RELAXION STARS AND RELAXION HALOS

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with A. Banerjee, D. Budker, H. Kim, and G. Perez (1902.08212)
+ O. Matsedonskii (19xx.xxxxx)

15th Annual PATRAS Workshop on Axions, WIMPs, and WISPs
3/6/2019

LIGHT SCALAR DARK MATTER:

SPACE OF 2-PARAMETER MODELS

MinMod: a pNGB w/ potential

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

$$\approx \frac{m_\phi^2}{2}\phi^2 - \frac{(m_\phi/f)^2}{4!}\phi^4 + \dots$$

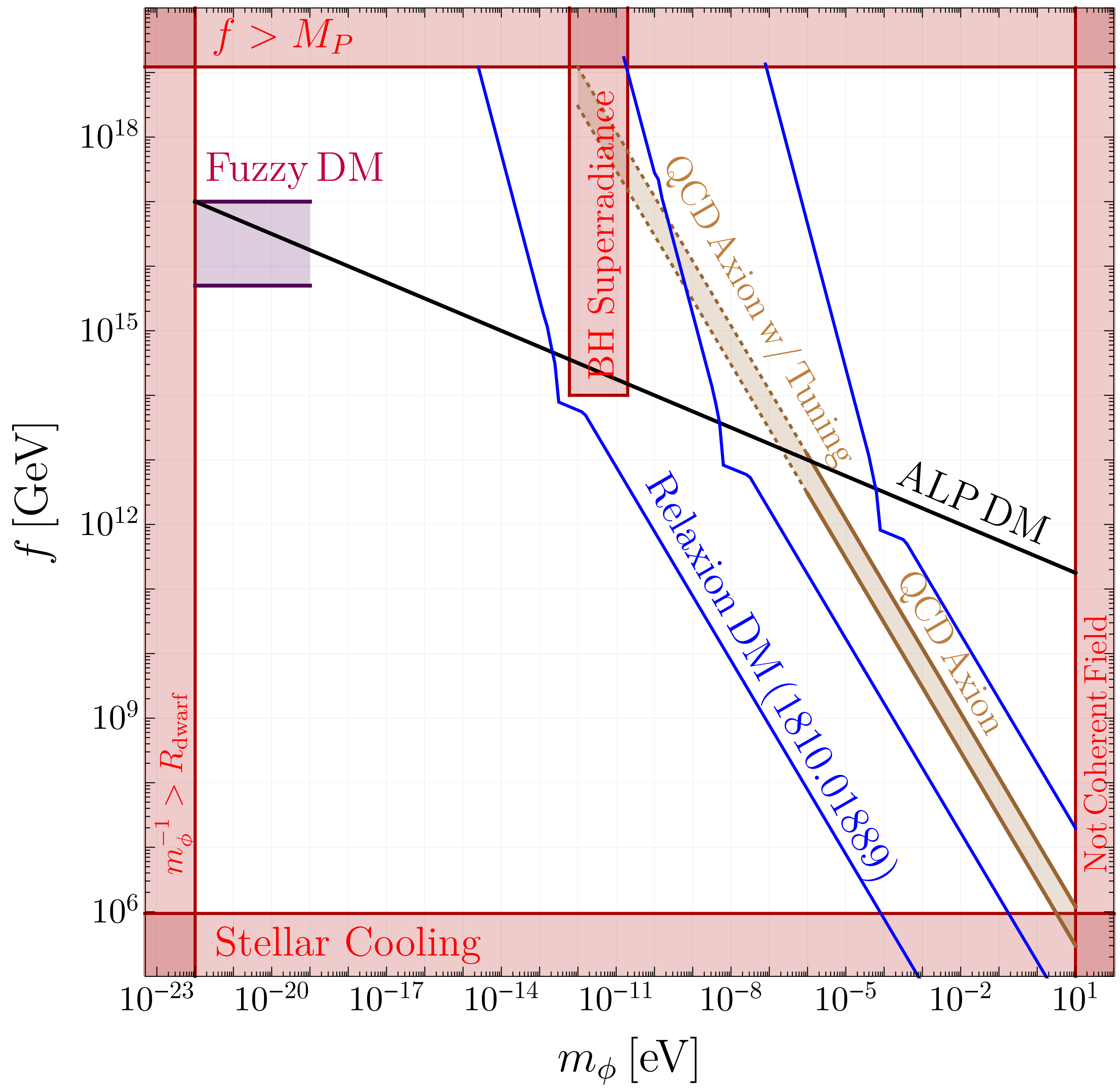
Index of Models

ALP = Minimal cosmological assumptions

FDM = Ultralight axion

QCD = Solve Strong CP problem

Relaxion = Breaks CP; has scalar couplings to matter



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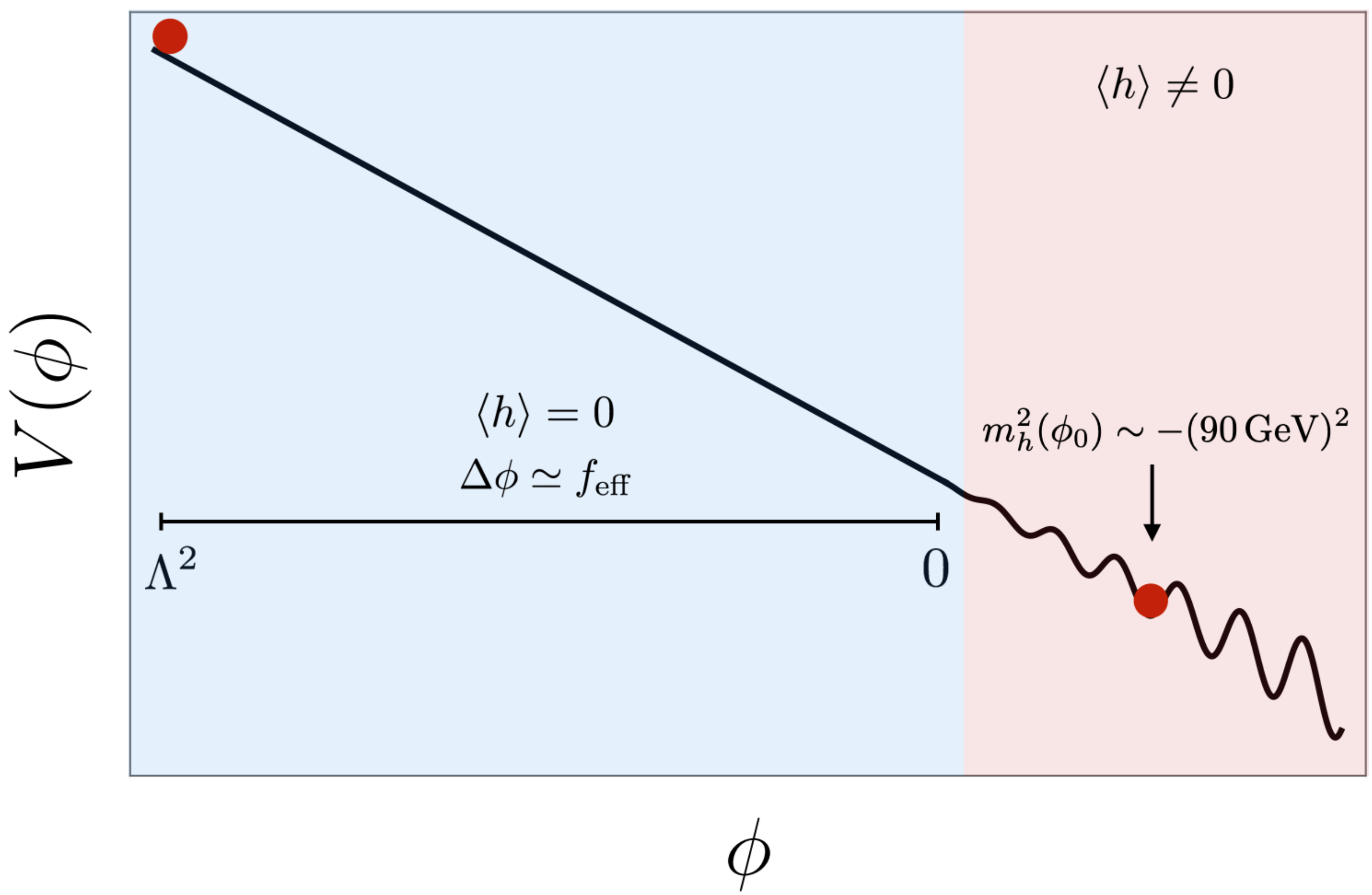
RELAXIONS

- Proposed to solve hierarchy problem

Dynamical selection of EW scale

$$V(\phi) = \left(\Lambda^2 - \frac{\Lambda^2}{f_{\rm eff}}\phi\right)|h|^2 - c\frac{\Lambda^4}{f_{\rm eff}}\phi \;+ \mu_b^2|h|^2\cos(\phi/f)$$



[Graham, Kaplan, Rajendran 15]

Slide by Hyungjin Kim

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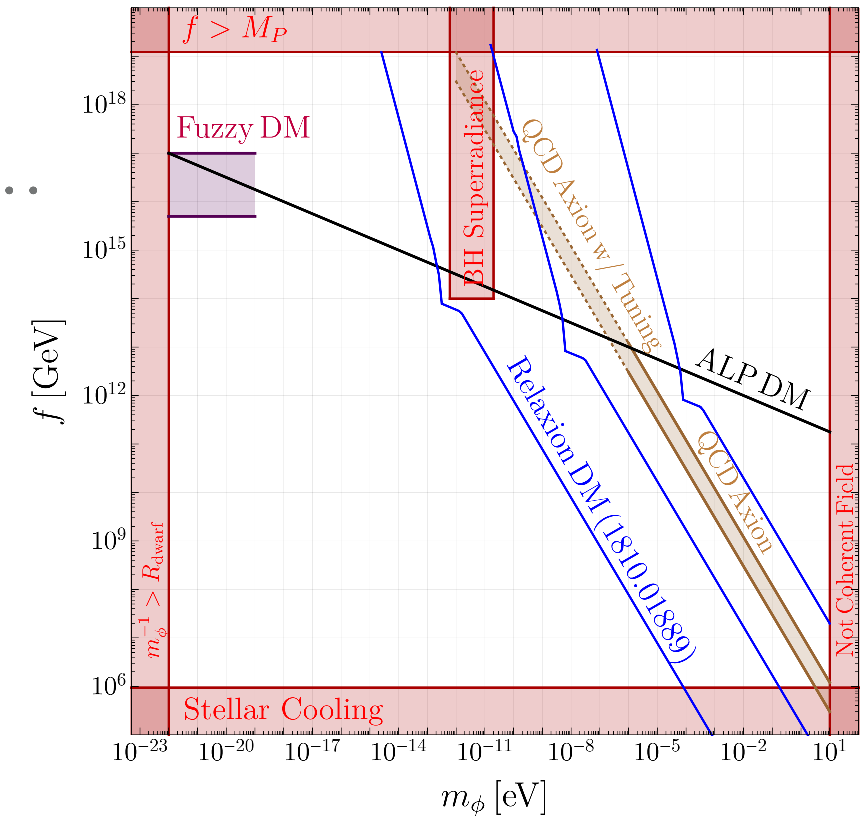
RELAXION DARK MATTER

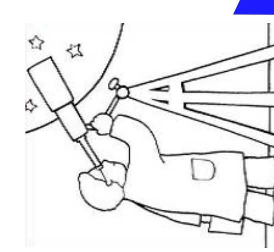
- DM abundance from misalignment
  Banerjee, Kim, Perez (1810.01889)
- Relaxion breaks CP, mixes with Higgs
  Flacke, Frugiuele, Fuchs, Gupta, Perez (1610.02025)
- Scalar + pseudoscalar couplings
- Oscillation of fundamental constants

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

$$\phi(t) \propto \cos(m_\phi t)$$

- Extremely difficult to probe scalar couplings





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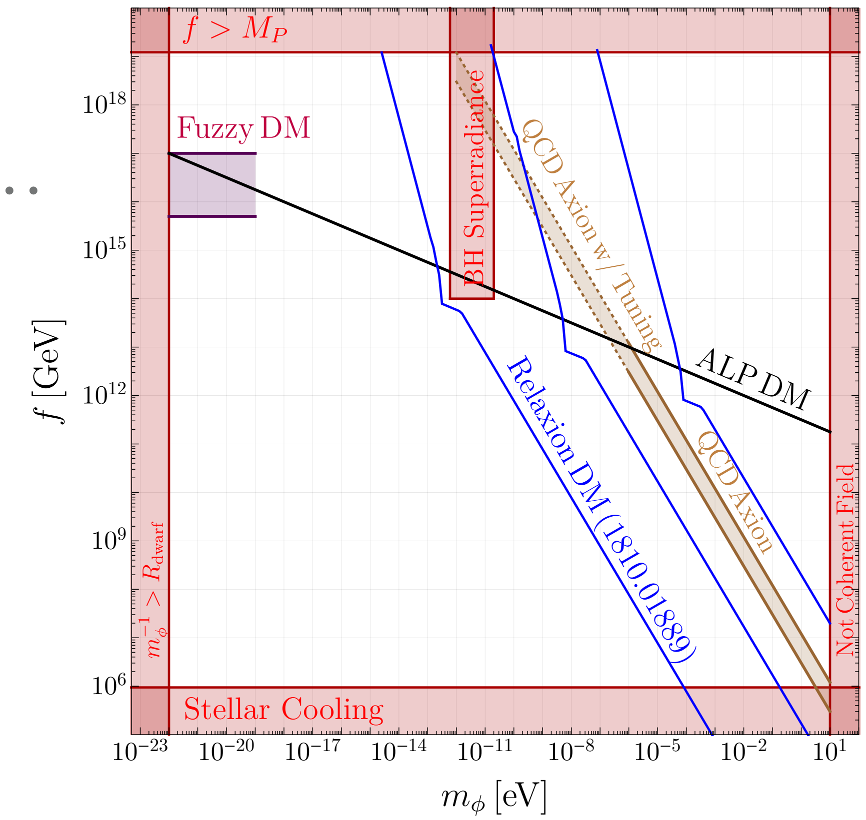
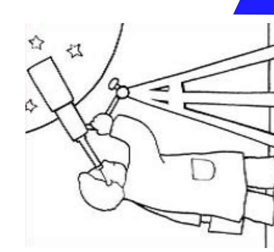




Benchmarks

(1) Natural Relaxion	*(2) Physical Relaxion*
$\delta m_\phi \lesssim m_\phi$	*Relaxion-Higgs Mixing:* $\sin\theta \sim \dfrac{v_{EW}}{f} \lesssim \dfrac{m_\phi}{v_{EW}}$

STRONG 5TH FORCE CONSTRAINTS

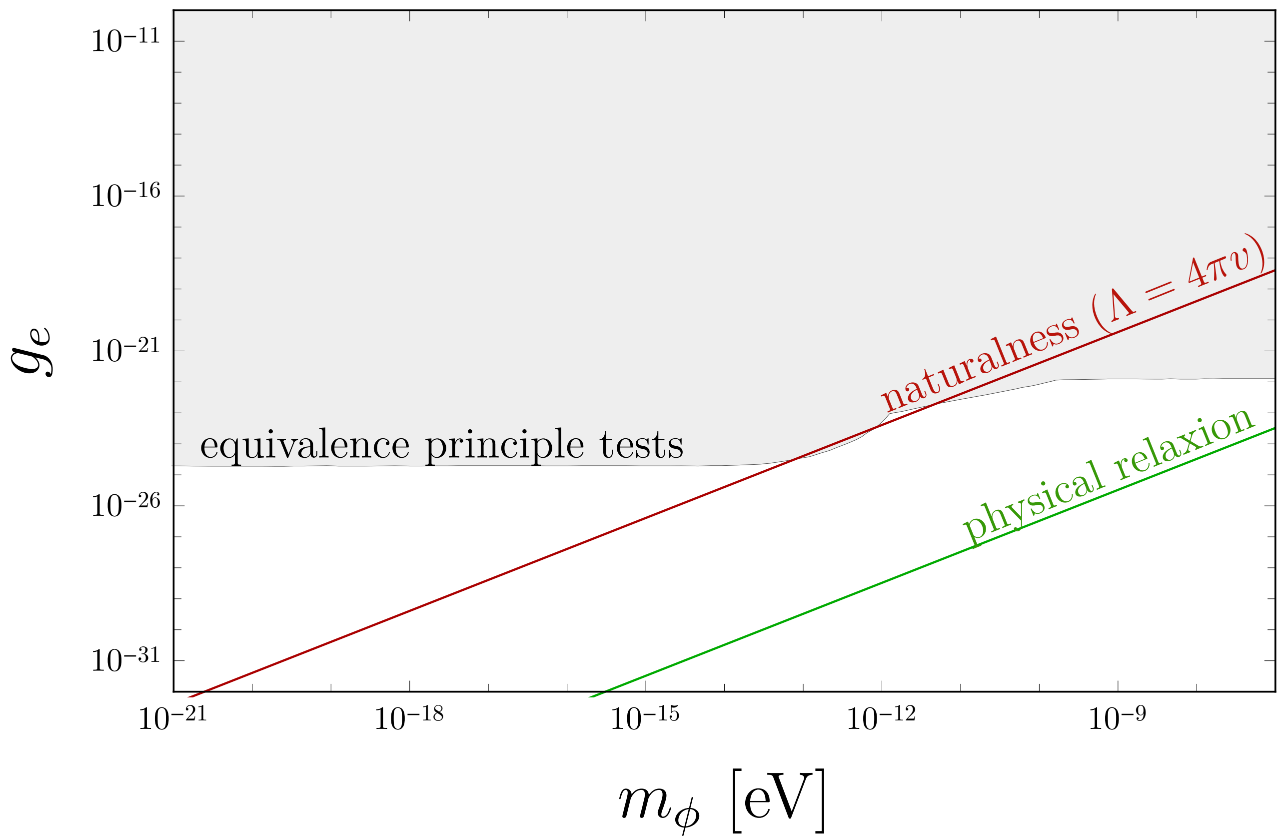
$$\mathscr{L} \supset g_e \phi \bar{e} e + \frac{g_\gamma}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

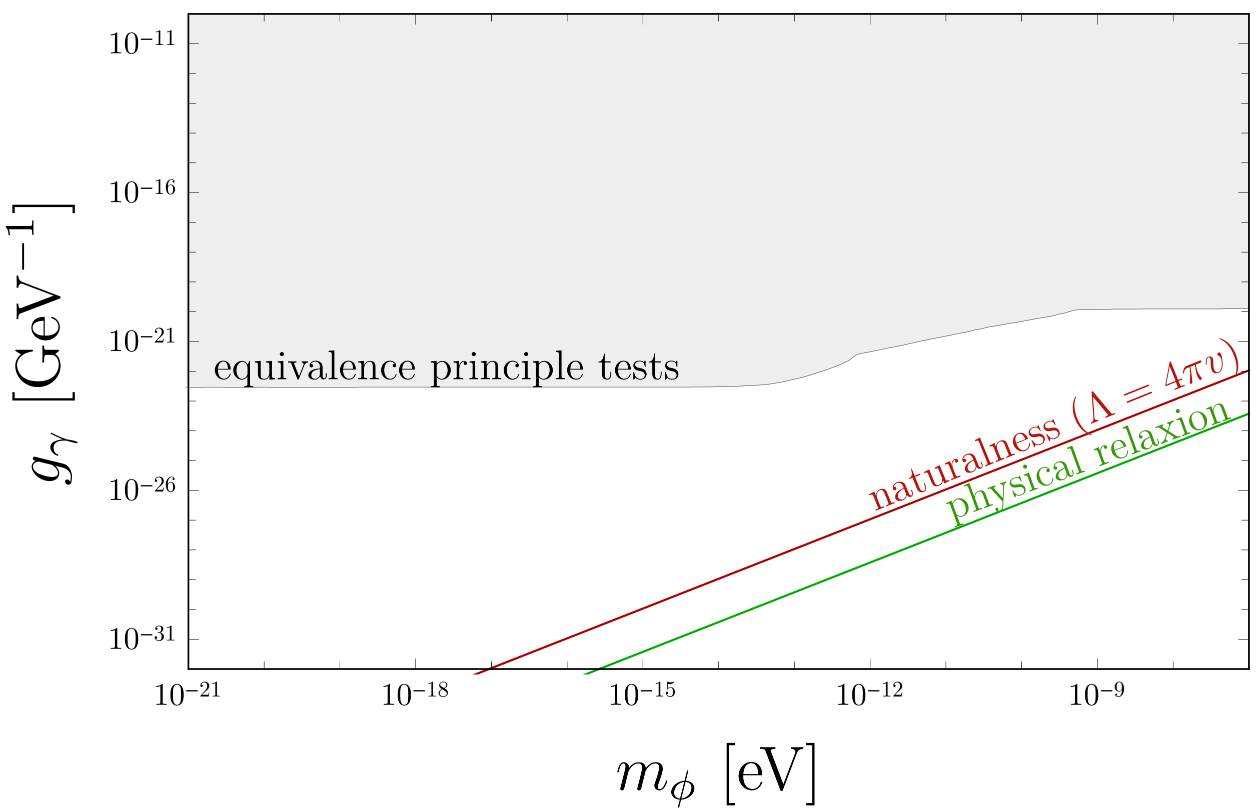
- Classic experiments look for long-range force from virtual ϕ

Arvanitaki, Huang, Van Tilburg (1405.2925)

Hees, Minazzoli, Savalle, Stadnik, Wolf (1807.04512)

[many more] …………





- Is there a way to do better??

