The QCD axion and density effects in stars

The CA21106 1st General Meeting

Stefan Stelzl
EPFL Lausanne

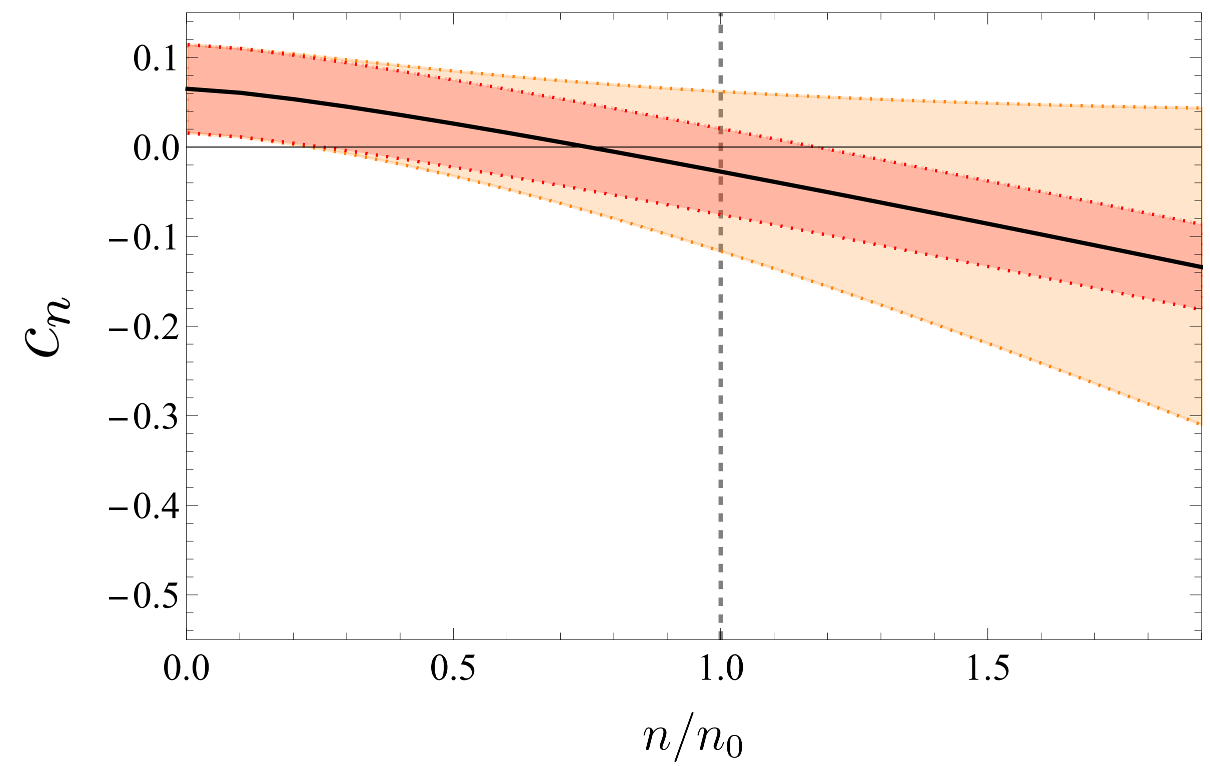
Based on 2211.02661 and 2307.14418 and work in progress
Reuven Balkin, Javi Serra, Konstantin Springmann,
Michael Stadlbauer, SS and Andreas Weiler

05.09.2023

Axion - finite density effects

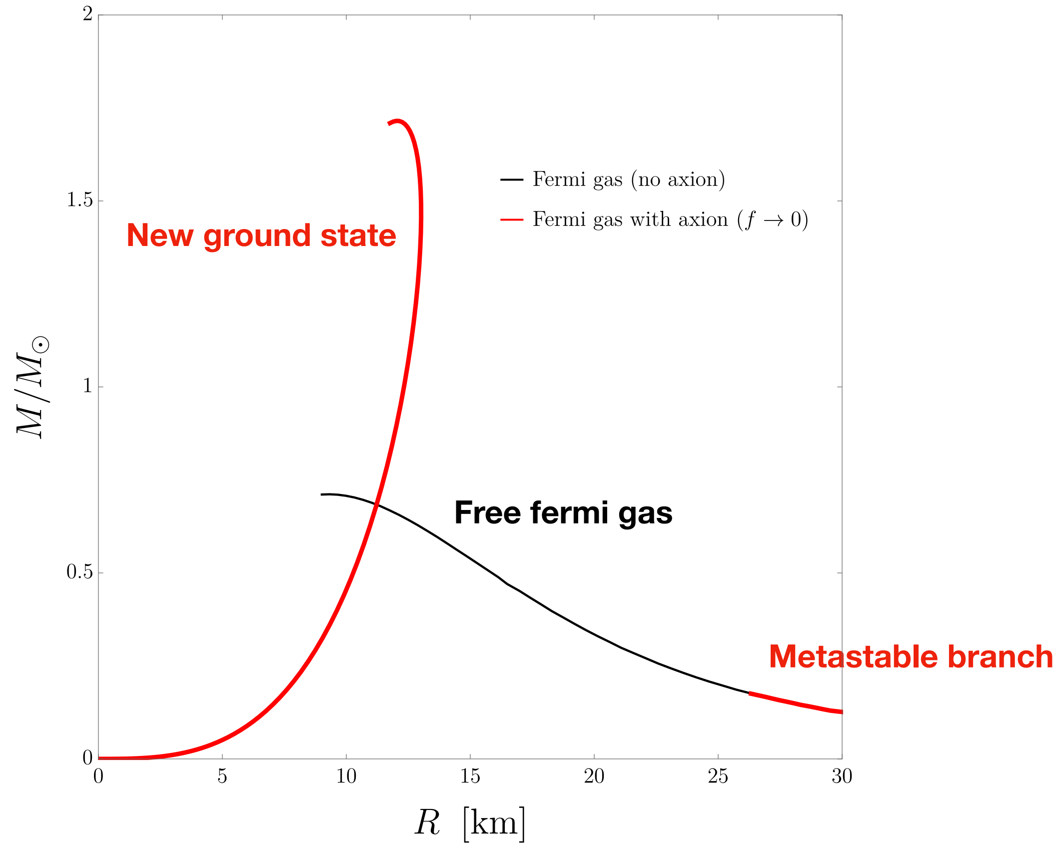
QCD axion coupling to nucleons at finite density

To appear soon
and *JHEP* 07 (2020) Balkin, Serra, Springmann, Weiler



Influence of light (pseudo-)scalars on structure of neutron stars

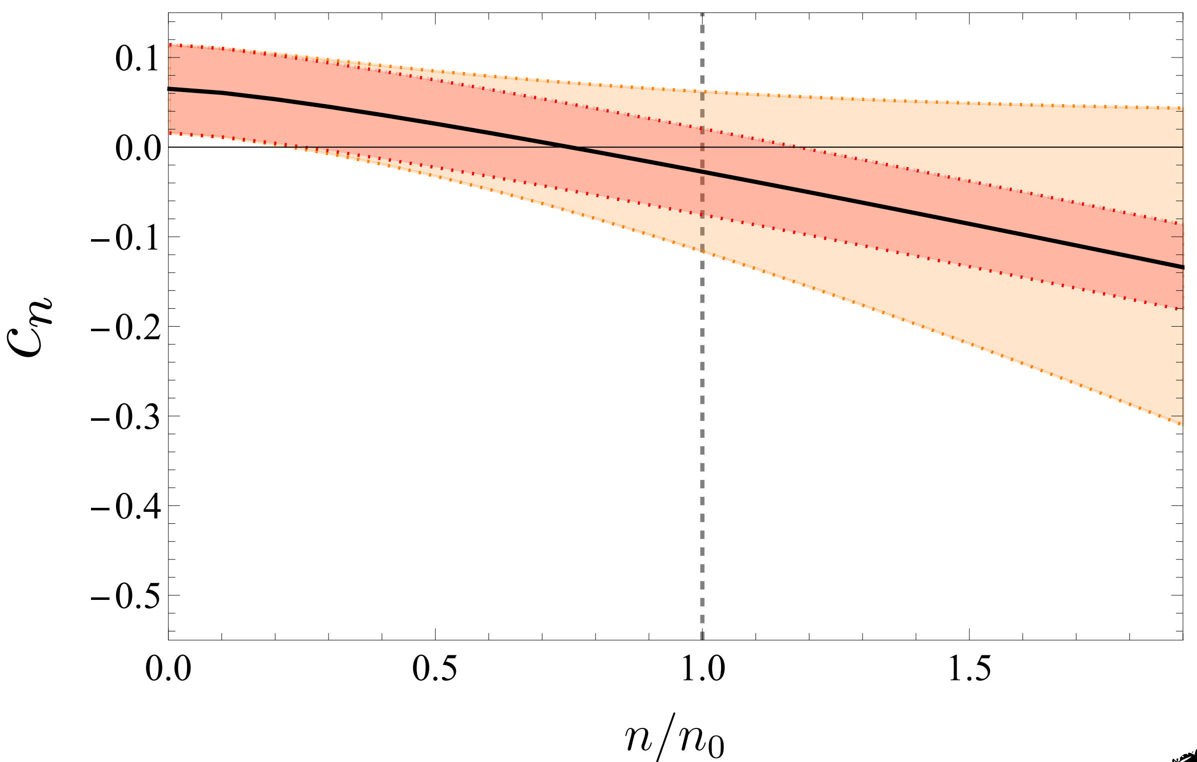
2211.02661 and 2307.14418
Balkin, Serra, Springmann, SS, Weiler



Axion - finite density effects

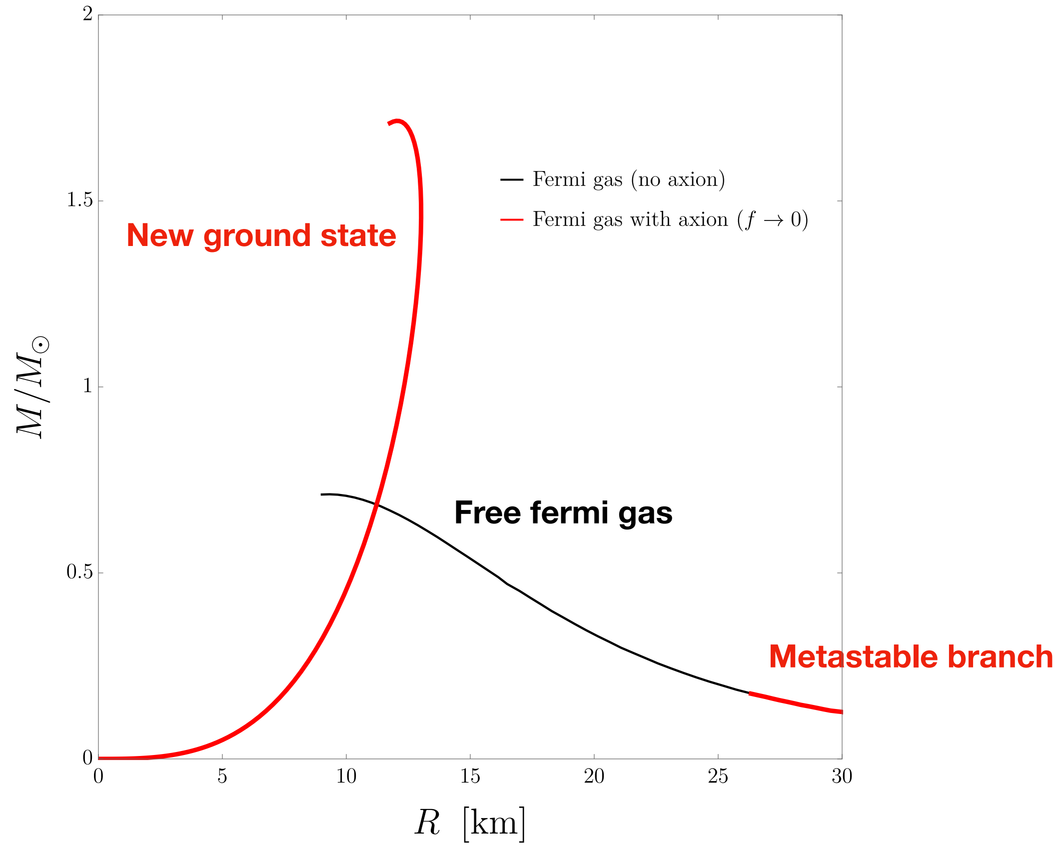
QCD axion coupling to nucleons at finite density

To appear soon
and *JHEP* 07 (2020) Balkin, Serra, Springmann, Weiler



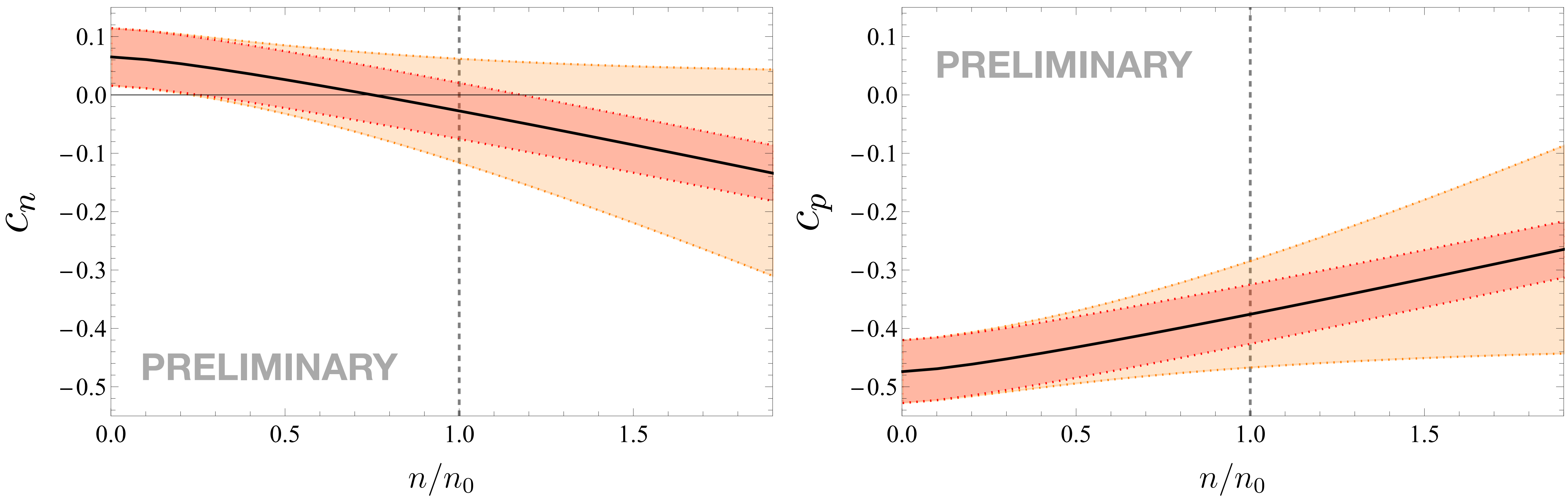
Influence of light (pseudo-)scalars on structure of neutron stars

2211.02661 and 2307.14418
Balkin, Serra, Springmann, SS, Weiler



QCD axion couplings at finite density

example: KSVZ axion



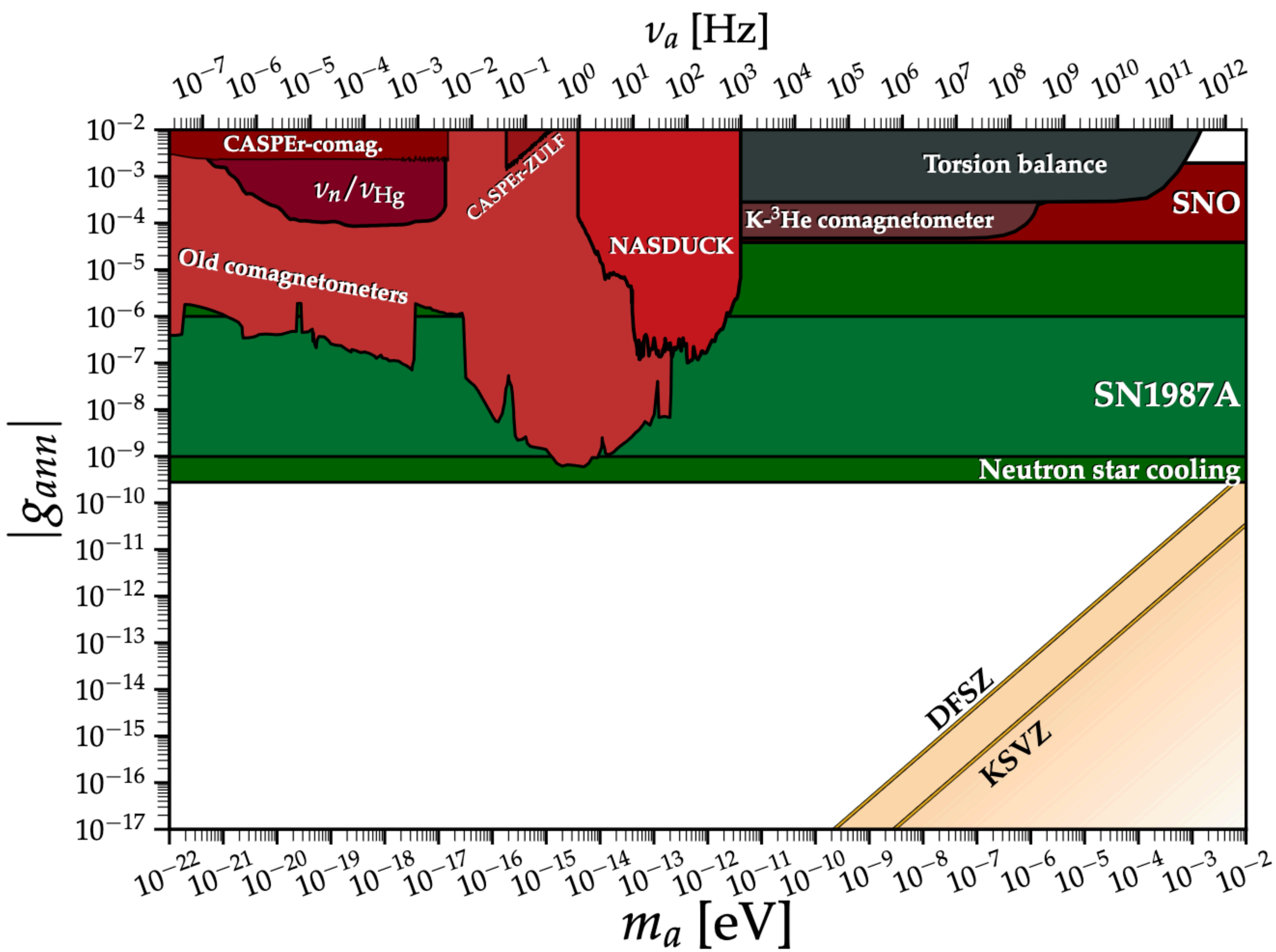
Axion couplings change in dense objects!

…but uncertainties become large at high densities…..

