

How **axions** change **stars**

DESY Theory Seminar

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March, 2023

Plan

Part 0: Neutron stars and white dwarfs simplified

Part I: White dwarfs as a probe of light QCD axions

Part II: Heavy neutron stars from light scalars

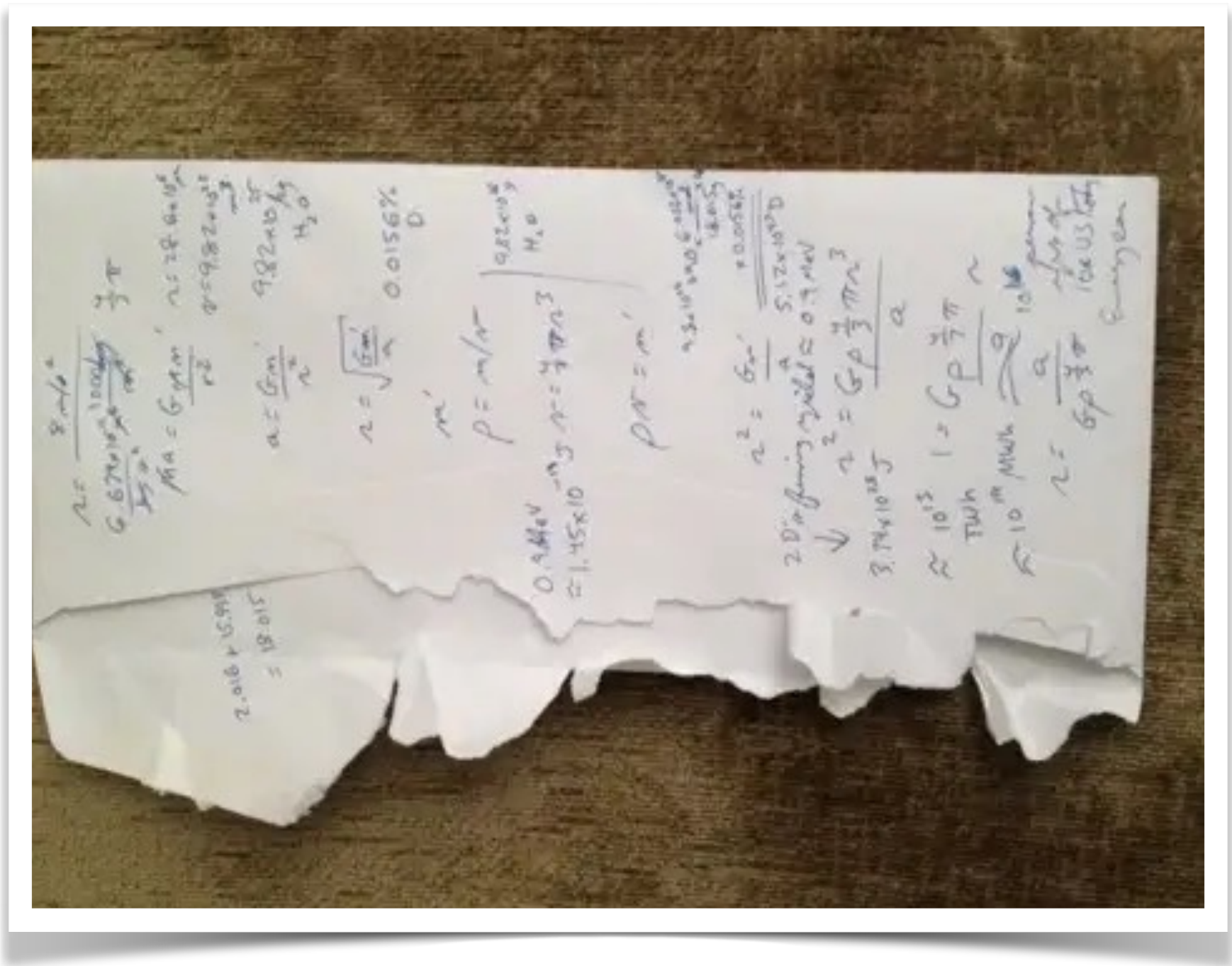
Conclusion and Outlook

Neutron stars



how big? how massive?

Back of the envelope approach



vs.

$$\begin{aligned} \phi'' \left[1 - \frac{2GM}{r} \right] + \frac{2}{r} \phi' \left[1 - \frac{GM}{r} - 2\pi G r^2 (\varepsilon - p) \right] &= \frac{\partial V}{\partial \phi} + \rho \frac{\partial m_{\psi}^*(\phi)}{\partial \phi} \equiv U(\phi, \rho), \\ p' &= -\frac{GM\varepsilon}{r^2} \left[1 + \frac{p}{\varepsilon} \right] \left[1 - \frac{2GM}{r} \right]^{-1} \left[1 + \frac{4\pi r^3}{M} \left(p + \frac{(\phi')^2}{2} \left\{ 1 - \frac{2GM}{r} \right\} \right) \right] - \phi' U(\phi, \rho), \\ M' &= 4\pi r^2 \left[\varepsilon + \frac{1}{2} \left(1 - \frac{2GM}{r} \right) (\phi')^2 \right]. \end{aligned}$$

Neutron stars simplified

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

$$E_{\text{Fermi}}/N = m_N \quad (\text{nucleon mass})$$

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

with $N \sim R_{\text{NS}}^3 \cdot n \sim R_{\text{NS}}^3 m_N^3$

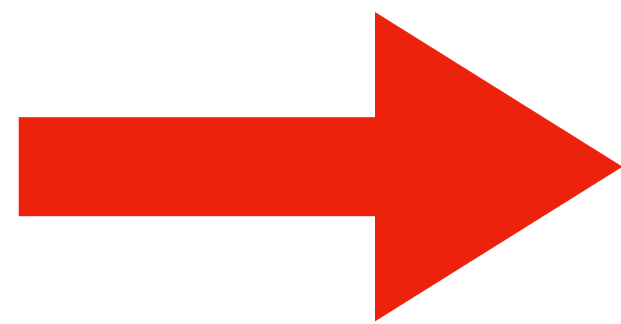
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$$R_{\text{NS}} \sim \frac{M_{\text{Planck}}}{m_N^2}$$

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Neutron star estimate

$$R_{\text{NS}} \sim \frac{M_{\text{Planck}}}{m_N^2} \quad M_{\text{NS}} \sim \frac{M_{\text{Planck}}^3}{m_N^2}$$

$$R_{\text{NS}} \sim (\text{few}) \text{ km} \quad M_{\text{NS}} \sim (\text{few}) 10^{30} \text{ kg} \sim M_{\odot}$$

Mass of the sun within a few km!

Planck scale

$$M_{\text{Planck}} \approx 10^{19} \text{ GeV}$$

nucleon mass

$$M_N \approx 1 \text{ GeV}$$

Neutron star estimate

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Let's compare to data!

Neutron stars: mass vs. radius

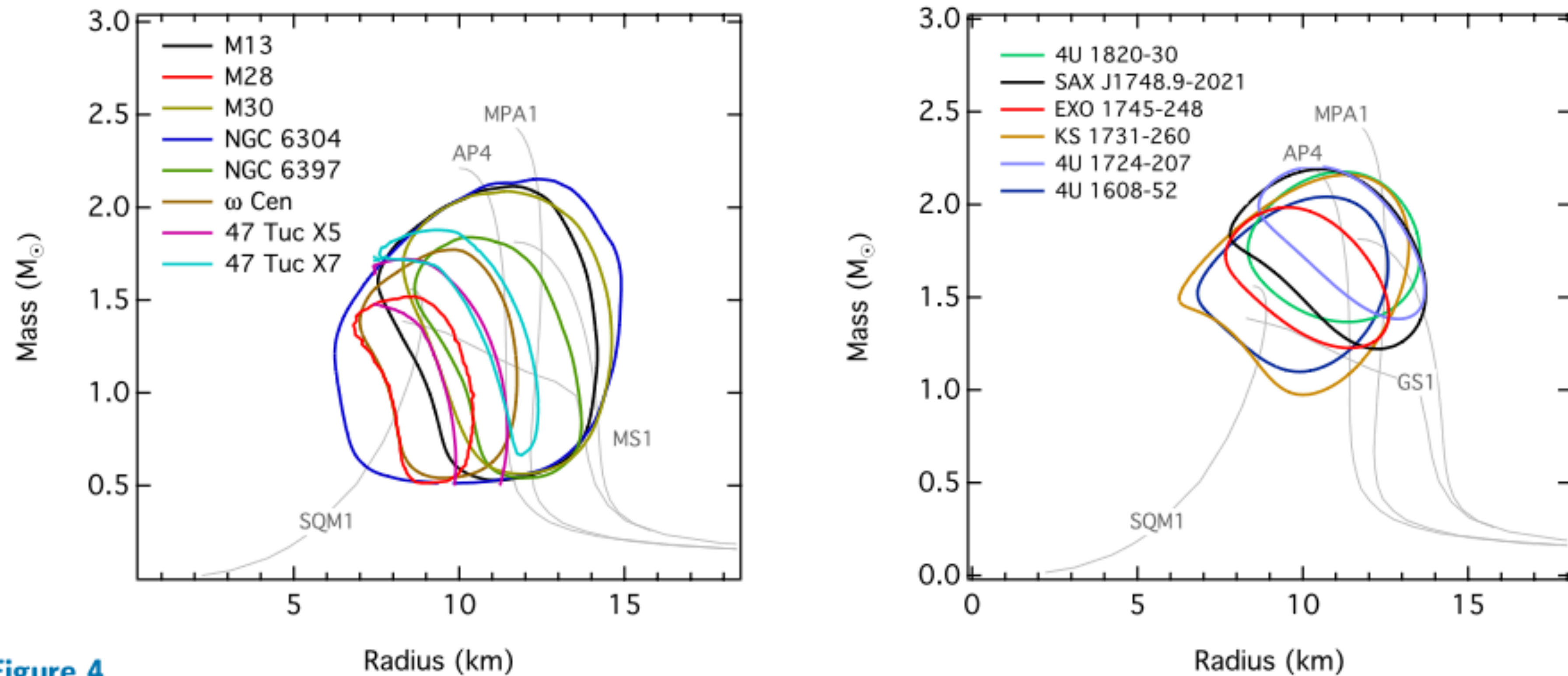
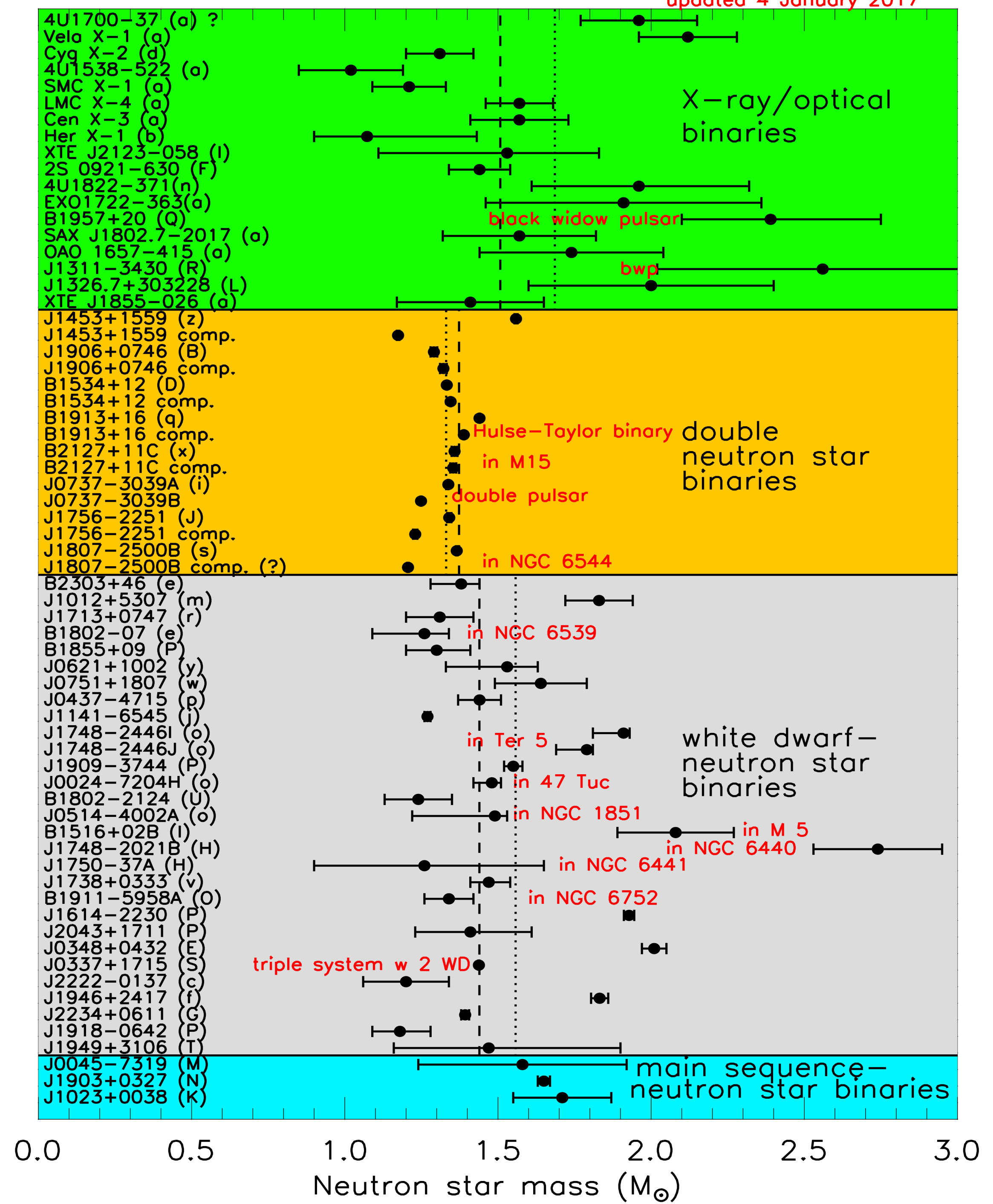
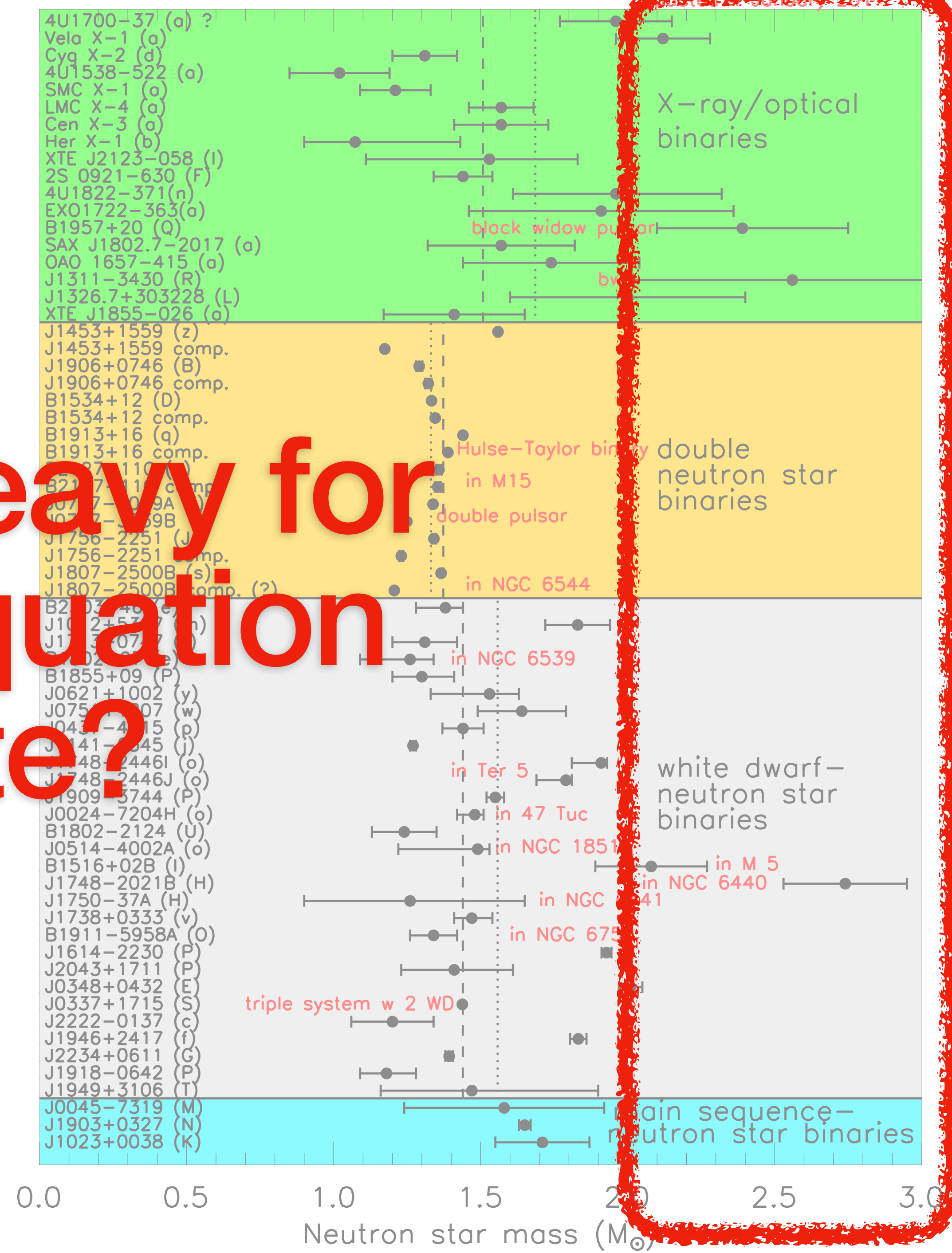


Figure 4

The combined constraints at the 68% confidence level over the neutron star mass and radius obtained from (Left) all neutron stars in low-mass X-ray binaries during quiescence (Right) all neutron stars with thermonuclear bursts. The light grey lines show mass-relations corresponding to a few representative equations of state (see Section 4.1 and Fig. 7 for detailed descriptions.)

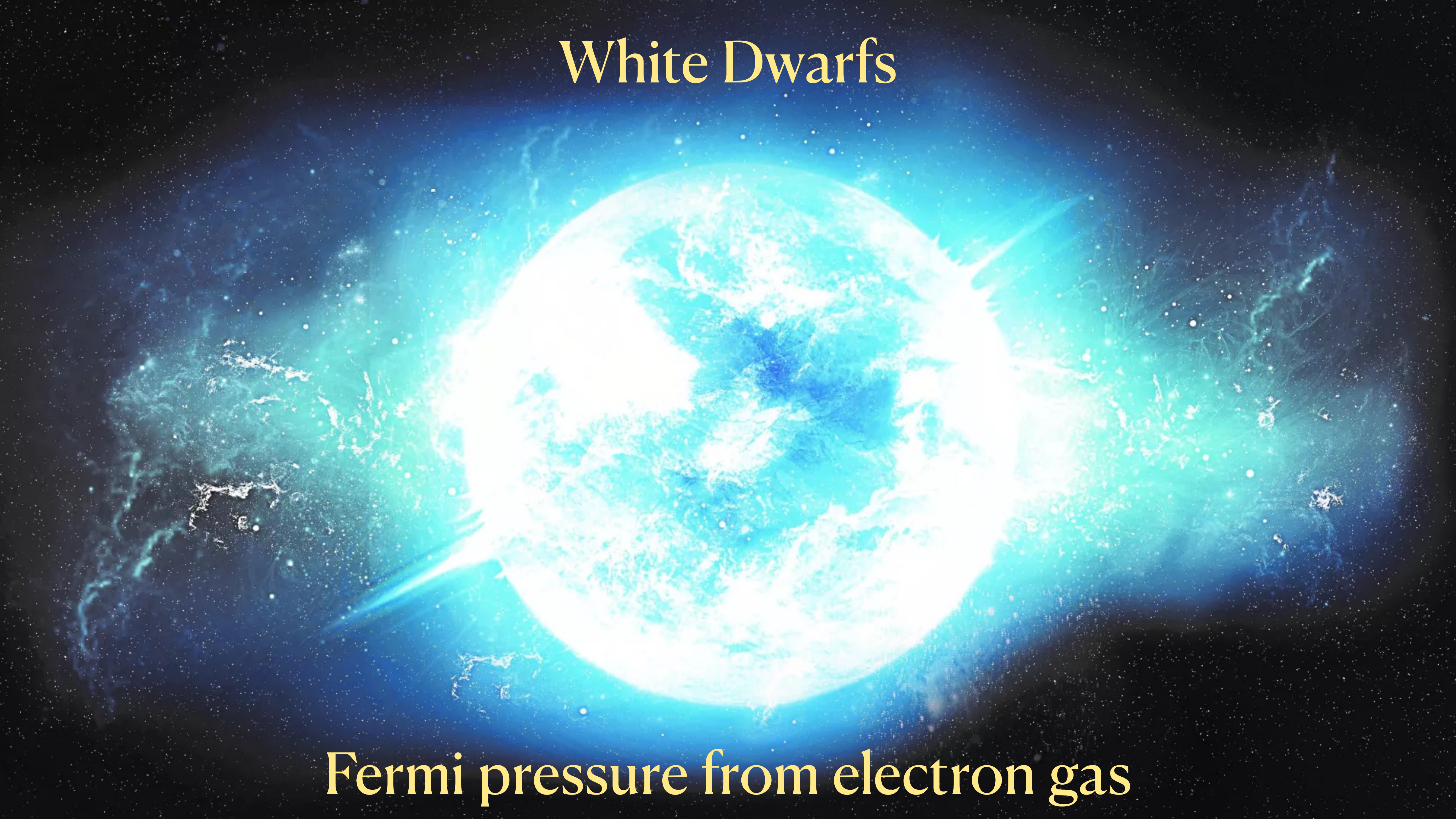


Too heavy for
SM equation
of state?



White Dwarfs

Fermi pressure from electron gas



White dwarf simplified


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

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

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

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

White dwarf simplified

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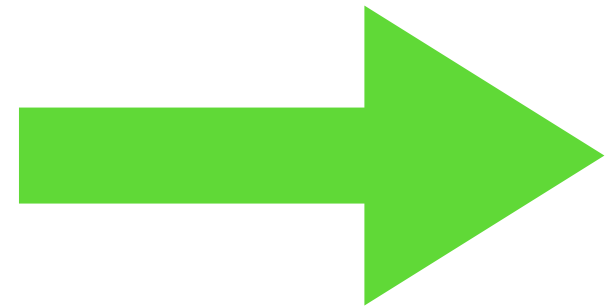
$$R_{\text{WD}} \sim \frac{M_{\text{planck}}}{m_e m_N} \sim \frac{m_N}{m_e} R_{\text{NS}}$$

larger radius

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

same mass

White dwarf estimate



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

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

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

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

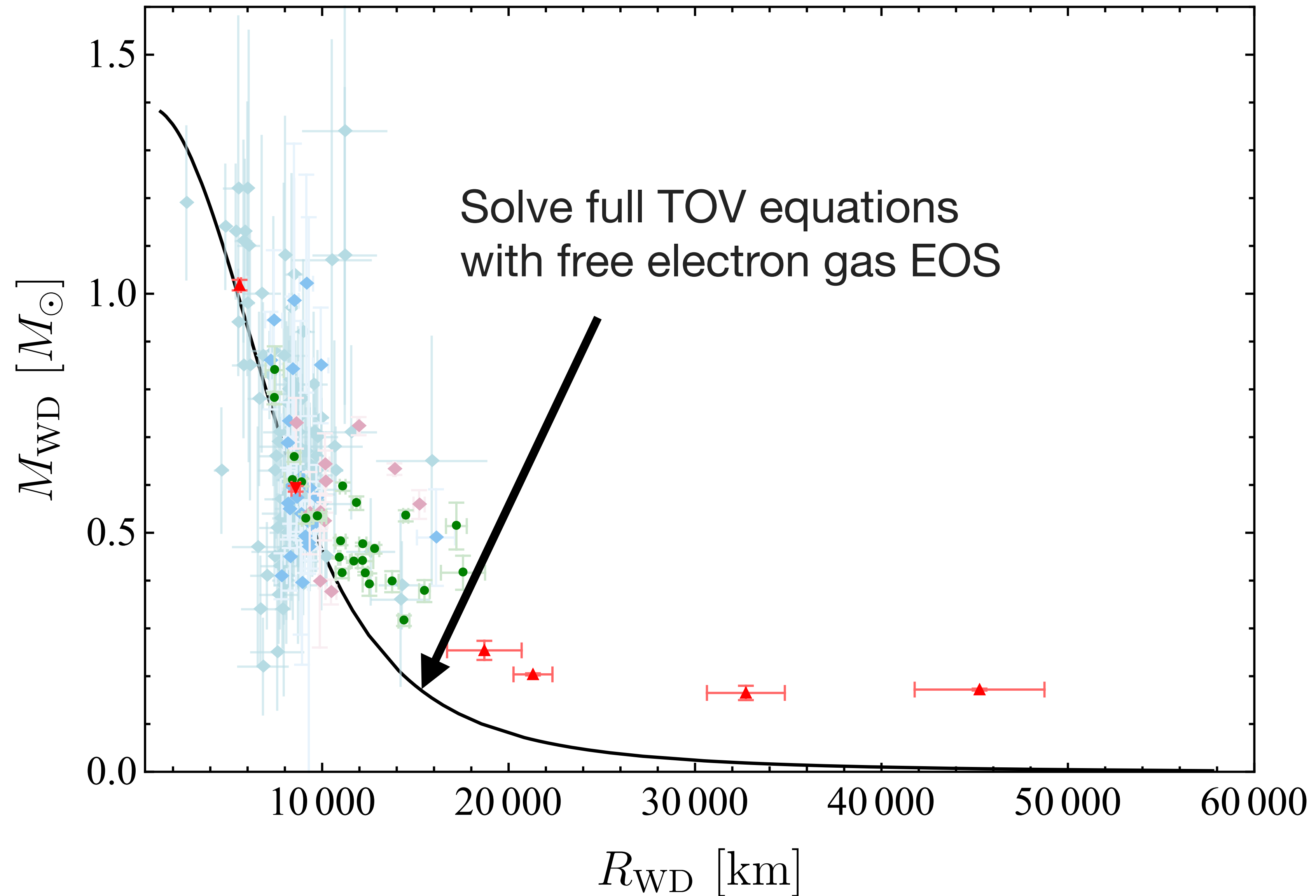
Mass of the sun at the size of the earth!

electron mass $m_e = 0.51099895000(15) \text{ MeV}$

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

nucleon mass $M_N \approx 1 \text{ GeV}$

White dwarf mass-radius curve



So let's use these very dense objects to study light QCD axions

Part I: White dwarfs as a probe of light QCD axions

Based on arXiv: 2211.02661

- Axions and their properties at finite density
- Toy Model: Equation of state of free Fermi gas with axion
- White dwarfs and the axion

The QCD Axion: Motivated by the strong CP Problem

CP violation in the strong sector

$$\mathcal{L}_{\text{QCD}} = \sum_q \bar{q} (i\not{D} - m_q e^{i\theta_q}) q - \frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a - \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{\mu\nu}^a$$

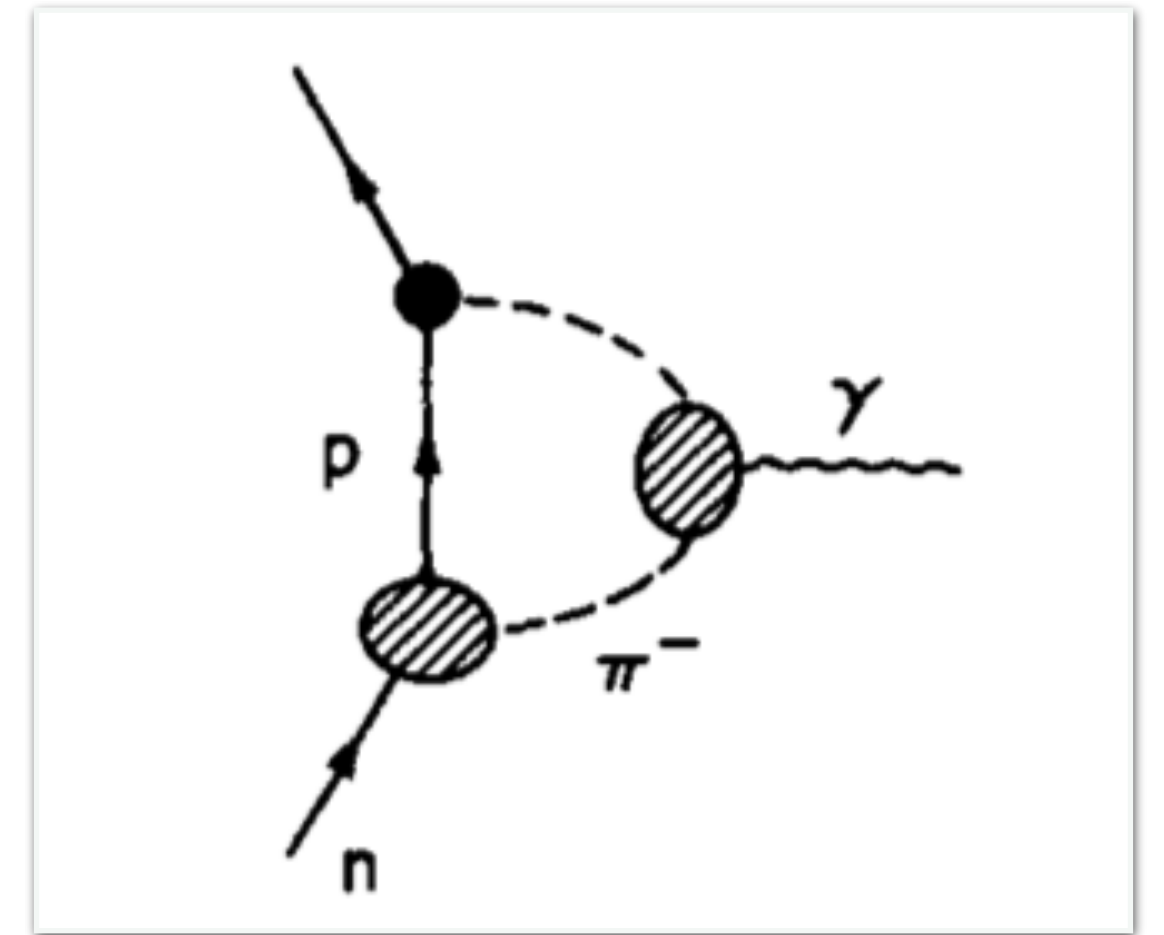
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Predicts a neutron EDM

$$\mathcal{L}_\chi \supset d_n \bar{n} \sigma^{\mu\nu} \gamma_5 n F_{\mu\nu}$$



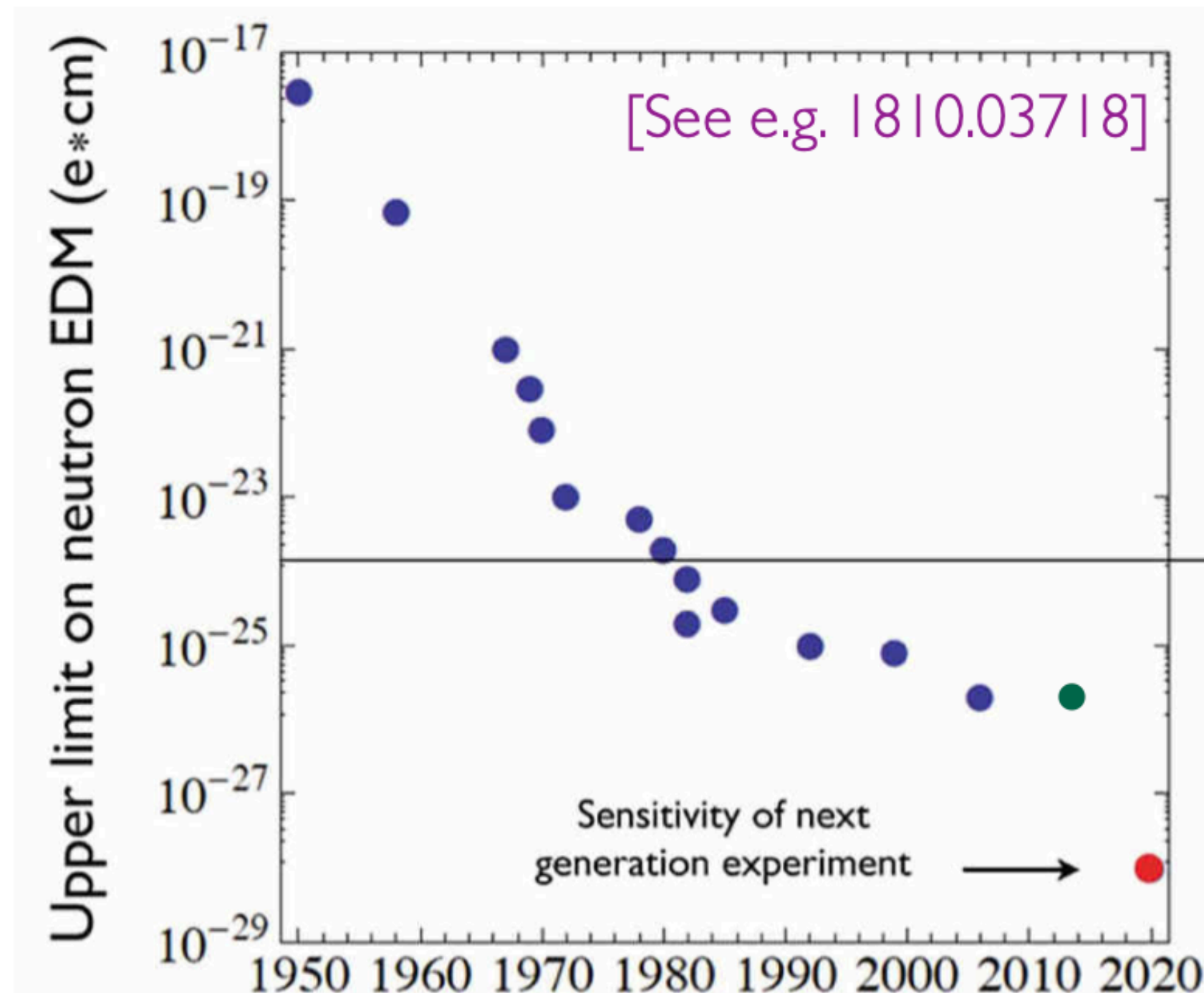
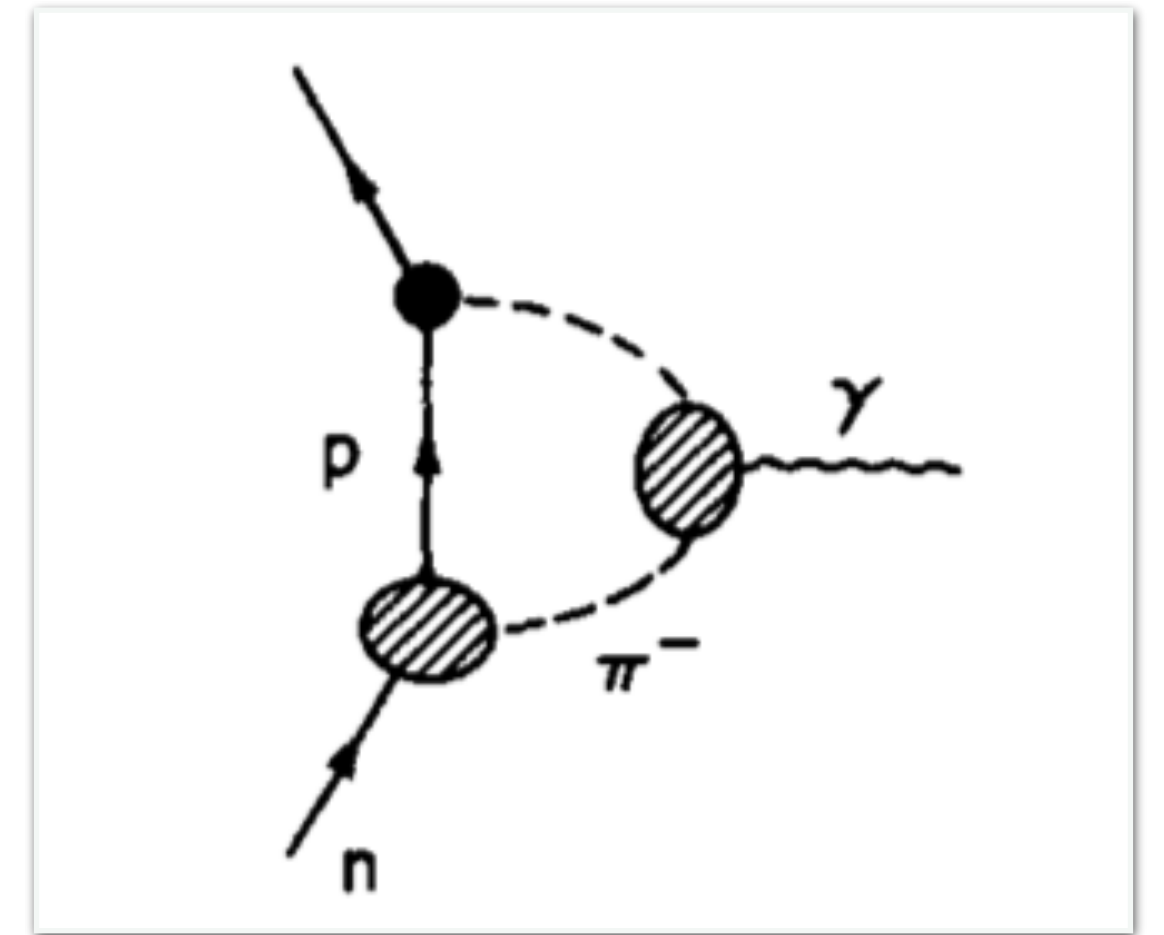
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$$d_n \approx \frac{e |\bar{\theta}| m_\pi^2}{m_n^3} \approx 10^{-16} |\bar{\theta}| e \text{ cm}$$