ATOMIC PHYSICS: A 'NEW' FRONTIER

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

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

$$\left(\frac{\delta m_e}{m_e}\right)_{exp} \simeq 10^{-18} \qquad \textit{(Near future) (1 year??)} \qquad \left(\frac{\delta \alpha}{\alpha}\right)_{exp} \simeq 10^{-18}$$

- Historically, constraints only at low mass / frequency. No longer!

$$(m_\phi \lesssim 10^{-15}\, eV \sim 1\, Hz)$$

e.g. Aharony et al. (1902.02788)

- For background DM density, this corresponds to

$$g_e \lesssim 10^{-20} \left(\frac{m_\phi}{10^{-15}\, eV}\right) \qquad g_\gamma \lesssim 10^{-18}\, GeV^{-1} \left(\frac{m_\phi}{10^{-15}\, eV}\right)$$

- Still too weak! (compared to 5th Force searches)
- However: direct searches are sensitive to $\phi(t) = \dfrac{\sqrt{2\rho_{local}}}{m_\phi} \cos(m_\phi t)$

LIGHT SCALAR SUBSTRUCTURE —> OVERDENSITY

- Small scales: Light scalar DM suppresses gravitationally-bound substructure at scales smaller than

$$\lambda_{dB} = 1\ AU \times \left(\frac{10^{-15}\ eV}{m_\phi}\right)\left(\frac{10^{-3}c}{v}\right)$$

- Substructure described by ground state of classical field
  - "***Boson star***", "***Axion condensate***", "***Soliton***", "***Oscillaton***", …
  - Boson star idea 50 years old; renaissance in last ∼10 years

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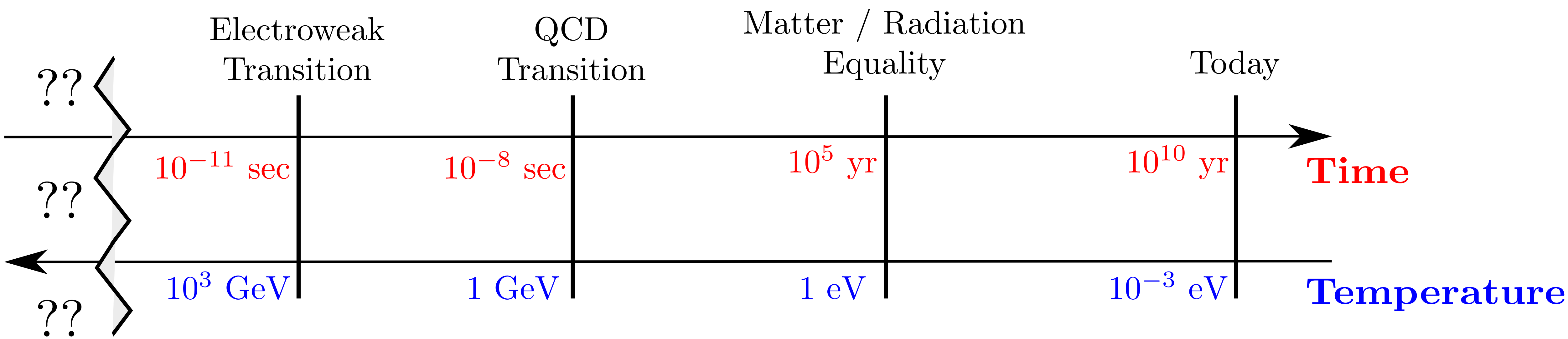
Two classes of questions:

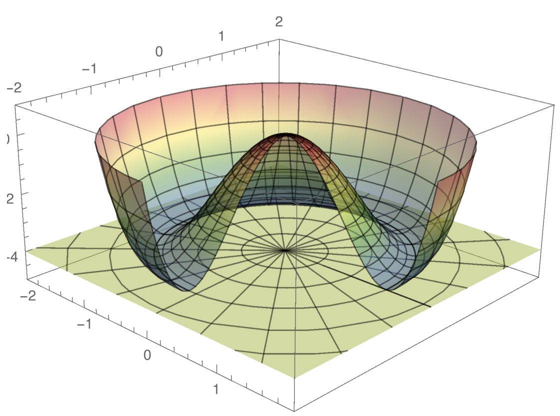
What kind of substructure is around?	*Given substructure, what to search for?*
(Formation, History, Spectrum)	*(Stability, Interactions, Signals)*
Kolb and Tkachev (PRL 1993), *Schive, Chiueh, Broadhurst (1406.6586)* *Levkov, Panin, Tkachev (1804.05857)* *Vaquero, Redondo, Stadler (1809.09241)* ………	*This talk*

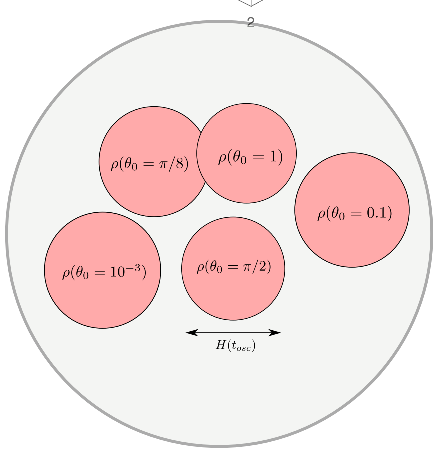
LIGHT SCALAR DM: COSMOLOGICAL HISTORY



High energy scale f:

Broken U(1) symmetry





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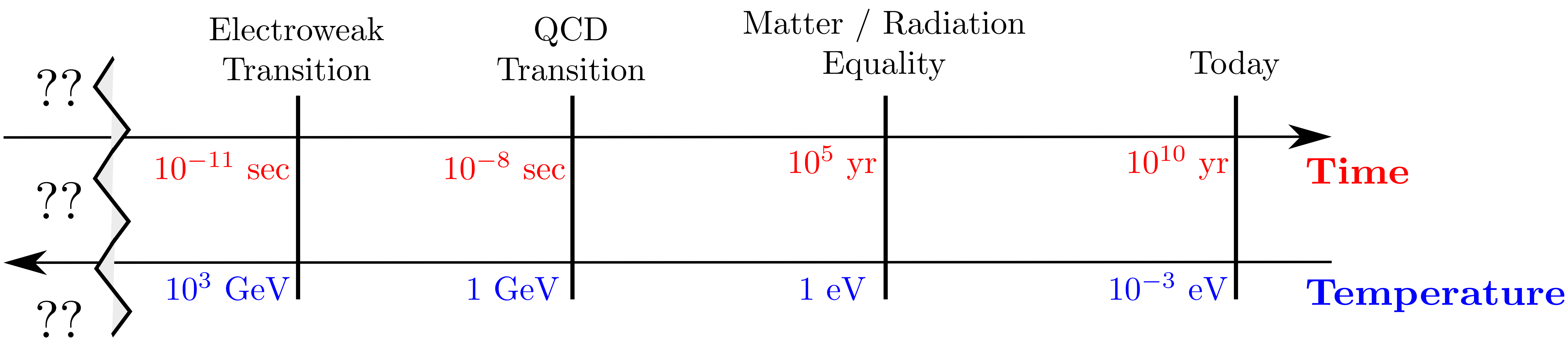

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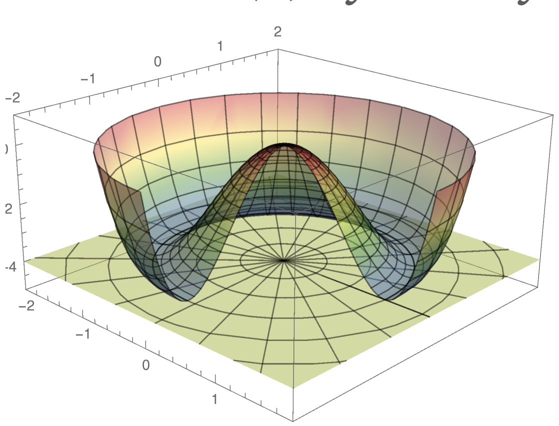
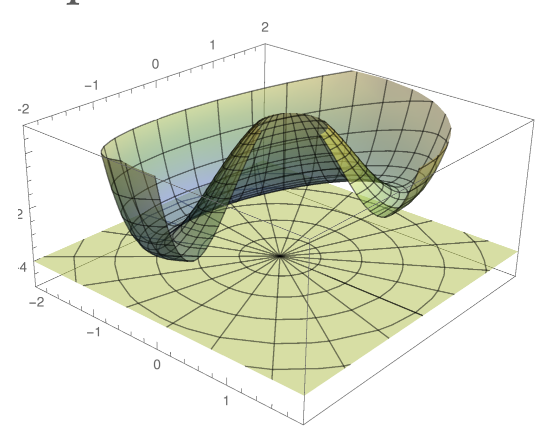
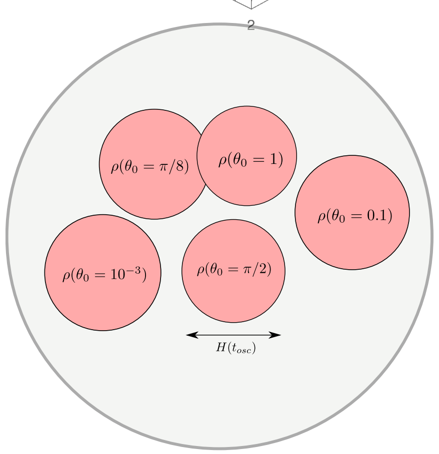


Lower energy scale $\Lambda = \sqrt{m_\phi f}$

Tilt potential, obtain mass

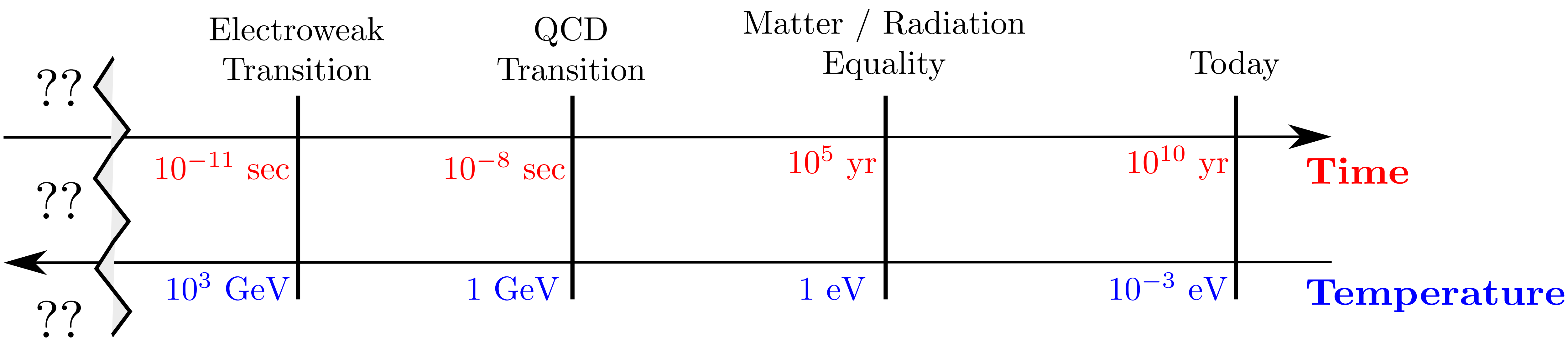




Axion

Miniclusters

LIGHT SCALAR DM: COSMOLOGICAL HISTORY



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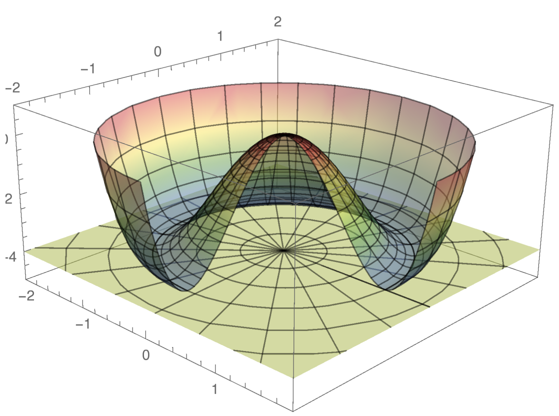

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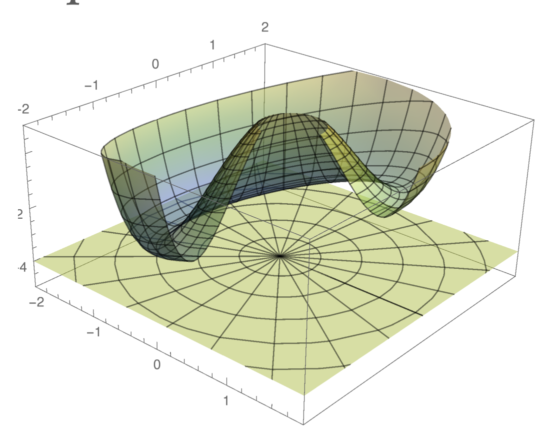


Coherently Oscillating Scalar Field

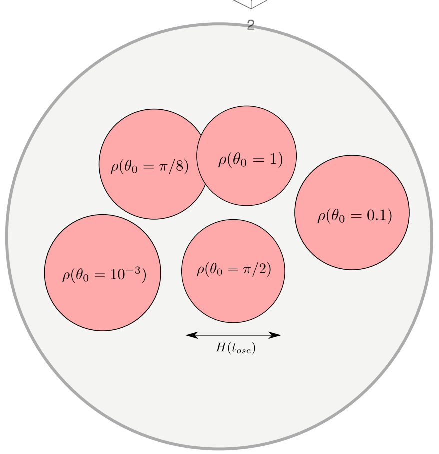
$$\phi(r,t) = \phi_0(r)\,\cos(\omega t)$$

$$\omega \simeq m_\phi$$

Relaxation?

Cooling?

Fragmentation?



Axion Miniclusters

Boson Stars

BOSON STARS

Gross-Pitaevskii+Poisson (GPP)

- Nonrelativistic, classical field:

Normalization

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

Poisson Gravity

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

(Attractive)

Leading time dependence

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

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

Kinetic energy
(Repulsive)

Self-interactions
For axion potential,

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

$$E(\psi) = \int d^3r \left[\frac{|\nabla\psi|^2}{2m_\phi} + \frac{1}{2}V_g|\psi|^2 - \frac{\lambda}{16m_\phi^2}|\psi|^4 + \frac{g}{m_\phi^5}|\psi|^6 - \dots\right]$$

$$\frac{E}{M_\star} \sim \underbrace{\frac{a}{R_\star^2} - \frac{b\,M_\star}{R_\star}}_{\text{Large radius}} - \underbrace{\frac{c\,M_\star}{R_\star^3} + \frac{d\,M_\star^2}{R_\star^6}}_{\text{Small radius}} - \dots$$

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STABLE BOUND STATES

Dilute *Chavanis (1103.2050), with Delfini (1103.2054)*

Dense *Braaten, Mohapatra, Zhang (1512.00108)*

- Energy minima = Bound states

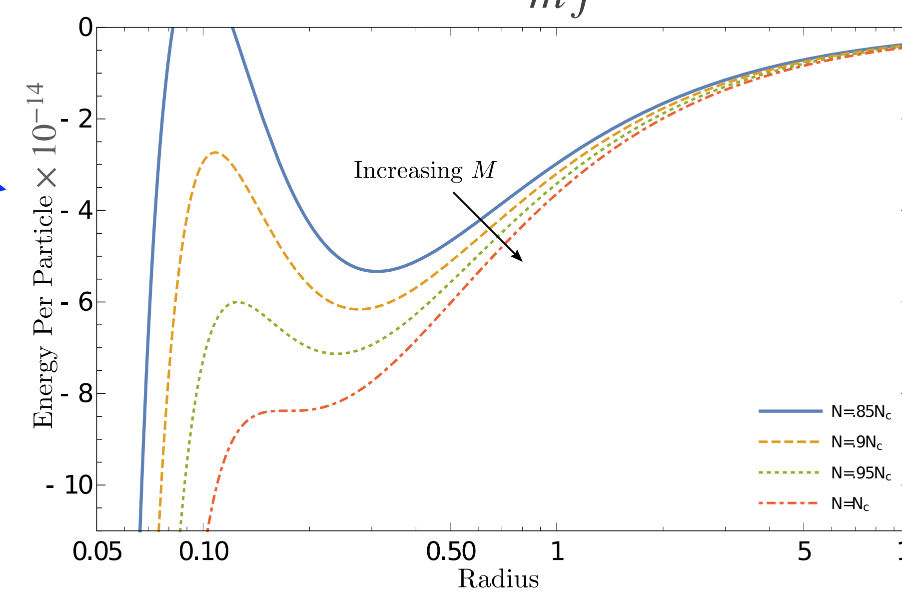
JE, Leembruggen, Suranyi, Wijewardhana (1608.06911)

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

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

$$\frac{E}{M_\star} \sim \overbrace{\frac{a}{R_\star^2} - \frac{b\, M_\star}{R_\star}} - \frac{c\, M_\star}{R_\star^3} + \frac{d\, M_\star^2}{R_\star^6} - \dots$$

$$R_\star \sim \frac{M_P}{m\, f}$$



Dilute

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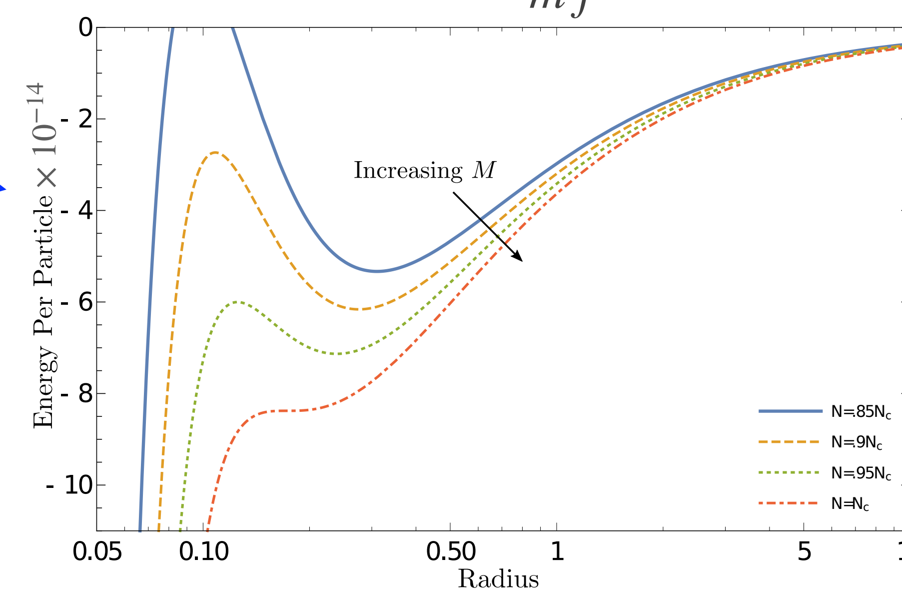
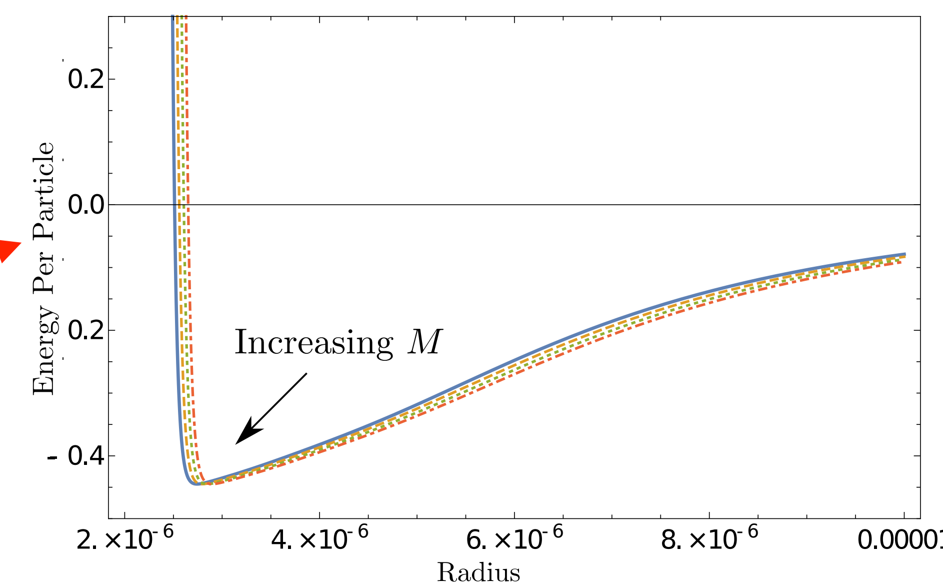
$$M_\star \approx m_\phi^2 f^2 R_\star^3$$

$$\rho \sim \Lambda^4$$



Dilute



Dense

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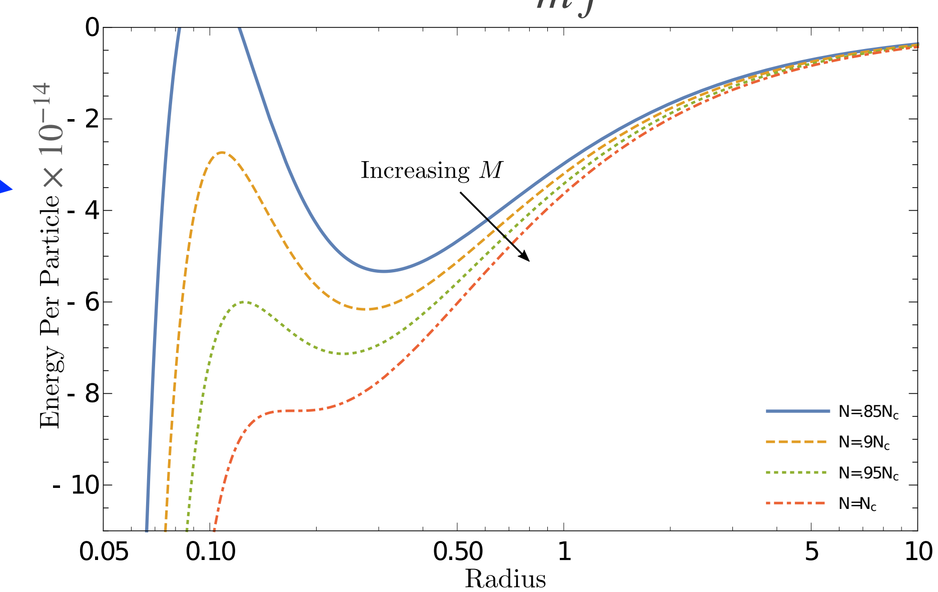
$$\rho \sim \Lambda^4$$



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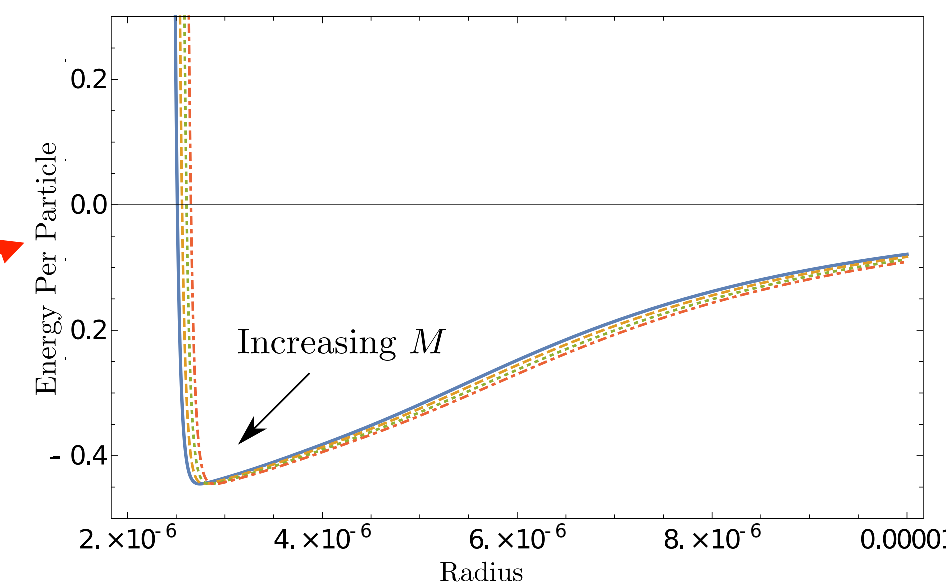


