Tales from the Stellar Graveyard: How Dead Stars Reveal New Physics

WPC Theoretical Physics Colloquium 2025, DESY, Hamburg

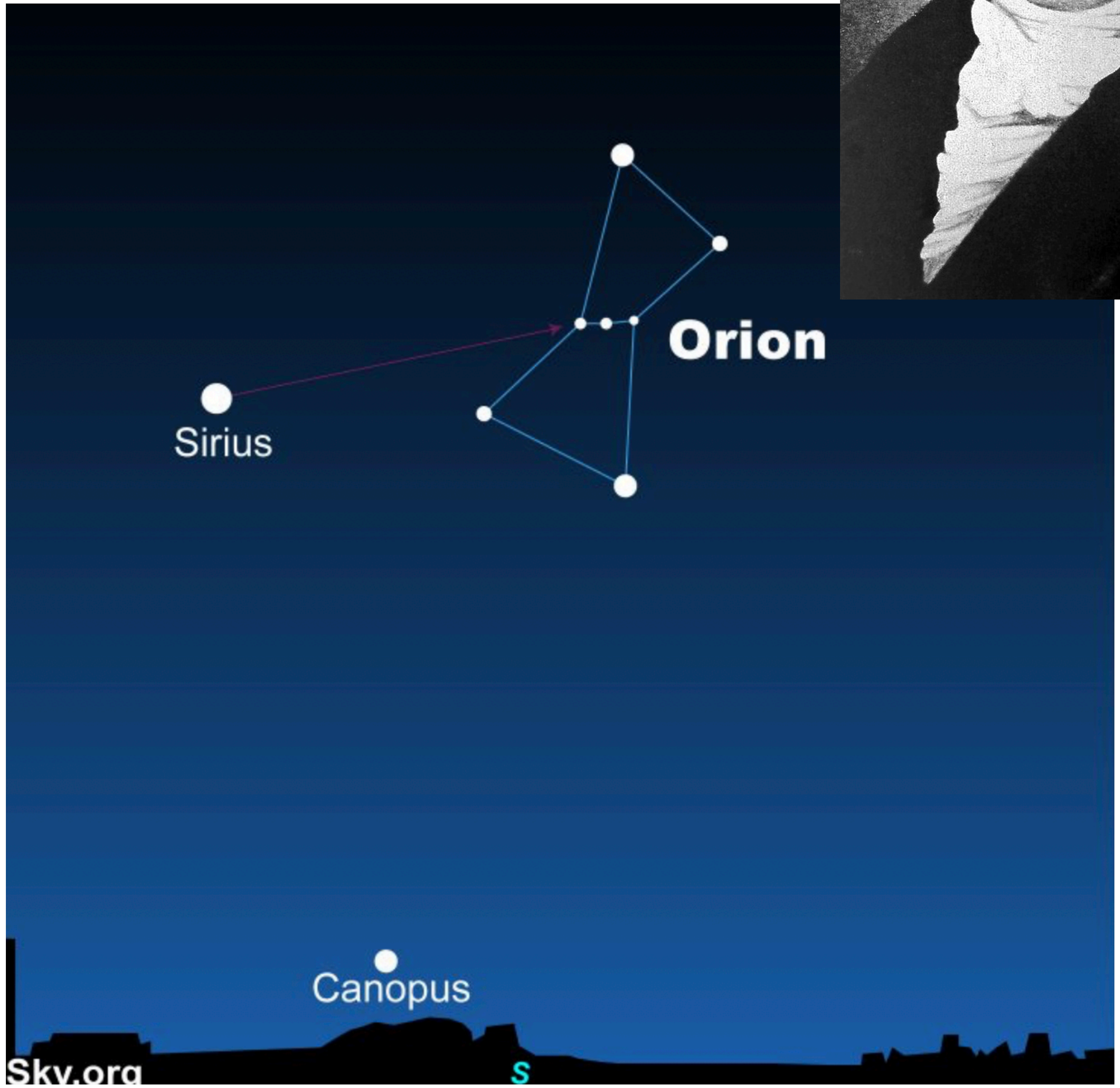
TUM

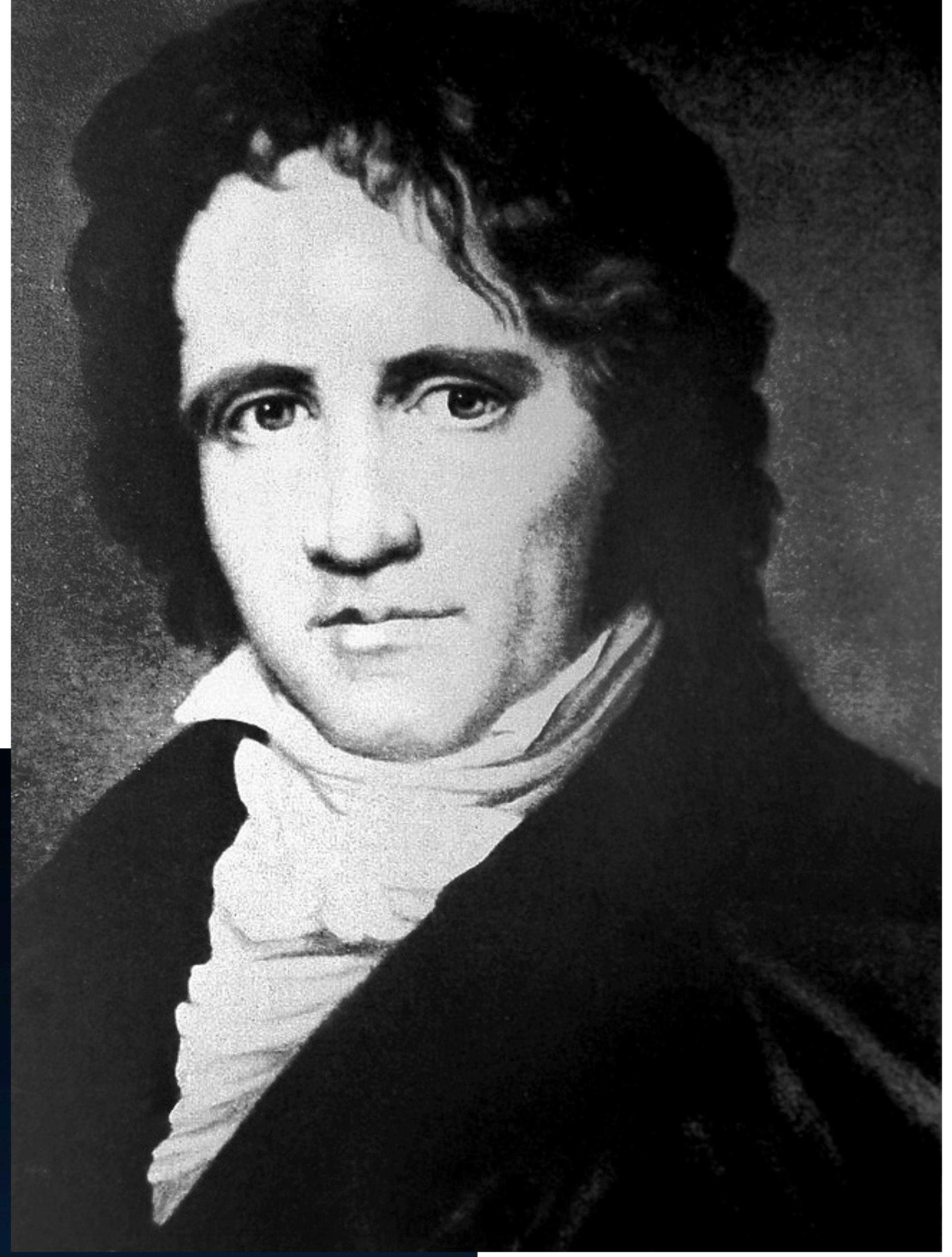
SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

Andreas Weiler (TUM), 14/5/25

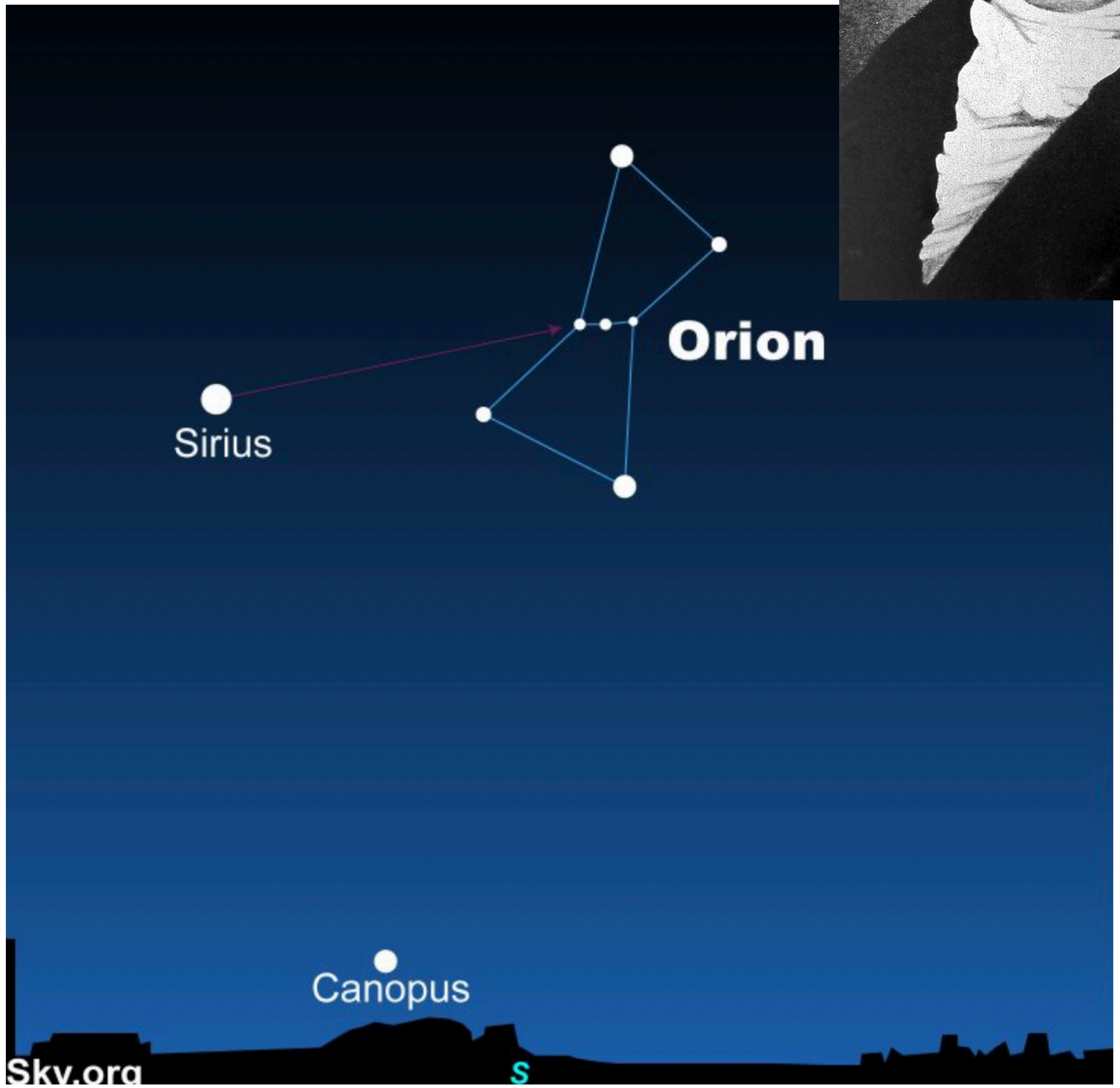
Bessel 1844

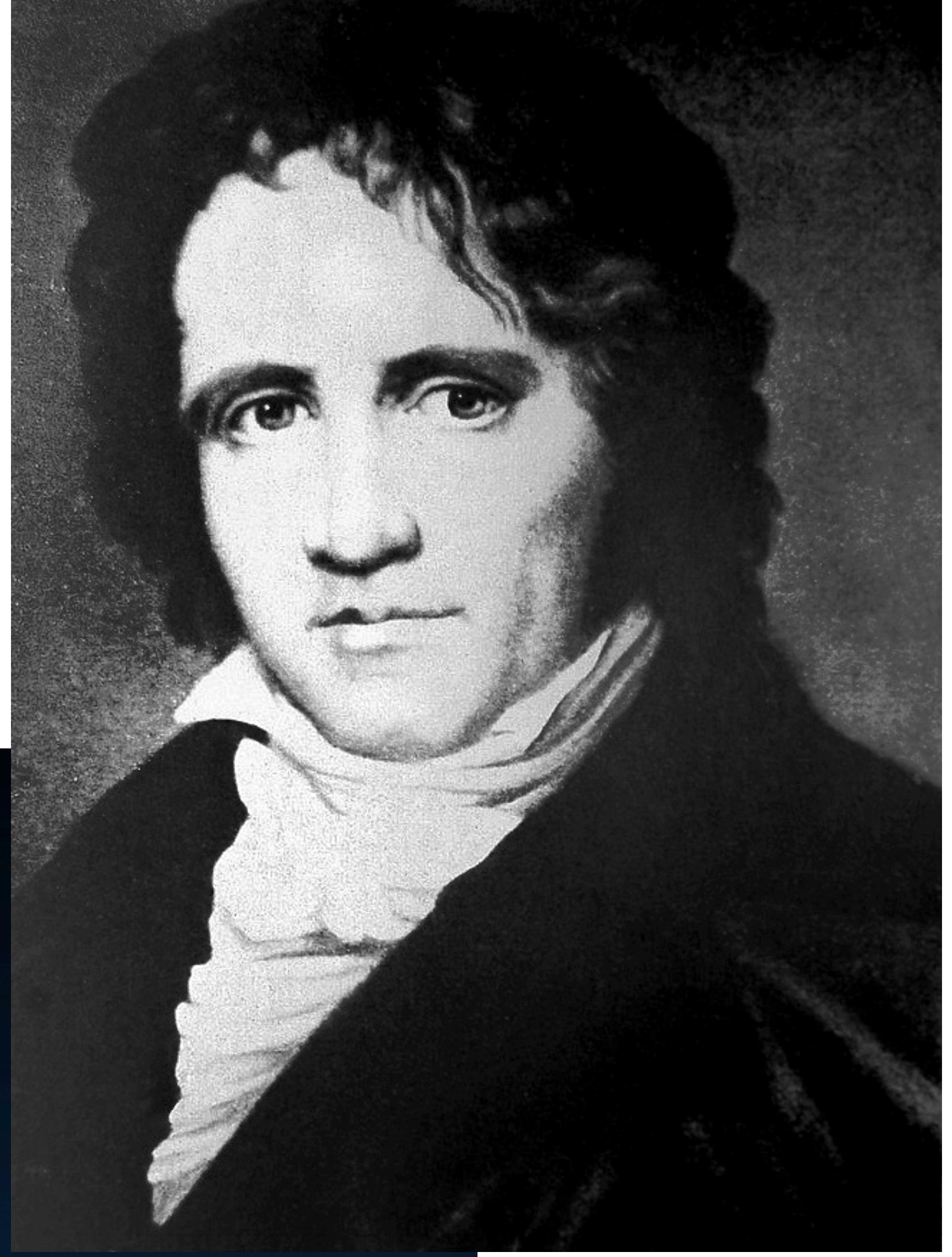


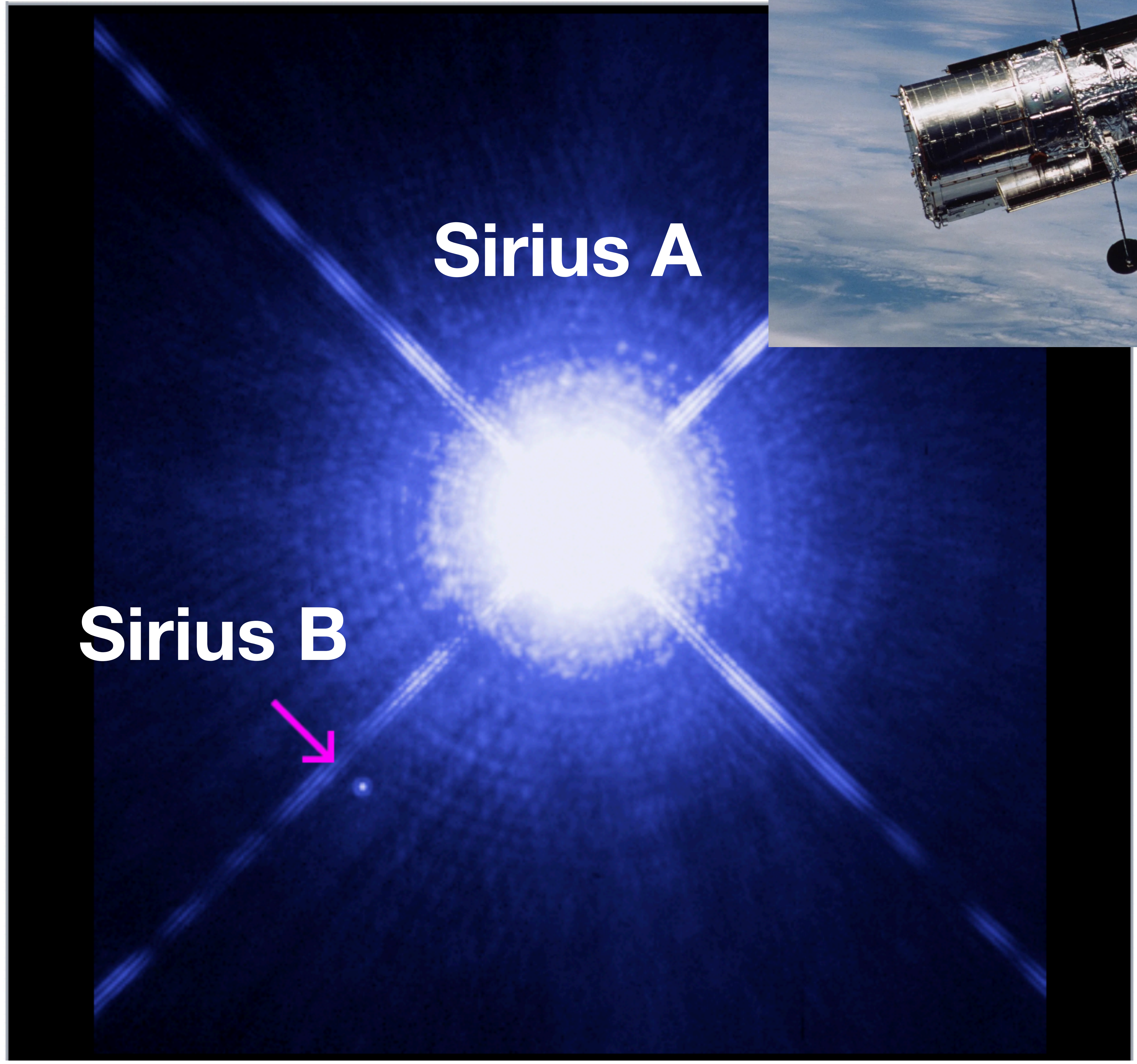


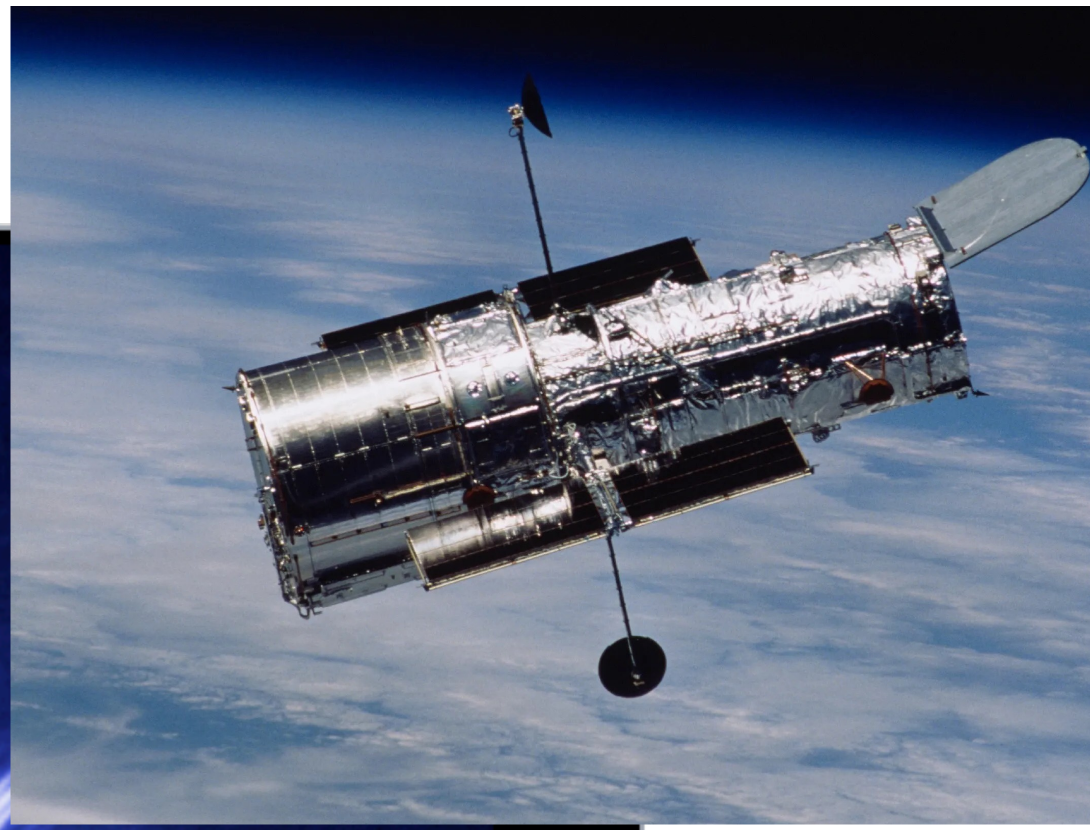
Bessel 1844

Hubble 2019









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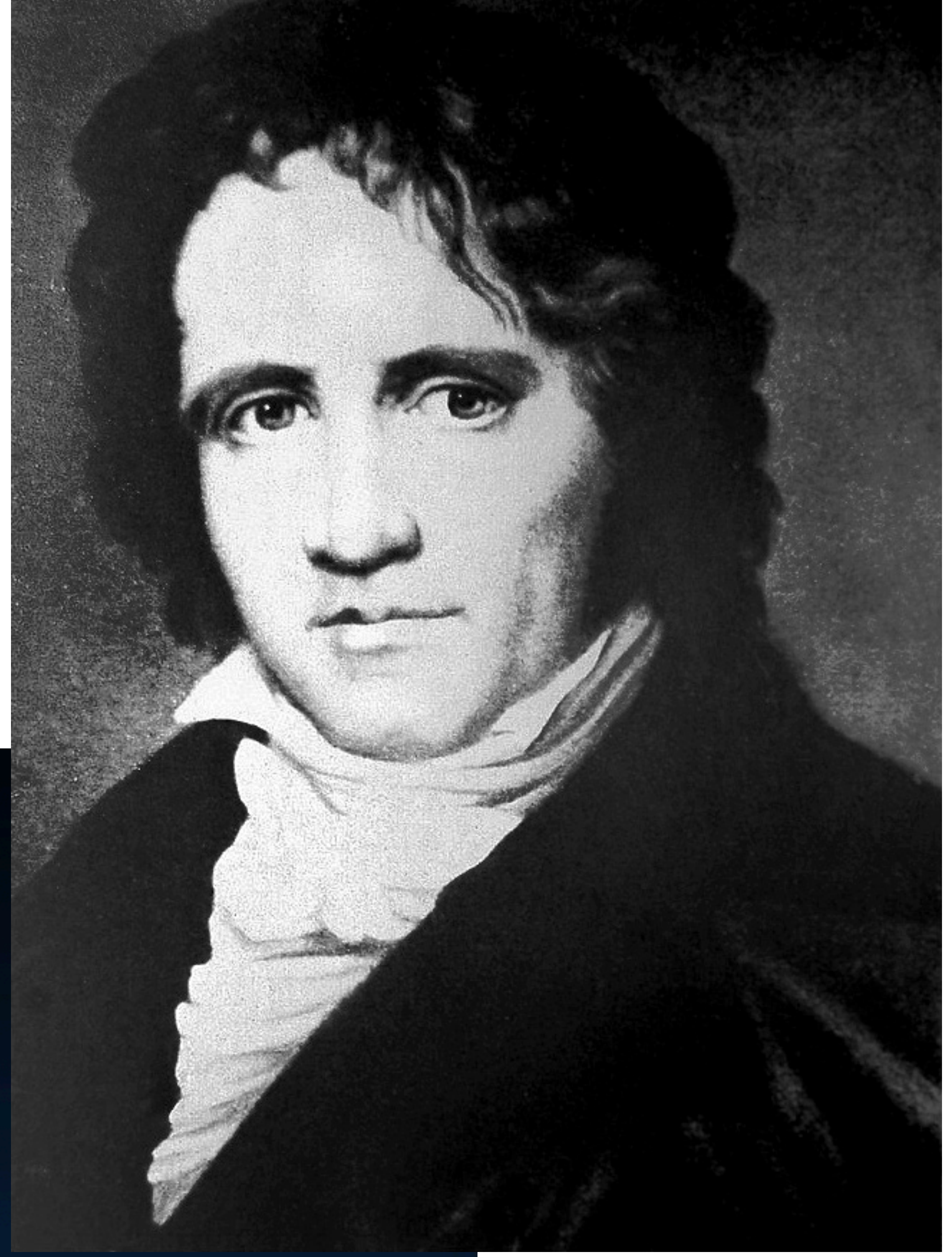

