A Solar Halo of Ultralight Dark Matter

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New Horizons for Psi
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cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

COSMIC WISPERS
CA21106

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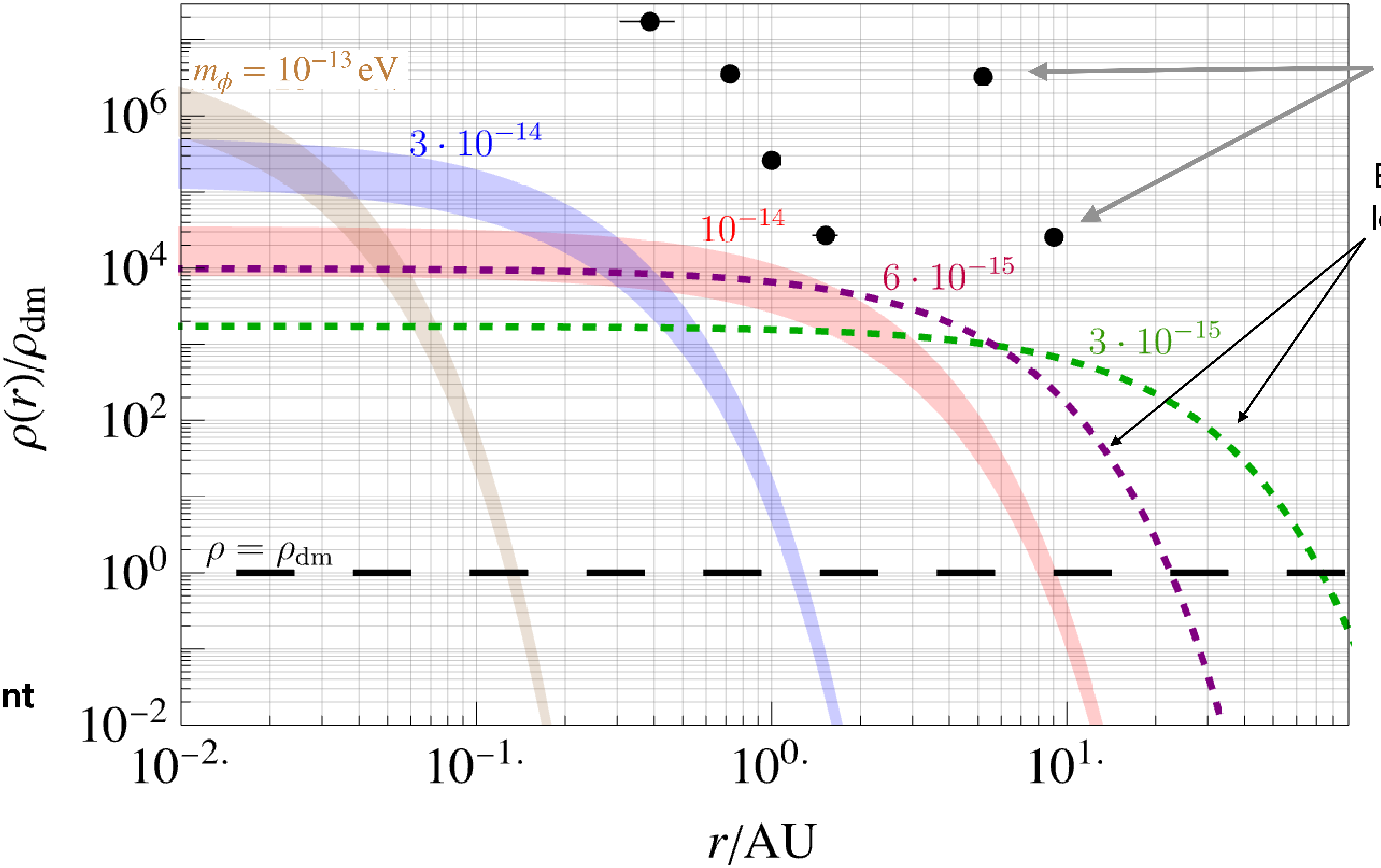
Conclusion: Solar Halo Density

Large modifications to the **very local density** from axions captured over **5Gyr (solar lifetime)**

(i.e. in our solar system)

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)



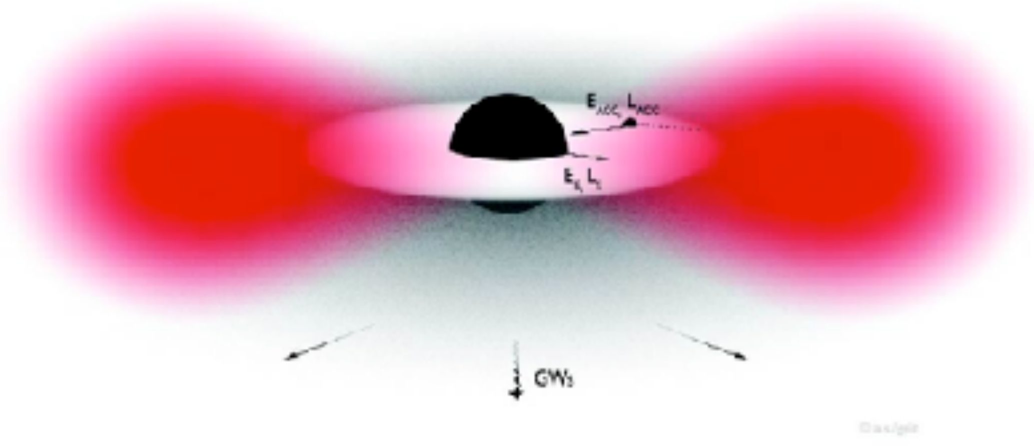
Direct constraints:
See H. Kim talk (Wednesday)

Exponentially-growing in low-velocity environment
$v_{\rm dm} \ll 200\,\mathrm{km/s}$

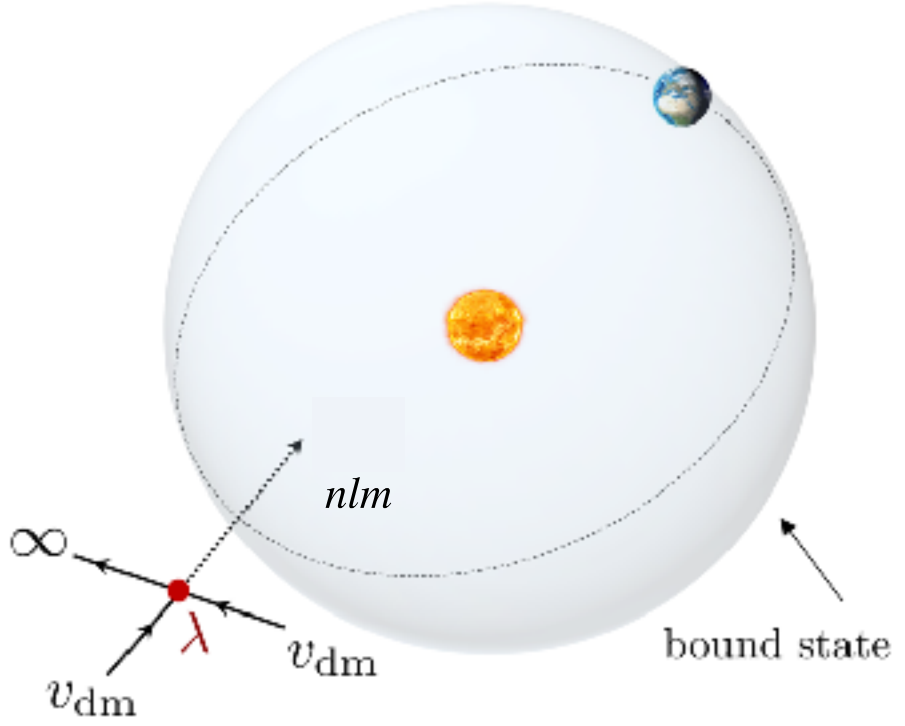
for axion decay constant

$f_a \simeq 10^7 - 10^8\,\mathrm{GeV}$

assuming $\lambda < 0$;
density could be larger for $\lambda > 0$



Gravitational Atoms



	Superradiance Many talks so far!	**Ultralight dark matter (ULDM) capture**
States populated	only $\ell \neq 0$ primarily $\ell = m$ small	all $n\ell m$ primarily $n\ell m = 100$
Efficient production on…	Rapidly rotating BHs with $M \sim \dfrac{1}{Gm_\phi}$ when $\omega_{n\ell m} \lesssim m\Omega_H$ Also stars (?) See J. McDonald talk (Wednesday)	Massive bodies with $M \gtrsim \dfrac{v_{\rm dm}}{2\pi G m_\phi}$ when $\lambda\phi^4$ is "strong enough"
Gravitational coupling	$\alpha_g \equiv GMm_\phi \sim \mathcal{O}(1)$	$\alpha_g \gtrsim \dfrac{v_{\rm dm}}{2\pi} \sim 10^{-4}$
Energy density from…	BH mass / spin	DM background

Gravitational Atoms

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \overset{\text{low density}}{\cancel{V_g\left(|\psi|^2\right)}} + V_{g,\mathrm{ext}}(r) + \overset{\text{low density}}{\cancel{\frac{\lambda}{8m_\phi^2}|\psi|^2}}\right]\psi$$

↓

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi$$

↓

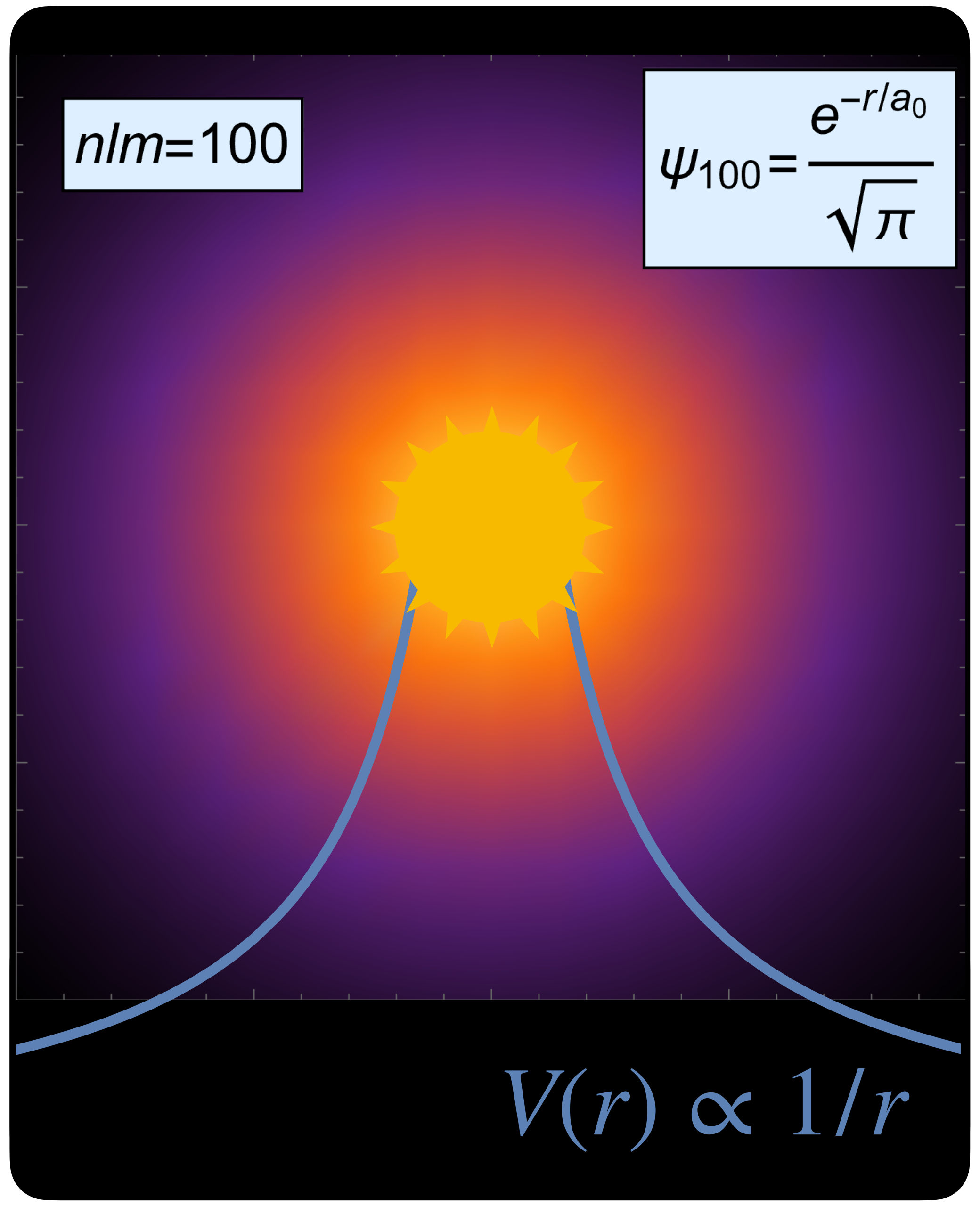
solutions

$$\psi = \psi_w + \psi_b$$

√[number density]

DM ‘waves’
(scattering states)

$$\sum_{nlm}\psi_{nlm}$$
(bound states)



Hydrogen atom E.o.M. with

Fine structure constant
$$\alpha \longrightarrow \alpha_g \equiv GMm_\phi$$
Gravitational coupling

Bohr radius
$$a_0 = \frac{1}{m_e\alpha} \longrightarrow R_\star \equiv \frac{1}{m_\phi\alpha_g}$$
Gravitational ‘Bohr radius’

DM Waves and Bound States

$$i\frac{\partial\psi}{\partial t} - \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi = 0$$

Hydrogenic E.o.M.

$$\psi = \psi_w + \psi_b$$

Bound states of gravitational atom

$$\psi_b(t,x) = \sum_{nlm} e^{-i\omega_n t}\,\psi_{nlm}(x)$$

$$\propto L^{2l+1}_{n-l-1}(r)\,Y^m_l(\theta,\varphi)$$

energy $\omega_n < m_\phi$

quantum numbers nlm

Scattering states (DM 'waves')

Solutions to Hydrogenic E.o.M.

$$\psi_w(t,x) = \int \frac{d^3k}{(2\pi)^3} f(k)\; e^{-i\omega_k t}\,\psi_k(x)$$

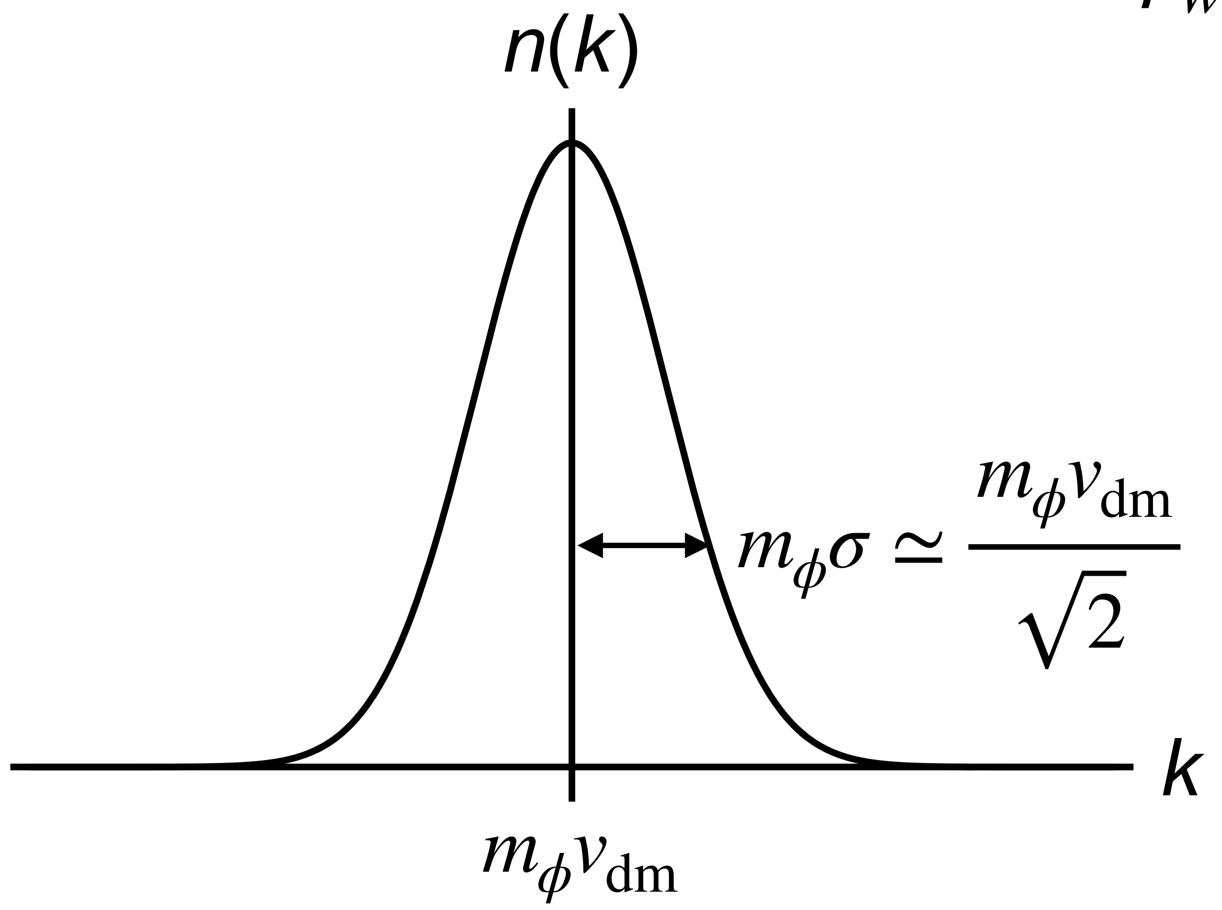
energy $\omega_k > m_\phi$

Statistical sampling of DM momenta in halo

$$\langle f^*(k) f(k')\rangle = (2\pi)^3\, n(k)\,\delta^3(k-k')$$

momentum distribution: Maxwell-Boltzmann

momentum distribution



Solutions: Coulomb Scattering States

Simple solutions in the limits

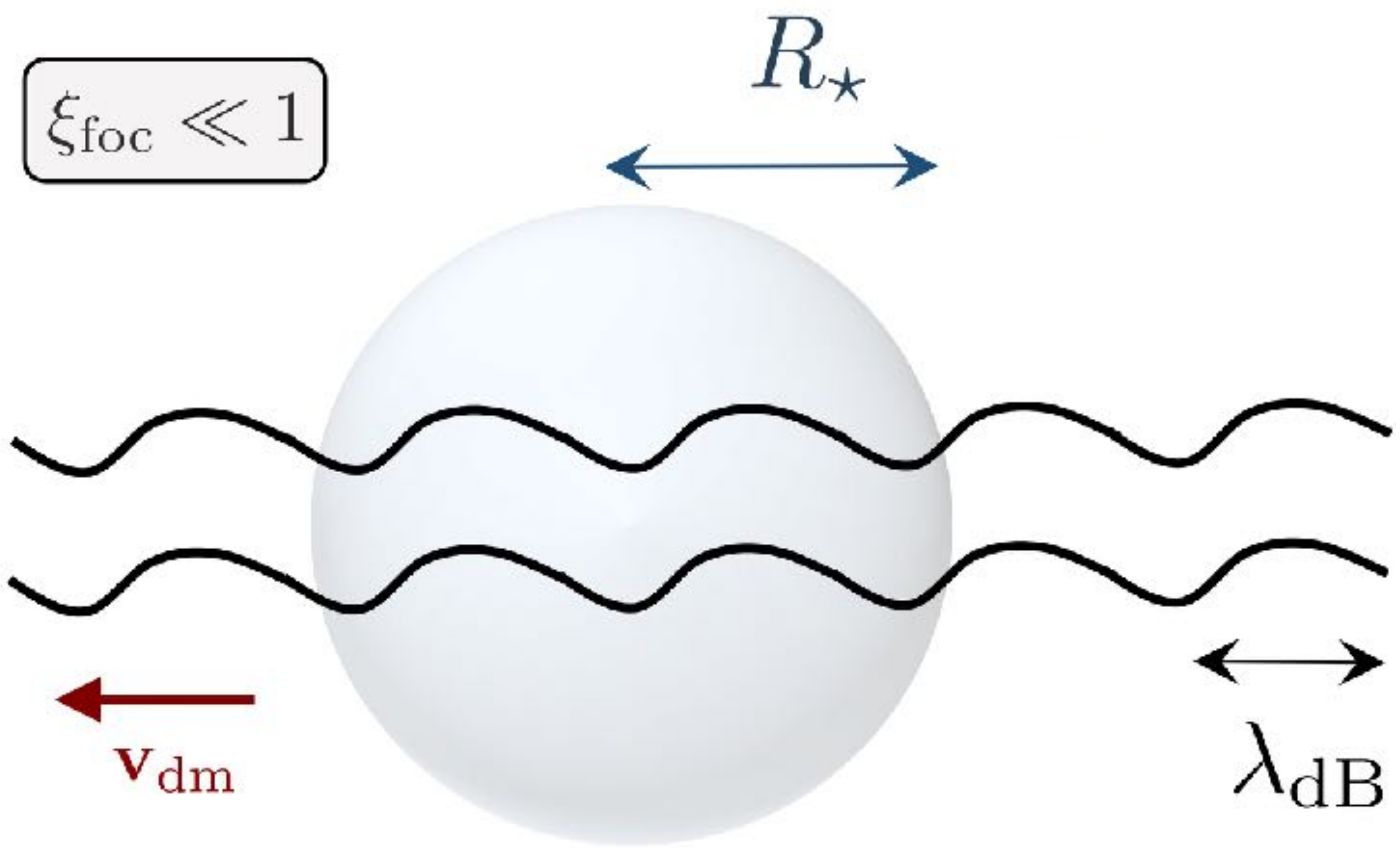
$kR_\star \gg (2\pi)^{-1}$ **and** $kR_\star \ll (2\pi)^{-1}$

We use $\xi_{\rm foc} \equiv \dfrac{2\pi}{kR_\star} = \dfrac{\lambda_{\rm dB}}{R_\star}$

DM Waves: Focusing

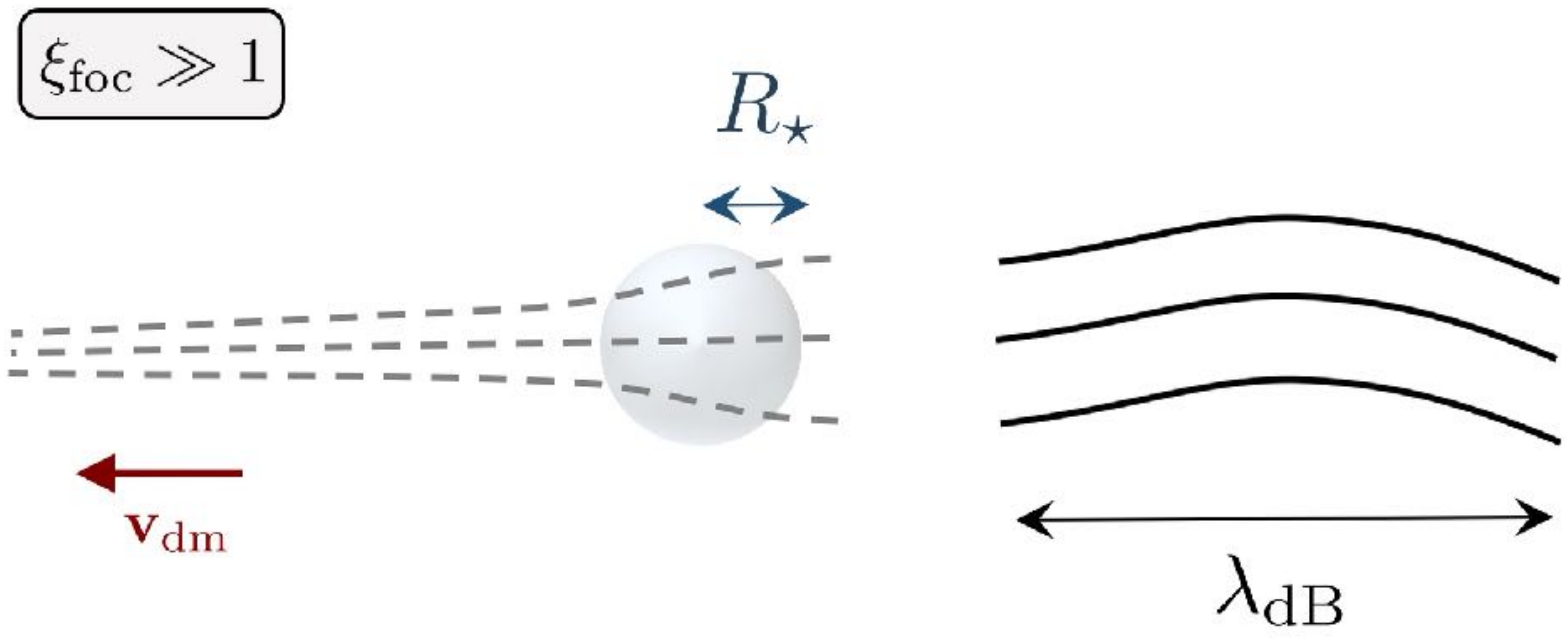
$$i\,\frac{\partial\psi_k}{\partial t} - \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi_k = 0$$

$$\xi_{\rm foc} \equiv \frac{\lambda_{\rm dB}}{R_\star} = \frac{2\pi\alpha_g}{v_{\rm dm}}$$ (dictates effectiveness of **‘gravitational focusing’**)



$\psi_k \longrightarrow e^{ik\cdot x}$,

typical energy $\overset{m_\phi v_{\rm dm}^2/2}{\omega_k} \gg \overset{m_\phi \alpha_g^2/2}{|\omega_n|}$



ψ_k **focused onto region of size** $\simeq R_\star$ **,**

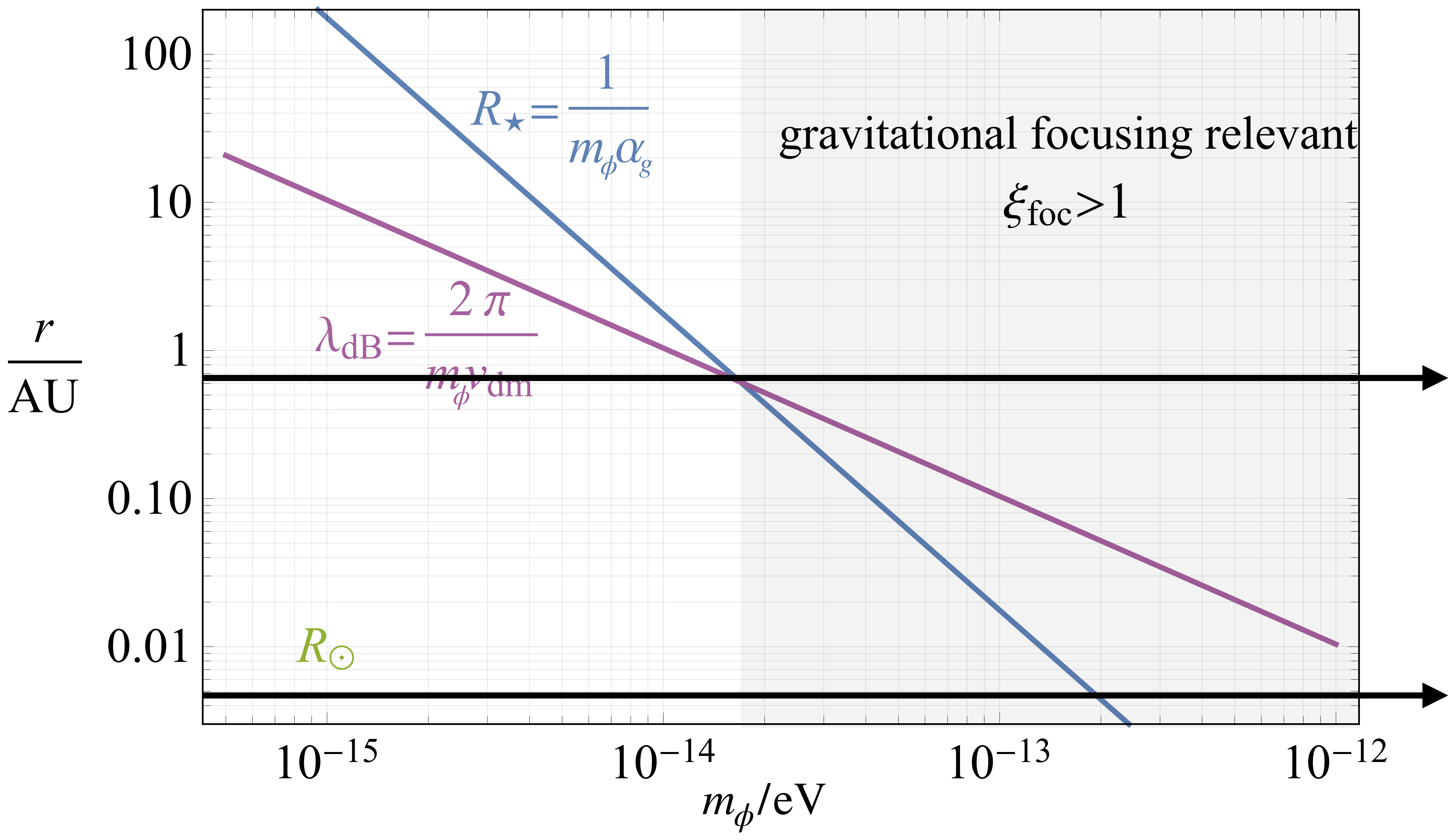
typical energy $\omega_k \ll |\omega_n|$

See Kim and Lenoci (2112.05718)

DM Waves in the Solar System

$$i\frac{\partial\psi_k}{\partial t} - \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi_k = 0$$

$$\xi_{\rm foc} \equiv \frac{\lambda_{\rm dB}}{R_\star} = \frac{2\pi\alpha_g}{v_{\rm dm}}$$ (dictates effectiveness of ‘**gravitational focusing**’)



For $M = M_\odot$ **,**

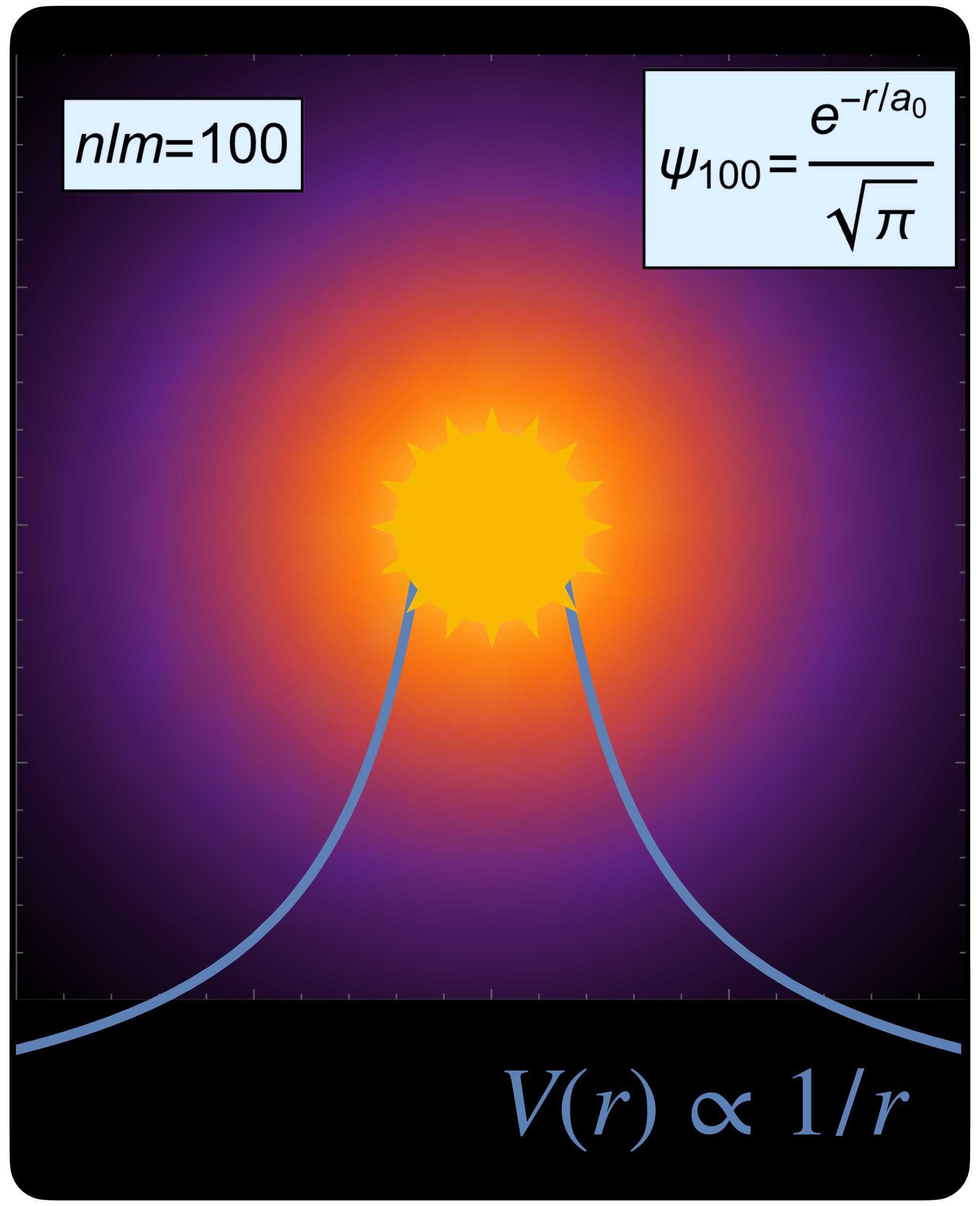
$R_\star \simeq \mathrm{AU}$ **at** $m_\phi \simeq 10^{-14}\,\mathrm{eV}$

