Dynamics and Phenomenology of Ultralight Bosons Around Compact Objects

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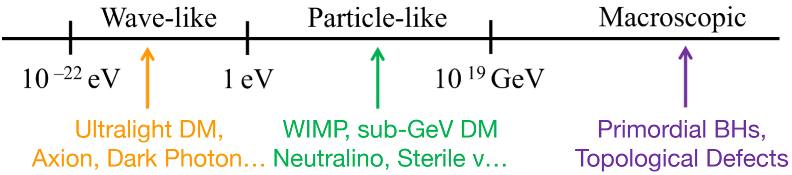
Outlines

Probing Ultralight Bosons

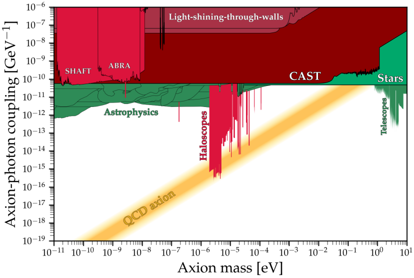
with Black Holes

Ultralight Dark Matter

- Landscapes of **dark matter** candidates:



- **QCD Axion**→neutron EDM∼ 0. μeV → **relic abundance**.
- **Extra dimensions**→ **axions** and **dark photons**…
- Astro and terrestrial probes.
- **Wave-like property** with high occupation number. $\Psi \approx \Psi_0 \cos[\omega t], \quad \omega \simeq \mu.$



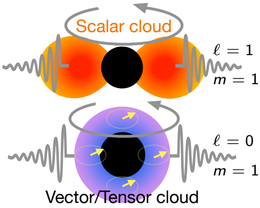
Gravitational Atoms

- **Gravitational bound state** between **BH** and boson:

  Gravitational atom: (n, ℓ, m) with $\alpha \equiv G_N M_{\rm BH} \mu$;

  Bohr radius: $r_B = r_g/\alpha^2$;

  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

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

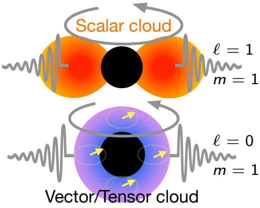
Dense Gravitational Atoms

- $M_{\rm cloud}$ can be at most $10\%\ M_{\rm BH}$:

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

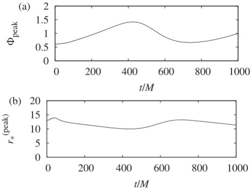
In comparison, local dark matter field:

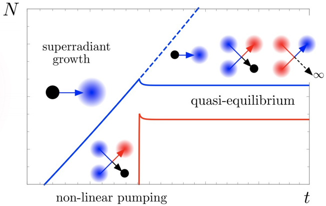
$$\Psi_0^{\odot} \sim \text{GeV}\left(\frac{10^{-12}\ \text{eV}}{\mu}\right)$$



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

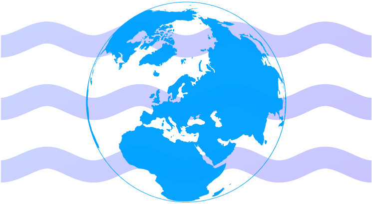
- e.g., **axion** with $V(a) = \mu^2 f_a^2\left(1 - \cos\frac{a}{f_a}\right) = \frac{\mu^2 a^2}{2} - \frac{\mu^2 a^4}{24 {f_a}^2} + \ldots;$



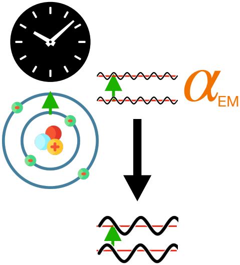


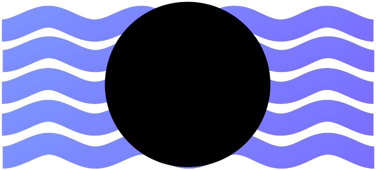
Saturated $a^{\rm GA}_{\rm max} \sim f_a < 10^{16}$ GeV [Yoshino et al 12, Baryakhtar et al 20, Omiya et al 22...].