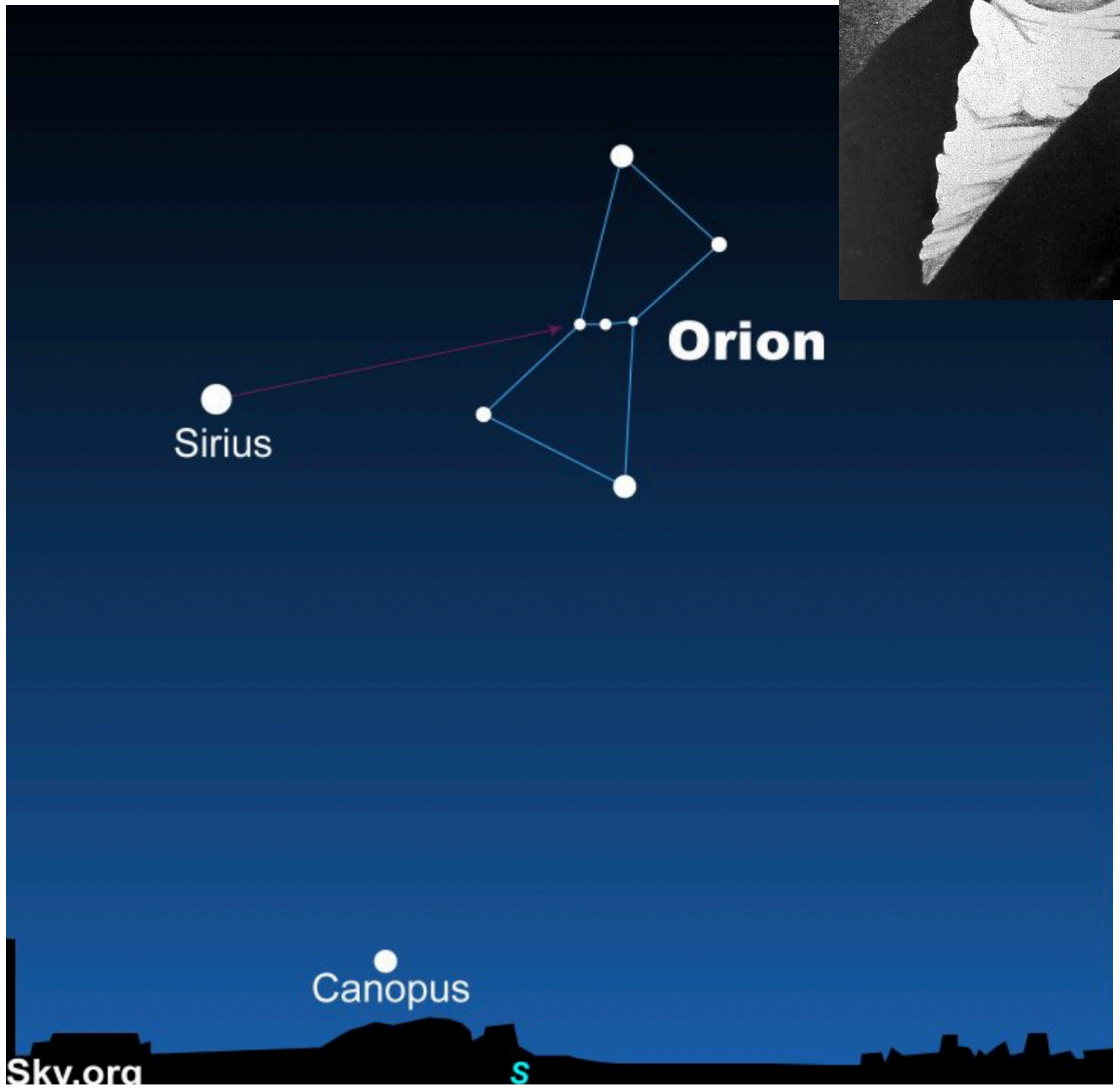

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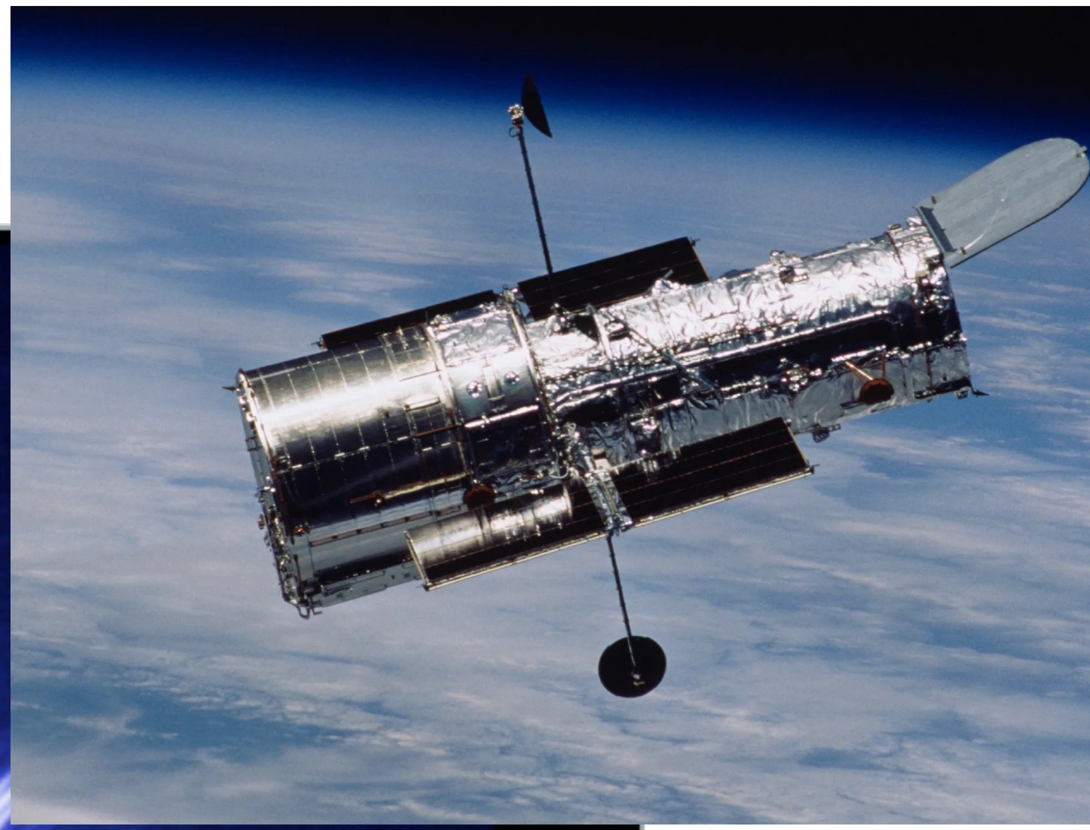
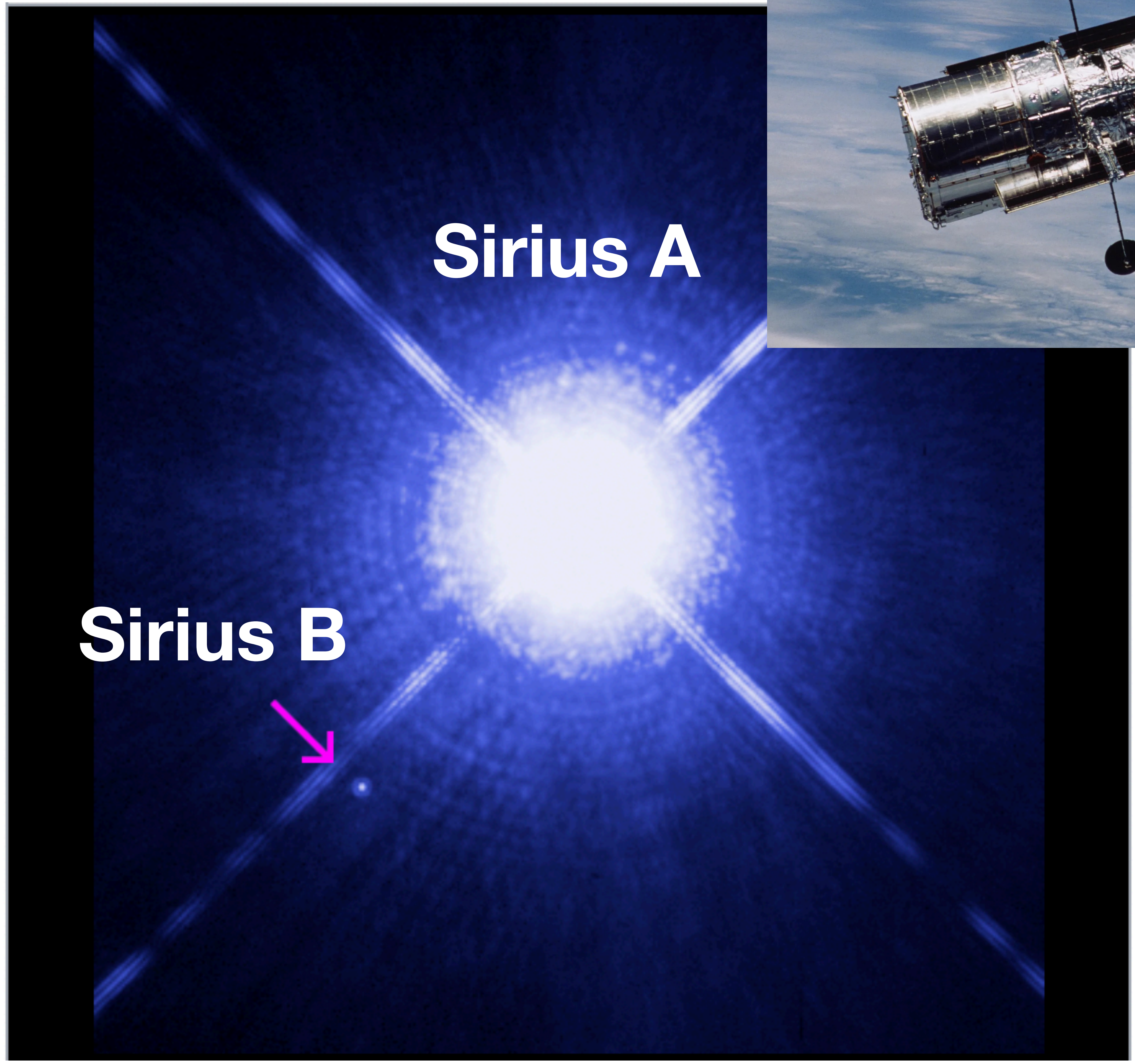
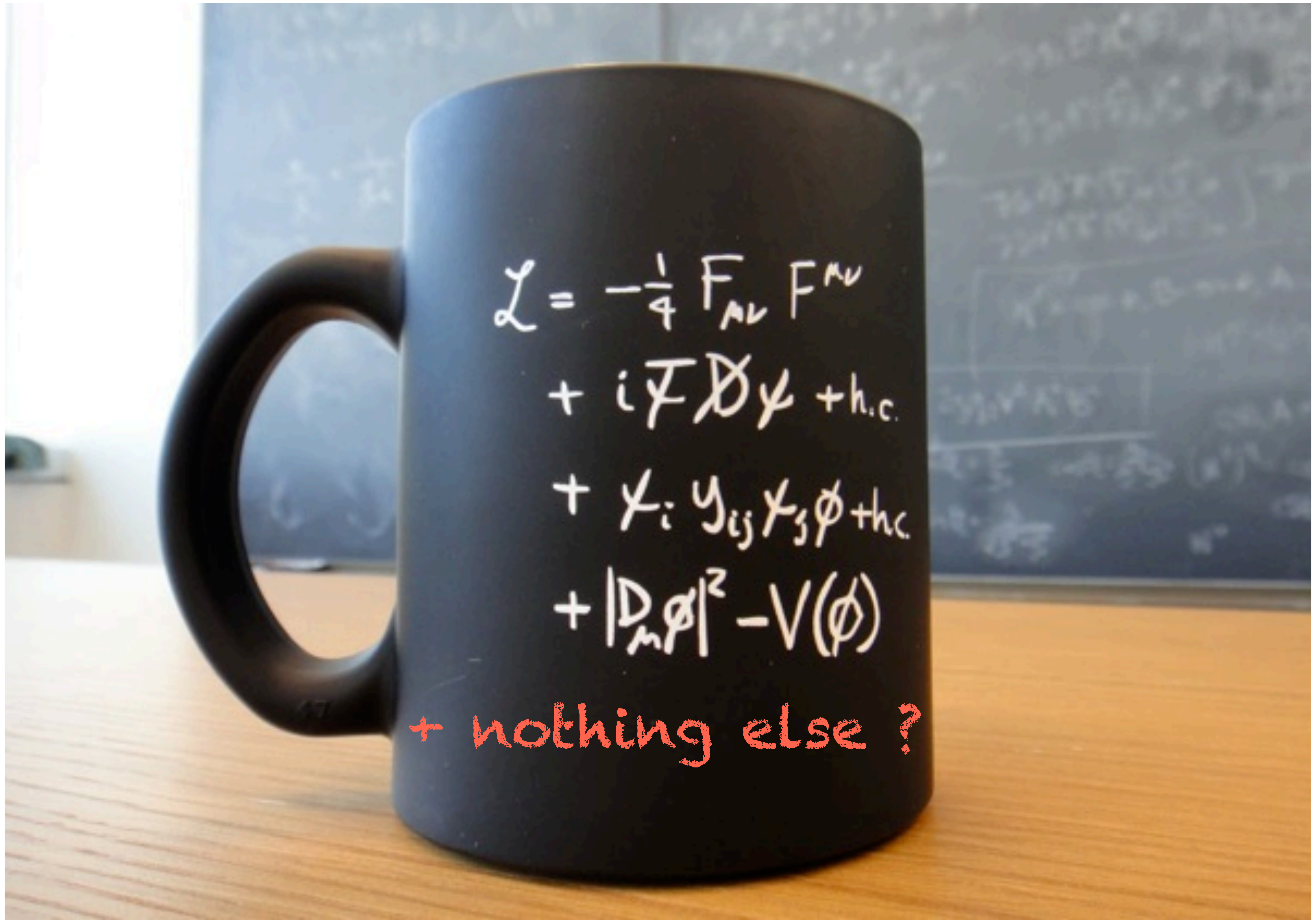




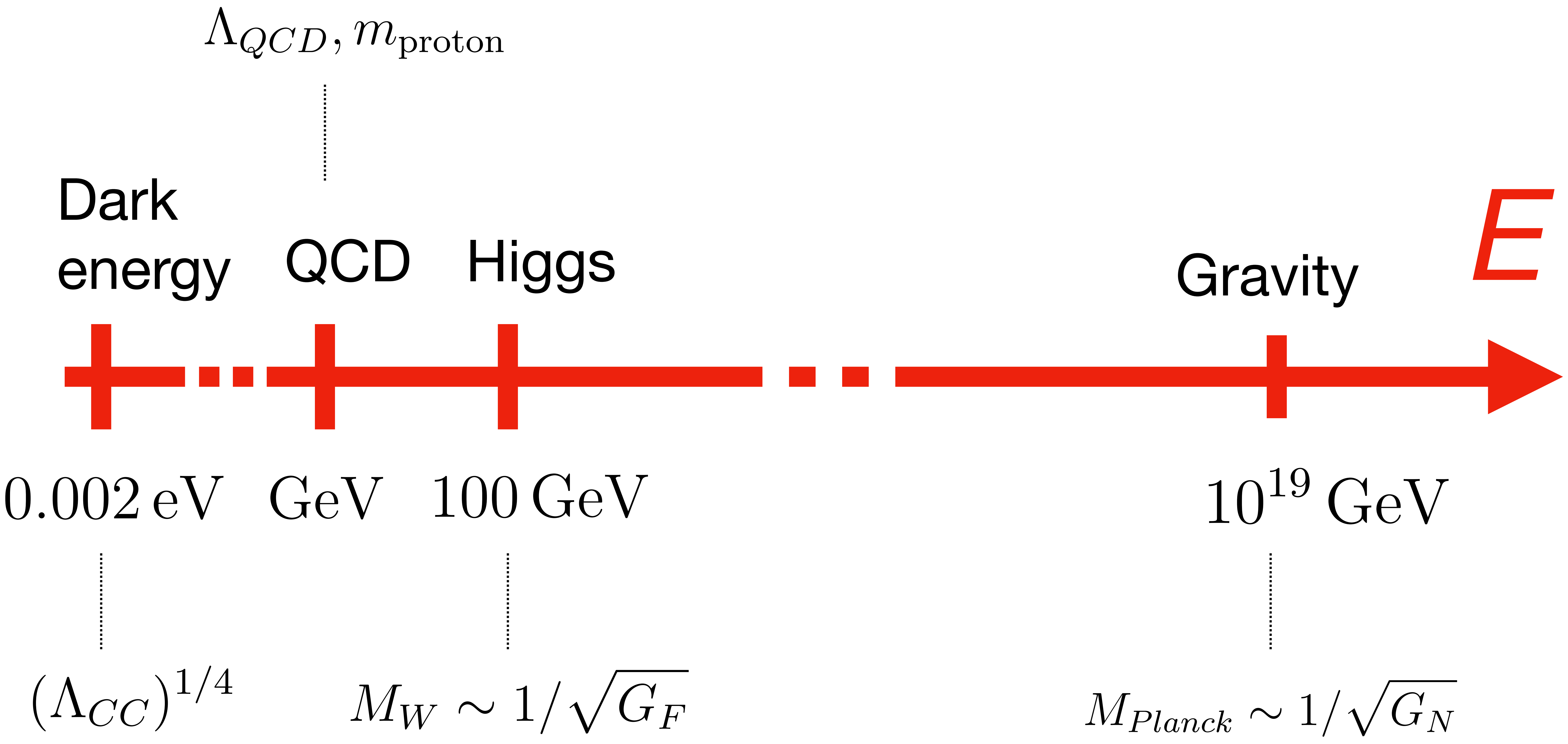
Sirius B is a white dwarf

The Standard Model of particle physics

where is the new physics?



Fundamental scales of Standard Model of particle physics



Large numbers are not the issue!

One ratio is natural; the other is not.

$$\frac{G_F \hbar^2}{G_N c^2} = 1.738\,59(15) \times 10^{33}$$

vs.

$$\frac{m_{\text{proton}}^{-2}}{G_N} \hbar c = 1.693 \times 10^{38}$$

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$$\frac{G_F \hbar^2}{G_N c^2} = 1.738\,59(15) \times 10^{33} \qquad \approx \frac{M_{\text{Planck}}^2}{M_{\text{W}}^2}$$

vs.

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Unnatural scale is the "*mass scale of a relevant operator not protected by a symmetry.*"

Two relevant operators in the SM

Higgs mass

$$\int d^4x \, \frac{\mu^2}{2} \, H^\dagger H$$

dim 2

Cosmological constant

$$\int d^4x \, \sqrt{-g} \, \Lambda_{CC}$$

dim 4

Neither is protected by symmetry in the SM.

see e.g. TASI lectures by Markus Luty

Two relevant operators in the SM

Higgs mass

$$\int d^4x \, \frac{\mu^2}{2} \, H^\dagger H \qquad \sim \int d^4x \, \Lambda^2 \, H^\dagger H$$

dim 2 quantum correction

Cosmological constant

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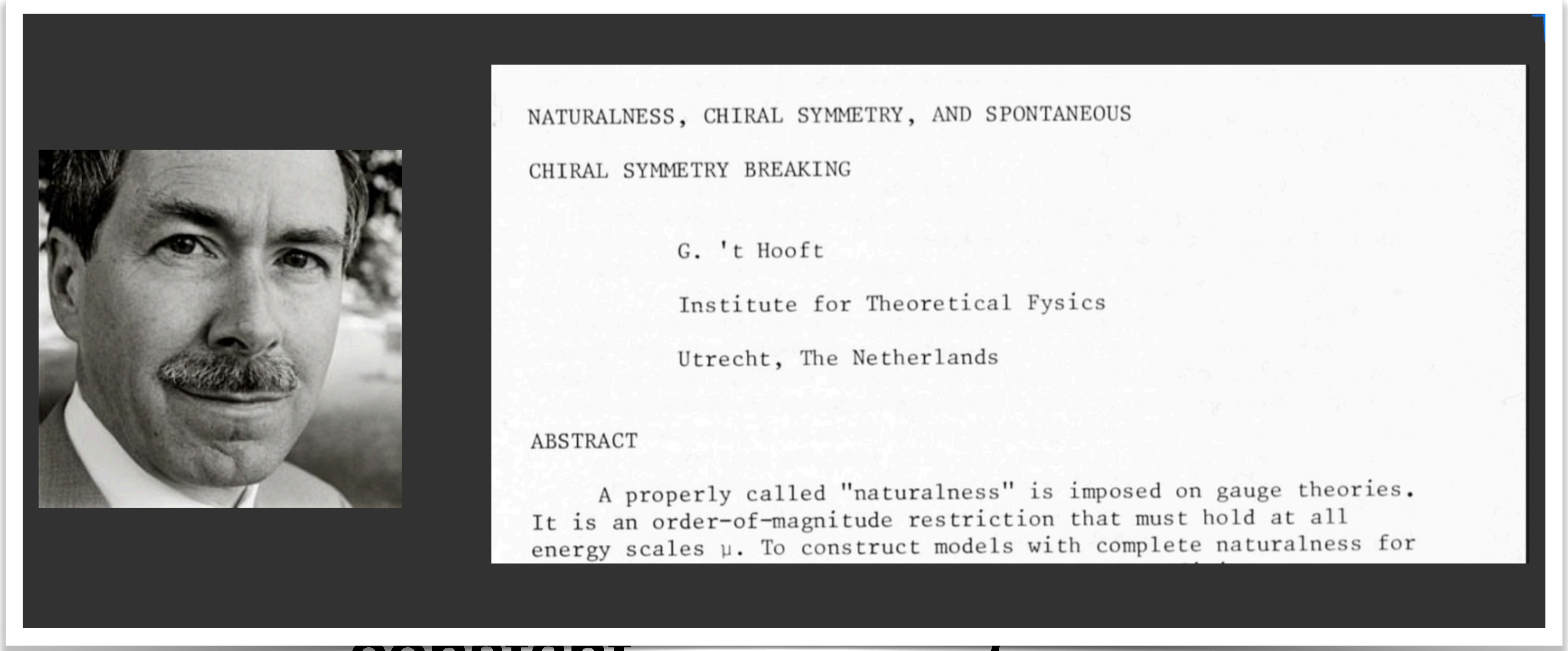

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS

CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

Utrecht, The Netherlands

ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for

$$\sim \int d^4x \, \Lambda^2 \, H^\dagger H$$

quantum correction

constant

$$\sim \int d^4x \, \sqrt{-g} \, \Lambda^4$$

dim 4

quantum correction

Neither is protected by symmetry in the SM.

see e.g. TASI lectures by Markus Luty

Standard model as an effective field theory

The SM is not UV complete

1) Gravity requires a consistent UV completion

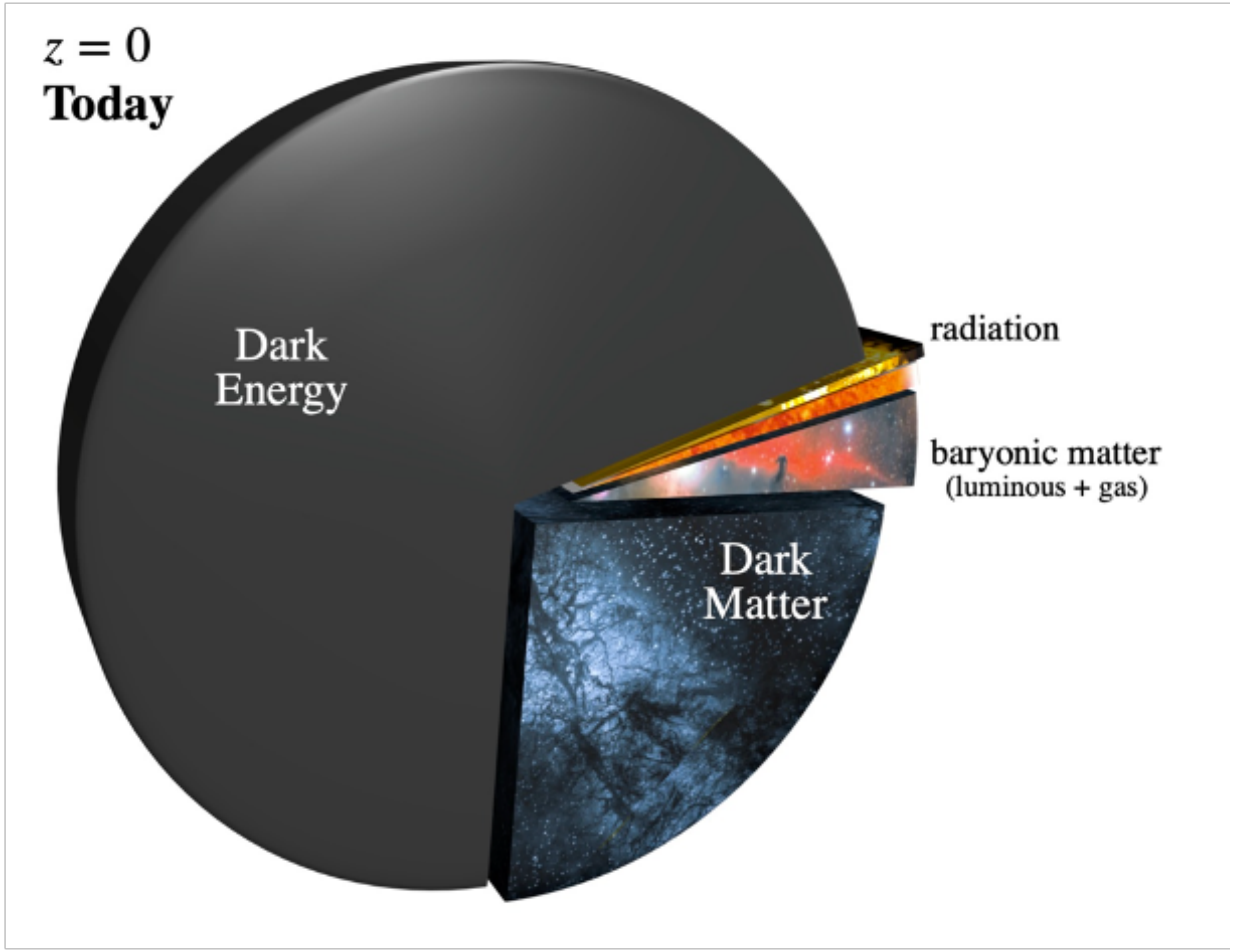
irrelevant op.

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

=> *talk by Hirosi Ooguri*

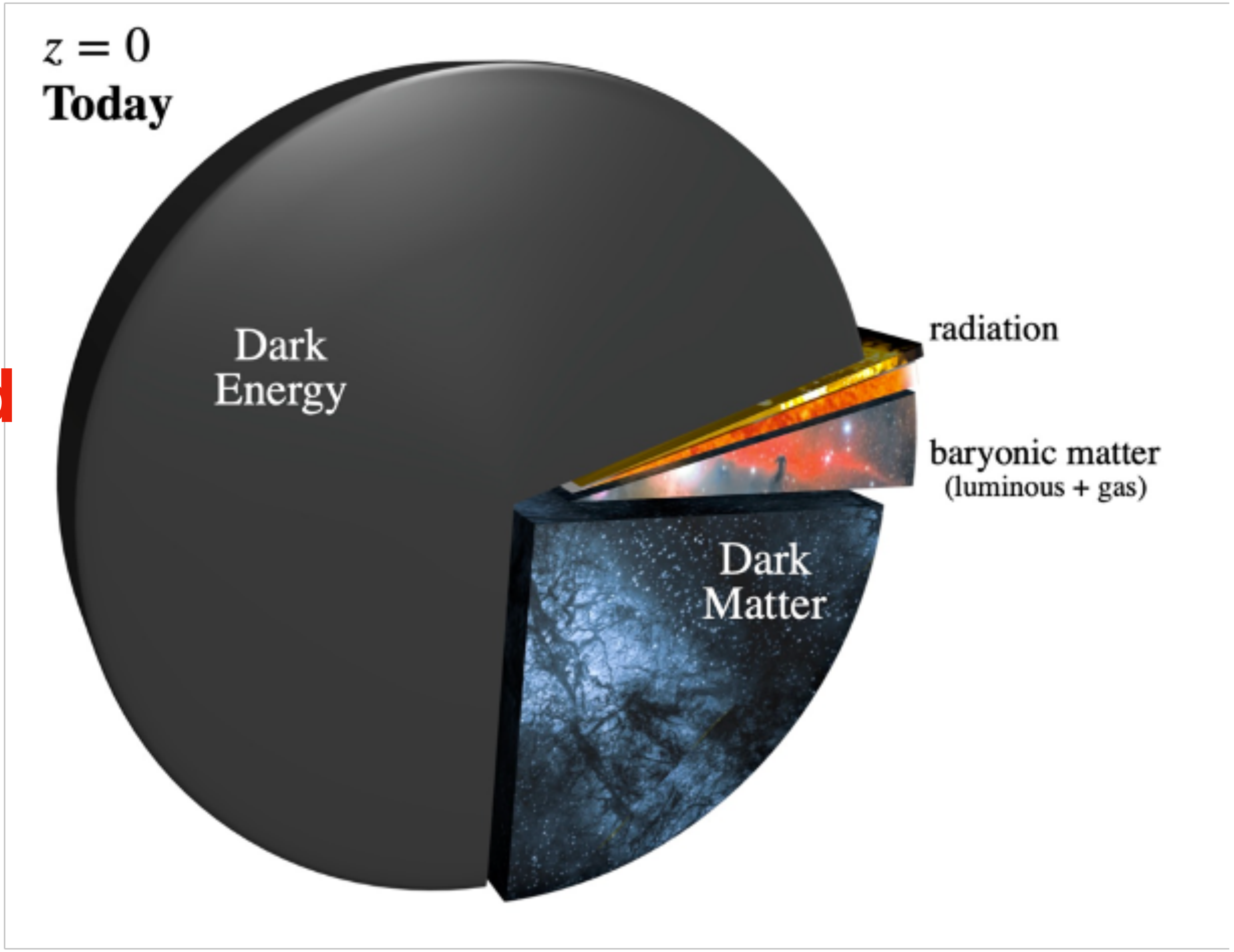
2) We know we need to add more quantum fields to SM, given evidence on dark matter, inflation, and baryogenesis, …

Inventory of the universe



Inventory of the universe

not understood



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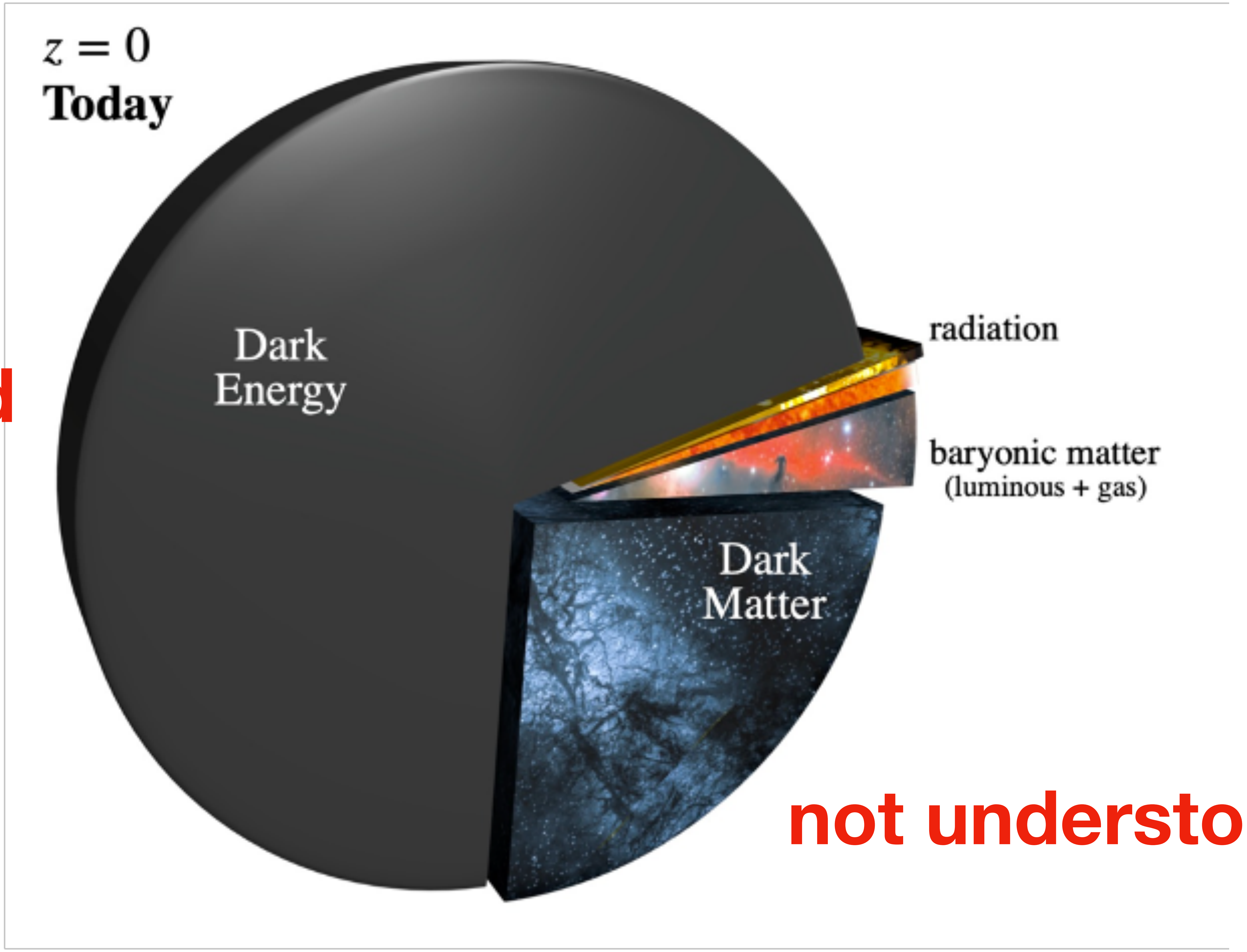

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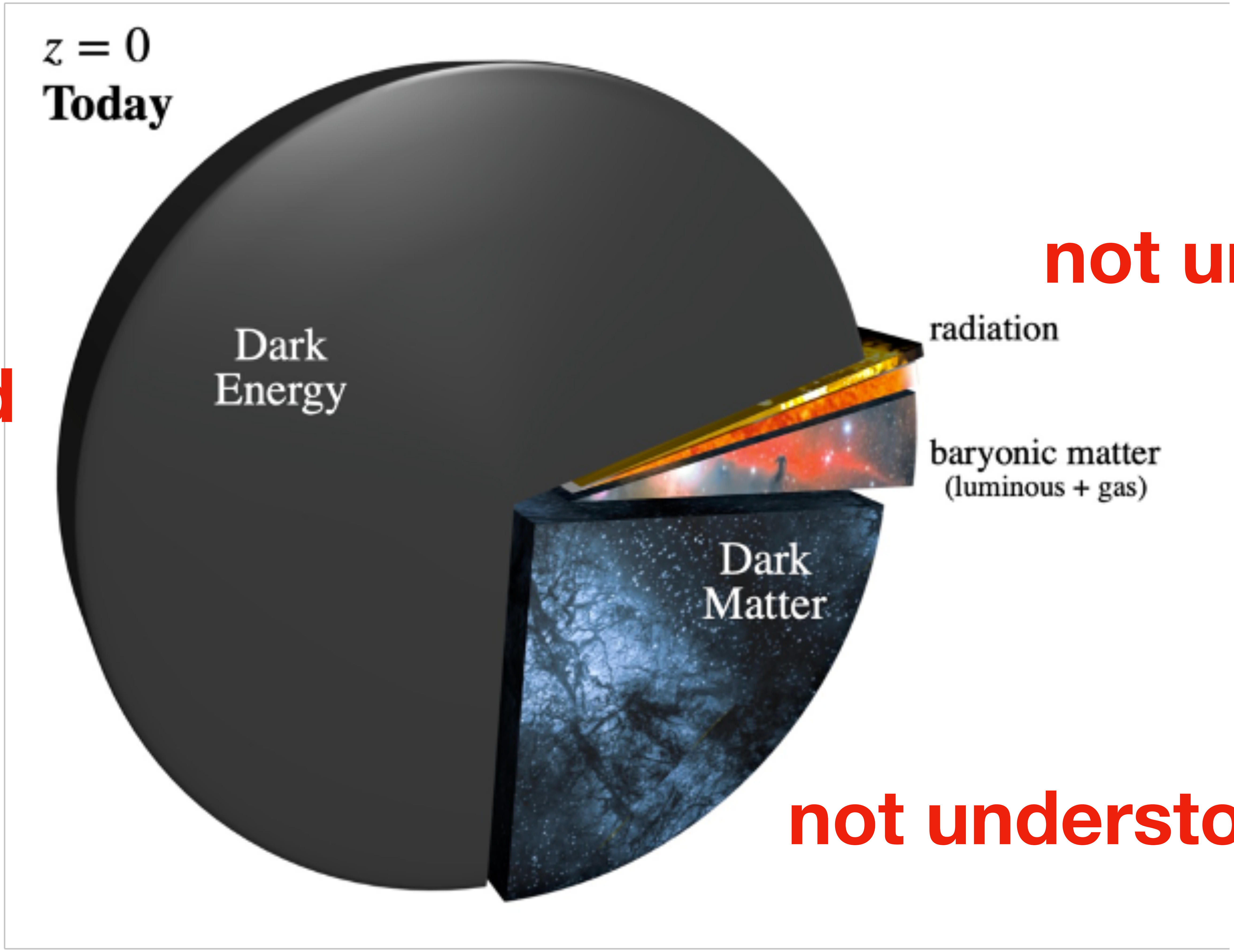

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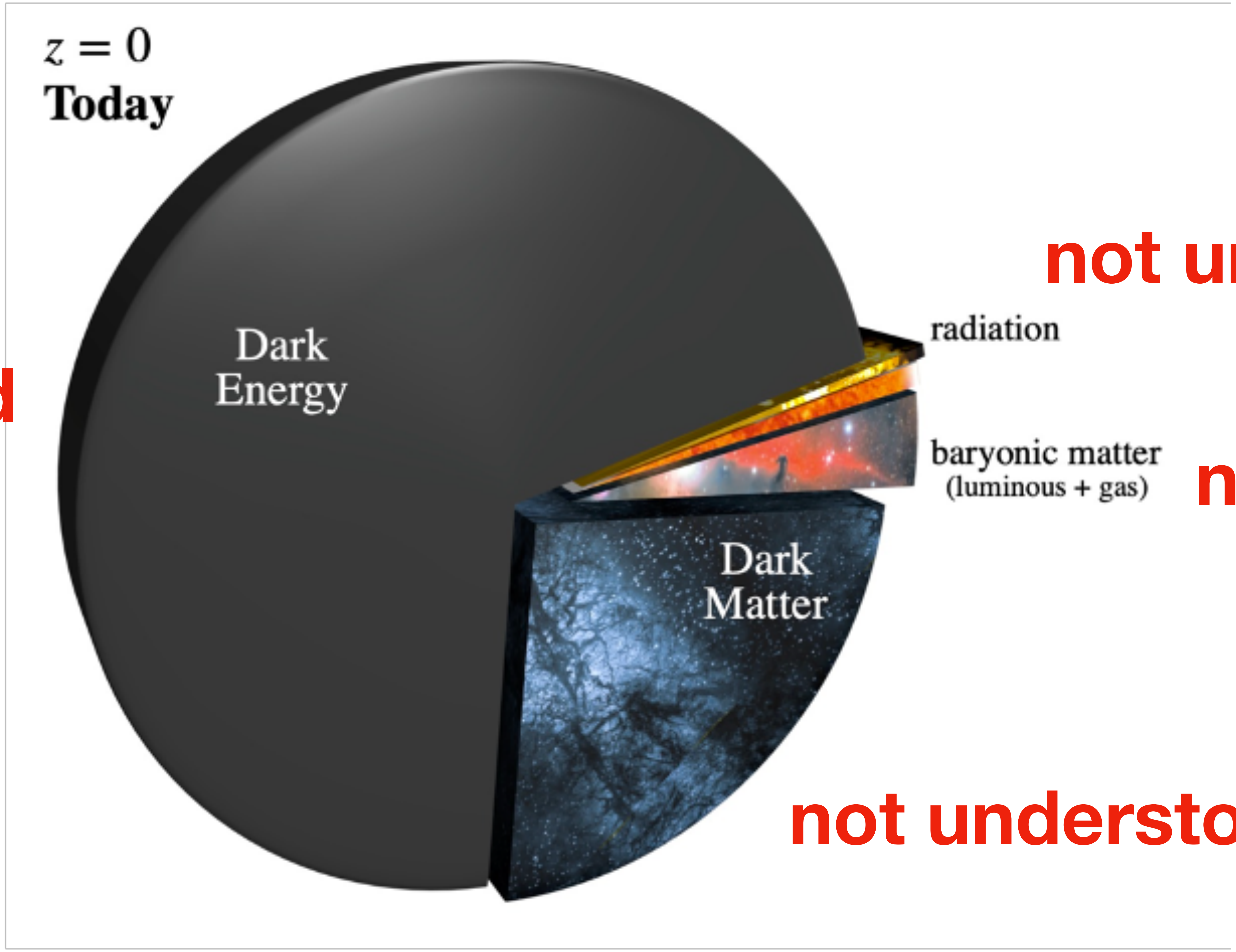