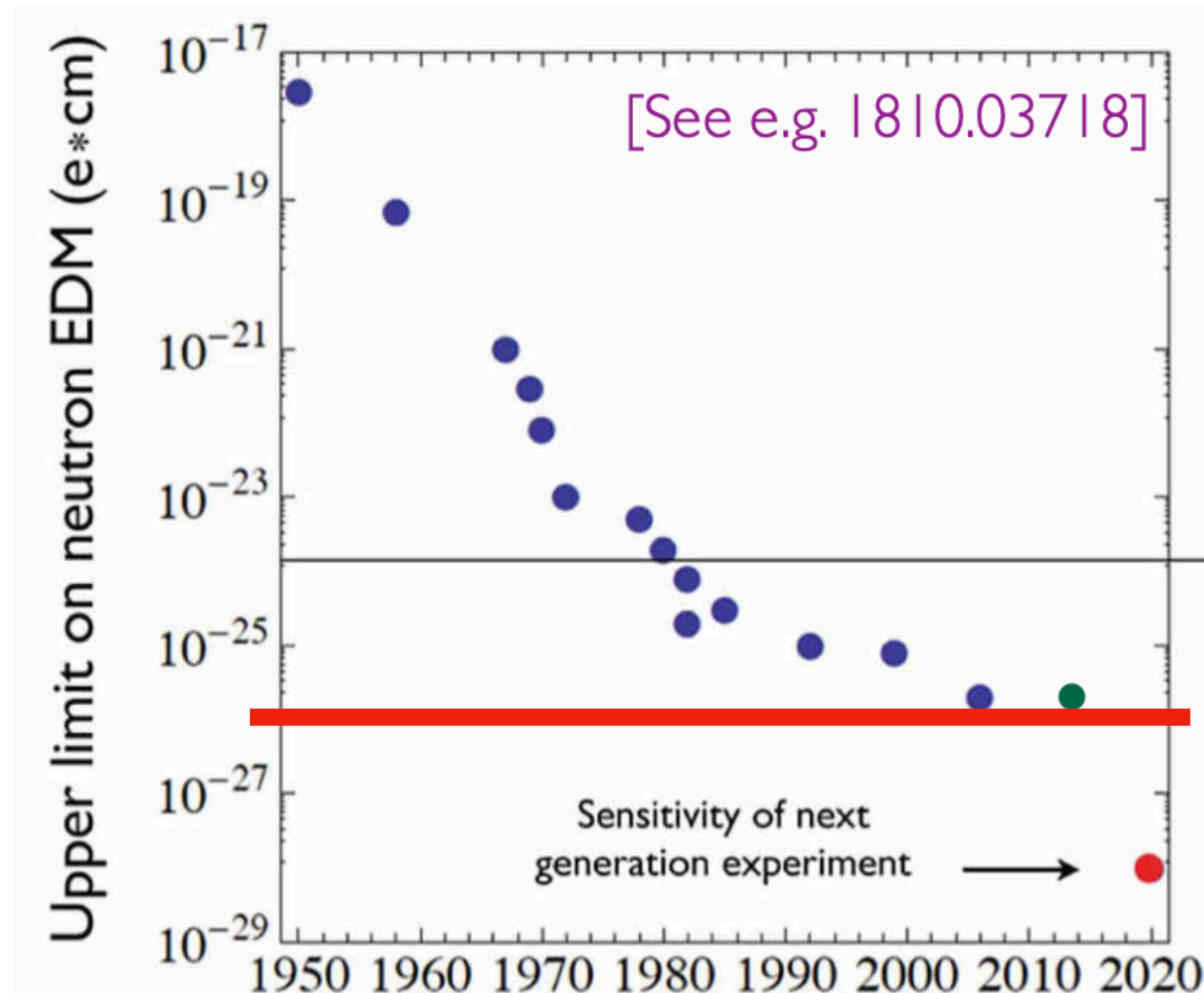
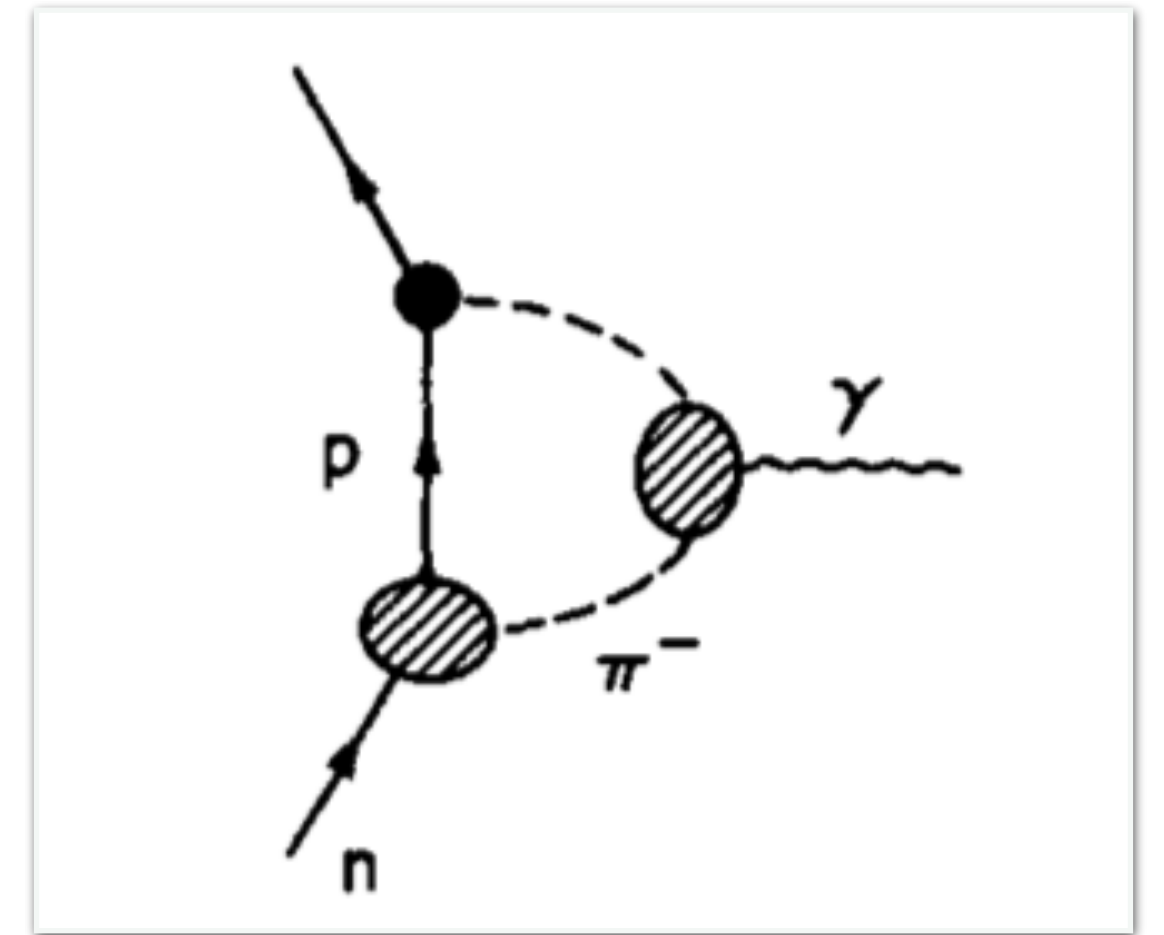
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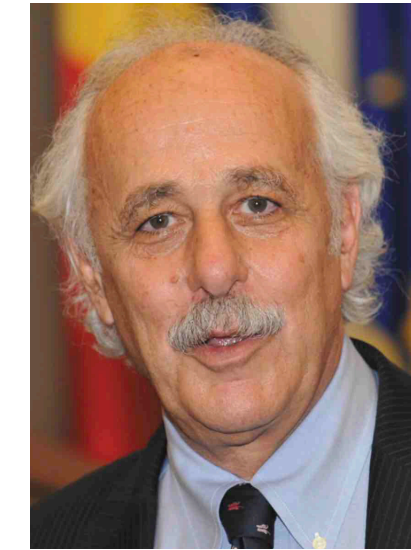
$$d_n \approx \frac{e |\bar{\theta}| m_\pi^2}{m_n^3} \approx 10^{-16} |\bar{\theta}| e \text{ cm}$$

Why so small?

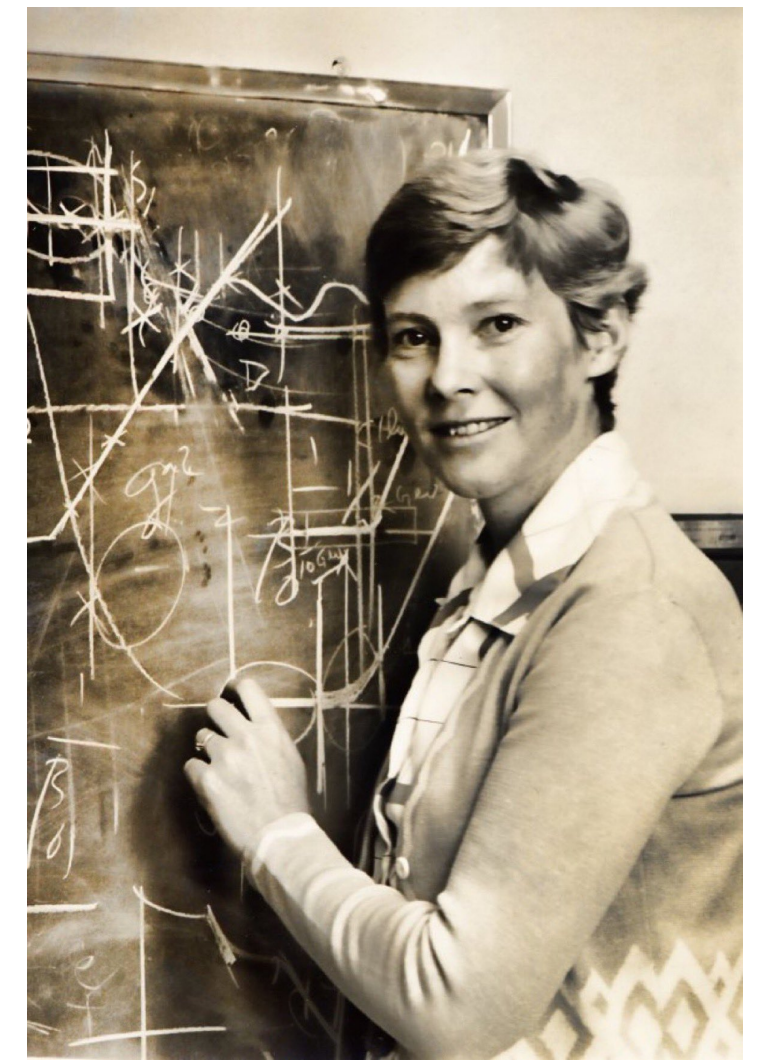
$$|\bar{\theta}| \lesssim 10^{-10}$$

The QCD Axion: Solution

- Axial PQ symmetry $U(1)_{\text{PQ}}$: spontaneously broken at the scale $\sim f$
- Explicitly broken at the quantum level by QCD anomaly
- pseudo-Nambu-Goldstone Boson (pNGB) arises: the QCD axion $\phi(x)$



Roberto Peccei



Helen Quinn

$$\mathcal{L} = \left(\frac{\phi(x)}{f_a} - \bar{\theta} \right) \frac{\alpha_s}{8\pi} G^{\mu\nu a} \tilde{G}_{\mu\nu}^a$$

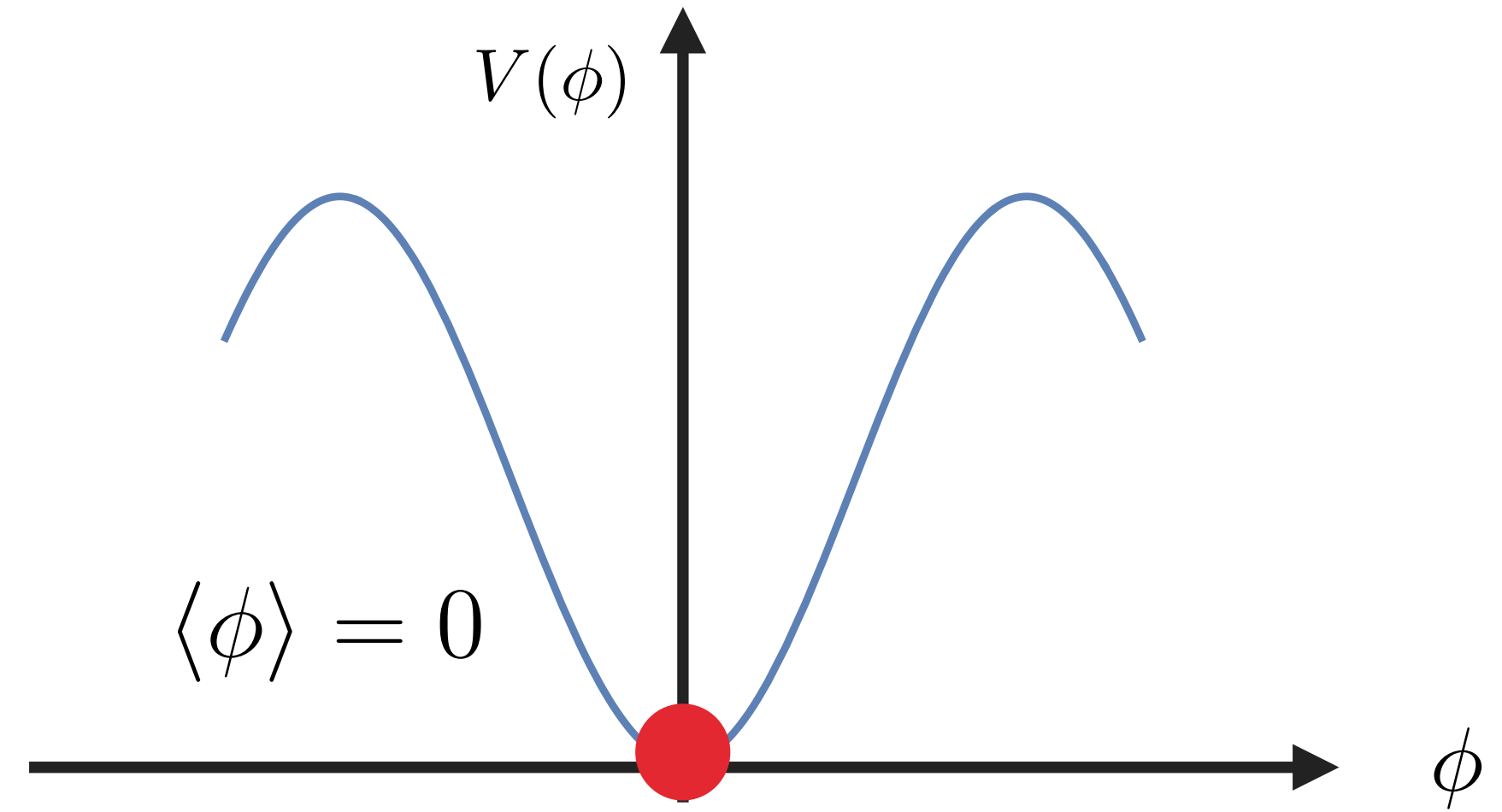
- Non-perturbative axion potential **relaxes to CP conserving minimum** below the QCD scale

$$\bar{\theta}_{\text{eff}} \equiv \langle \phi \rangle / f_a - \bar{\theta} \rightarrow 0$$

The QCD Axion: At low energies

Non-perturbative effects generate potential Λ_{QCD}

$$\frac{g_s^2}{32\pi^2} \frac{\phi}{f} G\tilde{G} \quad \xrightarrow{\text{UV} \rightarrow \text{IR}}$$



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

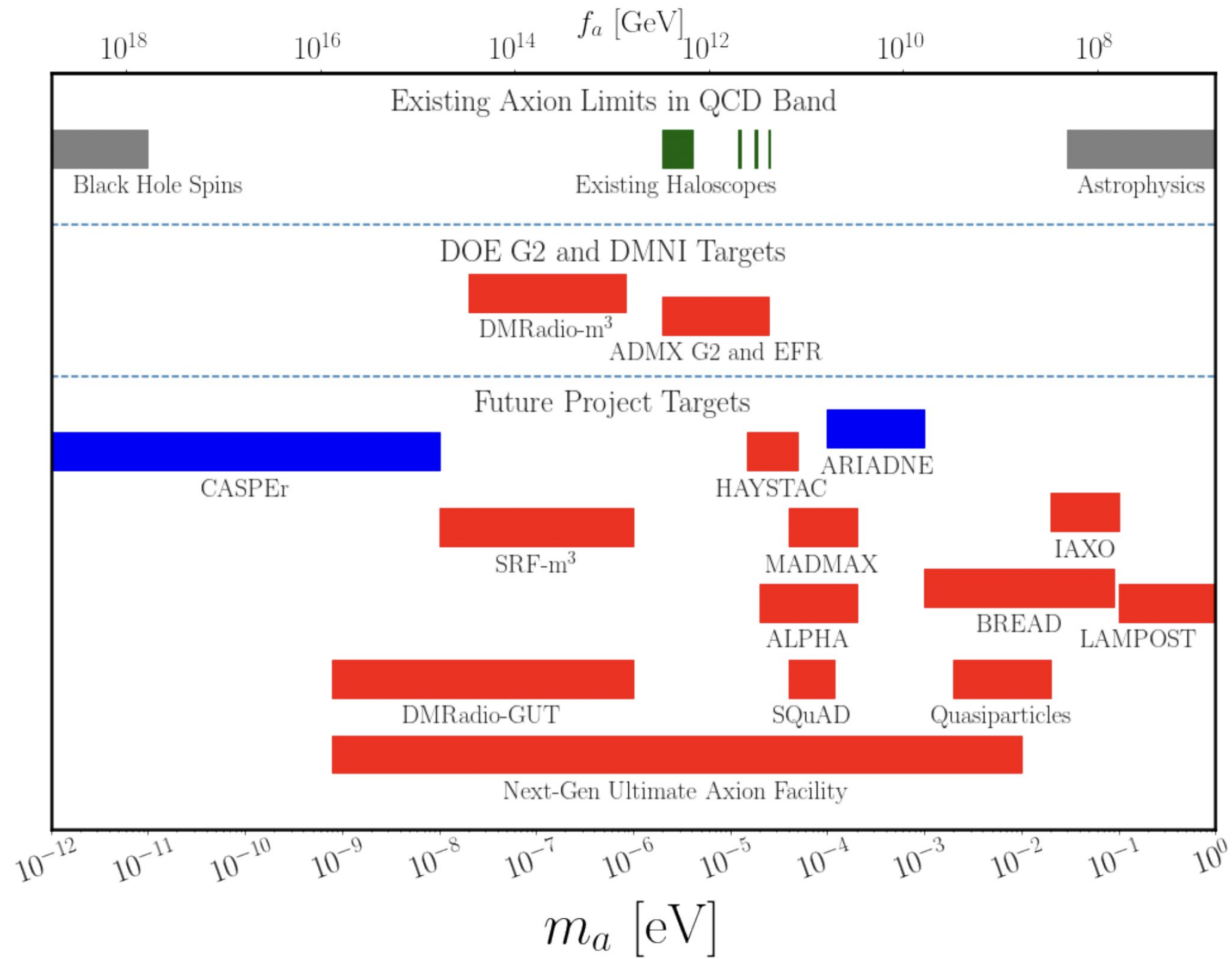
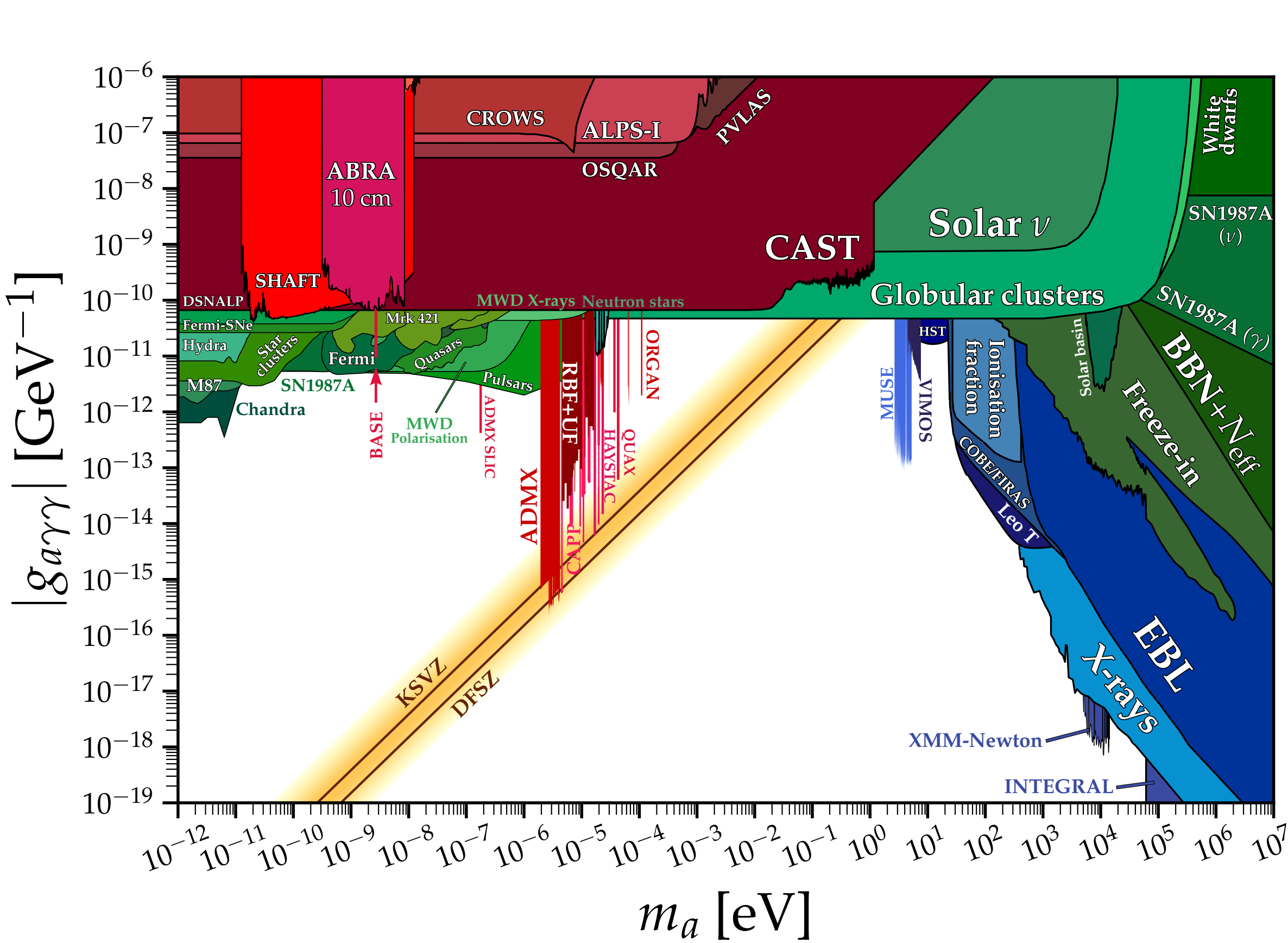
The QCD axion is very **predictive**

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

Couplings to nucleons, photons, electrons,...

Determined by the scale f

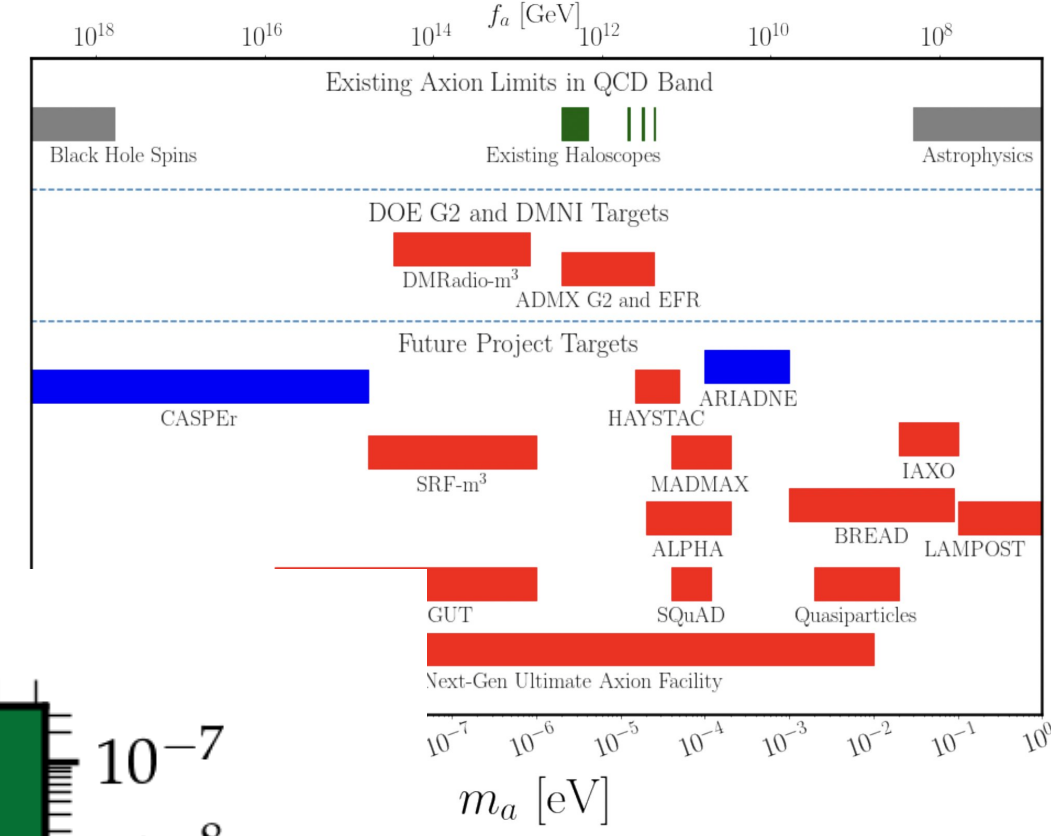
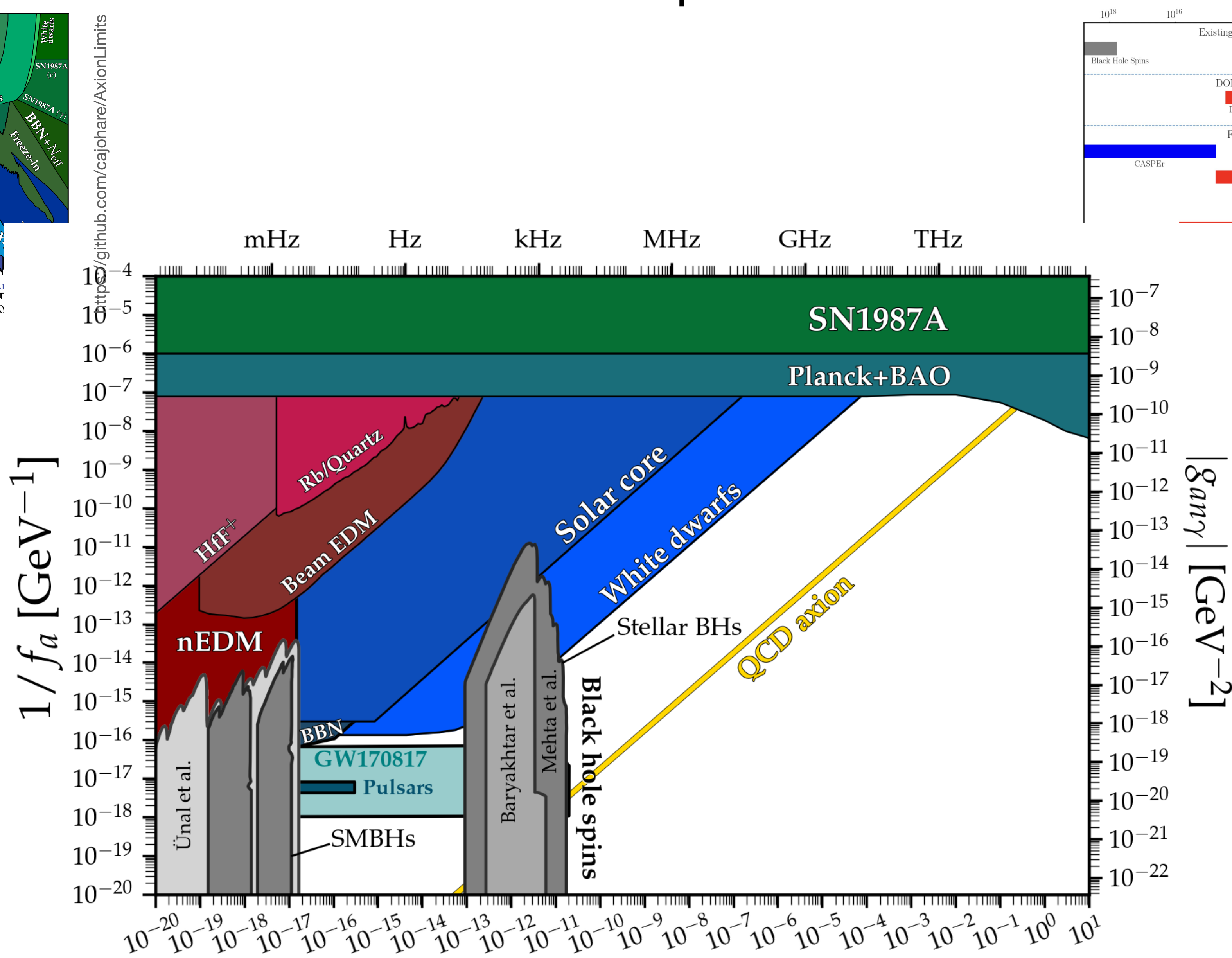
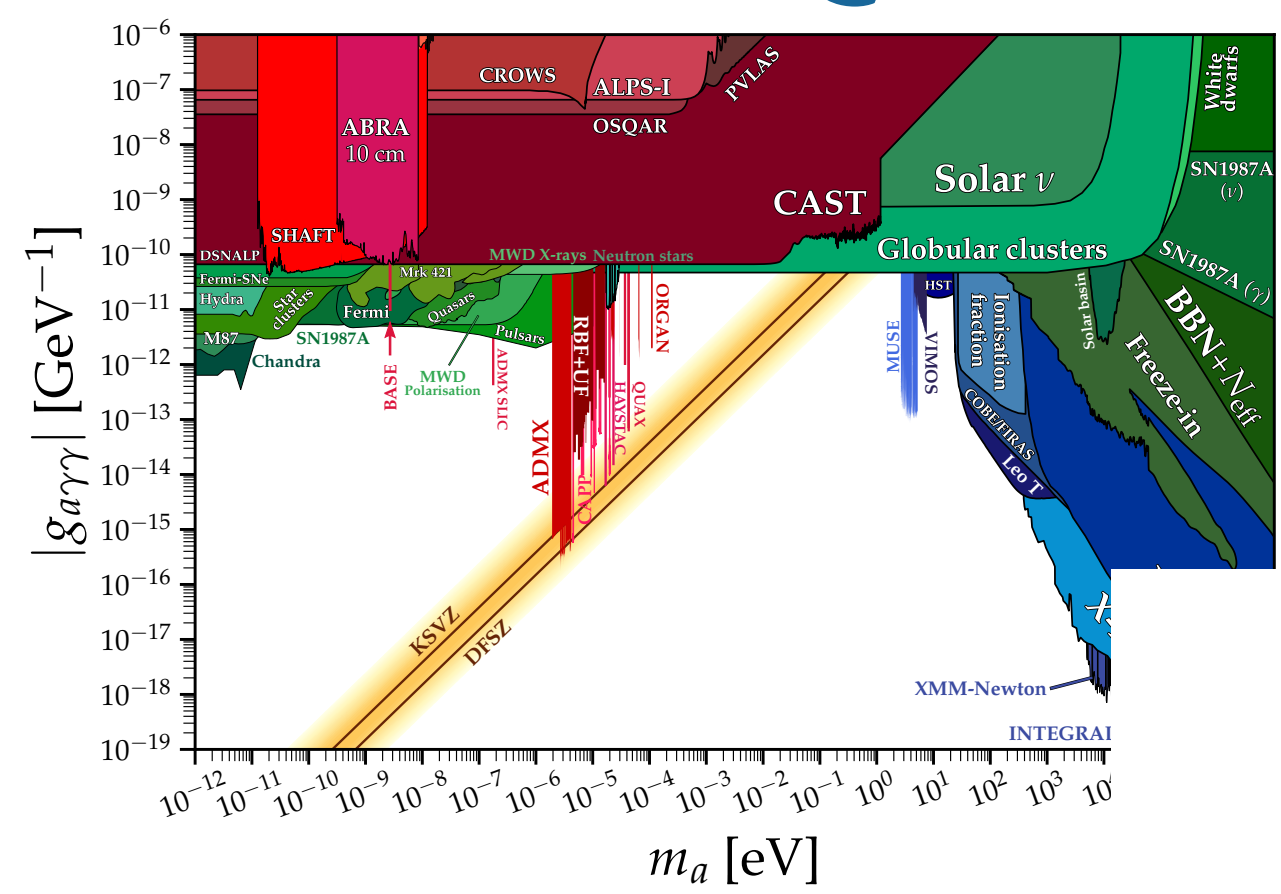
The QCD Axion: Plethora of experimental searches



