Recent Progress in Axion Searches

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17 July 2026, Beijing

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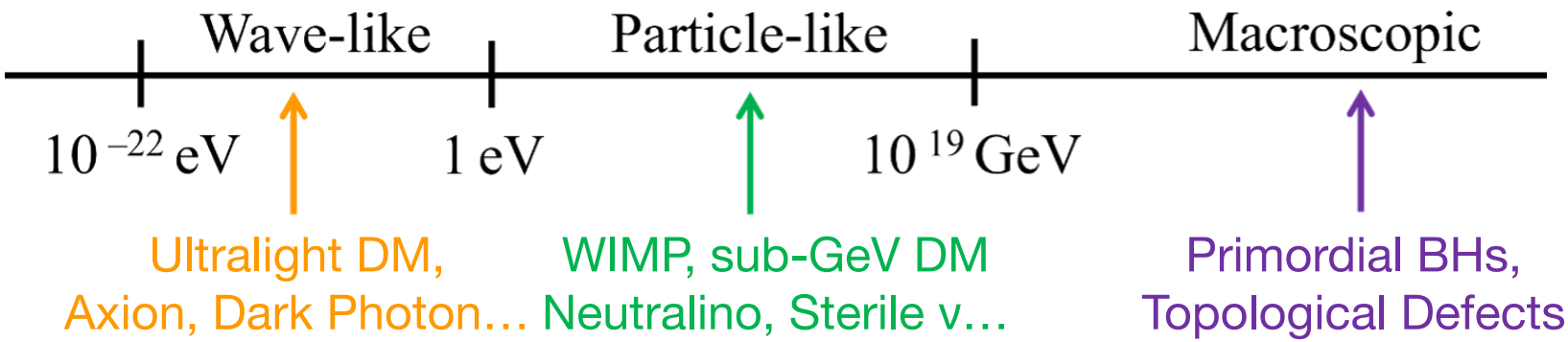
李政道研究所
TSUNG-DAO LEE INSTITUTE

Introduction to Axion

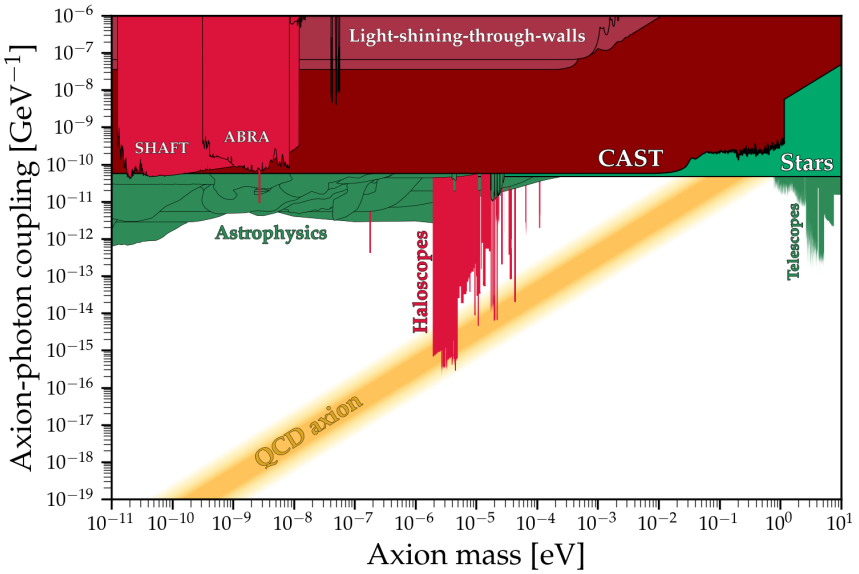
- Landscapes of **dark matter** candidates:



- **QCD Axion**→neutron EDM∼ 0.
  $m_a f_a \sim (100\,\mathrm{MeV})^2$.
  Minimal misalignment:
  $m_a \sim \mu$eV → **relic abundance**.

- **Extra dimensions**→
  axion-like particles...

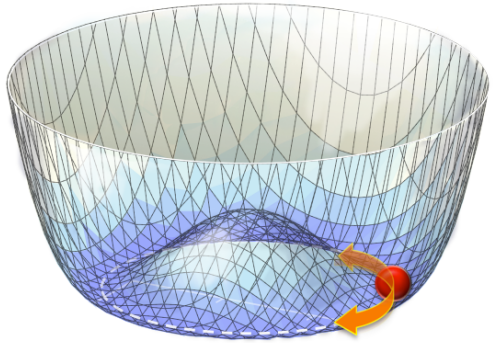
- Astro and terrestrial probes.



Axion Coupling to the Standard Model

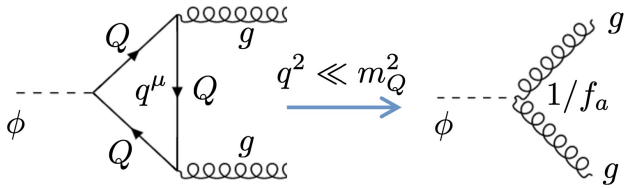
- **Axion-Fermion coupling**: $\partial_\mu a\, \bar{\psi}\gamma^\mu\gamma_5\psi/f_a$,

  Goldstone mode of chiral global symmetry.



- **Axion-Gluon coupling**: $\propto a\, G_{\mu\nu}\tilde{G}^{\mu\nu}/f_a$,

  Typical of **QCD axion**.



- **Axion-Photon coupling**: $\propto a\, F_{\mu\nu}\tilde{F}^{\mu\nu}/f_a$,

  Mixing with π_0/anomaly diagram.

