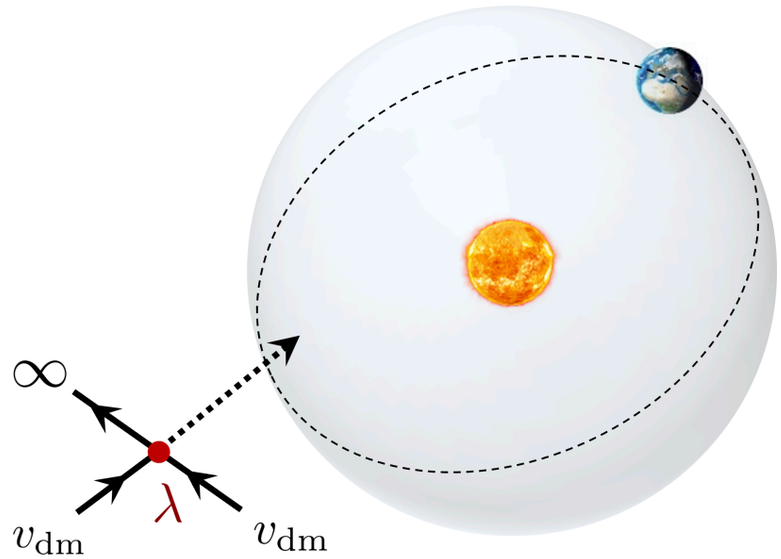
NNU · 南京师范大学
NANJING NORMAL UNIVERSITY

Formation and Detection of Ultralight DM Solar Halos

Based on : JCAP 12 (2023) 021
D. Budker, J. Eby, M. Gorghetto, MJ, G. Perez



Minyuan Jiang 蒋民源

Nanjing Normal University

2026.04.26 Chongqing

Content

- *Introduction*
- *Formation mechanism of ULDM solar halo*
- *Detection of ULDM solar halo*
- *Conclusion and outlook*

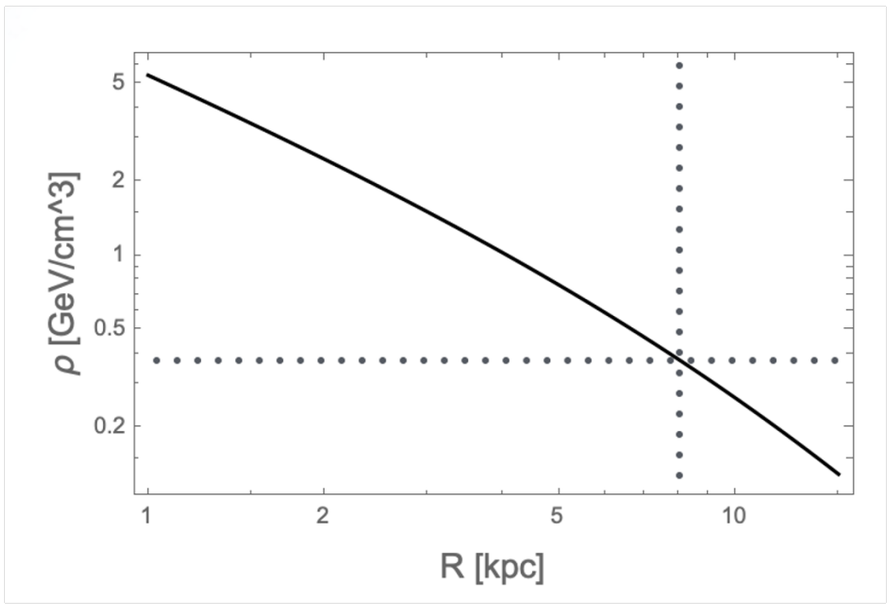
The Question:

What's the possible local DM distribution in our solar system?

Crucial information for any DM detection experiment !

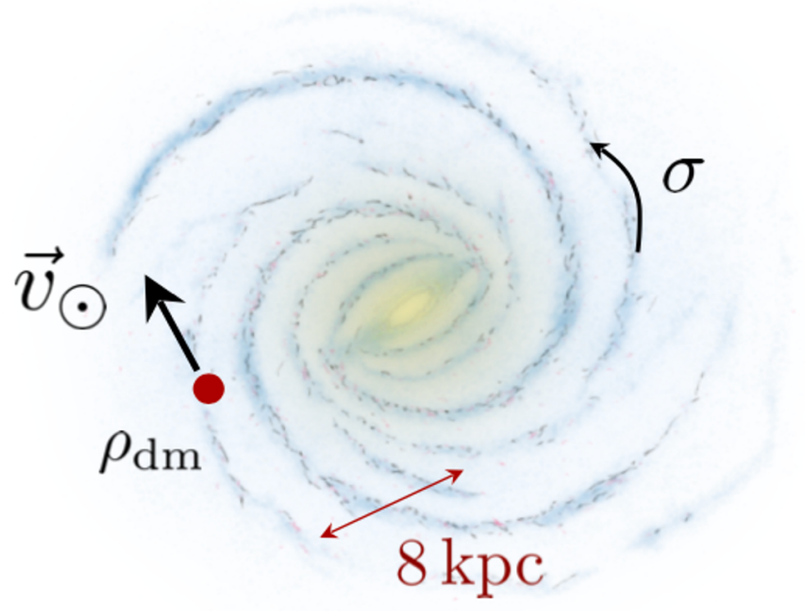
Standard halo model

(inferred from the measurements/simulation on galactic scale)

