New Forces at Finite Density: Supernovae, Compact Stars, and Axion Signals from the Stellar Graveyard

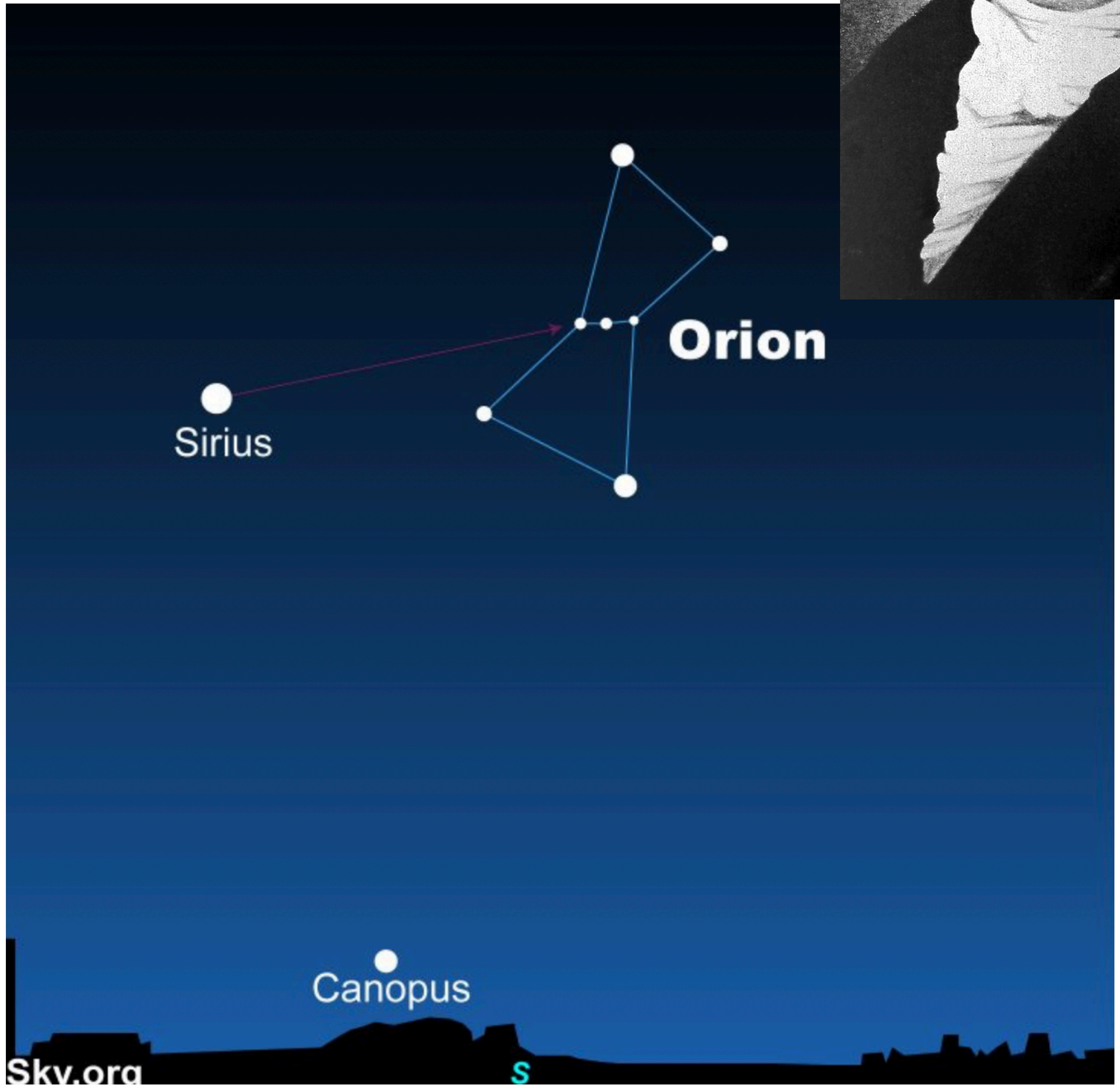
62nd International Winter Meeting on Nuclear Physics

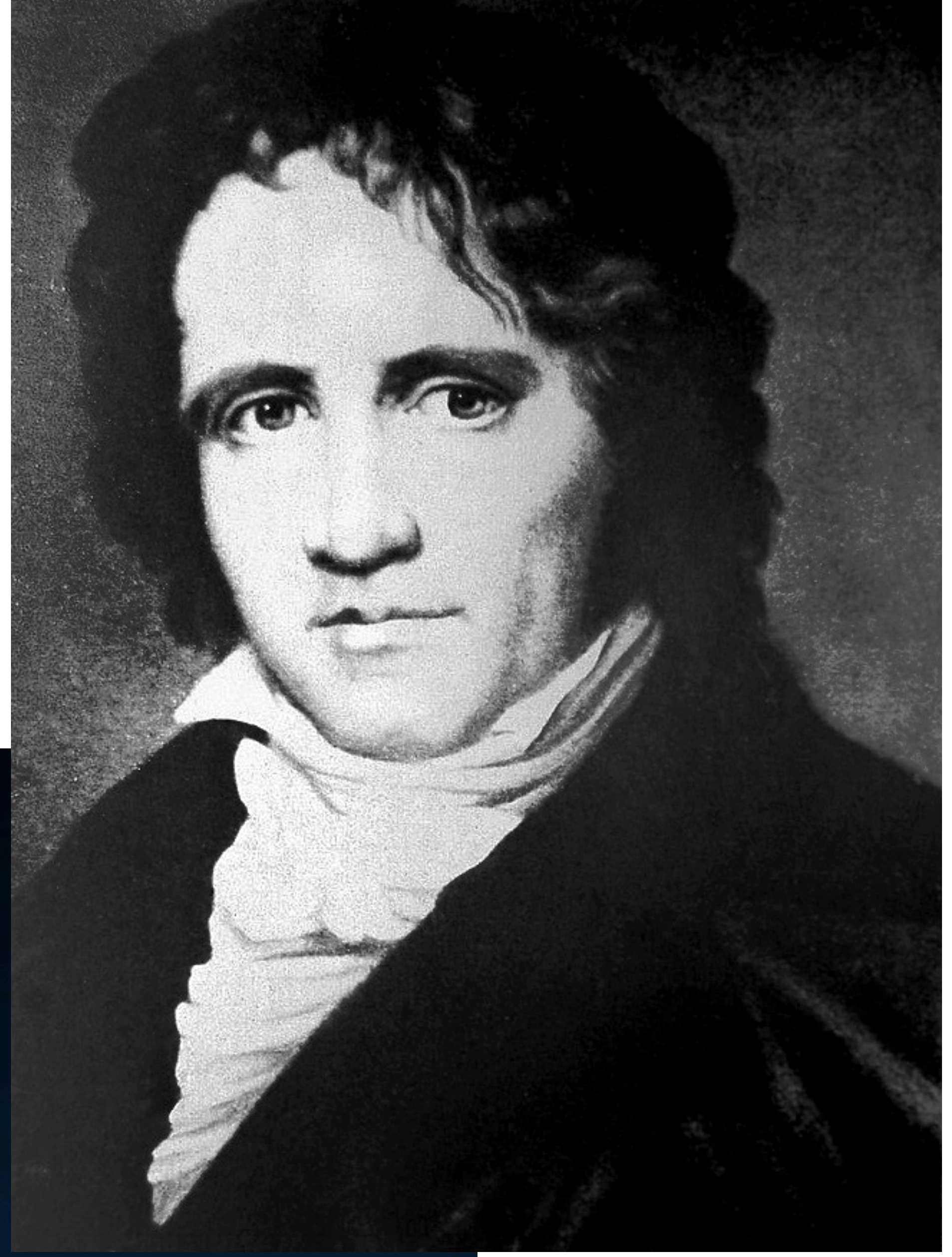
SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

Andreas Weiler (TUM), 22/1/26

Bessel 1844





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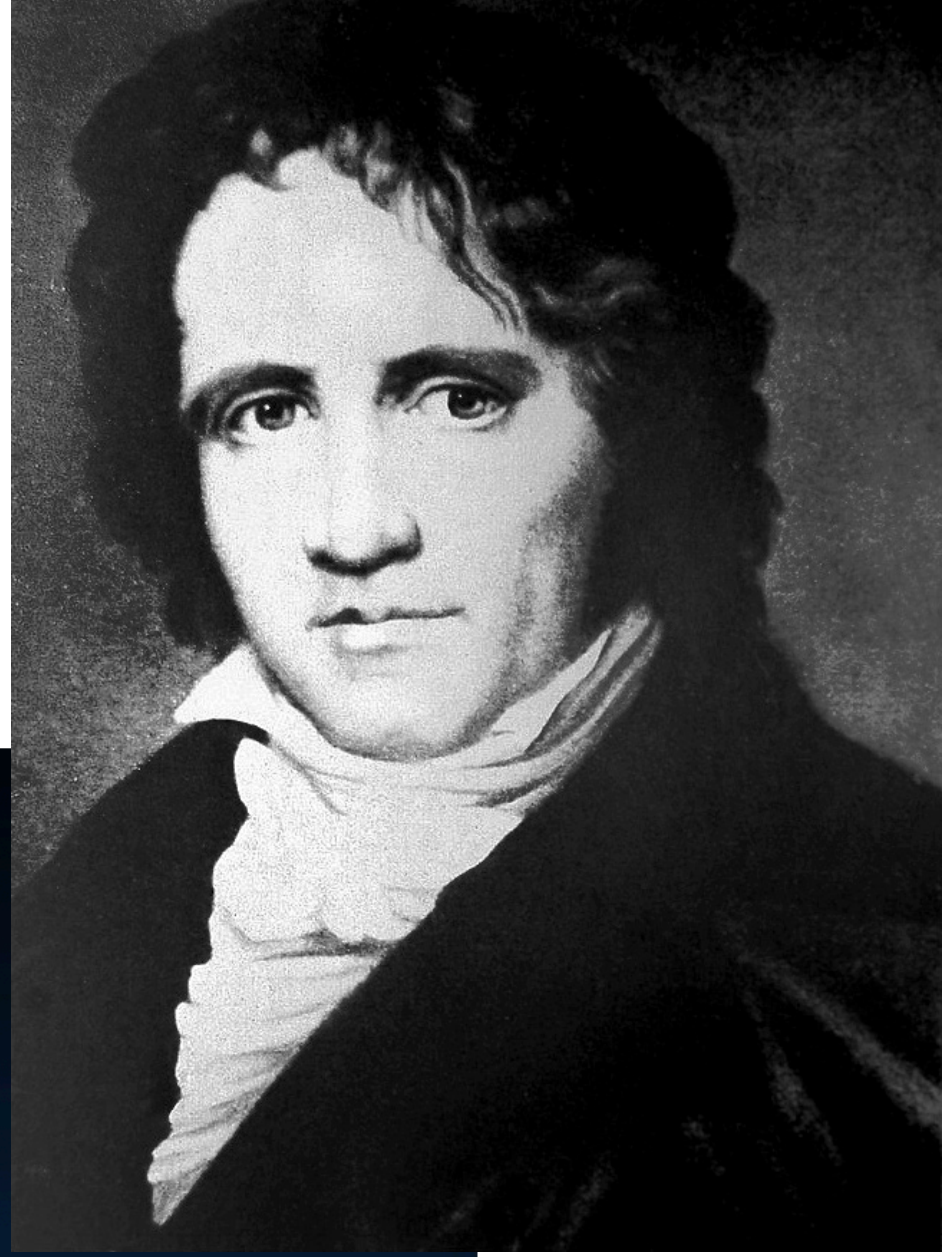
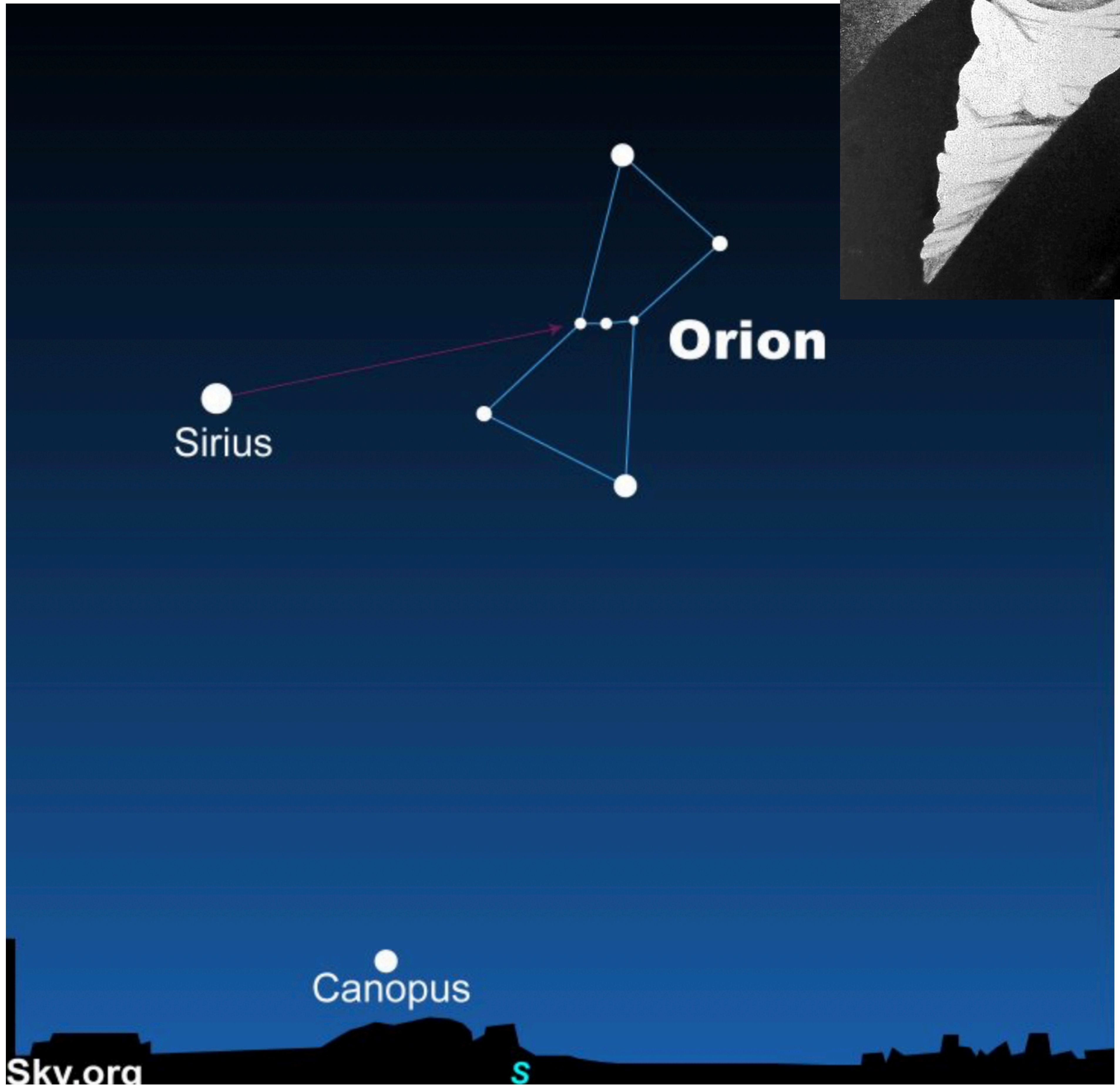
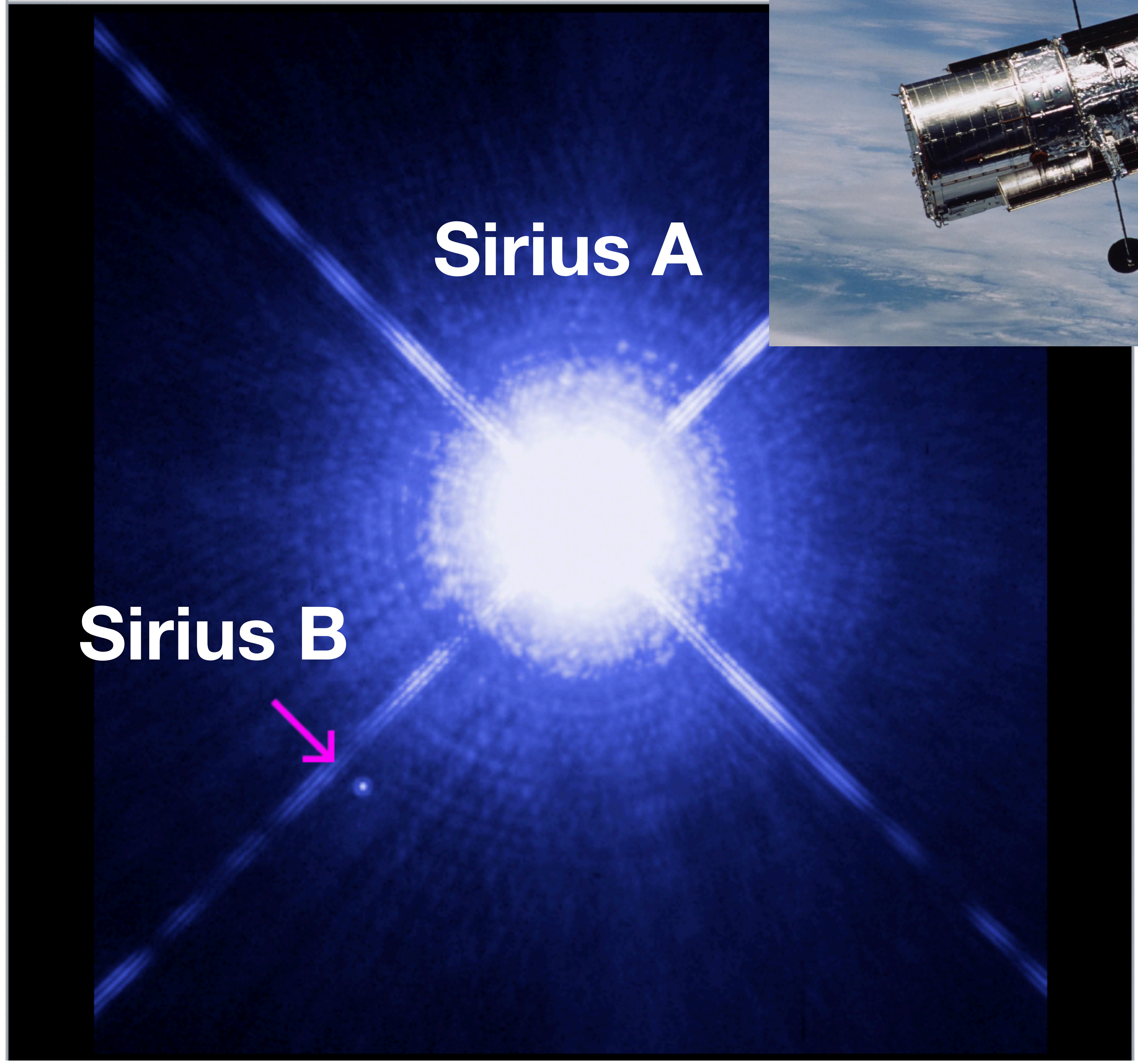
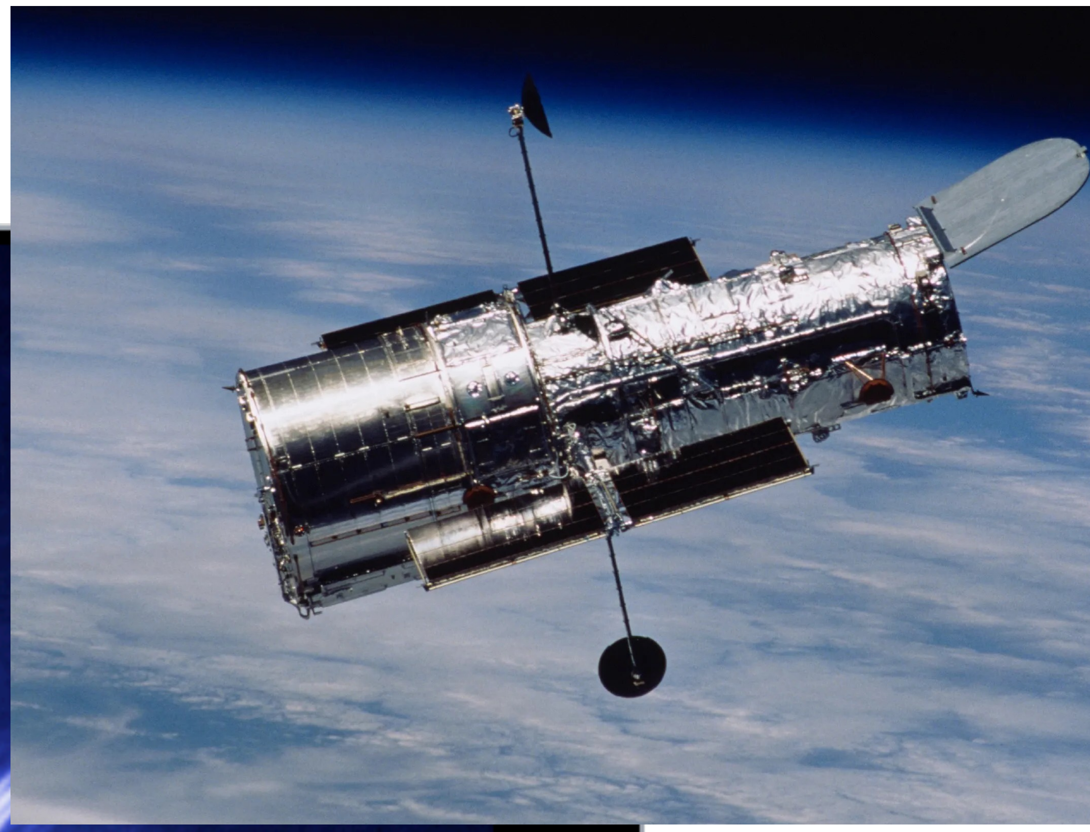




Hubble 2019





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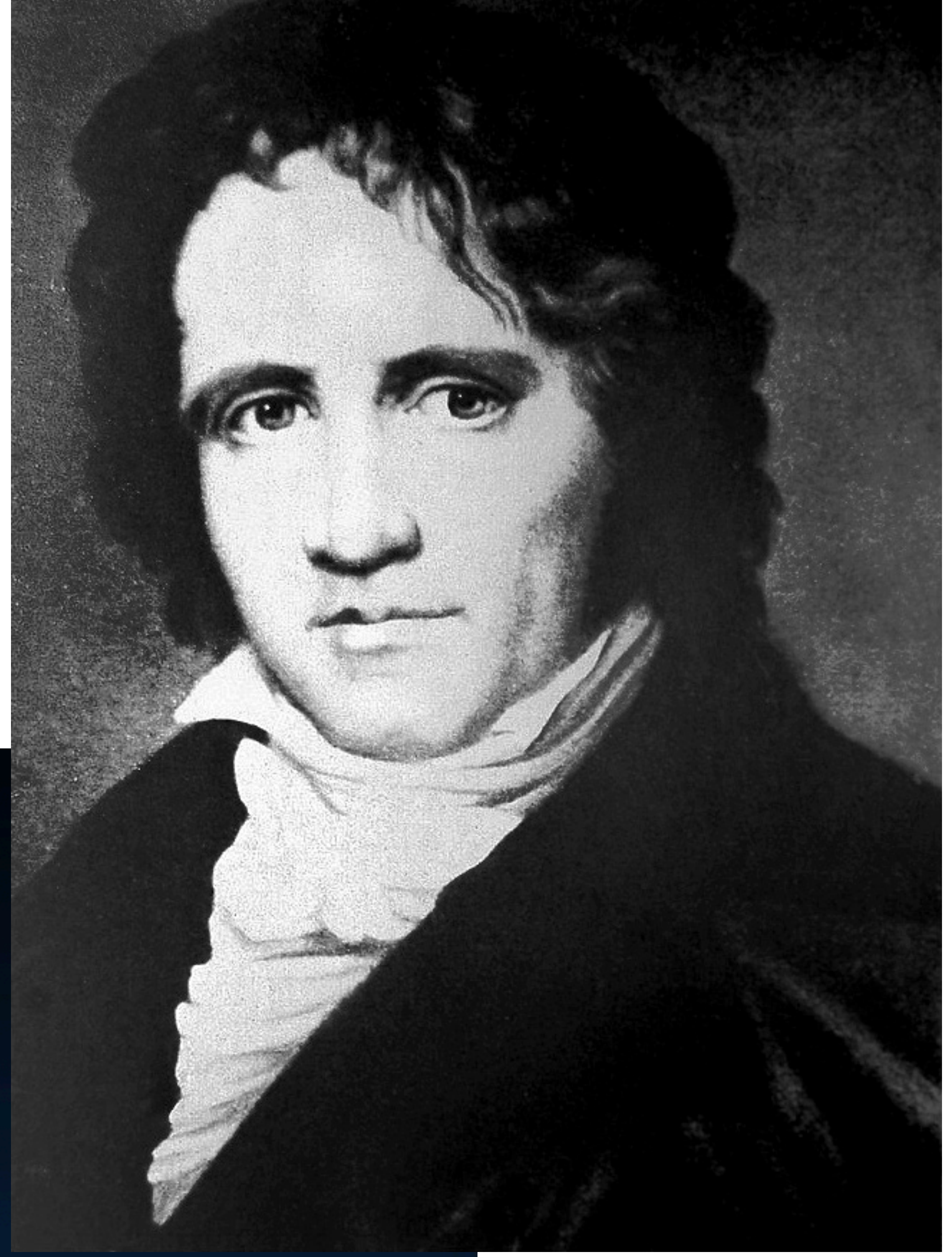

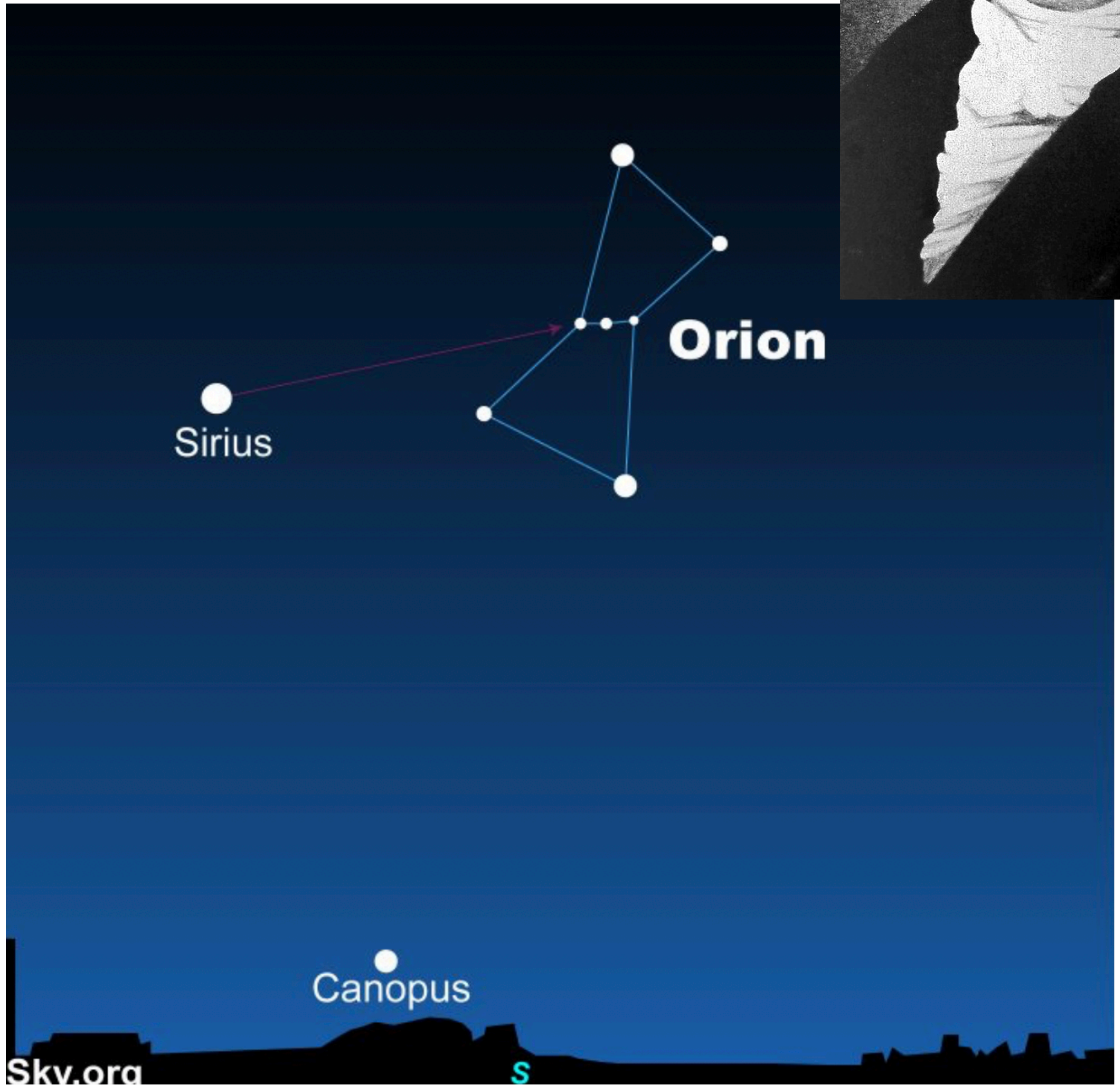

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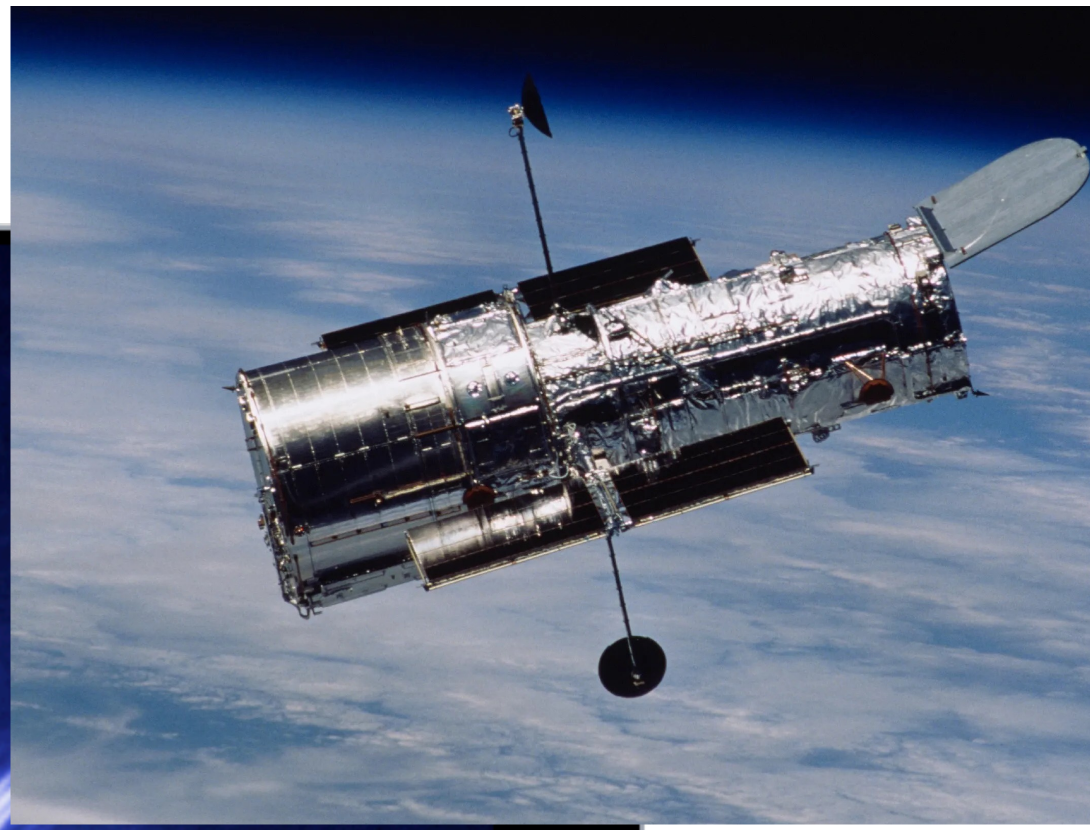

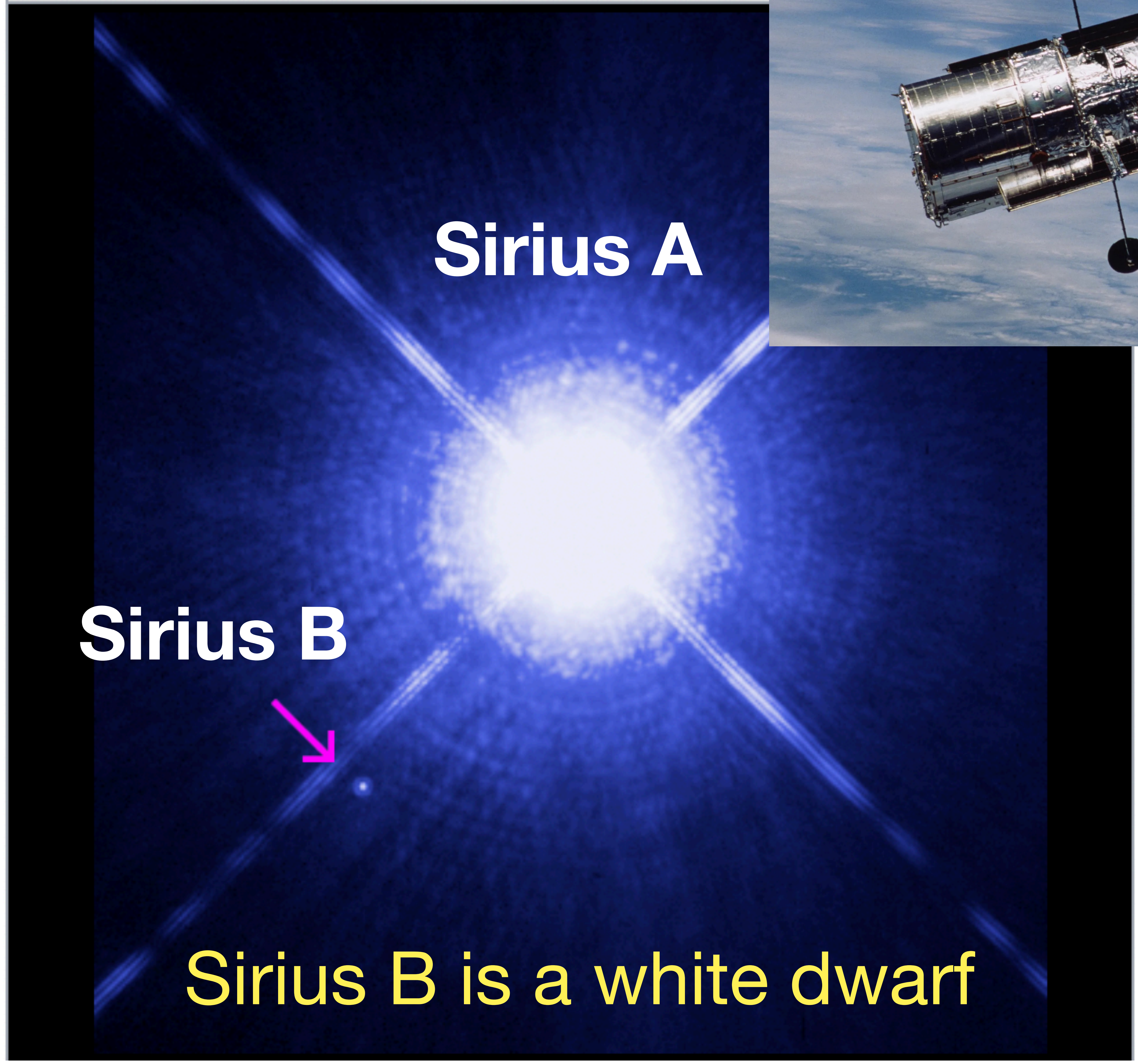

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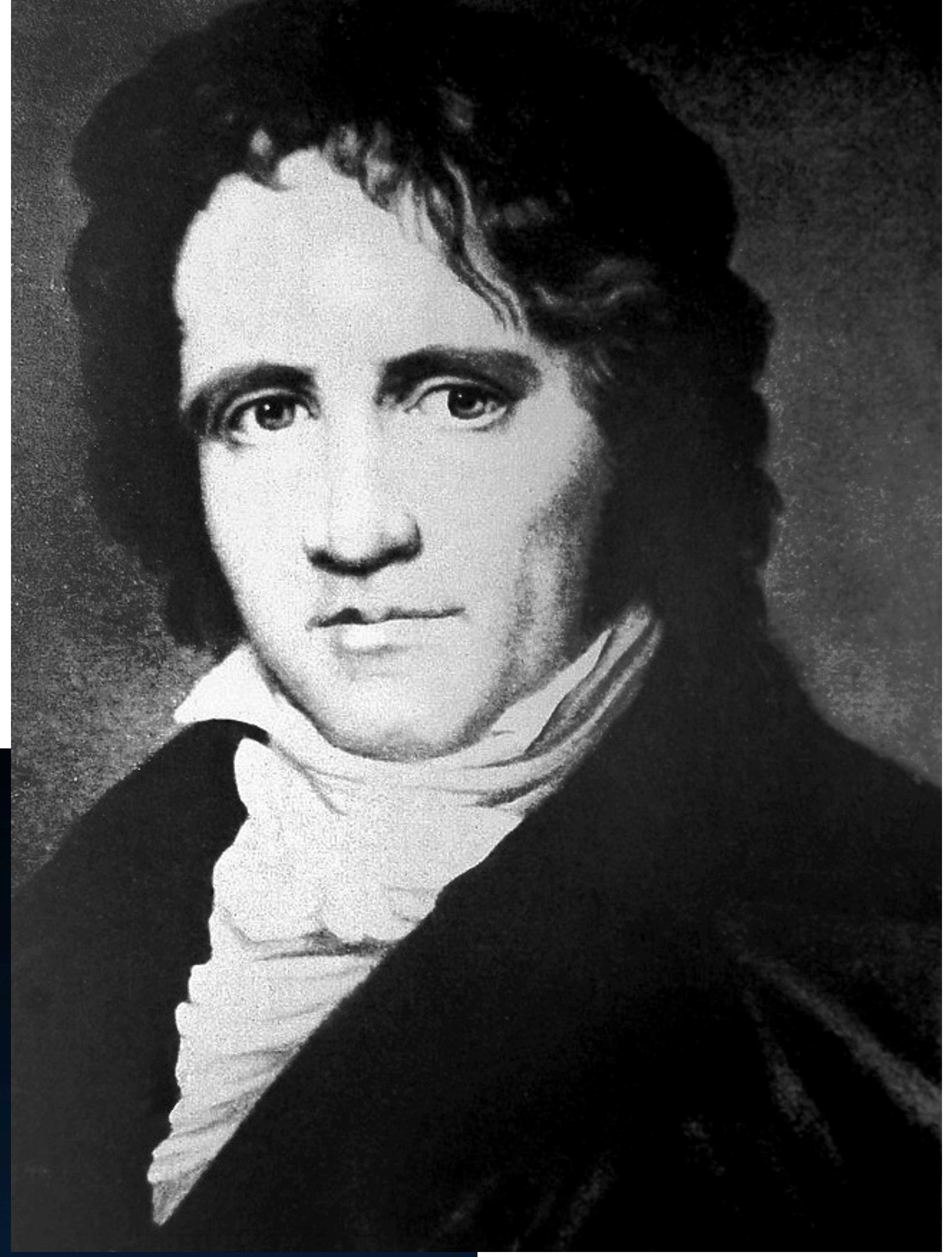

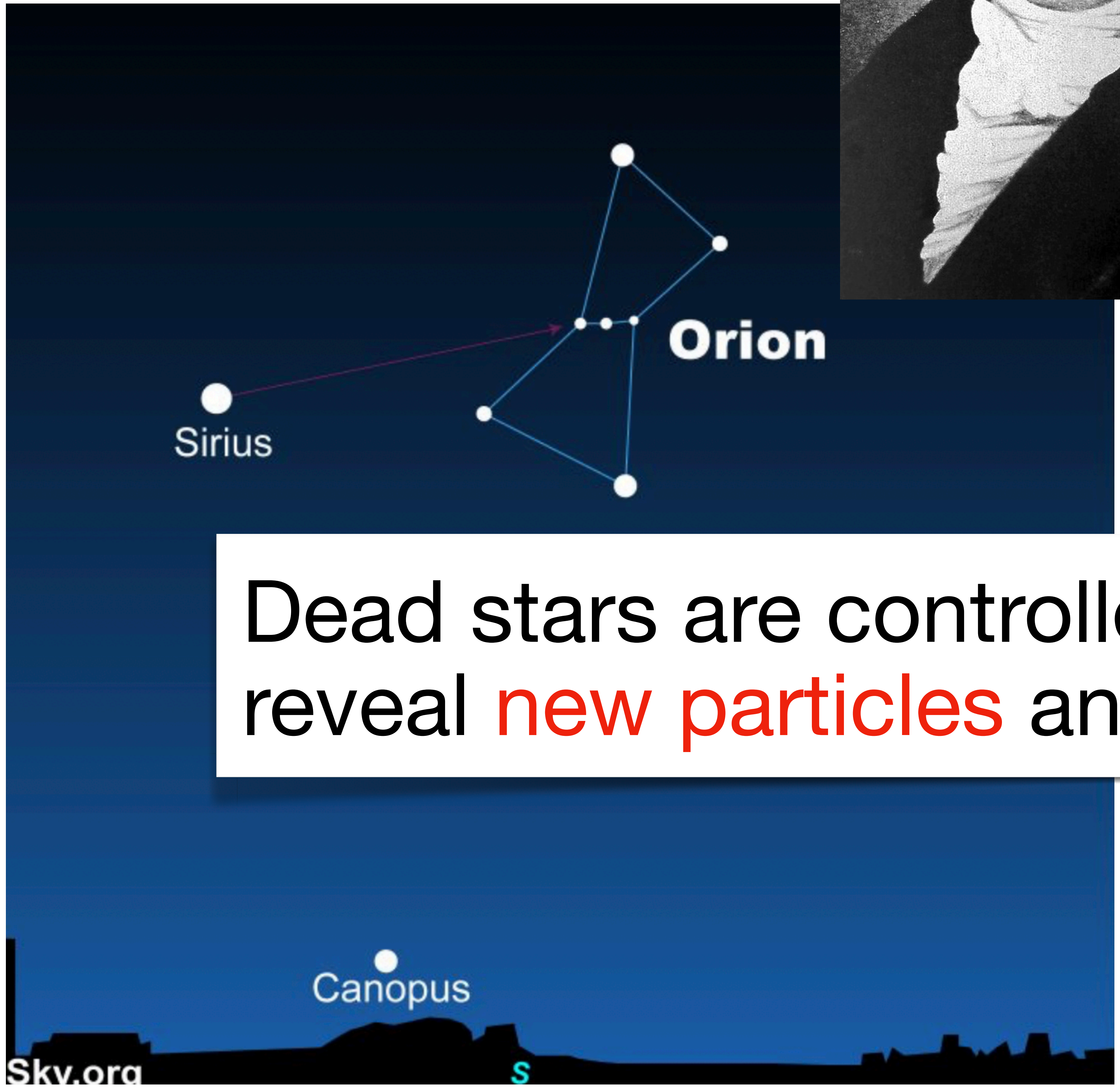

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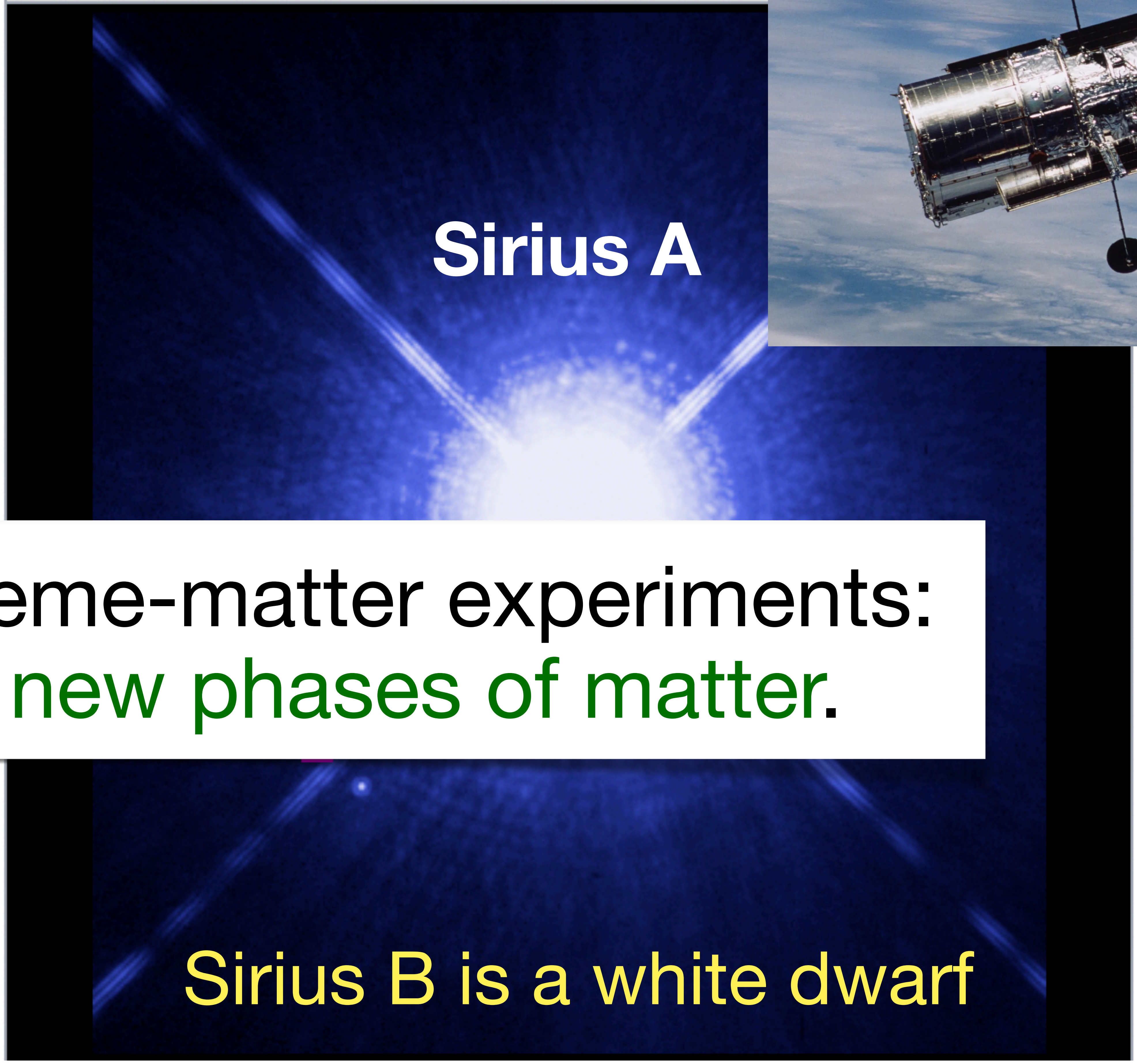
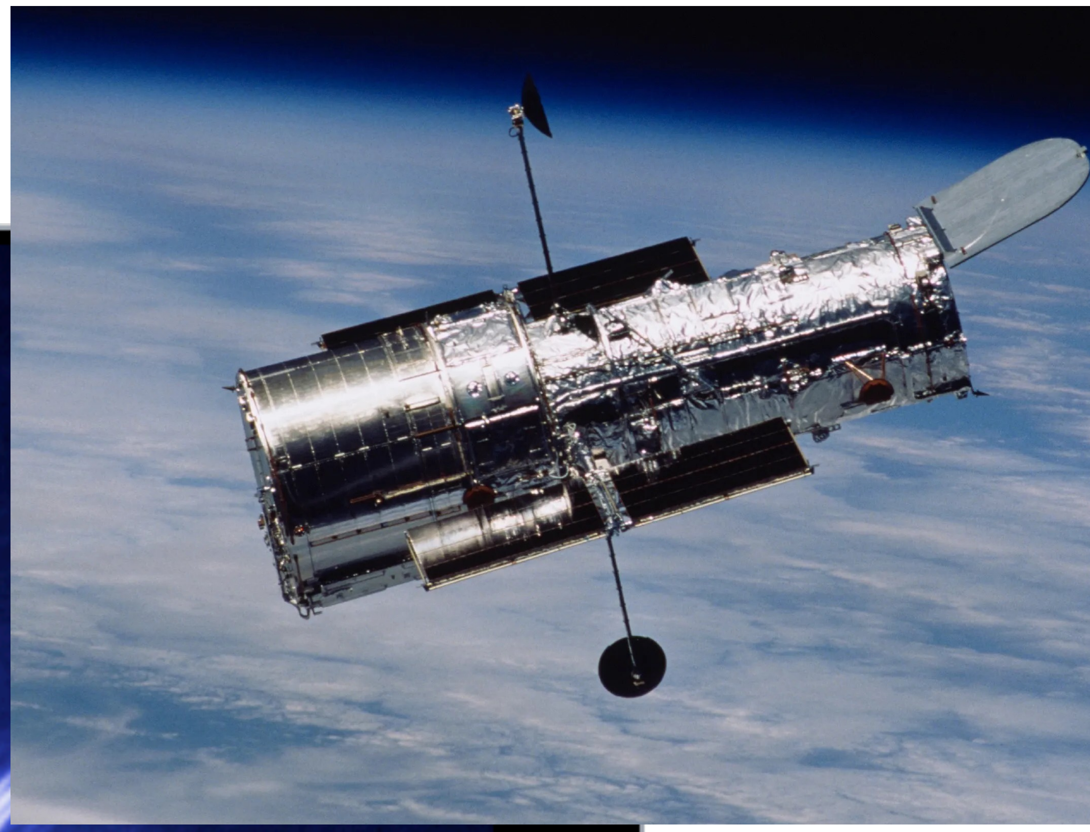
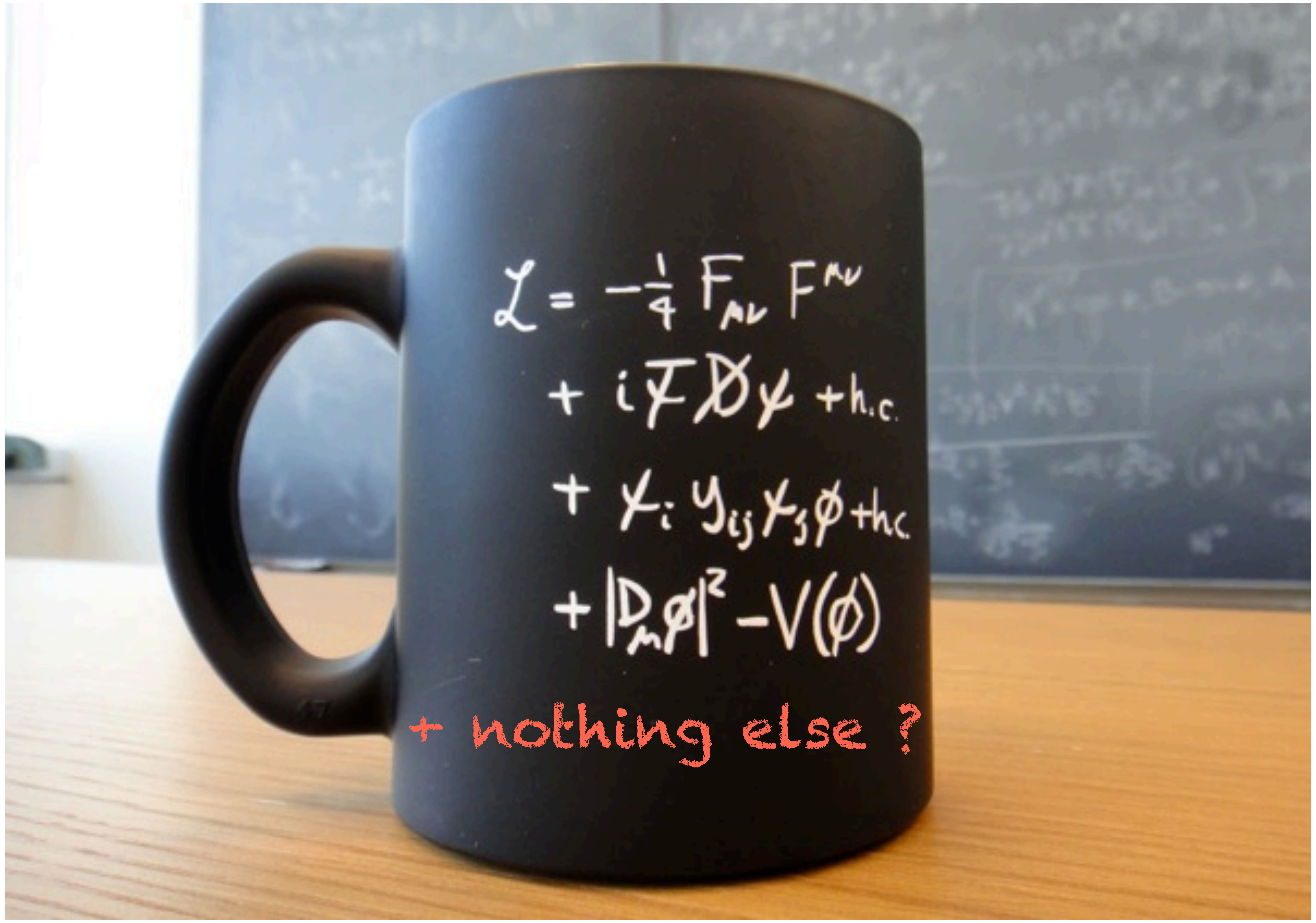




