

Dynamics and Frequency Conversion of Accreting Axion Clouds

Yifan Chen

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

10 August 2026, Qingdao

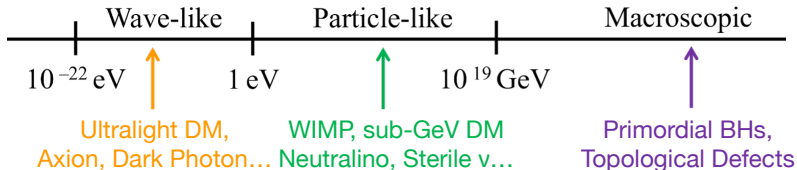
The Fifth International Conference on Axion Physics and
Experiment (Axion 2026)



李政道研究所
TSUNG-DAO LEE INSTITUTE

Ultralight Dark Matter

- ▶ Landscapes of **dark matter candidates**:

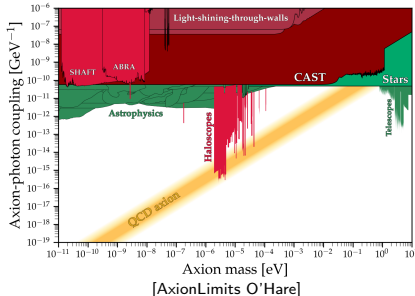


- ▶ **QCD Axion** $\rightarrow$ **neutron EDM** ~ 0 .
 $\mu\text{eV} \rightarrow$ **relic abundance**.

- ▶ **Extra dimensions** $\rightarrow$
axion-like particles...

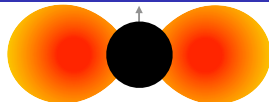
- ▶ **Astro** and **terrestrial** probes.

- ▶ **Classical wave**
 $a \simeq a_0 \cos \mu t$.



Dense Gravitational Atoms

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



- ▶ **Superradiance**: **exponential growth** around **Kerr BHs** when **axion** wavelength $\sim$ BH horizon [Penrose, Zeldovich, Starobinsky, Damour et al, Brito et al review].
- ▶ Up to $10\% M_{\text{BH}}$:

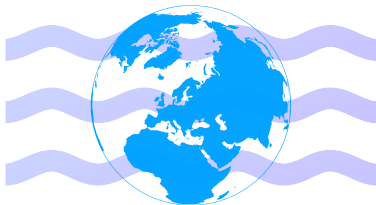
$$\frac{M_{\text{cloud}}}{M_{\text{BH}}} \sim 10\% \quad \Longleftrightarrow \quad a_{\text{max}}^{\text{GA}} \sim 10^{16} \text{ GeV}.$$

Local dark matter field:

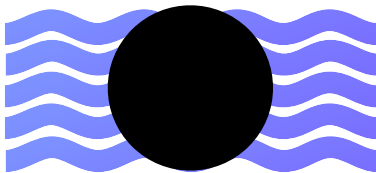
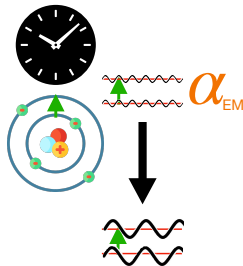
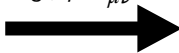
$$a_0^\odot \sim \text{GeV} \left(\frac{10^{-12} \text{ eV}}{\mu} \right).$$

- ▶ **Black holes are natural concentrators for ultralight bosons.**

Strong-Field Limit of Ultralight Boson



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



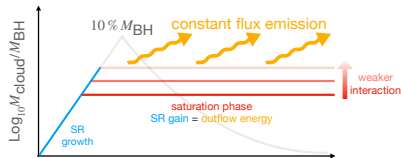
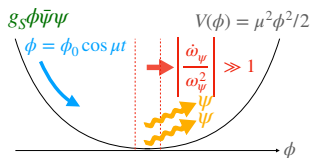
Strong-field limit :
 $\phi \rightarrow \phi_c \leq 10^{16} \text{ GeV}$



Consequences of Strong-Field Ultralight Boson

★ Strong-field frontier:

🔍 Parametric particle production: photon [Spieksma et al 23], fermion [YC et al 25].



