Axion Stars

and how we might find them

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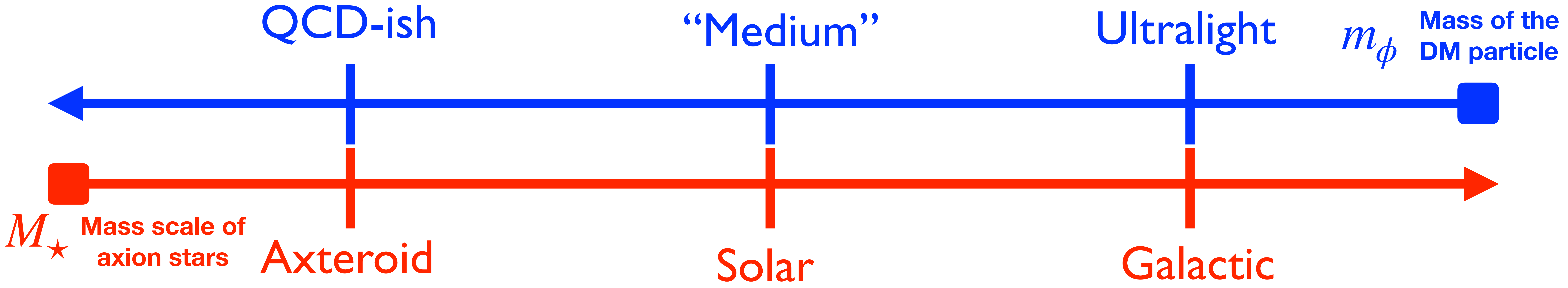
MITP YoungSt@rs
"Axions in the Lab"
06/10/2022

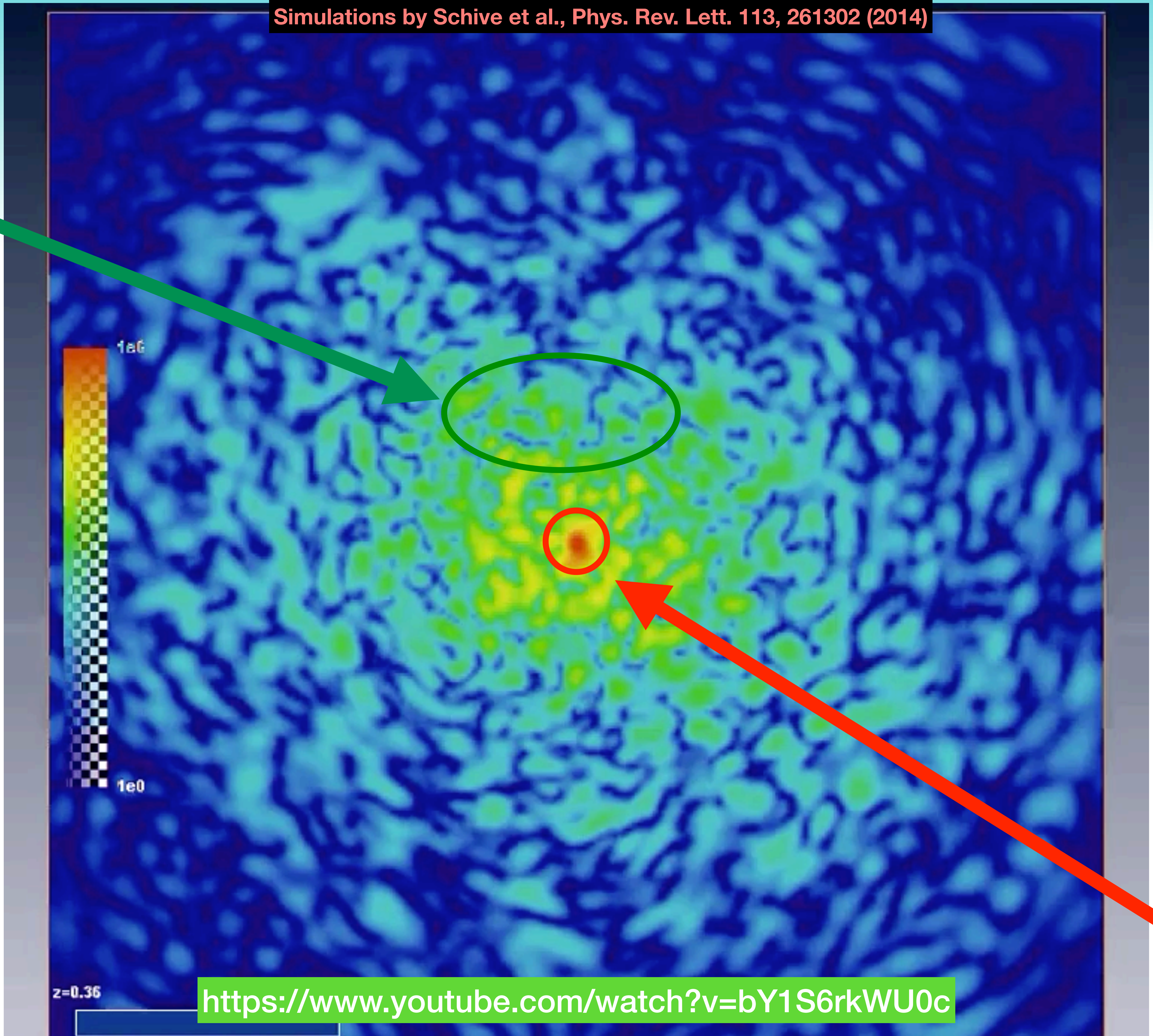
Outline

- What are axion stars?
- How to find (maybe) them: <u>a highly biased overview</u>
  - Ultralight axions: $10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-19}\,\mathrm{eV}$ (galaxy cores)
  - "Medium" axions: $10^{-15}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-8}\,\mathrm{eV}$ (lensing, Bosenovae)
  - QCD-ish axions: $10^{-7}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-2}\,\mathrm{eV}$ (transients)



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

Quasiparticles



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

(Light) axions are wavy

Axion Star

Equations of Motion

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

Poisson Gravity

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

(Attractive)

Coherent state → Oscillates

Leading time dependence

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

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

Normalization

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

Gradient energy

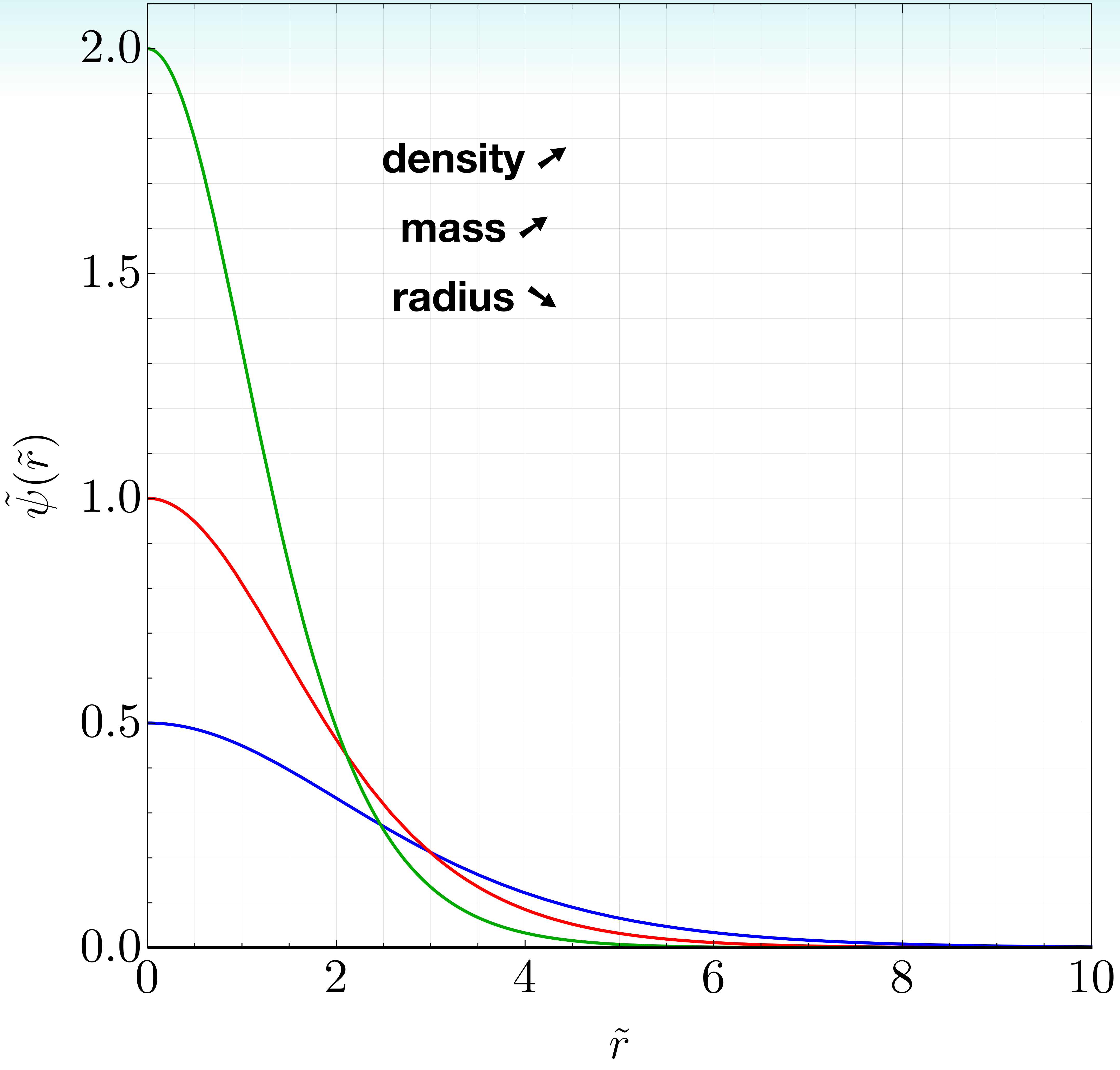
(Repulsive)

Self-interactions

For axion potential,

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

Axion Star



Ground-state solution of the GPP Equations

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

(at low density)

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

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

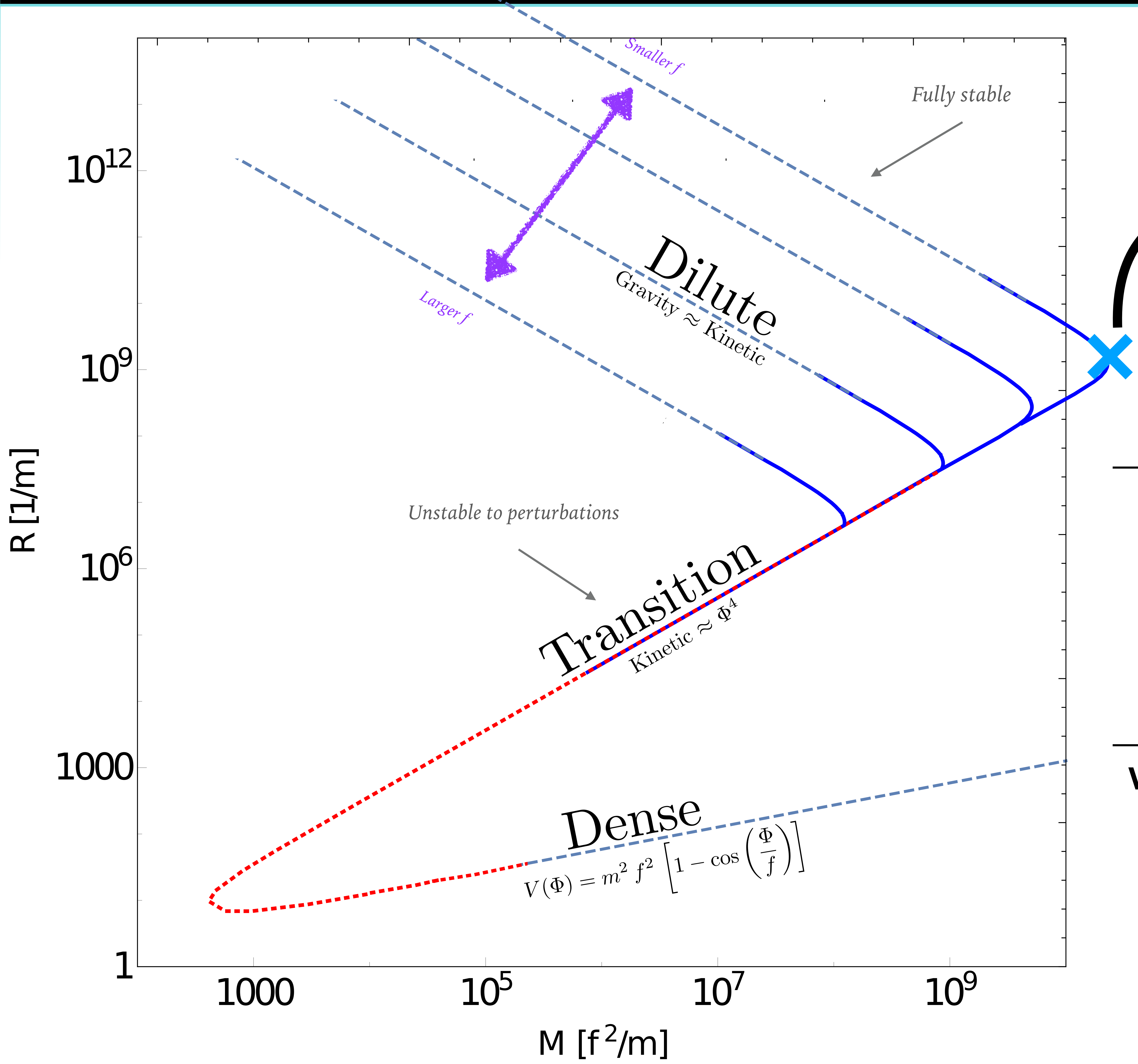
$$R_\star \simeq \frac{M_P^2}{m_\phi^2 M_\star} \simeq 100\,\mathrm{pc}\left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)^2\left(\frac{10^9\,M_\odot}{M_\star}\right)$$

$$\simeq 4\,R_\odot\left(\frac{10^{-13}\,\mathrm{eV}}{m_\phi}\right)^2\left(\frac{M_\odot}{M_\star}\right)$$

"Dilute axion star"

$$\simeq 300\,\mathrm{km}\left(\frac{10^{-5}\,\mathrm{eV}}{m_\phi}\right)^2\left(\frac{10^{-12}\,M_\odot}{M_\star}\right)$$

Mass-Radius Relation



Endpoint of (stable) **Dilute Branch**

fixed by turn-on of attractive self-interactions

$$M_c = \frac{10\,M_P}{\sqrt{-\lambda}} = \frac{10\,M_P\,f}{m_\phi}$$

Transition branch

is unstable under perturbations

Gravity negligible, bound by self-interactions; sometimes called "oscillons"

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

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

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

Very unstable to decay

"Axiton", "Oscillon", Kolb+Tkachev (astro-ph/9311037)

(Dilute) Axion Star Formation

Formed by "Gravitational cooling"

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

Can be understood analytically as <u>*gravitational relaxation*</u> of quasiparticles

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

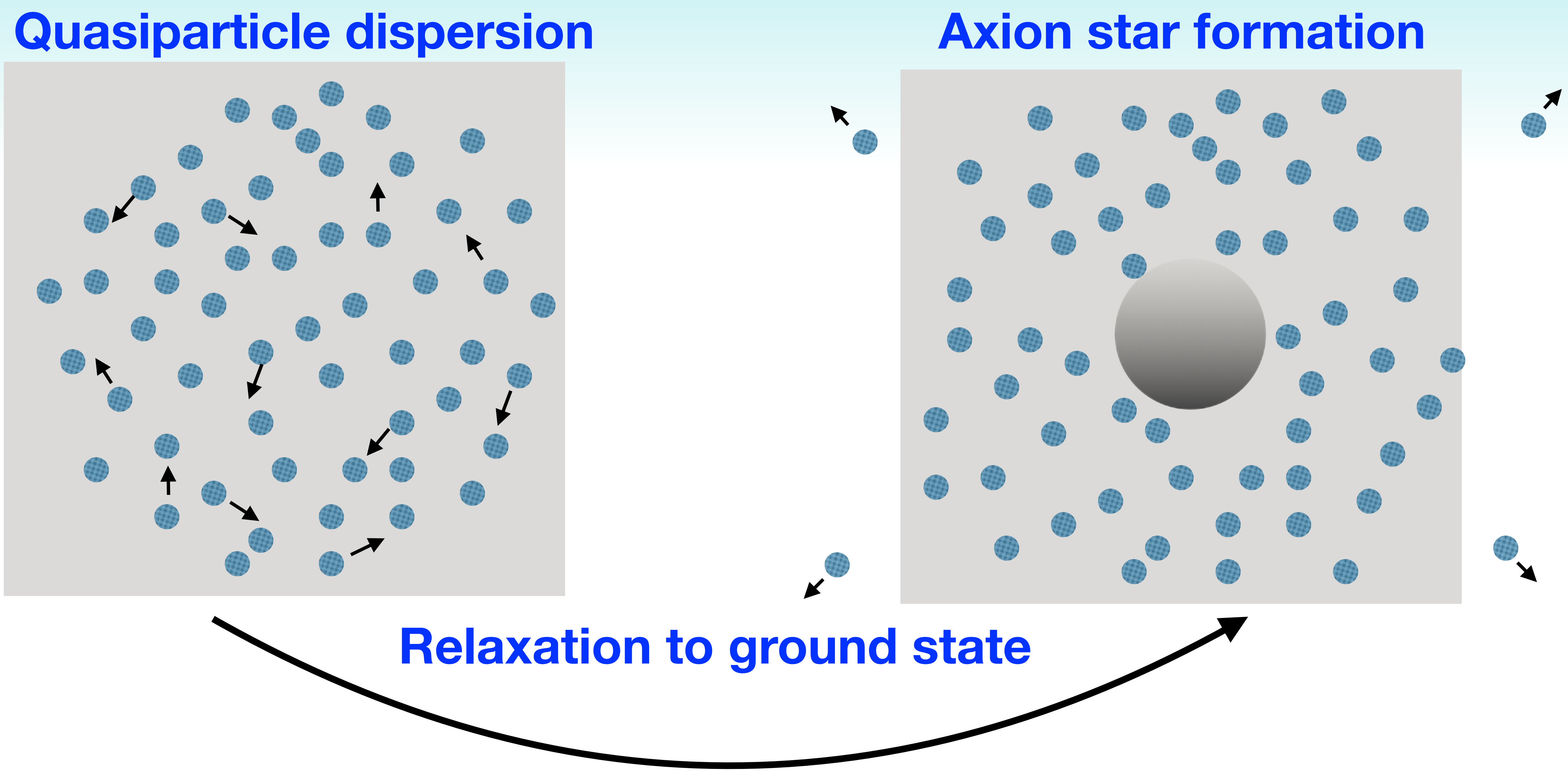
N objects scatter gravitationally, exchange energy

