科研費 KAKENHI

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Axion Solar Halos: From Earth and Space

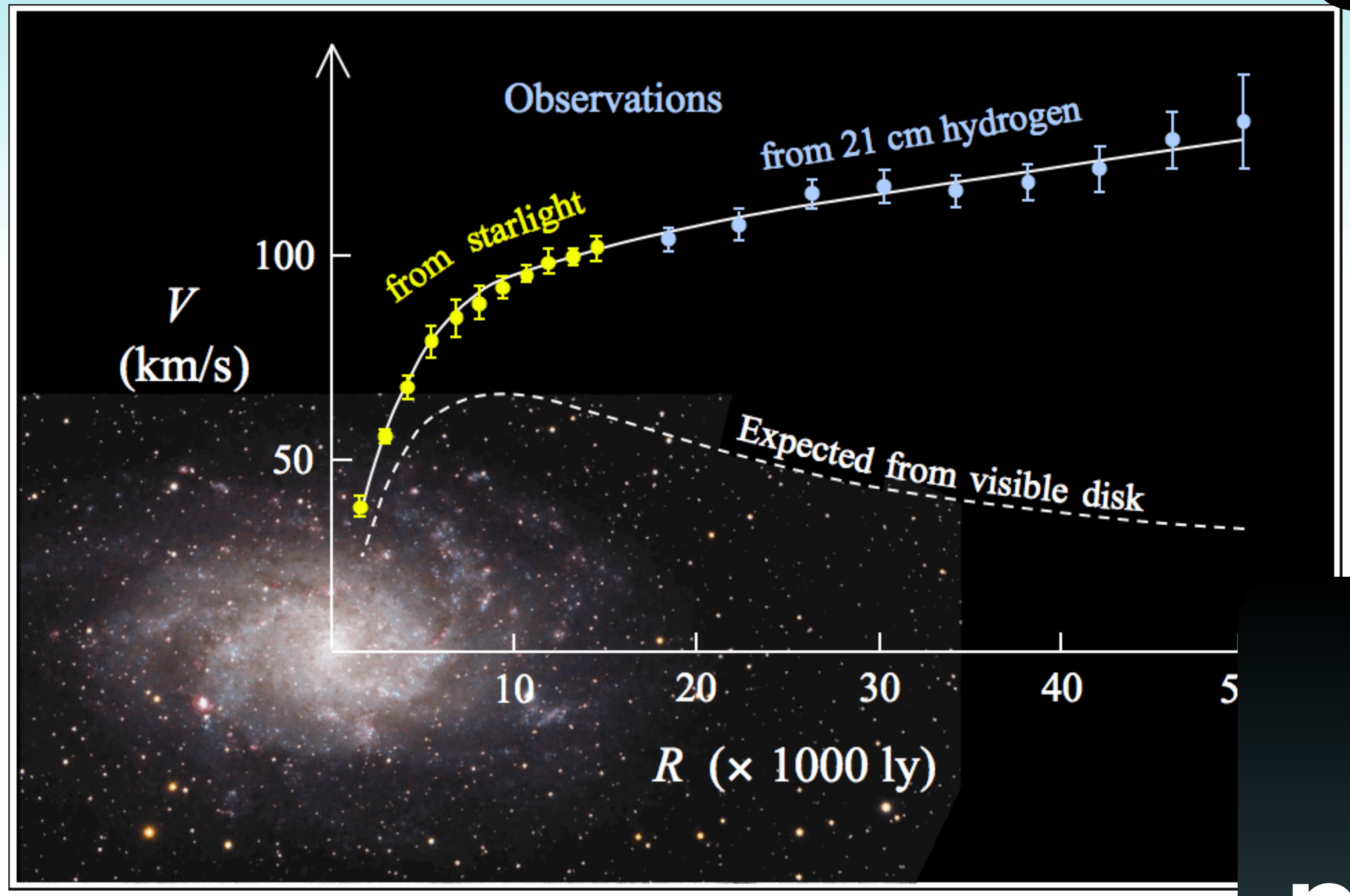
Joshua Eby
Kavli IPMU (WPI) UTIAS
University of Tokyo

Fermi National Accelerator Laboratory
Pheno Seminar
25/08/2022

ULDM Solar + Earth Halo Theory; Probes on Earth	**Banerjee, Budker, JE, Kim, Perez (1902.08212) + Flambaum, Matsedonskyi (1912.04295)**
Solar Halo Probes in Space	**Tsai, JE, Safronova (2112.07674) + Arakawa, Farnocchia (22xx.xxxxx)**
Solar Halo Formation	**JE, Gorghetto, Jiang, Kim, Perez (22xx.xxxxx)**

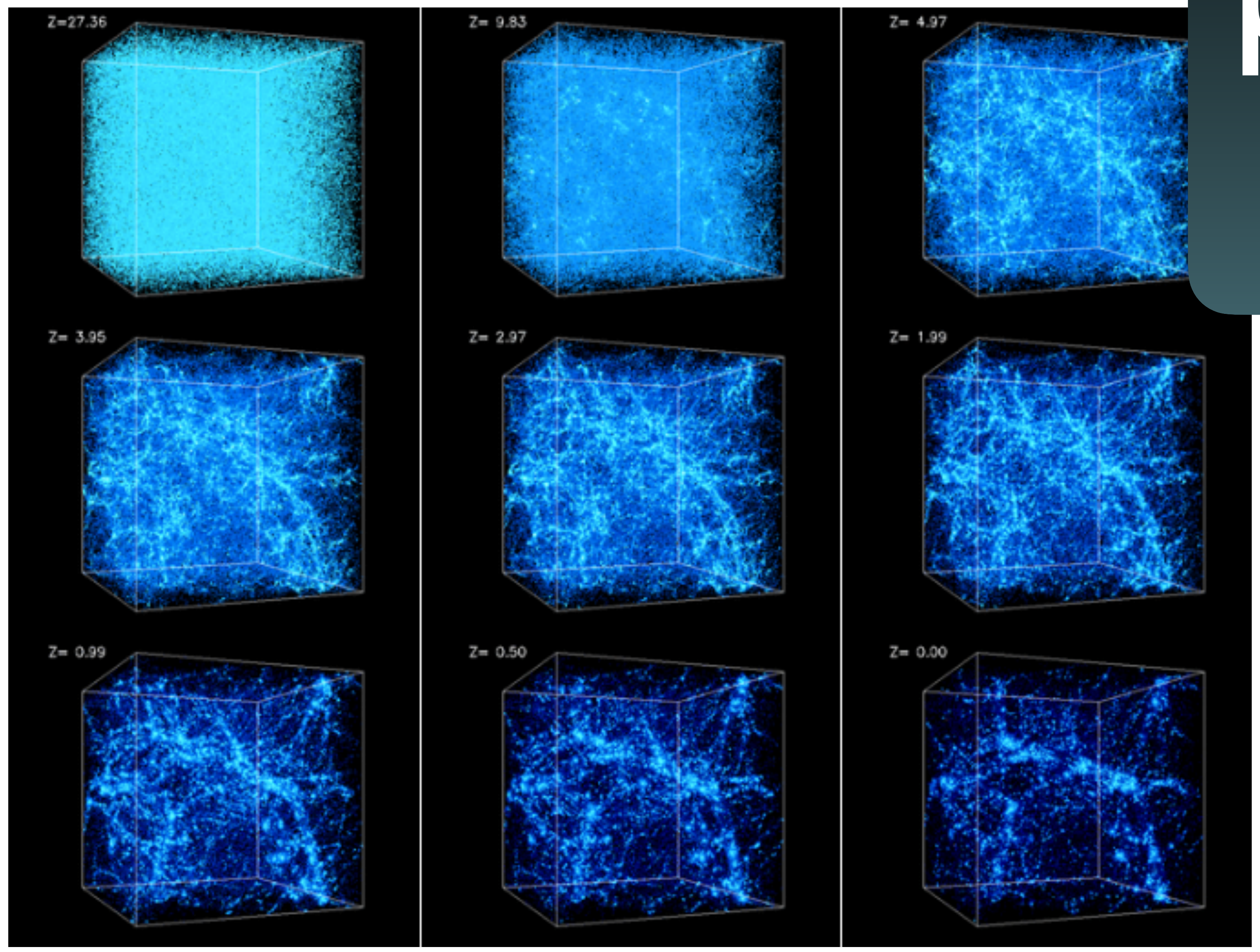
Big Question

Flat rotation curves

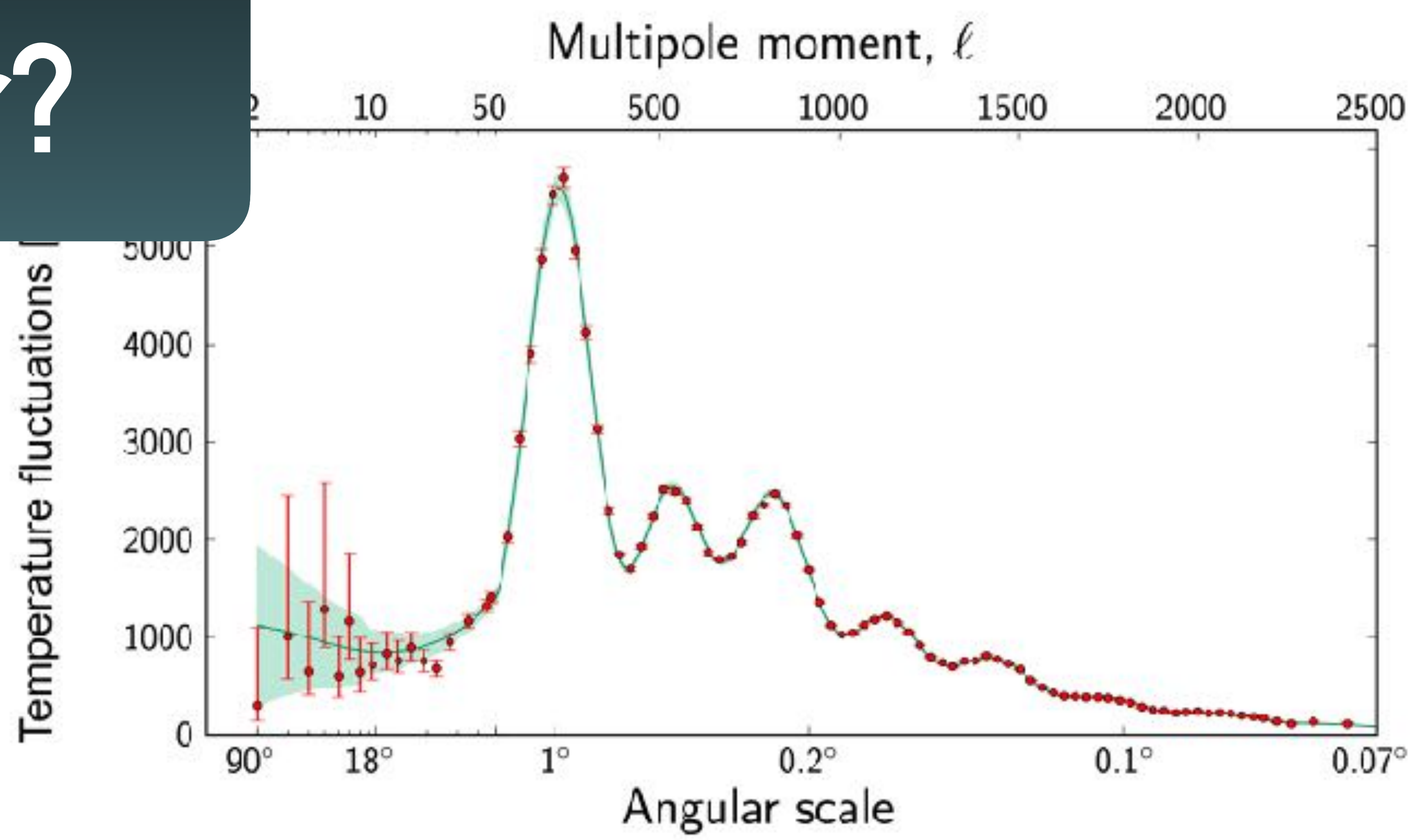


Galaxy cluster collisions

What is the particle nature of Dark Matter?



Large scale structure



Cosmic microwave background

Dark Matter Theories

Mass of the DM "particle" m_ϕ

$10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim \mathrm{eV}$ — **(Ultra)Light Dark Matter**

$\mathrm{keV} \lesssim m_\phi \lesssim 100\,\mathrm{TeV}$ — **WIMPs, SIMPs, Sterile Neutrinos, …**

$10^{-18} M_\odot \lesssim m_\phi$ — **Composite, Macroscopic Dark Matter**

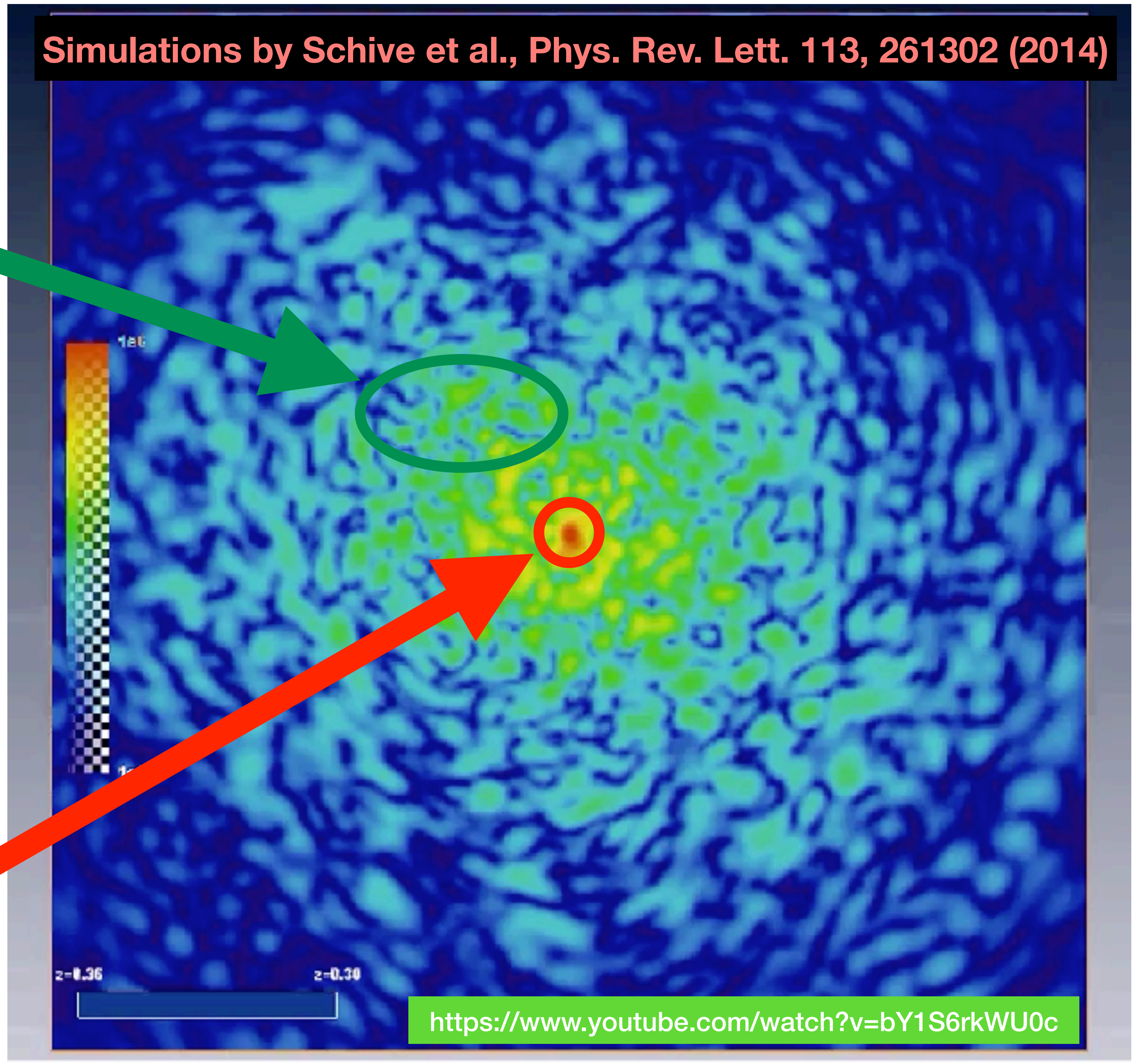
- ULDM particles must be bosons because phase space density $\mathcal{N} \left(\propto m_\phi^{-4} \right) \gg 1$

- ULDM is wave-like on distance scales of order

$$\lambda_{\mathrm{dB}} = \frac{1}{m_\phi \sigma_{\mathrm{vir}}} \sim \underbrace{R_E \left(\frac{10^{-10}\,\mathrm{eV}}{m_\phi} \right)}_{\text{size of Earth}} \sim \underbrace{\mathrm{AU} \left(\frac{10^{-14}\,\mathrm{eV}}{m_\phi} \right)}_{\text{size of solar system}} \sim \underbrace{\mathrm{kpc} \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi} \right)}_{\text{size of galaxy}}$$

"quasiparticles"

Quasiparticles



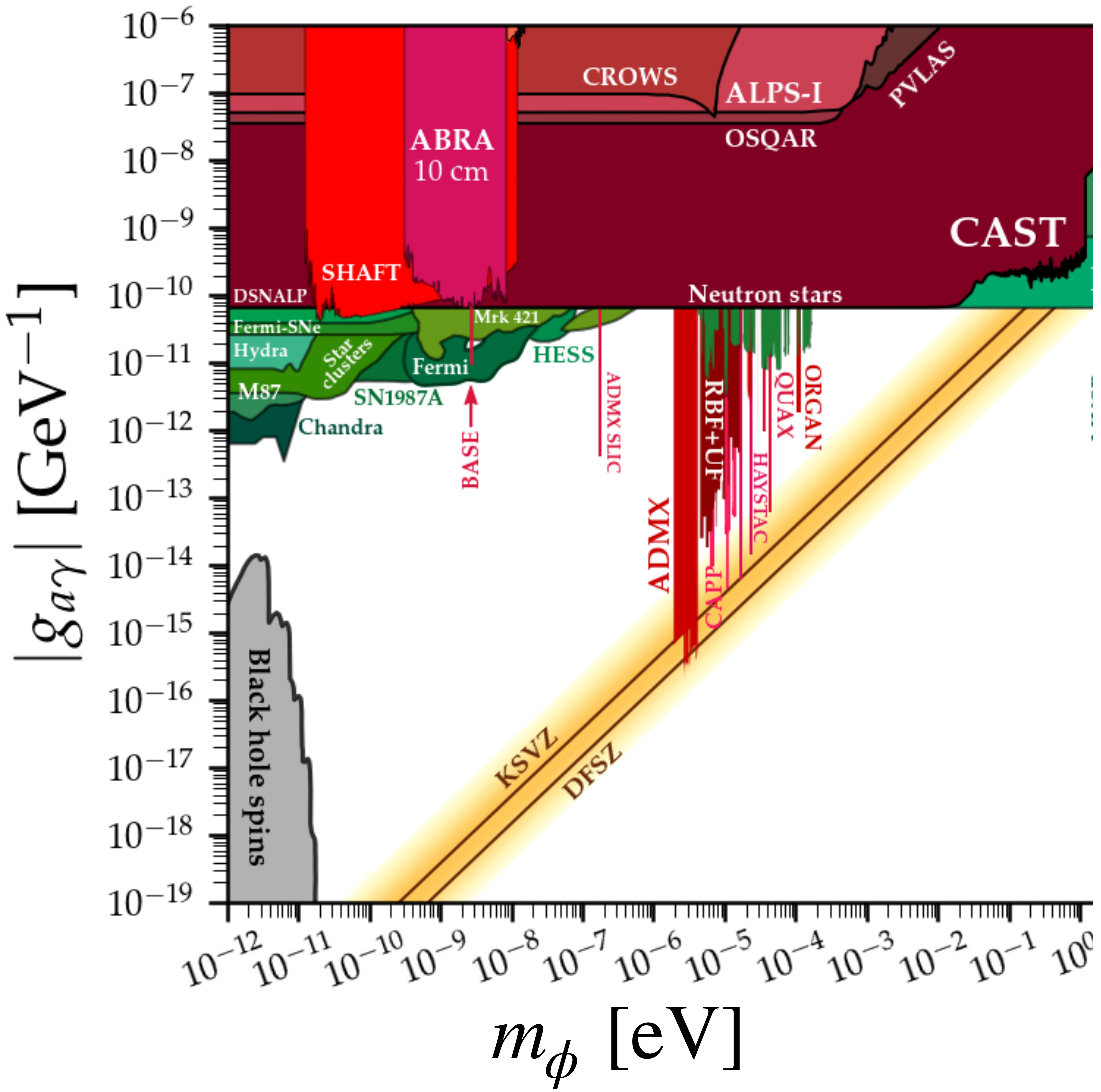
Boson Star

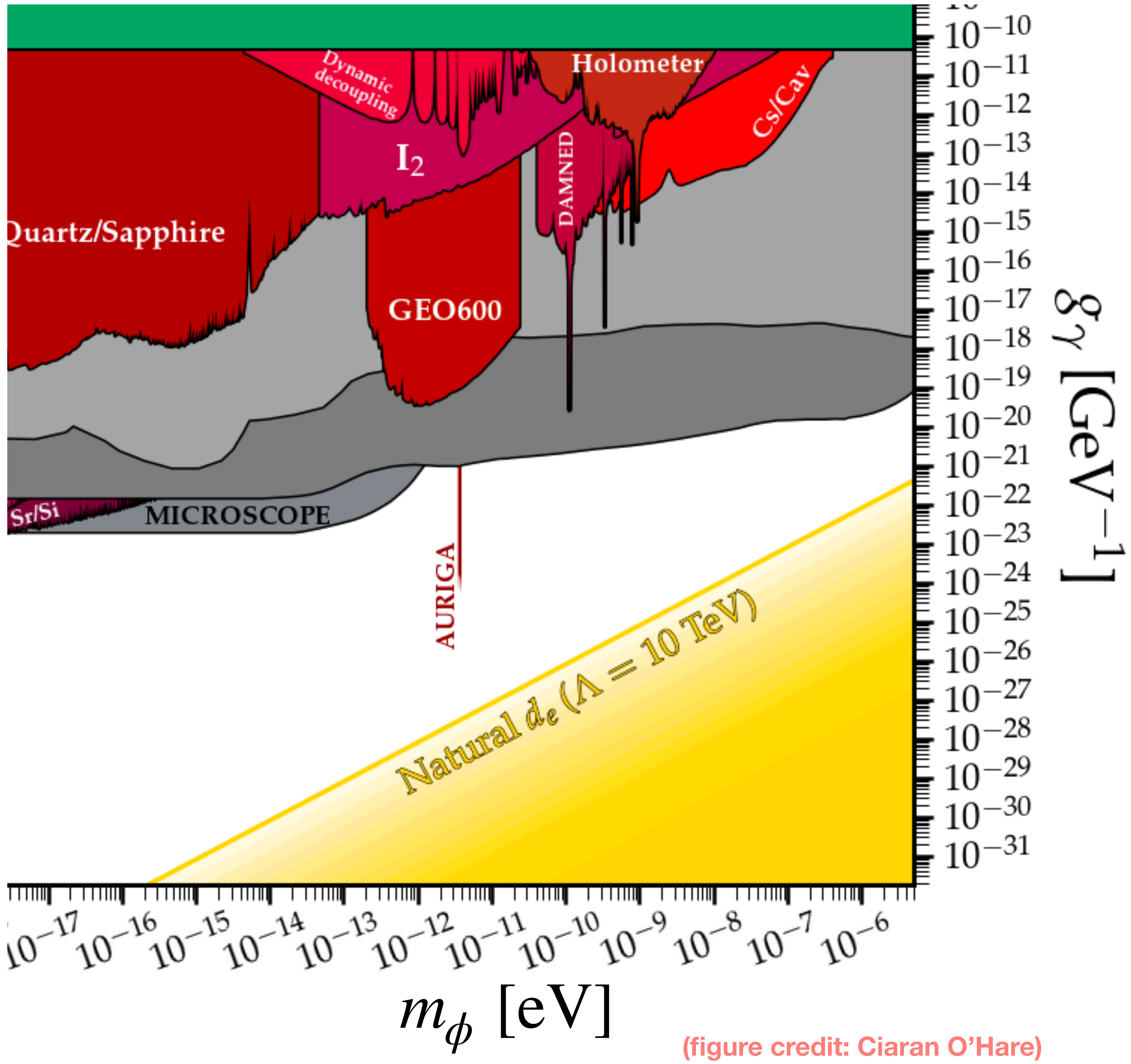
Searches for (pseudo)scalar particles

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

Consider, for example, photon couplings:

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





(figure credit: Ciaran O'Hare)

DM for Impatient People

- Let’s question basic assumptions
  - What is the DM density in the vicinity of Earth, really?

arXiv.org > astro-ph > arXiv:1205.4033

Search...

Help | Adv

Astrophysics > Astrophysics of Galaxies

[Submitted on 17 May 2012 (v1), last revised 29 Jun 2012 (this version, v2)]

On the local dark matter density

Jo Bovy, Scott Tremaine (IAS)

An analysis of the kinematics of 412 stars at 1-4 kpc from the Galactic mid-plane by Moni Bidin et al. (2012) has claimed to derive a local density of dark matter that is an order of magnitude below standard expectations. We show that this result is incorrect and that it arises from the assumption that the mean azimuthal velocity of the stellar tracers is independent of Galactocentric radius at all heights. We substitute the assumption, supported by data, that the circular speed is independent of radius in the mid-plane. We demonstrate that the assumption of constant mean azimuthal velocity is implausible by showing that it requires the circular velocity to drop more steeply than allowed by any plausible mass model, with or without dark matter, at large heights above the mid-plane. Using the approximation that the circular velocity curve is flat in the mid-plane, we find that the data imply a local dark-matter density of 0.008 +/- 0.003 Msun/pc^3 = 0.3 +/- 0.1 GeV/cm3, fully consistent with standard estimates of this quantity. This is the most robust direct measurement of the local dark-matter density to date.

measurements
<u>at the scale of the galaxy</u>
imply $\rho_{\rm local} \simeq 0.3\,{\rm GeV/cm}^3$

Outline

This talk: possibility of modifications in the DM *very local density* (at the scale of solar system)

1. **ULDM with $m_\phi \lesssim 10^{-9}\,\mathrm{eV}$ has large density fluctuations at these scales**
   (well-known, will review)
2. **(very) Local measurements allow $\rho \lesssim 10^{4-5}\rho_{\mathrm{local}}$ around 1 AU**
   planets → Pitjev and Pitjeva (1306.5534)
   asteroids → Tsai, JE, Arakawa, Farnocchia, Safronova (22xx.xxxxx)
3. **Plausible dynamical processes that can capture large ULDM densities**
   (ongoing work, hints only for now) JE, Gorghetto, Jiang, Kim, Perez (22xx.xxxxx)
4. **Signals are unique and detectable in terrestrial experiments** Banerjee, Budker, JE, Kim, Perez (1902.08212) + Flambaum, Matsedonskyi (1912.04295)
5. **Space missions with atomic clocks, motivated for other reasons, may be ideal probe in range of m_ϕ** Tsai, JE, Safronova (2112.07674)

So let's talk about bound states!

Equations of Motion

- Ultralight DM is non-relativistic field of very large occupation number ⇒ NR classical field
- Expand field ϕ in terms of non-relativistic wavefunction $\psi : \phi(t,r) = \frac{1}{\sqrt{2m_\phi}}\left[e^{-im_\phi t}\psi(t,r) + c.c.\right]$
- E.o.M is **Gross-Pitaevskii+Poisson (GPP)** equation:

Poisson Gravity

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

(Attractive)

Coherent state → Oscillates

Leading time dependence

$\dot\psi \sim (m_\phi - \omega_\phi)\psi \ll m_\phi \psi$

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

Gradient energy

(Repulsive)

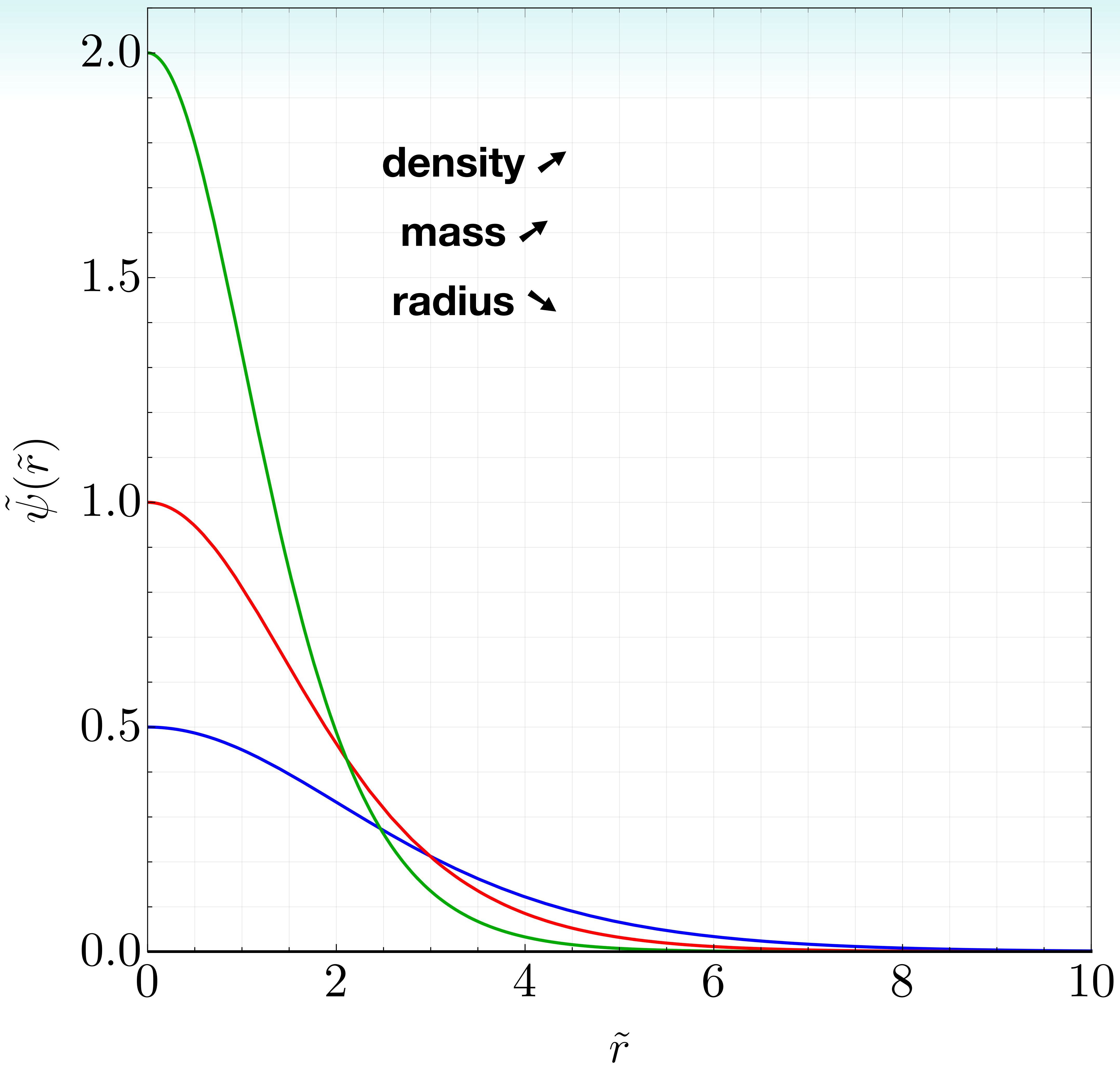
External Gravitating Source

(Attractive)

Normalization

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

Boson Star



Ground-state solution of the GPP Equations

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

$$\propto \frac{1}{{R_{\text{BS}}}^2} \qquad \propto -\frac{M_{\text{BS}}}{R_{\text{BS}}}$$

- Self-gravitating bound state: gradients ~ self-gravity

$$R_{\text{BS}} \simeq \frac{M_P^2}{m_\phi^2 M_{\text{BS}}} \simeq 2000\,\text{km}\left(\frac{10^{-10}\,\text{eV}}{m_\phi}\right)^2\left(\frac{10^{-2}\,M_\odot}{M_{\text{BS}}}\right)$$

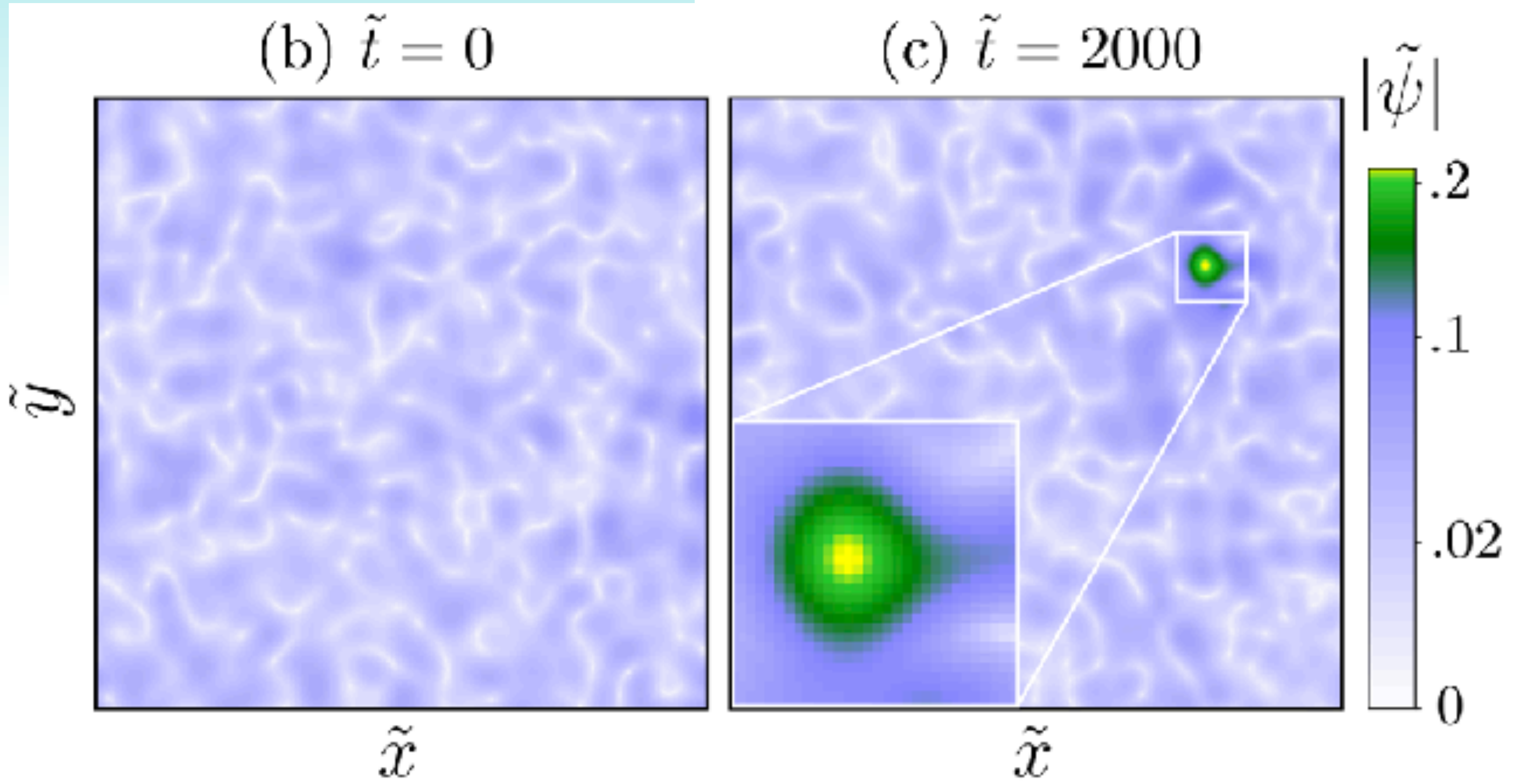
"Dilute boson star"