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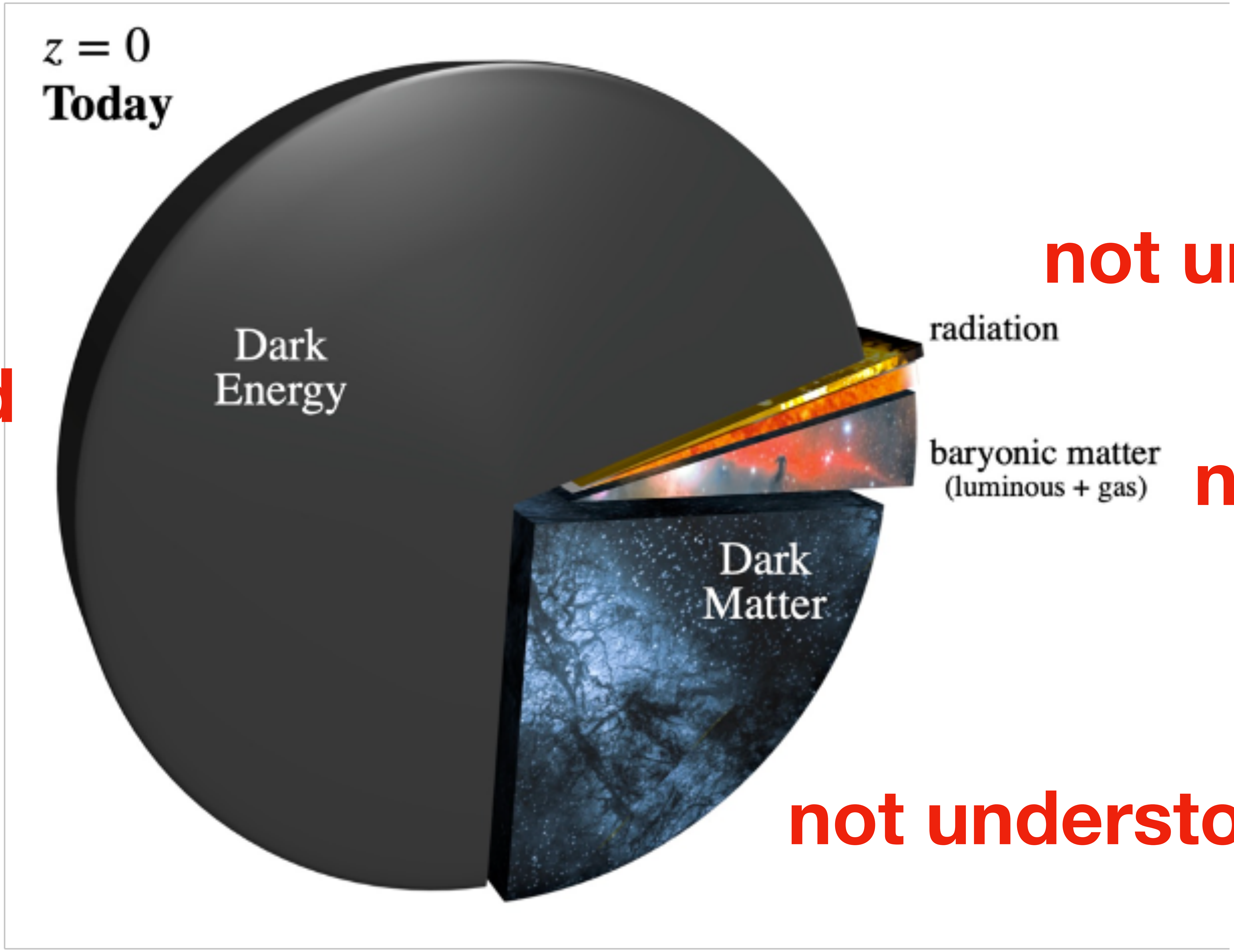

not understood

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Is it a constant?
Why so small?

not understood

not understood

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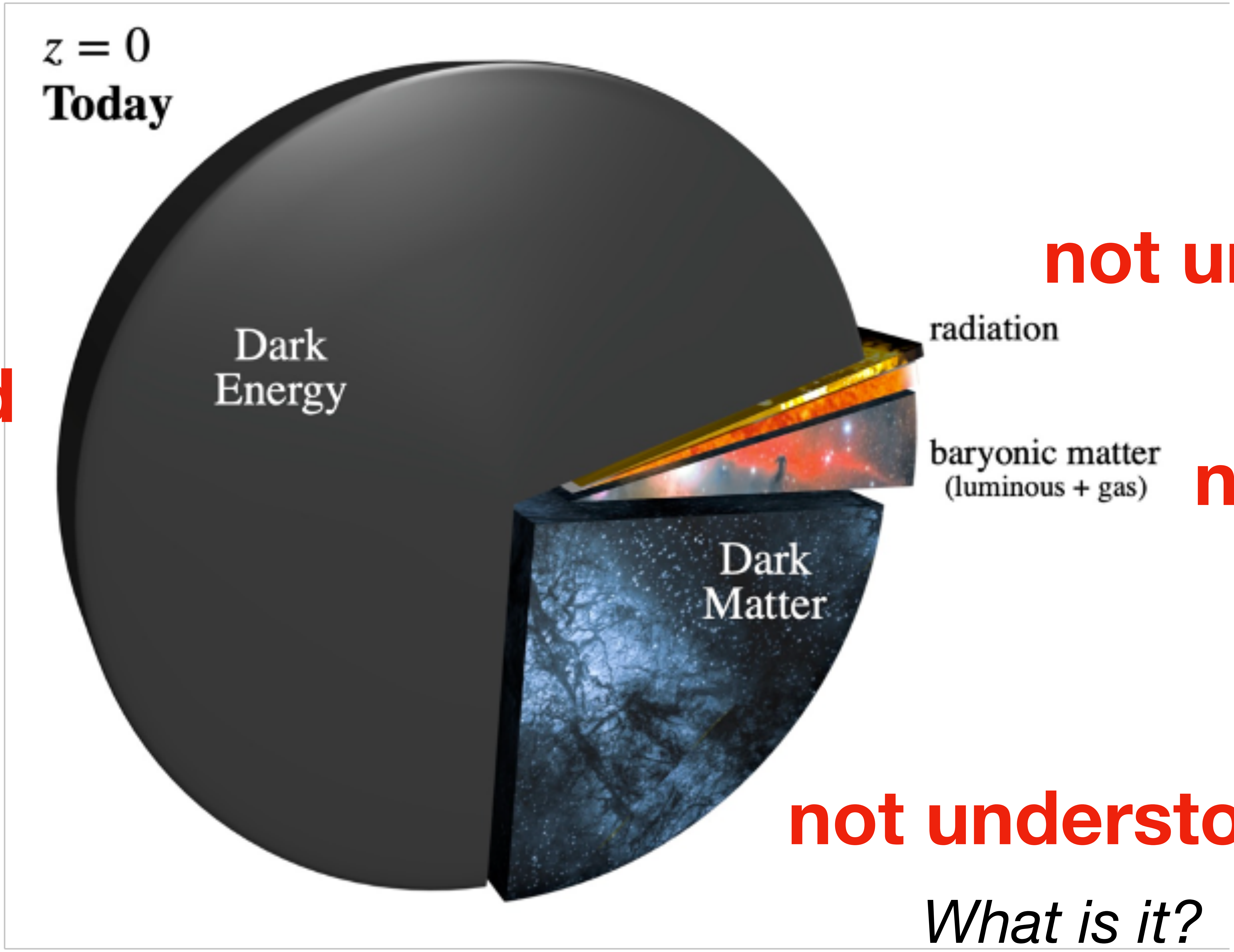

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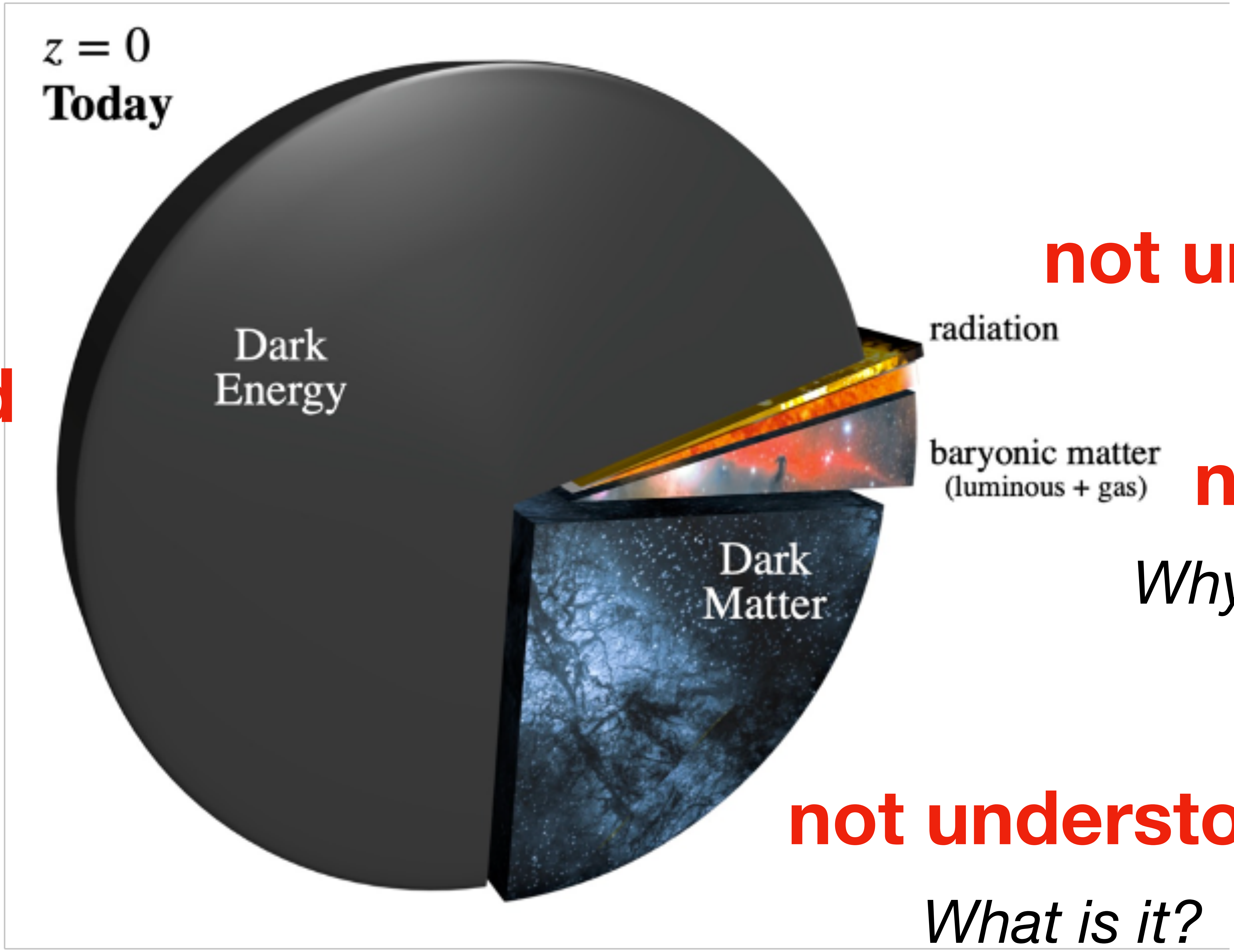

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Why is there more matter than antimatter?

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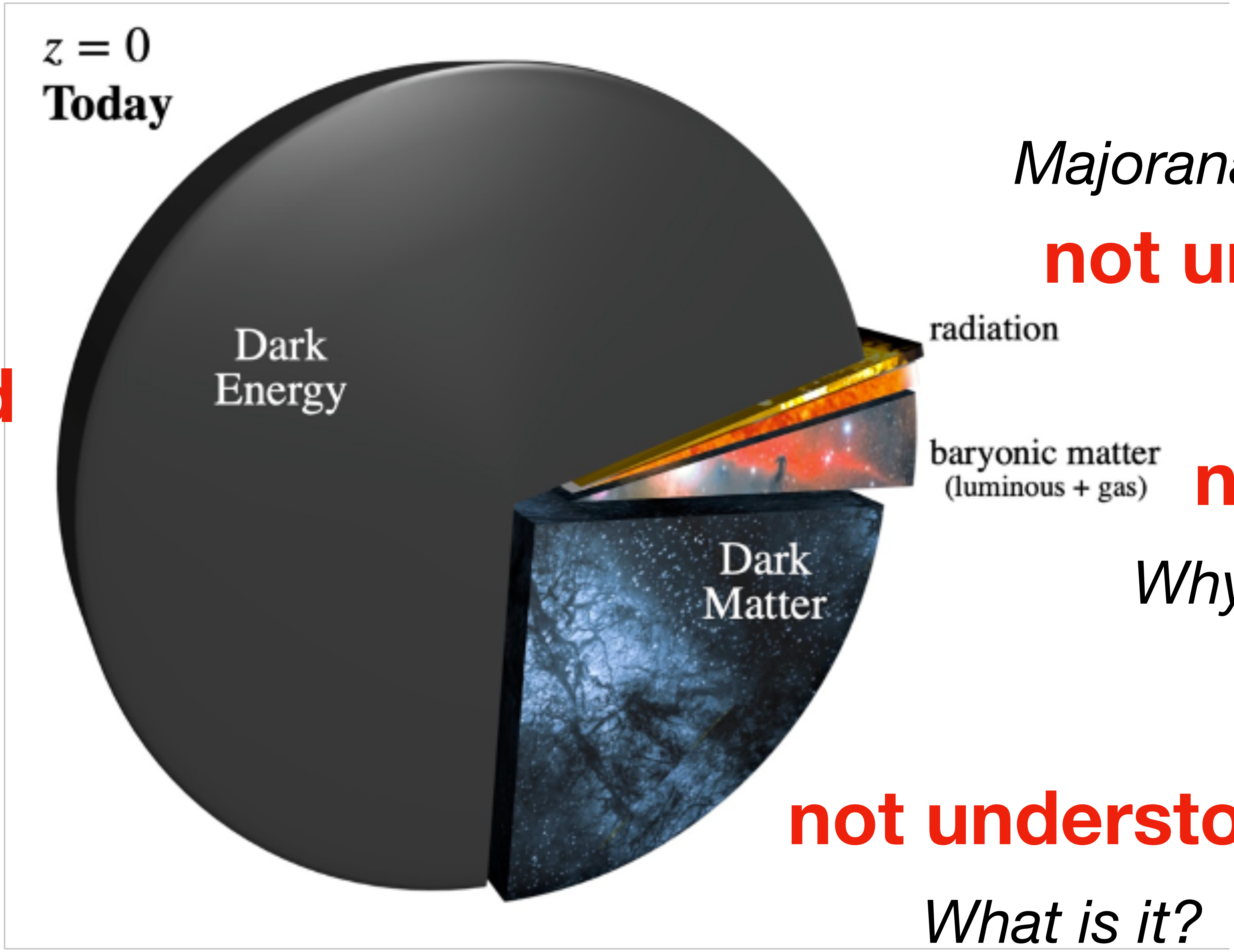

Majorana or Dirac neutrinos?

not understood

not understood

Is it a constant?
Why so small?

not understood

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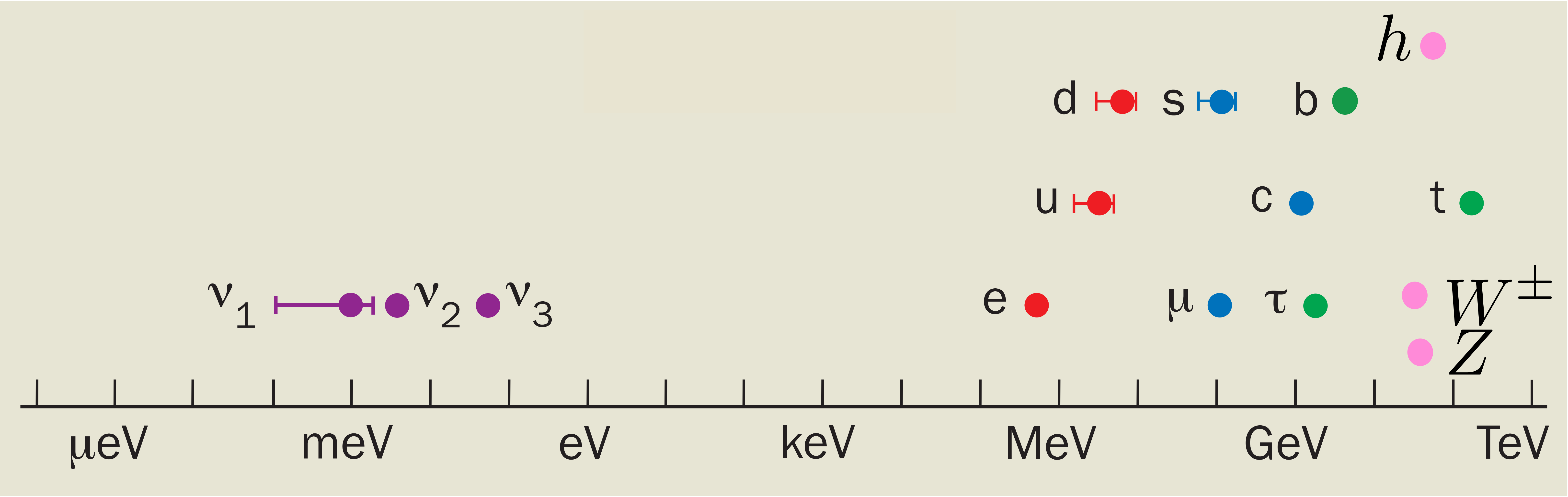
What is it?

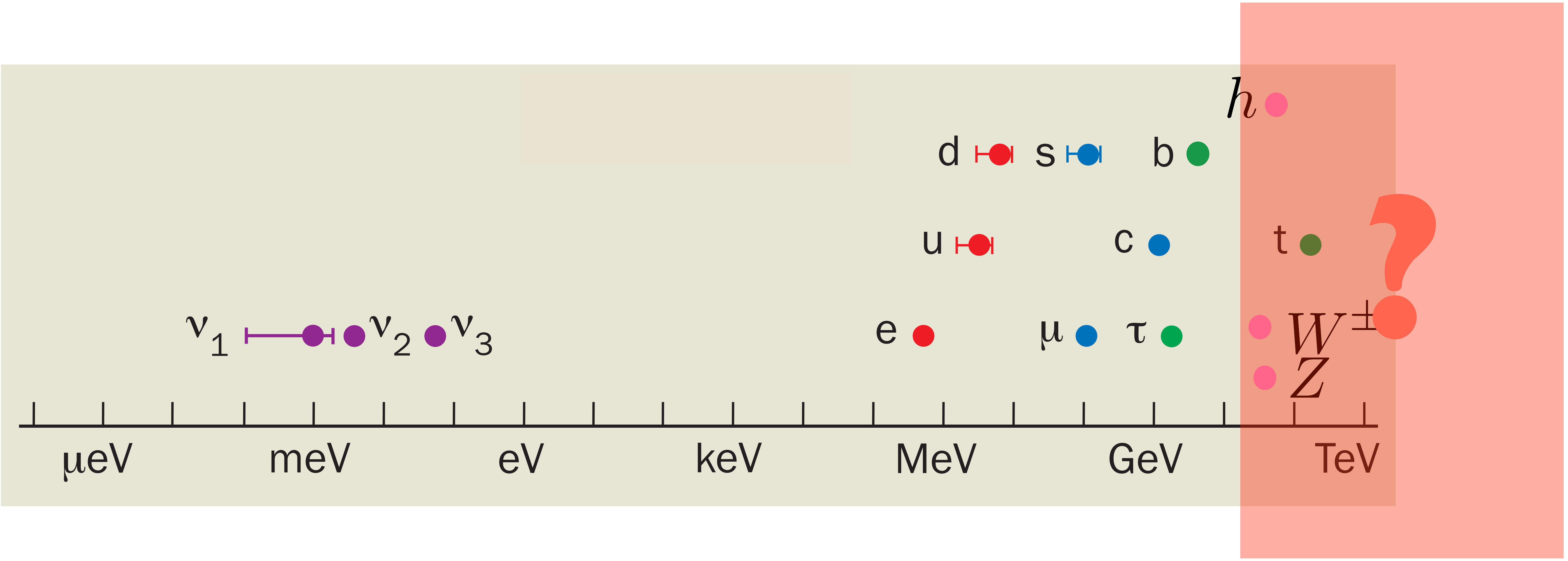
What is the scale of new physics?

The energy frontier



The energy frontier

Large Hadron collider



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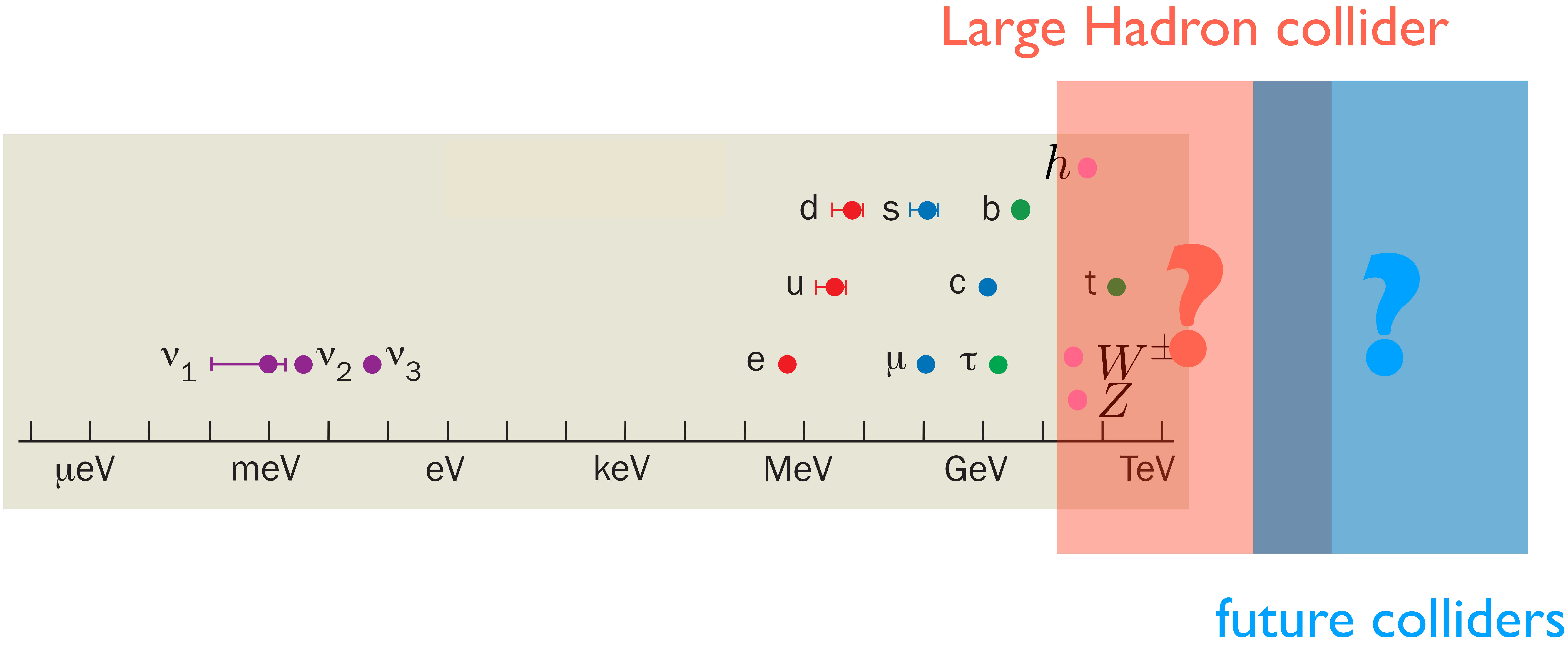
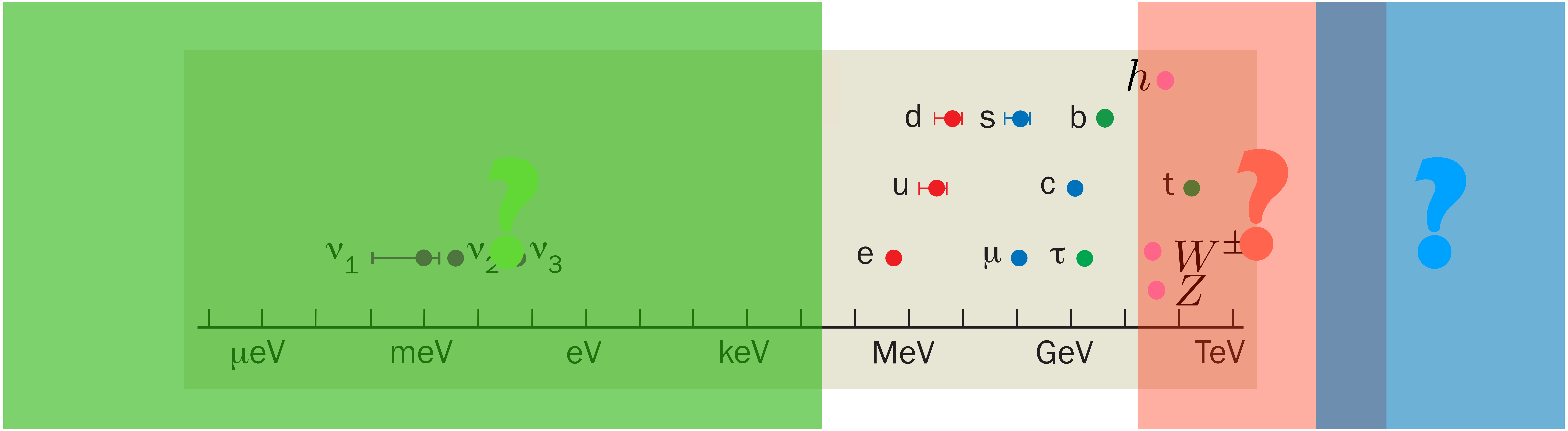


The energy frontier

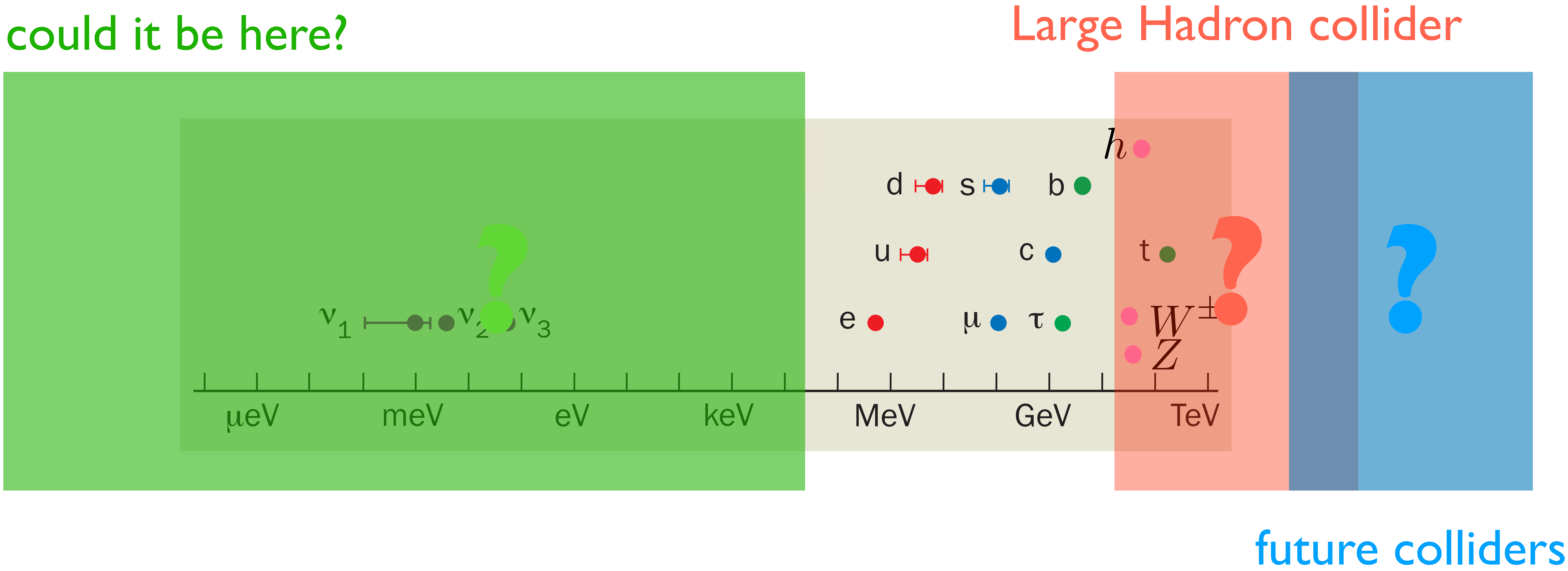
could it be here?

Large Hadron collider



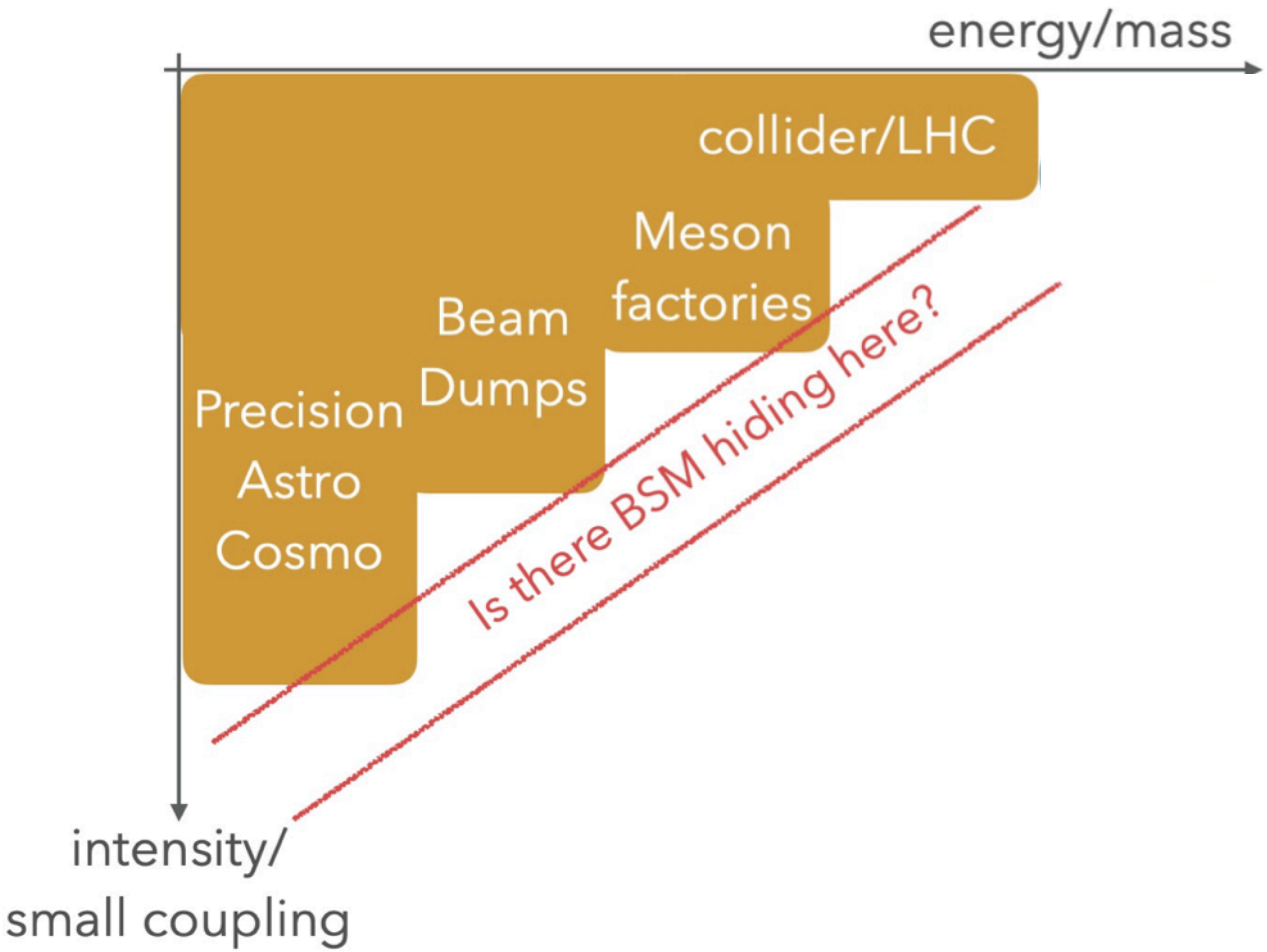
future colliders

The energy frontier



this should be a 2D plot

The energy intensity frontier



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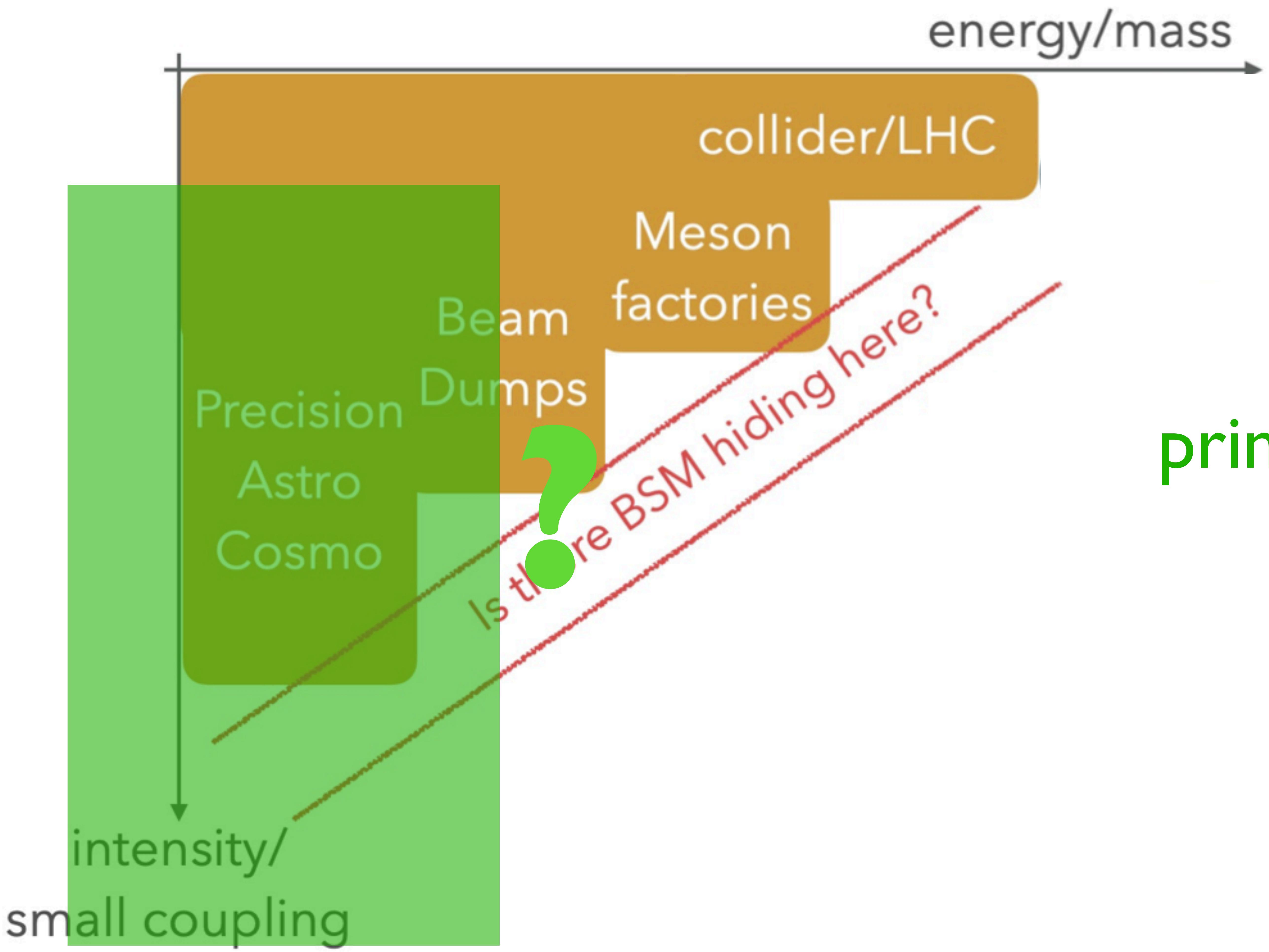

prime example: the **axion**

θ-parameter violates CP=T !

$$S = \int d^4x \left[-\frac{1}{4} G^{\mu\nu} G_{\mu\nu} - \frac{\theta}{4} G^{\mu\nu} \tilde{G}_{\mu\nu} + i\bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} M \psi \right]$$

QCD = theory of strong interactions

θ-parameter violates CP=T !

