How axions change stars

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

March, 2023

Plan

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

- Axions and their properties at finite density
- Toy Model: Free Fermi gas of neutrons with axion
- White dwarfs and light QCD axions

Part II: Heavy neutron stars from light scalars

- Motivation and simplest example
- What kind of equation of state?
- Parameter space

Conclusion and Outlook

Plan

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

- Axions and their properties at finite density

The QCD Axion: Motivated by the strong CP problem

CP violation in the strong sector

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

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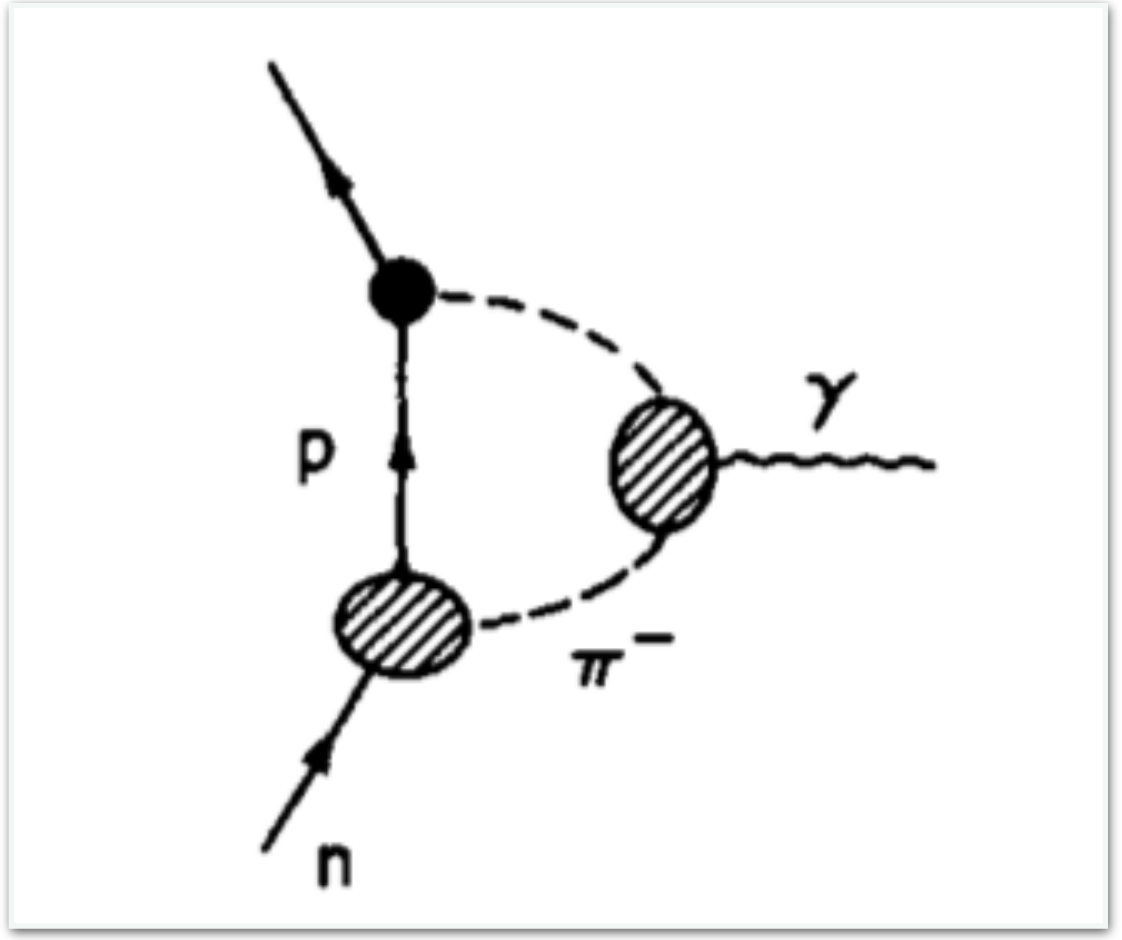

Predicts a neutron EDM $\quad \mathcal{L}_\chi \supset d_n \bar{n}\sigma^{\mu\nu}\gamma_5 n F_{\mu\nu}$

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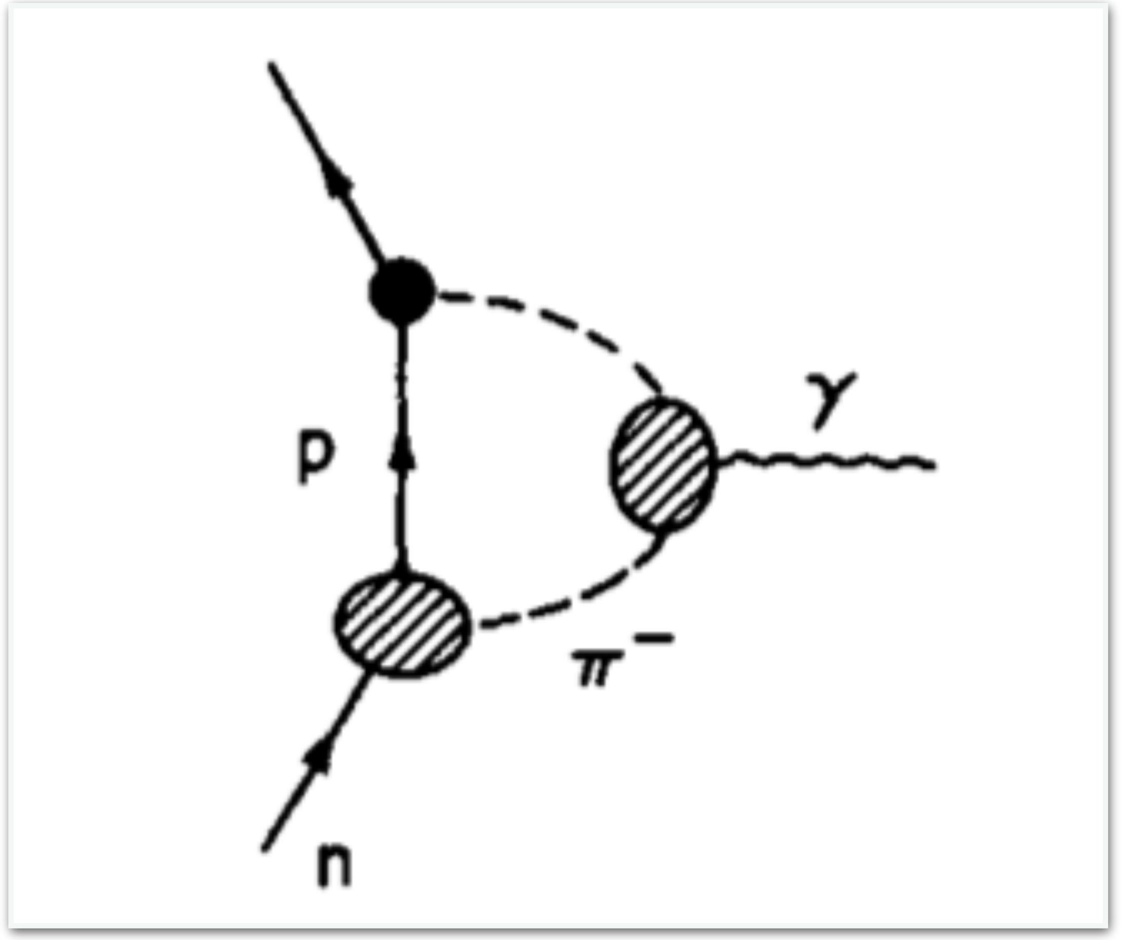

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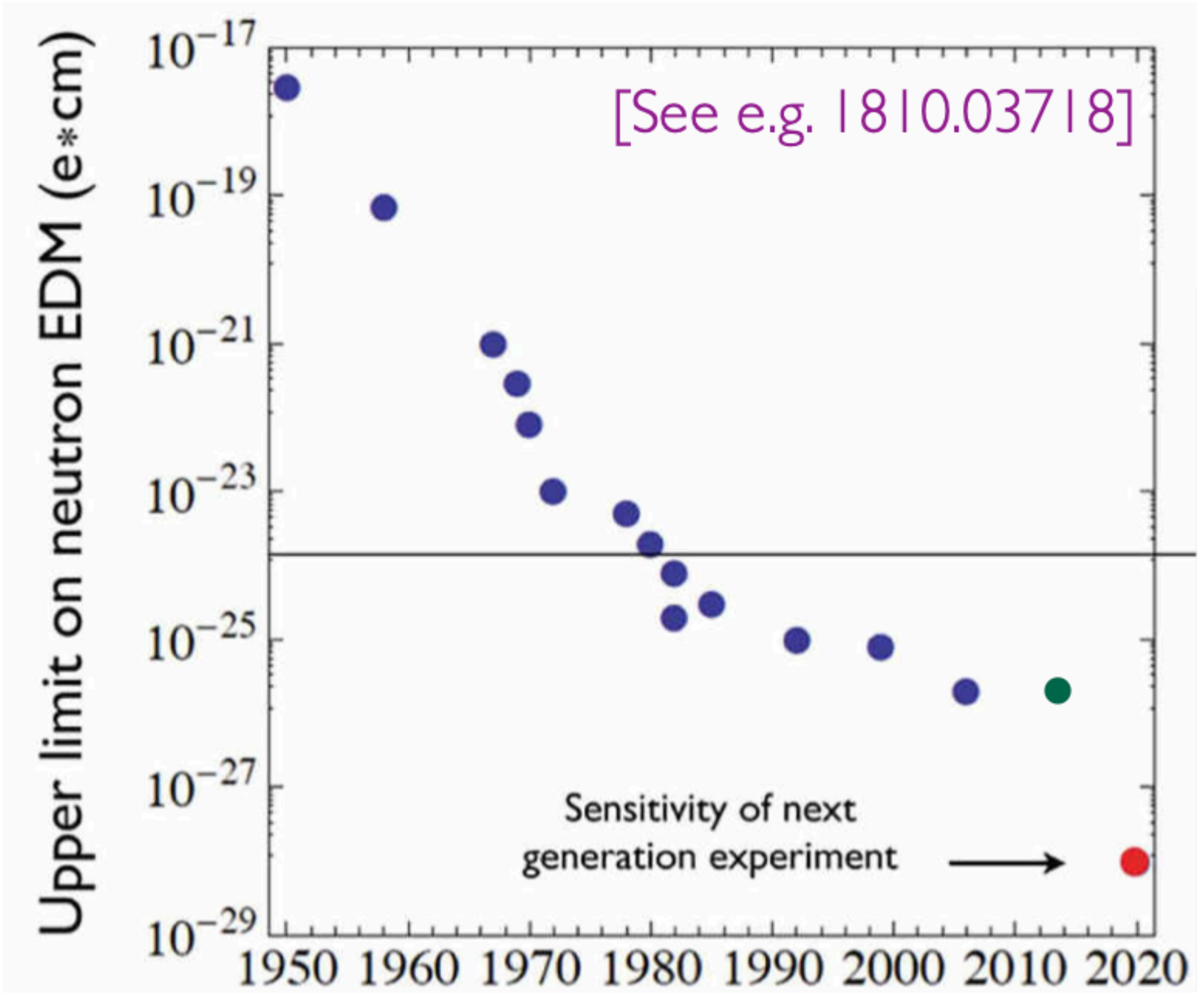

$$d_n \approx \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \approx 10^{-16}|\bar{\theta}|e\ \mathrm{cm}$$

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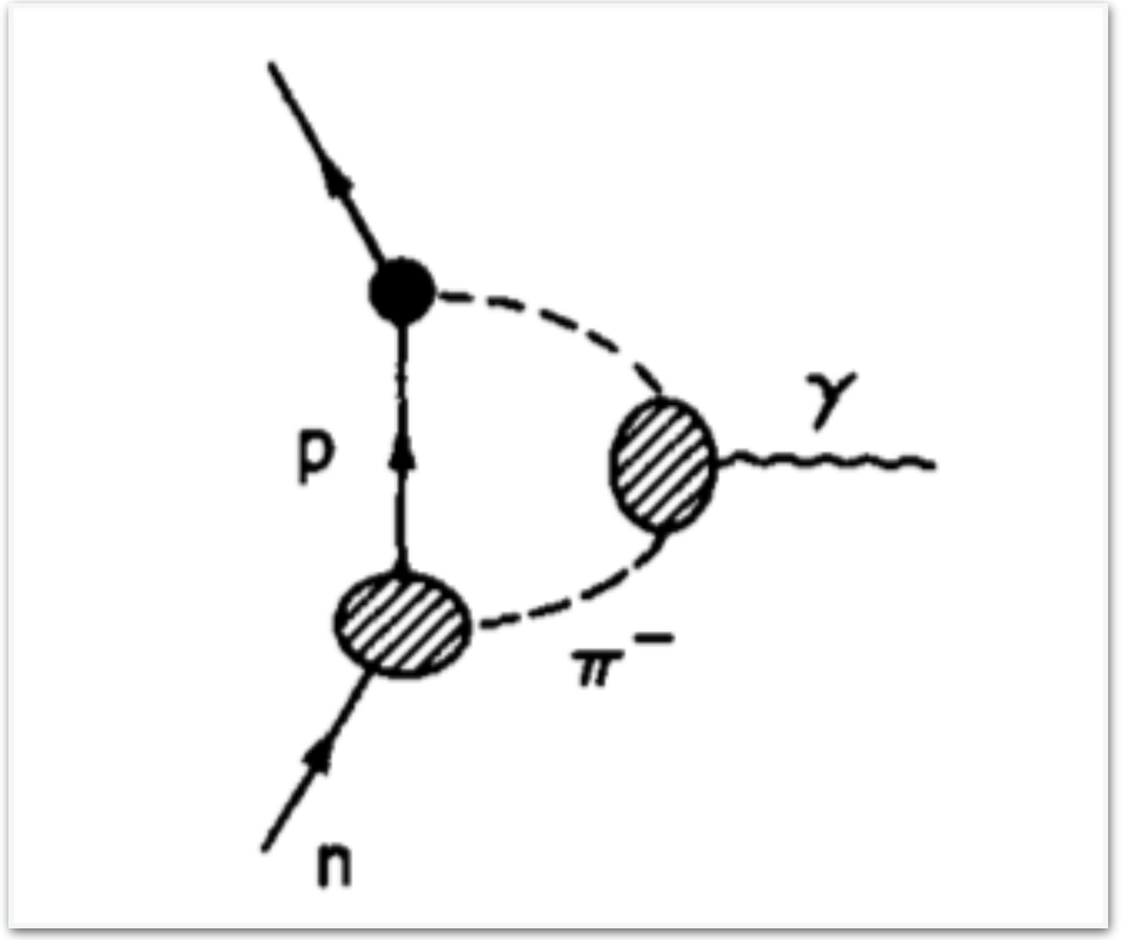

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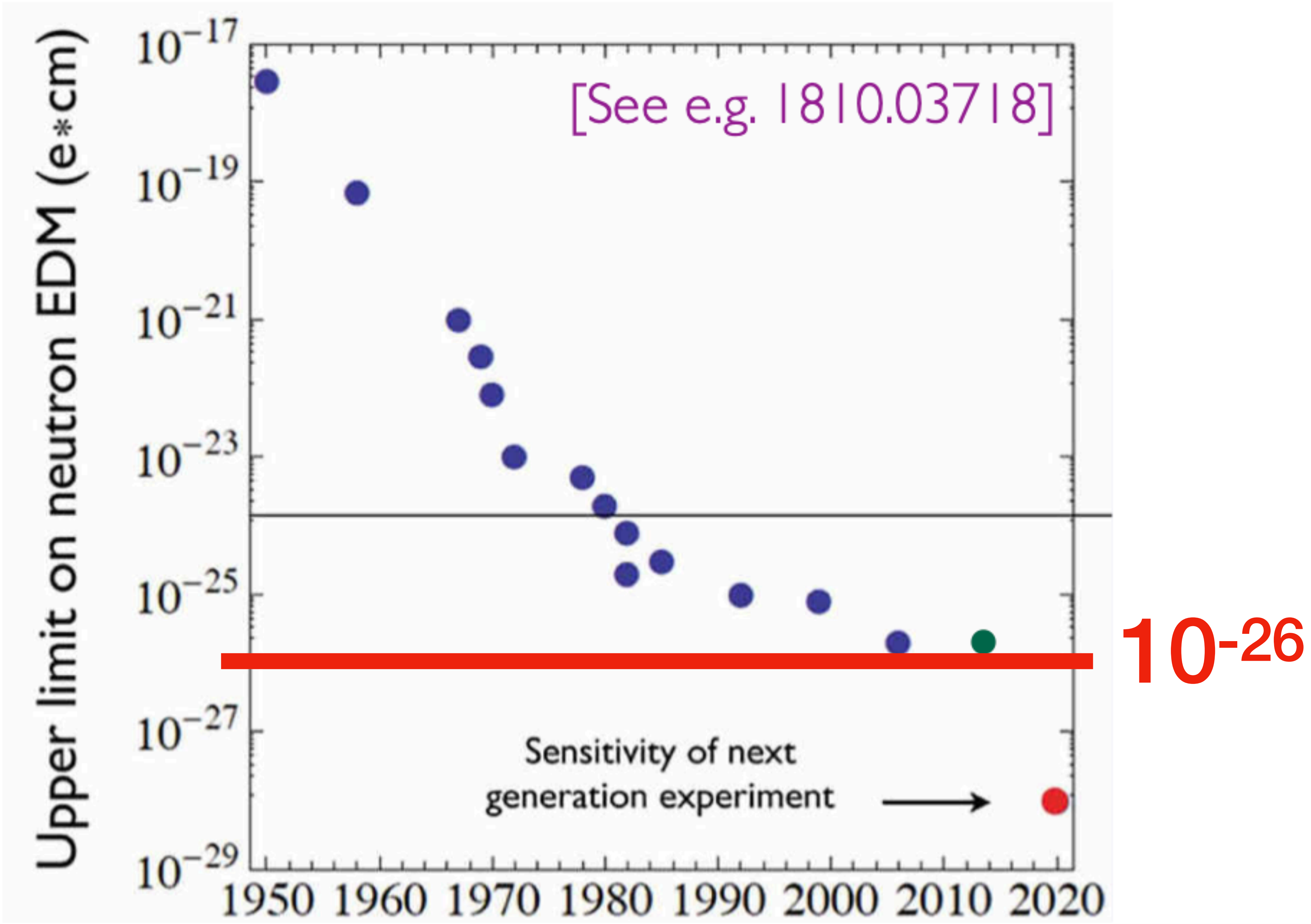


$$d_n \approx \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \approx 10^{-16}|\bar{\theta}|e\text{ cm}$$

Why so small ?

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

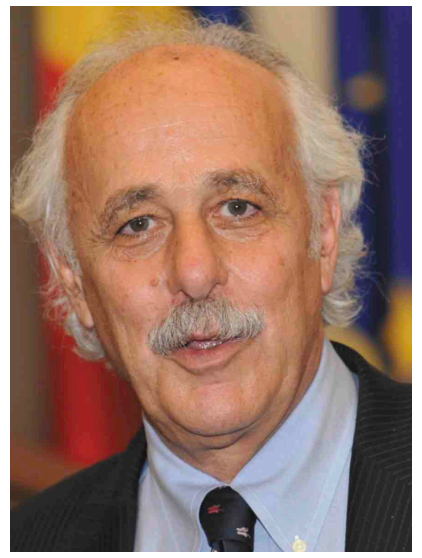
The QCD Axion: Solution

- Axial PQ symmetry $U(1)_{\rm PQ}$: 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 $\phi(x)$

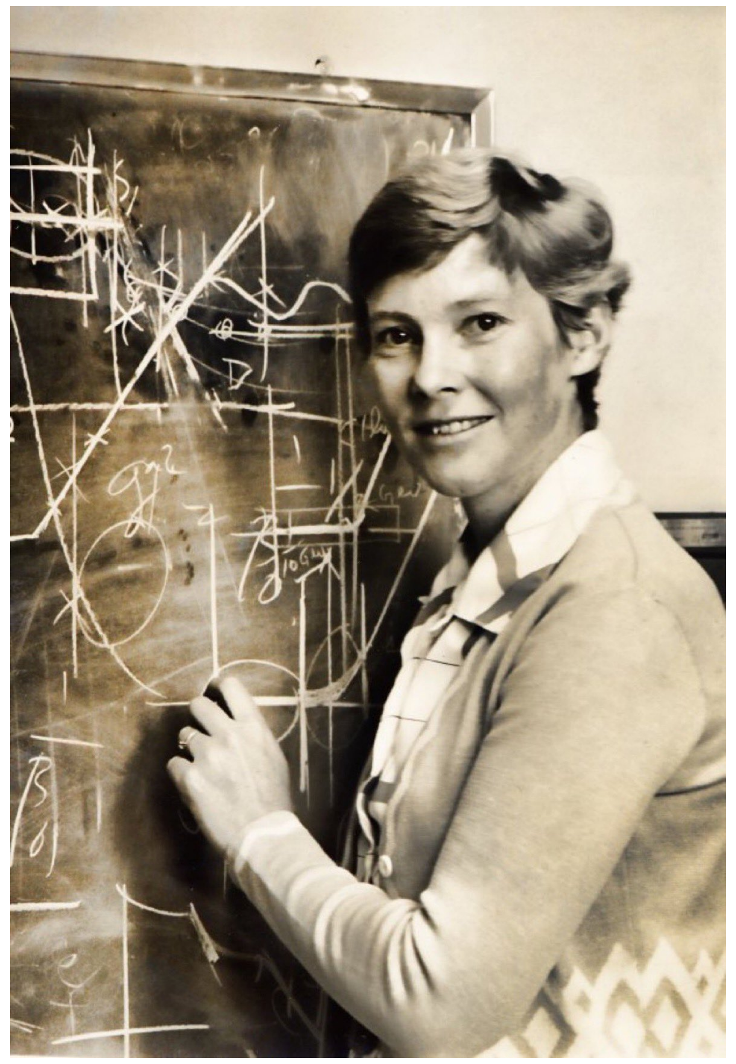
$$\mathcal{L} = \left(\frac{\phi(x)}{f_a} - \bar{\theta}\right)\frac{\alpha_s}{8\pi} G^{\mu\nu a}\tilde{G}^a_{\mu\nu}$$

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

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

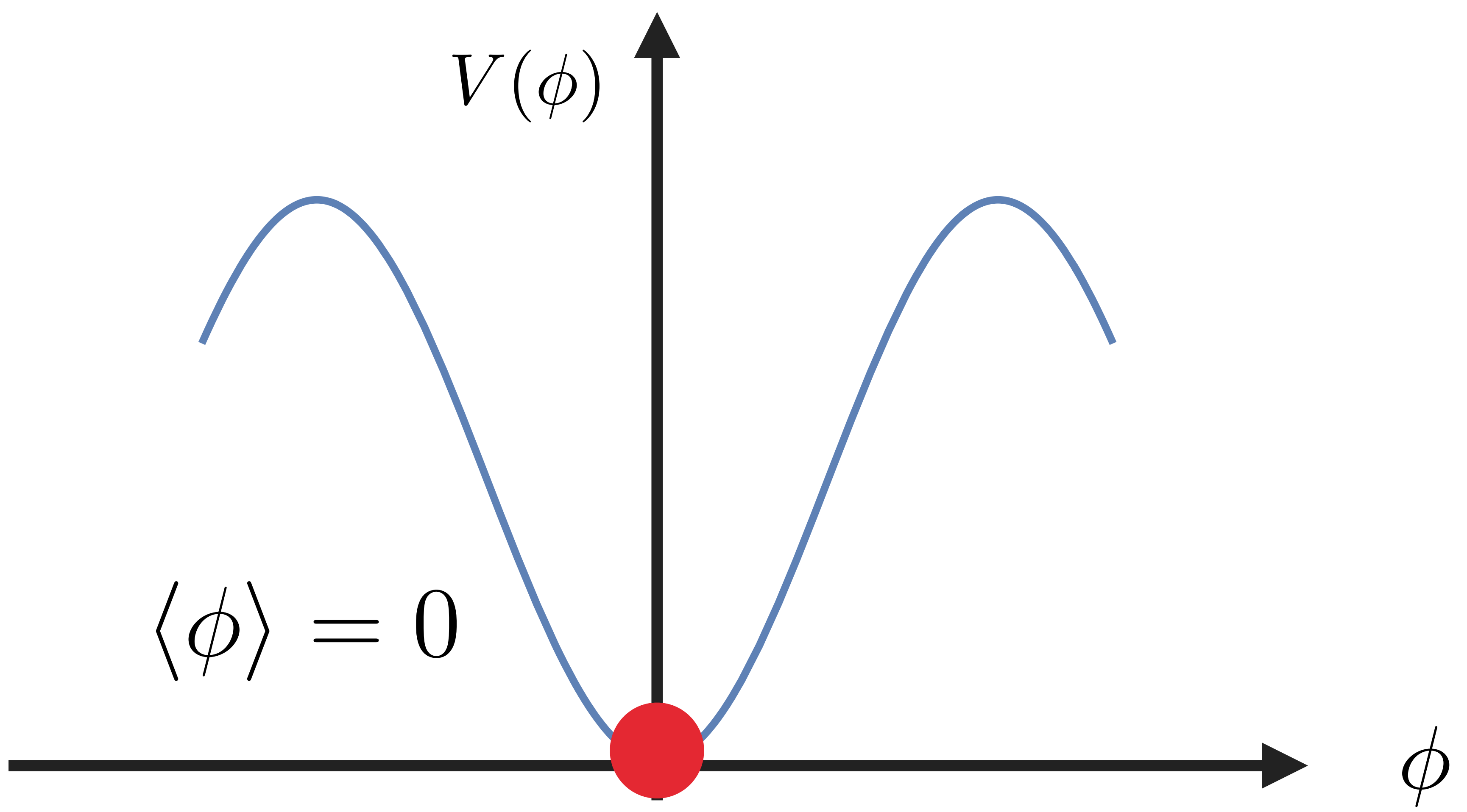


Roberto Peccei



Helen Quinn

The QCD Axion: At low energies



Non-perturbative effects generate potential

$$\frac{g_s^2}{32\pi^2}\frac{\phi}{f}G\tilde{G} \quad \xrightarrow{\text{UV} \qquad \text{IR}} \quad V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4}\left[\cos\left(\frac{\phi}{f}\right) - 1\right]$$

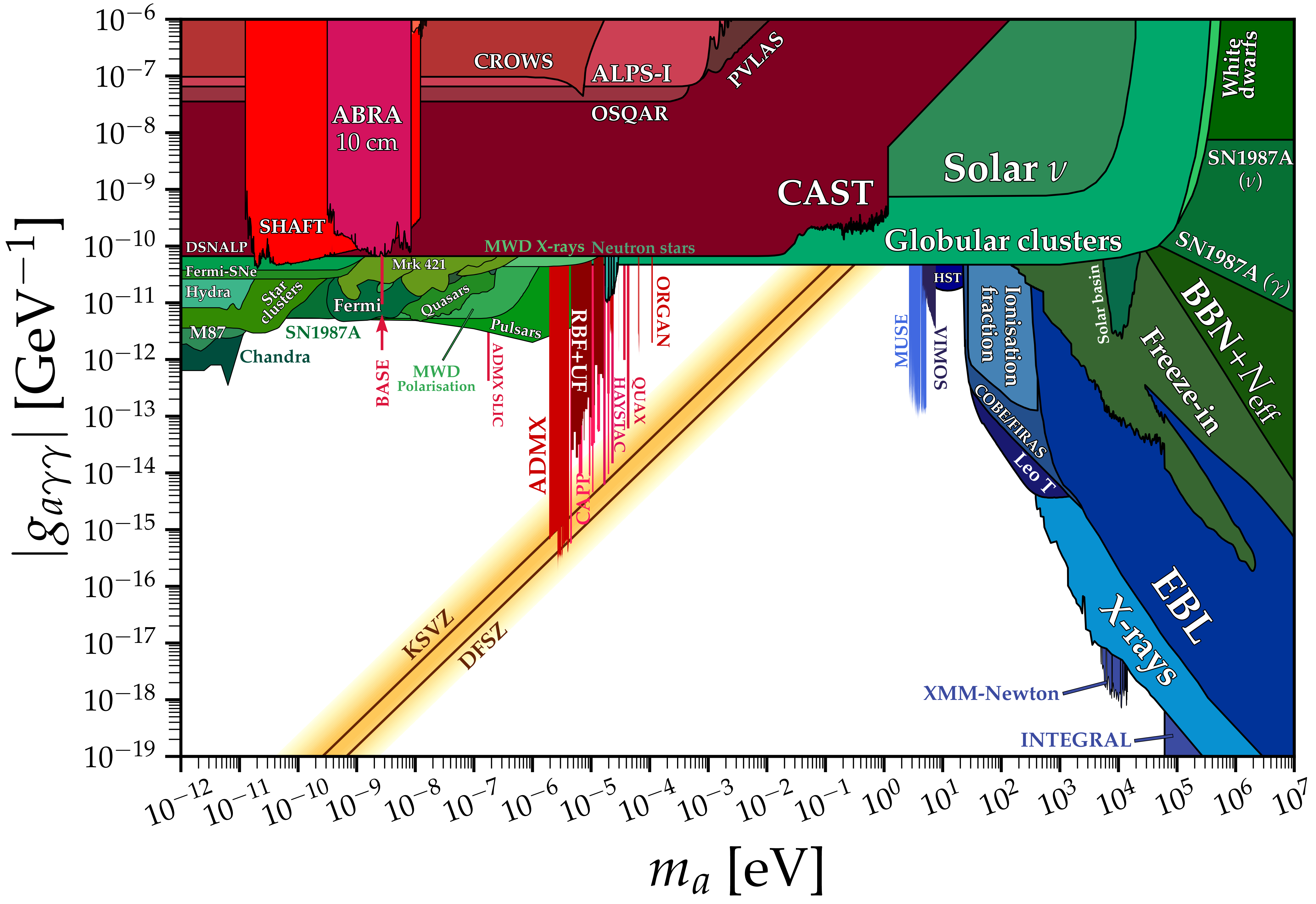
The QCD axion is very predictive

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

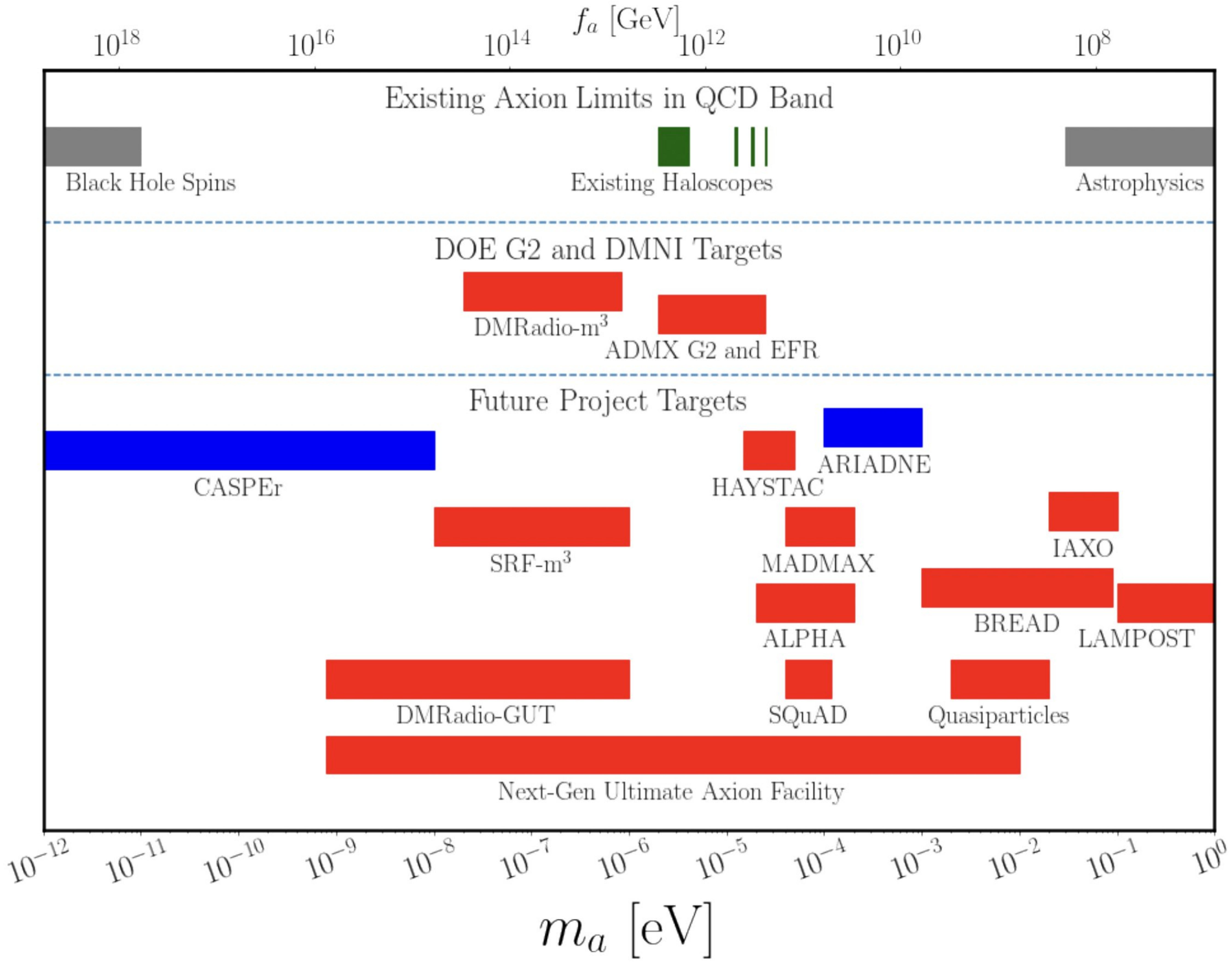
Couplings to nucleons, photons, electrons,...