Boson Star Formation

Gravitational relaxation of quasiparticles is sufficiently fast for formation to occur

Binney and Tremaine, “Galactic Dynamics, 2nd Edition”
Hui, Ostriker, Tremaine, Witten (1610.08297)
Bar-Or, Fouvry, Tremaine (1809.07673)

Levkov, Panin, Tkachev (1804.05857)



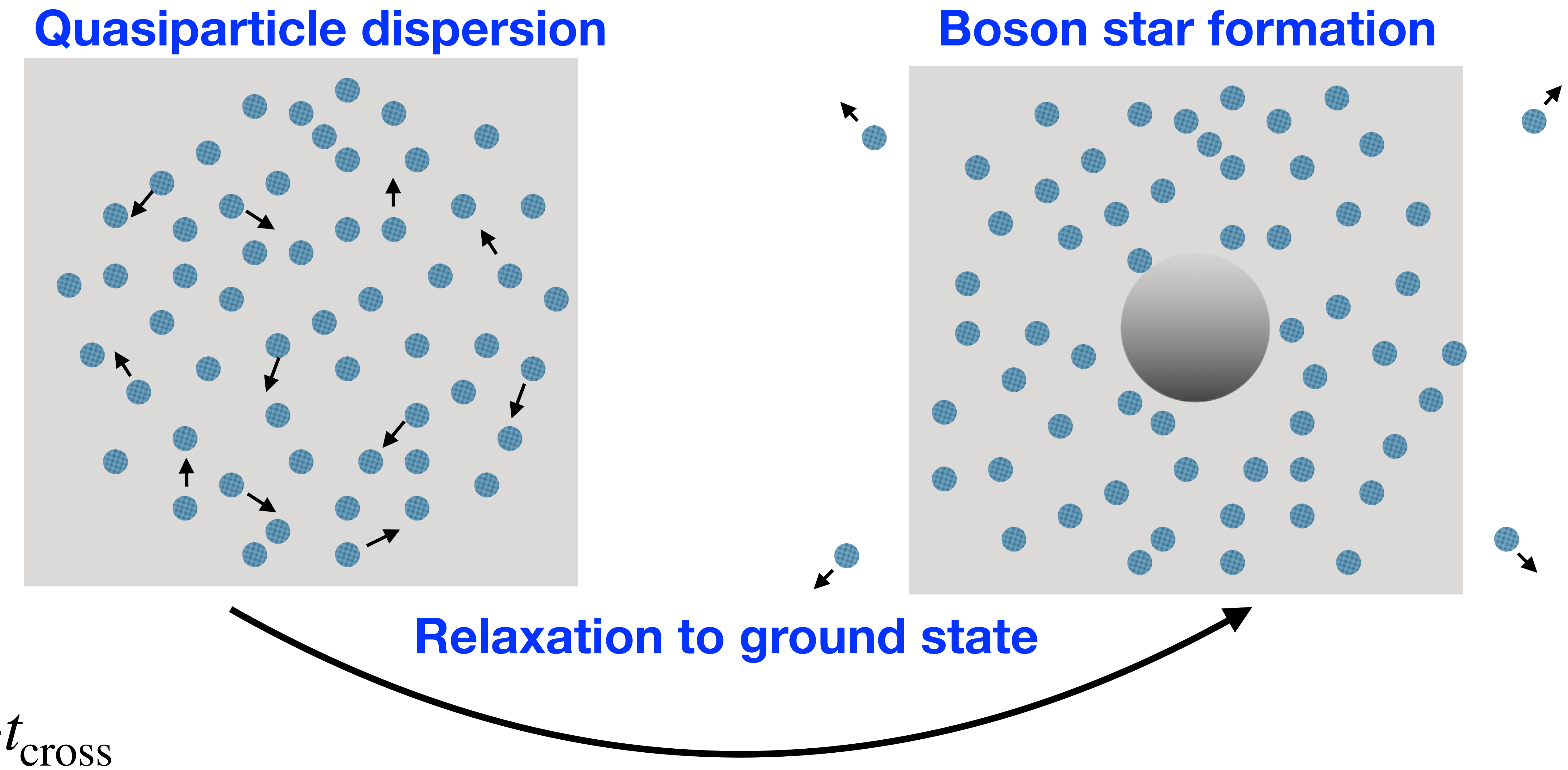
Velocity change per crossing

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

Fractional velocity change

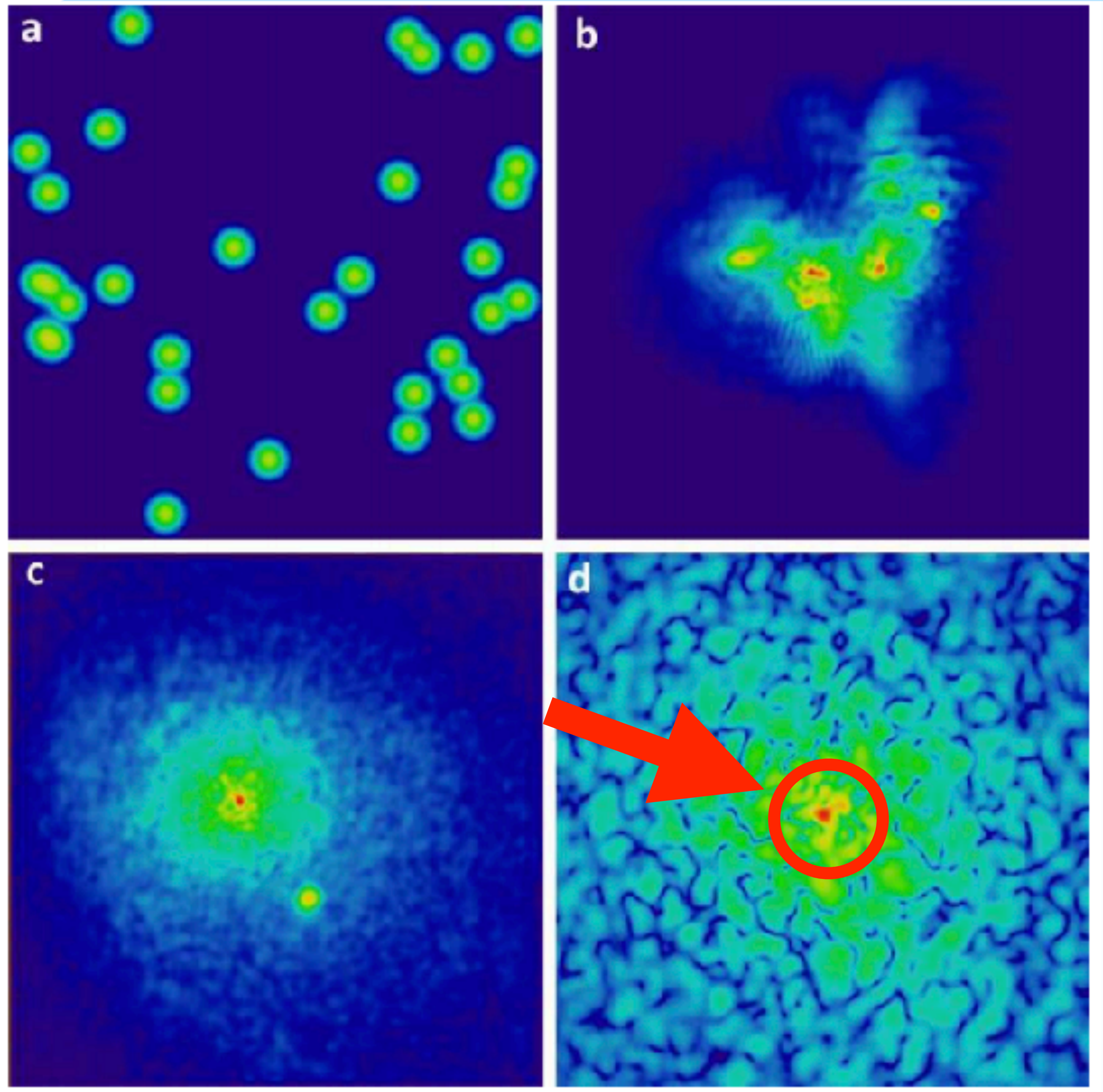
$$\frac{\Delta v^2}{v^2} \simeq \frac{8\ \ln N}{N}$$

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



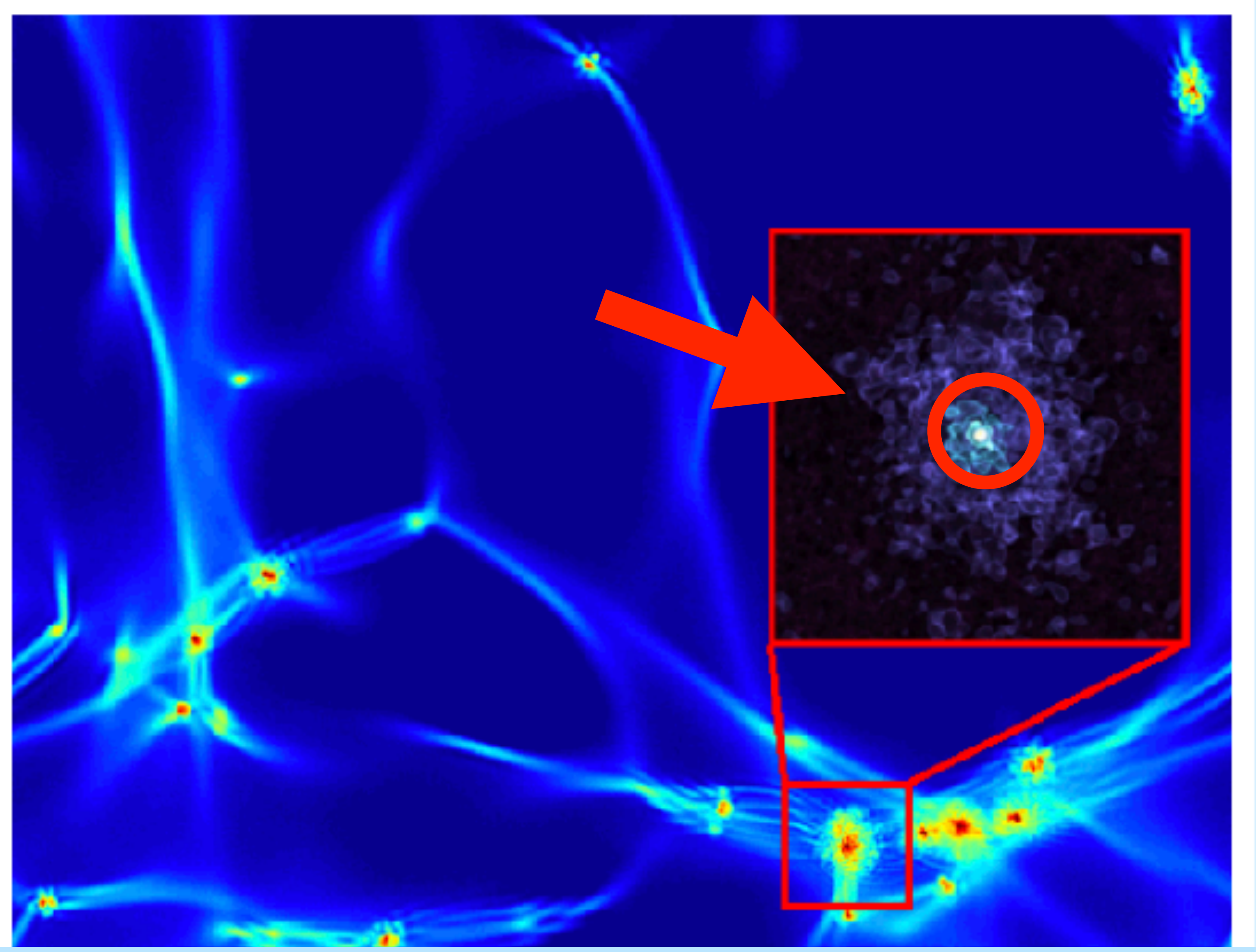
Analytic timescale matches simulation results!

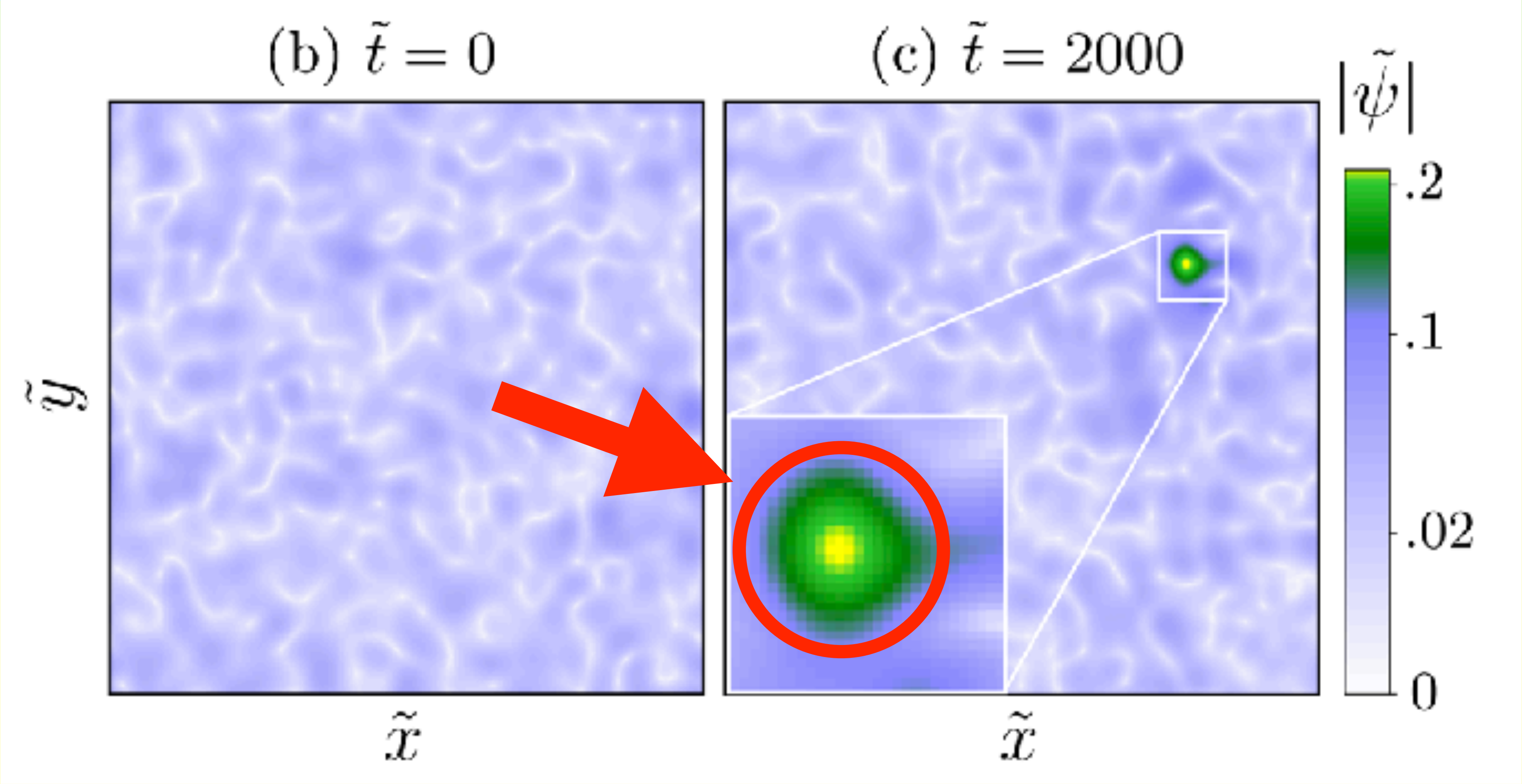
Boson Stars in Simulation



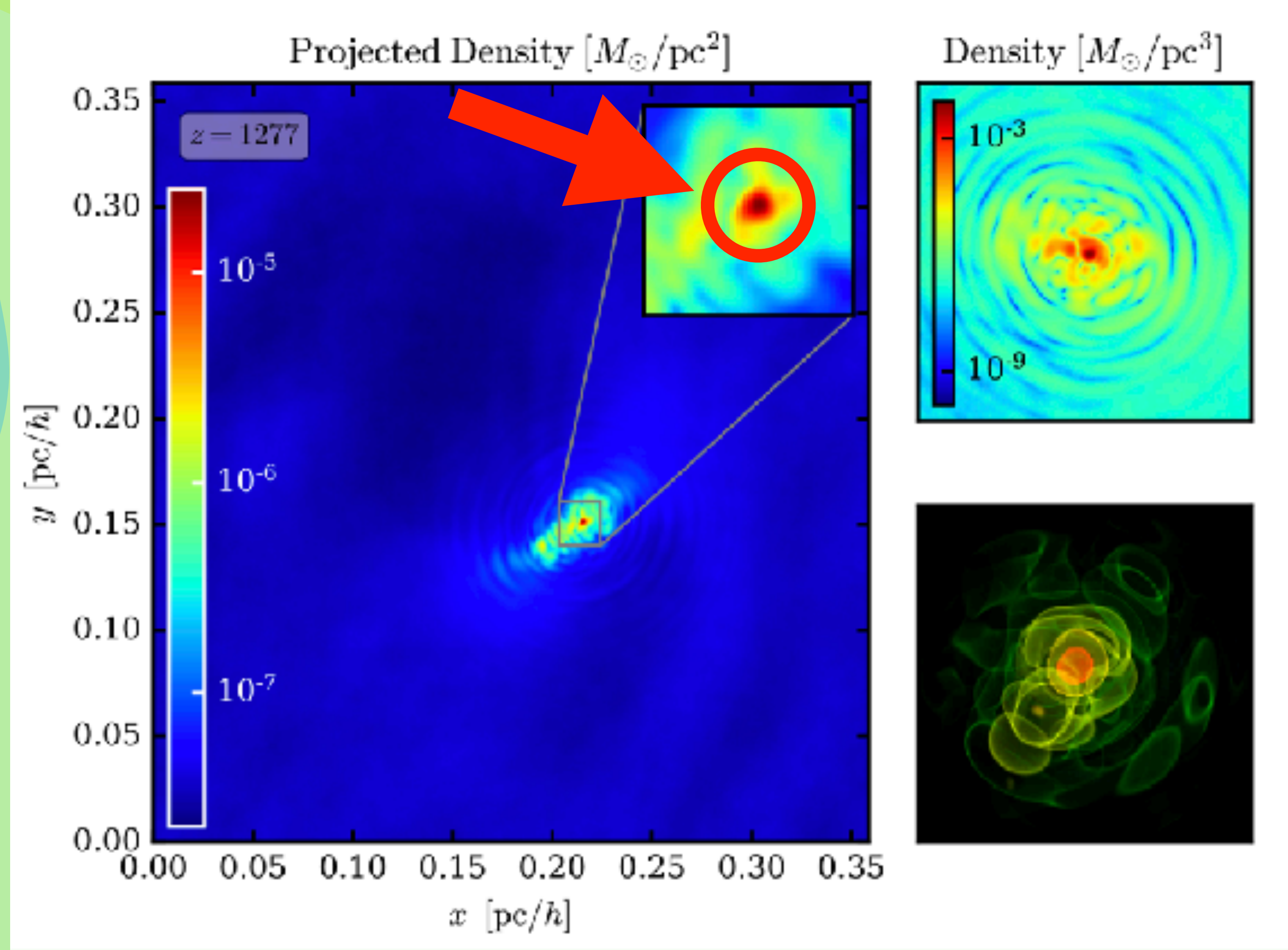
Schive et al.,
Phys. Rev. Lett. 113, 261302 (2014)

Mocz et al.,
MNRAS, Volume 471, Issue 4, November 2017



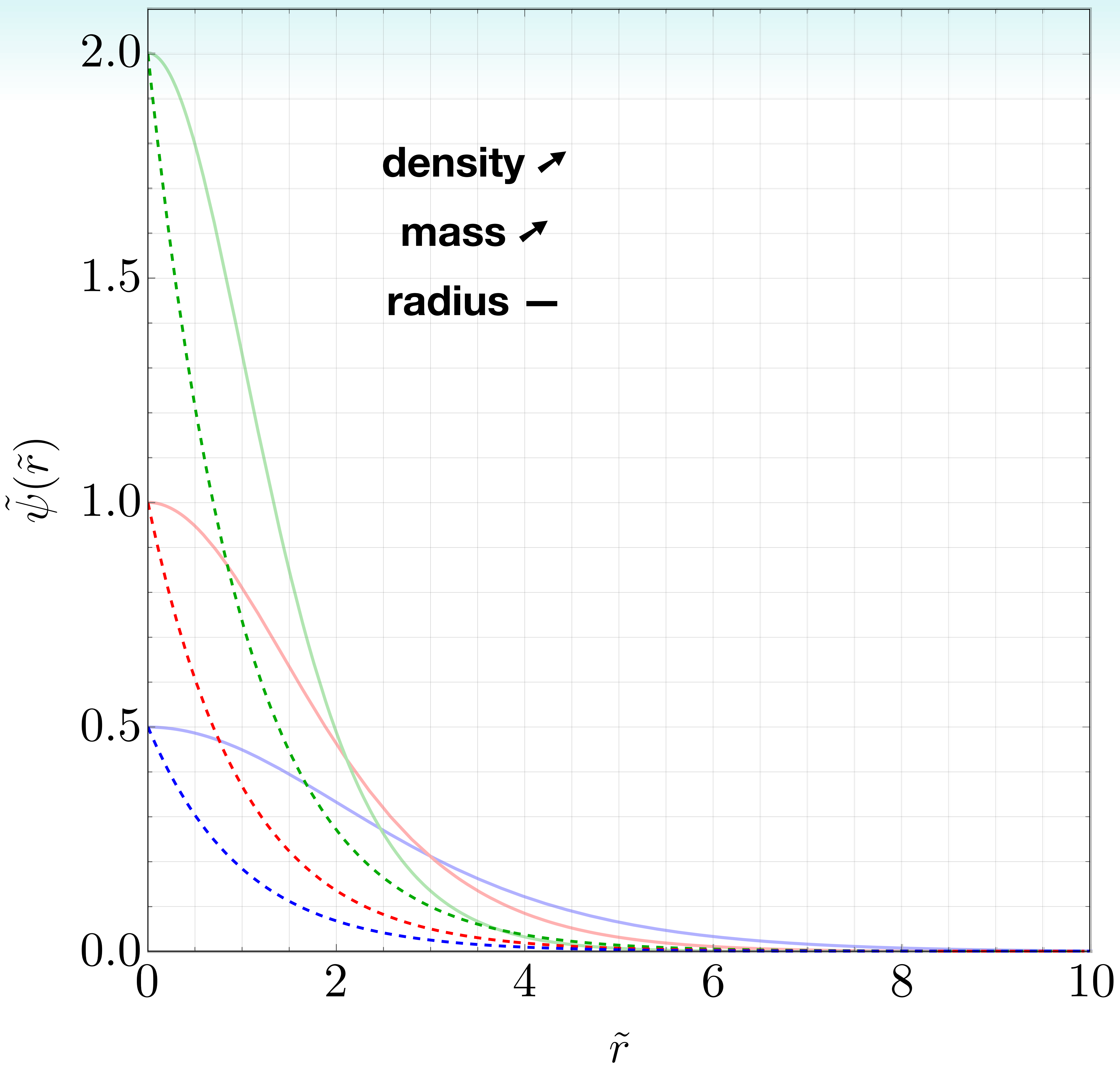


Levkov, Panin, Tkachev,
Phys. Rev. Lett. 121, 151301 (2018)



Eggemeier and Niemeyer,
Phys. Rev. D 100, 063528 (2019)

Bound Bosonic Halo



Ground-state solution of the GPP equations *with a source term*

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

$$\propto \frac{1}{R_\star{}^2} \qquad \propto -\frac{M_{\mathrm{ext}}}{R_\star}$$

- Bound state with external source: gradients ~ external gravity

$$R_\star \simeq \frac{M_P^2}{m_\phi^2 M_{\mathrm{ext}}} \simeq \mathrm{AU}\left(\frac{10^{-14}\,\mathrm{eV}}{m_\phi}\right)^2\left(\frac{M_\odot}{M_{\mathrm{ext}}}\right)$$

$M_\star \ll M_{\mathrm{ext}}$ a free parameter

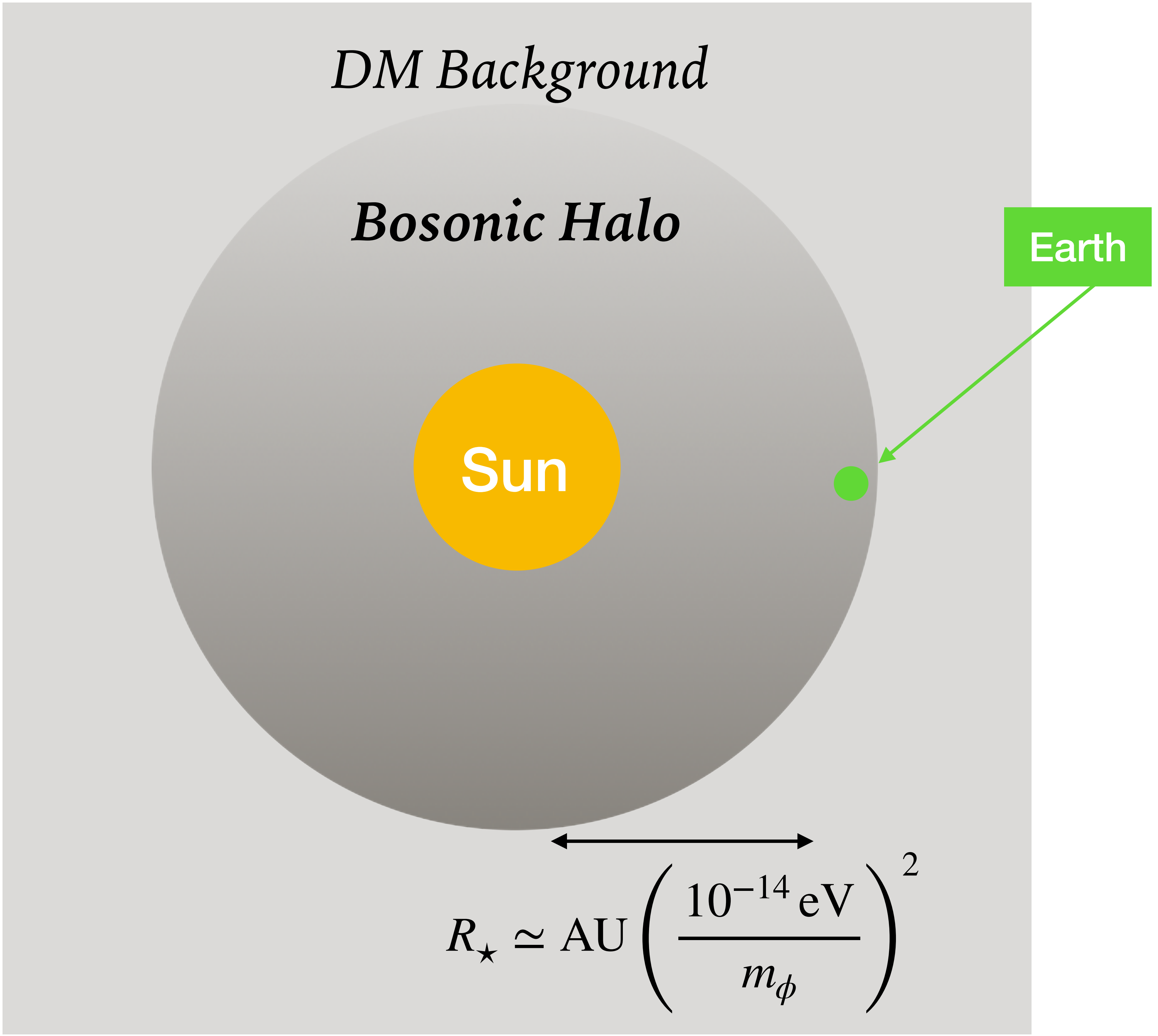
The Picture

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

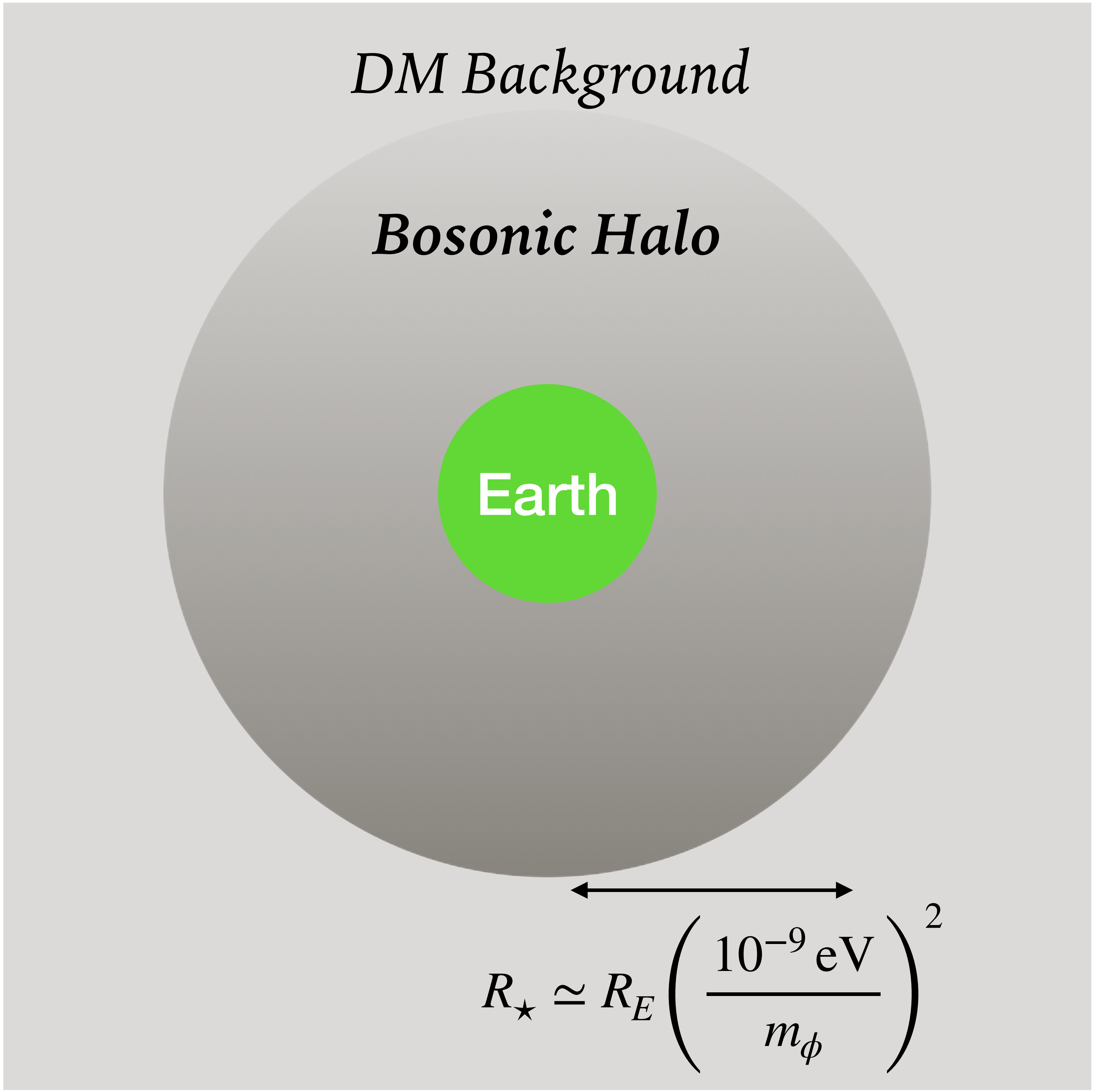
Halo supported by Sun
"Solar Halo"

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

Halo supported by Earth
"Earth Halo"



