MORTIMER B.
ZUCKERMAN
STEM LEADERSHIP
PROGRAM

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

Probing Novel Dark Matter Substructure at Galactic and Solar Scales

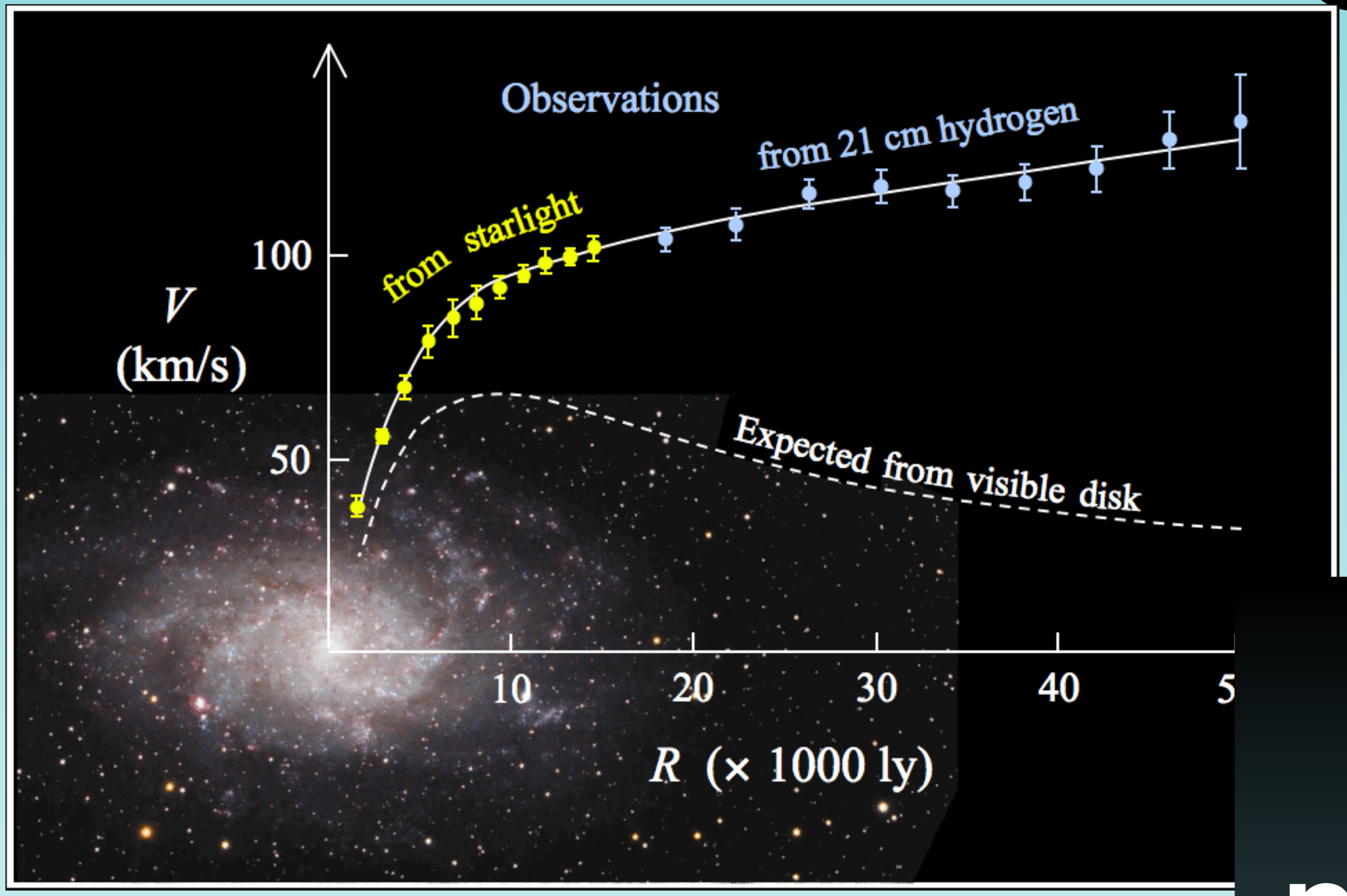
Joshua Eby
Weizmann Institute of Science

IPMU APEC Seminar
30/04/2020

Outline

- Light Scalar Dark Matter
- Substructure
  - …in Galaxies
  - …in Solar Systems
- Conclusions

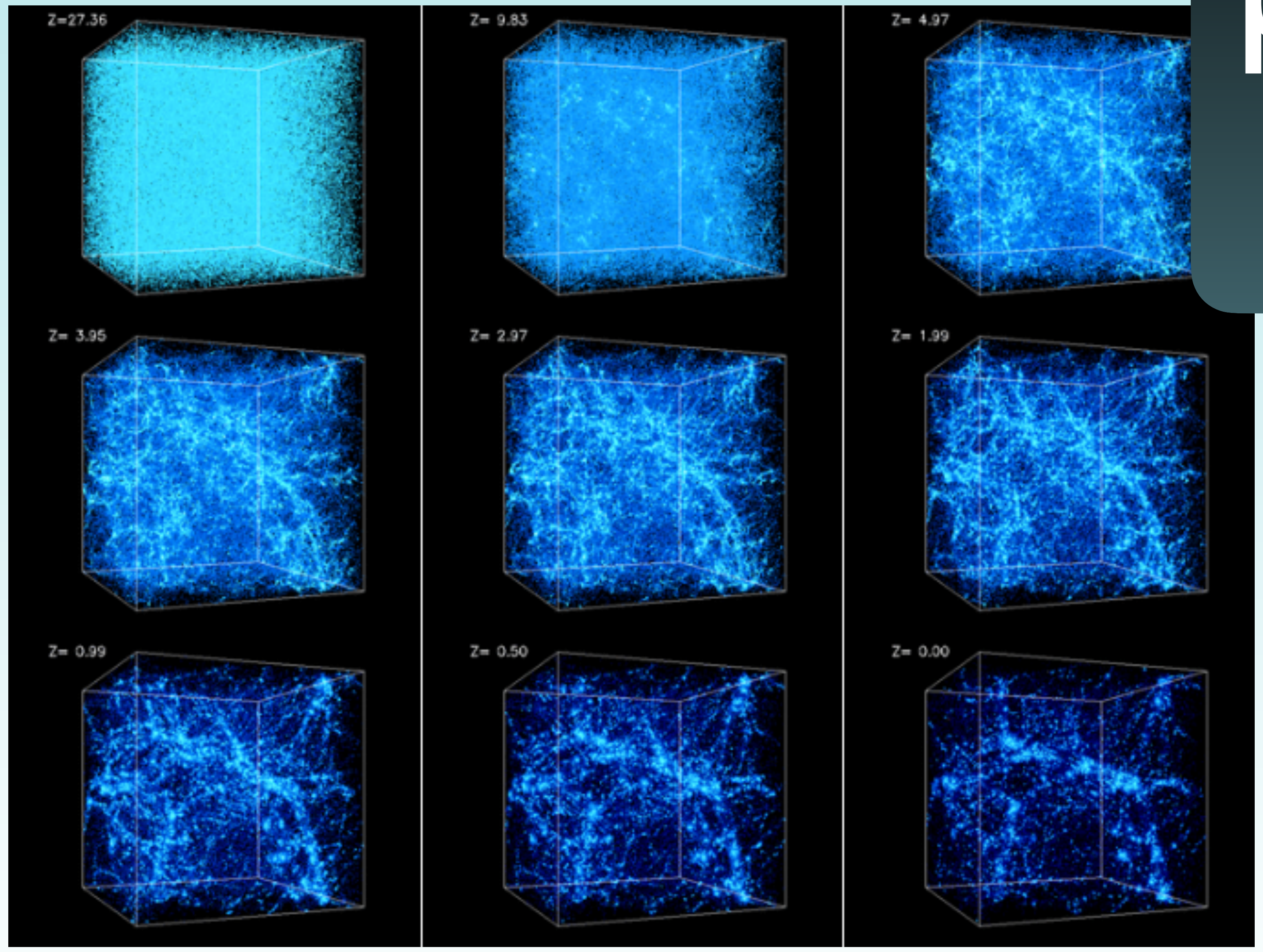
Big Question



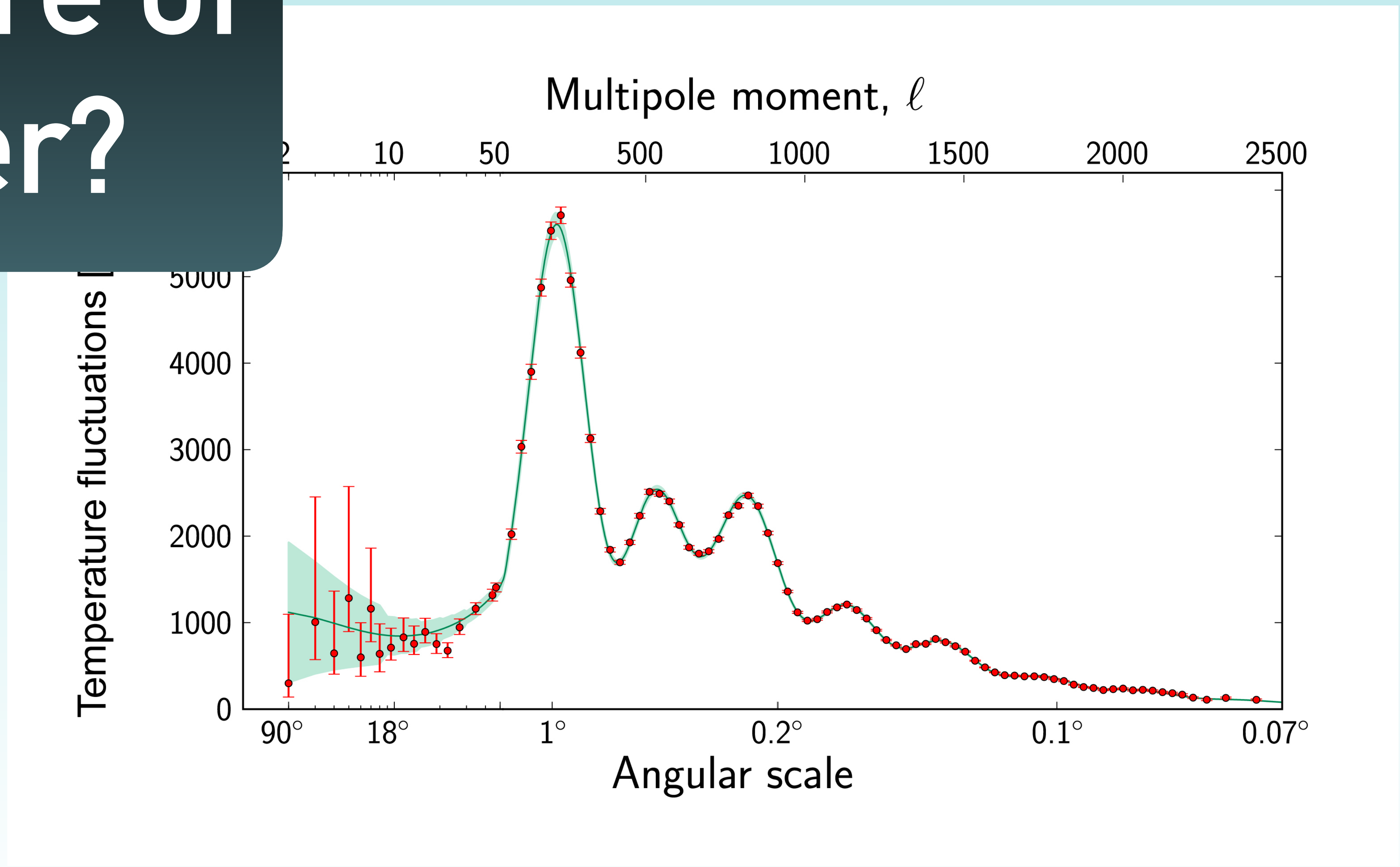
Flat rotation curves

Galaxy cluster collisions

What is the particle nature of Dark Matter?

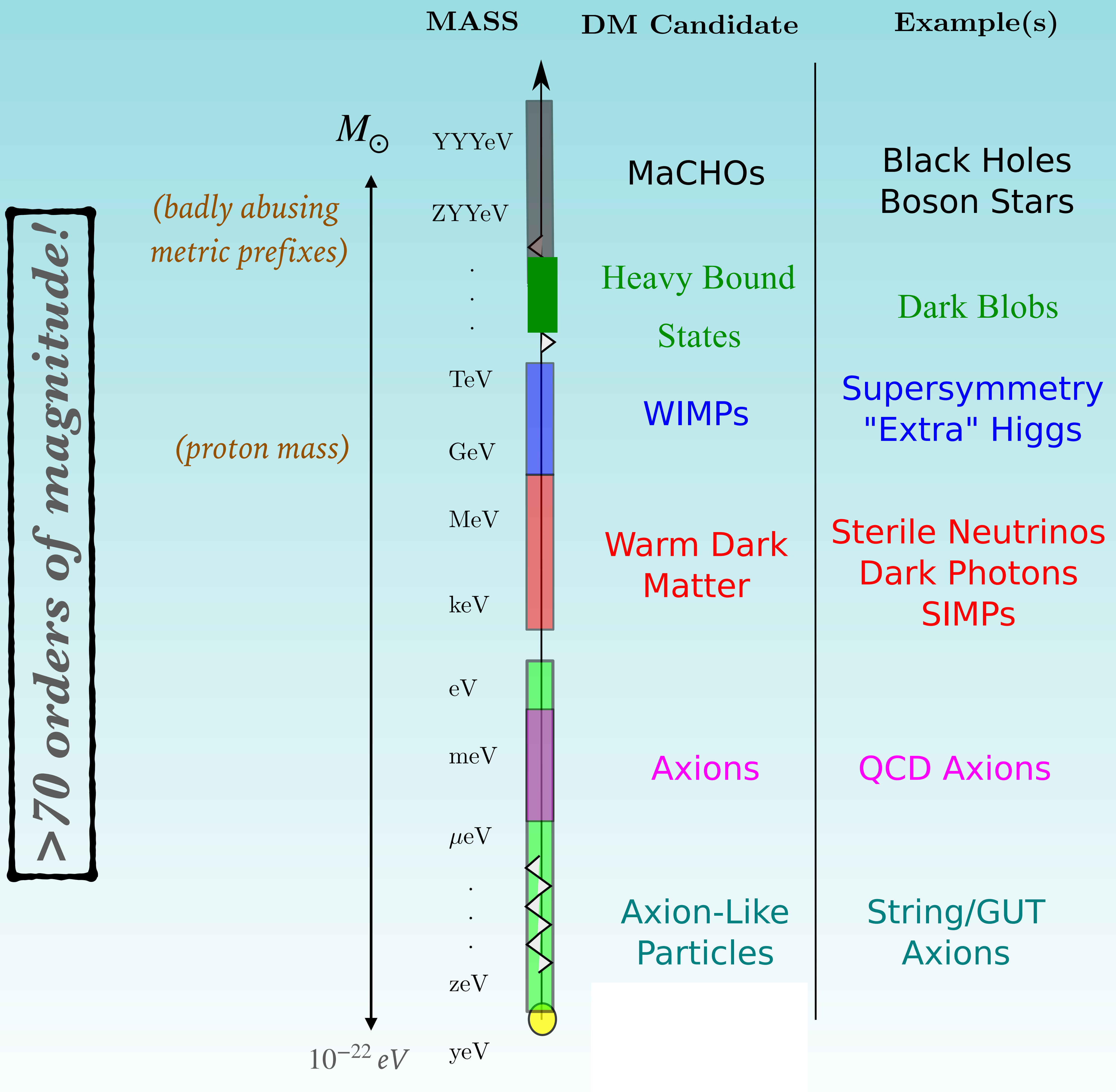


Large scale structure



Cosmic microwave background

Dark Matter Models



>70 orders of magnitude!

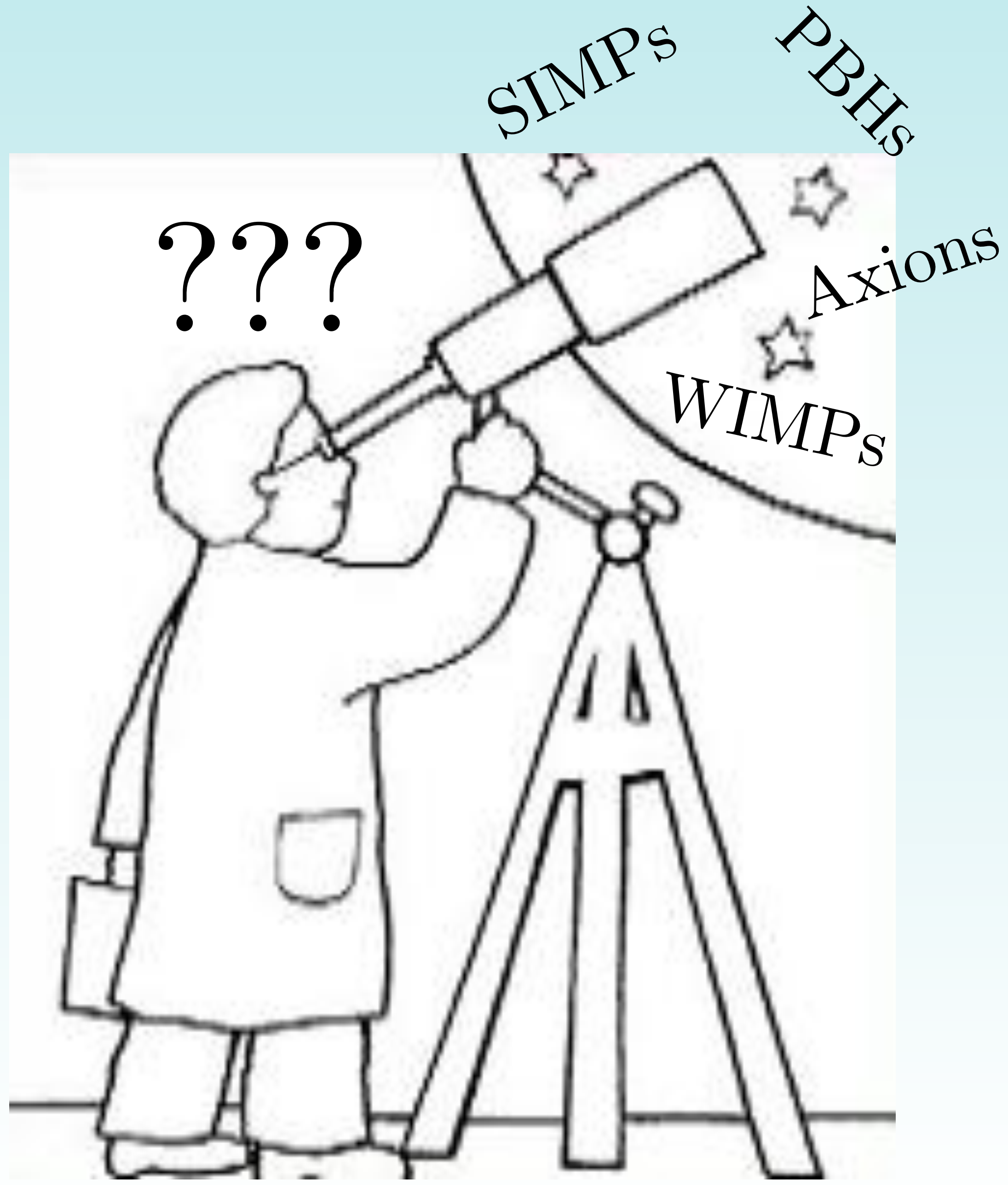
$M_{\odot}$

(badly abusing metric prefixes)

(proton mass)

$10^{-22}\,eV$

MASS	DM Candidate	Example(s)
YYYeV ZYYeV	MaCHOs	Black Holes Boson Stars
. . .	Heavy Bound States	Dark Blobs
TeV GeV	WIMPs	Supersymmetry "Extra" Higgs
MeV keV	Warm Dark Matter	Sterile Neutrinos Dark Photons SIMPs
eV meV	Axions	QCD Axions
μeV . . . zeV yeV	Axion-Like Particles	String/GUT Axions



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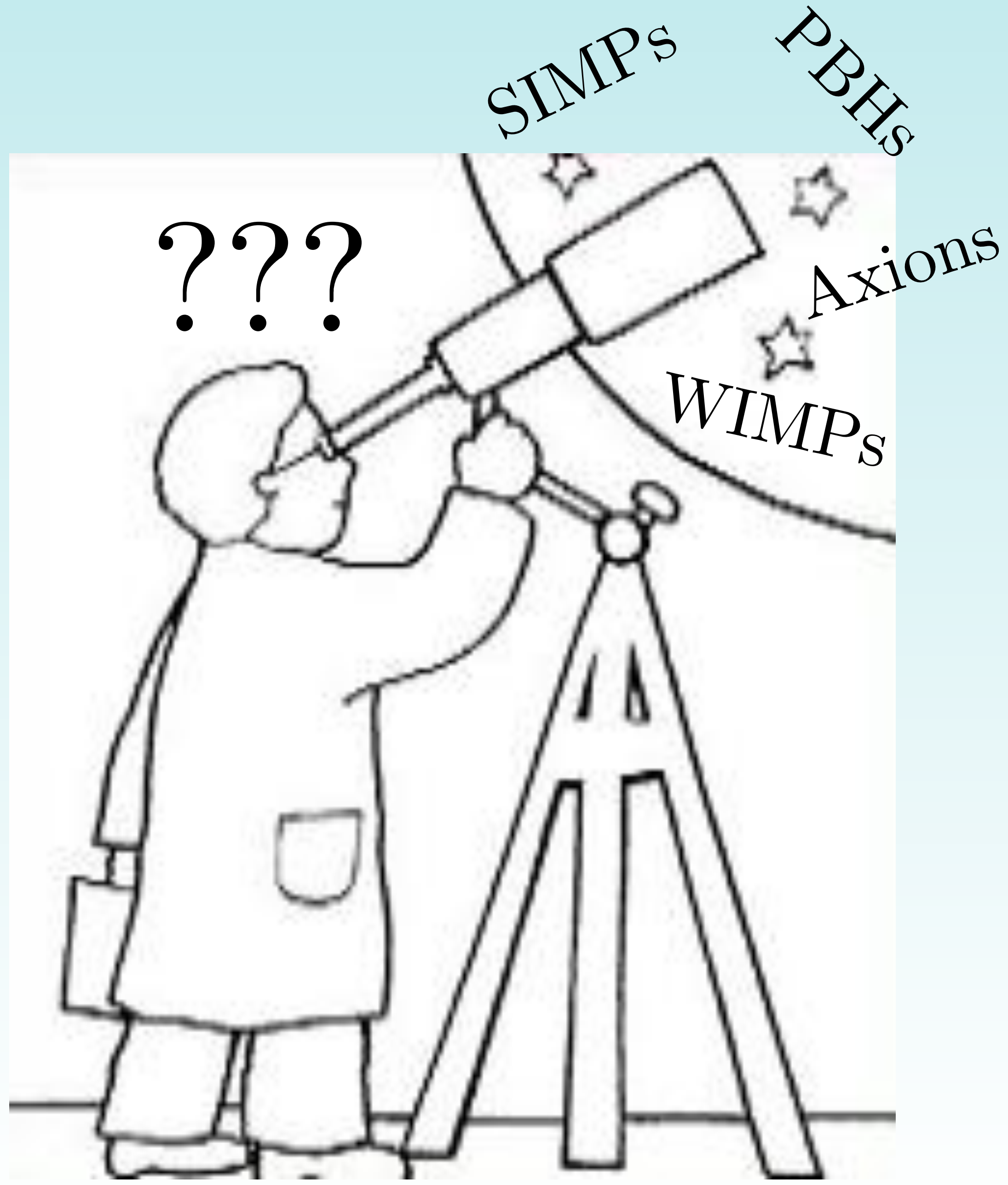

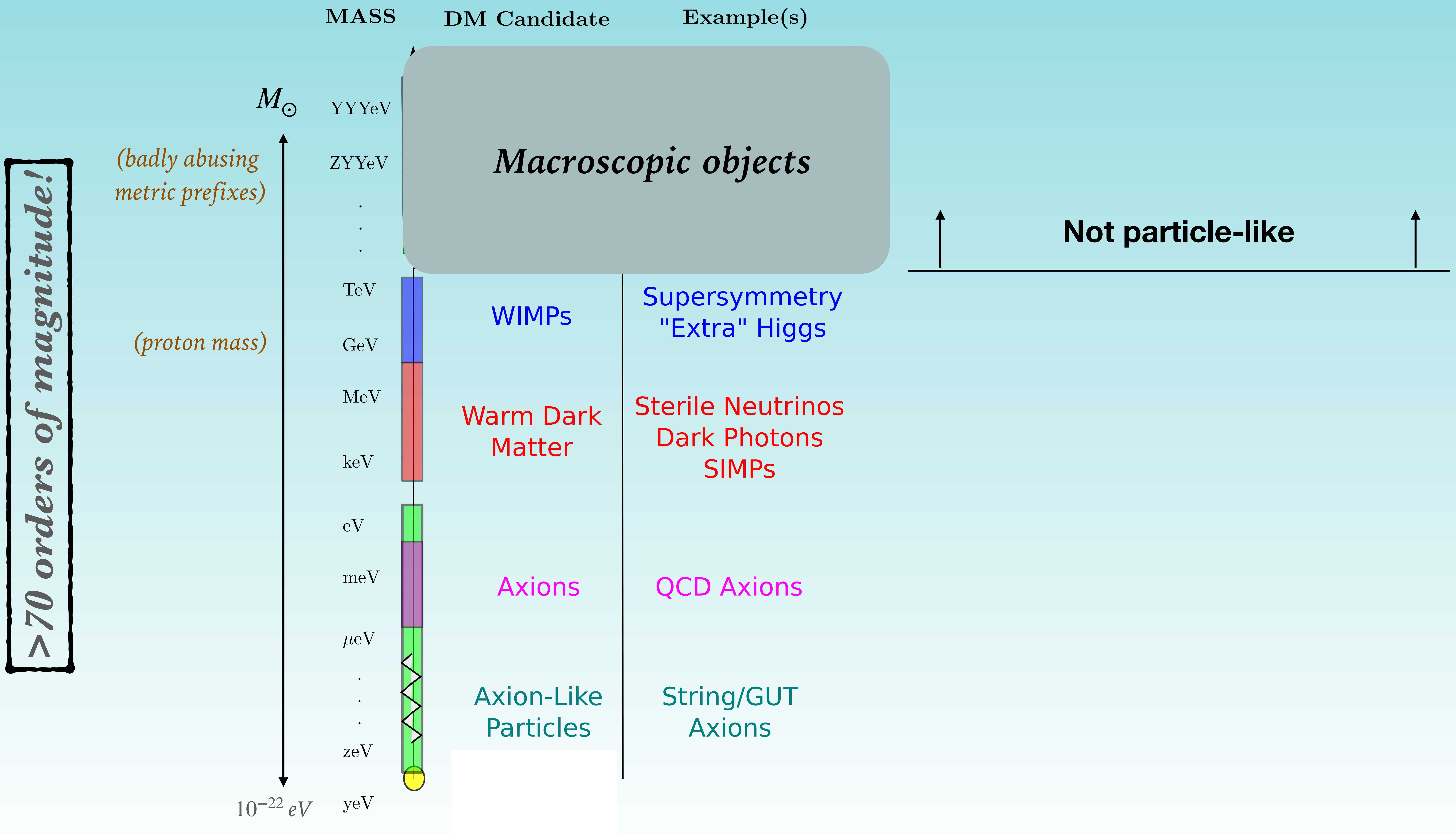

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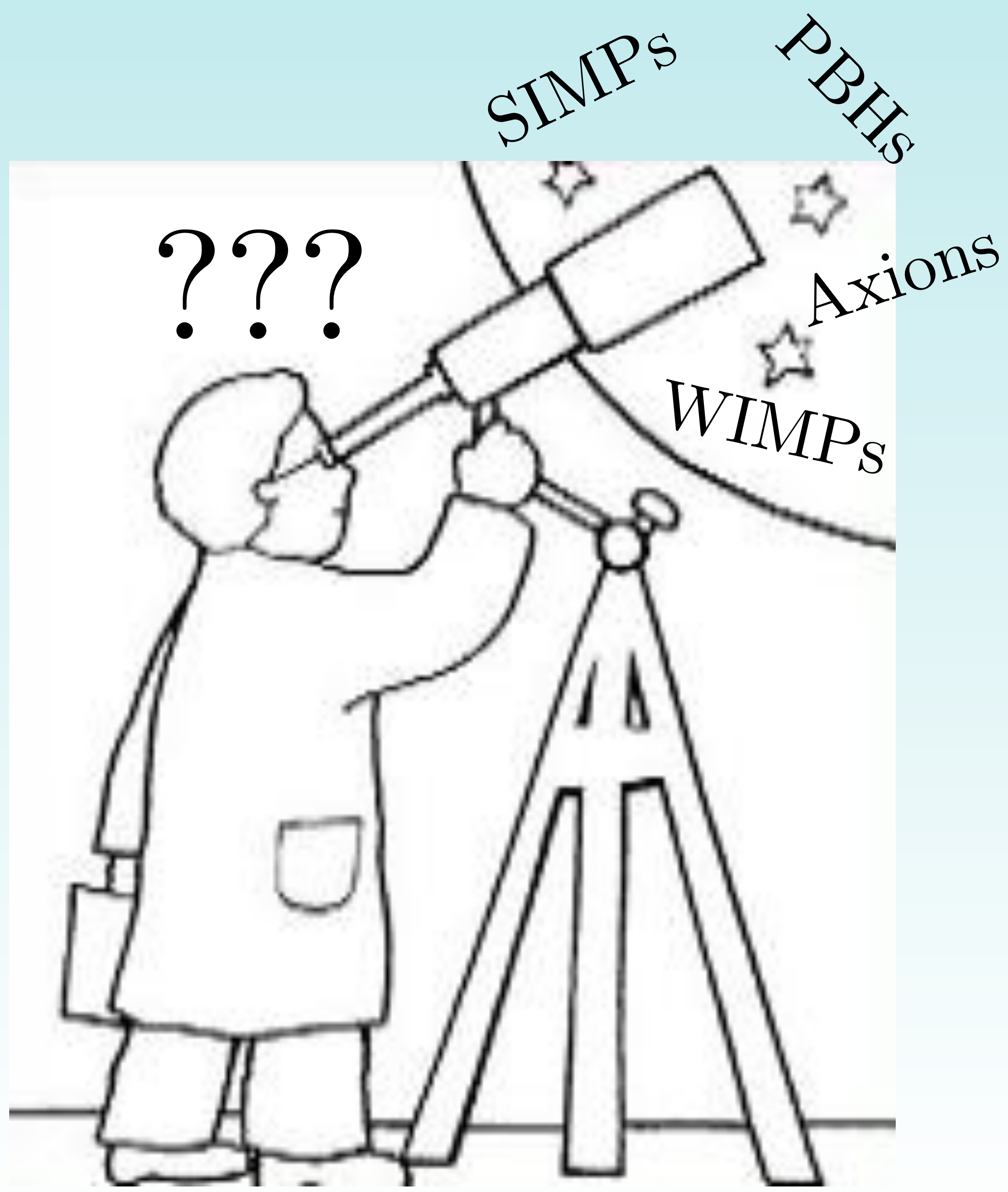
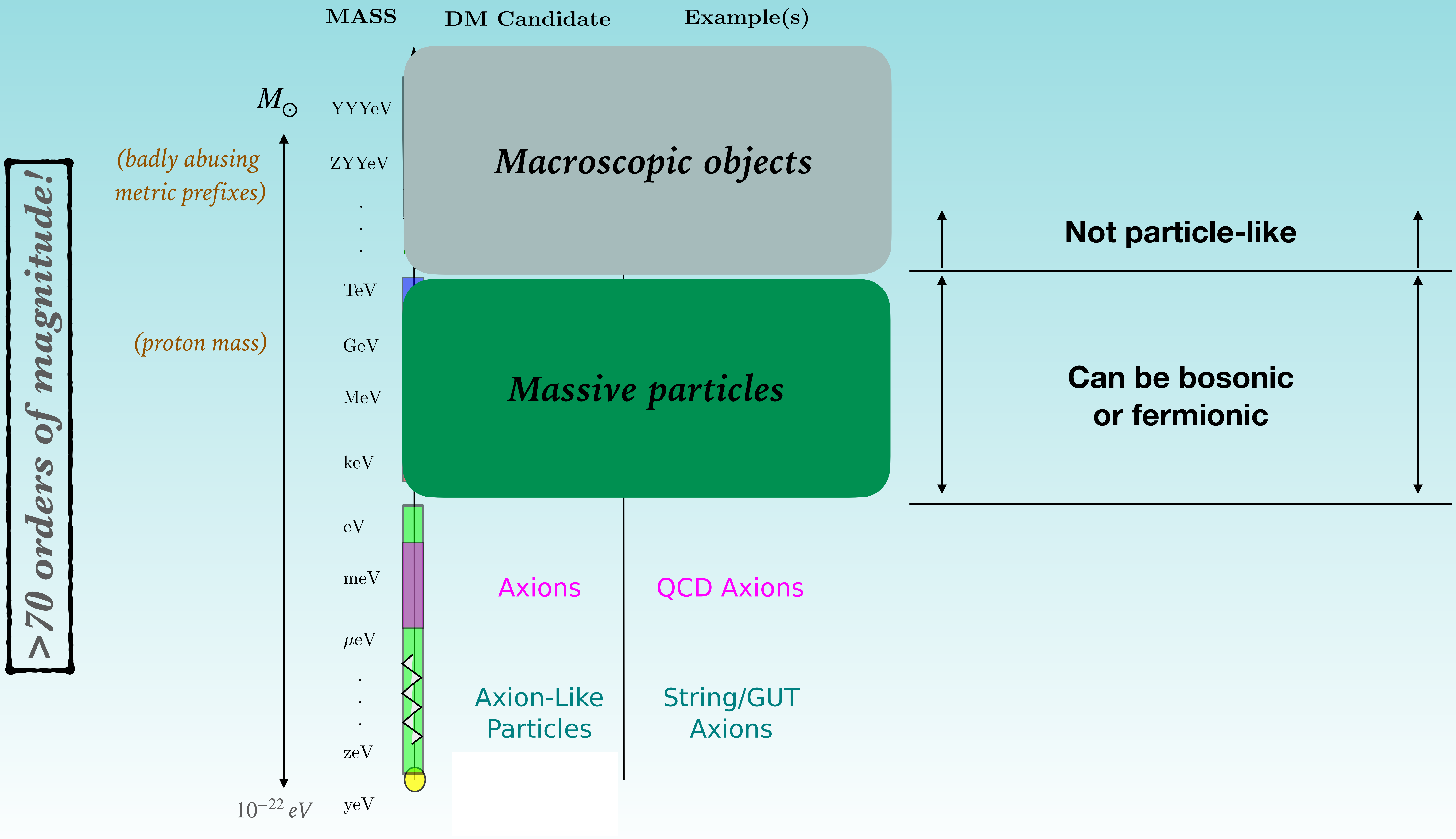
Not particle-like

Dark Matter Models





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Example(s)

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Macroscopic objects

Massive particles

Axions

QCD Axions

Axion-Like Particles

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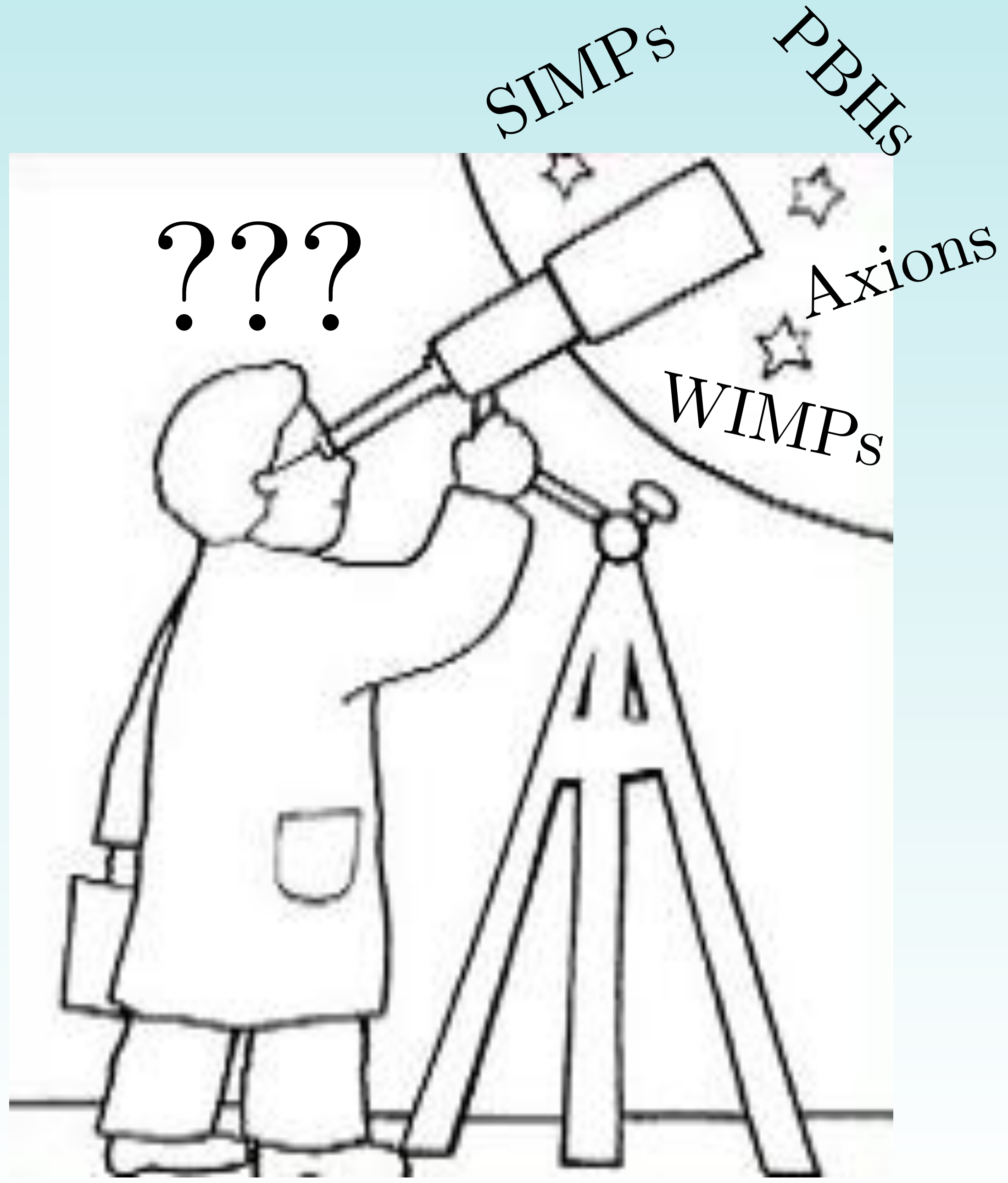
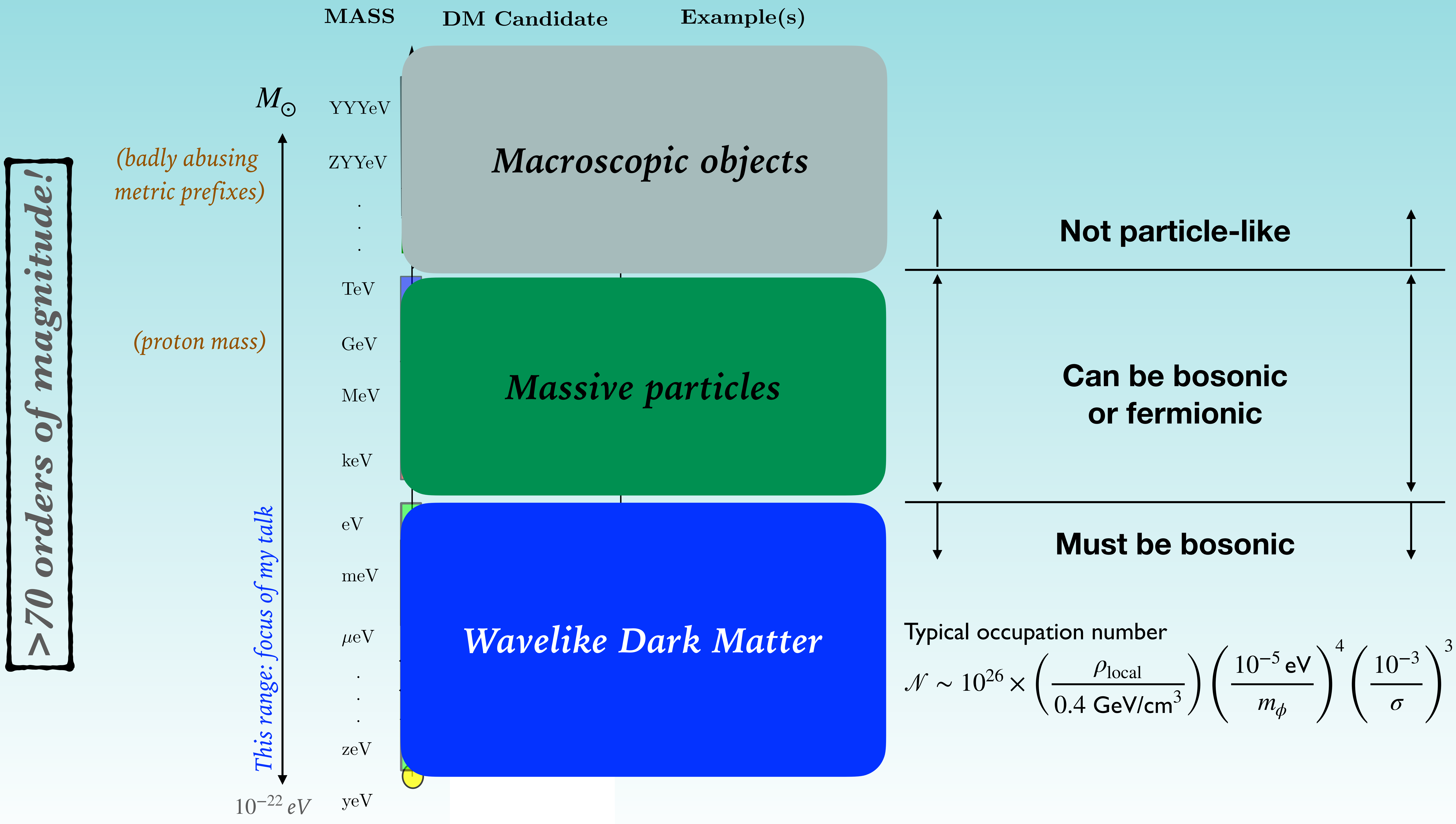
Not particle-like

Can be bosonic or fermionic

Dark Matter Models





MASS | DM Candidate | Example(s)

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This range: focus of my talk

$M_\odot$

YYYeV

ZYYeV

...