$R_\star \simeq R_\odot$ **at** $m_\phi \simeq 2 \times 10^{-13}\,\mathrm{eV}$

$R_\star \simeq R_S$ **at** $m_\phi \simeq 10^{-11}\,\mathrm{eV}$

A Solar Halo

$$i\,\frac{\partial\psi}{\partial t} - \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi = 0$$



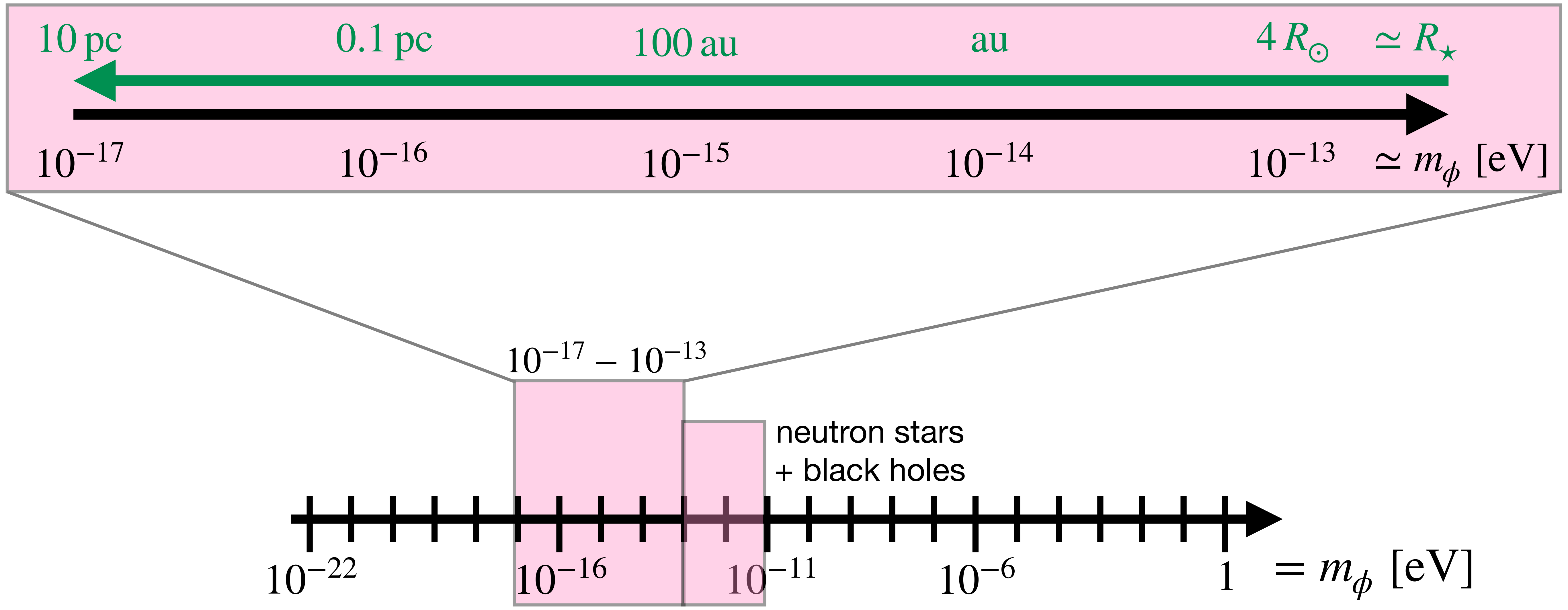
$$\alpha_g \equiv GMm_\phi \simeq 10^{-4}\left(\frac{m_\phi}{10^{-14}\,\mathrm{eV}}\right)\left(\frac{M}{M_\odot}\right)$$

$$\xi_{\rm foc} \equiv \frac{2\pi\alpha_g}{v_{\rm dm}} \sim \left(\frac{m_\phi}{10^{-14}\,\mathrm{eV}}\right)\left(\frac{M}{M_\odot}\right)\left(\frac{240\,\mathrm{km/sec}}{v_{\rm dm}}\right)$$

$$R_\star \equiv \frac{1}{m_\phi\alpha_g} \simeq 1\,\mathrm{au}\left(\frac{10^{-14}\,\mathrm{eV}}{m_\phi}\right)\left(\frac{M_\odot}{M}\right)$$

distance between stars

radius of Sun



10 pc	0.1 pc	100 au	au	$4\,R_\odot$	$\simeq R_\star$
10^{-17}	10^{-16}	10^{-15}	10^{-14}	10^{-13}	$\simeq m_\phi$ [eV]

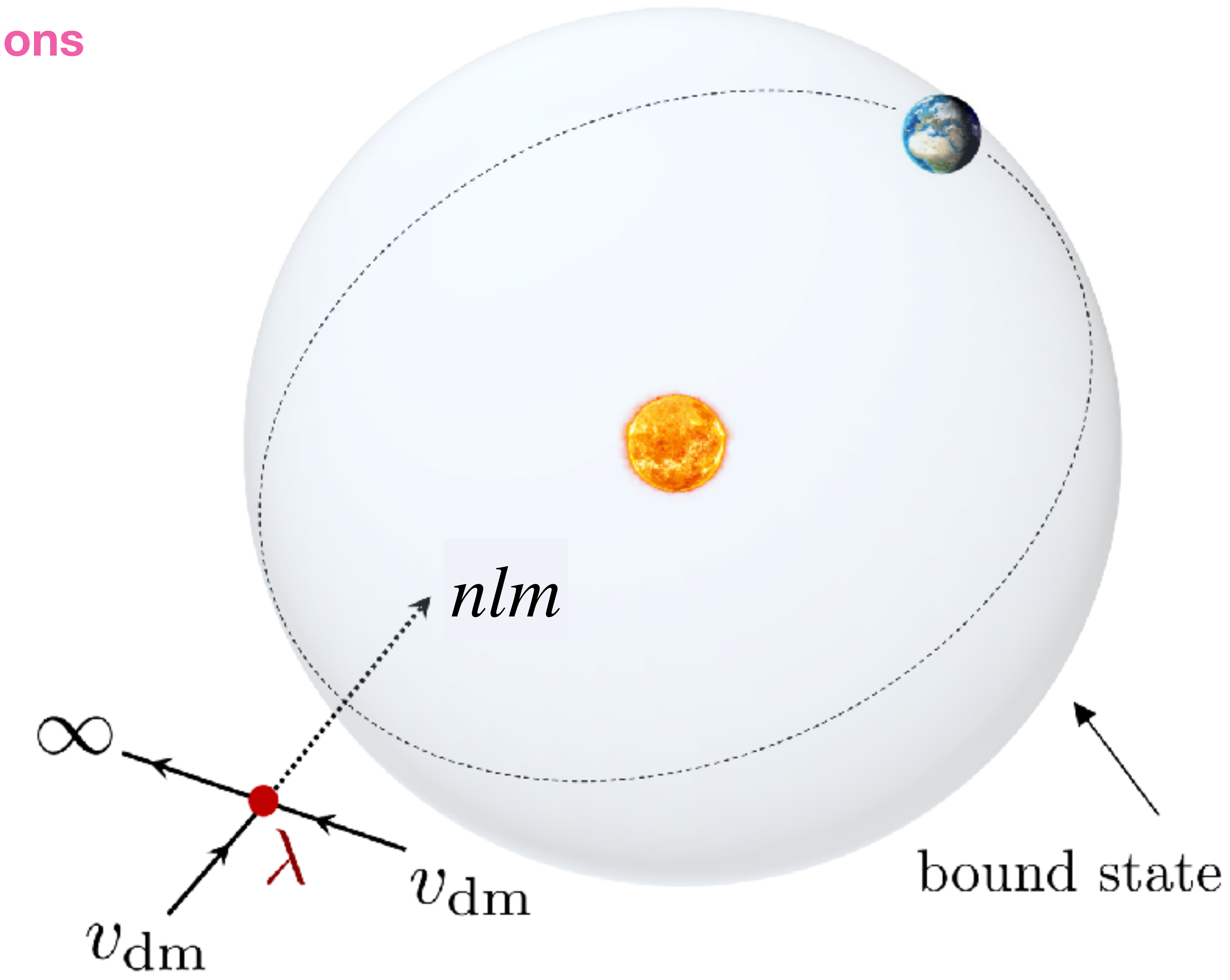
Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Self-Interactions

$$i\frac{\partial\psi}{\partial t} - \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r}\right]\psi = \frac{\lambda}{8m_\phi^2}|\psi|^2\psi$$

Hydrogenic E.o.M. + self-interactions

Self-interactions can move particles from scattering states to bound states (and vice versa)



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Mass Growth

phase space + energy conservation

$$\Delta\omega \equiv \omega_{k_1} + \omega_{k_2} - \omega_{k_3} - \omega_n$$

Initially: $N_{nlm}(t=0) = 0$

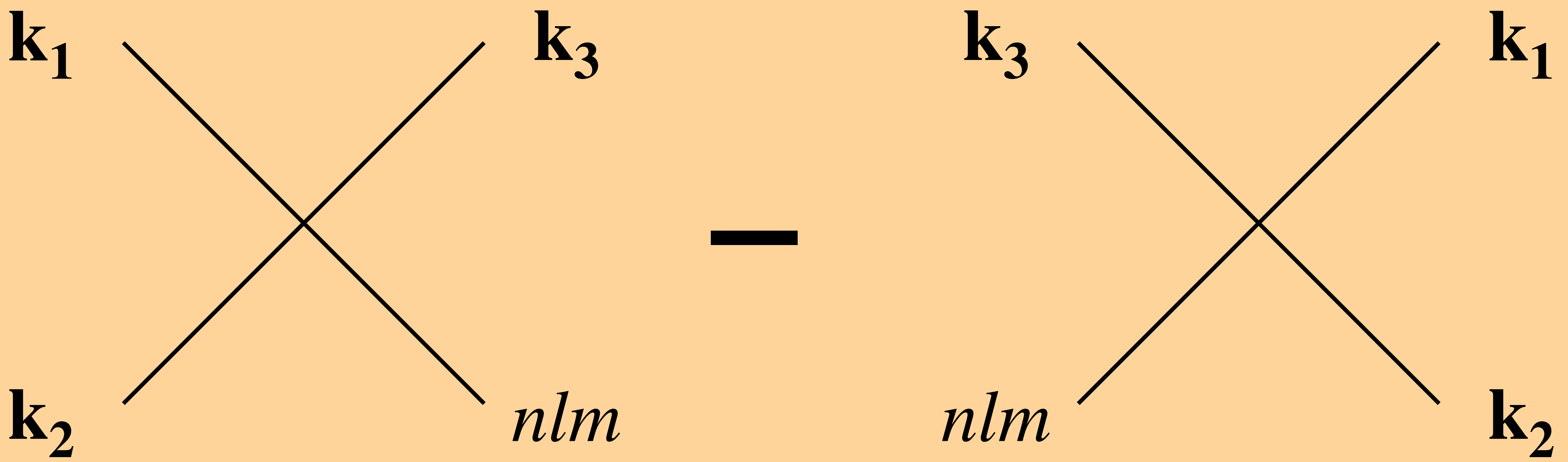
matrix element

$$\mathcal{M}_{nlm} \equiv \int \psi_{k_1}\psi_{k_2}\psi^*_{k_3}\psi^*_{nlm}\, d^3x$$

$$\frac{dM_\star}{dt} = m_\phi \sum_{nlm} \frac{dN_{nlm}}{dt} = \sum_{nlm} \frac{\pi\lambda^2}{16 m_\phi^3} \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\,\delta(\Delta\omega)\left|\mathcal{M}_{nlm}\right|^2$$

$$\times \Big[n(k_1)n(k_2)\big(n(k_3)+1\big)\big(N_{nlm}+1\big) - n(k_3)N_{nlm}\big(n(k_1)+1\big)\big(n(k_2)+1\big)\Big] + \mathcal{O}(N_{nlm}^2)$$

Boltzmann factors for the scattering rate



Excited states

$$\simeq \sum_{nlm} \frac{\pi\lambda^2}{16 m_\phi^3} \int \frac{d^3k_1}{(2\pi)^3}\frac{d^3k_2}{(2\pi)^3}\frac{d^3k_3}{(2\pi)^3}\,\delta(\Delta\omega)\left|\mathcal{M}_{nlm}\right|^2 \Big[n(k_1)n(k_2)n(k_3) + N_{nlm}\big(n(k_1)n(k_2) - 2n(k_2)n(k_3)\big)\Big]$$

simplify:

$nlm \to 100$

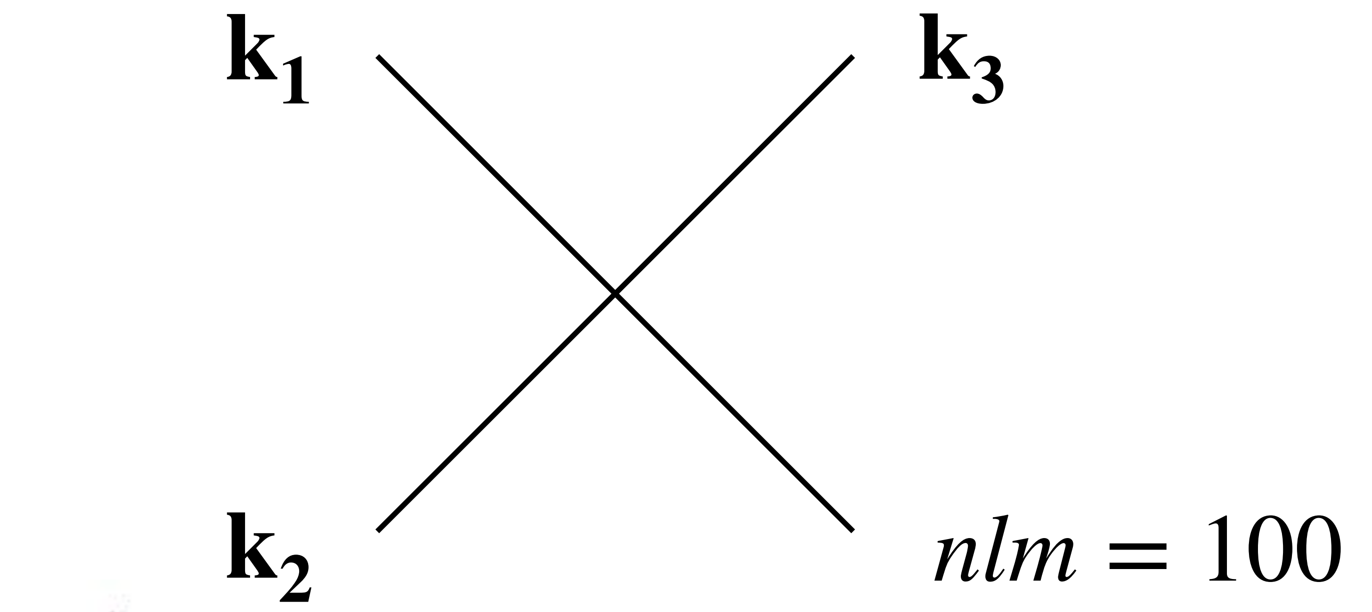
$N_{nlm} \to N_{100} = M_\star/m_\phi$

$$\boxed{\frac{dM_\star}{dt} \simeq C + (\Gamma_1 - 2\Gamma_2)\,M_\star}$$

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

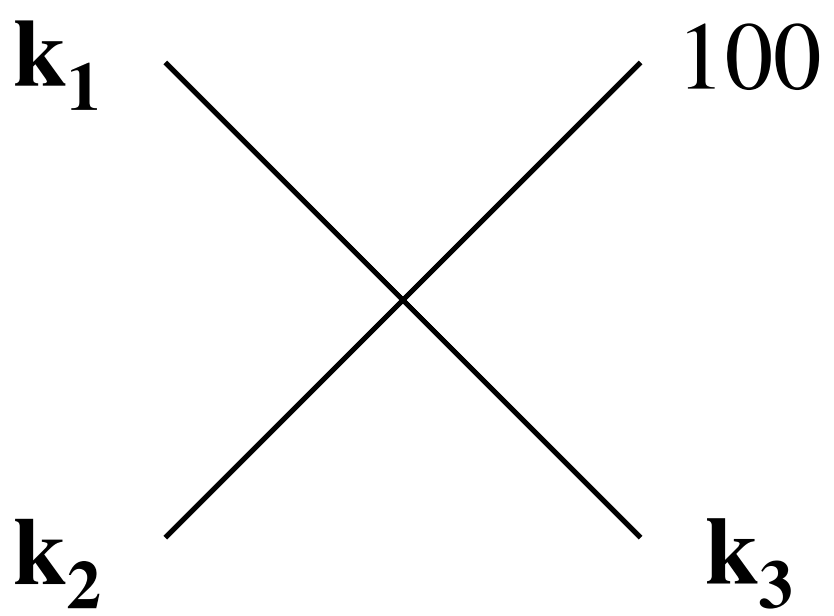
Time Evolution

Direct capture



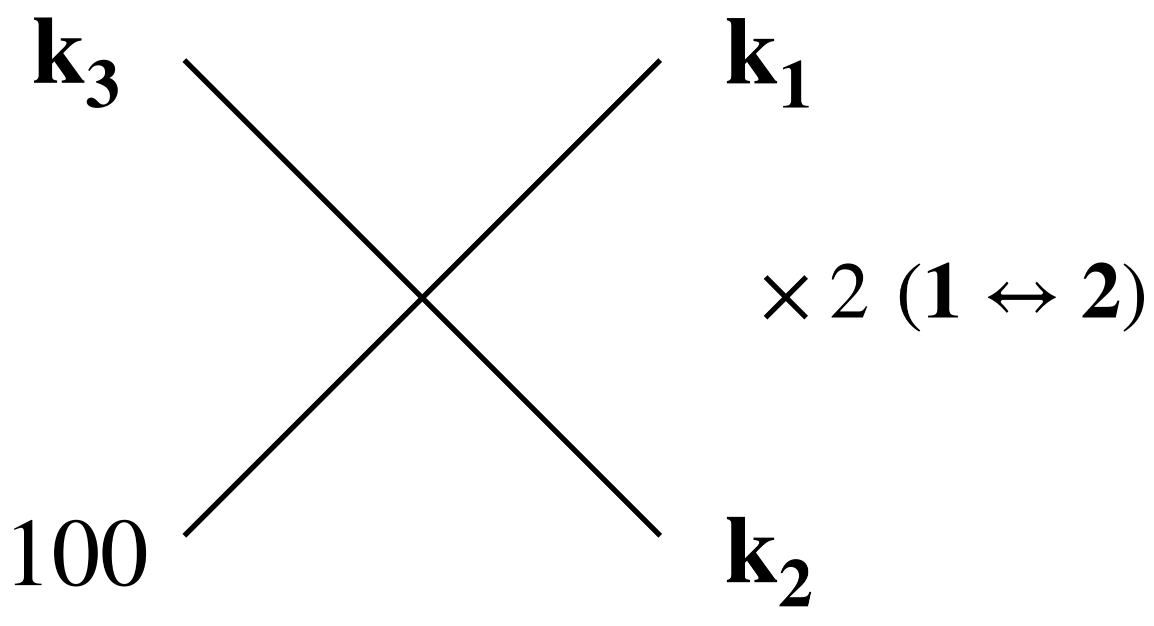
$C \propto n(k_1)n(k_2)n(k_3)$

Stimulated capture



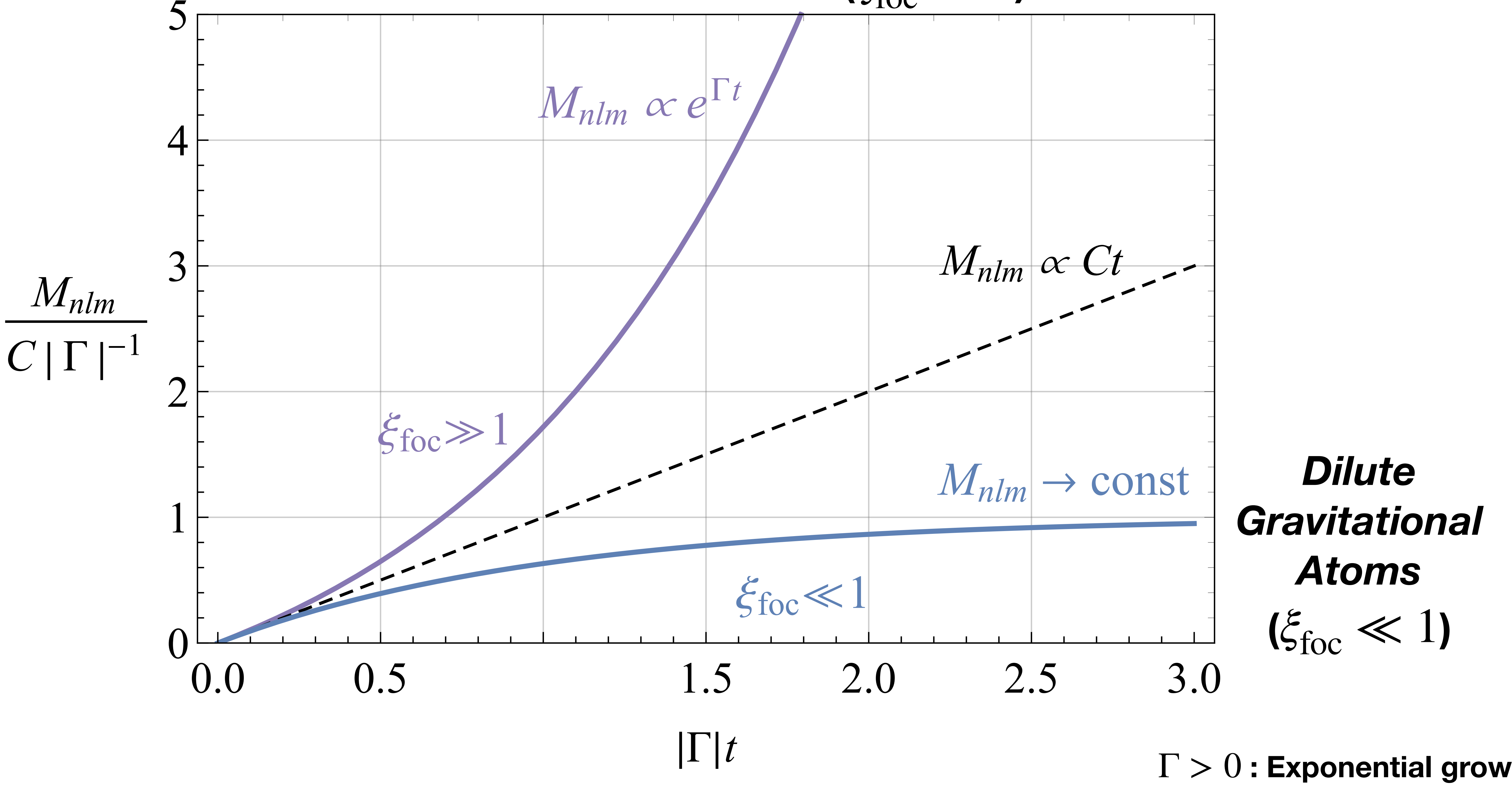
$\Gamma_1 \propto n(k_1)n(k_2)$

Ionization



$2\Gamma_2 \propto 2n(k_1)n(k_3)$

Dense Gravitational Atoms **($\xi_{\rm foc} \gg 1$)**



Dilute Gravitational Atoms **($\xi_{\rm foc} \ll 1$)**

$\Gamma > 0$ **: Exponential growth**
$\Gamma < 0$ **: Saturation**
determines late-time behavior

$$\frac{dM_\star}{dt} \simeq C + \overbrace{(\Gamma_1 - 2\Gamma_2)}^{\Gamma} M_\star$$

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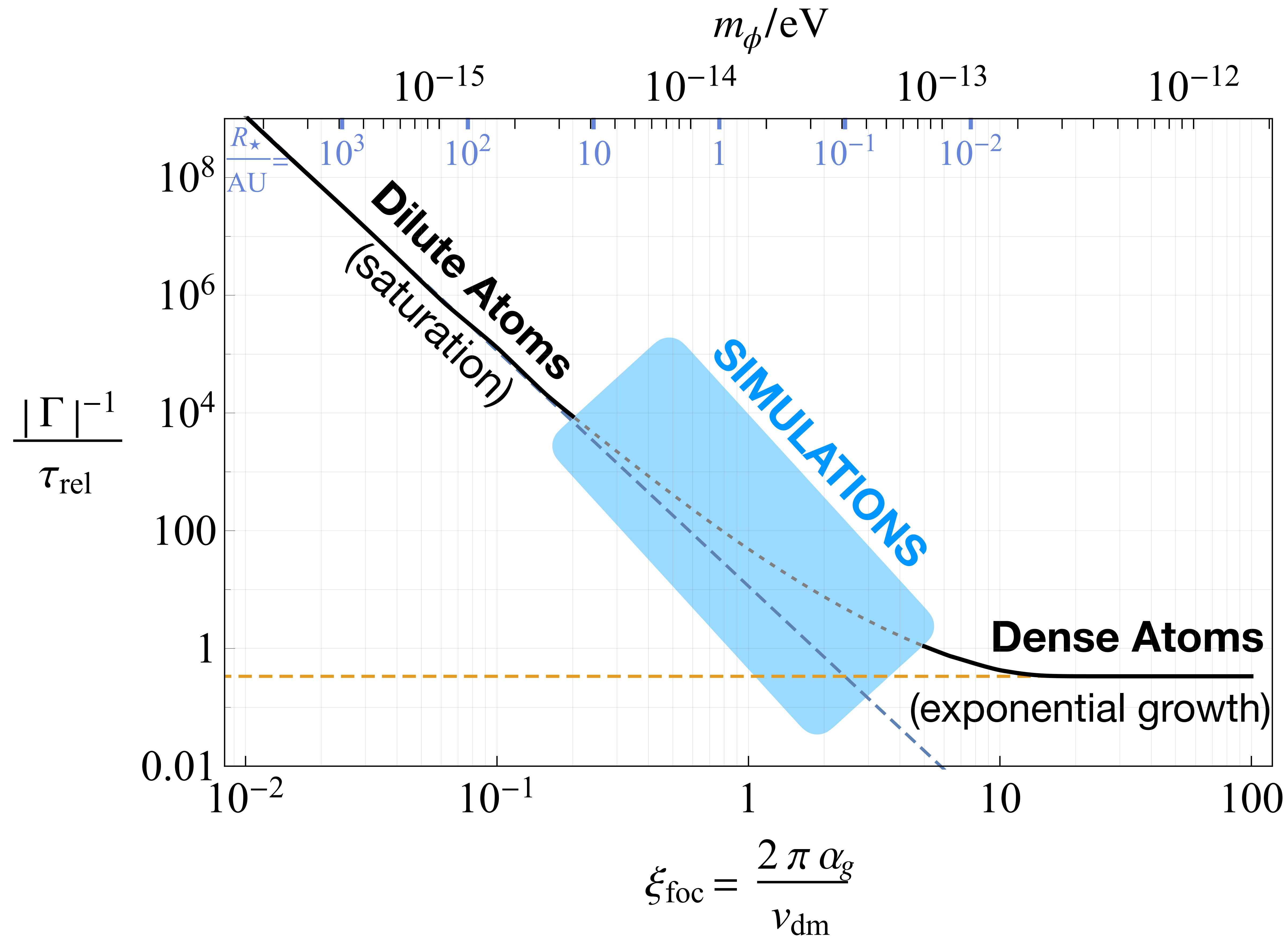
Relaxation Timescale

$$\tau_{\rm rel} \equiv \frac{64 m_\phi^7 v_{\rm dm}^2}{\lambda^2 \rho_{\rm dm}^2} = \frac{64 m_\phi^3 f_a^4 v_{\rm dm}^2}{\rho_{\rm dm}^2} \simeq 9\,{\rm Gyr}\left(\frac{f_a}{10^8\,{\rm GeV}}\right)^4 \left(\frac{m_\phi}{10^{-14}\,{\rm eV}}\right)^3 \left(\frac{0.4\,{\rm GeV/cm^3}}{\rho_{\rm dm}}\right)^2 \left(\frac{v_{\rm dm}}{240\,{\rm km/sec}}\right)^2$$

For axions,

$$\lambda = -\frac{m_\phi^2}{f_a^2}$$



Low decay constant f_a required for astrophysical timescale

Kinetic misalignment, Non-periodic potentials, etc.

