

How axions change stars

18th Patras 2023

KONSTANTIN SPRINGMANN

In collaboration with Reuven Balkin (Technion), Javi Serra (IFT Madrid), Stefan Stelzl (EPFL Lausanne), Andreas Weiler (TUM)

Based on arXiv: 2211.02661 and 23xx.xxxxx



July, 2023

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Plan

- White dwarfs simplified
- Axions and their properties at finite density
- Equation of state of free fermi gas with axion
- White dwarfs and the axion
- Conclusions

White Dwarfs Simplified

Fermi pressure from electron gas



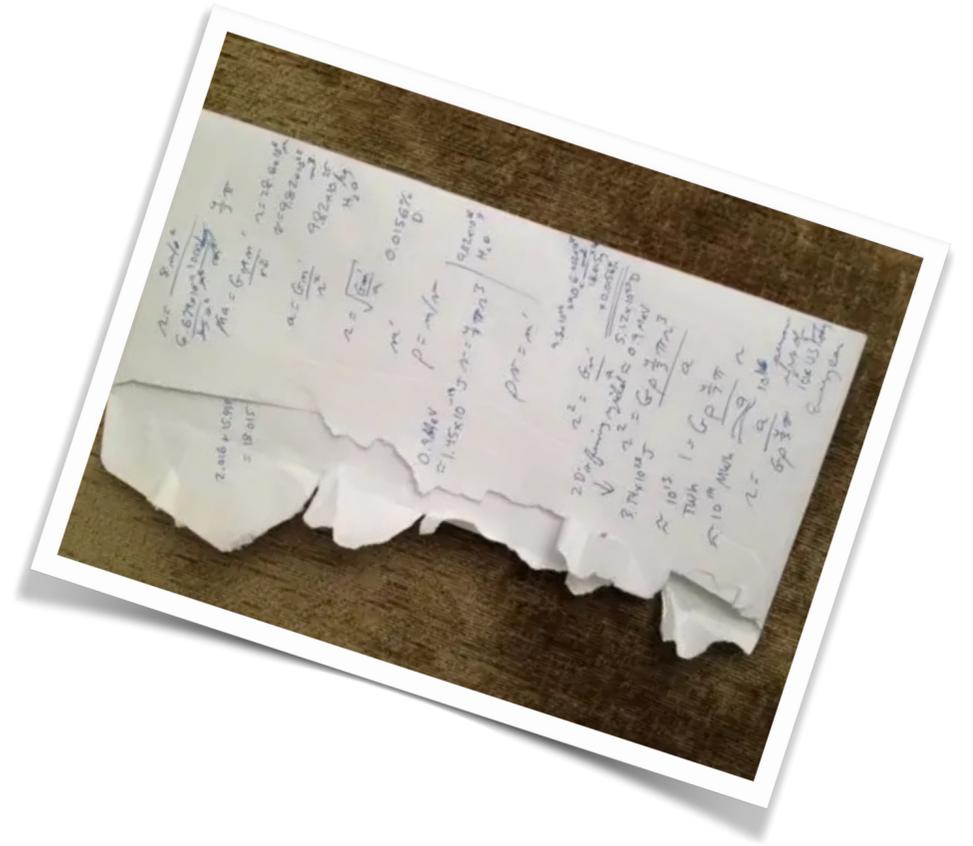
White dwarf simplified

$$E_{\text{Fermi}} \approx E_{\text{Gravity}}$$

$$E_{\text{Fermi}}/N = m_e$$

$$E_{\text{Gravity}} = -\frac{3}{5} \frac{GM_{\text{WD}}^2}{R_{\text{WD}}} \sim \frac{M_{\text{WD}}^2}{M_{\text{planck}}^2 R_{\text{WD}}} \sim \frac{N^2 m_N^2}{M_{\text{planck}}^2 R_{\text{WD}}}$$

$$N \sim R_{\text{WD}}^3 n \sim R_{\text{WD}}^3 m_e^3$$



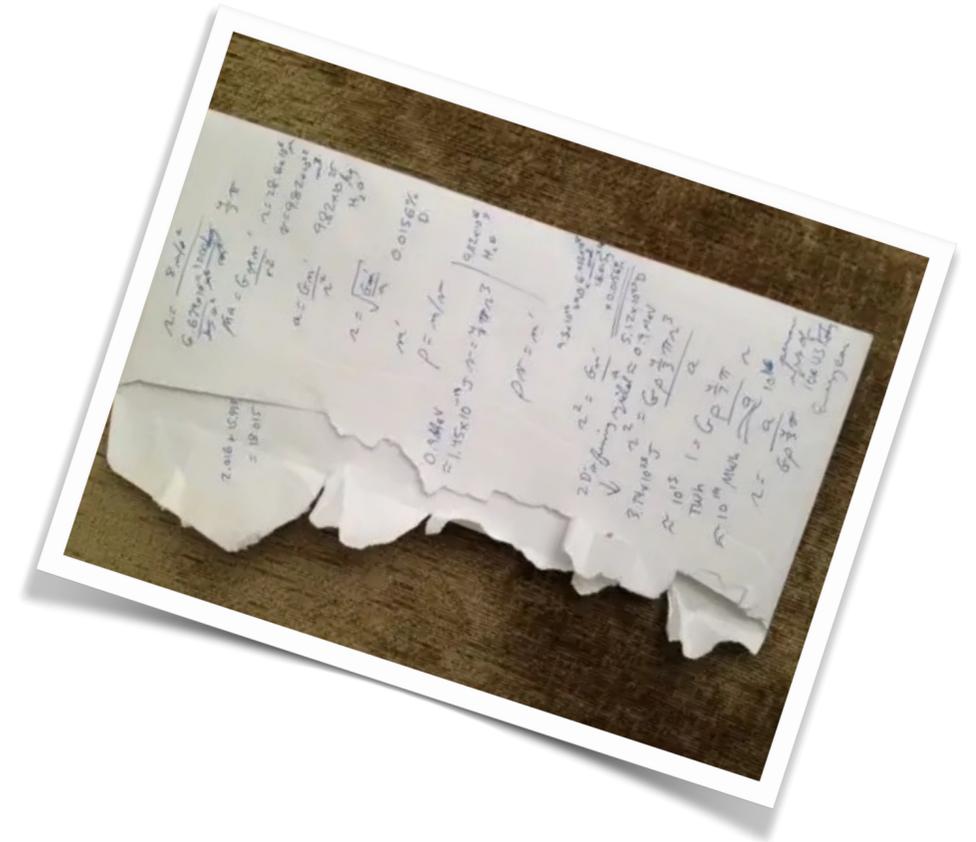
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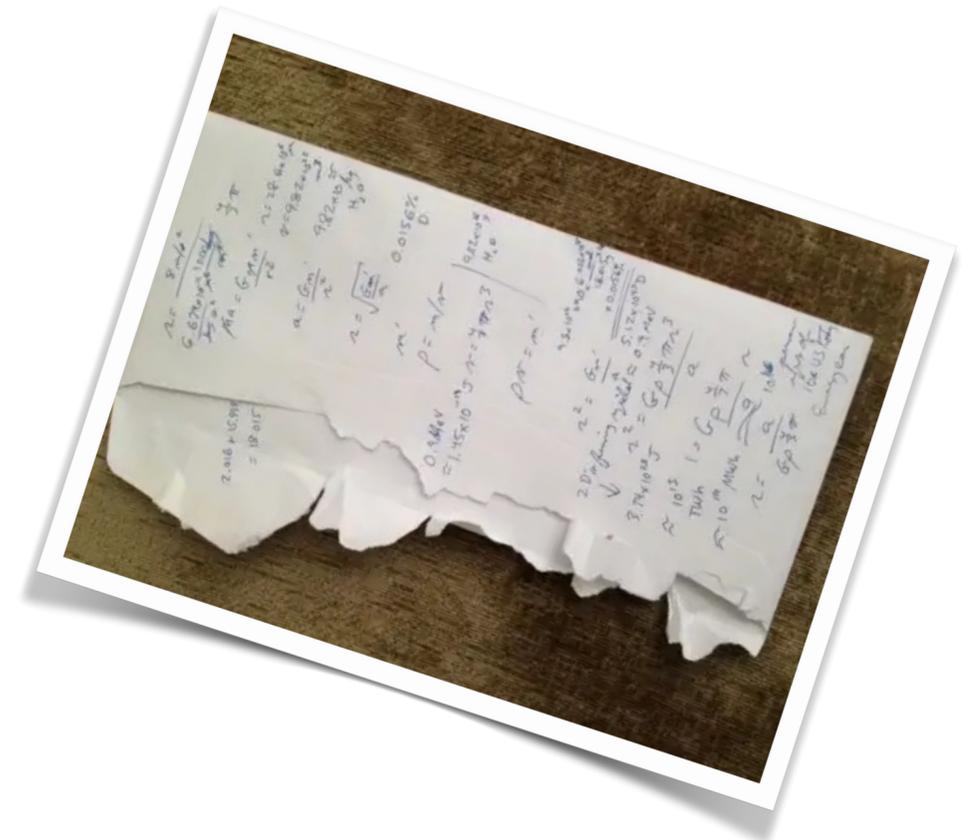
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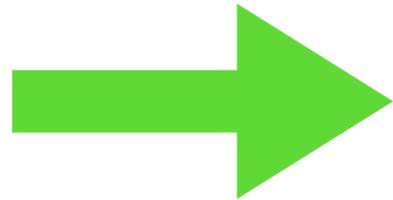
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$$R_{\text{WD}} \sim \frac{M_{\text{planck}}}{m_e m_N}$$

$$M_{\text{WD}} \sim \frac{M_{\text{planck}}^3}{m_N^2}$$



White dwarf estimate



$$R_{\text{WD}} \sim \frac{M_{\text{planck}}}{m_e m_N} \sim \frac{m_N}{m_e} R_{\text{NS}}$$

$$M_{\text{WD}} \sim \frac{M_{\text{planck}}^3}{m_N^2}$$

$$M_{\text{WD}} \sim (\text{few}) 10^{30} \text{ kg} \sim M_{\odot}$$

$$R_{\text{WD}} \sim (\text{few}) 10000 \text{ km}$$

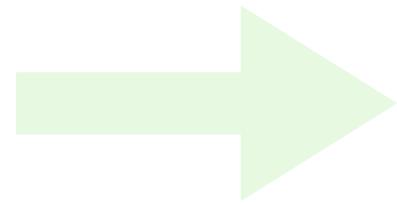
Mass of the sun at the size of the earth!

electron mass $m_e \simeq 0.5 \text{ MeV}$

Planck scale $M_{\text{Planck}} \simeq 10^{19} \text{ GeV}$

nucleon mass $m_N \simeq 1 \text{ GeV}$

White dwarf estimate



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Let's compare to data!

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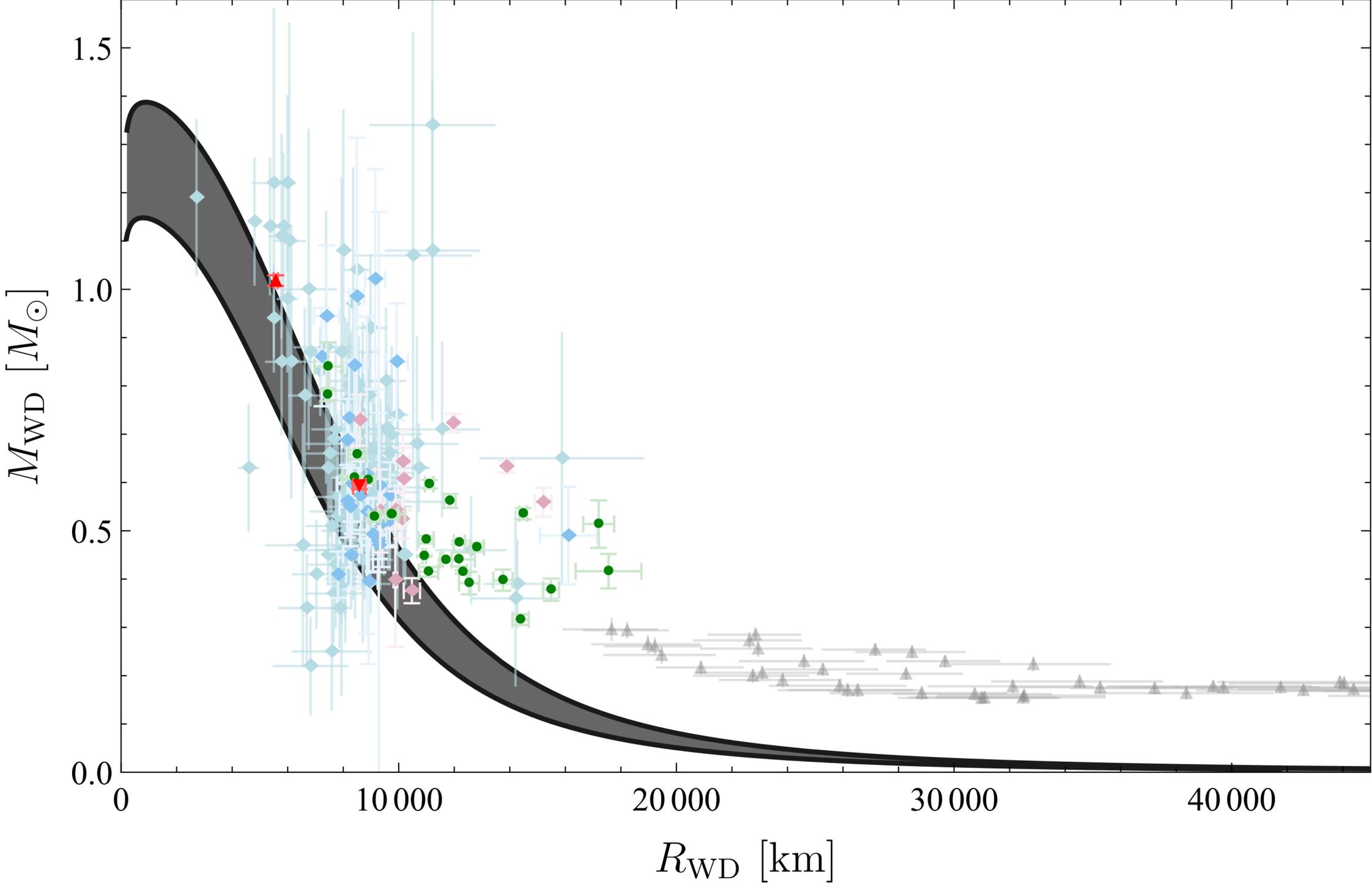
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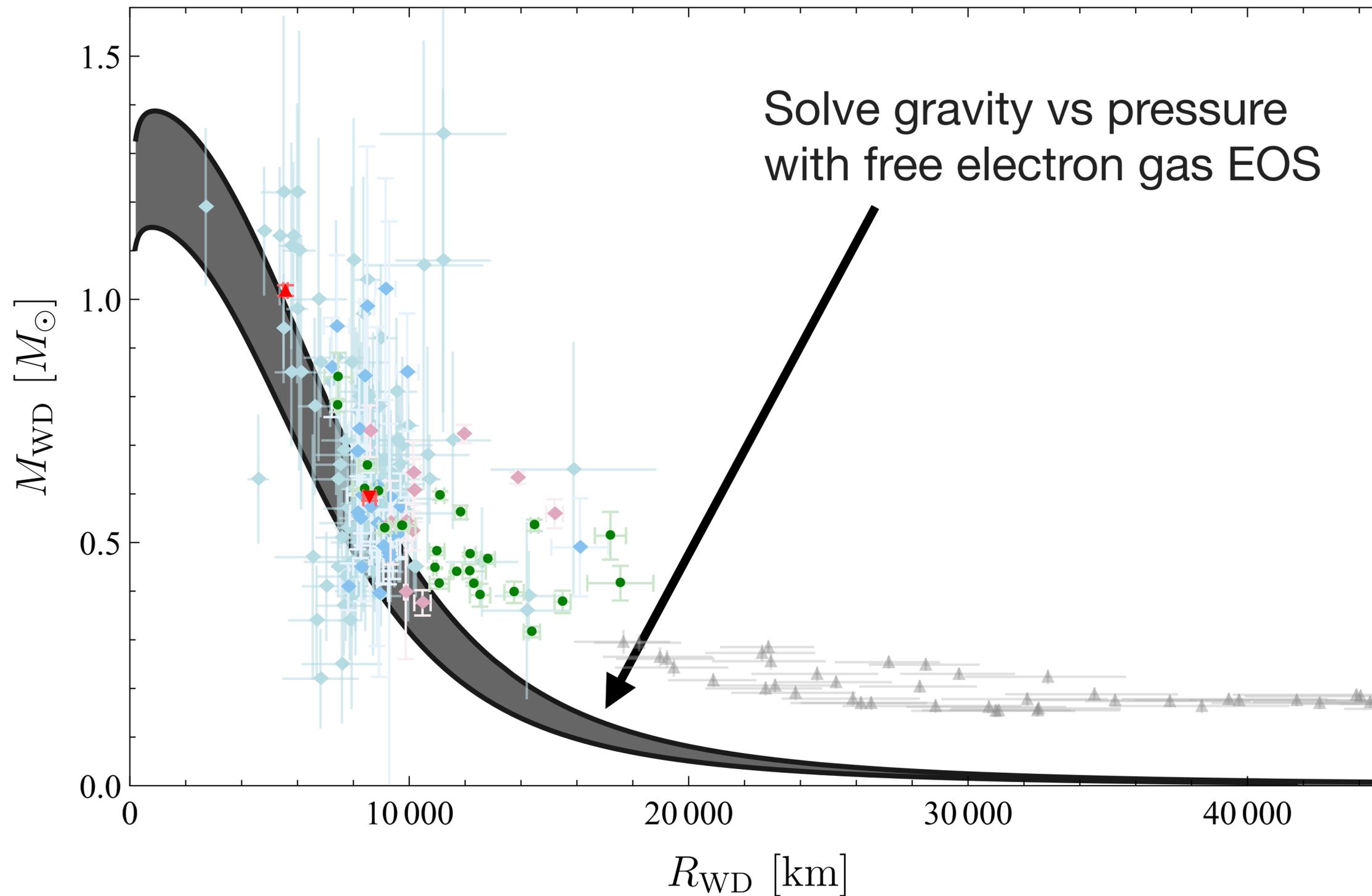
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White dwarf mass-radius curve



White dwarf mass-radius curve



**So let's use these very dense objects
to probe BSM physics**

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to probe BSM physics**

Focus on axion gluon coupling

$$\frac{g_s^2}{32\pi^2} \frac{\phi}{f} G\tilde{G}$$

The QCD Axion: At low energies

Non-perturbative effects generate potential Λ_{QCD}

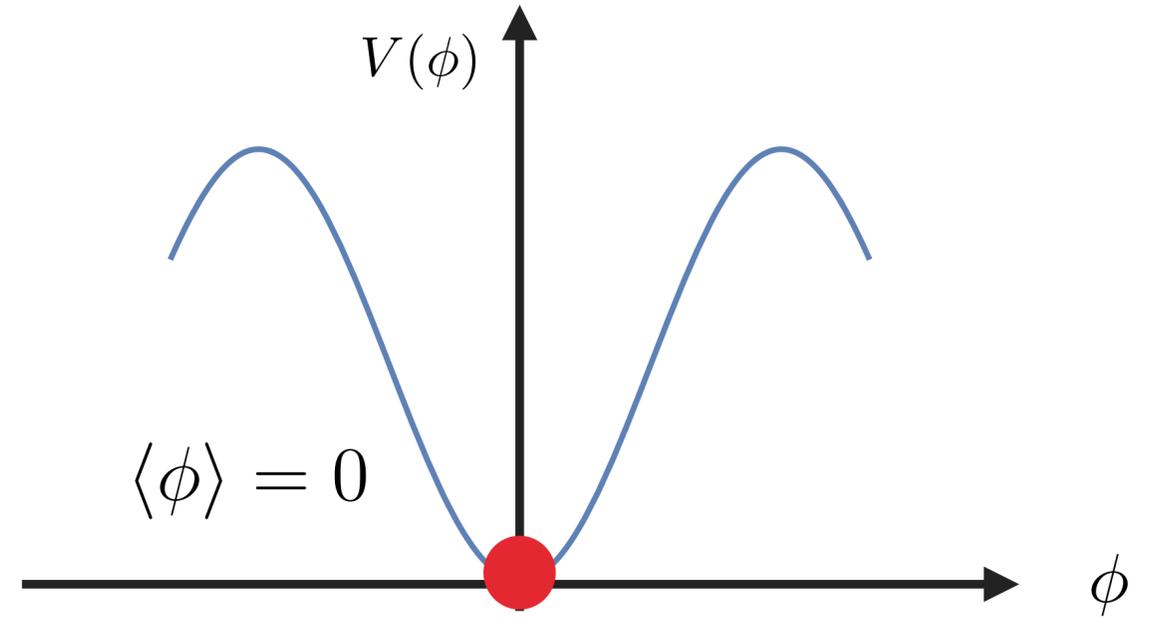
$$\frac{g_s^2}{32\pi^2} \frac{\phi}{f} G\tilde{G}$$

UV



IR

$$V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4} \left[\cos\left(\frac{\phi}{f}\right) - 1 \right]$$