Wave-like Axion Dark Matter

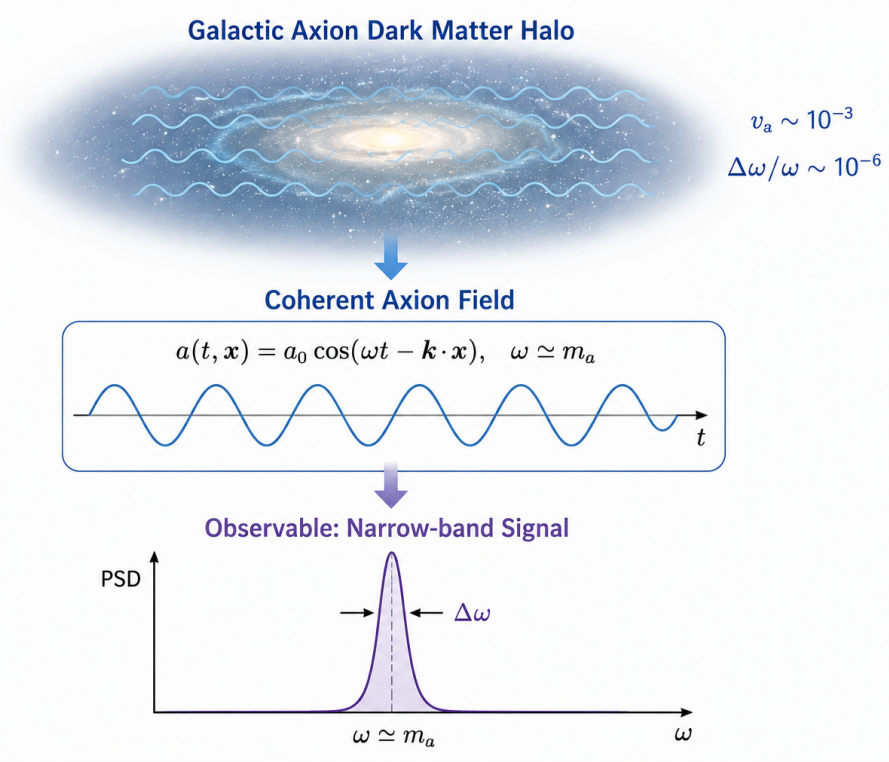
- **Ultralight axions** ($m_a \ll 1$ eV) form a **coherent classical field**

$$a(t, \mathbf{x}) = a_0 \cos(\omega t - \mathbf{k}\cdot\mathbf{x}), \qquad \omega \simeq m_a.$$

- **Virialized** Galactic halo:

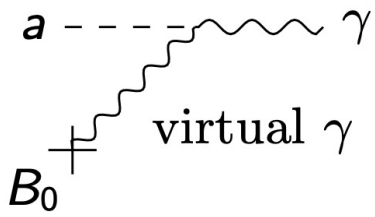
$$v_a \sim 10^{-3}, \qquad \Delta\omega/\omega \sim 10^{-6}.$$

- Axion couplings induce **oscillating signals** in SM observables.



Axion-Photon Coupling and Haloscope

- **Axion-photon coupling**: $\propto a F_{\mu\nu}\tilde{F}^{\mu\nu}$,

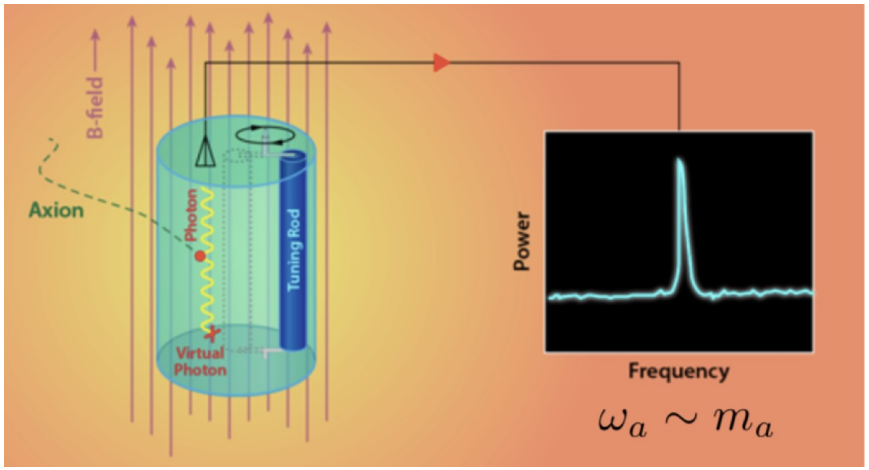


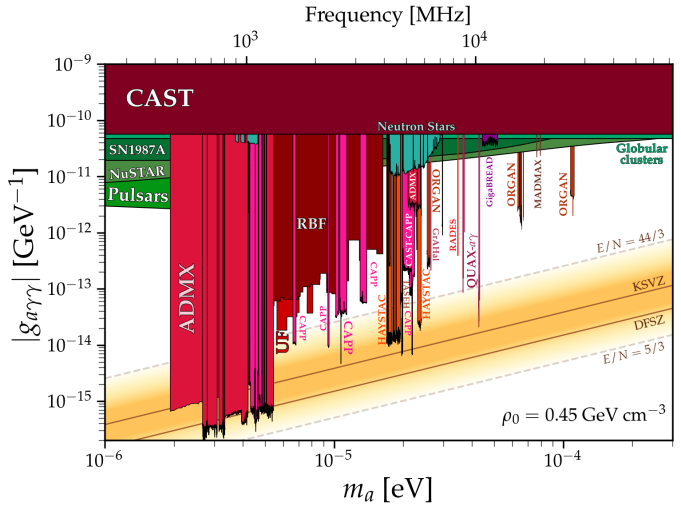
- **Effective current** under $\mathbf{B_0}$ [Sikivie 83]:

$$\mathbf{J}_{\rm eff}(t) \propto \mathbf{B}_0 \partial_t a \qquad \left(\partial_t^2 + \gamma\partial_t + \omega_{\rm rf}^2\right)\mathbf{E} = \partial_t \mathbf{J}_{\rm eff}(t).$$

- e.g. **resonant cavity**: ADMX, HAYSTAC, CAPP, ORGAN $\cdots$

  LC circuit: ABRACADABRA, DM radio $\cdots$





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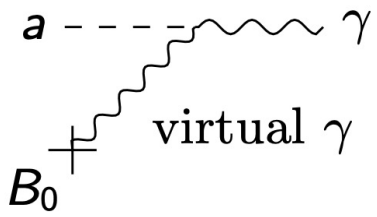