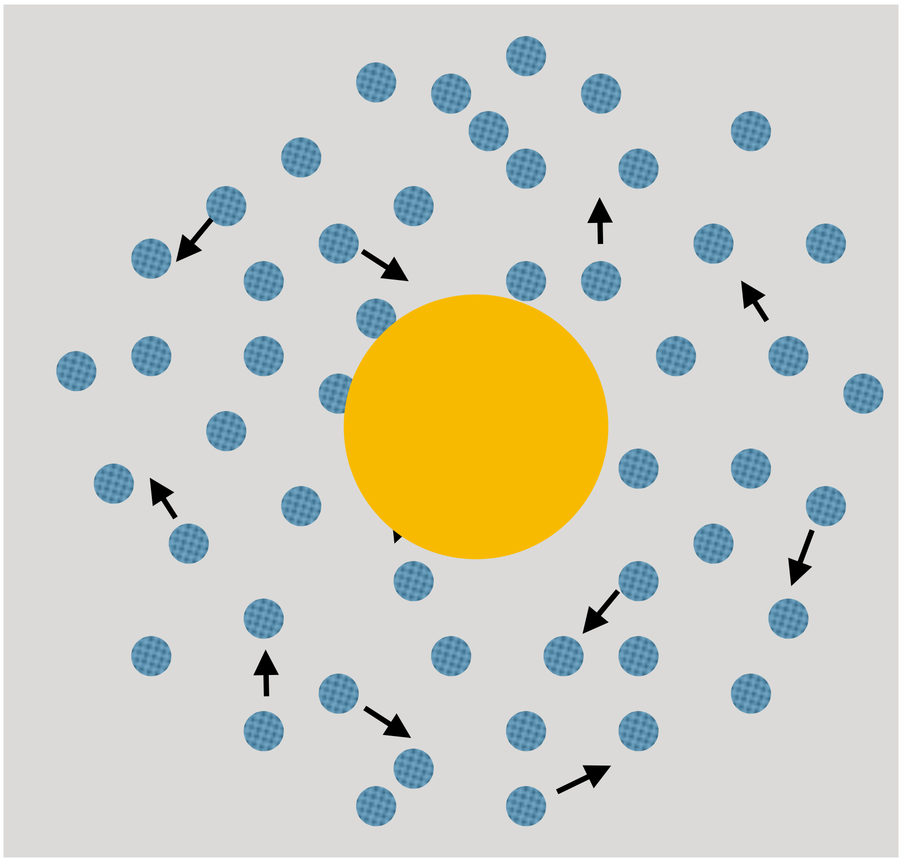
(this talk will focus on solar case)



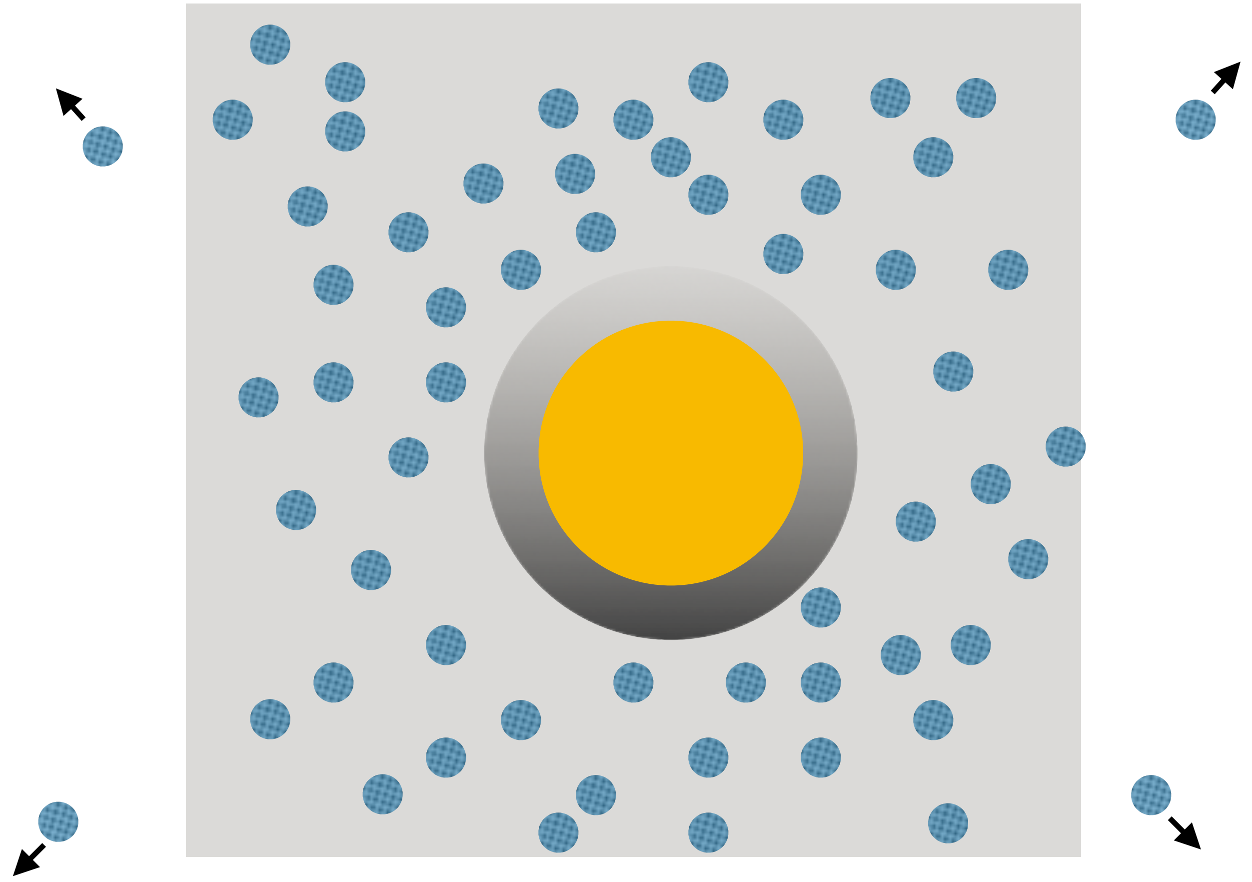
(maybe mention at the end)

Hints

- You: "But can these bound states really form?"
- Analytic argument: If QP relaxation occurs (as with boson stars), resulting ground state is plausibly an bound bosonic halo



Quasiparticle dispersion in the presence of star

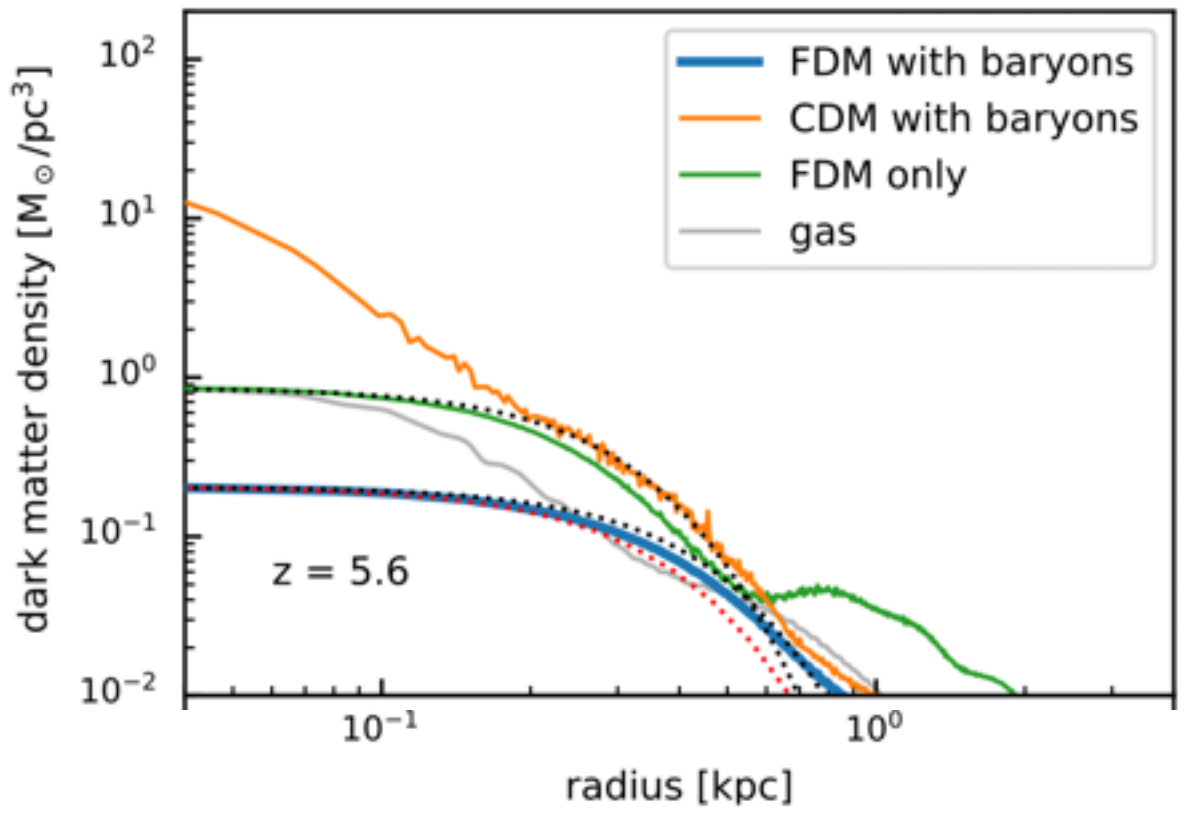


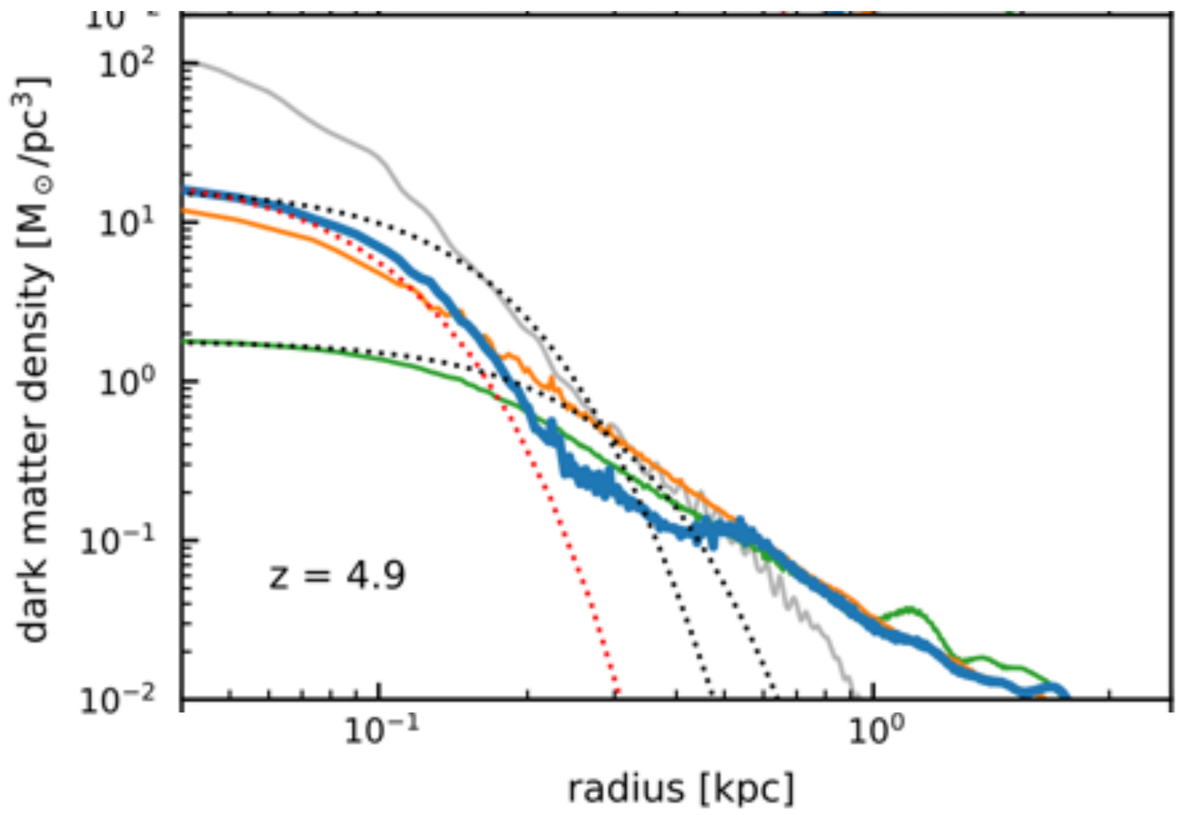
Bound halo formation??

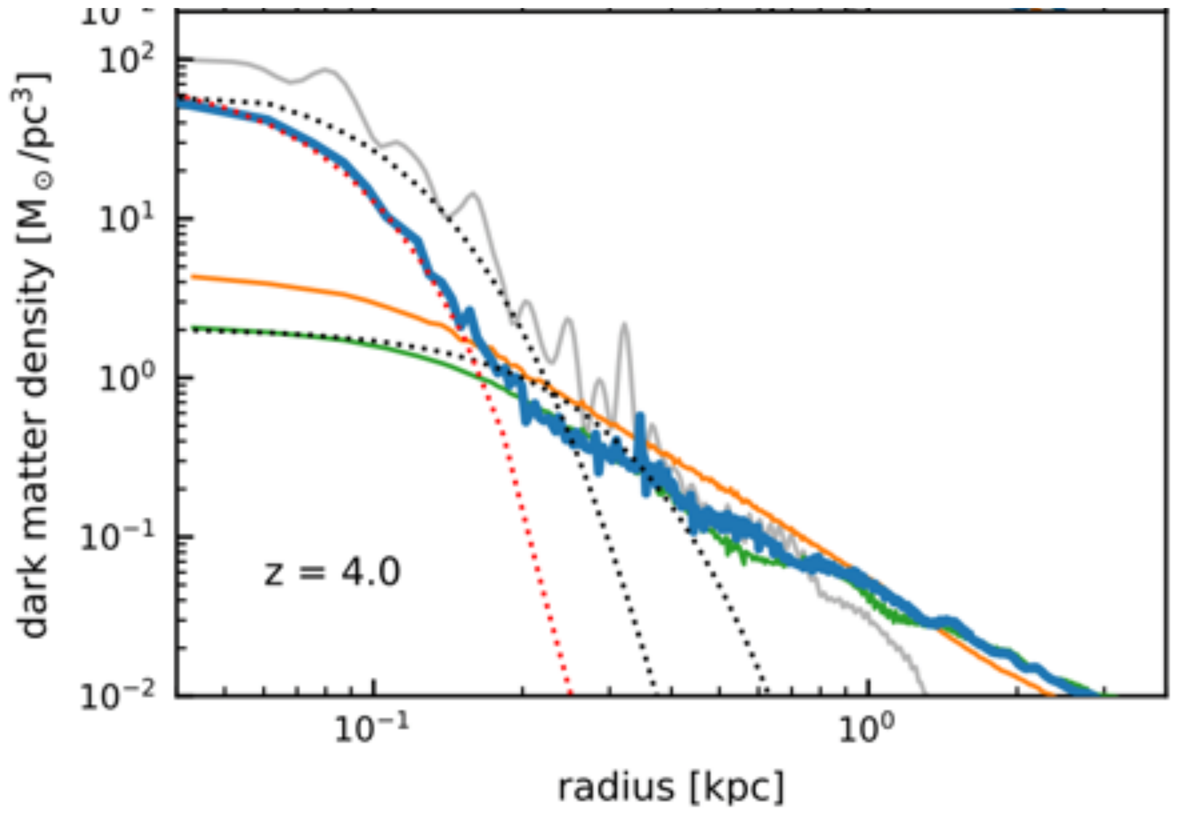
Relaxation to ground state?

Hints (2)

- Numerical simulation, ULDM ("FDM") + fixed central potential ("baryons")
- $m_\phi \simeq 10^{-22}\,\mathrm{eV}$ fixes total size of resulting cores (~few 100s parsec)







Upshot:

- **Baryonic core <u>accelerated</u> bosonic core formation**
- **Resulting "star" was bound to baryonic core, ~exponential profile (as we predicted!)**
- **If the same mechanism effective in solar environment, —> solar halo!**

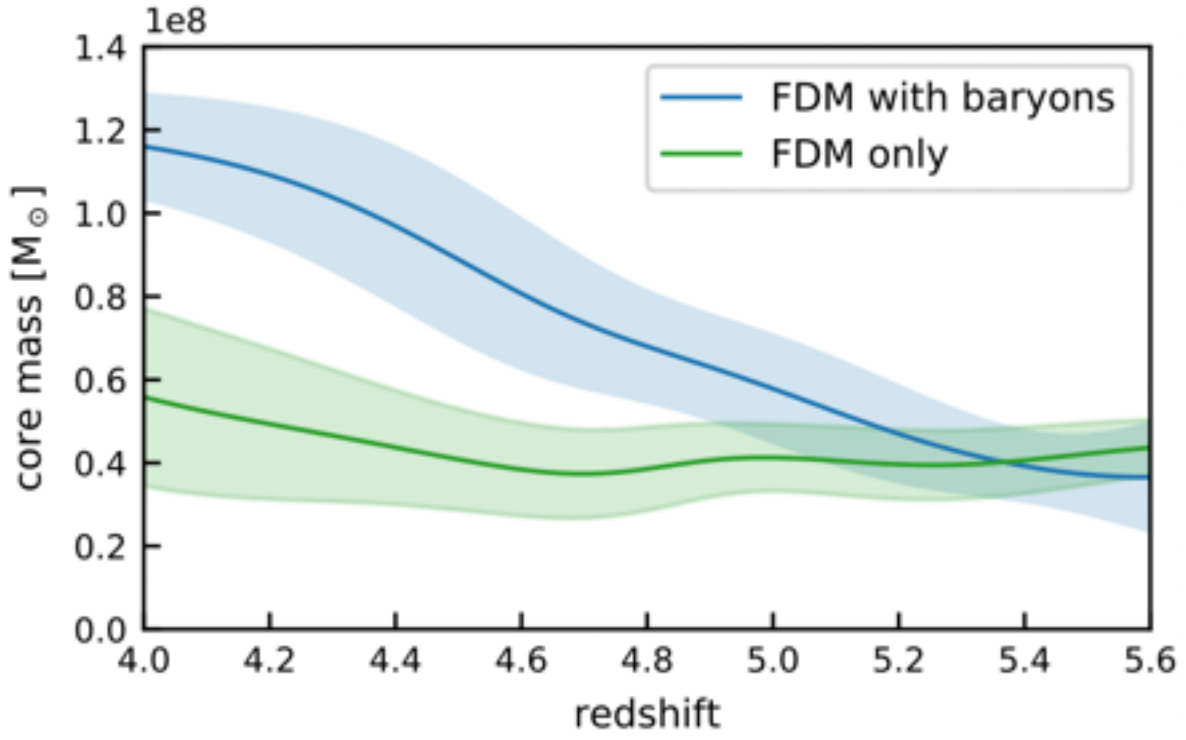
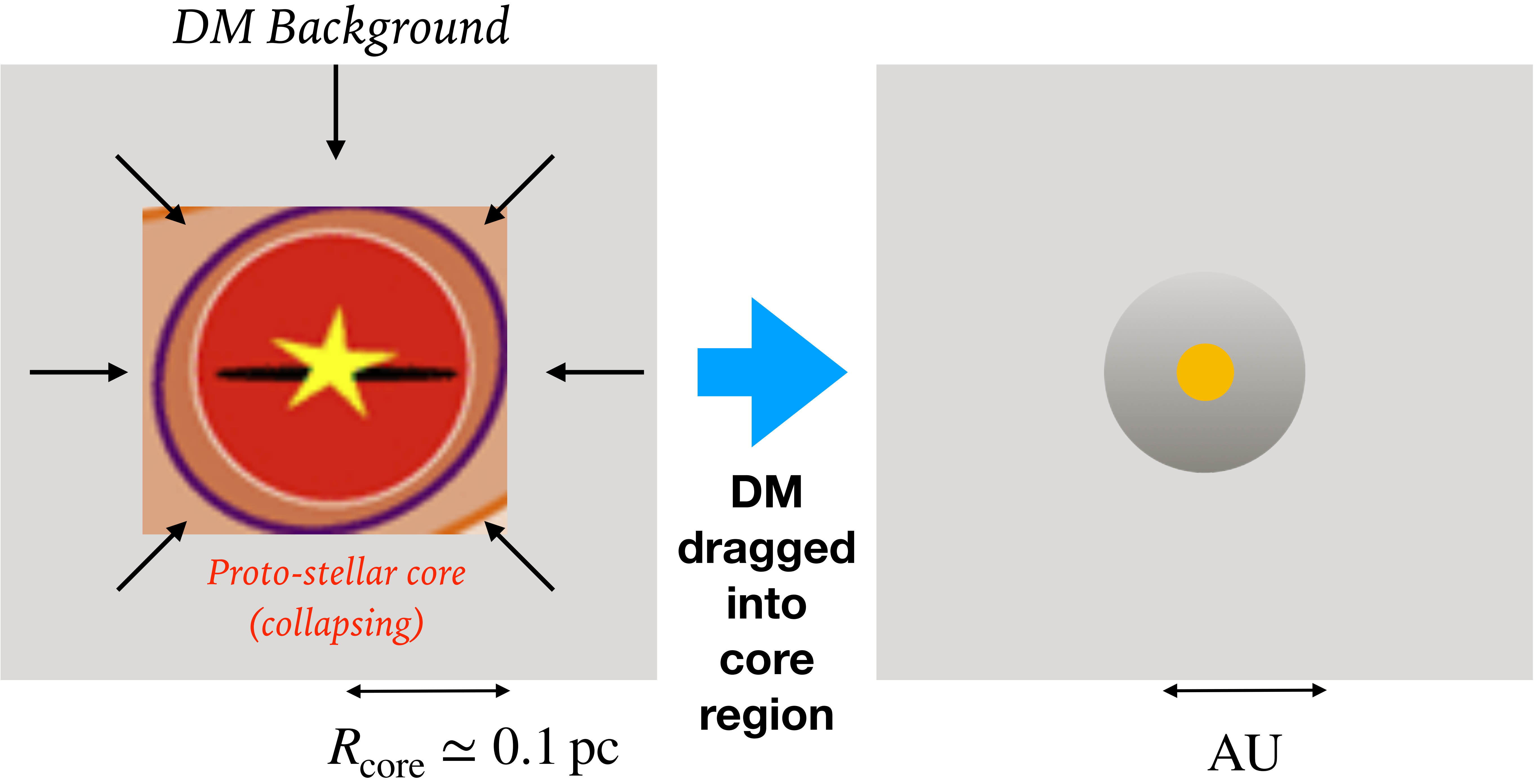


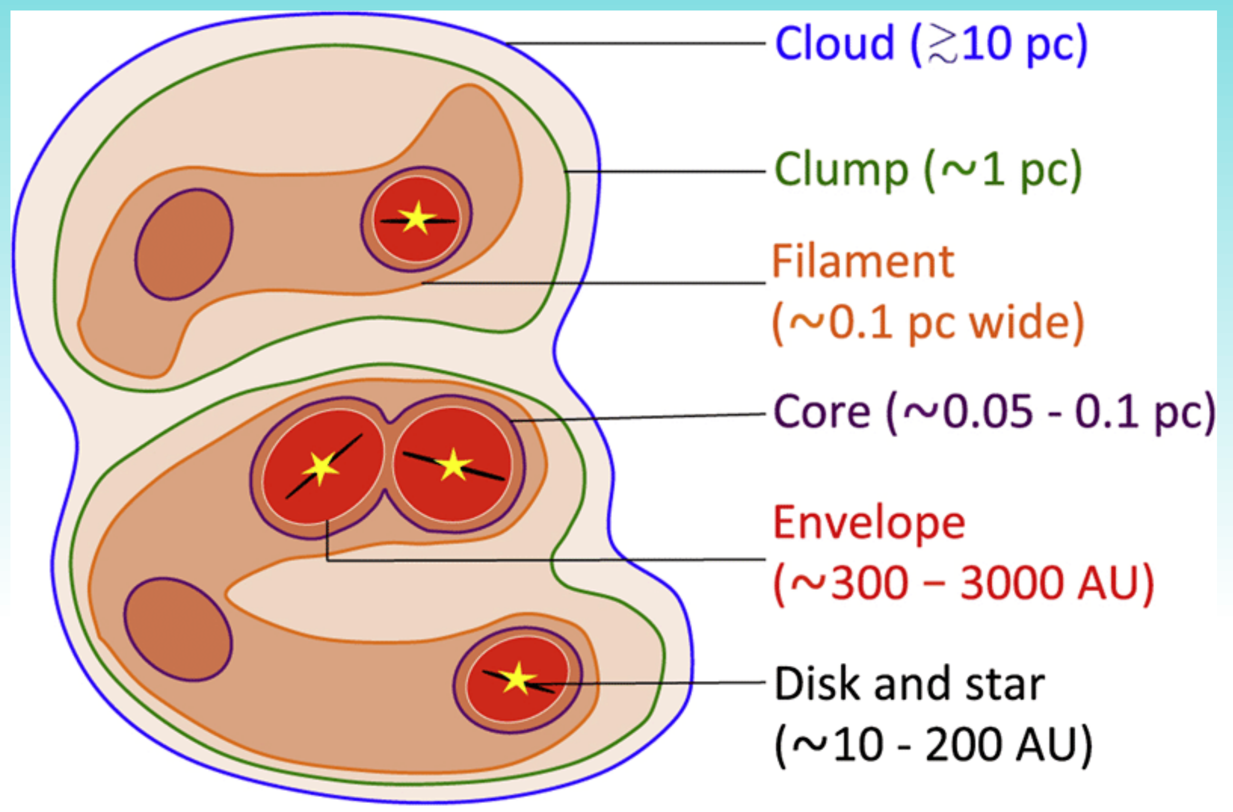
FIG. 5. Evolution of the core mass, defined as the dark matter mass within $\lambda_{\rm dB}/4$ from the center, where $\lambda_{\rm dB}$ is the de Broglie wavelength corresponding to $v_{\rm sol}$. The lines show the Gaussian filtered data points with $\sigma_z = 0.2$. The shaded regions represent the corresponding standard deviations.

Veltmaat, Schwabe, Neimeyer (1911.09614)

Hints (3)

- A small fraction of DM around star-forming molecular clouds can form dense, solar-bound structure through ***adiabatic contraction***





Star formation scales; figure from Rosen et al. (2005.07717)

$$\rho_\oplus \simeq 2\times 10^6 \rho_i \left(\frac{R_i}{\rm ly}\right)^{3/2} \qquad (4)$$

$$\simeq 0.06\,\frac{\rm GeV}{\rm cm^3}\left(\frac{M_{\rm DM}}{10^{-10}M_\odot}\right)\left(\frac{R_i}{\rm ly}\right)^{-3/2} \qquad (5)$$

Although we do not predict a specific density of Solar halo DM at Earth, very small initial abundances (a part in 10^{10}) give rise to local densities comparable to that of the Galactic halo; furthermore, planetary motion limits on the local population of DM allow densities several orders of magnitude higher. Therefore, we find that a detectable abundance is plausible, though we do not set any limits from non-detection.

Anderson, Partenheimer, Wiser (2007.11016)

So from here, we will assume such objects can form.

Though look out for

JE, Gorghetto, Jiang, Kim, Perez (22xx.xxxxx)

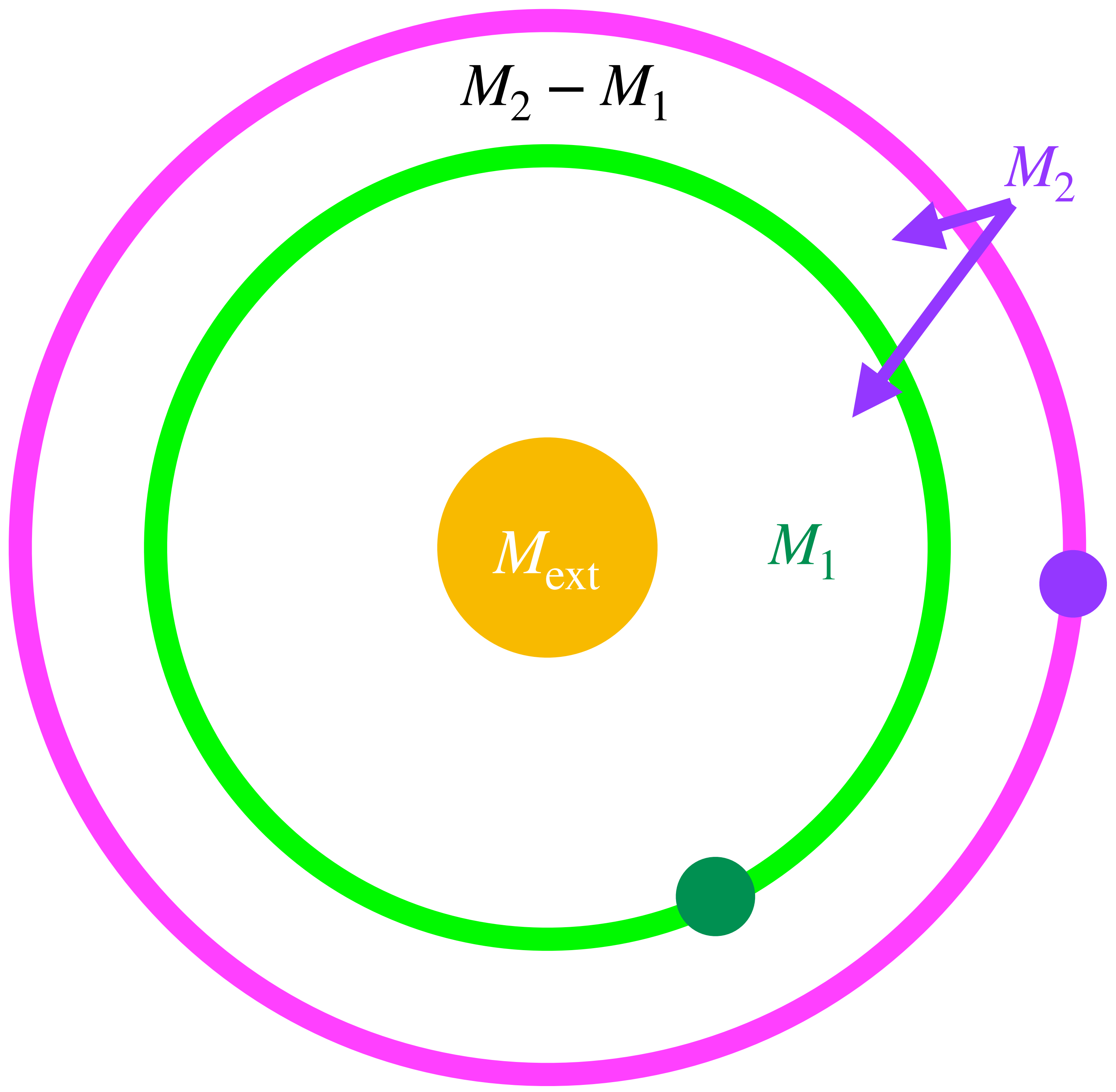
Coming Soon!