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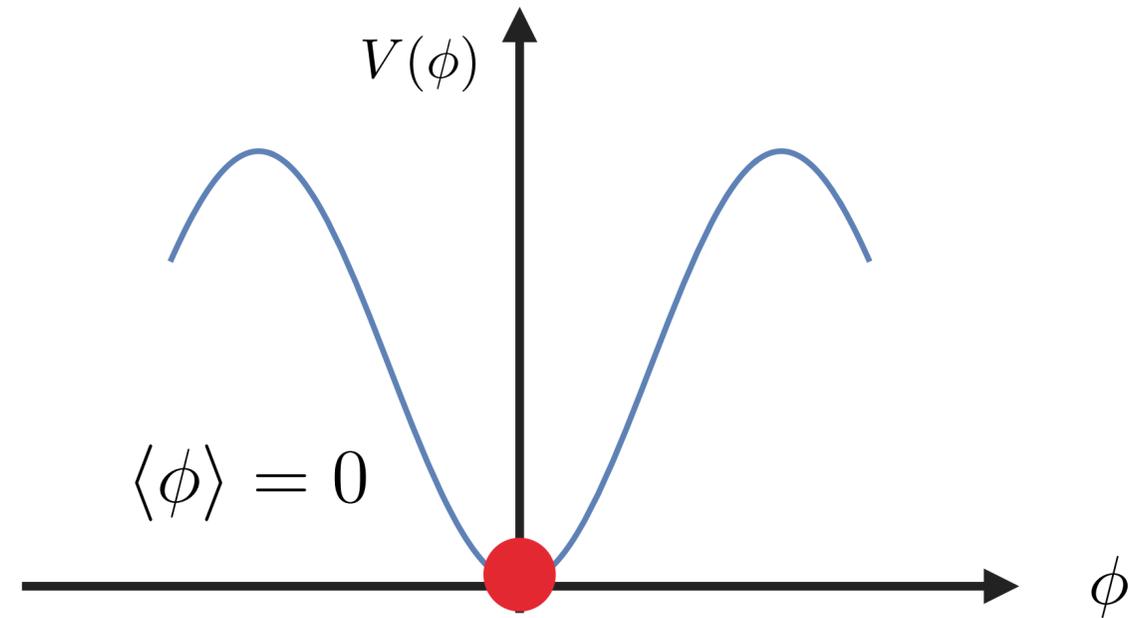
$$V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4} \left[\cos\left(\frac{\phi}{f}\right) - 1 \right]$$

$$m_\phi \sim \frac{m_\pi f_\pi}{f}$$

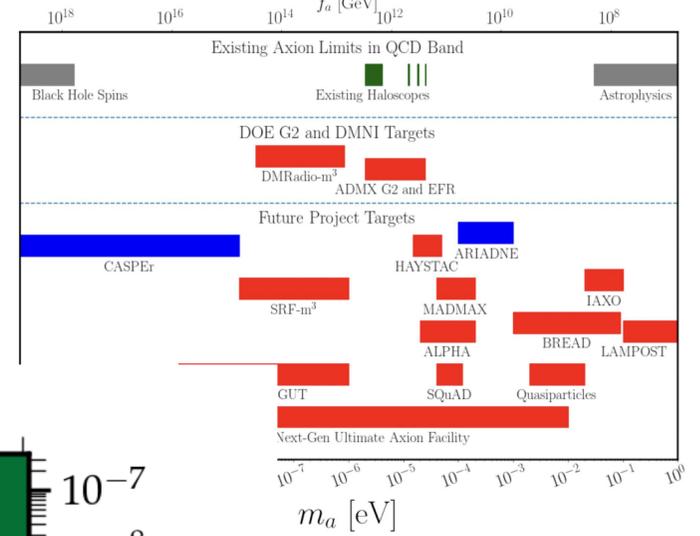
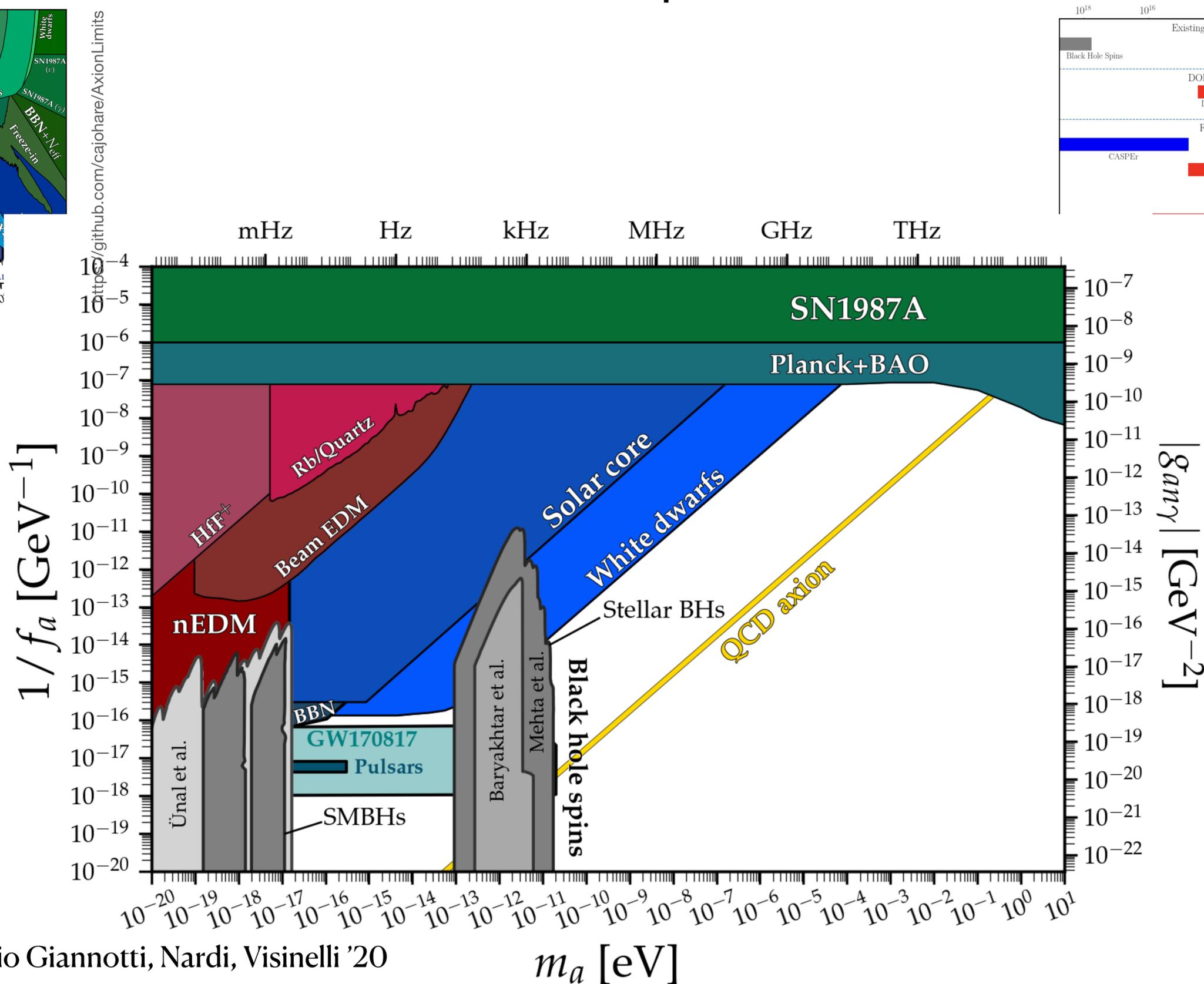
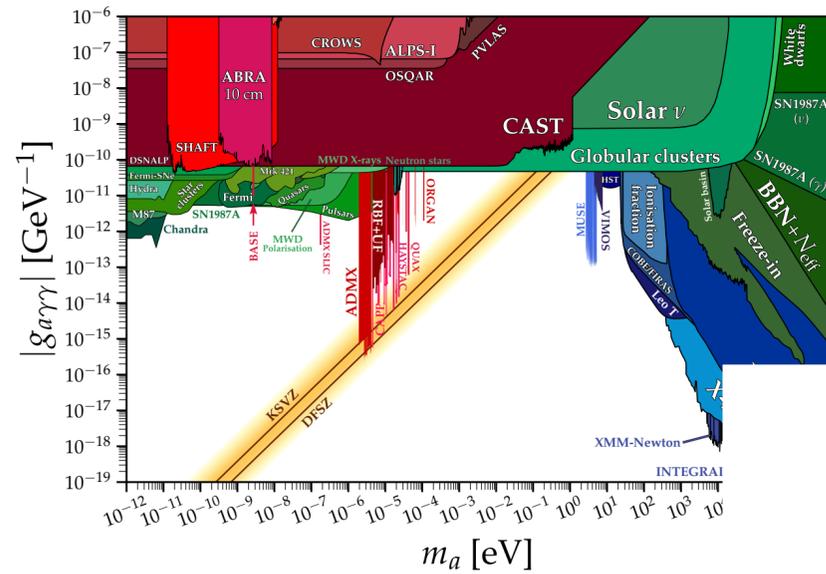
The QCD axion is very **predictive**

Couplings to nucleons, photons, electrons,...

Determined by the scale f



The QCD Axion: Plethora of experimental searches

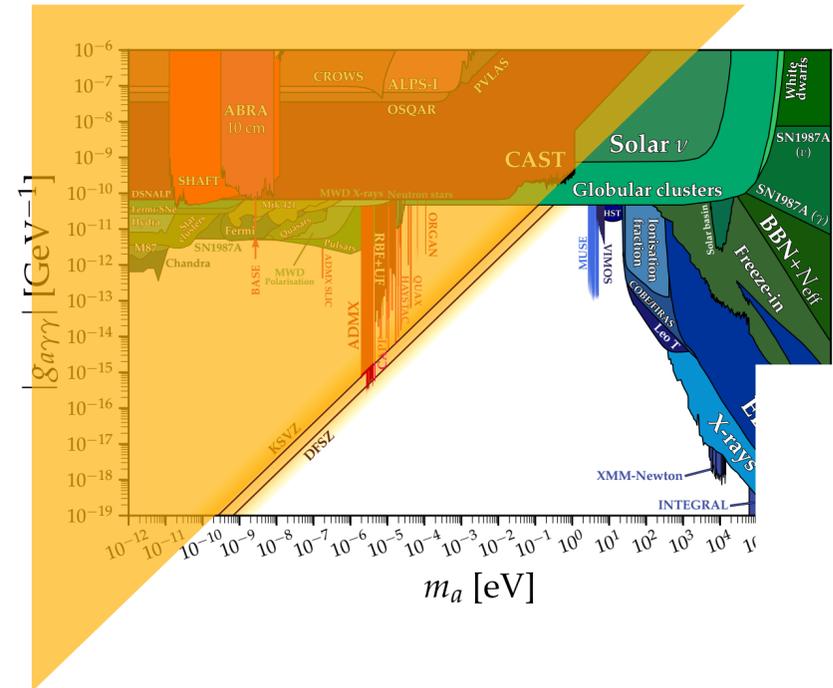


<https://github.com/cajohare/AxionLimits>

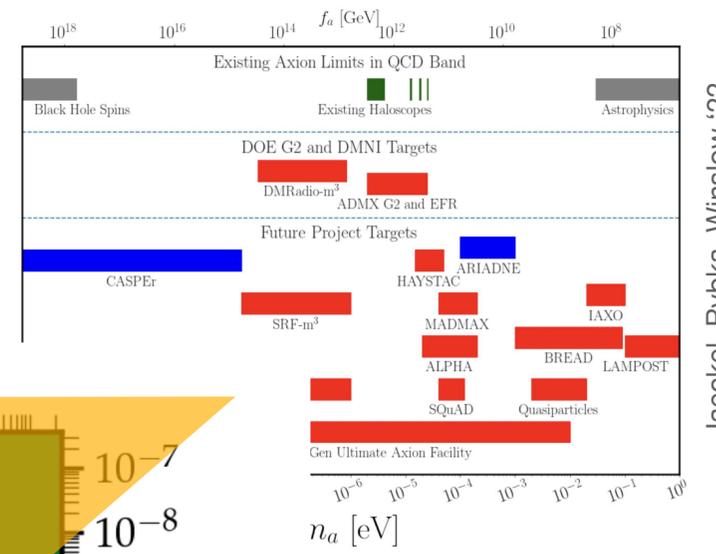
Jaeckel, Rybka, Winstlow '22

See e.g. G. Raffelt '06 and Di Luzio Giannotti, Nardi, Visinelli '20

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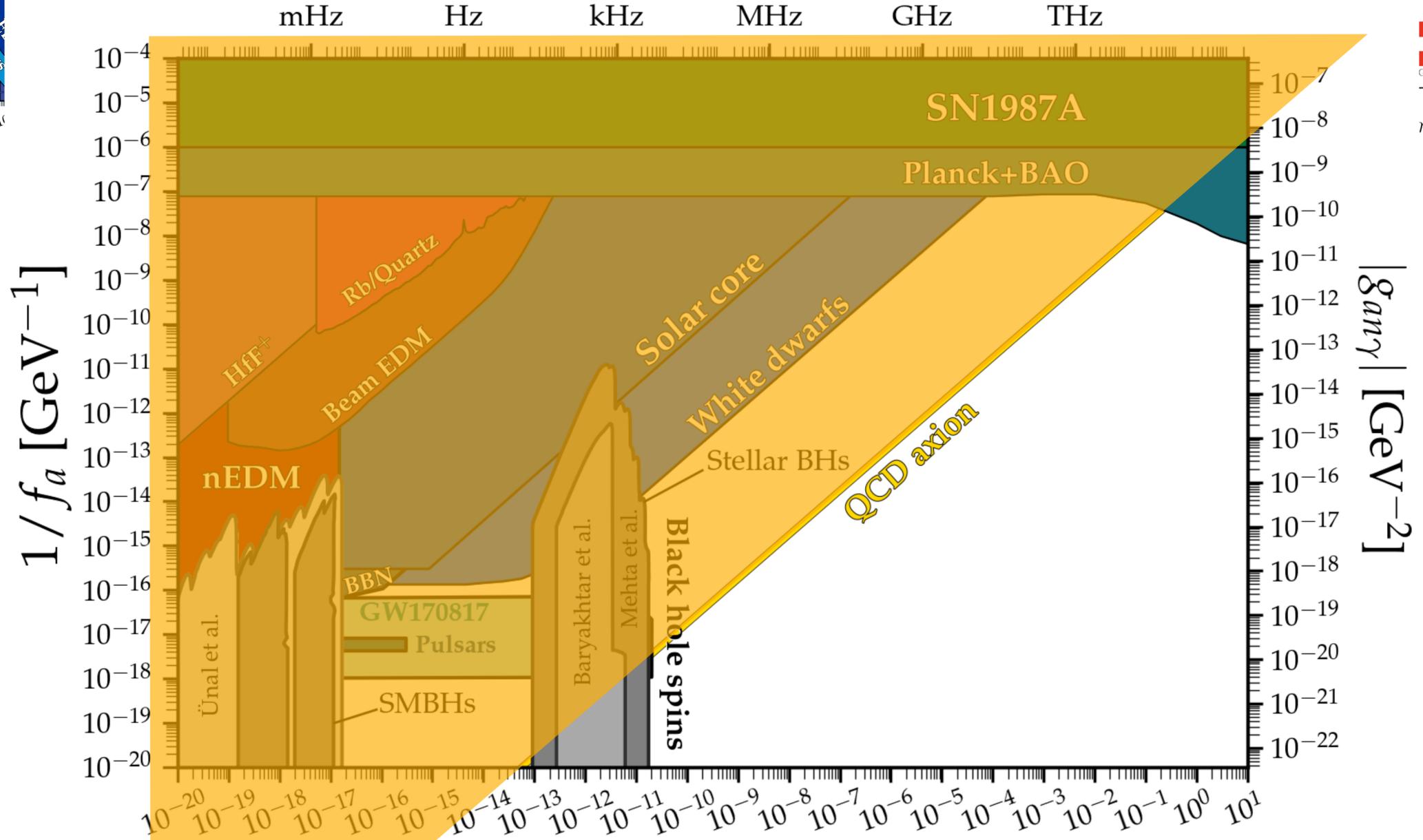


om/cajohare/AxionLimits



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Interesting region



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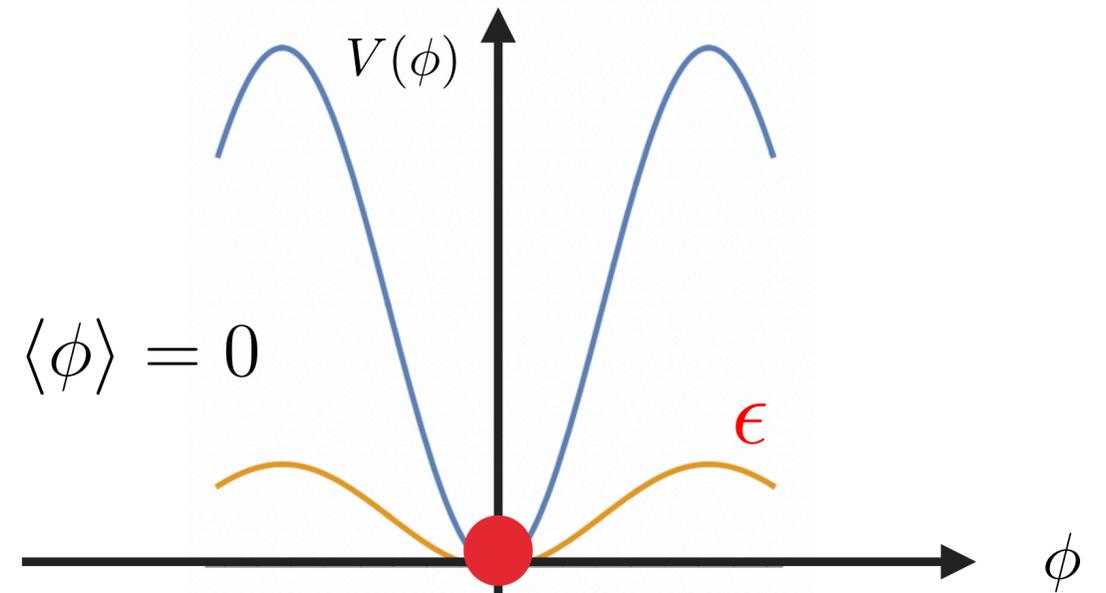
m_a [eV]

Light QCD Axions

Non-perturbative effects generate potential

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$$V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4} \left[\cos\left(\frac{\phi}{f}\right) - 1 \right]$$



... with smaller mass

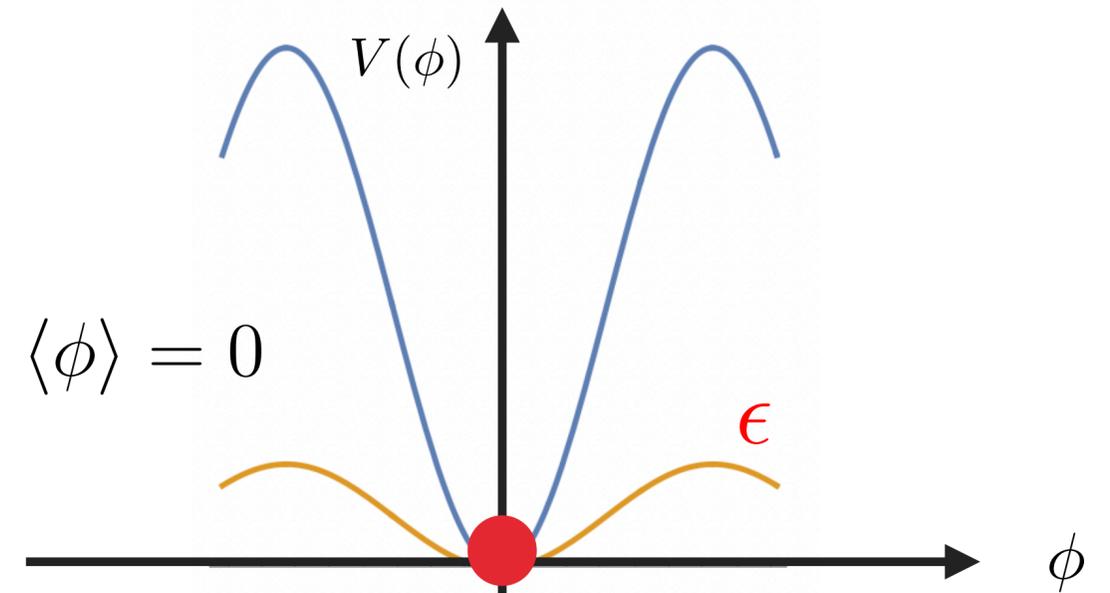
$$V(\phi) \simeq -\frac{\epsilon m_\pi^2 f_\pi^2}{4} \left[\cos\left(\frac{\phi}{f}\right) - 1 \right]$$

For symmetry based realizations, see (Hook, Huang '17, Hook '18, Di Luzio, Gavela, Quilez, Ringwald '21)