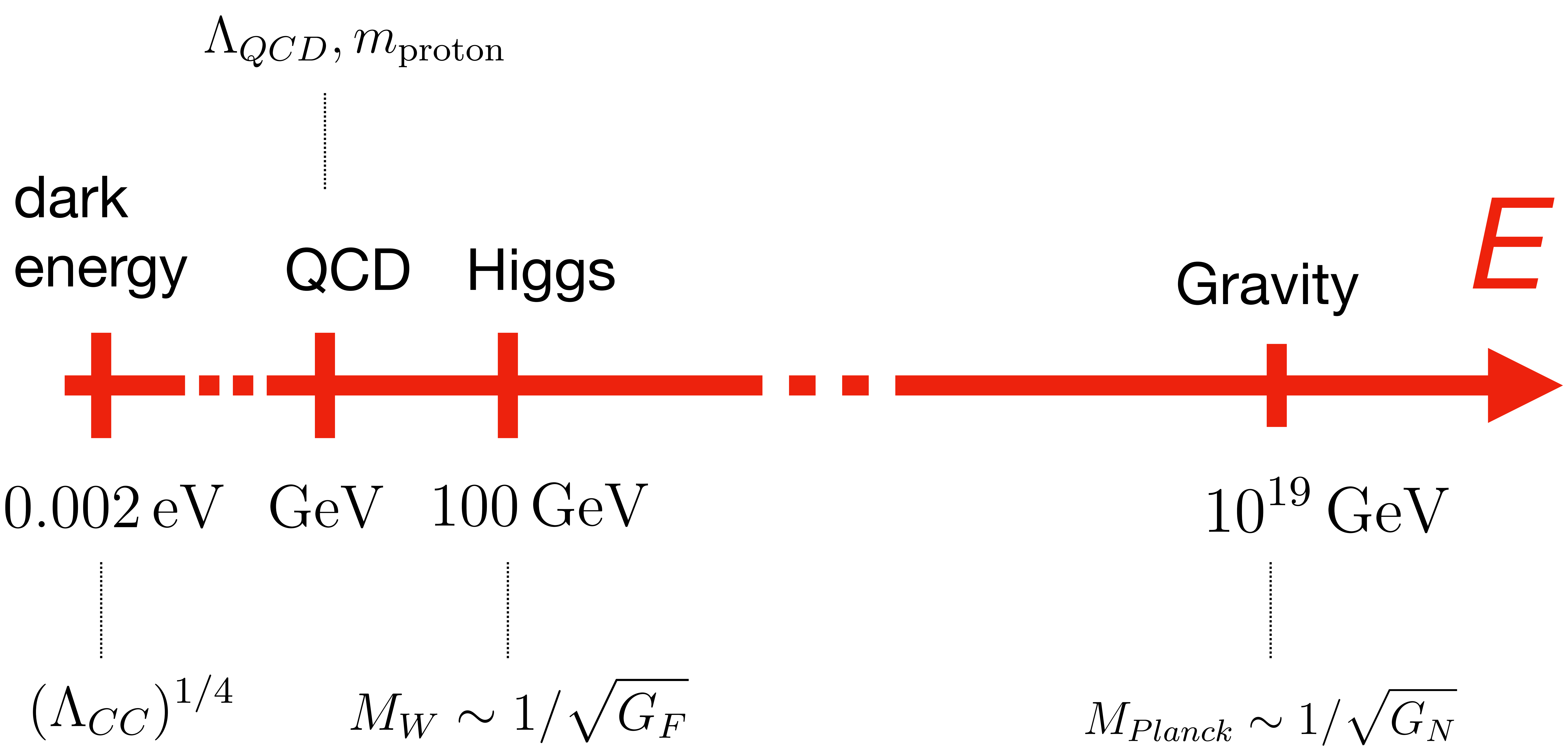
Dead stars are controlled extreme-matter experiments: reveal new particles and even new phases of matter.

The Standard Model of particle physics

It works. Where do we look next?



Fundamental scales of Standard Model of particle physics



Standard model as an effective field theory

The SM is not UV complete

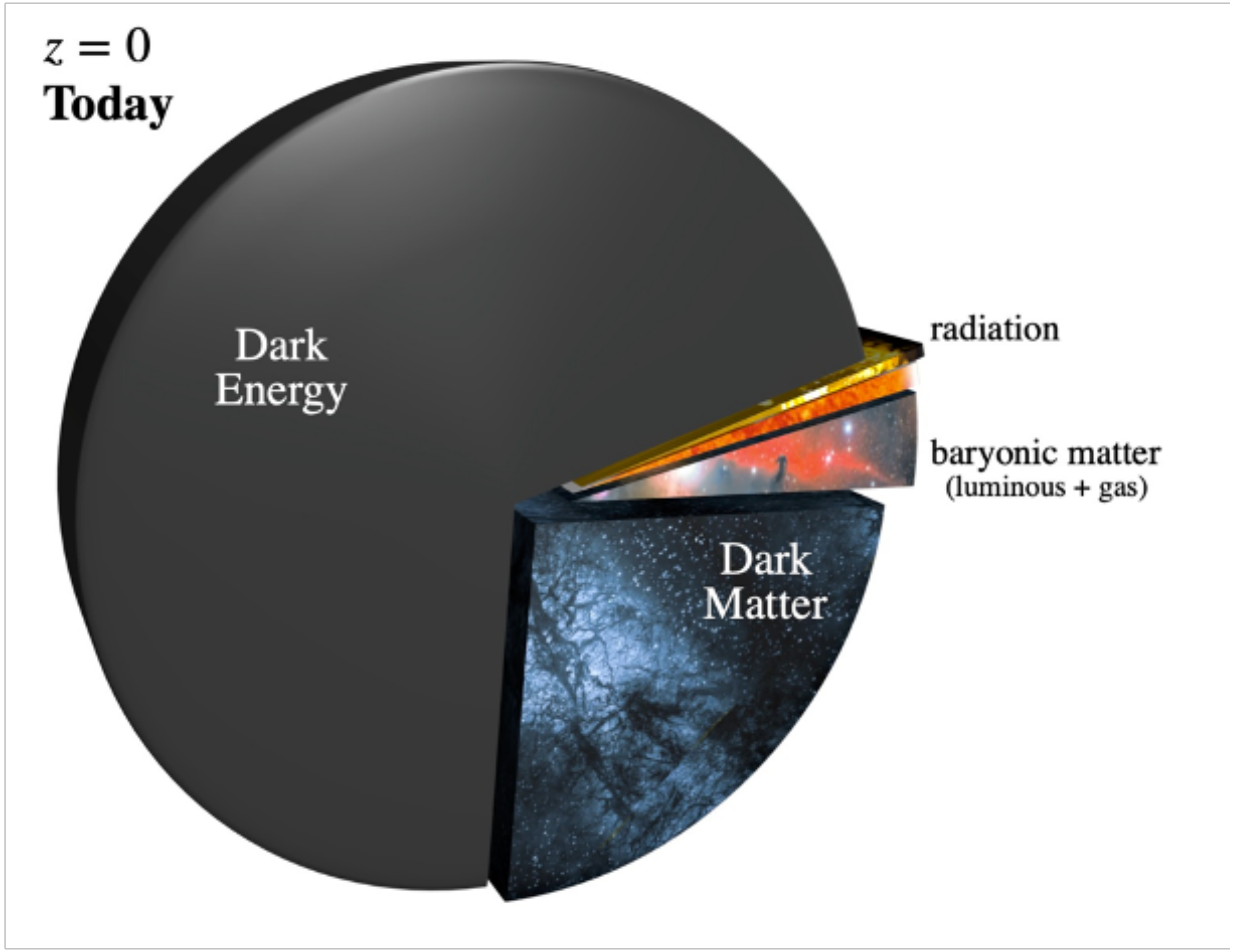
1) Gravity requires a consistent UV completion

irrelevant op.

$$S_{\rm EH} = -\frac{M_{pl}^2}{2}\int d^4x\sqrt{-g}R \sim \int d^4x\left(\frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{M_{pl}}h^2\Box h + \ldots\right)$$

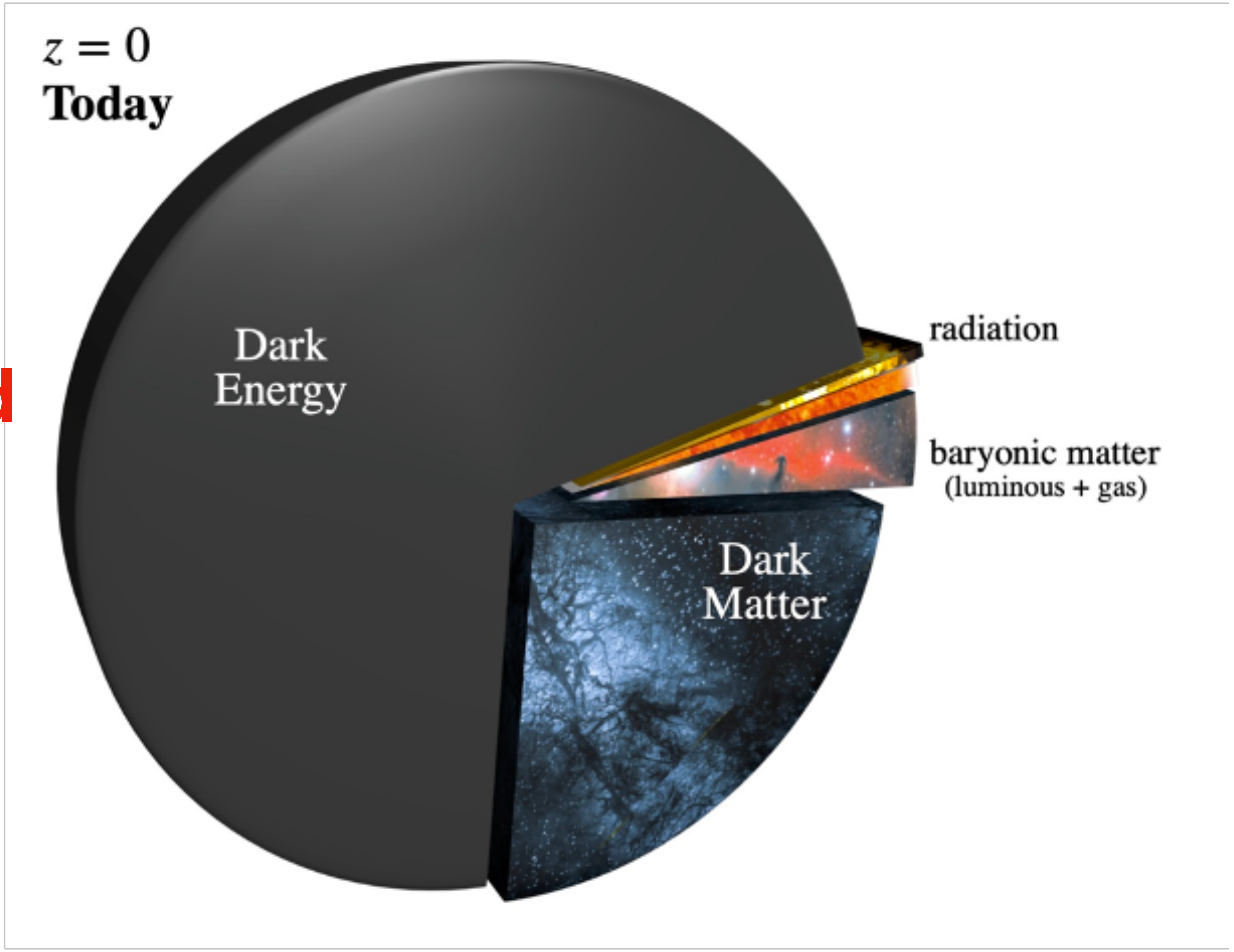
2) We know we need to add more quantum fields to SM, given evidence on dark matter, inflation, and baryogenesis, …

Inventory of the universe



Inventory of the universe

not understood



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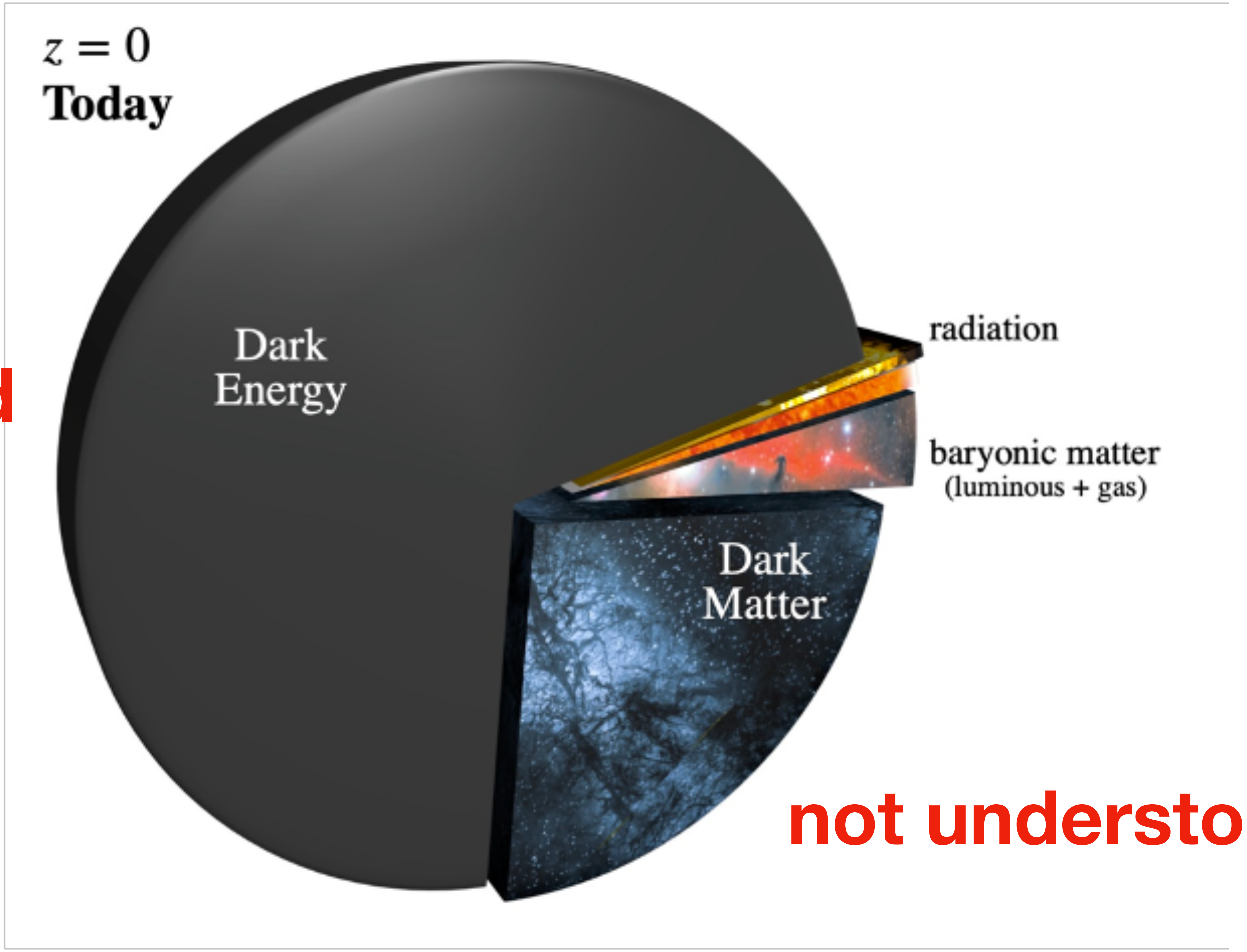

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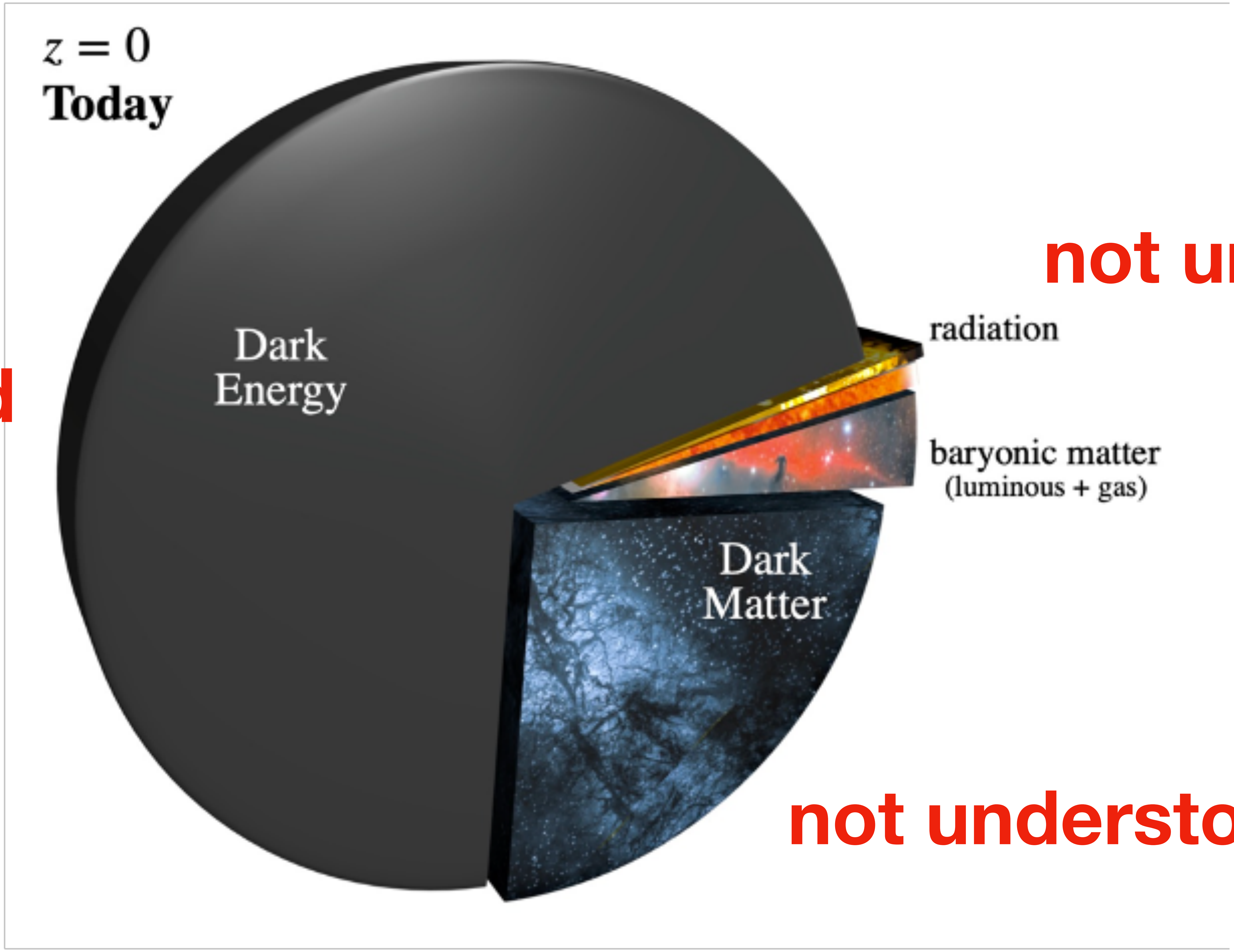

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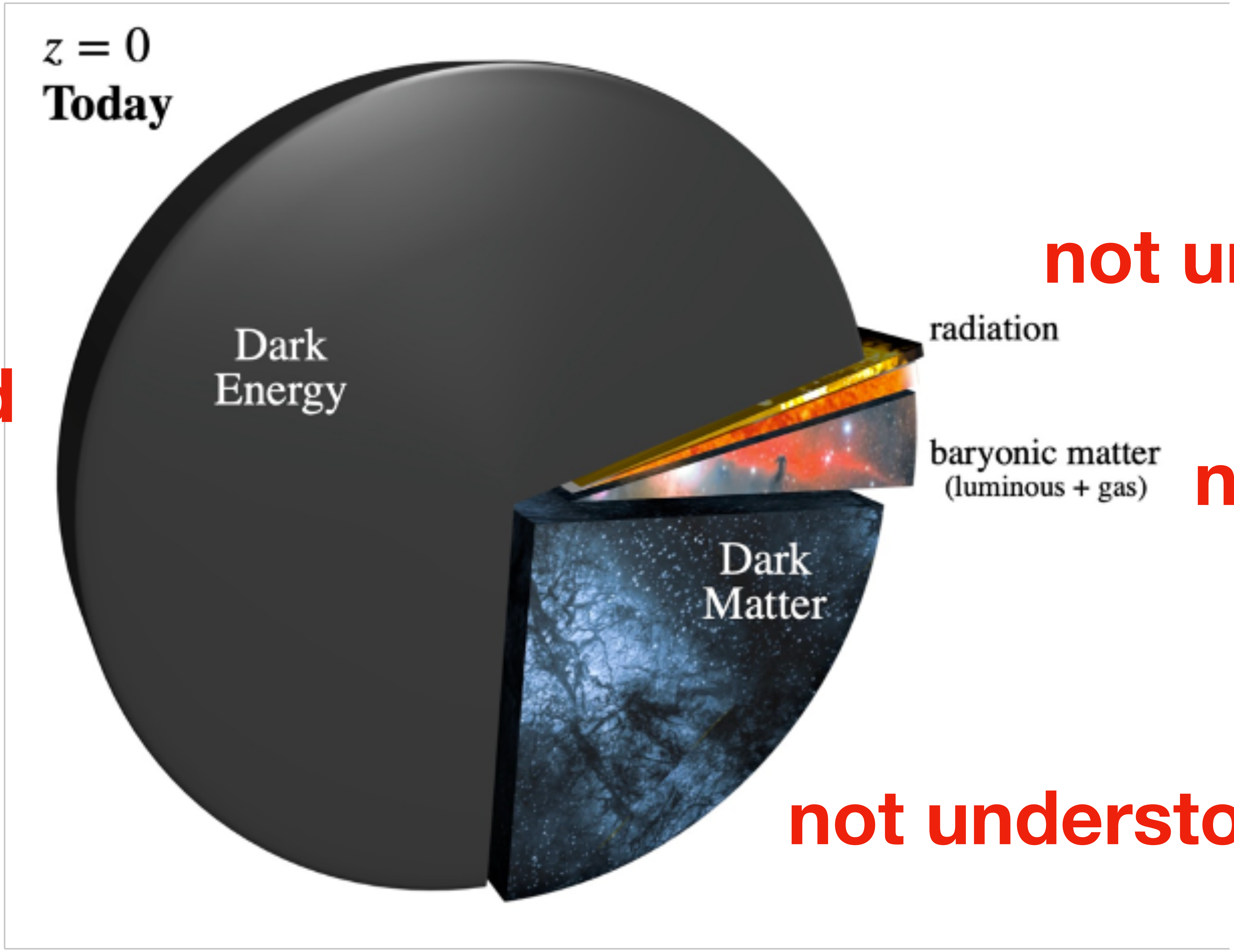

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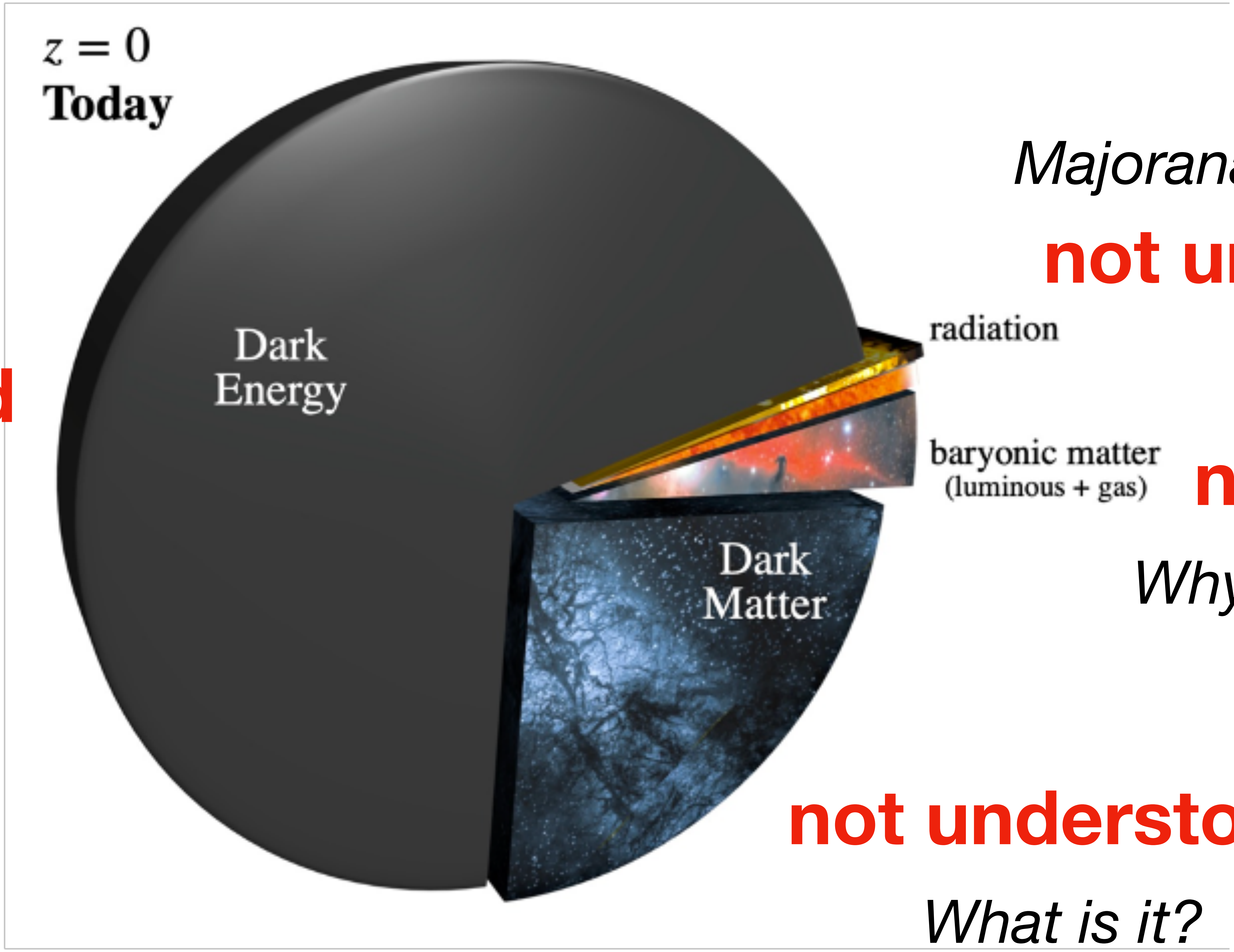


Majorana or Dirac neutrinos?

not understood

not understood

Is it a constant?
Why so small?

not understood

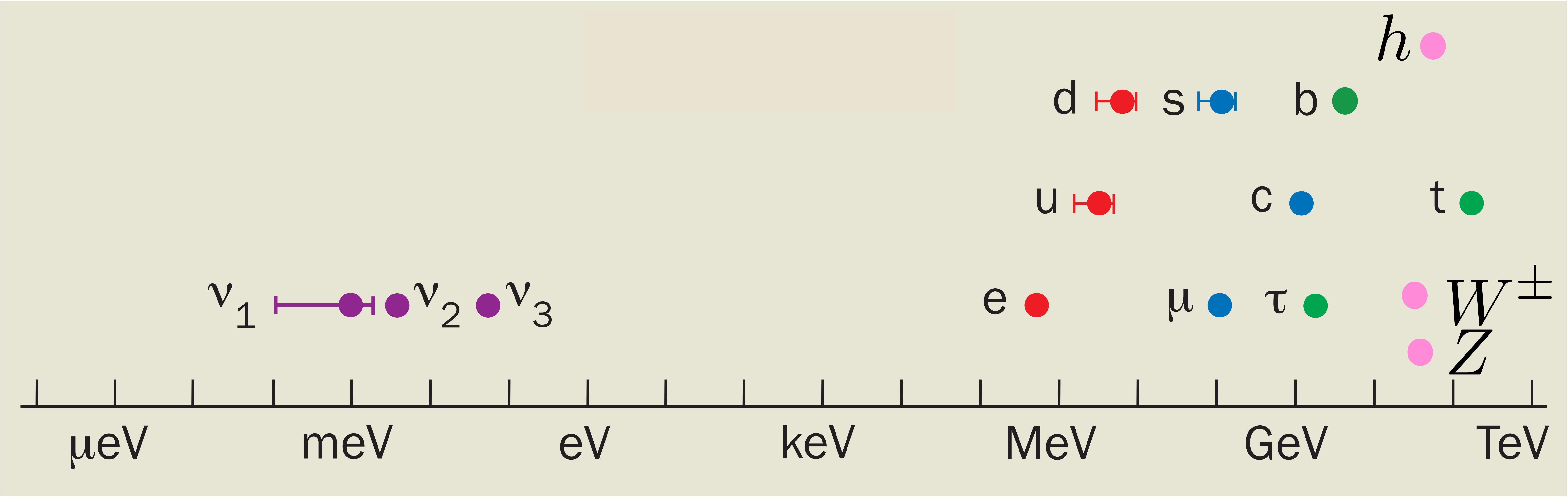
Why is there more matter than antimatter?

not understood

What is it?

What is the scale of new physics?

The energy frontier



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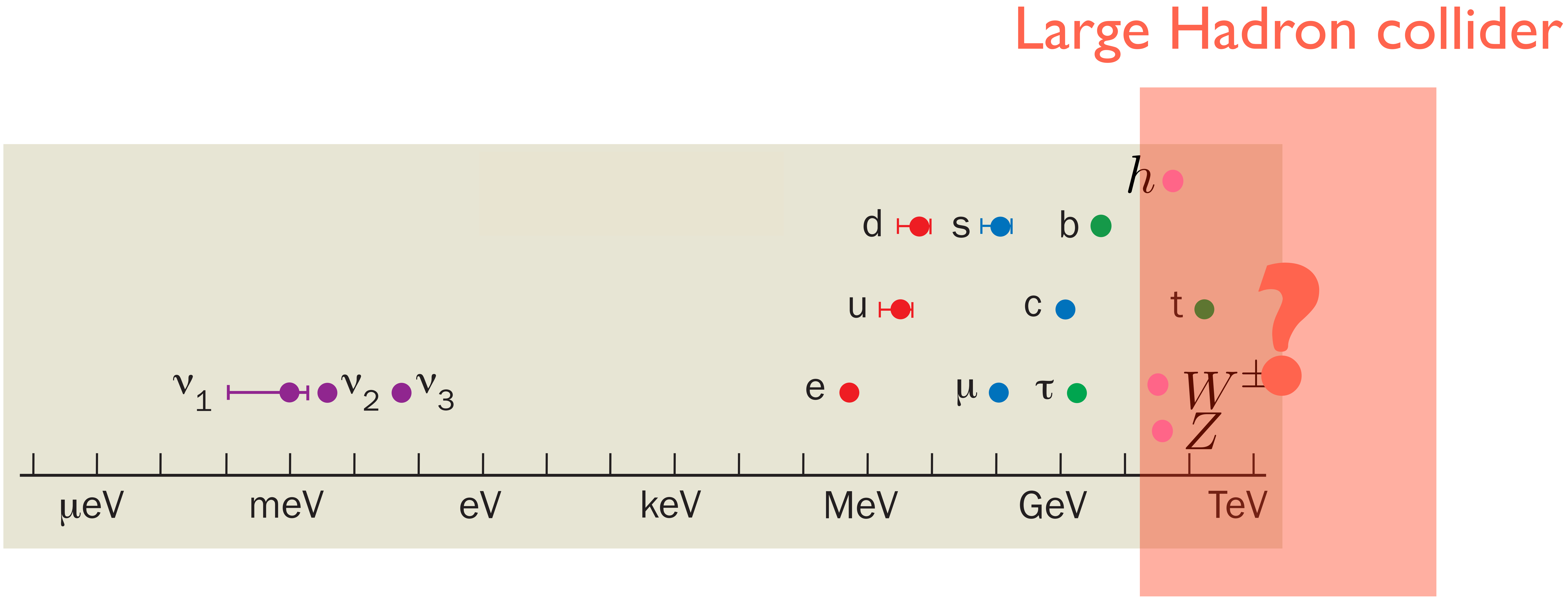

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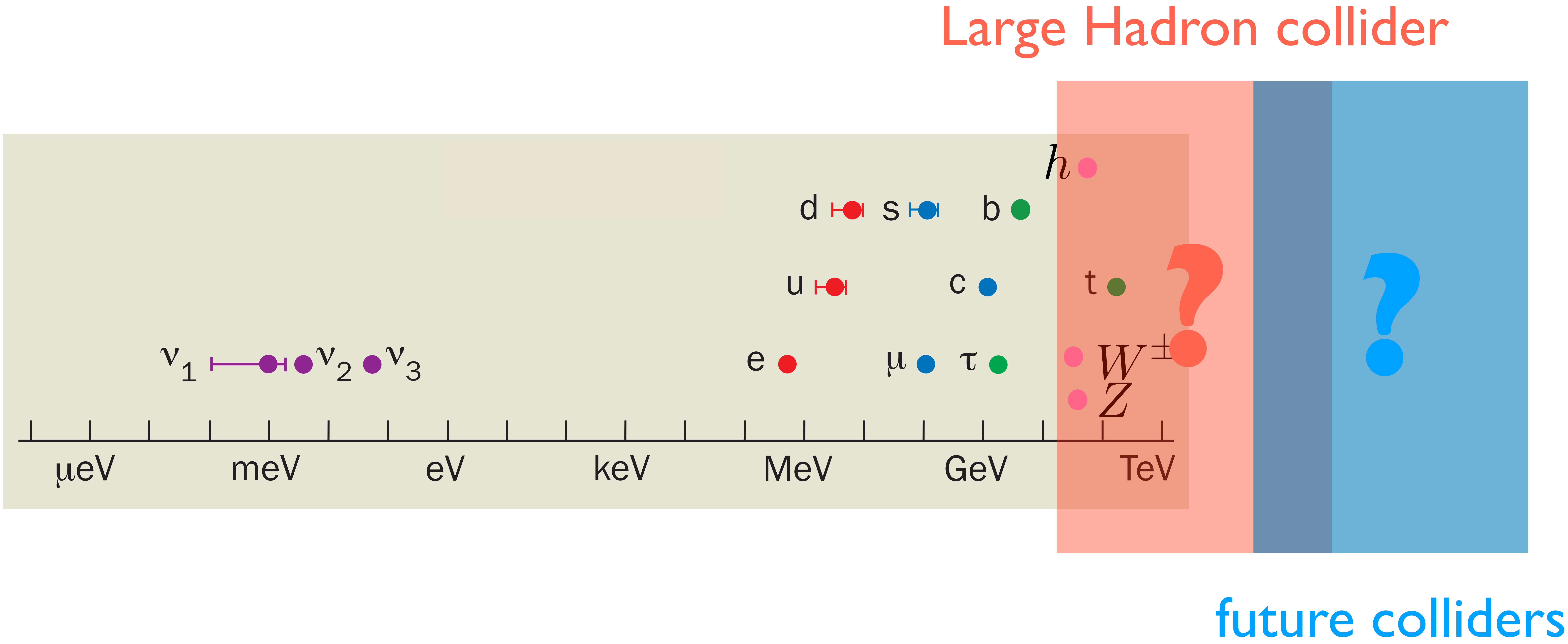

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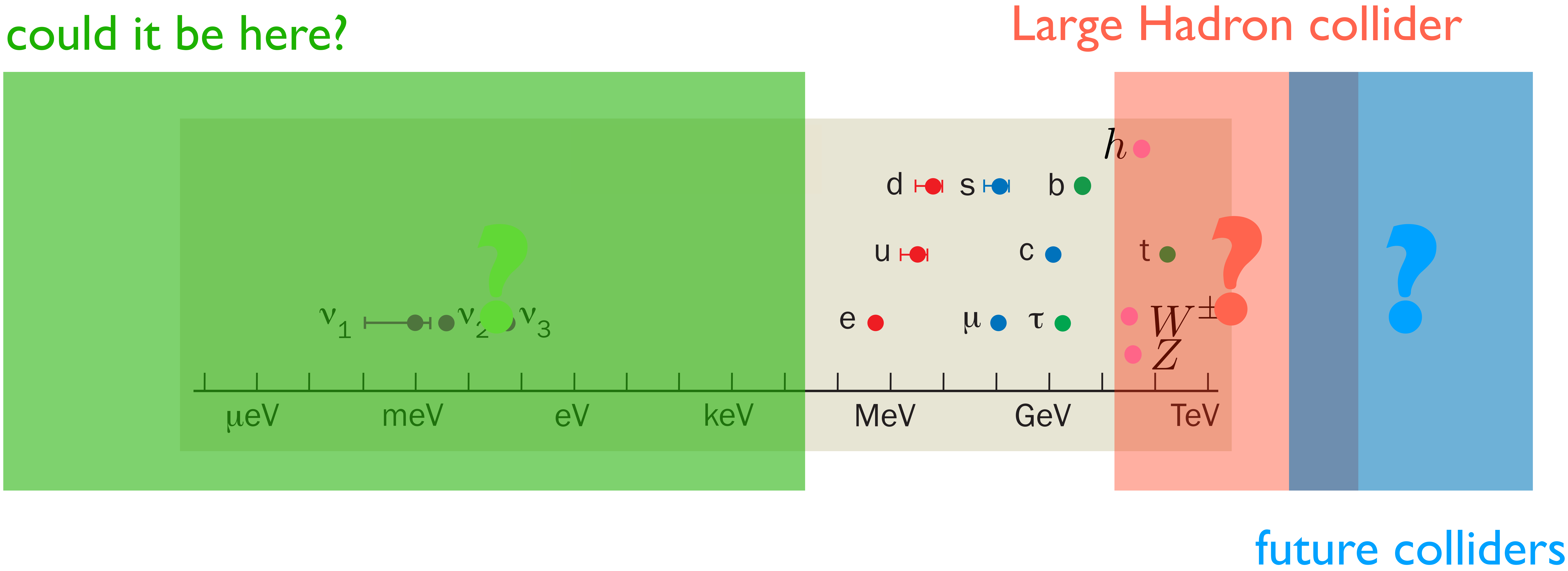

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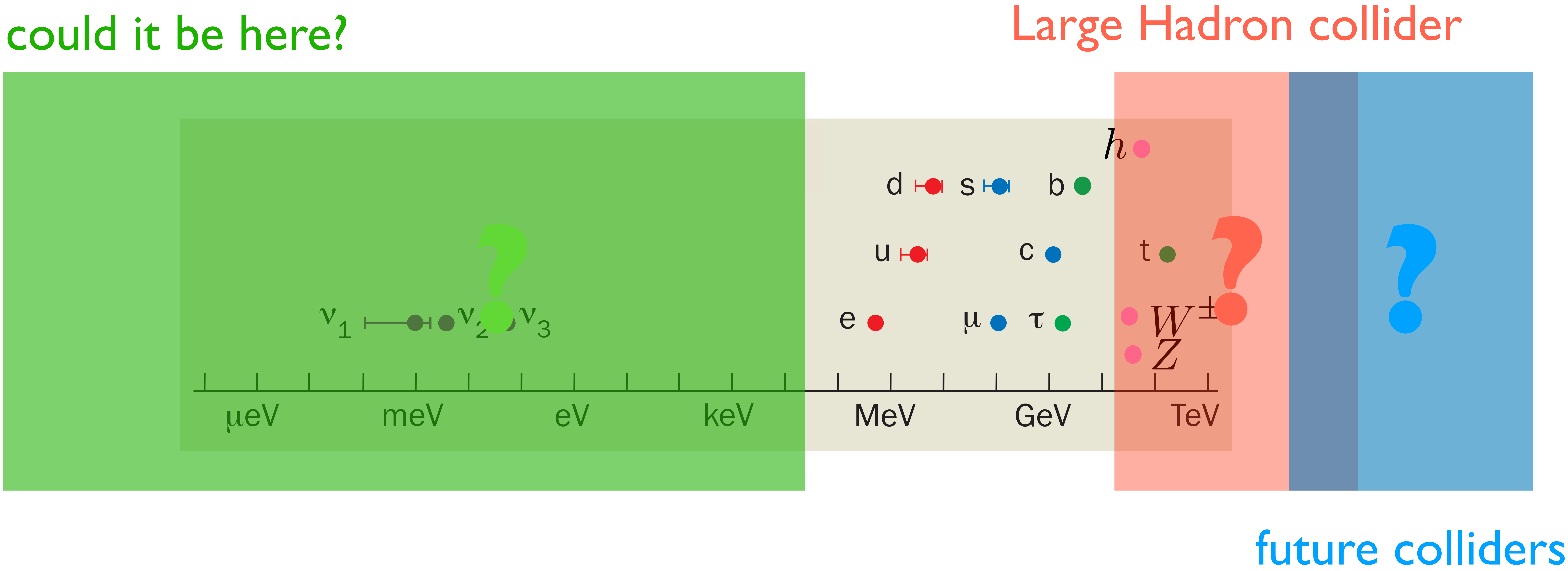
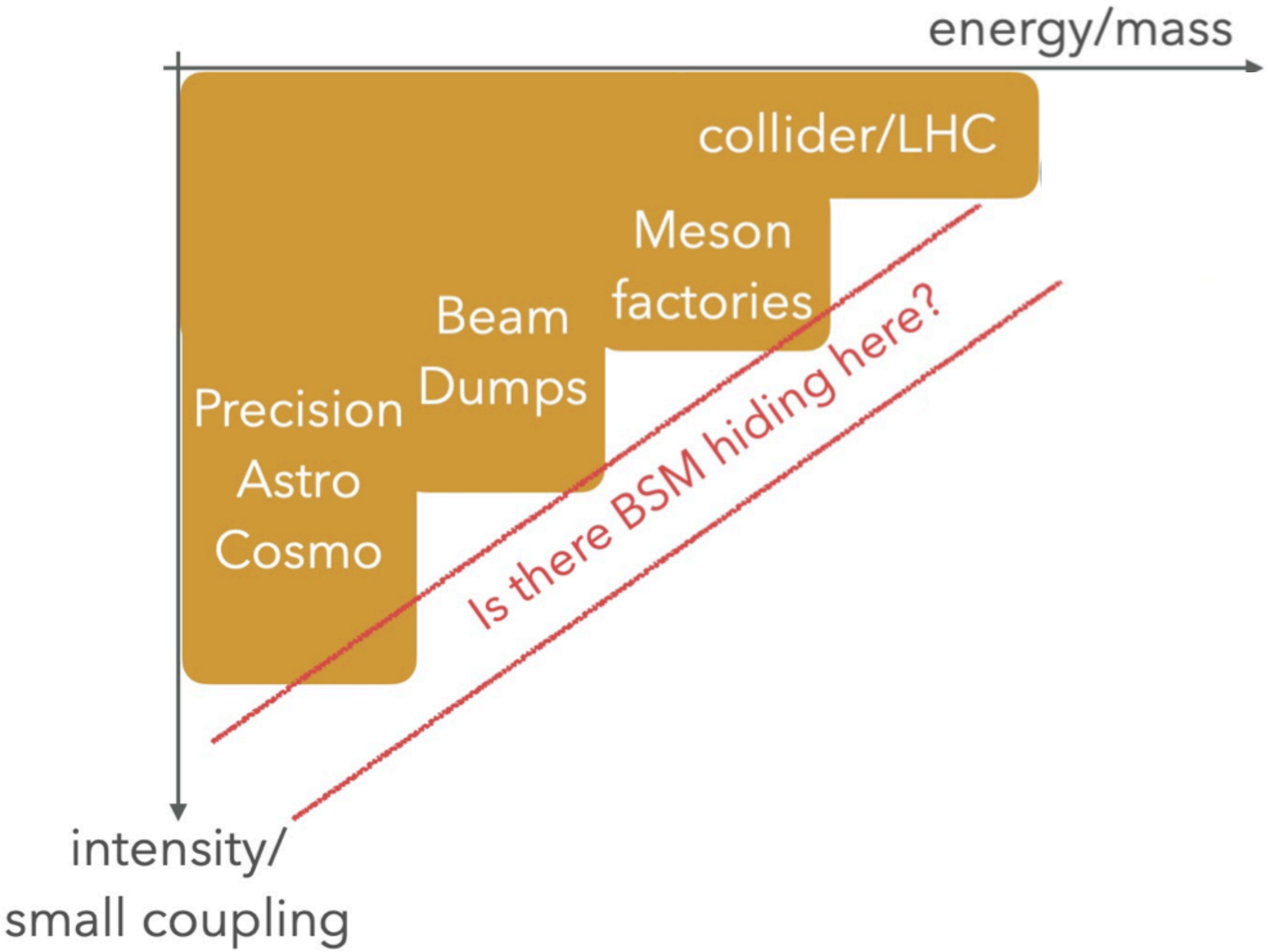


this should be a 2D plot?