Analogous to **preheating** and **strong field QED**.

🔍 Phase transition, defect production.

Consequences of Strong-Field Ultralight Boson

★ $a_0 \sim f_a$ phenomena:

👉 e.g. **Axion-induced birefringence** in **black hole image** [Chen, Shu, Xue, Yuan, Zhao et al, PRL 20, Nature. Astron. 22].

What about ...



Relaxation to Gravitational Atoms

Around **stars** and **Schwarzschild black holes**:

- **Relaxation** to **gravitational atom** from **ambient waves**:

[Budker, Eby, Gorghetto, Jiang, Perez 23]

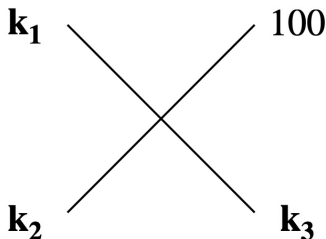
Spherical ground state with $\alpha > v_{\text{DM}}/2\pi$.

$$\tau_{\text{rel}} \sim \frac{1}{n_{\text{DM}} \sigma v_{\text{DM}}} \frac{1}{n_{\text{DM}} \lambda_{\text{dB}}^3} \sim \frac{\mu^3}{\rho_{\text{DM}}^2} \times \begin{cases} M_{\text{pl}}^4 v_{\text{DM}}^6, & \text{gravity;} \\ f_a^4 v_{\text{DM}}^2, & \text{self-interaction.} \end{cases}$$

- **Exponential growth** is efficient when

- High ρ_{DM} ;
 - **Galactic center.**
- Low μ ;
 - **Supermassive black holes.**
- Low f_a .

Stimulated capture



[Budker, Eby, Gorghetto, Jiang, Perez 23]

Relaxation to Gravitational Atoms

Around **stars** and **Schwarzschild black holes**:

- **Relaxation** to **gravitational atom** from **ambient waves**:

[Budker, Eby, Gorghetto, Jiang, Perez 23]

Spherical ground state with $\alpha > v_{\text{DM}}/2\pi$.

$$\tau_{\text{rel}} \sim \frac{1}{n_{\text{DM}} \sigma v_{\text{DM}}} \frac{1}{n_{\text{DM}} \lambda_{\text{dB}}^3} \sim \frac{\mu^3}{\rho_{\text{DM}}^2} \times \begin{cases} M_{\text{pl}}^4 v_{\text{DM}}^6, & \text{gravity;} \\ f_a^4 v_{\text{DM}}^2, & \text{self-interaction.} \end{cases}$$

- ★ **Dominant spherical ground** mode:

→ Cloud **dissipation** through

$3 \rightarrow 1, 5 \rightarrow 1, \dots$ **emissions**.



Evolution of Accreting Clouds

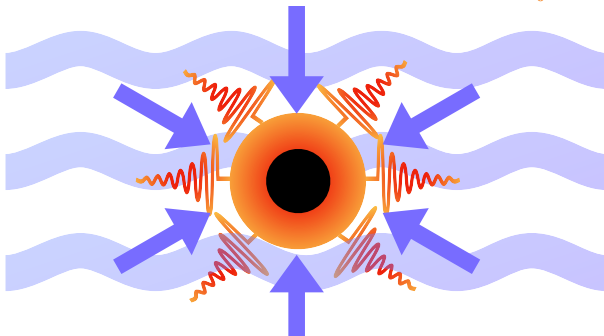
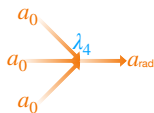
► 1D numerical simulation:

$$\square a = \frac{dV_{\text{int}}}{da} + \Gamma_{\text{rel}} \partial_t a, \quad V_{\text{int}} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$

► Semi-analytic evolution of **collective coordinates**

$$\dot{N}_a = 2\Gamma_{\text{rel}} N_a - 3\Gamma_{3 \rightarrow 1} + \dots ;$$

...