TeV

GeV

MeV

keV

eV

meV

μeV

...

zeV

yeV

$10^{-22}\ eV$

Macroscopic objects

Massive particles

Wavelike Dark Matter

Not particle-like

Can be bosonic or fermionic

Must be bosonic

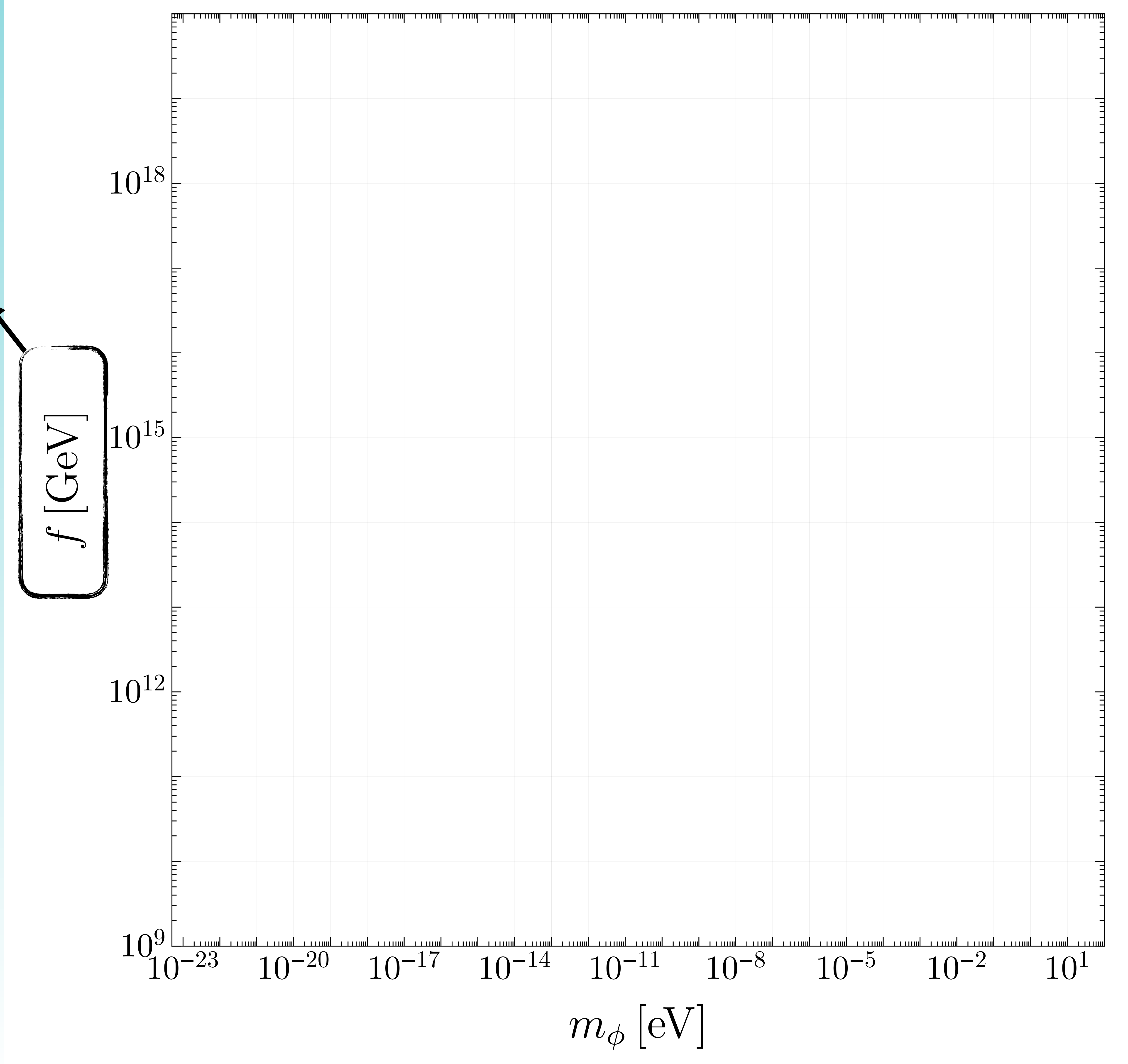
Typical occupation number

$$\mathcal{N} \sim 10^{26} \times \left(\frac{\rho_{\mathrm{local}}}{0.4\ \mathrm{GeV/cm}^3}\right)\left(\frac{10^{-5}\ \mathrm{eV}}{m_\phi}\right)^4\left(\frac{10^{-3}}{\sigma}\right)^3$$

Light Scalar Parameter Space

<u>Some high scale:</u>

- **Symmetry breaking**
- **Compactification**
- **Mass of UV fermions**
- **…etc**



"Generically",

$$V(\phi) = m_\phi^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]$$

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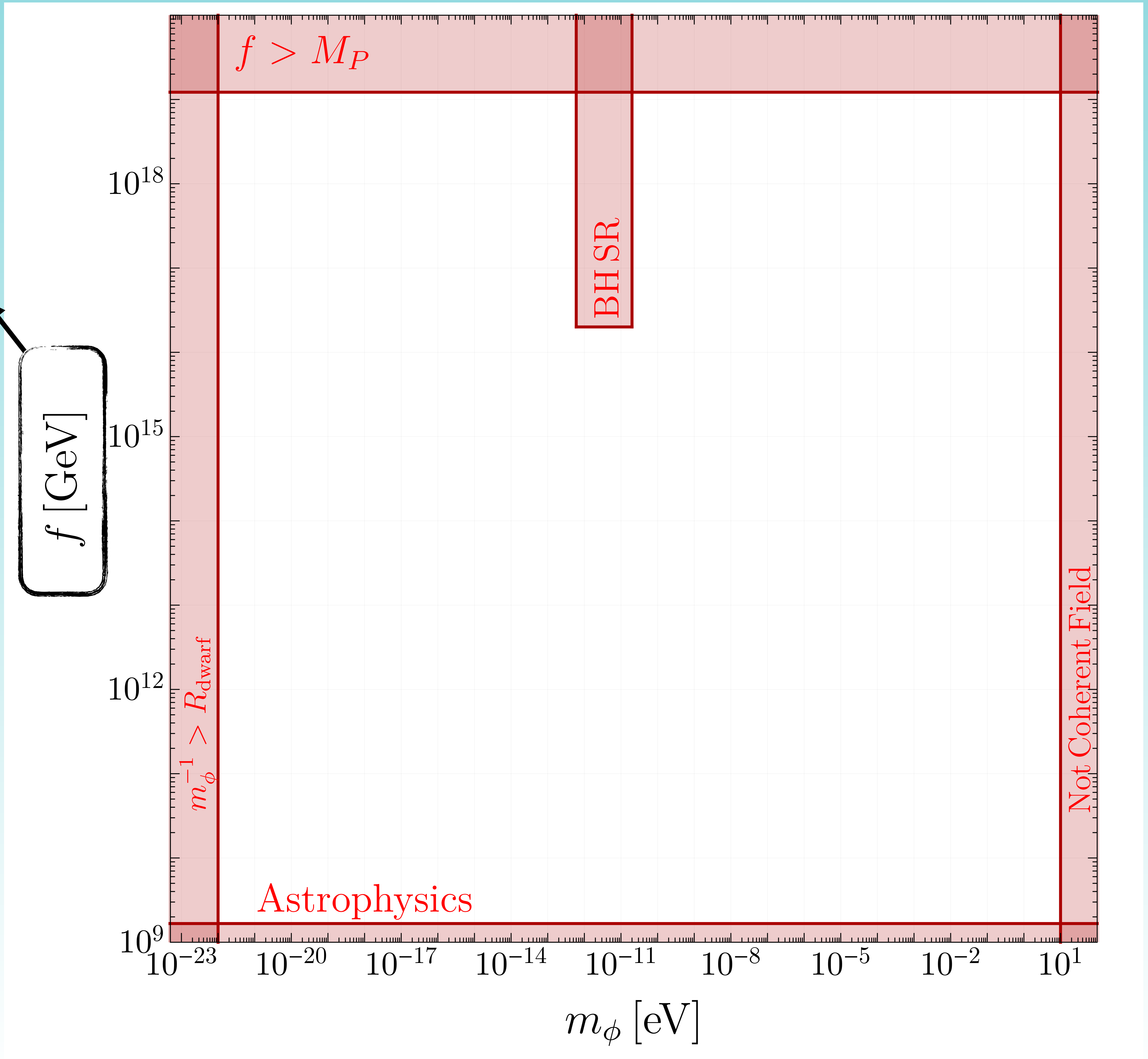

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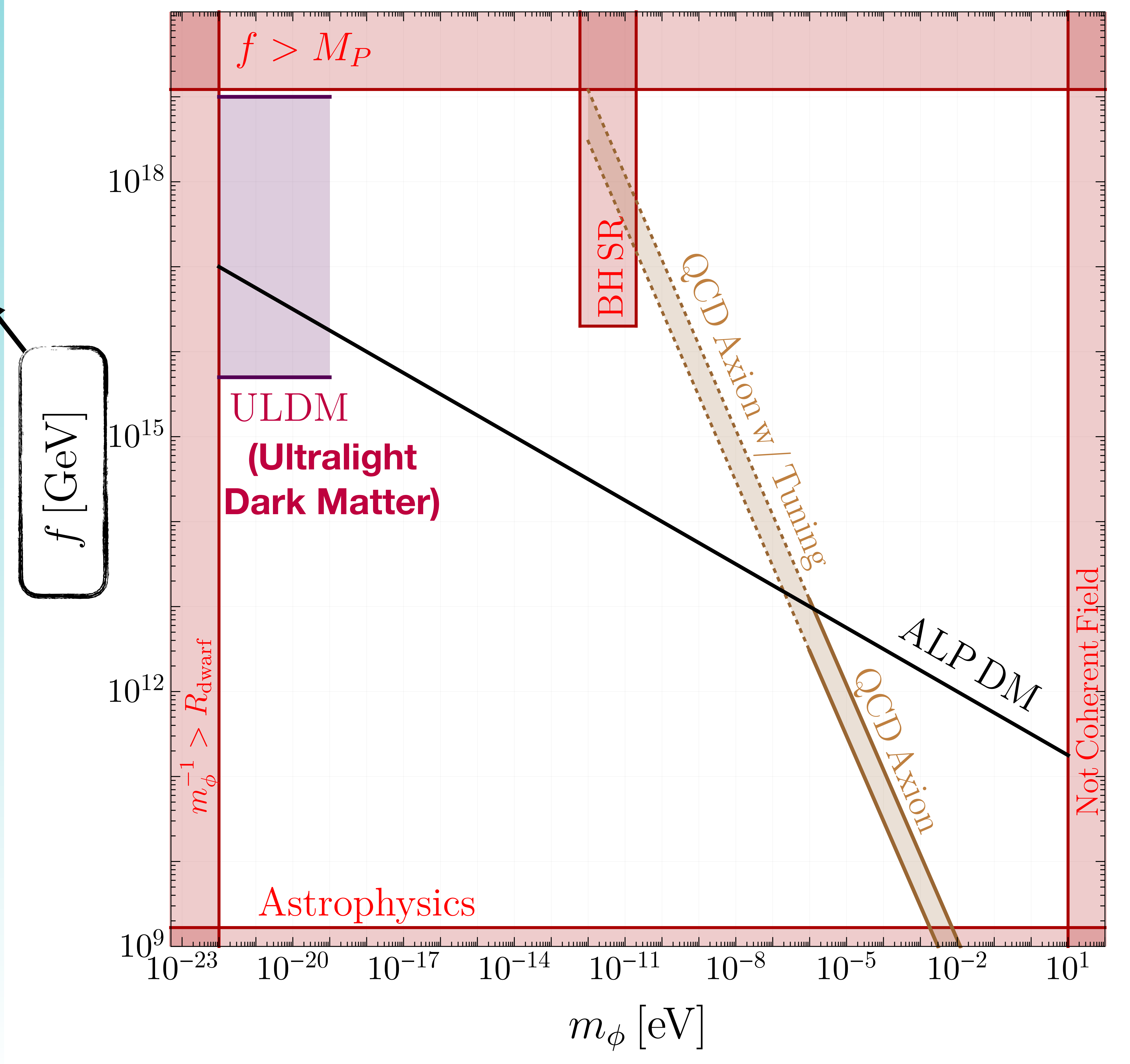

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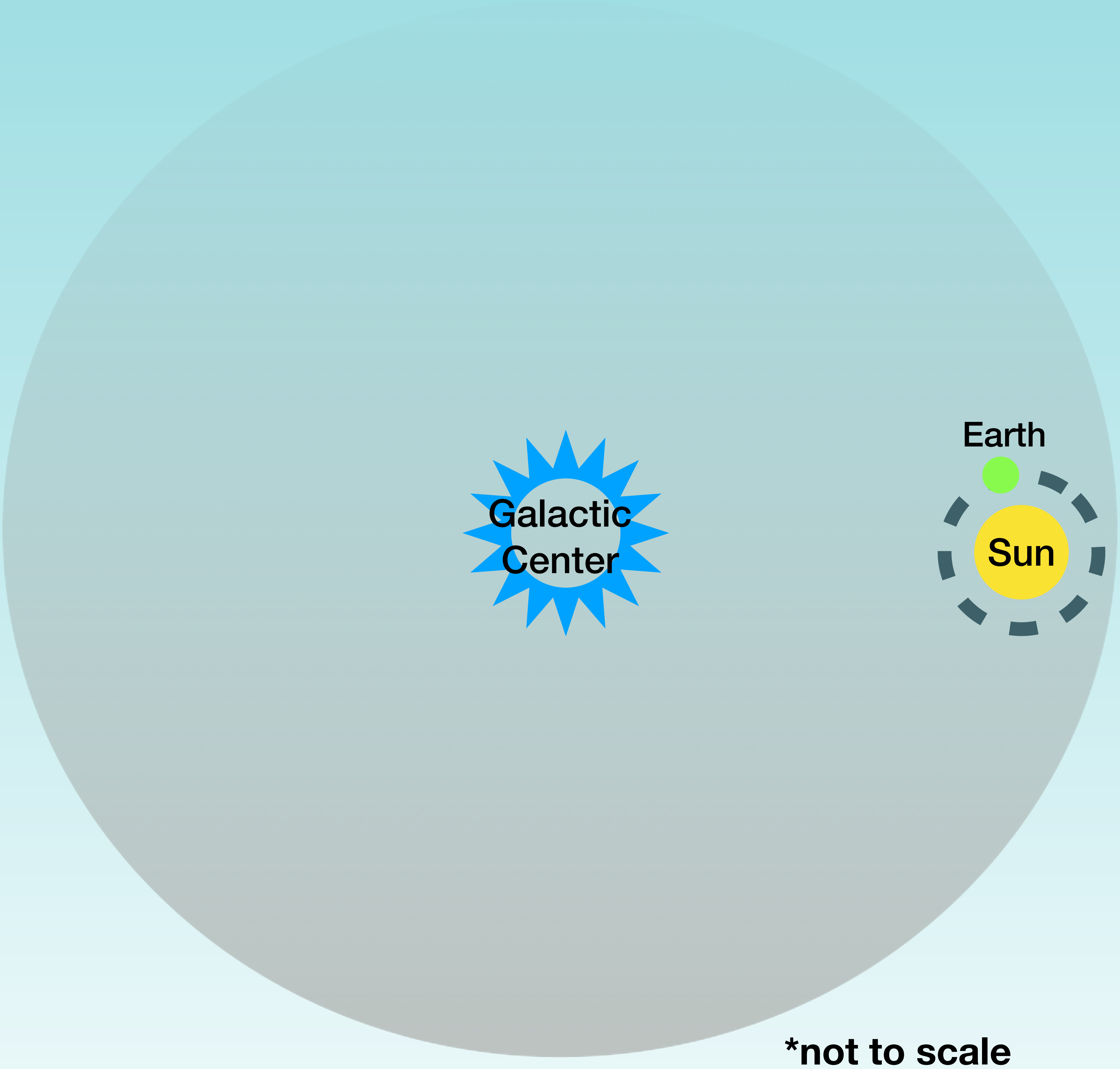
Our Dark Matter Halo

◉ In the standard picture,

- Roughly spherical halo
- Virial velocity $\sigma \simeq 10^{-3} \simeq 200\,\mathrm{km/sec}$
- Local DM density $\rho_{\mathrm{local}} \simeq 0.4\,\mathrm{GeV/cm^3}$



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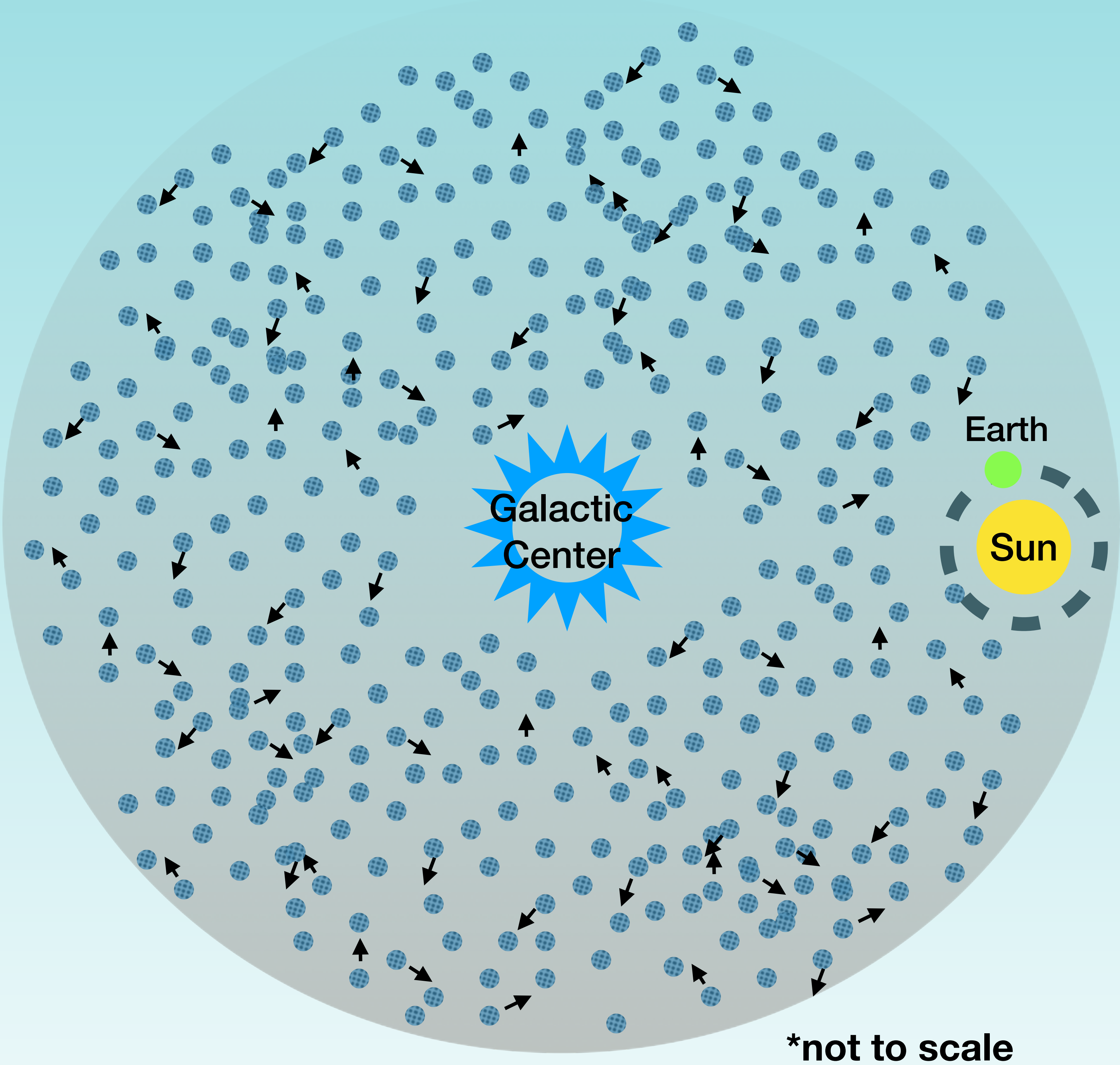
◉ For light scalar DM, however,

- Halo is “lumpy”!
- Lumps can form, travel, merge, coalesce, …



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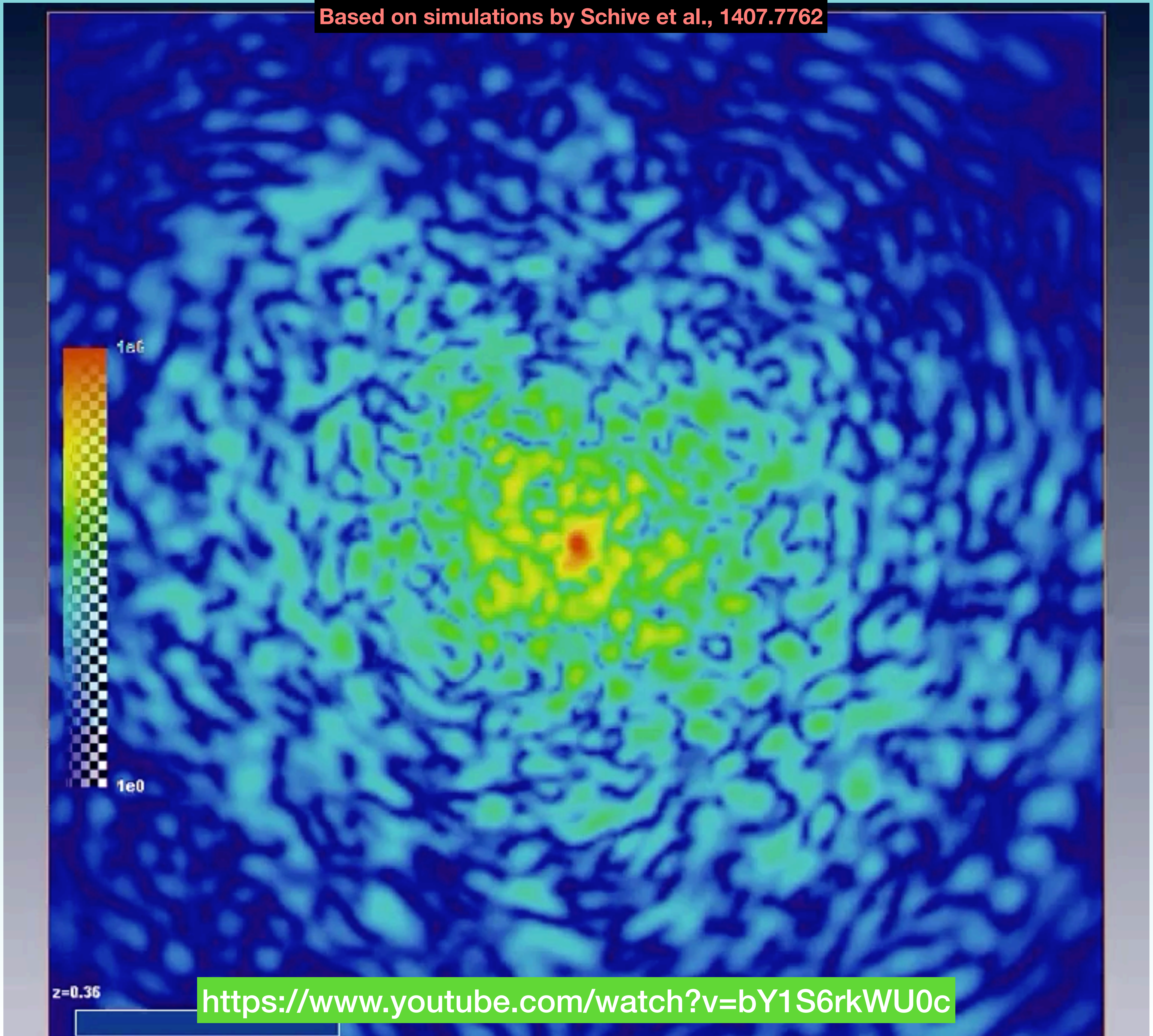

Based on simulations by Schive et al., 1407.7762

https://www.youtube.com/watch?v=bY1S6rkWU0c

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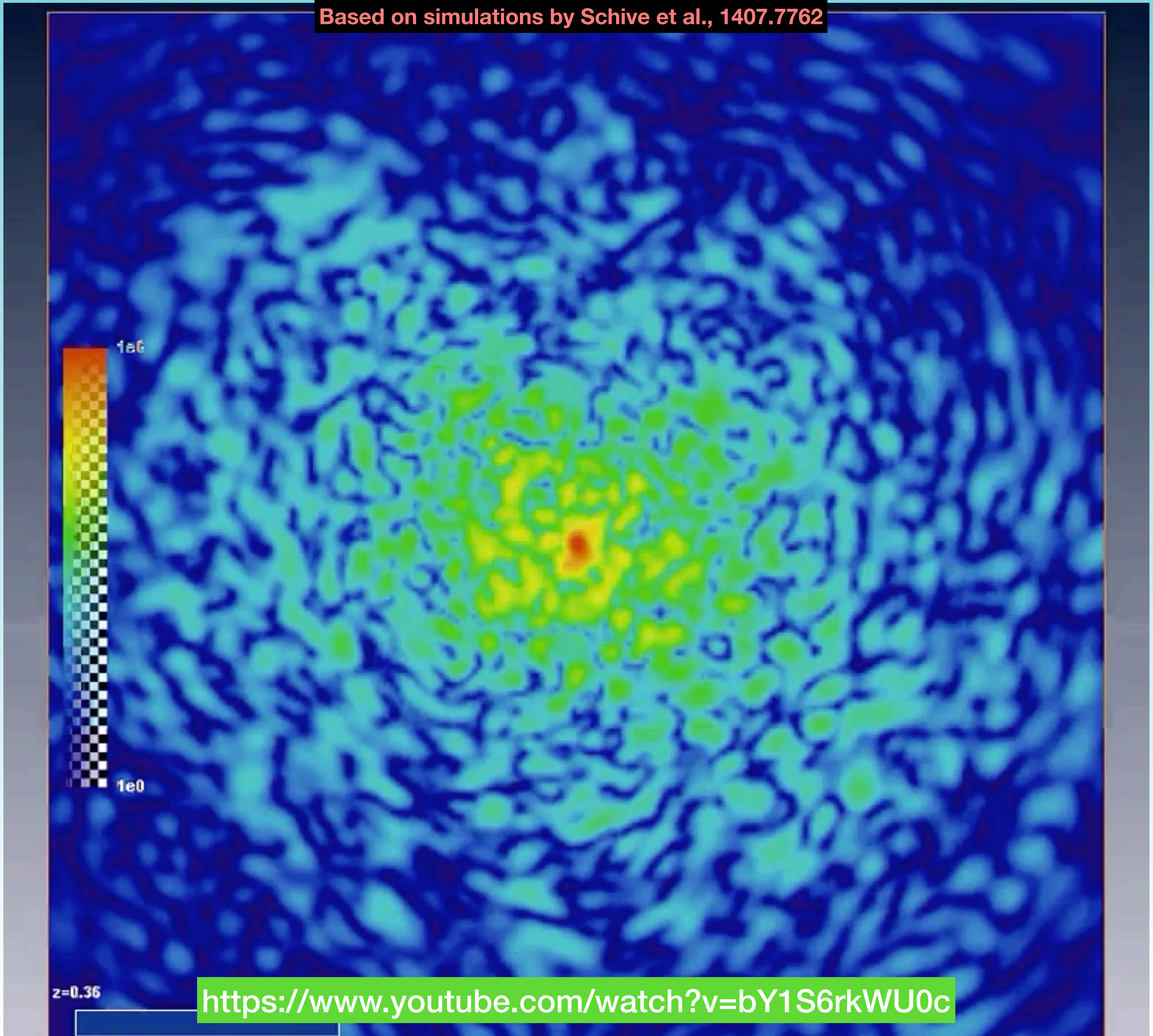

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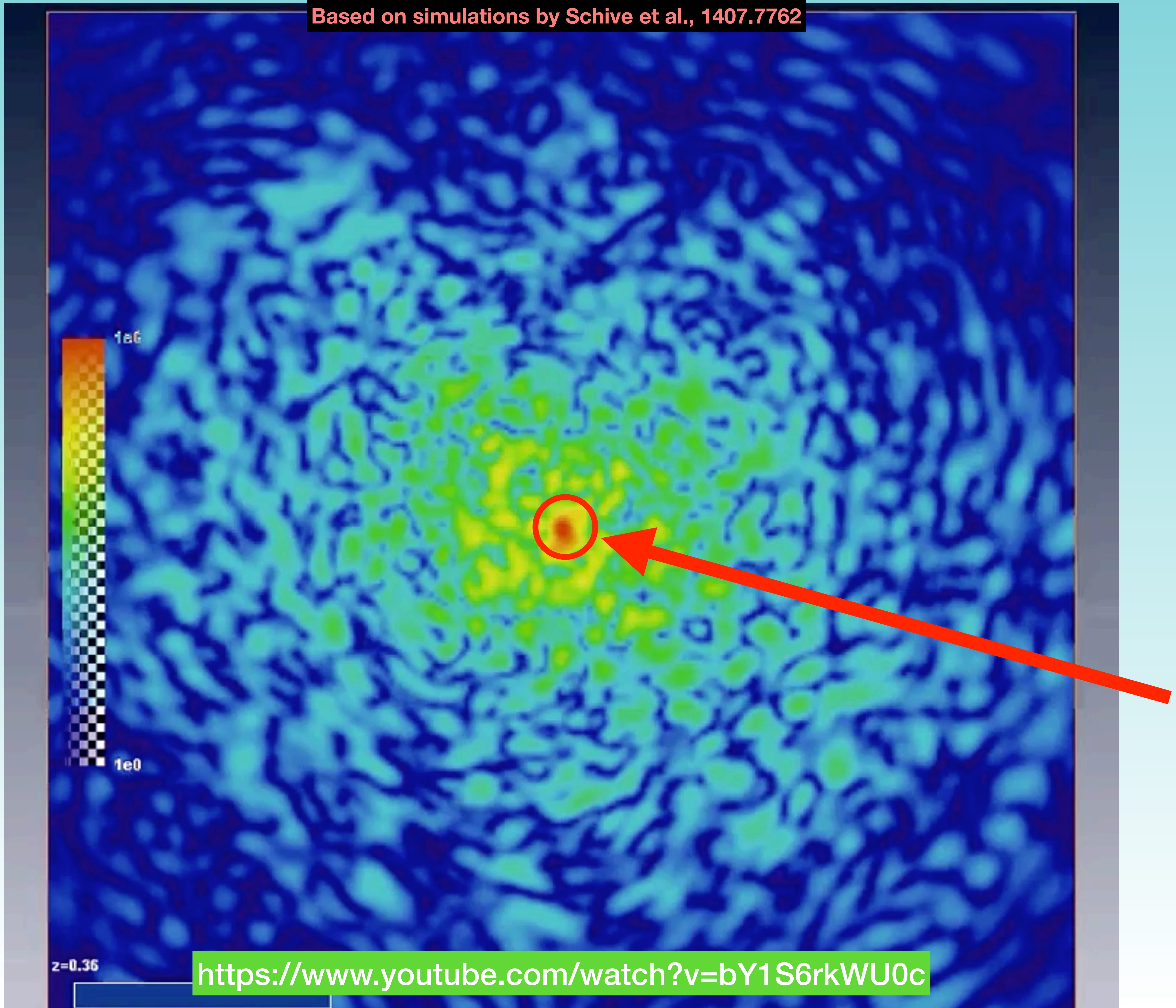

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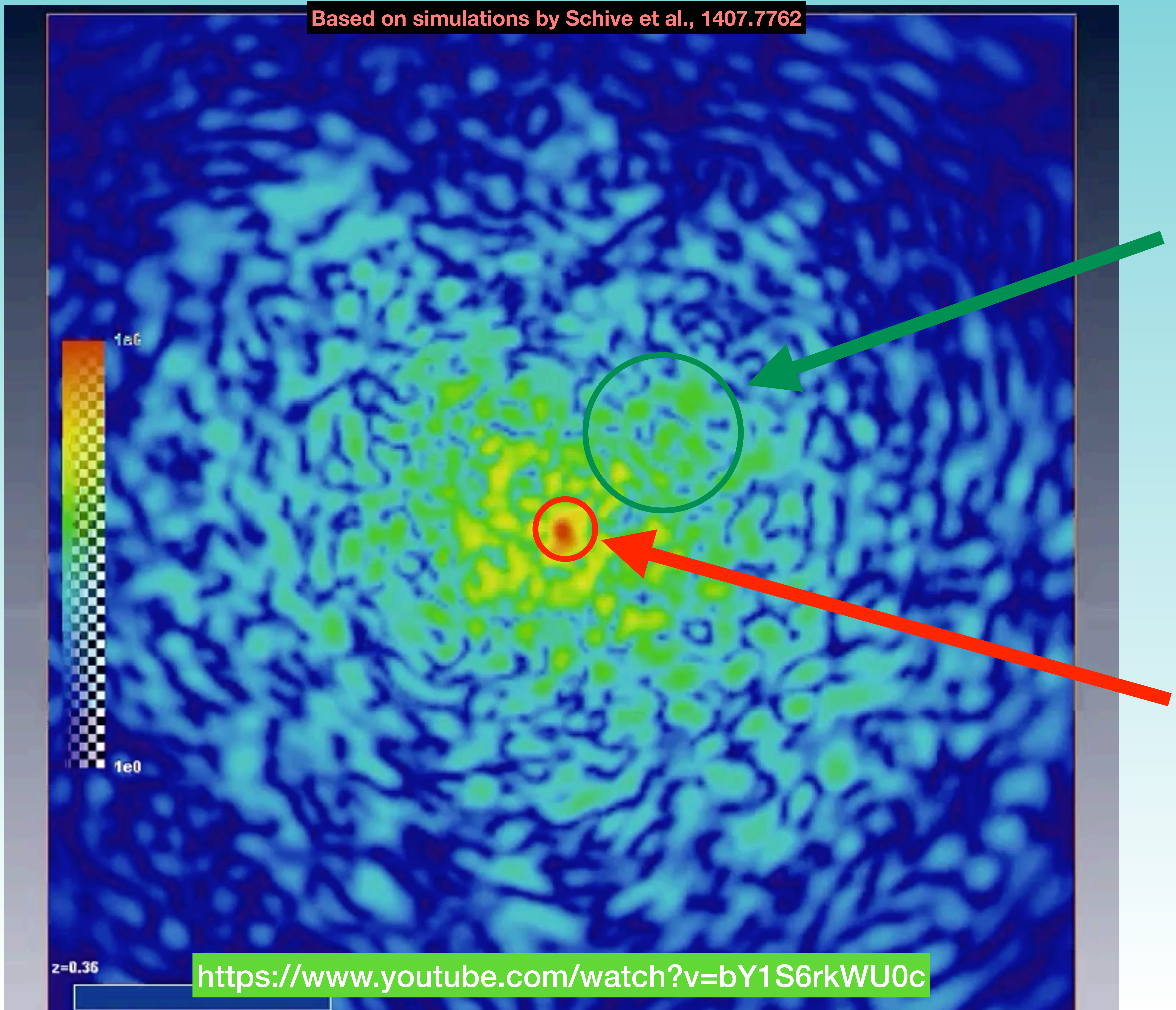

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Types of LSDM Substructure

1. Quasiparticles / Granules
2. Axion Stars / Solitons
3. Axion Halos around the Earth and Sun

LSDM Equations of Motion

- LSDM is non-relativistic, with high occupation numbers ⇒ NR classical field
- Expand field in terms of non-relativistic wavefunction: $\phi(t,r) = \frac{1}{\sqrt{2\,m_\phi}}\left[e^{-i\,m_\phi\,t}\,\psi(t,r) + c\,.\,c\,.\right]$
- E.o.M is Gross-Pitaevskii+Poisson (GPP) equation:

Poisson Gravity

$\nabla^2 V_g = 4\,\pi\,G\,m_\phi\,\left|\psi\right|^2$

(Attractive)

Normalization

$$m_\phi \int d^3r\,|\psi|^2 = M_\star$$

Coherent state → Oscillates

Leading time dependence

$\dot{\psi} \sim (m_\phi - \omega)\psi \ll m_\phi \psi$

$$i\,\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + V_g\left(\,|\psi|^2\,\right) + V_{int}\left(\,|\psi|^2\,\right)\right]\psi$$

Kinetic energy

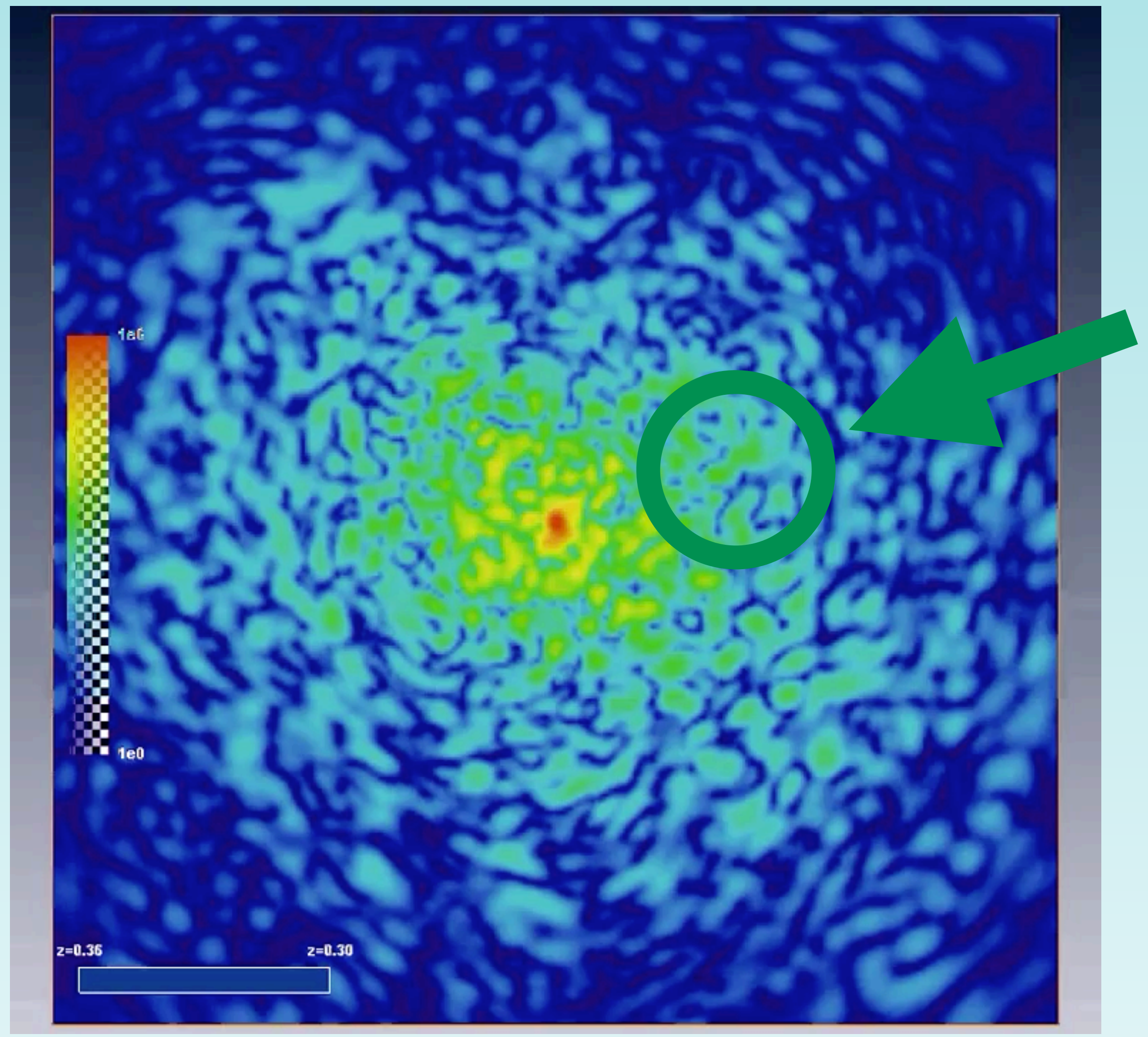
(Repulsive)

Self-interactions

For axion potential,

$$V(\phi) = m_\phi^2\,f^2\left[1 - \cos\left(\frac{\phi}{f}\right)\right] = \frac{m_\phi^2}{2}\phi^2 - \frac{1}{4!}\left(\frac{m_\phi}{f}\right)^2\phi^4 + \frac{1}{6!\,f^2}\left(\frac{m_\phi}{f}\right)^2\phi^6 - \ldots$$

Quasiparticles / Granules



- Within a deBroglie wavelength, **(assuming $\sigma \sim 10^{-3}$)**

$$\lambda_{\rm dB} = \frac{1}{m_\phi\,\sigma} \sim 2000\,{\rm km}\left(\frac{10^{-9}\,{\rm eV}}{m_\phi}\right) \sim 12\,{\rm AU}\left(\frac{10^{-15}\,{\rm eV}}{m_\phi}\right) \sim 600\,{\rm pc}\left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)$$

(Earth scale) **(Solar system scale)** **(Galaxy scale)**

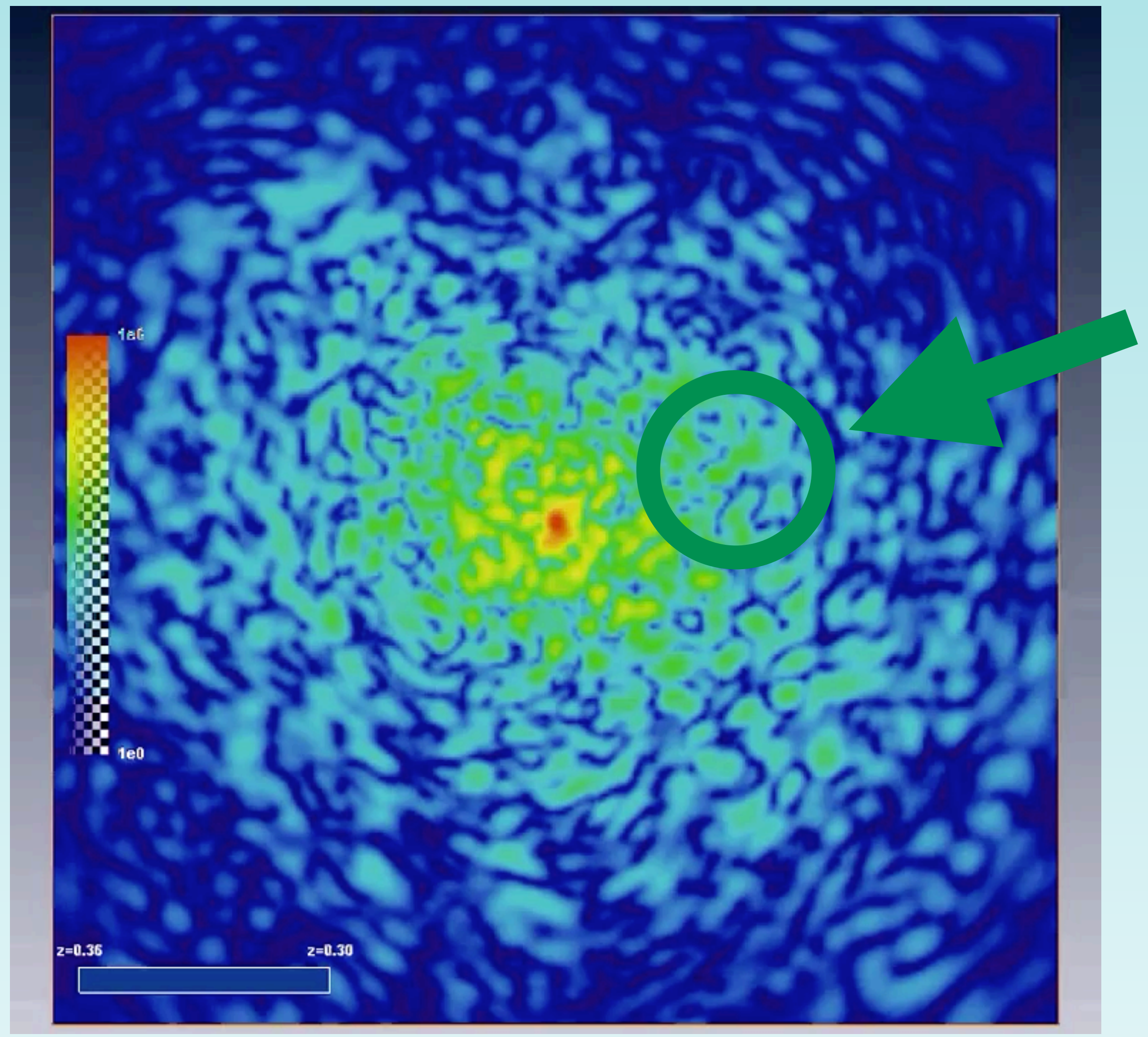
have very large occupation $\mathcal{N} \sim 10^{26} \times \left(\frac{\rho_{\rm local}}{0.4\ {\rm GeV/cm}^3}\right)\left(\frac{10^{-5}\,{\rm eV}}{m_\phi}\right)^4$

- These patches have random velocities, appear as <u>traveling waves</u> (“quasiparticles”)

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

- Generic expectation: $\mathcal{O}(1)$ fluctuations around background density on distance scales $\lambda_{\rm dB}$, from constructive / destructive interference of LSDM waves $\Rightarrow$ $\delta \equiv \frac{\rho}{\rho_{\rm local}} \sim \mathcal{O}(1)$

Quasiparticles / Granules



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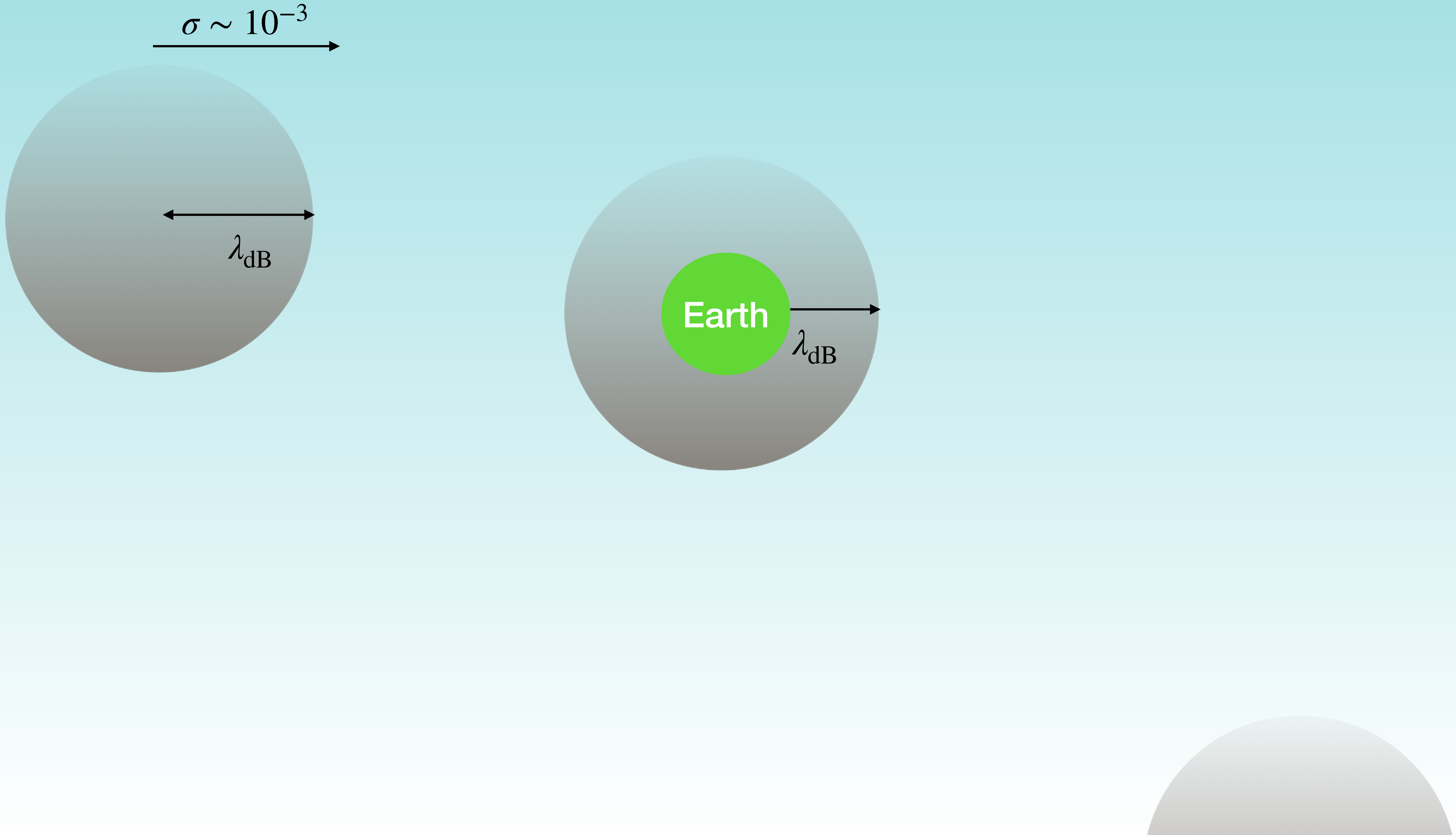
The (Very) Local DM Density



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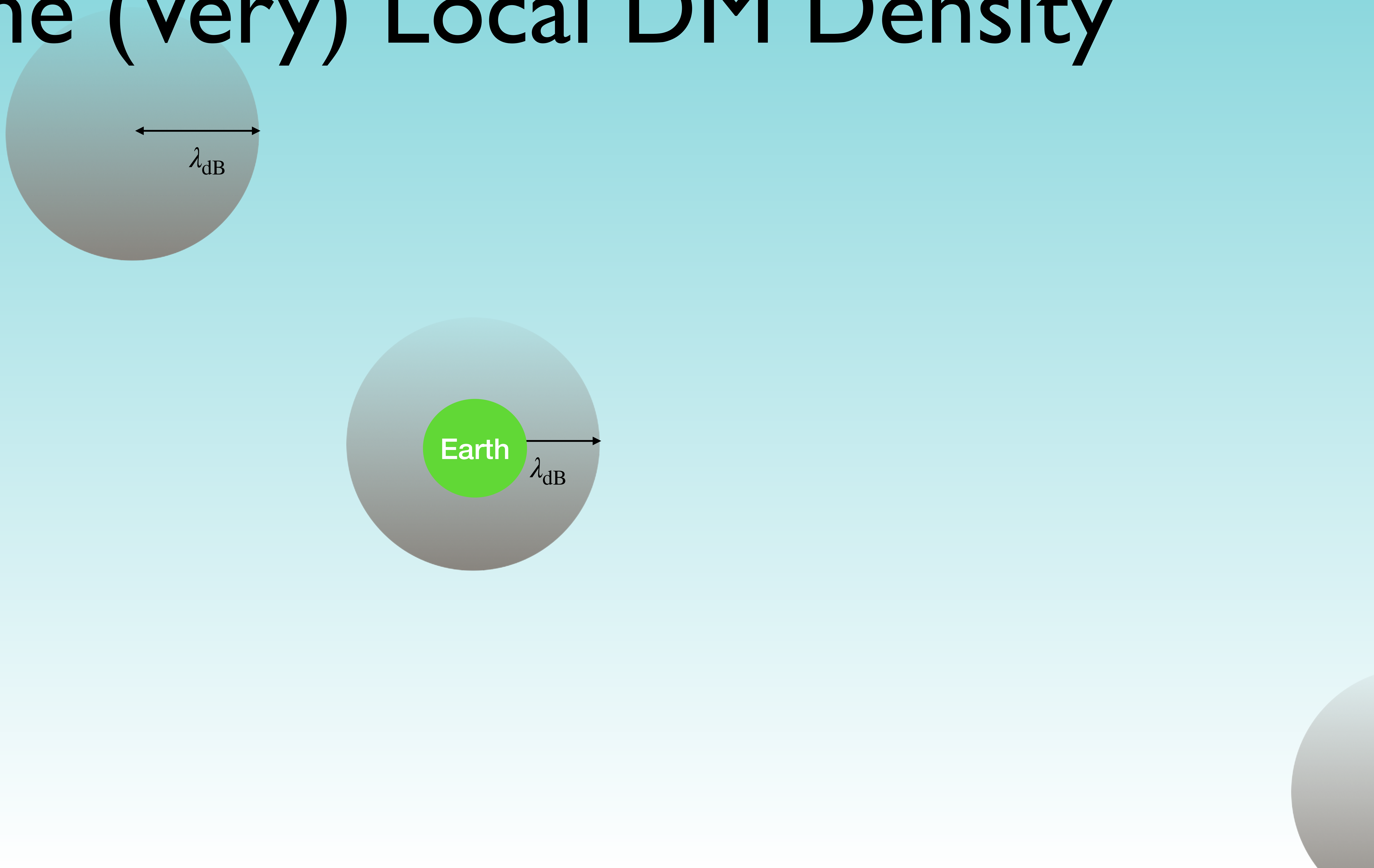