Determined by the scale f

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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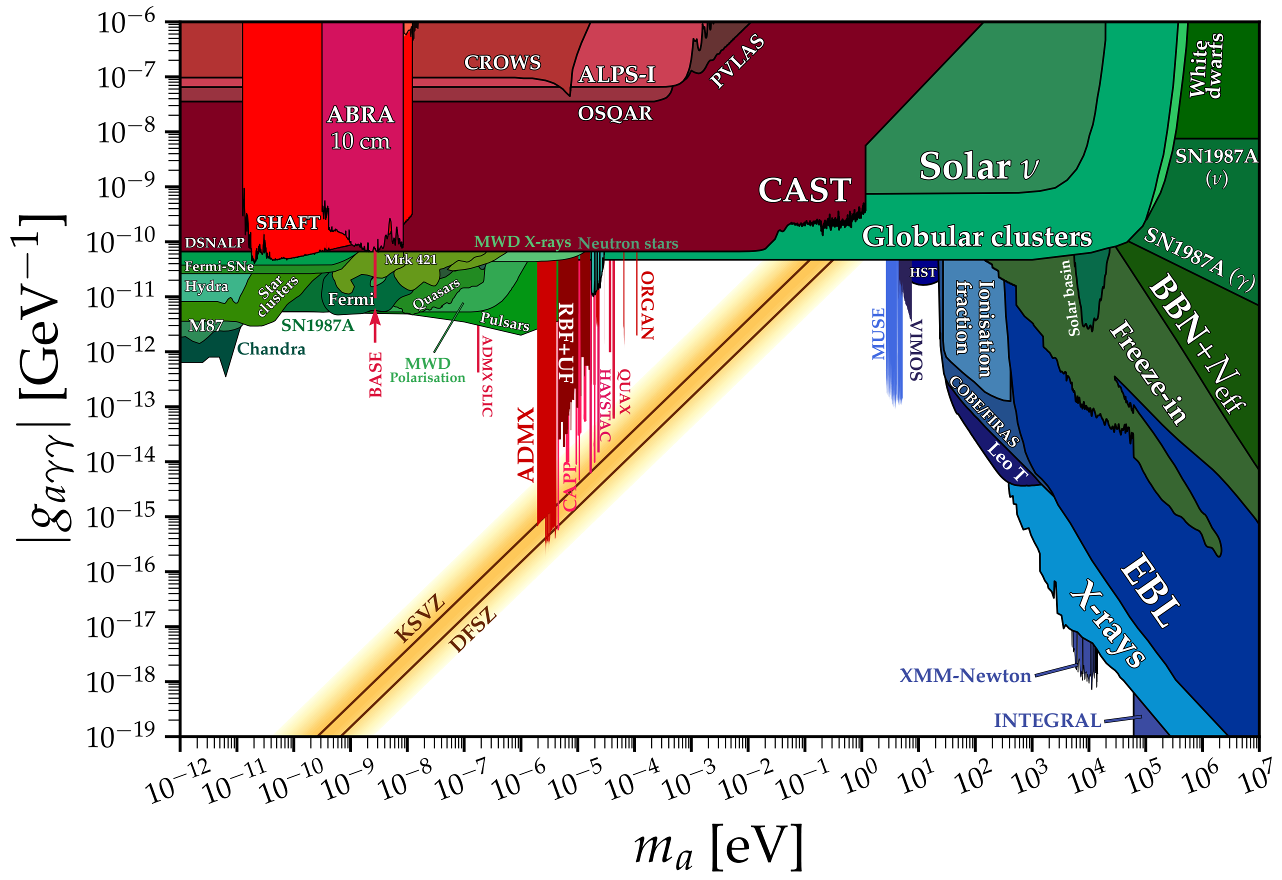

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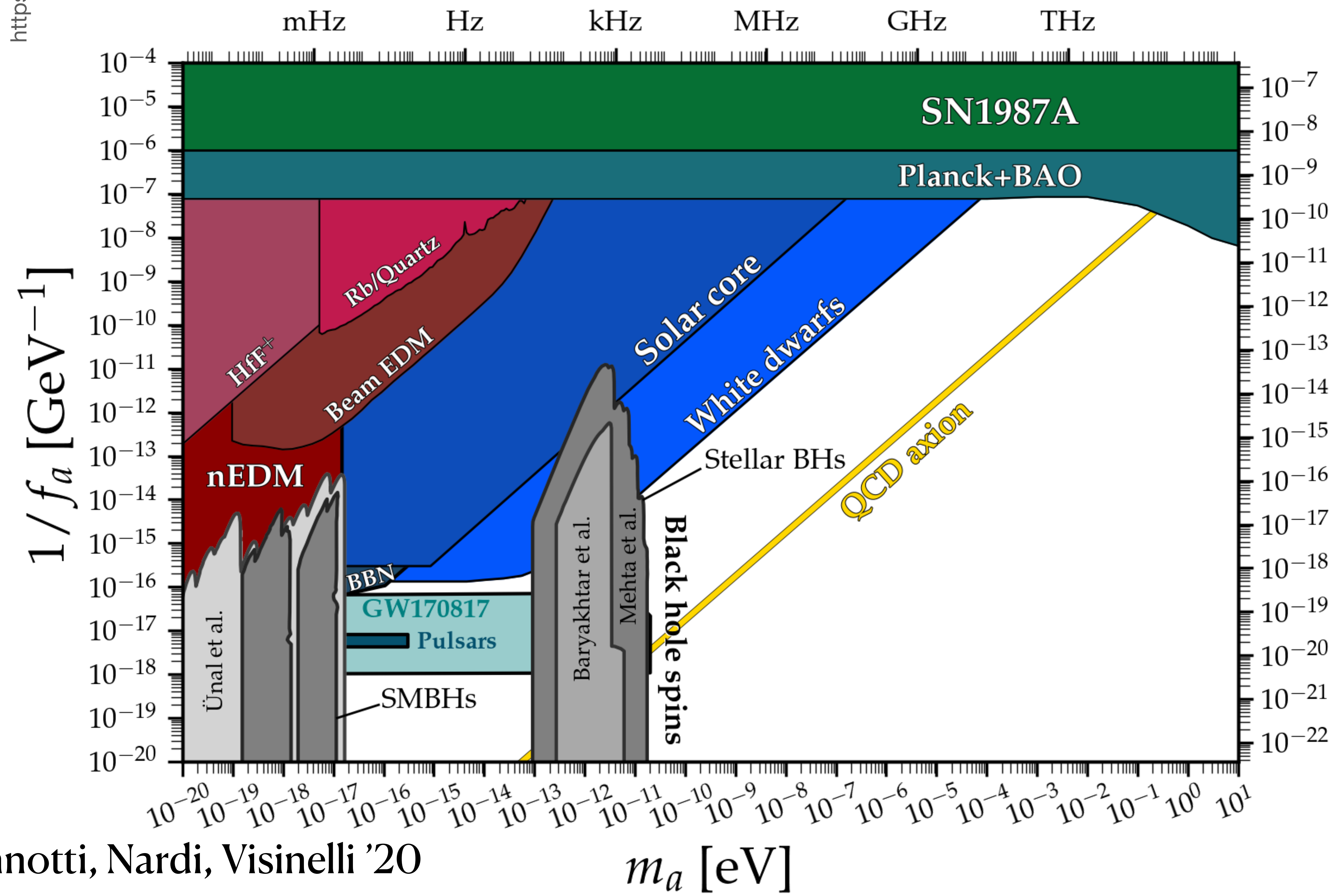

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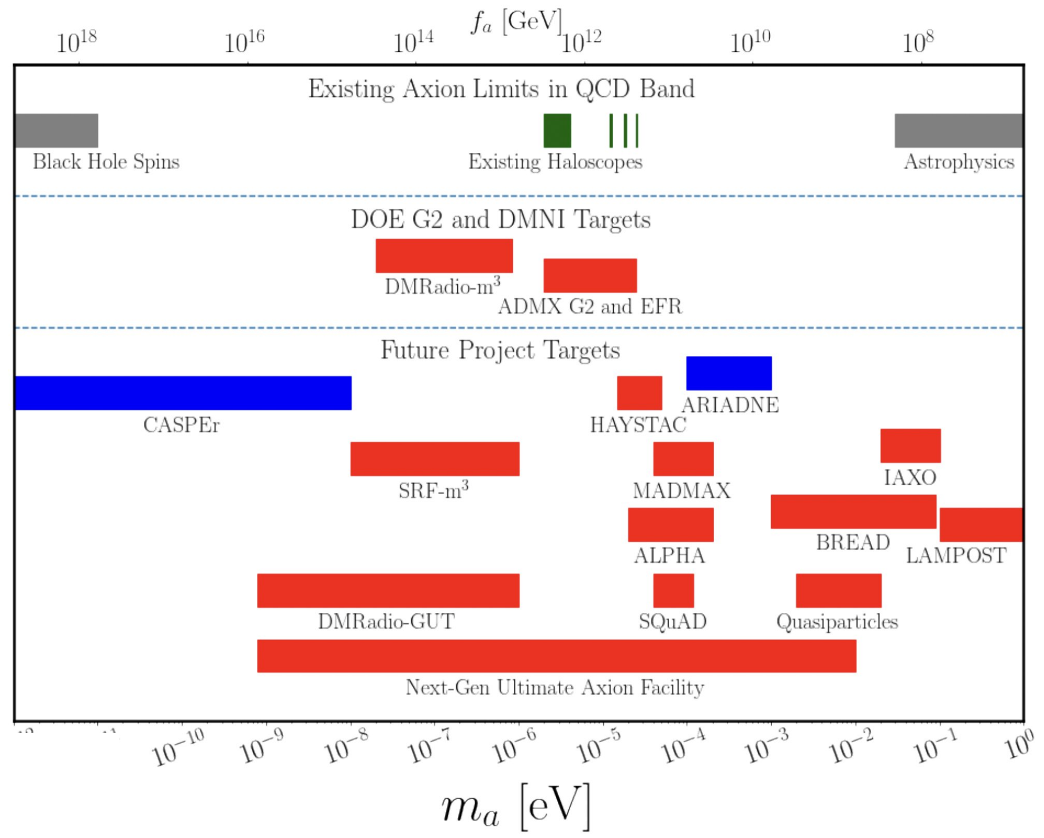

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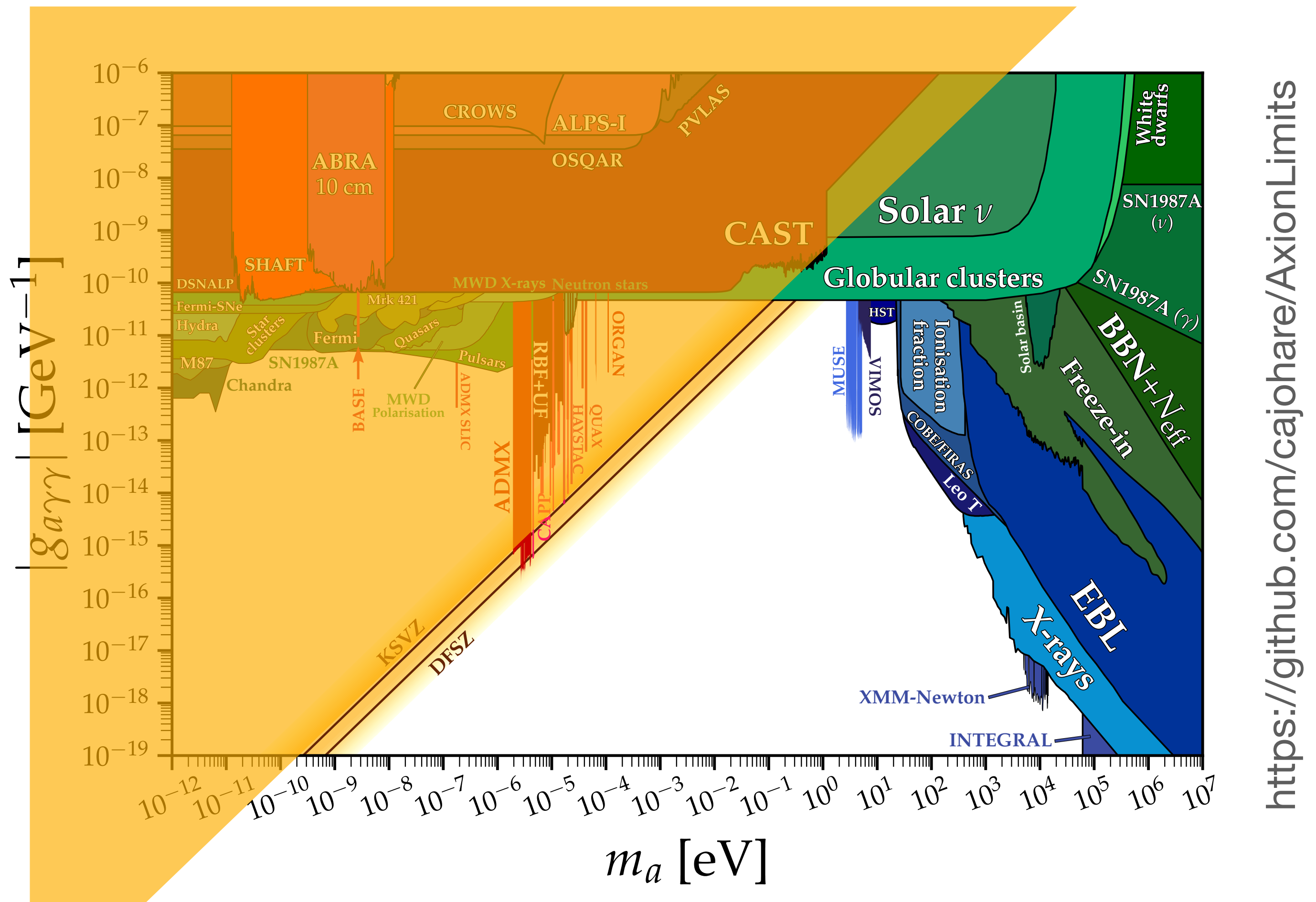

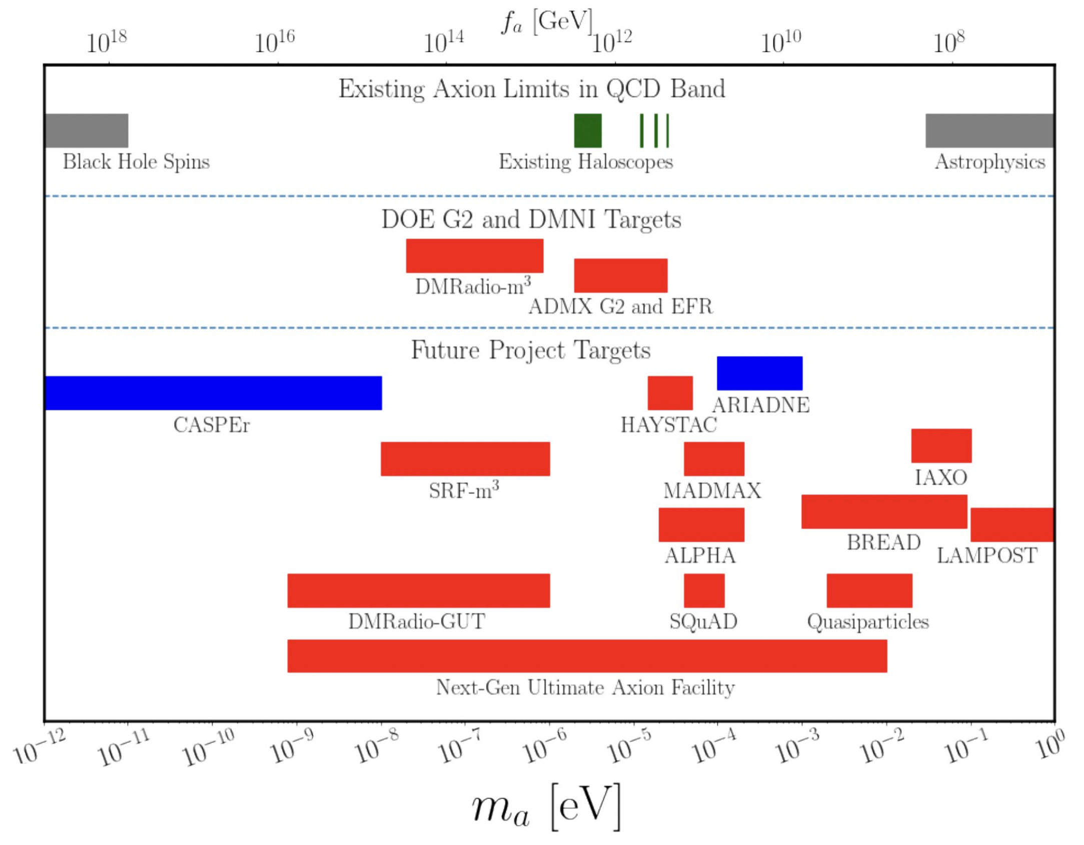

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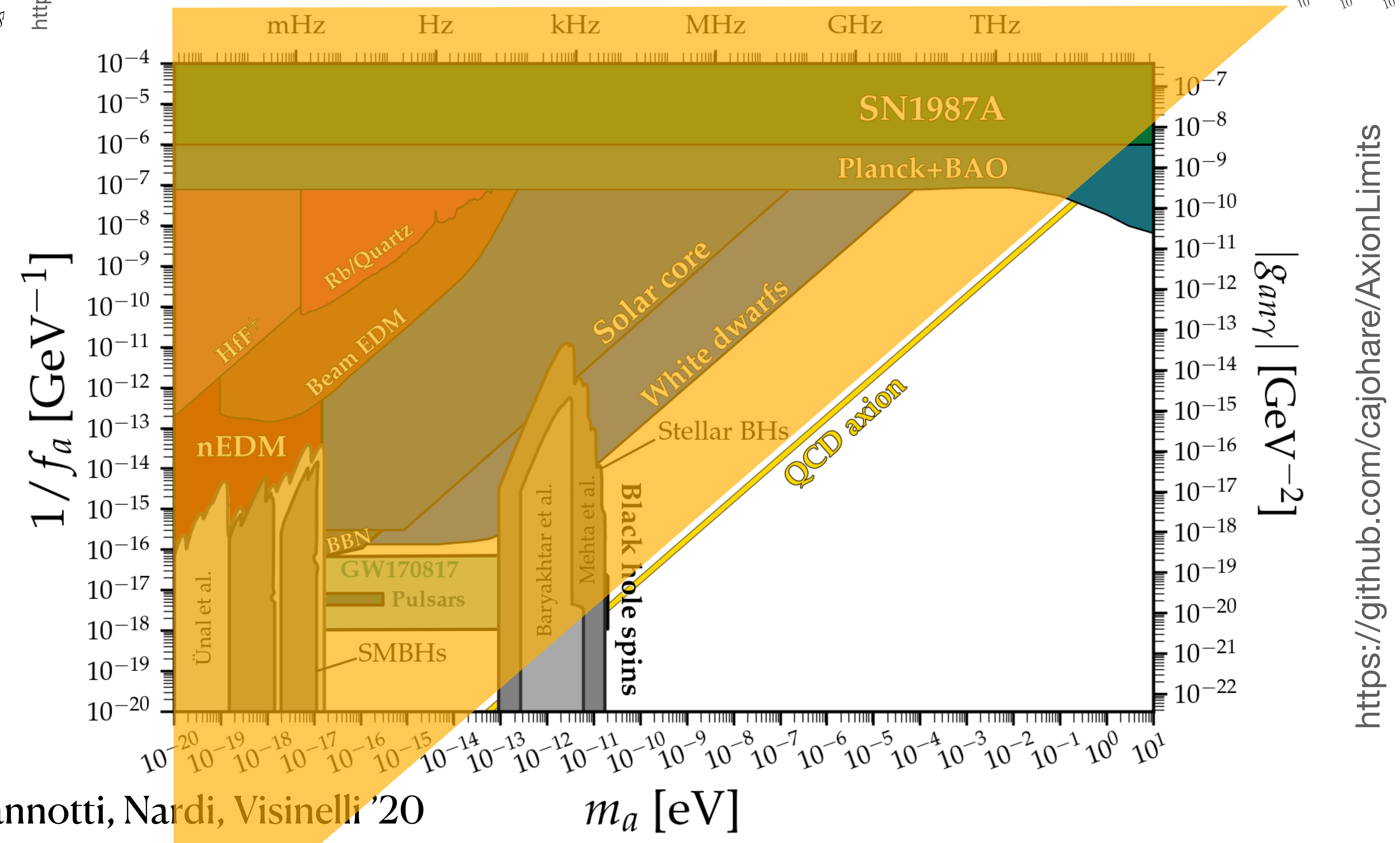
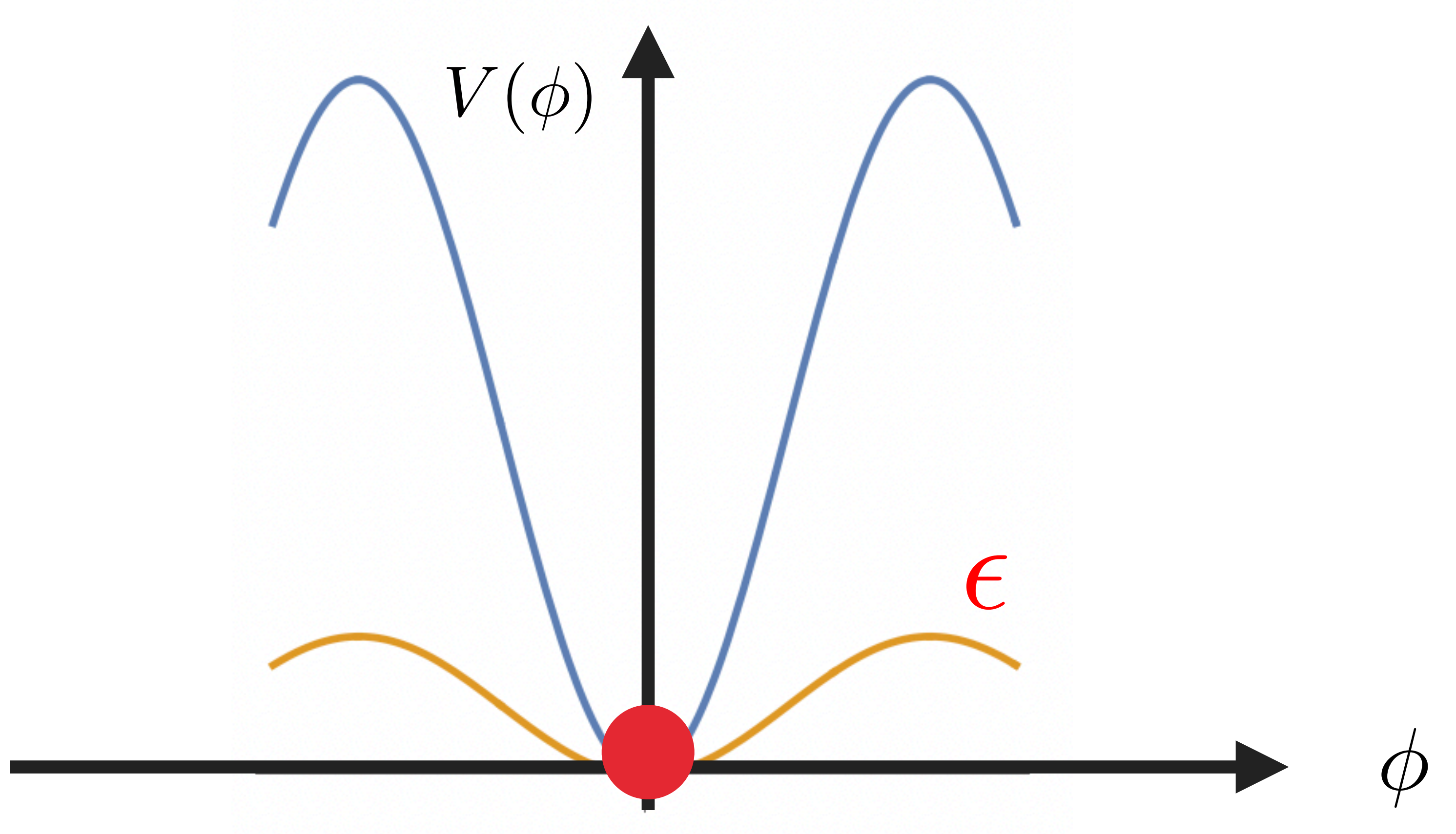


Interesting region

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

Light QCD Axions

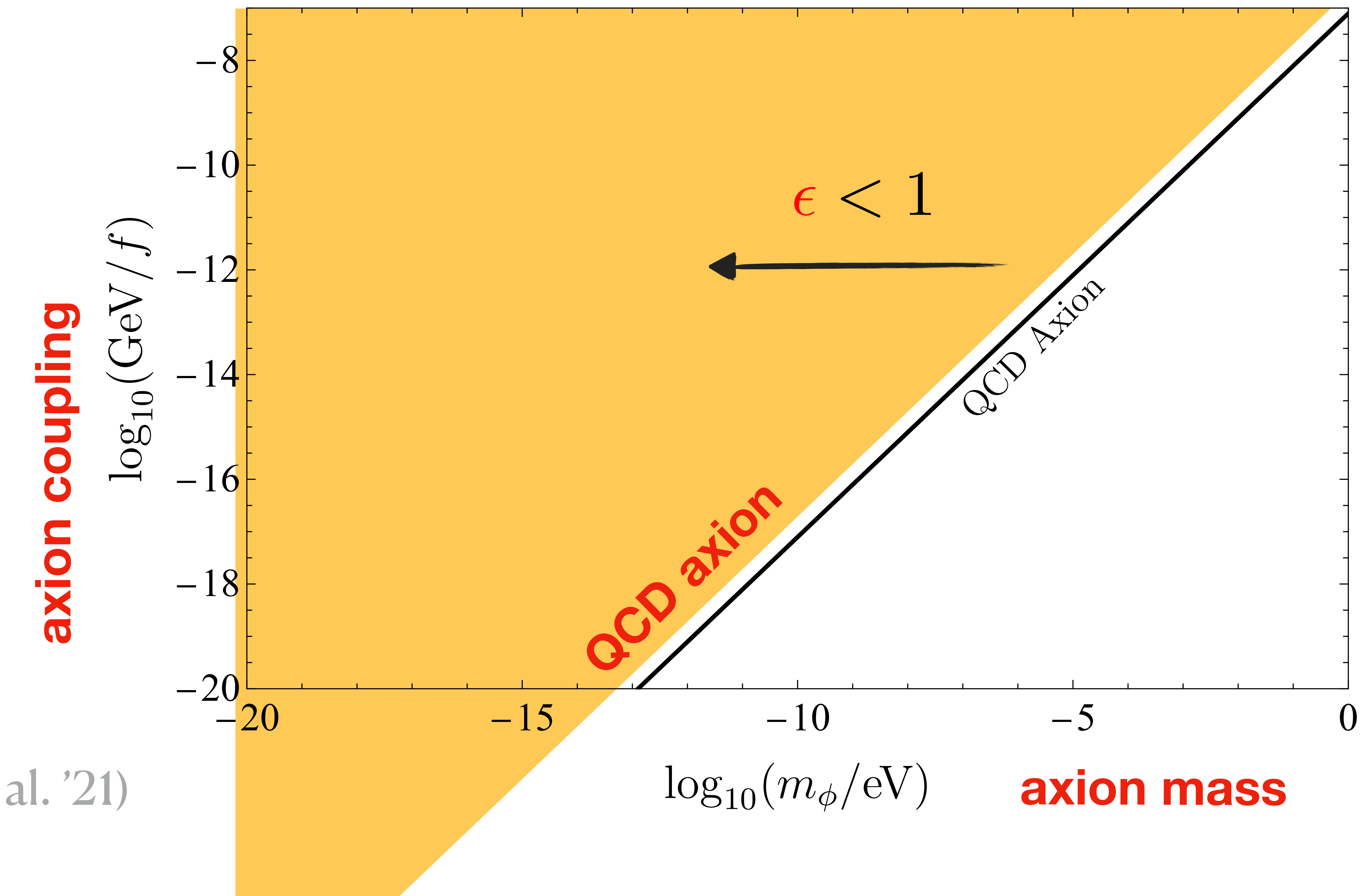
Non-perturbative effects generate potential



$$\frac{g_s^2}{32\pi^2}\frac{\phi}{f}G\tilde{G} \xrightarrow{\text{UV} \qquad \text{IR}} V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4}\left[\cos\left(\frac{\phi}{f}\right)-1\right]$$

... with smaller mass

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



For symmetry based realizations, see (Hook, Huang '17, Hook '18, Di Luzio et. al. '21)

Light QCD Axion: Coupling to nucleons

Nuclear Chiral Perturbation Theory with QCD axion

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

Leads to non-derivative coupling to nucleons:

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

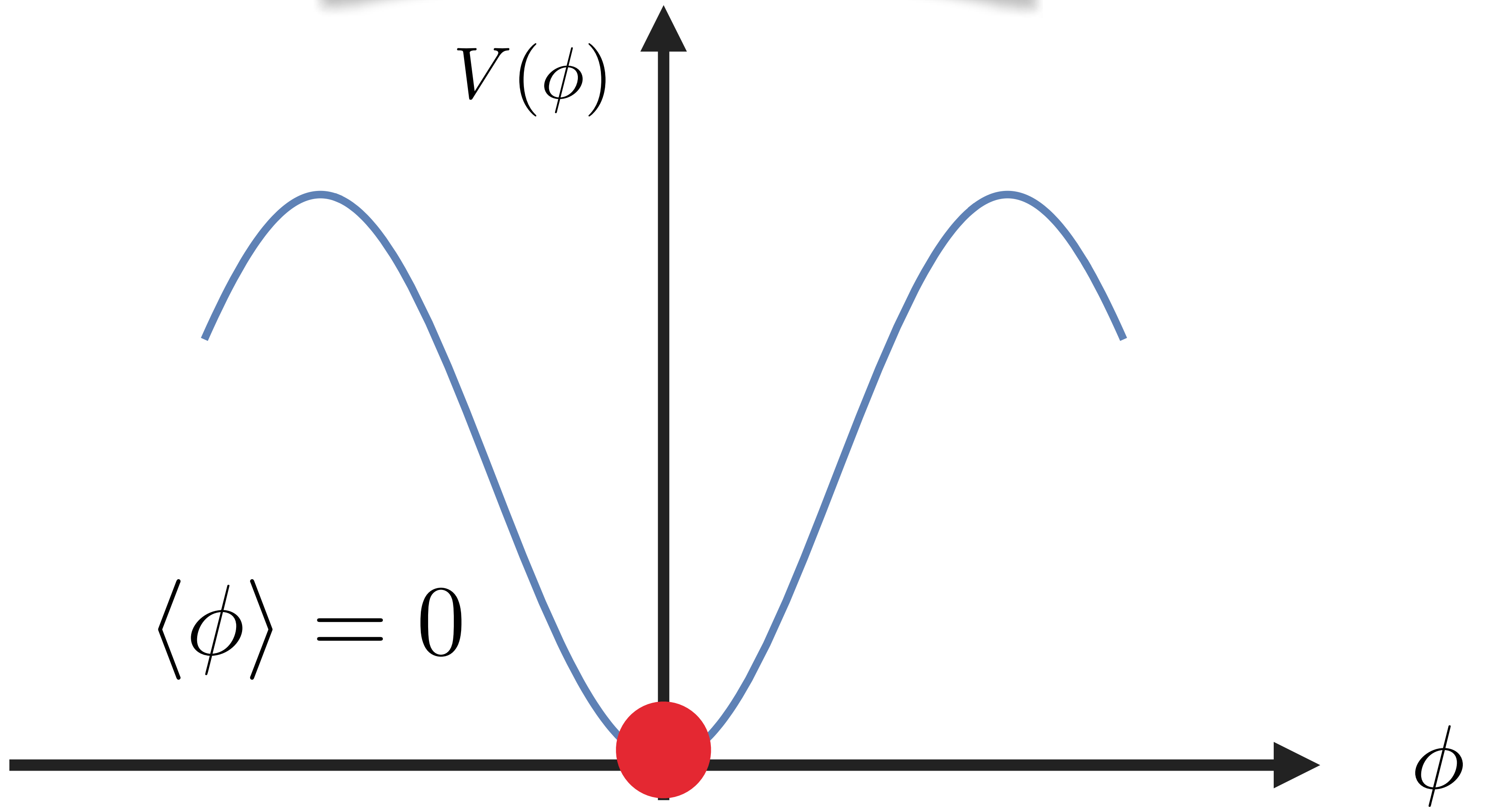
such that $\quad m_N(0) = m_N\,, \quad \sigma_{\pi N} \simeq 50\,\mathrm{MeV}$