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QCD = theory of strong interactions

$$\text{“} \sim \theta \vec{E} \cdot \vec{B} \text{”}$$

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"$\sim \theta \vec{E} \cdot \vec{B}$"

CP = T

$$\vec{E} \to \vec{E}$$

$$\vec{B} \to -\vec{B}$$

$$\vec{E} \cdot \vec{B} \to -\vec{E} \cdot \vec{B}$$

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~~CP = T~~

The CP problem of the strong interactions

CP violation in the strong sector

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

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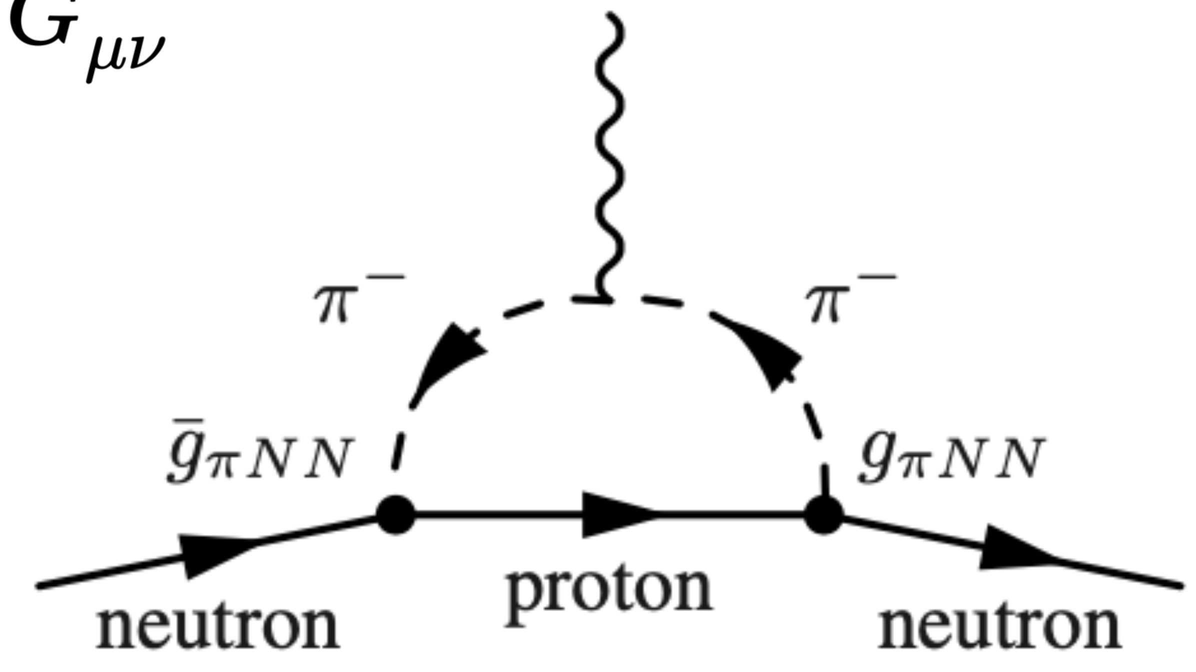
Predicts neutron EDM

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



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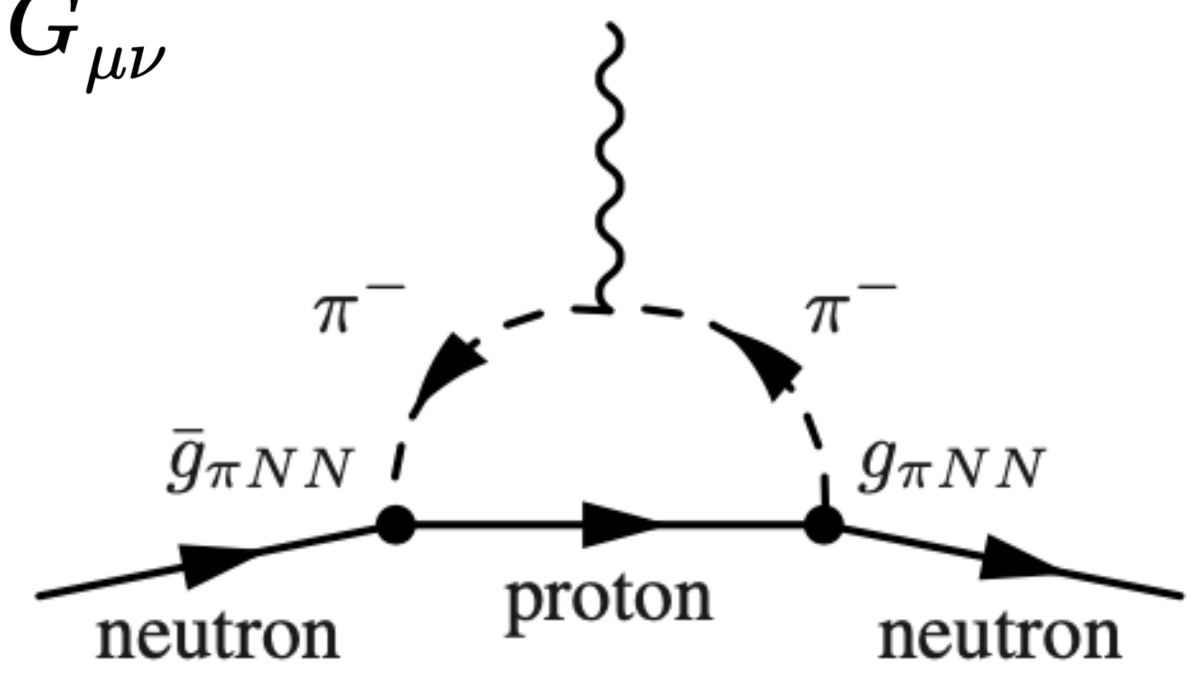

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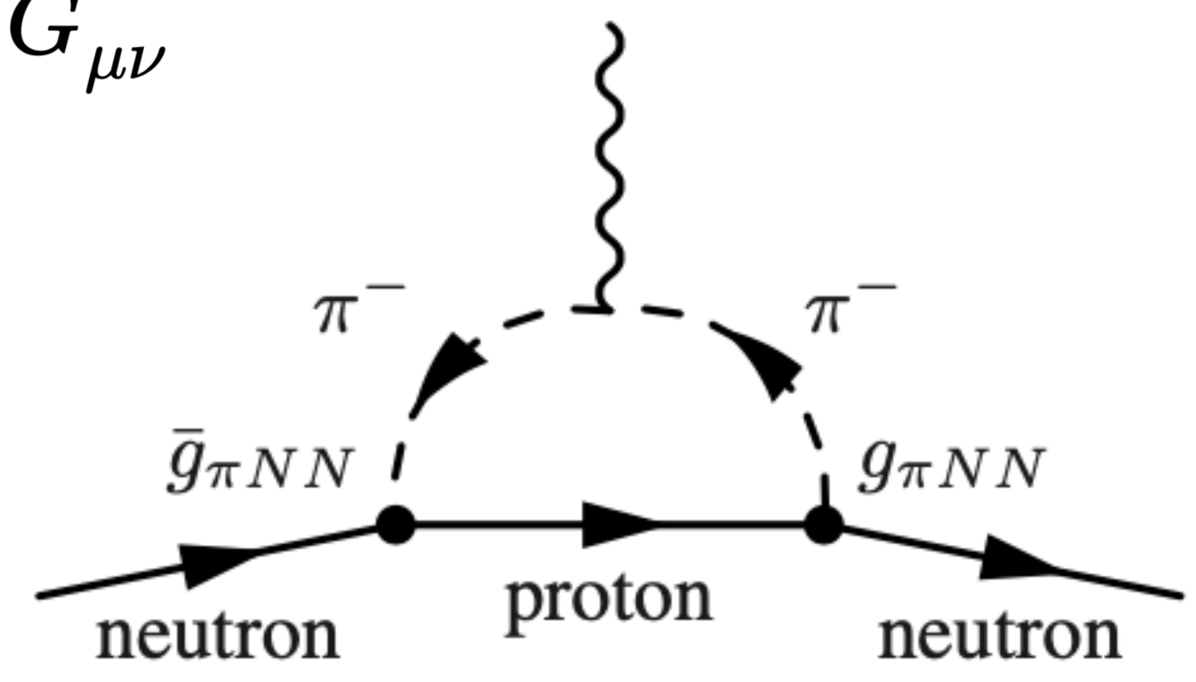


T

$$\vec{E} \to \vec{E}$$

$$\vec{S} \to -\vec{S}$$

$$\vec{E}\cdot\vec{S} \to -\vec{E}\cdot\vec{S}$$

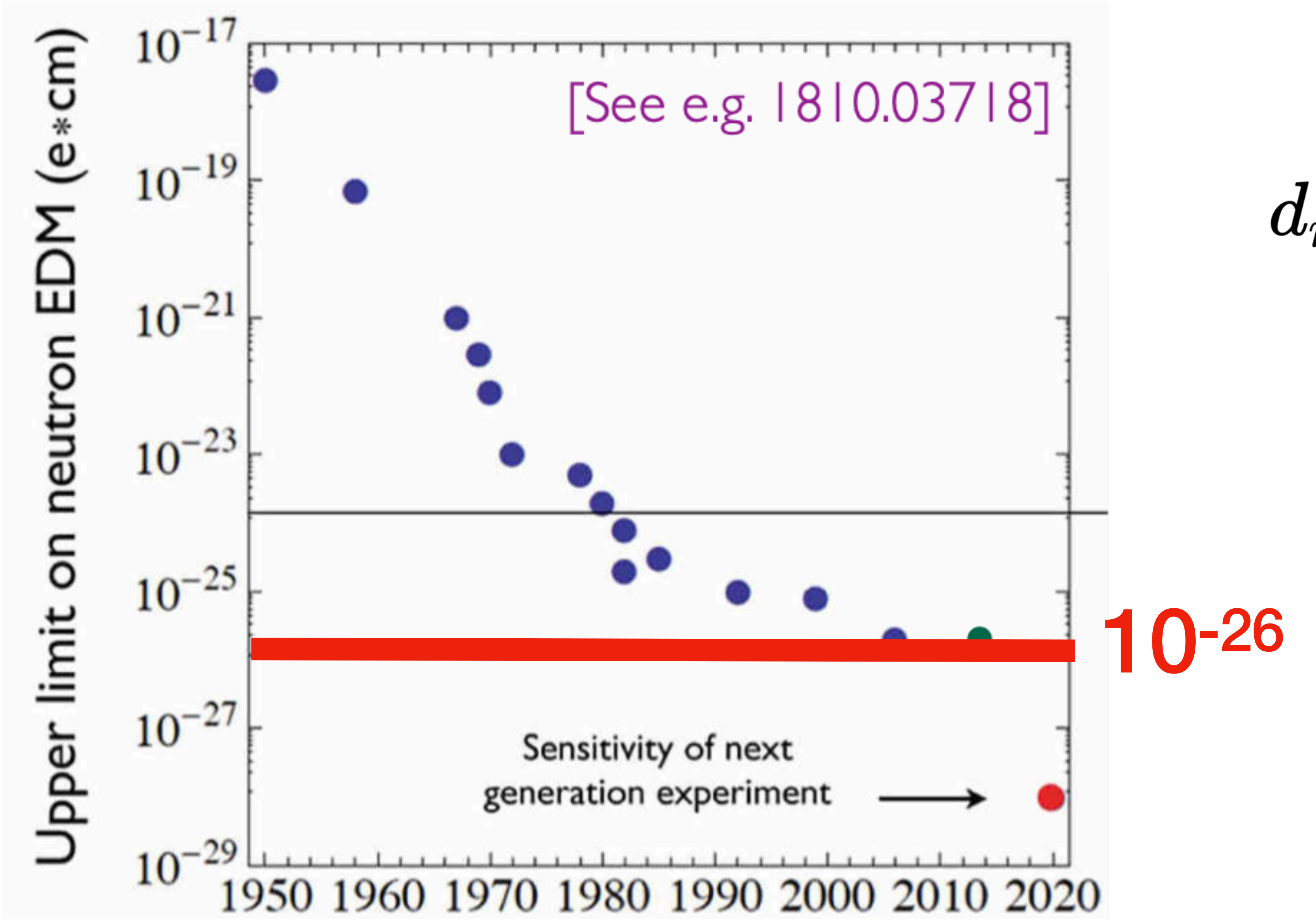
EDM violates T-invariance

No neutron EDM has been observed (so far)

$$\theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}^a_{\mu\nu}$$

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

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



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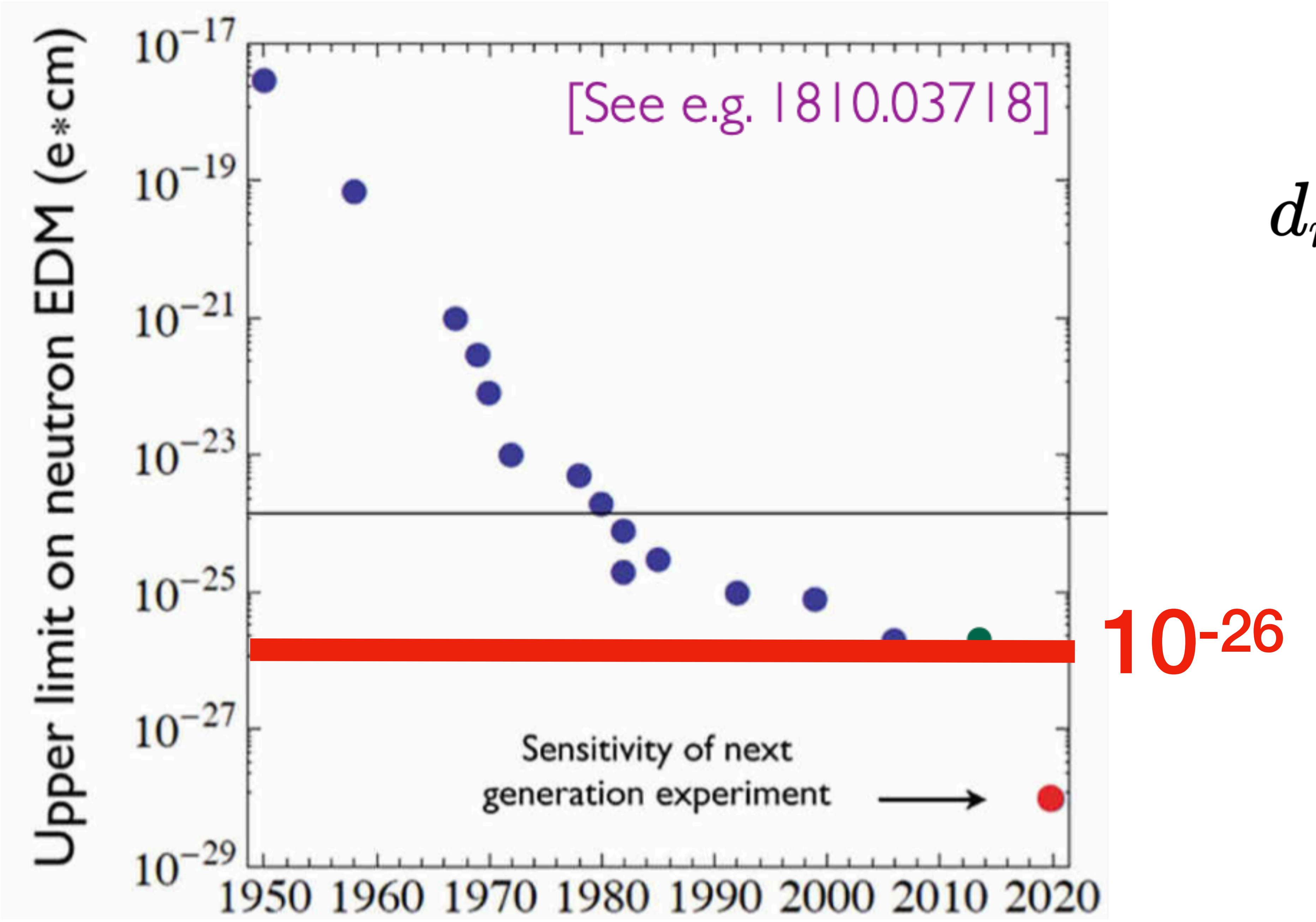


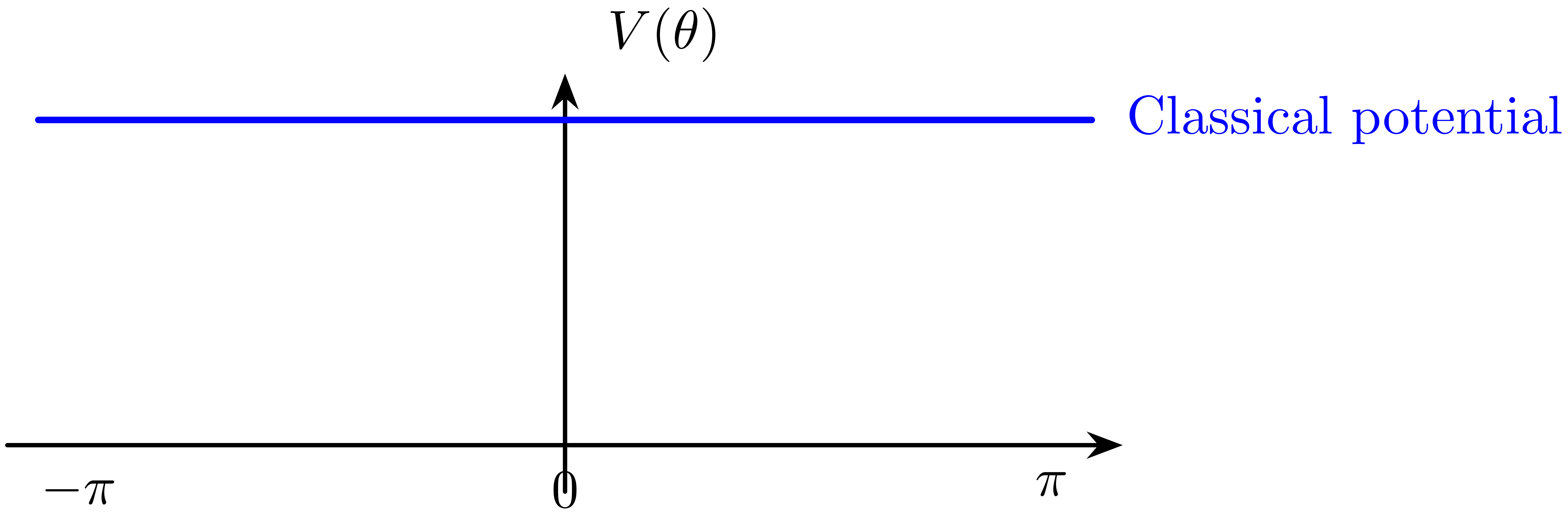
$$d_n \approx \frac{e|\bar{\theta}|m_\pi^2}{m_n^3} \approx 10^{-16} |\bar{\theta}| e \text{ cm}$$

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

Why so small ?

Compare to $\theta_{\rm CKM} \sim \mathcal{O}(1)$

Solution hinted within the problem



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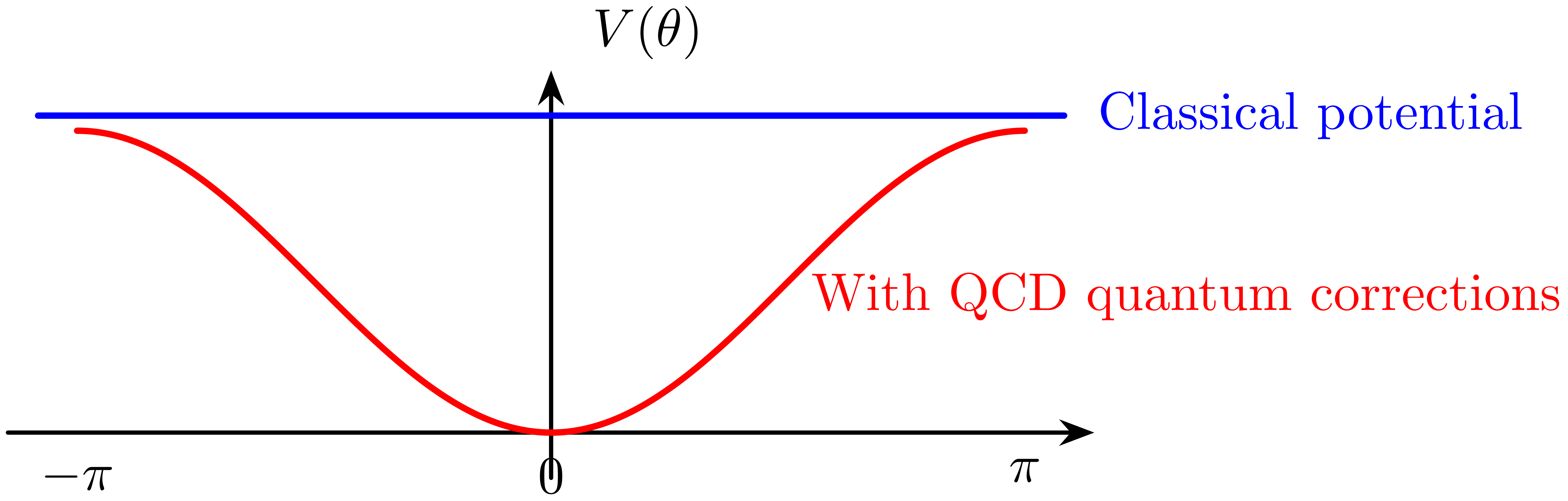
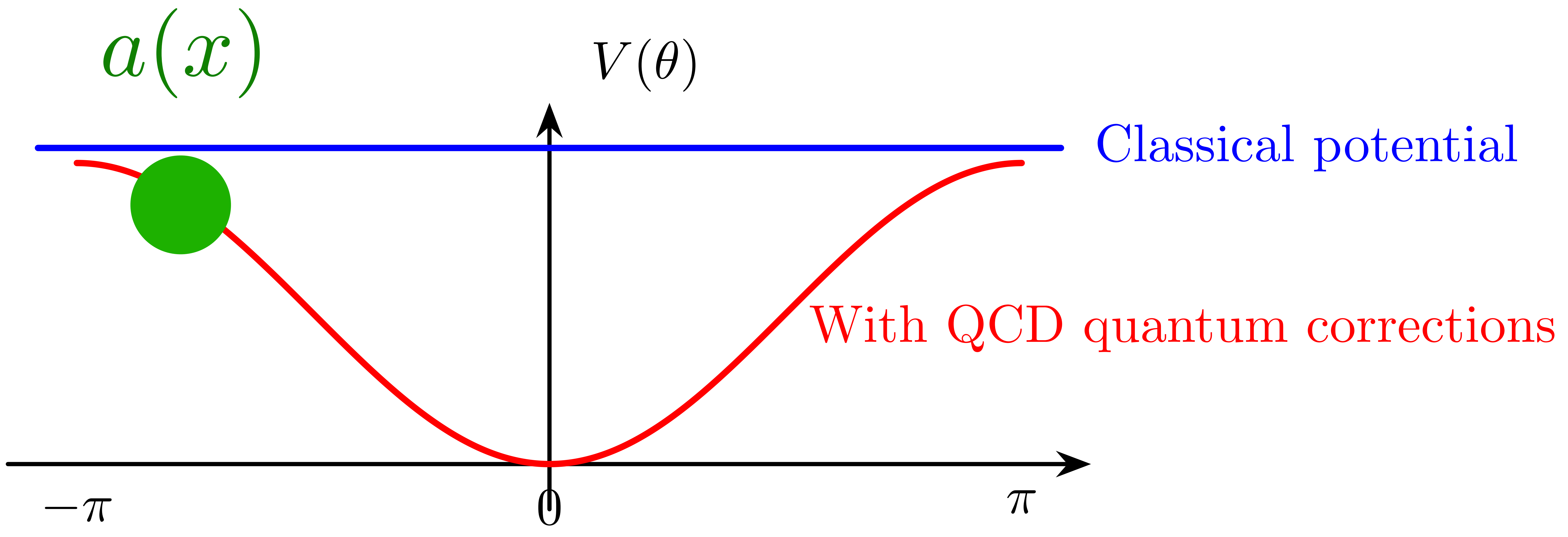


$$
\begin{aligned}
\exp\left(-\int_x V(a)\right) &= \left|\int \mathcal{D}A_\mu \, \exp\left(-S_{\text{eff}}[\phi, A^\mu]\right) \exp\left(-i\frac{a}{32\pi^2}\int_x G^{\mu\nu}\tilde{G}_{\mu\nu}\right)\right| \\
&\leq \int \mathcal{D}A_\mu \left|\exp\left(-S_{\text{eff}}[\phi, A^\mu]\right) \exp\left(-i\frac{a}{32\pi^2}\int_x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

Vafa-Witten ‘84

Make θ-parameter dynamical: axion field



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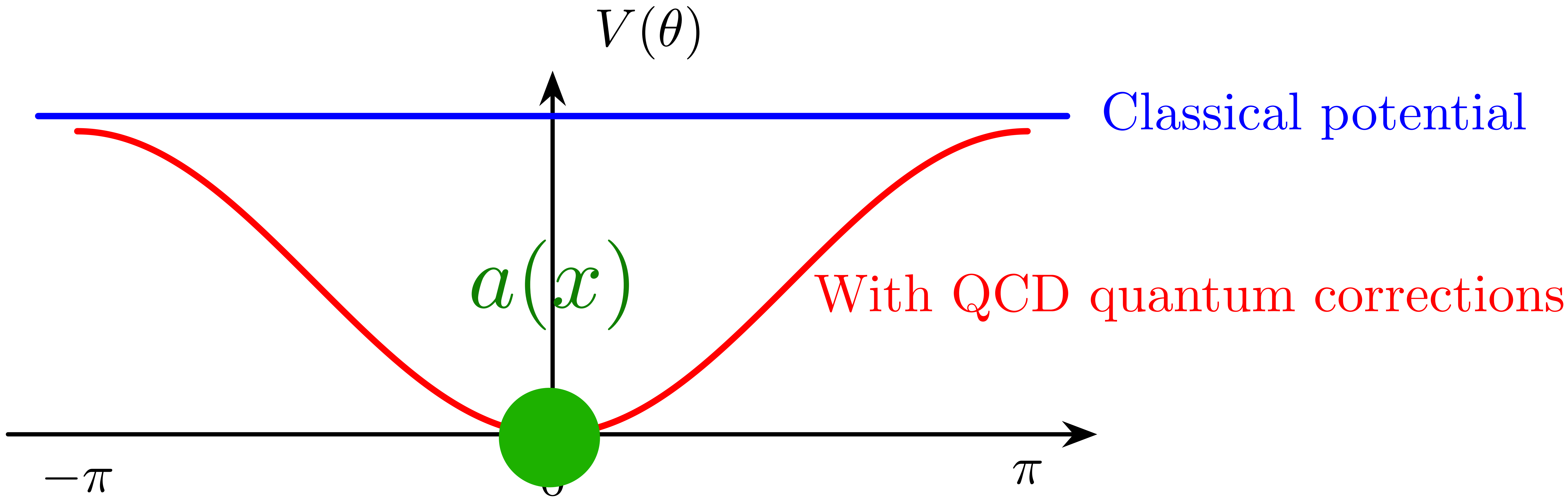
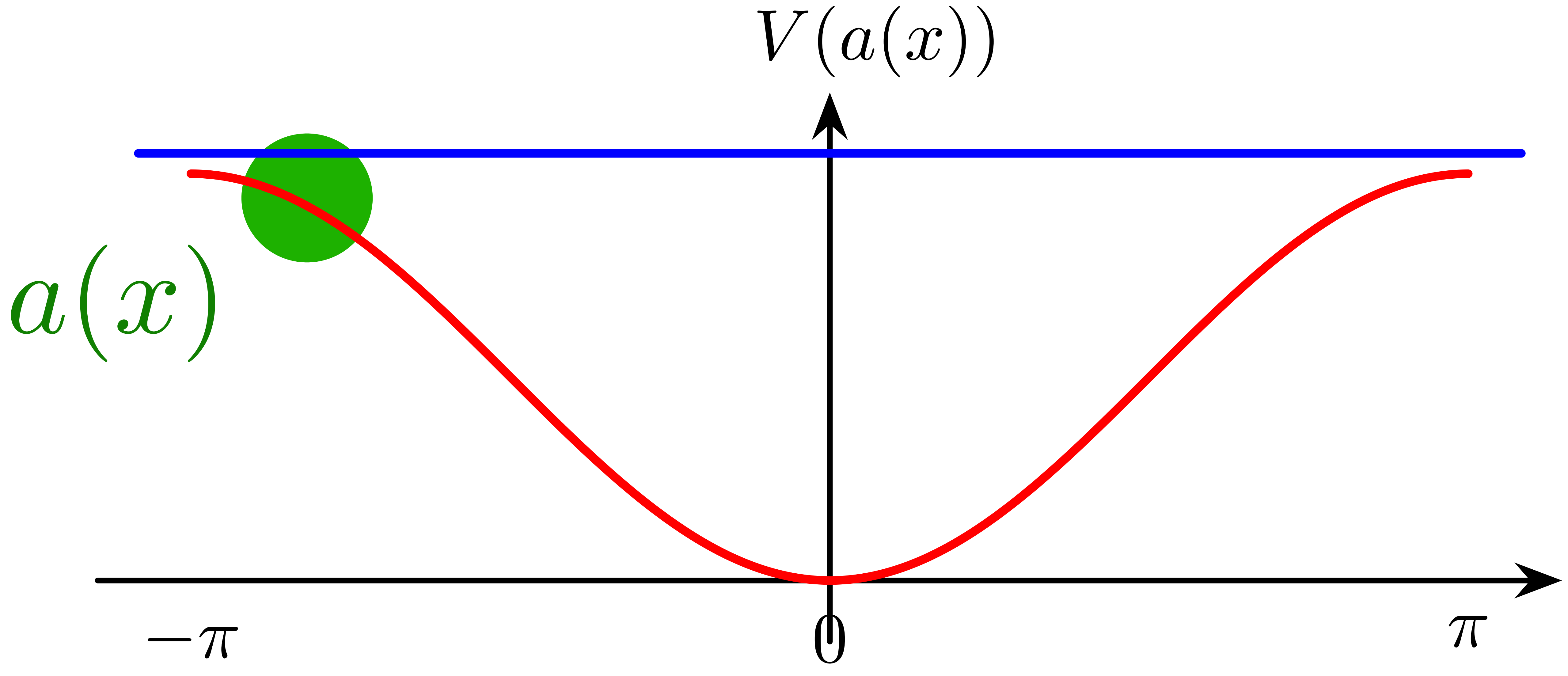
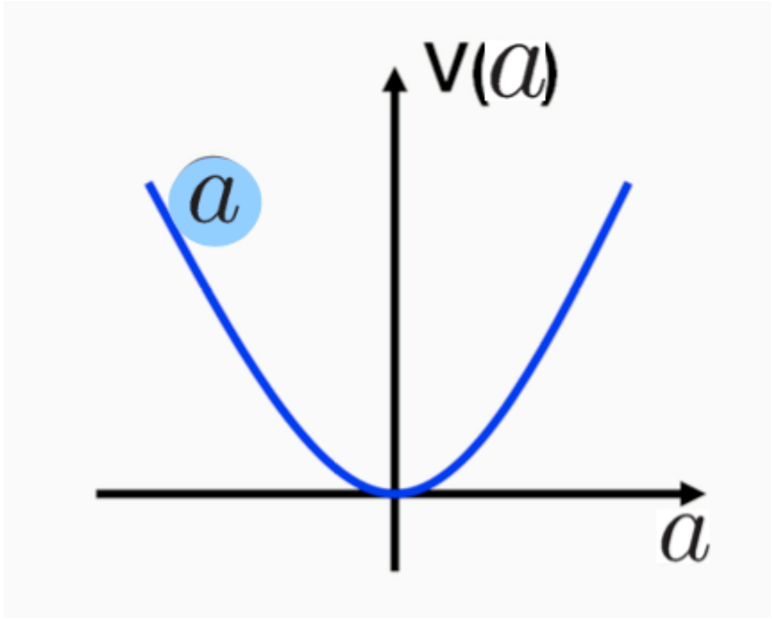