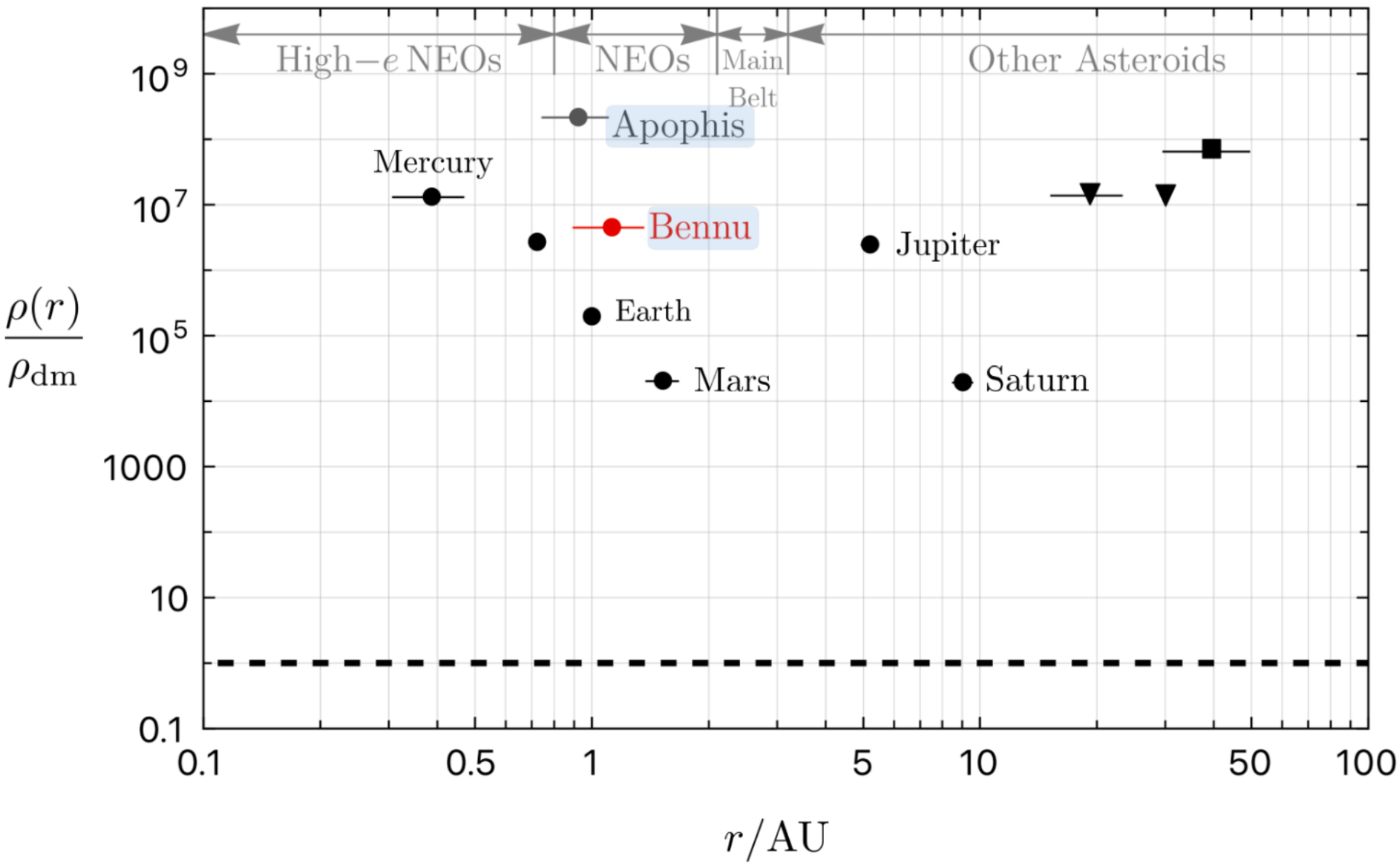


$\rho_{\rm dm} \approx 0.4\ {\rm GeV/cm^3}$

$v_{\rm dm} \approx 240\ {\rm km/s}$



The local DM density could be much different !



Ultralight Dark Matter

- $m \lesssim 1eV$, *occupation number* $N \sim n\lambda_{\rm db}^3 \sim (\rho_{\rm DM}/m)/(mv)^3 \gg 1$
- *Behave like classical field* $N = \langle a^\dagger a \rangle \gg [a, a^\dagger] = 1$
- *Naturally produced as dark matter*

  — *Scalar : Misalignment*

  — *Vector (Dark Photon): Gravitational production; axion/higgs decay…*

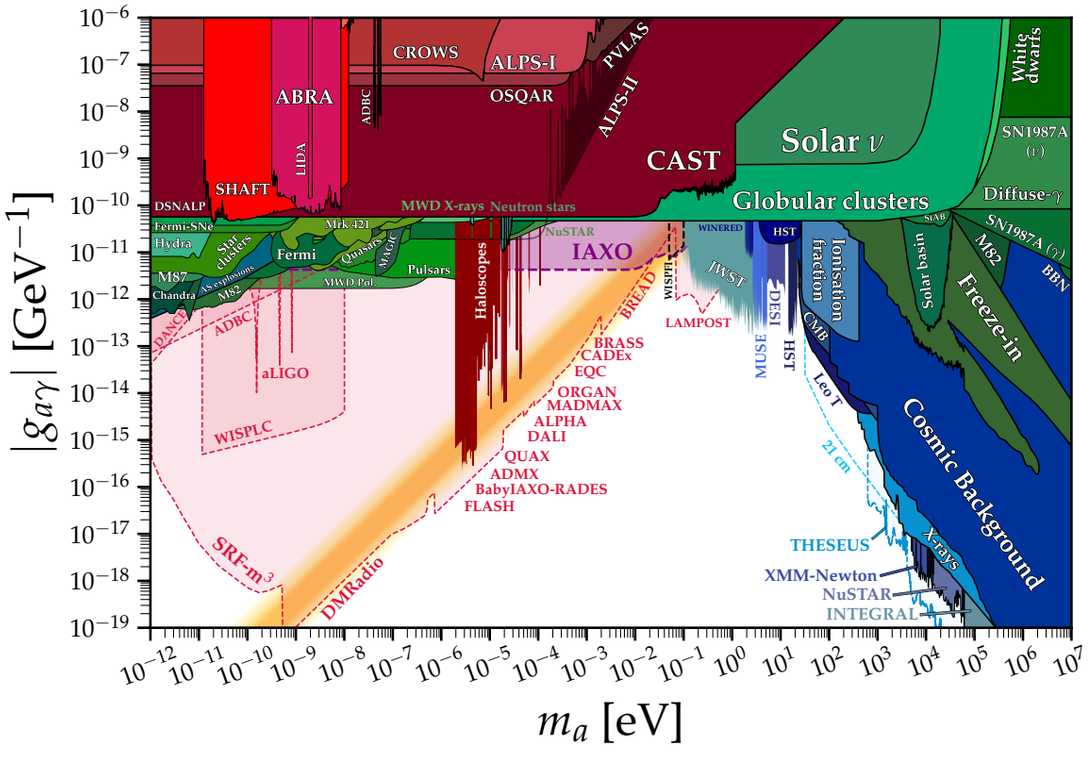
QCD Axion

- *An elegant solution to the strong CP problem:* $\mathscr{L} \supset \frac{g^2}{32\pi^2}(\bar{\theta} + \frac{a}{f_a})G\tilde{G}$
- *A natural candidate as ULDM*