Light QCD Axion: at Finite Density

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

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

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



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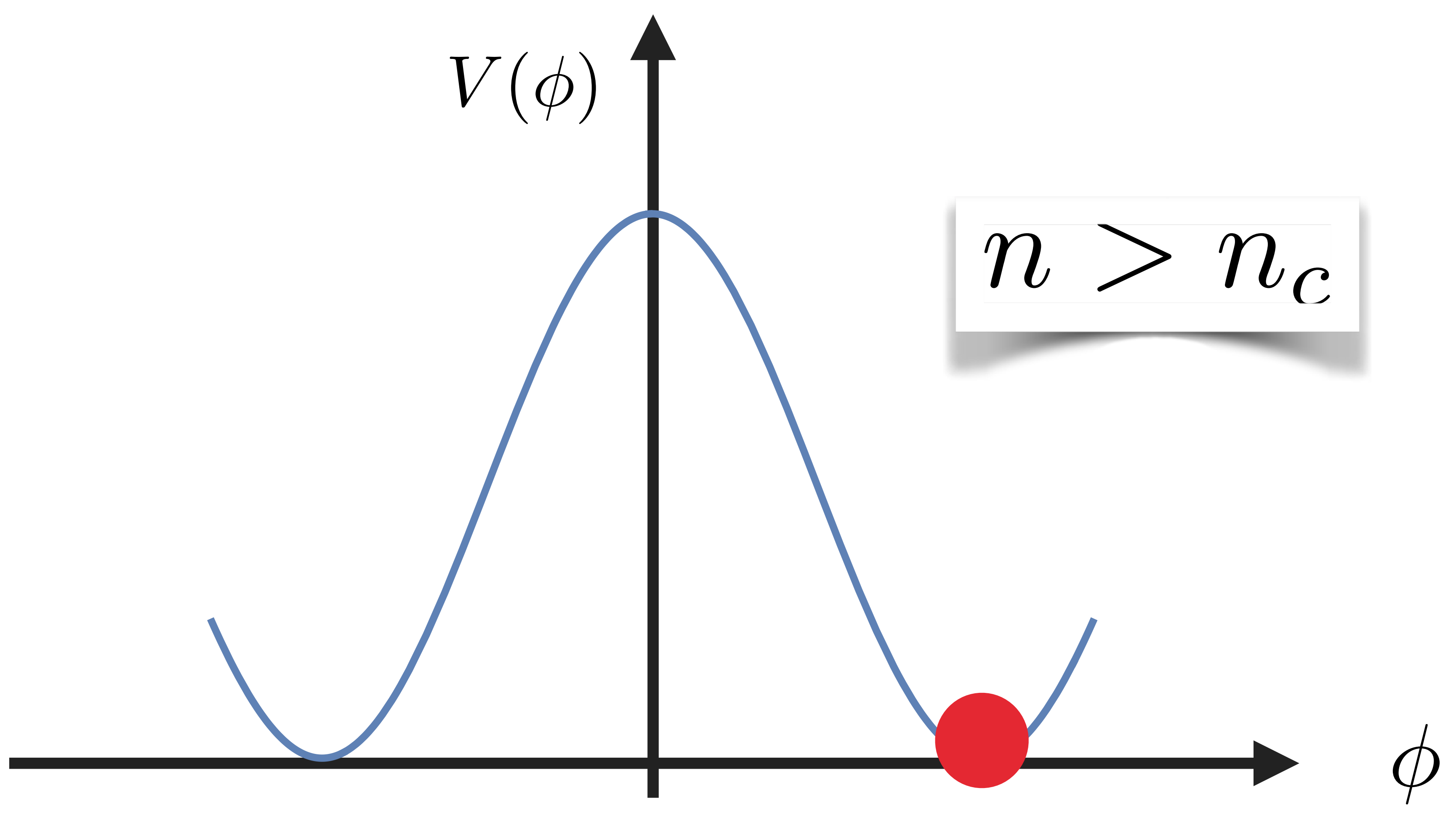

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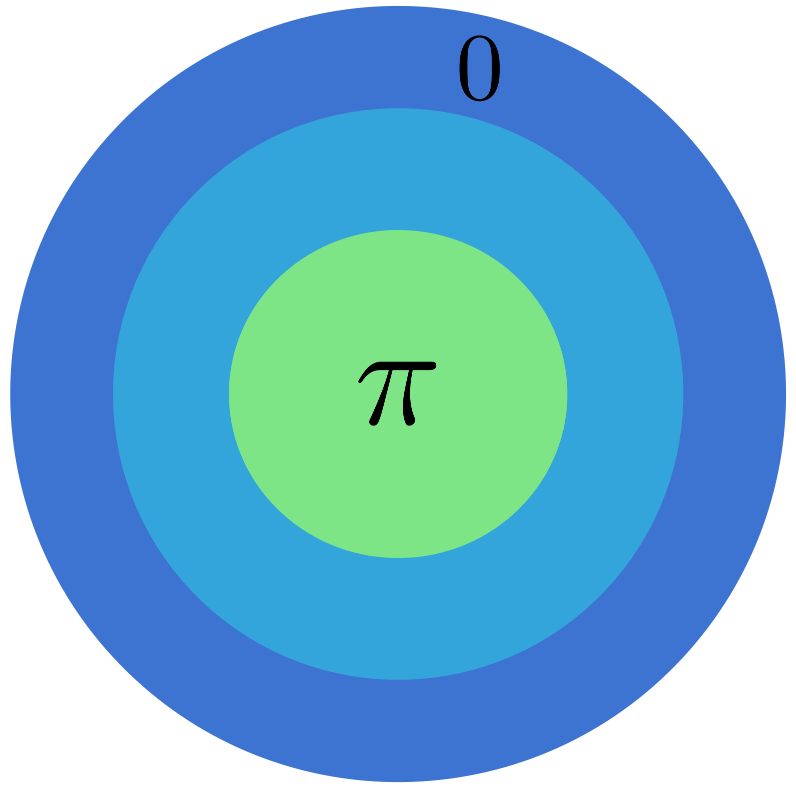
At critical density $n > n_c$:

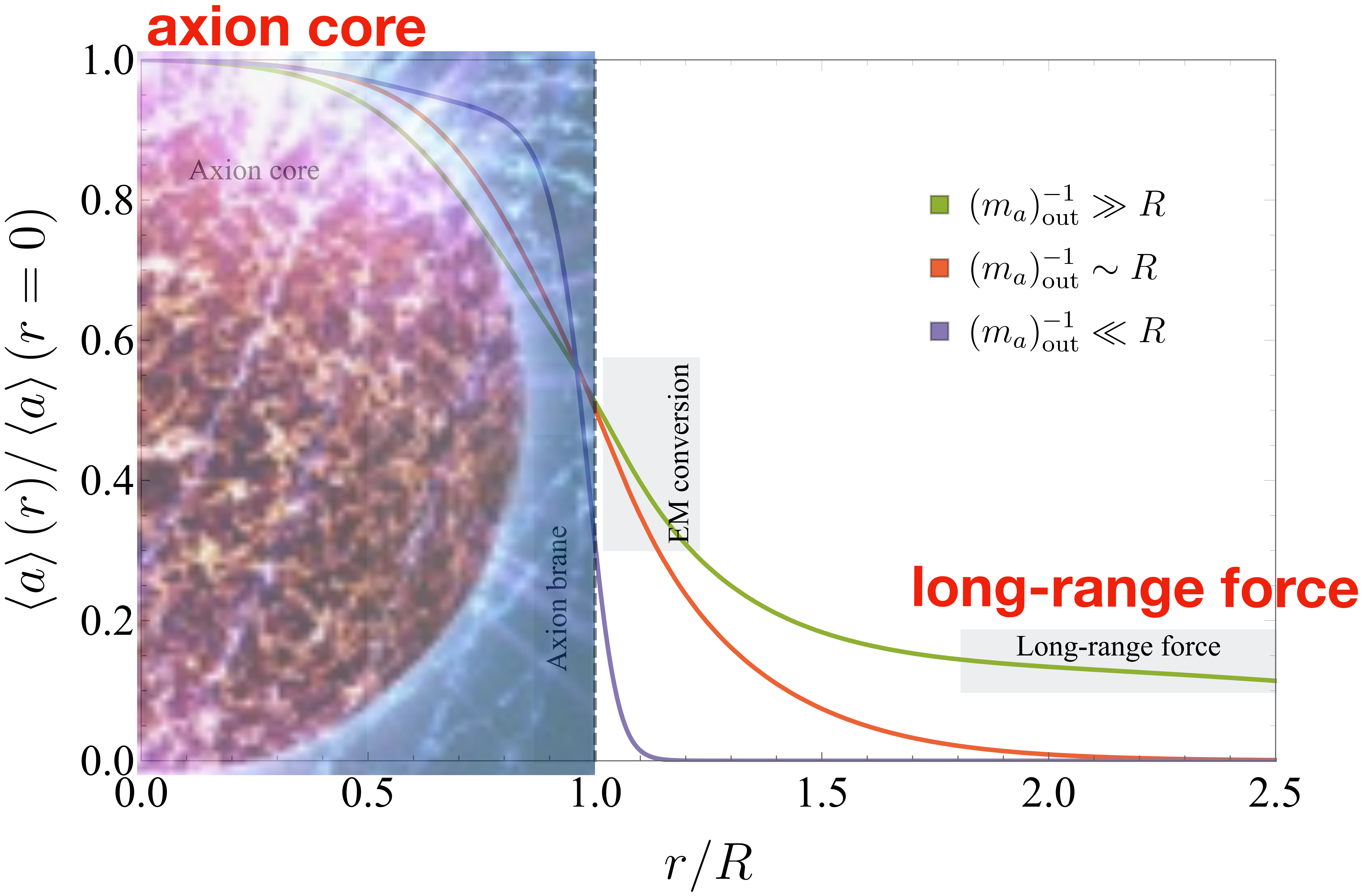
new minima appear at $\langle \phi \rangle = \pi f$

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

Axion Profile: in a neutron star

$\phi = \theta f$





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

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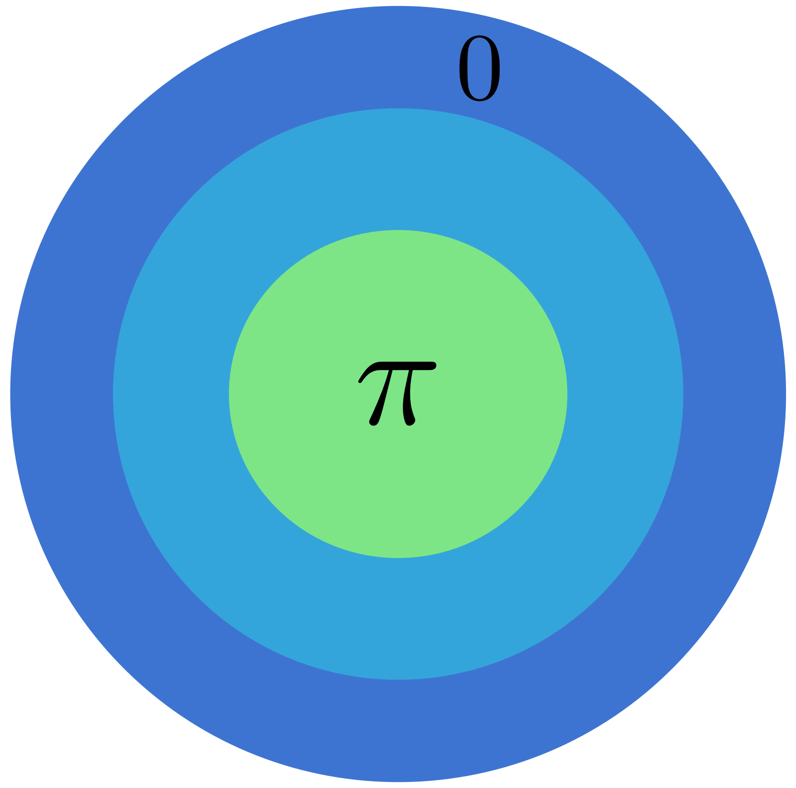
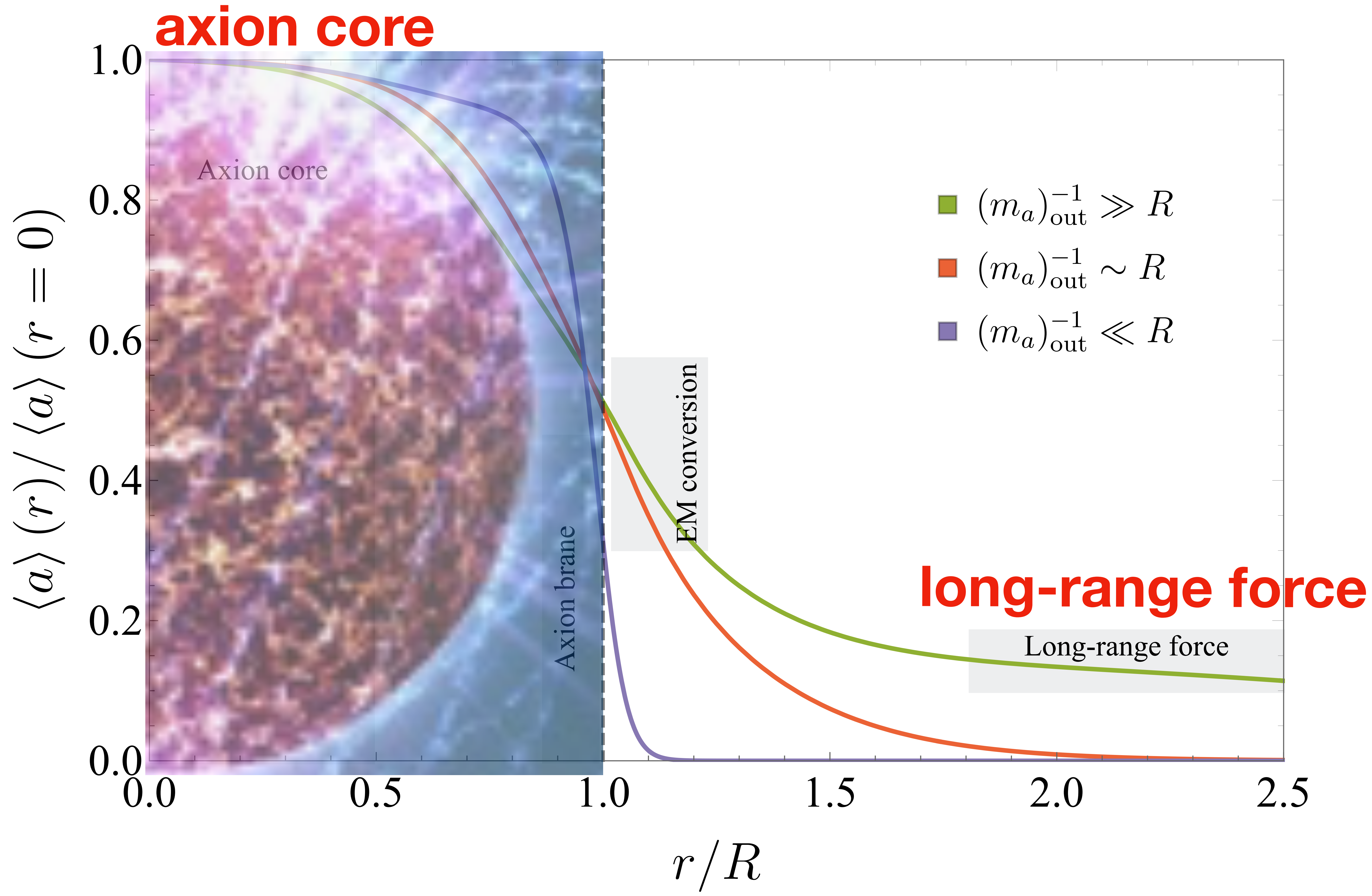
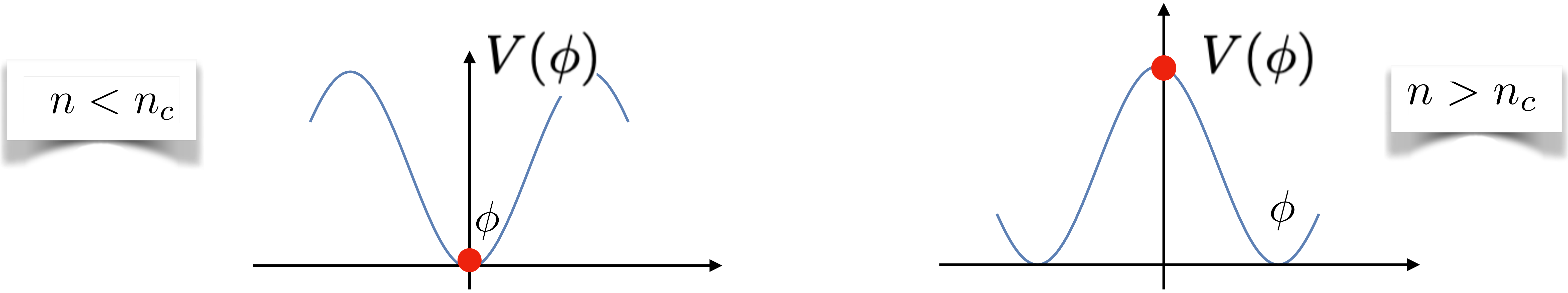




On the other hand: There is a back reaction on the system!

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

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

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

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

$r_{\rm critical} \sim 0.2\, cm$

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

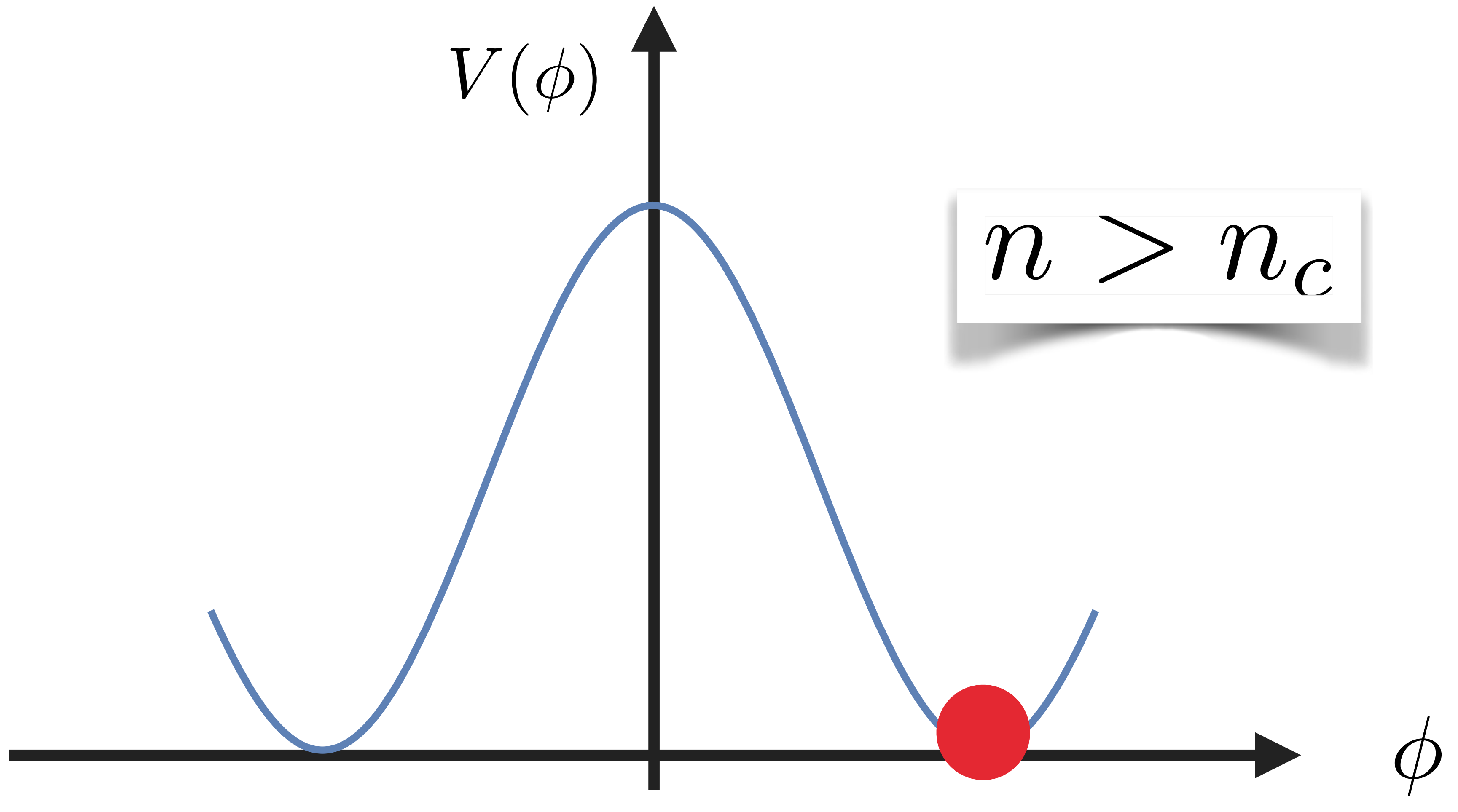
Light QCD Axion: at Finite Density

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

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

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

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



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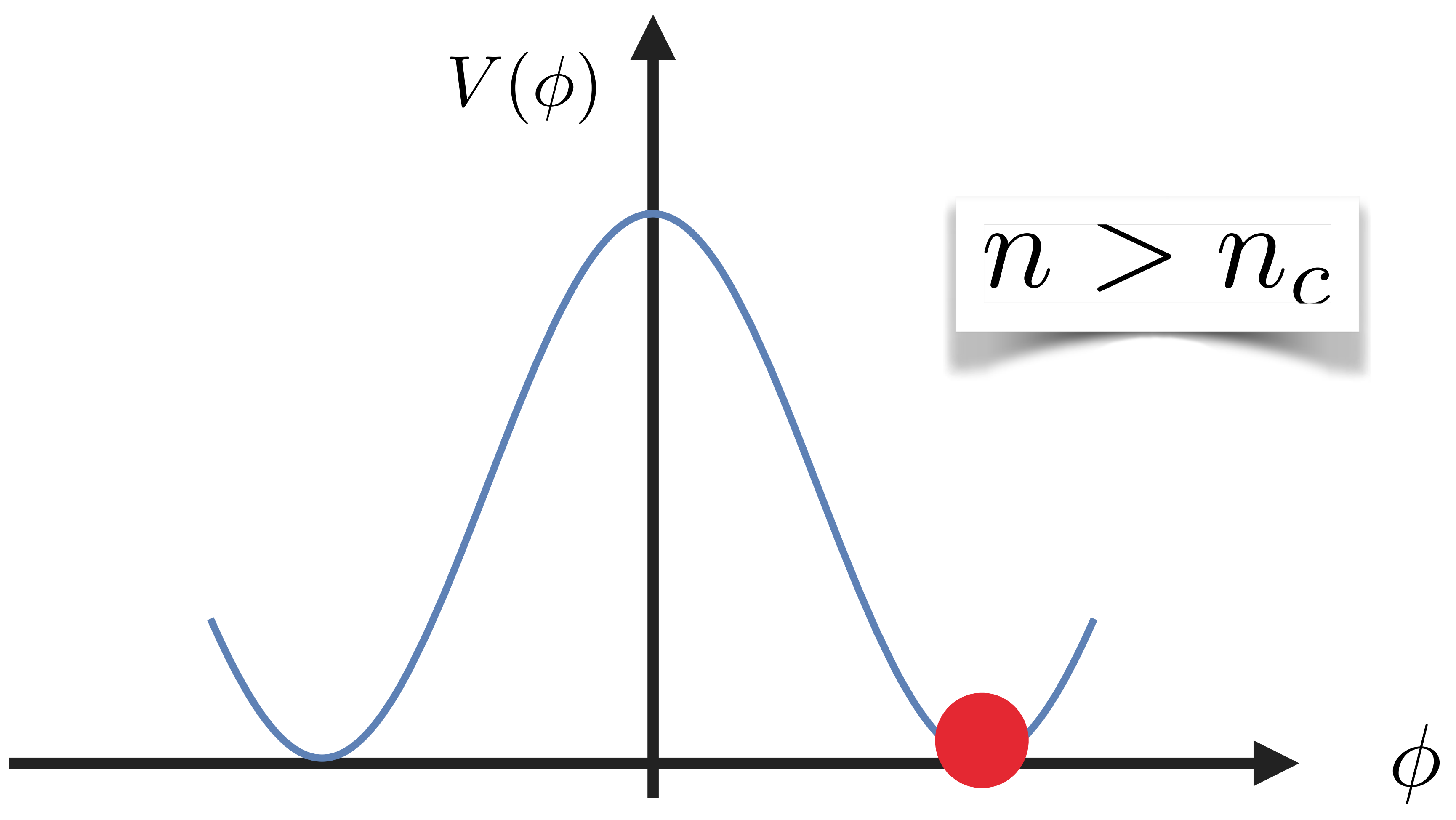

2) Energy density of the potential acts as energy density (similar to a CC) $V(\pi f) \simeq \epsilon m_\pi^2 f_\pi^2/2$

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

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

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

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

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

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

coupled system
Einstein equations and axion EOM

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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

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Limit of a thin wall bubble

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

The system effectively decouples: Solve for EOS ⟶ Solve pressure gravity equations

Equation of state

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

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

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

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

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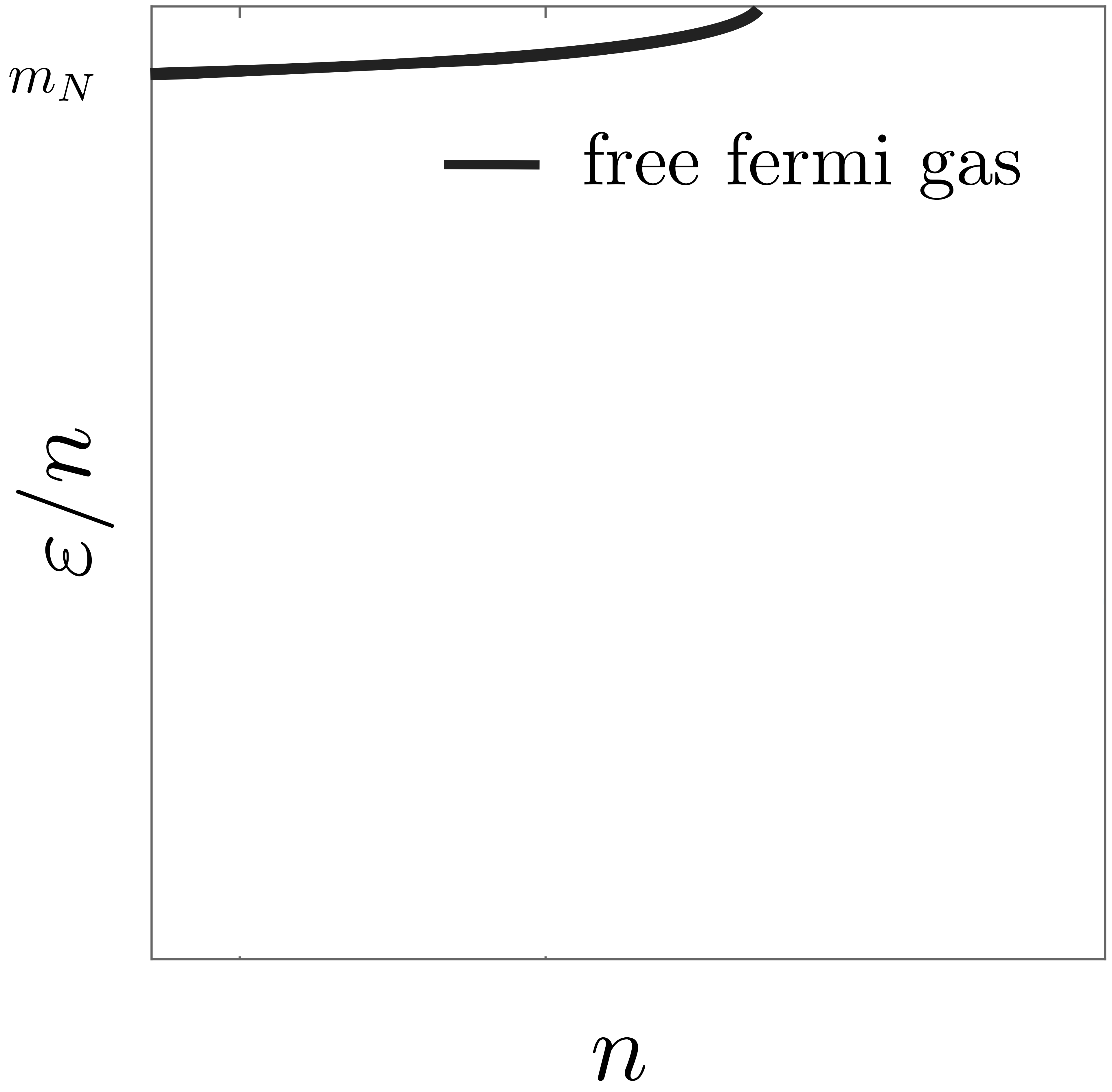
$$\longrightarrow \varepsilon(n), p(n)$$ equation of state

Energy per particle

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



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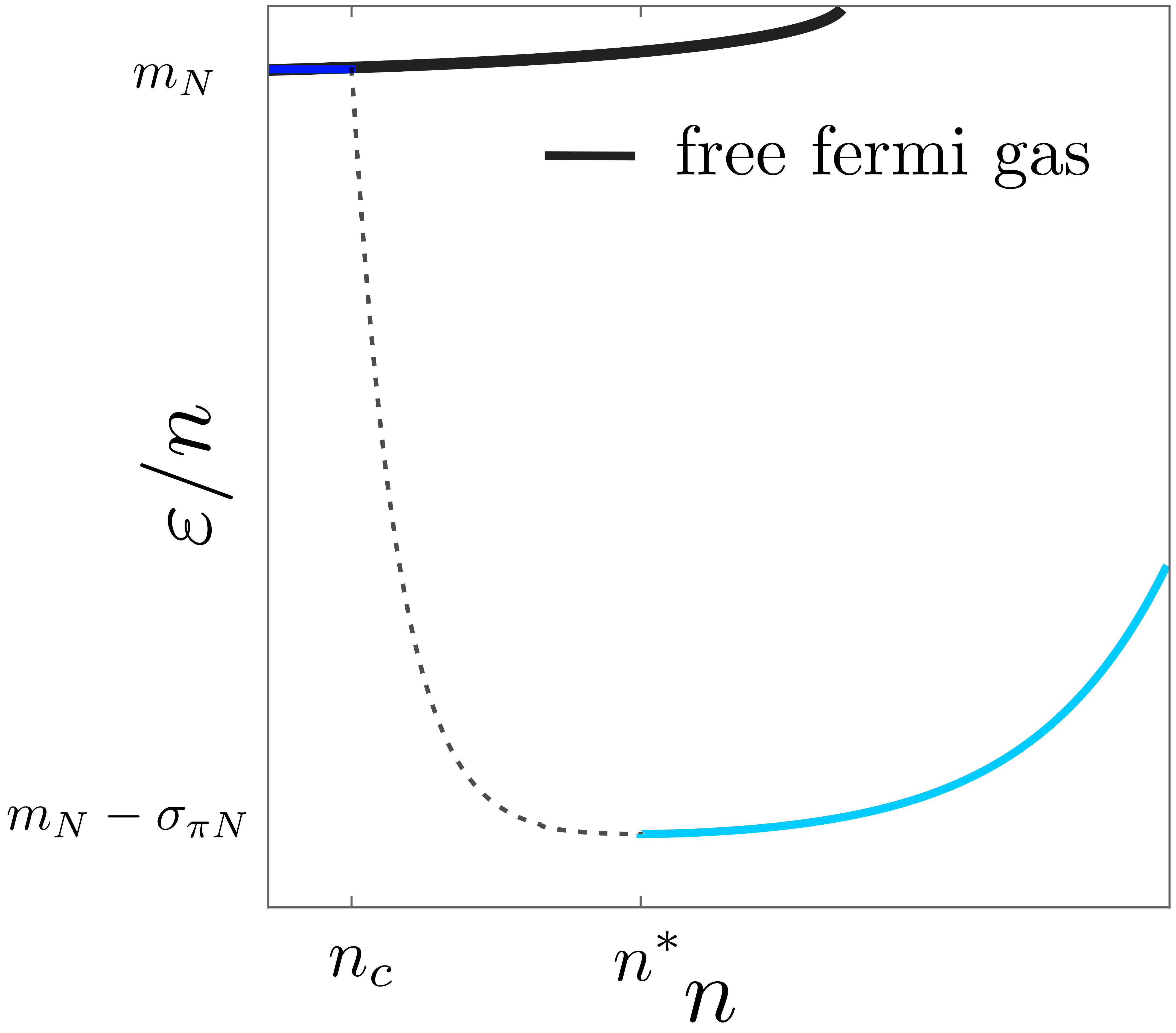
metastable $(\phi = 0)$ unstable stable $(\phi = \pi f)$