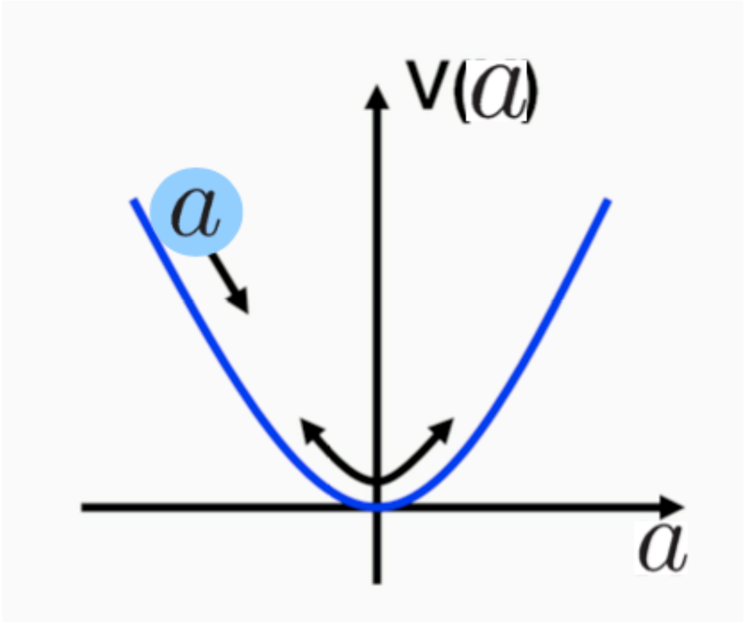
Axion can be dark matter

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0, \qquad H = \frac{\dot{R}(t)}{R(t)}$$



- $H \gg m_a \implies$ **overdamped oscillator**





- $H \ll m_a \implies$ **damped oscillator**

$$\rho_a(t) = \frac{\rho_{\text{ini}}}{R^3(t)} \implies \textbf{Dark Matter}$$

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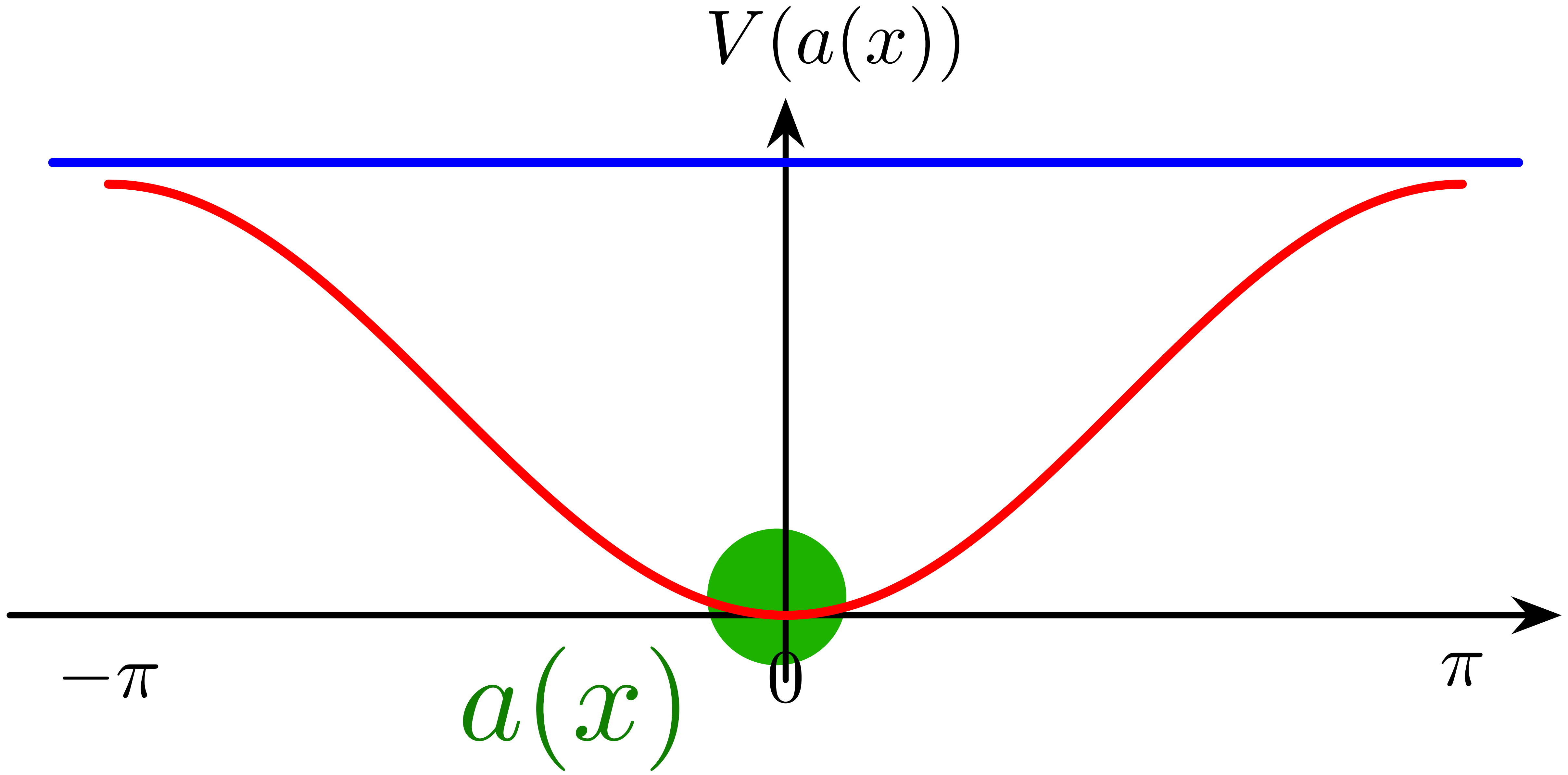

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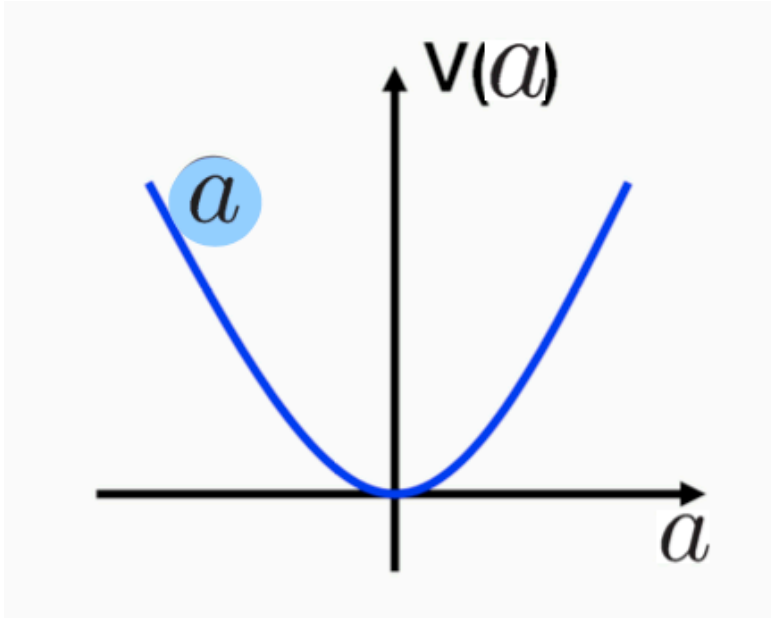
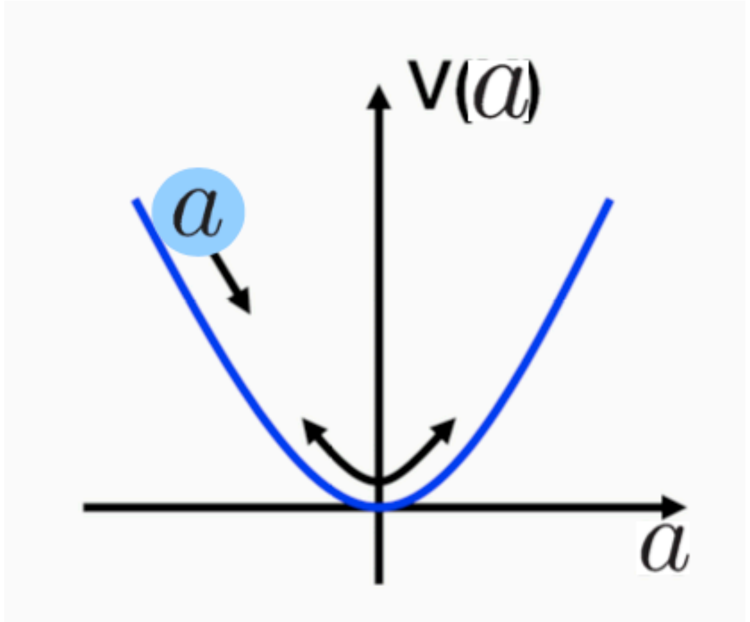


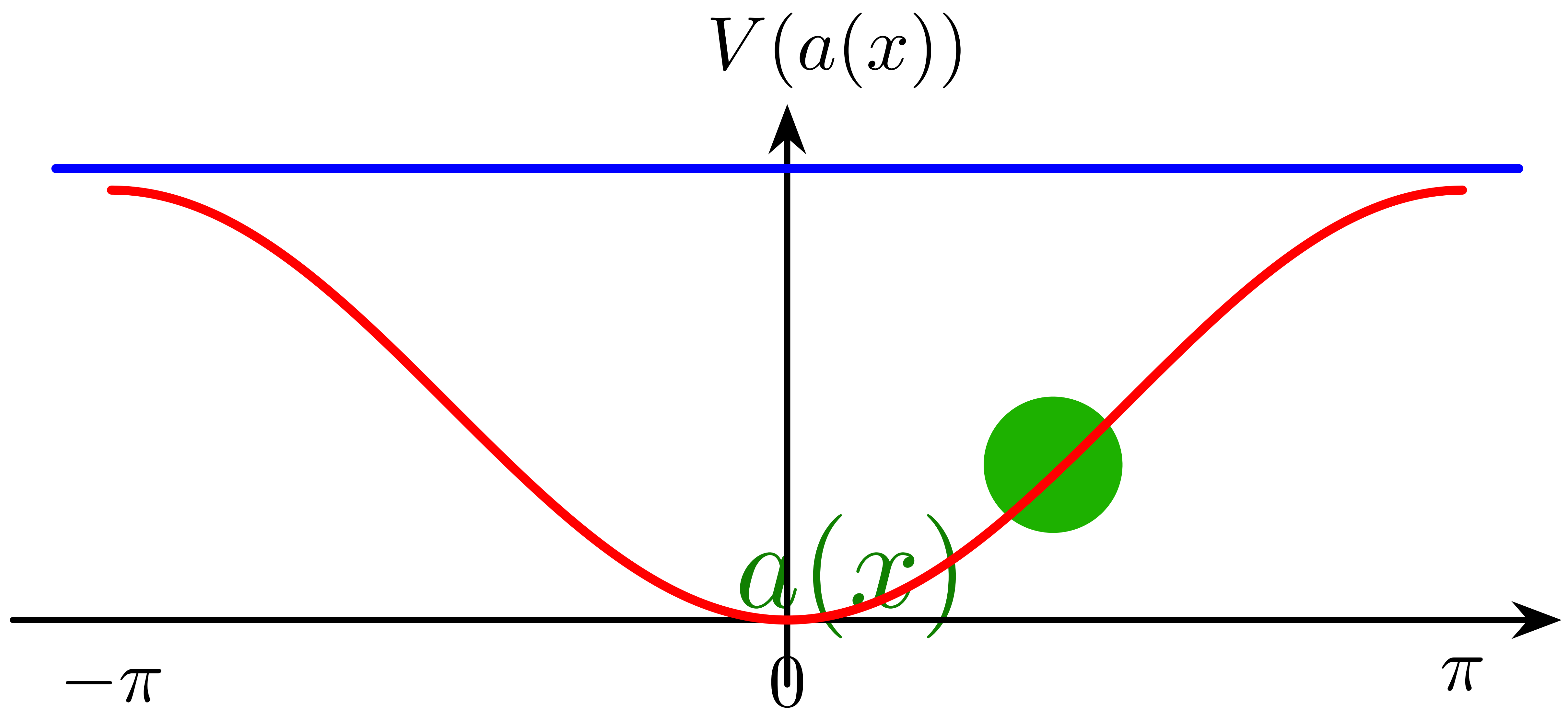


- $H \ll m_a \implies$ **damped oscillator**

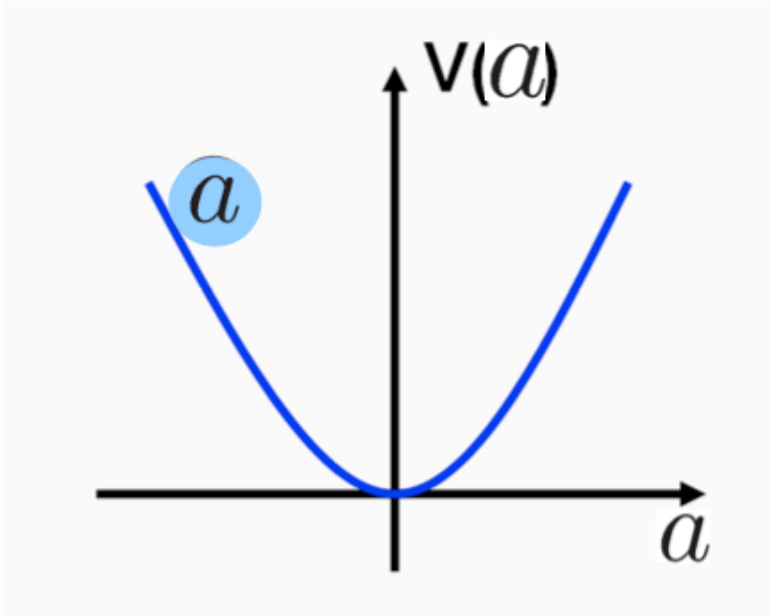
$$\rho_a(t) = \frac{\rho_{\text{ini}}}{R^3(t)} \implies \textbf{Dark Matter}$$

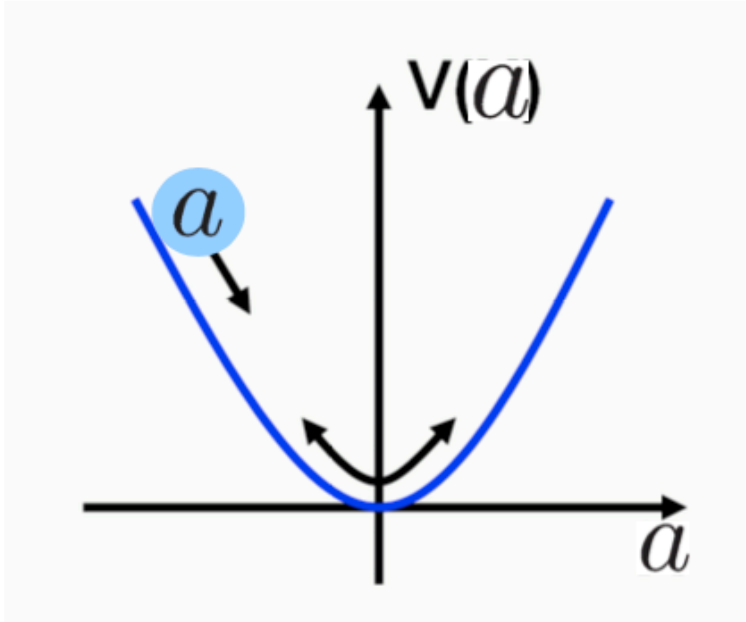
Axion can be dark matter

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0, \qquad H = \frac{\dot{R}(t)}{R(t)}$$



- $H \gg m_a \implies$ **overdamped oscillator**





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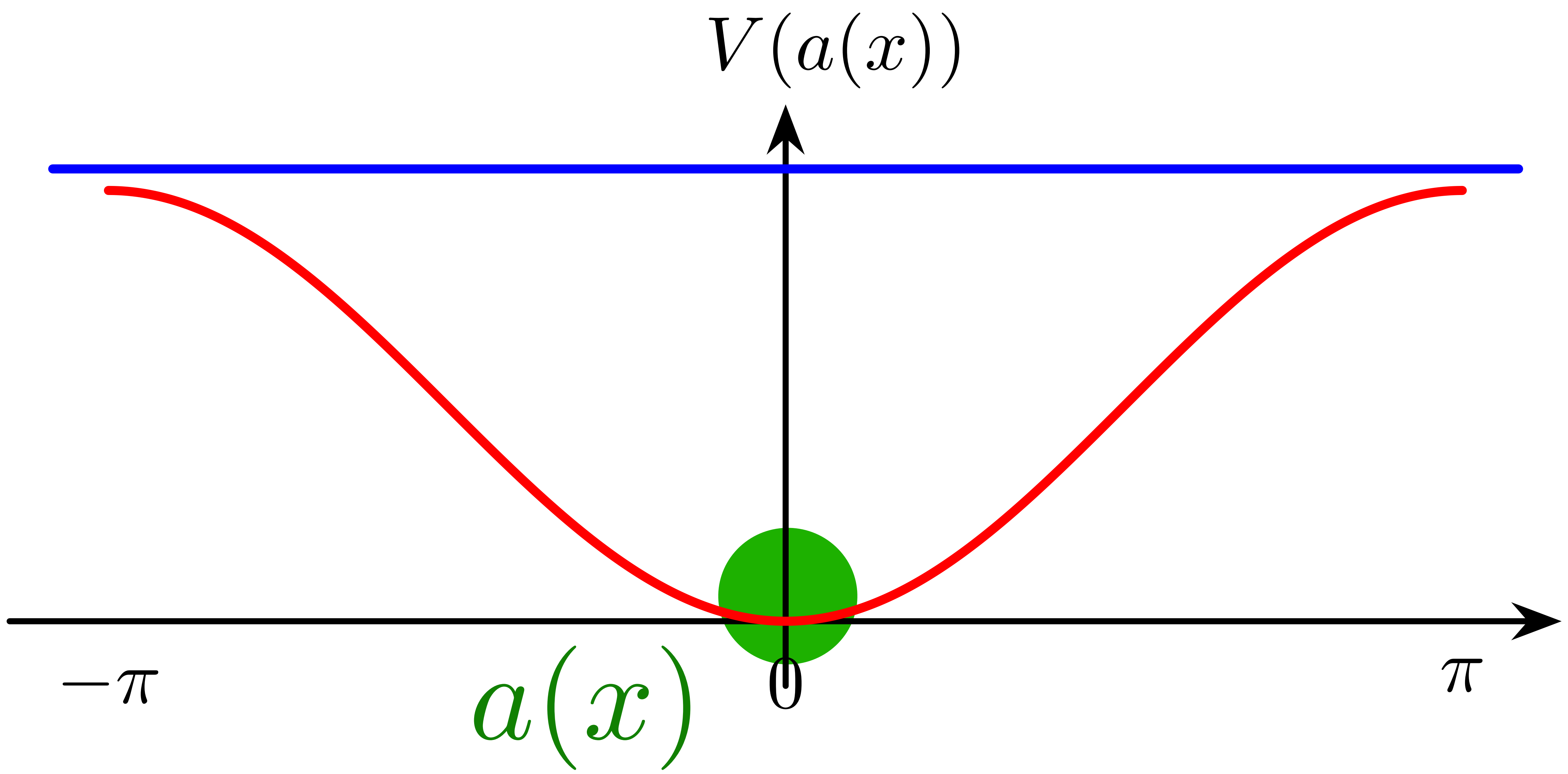

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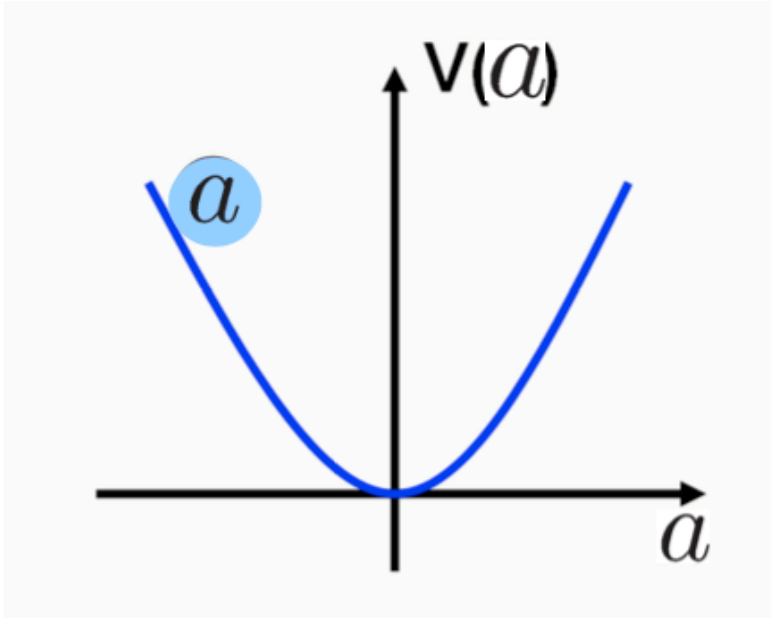

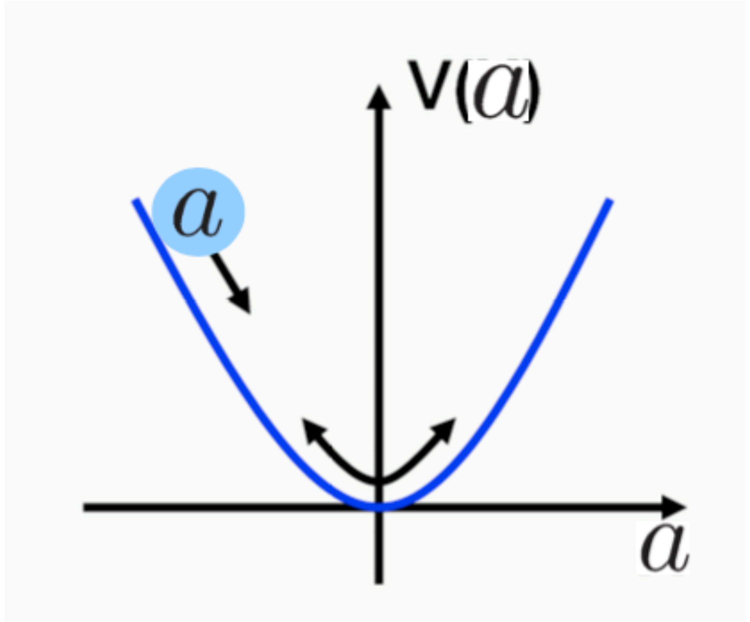

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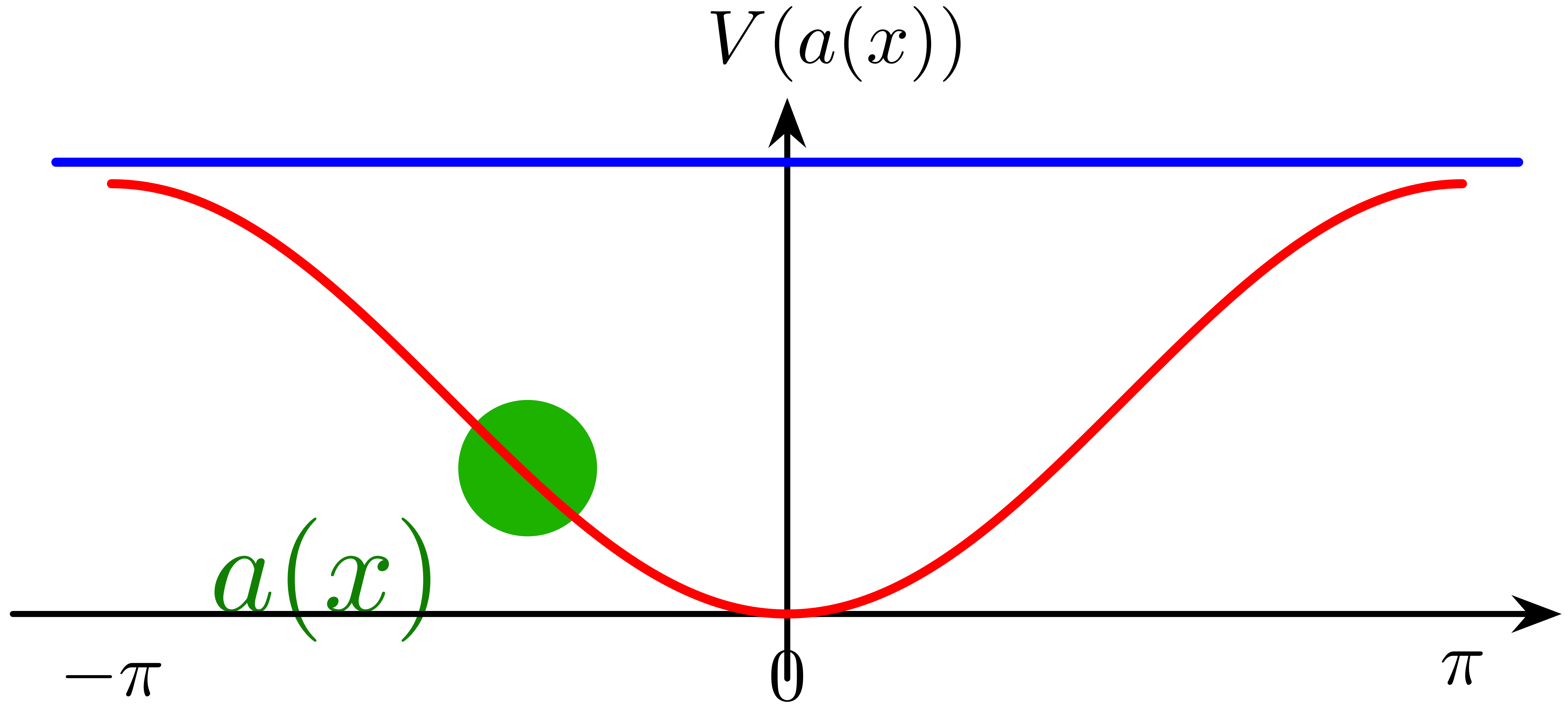

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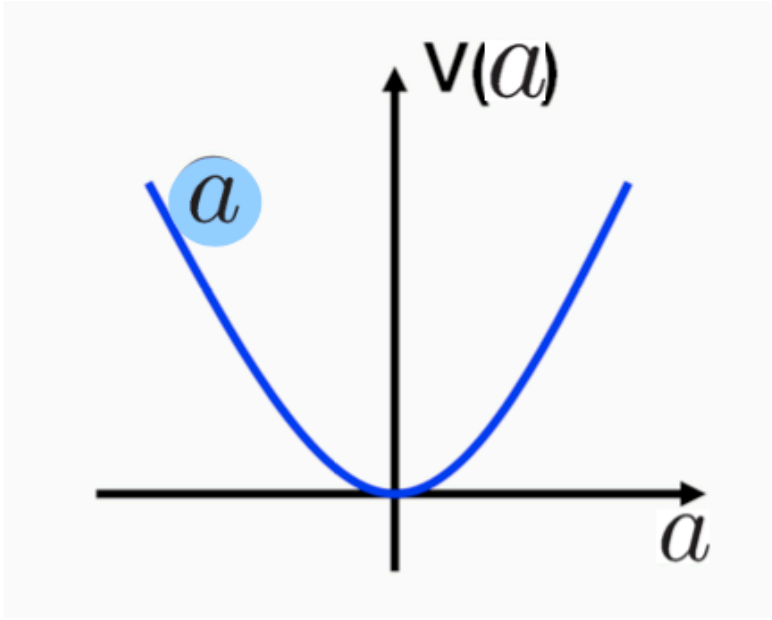

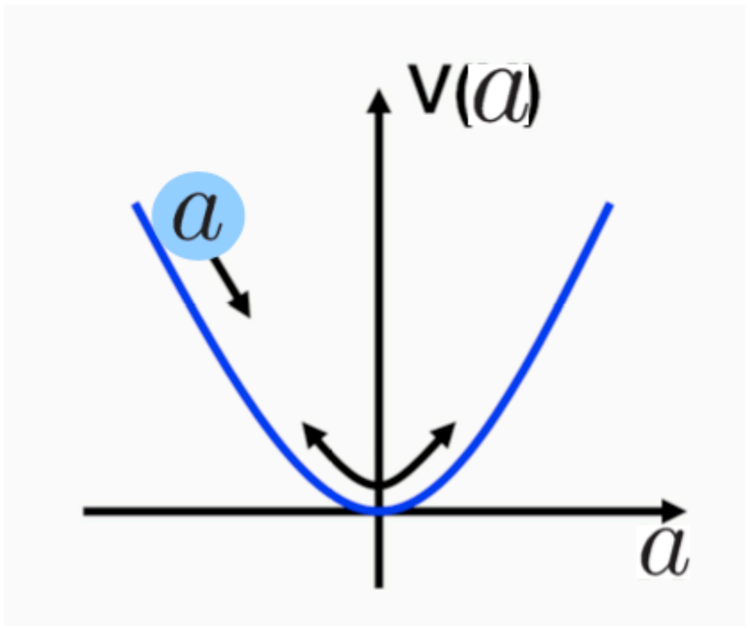

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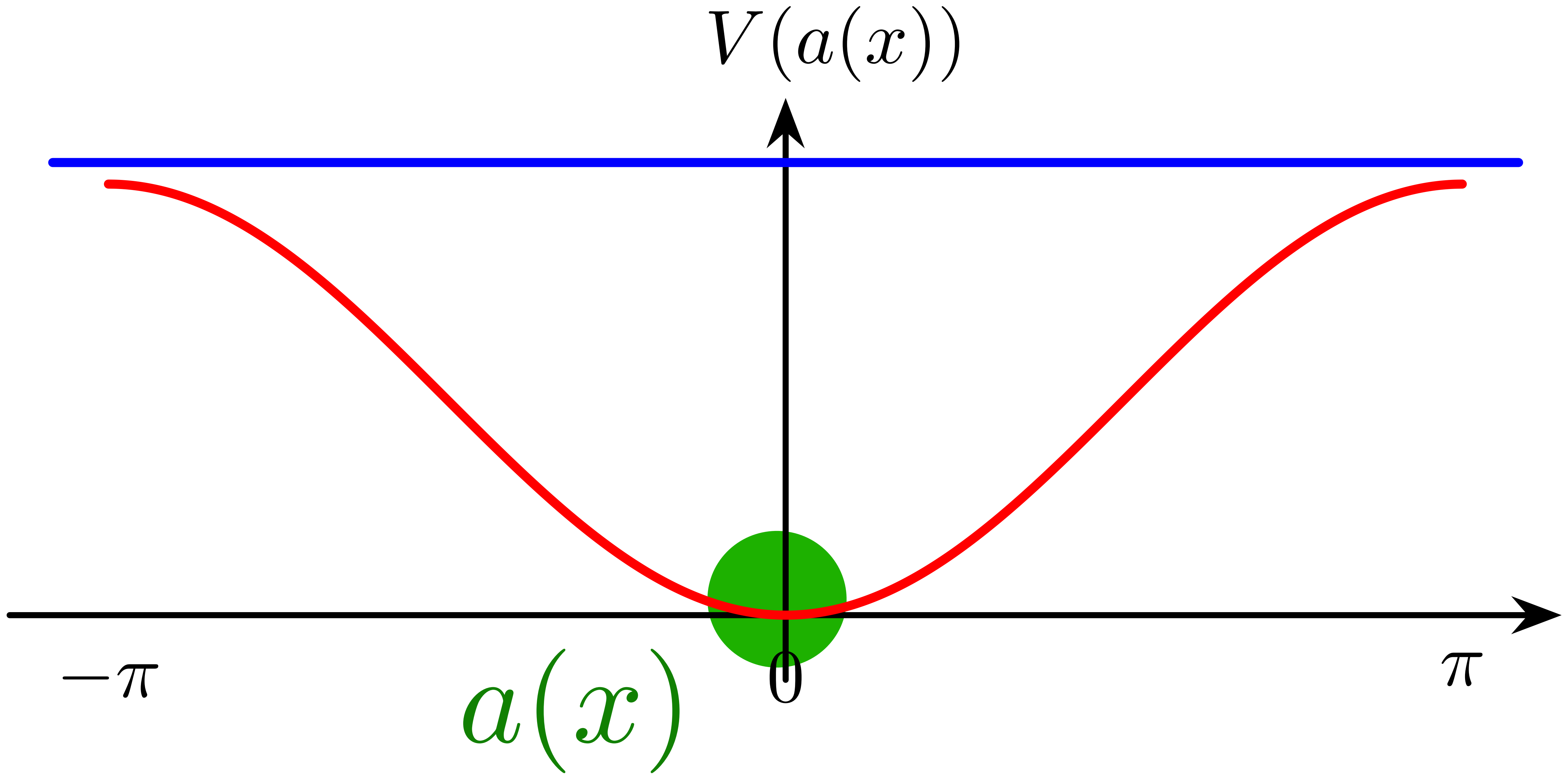