Light QCD Axions

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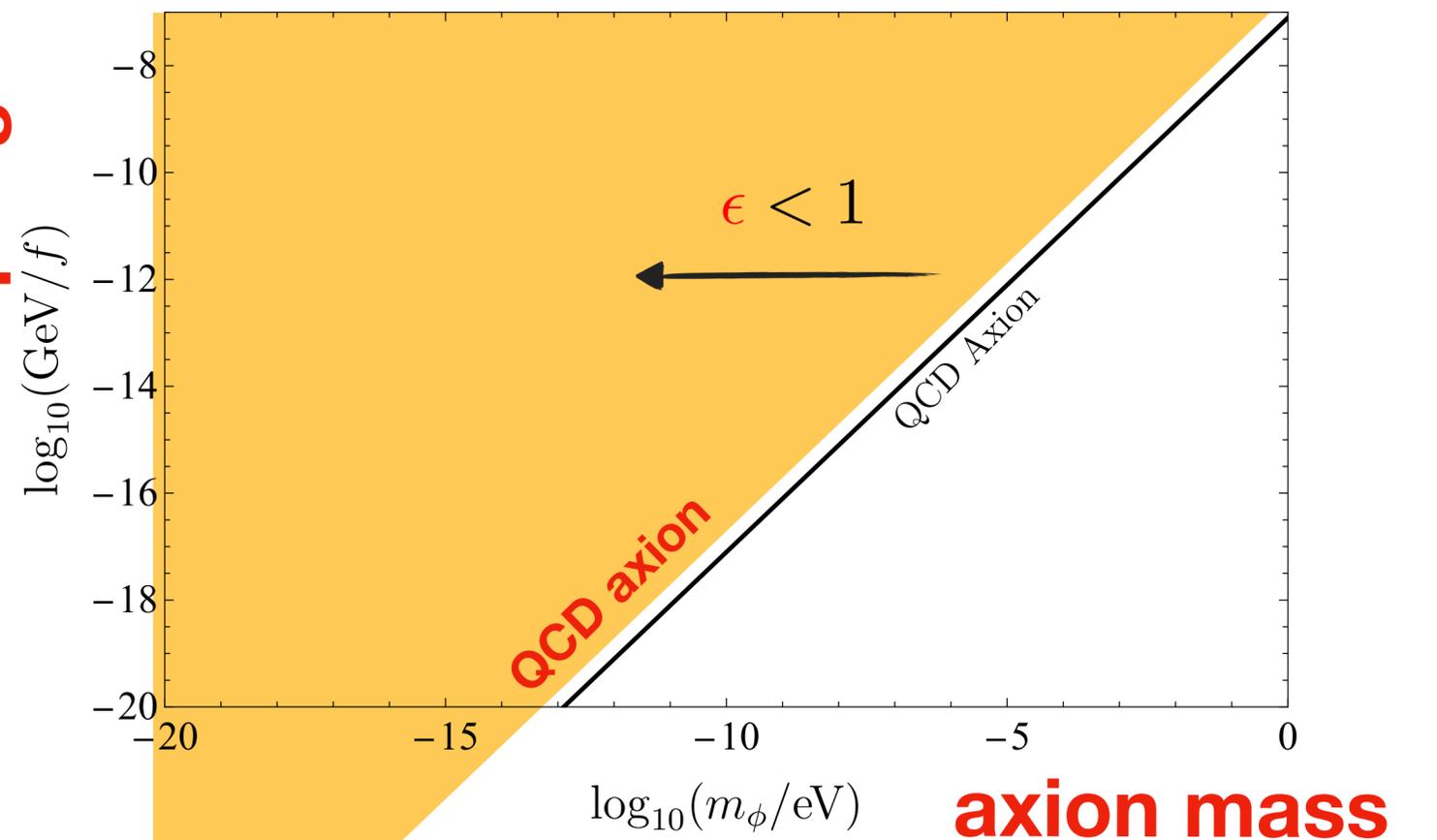


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axion coupling



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QCD Axion: Coupling to nucleons

Nuclear Chiral Perturbation Theory with QCD axion

$$\mathcal{L}_{\chi\text{PT}} \supset \frac{\sigma_{\pi N}}{2m_N} \text{Tr} \left[U M_q e^{i\phi/f} + \text{h.c.} \right] \bar{N} N + \dots$$

$$U = e^{i\pi/f_\pi}$$

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Leads to **non-derivative coupling to nucleons**:

$$\mathcal{L} \supset -m_N(\phi) \bar{N} N \quad \text{with} \quad m_N(\phi) \equiv m_N \left[1 + \frac{\sigma_{\pi N}}{2m_N} \left(\cos \frac{\phi}{f} - 1 \right) \right]$$

such that $m_N(0) = m_N$, $\sigma_{\pi N} \simeq 50 \text{ MeV}$

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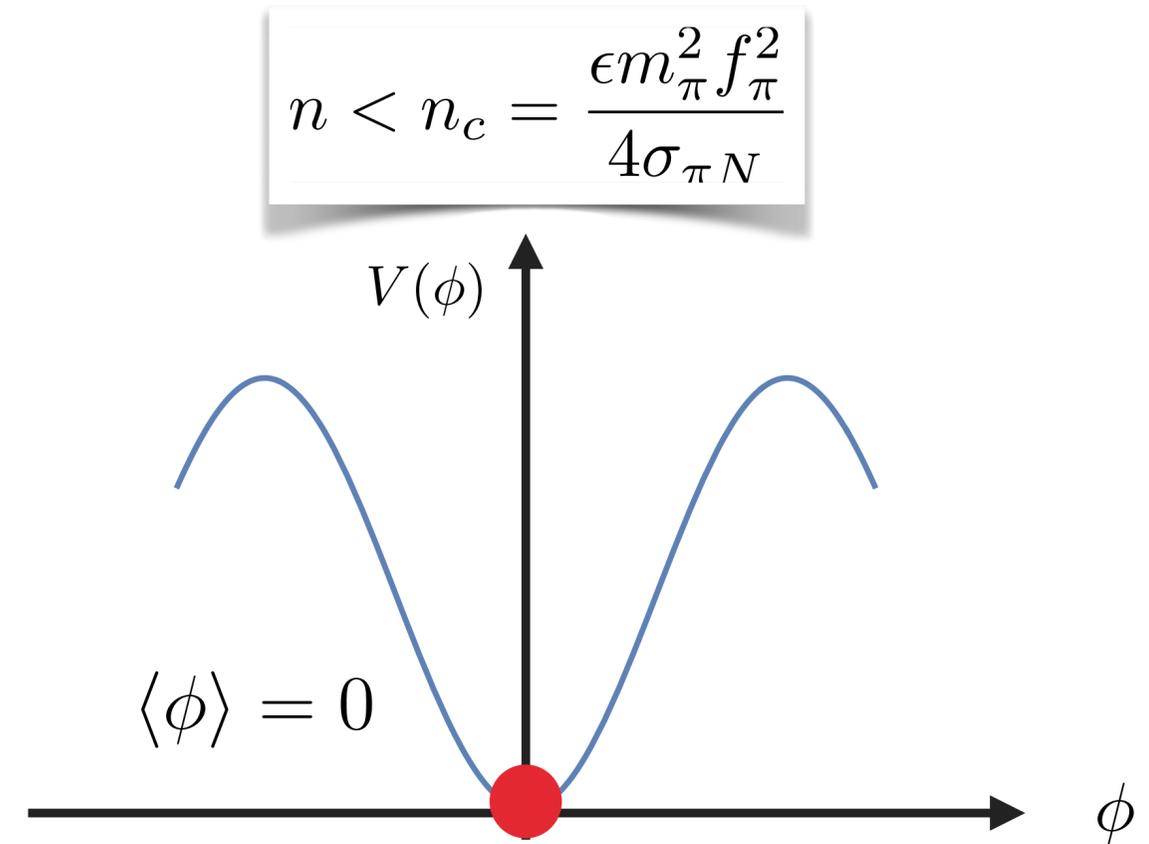
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Light QCD axions have the same coupling to SM matter

Light QCD Axion: at Finite Density

Turn on baryon density background $\langle \bar{N}N \rangle = n$

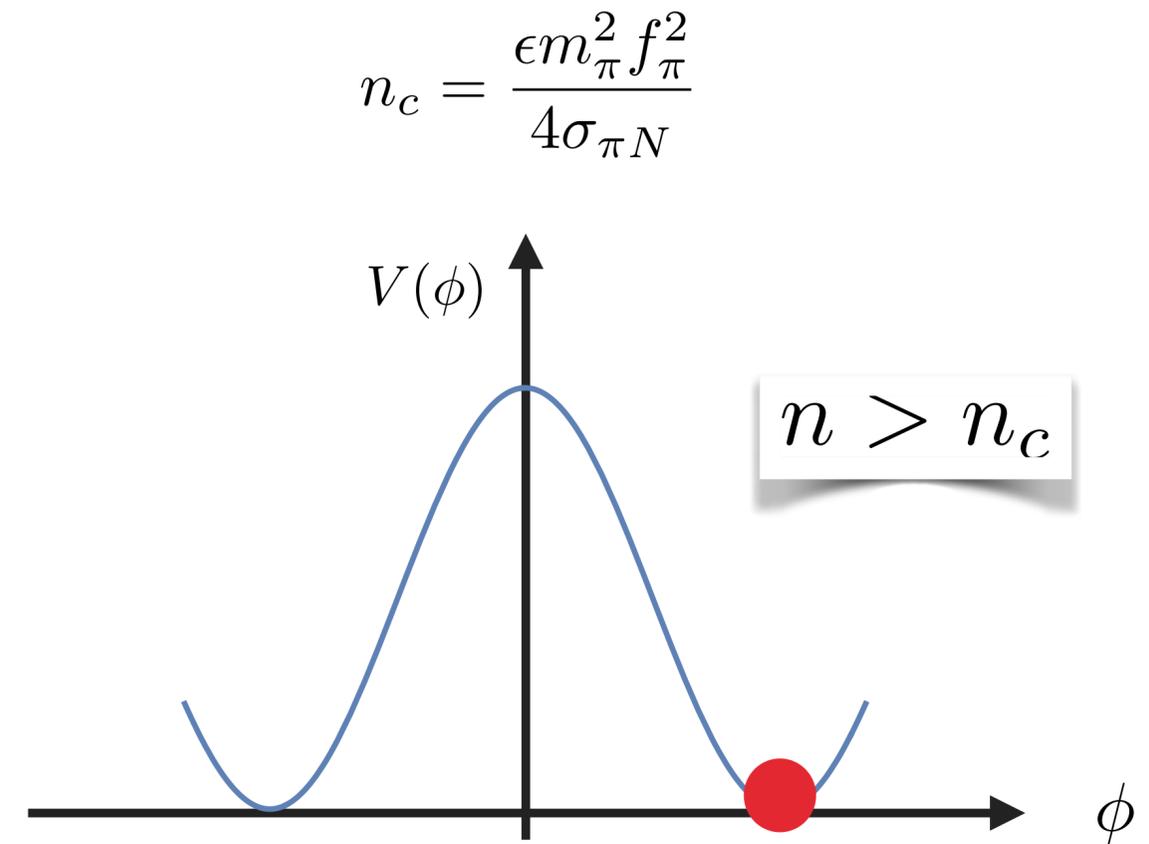
$$V(\phi) \simeq - \left[\frac{\epsilon m_\pi^2 f_\pi^2}{4} - \sigma_{\pi N} n \right] \left(\cos \frac{\phi}{f} - 1 \right)$$



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At **critical density** $n > n_c$:

new minima appear at $\langle \phi \rangle = \pi f$

Exciting effects appear once $\phi(x)$ develops a non-trivial profile

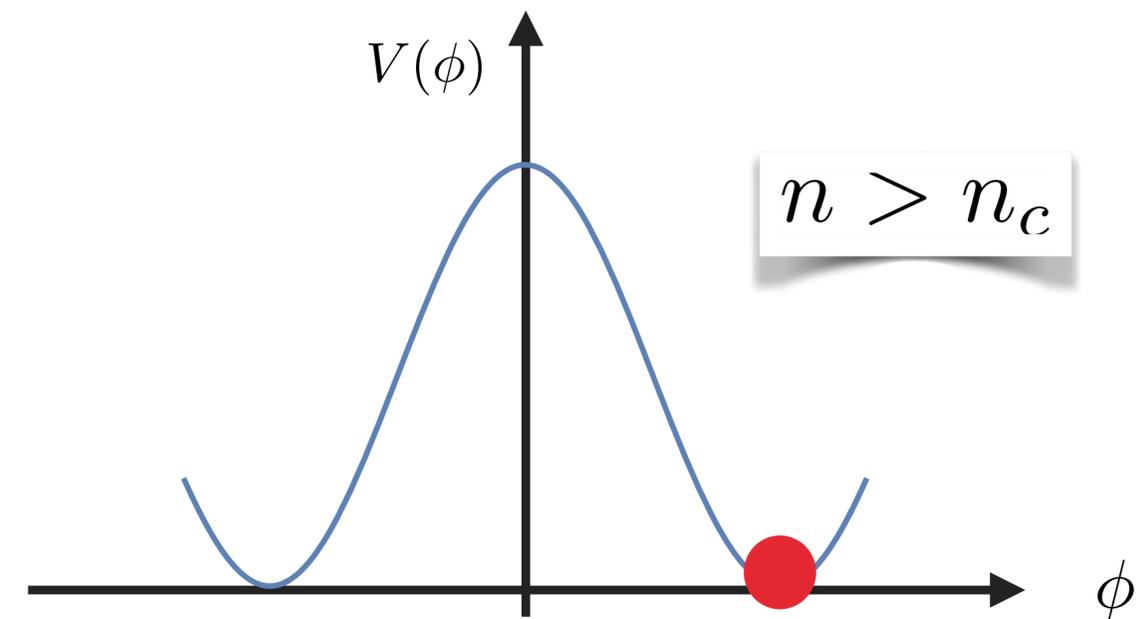
Light QCD Axion: at Finite Density

1) Nucleon mass is reduced once the axion is at $\langle \phi \rangle = \pi f$

$$m_N(\phi) \equiv m_N \left[1 + \frac{\sigma_{\pi N}}{2m_N} \left(\cos \frac{\phi}{f} - 1 \right) \right]$$

$$m_N(\pi f) \simeq m_N - \sigma_{\pi N}$$

$$n_c = \frac{\epsilon m_\pi^2 f_\pi^2}{4\sigma_{\pi N}}$$



Light QCD Axion: at Finite Density

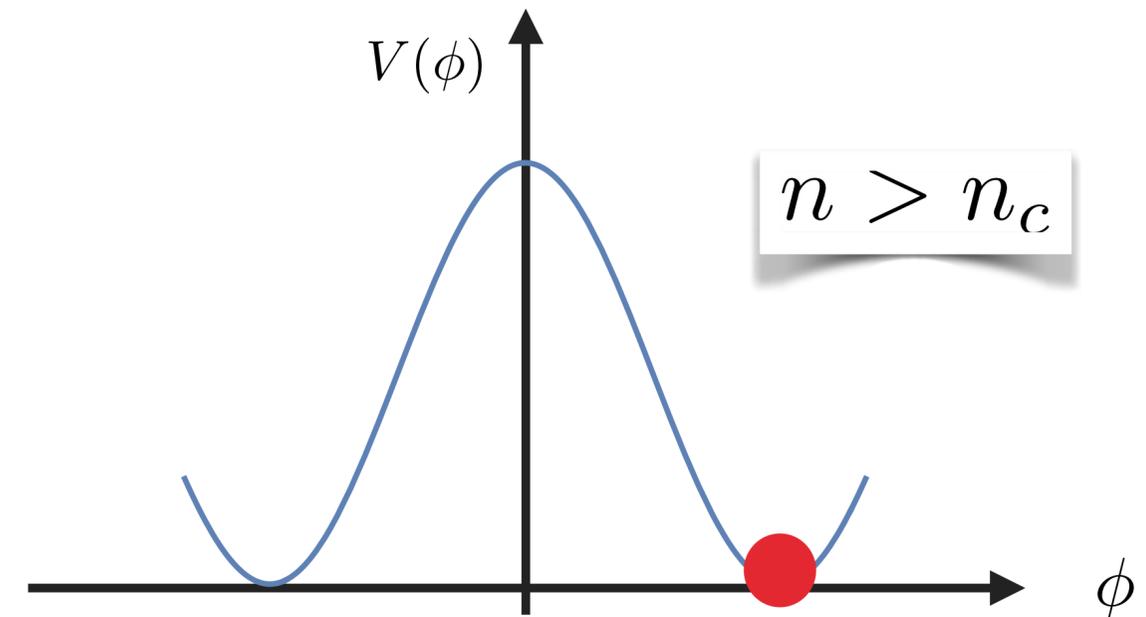
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Reduction of $\delta m_N \sim 50 \text{ MeV}$

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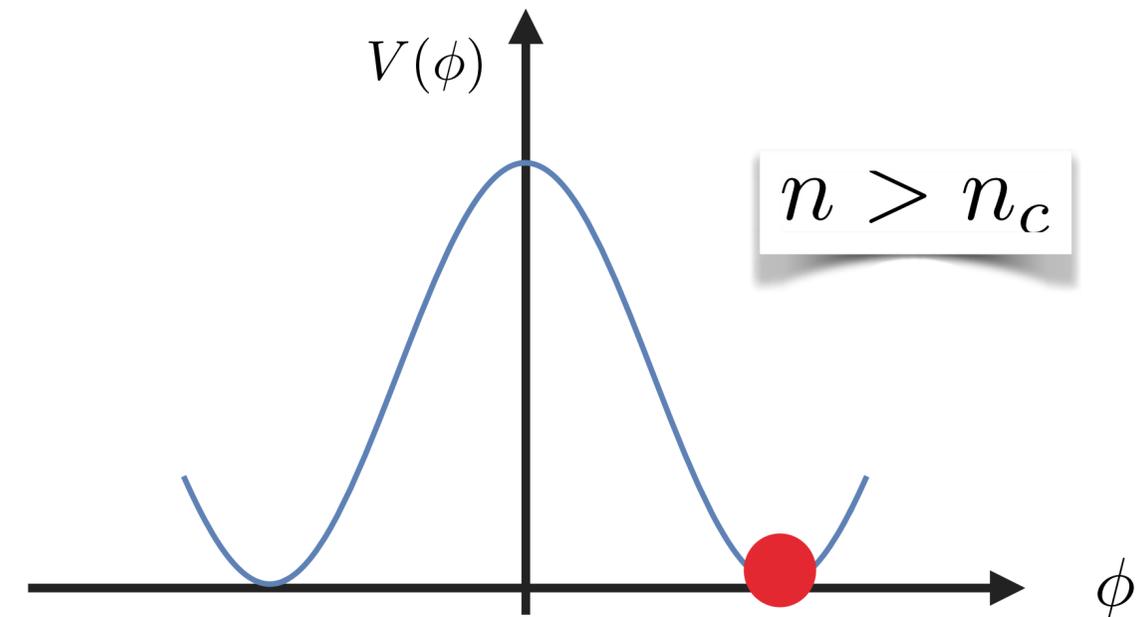
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Reduction of $\delta m_N \sim 50 \text{ MeV}$



2) Energy density of the potential acts as energy density (similar to a CC) $V(\pi f) \simeq \epsilon m_\pi^2 f_\pi^2 / 2$

see Bellazzini et. al. '15 and Csaki et. al. '18

$$\epsilon(n, \phi) = \epsilon_N(n, \phi) + V(\phi)$$

$$p(n, \phi) = p_N(n, \phi) - V(\phi)$$

Plan

- White dwarfs simplified ✓
- Axions and their properties at finite density ✓
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Free Fermi Gas of Neutrons with Axion

Minimizing the action

$$\frac{\delta S}{\delta g_{\mu\nu}} = \frac{\delta S}{\delta \phi} = 0$$

$$\mathcal{L}_{\psi\phi} = \sqrt{-g} \left[\bar{\psi} (ie^\mu_a \gamma^a D_\mu - m_*(\phi)) \psi + \frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right]$$

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$$\phi'' \left[1 - \frac{2GM}{r} \right] + \frac{2}{r} \phi' \left[1 - \frac{GM}{r} - 2\pi G r^2 (\varepsilon - p) \right] = \frac{\partial V}{\partial \phi} + \rho \frac{\partial m_\psi^*(\phi)}{\partial \phi} \equiv U(\phi, \rho),$$

$$p' = -\frac{GM\varepsilon}{r^2} \left[1 + \frac{p}{\varepsilon} \right] \left[1 - \frac{2GM}{r} \right]^{-1} \left[1 + \frac{4\pi r^3}{M} \left(p + \frac{(\phi')^2}{2} \left\{ 1 - \frac{2GM}{r} \right\} \right) \right] - \phi' U(\phi, \rho),$$

Einstein equations and axion EOM

$$M' = 4\pi r^2 \left[\varepsilon + \frac{1}{2} \left(1 - \frac{2GM}{r} \right) (\phi')^2 \right].$$

coupled system

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coupled system

can be solved numerically, very **technical**

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Luckily, there is a simplifying limit!