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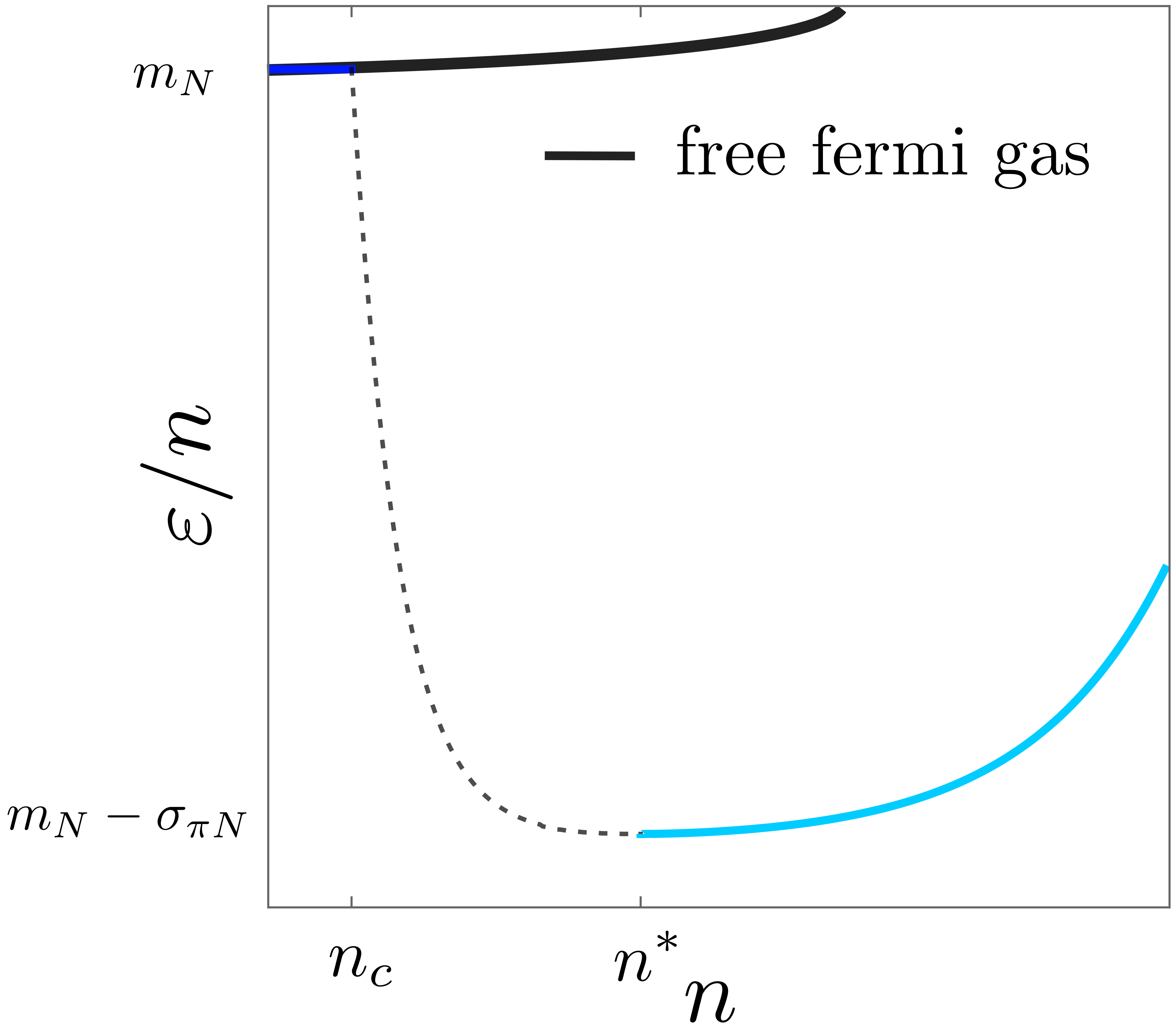

Energy per particle is related to pressure

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

Energy per particle

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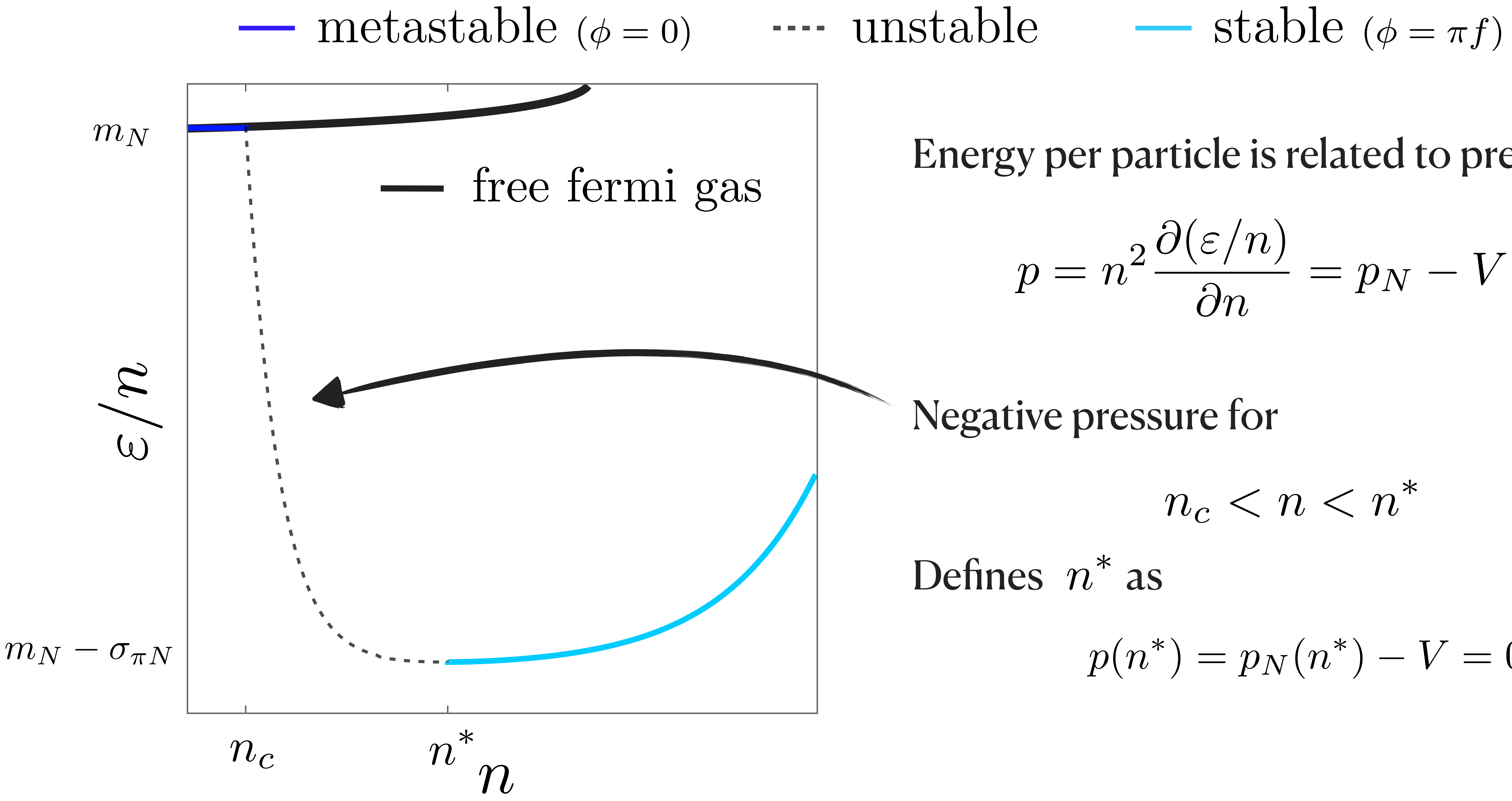


Energy per particle is related to pressure

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

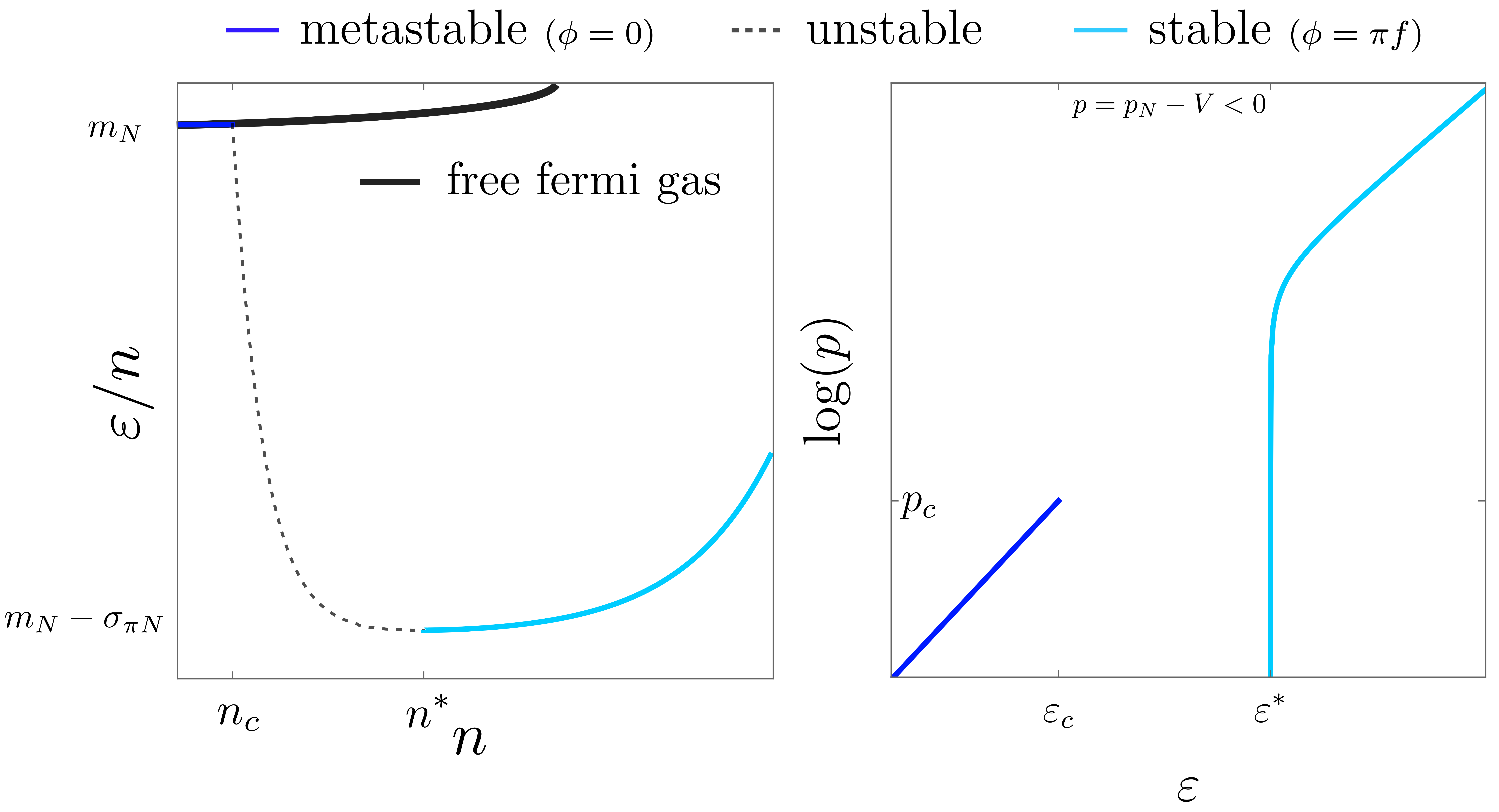
Negative pressure for

$$n_c < n < n^*$$

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 light QCD axions

White Dwarfs

Degenerate Fermi gas of electrons and light nuclei

- Balance gravity with electron degeneracy pressure
- Mass comes dominantly from nuclei $^{4}\mathrm{He}, \ldots, {}^{24}\mathrm{Mg}$ $\quad \varepsilon \simeq \varepsilon_{\mathrm{Nuclei}} = (A/Z) m_N n$

$A/Z \simeq 2$

- Charge neutrality $n_e = n_p \equiv n$
- Zero temperature EOS: $p_e(\varepsilon_{\mathrm{Nuclei}})$

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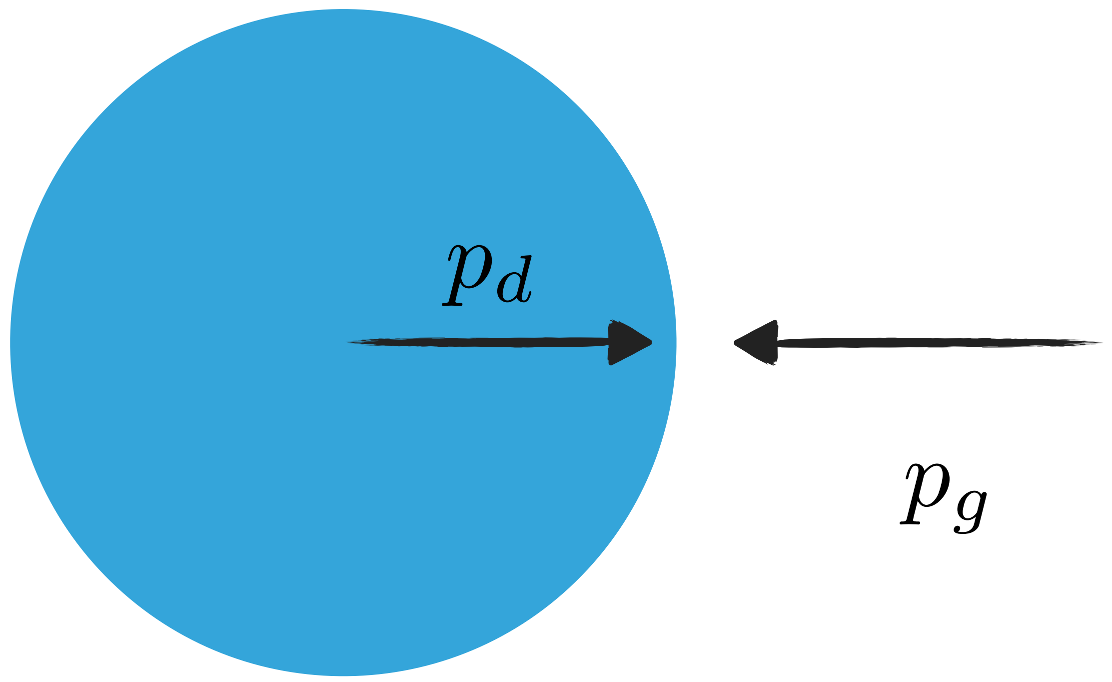
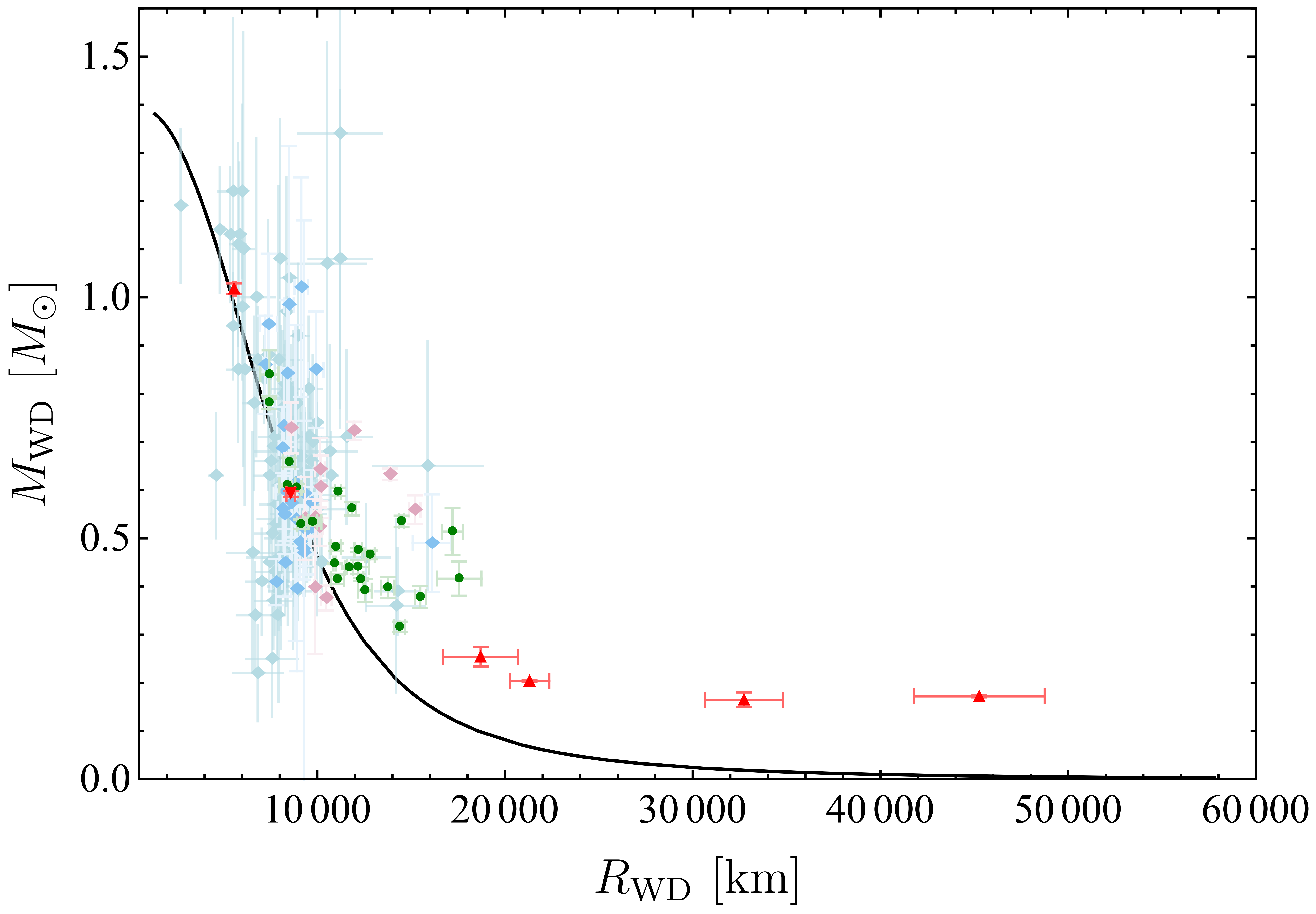
Solve static degeneracy vs. gravity equations

$$p' = -\frac{GM\varepsilon}{r^2},$$
$$M' = 4\pi r^2 \varepsilon,$$



White Dwarf: MR Curve



White Dwarfs with light QCD axion

- 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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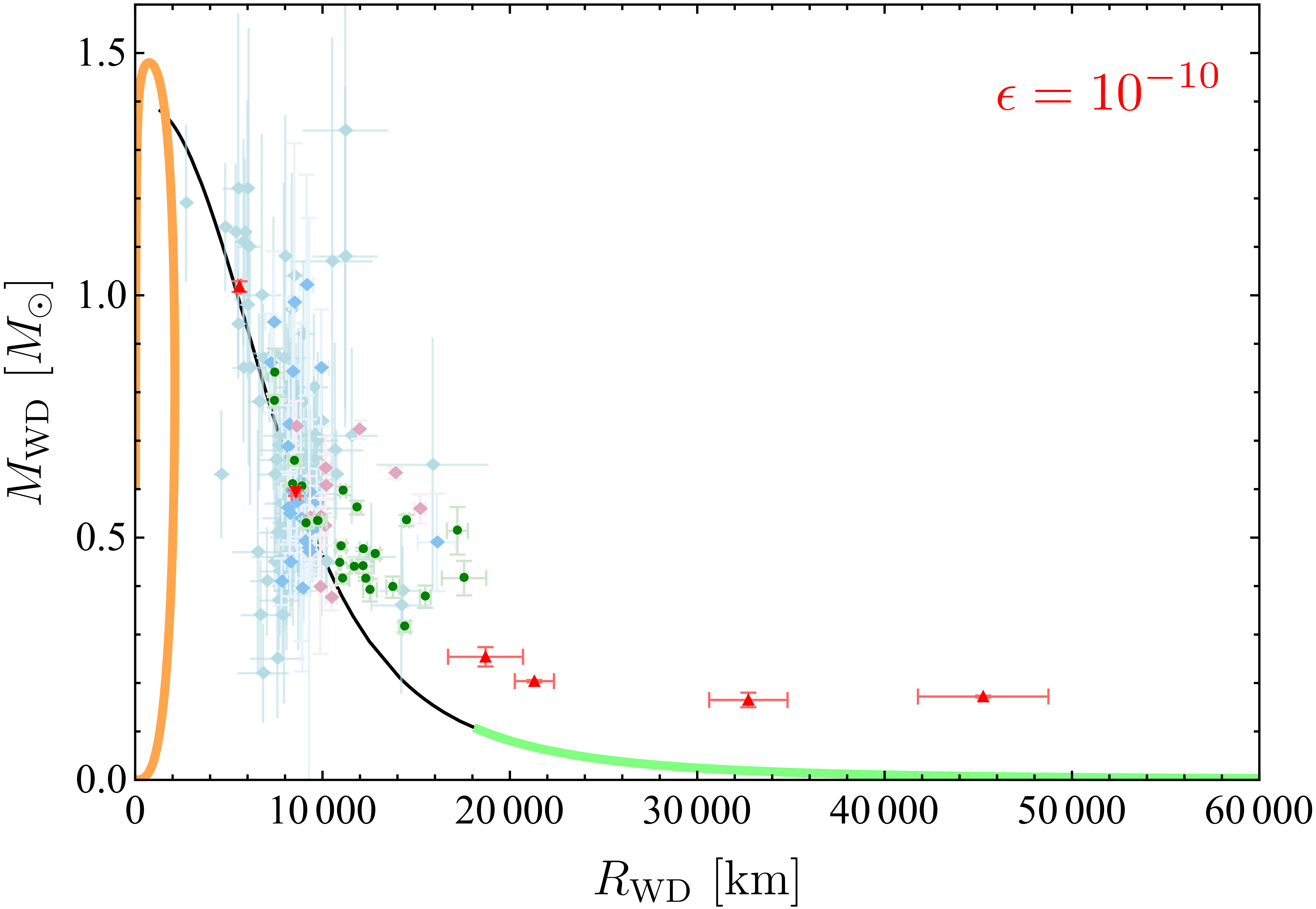
- New ground state density set by electron pressure $p_e(n^*) = p_e(n^*) - V = 0$

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

and no stable configuration:

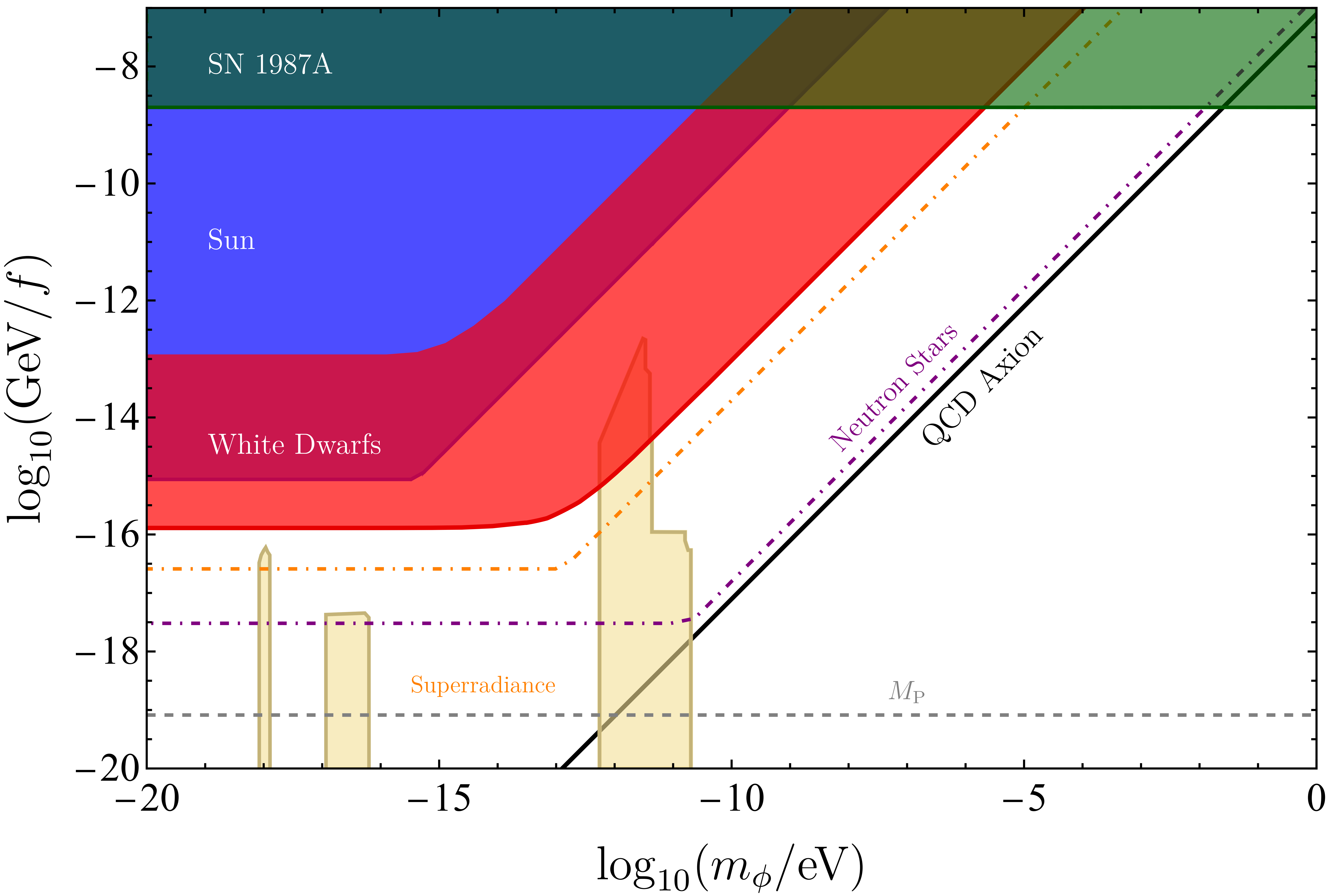
$\Rightarrow$ Translates to gap in the MR Curve

White Dwarfs with light QCD axion

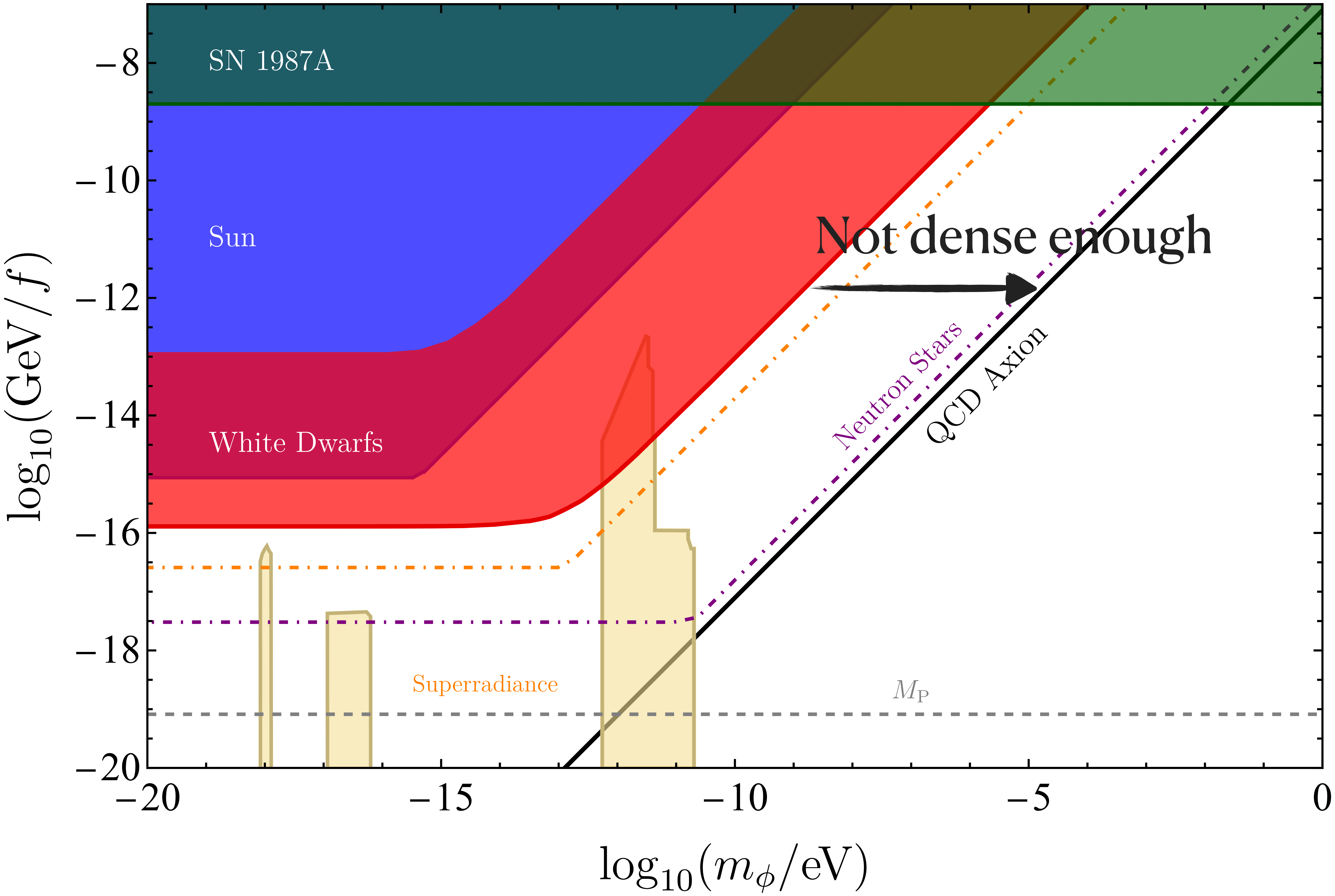


$$n_c = \frac{\epsilon m_\pi^2 f_\pi^2}{4\sigma_{\pi N}}$$

Axion Parameter Space



Axion Parameter Space



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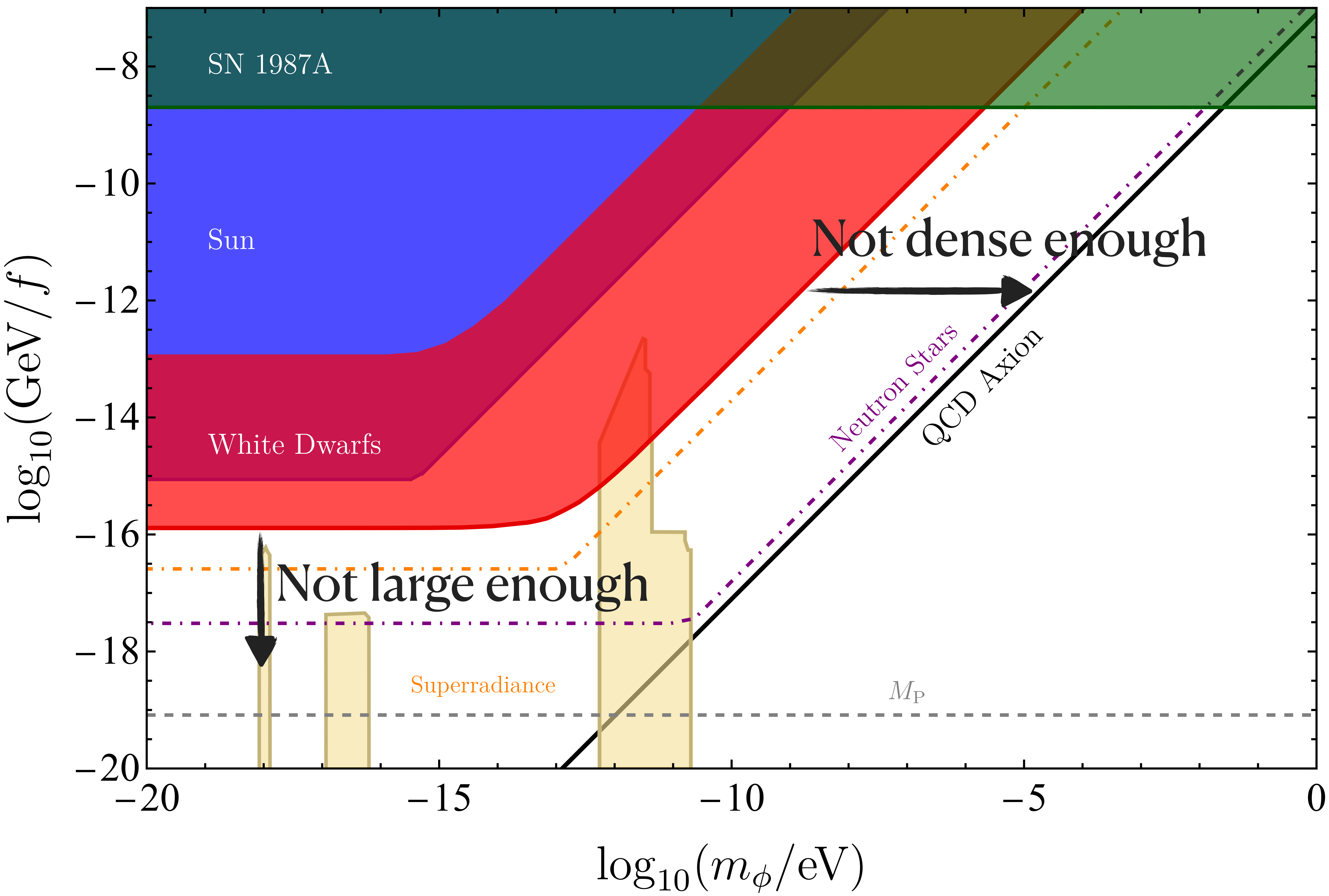
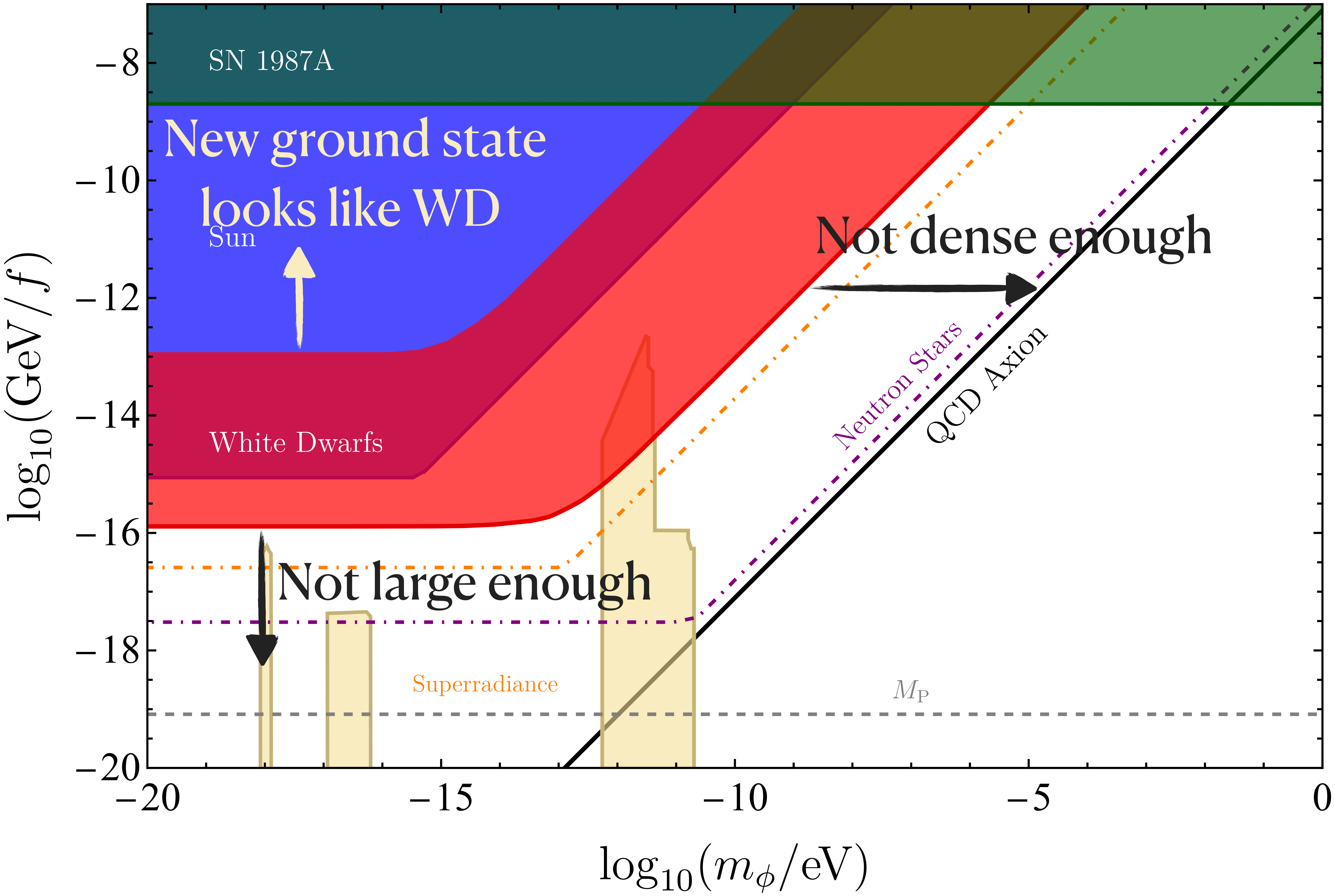


