Bosonic Halos:
Axion Stars and Dark Matter Capture


DALL-E 3 illustration
“Bosenova”

Joshua Eby
Oskar Klein Centre
Stockholm University

Barolo Astroparticle Meeting (BAM)
2024/06/13

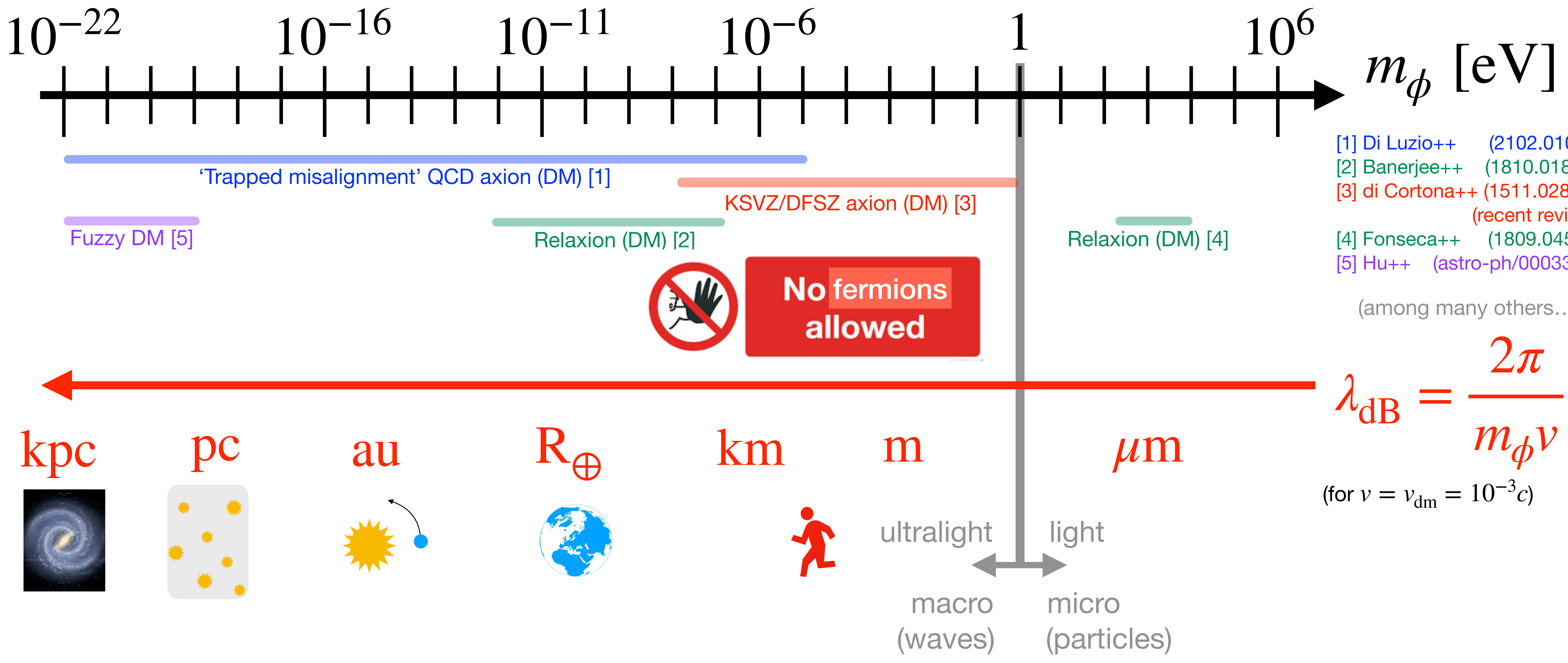
cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

COSMIC WISPERS
CA21106

Oskar Klein centre

Stockholms universitet

Light and Ultralight Dark Matter



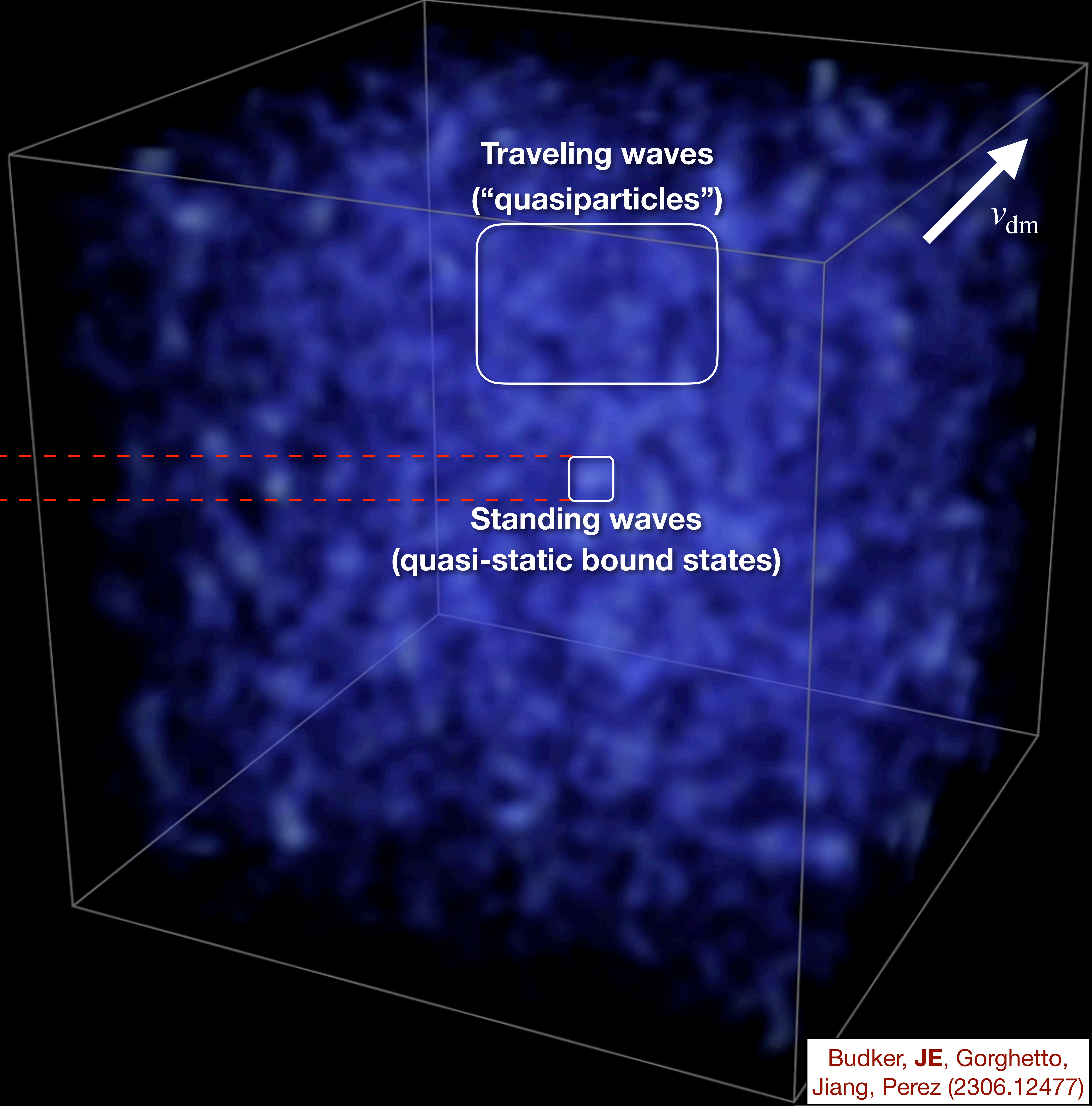
[1] Di Luzio++ (2102.01082)
[2] Banerjee++ (1810.01889)
[3] di Cortona++ (1511.02867) (recent review)
[4] Fonseca++ (1809.04534)
[5] Hu++ (astro-ph/0003365)

(among many others…)

$$\lambda_{\mathrm{dB}} = \frac{2\pi}{m_\phi v}$$

(for $v = v_{\mathrm{dm}} = 10^{-3}c$)

de Broglie wavelength $\lambda_{\rm dB}$



Traveling waves ("quasiparticles")

Standing waves (quasi-static bound states)

Wave amplitude $\Longleftrightarrow$ DM density ρ

Average local density

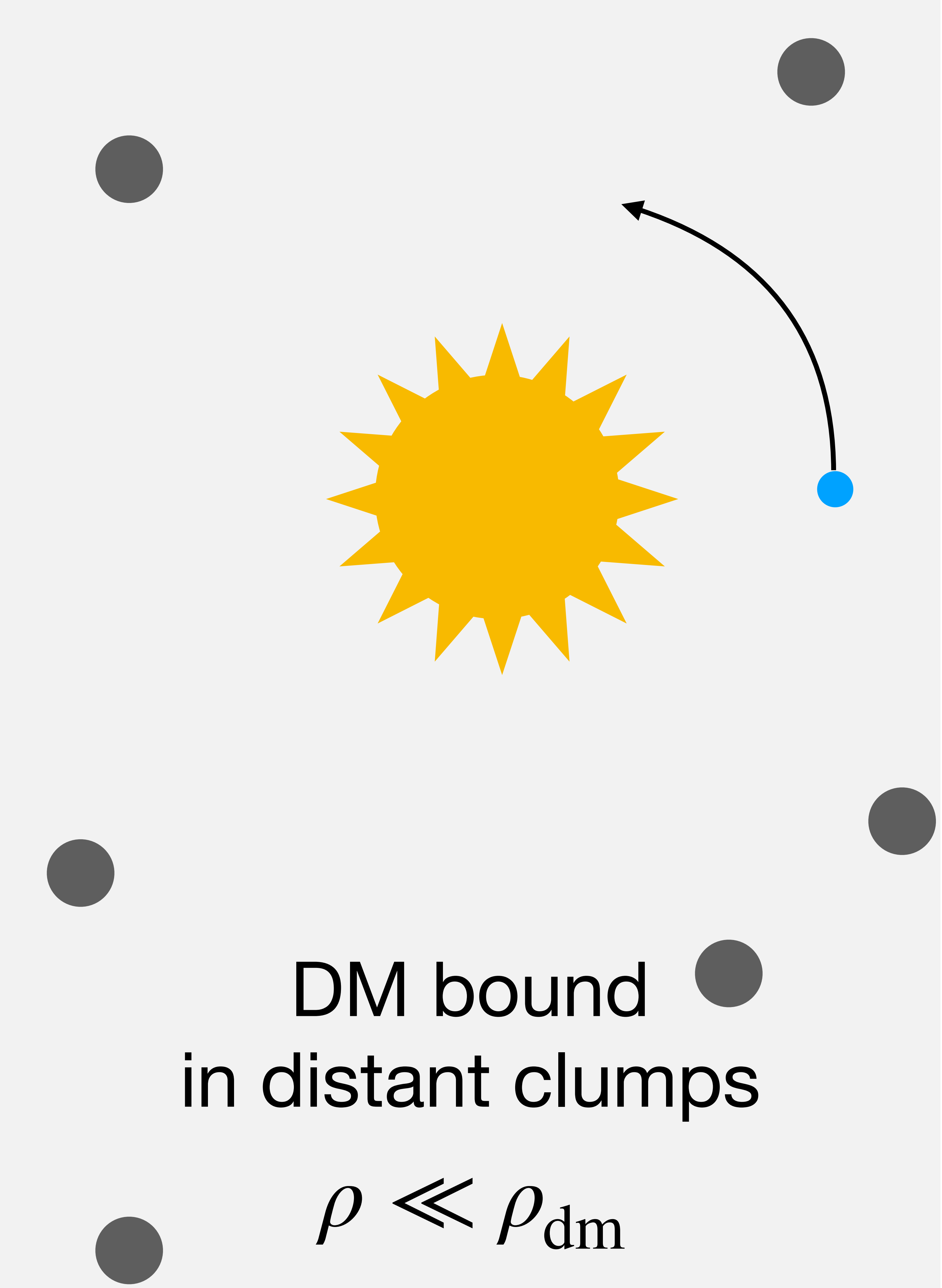
$$\rho_{\rm dm} = 0.4\,{\rm GeV/cm^3}$$

with variations on scales of order $\lambda_{\rm dB}$

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

The Very Local DM Density

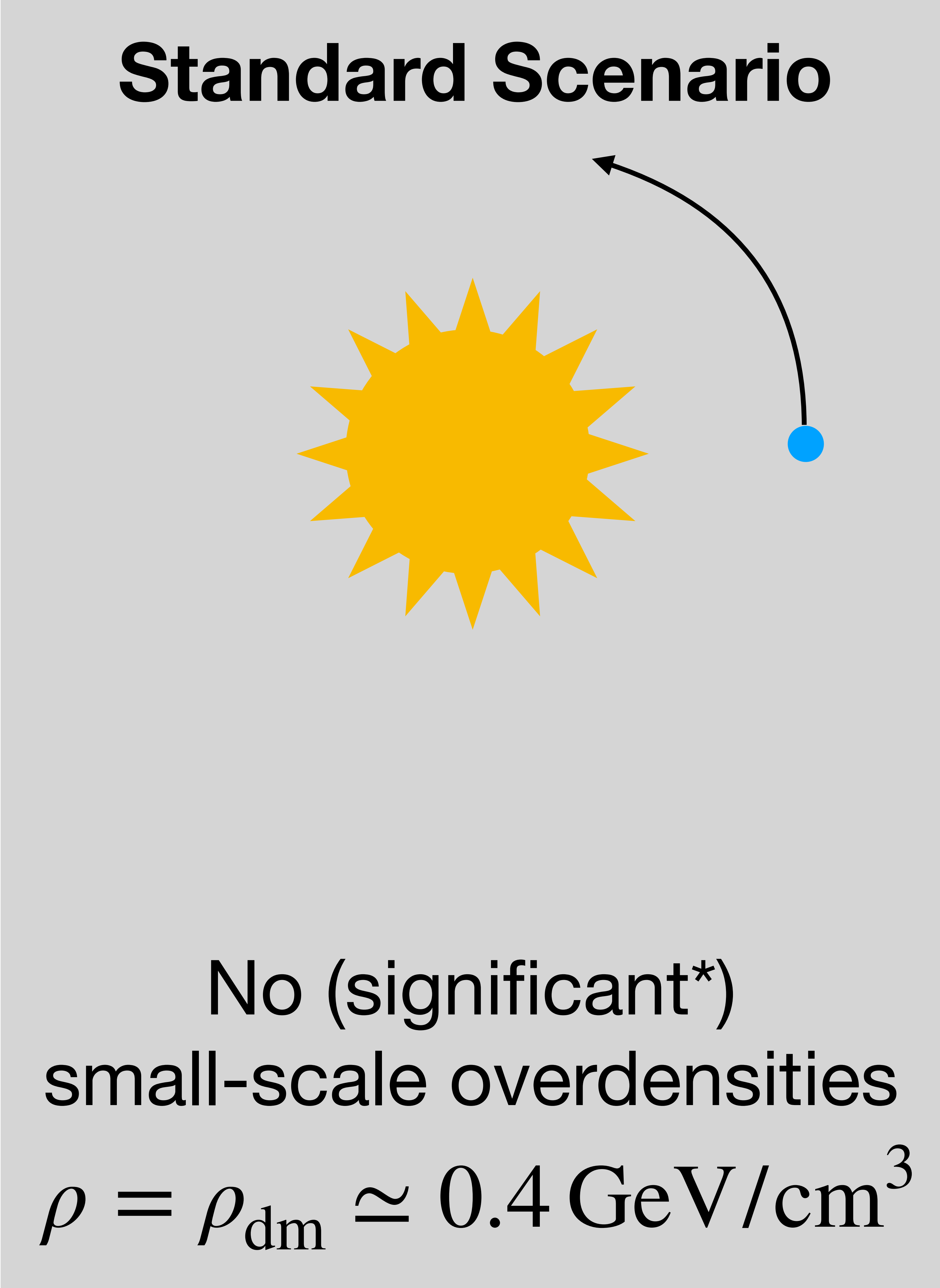
(inside the solar system)



DM bound
in distant clumps

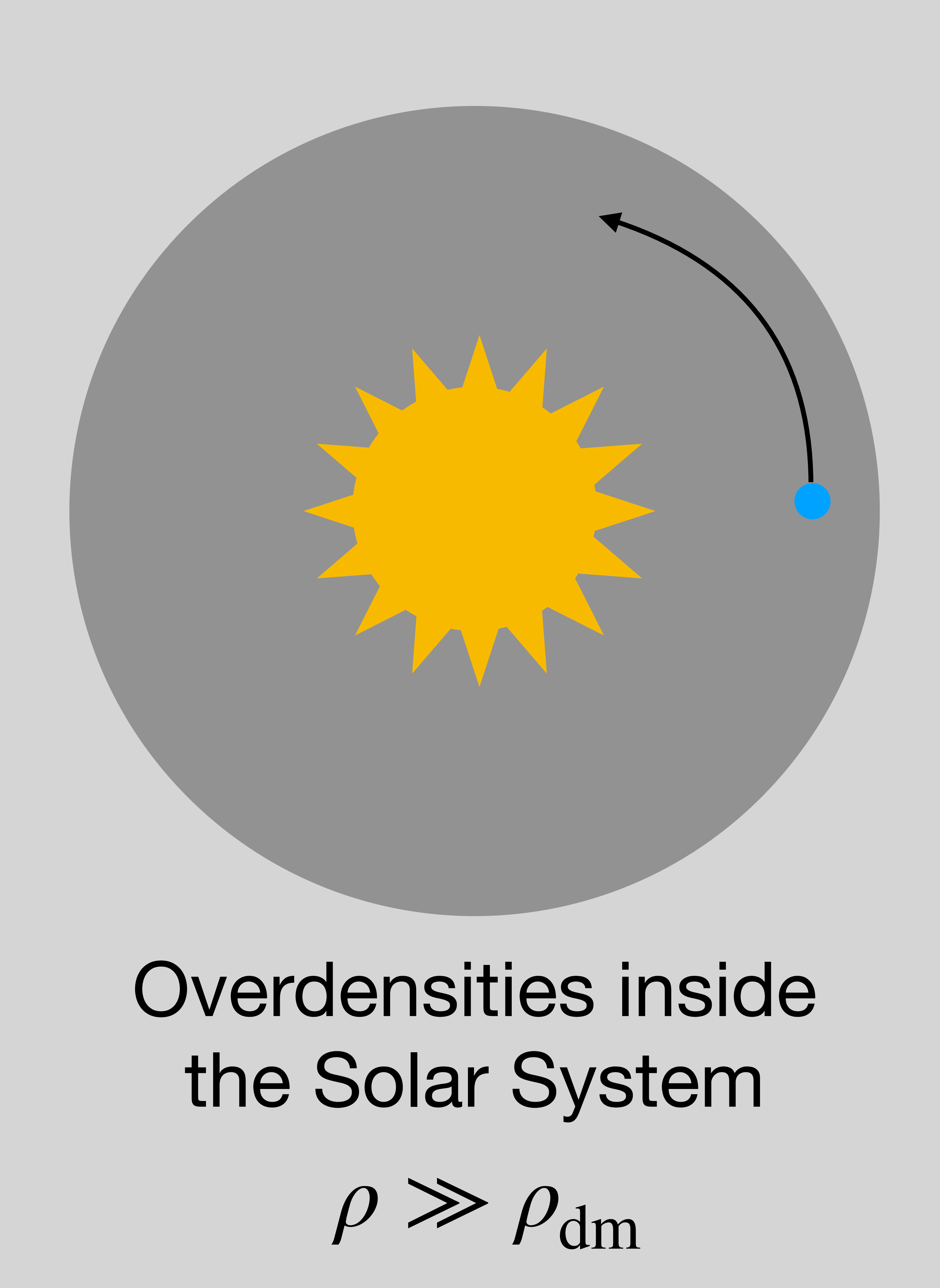
$$\rho \ll \rho_{\rm dm}$$

Standard Scenario



No (significant*)
small-scale overdensities

$$\rho = \rho_{\rm dm} \simeq 0.4\,{\rm GeV/cm^3}$$



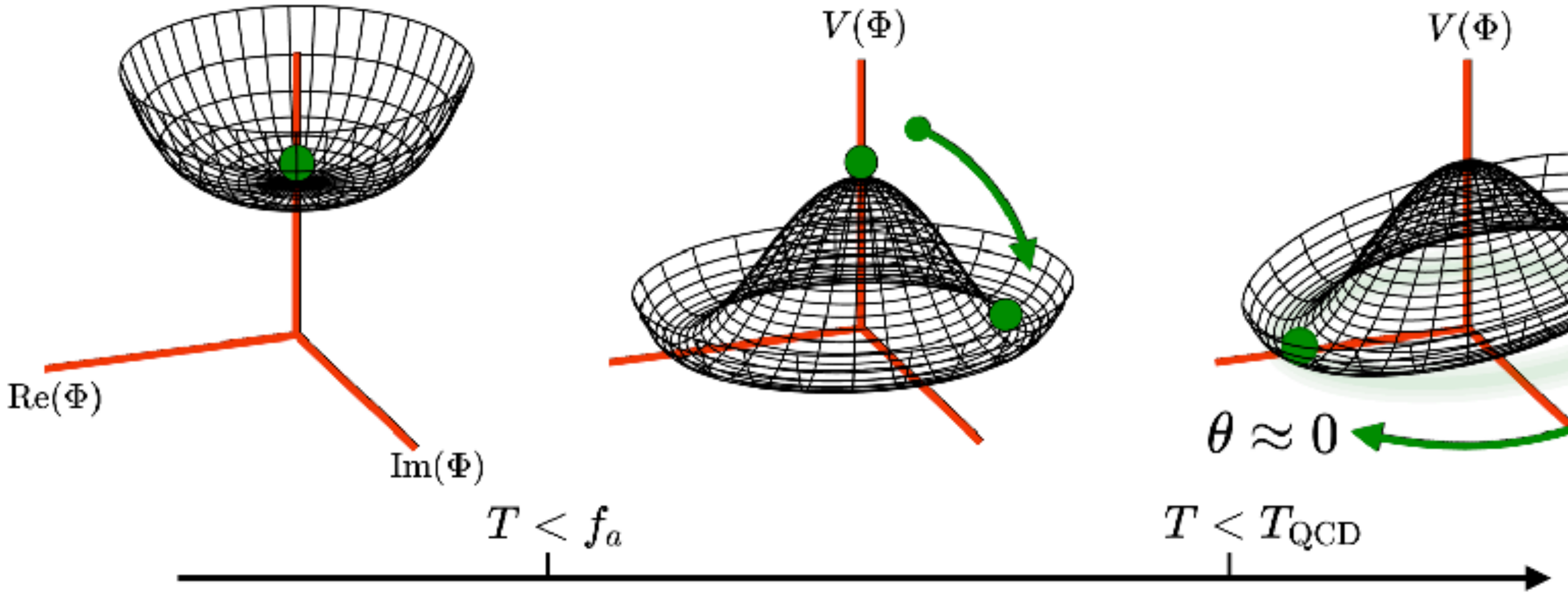
Overdensities inside
the Solar System

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

*for ULDM, *always* $\exists\ \mathcal{O}(1)$ fluctuations

Axion Cosmology

Recent review:
O'Hare (2403.17697)



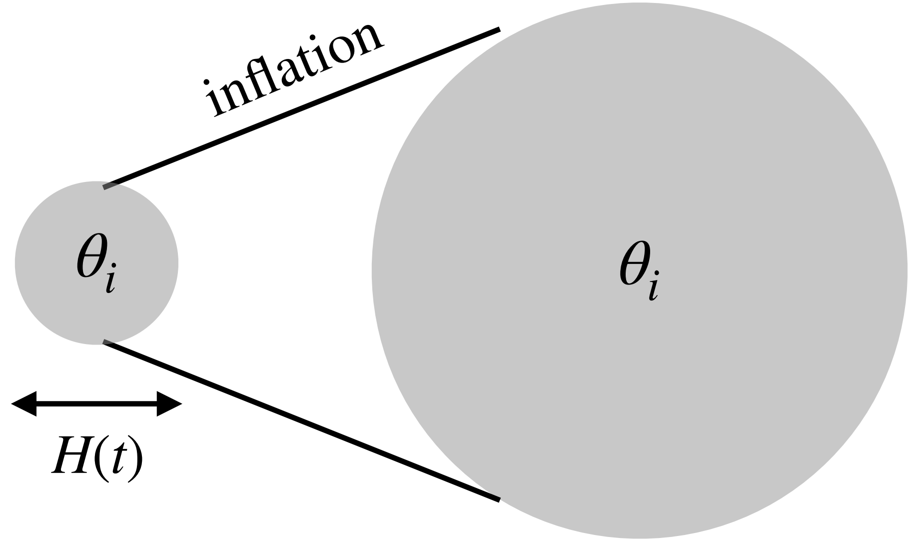
$$V(\Phi) = \lambda_\Phi \left(|\Phi|^2 - \frac{f_a^2}{2} \right)^2 + \Lambda^4 \left(1 - \cos \frac{\phi}{f_a} \right)$$

QCD axion:

$$V_\theta(\phi) = \left(\theta_{\mathrm{QCD}} + \frac{\phi}{f_a} \right) G^{\mu\nu} \tilde{G}_{\mu\nu} \longrightarrow 0 \qquad \Lambda_{\mathrm{QCD}}^4 \simeq m_\phi^2 f_a^2$$

Pre-inflationary

$f_a \gtrsim H_I$

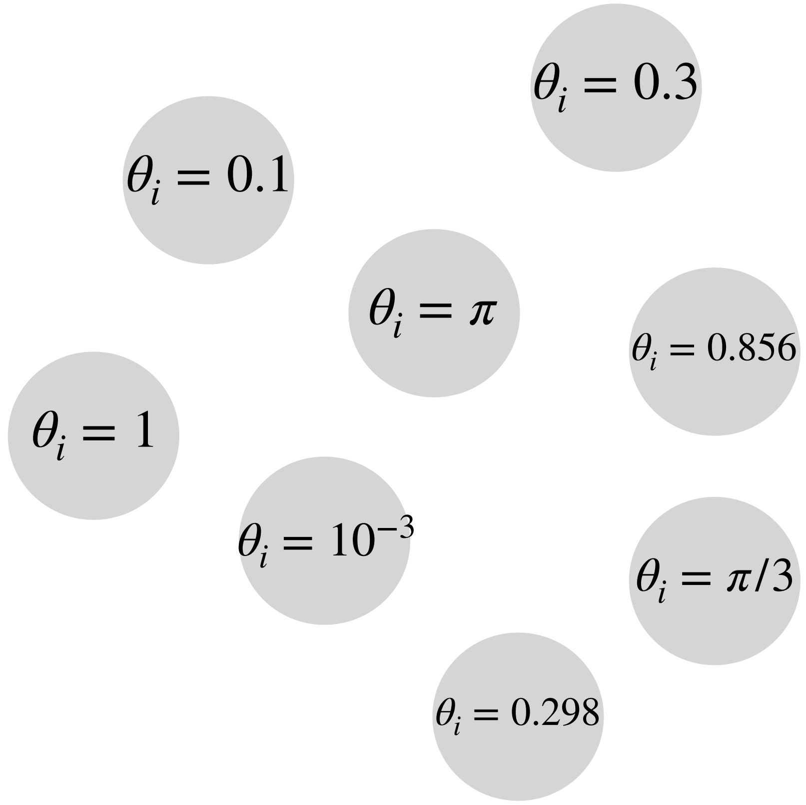


$$\longrightarrow \Omega_a^{\mathrm{misalignment}}(f_a, \theta_i) \simeq 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \boxed{\theta_i^2}$$

?

Post-inflationary

$f_a \lesssim H_I$



$$\longrightarrow \Omega_a^{\mathrm{misalignment}}(f_a) \simeq 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \boxed{\langle \theta_i^2 \rangle}$$

$\pi^2/3$

predictive !