Dense

- Nuggets of stable, nuclear-density dark matter??
  - Dense states decay fast to relativistic scalars

oscillon case:

Fodor, Forgacs, Horvath, Mezei (0903.0953)

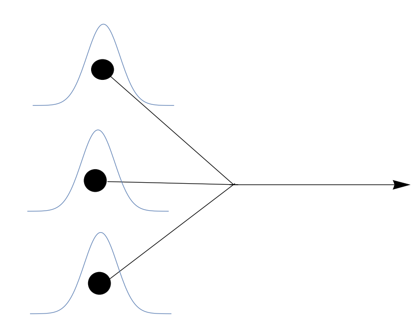
Hertzberg (1003.3459)

Mukaida, Takimoto, Yamada (1612.07750)

boson star case:

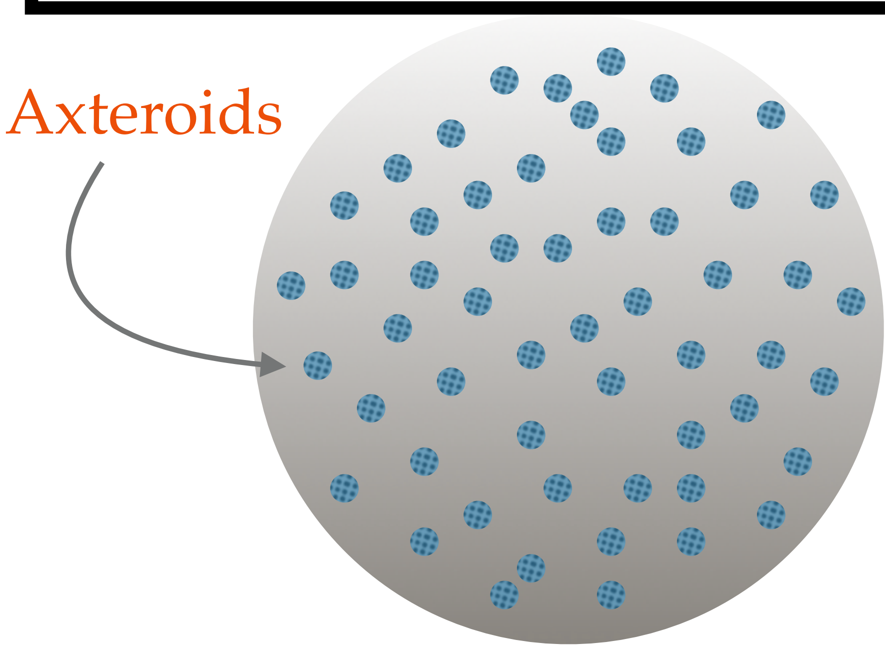
JE, Suranyi, Wijewardhana (1512.01709),

+ Ma (1705.05385)



SUBSTRUCTURE SCALES

QCD axion	FDM axion ("Fuzzy Dark Matter")
$m_\phi \sim 10^{-5}$ eV and $f \sim 10^{11}$ GeV	$m_\phi \sim 10^{-22}$ eV and $f \sim 10^{16}$ GeV
Natural clump scale	Natural clump scale
$M \sim 10^{-11} M_\odot$	$M \sim 10^{10} M_\odot$
$R \sim 100$ km	$R \sim 100$ pc

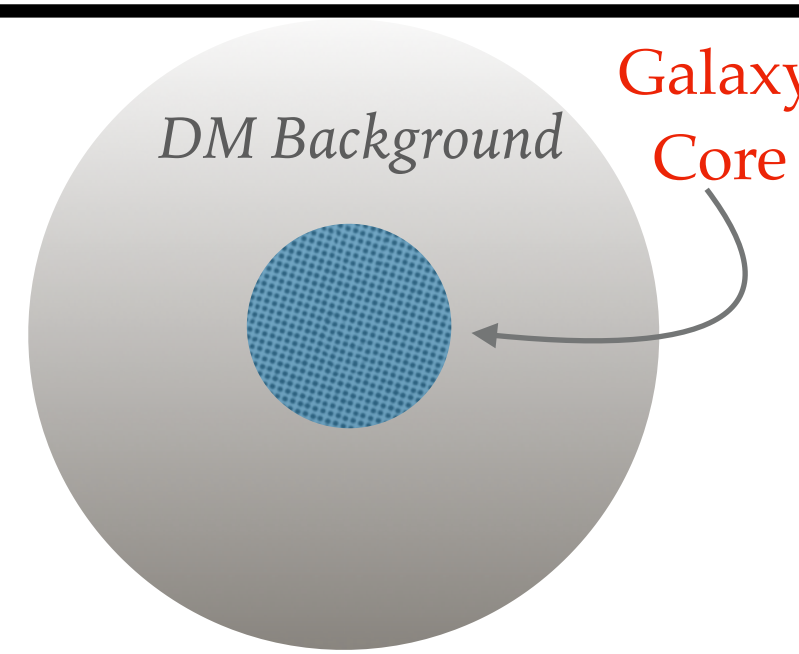


Kolb and Tkachev (PRL 1993)

Vaquero, Redondo, Stadler (1809.09241)

Can obtain very different models for halo substructure from simulations

Expect O(0.01-1) DM fraction in clumps



Schive, Chiueh, Broadhurst (1406.6586)

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COLLISIONS

- Won't these things hit us? (Should we worry?)

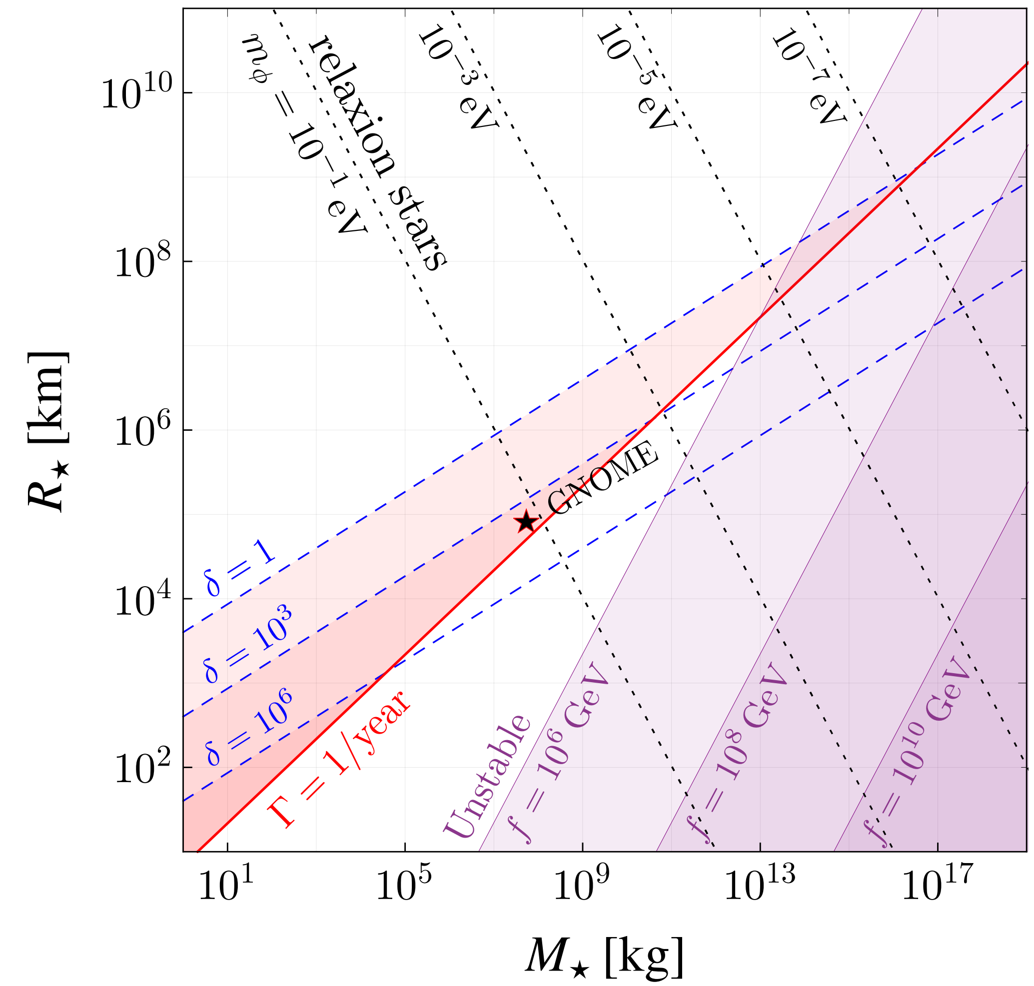
Collision rate $\Gamma_{collision} = n_\star \sigma v_\star$

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

But $M_\star \propto R_\star^{-1}$

so $\Gamma_{collision} \propto \rho_{local} R_\star^3\, m_\phi^2$

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



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COLLISIONS

➤ Won't these things hit us? (Should we worry?)

Collision rate $\Gamma_{collision} = n_\star \sigma v_\star$

$n_\star = \dfrac{\rho_{local}}{M_\star}$ $\qquad \sigma = \pi R_\star^2$ $\qquad v_\star = 200\, km/sec$

But $M_\star \propto R_\star^{-1}$

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

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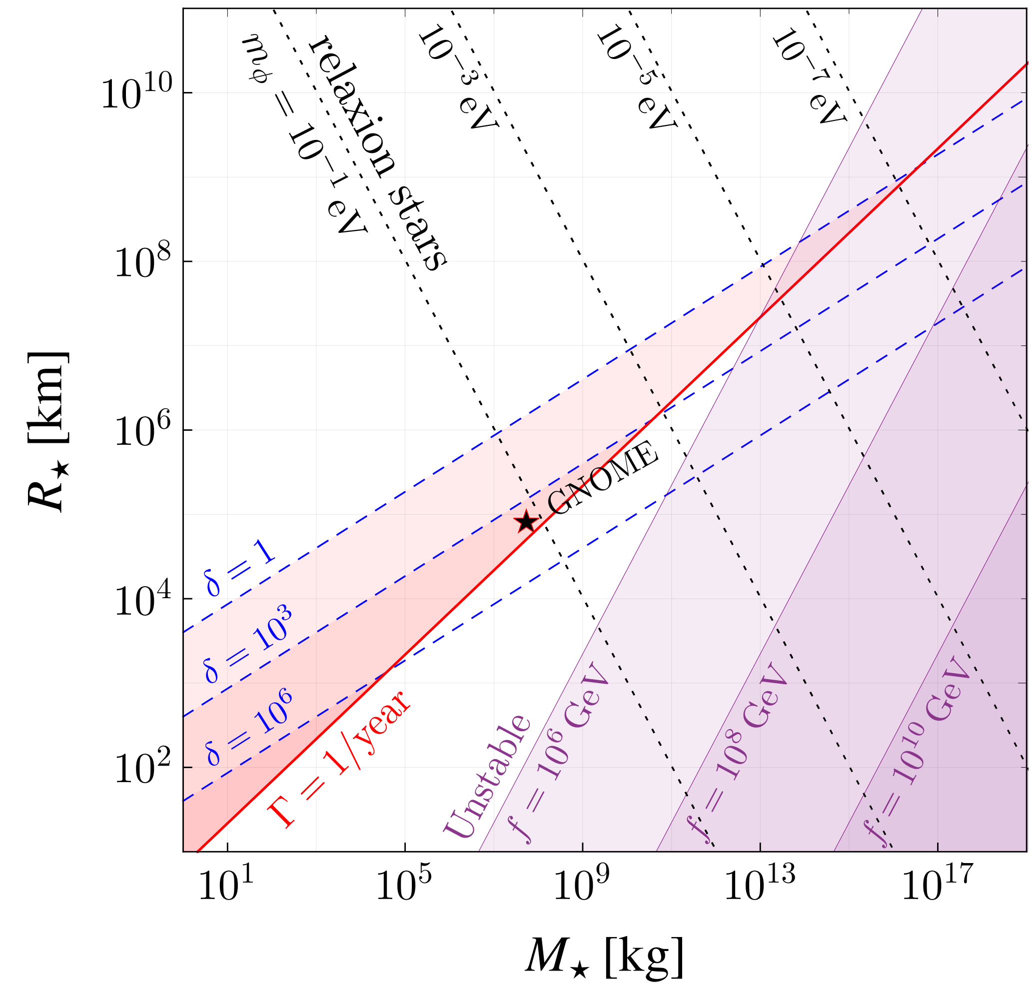
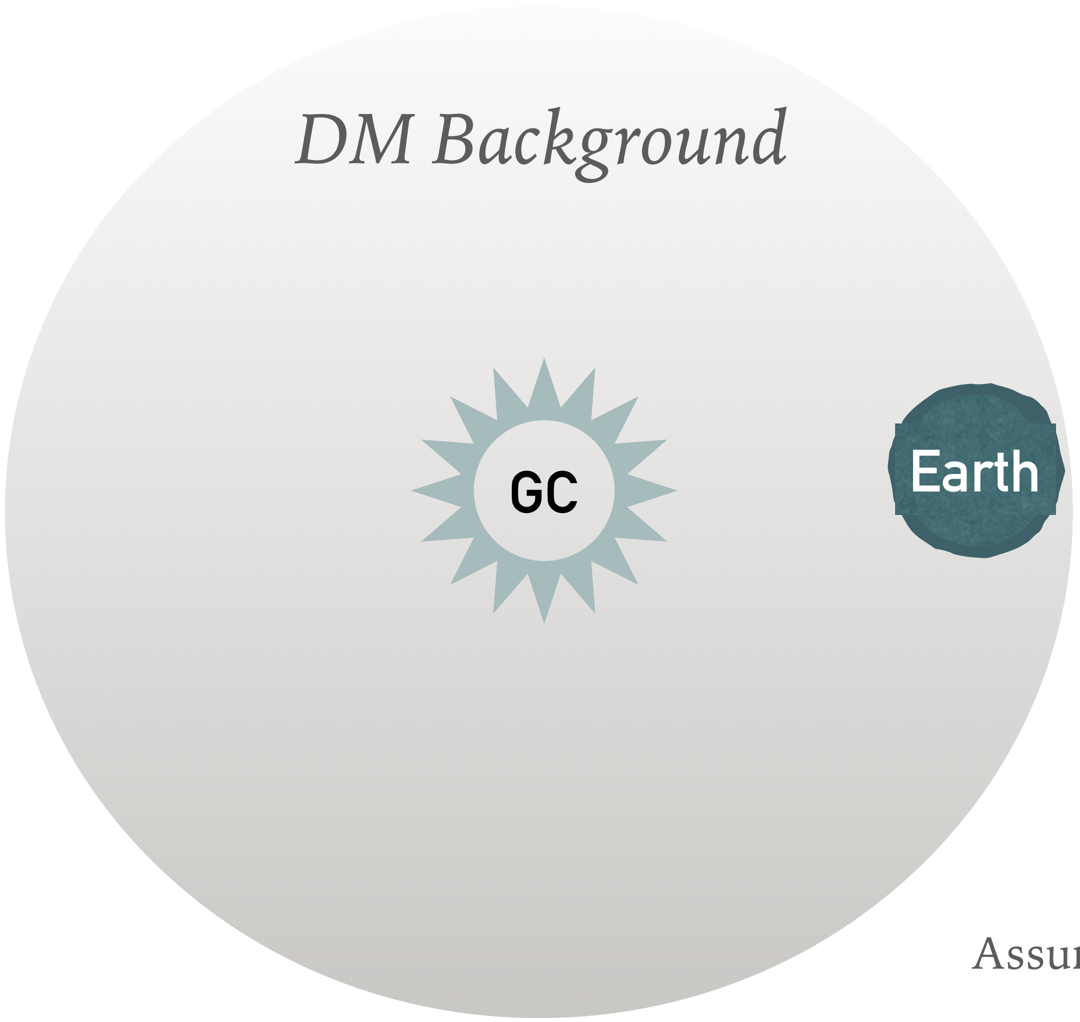


Collisions elsewhere in the galaxy?

- *Axion stars with other axion stars* — *Cotner (1608.00547)*
- *Axion stars with regular stars* — *JE, Leembruggen, Leeney, Suranyi, Wijewardhana (1701.01476)*
- *Axion stars with neutron stars (explain Fast Radio Bursts??)* — *Iwazaki (1410.4323), ...*

THE "LOCAL DENSITY"

- To do better: need to think outside the box.



Standard Picture
"Galaxy Halo"

As every child knows,

$\rho_{local} = 0.4\ GeV/cm^3$

Assumes viral equilibrium of galaxy

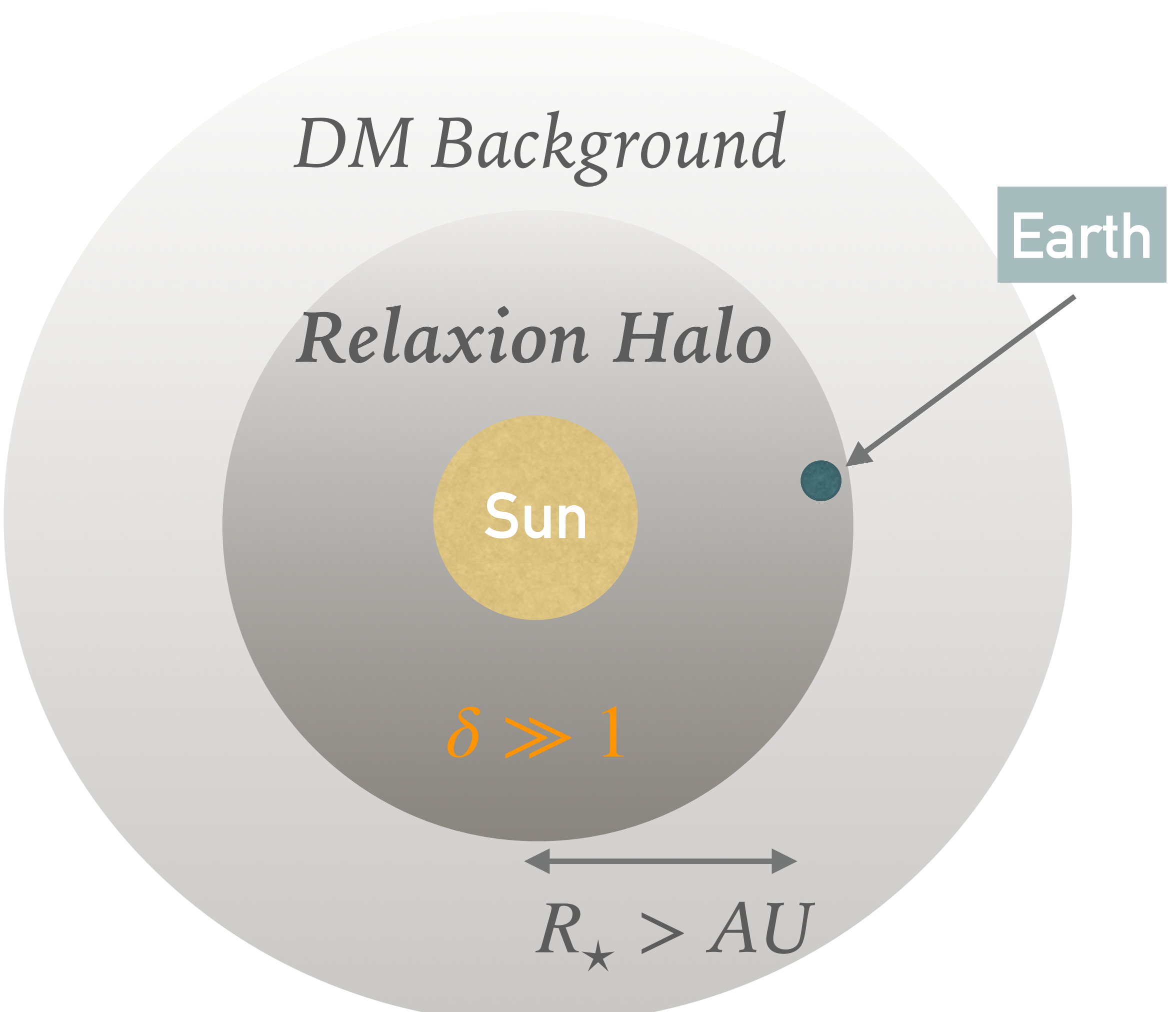
- Transient encounters with self-gravitating boson stars are rare
- Our Idea: Boson star supported by something other than self-gravity
- Large scalar field density allowed, if bound to Earth or Sun

RELAXION HALO SCENARIOS

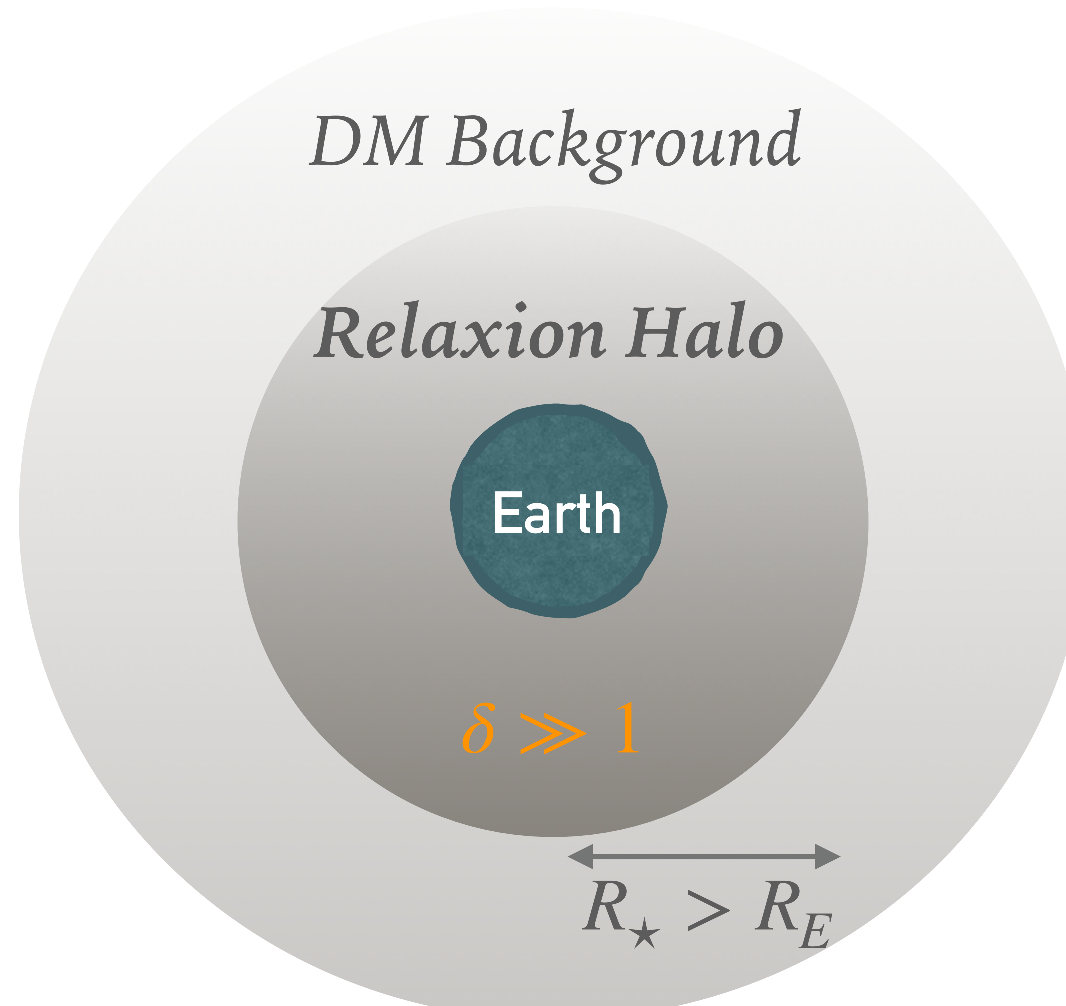
Halo supported by Sun
"Solar Halo"