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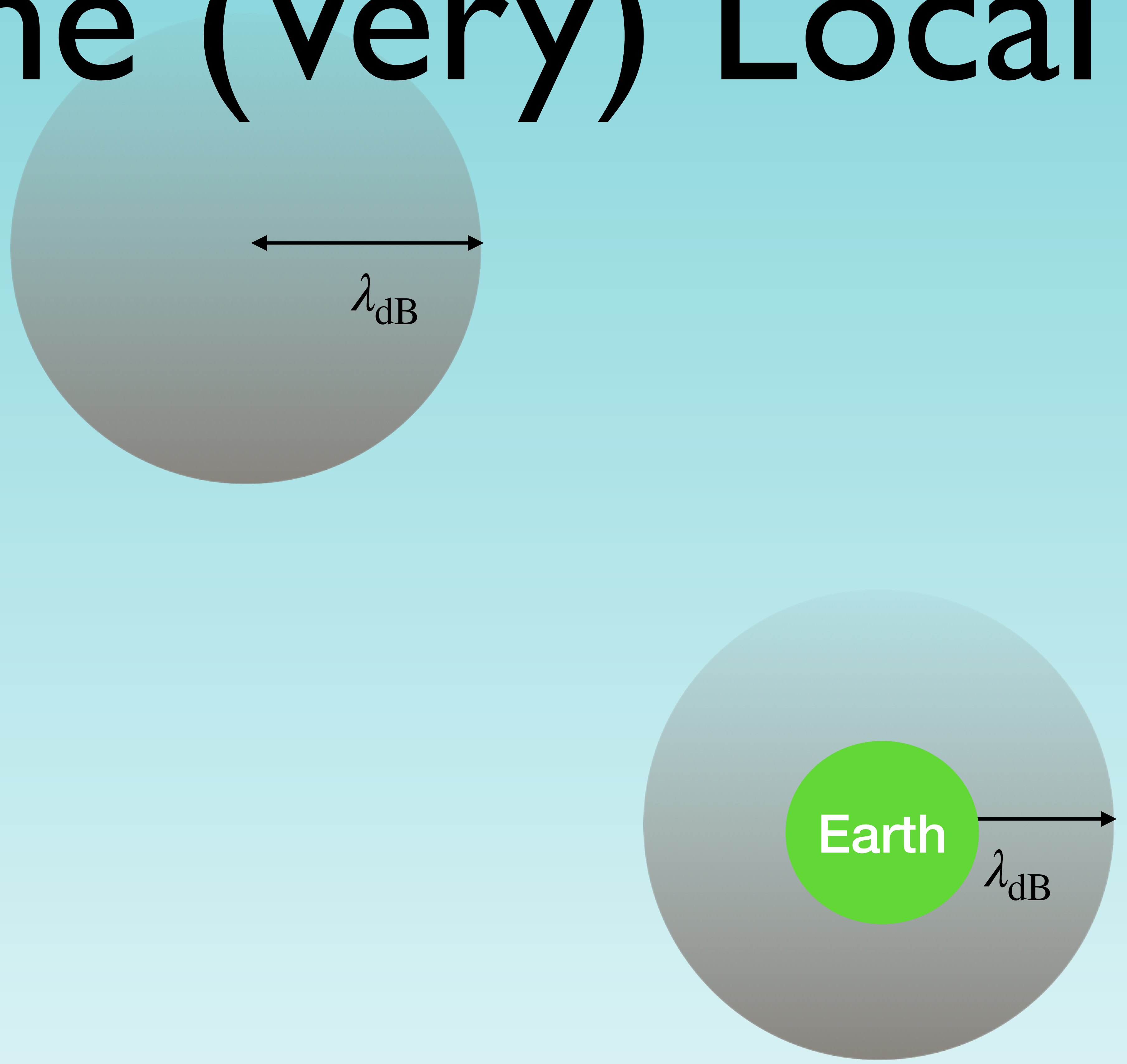
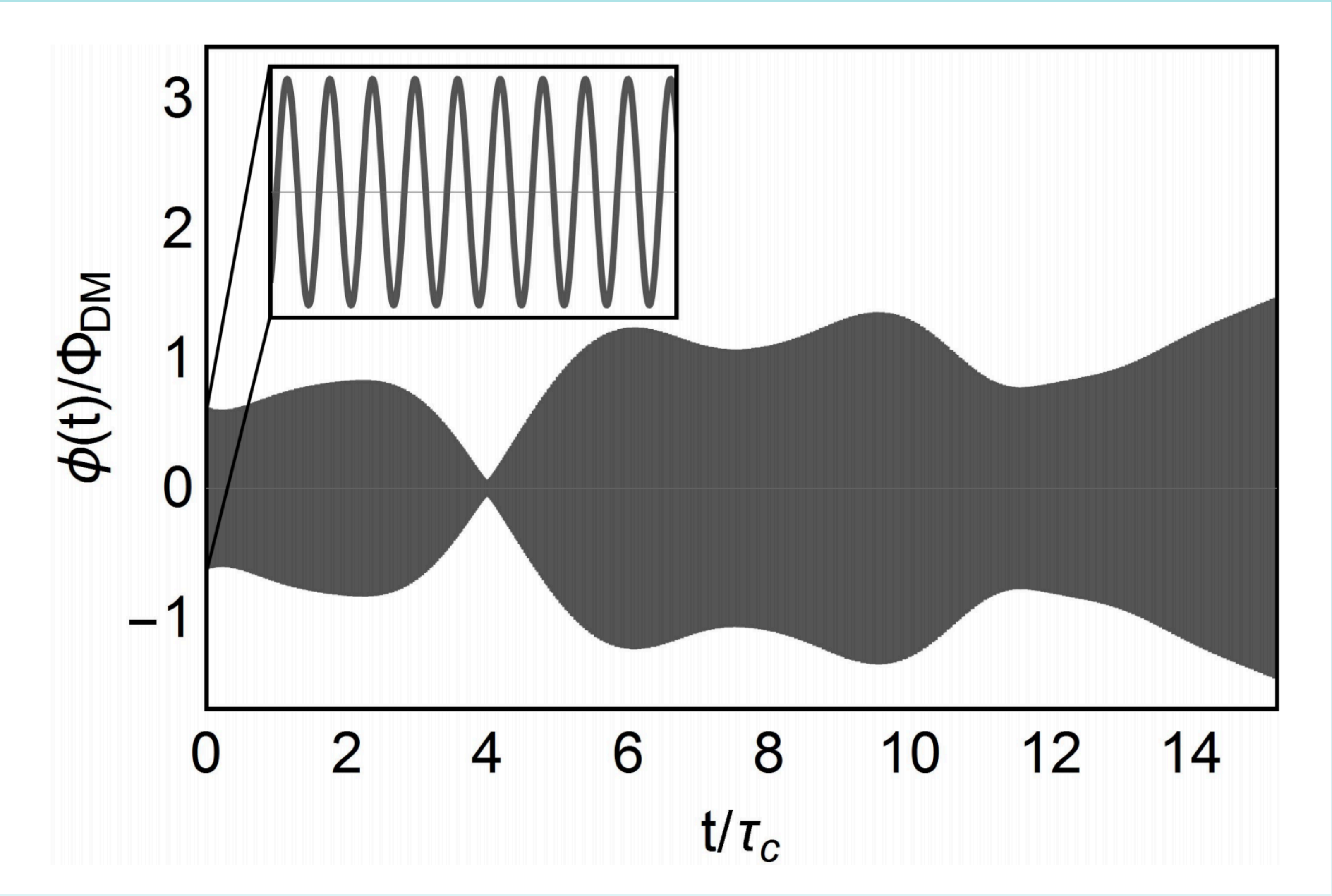
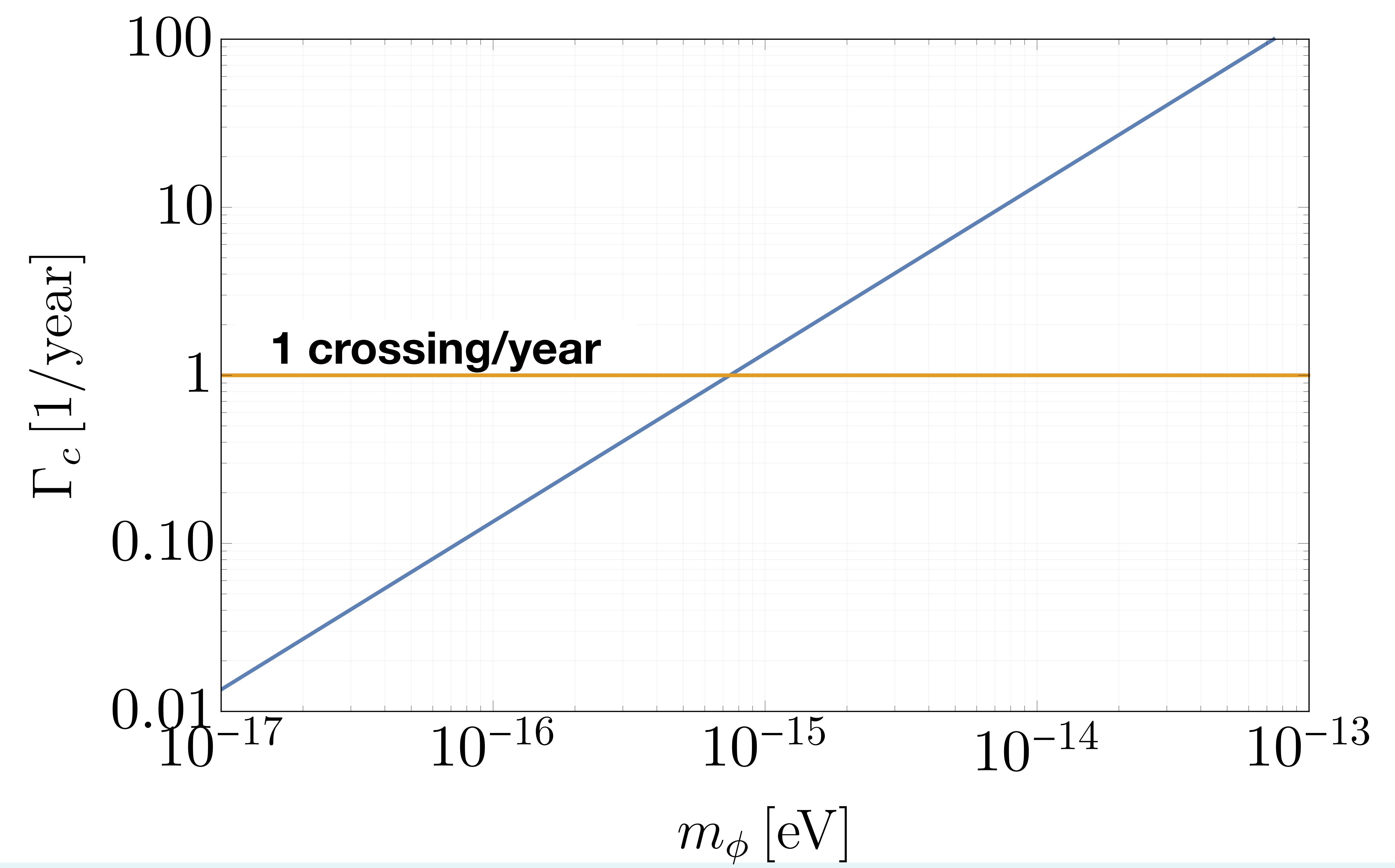




Centers et al. (1905.13650)

The (Very) Local DM Density (2)



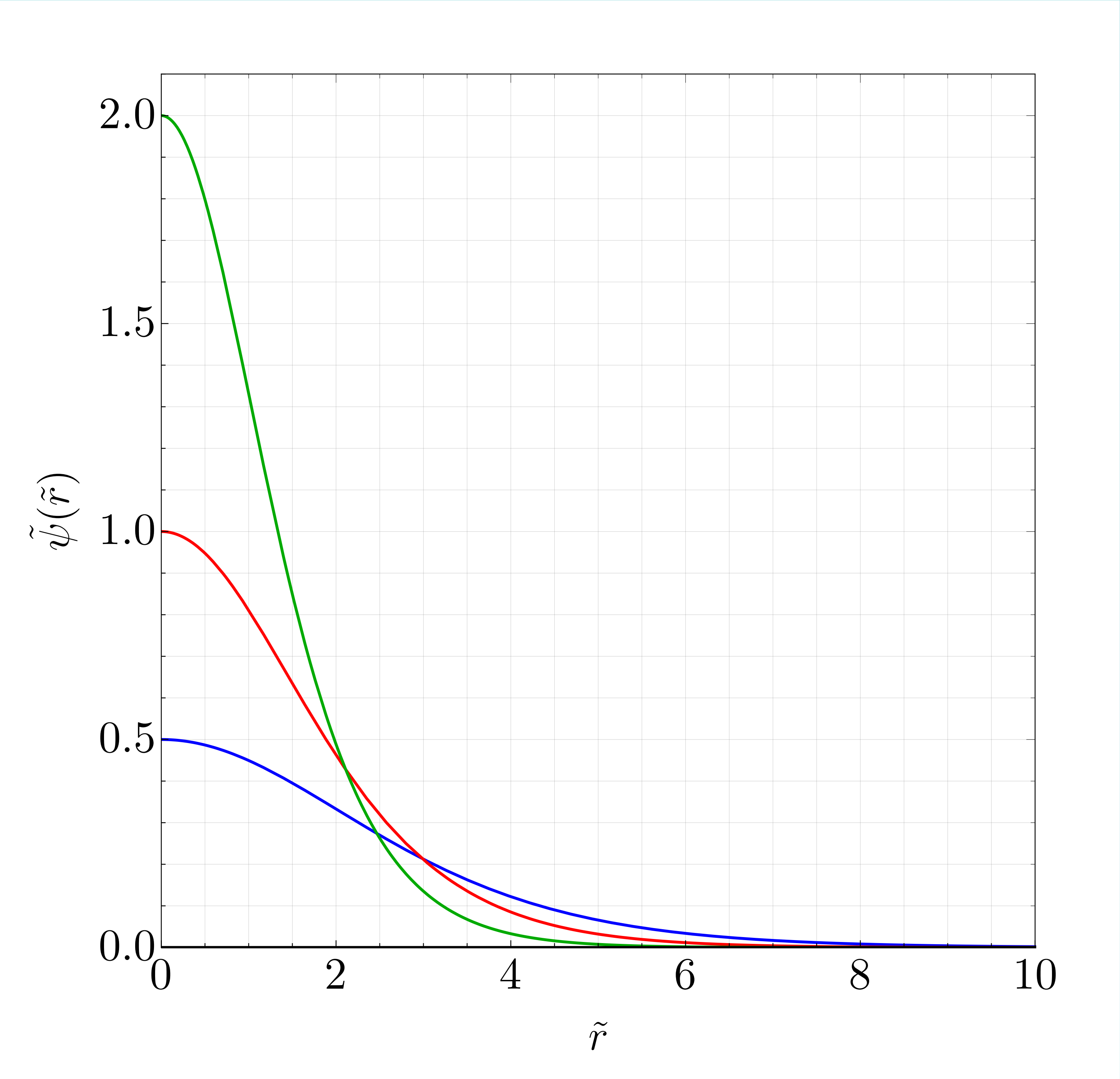
Local density roughly constant b/c $t_{\rm exp} \ll \tau_c$ ←

Local density roughly constant if signal averaged over many coherence times →

$$\Gamma_c \equiv \frac{1}{\tau_c} \simeq m_\phi \sigma^2 \simeq (m_\phi R_\star^2)^{-1}$$

Axion Stars / Solitons

- At fixed mass $M_\star$, GPP equations have a unique* ground state configuration

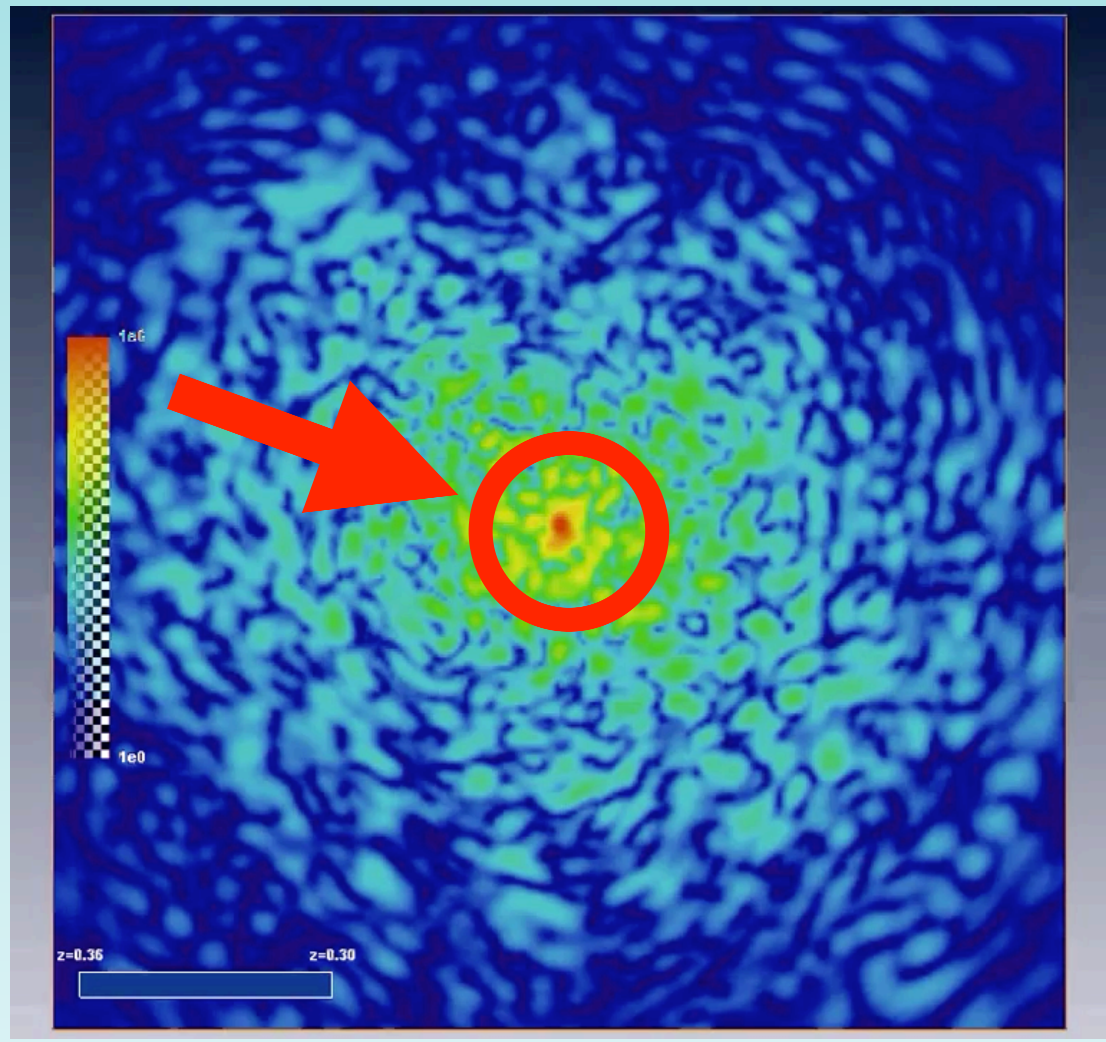


$$i\,\frac{\partial \psi}{\partial t} = \left[-\underbrace{\frac{\nabla^2}{2m_\phi} + V_g\left(|\psi|^2\right)}_{\text{Balance these forces}} + \cancel{V_{int}\left(|\psi|^2\right)} \right] \psi$$

Balance these forces

$$R_\star \simeq \frac{M_P^2}{m_\phi^2\, M_\star}$$

“Axion Star”



- Mass-Radius relation is inverse: $M_\star \simeq 10^{-11}\, M_\odot \left(\frac{10^{-5}\,\mathrm{eV}}{m_\phi^2} \right)^2 \left(\frac{200\,\mathrm{km}}{R_\star} \right)$,

  and over density is typically $\delta \equiv \frac{\rho}{\rho_{\rm local}} \gg \mathcal{O}(1)$

***small caveat: stable ground state is local (not global) minimum of the action**

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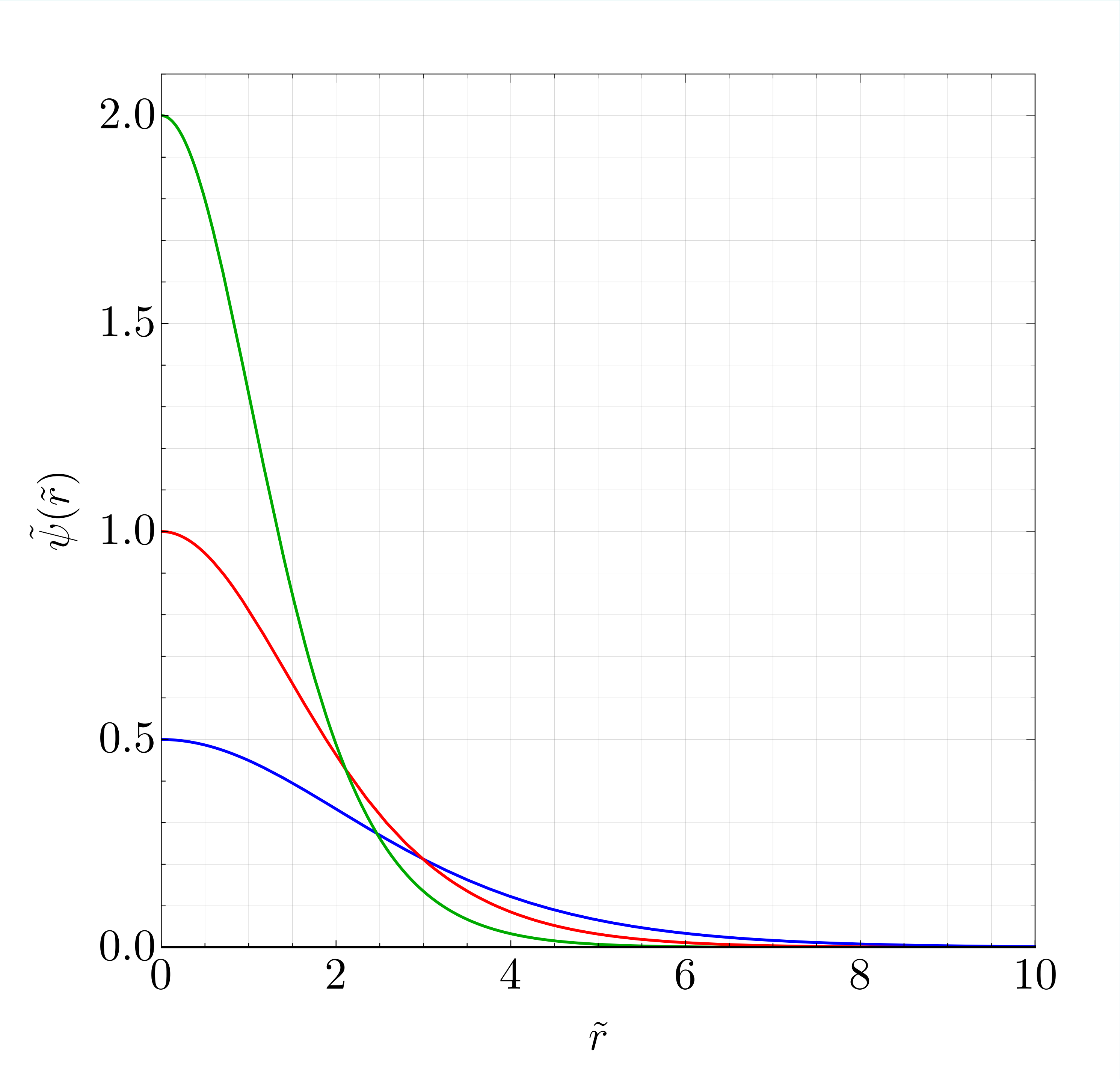

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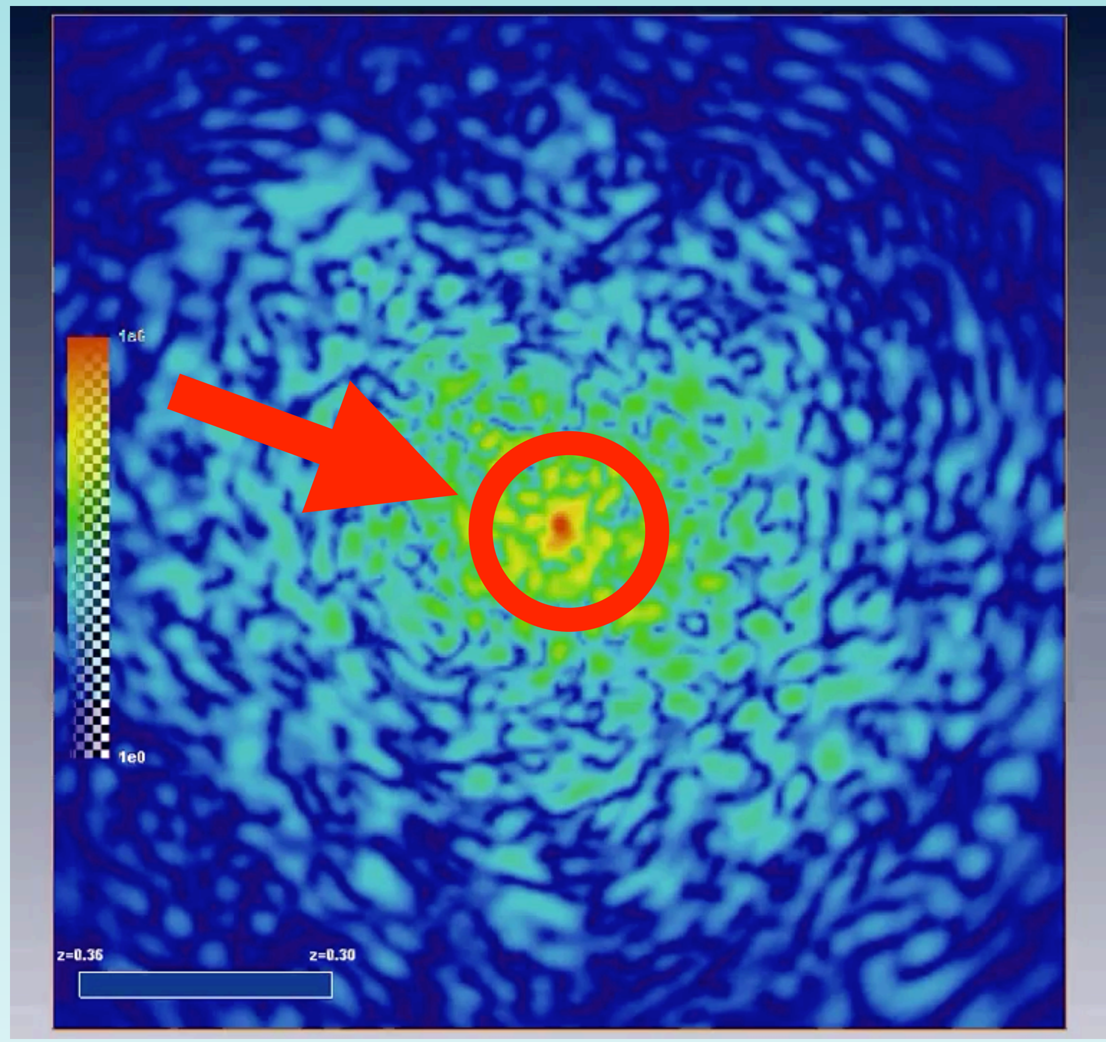

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Solving for (Spherical) Solitons

- Solitons exist along a continuous family of solutions

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

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

$$\nabla_x^2 \chi = 2\left(\Phi - \mu\right)\chi$$

$$\nabla_x^2 \Phi = \chi^2$$

Simple equations of motion

$$\psi(r,t) = \left(\frac{m_\phi M_P}{\sqrt{4\pi}}\right) e^{-i\mu m_\phi t}\chi(x)$$

$$V_g(r) = m_\phi \Phi(r)$$

$$r = x/m_\phi$$

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- In spherical symmetry, easy! Solve using shooting method
- In fact, all numerical solutions are related, by a scaling symmetry:

Let $\{\chi_1(x), \Phi_1(x), \mu_1\}$ **be the solution set such that** $\chi_1(0) = 1$**.**

This solution has the property

$$\frac{M_1}{M_\odot}\frac{R_1}{\mathrm{kpc}} \approx 2\times 10^8 \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)^2$$

Then any other solution $\{\chi_\lambda(r), \Phi_\lambda(r), \mu_\lambda\}$ **can be written as**

$$\chi_\lambda(x) = \lambda^2\chi_1(\lambda x), \qquad \Phi_\lambda(x) = \lambda^2\Phi_1(\lambda x), \qquad \mu_\lambda = \lambda^2\mu_1$$

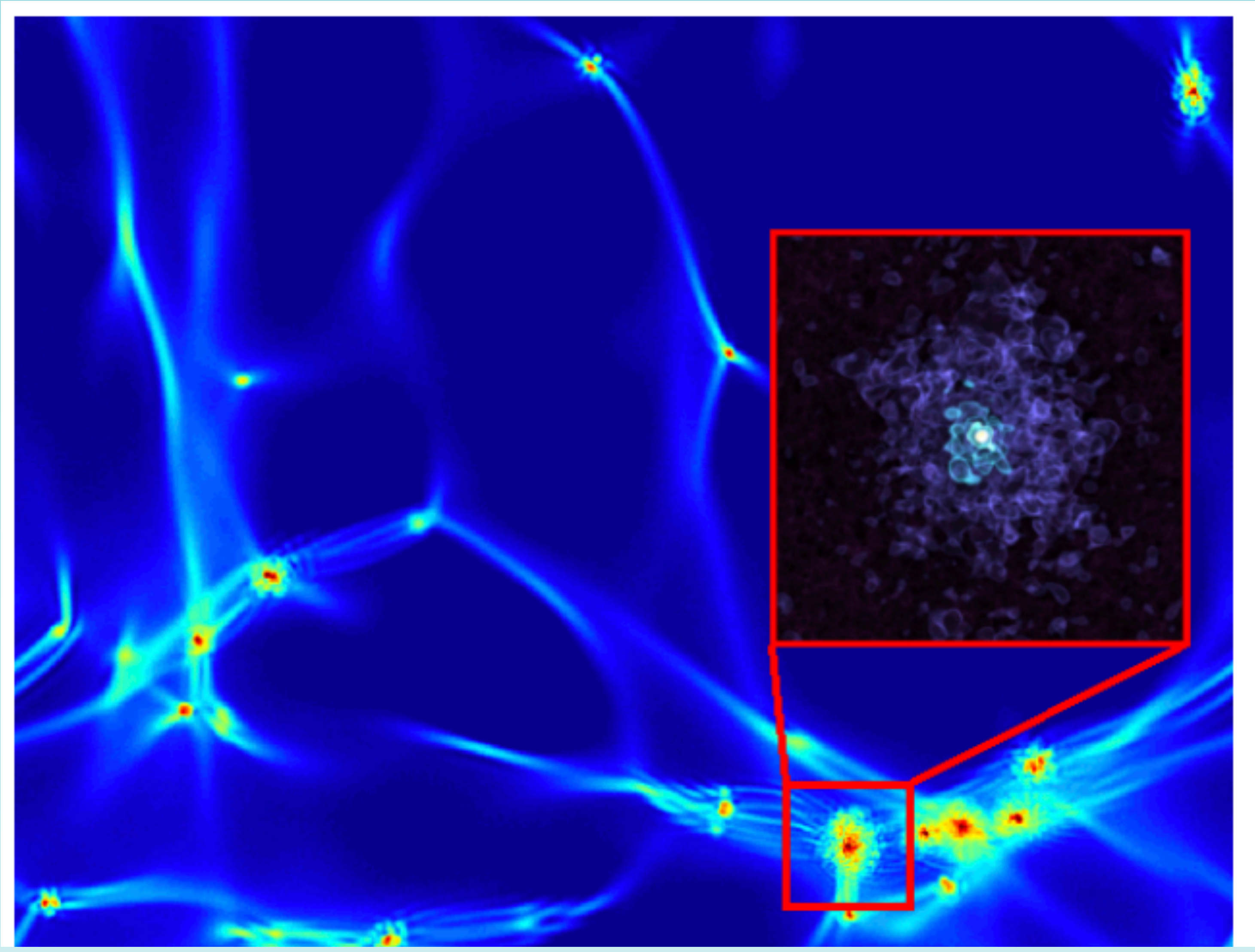
And they will have the properties

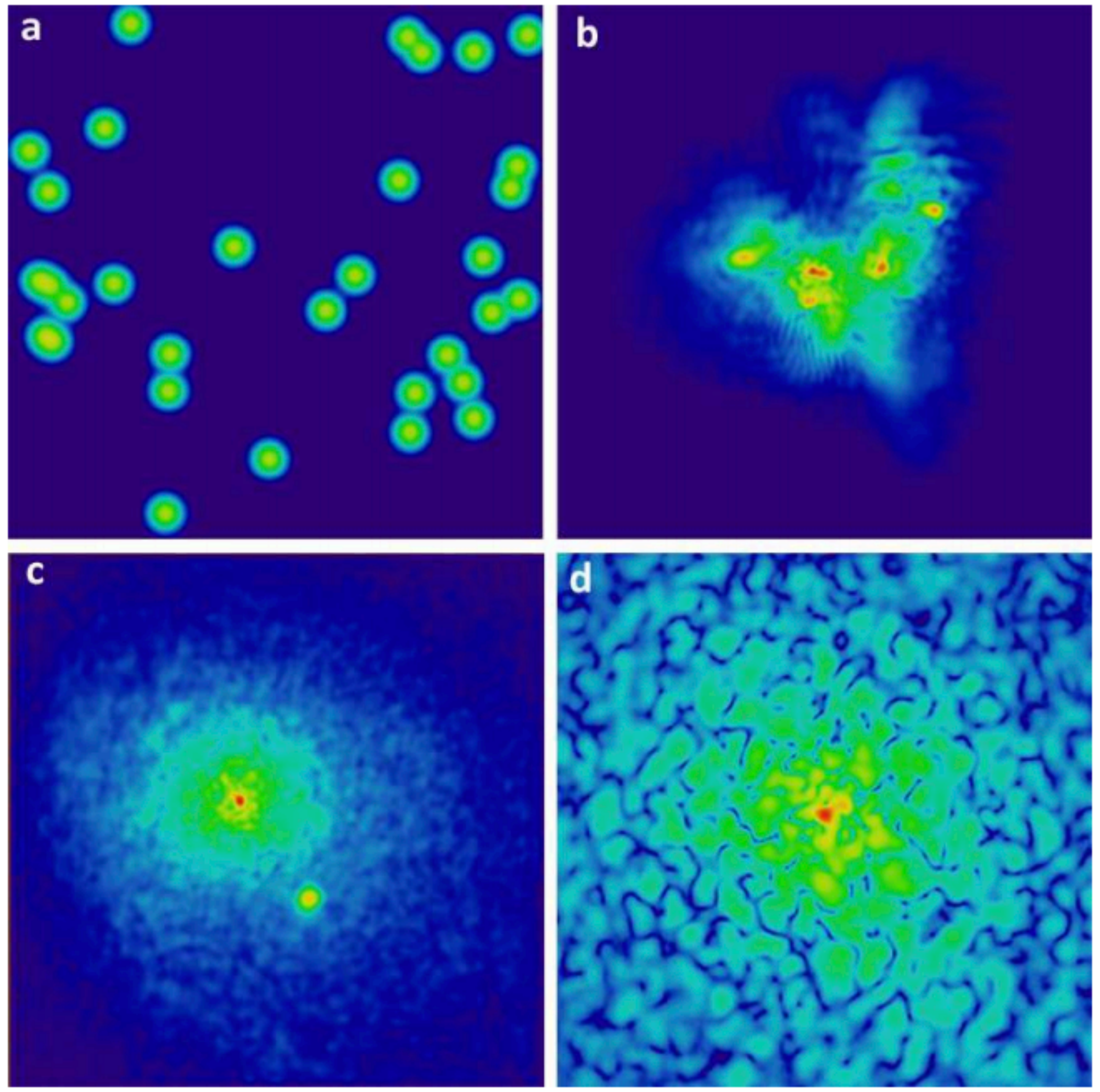
$$M_\lambda = \lambda M_1, \qquad R_\lambda = \lambda^{-1}R_1$$

Do Solitons actually Form?

- Evidence 1: Simulations

Mocz et al. (1705.05845)





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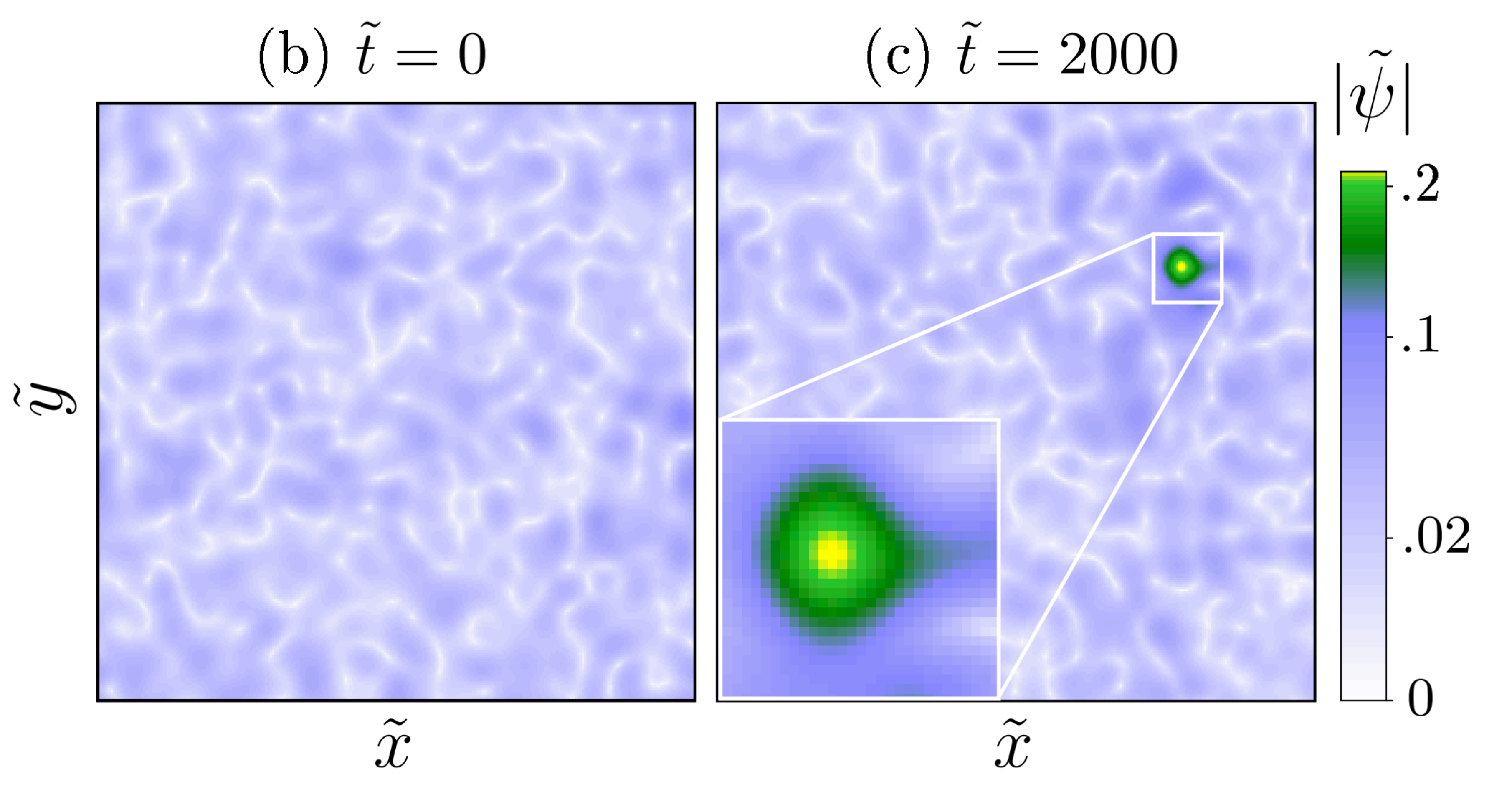
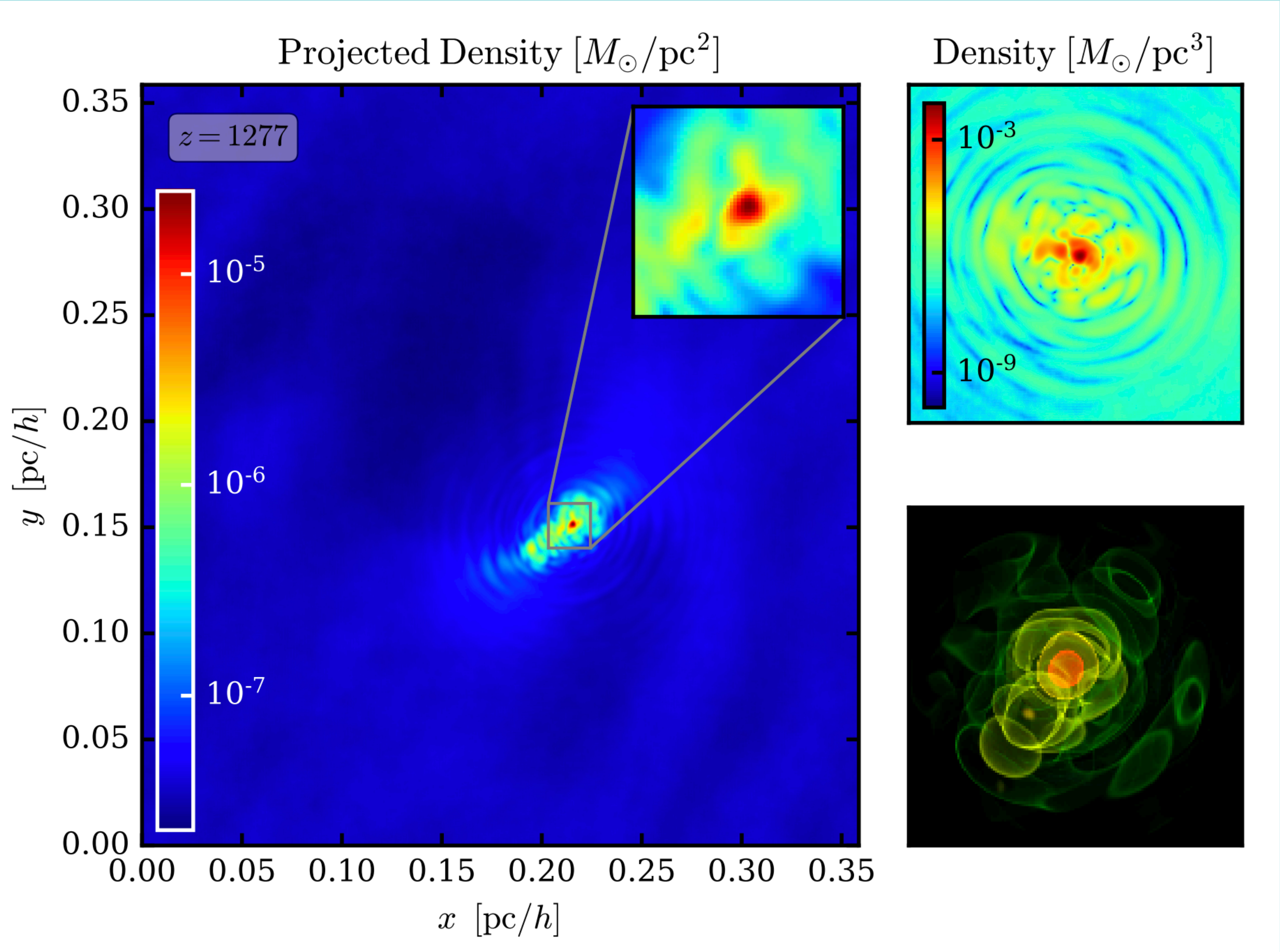


Levkov, Panin, Tkachev (1804.05857)



Eggemeier and Niemeyer (1906.01348)

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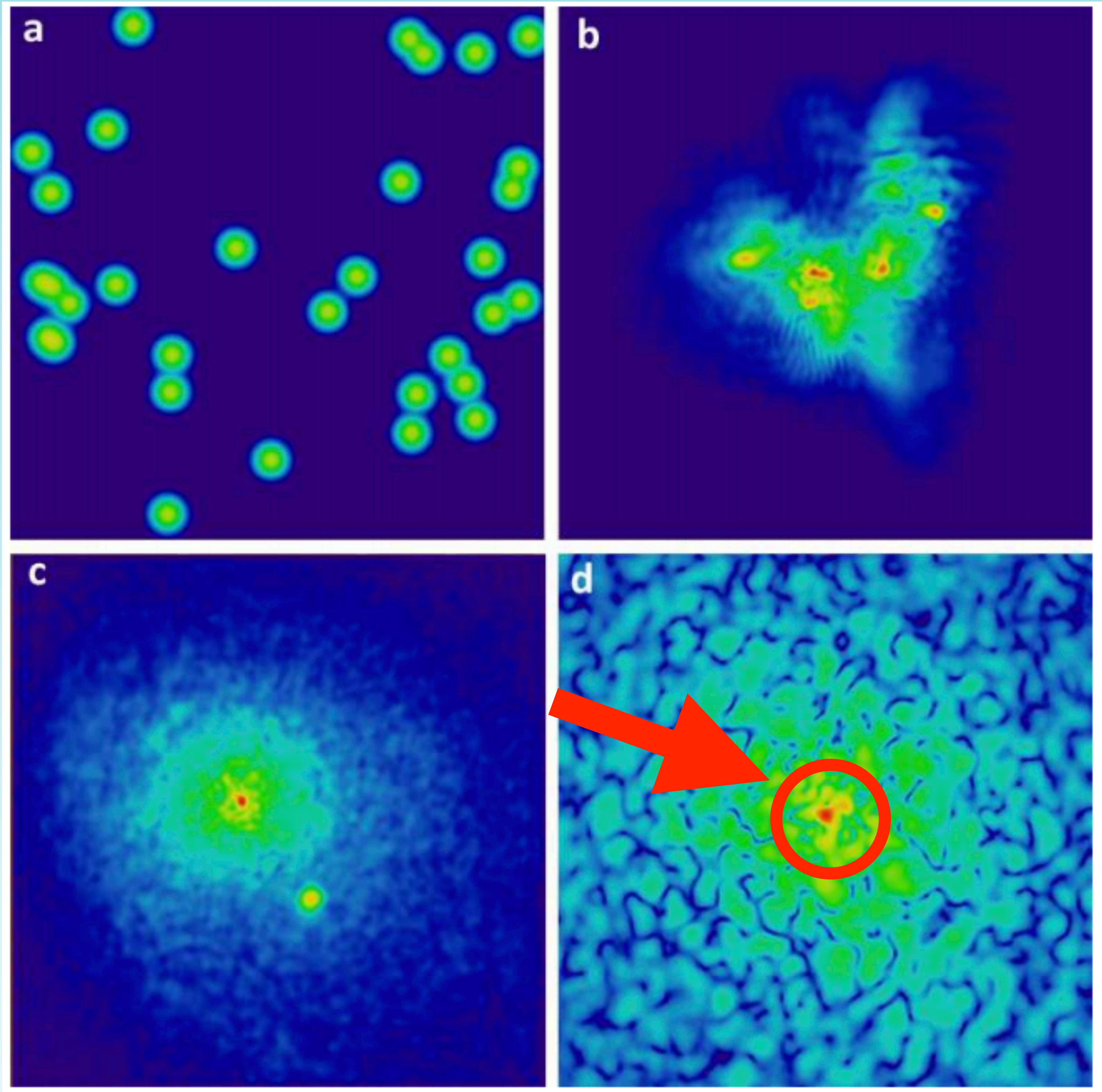

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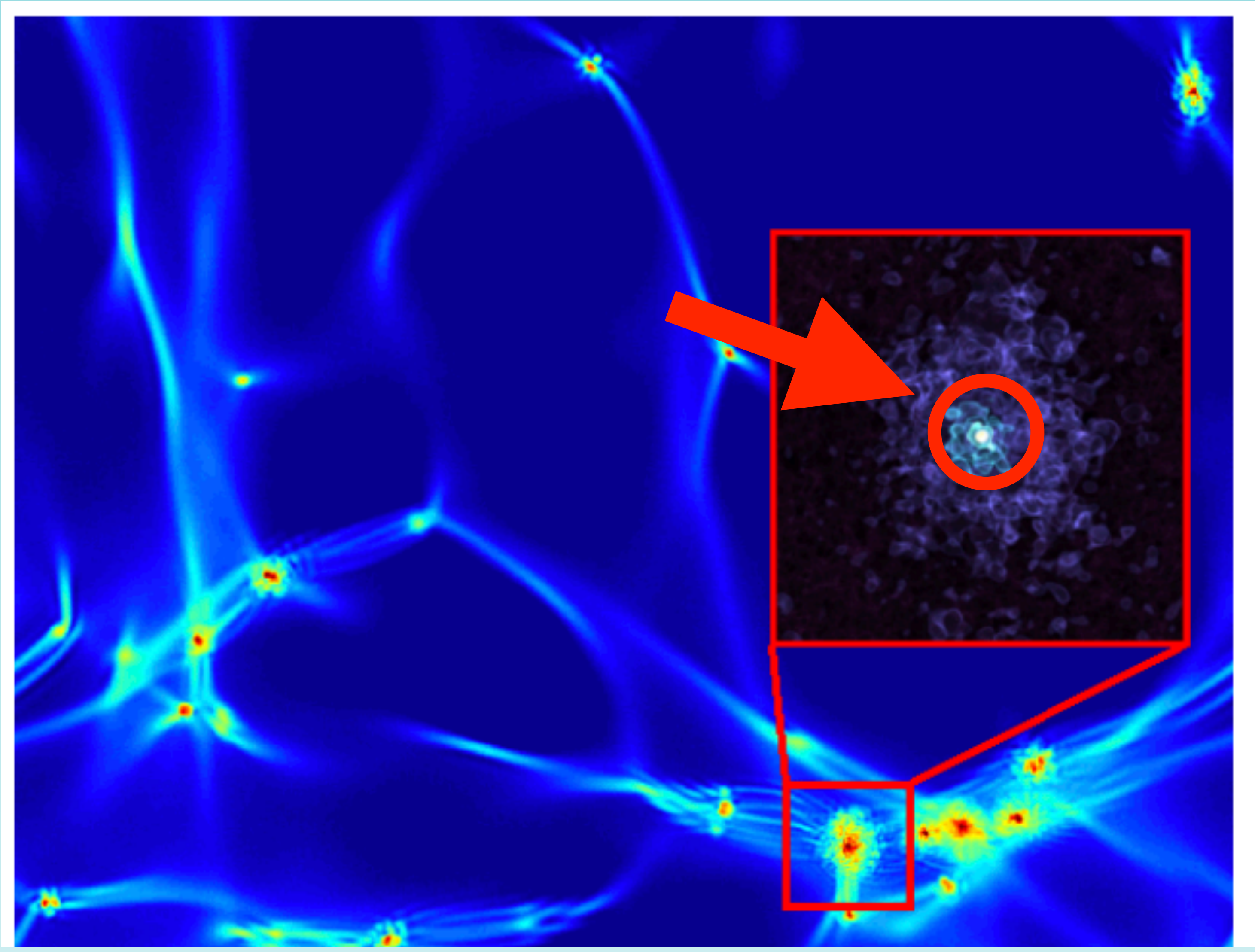