The energy intensity frontier



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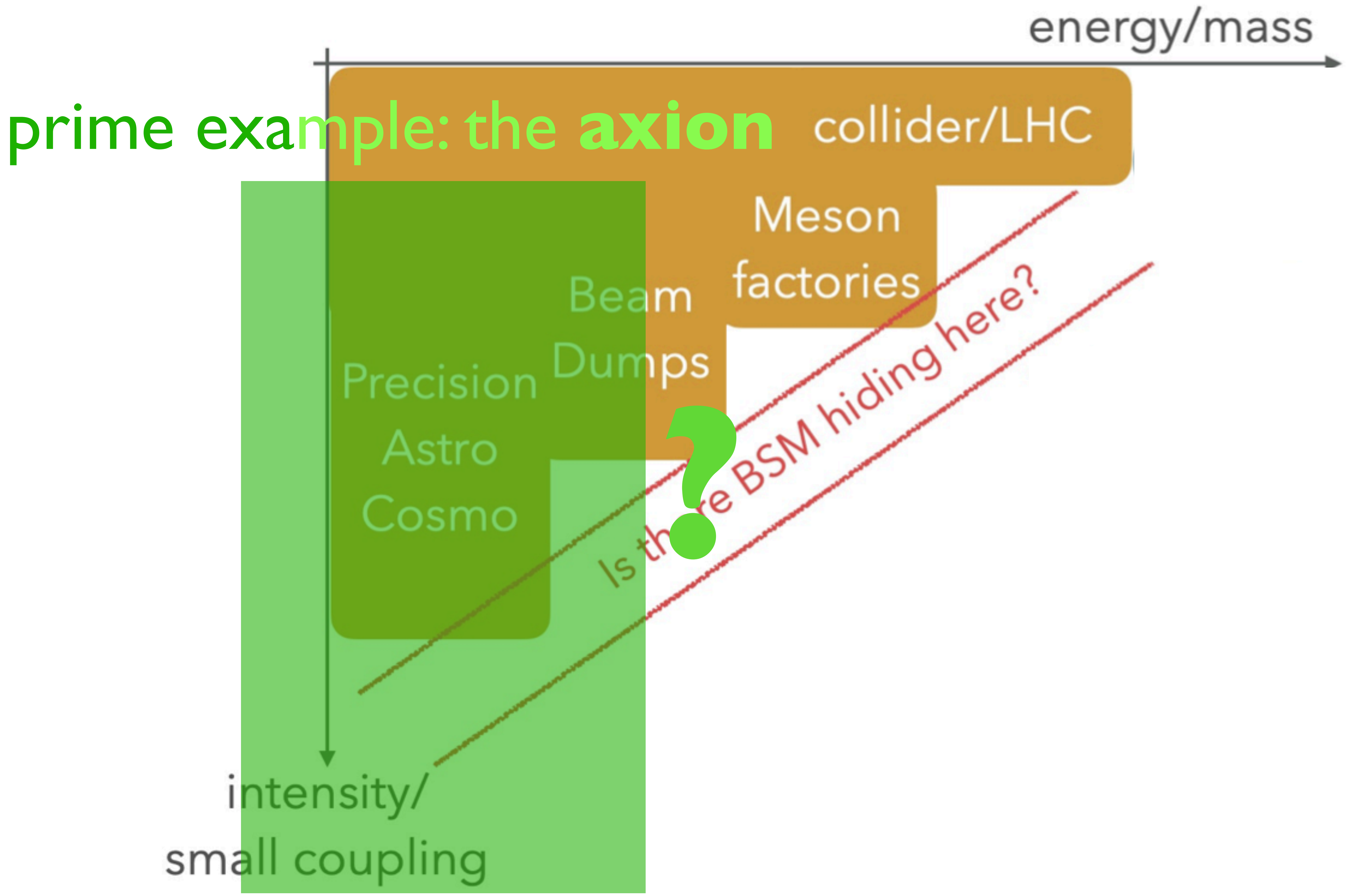

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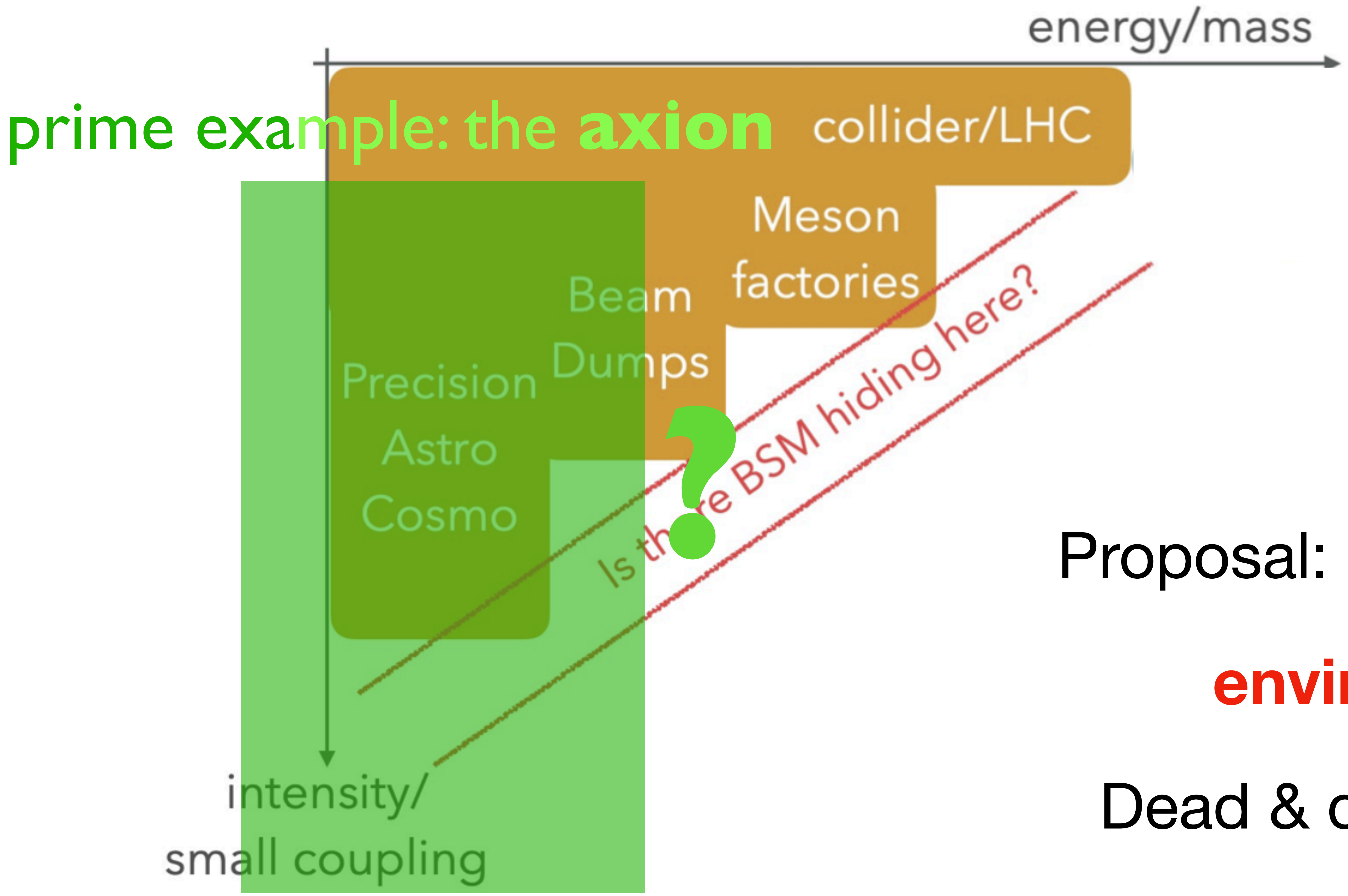


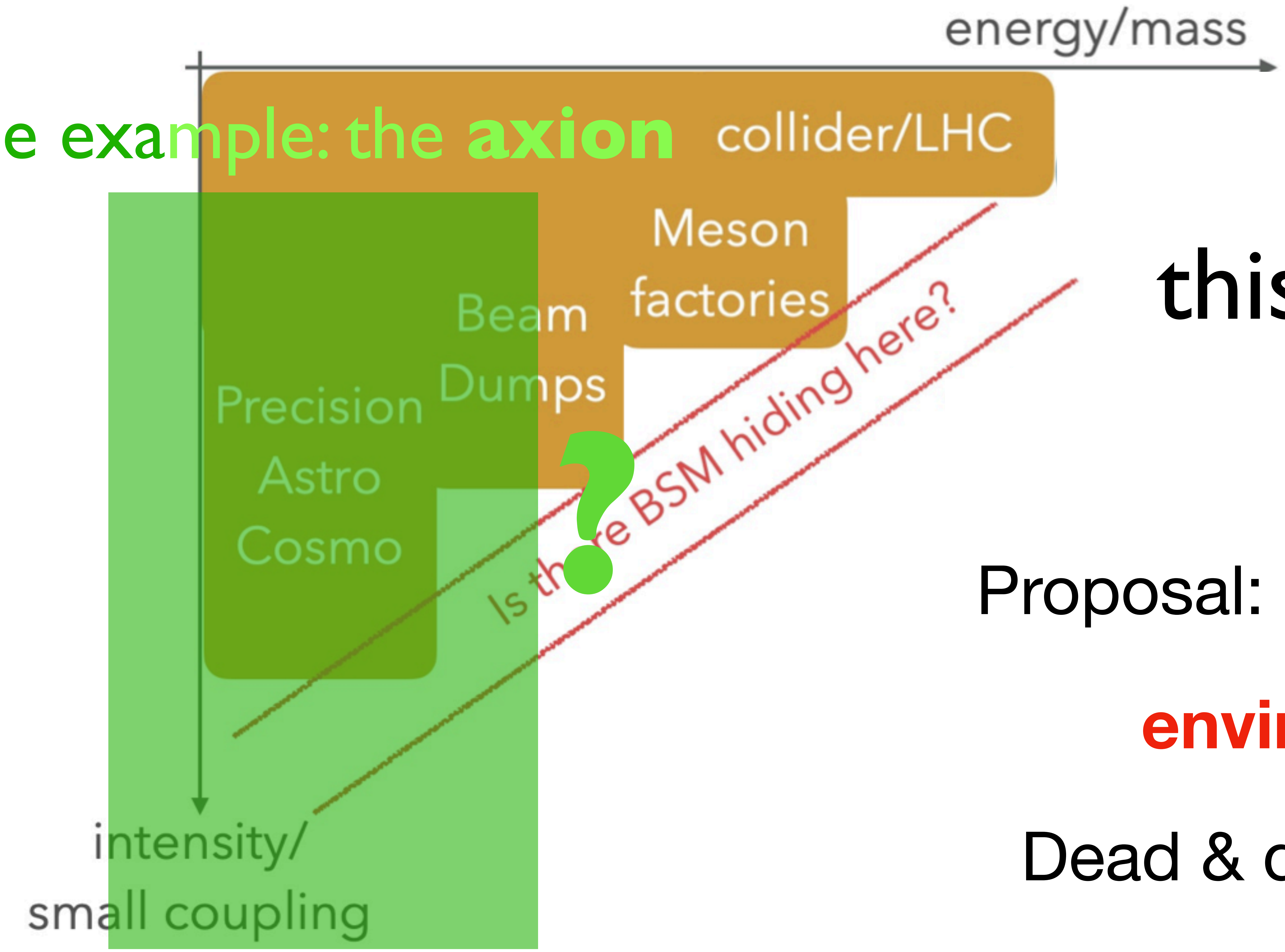
Proposal: use unexplored 3rd direction

environment (high density).

Dead & dying stars provide extreme environments.

The energy intensity frontier

prime example: the **axion**



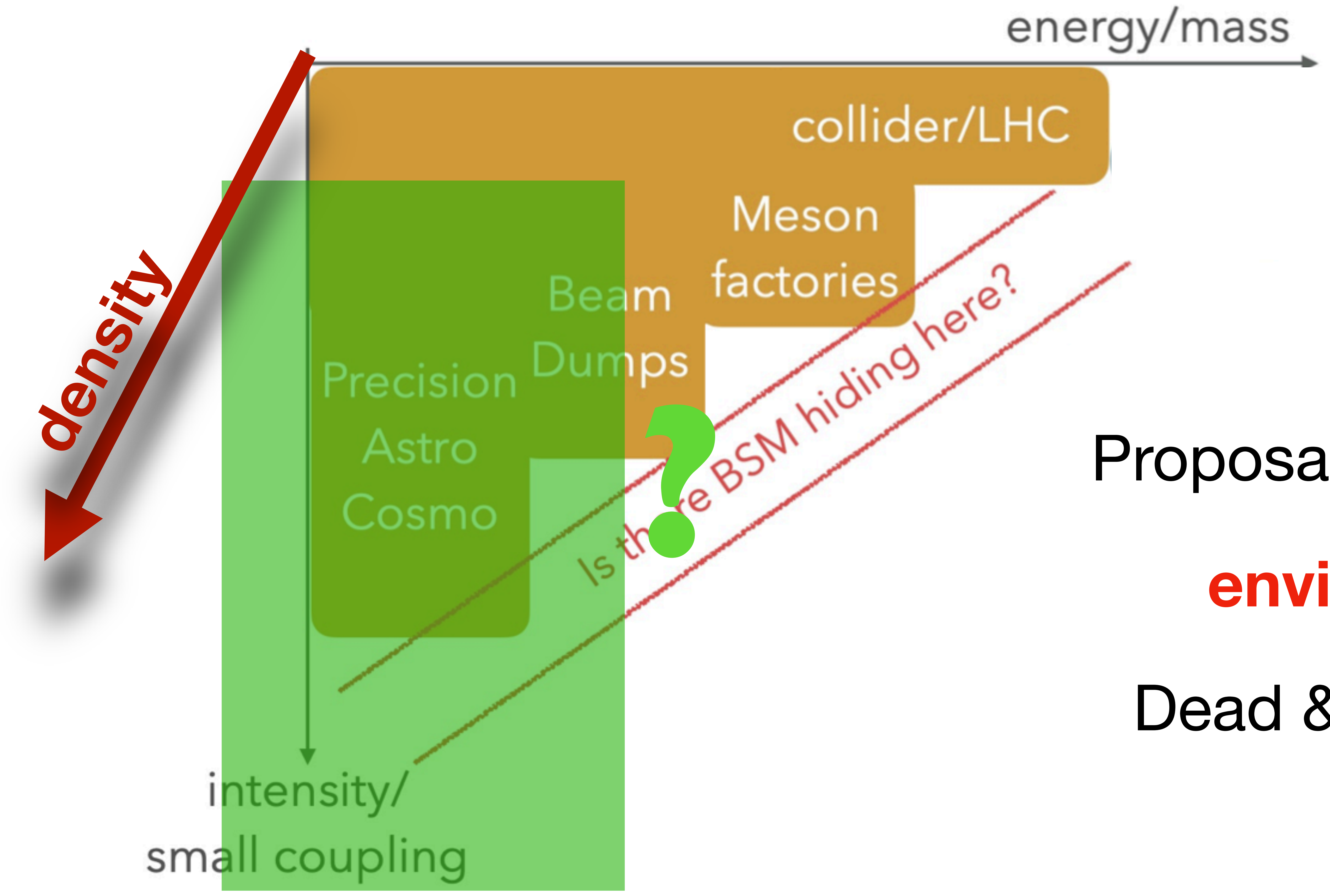
this should be a 3D plot?

Proposal: use unexplored 3rd direction

environment (high density).

Dead & dying stars provide extreme environments.

A third lever: environment (density)



Proposal: use unexplored 3rd direction

environment (high density,…).

Dead & dying stars provide extreme environments.

BSM TARGET: THE AXION

Strong CP problem

$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} \right]$$

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would induce electric dipole moment, violates CP

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

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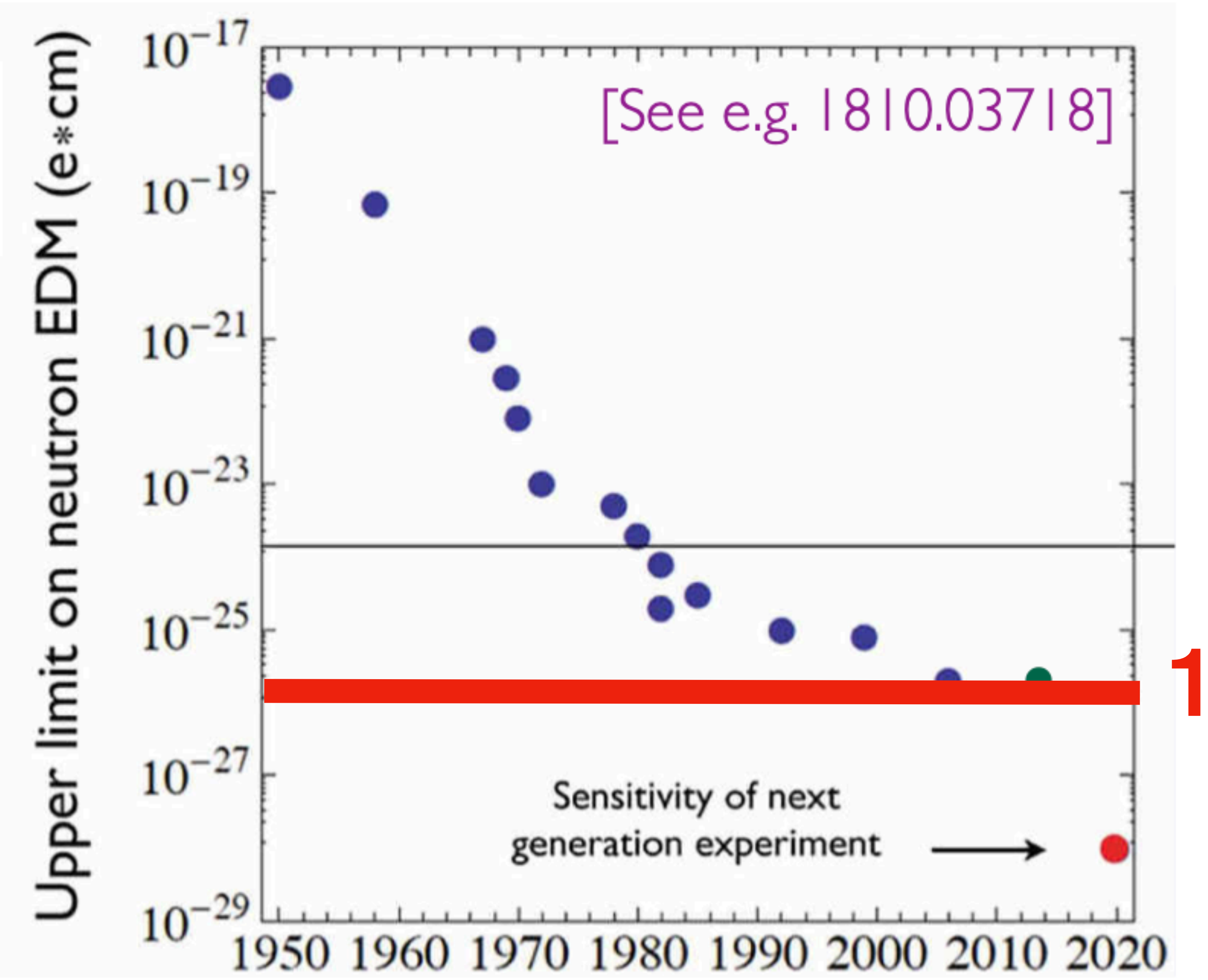
d_n



10^{-26}

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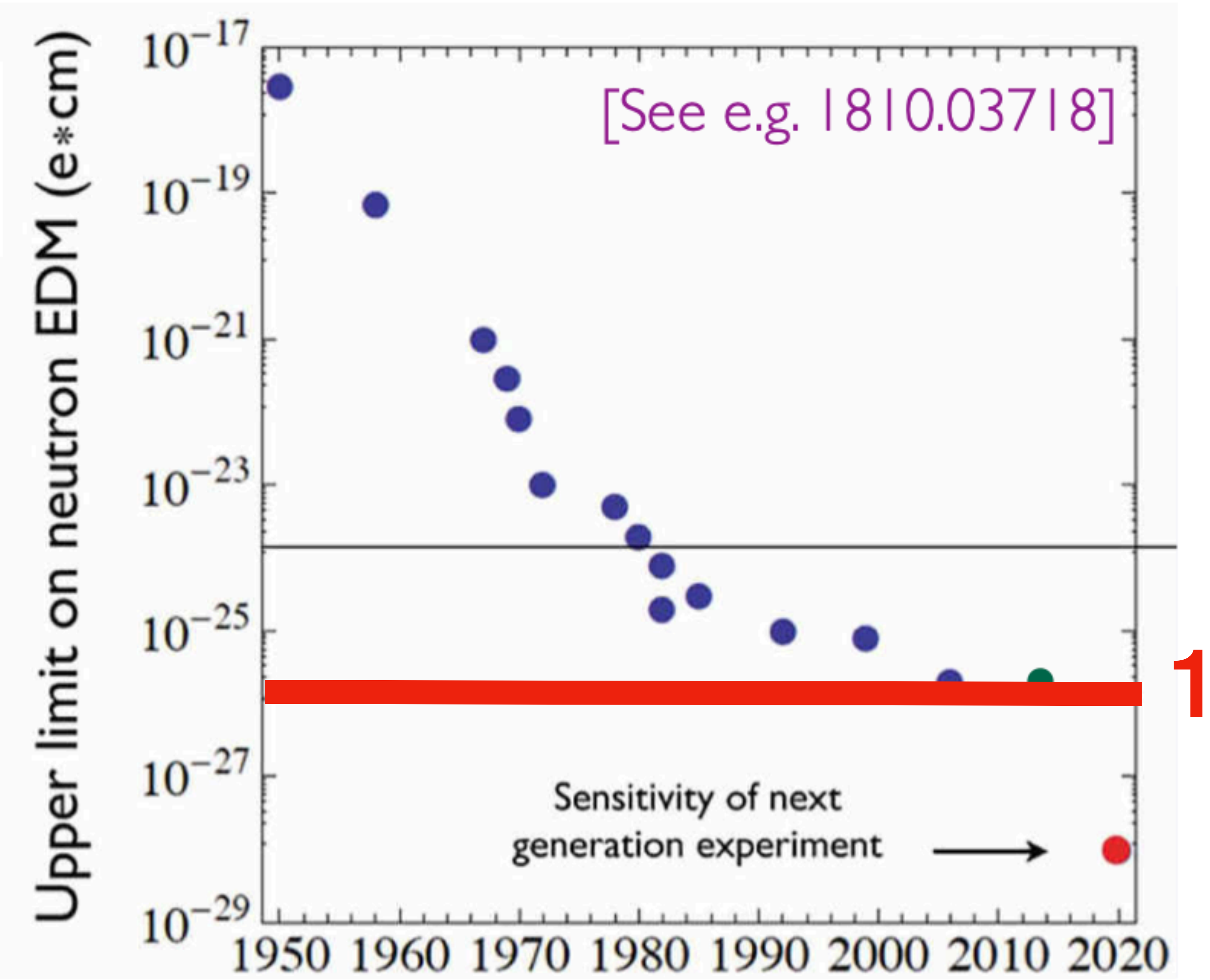


10^{-26}

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

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

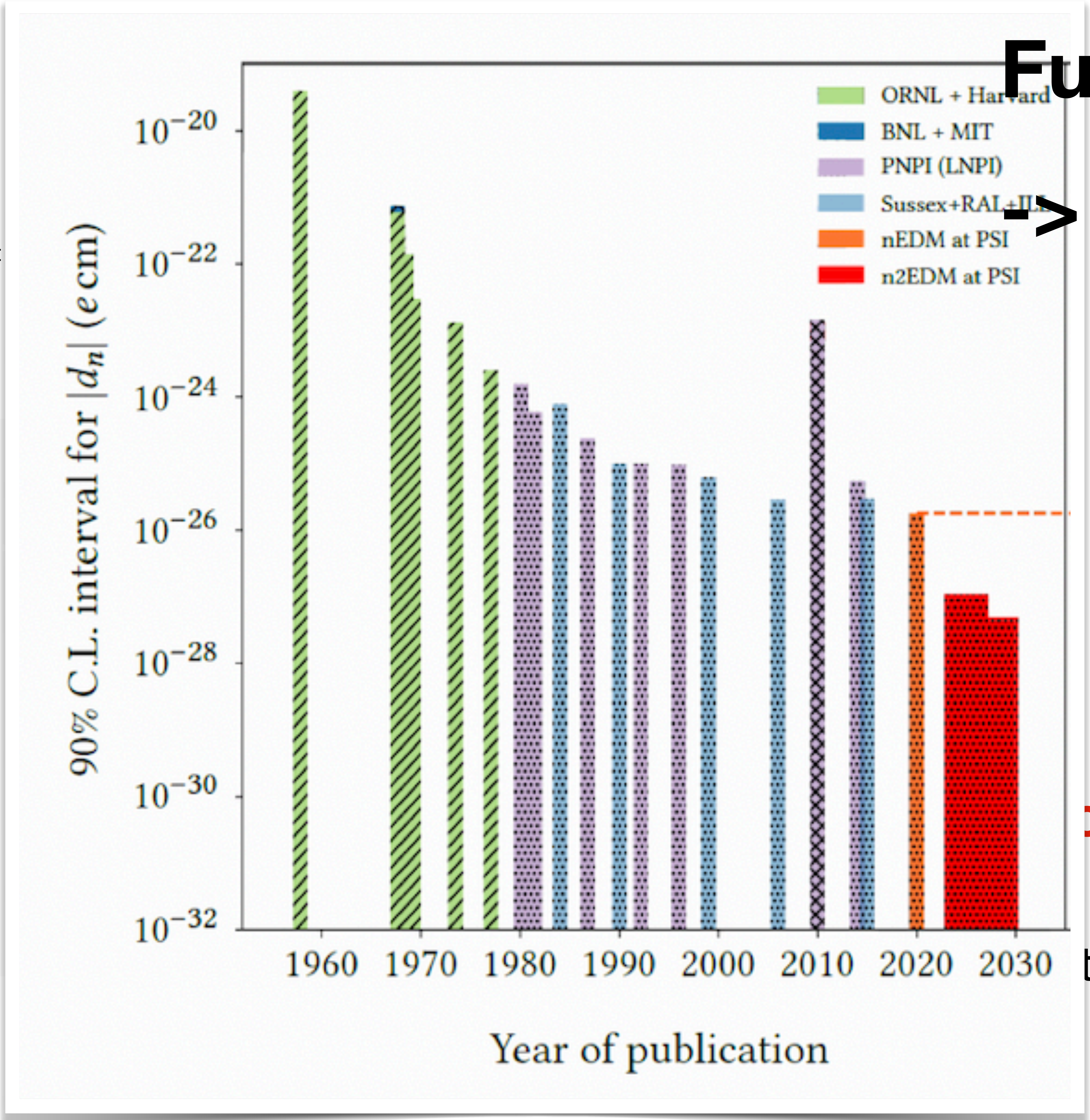
Why so small ?

Compare to $\theta_{\mathrm{CKM}} \sim \mathcal{O}(1)$ or $-\frac{1}{4} G^{\mu\nu} G_{\mu\nu}$

Future: 1-2 orders in d_n

-> n2EDM talk (Caratsch)

$S =$



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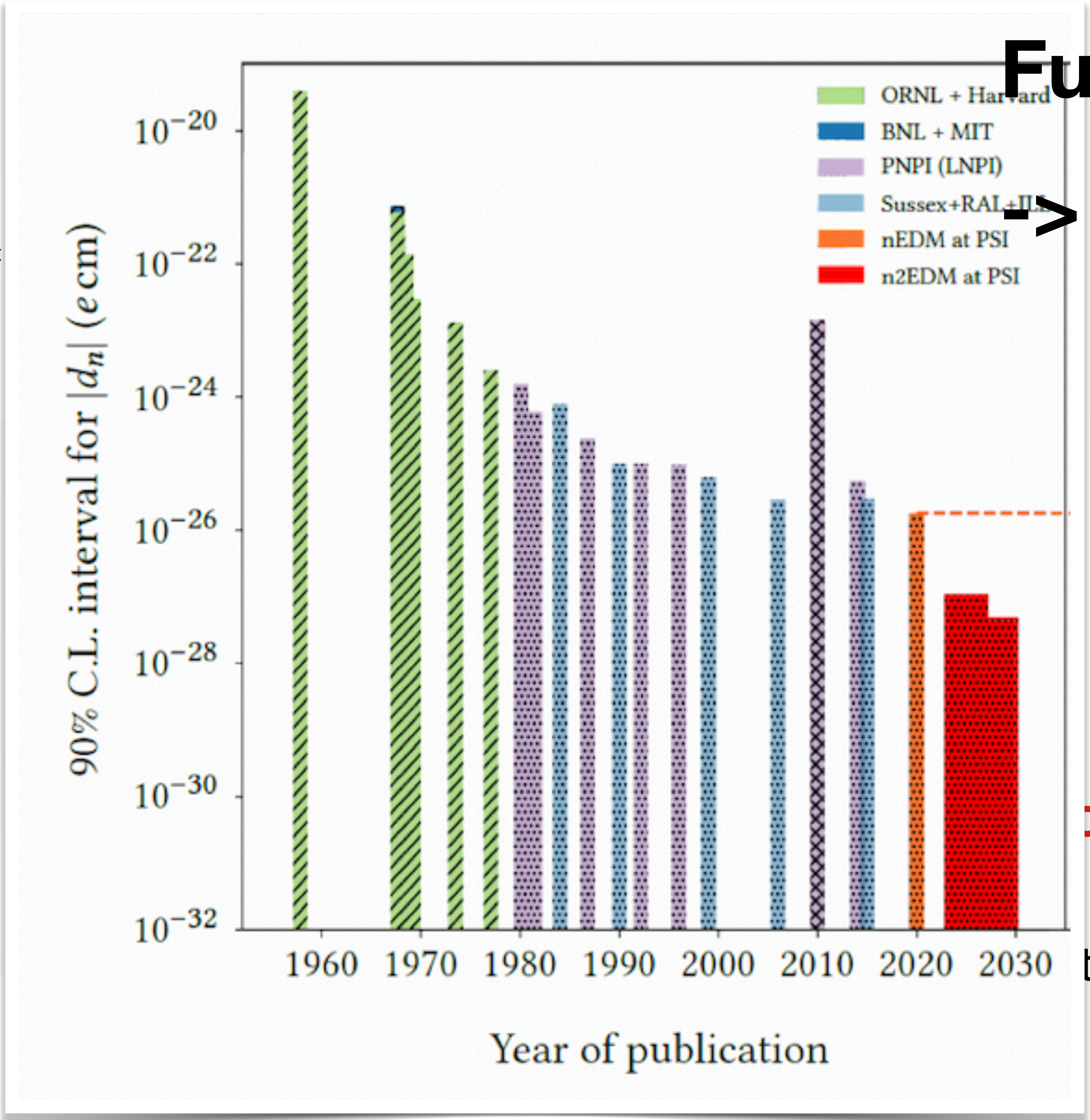

d_n

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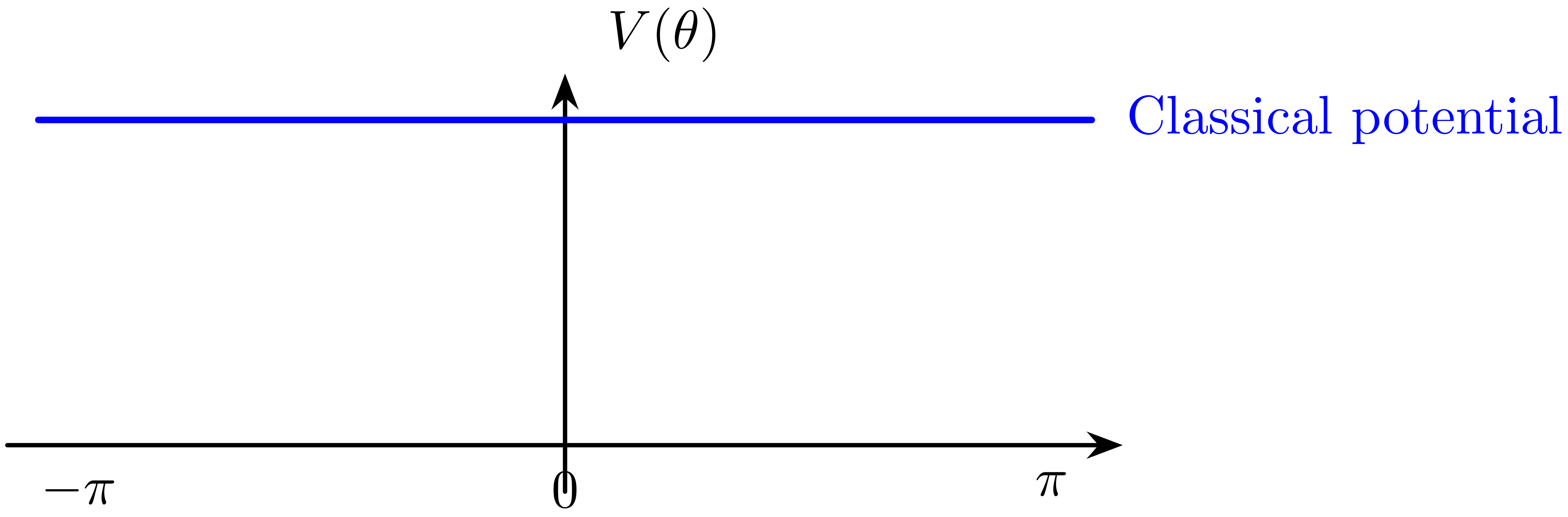
Solution hinted within the problem



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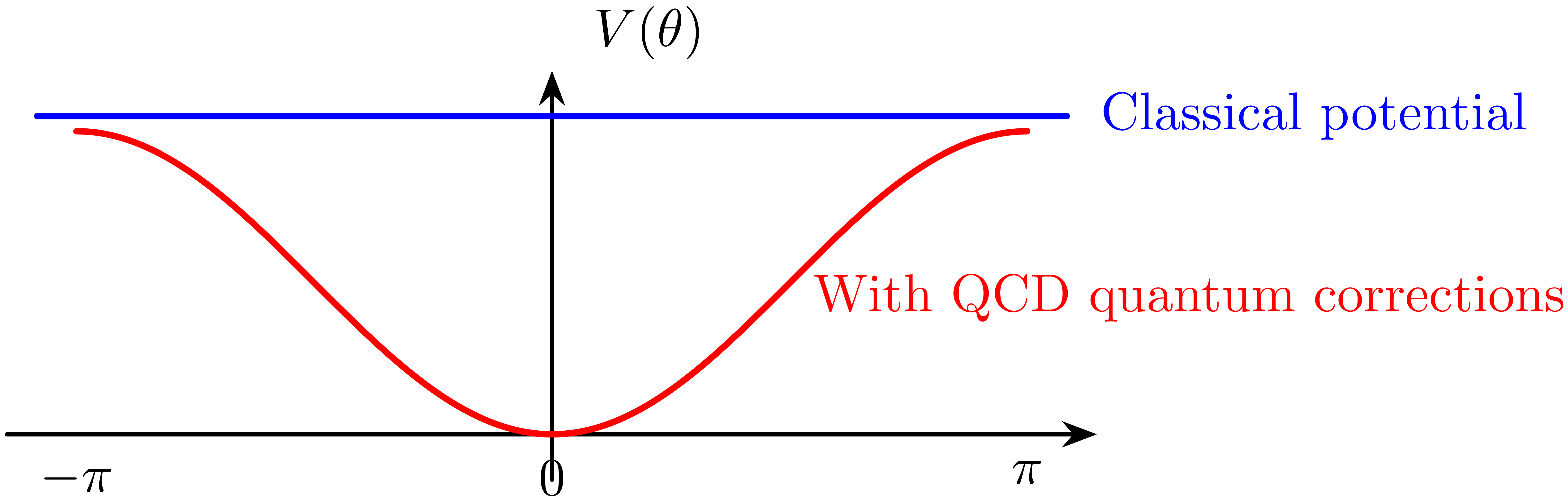
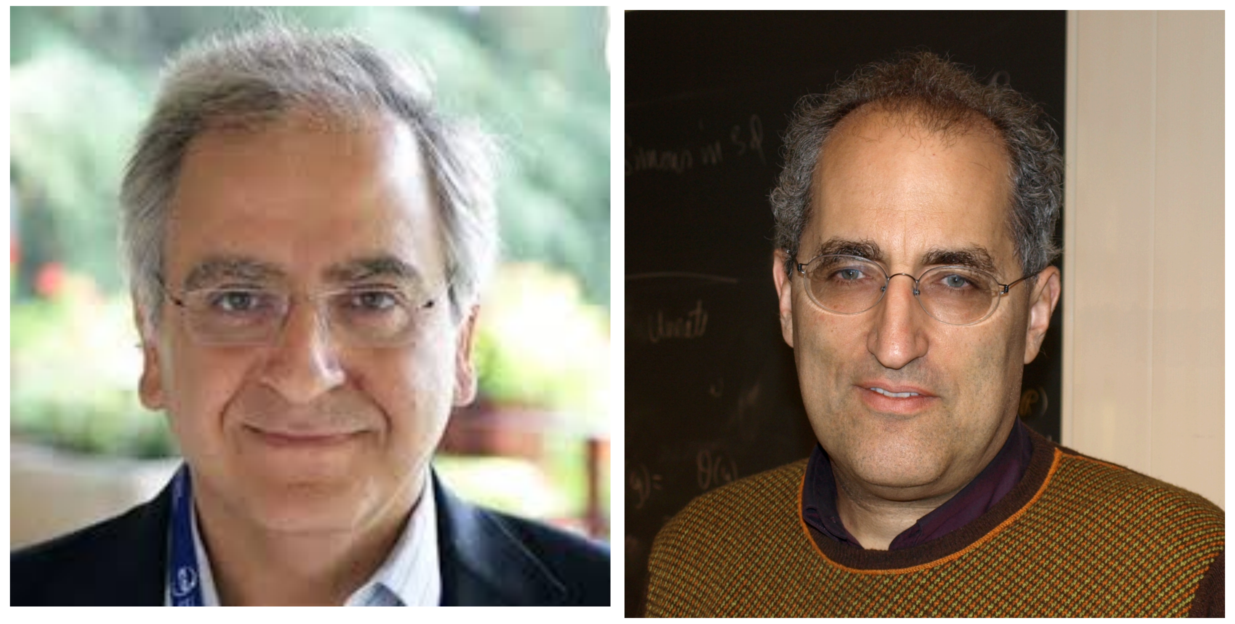
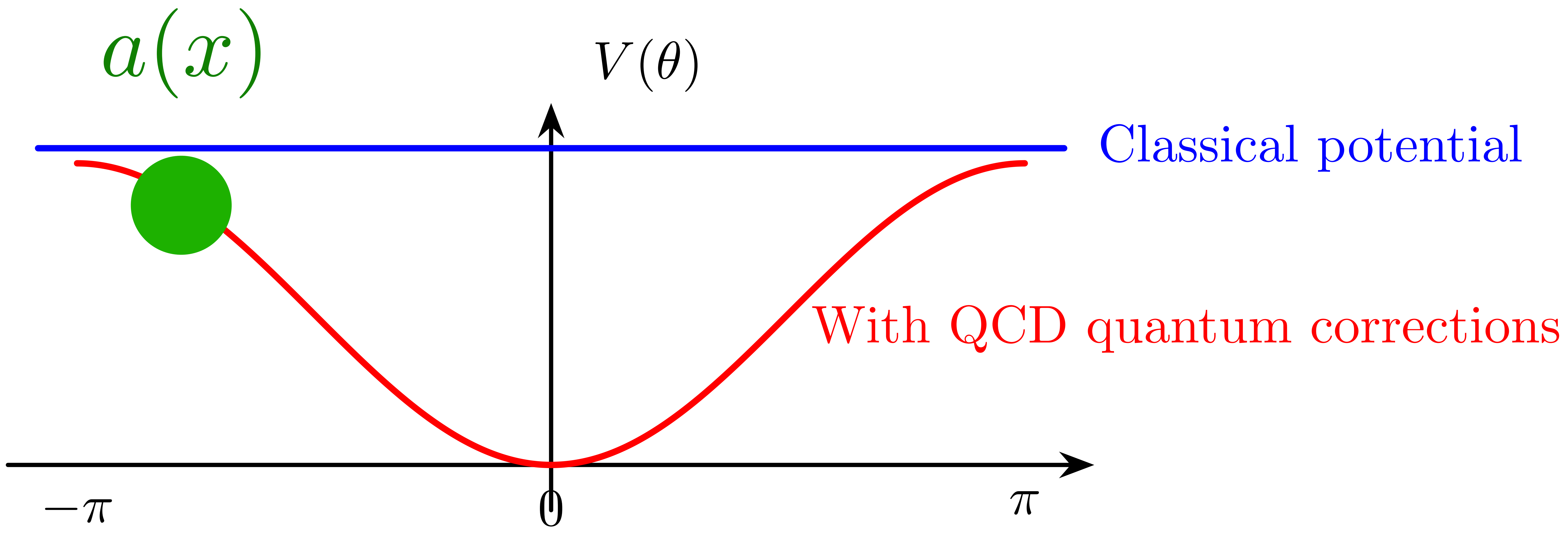


Vafa-Witten ‘84



$$
\begin{aligned}
\exp\left(-\int_x V(a)\right) &= \left|\int \mathcal{D}A_\mu \, \exp\left(-S_{\text{eff}}[\phi, A^\mu]\right) \exp\left(-i\frac{a}{32\pi^2}\int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \left|\exp\left(-S_{\text{eff}}[\phi, A^\mu]\right) \exp\left(-i\frac{a}{32\pi^2}\int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \, \exp\left(-S_{\text{eff}}[\phi, A^\mu]\right) \\
&\leq \exp\left(-\int_x V[0]\right)
\end{aligned}
$$

Make θ-parameter dynamical: axion field



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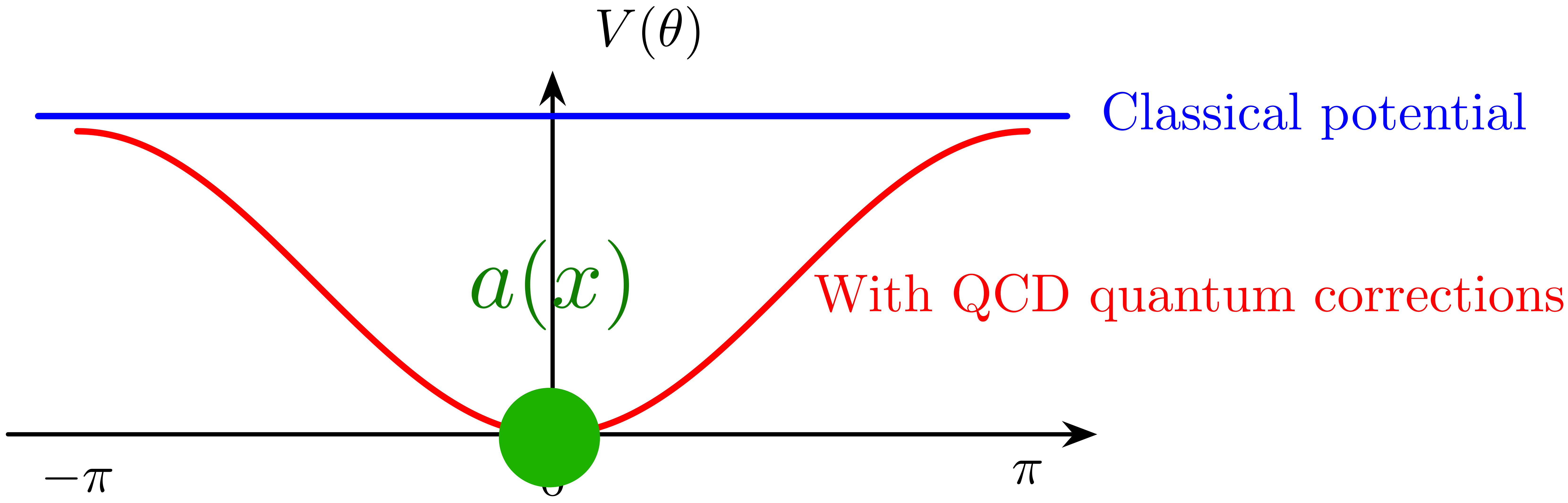

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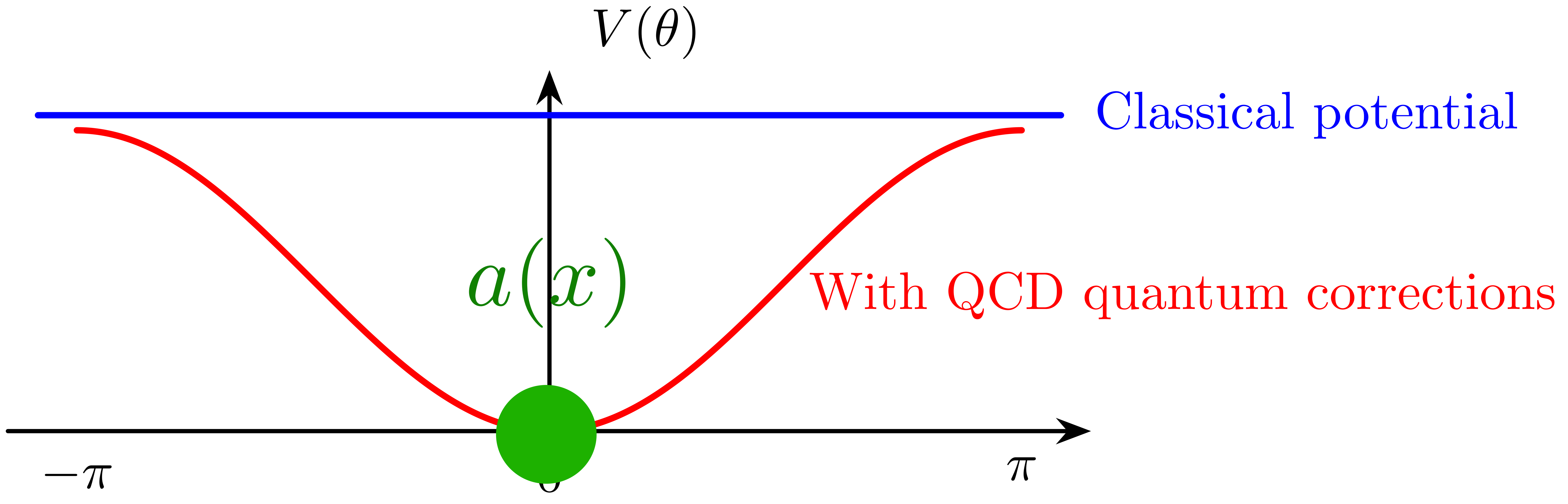

$$\bar{\theta} = \langle a(x) \rangle \approx 0$$

=> strong CP problem is solved

QCD Axion is predictive

Mass and couplings are determined by QCD

- In the IR, QCD confinement generates potential

UV

IR with quantum corrections

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

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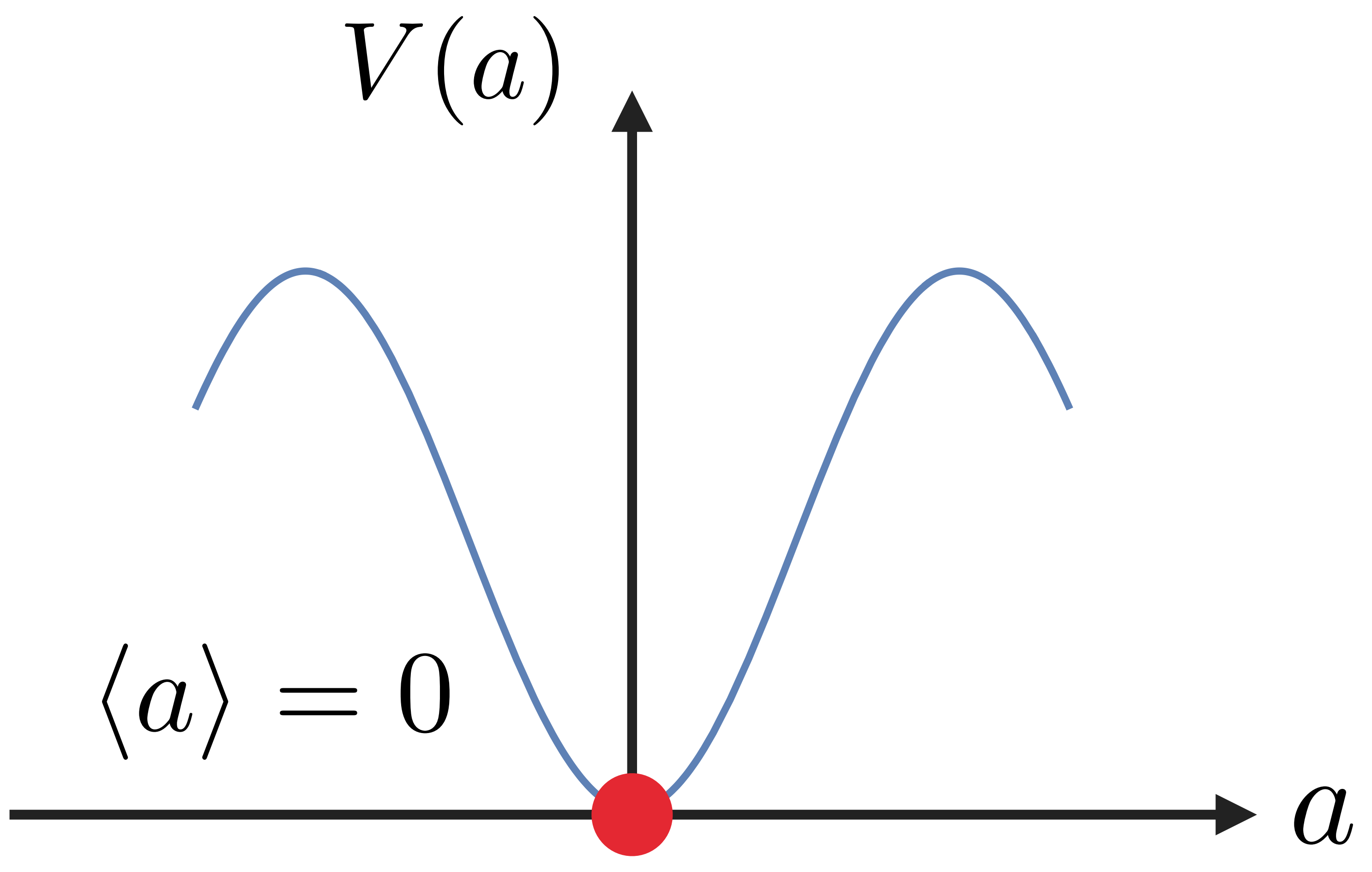