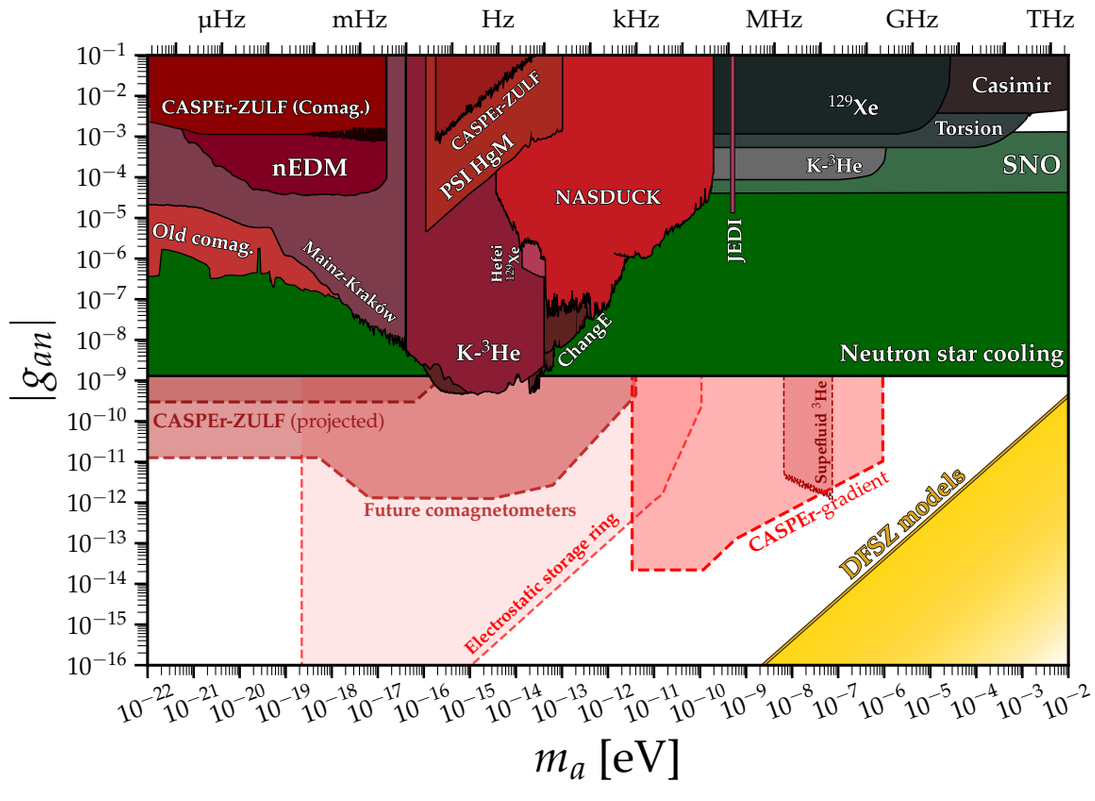
  Pre-inflation scenario: misalignment

  Post-inflation scenario: cosmic strings
- *Well motivated search target for experiments*

$$\mathscr{L} \supset \frac{1}{4} g_{a\gamma\gamma} a F\tilde{F}$$



$$\mathscr{L} \supset g_{an} \frac{\partial_\mu a}{2f_a} \bar{n}\gamma^\mu\gamma^5 n$$



Wave equation for free ultralight scalar DM :

$$(g^{\mu\nu}D_\mu\partial_\nu + m^2)\phi = 0$$

$$\phi \equiv \frac{1}{\sqrt{2m}}(\psi e^{-imt} + \text{c.c.})$$

ψ: non-relativistic field

$$g_{00} = 1+2\Phi \simeq \Phi_{\text{ex}} = -\frac{GM}{r}$$

M: external mass, e.g. Sun

$$(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r})\psi = 0 \qquad \alpha \equiv GMm$$

$$(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r})\psi = 0$$

Bound state (Gravitational atom) :

$$\psi = \sum_{nlm} c_{nlm}(t) e^{-i\omega_n t} \psi_{nlm}$$

$$\psi_{100} = \frac{1}{\sqrt{\pi R_\star^3}} e^{-r/R_\star}$$

$$N_{nlm} = |\, c_{nlm}(t)\,|^2$$

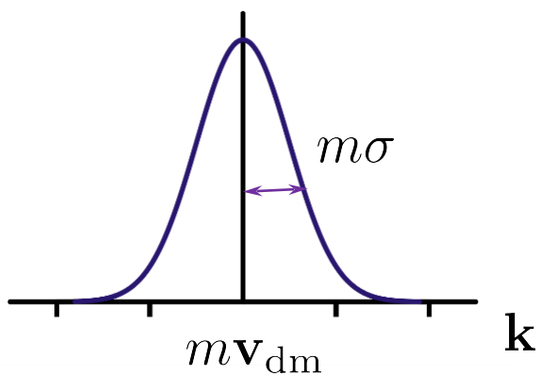
$$R_\star \equiv \frac{1}{m\alpha} = \frac{1}{GMm^2}$$

$$R_\star = \tfrac{1}{m\alpha} = 1\,\mathrm{AU} \left[\frac{1.3 \cdot 10^{-14}\,\mathrm{eV}}{m}\right]^2 \left[\frac{M_\odot}{M}\right]$$

$$(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r})\psi = 0$$

Scattering state (DM in the galactic halo):

$$\psi_w(t, \mathbf{x}) \equiv \int \frac{d^3k}{(2\pi)^3} a(\mathbf{k}) e^{-i\omega_k t} \psi_{\mathbf{k}}(\mathbf{x})$$



$$\langle a^*(\mathbf{k}) a(\mathbf{k}') \rangle = (2\pi)^3 f(\mathbf{k}) \delta(\mathbf{k} - \mathbf{k}')$$

$$\rho_{\rm dm} = \langle \rho_w \rangle = m \langle |\psi_w|^2 \rangle = m \int \frac{d^3k}{(2\pi)^3} f(\mathbf{k}) \,,$$

$0.4\,\mathrm{GeV/cm^3}$ $240\,\mathrm{km/s}$

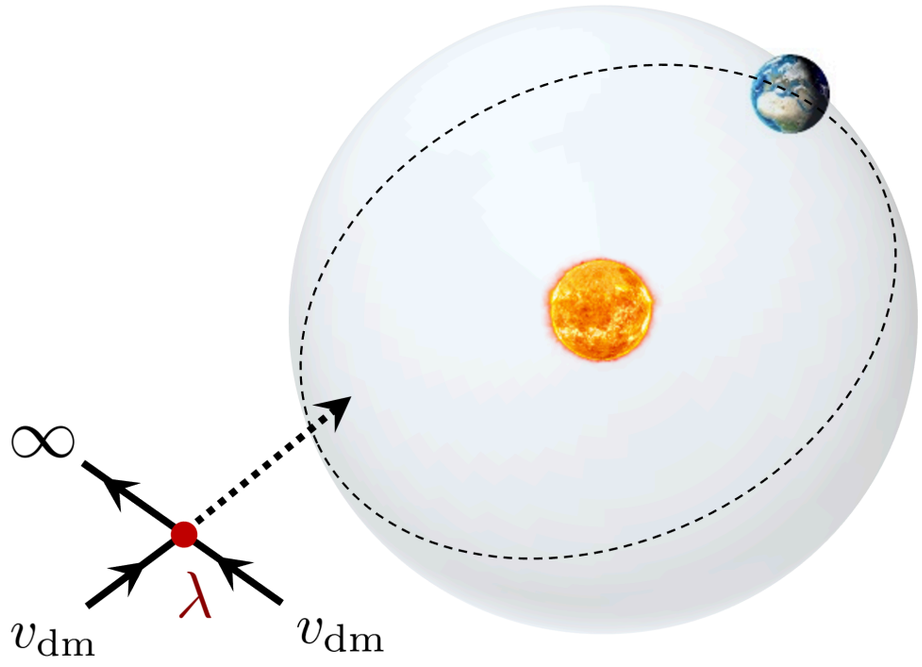
$$f(\mathbf{k}) = \frac{\rho_{\rm dm}}{\sigma^3 m^4} e^{-\frac{(\mathbf{k} - m\mathbf{v}_{\rm dm})^2}{2m^2\sigma^2}}$$

How to capture the DM from the galactic halo ?

$$\text{Scattering state} \xrightarrow{\ ?\ } \text{Bound state}$$

Scattering !