Axion Parameter Space



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Part II: Heavy stars from light scalars

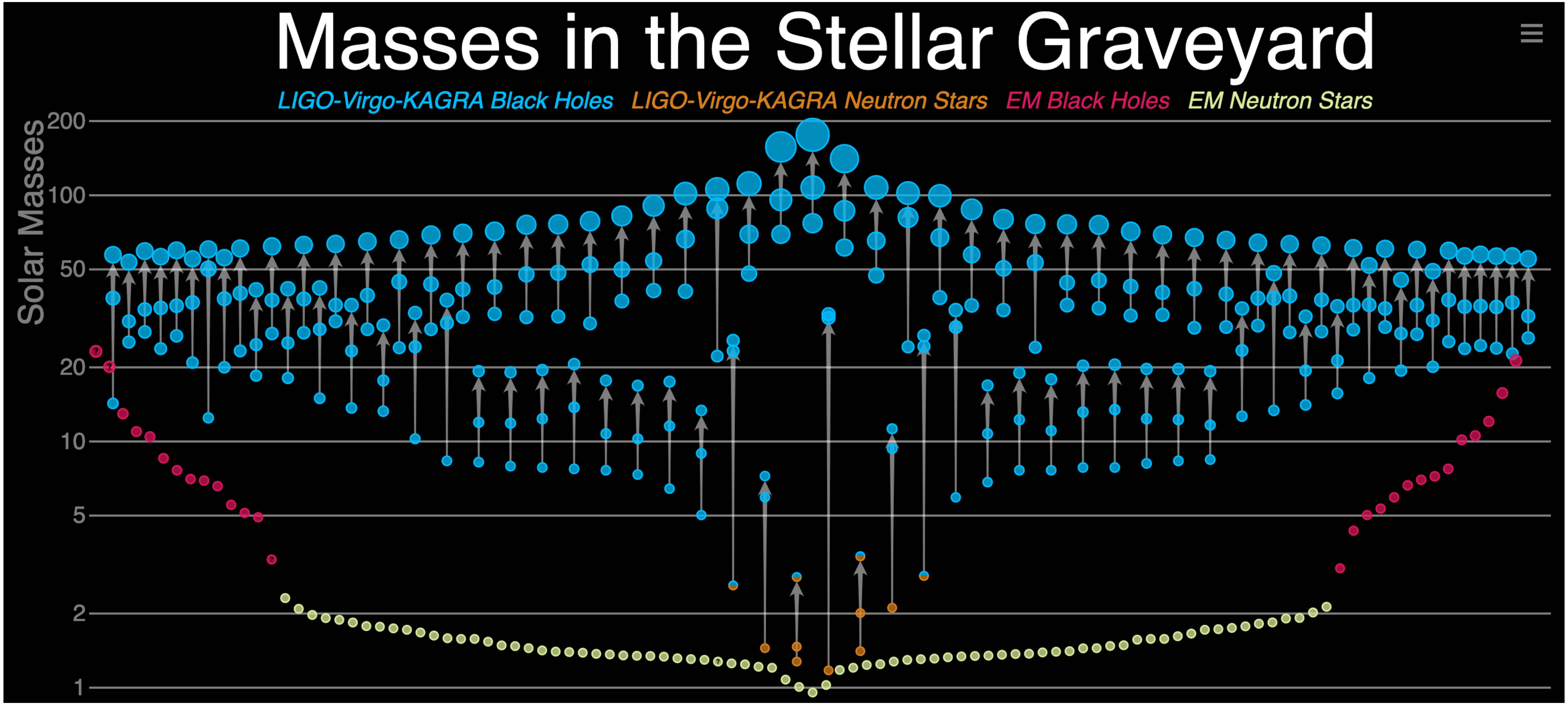
- Motivation and simplest example

Heavy Neutron Stars from light Scalars

… or Fat Zombies in the Stellar Graveyard

Motivation

Gravitational wave astronomy



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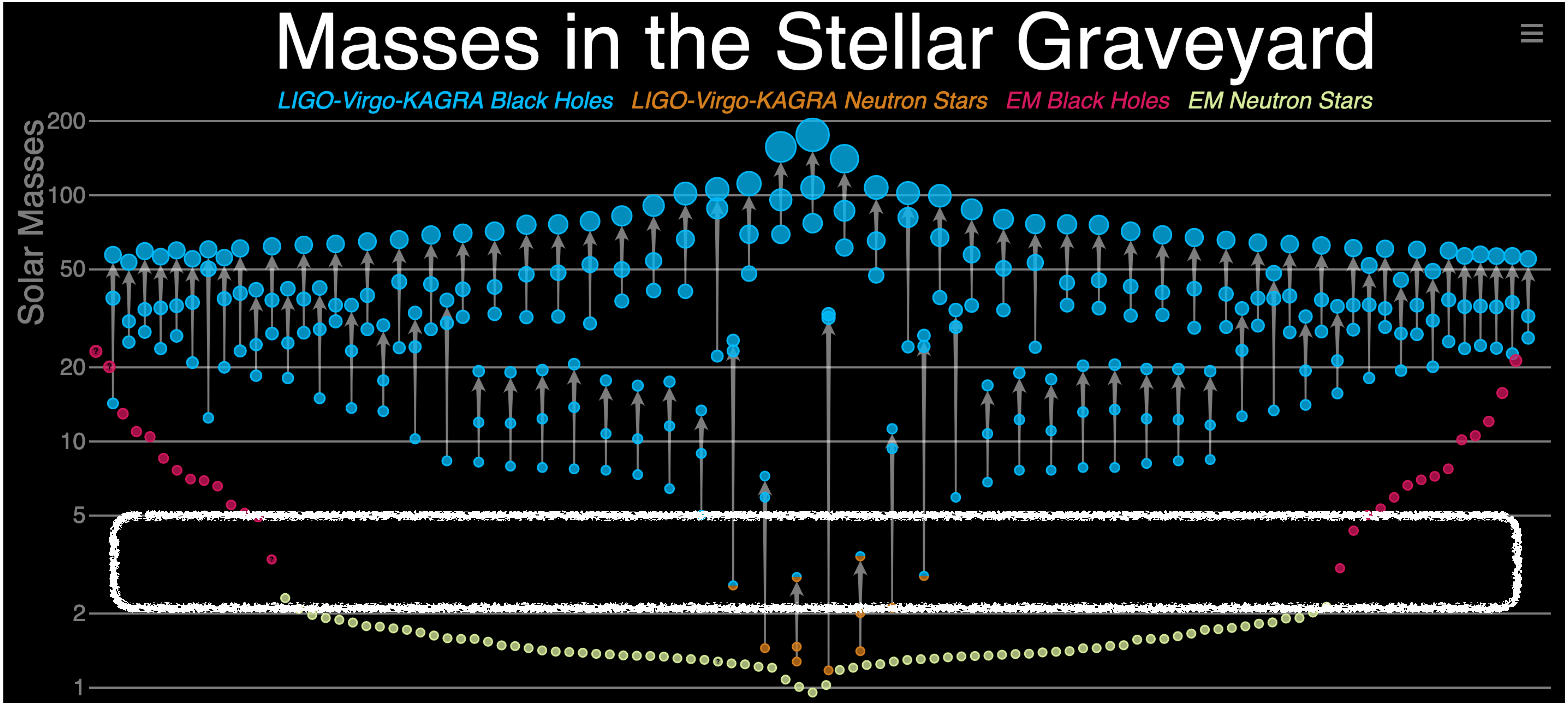
Gravitational wave astronomy



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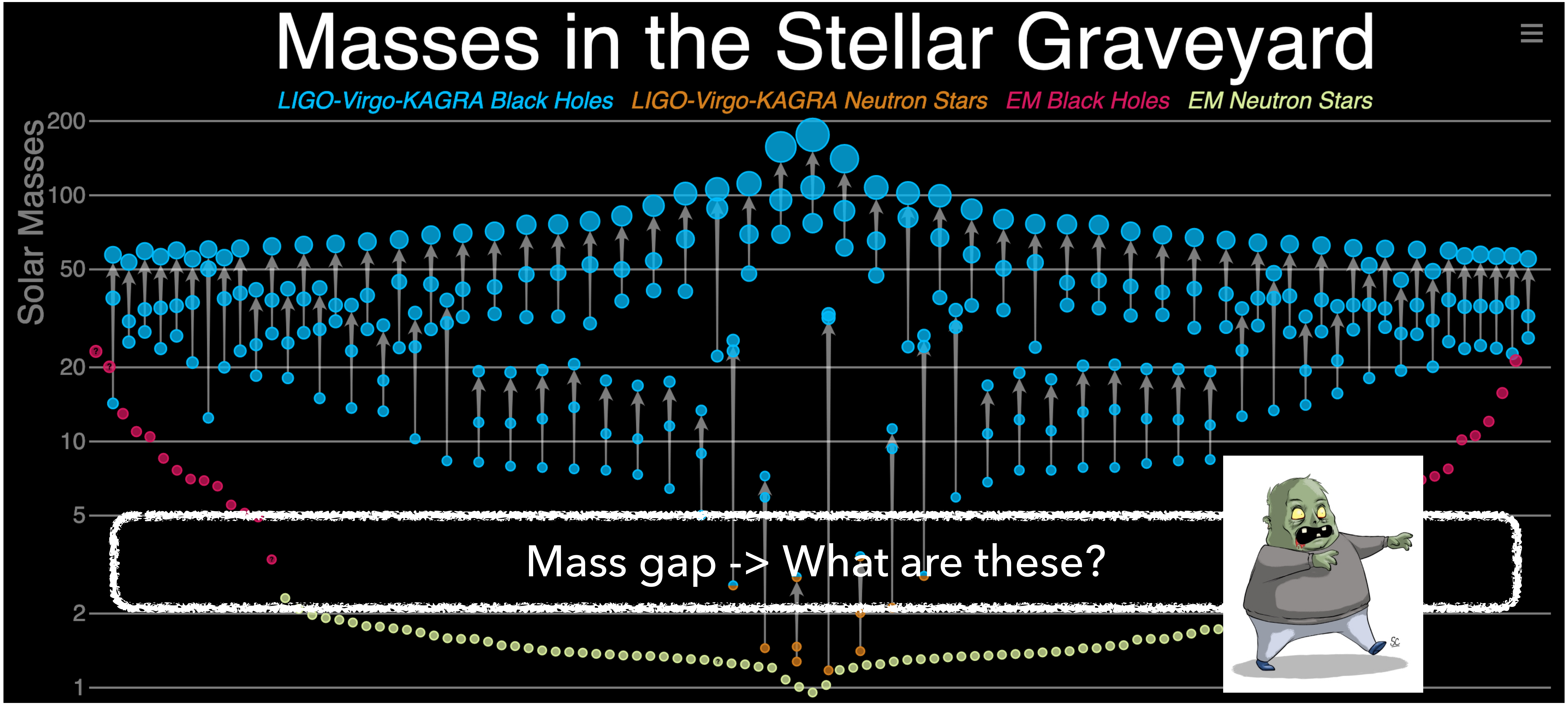
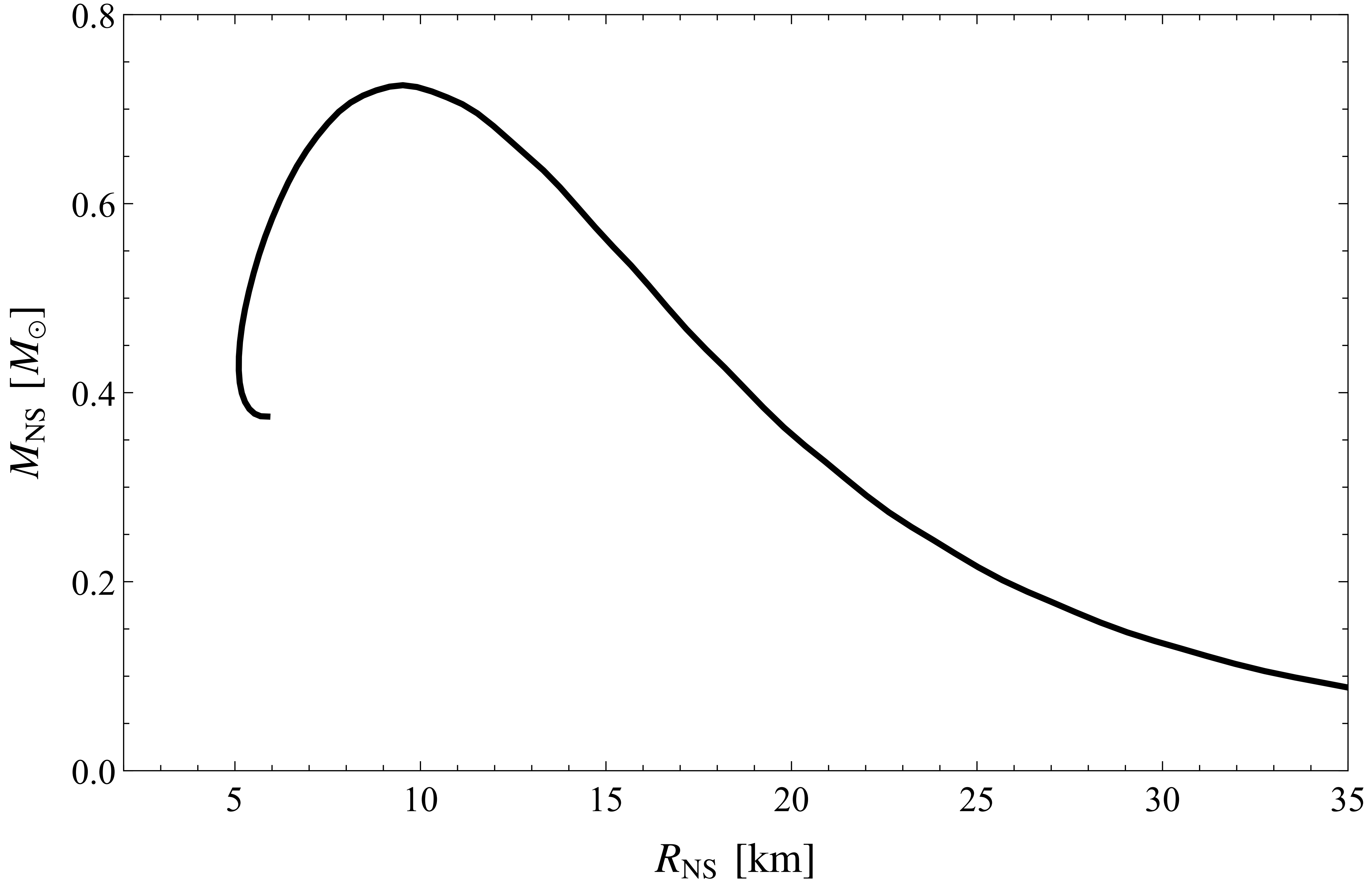


A simple example

Consider non-interacting Fermi gas of neutrons

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

$$\Rightarrow R_{\rm max} \simeq 10\,{\rm km}$$

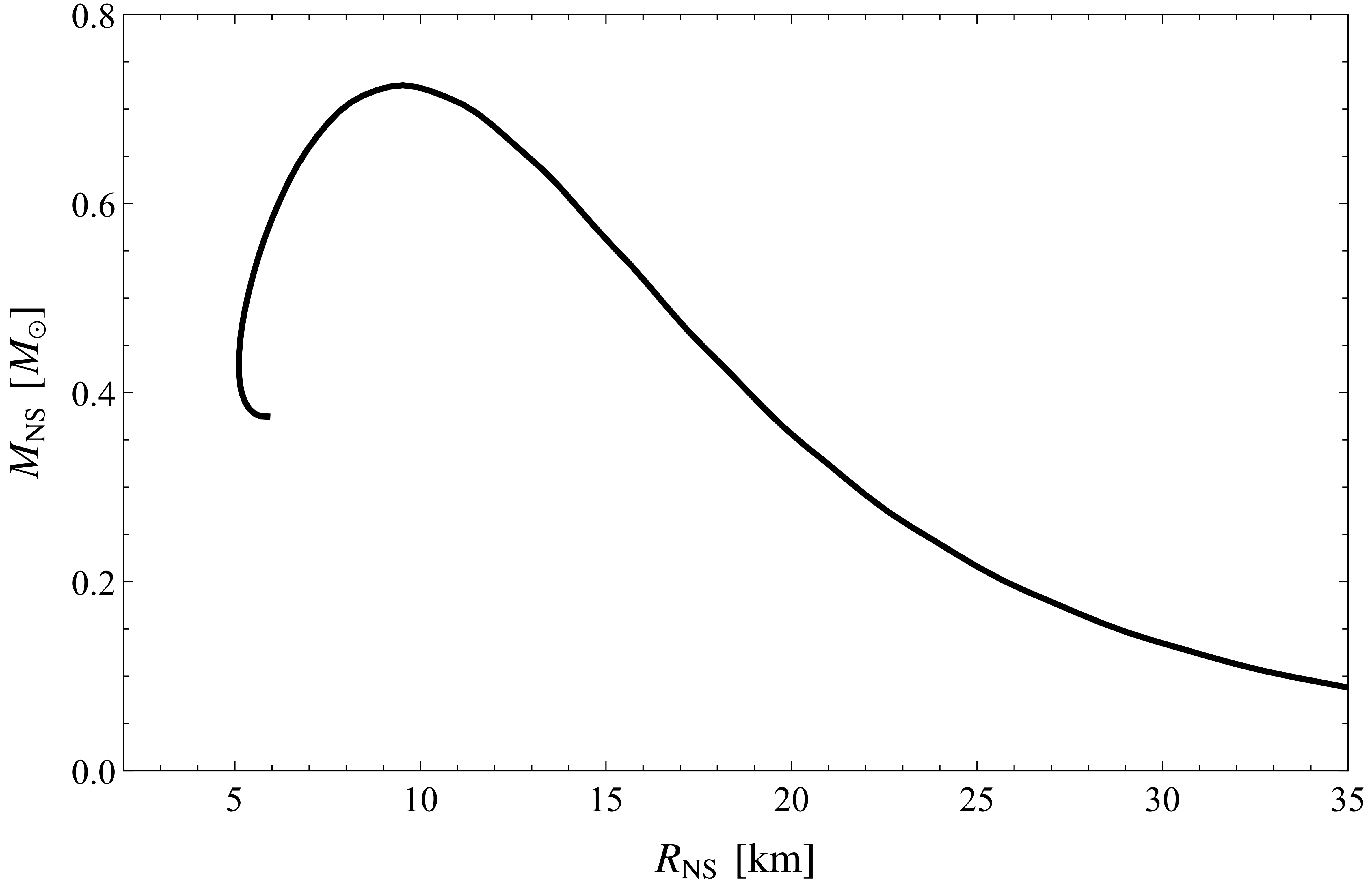


A simple example

Consider non-interacting Fermi gas of neutrons

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

$$\Rightarrow R_{\text{max}} \sim 10 \left(\frac{m_N}{m}\right)^2 \text{ km}$$



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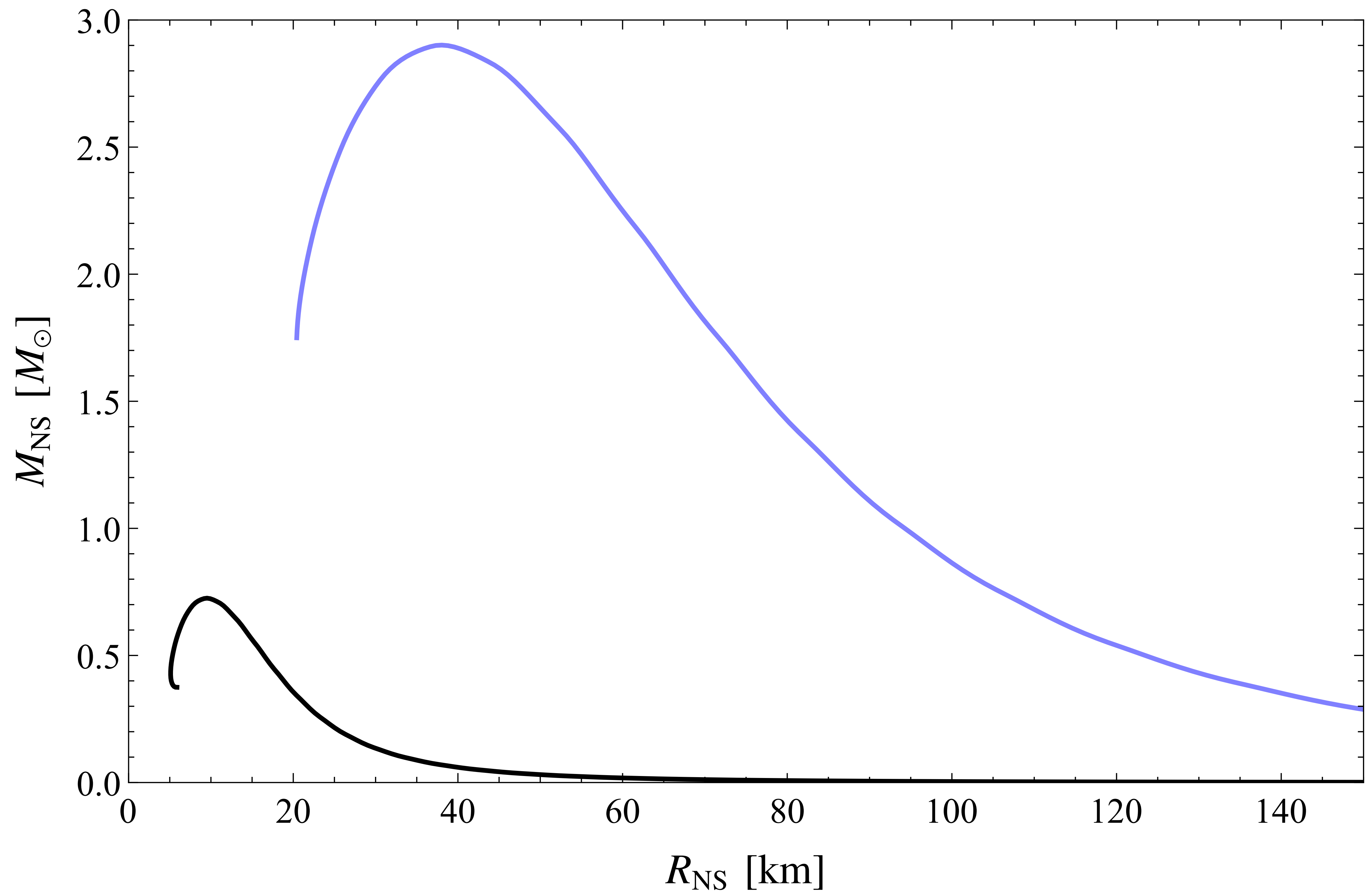

For lighter neutrons

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

A simple example

Consider non-interacting Fermi gas of neutrons

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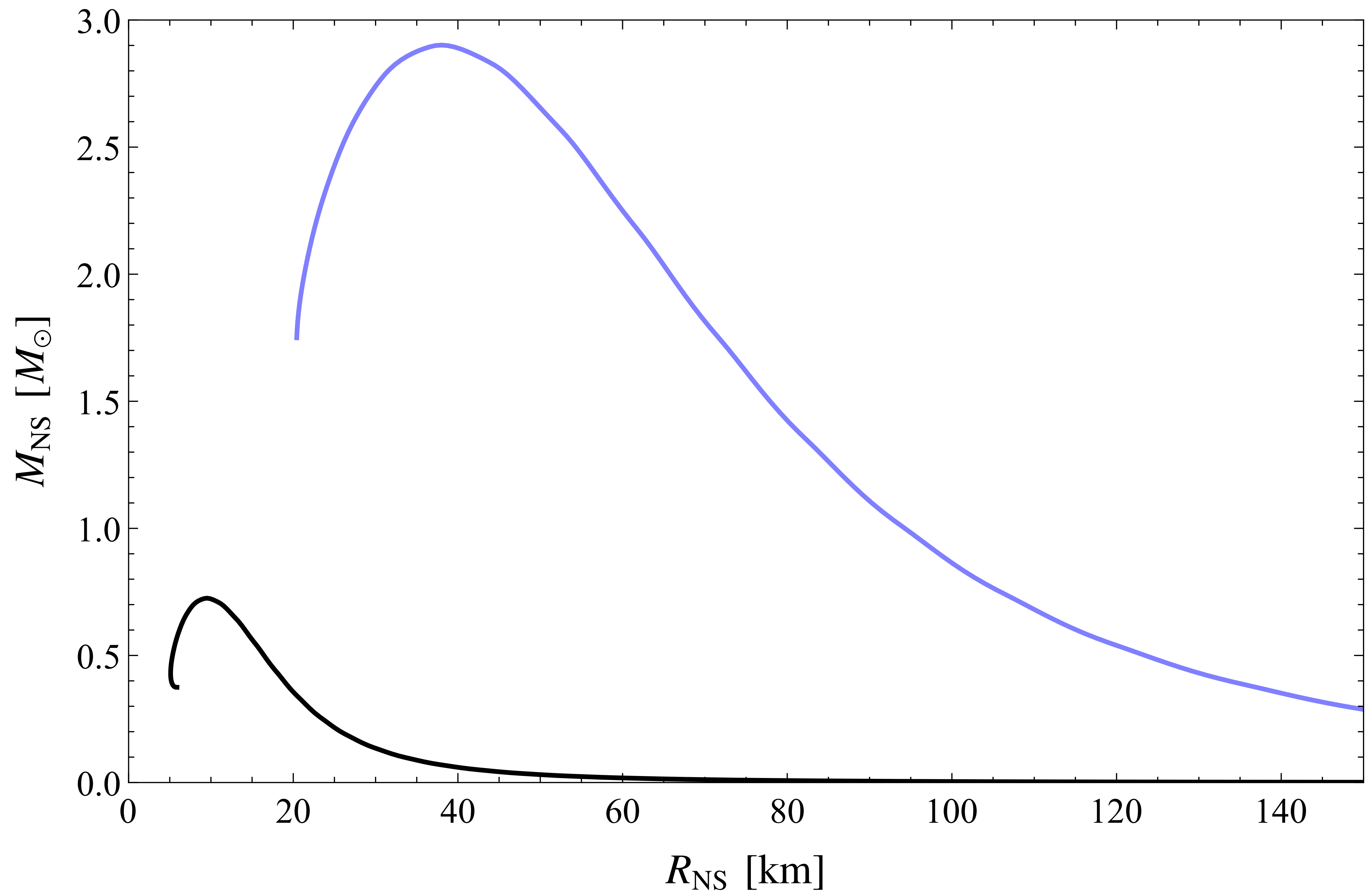

For lighter neutrons

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

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

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- What kind of equation of state?

Generic Scalar

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

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

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

What kind of EOS?