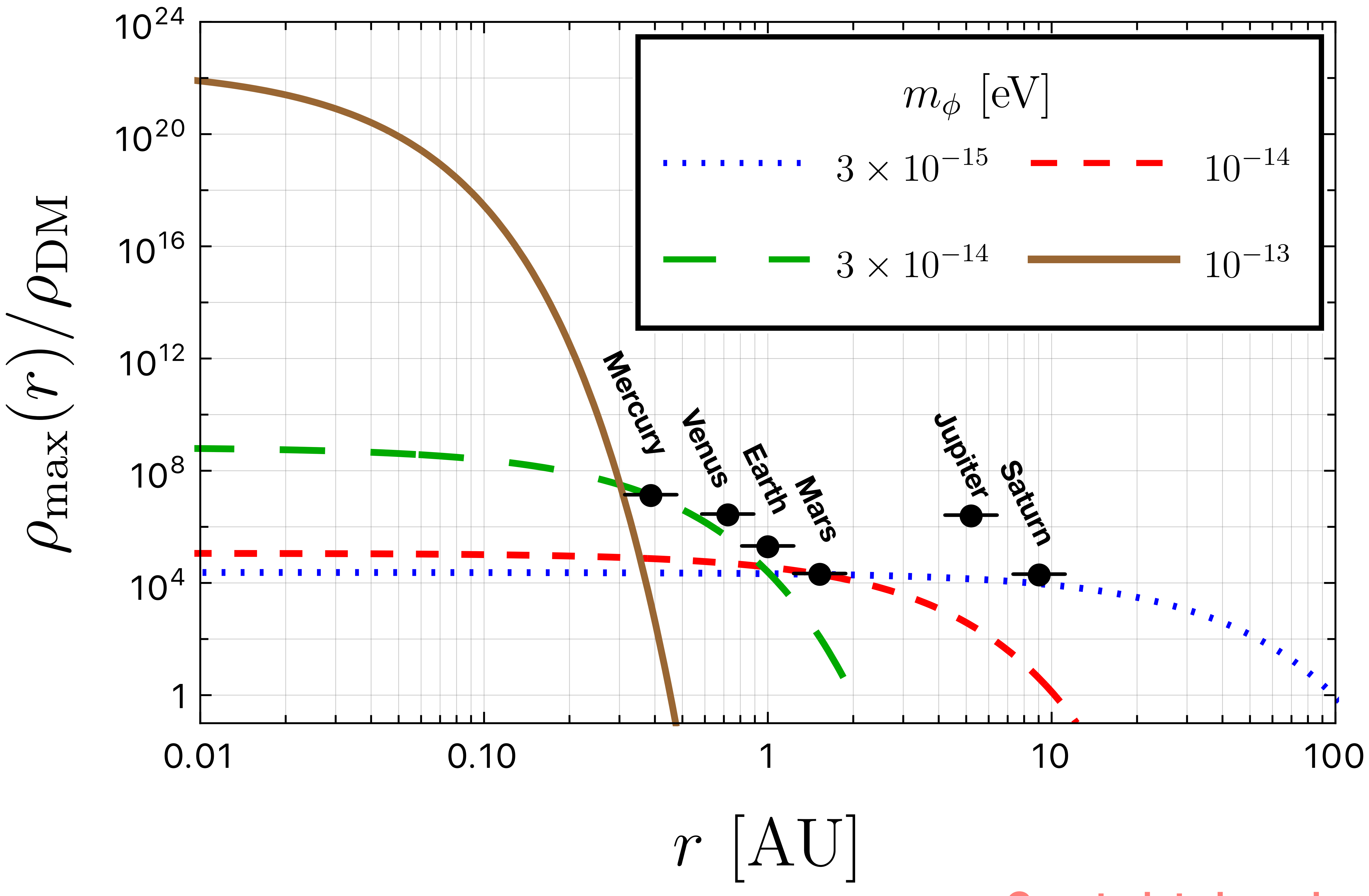
Let’s move on to Constraints and Signals

Constraints: “Extra” DM near Earth

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

Can measure effective mass nearby by comparing orbits:





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

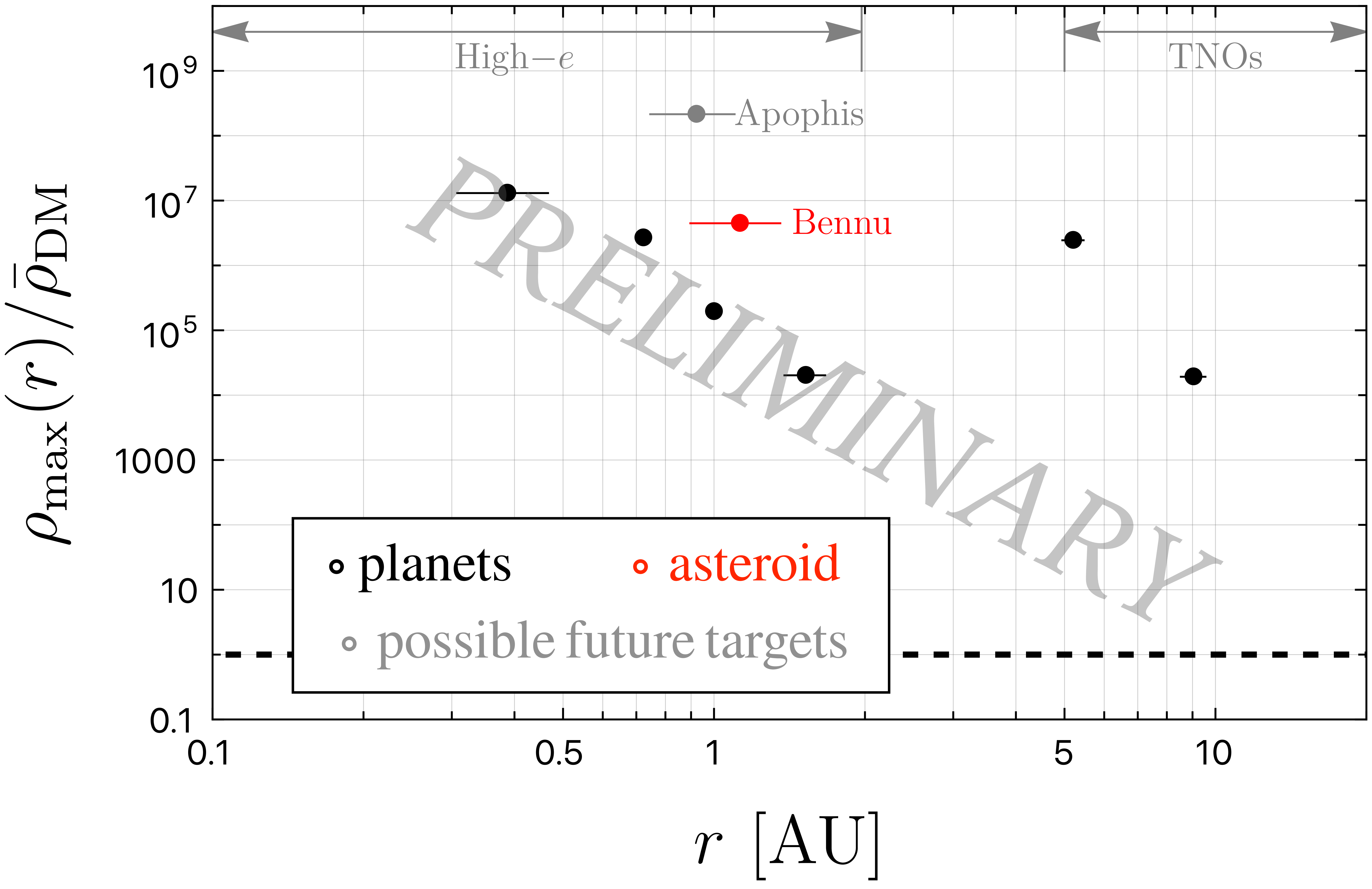
Outer orbit “measures” $M_2 + M_{\rm ext}$

Comparison of the two “measures” $M_2 - M_1$, **the “extra” mass contained between the orbits**

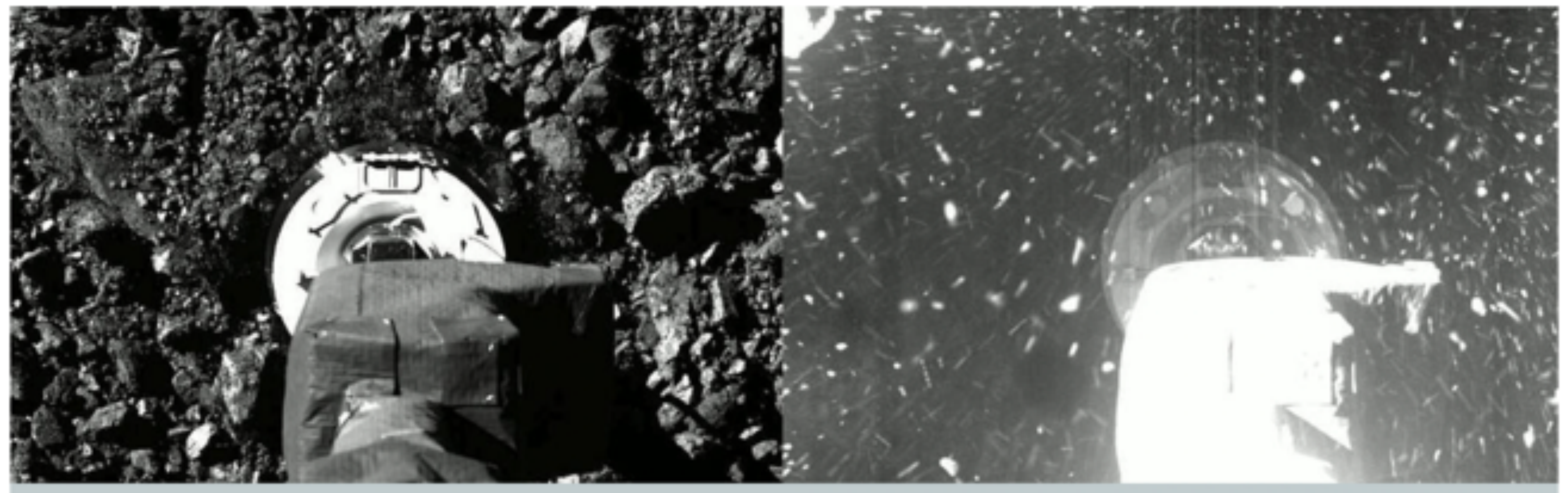
Constraints based on Pitjev and Pitjeva (1306.5534)

Planets and Asteroids!

Tsai, JE, Arakawa, Farnocchia, Safronova (22xx.xxxxx)



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



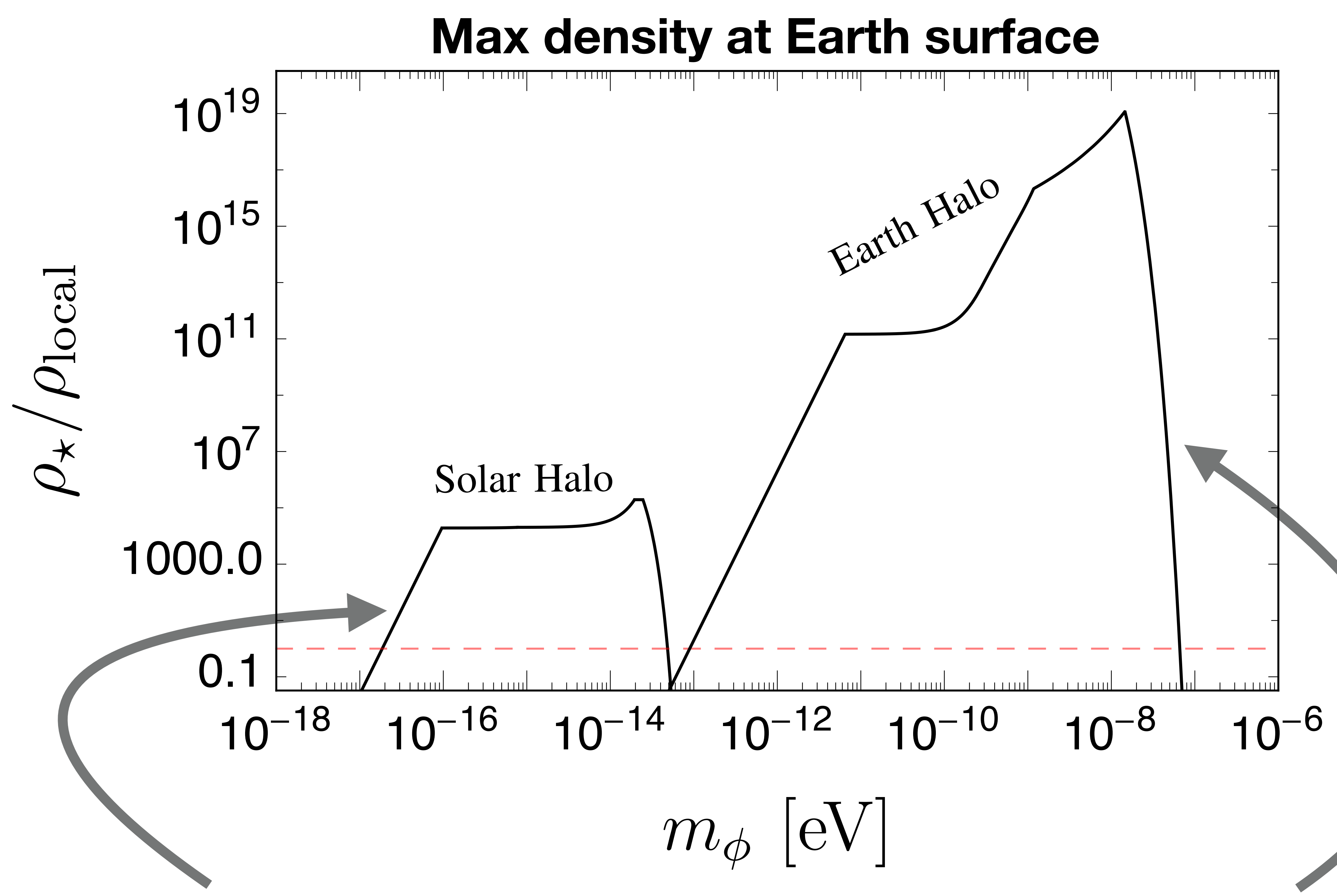
Side-by-side images from NASA's OSIRIS-REx spacecraft of the robotic arm as it descended towards the surface of asteroid Bennu (left) and as it tapped it to stir up dust and rock for sample collection (right). OSIRIS-REx touched down on Bennu at 6:08pm EDT on October 20, 2020. Credits: NASA's Goddard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

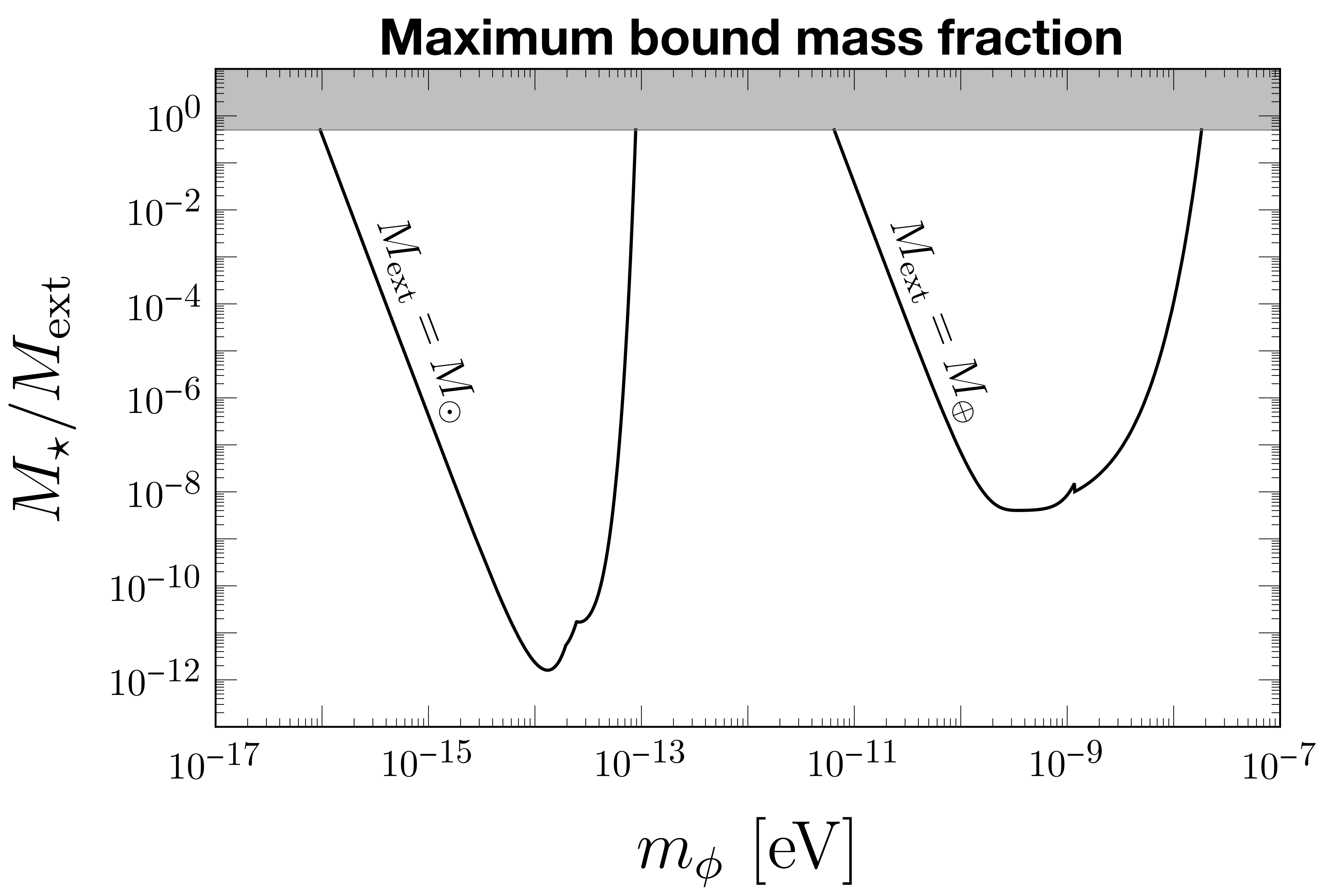
After delivering sample to Earth, will continue toward orbit of Aphophis (extended mission known as OSIRIS-APEx)

Possible Overdensity

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

Density can be very much enhanced relative to 'naive' expectation $\rho_{\rm local}$





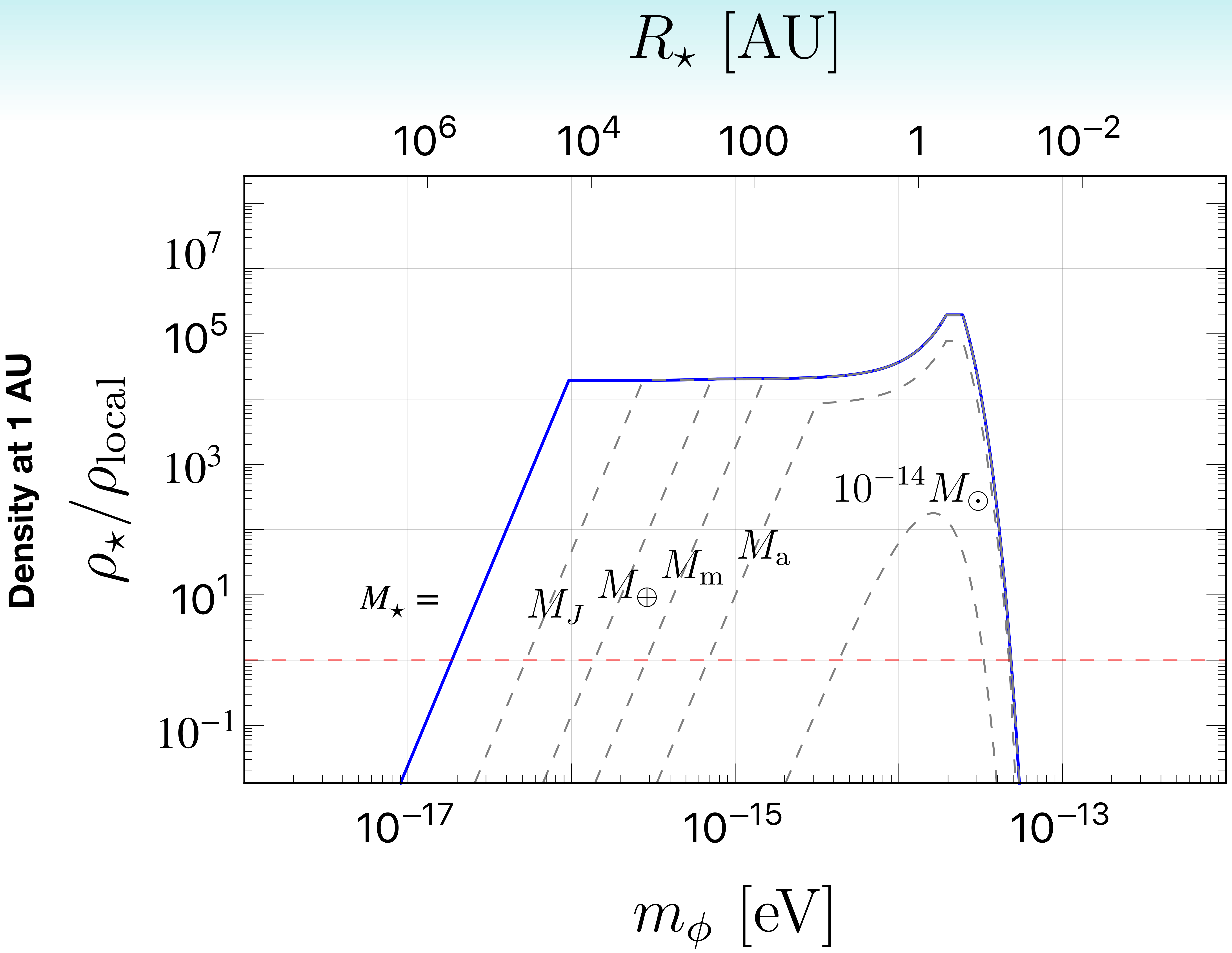
Solar System Ephemerides
(Mercury, Mars, Saturn)

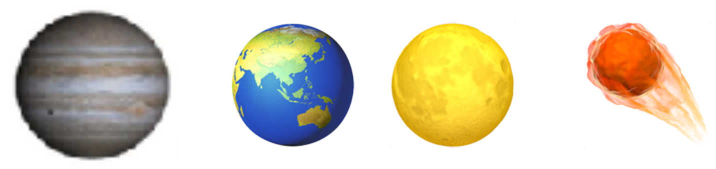
Pitjev and Pitjeva (1306.5534)

Lunar Laser Ranging
+ LAGEOS Satellite

Adler (0808.0899)

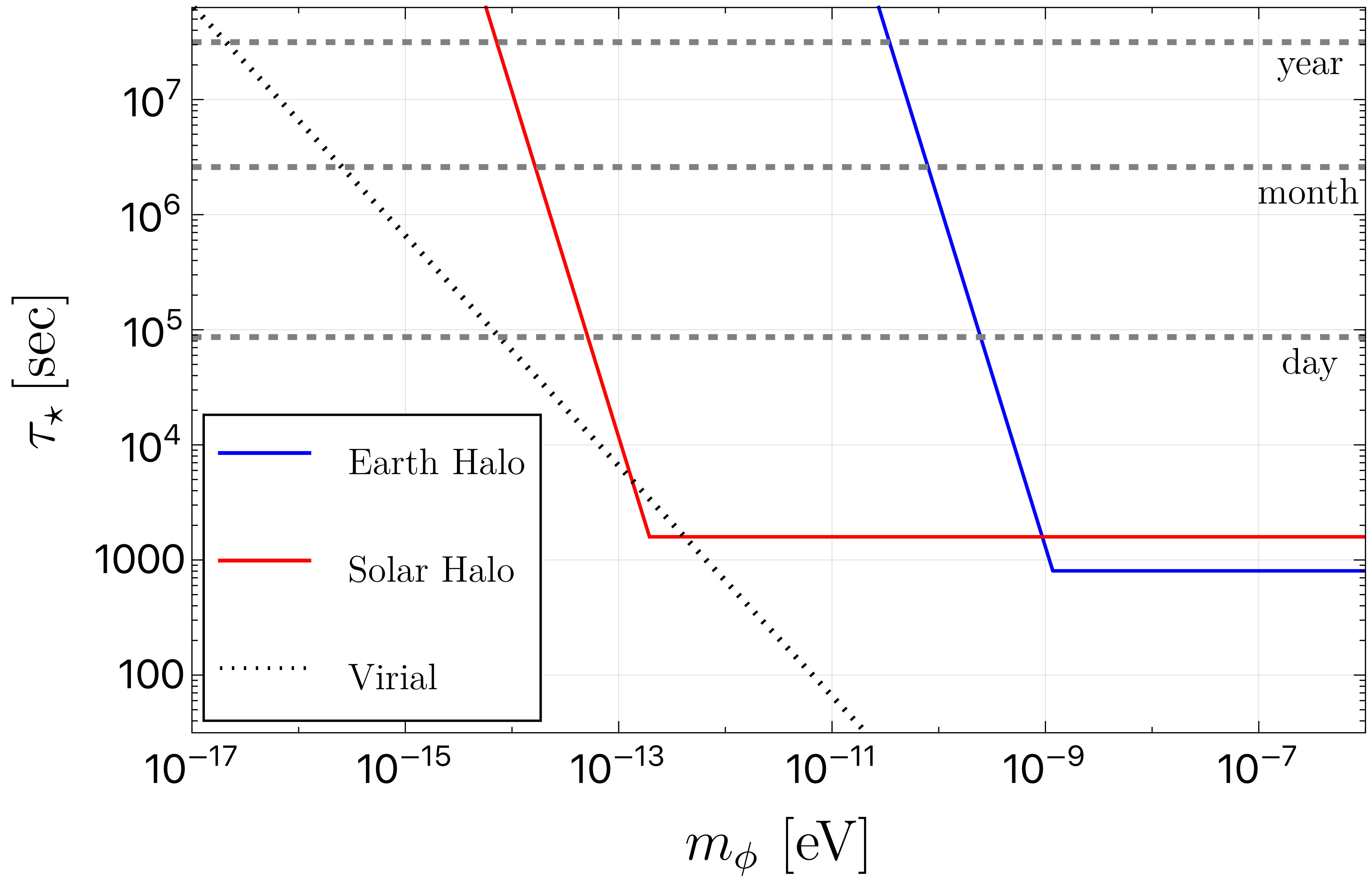
Small Bound Mass Still Matters

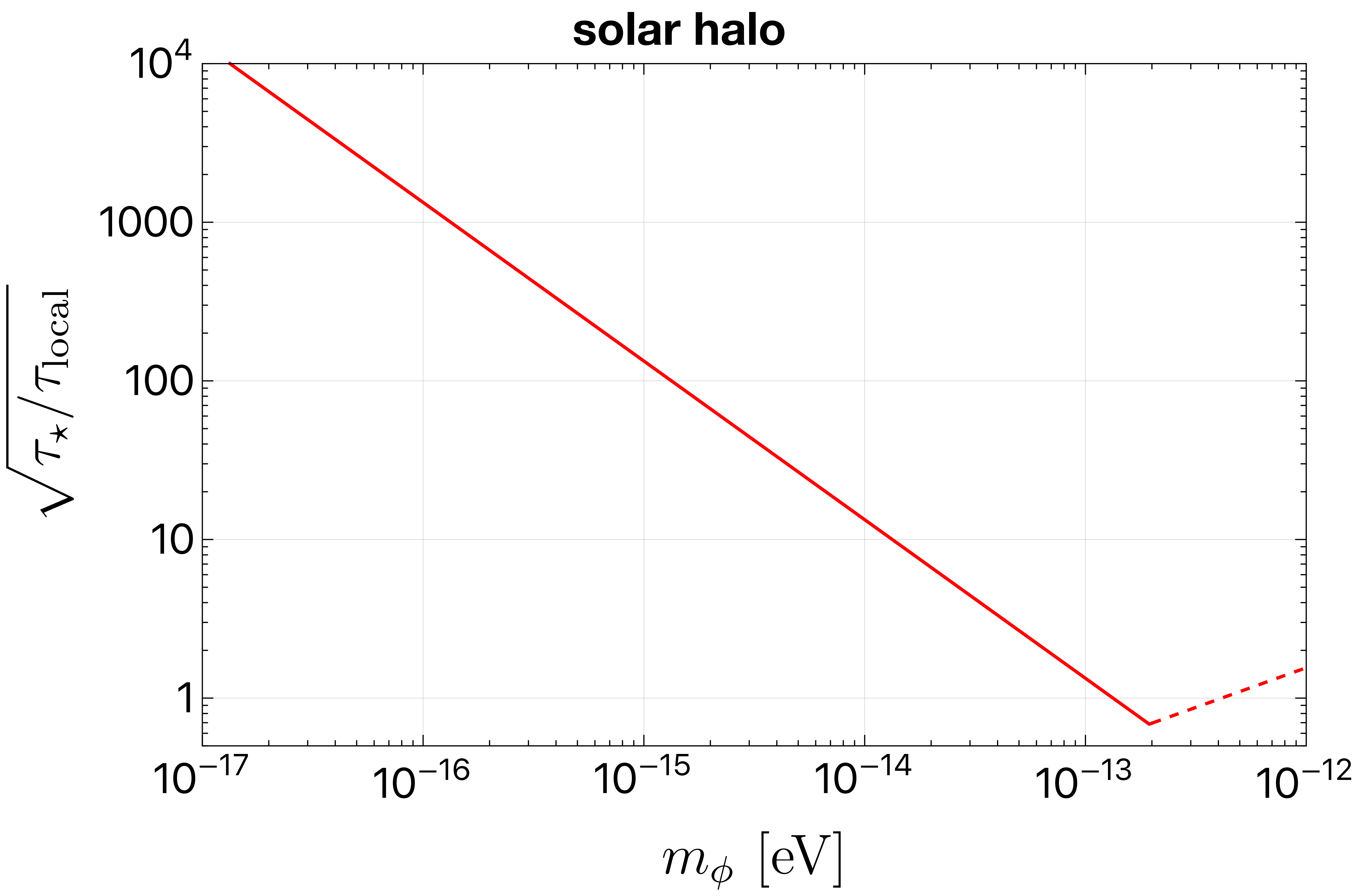


Just one extra:  **or even smaller!**

Coherence of the Signal

- "Direct detection" experiments for ULDM draw greater sensitivity from the long coherence time of the DM oscillations
- Can be much longer for bound states!





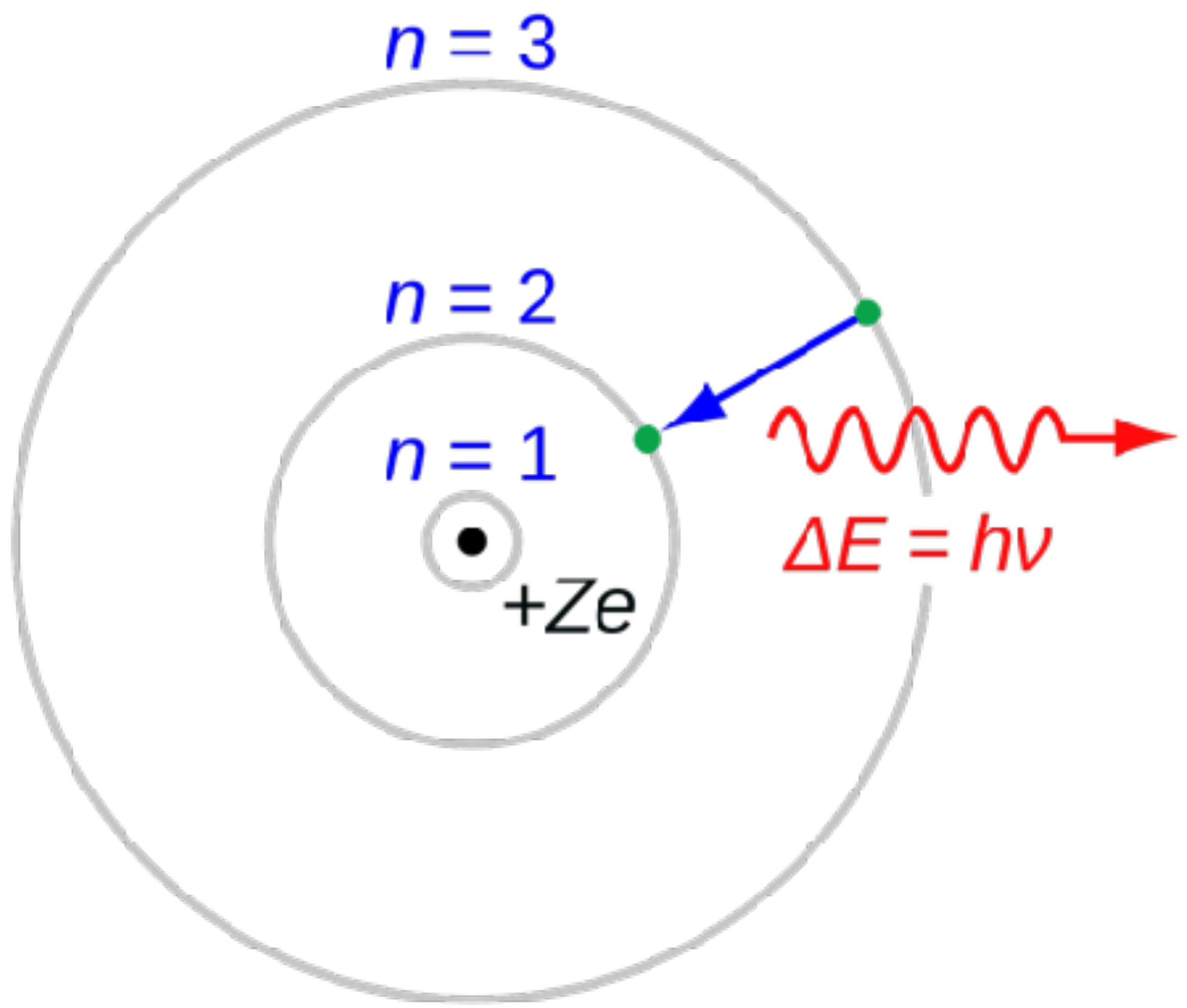
Signals for Scalars

- Recall the Lagrangian: $\mathscr{L} \supset \frac{d_\alpha}{4\tilde{M}_P}\phi\, F^{\mu\nu}F_{\mu\nu}$
- Oscillation of $\phi = \phi(t)$ induces effective variation of fine structure constant

$$\alpha(t) = \alpha_0\left(1 - d_\alpha \frac{\phi(t)}{\tilde{M}_P}\right) \quad \Rightarrow \quad \frac{\delta\alpha}{\alpha_0} \simeq \frac{d_\alpha\sqrt{2\rho_\phi}}{m_\phi \tilde{M}_P} \simeq 6\times 10^{-16} d_\alpha \left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)\sqrt{\frac{\rho_\phi}{\rho_{\mathrm{local}}}}$$

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

Derevianko + Pospelov (1311.1244)
Arvanitaki, Huang, Van Tilburg (1405.2925)
Stadnik and Flambaum (1412.7801, 1503.08540)
...



