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

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

Total intensity I

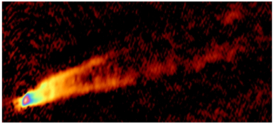


Linear polarization Q, U
EVPA $\chi \equiv \arg(Q + i\ U)/2$

- 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:

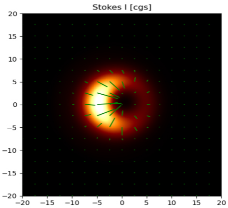
$r_g m_a \approx \mathcal{O}(1)$

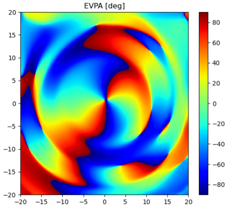
$$a^{\rm GA}(x^\mu) \simeq R_{11}(\mathbf{x}) \cos\left[m_a t - \phi\right] \sin\theta; \qquad a^{\rm GA}_{\rm max} \simeq \mathcal{O}(1)\, f_a; \qquad \omega \simeq m_a.$$

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

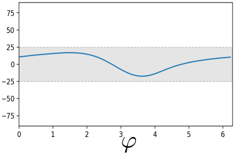
$$\text{Local frame}: \quad \frac{d(Q+i\ U)}{ds} = j_Q + i\, j_U + i\left(\rho_V^{\rm FR} - 2 g_{a\gamma}\frac{da^{\rm GA}}{ds}\right)(Q + i\ U).$$

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





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



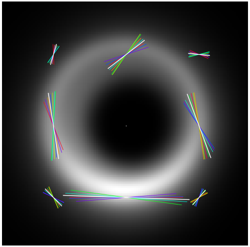
- $\Delta\langle\chi(\varphi)\rangle$: **propagating wave along** φ on the sky plane

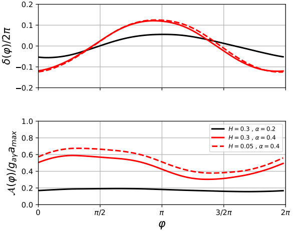
BL coordinate: $a^{\rm GA} \propto \cos\left[m_a t - \phi\right] \to \Delta\langle\chi(\varphi)\rangle \propto \mathcal{A}(\varphi)\cos\left[m_a t + \varphi + \delta(\varphi)\right].$

Axion Birefringence for RIAF around M87* (IPOLE simulation)

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

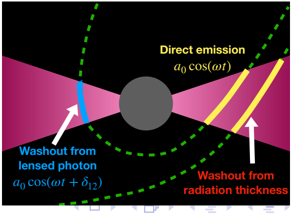
- Scan axion mass: $\alpha \equiv r_g m_a \in [0.10, 0.44]$ with **period [5, 20] days**.





- $\delta(\varphi) \approx -5\ \alpha\ \sin 17^\circ \cos\varphi$: 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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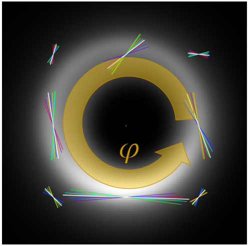

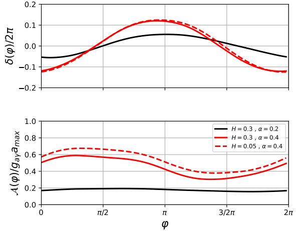

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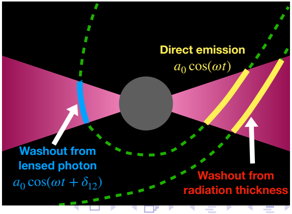
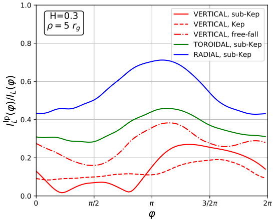
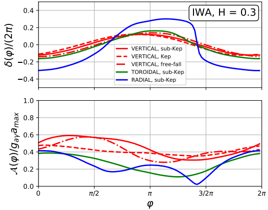


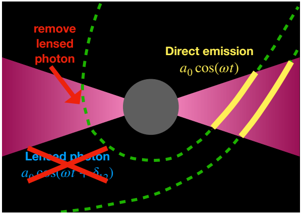
Lensed Photon Washout

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

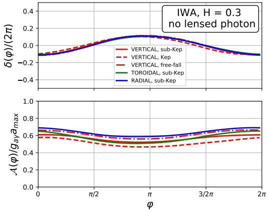




- **Universal birefringence signals** for direct emission only:

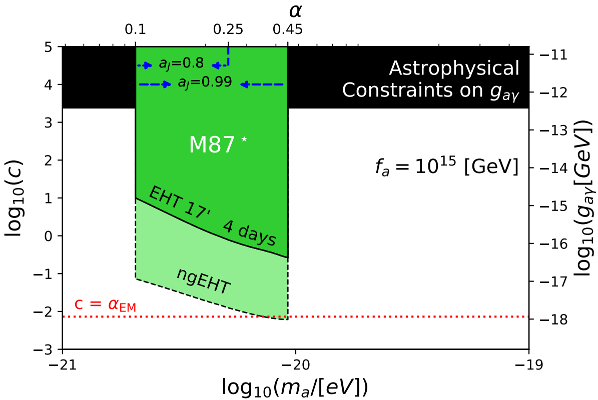


remove lensed photon →



Prospect for next-generation EHT

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



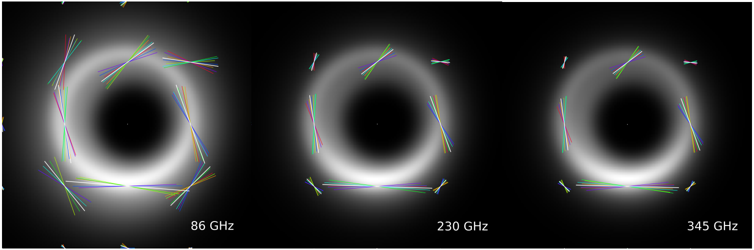
Recent updates:

- 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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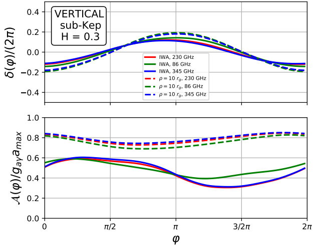
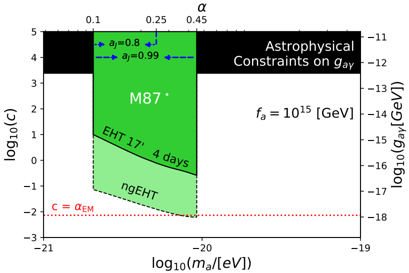




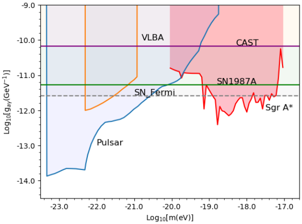
- Longer and sequential observations.

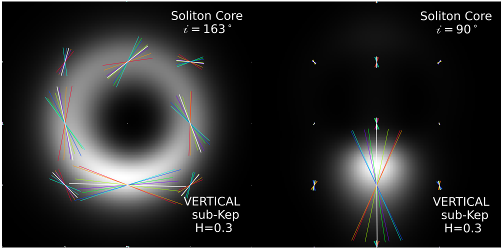
- Better resolution of EVPA.

- 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:

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

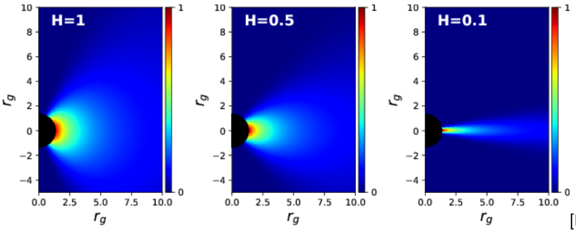
- Topological effect for each photon: only $a(x^{\mu}_{\mathrm{emit}})$ and $a(x^{\mu}_{\mathrm{obs}})$ dependent.

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:

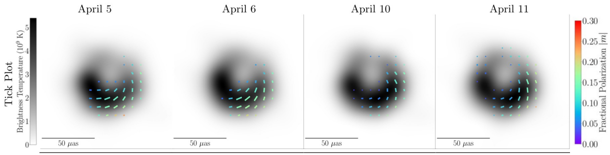


[Pu, Broderick 18]

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

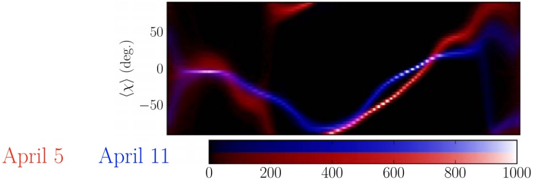
EHT Polarization Data Characterization

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



[EHT 21]

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



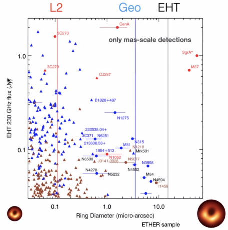
[EHT 21]

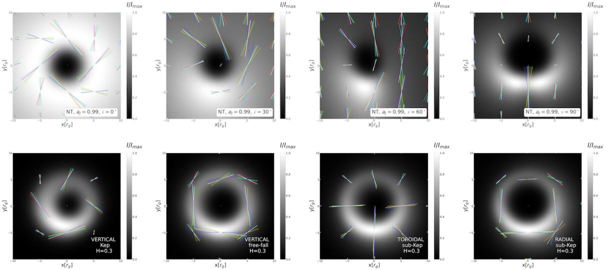
ranging from $\pm3^\circ$ to $\pm15^\circ$ for the bins used.

Landscape of SMBH and Accretion Flow (IPOLE simulation)

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

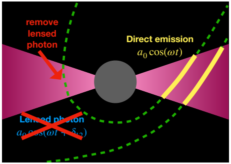
[Nagar ngEHT21]

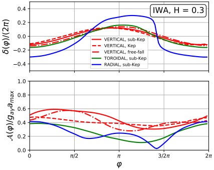




Broader range of axion mass: 10^{-22} eV to 10^{-17} eV.

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





remove lensed photon →