See G. Servant lectures (Monday)

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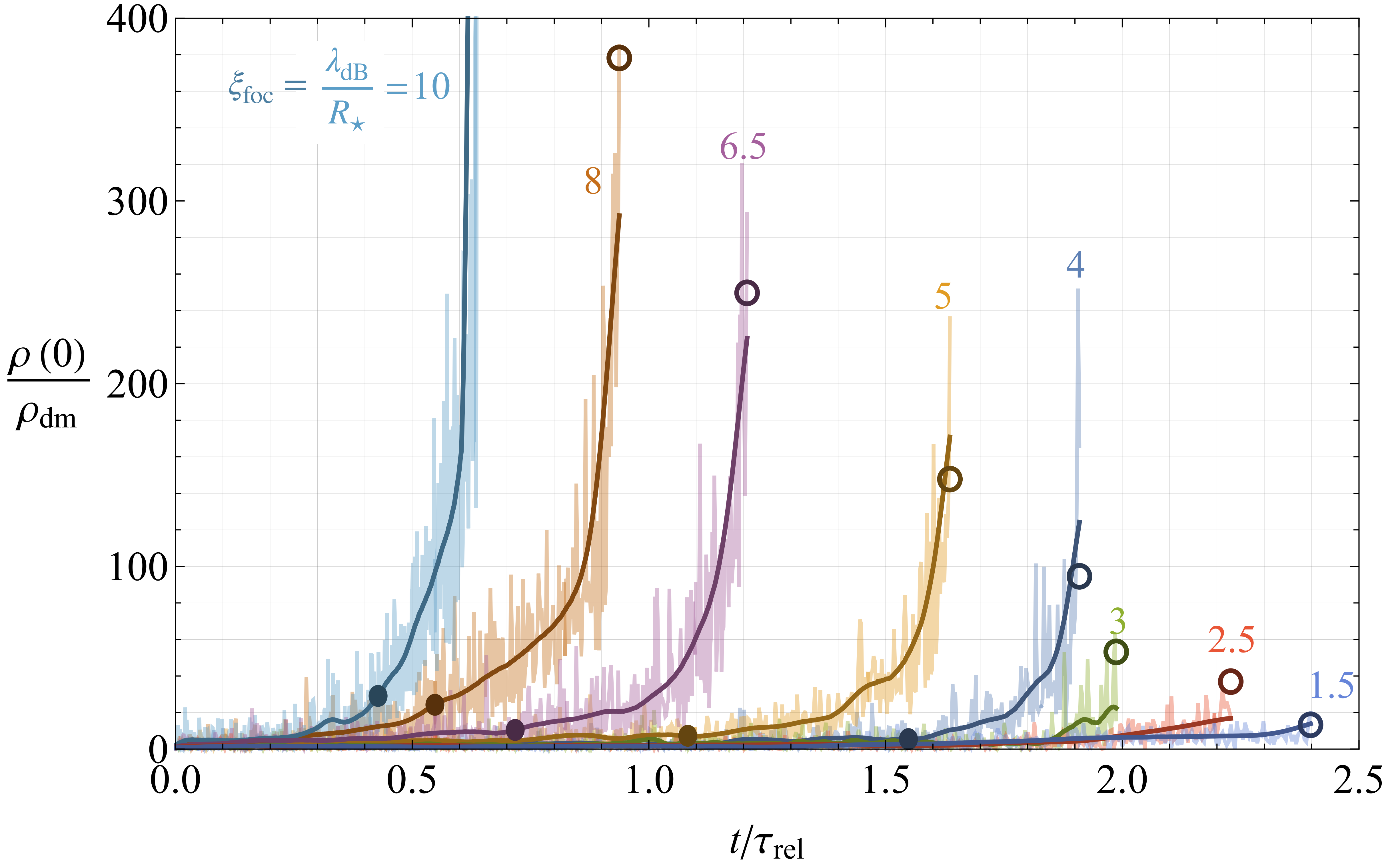
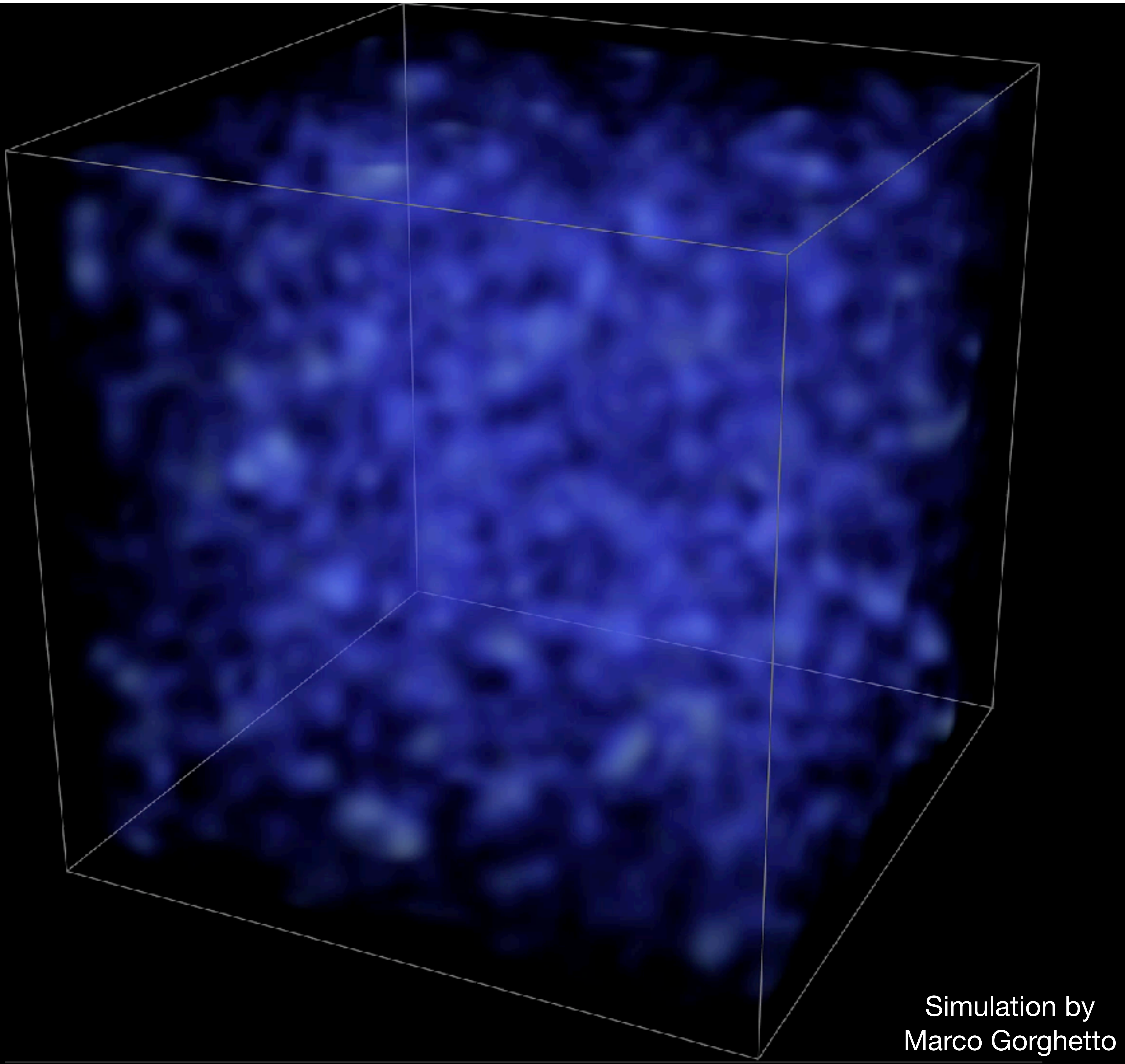
Numerical Simulations

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r} + \frac{\lambda}{8m_\phi^2}|\psi|^2\right]\psi$$





Simulation by Marco Gorghetto

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

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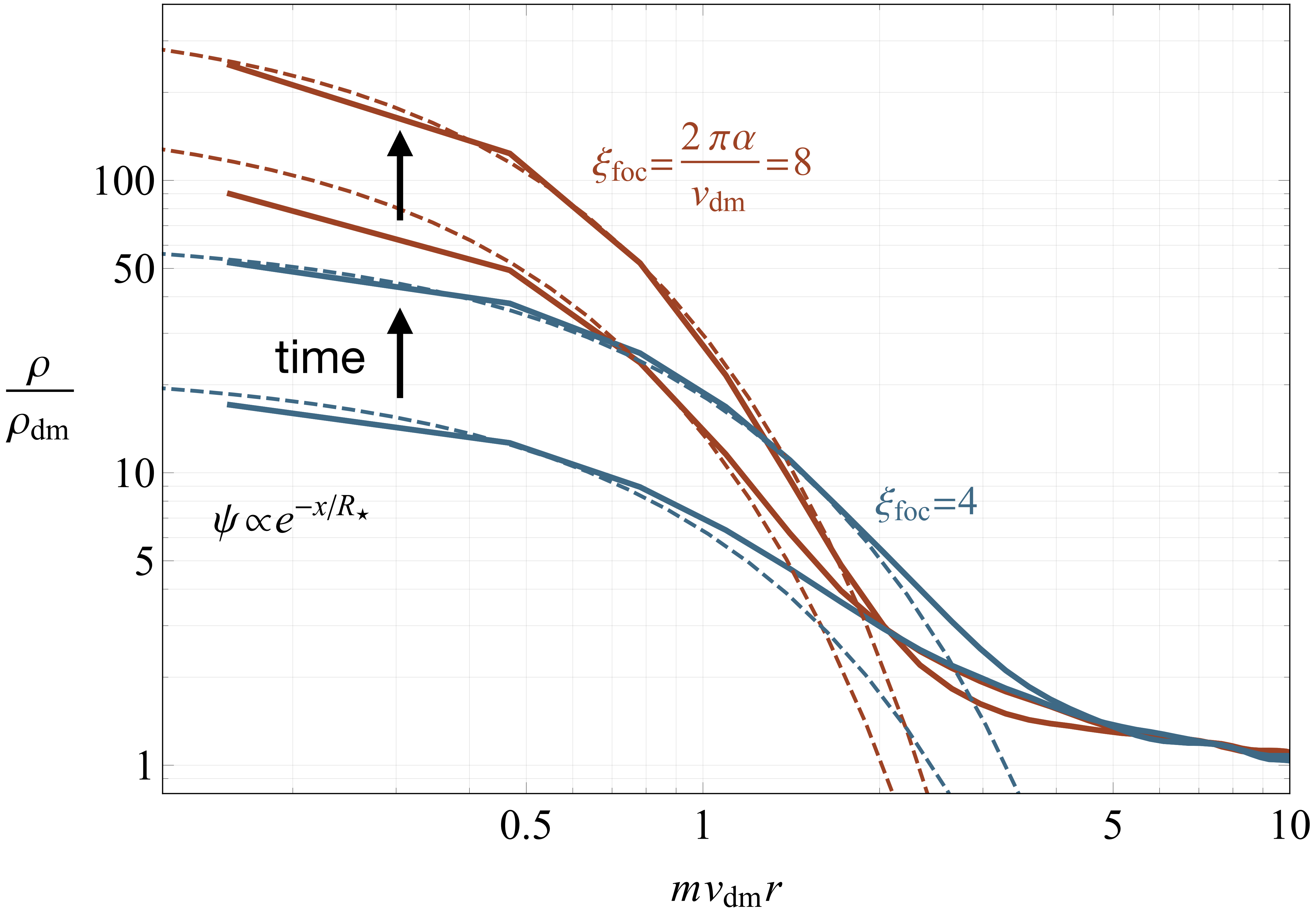
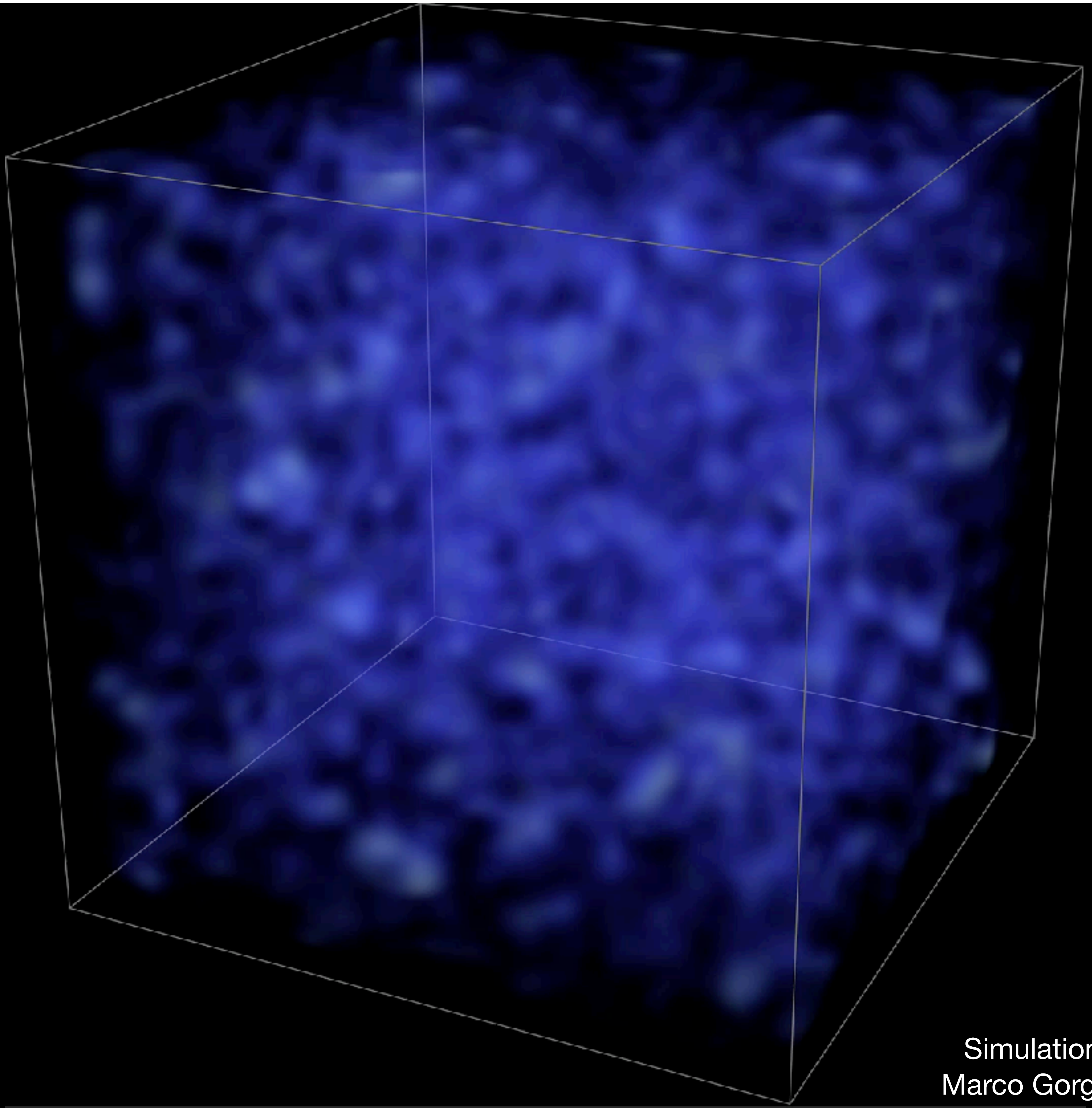




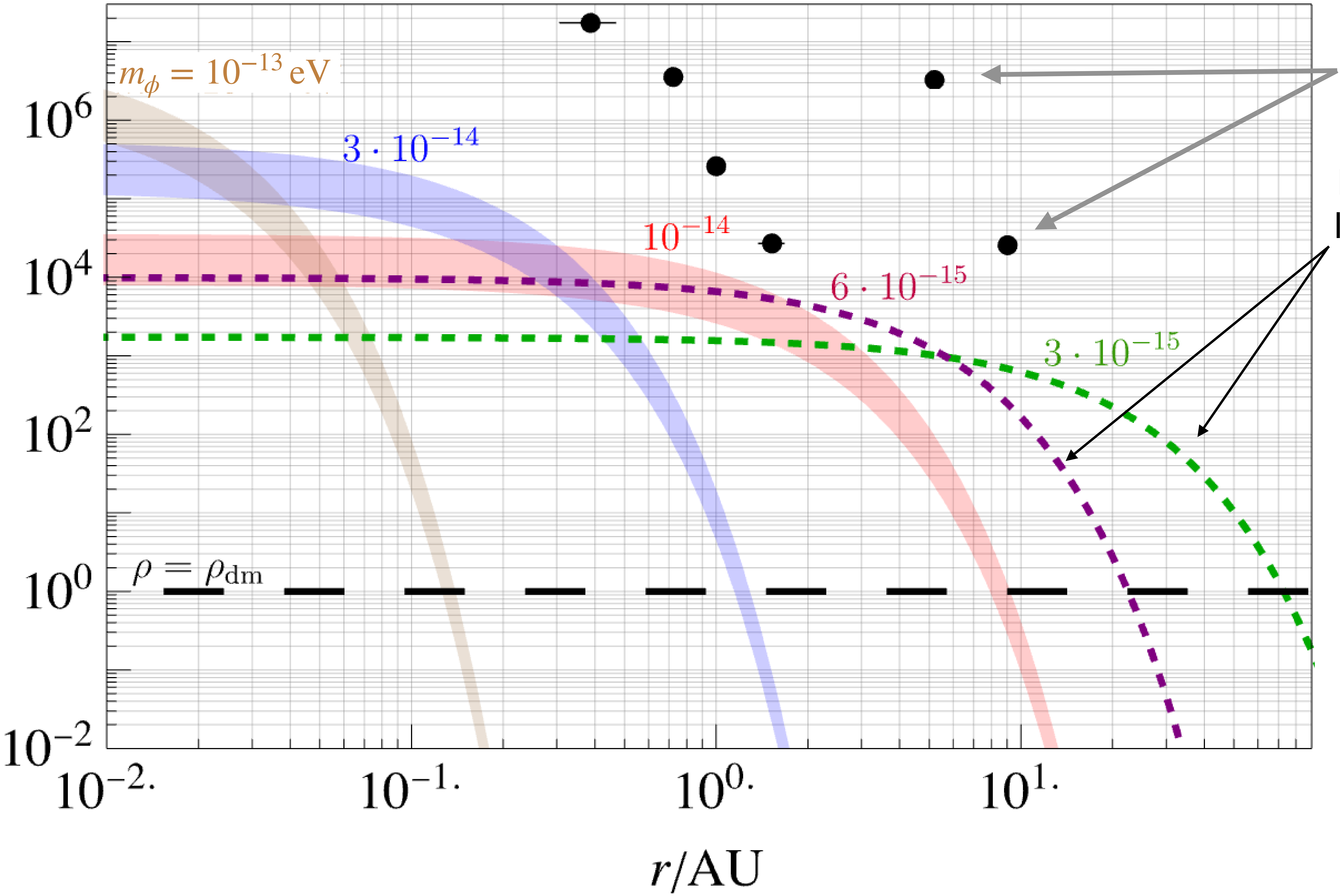
Simulation by
Marco Gorghetto

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Solar Halo Density

Large modifications to the **very local density** from axions captured over **5Gyr (solar lifetime)**

(i.e. in our solar system)



Direct constraints: See H. Kim talk (Wednesday)

Exponentially-growing in low-velocity environment $v_{\rm dm} \ll 200\,\mathrm{km/s}$

for axion decay constant

$f_a \simeq 10^7 - 10^8\,\mathrm{GeV}$

assuming $\lambda < 0$;
density could be larger for $\lambda > 0$

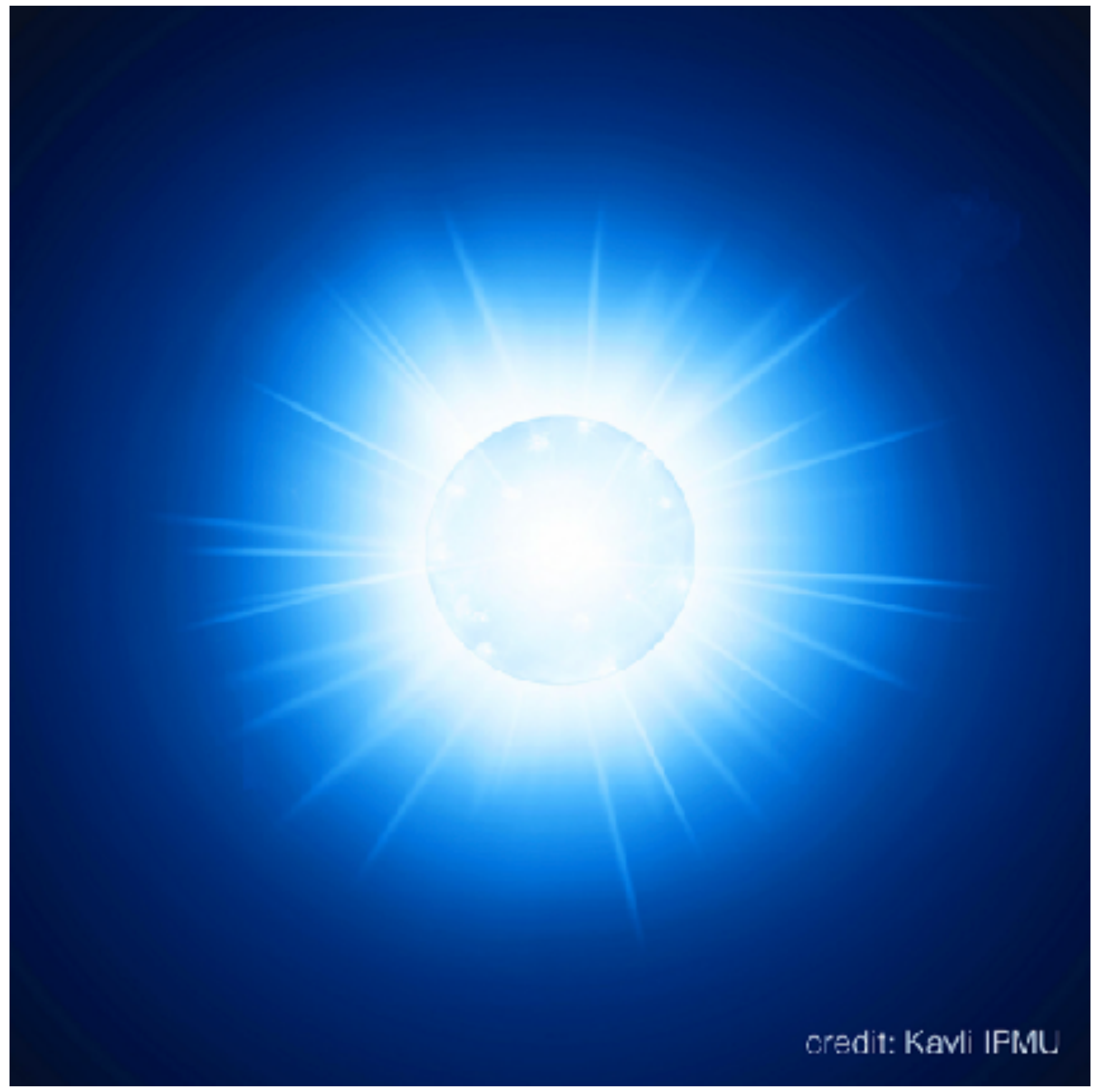
Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Fate of Gravitational Atoms

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r} + \frac{\lambda}{8m_\phi^2}|\psi|^2\right]\psi$$

Density grows $\Longleftrightarrow$ Self-interaction term grows

until $\frac{\alpha_g}{R_\star} \simeq \frac{|\lambda|}{8m_\phi^3}\rho$



Attractive self-interaction
$\lambda < 0$

Collapse! when

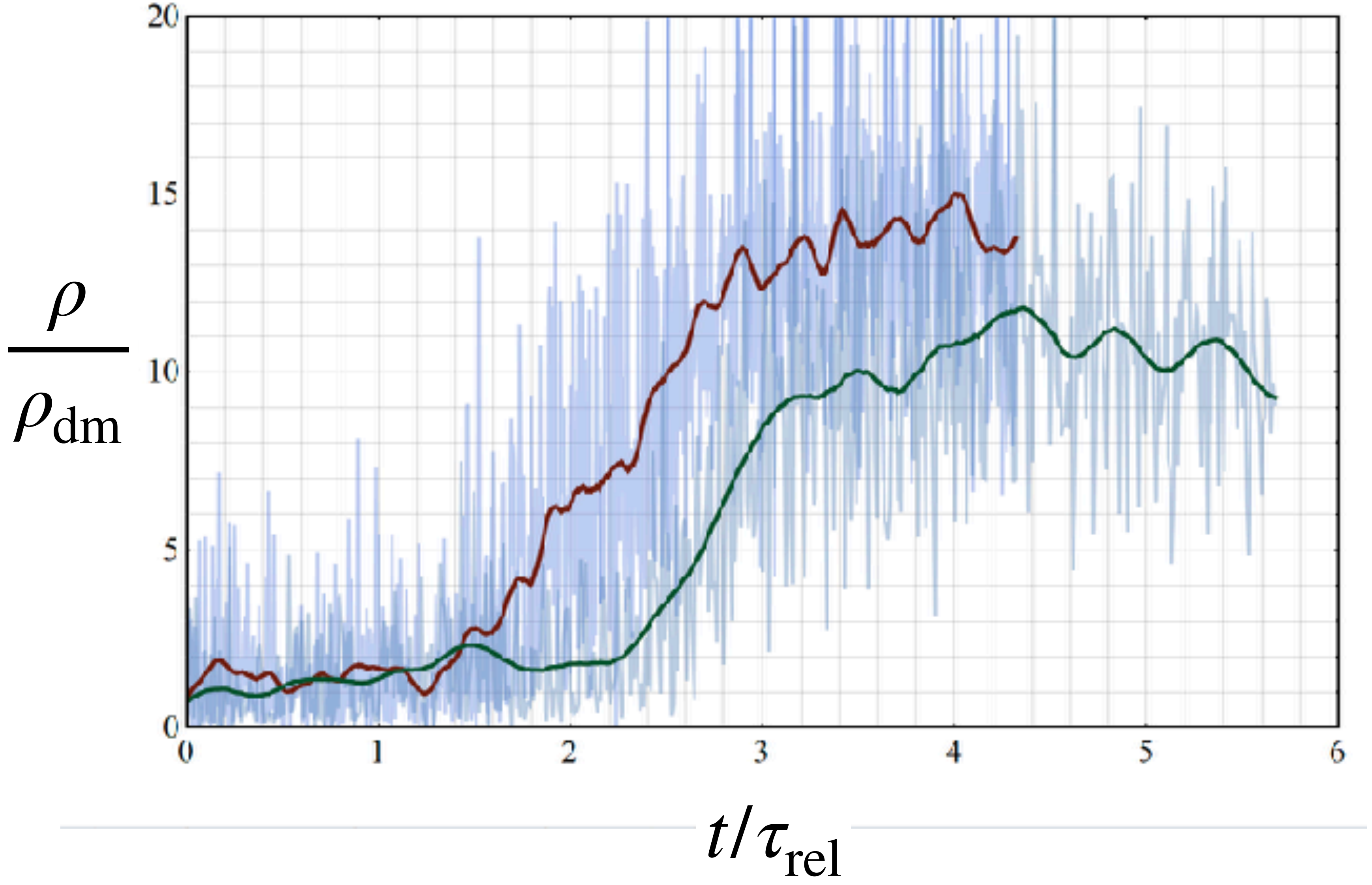
$$\rho = \rho_{\rm crit} \sim \frac{\alpha_g^2 m_\phi^4}{|\lambda|}$$

$\Longrightarrow$ **Bosenova emission of relativistic ULDM particles**

Ongoing work!

Repulsive self-interaction
$\lambda > 0$

Stable! Density saturates to large value

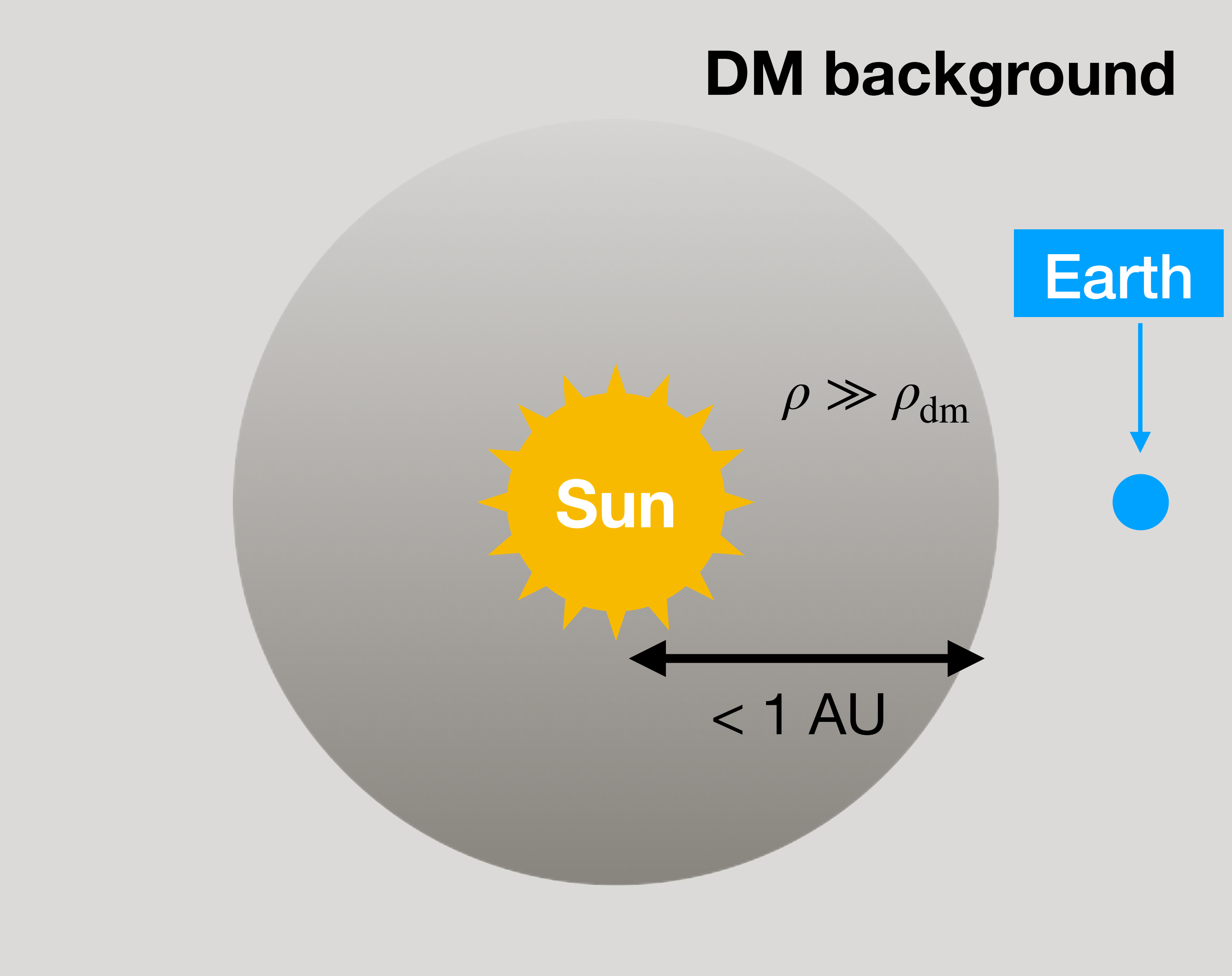


Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Density over Time

assuming $\lambda < 0$;
density could be larger for $\lambda > 0$

Phenomenology of Solar / Stellar Halos



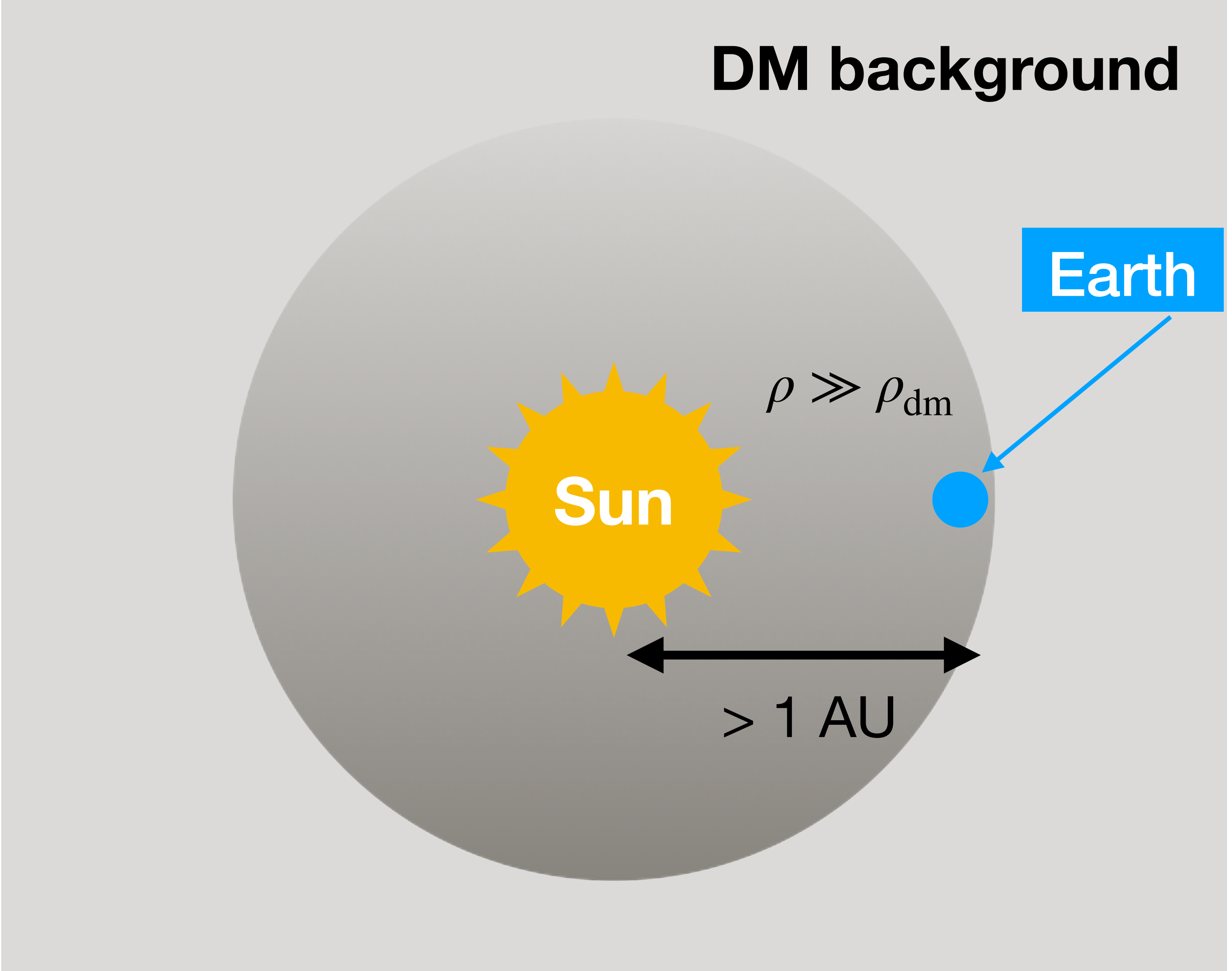
$m_\phi \simeq 10^{-14} - 2 \cdot 10^{-13}\,\mathrm{eV}$

Probes in Space

Tsai, **JE**, Safronova (2112.07674)
+ Arakawa, Farnocchia (2210.03749)

Signals from the Sun

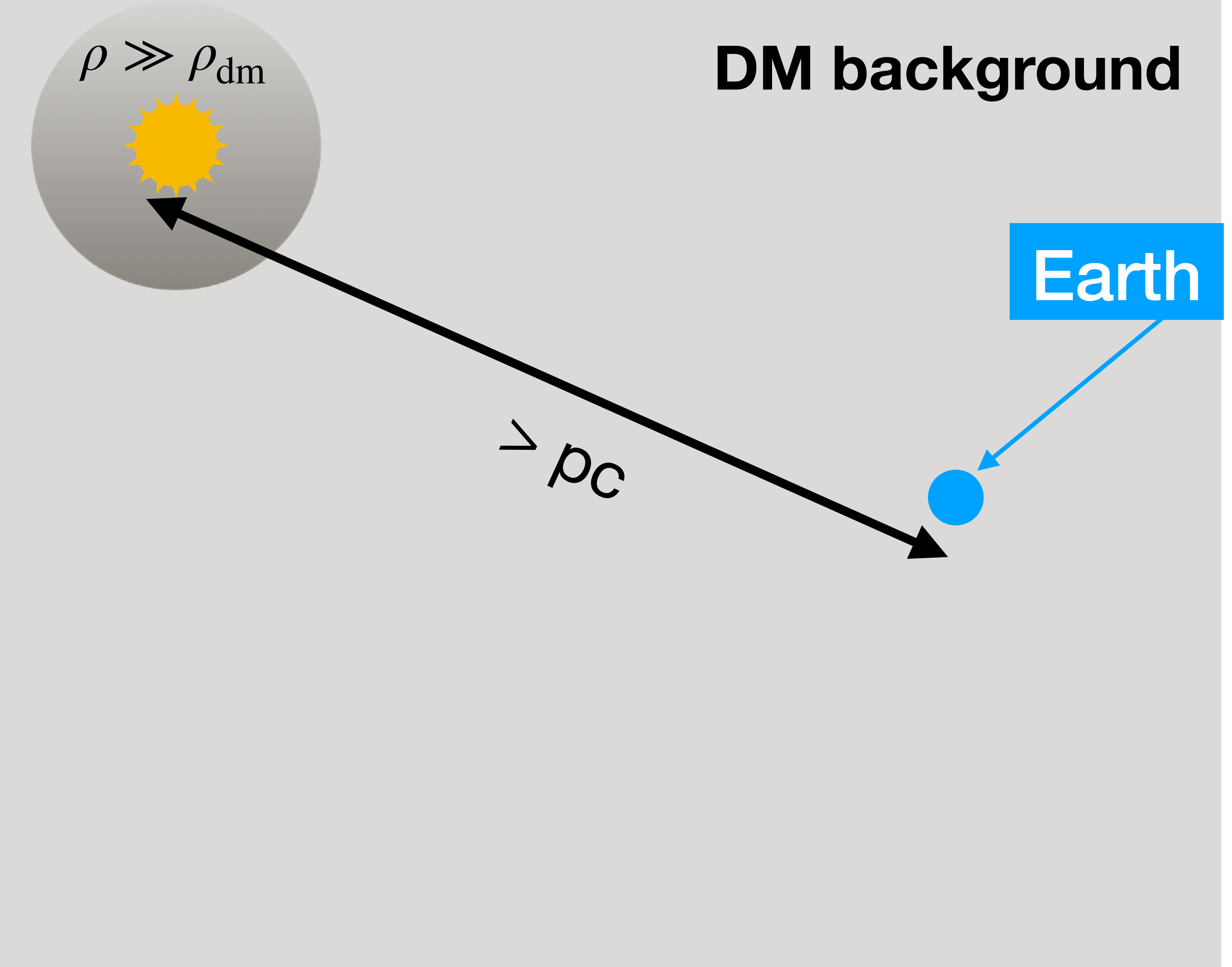
Ongoing work!