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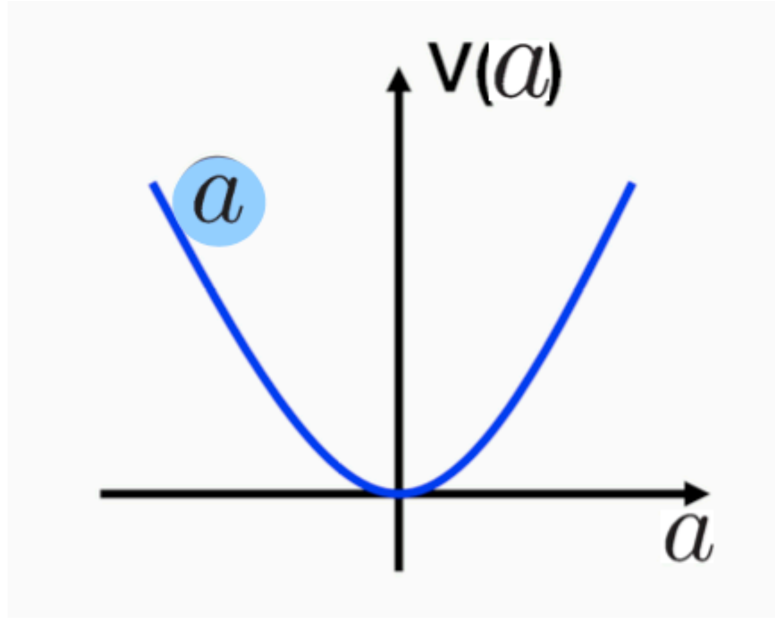

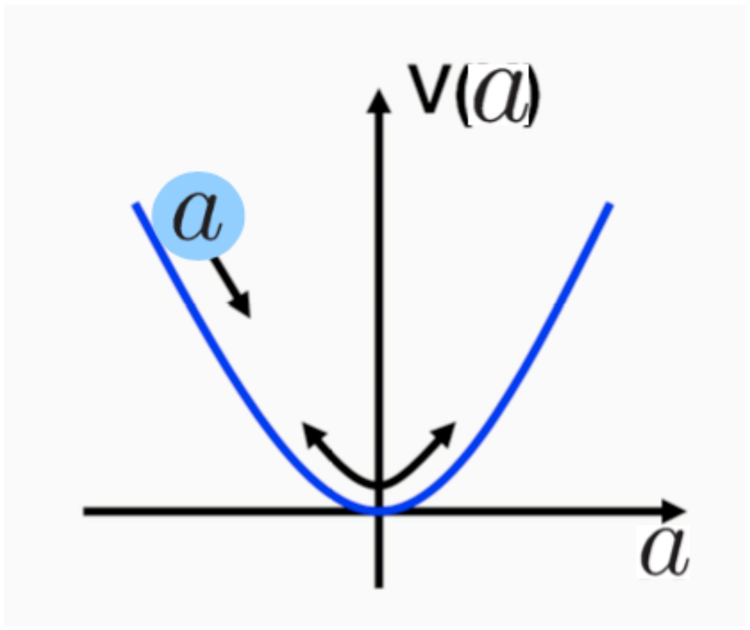

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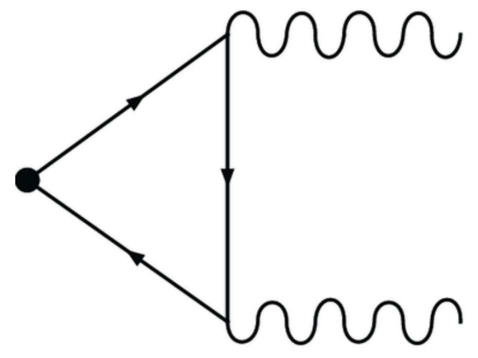
$$\rho_a(t) = \frac{\rho_{\text{ini}}}{R^3(t)} \implies \textbf{Dark Matter}$$

QCD axion solution to strong CP

- Axial PQ symmetry $U(1)_{\rm PQ}$: spontaneously broken at the scale f_a

- Explicitly broken at the quantum level by QCD anomaly



- pNGB: the QCD axion $a(x)$

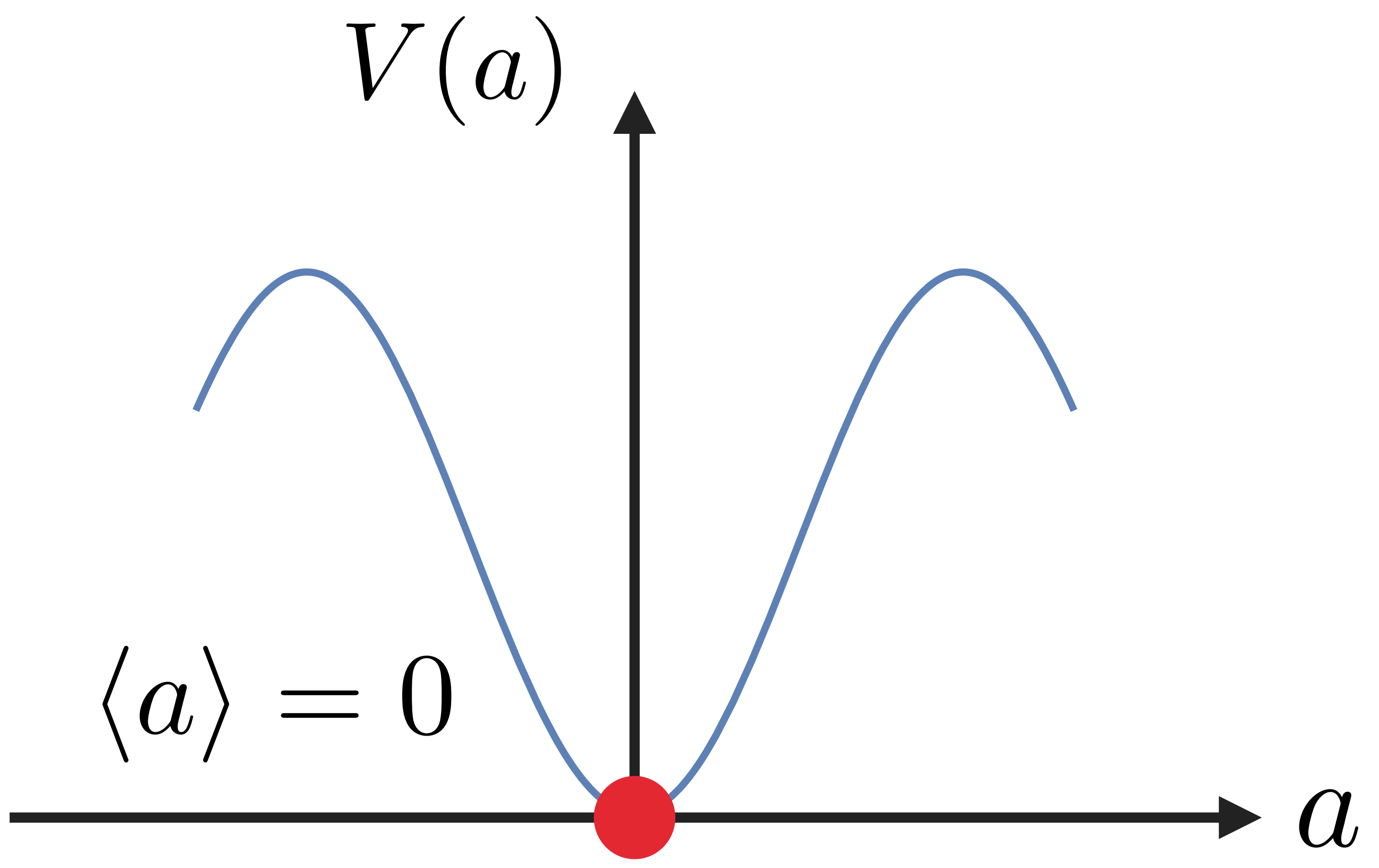
$$\mathcal{L} = \left(\frac{a}{f_a} - \bar{\theta}\right)\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\tilde{G}^{\mu\nu,a}$$

- Axion has an approximate shift-symmetry $a \to a + \bar{\theta} f_a$

Why Axions?

The QCD axion is predictive

- In the IR, QCD confinement generates potential



UV

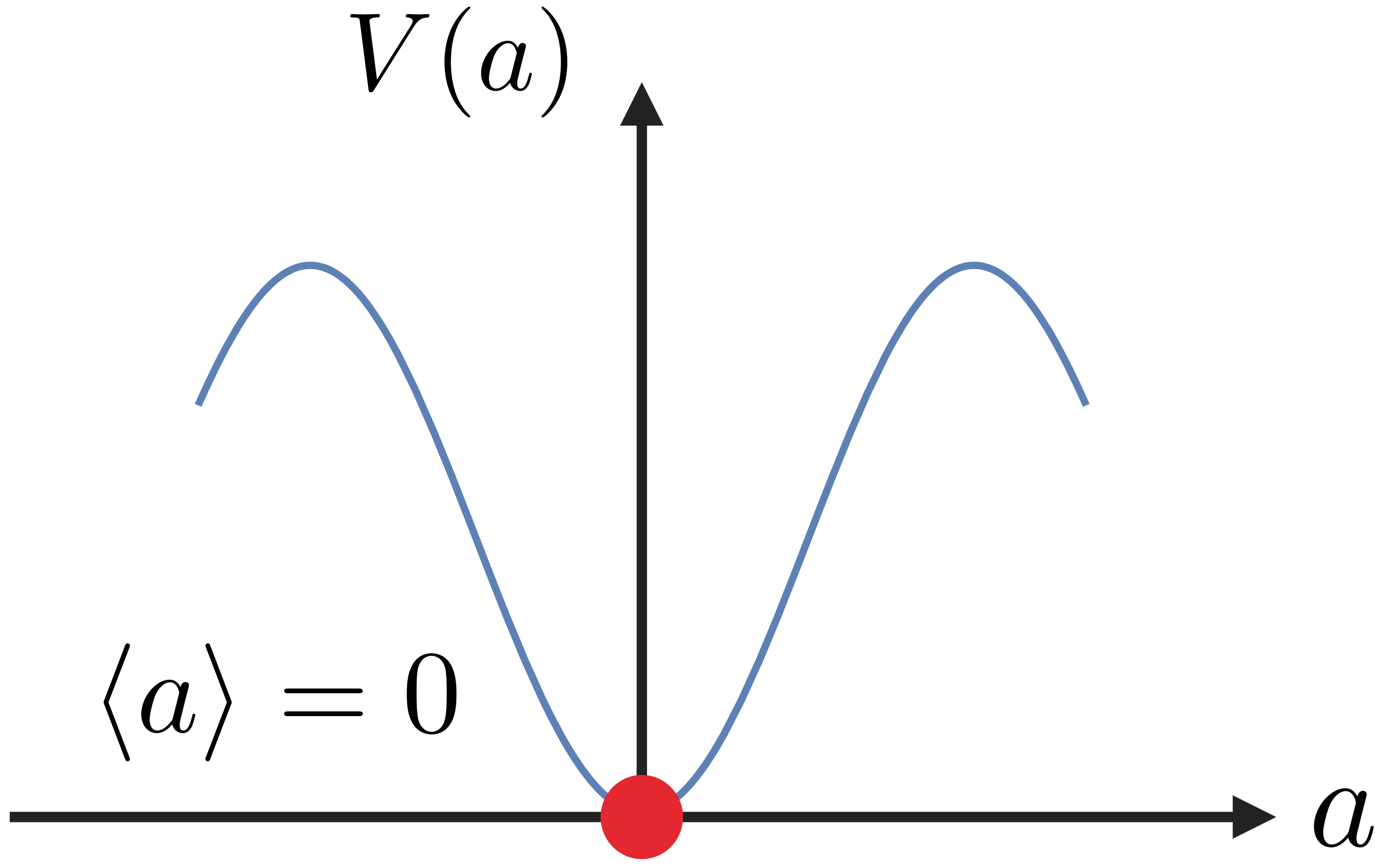
$$\frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} \longrightarrow$$

IR

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

$$m_a \simeq \frac{m_\pi f_\pi}{f_a}$$

Axion properties and signatures



The QCD axion is very predictive

- In the IR, QCD confinement generates potential

UV

IR

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

- Couples to electrons, nucleons, photons, …

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

Mostly determined by f_a

The DESY axion search program

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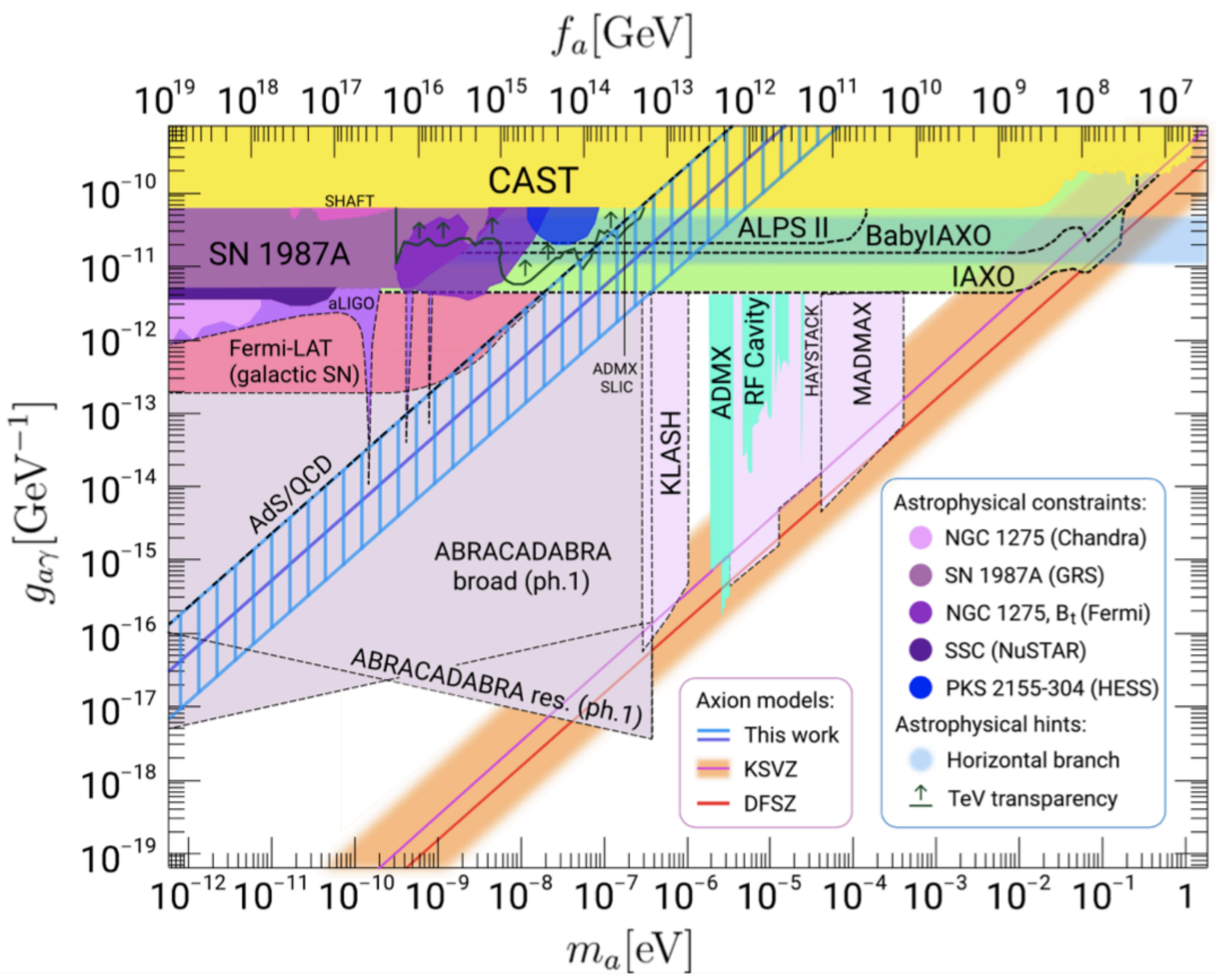
Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

February 14, 2023

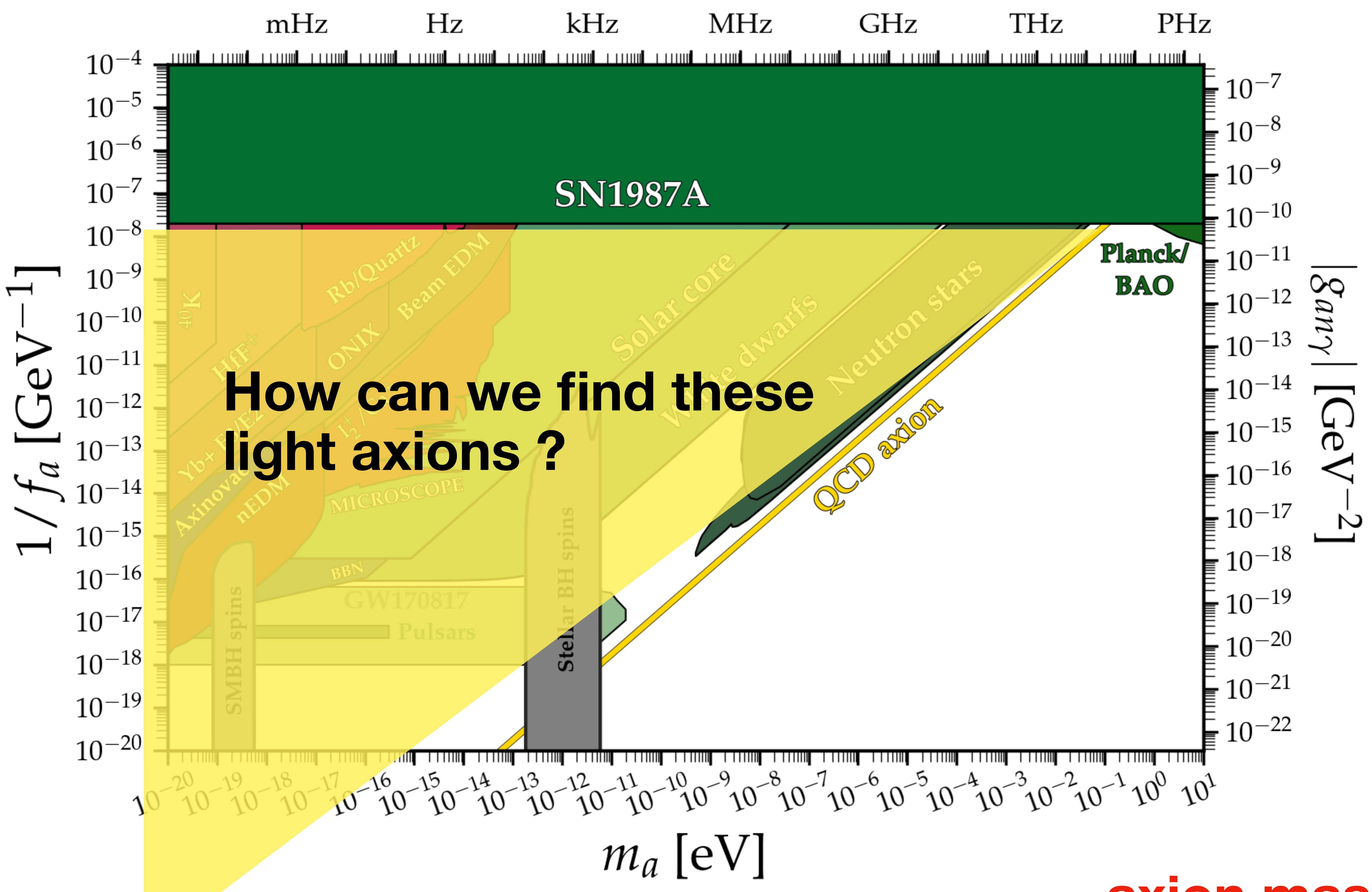
1 Introduction

Feebly Interacting Particles (FIPs) might offer the solution to (some of) the open questions beyond the Standard Models of particle physics and cosmology. At DESY in Hamburg, three non-accelerator-based experiments will search for FIPs as dark matter candidates (ALPS II, BabyIAXO) or constituting the dark matter in our home galaxy (MADMAX). Such experiments have to strive for sensitivities many orders beyond the reach of collider or beam-dump experiments. Among FIPs, the axion as motivated by the lack of any observed CP violation in Quantum Chromodynamics (QCD) [1, 2, 3, 4], is frequently being used as a benchmark to compare the sensitivities of experimental efforts. Axions result from a new global Peccei-Quinn symmetry $U(1)$ that spontaneously breaks at the scale f_a. For the detection of axions, all three experiments rely on the axion-



Axion parameter space

axion coupling



How can we find these light axions ?

axion mass

https://github.com/cajohare/AxionLimits

Presence of matter…

… modifies the axion potential—altering stellar behavior

… changes the couplings, affecting how physical processes unfold

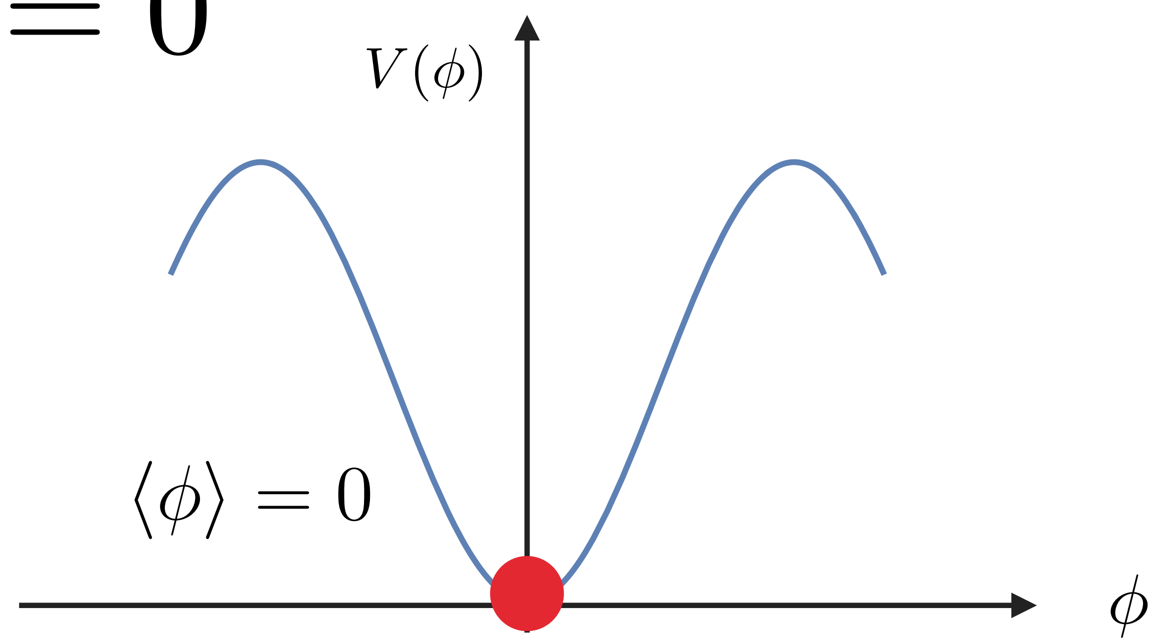
Axion properties are highly susceptible to matter effects

Potential changes with density *n*

2211.02661, 2307.14418, 2408.07740

$n = 0$

vacuum



Axion properties are highly susceptible to matter effects

Potential changes with density *n*

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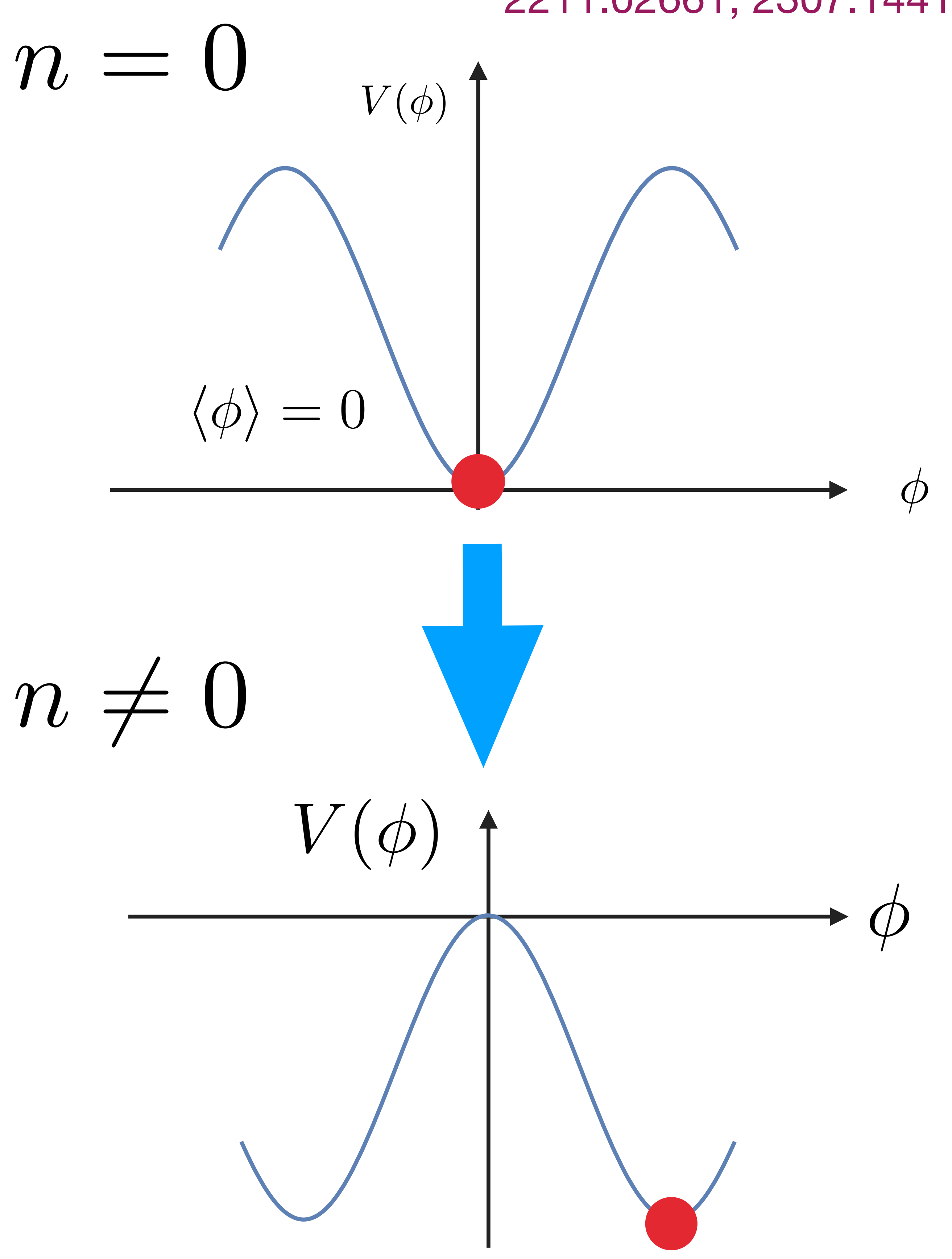
vacuum

inside star



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

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2211.02661, 2307.14418, 2408.07740

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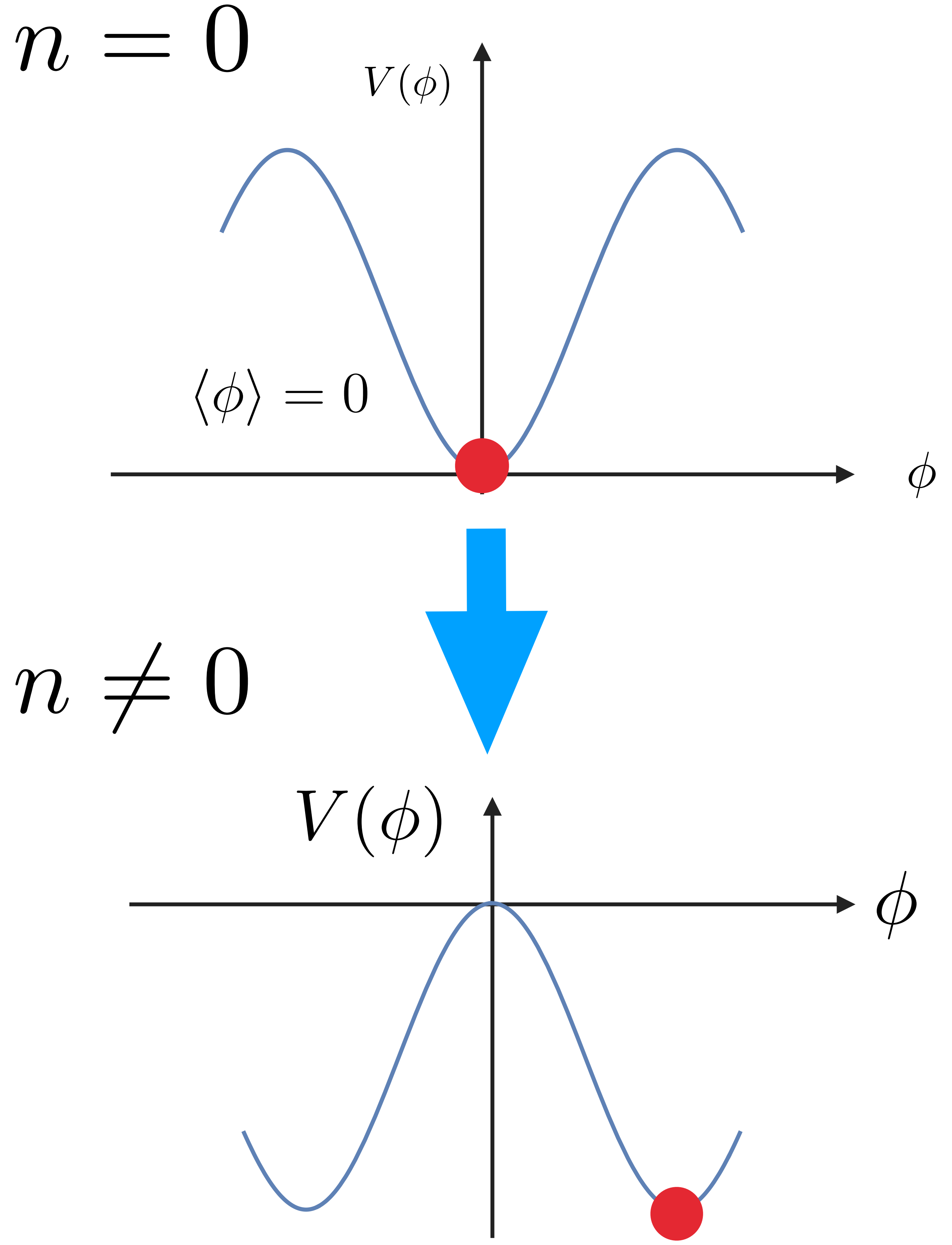


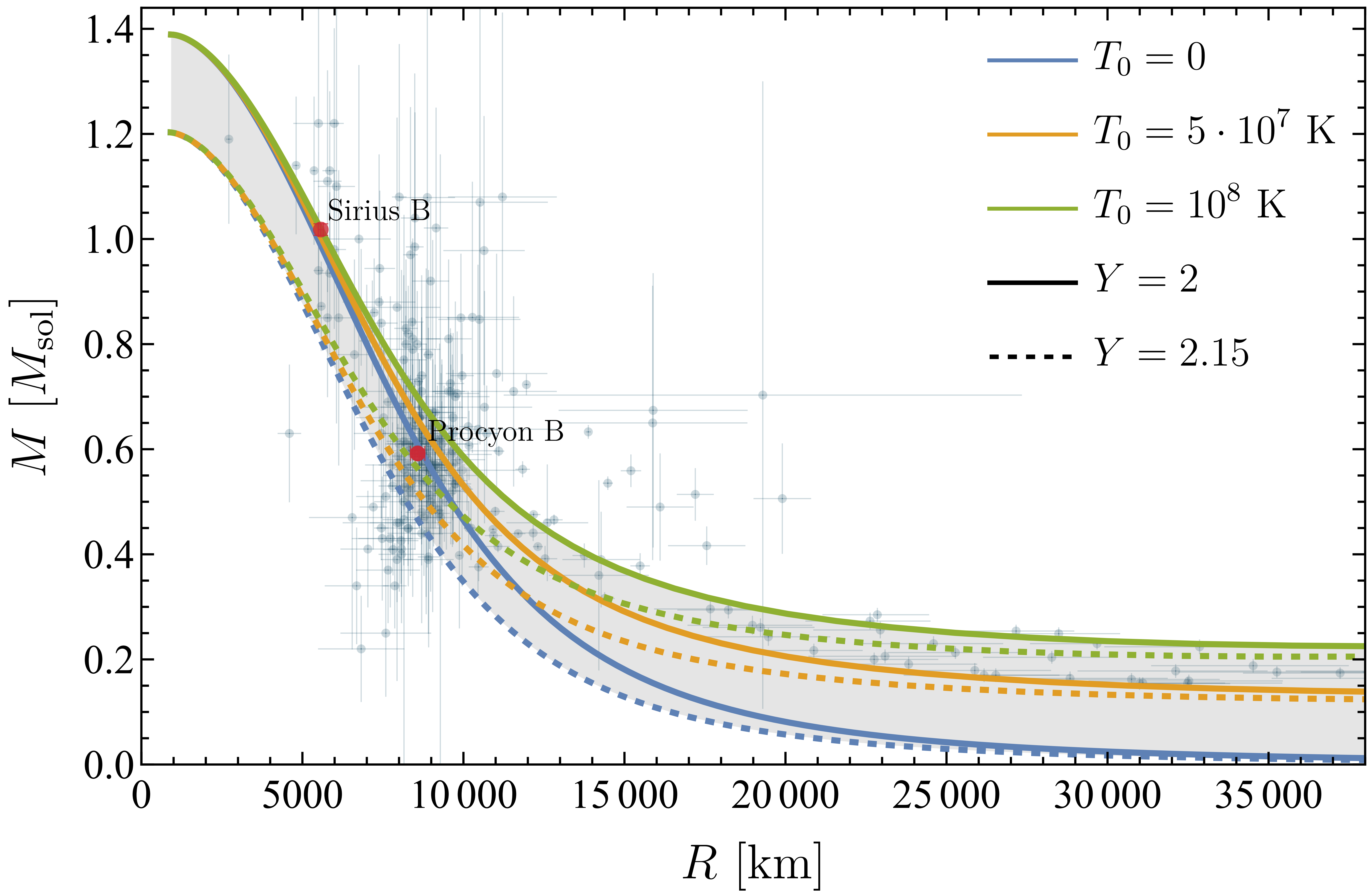
minimum becomes maximum at finite density!