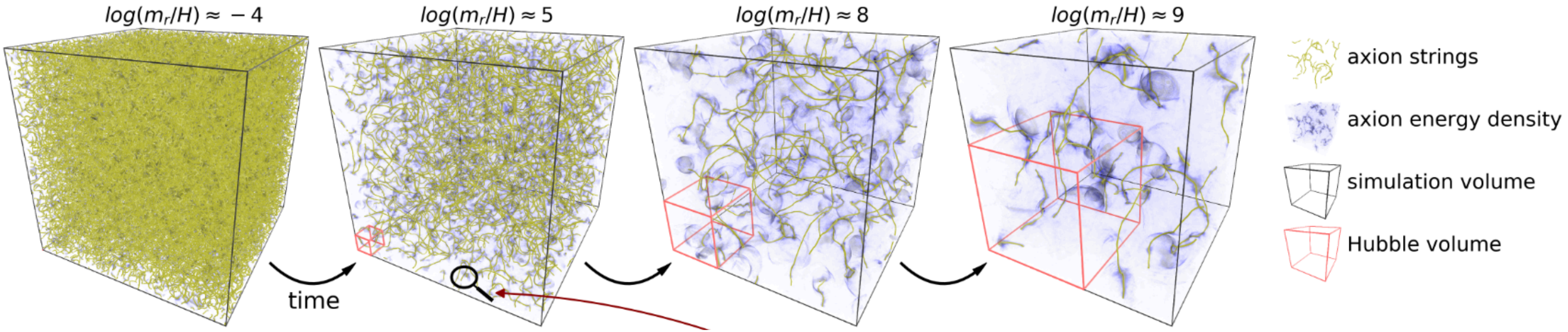
Credit: Ken’ichi Saikawa

World-leading simulations: $\log \frac{m_r}{H} \simeq 9$

Physical: $\log \frac{m_r}{H} \simeq 70$

Buschmann, Foster, Hook, Peterson, Willcox, Zhang, Safdi (2108.05368)

Another view



World-leading simulations: $\log \frac{m_r}{H} \simeq 9$

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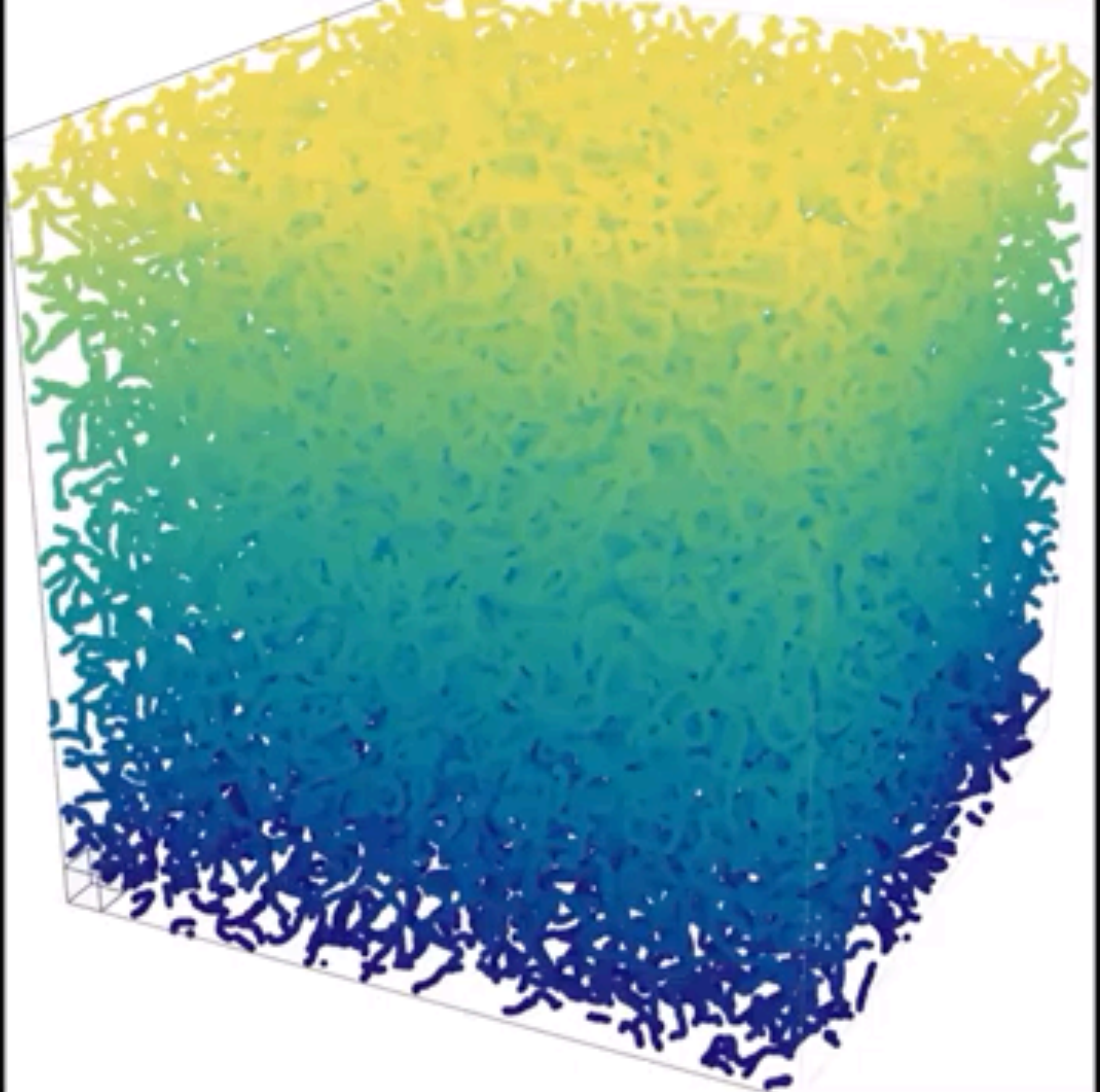


Gorghetto, Hardy, Villadoro
(2007.04990)

Movie via Marco Gorghetto
https://www.youtube.com/watch?v=DbvM7emtodo

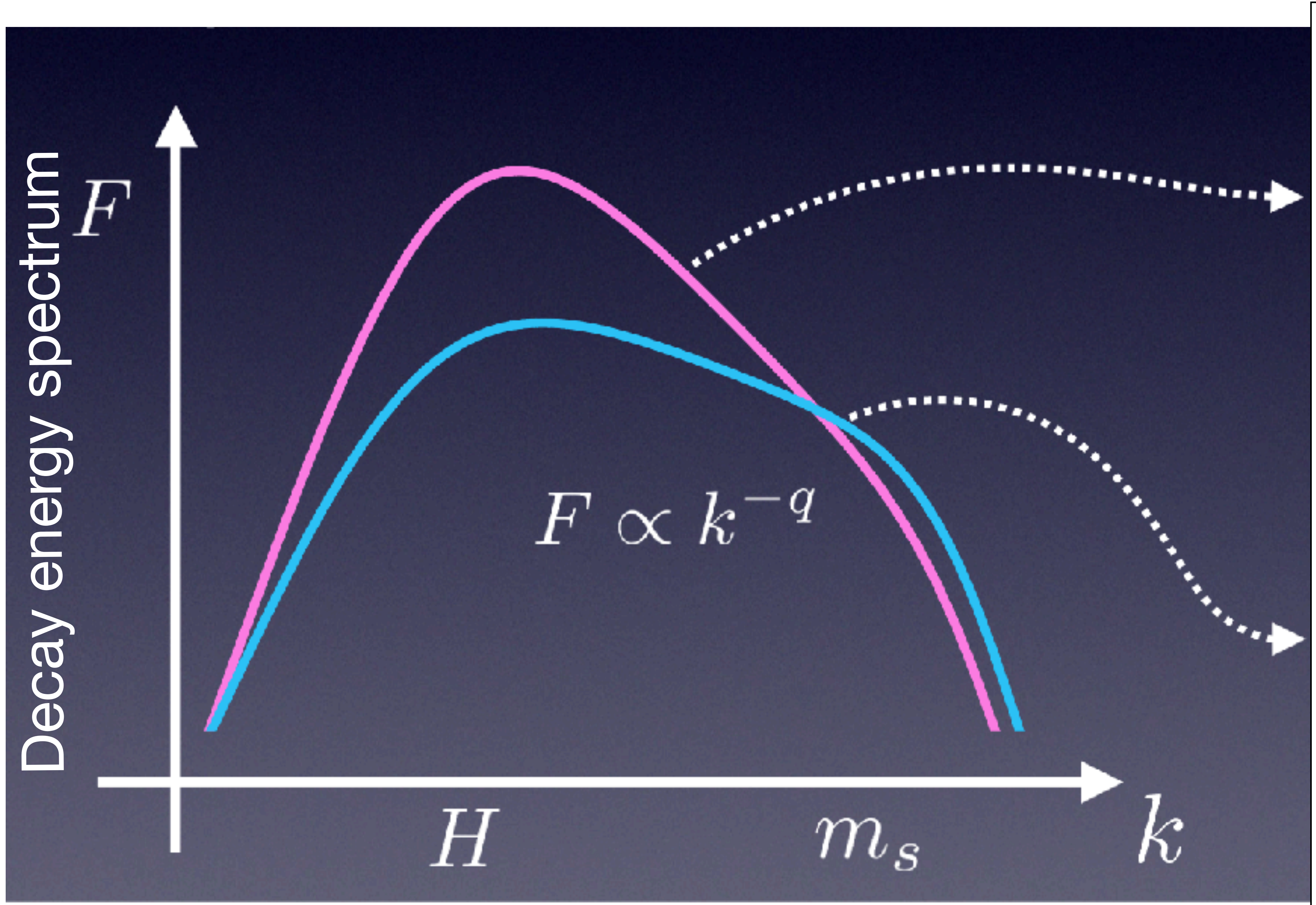
World-leading simulations: $\log \frac{m_r}{H} \simeq 9$

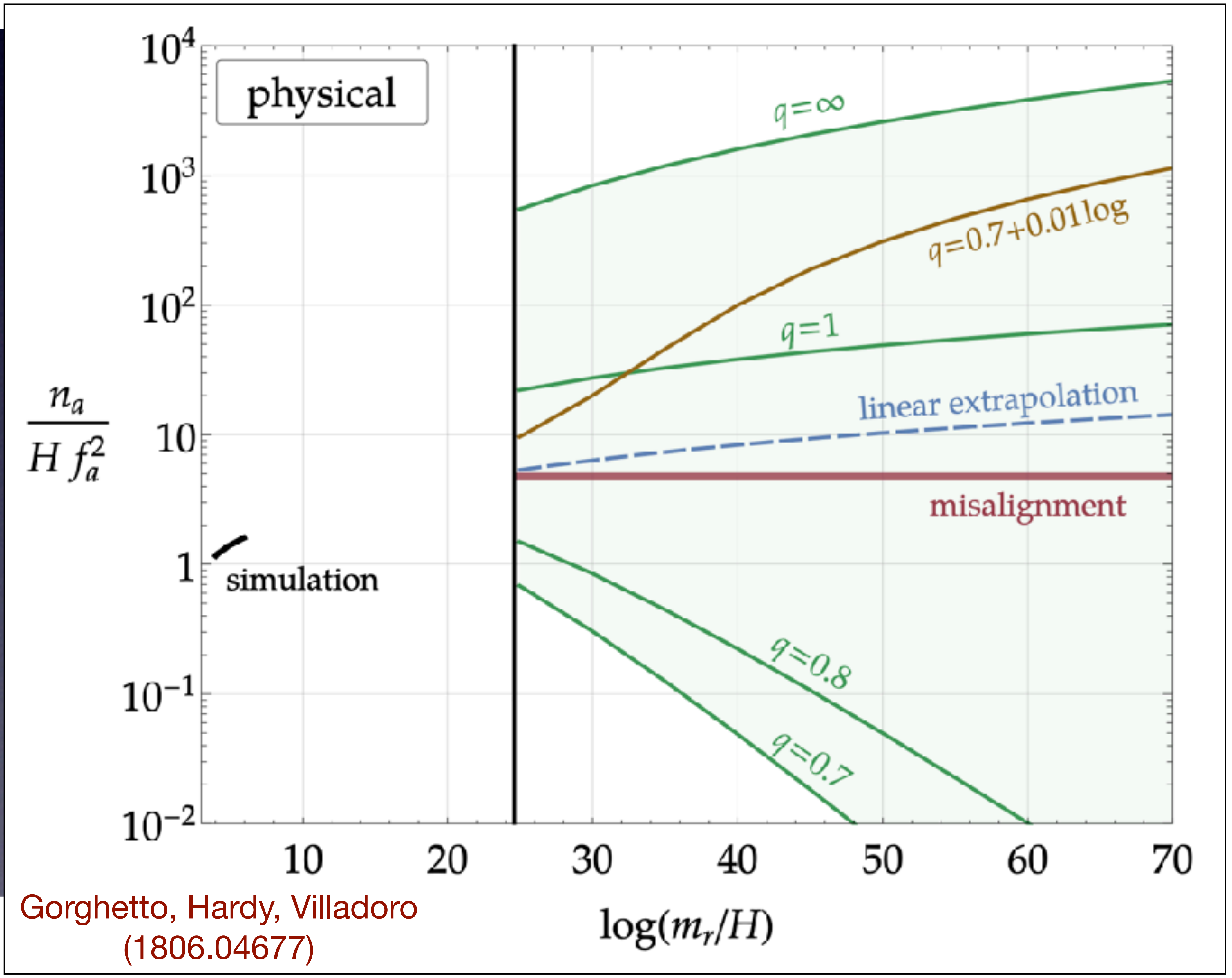
Physical: $\log \frac{m_r}{H} \simeq 70$

Axion String Decay

Post-inflationary scenario: $\Omega_a = \Omega_a^{\text{misalignment}}(f_a) + \Omega_a^{\text{strings}}(f_a)$

Credit: Ken'ichi Saikawa





Gorghetto, Hardy, Villadoro (1806.04677)

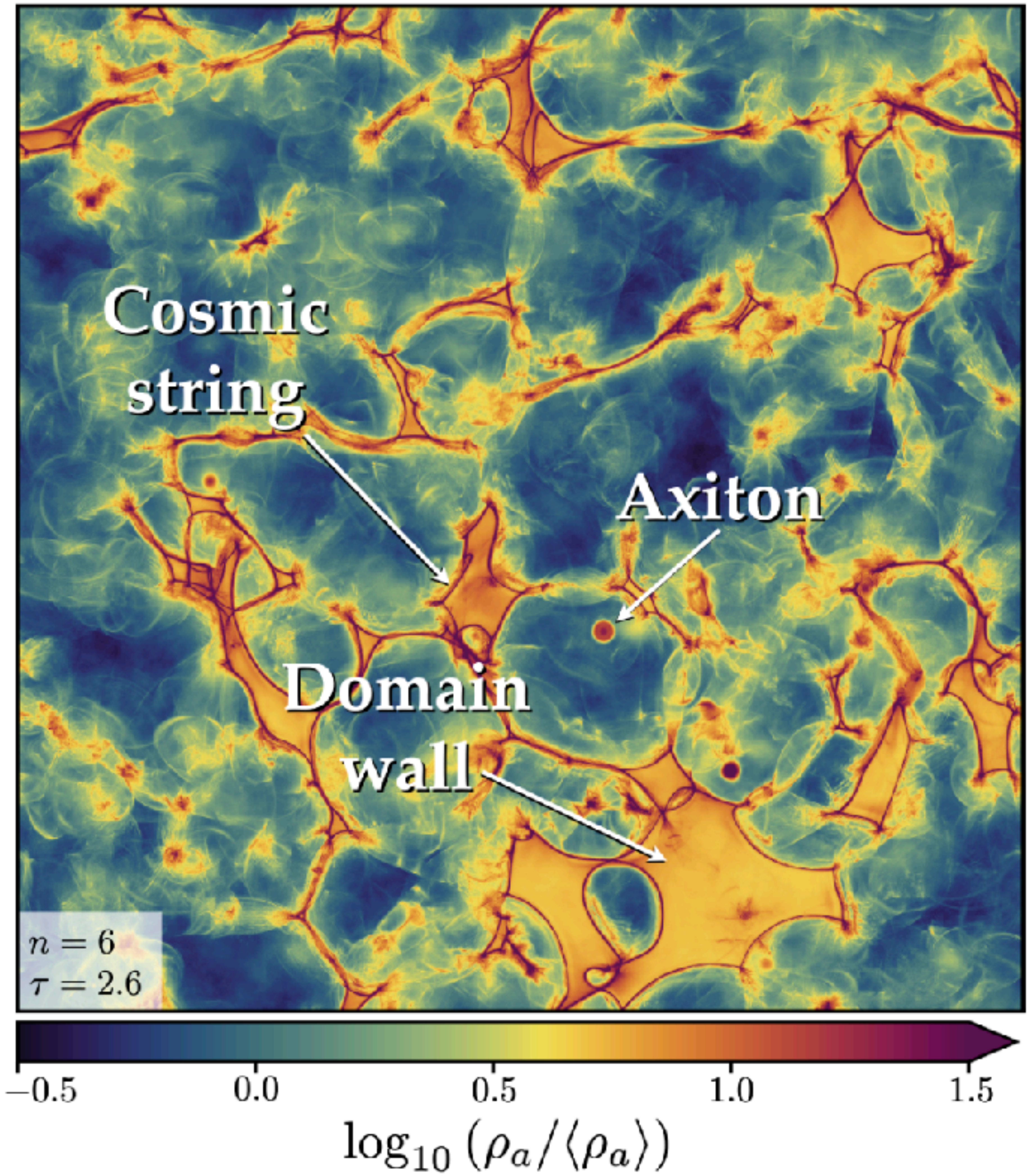
The “Predictive” Post-Inflationary QCD Axion

Saikawa, Redondo, Vaquero, Kaltschmidt (2401.17253)

Rest of this talk: more general because we take m_ϕ, f_a as free parameters (need not assume QCD axion)

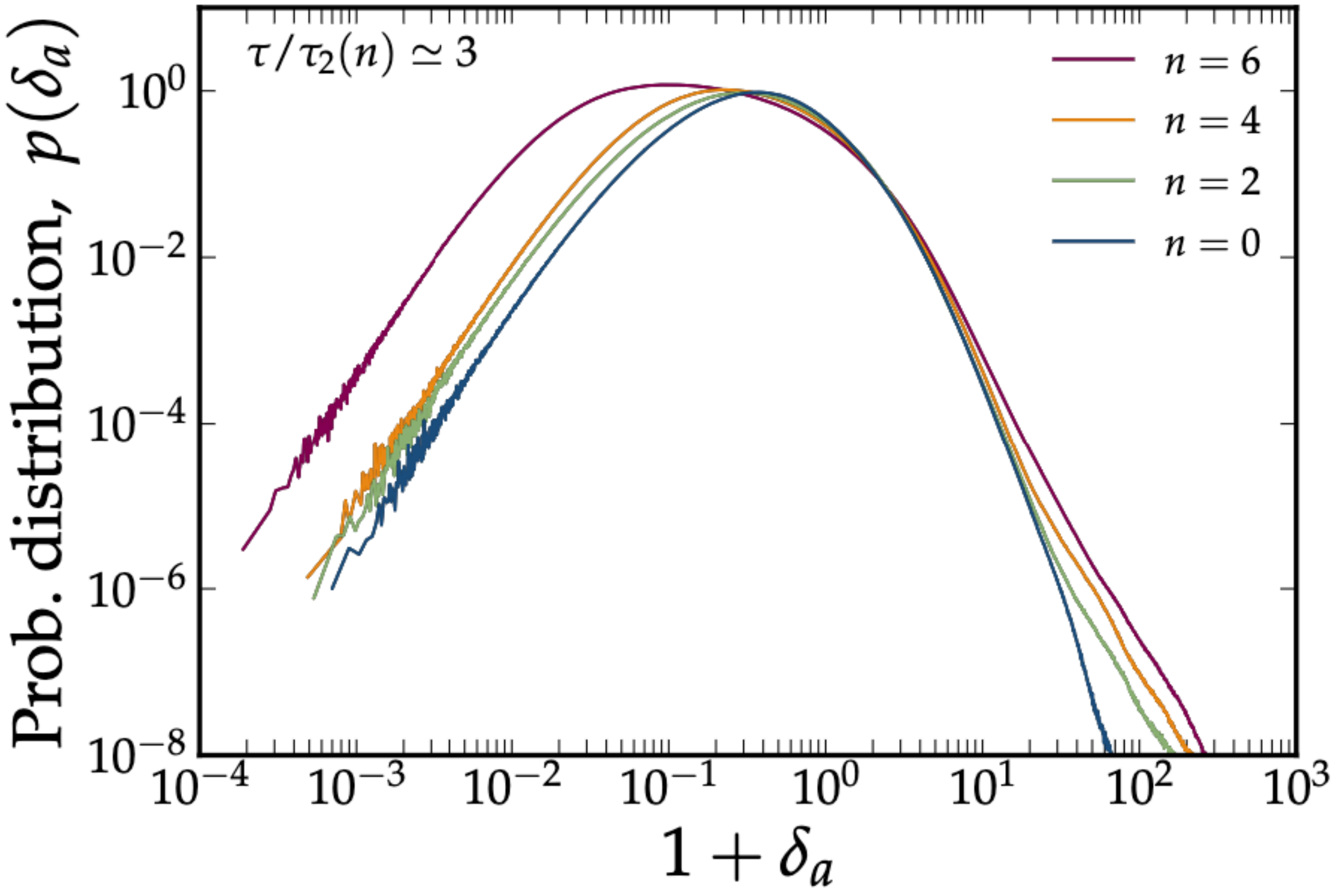
ALPs and Temperature Dependence

O'Hare, Pierson, Redondo, Wong (2112.05117)



$$\equiv \log_{10}(1+\delta_a)$$

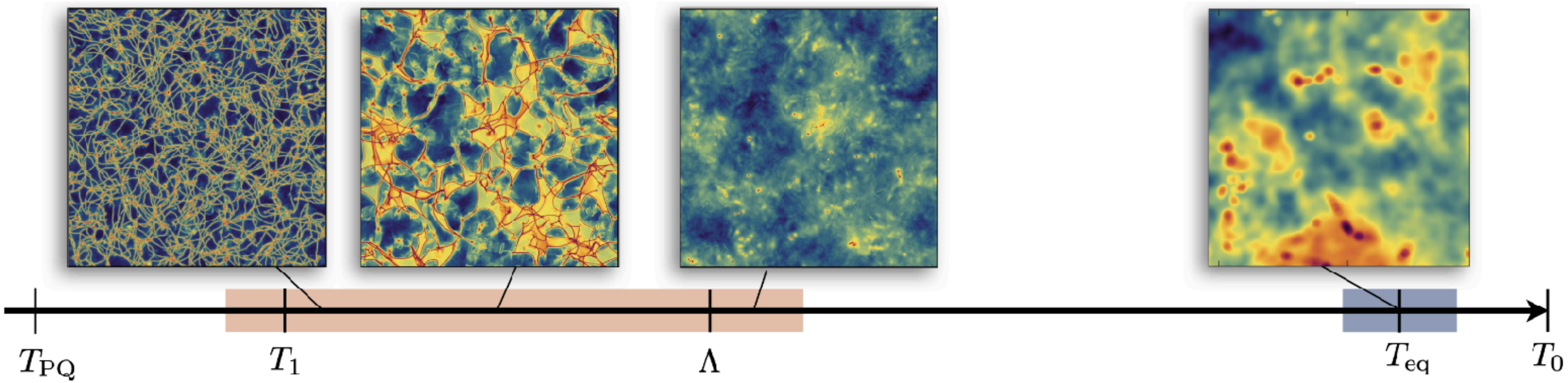
just after string-wall network decay



$$m_\phi(T)^2 \simeq m_\phi^2 \left(\frac{T_\star}{T}\right)^n$$

Axion Miniclusters

Hogan and Rees (PLB 1988)
Kolb and Tkachev (hep-ph/9303313)
…
O'Hare, Pierson, Redondo, Wong (2112.05117)

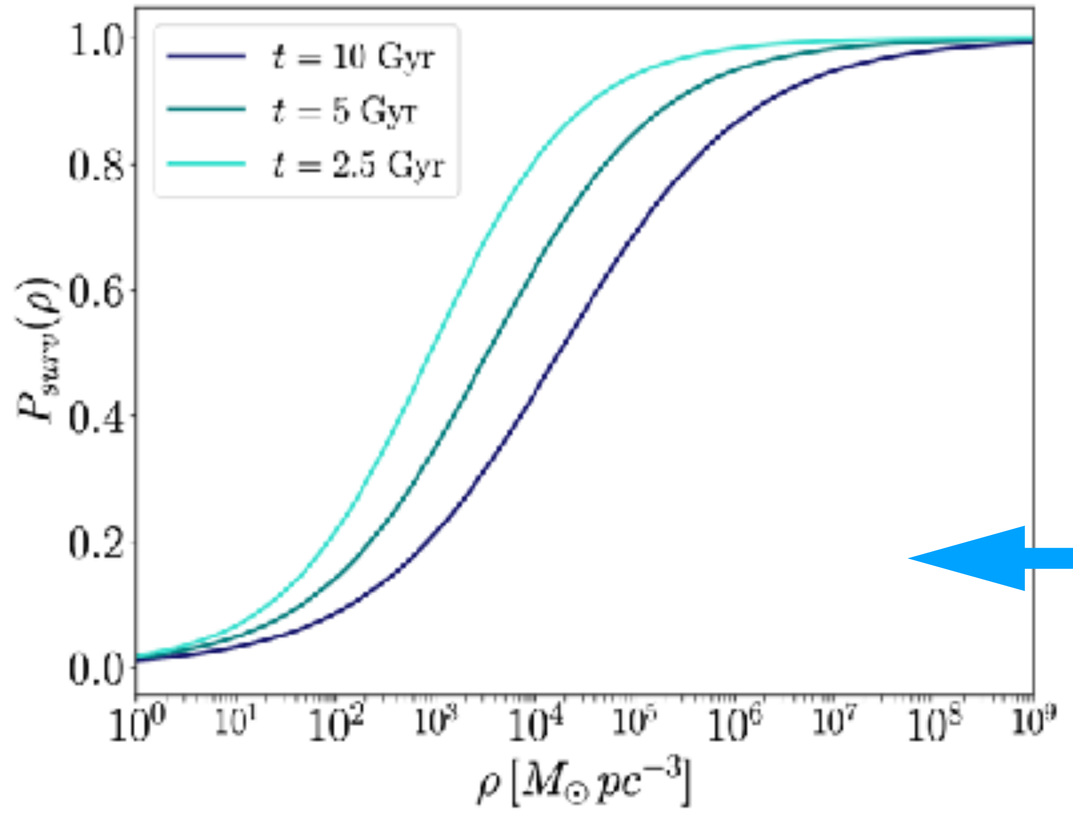


$\tau \ll 1$ Axion strings Massless axions $\xrightarrow{\text{Potential tilts}}$ $\tau \sim 1$ String/wall Network $\xrightarrow{\text{Collapse}}$ $\tau \gtrsim 3$ Axitons NR axions $\xrightarrow{\text{WKB}}$ $\tau \gtrsim 6$ Free-streaming Adiabatic evolution $\longrightarrow$ Gravitational collapse

'Typical' example with $m(T) = m$, i.e. $n = 0$

$$M_{\rm mc} \sim (1+\delta_a)M_0 \sim 10^{-10} M_\odot (1+\delta_a)\left(\frac{f_a}{10^{14}\,{\rm GeV}}\right)^2 \left(\frac{m_\phi}{10^{-10}\,{\rm eV}}\right)^2 \left(\frac{\rm GeV}{T_{\rm osc}}\right)^6$$

$$R_{\rm mc} \sim \frac{L_1}{z_{\rm eq}\delta_a} \sim \frac{10\,{\rm au}}{\delta_a}\left(\frac{10^{-10}\,{\rm eV}}{m_\phi}\right)^{1/2} \qquad \rho_{\rm mc} \sim \rho_{\rm eq}\delta_a^3(1+\delta_a)$$



Survive tidal disruption?