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

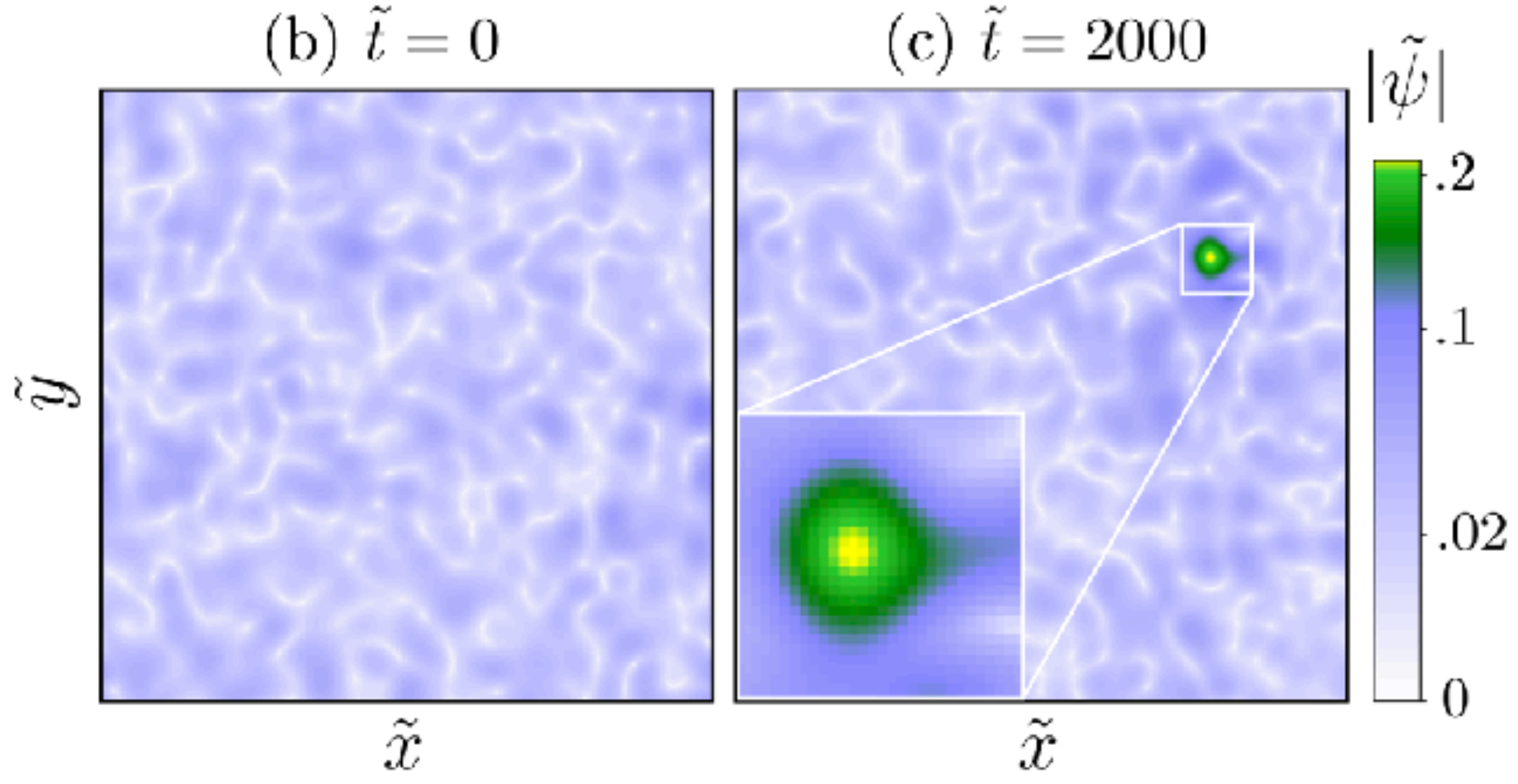
Velocity change per crossing

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

Binney and Tremaine, "Galactic Dynamics, 2nd Edition"

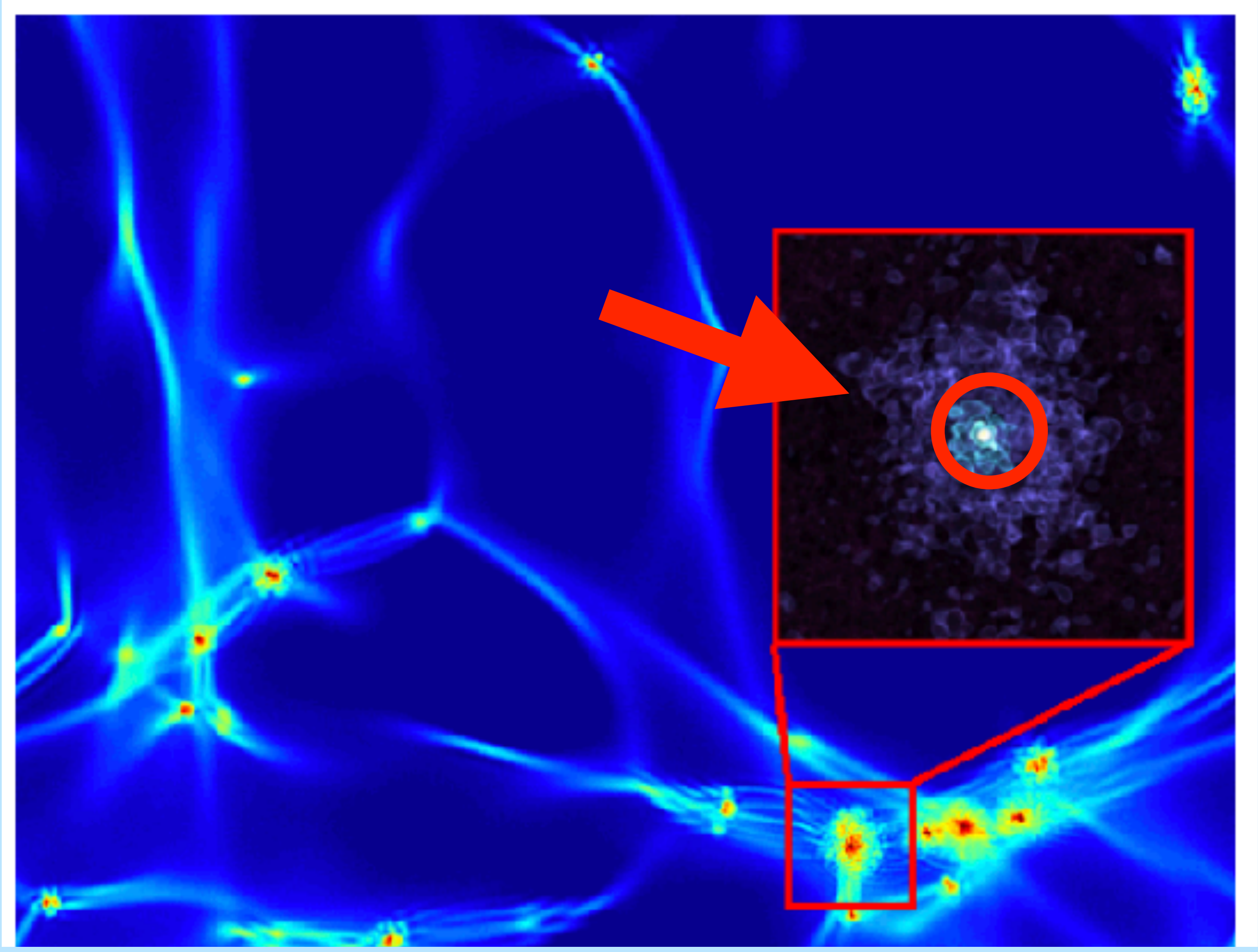


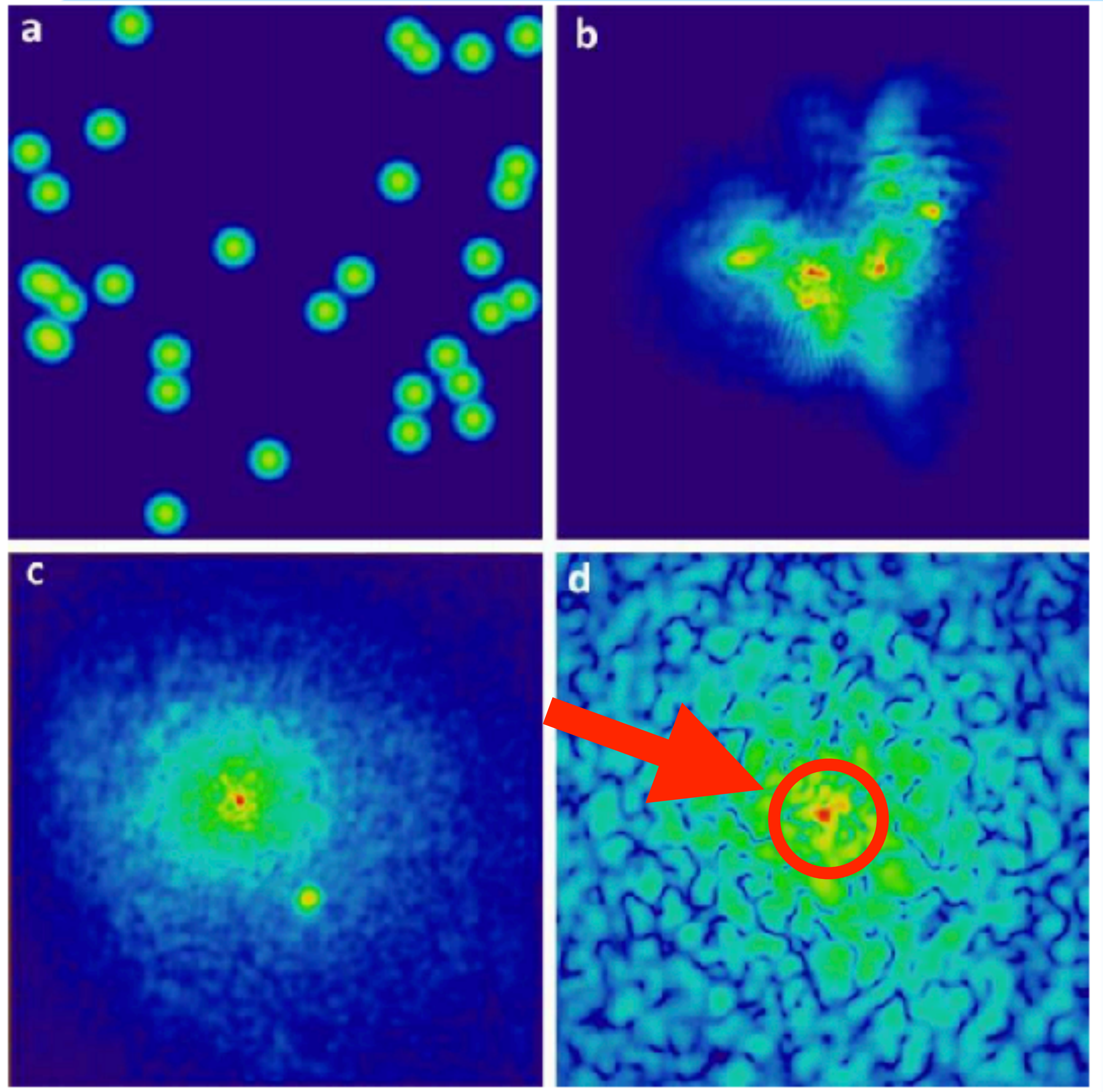
Levkov, Panin, Tkachev (1804.05857)



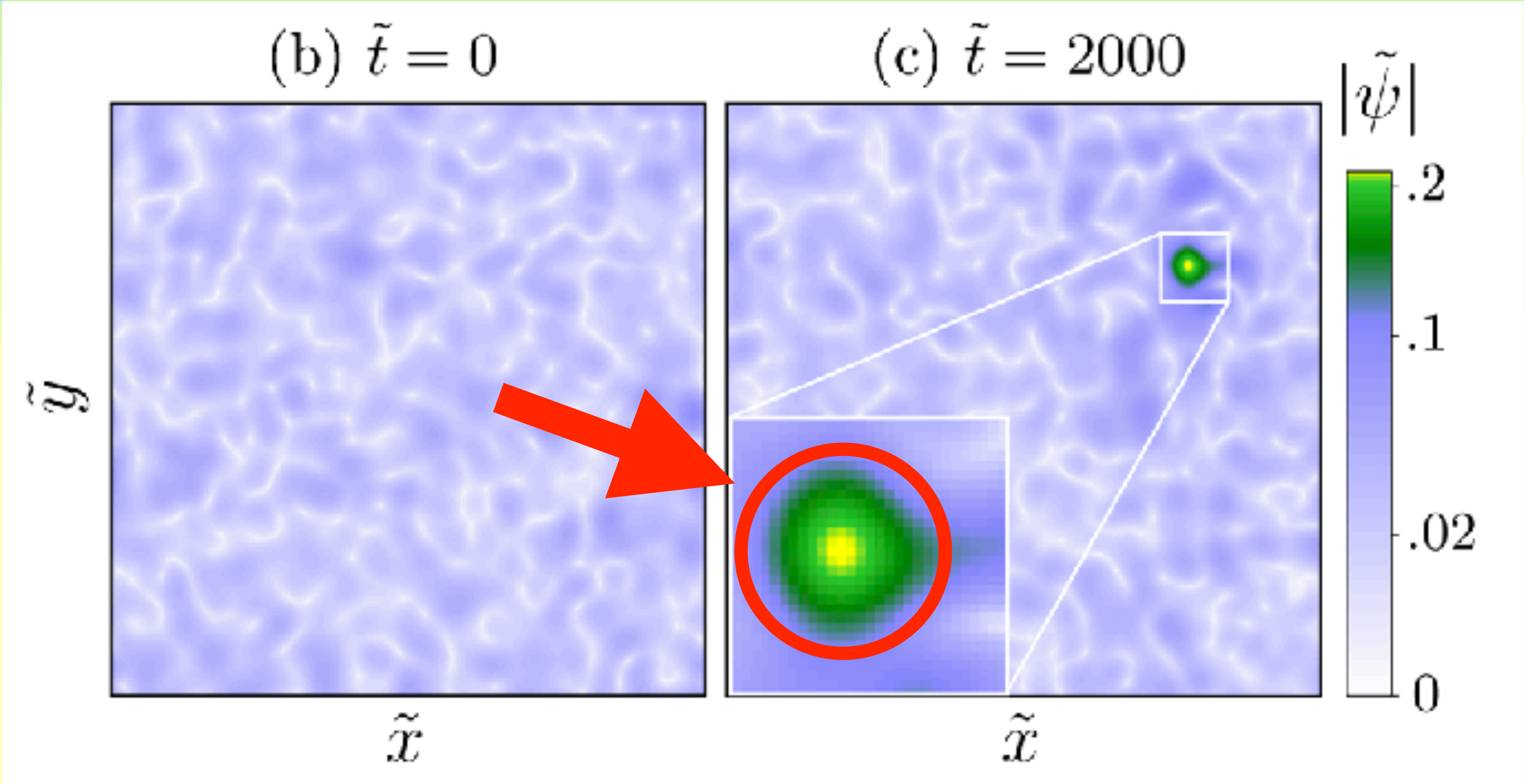
Axion Stars in Simulation

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

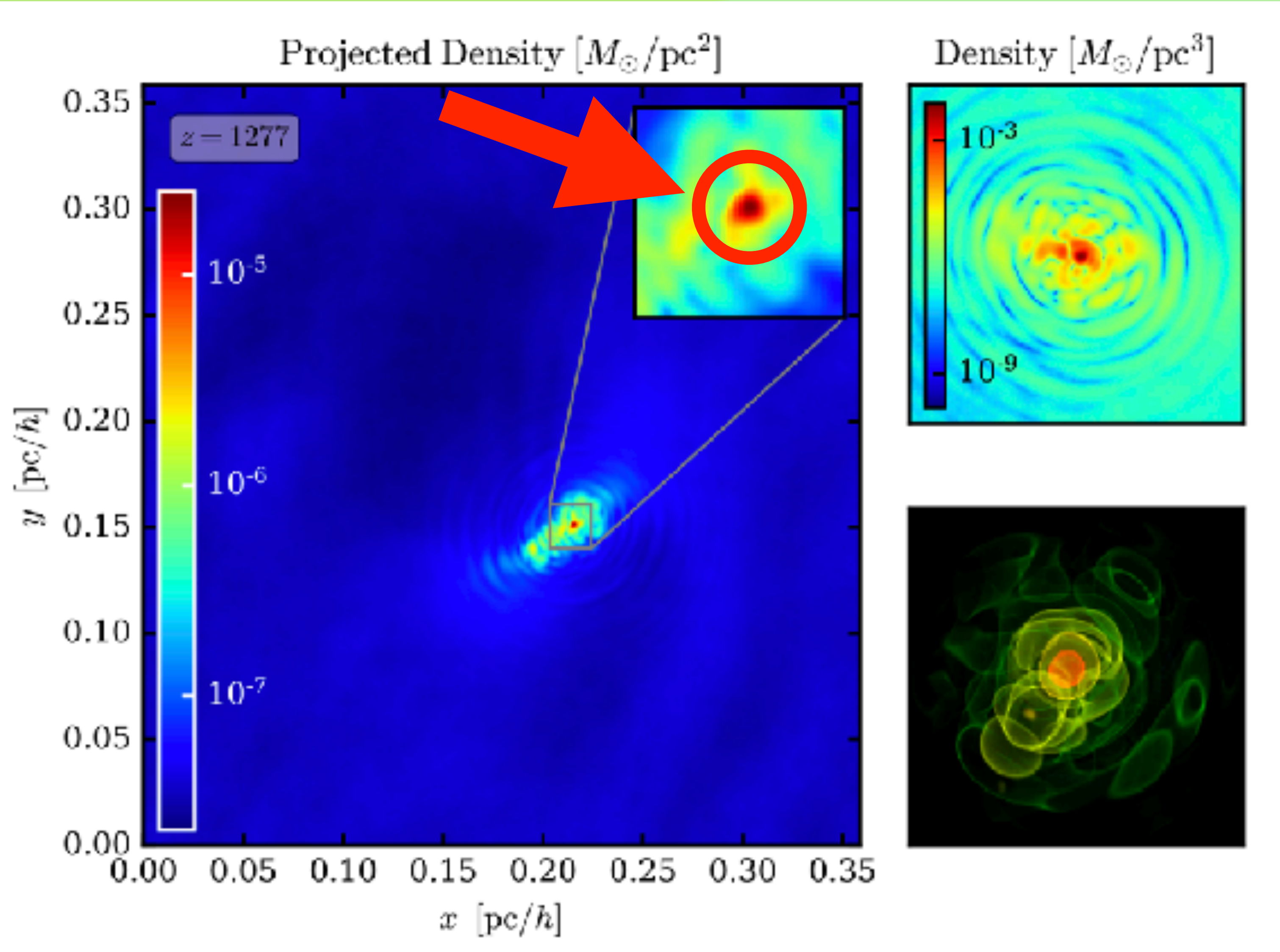




Schive et al.,
Phys. Rev. Lett. 113, 261302 (2014)



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



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

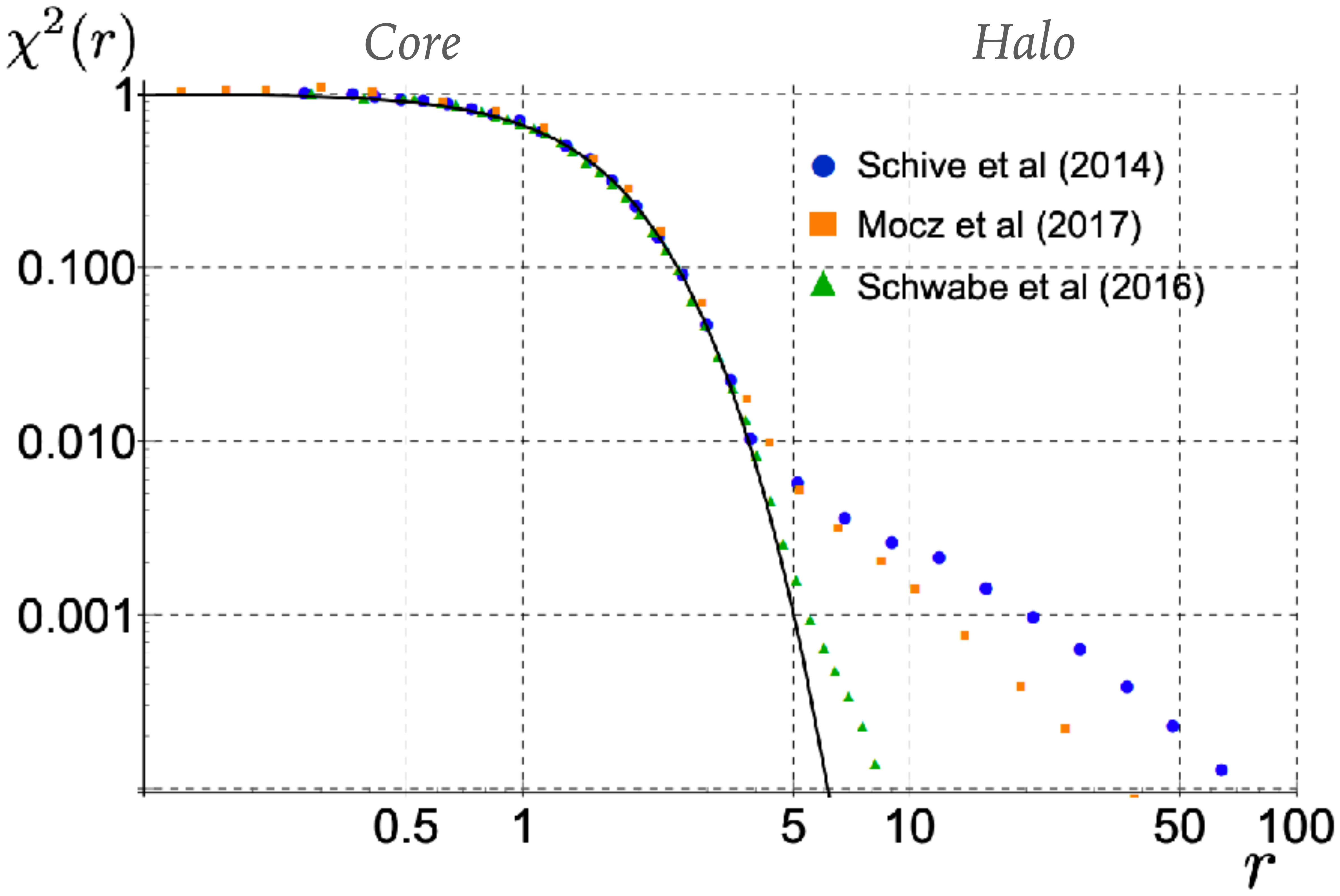
1. Ultralight Axions

$$10^{-22}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-19}\,\mathrm{eV}$$

Axion stars —> "solitons"
(form cores in center of galaxies)

Core-Halo Relation

◉ Simulations of ultralight fields suggest *a relation between core soliton and host halo*



Bar, Blas, Blum, Sibiryakov (1805.00122)

Classic result (2014): *

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

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

If true, we can predict mass of central soliton — sharp predictions!