(self-interaction)



$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \ldots$$

EoM: $$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r}\right)\psi = g\,|\psi|^2\psi\,. \qquad g \equiv \lambda/8m^2$$

$g < 0$ *Attractive interaction* $g > 0$ *Repulsive interaction*

Axion case: $V(\phi) = -\,m^2 f_a^2 \cos(\phi/f_a)$

$$g = -\,1/(8f_a^2)$$

$$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r} \right) \psi = g\,|\psi|^2 \psi\,.$$

Perturbation Theory:

$$\psi = \psi^{(0)} + \psi^{(1)} + \psi^{(2)} + \ldots$$

$$\psi^{(i)} = \sum_{nlm} c^{(i)}_{nlm}(t) e^{-i\omega_n t} \psi_{nlm} + \int \frac{d^3k}{(2\pi)^3} c^{(i)}_{\mathbf{k}}(t)\, e^{-i\omega_k t}\, \psi_{\mathbf{k}}$$

$$t = 0: \;\; \psi = \psi^{(0)} \equiv \psi_w = \int \frac{d^3k}{(2\pi)^3} a(\mathbf{k}) e^{-i\omega_k t} \psi_{\mathbf{k}}(\mathbf{x})$$

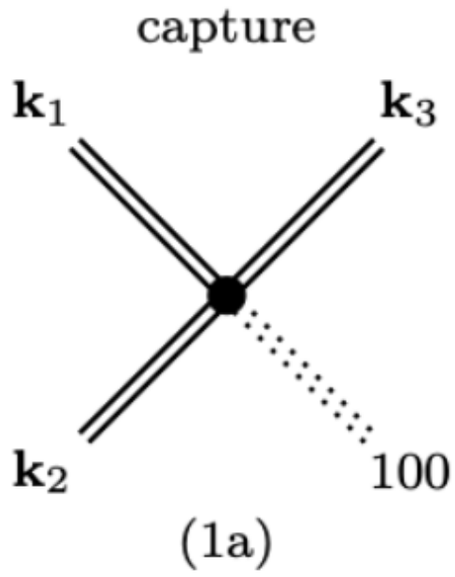
First Order Equation:

$$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r} \right) \psi^{(1)} = g\,|\psi^{(0)}|^2 \psi^{(0)}$$

Capture rate:

$$\langle \dot{N}_{nlm} \rangle = \frac{d}{dt} \langle \mid c^{(1)}_{nlm}(t) \mid^2 \rangle = 2g^2 \int [dk_1][dk_2][dk_3] f(\mathbf{k}_1) f(\mathbf{k}_2) f(\mathbf{k}_3) (2\pi) \delta(\Delta\omega) \mid \mathscr{M} \mid^2$$

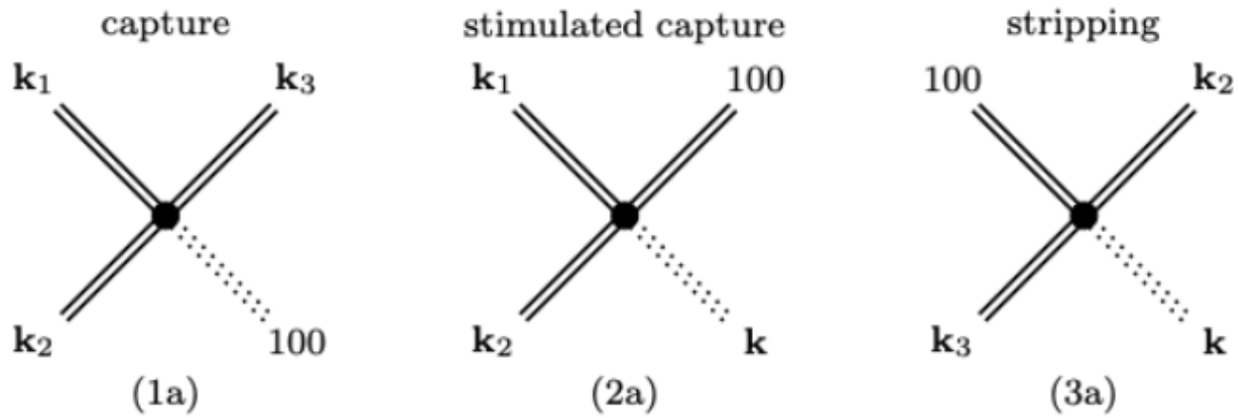
$$\mathscr{M}_{k_1+k_2 \to k_3+nlm} \equiv \int d^3x \psi^*_{nlm} \psi^*_{\mathbf{k}_3} \psi_{\mathbf{k}_1} \psi_{\mathbf{k}_2} \qquad \Delta\omega \equiv \omega_{k_1} + \omega_{k_2} - \omega_{k_3} - \omega_n$$



(1a)

How about bose enhancement & inverse processes?

Second order equations:



$$\left(i\partial_t + \frac{\nabla^2}{2m} + \frac{\alpha}{r} \right) \psi^{(2)} = g \left(\psi^{(0)2} \psi^{(1)*} + 2 \left| \psi^{(0)} \right|^2 \psi^{(1)} \right).$$