Zero Gradient Limit

Scale hierarchy

Scale of the system



Scale of ϕ

R

\gg

$\lambda_\phi = m_\phi^{-1} \sim$

$$\frac{f}{\sqrt{\sigma_{\pi N n} - \epsilon m_\pi^2 f_\pi^2}}$$

Zero Gradient Limit

Scale hierarchy

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Scale of ϕ

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Limit of a thin wall bubble

Gradient energy becomes negligible: $\phi'(r) = 0$

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The system effectively decouples: Solve for EOS \longrightarrow Solve pressure gravity equations

Equation of state

$$\frac{\partial \varepsilon}{\partial \phi} = 0 \quad \text{minimising the potential energy}$$

$$\frac{\partial V}{\partial \phi} + n \frac{\partial m_N(\phi)}{\partial \phi} = 0$$

$$\varepsilon(n, \phi) = \varepsilon_N(n, \phi) + V(\phi)$$

$$p(n, \phi) = p_N(n, \phi) - V(\phi)$$

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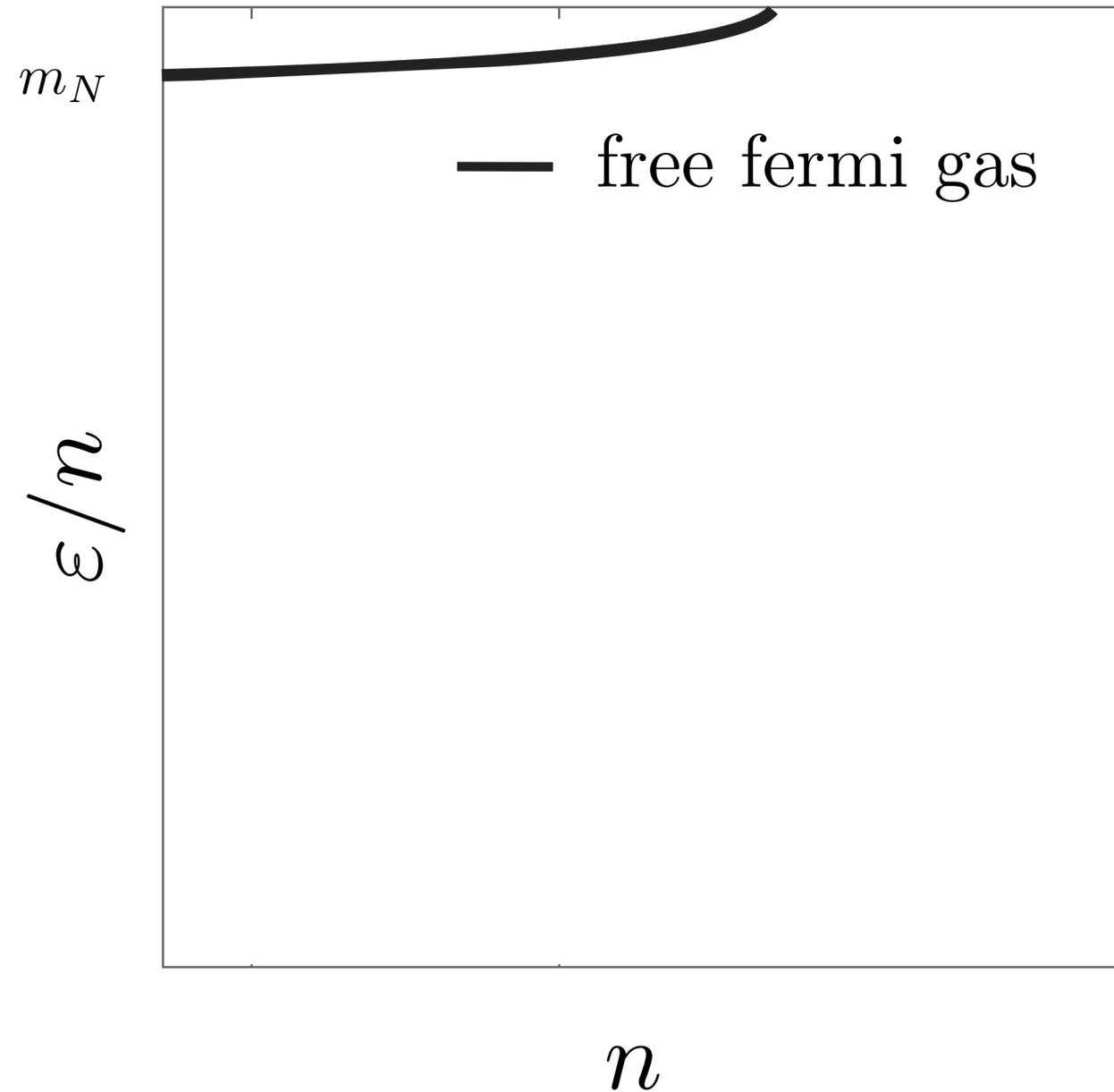


$$\varepsilon(n), p(n)$$

equation of state

Energy per particle

$$\frac{\varepsilon(n, 0)}{n} = \frac{\varepsilon_N(n, 0) + V(0)}{n}$$



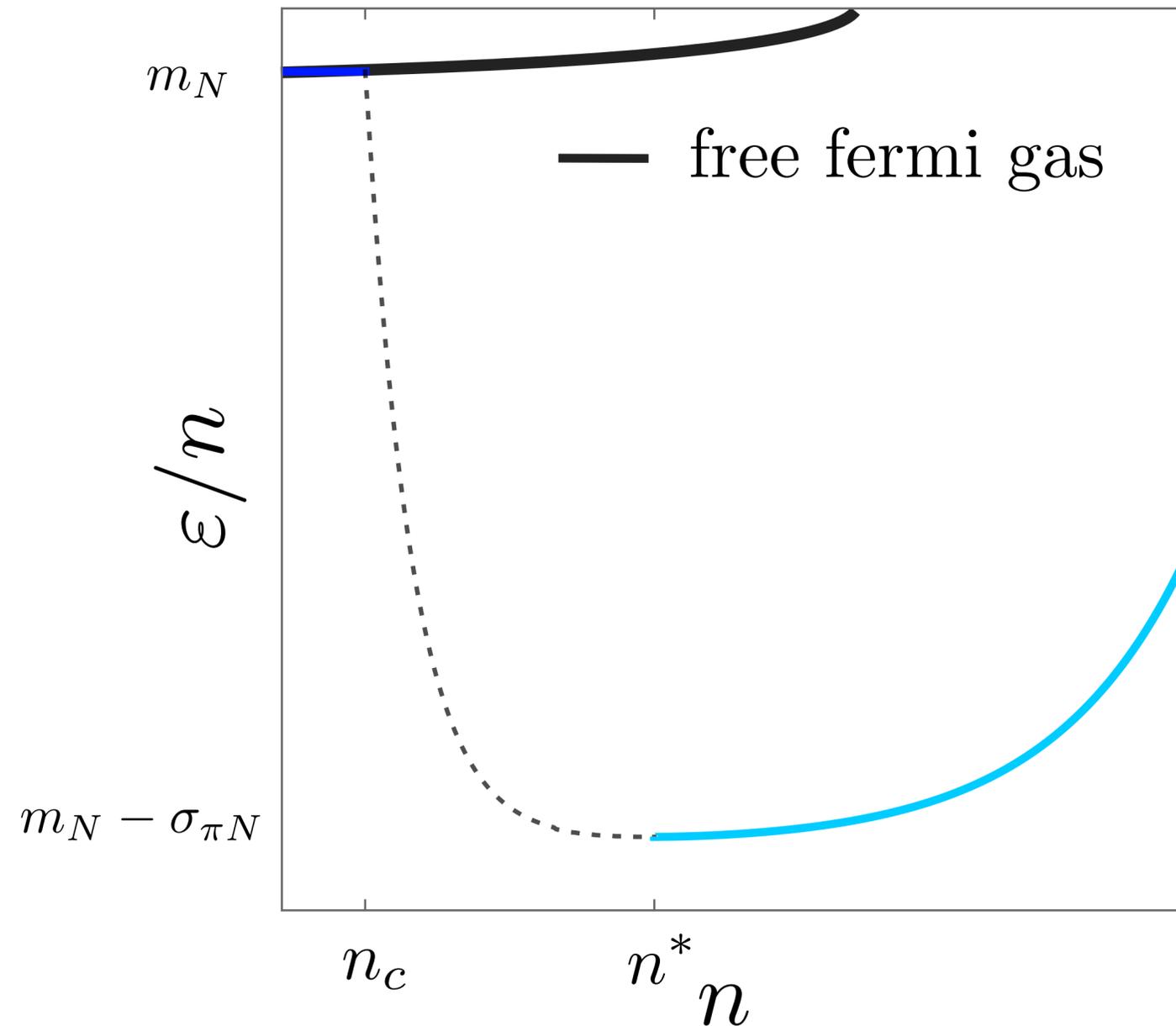
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— metastable ($\phi = 0$)

..... unstable

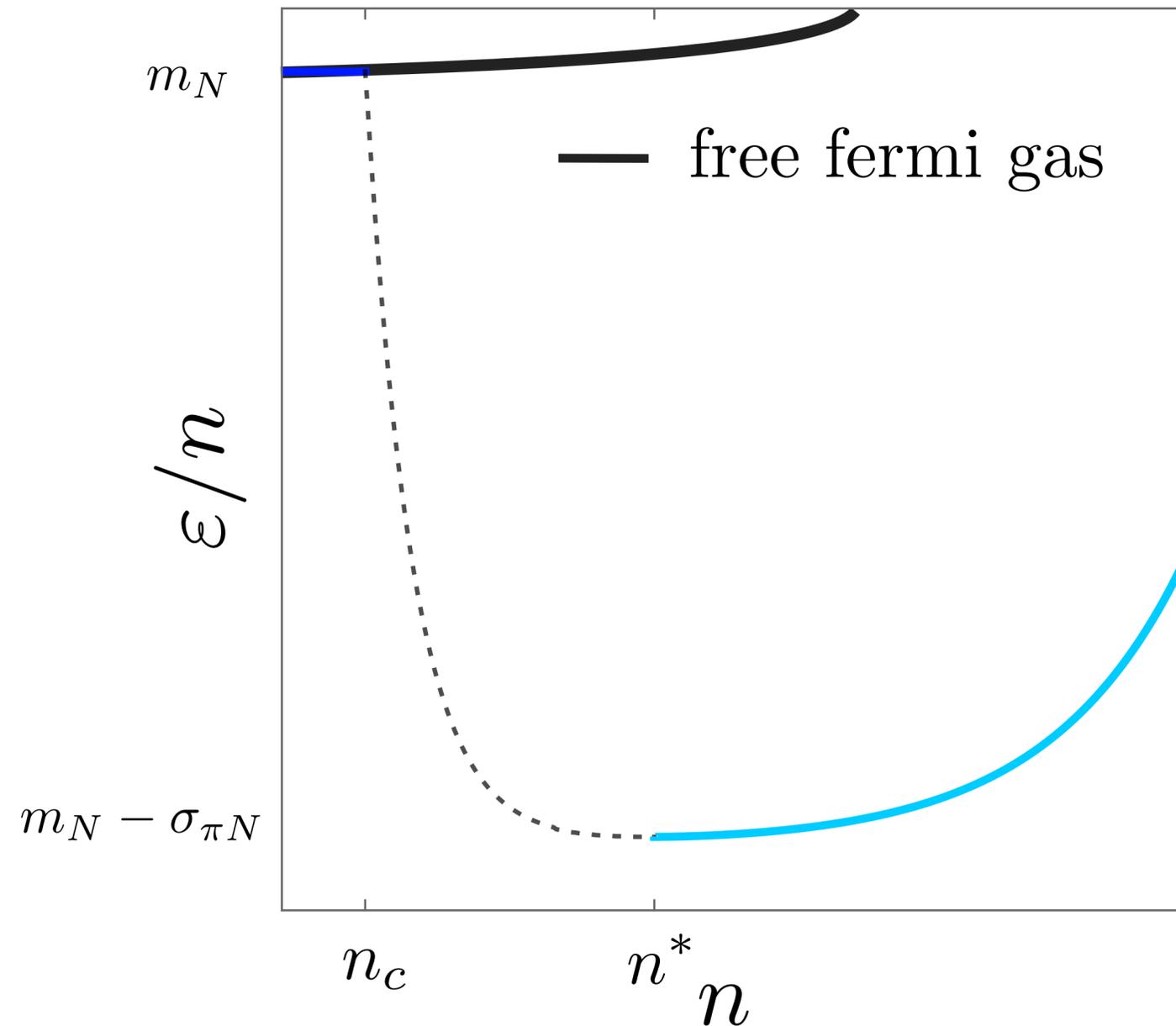
— New ground state ($\phi = \pi f$)



Energy per particle

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— metastable ($\phi = 0$) unstable — New ground state ($\phi = \pi f$)



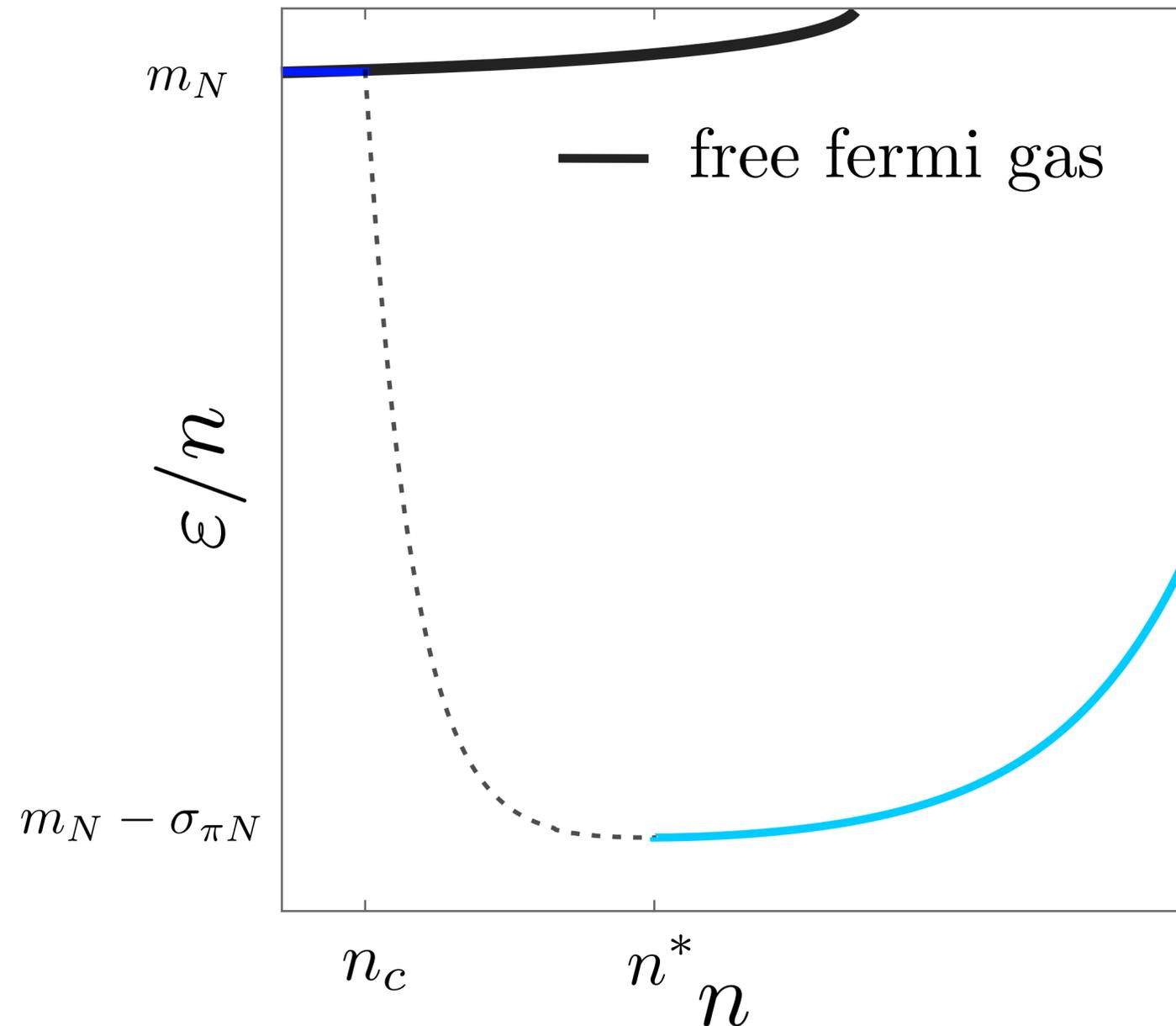
Energy per particle is related to pressure

$$p = n^2 \frac{\partial(\varepsilon/n)}{\partial n} = p_N - V \quad V(\pi f) \simeq \epsilon m_{\pi}^2 f_{\pi}^2 / 2$$

Energy per particle

$$\frac{\varepsilon(n, \phi)}{n} = \frac{\varepsilon_N(n, \phi) + V(\phi)}{n}$$

— metastable ($\phi = 0$) unstable — New ground state ($\phi = \pi f$)



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Negative pressure for

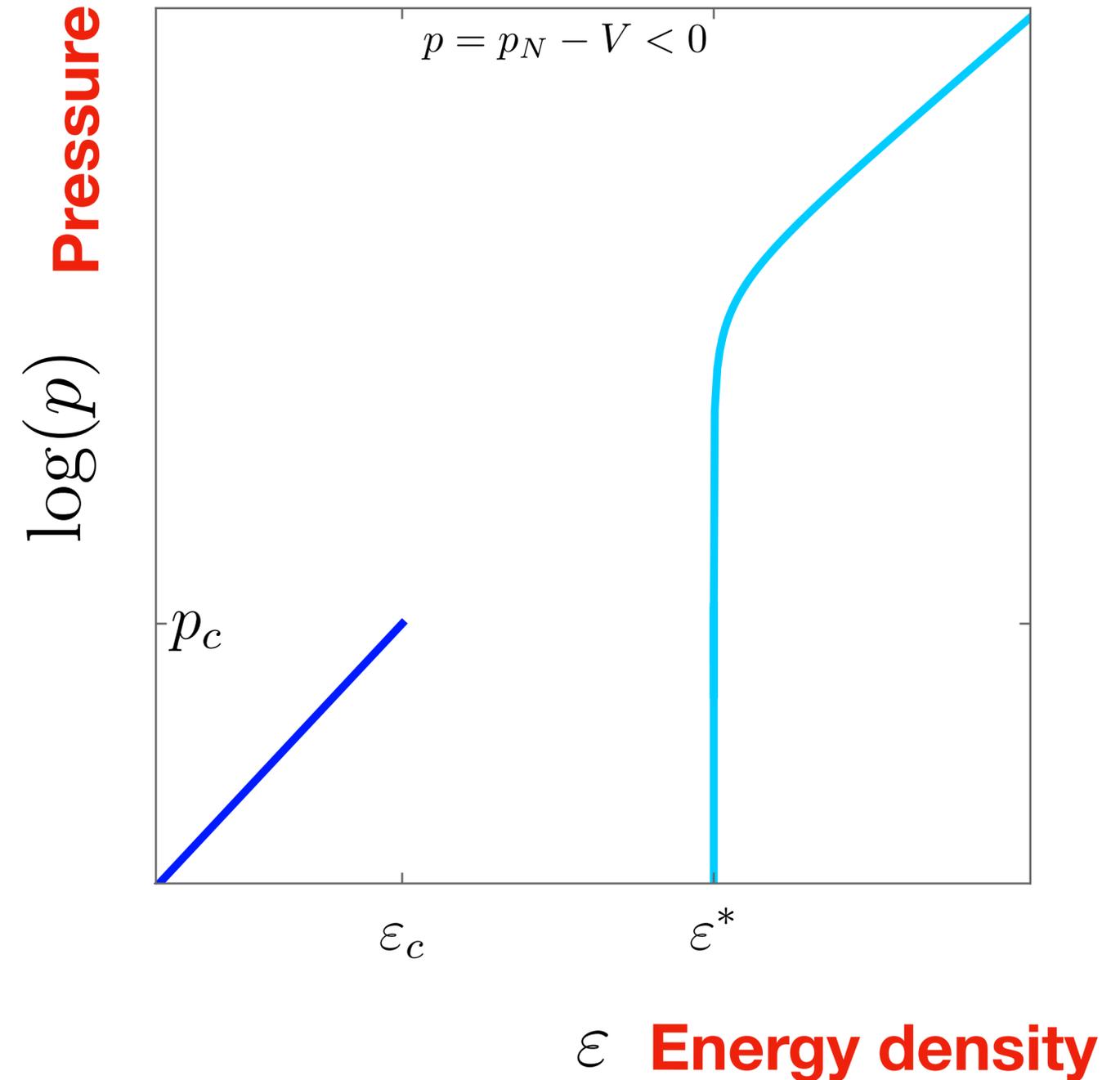
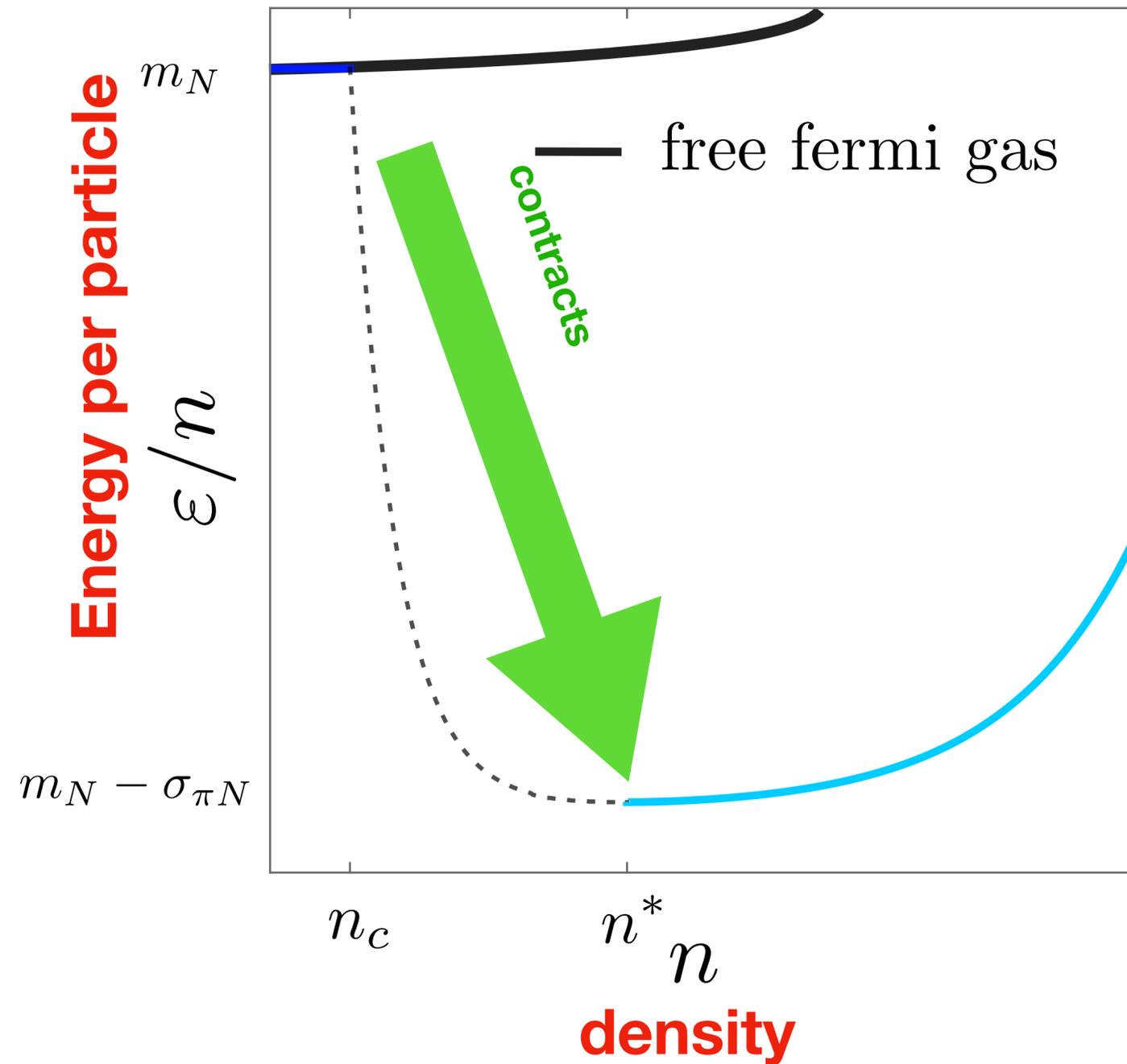
$$n_c < n < n^*$$