*** Some call 1/3 exponent into question; some evidence of variability between galaxies; see e.g.**

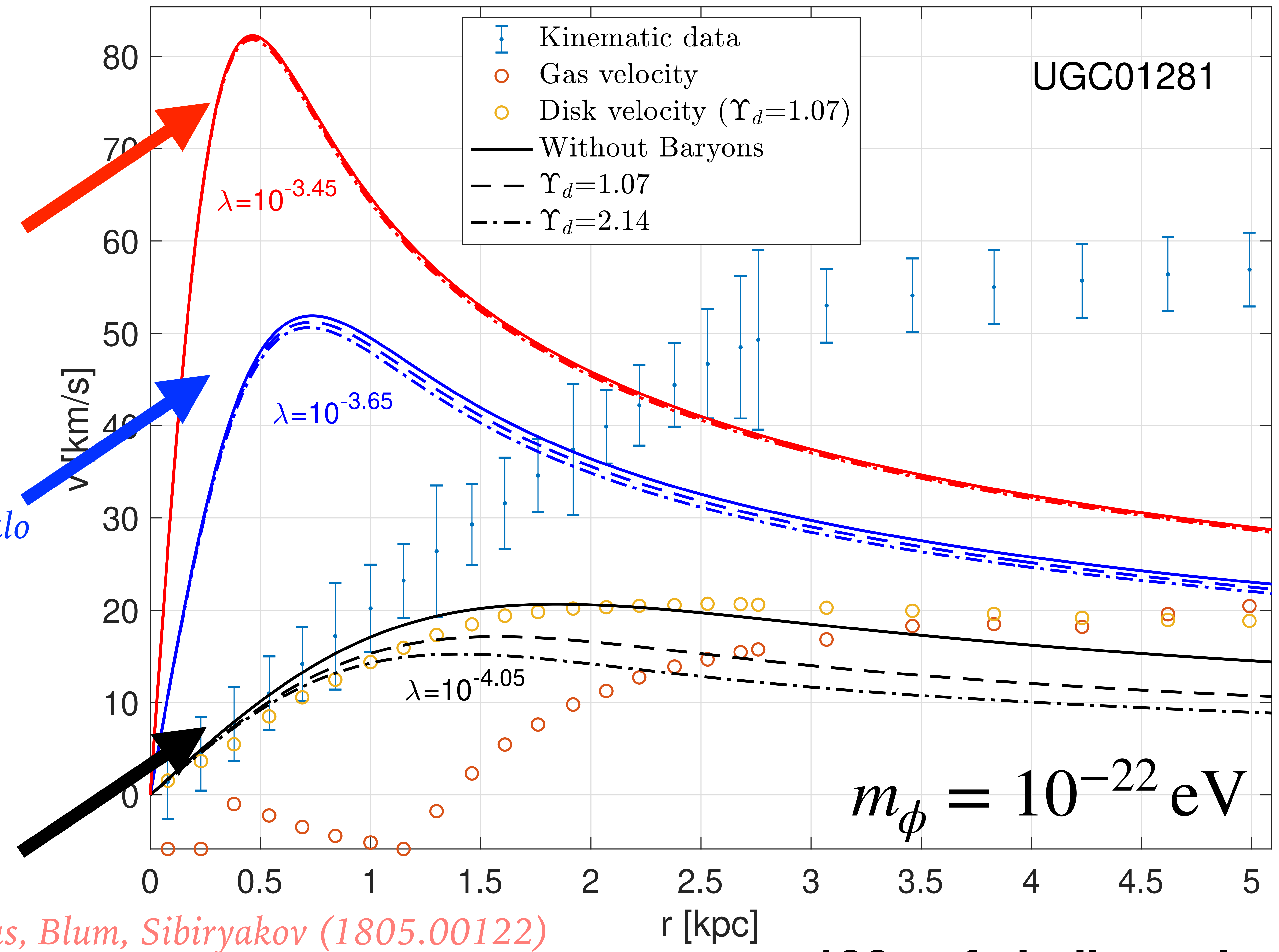
Yavetz, Li, Hui (2109.06125)

Stellar Rotational Velocities

Heavier solitons

Soliton-Halo Relation

Lighter solitons



Bar, Blas, Blum, Sibiryakov (1805.00122)

Bar, Blum, JE, Sato (1903.03402)

100s of similar galaxies in SPARC database

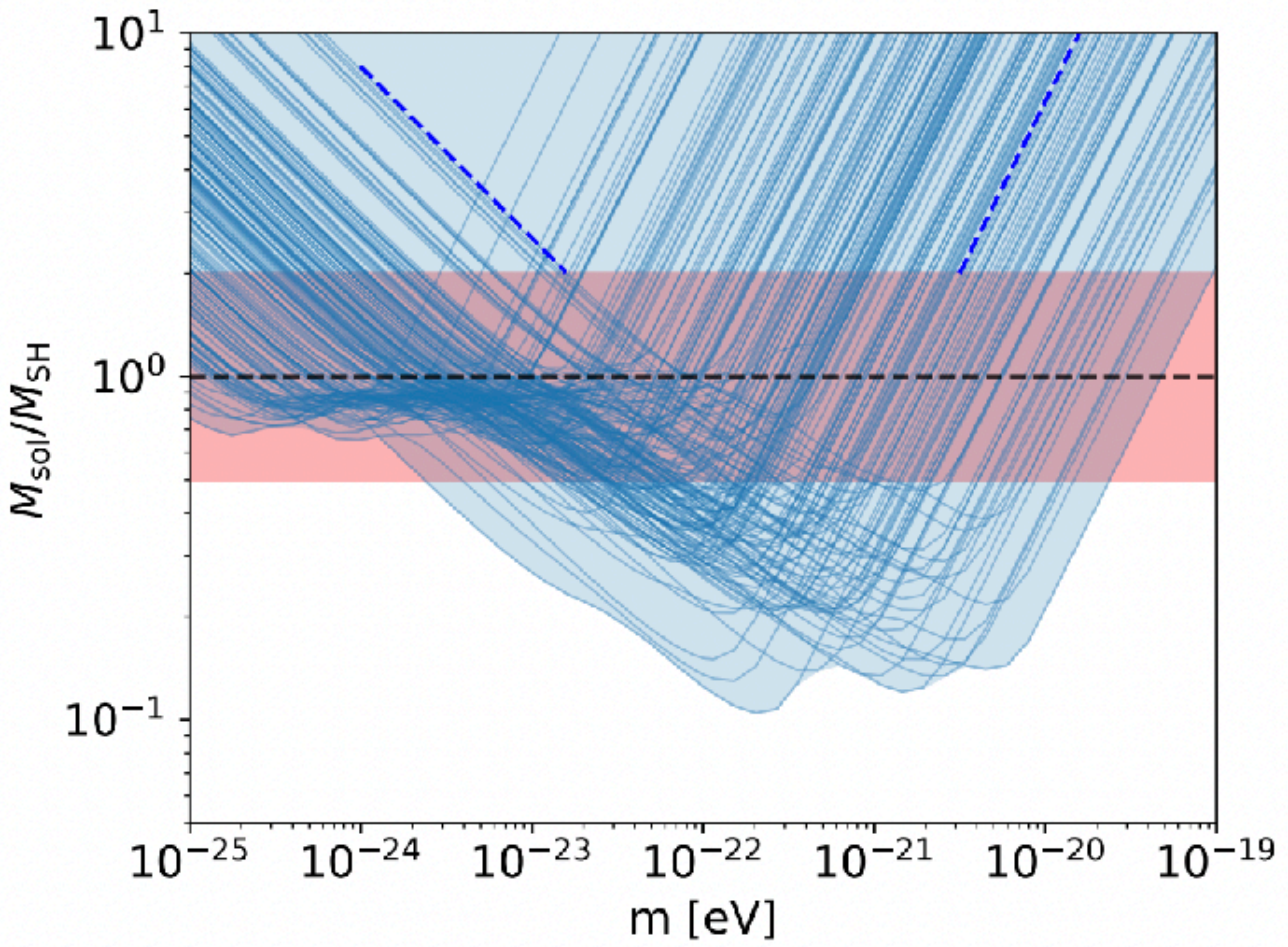
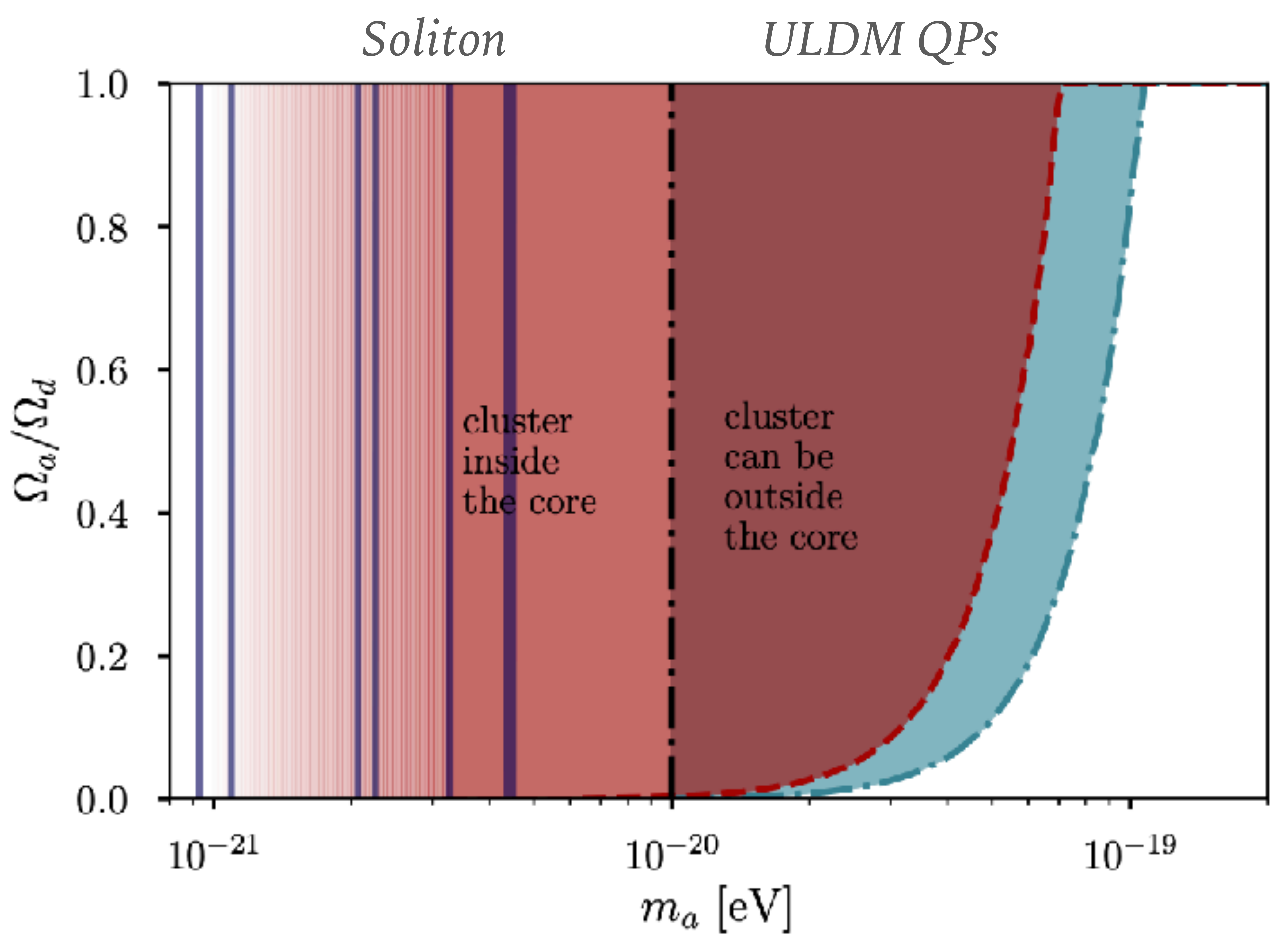


FIG. 1: The combined 95% C.L. constraints (solid blue) of SPARC galaxies on the mass of the soliton M, normalized by that predicted by soliton-host halo relation, $M_{\rm SH}$. Each blue line corresponds to a galaxy. The blue dashed lines highlight analytical approximations, valid at small and large m. The red band comes from allowing $M_{\rm SH}$ to vary by up to a factor of 2 up or down. See Sec. II B for more details of the computation.

Bar, Blum, Sun (2111.03070)

Other (tentative) constraints

- <u>Cold star clusters</u>
  - Fluctuations of ULDM induce "heating" of stellar populations, e.g. Eridanus II
    Marsh and Niemeyer (1810.08543)
  - Lingering soliton oscillations of $A \simeq 0.3$?
    Veltmaat, Niemeyer, Schwabe (1804.09647)



- <u>Solitons around SMBHs</u>
  - Orbits around Sgr A* "measure" mass enclosed

Bar, Blum,Lacroix, Panci (1905.11745)

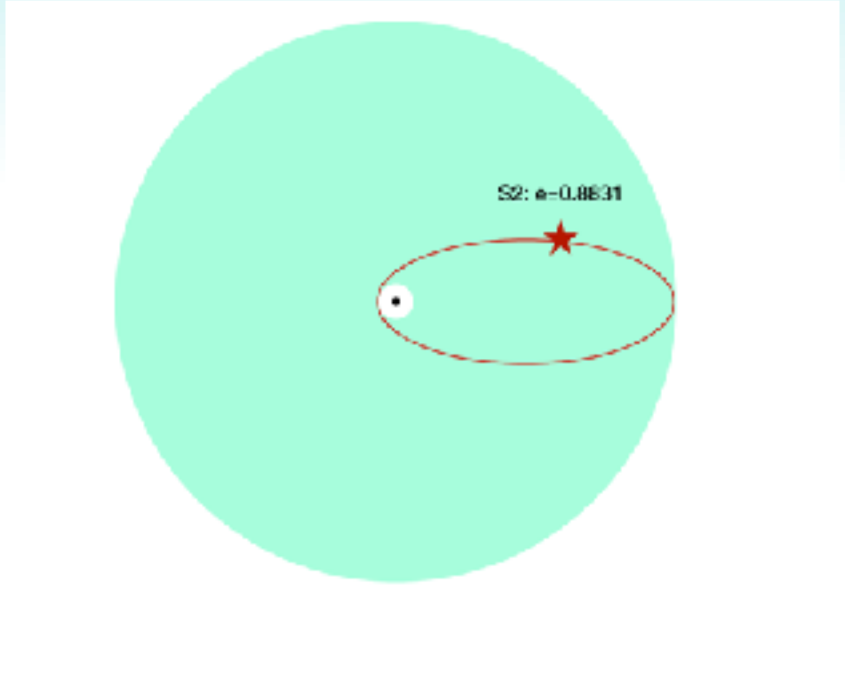
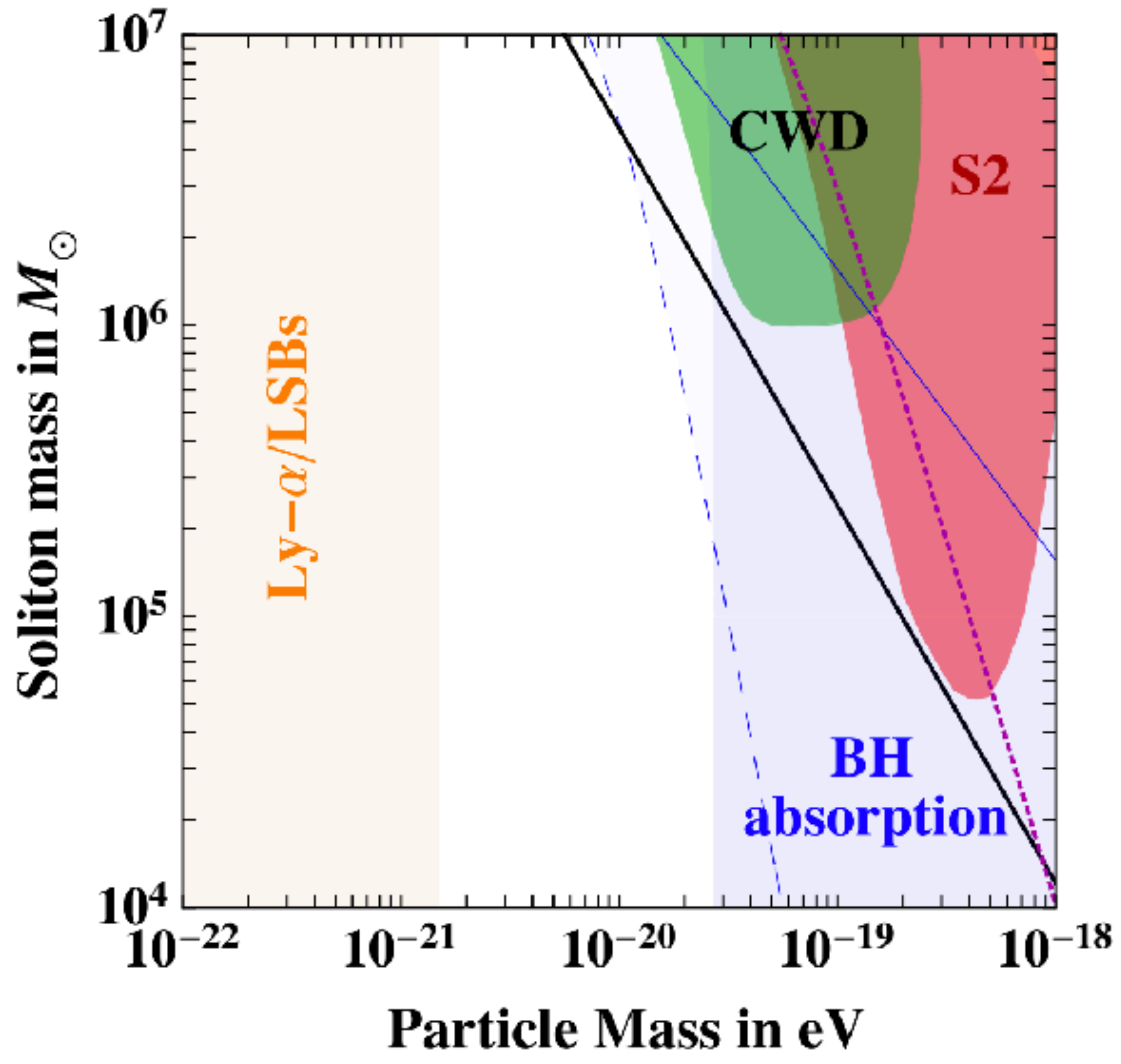


FIG. 1: Schematic view of the S2 elliptic orbit.

