Strong-Field Dynamics and Multimessenger Signatures of Ultralight Bosonic Dark Matter

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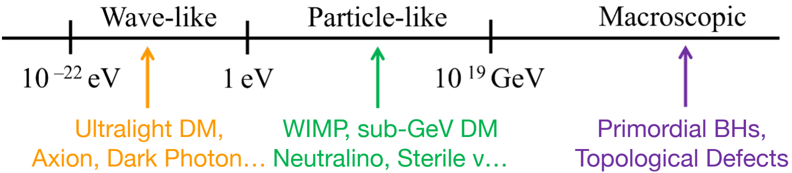
2026 Purple Mountain Dark Matter Workshop

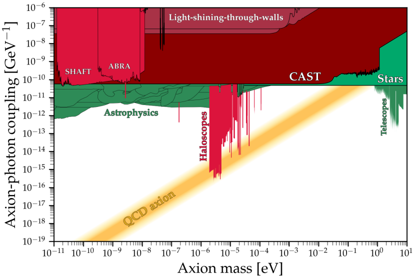
李政道研究所
TSUNG-DAO LEE INSTITUTE

Ultralight Dark Matter

- Landscapes of **dark matter** candidates:



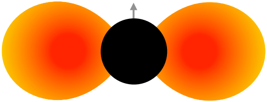
- **QCD Axion**→neutron EDM∼ 0. μeV → **relic abundance**.
- **Extra dimensions**→ **axion-like particles**…
- Astro and terrestrial probes.
- **Classical wave** $a \simeq a_0 \cos \mu t$.



[AxionLimits O'Hare]

Dense Gravitational Atoms

- **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].

- Up to 10% M_{BH}:

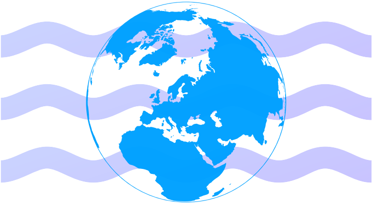
$$\frac{M_{\mathrm{cloud}}}{M_{\mathrm{BH}}} \sim 10\% \quad \Longleftrightarrow \quad a_{\mathrm{max}}^{\mathrm{GA}} \sim 10^{16}\,\mathrm{GeV}.$$

Local dark matter field:

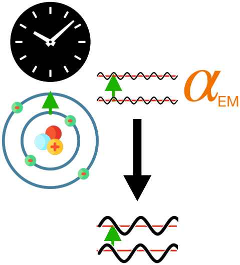
$$a_0^{\odot} \sim \mathrm{GeV}\left(\frac{10^{-12}\,\mathrm{eV}}{\mu}\right).$$

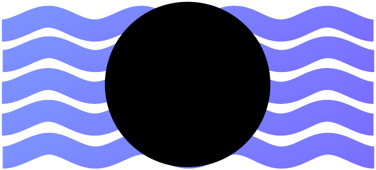
- **Black holes are natural concentrators for ultralight bosons.**

Strong-Field Limit of Ultralight Boson

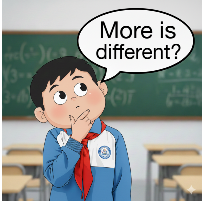


e.g., $\phi^2 F_{\mu\nu} F^{\mu\nu}$





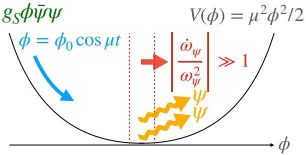
Strong-field limit :
$\phi \to \phi_c \leq 10^{16}$GeV

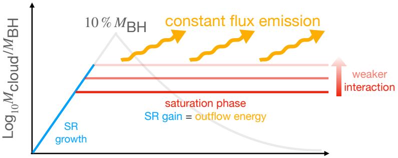


Consequences of Strong-Field Ultralight Boson

⋆ **Strong-field frontier**:

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



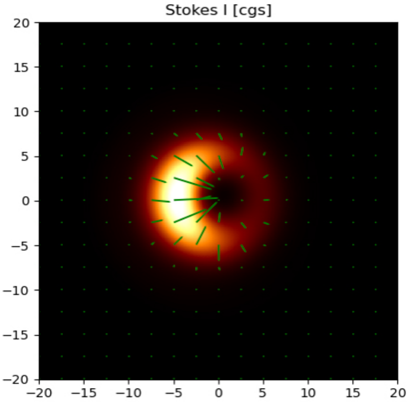


Analogous to **preheating** and **strong field QED**.