Dokuchaev, Eroshenko, Tkachev (1710.09586)

Kavanaugh, Edwards, Visinelli, Weniger (2011.05377)

Dandy, Schwetz, Todarello (2206.04619)

Shen, Xiao, Hopkins, Zurek (2207.11276)

Axion Miniclusters → New Searches 🙂

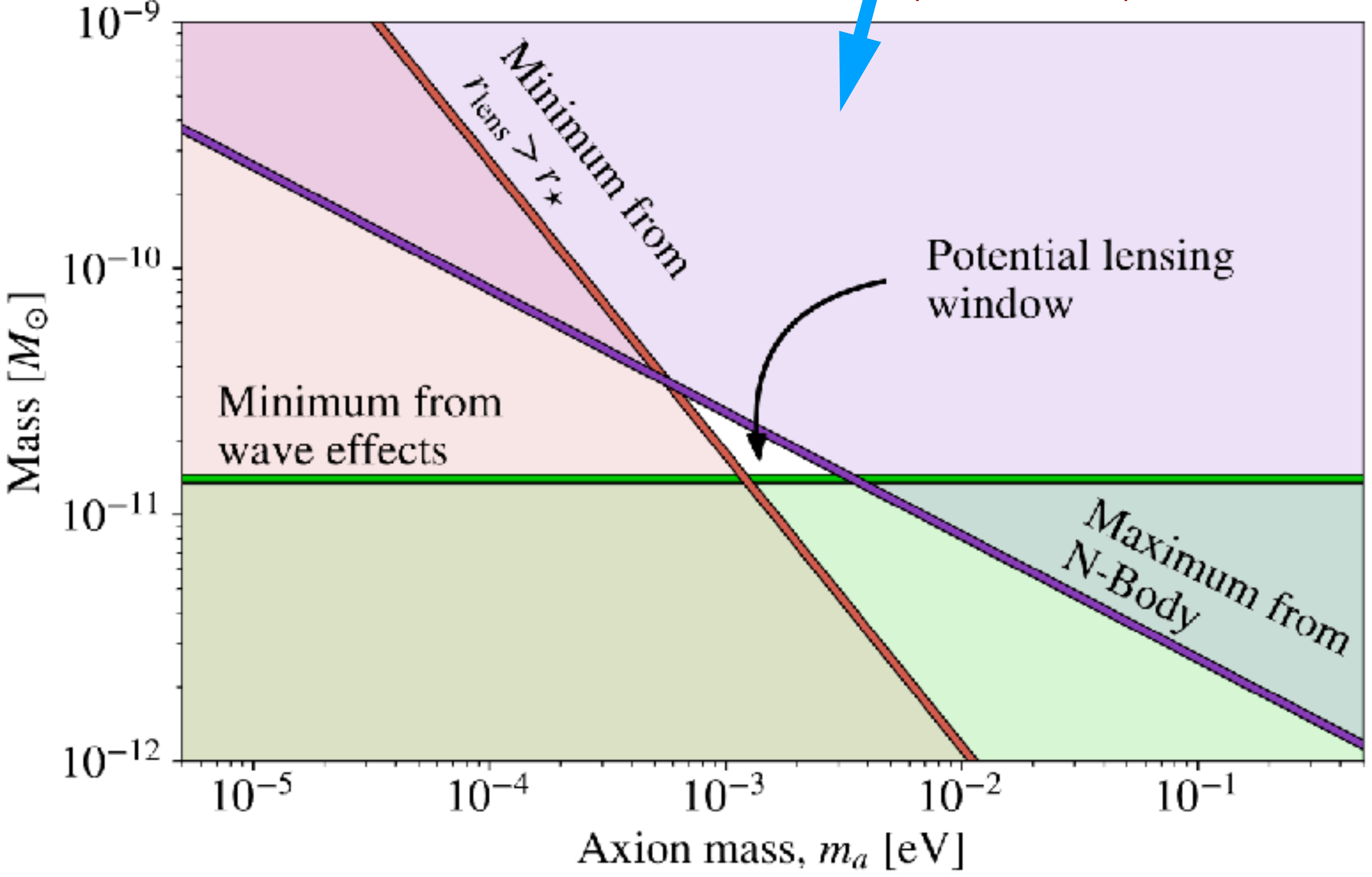
Gravitational microlensing

Early work

Fairbairn, Marsh (🇬🇧), Quevillon, Rozier (1707.03310)

including simulations

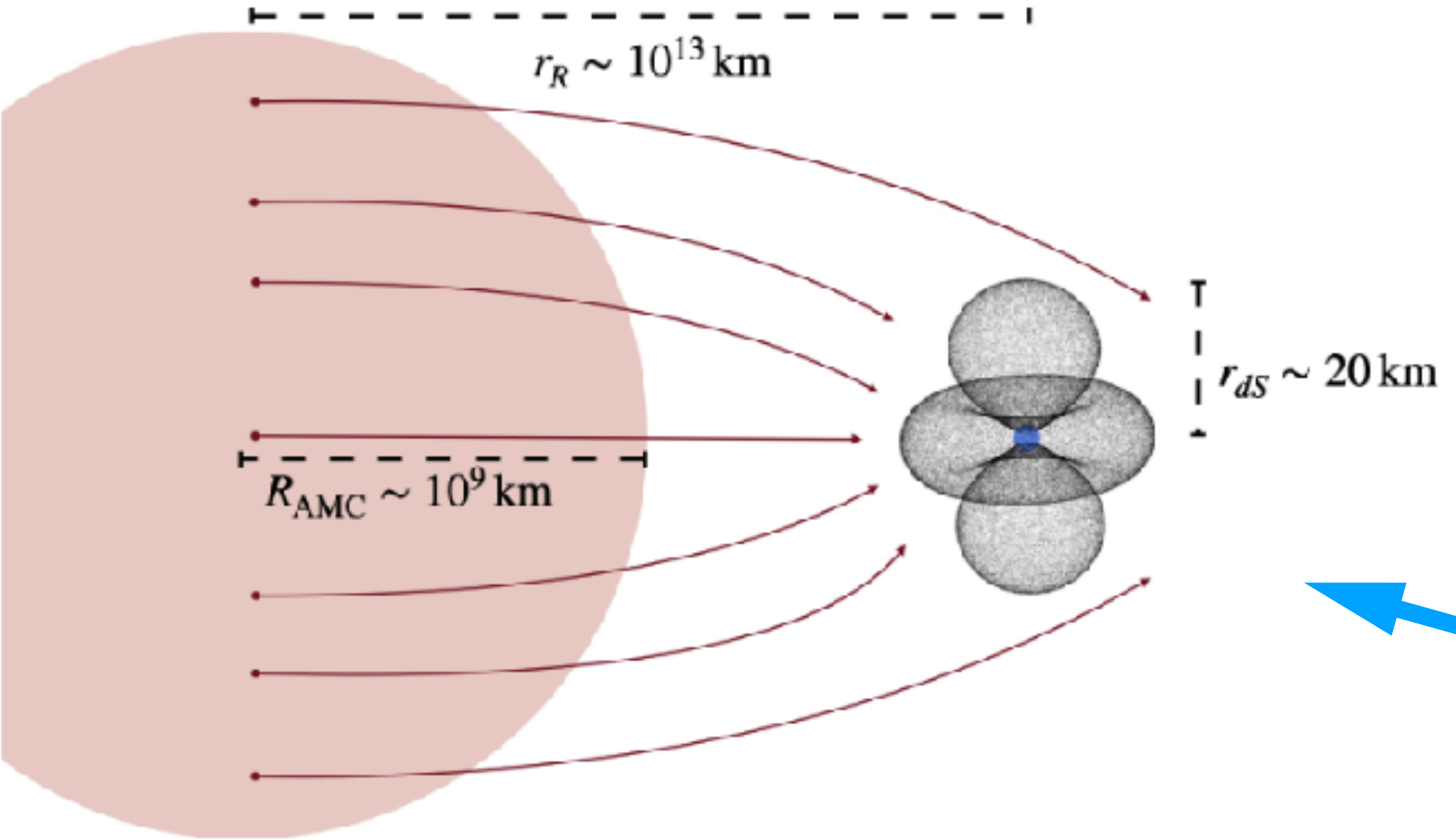
Ellis, Marsh (🇬🇧), Eggemeier, Niemeyer, Redondo, Dolan (2204.13187)



mc lensing modifies cluster lensing for highly-magnified stars

Dai and Miralda-Escudé (1908.01773)

Radio signals from neutron star encounters



Early work

Edwards, Kavanaugh, Visinelli, Weniger (2011.05378)

Detailed study, including e.g. tidal disruption

Witte, Baum, Lawson, Marsh (🇸🇪), Millar, Salinas (2212.08079)

Gravitational waves from axion miniclusters?

Sun, Zhang (2003.10527)

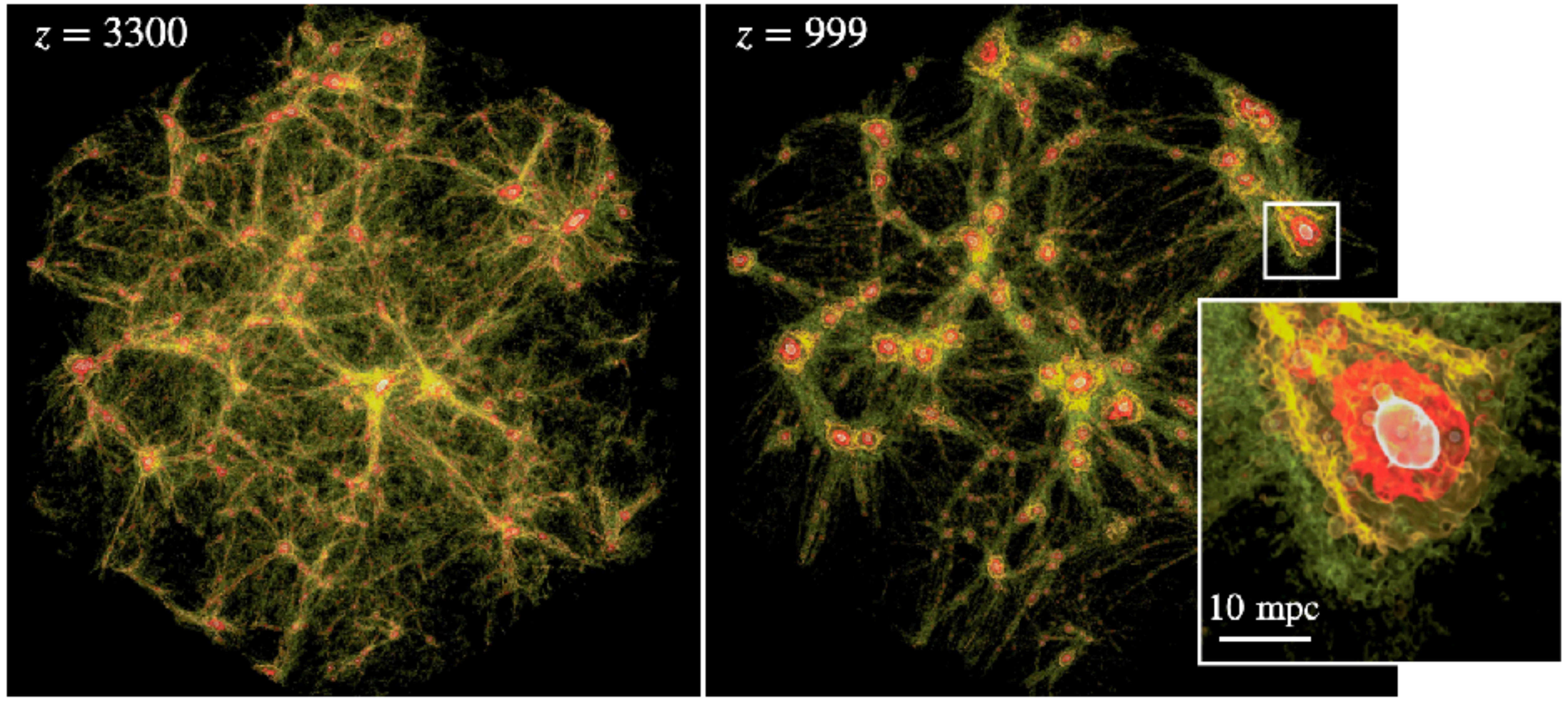
See also Urrutia (**https://pos.sissa.it/454/046/pdf**)

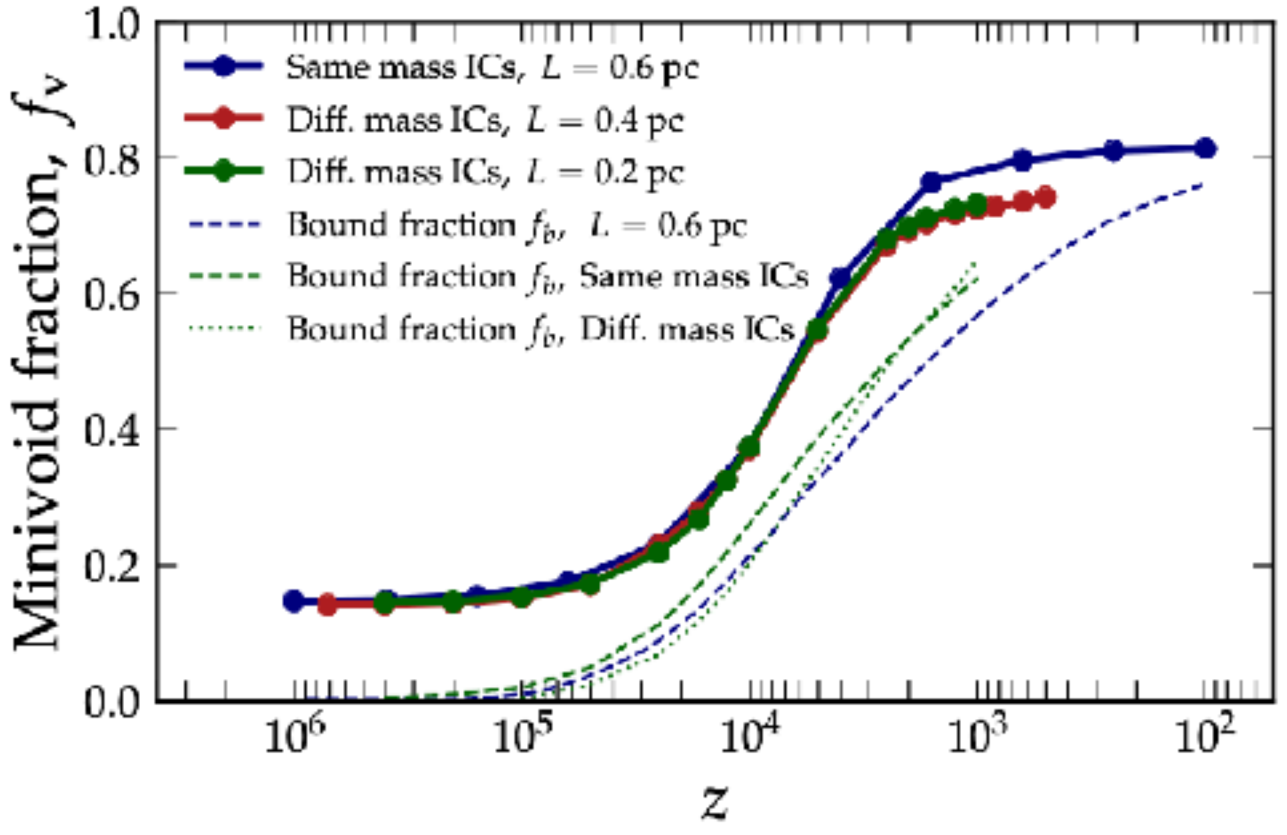
Explain surprisingly luminous early galaxies in JWST?

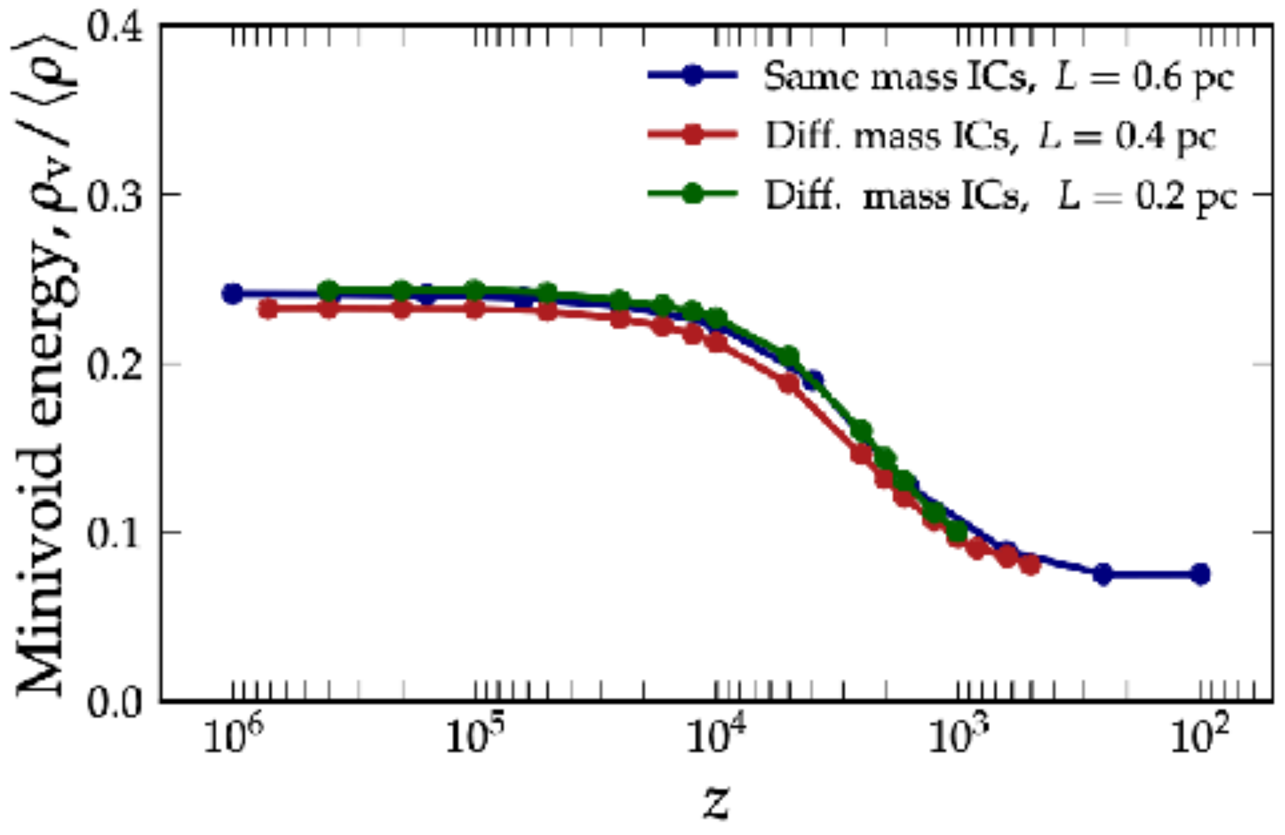
Hütsi, Raidal, Urrutia, Vaskonen, Veermäe (2211.02651)

Axion Miniclusters → Voids 🙁

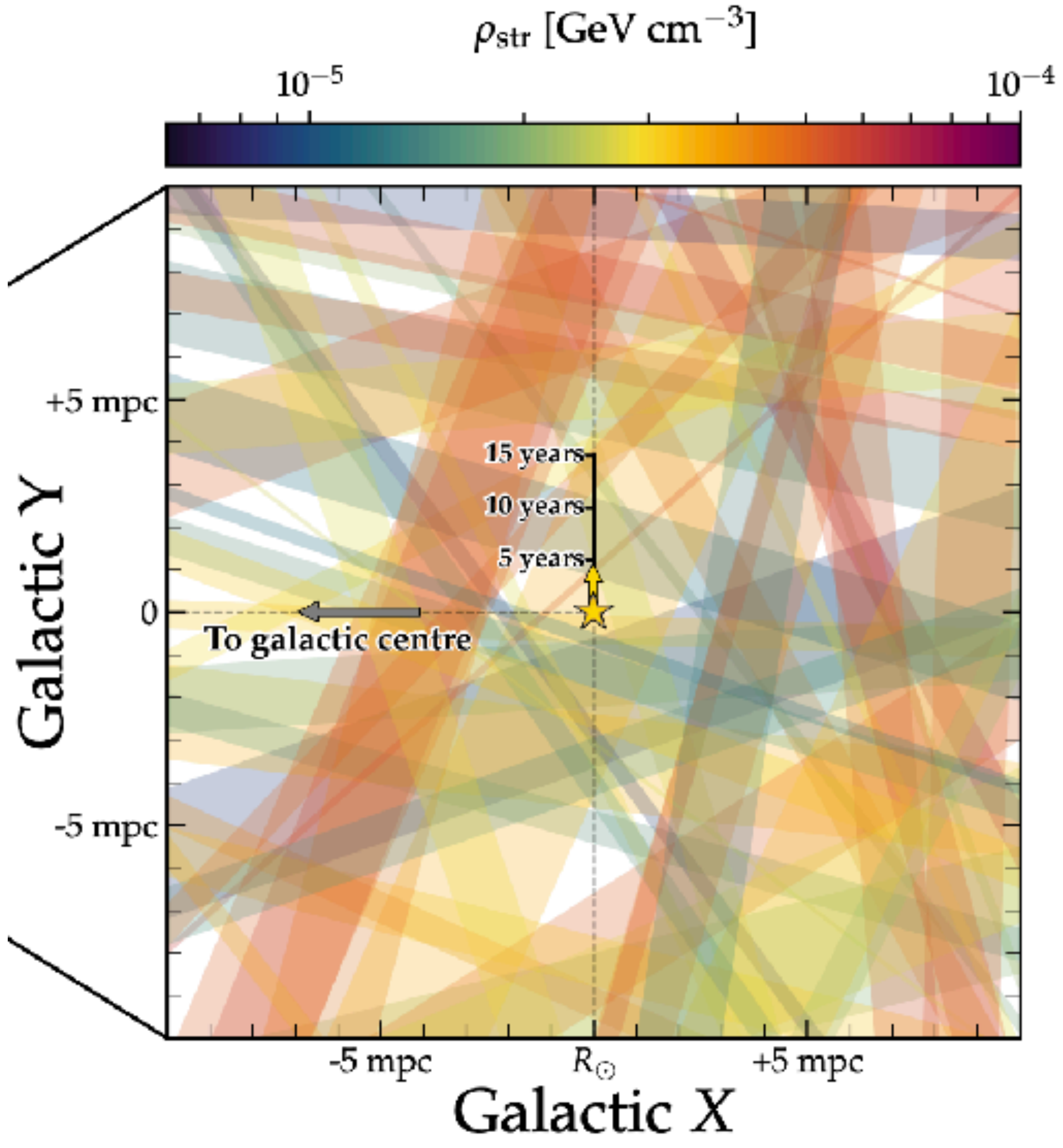
Eggemeier, O'Hare, Pierobon,
Redondo, Wong (2212.00560)





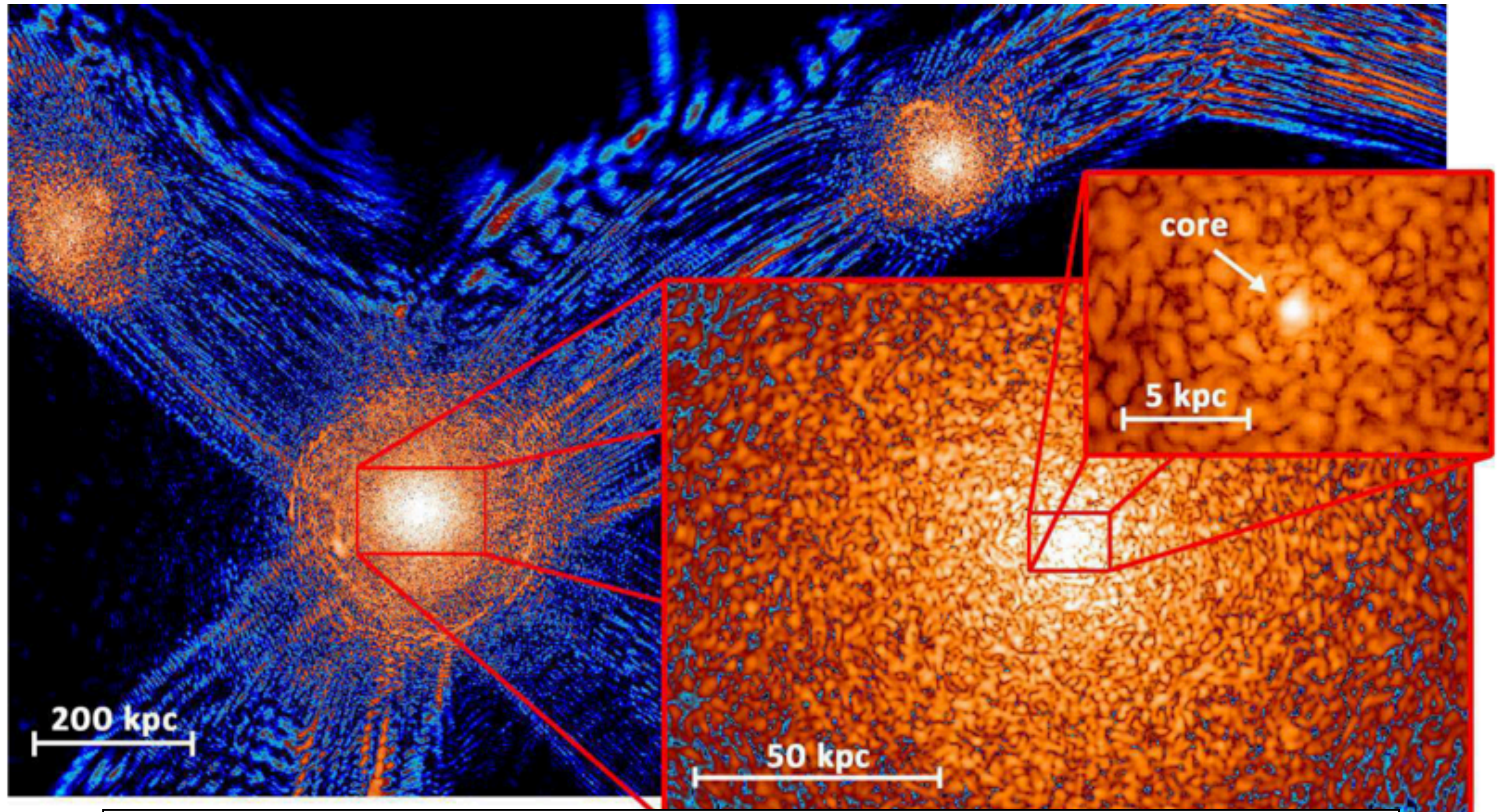


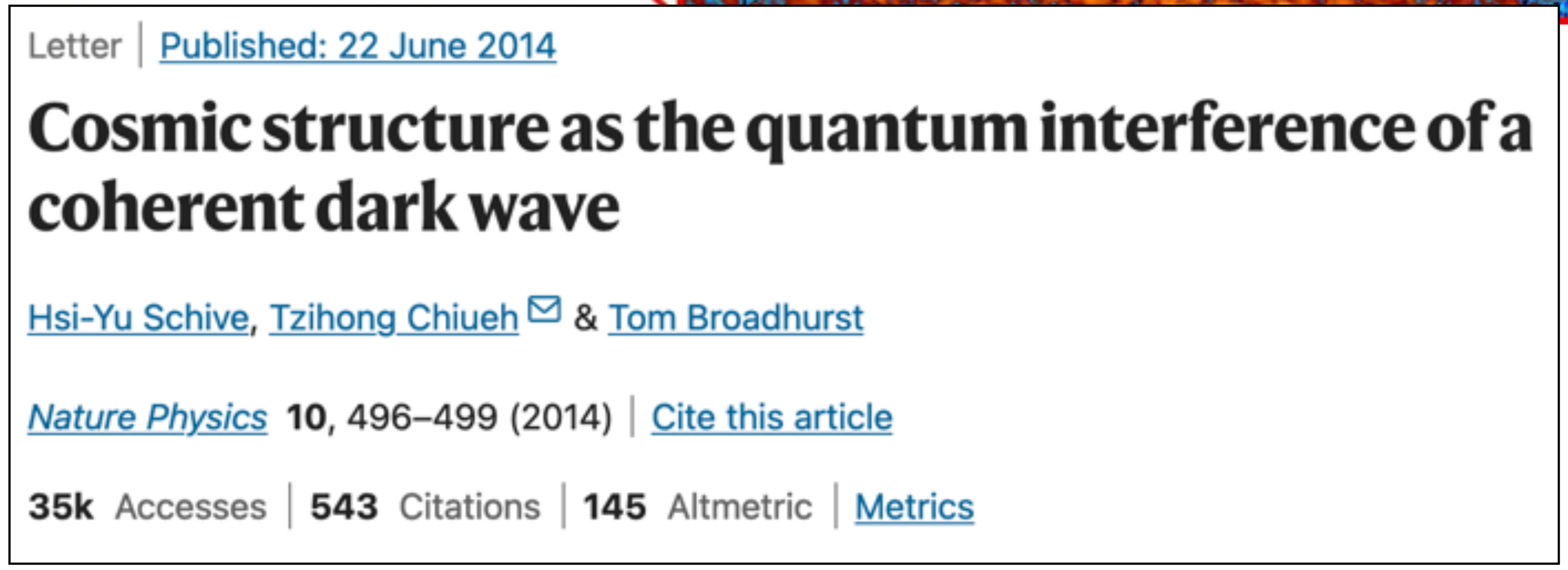
O'Hare, Pierobon,
Redondo (2311.17367)



Minicluster tidal disruption
→ numerous axion DM streams
→ some recovery of local density
+ nontrivial velocity distribution