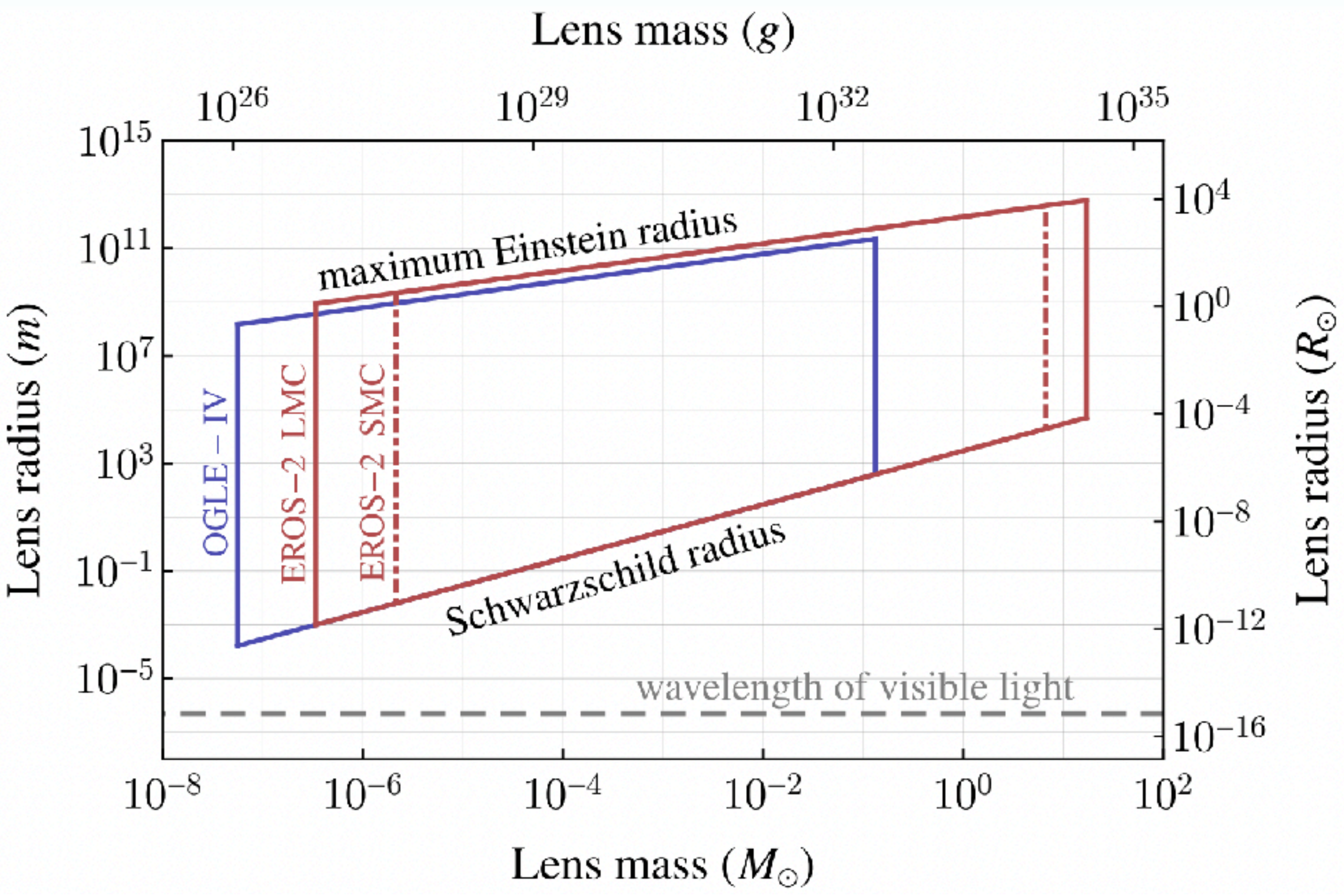


2. “Medium” Axions

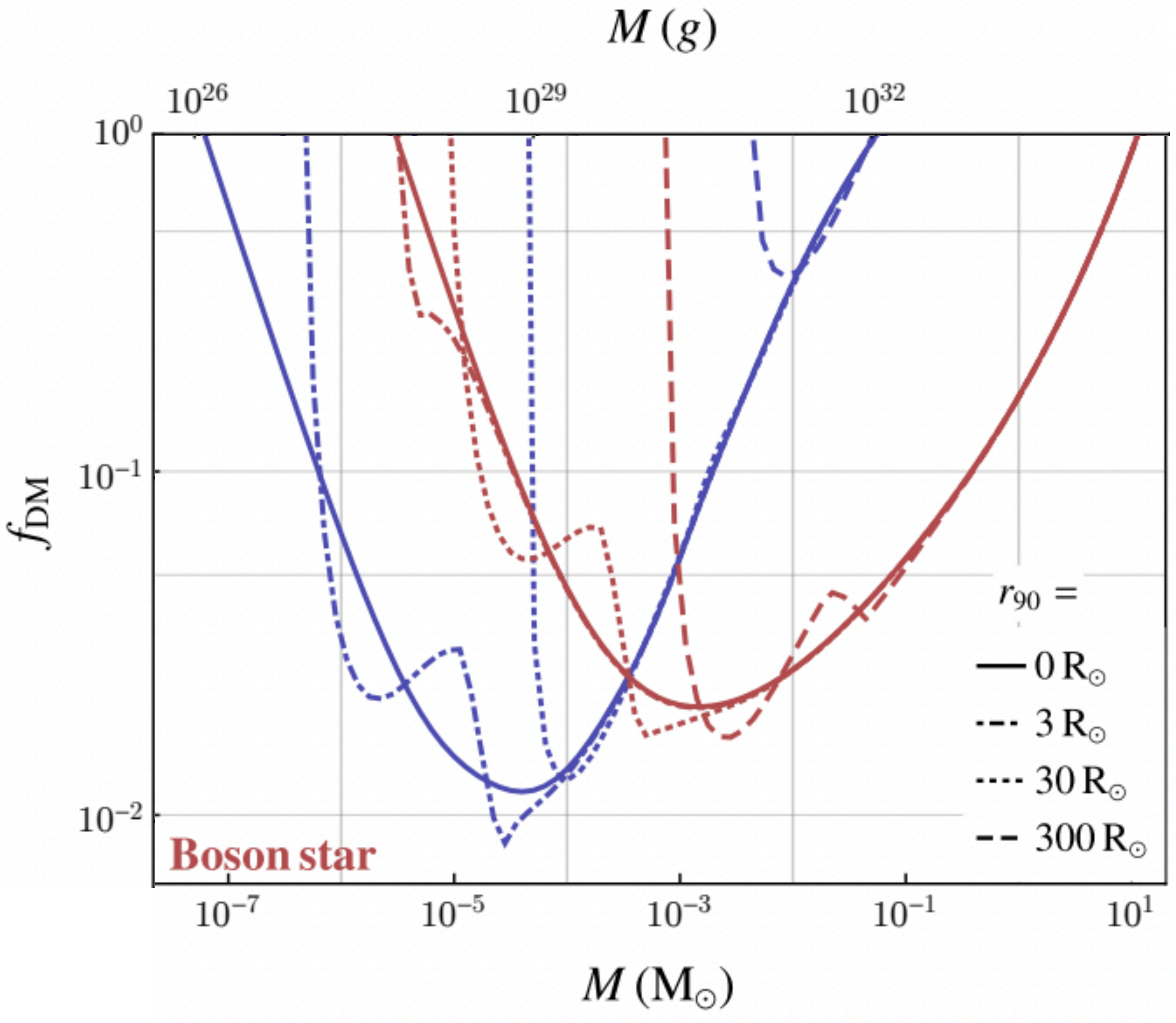
$$10^{-15}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-8}\,\mathrm{eV}$$

Axion stars —> actually kind of like stars
(at least in mass + radius)

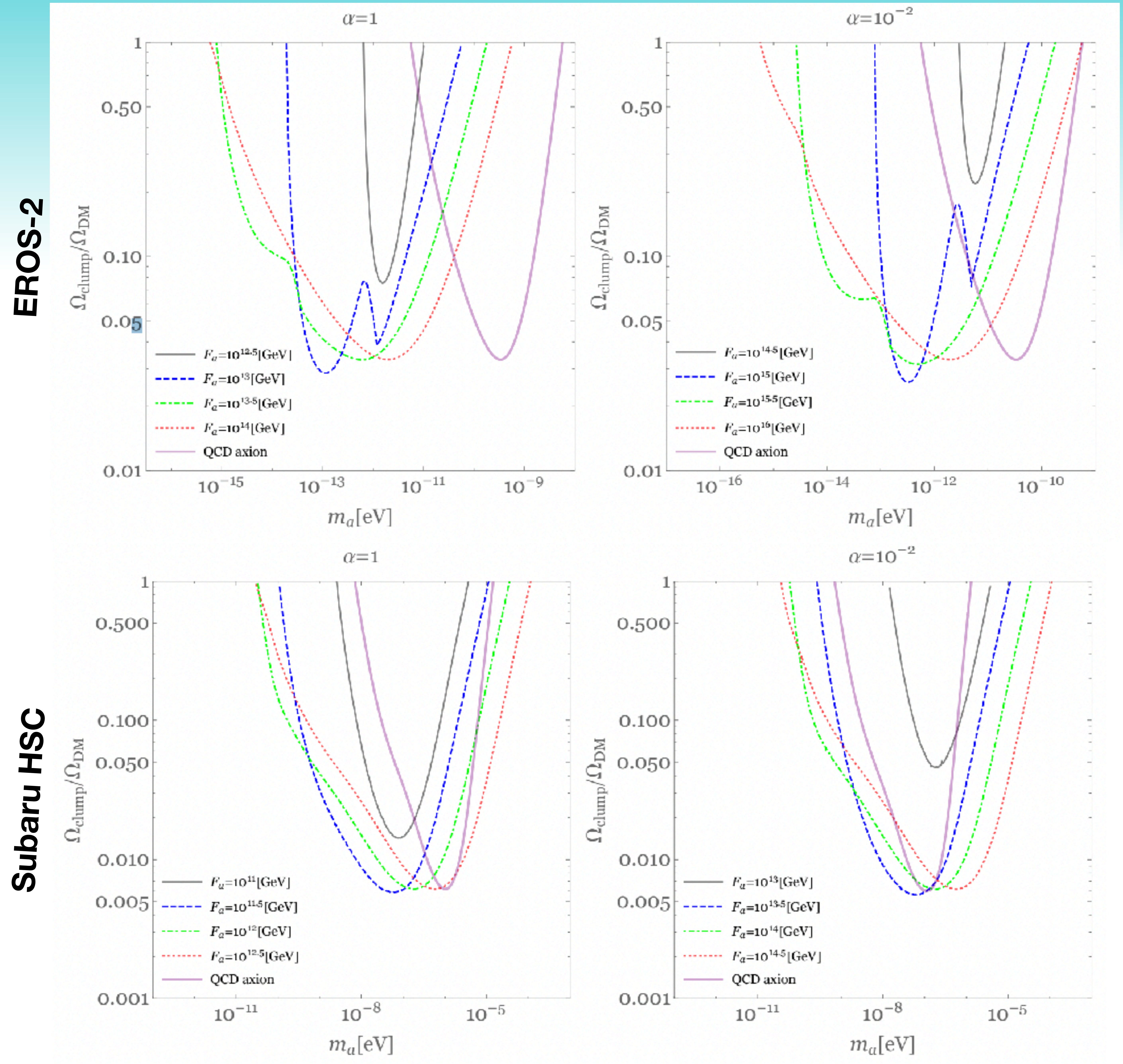
Gravitational Lensing of Axion Stars



projection for EROS-2 (red) and OGLE-IV (blue)



Croon, McKeen, Raj (2002.08962)



Constraints from Lensing

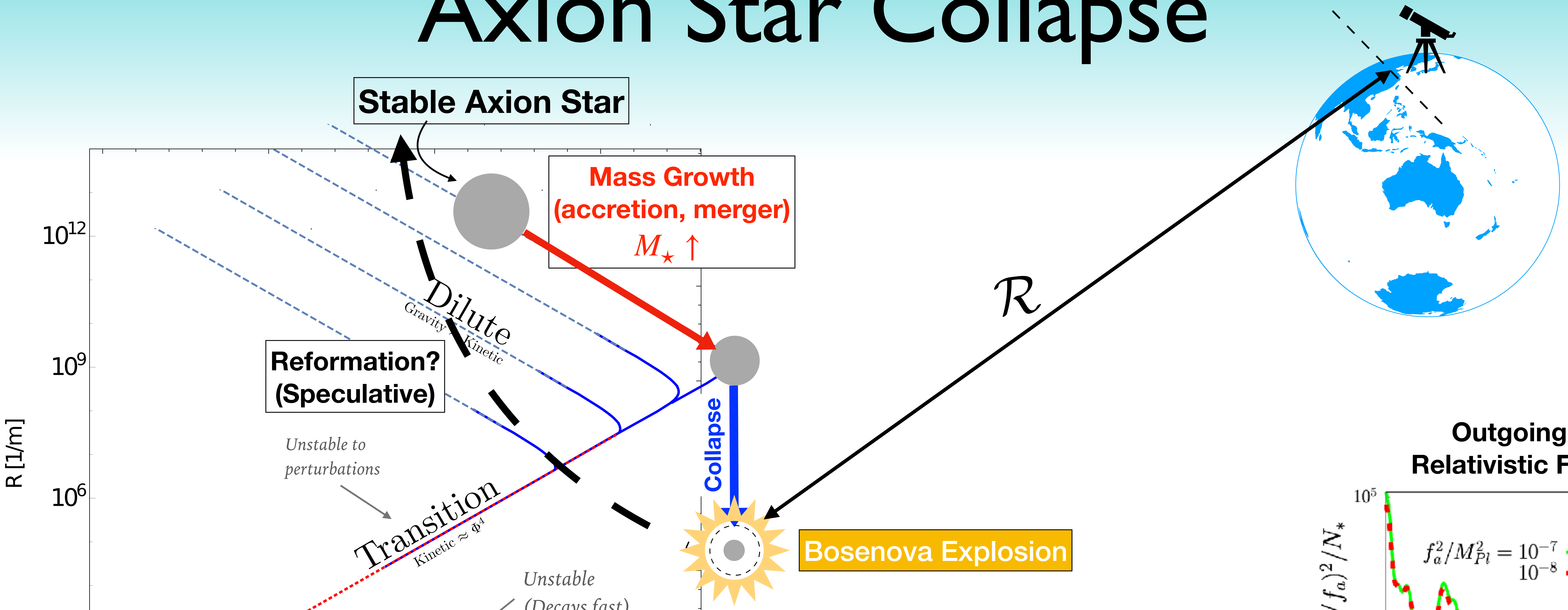
Note the change of notation:

$$M = \alpha M_c = \alpha \frac{10\, M_P\, f}{m}$$

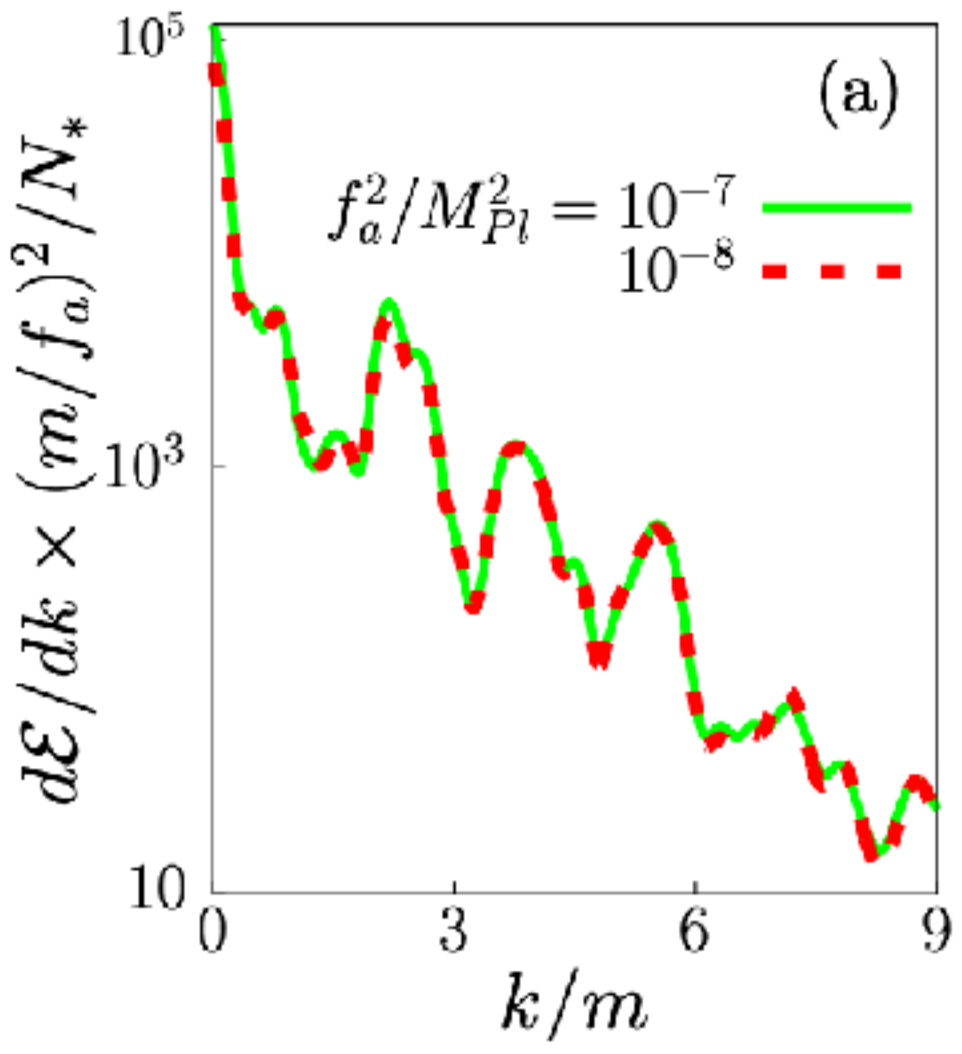
$$\simeq \alpha \times 10^{-5} M_\odot \left(\frac{f}{10^{14}\,\mathrm{GeV}}\right)\left(\frac{10^{-9}\,\mathrm{eV}}{m_\phi}\right)$$