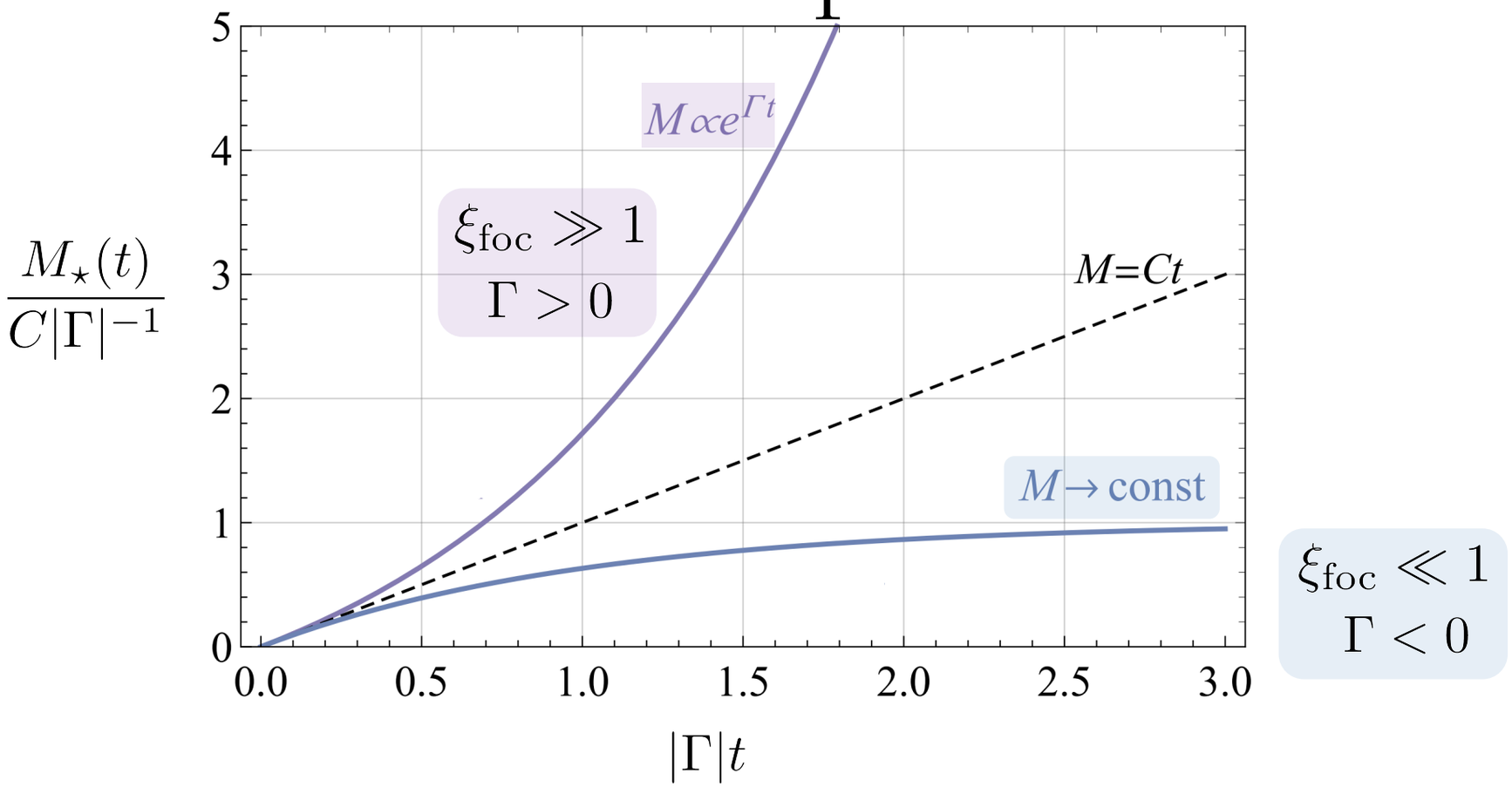
$$\langle \dot{N}_{nlm} \rangle = 2g^2 \int [dk_1][dk_2][dk_3](2\pi)\delta(\Delta\omega) \left| \mathscr{M} \right|^2$$

$$\times \{ \underbrace{f(\mathbf{k}_1) f(\mathbf{k}_2) f(\mathbf{k}_3)}_{C} + \underbrace{\langle N_{nlm} \rangle \left[f(\mathbf{k}_1) f(\mathbf{k}_2) \right.}_{\Gamma_1} - \underbrace{\left. 2 f(\mathbf{k}_2) f(\mathbf{k}_3) \right]}_{\Gamma_2} \}$$