Evolution of Accreting Clouds

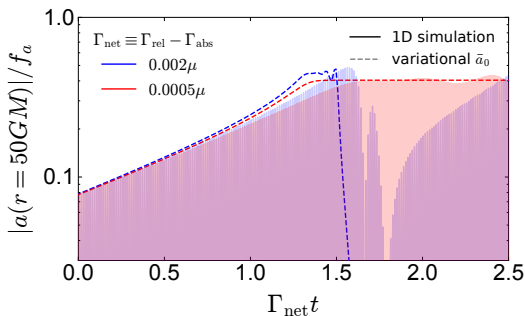
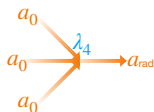
► 1D numerical simulation:

$$\square a = \frac{dV_{\text{int}}}{da} + \Gamma_{\text{rel}} \partial_t a, \quad V_{\text{int}} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$

► Semi-analytic evolution of **collective coordinates**

$$\dot{N}_a = 2\Gamma_{\text{rel}} N_a - 3\Gamma_{3 \rightarrow 1} + \dots ;$$

$$\dots$$



Evolution of Accreting Clouds

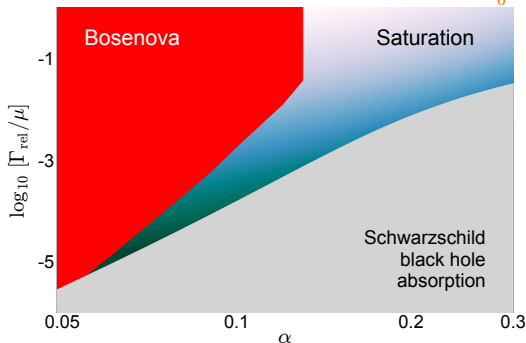
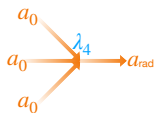
► **1D numerical simulation:**

$$\square a = \frac{dV_{\text{int}}}{da} + \Gamma_{\text{rel}} \partial_t a, \quad V_{\text{int}} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$

► Semi-analytic evolution of **collective coordinates**

$$\dot{N}_a = 2\Gamma_{\text{rel}} N_a - 3\Gamma_{3 \rightarrow 1} + \dots ;$$

...

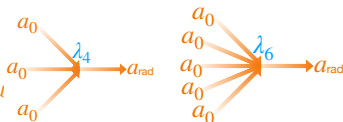


Axion Fluxes

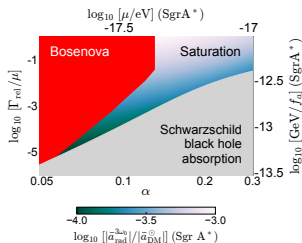
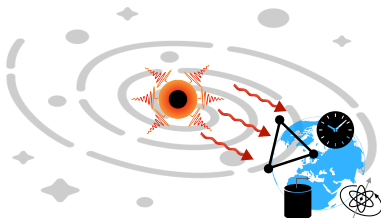
★ Signals

► **Dark matter:** $\omega \simeq \mu$

👉 **Predicted fluxes:** $\omega \simeq 3\mu, 5\mu, 7\mu$



► **Relativistic fluxes** from **SMBH Sgr A***:



• $aF\tilde{F}$ via **SRF cavity** [Berlin et al 20];

• $\partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi$ via **spin sensor** and **storage ring** [Budker, Graham et al 13, 20];

Relativistic fluxes $\rightarrow$ **signal enhancement** $\sim 10^3$.

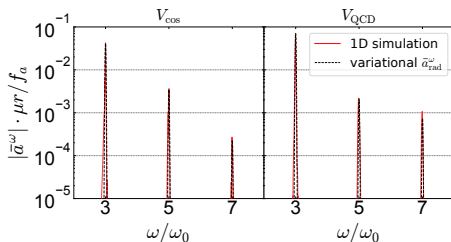
Axion Fluxes and Axion Potential

$$V_{\text{int}} = -\mu^2 f_a^2 \sum_{n=1} \lambda_{2n} \frac{(-1)^n}{(2n)!} \left(\frac{a}{f_a} \right)^{2n},$$

$2n$	4	6	8	...
$\lambda_{2n}^{(\text{cos})}$	1	1	1	...
$\lambda_{2n}^{(\text{QCD})}$	0.34	-0.13	0.88	...