Fujikura, Hertzberg, Schiappacasse, Yamaguchi (2109.04283)

Axion Star Collapse



Outgoing Relativistic Flux



Prediction:

JE, Leembruggen, Suranyi, Wijewardhana (1608.06911)

Simulation:

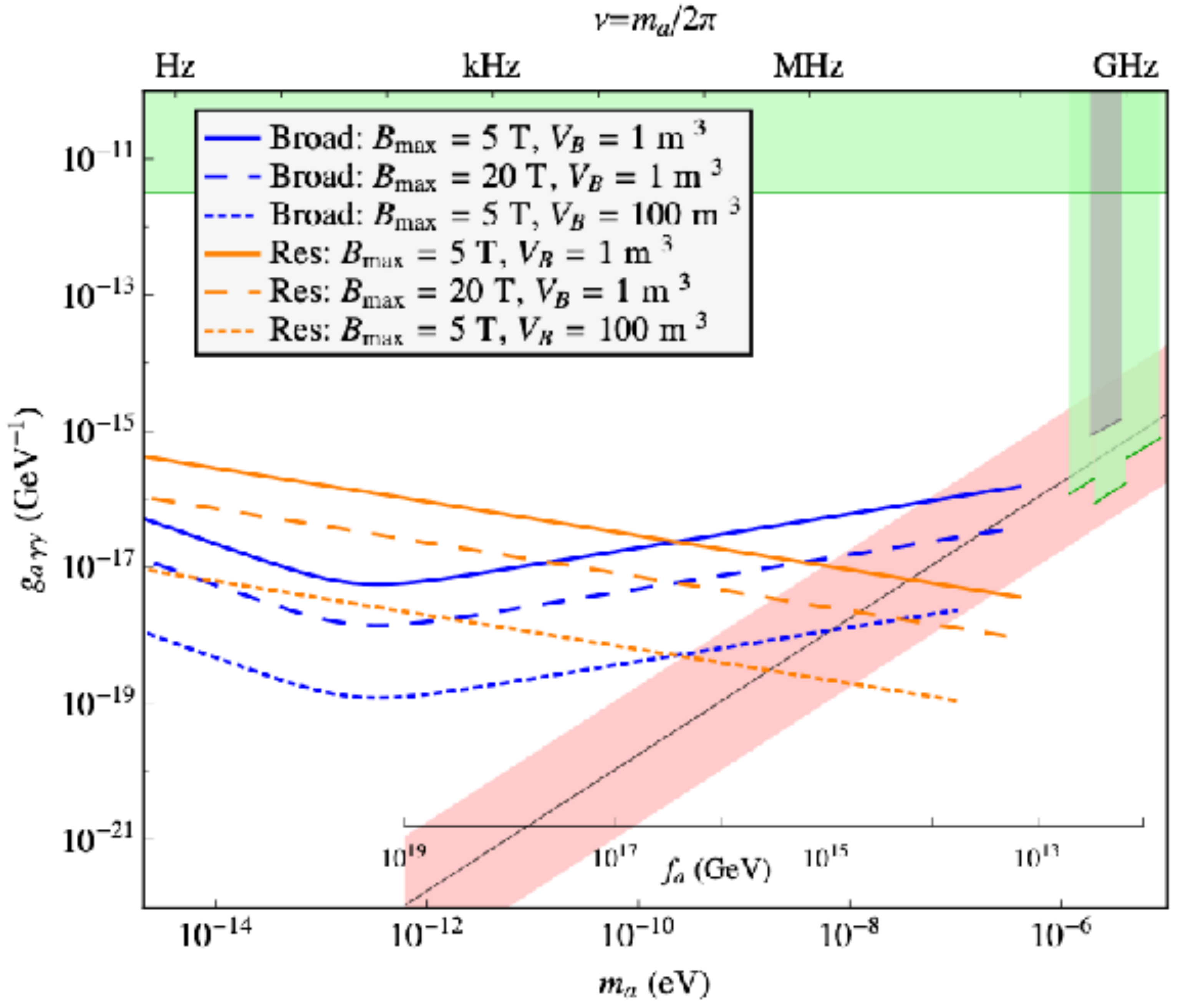
Levkov, Panin, Tkachev (1609.03611)

Bosenova Signal

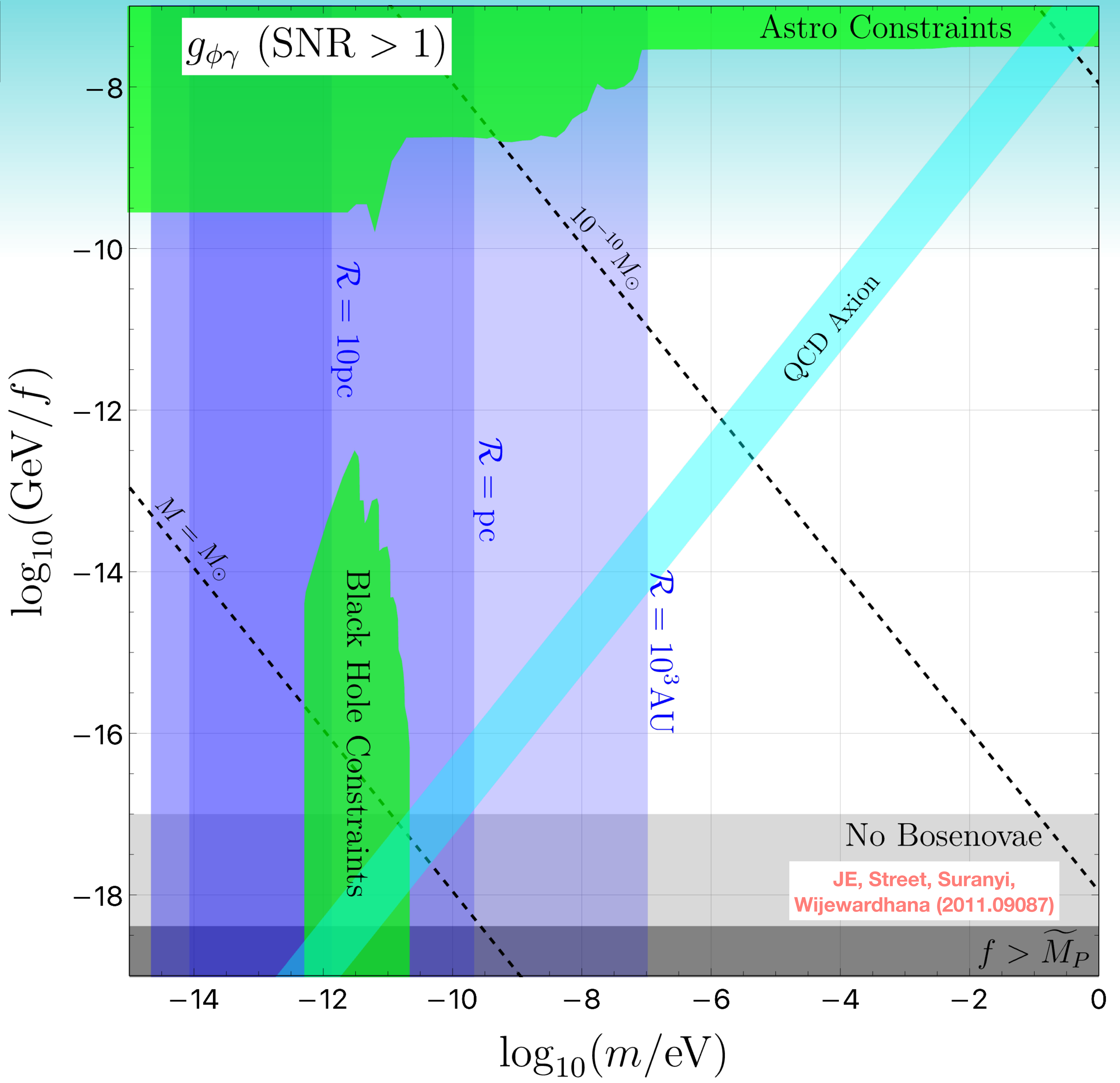
JE, Shirai, Stadnik, Takhistov (2106.14893)

For sensitivity estimate, we use ABRACADABRA broadband long-term reach

Kahn, Safdi, Thaler (1602.01086)



Though see also DMRadio (Snowmass2021) and SHAFT (2003.03348)



3. QCD-ish Axions

$$10^{-7}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-2}\,\mathrm{eV}$$

Axion stars —> much smaller / less massive than stars (more like asteroids (axteroids?))

Transient Signals

Sometimes they might pass through Earth?

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

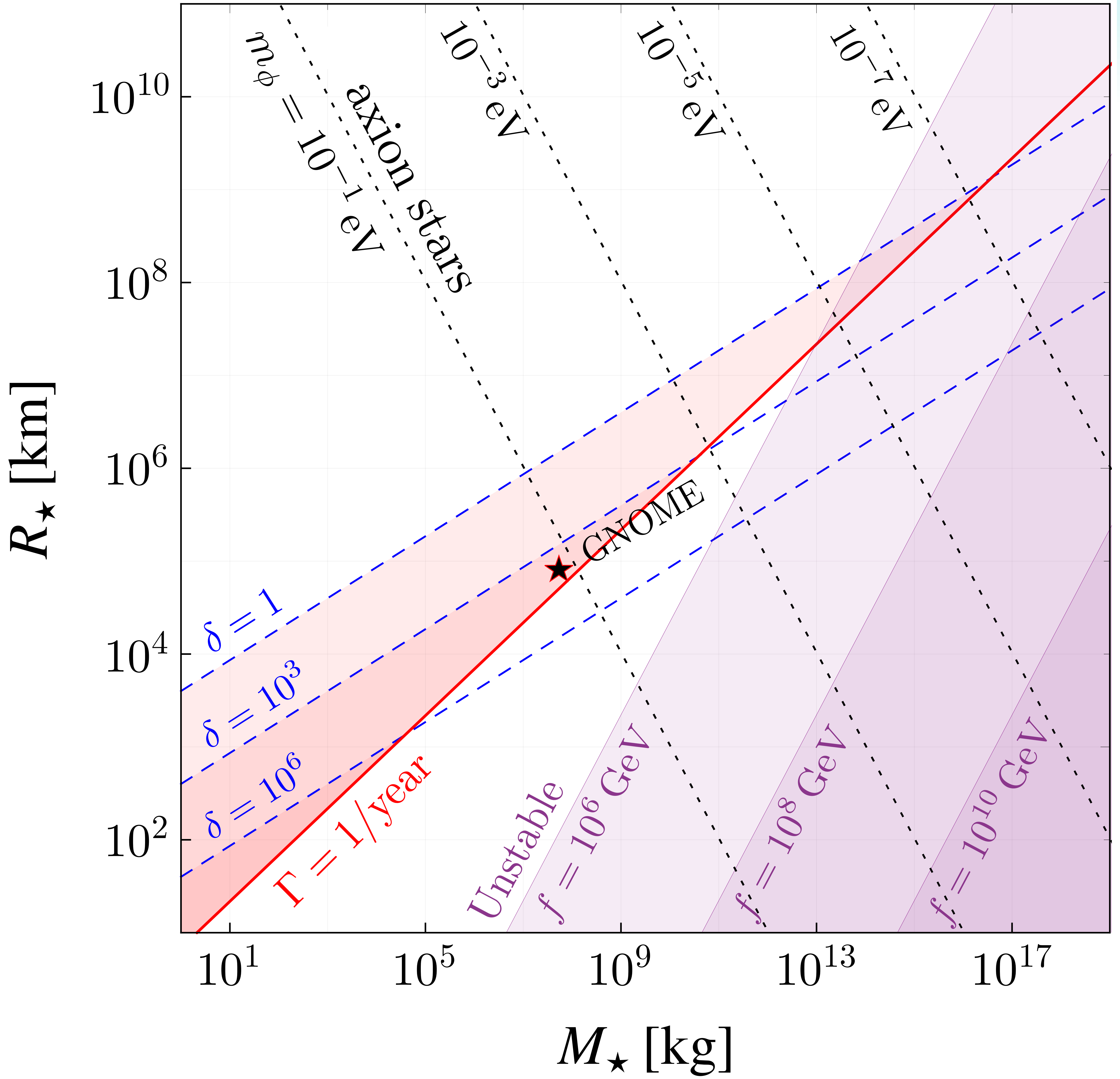
$$\frac{\rho_{local}}{M_\star} \qquad \pi R_\star^2 \qquad 200\, km/sec$$

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

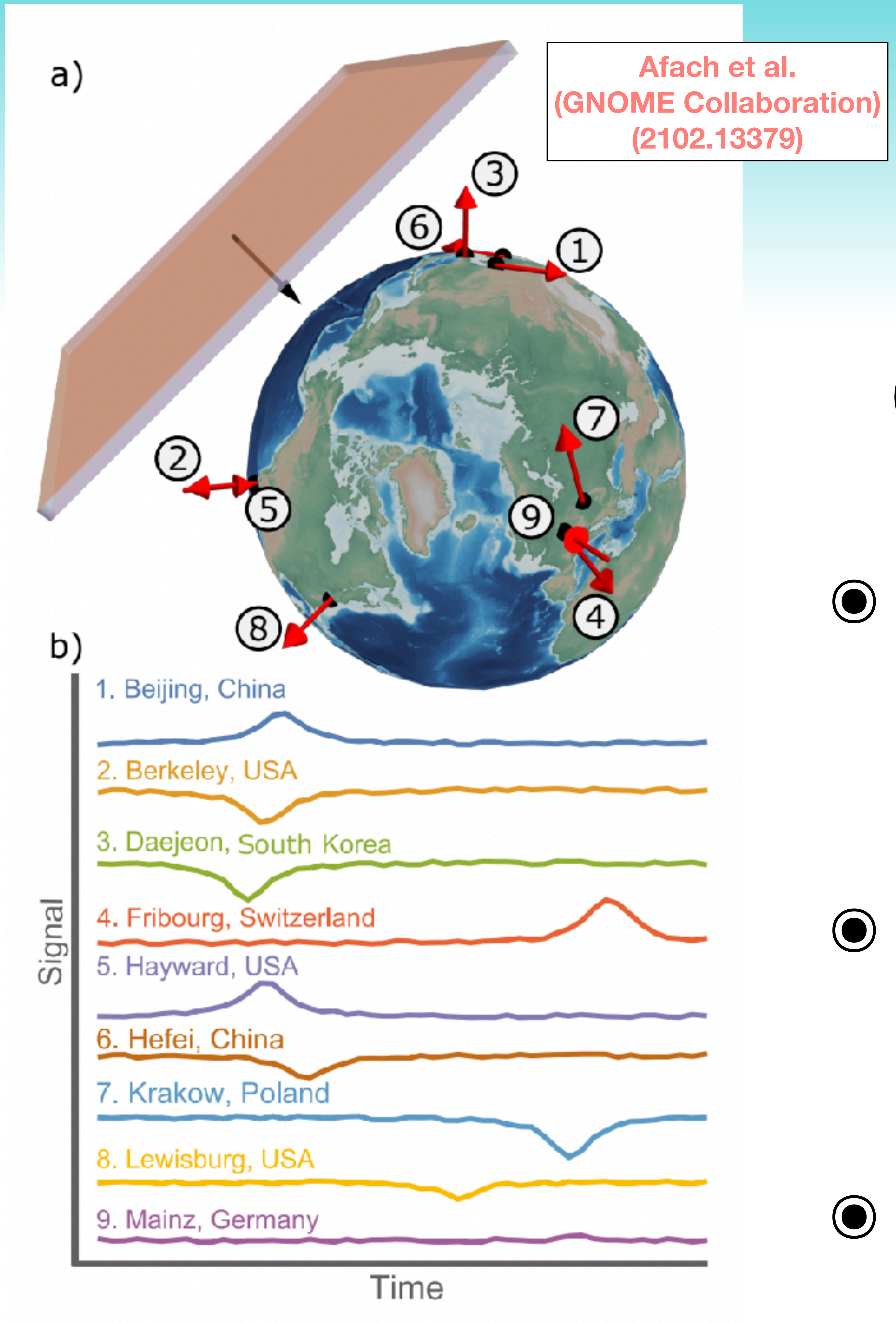
but $\delta \equiv \dfrac{\rho_\star}{\rho_{local}} \propto \rho_{local}^{-1} R_\star^{-4} m_\phi^{-2}$

Competition between density and rate!

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

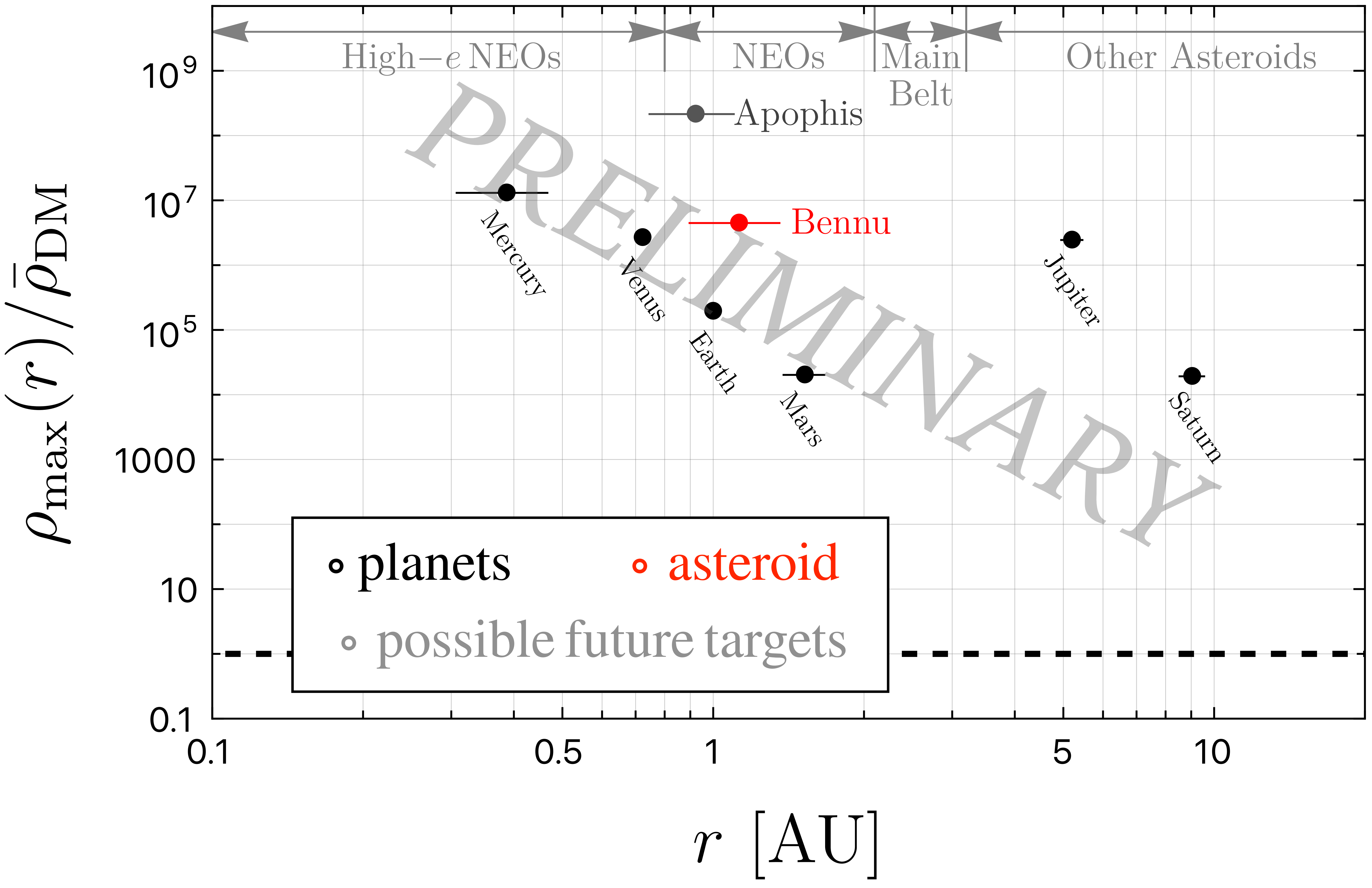


Rare Transient Events Motivate Global Network Searches



- E.g. Global Network of Optical Magnetometers for Exotic Physics (GNOME) Experiment
- Maximize cross section; allow for discrimination from large noise sources; potential for continuous running
- Difficult: share time-series data between experiments?