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

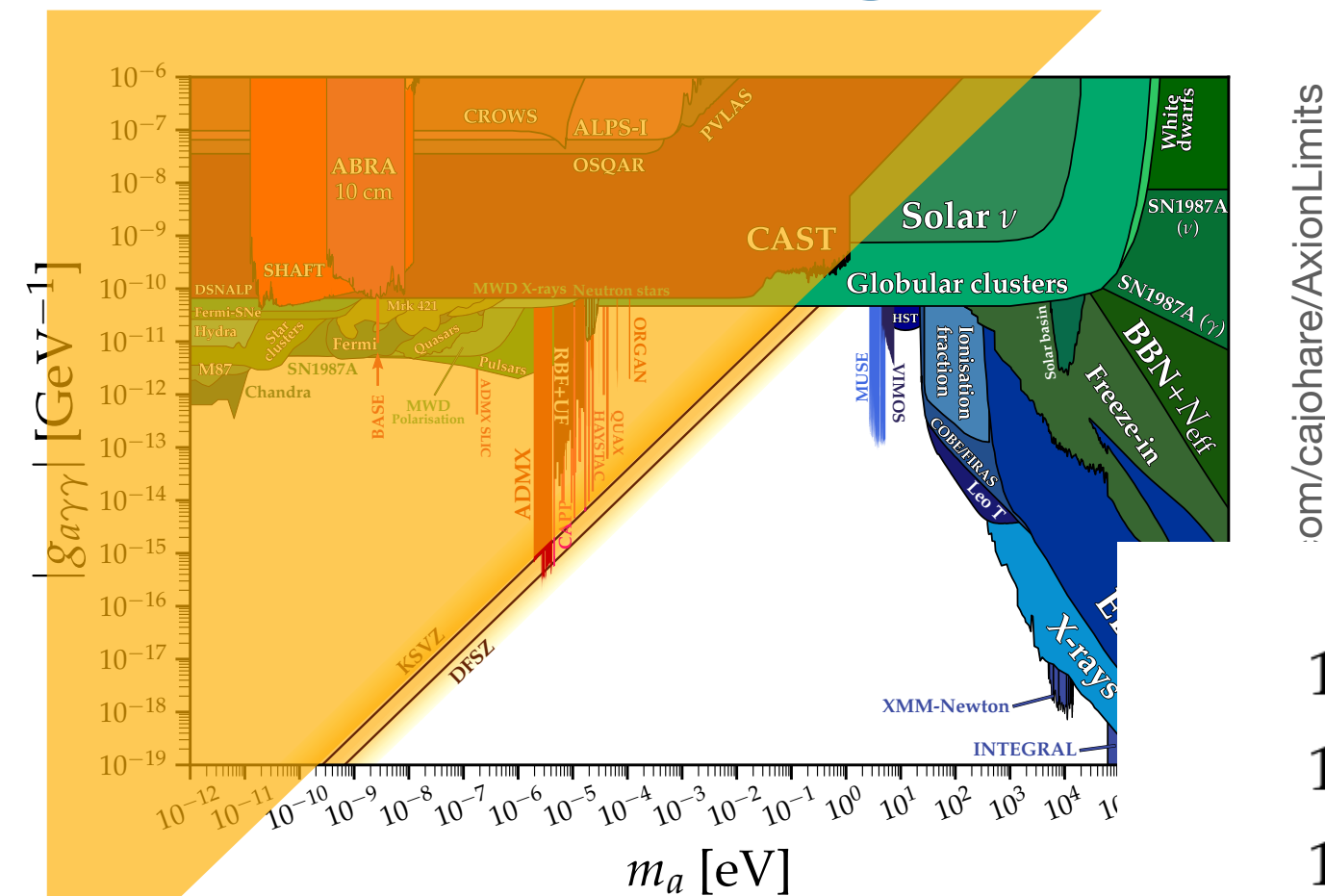
Jaeckel, Rybka, Winslow '22

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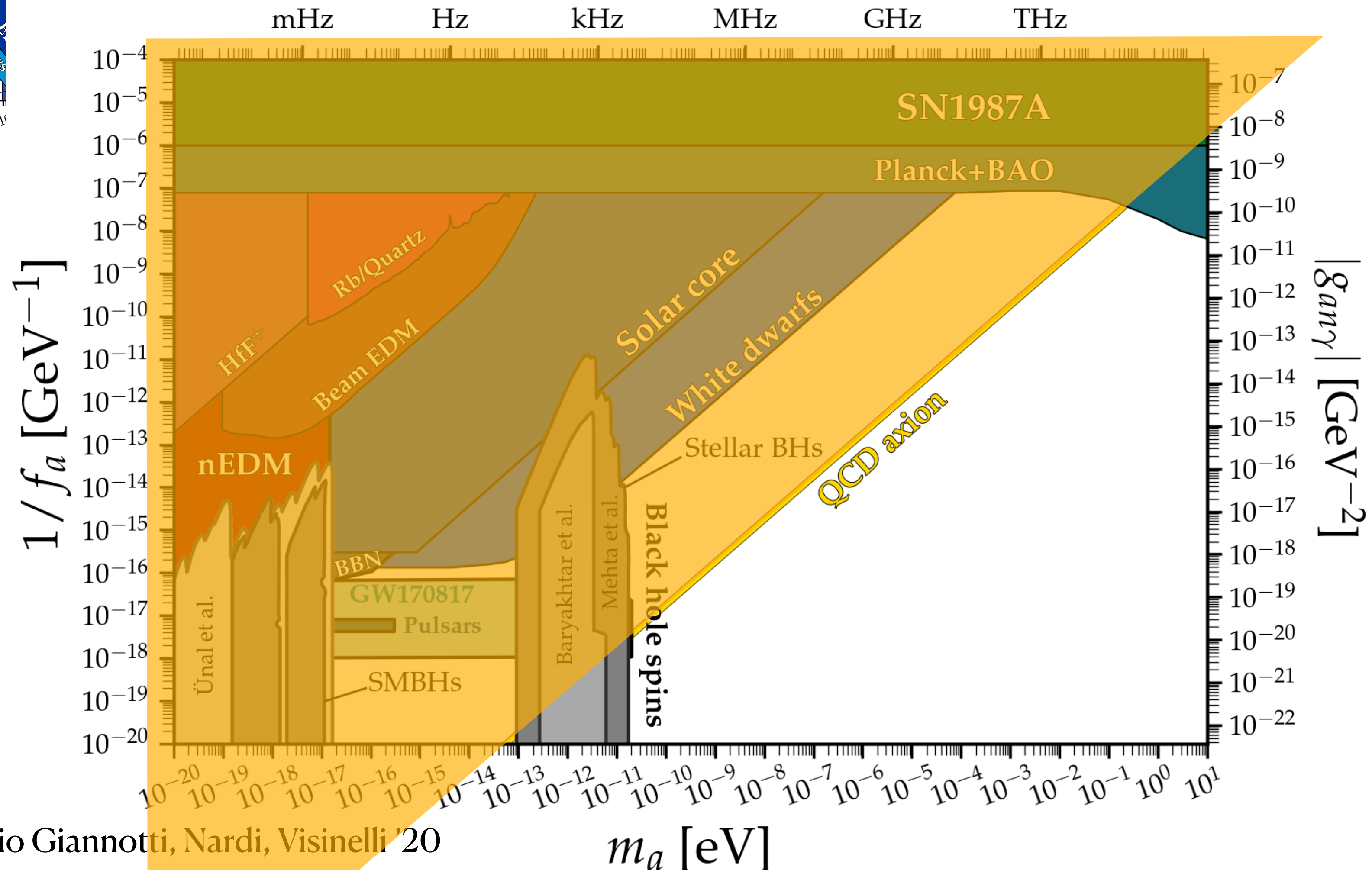


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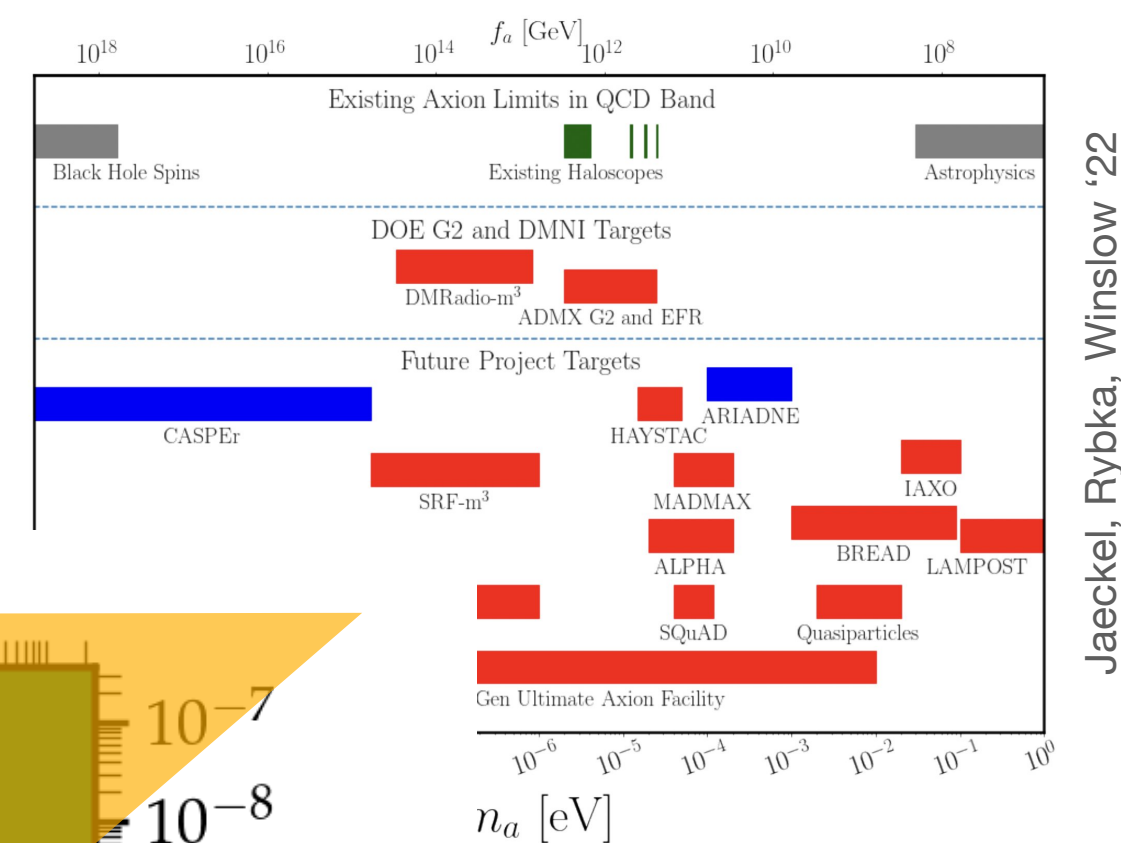
The QCD Axion: Plethora of experimental searches



om/cajohare/AxionLimits



Interesting region



Jaeckel, Rybka, Winslow '22

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

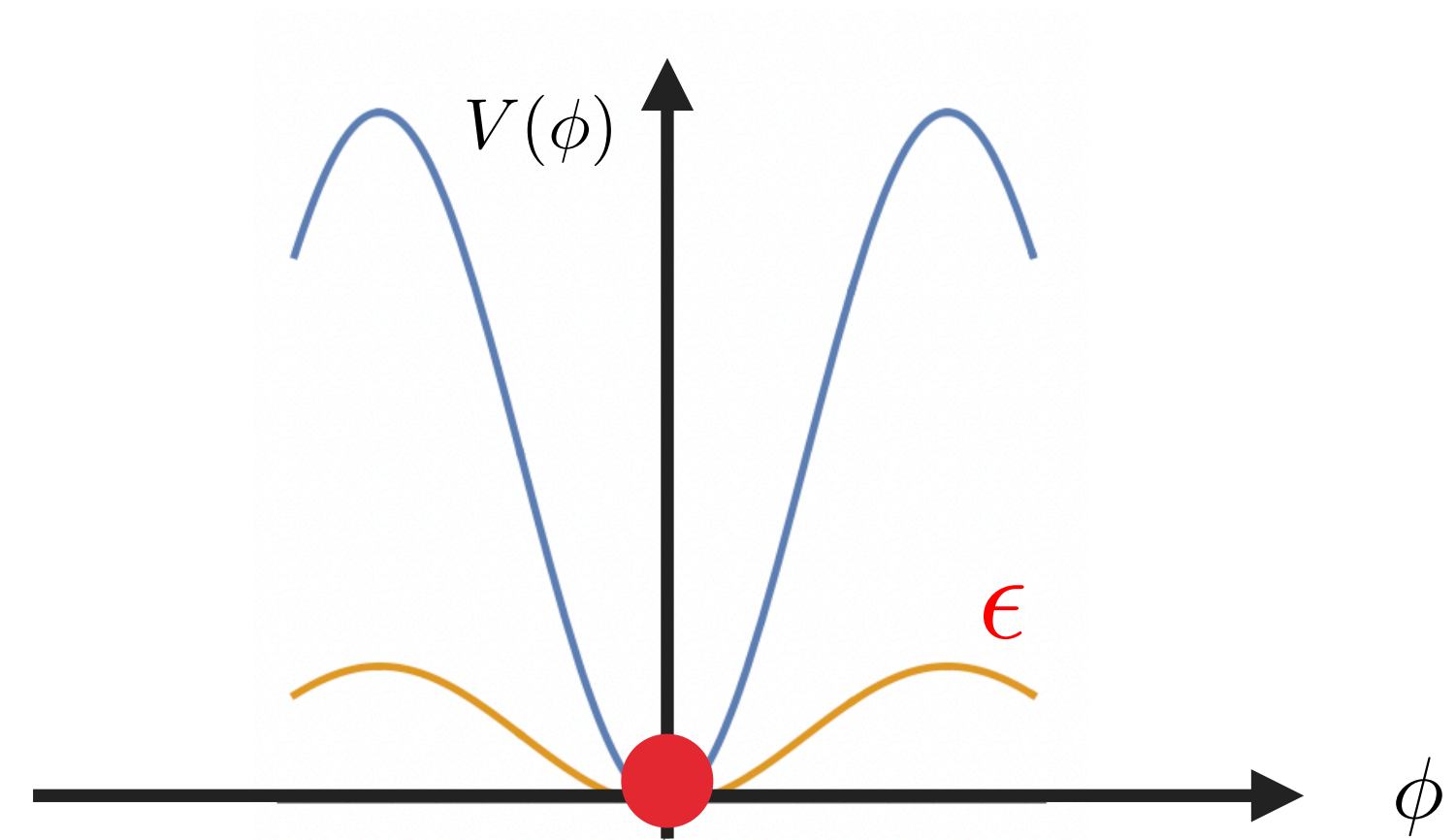
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 m_a [eV]

Light QCD Axions

Non-perturbative effects generate potential

$$\frac{g_s^2}{32\pi^2} \frac{\phi}{f} G\tilde{G} \quad \xrightarrow{\text{UV} \rightarrow \text{IR}}$$

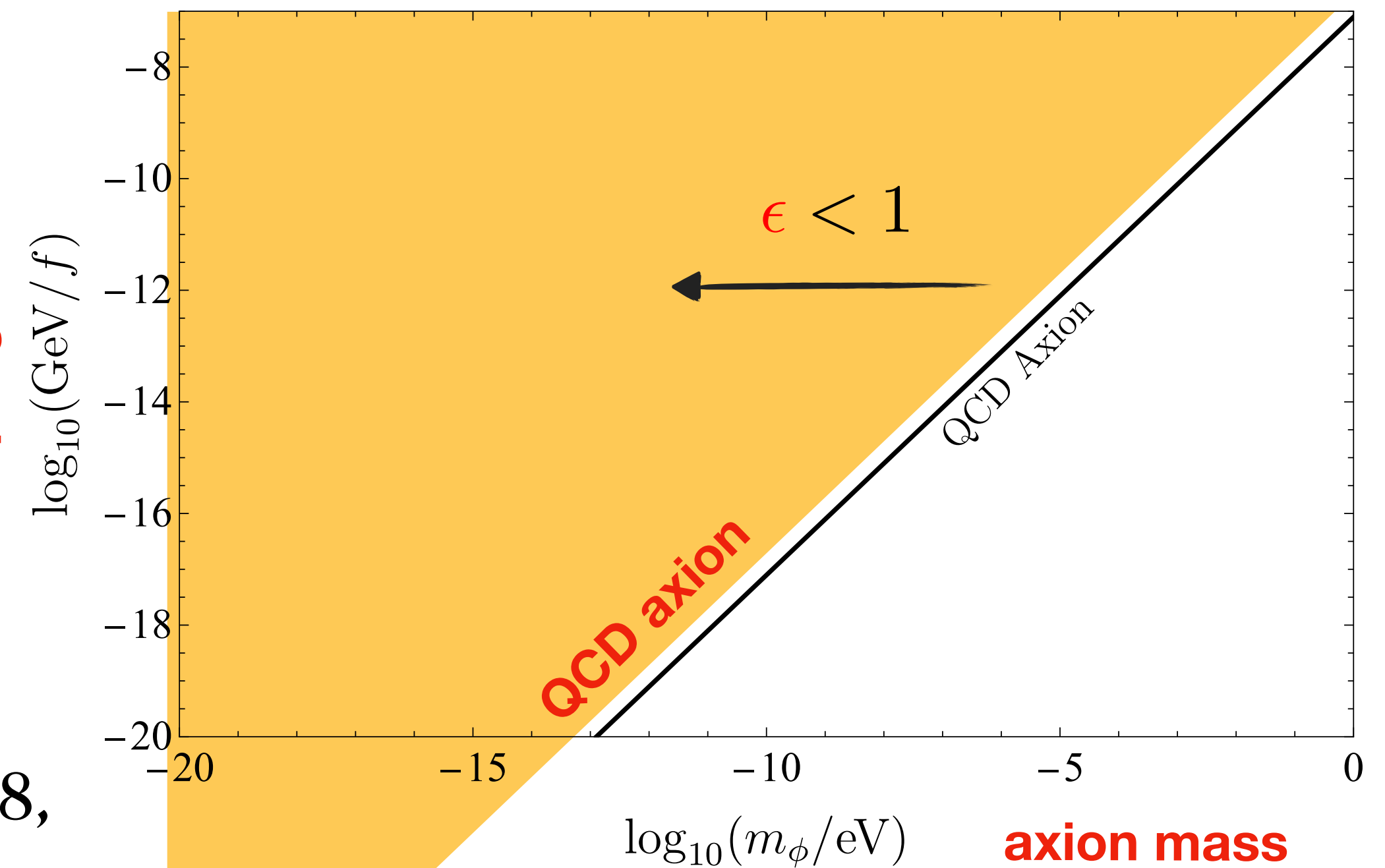


$$V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4} \left[\cos\left(\frac{\phi}{f}\right) - 1 \right]$$

... with smaller mass

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

axion coupling



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

QCD Axion: Coupling to nucleons

Nuclear Chiral Perturbation Theory with QCD axion

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

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

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

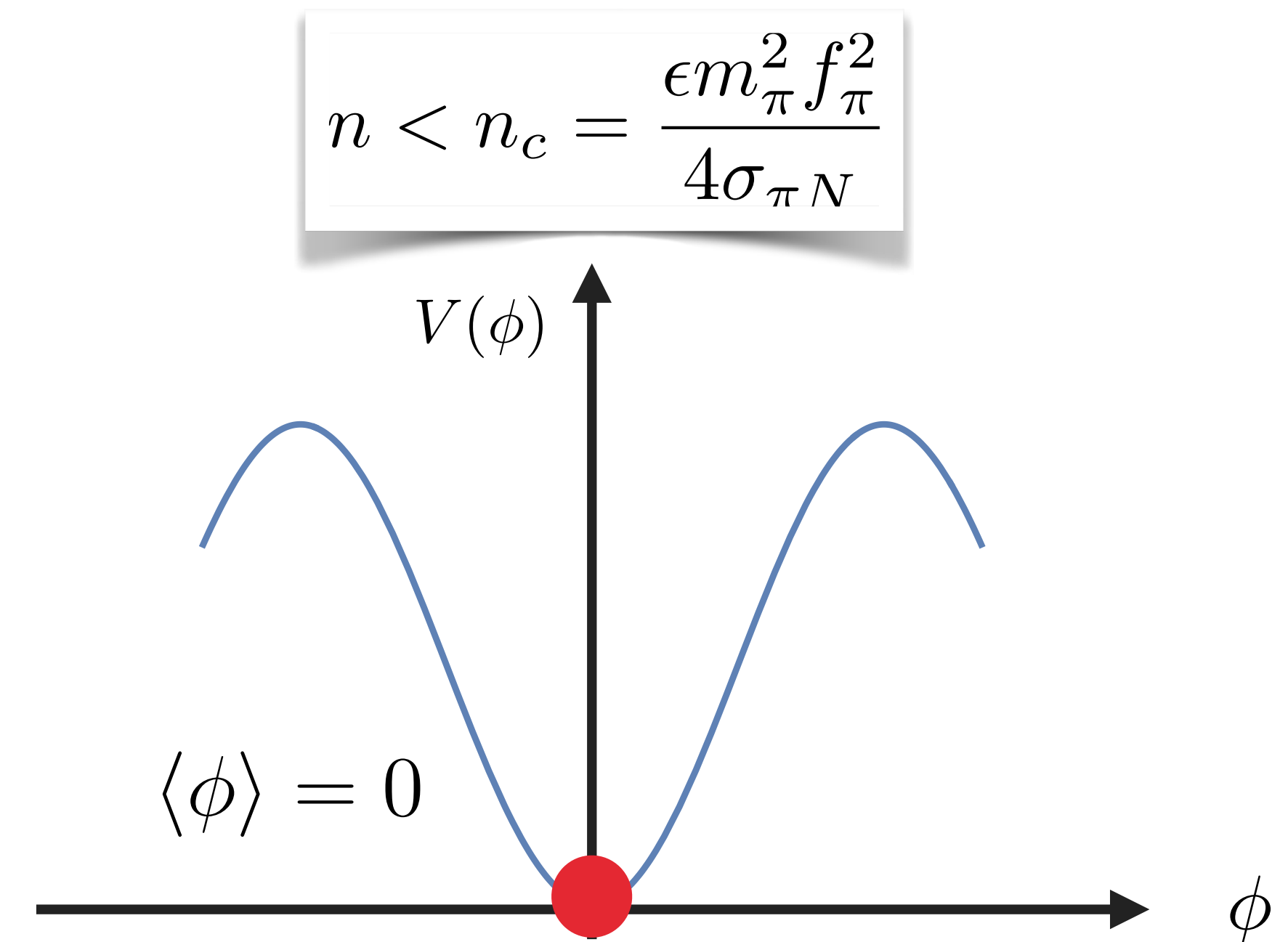
such that $m_N(0) = m_N$, $\sigma_{\pi N} \simeq 50 \text{ MeV}$

Light QCD axions have the same coupling to SM matter

Light QCD Axion: at Finite Density

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

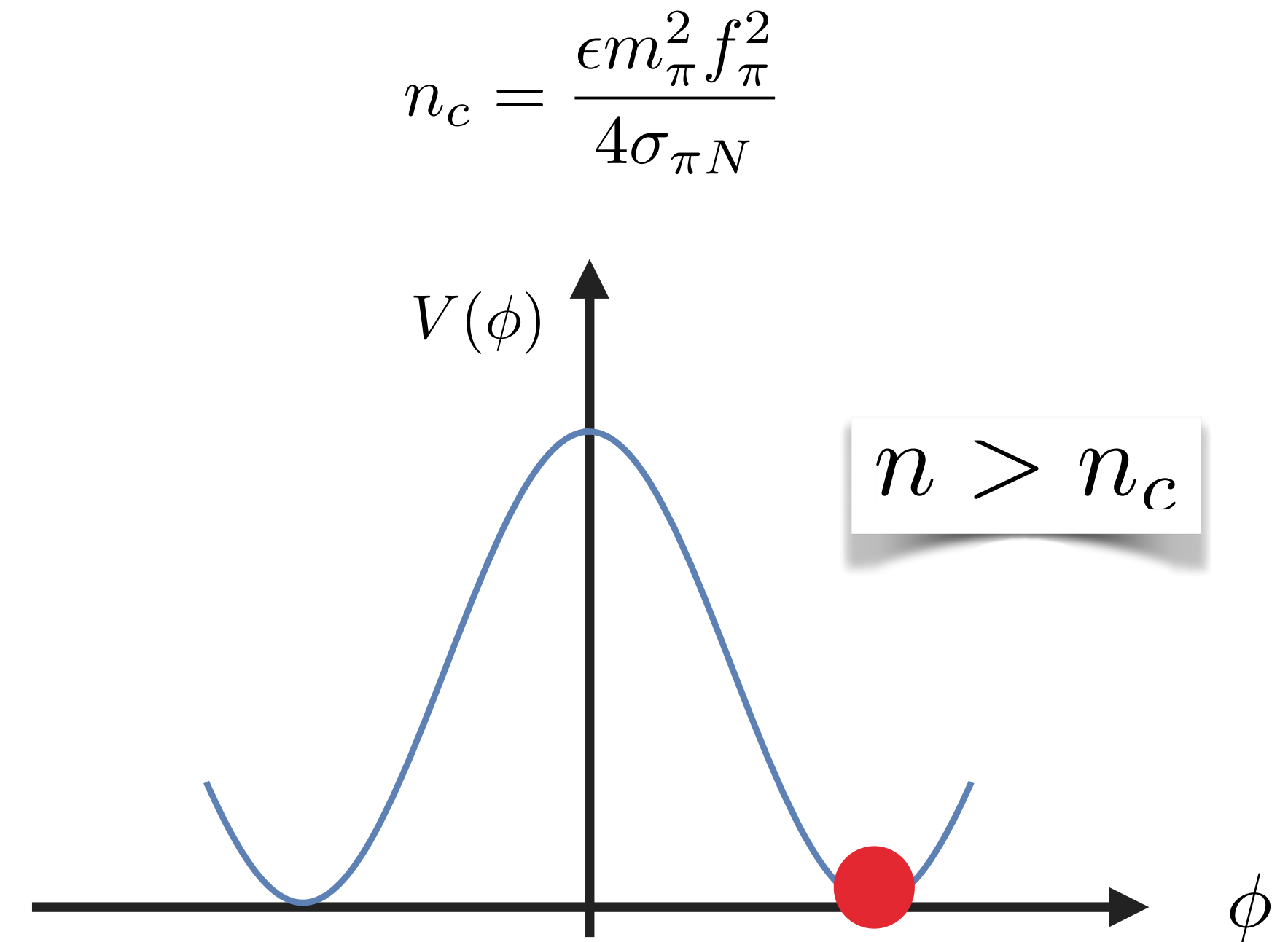
$$V(\phi) \simeq - \left[\frac{\epsilon m_\pi^2 f_\pi^2}{4} - \sigma_{\pi N} n \right] \left(\cos \frac{\phi}{f} - 1 \right)$$



Light QCD Axion: at Finite Density

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

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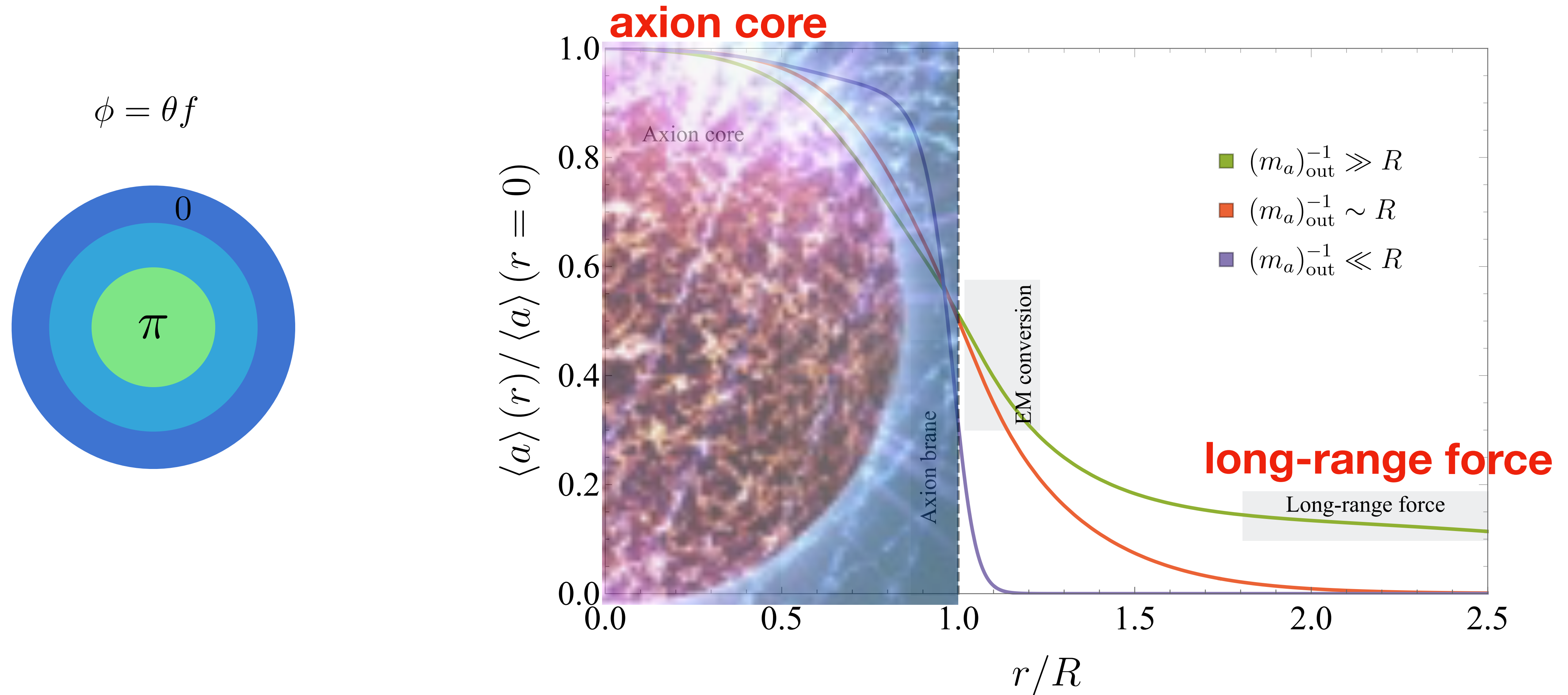


At **critical density** $n > n_c$:

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

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

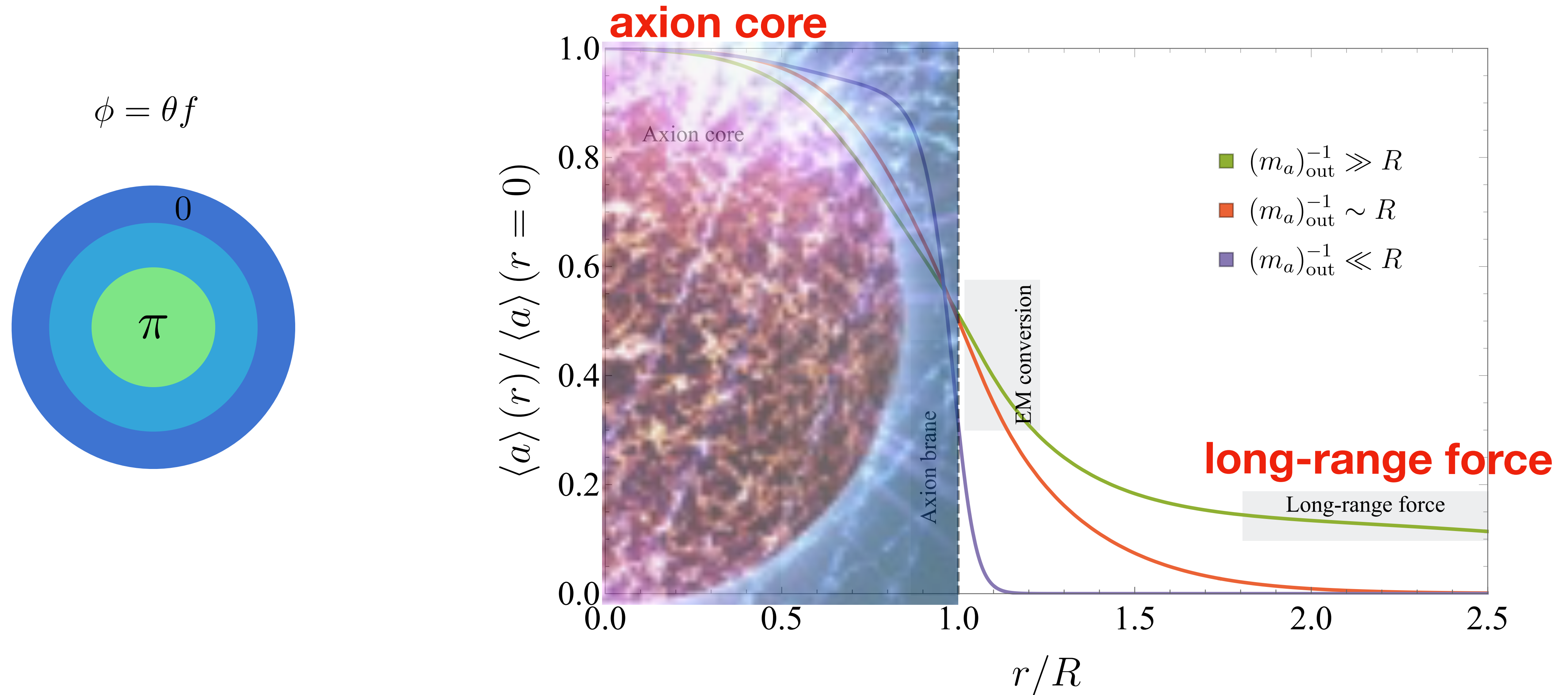
Axion Profile: in a neutron star



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!