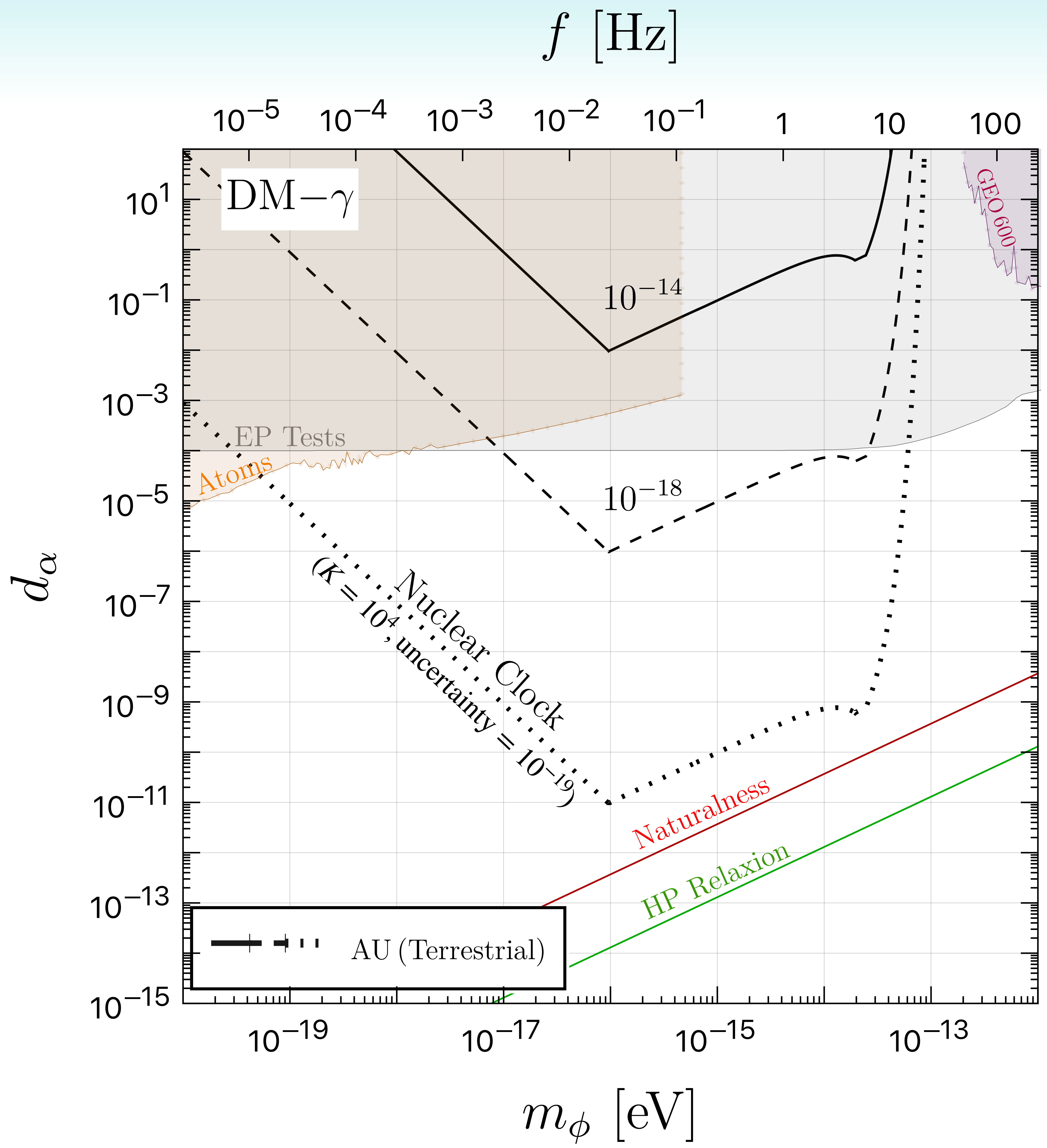
Modern optical clocks have achieved $\frac{\delta\alpha}{\alpha_0} \lesssim 10^{-18}$

Future nuclear clock may reach $\frac{\delta\alpha}{\alpha_0} \lesssim 10^{-23}$ **(though does not exist yet)**

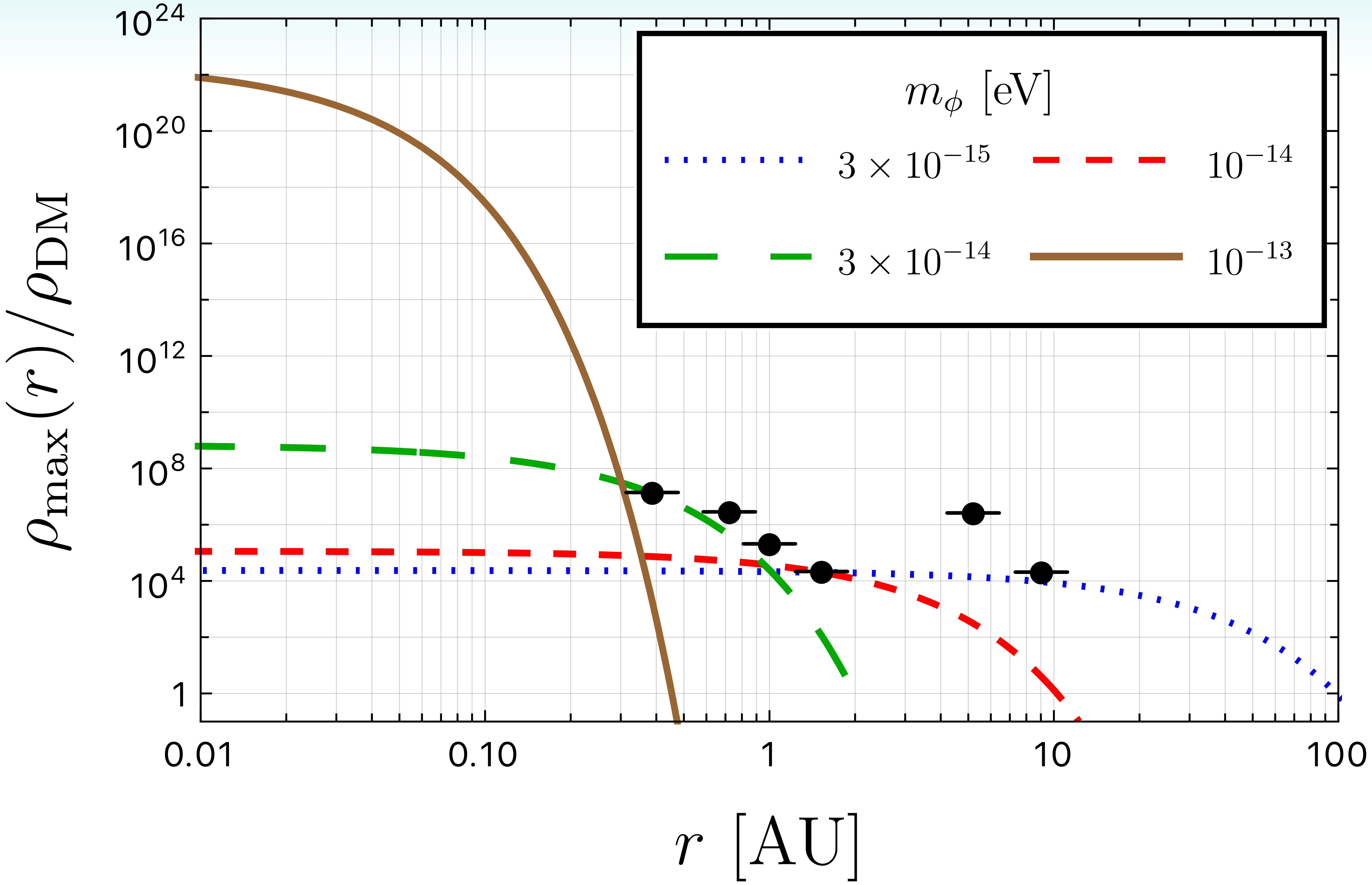
Terrestrial Searches

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

Tsai, JE, Safronova (2112.07674)



Reaching for the Star



For $\rho(r = \mathrm{AU})$ to be large, we are restricted to $m_\phi \lesssim 3 \times 10^{-14}\,\mathrm{eV}$

What if we could probe $\rho(r \ll \mathrm{AU})$??

Famous Greek myth of Icarus

image credit: delcarmat via Shutterstock

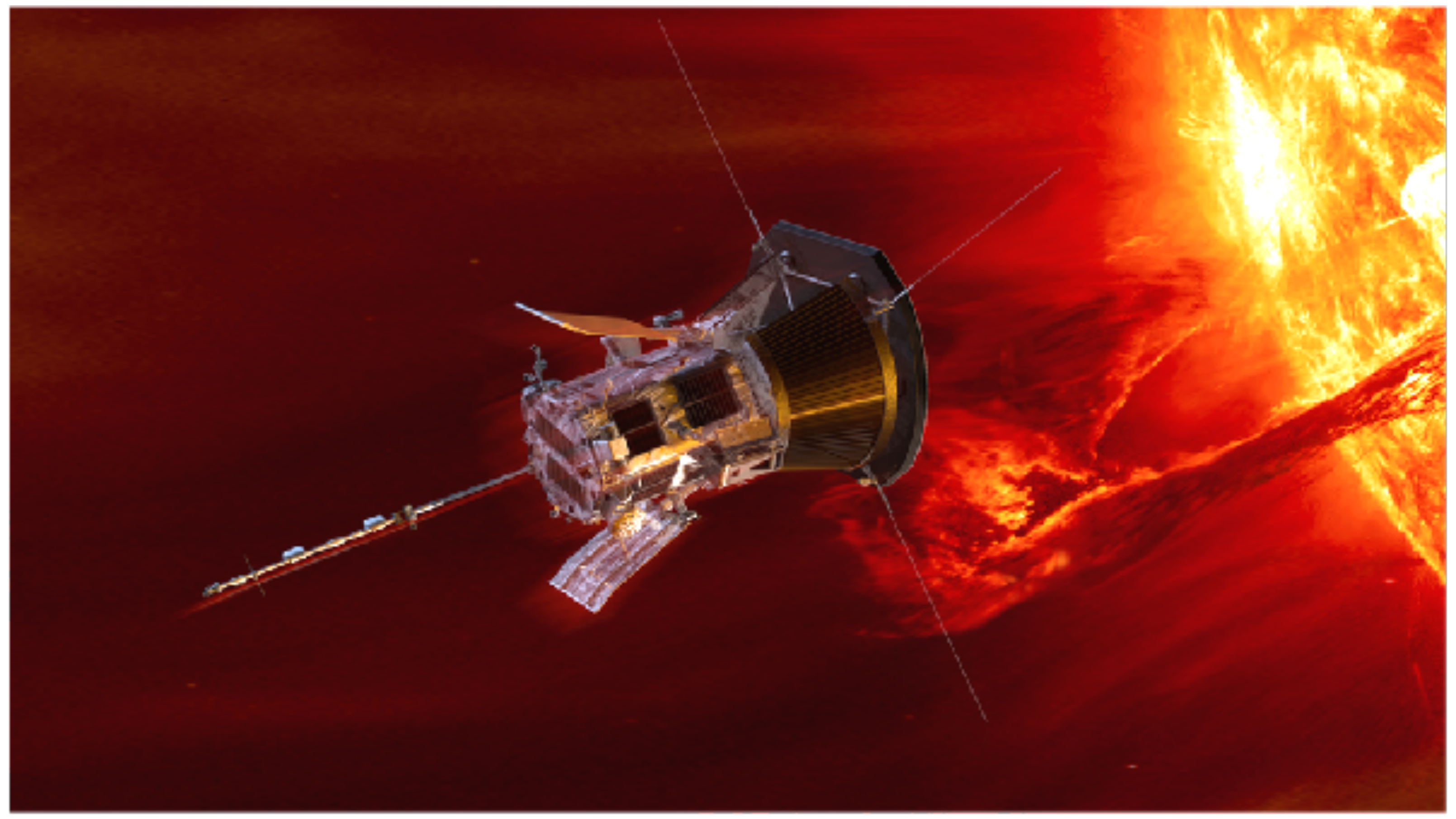
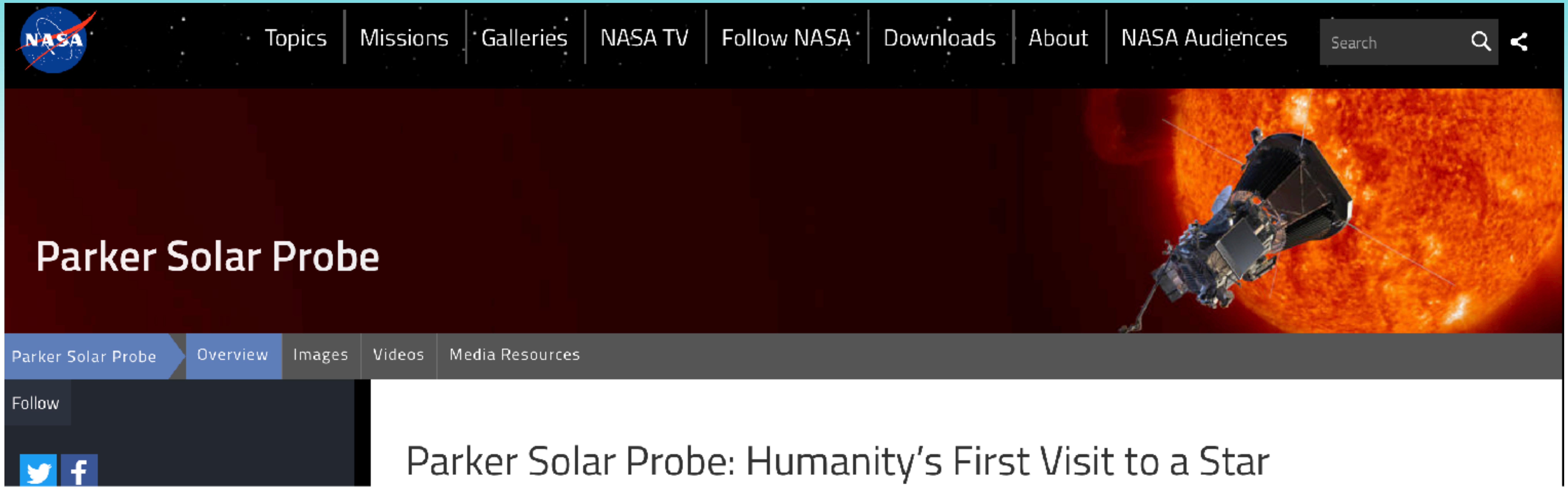
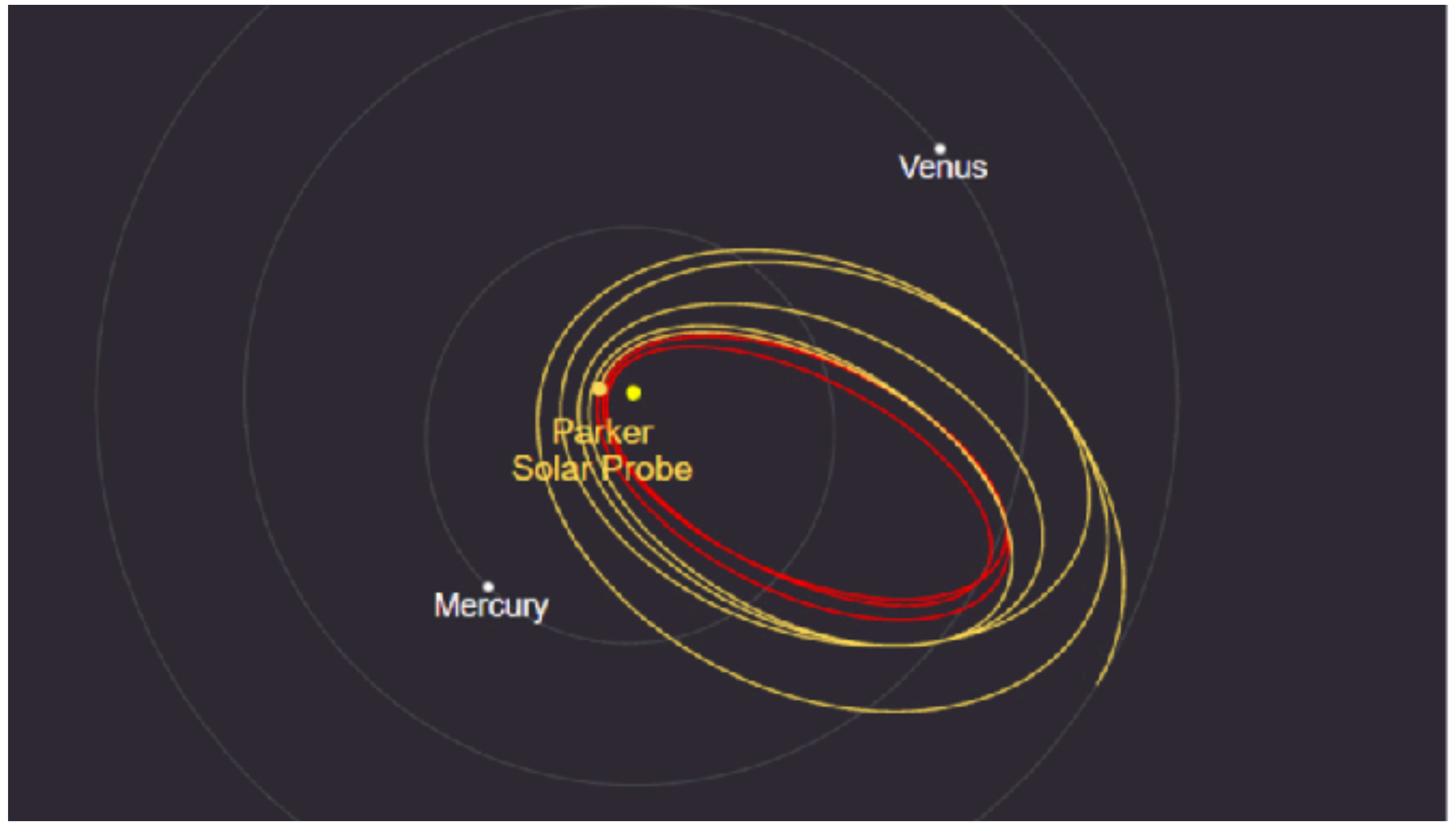


image credit: NASA-JHU-APL

Icarus should have brought a heat shield!



- Parker Solar Probe has been operational since 2018
- Has reached distance of 0.06 AU from Sun (current) (0.045 AU target)



credit: NASA

Missions in Space

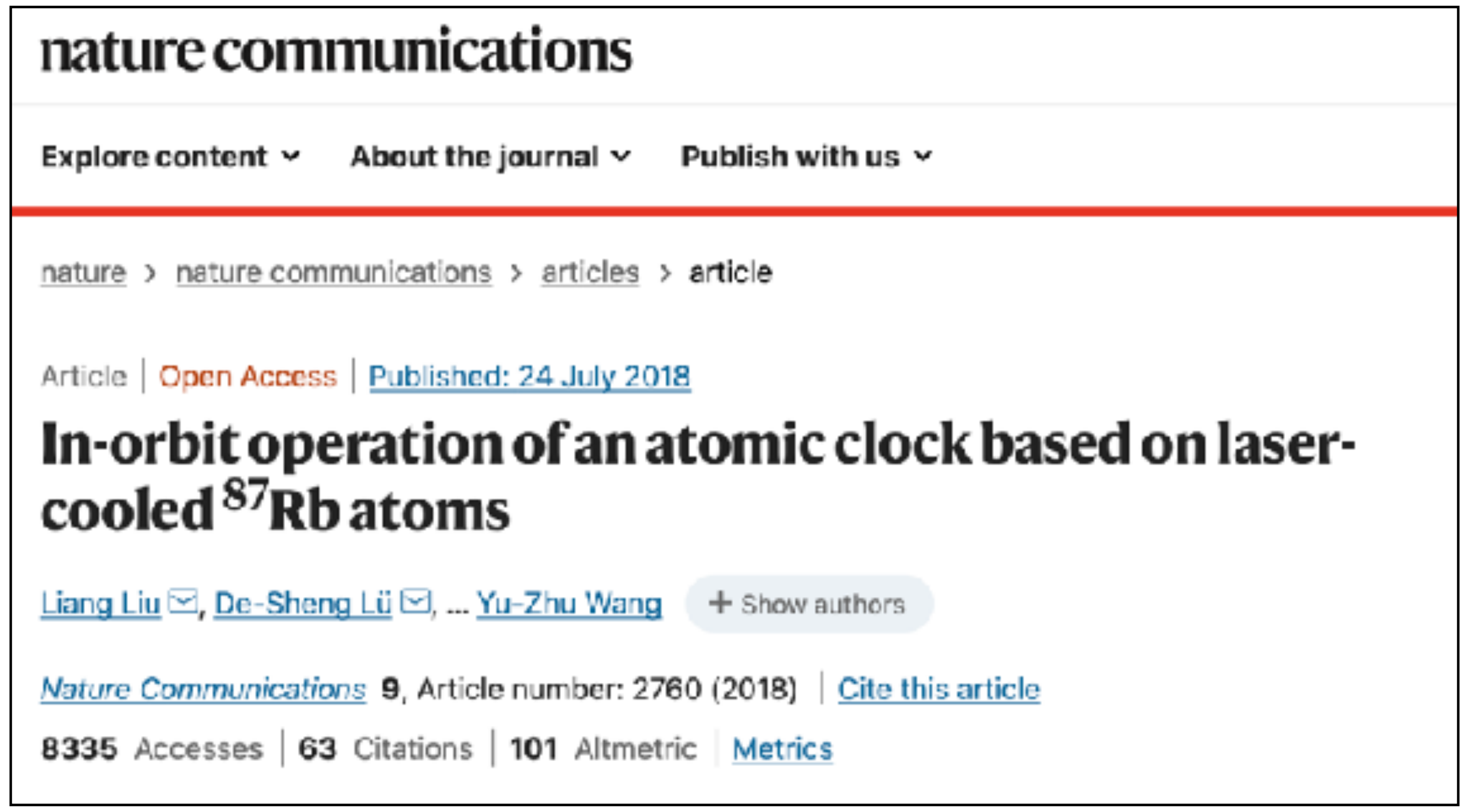
◉ International community developing technologies to put atomic clocks in space

NASA Deep Space Atomic Clock (DSAC) 🇺🇸


nature
Explore content ⌄ About the journal ⌄ Publish with us ⌄
nature › articles › article
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 $\sim 10^{-14}$

Cold Atom Clock Experiment in Space (CACES) 🇨🇳


nature communications
Explore content ⌄ About the journal ⌄ Publish with us ⌄
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 $\sim 10^{-14}$

Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite (PHARAO) 🇫🇷

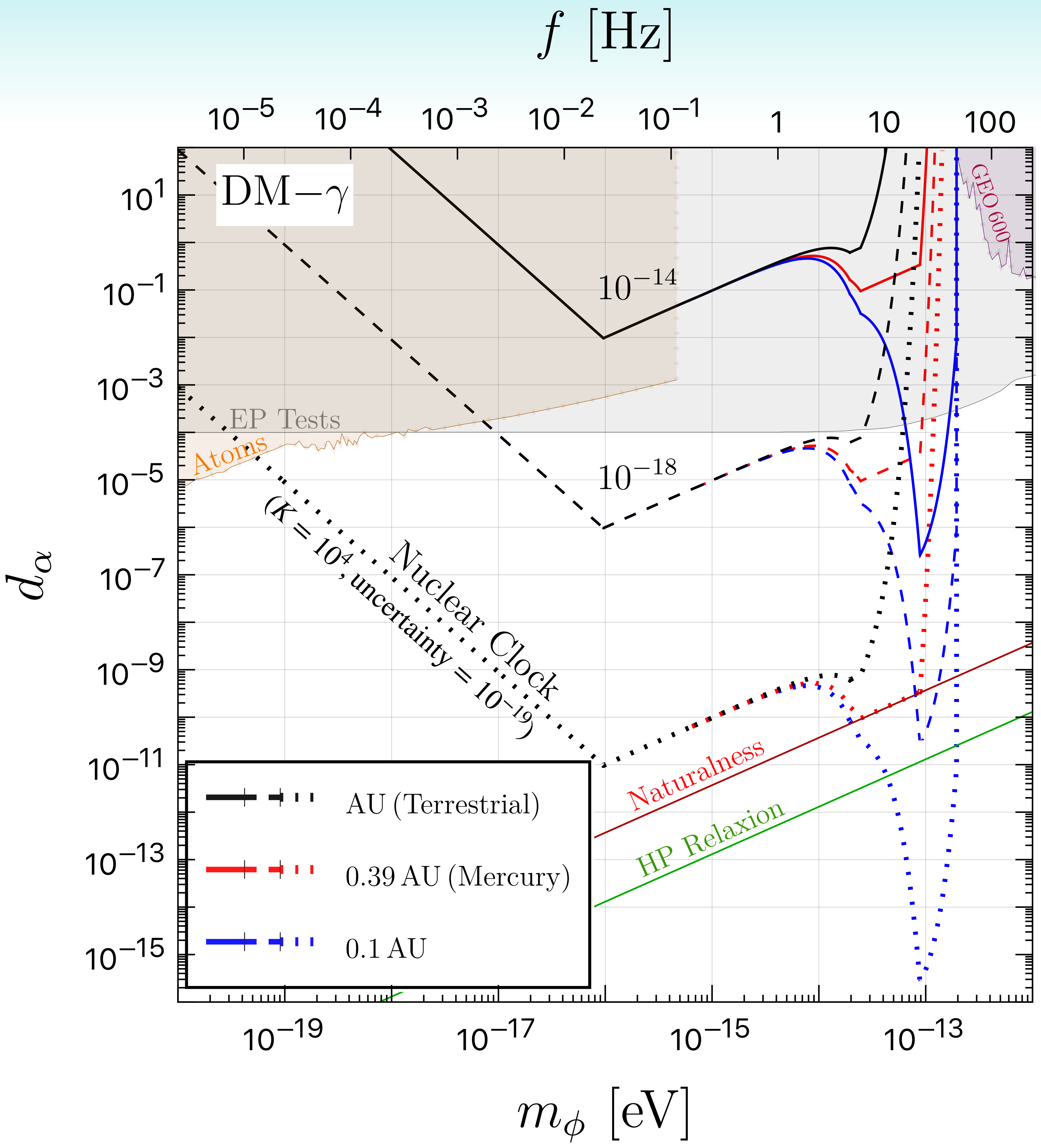
To launch this year!
Target stability $\sim 10^{-16}$

◉ Motivations:

- Better time-keeping on ISS
- Improved GPS
- Spacecraft navigation
- ULDM detection??

Space-Based Searches

Tsai, JE, Safronova (2112.07674)



Lots of work still needed to make this possible!

discussions with Parker Solar Probe scientists

On the space probe side:

- **Too hot for atomic clock? Heat shield enough?**
  - $(-40 \text{ to } 40)^\circ\mathrm{C}$ **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:

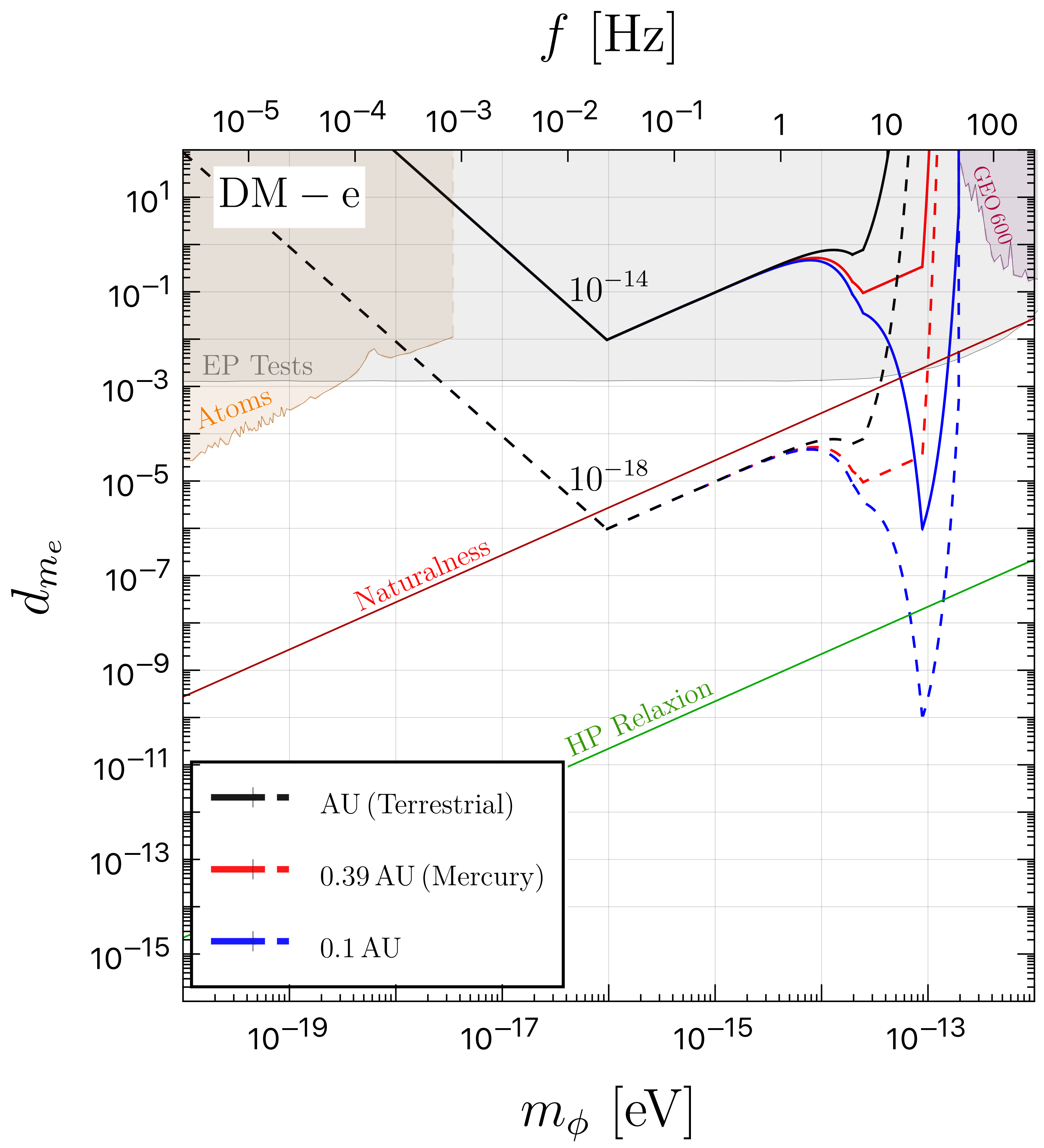
- **Need clocks which are**
  - **Portable + Automated**
  - **Lightweight**
  - **Optimized for 'high frequency' run**
- **Ideally, nuclear + optical clocks to probe many couplings**

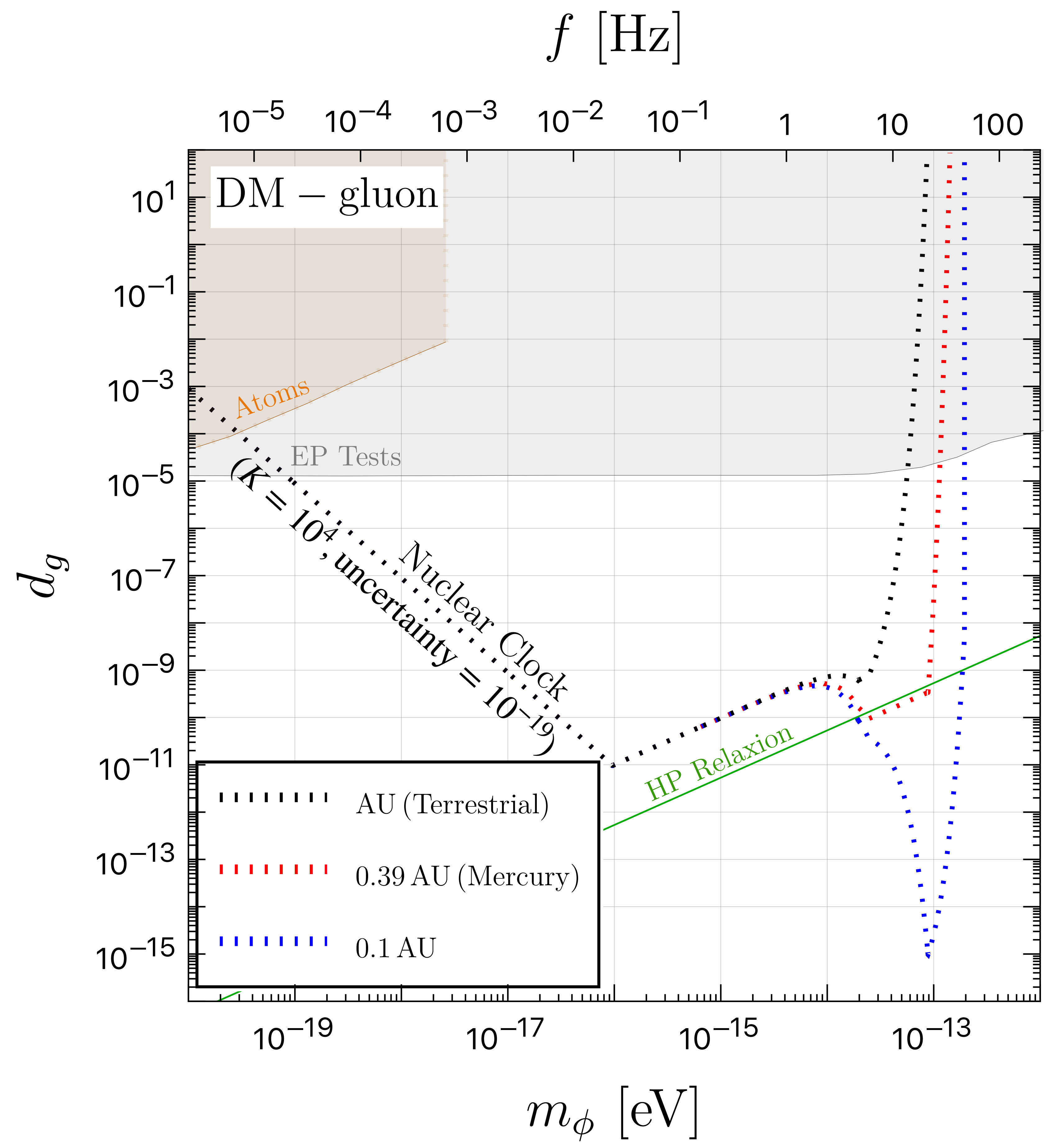
Non-Photon Scalar Couplings

Tsai, JE, Safronova (2112.07674)

$$\mathscr{L} \supset \frac{d_{m_e} m_e}{\tilde{M}_P}\phi\, \bar{e}e \rightarrow \frac{\delta(m_e/m_p)}{(m_e/m_p)_0} \simeq d_{m_e}\frac{\phi}{\tilde{M}_P}$$

$$\mathscr{L} \supset \frac{d_g \beta_3}{2\, g_s \tilde{M}_P}\phi\, G^A_{\mu\nu}G^{\mu\nu} \rightarrow \frac{\delta(m_q/\Lambda_{\rm QCD})}{(m_q/\Lambda_{\rm QCD})_0} \simeq d_g\frac{\phi}{\tilde{M}_P}$$





Other interesting implications!