Search inside our solar system?



Analysis of static overdensity

Tsai, JE, Arakawa, Farnocchia, Safronova (2210.xxxxx)

(appearing next week!)

What would the passage of a transient axion star do to the trajectory of a planet or asteroid?

Can we see this?

Conclusions

- Axion stars are known to form in many theories of light scalar fields
- Can be a useful astrophysical (or terrestrial) probe over a wide range of scales (galactic, solar, and smaller)
- Lot of ideas, lots of ways to search for them!

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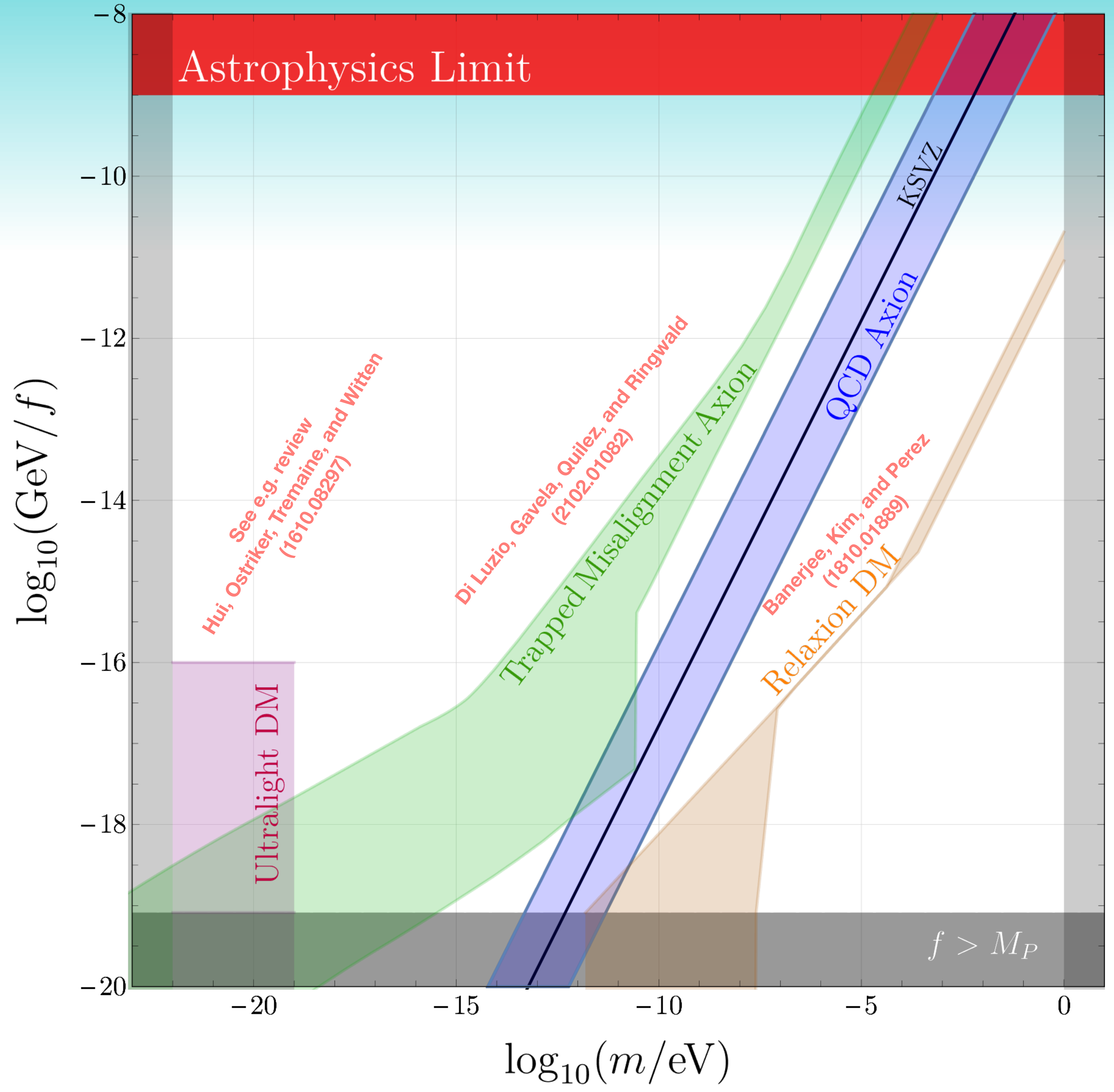
Thanks!

科研費 KAKENHI

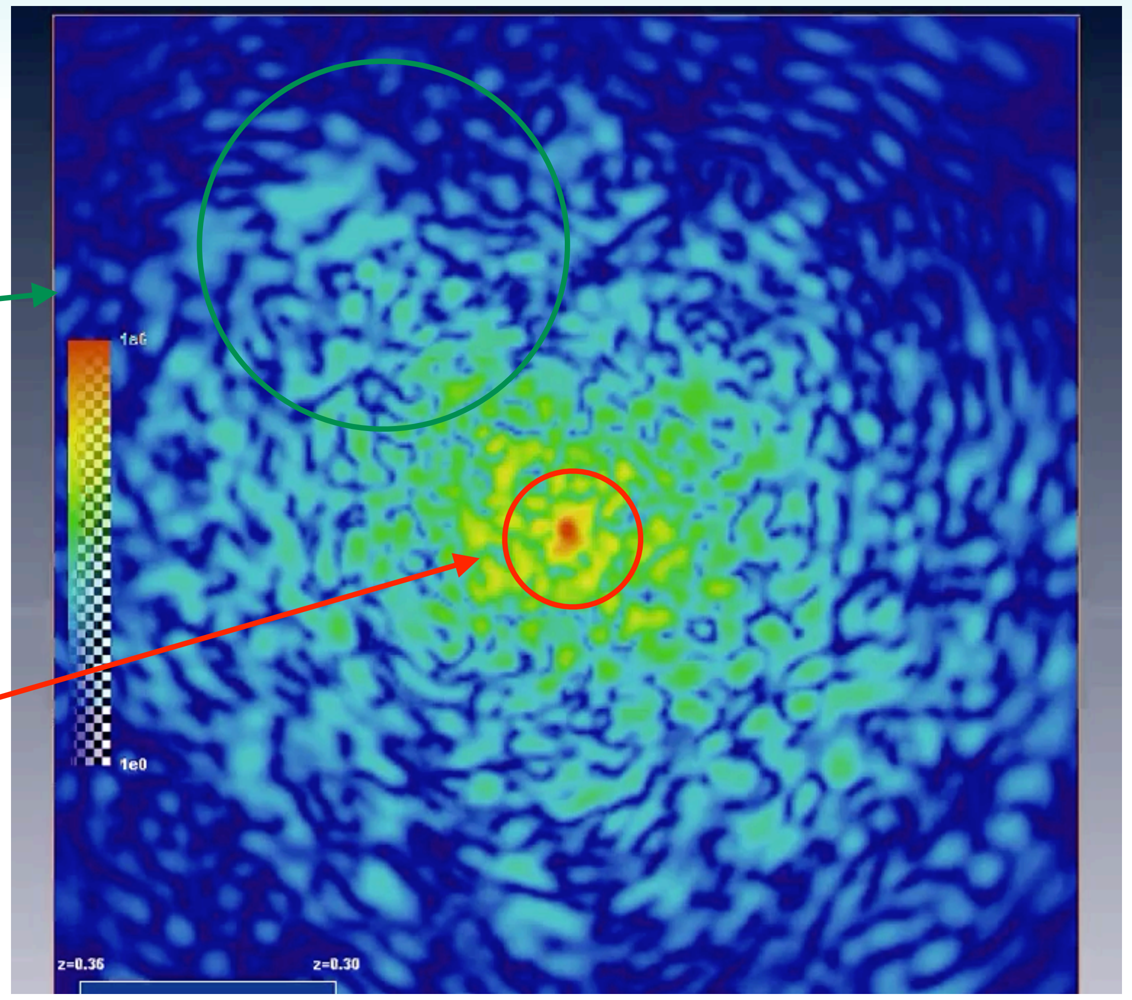
Bonus Round


Astrophysics Limit
KSVZ
QCD Axion
Trapped Misalignment Axion
Di Luzio, Gavela, Quilez, and Ringwald (2102.01082)
See e.g. review Hui, Ostriker, Tremaine, and Witten (1610.08297)
Banerjee, Kim, and Perez (1810.01889)
Relaxion DM
Ultralight DM
$f > M_P$
-8
-10
-12
-14
-16
-18
-20
-20
-15
-10
-5
0
$\log_{10}(\mathrm{GeV}/f)$
$\log_{10}(m/\mathrm{eV})$

Types of axion overdensities

1. Clumps as traveling waves of axion dark matter

   - Typical occupation number $\mathcal{N} \sim 10^{26} \times \left(\frac{\rho_{\rm local}}{0.4\ {\rm GeV/cm^3}}\right)\left(\frac{10^{-5}\ {\rm eV}}{m_\phi}\right)^4\left(\frac{10^{-3}}{\sigma}\right)^3$
   - "Quasiparticles", "granules", …
   - Typical over/under-density $\delta \equiv \frac{\rho}{\rho_{\rm local}} \sim \mathcal{O}(1)$

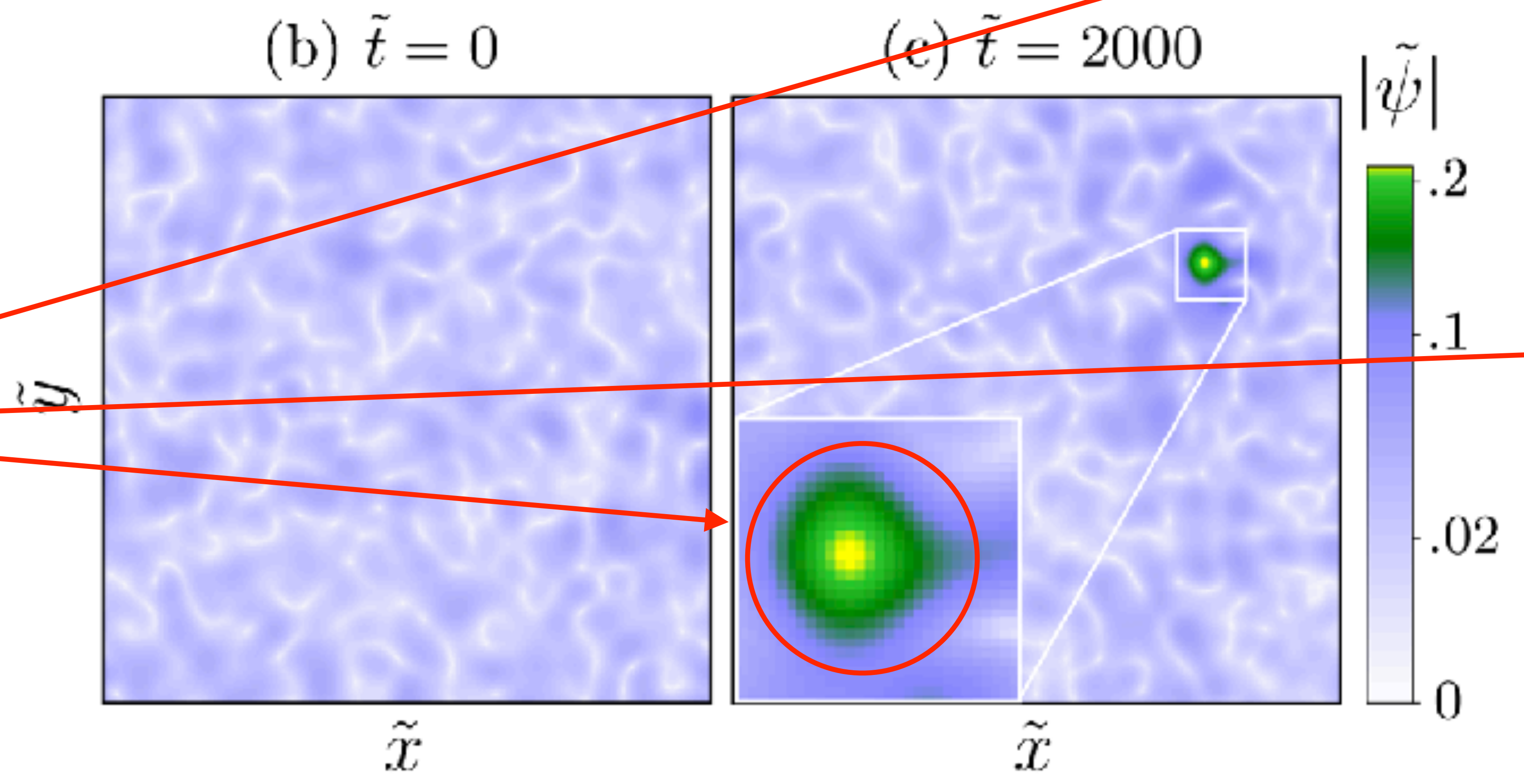


Schive et al. (1407.7762)

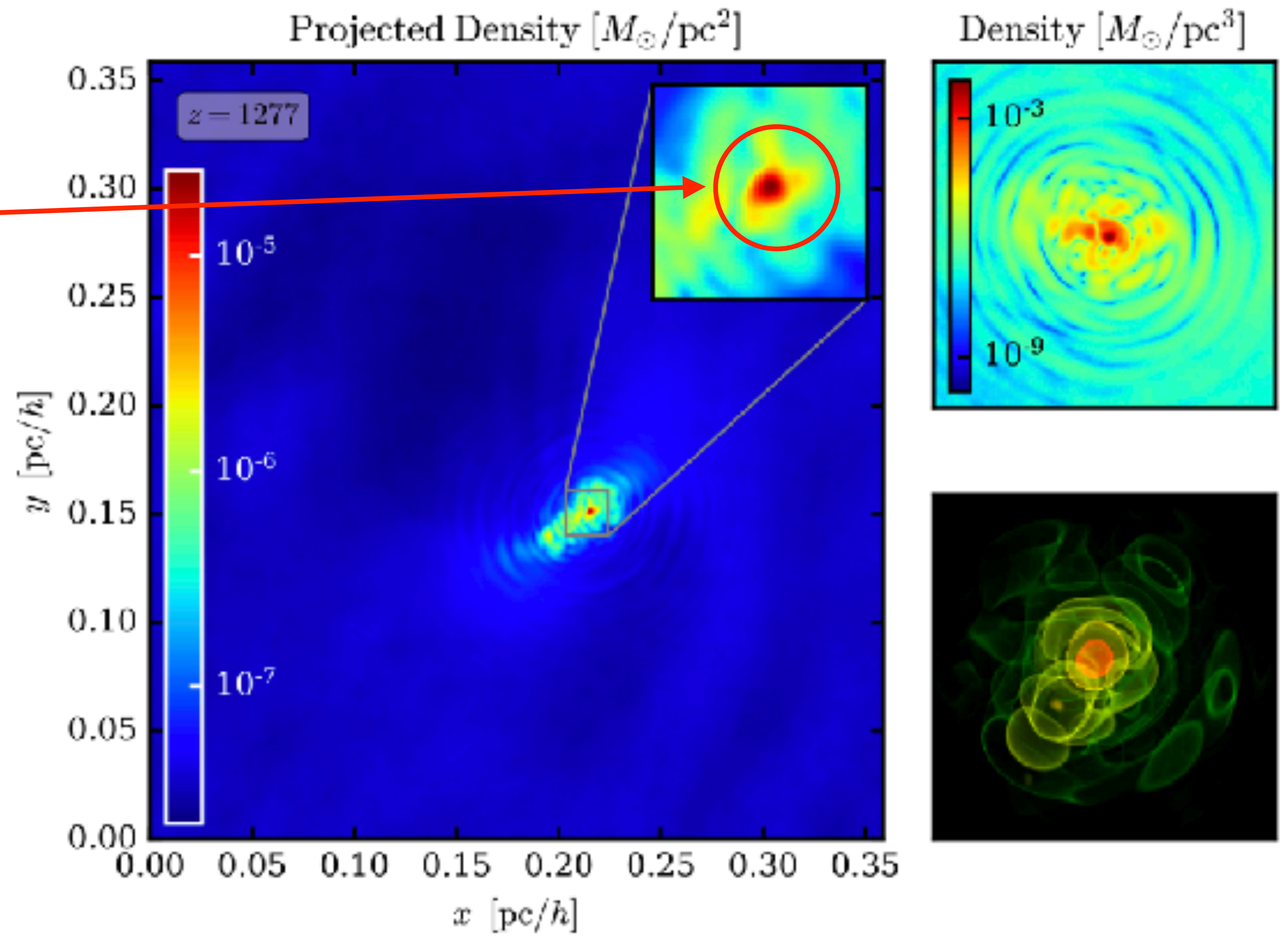
2. Virialized substructure: axion miniclusters

3. Self-gravitating clumps: axion stars

   - **Ground state configuration (at fixed mass)**
   - "BEC", "soliton", "oscillaton", …
   - Typical overdensity $\delta \gg \mathcal{O}(1)$



Levkov, Panin, Tkachev (1804.05857)



Eggemeier and Niemeyer (1906.01348)

Discovered and Re-Discovered

Kaup (Phys Rev 172, 1331 (1968))

