The stellar graveyard as a BSM laboratory

IPPP Theory Christmas Meeting

Andreas Weiler (TUM)
14/12/22

https://github.com/Stability-AI/stablediffusion

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work in collaboration with:

Reuven Balkin (Technion), Javi Serra (IFT Madrid),
Stefan Stelzl (EPFL), and Konstantin Springmann (TUM)

Plan for the next 44 Minutes

- White dwarfs and neutron stars simplified
- What happens to the QCD axion inside them?
- Can we learn about BSM studying these dead stars?

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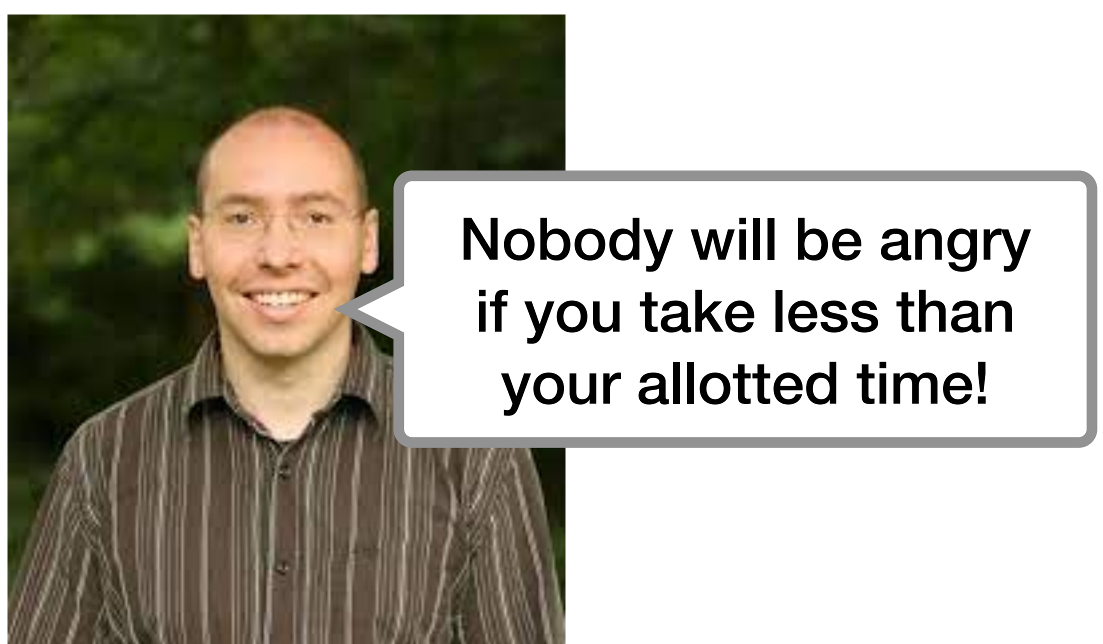
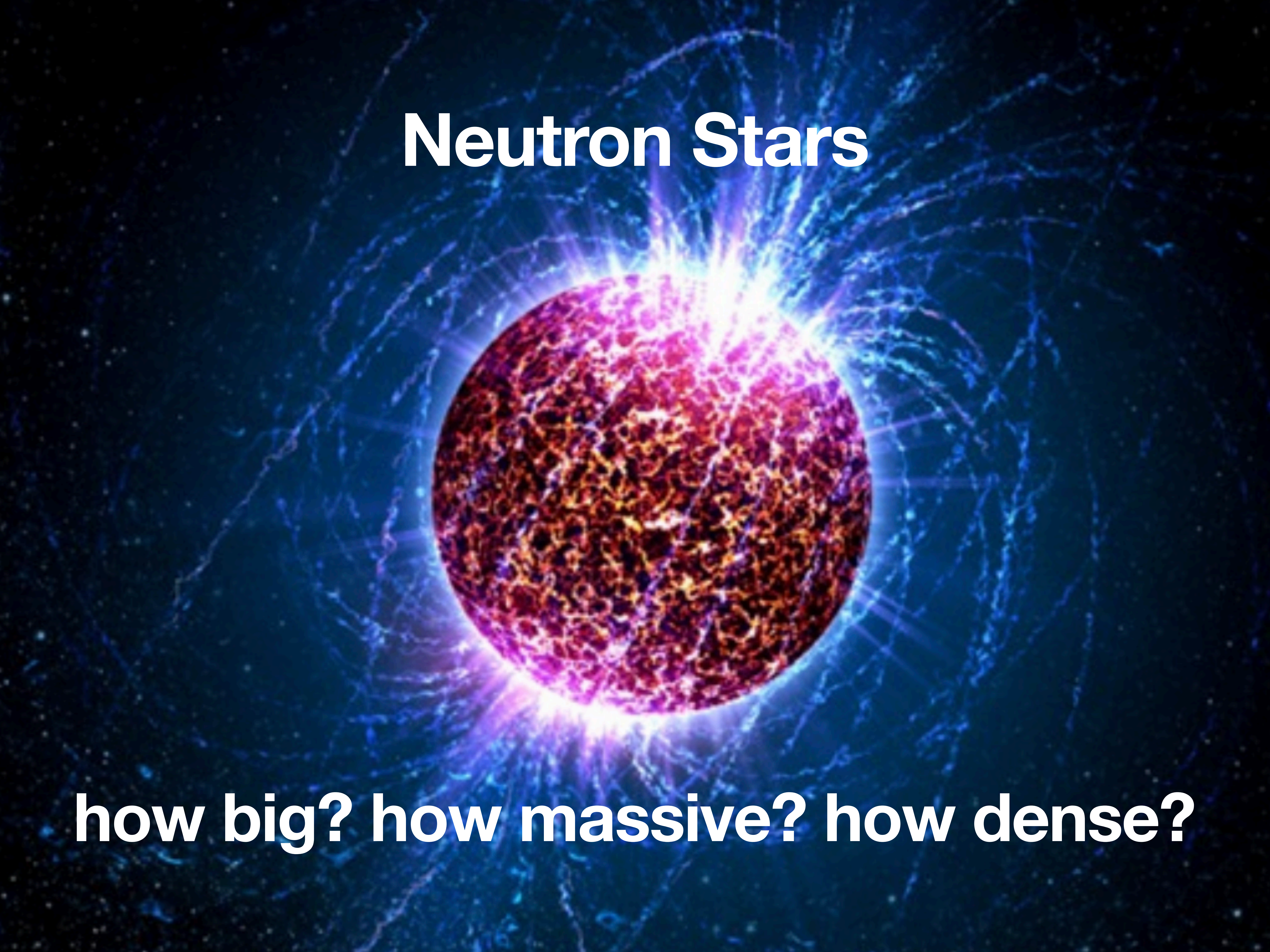


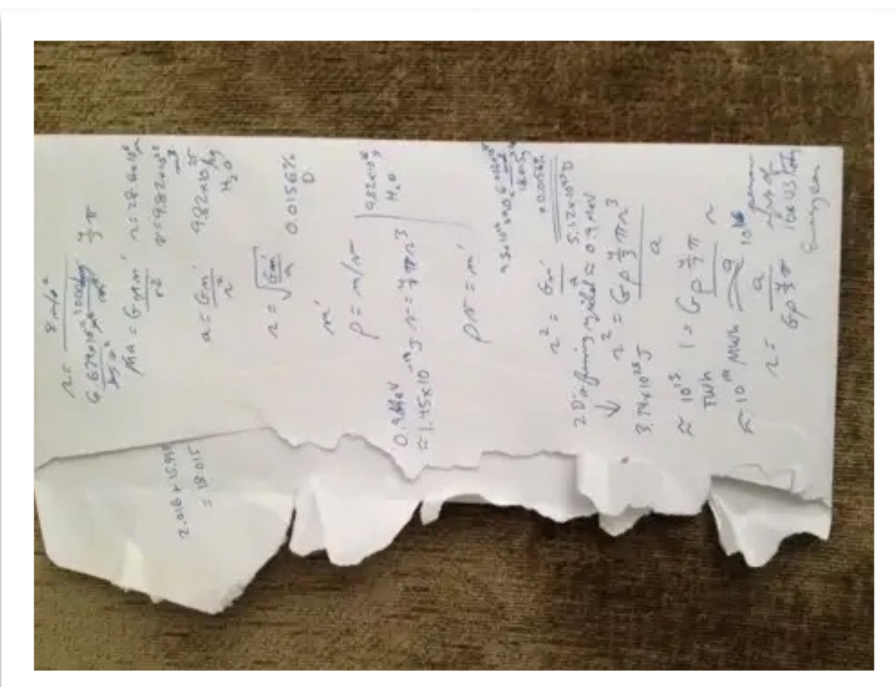
Neutron Stars



how big? how massive? how dense?

Back of the envelope …

… power of theory (laziness as a virtue)



vs.

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

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

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

Neutron stars simplified

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

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

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

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

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

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

Neutron star estimate

$$R_{\rm NS} \sim \frac{M_{\rm Planck}}{m_N^2} \qquad M_{\rm NS} \sim \frac{M_{\rm Planck}^3}{m_N^2}$$

$$R_{\rm NS} \sim ({\rm few})\ {\rm km} \qquad M_{\rm NS} \sim ({\rm few}) 10^{30}\,{\rm kg} \sim M_\odot$$

Mass of the sun within a few km!

Planck scale	$M_{\rm Planck} \approx 10^{19}\ {\rm GeV}$
nucleon mass	$M_N \approx 1\ {\rm GeV}$

Let’s compare to data

Jocelyn Bell Burnell

Neutron stars: mass vs. radius

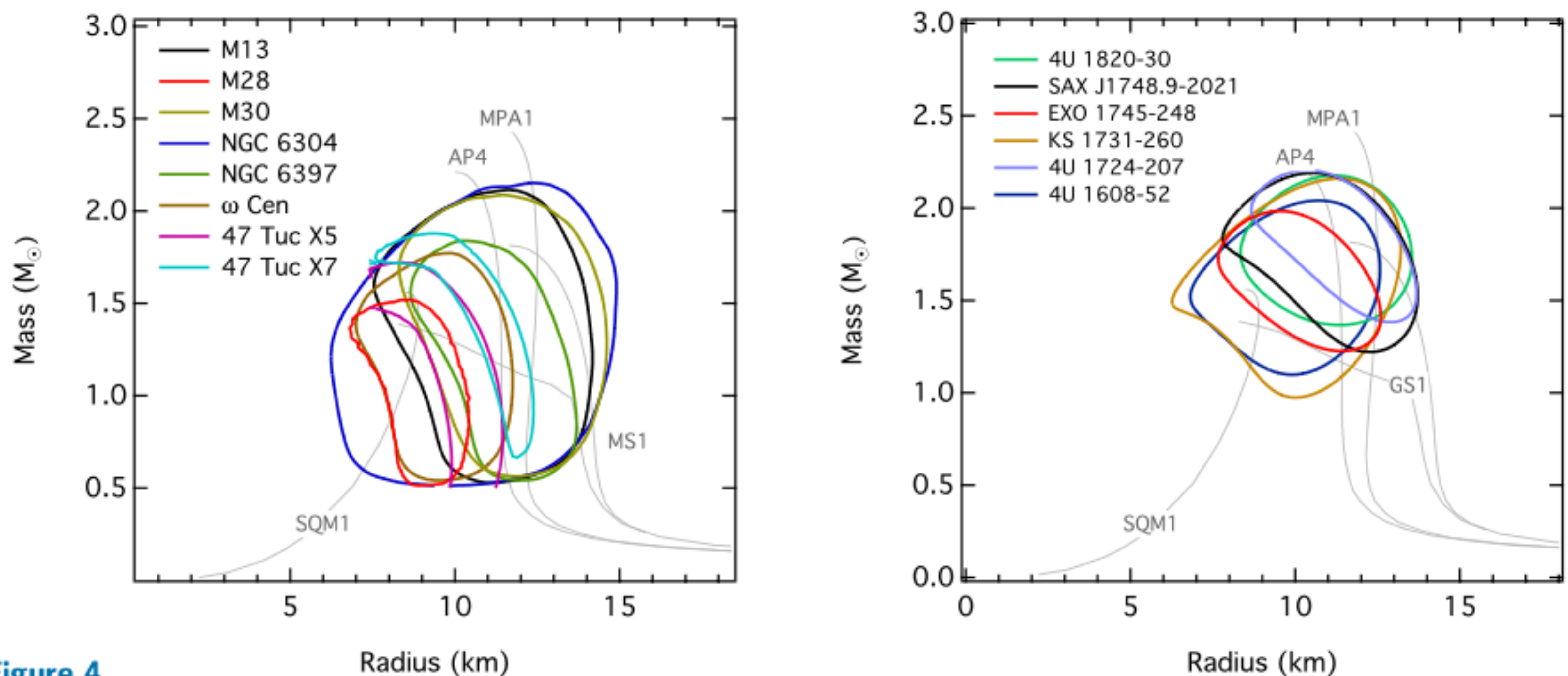

Figure 4

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.)

https://arxiv.org/abs/1603.02698v1

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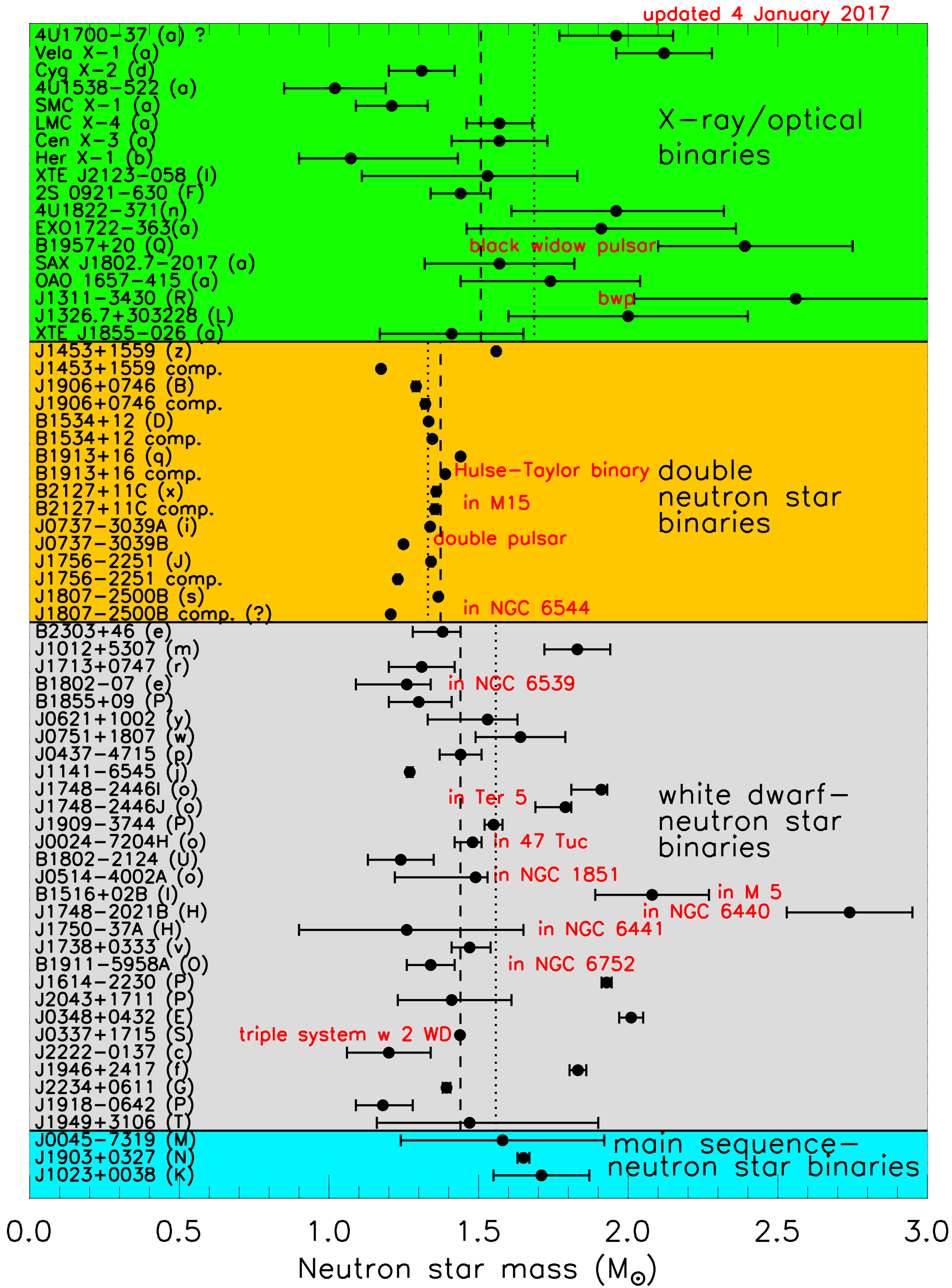
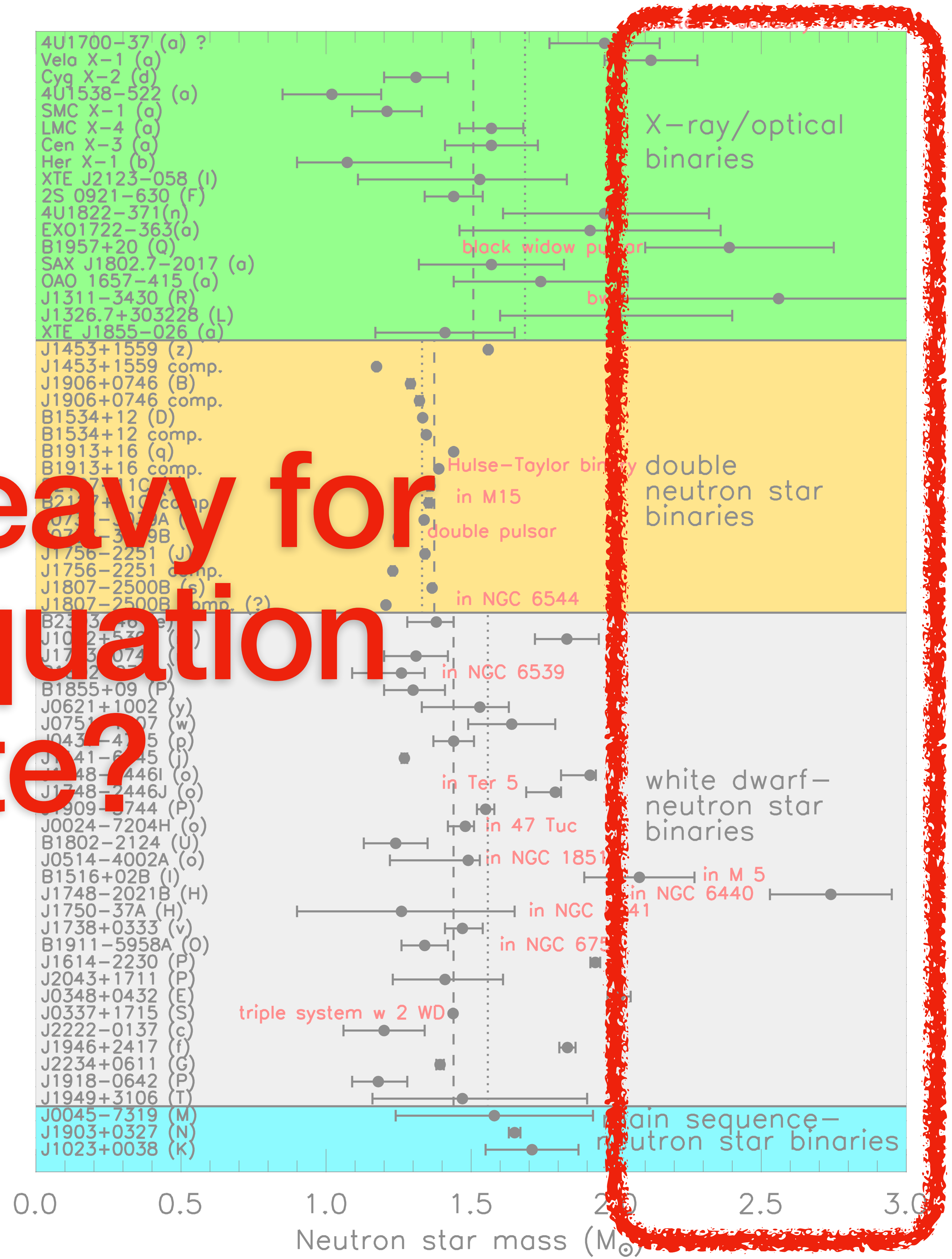
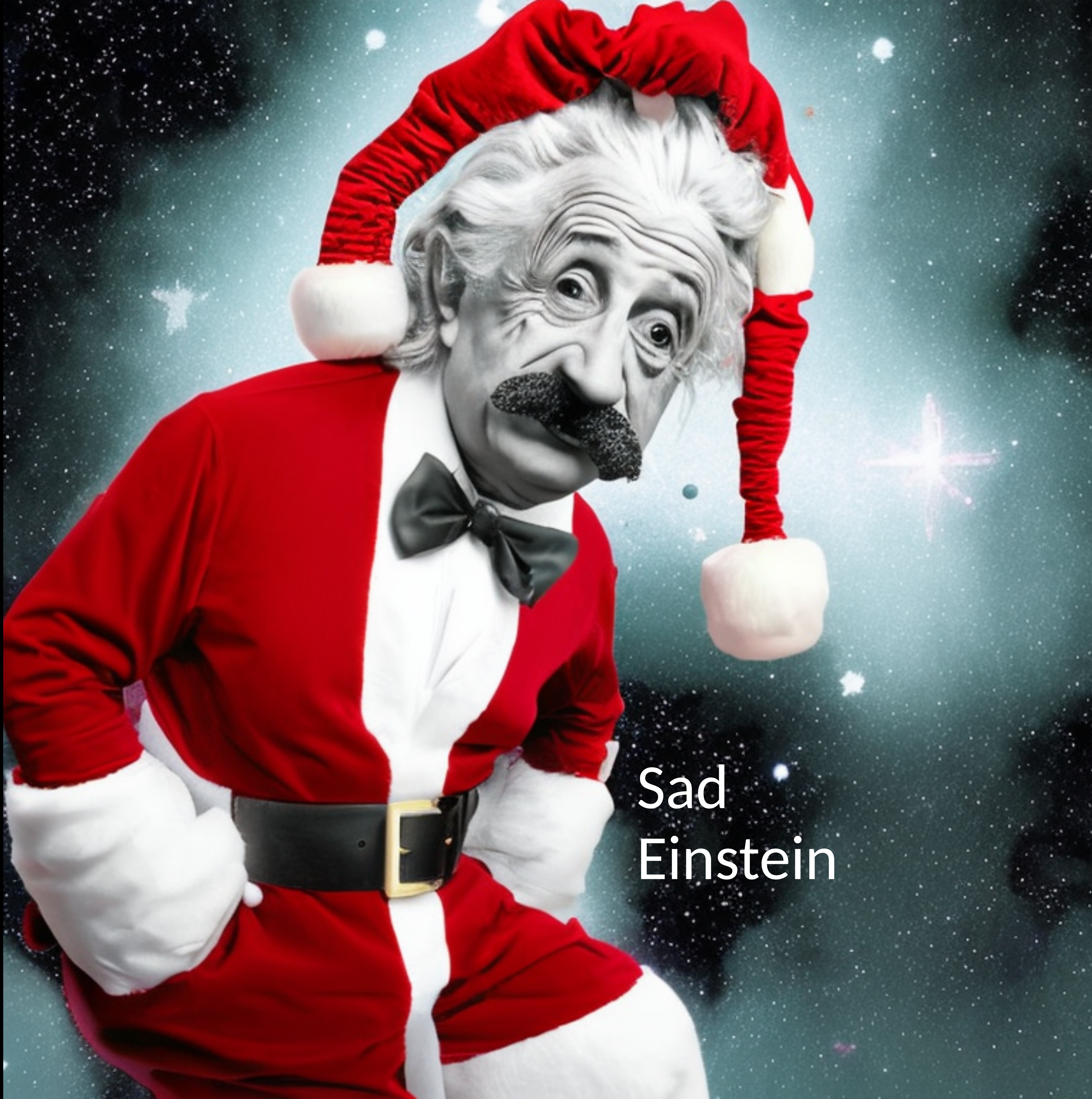

updated 4 January 2017
4U1700-37 (a) ?
Vela X-1 (a)
Cyg X-2 (d)
4U1538-522 (a)
SMC X-1 (a)
LMC X-4 (a)
Cen X-3 (a)
Her X-1 (b)
XTE J2123-058 (I)
2S 0921-630 (F)
4U1822-371(n)
EXO1722-363(a)
B1957+20 (Q)
SAX J1802.7-2017 (a)
OAO 1657-415 (a)
J1311-3430 (R)
J1326.7+303228 (L)
XTE J1855-026 (a)
black widow pulsar
bwp
X-ray/optical binaries
J1453+1559 (z)
J1453+1559 comp.
J1906+0746 (B)
J1906+0746 comp.
B1534+12 (D)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737-3039A (i)
J0737-3039B
J1756-2251 (J)
J1756-2251 comp.
J1807-2500B (s)
J1807-2500B comp. (?)
Hulse-Taylor binary
in M15
double pulsar
in NGC 6544
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802-07 (e)
B1855+09 (P)
J0621+1002 (y)
J0751+1807 (w)
J0437-4715 (p)
J1141-6545 (j)
J1748-2446I (o)
J1748-2446J (o)
J1909-3744 (P)
J0024-7204H (o)
B1802-2124 (U)
J0514-4002A (o)
B1516+02B (I)
J1748-2021B (H)
J1750-37A (H)
J1738+0333 (v)
B1911-5958A (O)
J1614-2230 (P)
J2043+1711 (P)
J0348+0432 (E)
J0337+1715 (S)
J2222-0137 (c)
J1946+2417 (f)
J2234+0611 (G)
J1918-0642 (P)
J1949+3106 (T)
in NGC 6539
in Ter 5
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
triple system w 2 WD
white dwarf-neutron star binaries
J0045-7319 (M)
J1903+0327 (N)
J1023+0038 (K)
main sequence-neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)



Too heavy for SM equation of state?