Why does this not affect large nuclei?

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



Field theory potential energy contains **gradient** term!

$$E = \frac{1}{2}(\partial_t \phi)^2 + U(\phi)$$

$$U = \frac{1}{2}(\nabla \phi)^2 + V(\phi)$$

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

... outweighs gradient energy price $(\nabla \phi)^2 \sim f^2 / r^2$

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

e.g. $f \sim 10^{12} \text{ GeV}$
 $r_{\text{critical}} \sim 0.2 \text{ cm}$

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

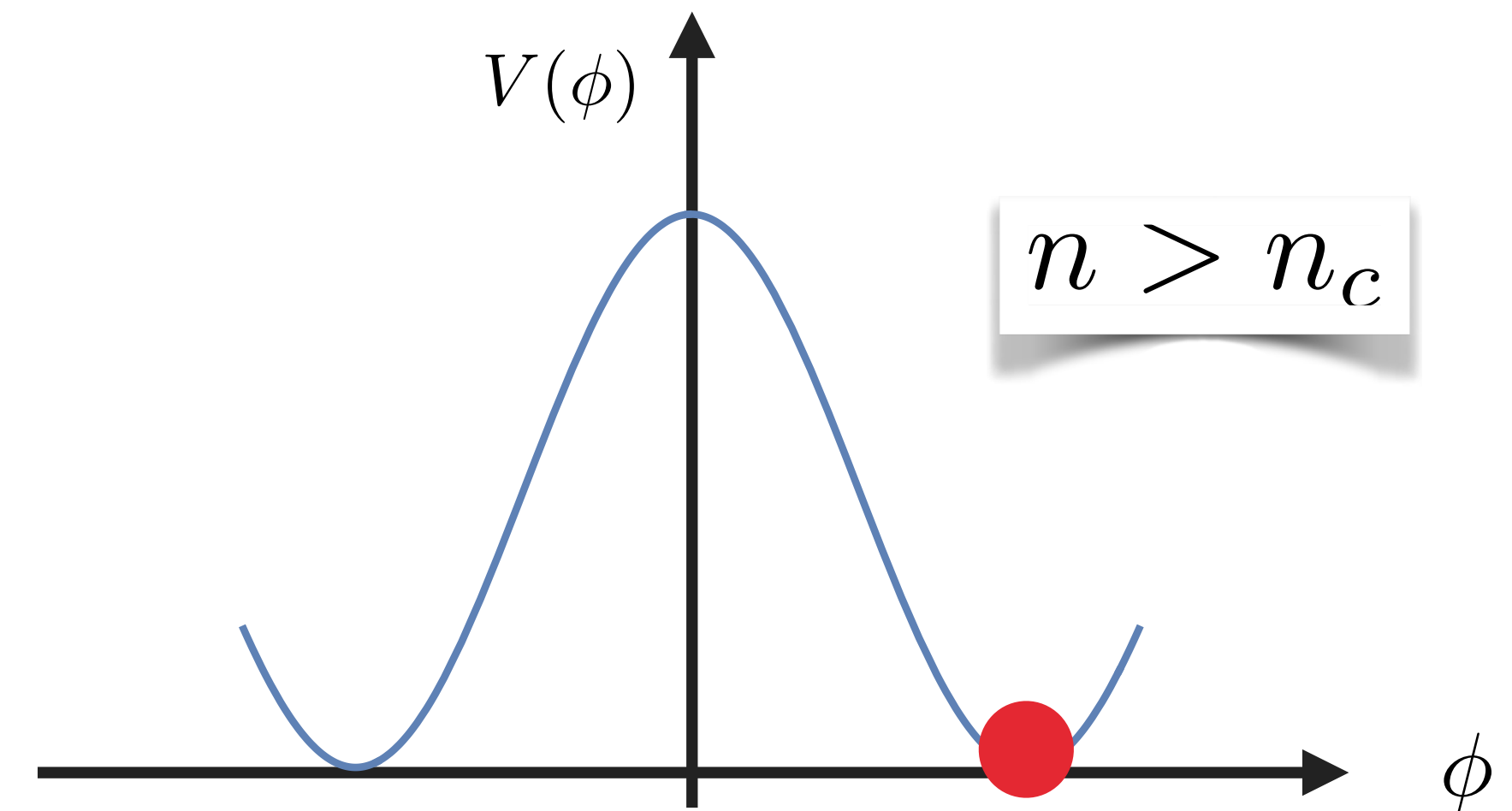
Light QCD Axion: at Finite Density

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

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

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

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



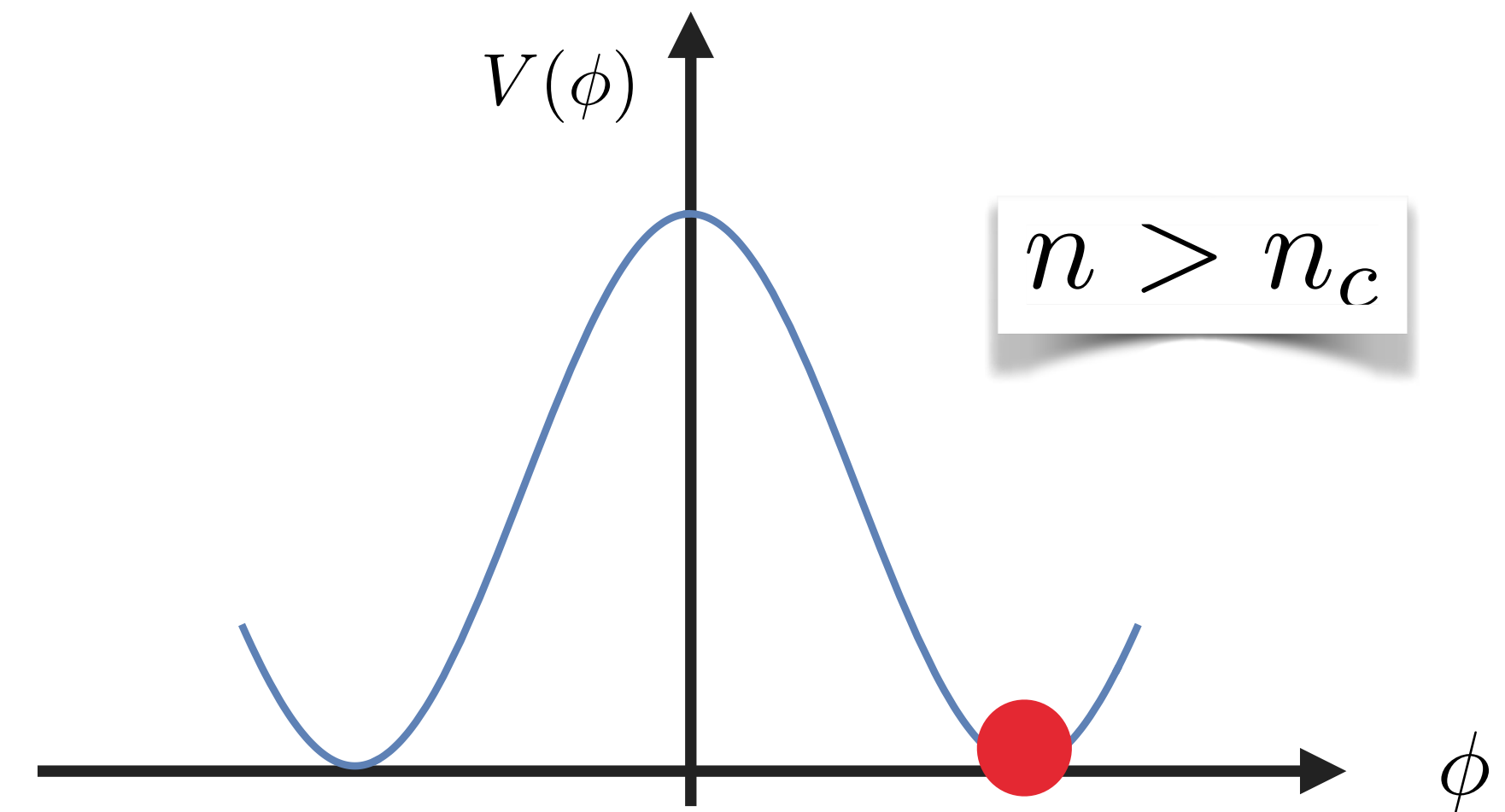
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$$m_N(\phi) \equiv m_N \left[1 + \frac{\sigma_{\pi N}}{2m_N} \left(\cos \frac{\phi}{f} - 1 \right) \right]$$

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



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

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

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

Plan

Part I: White dwarfs as a probe of light QCD axions

- Axions and their properties at finite density ✓
- Toy Model: Equation of state of free Fermi gas with axion

Free Fermi Gas of Neutrons with Axion

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

Minimizing the action

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

Free Fermi Gas of Neutrons with Axion

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Minimizing the action

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



coupled system

$$\begin{aligned} \phi'' \left[1 - \frac{2GM}{r} \right] + \frac{2}{r} \phi' \left[1 - \frac{GM}{r} - 2\pi G r^2 (\varepsilon - p) \right] &= \frac{\partial V}{\partial \phi} + \rho \frac{\partial m_\psi^*(\phi)}{\partial \phi} \equiv U(\phi, \rho), \\ p' &= -\frac{GM\varepsilon}{r^2} \left[1 + \frac{p}{\varepsilon} \right] \left[1 - \frac{2GM}{r} \right]^{-1} \left[1 + \frac{4\pi r^3}{M} \left(p + \frac{(\phi')^2}{2} \left\{ 1 - \frac{2GM}{r} \right\} \right) \right] - \phi' U(\phi, \rho), \\ M' &= 4\pi r^2 \left[\varepsilon + \frac{1}{2} \left(1 - \frac{2GM}{r} \right) (\phi')^2 \right]. \end{aligned}$$

Einstein equations and axion EOM

Free Fermi Gas of Neutrons with Axion

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

Minimizing the action

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

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

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

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

coupled system

Einstein equations and axion EOM

can be solved numerically, very **technical**

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coupled system

Einstein equations and axion EOM

can be solved numerically, very **technical**

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: $\phi'(r) = 0$

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

Equation of state

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

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

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

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

Equation of state

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$$\phi(n)$$

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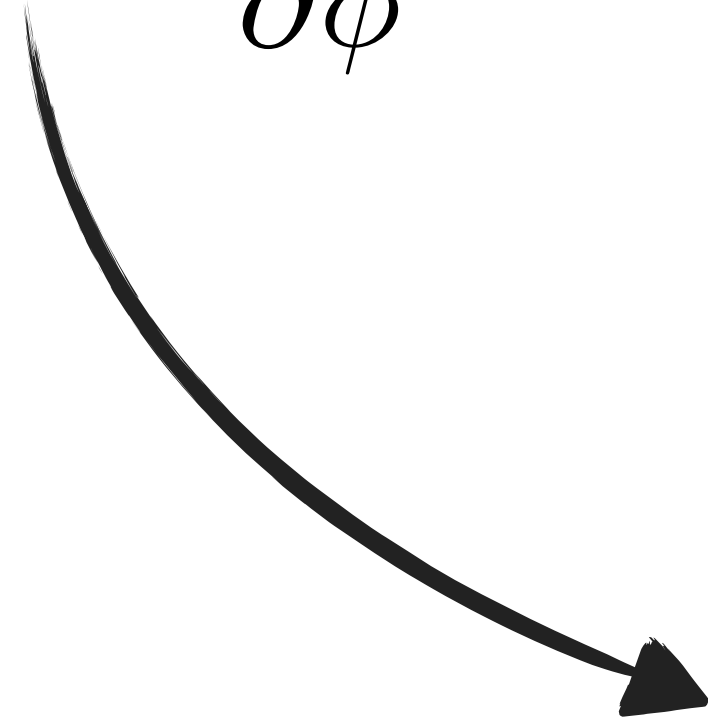
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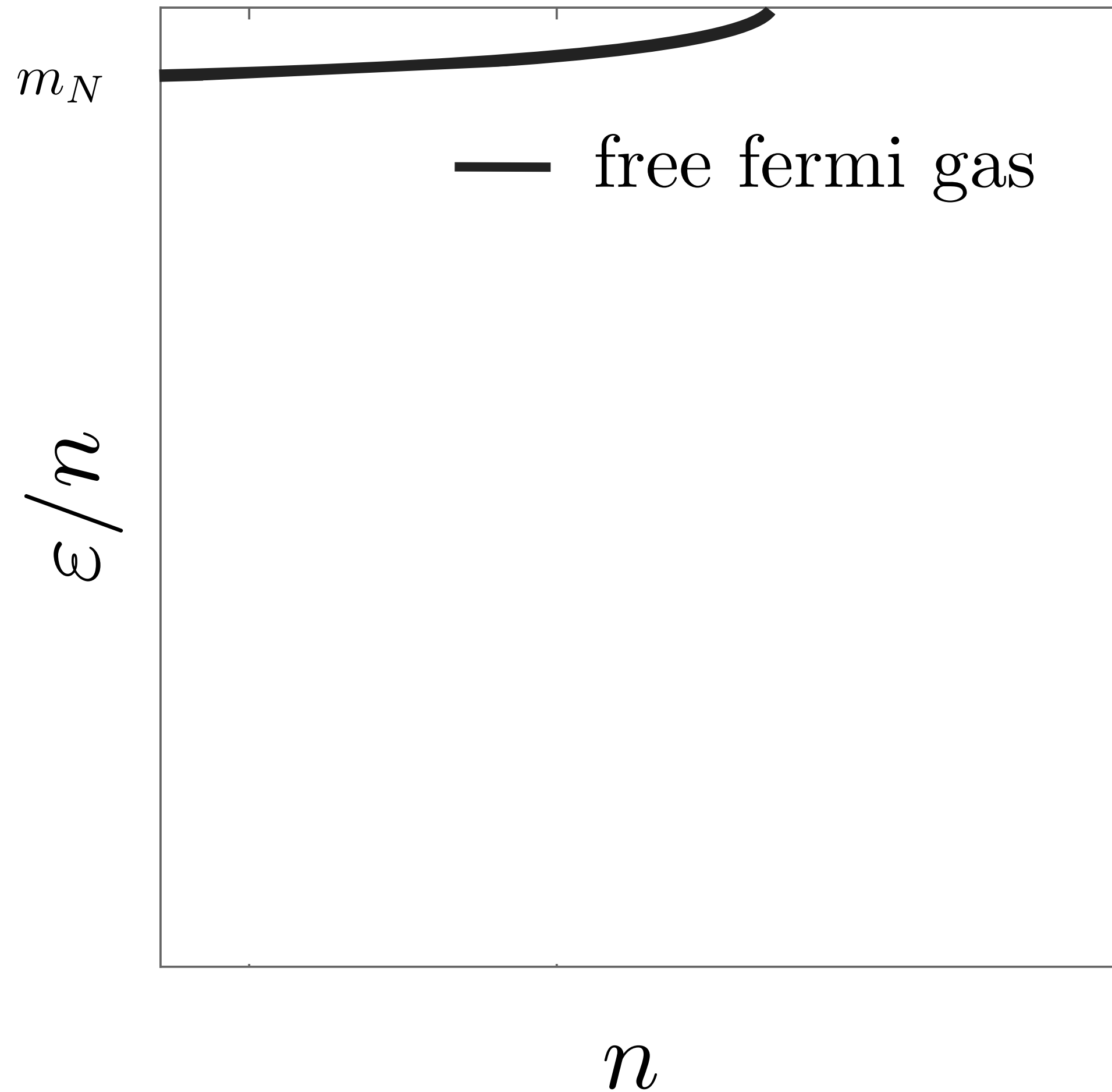


$$\varepsilon(n), p(n)$$

equation of state

Energy per particle

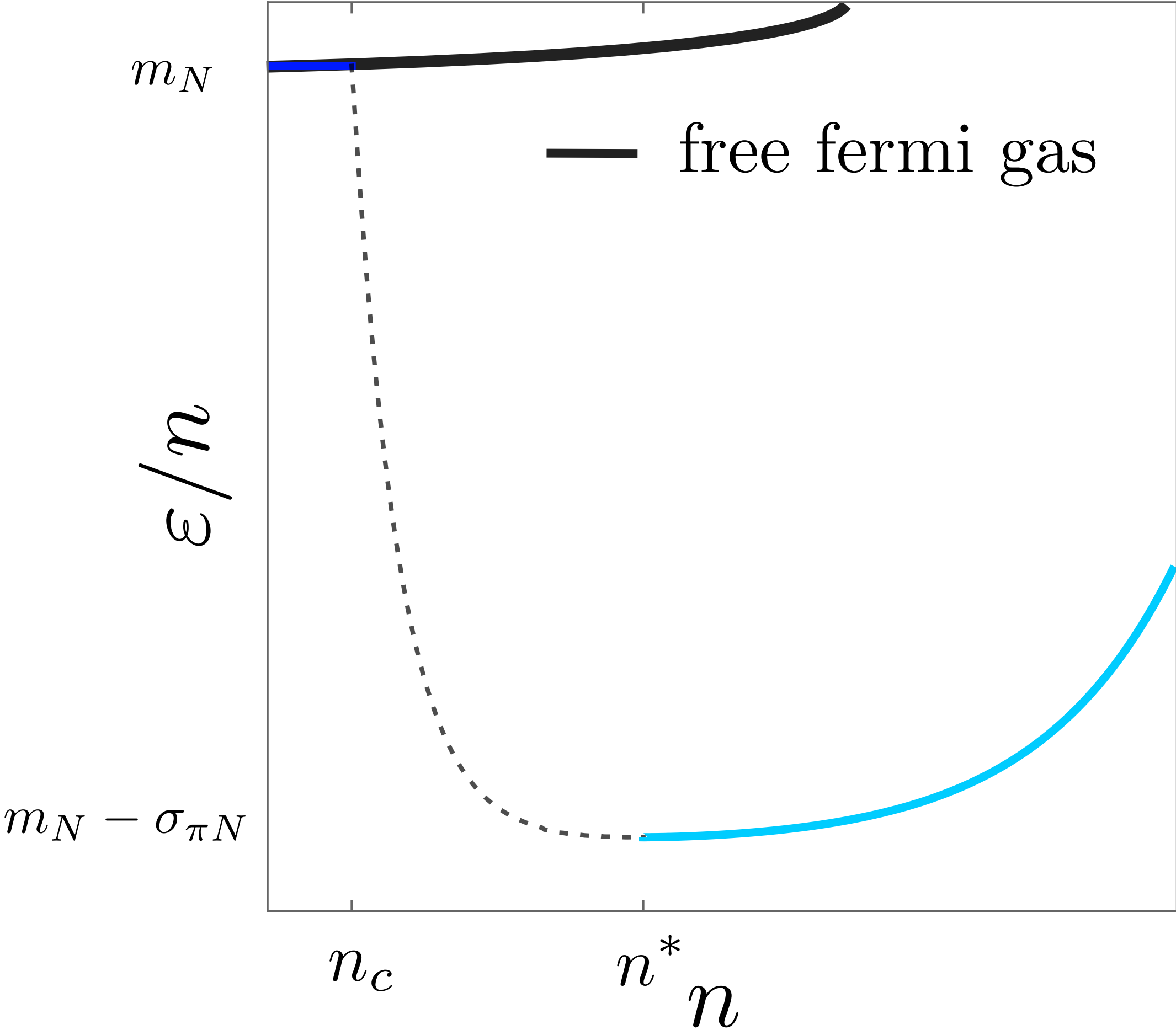
$$\frac{\varepsilon(n, 0)}{n} = \frac{\varepsilon_N(n, 0) + V(0)}{n}$$



Energy per particle

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

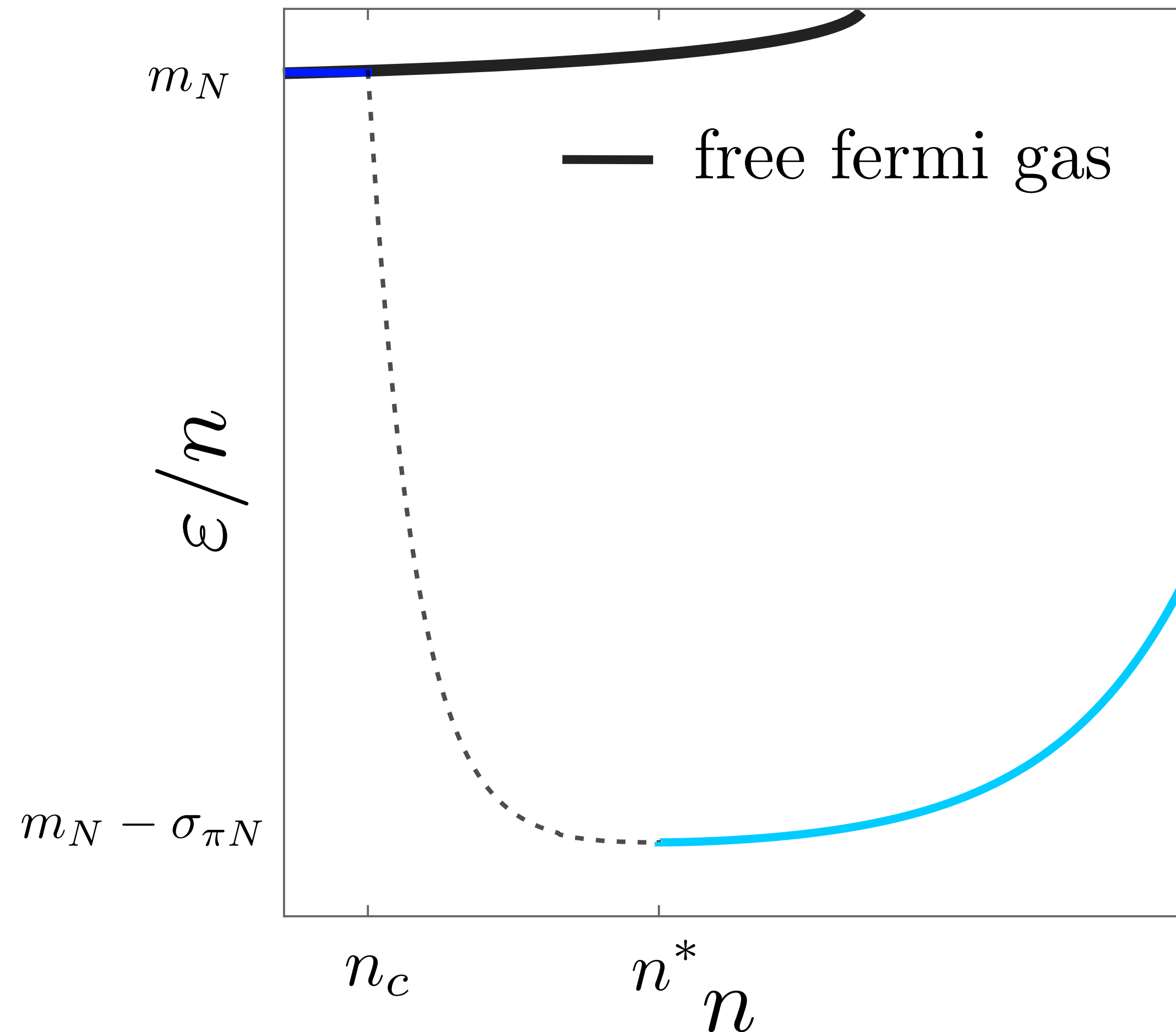
— metastable ($\phi = 0$) unstable — New ground state ($\phi = \pi f$)



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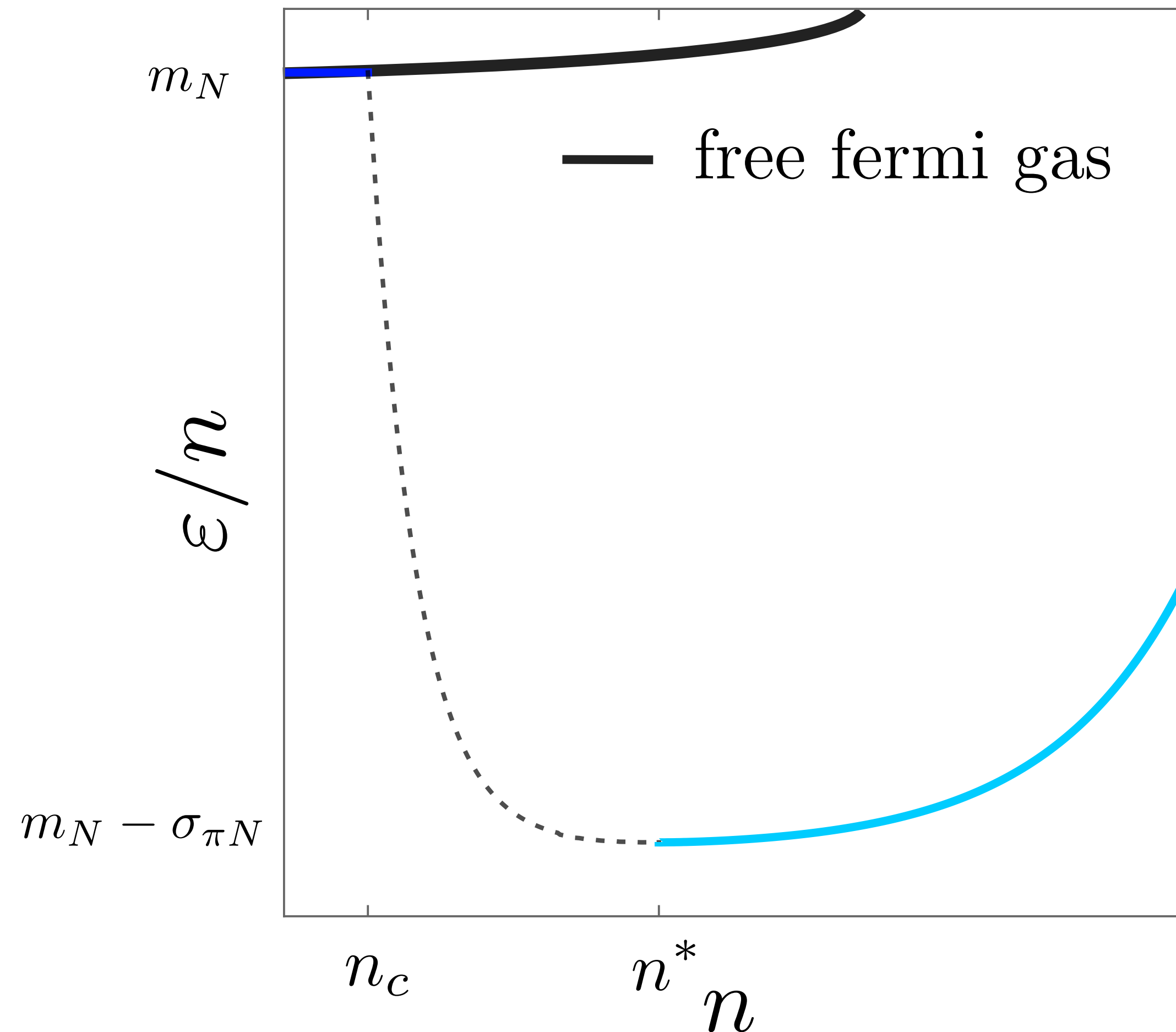
Energy per particle is related to pressure

$$p = n^2 \frac{\partial(\varepsilon/n)}{\partial n} = p_N - V$$

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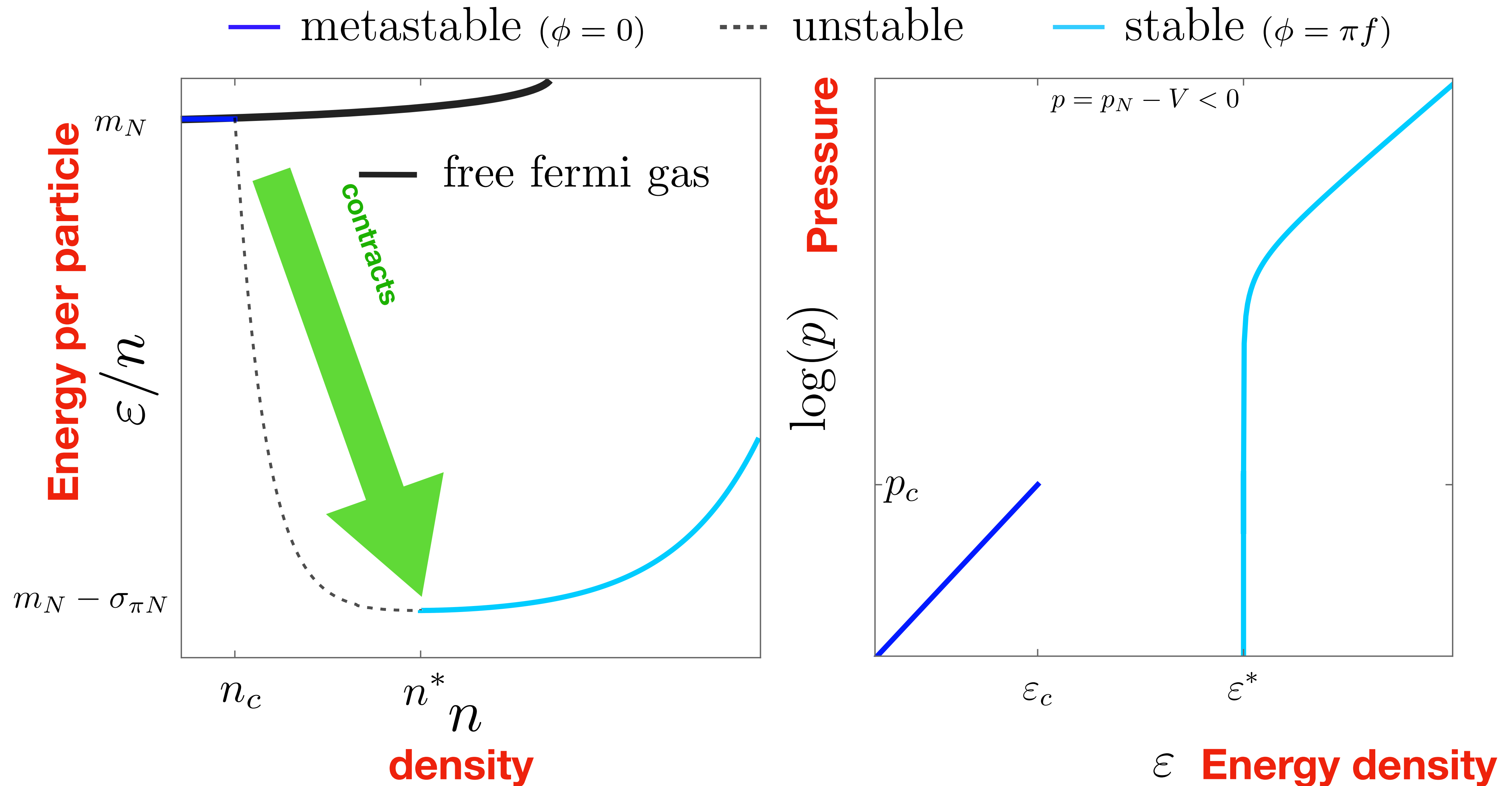
Negative pressure for

$$n_c < n < n^*$$

Defines n^* as

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

Energy per particle and pressure



Plan

Part I: White dwarfs as a probe of light QCD axions

- **Axions and their properties at finite density** ✓
- **Toy Model: Equation of state of free fermi gas with axion** ✓