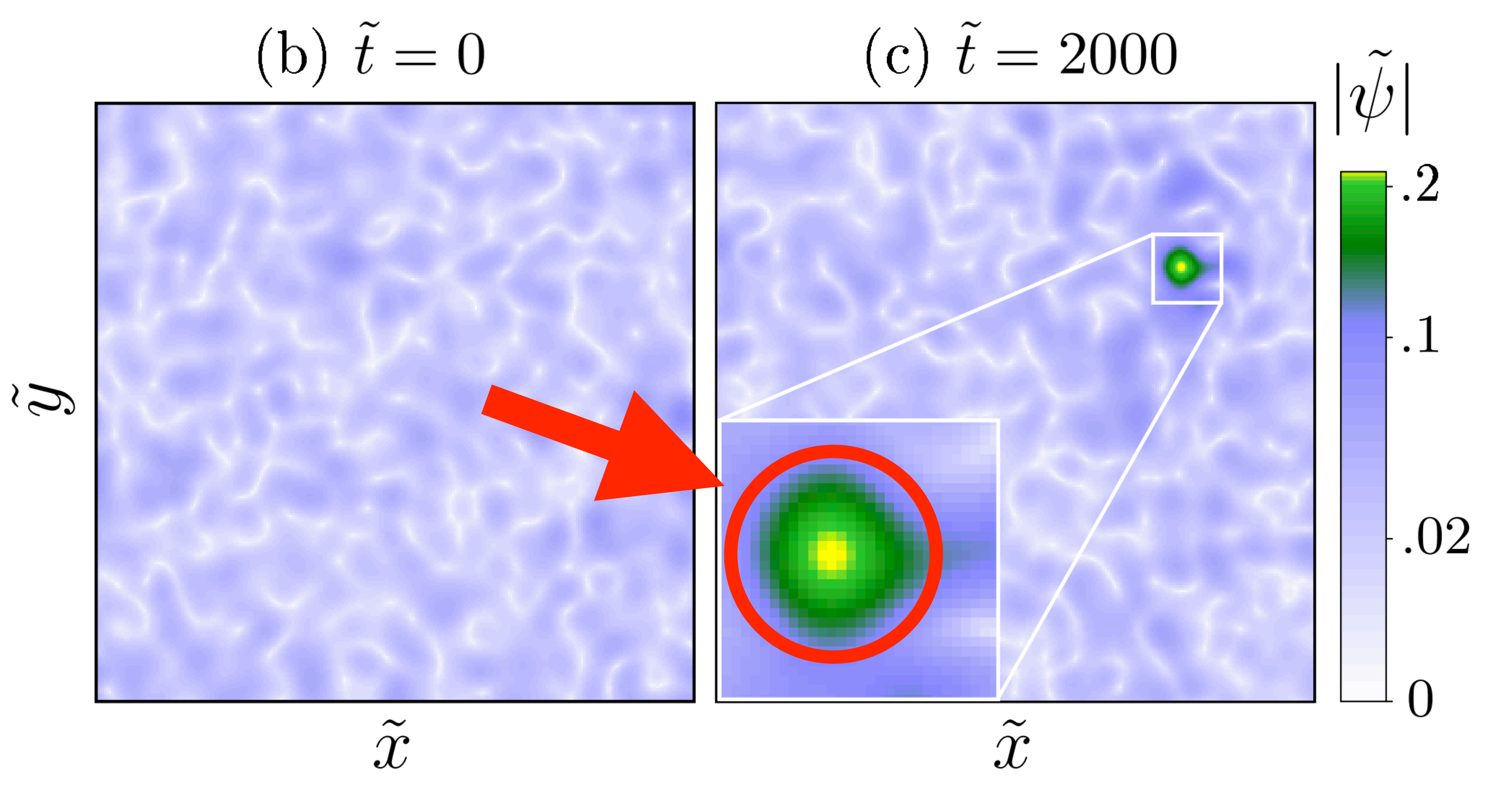

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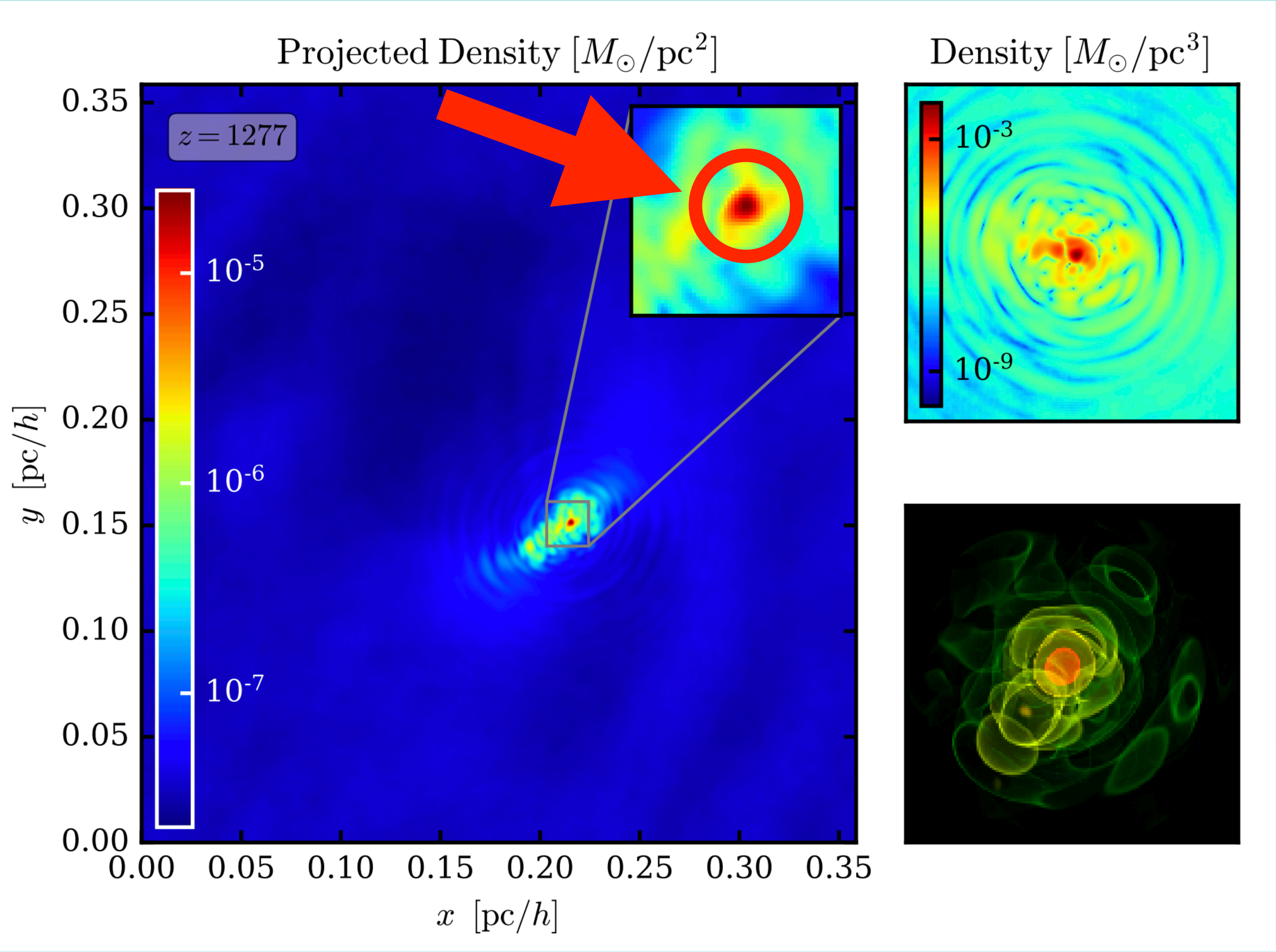


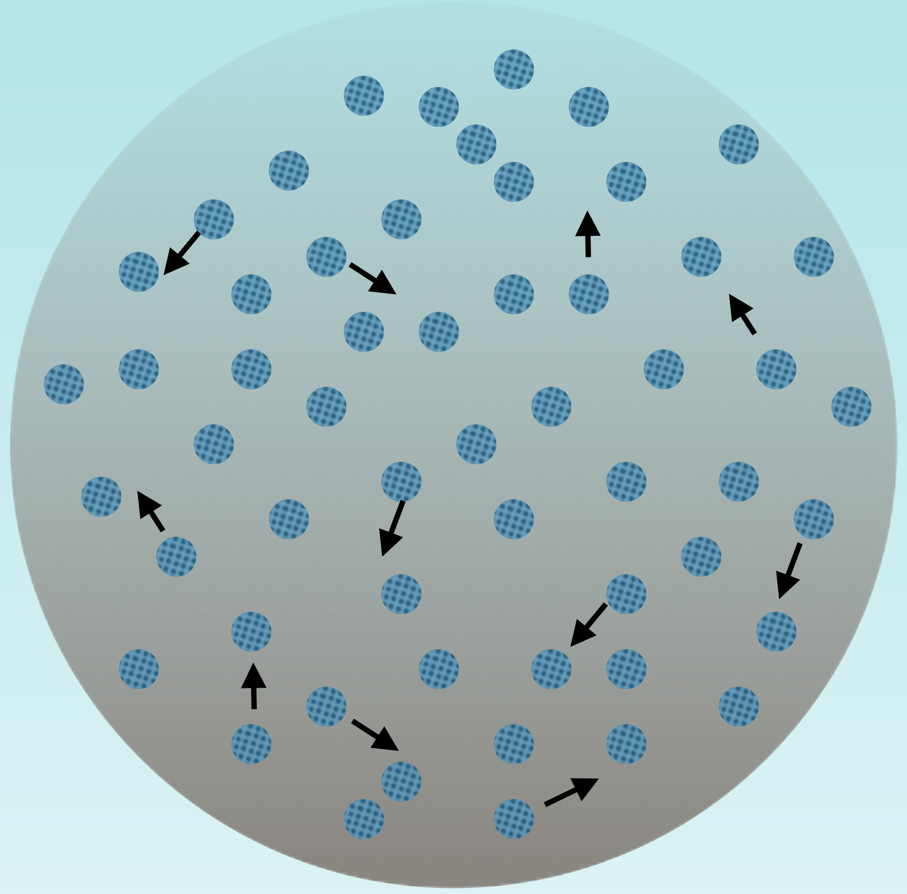
Eggemeier and Niemeyer (1906.01348)

Do Solitons actually Form? (2)

◉ Evidence 2: Analytic argument

- Gravitational relaxation of quasiparticles sufficient for formation

See e.g. Binney and Tremaine, “Galactic Dynamics, 2nd Edition”



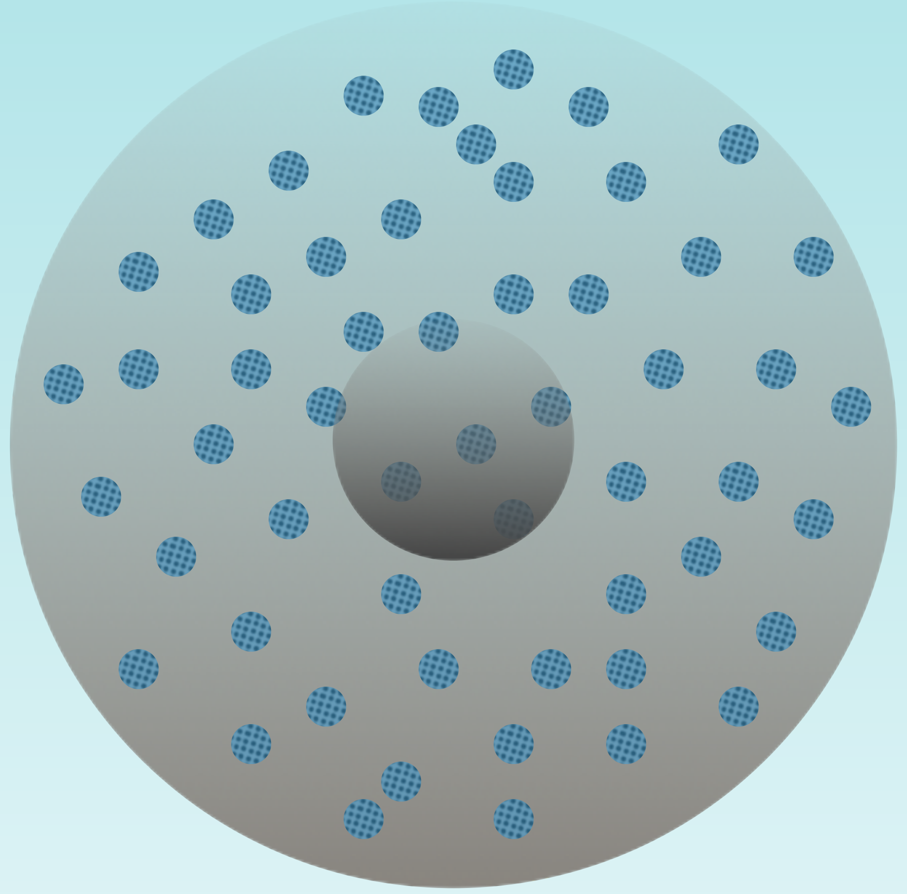
Quasiparticle dispersion

Velocity change per crossing

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

Fractional velocity change

$$\frac{\Delta v^2}{v^2} \simeq \frac{8\,\ln N}{N}$$



Soliton formation

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

Relaxation to ground state

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

Analytic timescale matches simulation results!

See also Levkov, Panin, Tkachev (1804.05857)

Axion Earth/Solar Halos

- A third substructure possibility: Can LSDM be captured by external bodies?
- At the level of the E.o.M., configuration is very stable under perturbations (if it forms)

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

Balance these forces

$$R_\star \simeq \frac{M_P^2}{m_\phi^2\,M_\star}$$

"Axion Star"

$$i\,\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m_\phi} + \cancel{V_g\left(|\psi|^2\right)} + V_{\rm ext}\left(|\psi|^2\right)\right]\psi$$

Balance these forces

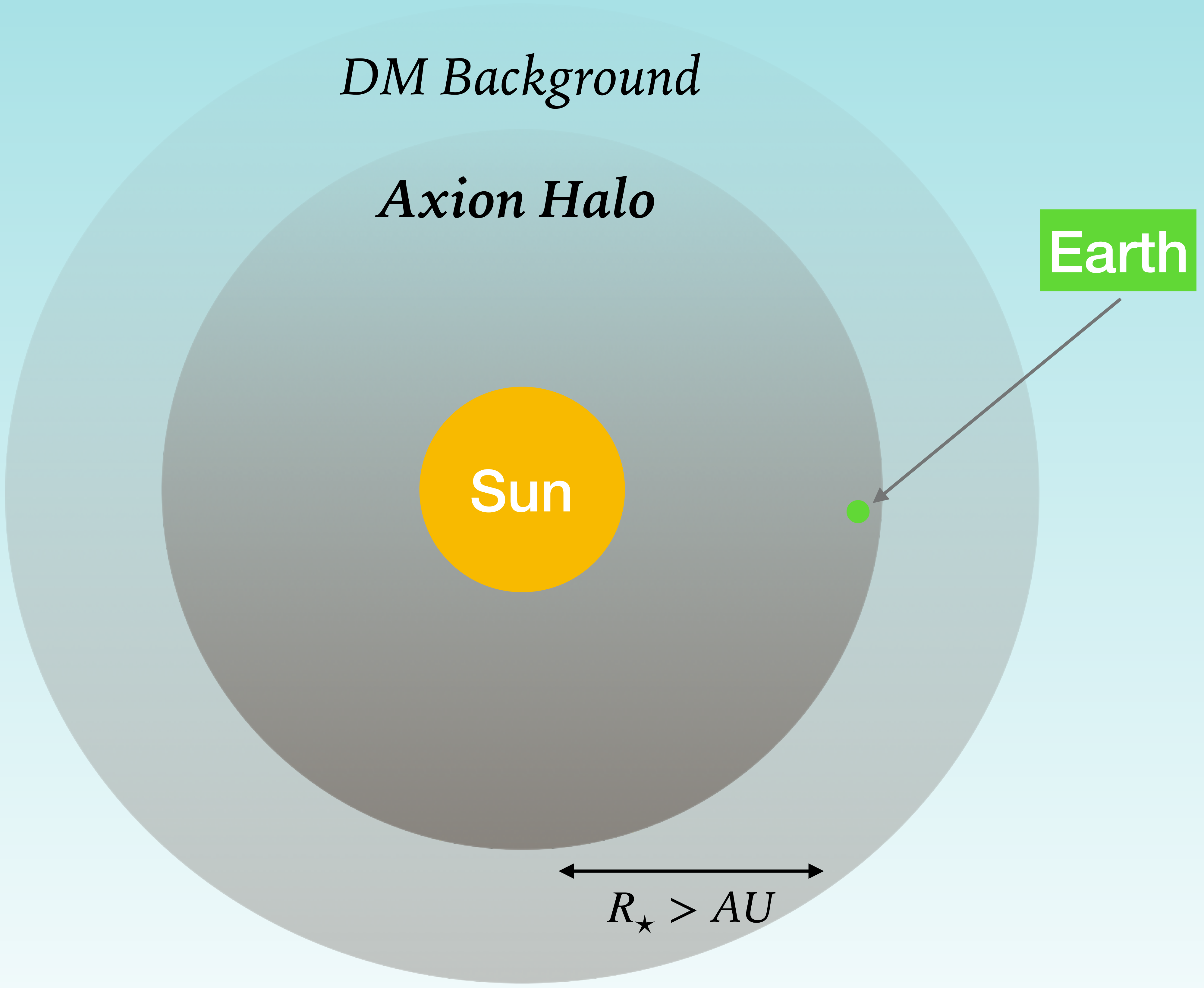
$$R_\star \simeq \frac{M_P^2}{m_\phi^2\,M_{\rm ext}}$$

"Axion Halo"

Dark Matter in the Solar System

$$R_\star \approx \frac{M_P^2}{m_\phi^2 M_{ext}}$$

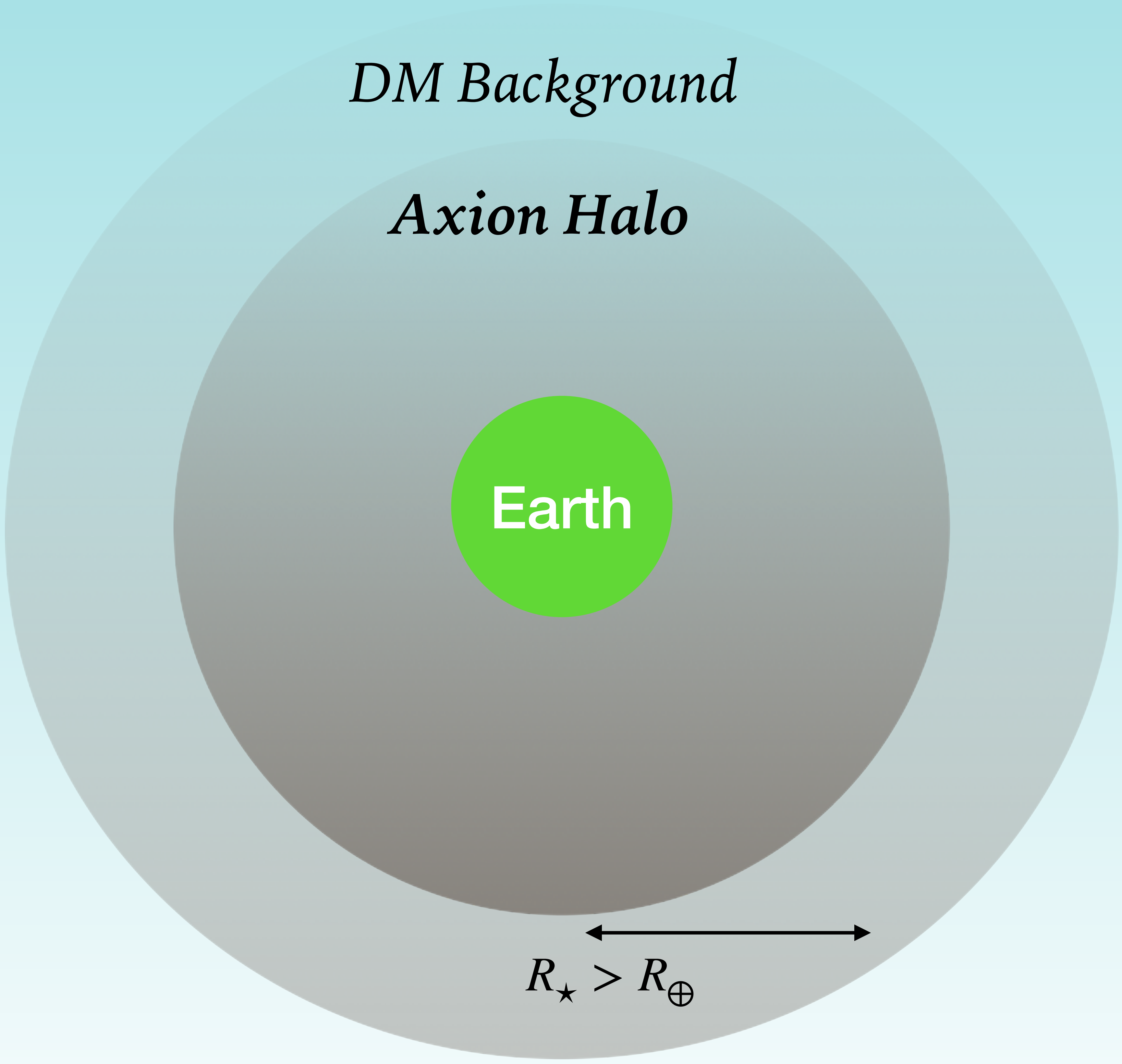
Halo supported by Sun
"Solar Halo"



$m_\phi = 10^{-17} \div 10^{-13}\, eV$

$\sim mHz \div 10\, Hz$

Halo supported by Earth
"Earth Halo"

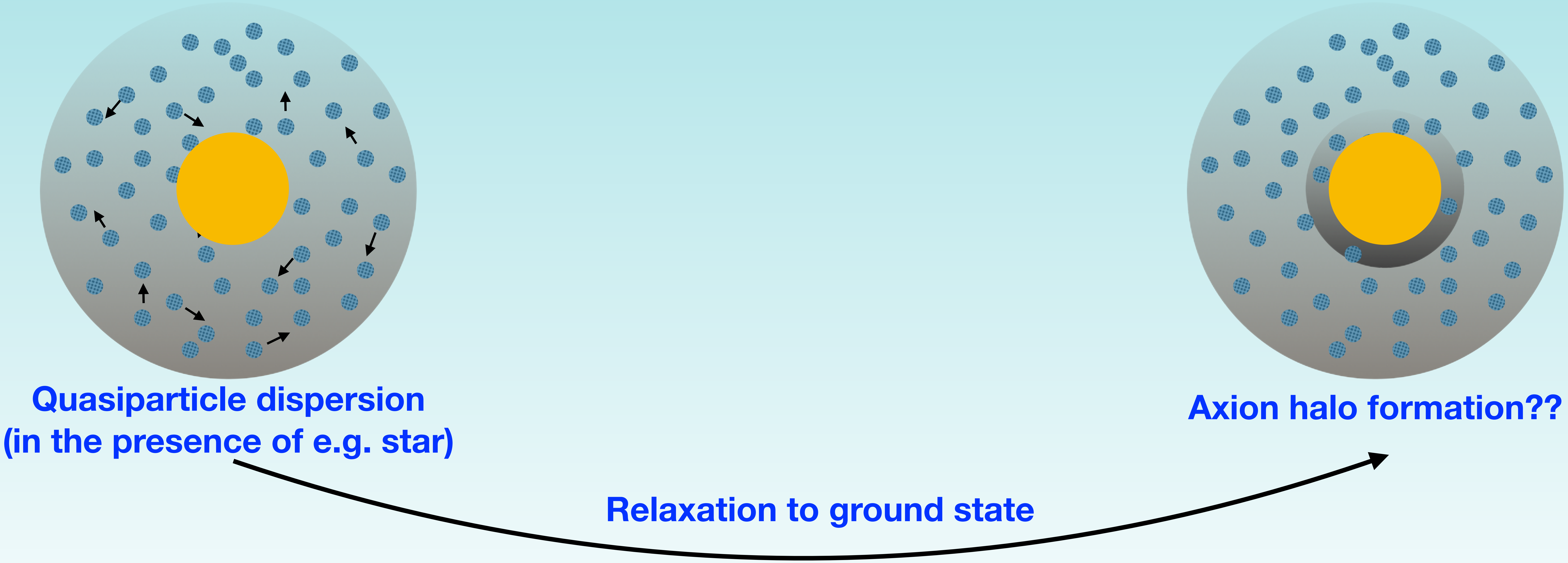


$m_\phi = 10^{-13} \div 10^{-8}\, eV$

$\sim 10\, Hz \div\ MHz$

Can Axion Earth/Solar Halos Form?

- No dedicated simulations
- Rough argument: If QP relaxation occurs (as with solitons), resulting ground state is plausibly an axion halo



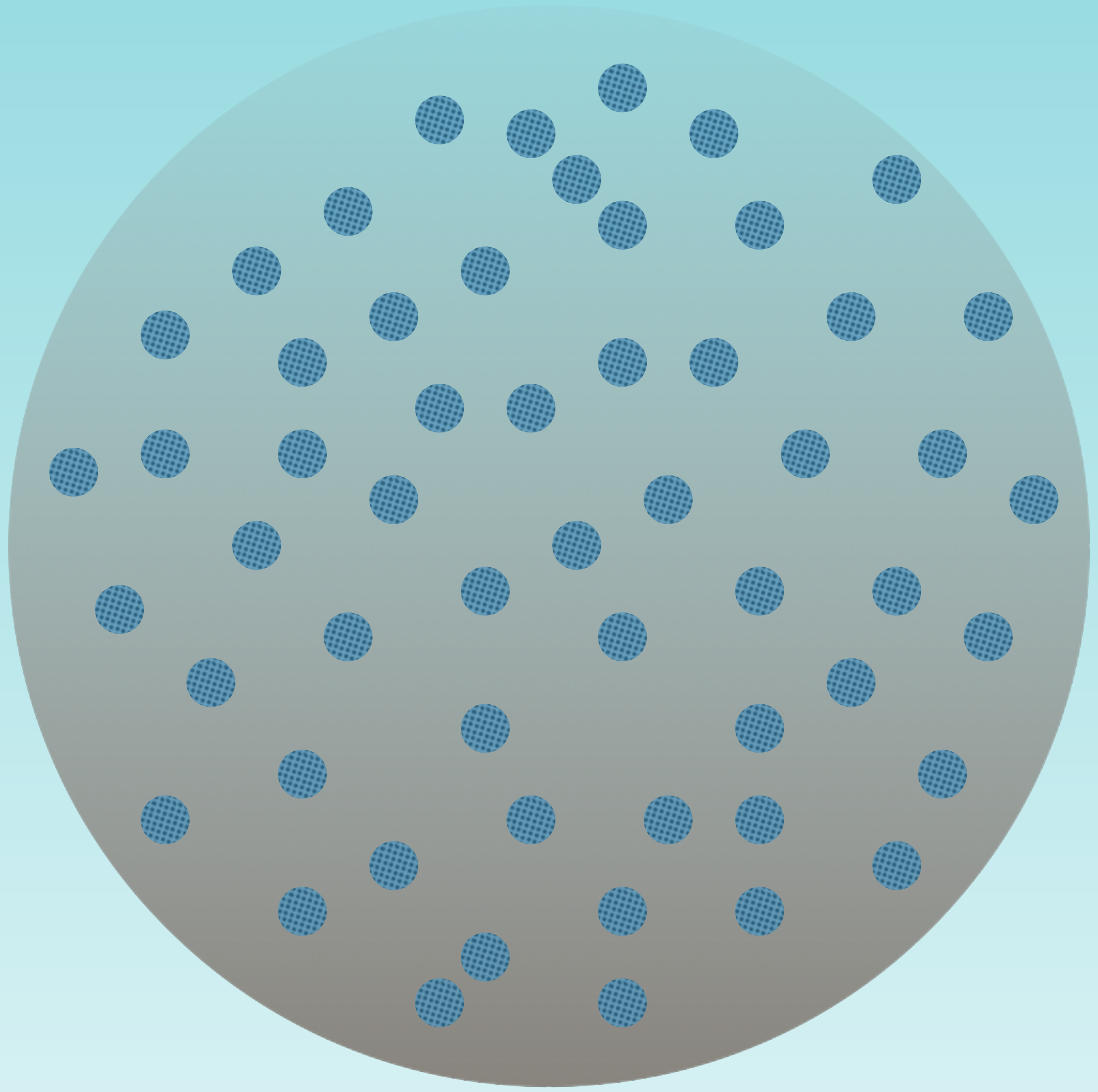
Quasiparticle dispersion (in the presence of e.g. star)

Relaxation to ground state

Axion halo formation??

- At present, can't compute δ, but can still ask what's still allowed / interesting

Substructure Summary



Quasiparticles / Granules

- Fundamental, irreducible waviness of LSDM halos
- Typical size $\lambda_{\text{dB}} = \dfrac{1}{m_\phi \sigma}$
- Typical density $\delta \simeq 1$

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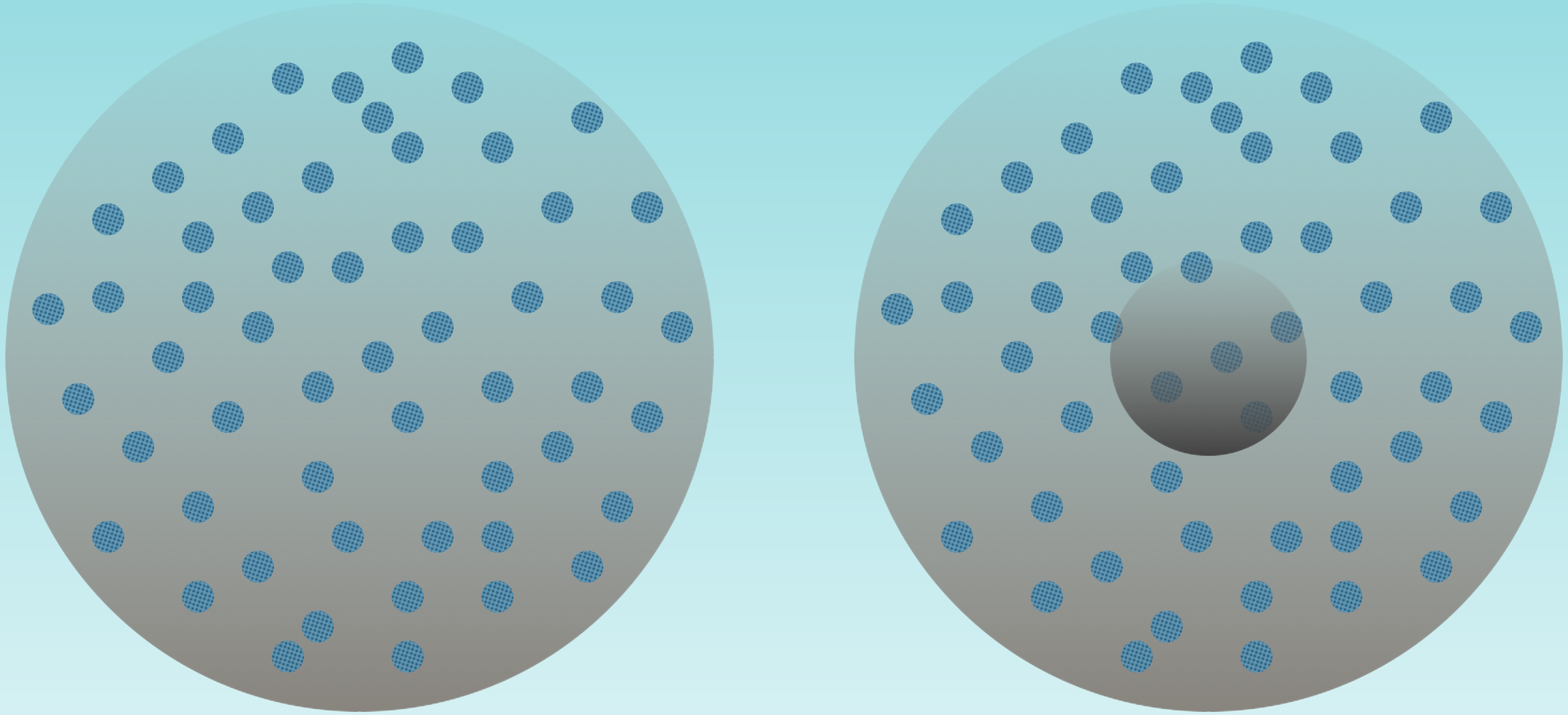

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Axion Stars / Solitons

- Self-gravitating bound states, formed by grav. relaxation
- Typical size $R_\star \simeq \dfrac{M_P^2}{m_\phi^2 M_\star}$
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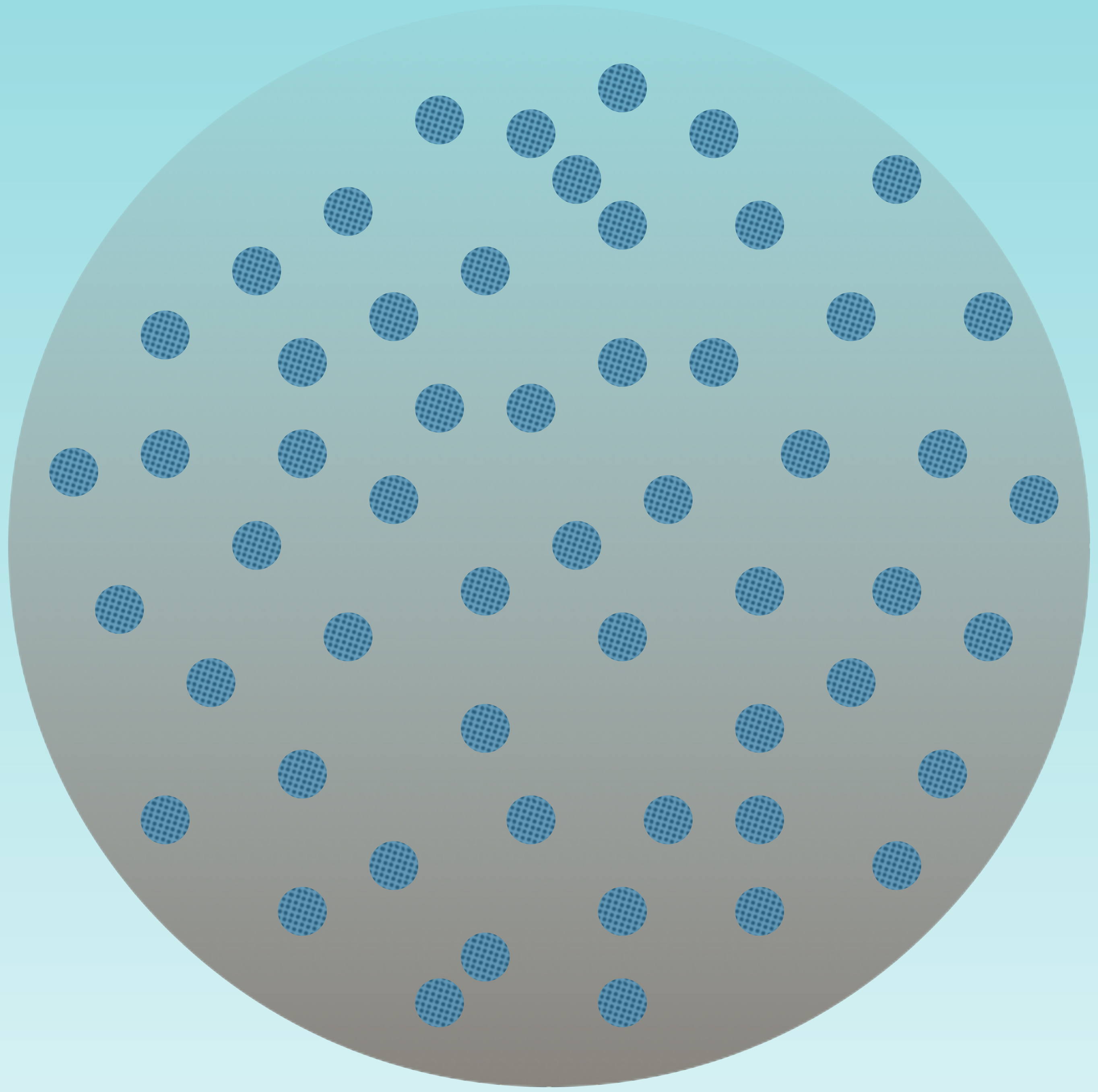

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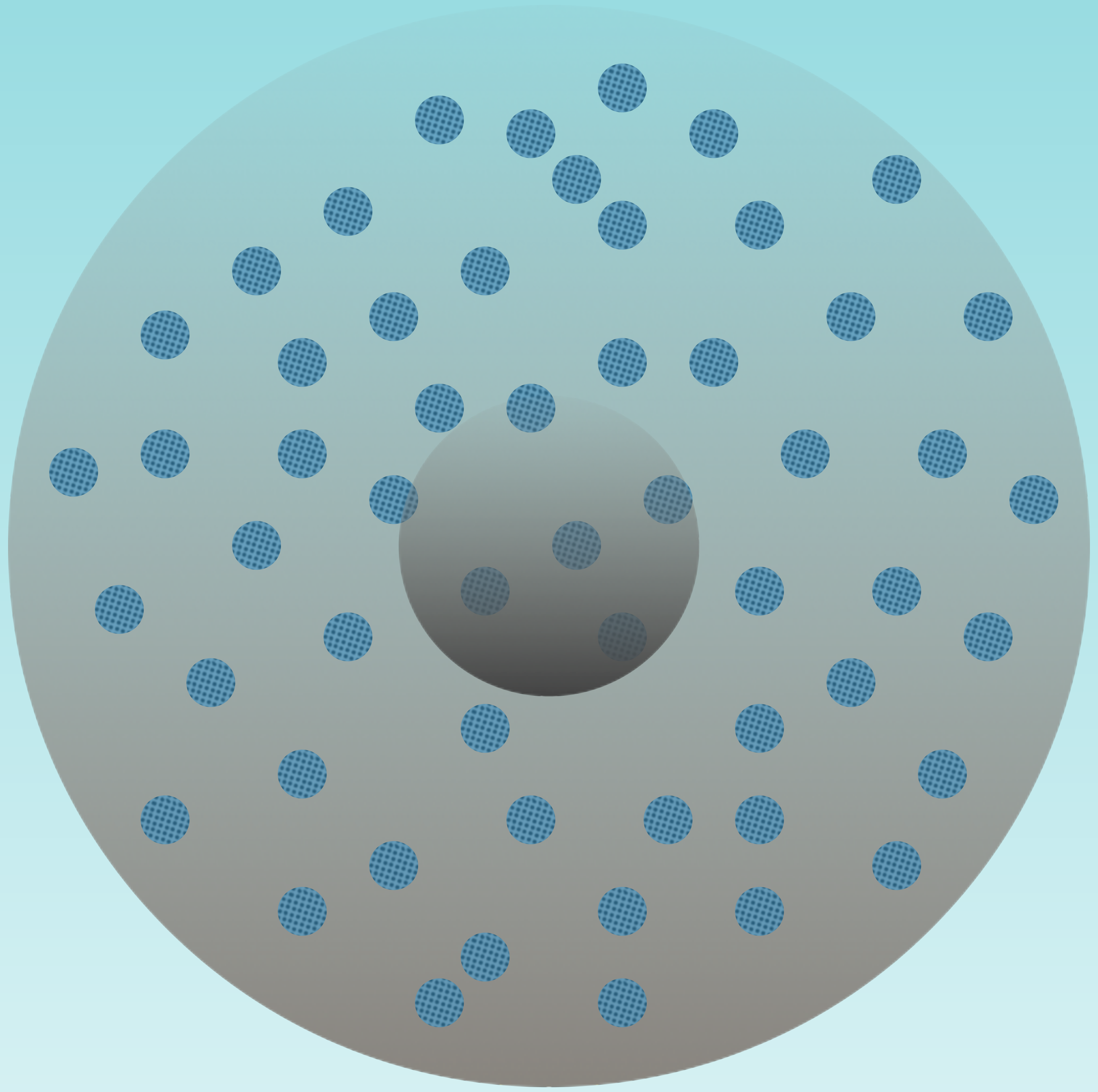

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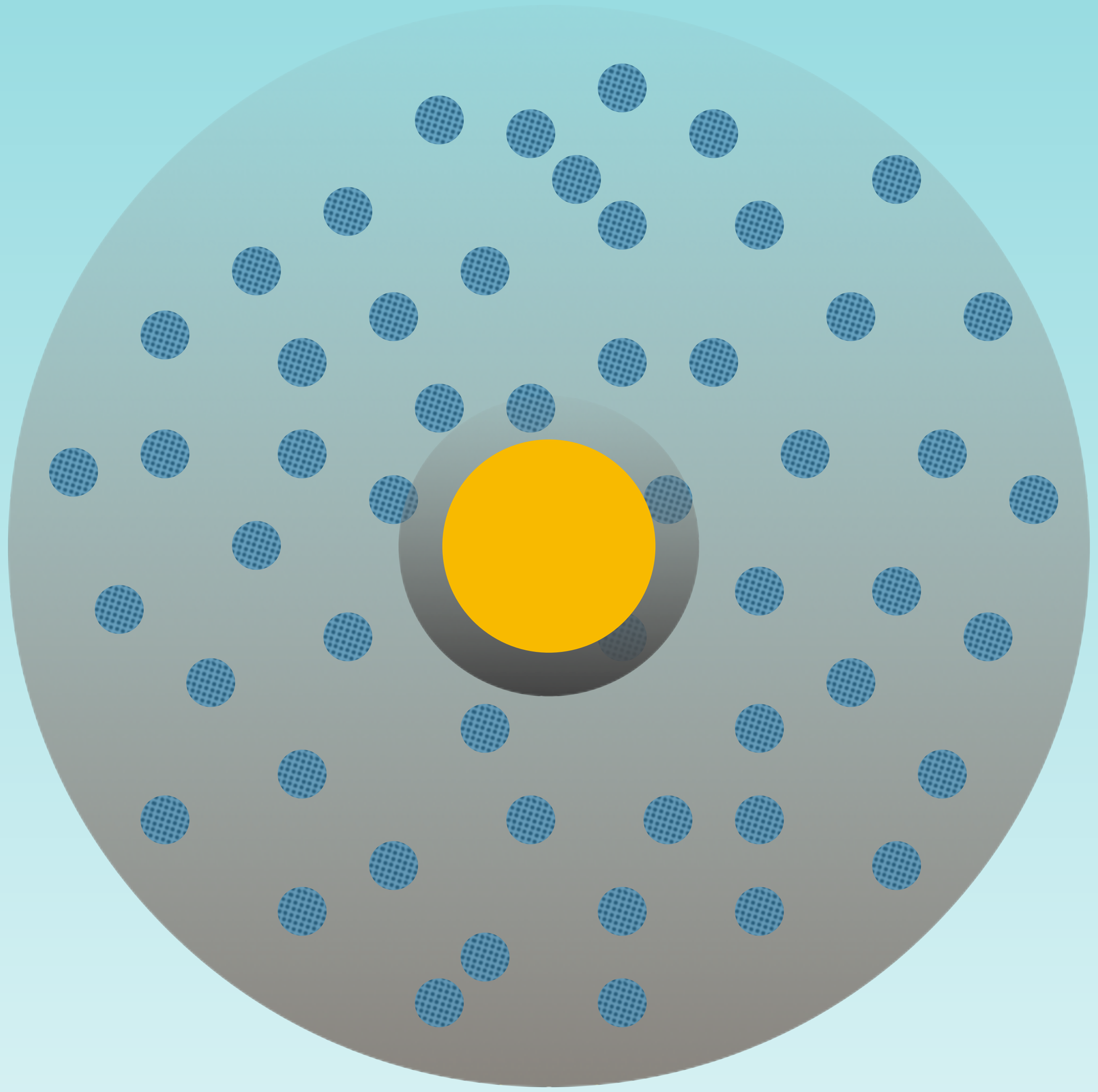
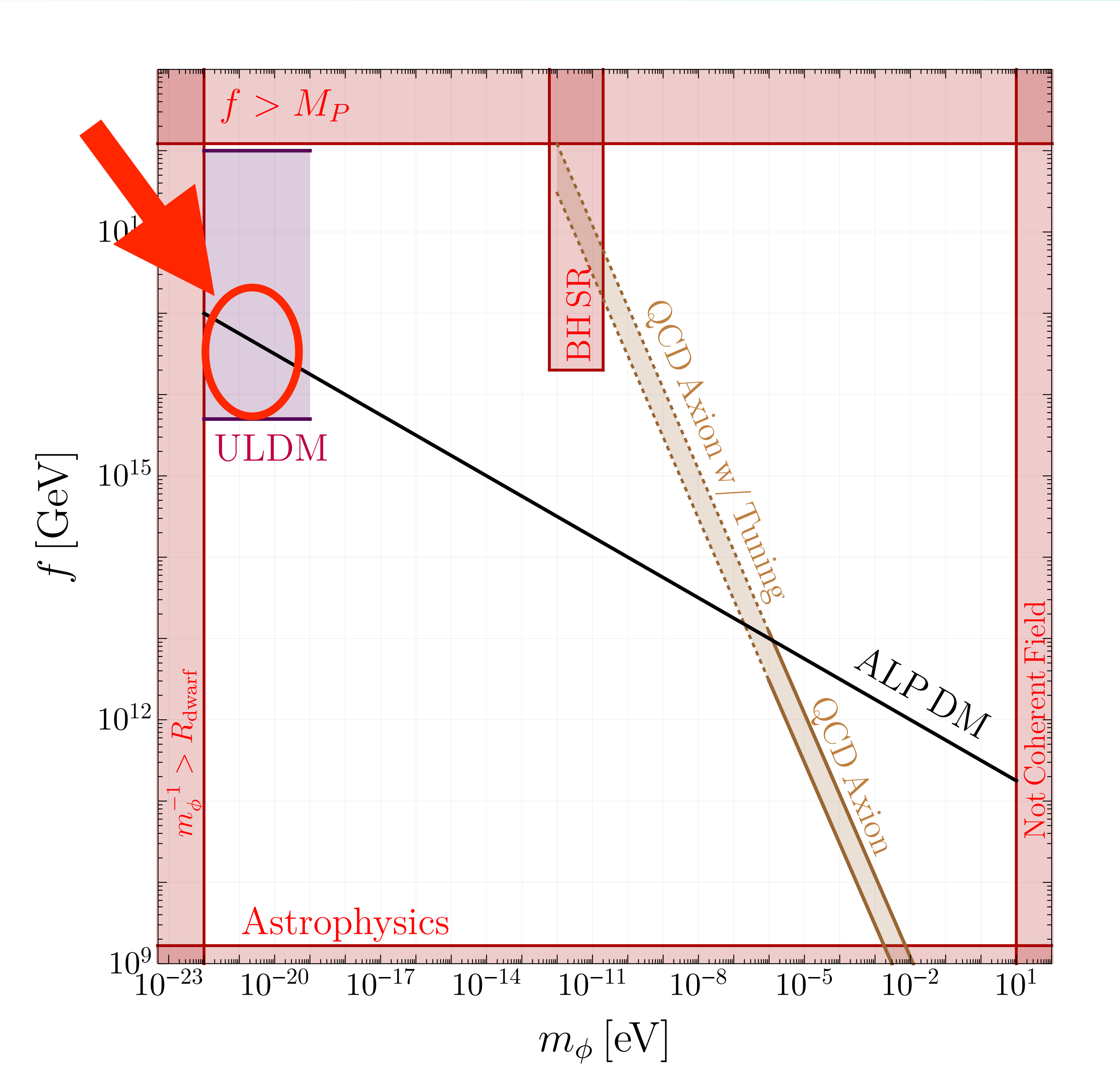


Earth Halo or Solar Halo

- Bound to external objects,
- Formation? Work in progress
- Typical size $R_\star \simeq \dfrac{M_P^2}{m_\phi^2 M_{\mathrm{ext}}}$
- Typical density $\delta = ???$

Substructure in Galaxies



Bar, Blas, Blum, Sibiryakov (1805.00122)

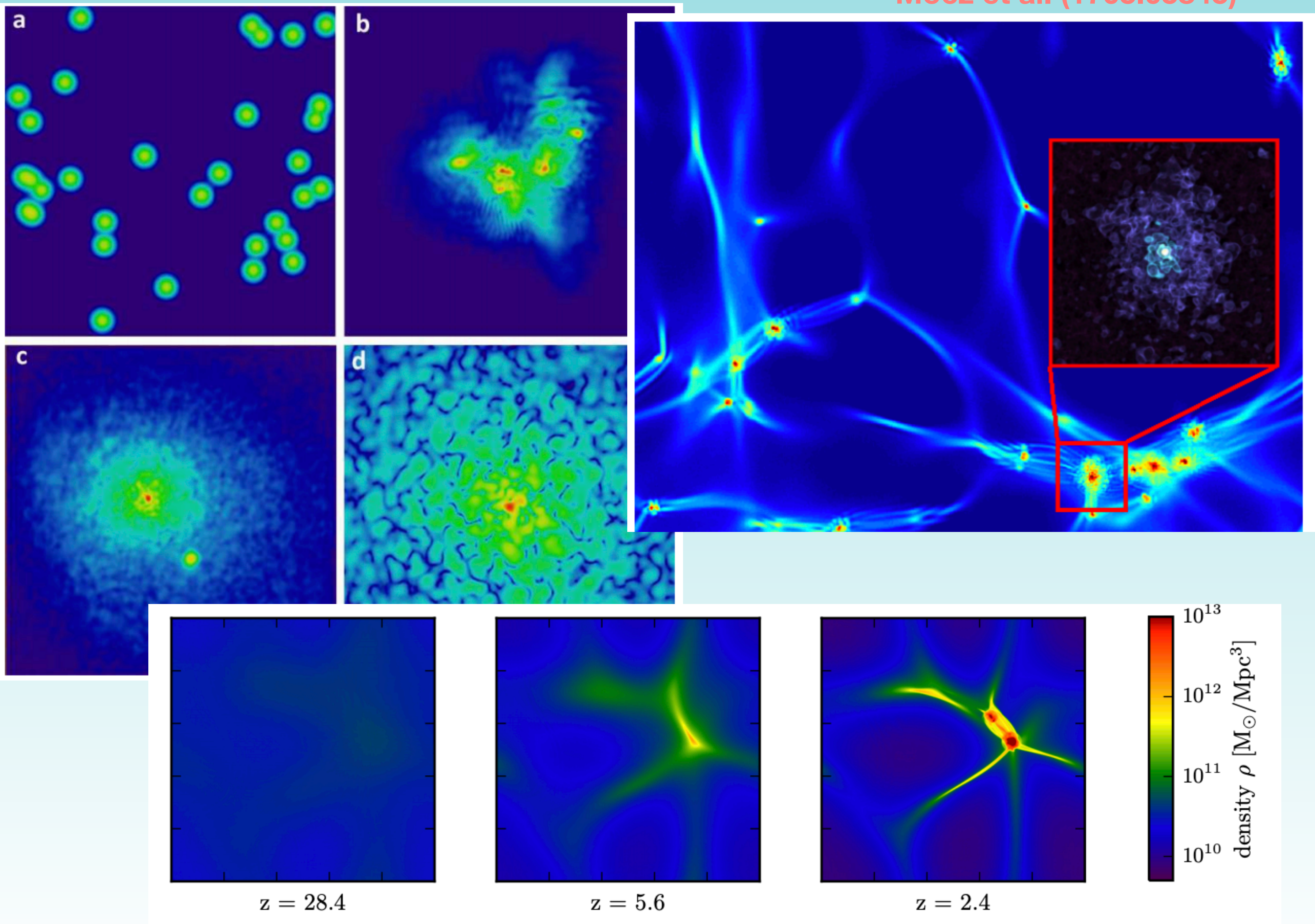
Bar, Blum, JE, Sato (1903.03402)