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

Halo supported by Earth
"Earth Halo"



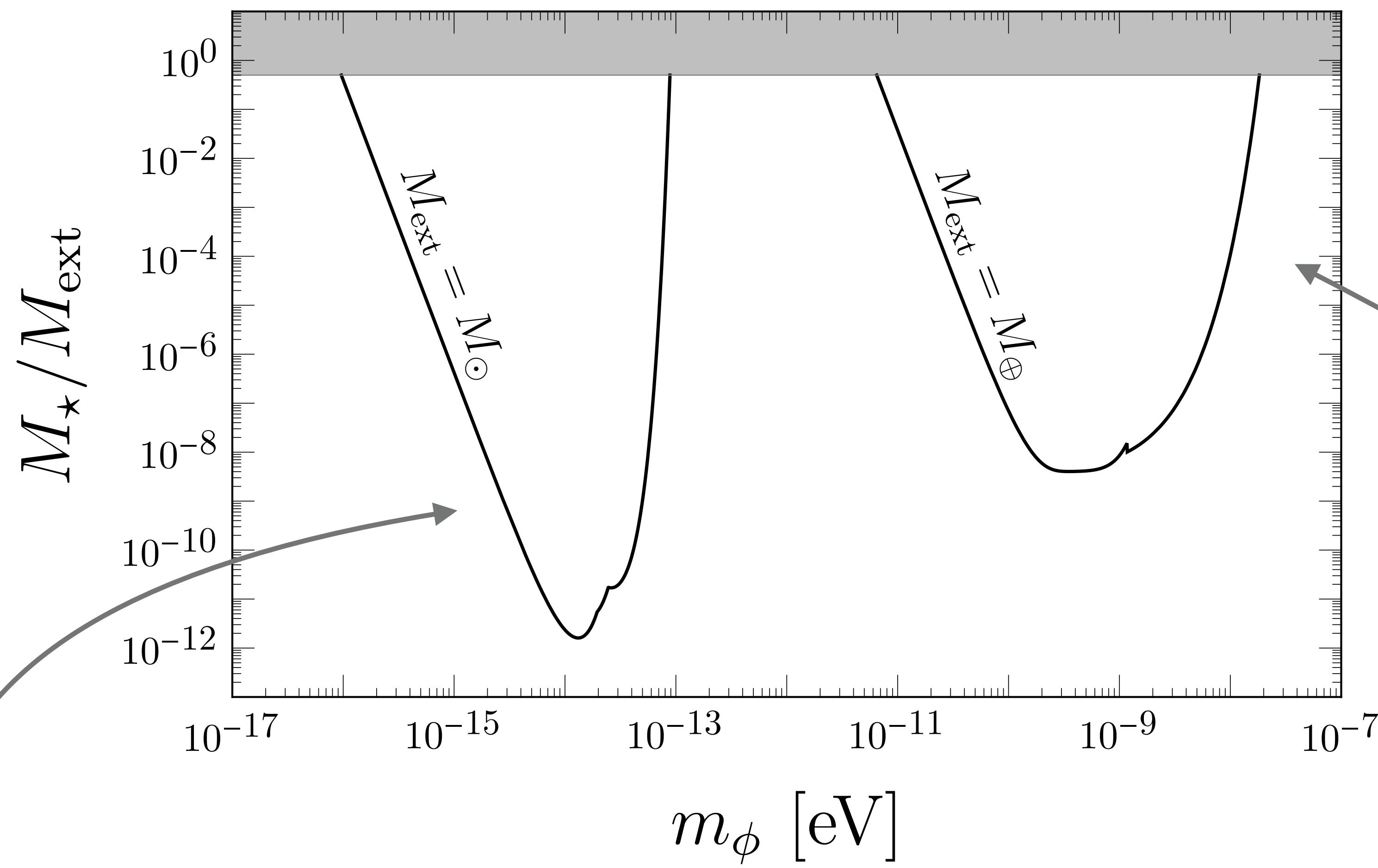
$$m_\phi = 10^{-17} \div 10^{-13}\, eV$$
$$\sim mHz \div 10\, Hz$$



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

CONSTRAINTS ON LOCAL OVERDENSITIES

- Gravitational measurements constrain the scenario



Solar System Ephemerides (Mercury, Mars, Saturn)

Pitjev and Pitjeva (1306.5534)

Lunar Laser Ranging + LAGEOS Satellite

Adler (0808.0899)

- Sort of degeneracy of parameters: constraint on g_e, $g_\gamma \Leftrightarrow M_\star$

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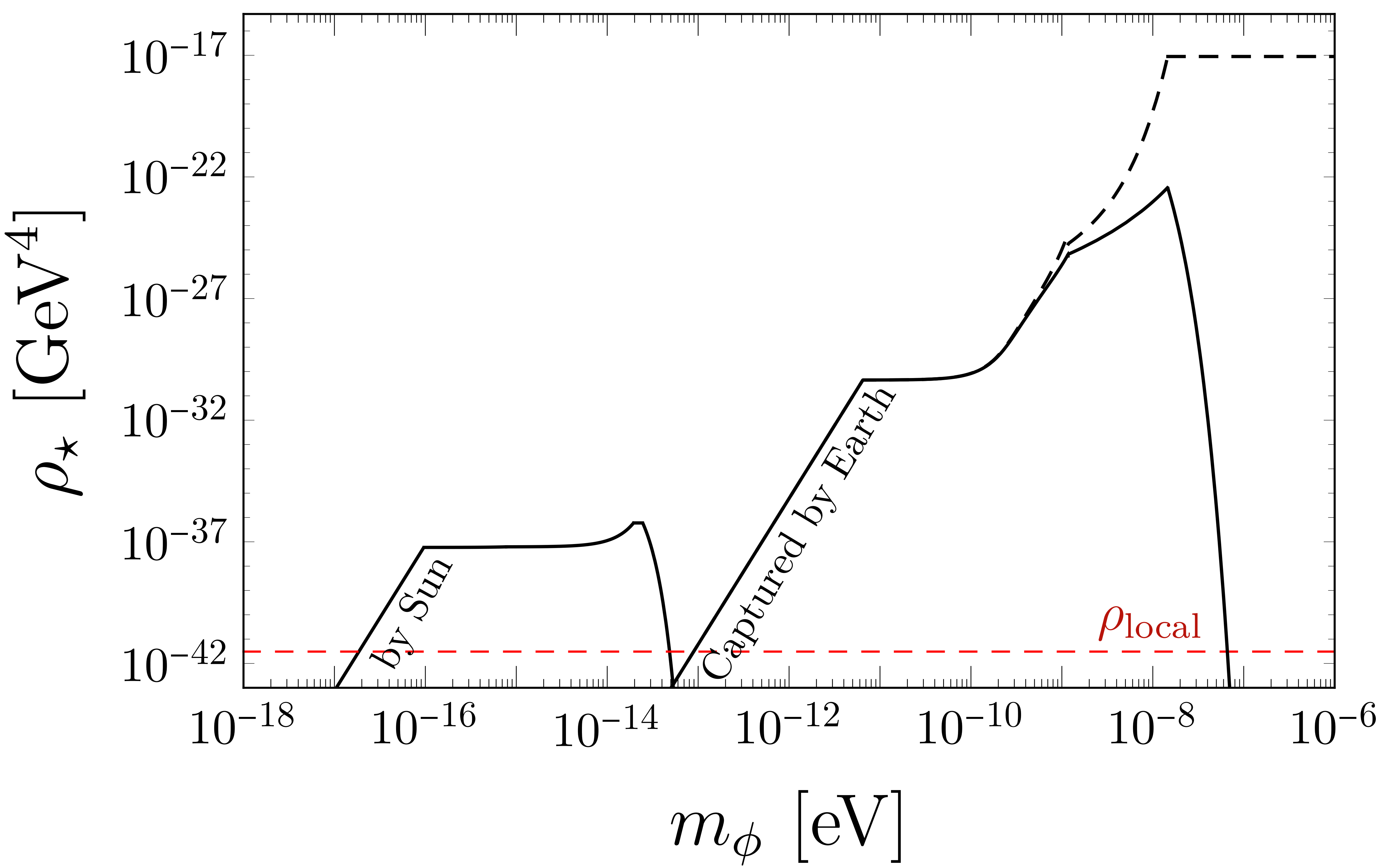
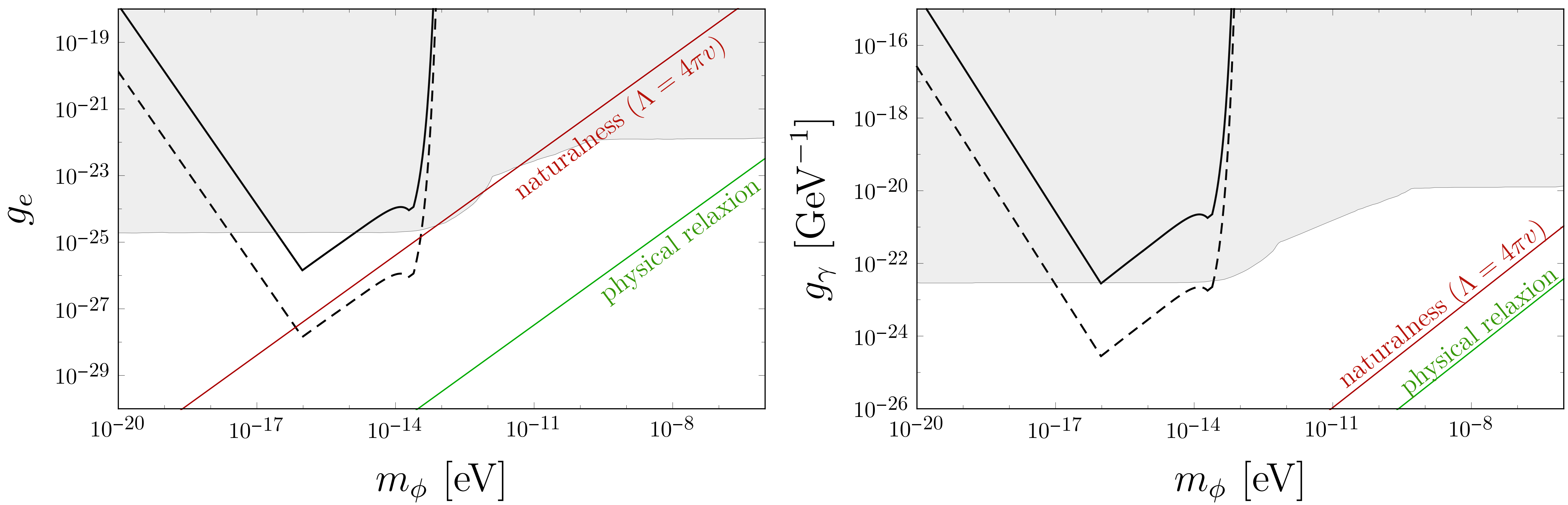
HALO OVERDENSITY



ATOMIC SENSITIVITY: SOLAR HALO

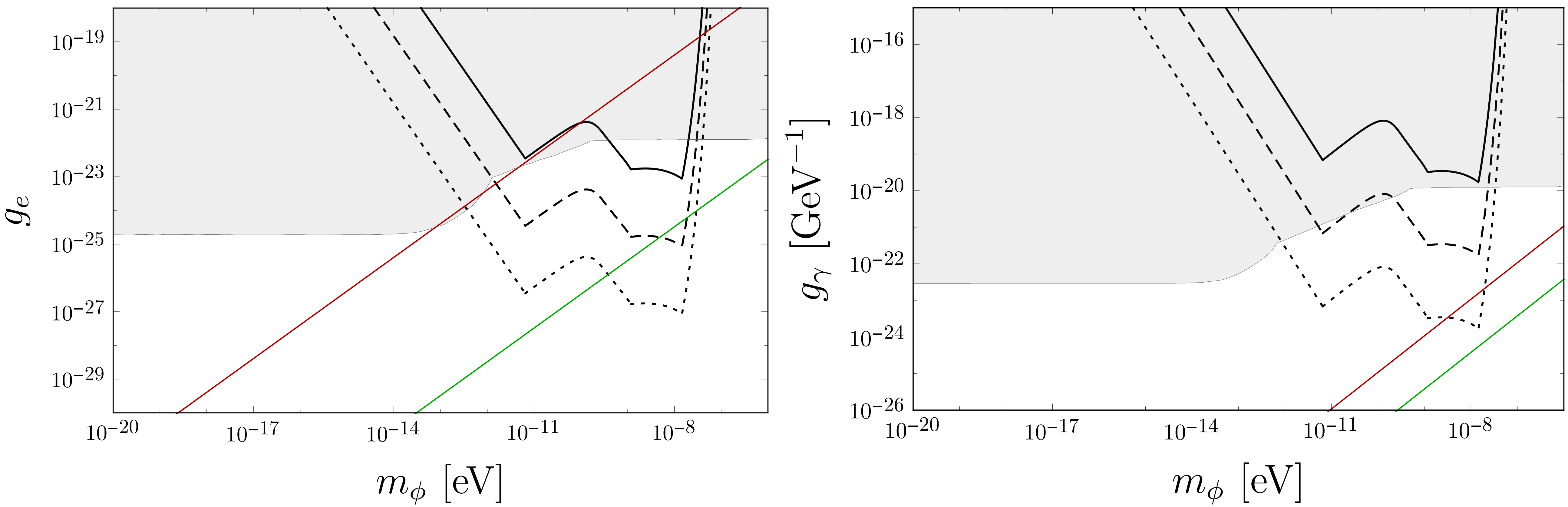
Sensitivity: *Solid:* 10^{-16} *Dashed:* 10^{-18}



- Can do better than EP tests, probing natural models near $m_\phi \sim 10^{-16} - 10^{-14}\,eV$

ATOMIC SENSITIVITY: EARTH HALO

<u>*Sensitivity*</u>: *Solid:* 10^{-14} *Dashed:* 10^{-16} *Dotted:* 10^{-18}

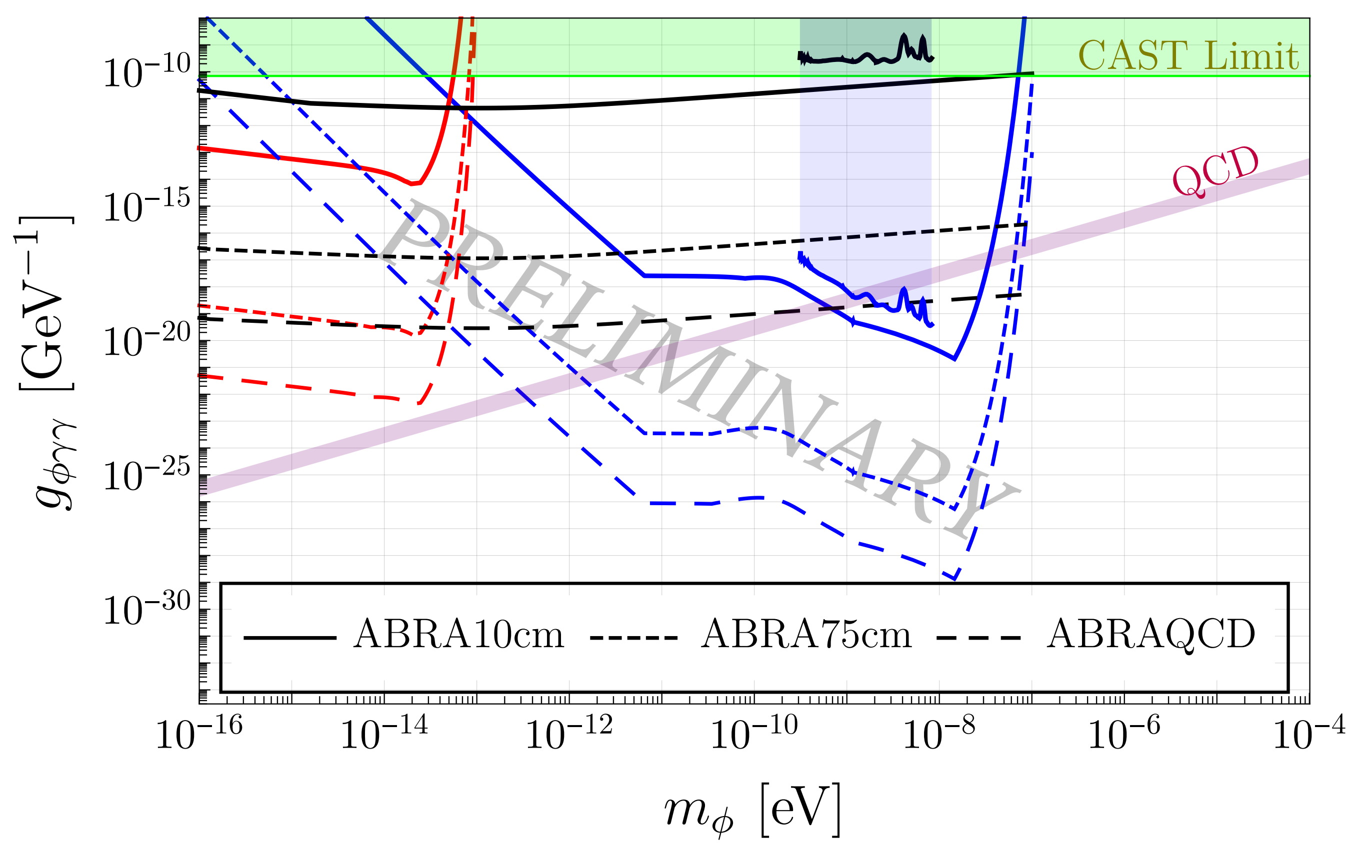


- Can probe physical relaxion models in near future!

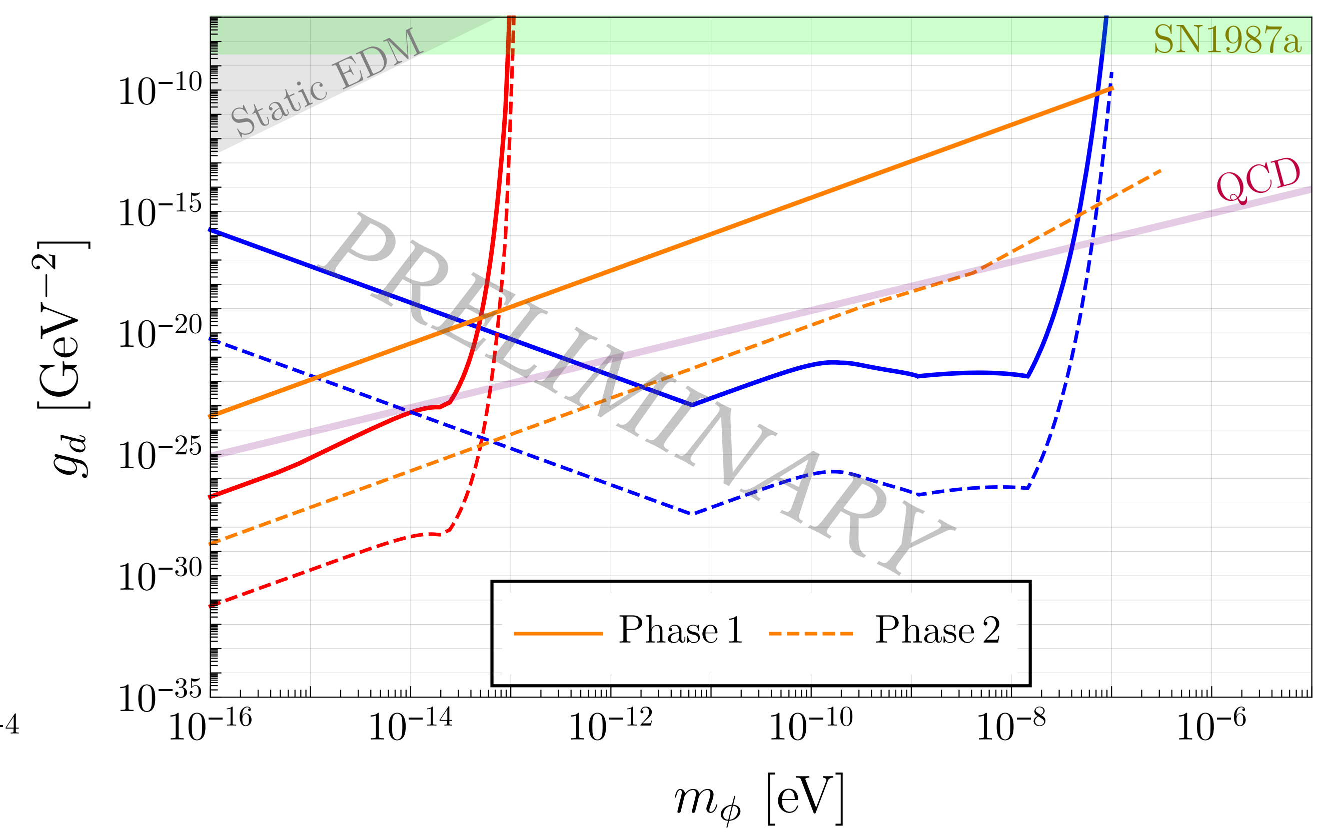
PSEUDOSCALAR COUPLINGS

➤ Ongoing work: modification to traditional axion searches

ABRACADABRA



CASPEr-Electric



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

$$\mathscr{L} \supset g_d\, \phi\, N^\dagger \left(\vec{\sigma}\cdot\vec{E}\right) N$$

➤ Updates soon!

CONCLUSIONS

- DM substructure is a unique handle on light scalar DM
- Can look for transient signals, or (!) consistent overdensity
  - For DM with scalar couplings, use atomic physics experiments to probe variation of fundamental constants
  - Halo formation story unclear; at this point, just some ideas (…)
  - Huge sensitivity enhancement in halo scenario
- Halo scenario also modifies sensitivity for pseudo scalar couplings!
  - CASPEr, ABRACADABRA, GNOME, DM Radio, … update soon!