Defines n^* as

$$p(n^*) = p_N(n^*) - V = 0$$

Energy per particle and pressure

— metastable ($\phi = 0$) unstable — stable ($\phi = \pi f$)



Plan

- White dwarfs simplified ✓
- Axions and their properties at finite density ✓
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White Dwarfs with light QCD axion

$$A/Z \simeq 2$$

- EOS analogous to free Fermi gas picture $\varepsilon = (A/Z)m_N^*n + \varepsilon_e(n) + V$
- New ground state density set by electron pressure $p_e(n^*) = p_e(n^*) - V = 0$

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There exists a range of densities $n_c < n < n^*$ with $p < 0$

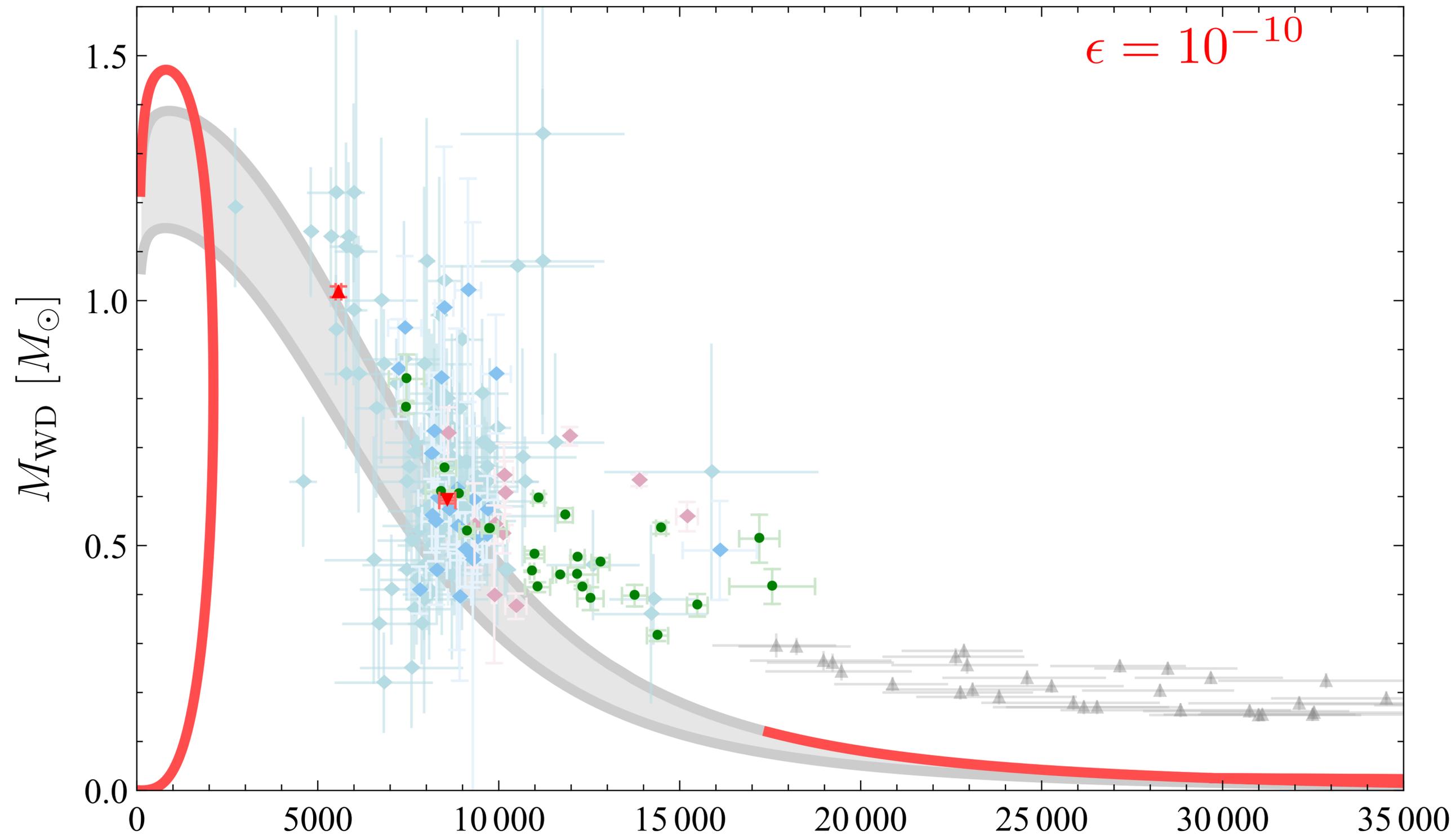
and no stable configuration:



Translates to gap in the MR Curve

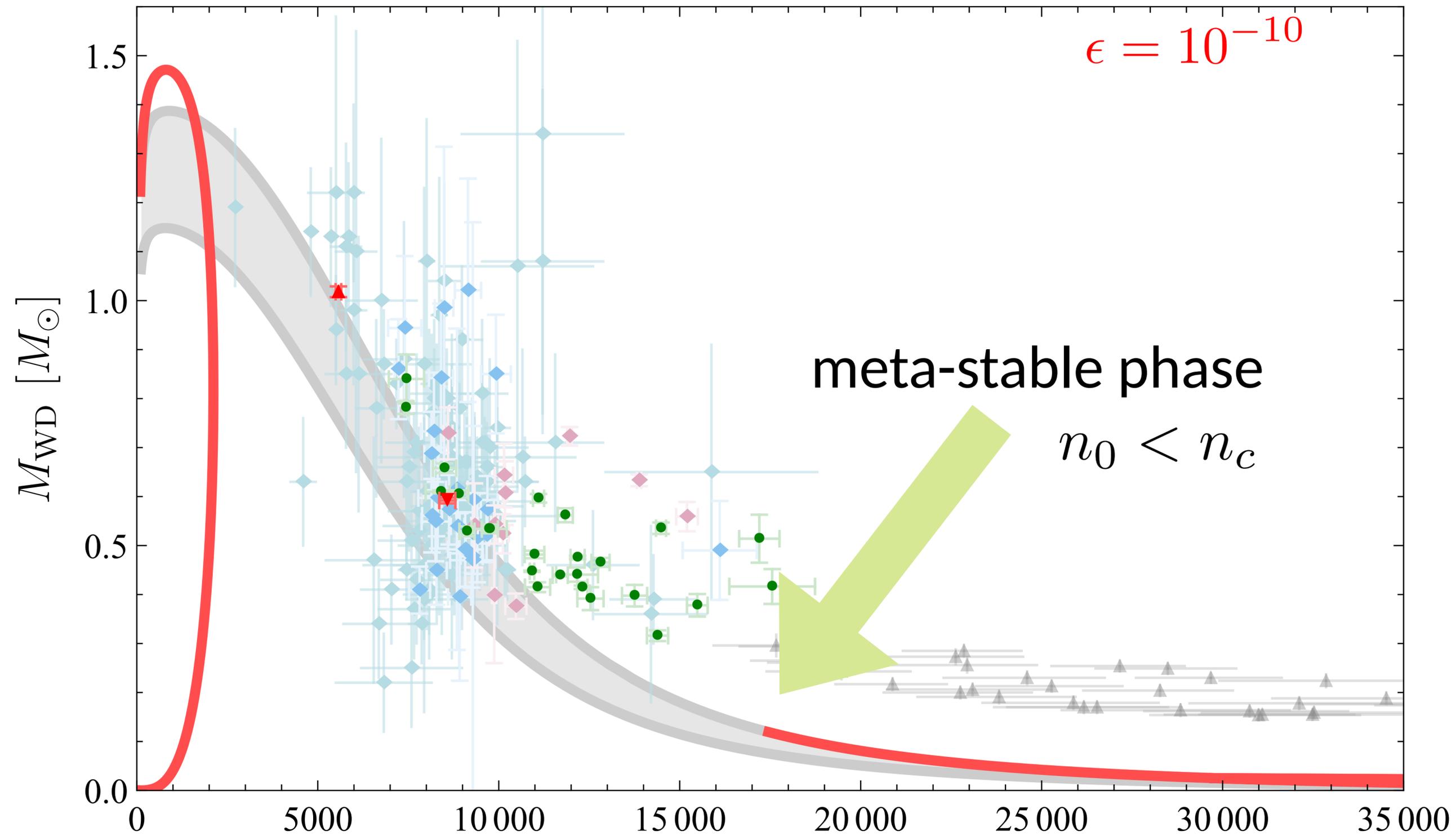
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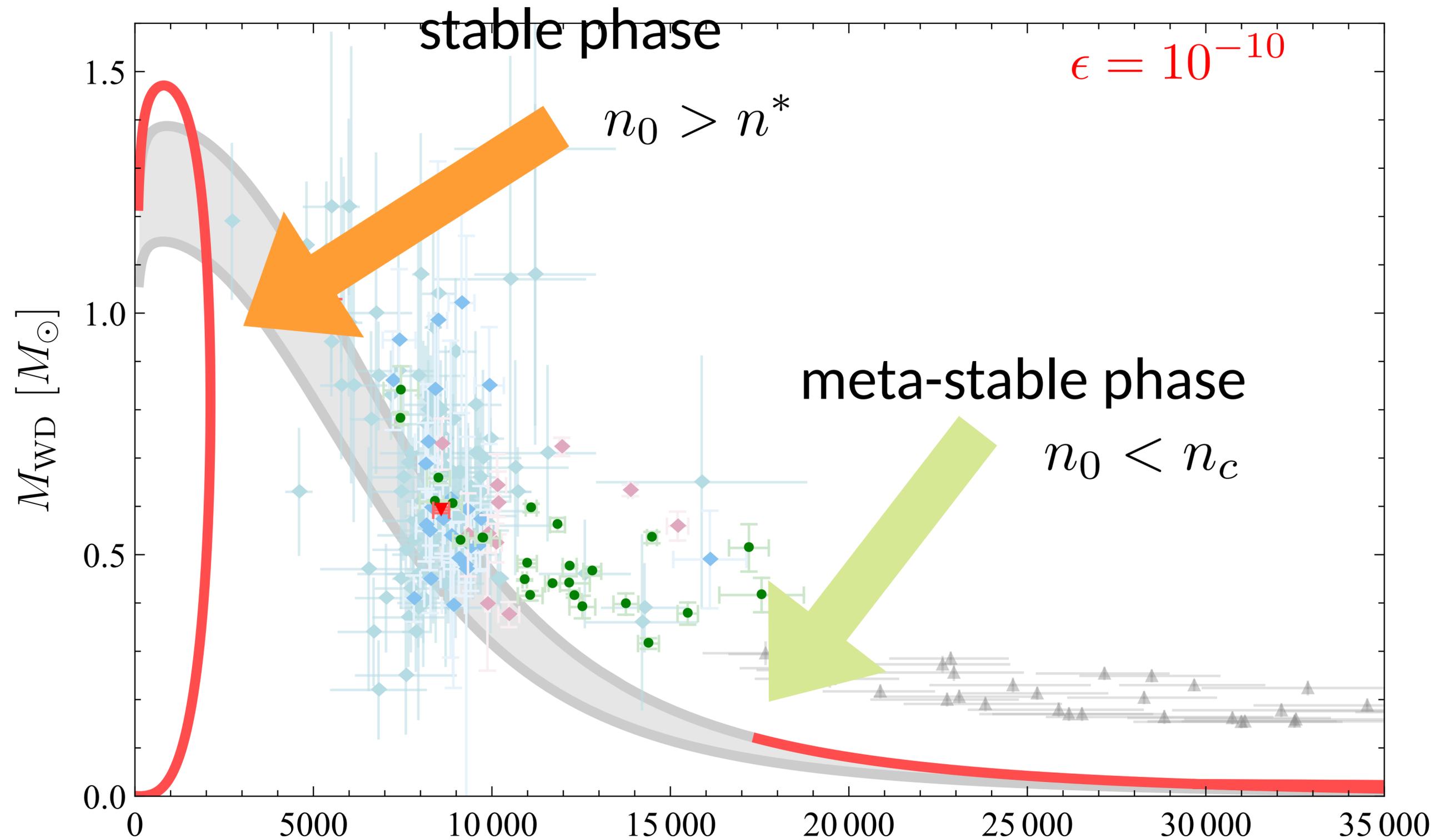
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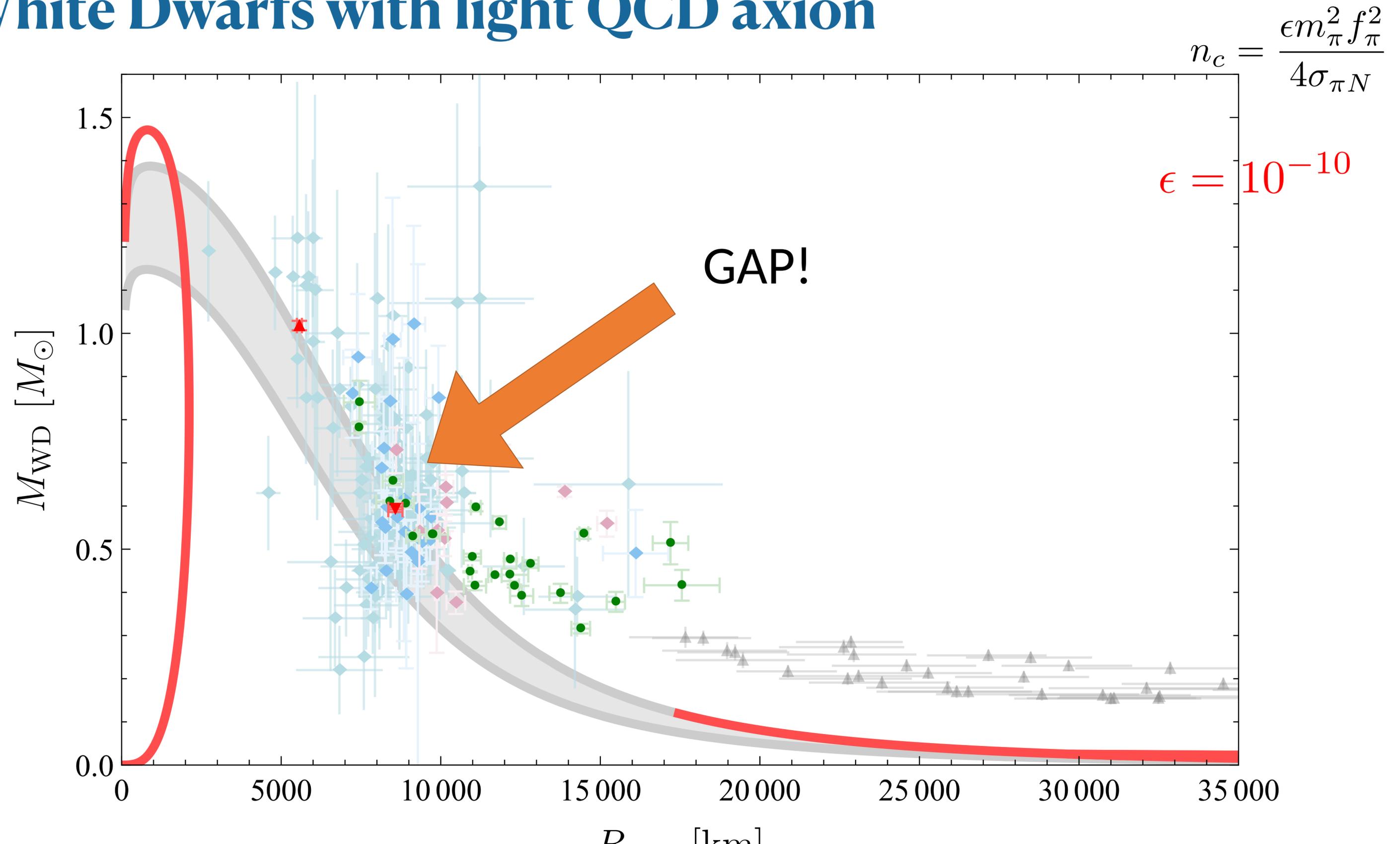