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White Dwarfs:

Fermi pressure from electron gas

White dwarfs simplified

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

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

(electron mass)

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

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

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

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

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

White dwarf estimate

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

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

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

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

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

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

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

White dwarf estimate

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$$M_{\rm WD} \sim \frac{M^3_{\rm planck}}{m_N^2} \sim M_{\rm NS}$$

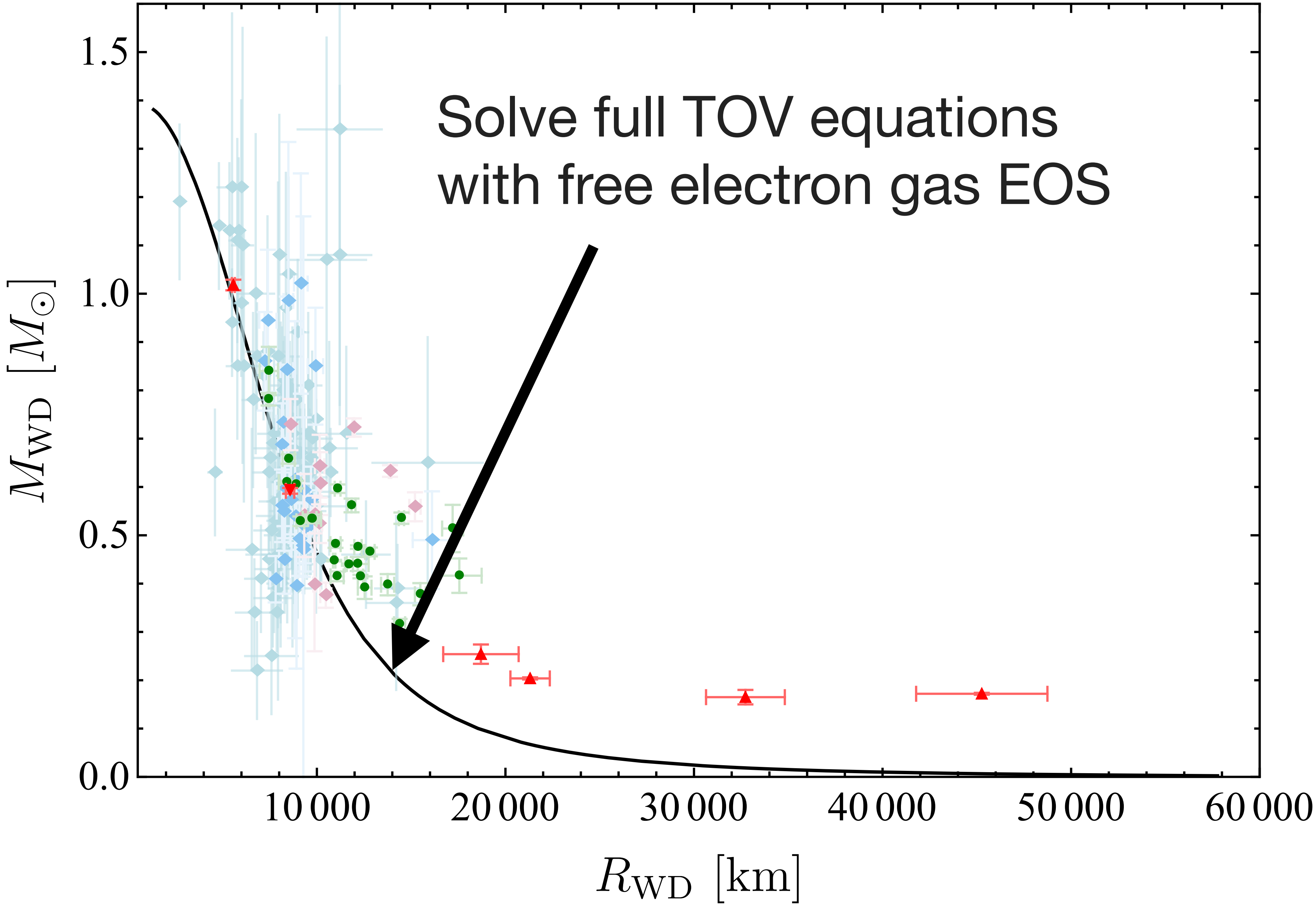
$$M_{\rm WD} \sim ({\rm few}) 10^{30}\,{\rm kg} \sim M_\odot$$

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

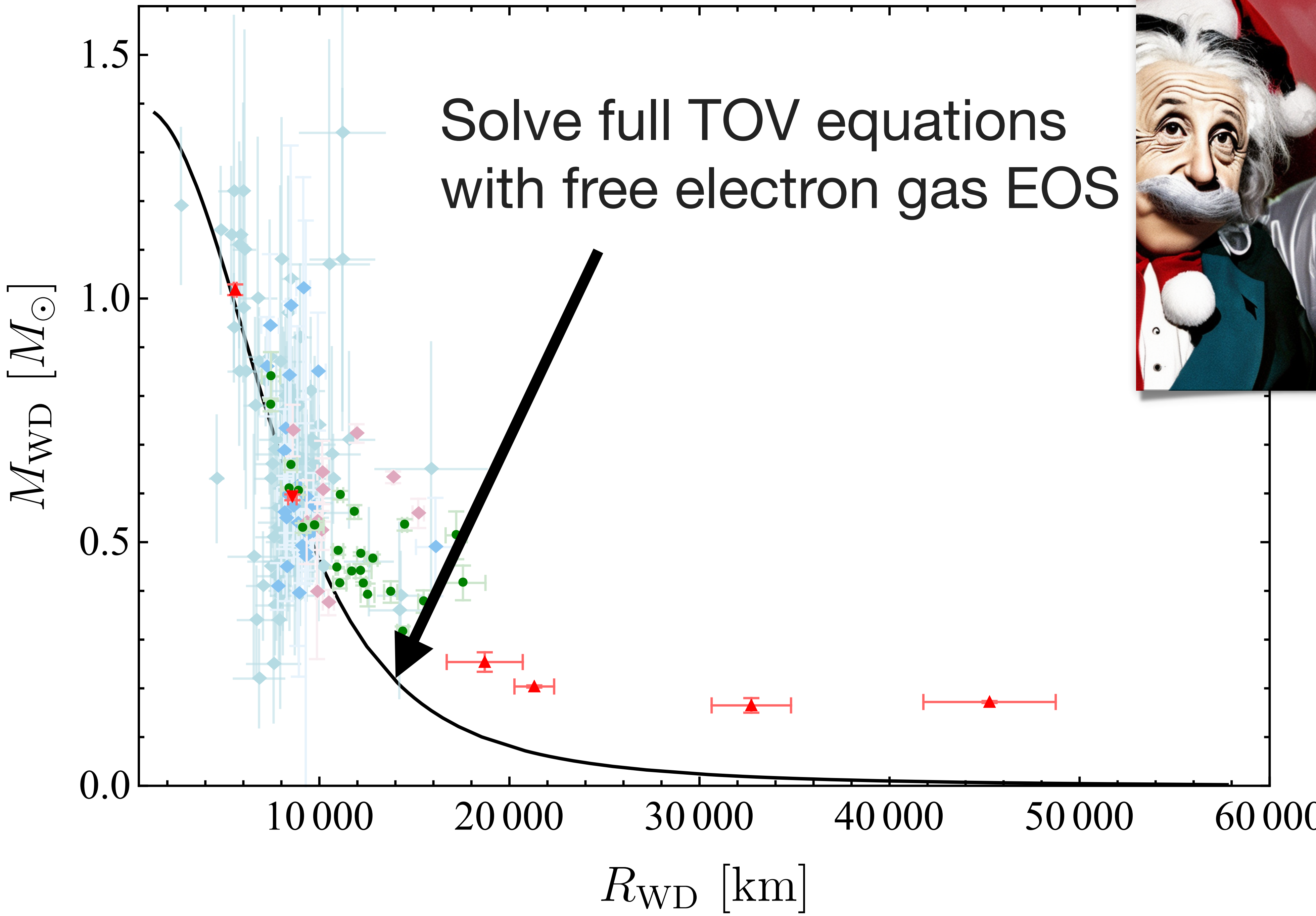
Mass of the sun at the size of the earth!

electron mass	$m_e = 0.51099895000(15)$ MeV
Planck scale	$M_{\rm Planck} \approx 10^{19}$ GeV
nucleon mass	$M_N \approx 1$ GeV

White dwarf mass-radius curve



White dwarf mass-radius curve



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

(and other light scalars)

QCD axion: motivated by the strong CP problem

CP violation in the strong sector

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

Predicts a neutron EDM:

QCD axion: motivated by the strong CP problem

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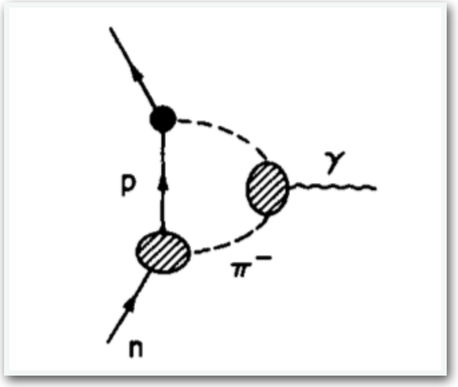

Predicts a neutron EDM: $\mathcal{L}_\chi \supset d_n \bar{n}\sigma^{\mu\nu}\gamma_5 n F_{\mu\nu}$

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

QCD axion: motivated by the strong CP problem

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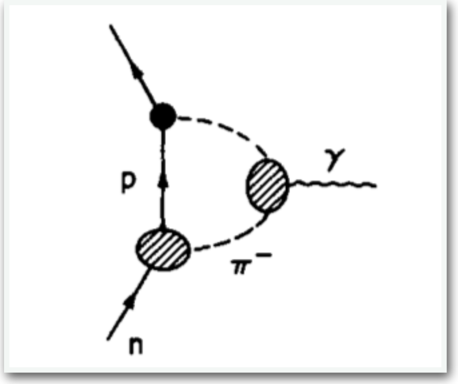

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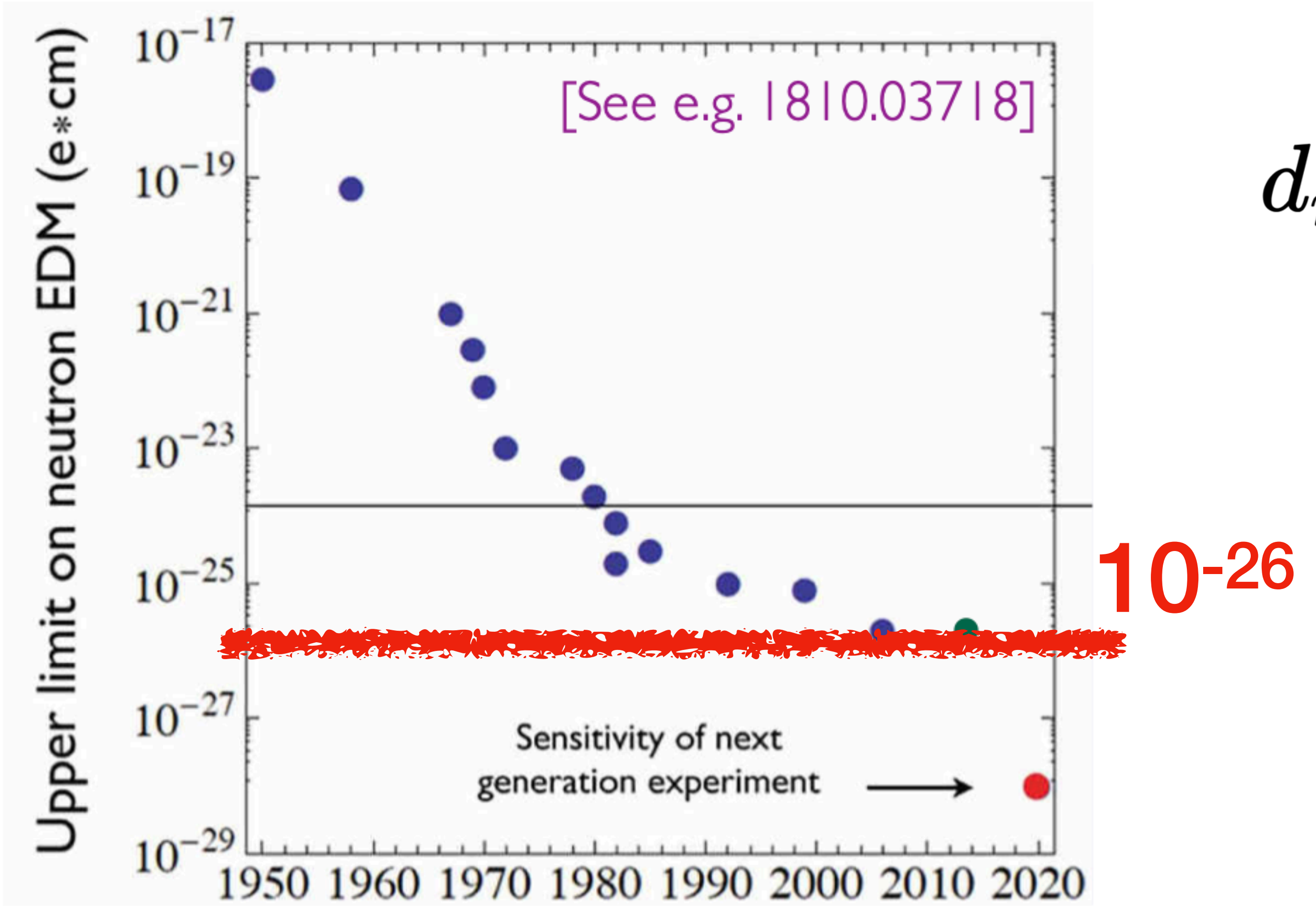


$$d_n \approx \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \approx 10^{-16}|\bar{\theta}|e\ \mathrm{cm}$$

Why so small ?

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

Axion Solution

Roberto Peccei

Helen Quinn

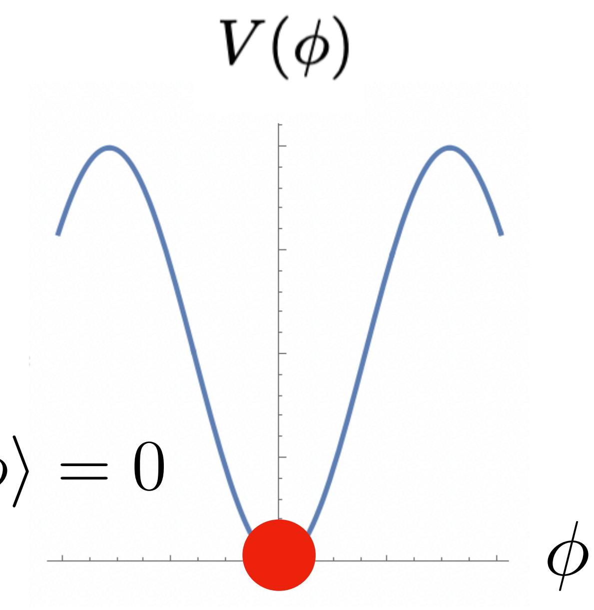
- PQ symmetry $U(1)_{\text{PQ}}$: spontaneously broken at scale ~ f_a
- explicitly broken at the quantum level by a mixed QCD anomaly
- pseudo-Nambu-Goldstone boson (pNG) arises: the QCD axion $\phi(x)$

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

- non-perturbative axion potential: axion relaxes to CP-conserving minimum

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

QCD Axions



The QCD axion potential at low energy

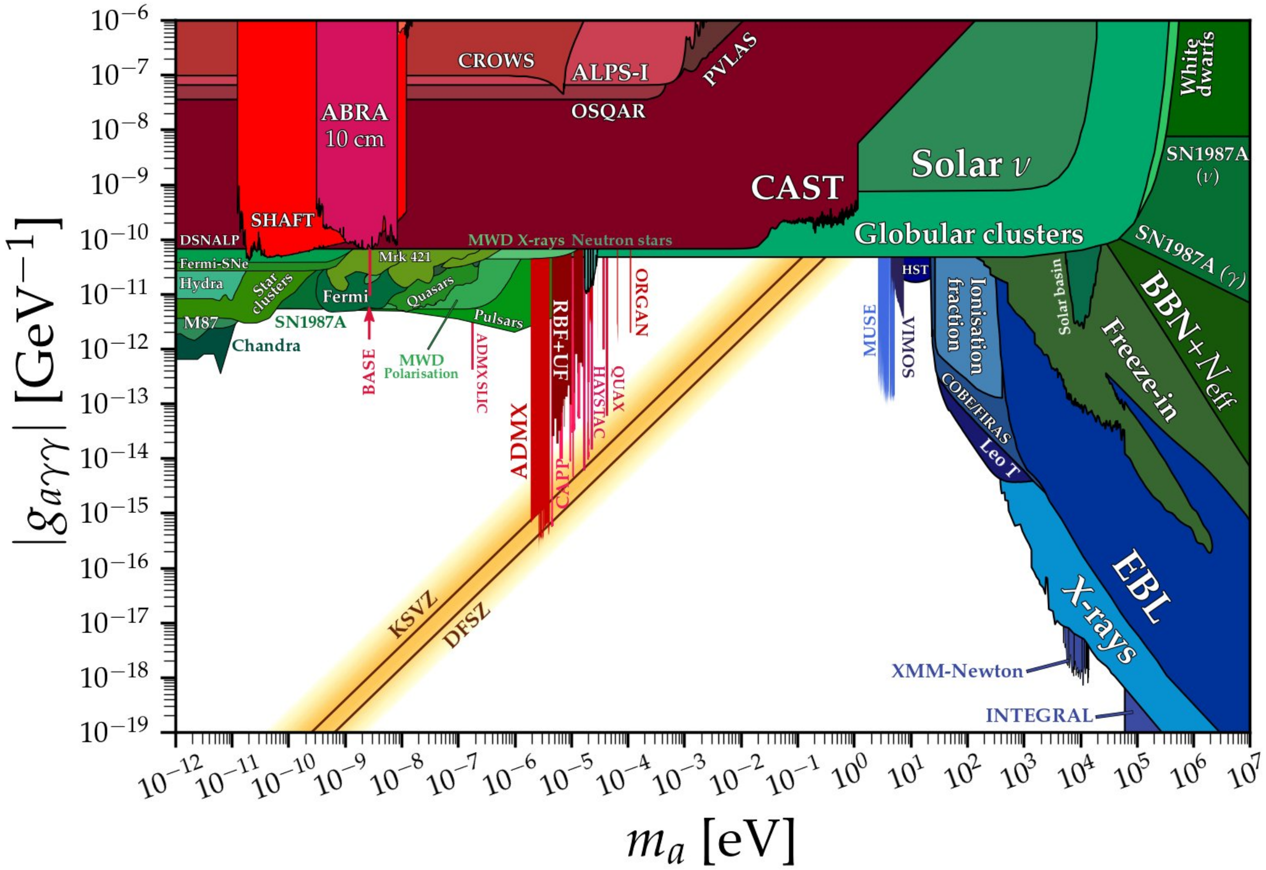
UV → IR

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

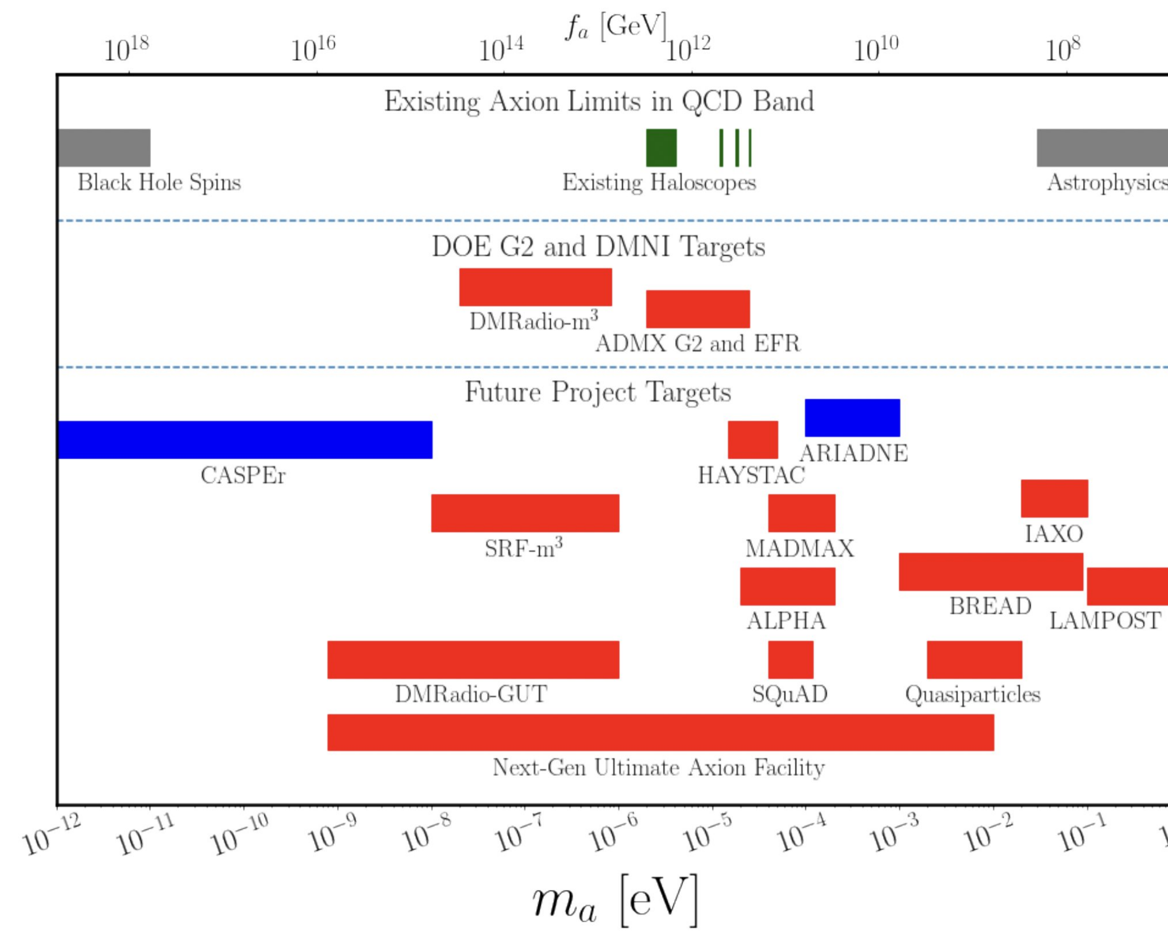
The QCD axion is very predictive:

couplings to photons, nucleons, electrons determined by scale **f**

Axion: plethora of new searches

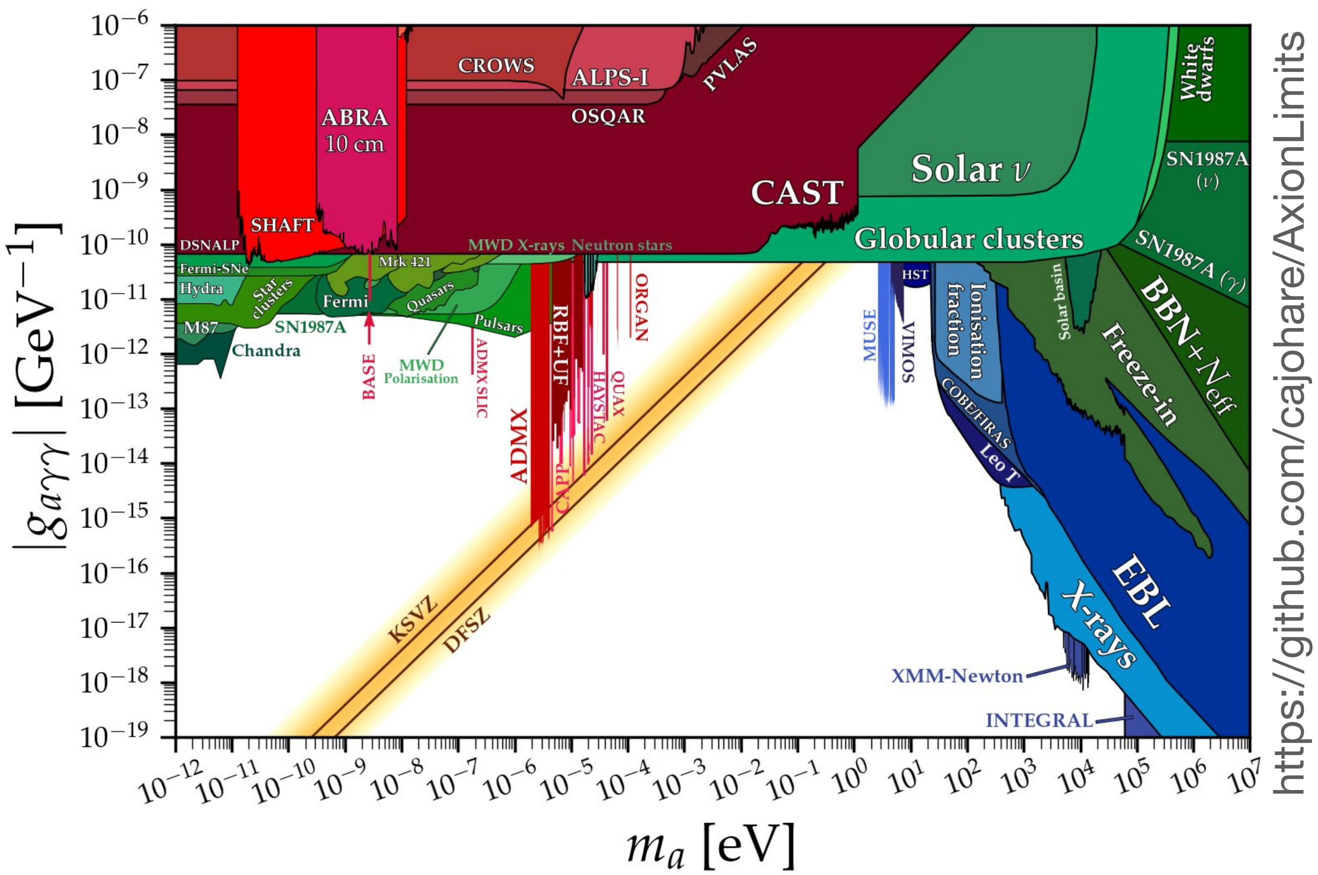


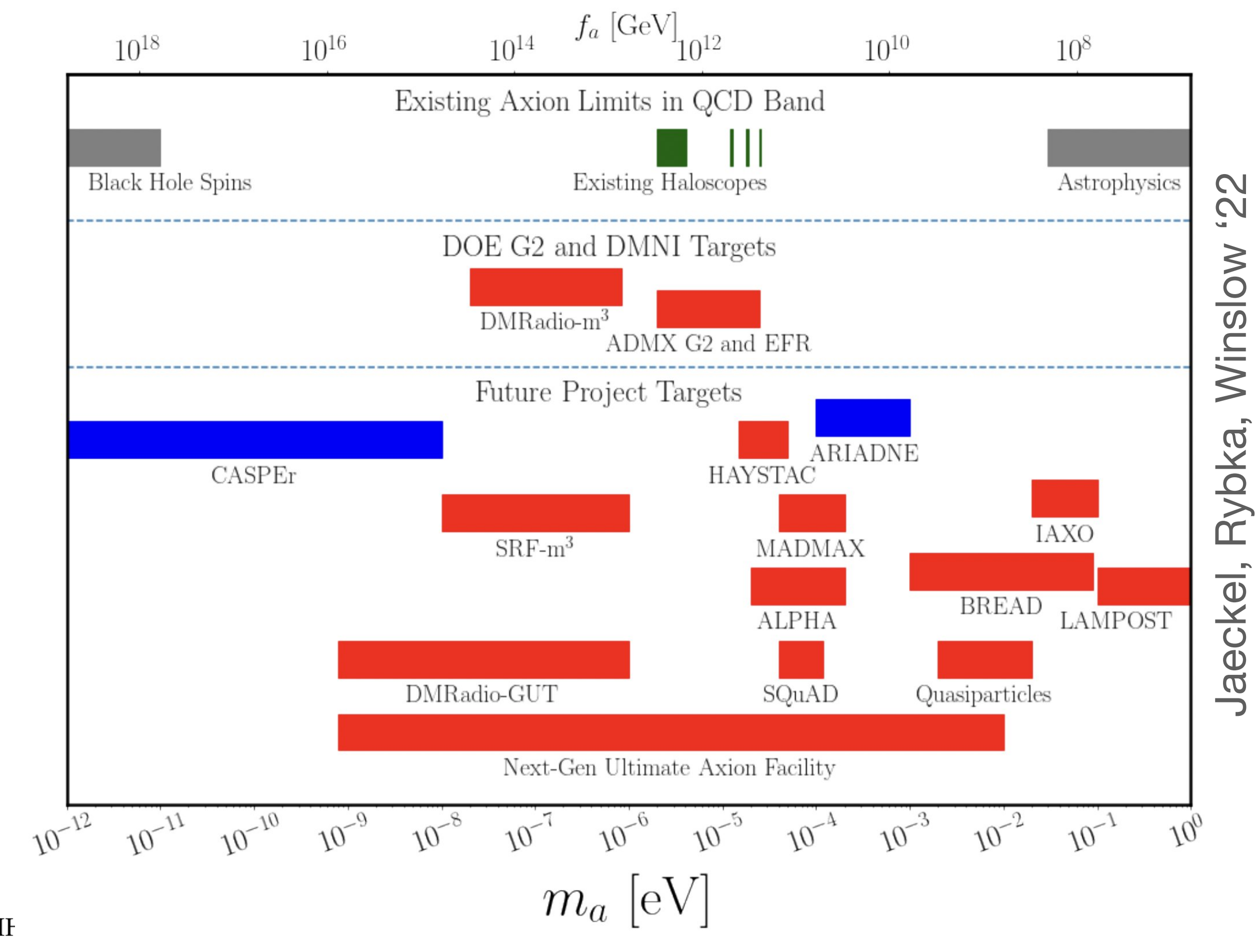
https://github.com/cajohare/AxionLimits

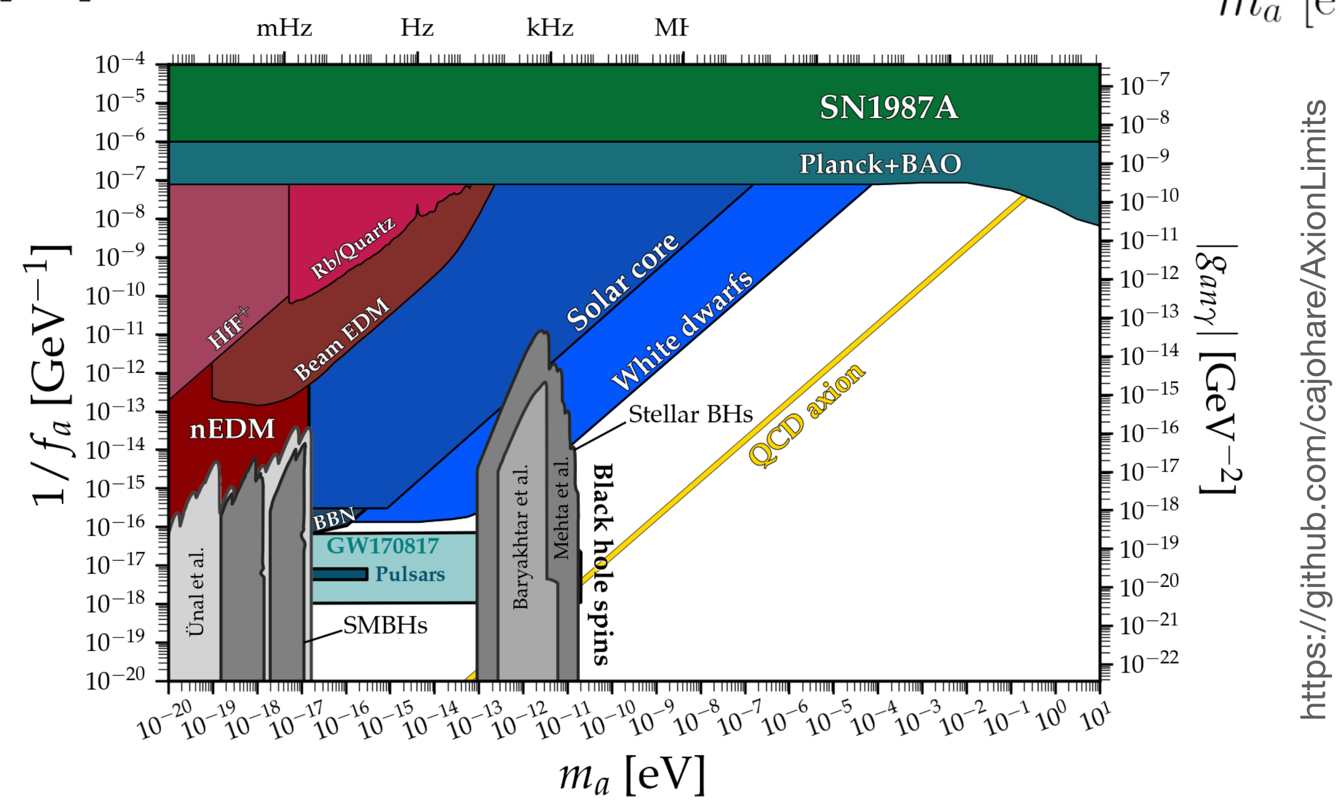


Jaeckel, Rybka, Winslow '22

Axion: plethora of new searches







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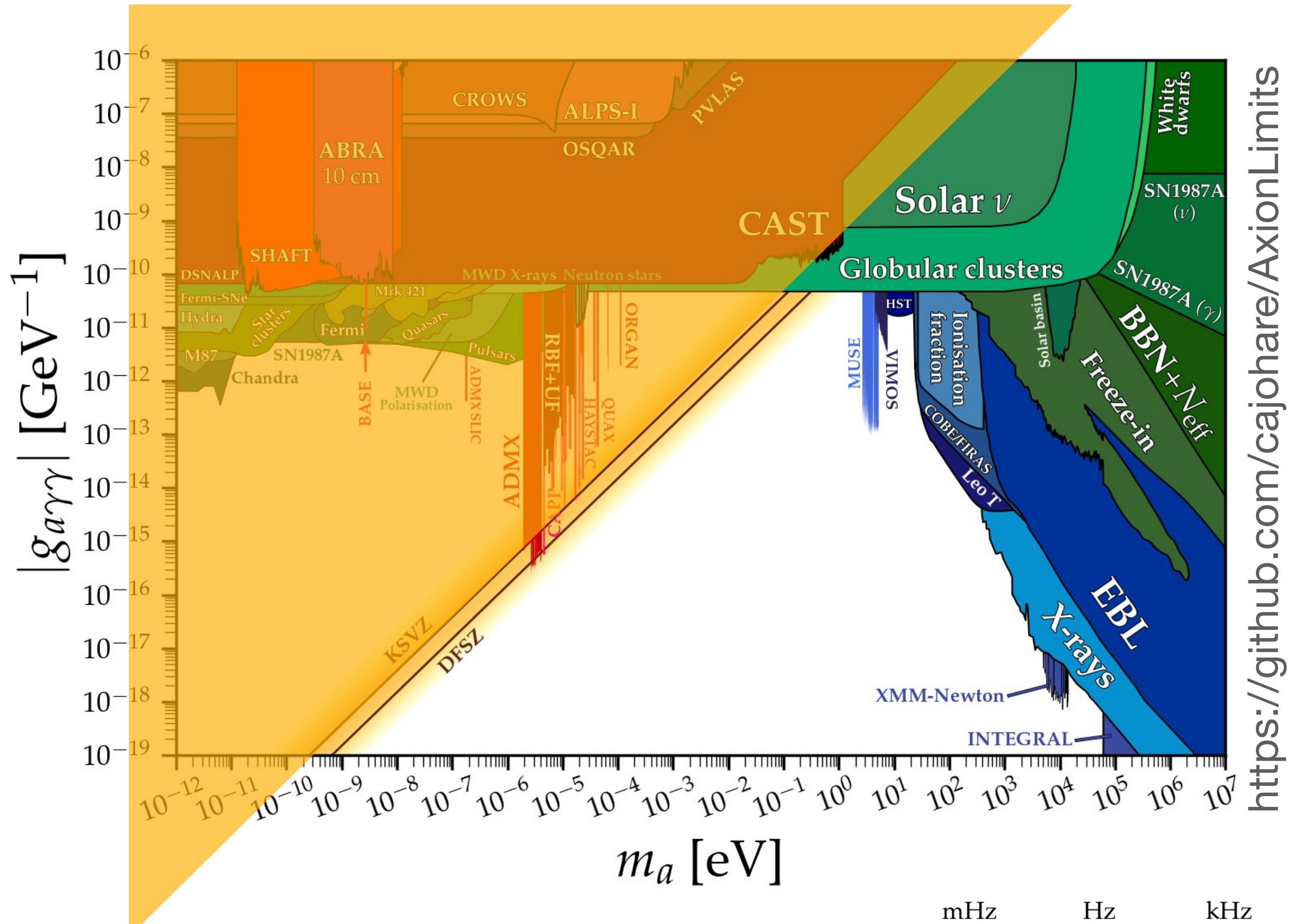
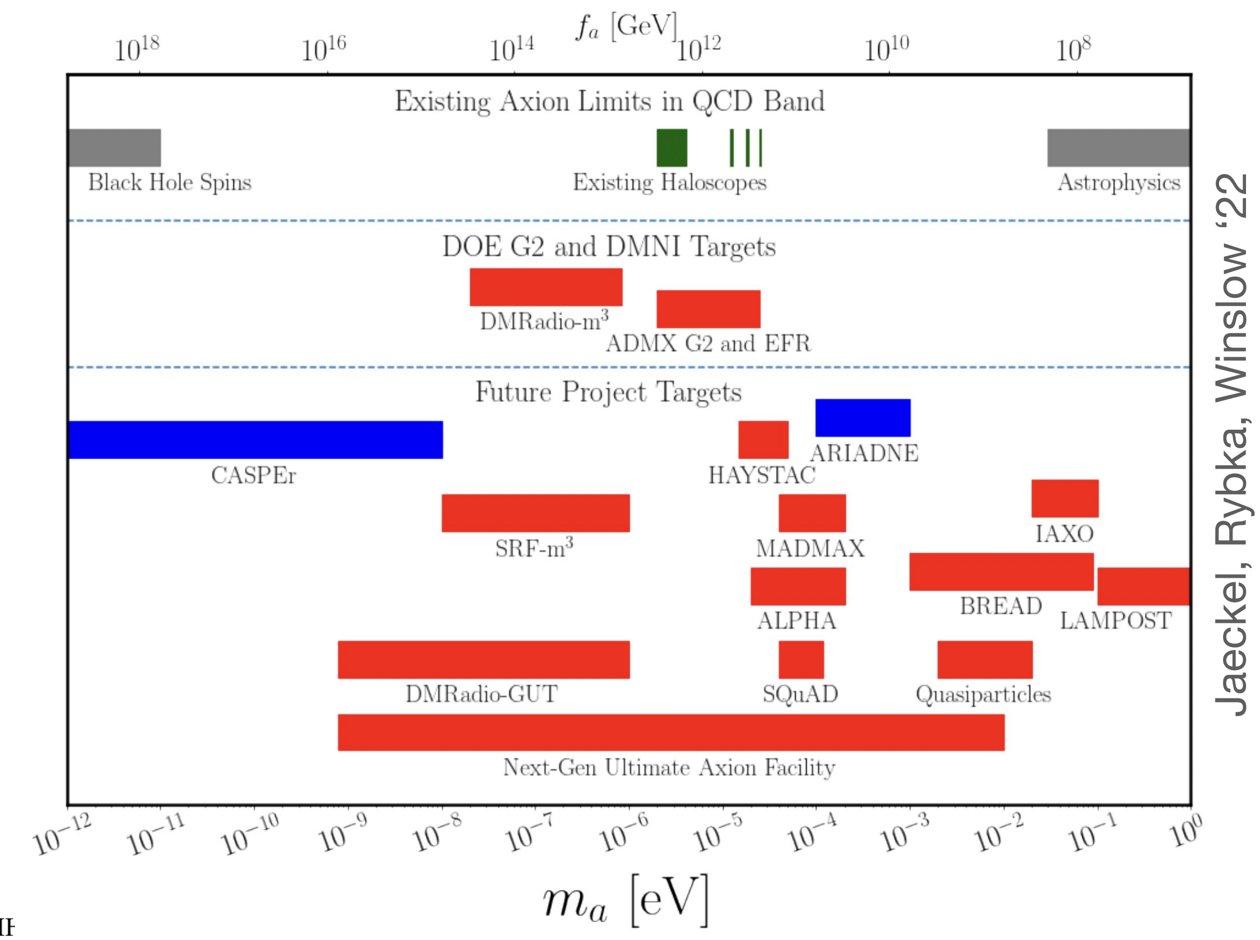
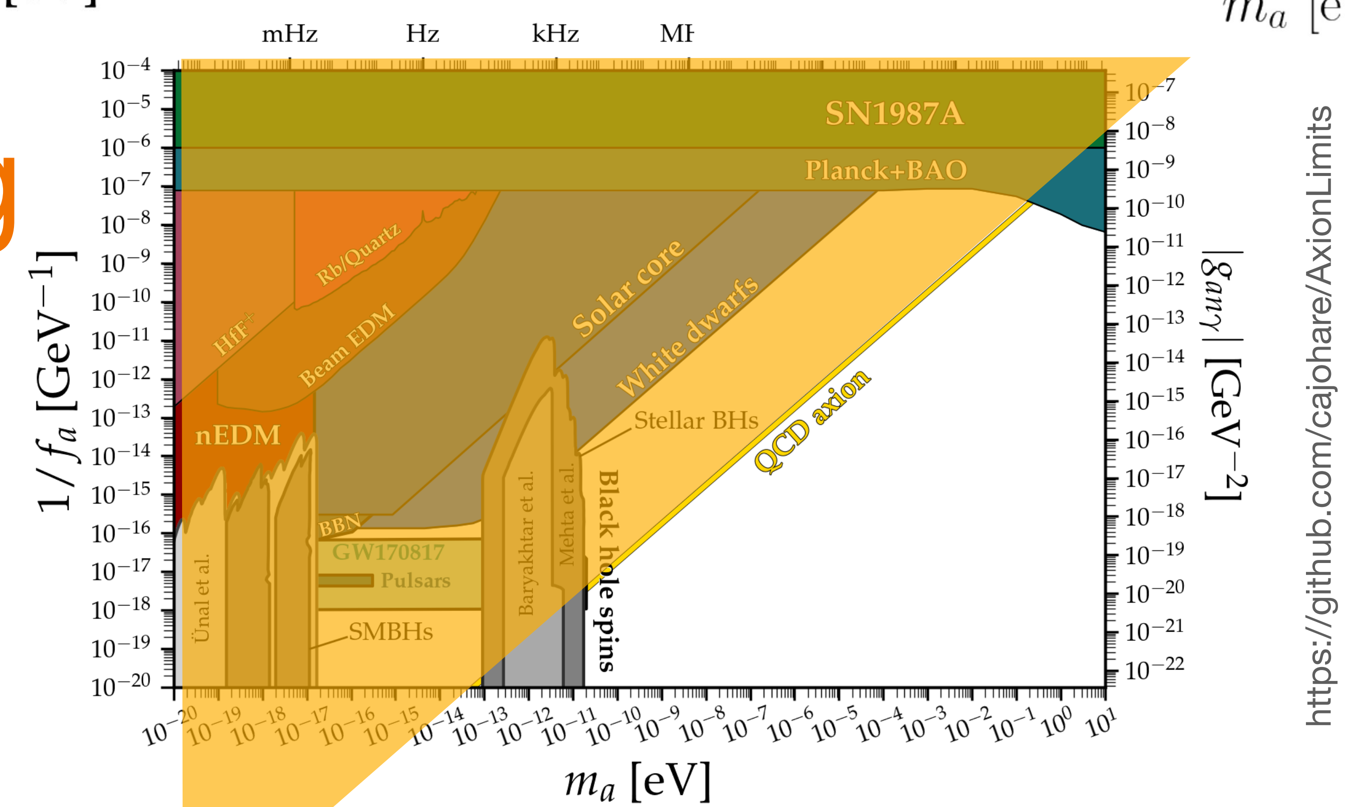


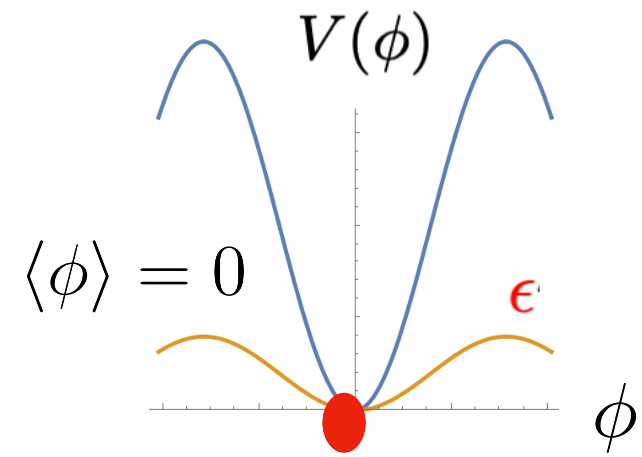


Interesting region



Light QCD Axions

The QCD axion potential at low energy

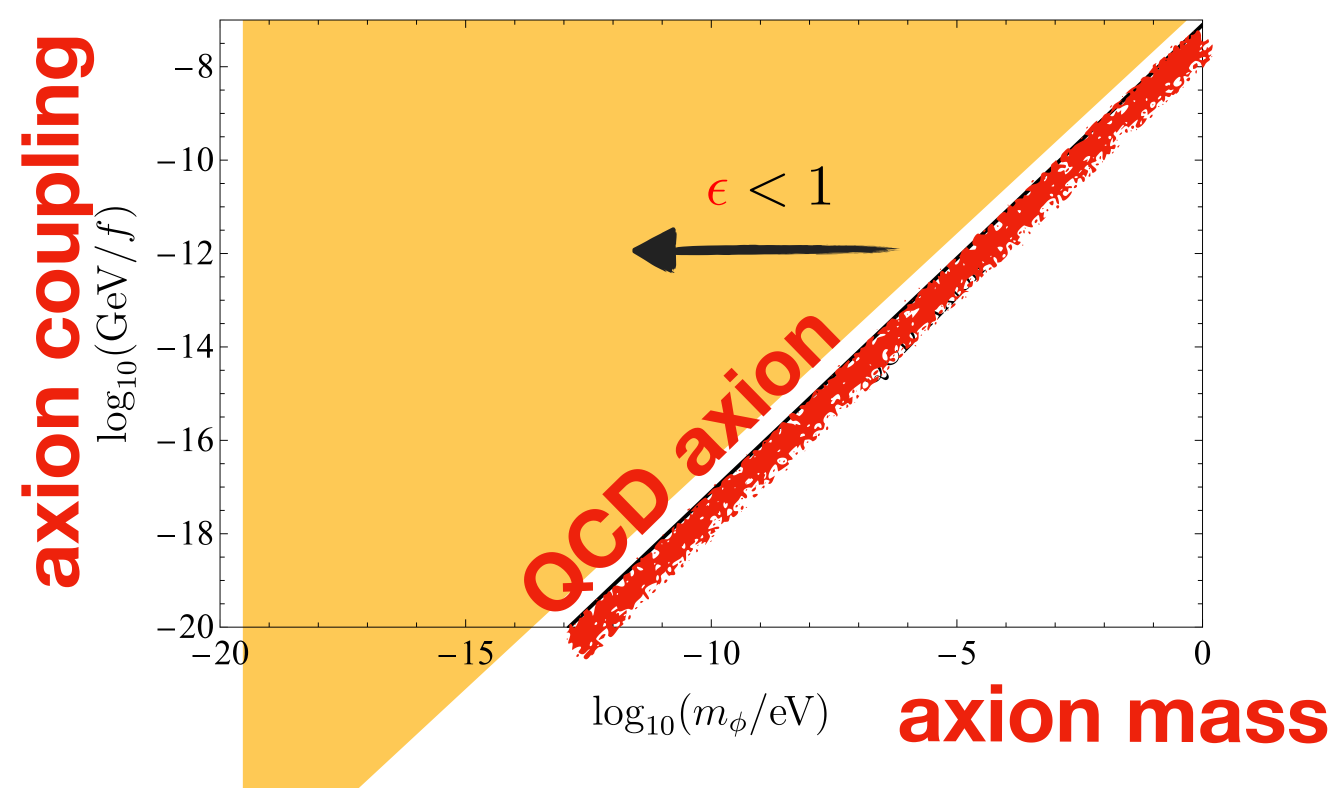


$$\frac{g_s^2}{32\pi^2}\frac{\phi}{f}G\tilde{G} \quad \xrightarrow{\text{UV} \qquad \text{IR}} \quad V(\phi) \simeq -\frac{m_\pi^2 f_\pi^2}{4}\left[\cos\left(\frac{\phi}{f}\right) - 1\right]$$