$m_\phi \sim 10^{-15} - 3 \cdot 10^{-14}\,\mathrm{eV}$

Probes on Earth

Banerjee, Budker, **JE**, Kim, Perez (1902.08212)
+ Flambaum, Matsedonskyi (1912.04295)



$m_\phi \simeq 10^{-16} - 10^{-12}\,\mathrm{eV}$

(supergiants to neutron stars)

Astrophysical signals

Ongoing work!

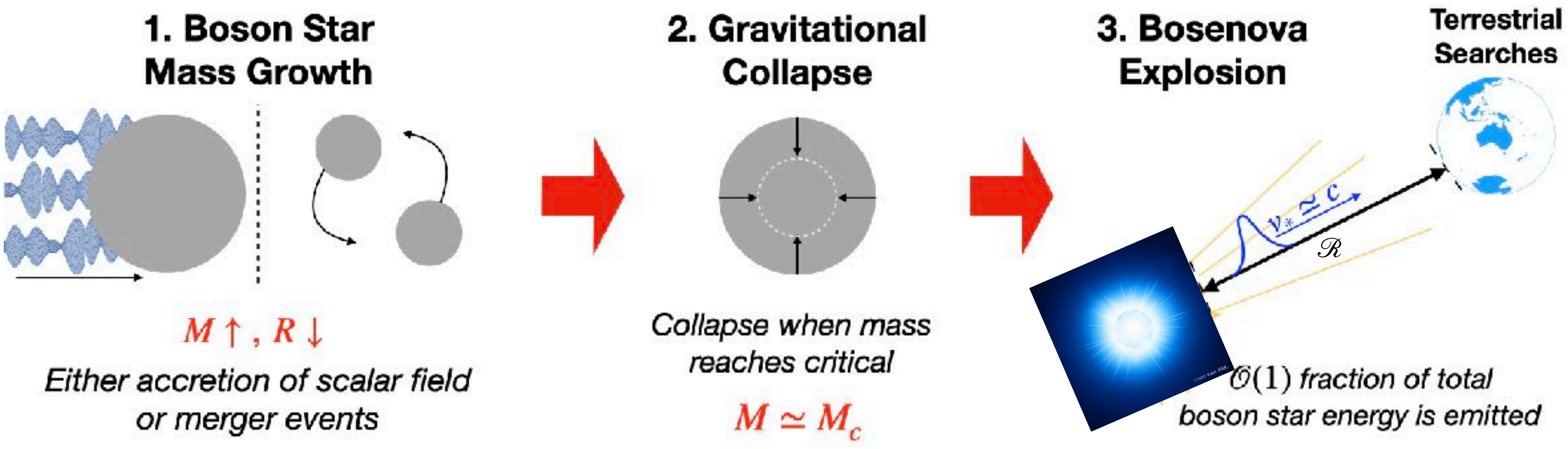
Bosenova signals

Ongoing work!

though see **JE**, Shirai, Stadnik, Takhistov (2106.14893)

Probes using Bosenovae

Widely-studied for bosenovae originating in axion star collapse



Transient Signals

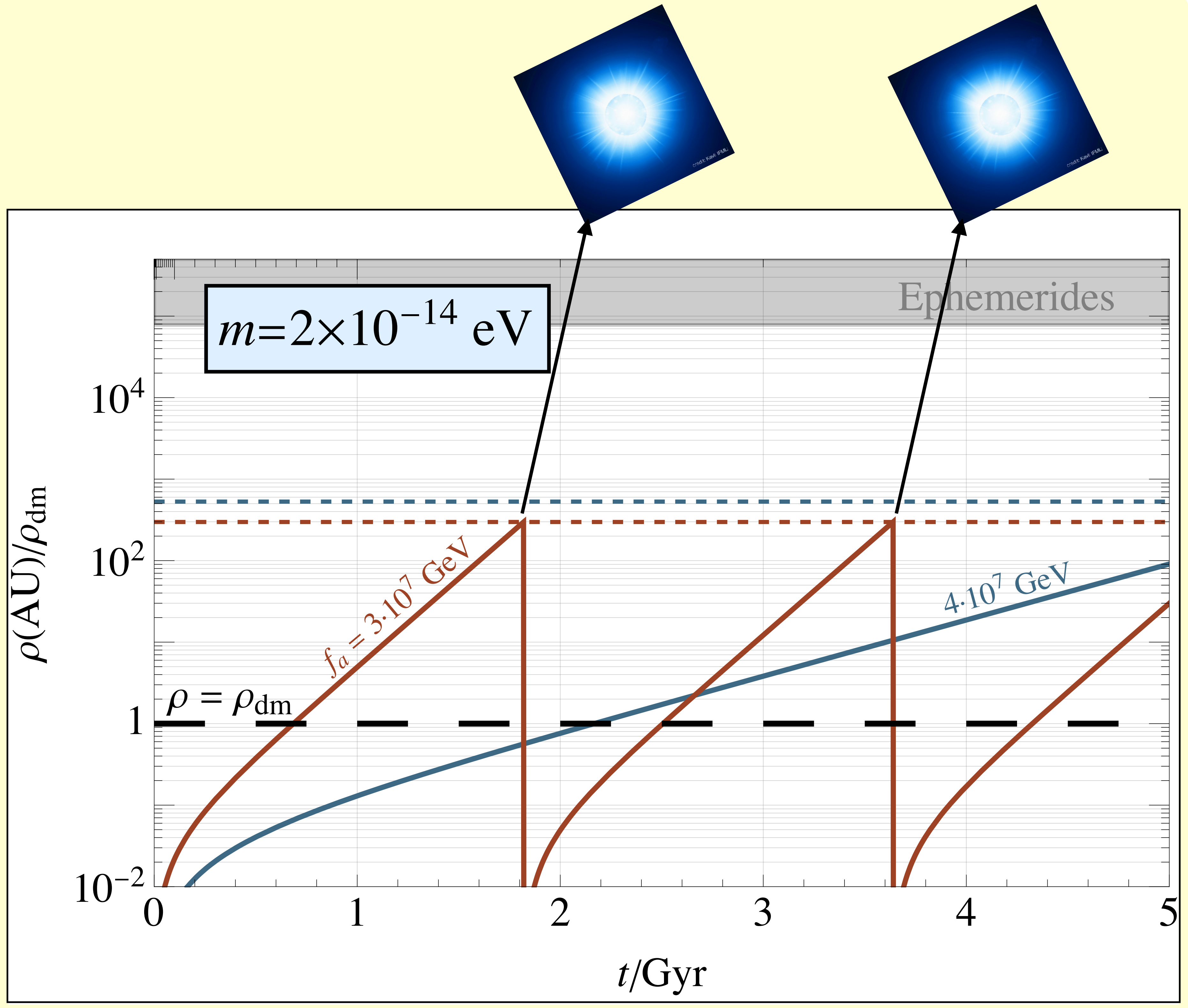
JE, Shirai, Stadnik, Takhistov (2106.14893)

Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468, 2402.06736)

Diffuse Axion Background

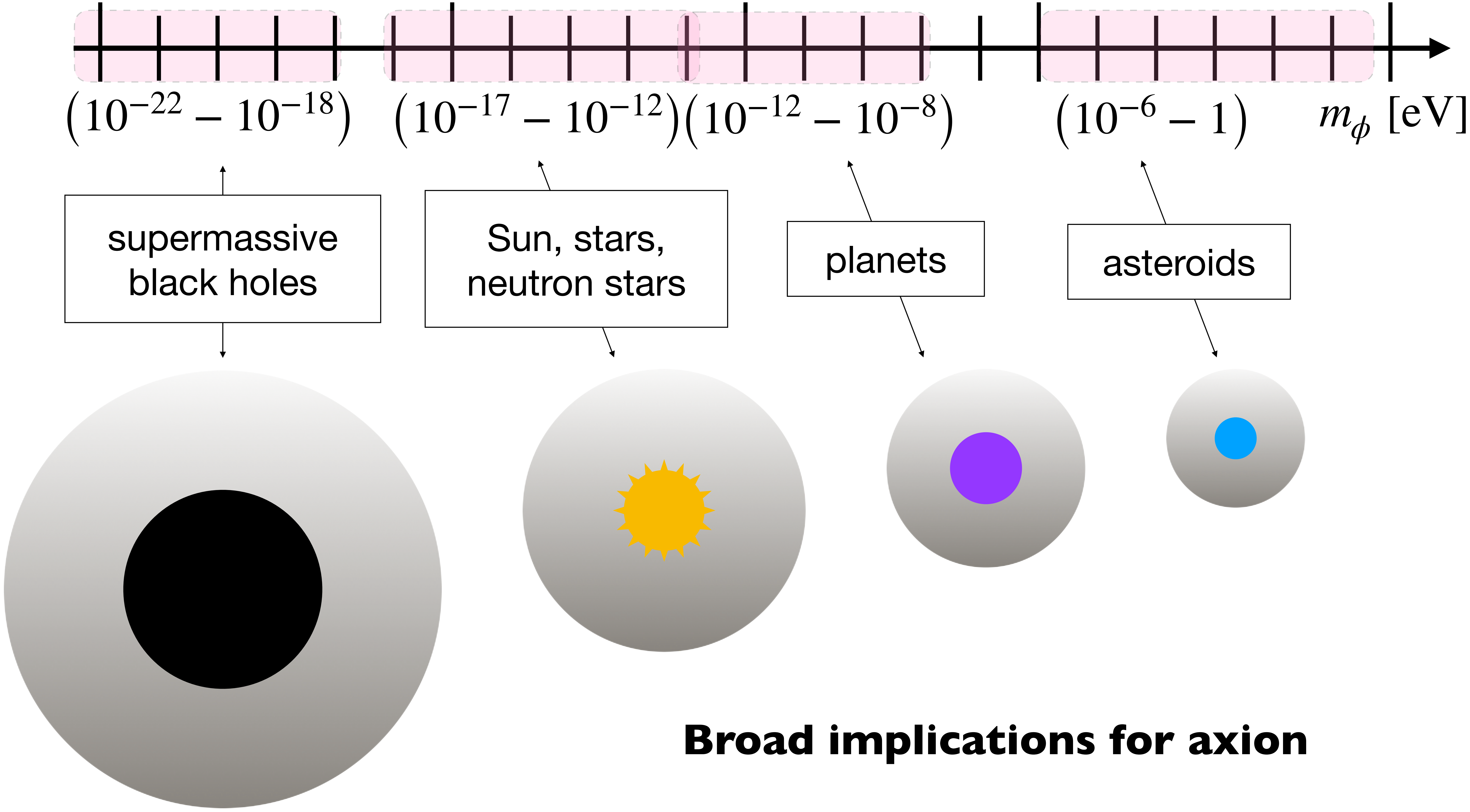
JE, Takhistov (2402.00100)

What about solar halo collapse?



Multiple, repeating bosenovae on stars all over the galaxy!

Gravitational Atoms Everywhere!



$(10^{-22} - 10^{-18})$ $(10^{-17} - 10^{-12})$ $(10^{-12} - 10^{-8})$ $(10^{-6} - 1)$ m_ϕ [eV]

supermassive black holes

Sun, stars, neutron stars

planets

asteroids

Broad implications for axion physics across model space!

Conclusions

Axions / ULDM captured gravitationally to astrophysical objects (e.g. the Sun), forming a gravitational atom

Complementary to superradiance: occurs in very different astrophysical environments

Formation occurs through 2→2 scattering; generic mechanism easily implies gravitational atoms elsewhere

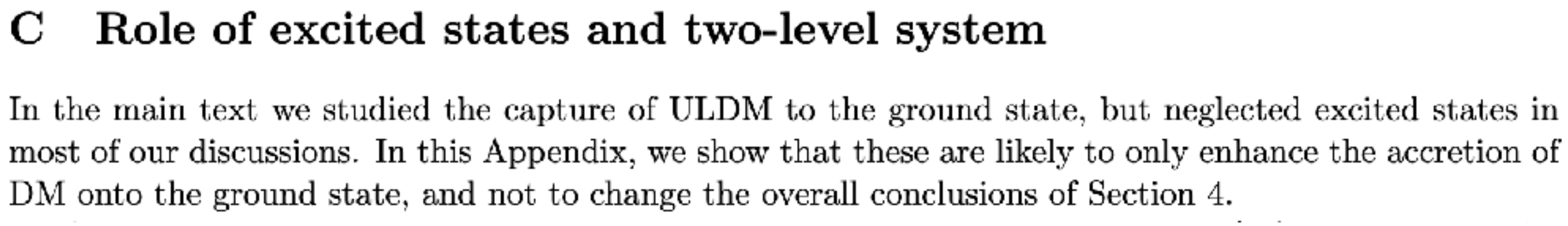
When it forms, a ***solar halo*** gives rise to striking new targets for experiment:

- ◉ On Earth: enhanced density and coherence time for $m_\phi \sim \text{few} \cdot 10^{-15} - \text{few} \cdot 10^{-14}\,\text{eV}$
- ◉ Future space missions can probe small, dense solar halos for $m_\phi \sim 10^{-13} - 10^{-14}\,\text{eV}$
- ◉ Astrophysical signals in other star systems: wider range of m_ϕ

Thank you for your attention!

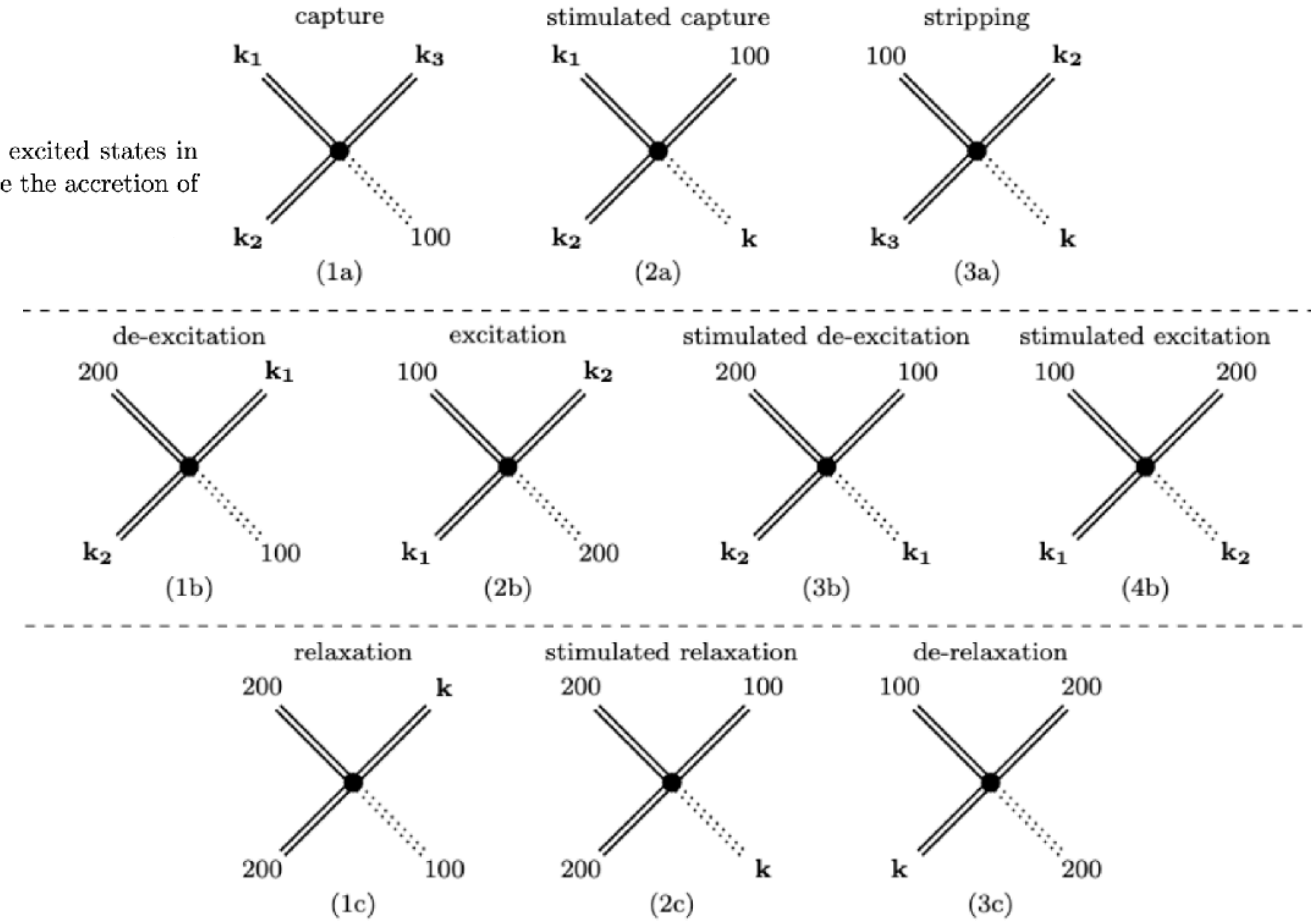
Bonus Round

“What about the Excited States?”



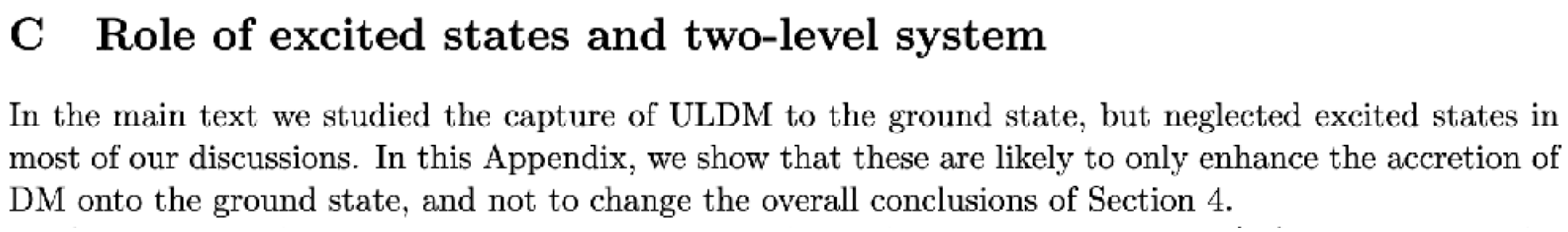
C Role of excited states and two-level system

In the main text we studied the capture of ULDM to the ground state, but neglected excited states in most of our discussions. In this Appendix, we show that these are likely to only enhance the accretion of DM onto the ground state, and not to change the overall conclusions of Section 4.



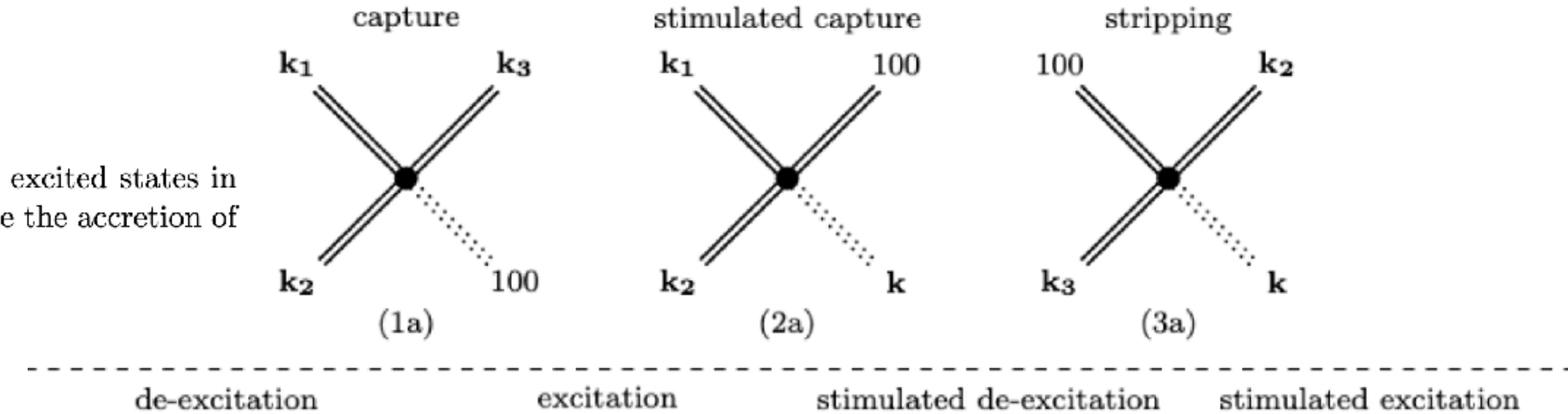
2-level system:
$nlm = 100, 200$

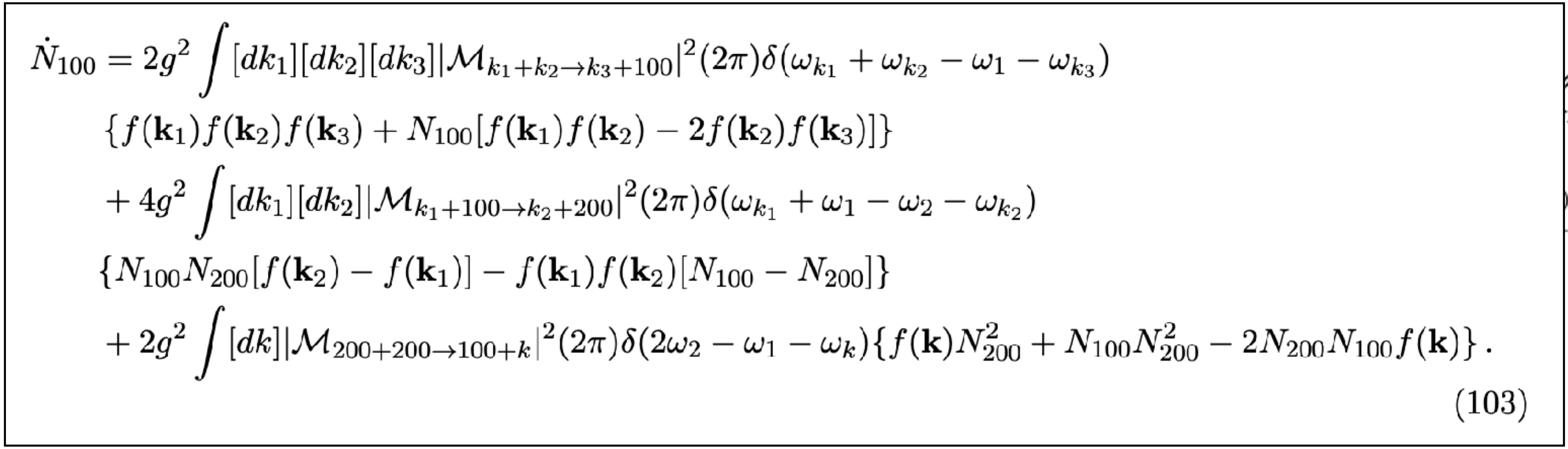
“What about the Excited States?” (2)



C Role of excited states and two-level system

In the main text we studied the capture of ULDM to the ground state, but neglected excited states in most of our discussions. In this Appendix, we show that these are likely to only enhance the accretion of DM onto the ground state, and not to change the overall conclusions of Section 4.

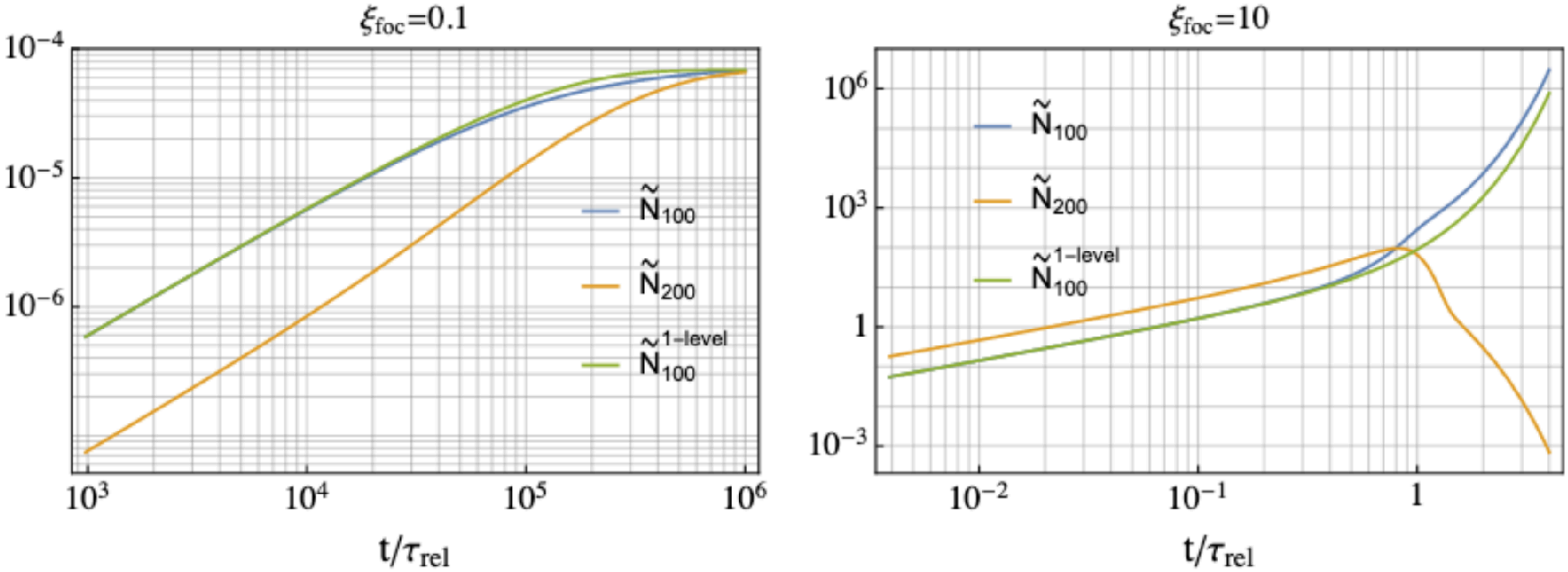




$$\dot{N}_{100} = 2g^2 \int [dk_1][dk_2][dk_3]|\mathcal{M}_{k_1+k_2\to k_3+100}|^2(2\pi)\delta(\omega_{k_1}+\omega_{k_2}-\omega_1-\omega_{k_3})$$
$$\{f(\mathbf{k}_1)f(\mathbf{k}_2)f(\mathbf{k}_3) + N_{100}[f(\mathbf{k}_1)f(\mathbf{k}_2) - 2f(\mathbf{k}_2)f(\mathbf{k}_3)]\}$$
$$+ 4g^2 \int [dk_1][dk_2]|\mathcal{M}_{k_1+100\to k_2+200}|^2(2\pi)\delta(\omega_{k_1}+\omega_1-\omega_2-\omega_{k_2})$$
$$\{N_{100}N_{200}[f(\mathbf{k}_2) - f(\mathbf{k}_1)] - f(\mathbf{k}_1)f(\mathbf{k}_2)[N_{100} - N_{200}]\}$$
$$+ 2g^2 \int [dk]|\mathcal{M}_{200+200\to 100+k}|^2(2\pi)\delta(2\omega_2-\omega_1-\omega_k)\{f(\mathbf{k})N_{200}^2 + N_{100}N_{200}^2 - 2N_{200}N_{100}f(\mathbf{k})\}\,. \quad (103)$$

2-level system:
$nlm = 100, 200$

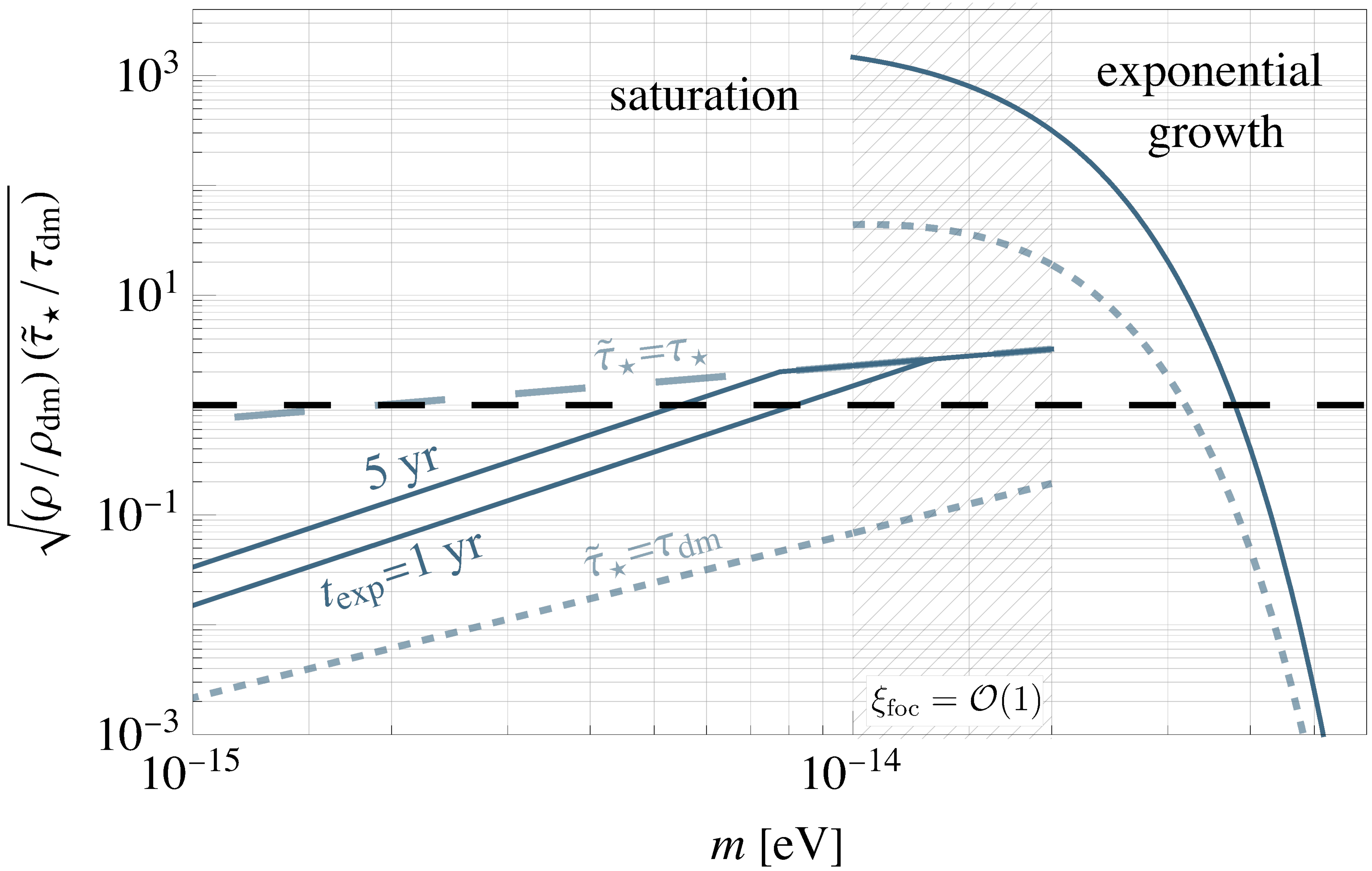
"What about the Excited States?" (3)



“What about the Dilute Atoms?”