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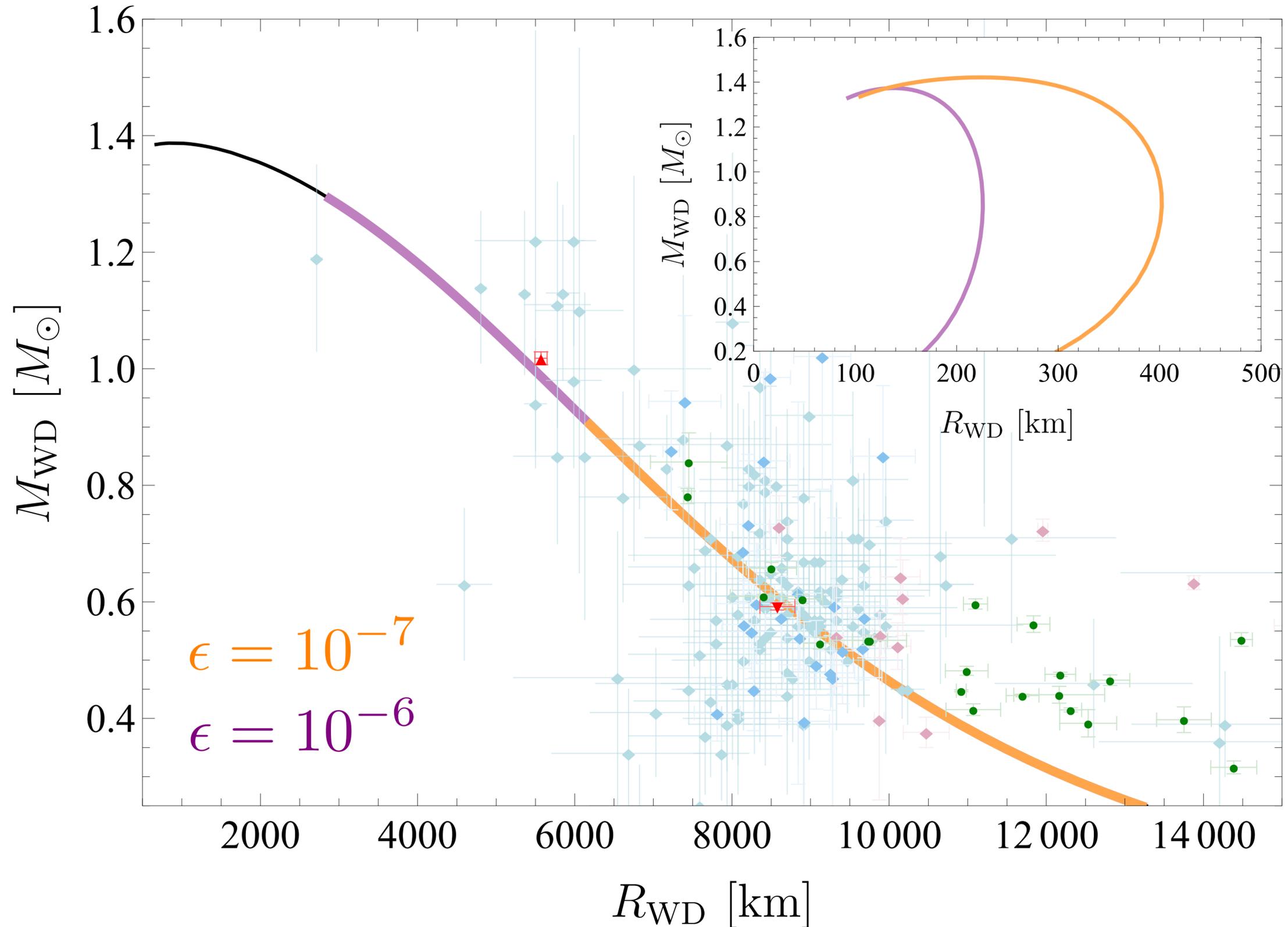
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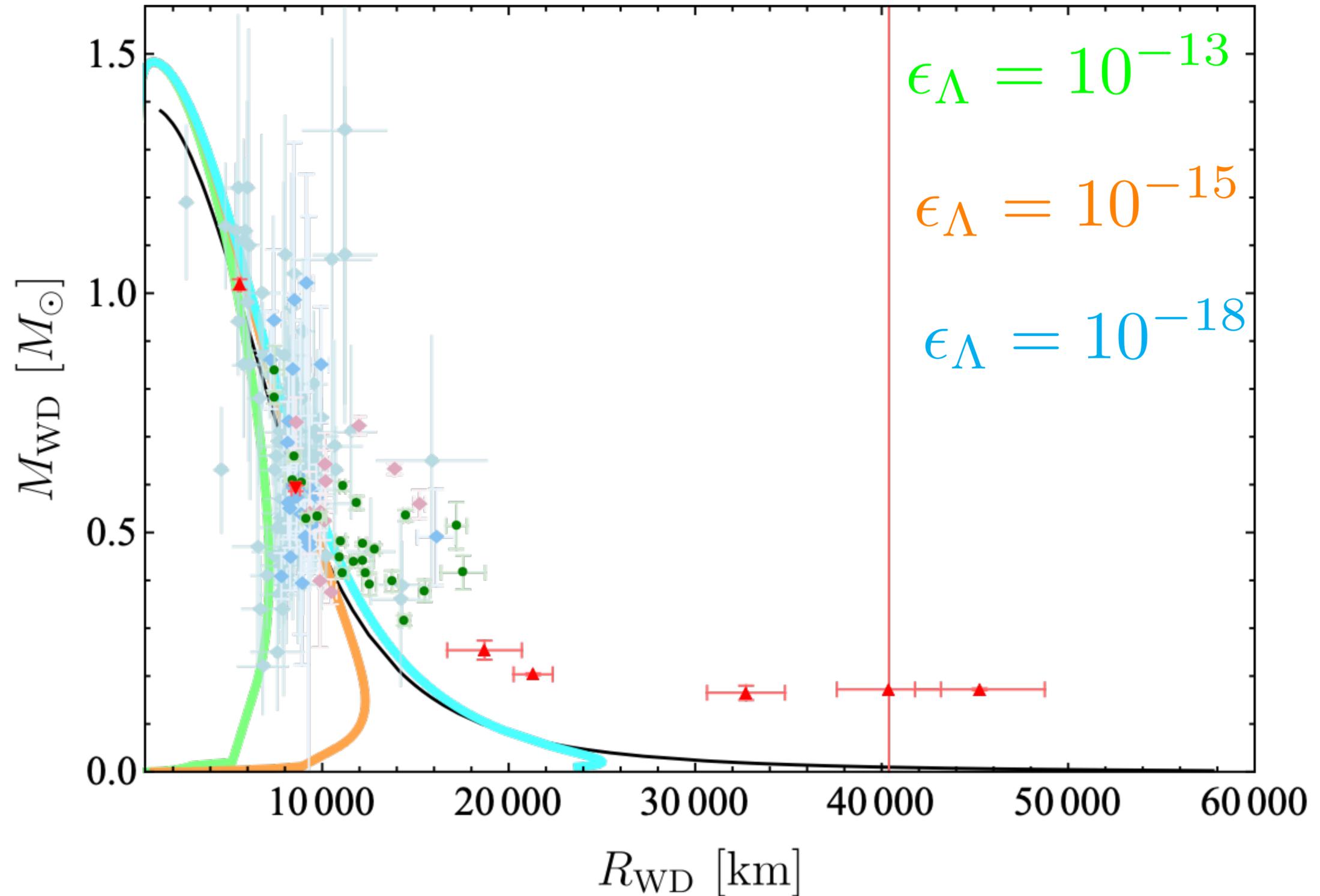
Negligible Gradient



White Dwarfs with light QCD axion

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Negligible Gradient



Gradient effects

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But, for large decay constants $f > 10^{13}$ GeV gradient effects become important

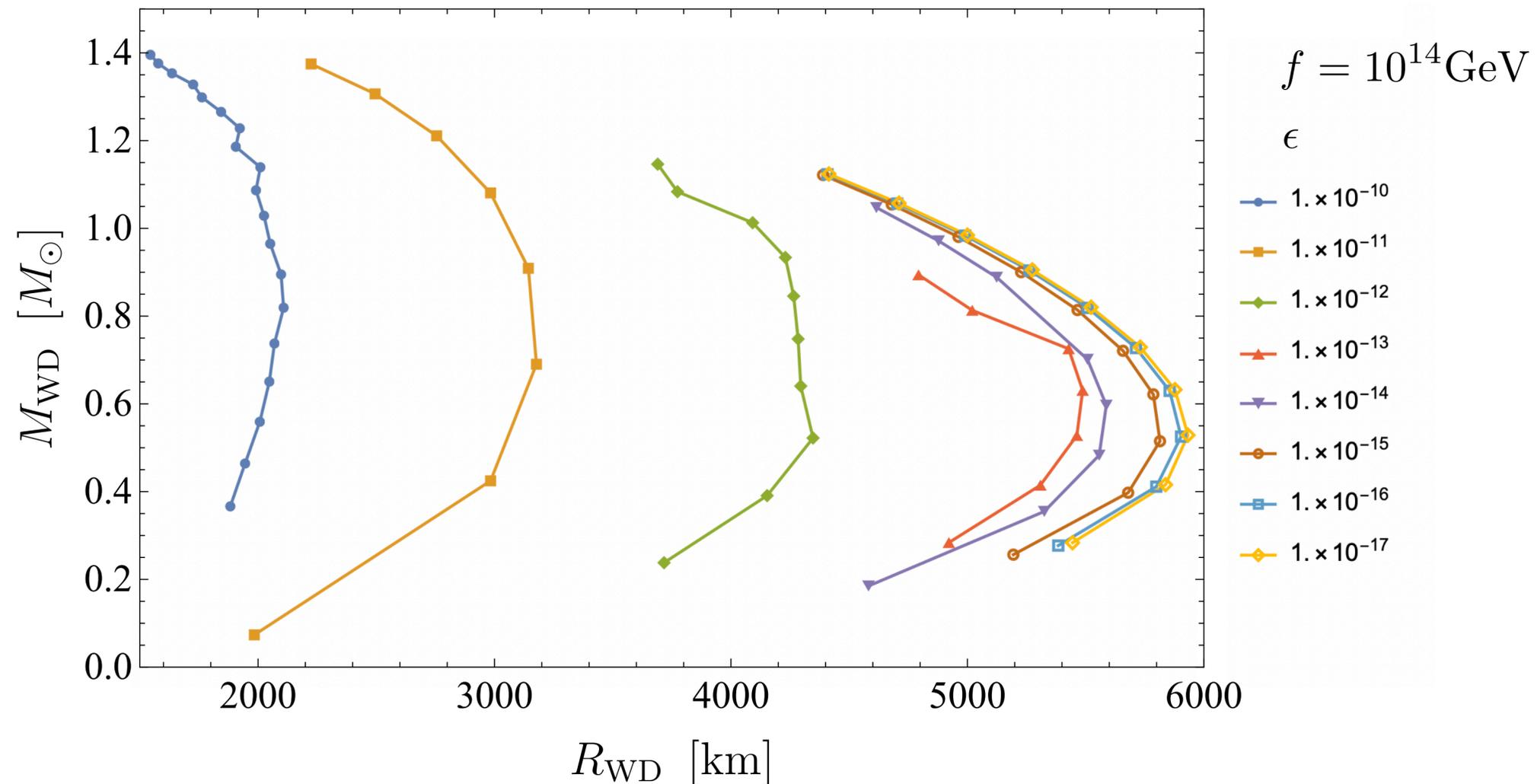
- 1) On **meta-stable branch**: minimum radius is fixed by $R_{min} \sim m_\phi^{-1}$

Gradient effects

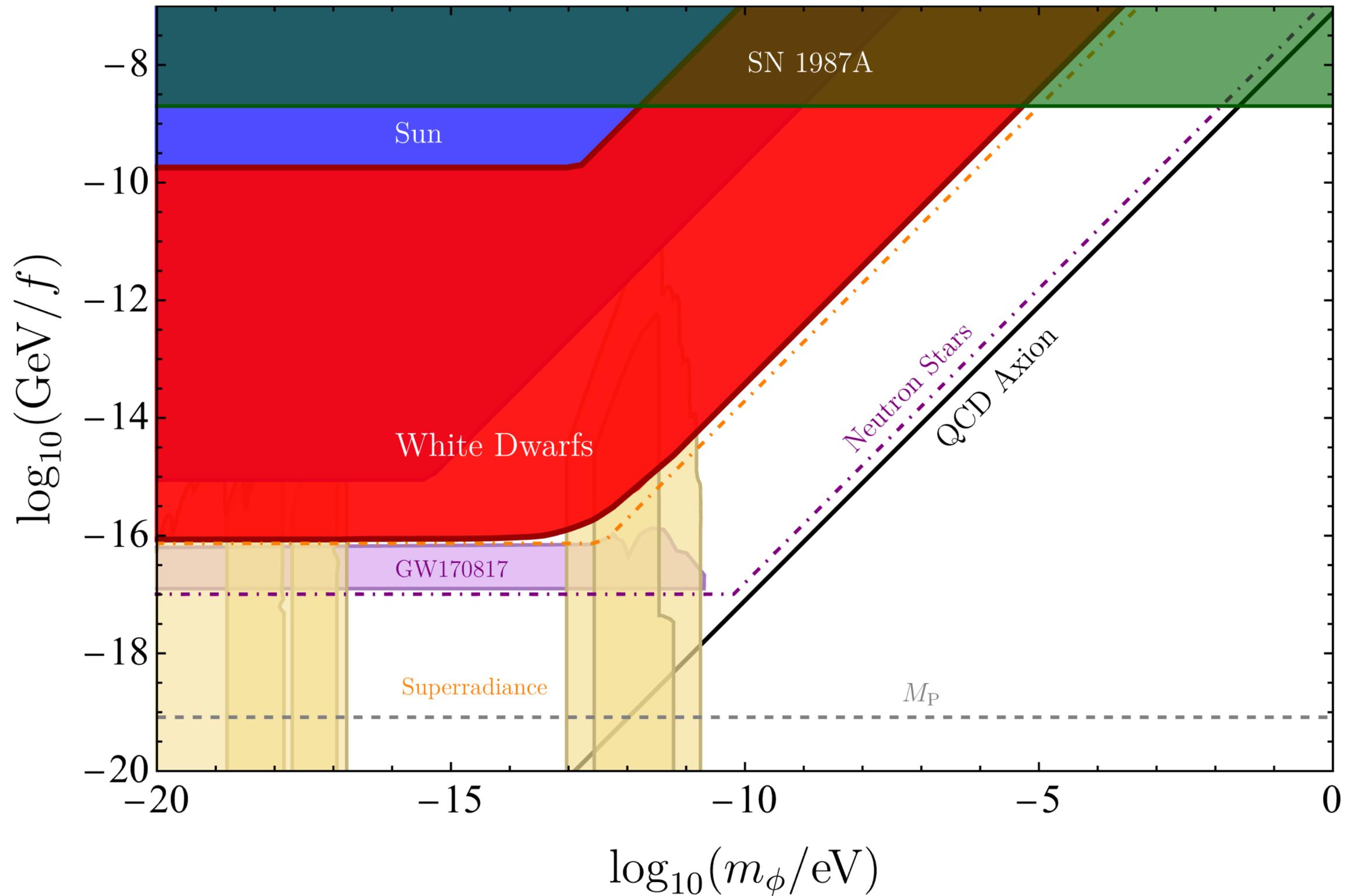
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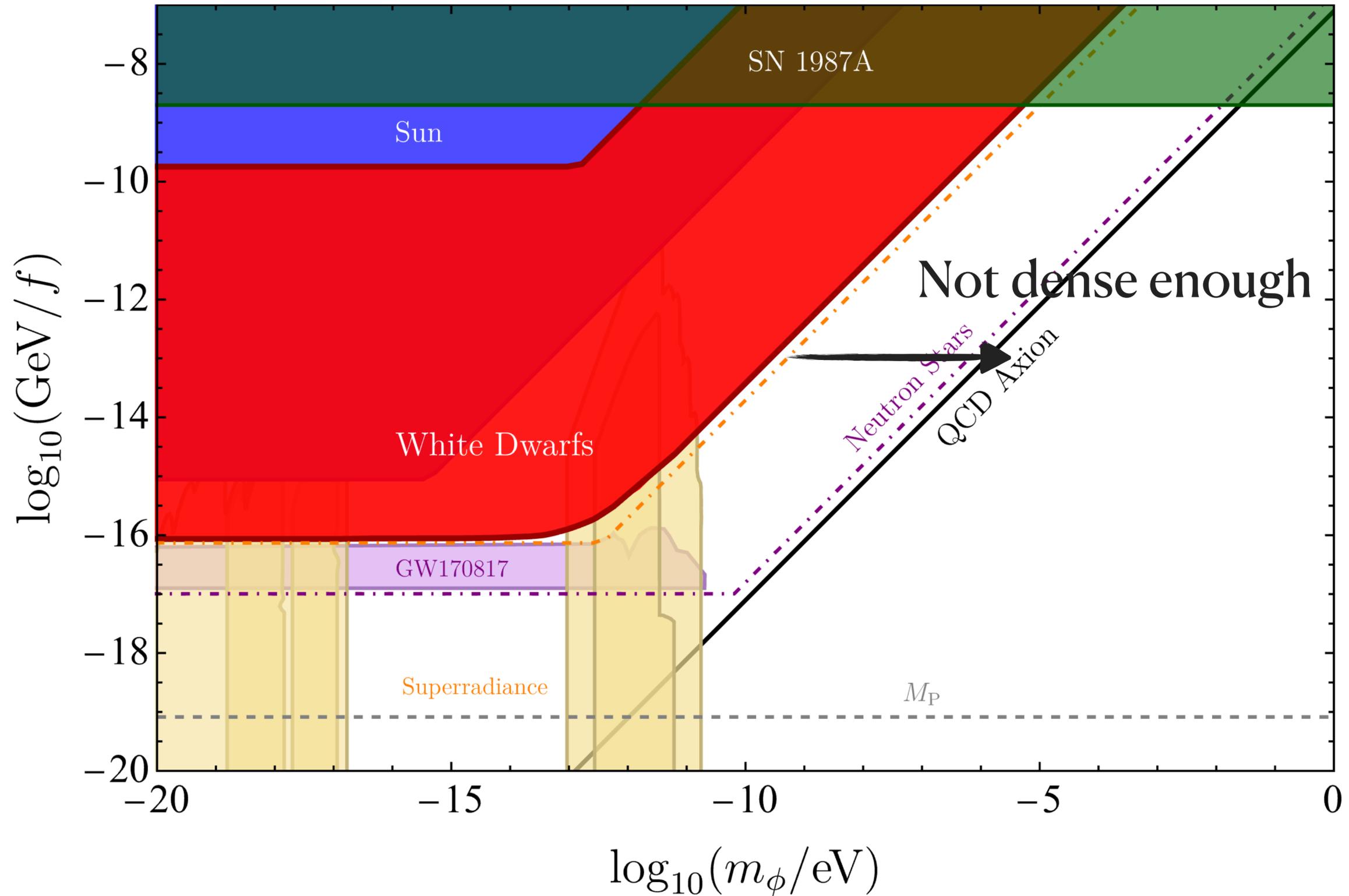
- 1) On **meta-stable branch**: minimum radius is fixed by $R_{min} \sim m_\phi^{-1}$
- 2) On **stable branch**: gradient pressure fixes maximal radius