Relaxation



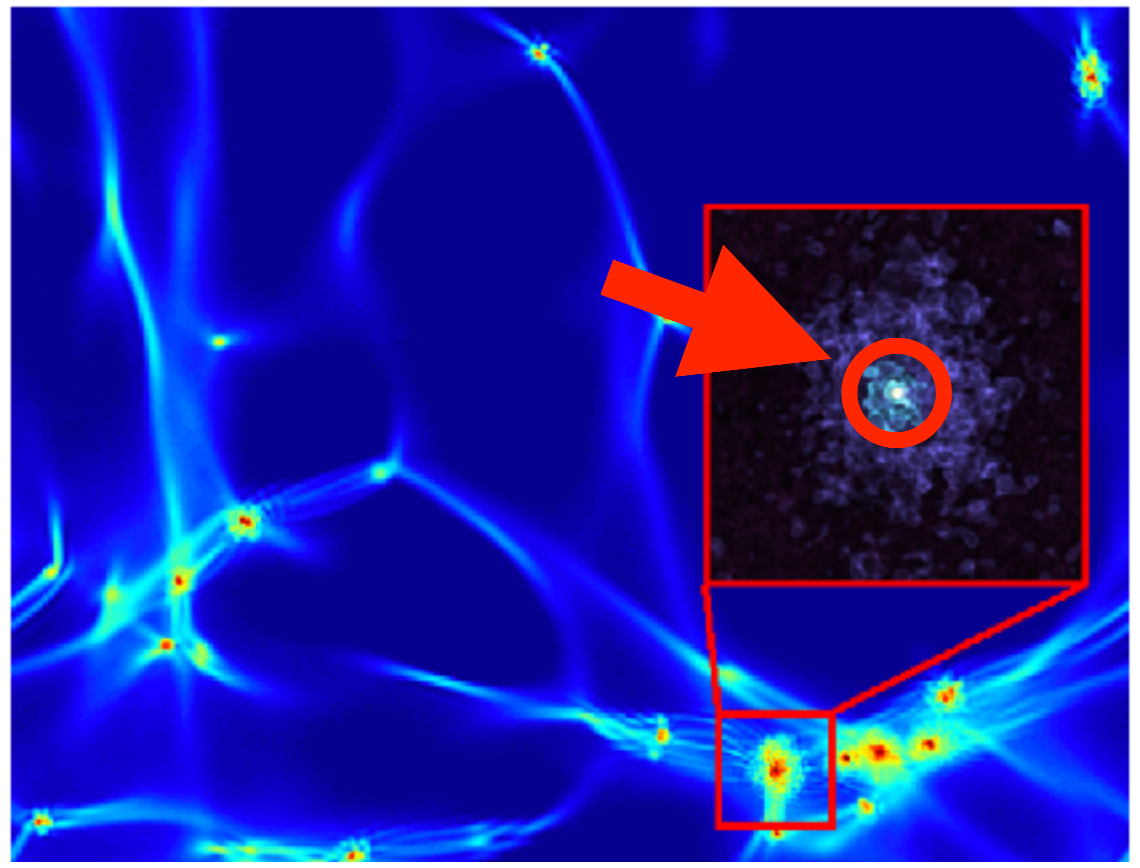

Letter | Published: 22 June 2014

Cosmic structure as the quantum interference of a coherent dark wave

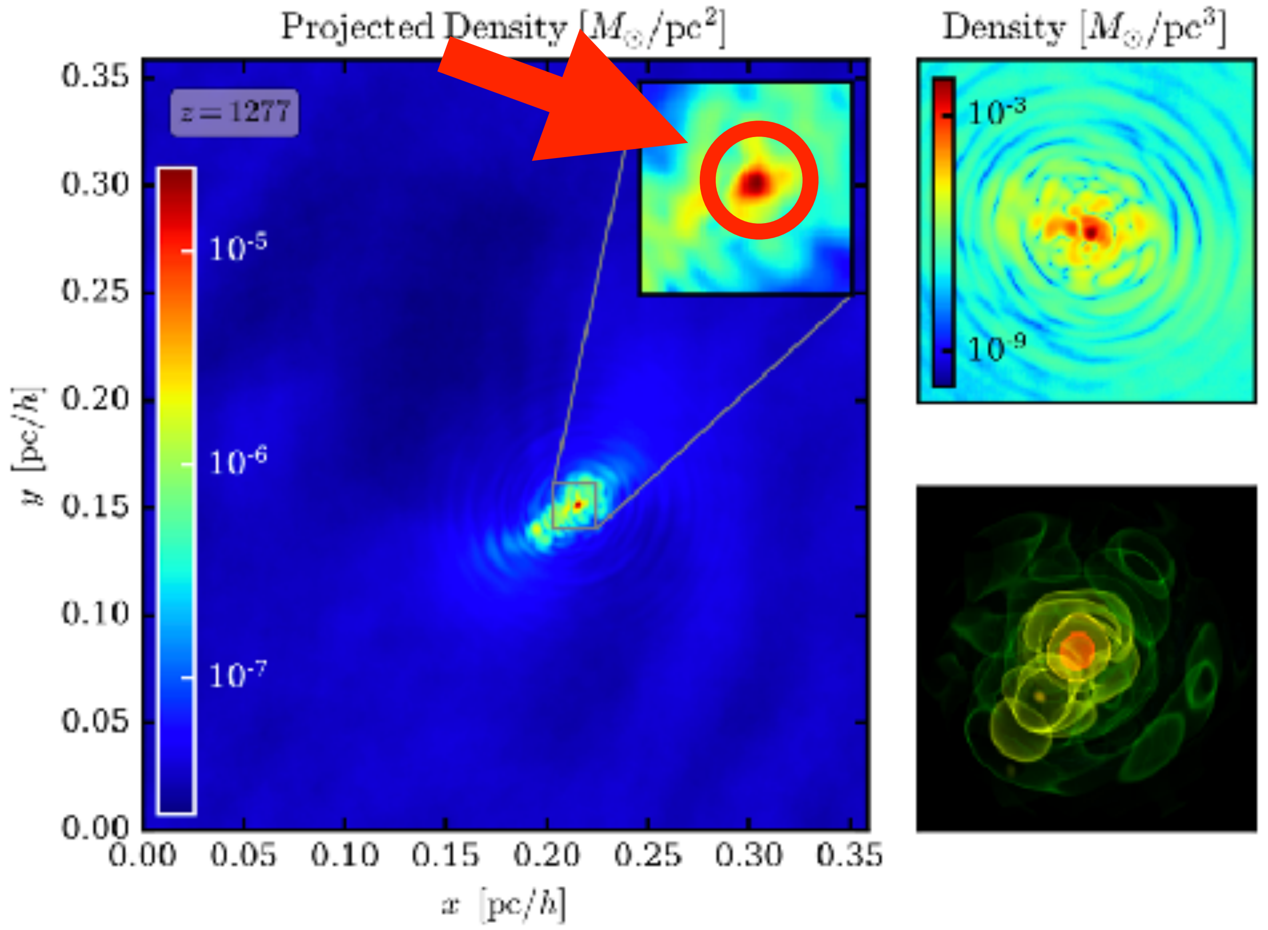
Hsi-Yu Schive, Tzihong Chiueh & Tom Broadhurst

Nature Physics **10**, 496–499 (2014) | Cite this article

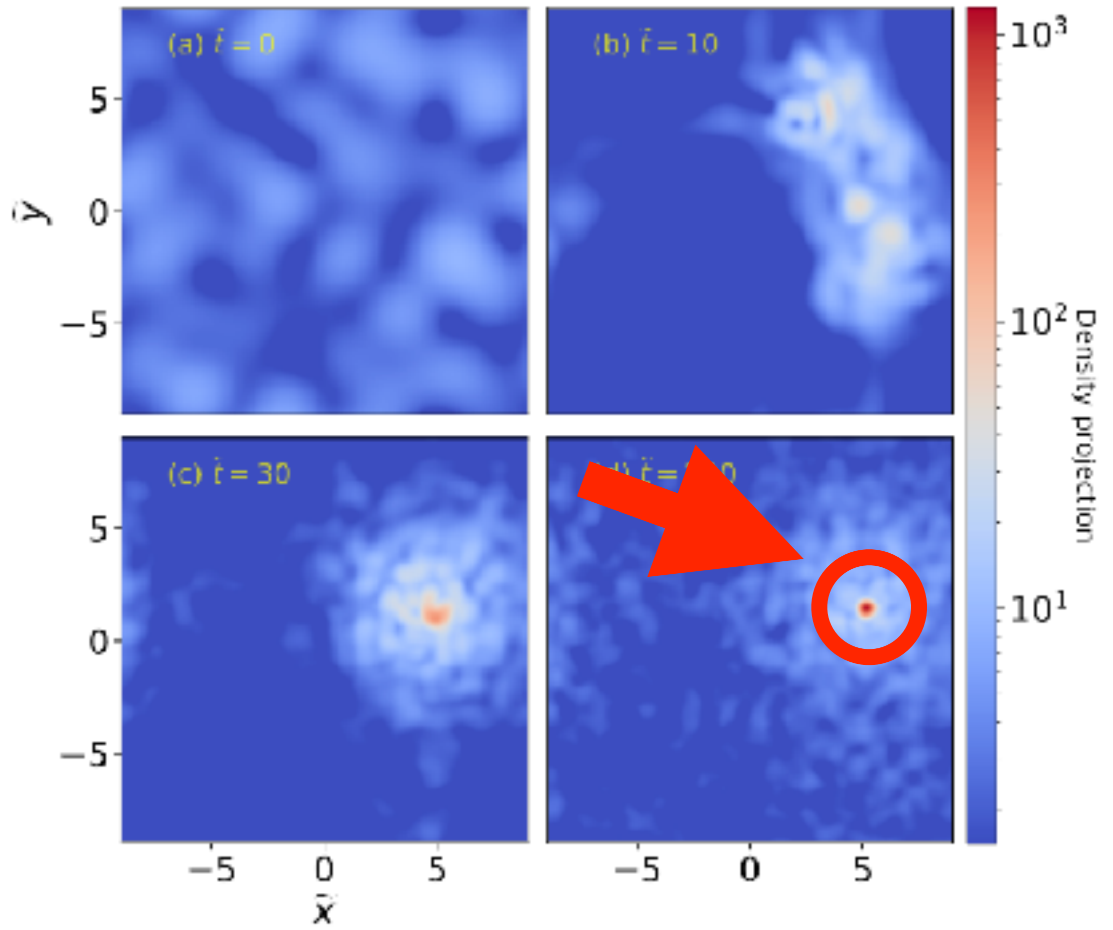
35k Accesses | **543** Citations | **145** Altmetric | Metrics


Mocz et al. (1705.05845)

Levkov, Panin, Tkachev (1804.05857)
Video via Alexander Panin on YouTube



Eggemeier and Niemeyer (1906.01348)



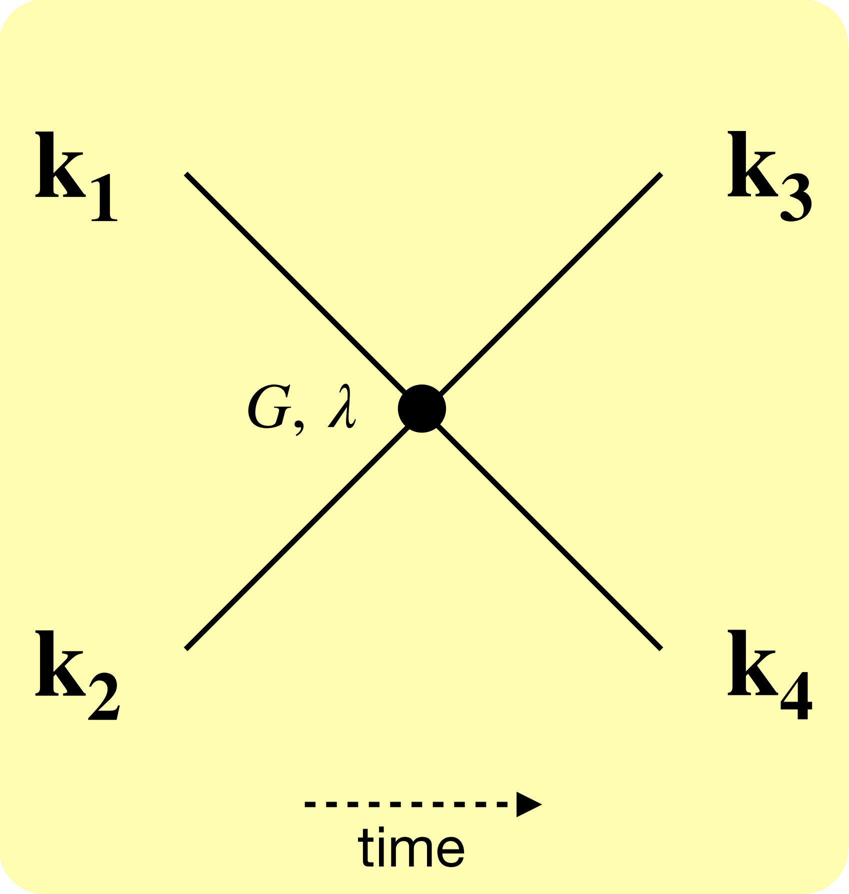
Chen et al. (2011.01333)

(among others!)

Relaxation Timescale*

Sikivie and Yang (0901.1106)
Levkov, Panin, Tkachev (1804.05857)
Kirkpatrick, Mirasola, Prescod-Weinstein (2007.07438)
Chen, Du, Lentz, Marsh (🇬🇧) (2109.11474)

$$\tau_{\rm relax} \sim \left(n_\phi \sigma v_{\rm dm} \mathscr{F}_\phi\right)^{-1} \sim \frac{1}{n_\phi \sigma v_{\rm dm}} \frac{1}{n_\phi \lambda_{\rm dB}^3}$$



gravity

$$\sigma_g \simeq \frac{8\pi G^2 m_\phi^2}{v_{\rm dm}^4} \ln\left(m_\phi v_{\rm dm} R_{\rm halo}\right)$$

$$\tau^g_{\rm relax} \simeq \frac{\sqrt{2}}{12\pi^2} \frac{m_\phi^3 v_{\rm dm}^6}{\rho^2 G^2}$$

$$\sim 10\,{\rm Gyr} \left(\frac{m_\phi}{10^{-21}\,{\rm eV}}\right)^3 \left(\frac{10\rho_{\rm dm}}{\rho}\right)^2 \left(\frac{v_{\rm dm}}{10^{-4}}\right)^6$$

self-interactions

$$\sigma_\lambda \simeq \frac{\lambda^2}{2\pi m_\phi^2} \simeq \frac{m_\phi^2}{2\pi f_a^4}$$

$$\tau^\lambda_{\rm relax} \simeq \frac{64 m_\phi^3 f_a^4 v_{\rm dm}^2}{\rho^2}$$

$$\sim 10\,{\rm Gyr} \left(\frac{m_\phi}{10^{-14}\,{\rm eV}}\right)^3 \left(\frac{f_a}{10^8\,{\rm GeV}}\right)^4 \left(\frac{\rho_{\rm dm}}{\rho}\right)^2 \left(\frac{v_{\rm dm}}{10^{-3}}\right)^2$$

Ratio: $r_{\lambda g} \equiv \dfrac{\tau^\lambda_{\rm relax}}{\tau^g_{\rm relax}} \simeq G^2 f_a^4 v_{\rm dm}^4 = \left(\dfrac{f_a\, v_{\rm dm}}{M_{\rm Pl}}\right)^4$

Note also a possible cross-term $\propto G\lambda$,

highly relevant when $r_{\lambda g} \sim \mathcal{O}(1)$ or λ repulsive

Jain, Wanichwecharungruang, Thomas (2310.00058)

**violent relaxation*, e.g. during merger,
is much faster (basically instantaneous)

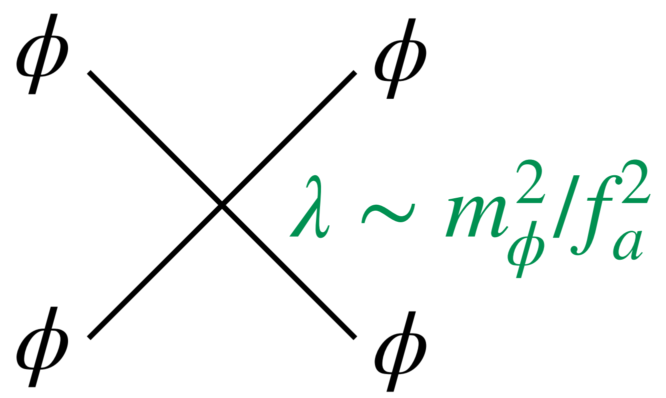
ULDM Ground States

"Quantum" pressure
(Repulsive)

Gravity
(Attractive)

Self-interactions
(usually attractive)

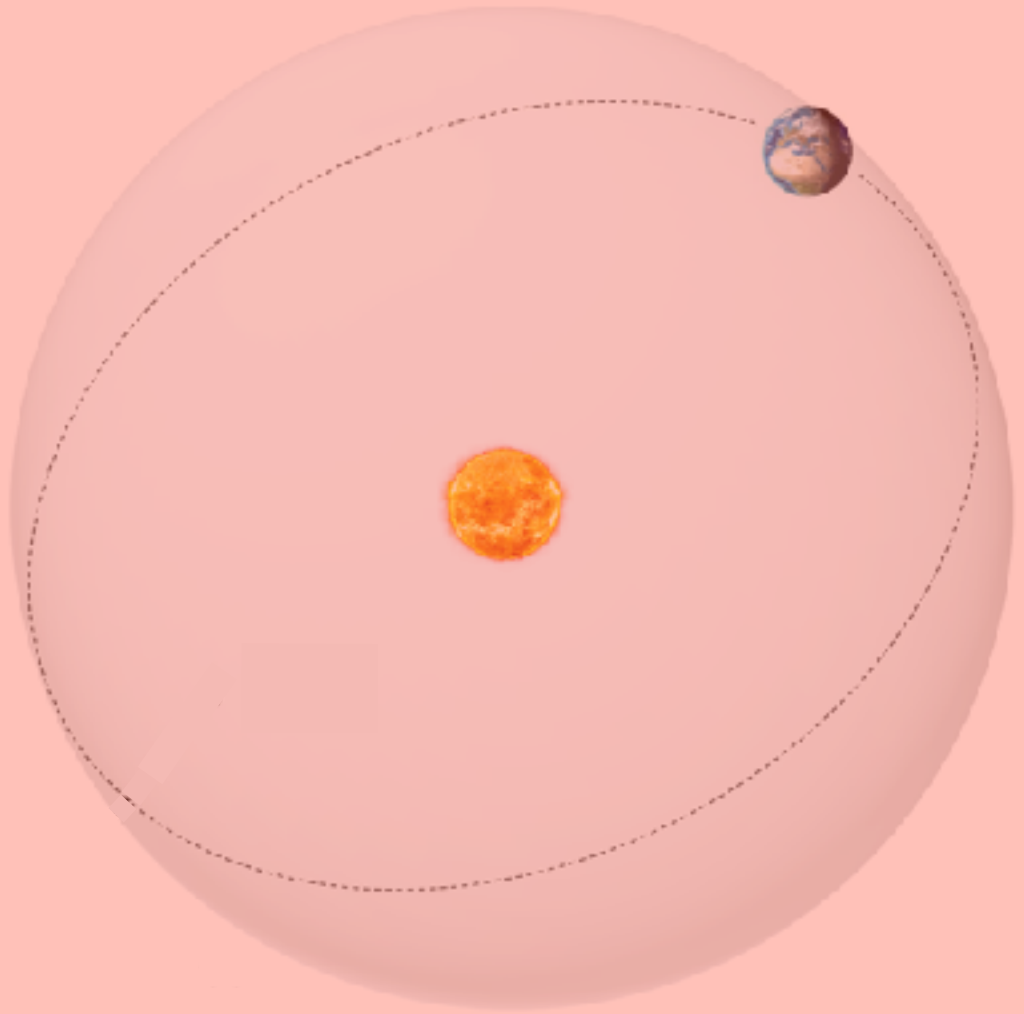
$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m_\phi} + V_g(\psi)\right]\psi - \frac{\lambda}{8m_\phi^2}|\psi|^2\psi$$



(small when density small,
return to this later)

(later)

Gravitational Atoms



Balance of gradient+gravity in the field

Structure depends on source of gravity

External source
(bound to other body)

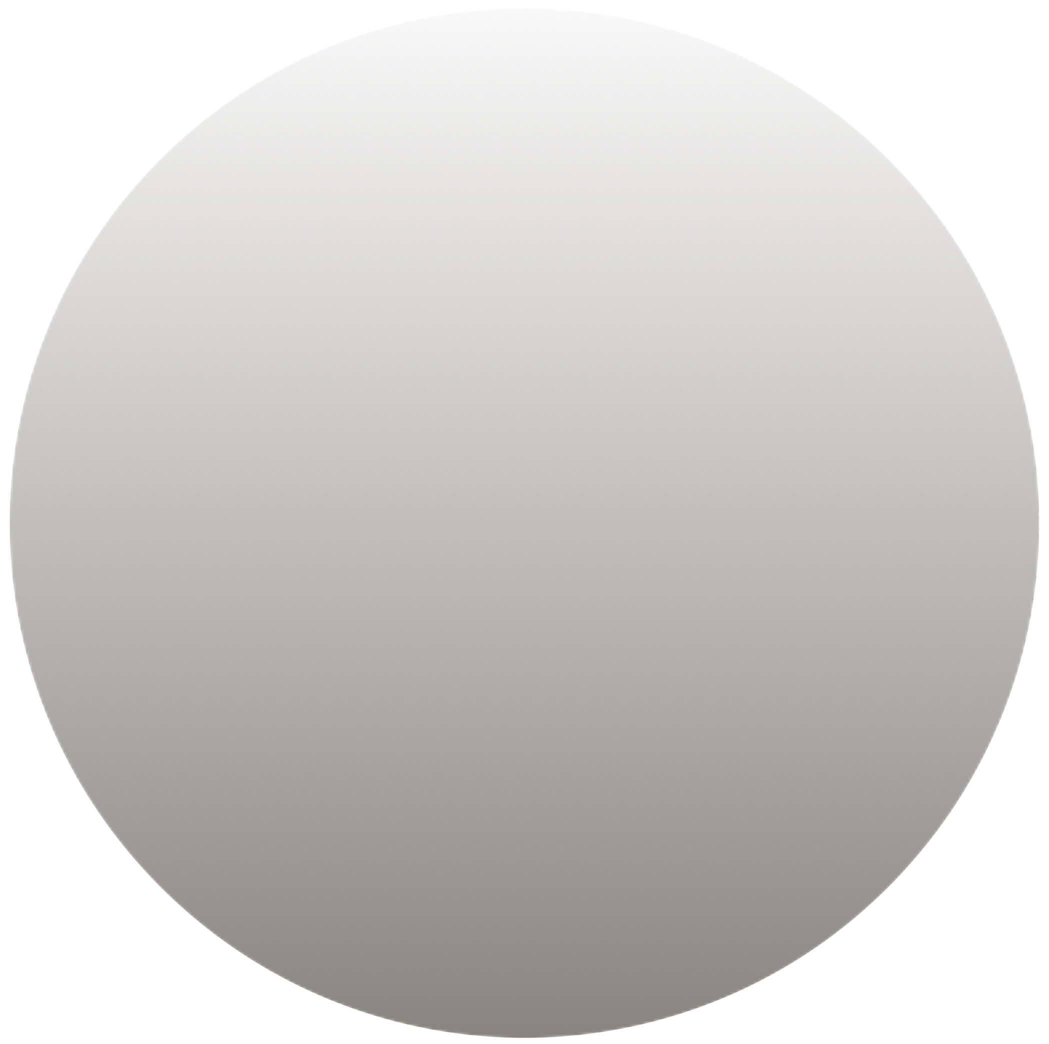
$$V_g(\psi) = \frac{GMm_\phi}{r}$$

ULDM itself
(self-gravity)

$$\nabla^2 V_g(\psi) = 4\pi G m_\phi^2|\psi|^2$$

(next)

Boson Stars



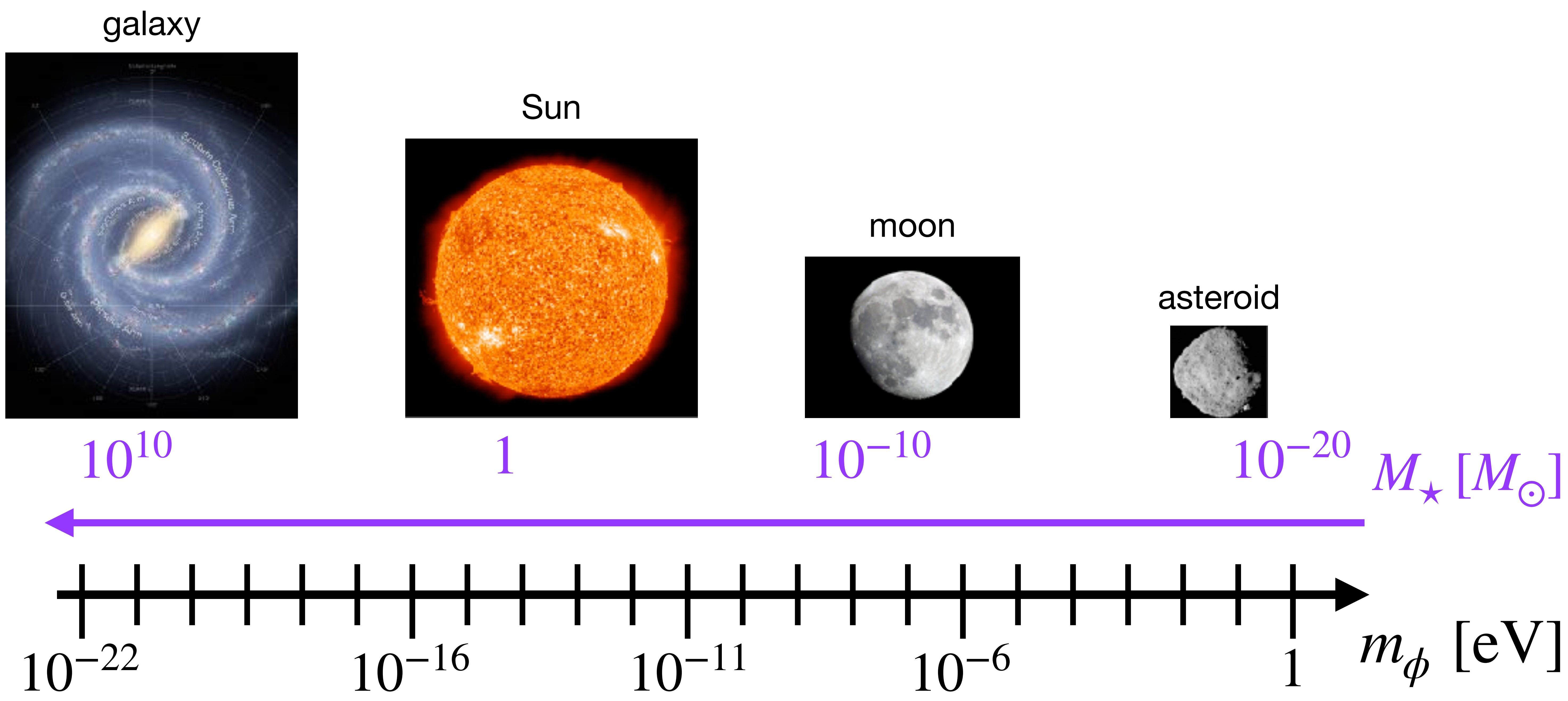
Chavanis (1103.2050)
Chavanis, Delfini (1103.2054)

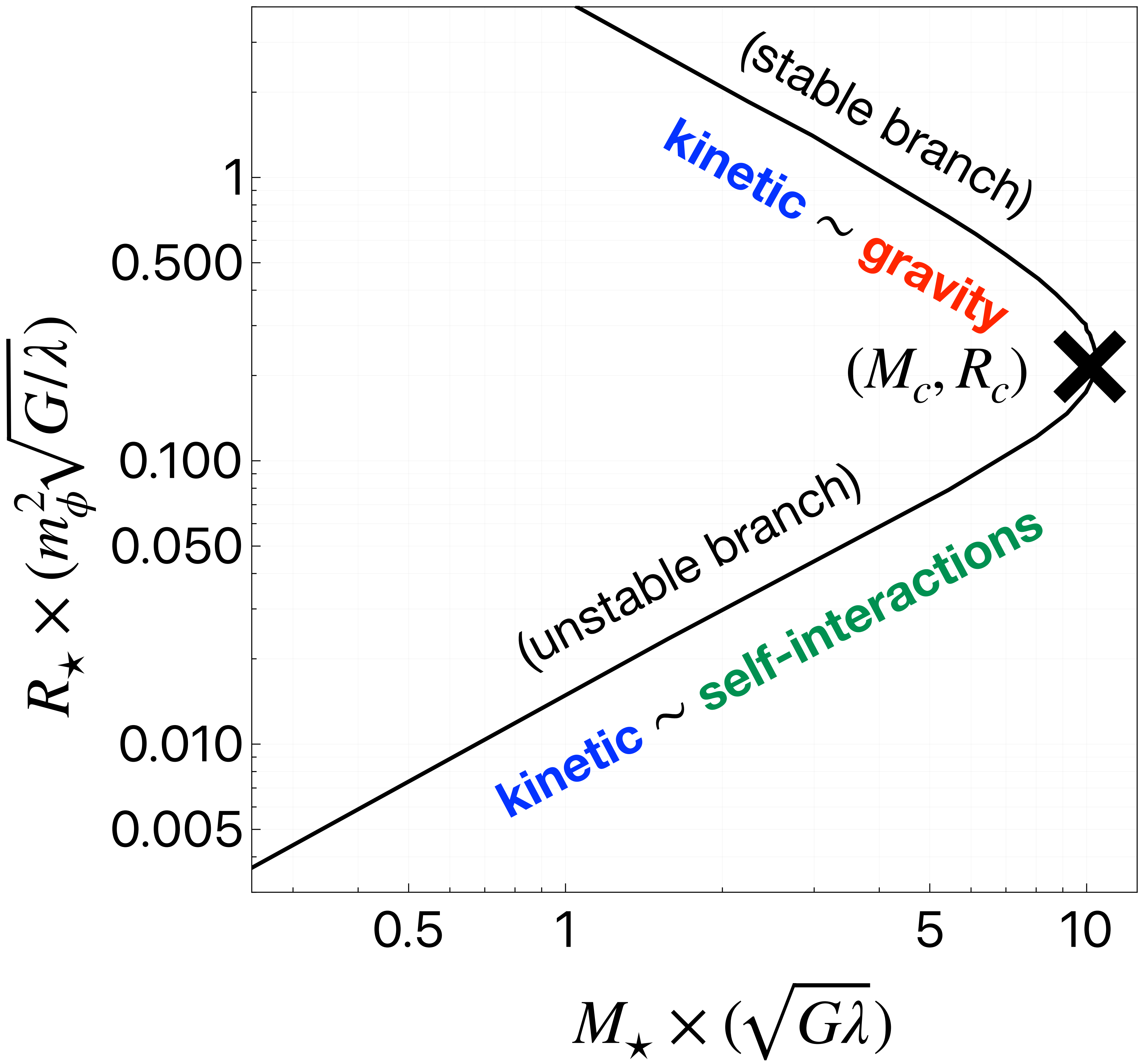
Size of a Boson Star

The most important fact about a boson star!

$$M_\star \simeq \frac{1}{G m_\phi^2 R_\star}$$

$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m_\phi} + V_\mathrm{g}(\psi) \right] \psi - \frac{\lambda}{8m_\phi^2} |\psi|^2 \psi$$