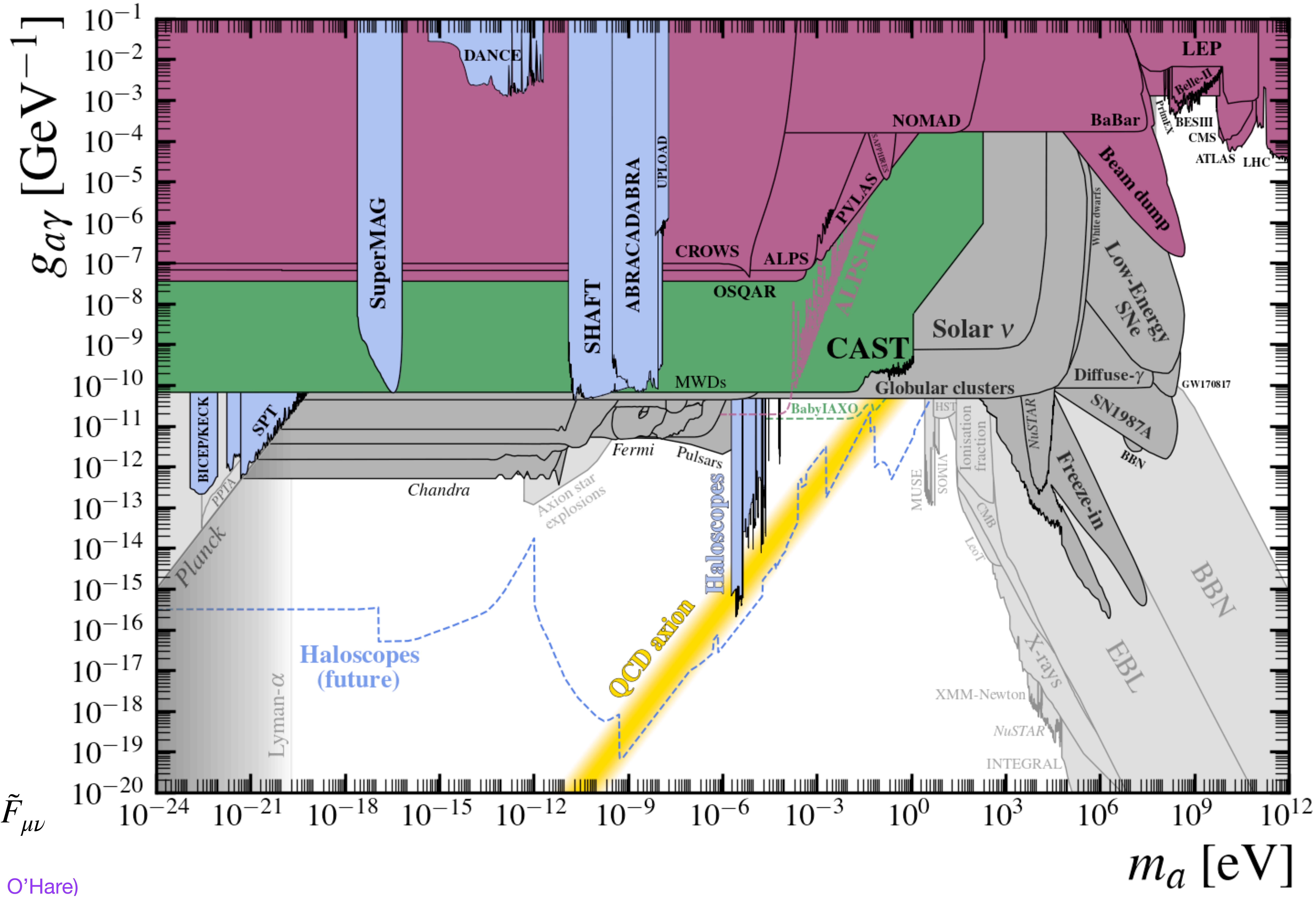
Signal in direct search typically grows as $\propto \sqrt{\rho t}$ as long as

$$t \lesssim \tau_\star \simeq \frac{2\pi}{m_\phi \alpha_g^2} = \left[\frac{2\pi}{\xi_{\rm foc}}\right]^2 \tau_{\rm dm} \simeq 2\,{\rm year}\left[\frac{10^{-14}\,{\rm eV}}{m_\phi}\right]^3$$



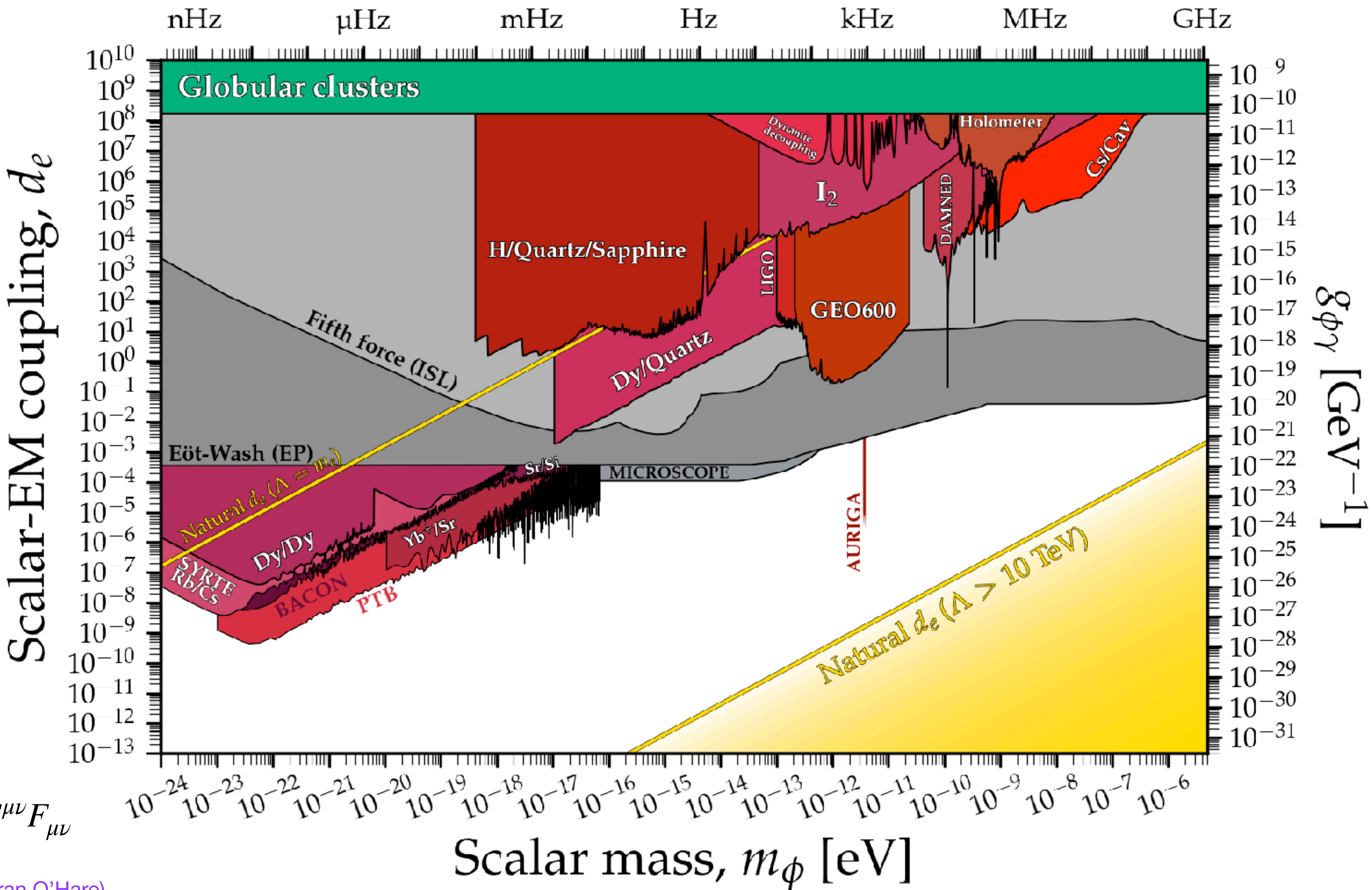
$\tilde{\tau}_\star \equiv \min(\tau_\star, t_{\rm exp})$

assuming $\lambda < 0$;
density could be larger for $\lambda > 0$



$$\mathscr{L} \supset \frac{g_{a\gamma}}{4}\phi\, F^{\mu\nu}\tilde{F}_{\mu\nu}$$

(figure credit: Ciaran O'Hare)

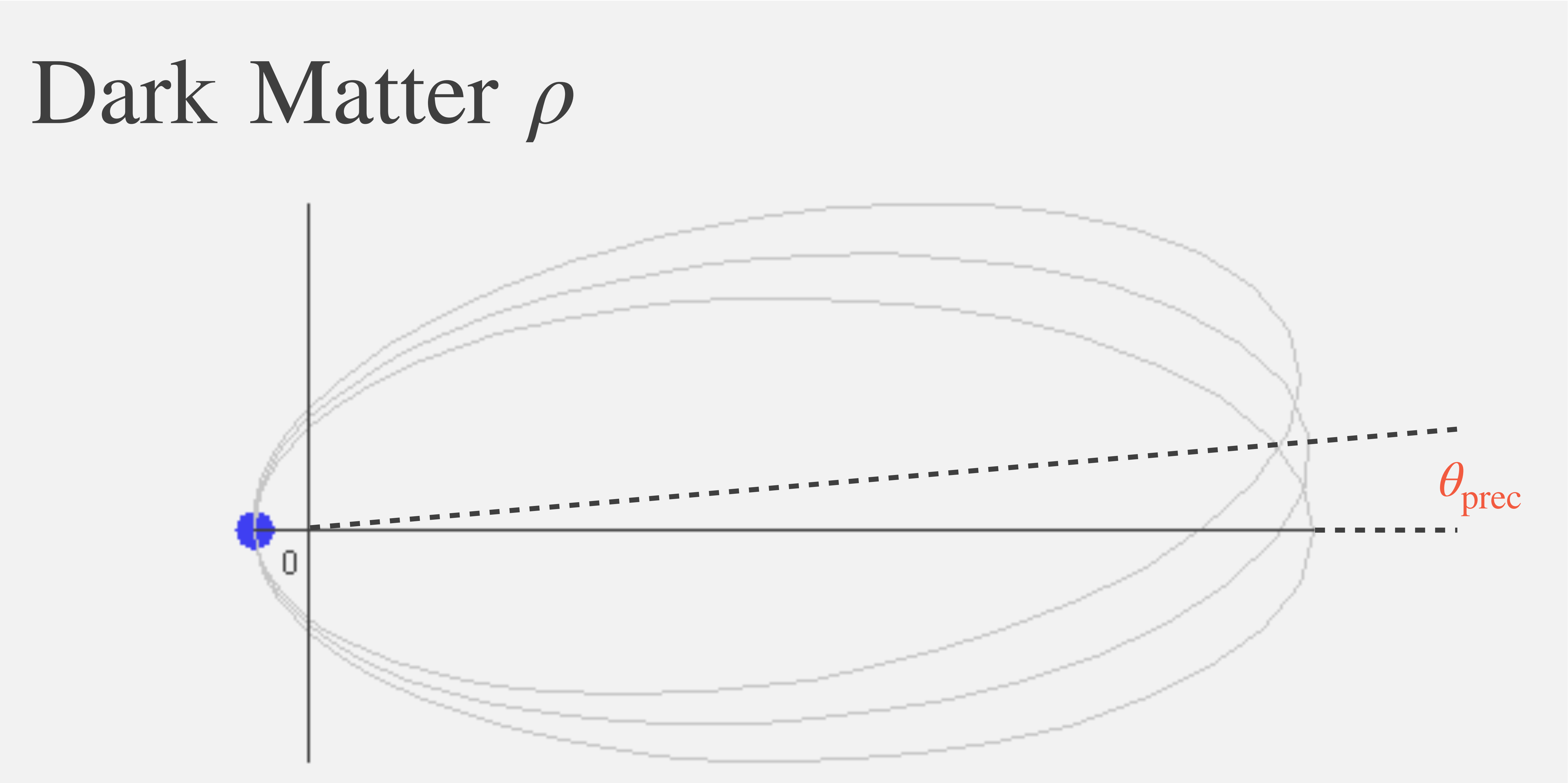


$$\mathcal{L} \supset \frac{g_{\phi\gamma}}{4} \phi F^{\mu\nu} F_{\mu\nu}$$

(figure credit: Ciaran O'Hare)

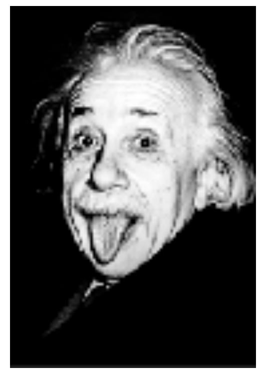
Probing the Very Local DM Density

(i.e. in our solar system)



Sources of perihelion precession:

◉ 3-body interactions	
• Jupiter, Venus, Earth	$91\,\%$
• Other planets	$1\,\%$
• Asteroids	10^{-6}
◉ Solar oblateness	$0.1\,\%$
◉ General Relativistic effects	$8\,\%$
◉ **"Extra" (*dark*) mass**	$< 10^{-7}$



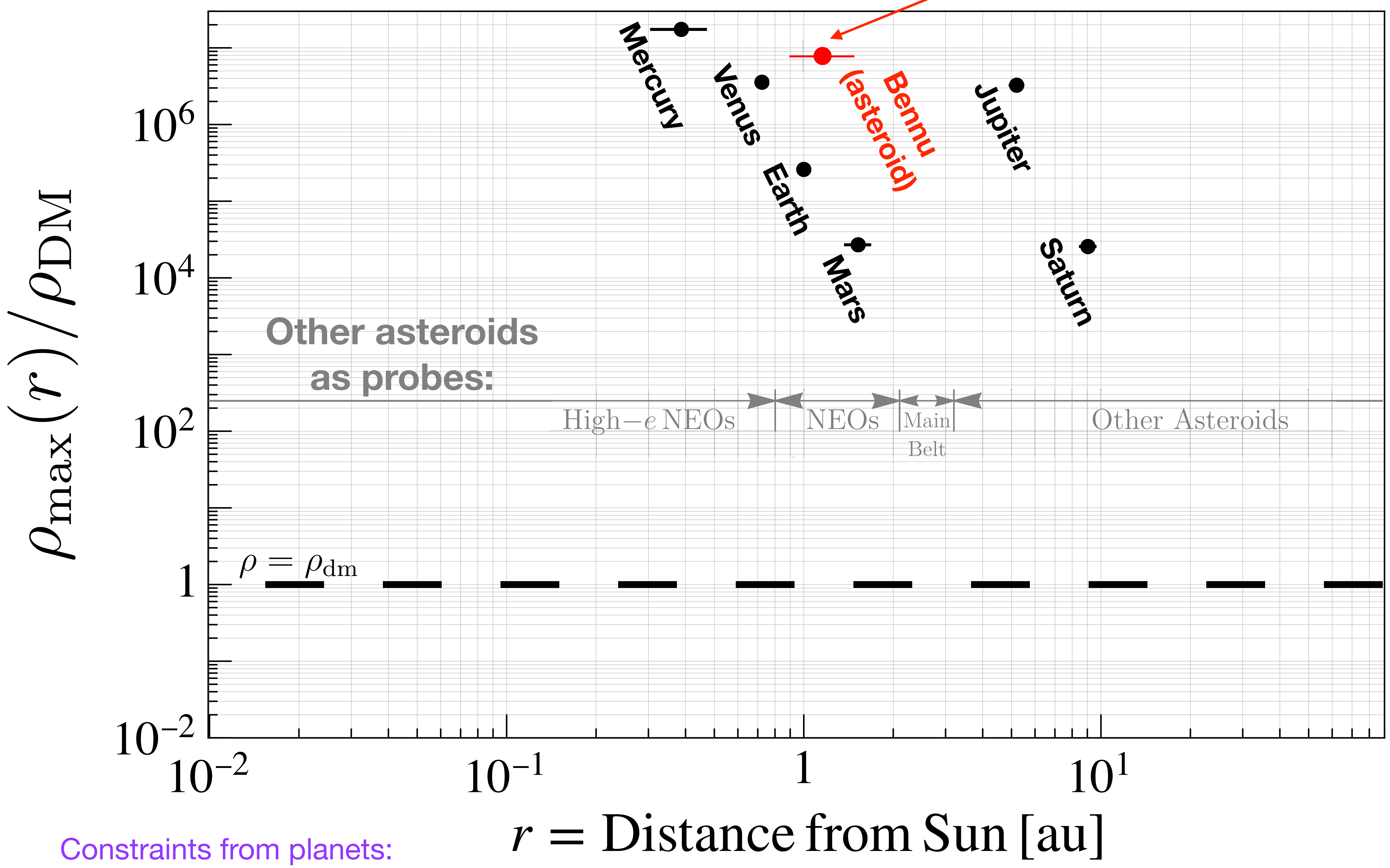
Consider **Mercury:** $\dot{\theta}_{\text{prec}} = 575.3100 \pm 0.0015 \, \dfrac{\text{arcsec}}{\text{century}}$

See Park et al. (*MESSENGER* collaboration), The Astronomical Journal, 153:121 (2017)

https://commons.wikimedia.org/wiki/File:Perihelion_precession.gif

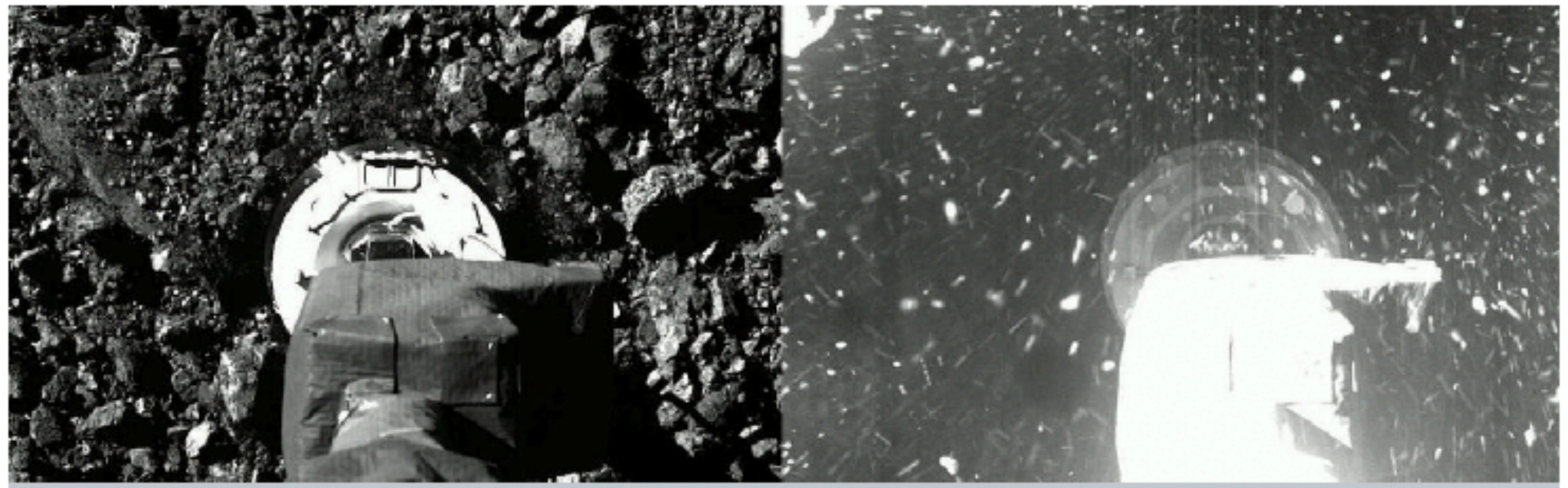
Constraints on DM in our Solar System

First constraint using asteroids:
Tsai, **JE**, Arakawa, Farnocchia,
Safronova (2210.03749)



Constraints from planets:
see Pitjev and Pitjeva (1306.5534)

Bennu: exceptional tracking data including dedicated OSIRIS-REx mission from NASA



Side-by-side images from NASA's OSIRIS-REx spacecraft of the robotic arm as it descended towards the surface of asteroid Bennu (left) and as it tapped it to stir up dust and rock for sample collection (right). OSIRIS-REx touched down on Bennu at 6:08pm EDT on October 20, 2020. Credits: NASA's Goddard Space Flight Center.

Of general interest:

Is there DM in the Solar System? How much?

How do we strengthen such constraints?

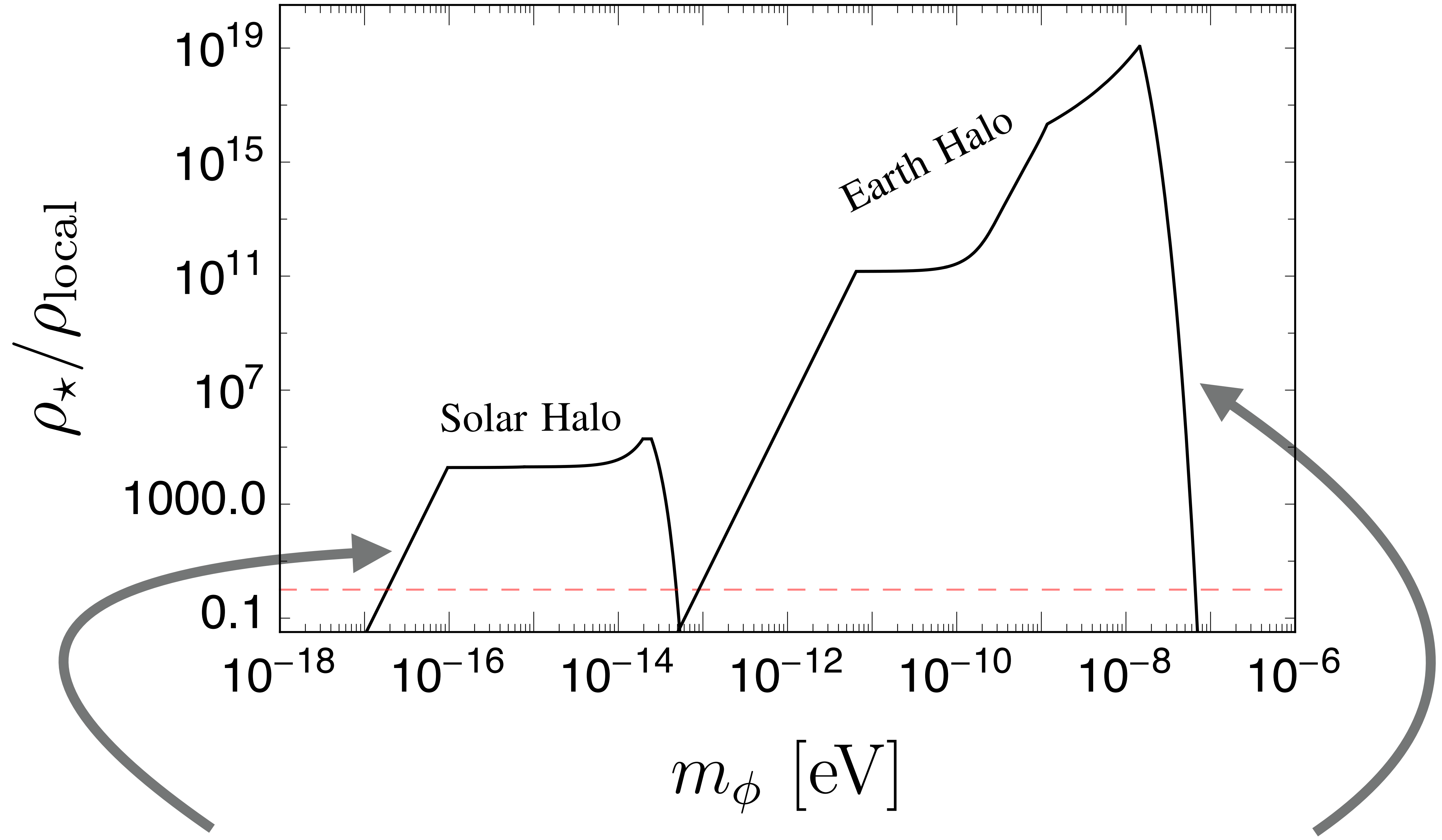
New ideas?

Possible Overdensity

Banerjee, Budker, JE, Kim, Perez (1902.08212)

Density can be very much enhanced relative to ‘naive’ expectation ρ_{local}

Max density at Earth surface



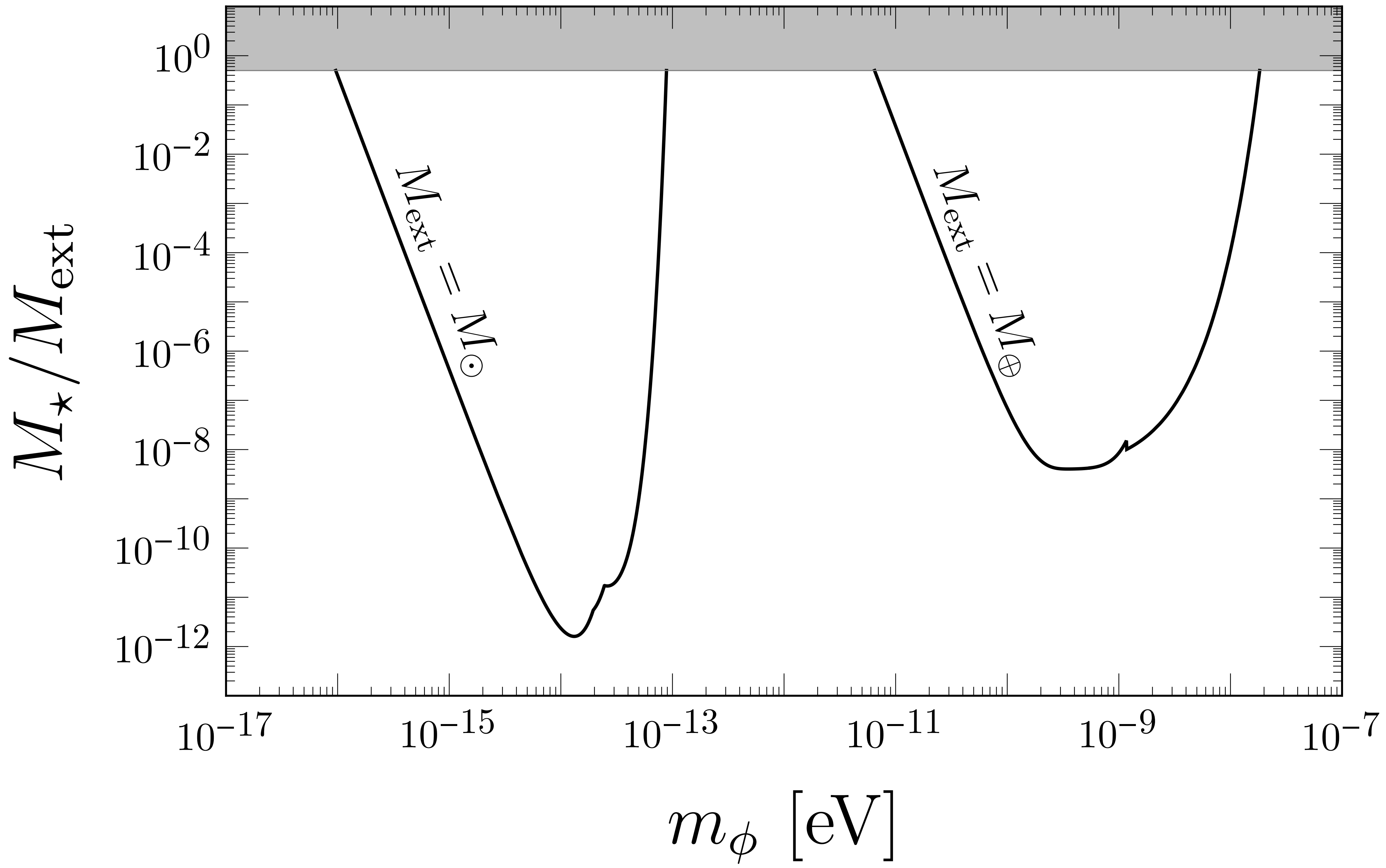
Solar System Ephemerides (Mercury, Mars, Saturn)

Pitjev and Pitjeva (1306.5534)

Lunar Laser Ranging + LAGEOS Satellite

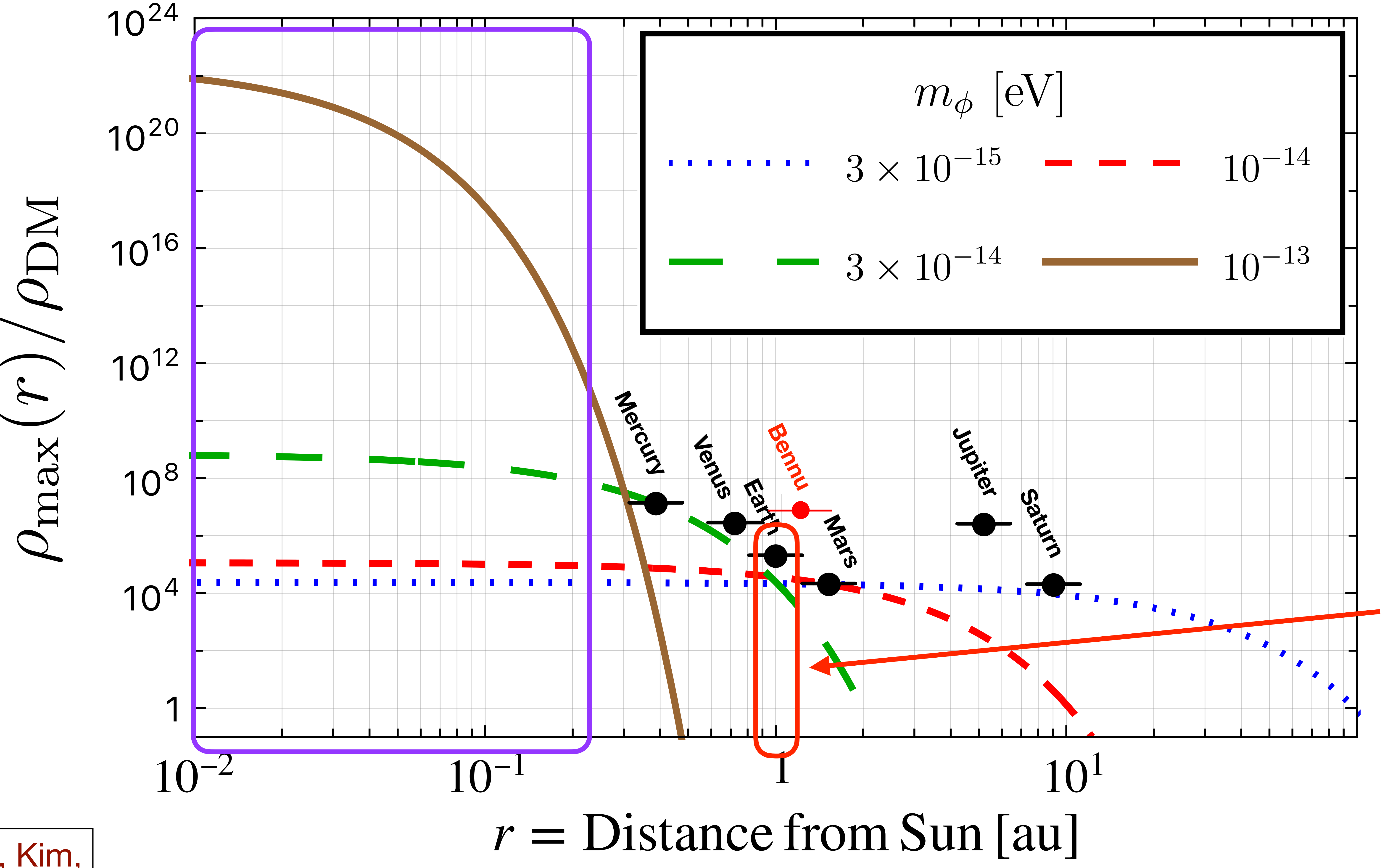
Adler (0808.0899)

Maximum bound mass fraction



Maximum Density of Solar Halo

Near the Sun: **density** $\rho \lesssim 10^{22}\rho_{\rm dm}$!! **mass** $10^{-14}\,{\rm eV} \lesssim m_\phi \lesssim 10^{-13}\,{\rm eV}$



On Earth: **density** $\rho \lesssim 10^4 - 10^5\rho_{\rm dm}$

mass $m_\phi \lesssim 3\cdot10^{-14}\,{\rm eV}$

Banerjee, Budker, **JE**, Kim, Perez (1902.08212)

"But can bound states really form?"