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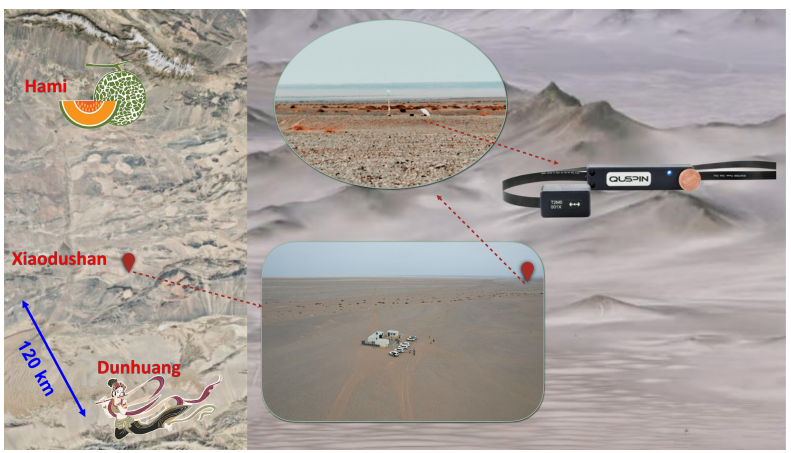
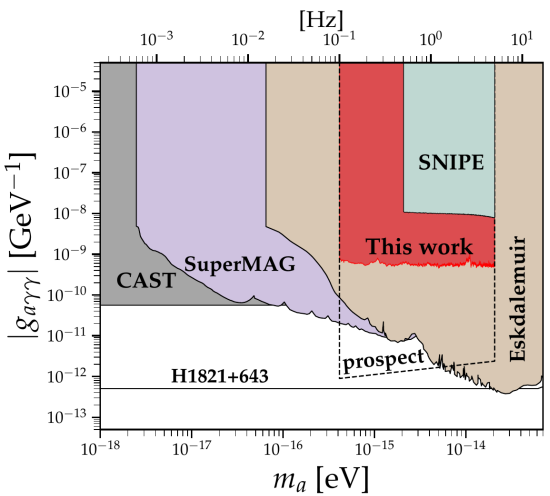
- e.g. **Geomagnetic field**: GPEX.





[GPEX 25]

Axion-Photon Coupling and Haloscope

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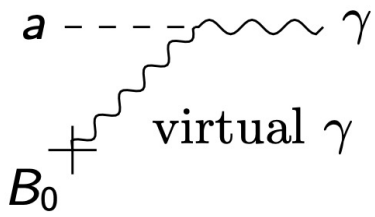

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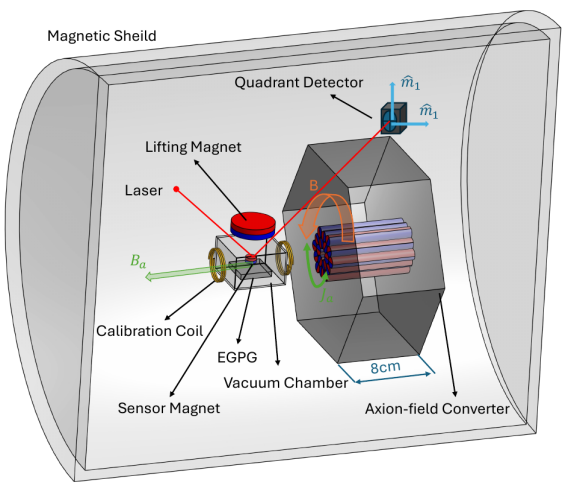
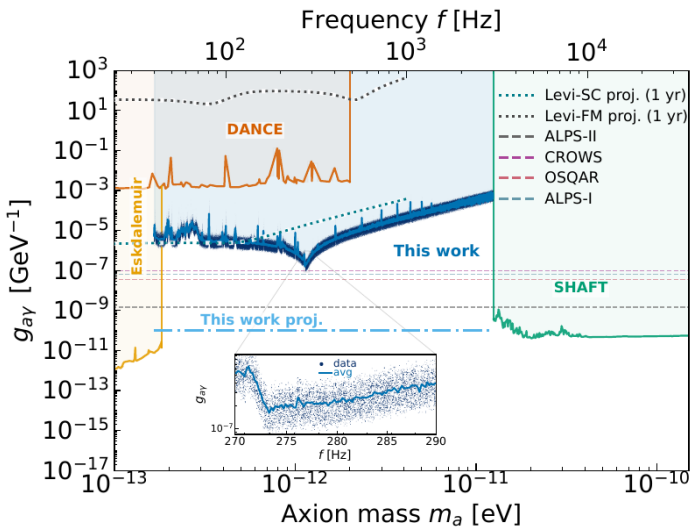
- e.g. **Levitated magnetometer**: PHOENIX.

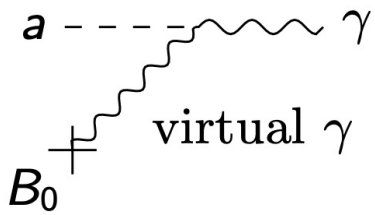




[PHOENIX 26]