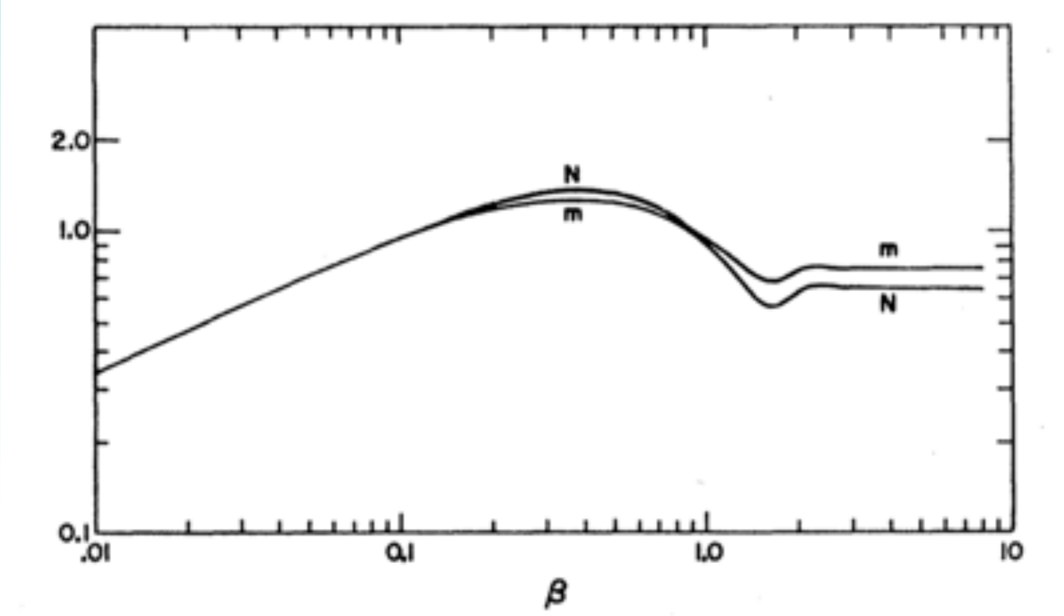
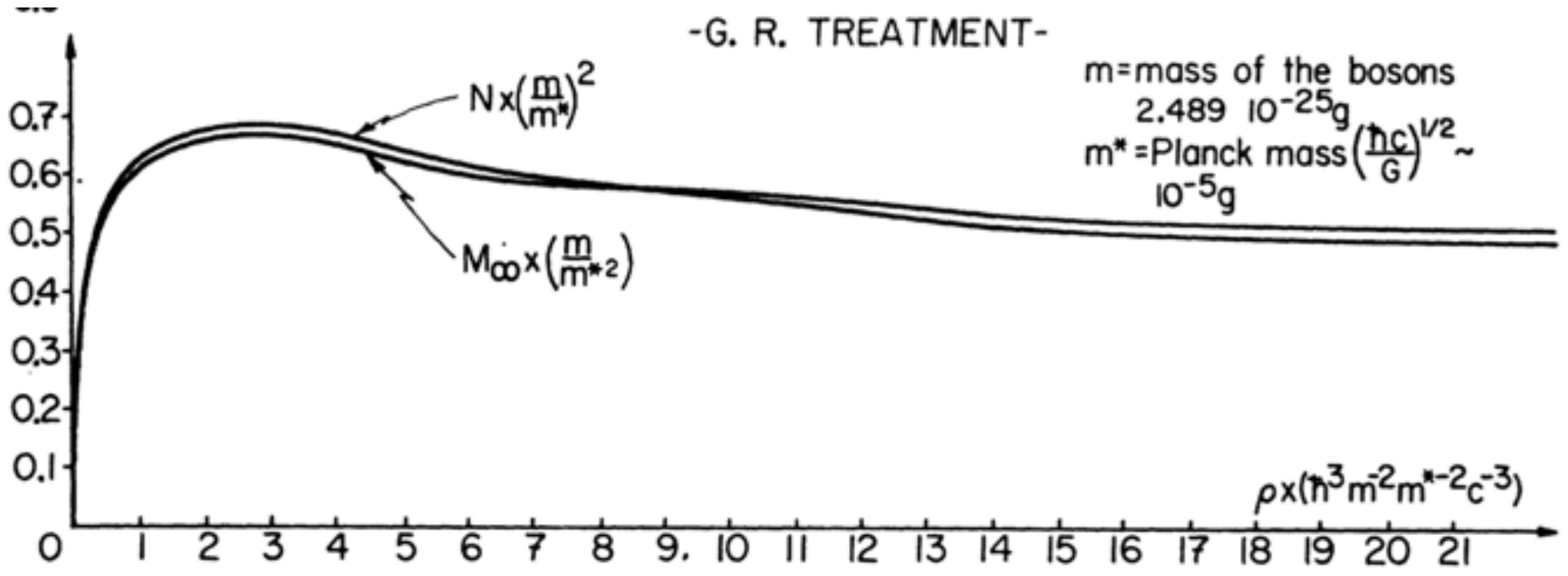
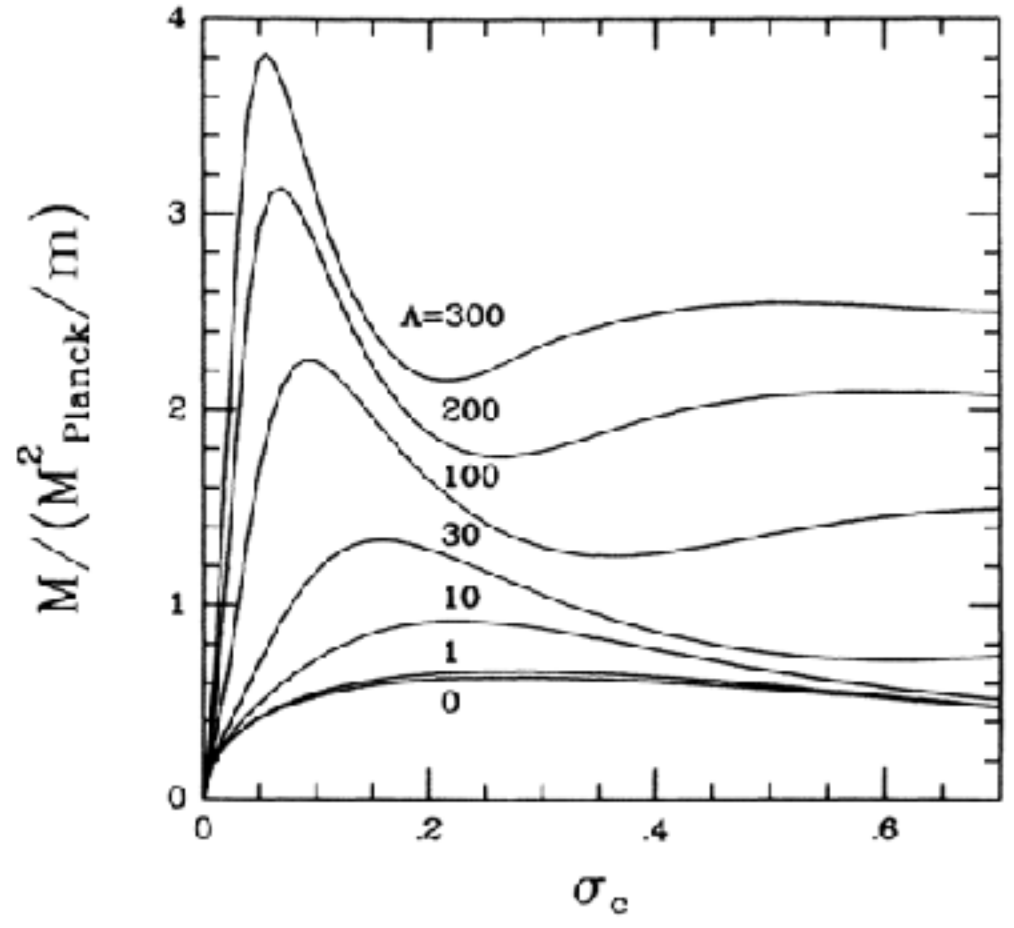


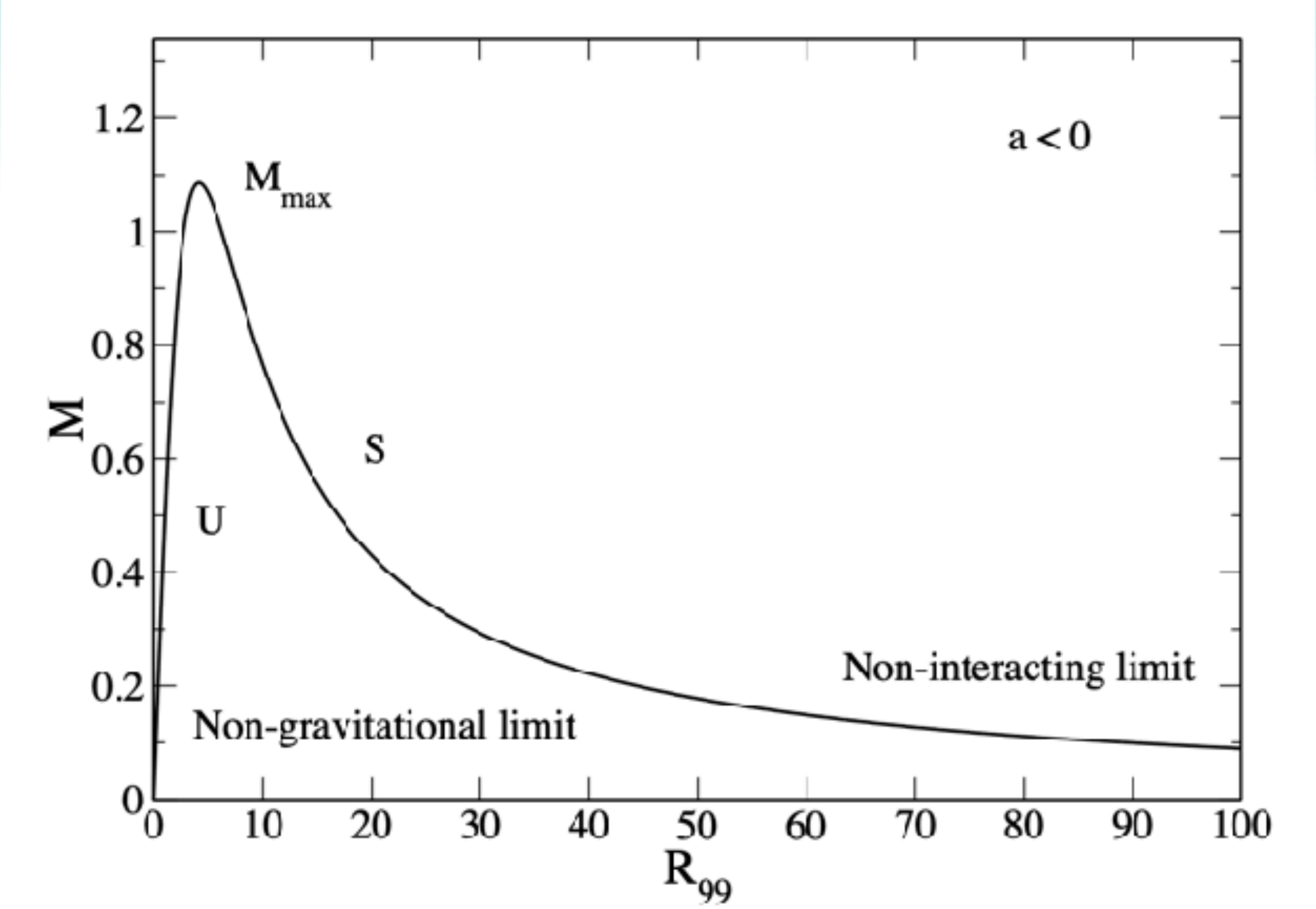
FIG. 2. Plot of m and N versus β.



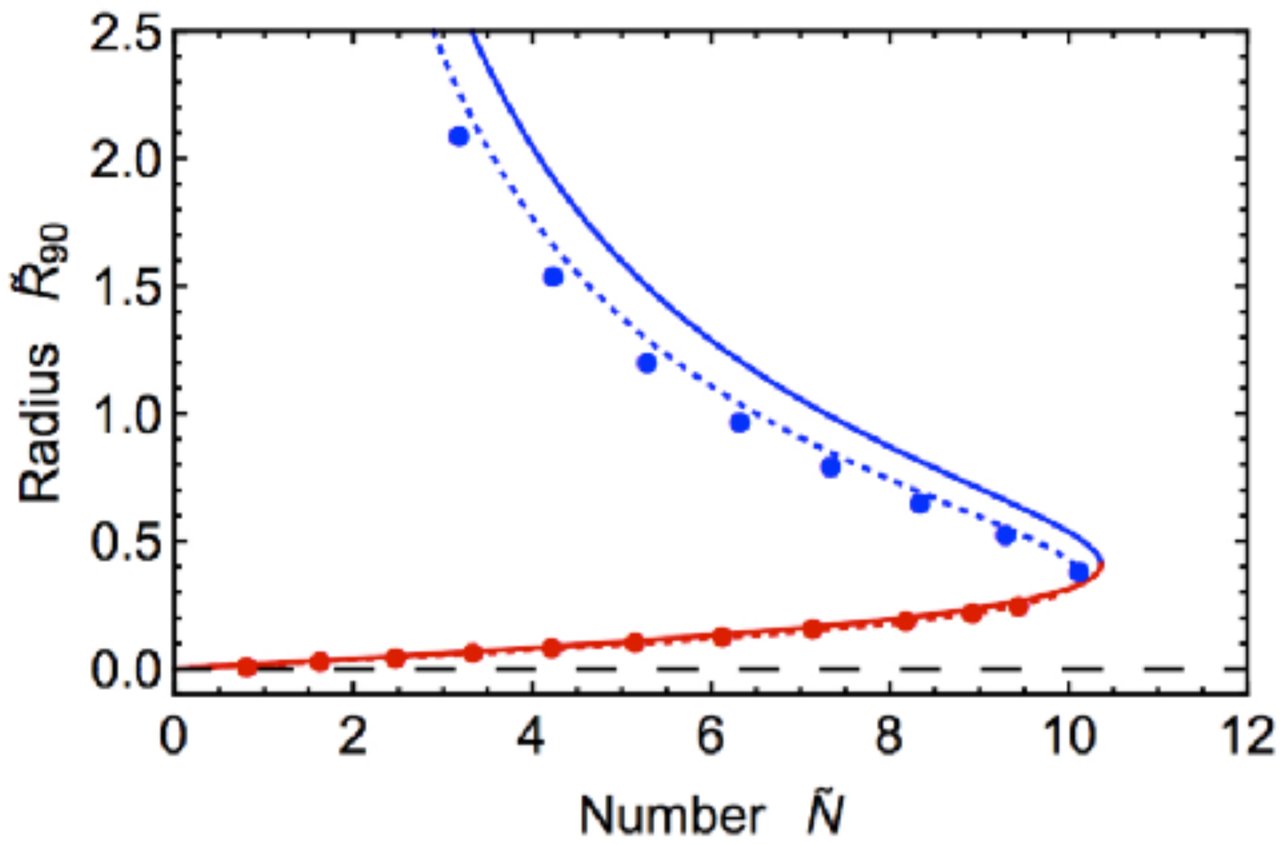
Ruffini + Bonazzola (Phys Rev 187, 1767 (1969))



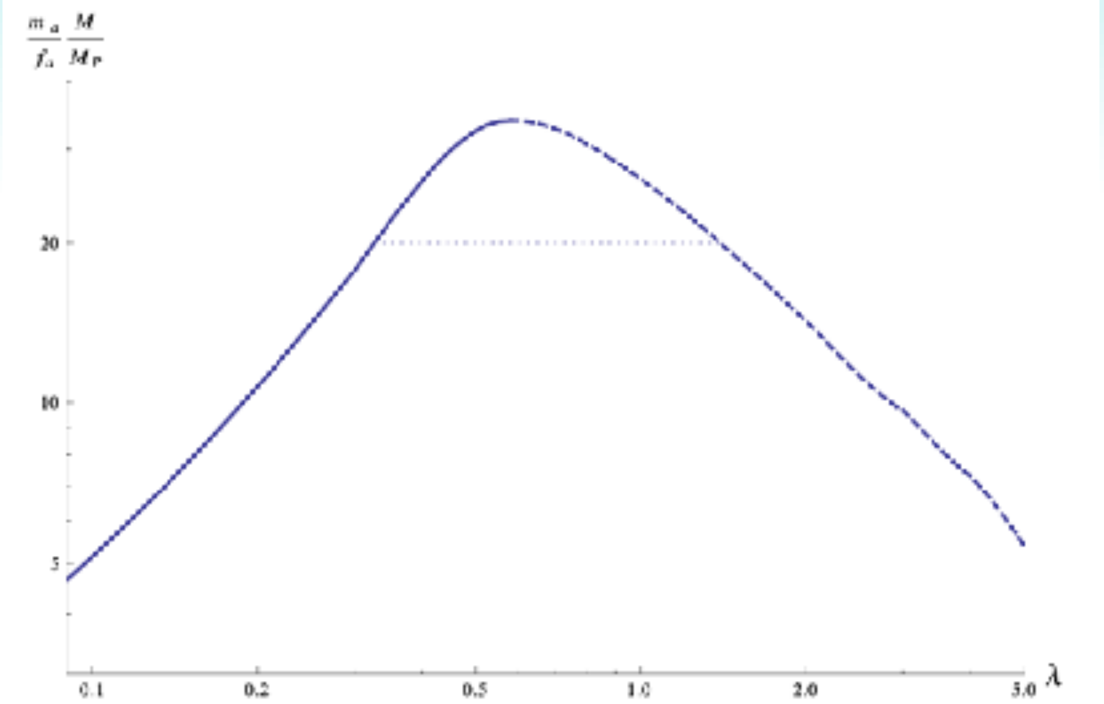
Colpi, Shapiro, Wasserman (PRL 57, 2485 (1986))



Chavanis (1103.2050)

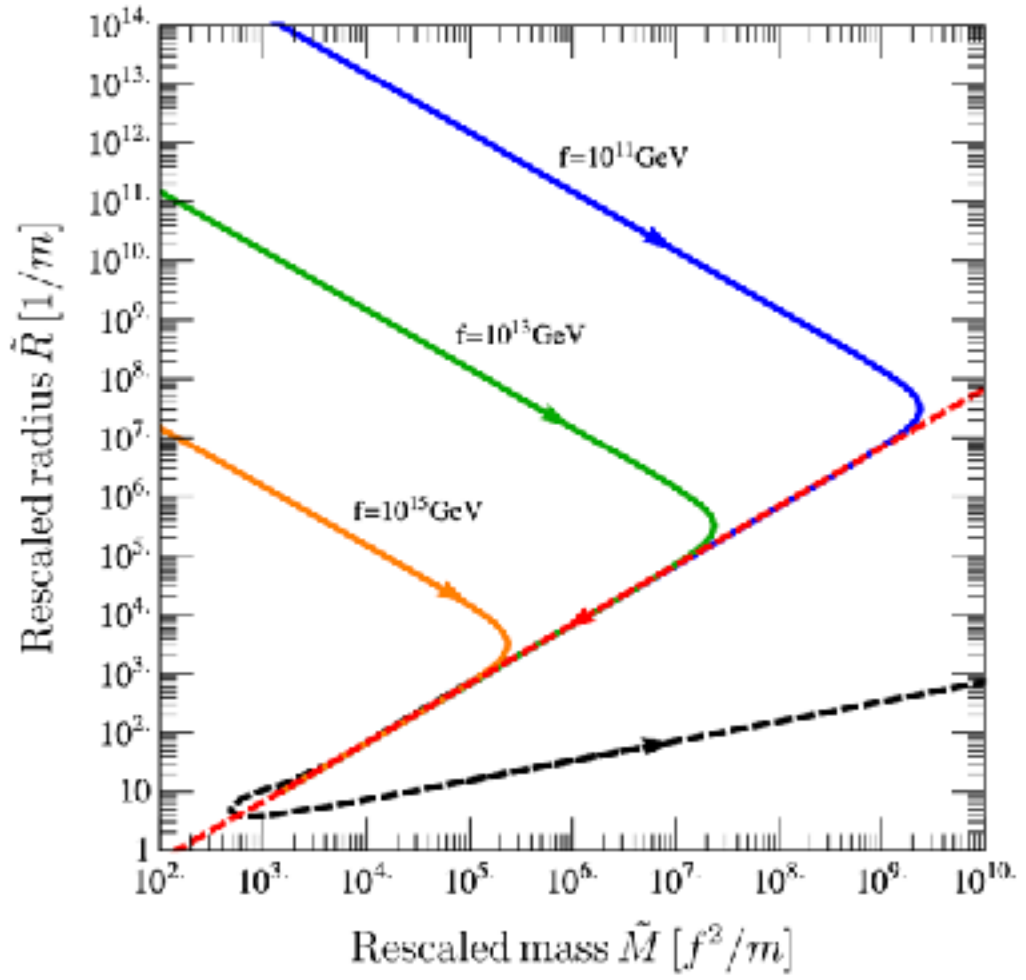


Schiappacasse and Hertzberg (1710.04729)



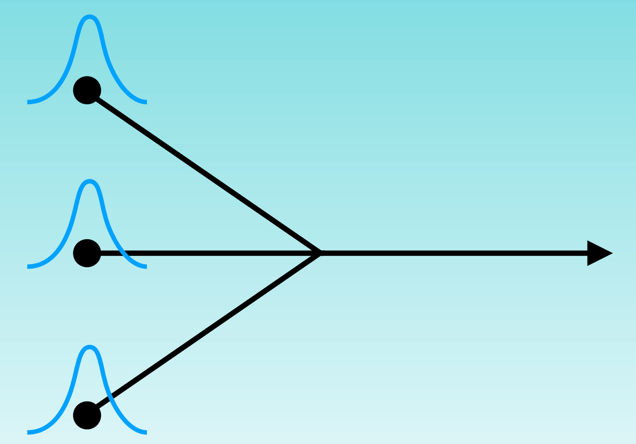
JE, Suranyi, Vaz, Wijewardhana (1412.3430)