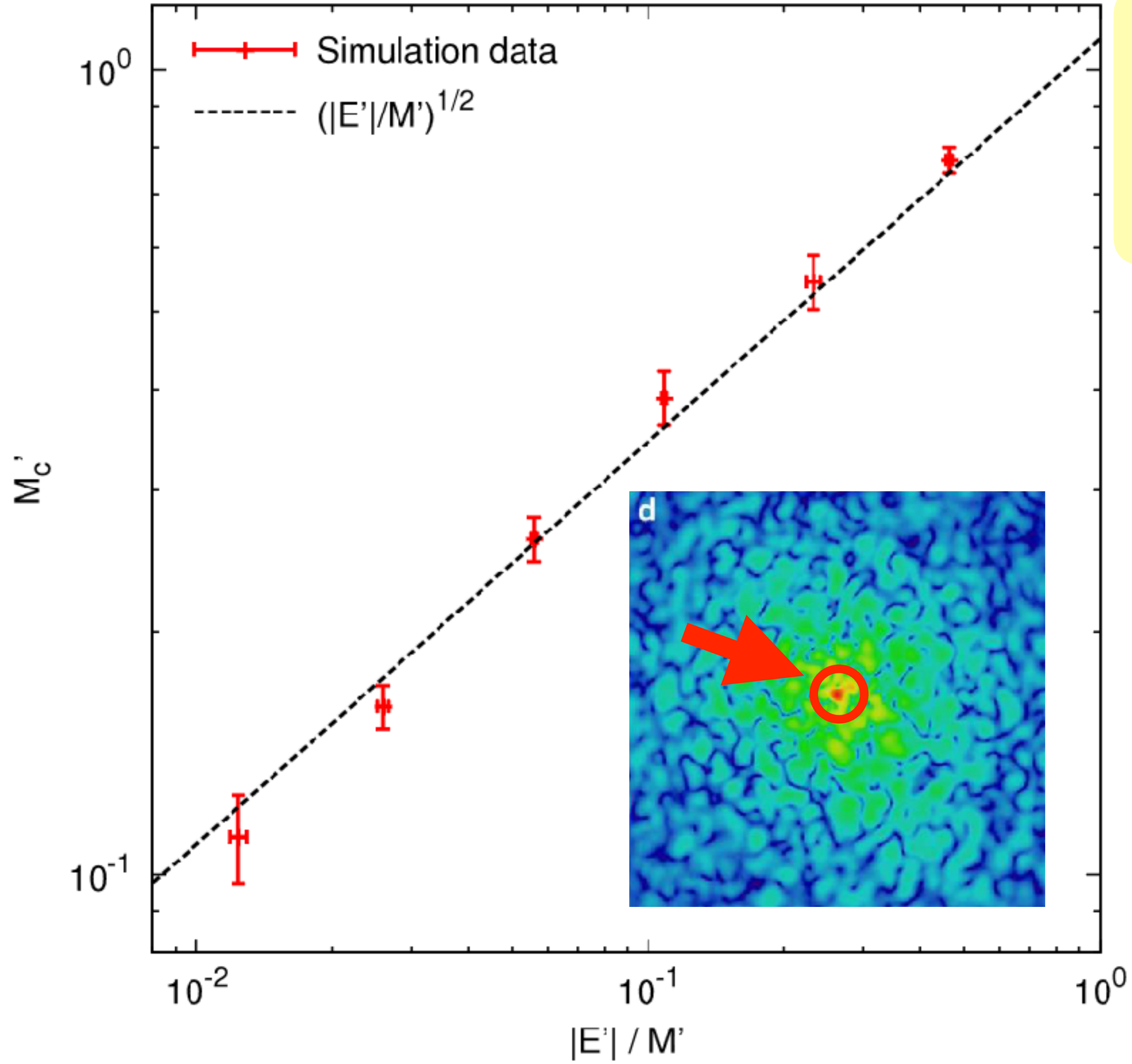




The Soliton—Host-Halo Relation

(or Core-Halo Relation)

Schive++ (1407.7762)



Rule: 1 boson star per halo with

$$M_{ch} \simeq 10^9 M_\odot \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)\left(\frac{M_\mathrm{halo}}{10^{12}\,M_\odot}\right)^{1/3}$$

equivalent to

$$\left(\frac{E}{M}\right)_\mathrm{soliton} = \left(\frac{E}{M}\right)_\mathrm{halo}$$

and therefore

$$\left(\frac{K}{M}\right)_\mathrm{soliton} = \left(\frac{K}{M}\right)_\mathrm{halo}$$

Bar, Blas, Blum, Sibiryakov (1805.00122)
Bar, Blum, **JE**, Sato (1903.03402)

Tested in simulations for

- halos with $M_\mathrm{halo} \sim (10^8 - 10^{12}) M_\odot$
- ULDM mass $m_\phi \sim (10^{-20} - 10^{-22})\,\mathrm{eV}$
- Other systems with small overdensities (e.g. QCD axion miniclusters)

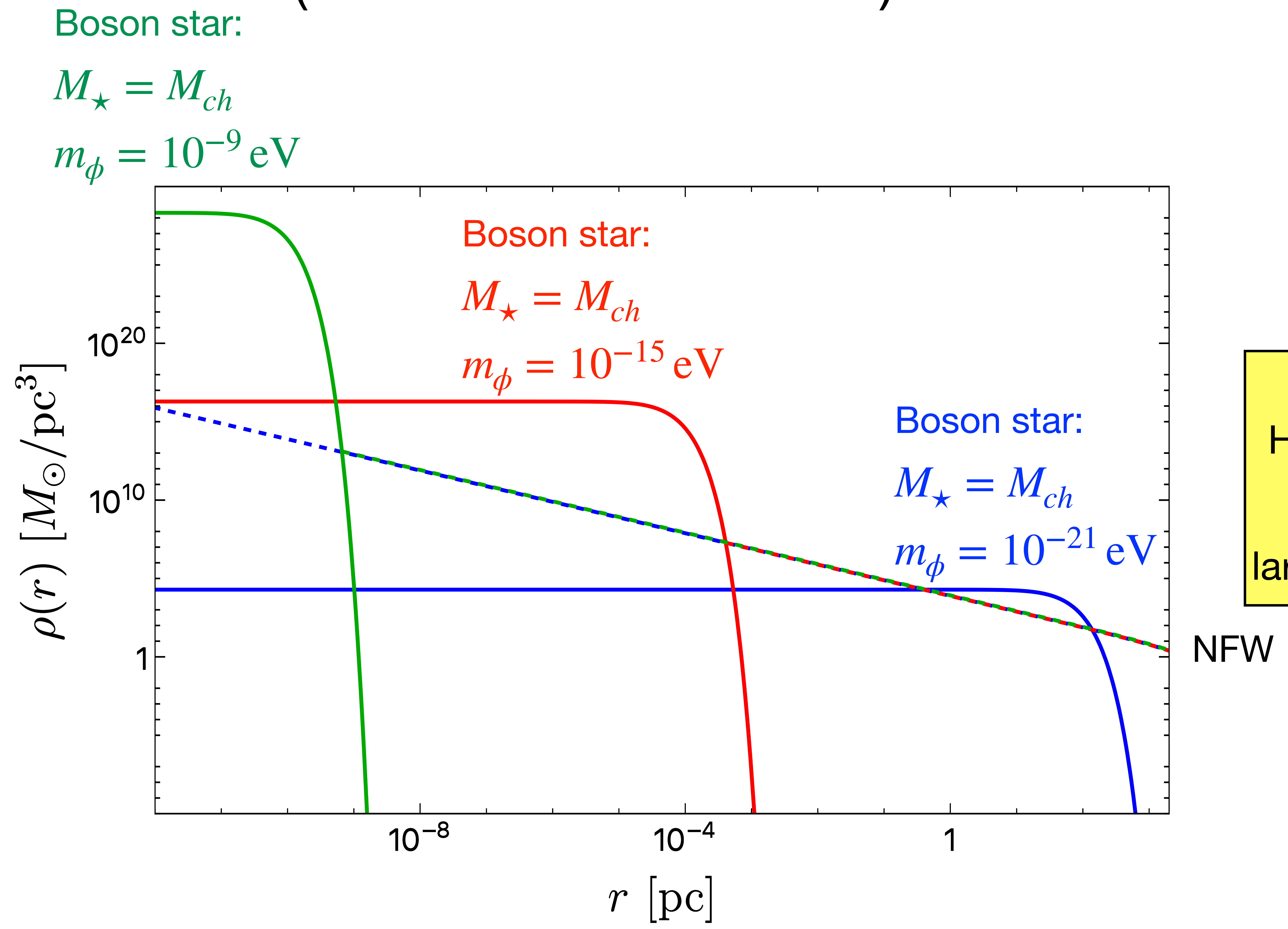
Reasons to be (at least a little bit) skeptical:

- larger simulation volumes $\longrightarrow$ scatter, $M_{ch} \propto M_\mathrm{halo}^{2/5}$? $M_\mathrm{halo}^{2/3}$?
- can't be valid for $M_{ch} \to M_\mathrm{halo}$
- Valid when m_ϕ is large? at fixed M_halo, predicts <u>very large overdensity</u>

Chan, Ferreira, May, Hayashi, Chiba (2110.11882)

The Soliton—Host-Halo Relation

(or Core-Halo Relation)



Clarity is still needed:
How is core-halo relation modified in case of large M_{halo} with large m_ϕ ?

- Valid when m_ϕ is small? at fixed M_{halo}, predicts very large overdensity

Boson Star Mass Distribution* Today

Maseizik, Sigl
(2404.07908)

Cosmological simulations

Model dependence:
$m_\phi, f_a, n, \ldots$
post-inflation ?

String++ decay

Extrapolation?
Power-law exponent
for string decay q ?

Density perturbations
→Miniclusters

Non-Gaussianity?
Merger history?
Tidal disruption?

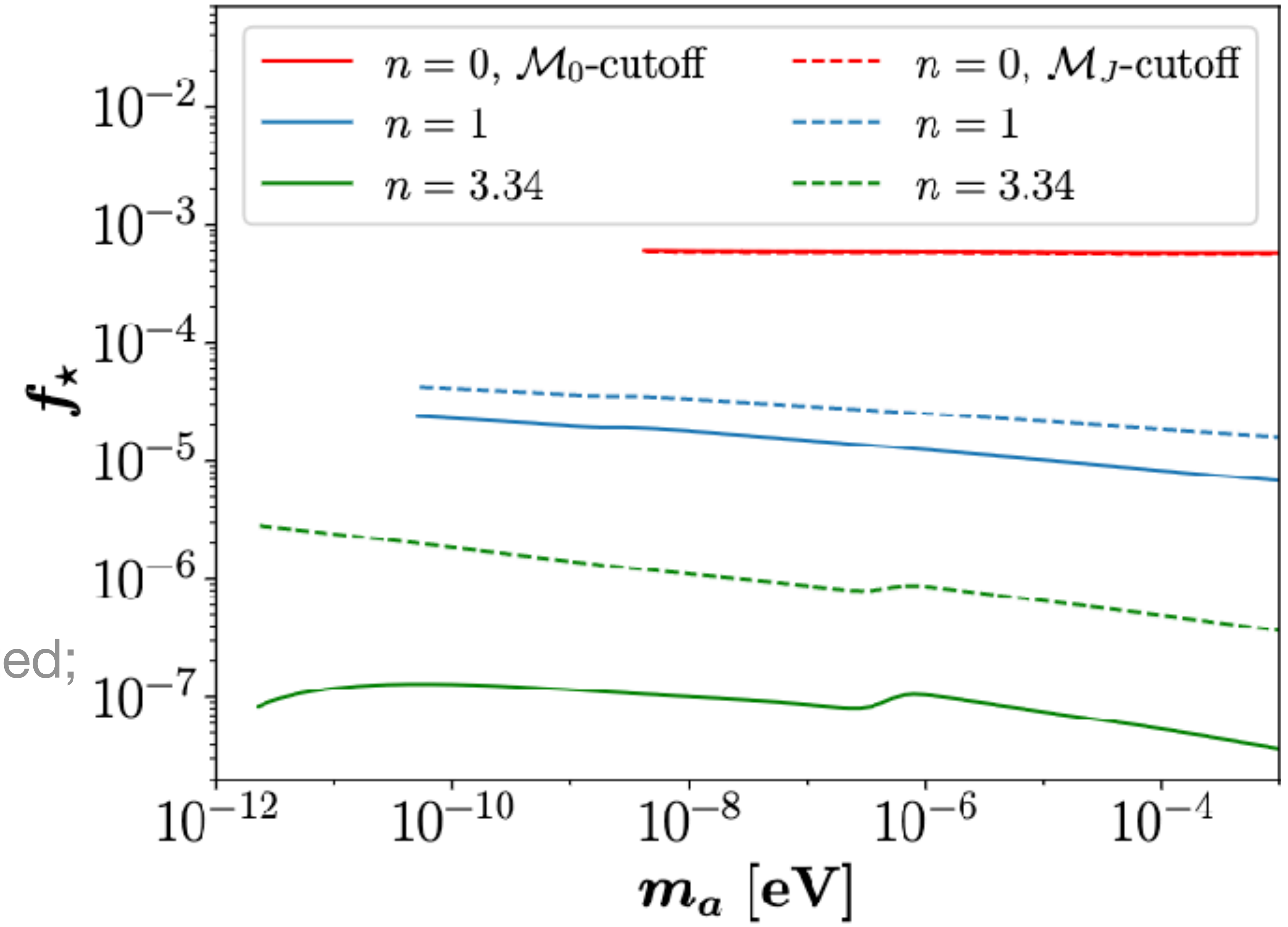
Relaxation
→ Boson stars

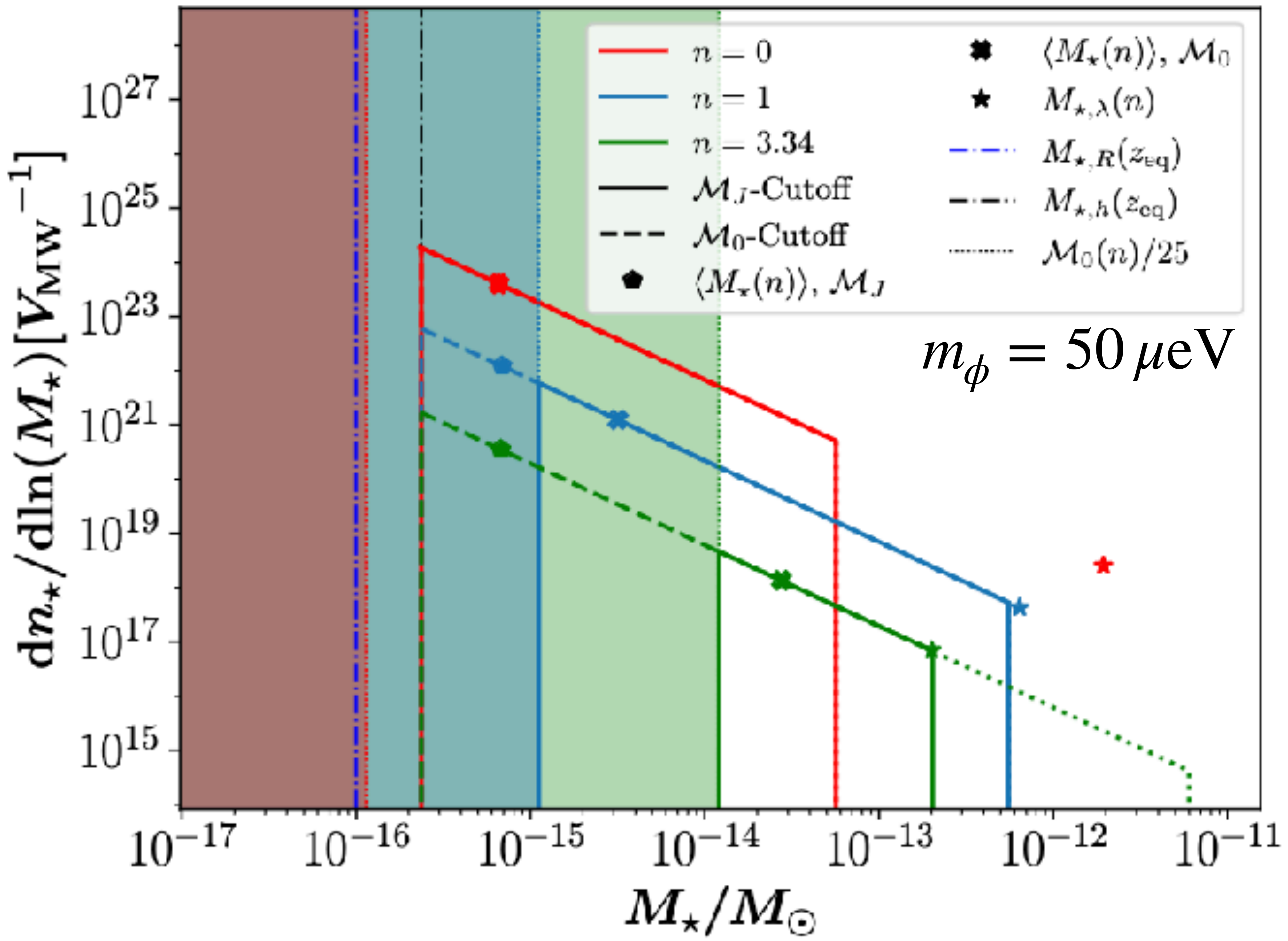
Core-halo relation?
[Accretion?]

DM MASS FRACTION

MASS DISTRIBUTION

(today)



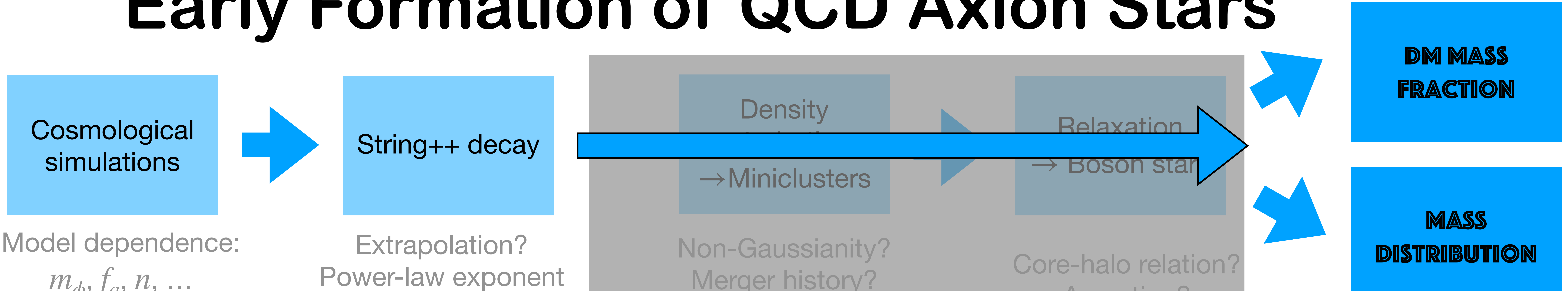


**accretion* not accounted for, still contested;
see

Levkov, Panin, Tkachev (1804.05857)
Eggemeier, Niemeyer (1906.01348)
Chen, Du, Lentz, Marsh, Niemeyer (2011.01333)
Chan, Sibiryakov, Xue (2207.04057)
Dmitriev, Levkov, Panin, Tkachev (2305.01005)

Early Formation of QCD Axion Stars

Gorghetto, Hardy, Villadoro (2405.19389)



Cosmological simulations

String++ decay

Density

→Miniclusters

Relaxation

→ Boson star

DM MASS FRACTION

MASS DISTRIBUTION

(at MRE)

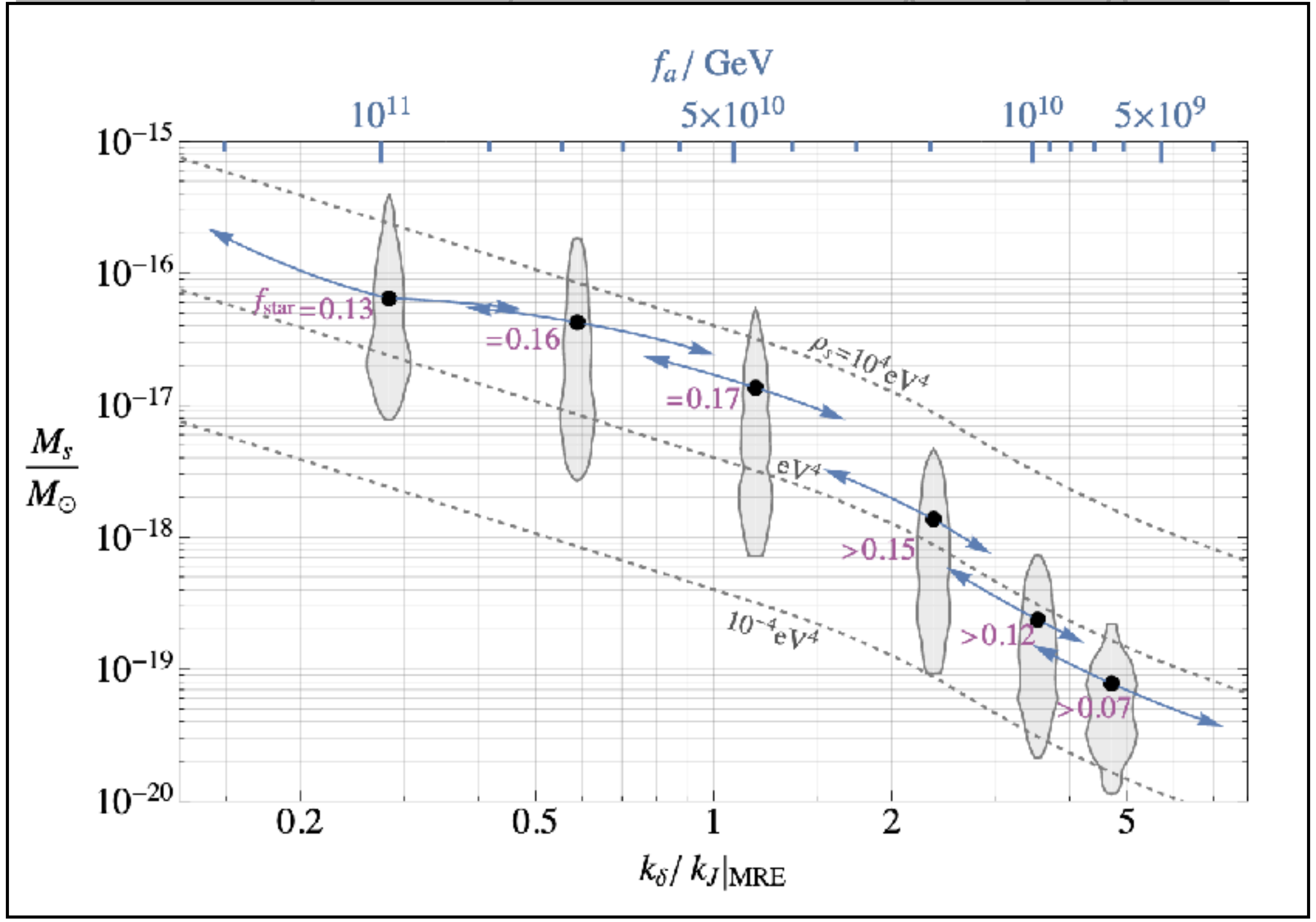
Model dependence: $m_\phi, f_a, n, \ldots$ post-inflation ?

Extrapolation? Power-law exponent for string decay q ?

Non-Gaussianity? Merger history?

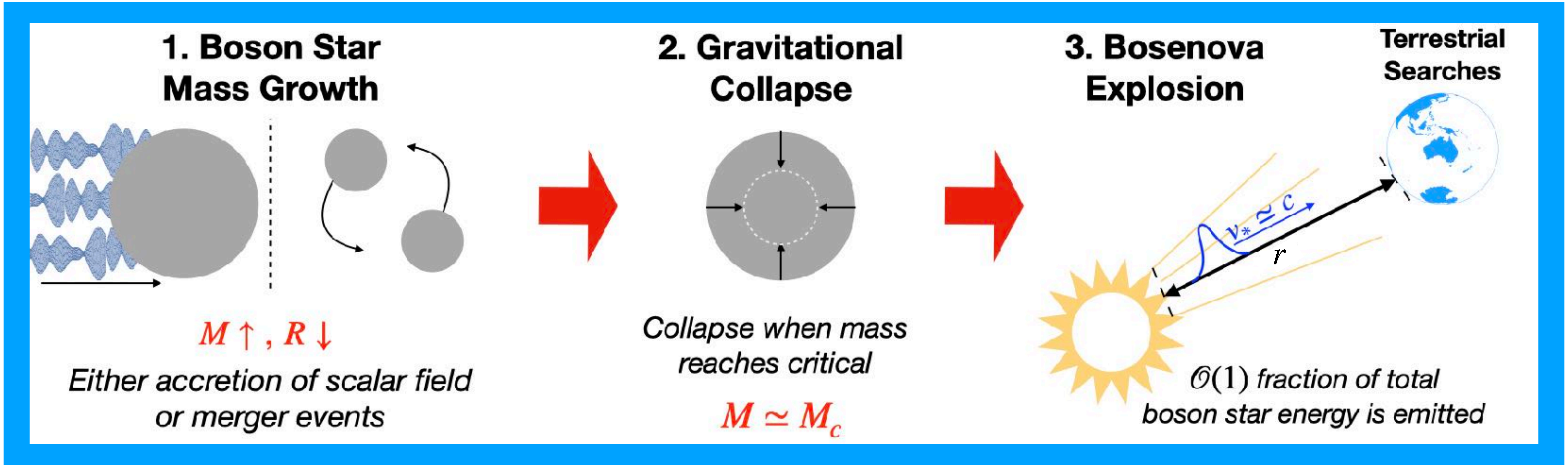
Core-halo relation?

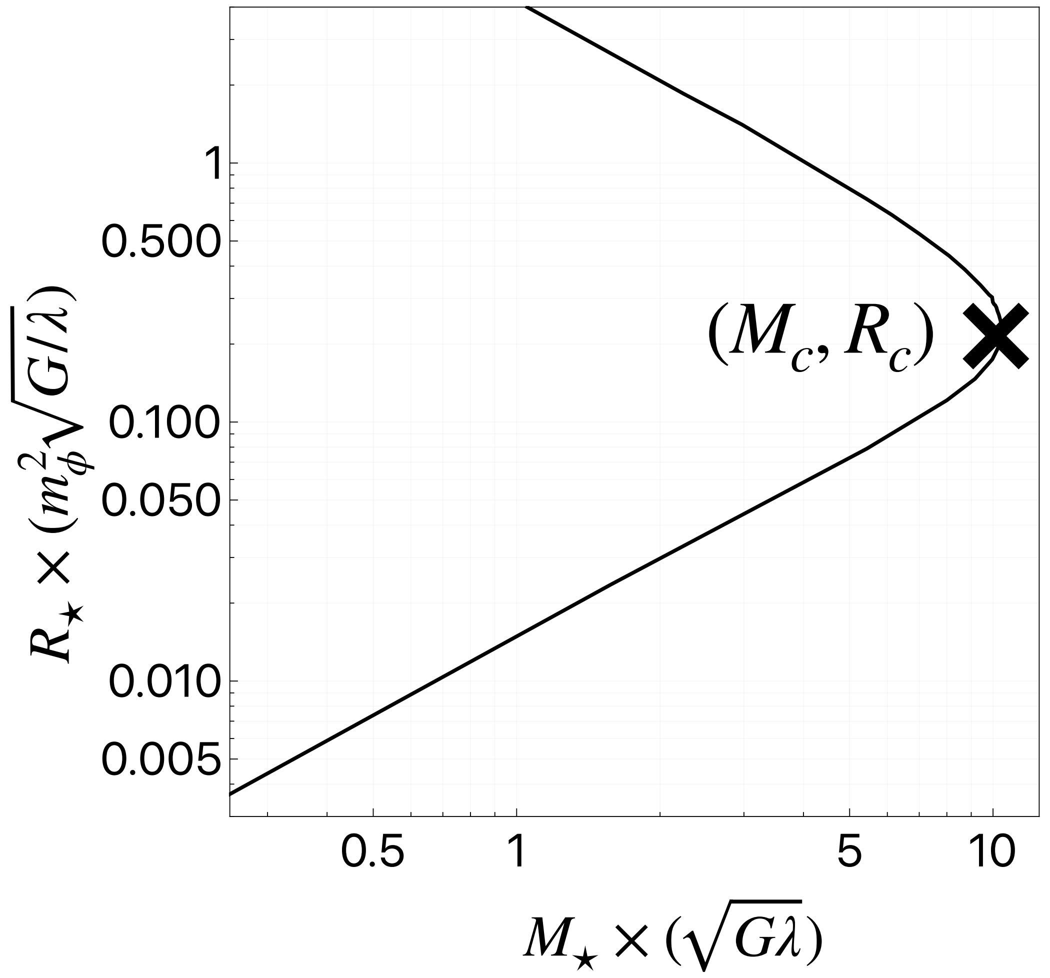
In preferred QCD axion DM range, collapse at MRE directly leads to $f_{\rm dm} \sim \text{few} - 20\,\%$ DM fraction in boson stars!