QCD axion couplings at finite density

Some of the best bounds on QCD axion from SN and NS cooling

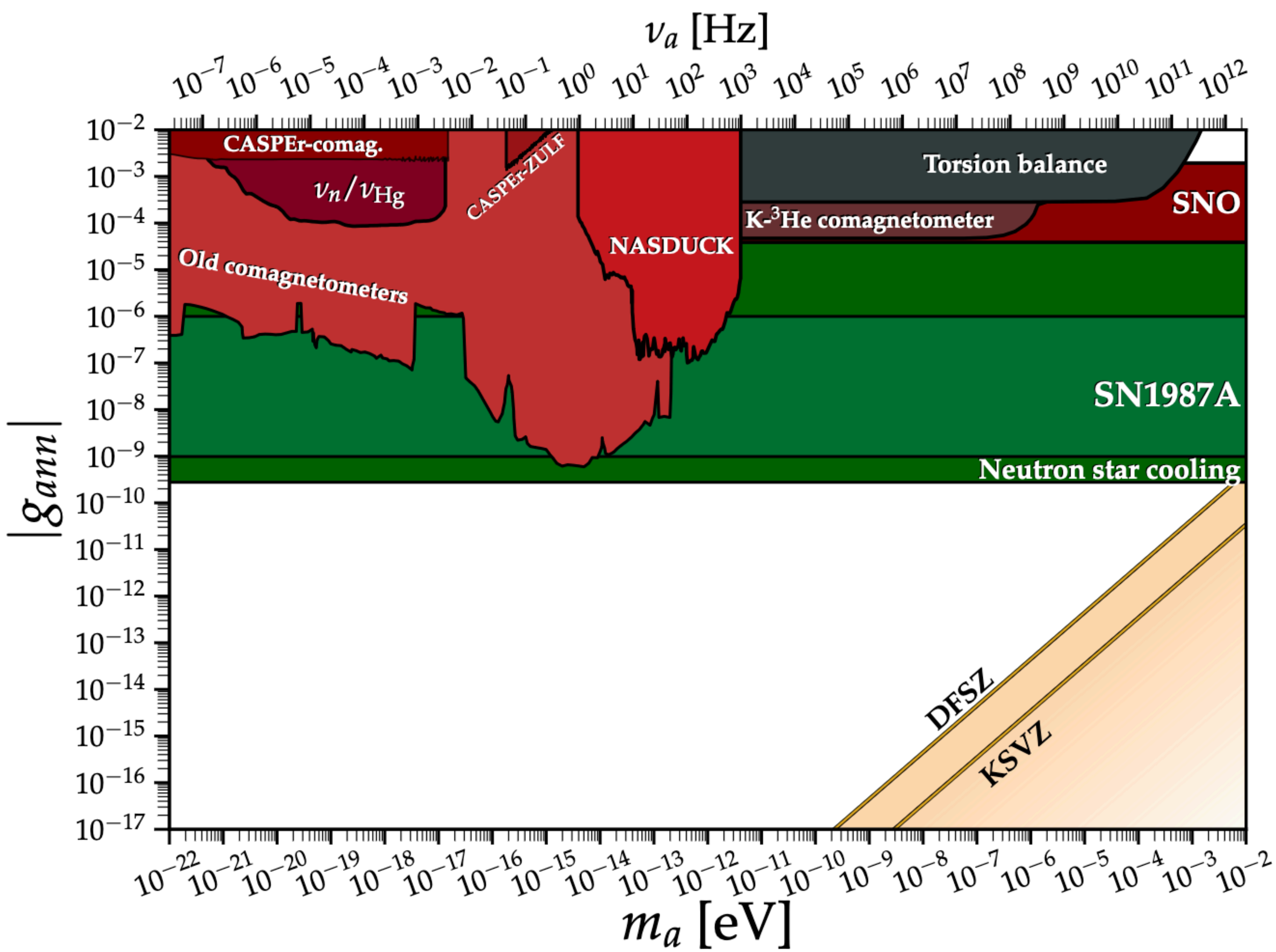
For recent bounds see e.g. Carenza et al. ’19 (SN), Buschmann et al. (NS) ‘21



QCD axion couplings at finite density

Some of the best bounds on QCD axion from SN and NS cooling

For recent bounds see e.g. Carenza et al. '19 (SN), Buschmann et al. (NS) '21



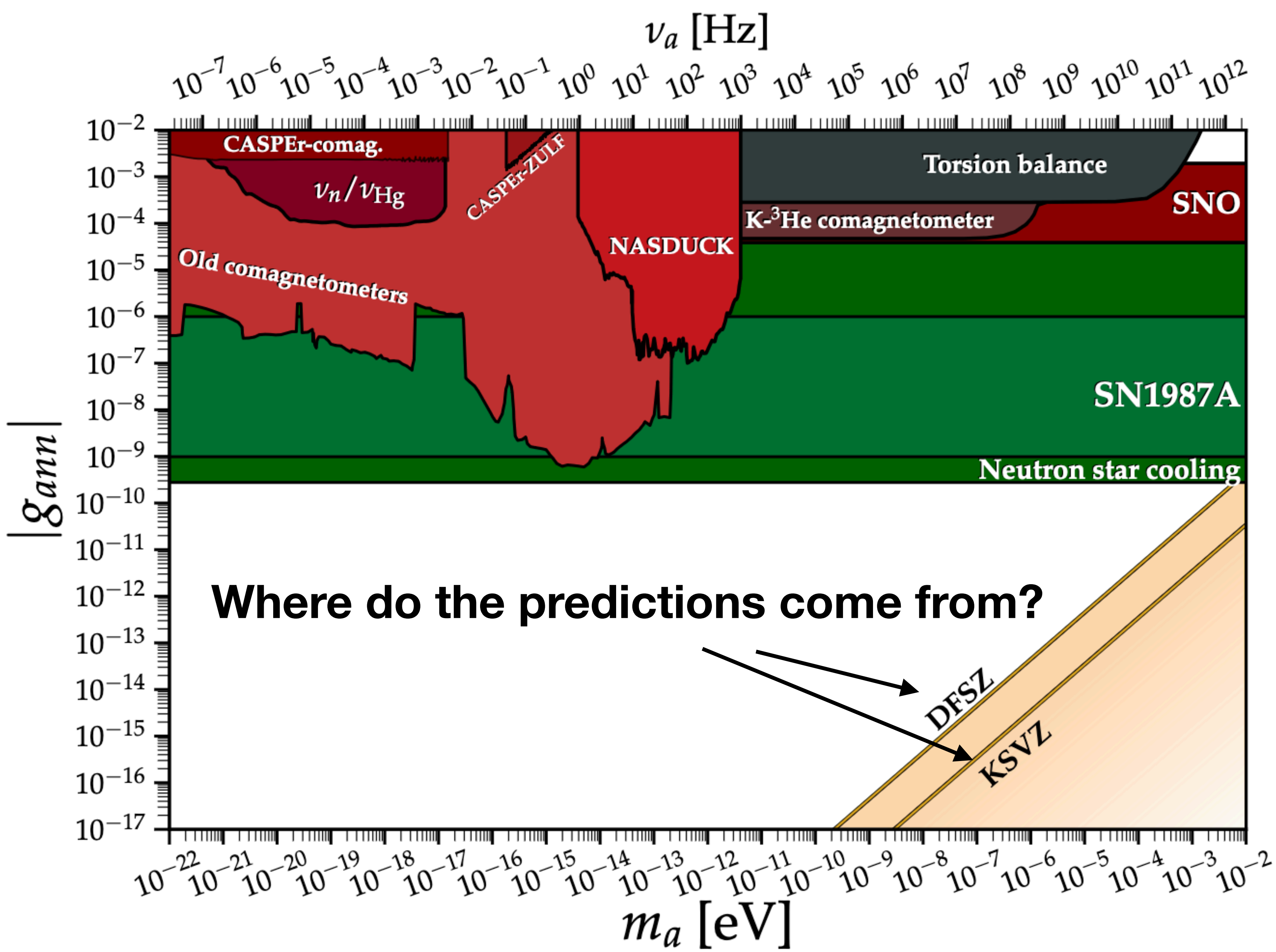
Current bounds use vacuum couplings*

*this is not completely true…

QCD axion couplings at finite density

Some of the best bounds on QCD axion from SN and NS cooling

For recent bounds see e.g. Carenza et al. '19 (SN), Buschmann et al. (NS) '21



Current bounds use vacuum couplings*

*this is not completely true…

QCD axion couplings in vacuum

GG di Cortona et al. '15

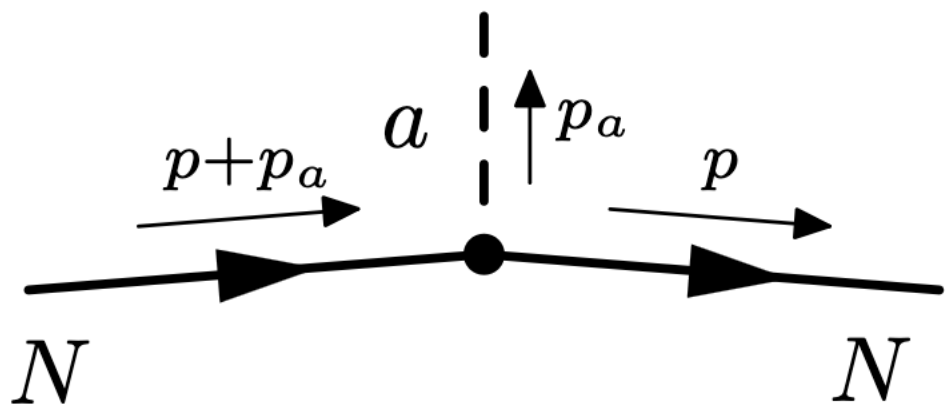
Construct low energy EFT of nucleons, pions and the QCD axion

QCD axion couplings in vacuum

GG di Cortona et al. '15

Construct low energy EFT of nucleons, pions and the QCD axion

Leading order:



$$= \quad -\frac{1}{f_a} c_N S \cdot p_a$$

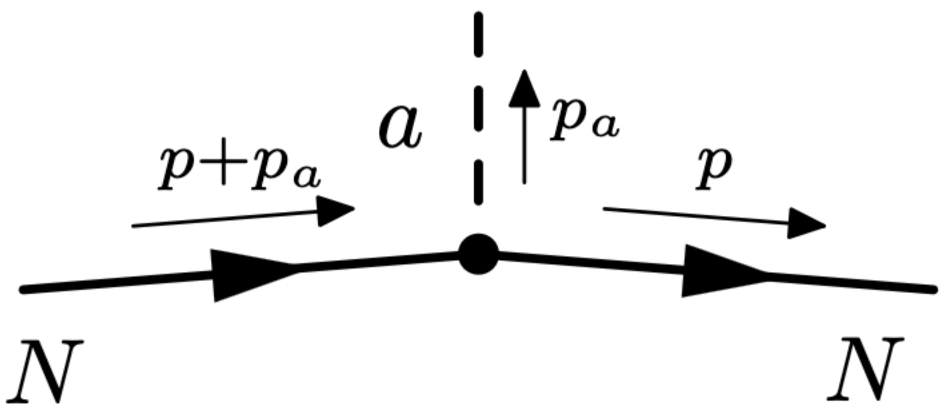
$$c_p^{\mathrm{LO,\,KSVZ}} = -0.426(36), \quad c_n^{\mathrm{LO,\,KSVZ}} = -0.008(29),$$

QCD axion couplings in vacuum

GG di Cortona et al. ‘15

Construct low energy EFT of nucleons, pions and the QCD axion

Leading order:



$$= \quad -\frac{1}{f_a} c_N S \cdot p_a$$

$$c_p^{\mathrm{LO,\,KSVZ}} = -0.426(36), \quad c_n^{\mathrm{LO,\,KSVZ}} = -0.008(29),$$

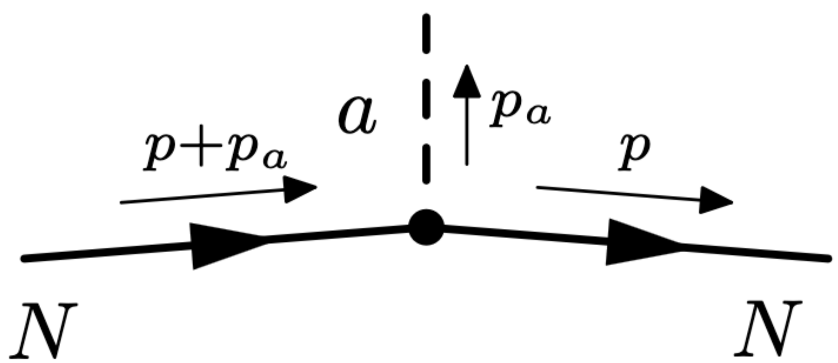
Small due to a cancellation of two unrelated terms!

QCD axion couplings in vacuum

GG di Cortona et al. '15

Construct low energy EFT of nucleons, pions and the QCD axion

Leading order:



$$= \quad -\frac{1}{f_a} c_N S \cdot p_a$$

Higher order terms also contribute → **They change vacuum couplings!**

See also Vonk et al. 2021

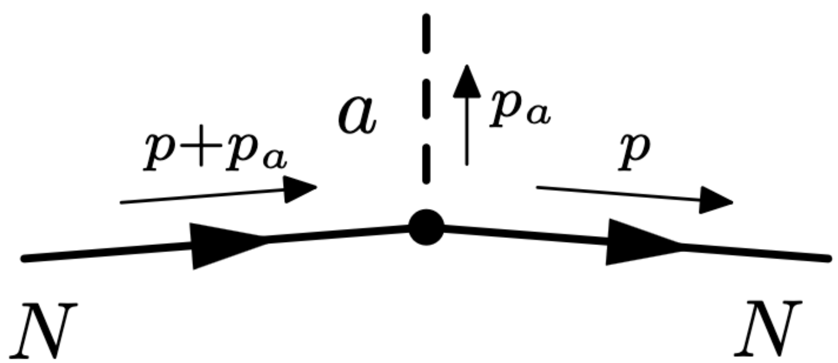
→ **They give rise to density corrections!**

QCD axion couplings in vacuum

GG di Cortona et al. ‘15

Construct low energy EFT of nucleons, pions and the QCD axion

Leading order:



$$= \quad -\frac{1}{f_a} c_N S \cdot p_a$$

Higher order terms also contribute → **They change vacuum couplings!**

See also Vonk et al. 2021

↘ **They give rise to density corrections!**

What is the validity of this EFT?

Low-lying resonances e.g. $\Delta(1232)$ **have been integrated out…**

…some terms are enhanced!

QCD axion couplings at finite density

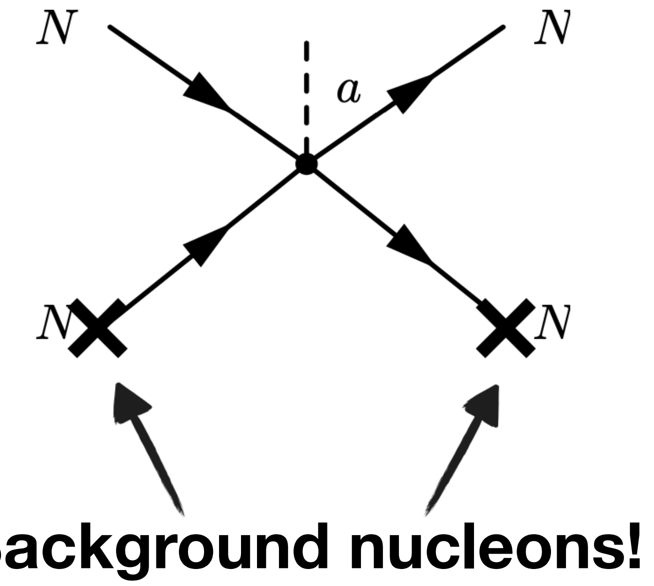
Schematic example:

$$\mathcal{L}_{\pi NN}^{(2)} = \frac{c_D}{2 f_\pi^2 \Lambda_\chi} \left(\bar{N} N\right) \left(\bar{N} S \cdot u N\right)$$

QCD axion couplings at finite density

Schematic example:

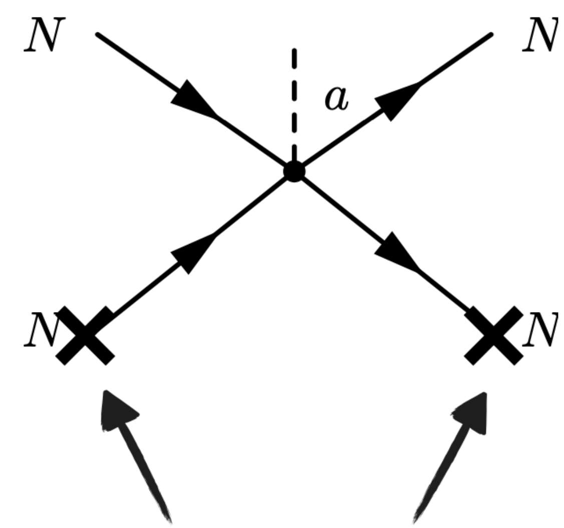
$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2 f_\pi^2 \Lambda_\chi} \left(\bar{N} N\right) \left(\bar{N} S \cdot u N\right)$$



QCD axion couplings at finite density

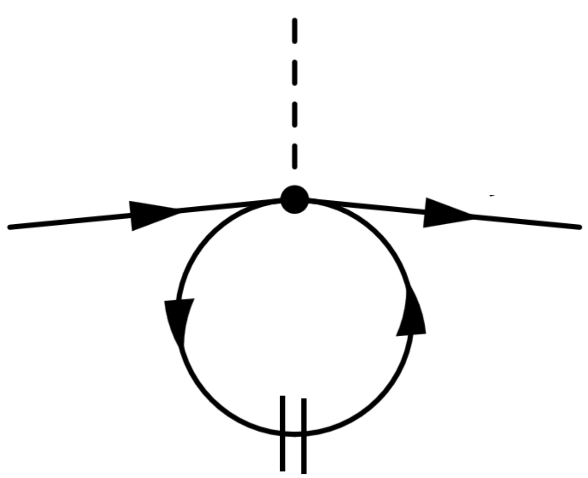
Schematic example:

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2f_\pi^2\Lambda_\chi}\left(\bar{N}N\right)\left(\bar{N}S\cdot uN\right)$$



Background nucleons!

More concretely:



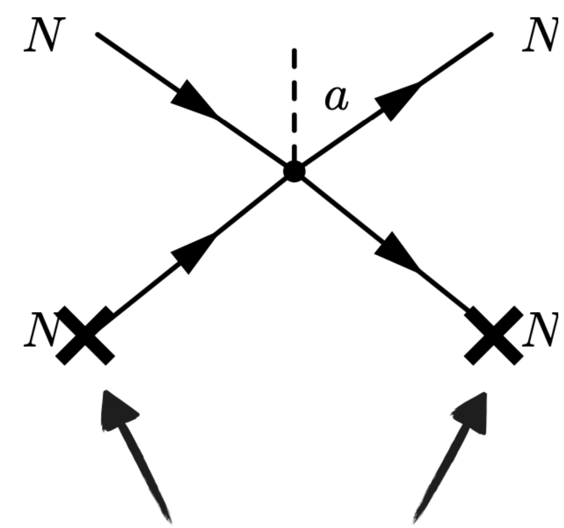
With finite density propagator:

$$iG(k) = \frac{i}{k^0 + i\epsilon} - 2\pi\delta(k^0)\theta(k_f - |\vec{k}|)$$

QCD axion couplings at finite density

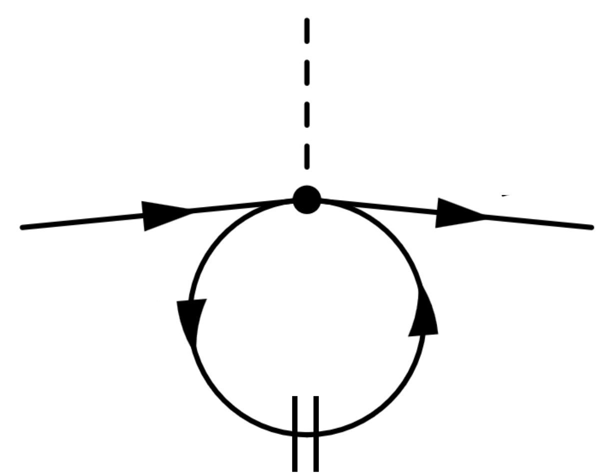
Schematic example:

$$\mathcal{L}^{(2)}_{\pi NN} = \frac{c_D}{2 f_\pi^2 \Lambda_\chi} \left(\bar{N} N\right) \left(\bar{N} S \cdot u N\right)$$



Background nucleons!