Formed by "gravitational cooling"

Seidel and Suen (gr-qc/9309015)
Guzman and Urena-Lopez (astro-ph/0603613)

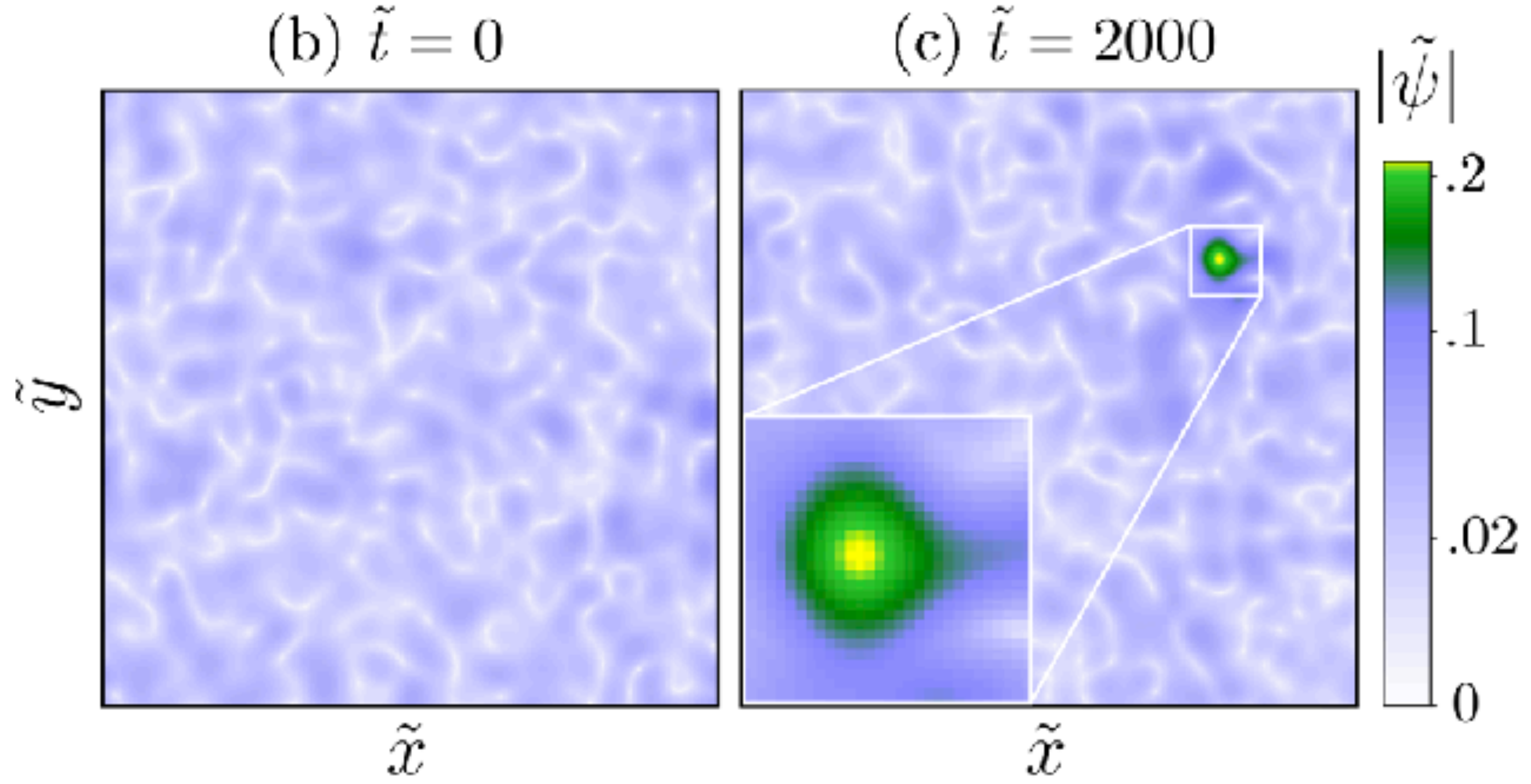
Can be understood analytically as *gravitational relaxation* of quasiparticles

Hui, Ostriker, Tremaine, Witten (1610.08297)
Bar-Or, Fouvry, Tremaine (1809.07673)

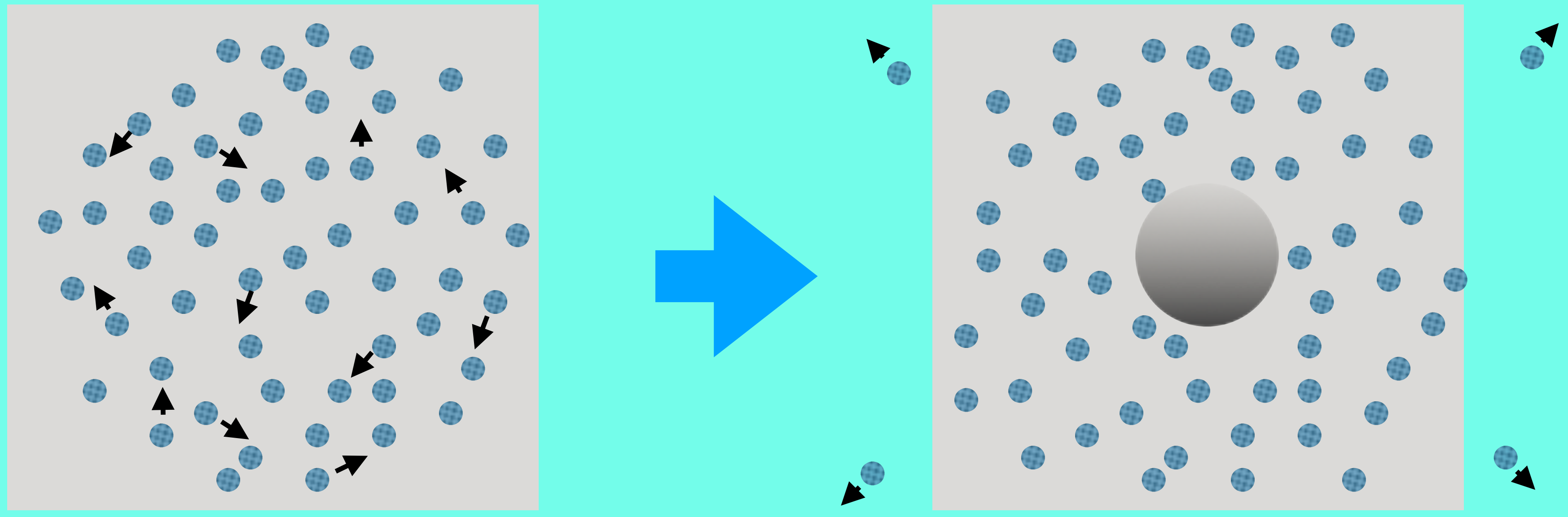
For axion stars:

dedicated simulations confirm this picture

Levkov, Panin, Tkachev (1804.05857)



N objects scatter gravitationally, exchange energy



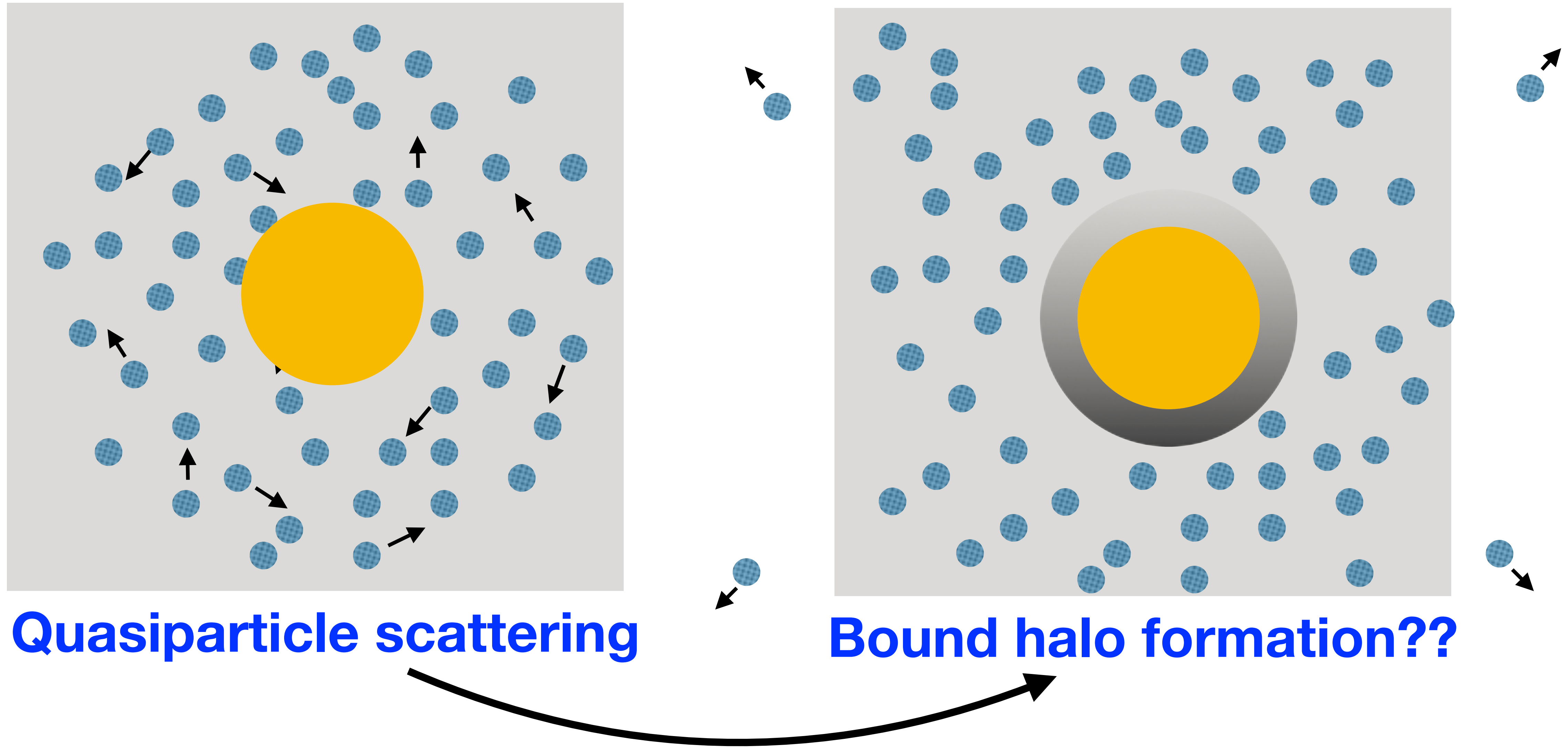
$$\Delta v^2 \simeq 8\,N \left(\frac{G\,M}{R_{\rm gal}\,v}\right) \ln N \quad \longrightarrow \quad \frac{\Delta v^2}{v^2} \simeq \frac{8\,\ln N}{N}$$

Velocity change per crossing

Binney and Tremaine, "Galactic Dynamics"

$$\Longrightarrow \quad t_{\rm relax} \simeq \frac{0.1\,N}{\ln N} t_{\rm cross}$$

For gravitational atoms: so far, *ours is the only dedicated analysis*



Quasiparticle scattering

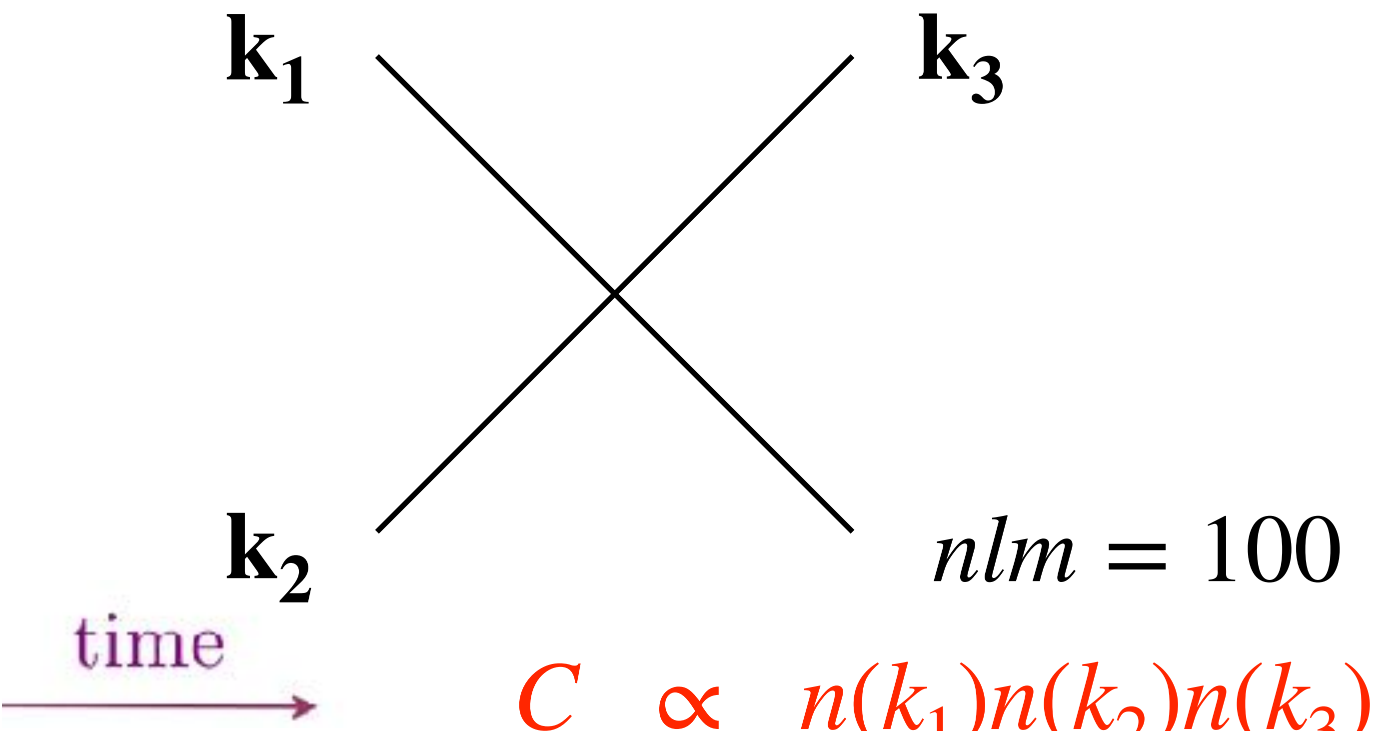
Bound halo formation??

Relaxation to ground state?

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

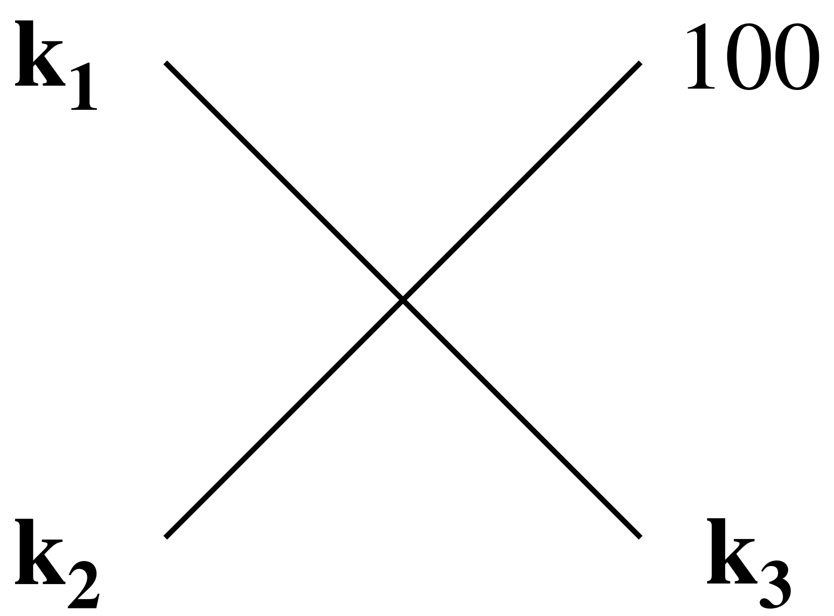
Dilute Gravitational Atoms

Direct capture



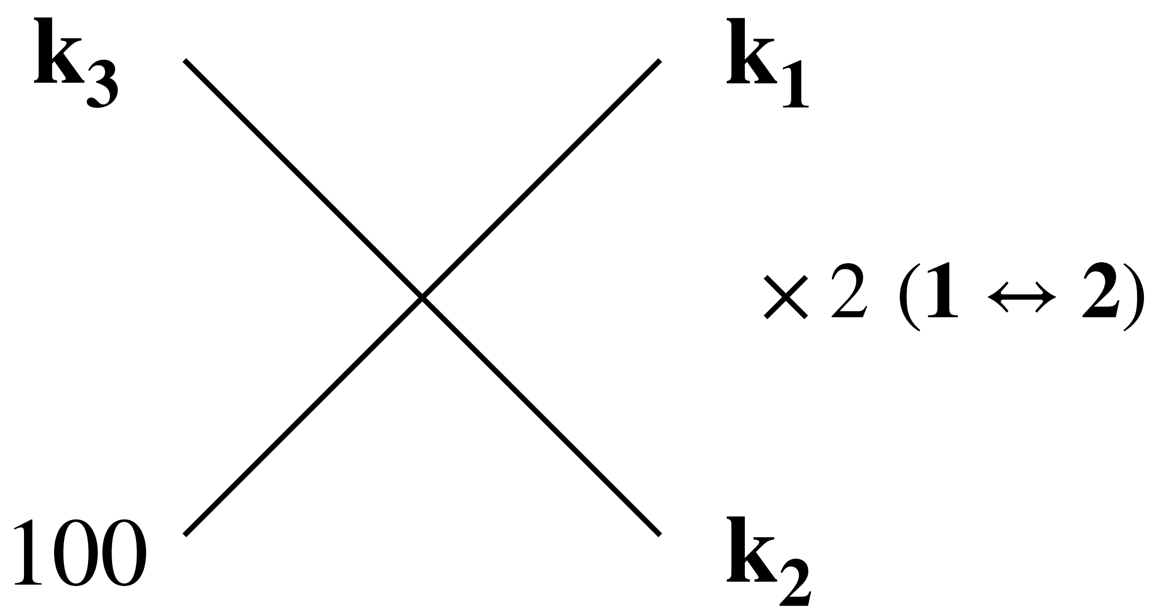
$C \propto n(k_1)n(k_2)n(k_3)$

Stimulated capture



$\Gamma_1 \propto n(k_1)n(k_2)$

Ionization



$2\Gamma_2 \propto 2n(k_1)n(k_3)$

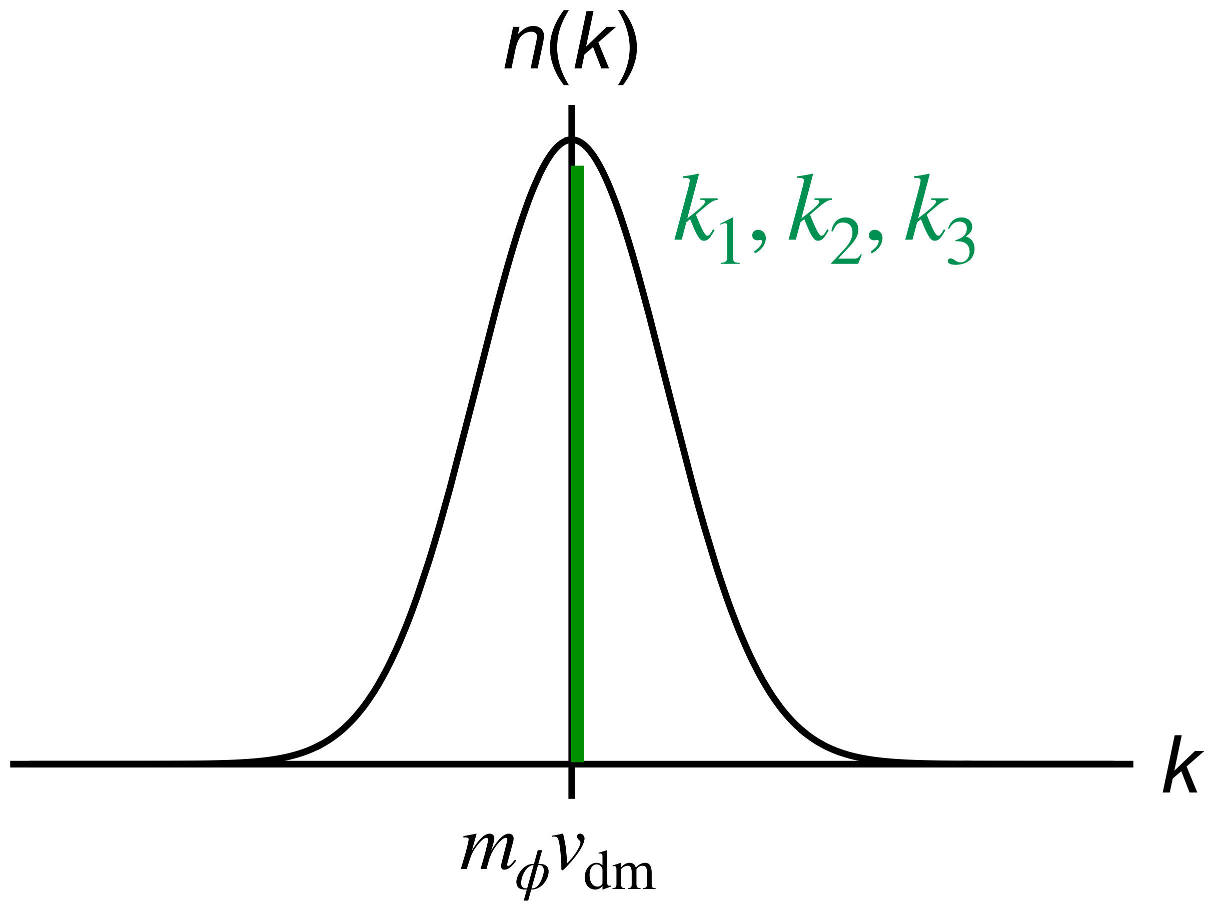
$$\frac{dM_\star}{dt} \simeq C + \overbrace{(\Gamma_1 - 2\Gamma_2)}^{\Gamma} M_\star$$

$\Gamma > 0$ **: Exponential growth**
$\Gamma < 0$ **: Saturation**
determines late-time behavior

Recall $\xi_{\rm foc} \equiv \dfrac{\lambda_{\rm dB}}{R_\star} = \dfrac{2\pi\alpha_g}{v_{\rm dm}} \ll 1$

implies
$m_\phi v_{\rm dm}^2 \gg m_\phi \alpha_g^2$

$k_1 \sim k_2 \sim k_3 \sim m_\phi v_{\rm dm} \quad \Rightarrow \Gamma_1 \simeq \Gamma_2$



$$\Longrightarrow M_\star^{\rm eq} = \frac{C}{\Gamma_2} \simeq 10\rho_{\rm dm}\lambda_{\rm dB}^3$$

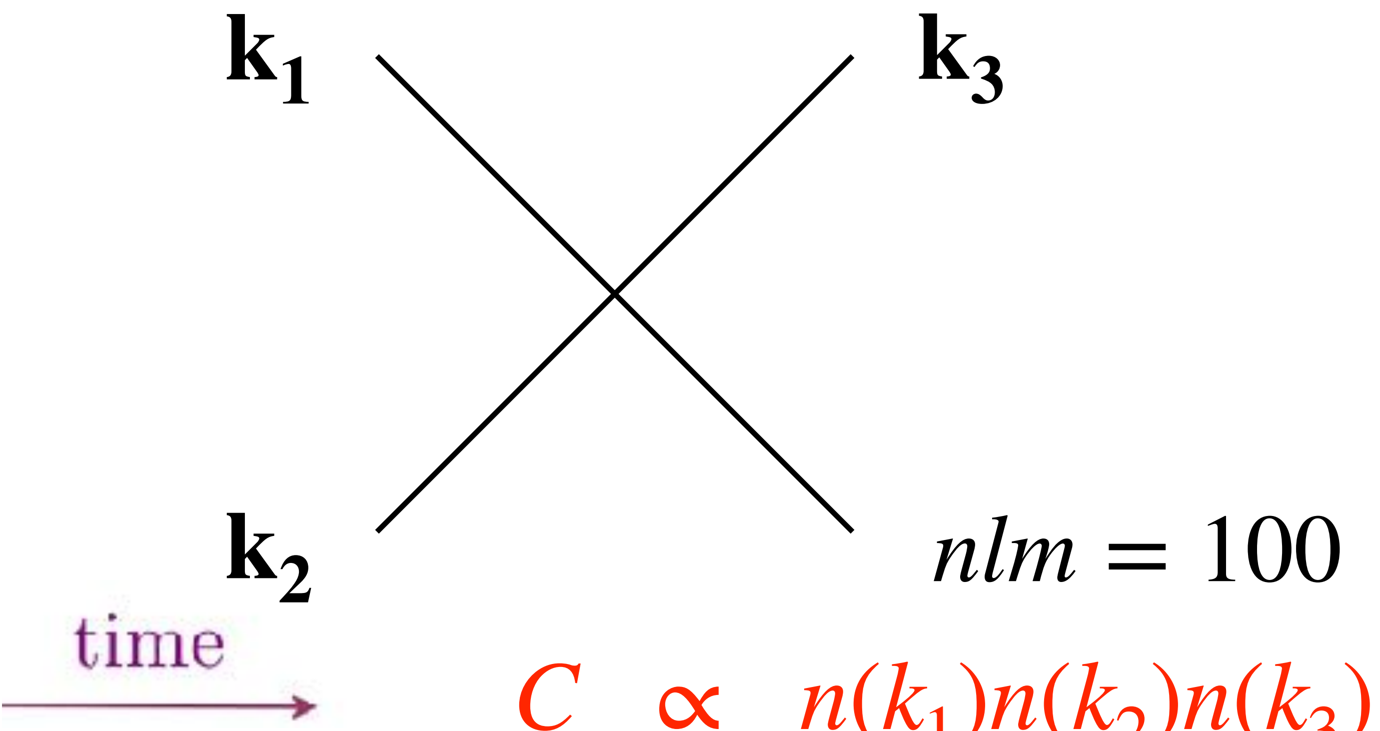
$$\Longrightarrow \rho \ll \rho_{\rm dm}$$

“dilute”

<u>Dense</u> Gravitational Atoms

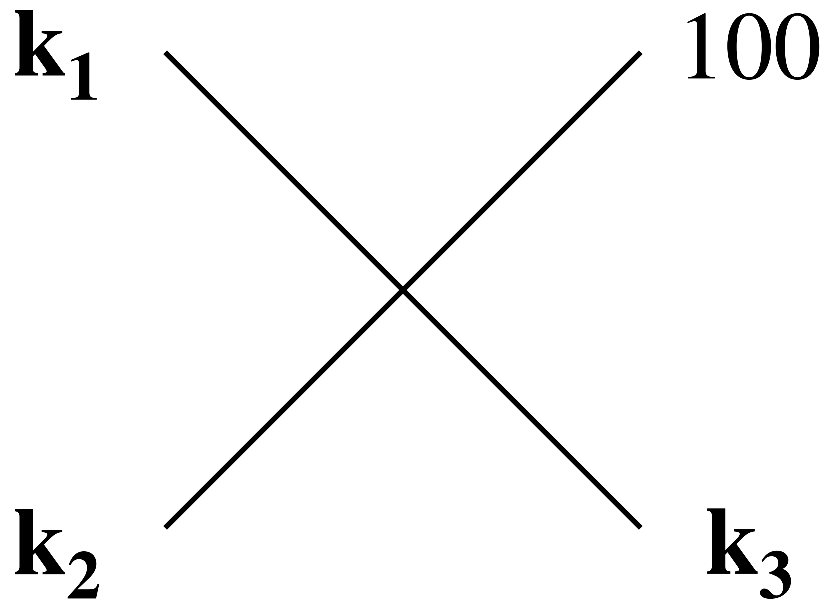
Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Direct capture



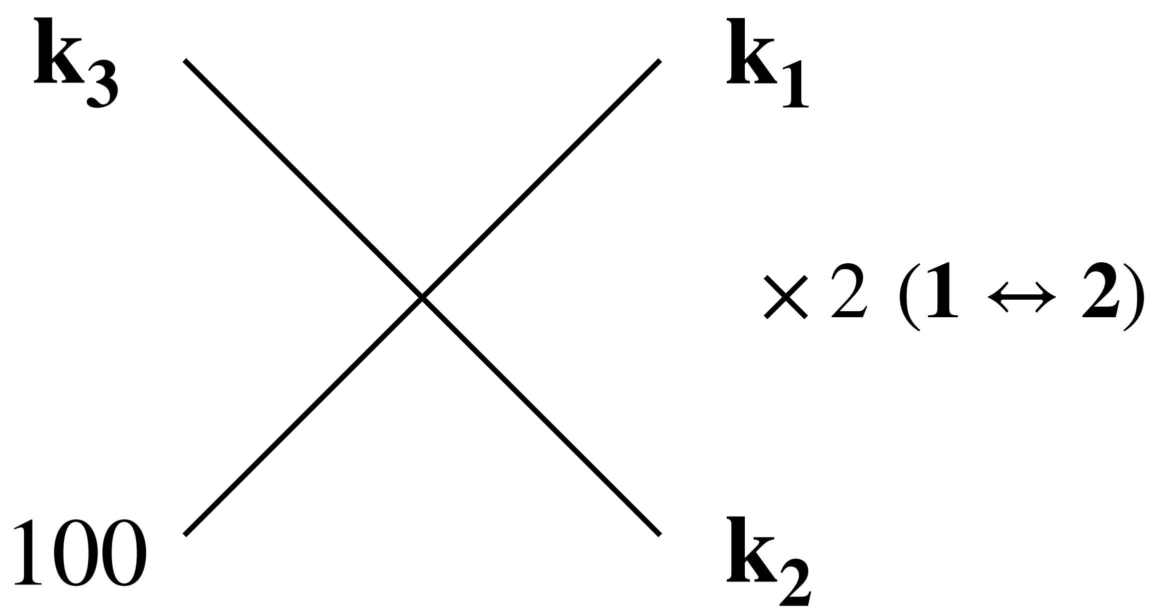
$C \propto n(k_1)n(k_2)n(k_3)$

Stimulated capture



$\Gamma_1 \propto n(k_1)n(k_2)$

Ionization



$2\Gamma_2 \propto 2n(k_1)n(k_3)$

$$\frac{dM_\star}{dt} \simeq C + \overbrace{(\Gamma_1 - 2\Gamma_2)}^{\Gamma} M_\star$$