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

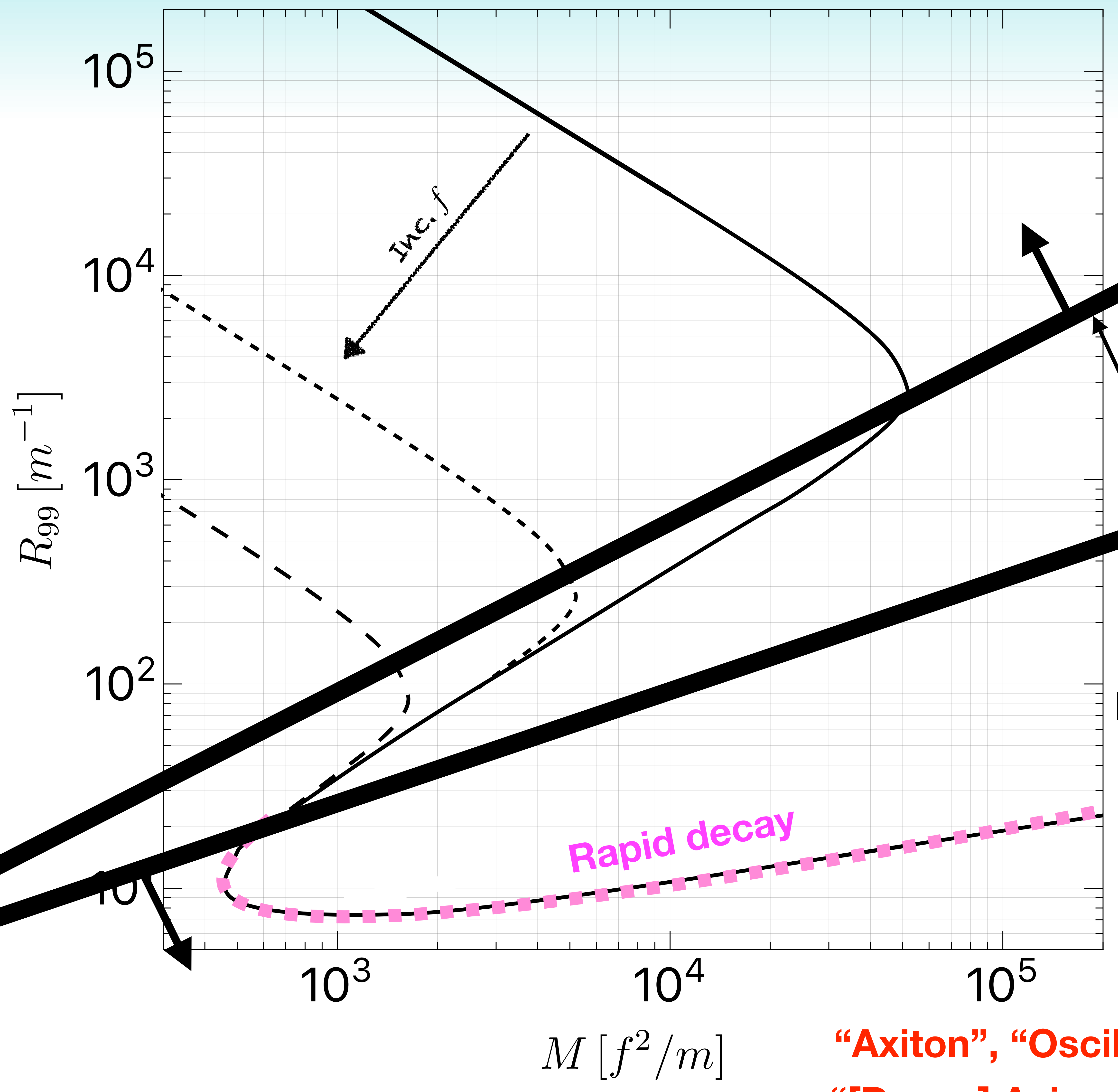
"[Transition] Axion Star", "Oscillon"

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)

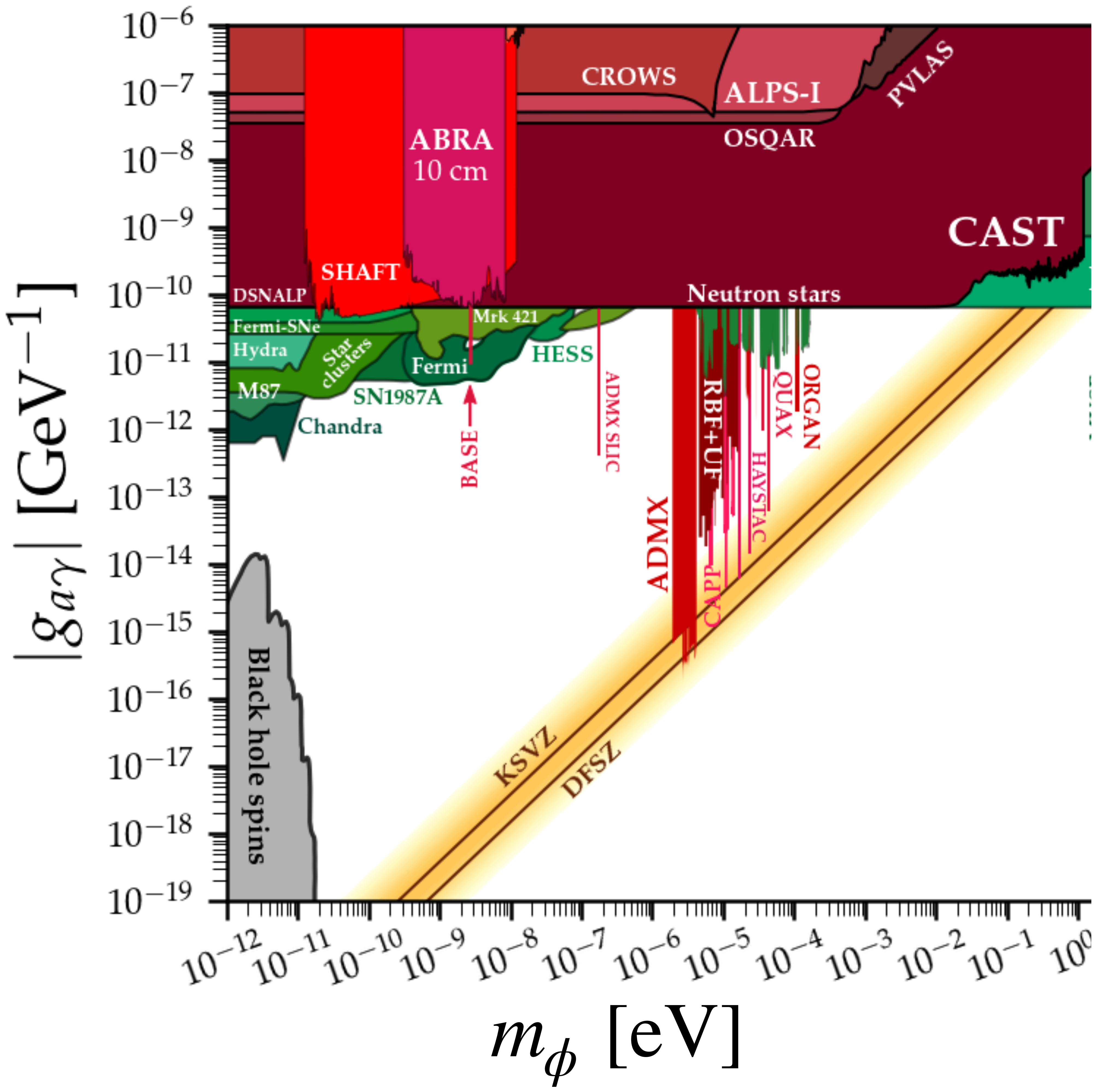
Braaten, Mohapatra, Zhang (1512.00108)

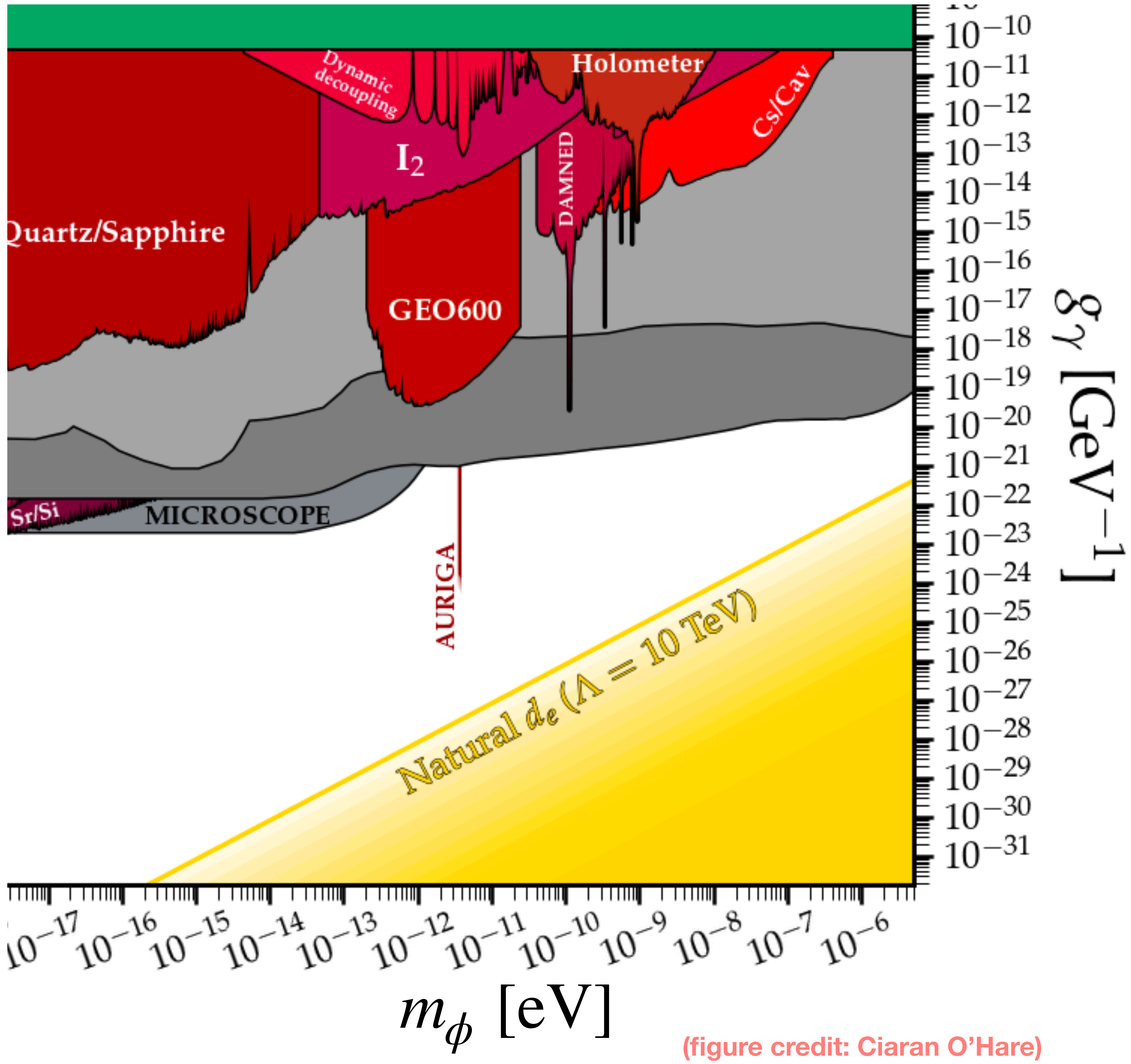
Searches for (pseudo)scalar particles

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

Consider, for example, photon couplings:

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



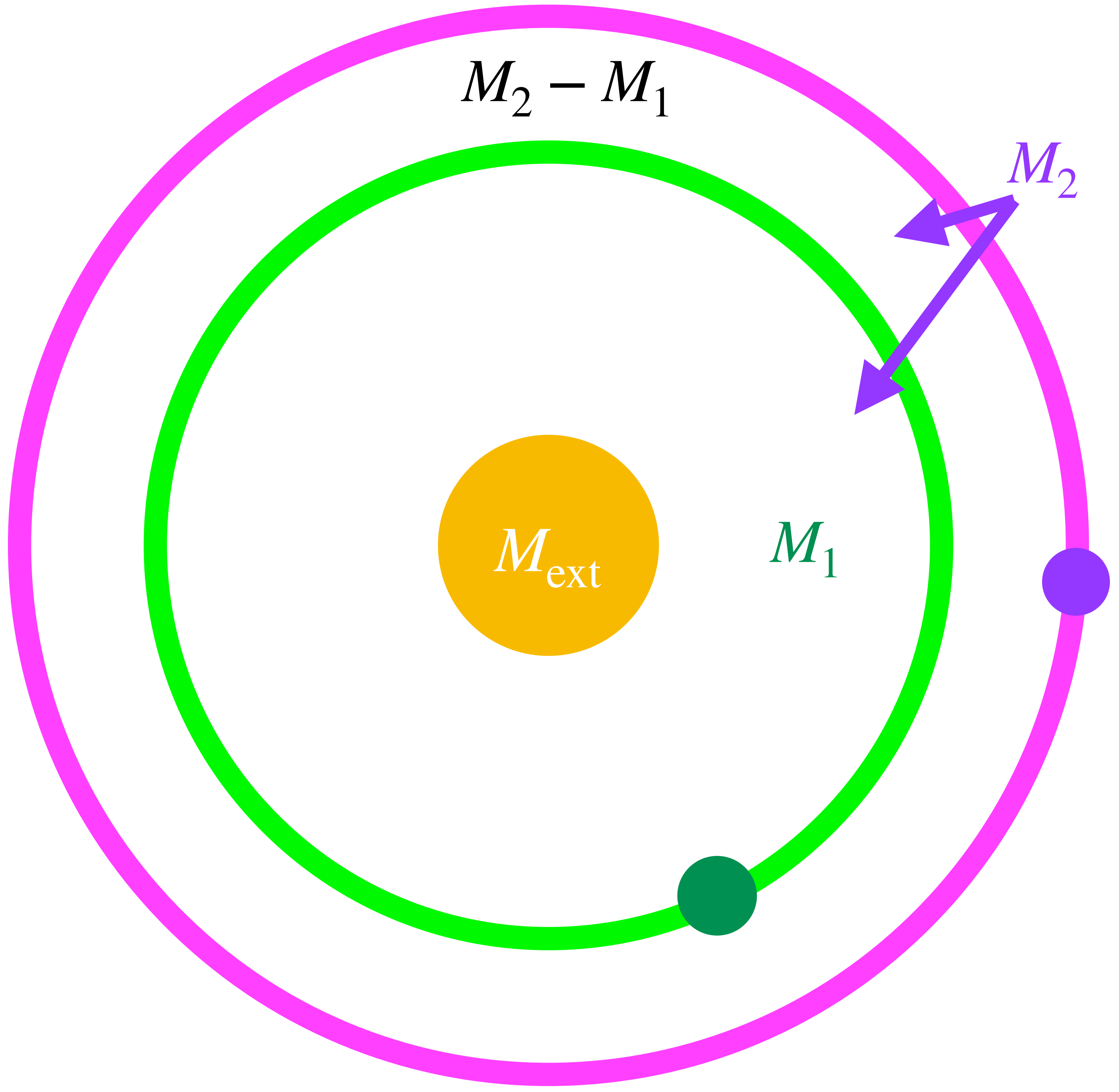


(figure credit: Ciaran O'Hare)

Constraints: "Extra" DM near Earth

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

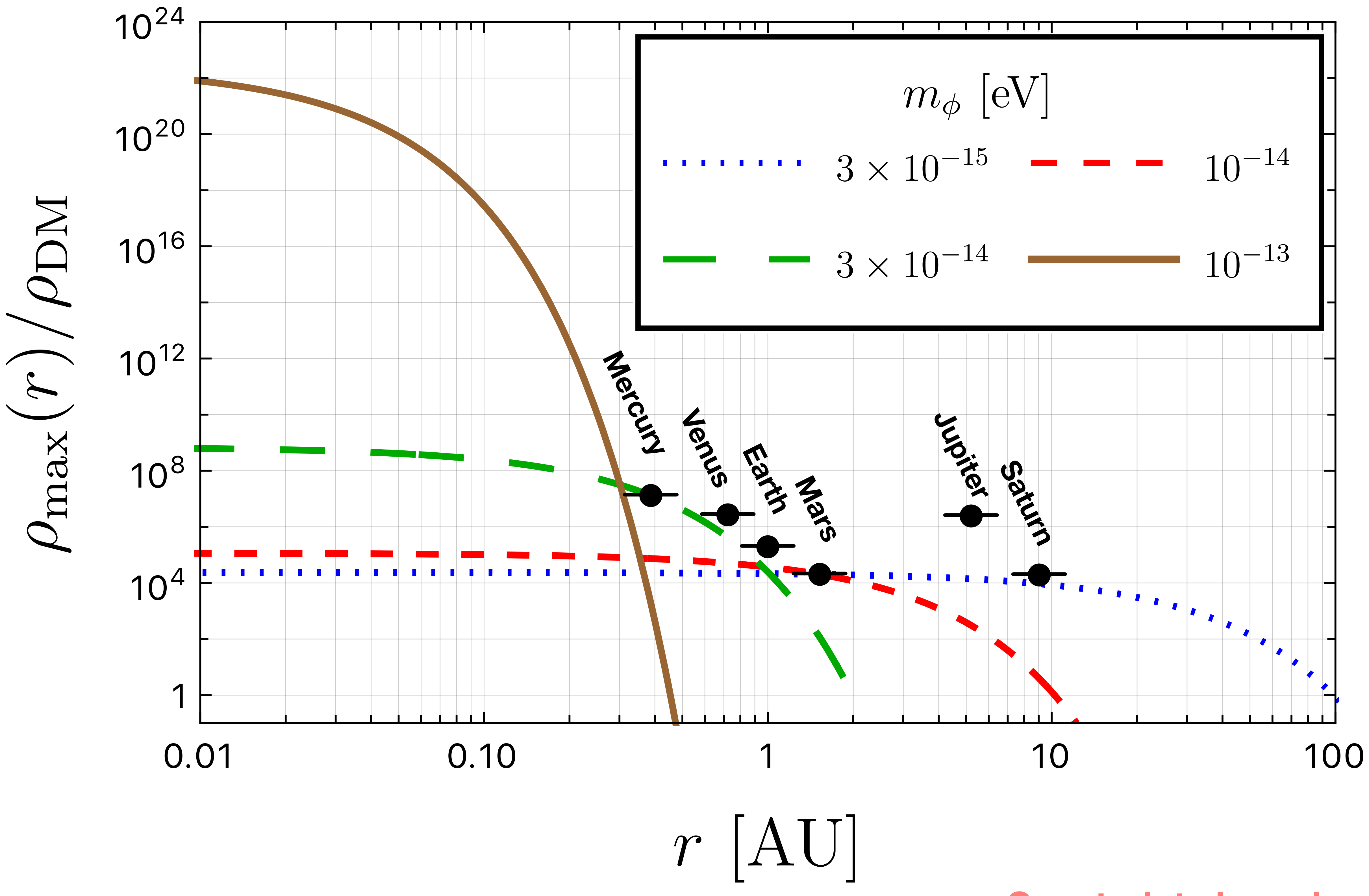
Can measure effective mass nearby by comparing orbits:



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

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

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



Constraints based on Pitjev and Pitjeva (1306.5534)