White dwarfs and the axion

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 $p_e(n^*) = p_e(n^*) - V = 0$

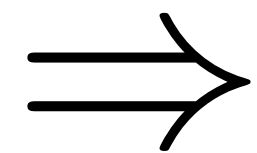
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There exists a range of densities $n_c < n < n^*$ with $p < 0$

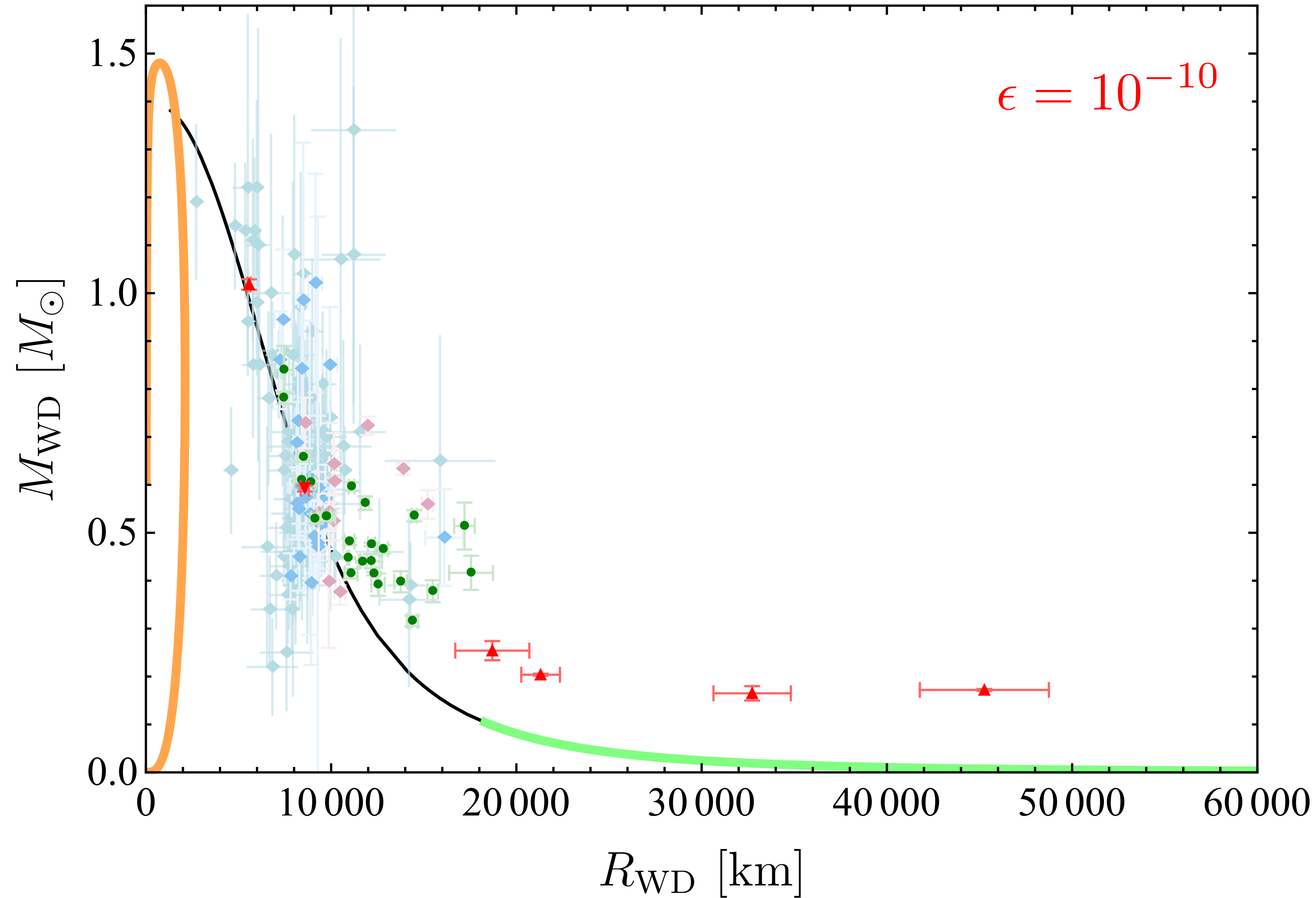
and no stable configuration:



Translates to gap in the MR Curve

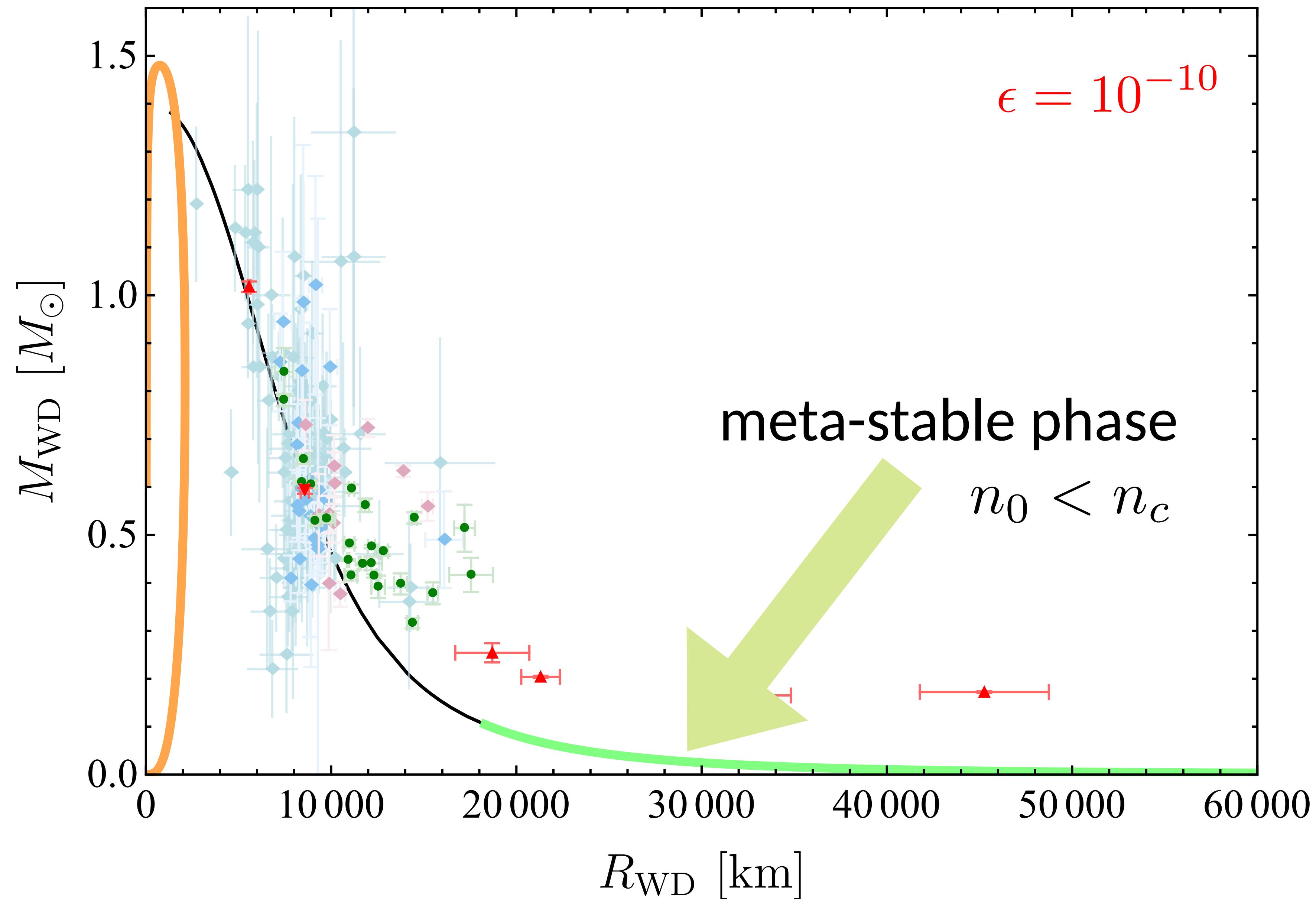
White Dwarfs with light QCD axion

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



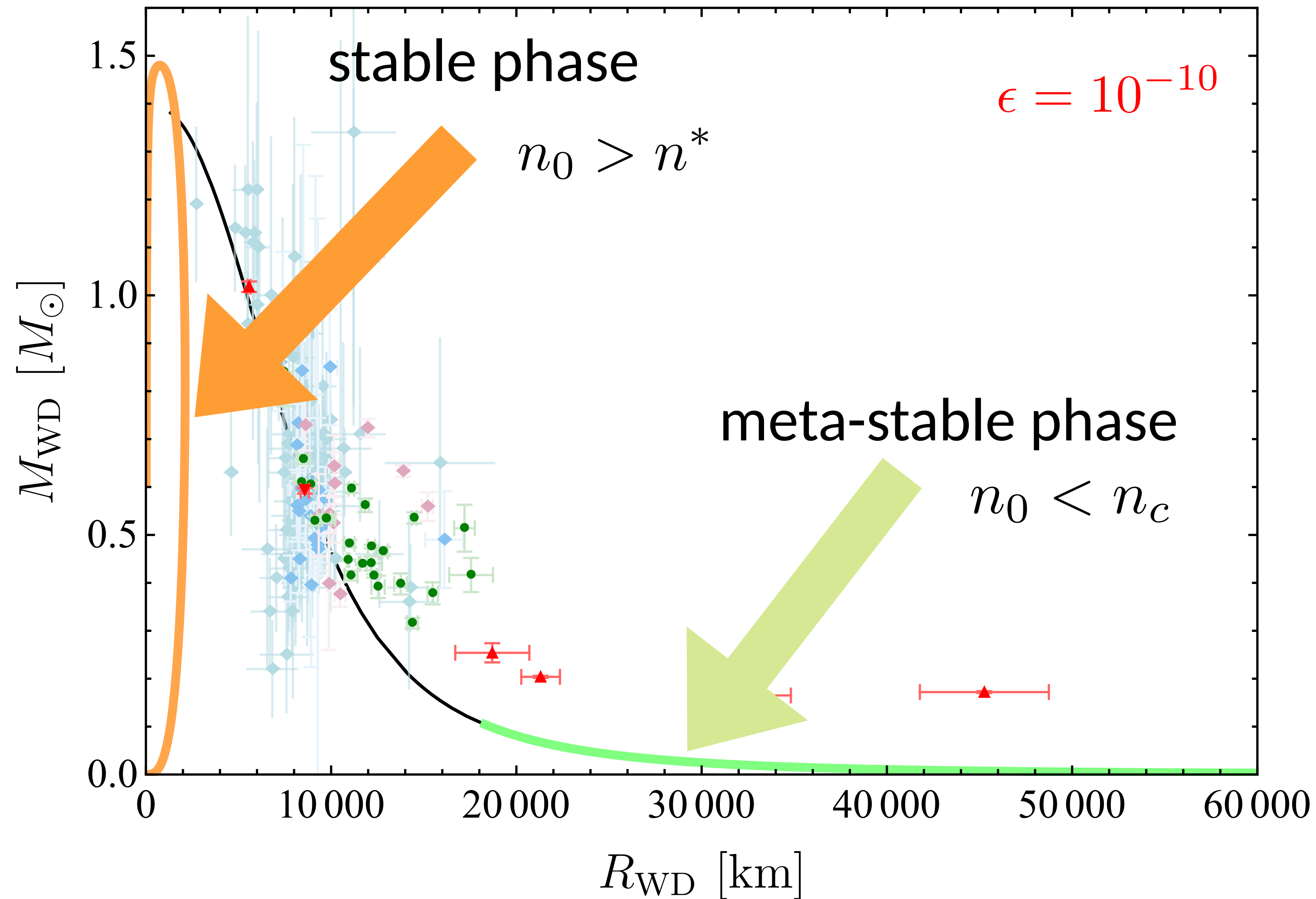
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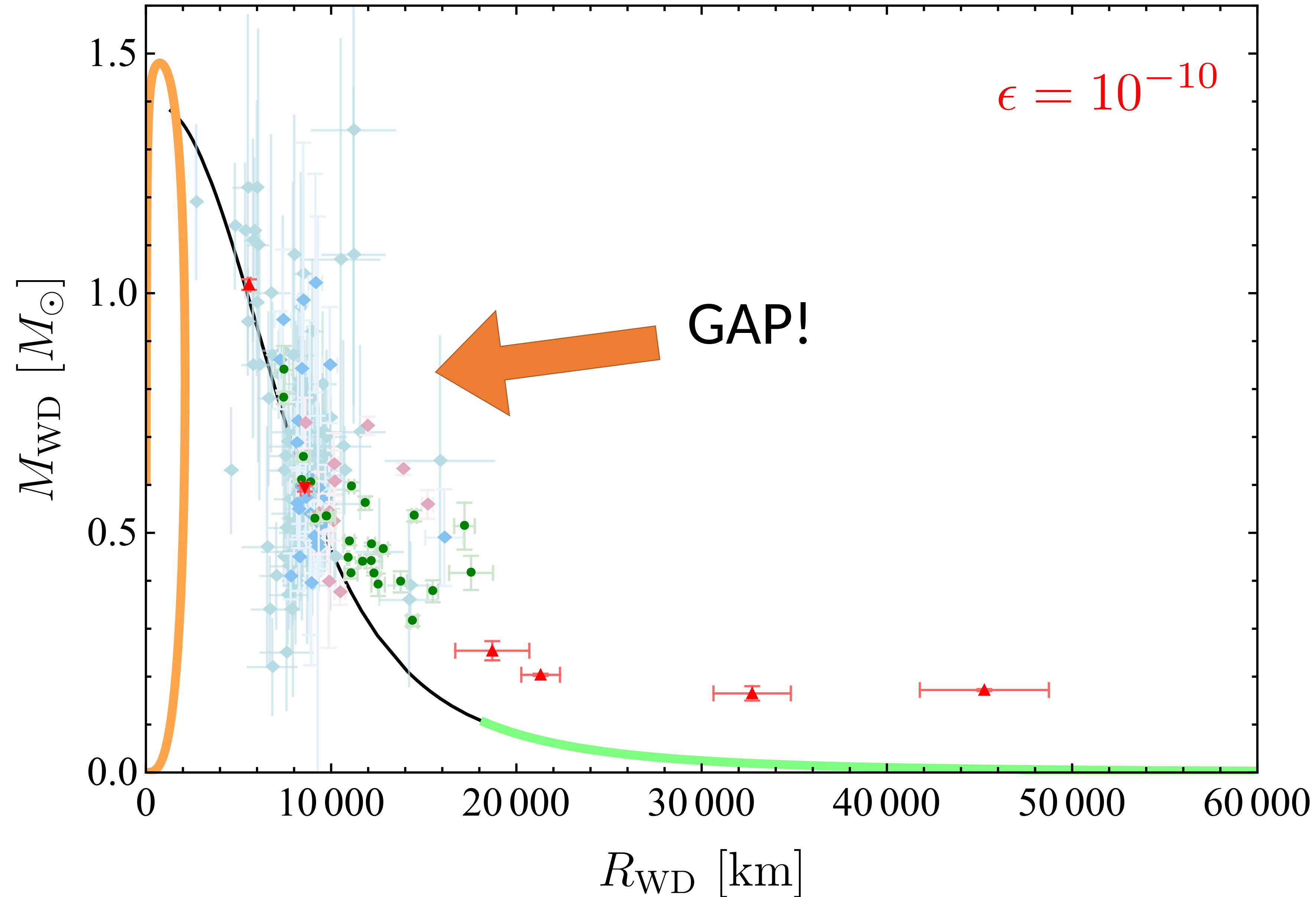
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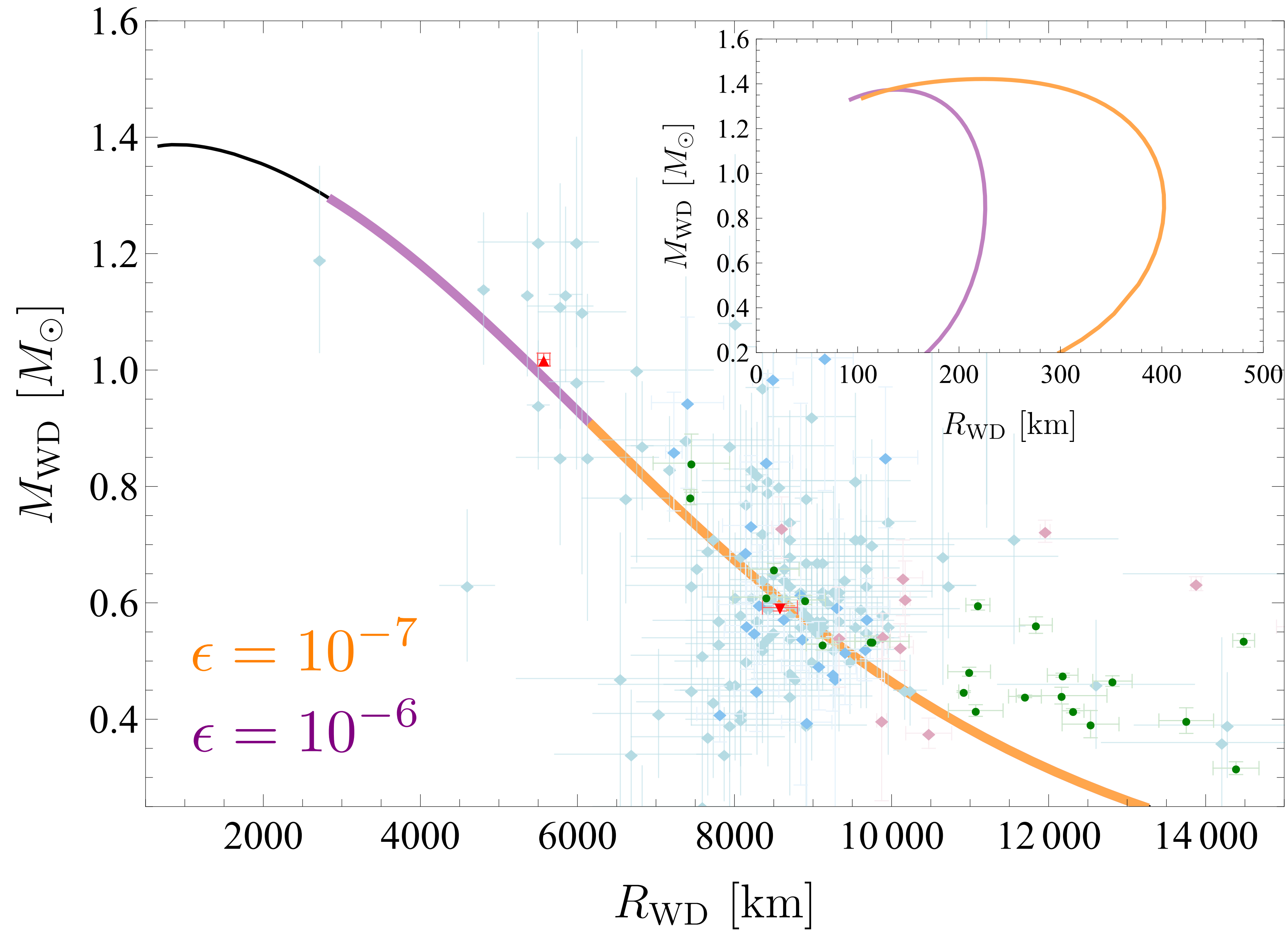
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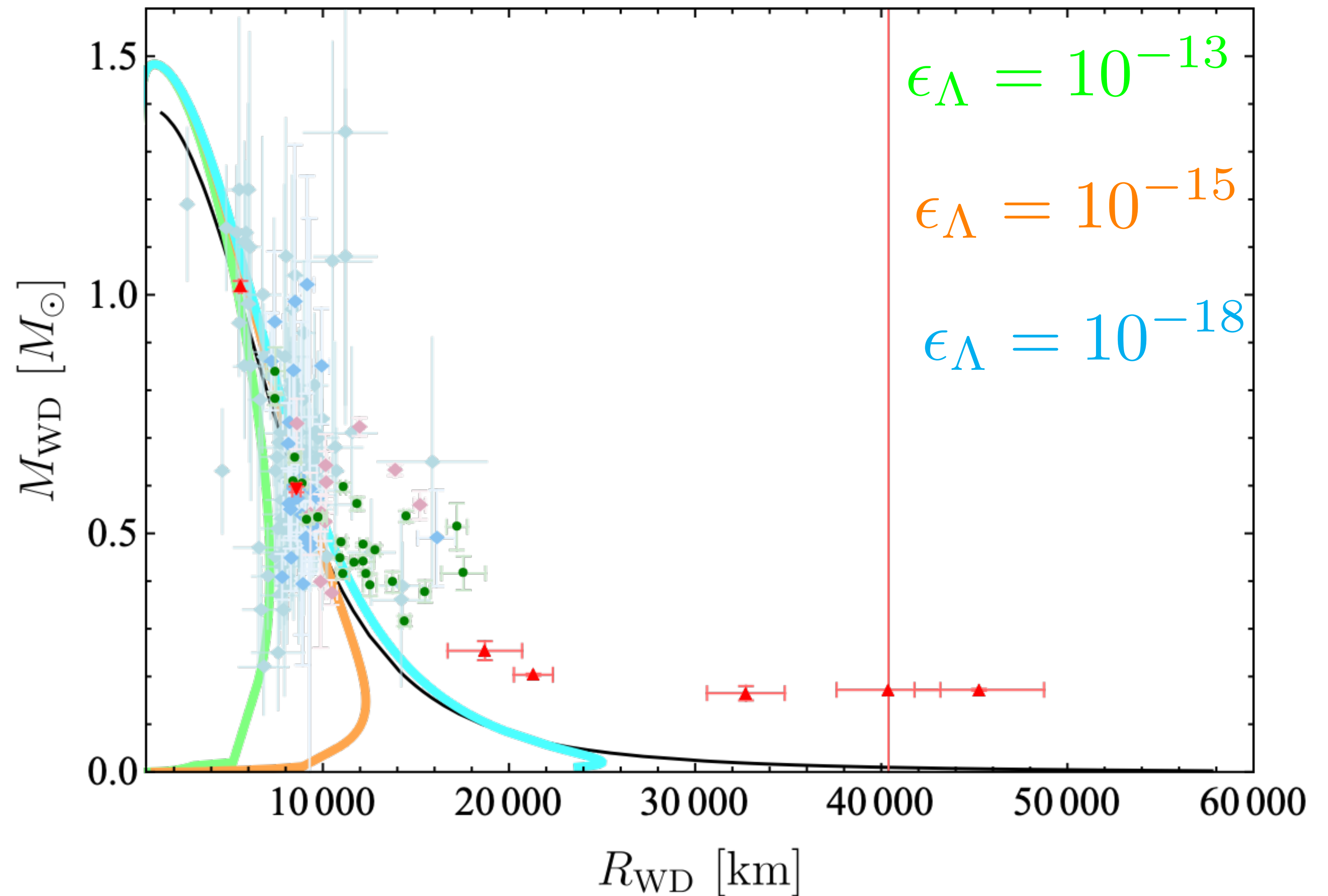
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White Dwarfs with light Axion

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

Negligible Gradient



White Dwarfs with light Axion

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

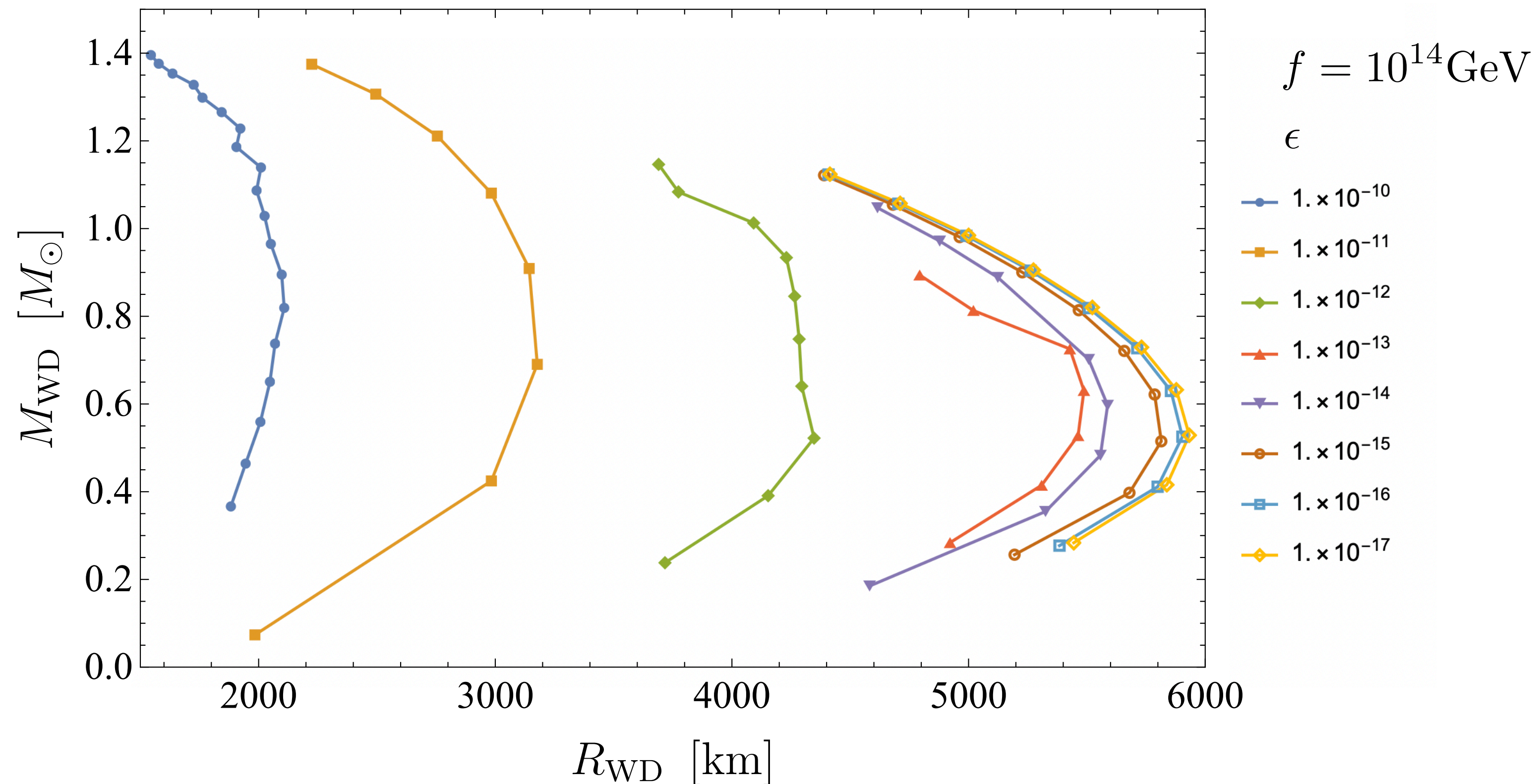
- 1) On **meta-stable branch**: minimum radius is fixed by $R_{min} \sim m_\phi^{-1}$

White Dwarfs with light Axion

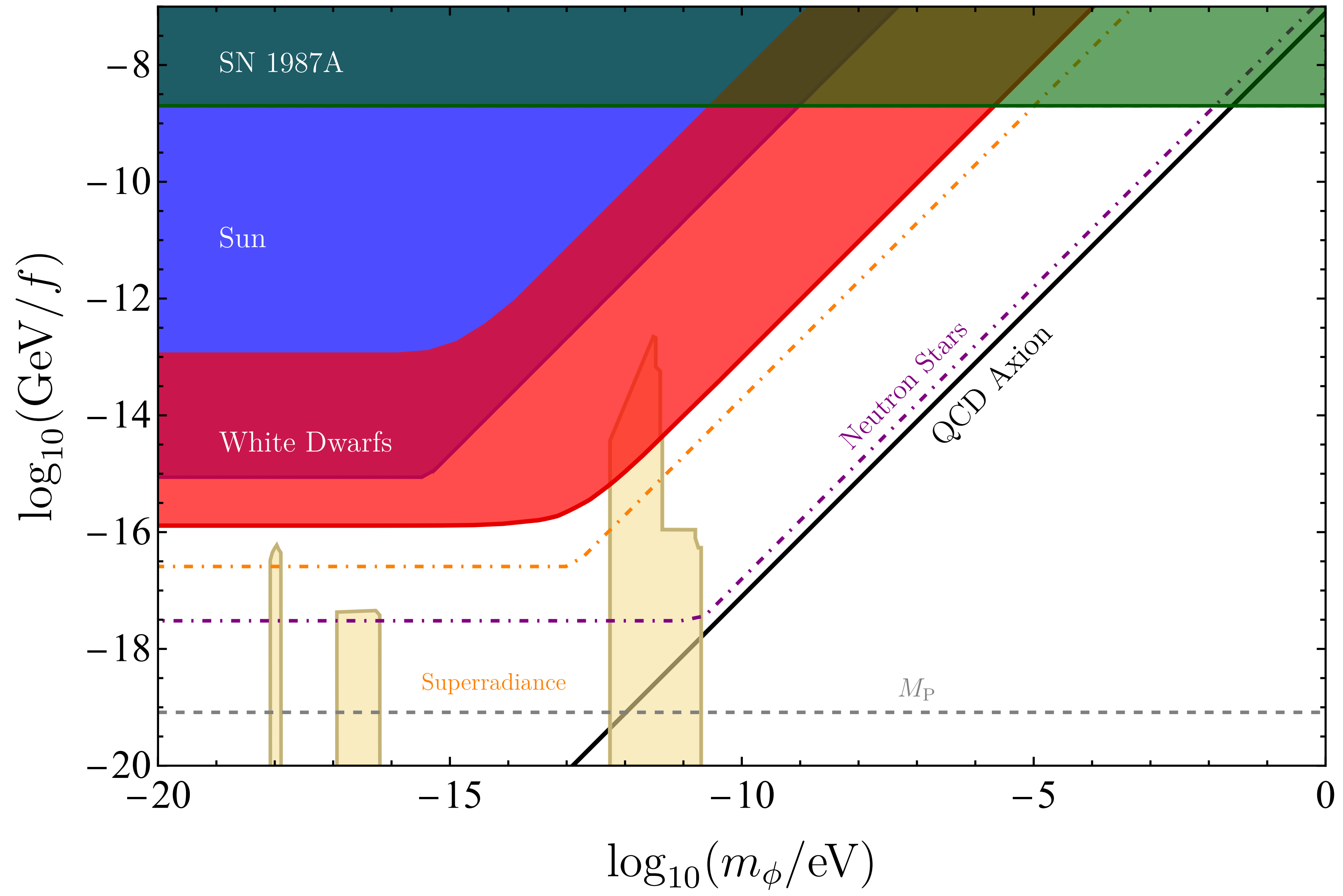
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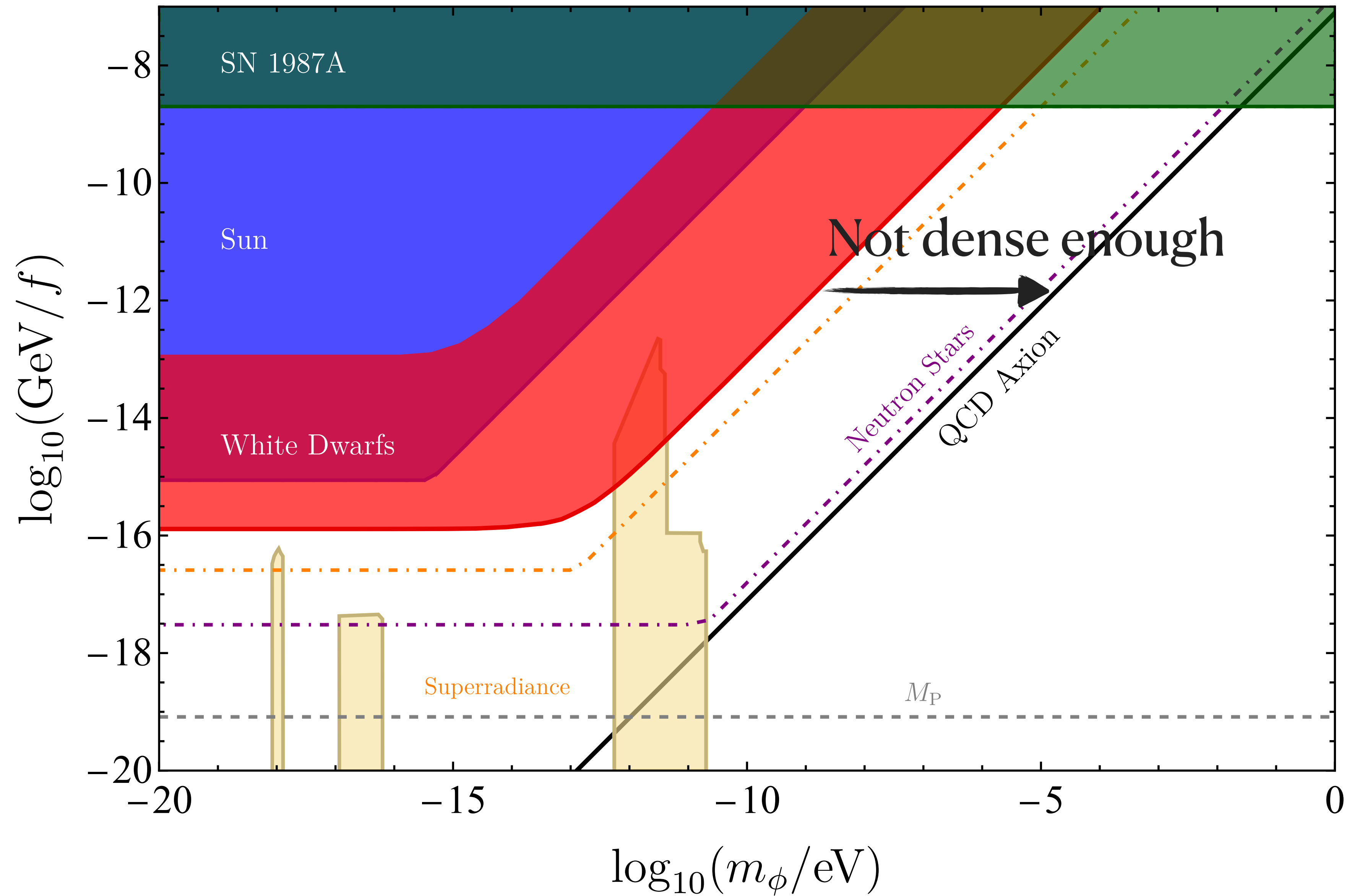
- 1) On **meta-stable branch**: minimum radius is fixed by $R_{min} \sim m_\phi^{-1}$
- 2) On **stable branch**: gradient pressure fixes maximal radius