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$$m_a \simeq \frac{m_\pi f_\pi}{f_a} \simeq 0.1\,\text{meV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

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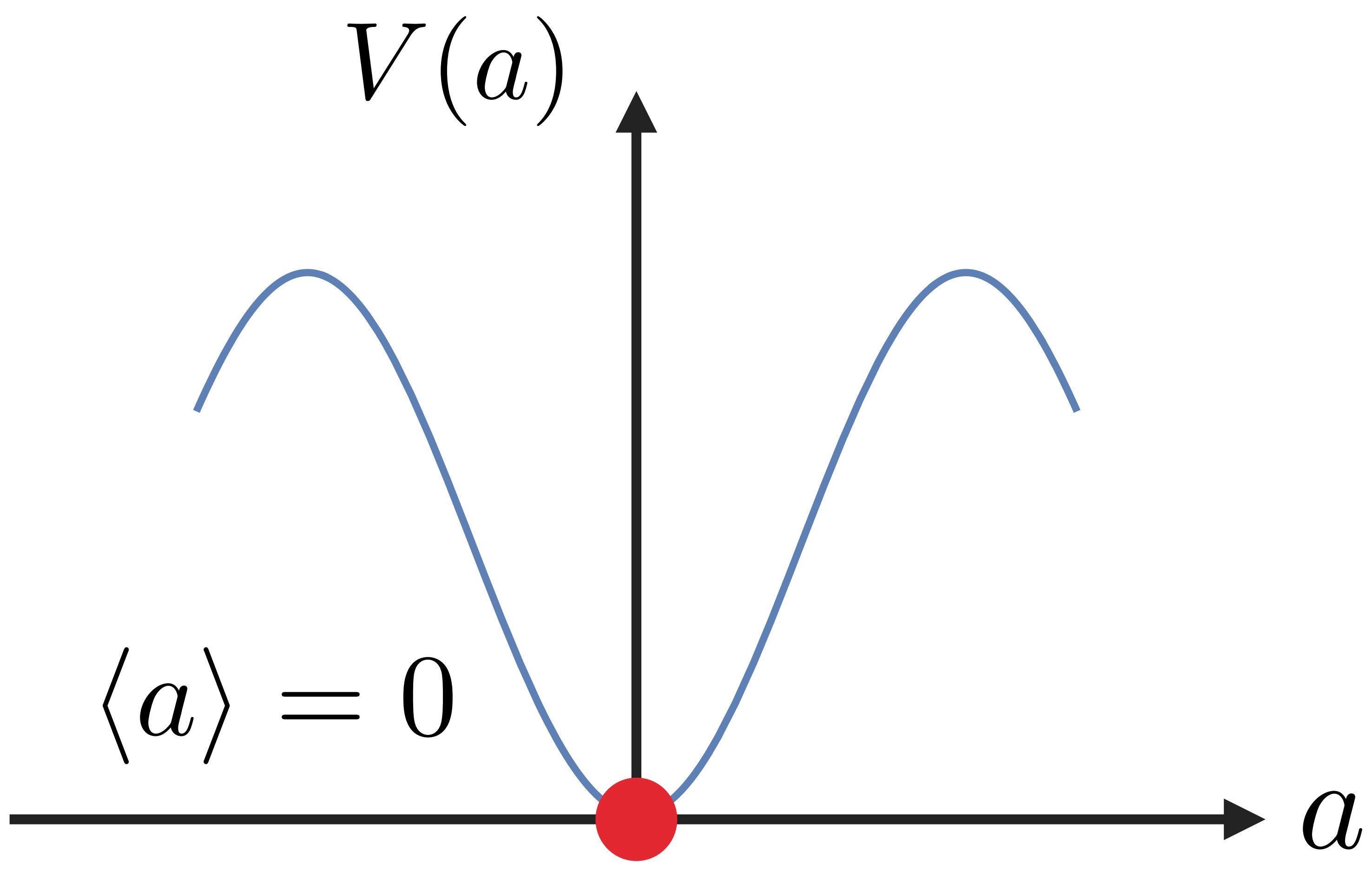

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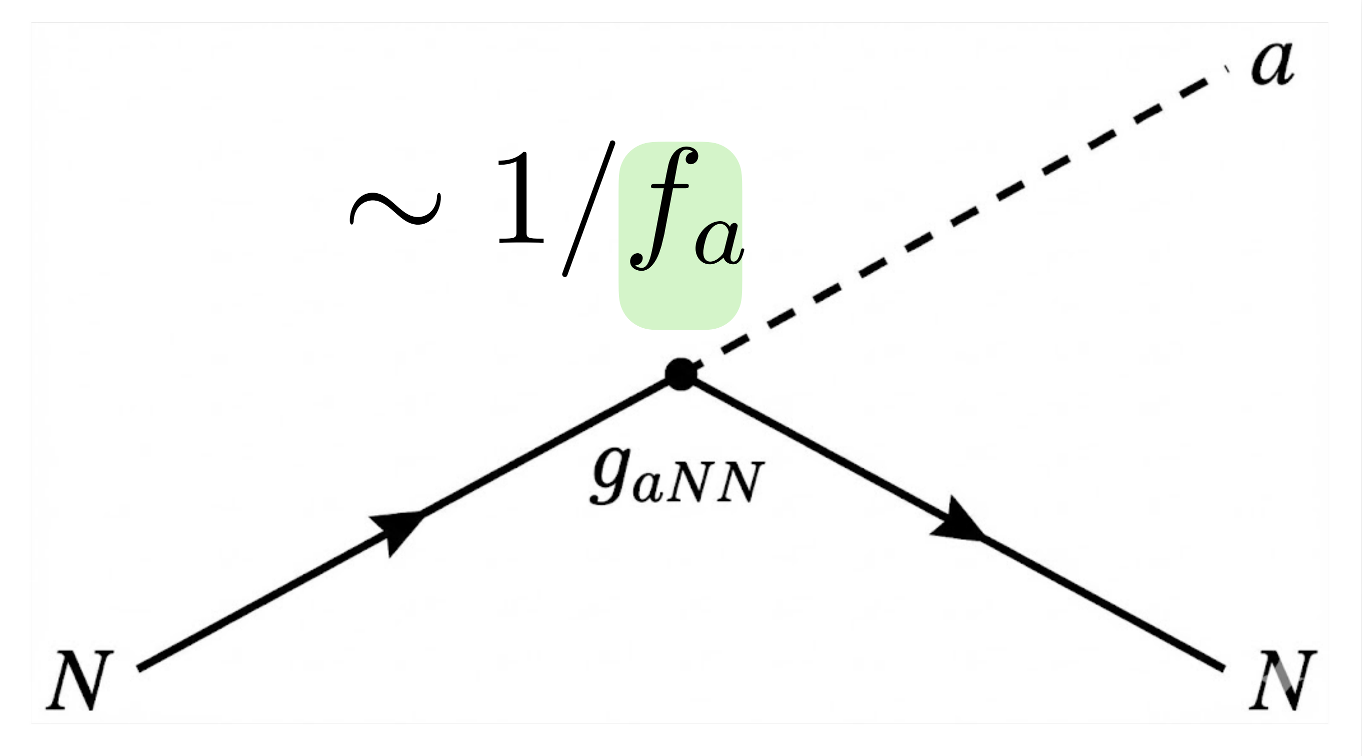
- Couples to electrons, nucleons, photons, …

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a}\bar{\psi}_i c_i \gamma^\mu \gamma_5 \psi_i, \quad i = e, p, n, \ldots$$

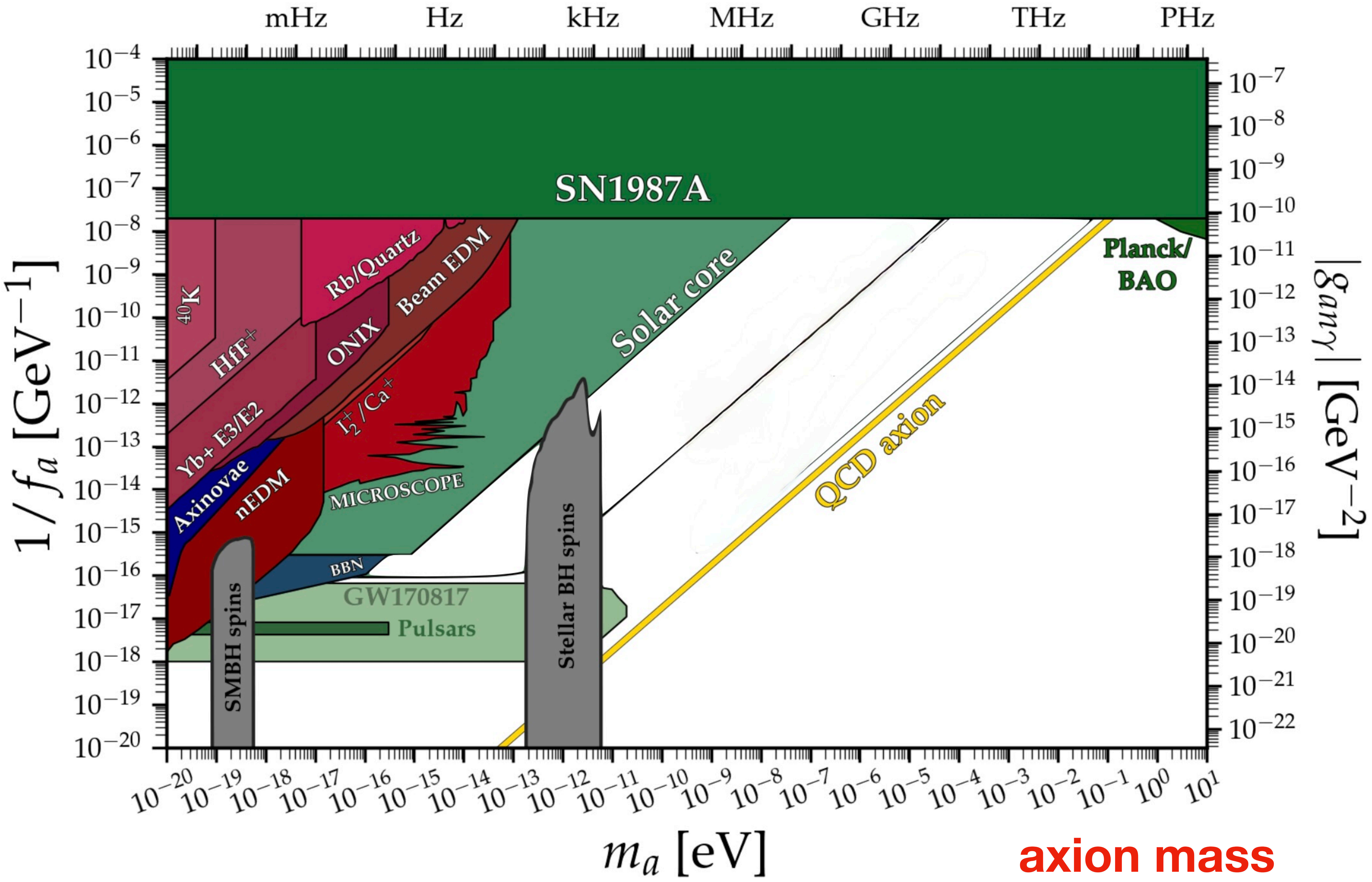


Pheno determined by f_a

https://github.com/cajohare/AxionLimits

Axion parameter space

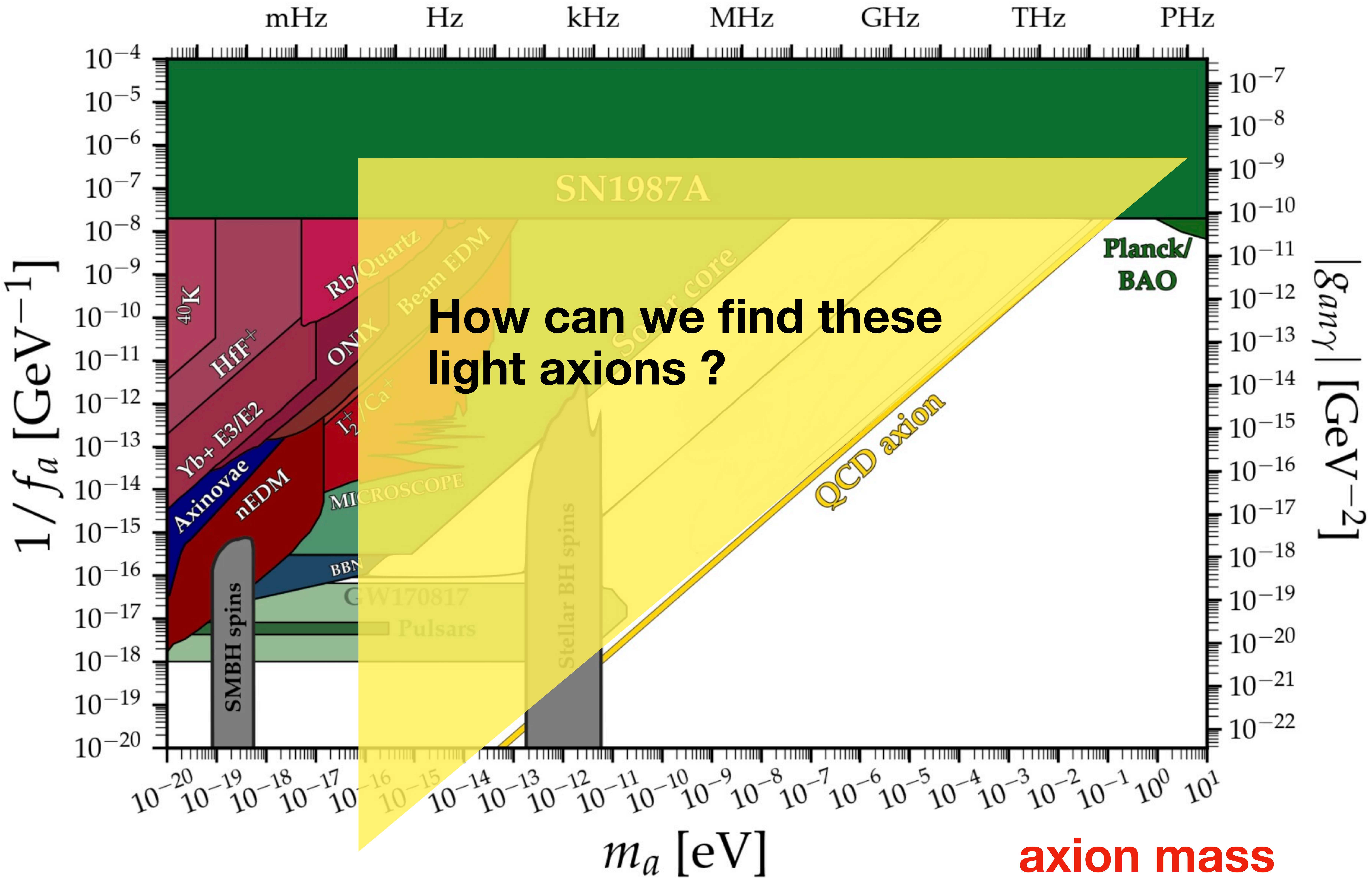
axion coupling



axion mass

Axion parameter space

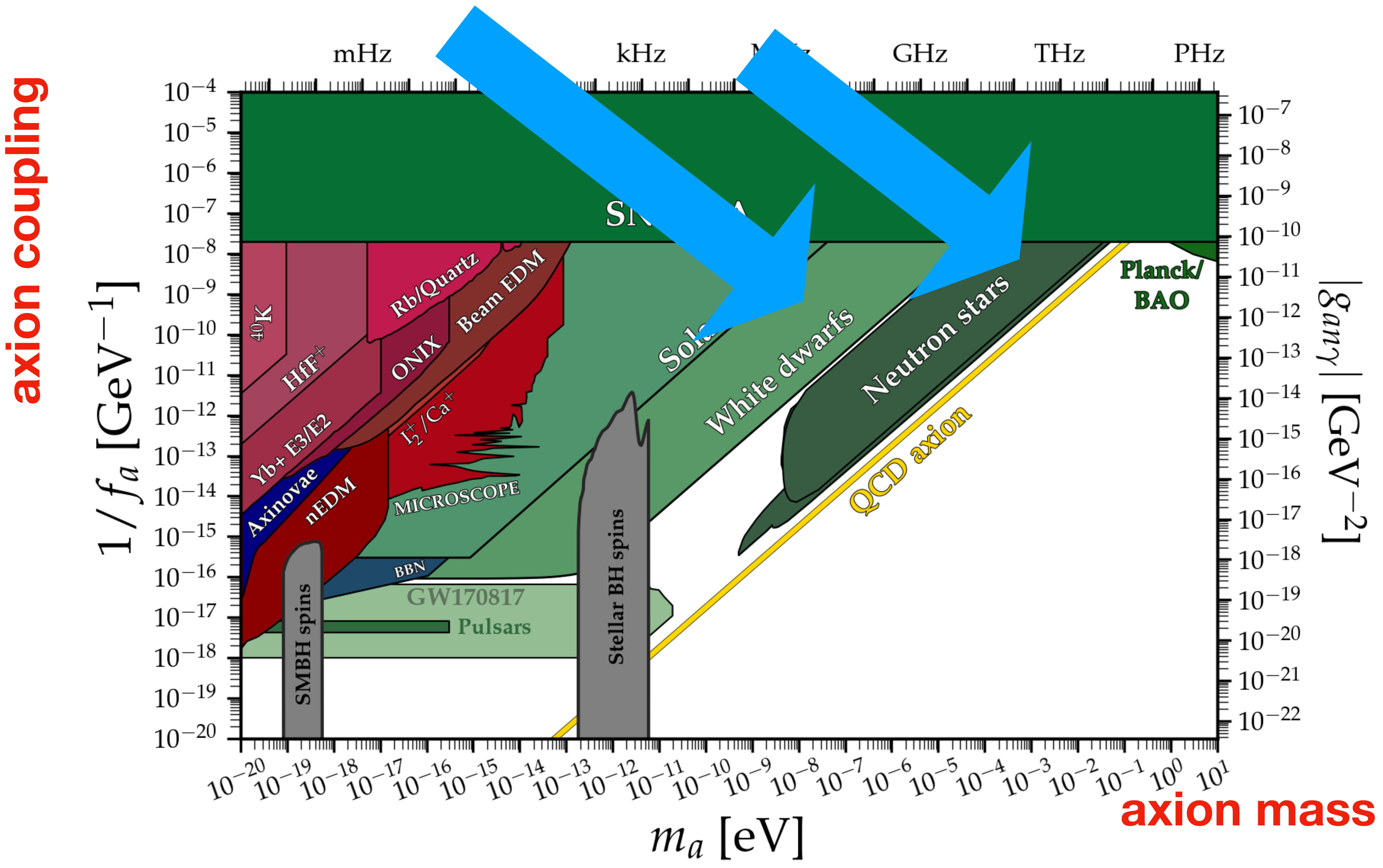
axion coupling



How can we find these light axions ?

axion mass

Punchline: Finite-density effects can qualitatively change axion physics.
We found they destabilize the vacuum -> stellar-structure signatures (WD/NS)



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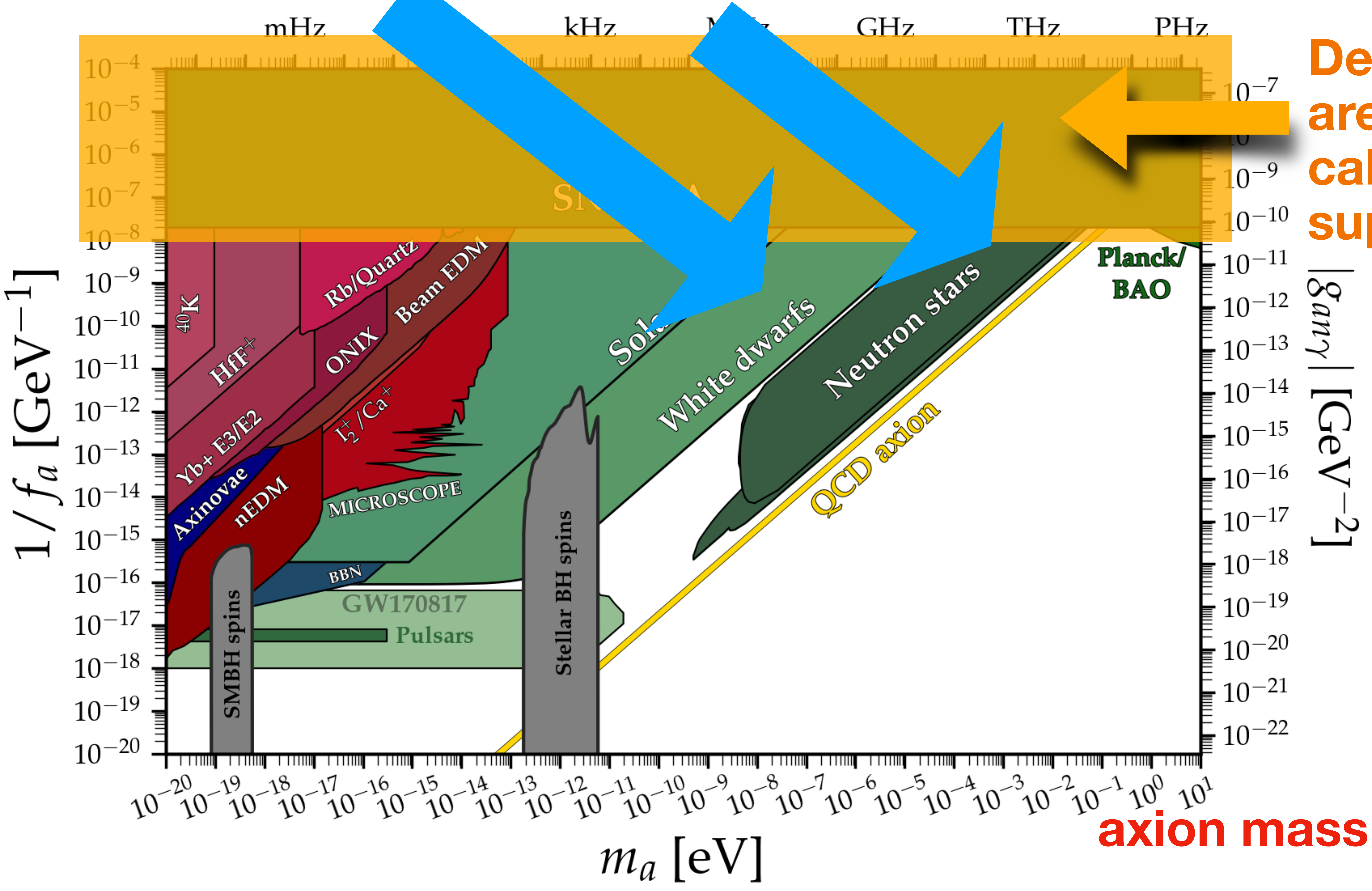
axion coupling



Density corrections are crucial in the calculation of the supernova bound

axion mass

Presence of matter…

… modifies the axion potential—altering stellar behavior

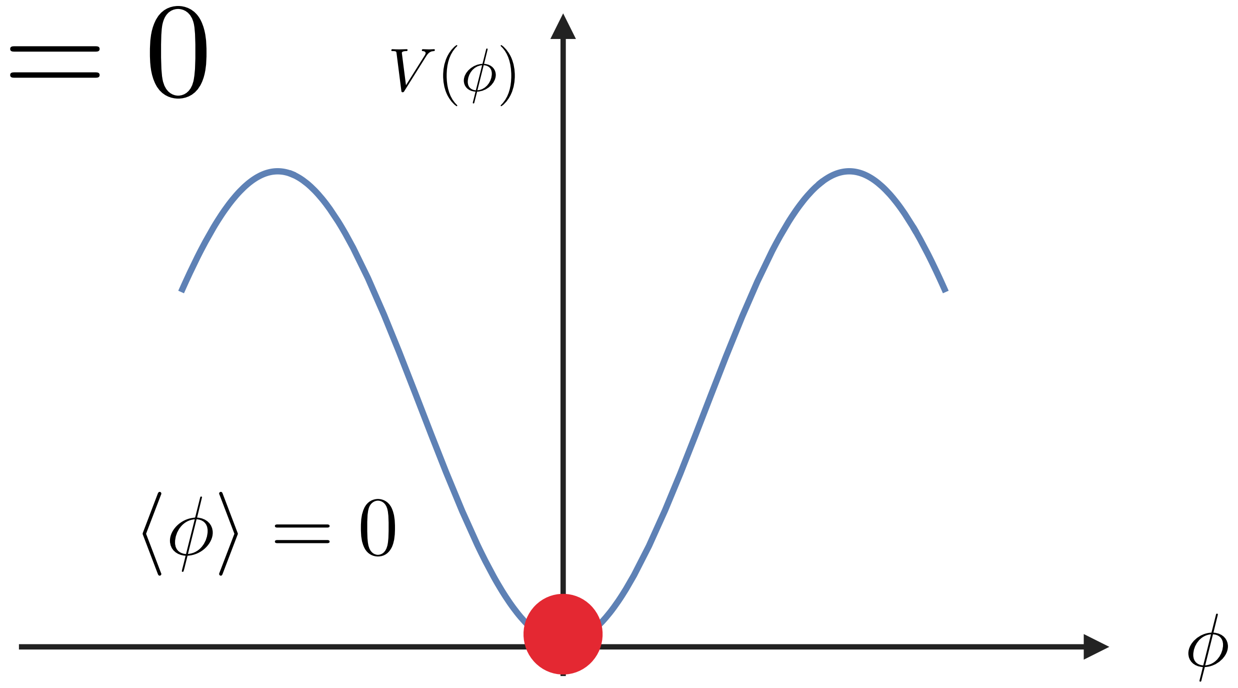
… changes the couplings, affecting how physical processes unfold

Axion properties are highly susceptible to matter effects

Potential changes with density n 2211.02661, 2307.14418, 2408.07740

$n = 0$

vacuum



$$\langle a(x) \rangle_{\mathrm{vacuum}} \approx 0$$

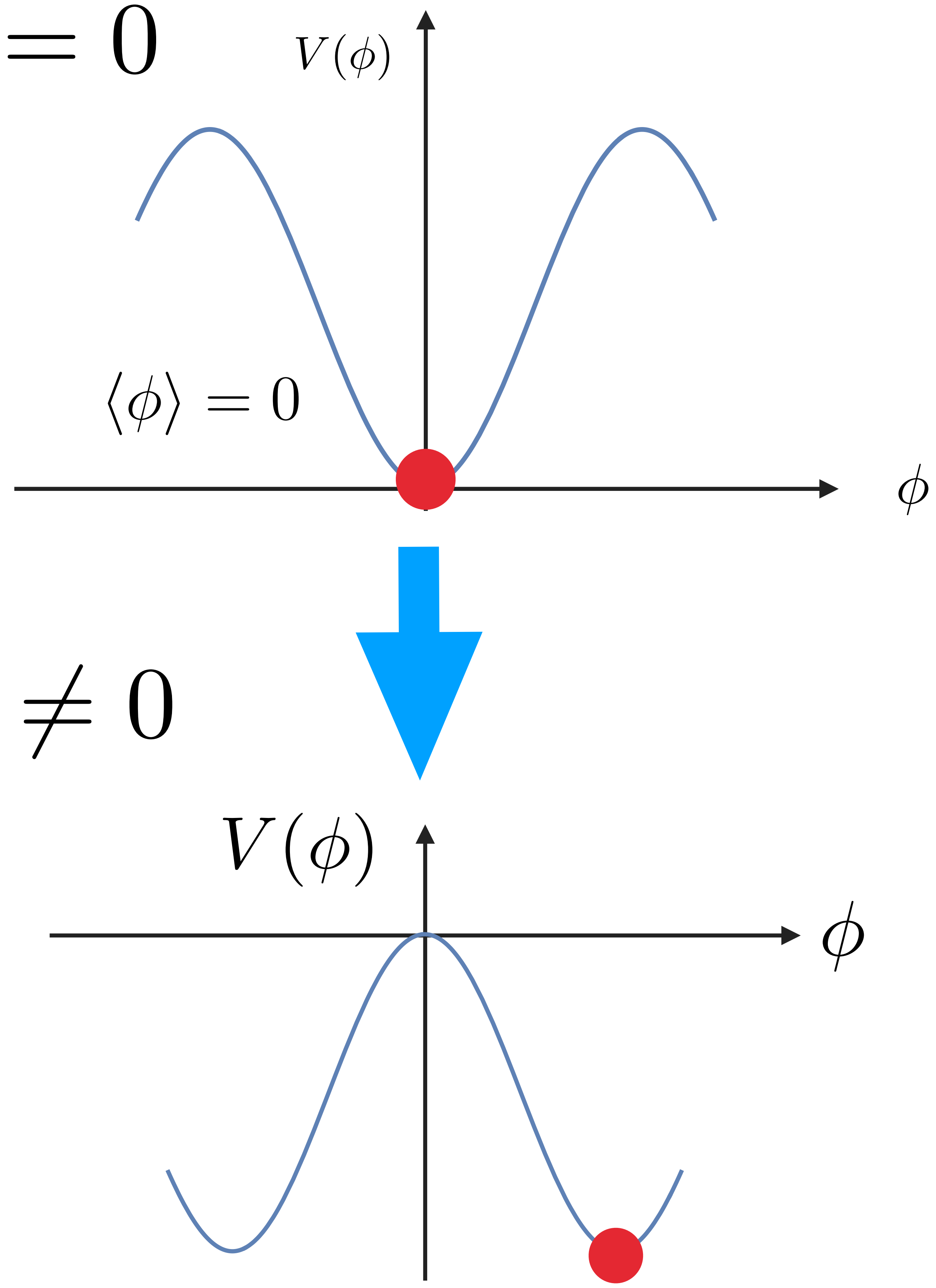
Axion properties are highly susceptible to matter effects

2211.02661, 2307.14418, 2408.07740

Potential changes with density *n*

vacuum

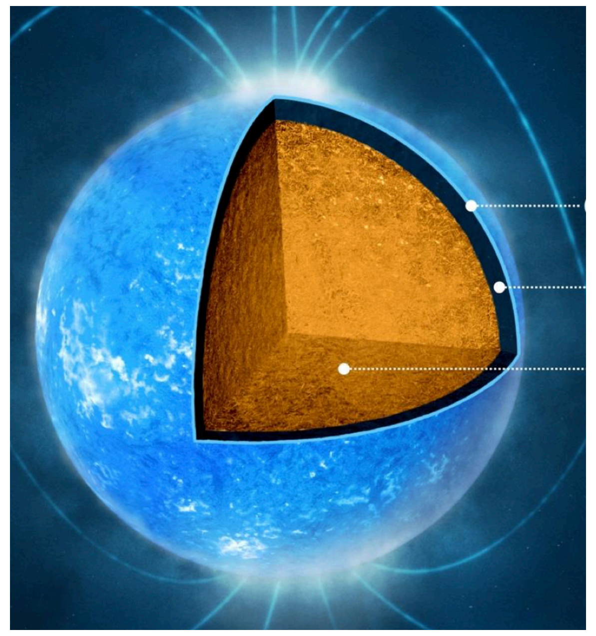
$n = 0$



$n \neq 0$

$$\langle a(x)\rangle_{\text{vacuum}} \approx 0$$

inside star



$$\langle a(x)\rangle_{\text{star}} \approx \pi f_a$$

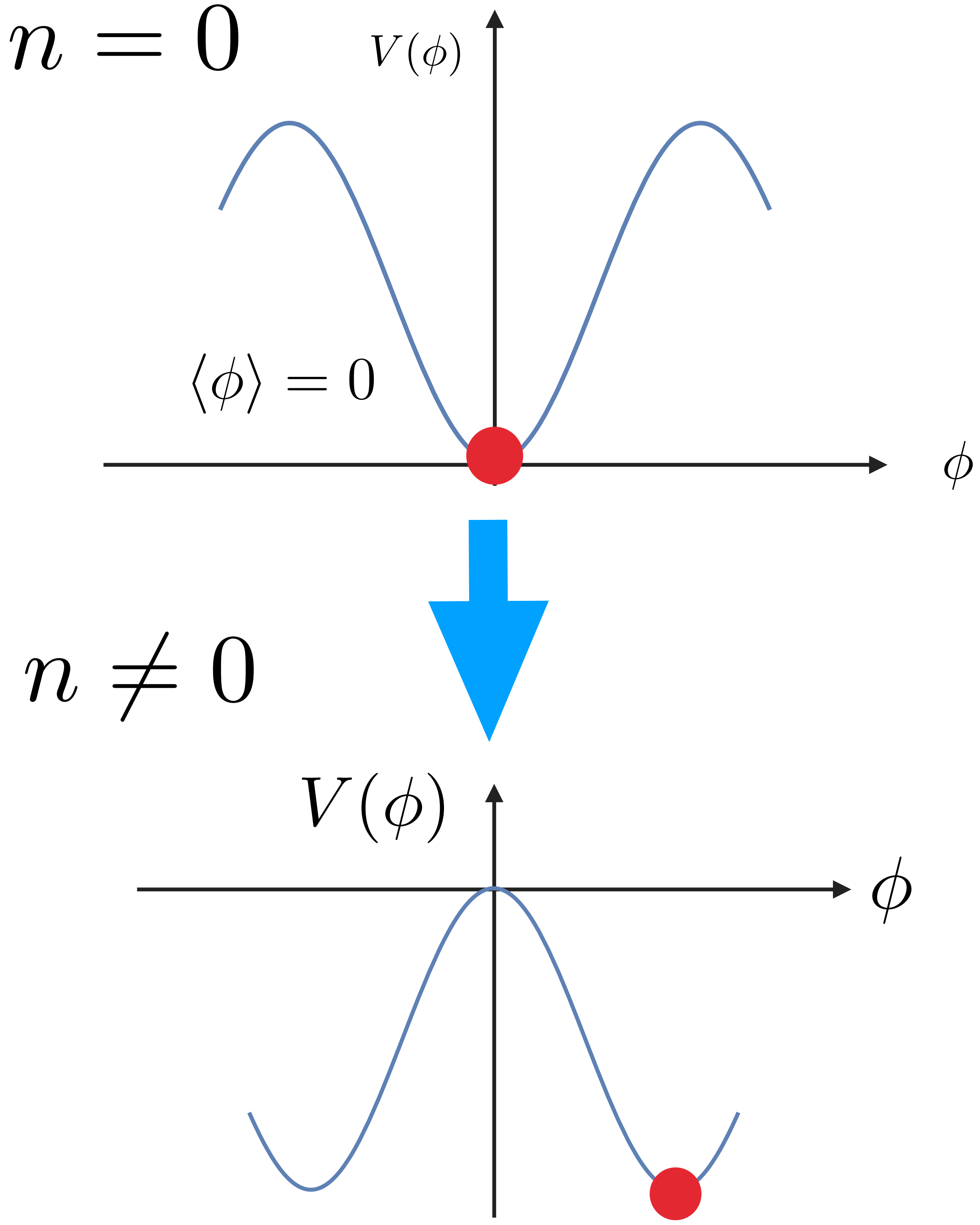
Hook, Huang ’17, Balkin, Serra, Springmann, Stelzl, AW ’22

Axion properties are highly susceptible to matter effects

2211.02661, 2307.14418, 2408.07740

Potential changes with density n

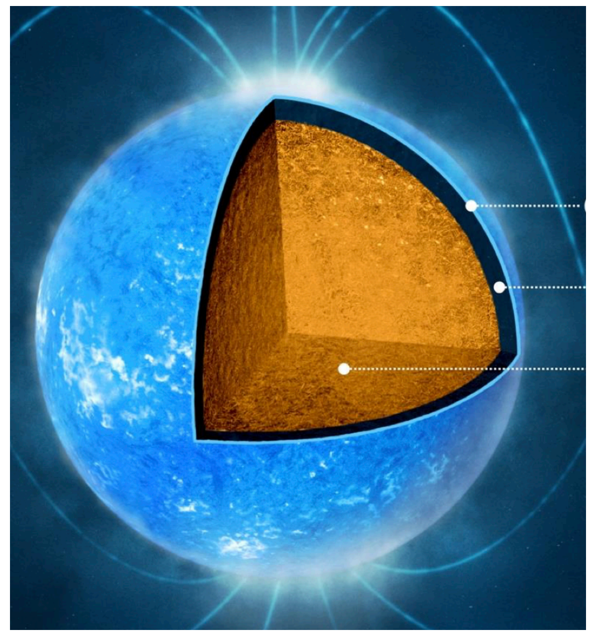
vacuum



$$\langle a(x) \rangle_{\text{vacuum}} \approx 0$$

Minimum becomes maximum at finite density!

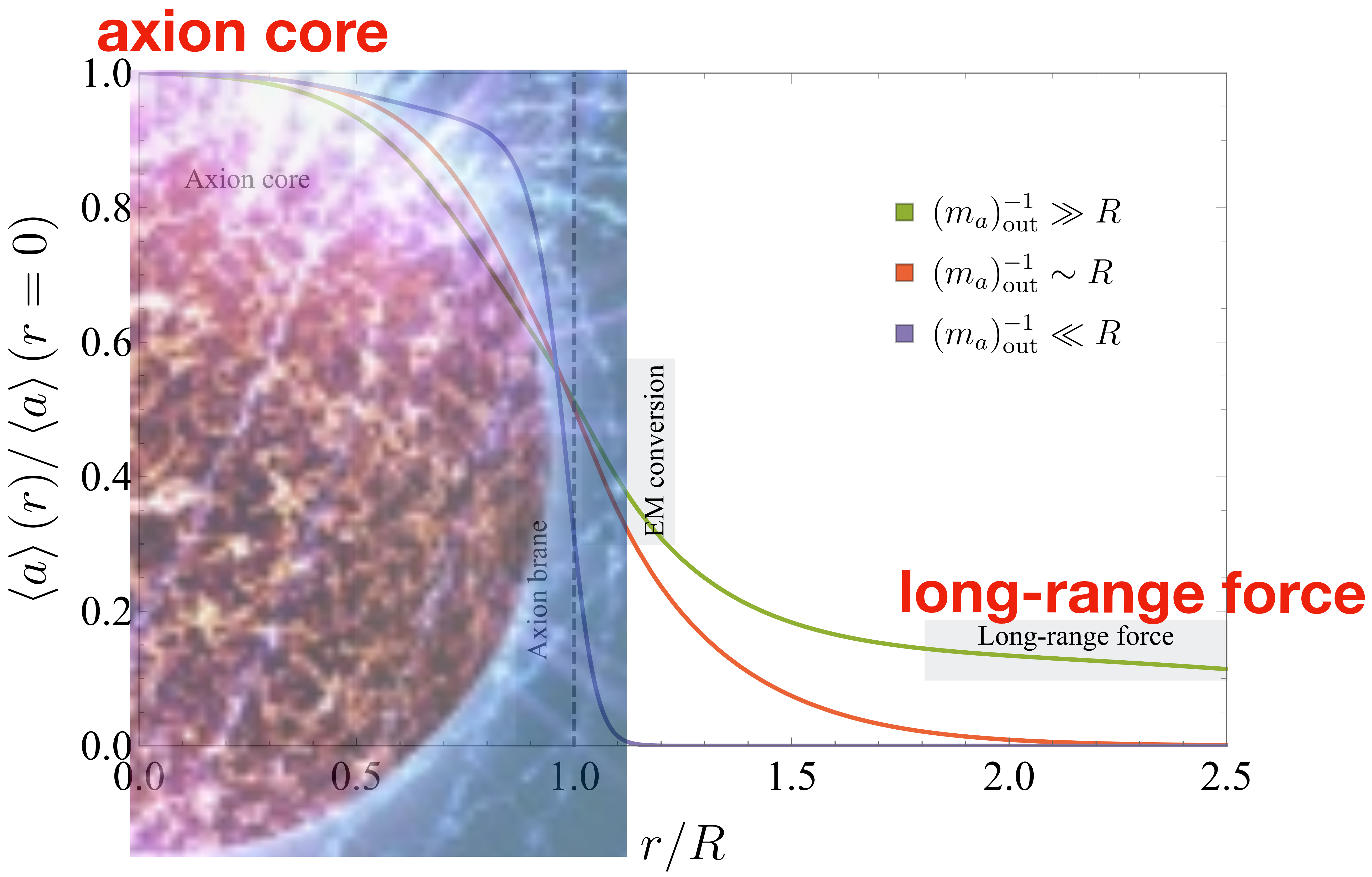
inside star



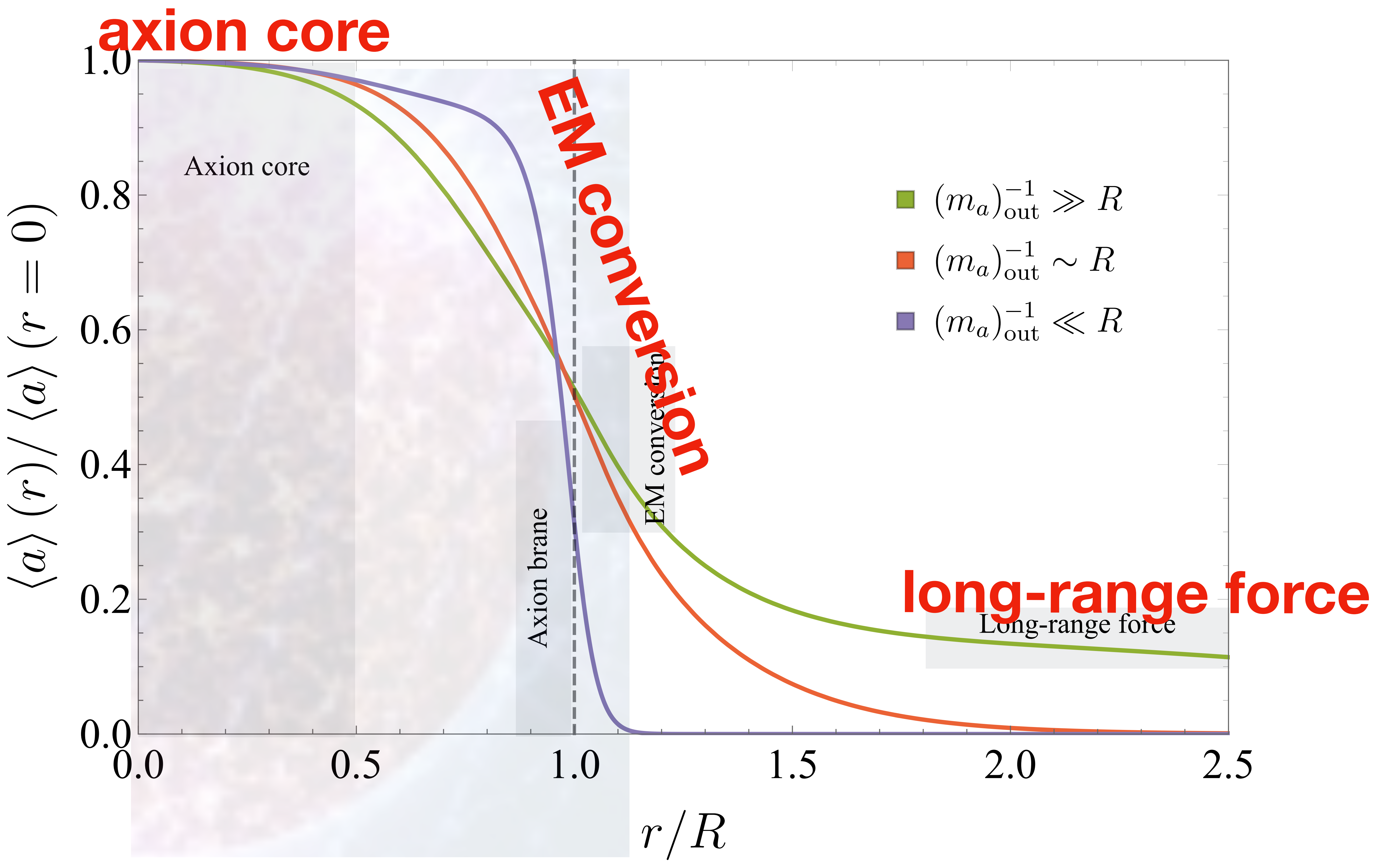
$$\langle a(x) \rangle_{\text{star}} \approx \pi f_a$$

Hook, Huang '17, Balkin, Serra, Springmann, Stelzl, AW '22

Axion Profile



Axion Profile

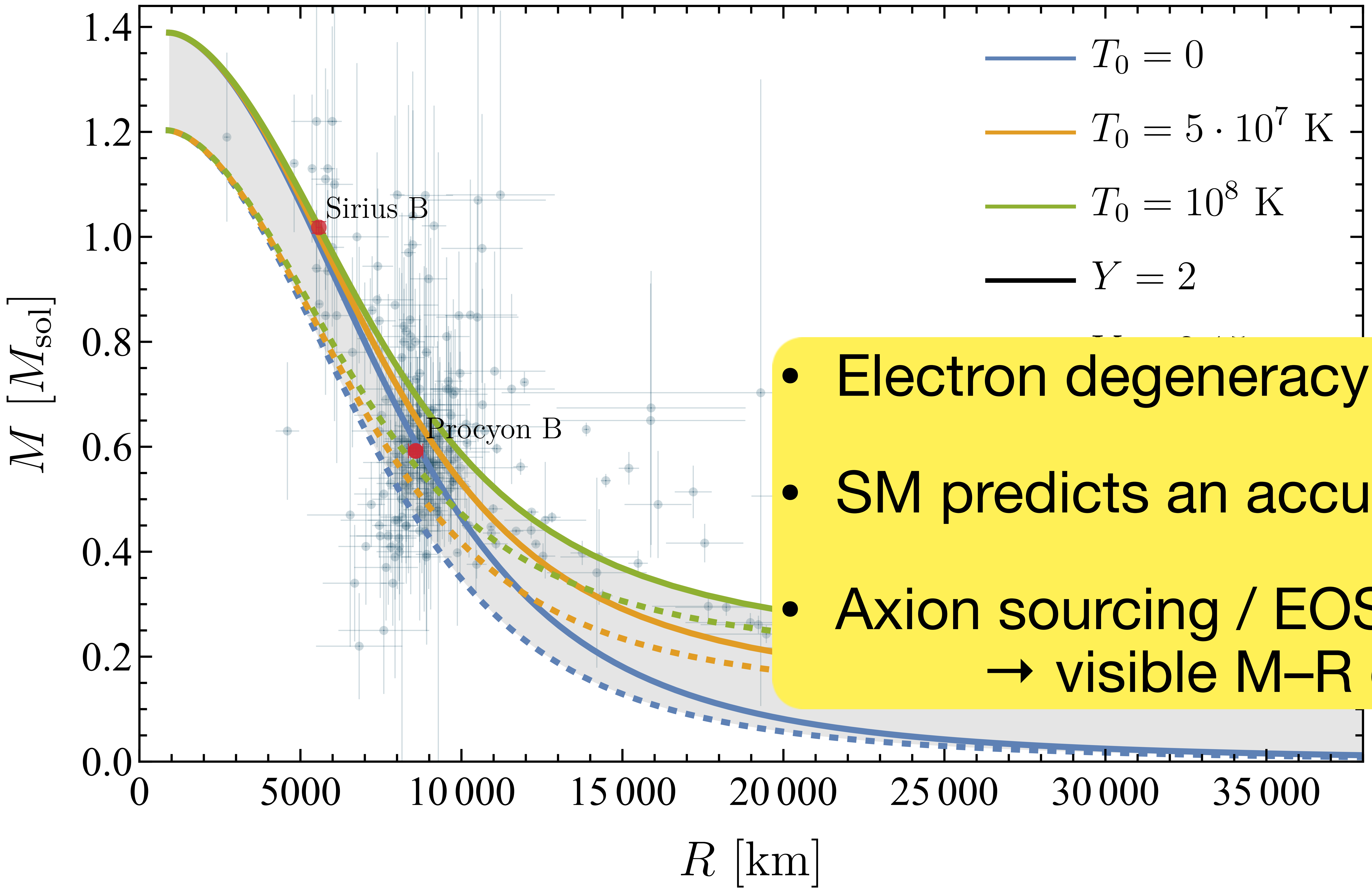


Stars can develop an axion ‘core’ + long-range field outside.