THANK YOU!

Thanks to Zuckerman STEM Leadership Program for financial support

DIRECTOR'S CUT (INCLUDES DELETED SCENES)

MASS-RADIUS RELATION

- Possible we live in a (*very*) local over/underdensity
- Intriguing that scalar field bound to external object has stable ground-state configuration with size independent of $M_\star$!

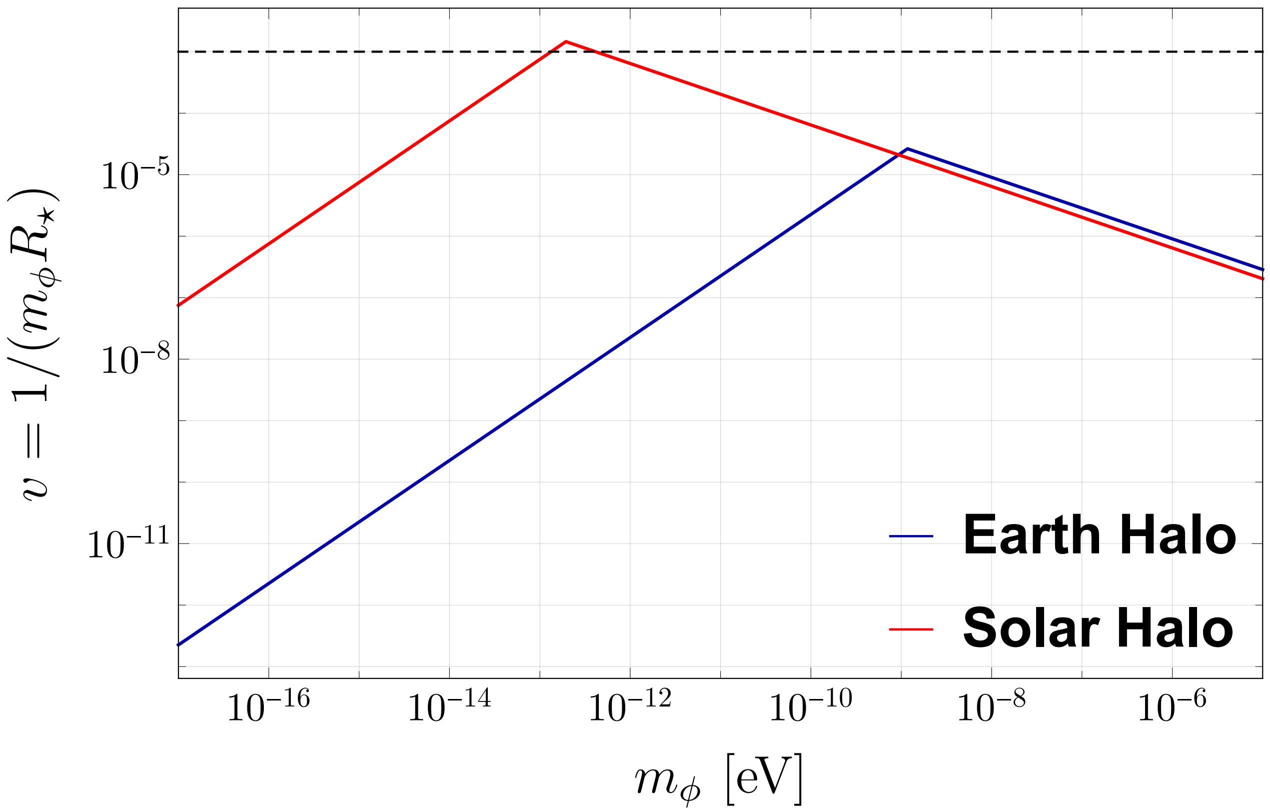
$$i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + V_g + V_{ext}\right]\psi \xrightarrow{M_{ext} \gg M_\star} \boxed{R_\star \approx \frac{M_P^2}{m_\phi^2 M_{ext}}}$$

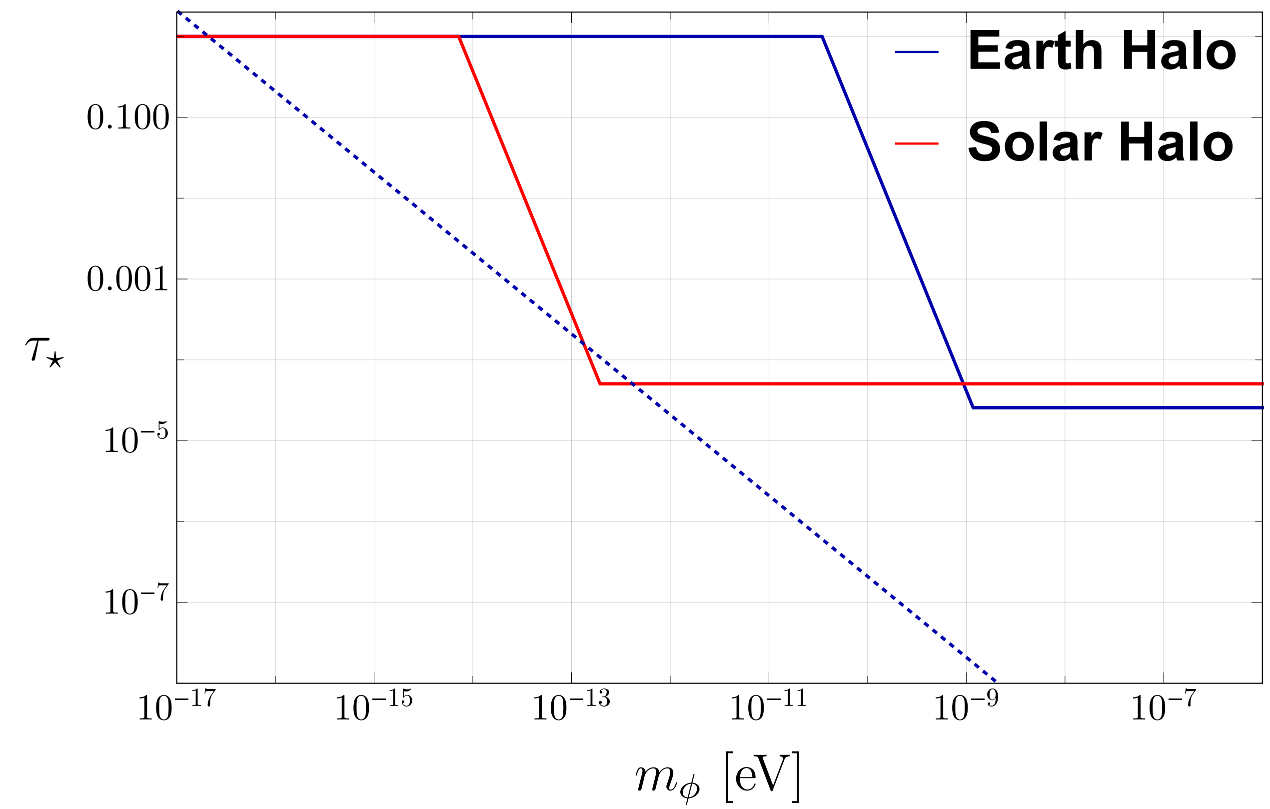
- $M_\star$ only constrained by measurements of local gravity

HALO COHERENCE LENGTH / TIME

- Relaxion halo is coherently oscillating state
- Coherence length $$R_\star = \frac{M_P^2}{m_\phi^2 M_{ext}} = \frac{1}{m_\phi v}$$
- Coherence time $$\tau_\star = \frac{1}{m_\phi v^2} \approx \begin{cases} 10^3\, sec\ \times (10^{-9}\, eV/m_\phi)^3 & for\ R_\star > R_\oplus \\ 10^3\, sec & for\ R_\star \lesssim R_\oplus \end{cases}$$

(for Earth halo)



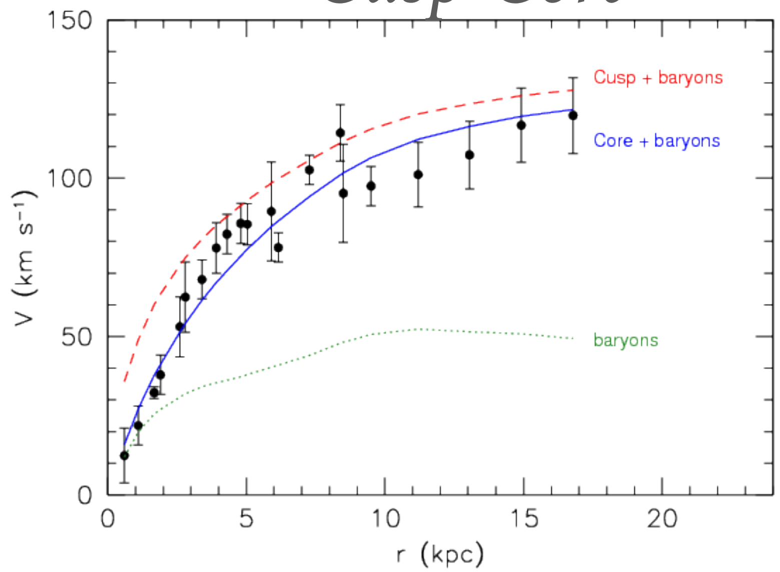


SMALL-SCALE CONTROVERSIES

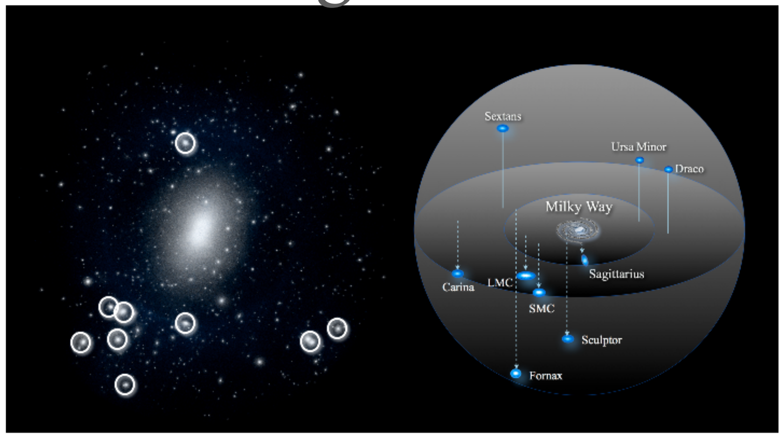
- A big problem?

Weinberg et al. (1306.0913)

"Cusp-Core"



"Missing Satellites"



- No problem?

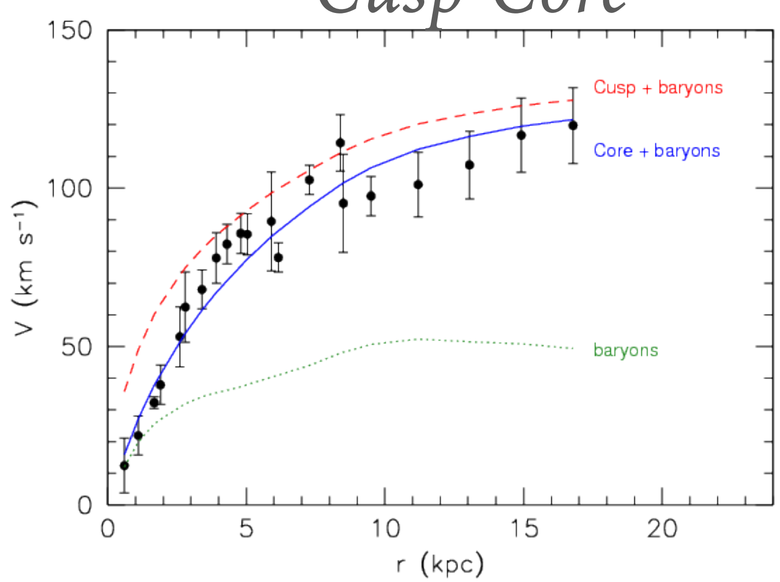
J. Eby, Weizmann Institute

SMALL-SCALE CONTROVERSIES

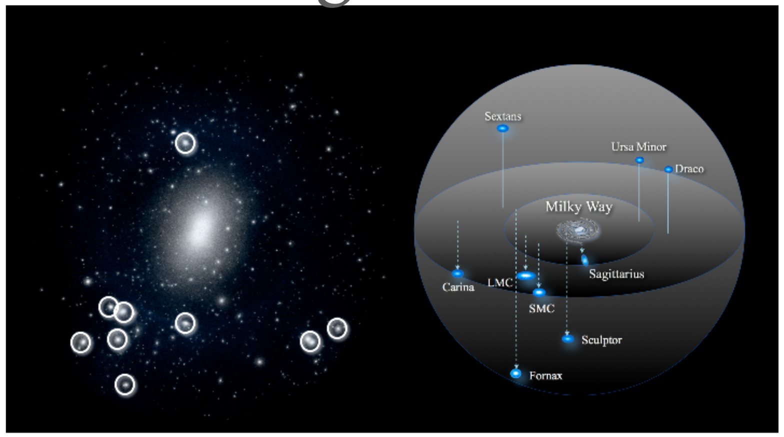
➤ A big problem?

Weinberg et al. (1306.0913)

"Cusp-Core"



"Missing Satellites"



➤ No problem?

Forged in FIRE: cusps, cores, and baryons in low-mass dwarf galaxies

Jose Oñorbe, Michael Boylan-Kolchin, James S. Bullock, Philip F. Hopkins, Dušan Kereš, Claude-André Faucher-Giguère, Eliot Quataert, Norman Murray

(Submitted on 6 Feb 2015 (v1), last revised 17 Oct 2015 (this version, v2))

Dark Matter Self-interactions and Small Scale Structure

Sean Tulin, Hai-Bo Yu

(Submitted on 5 May 2017 (v1), last revised 24 Nov 2017 (this version, v2))

Can Light Dark Matter Solve the Core-Cusp Problem?

Heling Deng, Mark P. Hertzberg, Mohammad Hossein Namjoo, Ali Masoumi

(Submitted on 16 Apr 2018)

Deng et al: "No."

Me: "…maybe, but it's fine either way."

There is No Missing Satellites Problem

Stacy Y. Kim, Annika H. G. Peter, Jonathan R. Hargis

(Submitted on 16 Nov 2017 (v1), last revised 12 Jun 2018 (this version, v3))

Phat ELVIS: The inevitable effect of the Milky Way's disk on its dark matter subhaloes

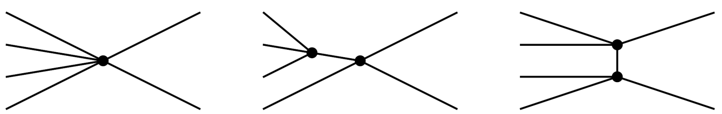
Tyler Kelley, James S. Bullock, Shea Garrison-Kimmel, Michael Boylan-Kolchin, Marcel S. Pawlowski, Andrew S. Graus

(Submitted on 29 Nov 2018)

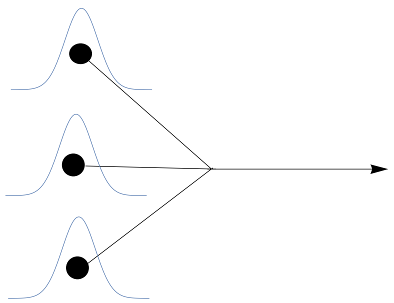
predict galaxies with pericenters smaller than 20 kpc. 3) The enhanced destruction produces a tension opposite to that of the classic `missing satellites' problem: in order to account for ultra-faint galaxies known within 30 kpc of the Galaxy, we must populate haloes with $V_{peak} \simeq 7$ km s^{-1} ($M \simeq 3 \times 10^7$ M$_\odot$ at infall), well below the atomic cooling limit of $V_{peak} \simeq 16$ km s^{-1} ($M \simeq 5 \times 10^8$ M$_\odot$ at infall). 4) If such tiny haloes do host ultra-faint dwarfs, this implies the

DENSE: NOT SO STABLE AFTER ALL

- Recall that axions are ***real*** scalars: no number conservation
  - Decay to photons: $a \to \gamma\gamma$, small rate if $m \lesssim eV$
  - Can decay through self-interactions:
    - On-shell: $4\,a \to 2\,a$
      Braaten, Mohapatra, Zhang (1609.05182)



    - Off-shell decays in bound state: $3\,a_{bound} \to a_{free}$
      JE, Suranyi, Wijewardhana (1512.01709), with Ma (1705.05385)



- 3—>1 dominant, large when $|E - m| \lesssim 0.998$

$$\frac{dM}{dt} \propto e^{-1/\sqrt{1-(E/m)^2}}$$

Known from oscillon literature,

(bound state of no gravity)

Fodor, Forgacs, Horvath, Mezei (0903.0953)

Hertzberg (1003.3459)

Mukaida, Takimoto, Yamada (1612.07750)

J. Eby, Weizmann Institute

…ALSO NOT SO NON-RELATIVISTIC

- Non-relativistic limit assumes field energy $E = \mathcal{O}(m)$
- Relativistic corrections are legion:

a. Special Relativity: $E_K = \sqrt{p^2 + m^2} - m \approx \dfrac{p^2}{2m} - \dfrac{p^4}{8\,m^3} + \dots$

b. Scalar field contains higher harmonic modes:

$$\phi = \left[\phi_1\, e^{-iEt} + \phi_3\, e^{-3iEt} + \dots\right] + h.c.$$

c. General Relativity??

! (thankfully, gravity is small in crossover to dense region!)

‘FULL’ MASS SPECTRUM

JE, Suranyi, Wijewardhana (1712.04941)

Upshot:

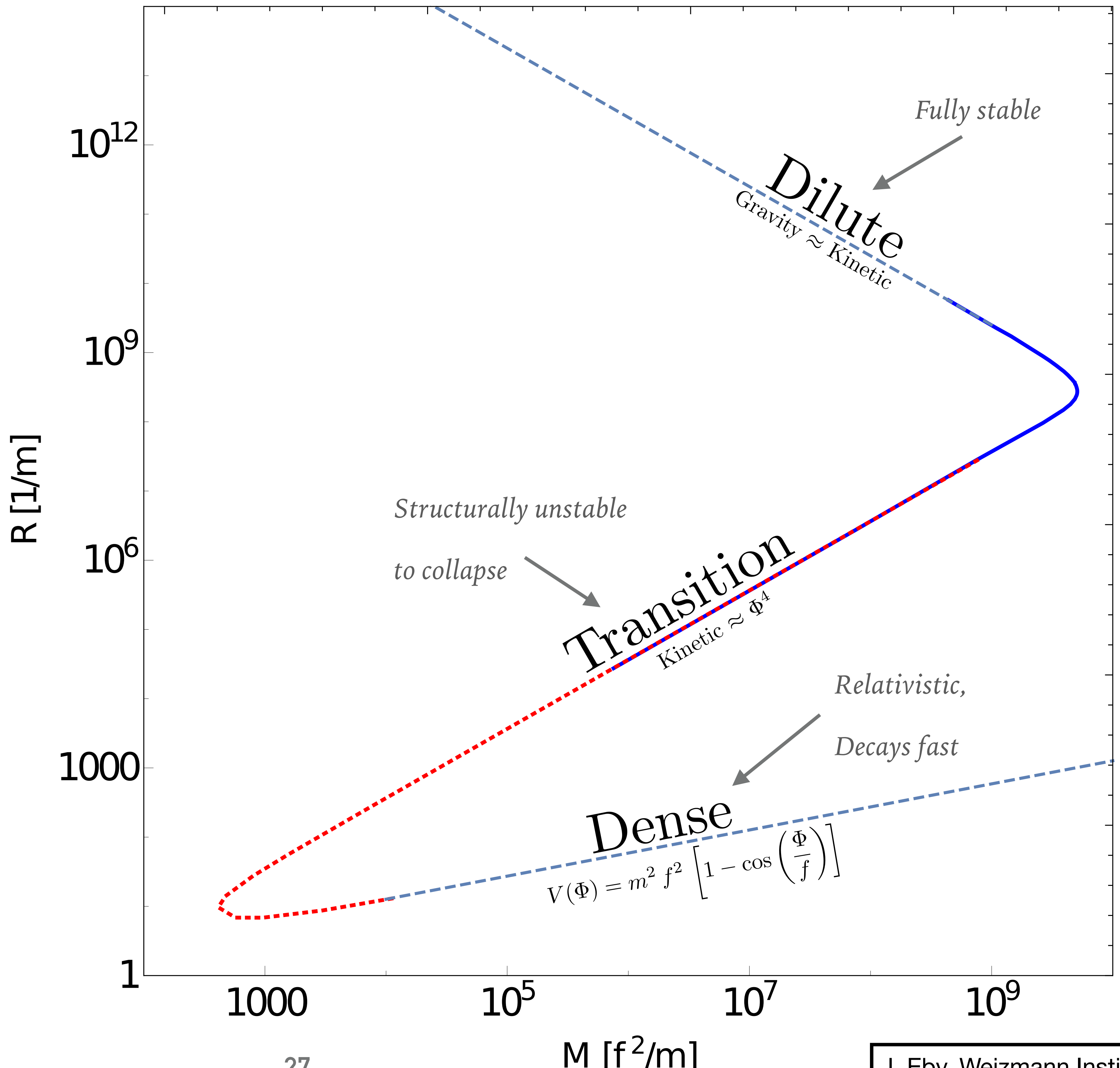
Dilute boson stars are what we have to work with

Other versions of ‘classical nonrelativistic real scalar field effective field theory’ (CNREFT):

Namjoo, Guth, Kaiser (1712.00445)

Braaten, Mohapatra, Zhang (1806.01898)

JE, Mukaida, Takimoto, Wijewardhana, Yamada (1807.09795)



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A PHENOMENOLOGICAL APPROACH (GNOME)