Boson Star Collapse ⟶ Bosenova

Image: Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468)





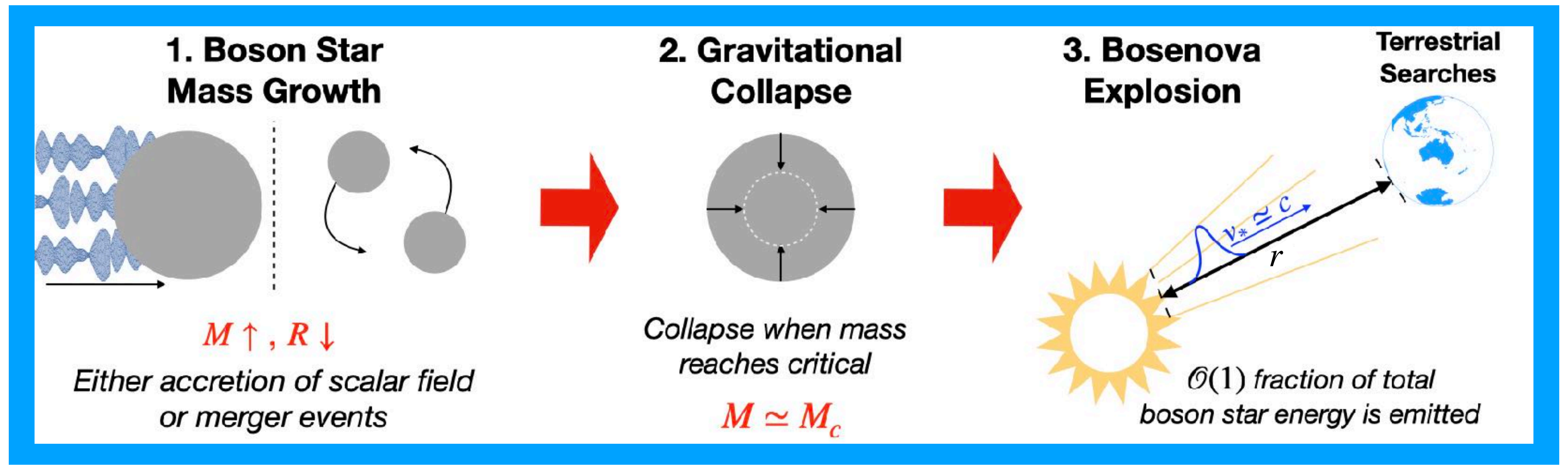
Explicit rate calculation:
bosenovae/galaxy today
can be as large as few/day

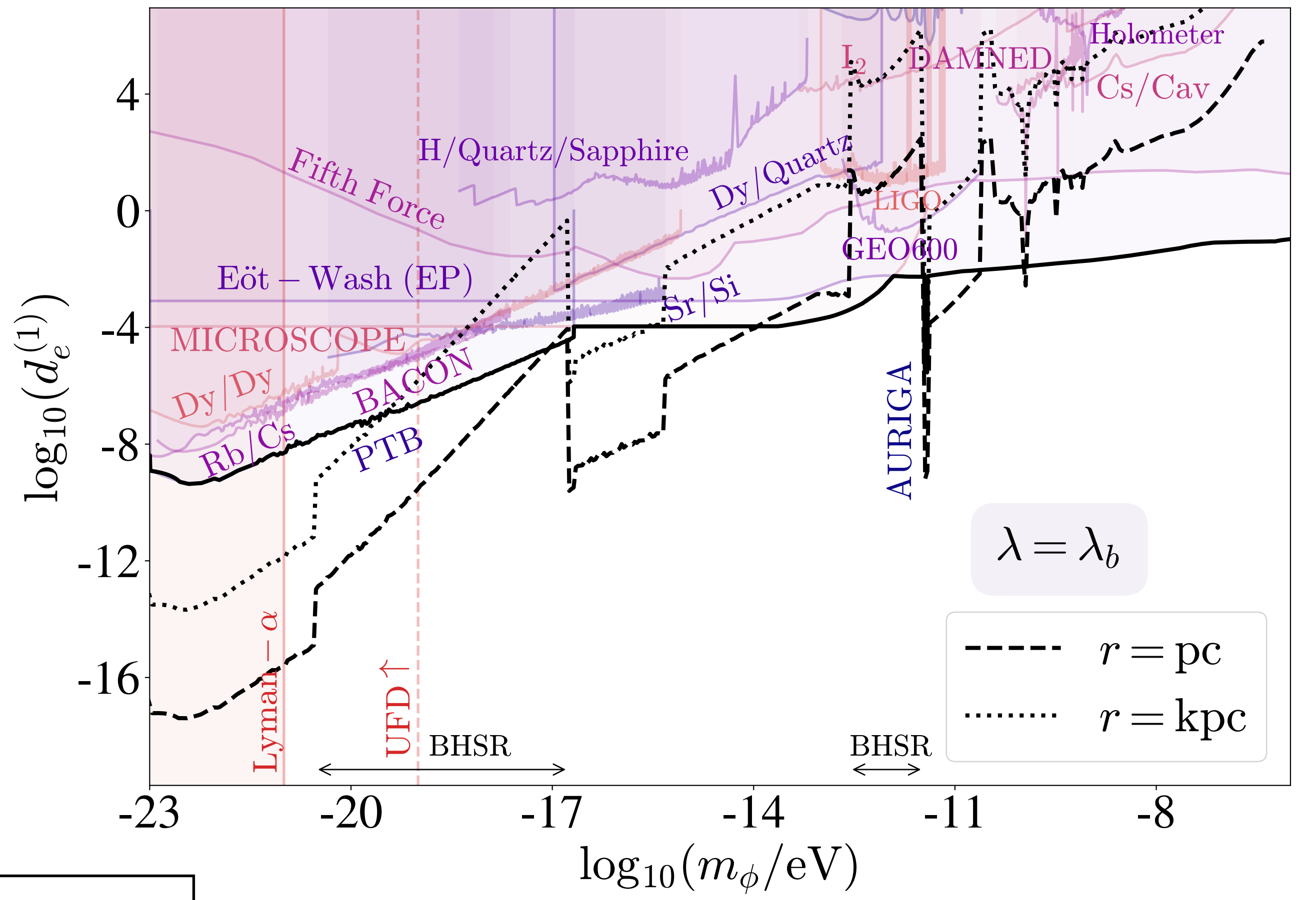
Maseizik, Sigl (2404.07908)

Boson Star Collapse ⟶ Bosenova ⟶ Signals

JE, Shirai, Stadnik, Takhistov (2106.14893)
Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468, 2402.06736)

Direct search for relativistic axion waves in terrestrial experiments





Caveats

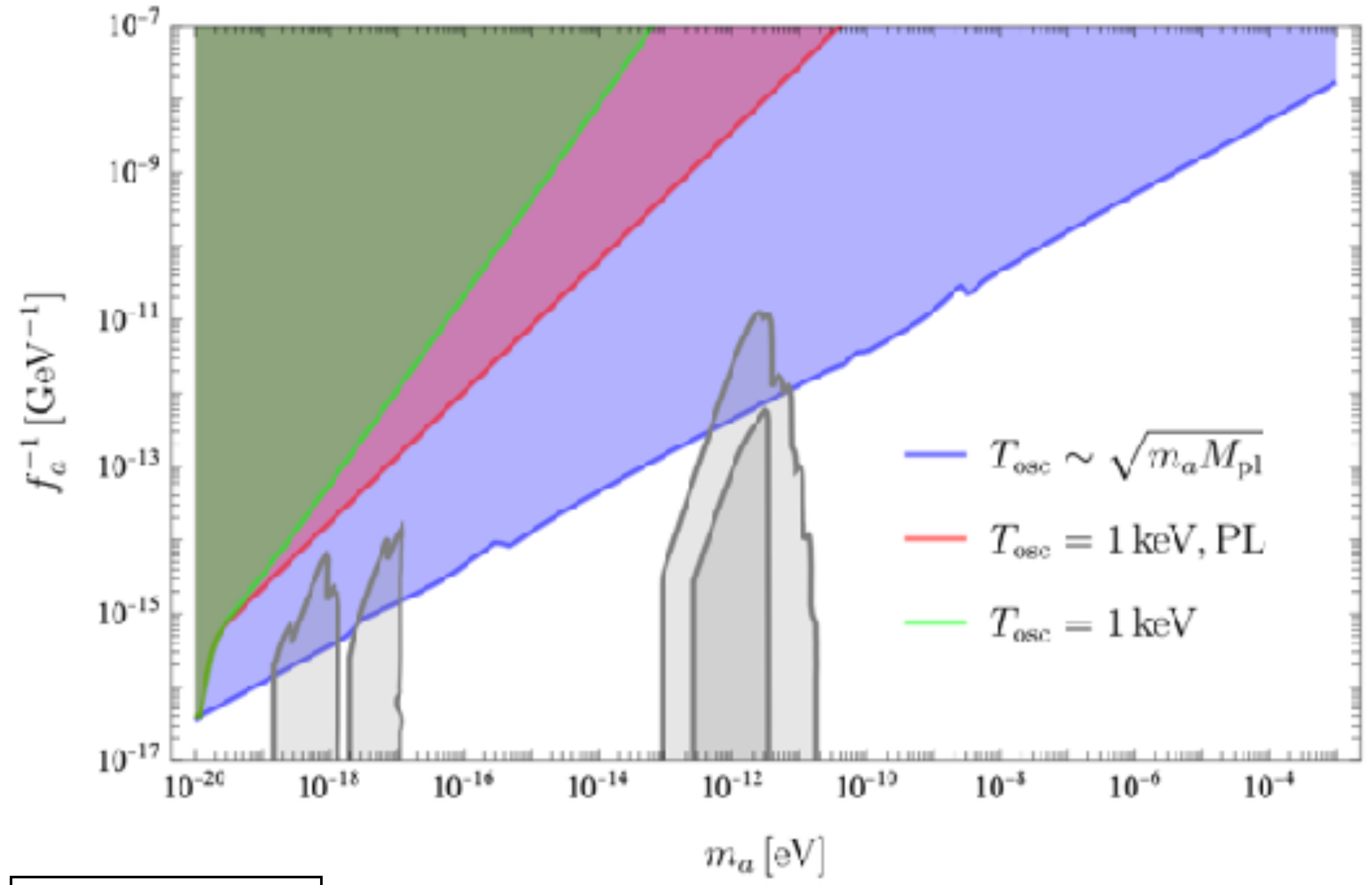
- Need nearby collapse, likely rate-limited
- Rate is *highly* model-dependent

Fox, Weiner, Xiao (2302.00685)

Bosenovae deplete DM at $z \gtrsim 20$, constrain total emitted energy

CMB/SDSS limit

$$f_{dDM} \equiv \frac{\Omega_{dDM}}{\Omega_{dDM} + \Omega_{DM}} \leq 2.62\,\% \ \ (\text{at } 2\sigma)$$

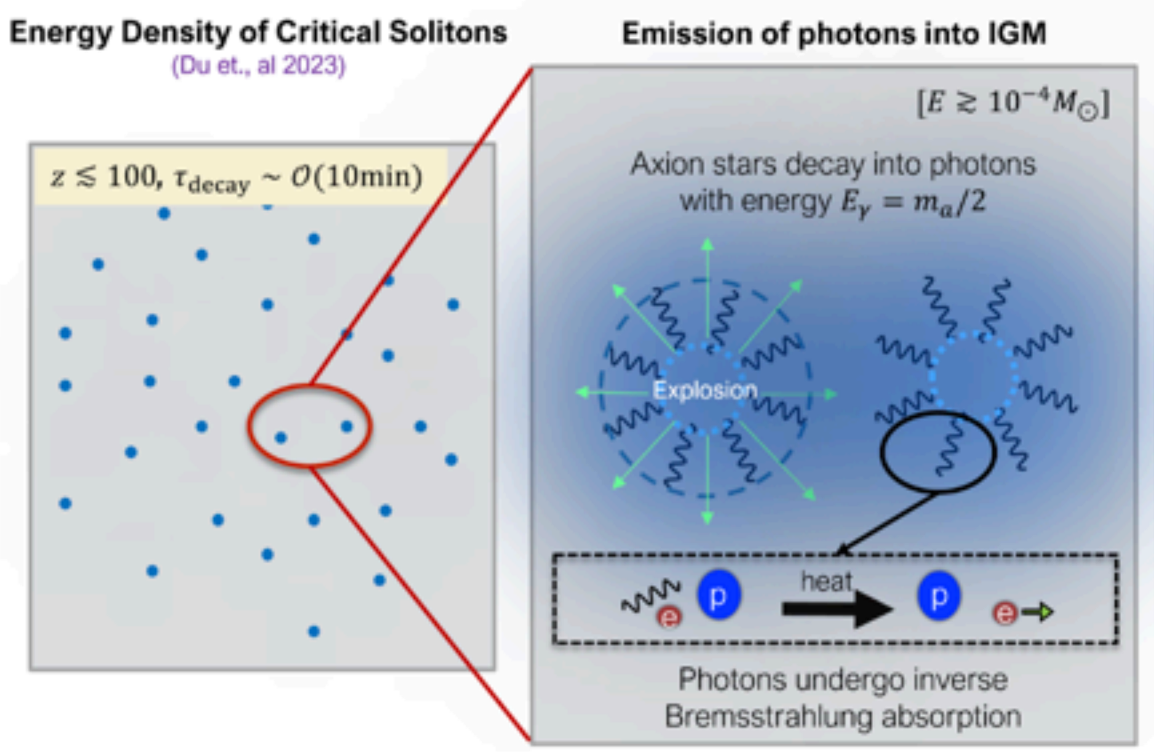


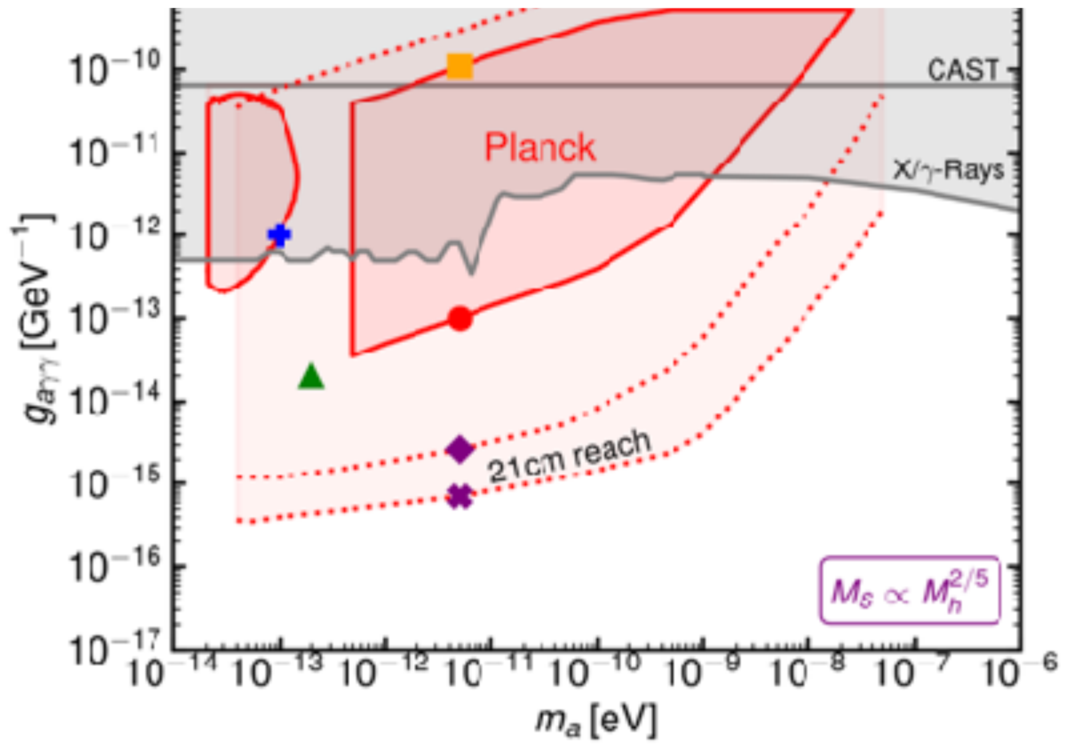
Caveats

- Requires enhancement of small-scale matter power spectrum
- Assumptions about growth rate

Escudero, Pooni, Fairbairn, Blas, Du, Marsh (🇬🇧) (2302.10206)

For boosted $g_{\phi\gamma}$, **bosenova of photons instead, look for indirect signals** (e.g. IGM heating)



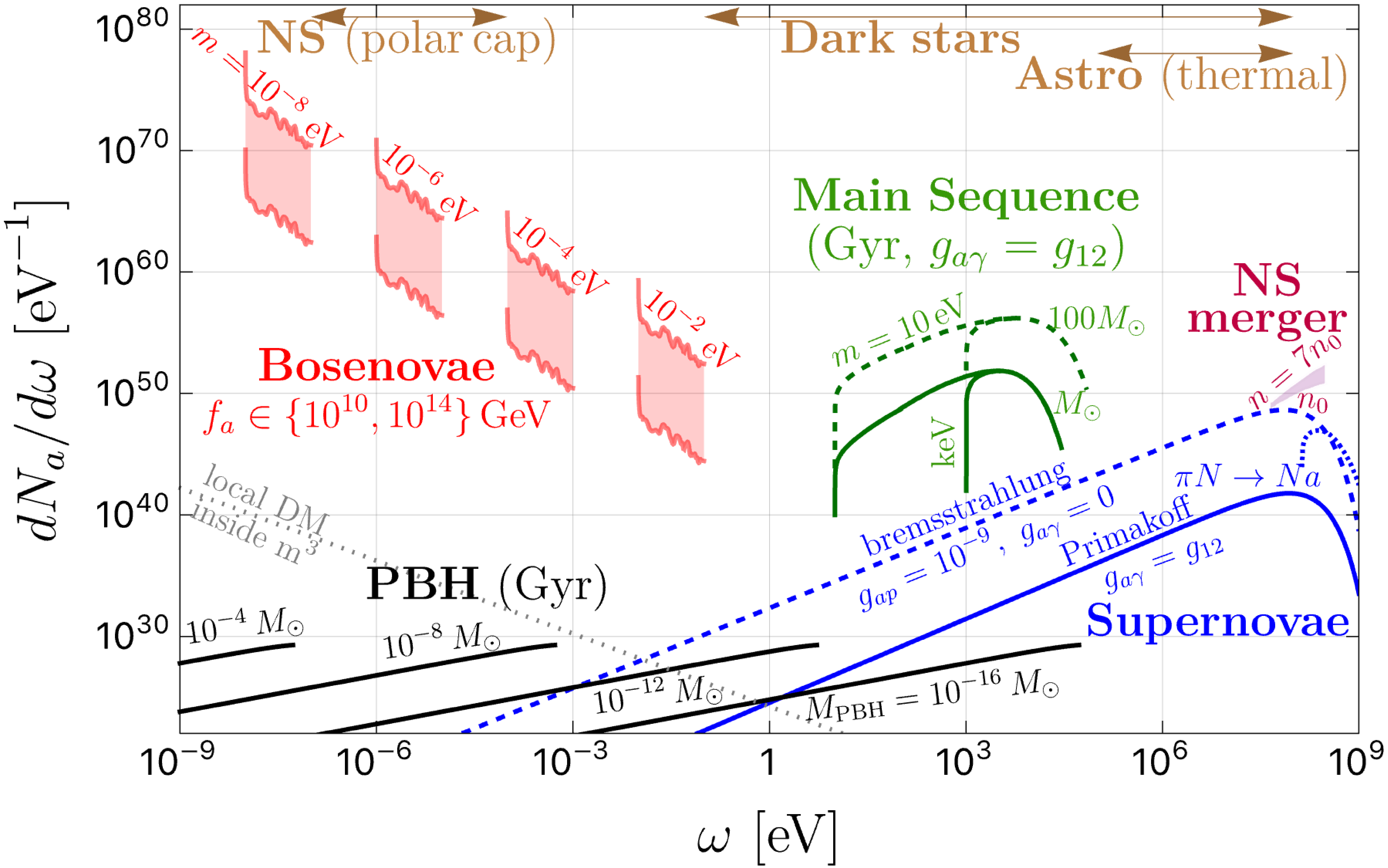


Caveats

- Requires extrapolation of core-halo relation to large m_ϕ
- Need enhanced $g_{\phi\gamma}$ relative to simplest model

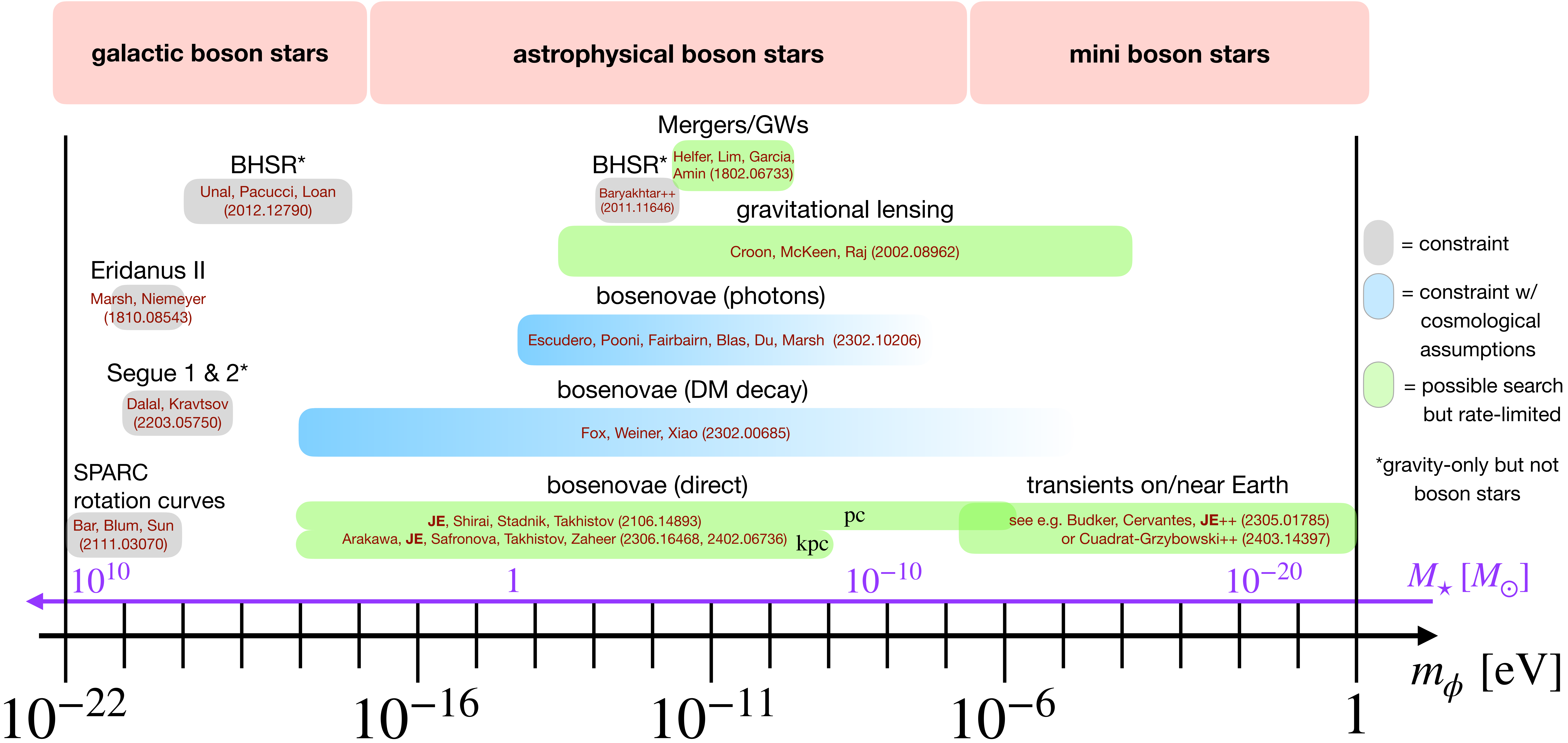
Diffuse Axion Background from Axion Bursts

(including bosenovae)



Eby, Takhistov
(2402.00100)

Searches for Boson Stars



galactic boson stars

astrophysical boson stars

mini boson stars

Mergers/GWs
Helfer, Lim, Garcia, Amin (1802.06733)

BHSR*
Unal, Pacucci, Loan (2012.12790)

BHSR*
Baryakhtar++ (2011.11646)

gravitational lensing
Croon, McKeen, Raj (2002.08962)

Eridanus II
Marsh, Niemeyer (1810.08543)

bosenovae (photons)
Escudero, Pooni, Fairbairn, Blas, Du, Marsh (2302.10206)

Segue 1 & 2*
Dalal, Kravtsov (2203.05750)

bosenovae (DM decay)
Fox, Weiner, Xiao (2302.00685)

SPARC rotation curves
Bar, Blum, Sun (2111.03070)

bosenovae (direct)
JE, Shirai, Stadnik, Takhistov (2106.14893)
Arakawa, **JE**, Safronova, Takhistov, Zaheer (2306.16468, 2402.06736)

transients on/near Earth
see e.g. Budker, Cervantes, **JE**++ (2305.01785)
or Cuadrat-Grzybowski++ (2403.14397)

= constraint

= constraint w/ cosmological assumptions

= possible search but rate-limited

*gravity-only but not boson stars

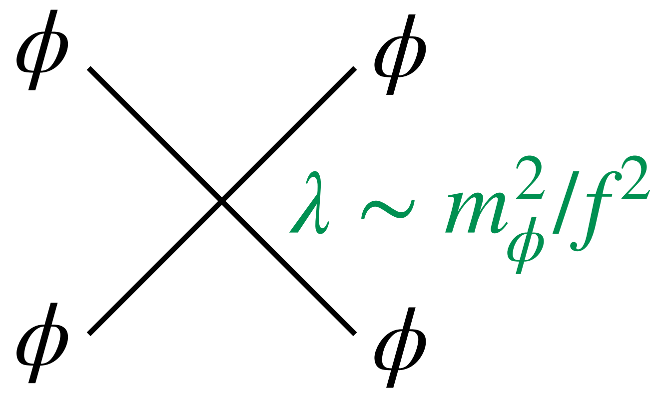
ULDM Ground States

“Quantum” pressure (Repulsive)

Gravity (Attractive)

Self-interactions (usually attractive)

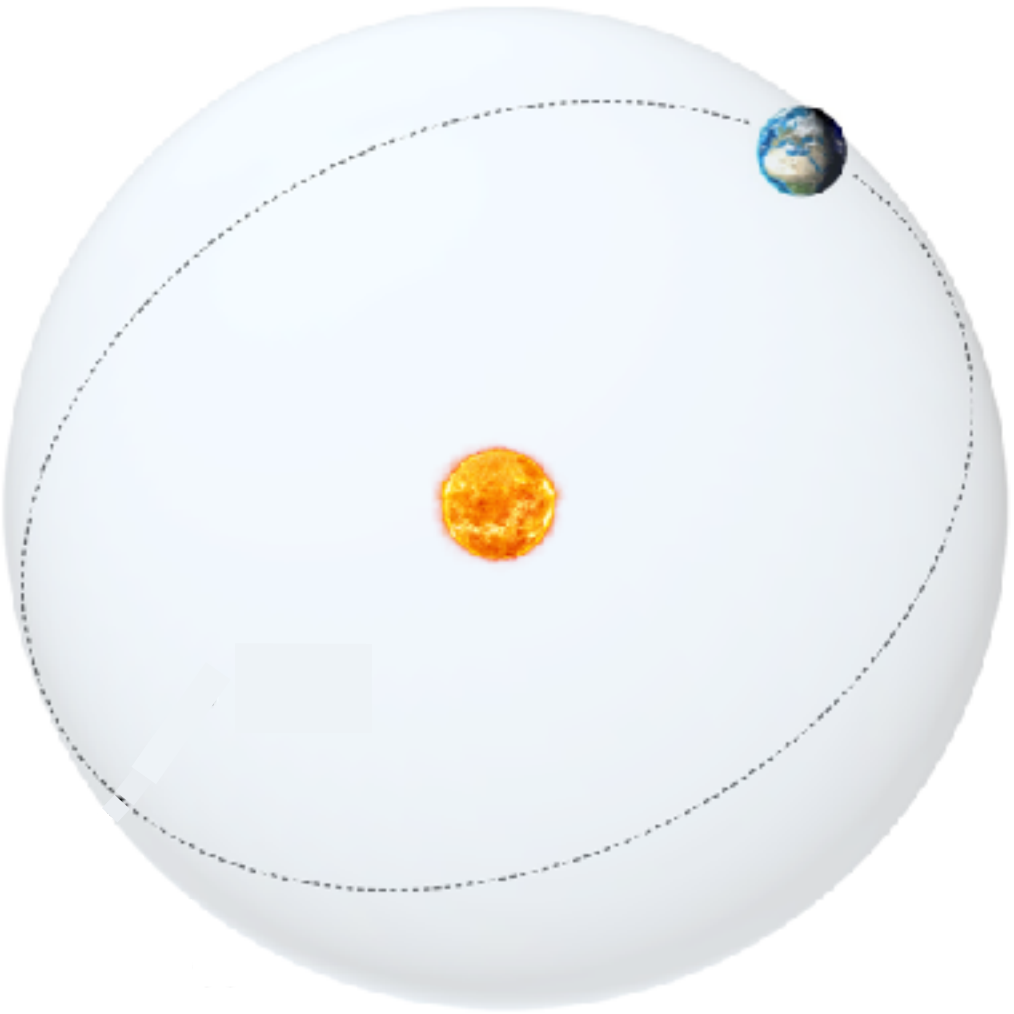
$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m_\phi} + V_g(\psi)\right]\psi - \frac{\lambda}{8m_\phi^2}|\psi|^2\psi$$



(small when density small, return to this later)

(now)

Gravitational Atoms



Balance of gradient+gravity in the field

Structure depends on source of gravity

External source (bound to other body)

$$V_g(\psi) = \frac{GMm_\phi}{r}$$

ULDM itself (self-gravity)

$$\nabla^2 V_g(\psi) = 4\pi G m_\phi^2 |\psi|^2$$

(done)

Boson Stars

What is a Gravitational Atom?