This changes hydrostatic equilibrium and can open new observational channels.


White Dwarfs:
Fermi pressure from electron gas

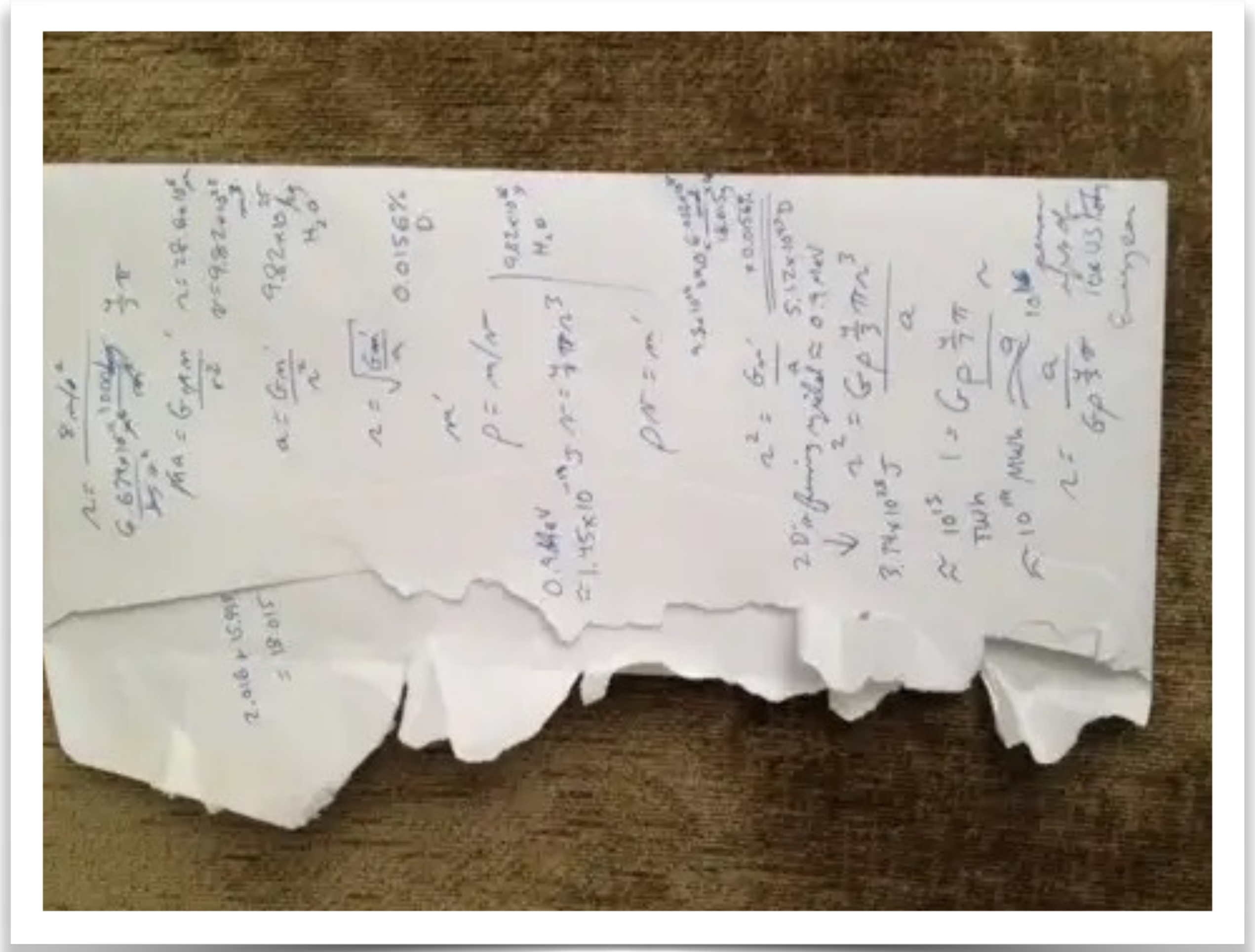
Mass radius curve for white dwarfs



- Electron degeneracy pressure is well understood
- SM predicts an accurate M–R curve
- Axion sourcing / EOS change
  → visible M–R distortion

Back of the envelope …

… power of dimensional analysis (aka laziness)



vs.

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

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

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

White dwarfs simplified

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

White dwarfs simplified

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

$$E_{\text{Fermi}}/N = m_e$$ (electron mass)

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

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

White dwarfs simplified

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

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

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

White dwarfs simplified

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

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

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

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

Mass of the sun at the size of the earth.

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

Now derive the same for neutron stars.

What do we need to change?

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

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

$$R_{\text{NS}} \sim (\text{few})\ \text{km}$$

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

Mass of the sun within a few km

Neutron stars simplified

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

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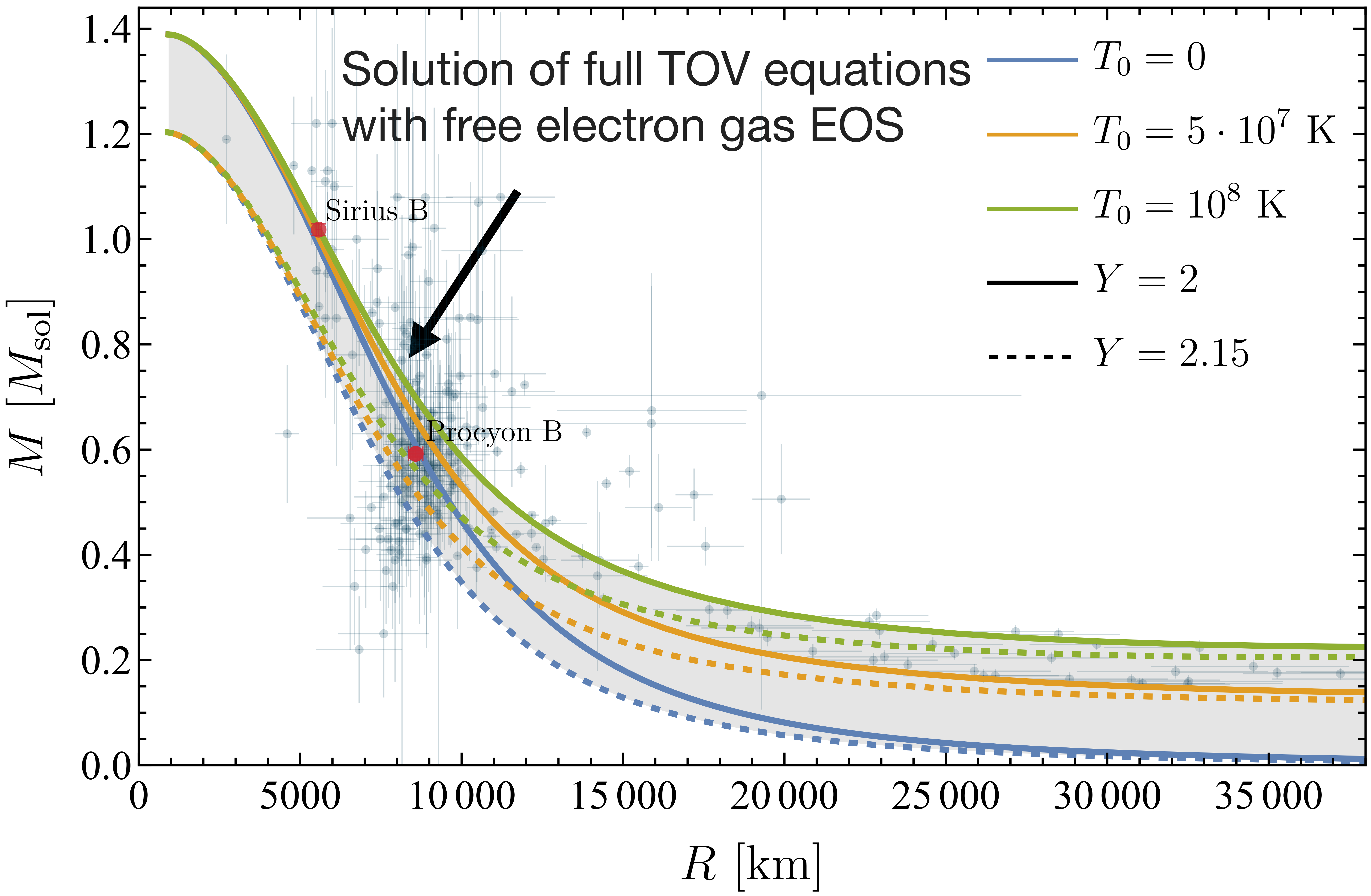
$$M_{\text{NS}} \sim (\text{few})10^{30}\,\text{kg} \sim M_{\odot}$$

Mass of the sun within a few km

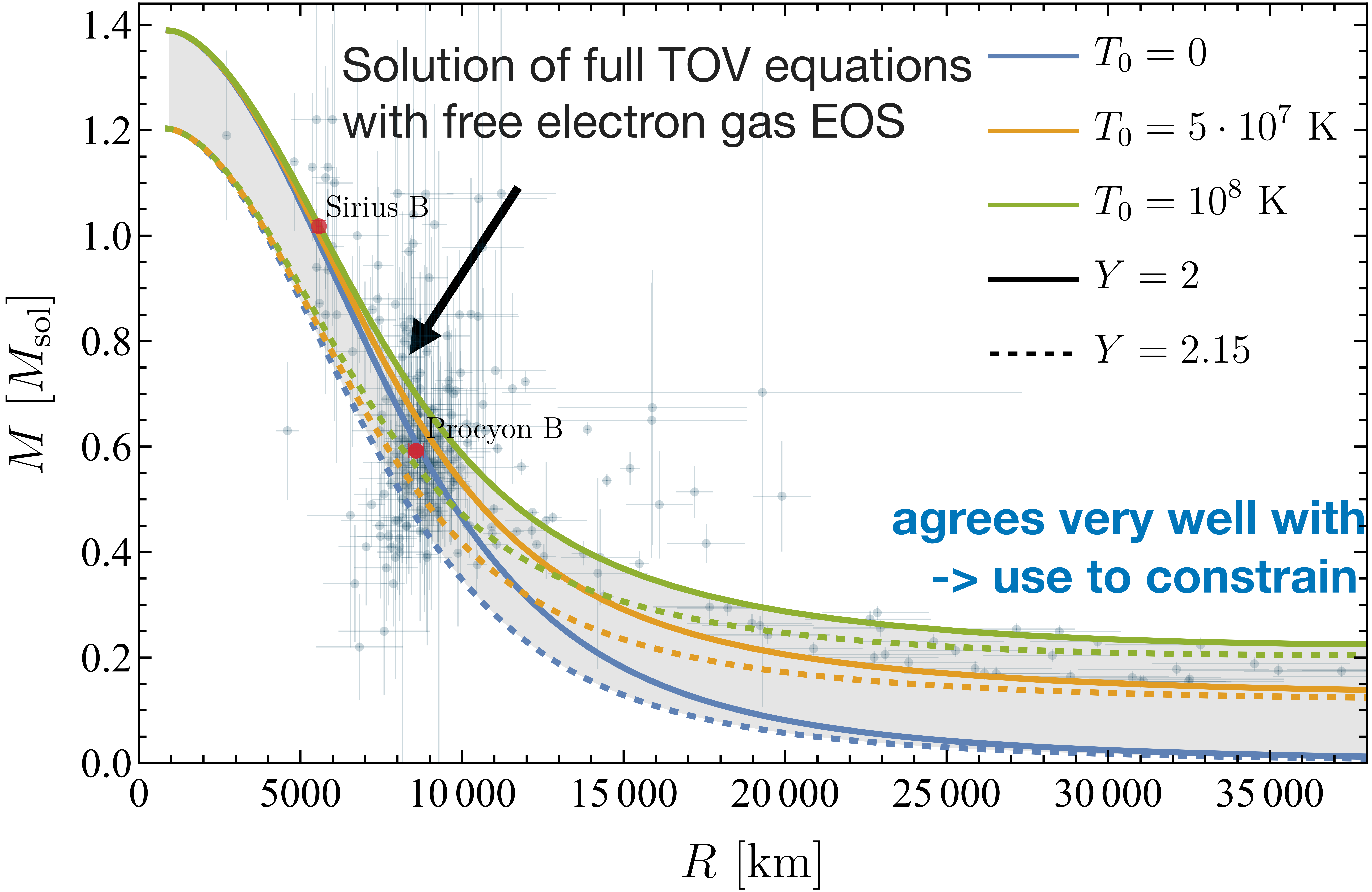
$$R_{\mathrm{WD}} \sim \frac{m_N}{m_e} R_{\mathrm{NS}}$$

$$M_{\mathrm{WD}} \sim M_{\mathrm{NS}}$$

White dwarf mass-radius curve



White dwarf mass-radius curve



agrees very well with SM
-> use to constrain BSM

Stellar Structure with New Scalars

- Hydrostatic equilibrium equation (include GR effects):

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

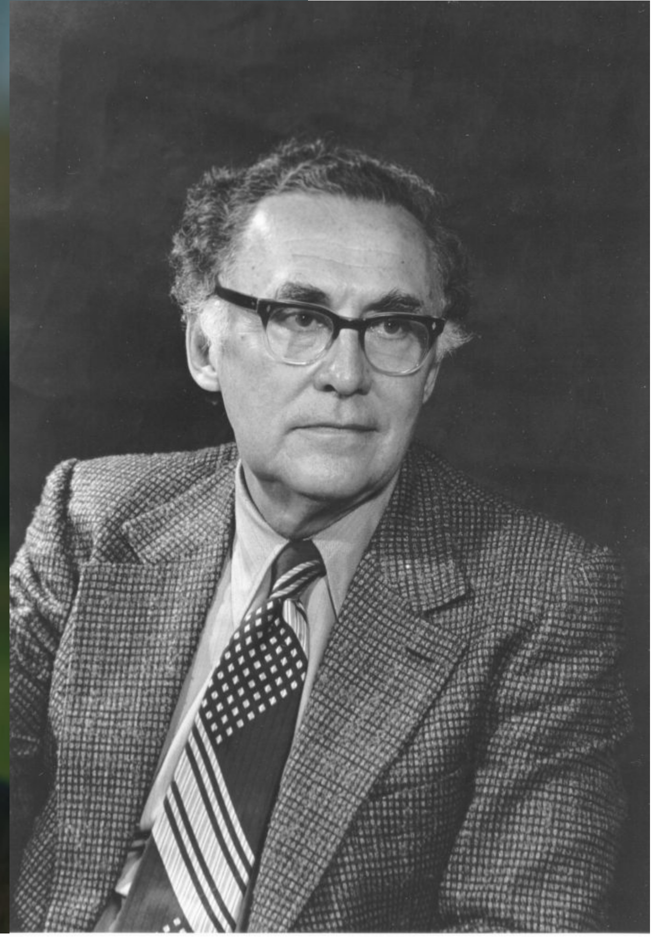
- Mass conservation:

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

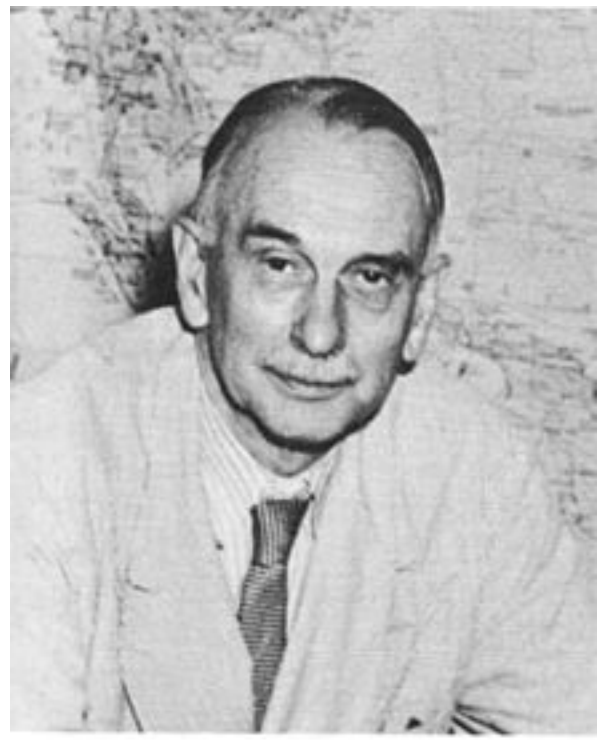
- Axion EOM:

$$\phi''\left[1-\frac{2GM}{r}\right]+\frac{2}{r}\phi'\left[1-\frac{GM}{r}-2\pi G r^2(\varepsilon-p)\right]=\frac{\partial V}{\partial\phi}$$

Oppenheimer



Volkoff



Tolman

Stellar Structure with New Scalars

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]
[Balkin, Serra, Springmann, Stelzl, Weiler, 2307.14418]

- Hydrostatic equilibrium equation (include GR effects):

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

- Mass conservation:

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

- Axion EOM:

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

- Changed EOS:

$$\varepsilon = \varepsilon_m(n, m_\psi(\phi)) + V(\phi)$$
$$p = p_m(n, m_\psi(\phi)) - V(\phi)$$

m_ψ : proton/neutron mass

Stellar Structure with New Scalars

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]
[Balkin, Serra, Springmann, Stelzl, Weiler, 2307.14418]

- Hydrostatic equilibrium equation (include GR effects):

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

- Mass conservation:

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

$$m_N(a) = m_N\left(1-\frac{\sigma_N}{m_N}\cos\left(\frac{a}{f_a}\right)\right)$$

- Axion EOM:

$$0 = \frac{\partial V}{\partial \phi} + n\frac{\partial m_\psi(\phi)}{\partial \phi} = \frac{\partial V_{\text{eff}}}{\partial \phi}$$

- **Changed EOS:**

$$\varepsilon = \varepsilon_m(n, m_\psi(\phi)) + V(\phi)$$
$$p = p_m(n, m_\psi(\phi)) - V(\phi)$$

Punchline

Scalar changes the EOS and sources itself in matter

In large stars gradients are often negligible → algebraic minimization of an effective potential

This is why new phases / branches appear

Scalar effective potential

Example: Light QCD axion

$$\mathcal{L} \supset -V(a) - \sigma_N \bar{N} N \left(\cos\left(\frac{a}{f_a}\right) - 1 \right)$$

Scalar effective potential

Example: Light QCD axion

$$\mathcal{L} \supset -V(a) - \sigma_N \bar{N} N \left(\cos\left(\frac{a}{f_a}\right) - 1 \right)$$

Scalar effective potential

Example: Light QCD axion

$$\mathcal{L} \supset -V(a) - \sigma_N \bar{N}N \left(\cos\left(\frac{a}{f_a}\right) - 1\right)$$

$$\bar{N}N \to \langle \bar{N}N \rangle \approx n$$

$$\mathcal{L} \supset -V(a) - \sigma_N n \left(\cos\left(\frac{a}{f_a}\right) - 1\right) = -V_{\text{eff}}(a)$$

Scalar effective potential

Example: Light QCD axion

$$\mathcal{L} \supset -V(a) - \sigma_N \bar{N}N \left(\cos\left(\frac{a}{f_a}\right) - 1\right)$$

$$\bar{N}N \to \langle \bar{N}N \rangle \approx n$$

$$\mathcal{L} \supset -V(a) - \sigma_N n \left(\cos\left(\frac{a}{f_a}\right) - 1\right) = -V_{\text{eff}}(a)$$

= 1 for qcd axion,
<< 1 for “light” axion

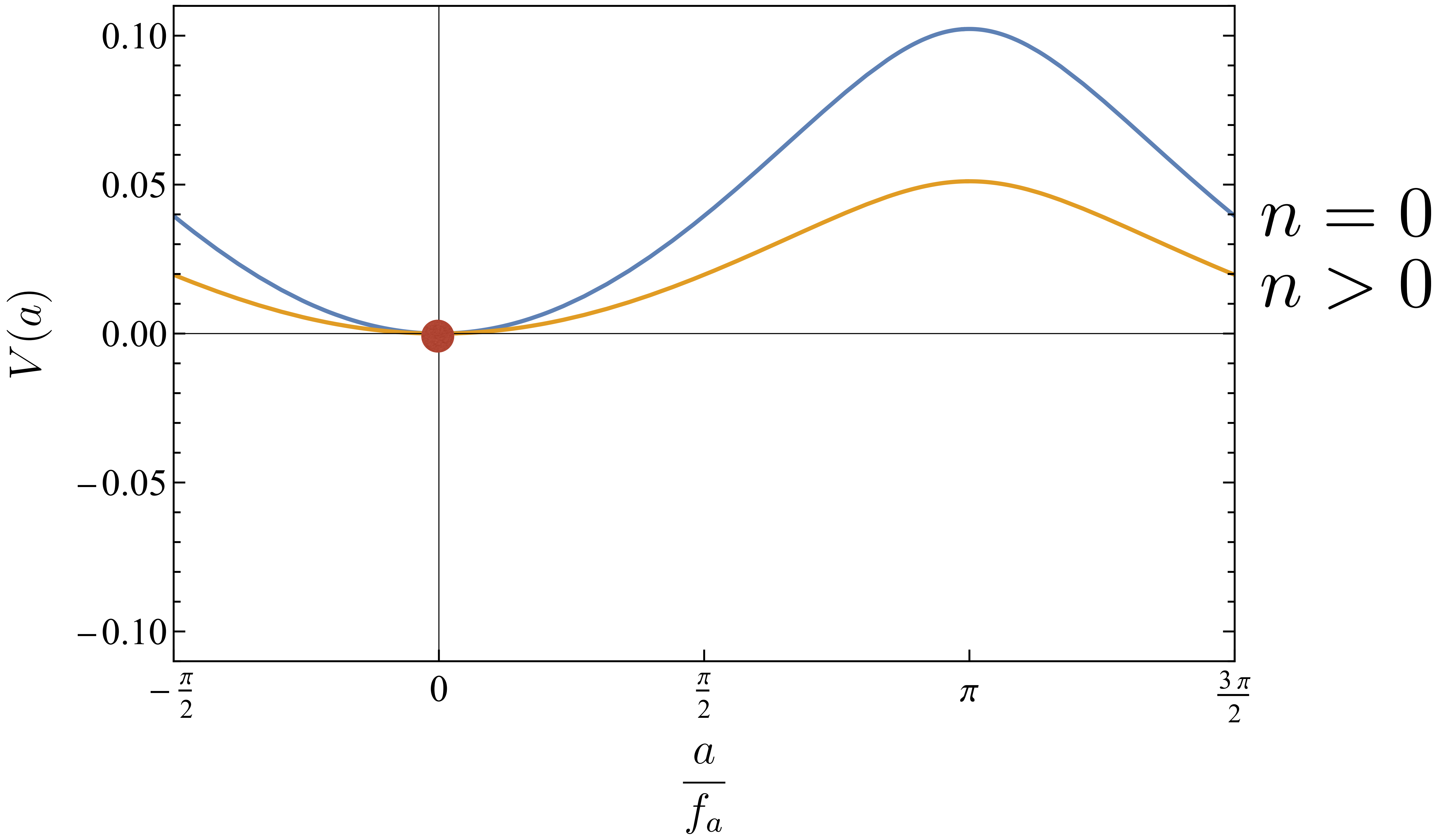
Combine with axion/scalar “bare” mass:

$$V_{\text{eff}} = V(\phi) + \varepsilon_m(n, m_\psi(\phi)) \approx (\varepsilon m_\pi^2 f_\pi^2 - \sigma_N n)\left(\cos\left(\frac{a}{f_a}\right) - 1\right)$$

Scalar effective potential

$$V_{\text{eff}} = V(\phi) + \varepsilon_m(n, m_\psi(\phi)) \approx \left(\varepsilon m_\pi^2 f_\pi^2 - \sigma_N n\right)\left(\cos\left(\frac{a}{f_a}\right) - 1\right)$$

Light QCD axion

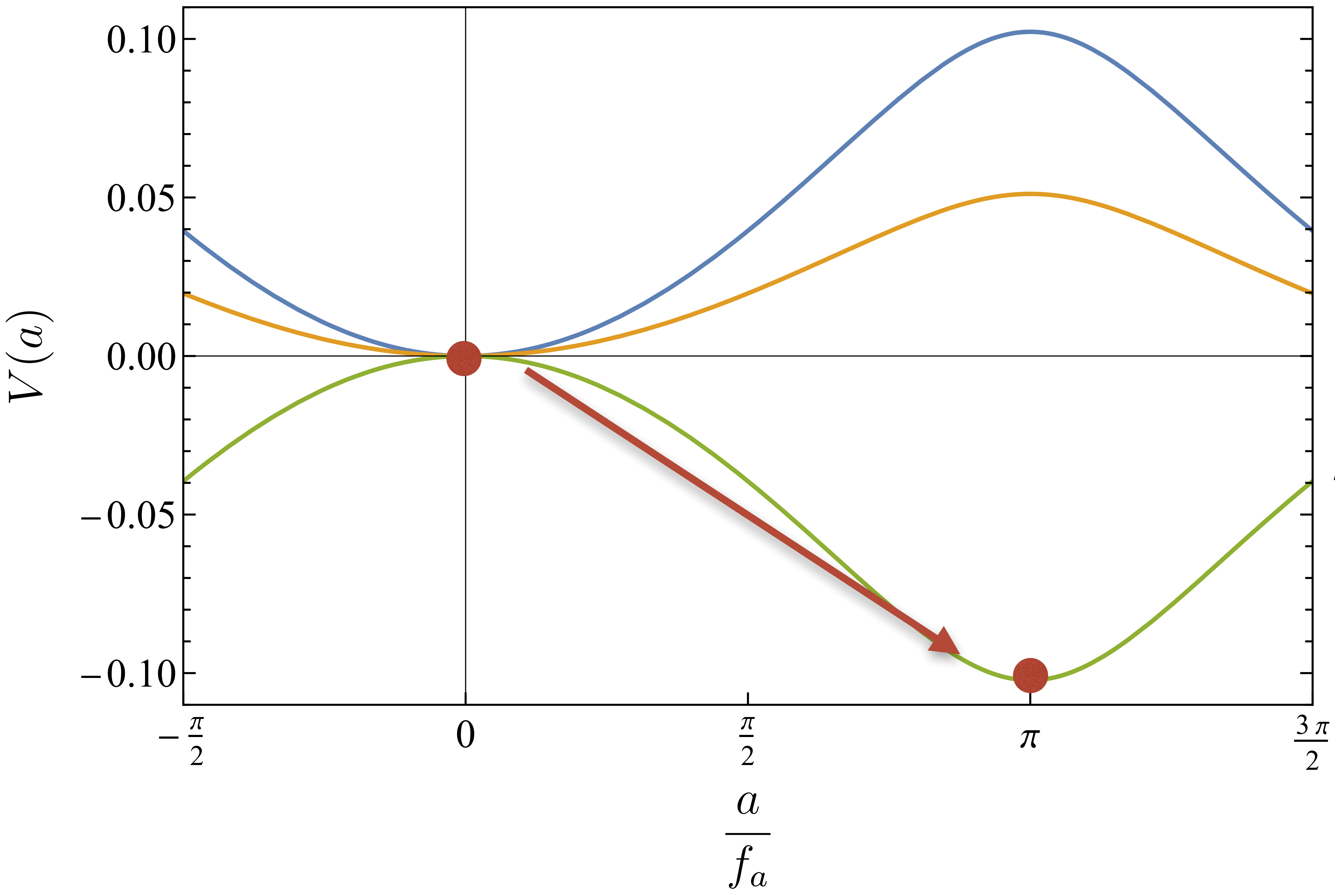


Hook, Huang '17, Balkin, Serra, Springmann, Stelzl, AW '22

Above a critical density, a new axion minimum appears

$$V_{\text{eff}} = V(\phi) + \varepsilon_m(n, m_\psi(\phi)) \approx (\varepsilon m_\pi^2 f_\pi^2 - \sigma_N n)\left(\cos\left(\frac{a}{f_a}\right) - 1\right)$$

Light QCD axion



$n = 0$

$n > 0$

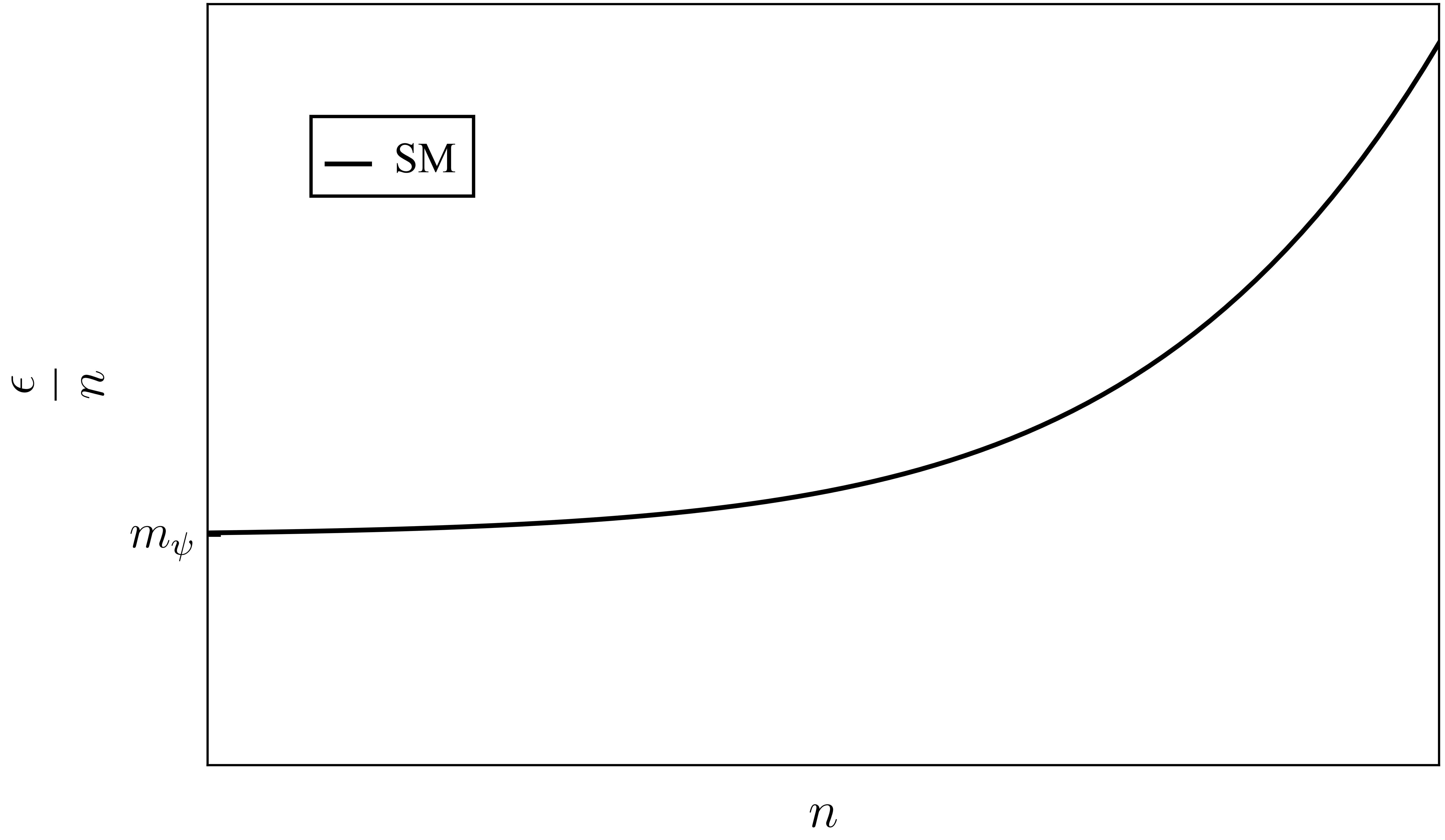
$n > n_c = \frac{\epsilon m_\pi^2 f_\pi^2}{\sigma_N}$

$\Longrightarrow$ Scalar field gets sourced at finite density

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]
[Balkin, Serra, Springmann, Stelzl, Weiler, 2307.14418]

Scalar Induced Phase Transition

Phase structure best understood by looking at energy per particle $\frac{\varepsilon}{n}$



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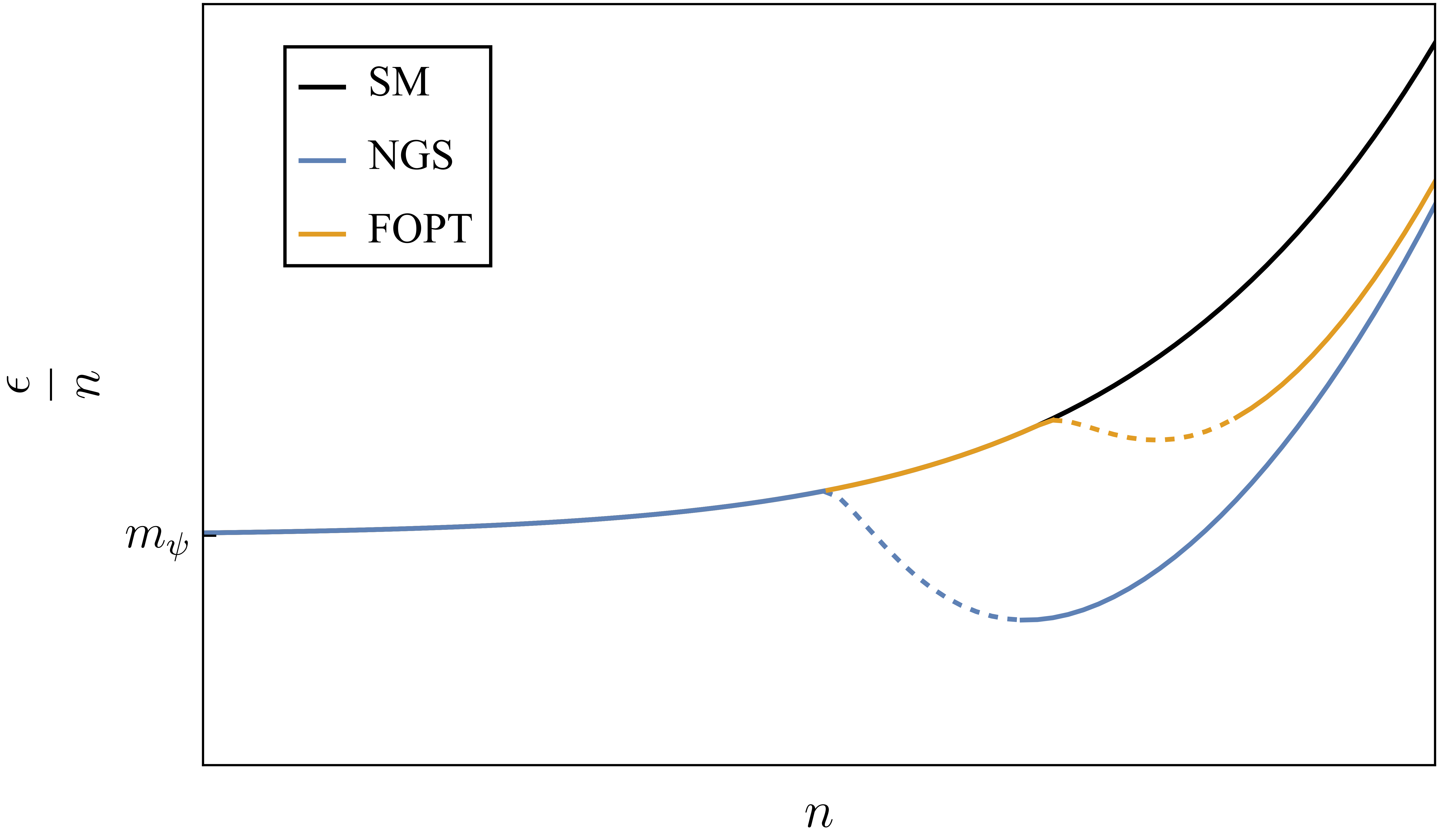

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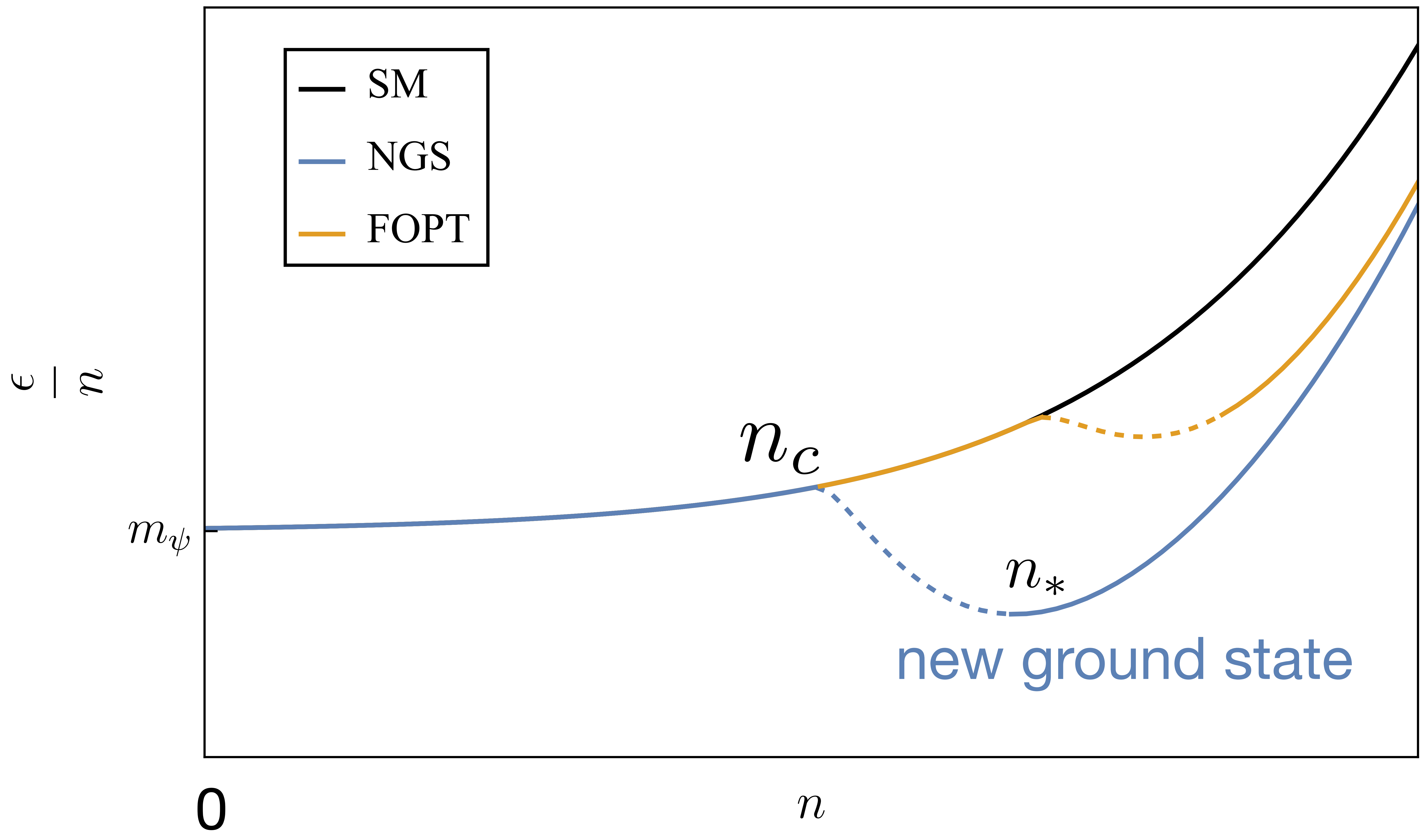


New Ground State (NGS):

lowest $\frac{\varepsilon}{n}$ at n_*

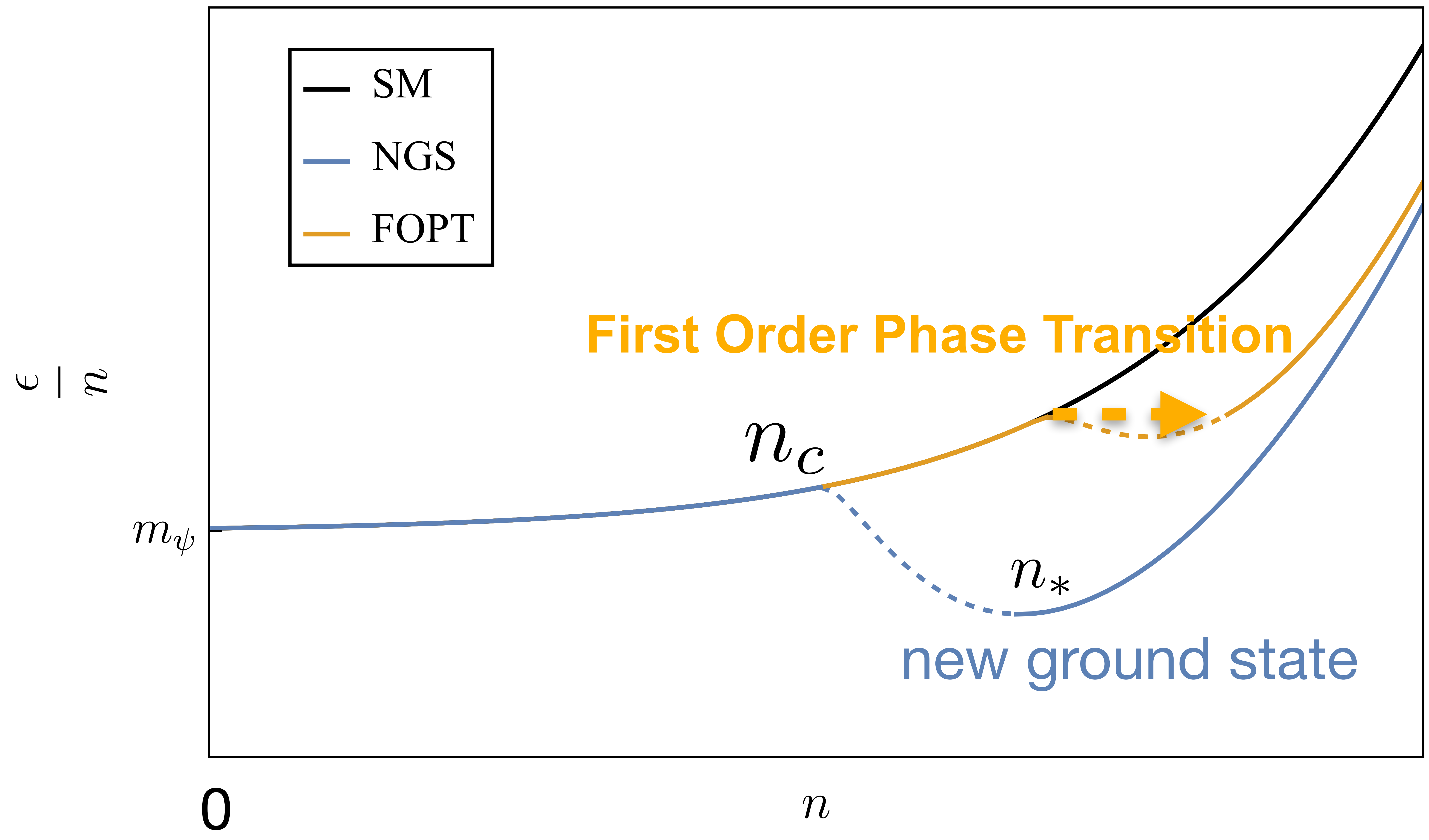
$\Longrightarrow$ ground state of matter

$n < n_c$: metastable

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]
[Balkin, Serra, Springmann, Stelzl, Weiler, 2307.14418]

Scalar Induced Phase Transition

Phase structure best understood by looking at **energy per particle** $\frac{\varepsilon}{n}$