More concretely:



Filled 'Fermi sea'

With finite density propagator:

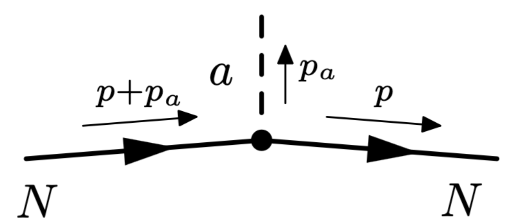
$$iG(k) = \frac{i}{k^0 + i\epsilon} - 2\pi\delta(k^0)\theta(k_f - |\vec{k}|)$$

NR fermion propagator

QCD axion couplings at finite density

Systematic expansion in nucleon momenta: $\left(\frac{k}{4\pi f_\pi}\right)^\nu \to \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

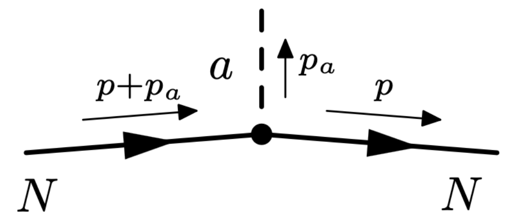
$$\left(\frac{k_f}{4\pi f_\pi}\right)^0$$



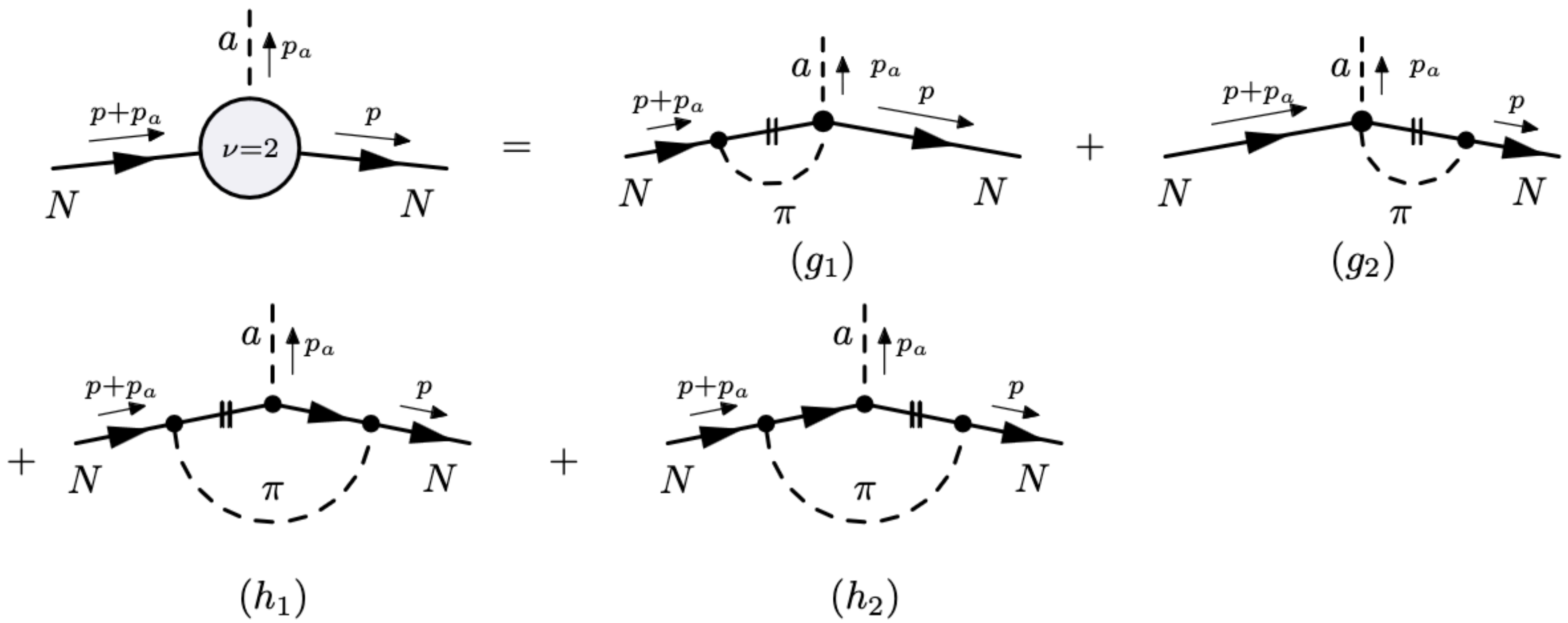
QCD axion couplings at finite density

Systematic expansion in nucleon momenta: $\left(\frac{k}{4\pi f_\pi}\right)^\nu \to \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

$\left(\frac{k_f}{4\pi f_\pi}\right)^0$



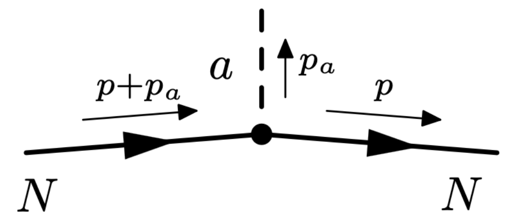
$\left(\frac{k_f}{4\pi f_\pi}\right)^2$



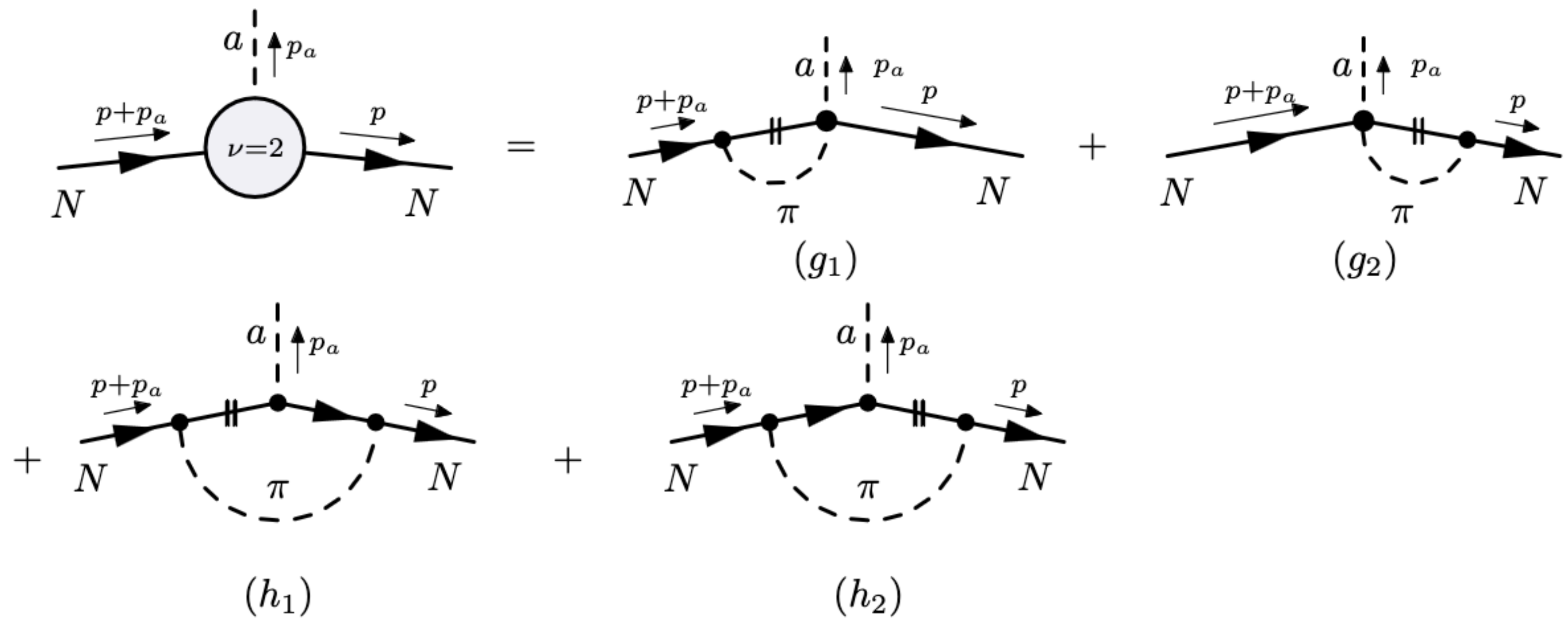
QCD axion couplings at finite density

Systematic expansion in nucleon momenta: $\left(\frac{k}{4\pi f_\pi}\right)^\nu \to \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

$$\left(\frac{k_f}{4\pi f_\pi}\right)^0$$



$$\left(\frac{k_f}{4\pi f_\pi}\right)^2$$



Naively this is suppressed in the chiral expansion…

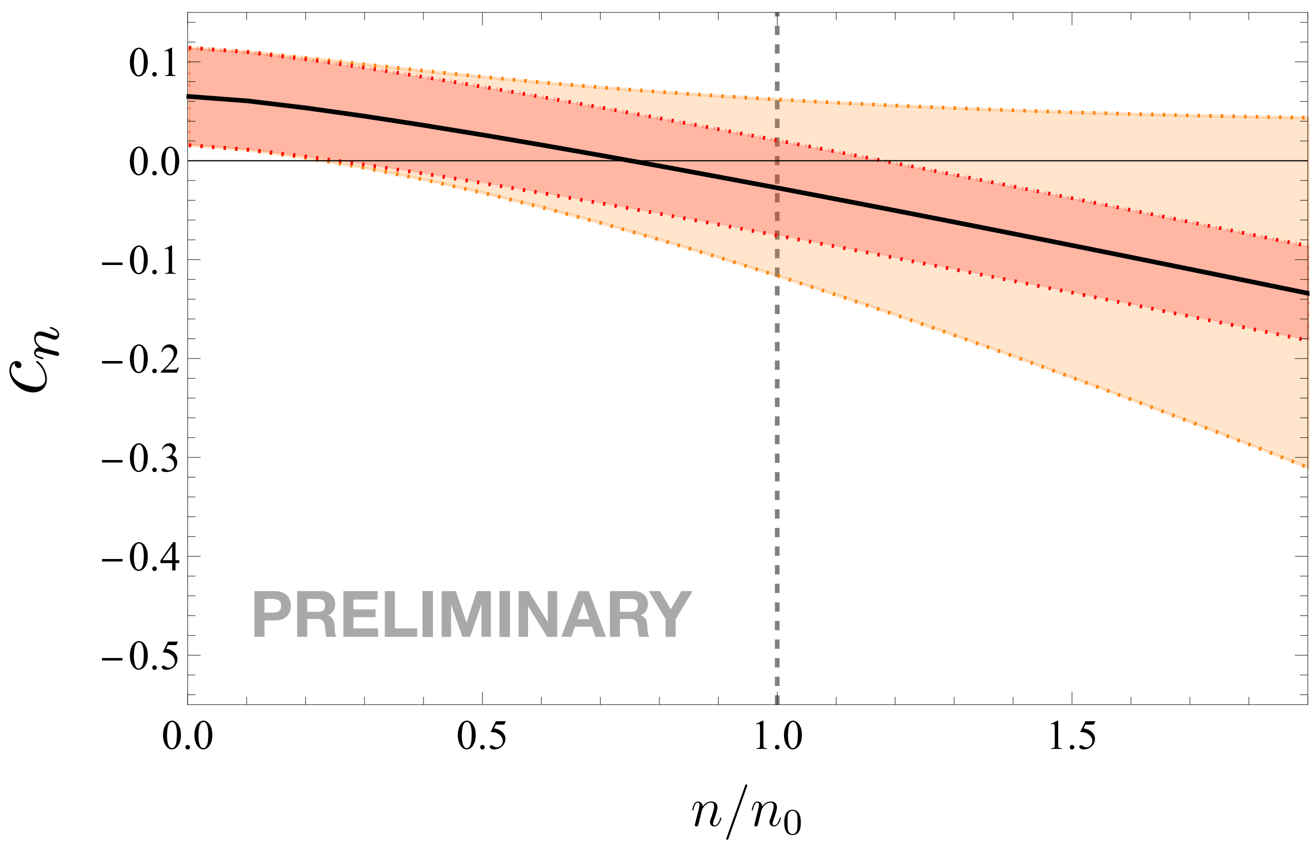
… but due to $\Delta(1232)$ resonances some corrections are large!

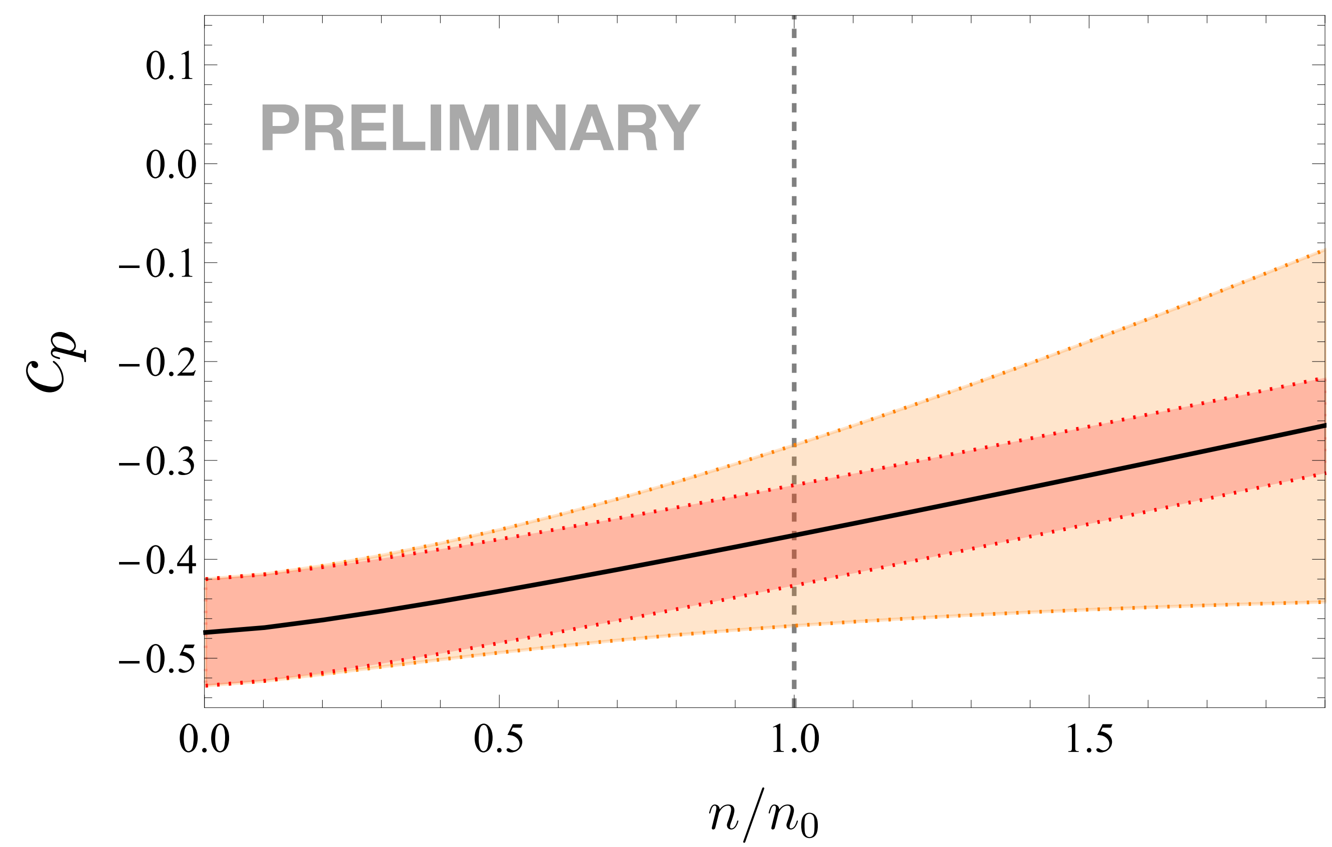
This happens the first time at $\nu = 3$

Results

Example 1:

KSVZ axion

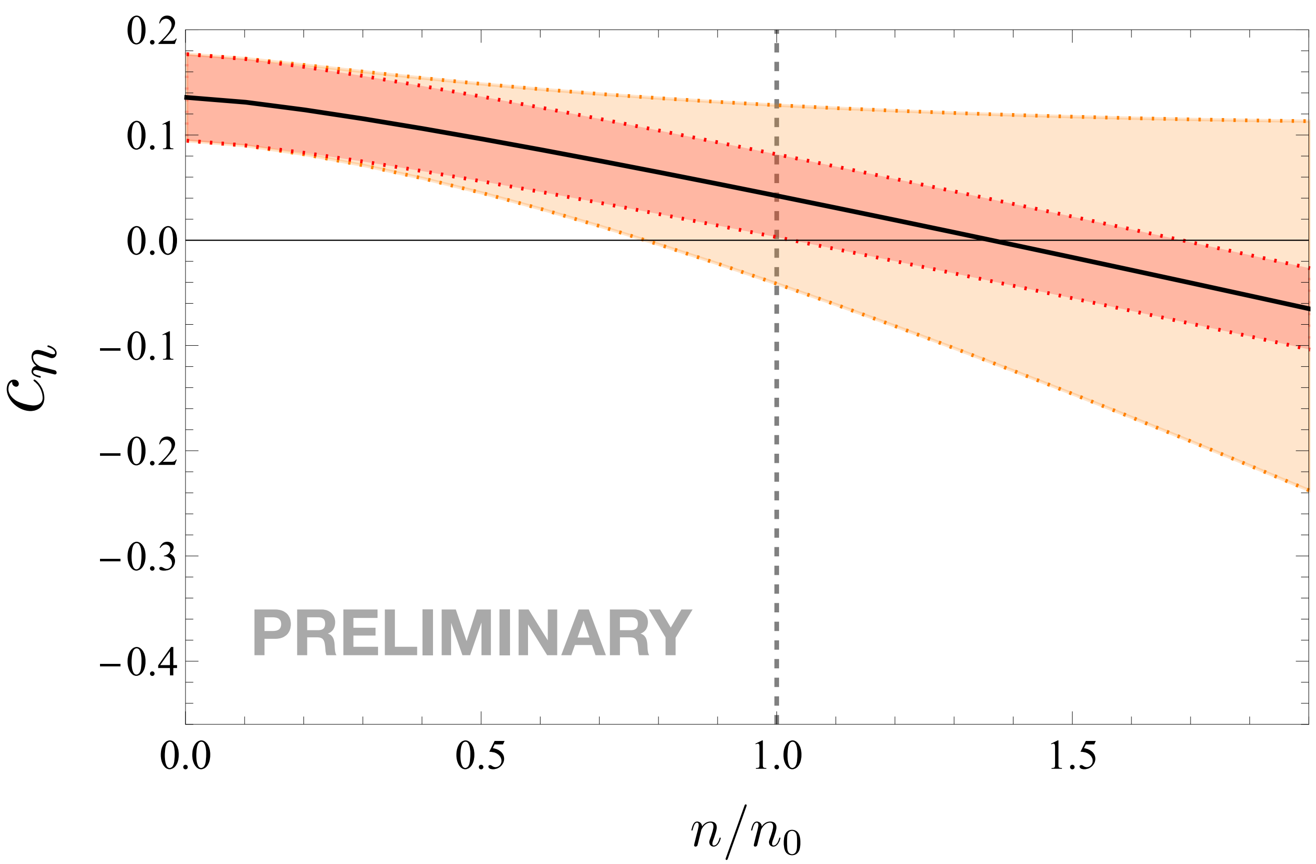


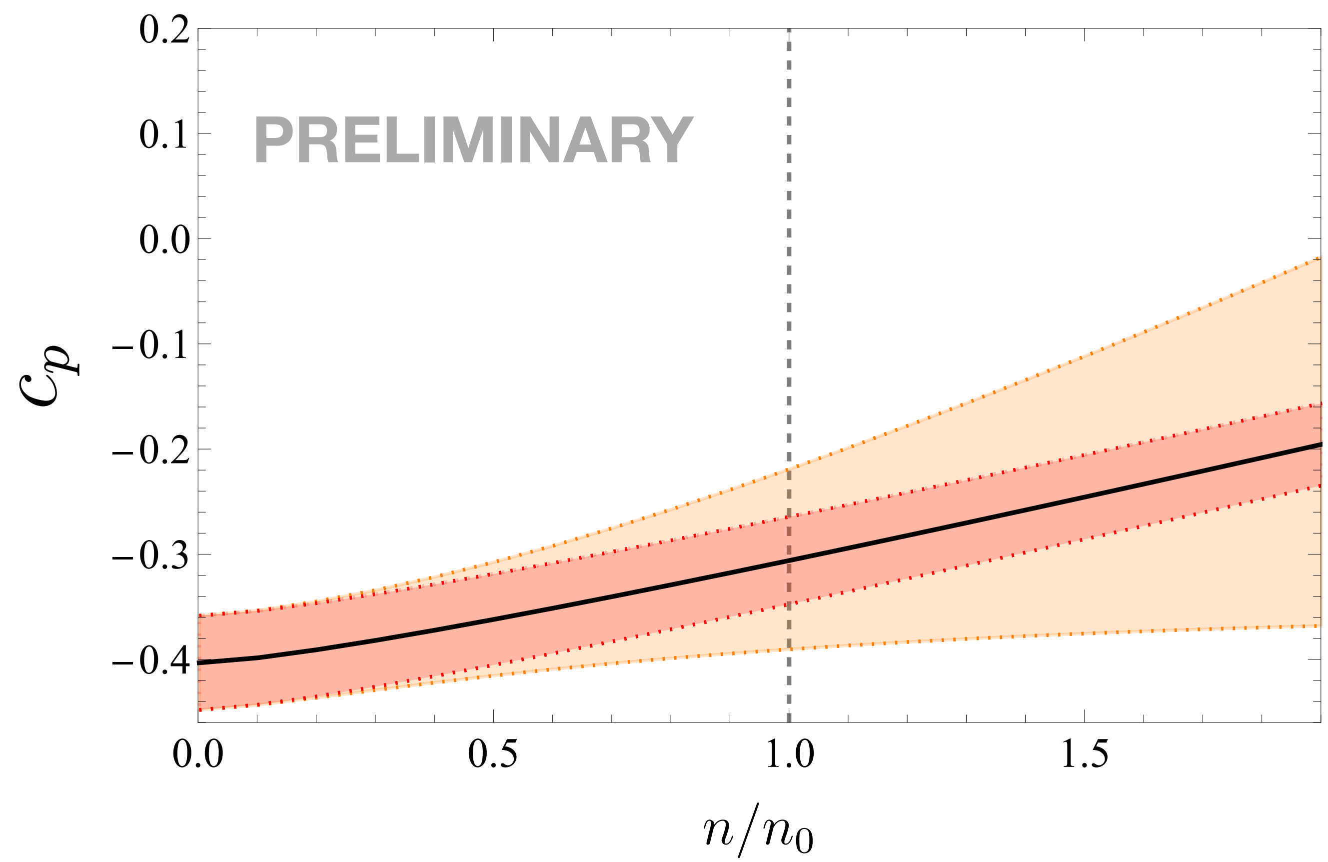


Results

Example 2:

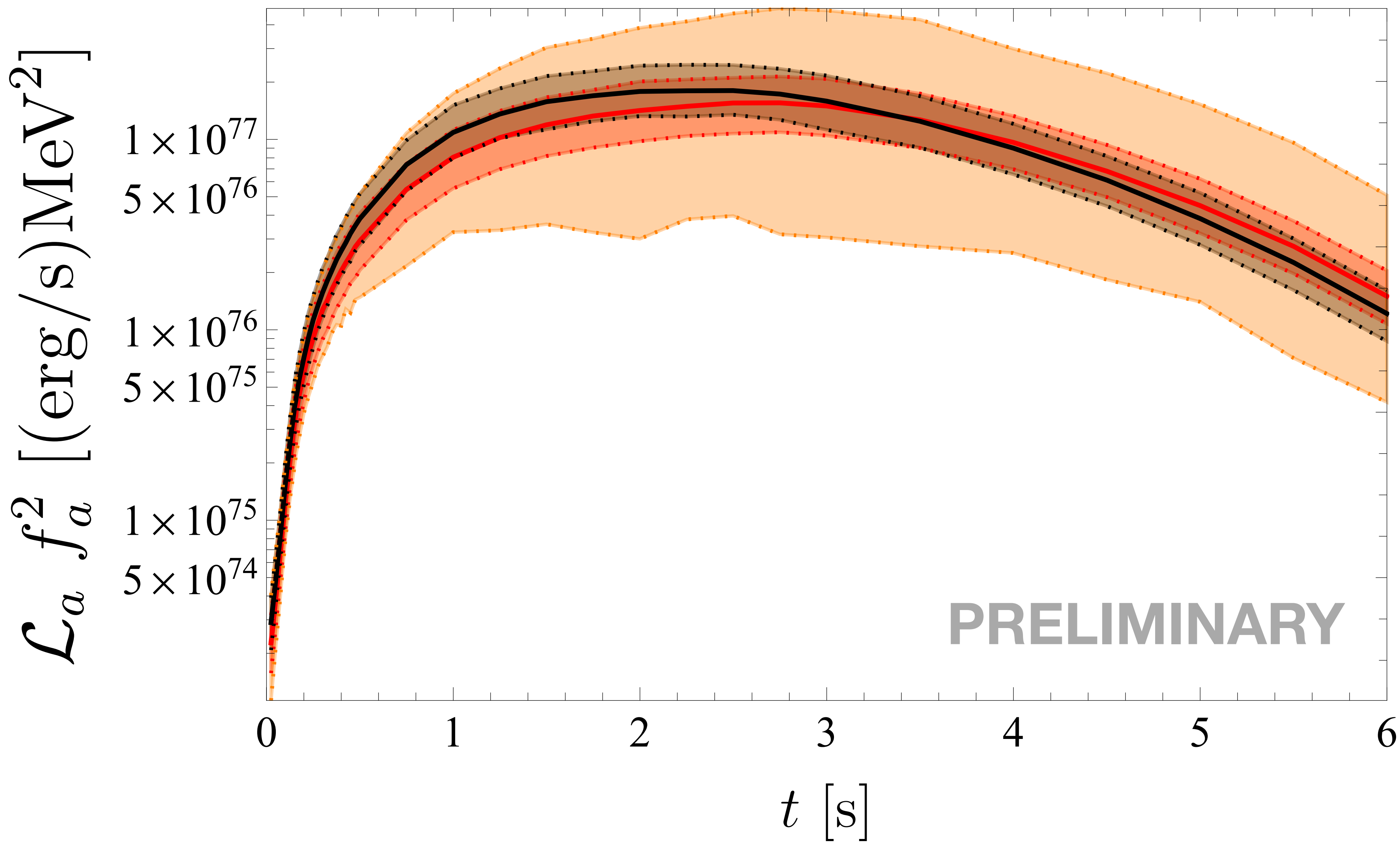
DFSZ axion $\sin^2(\beta) = 1/2$





Implications for supernova bound

example: KSVZ axion



Supernova profile from https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

Changes the SN bound by O(1)

Adds large uncertainty

Implications for neutron star cooling

High densities inside NS of $n \sim O(\mathrm{few}) n_0$

ChPT expansion breaks down at these densities!

Implications for neutron star cooling

High densities inside NS of $n \sim O(\mathrm{few}) n_0$

ChPT expansion breaks down at these densities!

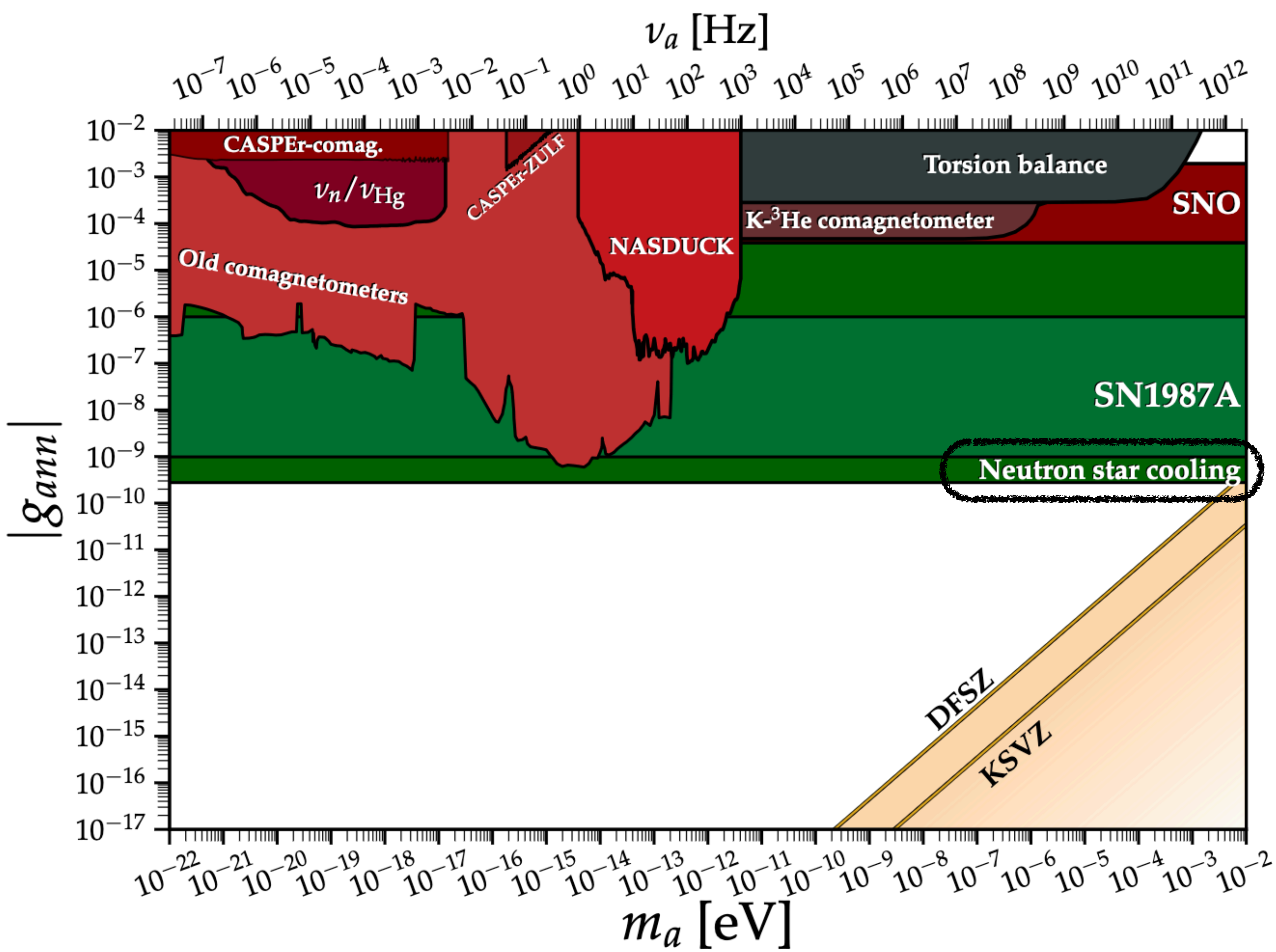
No way to consistently calculate the axion couplings

↓

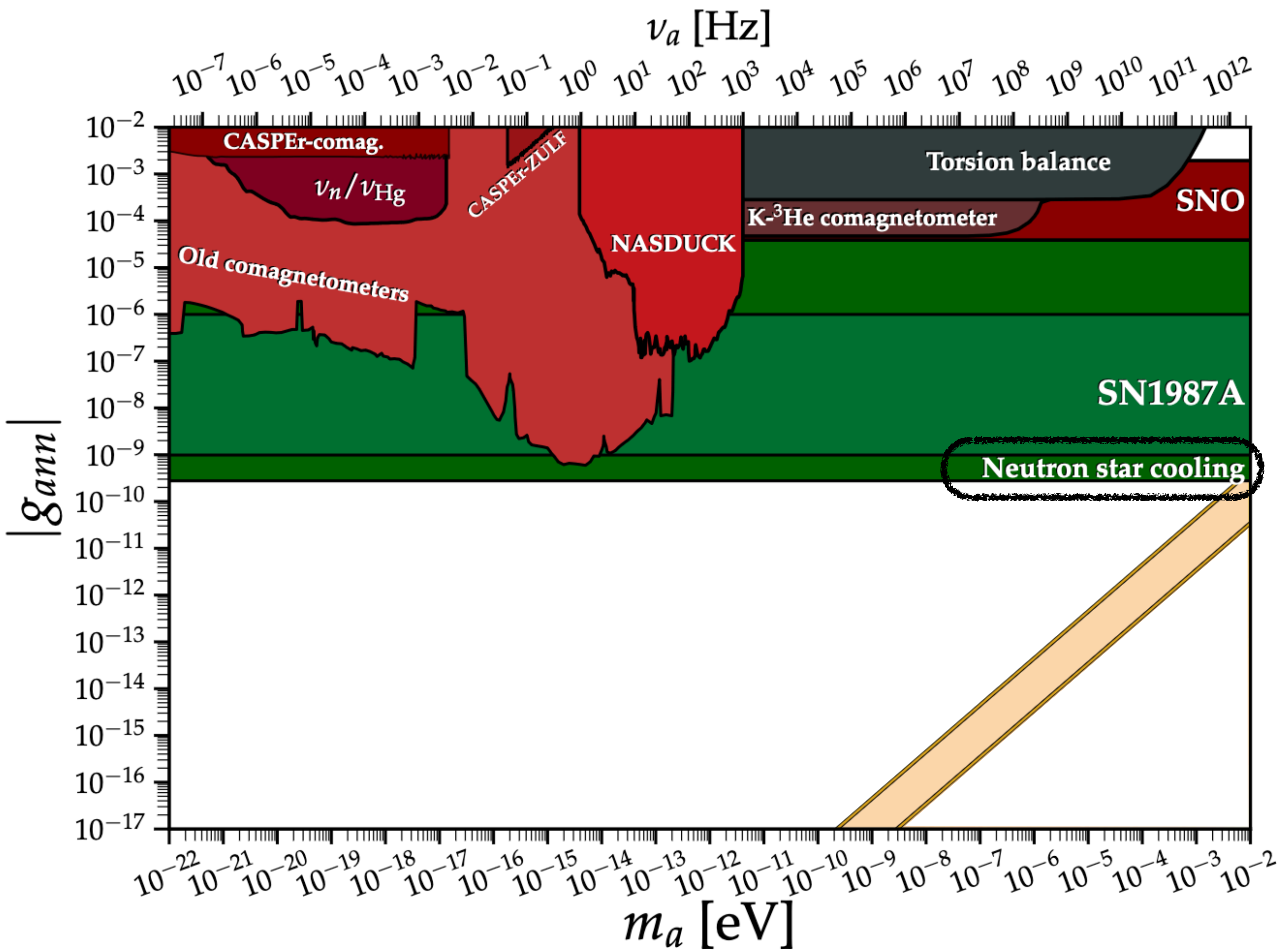
No distinction between models possible, only order of magnitude estimates

e.g. $|c_N| \sim O(0.3) \pm 0.3$

Implications for neutron star cooling



Implications for neutron star cooling



Astrophobic axions or a model-independent SN bound

di Luzio et al. ‘15

Some aspects of ‘astrophobic axion’ survive at finite density, only subleading corrections

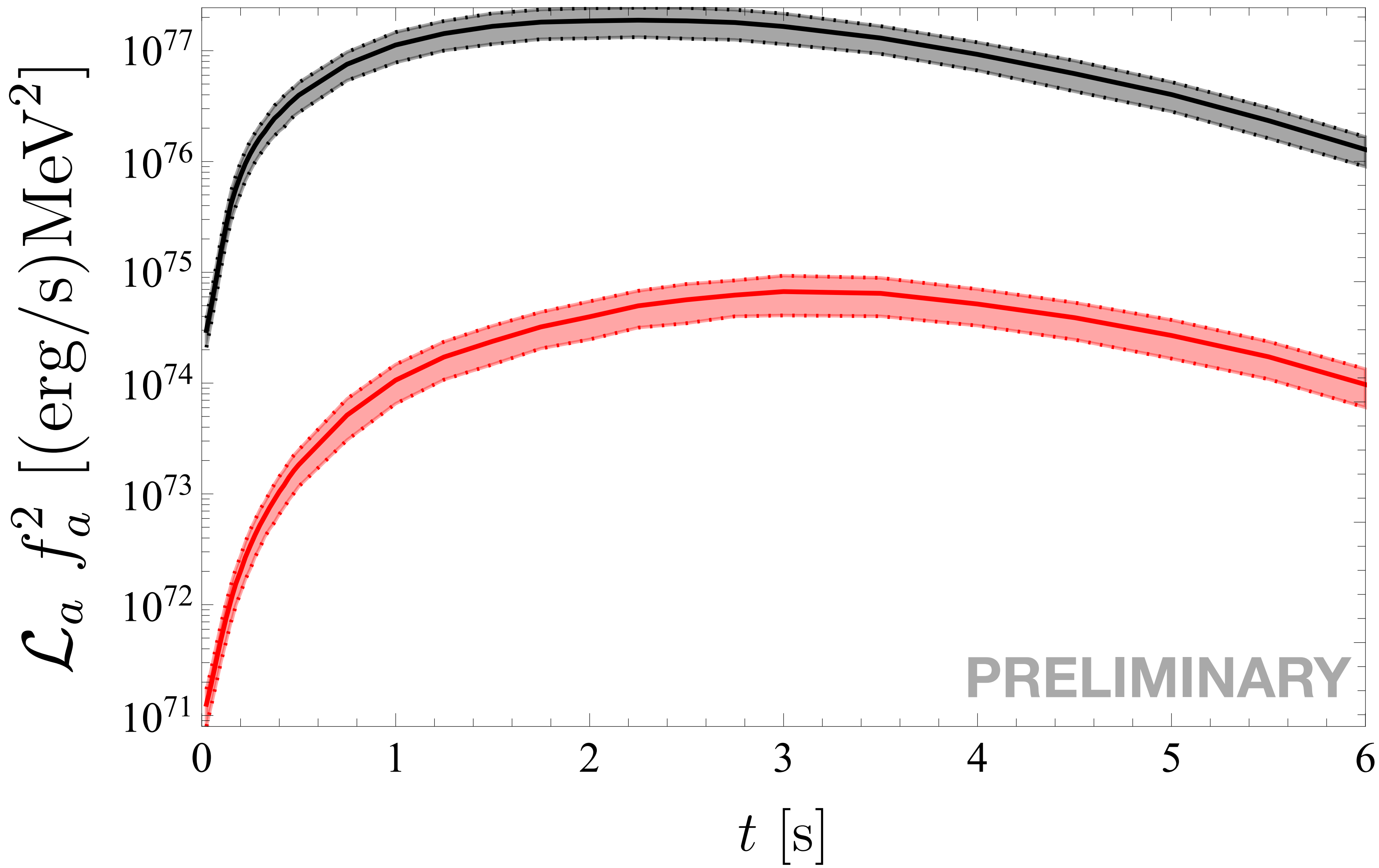
Astrophobic axions or a model-independent SN bound

di Luzio et al. '15

Some aspects of 'astrophobic axion' survive at finite density, only subleading corrections