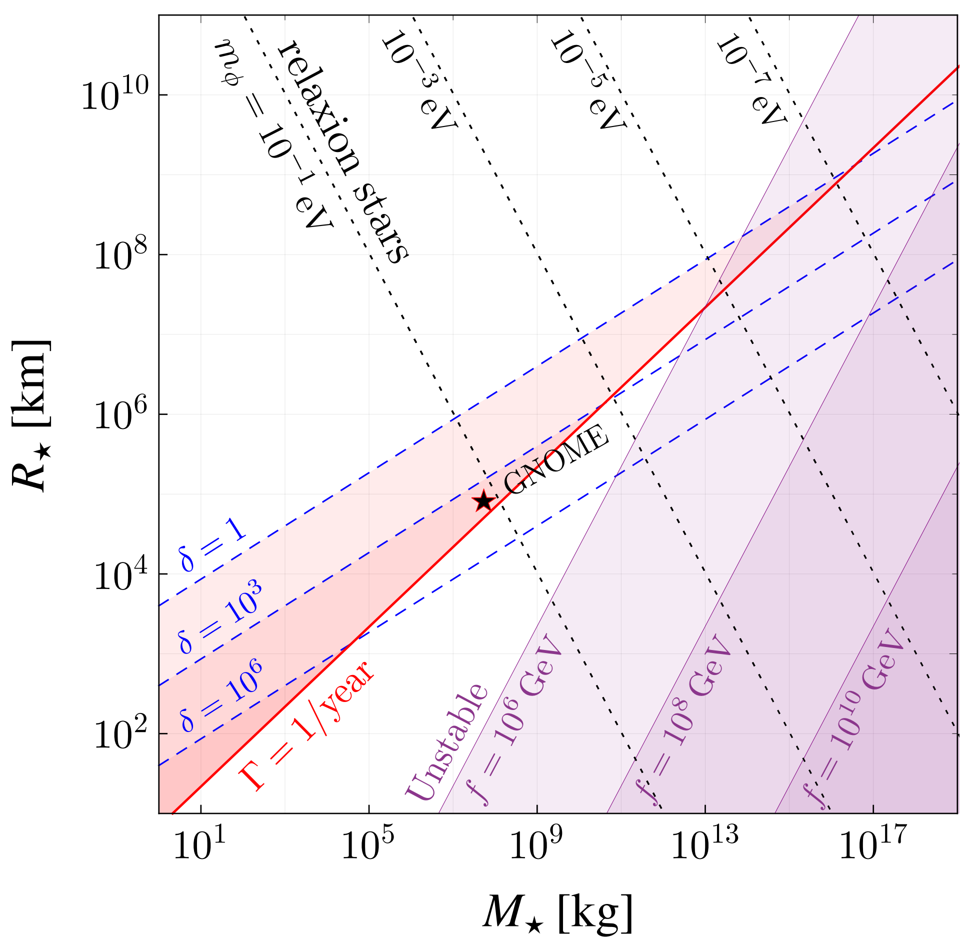
- Assume $\Gamma_{collision} = 1/year, \delta = 10^4$

  $$\Rightarrow M_\star \sim 2 \times 10^7\, kg, R_\star \sim 10\, R_E$$

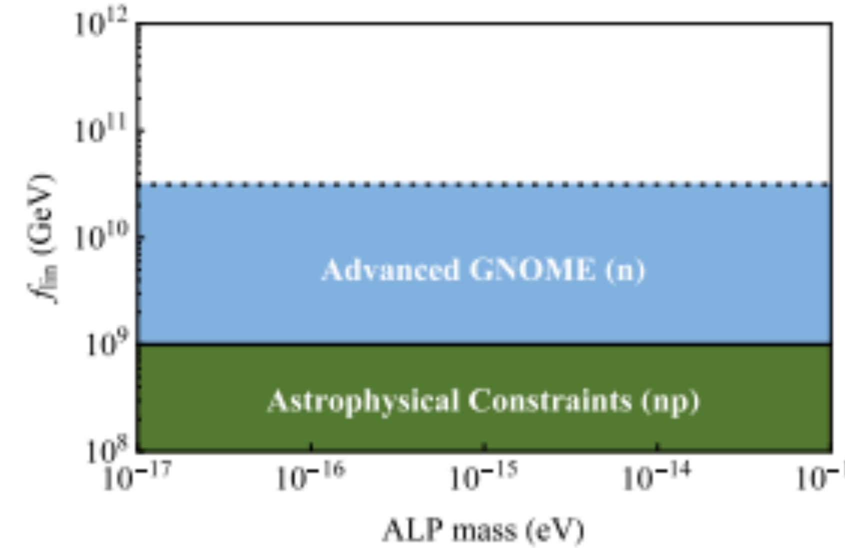
- Global Network of Optical Magnetometers

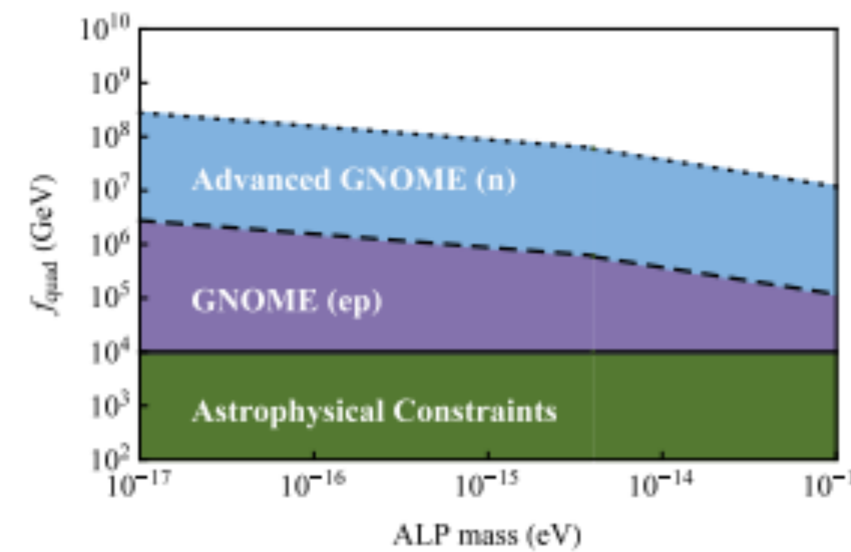
  To search for Exotic Physics (GNOME)

- But…



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

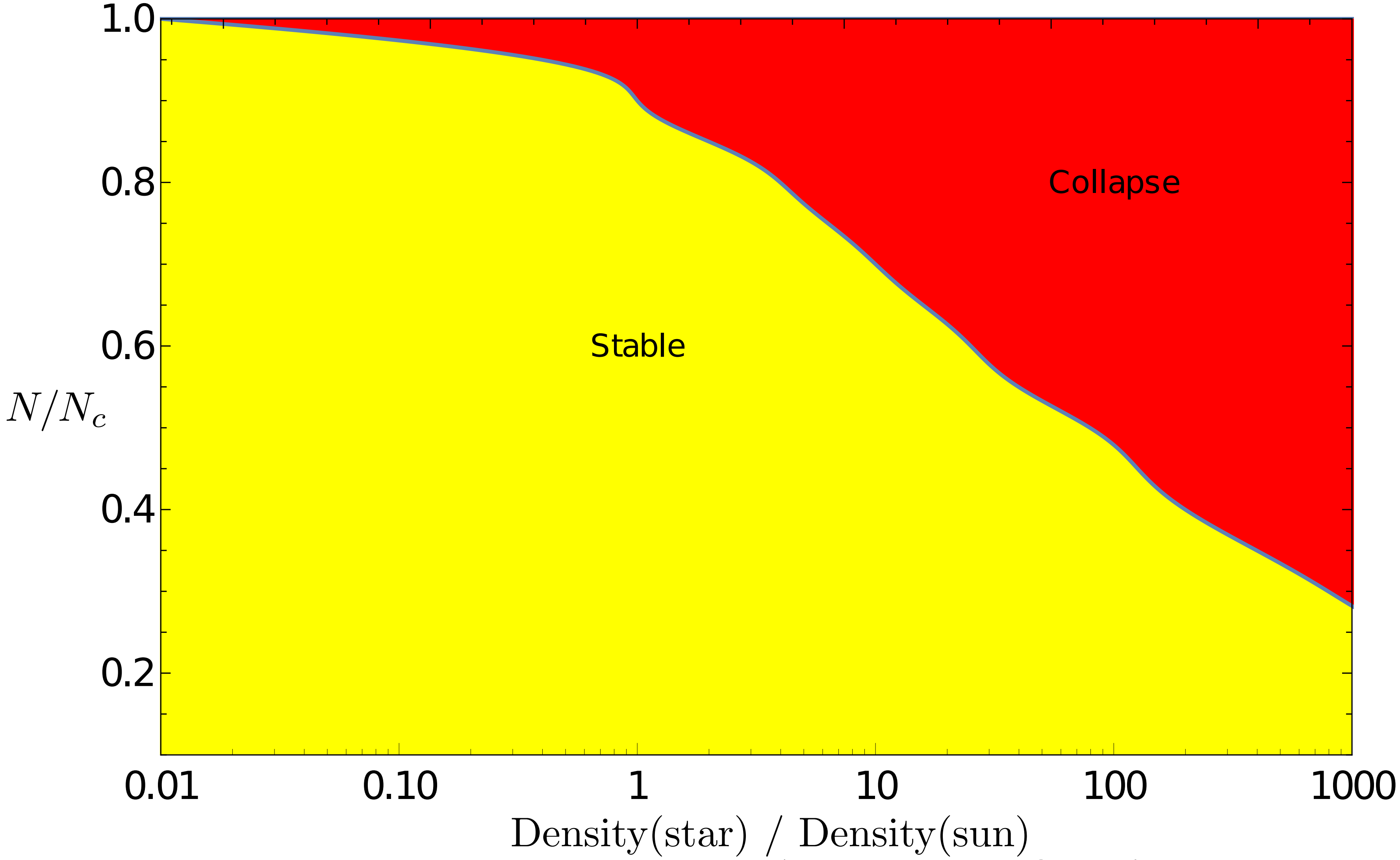




$$\mathscr{L} \supset \frac{\nabla\phi \cdot S}{f_{lin}} + \frac{\phi\nabla\phi \cdot S}{f_{quad}^2}$$

Kimball, Budker, JE et al. (1710.04323)

EXAMPLE: COLLISIONS WITH STARS



(Next step for this scenario: simulate galaxy stars, including spectrum of axion stars)

(Some other talk…)

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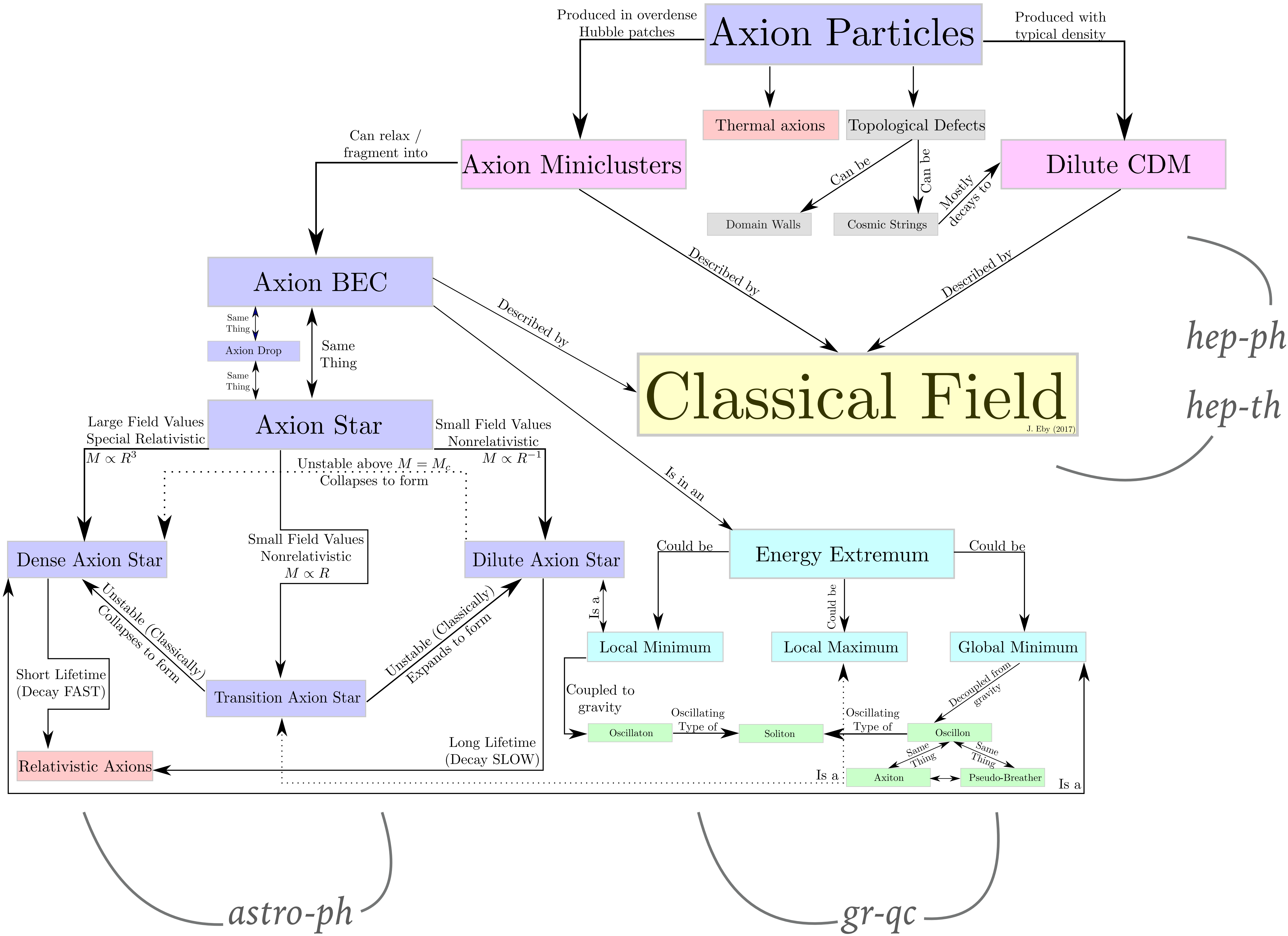

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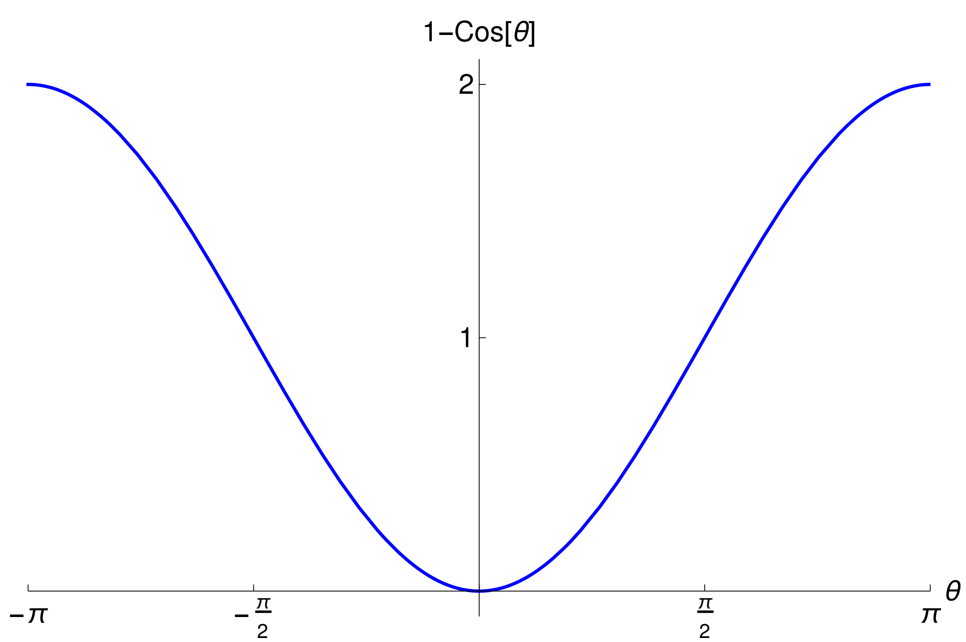
AXION POTENTIAL

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

$$= \frac{m^2}{2}\phi^2 - \frac{m^2}{4!\,f^2}\phi^4 + \ldots$$



NR Limit:

$$\phi = \frac{1}{\sqrt{2m}}\left[e^{-imt}\psi \underbrace{+c.c.}\right]$$

ϕ *(If is real)*

$$V_{eff} = V(\phi) - \frac{m^2}{2}\phi^2$$

$$= m^2 f^2 \left[1 - J_0\left(\sqrt{\frac{\psi^* \psi}{2\,m\,f^2}}\right)\right] - \frac{m}{2}|\psi|^2 + \mathcal{O}(e^{\pm imt})$$

$$= -\frac{1}{8f^2}|\psi|^4 + \ldots$$

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

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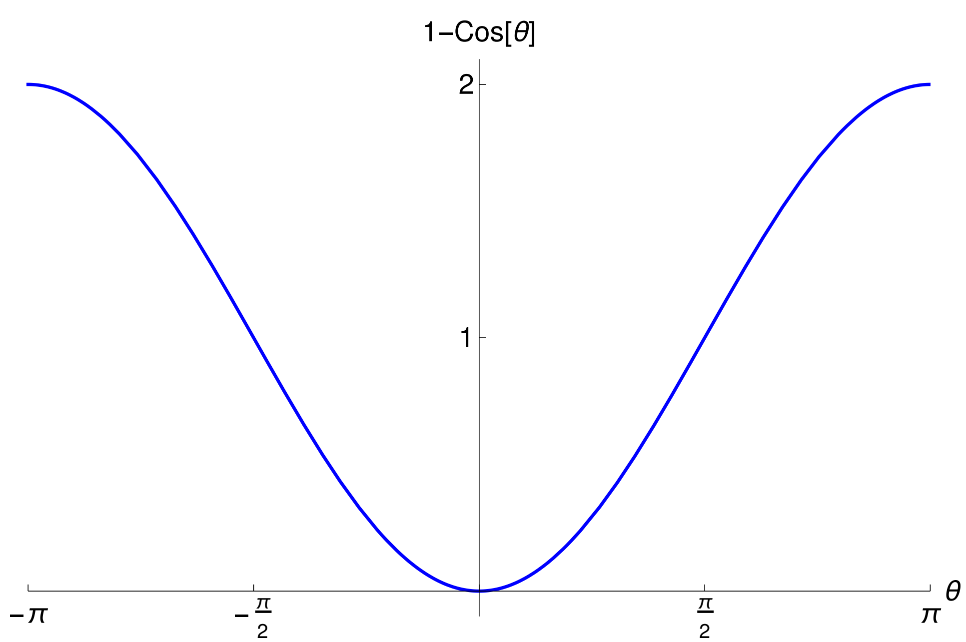

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$$\phi = \frac{1}{\sqrt{2m}}\left[e^{-imt}\psi \underbrace{+c.c.}\right]$$

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$$V_{eff} = V(\phi) - \frac{m^2}{2}\phi^2$$

$$= m^2 f^2 \left[1 - J_0\left(\sqrt{\frac{\psi^*\psi}{2\,m\,f^2}}\right)\right] - \frac{m}{2}|\psi|^2 + \cancel{\mathcal{O}(e^{\pm imt})}$$