Axion-Photon Coupling and Haloscope

- **Axion-photon coupling**: $\propto a F_{\mu\nu}\tilde{F}^{\mu\nu}$,



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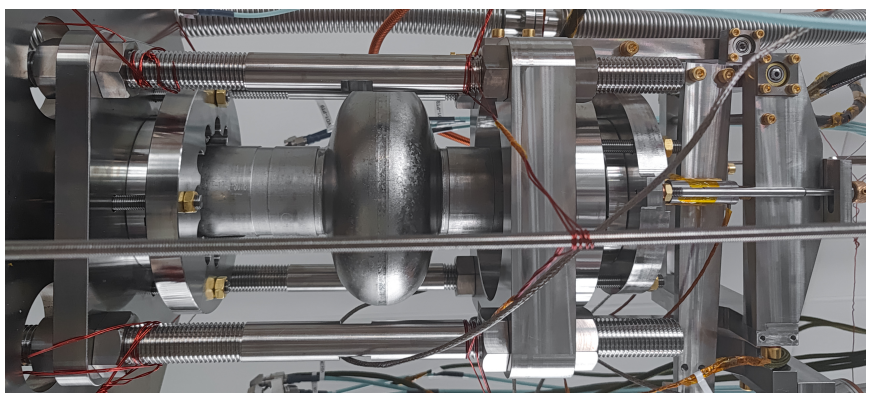
- Under preparation for B_0: APEX, SHANHE (SRF), USTC/ZJU (dielectric) $\cdots$

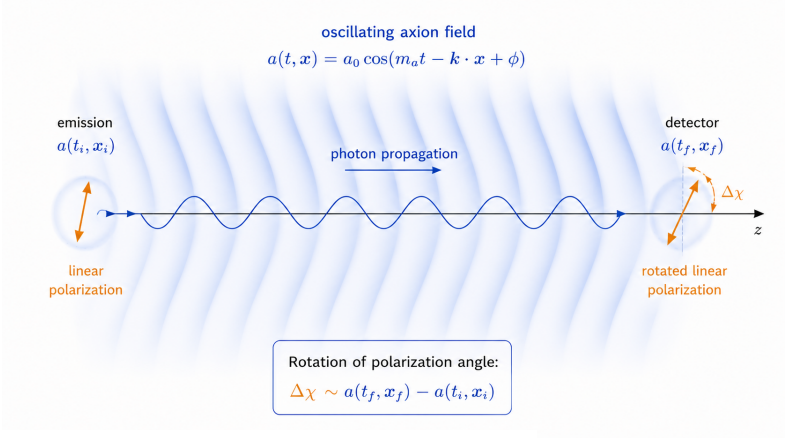


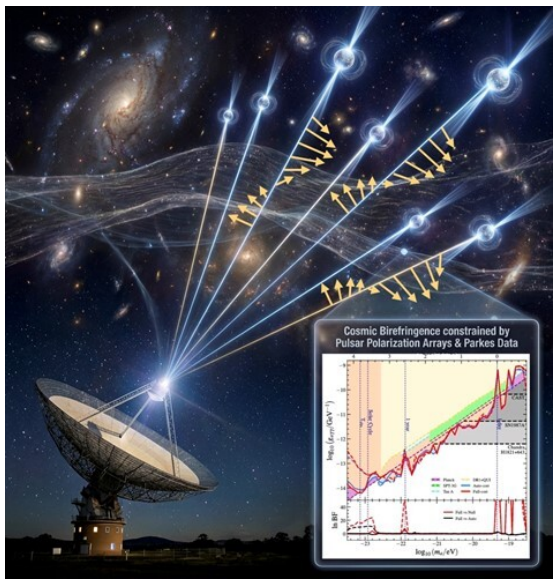
[SHANHE]

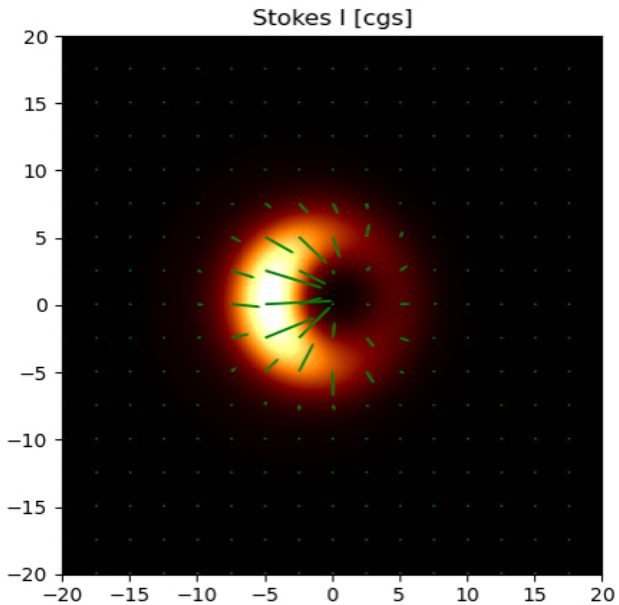
Axion-Photon Coupling and Birefringence

- **Axion-photon coupling**: $\propto a F_{\mu\nu}\tilde{F}^{\mu\nu}$,
- Photon propagating in axion background:

  Birefringence $\Delta\chi \sim a(t_f, \mathbf{x}_f) - a(t_i, \mathbf{x}_i)$.







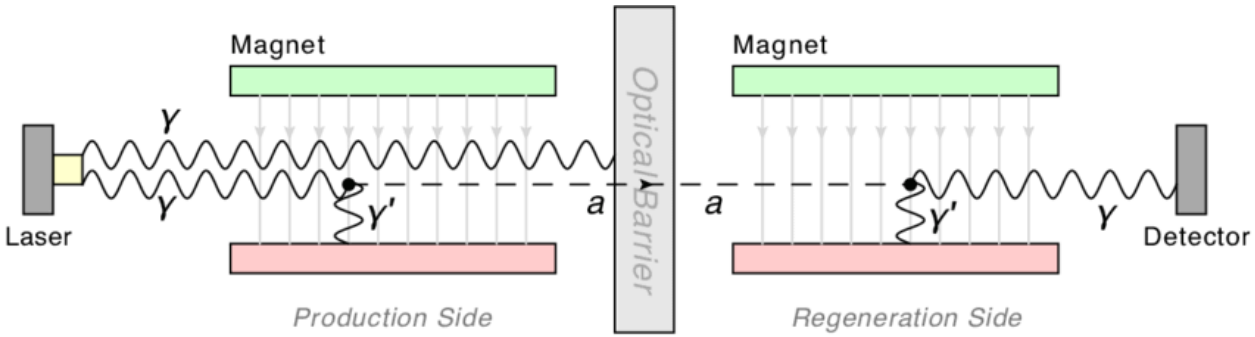
- e.g. **pulsars** [Liu, Zhao, Ren et al, PRD 20, PRL 23 26],

  black hole image [Chen, Shu, Xue, Yuan, Zhao et al, PRL 20, Nature. Astron. 22].