☞ 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**:

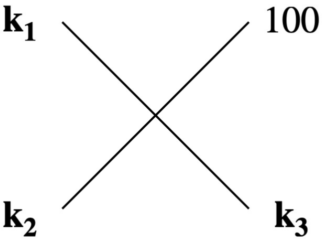
- **Relaxation** to **gravitational atom** from ambient waves:
  [Budker, Eby, Gorghetto, Jiang, Perez 23]

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

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

- **Exponential growth** is efficient when
  - High $\rho_{\rm DM}$;
    - **Galactic center.**
  - Low μ;
    - **Supermassive black holes.**
  - Low f_a.

Stimulated capture



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

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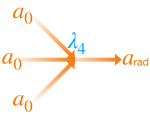
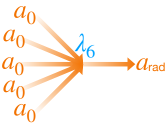
☆ **Dominant spherical ground** mode:

$\rightarrow$ Cloud **dissipation** through

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



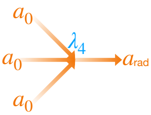


Evolution of Accreting Clouds

- **1D numerical simulation**:

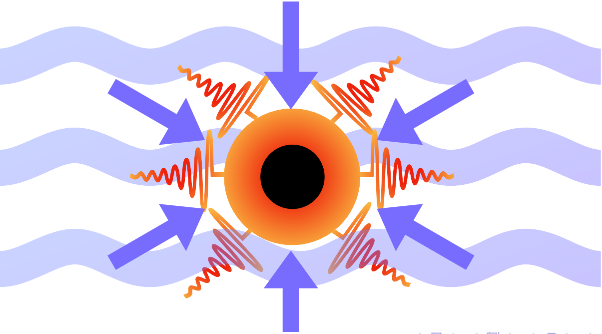
$$\Box a = \frac{\mathrm{d}V_{\rm int}}{\mathrm{d}a} + \Gamma_{\rm rel}\partial_t a, \qquad V_{\rm int} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$

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



$$\dot{N}_a = 2\Gamma_{\rm rel} N_a - 3\Gamma_{3\to1} + \cdots ;$$

$$\ldots$$



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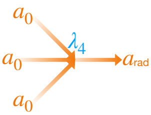

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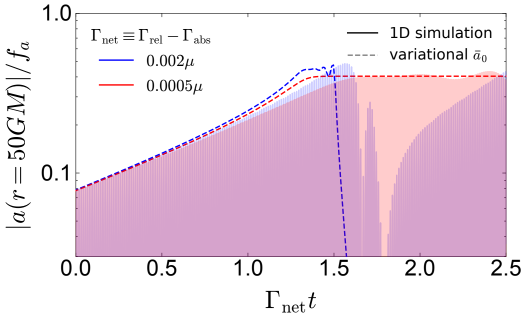

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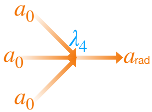
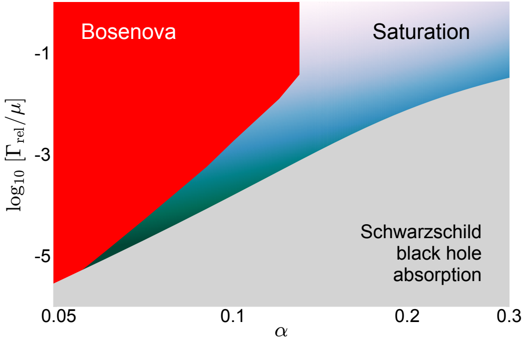
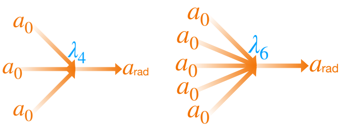