Model independent SN bound for all axions that solve strong CP problem

For current best bound see Lucente et al. '22



Supernova profile from https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

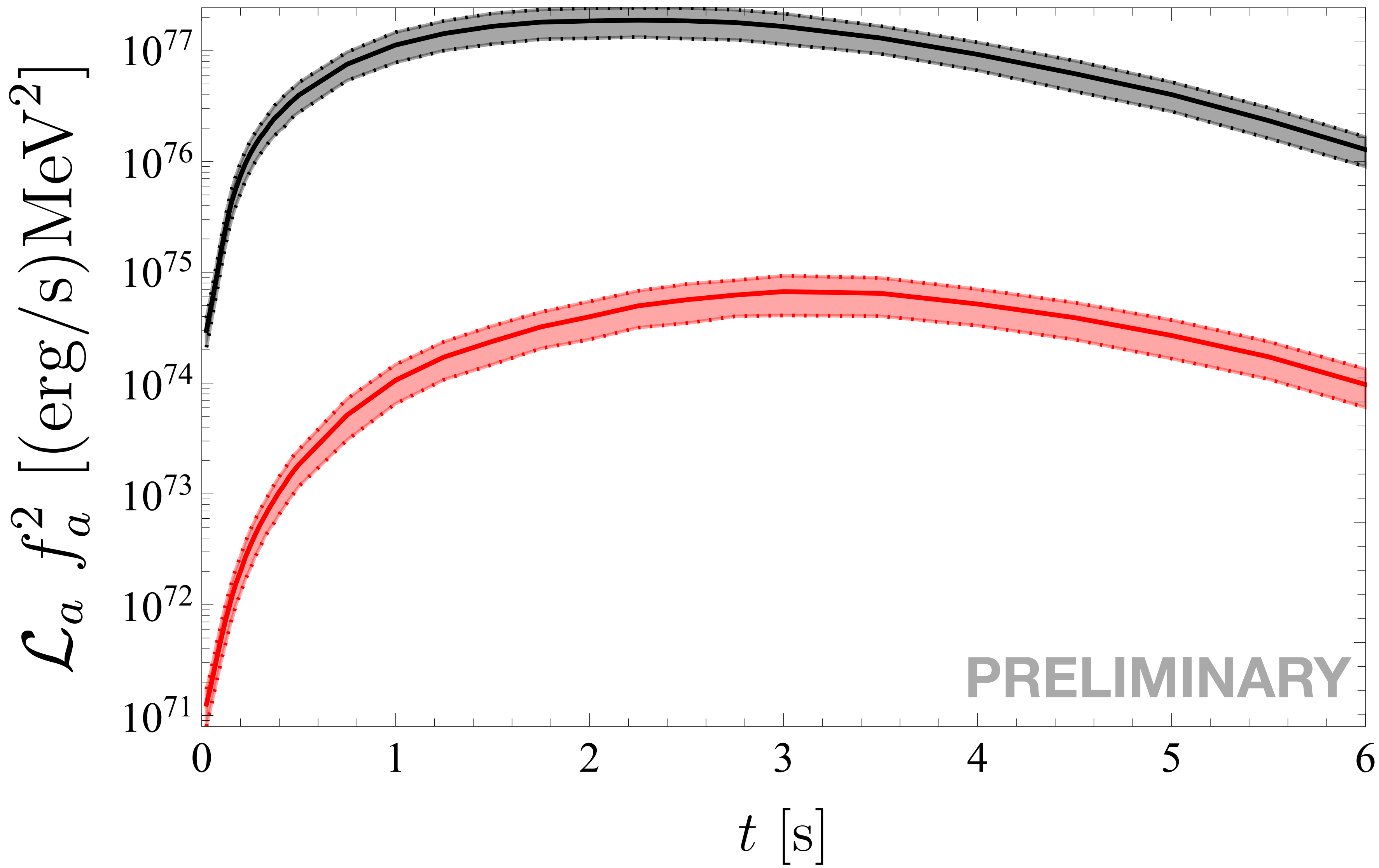
Astrophobic axions or a model-independent SN bound

di Luzio et al. '15

Some aspects of 'astrophobic axion' survive at finite density, only subleading corrections

Model independent SN bound for all axions that solve strong CP problem

For current best bound see Lucente et al. '22



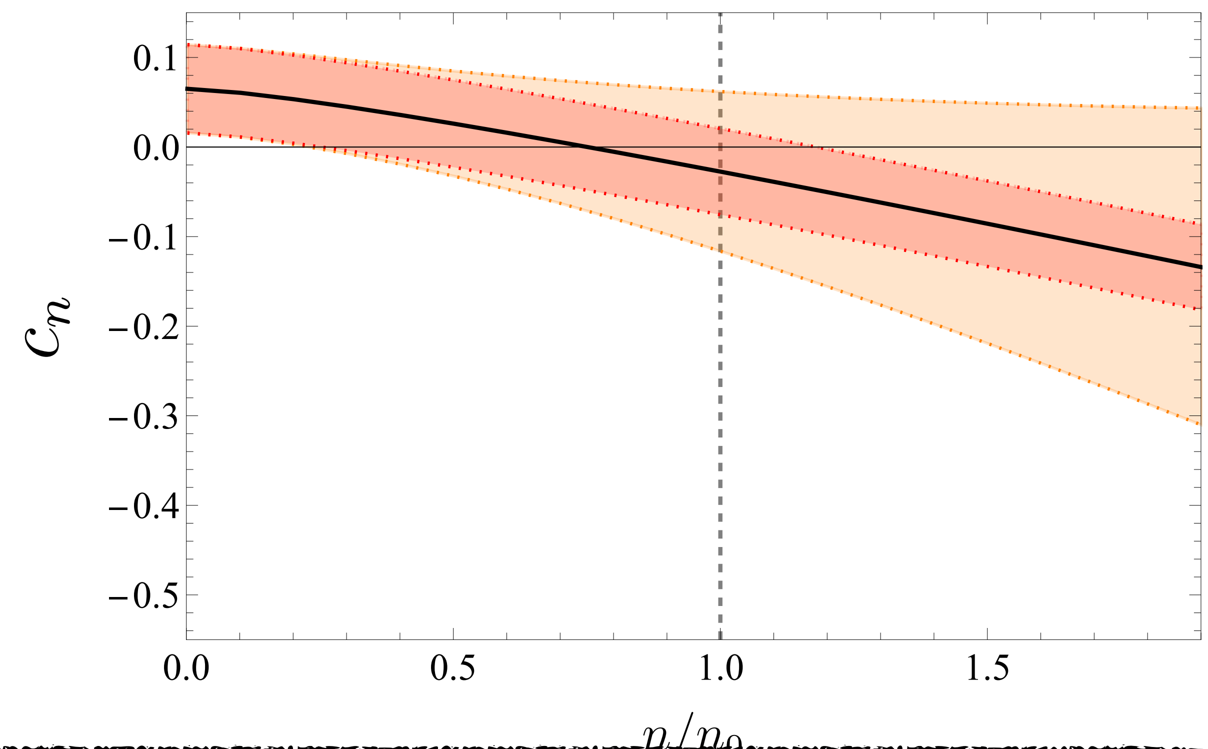
Supernova profile from https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

Leads to $f_a \gtrsim O(5) \times 10^7\,\mathrm{GeV}$

Axion - finite density effects

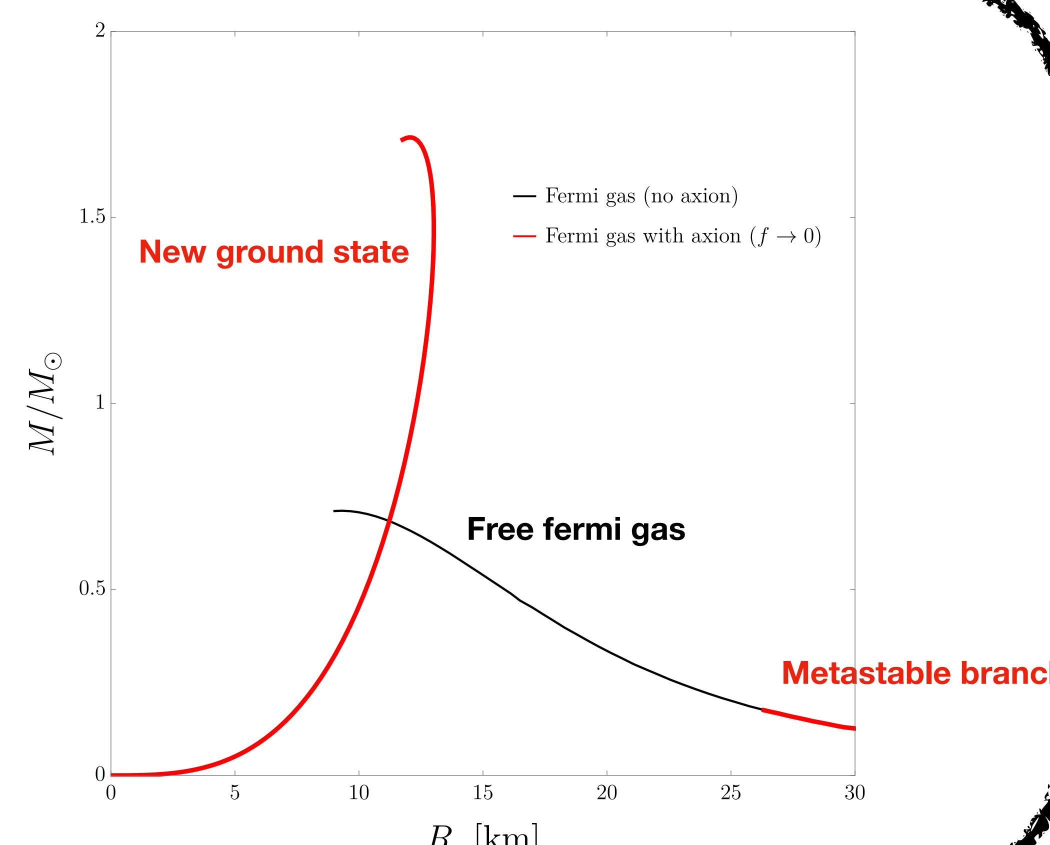
QCD axion coupling to nucleons at finite density

To appear soon
and *JHEP* 07 (2020) Balkin, Serra, Springmann, Weiler



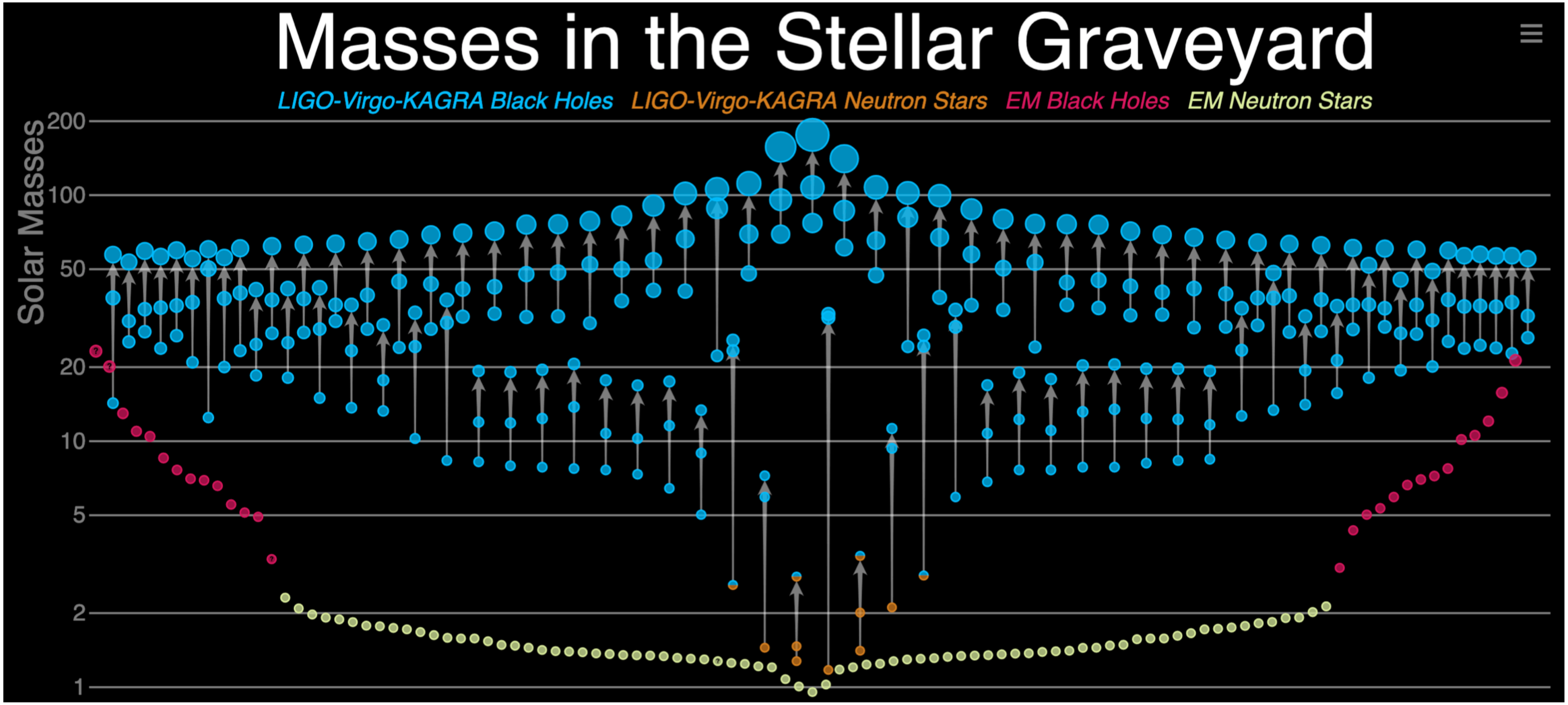
Influence of light (pseudo-)scalars on structure of neutron stars

2211.02661 and 2307.14418
Balkin, Serra, Springmann, SS, Weiler



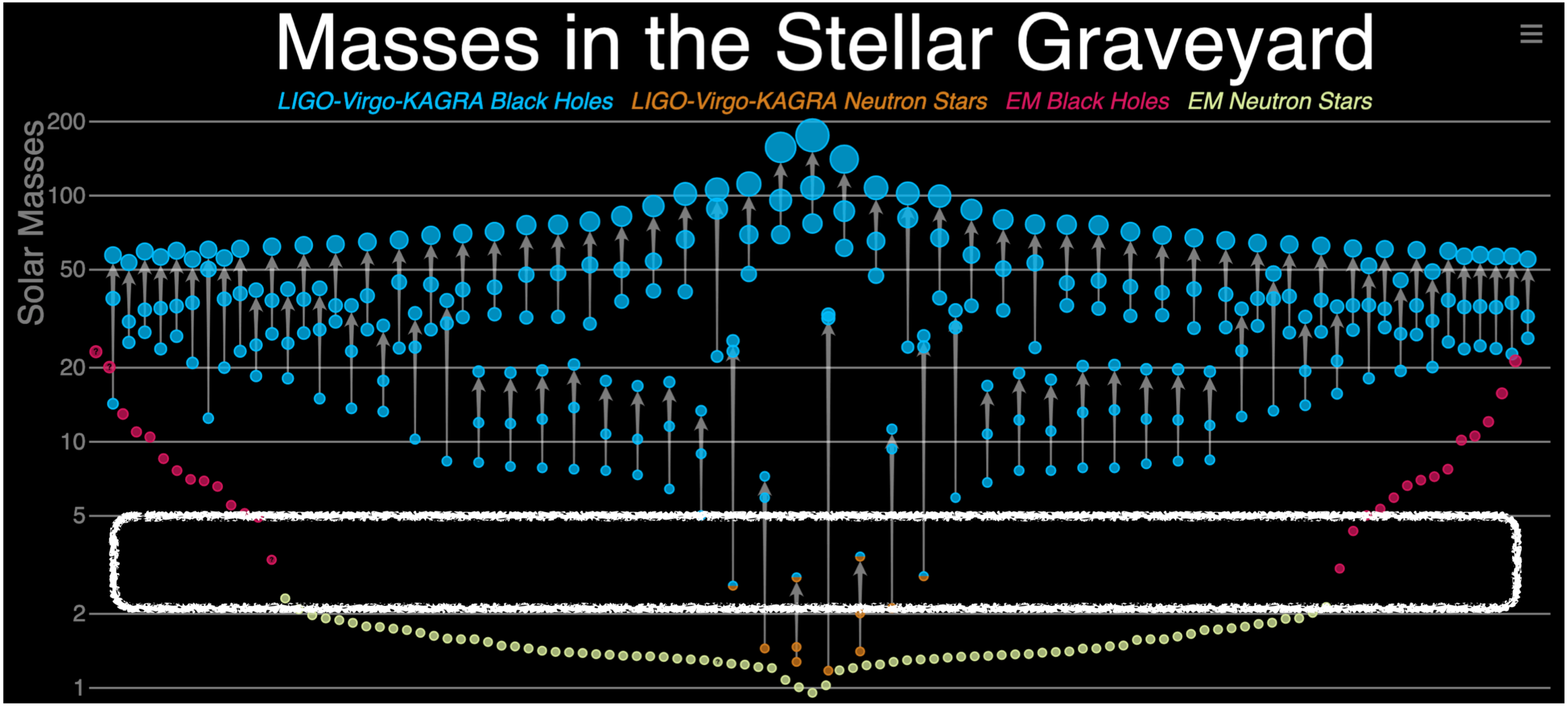
Heavy neutron stars from light scalars

… or how axions (ALPs) change stars



Heavy neutron stars from light scalars

… or how axions (ALPs) change stars



Can new (light) physics make neutron stars heavier?