Blum, JE, Kim (To Appear)

Look at Simulations again

Schive et al. (1407.7762)

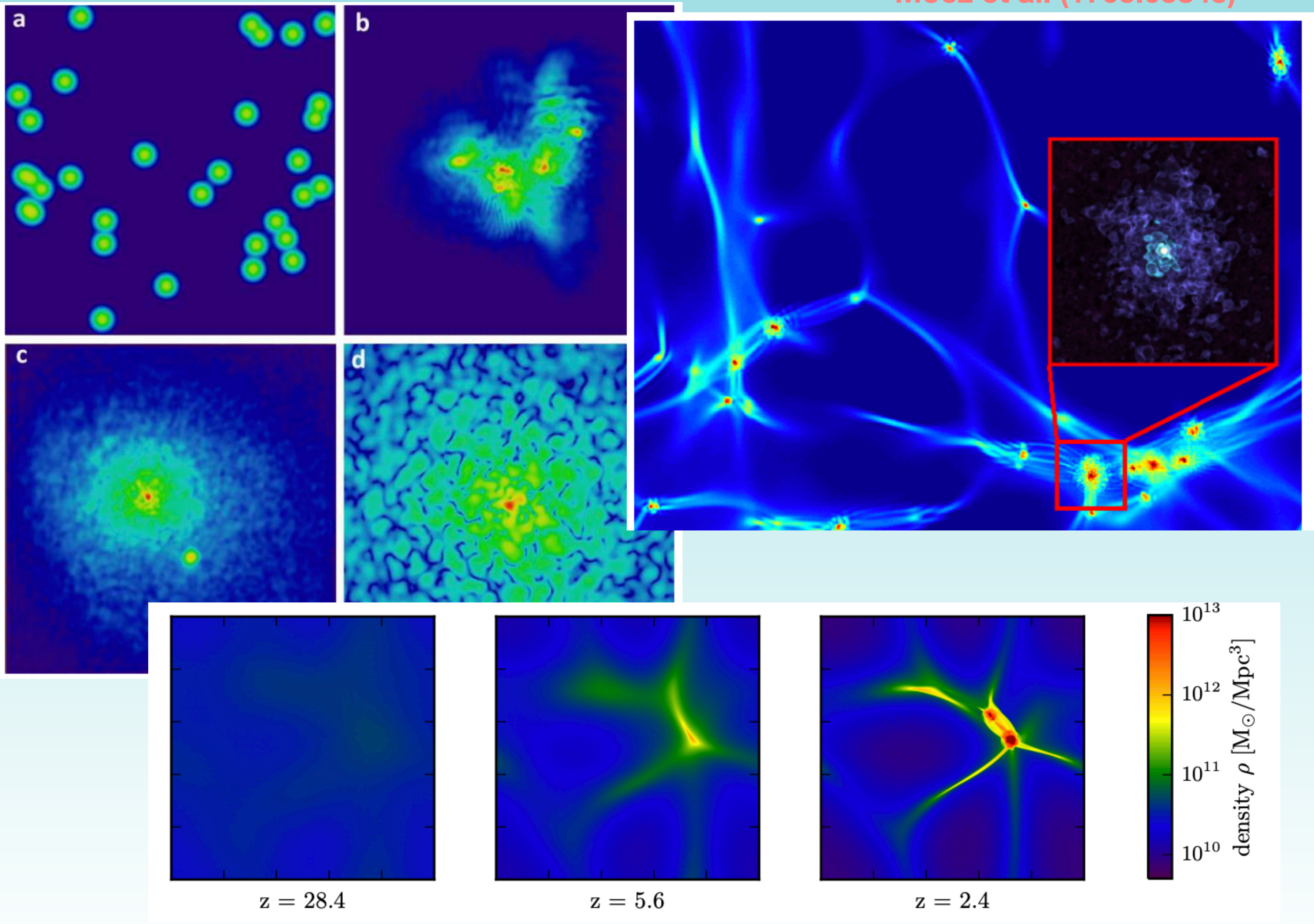
Mocz et al. (1705.05845)



Veltmaat and Niemeyer (1608.00802)

Look at Simulations again

- “Emperical” relation between soliton core and its host halo



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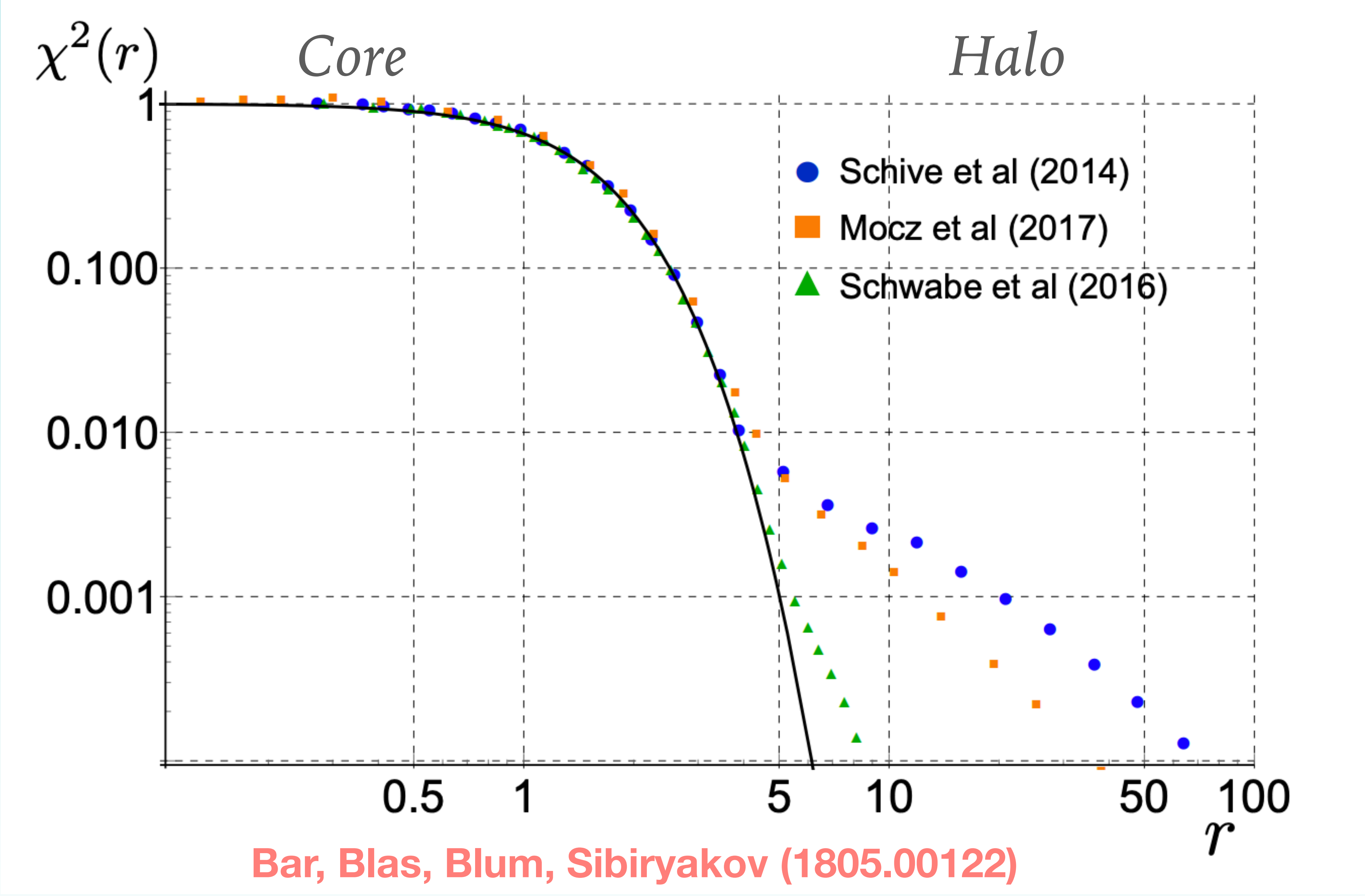

Bar, Blas, Blum, Sibiryakov (1805.00122)

The Soliton-Host Halo Relation

- Curious connection between central soliton and its host halo:

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

Picks out one soliton solution from the λ-family

- Tested in the ranges $10^{-22}\,{\rm eV} \lesssim m_\phi \lesssim 10^{-20}\,{\rm eV}$ and $10^9 M_\odot \lesssim M_{\rm h} \lesssim 10^{12} M_\odot$
- Verified by multiple independent simulations

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Includes NFW-like profile, flat rotation curve

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- ◉ Verified by multiple independent simulations
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$$\boxed{\left(\frac{K}{M}\right)_{\rm soliton}} \simeq \boxed{\left(\frac{K}{M}\right)_{\rm halo}}$$

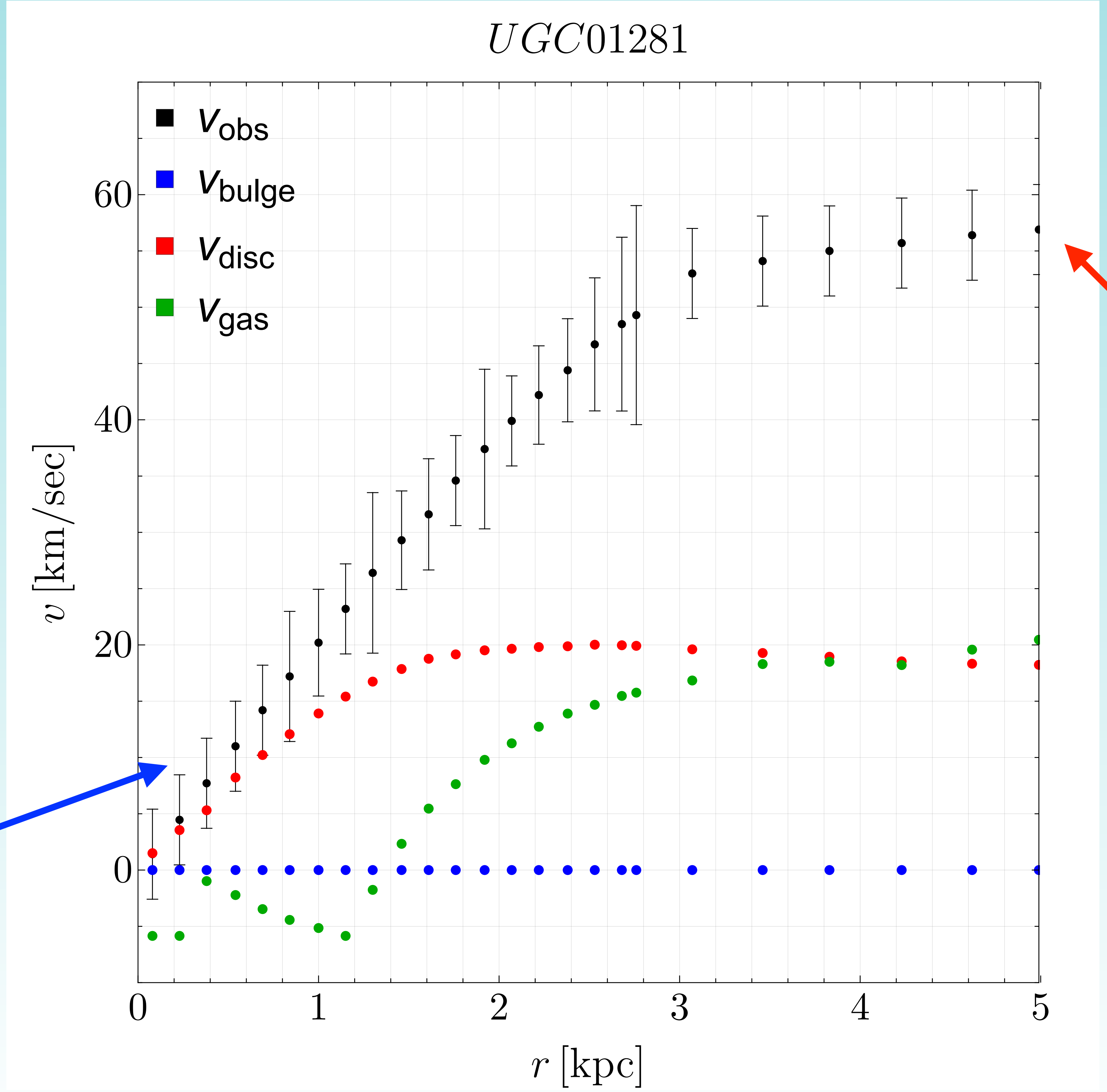
Look for corresponding velocity peak in central core of galaxies!

Includes NFW-like profile, flat rotation curve

How do we test it?

- SPARC database: 175+ galaxies, with disc, bulge, and (sometimes) gas modeling

Lelli, McGaugh, Schombert (1606.09251)



NFW part ☑

Can we see a peak in the inner core?

(one example of dozens of similar candidates)

ULDM Tests using SPARC:

- *DM-only (spherical)*

Bar, Blas, Blum, Sibiryakov (1805.00122)

- *w/ Baryons (azimuthal)*

Bar, Blum, JE, Sato (1903.03402)

Solving for (Non-Spherical) Solitons

- Baryonic effects introduce (disc-like) background potential

$$\nabla_x^2 \chi = 2\left(\Phi - \mu\right)\chi$$

$$\nabla_x^2 \Phi = \chi^2$$

Simple equations of motion

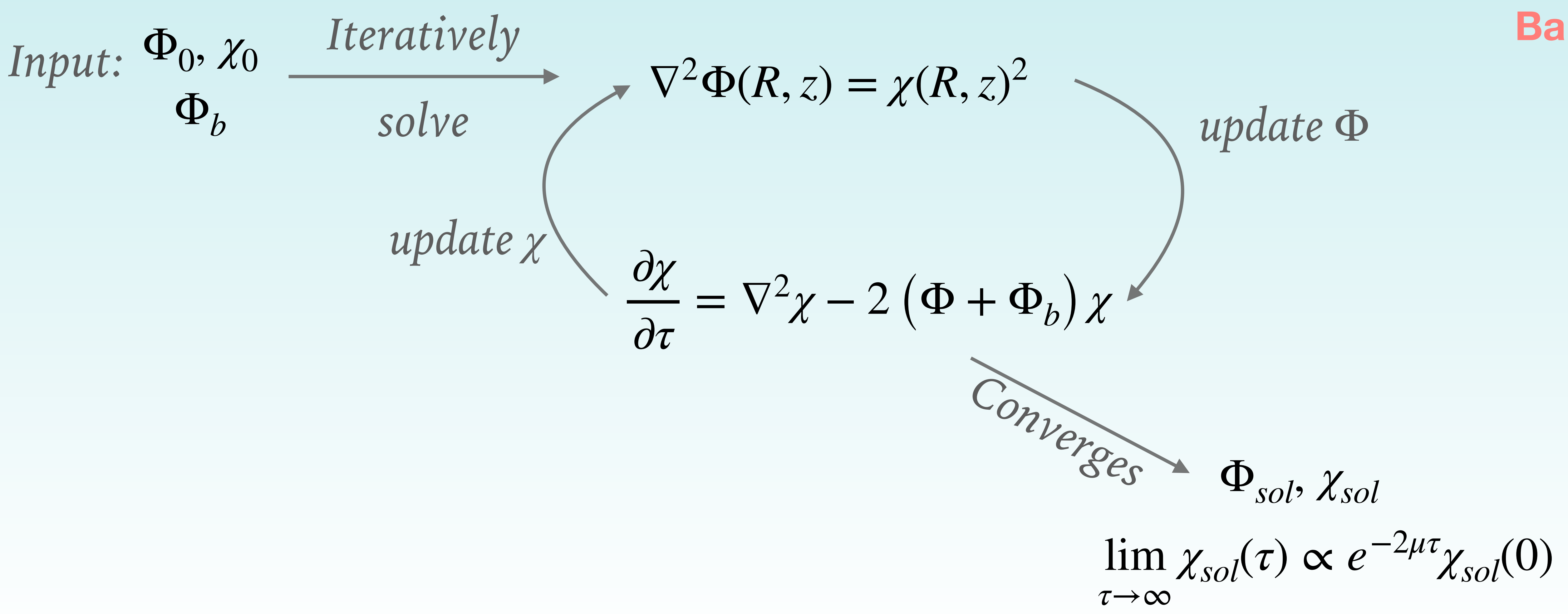
$$\nabla_x^2 \chi = 2\left(\Phi + \Phi_b - \mu\right)\chi$$

$$\nabla_x^2 \Phi = \chi^2$$

Less simple equations of motion!

- Our work: develop simple algorithm to solve for soliton in azimuthally-symmetric potential

Bar, Blum, JE, Sato (1903.03402)



Input: Φ_0, χ_0 Φ_b

Iteratively solve

$$\nabla^2 \Phi(R,z) = \chi(R,z)^2$$

update Φ

$$\frac{\partial \chi}{\partial \tau} = \nabla^2 \chi - 2\left(\Phi + \Phi_b\right)\chi$$

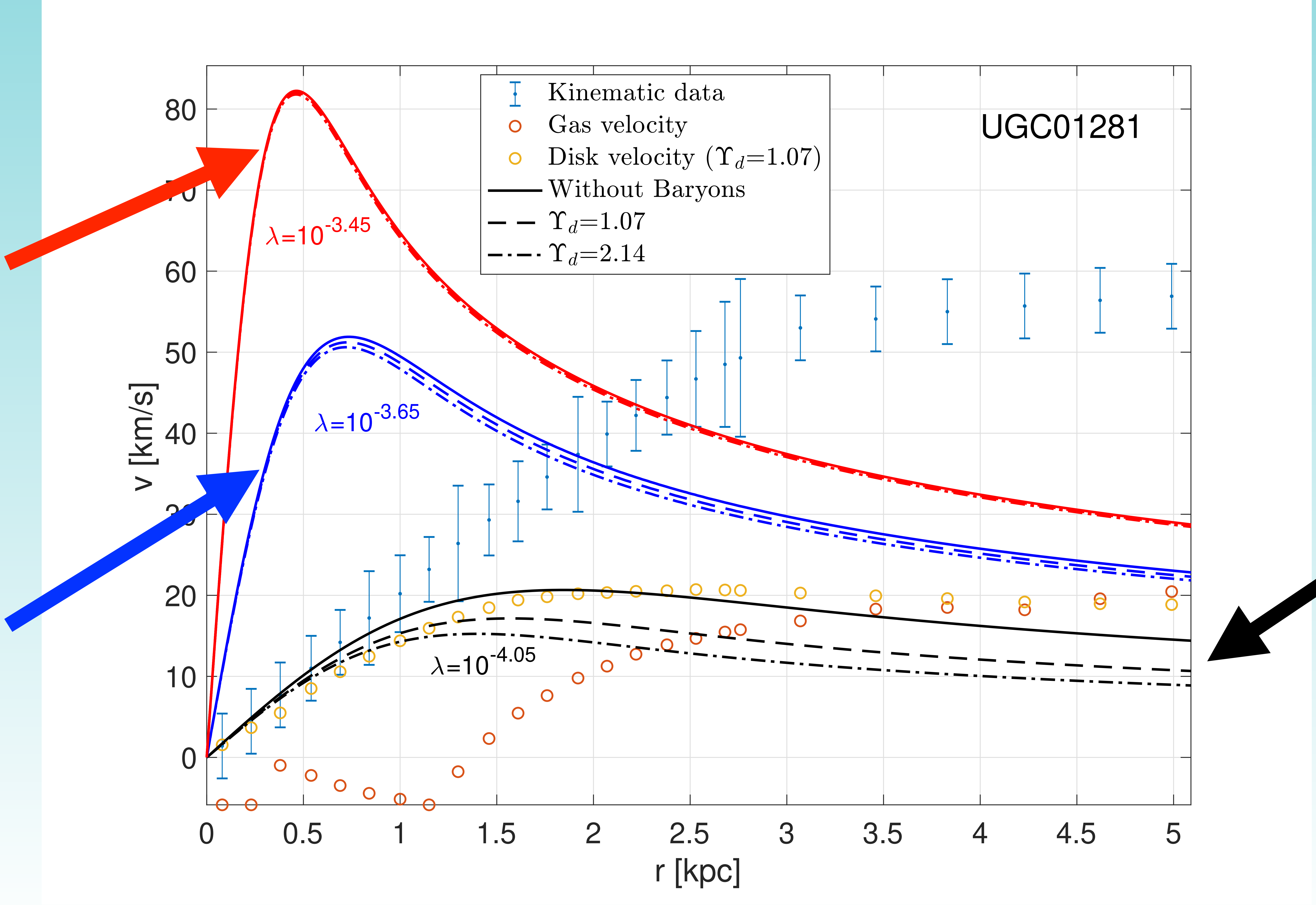
update χ

Converges

Φ_{sol}, χ_{sol}

$$\lim_{\tau \to \infty} \chi_{sol}(\tau) \propto e^{-2\mu\tau}\chi_{sol}(0)$$

SPARC example: Soliton with $m_\phi = 10^{-22}\,\mathrm{eV}$



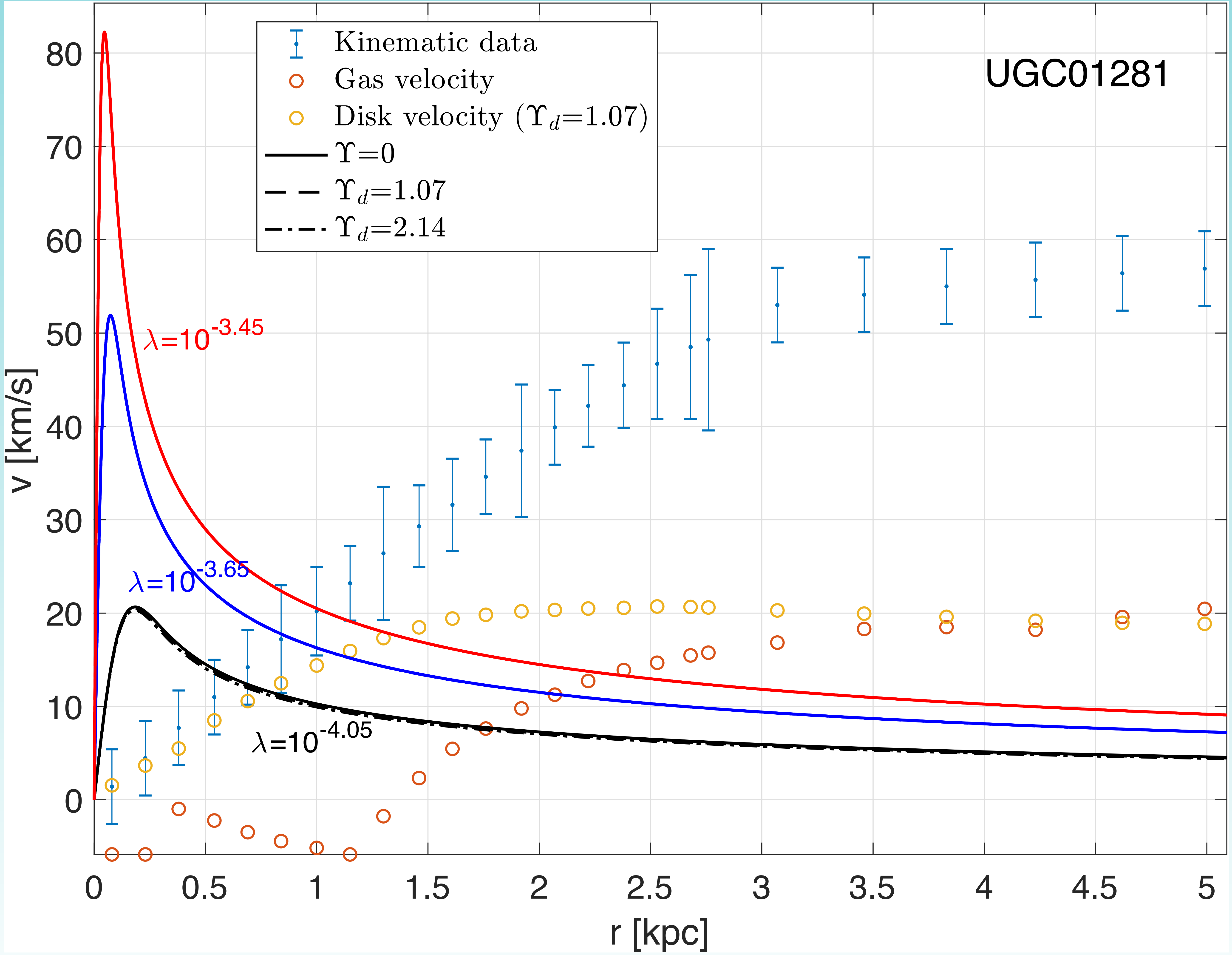
Heavier solitons

Soliton-Host Halo Relation

Lighter solitons

No sign of the predicted peak in rotational velocity!

SPARC example: Soliton with $m_\phi = 10^{-21}\,\mathrm{eV}$

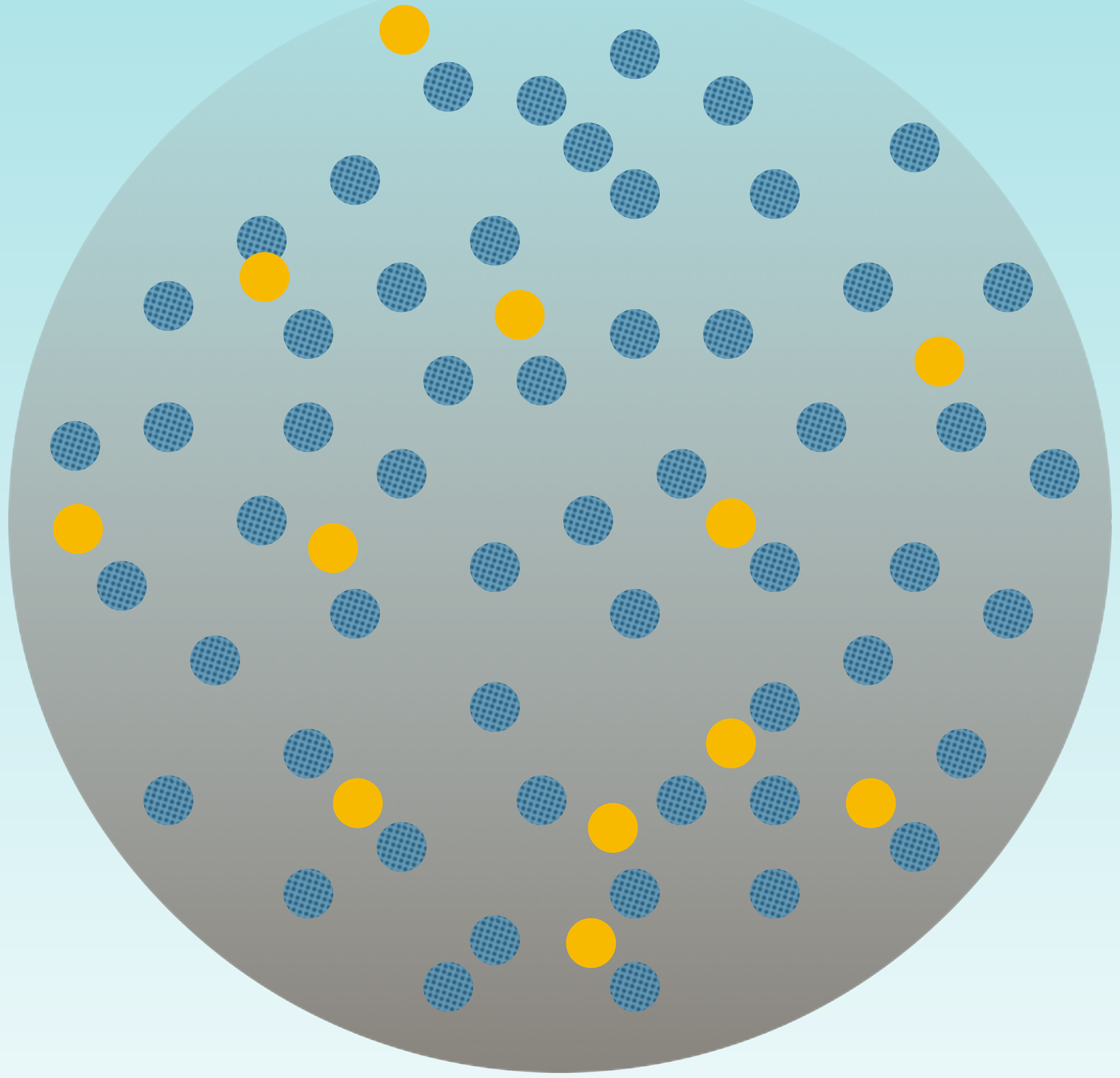


Final constraint*: $m_\phi \gtrsim 10^{-21}\,\mathrm{eV}$, **<u>gravity only!</u>**

***if simulations didn't miss something important**

Another Observable: QP Fluctuations Outside of the Core

- Stars, moving the the LSDM background, get stochastically ‘kicked’ by QPs



  - QPs can be extremely massive, even with $\delta \simeq 1$:

$$m_{\rm eff} \approx \frac{\rho}{(m_\phi \sigma)^3} \approx 10^2 \, M_\odot \left(\frac{10^{-21}\,{\rm eV}}{m_\phi}\right)^3 \left(\frac{10^{-3}}{\sigma}\right)^3 \left(\frac{\rho}{0.01\frac{M_\odot}{{\rm pc}^3}}\right)$$

$$\lambda_{\rm dB} \approx \frac{1}{m_\phi \sigma} \approx 100\,{\rm pc} \left(\frac{10^{-21}\,{\rm eV}}{m_\phi}\right)\left(\frac{10^{-3}}{\sigma}\right)$$

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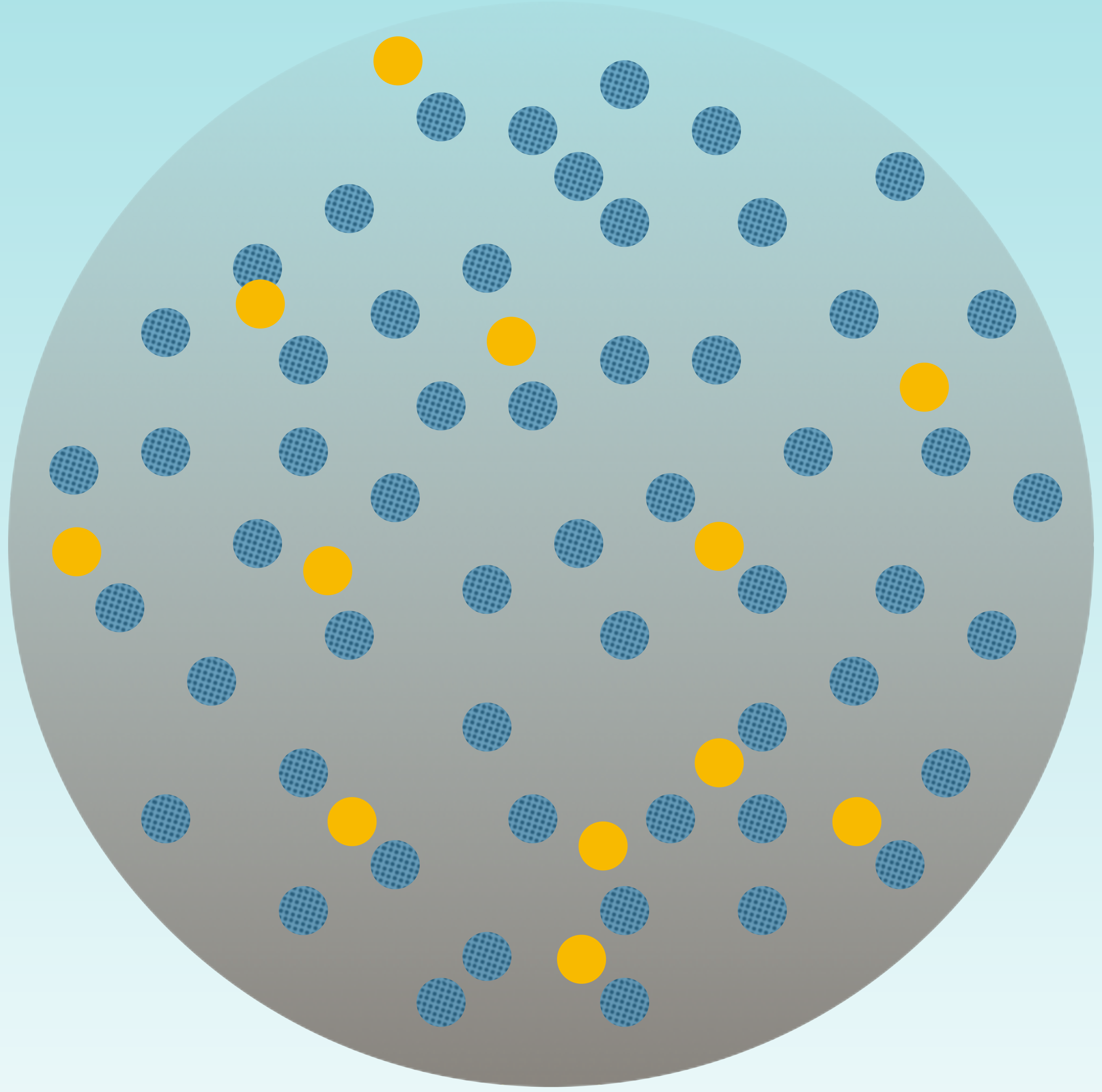

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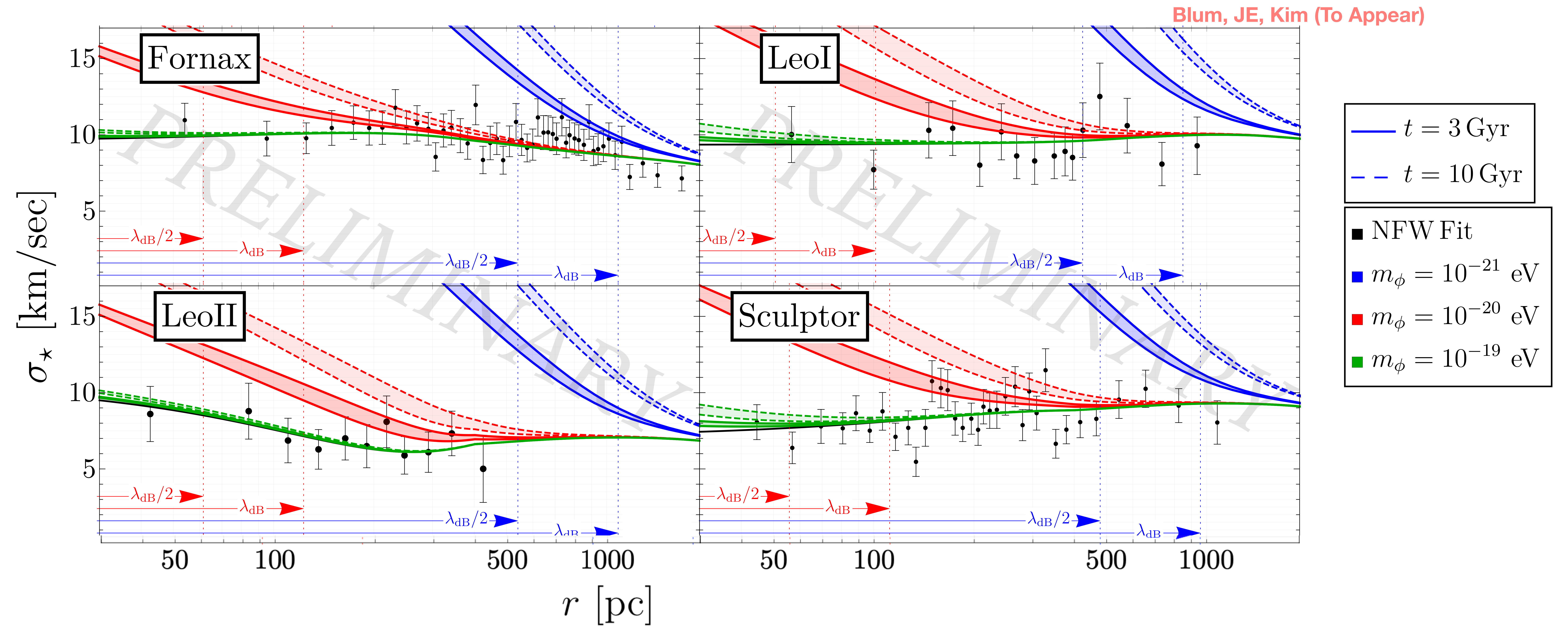
Bar-Or, Fouvry, Tremaine (1809.07673)

- Induces ‘heating’, increased velocity dispersion in population

$$\frac{d\sigma_\star^2}{dt} \simeq \frac{\sigma^2}{T_{\text{heat}}}\left(1 + \frac{2\,\sigma_\star^2}{\sigma^2}\right)^{-\frac{3}{2}} \quad \text{with } T_{\text{heat}} \simeq 0.14\,\text{Gyr}\left(\frac{m_\phi}{10^{-21}\,\text{eV}}\right)^3 \left(\frac{0.01\frac{M_\odot}{\text{pc}^3}}{\rho}\right)^2 \left(\frac{\sigma}{10\,\frac{\text{km}}{\text{sec}}}\right)^6$$

This has been used previously to constrain LSDM using limits on Milky Way disk thickness; see Church, Ostriker, Mocz (1809.04744)

Constraints in Milky Way Dwarfs?

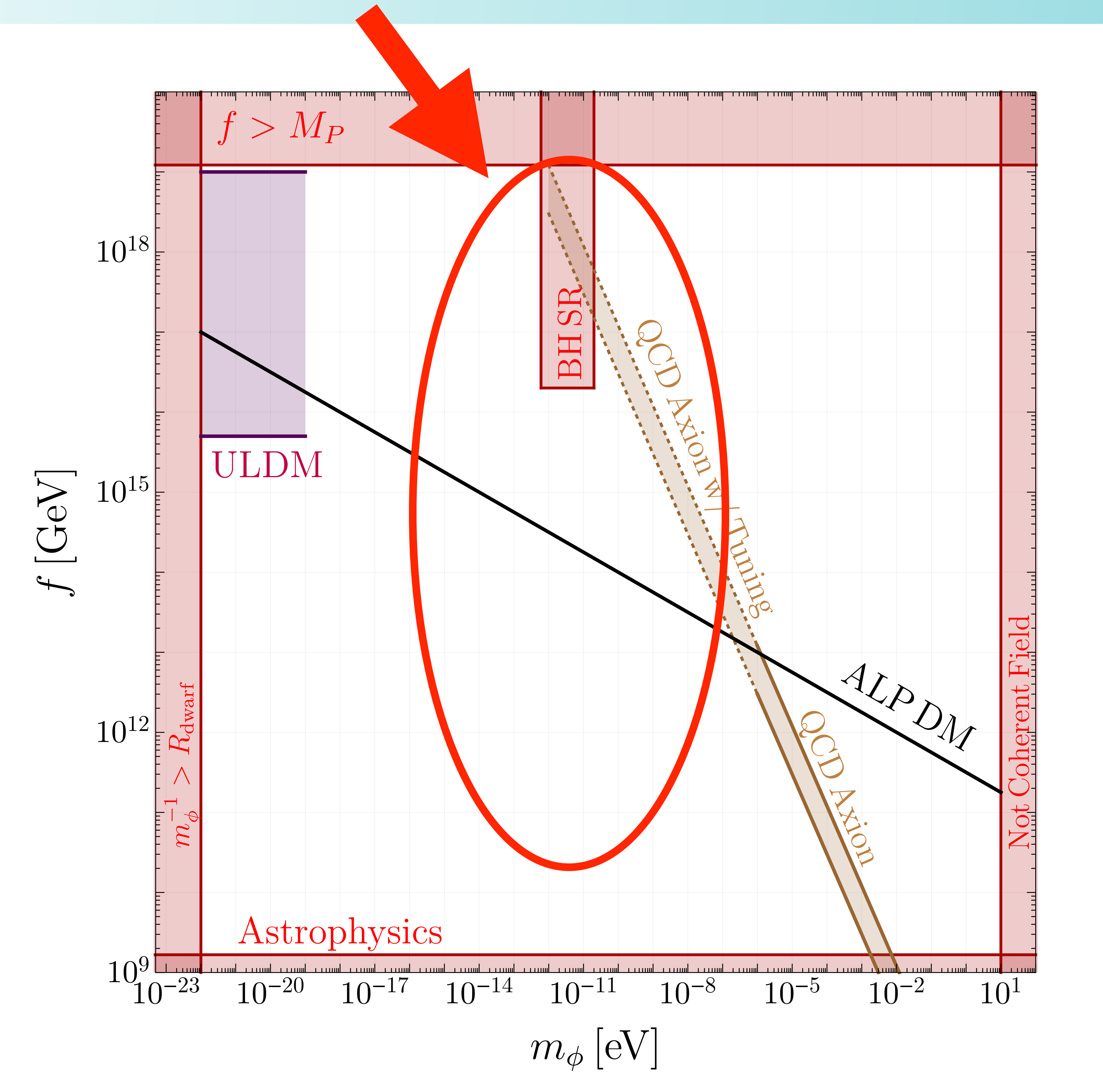


- Potential probe of LSDM in the range $10^{-21}\,{\rm eV} \lesssim m_\phi \lesssim 10^{-20}\,{\rm eV}$, again gravity only!

LSDM in Galaxies Summary

- ◉ Simulations predict the formation of a central soliton in galaxies when LSDM mass is $10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-20}\,\mathrm{eV}$
  - Soliton-Host Halo Relation tells us the (likely) properties of this soliton
  - Translates into kinematic constraint: Peak in rotational velocity not observed in large sample of SPARC galaxies! Constraint: $m_\phi \gtrsim 10^{-21}\,\mathrm{eV}$
  - Baryons do not seem to spoil the picture
- ◉ Quasiparticle fluctuations in the outer halos 'heat' stellar populations
  - Measured velocity dispersion of Milky Way Dwarf Spheroidal galaxies can potentially probe $10^{-21}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-20}\,\mathrm{eV}$

Substructure in our Solar System



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

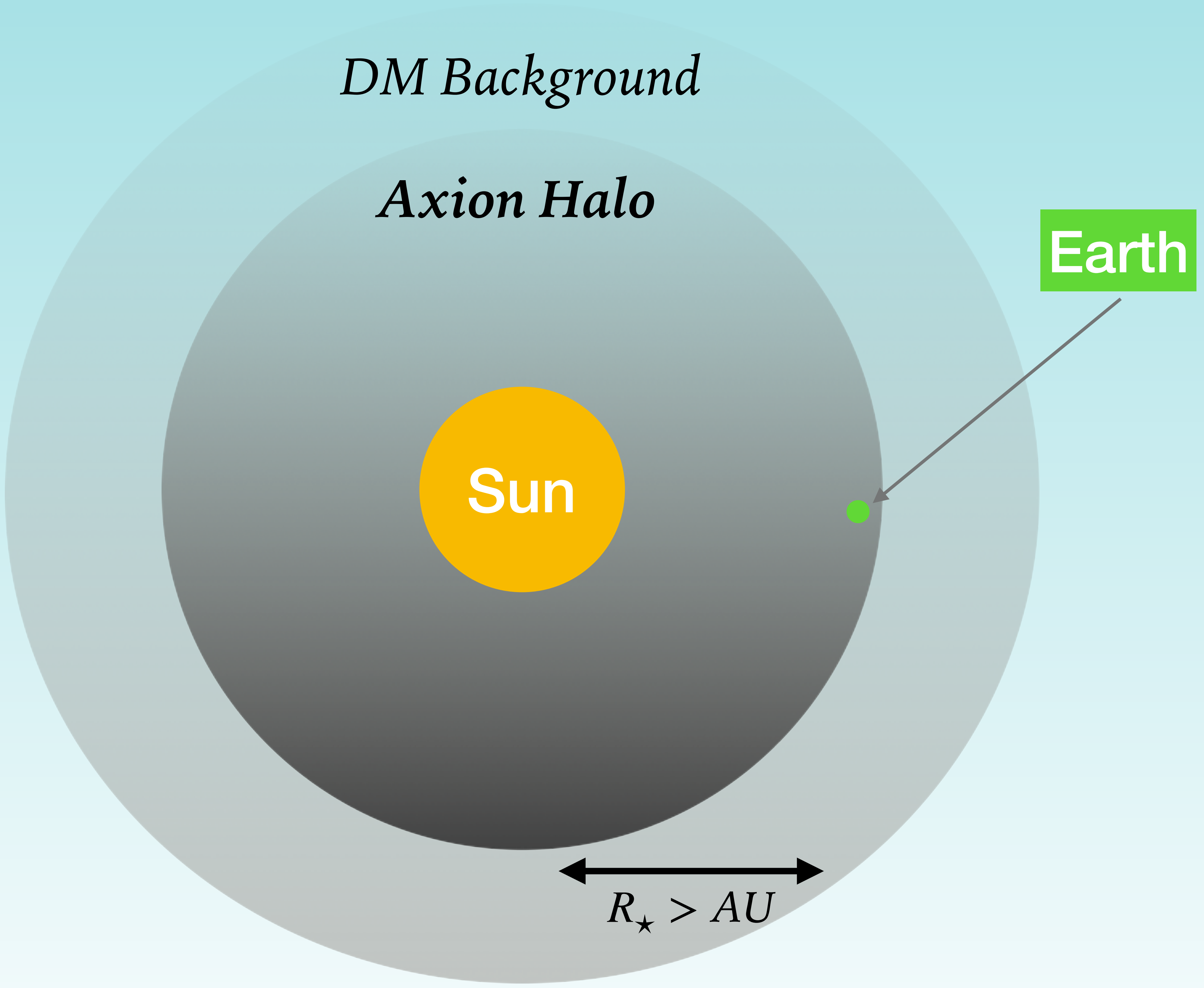
Banerjee, Budker, Flambaum, JE, Kim, Matsedonskyi, Perez (1912.04295)

Recall the Picture:

Halo supported by Sun
"Solar Halo"

$$R_\star \approx \frac{M_P^2}{m_\phi^2 M_{ext}}$$

Halo supported by Earth
"Earth Halo"



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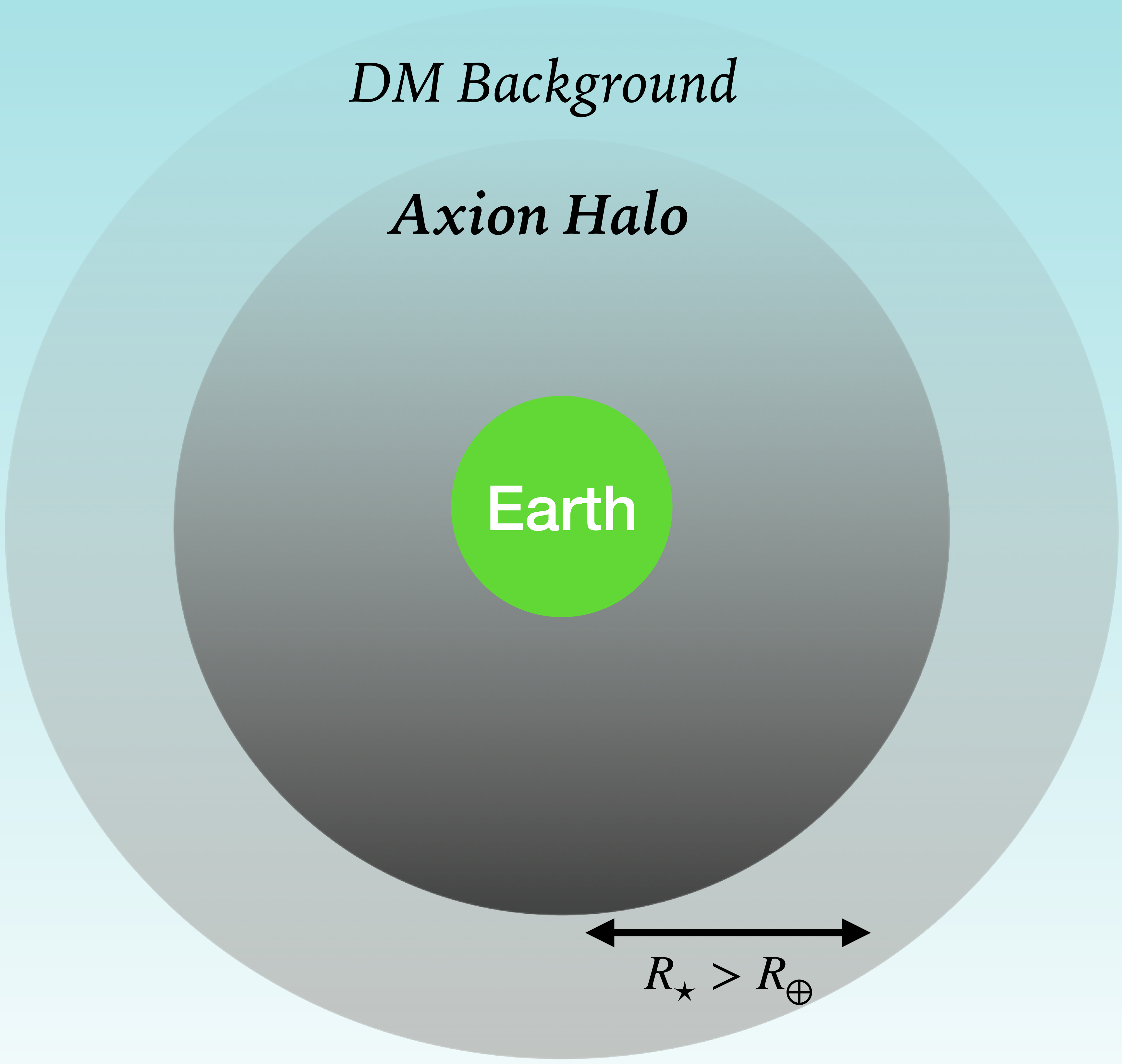
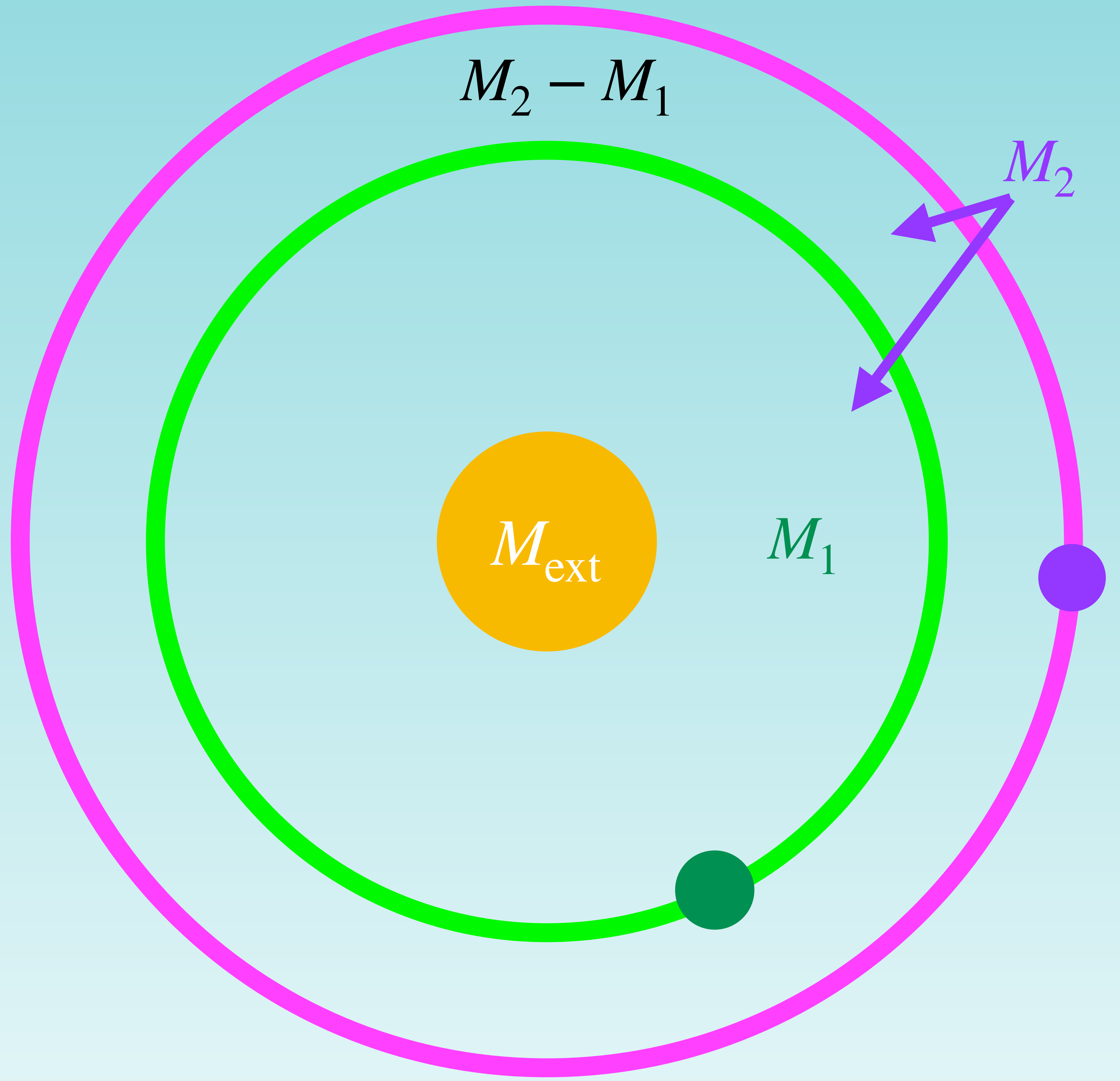


$$m_\phi = 10^{-13} \div 10^{-8}\, eV$$
$$\sim 10\, Hz \div \, MHz$$

Constraints on "Extra" Local DM?