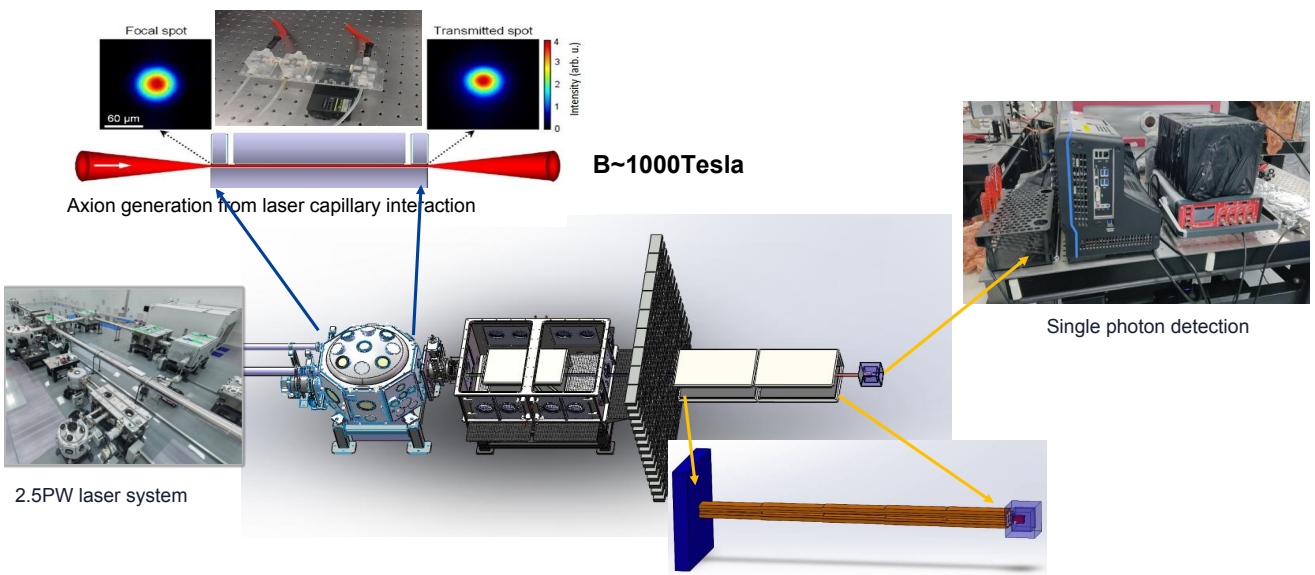
Axion-Photon Coupling and Light-Shining through Wall

- **Axion-photon coupling**: $\propto aF_{\mu\nu}\tilde{F}^{\mu\nu}$,

- **Light-shining through Wall**:



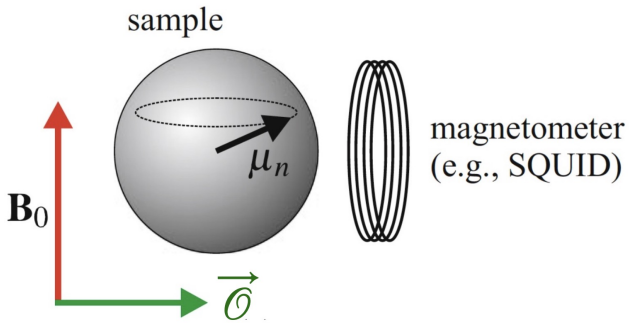
- e.g. ALPS I&II, Wakefield LSW $\cdots$



Axion-Fermion Coupling and Magnetometer

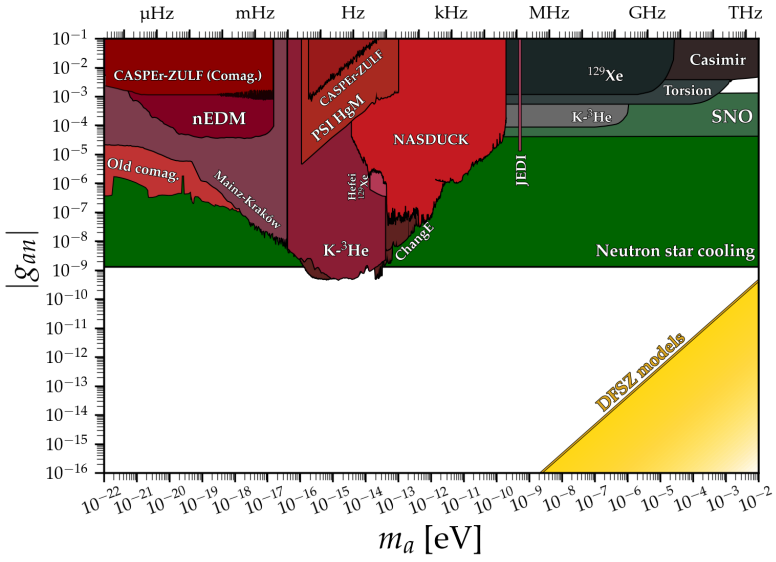
- **Axion-fermion coupling**:

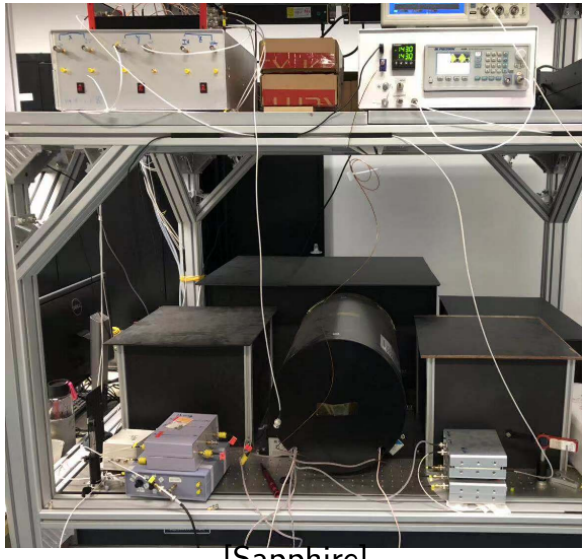
$$\propto \partial_\mu a\, \bar{\psi}\gamma^\mu\gamma^5\psi \to \vec{\nabla} a \cdot \vec{\sigma}_\psi .$$



- Axion gradient $\vec{\nabla} a$ triggers spin precession

[Graham, Rajendran, Budker et al].