Heavy neutron stars from light scalars

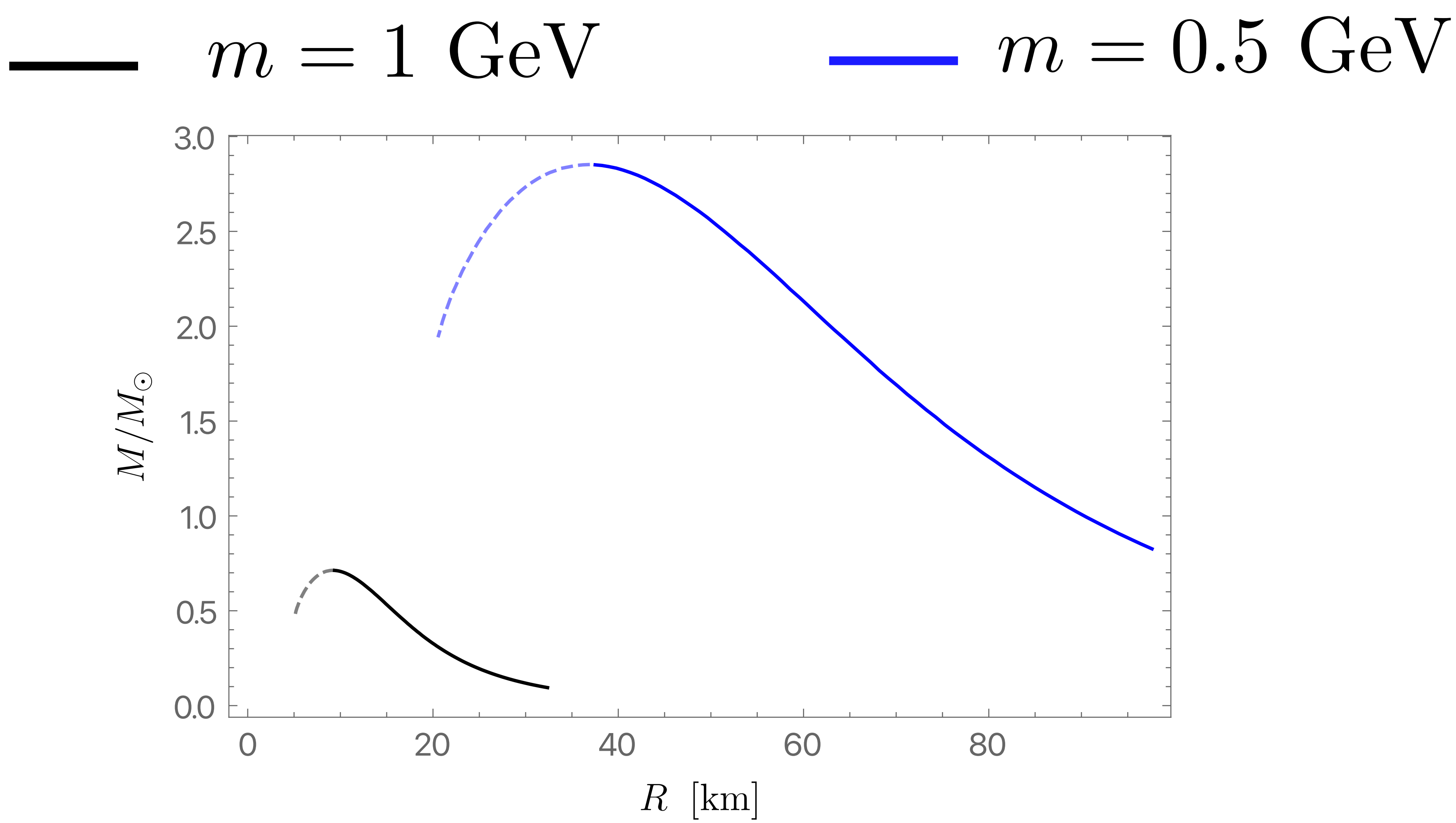
How would NSs look like if neutrons would be lighter?

Toy model: Free Fermi gas of neutrons

Heavy neutron stars from light scalars

How would NSs look like if neutrons would be lighter?

Toy model: Free Fermi gas of neutrons

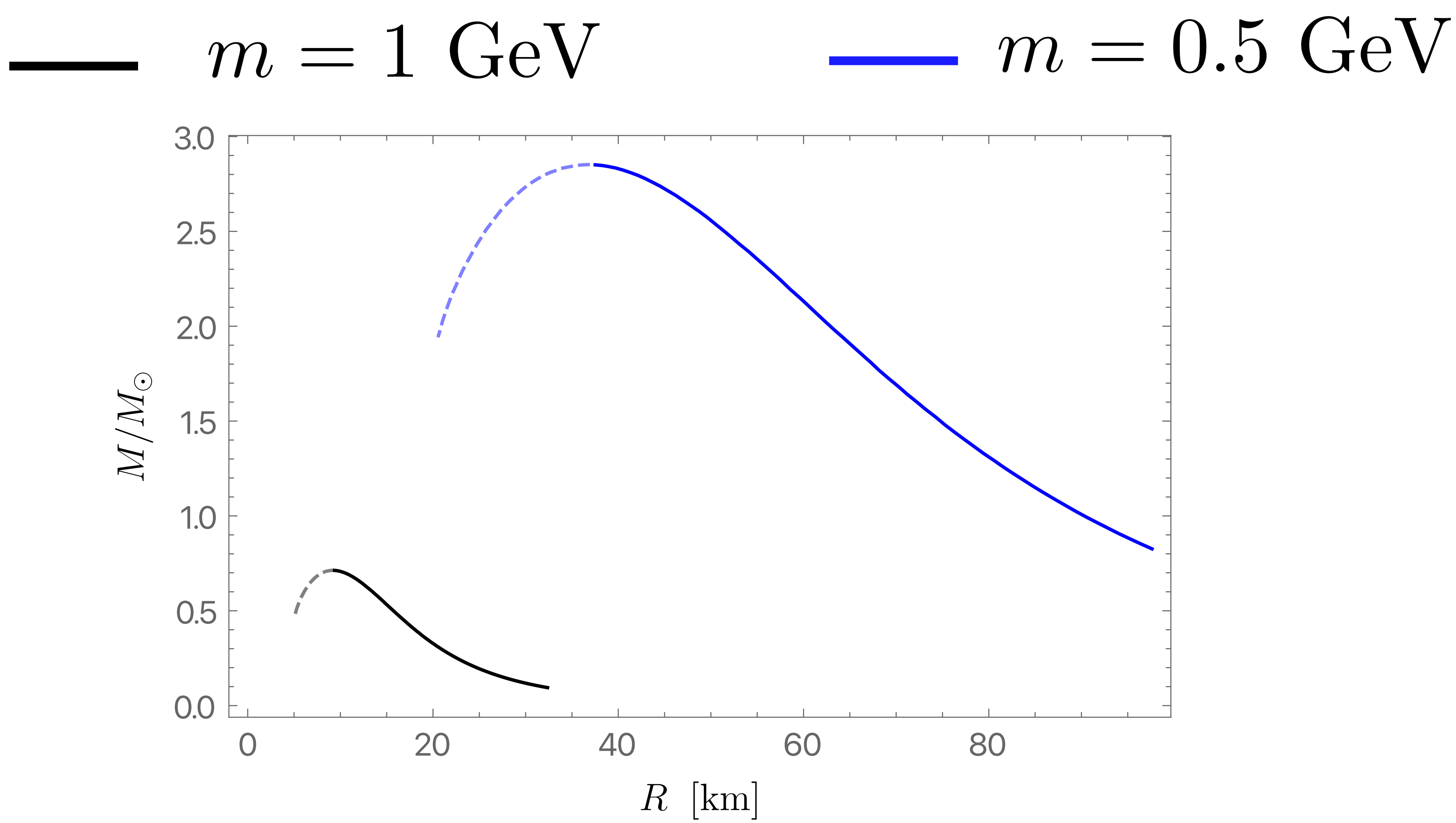


$$\frac{M_{\max}(m_1)}{M_{\max}(m_2)} = \left(\frac{m_2}{m_1}\right)^2$$

Heavy neutron stars from light scalars

How would NSs look like if neutrons would be lighter?

Toy model: Free Fermi gas of neutrons



Why? In NR limit: at fixed energy density, need more neutrons! $\epsilon \sim n m_N$

Heavy neutron stars from light scalars

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

Heavy neutron stars from light scalars

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

Shift symmetry breaking coupling: $O_{\phi N} = -g m_N \bar{N} N \left(\cos(\phi/f) - 1\right)$

↓

Field dependent nucleon mass $m_N(\phi) = 1 - g\left(\cos\left(\frac{\phi}{f}\right) - 1\right)$

Heavy neutron stars from light scalars

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

Shift symmetry breaking coupling: $O_{\phi N} = -g m_N \bar{N} N \left(\cos(\phi/f) - 1\right)$

↓

Field dependent nucleon mass $m_N(\phi) = 1 - g\left(\cos\left(\frac{\phi}{f}\right) - 1\right)$

This happens for the vanilla QCD axion with $g \sim 0.025$

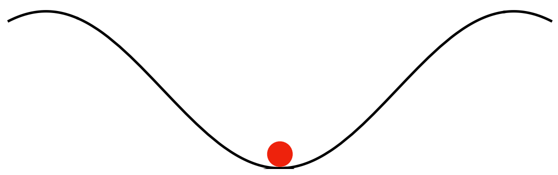
Heavy neutron stars from light scalars

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

Shift symmetry breaking coupling: $O_{\phi N} = -g m_N \bar{N} N \left(\cos(\phi/f) - 1\right)$

In a background density of neutrons $\langle \bar{N} N \rangle_n \simeq \langle N^\dagger N \rangle_n = n$

Potential can get destabilized



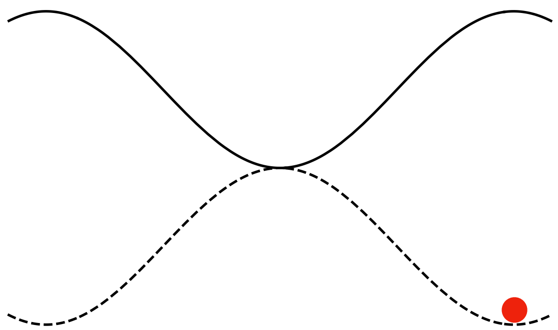
Heavy neutron stars from light scalars

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

Shift symmetry breaking coupling: $O_{\phi N} = -g m_N \bar{N} N \left(\cos(\phi/f) - 1\right)$

In a background density of neutrons $\langle \bar{N} N \rangle_n \simeq \langle N^\dagger N \rangle_n = n$

Potential can get destabilized



$n \gtrsim \Lambda^4 / g m_N$

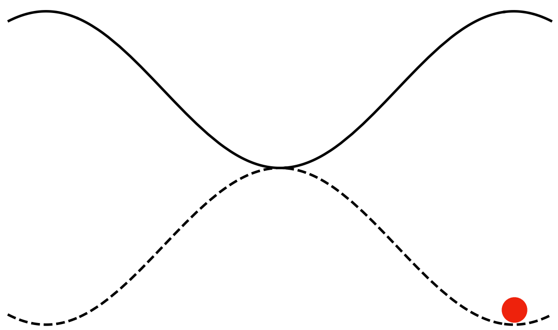
Heavy neutron stars from light scalars

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

Shift symmetry breaking coupling: $O_{\phi N} = -g m_N \bar{N} N \left(\cos(\phi/f) - 1\right)$

In a background density of neutrons $\langle \bar{N} N \rangle_n \simeq \langle N^\dagger N \rangle_n = n$

Potential can get destabilized



$n \gtrsim \Lambda^4 / g m_N$

ALP develops a non-trivial expectation value around dense objects!

Fermi gas - axion system

Consists of complicated coupled equations of gravity and scalar field EOMs.

… can be solved numerically ✓

Fermi gas - axion system

Consists of complicated coupled equations of gravity and scalar field EOMs.

… can be solved numerically ✓

… but there is a simplifying limit:

Hierarchy of scales

$$R \gg m_\phi^{-1}(n) \sim \frac{\pi f}{\sqrt{g m_N n - \Lambda^4}}$$

Size of star **size of scalar field**

Fermi gas - axion system

Consists of complicated coupled equations of gravity and scalar field EOMs.

… can be solved numerically ✓

… but there is a simplifying limit:

Hierarchy of scales

$$R \gg m_\phi^{-1}(n) \sim \frac{\pi f}{\sqrt{g m_N n - \Lambda^4}}$$

Size of star **size of scalar field**

All gradient effects of the axion become negligible

Fermi gas - axion system

Consists of complicated coupled equations of gravity and scalar field EOMs.

… can be solved numerically ✓

… but there is a simplifying limit:

Hierarchy of scales

$$R \quad \gg \quad m_\phi^{-1}(n) \sim \frac{\pi f}{\sqrt{g m_N n - \Lambda^4}}$$

Size of star **size of scalar field**

All gradient effects of the axion become negligible

Opposite hierarchy of scales prevents us from seeing it on earth: $R_{\text{nucleus}} \ll m_\phi^{-1}$

Axion Fermi gas equation of state

Axion follows its potential

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

$$\downarrow$$

$$\phi(n)$$

Axion Fermi gas equation of state

Axion follows its potential

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

$$\downarrow$$

$$\phi(n)$$

$$\downarrow$$

Usual free fermi gas with field dependent mass

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

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

Equation of state

Axion Fermi gas equation of state

Equation of state

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

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

Competing effects:

More pressure at same energy density

Mass reduction: stiffens the equation of state

Potential: softens the equation of state

Less pressure at same energy density

Axion Fermi gas equation of state

Equation of state

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

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

Parameter space splits in two regions

Coexistence region

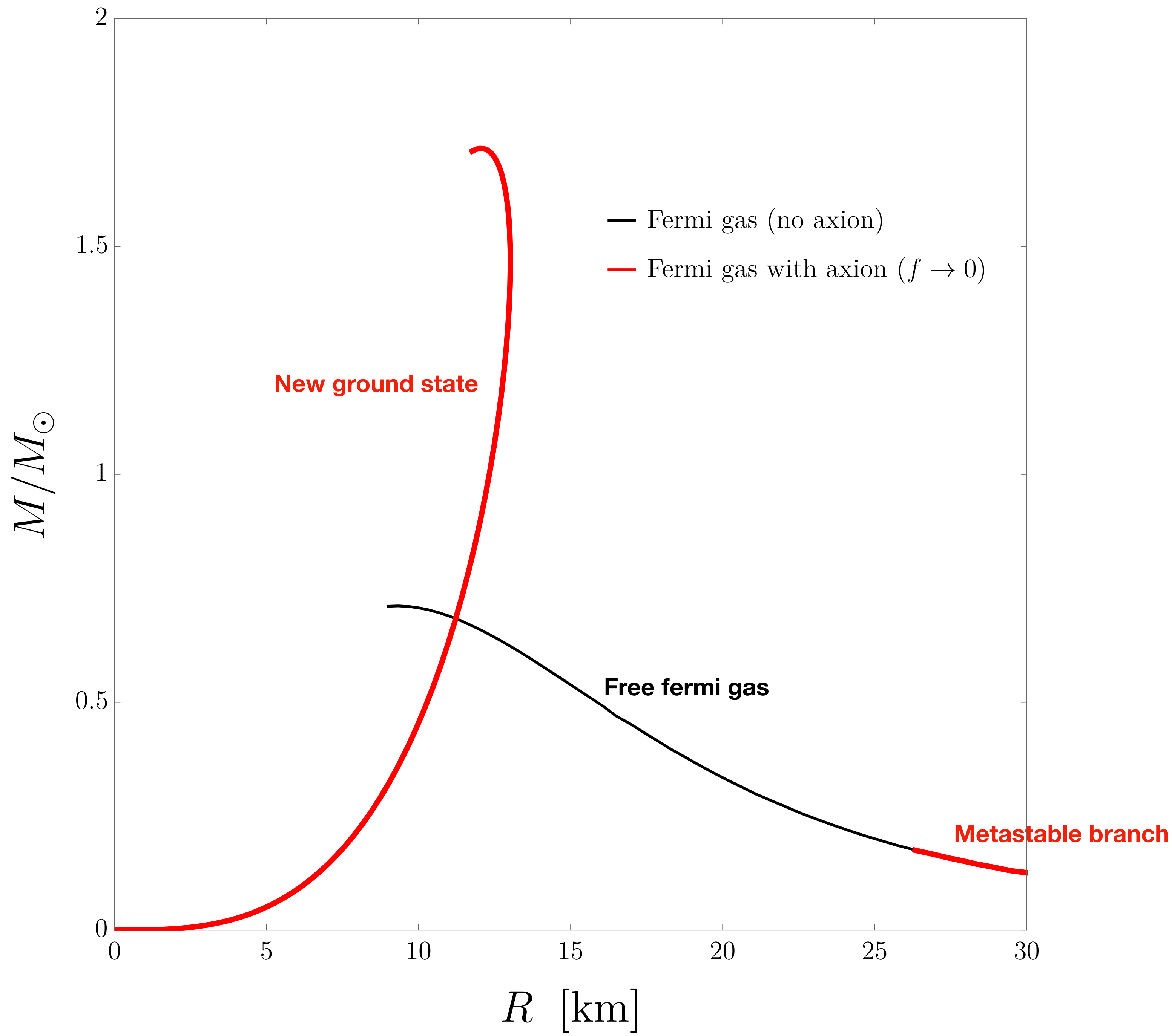
1st order PT inside star

New ground state of matter!

Energy per particle:

$$\frac{\epsilon}{n} < m_N$$

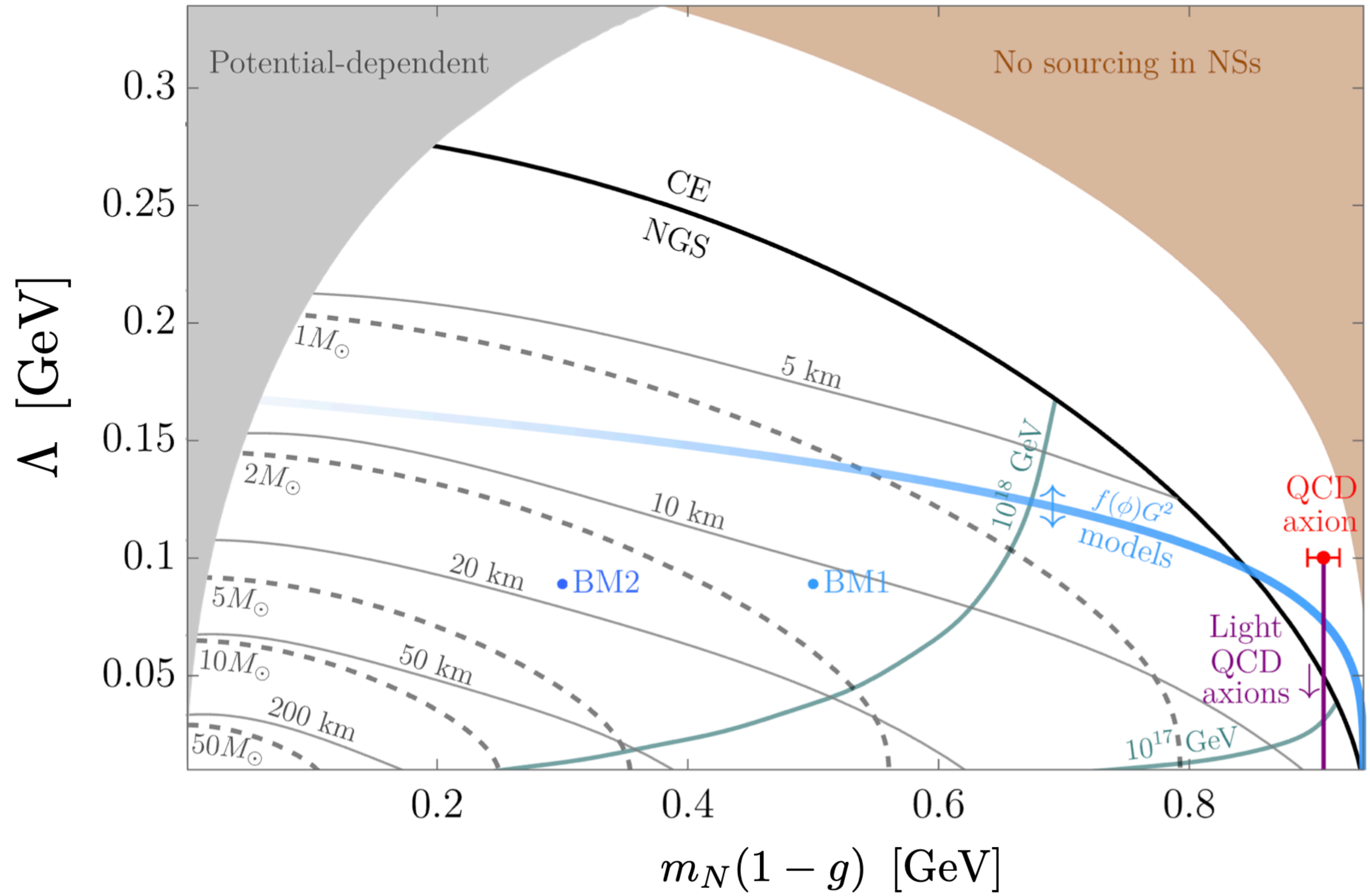
Heavy neutron stars from light scalars



New ground state: Energy per particle less than for separated nucleons m_N

In absence of gravity bound by ALP field!