1) Mass reduction $m_N^* < m_N$ stiffens the EOS

$\varepsilon = \text{const.} = m_N^* \rho$

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

2) Vacuum energy $V(\pi f) = 2\Lambda^4$ softens the EOS additional energy density gravitates

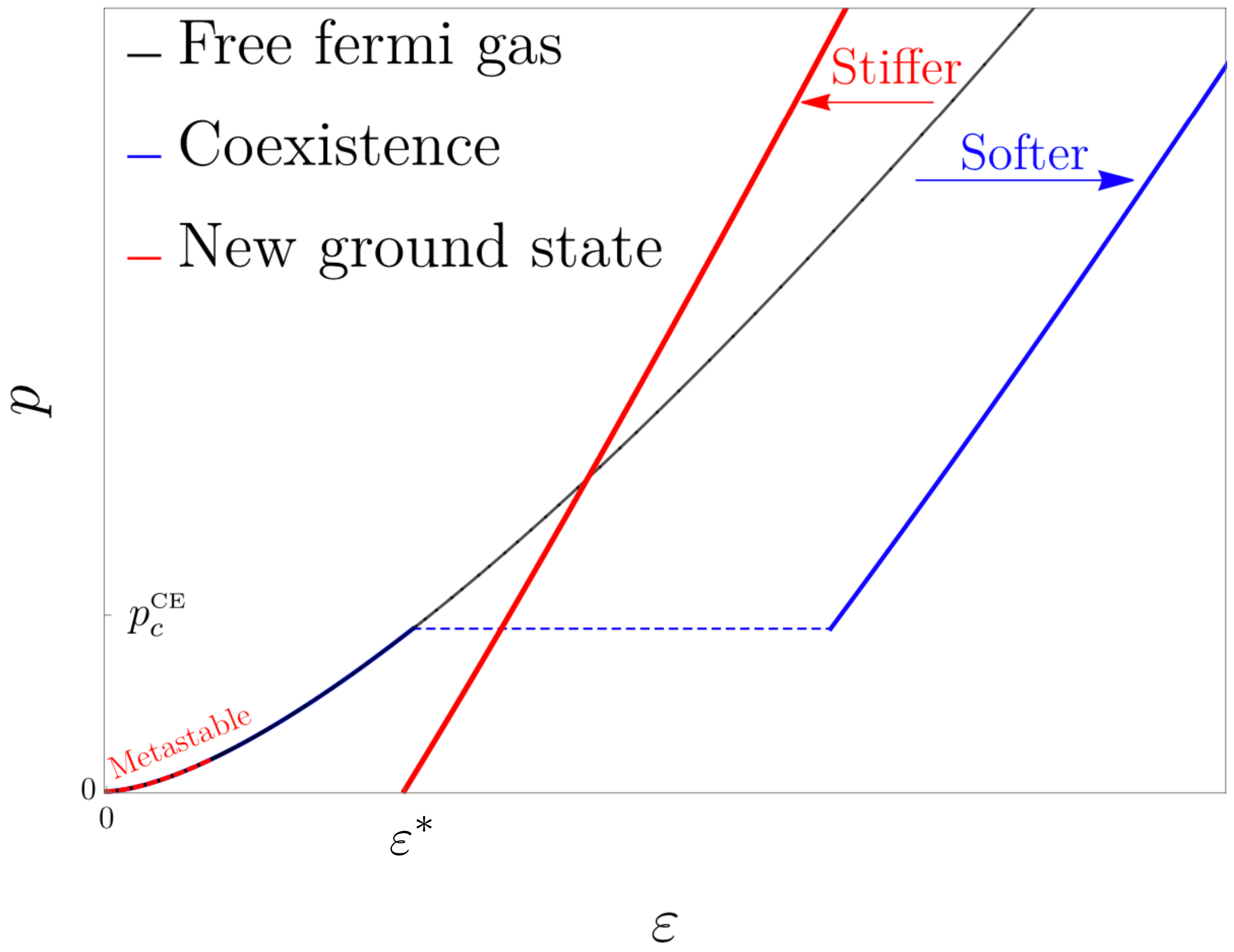
see Bellazzini et. al. ’15 and Csaki et. al. ’18

Generic Scalar

Parameter space is split

Potential dominating: $\varepsilon/n > m_N$

Coexistence First order PT: hybrid stars with softer EOS



Generic Scalar

Parameter space is split

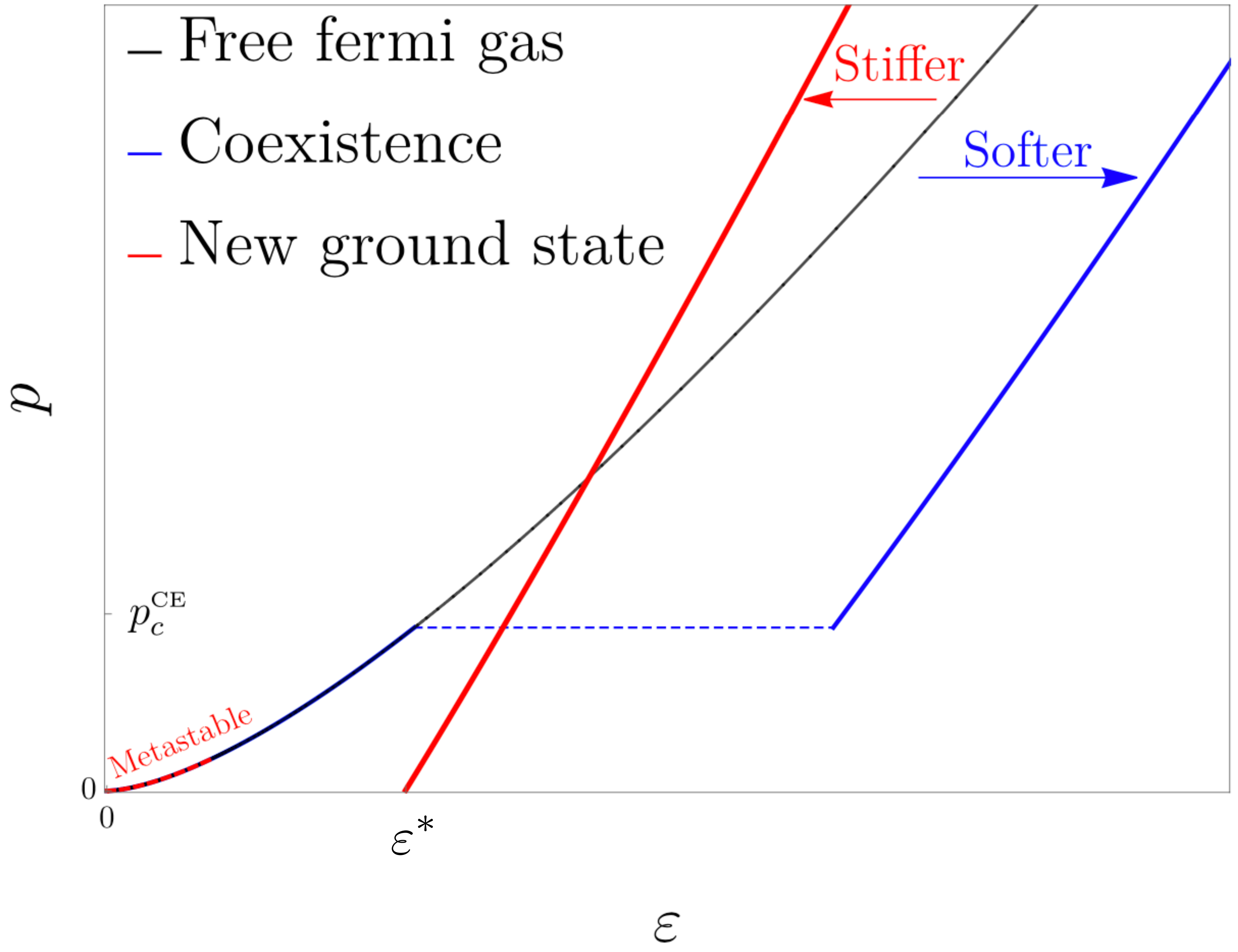
Potential dominating: $\varepsilon/n > m_N$

Coexistence First order PT: hybrid stars with softer EOS

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

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

like SQM



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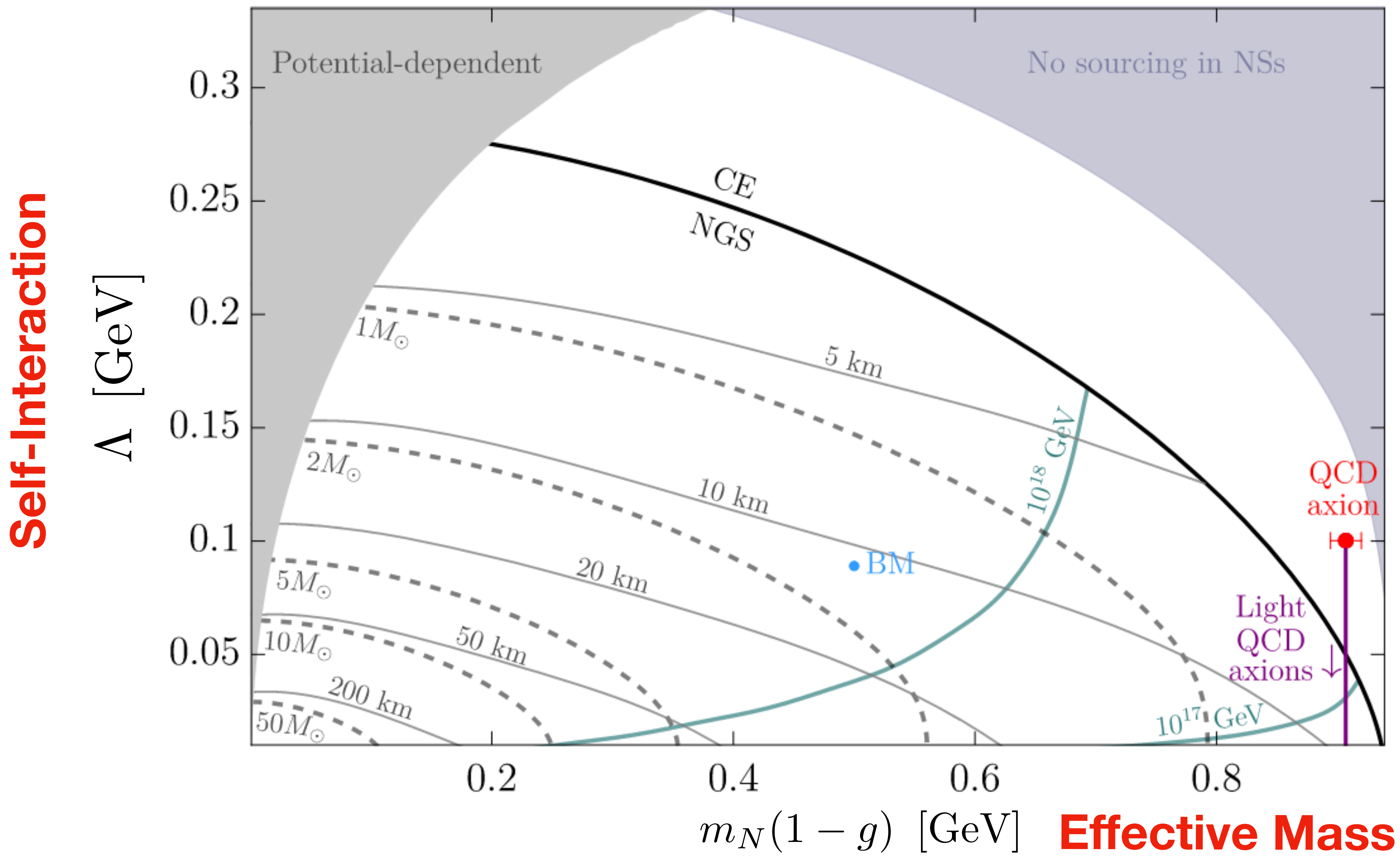
Parameter space



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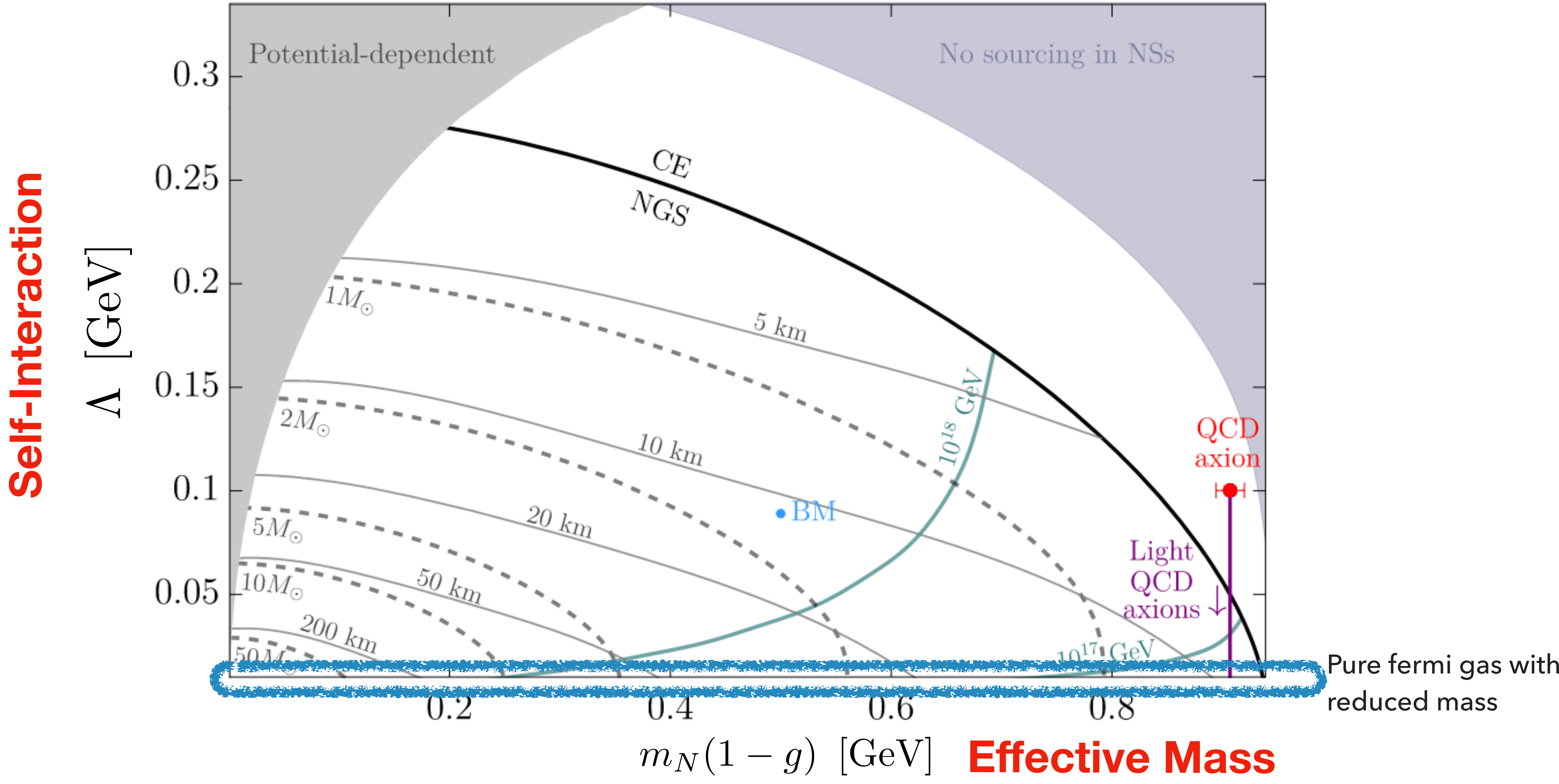

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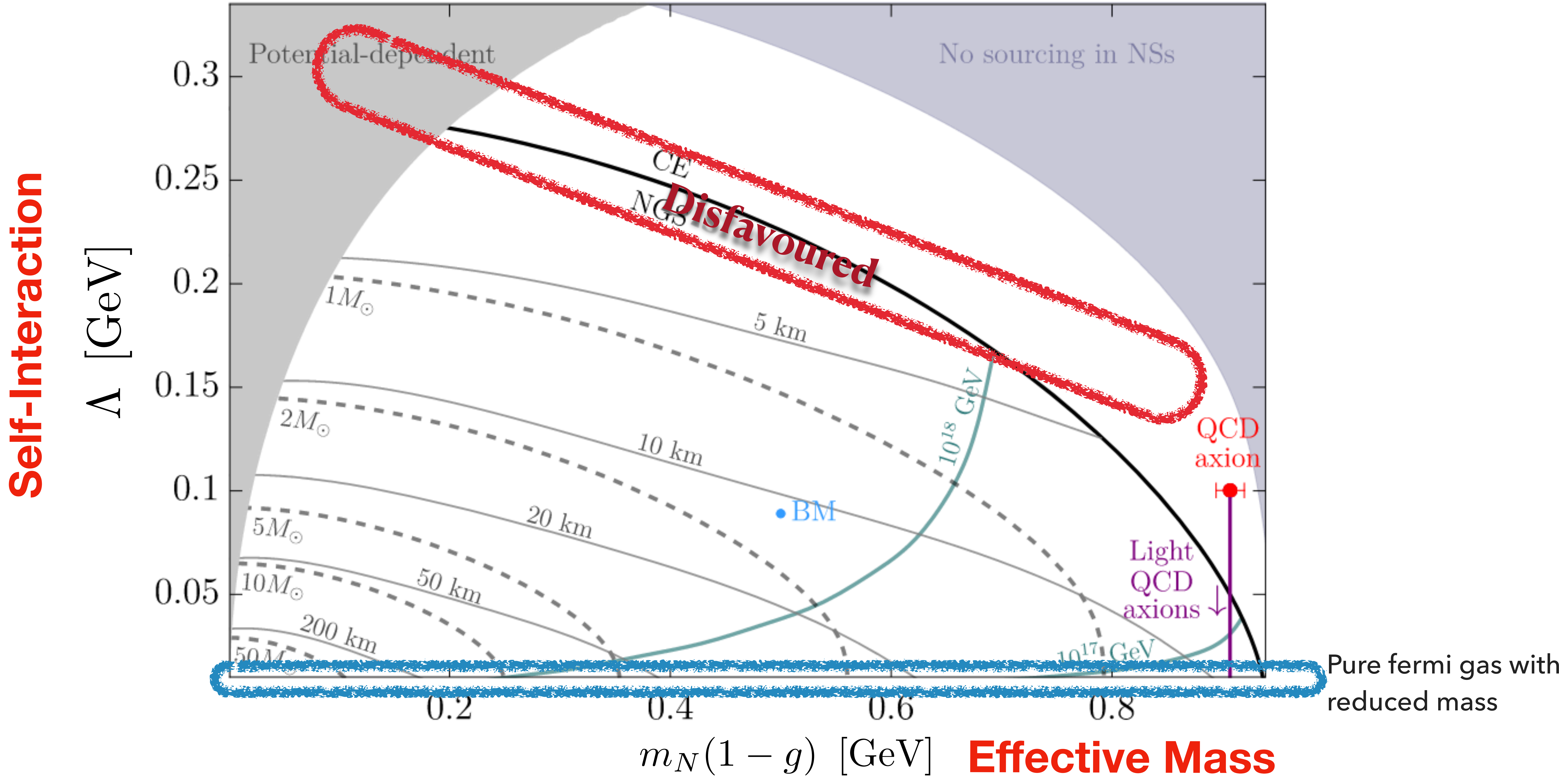

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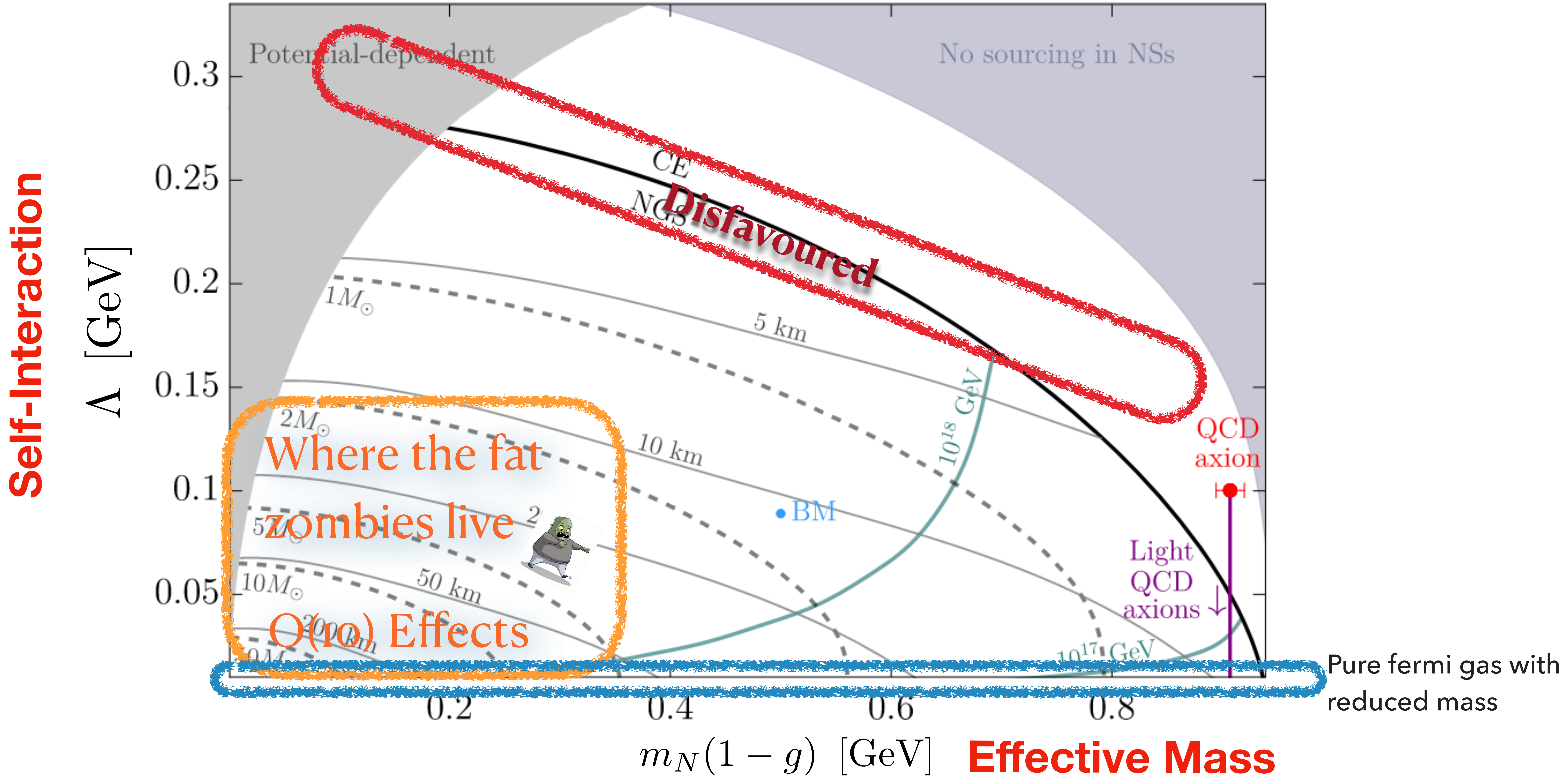


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1

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- Motivation and simplest example ✓
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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
- Allows to exclude large chunk of parameter space
- 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

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More to do

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

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Thank you!

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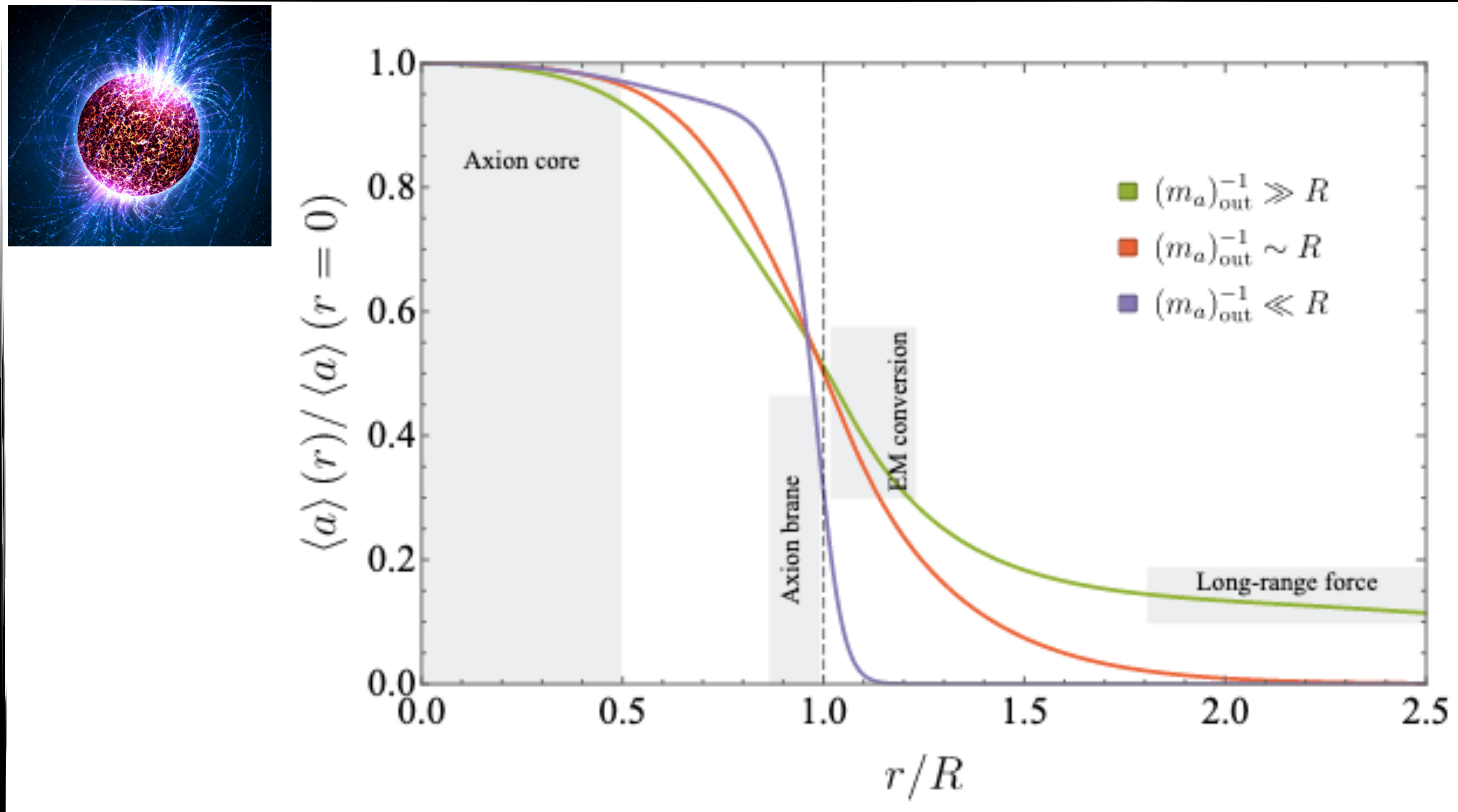
More to do

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

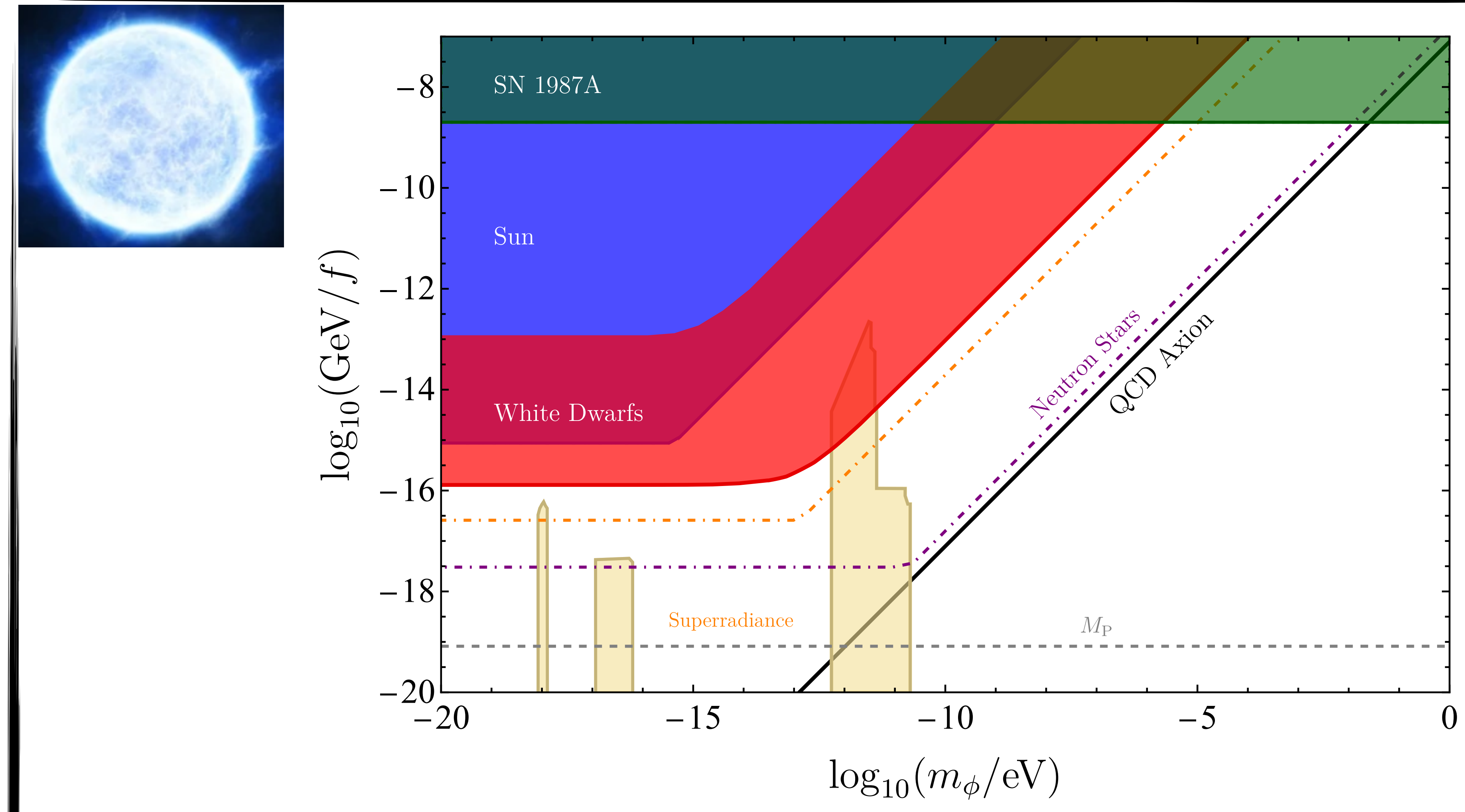
Backup

Studying density effects is fun!