$$= -\frac{1}{8f^2}|\psi|^4 + \ldots$$

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

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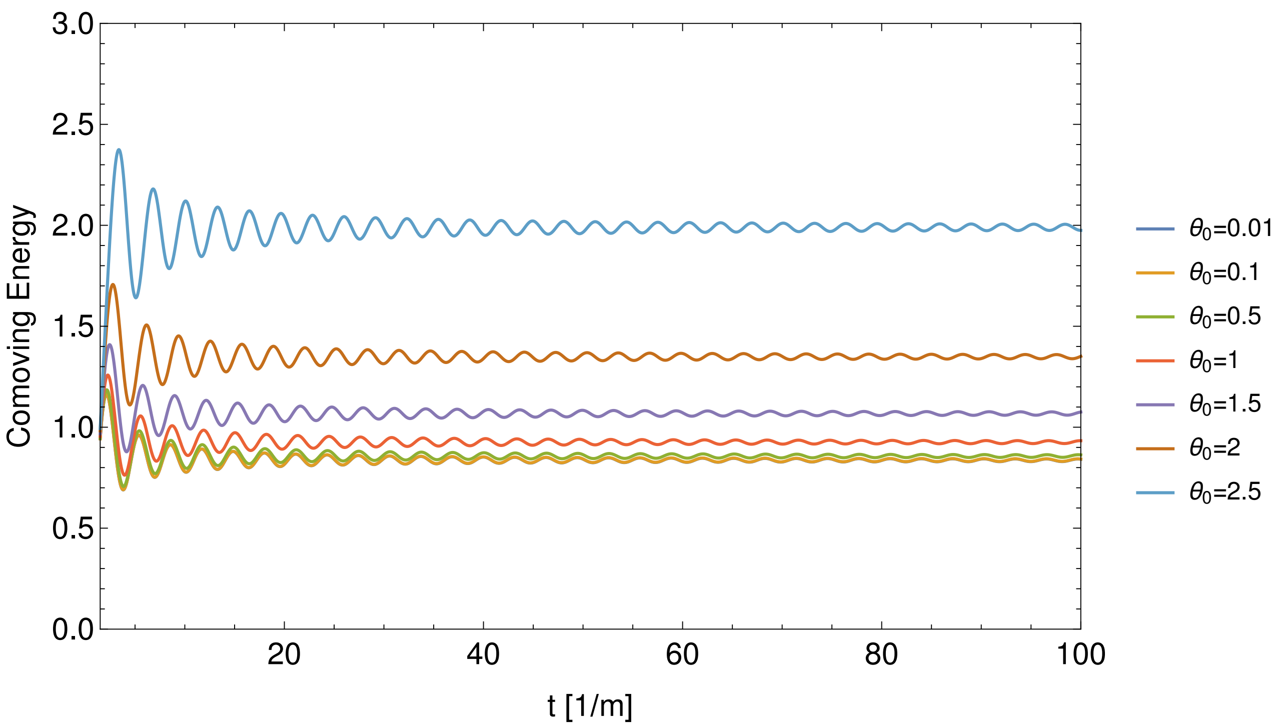
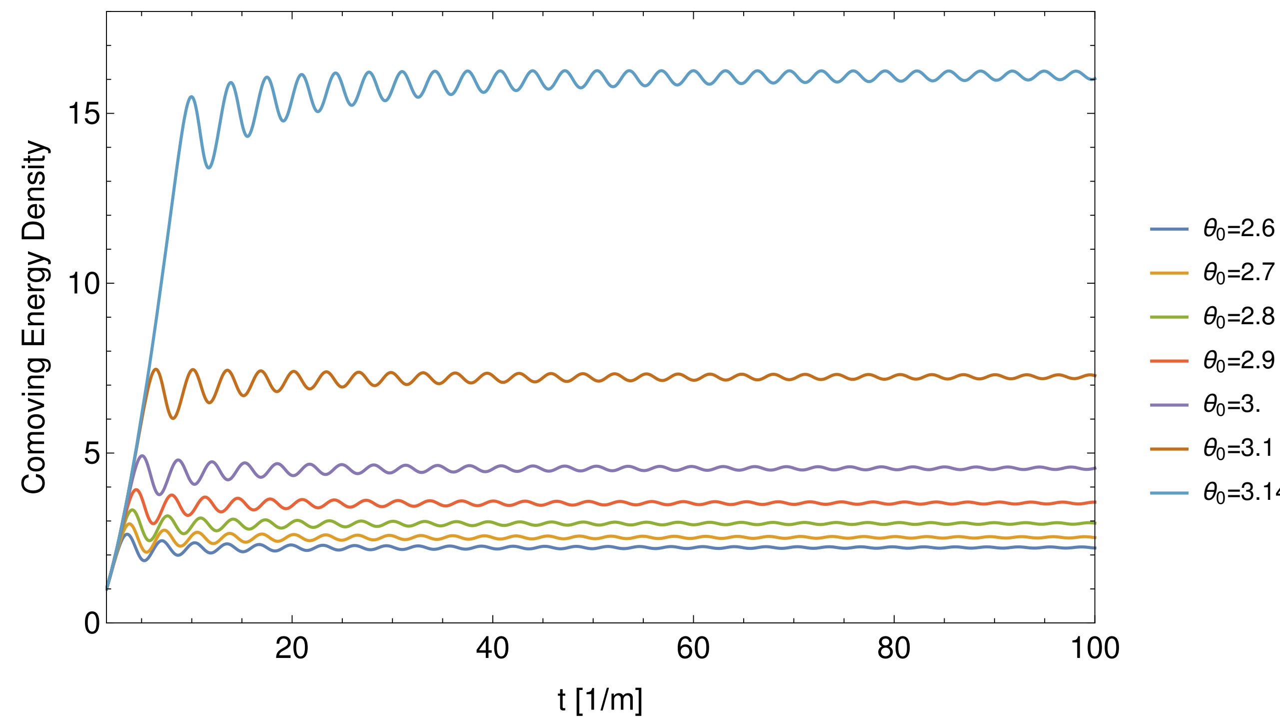
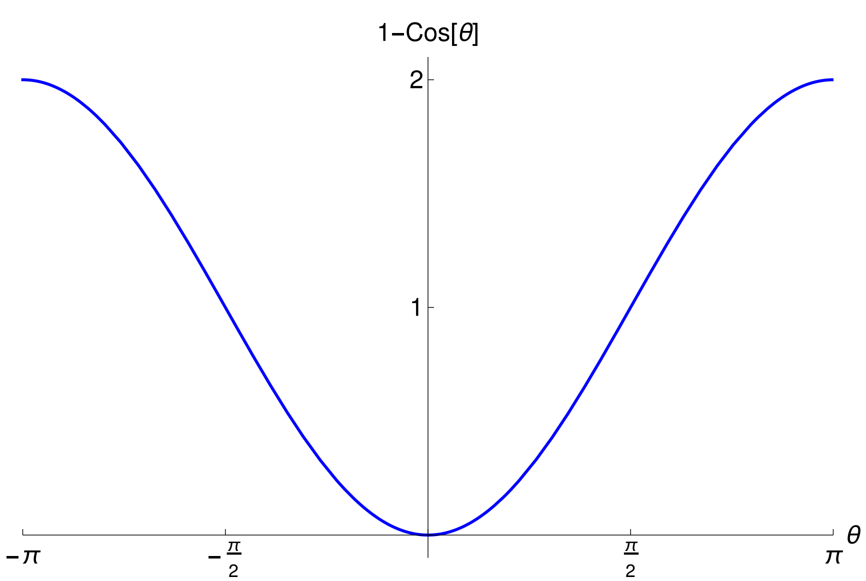
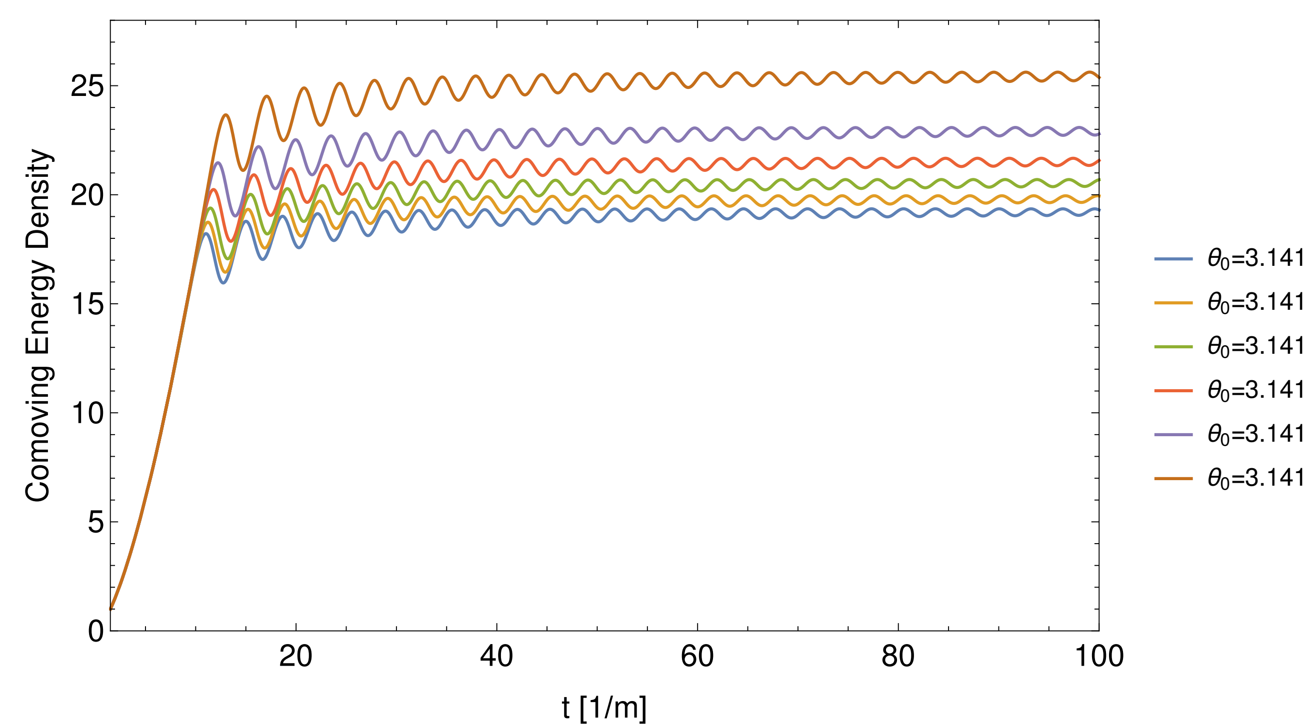
EARLY UNIVERSE OVERDENSITIES









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ORIGINAL AXION MINICLUSTER SIMULATIONS

VOLUME 71, NUMBER 19 PHYSICAL REVIEW LETTERS 8 NOVEMBER 1993

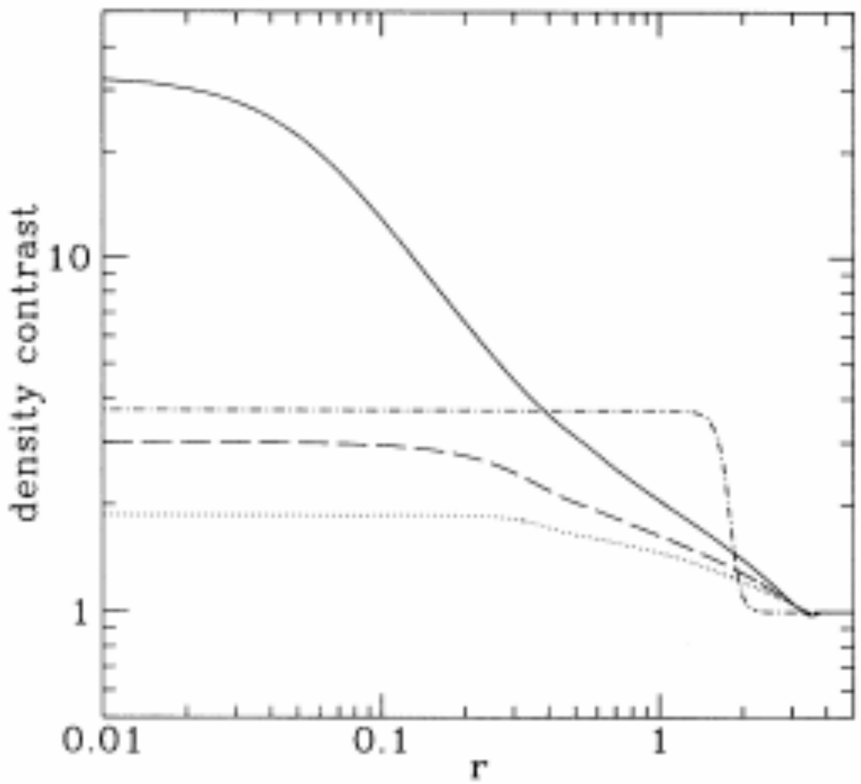


FIG. 2. Energy density profiles at $\bar{\eta}=4$ for identical initial fluctuations evolved with different Lagrangians. Solid line: axion case; dashed line: $V(\theta)\propto\theta^2/2$; dotted line: $V(\theta)\propto\theta^2/2+\theta^4/4$; dash-dotted line: axion potential with field gradients switched off.

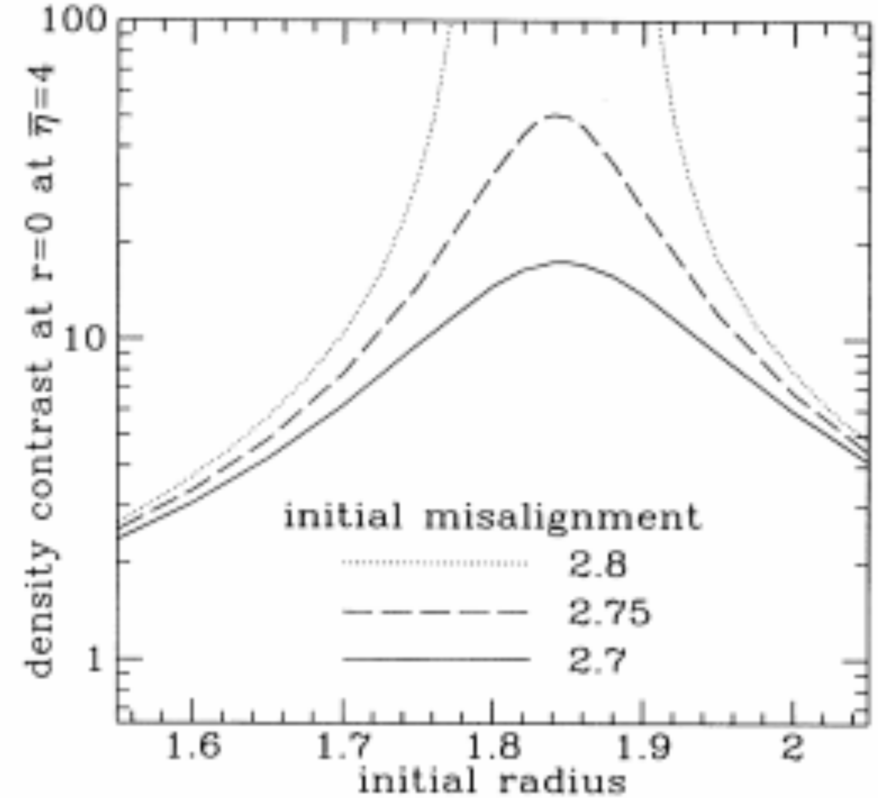


FIG. 3. Dependence of density contrast in the center of a fluctuation at $\bar{\eta}=4$ upon the initial radius of a fluctuation for several values of the initial misalignment angle inside the fluctuation.

[Kolb and Tkachev, PRL 1993]

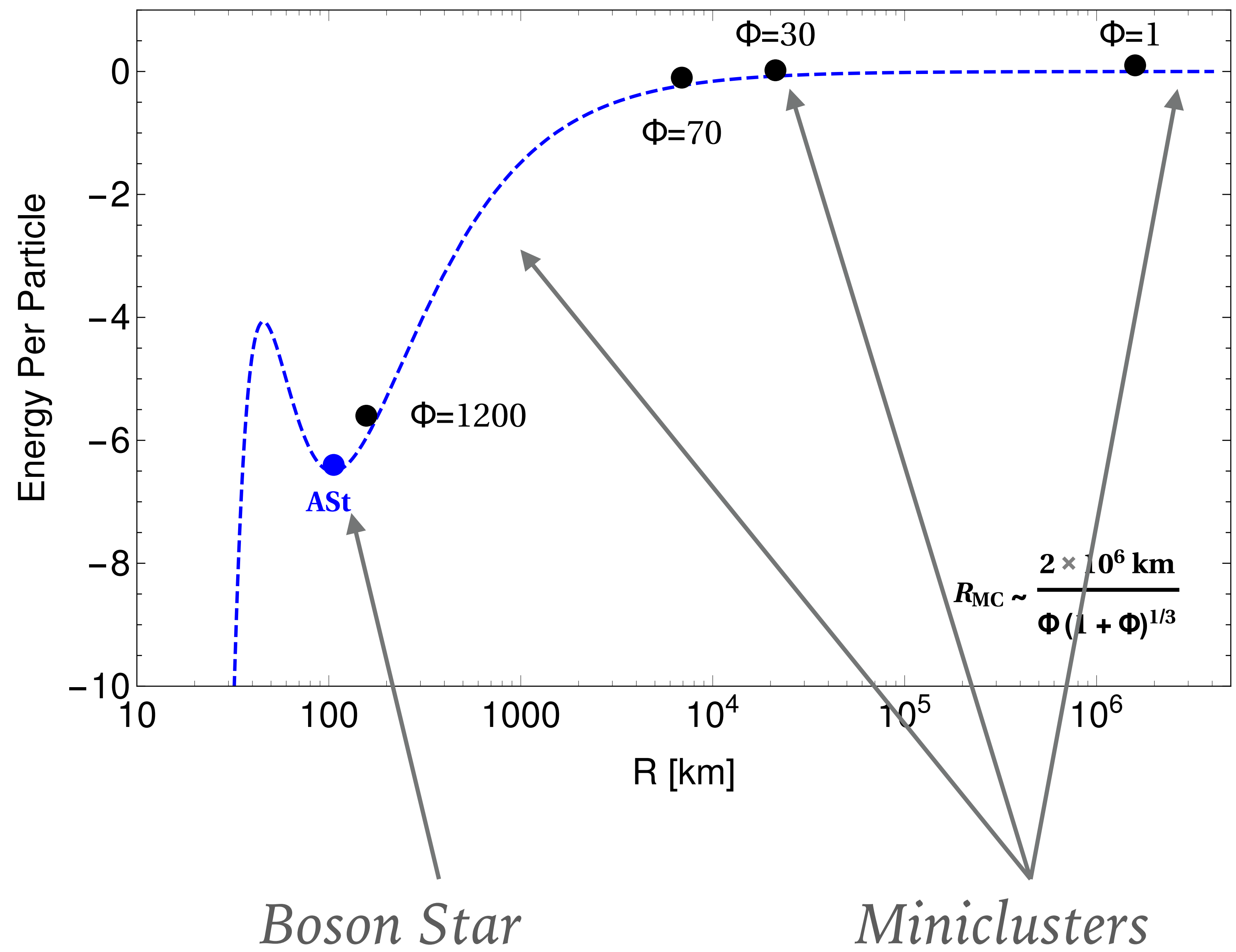
RELAXATION?

- Initial overdensity

$$\rho_{mc,osc} \equiv \delta_0\, \rho_{bg,osc}$$

- Grows with scale factor

$$\rho_{mc} \propto \delta_0^4\, \rho_{bg}$$



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RECENT SIMULATIONS: BOSE STAR FORMATION

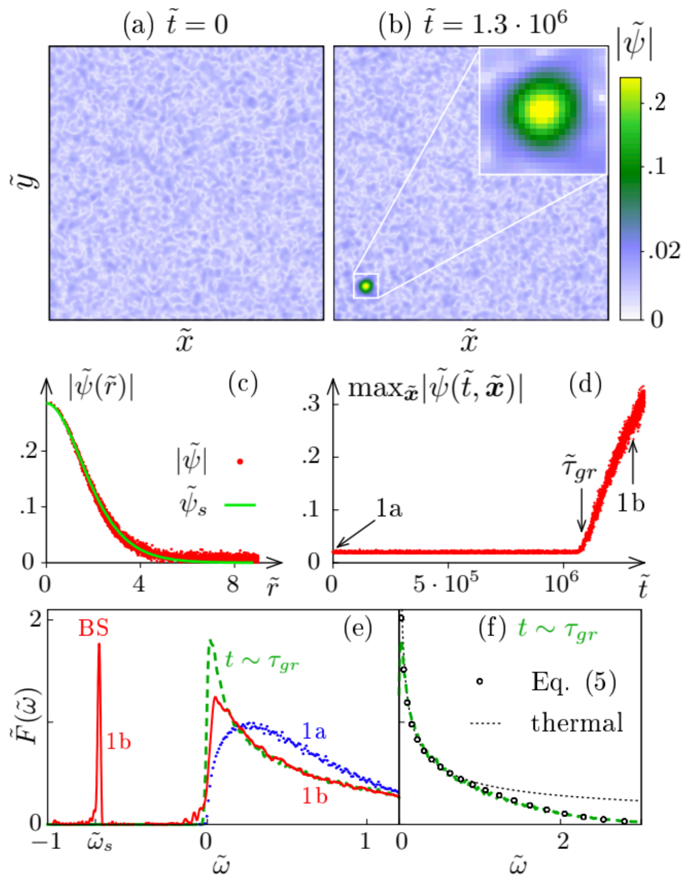


FIG. 1. Formation of Bose star from random field with initial distribution $|\tilde\psi_{\tilde{\boldsymbol p}}|^2 \propto e^{-\tilde{\boldsymbol p}^2}$ and total mass $\tilde N = 50$ in the box $0 \le \tilde x, \tilde y, \tilde z < 125$. These values correspond to the center of the axion minicluster with $M_c \sim 10^{-13} M_\odot$ and $\Phi \sim 2.7$ in Sec. 8. (a), (b) Sections $\tilde z =$ const of the solution $|\tilde\psi(\tilde t, \tilde{\boldsymbol x})|$ at (a) $\tilde t = 0$ and (b) $\tilde t > \tilde\tau_{gr} \approx 1.08 \cdot 10^6$. (c) Radial profile $|\tilde\psi(\tilde r)|$ of the object in Fig. 1b (points) compared to the Bose star $\tilde\psi_s(\tilde r)$ with $\tilde\omega_s \approx -0.7$ (line). (d) Maximum of $|\tilde\psi(\tilde{\boldsymbol x})|$ over the box as a function of time. (e) Spectra (3) at times of Figs. 1a, b and at the eve of Bose star nucleation, $\tilde t = 1.05 \cdot 10^6 \sim \tilde\tau_{gr}$. (f) The spectrum at $t \sim \tau_{gr}$ (dashed line) versus the solution of Eq. (5) (circles) and thermal law $\tilde F \propto \tilde\omega^{-1/2}$ (dots).

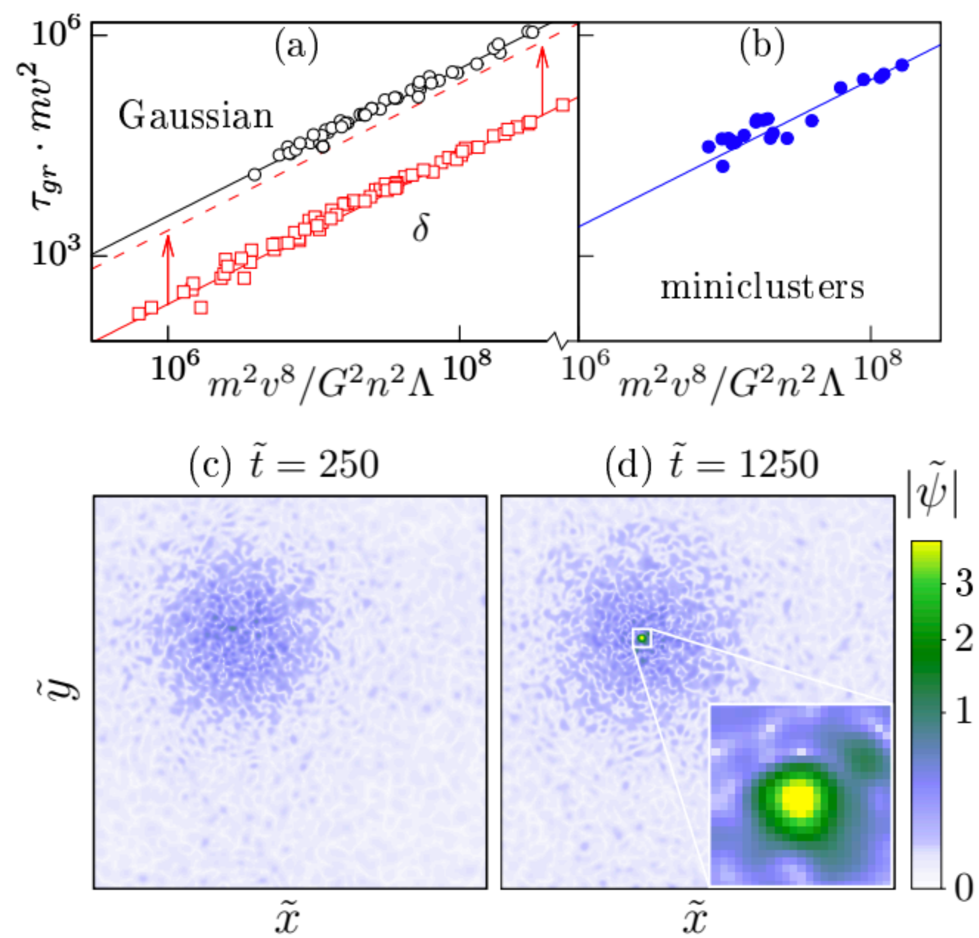


FIG. 2. (a) Time to Bose star formation in the cases of Gaussian (○) and δ-peaked (□) initial distributions. The δ-graphs are shifted downwards ($\tau_{gr} \to \tau_{gr}/10$) for visualization purposes. Lines depict fits by Eq. (4). (b) The same for isolated miniclusters. (c), (d) Slices $\tilde z =$ const of the solution $|\tilde\psi(\tilde t, \tilde{\boldsymbol x})|$ describing formation of a Bose star in the center of a minicluster; $\tilde N = 290$, $\tilde L \approx 63$.