$\Gamma > 0$ **: Exponential growth**

$\Gamma < 0$ **: Saturation**

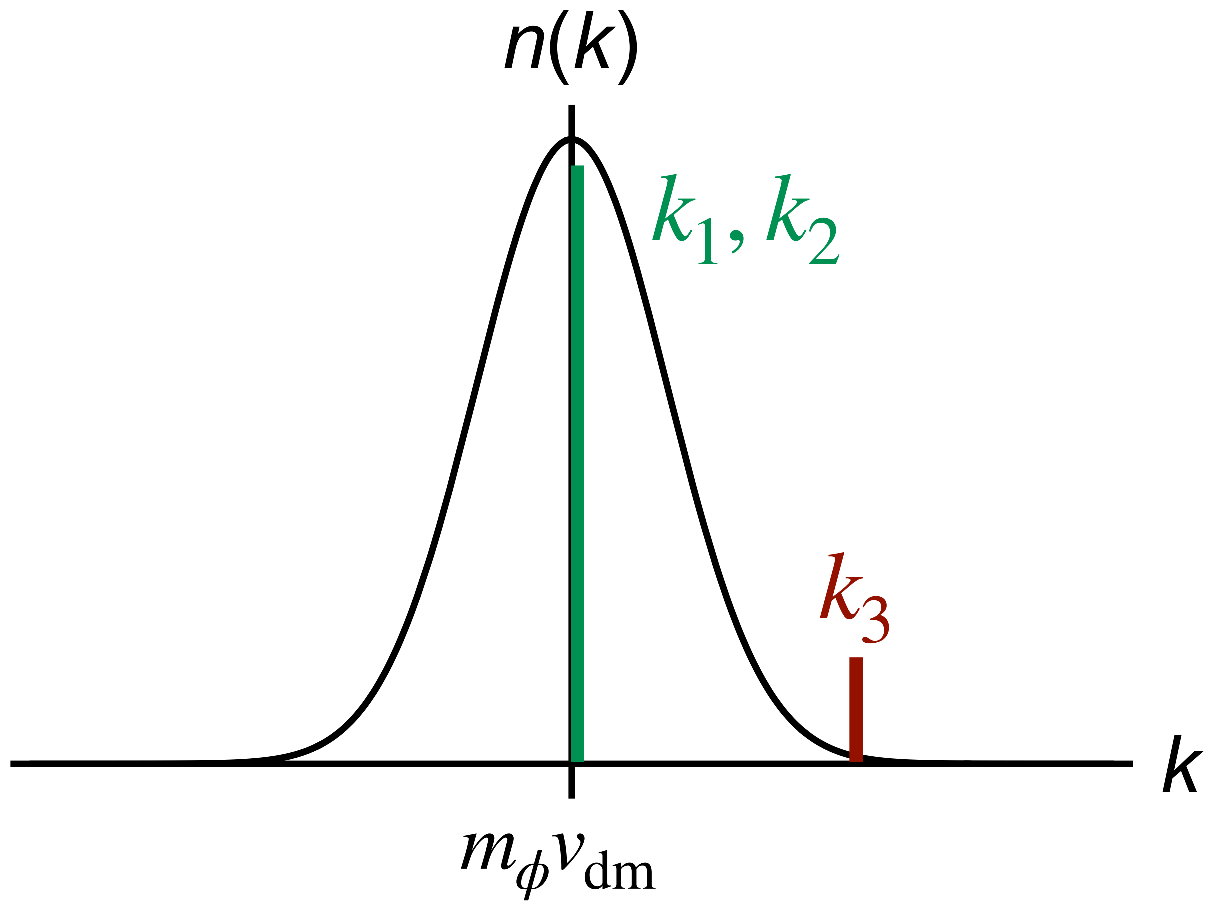
determines late-time behavior

However, $\xi_{\rm foc} \equiv \frac{\lambda_{\rm dB}}{R_\star} = \frac{2\pi\alpha_g}{v_{\rm dm}} \gg 1$

implies instead

$m_\phi v_{\rm dm}^2 \ll m_\phi \alpha_g^2$

$k_1 \sim k_2 \sim m_\phi v_{\rm dm} \ll k_3 \qquad \Rightarrow \Gamma_1 \gg \Gamma_2$



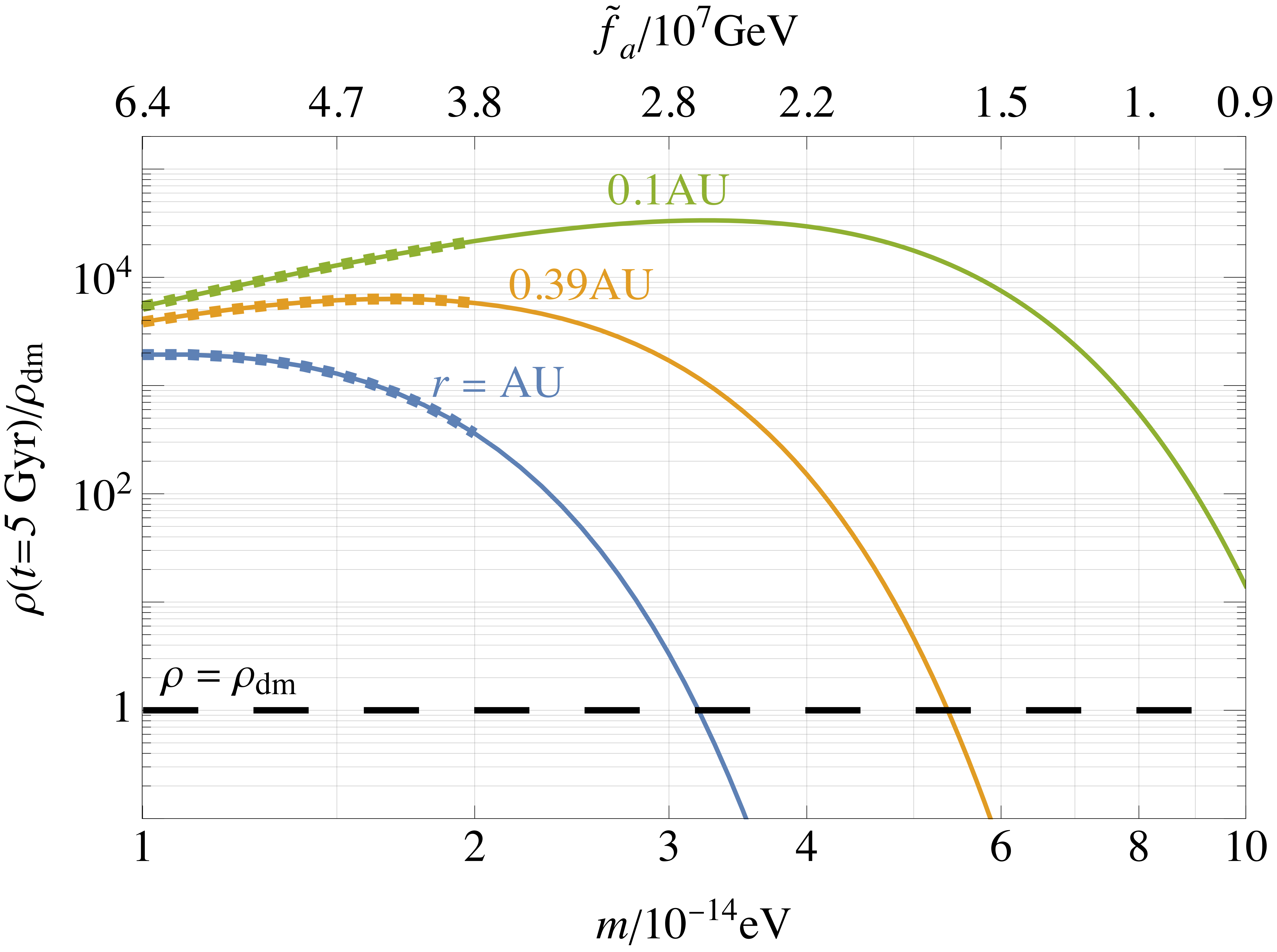
$$\Longrightarrow M_\star(t) \simeq 10\rho_{\rm dm}\lambda_{\rm dB}^3\left(e^{\Gamma_1 t} - 1\right)$$

$$\Longrightarrow \rho \gg \rho_{\rm dm}$$

“dense”

Very Local Density from Capture

(i.e. in our solar system)



assuming $\lambda < 0$;
density could be larger for $\lambda > 0$

Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Constraints from Large-Scale Structure

Evolution of cosmological density perturbations is modified by wavelike structure of ULDM fields

$$\ddot{\delta}_k + 2H\dot{\delta}_k - 4\pi G\bar{\rho}\left[1 - \left(\frac{k}{k_J}\right) \pm \left(\frac{k}{k_\lambda}\right)^2\right]$$

suppression of structure on 'small' scales due to ultralight mass

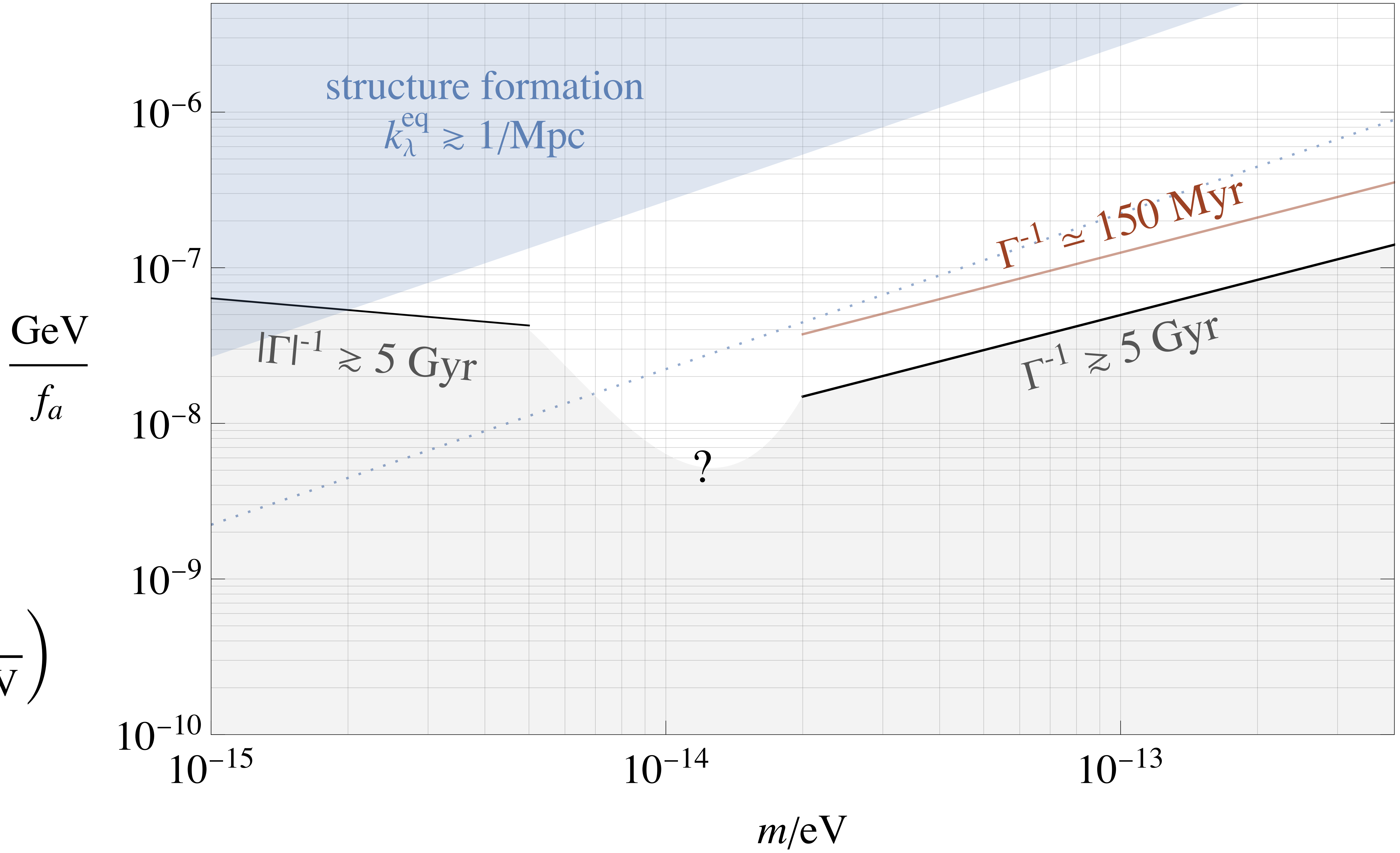
$$k_J \simeq 10\,\mathrm{Mpc}^{-1}\left(\frac{a}{a_{\mathrm{eq}}}\right)^{1/4}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

e.g. Lyman-α constraints, see
Iršič++ (1703.04683),
Rogers, Peiris (2007.12705)

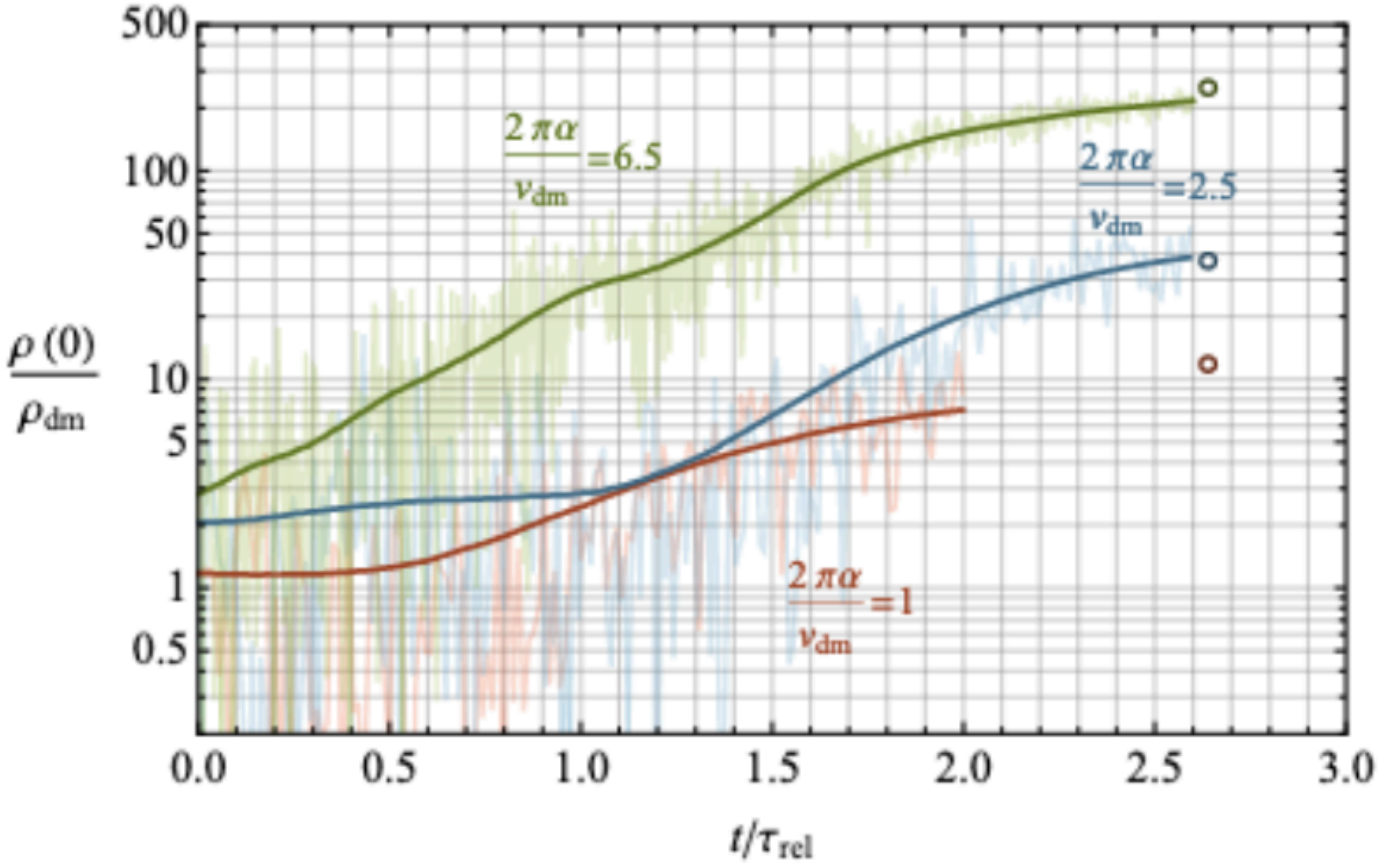
suppression (or enhancement) of structure due to strong self-interactions in the early universe

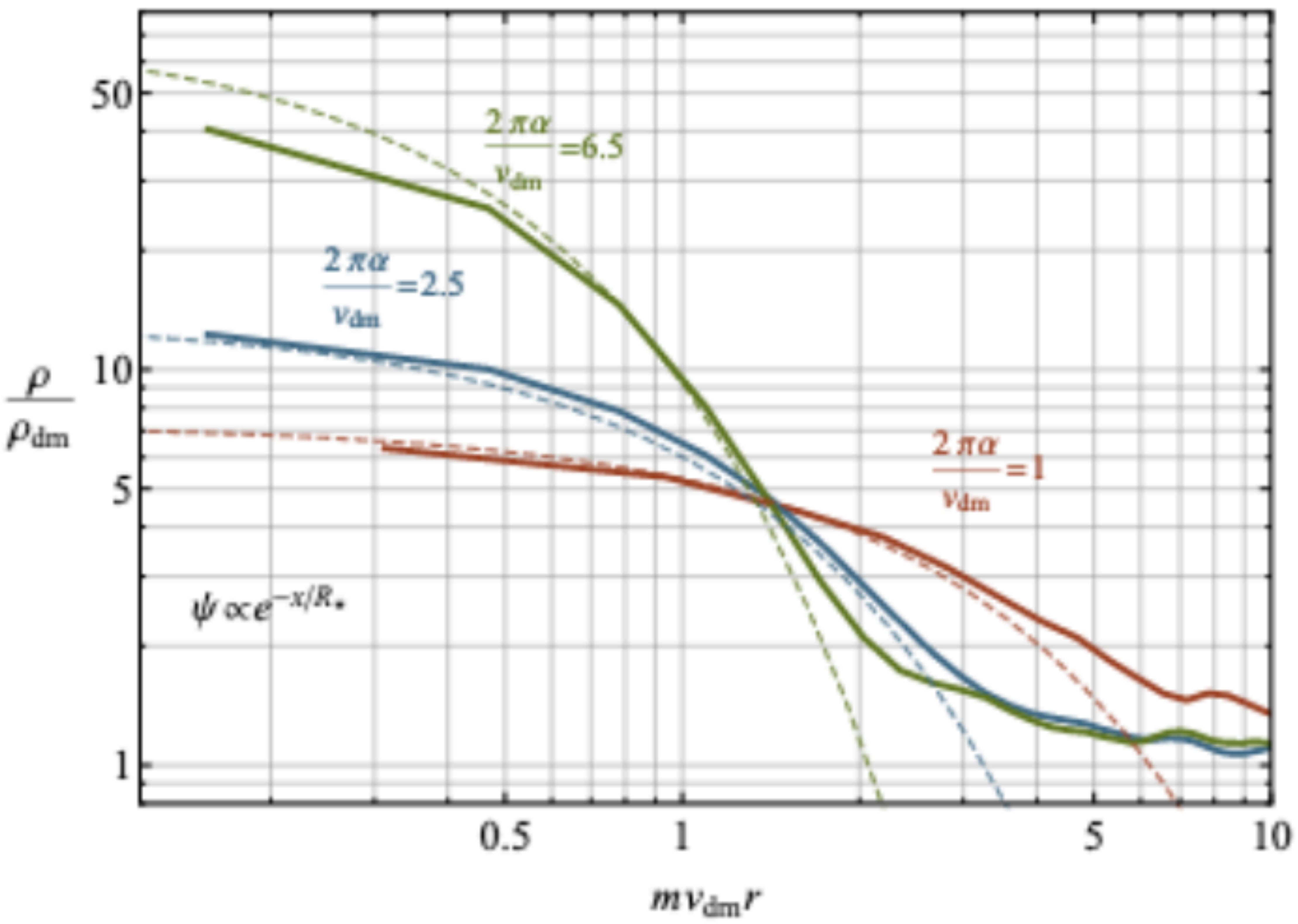
$$k_\lambda \simeq 2.7\,\mathrm{Mpc}^{-1}\left(\frac{a}{a_{\mathrm{eq}}}\right)\left(\frac{m}{10^{-14}\,\mathrm{eV}}\right)\left(\frac{f_a}{10^7\,\mathrm{GeV}}\right)$$

see e.g.
Arvanitaki, Huang, Van Tilburg (1405.2925)
Fan (1603.06580)
Cembranos++ (1805.08112)



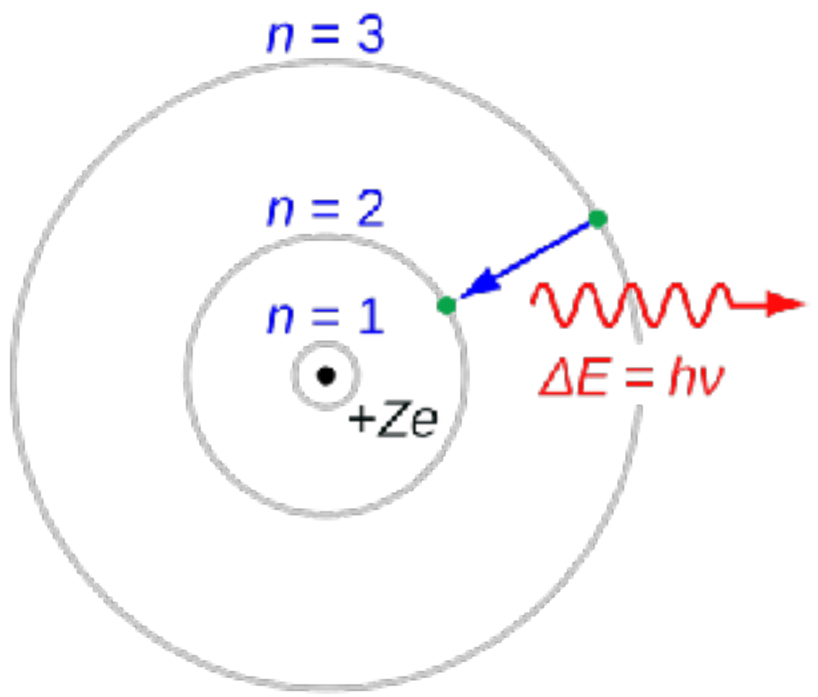
Simulations





Banerjee, Budker, **JE**, Kim, Perez (1902.08212)

Probes on Earth



ULDM-photon interaction (example):

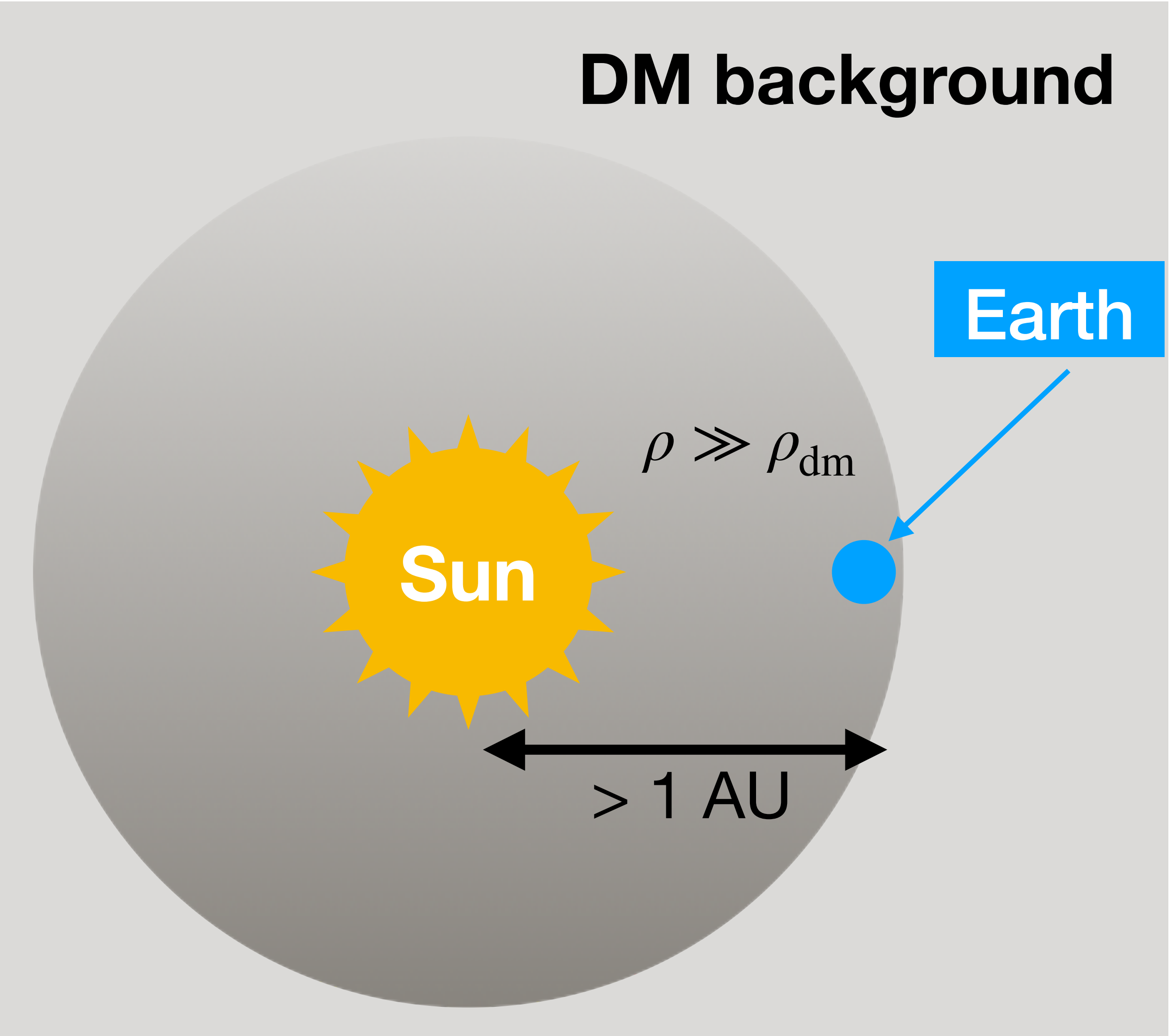
$$\mathscr{L} \supset \frac{d_\alpha}{4\tilde{M}_P}\phi\, F^{\mu\nu}F_{\mu\nu}$$

Oscillation of $\phi = \phi(t)$ induces oscillation of fundamental constants of nature

$$\alpha(t) = \alpha_0\left(1 - d_\alpha \frac{\phi(t)}{\tilde{M}_P}\right)$$

$$\Rightarrow \quad \frac{\delta\alpha}{\alpha_0} \simeq \frac{d_\alpha\sqrt{2\rho}}{m_\phi \tilde{M}_P} \simeq 10^{-15} d_\alpha \left(\frac{10^{-15}\,\text{eV}}{m_\phi}\right)\sqrt{\frac{\rho}{\rho_{\text{local}}}}$$

w/ oscillation frequency $\omega_\phi \simeq m_\phi \simeq \text{few Hz}\left(\frac{m_\phi}{10^{-15}\,\text{eV}}\right)$

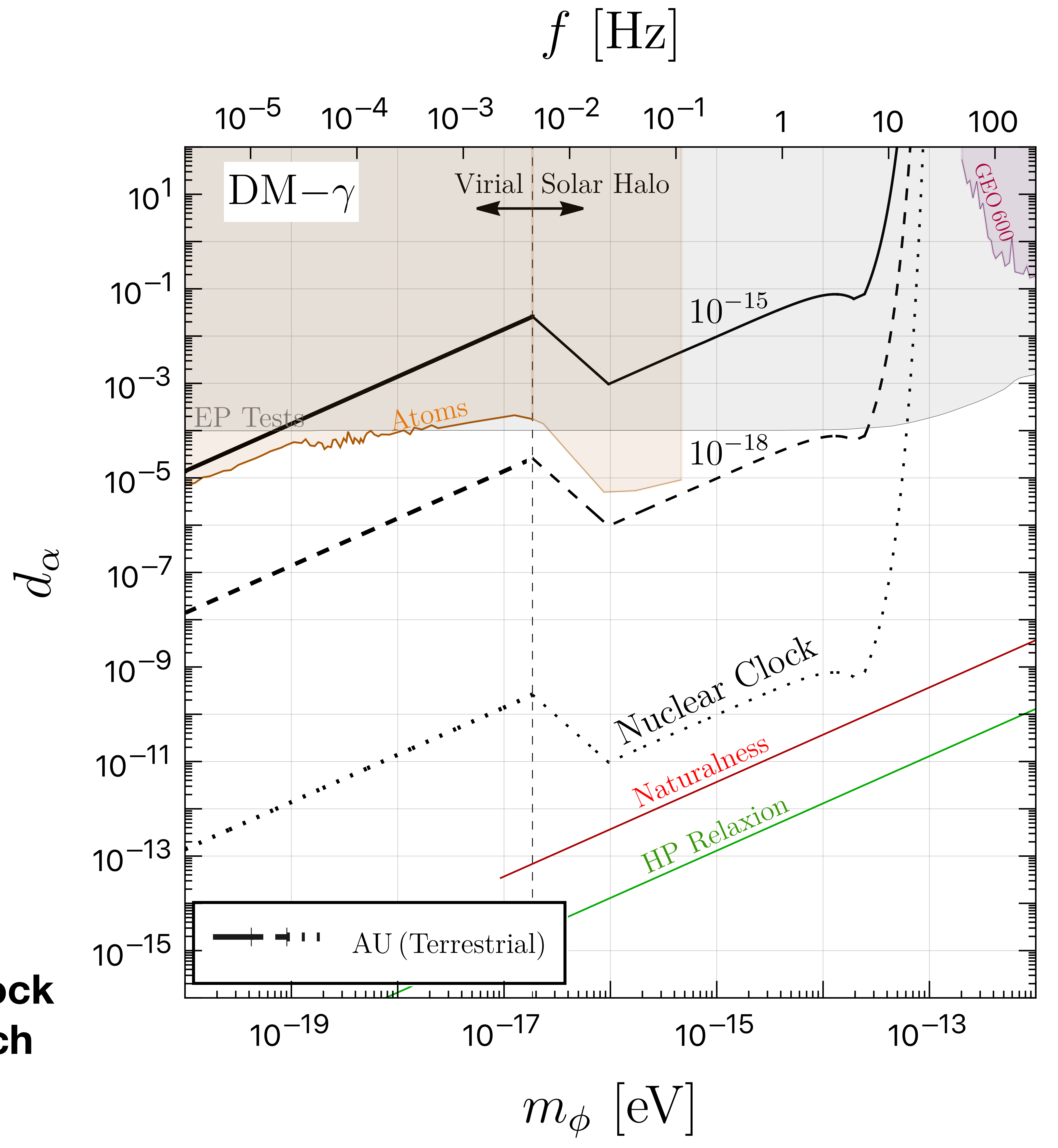


Modern optical clocks have achieved

$$\frac{\delta\alpha}{\alpha_0} \lesssim 10^{-18}$$

Future nuclear clock projected to reach

$$\frac{\delta\alpha}{\alpha_0} \lesssim 10^{-23}$$



Going to Space

Parker Solar Probe (NASA)

https://blogs.nasa.gov/parkersolarprobe/

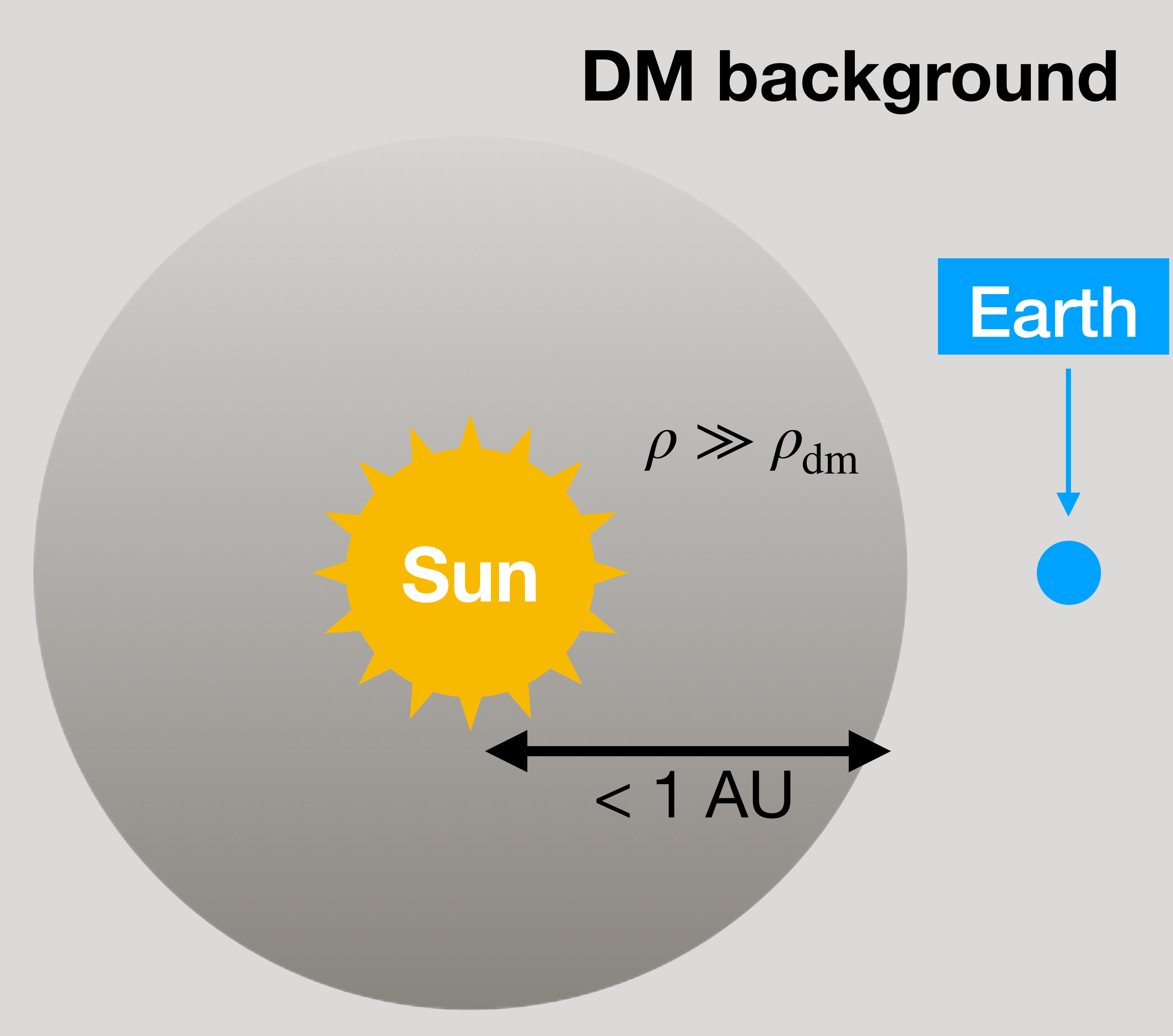
Launch: Aug 12, 2018

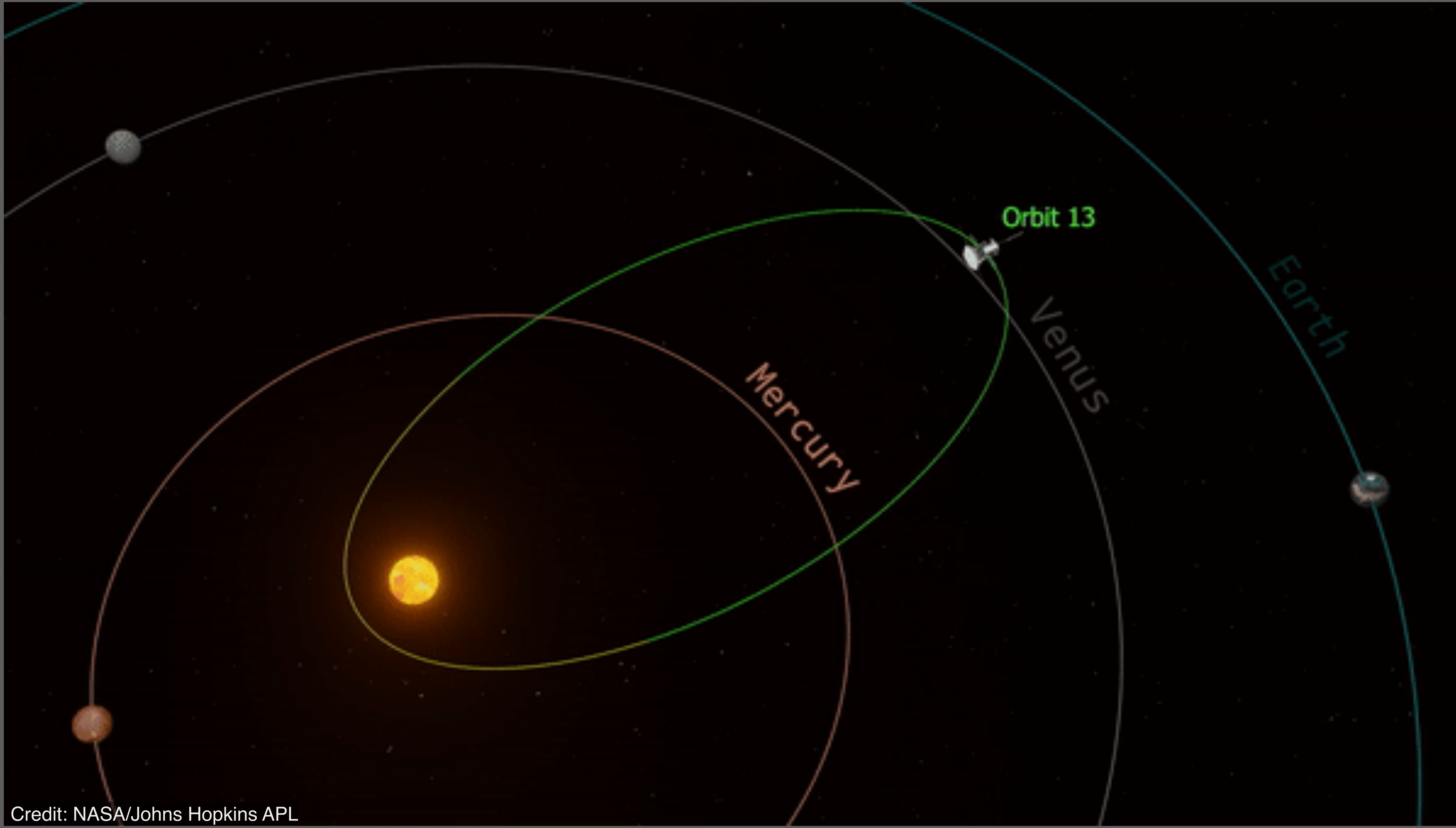
Most recent perihelion:

◉ March 17, 2023 (15 of 24 planned)

◉ Approach: 0.057 au from Sun

◉ Temperature:
2500°F (1370°C) heat shield,
85°F (30°C) interior





Credit: NASA/Johns Hopkins APL

Can we send an atomic clock to the Sun?