New Ground State (NGS):

lowest $\frac{\varepsilon}{n}$ at n_*

$\Longrightarrow$ ground state of matter

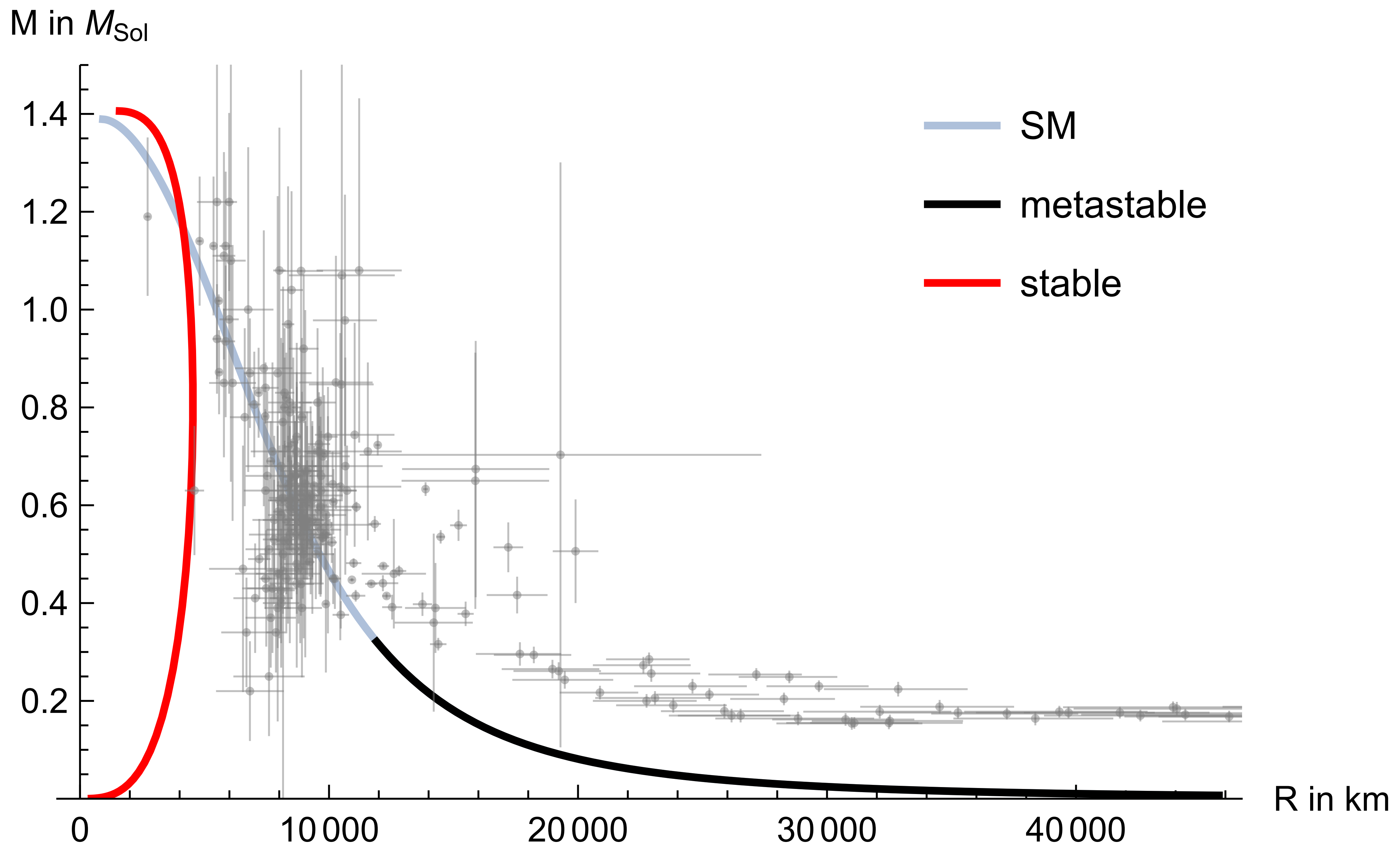
$n < n_c$: metastable

First Order Phase Transition:

lowest $\frac{\varepsilon}{n}$ at $n = 0$

$\Longrightarrow$ jump in density as field becomes sourced

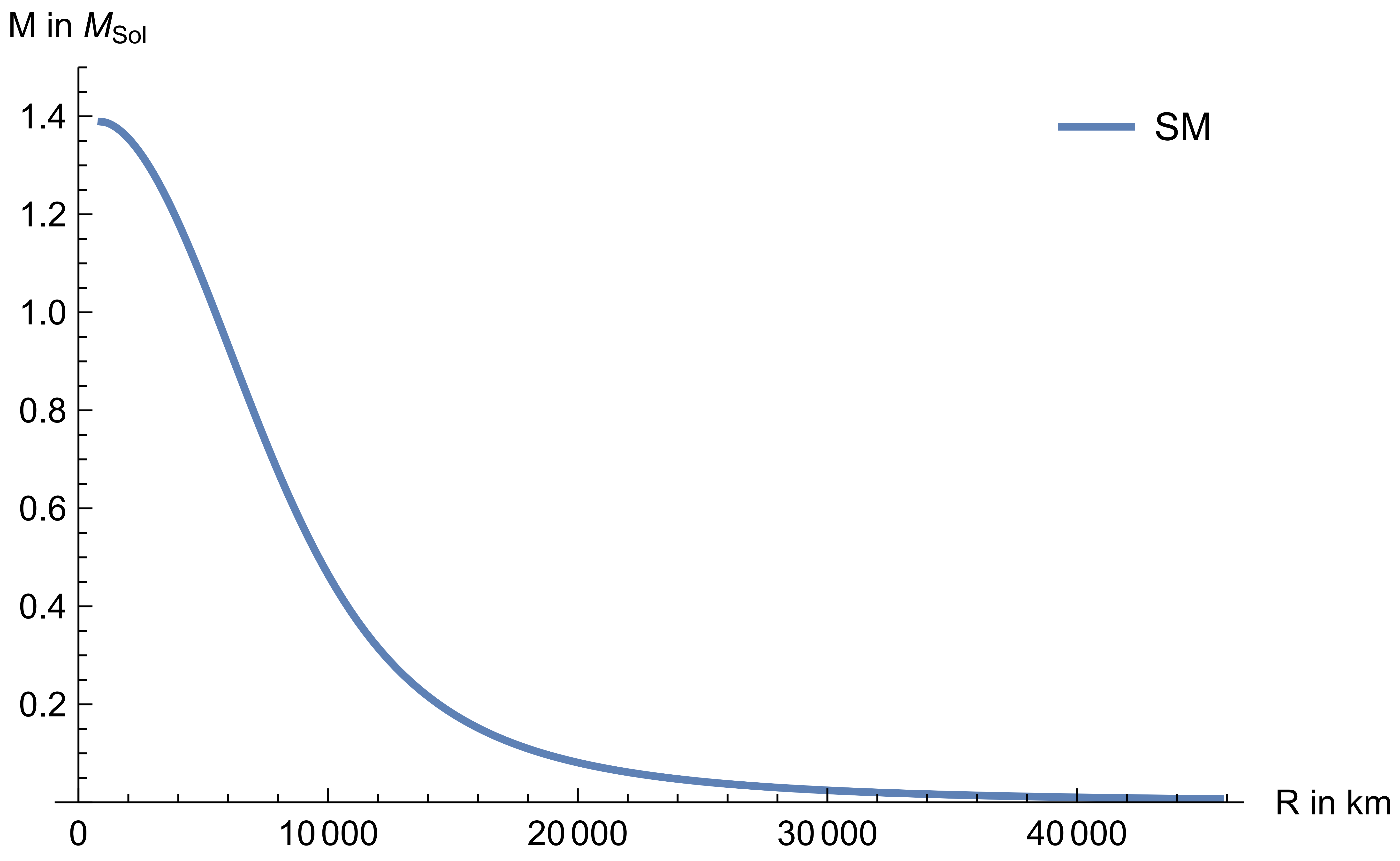
Constraints from White Dwarf Mass Radius Relationship



Observing New Ground States

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]

SM: continuous prediction



Observing New Ground States

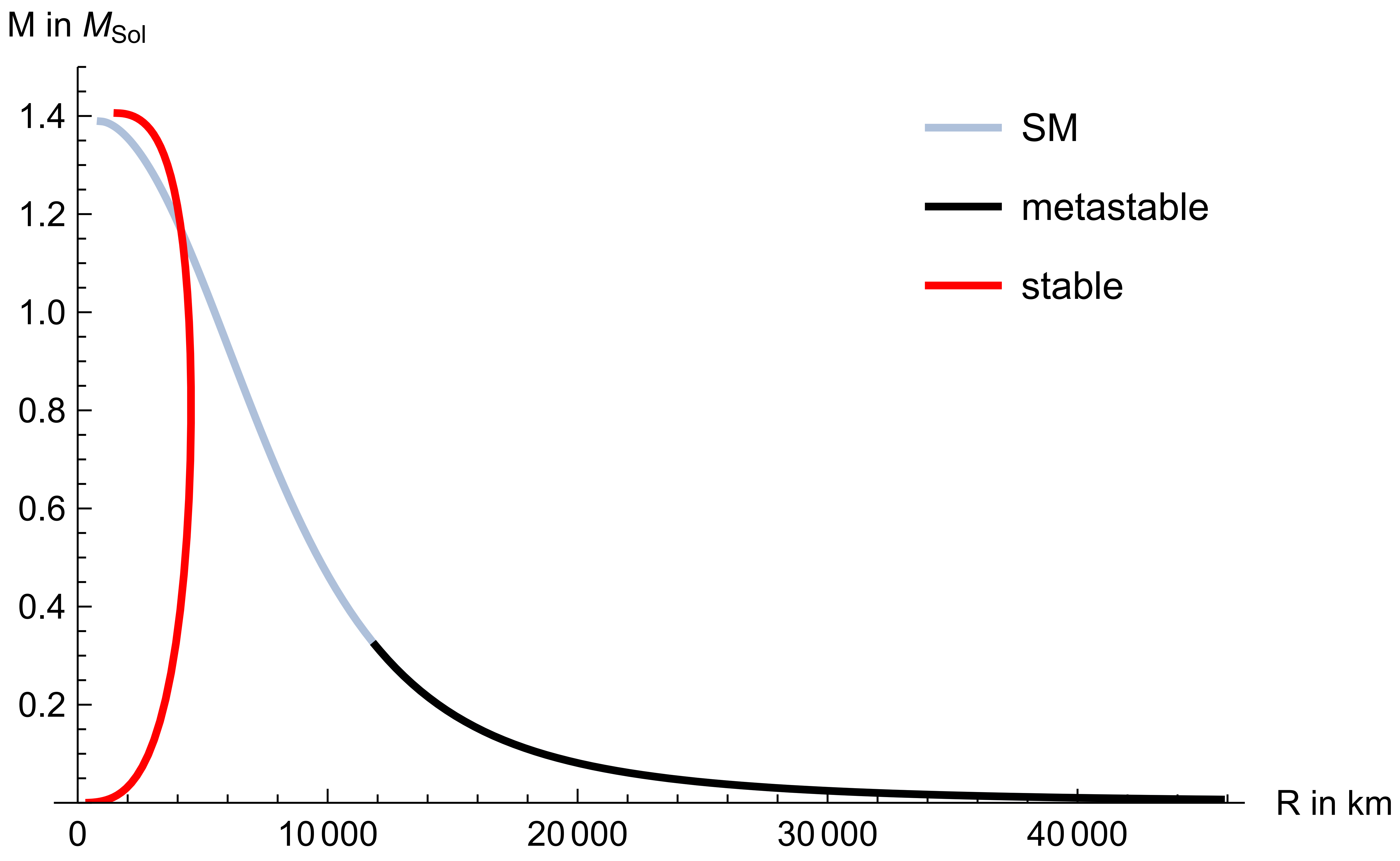
[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]

SM: continuous prediction

With NGS: two branches:

- $\phi = 0$: metastable
- $\phi \neq 0$: stable

$\Longrightarrow$ gap in radius



Observing New Ground States

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]

SM: continuous prediction

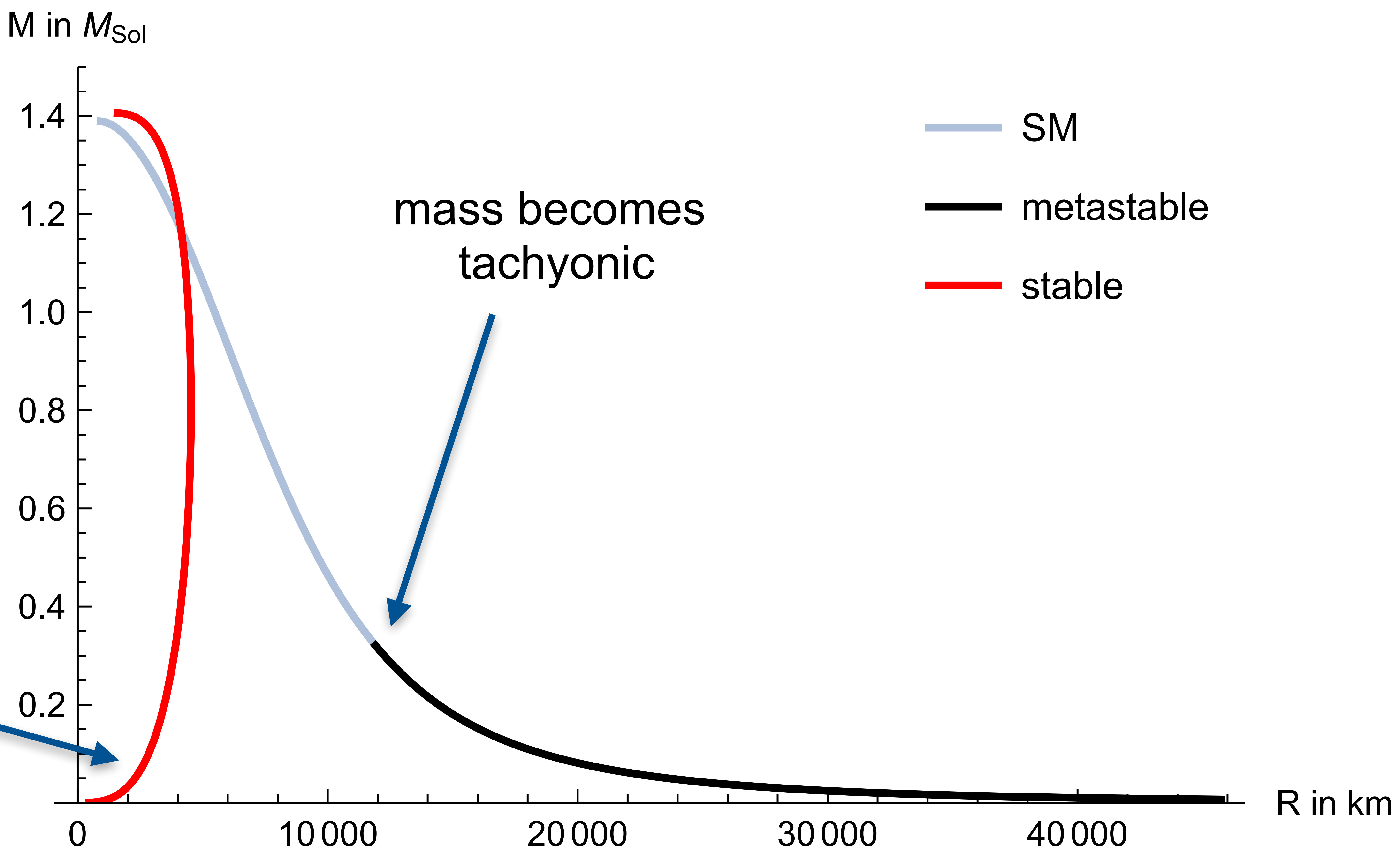
With NGS: two branches:

- $\phi = 0$: metastable
- $\phi \neq 0$: stable

$\Longrightarrow$ gap in radius

constant density object

$n = n_*$



Observing New Ground States: **ϕ-dwarfs**

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]

SM: continuous prediction

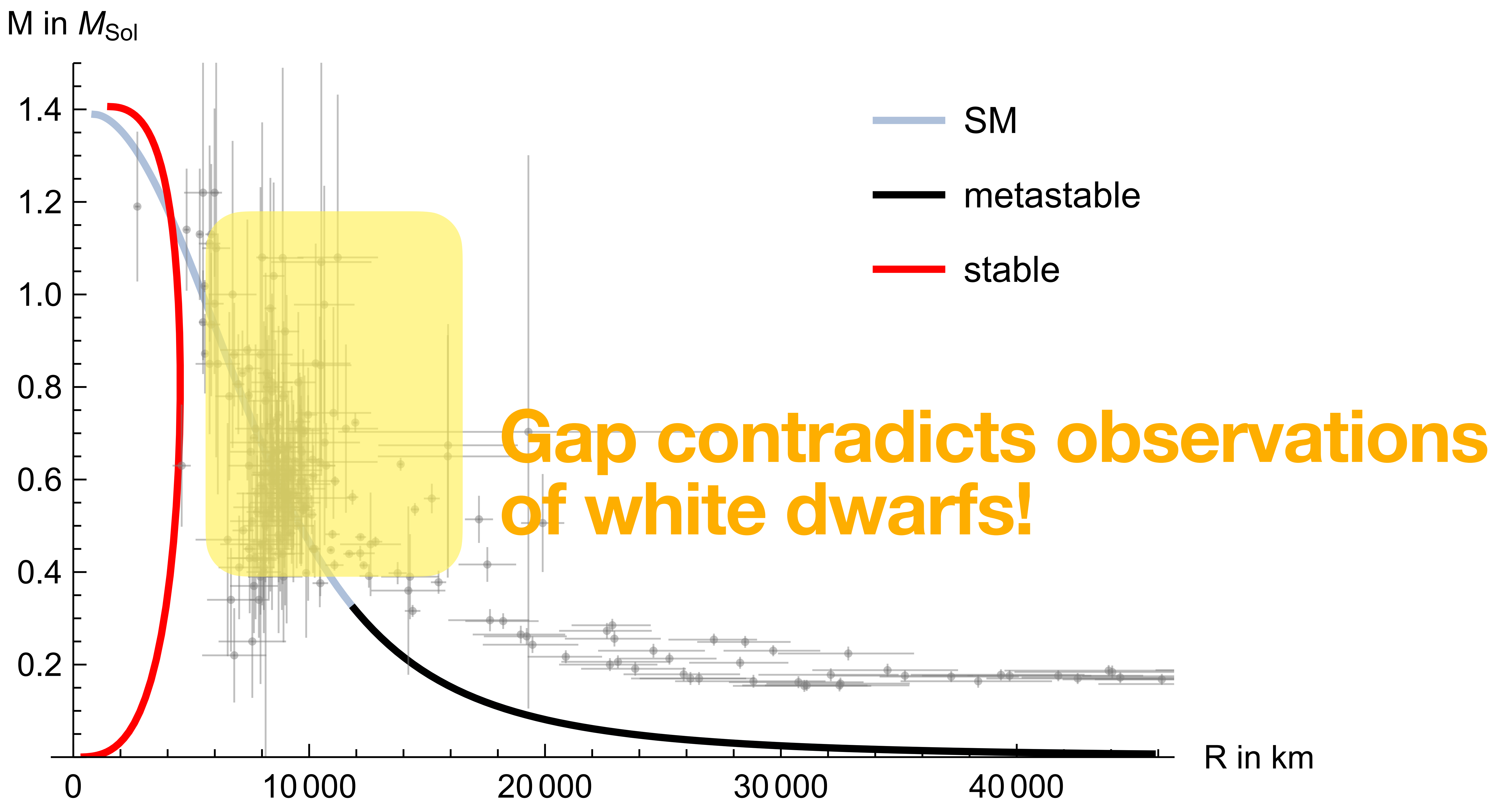
With NGS: two branches:

- $\phi = 0$: metastable
- $\phi \neq 0$: stable

$\Longrightarrow$ gap in radius

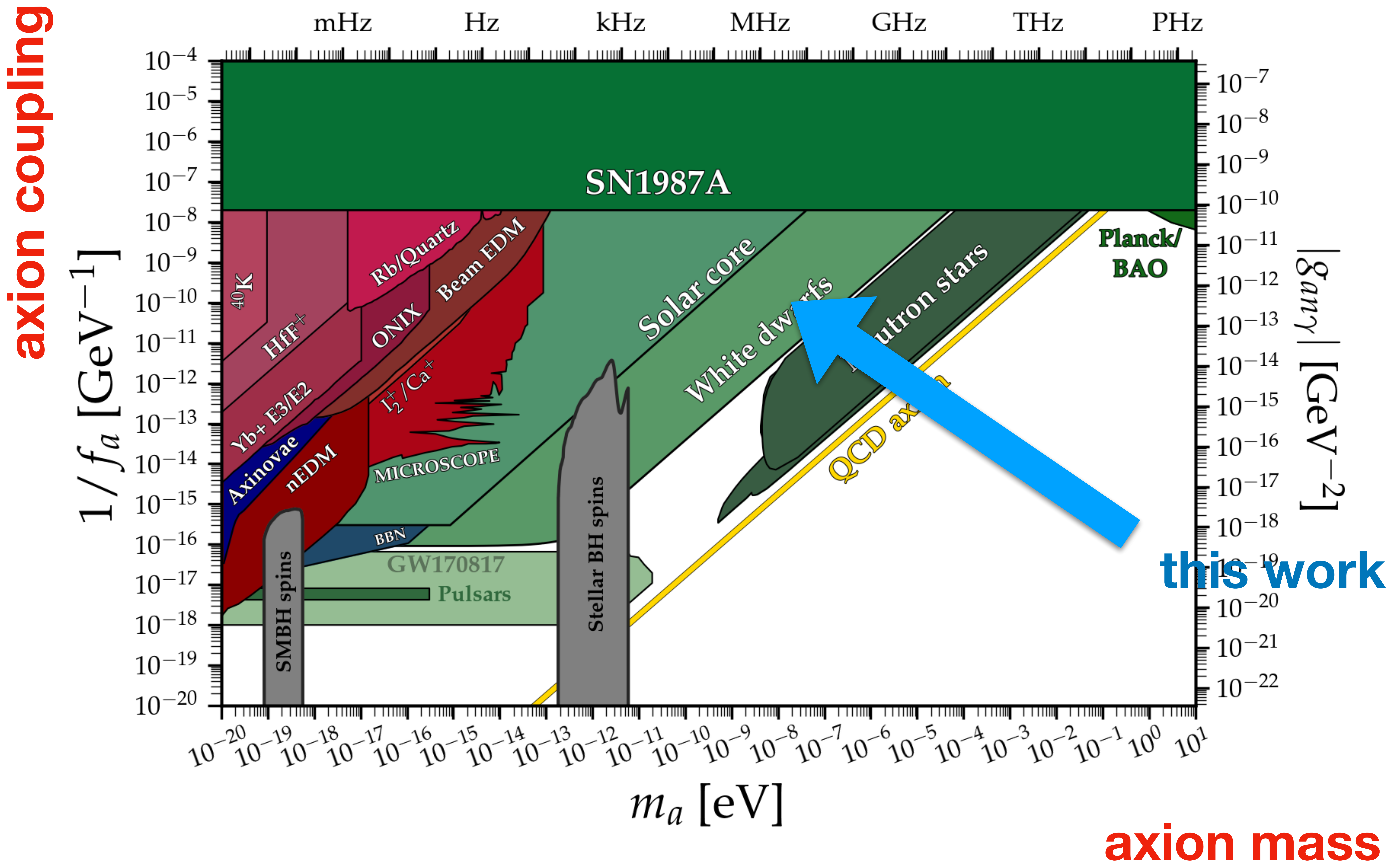
Observe WDs in this gap

$\Longrightarrow$ exclusion



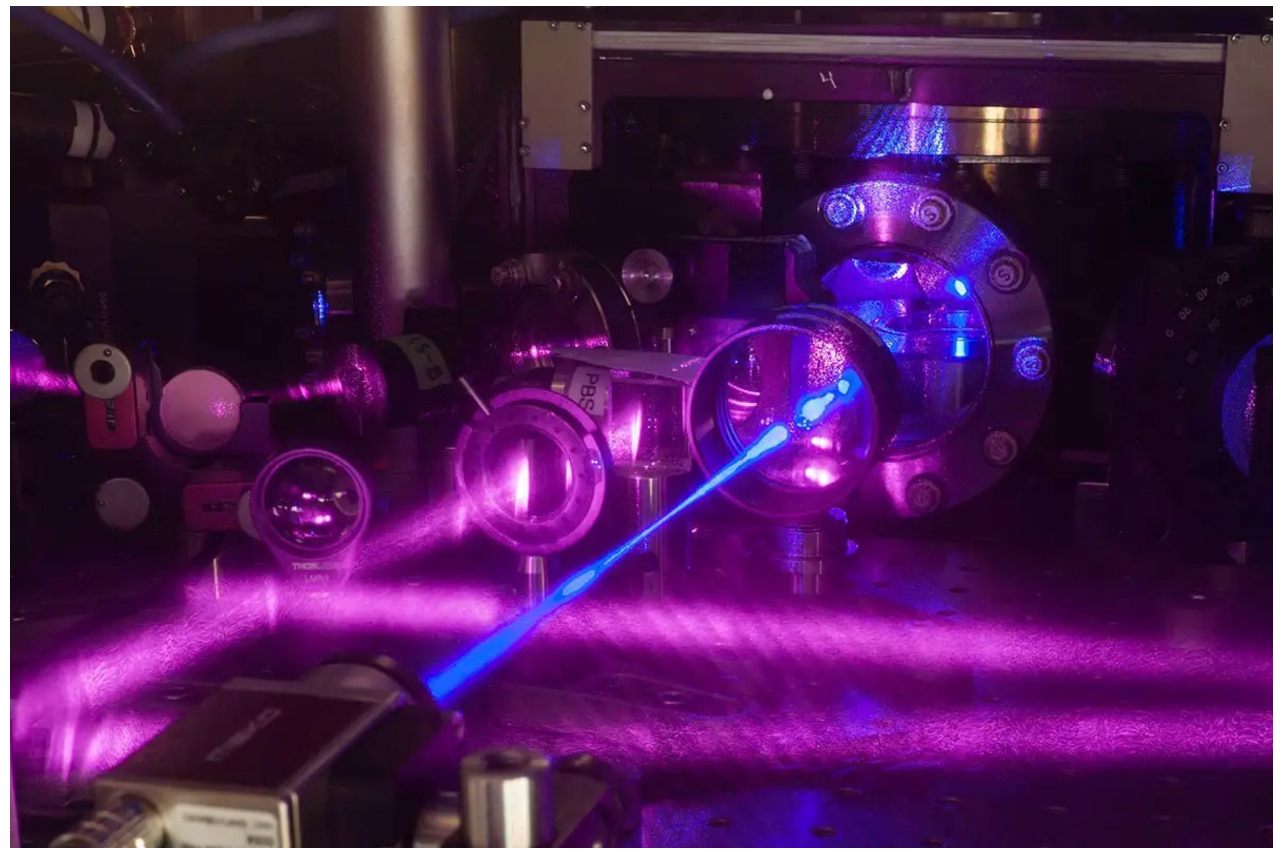
Axion parameter space

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]



https://github.com/cajohare/AxionLimits

[Bartnick, Springmann, Stelzl, Weiler '25]



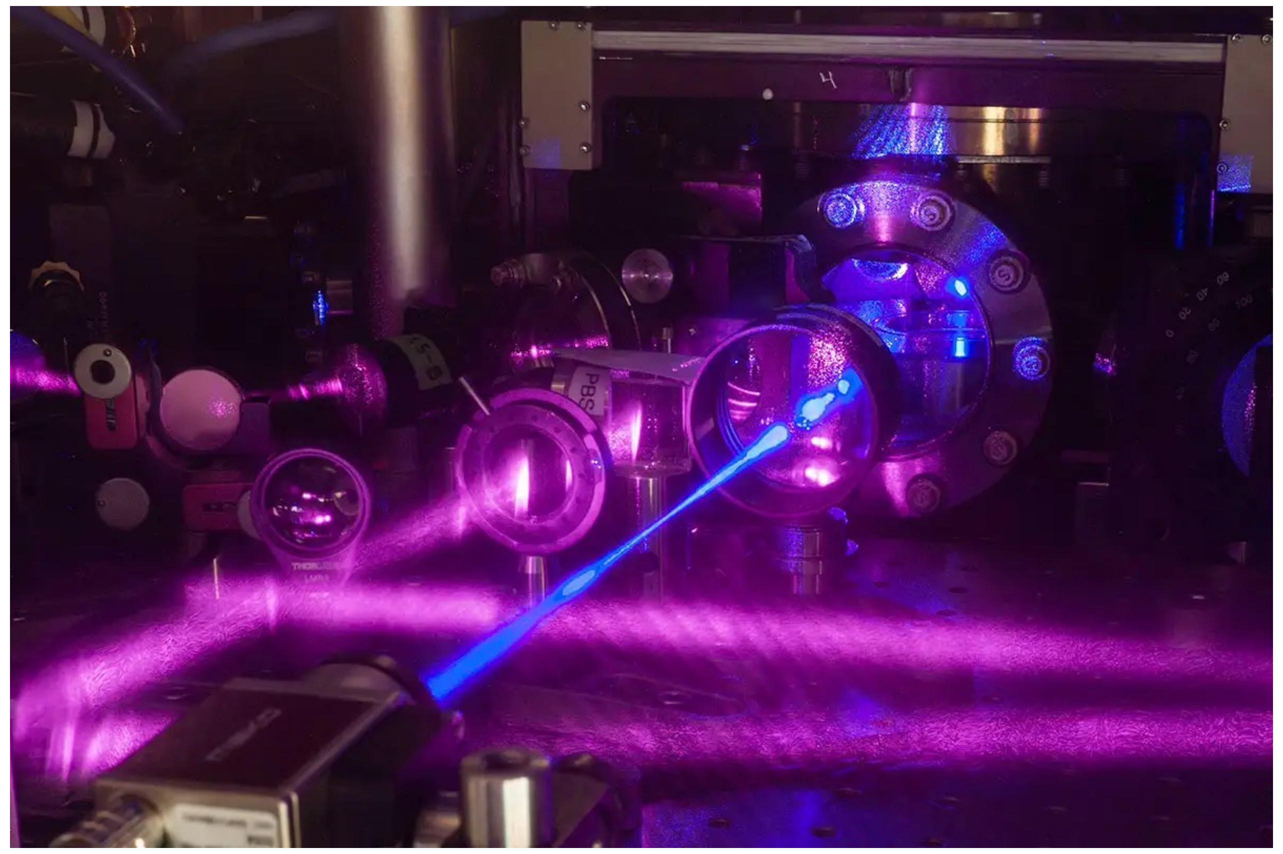
vs.

beyond axion-like theories

$$\mathcal{L}_{\text{int}} = \frac{d_{m_e}^{(2)}}{2M_p^2} m_e \phi^2 \bar{\psi}_e \psi_e$$

scalar-electron coupling

[Bartnick, Springmann, Stelzl, Weiler '25]



vs.

beyond axion-like theories

$$\mathcal{L}_{\rm int} = \frac{d_{m_e}^{(2)}}{2M_p^2} m_e \phi^2 \bar{\psi}_e \psi_e$$

scalar-electron coupling

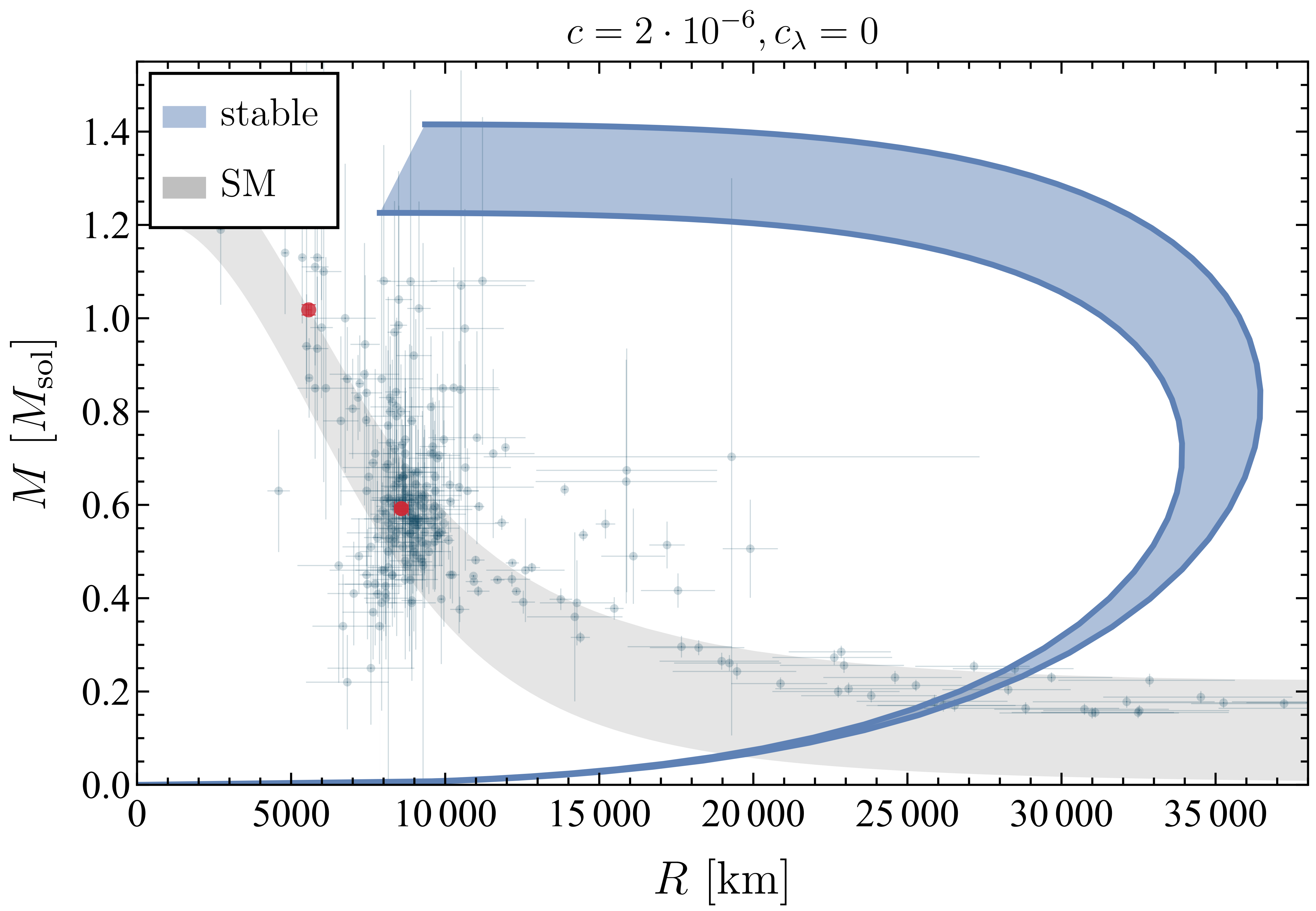
$$\mathcal{L}_{\rm int} \approx \frac{d_{m_N}^{(2)}}{2M_p^2} m_N \phi^2 \bar{\psi}_N \psi_N$$

scalar-nucleon coupling

Observing New Ground States (general couplings)

[Bartnick, Springmann, Stelzl, Weiler ’25]

$$\mathcal{L}_{\text{int}} = \frac{d_{m_e}^{(2)}}{2M_p^2} m_e \phi^2 \bar{\psi}_e \psi_e$$

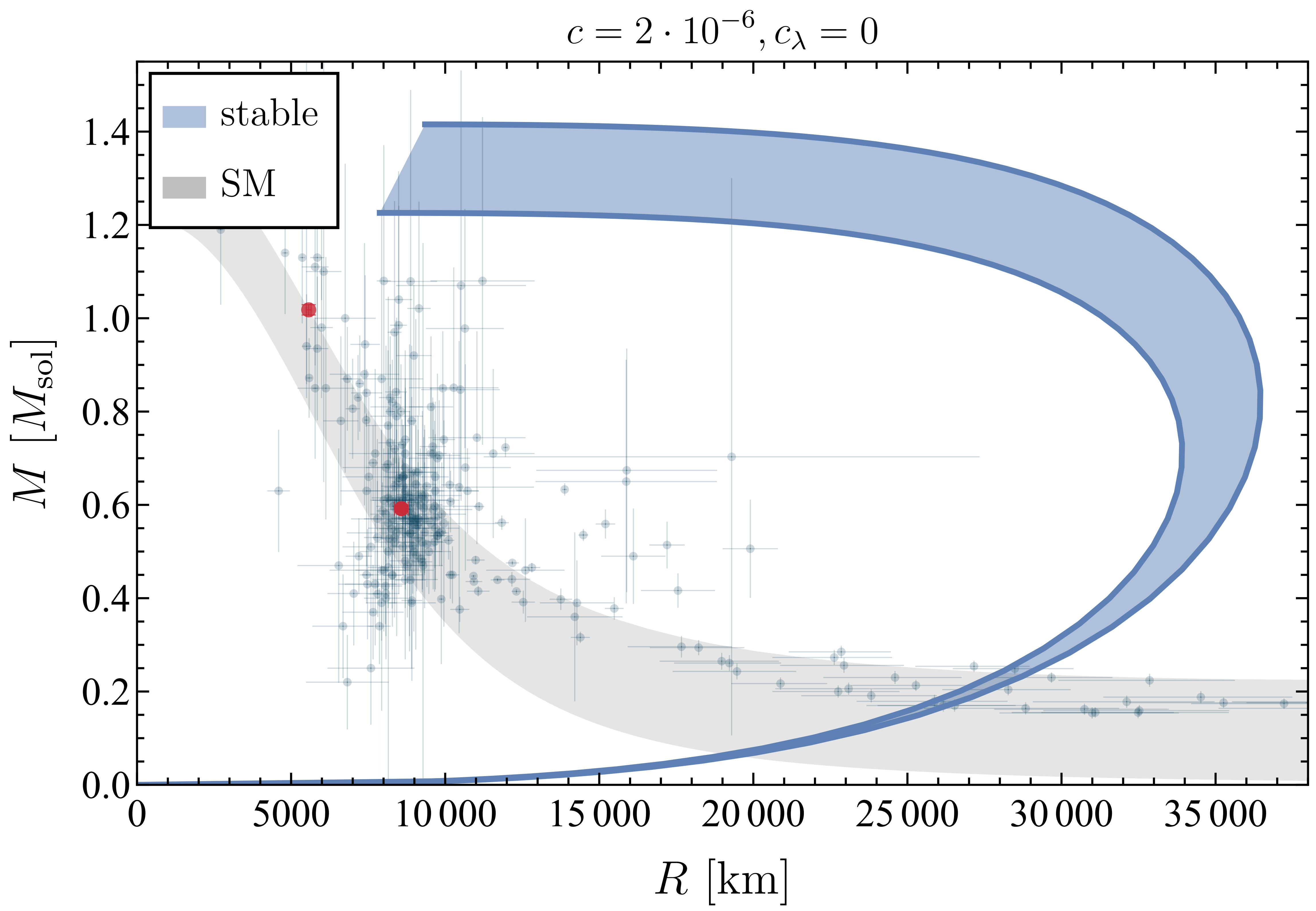


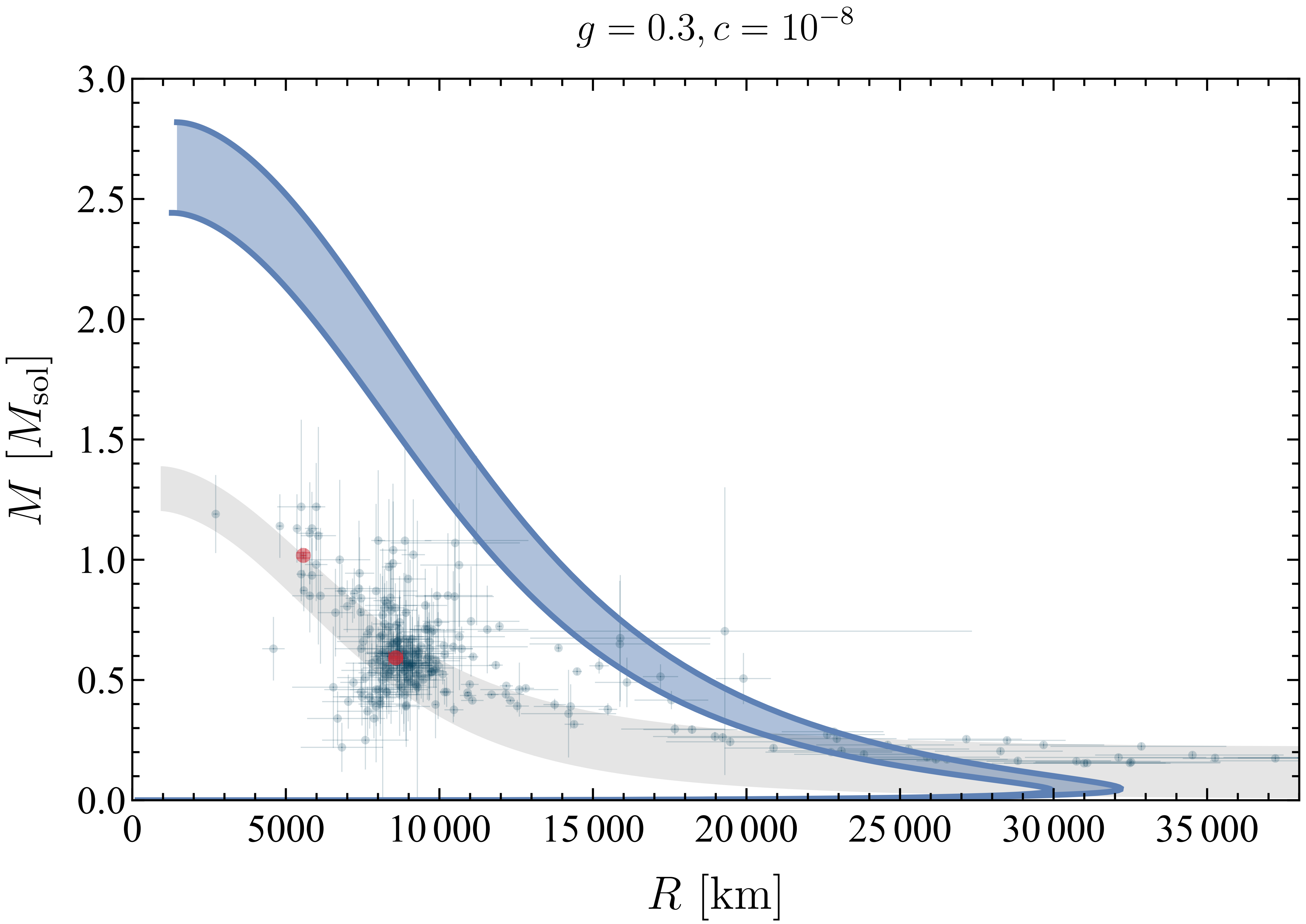
Observing New Ground States (general couplings)

[Bartnick, Springmann, Stelzl, Weiler '25]

$$\mathcal{L}_{\text{int}} = \frac{d_{m_e}^{(2)}}{2M_p^2} m_e \phi^2 \bar{\psi}_e \psi_e$$

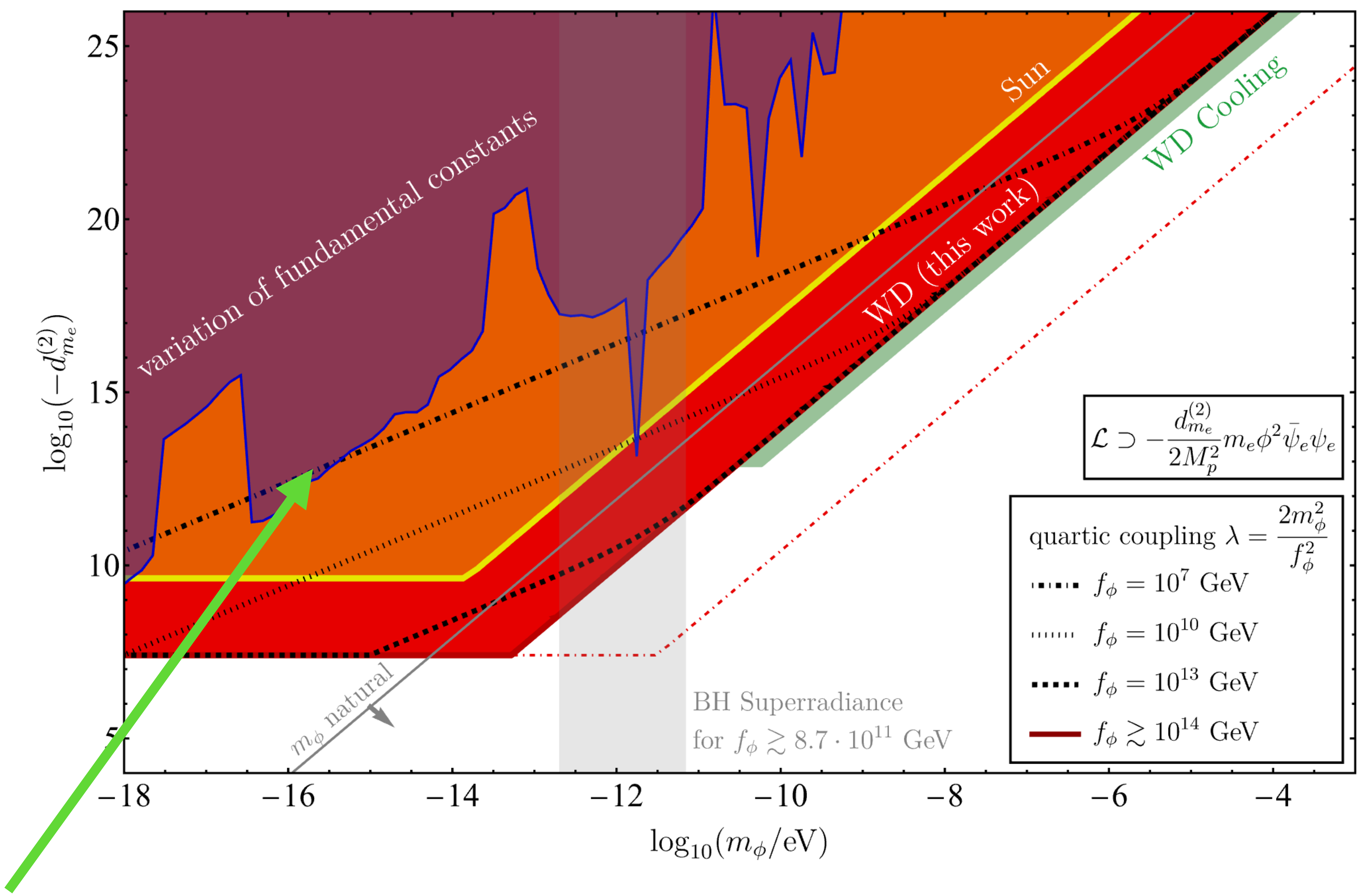
$$\mathcal{L}_{\text{int}} \approx \frac{d_{m_N}^{(2)}}{2M_p^2} m_N \phi^2 \bar{\psi}_N \psi_N$$





White dwarfs beat terrestrial probes (and don't need DM abundance)

[Bartnick, Springmann, Stelzl, Weiler '25]



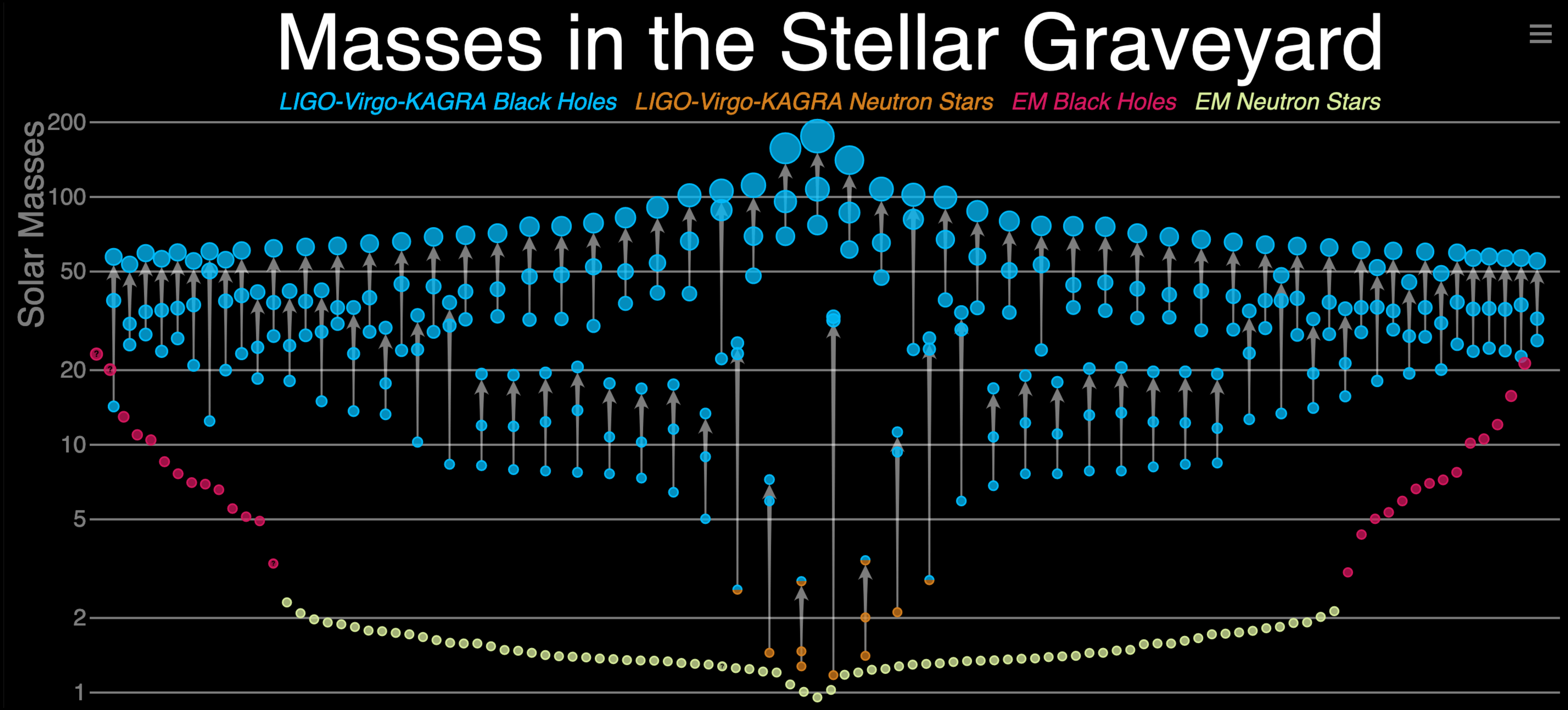
WD mass-radius constraints reach well beyond atomic/nuclear clocks

Clocks require the scalar to be a sizable DM fraction; WD structure does not

Part 2 : Neutron stars become zombies thanks to the axion

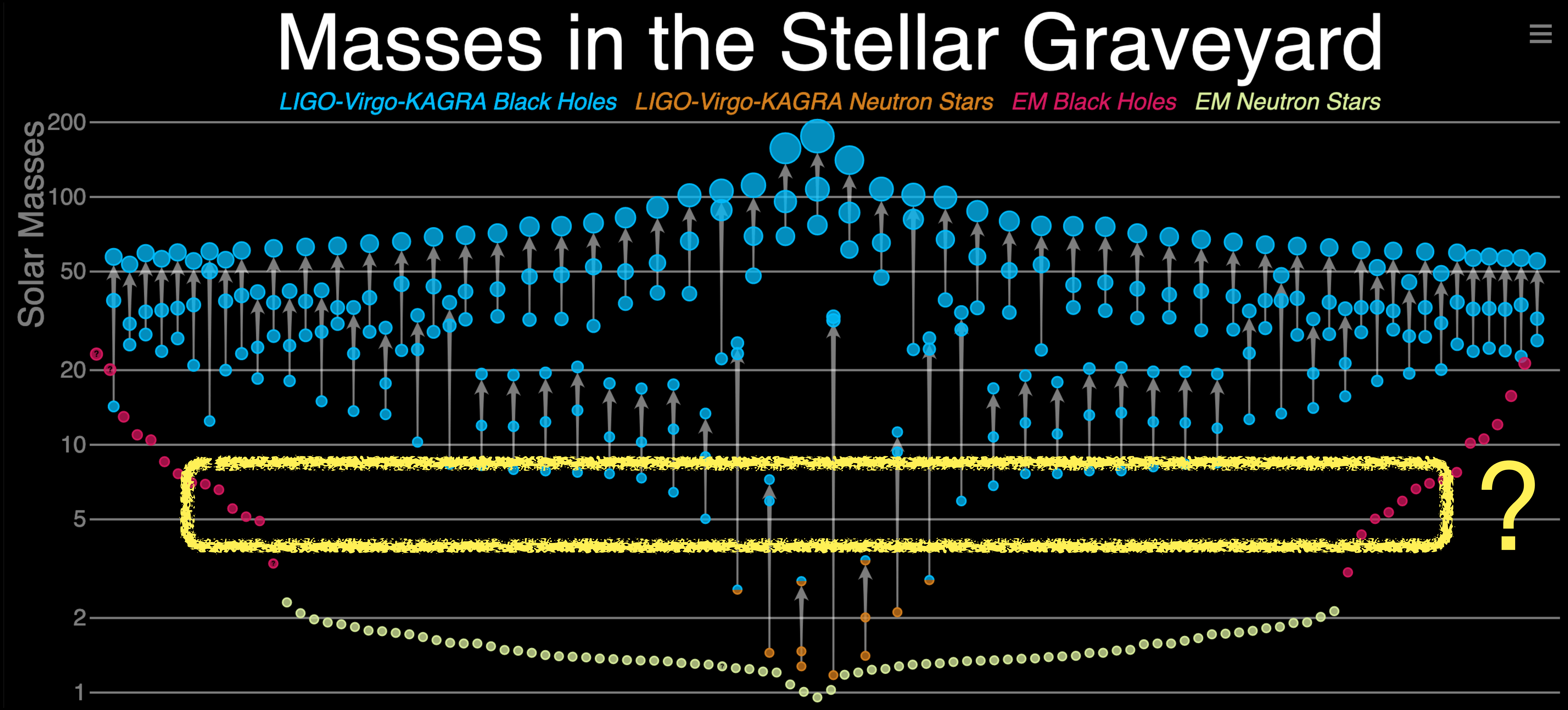
Neutron Stars

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

Motivation: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EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
?