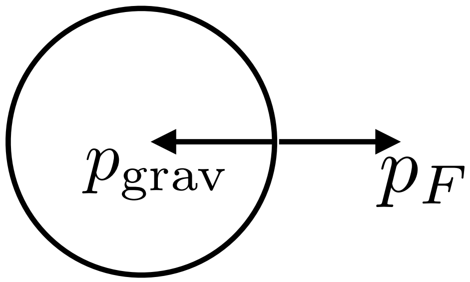
Heavy neutron stars from light scalars



Future GW experiments can distinguish BHs and other compact objects

Brown et al. '21

White dwarfs as a probe of light QCD axions



What is a WD?

Electron degeneracy pressure vs gravity

White dwarfs are much less dense than NSs

↓

EOS is much better understood!

↓

Can be used to test models that change the structure of WDs

White dwarfs as a probe of light QCD axions

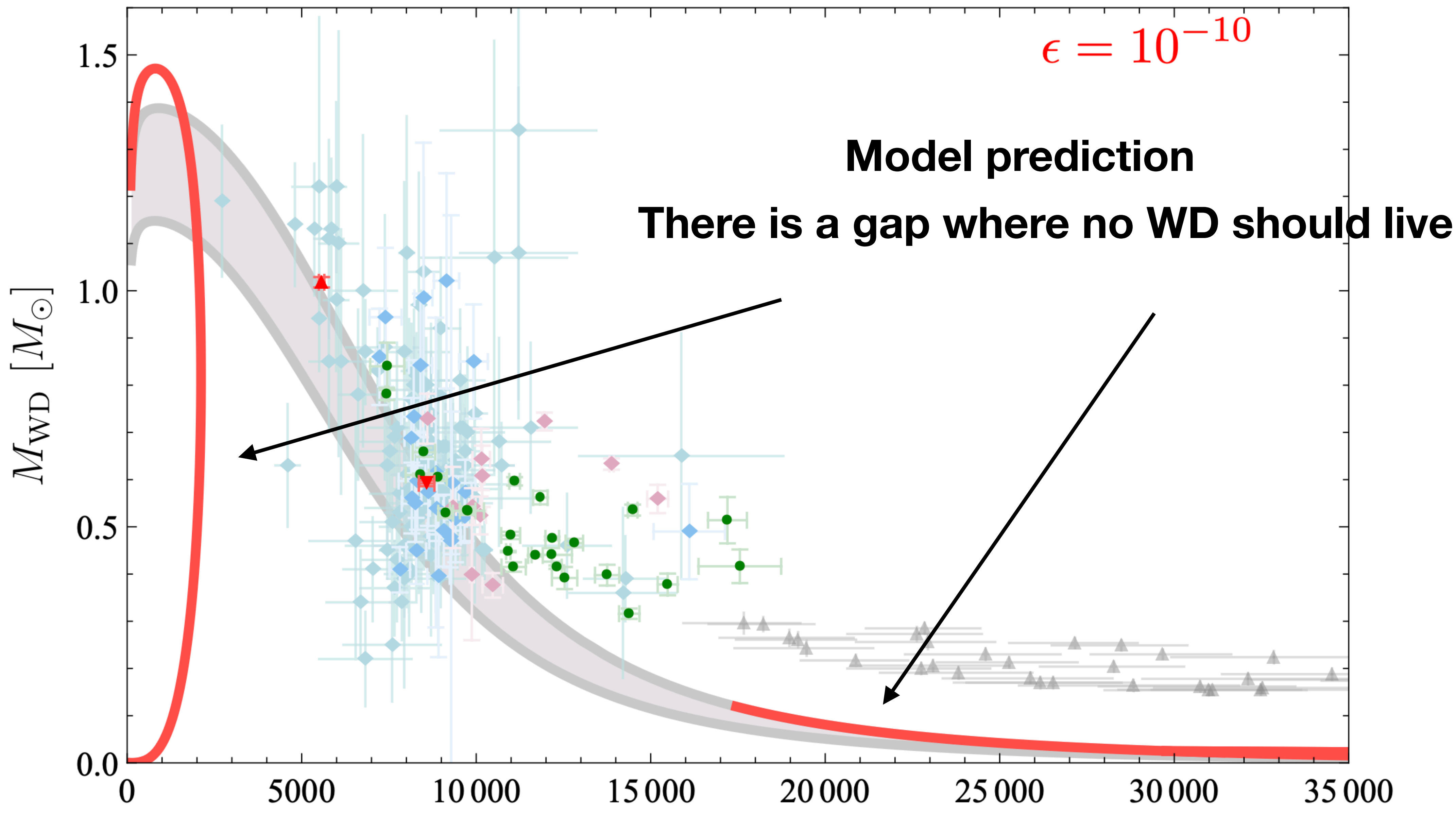
Light QCD axion:

$$V(\phi) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\phi}{2f}\right)}$$ **with** $\epsilon \ll 1$

White dwarfs as a probe of light QCD axions

Light QCD axion:

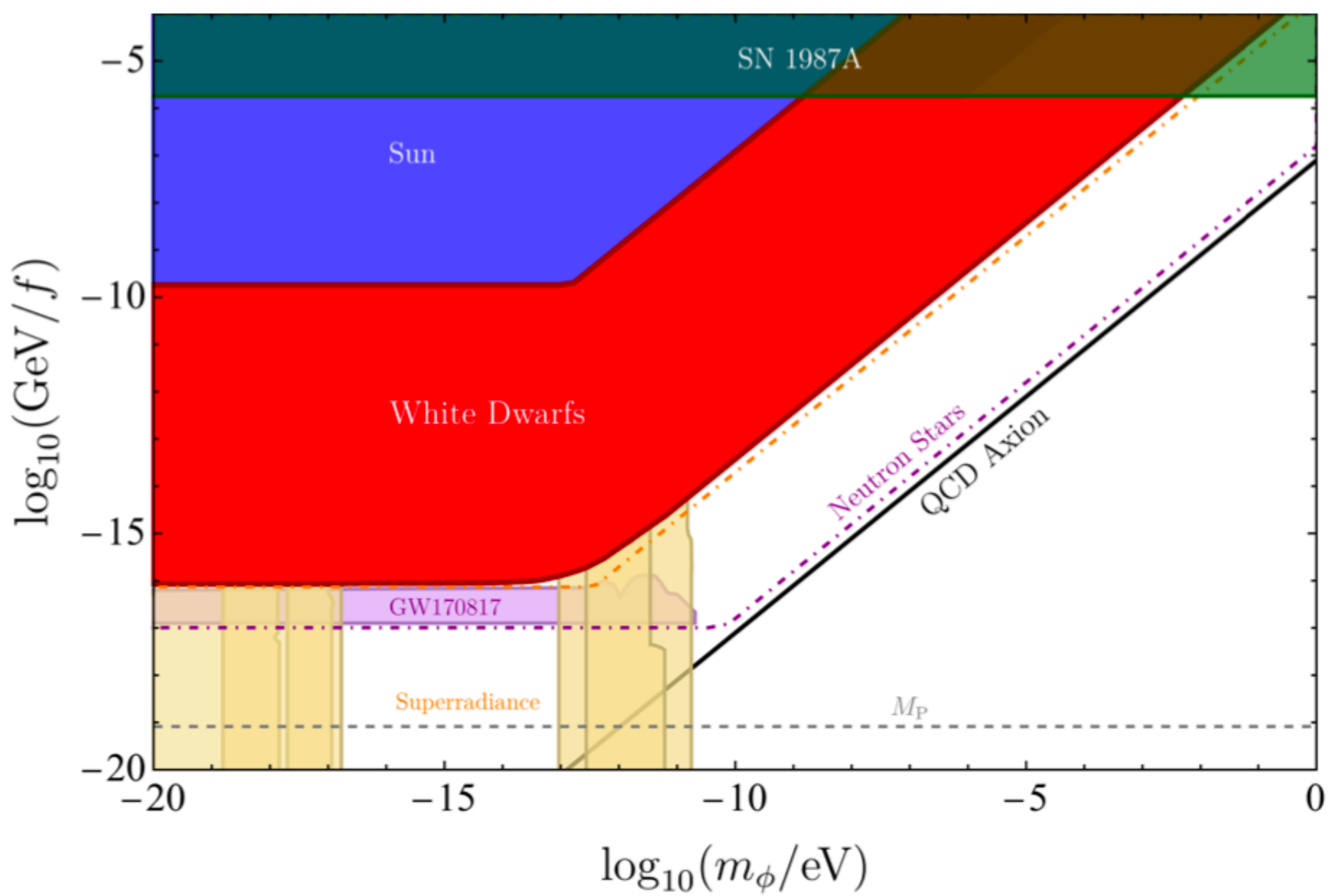
$$V(\phi) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\phi}{2f}\right)} \quad \textbf{with} \quad \epsilon \ll 1$$



White dwarfs as a probe of light QCD axions

Light QCD axion:

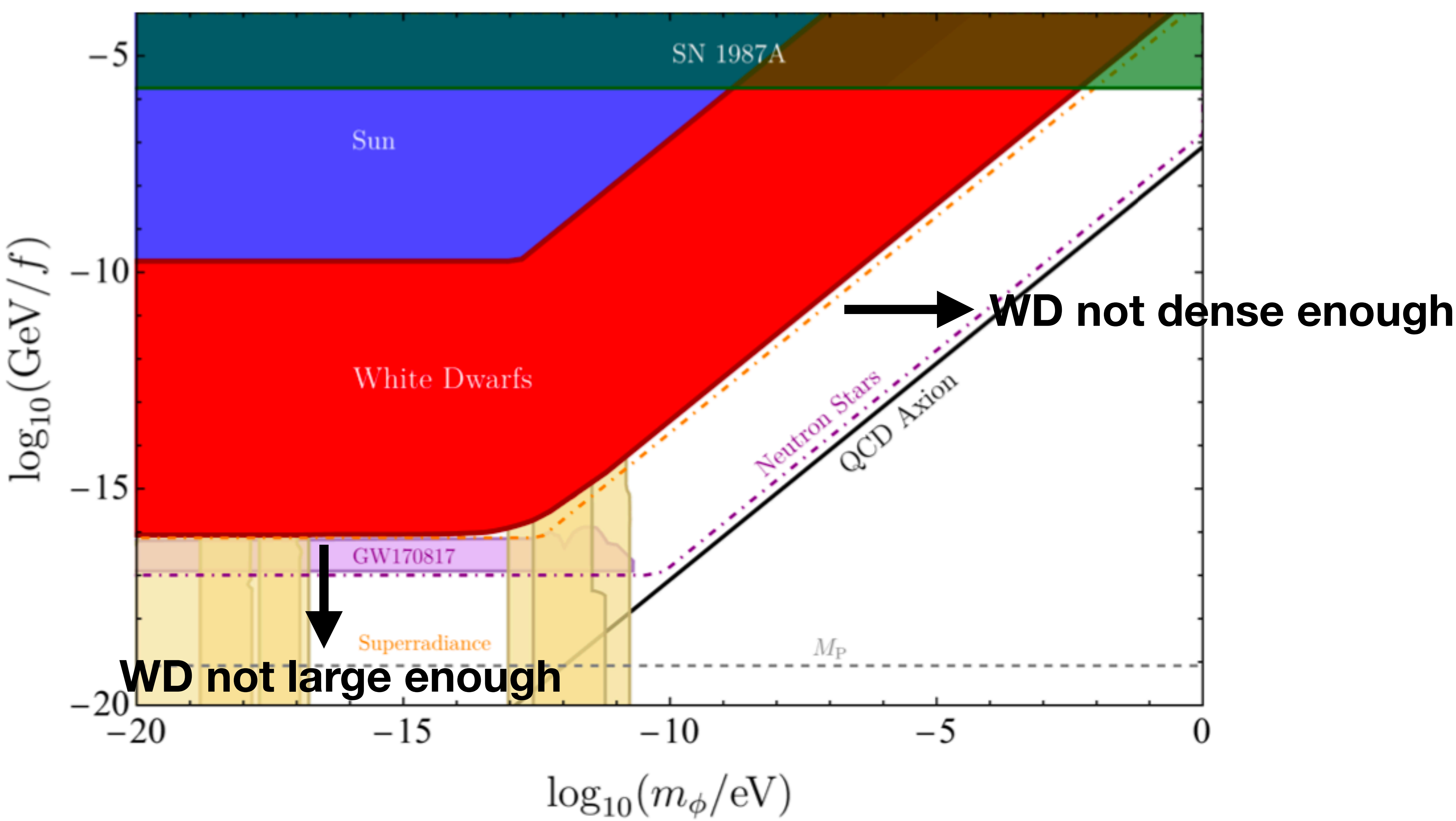
$$V(\phi) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\phi}{2f}\right)} \quad \textbf{with} \quad \epsilon \ll 1$$



White dwarfs as a probe of light QCD axions

Light QCD axion:

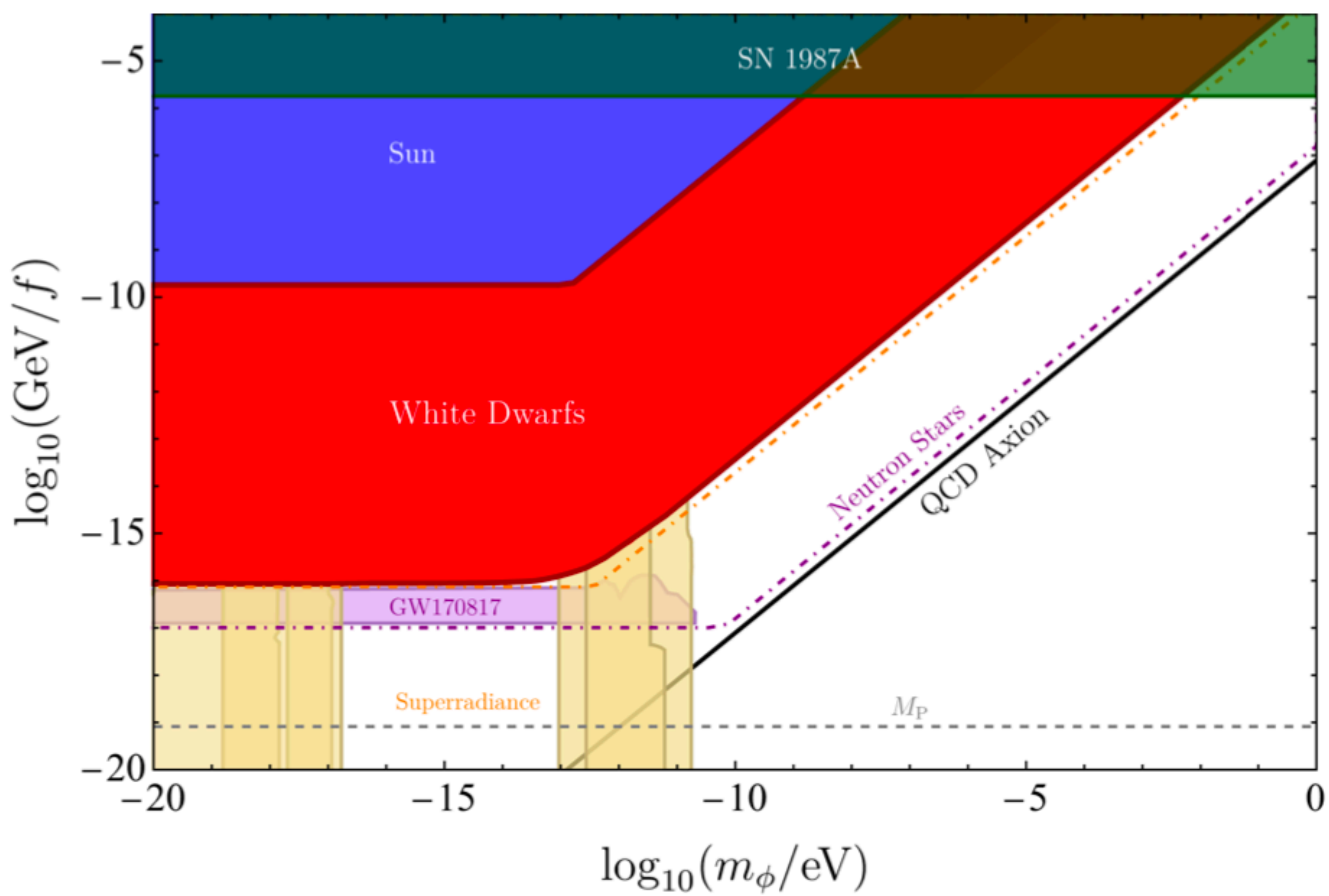
$$V(\phi) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\phi}{2f}\right)} \quad \textbf{with} \quad \epsilon \ll 1$$



White dwarfs as a probe of light QCD axions

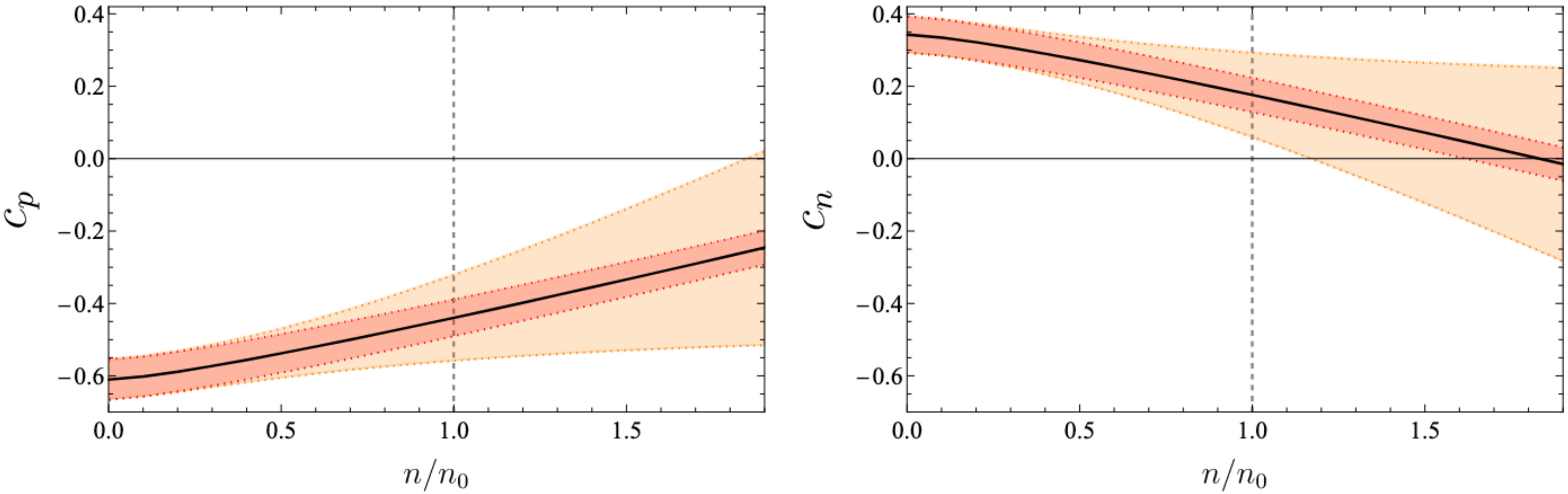
Light QCD axion:

$$V(\phi) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{\phi}{2f}\right)} \quad \textbf{with} \quad \epsilon \ll 1$$