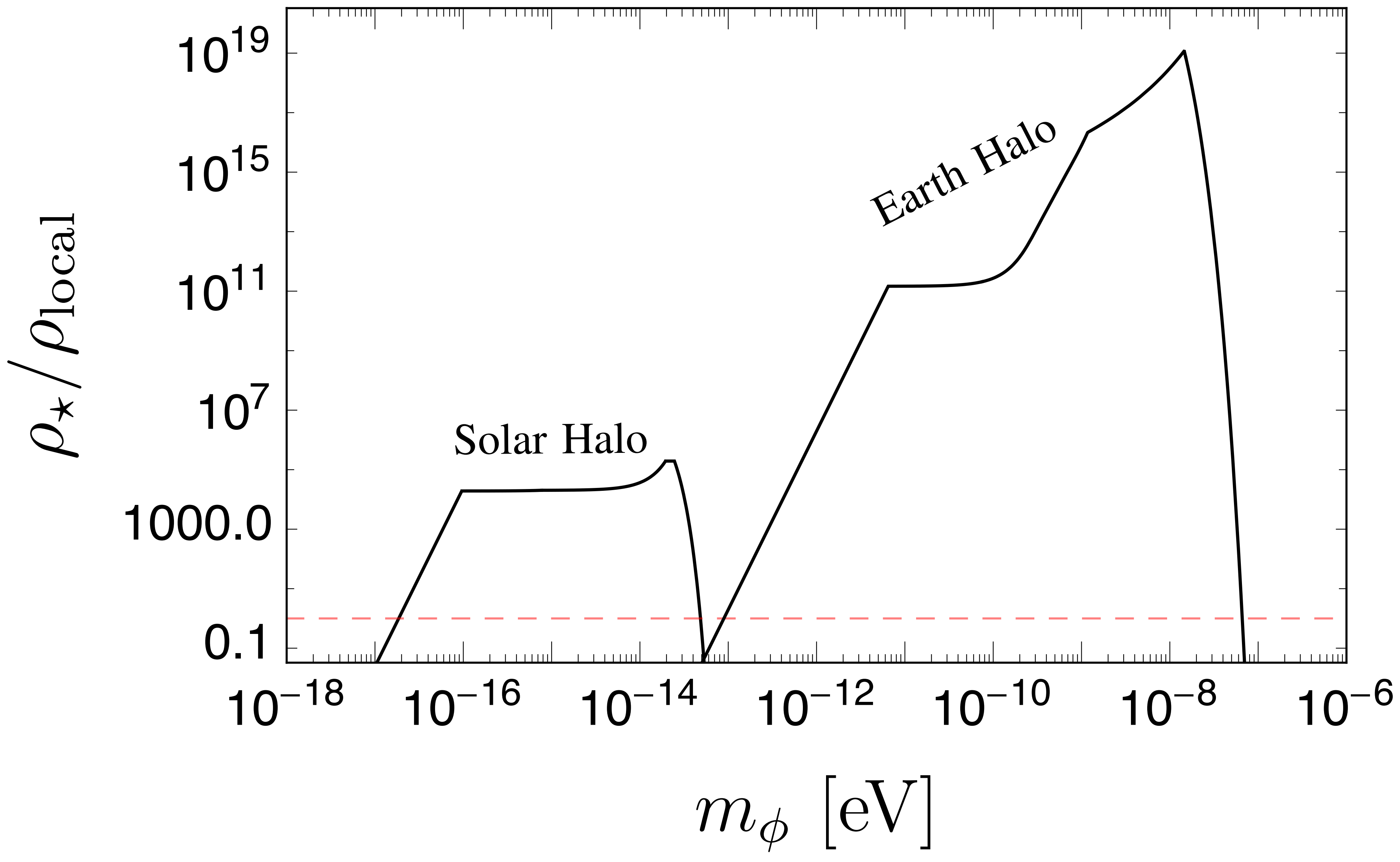
(if there's time)

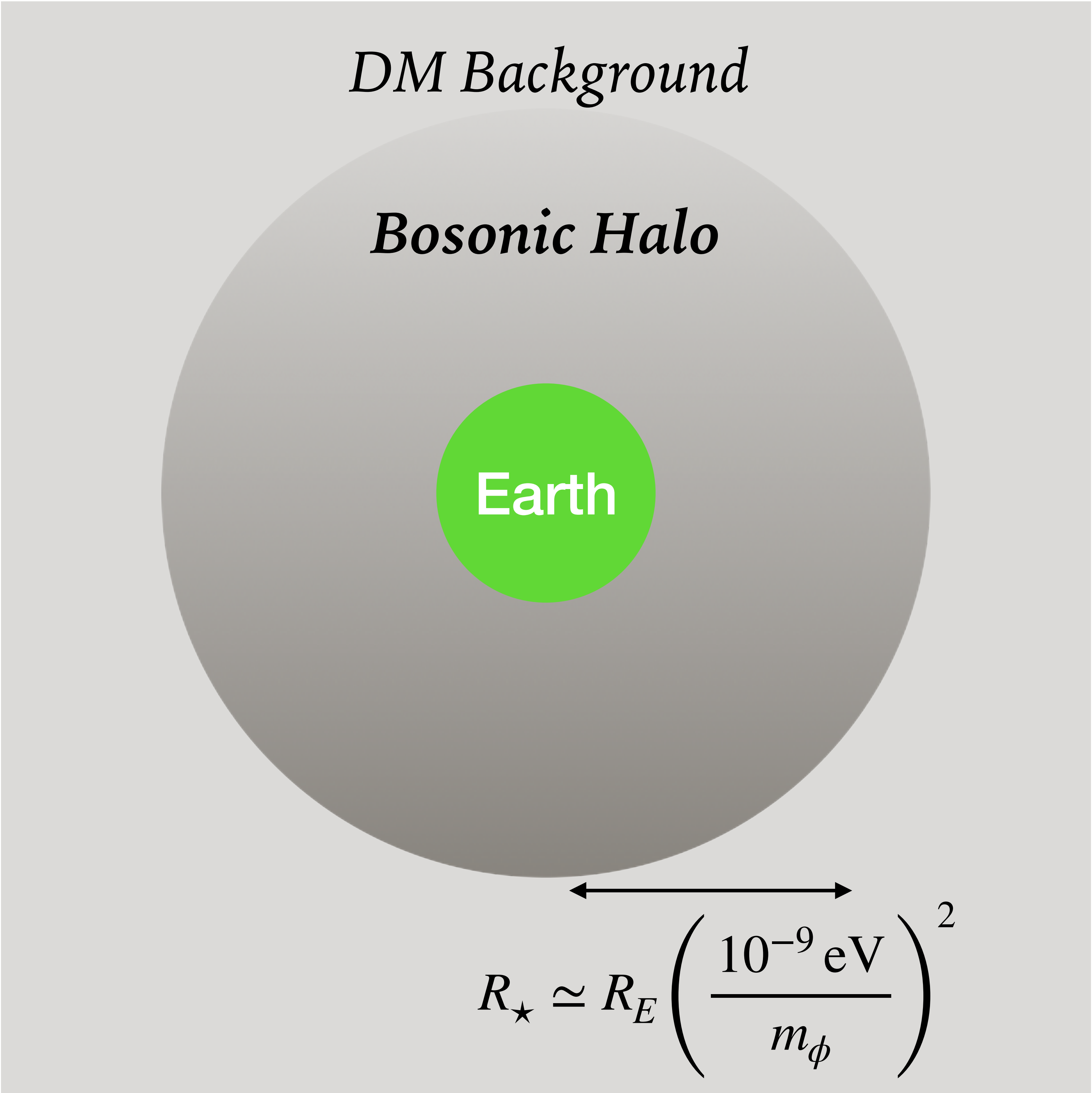
What about Earth-Bound Halos?

- Smaller halo size ⇔ larger m_ϕ ⇔ higher frequency

- Rapid development of quantum clock technologies in kHz – Mhz range ⇔ $m_\phi = \{10^{-12} - 10^{-9}\}$ eV

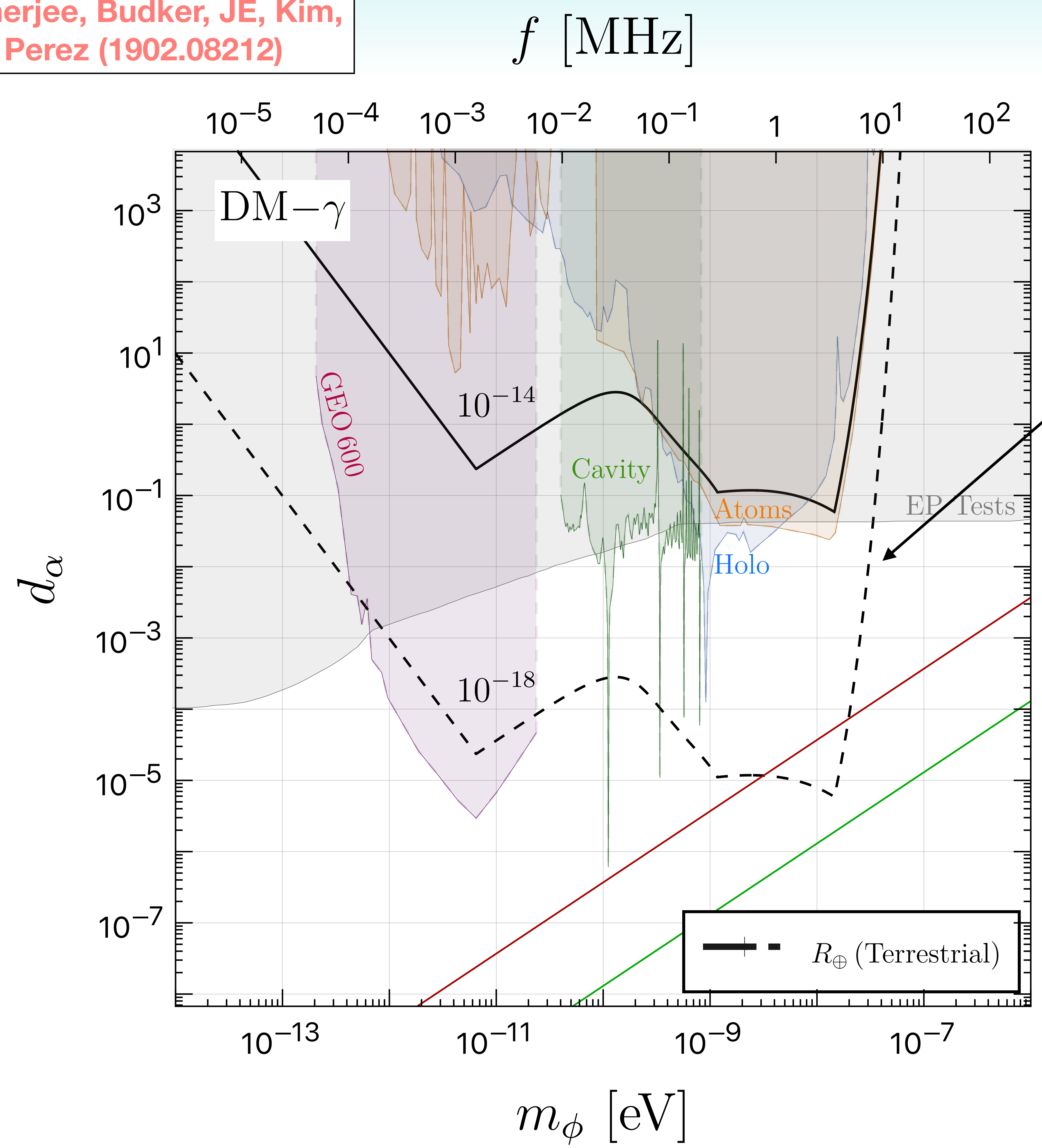
Halo supported by Earth
"Earth Halo"





Searches for Bound Earth Halos with Scalar Interaction

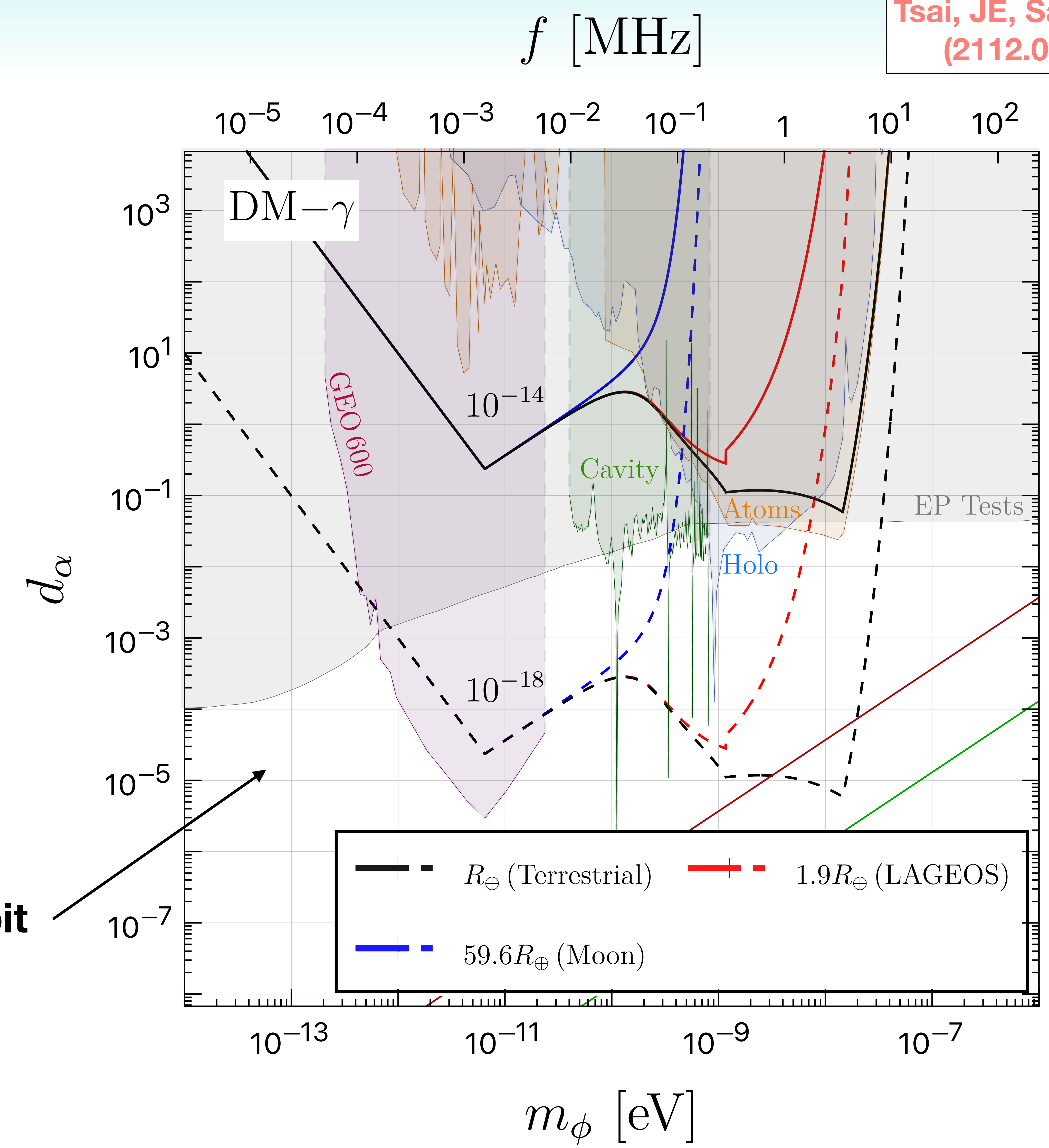
Banerjee, Budker, JE, Kim, Perez (1902.08212)



Terrestrial

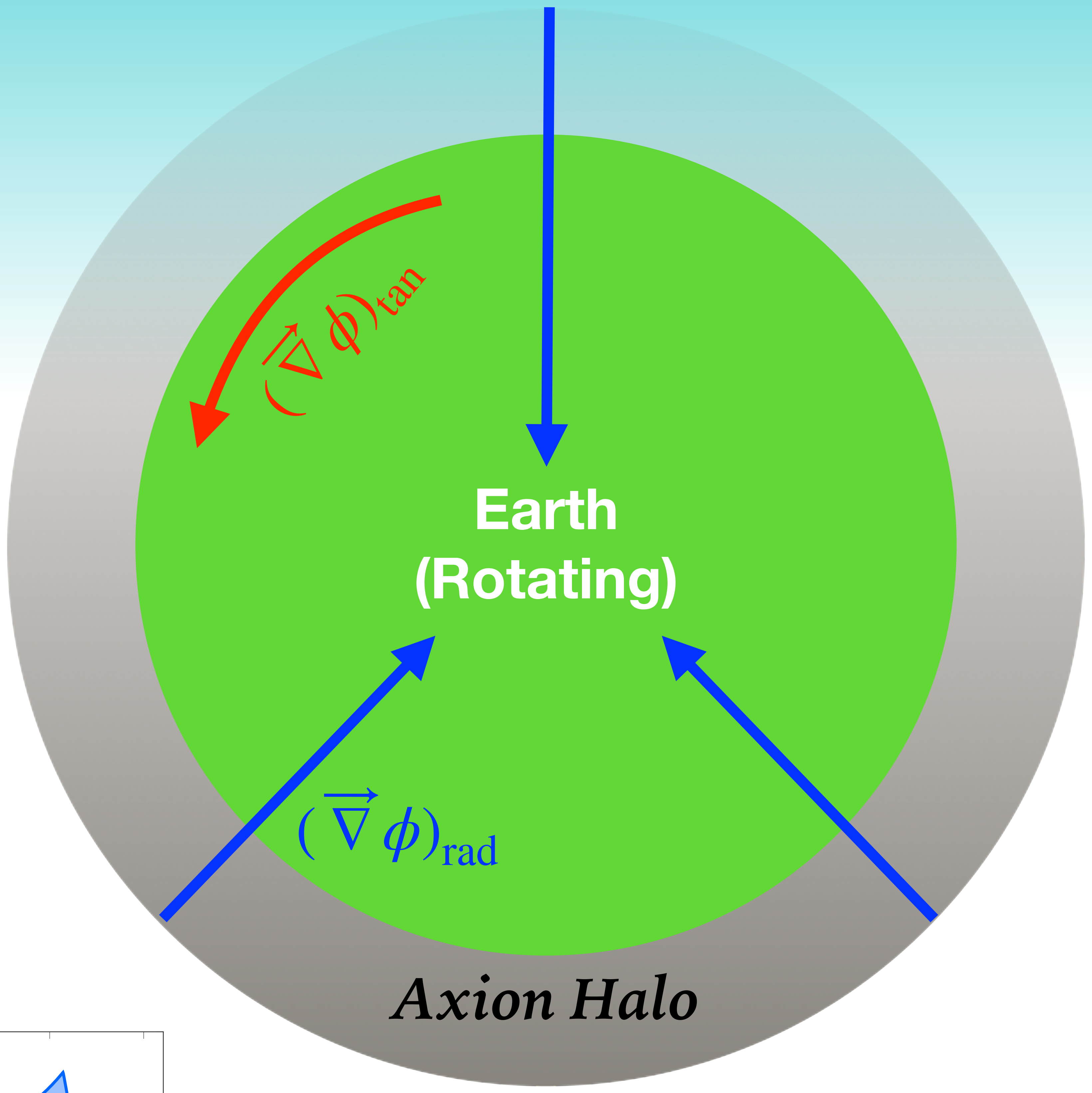
In Earth Orbit

Tsai, JE, Safronova (2112.07674)



Modified Gradients and "Wind"

Some experimental signals $\propto \nabla\phi$
(e.g. CASPEr-Wind, GNOME, …)

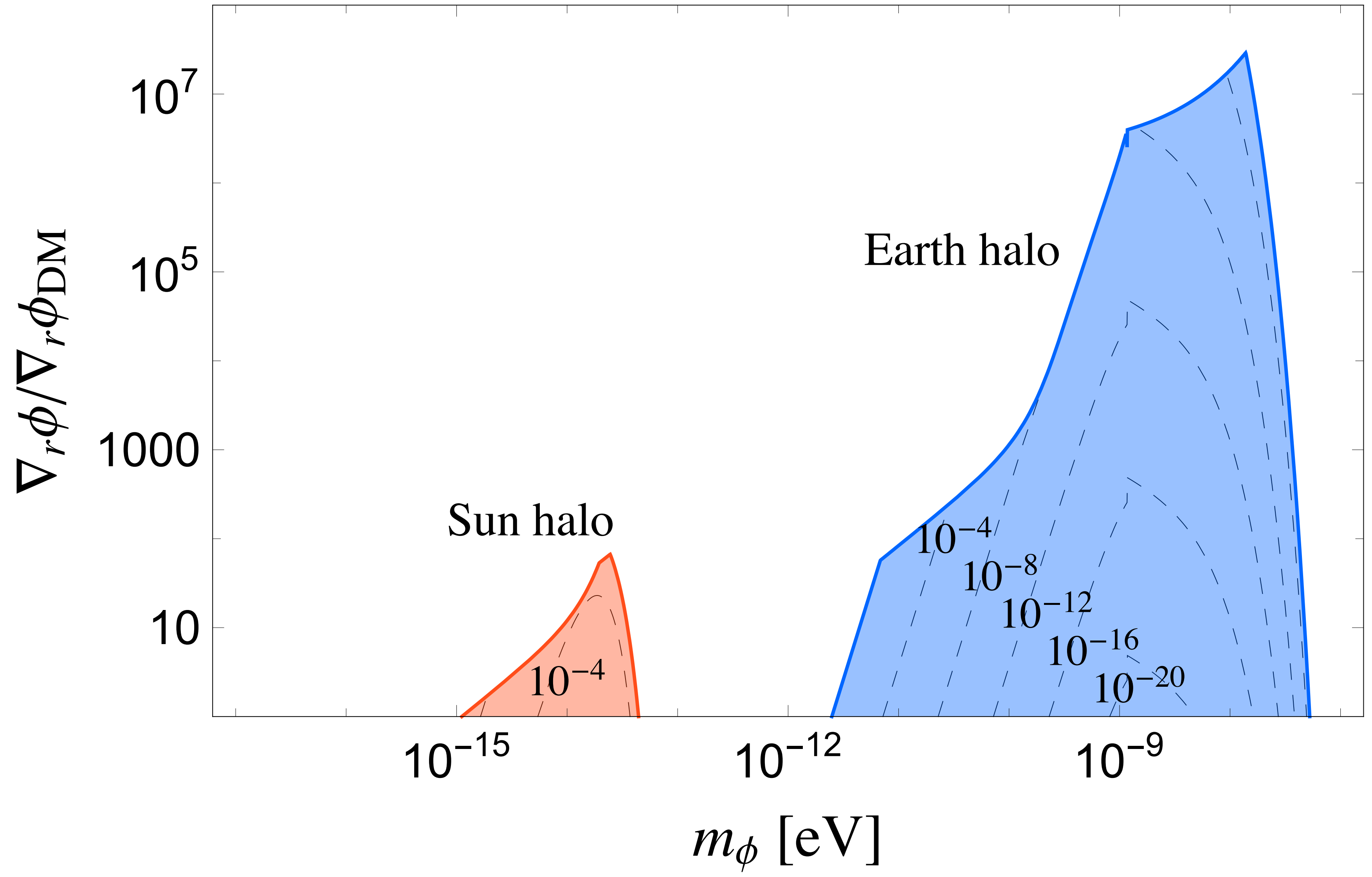


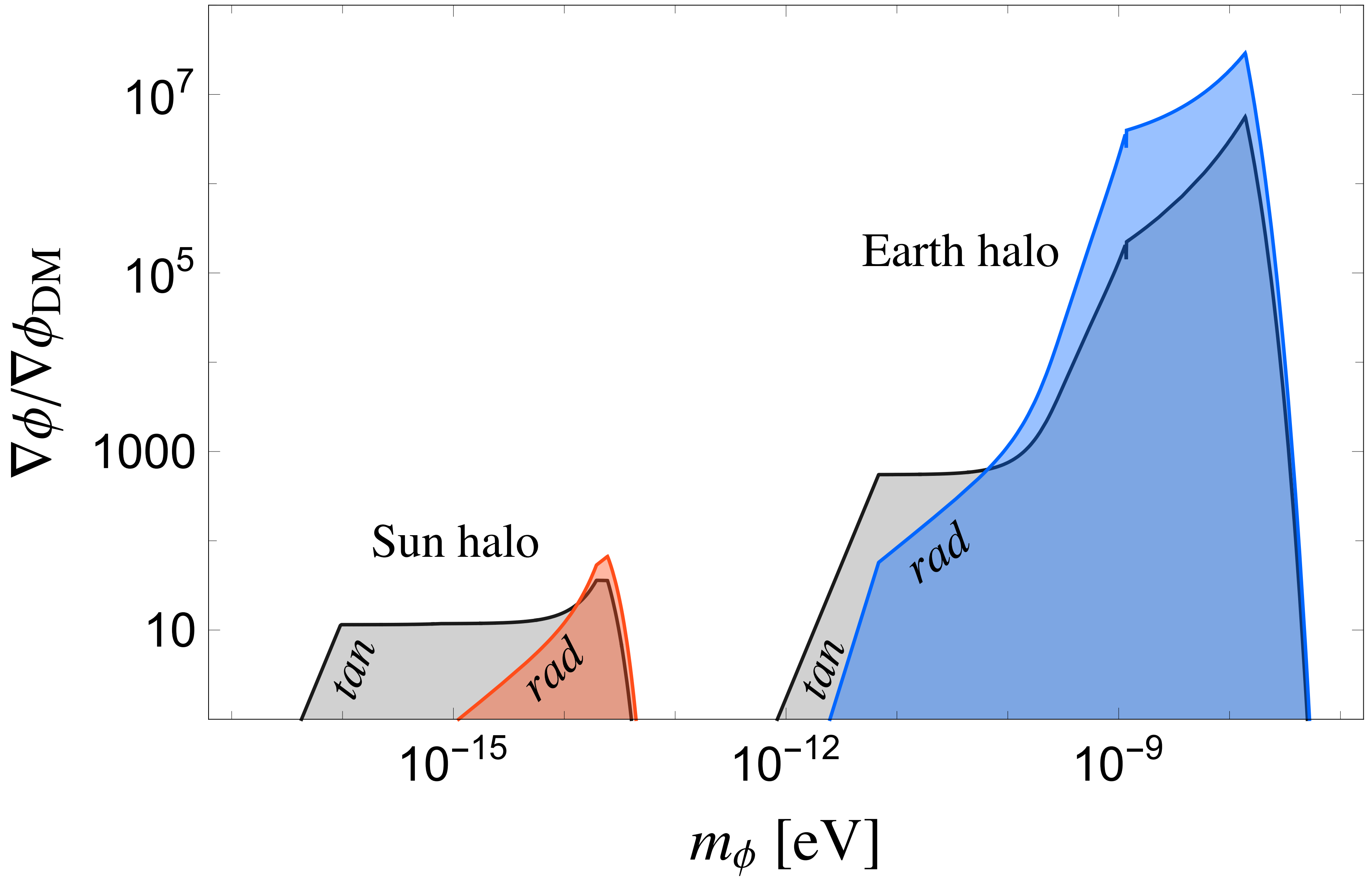
Wavefunction is hydrogen-like,
$\phi(r) \propto \exp(-r/R_\star)$

$\Rightarrow \nabla_{\rm rad}\phi \propto \dfrac{1}{R_\star}$, "radial gradient"

Experiment, on Earth,
moves *through* bound halo

$\Rightarrow \nabla_{\rm tan}\phi \propto v_{\rm rel}$, "tangential gradient"

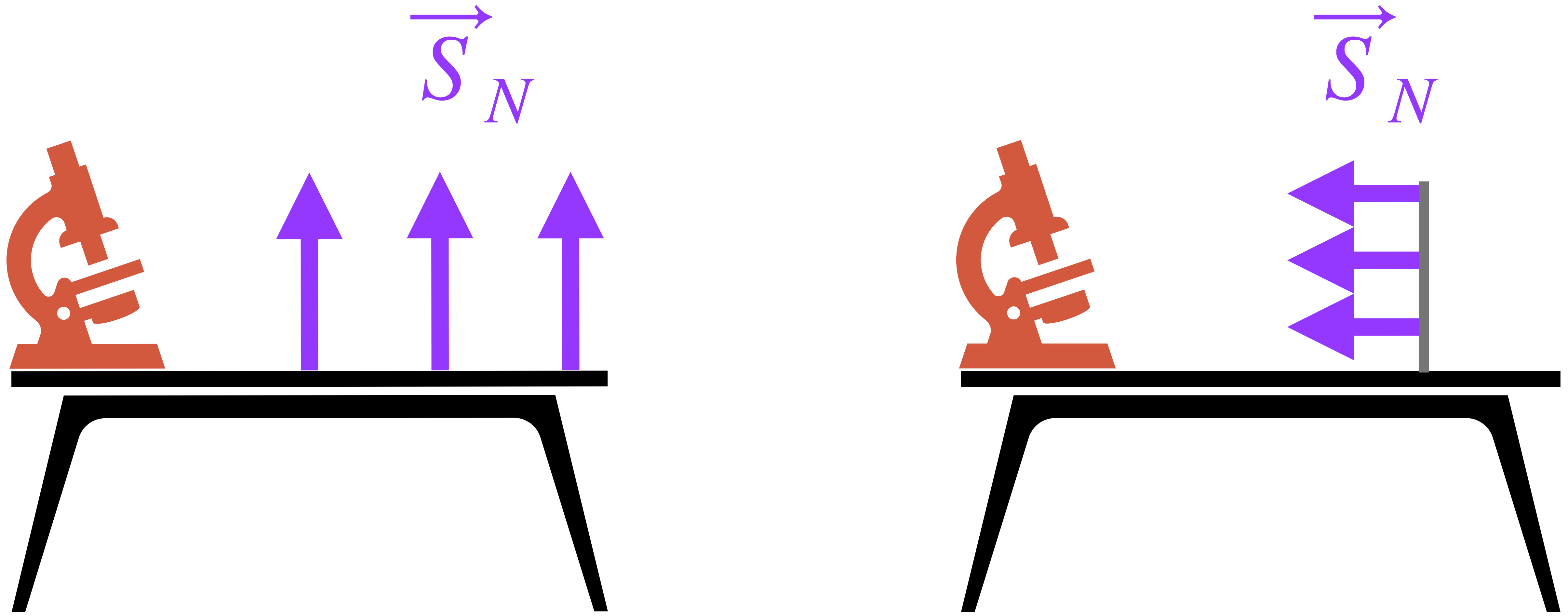


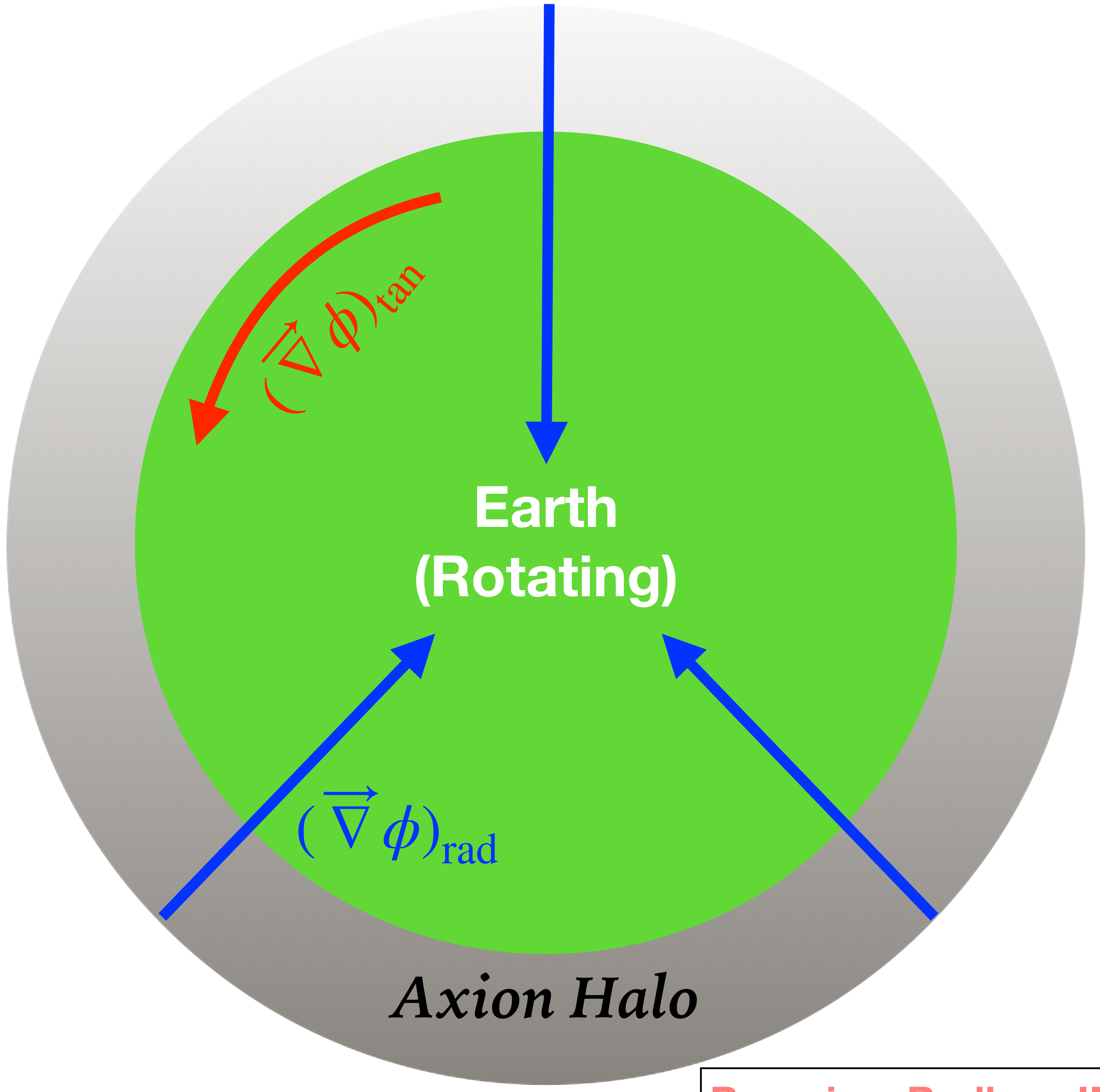


Banerjee, Budker, JE, Flambaum, Kim, Matsedonskyi, Perez (1912.04295)