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

White Dwarfs:

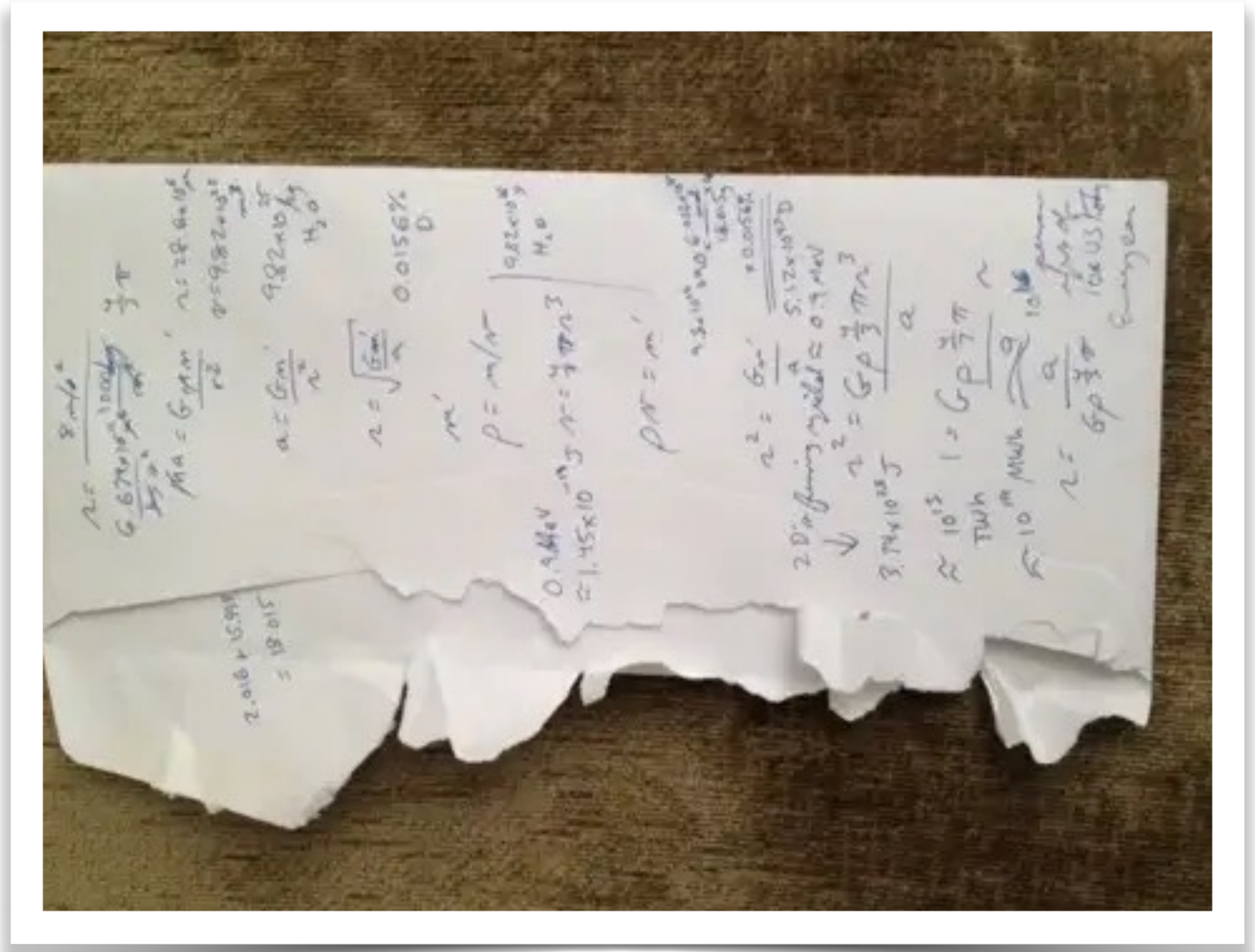
Fermi pressure from electron gas

Mass radius curve for white dwarfs



Back of the envelope …

… power of dimensional analysis (laziness as a virtue)



vs.

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

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

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

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

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

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

White dwarfs simplified

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

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

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

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

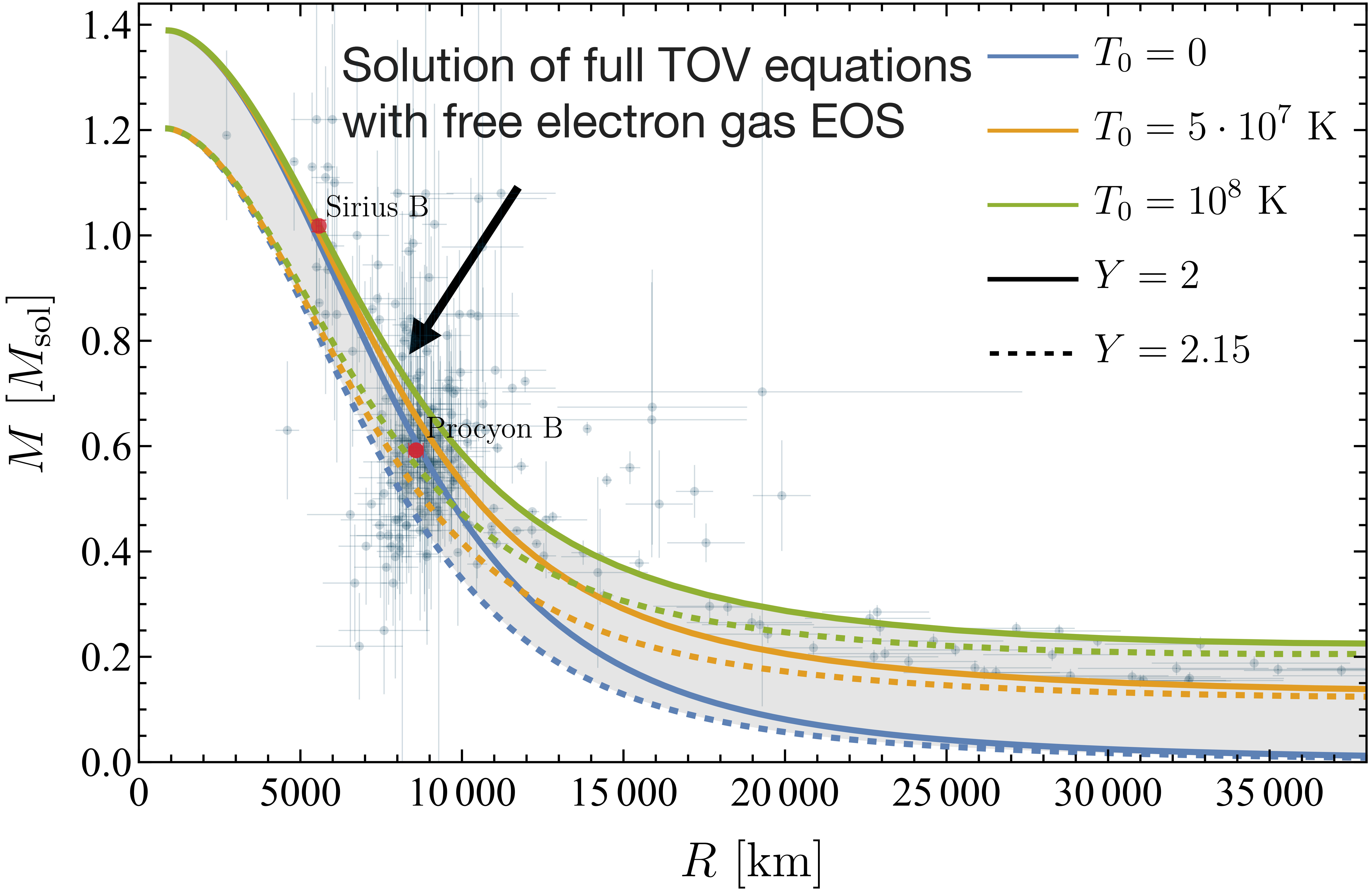
$$M_{\text{WD}} \sim (\text{few})10^{30}\,\text{kg} \sim M_\odot$$

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

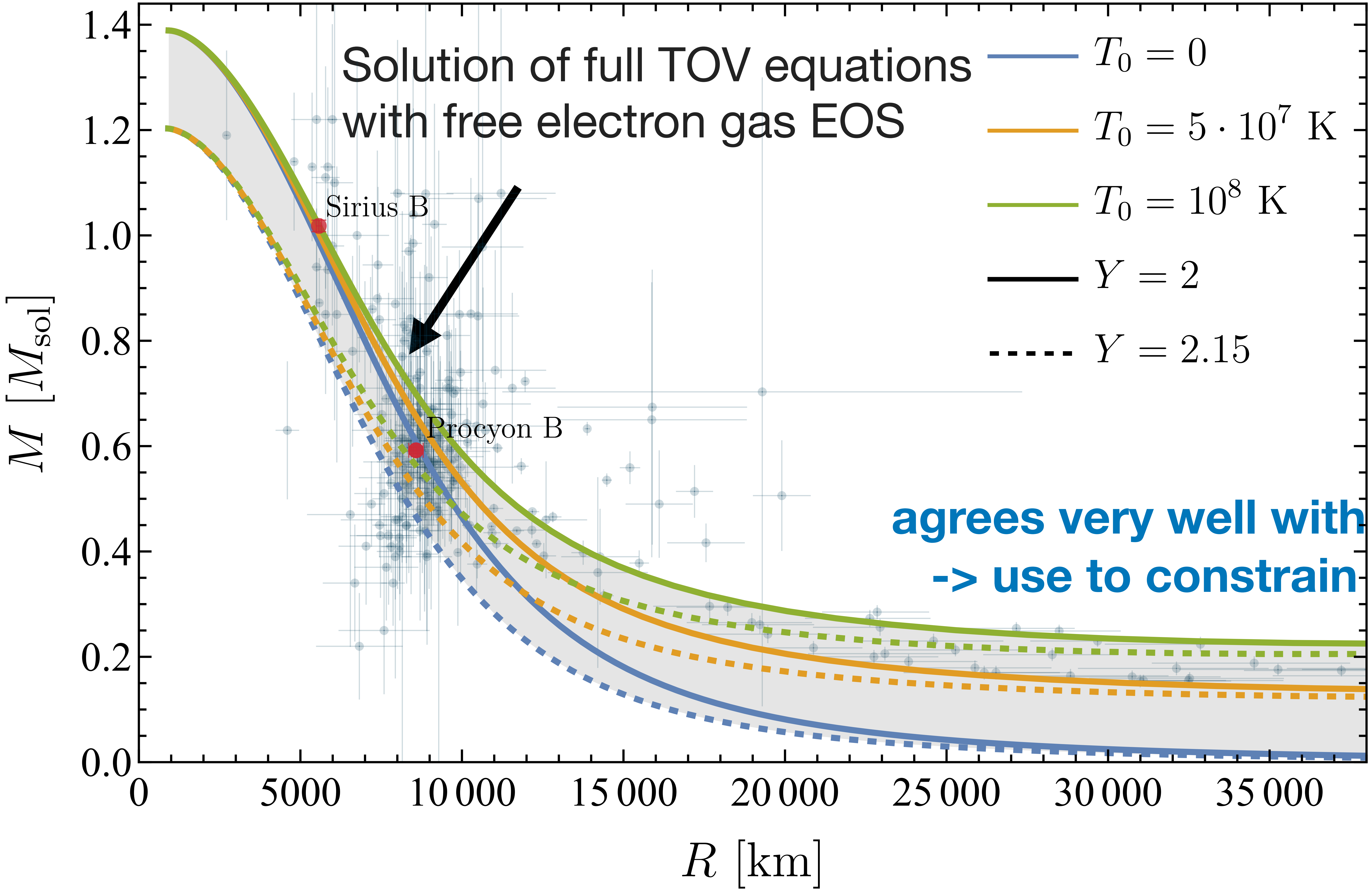
Mass of the sun at the size of the earth.

electron mass	$m_e = 0.51099895000$
Planck scale	$M_{\text{Planck}} \approx 10^{19}$ GeV
nucleon mass	$M_N \approx 1$ GeV

White dwarf mass-radius curve



White dwarf mass-radius curve



agrees very well with SM
-> use to constrain BSM

Stellar Structure

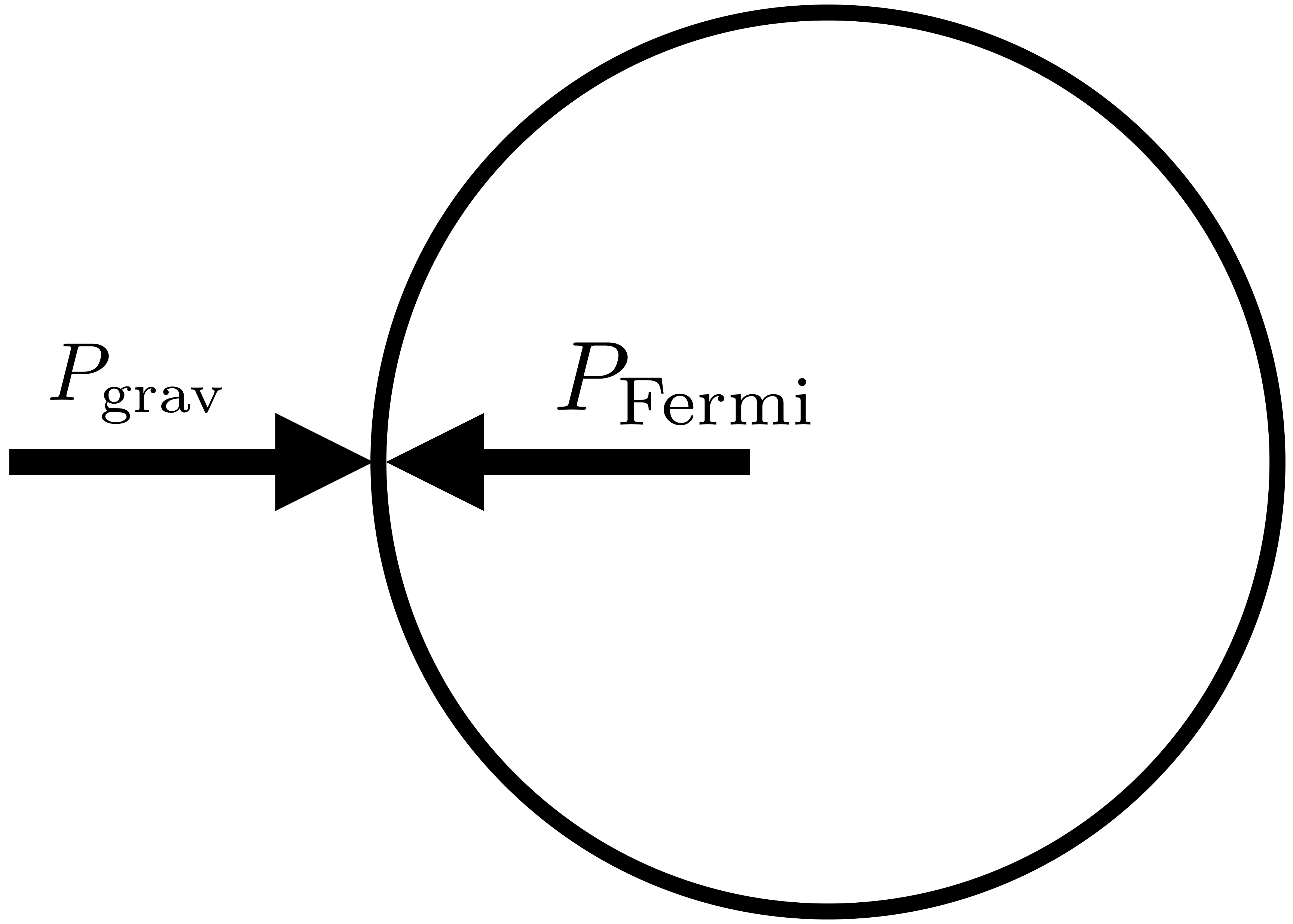
Star: pressure balance between gravity and internal pressure

- Hydrostatic equilibrium equation:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{GM\varepsilon}{r^2}$$

- Mass conservation:

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2 \varepsilon$$



Simple Relation between p and ε : Equation of State (EOS) $p(\varepsilon)$

White Dwarfs: $p_{\mathrm{int}} = p_{\mathrm{Fermi}}$

Stellar Structure with New Scalars

- Hydrostatic equilibrium equation (include GR effects):

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

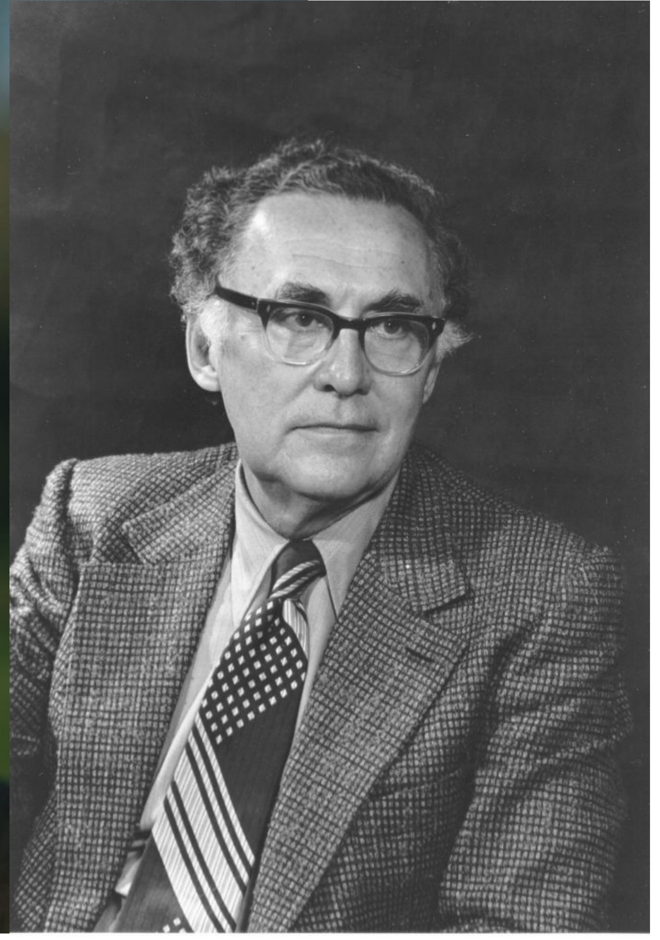
- Mass conservation:

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

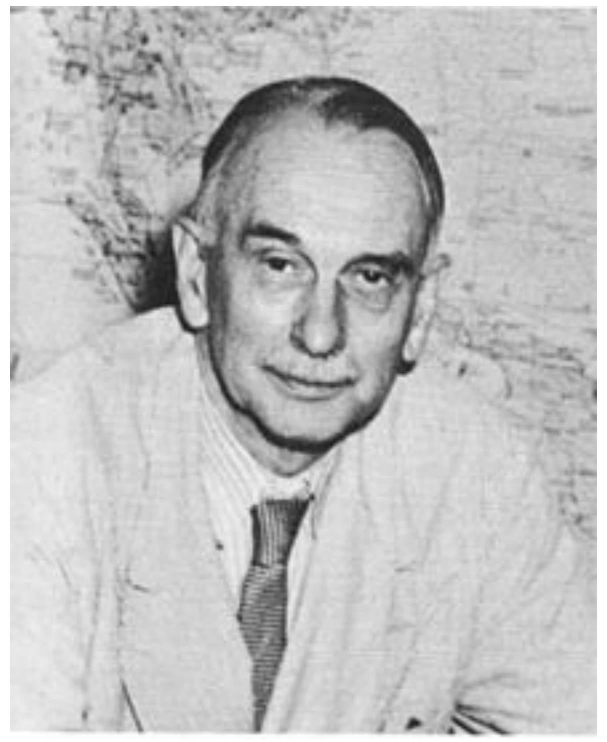
- Scalar EOM:

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

Oppenheimer



Volkoff



Tolman

Stellar Structure with New Scalars

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

- Mass conservation:

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

- Scalar EOM:

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

Stellar Structure with New Scalars

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- Mass conservation:

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

include BSM scalar in TOV equation

- Scalar EOM:

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

Stellar Structure with New Scalars

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

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- Mass conservation:

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

Switch on the coupling:
$m_\psi \to m_\psi(\phi)$

- Scalar 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]

Simplifying limit:

Scalar gradient costs energy: $E = (\nabla\phi)^2 + V(\phi)$

$\Longrightarrow$ scale for scalar gradient: $\lambda_\phi \sim \dfrac{1}{m_\phi(\rho)}$

Neglect Gradient in large objects if $\lambda_\phi \ll R_{\text{Star}}$

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

Stellar Structure with New Scalars

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- Mass conservation:

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

Neglect Gradient in large objects:
Drop ϕ', ϕ''

- Scalar EOM:

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

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Stellar Structure with New Scalars

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

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Neglect Gradient :
Drop ϕ', ϕ''

Stellar Structure with New Scalars

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- Mass conservation:

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

- Scalar EOM:

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

- **Changed EOS:**

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

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

$$m_\psi(\phi) = m_\psi\left(1-\frac{d^{(2)}_{m_\psi}}{2M_p}\phi^2\right)$$

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

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

Scalar effective potential

Example: Light QCD axion

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

$$\Downarrow$$

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

$$\Downarrow$$

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

Scalar effective potential

Example: Light QCD axion

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

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

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

= 1 for qcd axion,
<< 1 for "light" axion

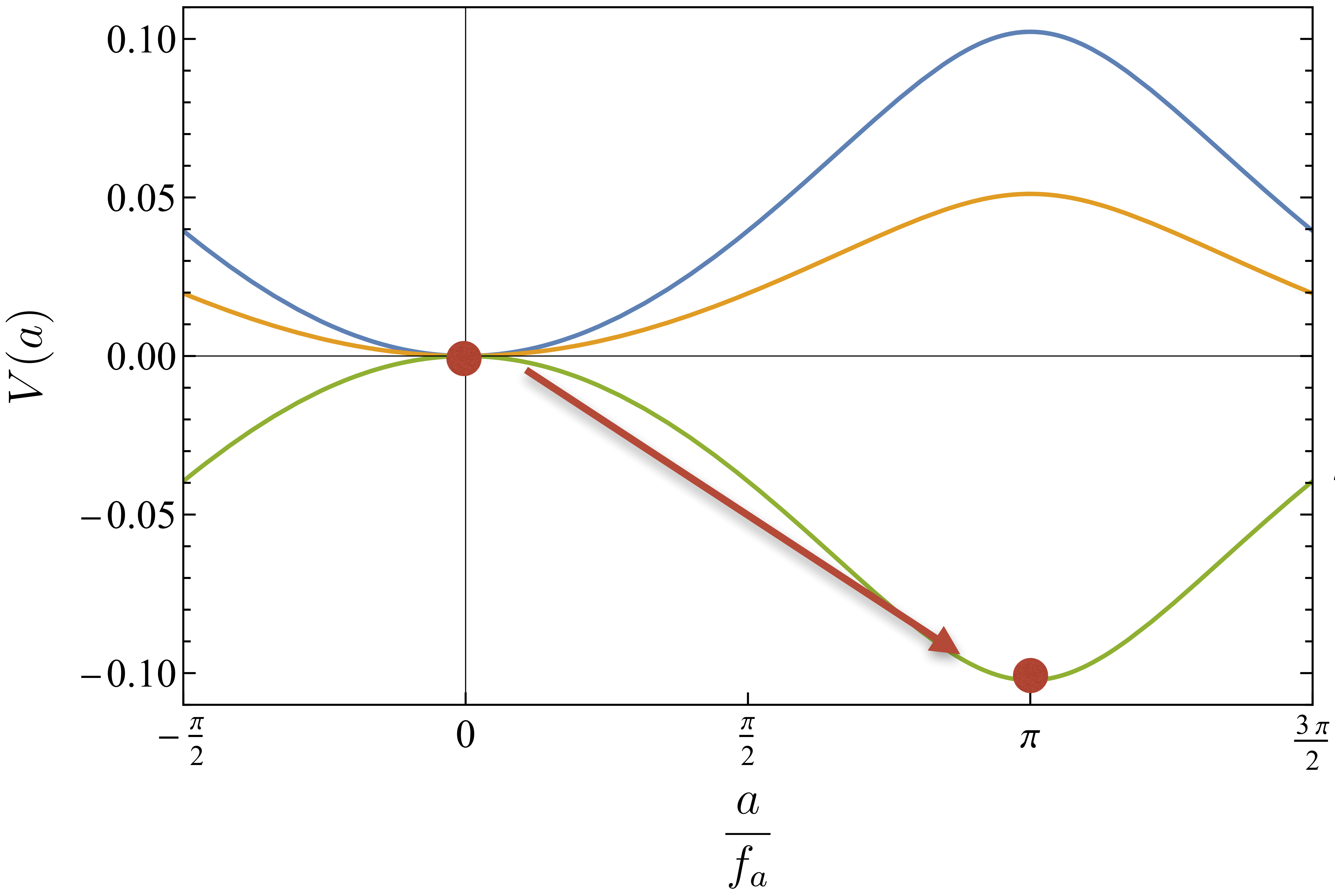
Combine with axion/scalar "bare" mass:

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

Scalar effective potential

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

Light QCD axion



$n = 0$

$n > 0$

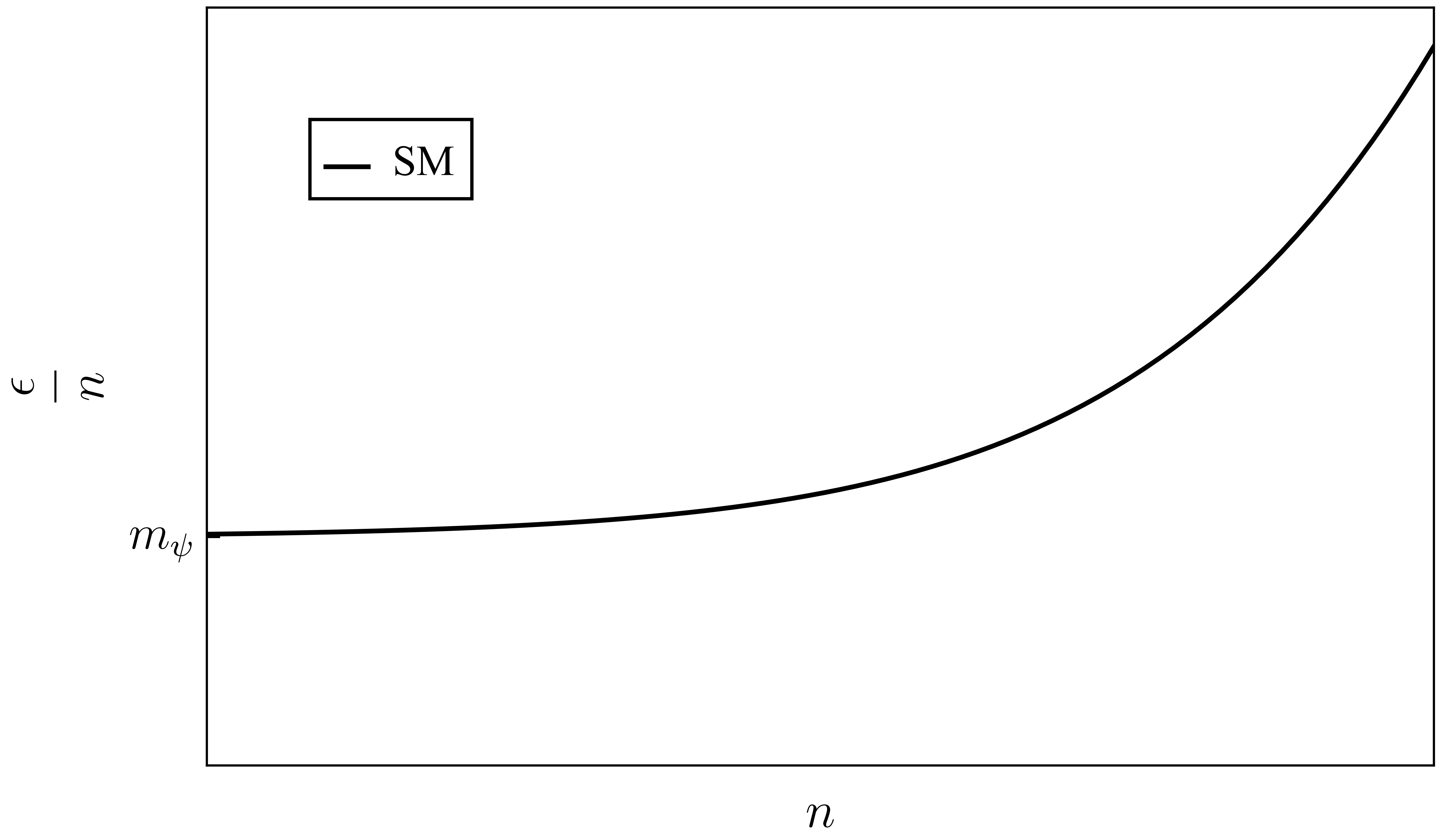
$n > n_c = \dfrac{\epsilon m_\pi^2 f_\pi^2}{\sigma_N}$

$\Longrightarrow$ 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 $\frac{\varepsilon}{n}$