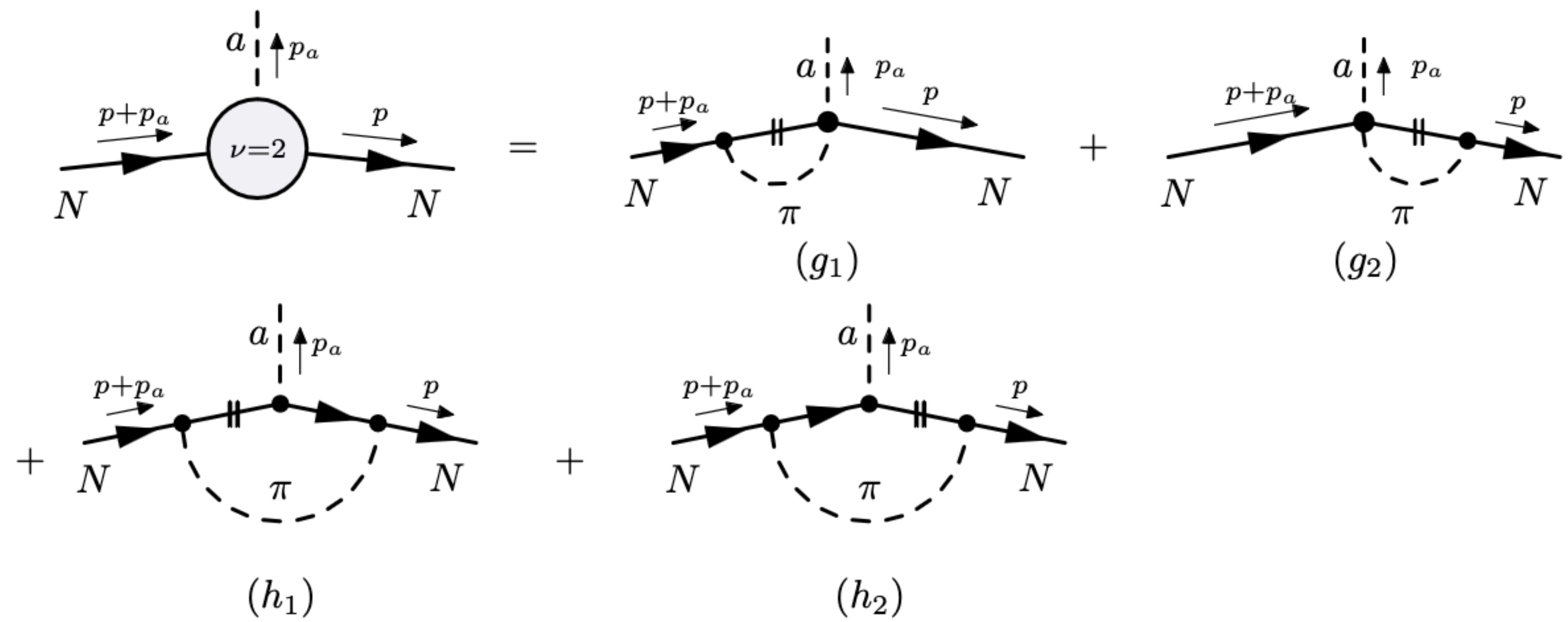


Backup Slides

DFSZ axion with $\sin^2\beta = 0.1$



Example calculation of finite density loops



$$(h_1) + (h_2) = \int \frac{d^4k}{(2\pi)^4} \left[-\frac{g_A}{2f_\pi} \vec{\sigma} \cdot (\vec{k} - \vec{p}) \tau^a \right] \left[\frac{i}{k^0} - 2\pi\delta(k^0)\theta(k_f - |\vec{k}|) \right] \left[\frac{c_N}{2f_a} \vec{\sigma} \cdot \vec{p}_a \right]$$

$$\times \left[\frac{i}{k^0 + p_a^0} - 2\pi\delta(k^0 + p_a^0)\theta(k_f - |\vec{k} + \vec{p}_a|) \right] \left[\frac{g_A}{2f_\pi} \vec{\sigma} \cdot (\vec{k} - \vec{p}) \tau^b \right] \left[\frac{-i\delta^{ab}}{m_\pi^2 - (k-p)^2} \right].$$

Backup - Coupled system NS - scalar

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

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

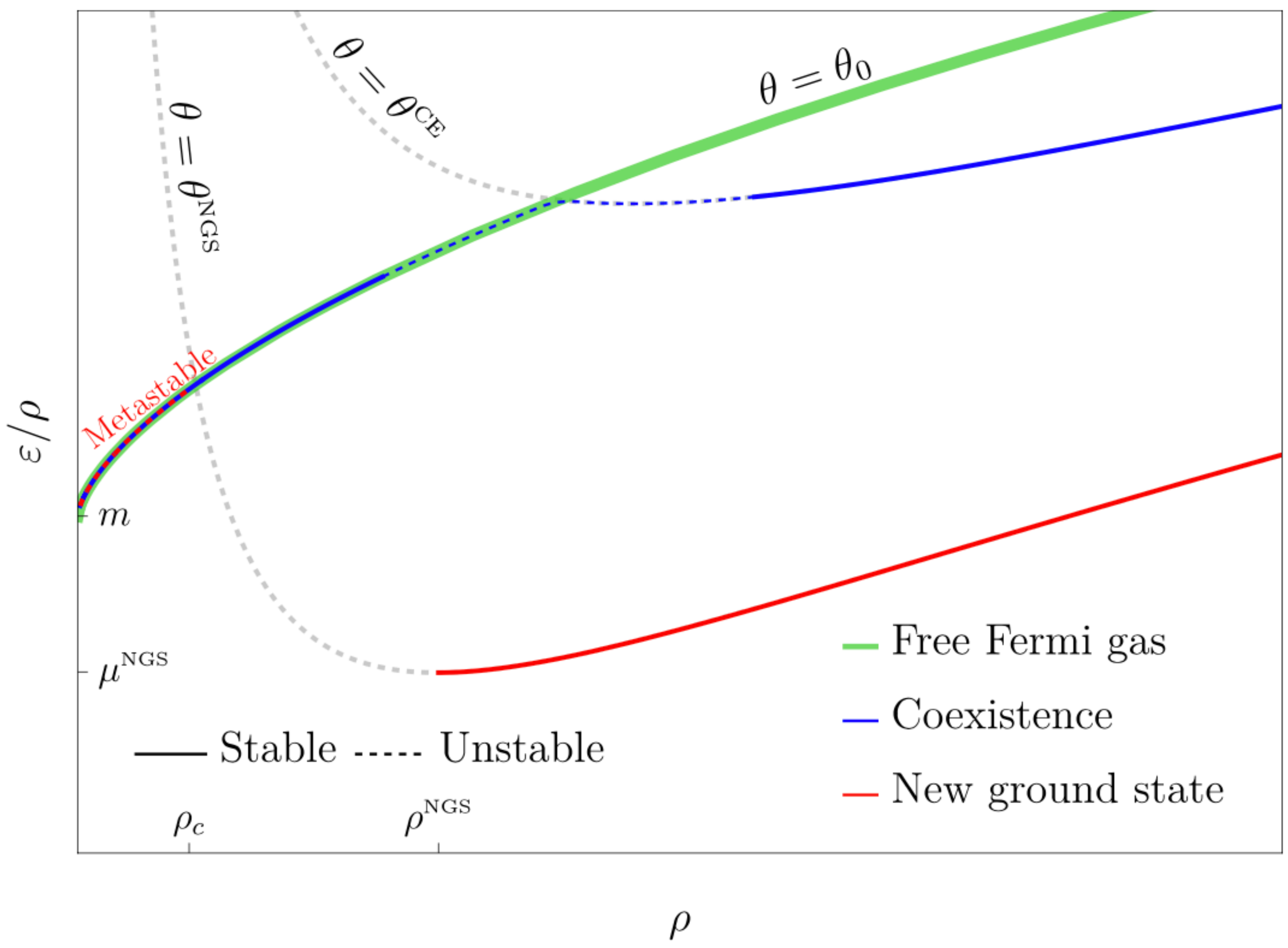
$$\phi'' + \frac{2}{r} \left[\frac{1 + e^{\sigma}}{2} + \frac{\kappa r^2 e^{\sigma}}{4} (p - \epsilon)\right] \phi' = e^{\sigma} \frac{\mathrm{d}V}{\mathrm{d}\phi}.$$

Simplify in negligible gradient limit to normal TOV equations

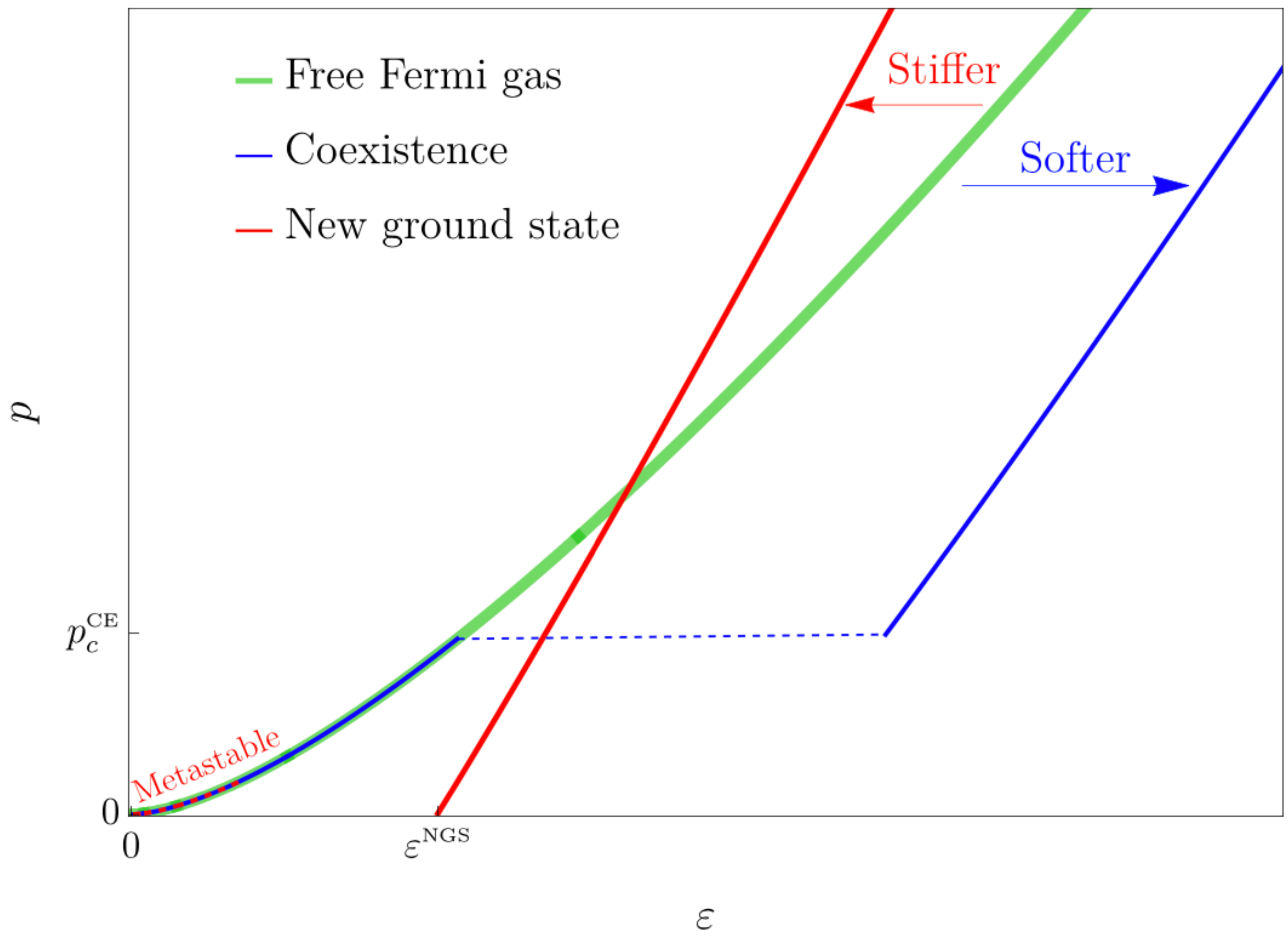
$$p' = -\frac{(p + \varepsilon)}{M_{\mathrm{P}}^2 r^2} \left(1 - \frac{2M}{r M_{\mathrm{P}}^2}\right)^{-1} \left(4\pi r^3 p + M\right)\ ,$$

$$M' = 4\pi r^2 \varepsilon\, ,$$

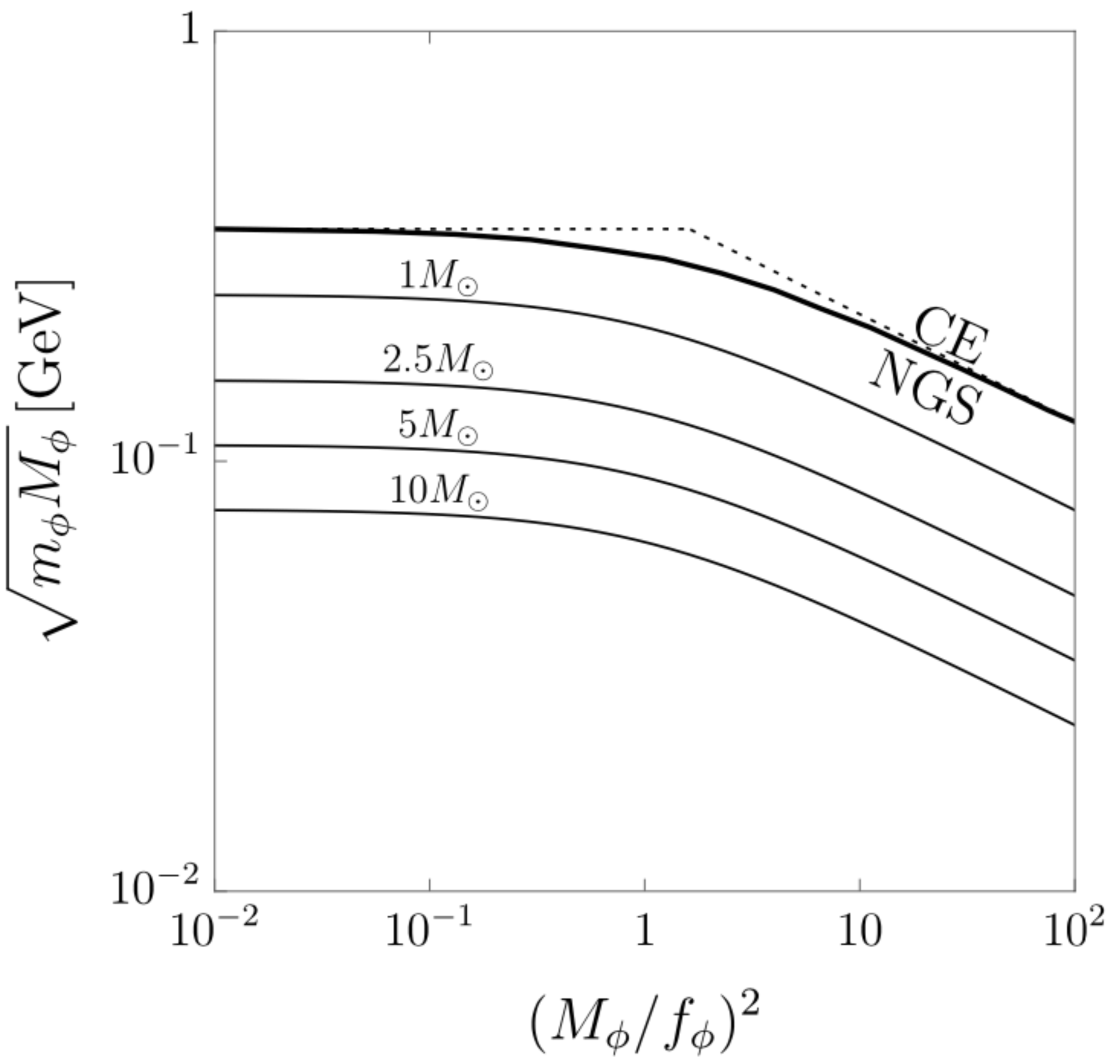
Energy per particle

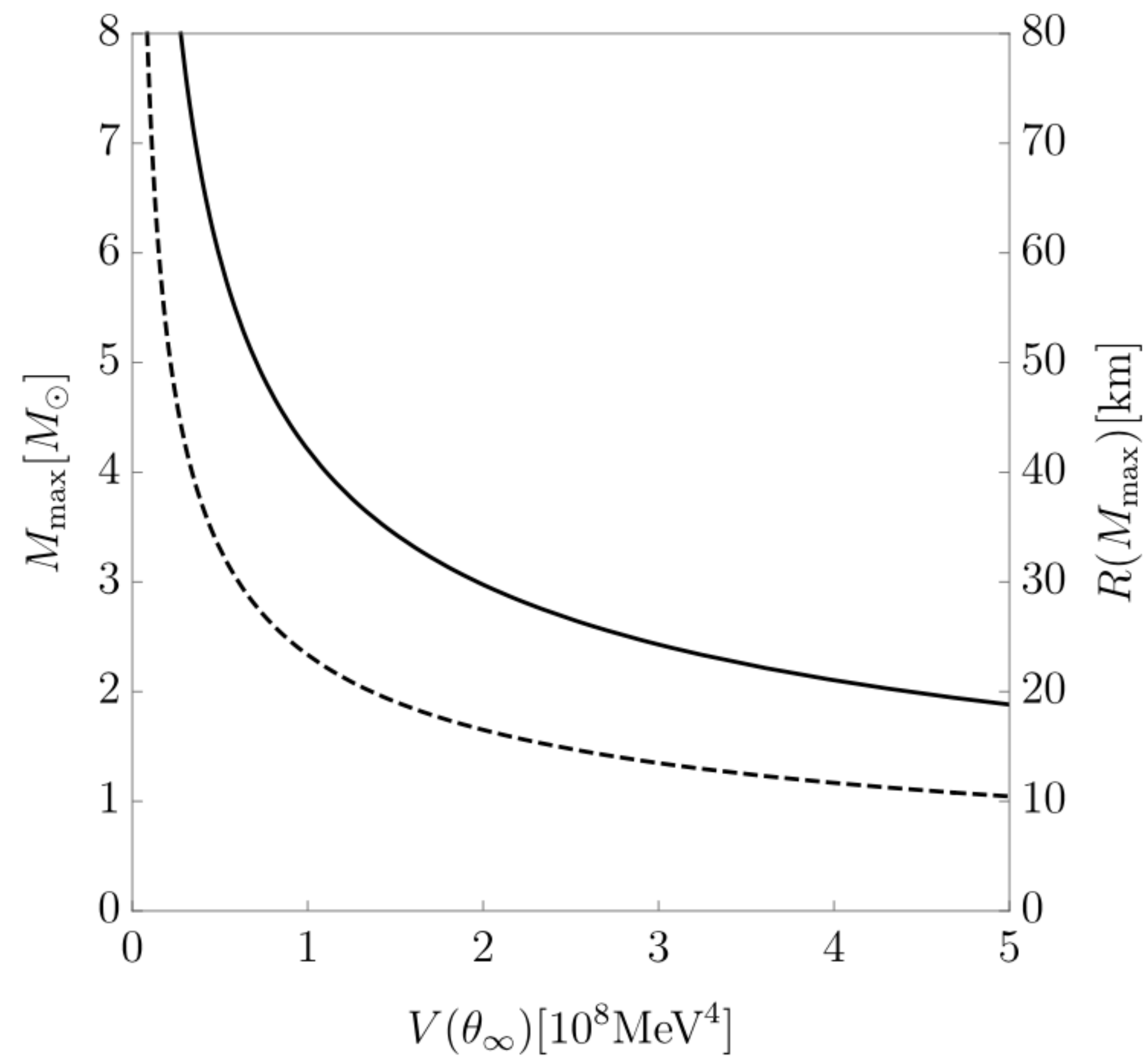


Pressure over energy density (EOS)



Not limited to periodic functions - quadratic coupling





Global view of stellar remnants with new ground state