Strong-Field Limit of Ultralight Boson



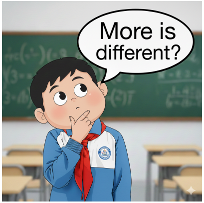
e.g., $\phi^2 F_{\mu\nu}F^{\mu\nu}$





Strong-field limit :

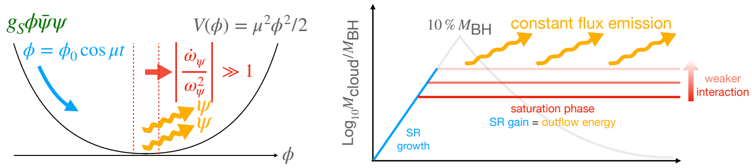
$\phi \to \phi_c \leq 10^{16}$GeV



Consequences of Strong-Field Ultralight Boson

- Trigger **non-perturbative** phenomenon:

  - Parametric matter production: photon [Spieksma et al 23], fermion [YC et al 25].



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

  Production rate significantly higher than perturbative decays.

  - Phase transition, defect production.

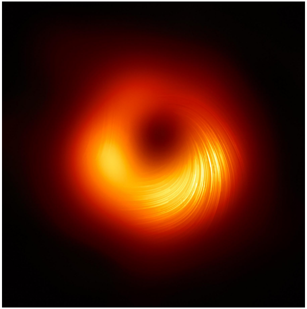
- **Enhanced phenomenology**:

  e.g., $a_0 \sim f_a$ phenomenology for axion.

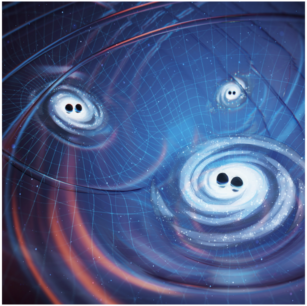
Illuminating the Dark with Black Holes

Modern **black hole** observations:

- **Black hole images**:



- **Gravitational waves**:



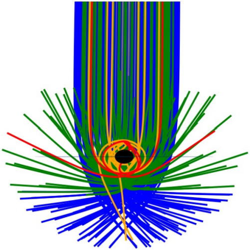
- How do **black hole** observations serve as particle detectors?

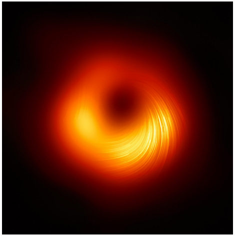
EHT and Future VLBI Arrays for Ultralight Bosons

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

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

Photon orbits [KGEO]





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

Photon ring: bound orbits.

Synchrotronic linear polarization.

Geodesics deviation:

$T^{\rm cloud}_{\mu\nu} \propto \cos(2\mu t)$

$\to h_{\mu\nu} \propto \cos(2\mu t)$

Axion birefringence:

$g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}/2 \to$

$\Delta\chi = g_{a\gamma}[a_{\rm obs} - a_{\rm emit}]$.

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

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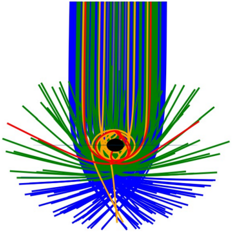

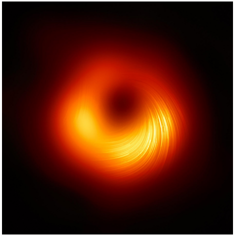

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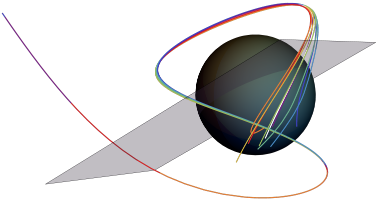

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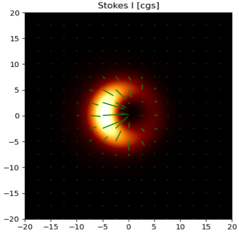