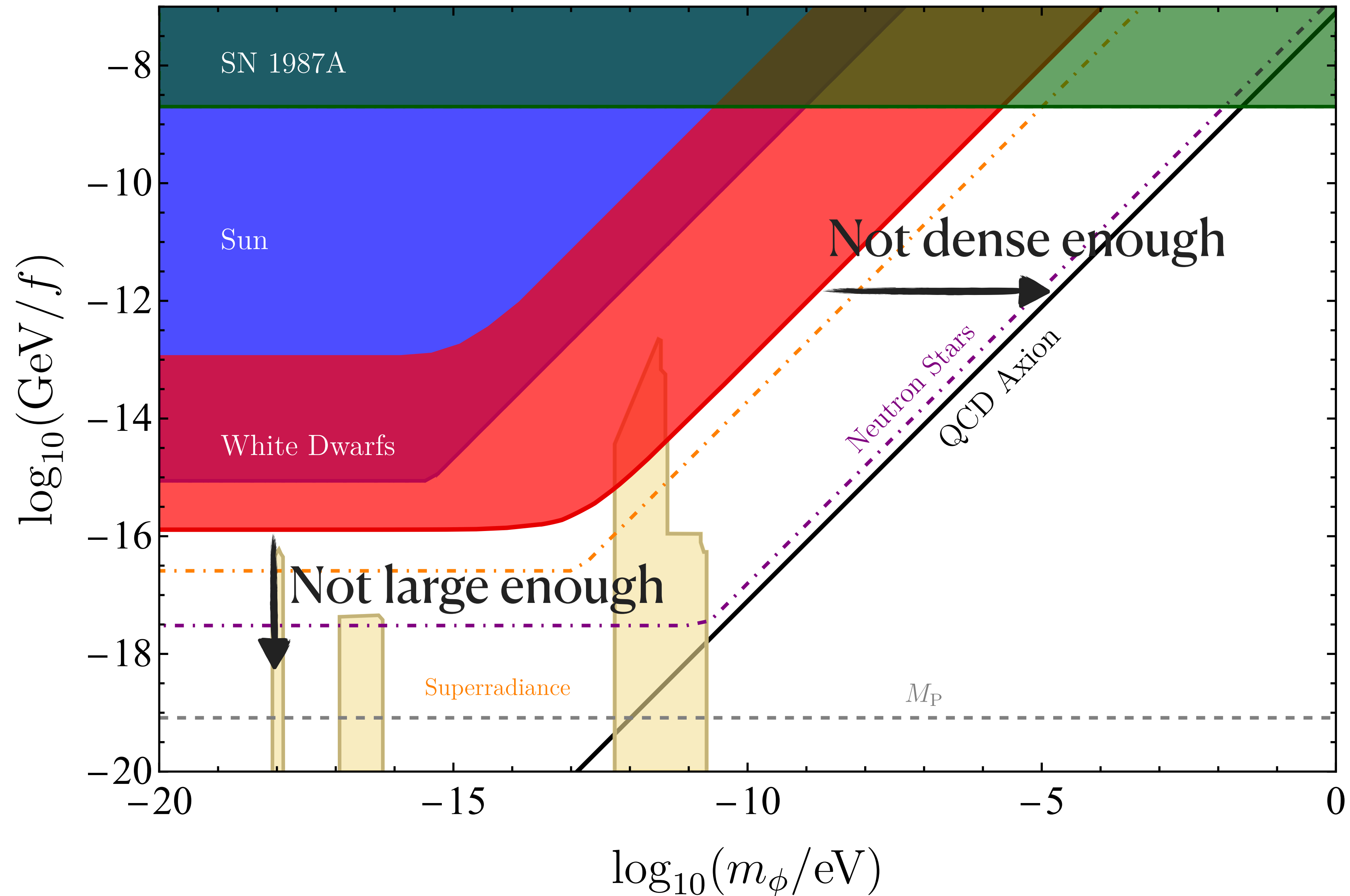
Axion Parameter Space



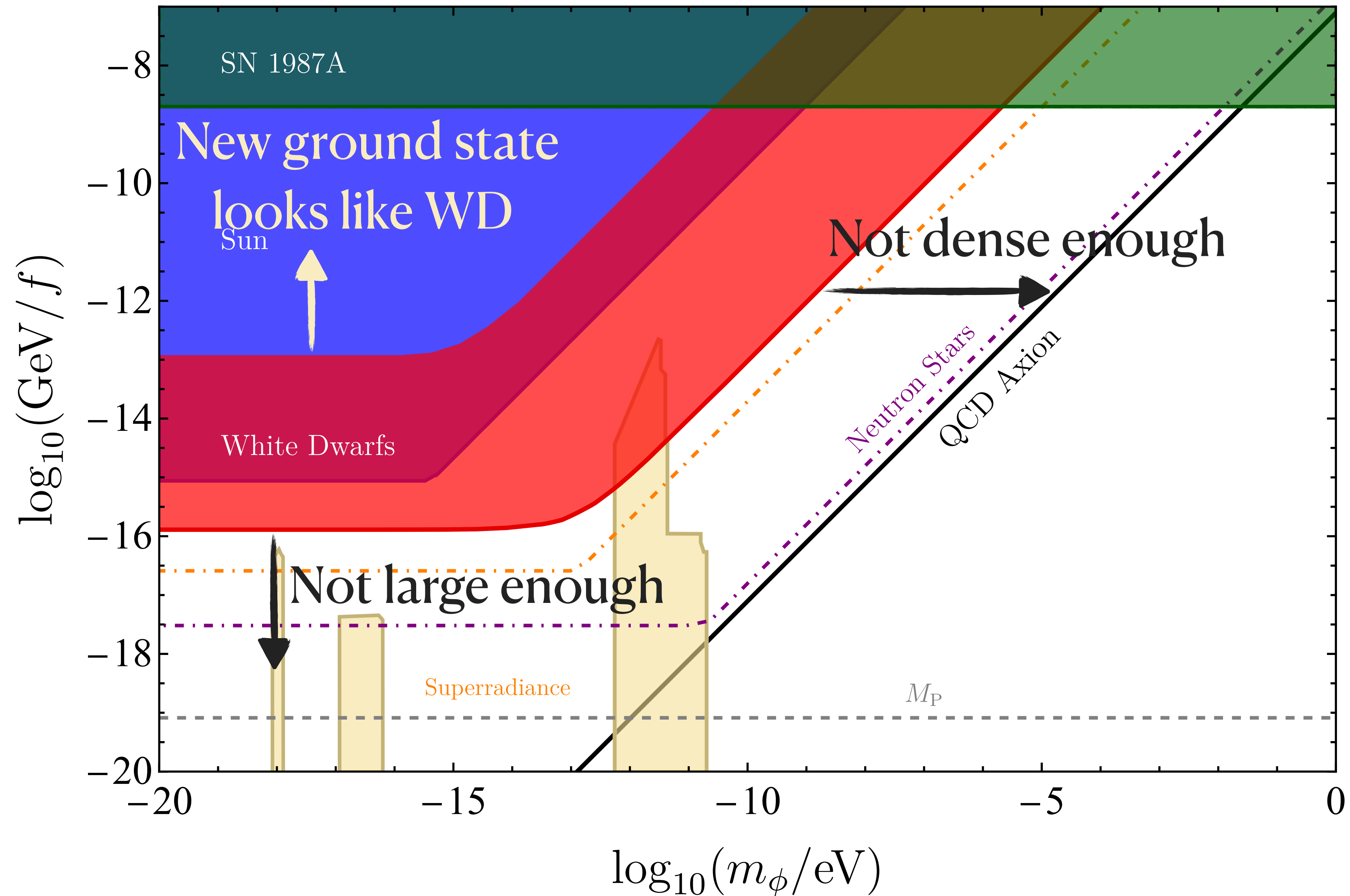
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Axion Parameter Space



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- White dwarfs and the axion ✓

Part II: Heavy stars from light scalars

- Motivation and simplest example

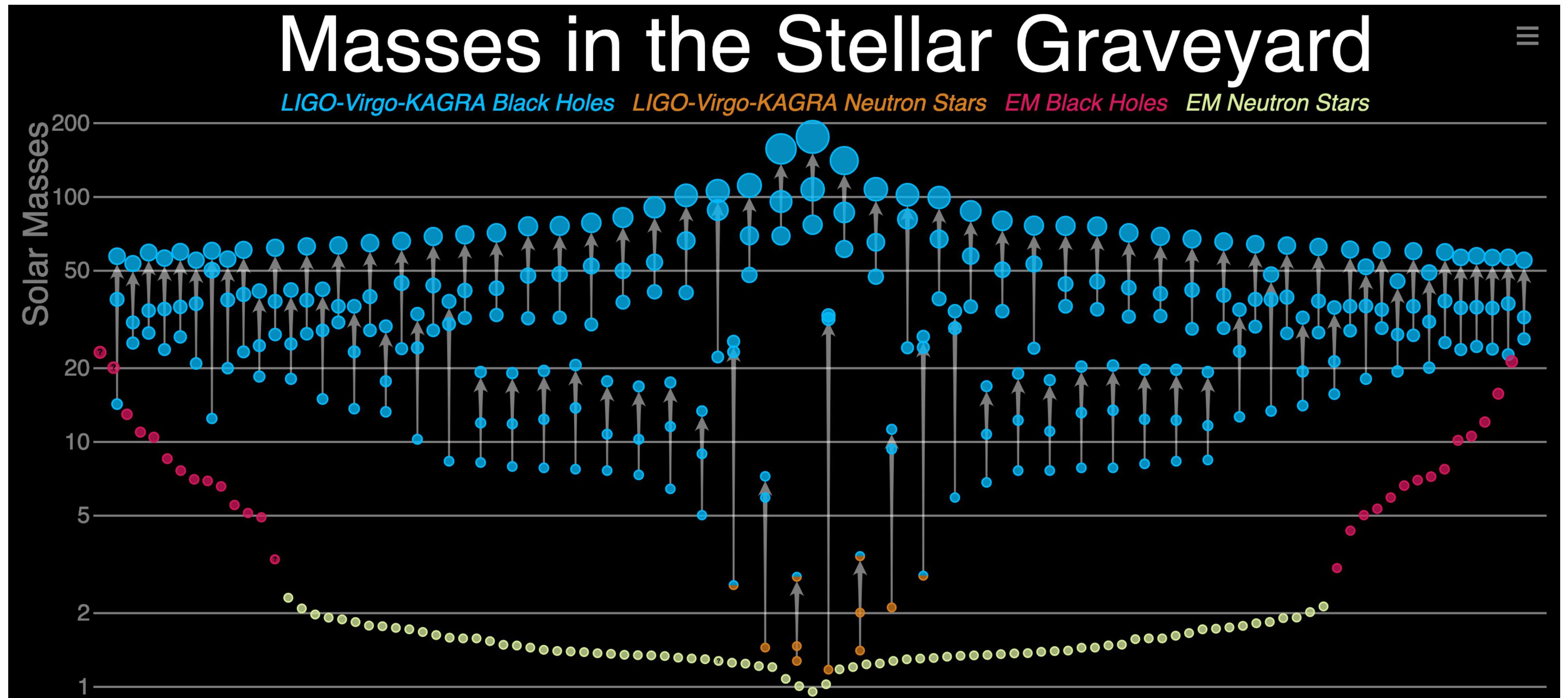
Heavy Neutron Stars from light Scalars

... or Fat Zombies in the Stellar Graveyard



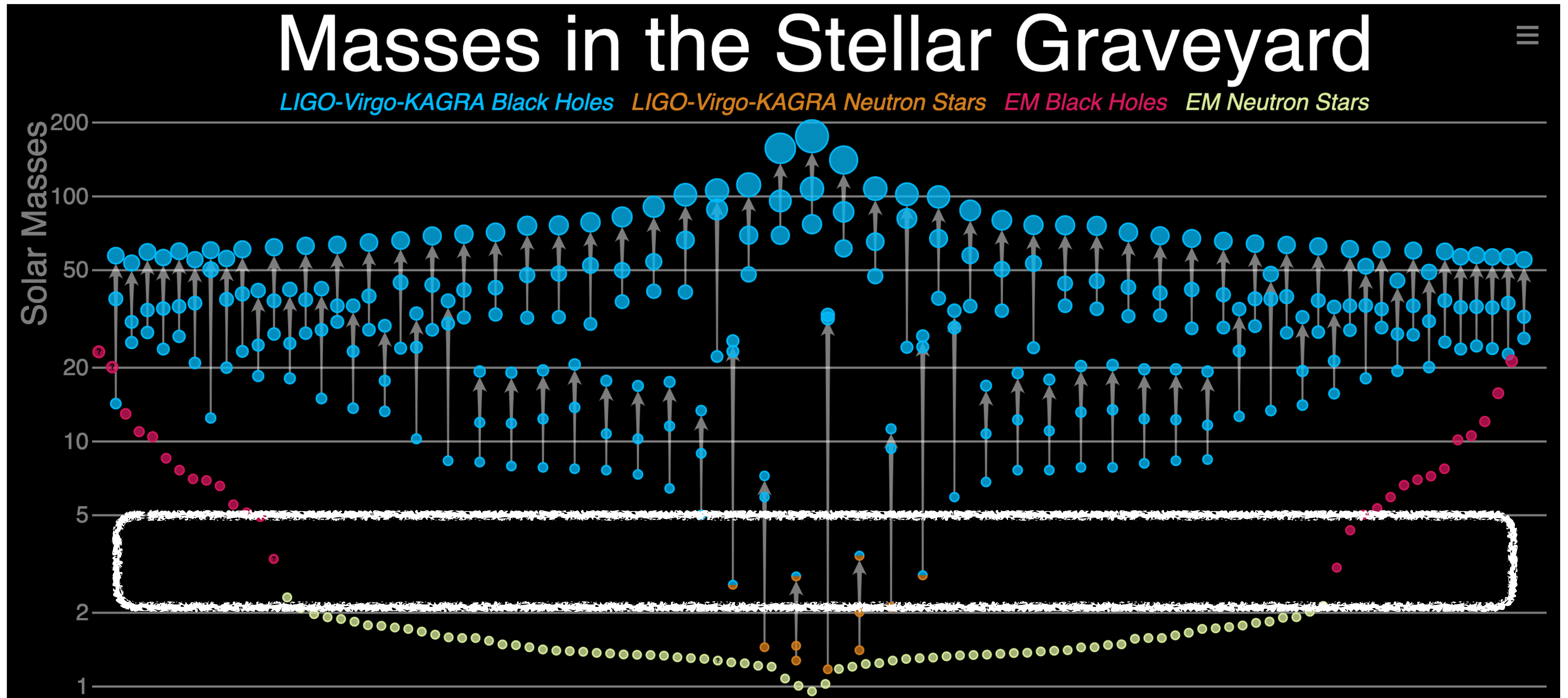
Motivation

Gravitational wave astronomy



Motivation

Gravitational wave astronomy

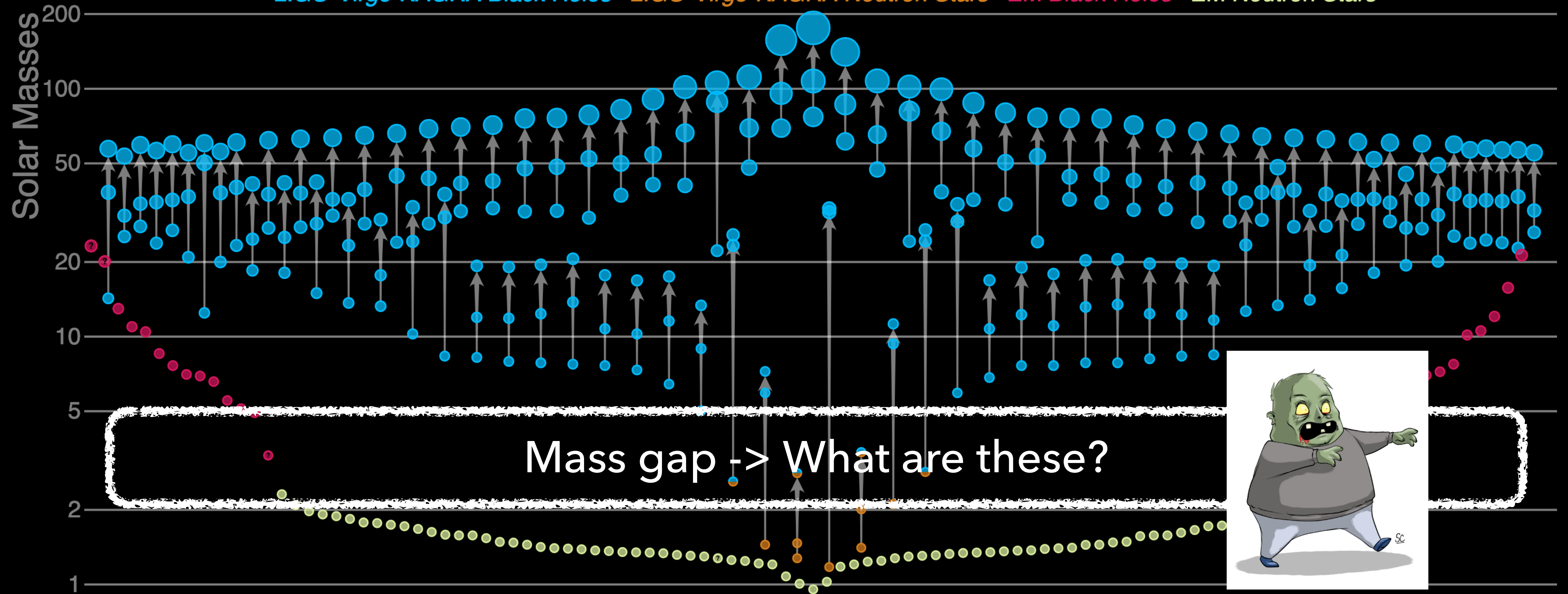


Motivation

Gravitational wave astronomy

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*

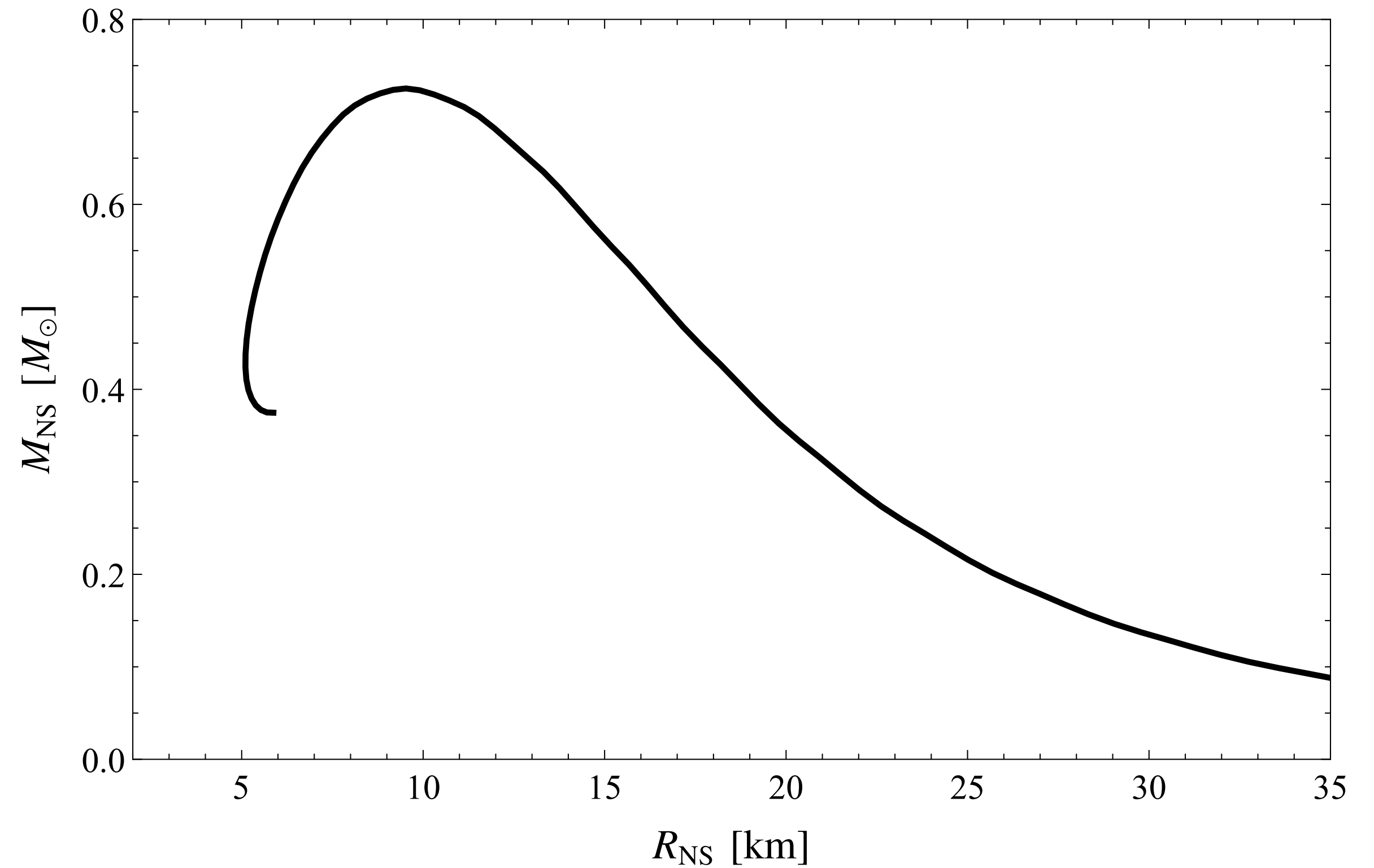


A simple example

Consider non-interacting Fermi gas of neutrons

$$\Rightarrow M_{\text{max}} \sim 0.7 M_{\odot}$$

$$\Rightarrow R_{\text{max}} \simeq 10 \text{ km}$$

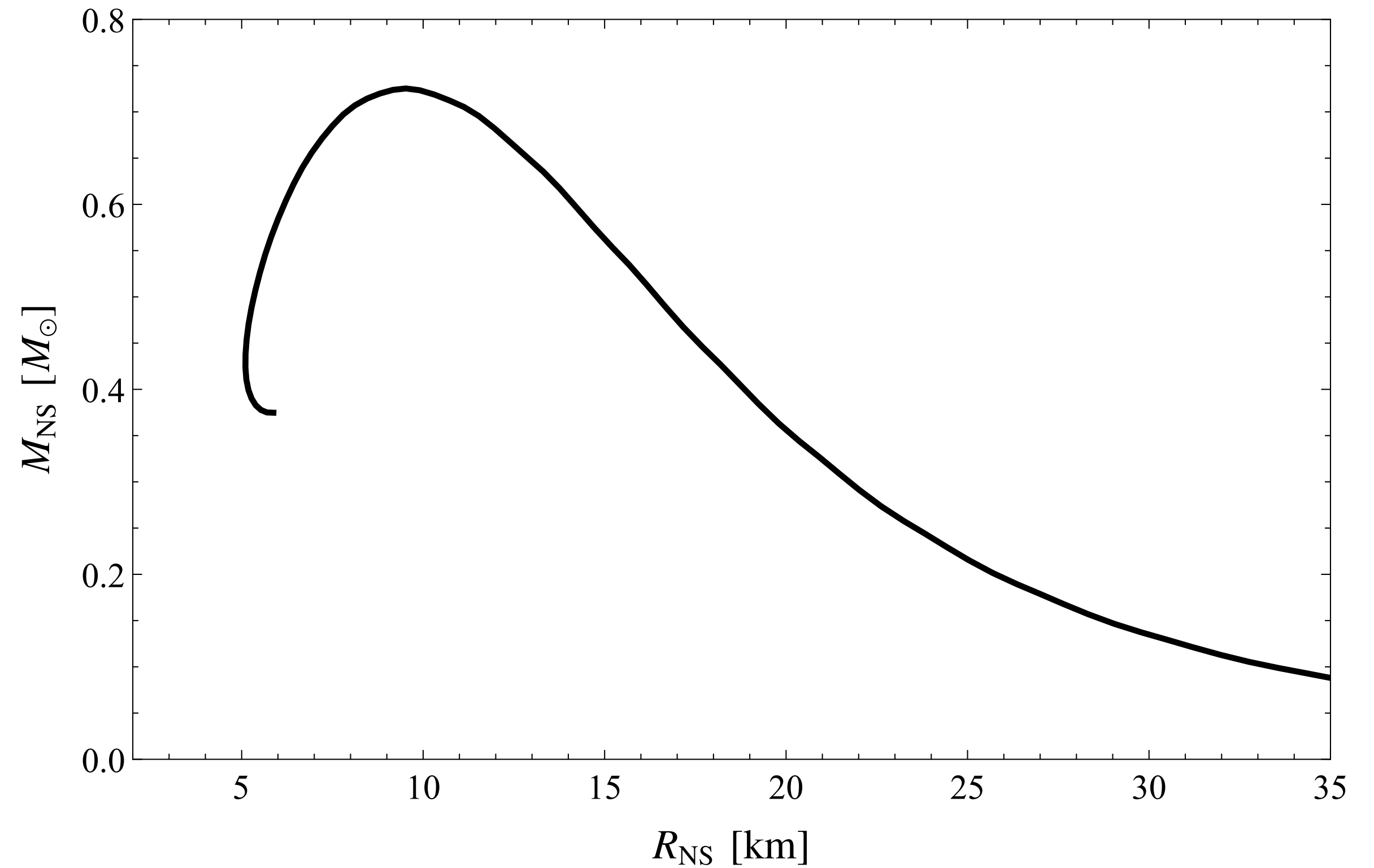


A simple example

Consider non-interacting Fermi gas of neutrons

$$\Rightarrow M_{\text{max}} \sim 0.7 \left(\frac{m_N}{m} \right)^2 M_{\odot}$$

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A simple example

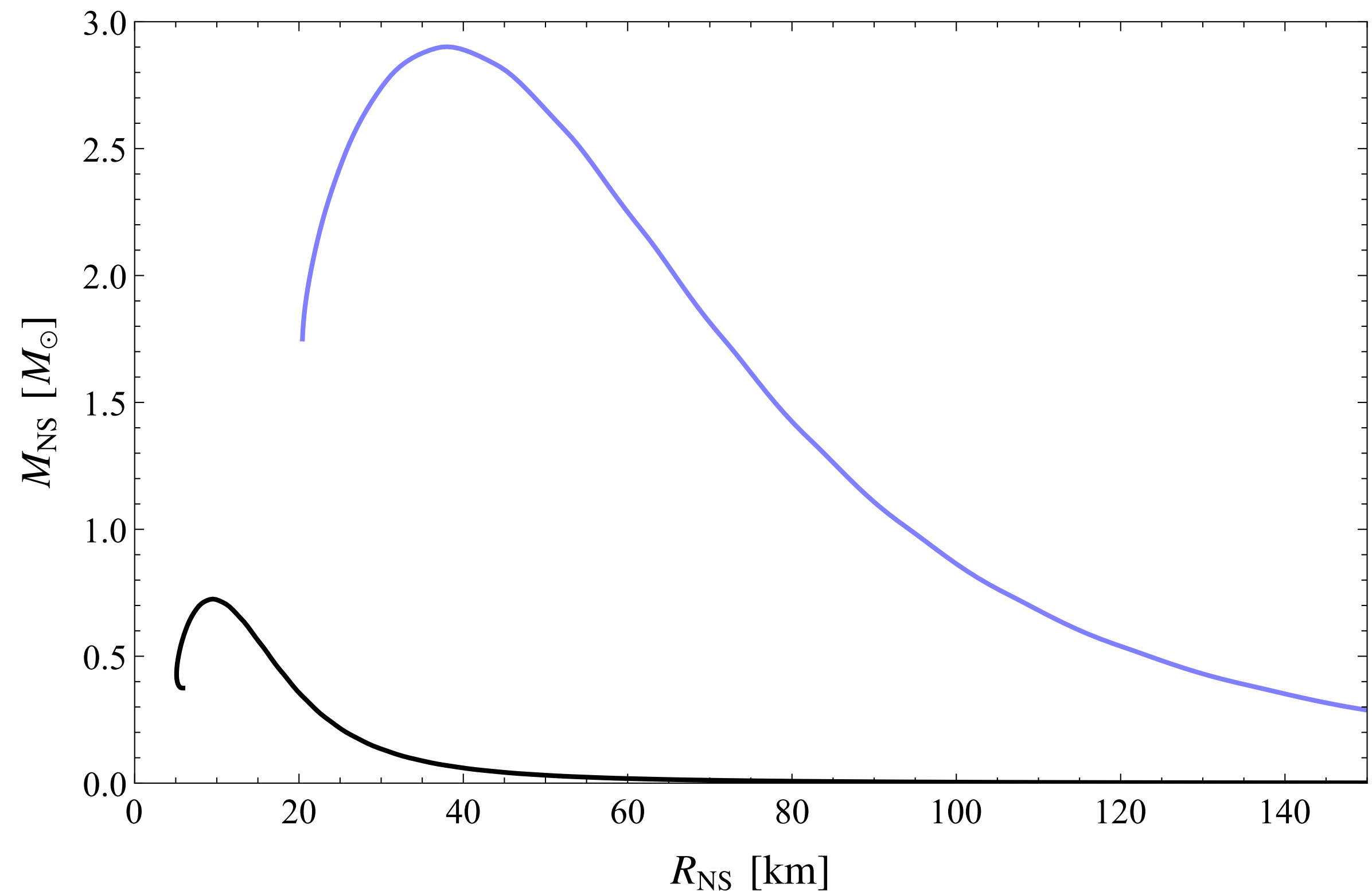
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For lighter neutrons

$$m \sim m_N/3 \rightarrow \mathcal{O}(10)$$



A simple example

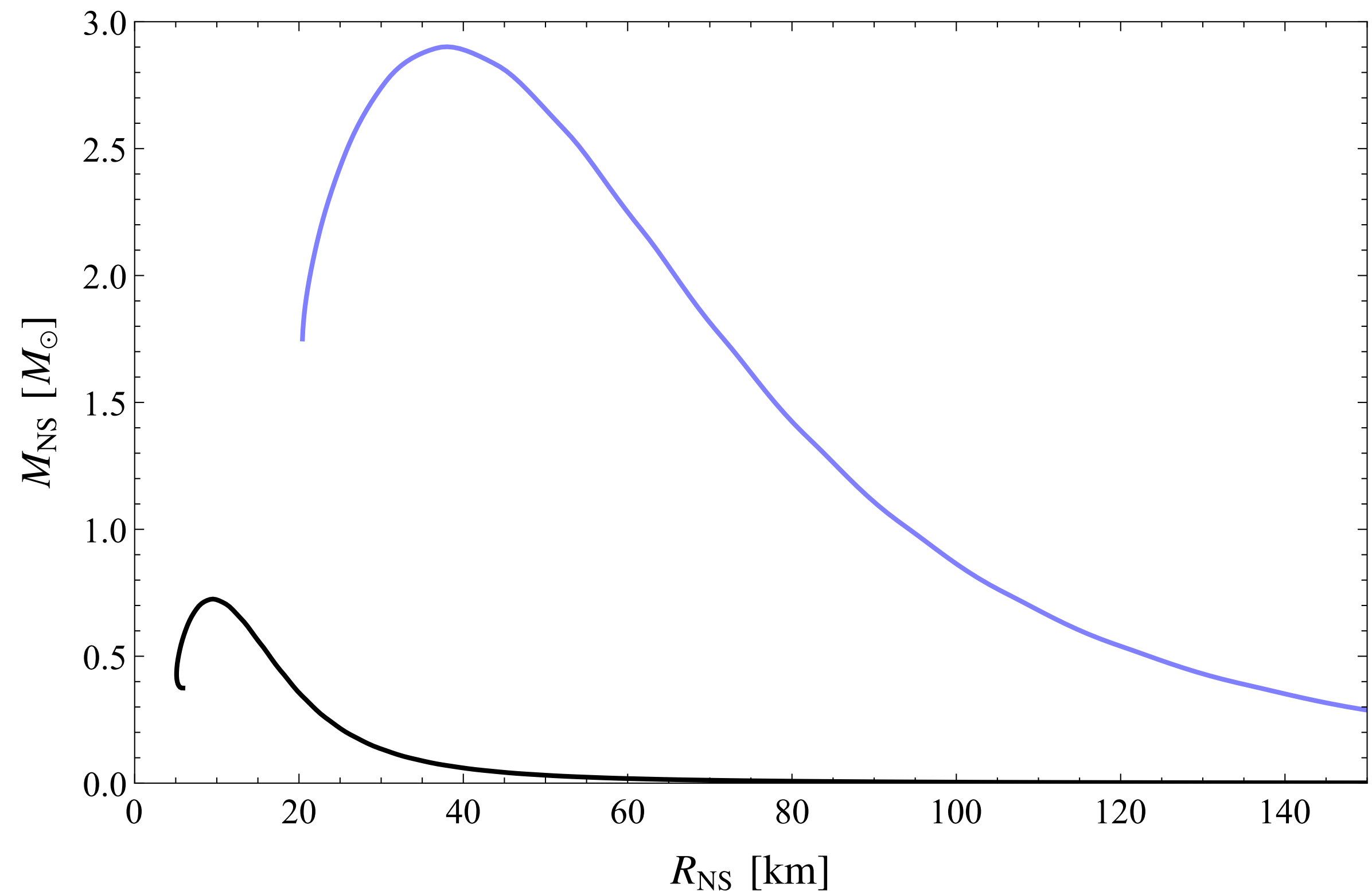
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Why is that? At fixed energy density, need more neutrons $\varepsilon_0 = m_N n$

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- White dwarfs and the axion ✓

Part II: Heavy stars from light scalars

- Motivation and simplest example ✓
- What kind of equation of state?