Capture *Stimulated capture* *Stripping*

Phases of halo formation

$$\dot{M}_{nlm} = C + \underbrace{(\Gamma_1 - \Gamma_2)}_{\Gamma} M_{nlm}$$

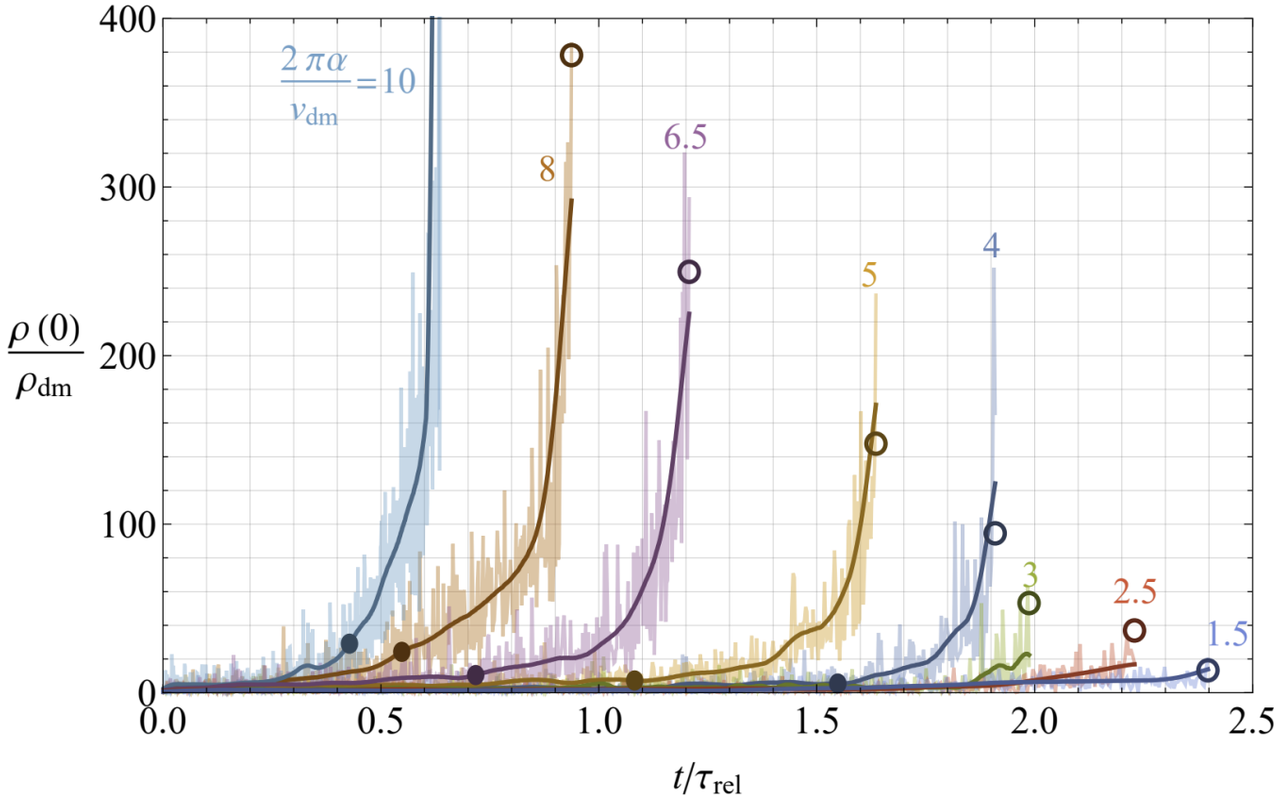


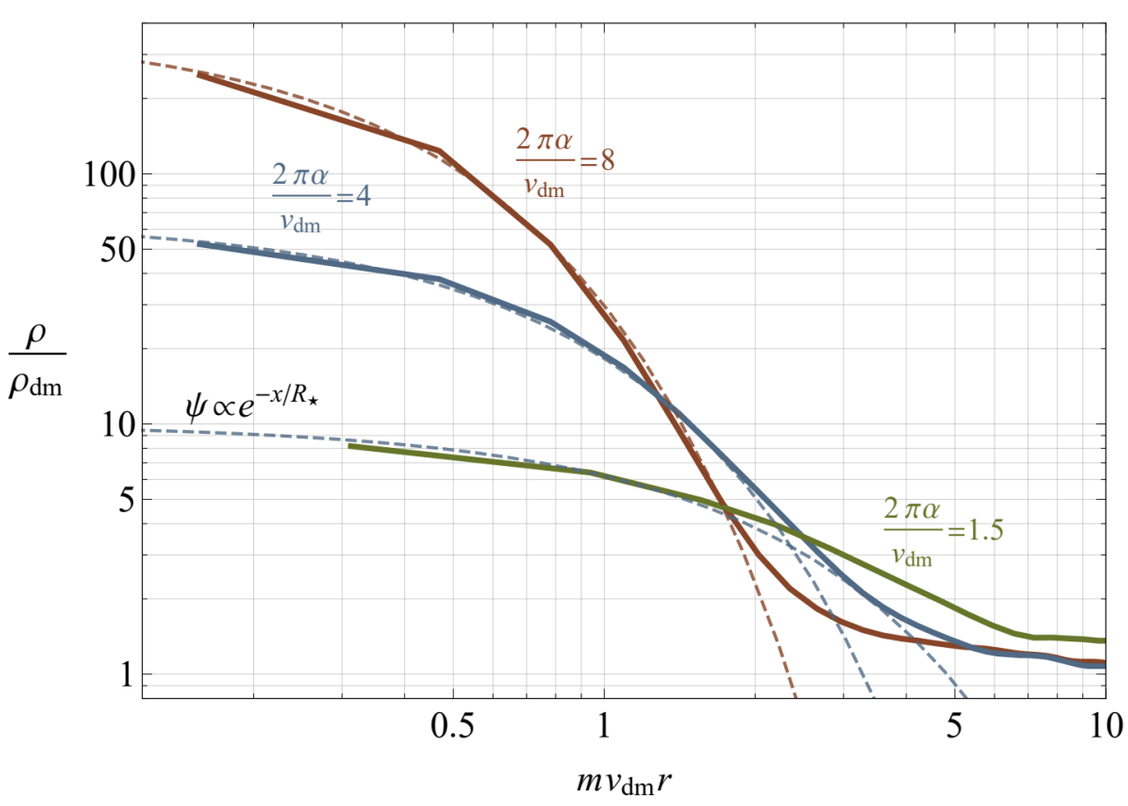
$$\xi_{\rm foc} = \frac{2\pi\alpha}{v_{\rm dm}} \simeq \left[\frac{m}{1.7\times10^{-14}\,{\rm eV}}\right]\left[\frac{M}{M_\odot}\right]\left[\frac{240\,{\rm km/s}}{v_{\rm dm}}\right]$$

When $\xi_{\rm foc} \gg 1$ $\quad \Gamma^{-1} \leftrightarrow$ relaxation time

$$\tau_{\rm rel} \equiv \frac{m^3 v_{\rm dm}^2}{g^2\rho_{\rm dm}^2} \simeq 9\,{\rm Gyr}\left[\frac{f_a}{10^8\,{\rm GeV}}\right]^4\left[\frac{m}{10^{-14}\,{\rm eV}}\right]^3\left[\frac{0.4\,{\rm GeV/cm^3}}{\rho_{\rm dm}}\right]^2\left[\frac{v_{\rm dm}}{240\,{\rm km/s}}\right]^2$$

Comparison with simulations





The fate of the exponential growth

Breaks down of perturbation theory :

$$\rho_{\rm crit} \equiv \frac{2\Phi_{\rm ex} m^2}{|g|} \simeq 2\frac{\alpha^2 m^2}{|g|} \simeq 6\cdot 10^4 \rho_{\rm dm} \left[\frac{f_a}{5\cdot 10^7\,{\rm GeV}}\right]^2 \left[\frac{m}{1.7\cdot 10^{-14}\,{\rm eV}}\right]^4 \left[\frac{M}{M_\odot}\right]^2 \left[\frac{0.4\,{\rm GeV/cm^3}}{\rho_{\rm dm}}\right]$$

Attractive self-interaction ($g < 0$) (axion)