… with a smaller mass:

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

above QCD axion line



ϵ symmetry realization, see (Hook, Huang ’17, Hook ‘18, Di Luzio et. al. ’21)

QCD Axion: Coupling to Nucleons

Nuclear Chiral Perturbation theory

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

leads to non-derivative coupling of axions to nucleons:

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

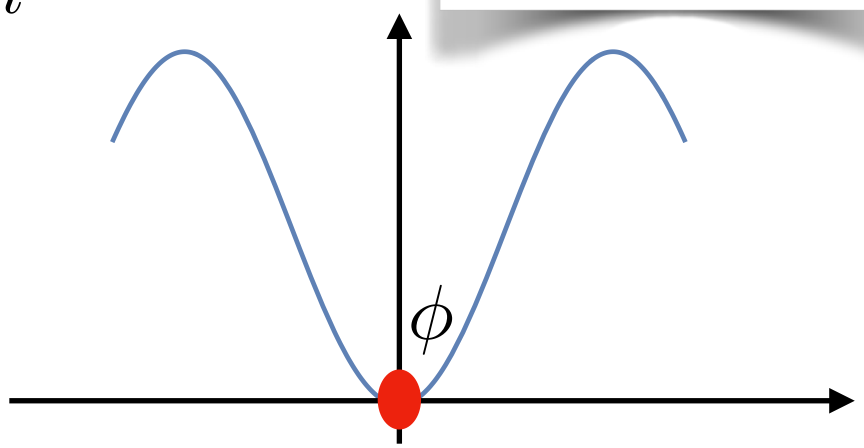
such that $m_N(0) = m_N, \quad \sigma_{\pi N} \simeq 50\,\mathrm{MeV}$

Light QCD Axion at Finite Density

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

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

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



Light QCD Axion at finite density

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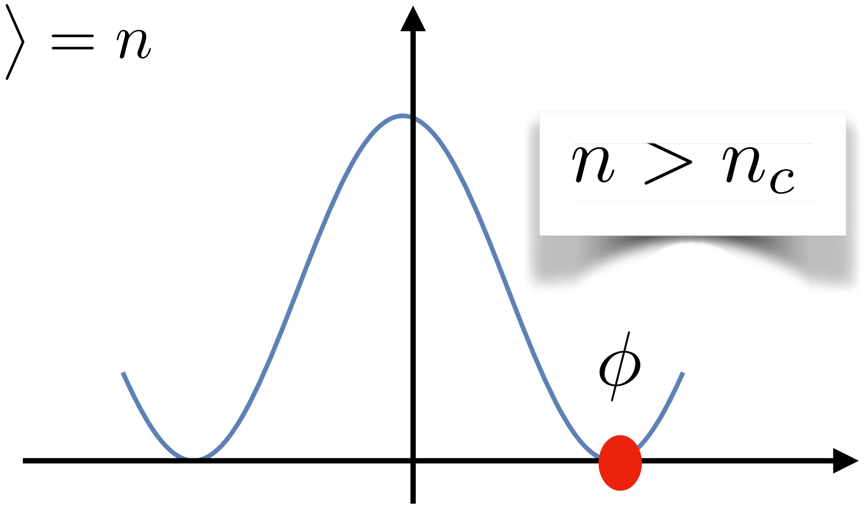
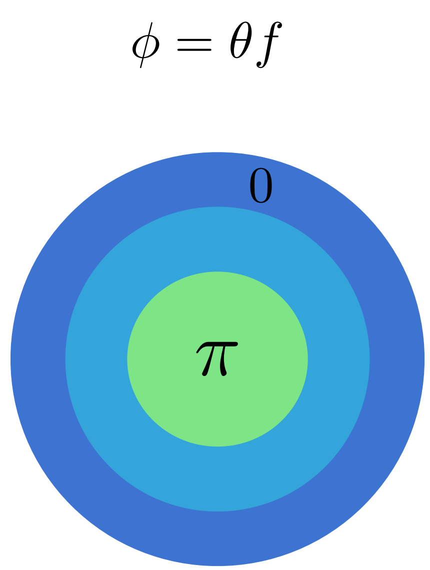


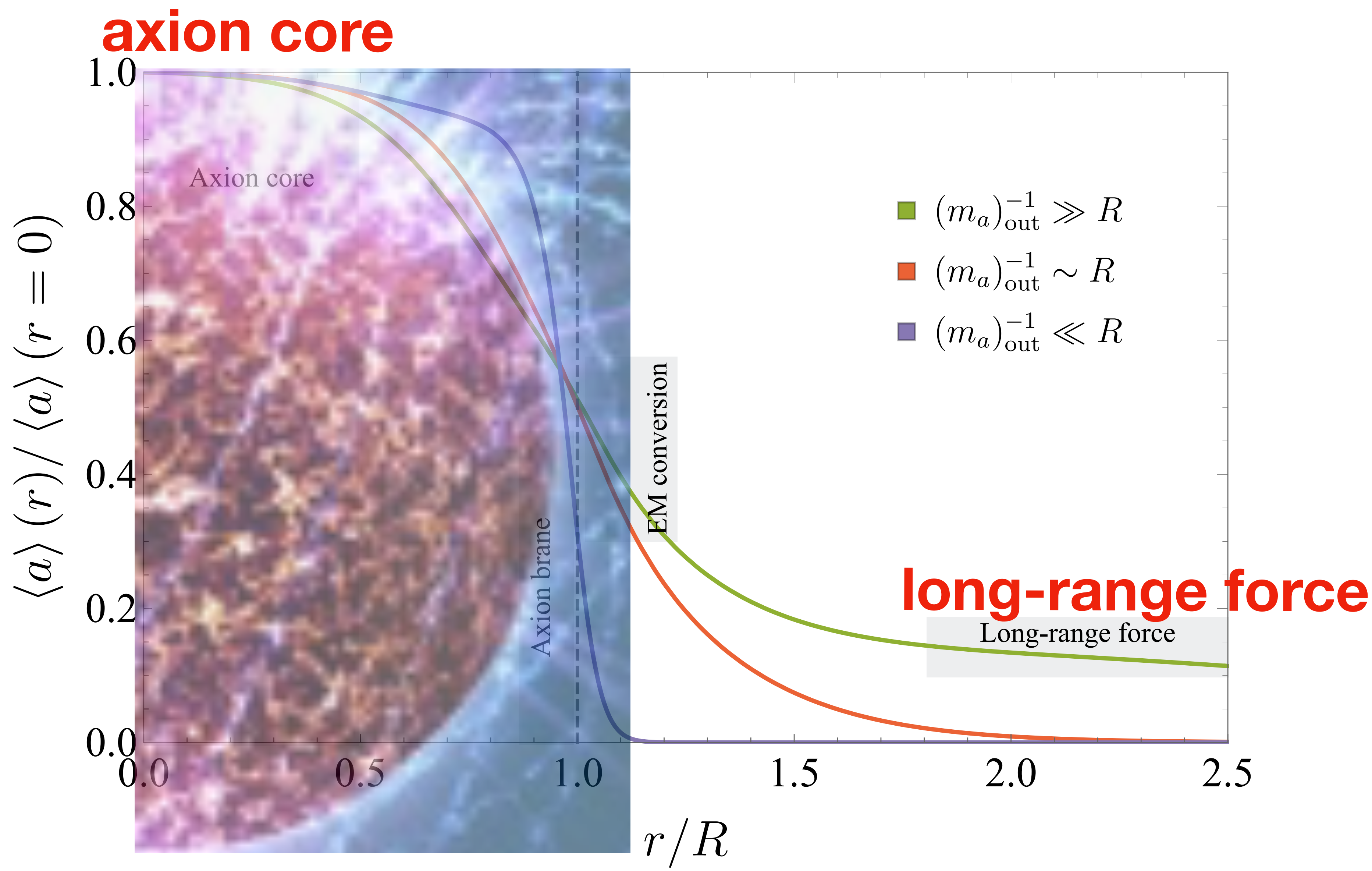
Above critical density $n > n_c$:

new minimum at $\langle \phi \rangle = \pi f$

Exciting effects appear once ϕ develops a non-trivial **profile**

Axion Profile

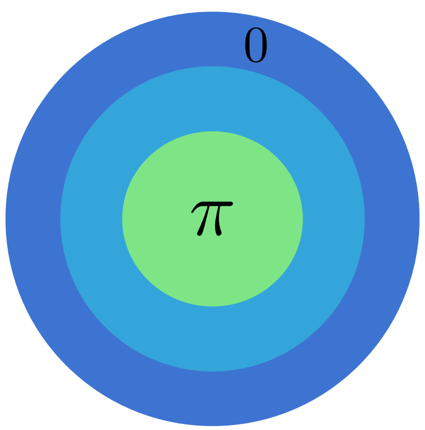


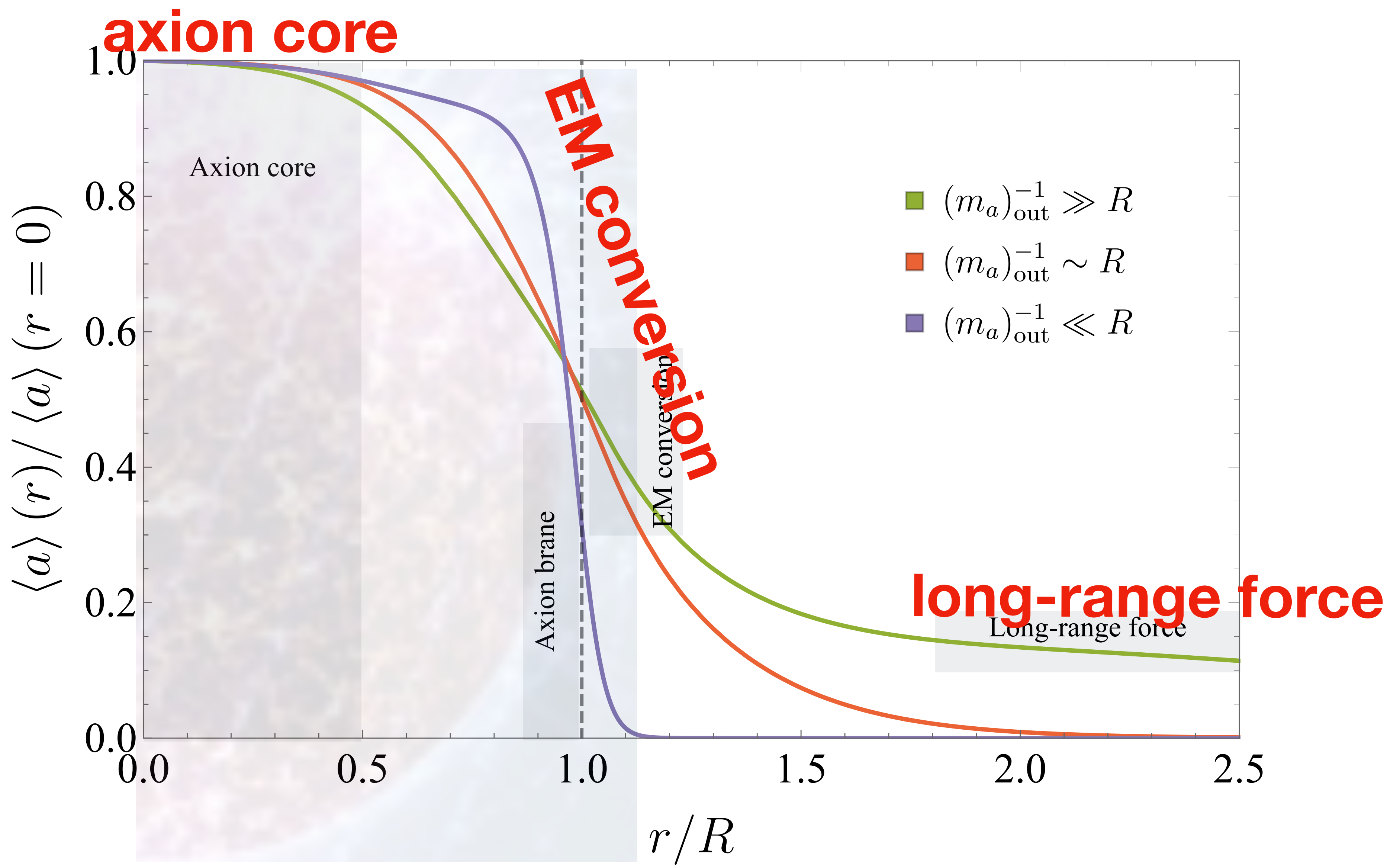


see Hook, Huang ’17 and Balkin, Serra, Springmann, AW ‘20

Axion Profile

$\phi = \theta f$

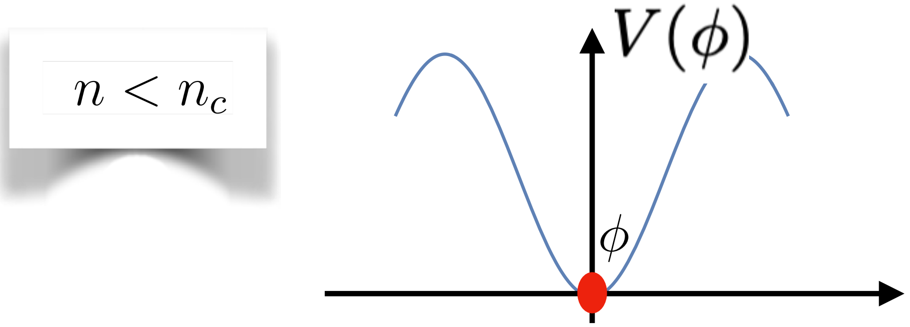


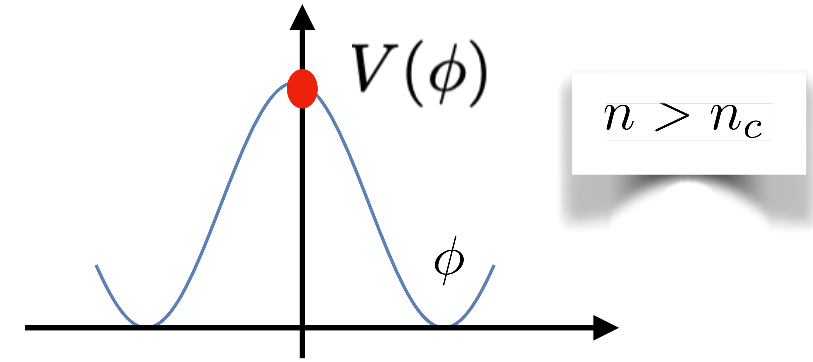


see Hook, Huang '17 and Balkin, Serra, Springmann, AW '20

Why does this not affect large nucleons?

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



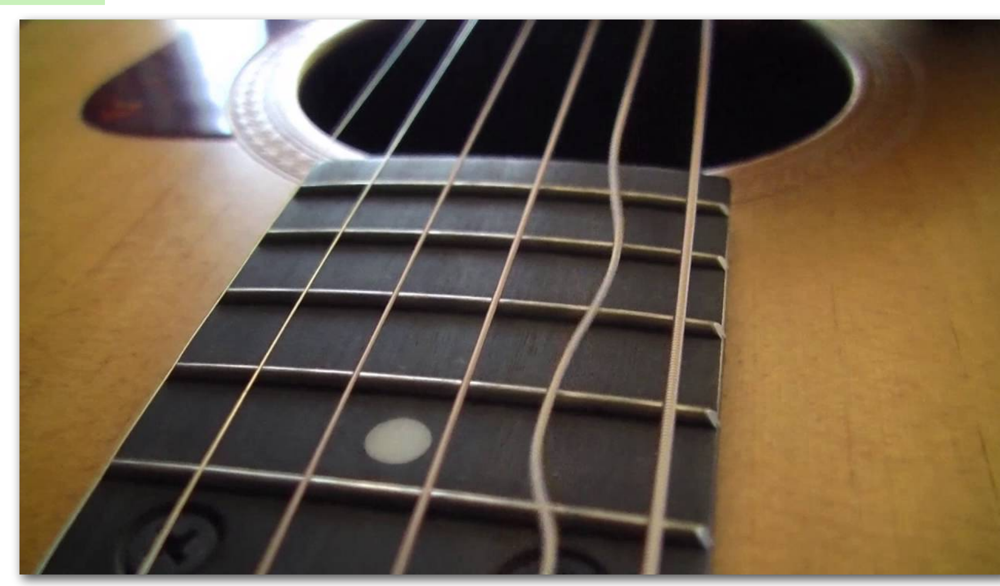


Field theory potential energy contains gradient term!

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

Resists change in profile

("string does not want to be bend")



Why does this not affect large nucleons?

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 $(\nabla\phi)^2 \sim f^2/r^2$

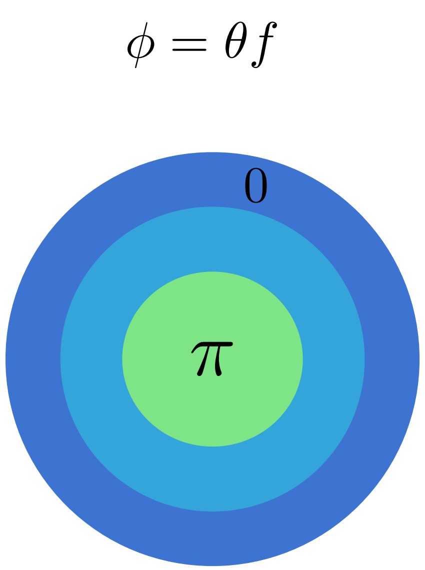
$$r_{\text{critical}} > 1/m_\phi^{\text{inside}}$$

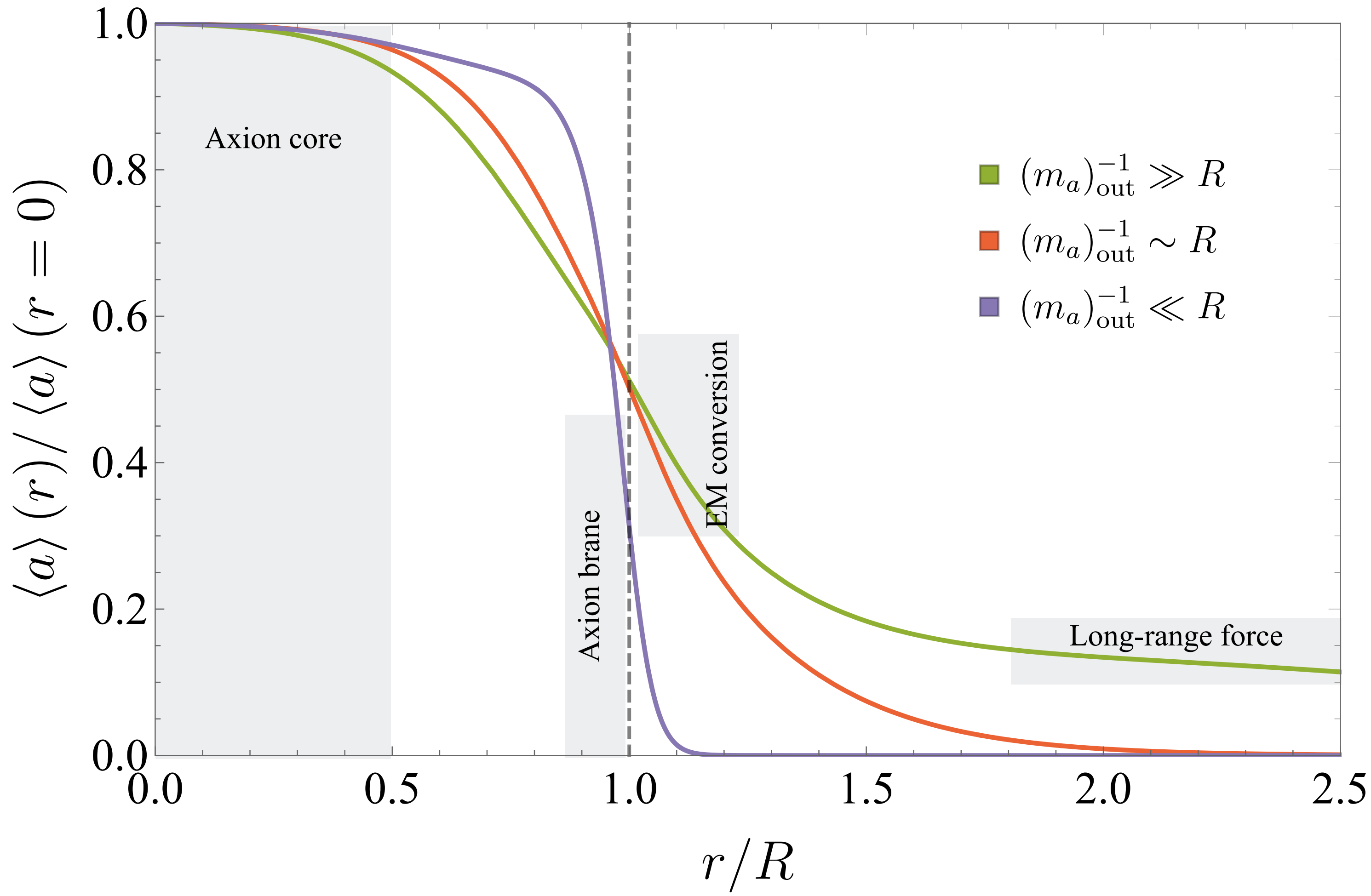
e.g. $f \sim 10^{12}\,\text{GeV}$

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

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

Axion Profile

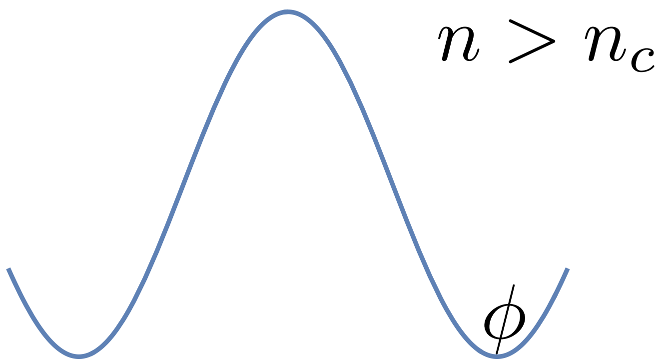




What happens to neutrons stars and white dwarfs with an axion sourced inside?