Generic Scalar

Potential and coupling

$$V(\phi) = -\Lambda^4 (\cos(\phi/f) - 1) \qquad \mathcal{O}_{\phi N} = \frac{g m_N}{2} \bar{N} N \cos\left(\frac{\phi}{f}\right)$$

Relax the coupling

$$m_N^* = \begin{cases} m_N & \phi = 0 \\ m_N(1 - g) & \phi = \pi \end{cases} \qquad 1 > g > 0$$

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What kind of EOS?

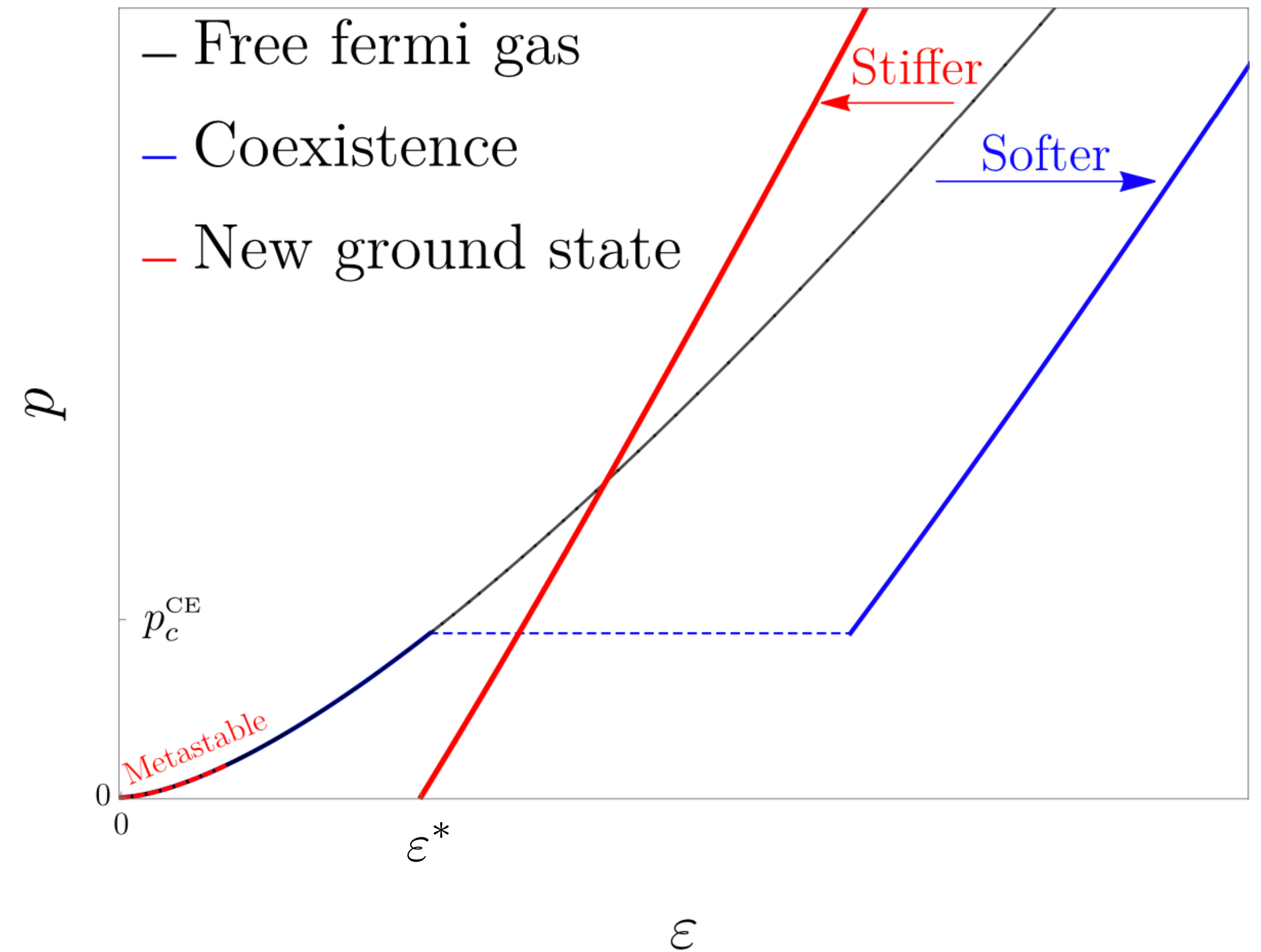
- 1) Mass reduction $m_N^* < m_N$ **stiffens** the EOS $\varepsilon = \text{const.} = m_N^* \rho$
 $\Rightarrow M_{\text{max}} \sim 0.7 \left(\frac{m_N}{m}\right)^2 M_{\odot}$
- 2) Vacuum energy $V(\pi f) = 2\Lambda^4$ **softens** the EOS additional energy density gravitates

Generic Scalar

Parameter space is split

Potential dominating: $\varepsilon/n > m_N$

Coexistence First order PT: softens the EOS



Generic Scalar

Parameter space is split

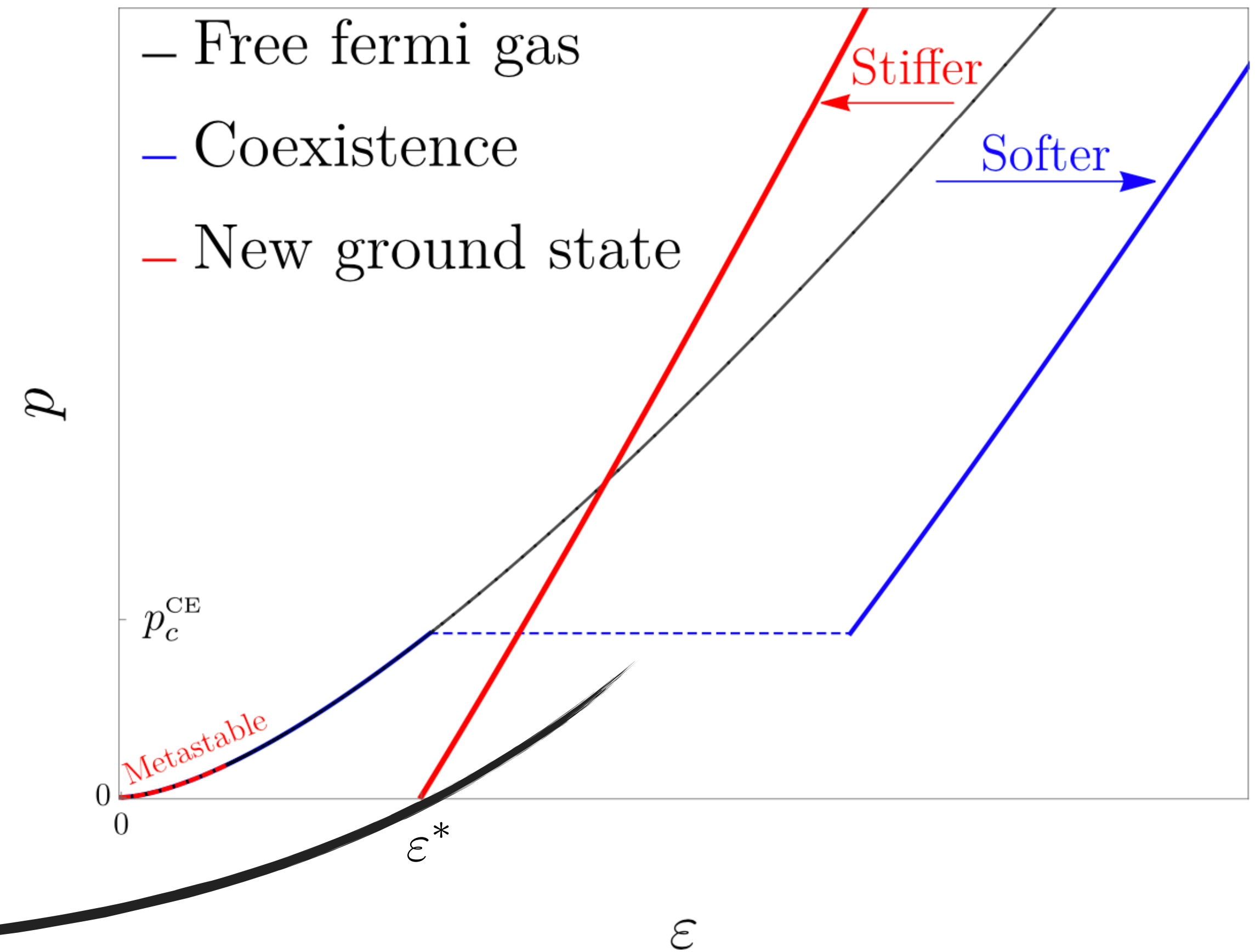
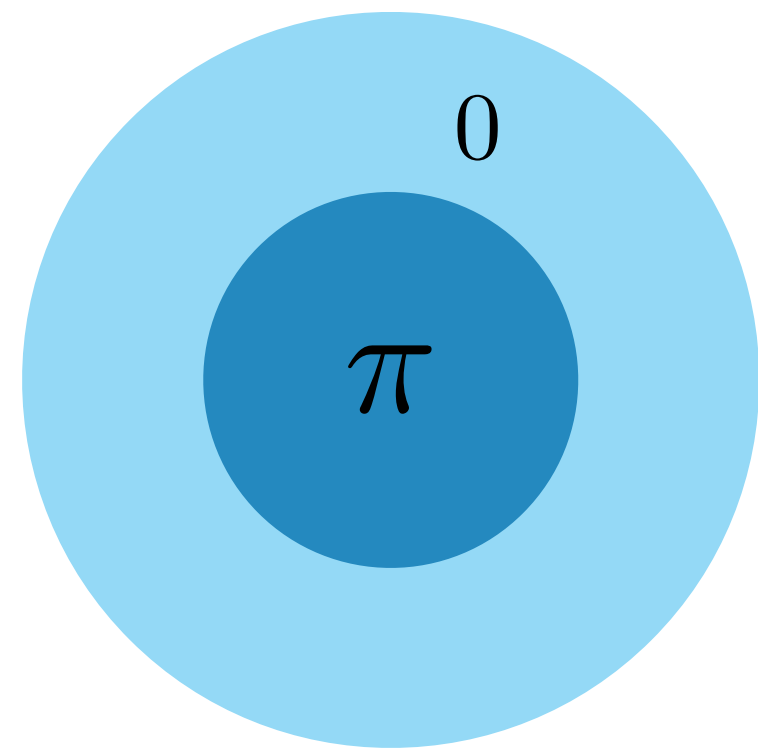
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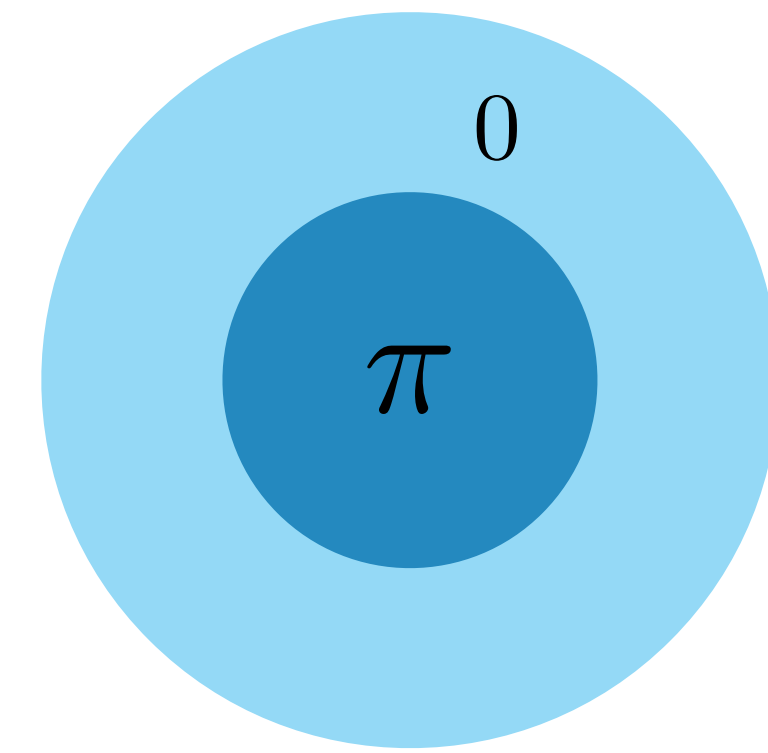
Hybrid stars

$$M_{\max} \lesssim 1 M_{\odot}$$

EOS is softer!



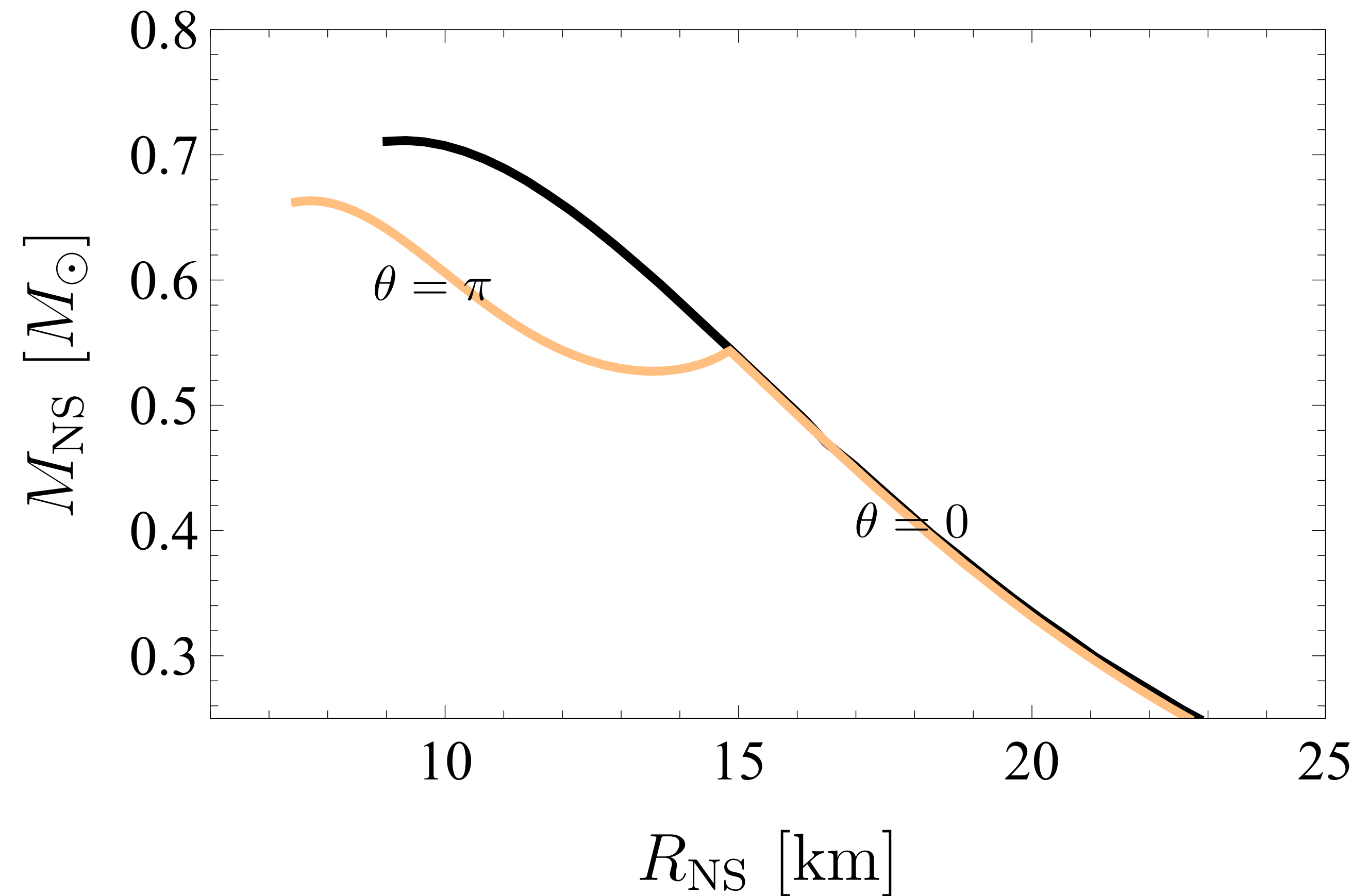
Coexistence Phase: MR Curve



1st order phase transition:

- Generically softens EOSs
e.g. Kaon condensation
- Disfavoured

Gravitational wave signal?



Generic Scalar

Parameter space is split

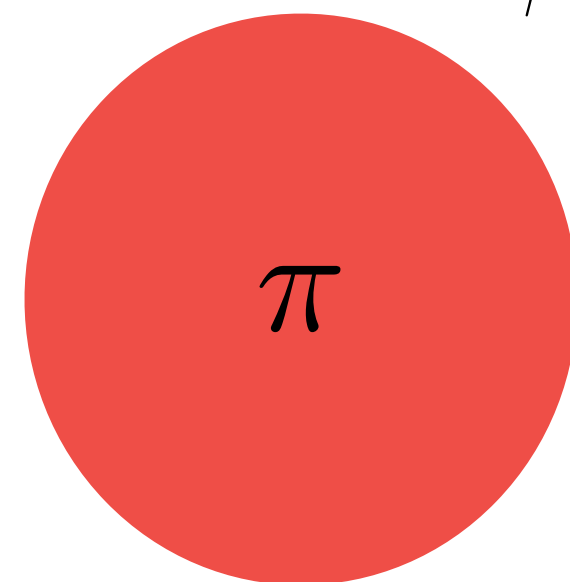
Mass change dominating: $\varepsilon/n < m_N$

New ground state $p = 0, \quad \varepsilon \geq \varepsilon^*$

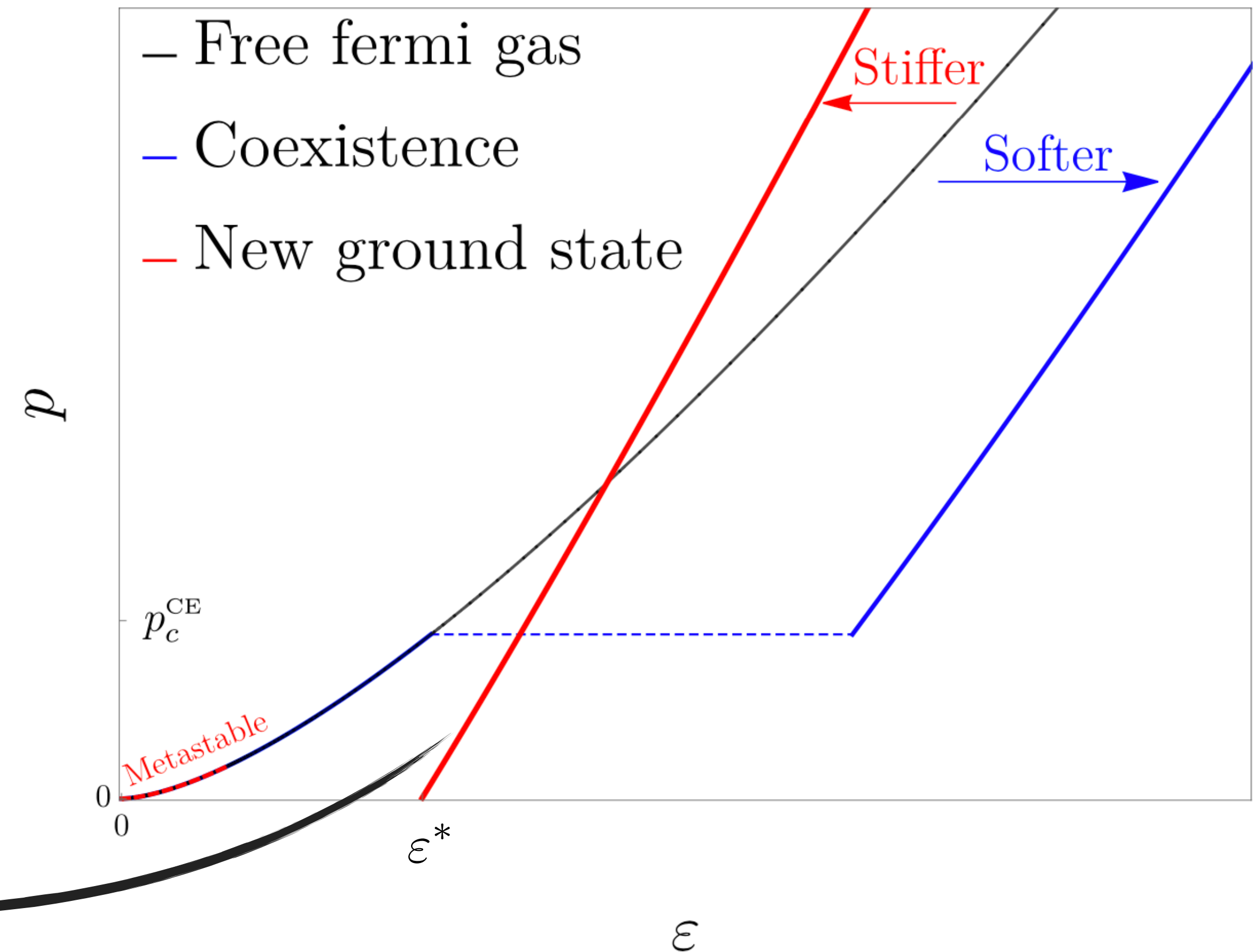
like SQM

New ground state
 $\max[M_{\max}] \gg M_{\odot}$

EOS (can be) stiffer!



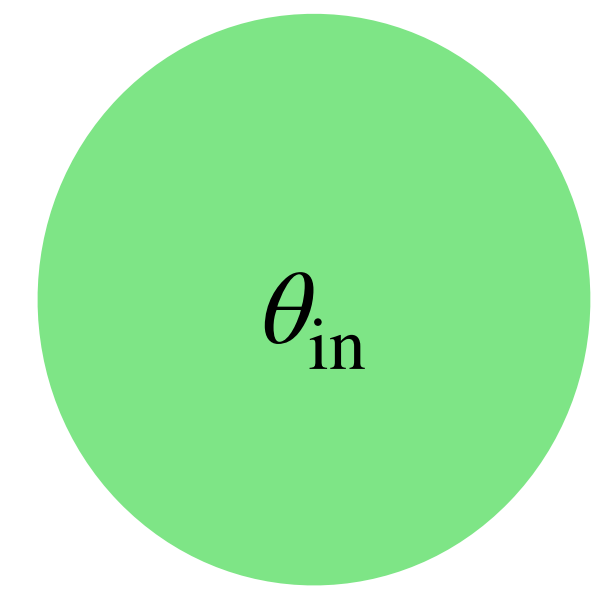
$$\phi = \theta f$$



New Ground State Phase

New ground state
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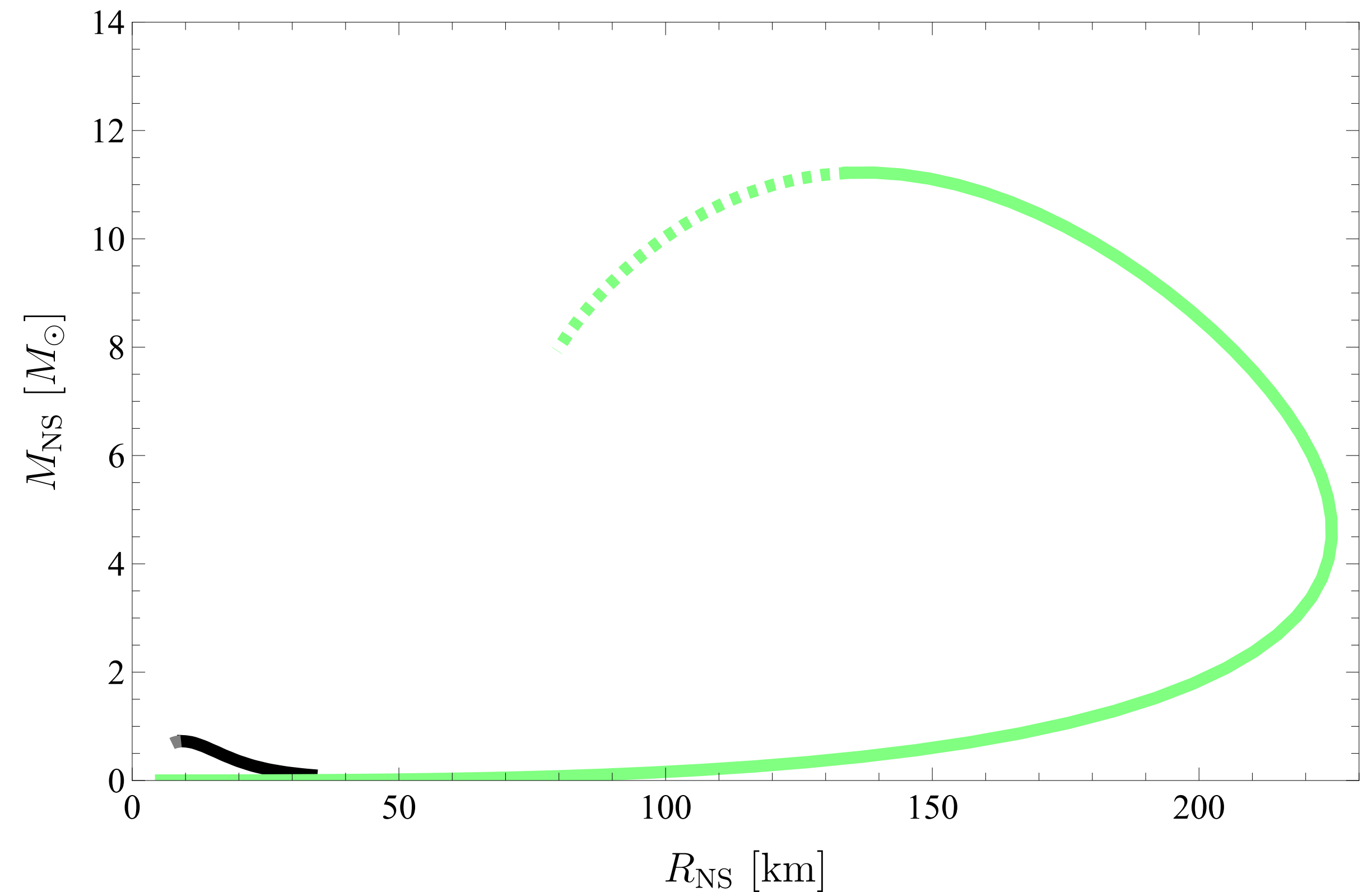


NGS for $\Lambda = 5 \text{ MeV}$, $g = 0.75$

This can be a large effect

$$M_{\max} \simeq 11.2 M_{\odot}$$

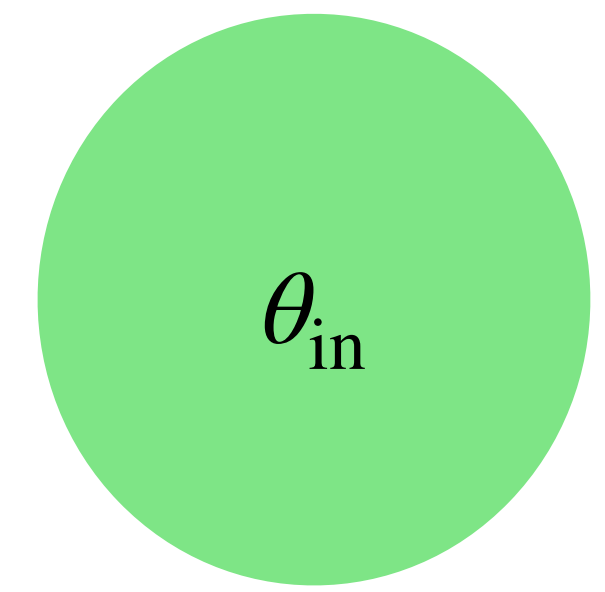
$$R_{\max} \simeq 160 \text{ km}$$



New Ground State Phase

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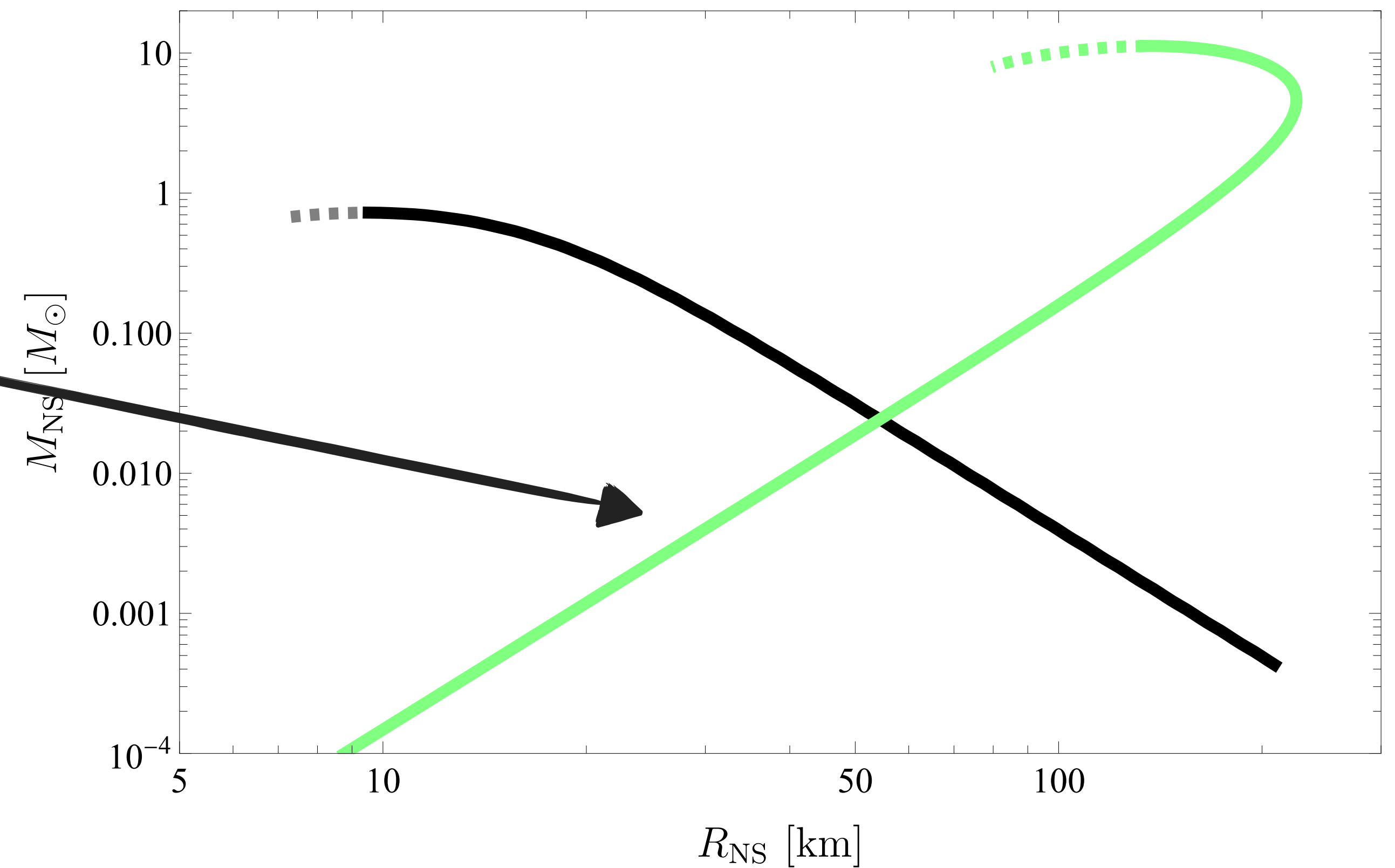
Self bound objects

$$M \simeq \varepsilon^{\text{NGS}} R^3$$

Minimal size given by gradient

$$R_{\min} \simeq \frac{f}{\Lambda^2}$$

Field has to fit inside R^3



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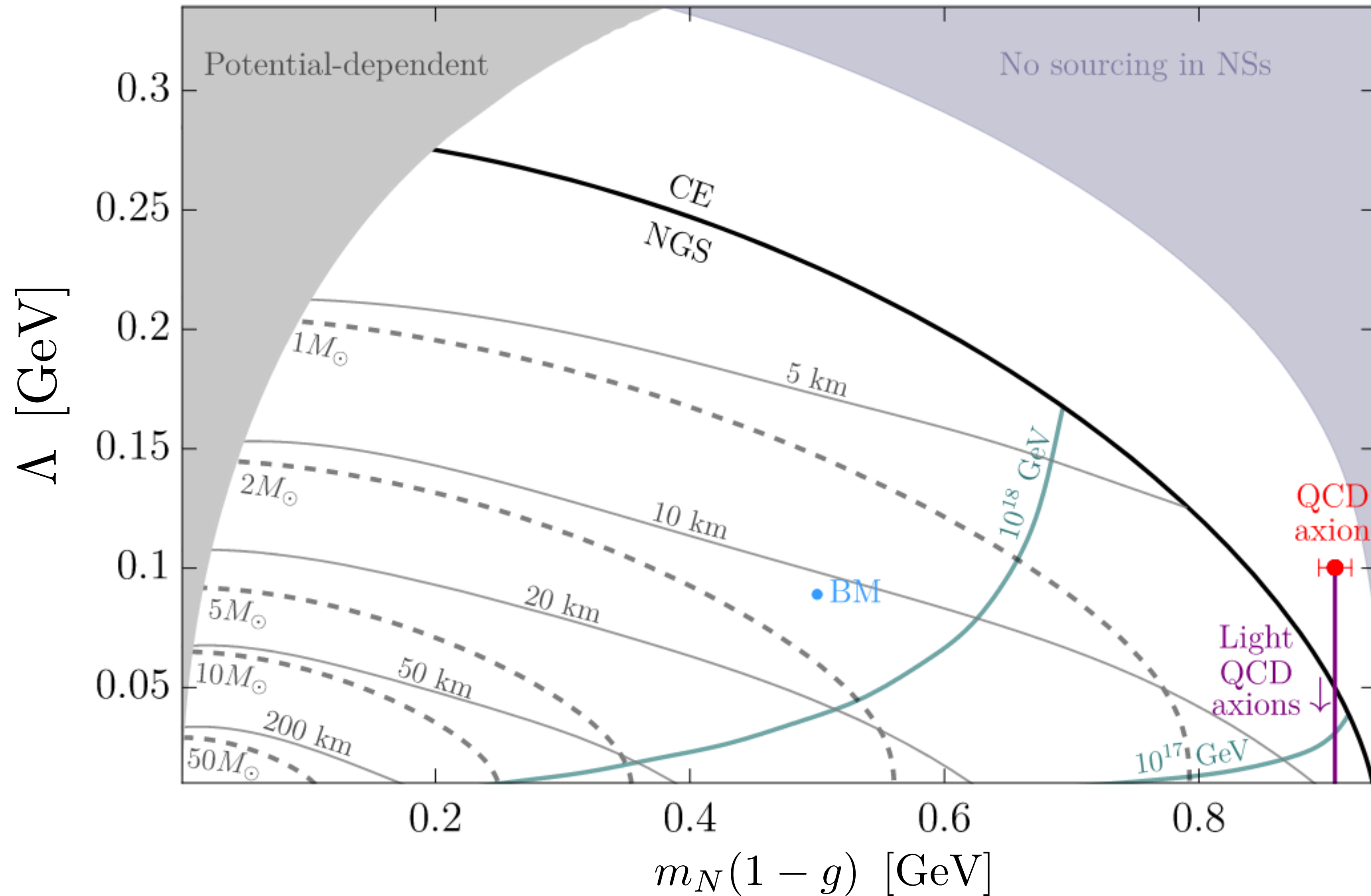
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- What kind of equation of state? ✓
- Parameter space