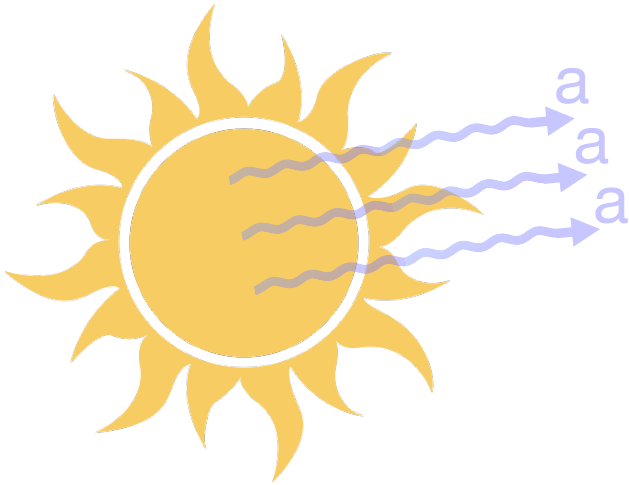


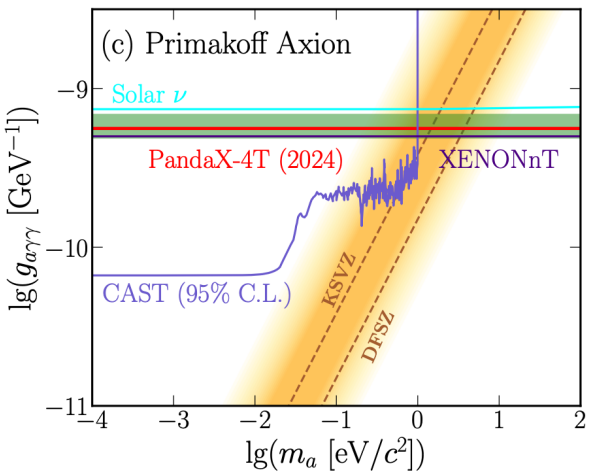
[Sapphire]

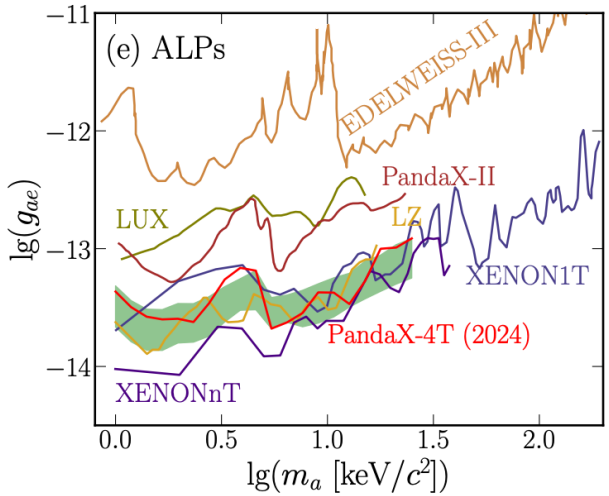
- e.g., Sapphire [Nature Phys. 21, Nature 26], ChangE [Commun.Phys. 24, Rept.Prog.Phys. 25].

Axion Emission from Stars

- Thermal production in **stellar interiors**:
- Cooling constrains via **excess energy loss**.
- **Solar axions** $\rightarrow$ **direct detection experiments**.





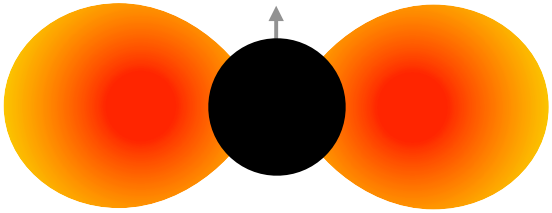


[PandaX]

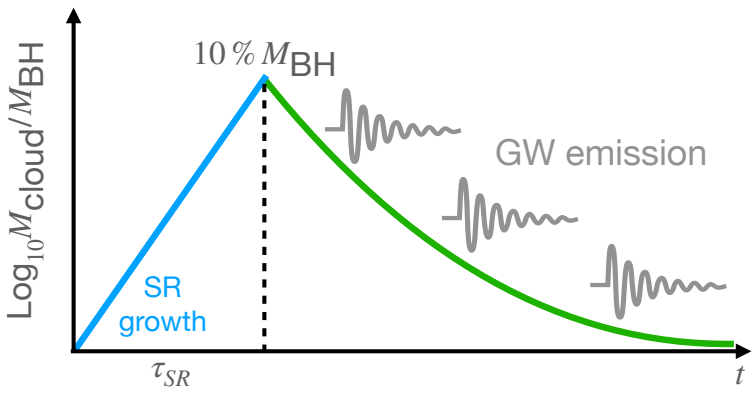
e.g., PandaX [PRL 17, 25], CDEX [PRD 20].