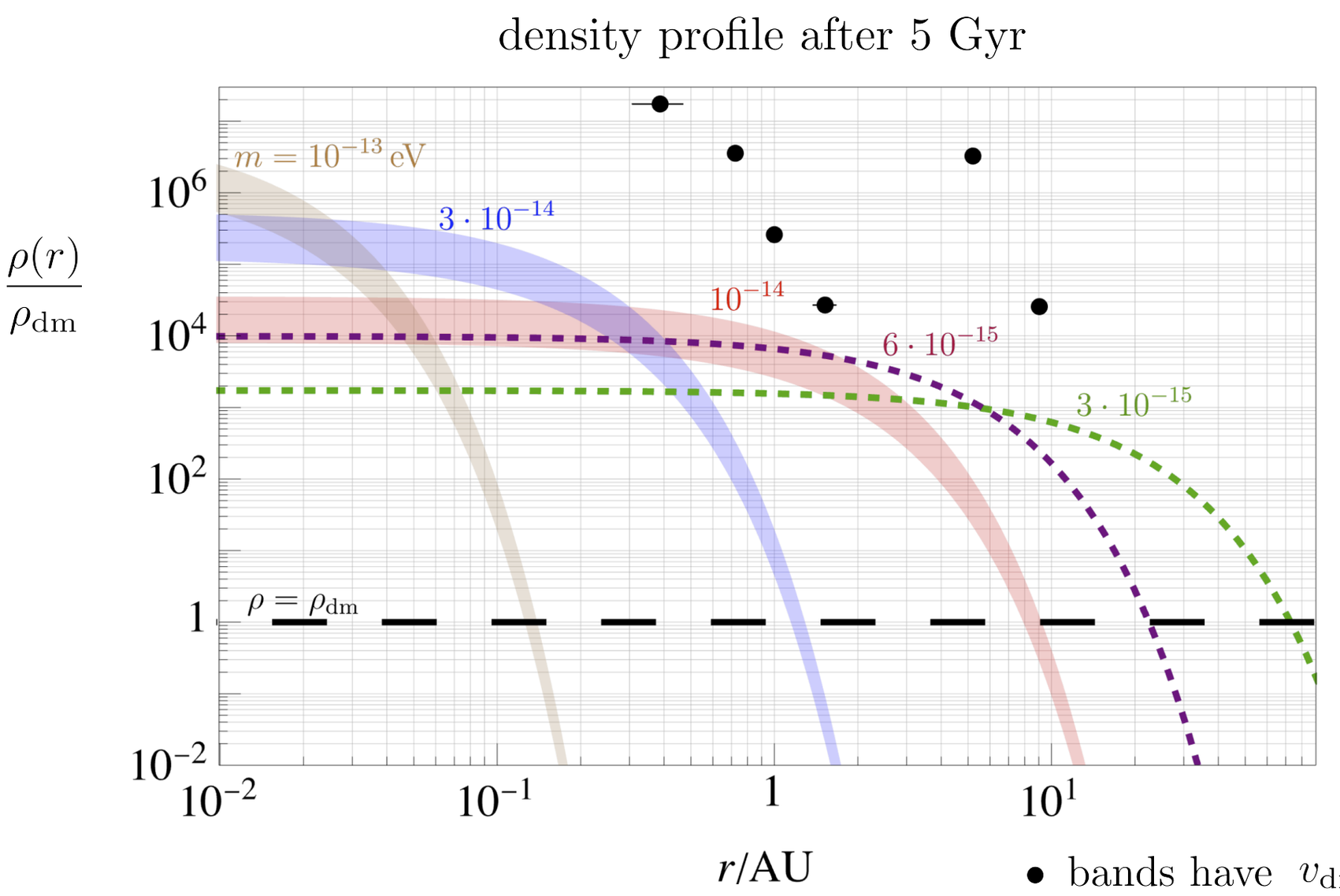
Collapse $\xrightarrow{?}$

$$\begin{matrix} 100 \\ 100 \\ 100 \end{matrix} \rightarrow \cdots\cdots \text{relativistic}$$

Repulsive self-interaction ($g > 0$) : Gravity balanced with self-interaction

Search for the solar halo

Enhanced density | Distinct density profile | Large coherence time



- bands have $v_{\rm dm} = 50 \div 240\,\mathrm{km/s}$
- f_a (or λ) fixed in $10^7 \div 10^8\,\mathrm{GeV}$

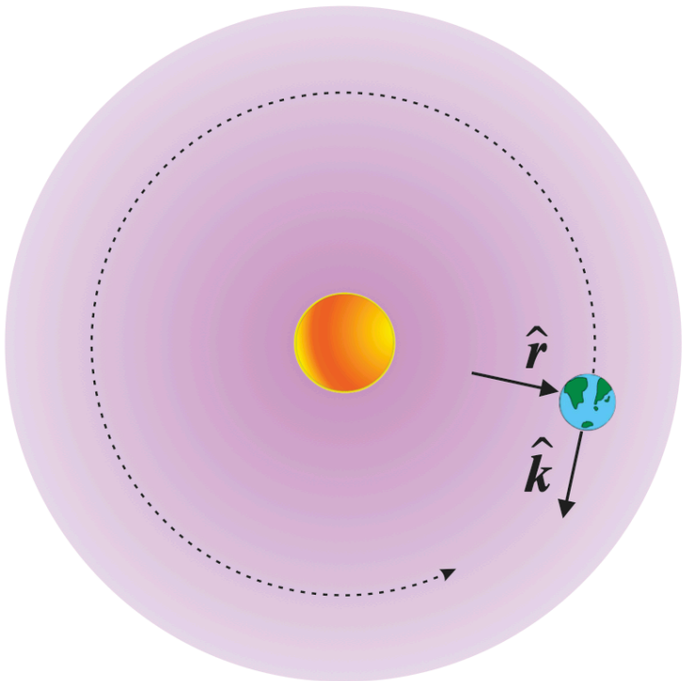
Search for the solar halo

Enhanced density | Distinct density profile | Large coherence time

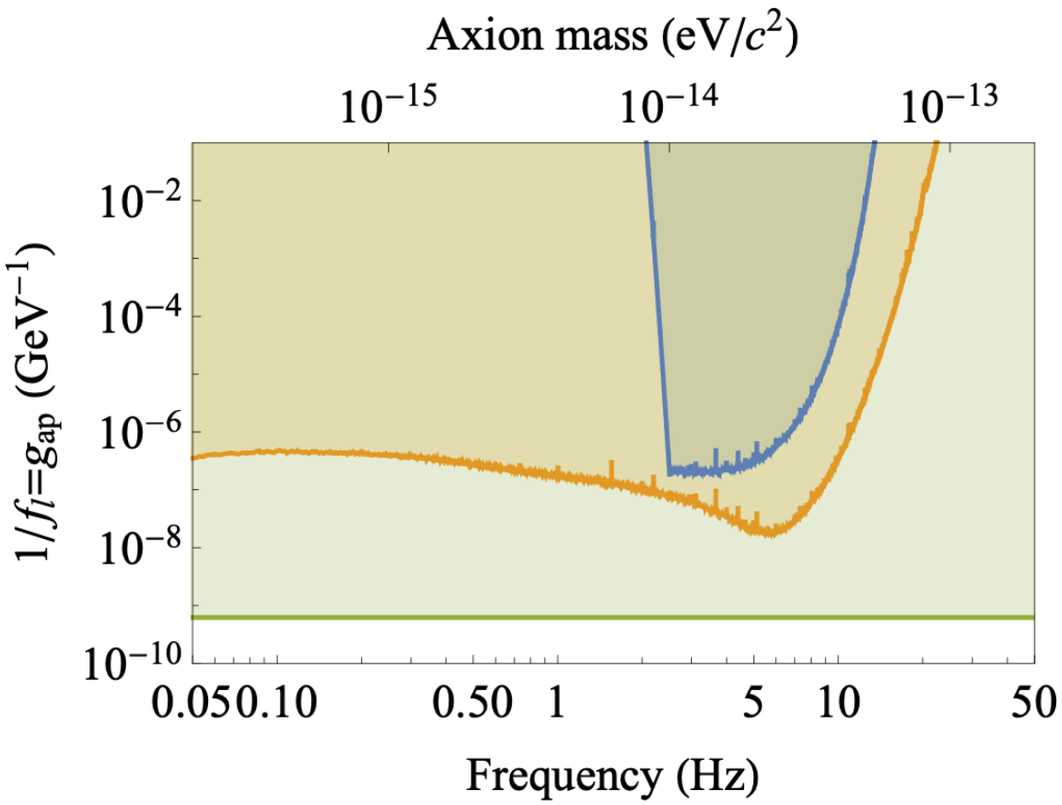
Search for a solar-bound axion halo using the Global Network of Optical Magnetometers for Exotic physics searches

T Z. Wilson, D F. Kimball, S. Afach, J. Bi, B.C. Buchler et al. (2025)

$$\mathcal{H}_l = -\frac{2(\hbar c)^{3/2}}{f_l}\boldsymbol{S}\cdot\boldsymbol{\nabla}a(\boldsymbol{r},t)$$



$$a(\boldsymbol{r},t) \approx a_0 \cos\left(\omega_a t - \boldsymbol{k}\cdot\boldsymbol{r} + \theta\right)e^{-r/R_\star}$$