(Should we?)

Quantum Clocks in Space

International community rapidly developing technologies to put atomic clocks in space

NASA Deep Space Atomic Clock (DSAC) 🇺🇸

nature

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Article | Published: 30 June 2021

Demonstration of a trapped-ion atomic clock in space

E. A. Burt, J. D. Prestage, R. L. Tjoelker, D. G. Enzer, D. Kuang, D. W. Murphy, D. E. Robison, J. M. Seubert, R. T. Wang & T. A. Ely

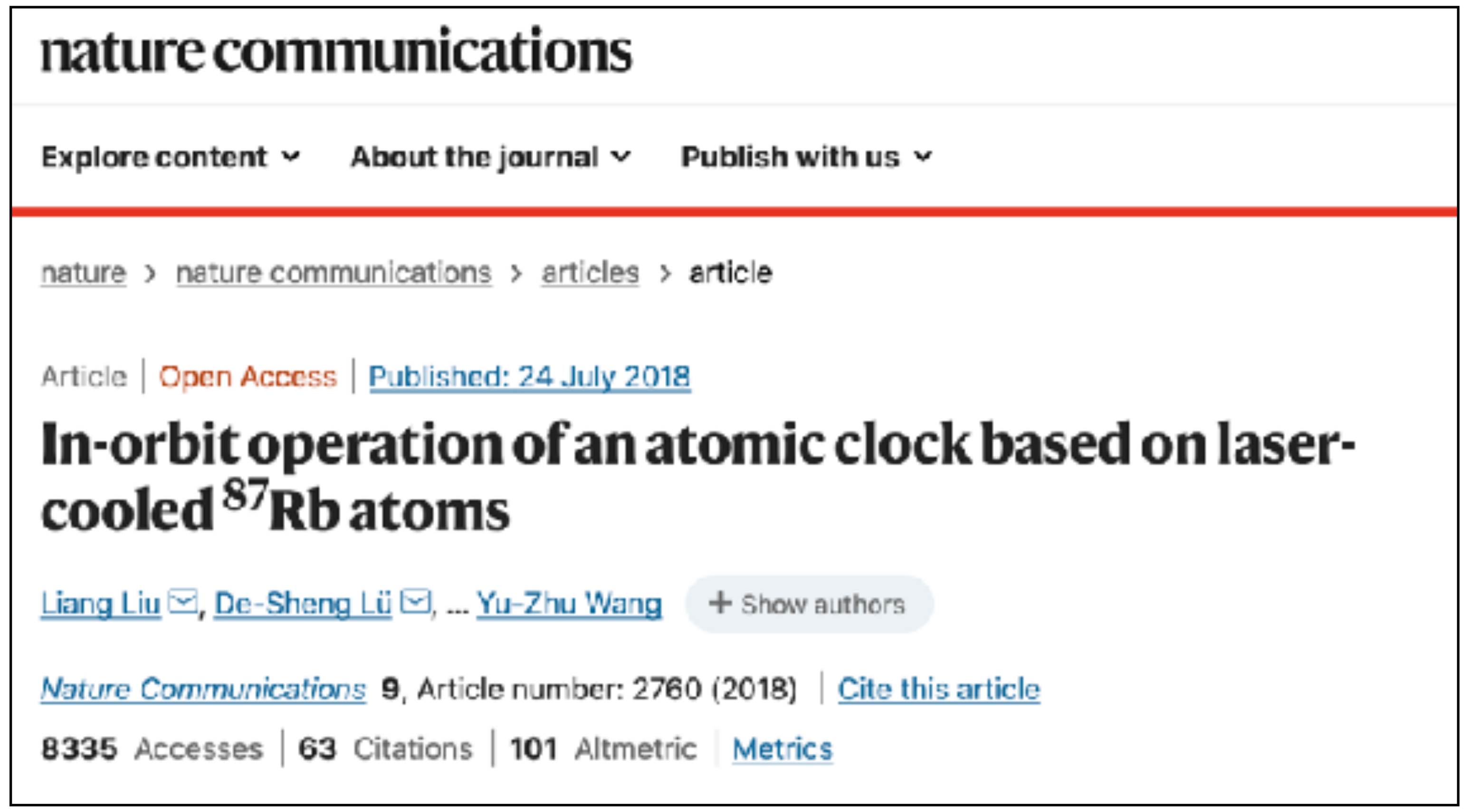
Nature **595**, 43–47 (2021) | Cite this article

6205 Accesses | **3** Citations | **247** Altmetric | Metrics

Demonstrated stability in space $\sim 10^{-14}$

DSAC-2 may visit Venus, launch ~2028!

Cold Atom Clock Experiment in Space (CACES) 🇨🇳



nature communications

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nature › nature communications › articles › article

Article | Open Access | Published: 24 July 2018

In-orbit operation of an atomic clock based on laser-cooled ^{87}Rb atoms

Liang Liu, De-Sheng Lü, … Yu-Zhu Wang + Show authors

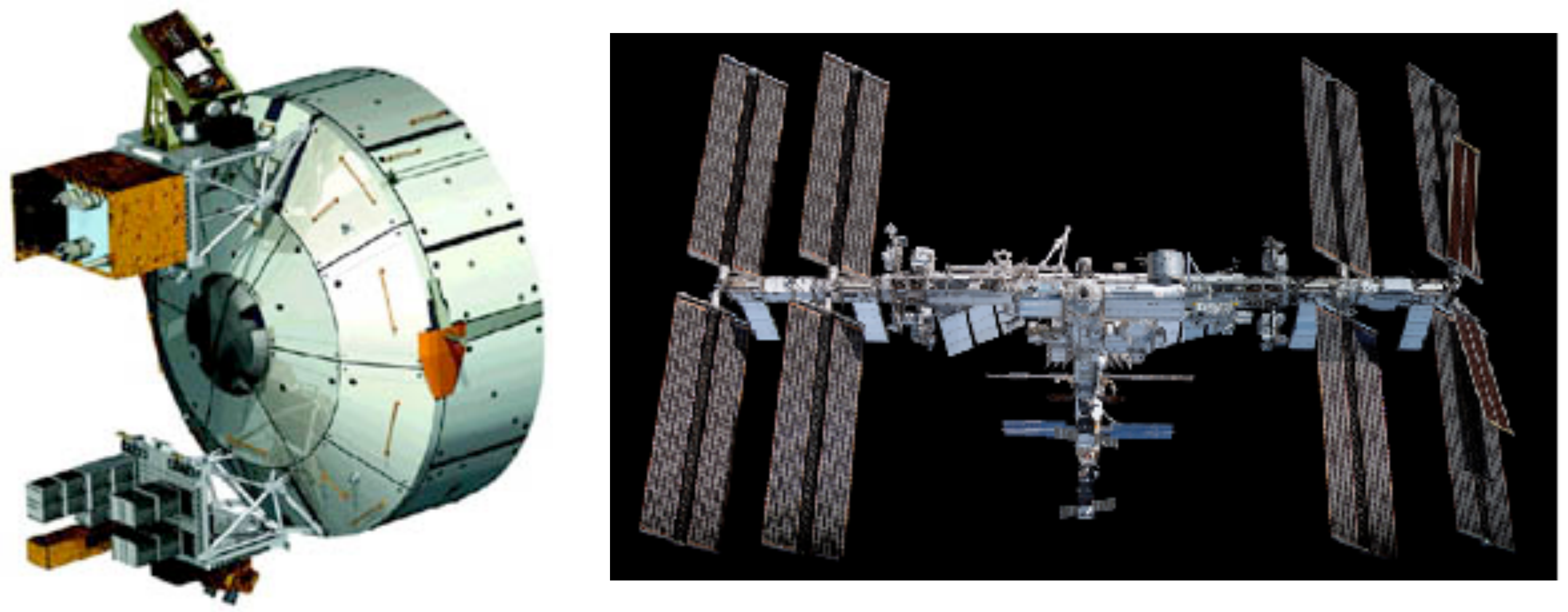
Nature Communications **9**, Article number: 2760 (2018) | Cite this article

8335 Accesses | **63** Citations | **101** Altmetric | Metrics

Demonstrated stability in space $\sim 10^{-14}$

Goal for Tiangong space station $\sim 10^{-18}$

Atomic Clock Ensemble in Space (ACES)



Launch date: 2025 (?)

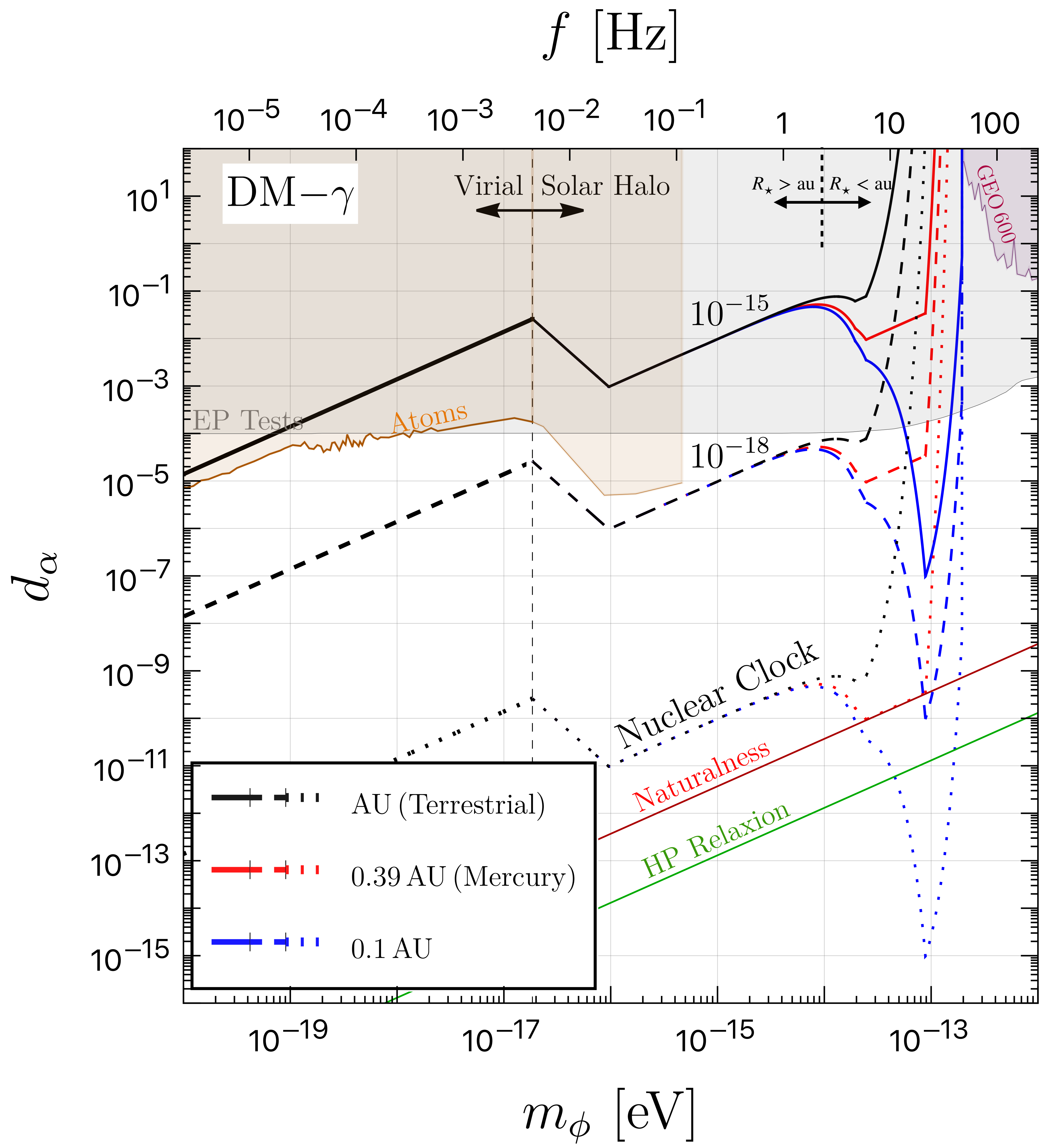
Target stability $\sim 10^{-16}$

Motivations:

- Better time-keeping on ISS
- Improved GPS
- Comparison with ground clocks
- Spacecraft navigation
- Communication w/ moon / Mars / (?)
- ULDM detection??

Tsai, **JE**, Safronova
(2112.07674)

Probes in Space



Lots of work still needed to make this possible!

On the space probe side:

discussions with Parker Solar Probe scientists

- Temperature variations?
  - $(-40\text{ to }40)^\circ$C variation behind heat shield
  - Maybe cold is more dangerous than hot!
- Magnetic field variations?
  - $\pm 100\,\mathrm{nT}$ variation on ~sec timescales

On the clock side:

discussions with quantum sensor / atomic or nuclear clock experts

- Need clocks which are
  - Portable + Automated
  - Lightweight
  - Optimized for ‘high frequency’ run
- Ideally, nuclear + optical clocks to probe many couplings

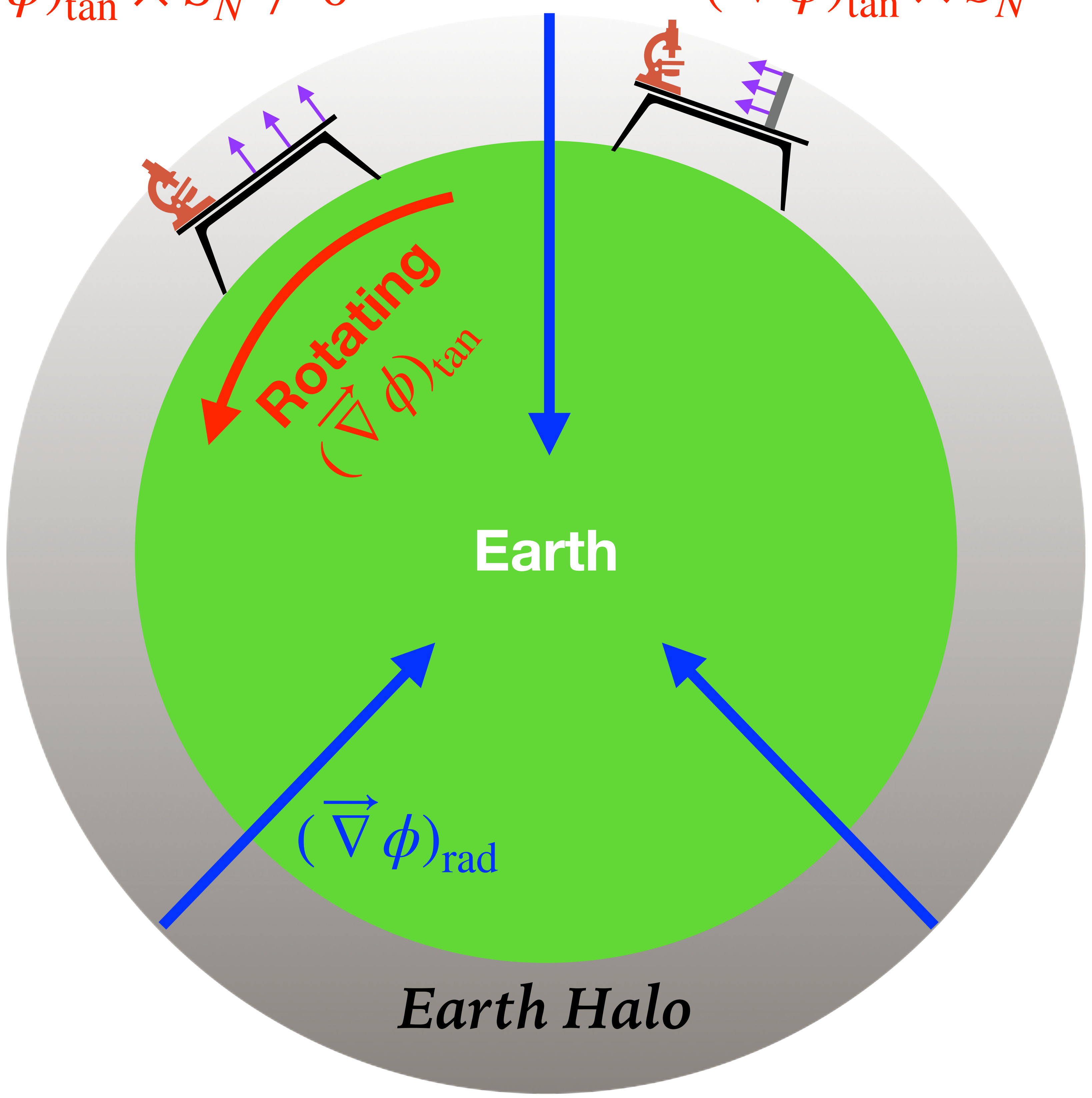
Orientation and DM Wind

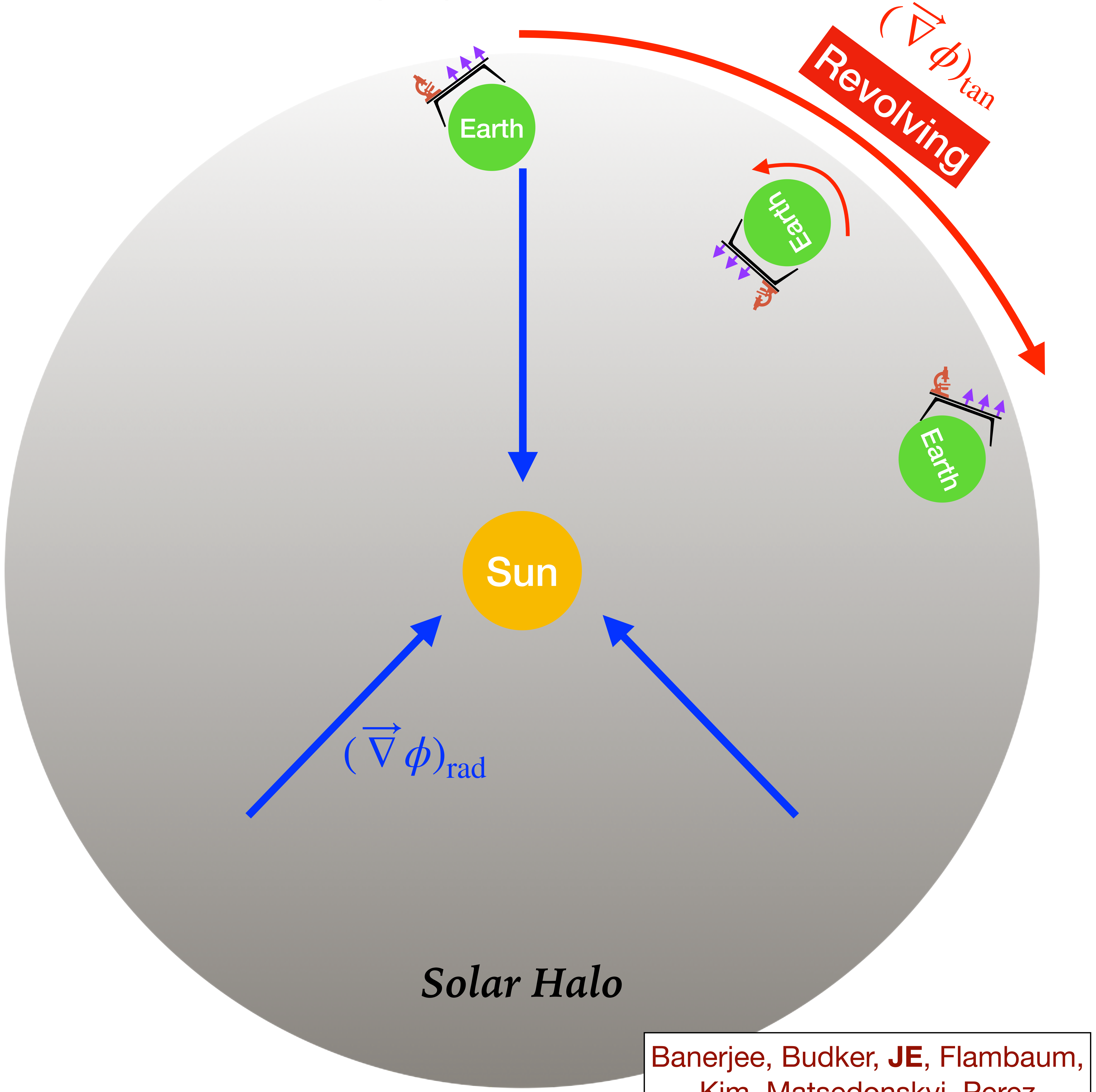
$(\vec{\nabla}\phi)_{\rm rad} \times \vec{S}_N \to 0$

$(\vec{\nabla}\phi)_{\rm tan} \times \vec{S}_N \neq 0$

$(\vec{\nabla}\phi)_{\rm rad} \times \vec{S}_N \neq 0$

$(\vec{\nabla}\phi)_{\rm tan} \times \vec{S}_N \to 0$



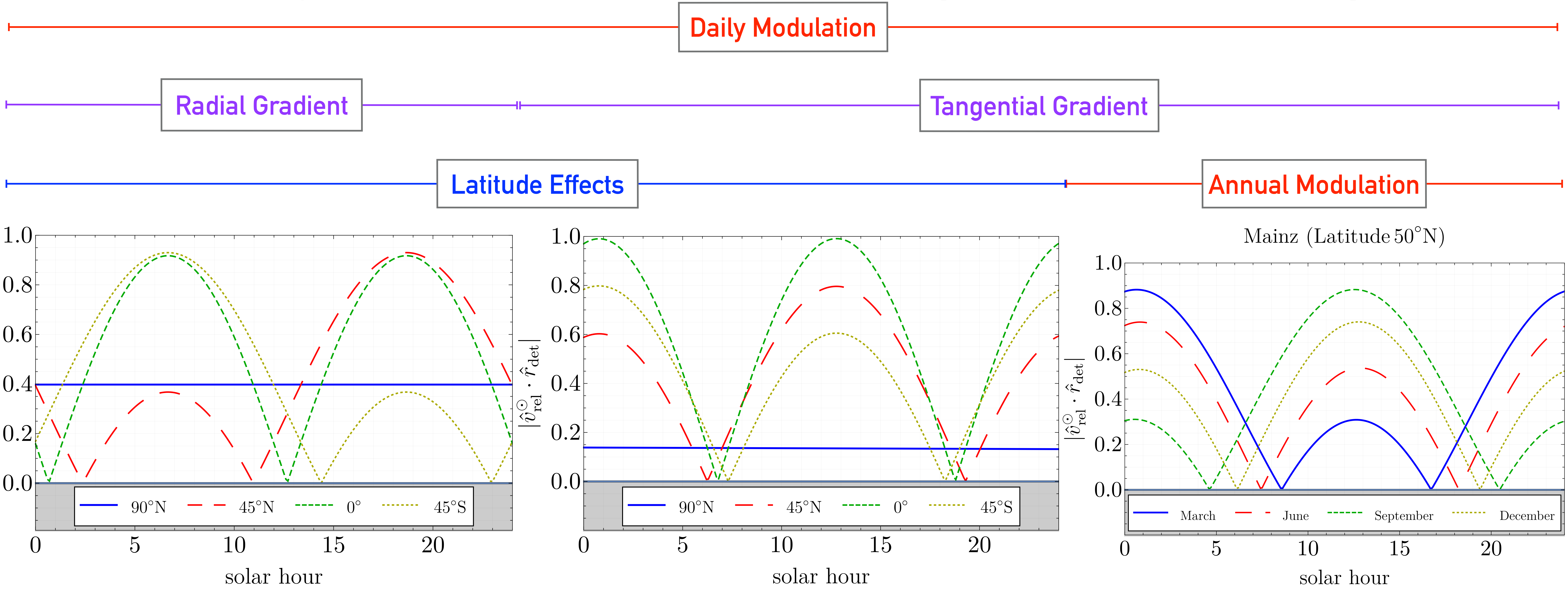


Signal depends both on detector orientation and latitude!

Daily and annual modulation of the signal!

Banerjee, Budker, **JE**, Flambaum,
Kim, Matsedonskyi, Perez
(1912.04295)

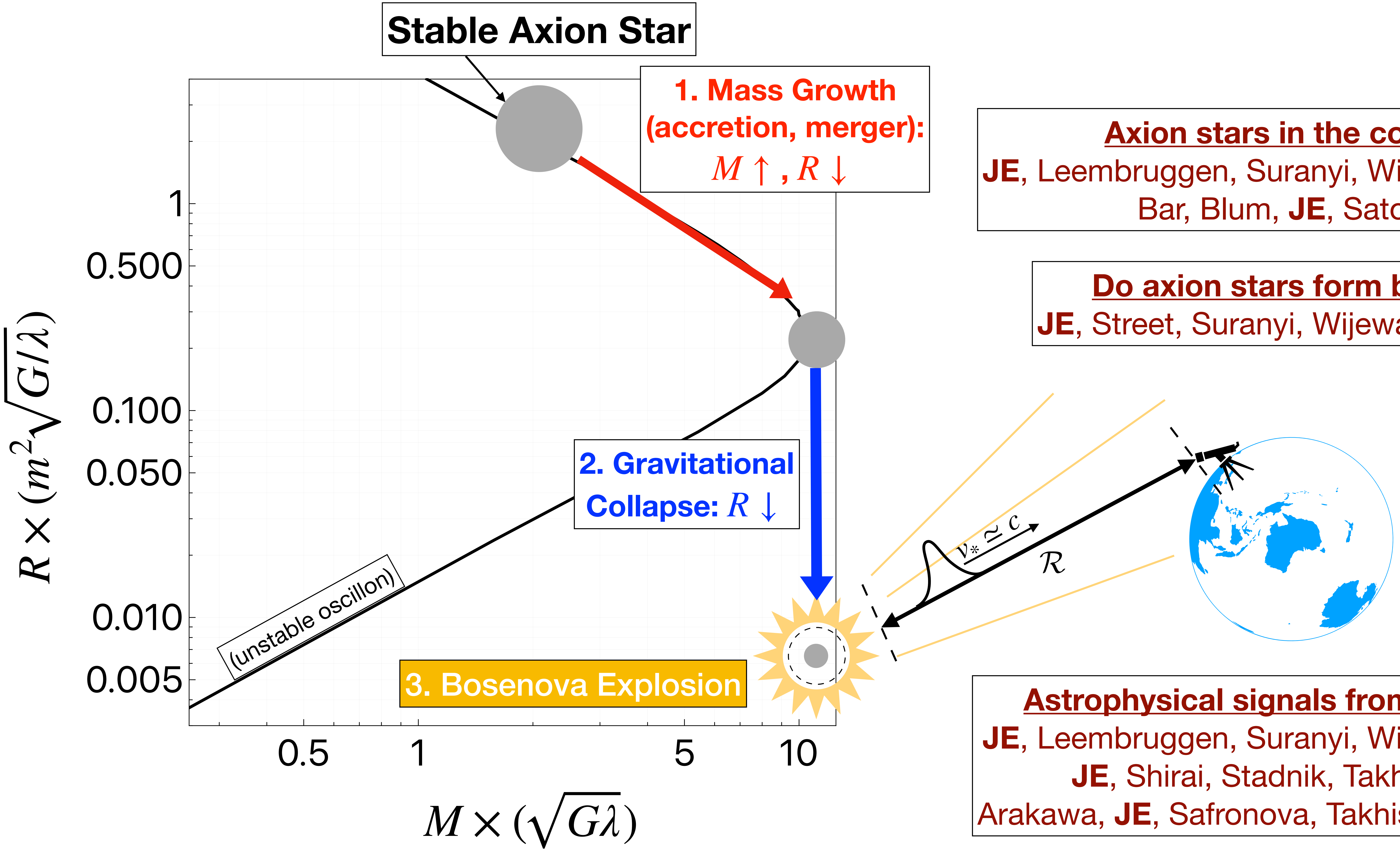
Signal Modulation (Solar Halo)



- ◉ Upshot: Sideband analysis in existing axion experiments can distinguish virialized ULDM from bound axion halos in our solar system
- ◉ Also motivates <u>network searches</u> (see e.g. GNOME 2305.01785)

Banerjee, Budker, **JE**, Flambaum, Kim, Matsedonskyi, Perez (1912.04295)

Axion Stars (ask me later 😊)



Axion stars in the cores of galaxies:
JE, Leembruggen, Suranyi, Wijewardhana (1805.12147)
Bar, Blum, **JE**, Sato (1903.03402)

Do axion stars form black holes? (no)
JE, Street, Suranyi, Wijewardhana (2011.09087)

Astrophysical signals from axion star collapse:
JE, Leembruggen, Suranyi, Wijewardhana (1608.06911)
JE, Shirai, Stadnik, Takhistov (2106.14893)
Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468)