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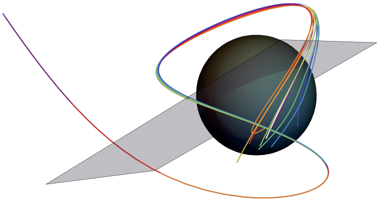
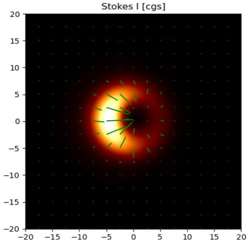




Geodesics deviation:

- **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]

Axion birefringence:

- **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 the next-generation Event Horizon Telescope, Living Rev.Rel. 25]

Dynamics and Emissions of Accreting Axion Clouds

[Ximeng Li, Zhen Zhong, YC, Vitor Cardoso, ongoing]

What about

Relaxation to Gravitational Atoms

Outside **stars** or **Schwarzschild black holes**:

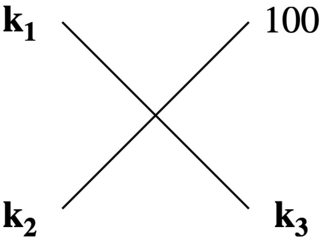
- **Relaxation** to **gravitational atom** from ambient ultralight boson waves:
  [Budker, Eby, Gorghetto, Jiang, Perez 23]

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

$$\tau_{\rm rel} \sim \frac{1}{n_{\rm DM}\sigma v_{\rm DM}} \frac{1}{n_{\rm DM}\lambda_{\rm dB}^3} \sim \frac{\mu^3}{\rho_{\rm DM}{}^2} \times \begin{cases} M_{\rm pl}^4 v_{\rm DM}^6, & \text{self-gravity;} \\ f_a{}^4 v_{\rm DM}^2, & \lambda_4 a^4 \text{ with } \lambda_4 = \mu^2/f_a{}^2. \end{cases}$$

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

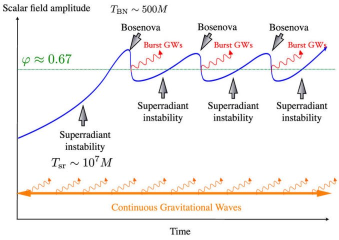
Stimulated capture



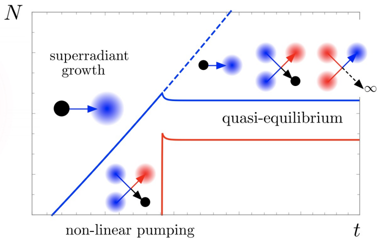
[Budker, Eby, Gorghetto, Jiang, Perez 23]

Bosenova or Saturation?

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

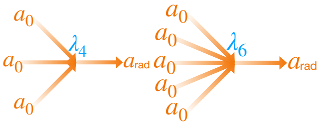


[Yoshino et al 12]



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

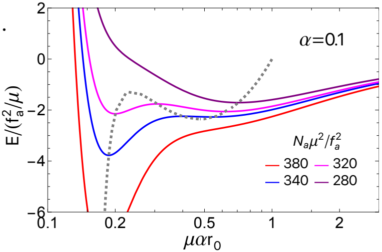
- Effective potential:

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

- 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

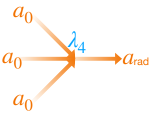
→ **Bosenova**.

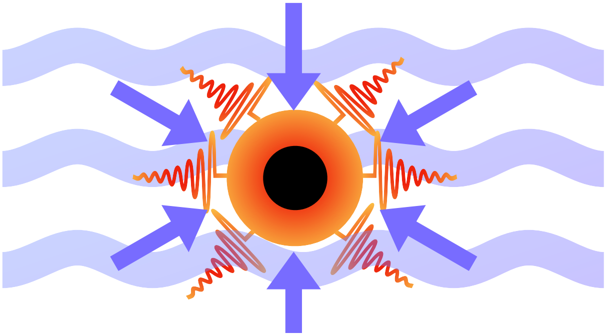
Condition for Saturation

- **Variational method**:

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

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





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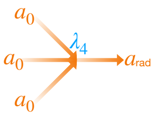
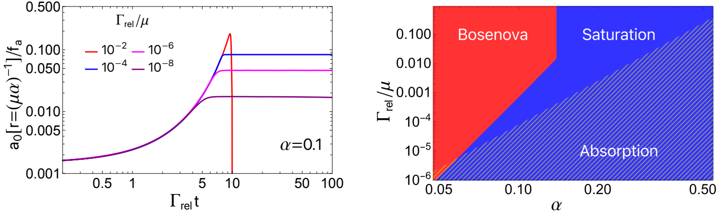




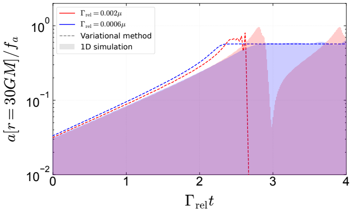
[Ximeng Li, preliminary]

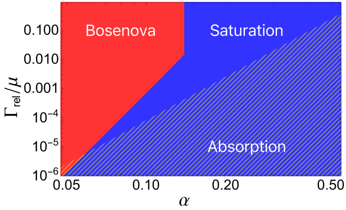
- For sufficiently small $\Gamma_{\rm rel}/\mu$, $\tilde{N}_a^S \lesssim \tilde{N}_a^B$, always **saturation**.

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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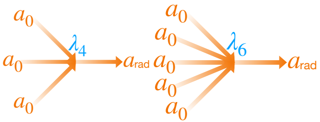
Axion Fluxes and Axion Potential

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

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

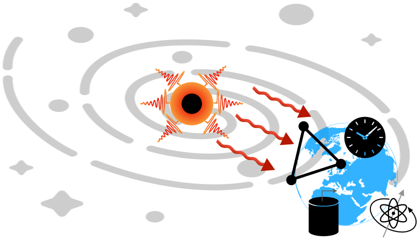
- **Detection**: axion **dark matter** at $\omega \sim \mu$ and **fluxes** at $\omega \sim 3\mu, 5\mu, 7\mu \cdots$.



- **Fluxes** from Galactic Center:

  •**SRF cavity broadband mode** [Berlin et al 20] for mHz axions from SMBH Sgr A*;

  • **Magnetometers** [Garcon et al 17] for kHz axions from stars.



- **Axion potential reconstruction**:

Axion Fluxes and Axion Potential

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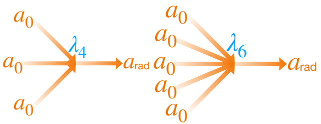

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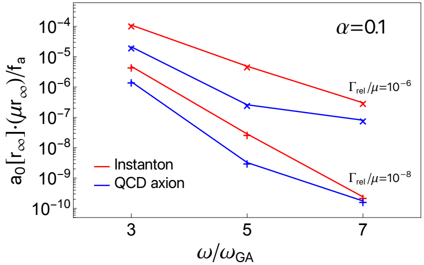


[Ximeng Li, preliminary]

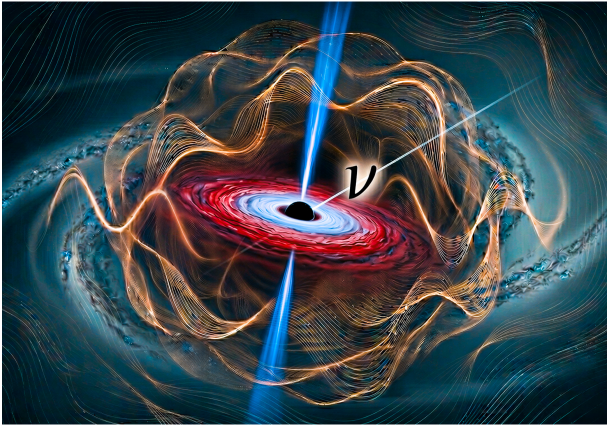
- **Axion potential reconstruction**:

Shaping Flavors of High-Energy Neutrinos in Ultralight Dark Matter Cores

[Zhaoyu Bai, YC, Qinrui Liu, Xin Wang, ongoing]

ν in Soliton Core Dark Matter

At large scales:



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

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

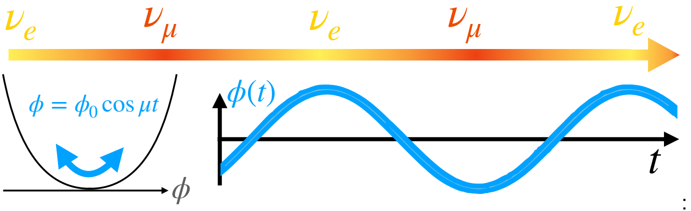
- How do ν **propagate** through this background?

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]

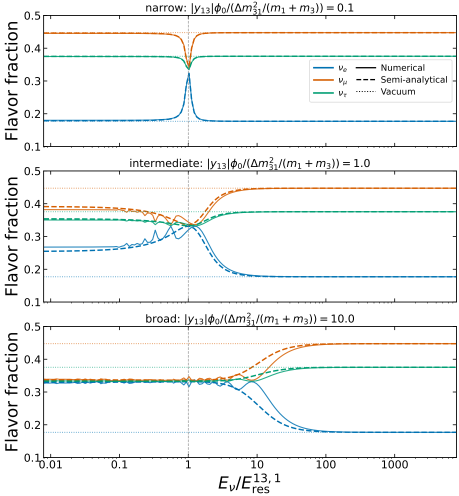
$$\mu \sim \frac{\Delta m_{ij}^2}{2E_\nu}, \qquad \mu \sim 10^{-18}\ \text{ev} \iff E_\nu^{\rm res} \sim \text{PeV}.$$



- 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:

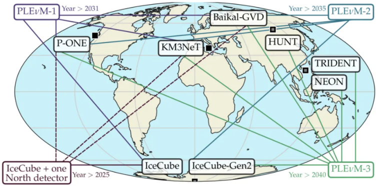


[Bai, YC, Liu, Wang, preliminary]

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

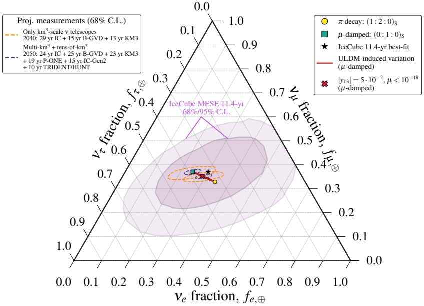
Detection Prospect

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



Global neutrino detector network

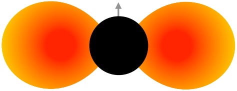
[Bustamante]



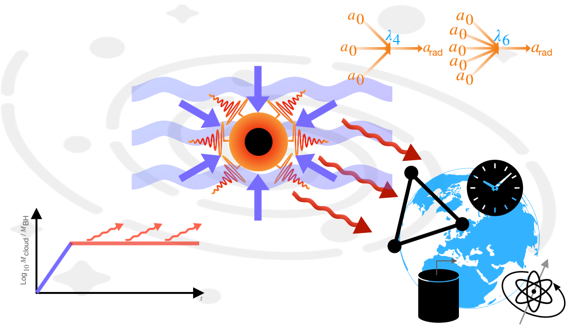
[Qinrui Liu, preliminary]

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

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**.
- **Ultralight bosons** can distort ν **oscillations**, shaping **flavor spectra**.

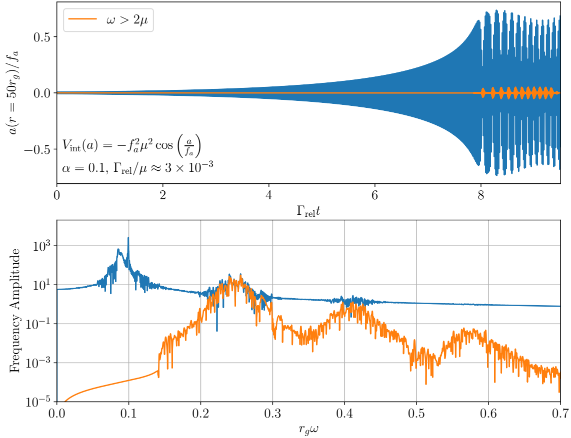
Thank you!