Parameter space

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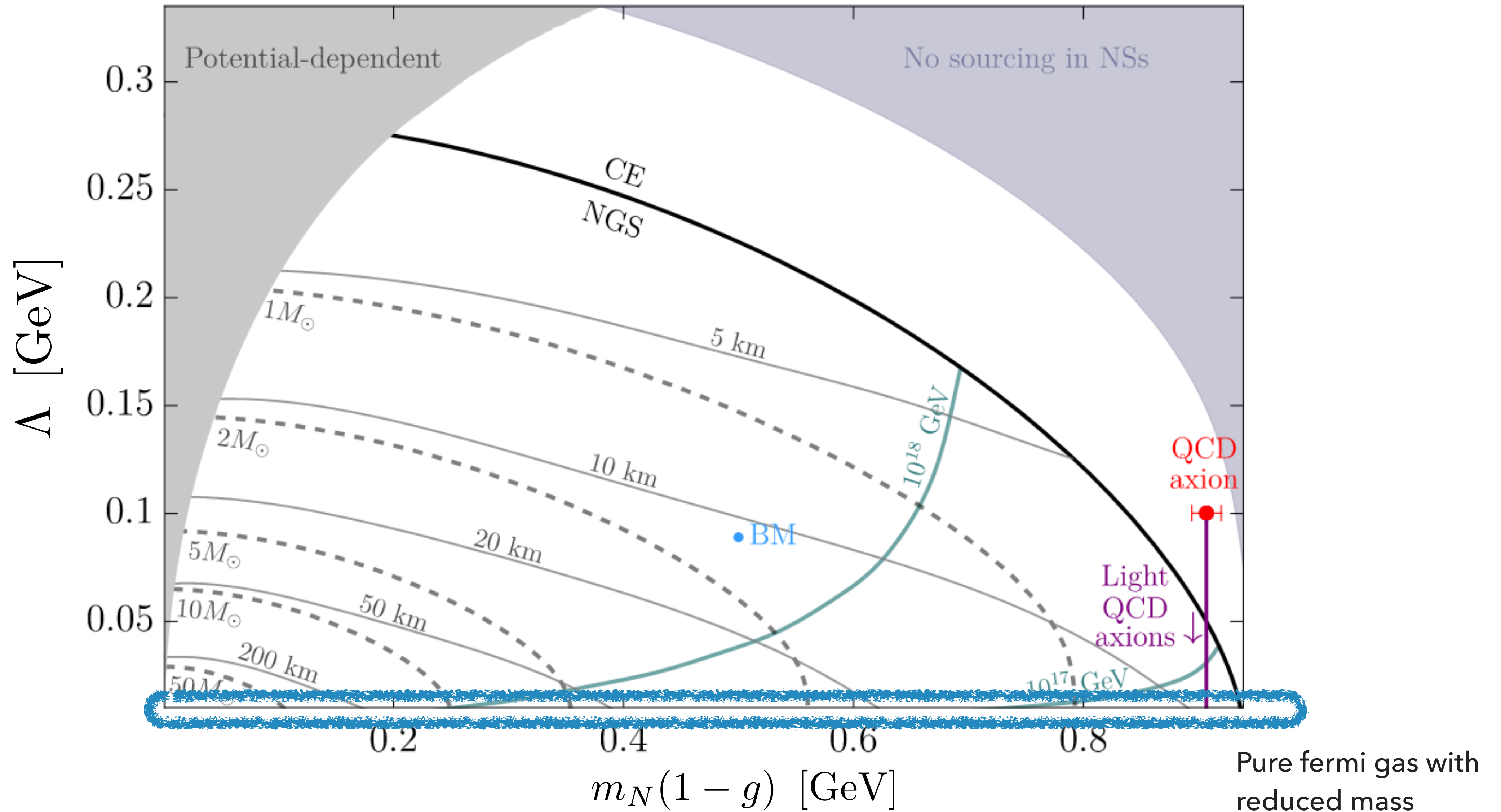
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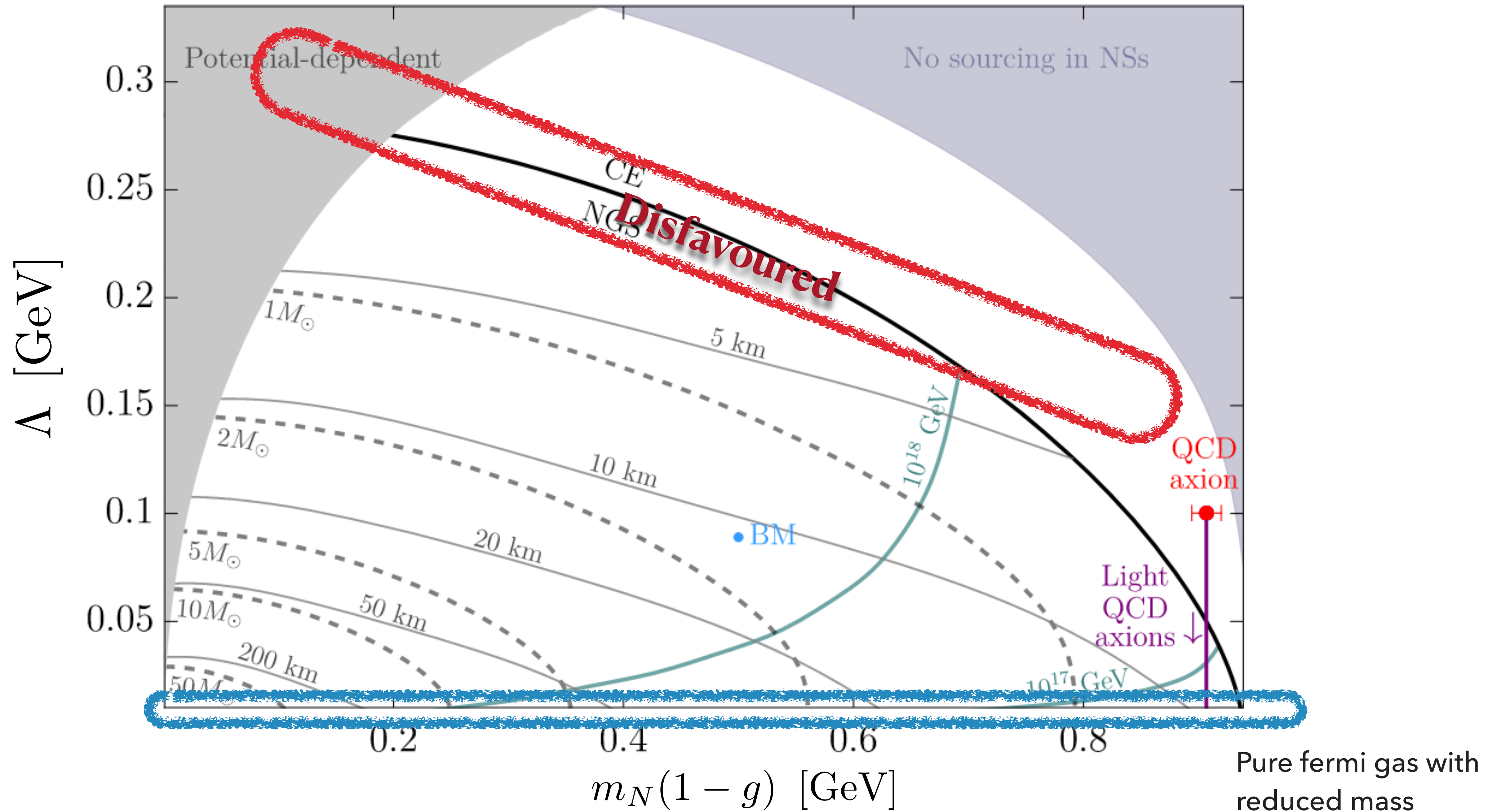
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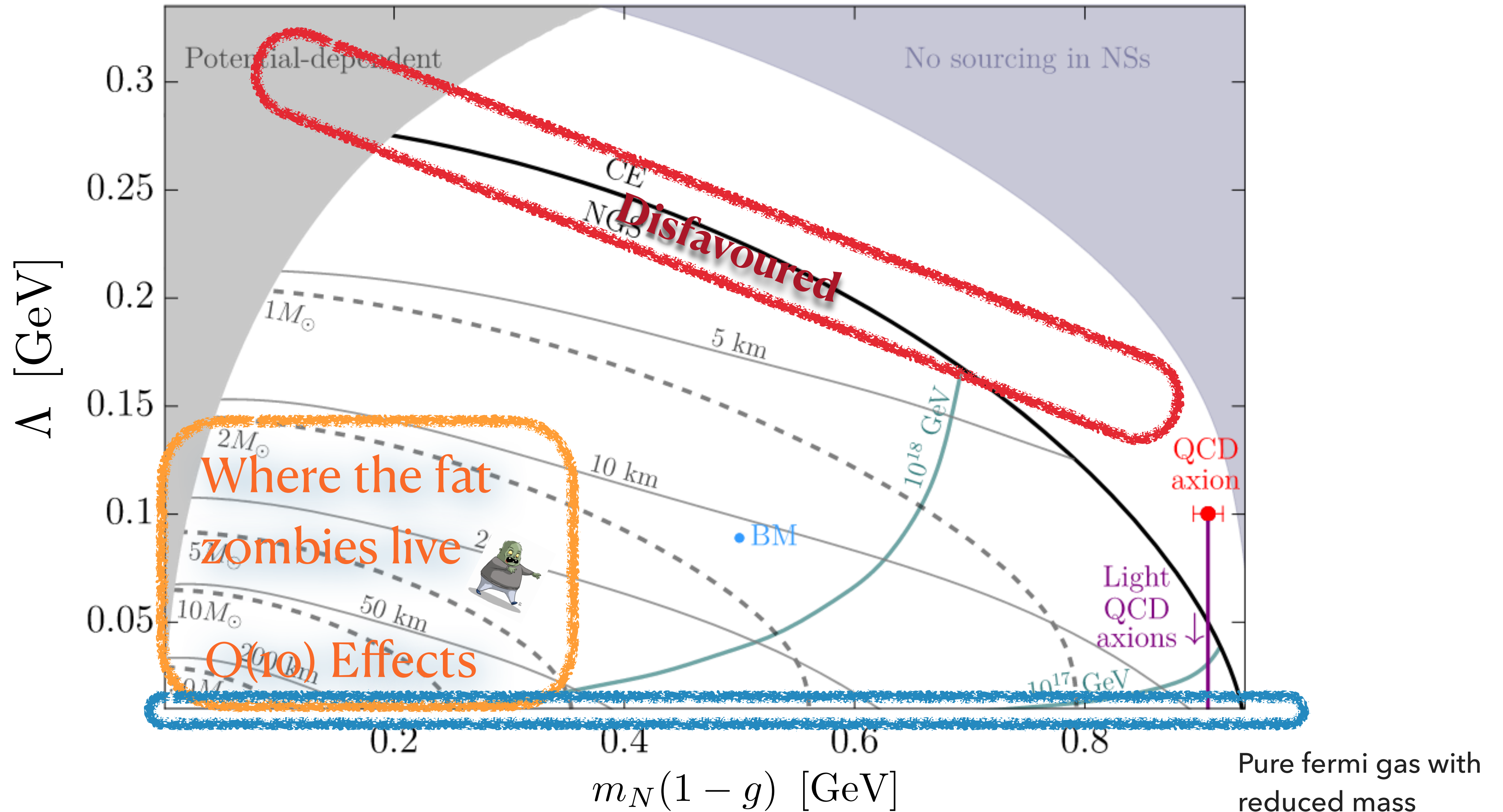
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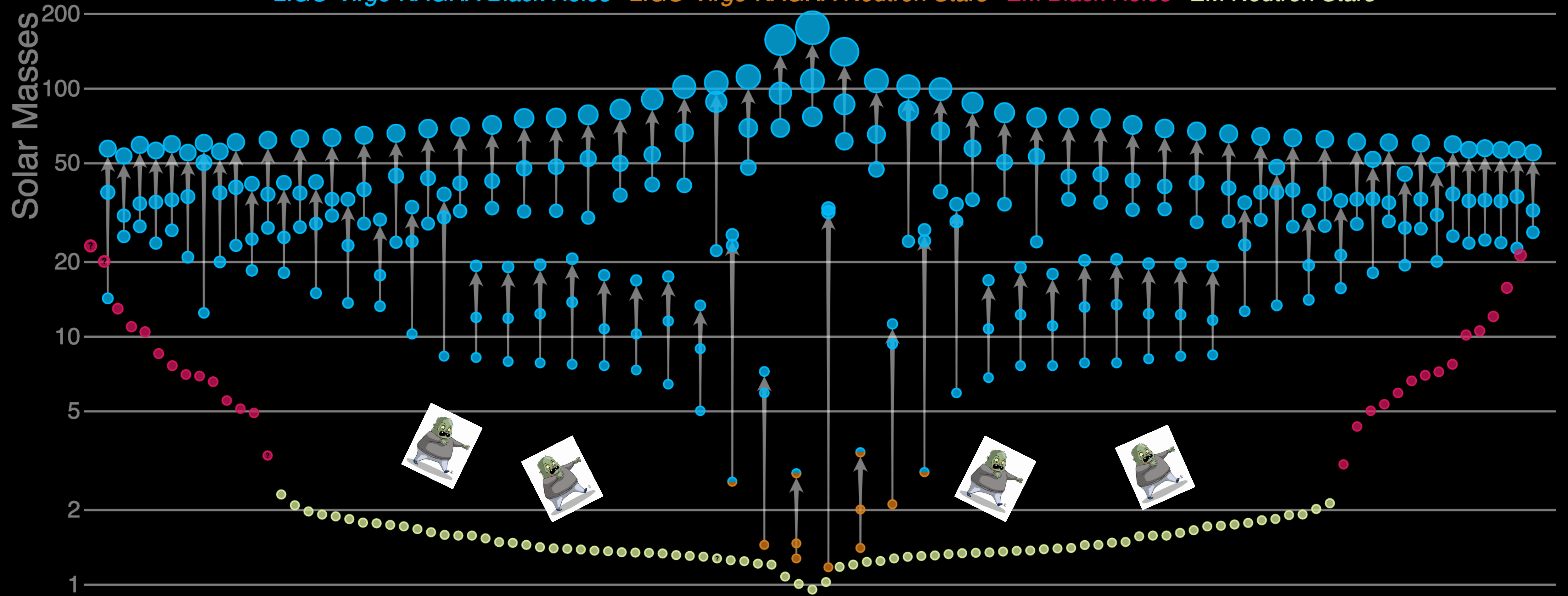
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Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes *LIGO-Virgo-KAGRA Neutron Stars* *EM Black Holes* *EM Neutron Stars*



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Conclusion and Outlook

White dwarfs as a probe of light QCD axions

- Light QCD axions can get sourced in White Dwarfs leading to a NGS
- There is a gap in densities between the Meta Stable and the NGS branch...
- ... which translates to a gap in the M-R curve
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- This does **not** rely on the axion being DM

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Heavy Neutron Stars from light Scalars

- Light Scalars with non-derivative coupling to nucleons make them lighter
- Coexistence Phase: Hybrid stars with softer EOS
- New ground state: Large effects on maximal mass

Conclusion and Outlook

White dwarfs as a probe of light QCD axions

- Light QCD axions can get sourced in White Dwarfs leading to a NGS
- There is a gap in densities between the Meta Stable and the NGS branch...
- ... which translates to a gap in the M-R curve
- Allows to exclude large chunk of parameter space
- This does **not** rely on the axion being DM

Heavy Neutron Stars from light Scalars

- Light Scalars with non-derivative coupling to nucleons make them lighter
- Coexistence Phase: Hybrid stars with softer EOS
- New ground state: Large effects on maximal mass

More to do

Self bound objects as DM, Coupling to electrons, GW from 1st order PT, what about Supernovae?...

Conclusion and Outlook

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Thank you!

Heavy Neutron Stars from light Scalars

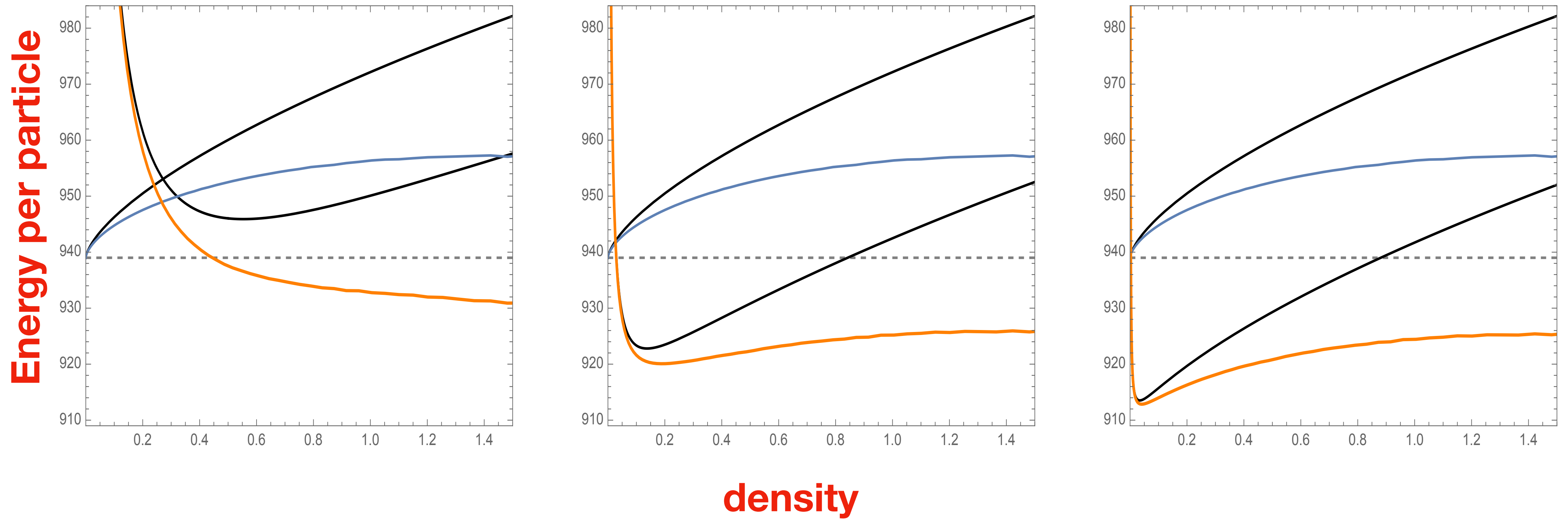
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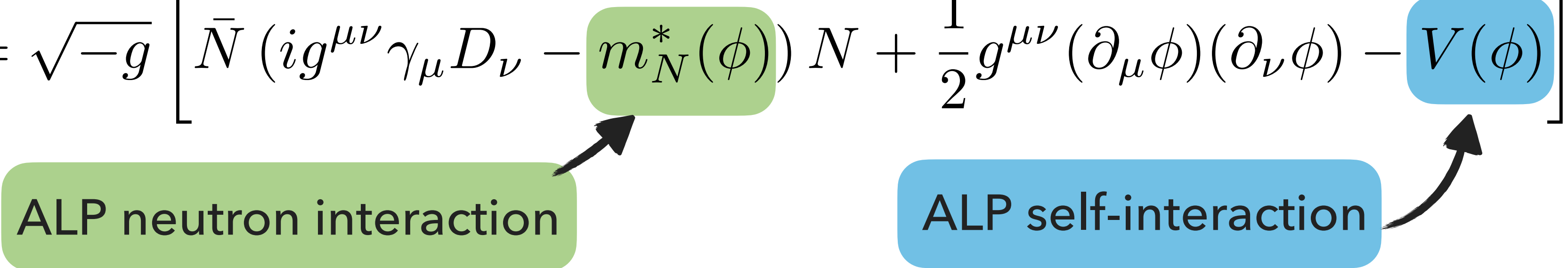
Backup

ChPT EOS with the axion



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

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

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

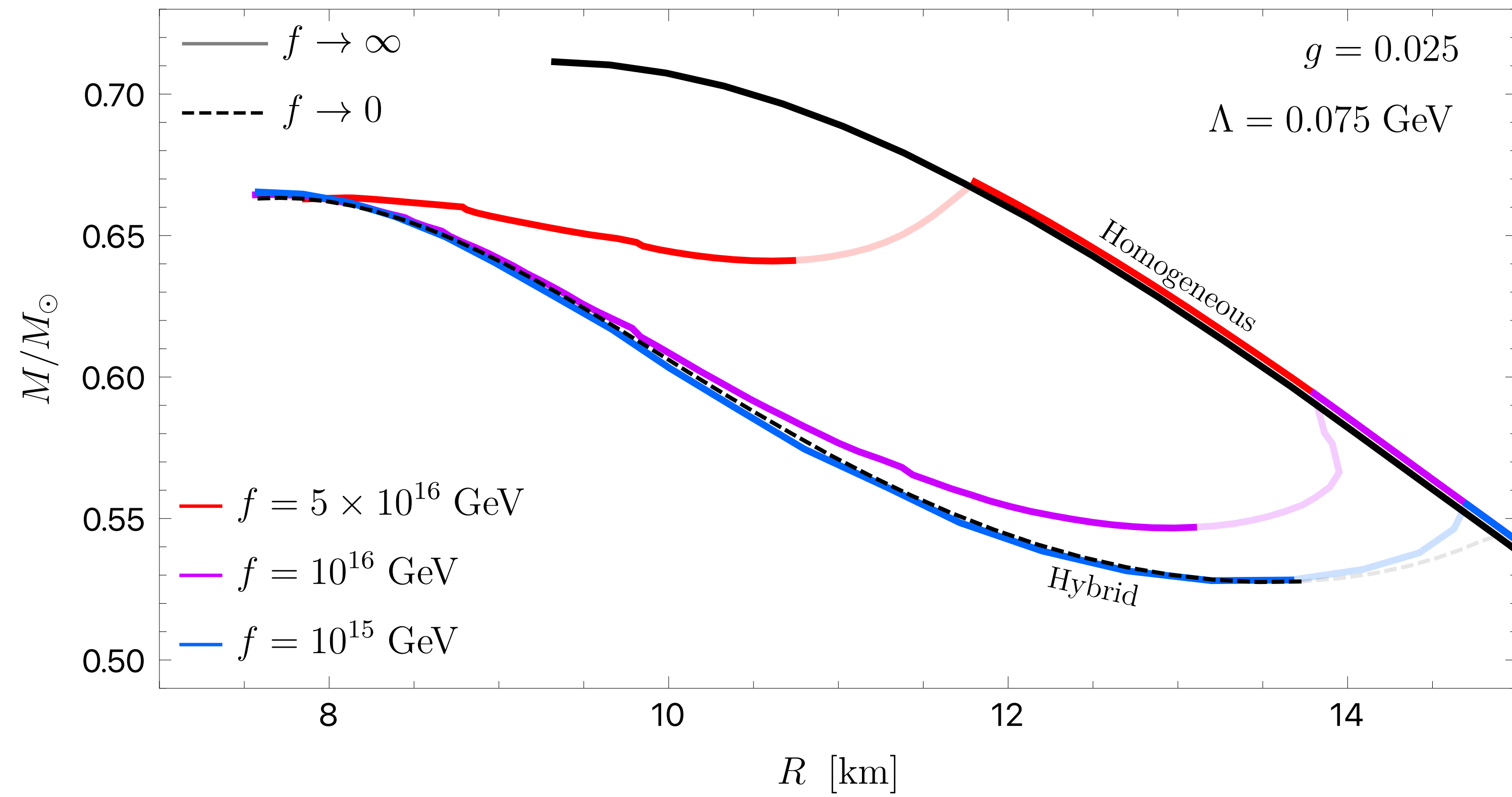
$$E(R) \simeq R^2 \Delta R \left(\frac{f}{\Delta R} \right)^2 + R^3 \varepsilon_{\text{pot}} \simeq R^3 \varepsilon_{\text{pot}}$$

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

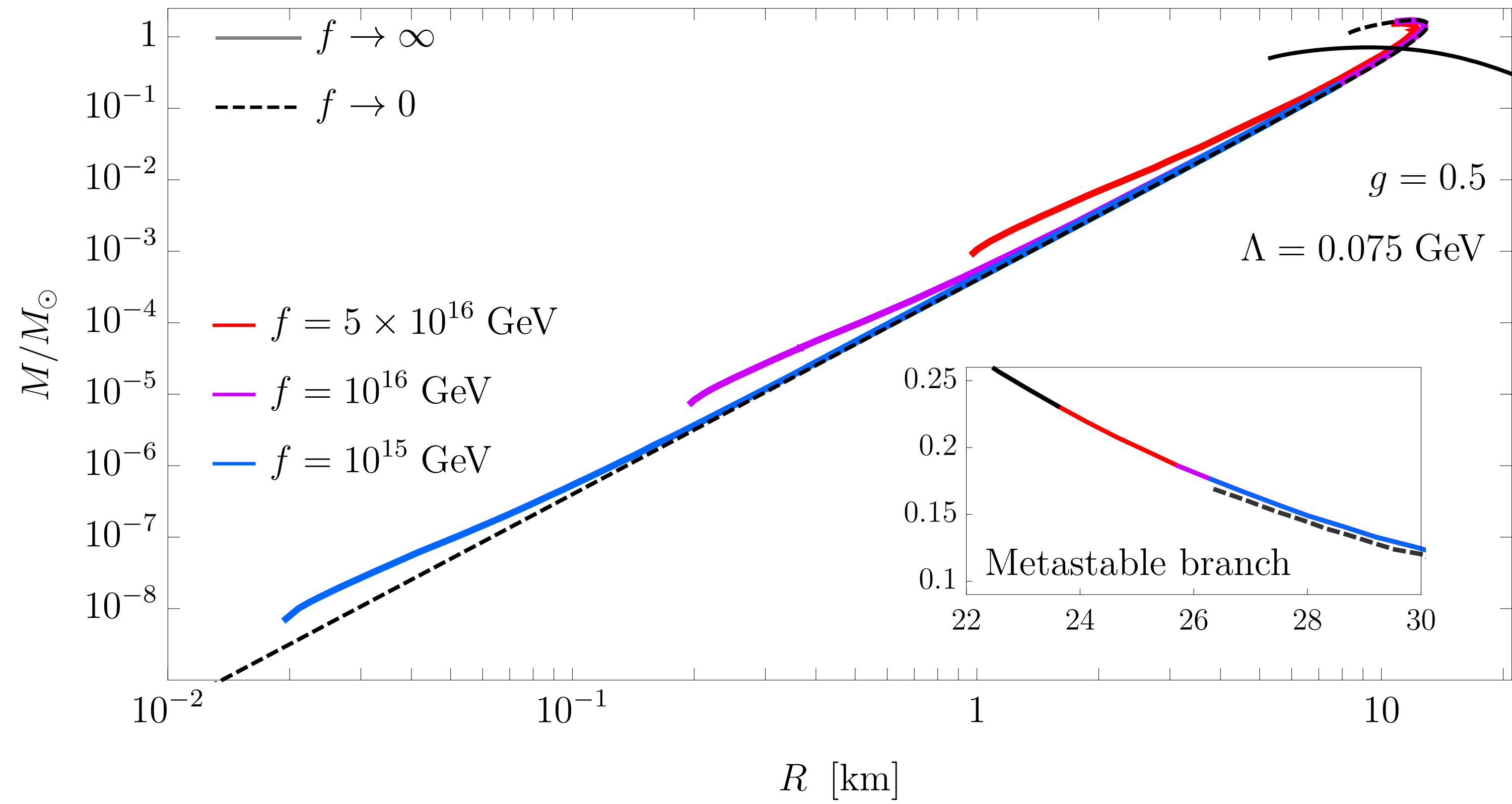
This is very nice because now the system is effectively decoupled!

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

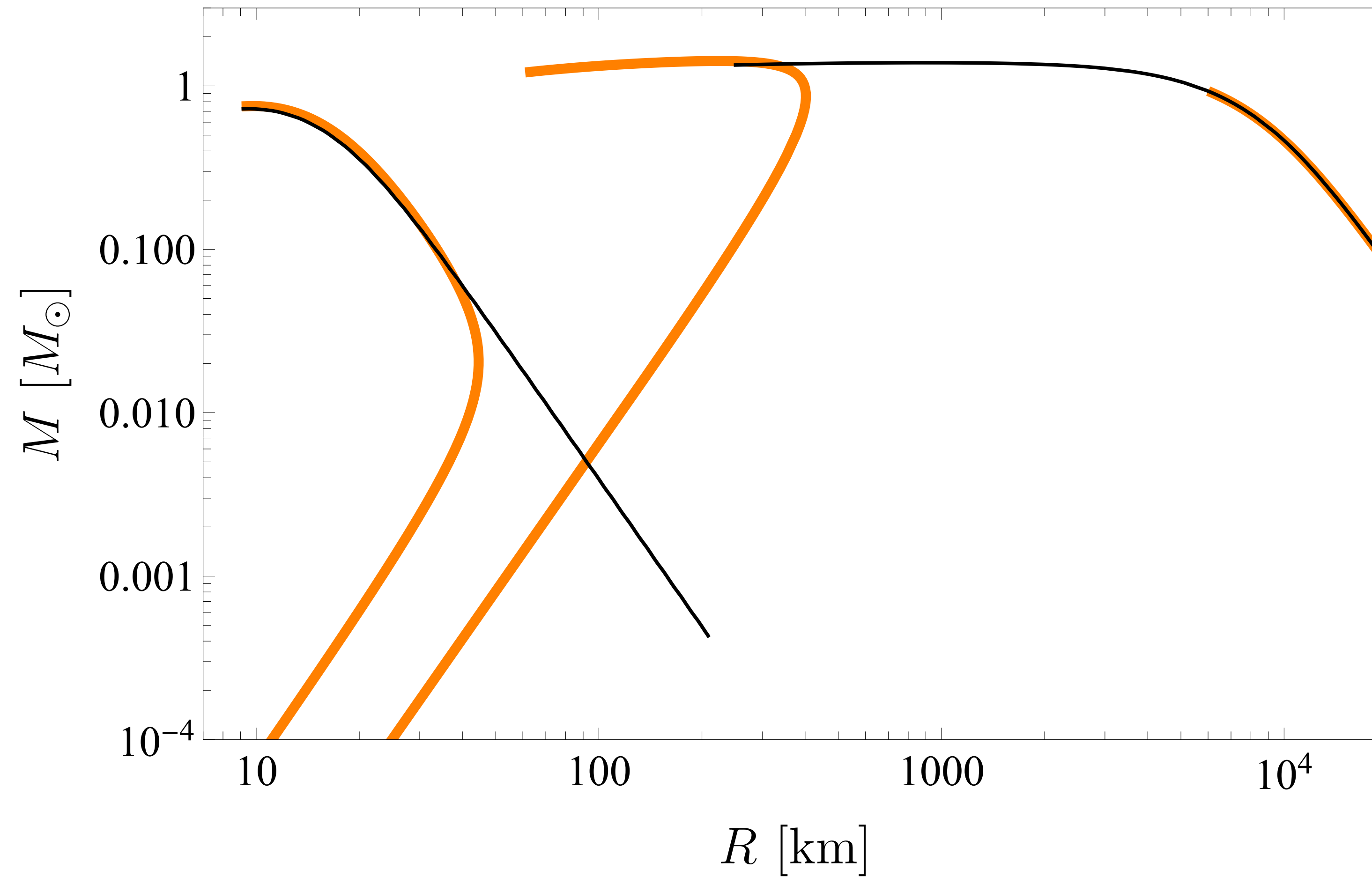
$\frac{\delta S}{\delta g_{\mu\nu}} = 0$ $\longrightarrow$ Pressure - Gravity balance equations
(Also known as TOV equations)



MR-LOG



Global view



Studying density effects is fun!