★ **Odd harmonics** at $\omega \simeq 3\mu, 5\mu, 7\mu, \dots$

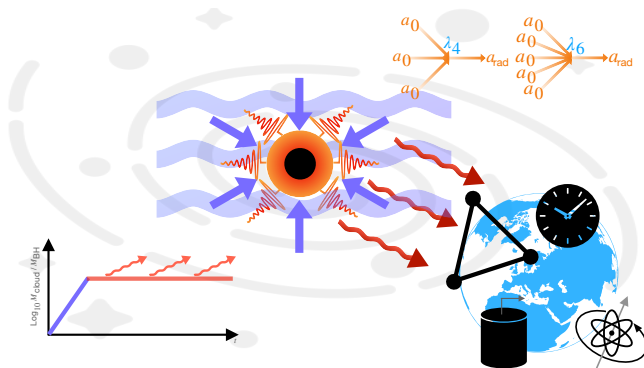
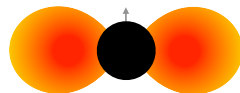
🔗 **Axion potential reconstruction:**



► Probe the **full non-perturbative potential**.

Summary

- ▶ Compact objects **concentrate** ultralight bosons.
- ▶ Strong field frontier: up to $\sim 10^{16}$ GeV.



- ▶ Accreting axion cloud produces **discrete fluxes**;
- Terrestrial detection** can reconstruct **axion potentials**.

Thank you!



Thank you!

AXION-PHOTON CONVERSION: TERRESTRIAL AND COSMIC SEARCHES

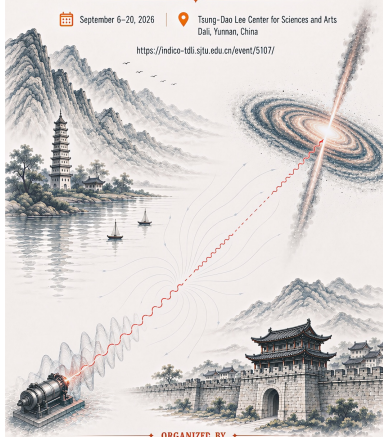


September 6-20, 2026



Tsung-Dao Lee Center for Sciences and Arts
Dali, Yunnan, China

<https://indico-tdli.sjtu.edu.cn/event/5107/>



ORGANIZED BY

TSUNG-DAO LEE INSTITUTE
SHANGHAI JIAO TONG UNIVERSITY

STATE KEY LABORATORY
OF DARK MATTER PHYSICS

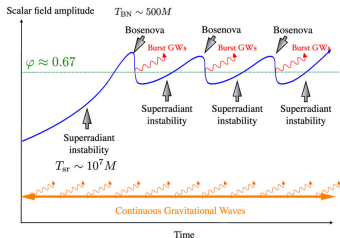
KEY LABORATORY
FOR LASER PLASMAS

TSUNG-DAO LEE CENTER
FOR SCIENCES AND ARTS

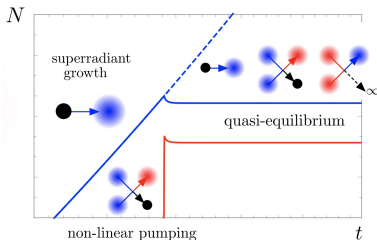
Backup

Bosenova or Saturation?

Consequences of **gravitational atom** when a_0 is close to f_a ?



[Yoshino et al 12]



[Baryakhtar et al 20]

► Understanding of **superradiance** shifts from **bosenova** to **saturation**.