Stars with a sourced axion profile

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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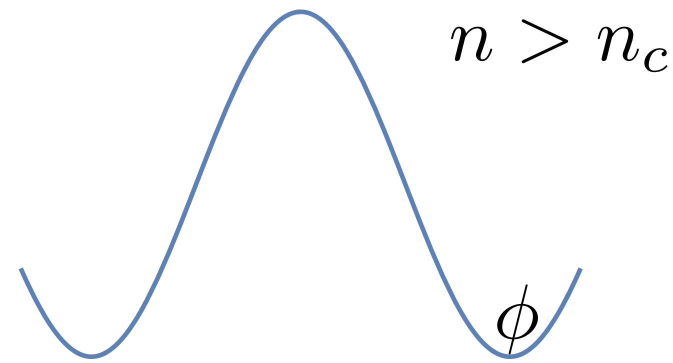

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2) Energy density of the potential acts as vacuum energy (like a CC)

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

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

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

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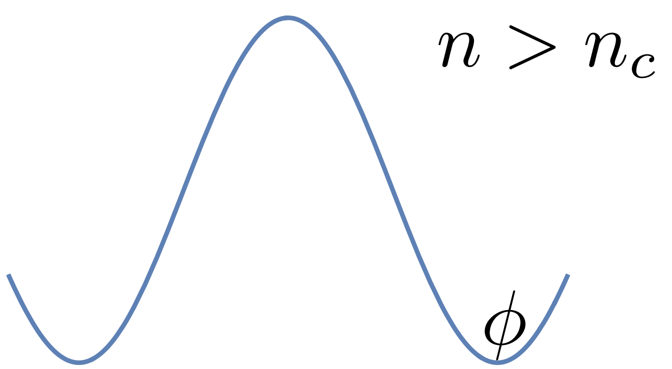

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Free Fermi Gas of Neutrons with an Axion

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

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

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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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coupled system
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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

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$$R \gg \lambda_\phi = m_\phi^{-1} \sim \frac{f}{\sqrt{\sigma_{\pi N} n - \epsilon m_\pi^2 f_\pi^2}}$$

→ 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

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

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

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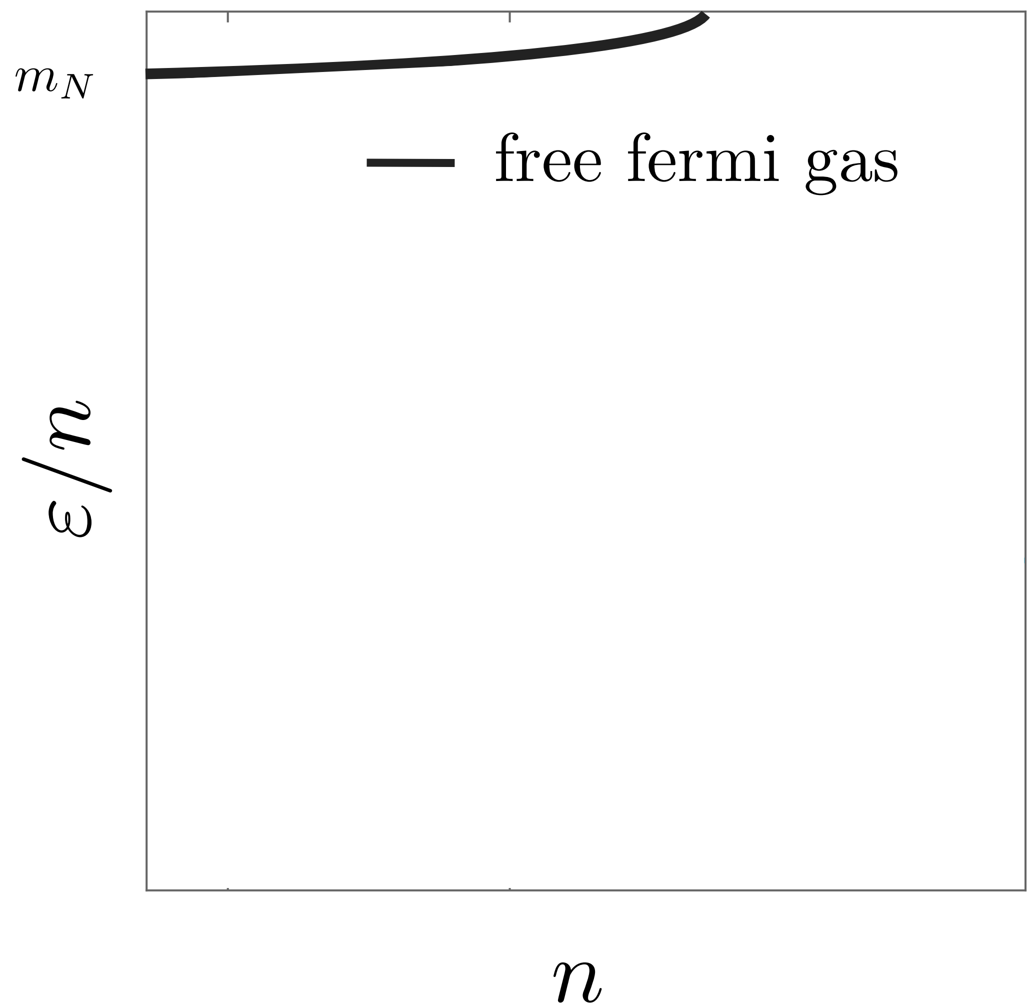
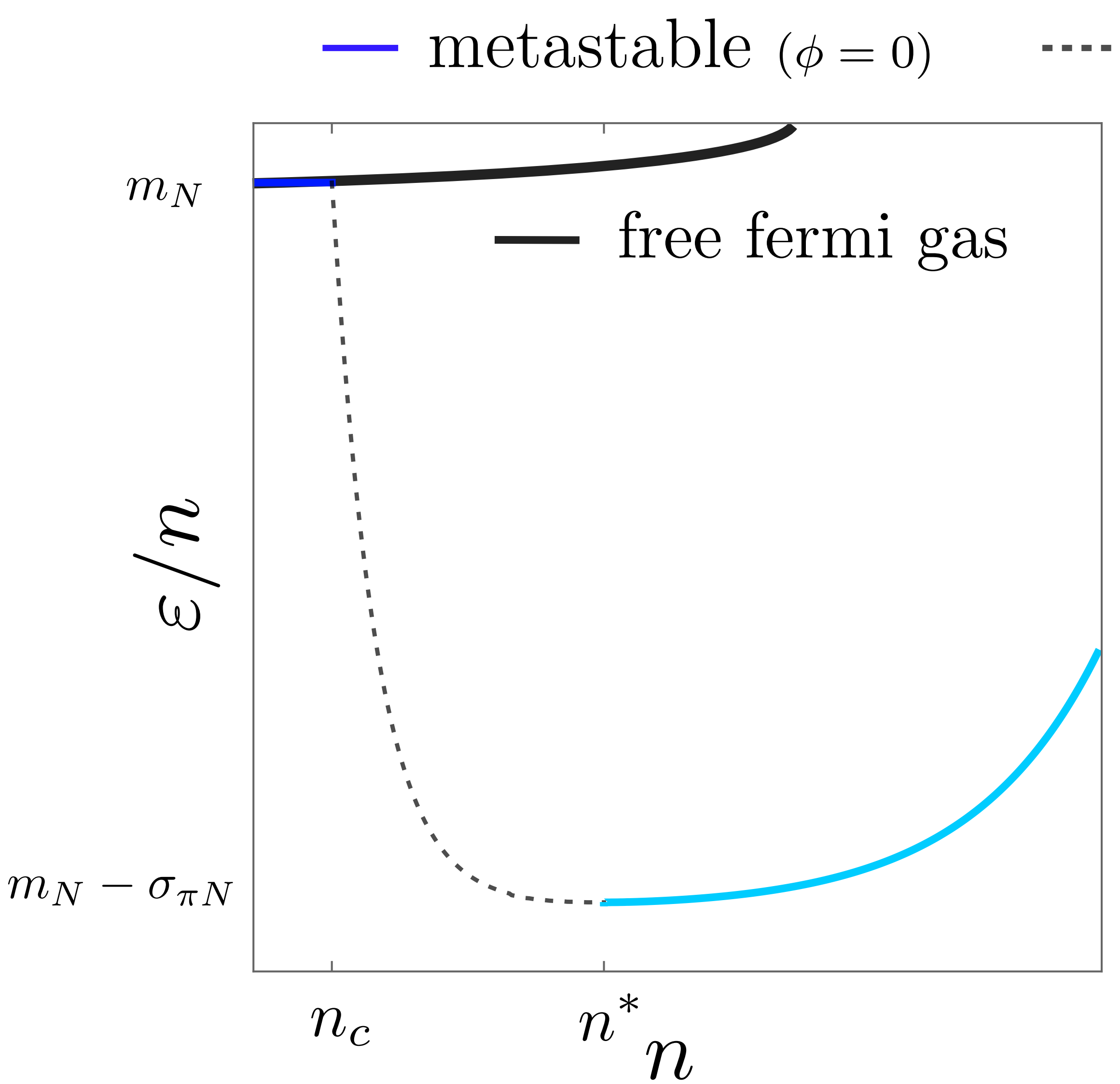
$$\longrightarrow \varepsilon(n), p(n)$$ equation of state

Energy per particle



Energy per particle



Energy per particle is related to pressure

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

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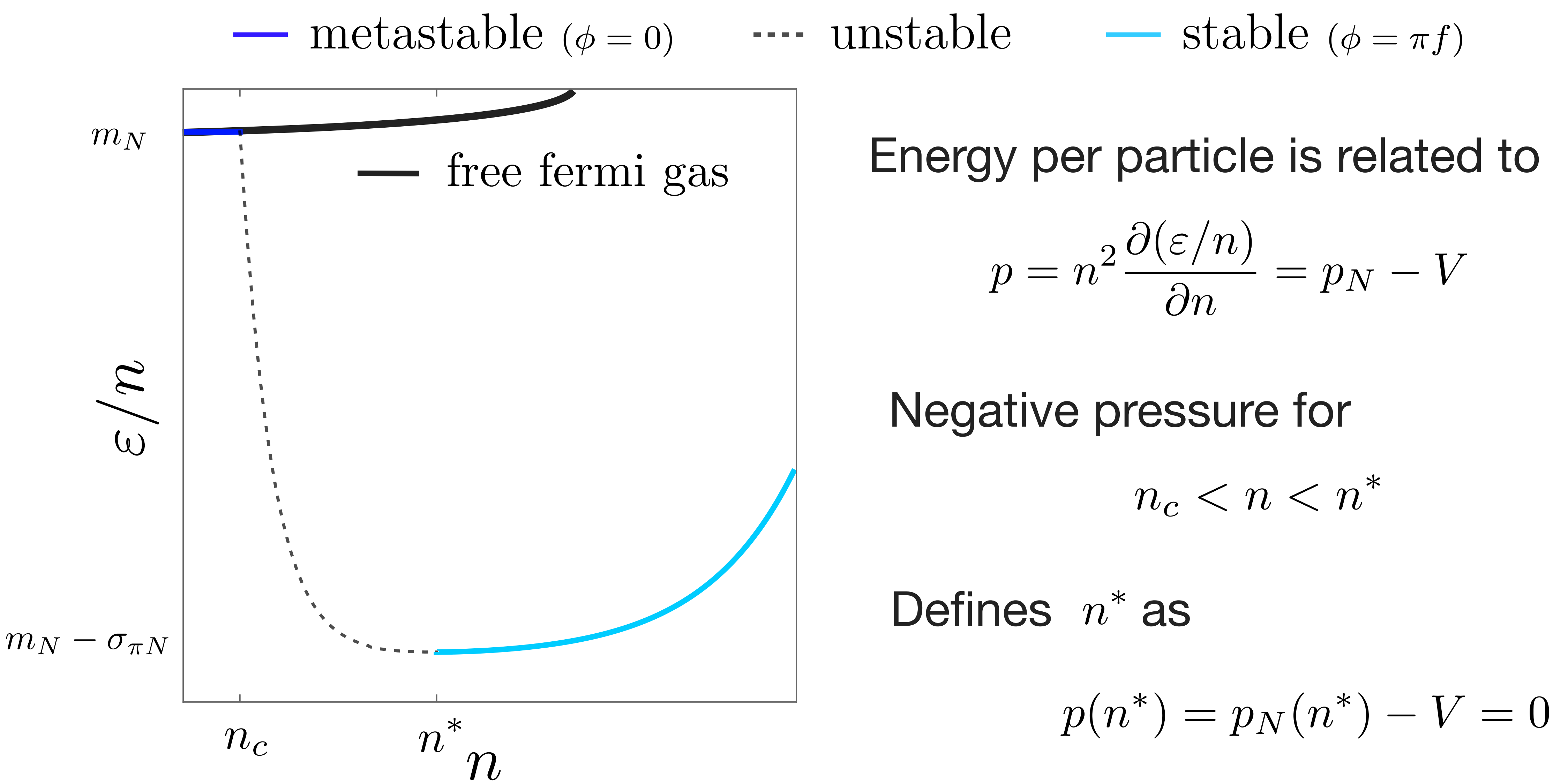

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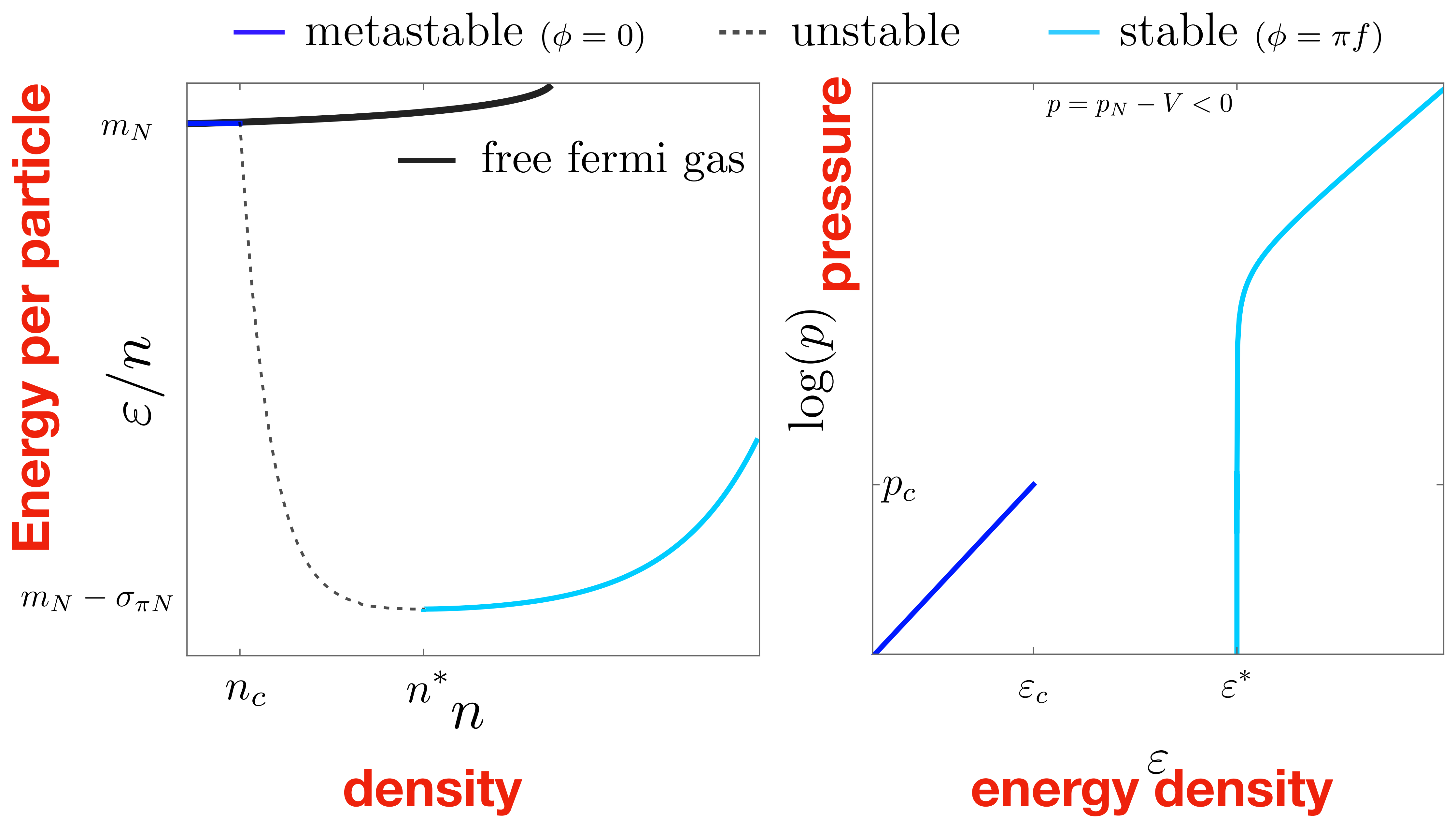
Negative pressure for

$$n_c < n < n^*$$

Defines n^* as

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

Energy per particle vs pressure inside



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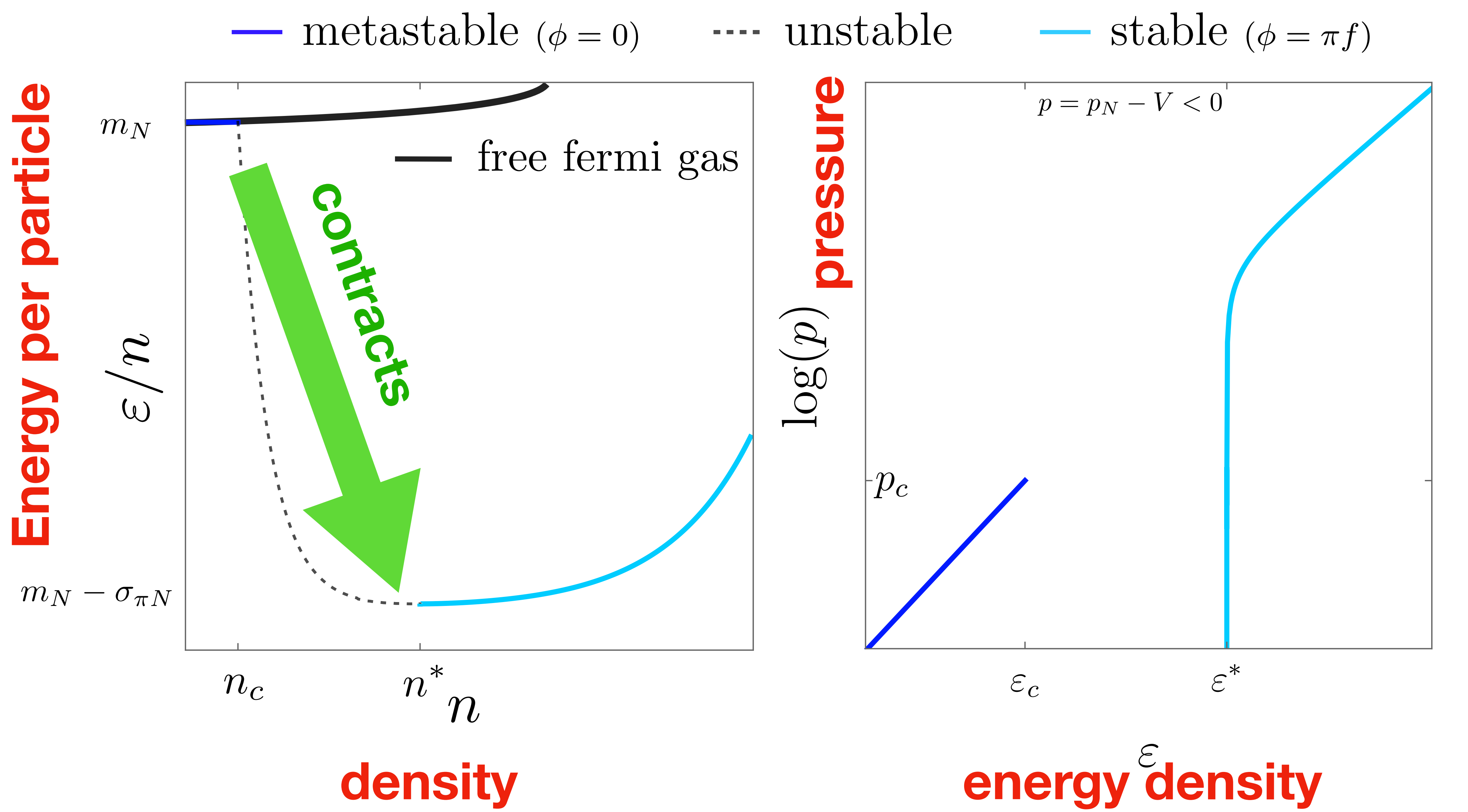
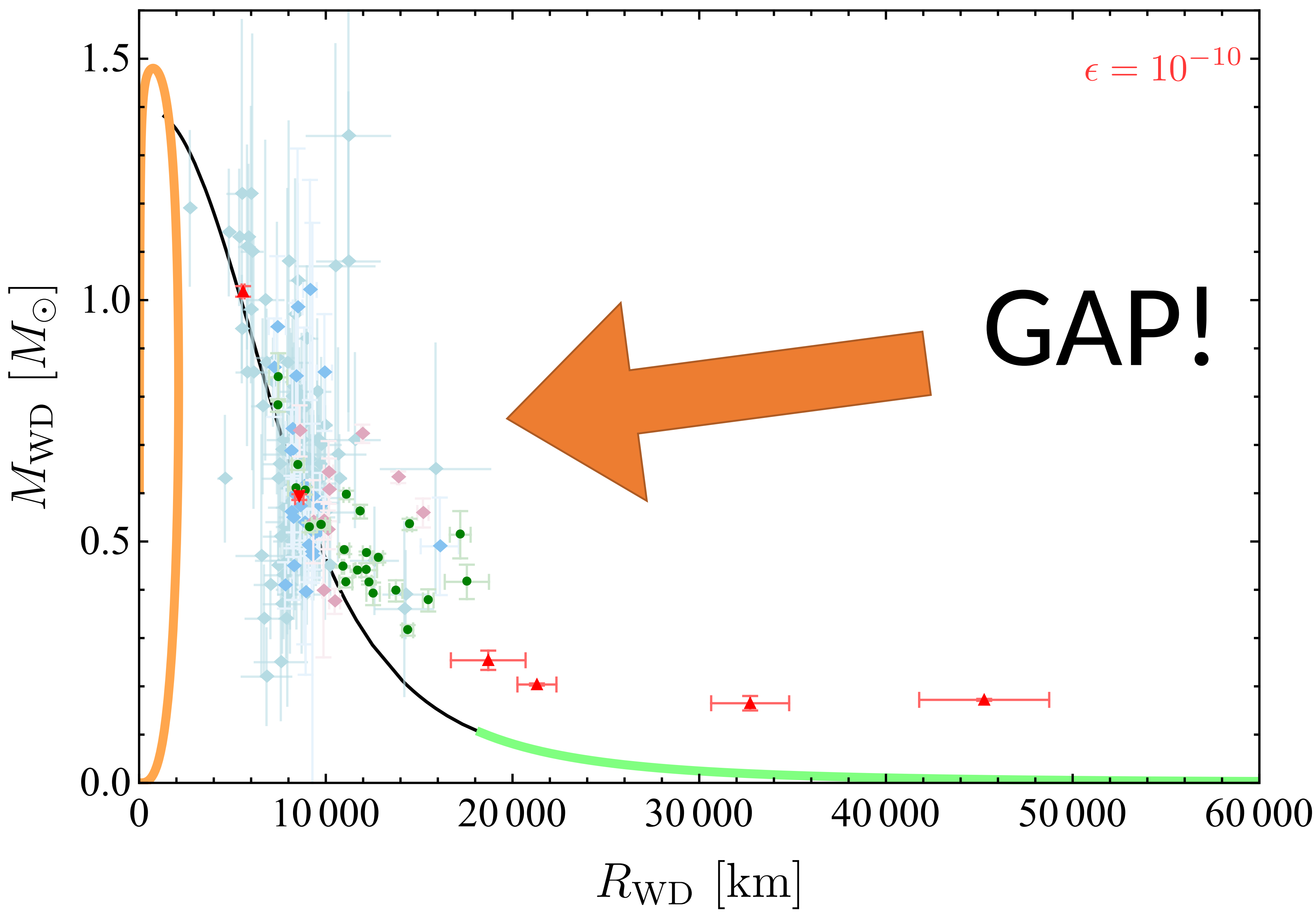