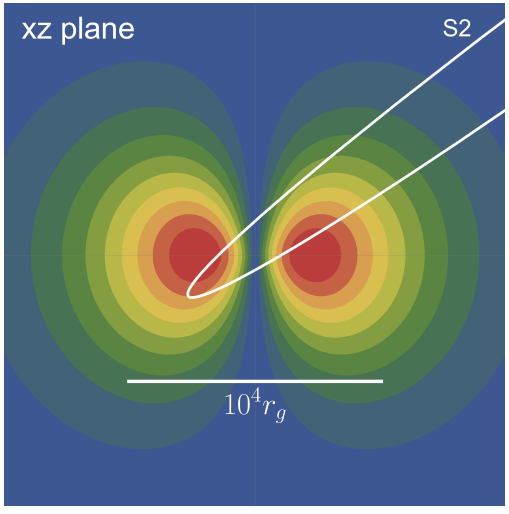
Probing Axions with Black Hole Superradiance

- **Gravitational atoms** form around **black holes**:



- **Superradiance**: **exponential growth** around **Kerr BHs** when axion wavelength $\sim$ BH horizon [Penrose, Zeldovichi, Starobinsky, Damour et al, Brito et al review].





- **BH spins** and **GWs** constrain high-f_a axions.

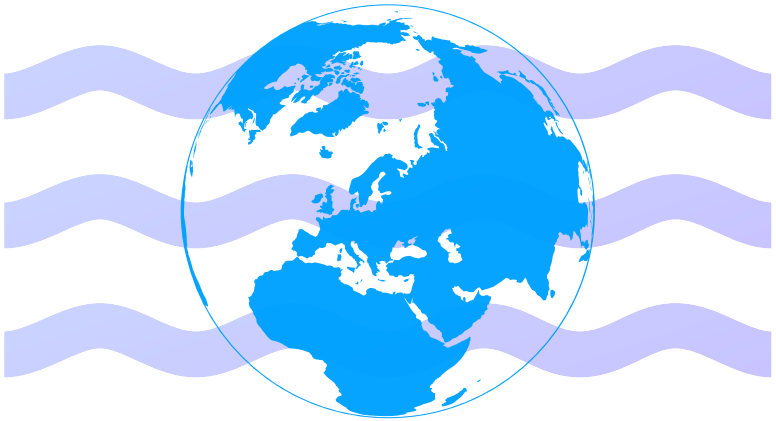
  e.g., [Bao, Zhang et al PRD 22].

- **Birefringence** and oscillating **fundamental constants**.

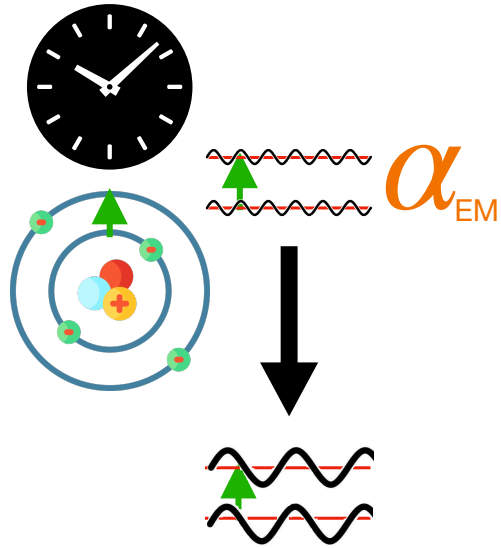
  e.g., [Chen et al JCAP 26].

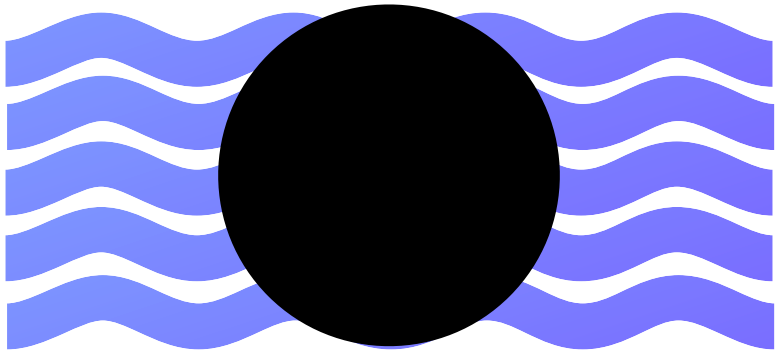
Strong-Field Limit of Axion

- **Strong field frontier**: field value $a_0 \sim f_a \leq 10^{16}$ GeV.



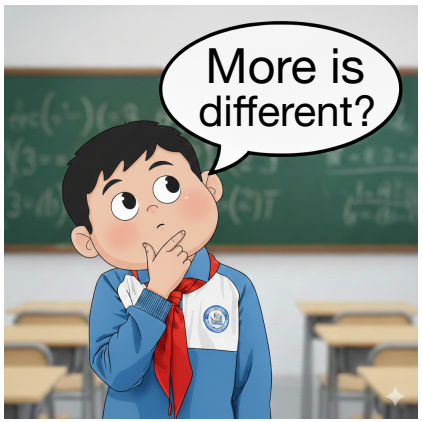
e.g., $\phi^2 F_{\mu\nu}F^{\mu\nu}$





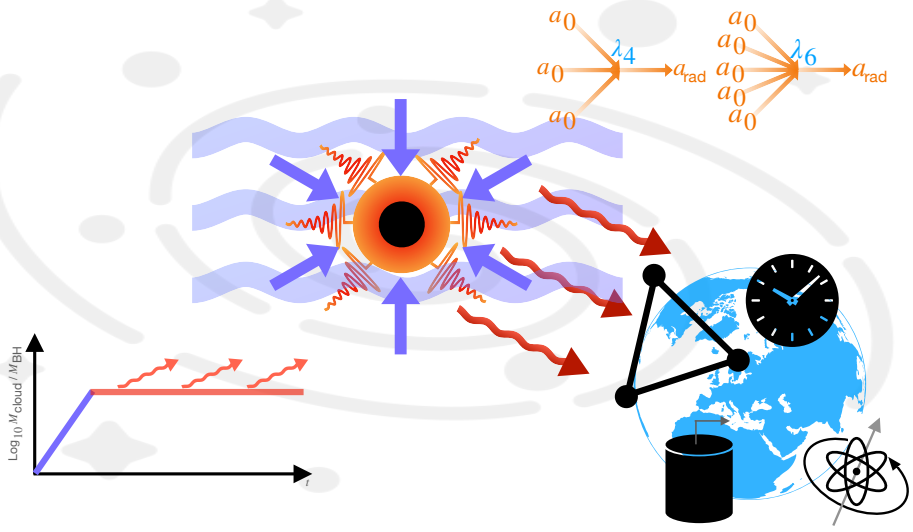
Strong-field limit :