► Key differences of **relaxation**:

- **Spherical ground (1,0,0) mode** dominates.
- ρ_{DM} and f_a -dependent **relaxation** rate.
- Cloud **dissipation** through $3 \rightarrow 1, 5 \rightarrow 1, \dots$ **emissions**.



Condition for Bosenova

Variational ansatz: $a = \frac{1}{\sqrt{2\mu}} (\psi e^{-i\mu t} + h.c.), \psi = \sqrt{\frac{N_a}{\pi r_0^3}} e^{-r/r_0}.$

► **Effective potential:**

$$\begin{aligned} E(N_a, r_0) &= \int d^3r \left(\frac{1}{2\mu} |\nabla \psi|^2 - \frac{\alpha}{r} |\psi|^2 + V_{\text{int}}(\psi) \right) \\ &= \frac{N_a}{2\mu r_0^2} - \frac{\alpha N_a}{r_0} - \frac{N_a^2}{128 \pi f_a^2 r_0^3} + \dots \end{aligned}$$

► Minimizing potential $\partial E / \partial r_0 = 0$ gives

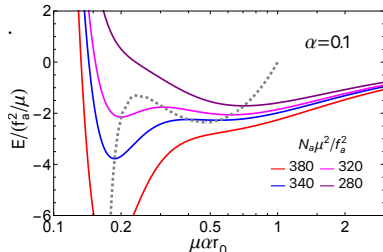
$$r_0^{\min} = \frac{1}{2\mu\alpha} \left(1 \pm \sqrt{1 - \frac{3}{32\pi} \frac{\mu^2}{f_a^2} \alpha N_a} \right) + \dots$$

Initial minimum: $r_0^{\min} \approx 1/(\mu\alpha) \equiv r_B.$

► When $N_a > \tilde{N}_a^B \sim \frac{32\pi}{3} \frac{f_a^2}{\alpha \mu^2}$:

Phase transition in effective potential

→ **Bosenova.**



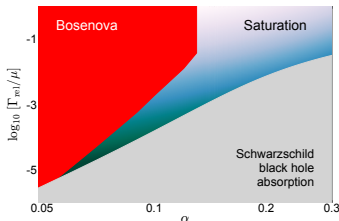
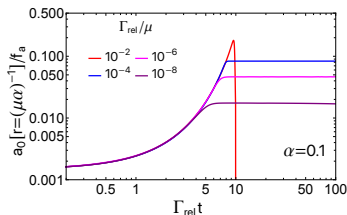
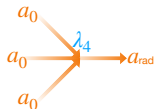
[Ximeng Li, preliminary]

Condition for Saturation

► **Variational method:**

$$\dot{N}_a = 2\Gamma_{\text{rel}} N_a - 3\Gamma_{3 \rightarrow 1} + \dots;$$

$$N_a \ddot{r}_0 - \frac{1}{\mu} \frac{\partial E}{\partial r_0} = 0.$$



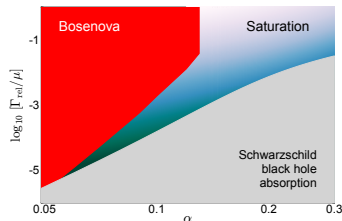
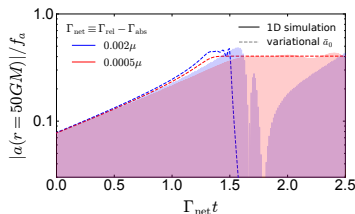
[Ximeng Li, preliminary]

- For sufficiently small Γ_{rel}/μ , $\tilde{N}_a^S \lesssim \tilde{N}_a^B$, always **saturation**.

Condition for Saturation

- **1-dim simulation** with initial profile of **(1,0,0) gravitational atom**:

$$\square a = \frac{dV_{\text{int}}}{da} + \Gamma_{\text{rel}} \partial_t a, \quad V_{\text{int}} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$



[Zhen Zhong, Ximeng Li preliminary]

- For sufficiently small Γ_{rel}/μ , $\tilde{N}_a^S \lesssim \tilde{N}_a^B$, always **saturation**.