Inner orbit "measures" $M_1 + M_{\rm ext}$

Outer orbit "measures" $M_2 + M_{\rm ext}$

Comparison of the two "measures" $M_2 - M_1$, the "extra" mass contained between the orbits

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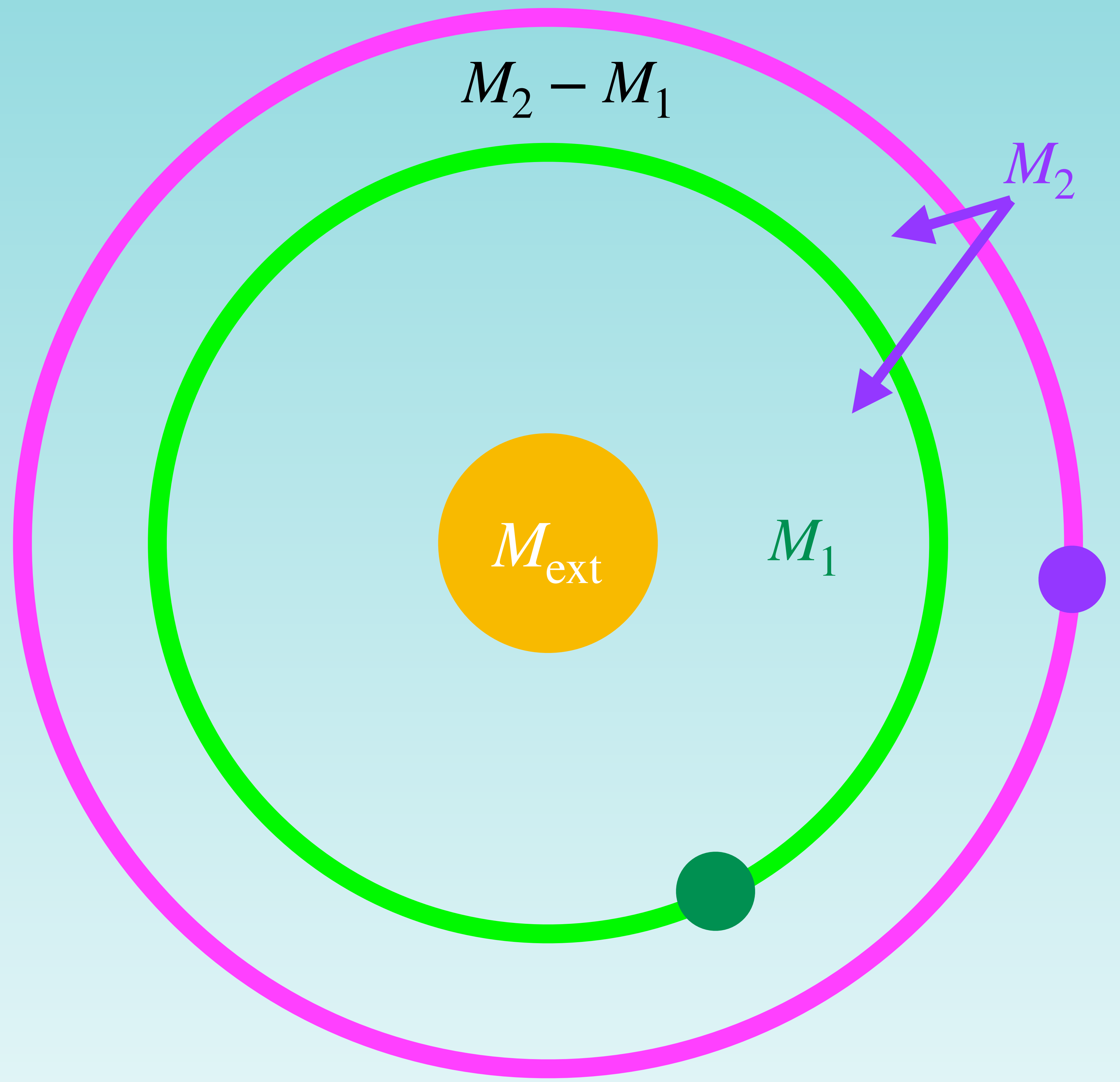

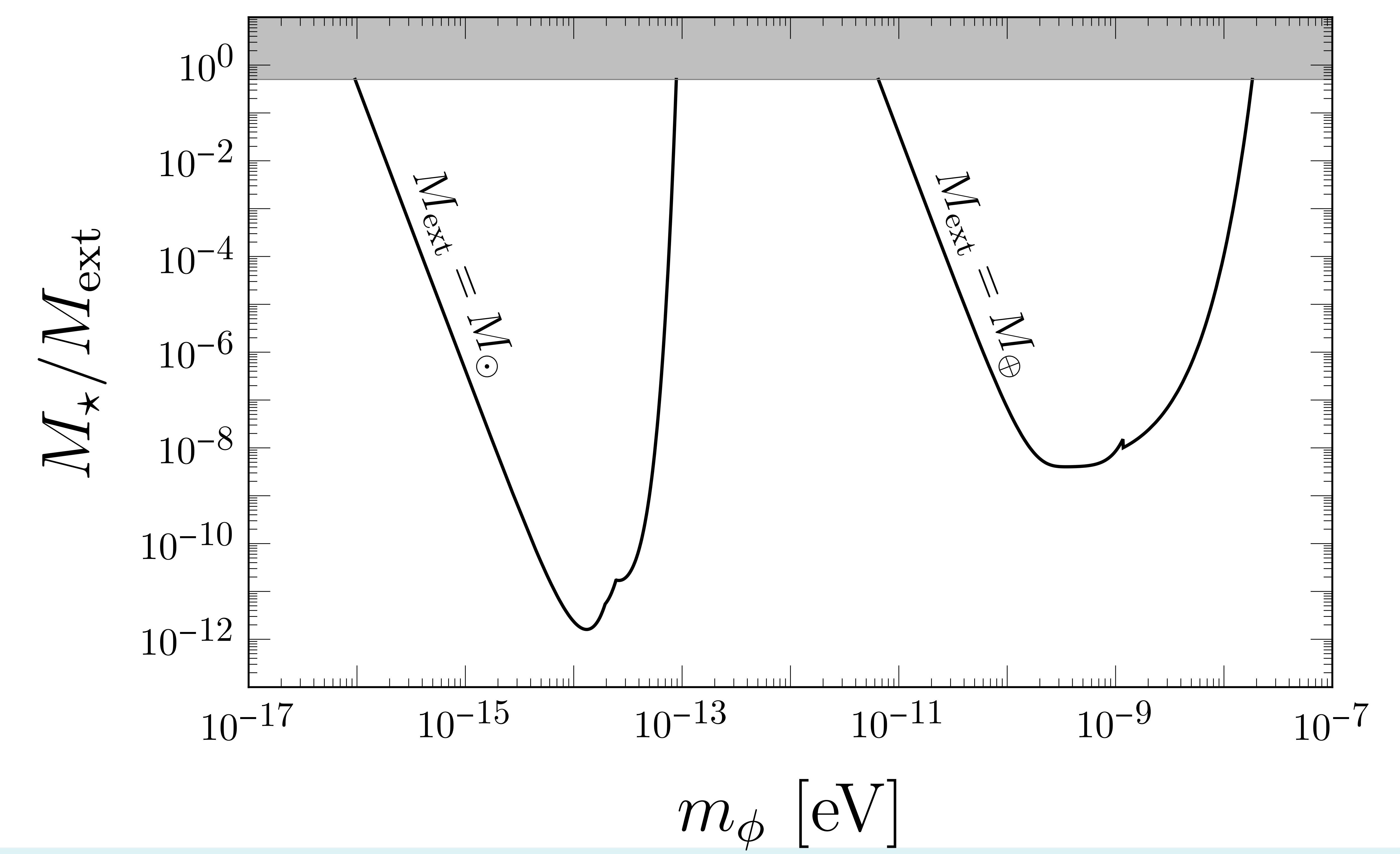

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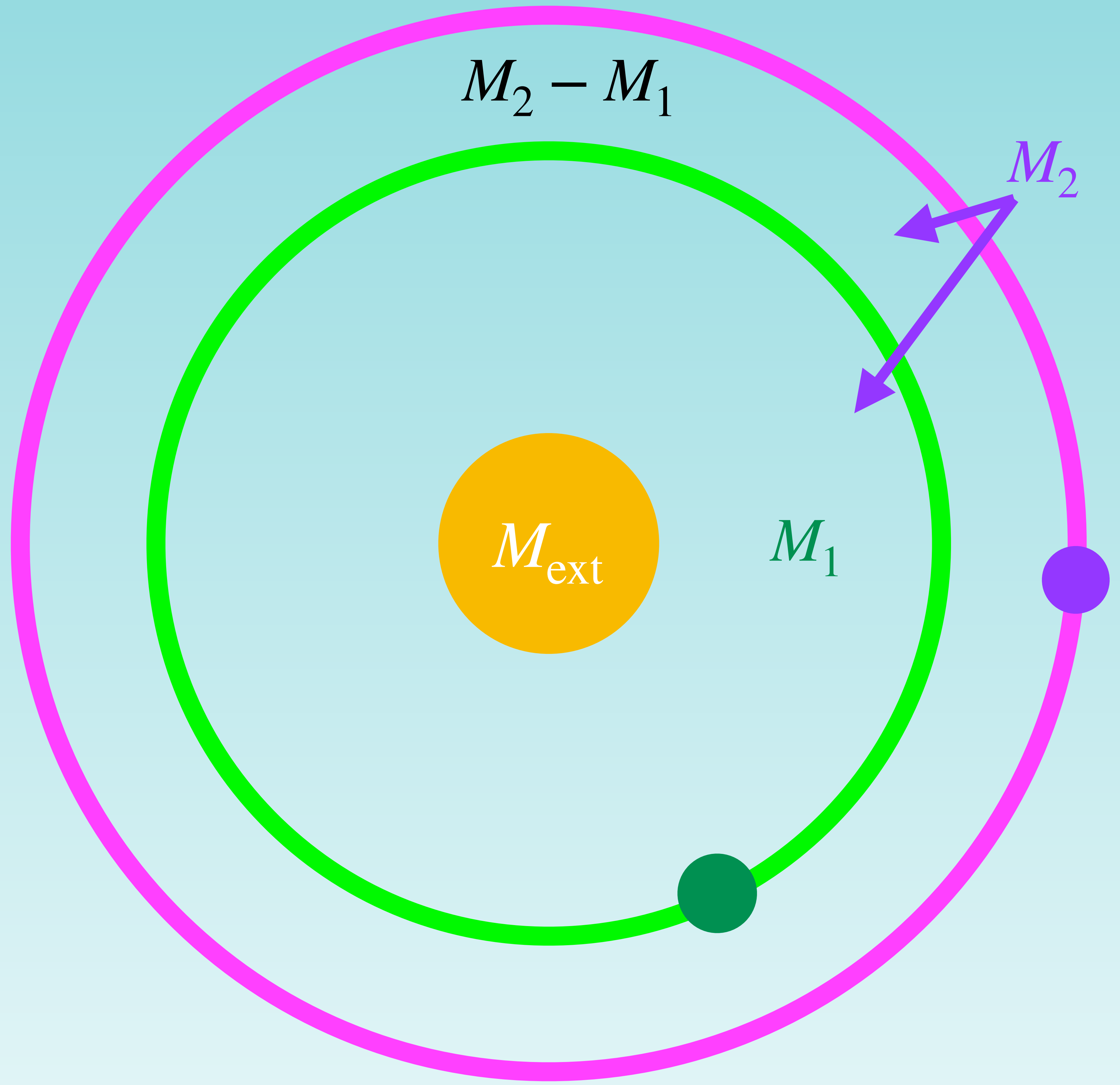

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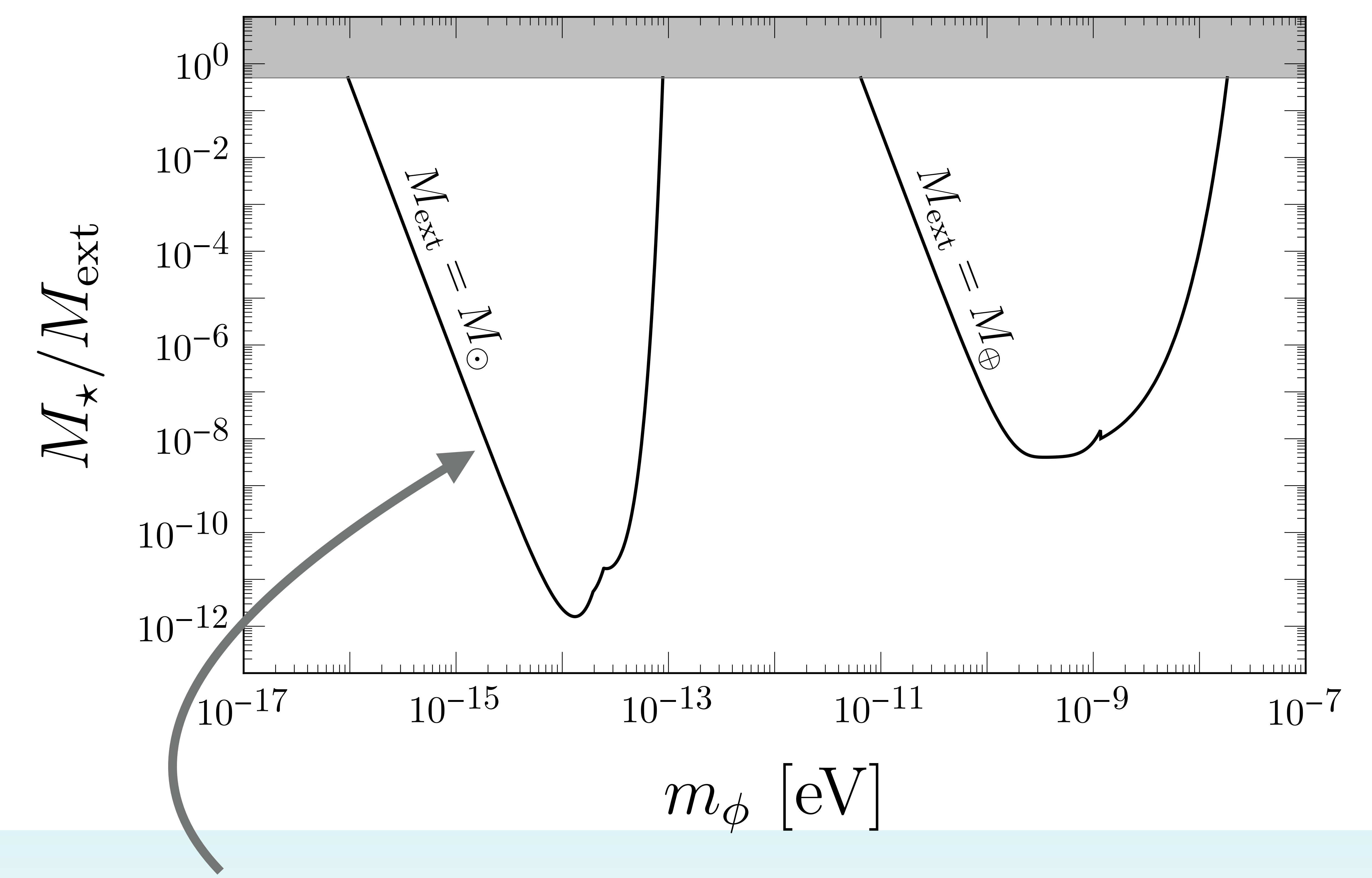

Solar System Ephemerides (Mercury, Mars, Saturn)

Pitjev and Pitjeva (1306.5534)

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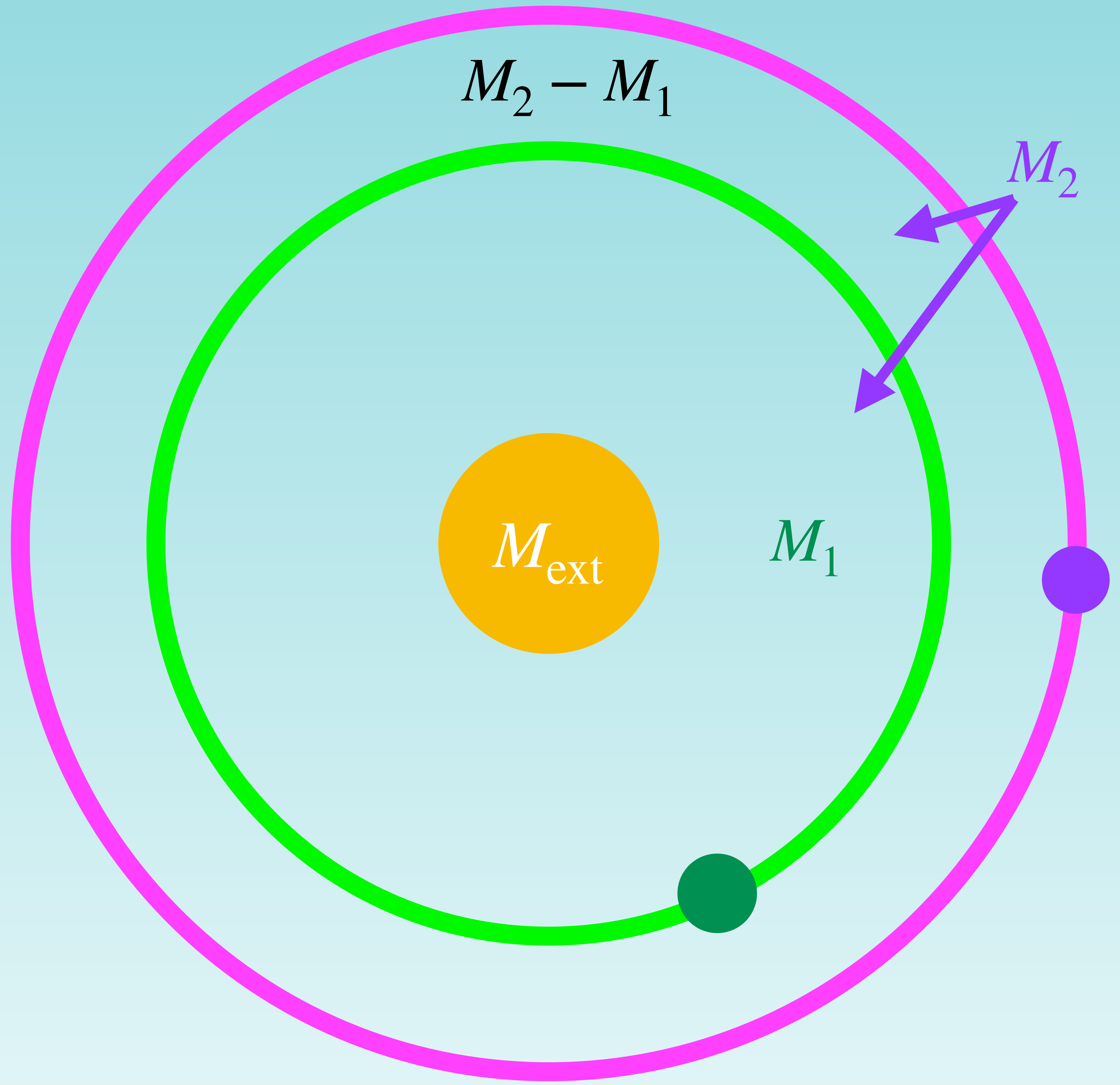

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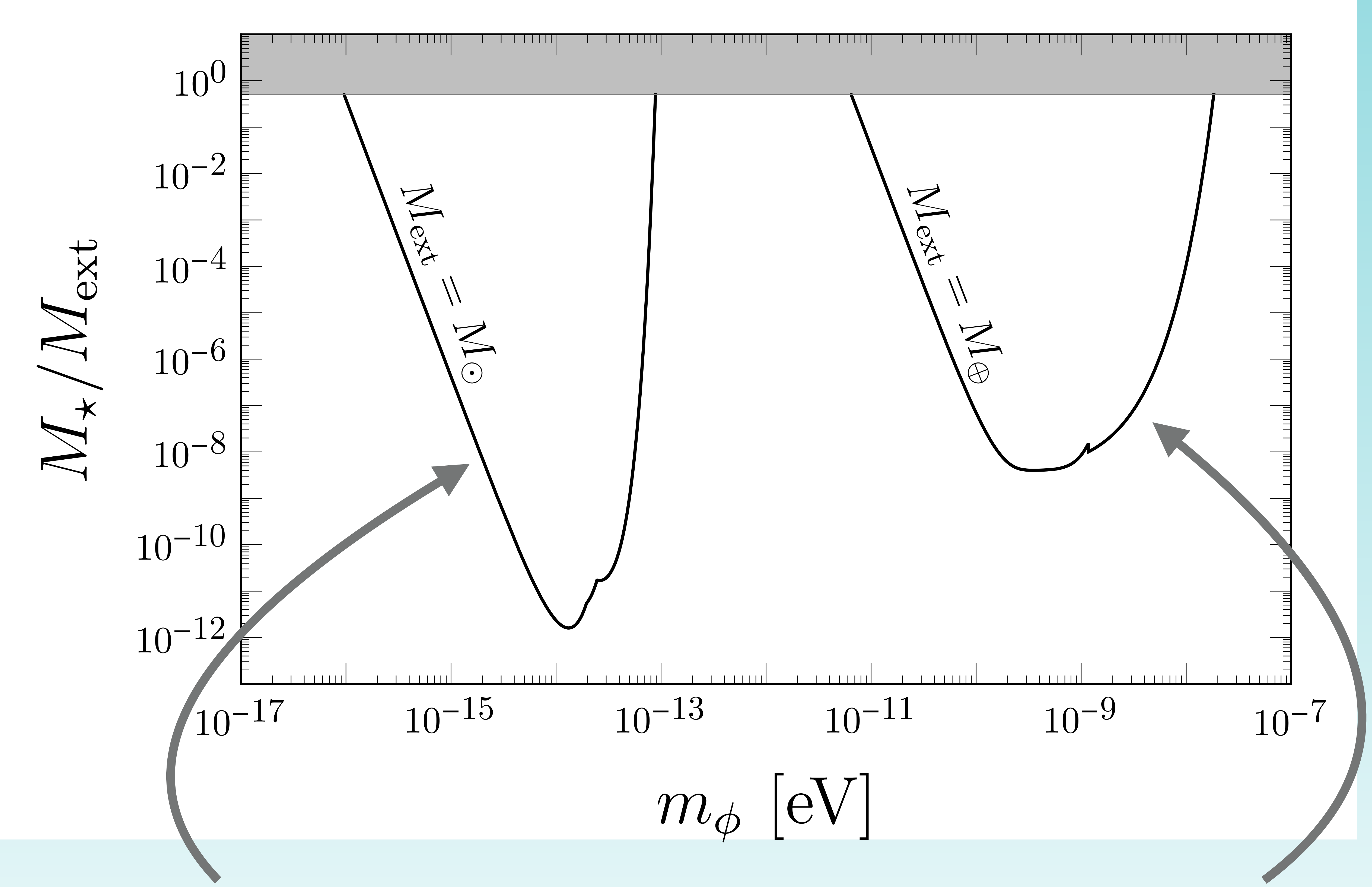


Solar System Ephemerides (Mercury, Mars, Saturn)

Pitjev and Pitjeva (1306.5534)

Lunar Laser Ranging + LAGEOS Satellite

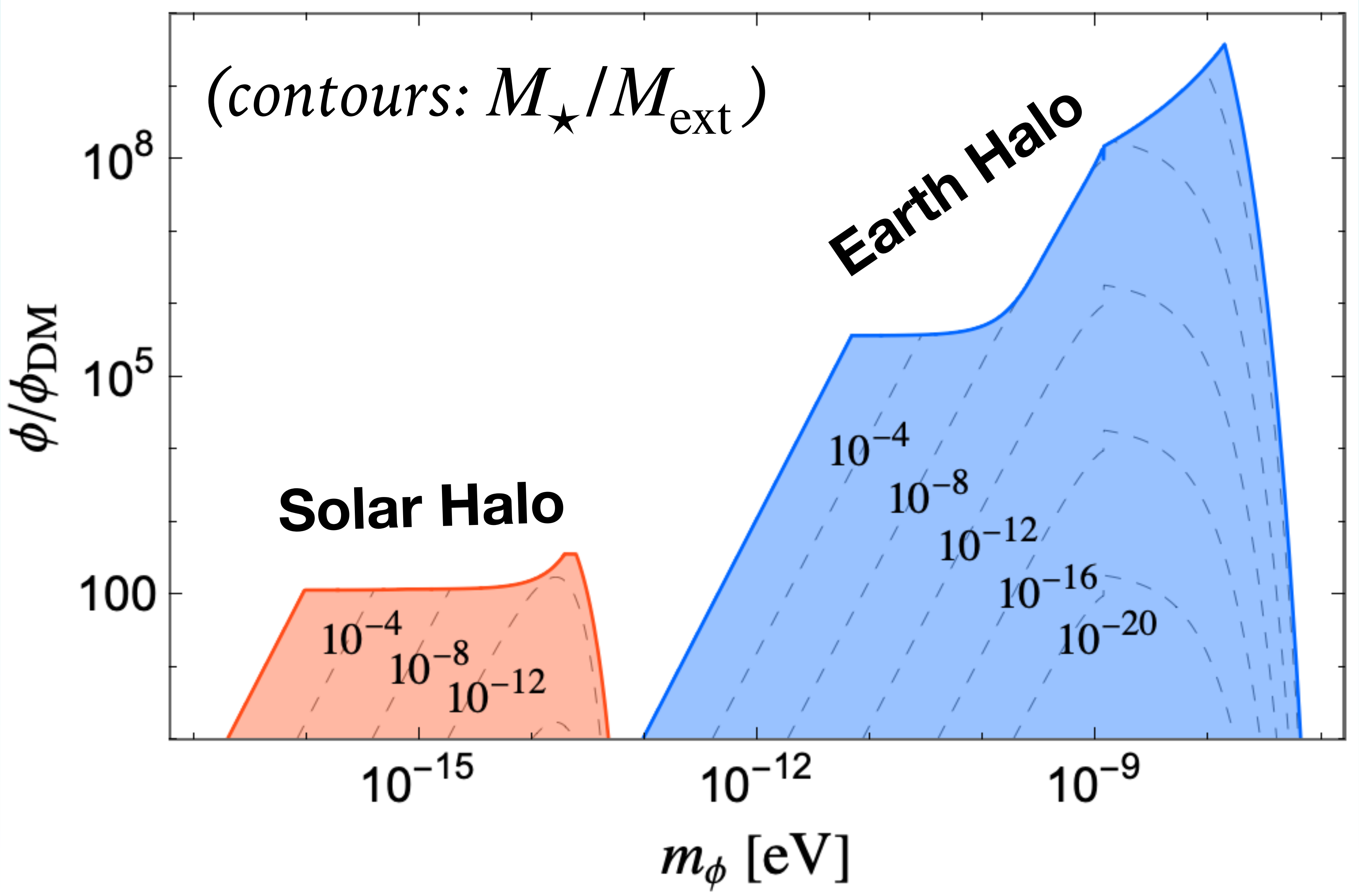
Adler (0808.0899)

Effects on Experimental Sensitivity

1. **Increased density**:

   Experimental signals $\propto \phi$

   Can be many orders of magnitude above “naive” local DM density



Effects on Experimental Sensitivity

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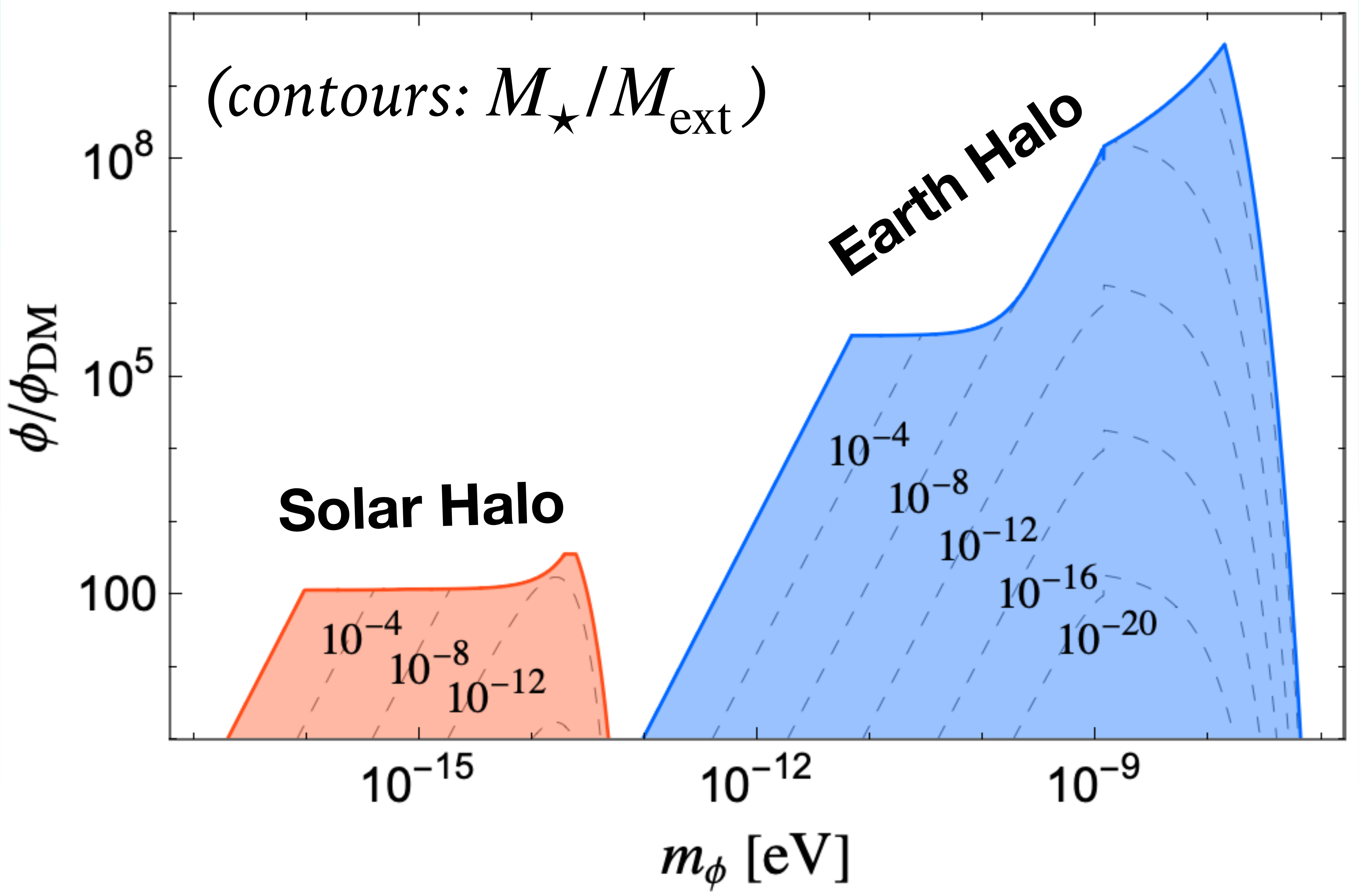
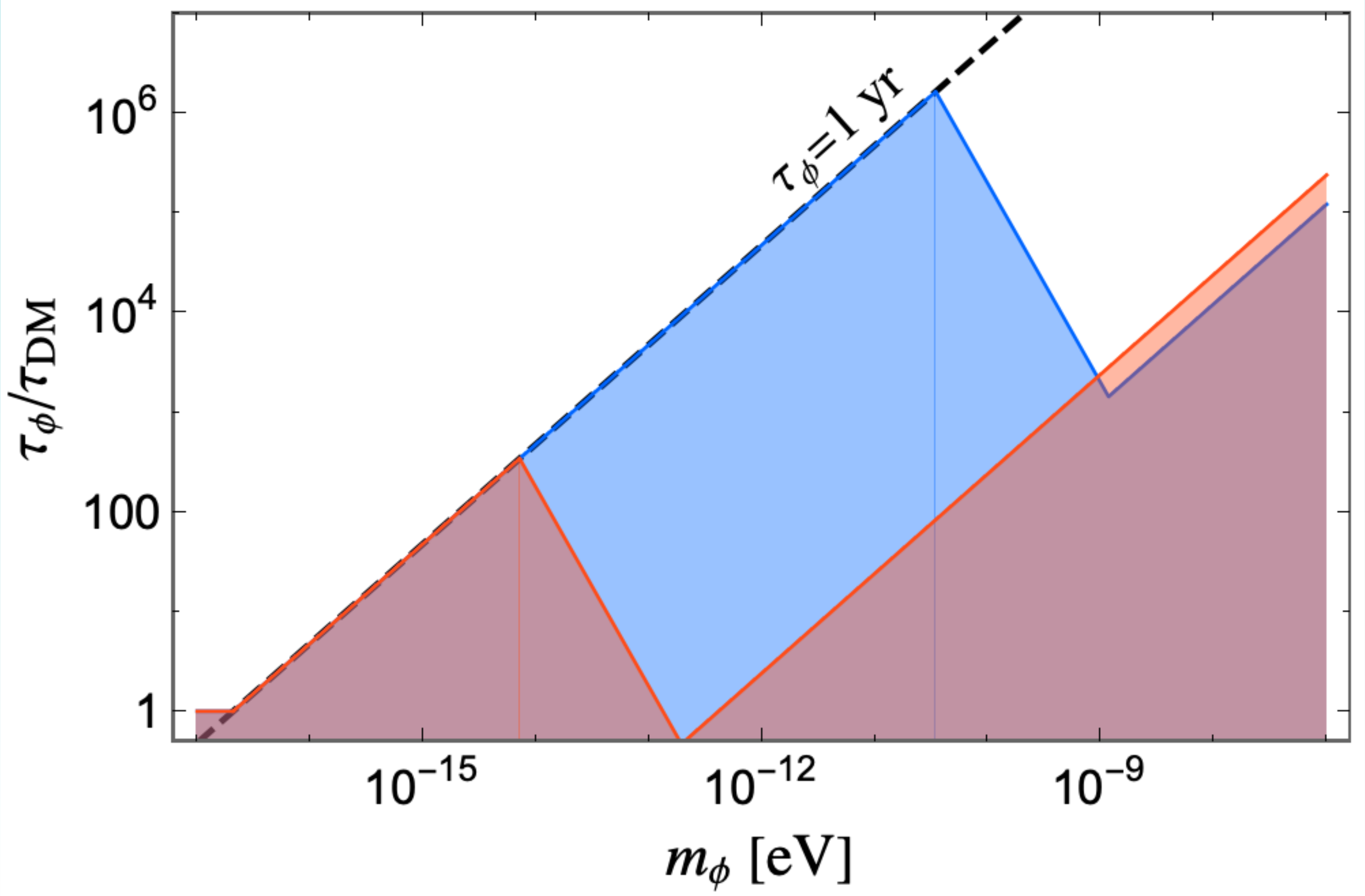
2. **Long timescale for coherent oscillation**

$$\tau_\phi \gtrsim 10^3\,\mathrm{sec}\left(\frac{10^{-9}\,\mathrm{eV}}{m_\phi}\right)^3 \quad \text{(Earth halo)}$$

$$\tau_\phi \gtrsim 10^{10}\,\mathrm{sec}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)^3 \quad \text{(Solar halo)}$$





Example: CASPEr Electric

- Based in Boston University
- Search for axion coupling

$$\mathscr{L} \supset \frac{i\, g_d}{2} \phi\, \bar{N}\, \sigma_{\mu\nu} \gamma_5\, N\, F^{\mu\nu}$$

- Induces oscillating atomic EDM signal

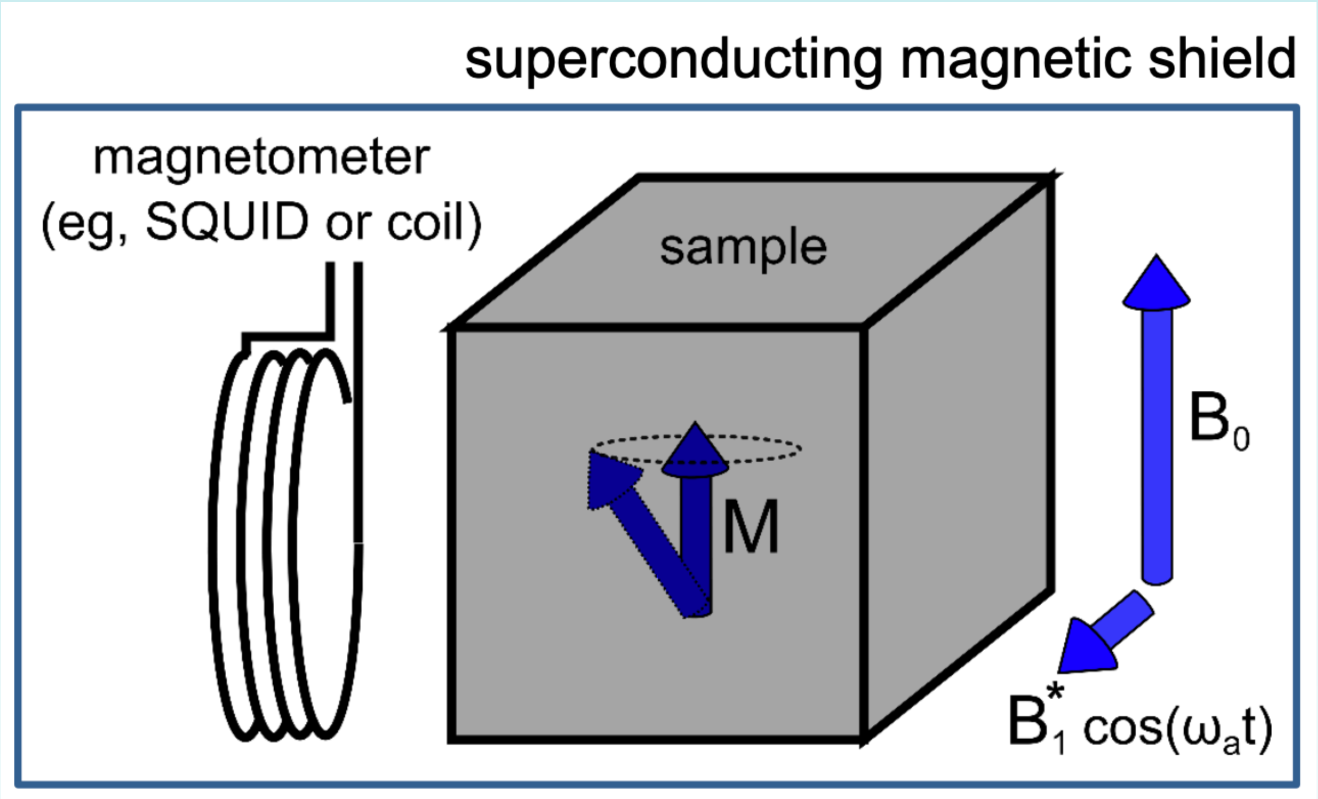
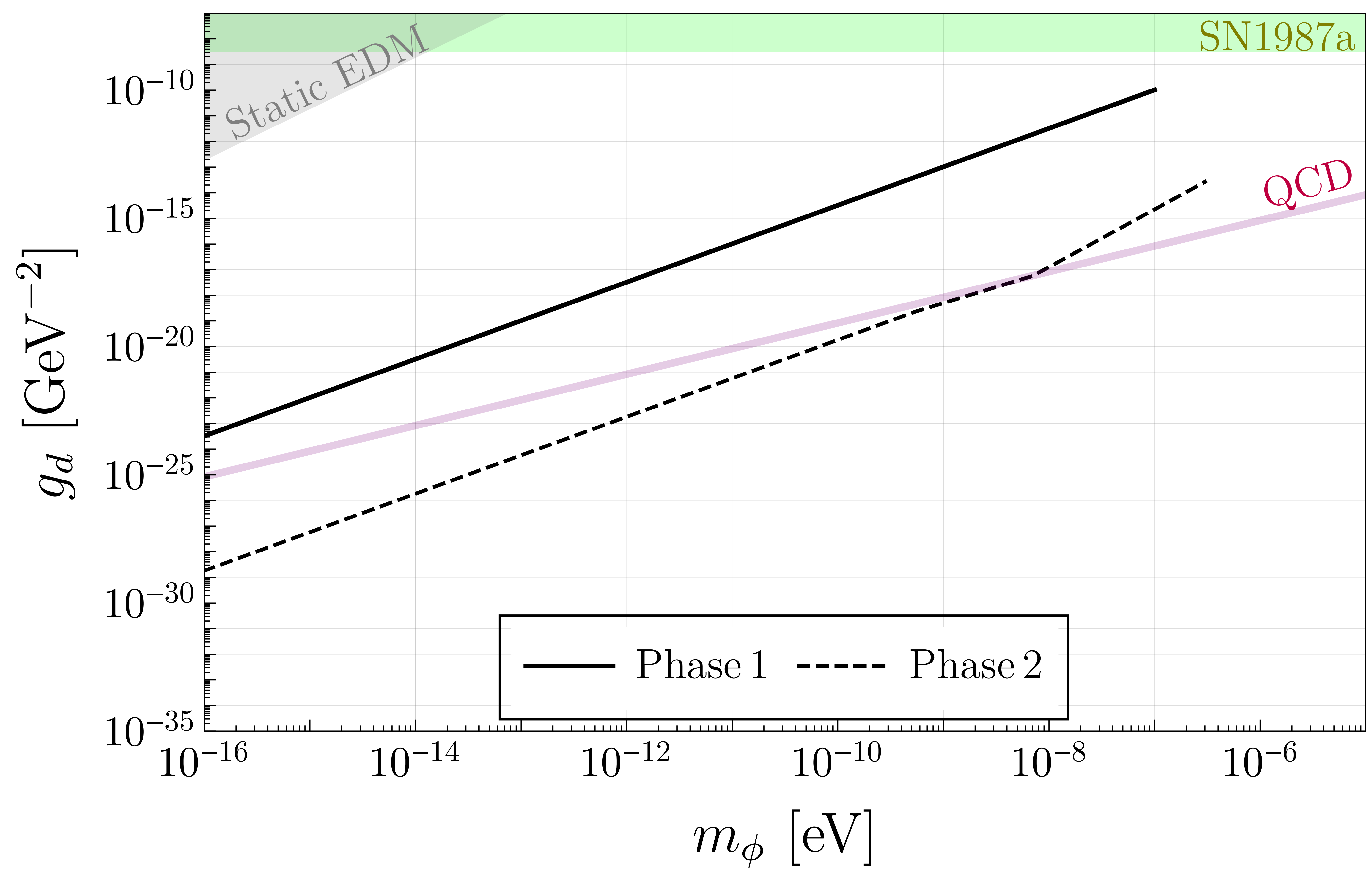


Figure from Alex Sushkov of Boston University



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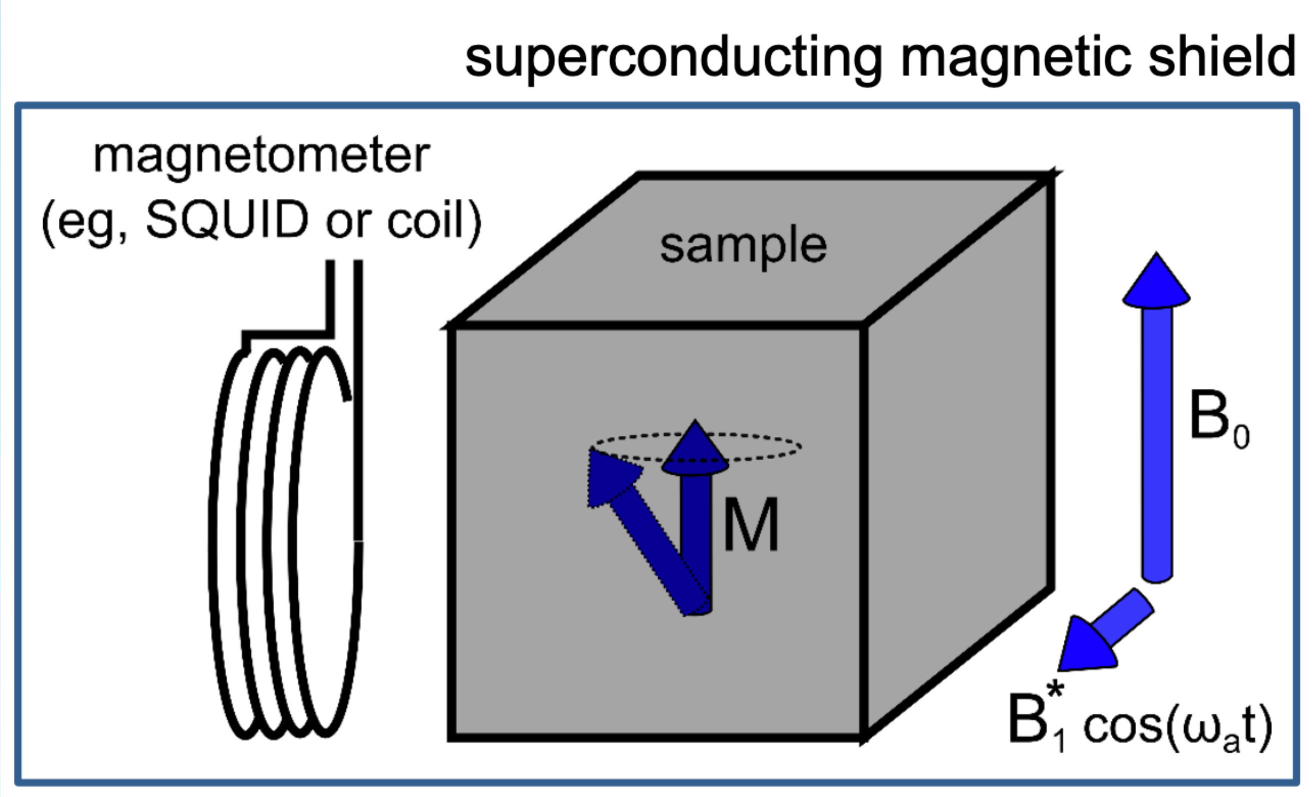