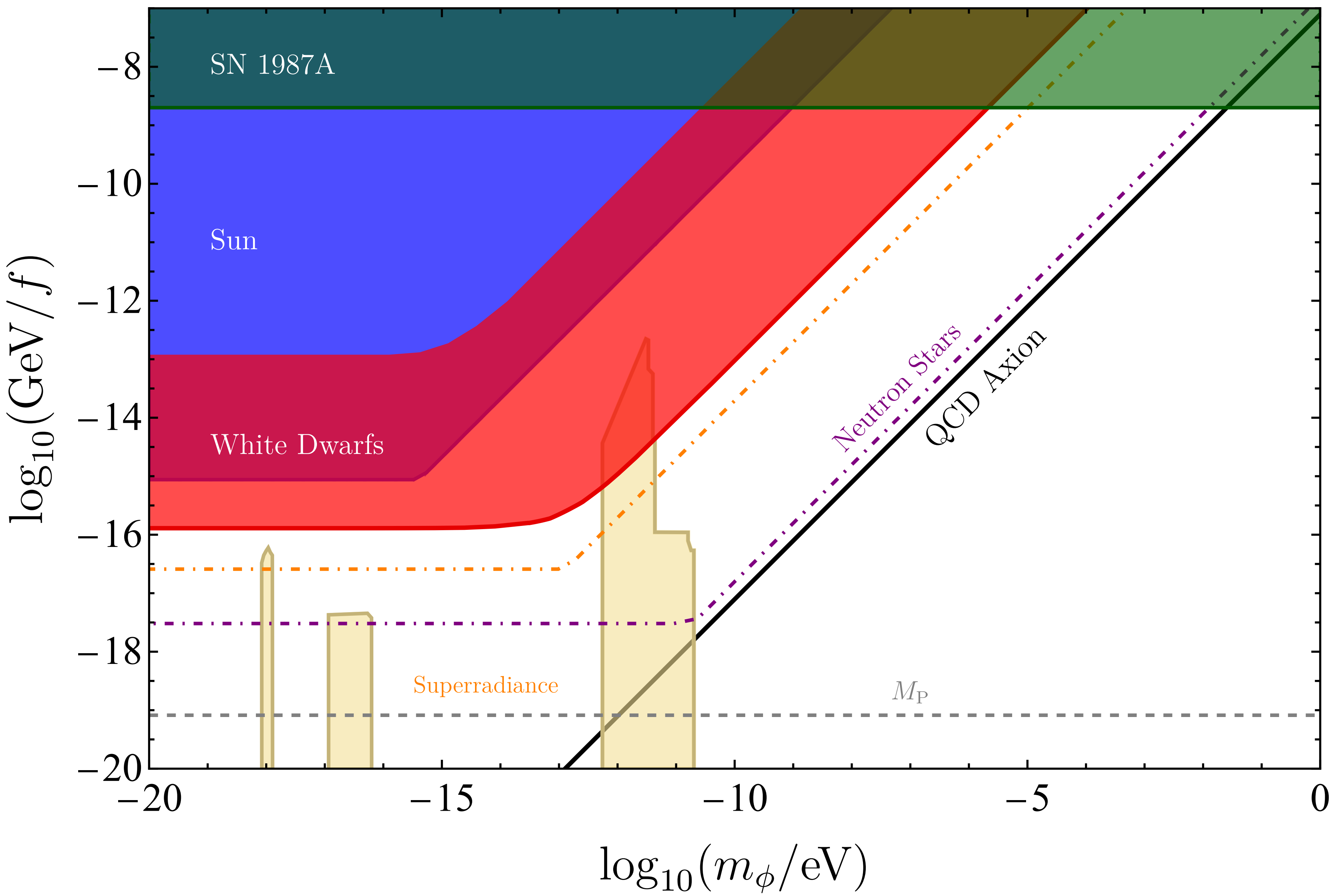
White Dwarfs with a light Axion

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



Balkin, Serra, Stelzl, Springmann, AW 2202.0

Axion Parameter Space



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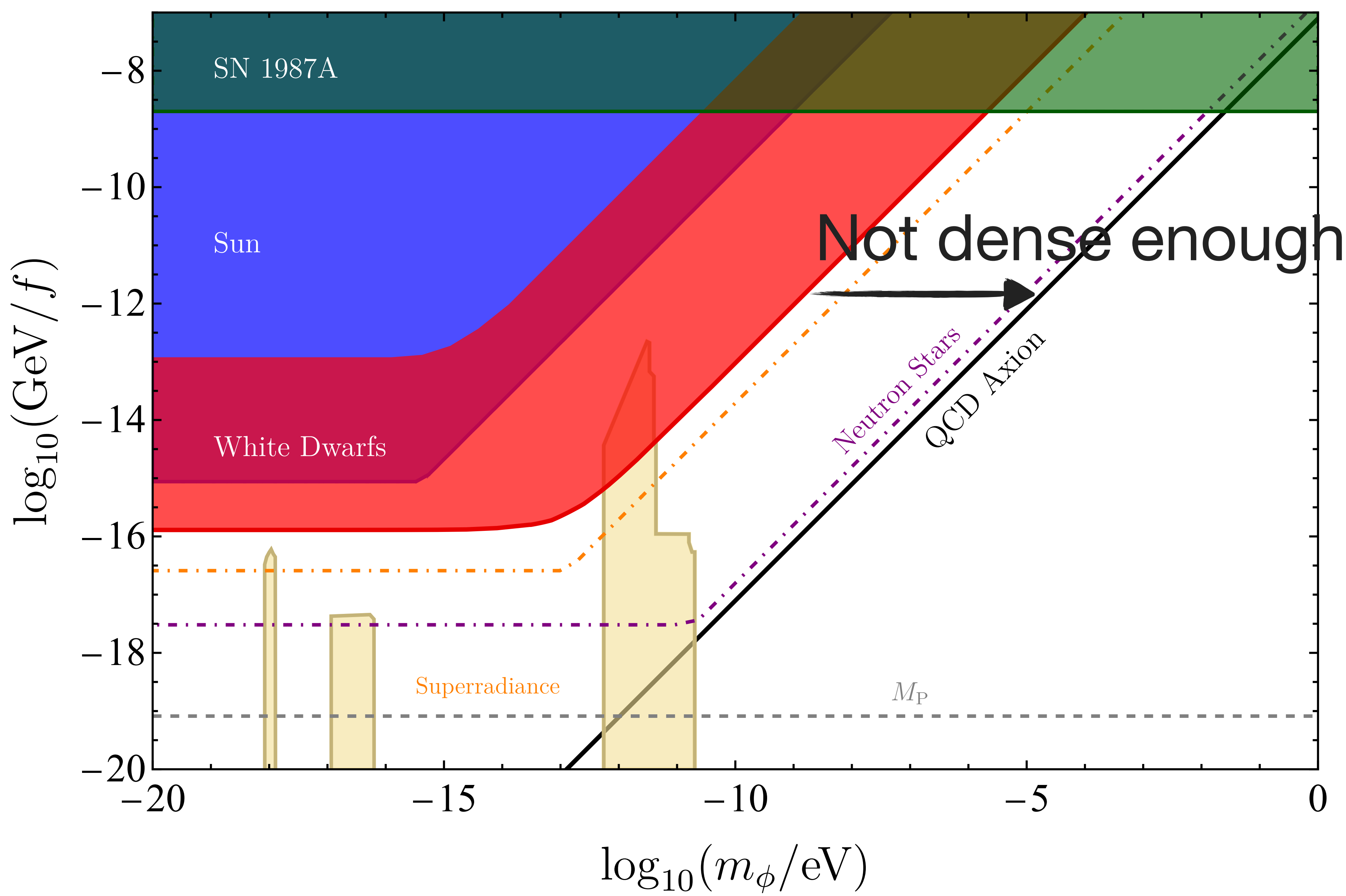

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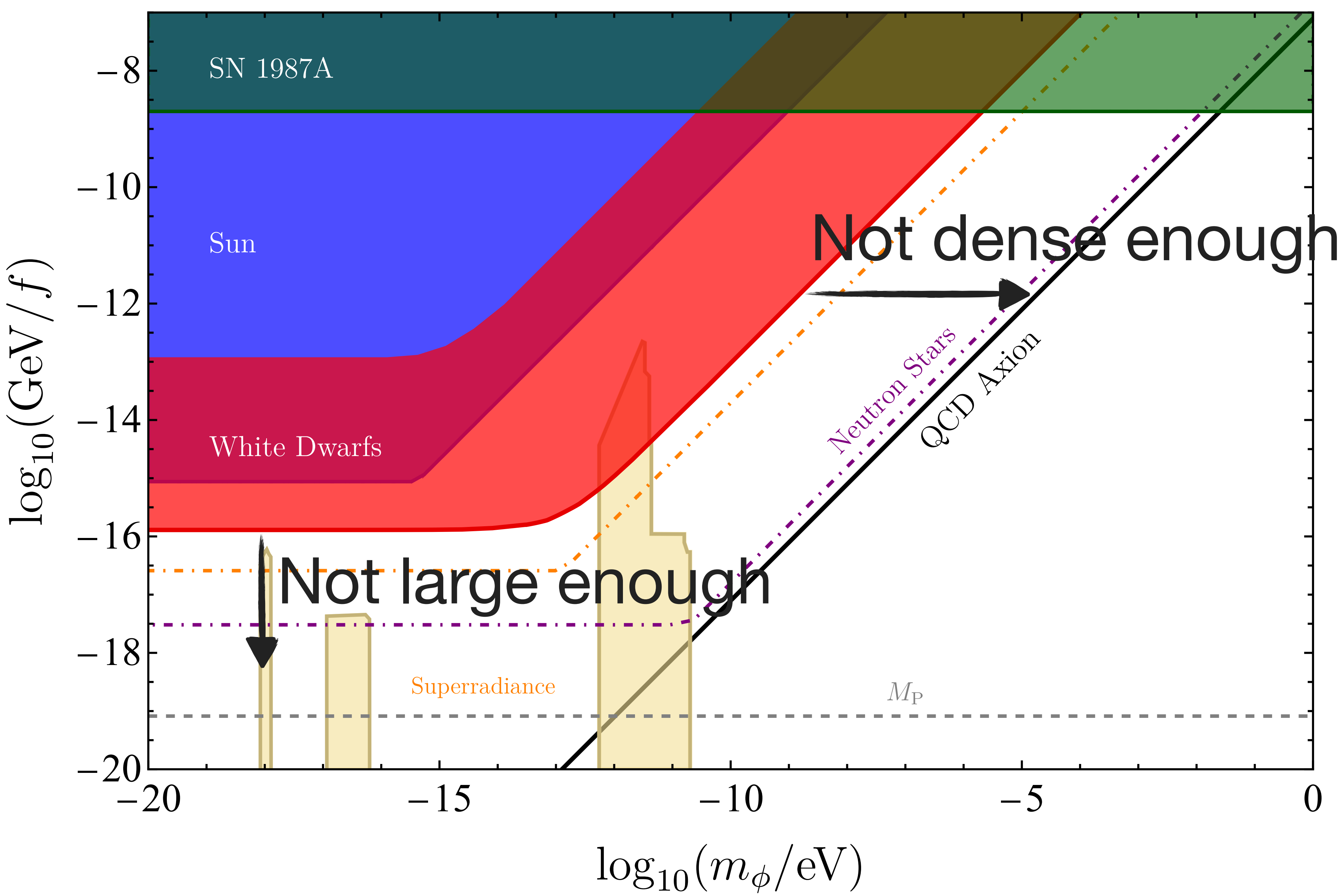

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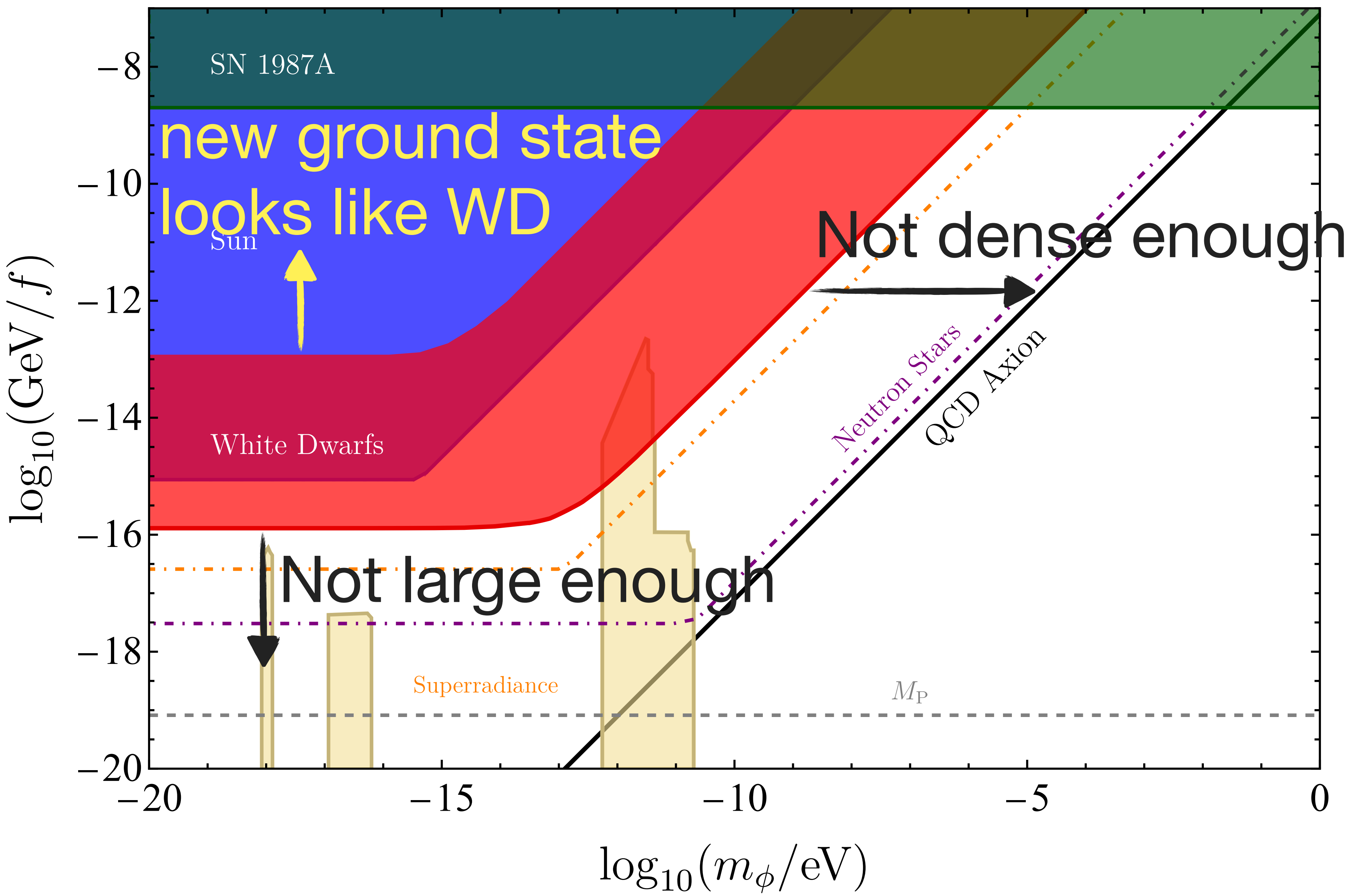
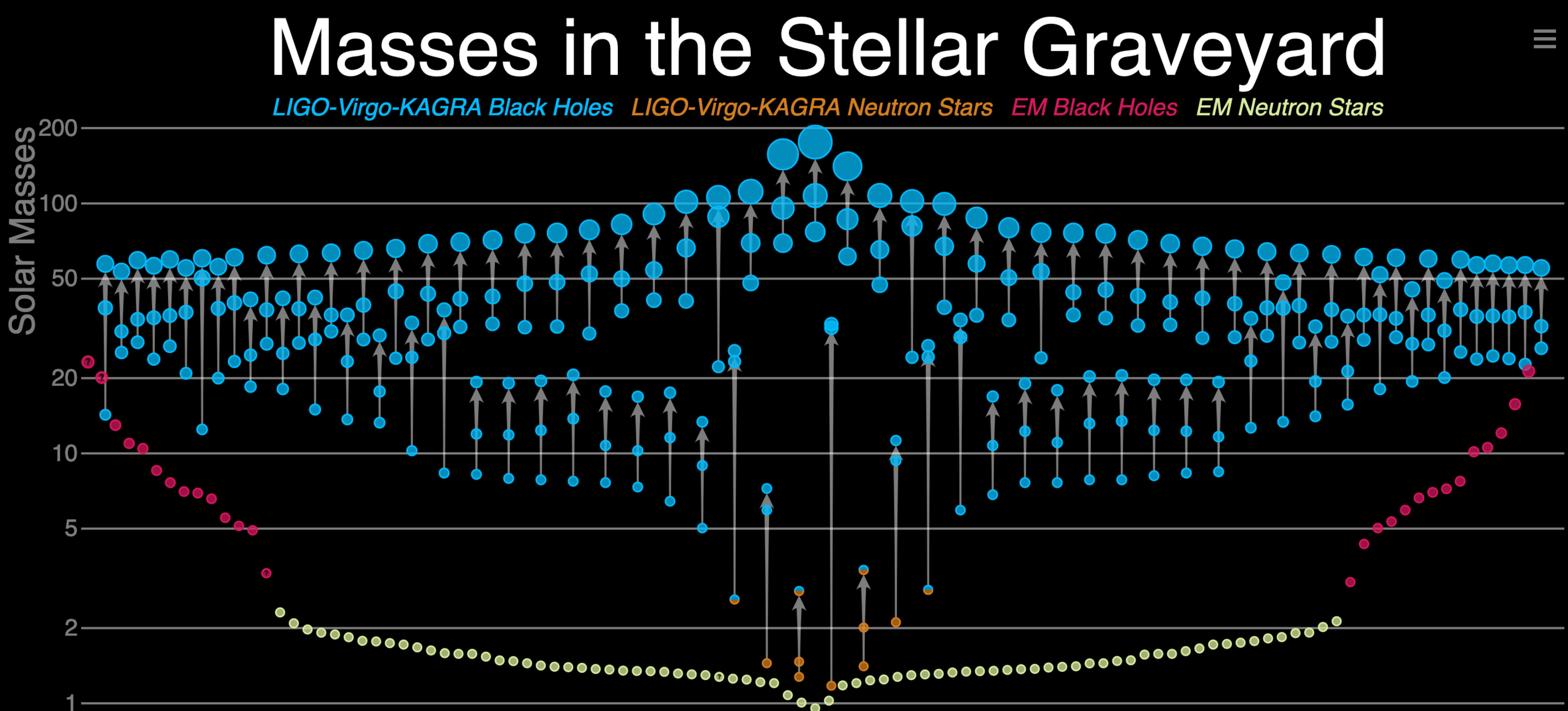


Heavy Neutron Stars from light Scalars

… or Fat Zombies in the Stellar Graveyard

Motivation:



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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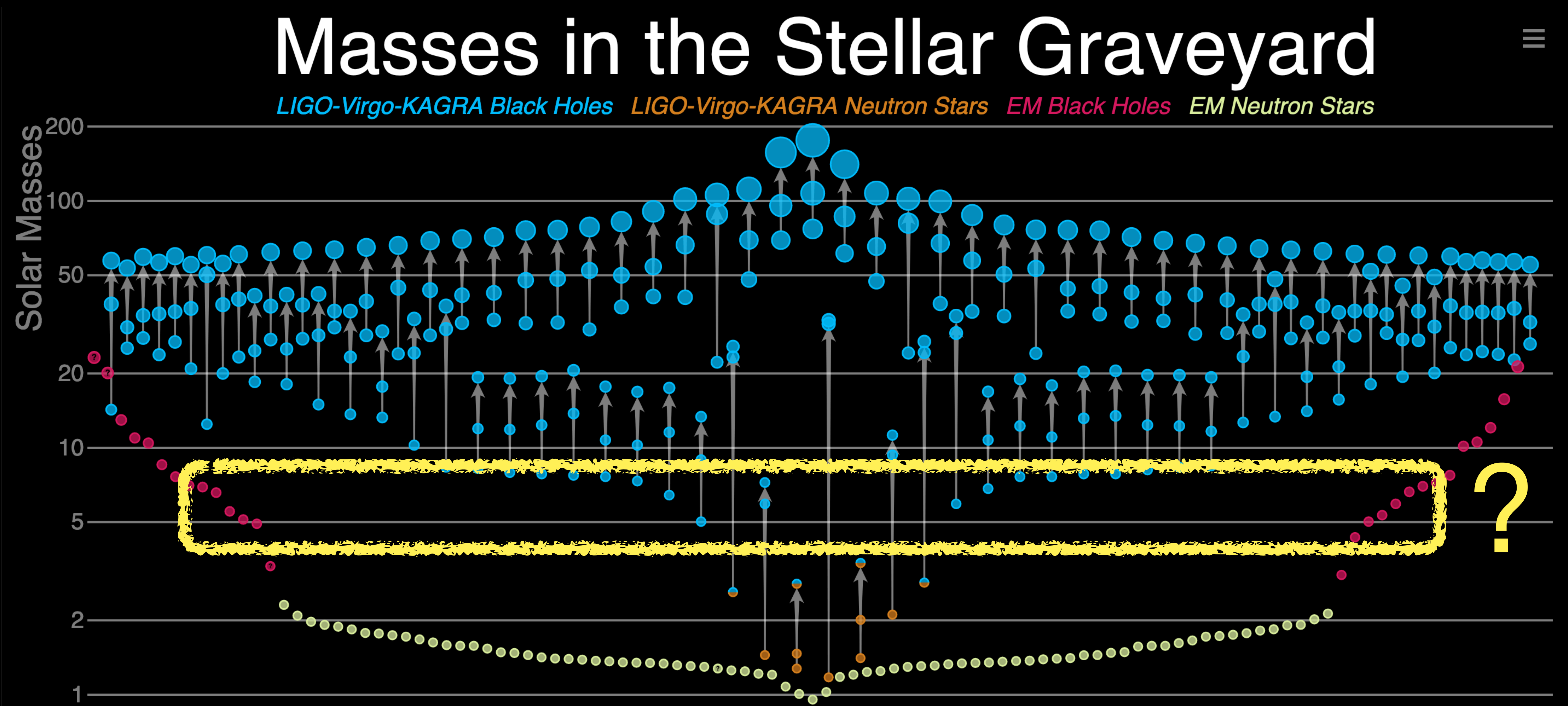

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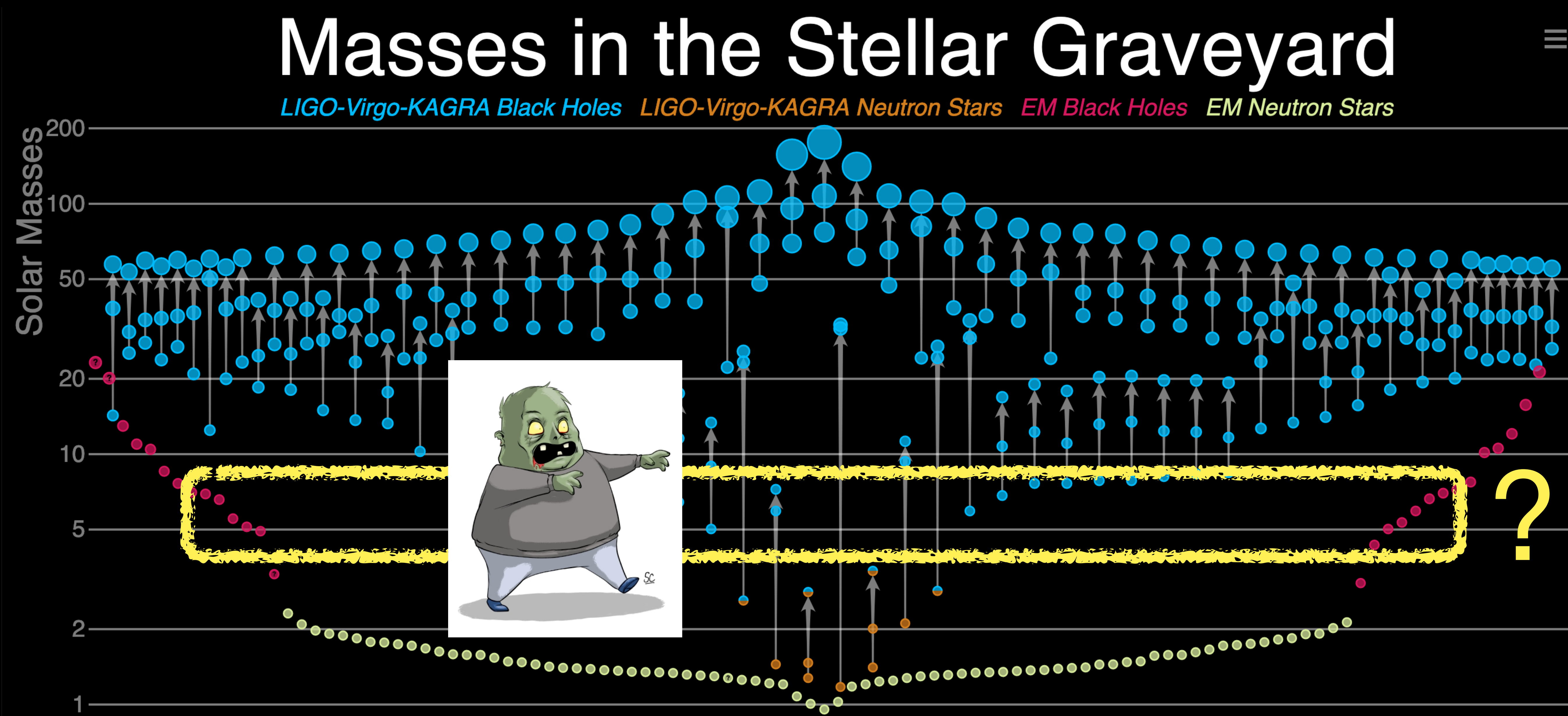

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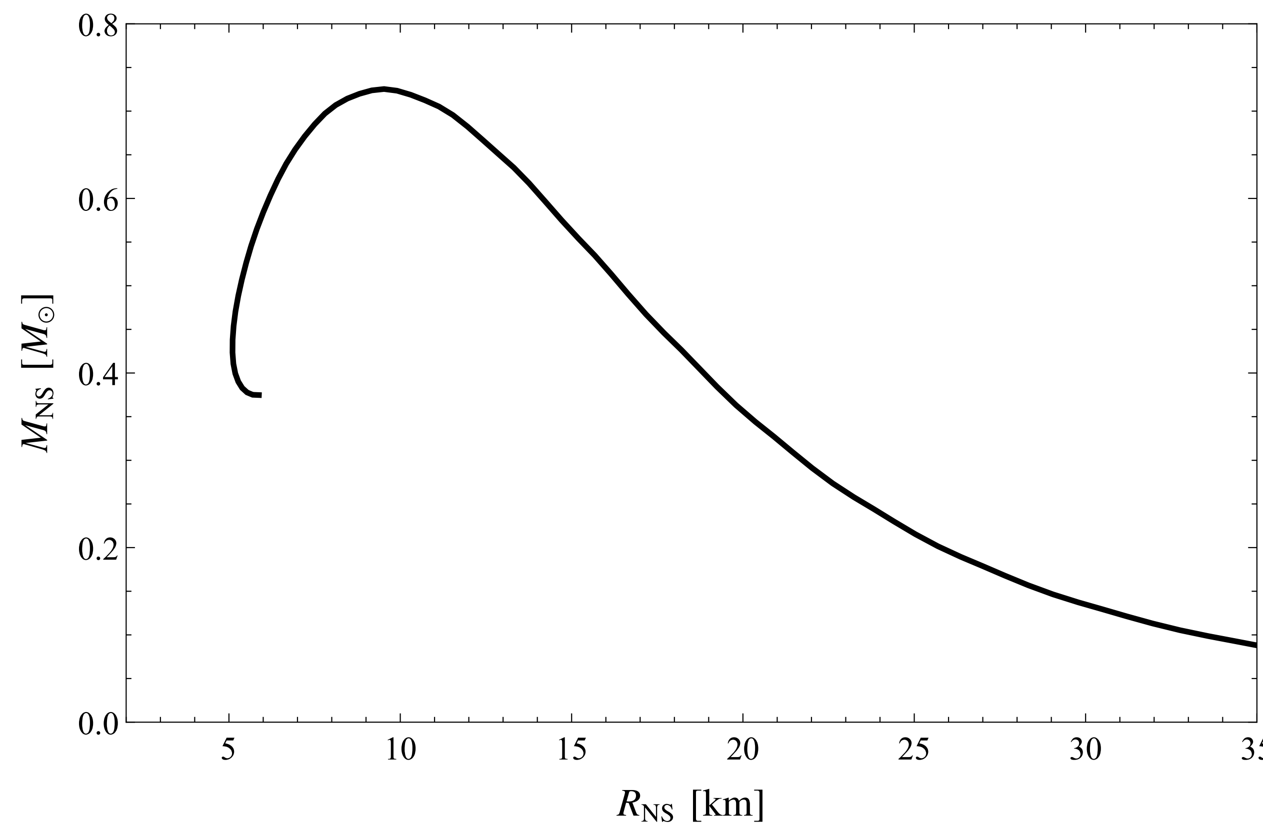
Free fermi-gas toy model