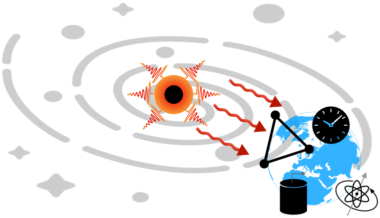
Axion Fluxes

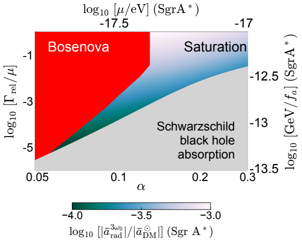
☆ **Signals**

- ▶ **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];

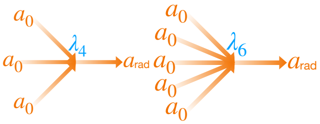
Relativistic fluxes $\rightarrow$ signal enhancement $\sim 10^3$.

Axion Fluxes and Axion Potential

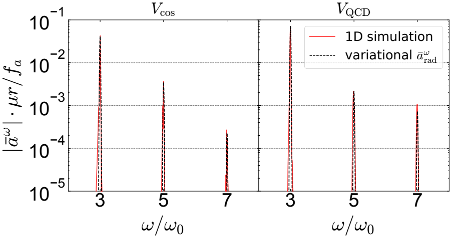
$$V_{\text{int}} = -\mu^2 f_a^2 \sum_{n=1} \lambda_{2n} \frac{(-1)^n}{(2n)!} \left(\frac{a}{f_a}\right)^{2n},$$

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

☆ **Odd harmonics** at $\omega \simeq 3\mu, 5\mu, 7\mu, \cdots$

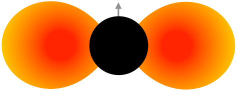


☞ **Axion potential reconstruction**:

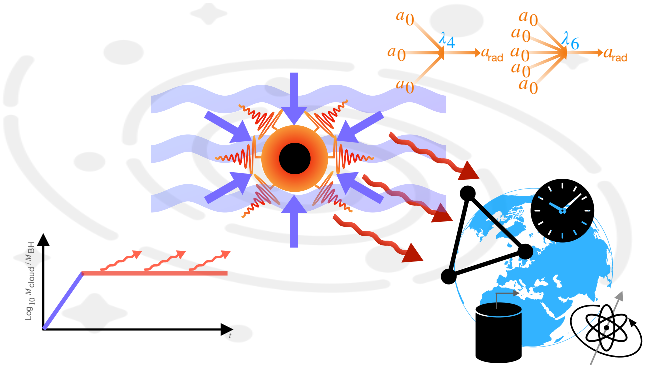


▶ Probe the **full non-perturbative potential**.

Summary



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



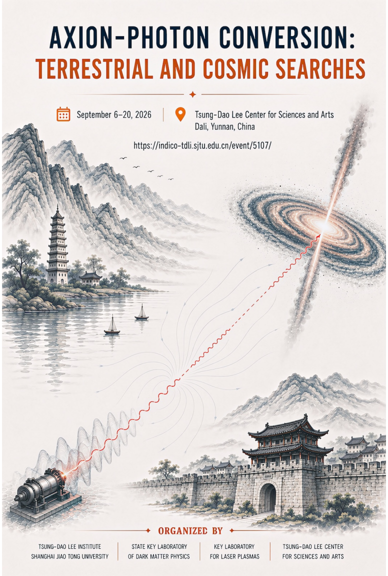
- **Accreting axion cloud** produces **discrete fluxes**;

  Terrestrial detection can reconstruct **axion potentials**.

Thank you!

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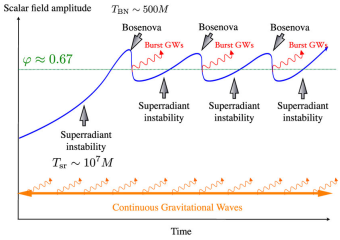
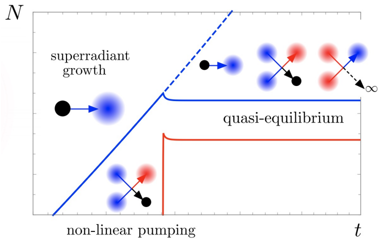
Backup

Bosenova or Saturation?