$\phi \to \phi_c \leq 10^{16}$GeV

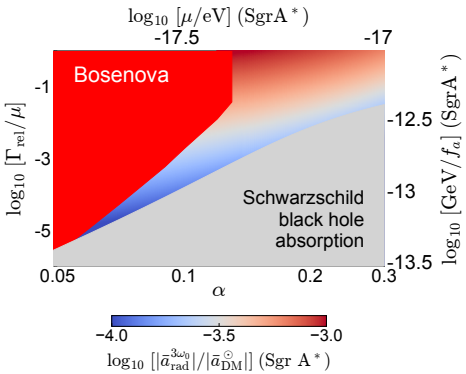


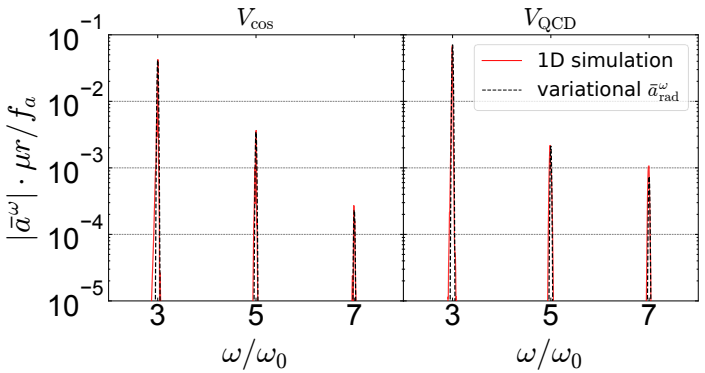
Axion Emission from Stars

- **Accreting axion cloud** produces **discrete fluxes**;



- Terrestrial detection can **reconstruct axion potentials**.





[Li, Zhong, Chen, Zhao, Cardoso, Omiya, to appear soon].

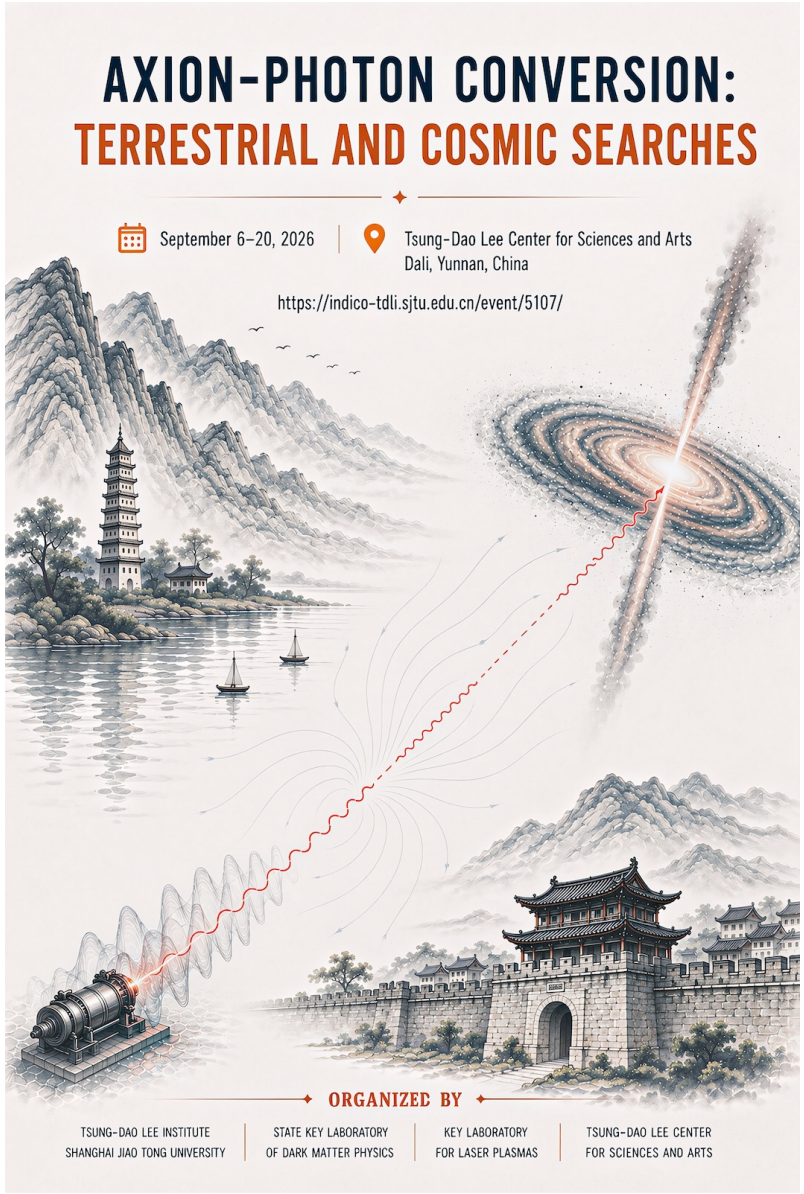
Summary

- **Axions**: among the **best-motivated** hypothetical particles.
- Complementary terrestrial and astro searches.
- New frontier: **black holes** as axion detectors.

Thank you!


2nd New Horizons for Psi Workshop
Black Holes and Fundamental Fields
Beijing, China | 24–28 August 2026
Hosted by: International Centre for Theoretical Physics Asia-Pacific (ICTP-AP)

Thank you!


AXION-PHOTON CONVERSION:
TERRESTRIAL AND COSMIC SEARCHES
September 6–20, 2026
Tsung-Dao Lee Center for Sciences and Arts
Dali, Yunnan, China
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