Levkov, Panin, Tkachev (1804.05857)

RECENT SIMULATIONS: MINICLUSTERS

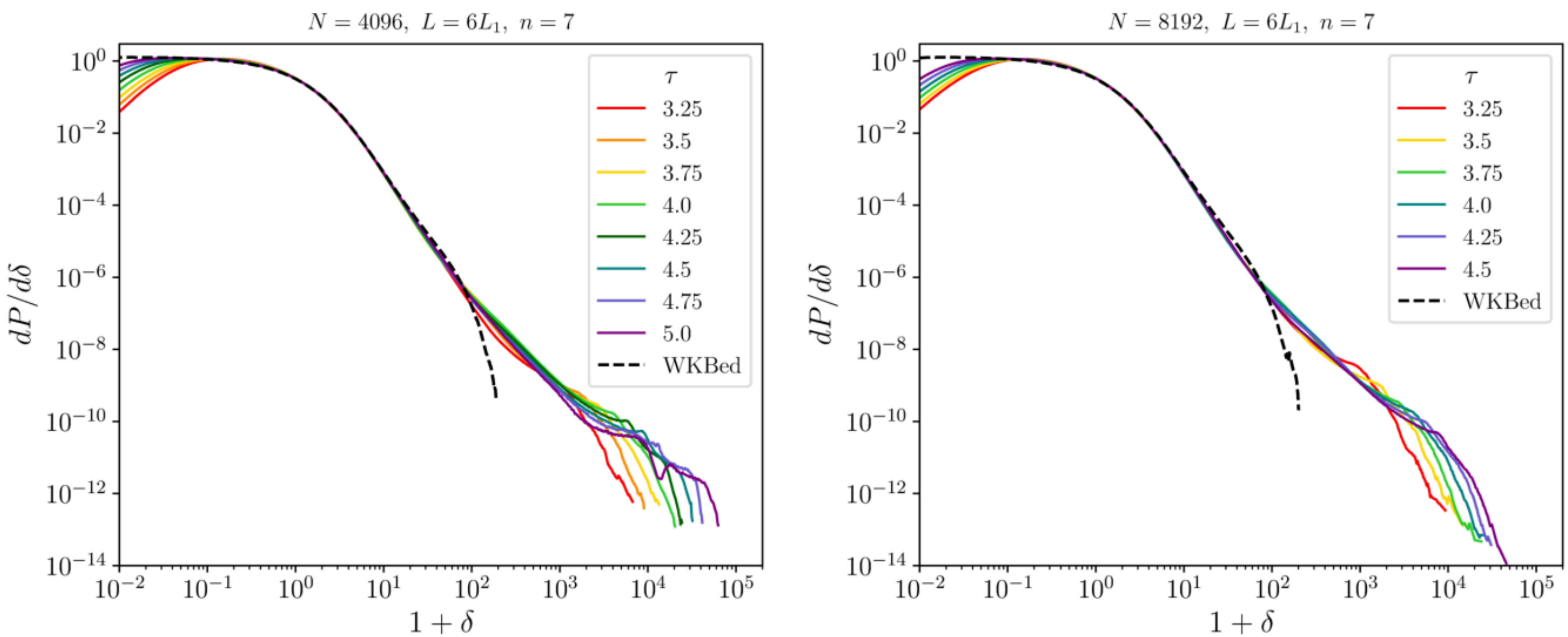
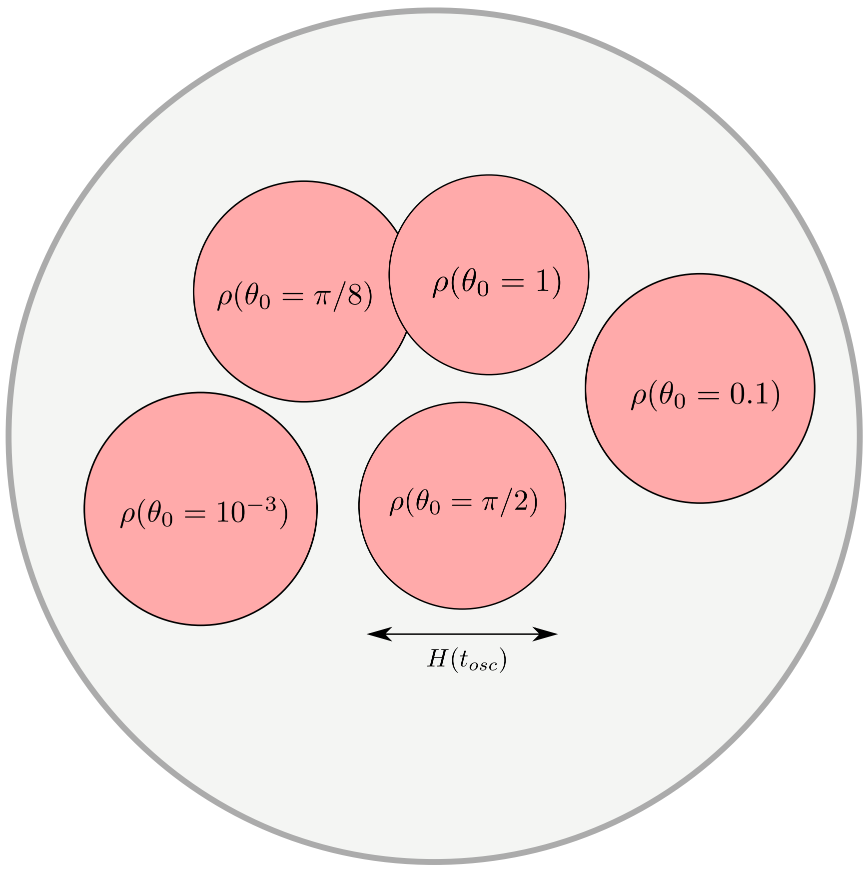


Figure 7: The distribution of overdensities in each point of our simulation grid as a function of conformal time. These results where obtained on grids of length $L = 6L_1$ using $n = 7$ and $N = 4096^3$ (left) or $N = 8192^3$ (right) points. The dashed black line, labelled 'WKBed', is obtaining by free-streaming the axion field at the end of the simulation.

Vaquero, Redondo, Stadler (1809.09241)

FORMATION IN EARLY UNIVERSE (QCD)

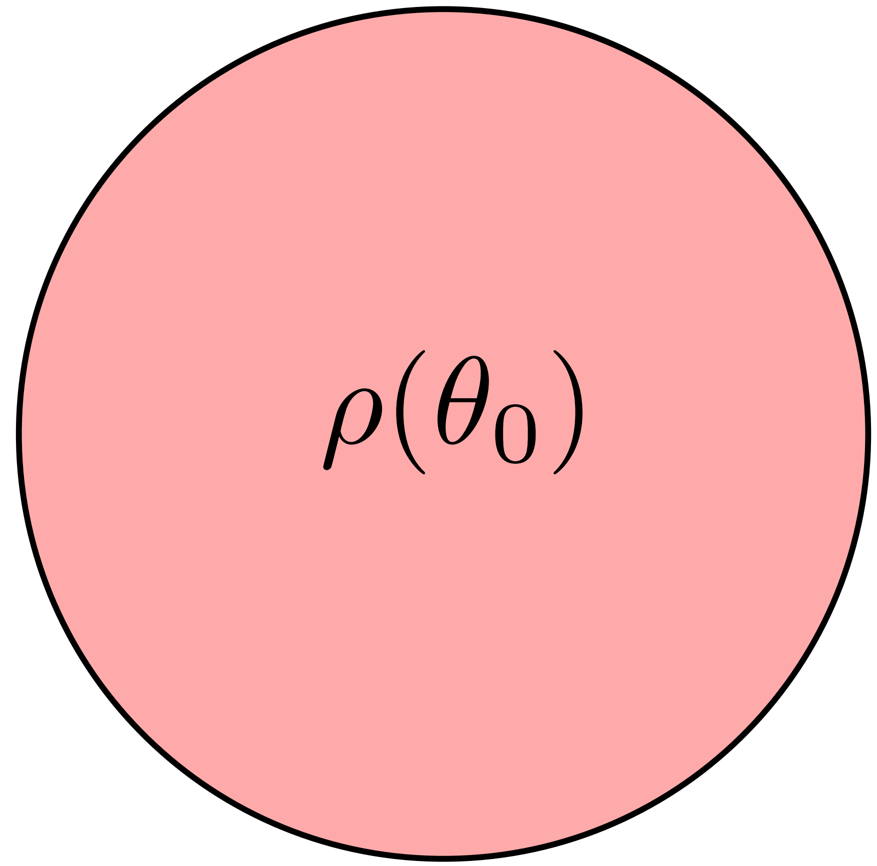
Inflation before PQ breaking



$$\Omega_a \sim \left(\frac{f}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \langle {\theta_0}^2 \rangle$$

Axion Miniclusters

Inflation after PQ breaking



$$\Omega_a \sim \left(\frac{f}{10^{12}\,\mathrm{GeV}}\right)^{7/6} {\theta_0}^2$$

Isocurvature Only

MINICLUSTER MASS SPECTRUM (QCD)

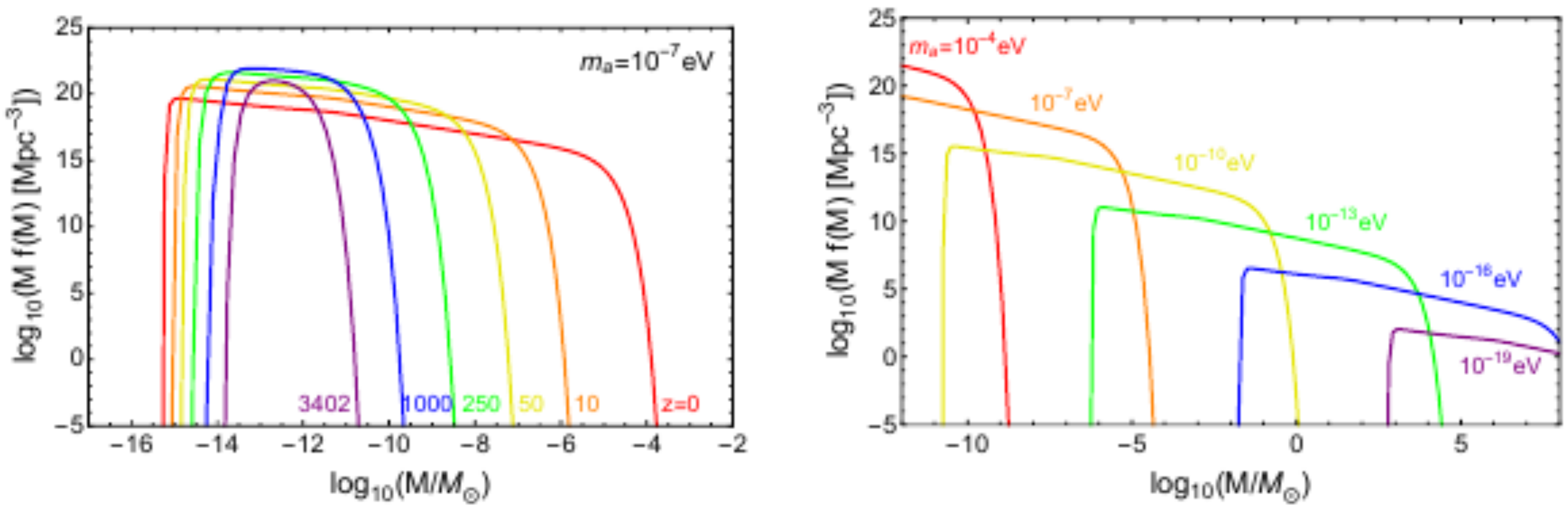


FIG. 5. **The MCH Mass Function:** *Left Panel:* HMF as a function of time for fixed axion mass. The initial miniclusters at M_0 spread over time to form more massive objects due to hierarchical structure formation. Lighter objects are also formed as the late-time Jeans scale cutting off the mass function moves to scales smaller than M_0. *Right Panel:* Minicluster mass function today for various axion masses.

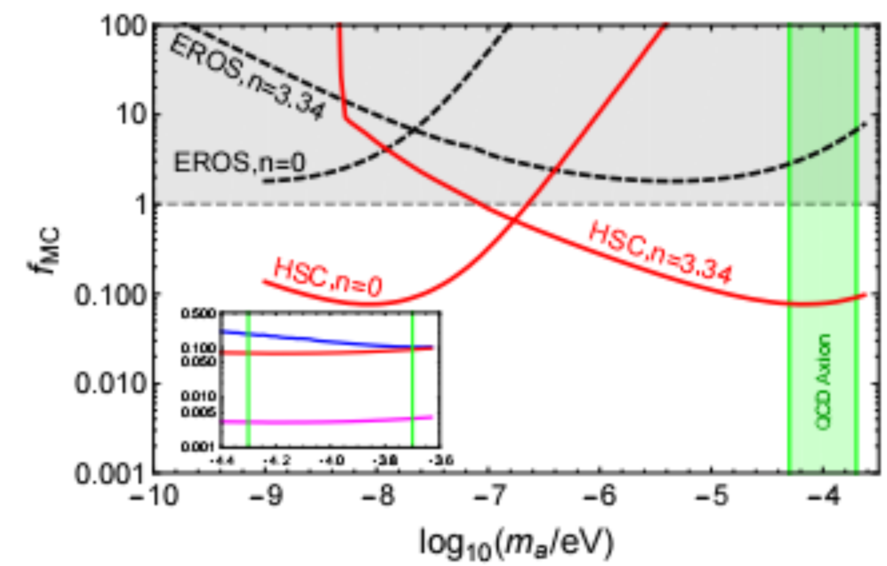
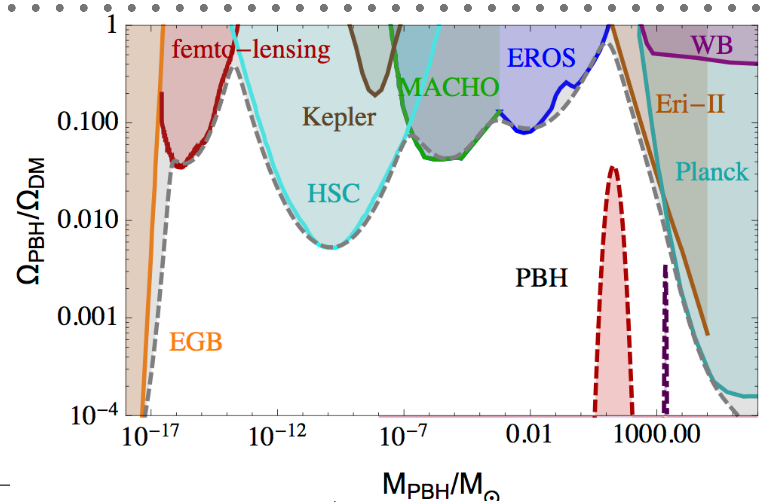


FIG. 16. **Limits on the Fraction of DM collapsed into Miniclusters**: The model adopted is for "isolated miniclusters", which we consider the most realistic. The shaded region shows the allowed mass for the QCD axion with miniclusters. Where the $n = 3.34$ lines intersect this region, $f_{\rm MC}$ is constrained for the QCD axion. The inset shows a zoom-in. The magenta (blue) line in the inset shows a hypothetical improved observation by HSC ten nights with an efficiency $\epsilon \sim 1$ in the case of isolated miniclusters (dense MHCs).

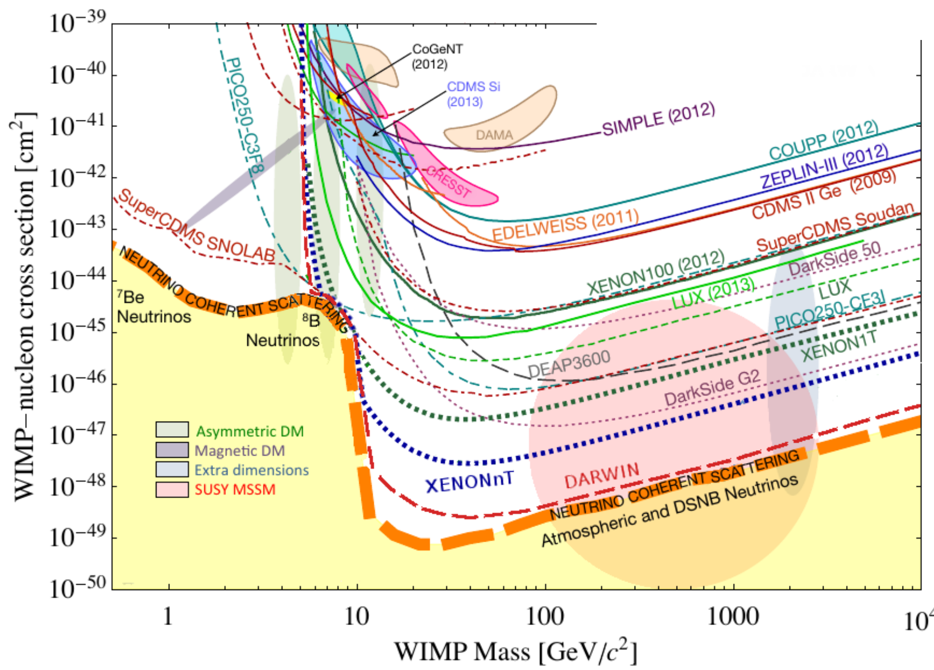
[Fairbairn, Marsh, Quevillion, and Rozier, 1707.03310]

HEAVY DM: A (BIASED) REVIEW



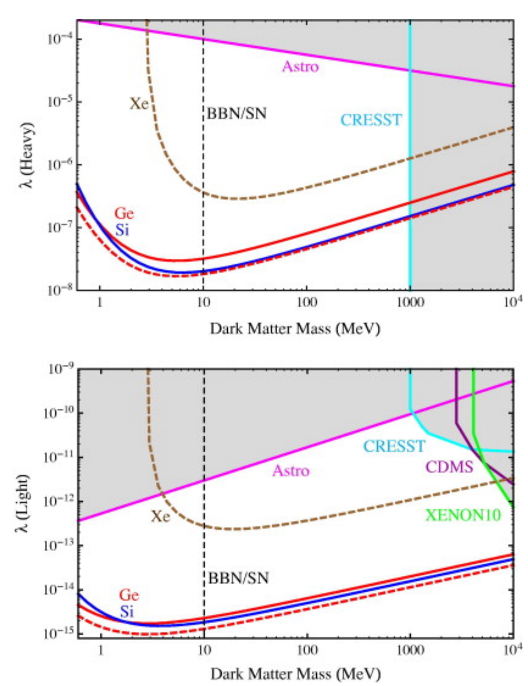
Garcia-Bellido and Clesse

(1710.04694)



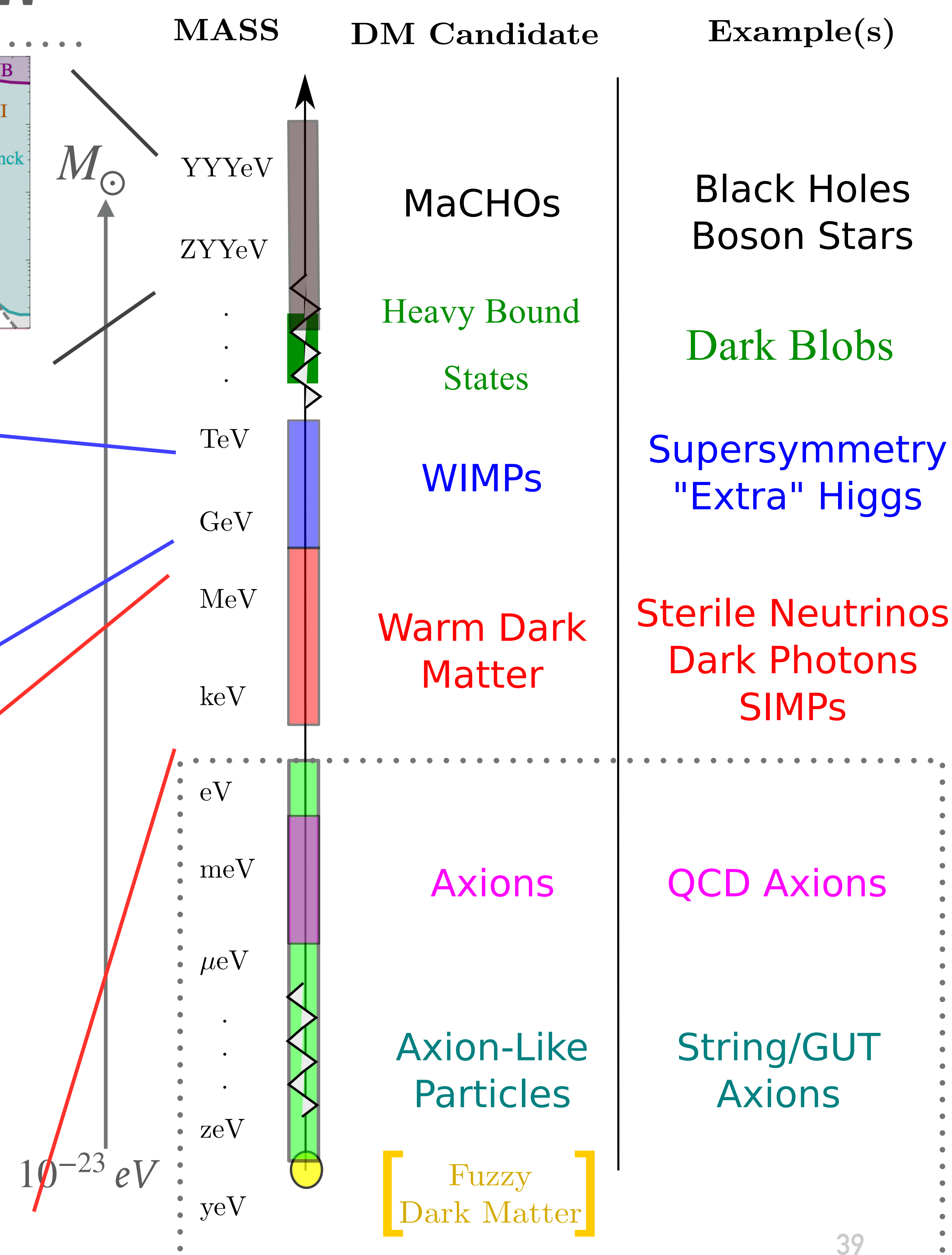
Baundis

(1408.4371)

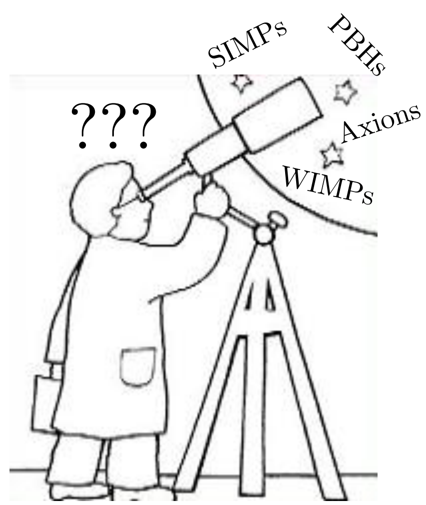


Graham et al.

(1203.2531)



DM CANDIDATES



- *Many, many orders of magnitude in mass*
- *Ideas at every scale*

- *Below here, must be bosonic. Why?*

$$\mathcal{N} \sim \frac{\rho_{local}}{m^4\,\delta v^3} \sim 10^6 \cdot \left(\frac{\rho_{local}}{0.4\ \mathrm{GeV/cm^3}}\right) \cdot \left(\frac{\mathrm{eV}}{m}\right)^4 \cdot \left(\frac{10^{-3}\,c}{\delta v}\right)^3$$

- *Pauli Exclusion precludes* $\mathcal{N} > 1$