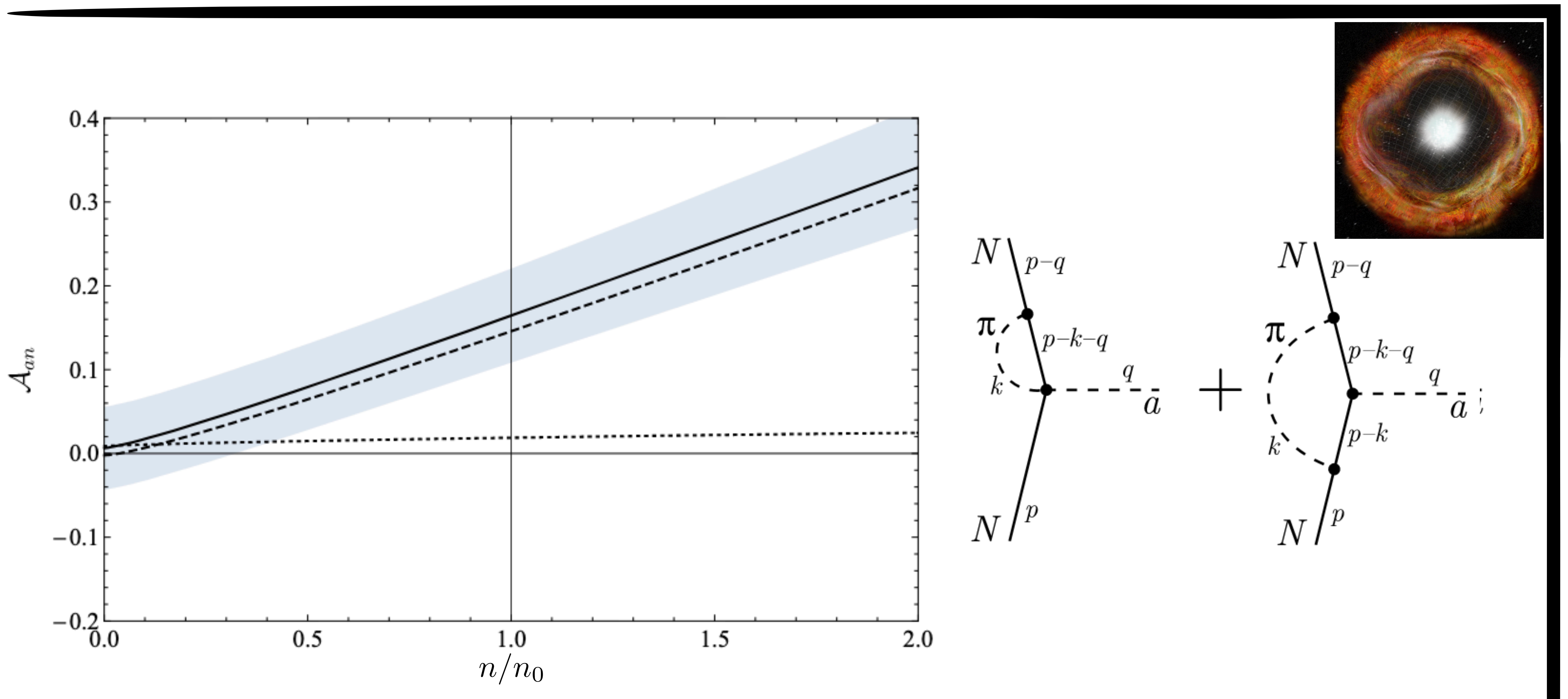
The QCD axion at finite density

JHEP 07 (2020) 221 with Balkin, Serra, Weiler



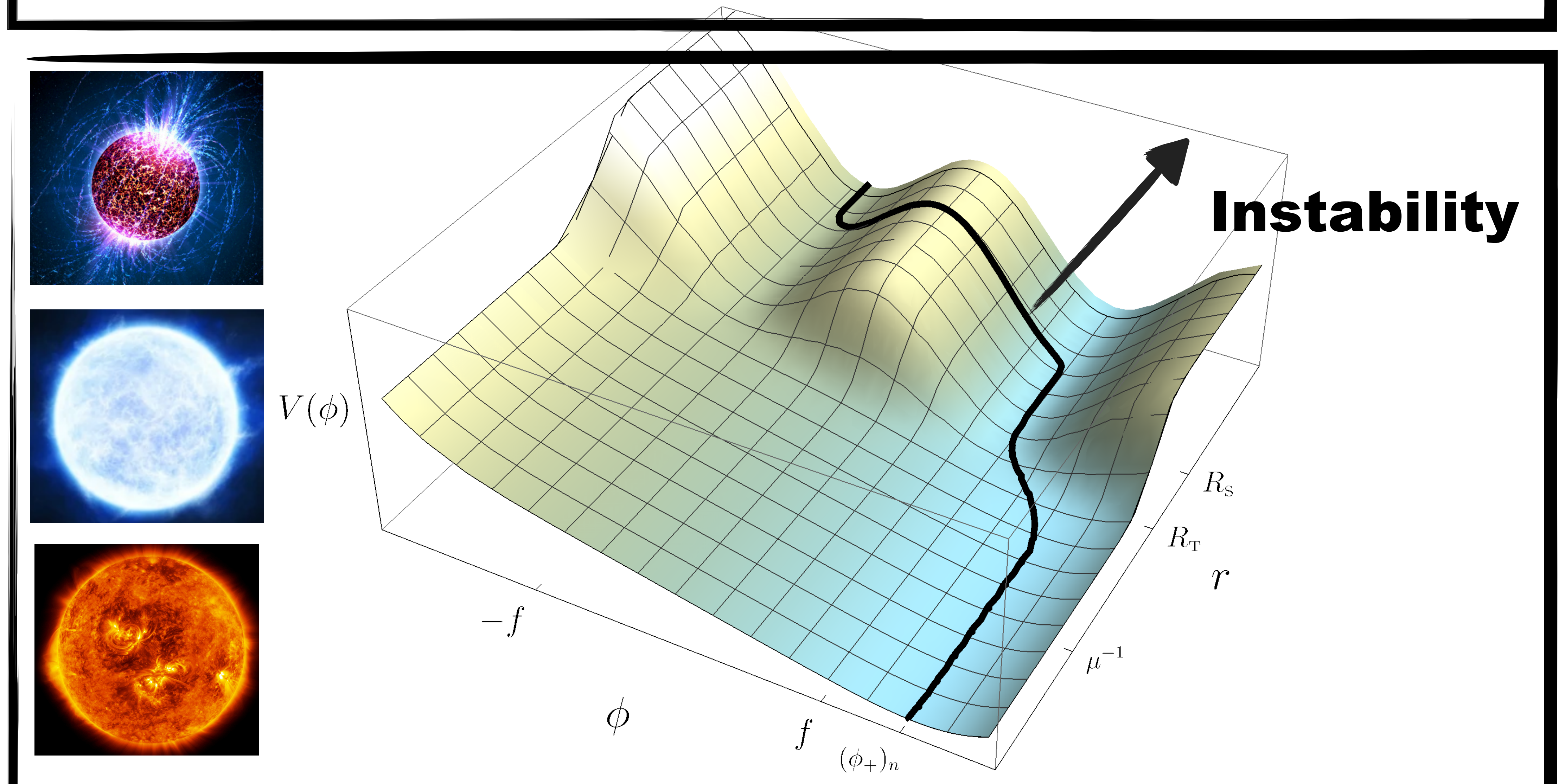
Light QCD axions in White Dwarfs

2211.02661 with Balkin, Serra, Stelzl, Weiler



QCD-axion—Nucleon coupling at finite density

To appear soon



Phase Transitions from Stars

2105.13354 with Balkin, Serra, Stelzl, Weiler

White Dwarfs with light Axion

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

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

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

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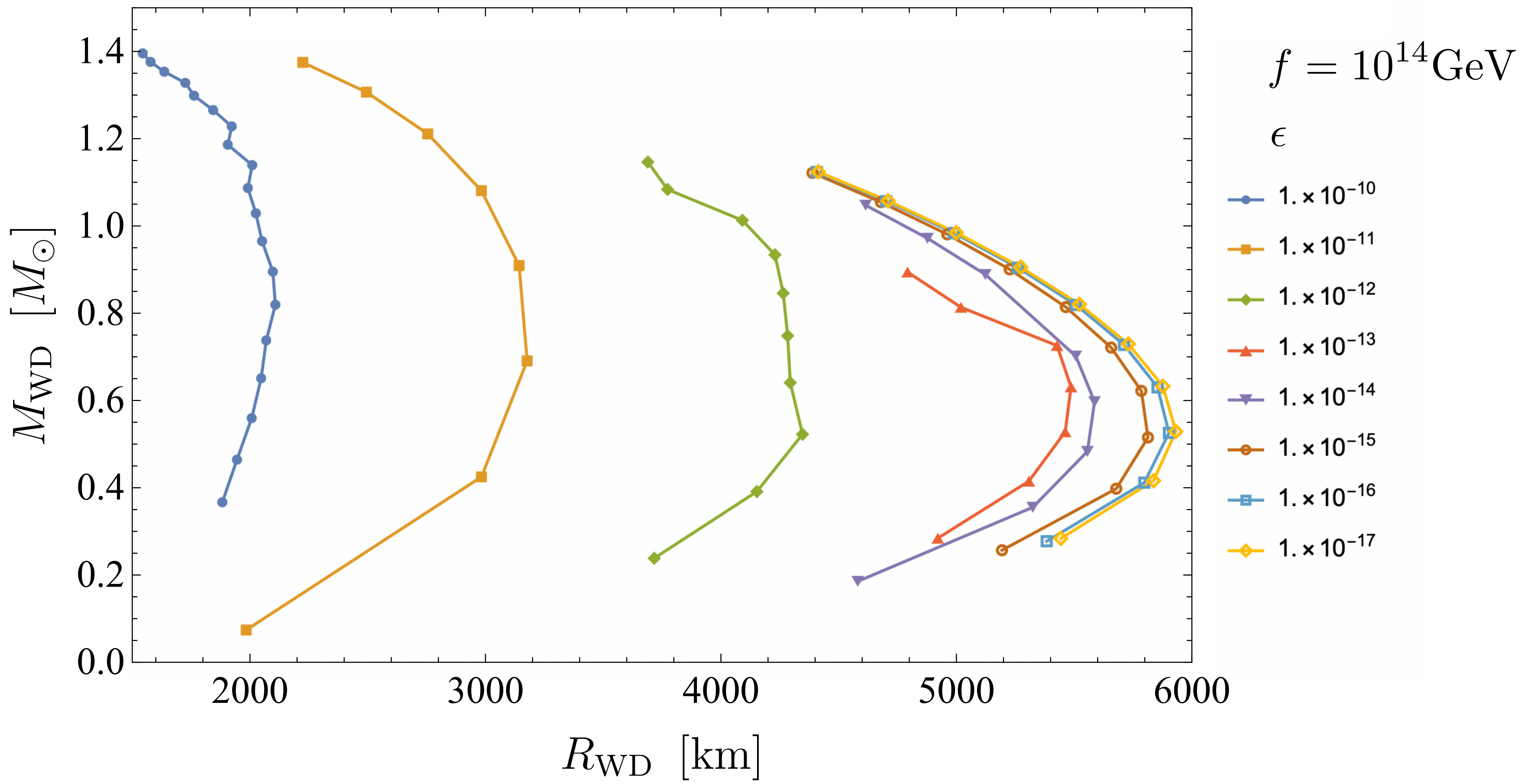
But, for large decay constants $f > 10^{13}\text{GeV}$ gradient effects become important

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

2) On stable branch: gradient pressure fixes maximal radius



ALP-FERMION-GRAVITY SYSTEM

Consider one Fermion N, gravity and the ALP

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

ALP neutron interaction ($m_N^*(\phi)$)

ALP self-interaction ($V(\phi)$)

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

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

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

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

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 $\partial_\mu \phi = 0$

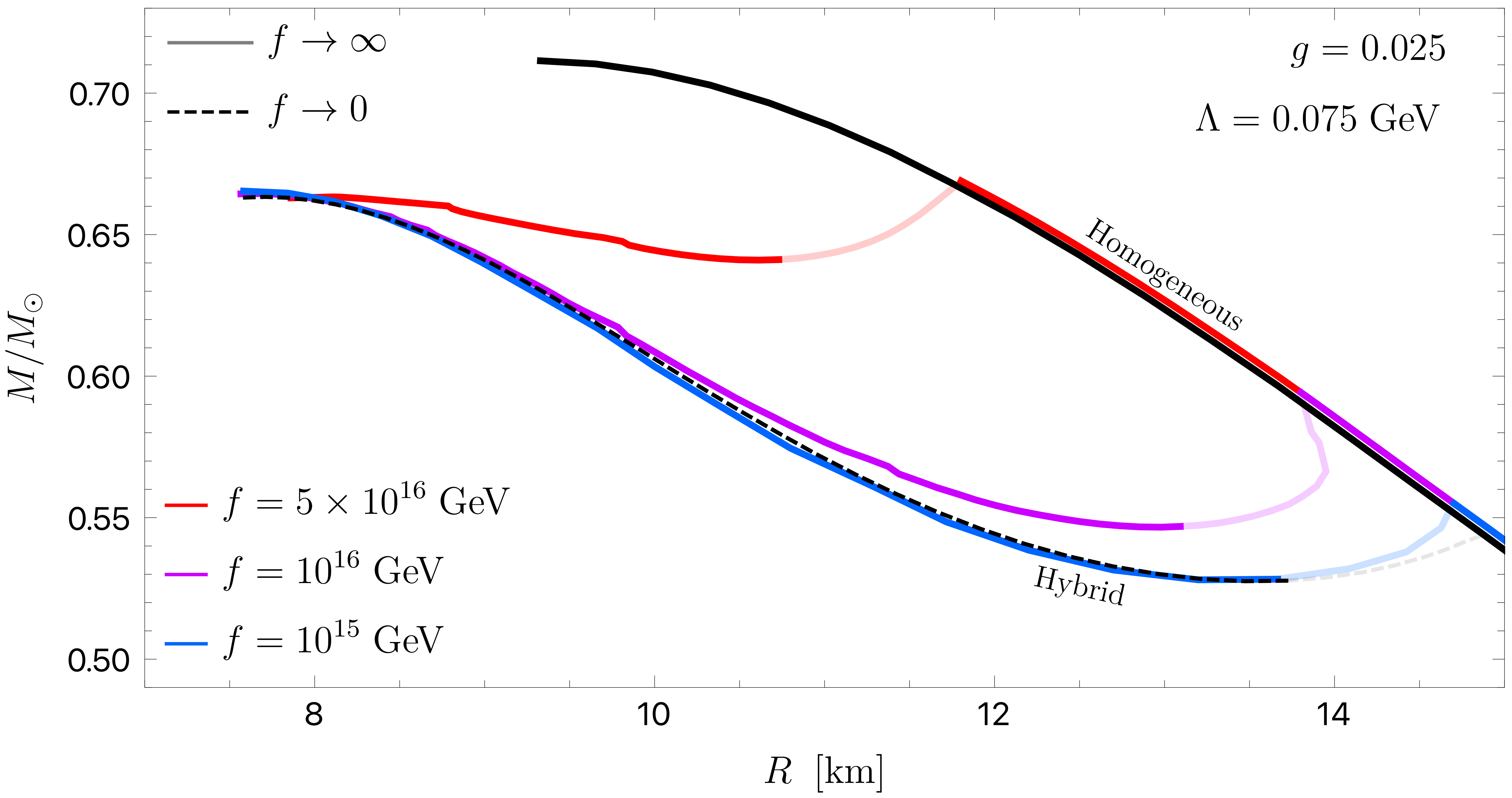
This is very nice because now the system is effectively decoupled!

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

$\frac{\delta S}{\delta g_{\mu\nu}} = 0$ → Pressure - Gravity balance equations

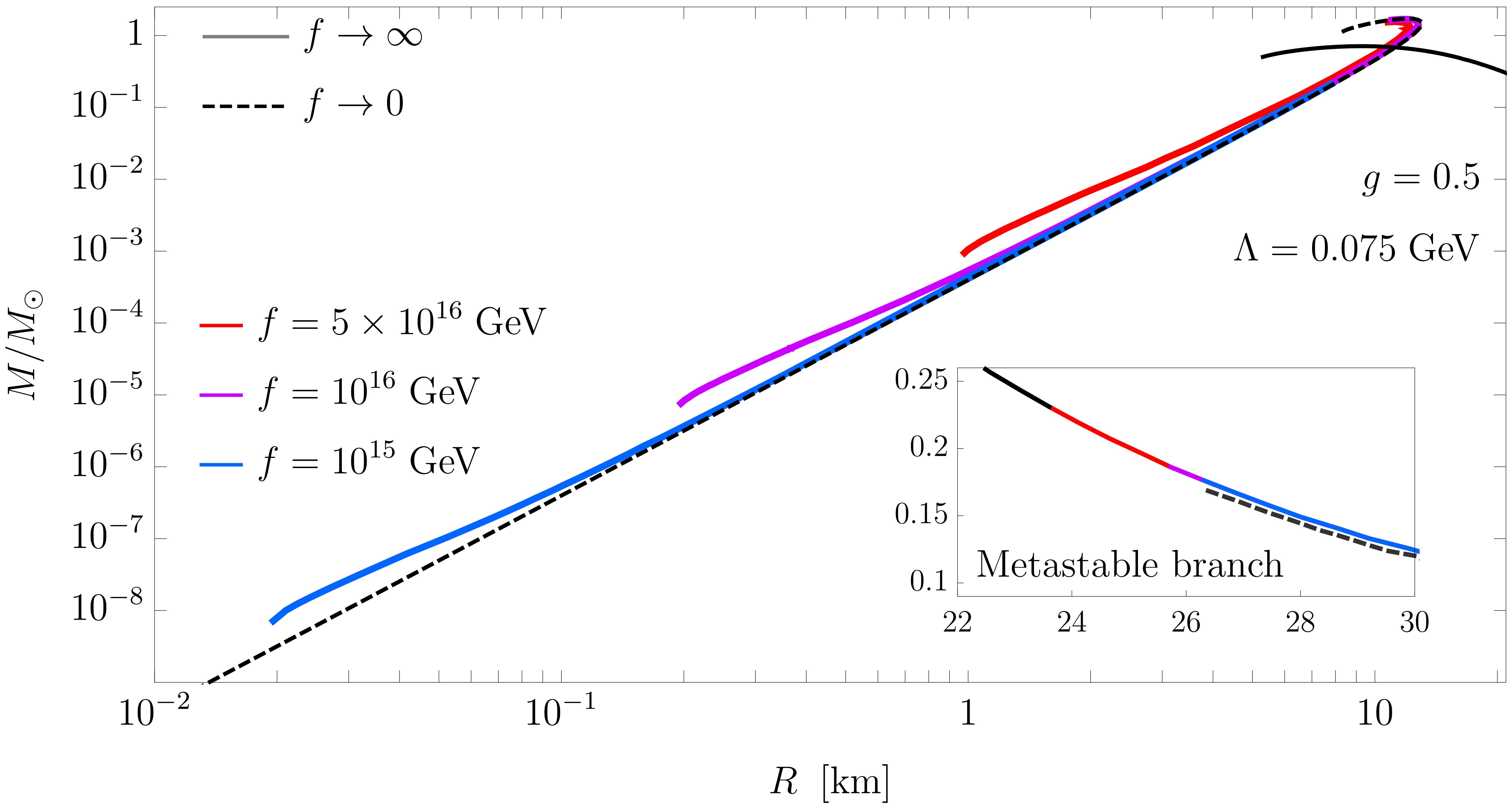
(Also known as TOV equations)

MR



$f \to \infty$
$f \to 0$
$g = 0.025$
$\Lambda = 0.075$ GeV
Homogeneous
Hybrid
$f = 5 \times 10^{16}$ GeV
$f = 10^{16}$ GeV
$f = 10^{15}$ GeV
0.70
0.65
0.60
0.55
0.50
$M/M_{\odot}$
8
10
12
14
R [km]

MR-LOG

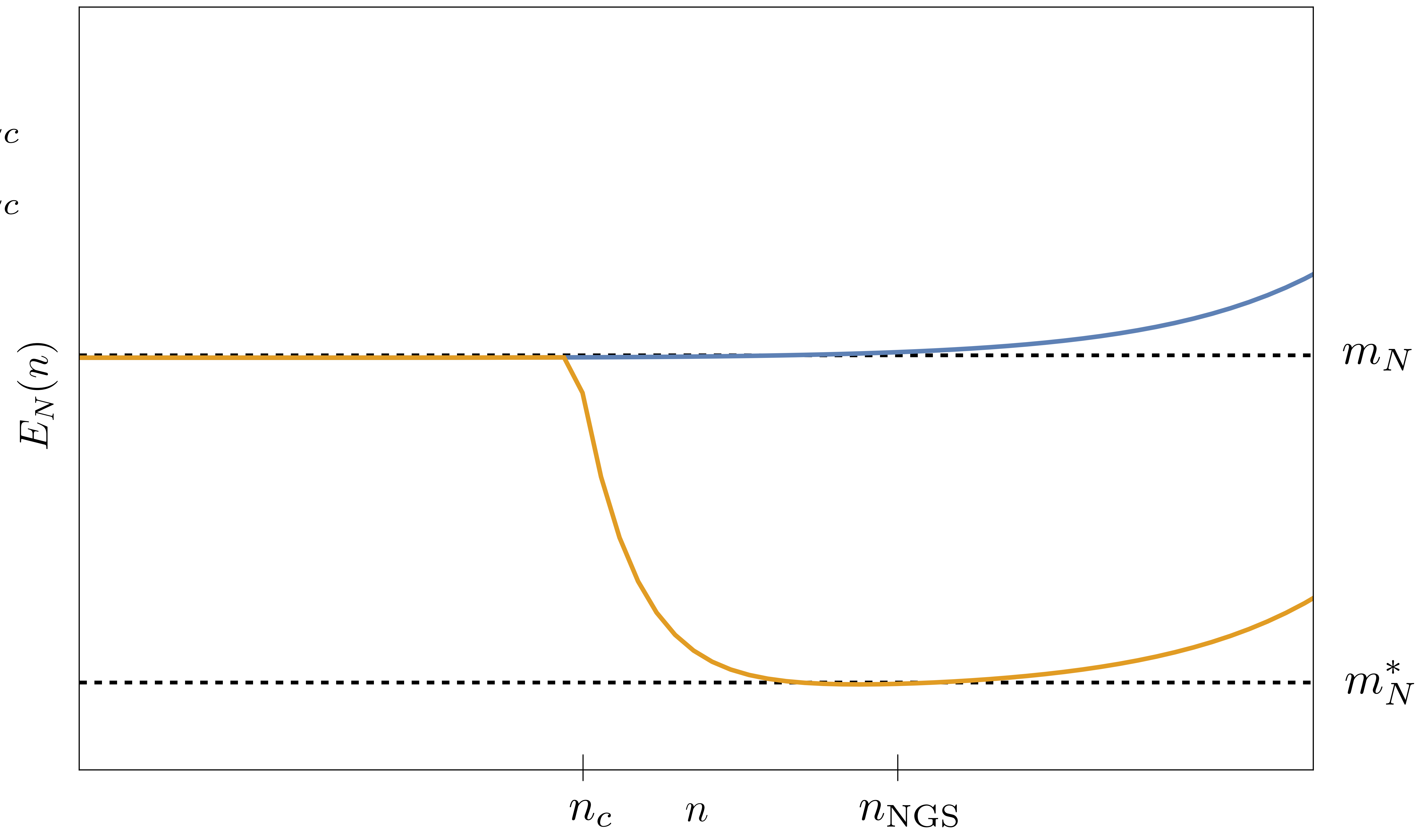


$f \to \infty$
$f \to 0$
$g = 0.5$
$\Lambda = 0.075$ GeV
$f = 5 \times 10^{16}$ GeV
$f = 10^{16}$ GeV
$f = 10^{15}$ GeV
Metastable branch
$M/M_\odot$
R [km]

ENERGY PER PARTICLE

Energy per particle of non-relativistic neutrons $$E_N(n) = \frac{\varepsilon_N(n) + V(n)}{n}$$

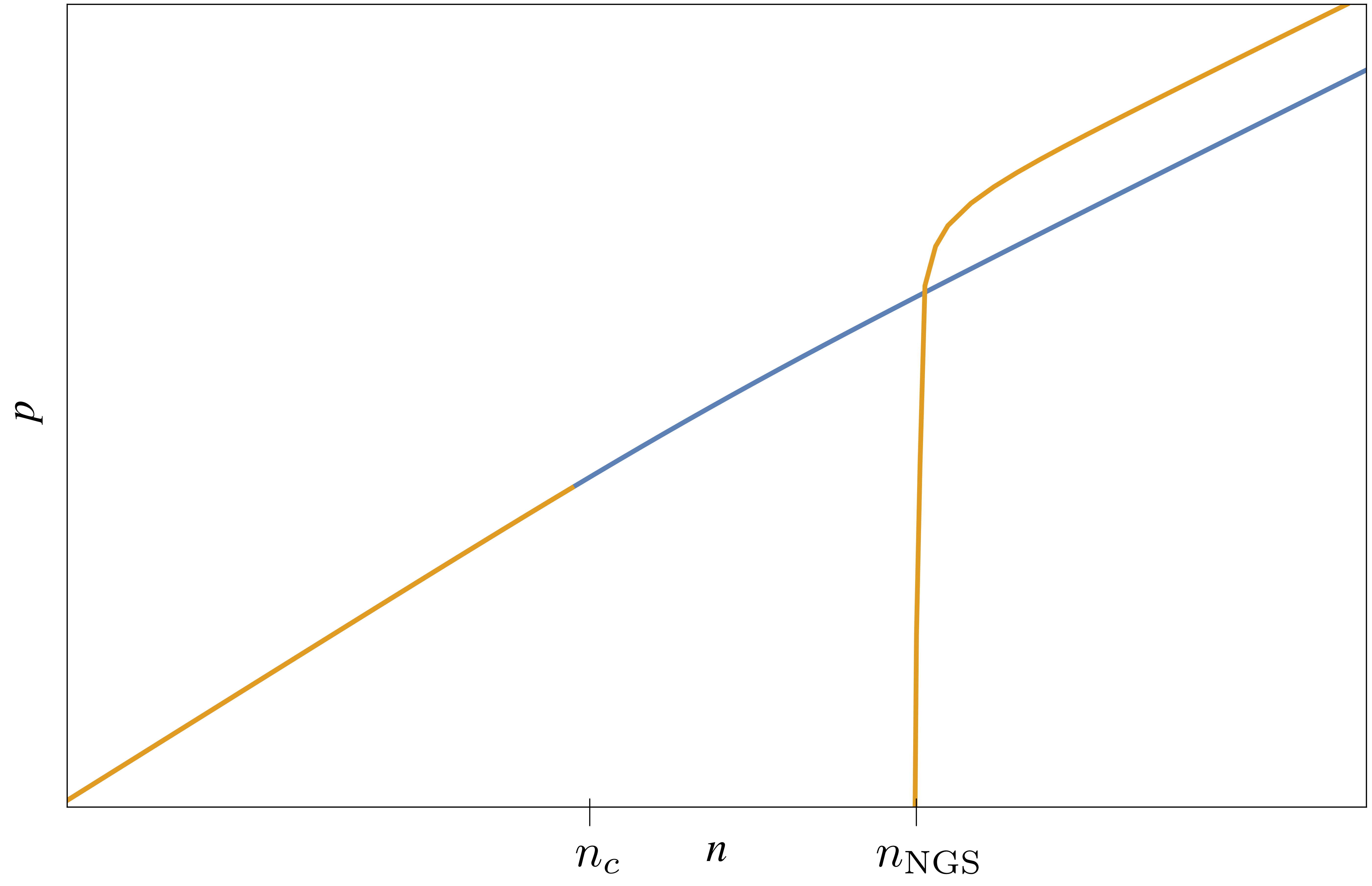
$$E_N(n) \simeq \begin{cases} m_N + \frac{2.7 n^{2/3}}{m_N}, & n \le n_c \\ m_N^* + \frac{\epsilon m_\pi^2 f_\pi^2}{4n} + \frac{2.7 n^{2/3}}{m_N^*}, & n > n_c \end{cases}$$



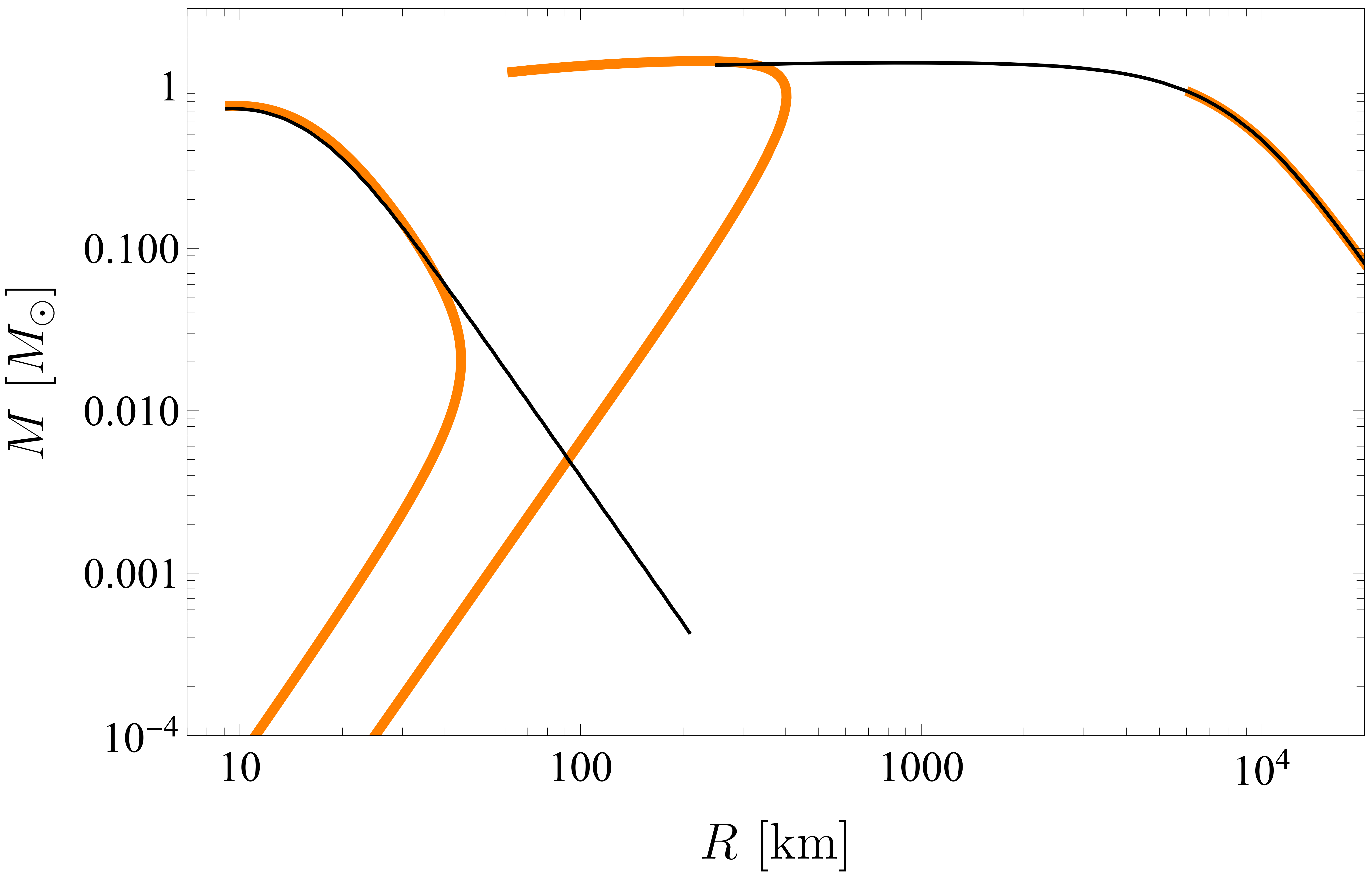
Equation of state

$$p = n^2 \frac{\partial E_N(n)}{\partial n}$$

Pressure

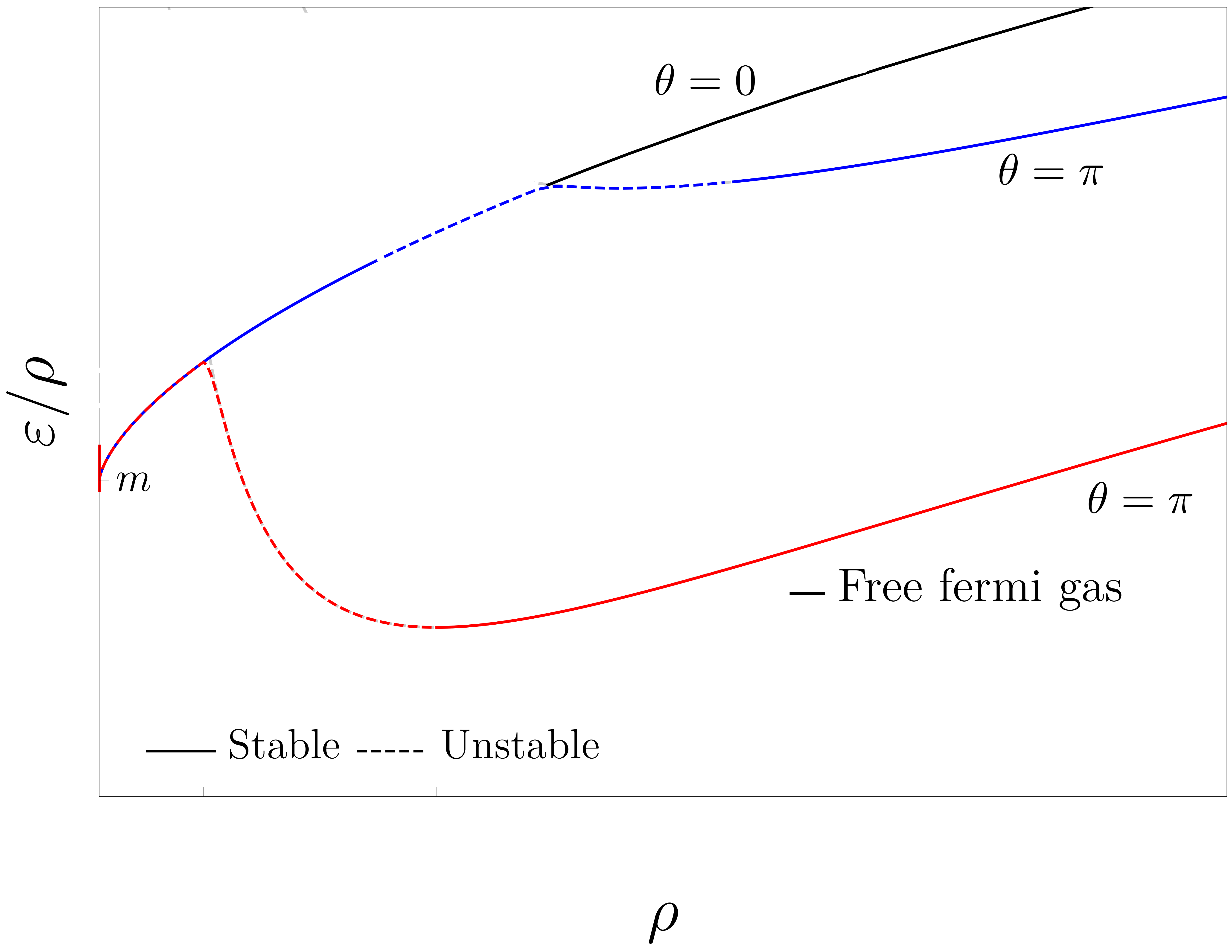


Global view



ENERGY PER PARTICLE

Difference between NGS and CE region



$$p = \rho^2 \frac{\partial(\varepsilon/\rho)}{\partial \rho}$$

New ground state: $\{\Lambda_1, g\}$

$\varepsilon/\rho < m_N$ for some ρ

- At lower densities, energy density dominated by $m_N \rho$
- Can even reach less energy per particle as well separated ordinary neutrons!
- Nucleons want to be at finite density!