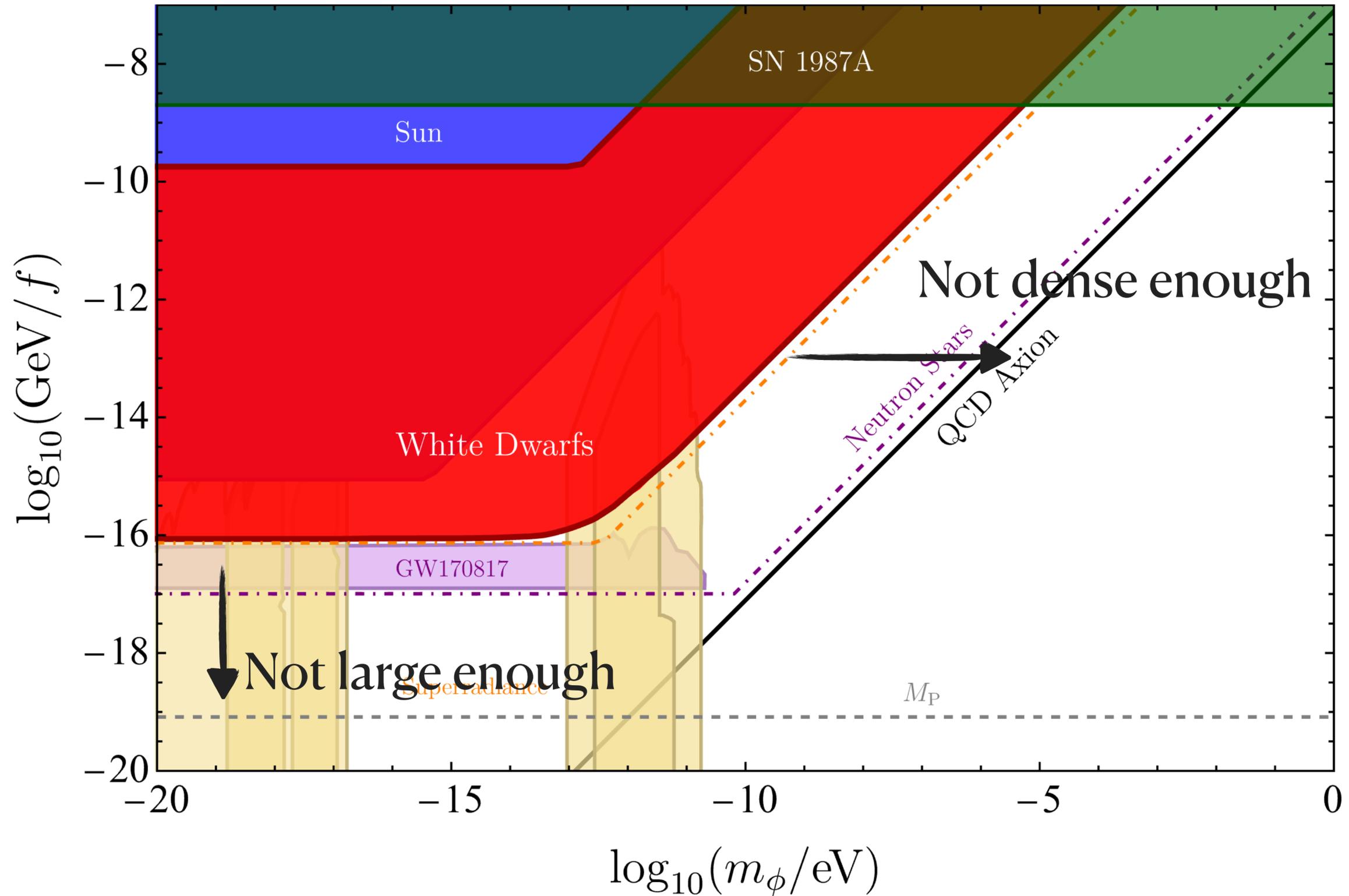
Axion Parameter Space



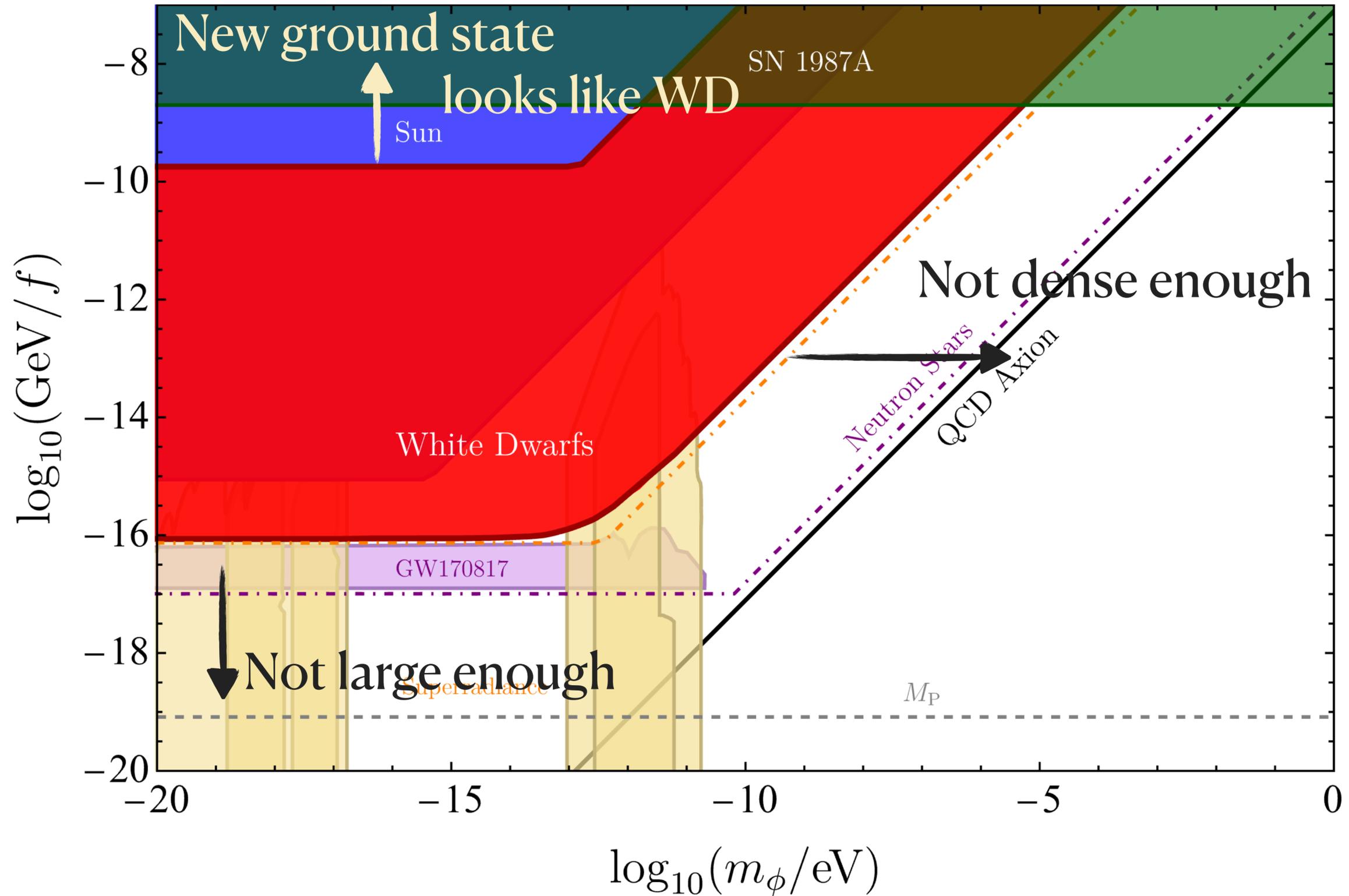
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Axion Parameter Space



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Conclusion and Outlook

White dwarfs as a probe of light QCD axions

- Light QCD axions can lead to a **new ground state**
- Instability in the equation of state \longrightarrow gap in the M-R curve
- Allows to exclude large chunk of parameter space
- This does **not** rely on the axion being DM

Conclusion and Outlook

White dwarfs as a probe of light QCD axions

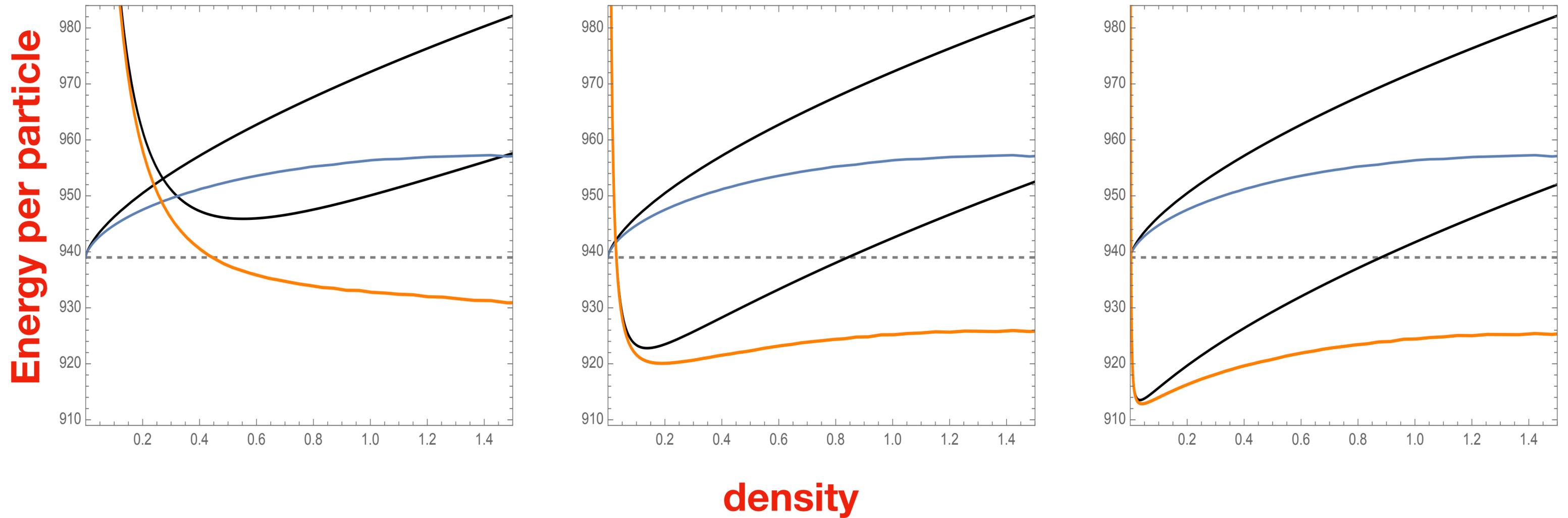
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Thank you!

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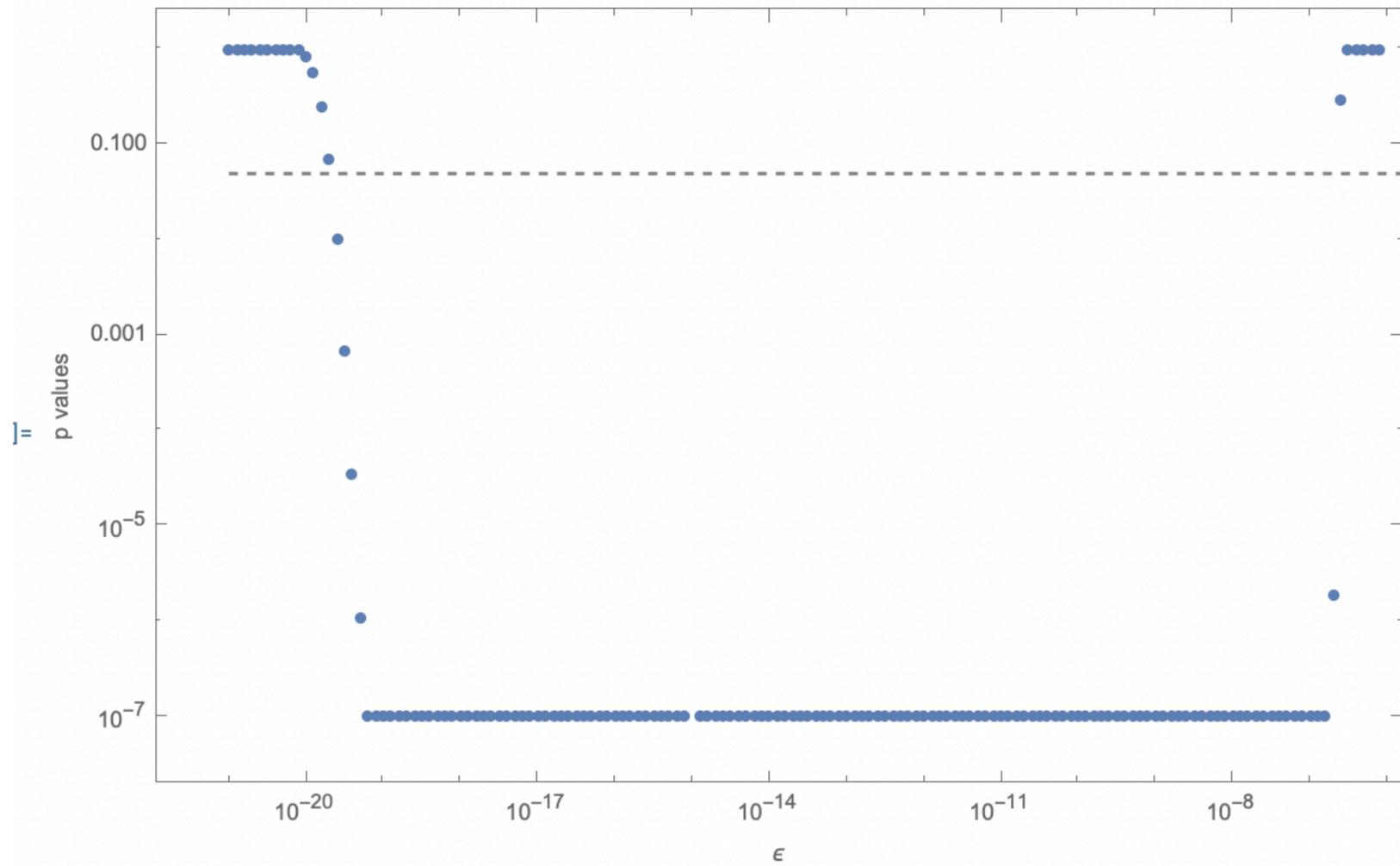
Backup

ChPT EOS with the axion

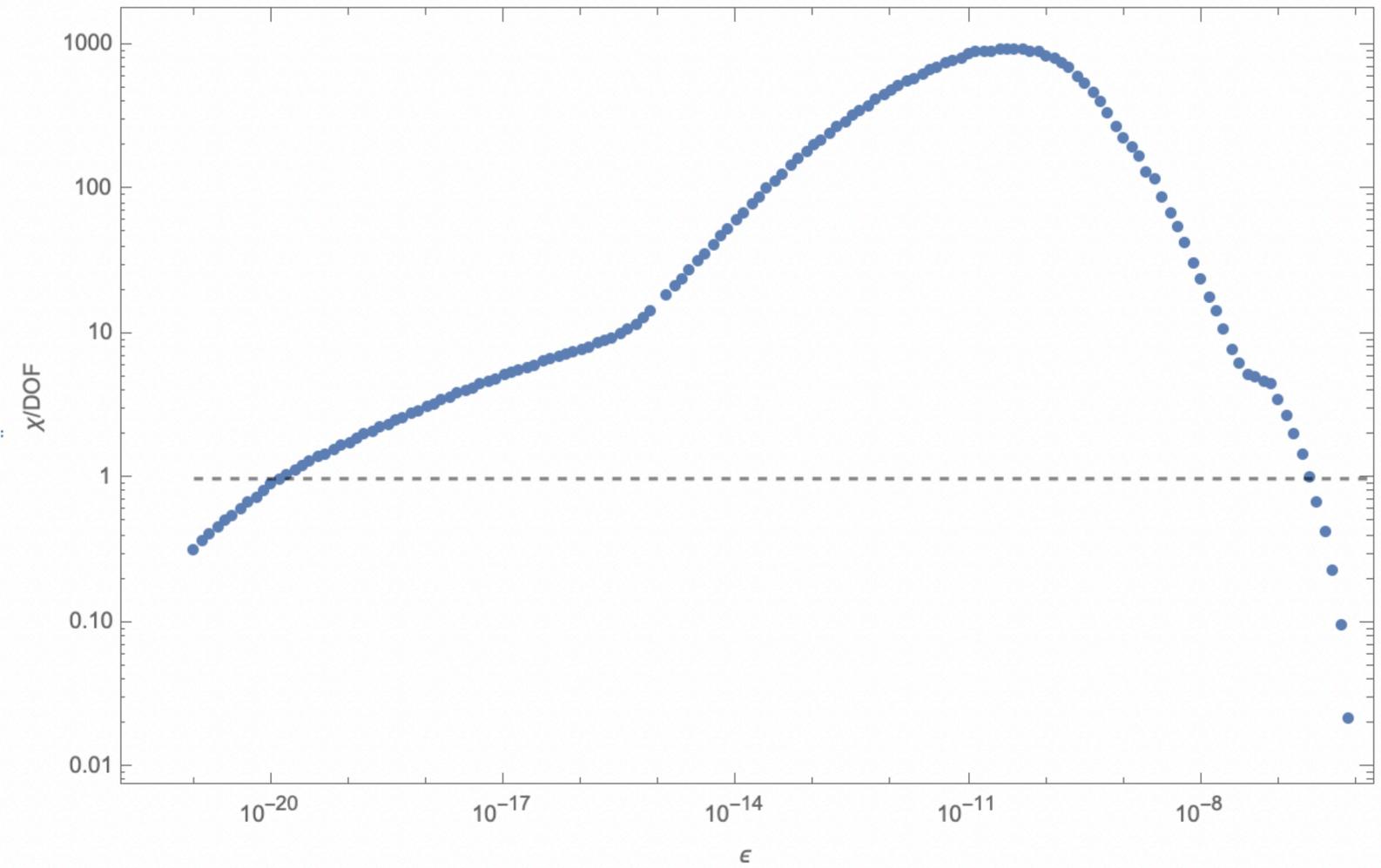


White dwarf statistics

P-value as fn of epsilon



Chi/d.o.f.



ALP-FERMION-GRAVITY SYSTEM

Consider one Fermion N , gravity and the ALP

$$\mathcal{L}_{N\phi} = \sqrt{-g} \left[\bar{N} (i g^{\mu\nu} \gamma_\mu D_\nu - m_N^*(\phi)) N + \frac{1}{2} g^{\mu\nu} (\partial_\mu \phi)(\partial_\nu \phi) - V(\phi) \right],$$

ALP neutron interaction

ALP self-interaction

Outside the dense object

$$\left. \frac{\partial V(\phi)}{\partial \phi} \right|_{\phi_0} = 0 \quad V(\phi_0) = 0 \quad m_N^*(\phi_0) = m_N$$

Effectively decoupled

COUPLED EOMS

The full coupled system

$$p' + \phi' \left(\frac{dV}{d\phi} \right) = -\frac{(\epsilon + p) e^\sigma}{2r} \left[1 - e^{-\sigma} + \kappa r^2 \left(p + \frac{e^{-\sigma}}{2} (\phi')^2 \right) \right],$$

$$\sigma' = \kappa r e^\sigma \left[\epsilon + \frac{e^{-\sigma}}{2} (\phi')^2 \right] - \frac{e^\sigma - 1}{r},$$

$$\phi'' + \frac{2}{r} \left[\frac{1 + e^\sigma}{2} + \frac{\kappa r^2 e^\sigma}{4} (p - \epsilon) \right] \phi' = e^\sigma \frac{dV}{d\phi}.$$

ZERO GRADIENT LIMIT

Corresponds to systems much larger than the typical scale of ϕ

$$E(R) \simeq R^2 \Delta R \left(\frac{f}{\Delta R} \right)^2 + R^3 \varepsilon_{\text{pot}} \simeq R^3 \varepsilon_{\text{pot}}$$

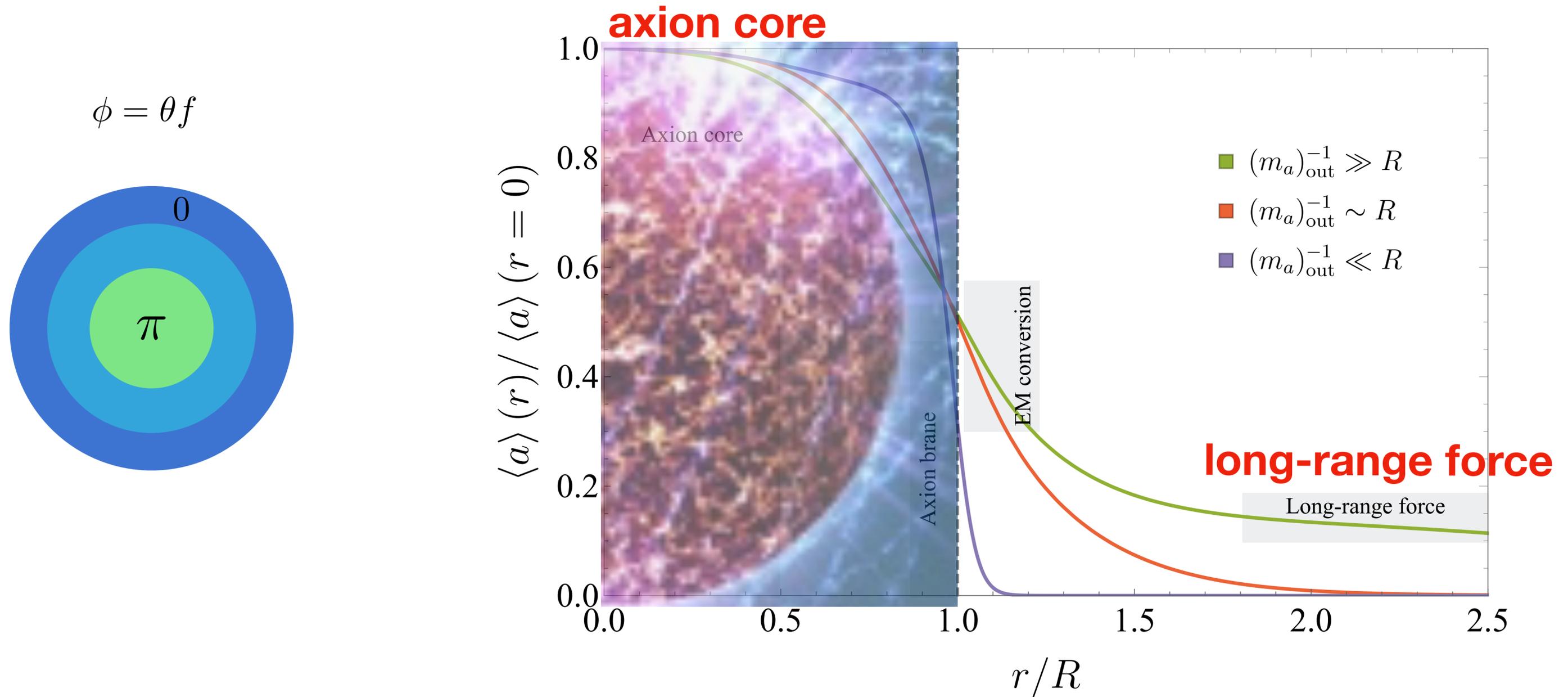
 Can forget about the scalar gradient $\partial_\mu \phi = 0$

This is very nice because now the system is effectively decoupled!