Backup

Bosenova or Saturation?

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

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



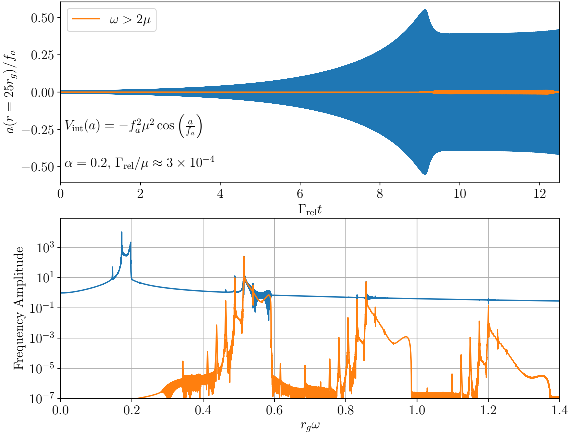
[Zhen Zhong, preliminary]

- **Periodic bosenova** for $\alpha = 0.1, \Gamma_{\rm rel}/\mu = 5\times10^{-4}$.

Bosenova or 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, preliminary]

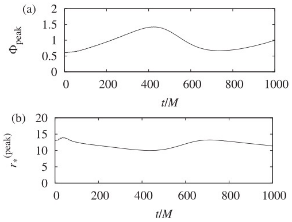
- Nearly **saturating** when $\Gamma_{\rm rel}/\mu$ decreases to 1.25×10^{-4}.

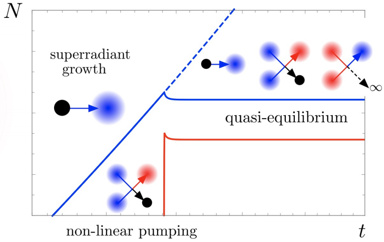
Weakly Saturating Axion Cloud

- Strong self-interaction region $a_{\max}^{\rm GA} \sim f_a$ happens when $f_a < 10^{16}$ GeV:

$$V(a) = \mu^2 f_a^2 \left(1 - \cos\frac{a}{f_a}\right) = \frac{\mu^2 a^2}{2} - \frac{\mu^2 a^4}{24 f_a^2} + \ldots;$$

- Quasi-equilibruim phase where **superradiance and axion emission balance** with $a_{\max}^{\rm GA} \sim \alpha\, f_a$ [Yoshino et al 12, Baryakhtar et al 20, Omiya et al 22...].



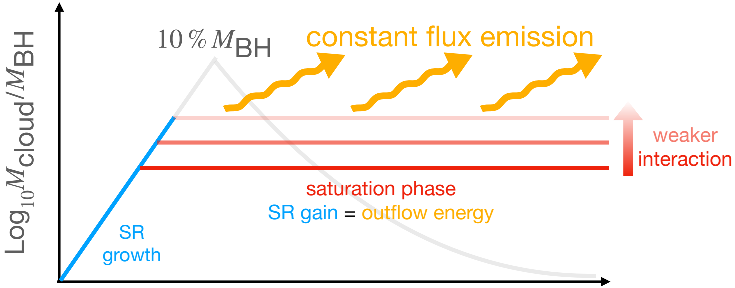


- $a_0 \sim f_a$ **phenomenology**:

  Axion waves from gravitational atom excitation/ionization for $a_0 \sim f_a < 10^{16}$ GeV [Yoshino et al 12, Baryakhtar et al 20].

Matter Production from Strong-Field Ultralight Bosons

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



- **Photon production** from axion cloud [Spieksma et al PRD 2306.16447].
- **Fermion production and acceleration** from boson clouds [YC et al JCAP 2308.00741].

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

  Production rate significantly higher than perturbative decays.