Consider non-interacting Fermi gas of neutrons

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

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

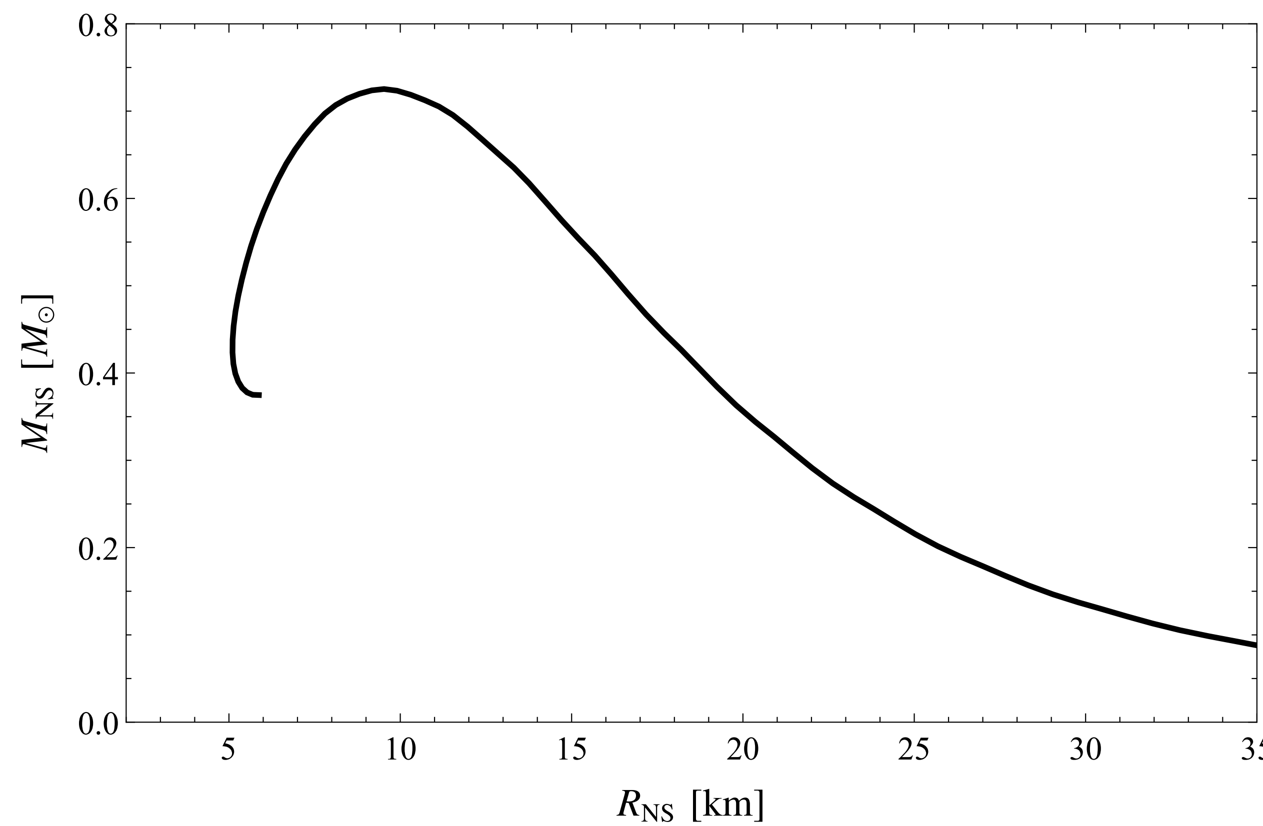


Free fermi-gas toy model

Consider non-interacting Fermi gas of neutrons

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

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



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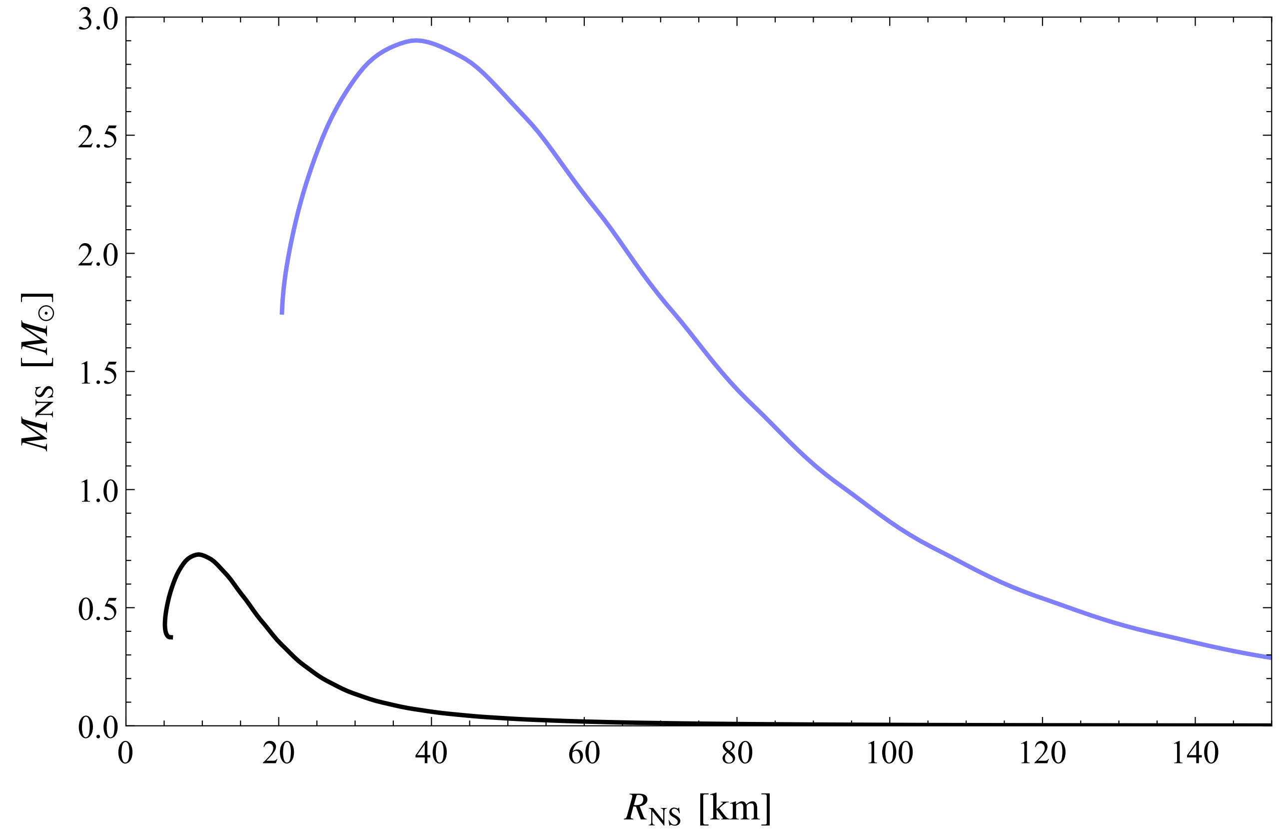

For lighter neutrons

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

Also obvious from our neutron star estimates:

$$R_{\rm NS} \sim \frac{M_{\rm Planck}}{m_N^2} \qquad M_{\rm NS} \sim \frac{M_{\rm Planck}^3}{m_N^2}$$

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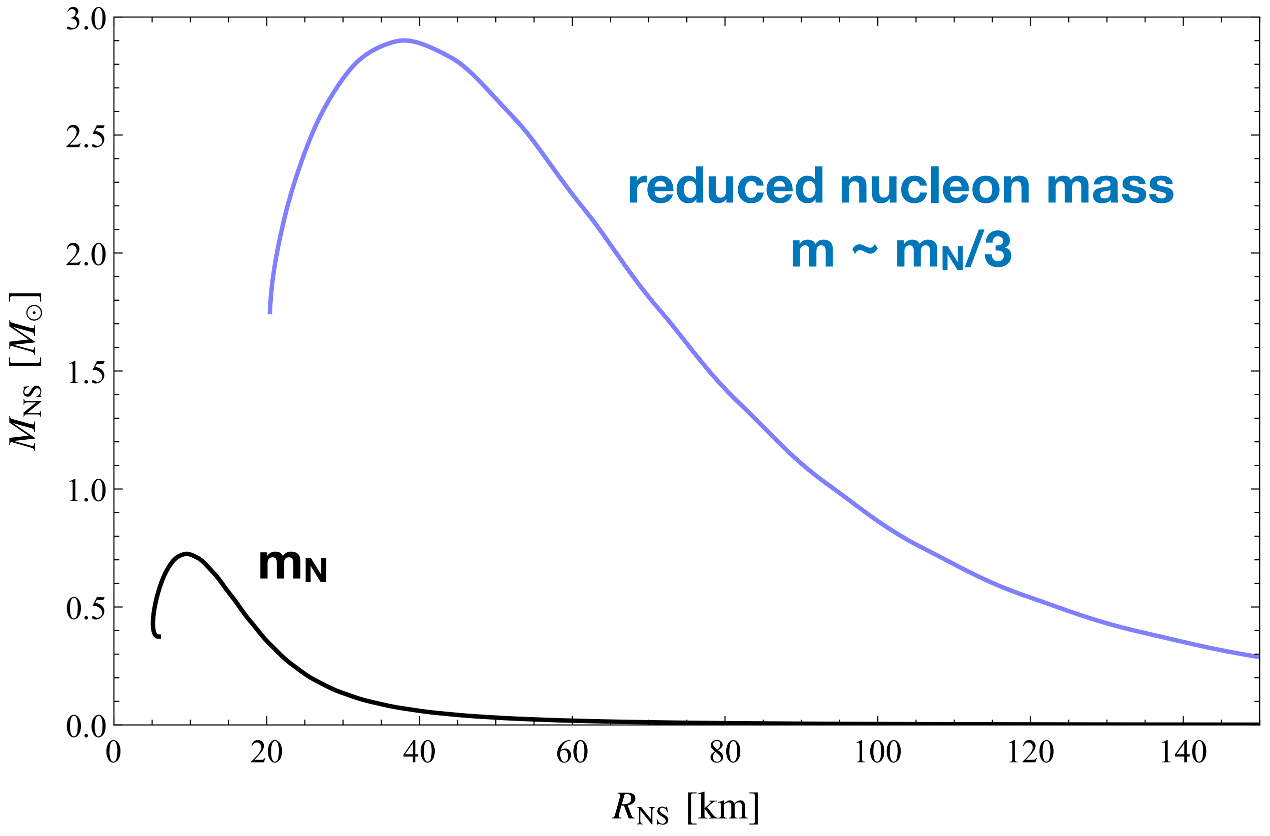

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Light scalar coupled to nucleons

Potential and coupling

$$V(\phi) = -\Lambda^4 \left(\cos\left(\phi/f\right) - 1\right)$$

$$\mathcal{O}_{\phi N} = \frac{g\, m_N}{2} \bar{N} N \cos\left(\frac{\phi}{f}\right)$$

Effective nucl. mass

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

What kind of EOS?

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

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

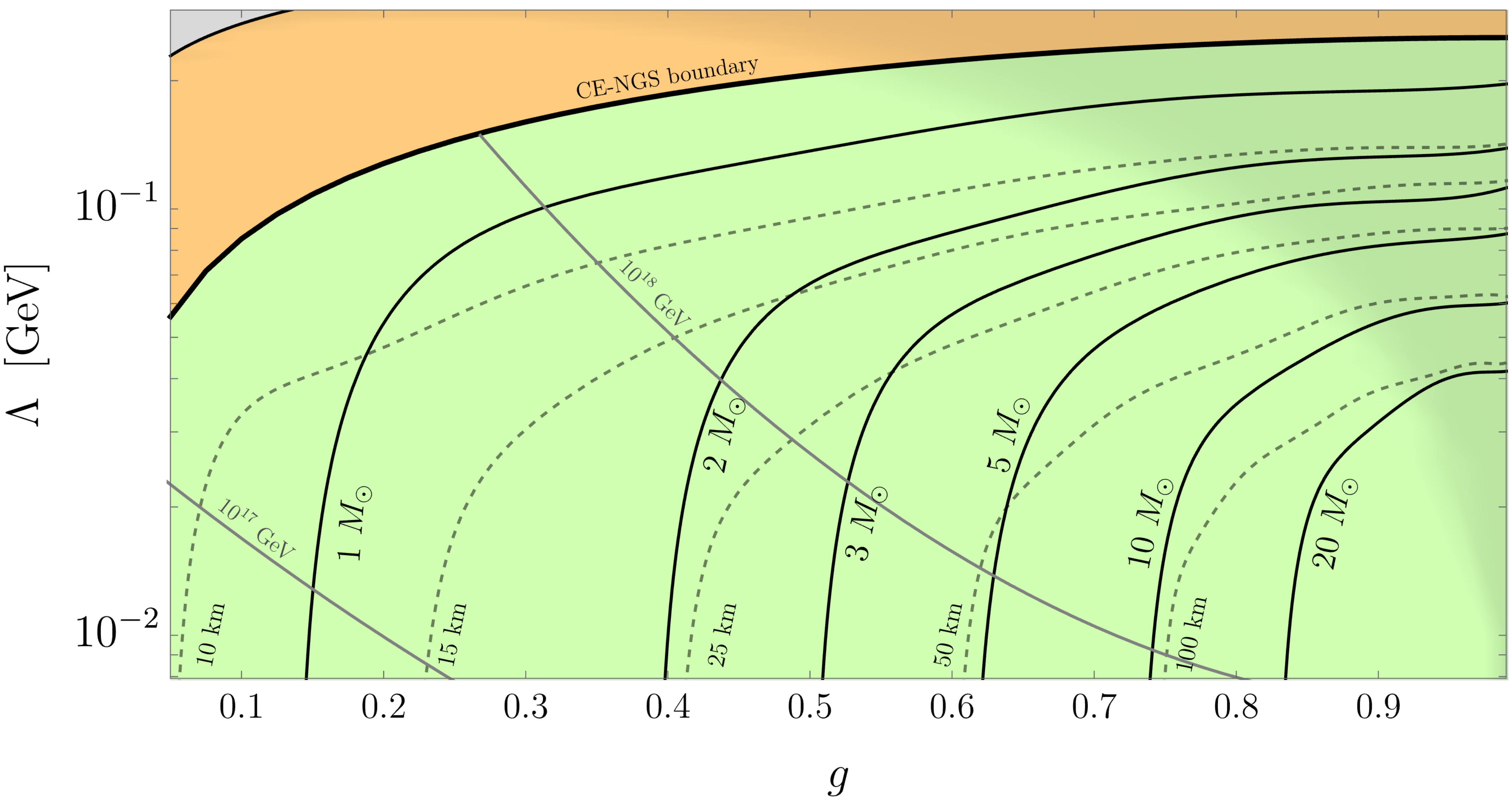
$$\Rightarrow M_{\max} \sim 0.7 \left(\frac{m_N}{m}\right)^2 M_\odot$$

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

Neutron stars with light scalars



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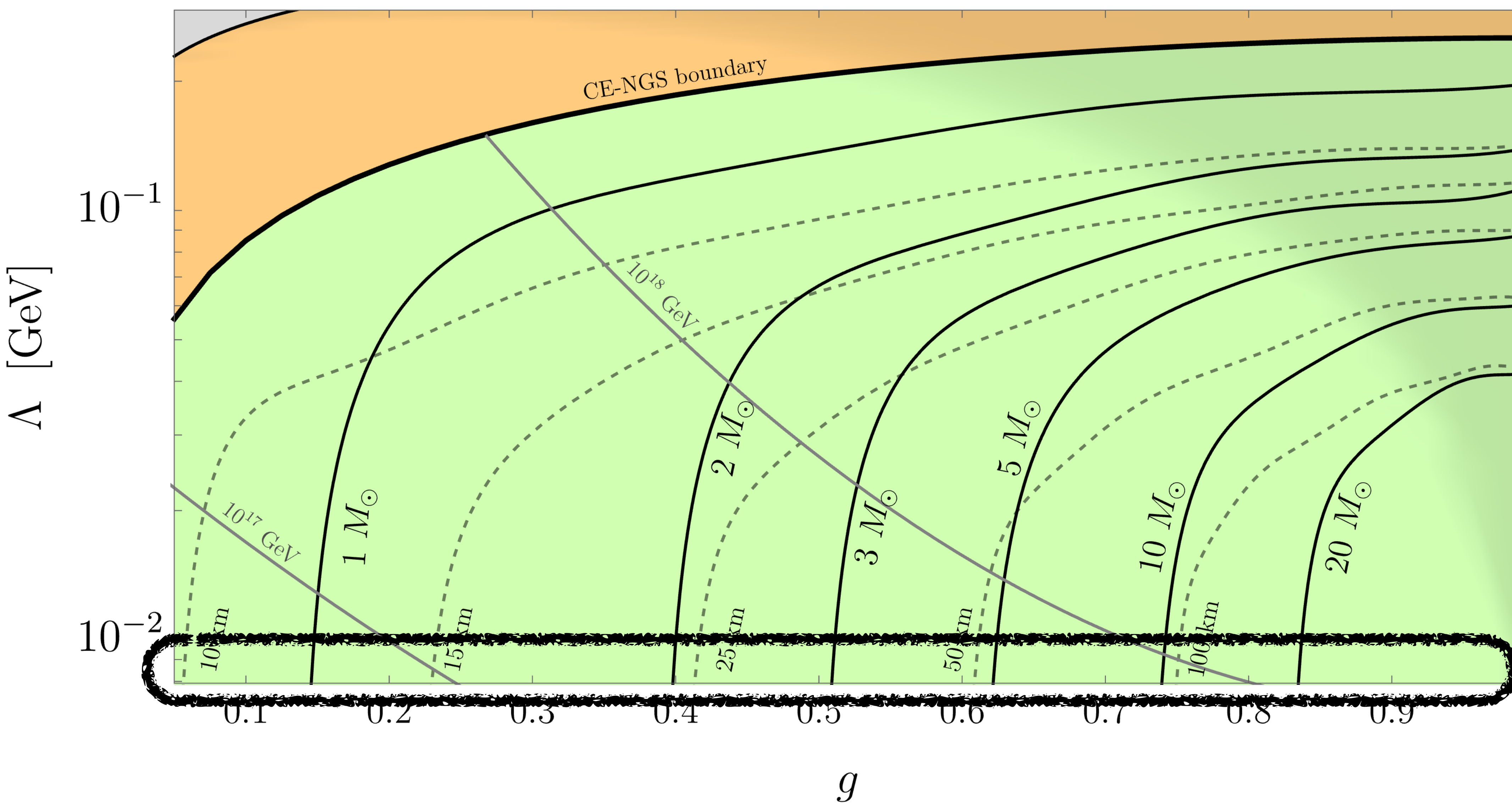
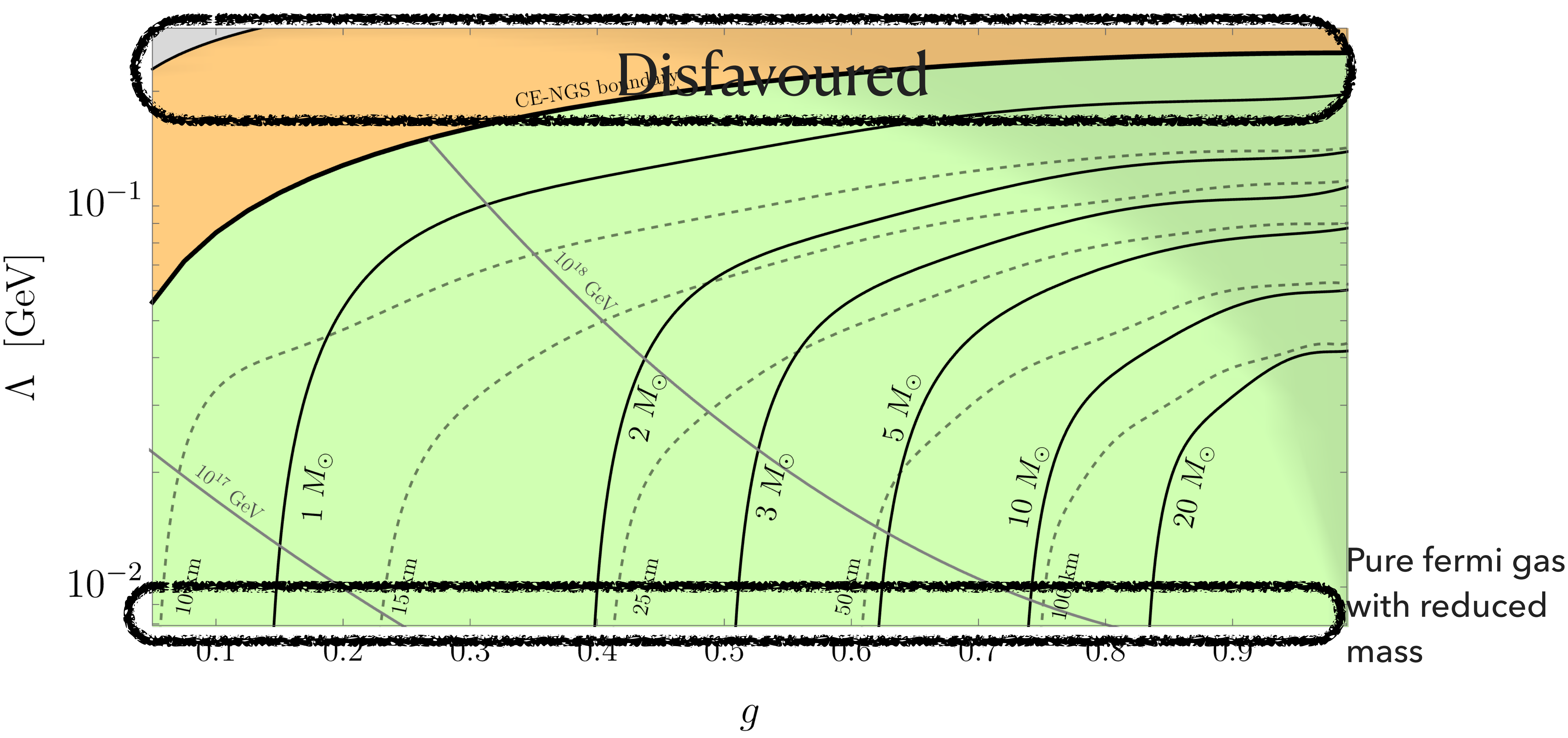