$\frac{\partial \varepsilon}{\partial \phi} = 0$ + Neutron Fermi gas \longrightarrow Equation of state

$\frac{\delta S}{\delta g_{\mu\nu}} = 0$ \longrightarrow Pressure - Gravity balance equations
(Also known as TOV equations)

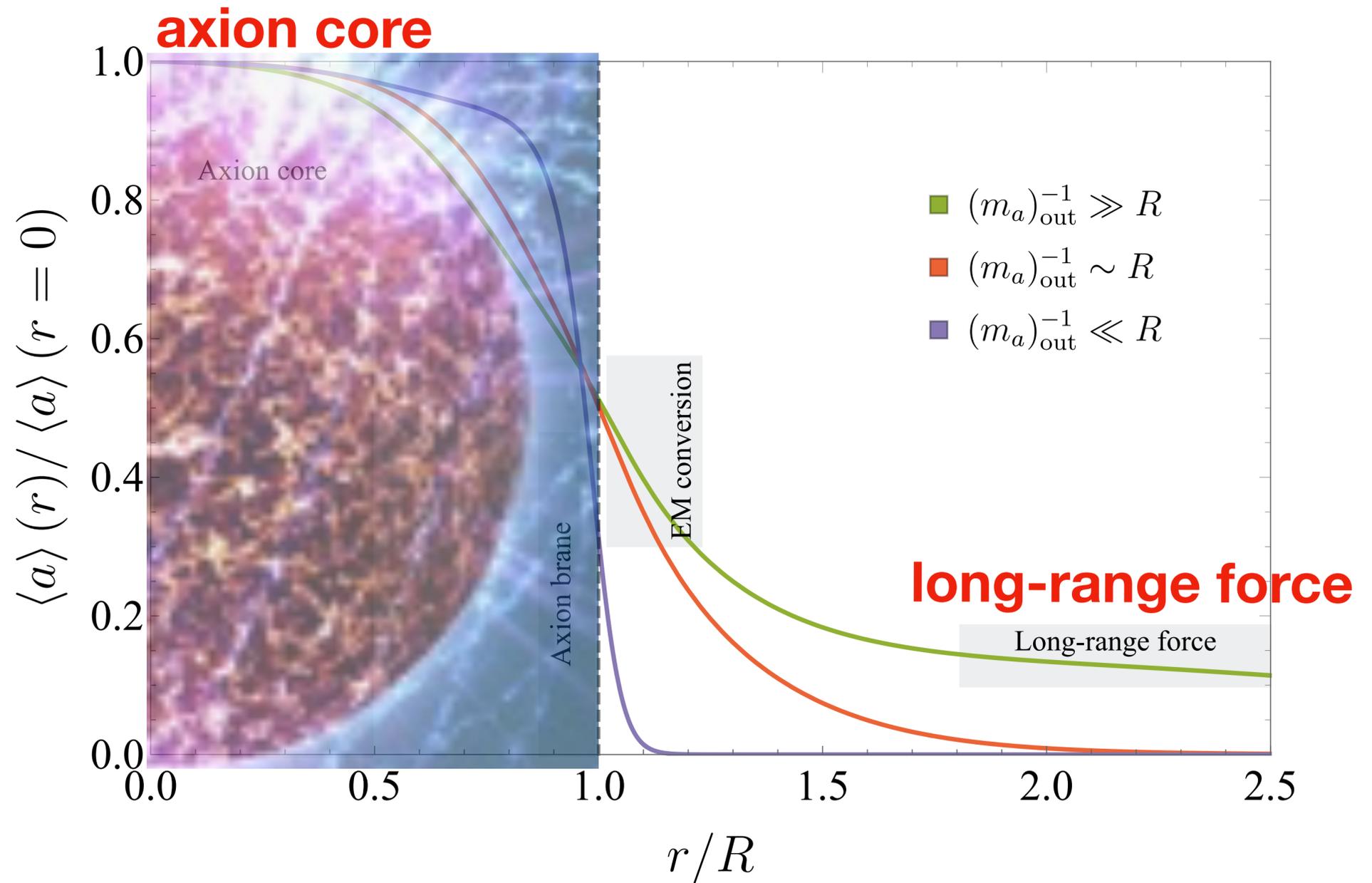
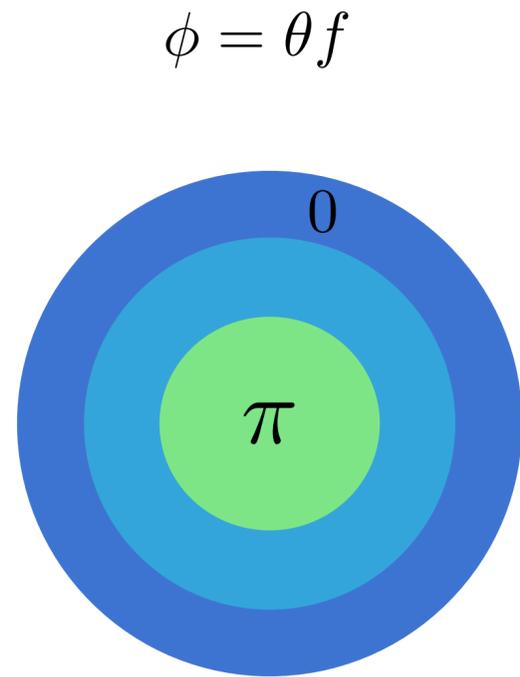
Axion Profile: in a neutron star



Long range forces, axion conversion in magnetosphere of NSs

see Hook, Huang '17 and Balkin, Serra, KS, Weiler '20

Axion Profile: in a neutron star

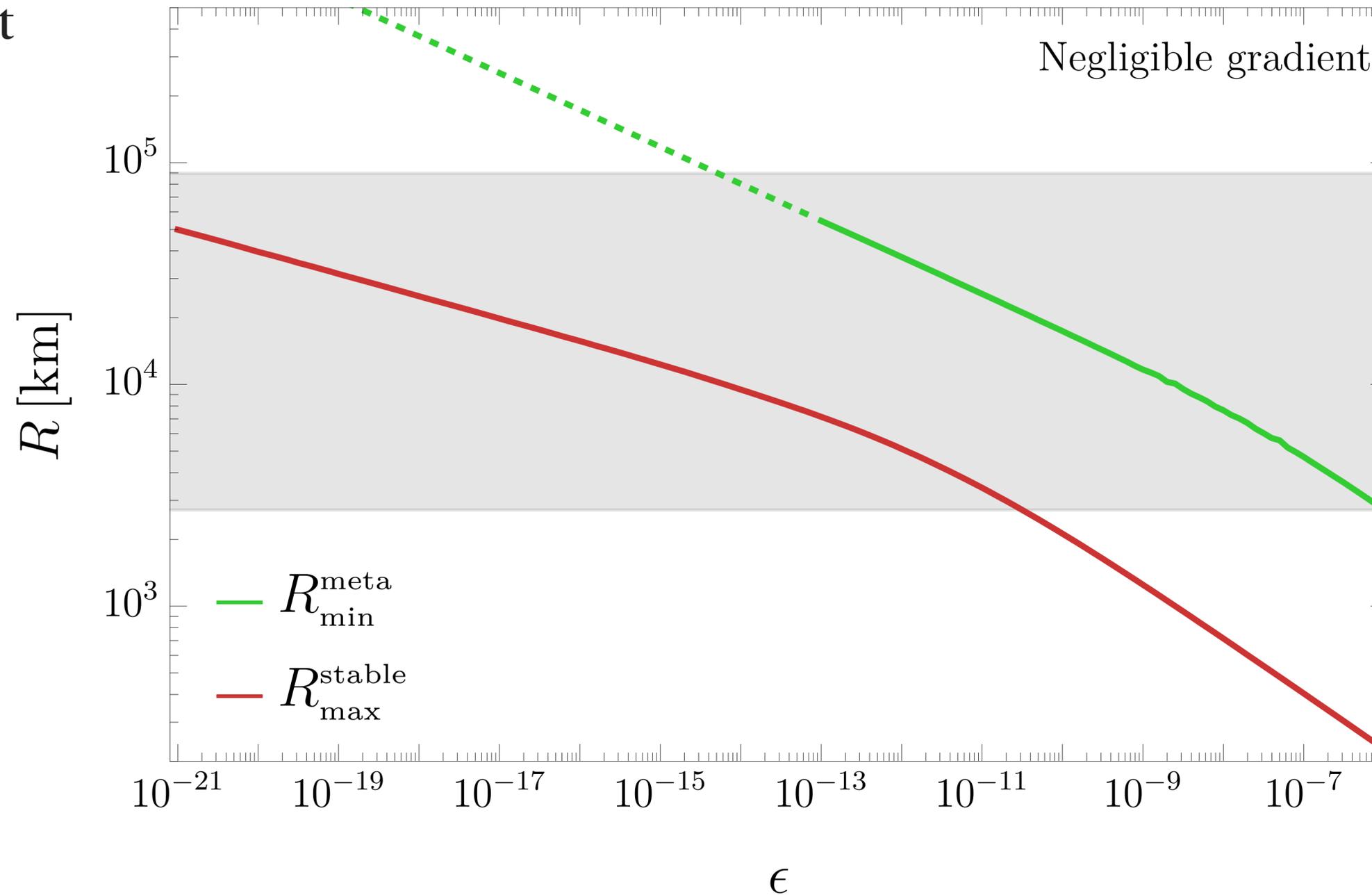


On the other hand: There is a back reaction on the system!

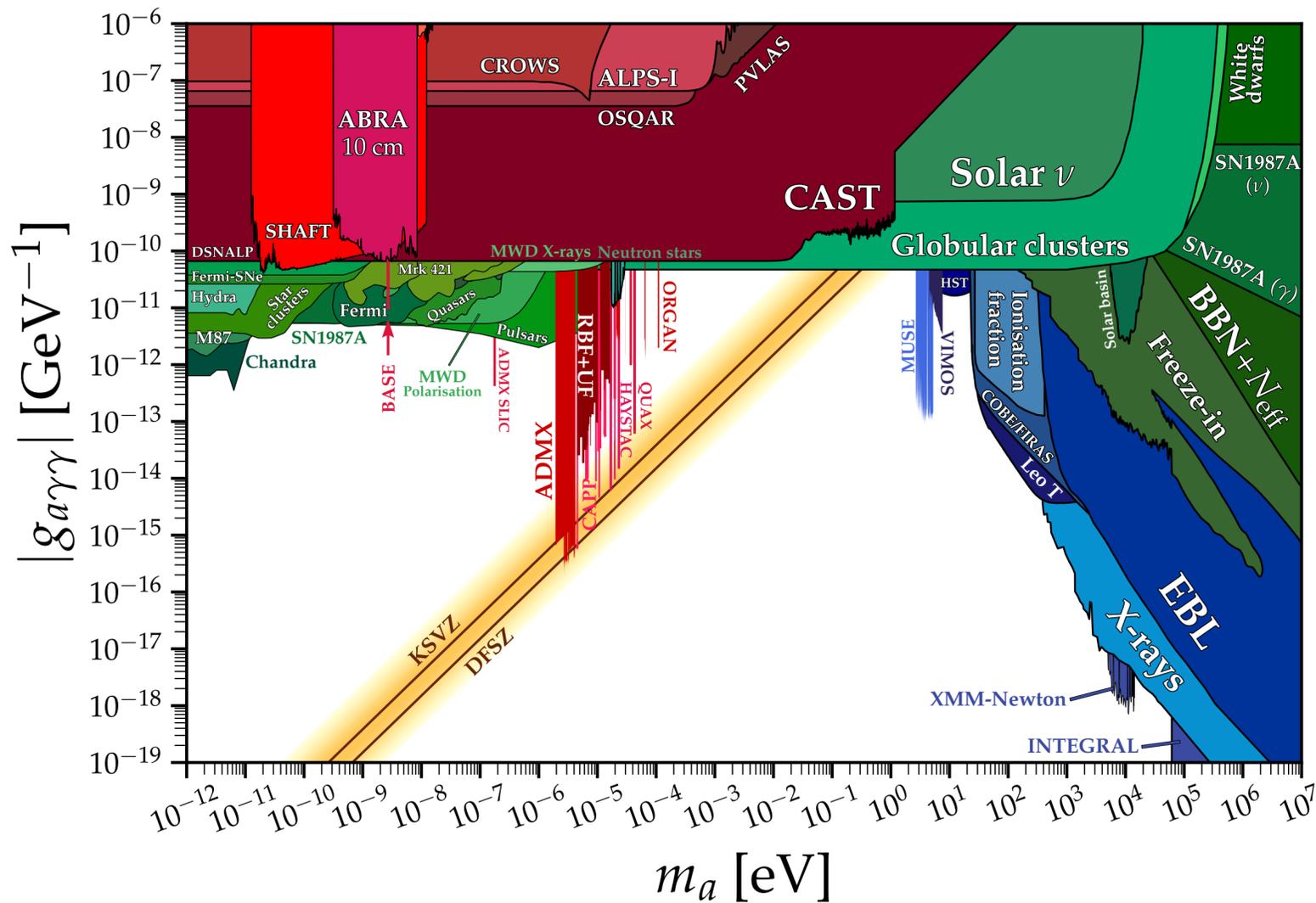
Gap as a function of ϵ

$$n_c = \frac{\epsilon m_\pi^2 f_\pi^2}{4\sigma_\pi N}$$

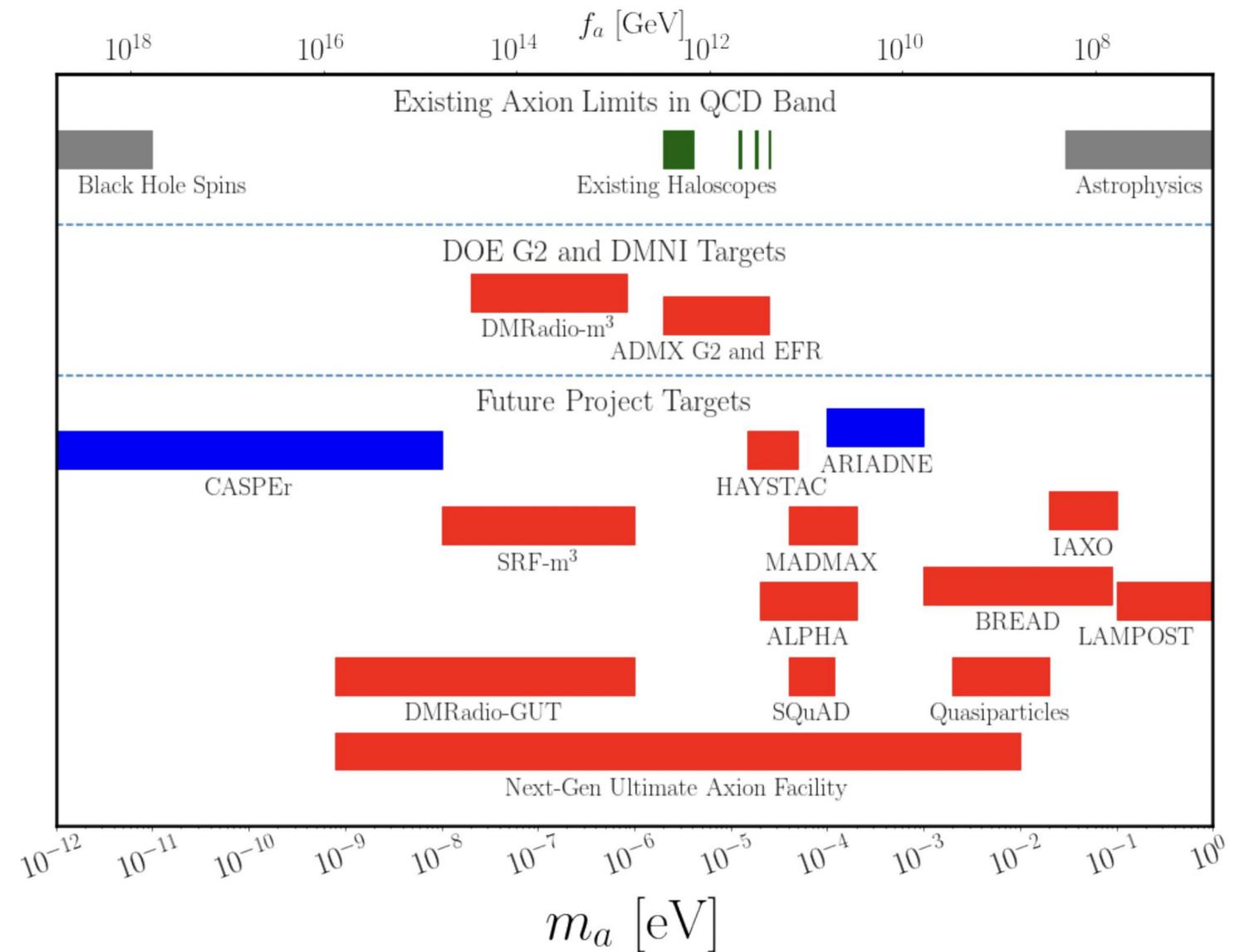
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The QCD Axion: Plethora of experimental searches



<https://github.com/cajohare/AxionLimits>

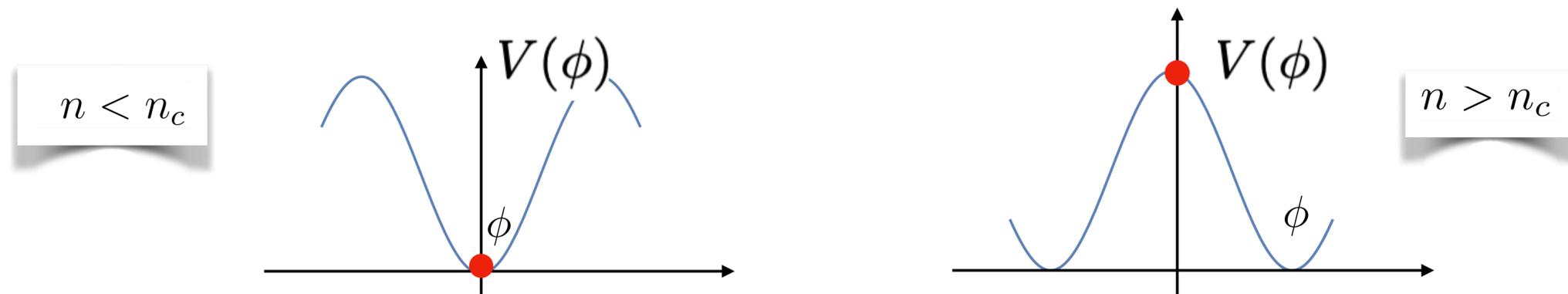


Jaeckel, Rybka, Winslow '22

See e.g. G. Raffelt '06 and Di Luzio Giannotti, Nardi, Visinelli '20

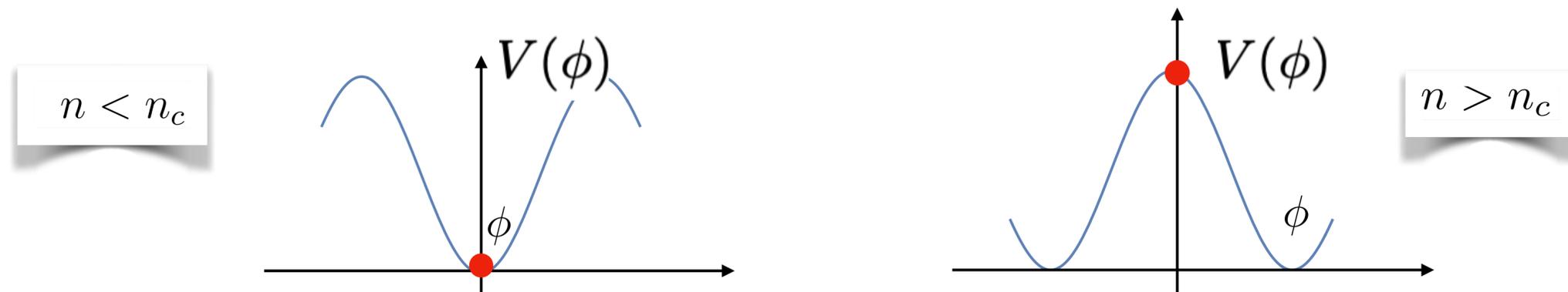
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We gain energy by being in the **true vacuum** inside dense object.



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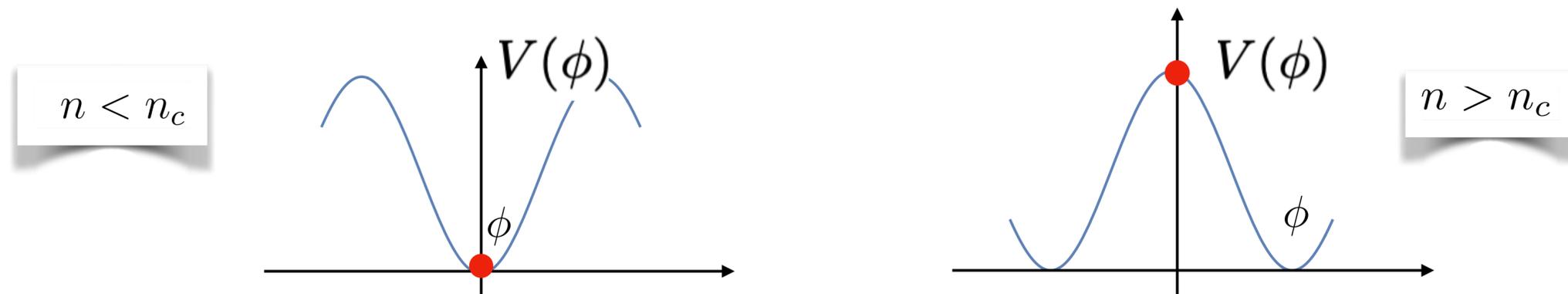
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Resists change in profile

(“string does not want to be bend”)



Why does this not affect large nuclei?

Condition for non-trivial profile:

Potential gain... $m_{\pi}^2 f_{\pi}^2 \left(\epsilon - \frac{\sigma_N n_N}{m_{\pi}^2 f_{\pi}^2} \right)$

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$$r_{\text{critical}} > 1/m_\phi^{\text{inside}}$$

e.g. $f \sim 10^{12} \text{ GeV}$

$$r_{\text{critical}} \sim 0.2 \text{ cm}$$

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Objects must be **large** enough. No effects in particle physics experiments.