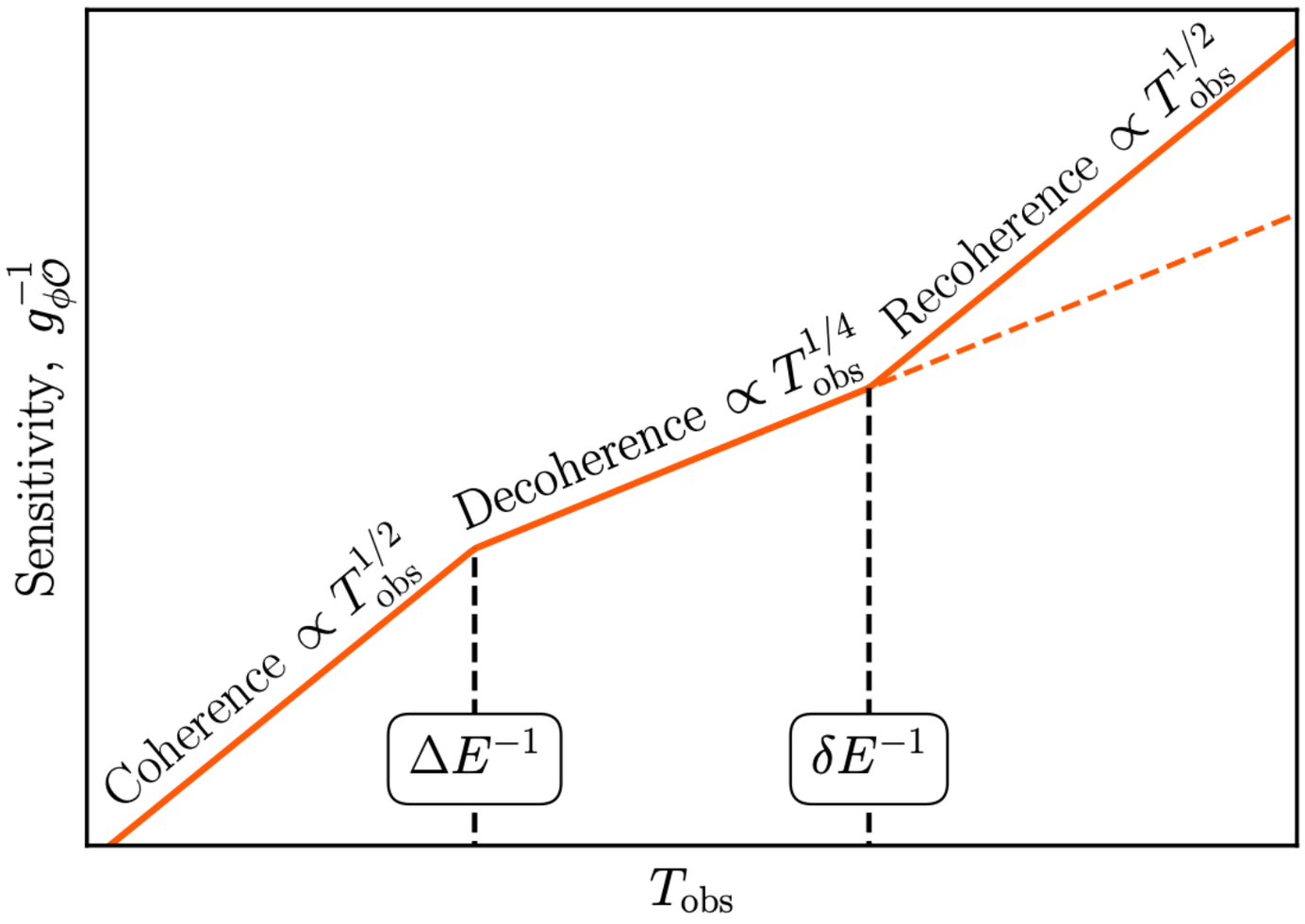
Search for the solar halo

Enhanced density | Distinct density profile | Large coherence time

Coherence time of Galactic halo $\tau_{\rm dm} \sim 1/\Delta E \sim 1/(m v_{\rm dm}^2)$

Dark Matter Recoherence

C. Paranjape, G. Perez, W. Ratzinger, and S. Sankaranarayanan, 2026



Summary

- *Gravitational atom structure exists for ultralight DM*

$$R_\star = \frac{1}{m\alpha} = 1\,\mathrm{AU}\left[\frac{1.3\cdot 10^{-14}\,\mathrm{eV}}{m}\right]^2\left[\frac{M_\odot}{M}\right]$$

- *Capture from scattering process (self-interaction)*

- *Exponential growth & large over density when* $\xi_{\mathrm{foc}} \gg 1$

$$\xi_{\mathrm{foc}} = \frac{2\pi\alpha}{v_{\mathrm{dm}}} \simeq \left[\frac{m}{1.7\times 10^{-14}\,\mathrm{eV}}\right]\left[\frac{M}{M_\odot}\right]\left[\frac{240\,\mathrm{km/s}}{v_{\mathrm{dm}}}\right]$$

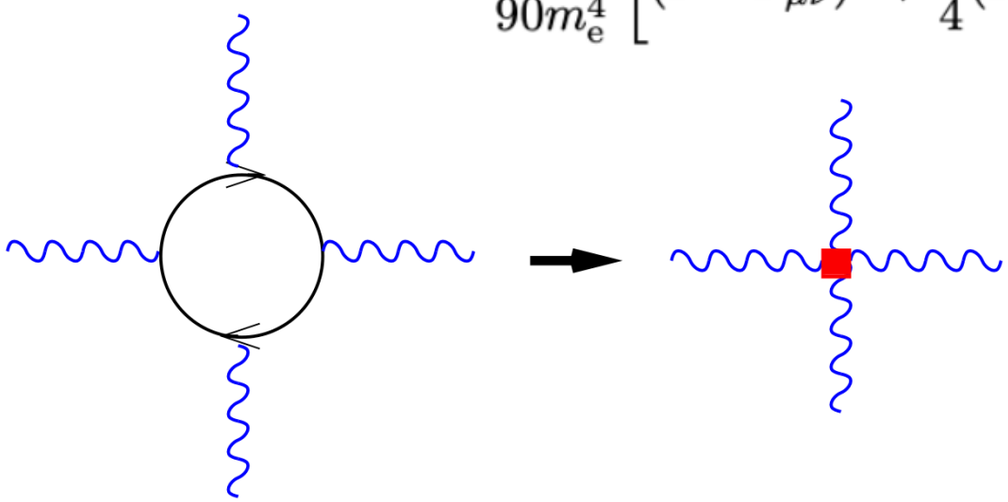
- *Change the DM detection strategy dramatically*

Outlook

- *Dark photon halo ?*

— *dark electron scenario*

$$\frac{\alpha^2}{90m_e^4}\left[(F^{\mu\nu}F_{\mu\nu})^2+\frac{7}{4}(F^{\mu\nu}\tilde{F}_{\mu\nu})^2\right]$$



— *dark higgs scenario*