Bound states around an external body, parameterised by $\psi_{n\ell m} = R_{n\ell}(r)Y_{\ell m}(\theta,\phi)$

Gravitational potential:

$$V_g(r) = -\frac{\alpha_g}{r} = -\frac{G m_\phi M_\odot}{r}$$

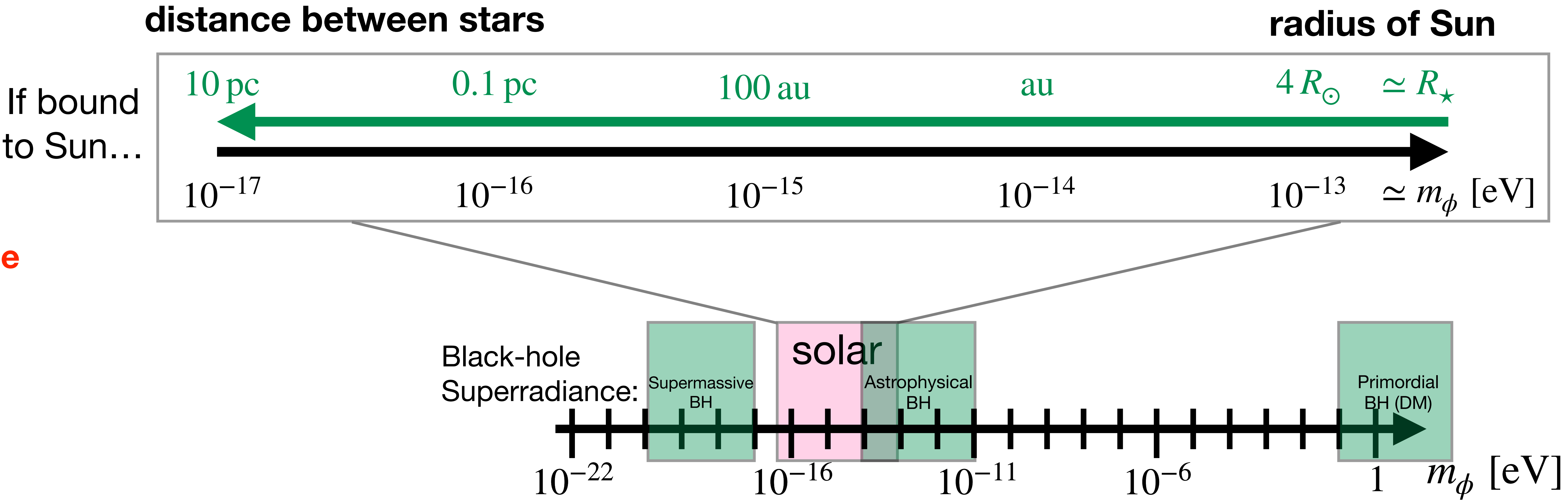
Gravitational "Bohr radius":

$$R_\star = (m_\phi \alpha_g)^{-1} \simeq \frac{1}{G m_\phi^2 M_\odot}$$

compare to Hydrogen:

Coulomb potential: $V(r) = -\dfrac{\alpha}{r}$

Bohr radius: $a_0 = (m_e \alpha)^{-1}$



distance between stars

radius of Sun

If bound to Sun…

$10\ \mathrm{pc}$ — $0.1\ \mathrm{pc}$ — $100\ \mathrm{au}$ — au — $4R_\odot$ — $\simeq R_\star$

10^{-17} — 10^{-16} — 10^{-15} — 10^{-14} — 10^{-13} — $\simeq m_\phi$ [eV]

Black-hole Superradiance:

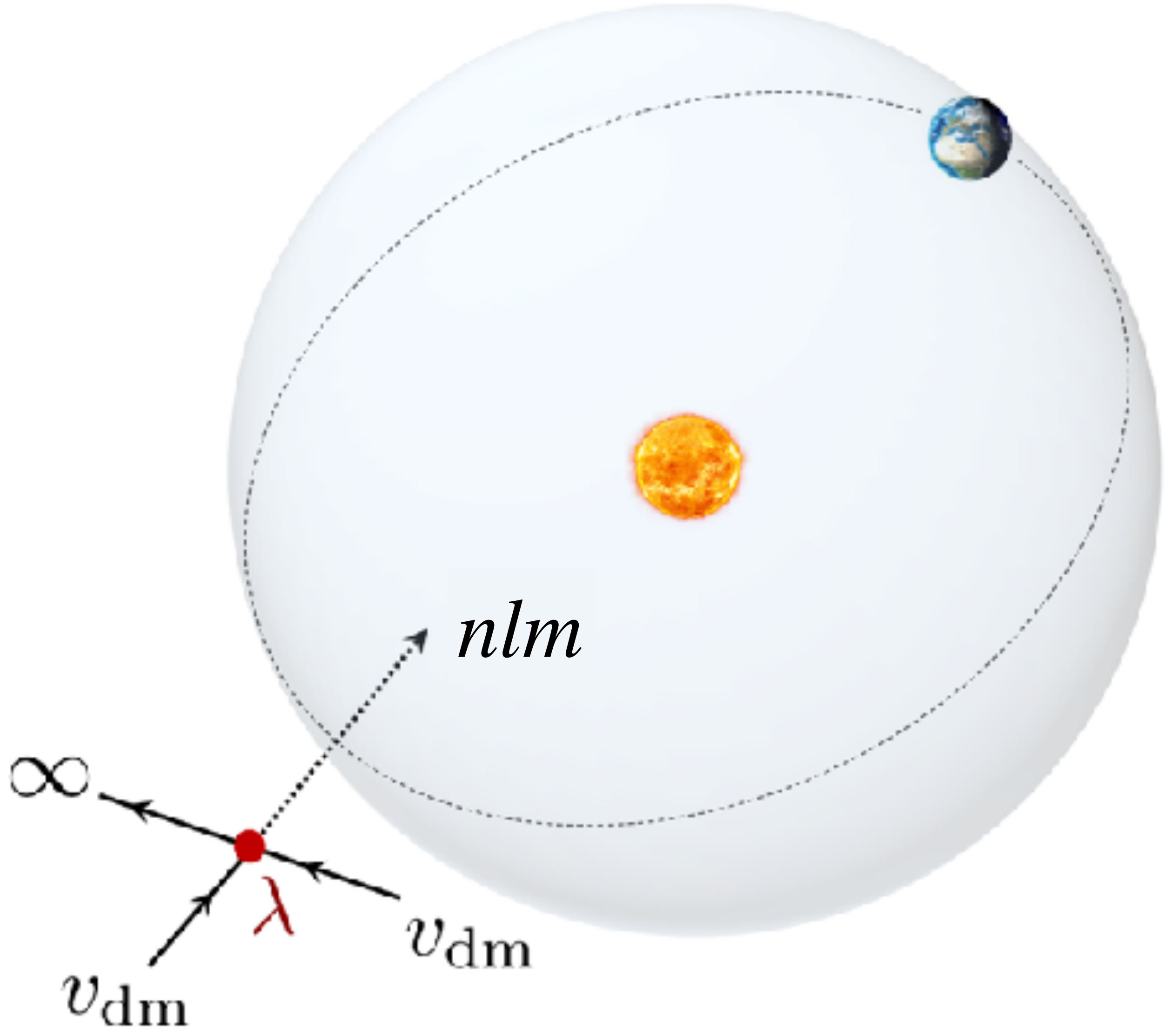
"Quantum" pressure (Repulsive)

Gravity from source (Attractive)

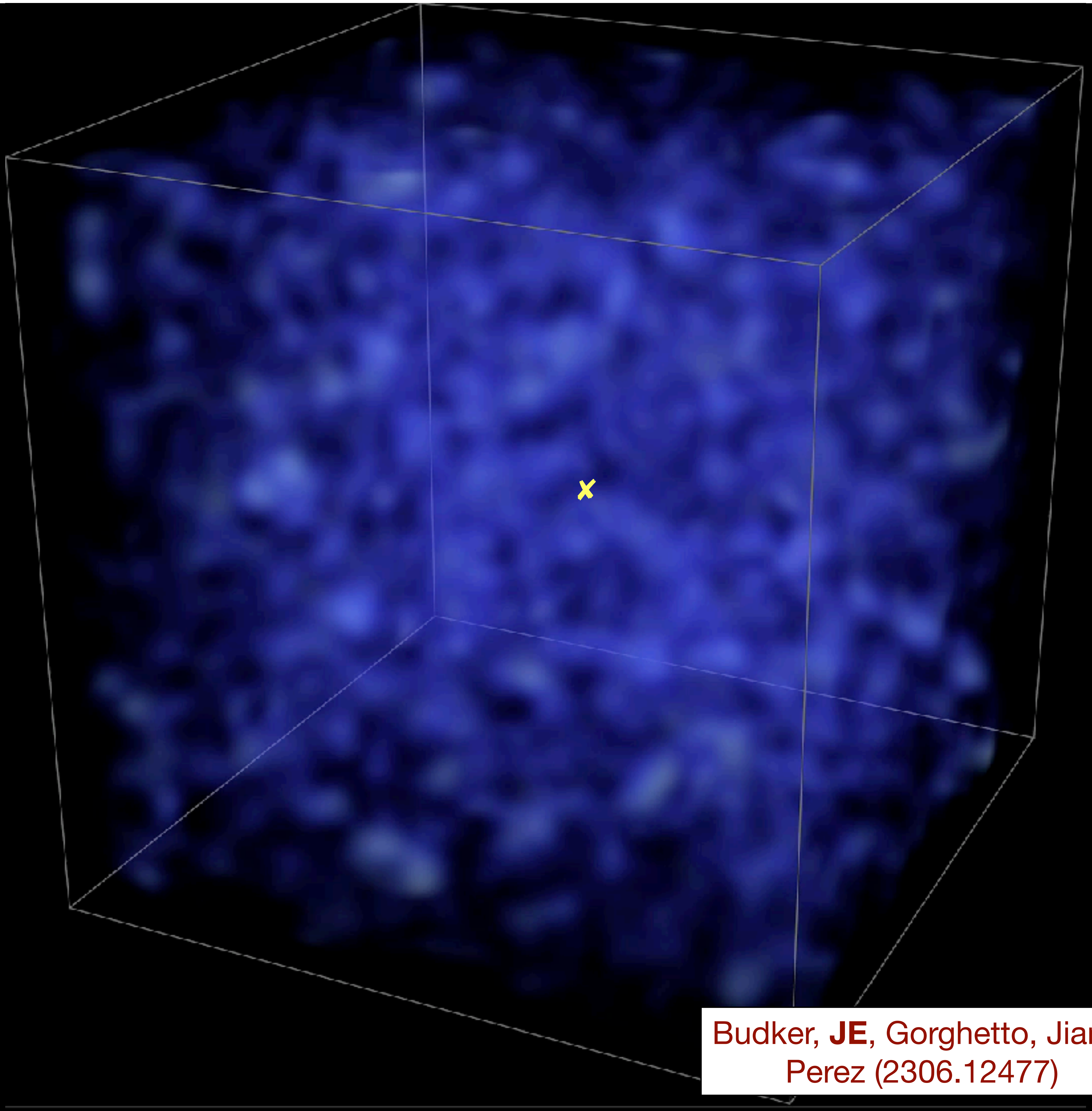
$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m_\phi} + V_g(\psi)\right]\psi$$

Gravitational Atoms from ULDM Capture

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



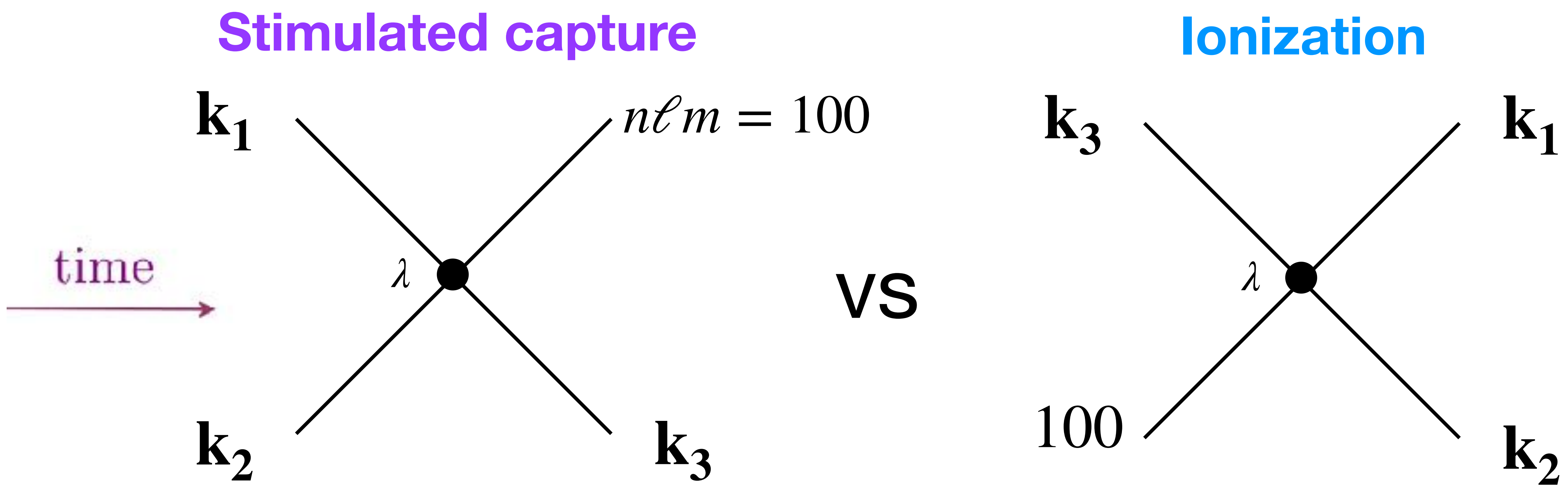
Self-interactions can move particles from scattering states to bound states (and vice versa)



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

Gravitational Atoms from ULDM Capture

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

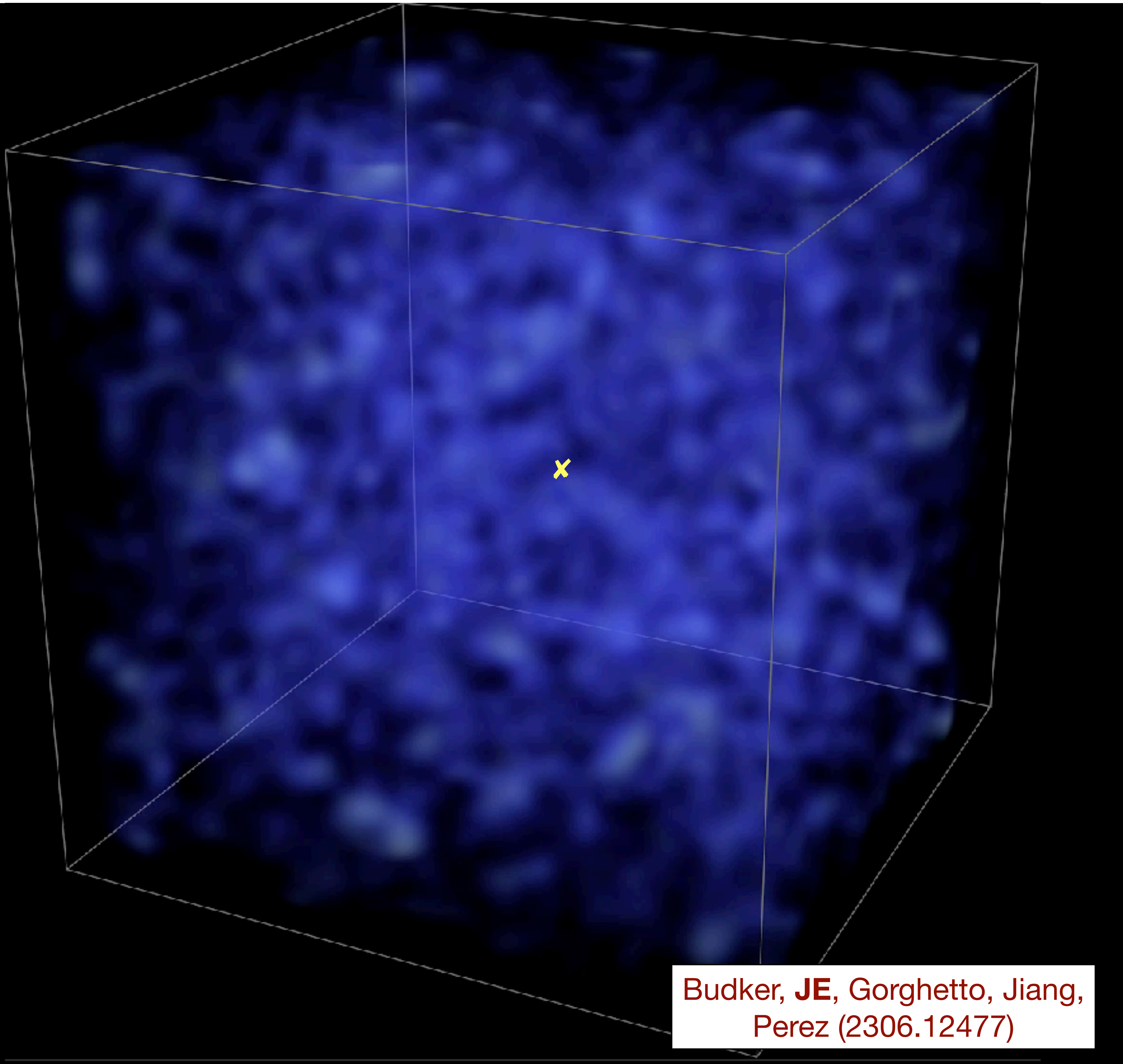


$$\frac{dM_\star}{dt} \simeq C + \overset{\Gamma}{\boxed{(\Gamma_1 - 2\Gamma_2)}}\, M_\star$$

$\Gamma > 0$: Exponential growth

$\Gamma < 0$: Saturation

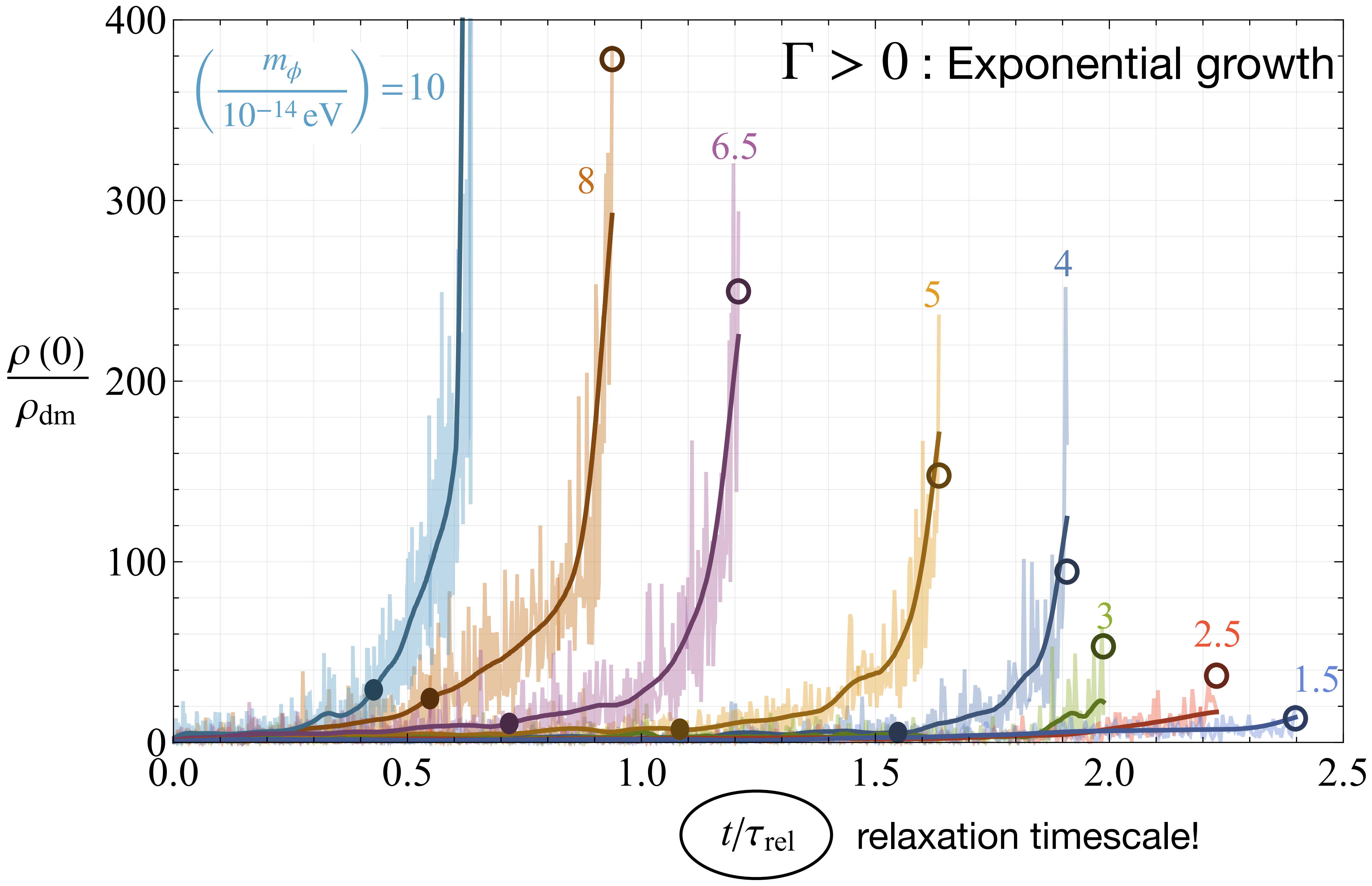
determines late-time behavior

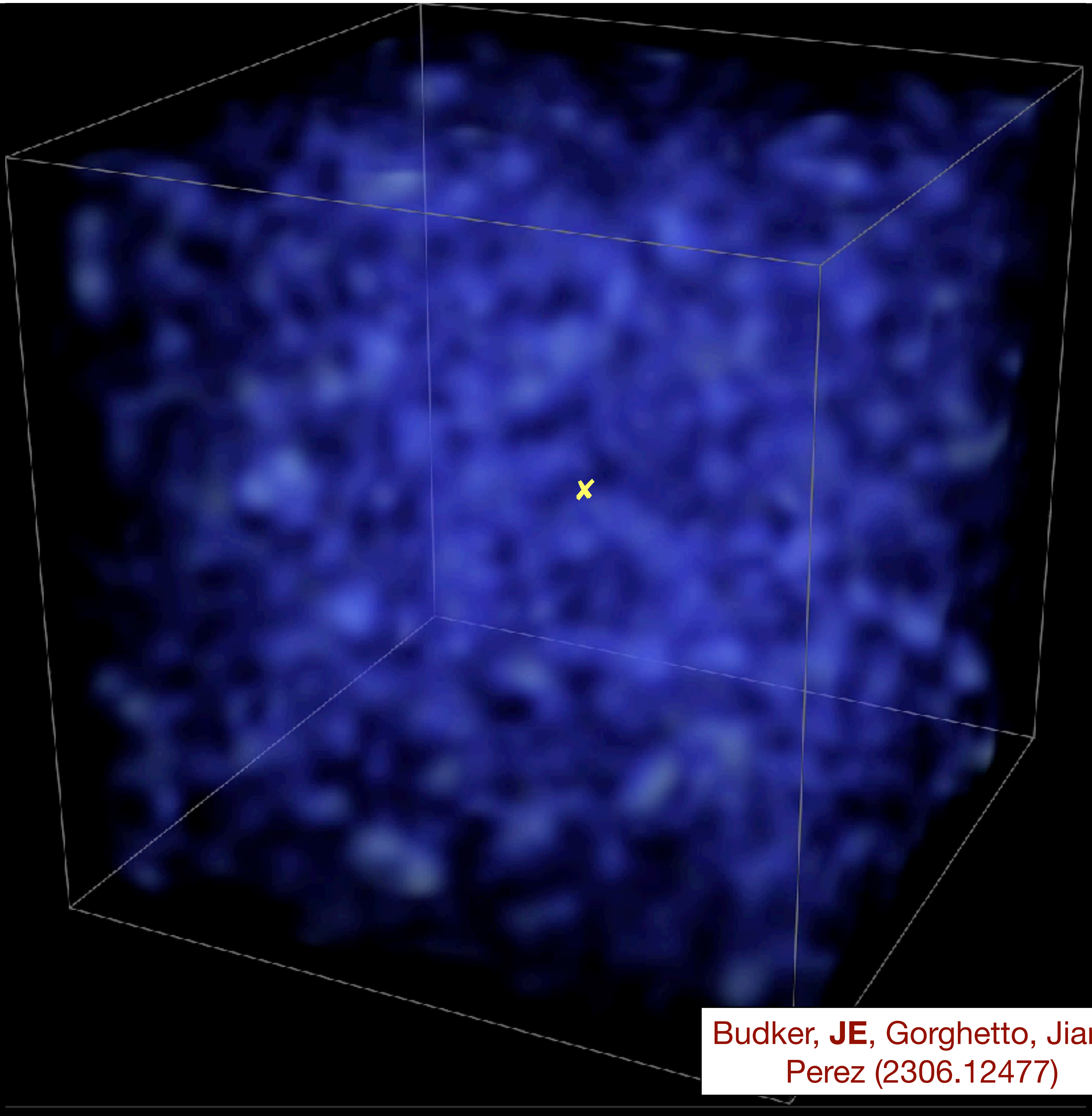


Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Gravitational Atoms from ULDM Capture

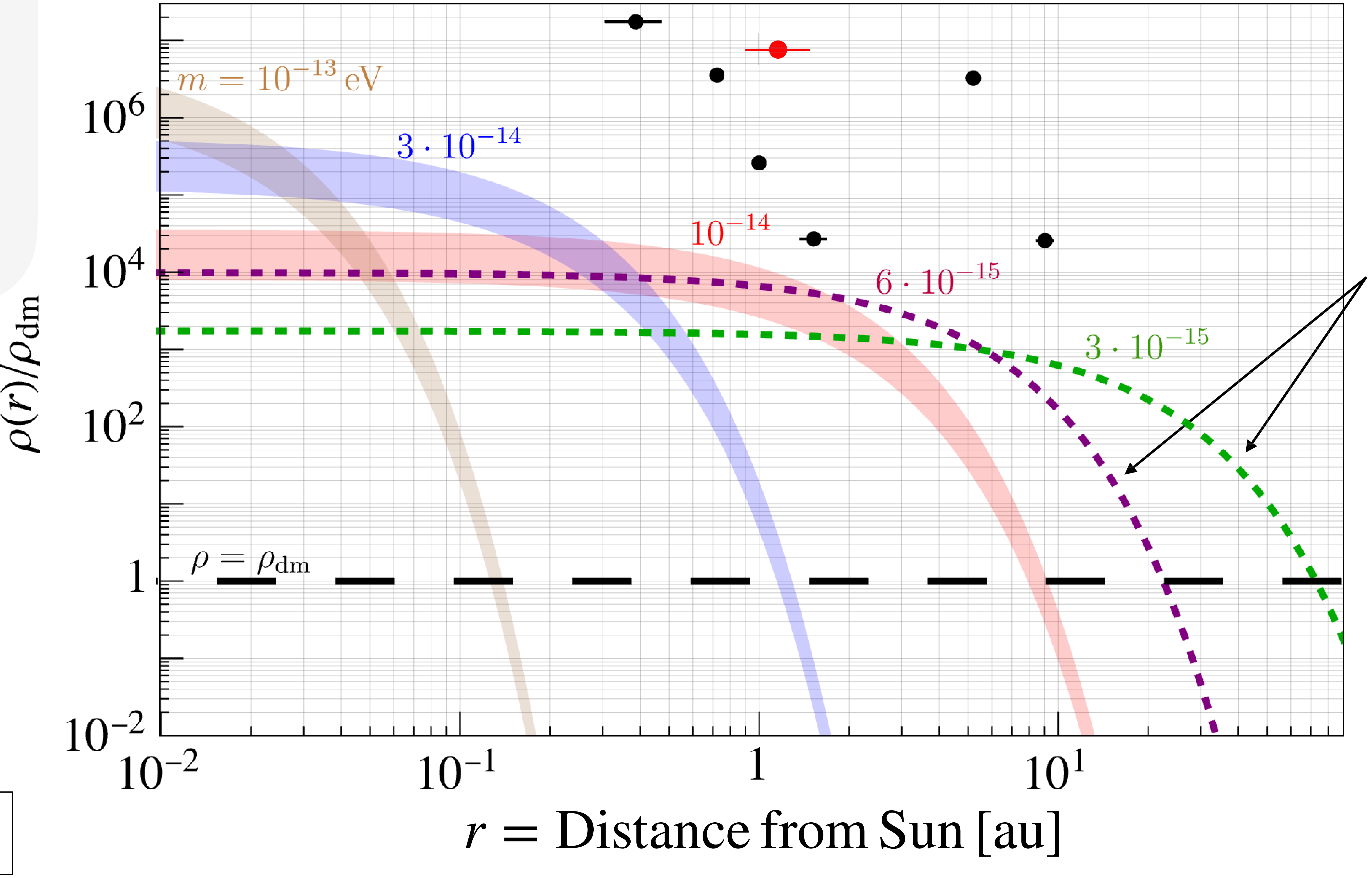
$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \frac{\alpha_g}{r} - \frac{\lambda}{8m_\phi^2}|\psi|^2\right]\psi$$