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

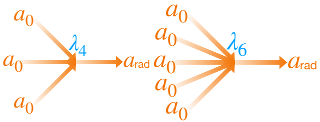


[Yoshino et al 12]



[Baryakhtar et al 20]

- Understanding of **superradiance** shifts from **bosenova** to **saturation**.
- Key differences of **relaxation**:
  - **Spherical ground (1,0,0) mode** dominates.
  - $\rho_{\rm DM}$ and f_a-dependent **relaxation** rate.
  - Cloud **dissipation** through $3 \to 1$, $5 \to 1, \cdots$ **emissions**.



Condition for Bosenova

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

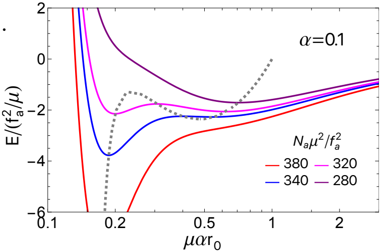
- Effective potential:

$$E(N_a, r_0) = \int d^3 r \left(\frac{1}{2\mu} |\nabla\psi|^2 - \frac{\alpha}{r} |\psi|^2 + V_{\rm int}(\psi) \right)$$
$$= \frac{N_a}{2\mu r_0{}^2} - \frac{\alpha N_a}{r_0} - \frac{N_a{}^2}{128\,\pi f_a{}^2 r_0{}^3} + \cdots .$$

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

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

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



[Ximeng Li, preliminary]

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

Phase transition in effective potential

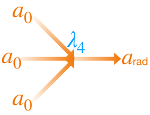
→ **Bosenova**.

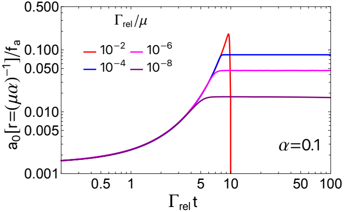
Condition for Saturation

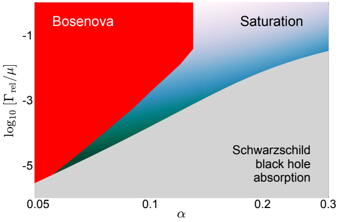
- **Variational method**:

$$\dot{N}_a = 2\Gamma_{\rm rel} N_a - 3\Gamma_{3\to 1} + \cdots ;$$

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







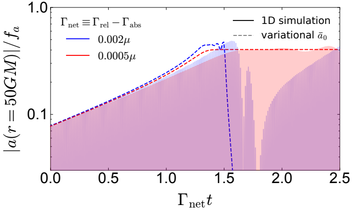
[Ximeng Li, preliminary]

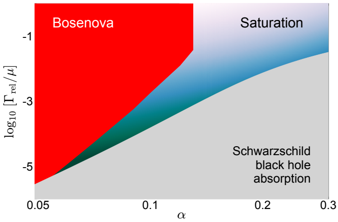
- For sufficiently small $\Gamma_{\rm rel}/\mu$, $\tilde{N}_a^S \lesssim \tilde{N}_a^B$, always **saturation**.

Condition for Saturation

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

$$\Box a = \frac{\mathrm{d}V_{\rm int}}{\mathrm{d}a} + \Gamma_{\rm rel}\partial_t a, \qquad V_{\rm int} = -\mu^2 f_a^2 \cos\left(\frac{a}{f_a}\right)$$





[Zhen Zhong, Ximeng Li preliminary]