NS toy model

Recall our neutron star estimates:

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

If axion reduces nucleon mass, large effect on M vs R or neutron star, e.g.

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

Light scalars coupled to nucleons

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

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

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

What kind of EOS?

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

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

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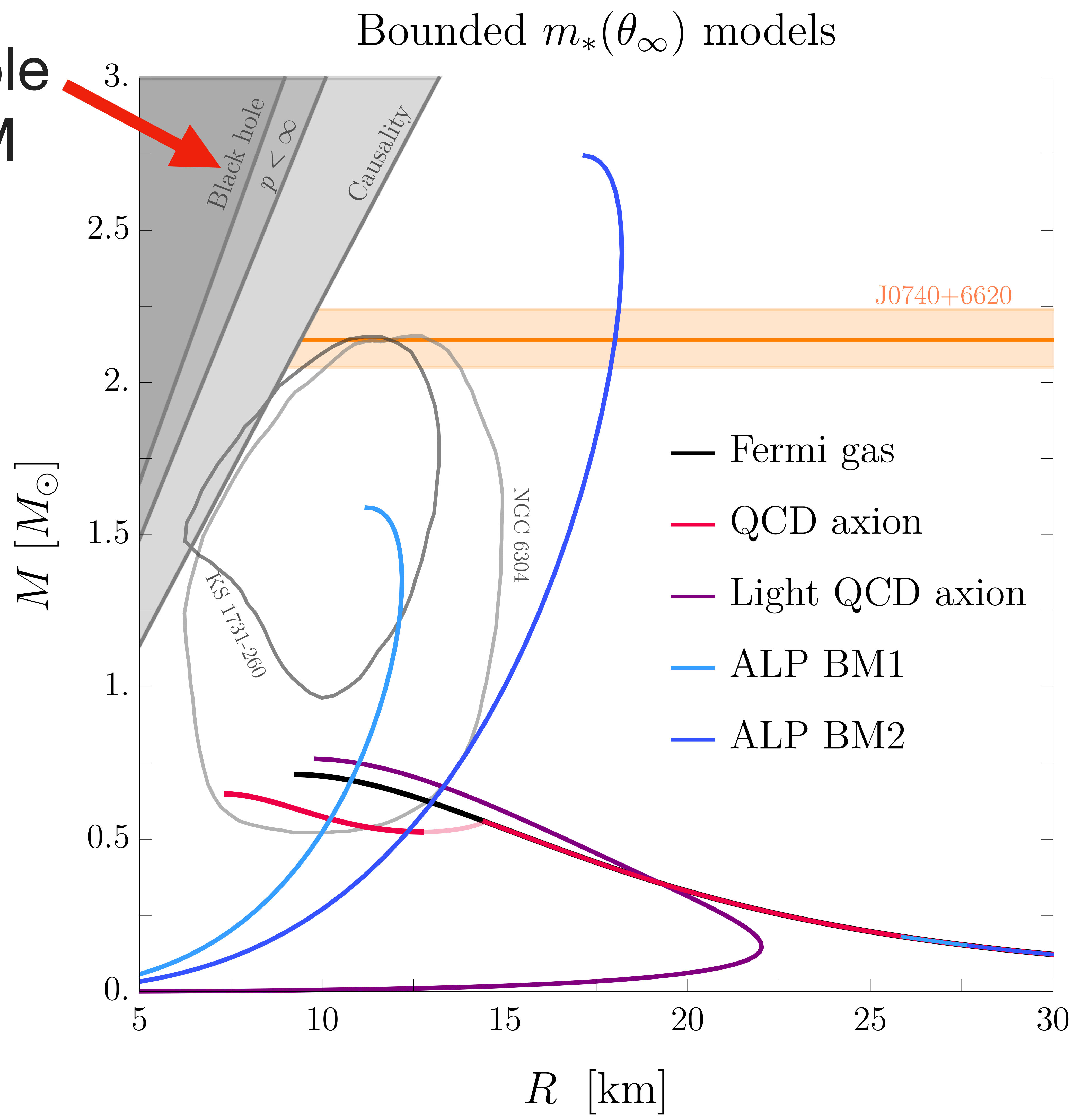
additional energy density gravitates

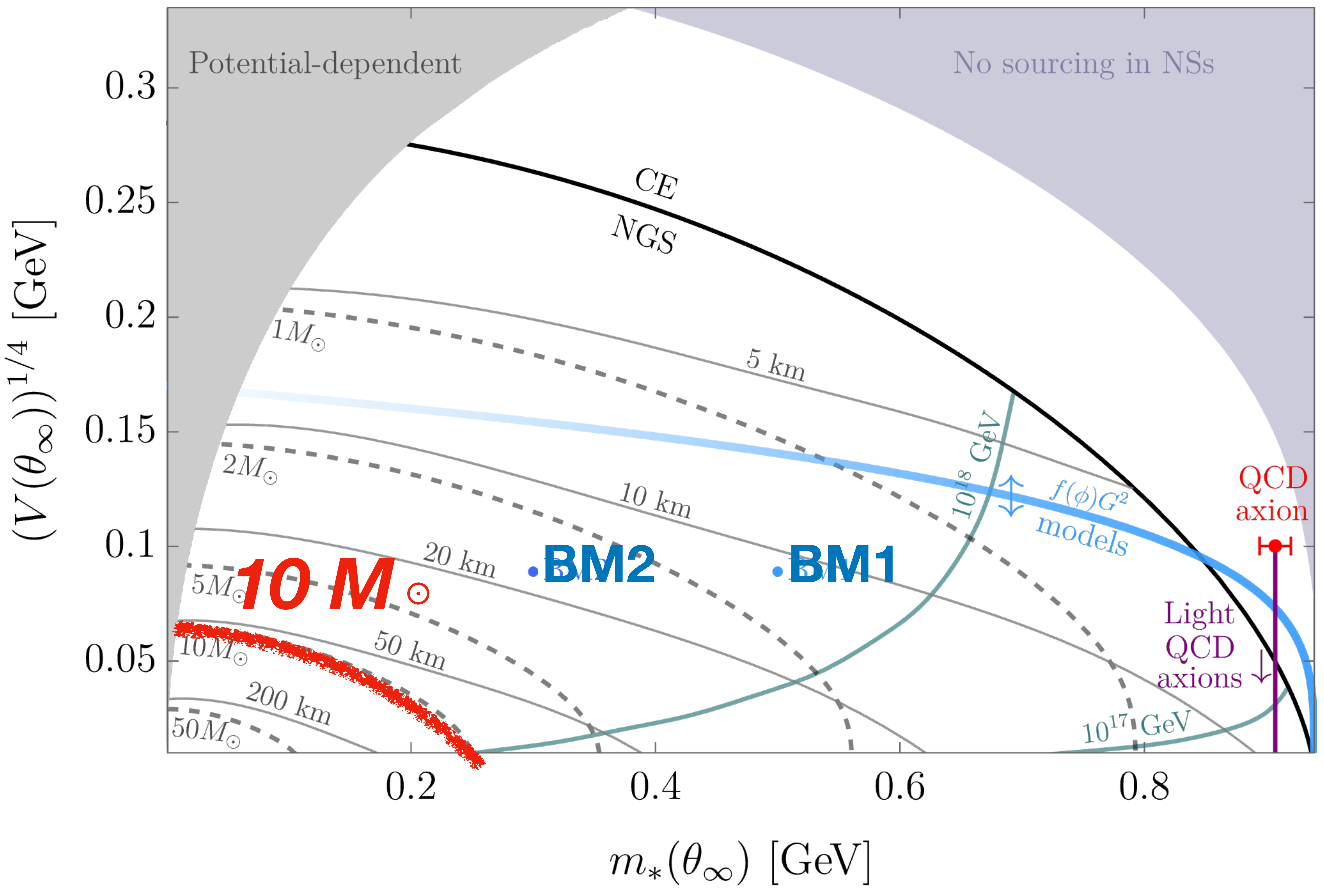
could ignore in white dwarfs

Mass vs. Radius of NS

Black Hole
R = 2 GM



Neutron stars with light scalars



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

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

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

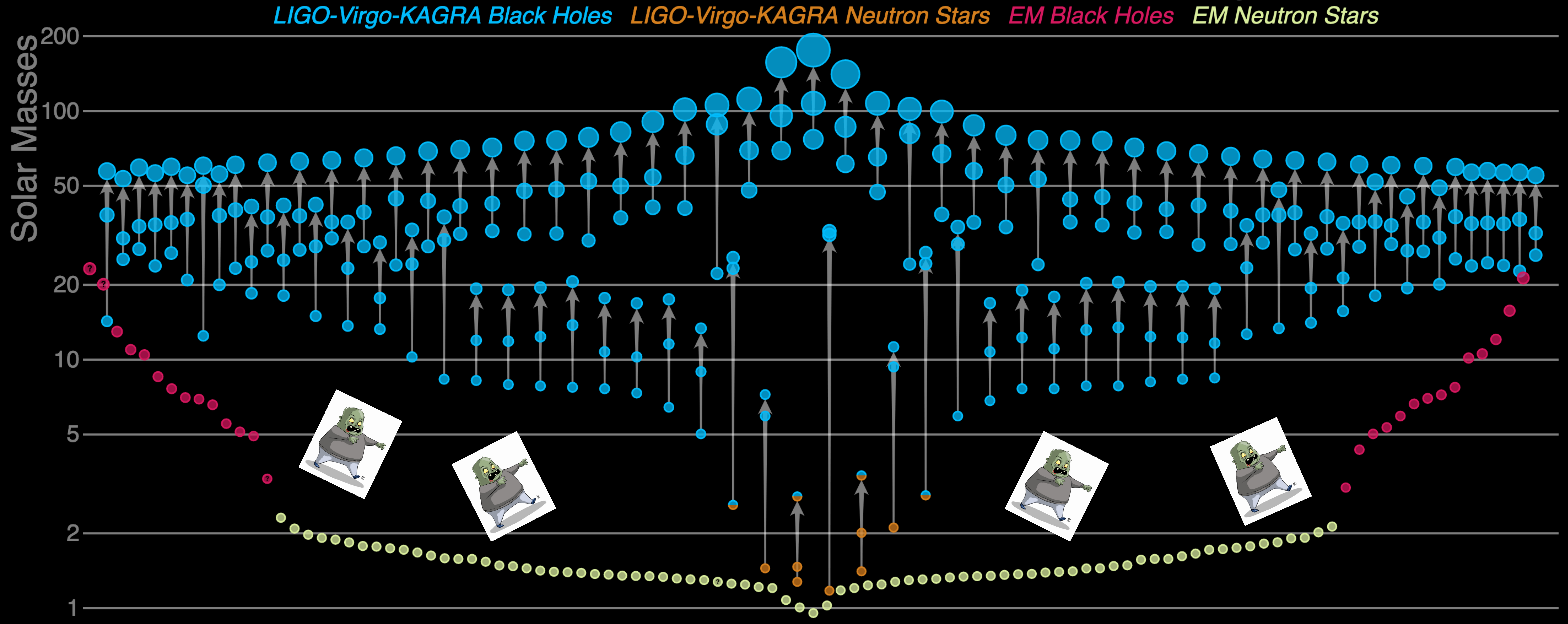
Two benchmarks

BM1 $\quad m_*(\theta_\infty) = m_N/2$

BM2 $\quad m_*(\theta_\infty) = m_N/3$

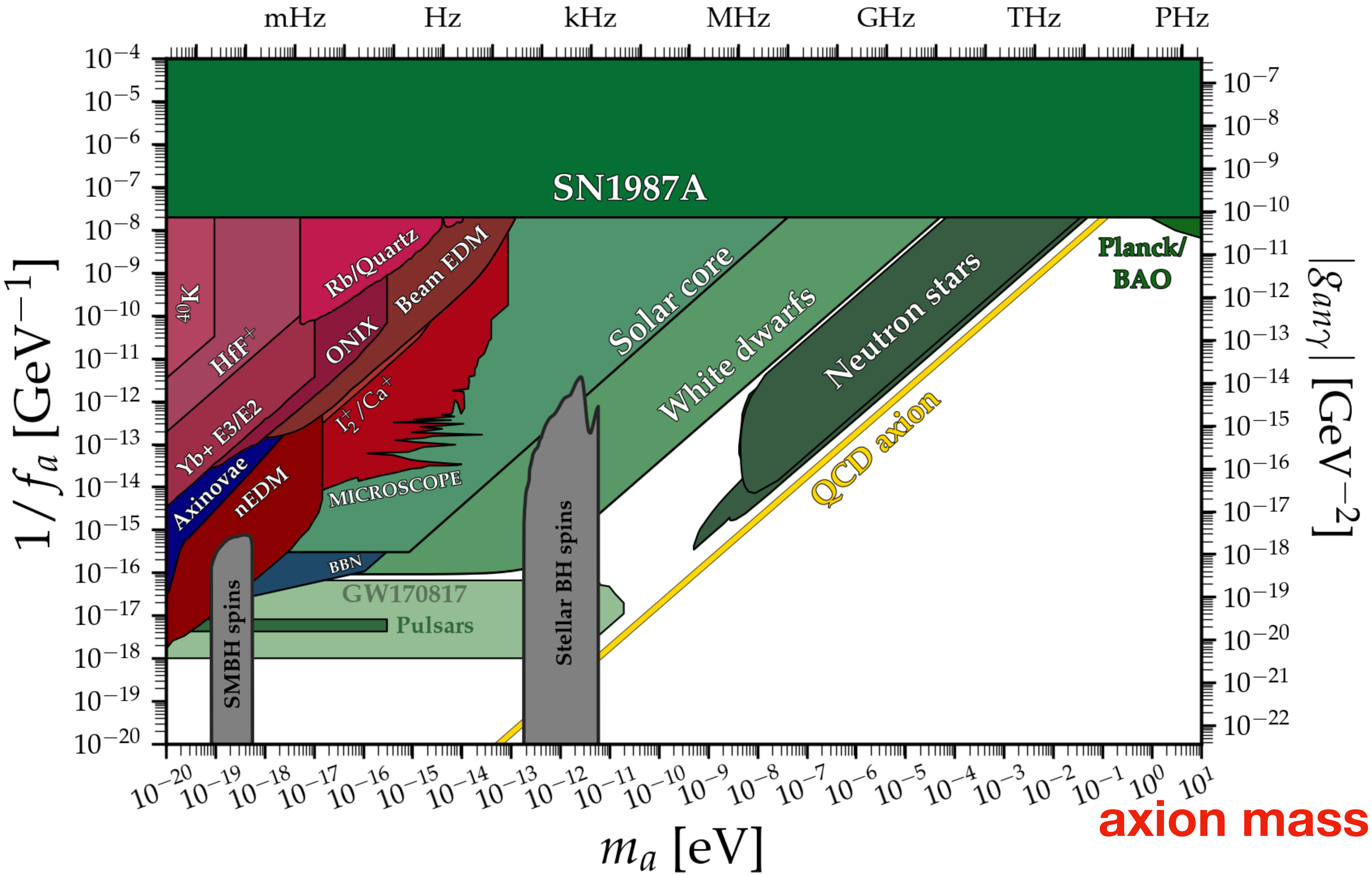
$$V(\theta_\infty) = 2 \times (0.075 \text{ GeV})^4$$

Masses in the Stellar Graveyard

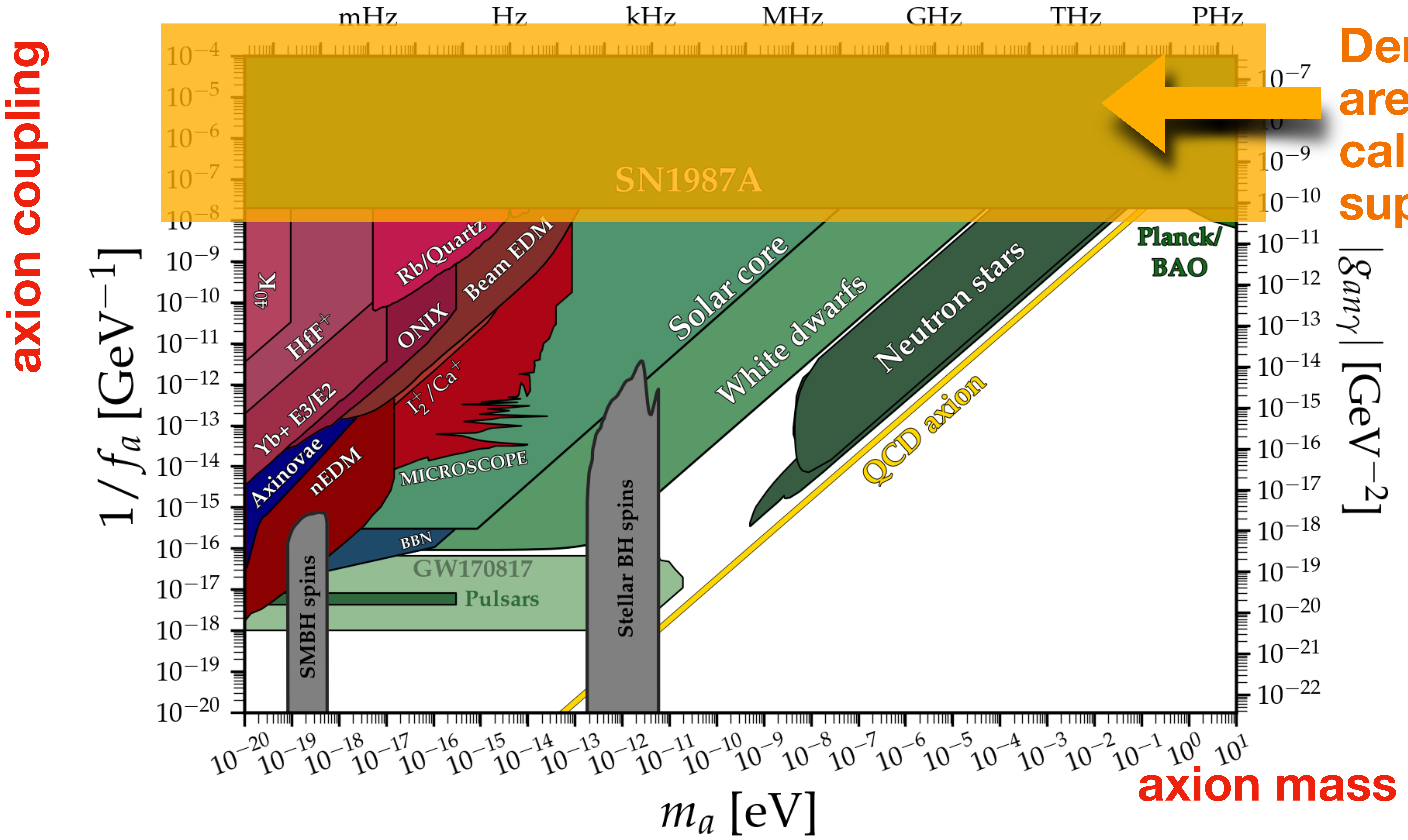


Part 3 : Axion emission in SN

axion coupling



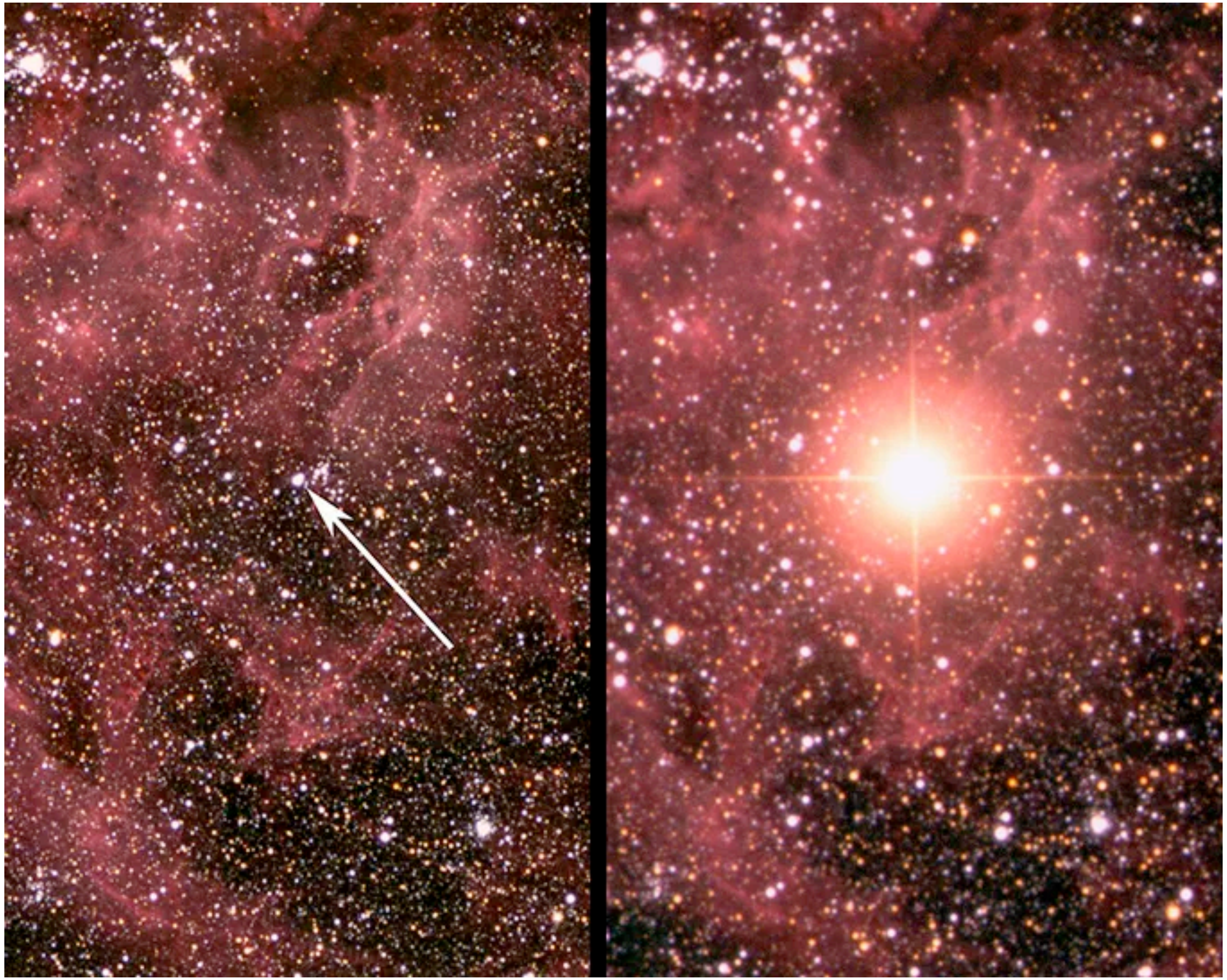
axion mass



Density corrections are crucial in the calculation of the supernova bound

Bound from SN 1987A

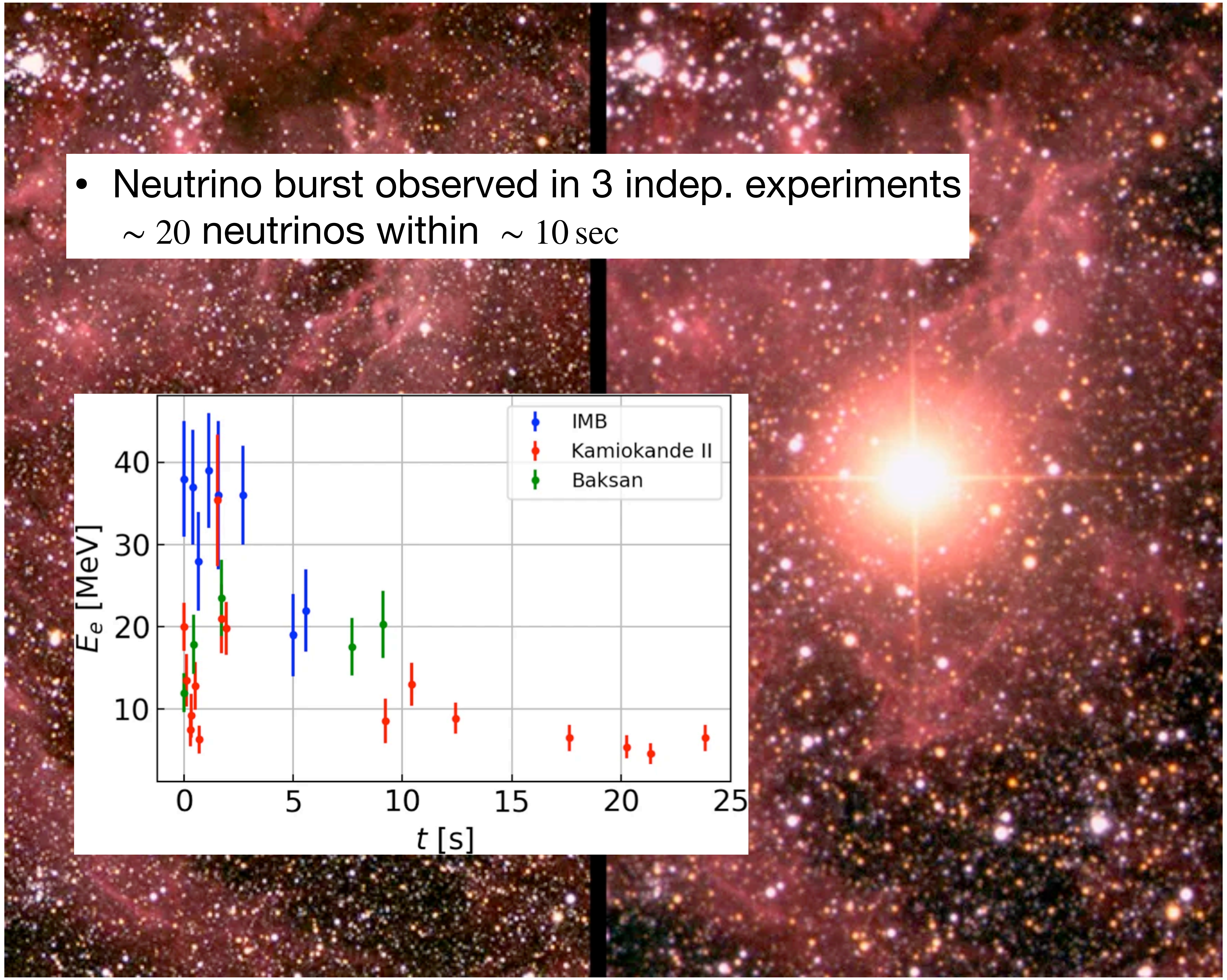
Have observed a core-collapse (type II) SN in 1987 in the Large Magellanic Cloud



Bound from SN 1987A

Have observed a core-collapse (type II) SN in 1987 in the Large Magellanic Cloud

- Neutrino burst observed in 3 indep. experiments
  ~ 20 neutrinos within $\sim 10\,\mathrm{sec}$



Bound from SN 1987A

- If new lightly coupled particle gets produced, it could shorten the duration of the neutrino signal

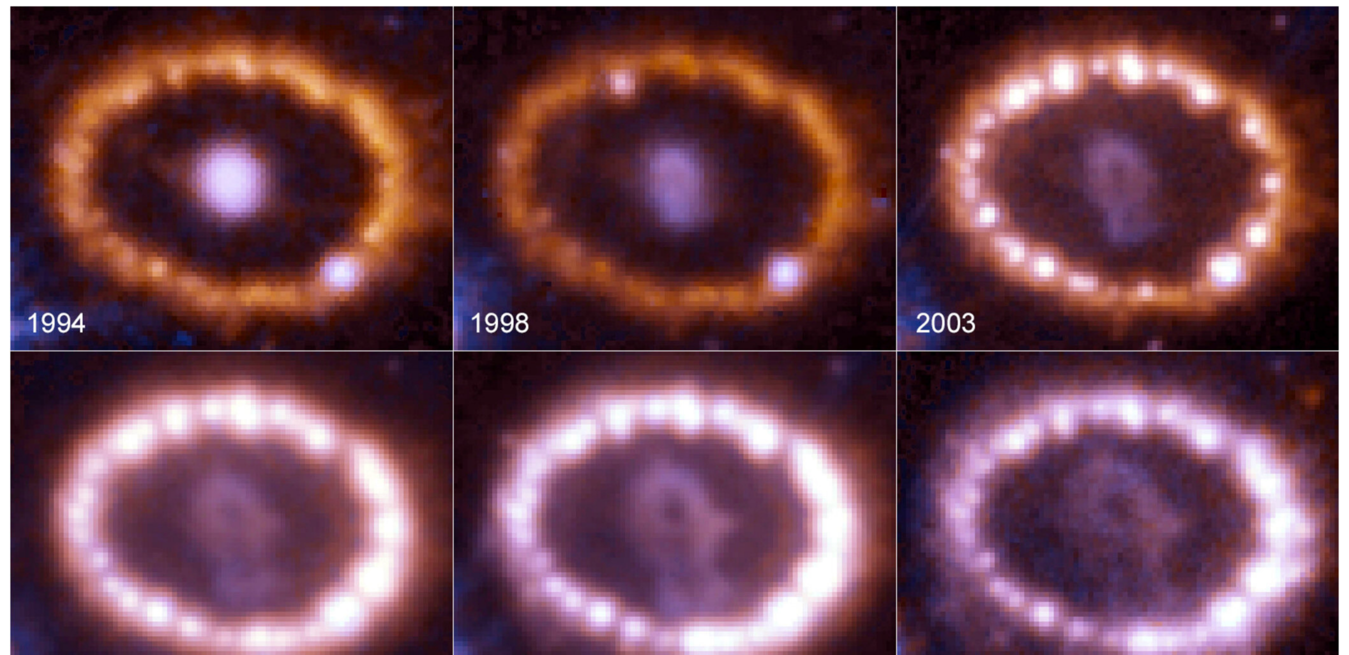
Raffelt, Lect.Notes Phys. 741 (2008) 51-71

Raffelt criterion: $L_{\rm new} \lesssim L_\nu(t=1{\rm s}) \simeq 3\times 10^{52}{\rm erg\,s}^{-1}$

- For QCD axion, this directly gives constraint on f_a

- Uncertainty in SN dynamics and axion production

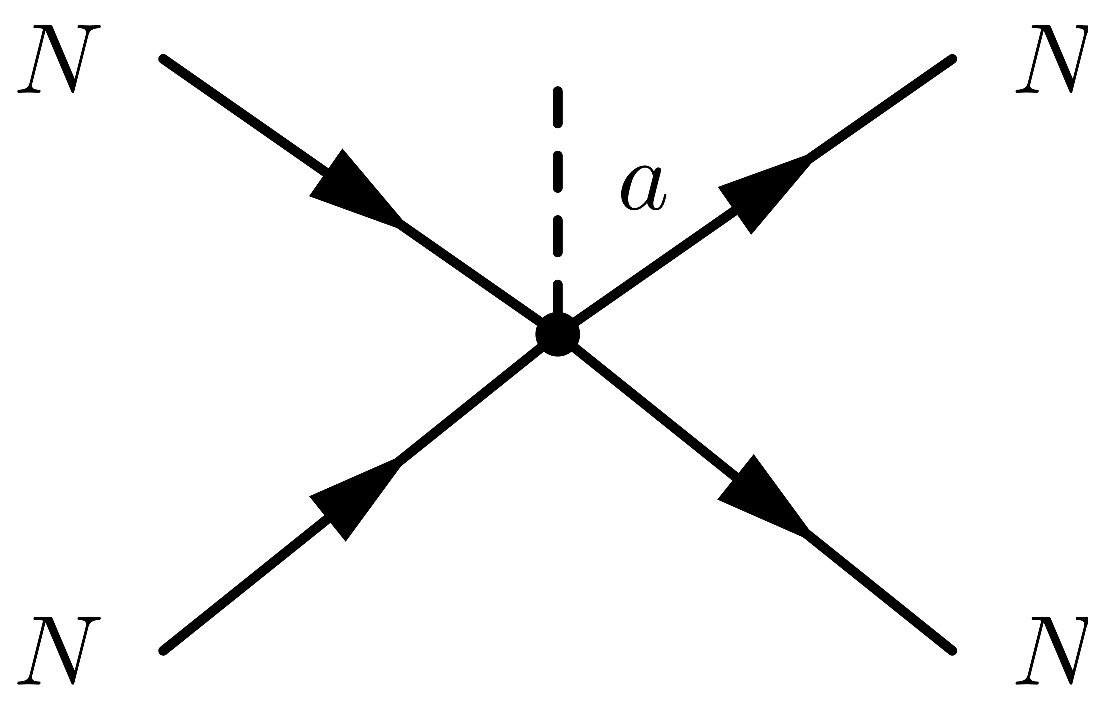
Bar, Blum, D'Amico ('19)



Axion-Nucleon Coupling: Finite density

- **Schematic example:**

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



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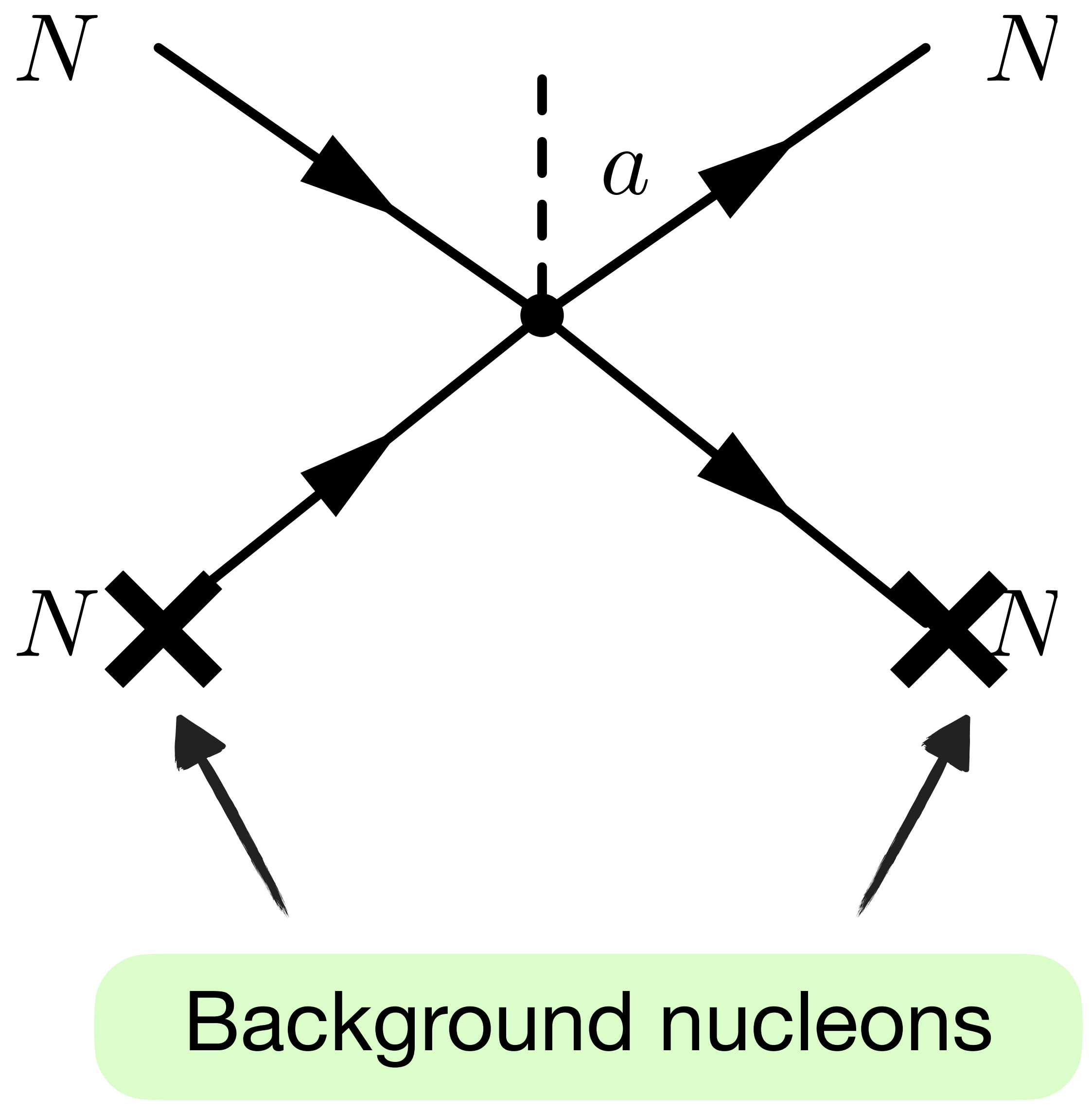

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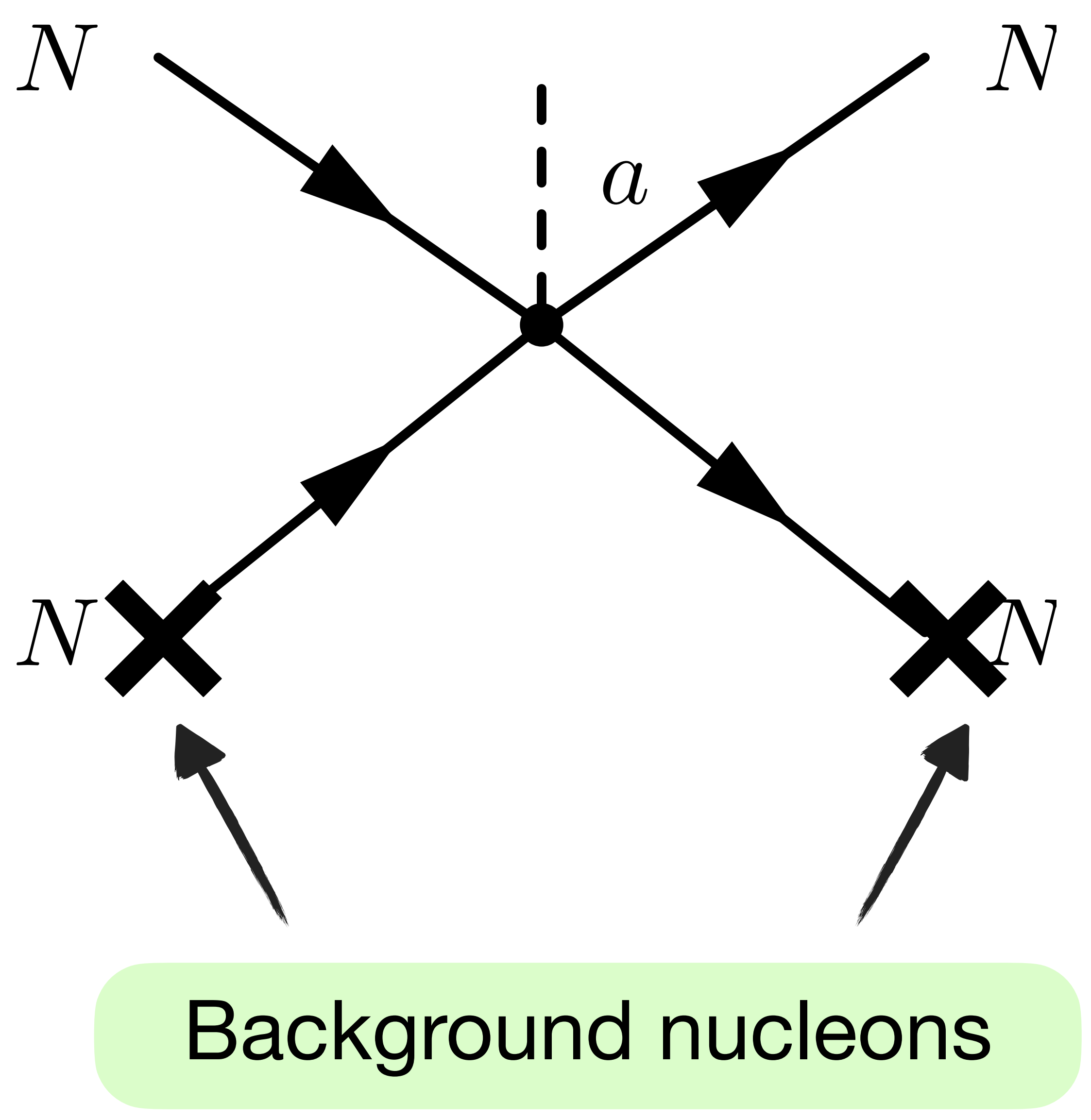
$$\langle \bar{N}N\rangle = n$$

Number density



- **Gives contribution to coupling:** $\sim \dfrac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi}$

Axion-Nucleon Coupling: Finite density

- **Schematic example:**

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

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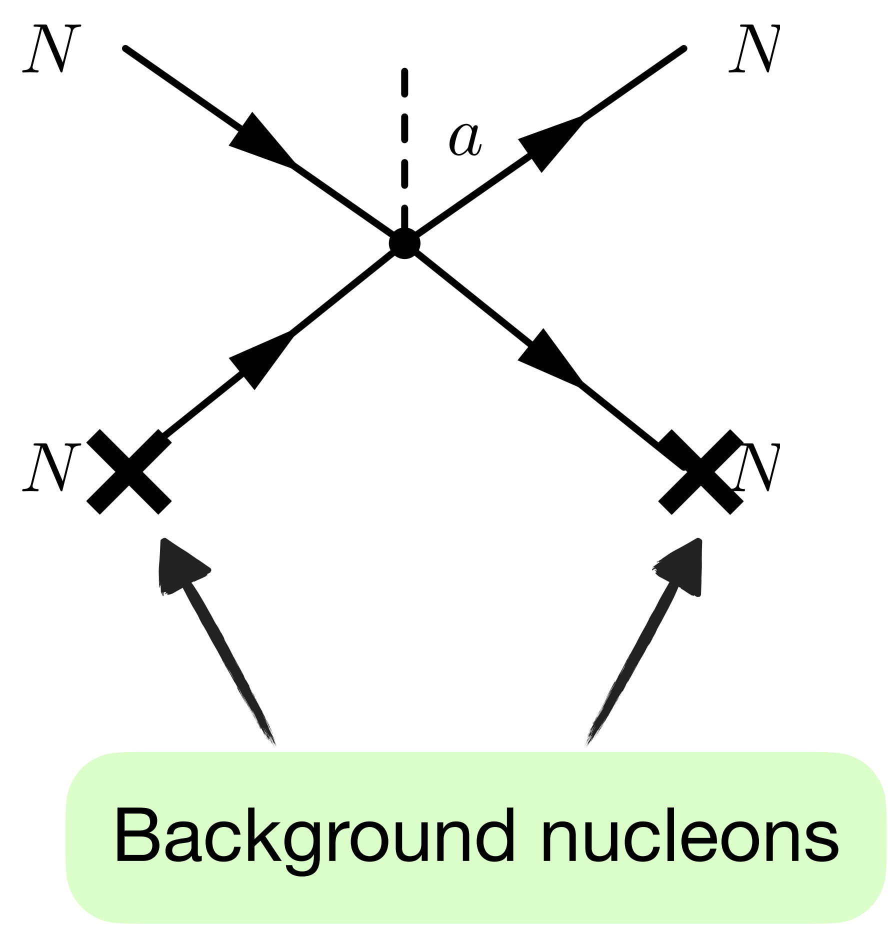
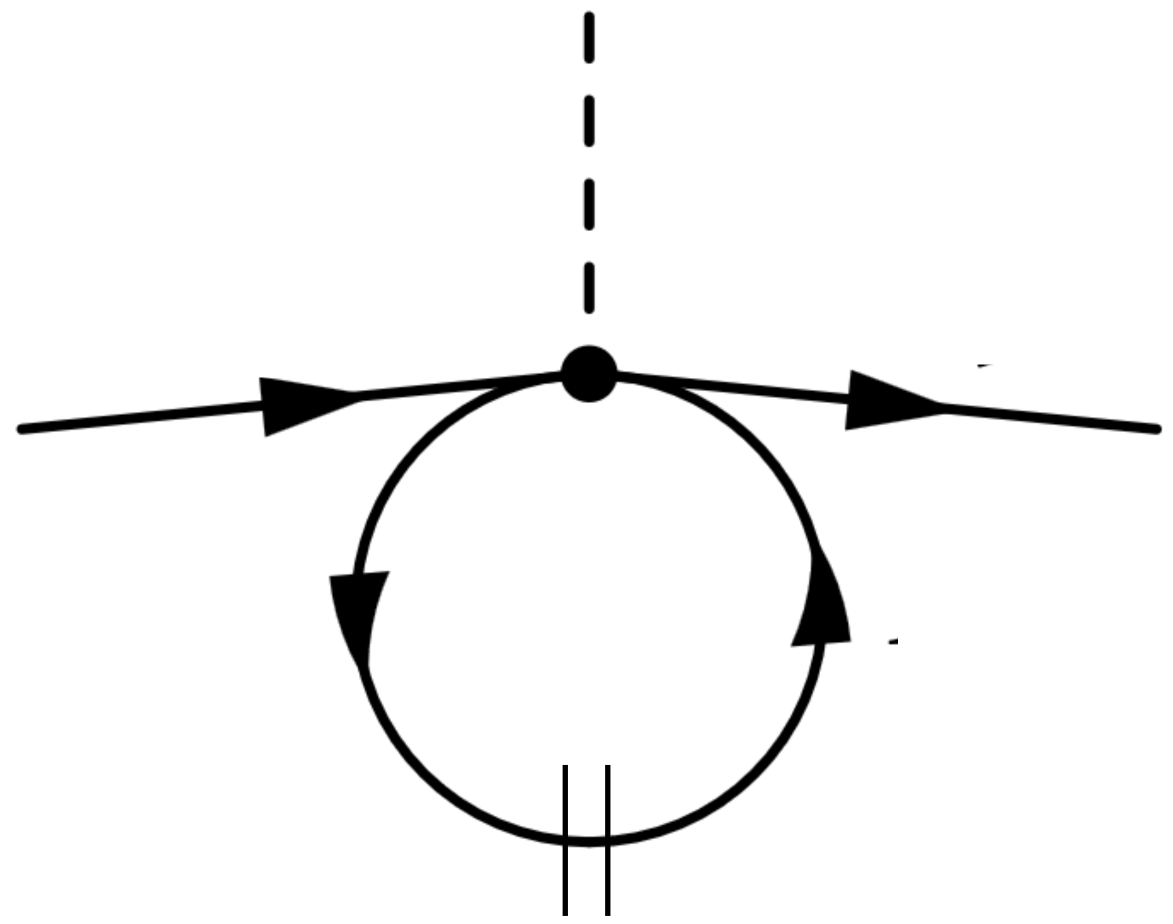