Searches for Gradient Interactions

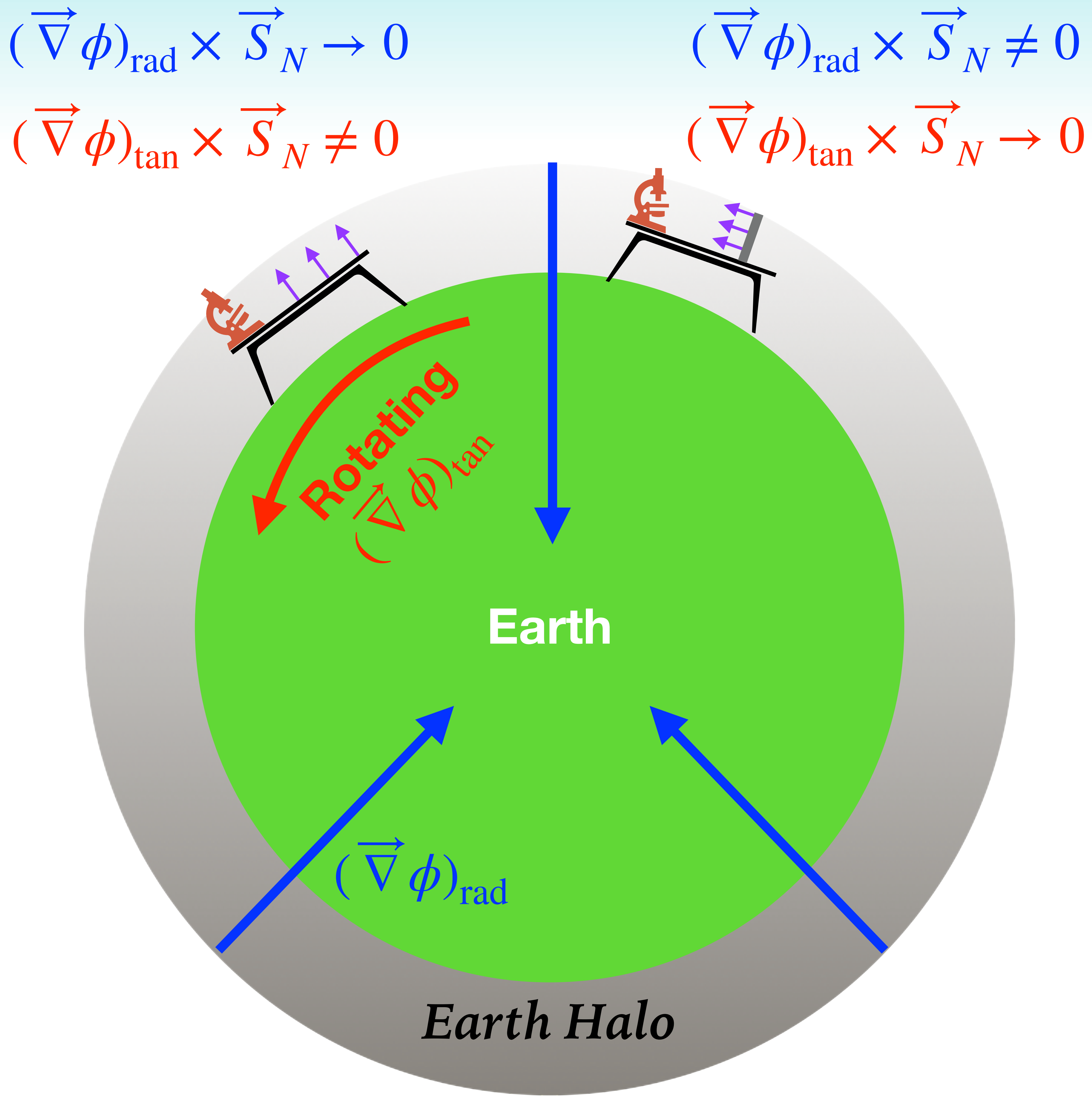
- Nuclear Magnetic Resonance often used to search for pseudoscalar LSDM couplings, e.g. in CASPEr-Wind or GNOME experiments
- Signal is $\propto (\vec{\nabla}\phi) \times \vec{S}_N$

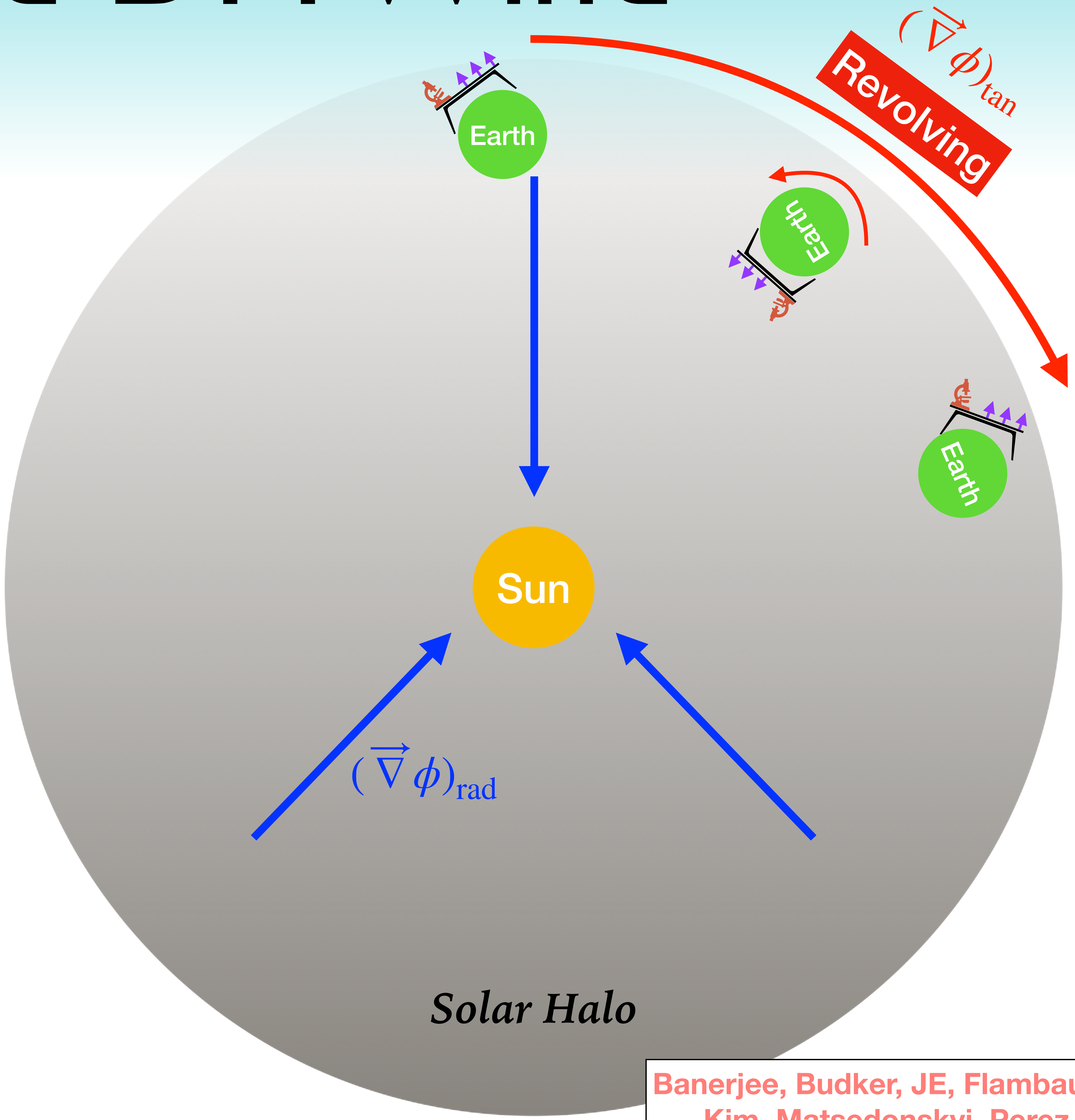




Banerjee, Budker, JE, Flambaum, Kim, Matsedonskyi, Perez (1912.04295)

Orientation and DM Wind





Signal depends both on detector orientation and latitude!

Daily and annual modulation of the signal!

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

Conclusions

- Boson stars are known to form in many ULDM theories
- Can the same dynamics give rise to ULDM bound states around other objects, e.g. Solar Halos?
  - What is the plausible range of bound mass? Very local density $\rho_{\text{very local}} = \;??$

    Ongoing work, stay tuned!
- If they form, bound bosonic halos give rise to new targets for experiment
- *Gravity-only constraints* on DM in our solar system $\rho_{\text{very local}}$ is crucial (planets & asteroids)
- *Direct detection* possibly probe 'natural' parameter space for scalars, surpassing EP limits even for very small bound mass
- Future space missions can probe small, dense solar halos!

Thanks!

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

科研費 KAKENHI

This work was supported by the World Premier International Research Center Initiative (WPI), MEXT, Japan and by the JSPS KAKENHI Grant Numbers 21H05451 and 21K20366.

Bonus Round

Discovered and Re-Discovered

Kaup (Phys Rev 172, 1331 (1968))

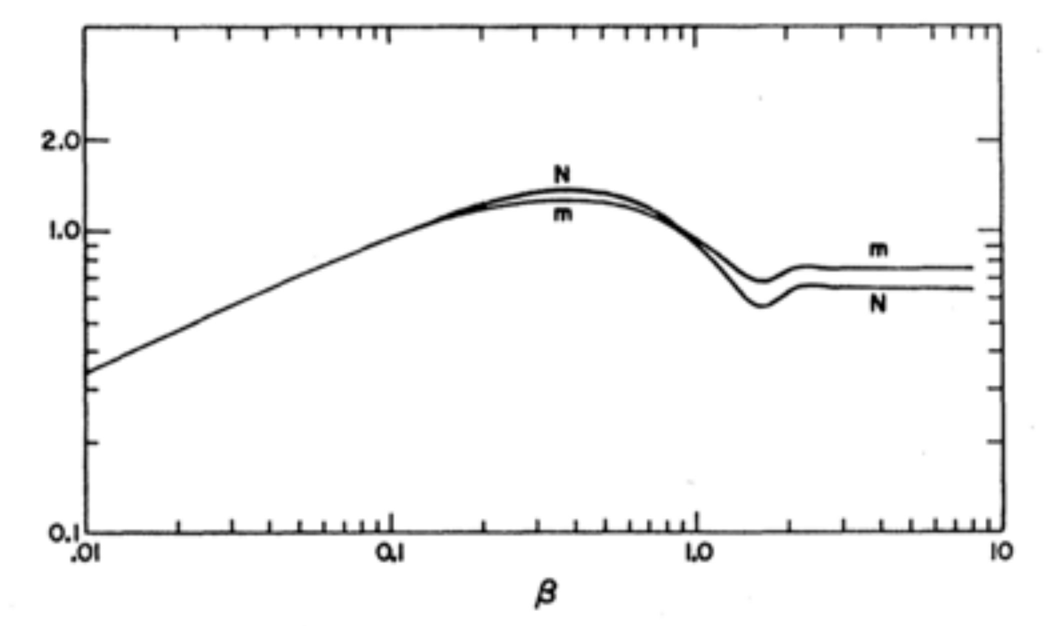
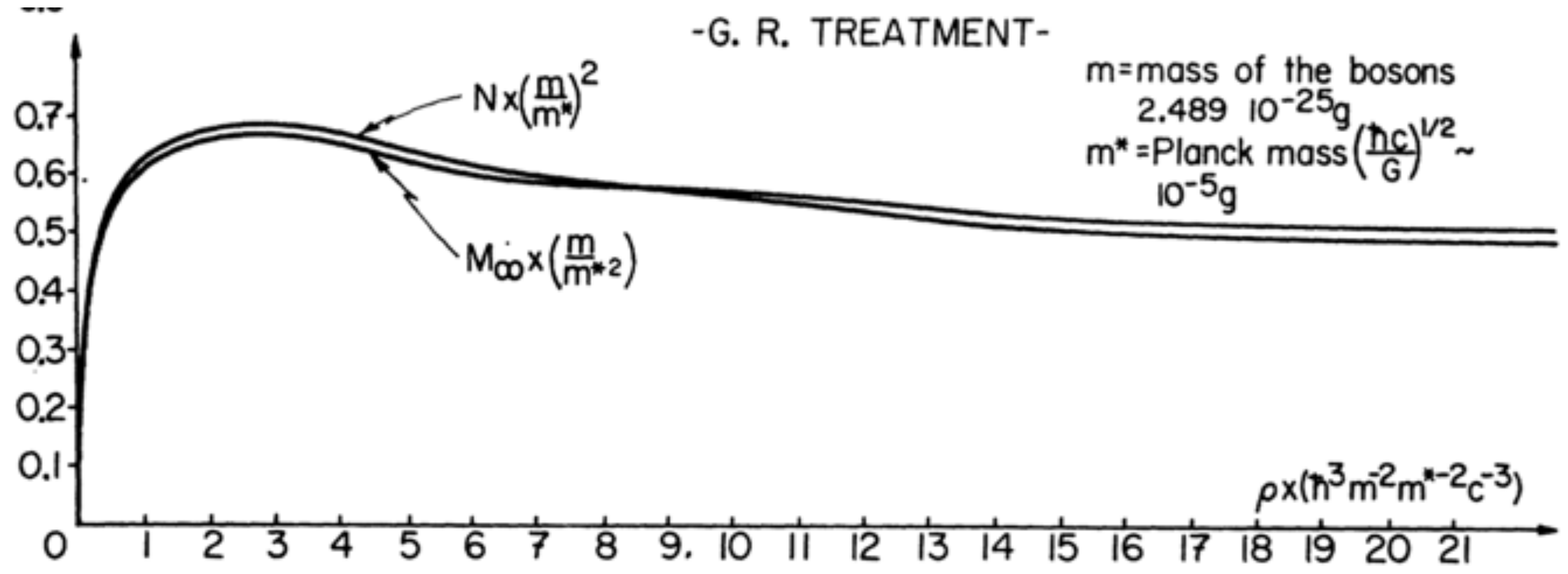
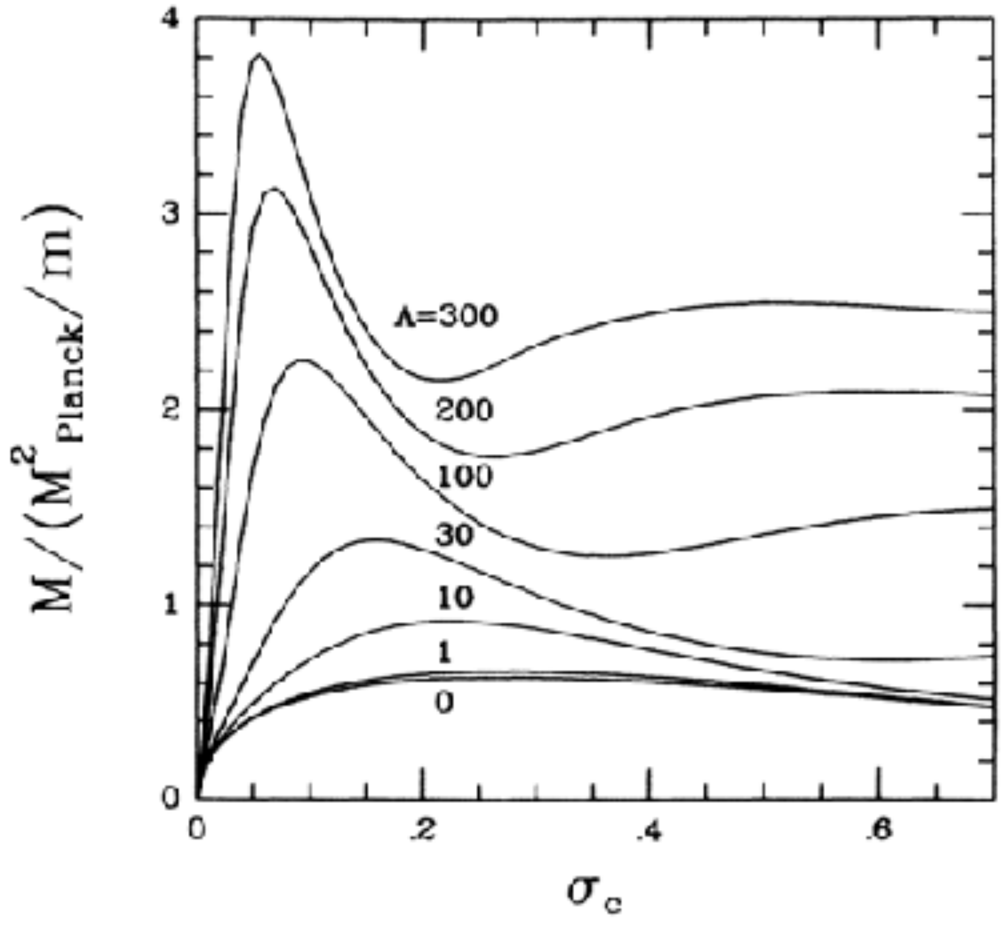


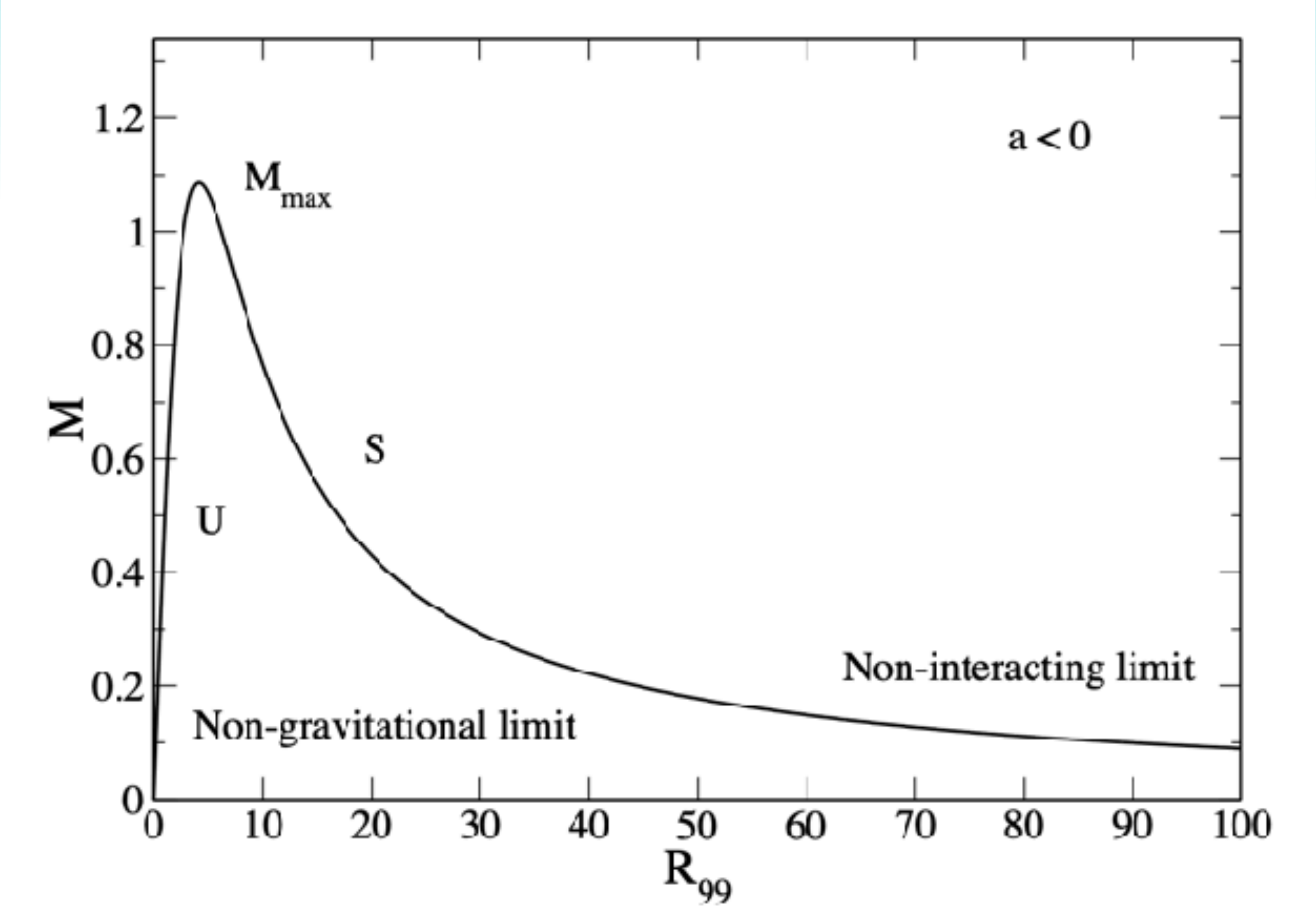
FIG. 2. Plot of m and N versus β.



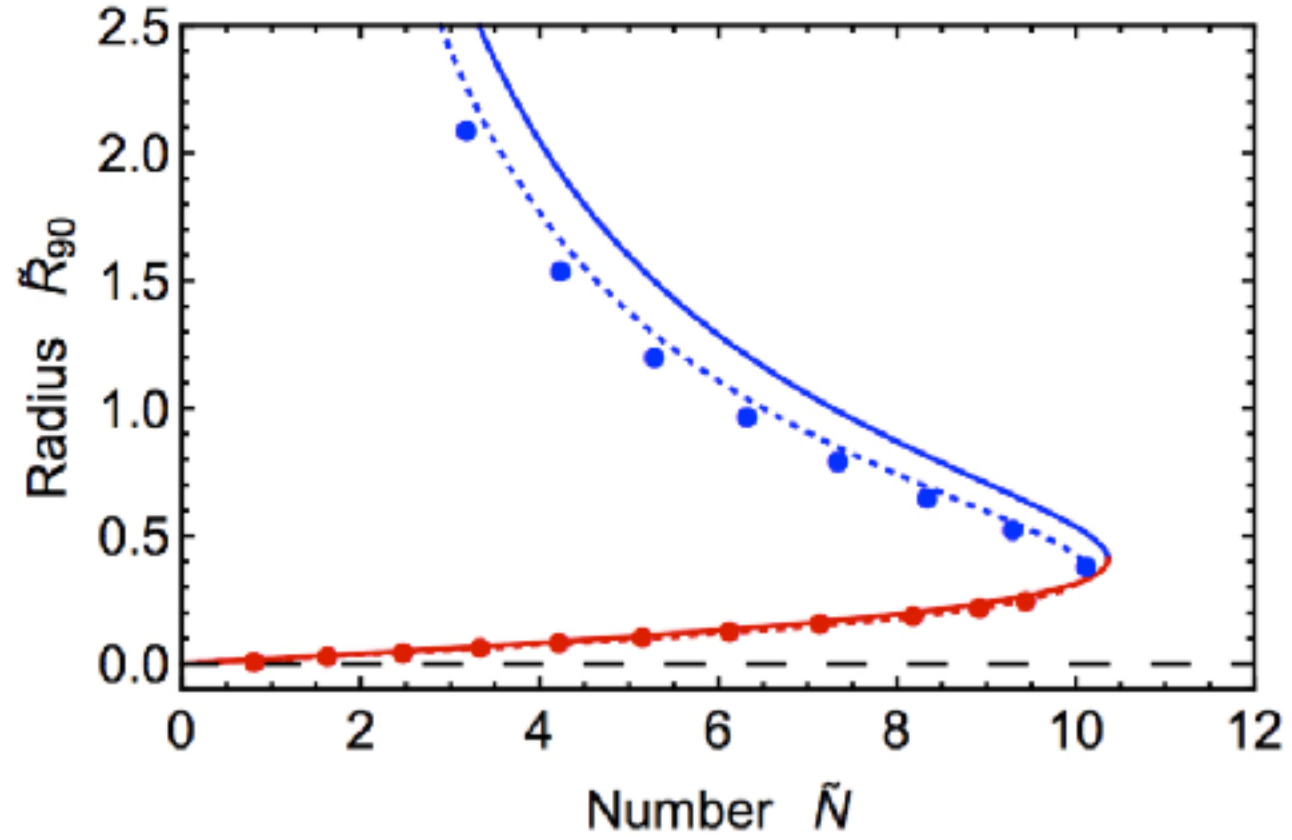
Ruffini + Bonazzola (Phys Rev 187, 1767 (1969))



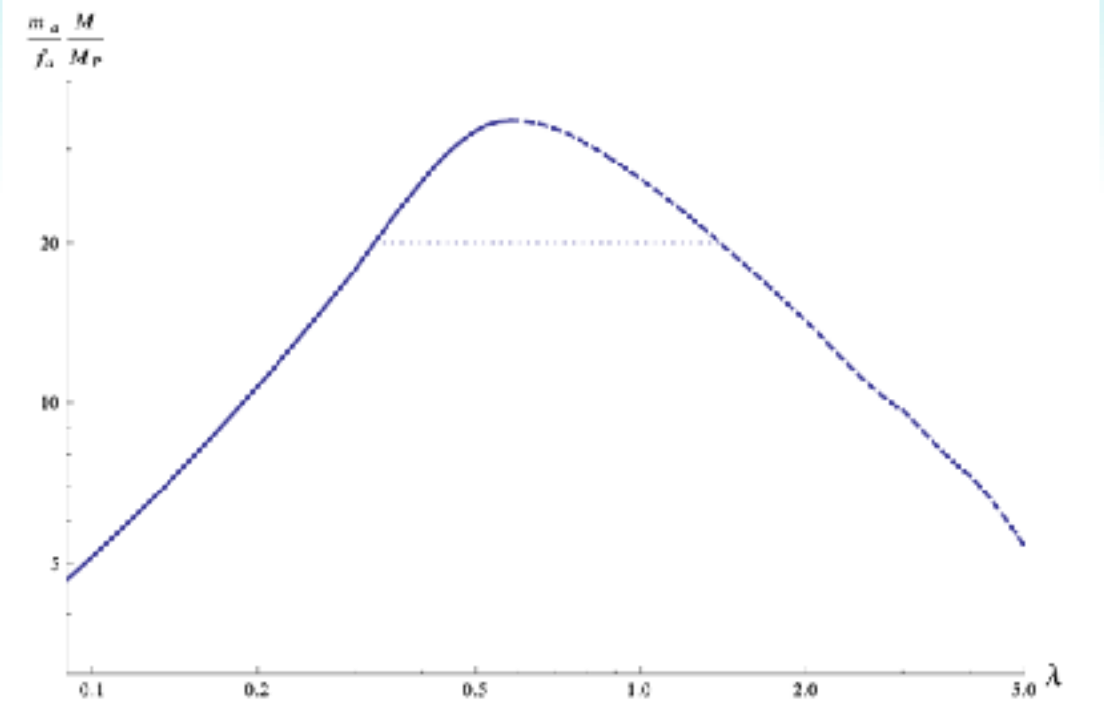
Colpi, Shapiro, Wasserman (PRL 57, 2485 (1986))



Chavanis (1103.2050)

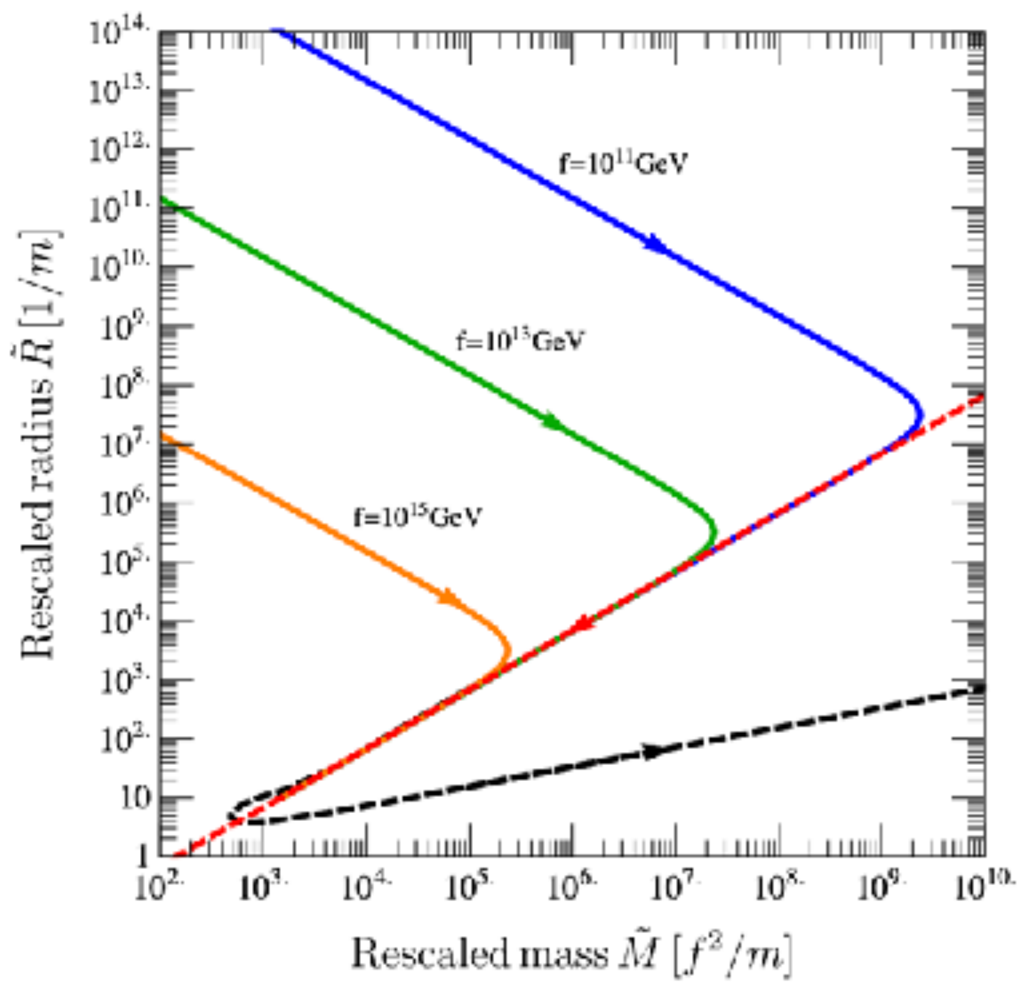


Schiappacasse and Hertzberg (1710.04729)



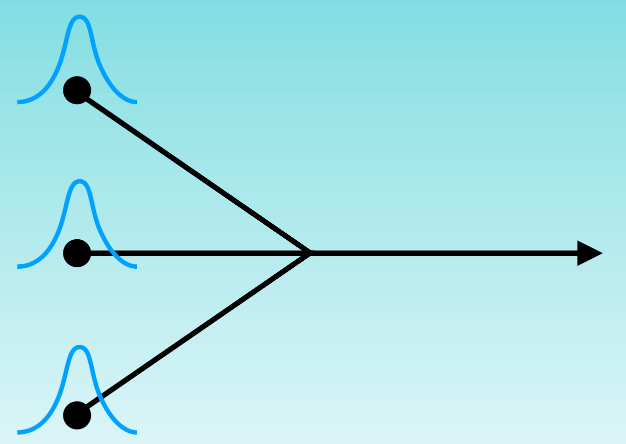
JE, Suranyi, Vaz, Wijewardhana (1412.3430)

Axion star radius vs mass



Visinelli, Baum, Redondo, Freese, Wilczek (1710.08910)

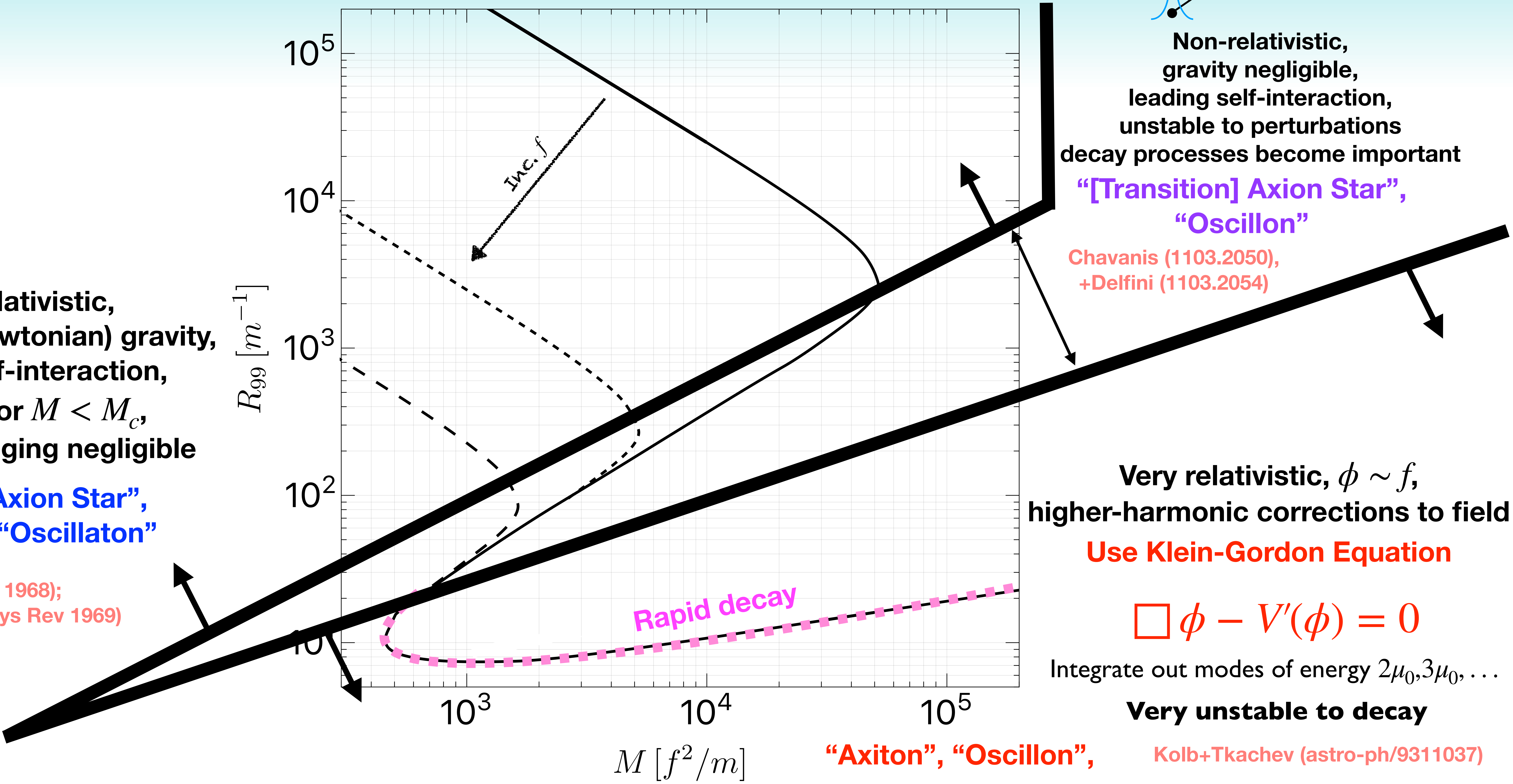
What is an Axion Star



Non-relativistic,
gravity negligible,
leading self-interaction,
unstable to perturbations
decay processes become important

"[Transition] Axion Star", "Oscillon"

Chavanis (1103.2050), +Delfini (1103.2054)



**Non-relativistic,
coupled to (Newtonian) gravity,
leading self-interaction,
STABLE for $M < M_c$,
number-changing negligible**

"[Dilute] Axion Star", "Soliton", "Oscillaton"

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

**Very relativistic, $\phi \sim f$,
higher-harmonic corrections to field**

Use Klein-Gordon Equation

$$\Box \phi - V'(\phi) = 0$$

Integrate out modes of energy $2\mu_0, 3\mu_0, \ldots$

Very unstable to decay

"Axiton", "Oscillon", "[Dense] Axion Star"