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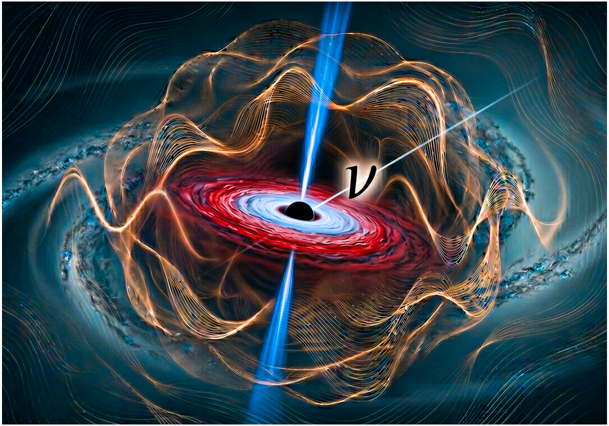
ν in Soliton Core Dark Matter

At large scales:



- Ultralight dark matter forms a **soliton core** with [Schive et al 14]

$$r_c \sim \mathcal{O}(10^3)\,\mu^{-1}, \qquad \phi_0 \sim 10^{11}\ \text{GeV}.$$

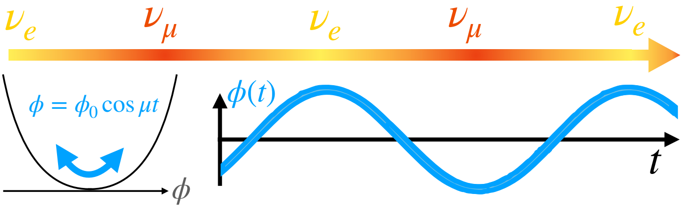
- How do ν **propagate** through this background?

Neutrino Parametric Oscillation in ULDM Background

- $y_{ij}\,\phi(t)\,\nu_i\nu_j\,(i \neq j) \Rightarrow$ oscillating off-diagonal **mass terms**.

- **Parametric resonance**: [Losada et al. 2022]

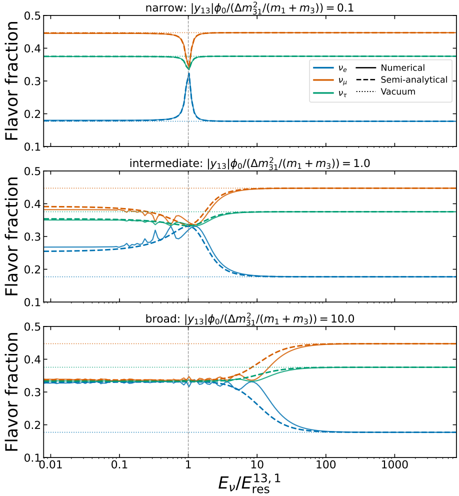
$$\mu \sim \frac{\Delta m_{ij}^2}{2E_\nu}, \qquad \mu \sim 10^{-18}\ \text{ev} \iff E_\nu^{\rm res} \sim \text{PeV}.$$



- Near $E_\nu^{\rm res}$: **enhanced flavor conversion** with bandwidth $\sim |y_{ij}|\phi_0$.

Neutrino Parametric Oscillation in ULDM Soliton Core

- **Flavor ratios** on Earth:

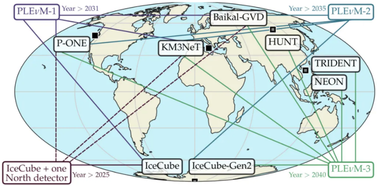


[Bai, YC, Liu, Wang, preliminary]

- **Floquet** solution validates analytic resonance and bandwidth.
- **Broad resonance**: fully mixed (low E_ν) $\to$ vacuum (high E_ν).

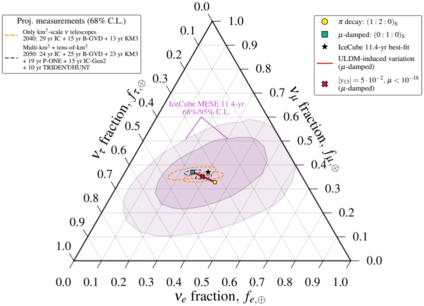
Detection Prospect

- **Flavor-ratio** or ν_μ spectral **distortion**:



Global neutrino detector network

[Bustamante]



[Qinrui Liu, preliminary]

- **Future neutrino detectors** can resolve the **flavor transition**.