- **Systematically via QFT in Real-Time Formalism:**

Nucleon propagator at finite density

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



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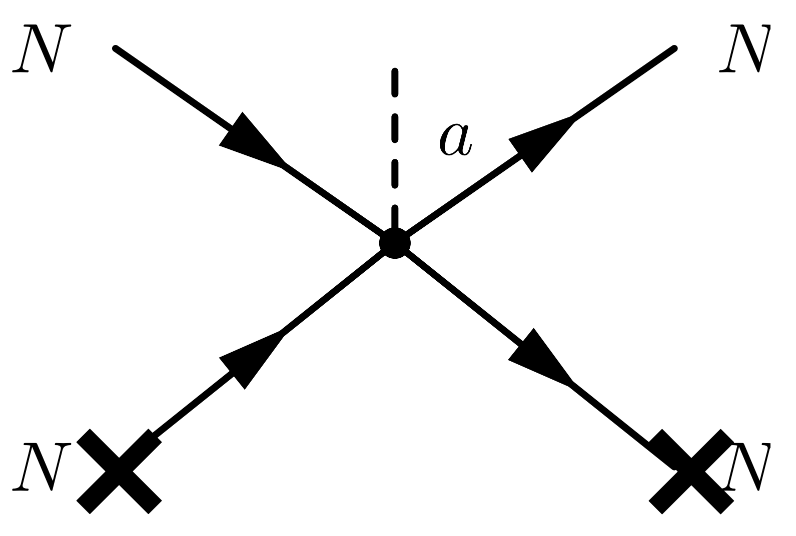


Background nucleons

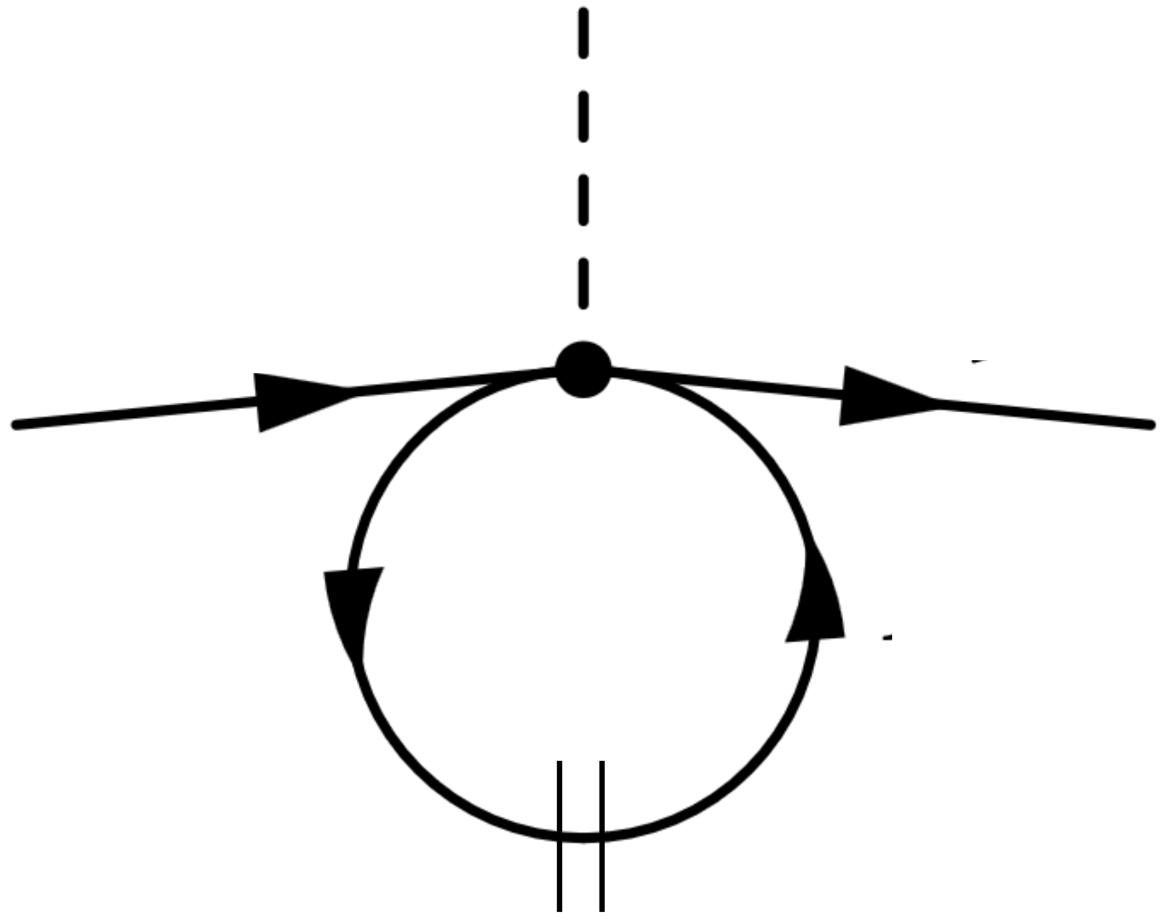
- **Systematically via QFT in Real-Time Formalism:**

Nucleon propagator at finite density

Filled 'Fermi sea'

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

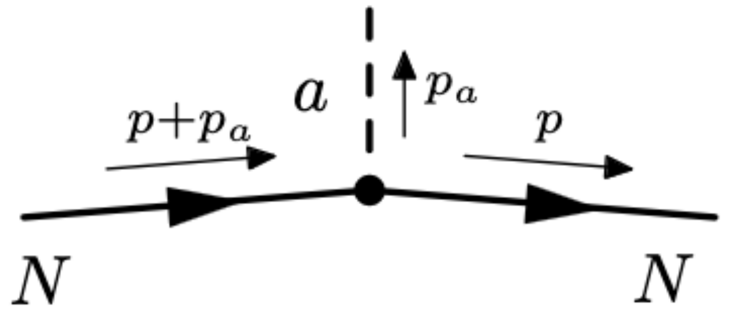
NR fermion propagator



Axion-Nucleon Coupling: Loop corrections

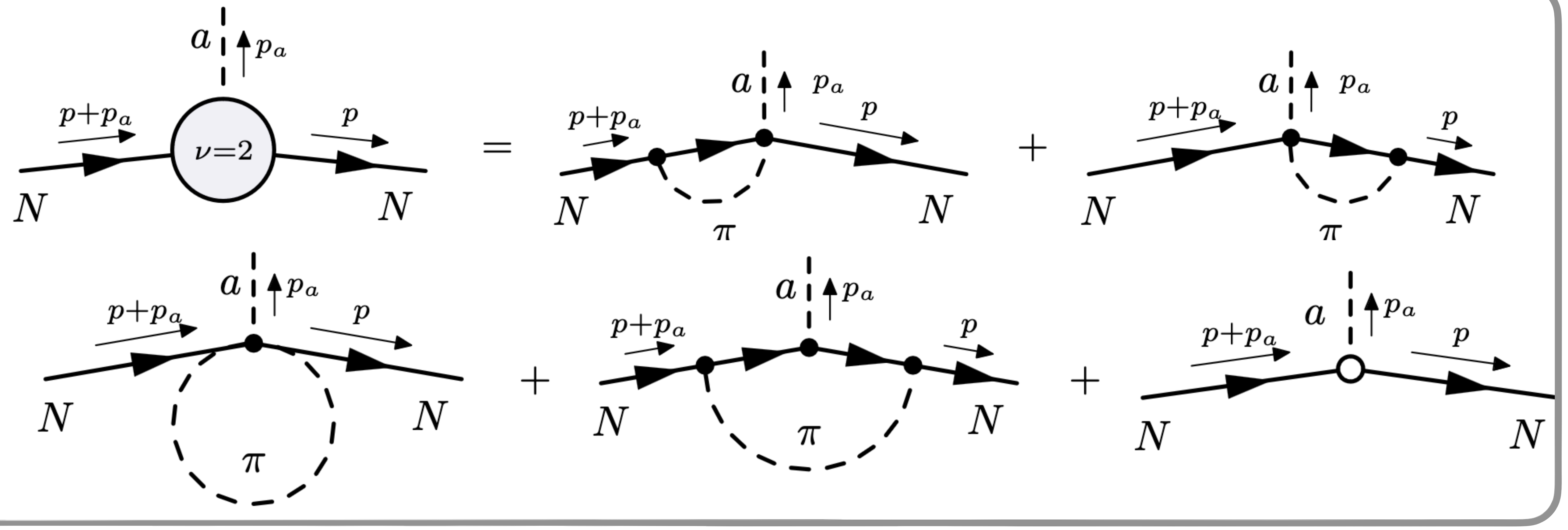
Corrections to the coupling can be calculated systematically in $\left(\frac{p}{4\pi f_\pi}\right)^\nu$

LO:



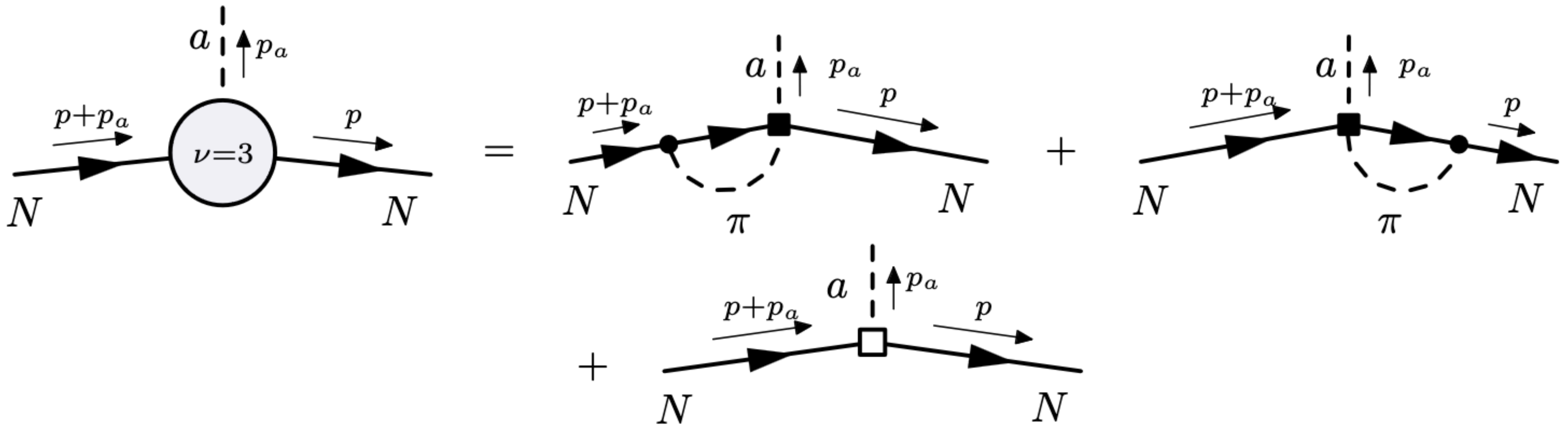
NLO:

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



NNLO:

$$\left(\frac{p}{4\pi f_\pi}\right)^2 \left(\frac{p}{\Lambda_\chi}\right)$$

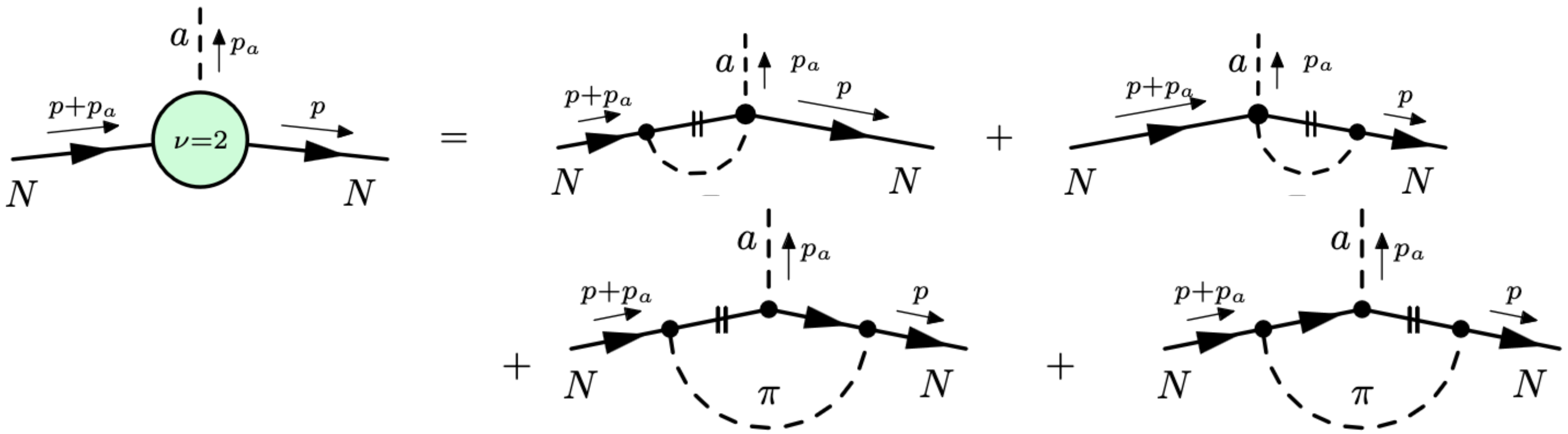


$\Lambda_\chi \sim (300 - 750)\,\mathrm{MeV}$

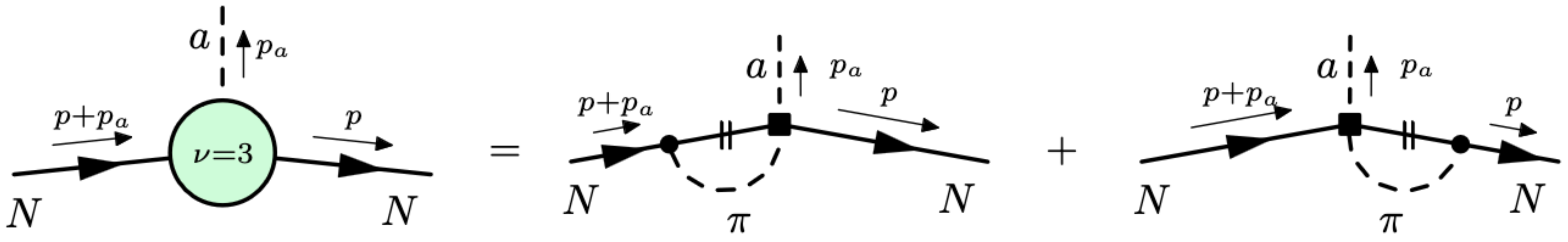
Axion-Nucleon Coupling: Finite density

Get corrections systematically $\left(\frac{p}{4\pi f_\pi}\right)^\nu \to \left(\frac{k_f}{4\pi f_\pi}\right)^\nu$

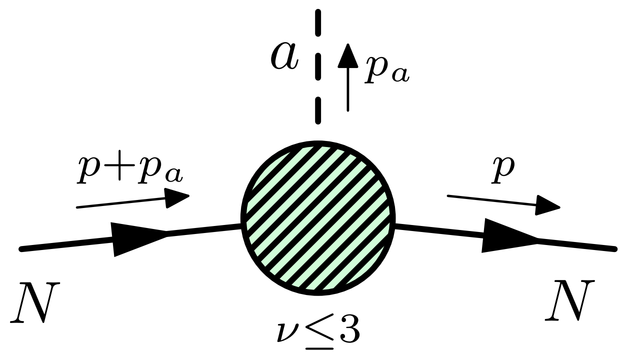
$$\left(\frac{k_f}{4\pi f_\pi}\right)^2$$



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

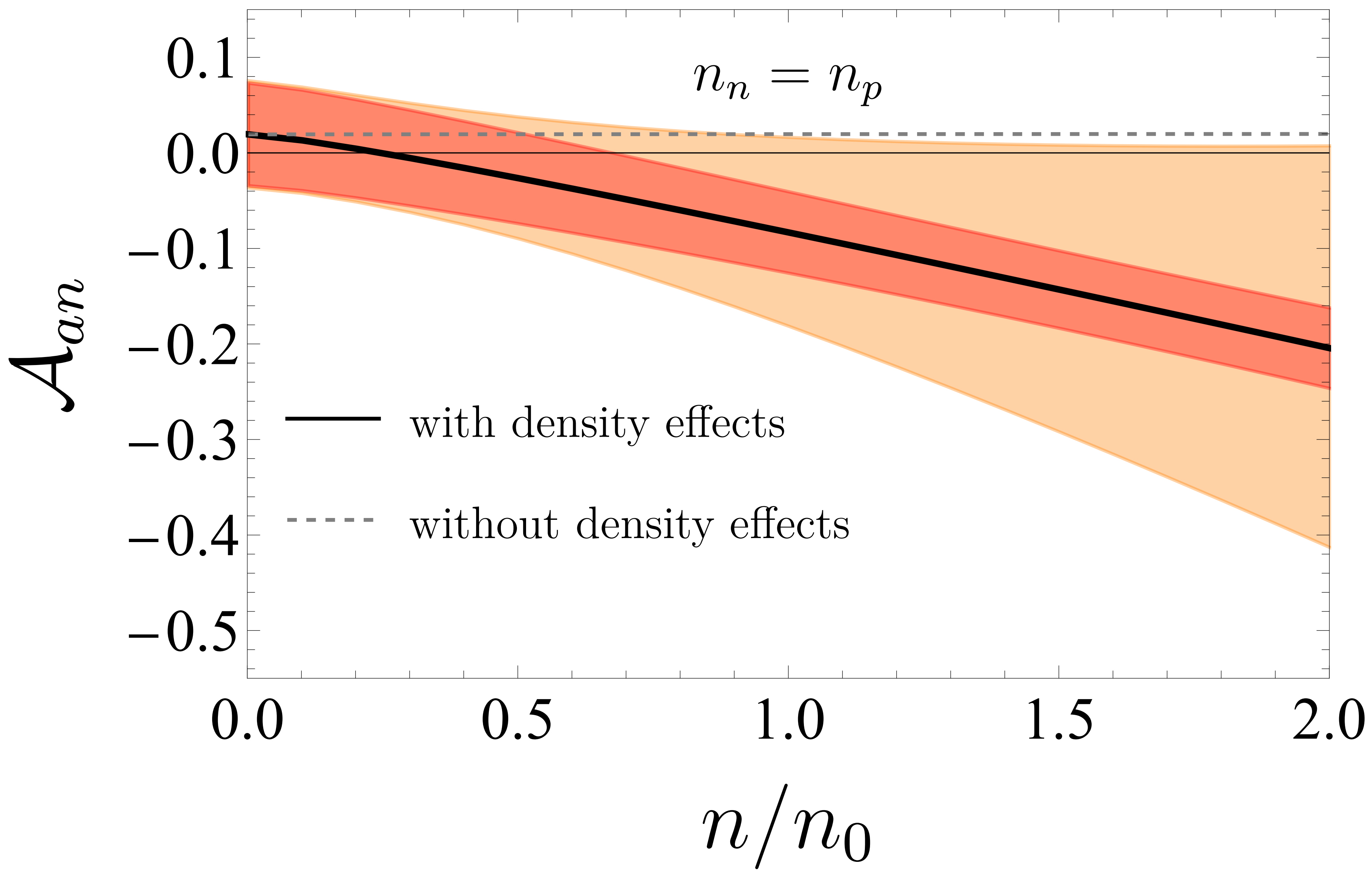


Axion-Nucleon Coupling: Finite density

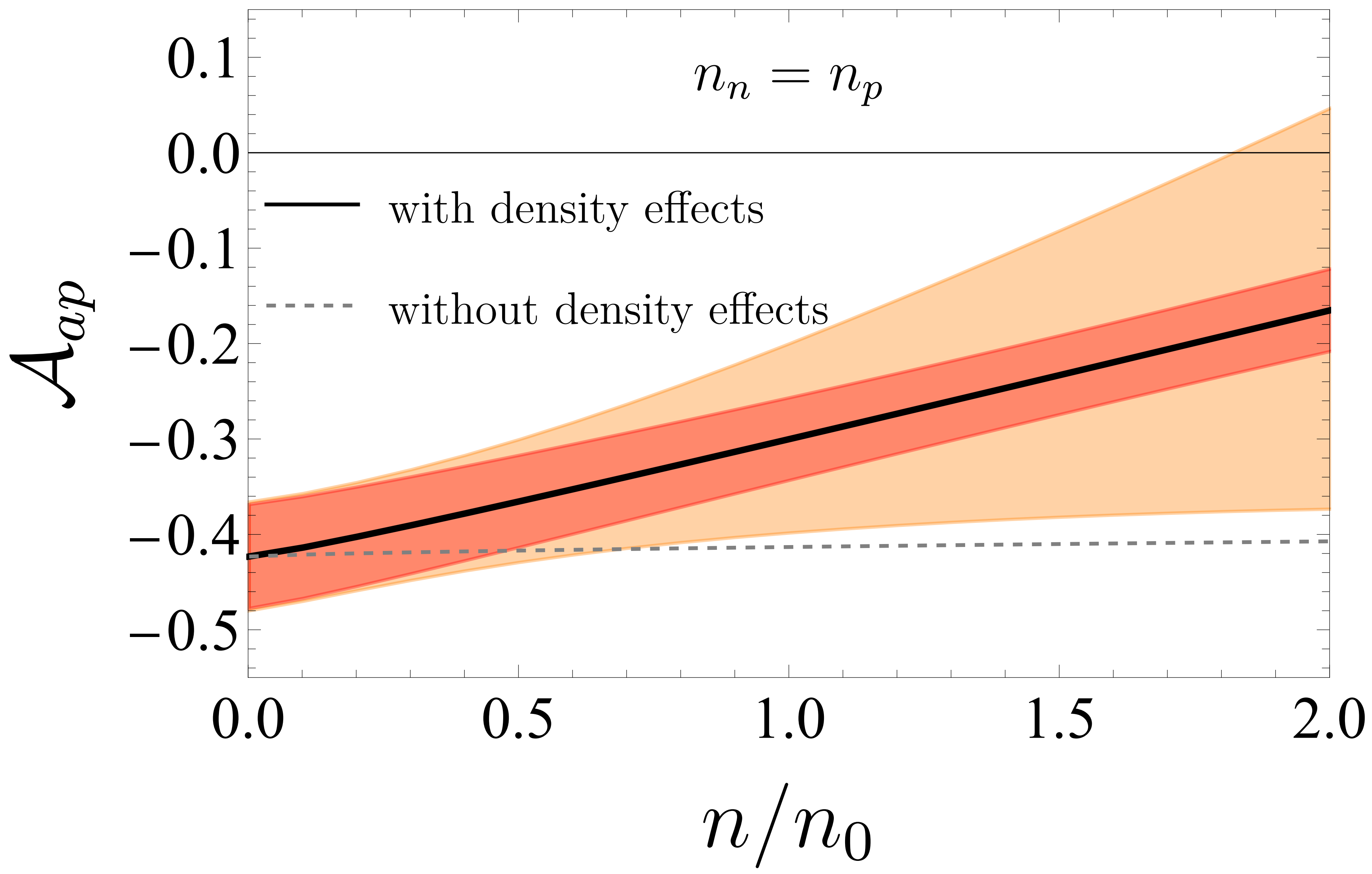


$$= -\frac{1}{f_a}\mathcal{A}^{\nu\leq 3}(k_f,p_a)\,S\cdot p_a - \frac{1}{f_a}\mathcal{B}^{\nu\leq 3}(k_f,p_a)\,S\cdot p$$

Neutron



Proton

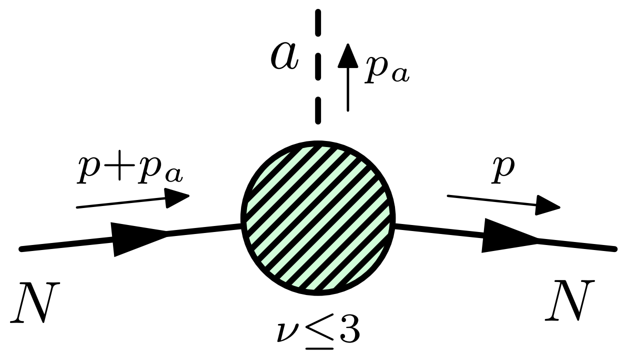


At finite density $\mathcal{A}_{an}^{\text{KSVZ}}(n_0) = -0.1(4)(9)$

vs. vacuum $\mathcal{A}_{an}^{\text{KSVZ}}(0) = 0.02(5)$

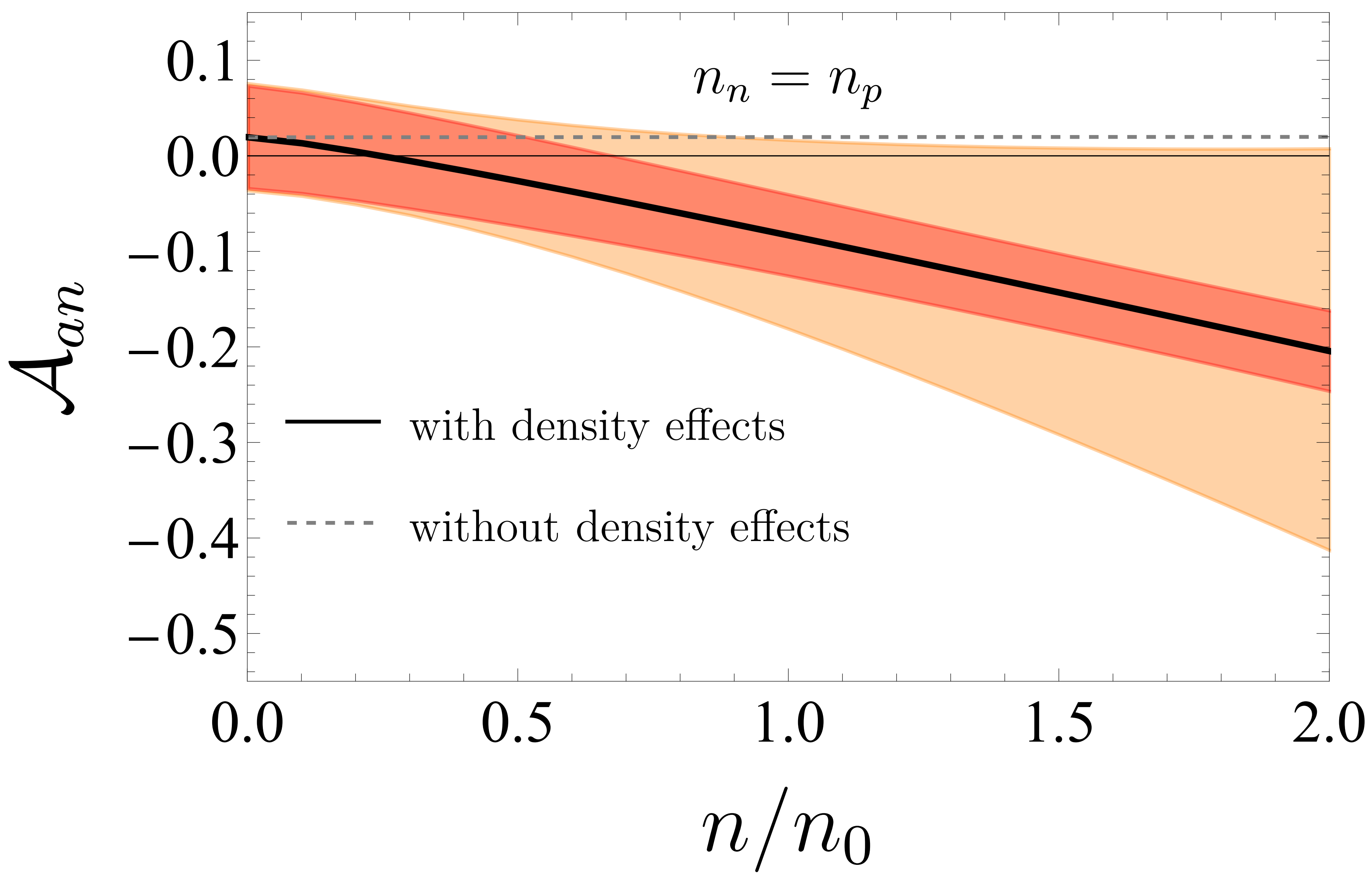
Stadlbauer, Springmann, Stelzl, Weiler '24

Axion-Nucleon Coupling: Finite density

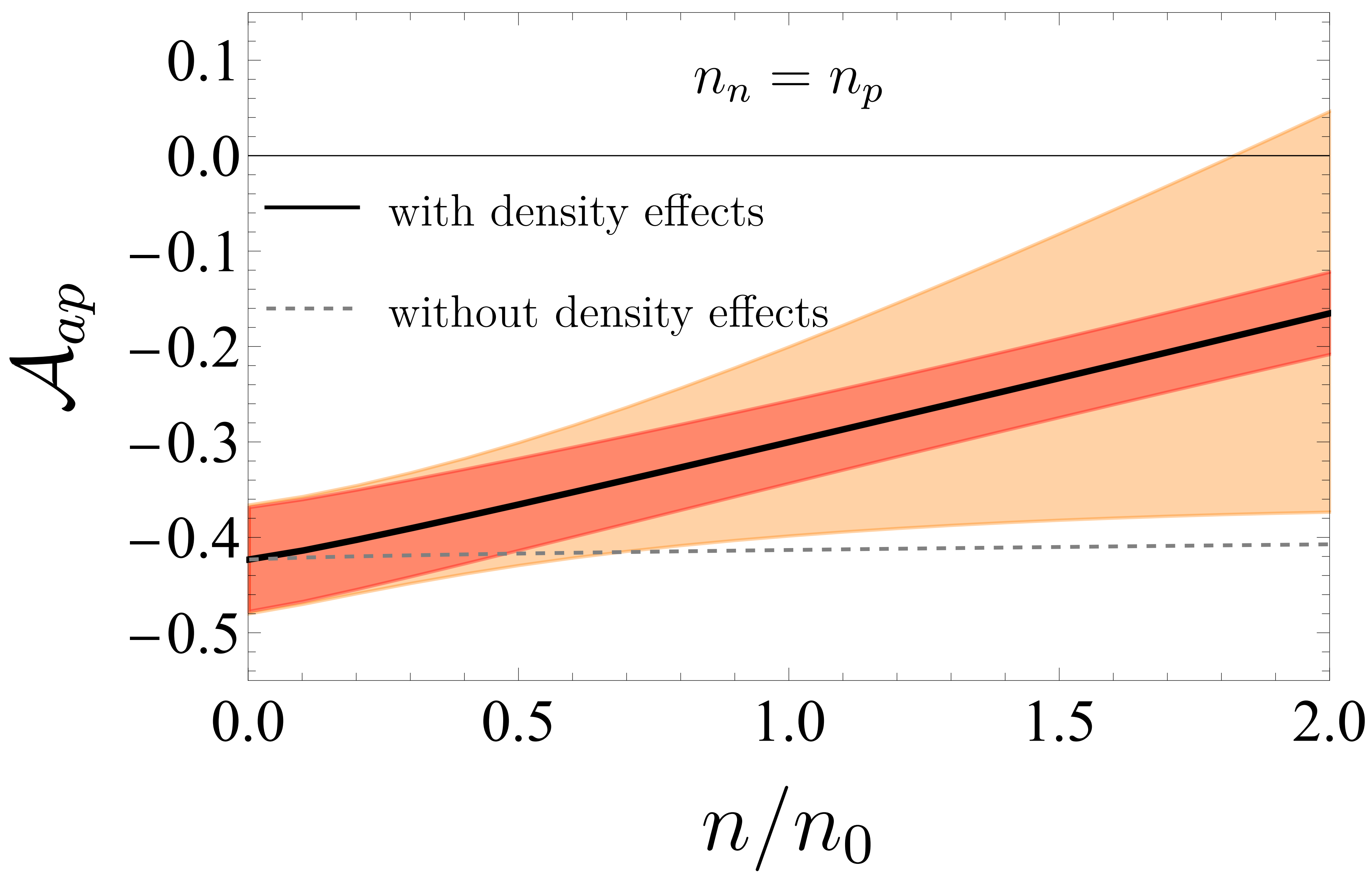


$$= -\frac{1}{f_a}\mathcal{A}^{\nu\leq 3}(k_f, p_a)\, S\cdot p_a - \frac{1}{f_a}\mathcal{B}^{\nu\leq 3}(k_f, p_a)\, S\cdot p$$

Neutron



Proton



At finite density $\mathcal{A}_{an}^{\mathrm{KSVZ}}(n_0) = -0.1(4)(9)$

vs. vacuum $\mathcal{A}_{an}^{\mathrm{KSVZ}}(0) = 0.02(5)$

Accidental cancellation is lifted, 5x larger!

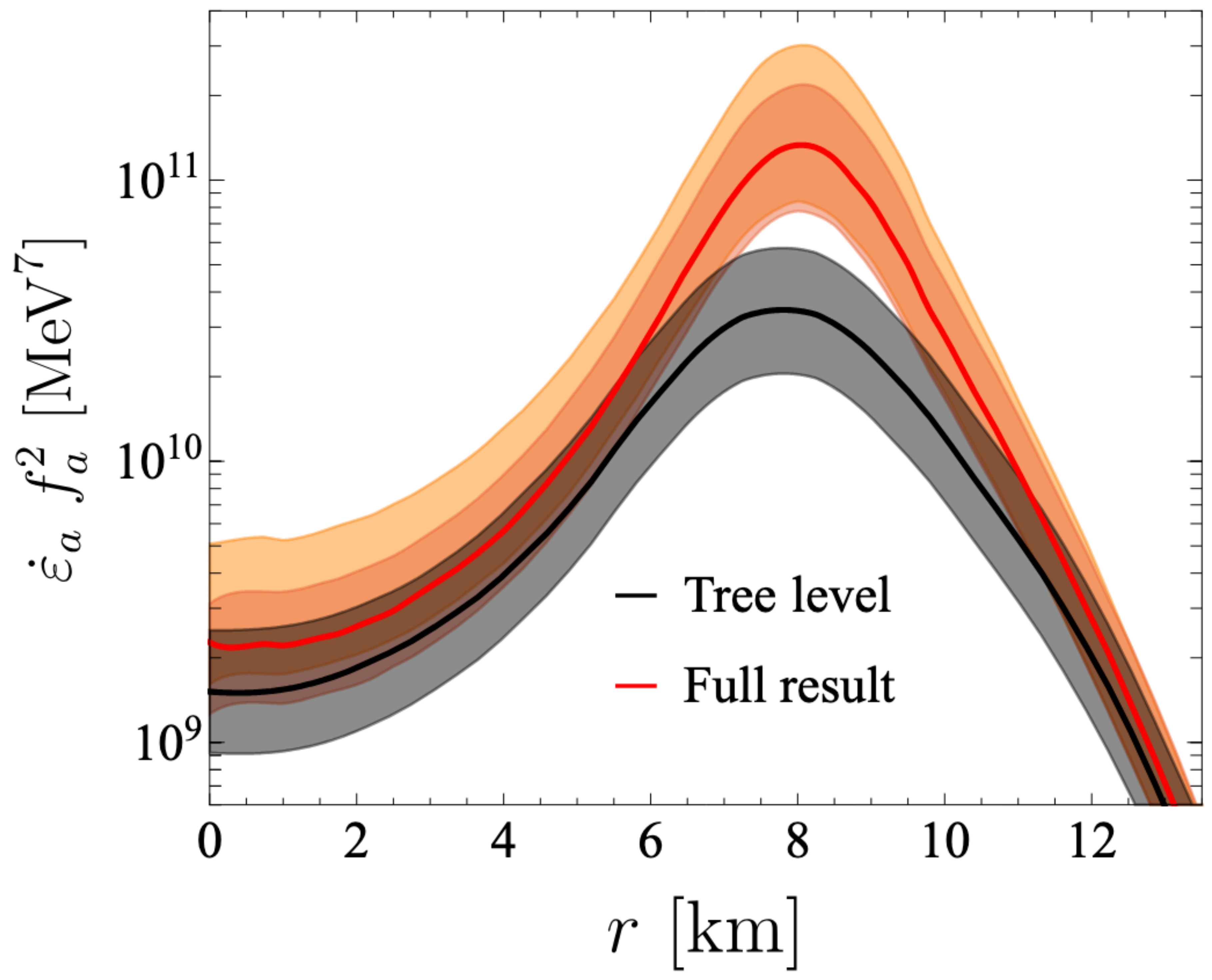
Stadlbauer, Springmann, Stelzl, Weiler ‘24

Stadlbauer, Springmann, Stelzl, Weiler ‘24

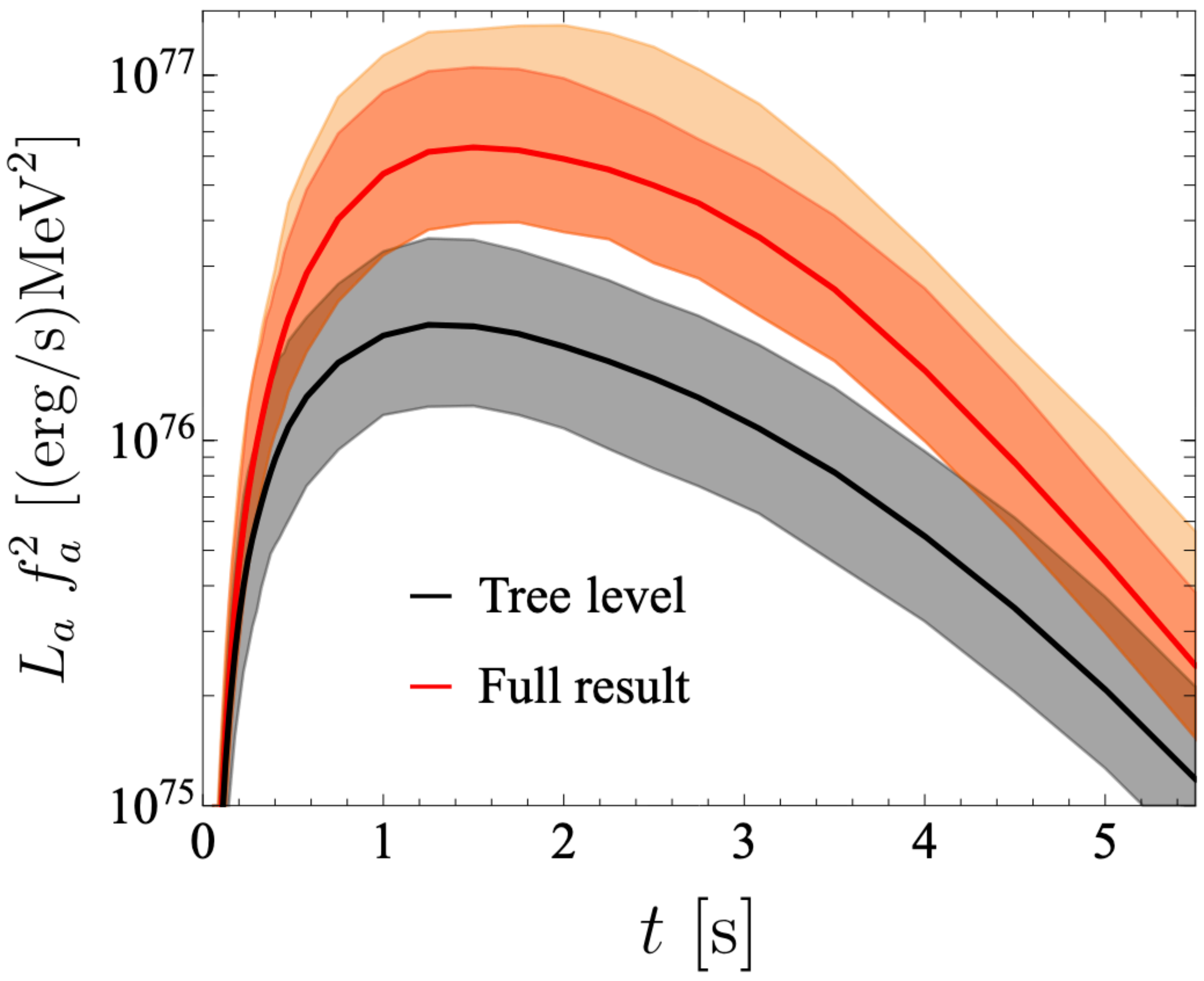
Supernova bound revisited

KSVZ axion

Emissivity



Luminosity



Stadlbauer, Springmann, Stelzl, Weiler '24

Supernova bound revisited

KSVZ axion

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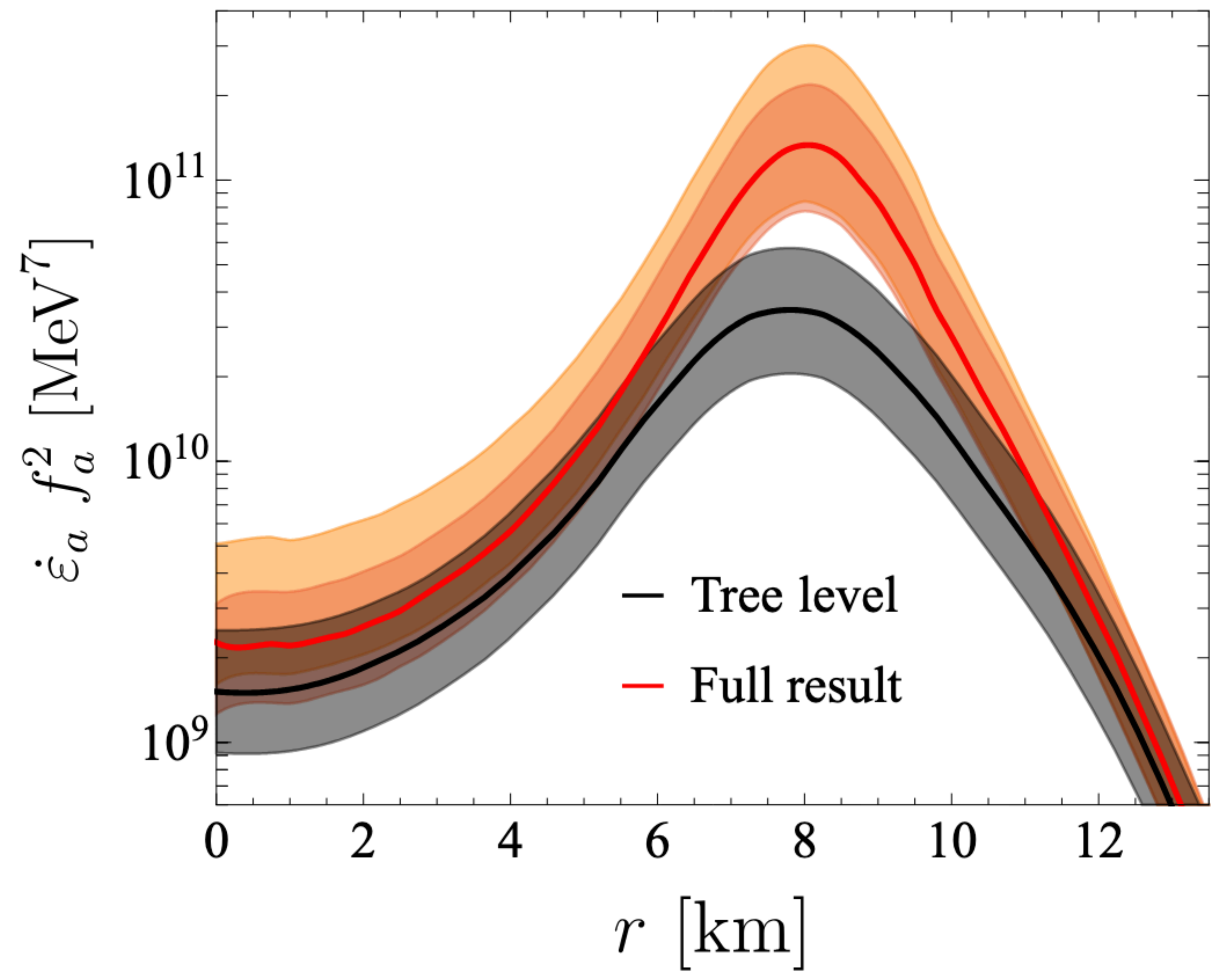
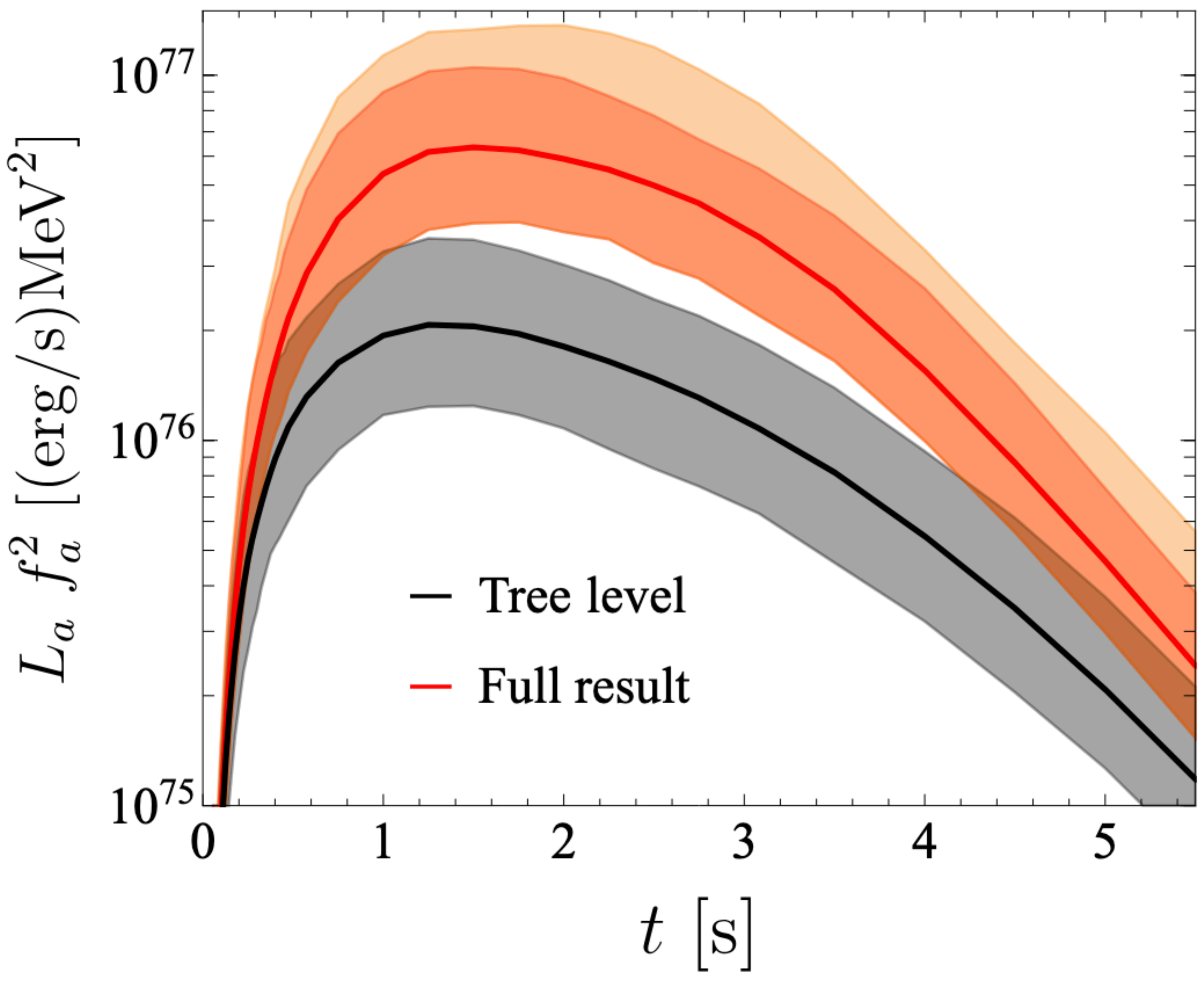


Luminosity



Tree level: $f_a \gtrsim 6.1^{+1.7}_{-1.4} \times 10^8\,\mathrm{GeV}, \quad m_a \lesssim 9.8^{+3.0}_{-2.2}\,\mathrm{meV}.$

Vertex corrections: $f_a \gtrsim 1.0^{+0.5}_{-0.2} \times 10^9\,\mathrm{GeV}, \quad m_a \lesssim 5.9^{+1.8}_{-2.0}\,\mathrm{meV}.$

Where we need nuclear input

- We used HBχPT + finite-density corrections → big effect already.
- At higher density the expansion breaks down. Opportunity for nuclear QCD experts (theory & experiment)
- Need: reliable response for SN, NS cooling, mergers.

Conclusions

- The Big Question: Is the Standard Model completion natural? What is it?
- The **Third** Frontier: Beyond Energy and Intensity, we must explore Density.
- White Dwarfs and Neutron Stars are not just graveyards; they are controlled experiments for finite-density QFT.
- Density can trigger phase transitions and destabilize the vacuum.
- The Future: Precision astrometry + Gravitational Waves = A new era for Nuclear-Particle physics.
- We need your help to understand QCD at extreme densities to sharpen the sensitivies

work in collaboration with:

Reuven Balkin (TUM->UC Santa Cruz),
Javi Serra (TUM->IFT Madrid),
Stefan Stelzl (TUM->EPFL),
Konstantin Springmann (TUM->Weizmann/DESY)
Kai Bartnick (Oxford->TUM),
Michael Stadlbauer (TUM->EPFL)