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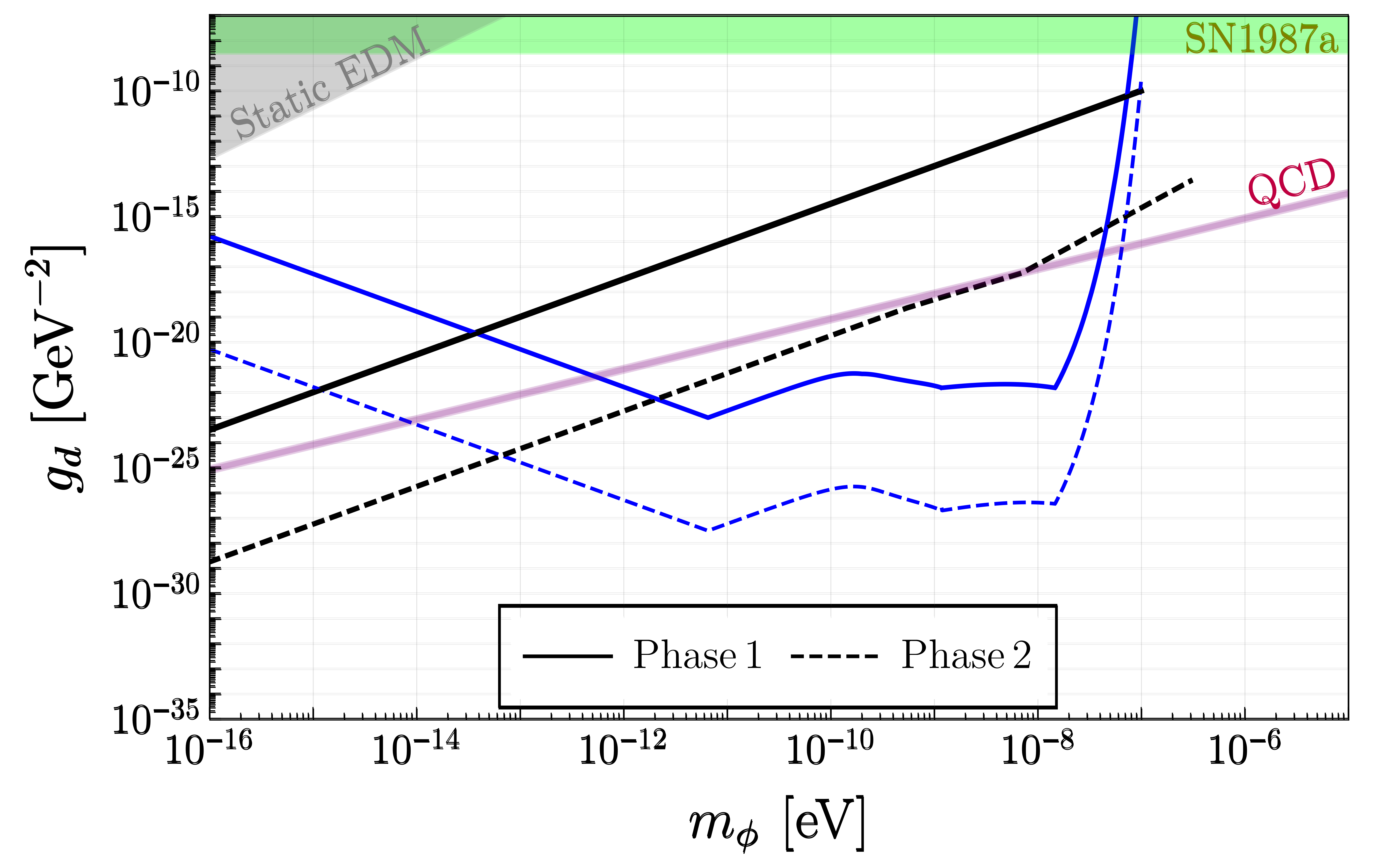

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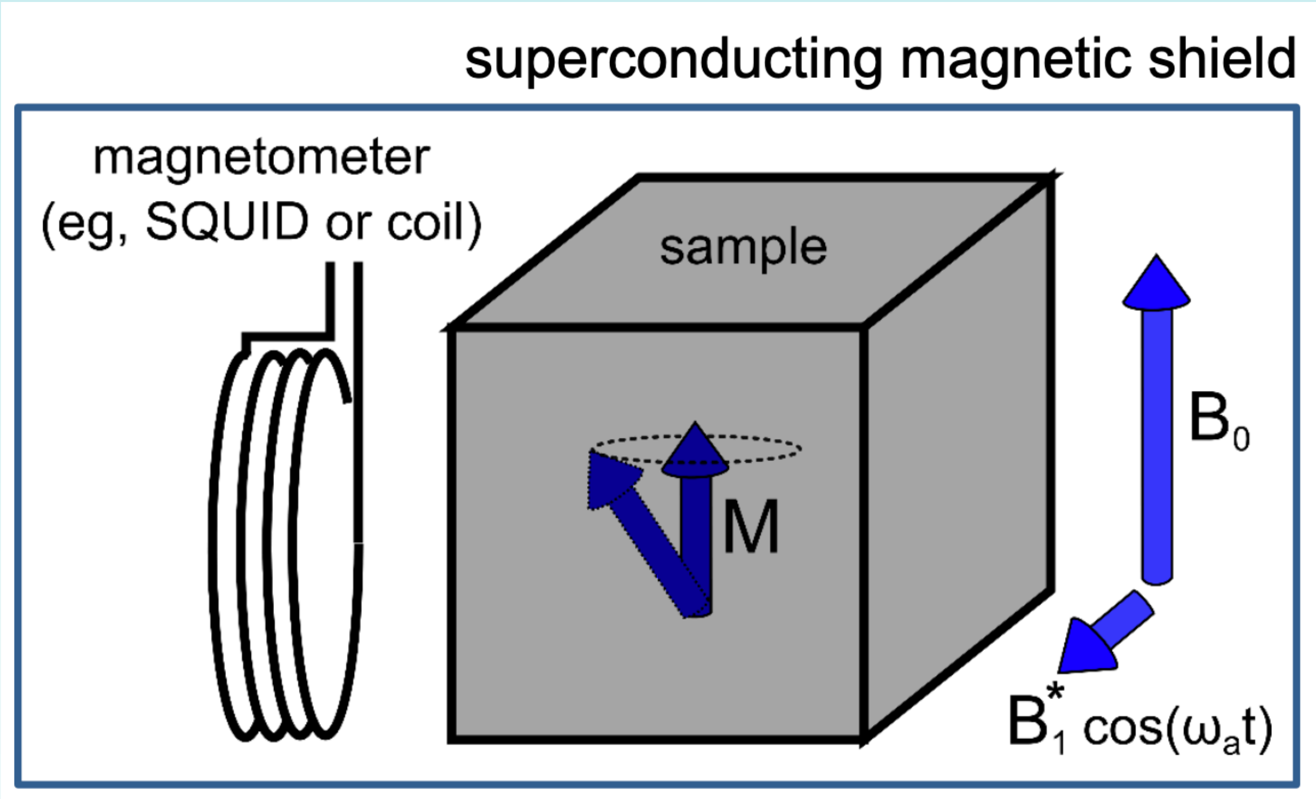

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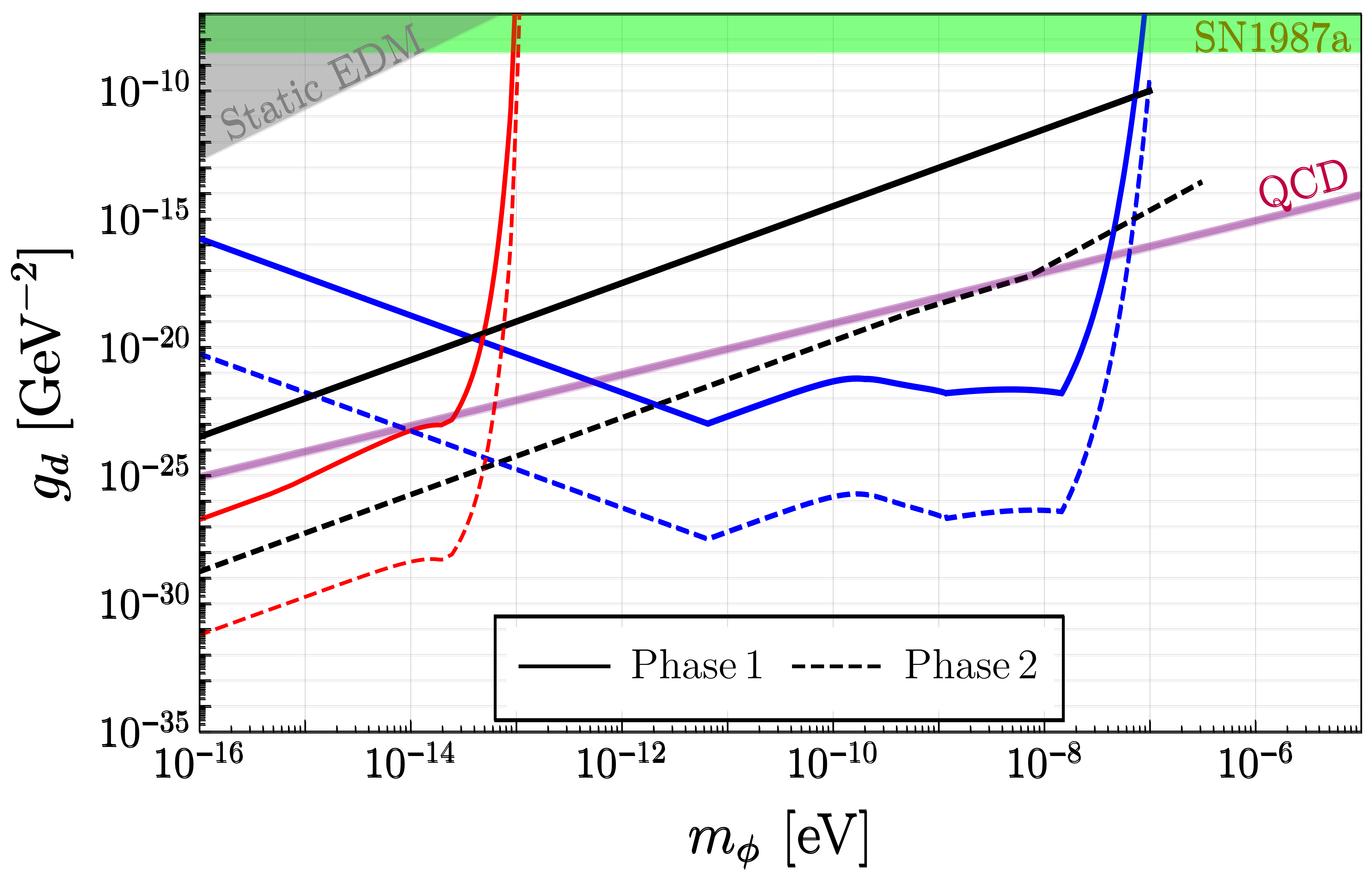


Effects on Experimental Sensitivity (2)

3. **Modified velocity dispersion**:

   Some experimental signals $\propto \nabla\phi$

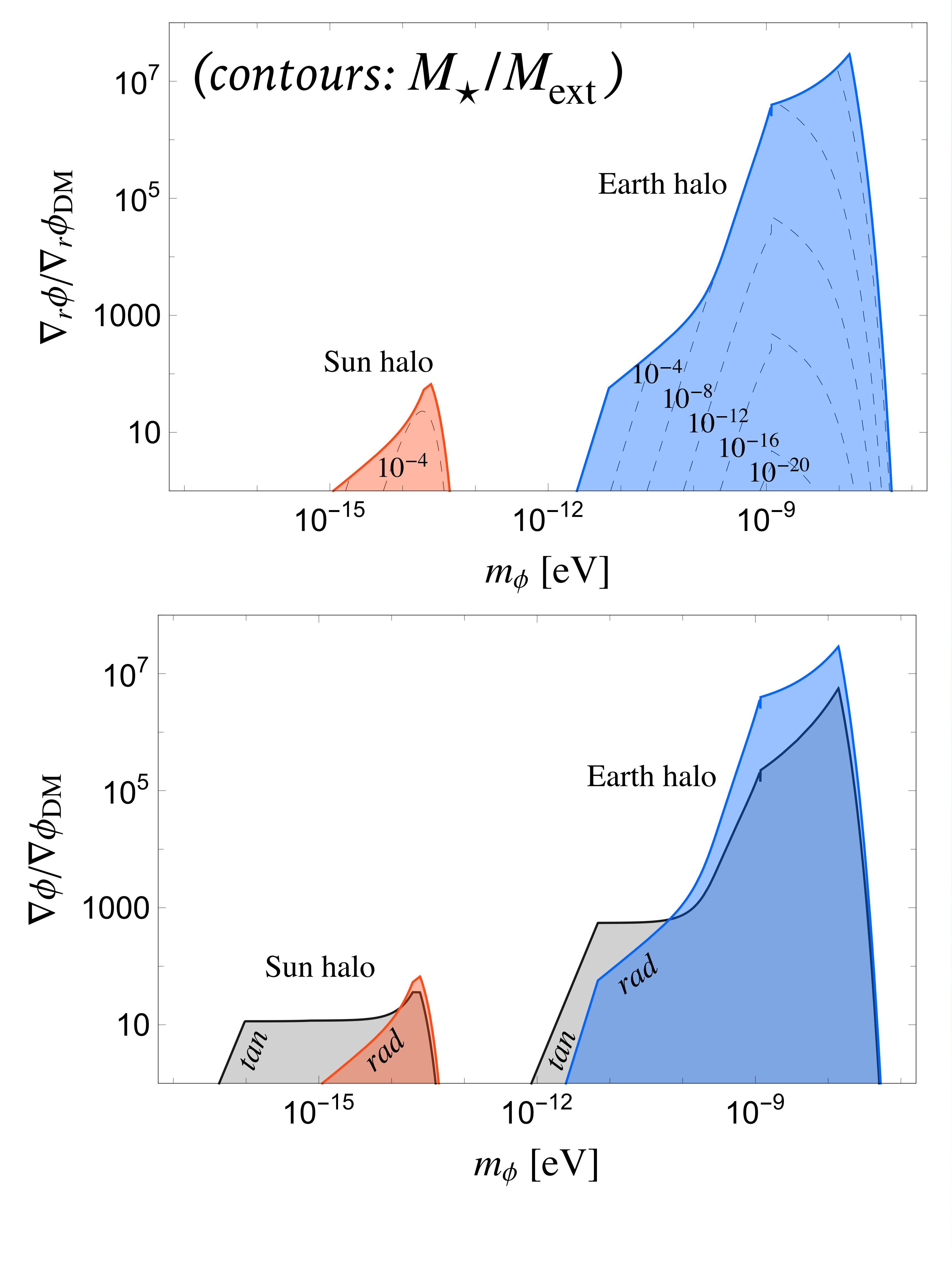
   (e.g. CASPEr-Wind, GNOME, …)

- Two components:
  - Wavefunction is hydrogen-like, $\phi(r) \propto \exp(-r/R_\star)$

    $$\Rightarrow \nabla_{\rm rad}\phi \propto \frac{1}{R_\star}, \text{“radial gradient”}$$

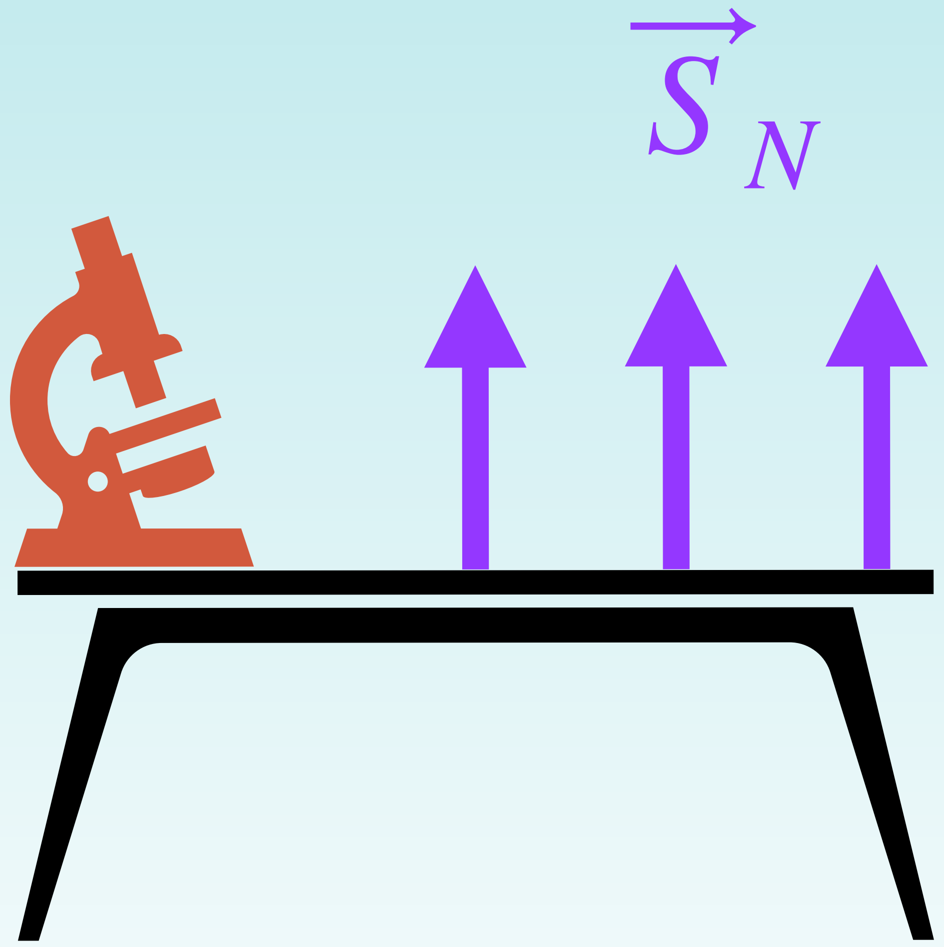
  - Experiment, on Earth, moves *through* axion halo

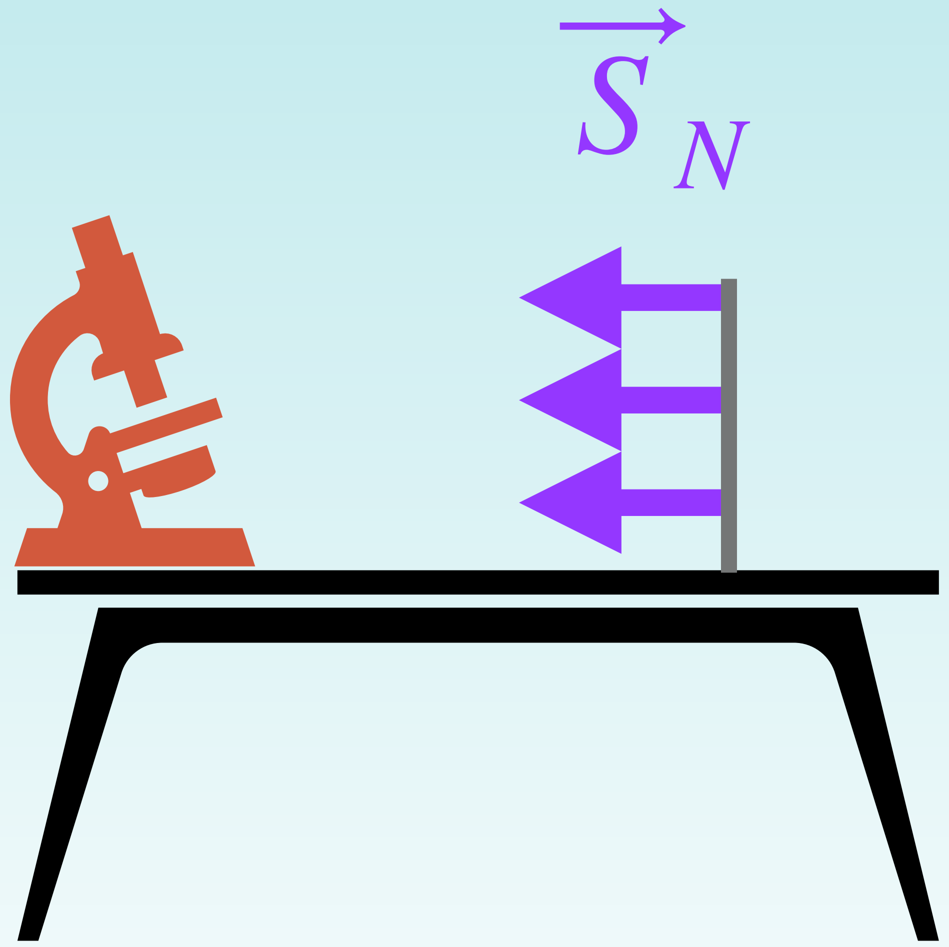
    $$\Rightarrow \nabla_{\rm tan}\phi \propto v_{\rm rel}, \text{“tangential gradient”}$$

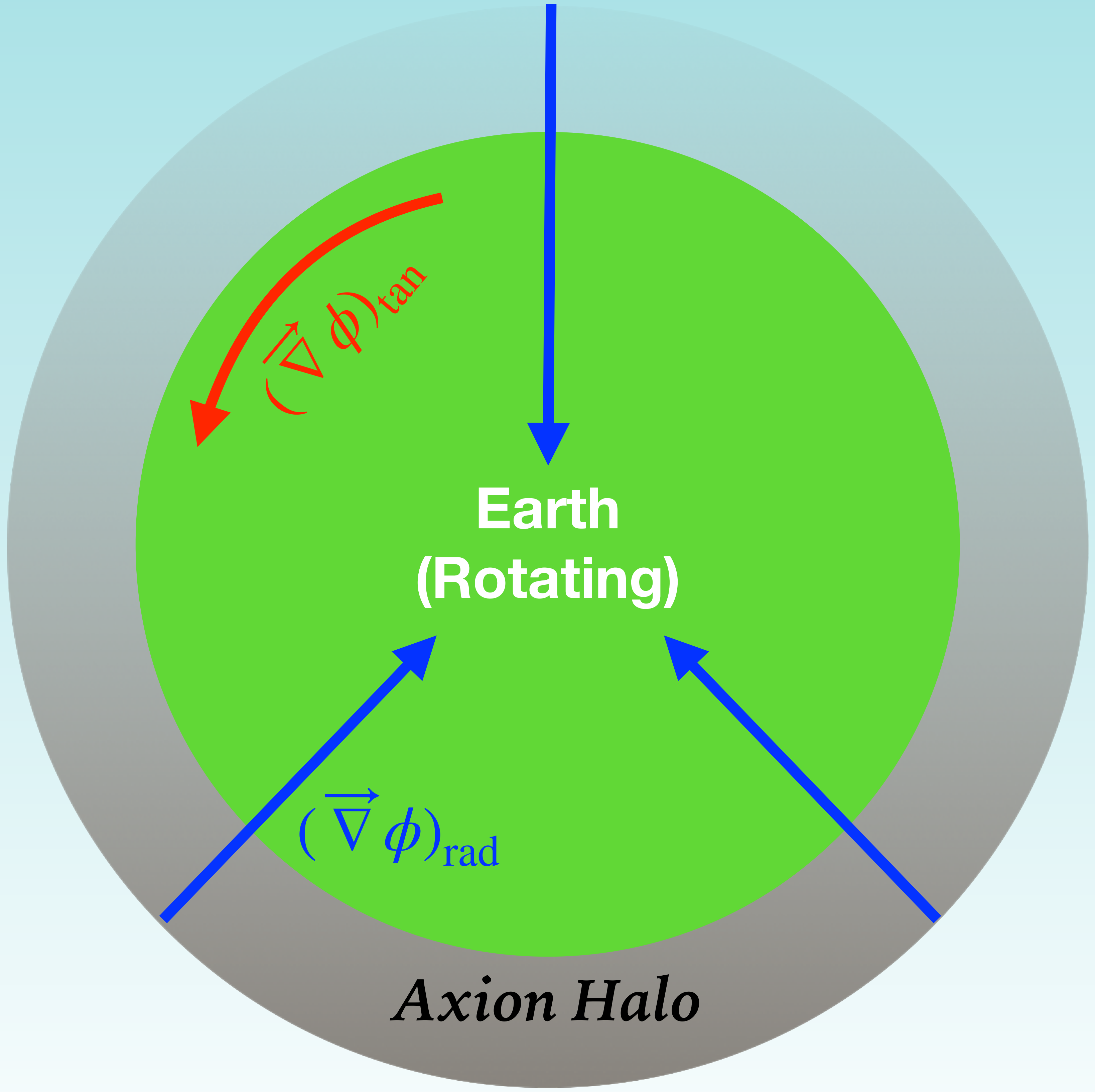


The Effect of the Gradient

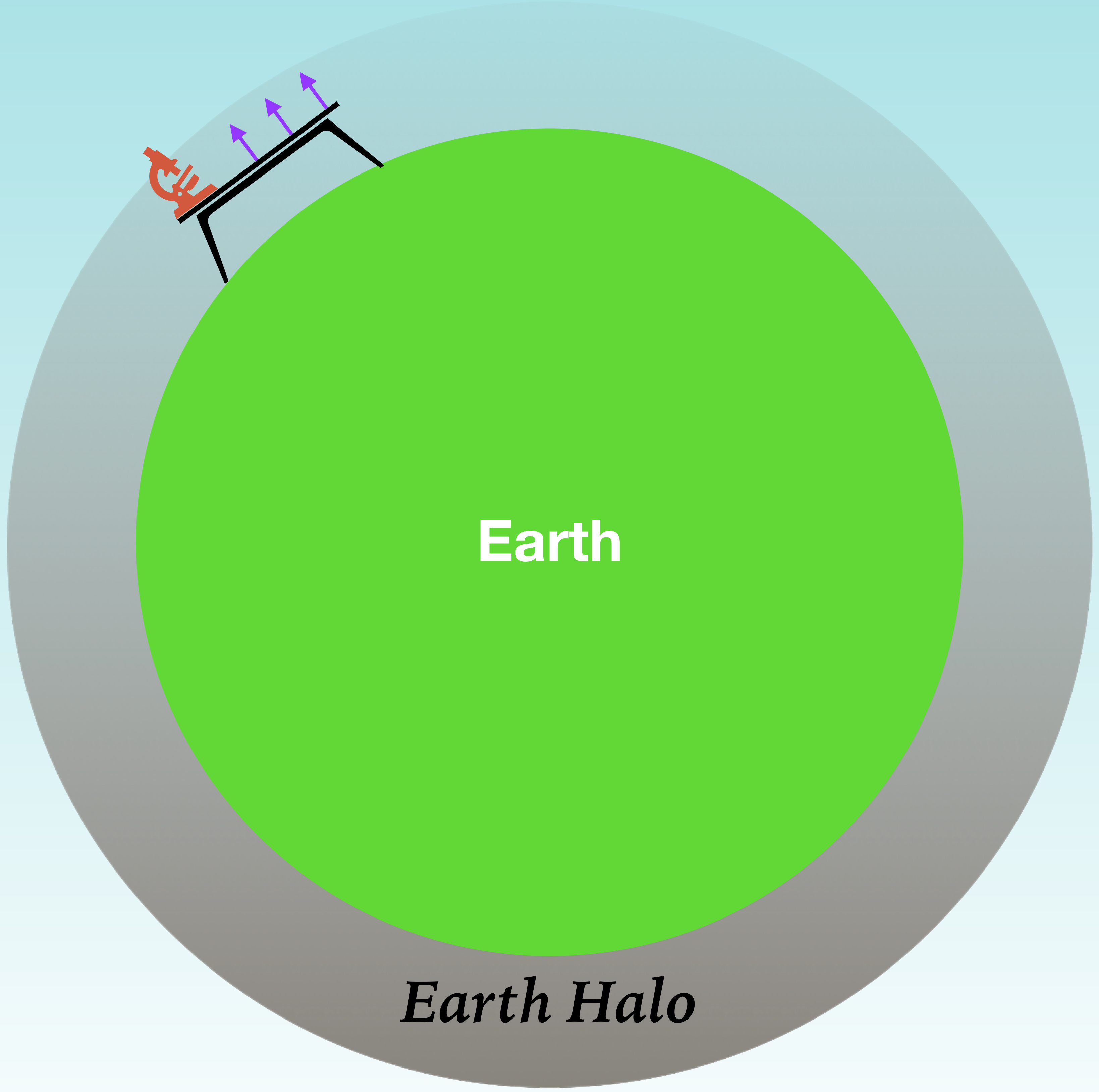
- Nuclear Magnetic Resonance often used to search for pseudoscalar LSDM couplings, e.g. in CASPEr-Wind experiment
- Signal is $\propto (\vec{\nabla}\phi) \times \vec{S}_N$





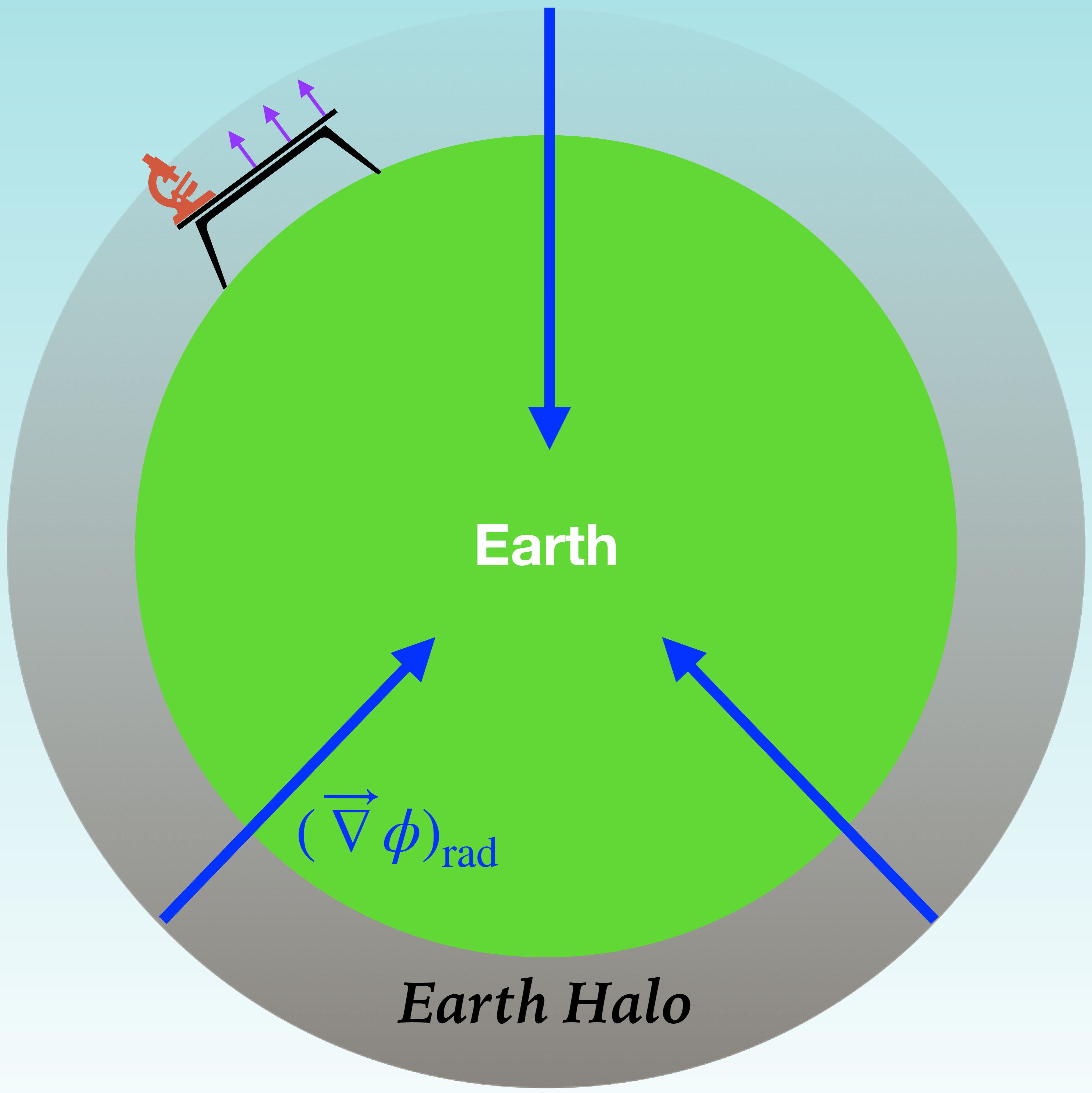


Orientation and DM Wind



Orientation and DM Wind

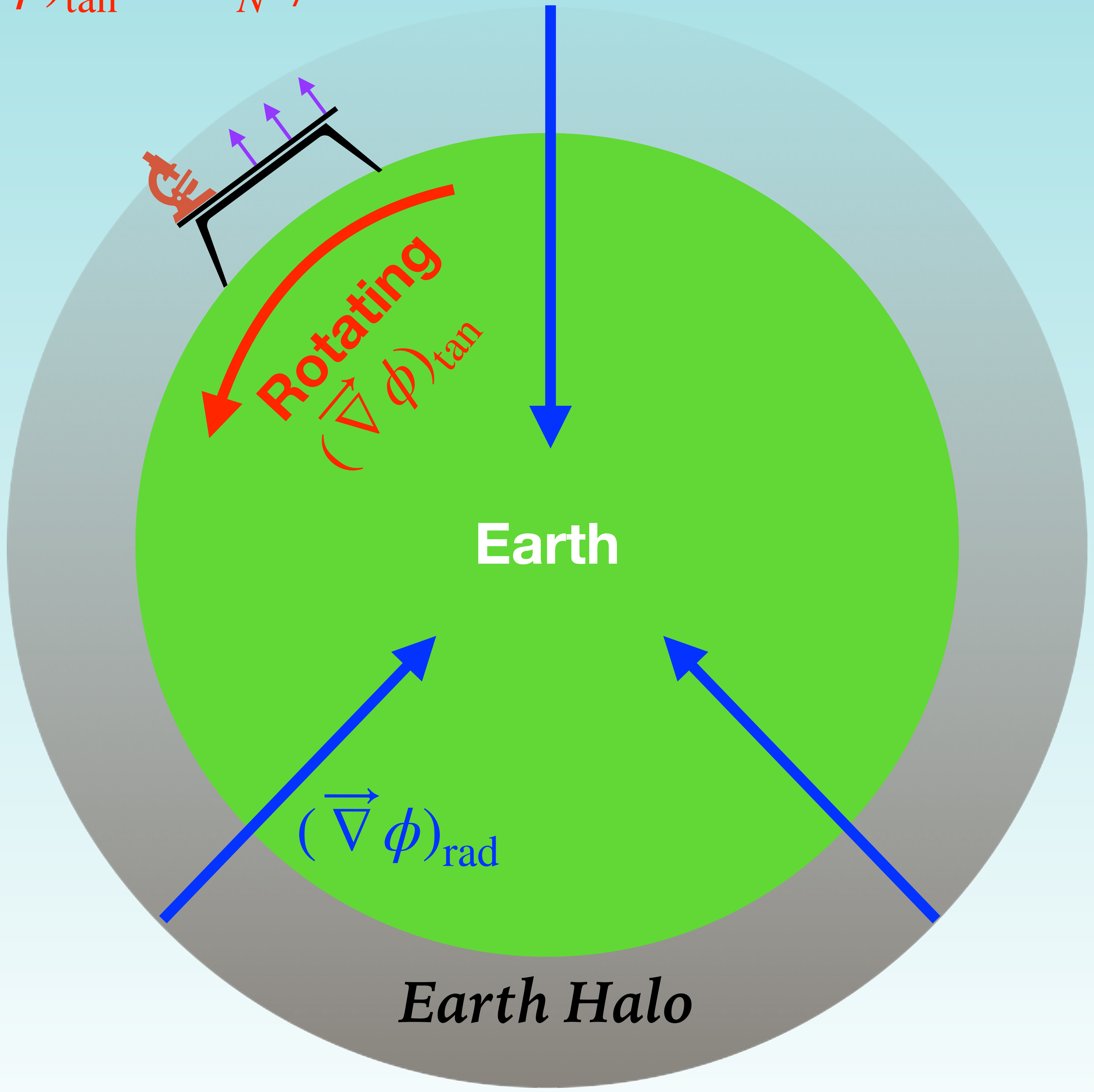
$(\vec{\nabla}\phi)_{\rm rad} \times \vec{S}_N \to 0$



Orientation and DM Wind

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

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



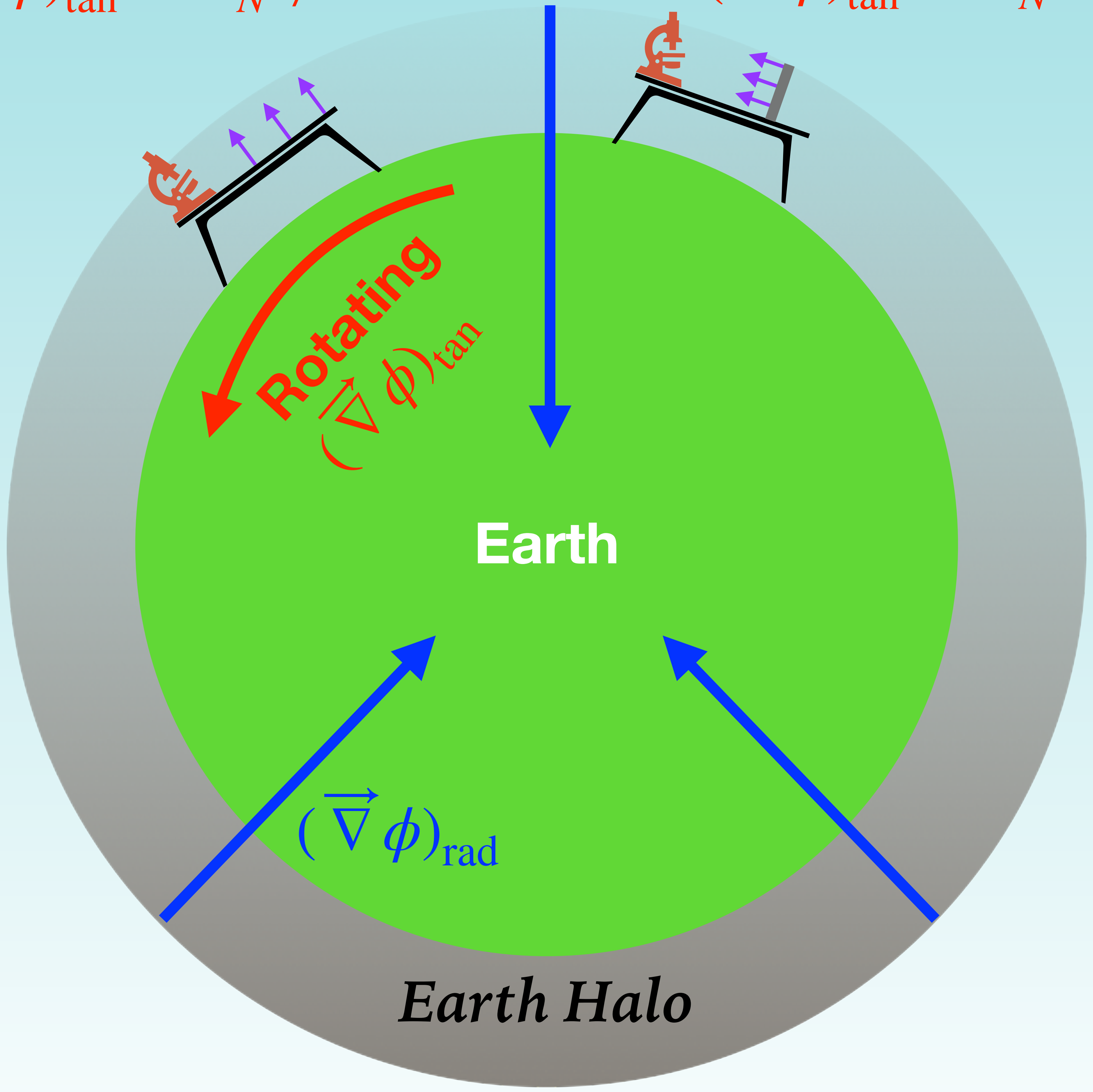
Orientation and DM Wind

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

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

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

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



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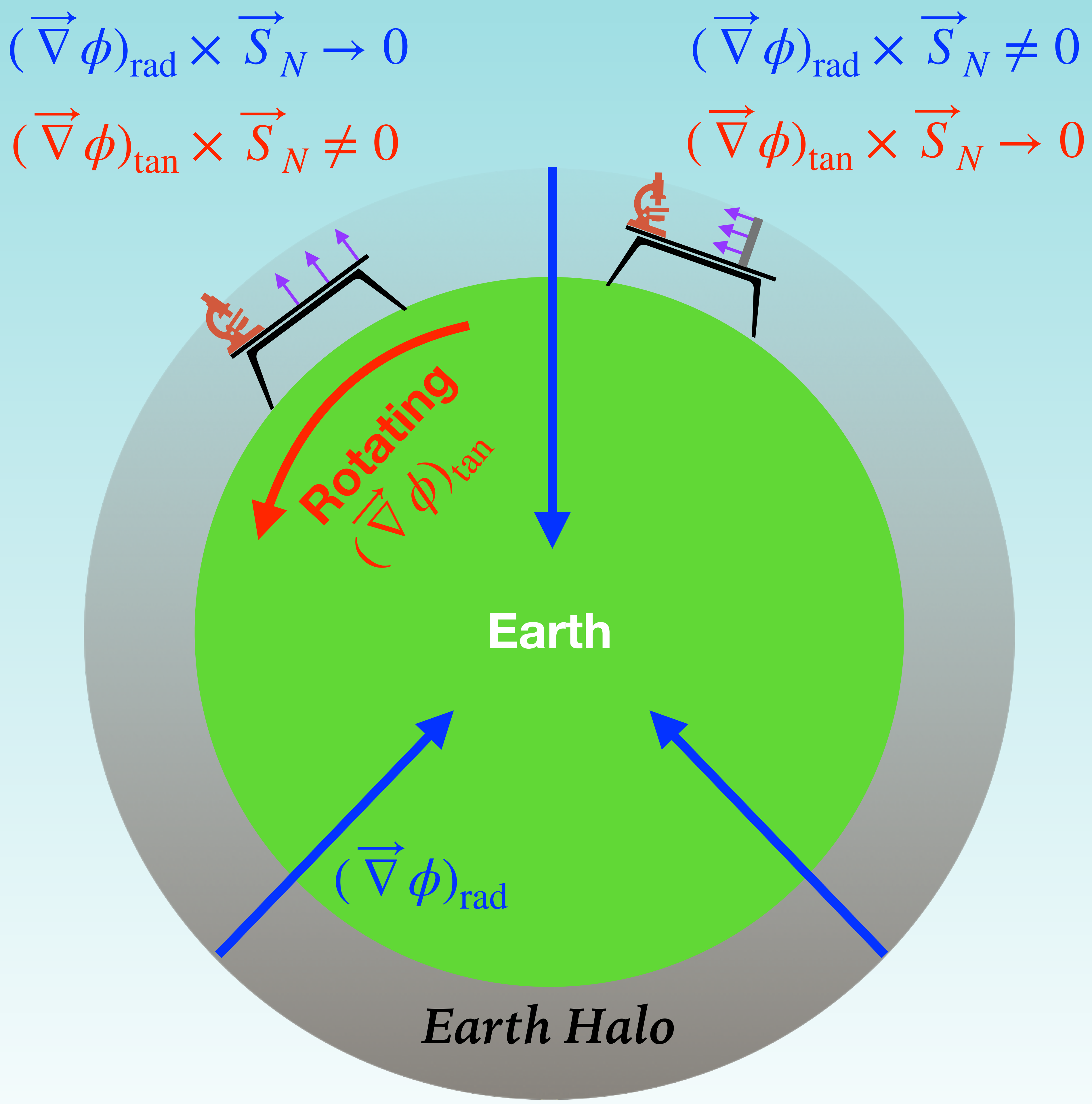

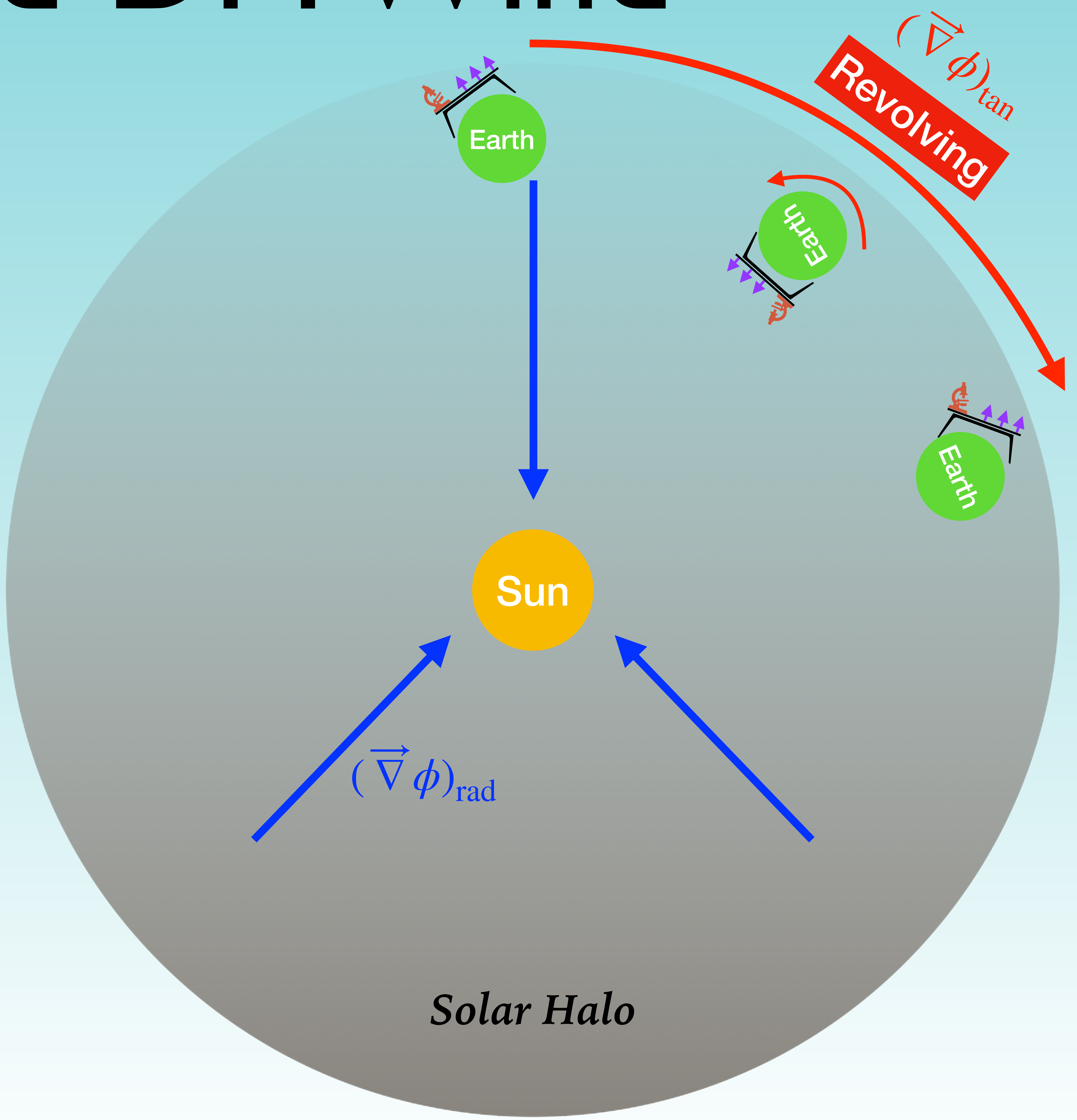

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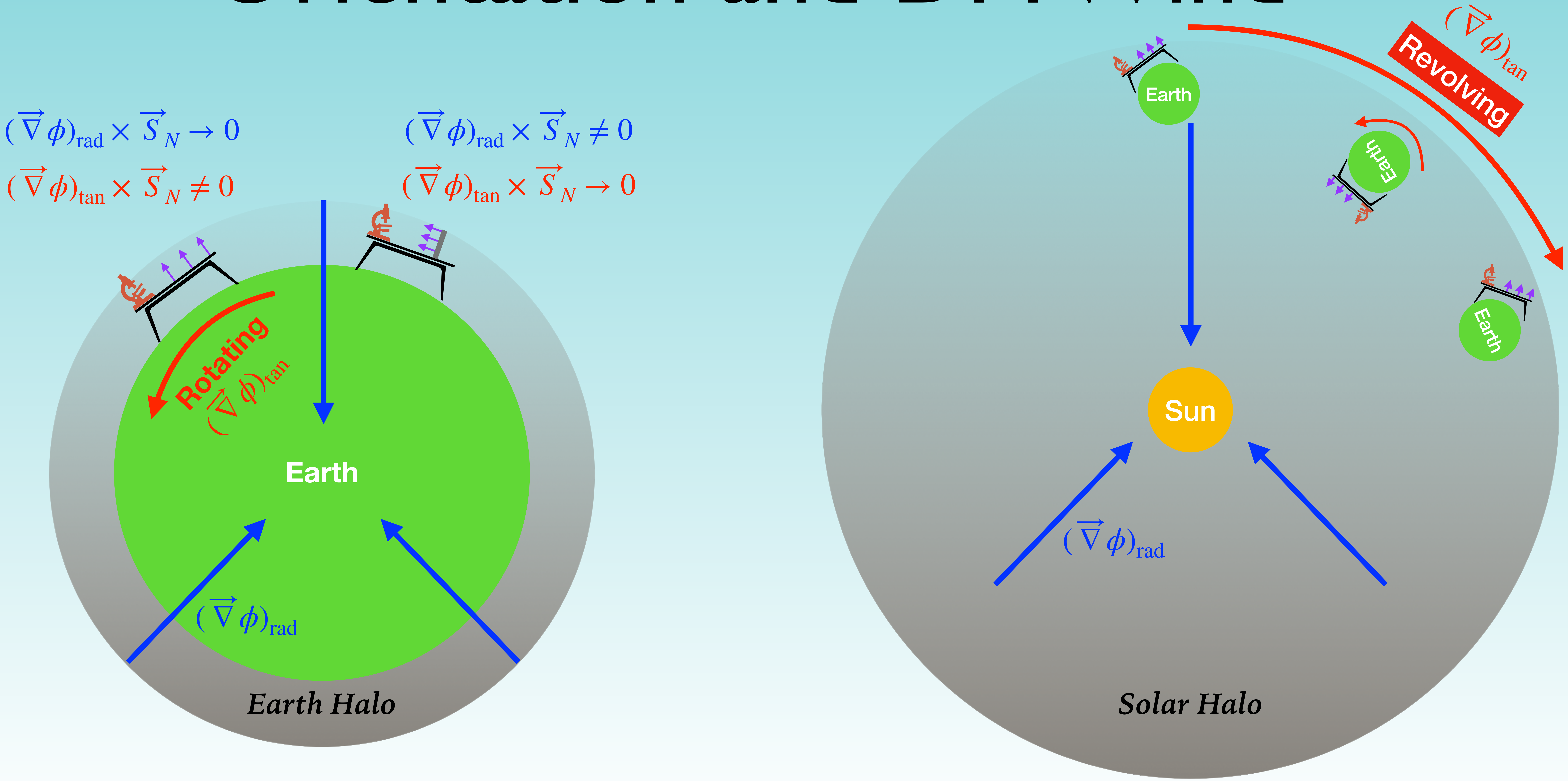


$(\vec{\nabla}\phi)_{\rm rad} \times \vec{S}_N \to 0$

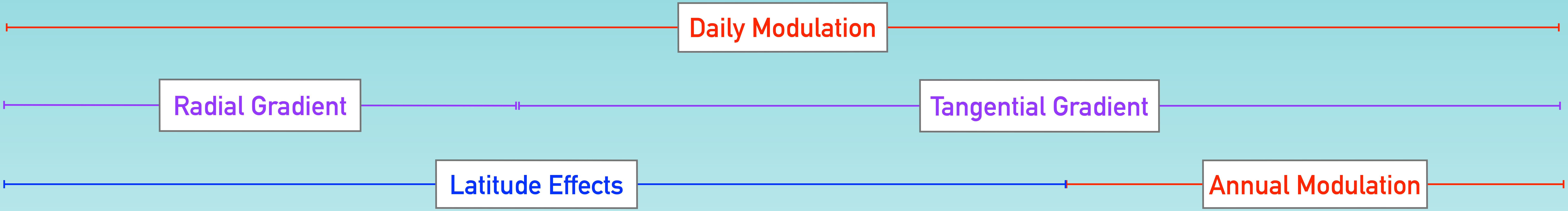
$(\vec{\nabla}\phi)_{\rm tan} \times \vec{S}_N \neq 0$

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

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

Signal depends both on detector orientation and latitude!