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

Gravitational Atom in our Solar System



relevant when DM velocity is very low, $v_{\rm dm} \ll 200\,\mathrm{km/s}$

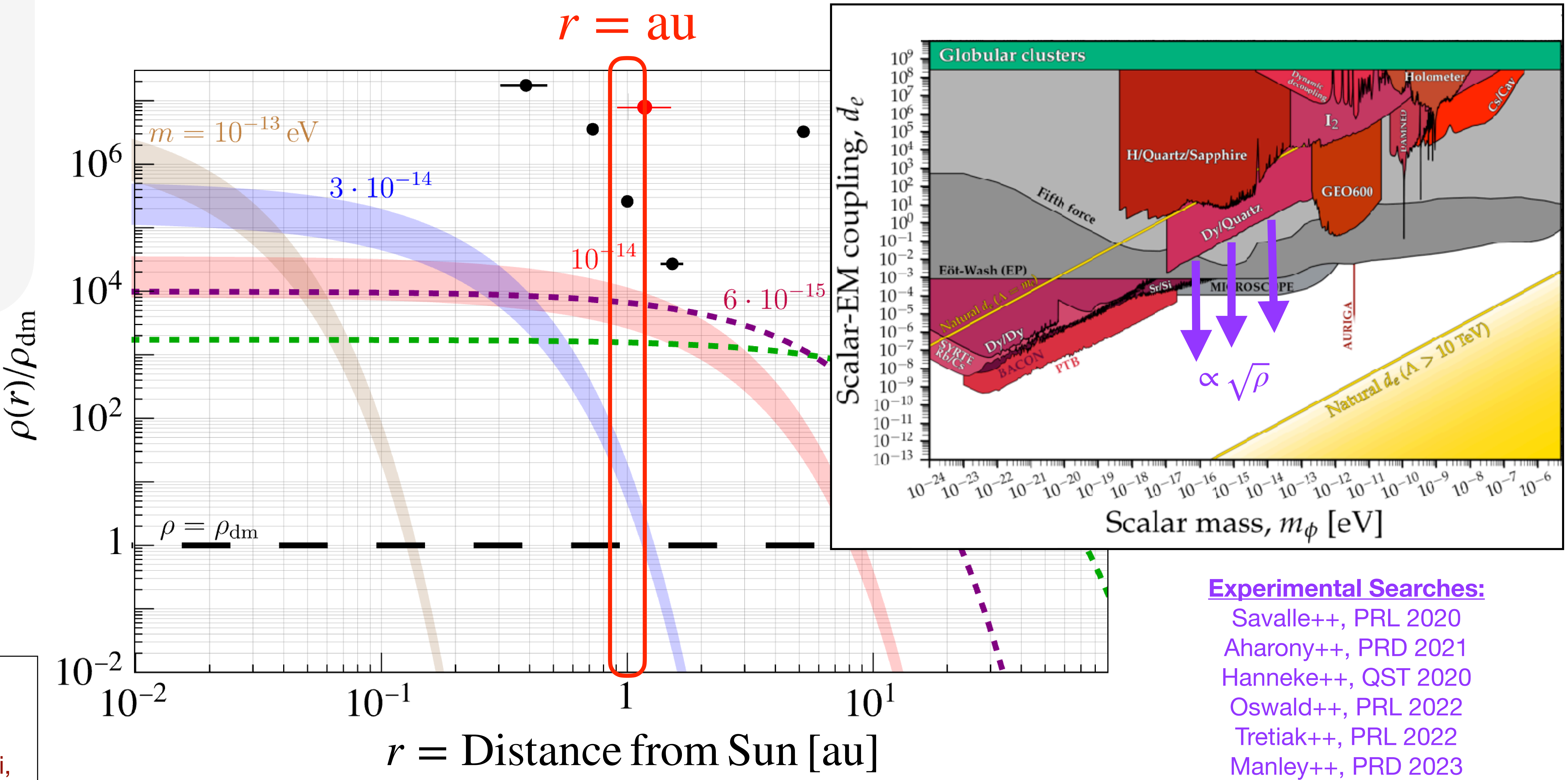
Budker, **JE**, Gorghetto, Jiang, Perez (2306.12477)

Black points: Constraints from planets
Piitjev and Pitjeva (1306.5534)

Red point: Constraint from Bennu asteroid
Tsai, **JE**, Arakawa, Farnocchia, Safronova (2210.03749)

Gravitational Atom in our Solar System

Searches on Earth

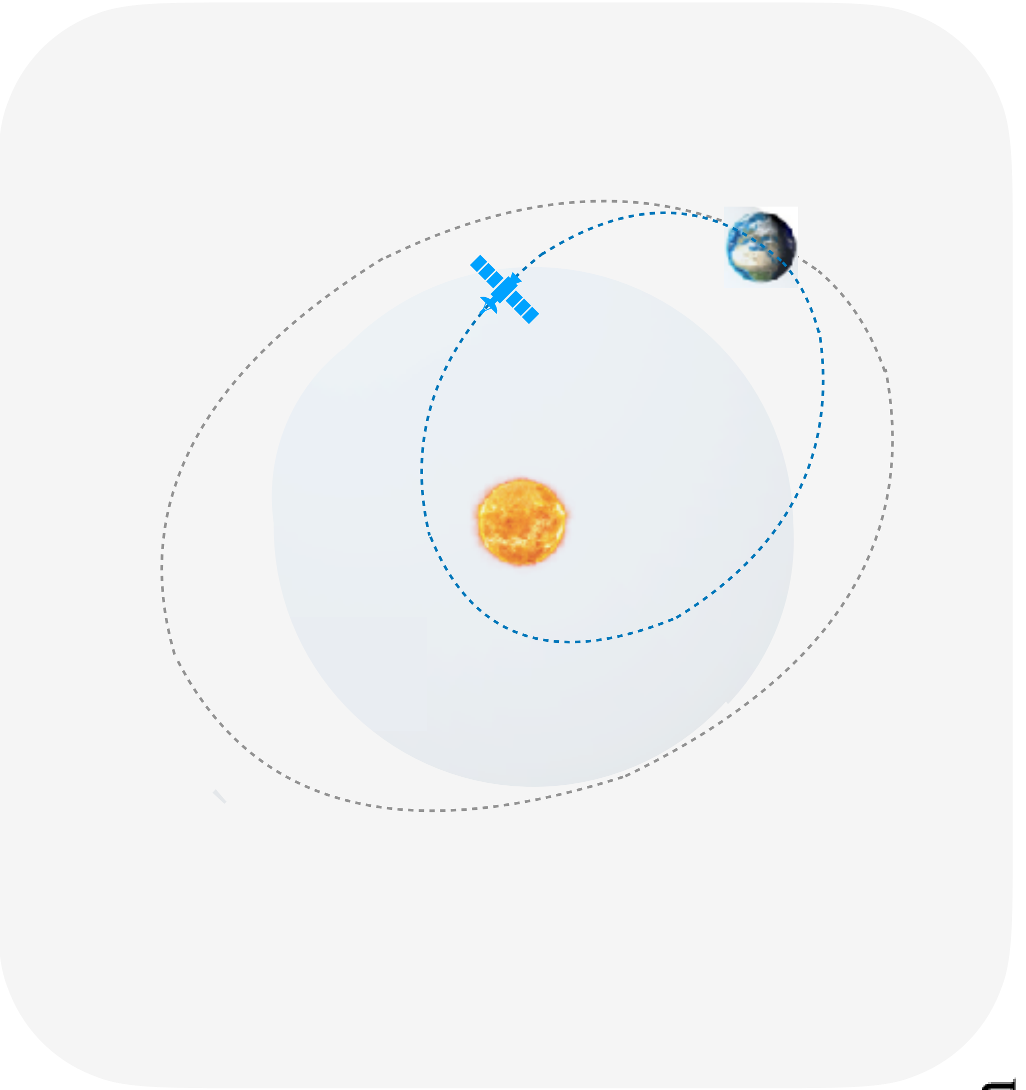


Banerjee, Budker, **JE**, Kim, Perez (1902.08212)

with Flambaum, Matsedonskyi, (1912.04295)

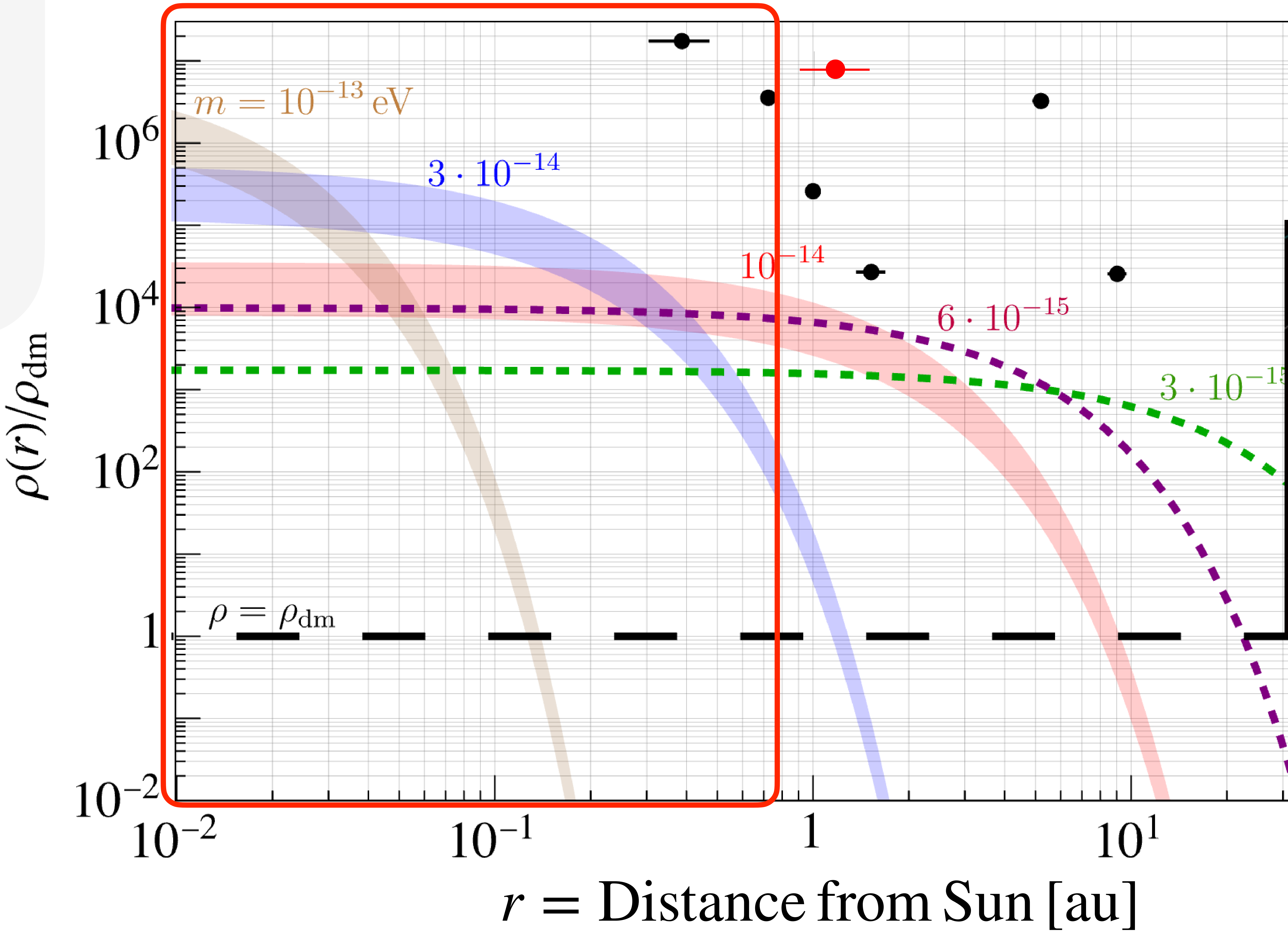
Experimental Searches:
Savalle++, PRL 2020
Aharony++, PRD 2021
Hanneke++, QST 2020
Oswald++, PRL 2022
Tretiak++, PRL 2022
Manley++, PRD 2023
…

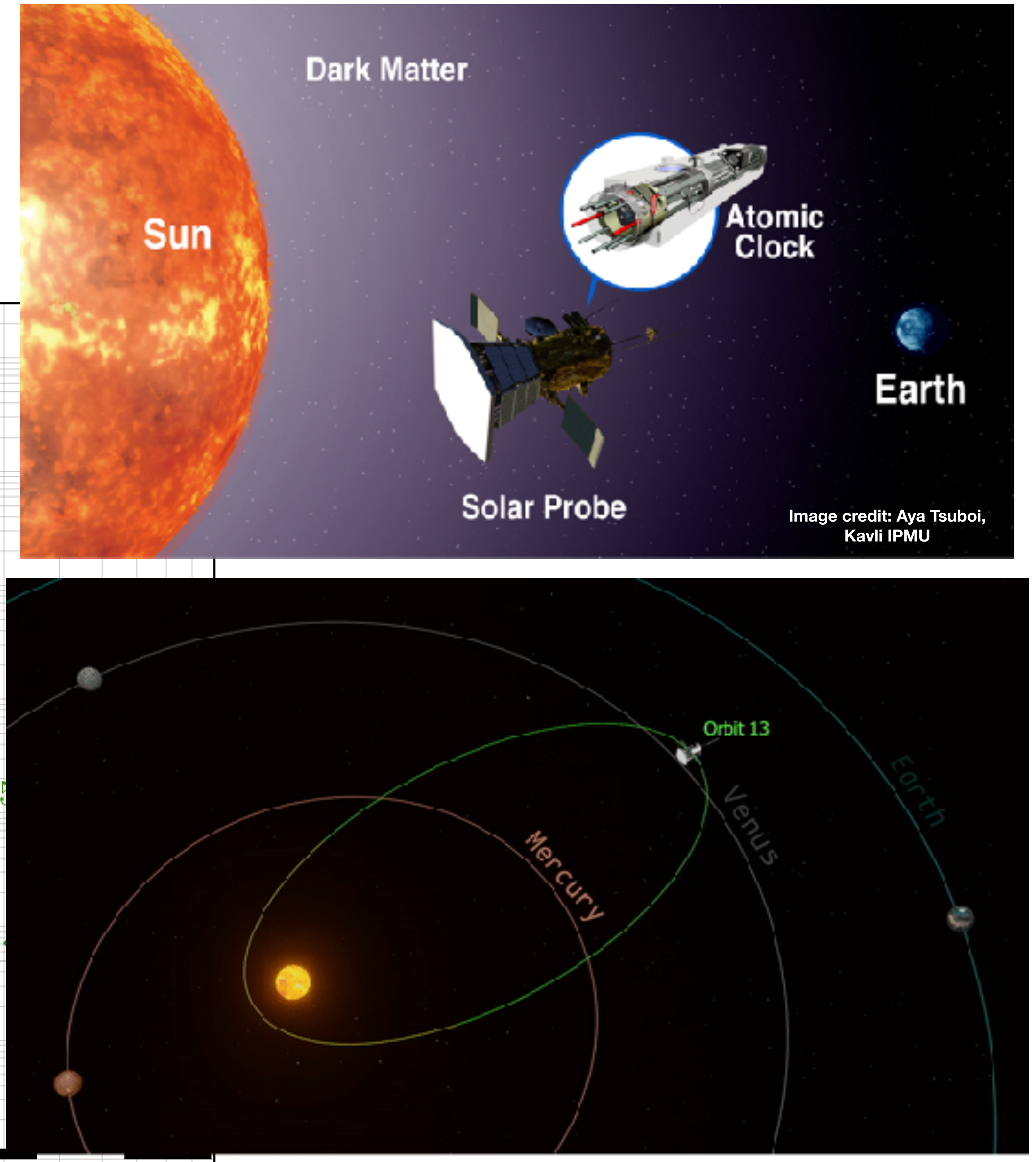
Gravitational Atom in our Solar System



Space missions near the Sun

$r <$ au

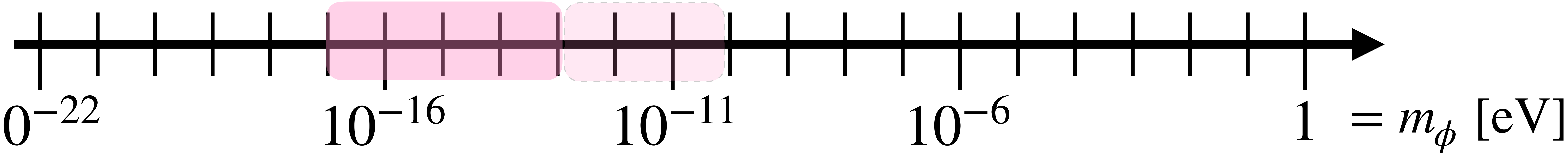




Proposal for future space missions to search near the Sun, where the ULDM density is expected to be largest

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

ULDM Across the Galaxy



Gravitational atoms bound to…

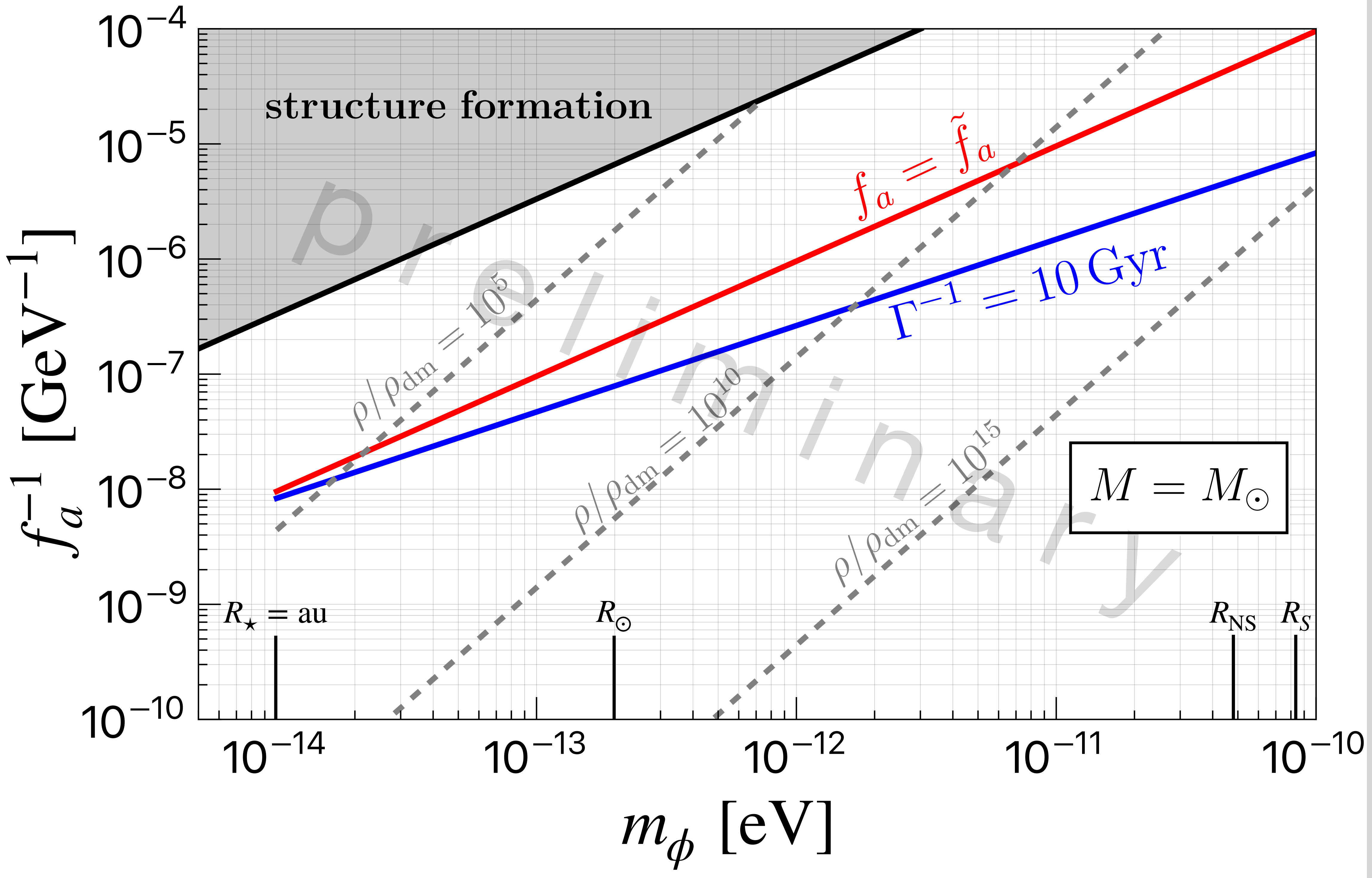
Sun/stars

Budker, **JE**, Perez,	
…with Banerjee, Kim	(1902.08212)
+ Flambaum, Matsedonskyi	(1912.04295)
…with Gorghetto, Jiang	(2306.12477)

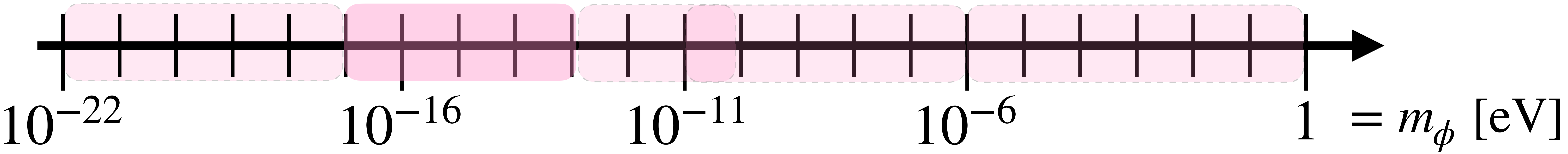
neutron stars / astro BHs

Ongoing work!

Samuel Gómez
Master's Student
Uppsala University



ULDM Across the Galaxy



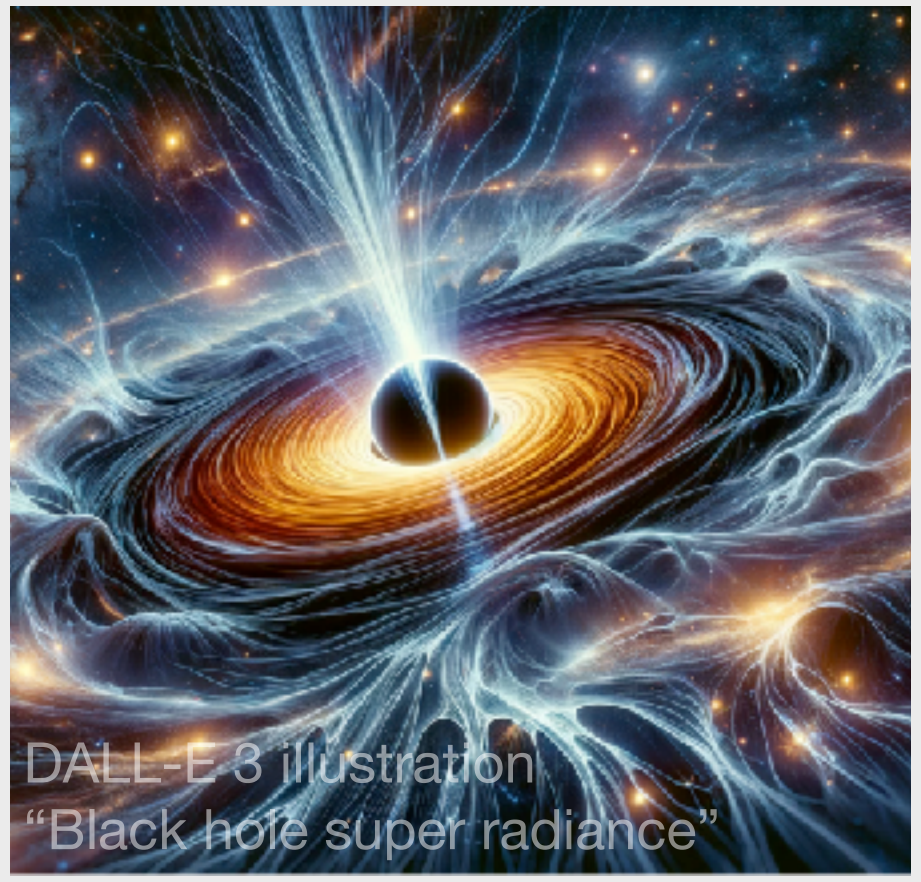
Gravitational atoms bound to…

supermassive black holes

Sun/stars

Budker, **JE**, Perez,
…with Banerjee, Kim (1902.08212)
+ Flambaum, Matsedonskyi (1912.04295)
…with Gorghetto, Jiang (2306.12477)

Birefringence signals:
Gan, Wang, Xiao (2311.02149)



DALL-E 3 illustration
"Black hole super radiance"

neutron stars / astro BHs

Ongoing work!

Samuel Gómez
Master's Student
Uppsala University

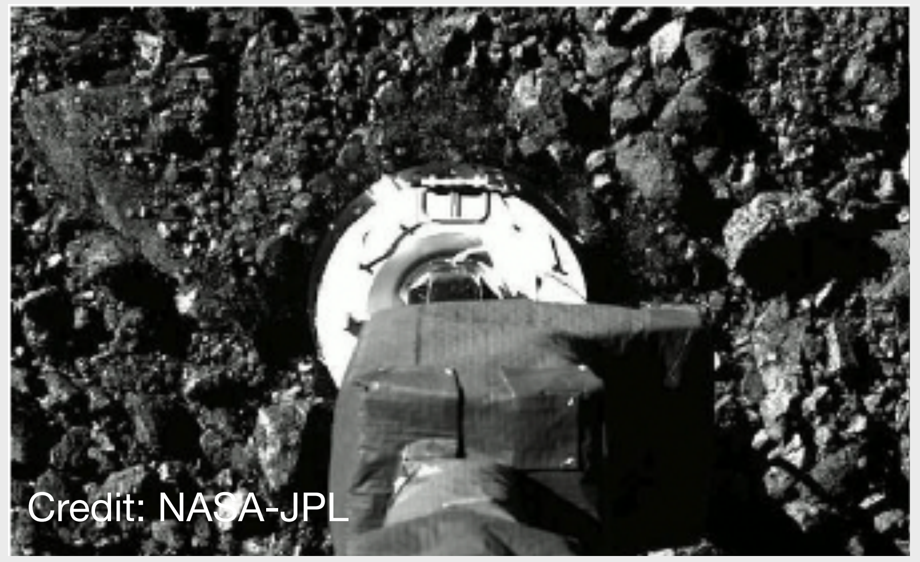
planets

JUNO mission to Jupiter

Credit: NASA-JPL

asteroids

OSIRIS-REx → OSIRIS-APEx



Credit: NASA-JPL

Utilize the rapidly growing subfield of asteroid tracking!

+ future asteroid missions

Earth-bound Gravitational Atoms:

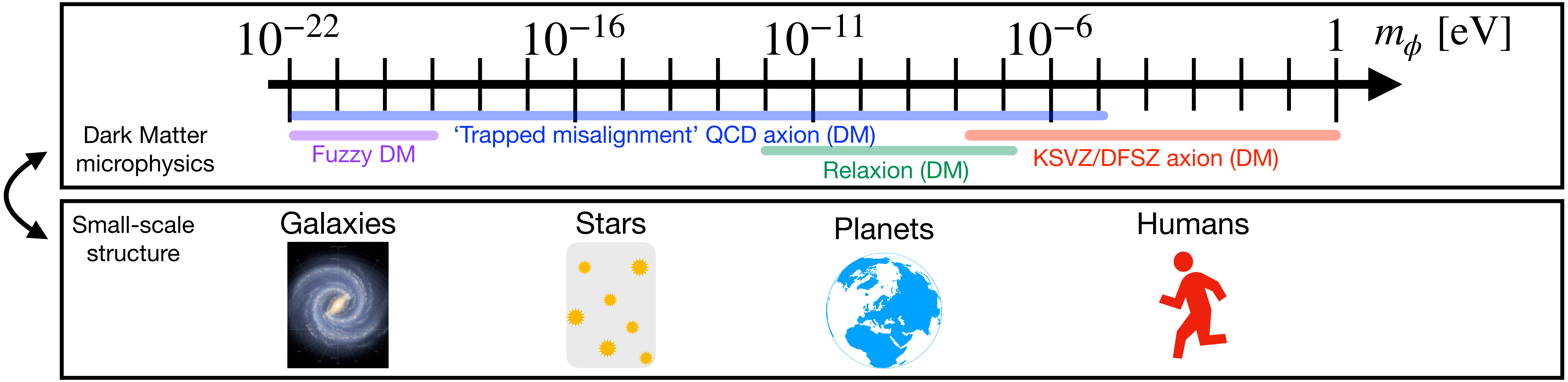
Gravimeters: Hu++ (1912.01900)

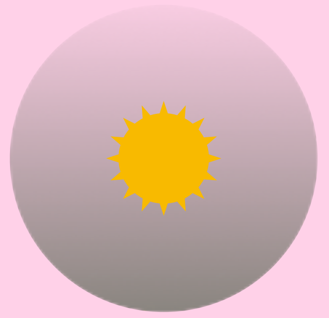
Atomic clocks: Kouvaris++ (2106.06023)

Neutrinos: Gherghetta, Shkerin (2305.06441)

Radio telescopes: Gong++ (2308.08477)

Conclusion: New Paths to Discovery



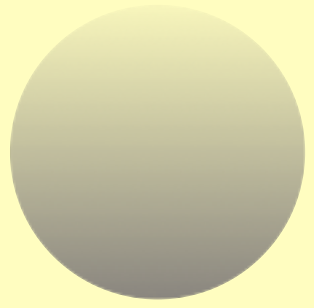


Gravitational Atoms

galactic | **astrophysical** | **mini**

bound to…

supermassive black holes | **Sun/stars** | **NS** | **planets** | **asteroids?**



Boson Stars

We are exploring the unavoidable and unexplored consequences of the theory, to elucidate the nature of ULDM and find new paths to discovery

Big open questions remain:

- Core-halo relation? mass growth rate? Mass distribution of boson stars?
- Signals from GAs across the galaxy?

DALL-E 3 illustration
“Cosmic WISPers”

Thank you for
your attention!