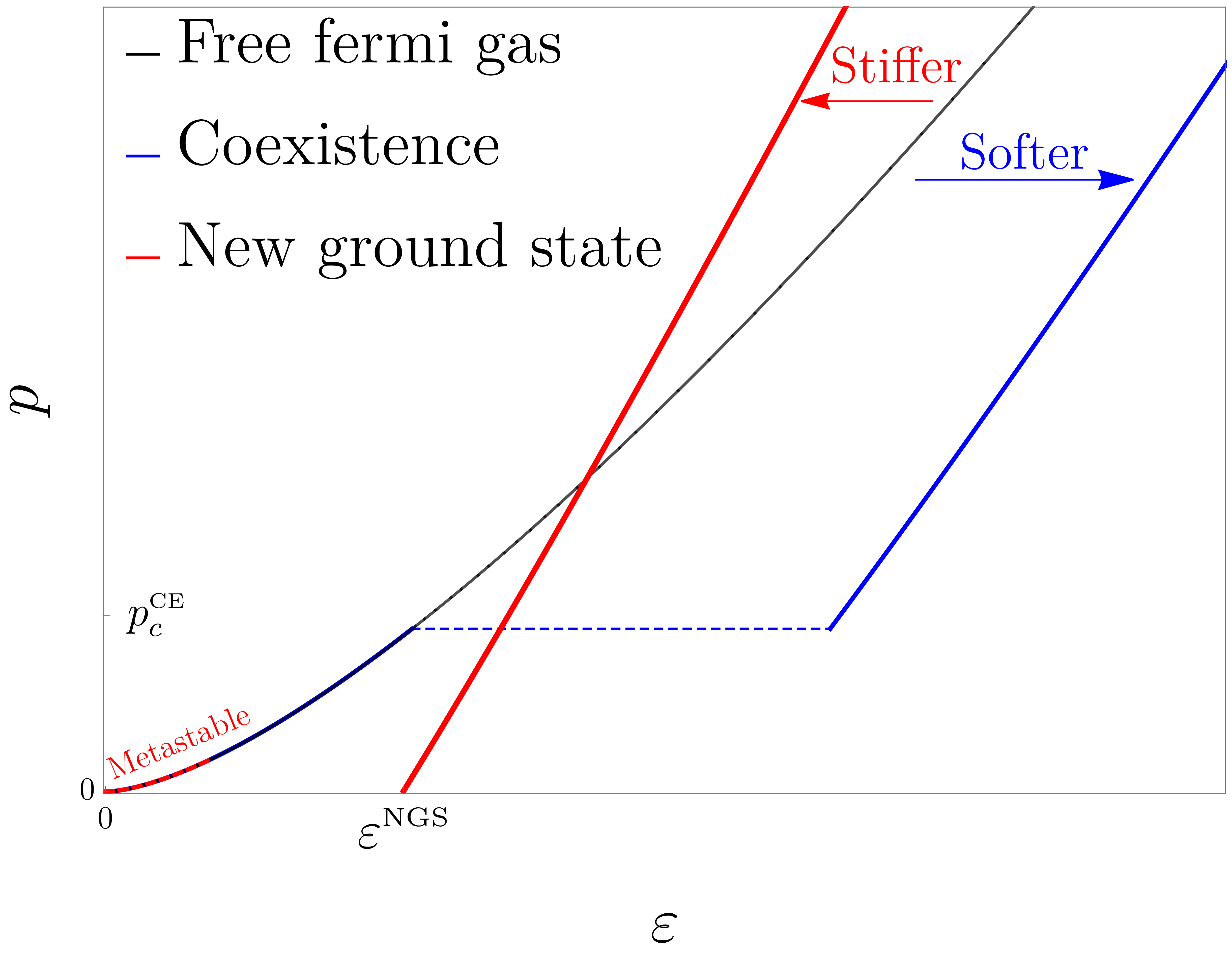
Coexistence: $\{\Lambda_2, g\}$

$\varepsilon/\rho > m_N$ for all ρ

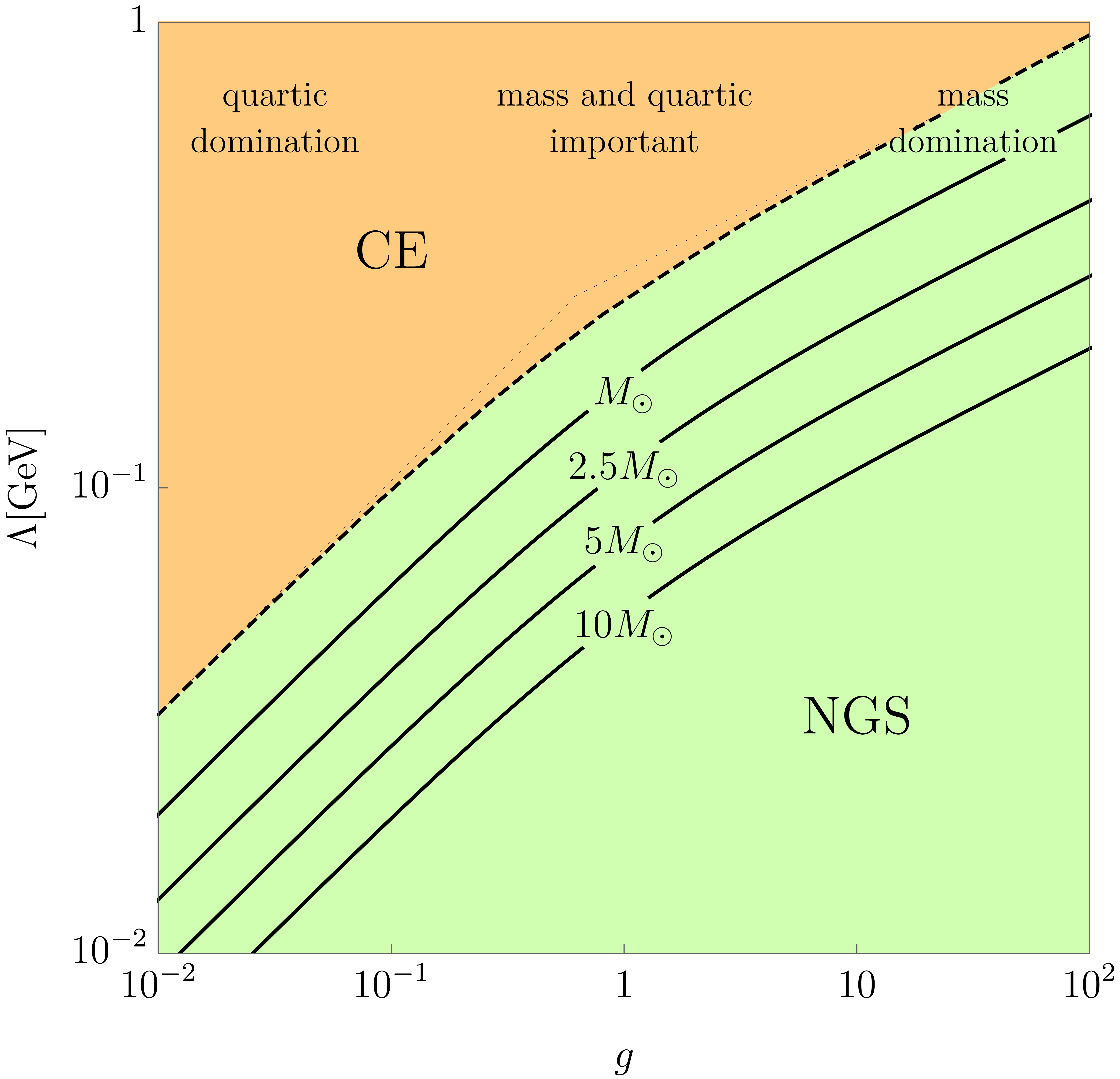
- At higher densities, mass contributes less to the total energy density

PRESSURE – ENERGY DENSITY

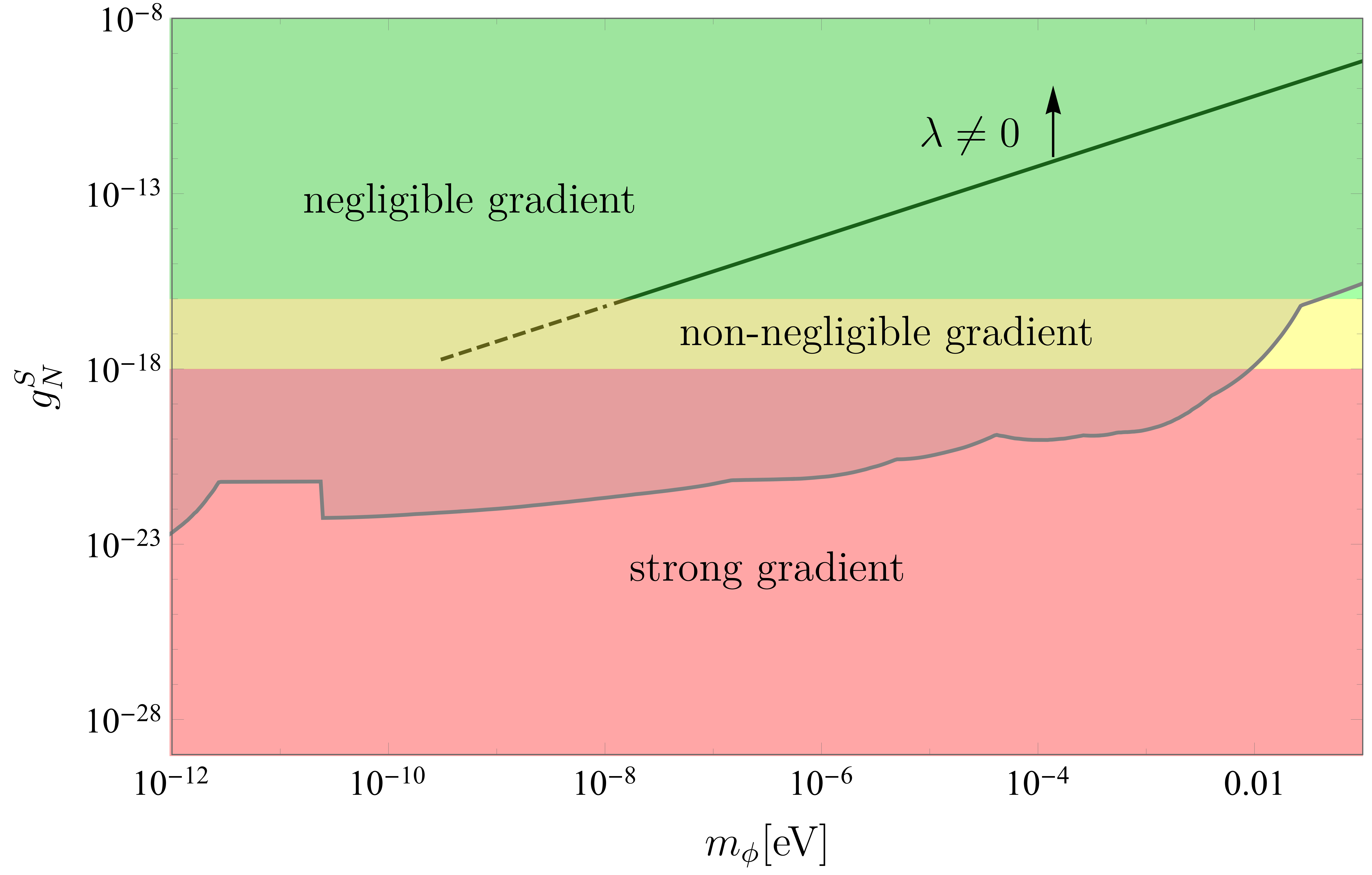
$$p = \rho^2 \frac{\partial(\varepsilon/\rho)}{\partial \rho}$$



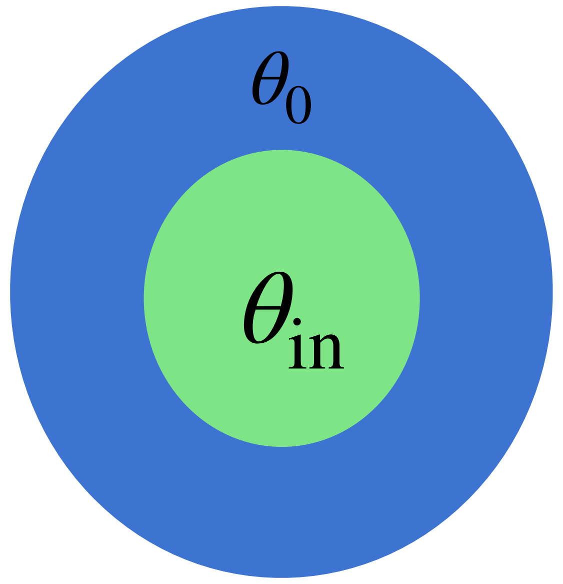
QUADRATIC COUPLING PARAMETER SPACE



LINEAR COUPLING PARAMETER SPACE



Coexistence Phase: MR Curve



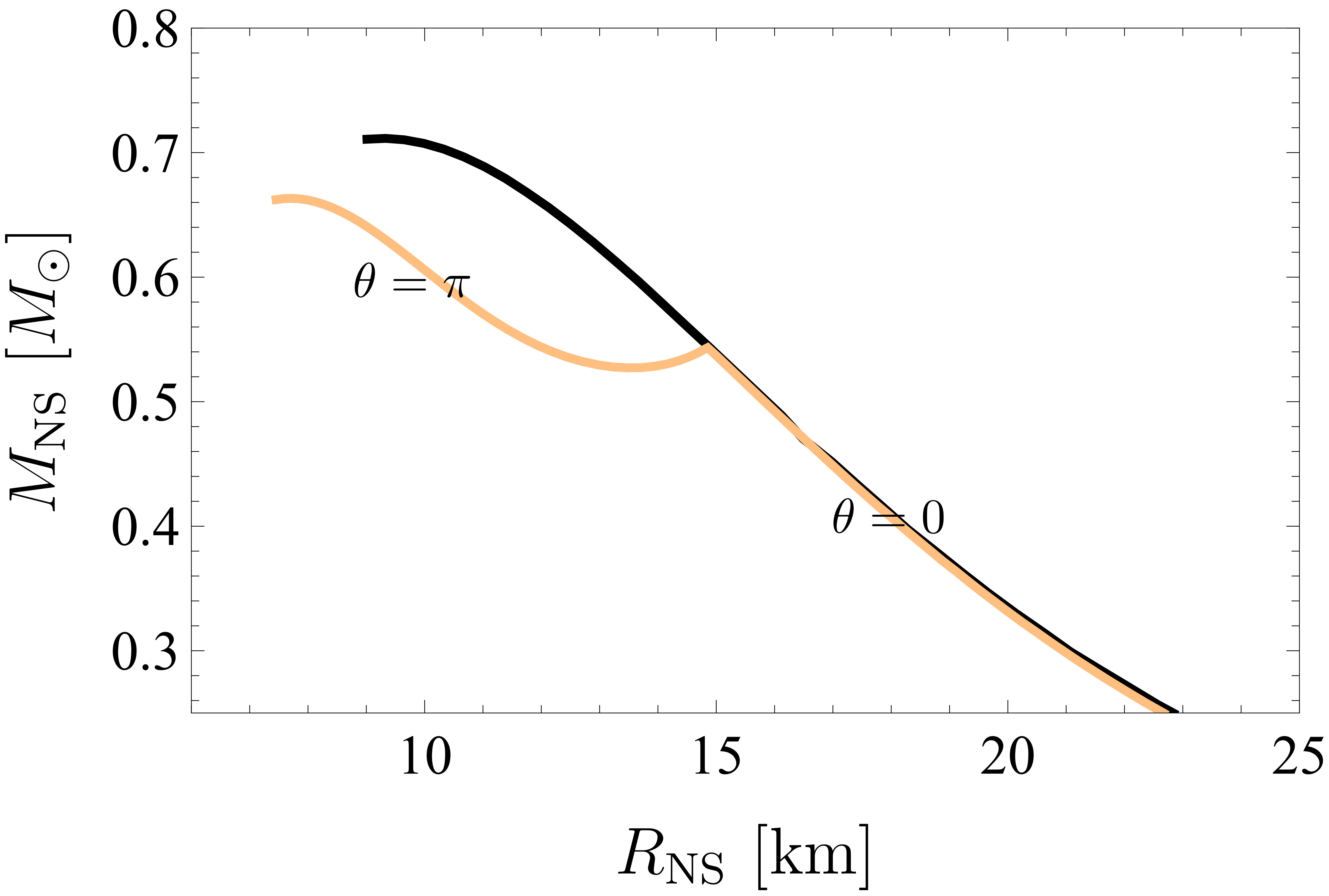
1st order phase transition:

- Generically softens EOSs

  e.g. Kaon condensation

- Clearly disfavoured

Gravitational wave signal?

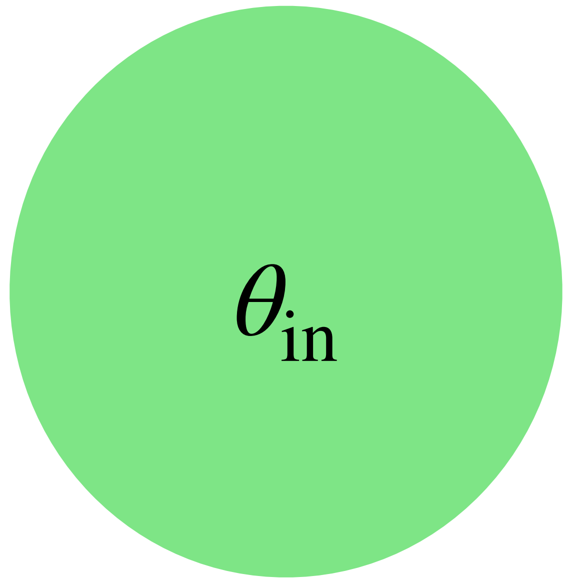


New Ground State Phase

New ground state

$\max[M_{\max}] \gg M_{\odot}$

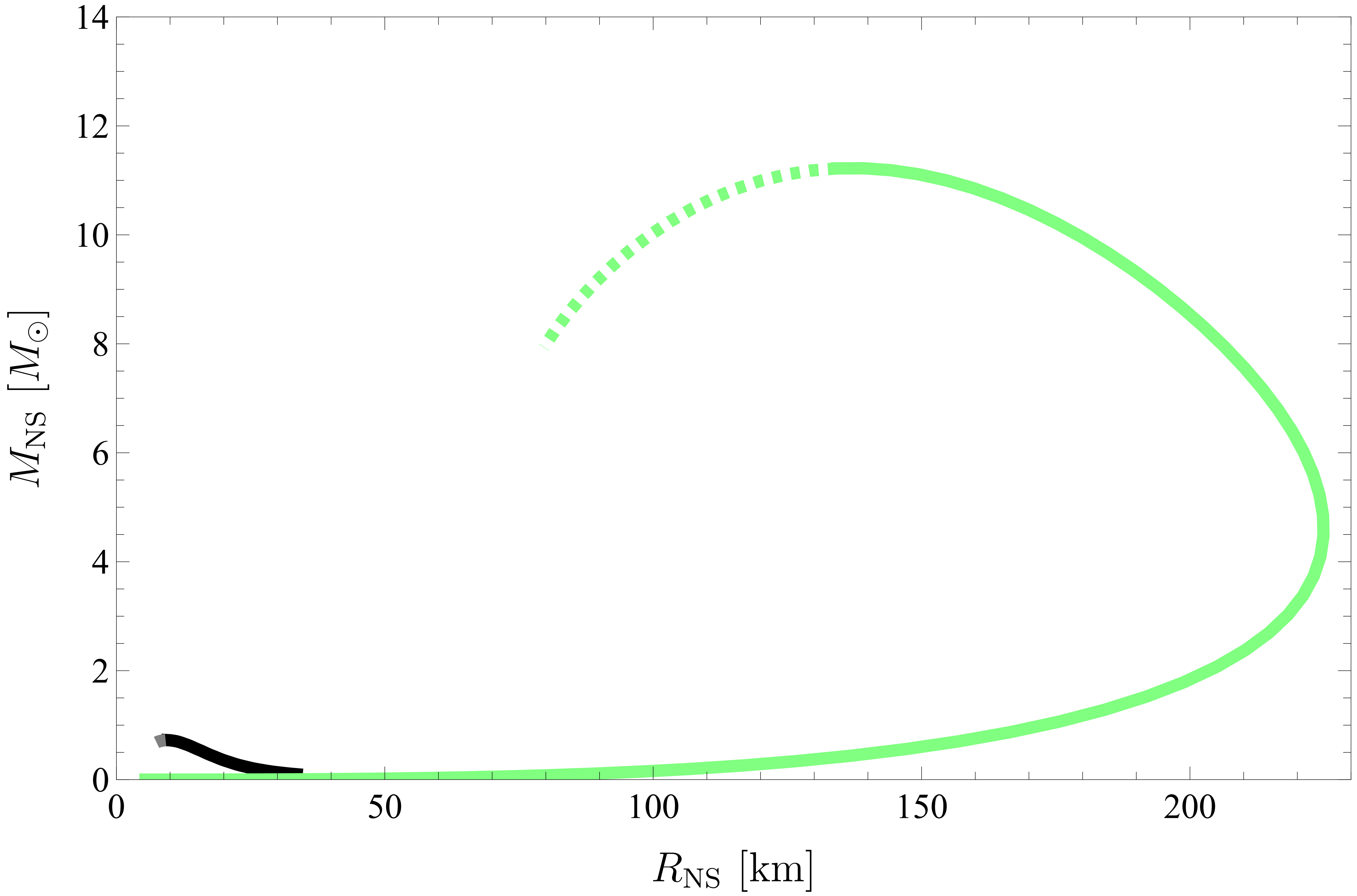
EOS (can be) stiffer!



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

This can be a large effect

$$M_{\max} \simeq 11.2 M_{\odot}$$
$$R_{\max} \simeq 160\,\mathrm{km}$$

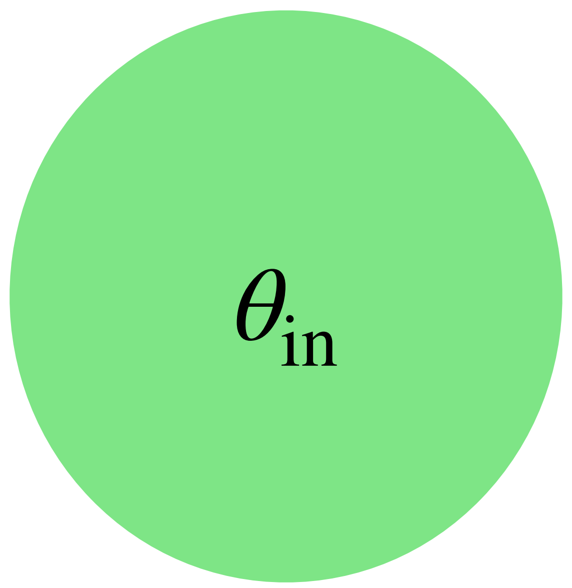


New Ground State Phase

New ground state

$\max[M_{\rm max}] \gg M_\odot$

EOS (can be) stiffer!



Also interesting on a log plot

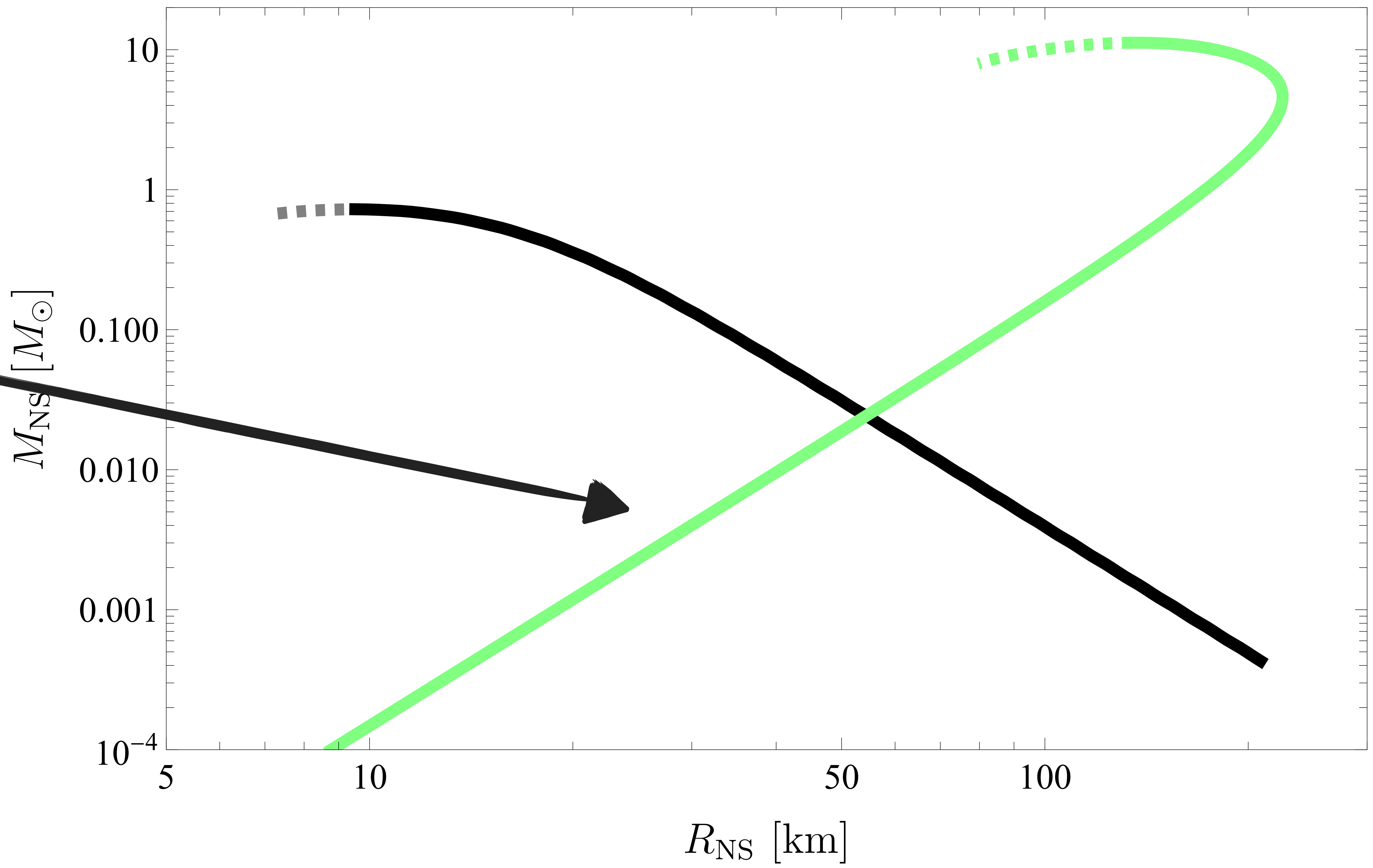
Self bound objects

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

Minimal size given by gradient

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

Field has to fit inside R^3

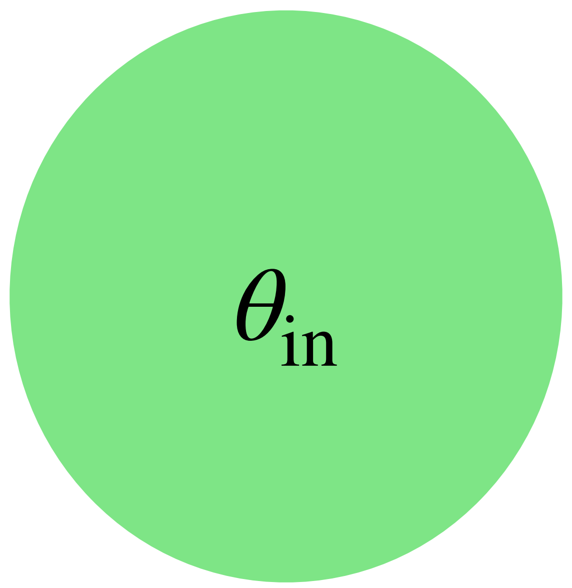


New Ground State Phase

New ground state

$\max[M_{\max}] \gg M_\odot$

EOS (can be) stiffer!



Also interesting on a log plot

Gravity becomes important

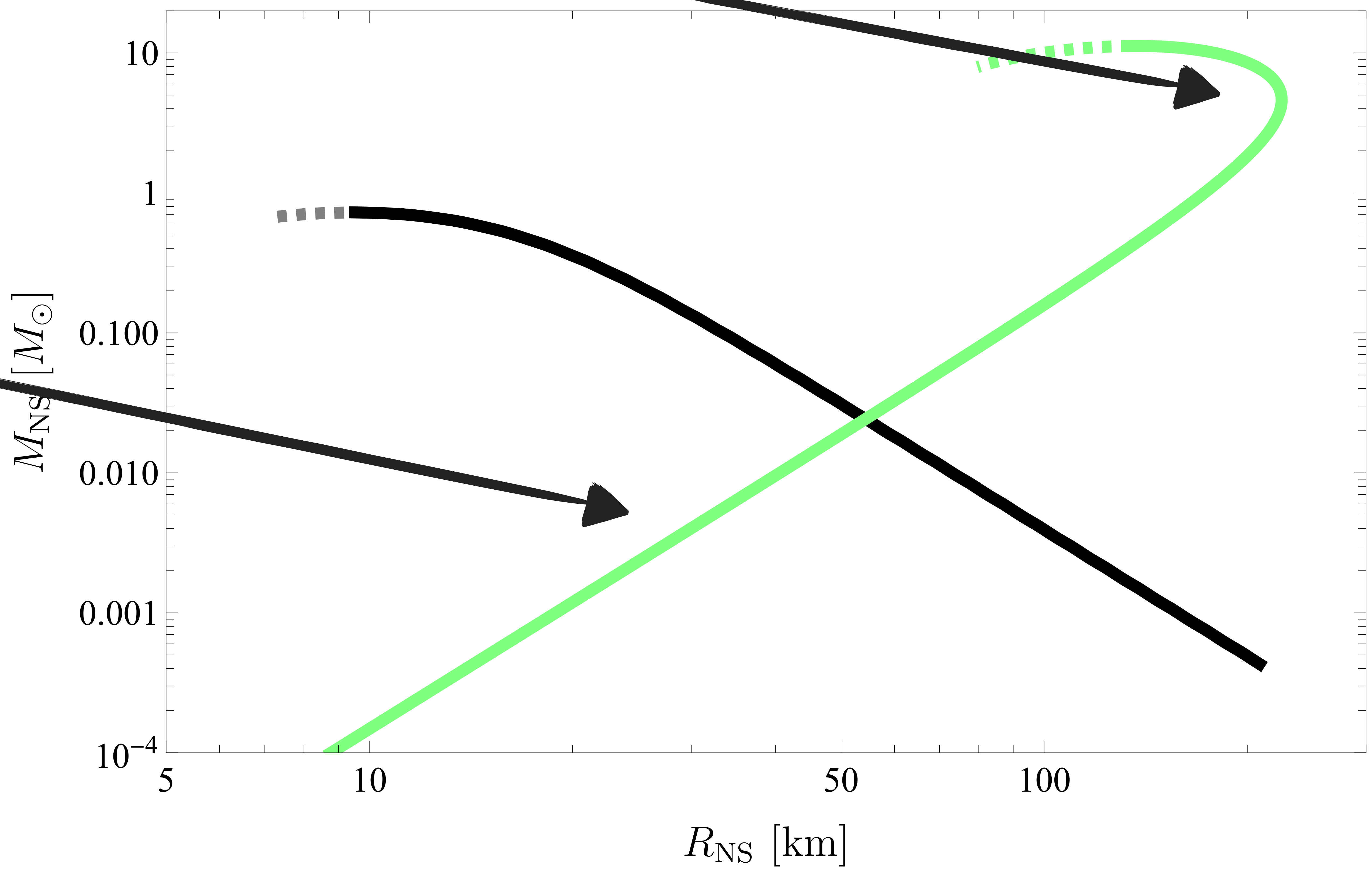
Self bound objects

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

Minimal size given by gradient

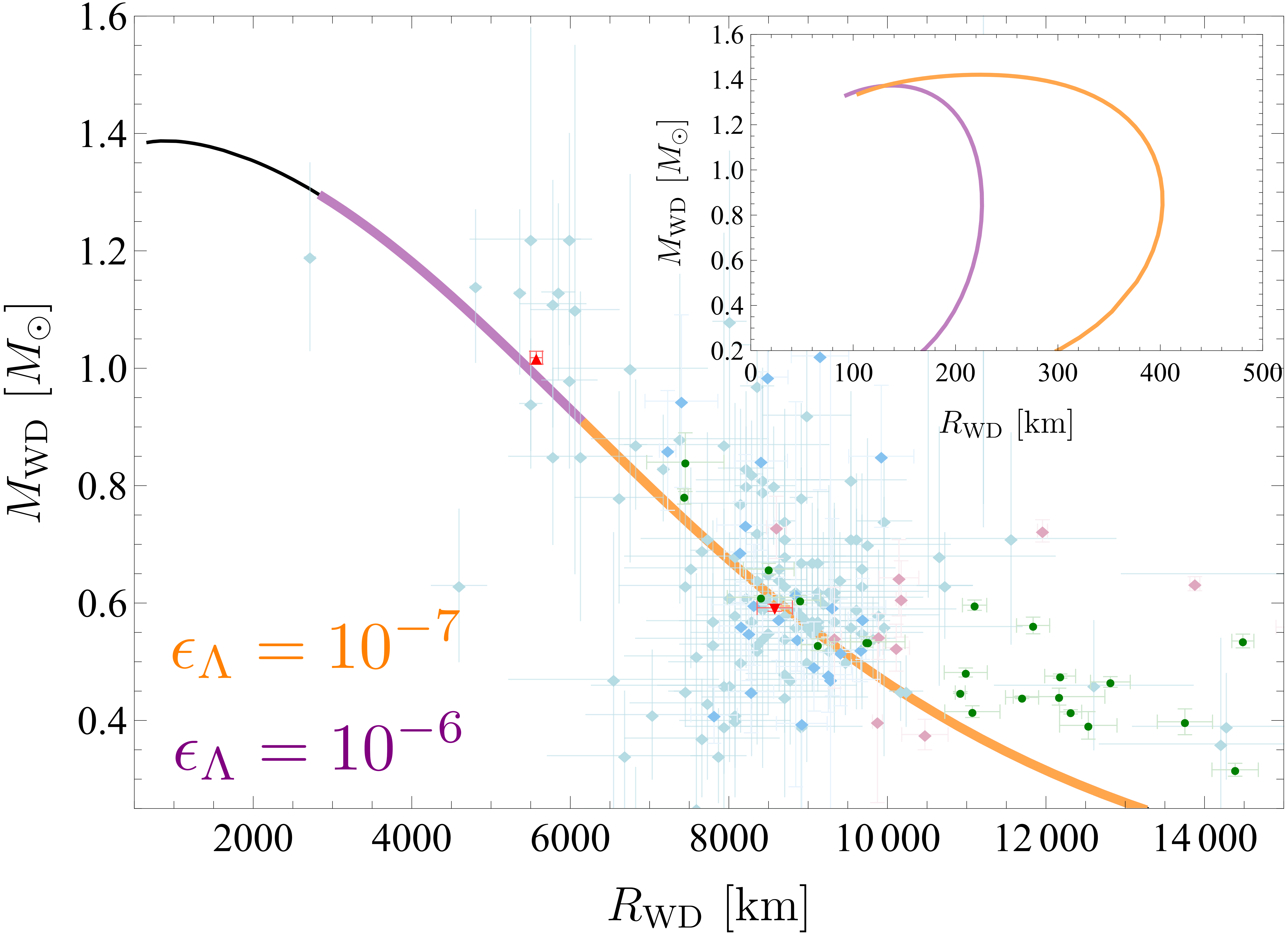
$$R_{\min} \simeq \frac{f}{\Lambda^2}$$

Field has to fit inside R^3



White Dwarfs with light Axion

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



White Dwarfs with light Axion

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

Negligible Gradient