Pure fermi gas with reduced mass

Neutron stars with light scalars



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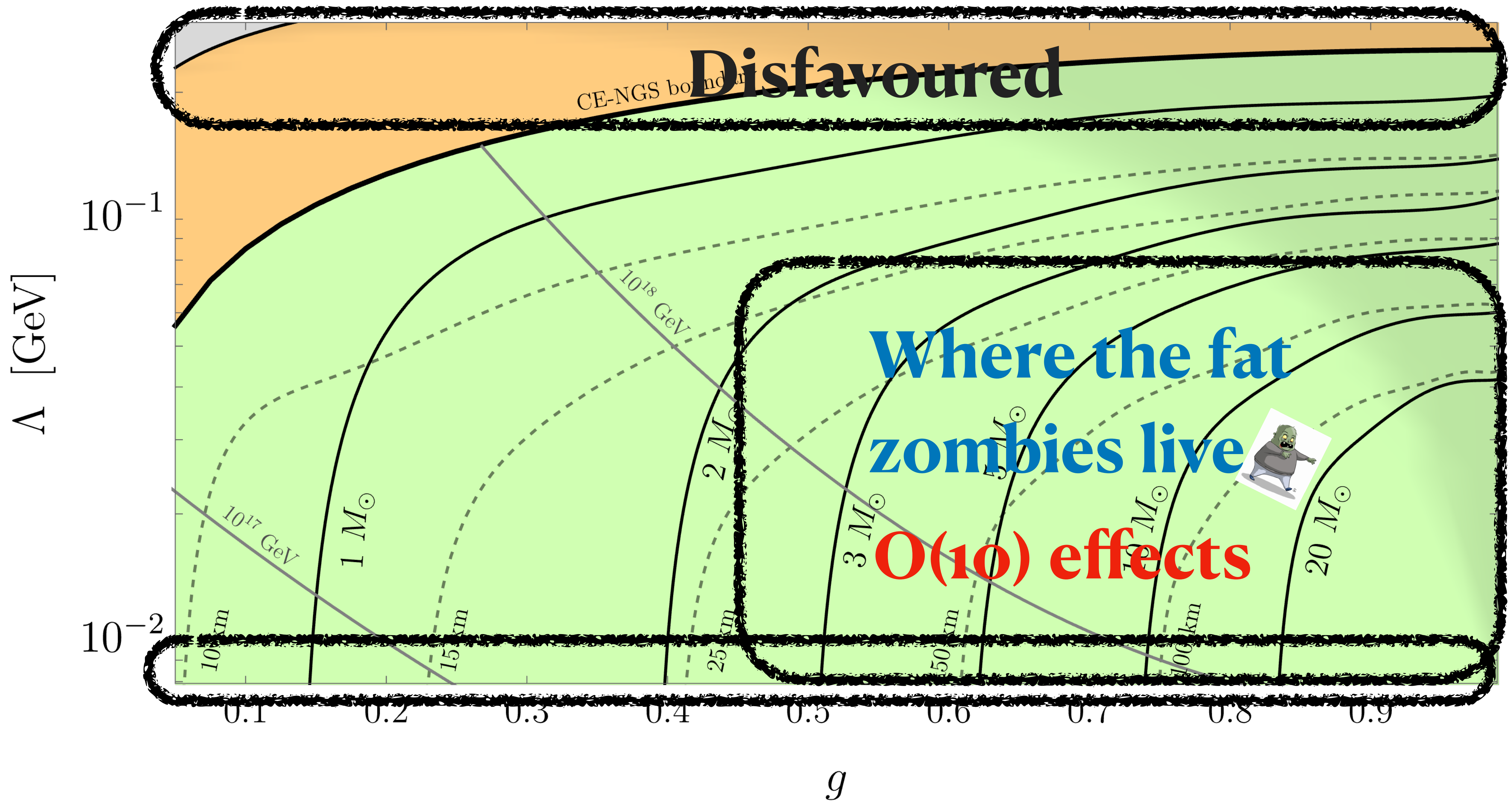

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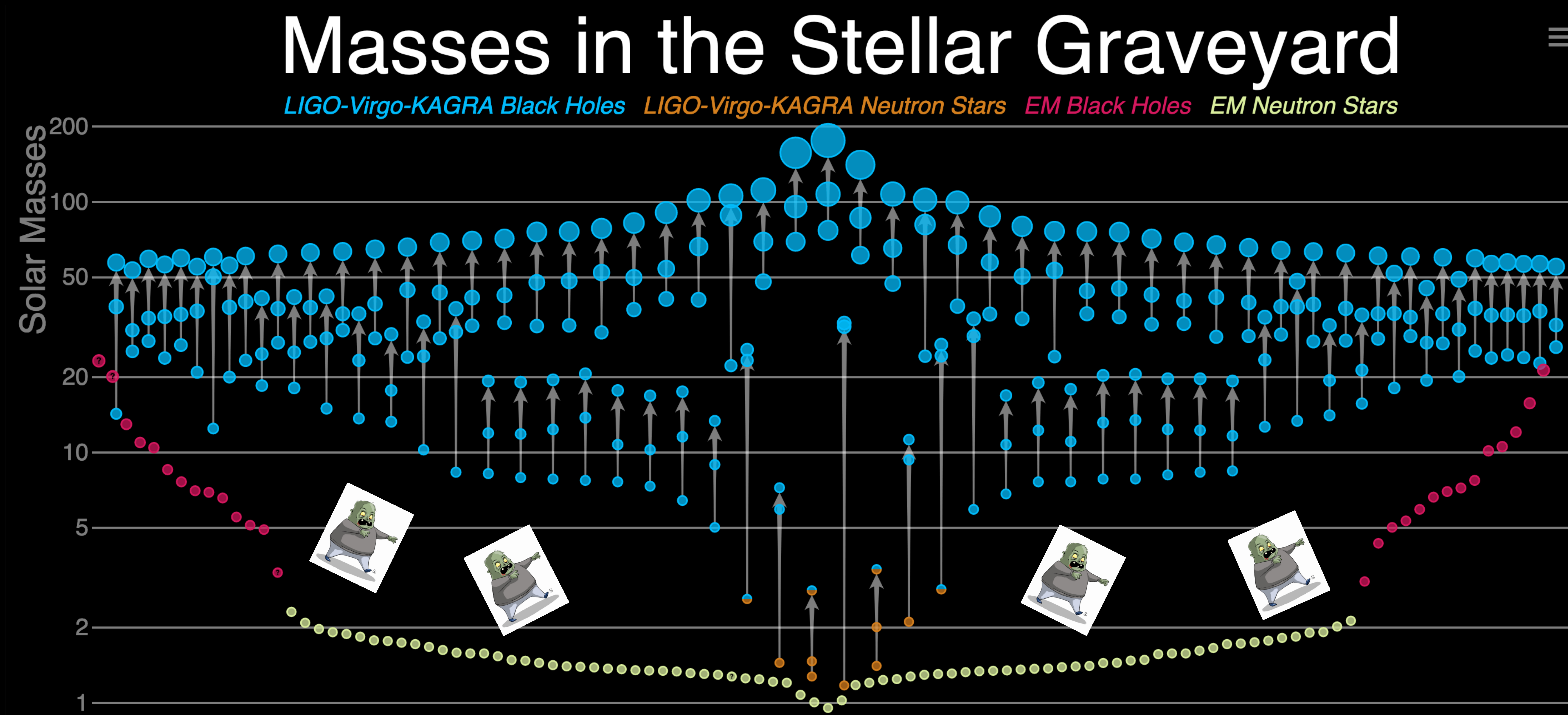
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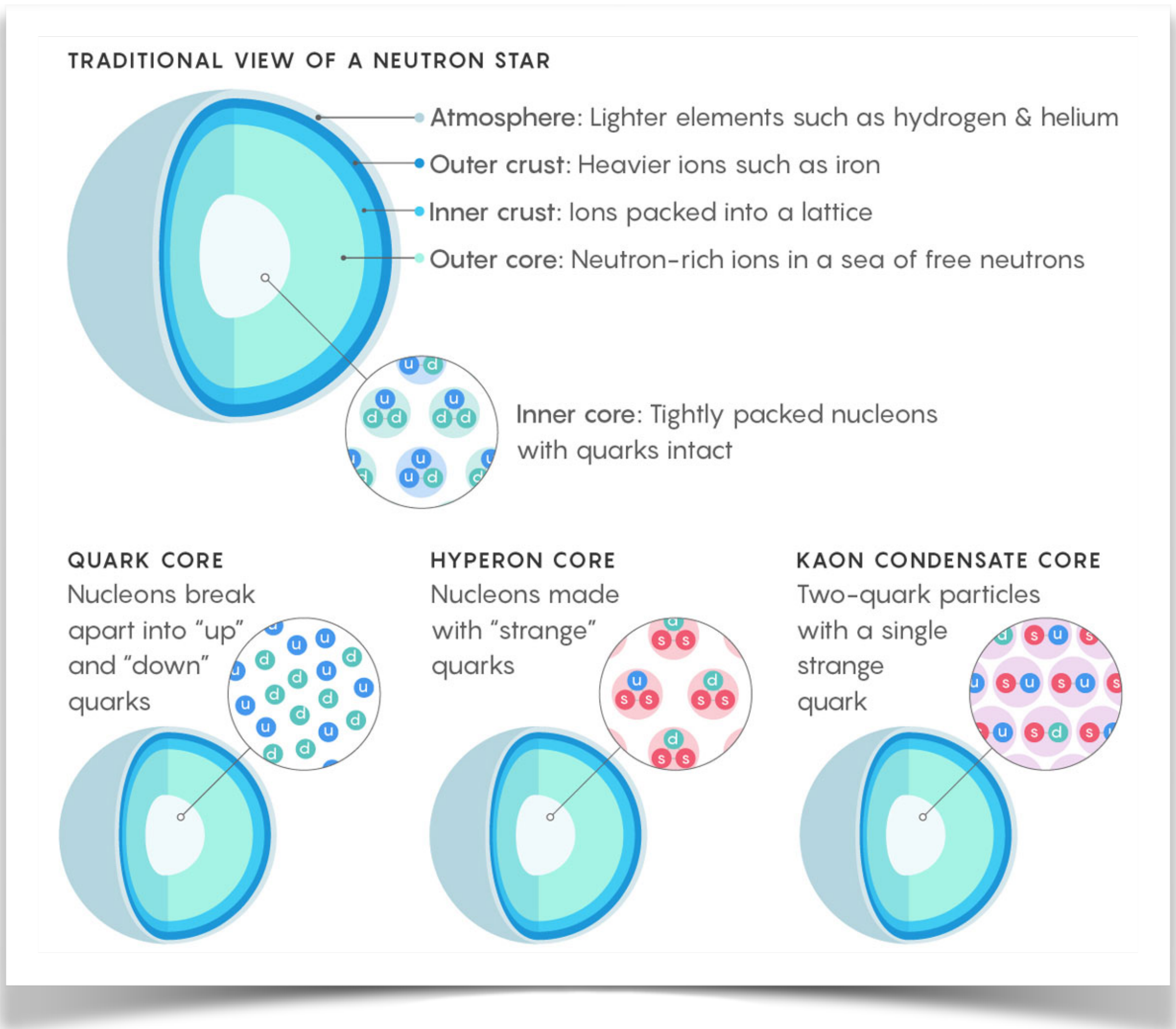
Outlook

Actual QCD Axion inside neutron stars

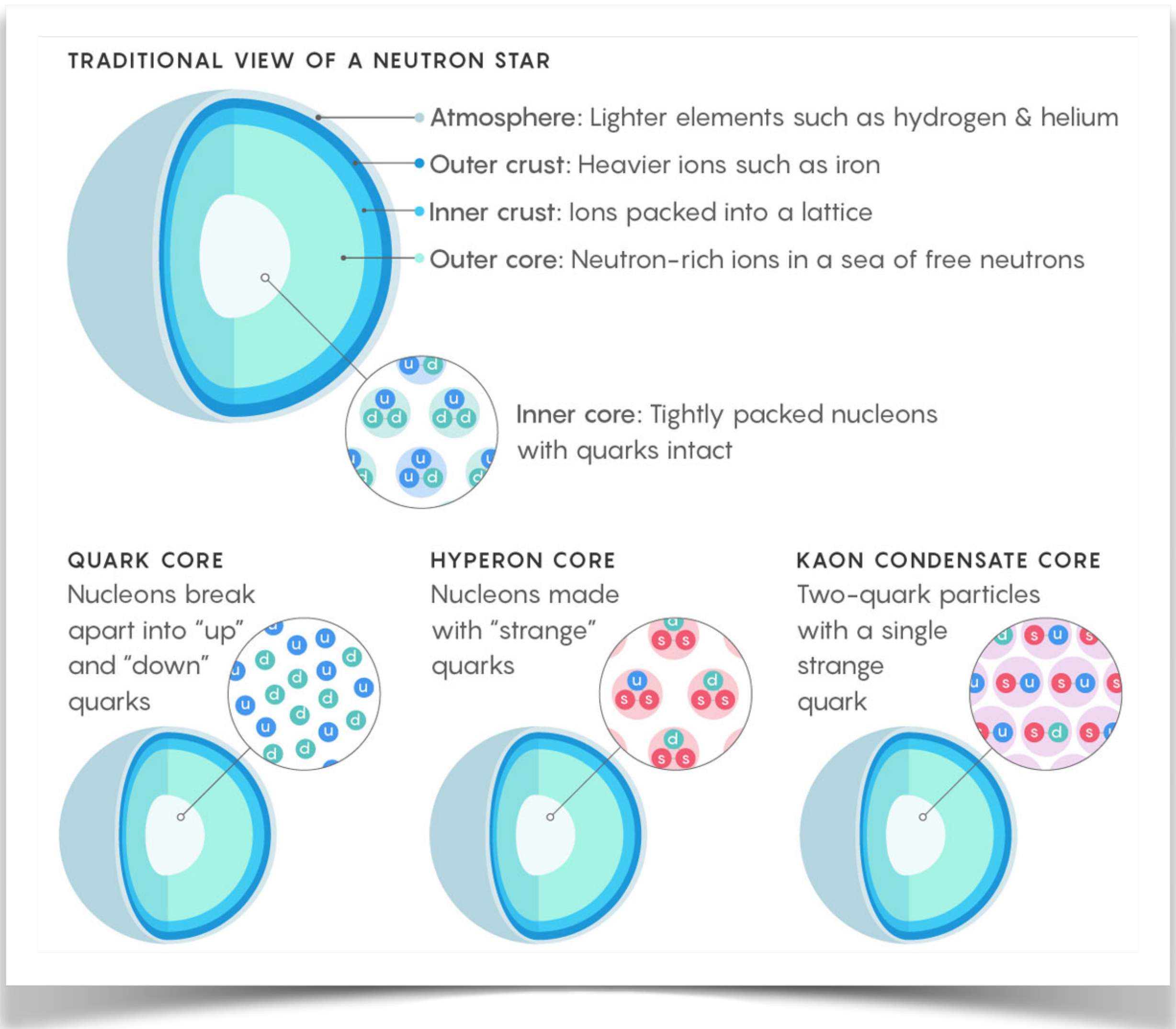


QCD phase transition sources axion:

Kaon condensation

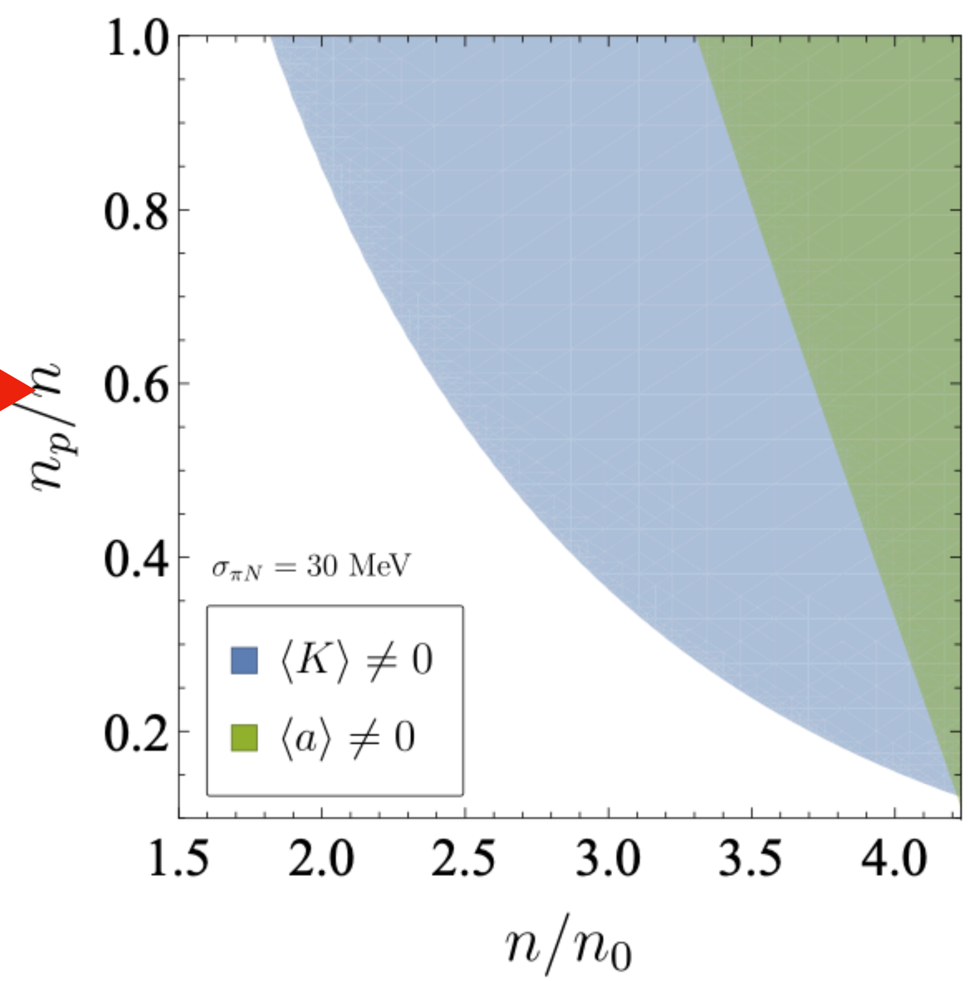
color-flavor locking at asymptotic densities

Actual QCD Axion inside neutron stars



works with QCD axion mass rela

$\epsilon \approx 1$



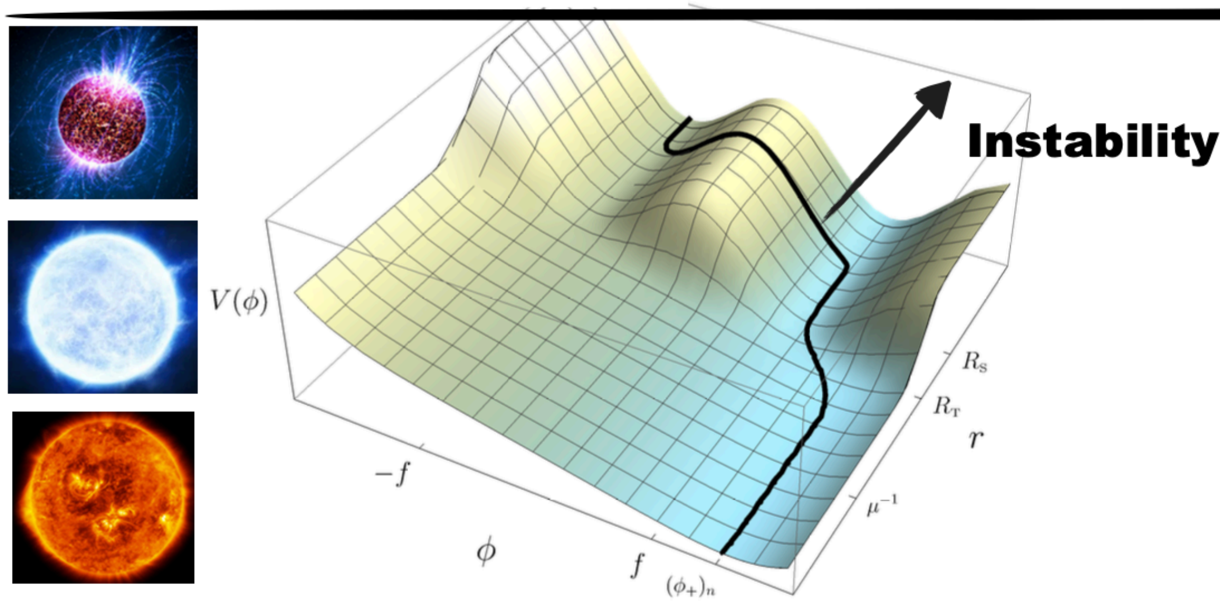
Balkin, Serra, Springmann, AW '20

QCD phase transition sources axion:

Kaon condensation

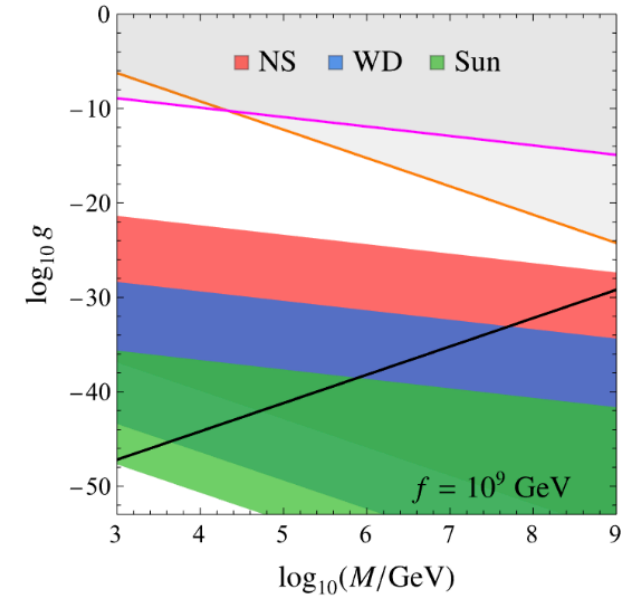
color-flavor locking at asymptotic densities

Studying density effects is fun and rewarding



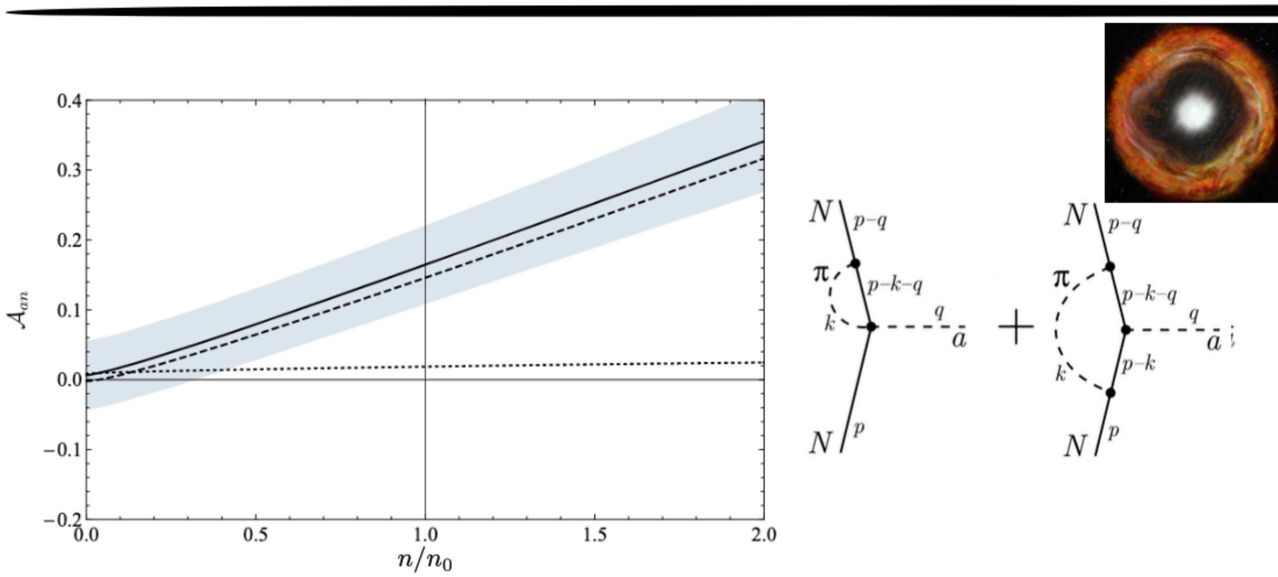
Phase Transitions from Stars

2105.13354 Balkin, Stelzl, Serra, Springman, AW



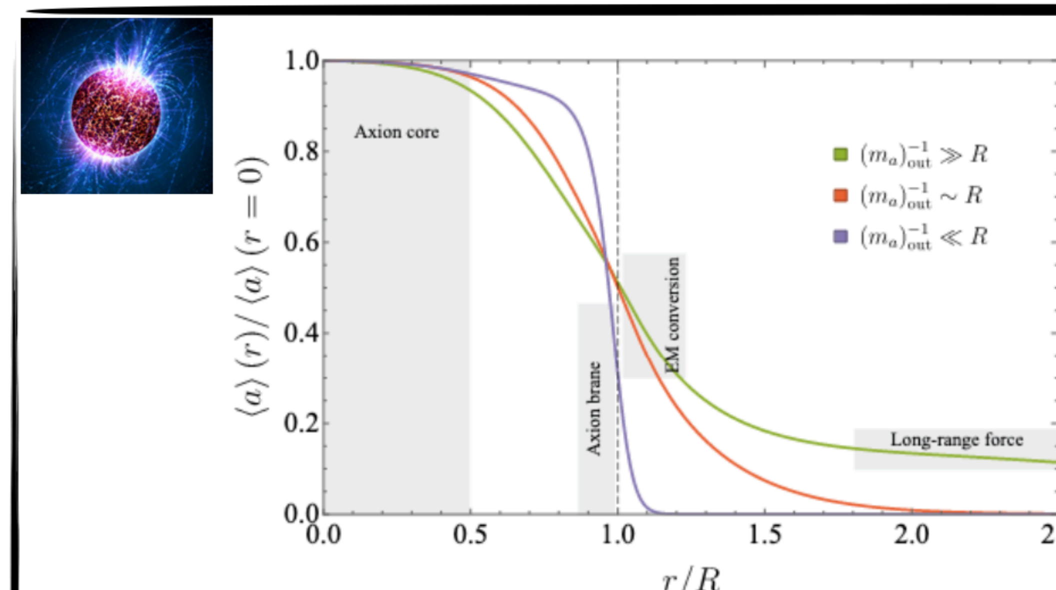
Bounds on Relaxion Models

JHEP 06 (2022) 023 Balkin, Stelzl, Serra, Springman, AW



QCD-axion—Nucleon coupling at finite density

To appear soon



The QCD axion at finite density

JHEP 07 (2020) 221 Balkin, Serra, Springman, AW

Conclusions

White dwarfs as a probe of light QCD axions

- Light QCD axions can get sourced in White Dwarfs leading to a new ground state (NG
- 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?…

Thanks and happy holidays!