Signal Modulation (Solar Halo)



Daily Modulation

Radial Gradient

Tangential Gradient

Latitude Effects

Annual Modulation

- Upshot: Sideband analysis in existing axion experiments can distinguish virialized LSDM from bound axion halos in our solar system

Conclusions

- ◉ Substructure is a generic prediction of LSDM, relevant over very wide mass range

- ◉ For LSDM at galactic scales:
  - Solitons not found in large sample of galactic rotation curves; constrain $10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-21}\,\mathrm{eV}$
  - Absence of excess velocity dispersion in Milky Way Dwarf Spheroidal galaxies potentially probes $10^{-21}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-20}\,\mathrm{eV}$

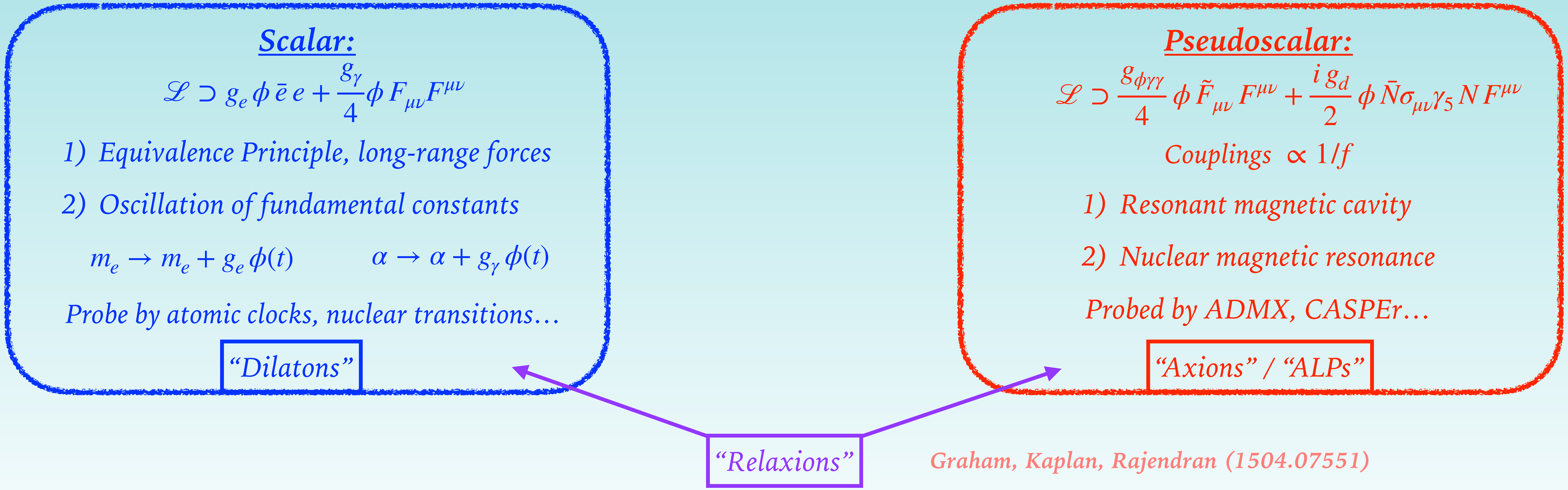
- ◉ For LSDM at solar system scale:
  - Scalar 'halos' bound to Earth or Sun offer novel modulating signals and directional information (if they in fact form)
  - Phenomenology interesting! Such halos can be probed even for very small couplings, due to large density and enhancement to coherence properties (compared to virialized DM)

Thanks!

Bonus Round

Light Scalars: Phenomenological Story

- DM field ϕ with extremely small mass $10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim \mathrm{eV}$
- Can have scalar or pseudoscalar couplings to matter



Scalar:

$$\mathscr{L} \supset g_e \phi\, \bar{e}\, e + \frac{g_\gamma}{4} \phi\, F_{\mu\nu} F^{\mu\nu}$$

1) Equivalence Principle, long-range forces

2) Oscillation of fundamental constants

$m_e \to m_e + g_e\, \phi(t)$ $\alpha \to \alpha + g_\gamma\, \phi(t)$

Probe by atomic clocks, nuclear transitions…

“Dilatons”

Pseudoscalar:

$$\mathscr{L} \supset \frac{g_{\phi\gamma\gamma}}{4} \phi\, \tilde{F}_{\mu\nu} F^{\mu\nu} + \frac{i\, g_d}{2} \phi\, \bar{N} \sigma_{\mu\nu} \gamma_5\, N\, F^{\mu\nu}$$

Couplings $\propto 1/f$

1) Resonant magnetic cavity

2) Nuclear magnetic resonance

Probed by ADMX, CASPEr…

“Axions” / “ALPs”

“Relaxions”

Graham, Kaplan, Rajendran (1504.07551)

Flacke, Frugiuele, Fuchs, Gupta, Perez (1610.02025)

- Might couple only gravitationally…!

Minimizing NR energy

$$E[\psi] = \int d^3r \left[\frac{|\nabla\psi|^2}{2m_\phi} + \frac{1}{2}V_g\,|\psi|^2 - \frac{1}{16f^2}\,|\psi|^4 + \frac{1}{288\,m_\phi\,f^4}\,|\psi|^6 - \dots \right]$$

or

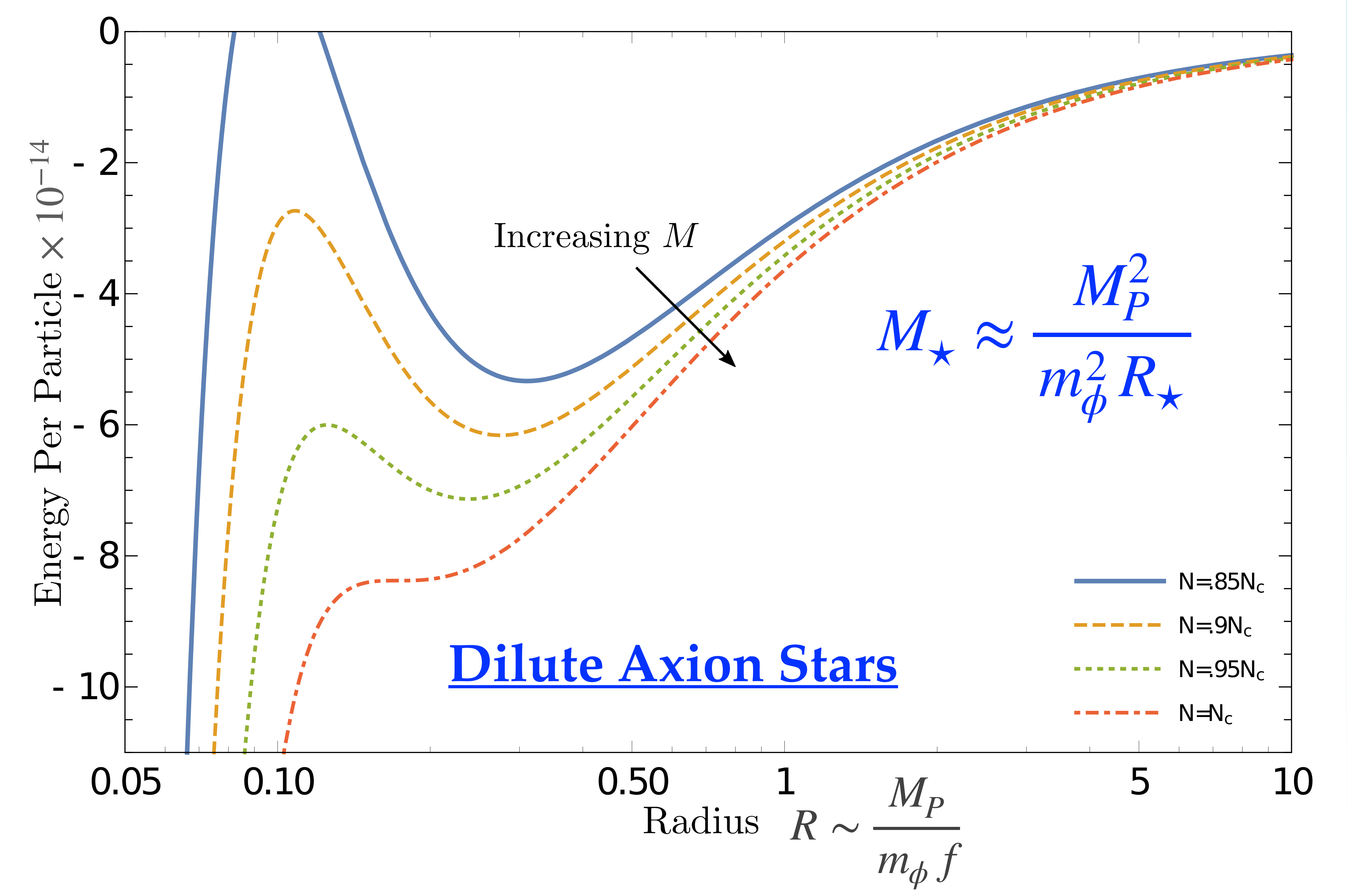
$$\frac{E(R_\star)}{M_\star} \sim \frac{a}{m_\phi^2\,R_\star^2} - \frac{b\,G\,M_\star}{R_\star} - \frac{c\,M_\star}{m_\phi^2\,f^2\,R_\star^3} + \frac{d\,M_\star^2}{m_\phi^4\,f^4\,R_\star^6} - \dots$$

Large $R_\star$: Balance these forces

Dilute Axion Stars

Kaup (Phys Rev 1968);
Ruffini and Bonazzola (Phys Rev 1969)

Chavanis (1103.2050), with Delfini (1103.2054)



$$M_\star \approx \frac{M_P^2}{m_\phi^2\,R_\star}$$

Dilute Axion Stars

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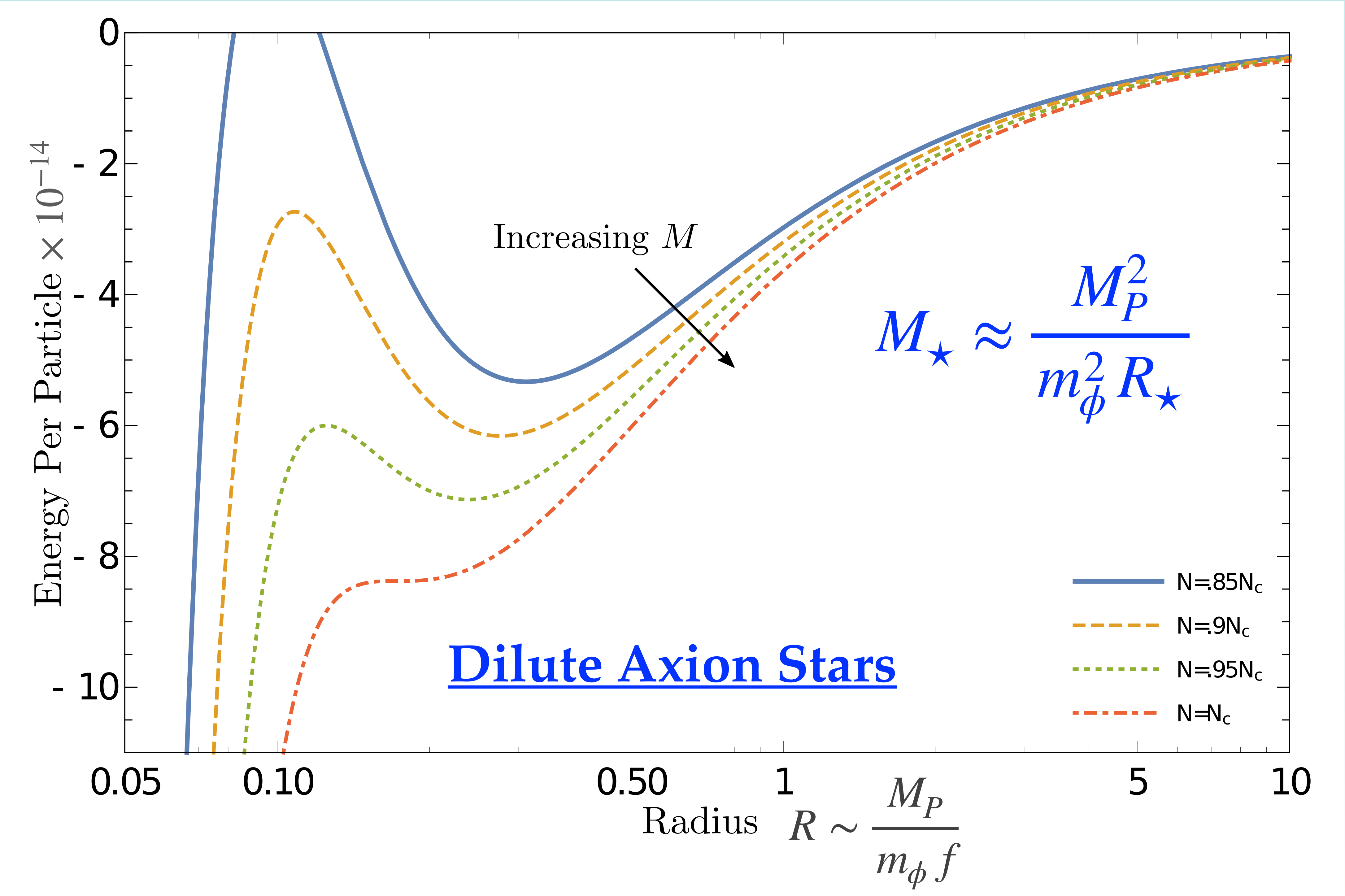
Large $R_\star$: Balance these forces

Maximum stable mass:

$$M_{max} \approx 10\frac{M_P\,f}{m_\phi}$$



- Example: QCD axion

$$M_{max} \sim \mathcal{O}(10^{-11})M_\odot$$

$$R_{dilute} \sim \mathcal{O}(100)\ km$$

$$\rho_{dilute} \sim m_\phi^2 f^2 \left(\frac{f^2}{M_P^2}\right) \lesssim \rho_{water}$$

Minimizing NR energy

$$E[\psi] = \int d^3r \left[\frac{|\nabla\psi|^2}{2m_\phi} + \frac{1}{2}V_g\,|\psi|^2 - \frac{1}{16 f^2}\,|\psi|^4 + \frac{1}{288\, m_\phi\, f^4}\,|\psi|^6 - \ldots \right]$$

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Large $R_\star$: **Balance these forces**

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Dilute Axion Stars

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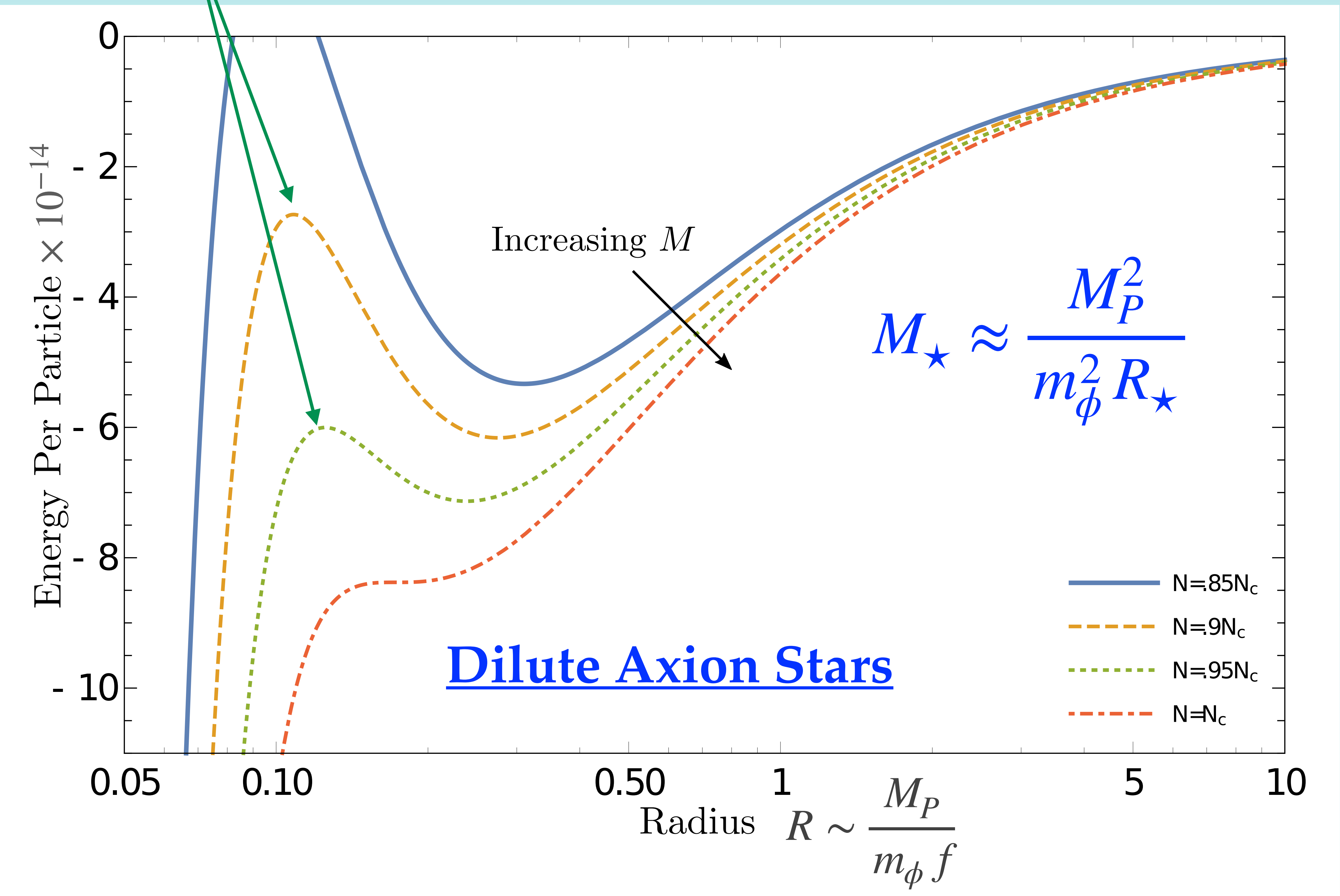
Transition Branch (unstable)



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Minimizing NR energy (2)

Dense Axion Stars

Braaten, Mohapatra, Zhang (1512.00108)

$$E[\psi] = \int d^3r \left[\frac{|\nabla\psi|^2}{2m_\phi} + \frac{1}{2}V_g\,|\psi|^2 - \frac{1}{16f^2}|\psi|^4 + \frac{1}{288\,m_\phi f^4}|\psi|^6 - \ldots \right]$$

or $$\frac{E(R_\star)}{M_\star} \sim \frac{a}{m_\phi^2 R_\star^2} - \frac{b\,G\,M_\star}{R_\star} - \frac{c\,M_\star}{m_\phi^2 f^2 R_\star^3} + \frac{d\,M_\star^2}{m_\phi^4 f^4 R_\star^6} - \ldots$$

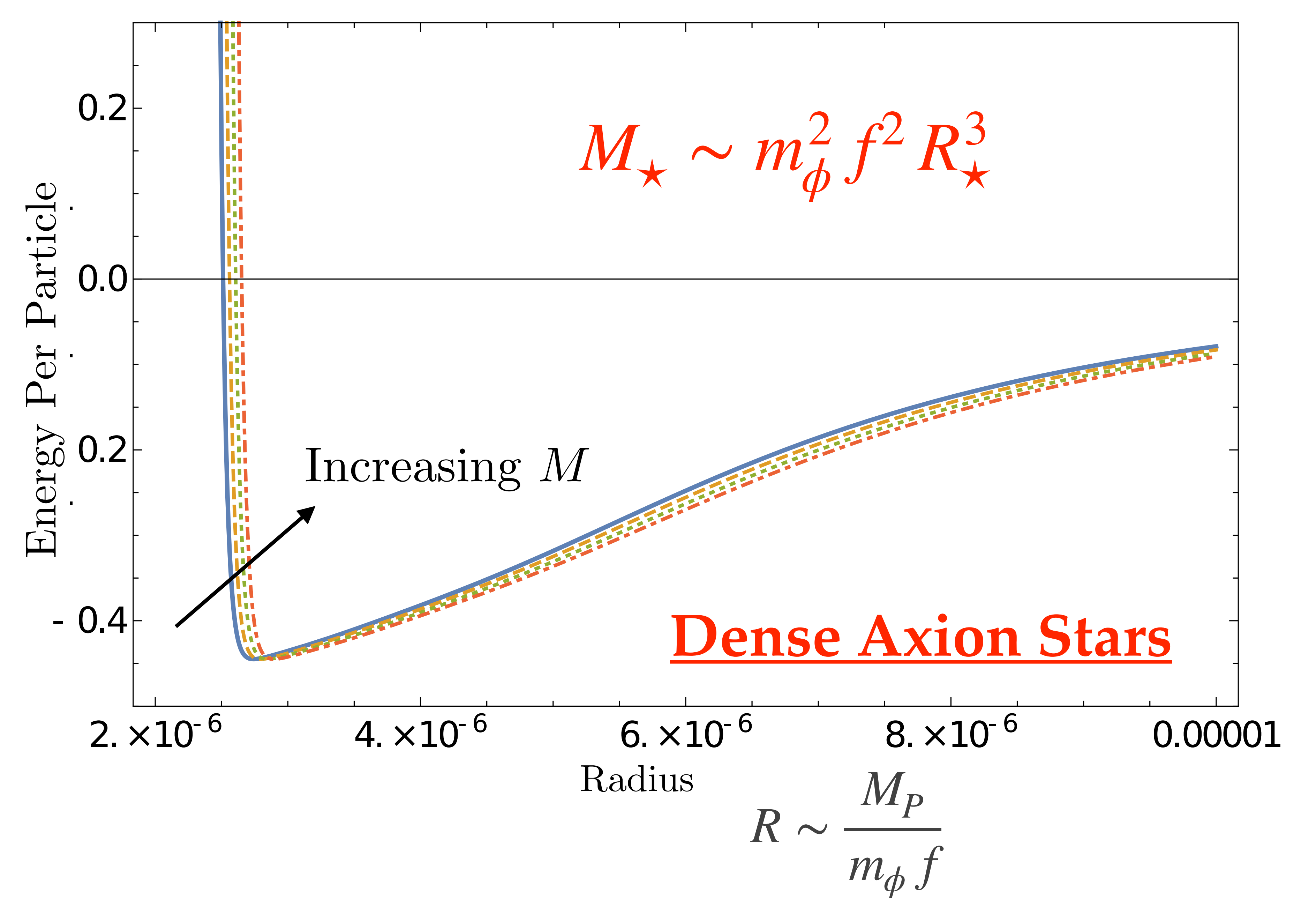
Small $R_\star$: Balance these forces

- Example: QCD axion

$M \sim \mathcal{O}(10^{-11})M_\odot$

$R_{dense} \sim \mathcal{O}(10)\ cm$

$\rho_{dense} \sim m_\phi^2 f^2 \sim \Lambda_{QCD}^4$



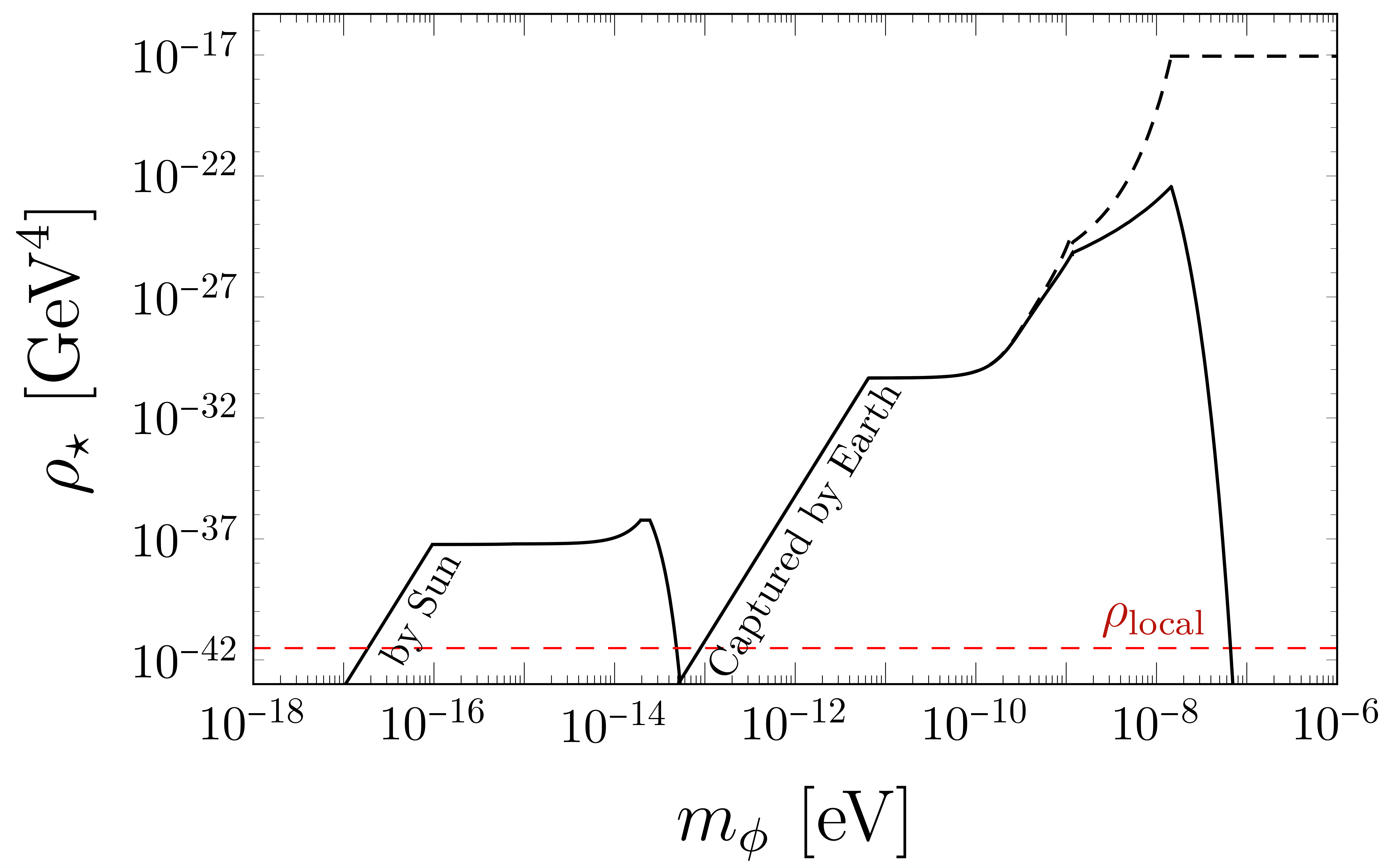
$M_\star \sim m_\phi^2 f^2 R_\star^3$

Dense Axion Stars

$R \sim \frac{M_P}{m_\phi f}$

- **However, very unstable to decay (to relativistic axions)**

Maximum Axion Halo Density



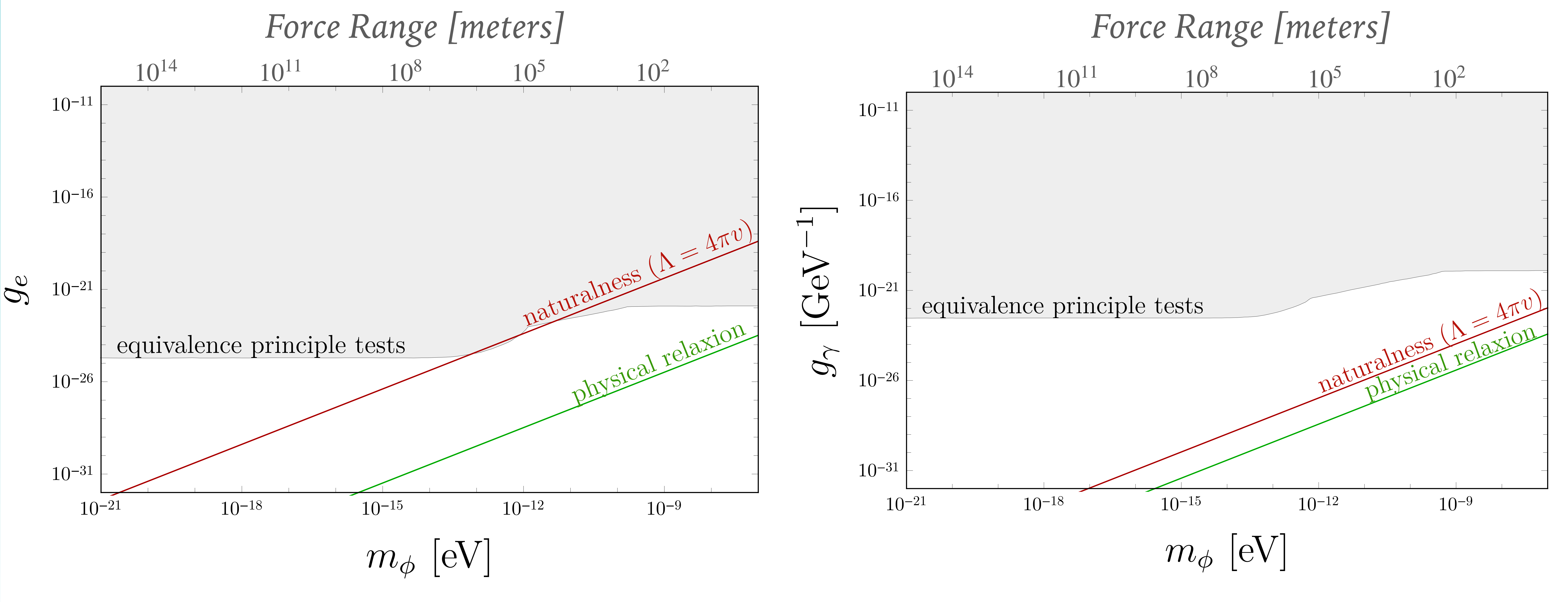
Scalar LSDM Couplings

$$\mathscr{L} \supset g_e \phi \bar{e} e + \frac{g_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

- Classic experiments look for long-range force from virtual ϕ exchange

(Effective Yukawa potential)

Arvanitaki, Huang, Van Tilburg (1405.2925)
Hees, Minazzoli, Savalle, Stadnik, Wolf (1807.04512)
[many more] …………



➤ Is there a way to do better??

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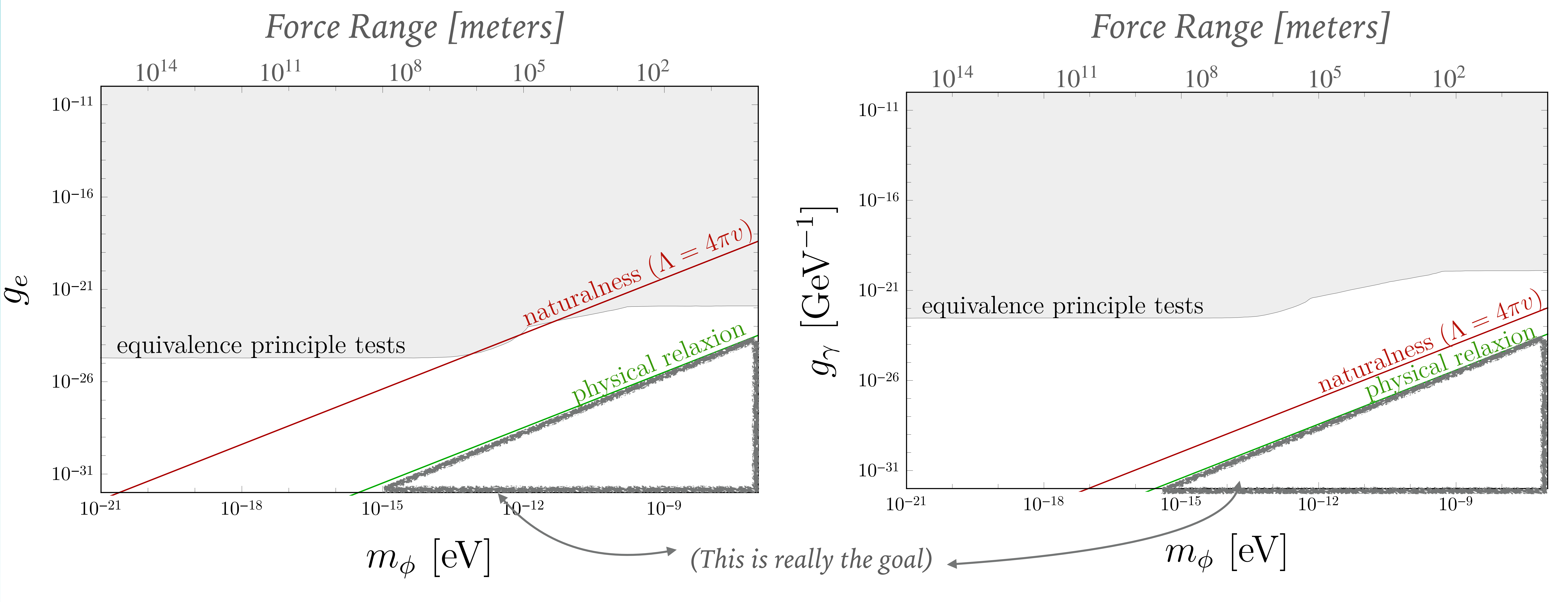


(This is really the goal)

➤ Is there a way to do better??

Atomic Physics Probes

$$\mathscr{L} \supset g_e \phi \bar{e} e + \frac{g_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

- Cutting-edge atomic experiments are achieving incredible sensitivity to variation of fundamental constants!

$$\left(\frac{\delta m_e}{m_e}\right)_{exp} \simeq 10^{-14} \qquad \text{(Today)} \qquad \left(\frac{\delta \alpha}{\alpha}\right)_{exp} \simeq 10^{-16}$$

$$\left(\frac{\delta m_e}{m_e}\right)_{exp} \simeq 10^{-18} \qquad \text{(Near future)} \qquad \left(\frac{\delta \alpha}{\alpha}\right)_{exp} \simeq 10^{-18}$$

- Now possible at high frequency!

see e.g. Dynamical decoupling — Aharony, Ackerman, Ozeri, Perez, Savoray, Shaniv (1902.02788)

Atomic spectroscopy — Antypas, Tretiak, Garcon, Ozeri, Perez, Budker (1905.02968)

$10^{-8}\ eV \Leftrightarrow 1\ MHz$

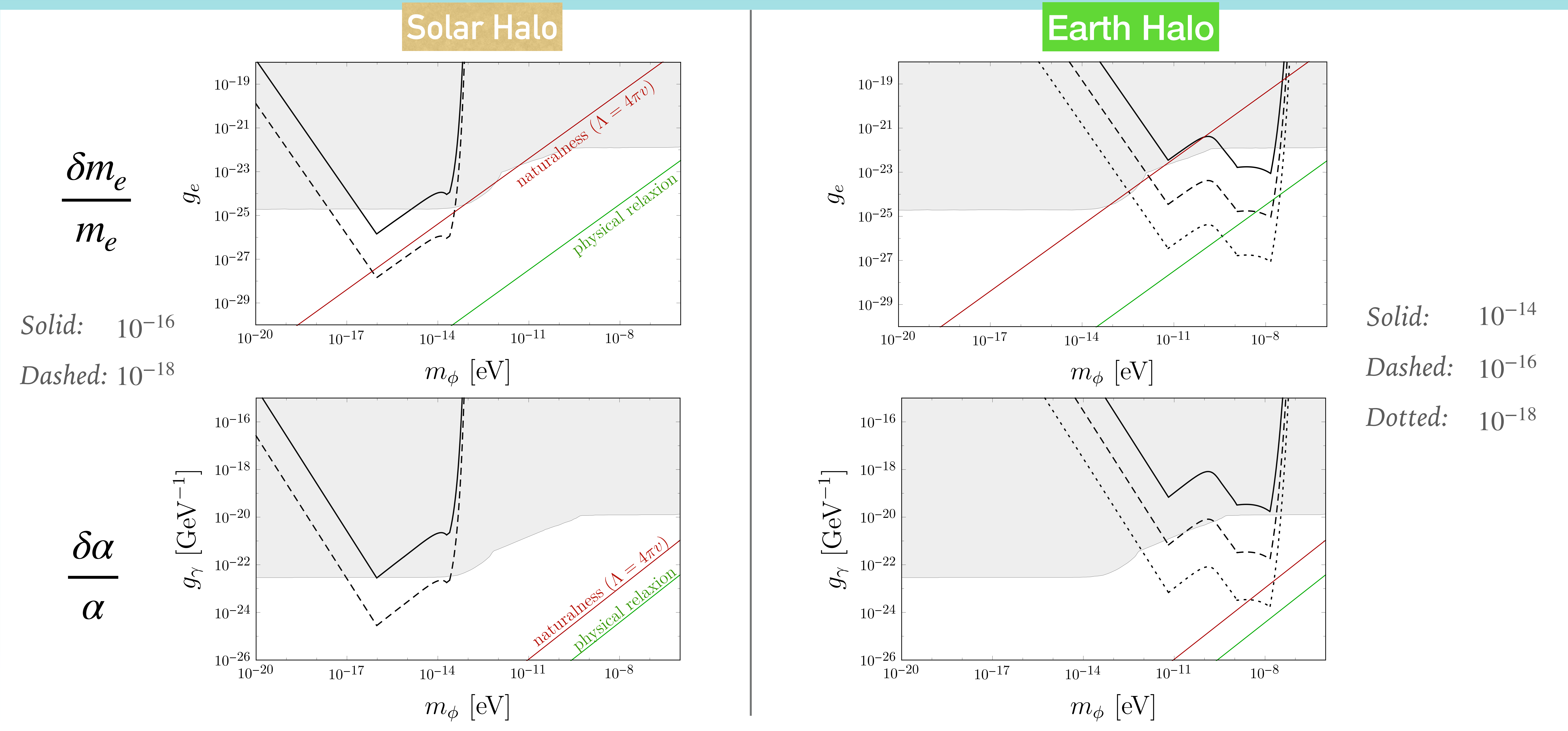
$10^{-15}\ eV \Leftrightarrow 1\ Hz$

- Advantage: direct coupling to scalar field density $|\phi| = \sqrt{2\rho_{DM}}/m_\phi$

Sensitivity to Axion Halos

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

- Big boost in the presence of an axion halo!



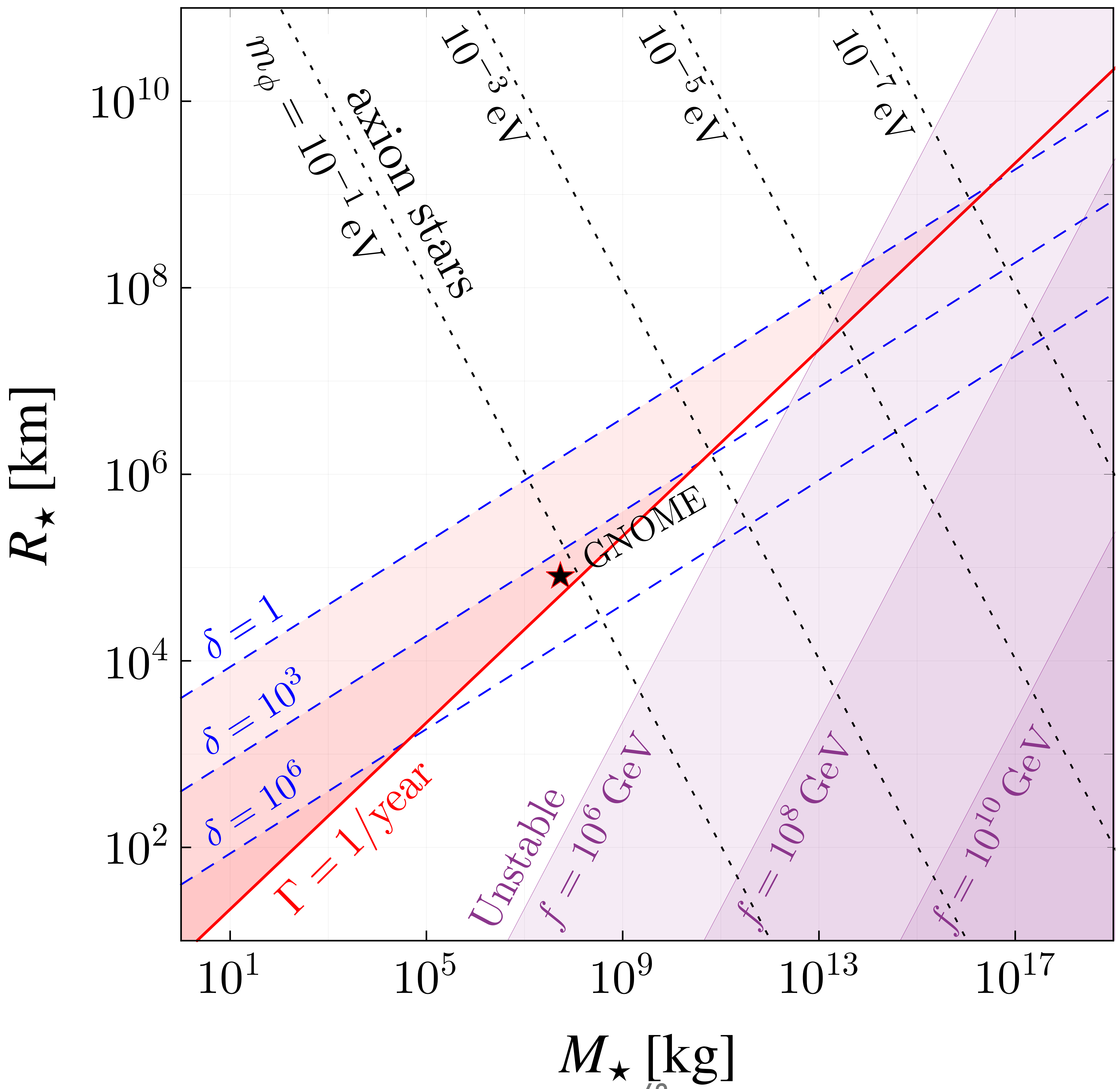
Detect transient axion stars on earth?

(Difficult)

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

$\delta \propto \rho_{local}^{-1} R_\star^{-4} m_\phi^{-2}$

$\Gamma \propto \rho_{local} R_\star^3 m_\phi^2$



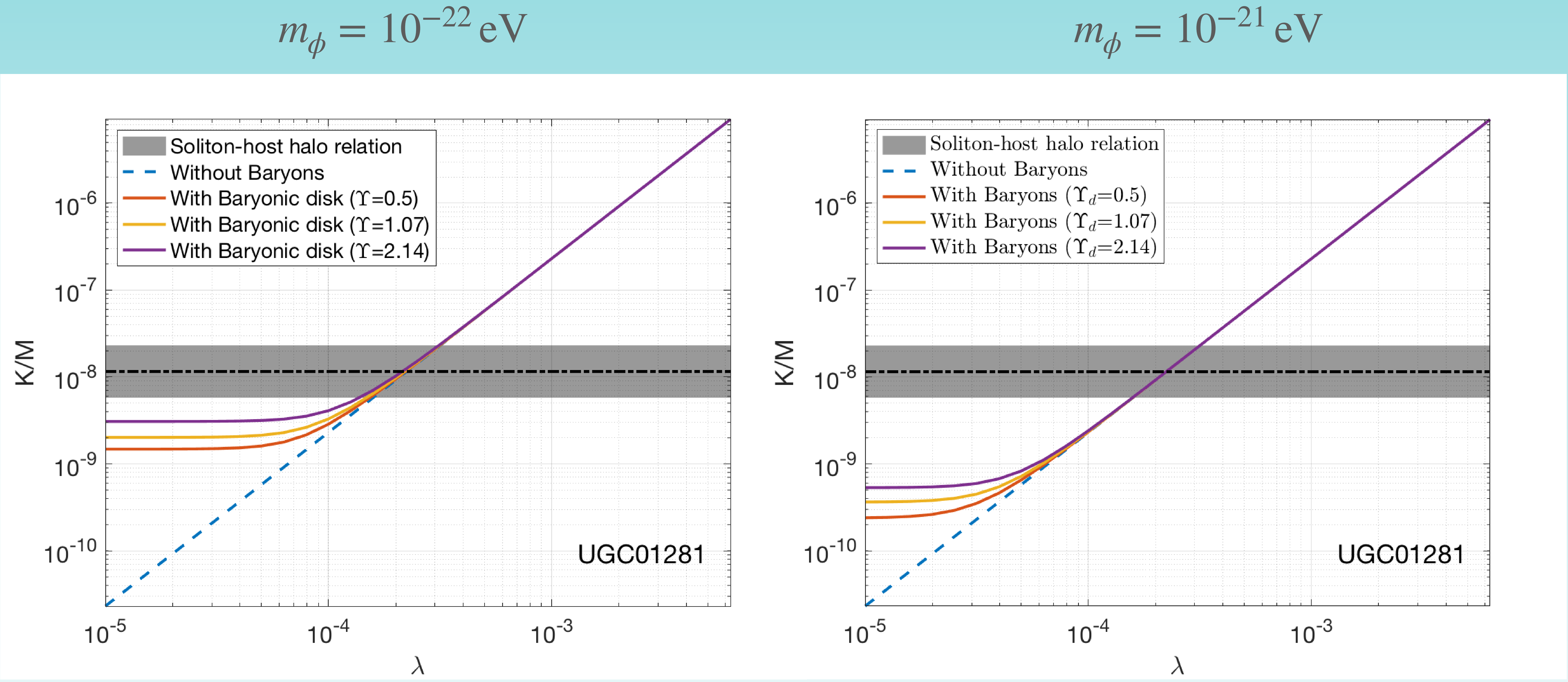
Solving for Solitons (1.5)

- The energy in the soliton is

$$E = \int d^3x \left[\frac{|\nabla\psi|^2}{2\,m_\phi^2} + \frac{\Phi\,|\psi|^2}{2} \right] = \frac{M_P^2}{4\pi\, m_\phi} \int d^3x \left[\frac{\nabla\chi^2}{2} + \frac{\Phi\,\chi^2}{2} \right] = \frac{\mu}{3} M$$

- Therefore $E_\lambda = \frac{\mu_\lambda}{3} M_\lambda = \frac{\lambda^3}{3} \mu_1\, M_1 \approx -0.476\,\lambda^3\, \frac{M_P^2}{m_\phi}$, and $M_\lambda \approx 2.06\,\lambda\, \frac{M_P^2}{m_\phi}$

Do baryons shift the soliton-host halo relation?



$m_\phi = 10^{-22}\,\mathrm{eV}$

$m_\phi = 10^{-21}\,\mathrm{eV}$

Bar, Blum, JE, Sato (1903.03402)