Kolb+Tkachev (astro-ph/9311037)
Braaten, Mohapatra, Zhang (1512.00108)

Transient Signals

➤It's hard! Depends on

$$\Gamma = n_\star \sigma v_\star$$

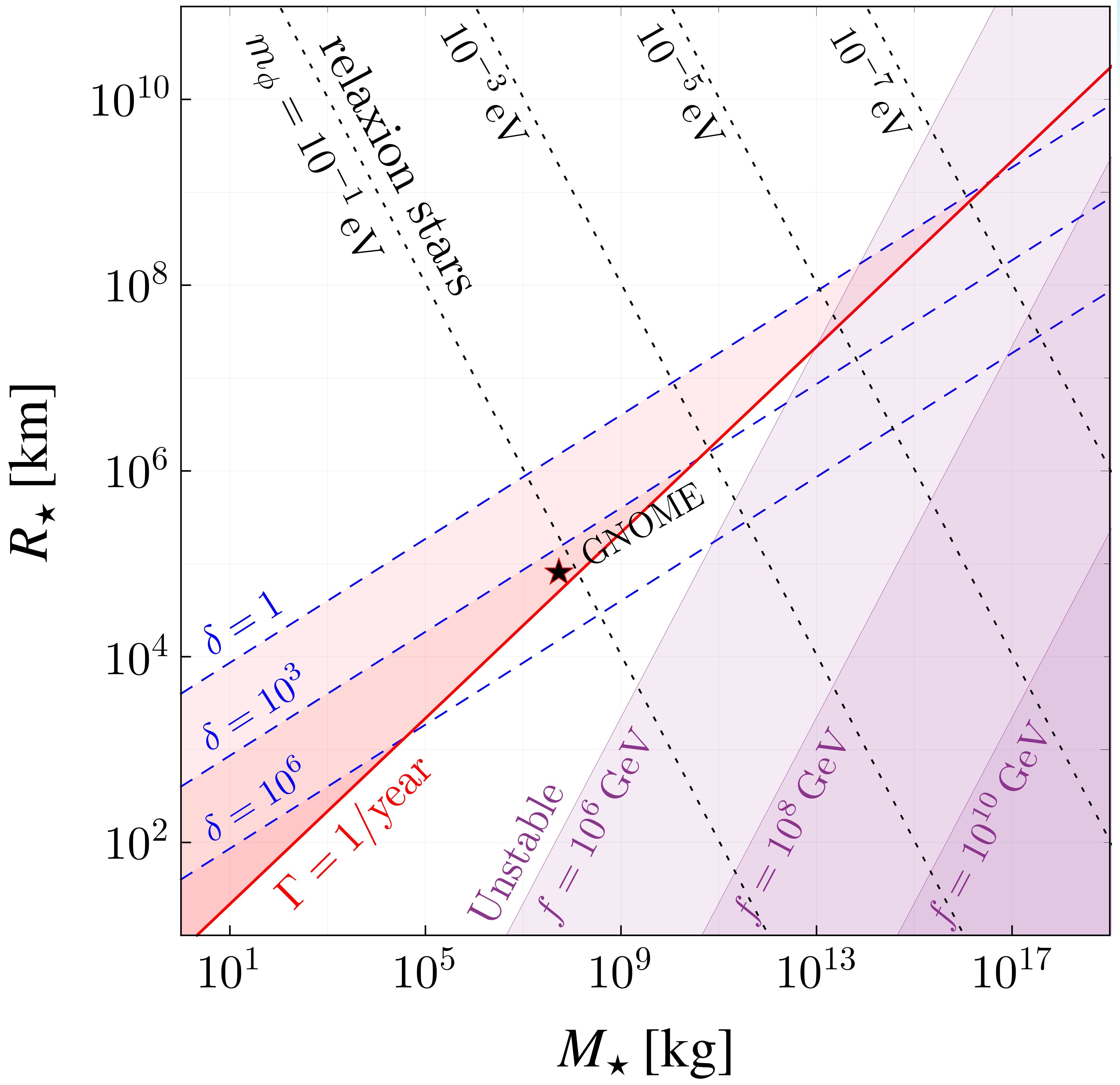
$$\frac{\rho_{local}}{M_\star} \qquad \pi R_\star^2 \qquad 200\, km/sec$$

so

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

but

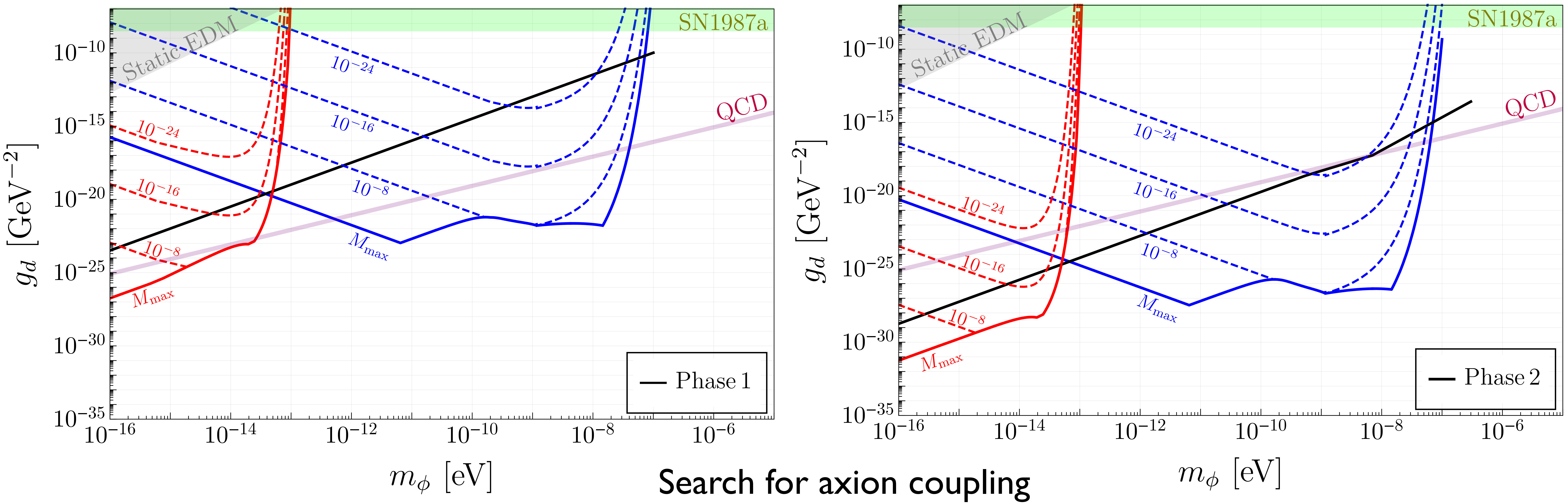
$$\delta \equiv \frac{\rho_\star}{\rho_{local}} \propto \rho_{local}^{-1} R_\star^{-4}\, m_\phi^{-2}$$



CASPEr Electric

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

(contours: $M_\star / M_{\rm ext}$)

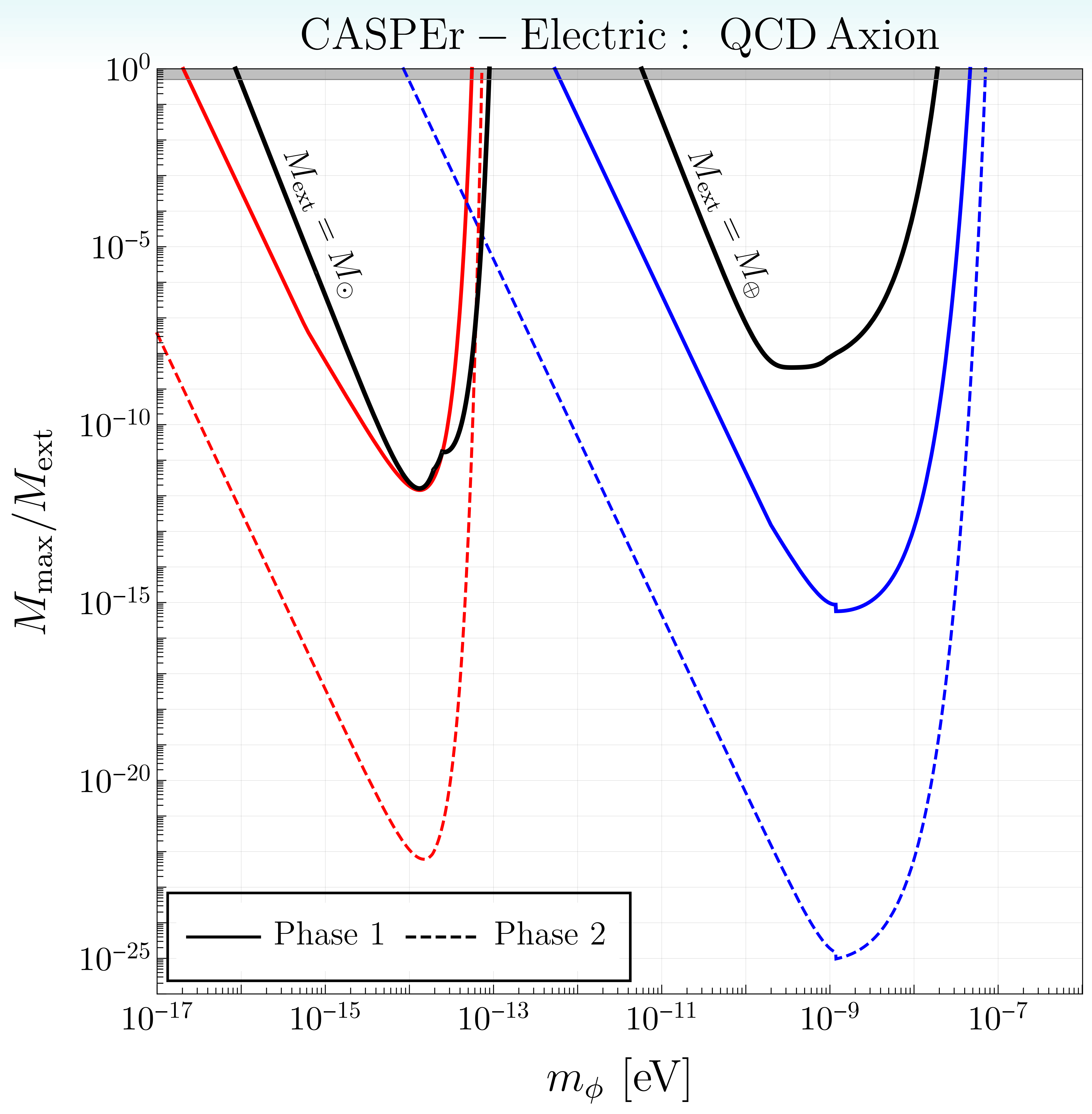


Search for axion coupling

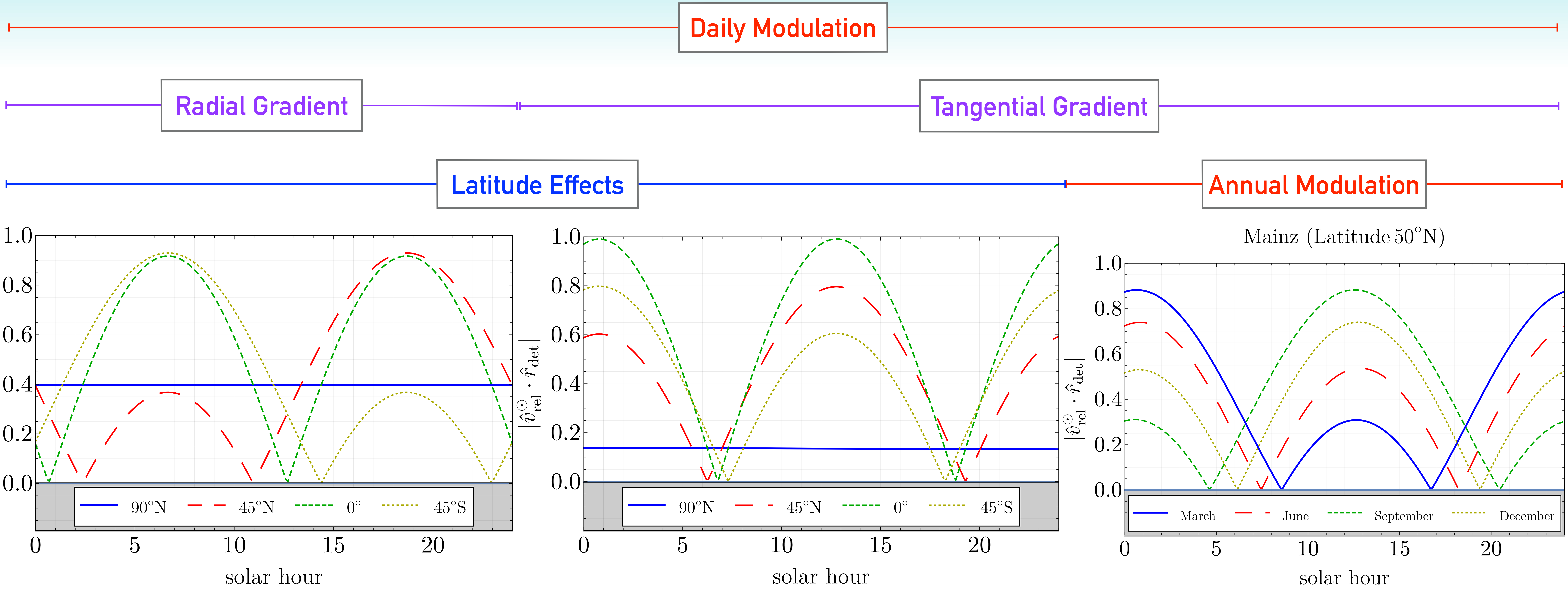
$$\mathscr{L} \supset \frac{i\, g_d}{2} \phi \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

Probing the QCD Axion

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



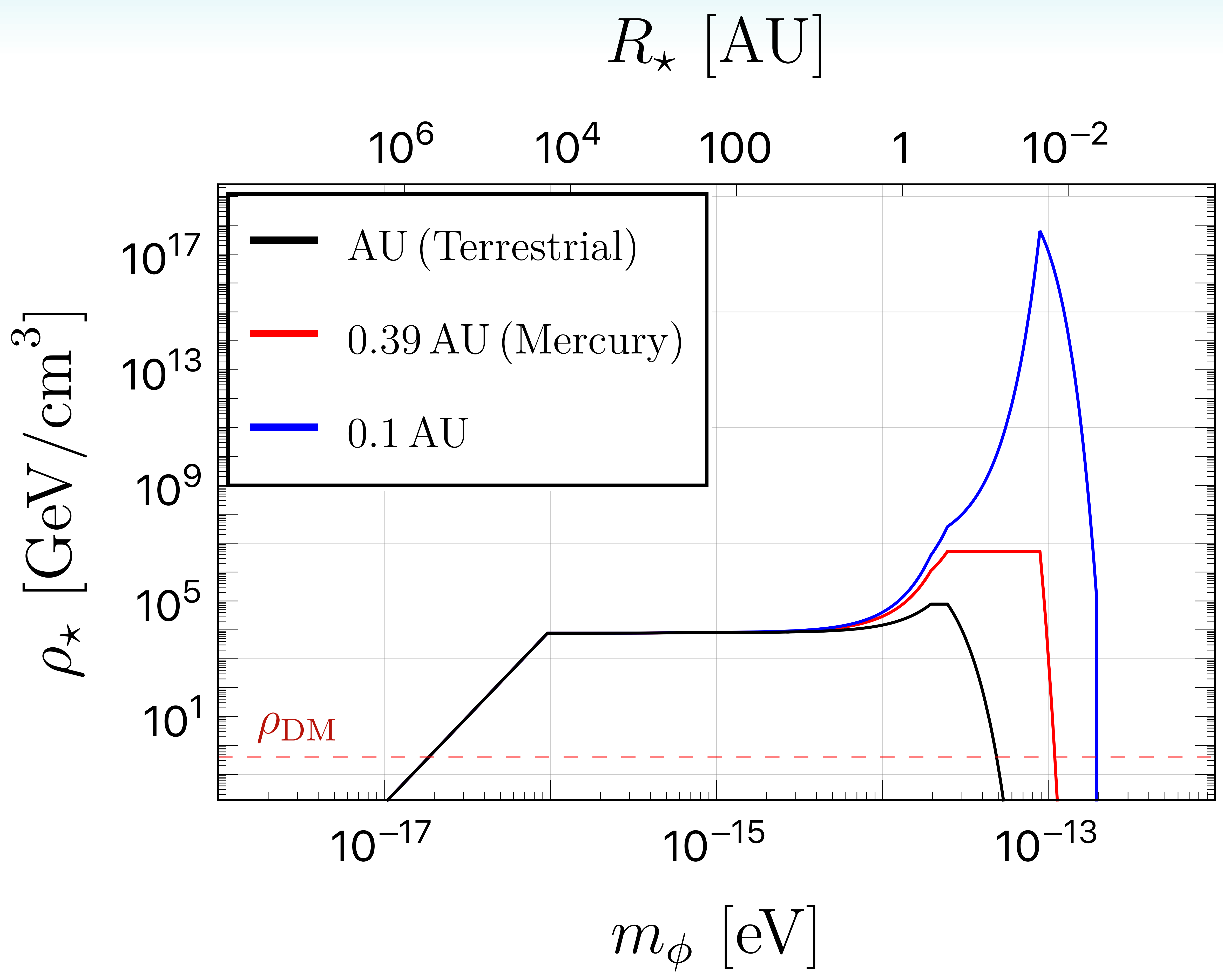
Signal Modulation (Solar Halo)

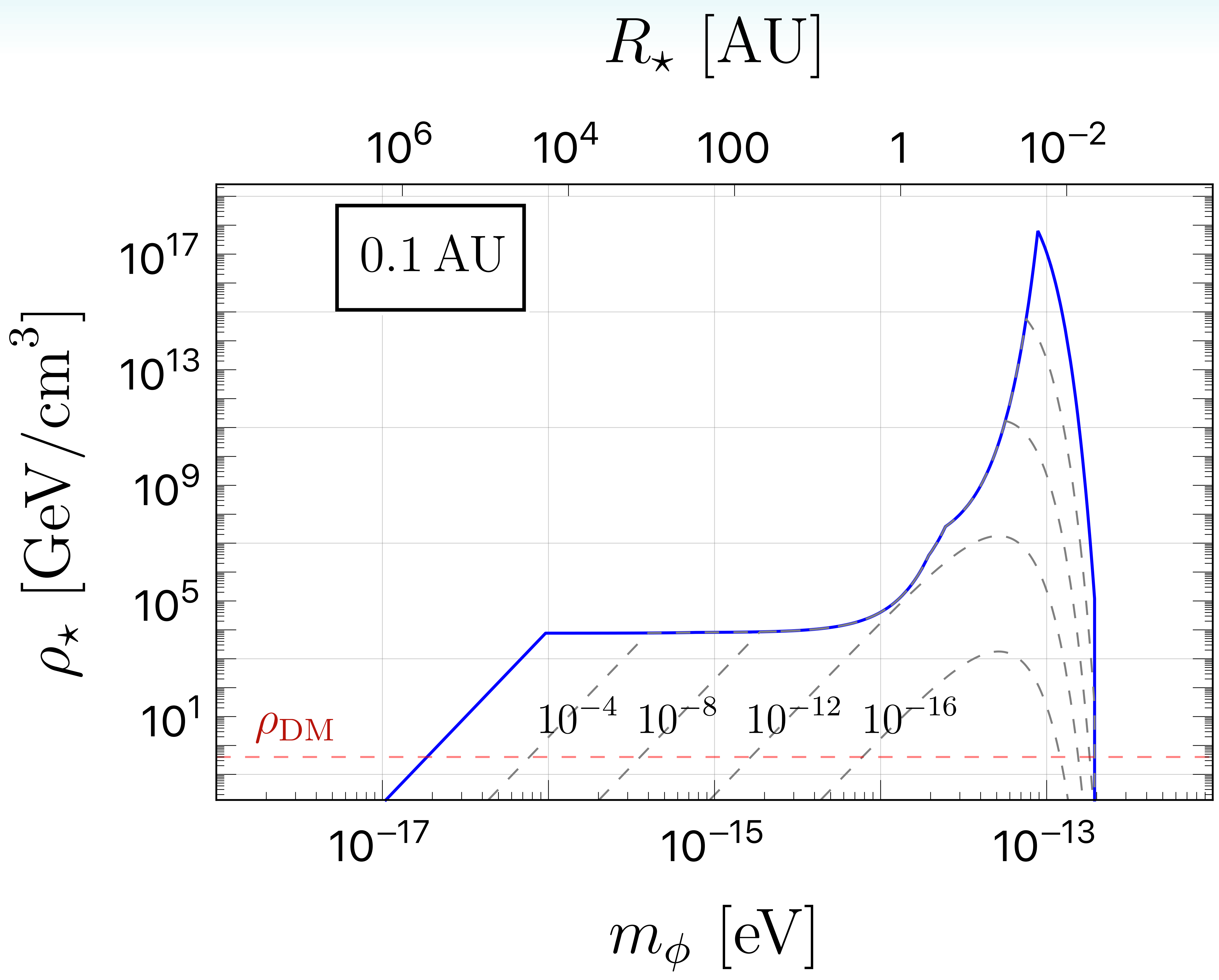


- Upshot: Sideband analysis in existing axion experiments can distinguish virialized LSDM from bound axion halos in our solar system

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

Max Density within 1 AU





Basics of Atomic Clock Searches

Basic procedure:
Compare two "clocks"

Atom transition 1 <—> Atom transition 2
Atom transition <—> Cavity
... <—> ...

ν_1   ν_2

Look for peak in Fourier spectrum at DM Compton frequency

$$2\pi\nu \simeq m_\phi \simeq \text{few Hz}\left(\frac{m_\phi}{10^{-15}\,\text{eV}}\right)$$

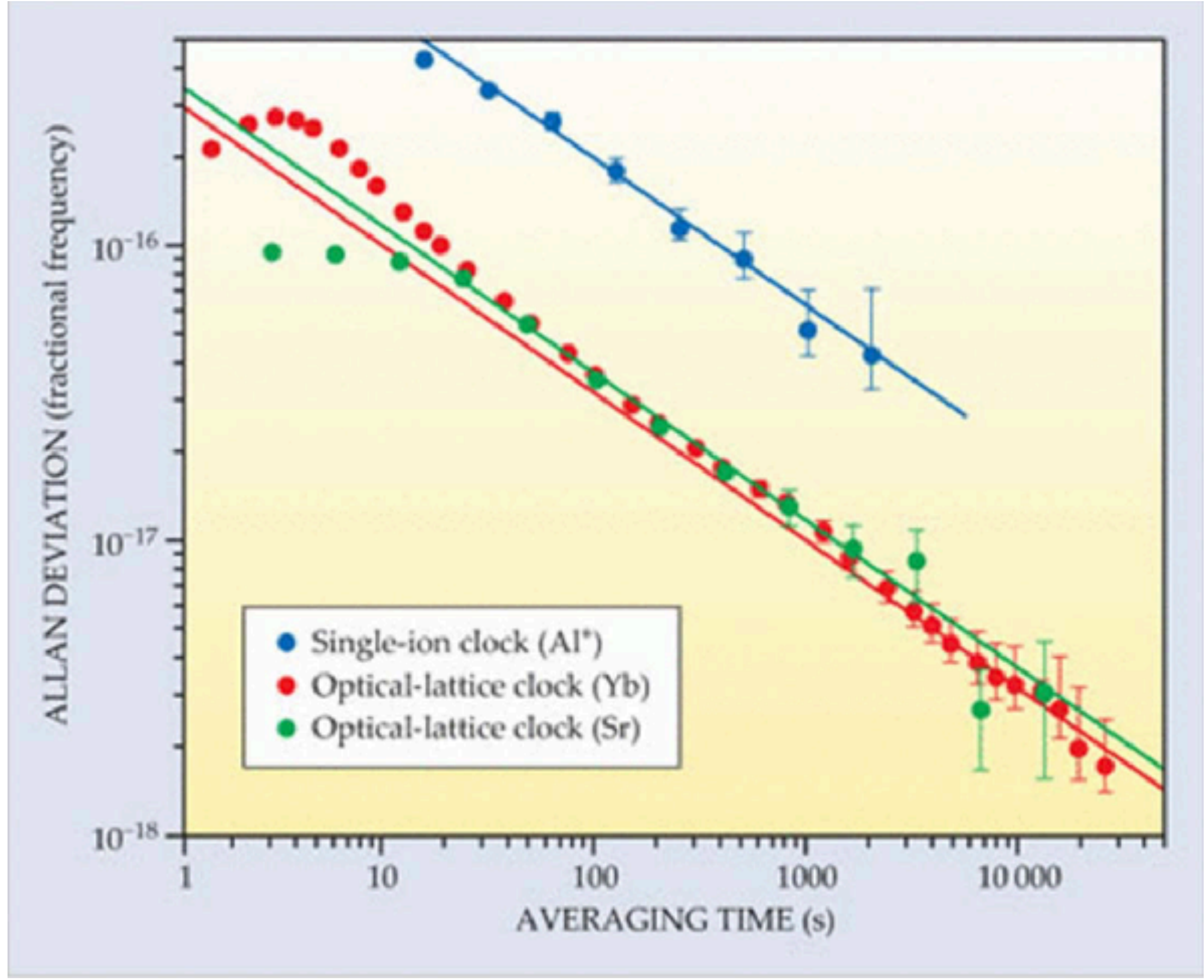
"Master equations" that dictate sensitivity:

1. **Clock instability / Allen Deviation:**

$$\sigma(\tau) \simeq \frac{1}{2\pi\nu_0\sqrt{N_T T_m \min(\tau, \tau_\star)}}$$

Finally limited by *uncertainty*, how well do we understand the theory and physical processes?

Ludlow et al. (1407.3493)



2. $$\delta\left(\ln\frac{\nu_2}{\nu_1}\right) = (K_2 - K_1)\,\delta\left(\ln\alpha\right)$$

limited by *instability* or *uncertainty*

property of the clock / transition

thing we want to measure!

Current and Future Clocks

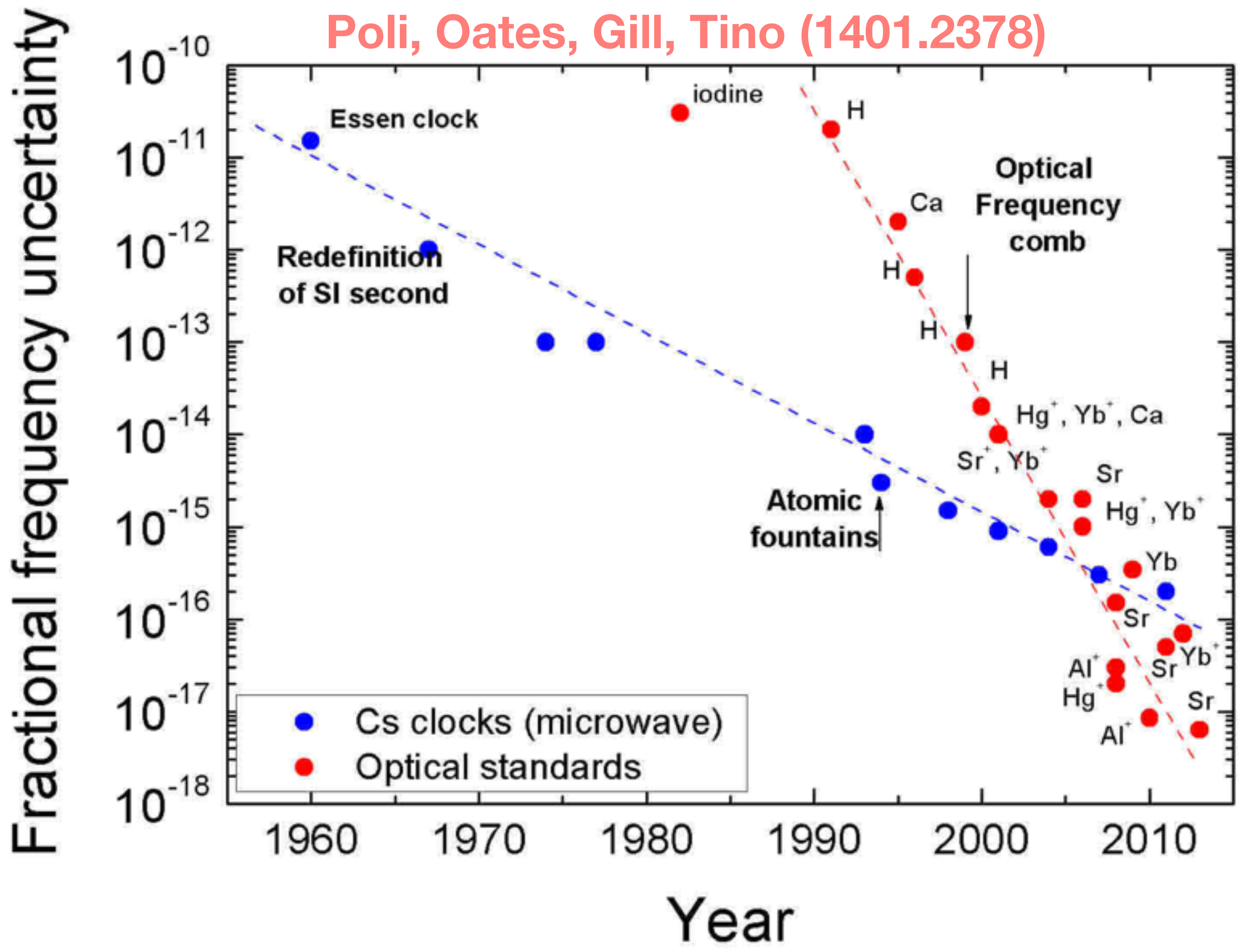
$$\sigma(\tau) \simeq \frac{1}{2\pi\nu_0\sqrt{N_T T_m \min(\tau, \tau_\star)}}$$

$$\delta\left(\ln\frac{\nu_2}{\nu_1}\right) = (K_2 - K_1)\,\delta\left(\ln\alpha\right)$$

◉ Many clock technologies exist currently. Incomplete summary:

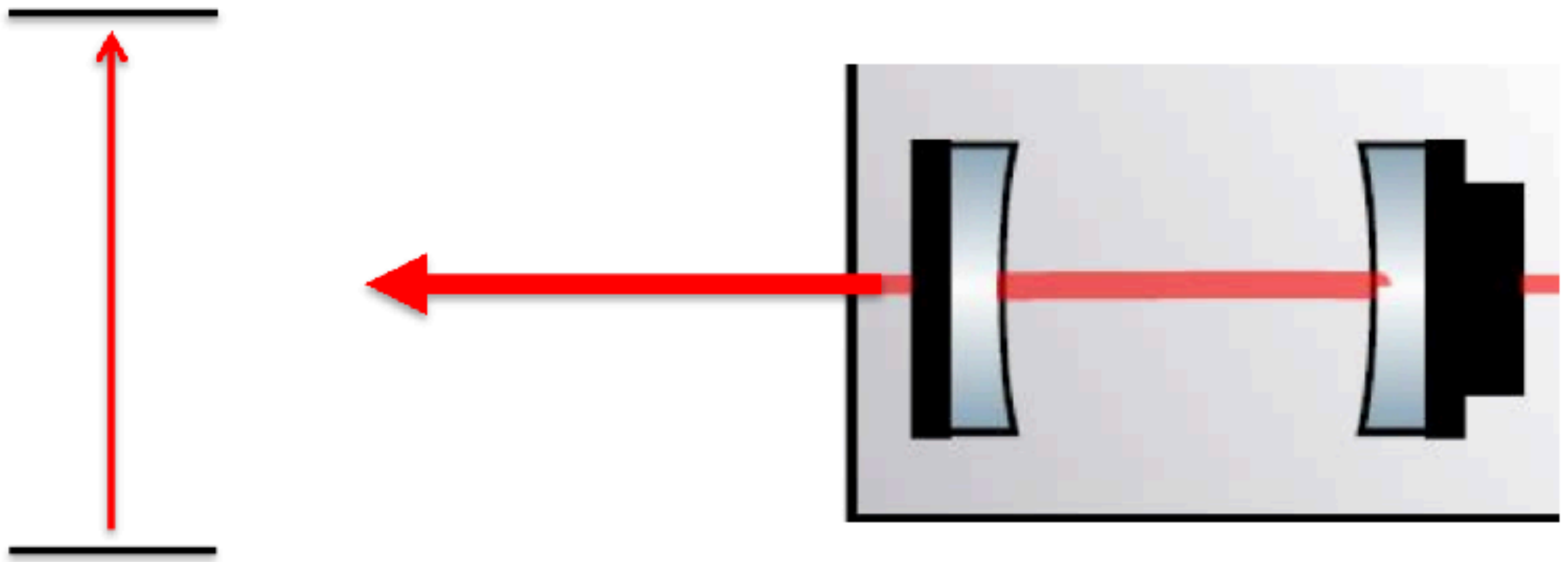
- Microwave clocks: $\nu_0 \sim$ few 10^9 Hz, $|K| \sim 1-3$
  - Current best uncertainty $\sim 10^{-16}$
- Optical clocks: $\nu_0 \sim 10^{15}$ Hz, $|K| \sim 0.01-6$
  - Current best uncertainty $\sim 10^{-18}$
- Nuclear / charged ion / lattice / molecular clocks:
  - Don't exist yet
  - Expectation is $|K| \sim 10-10^4$ w/ uncertainty $\sim 10^{-19}$!

Poli, Oates, Gill, Tino (1401.2378)



Dynamical Decoupling

Relative frequency oscillations



$R_\infty \propto \alpha^2 m_e$

$a_0 \propto (m_e \alpha)^{-1}$

$$\frac{\delta f_{\rm ion}(\nu)}{f_{\rm ion}} = 2\frac{\delta\alpha(\nu)}{\alpha} + \frac{\delta m_e(\nu)}{m_e}$$

$$\frac{\delta f_{\rm laser}(\nu)}{f_{\rm laser}} = \left(\frac{\delta\alpha(\nu)}{\alpha} + \frac{\delta m_e(\nu)}{m_e}\right) \times F(\nu)$$

~ kHz

- Long integration times to get to 10^{-18}
- Oscillation freq. ? Probe high frequencies

(slide by Roee Ozeri)