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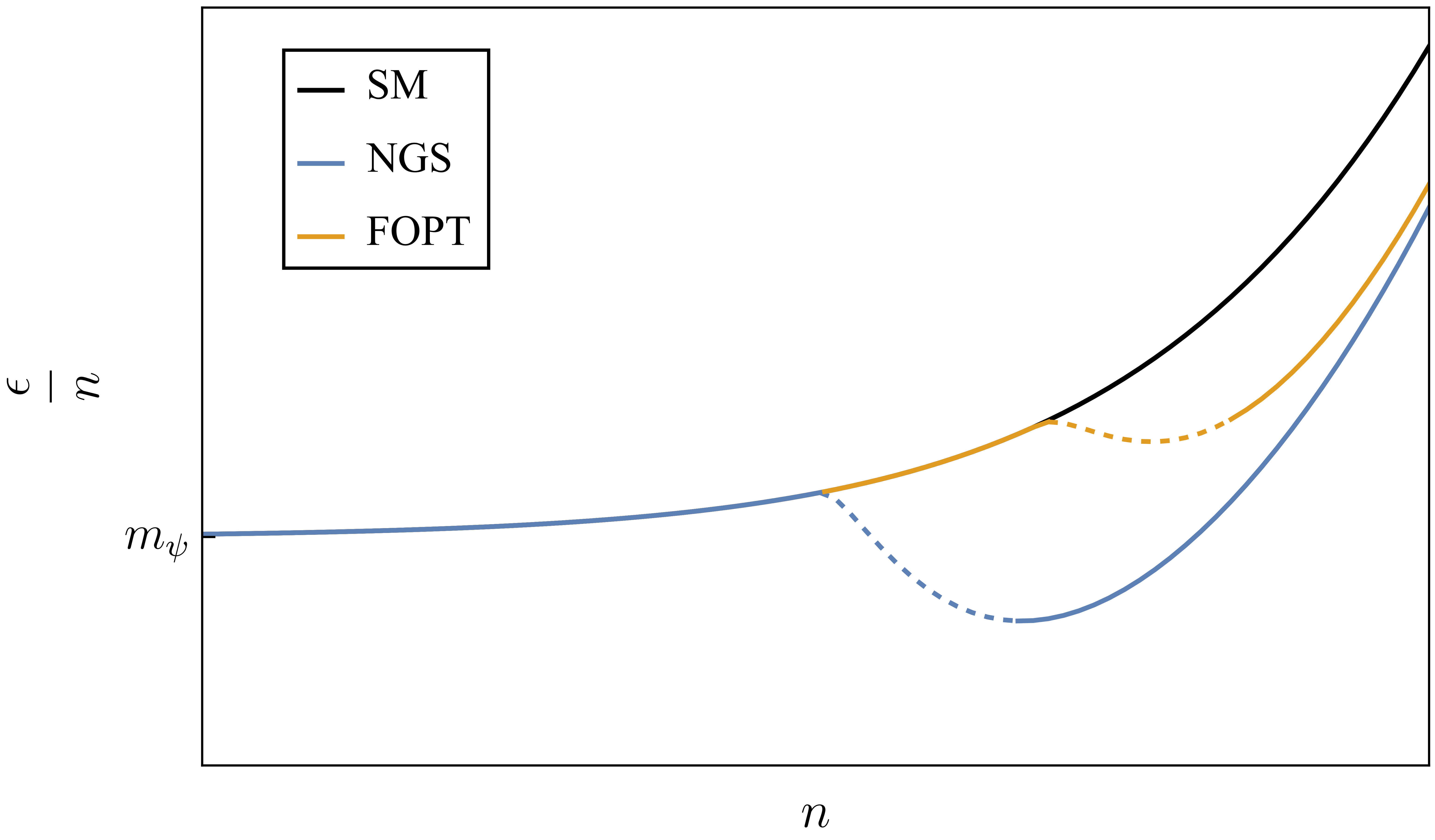

[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]
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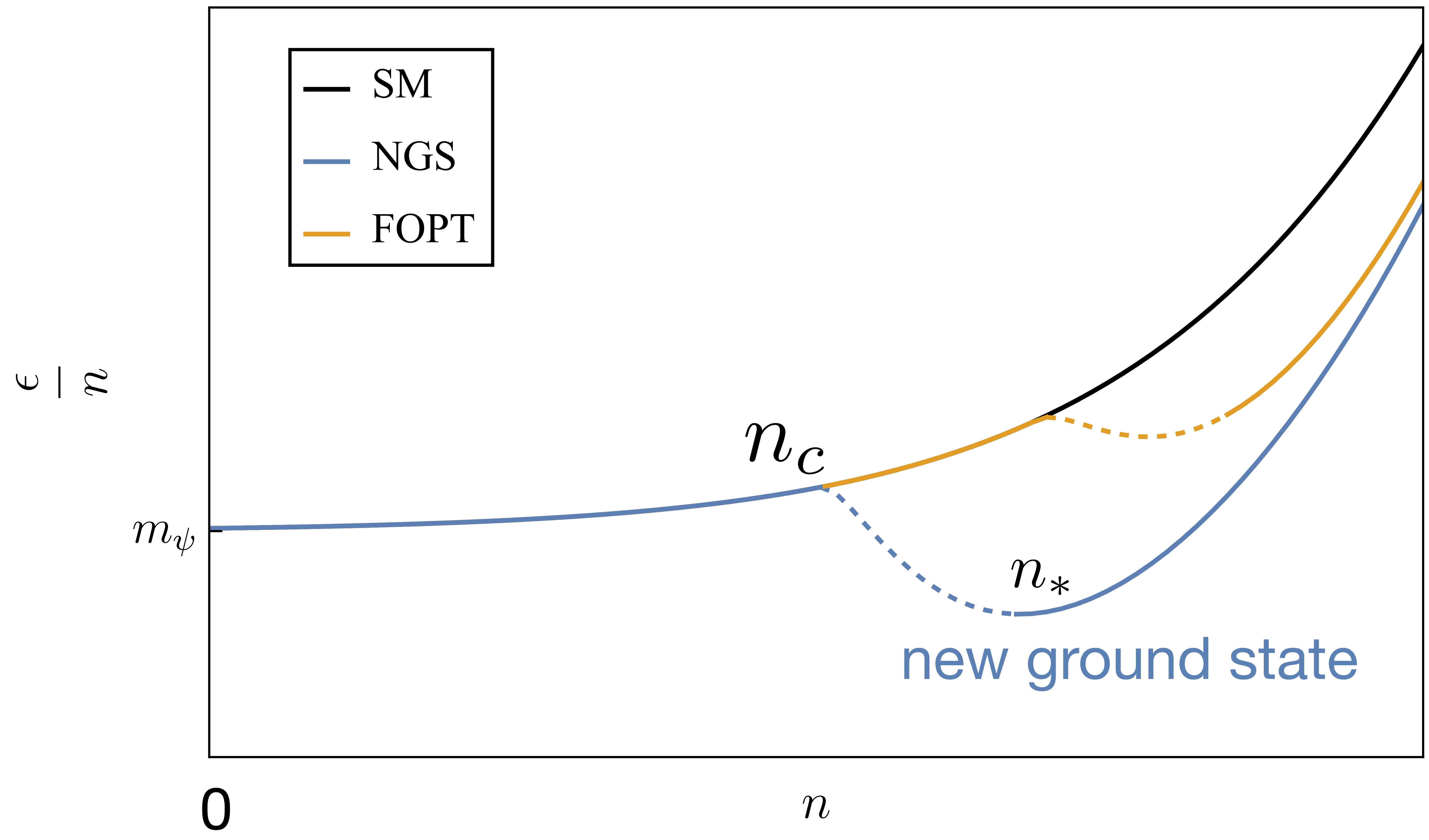

New Ground State (NGS):

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]

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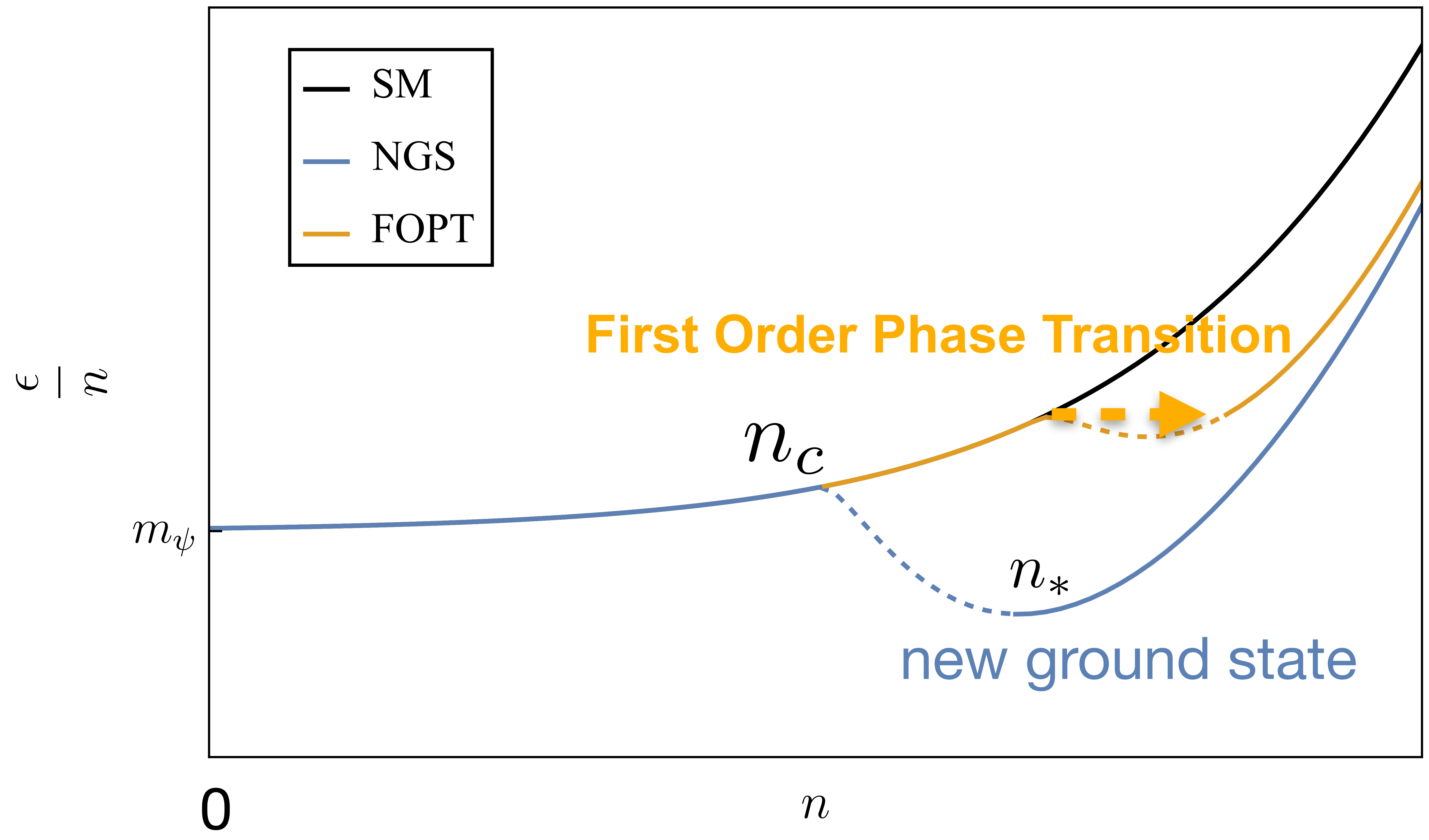


New Ground State (NGS):

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

$\Longrightarrow$ ground state of matter

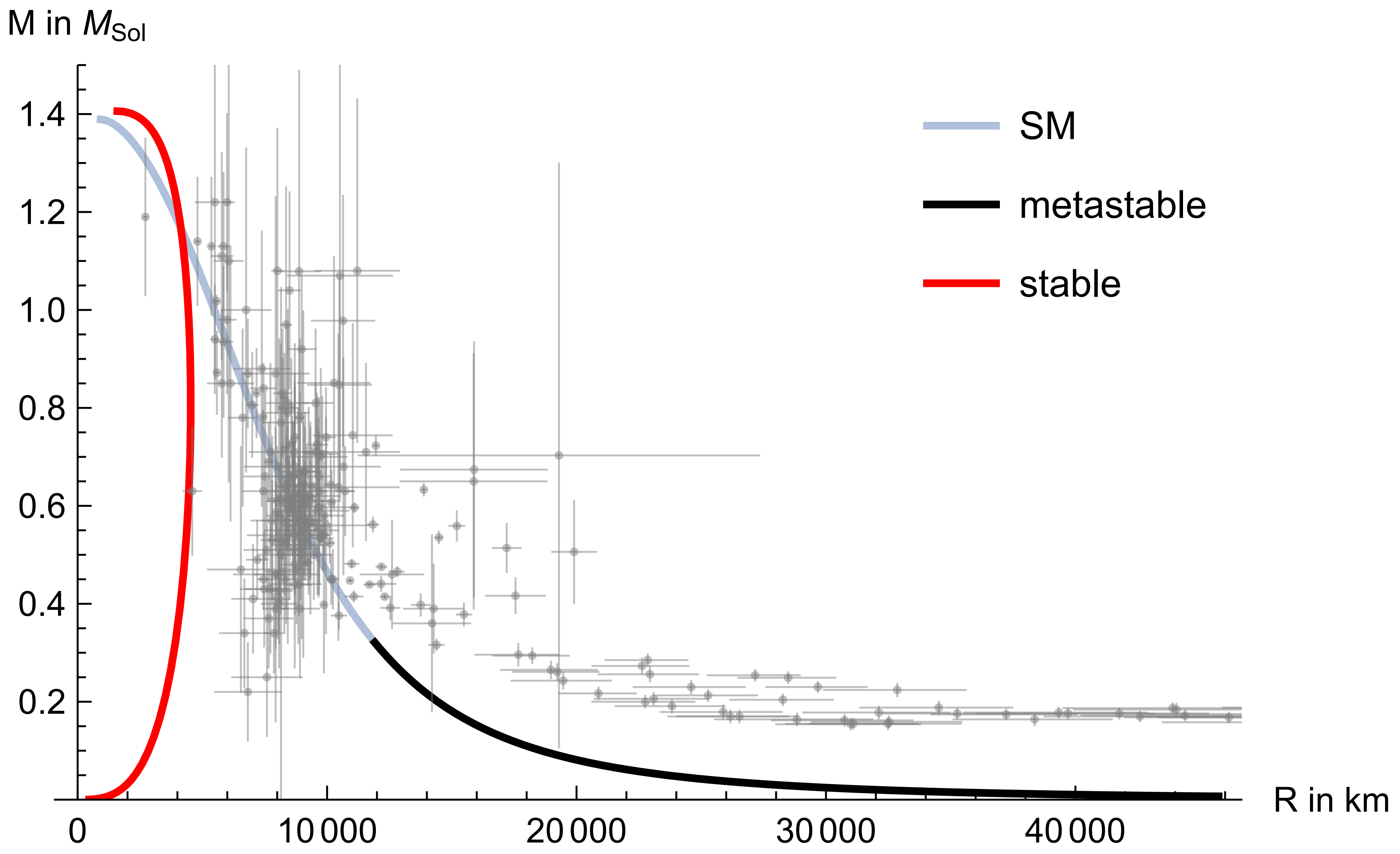
$n < n_c$: metastable

First Order Phase Transition:

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

$\Longrightarrow$ jump in density as field becomes sourced

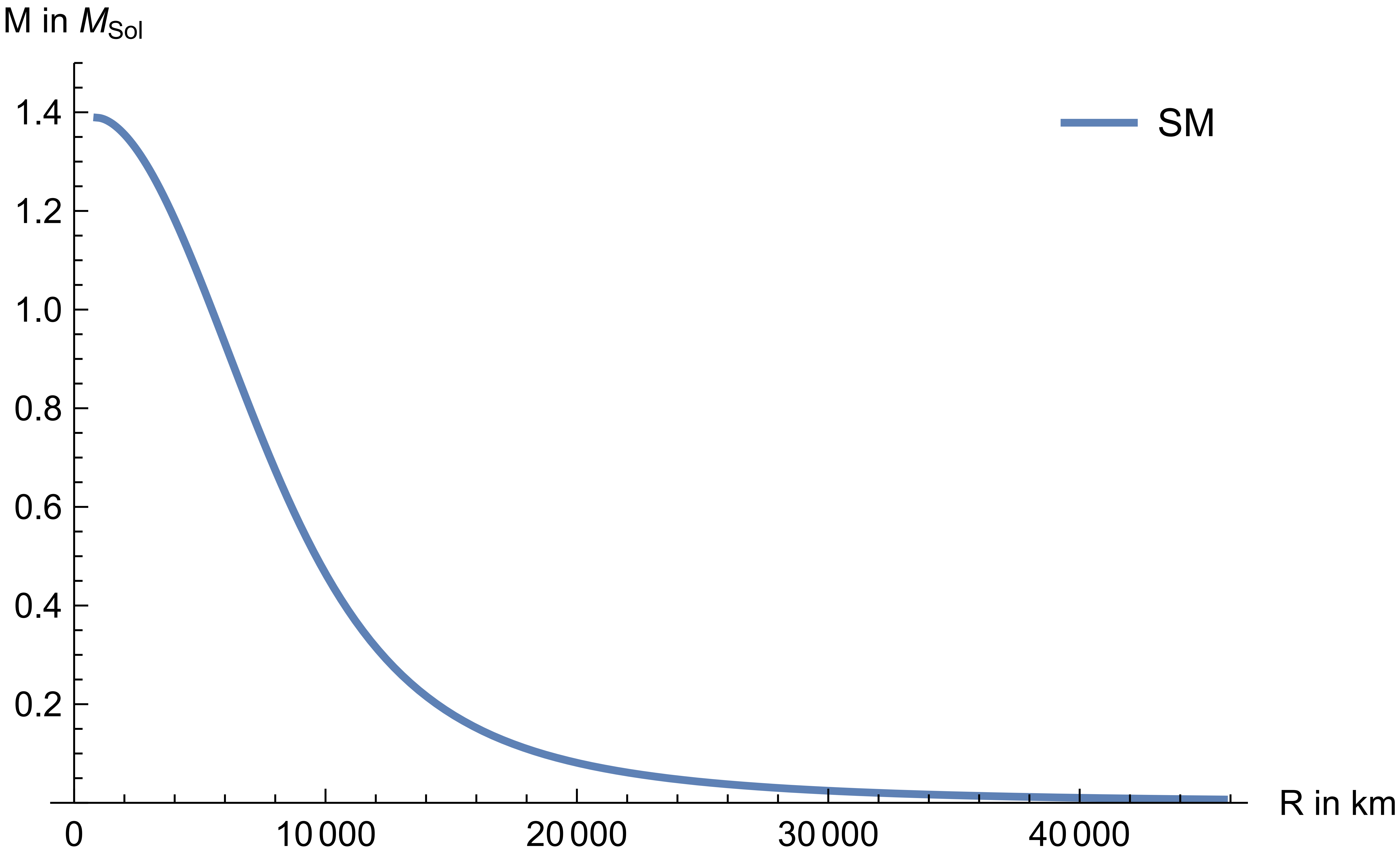
Constraints from White Dwarf Mass Radius Relationship



Observing New Ground States

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

SM: continuous prediction



Observing New Ground States

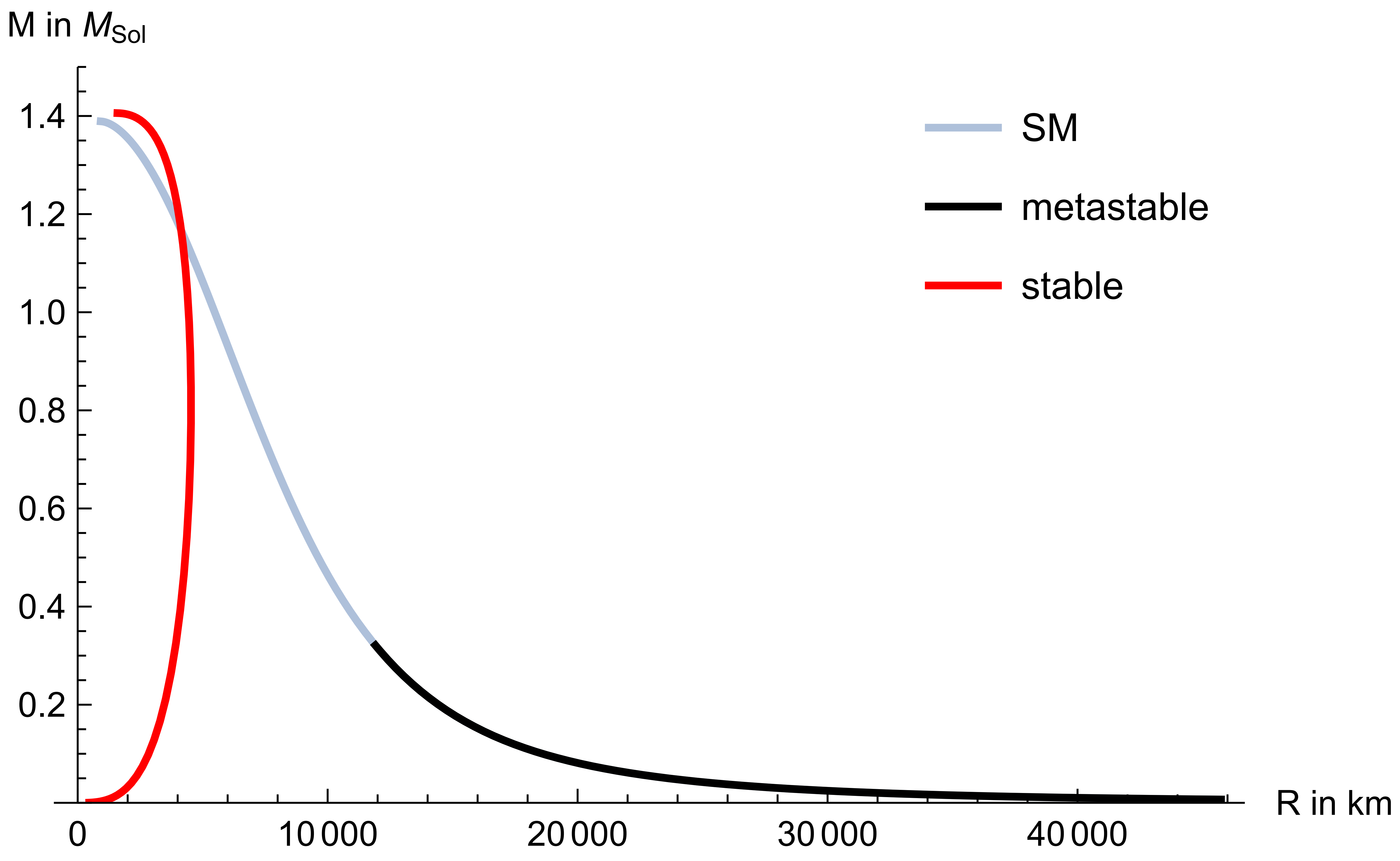
[Balkin, Serra, Springmann, Stelzl, Weiler, 2211.02661]

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]

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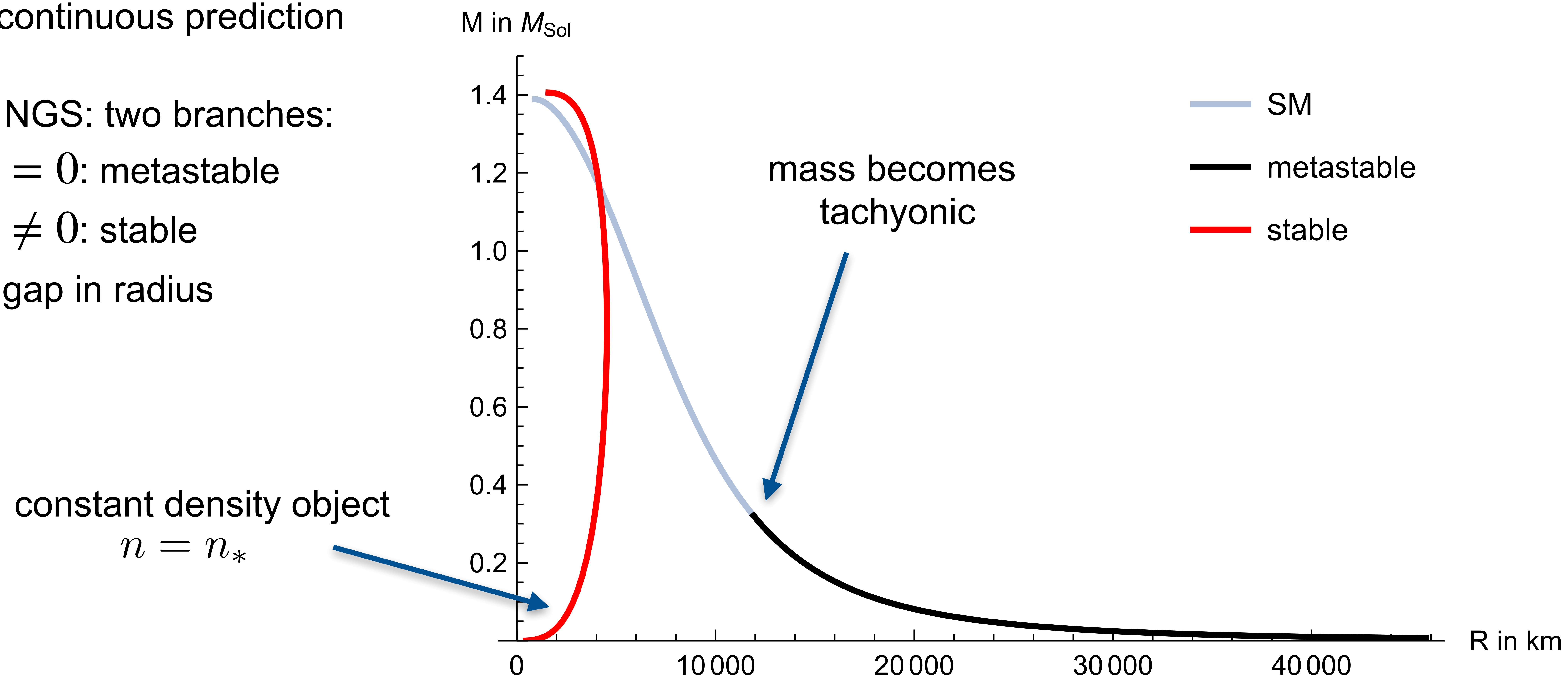


Observing New Ground States: **ϕ-dwarfs**

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

SM: continuous prediction

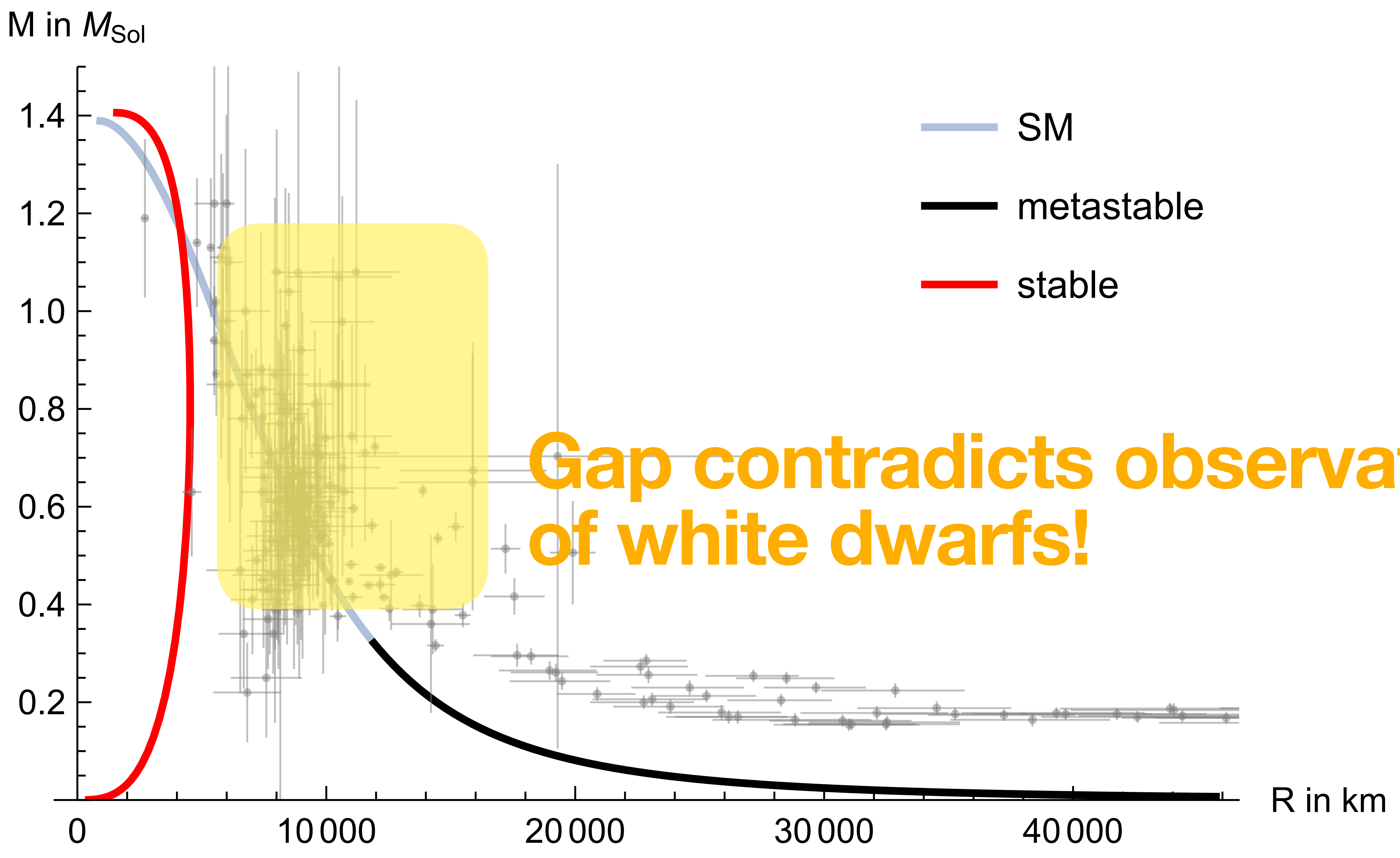
With NGS: two branches:

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

$\Longrightarrow$ gap in radius

Observe WDs in this gap

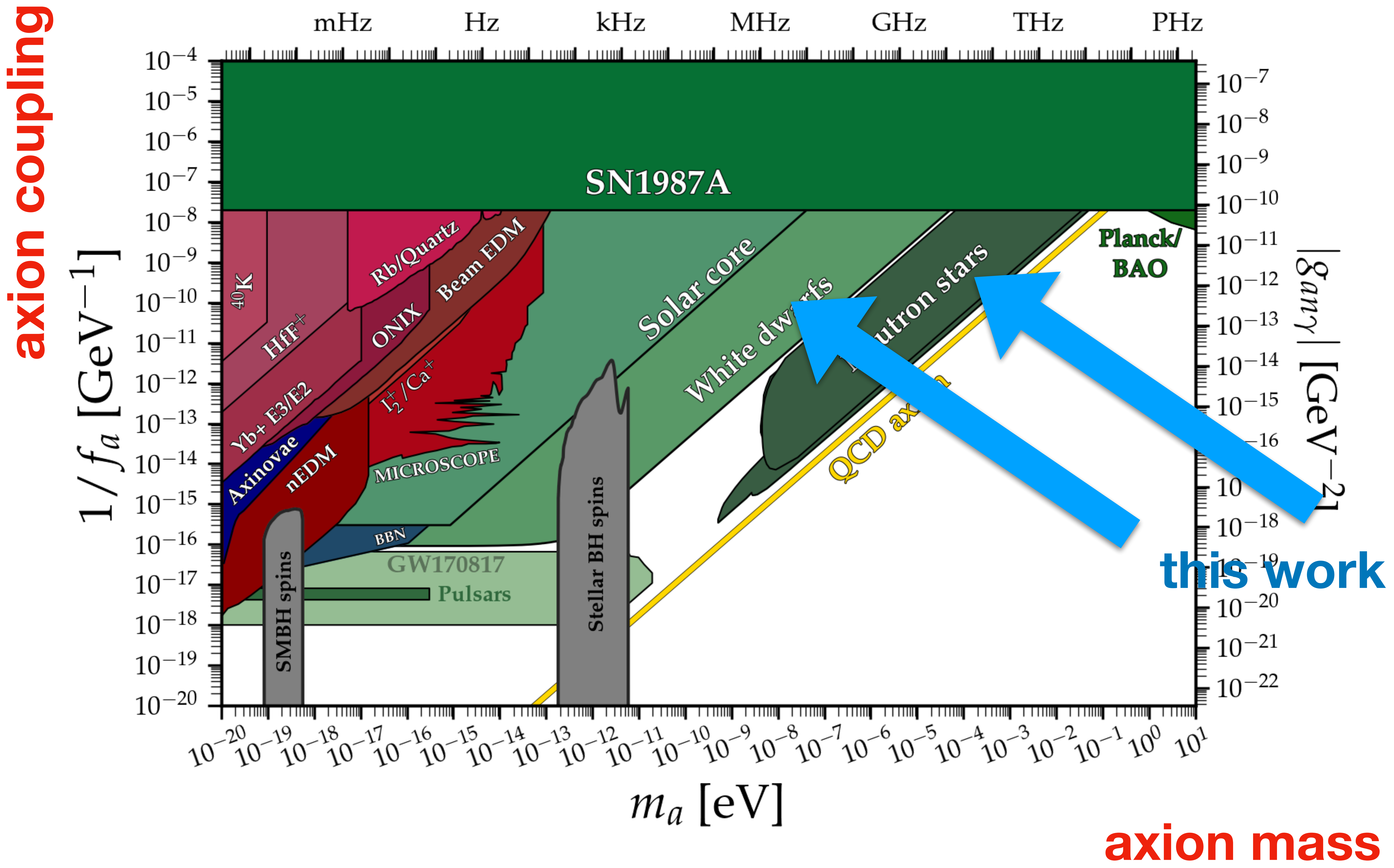
$\Longrightarrow$ exclusion



Gap contradicts observations of white dwarfs!

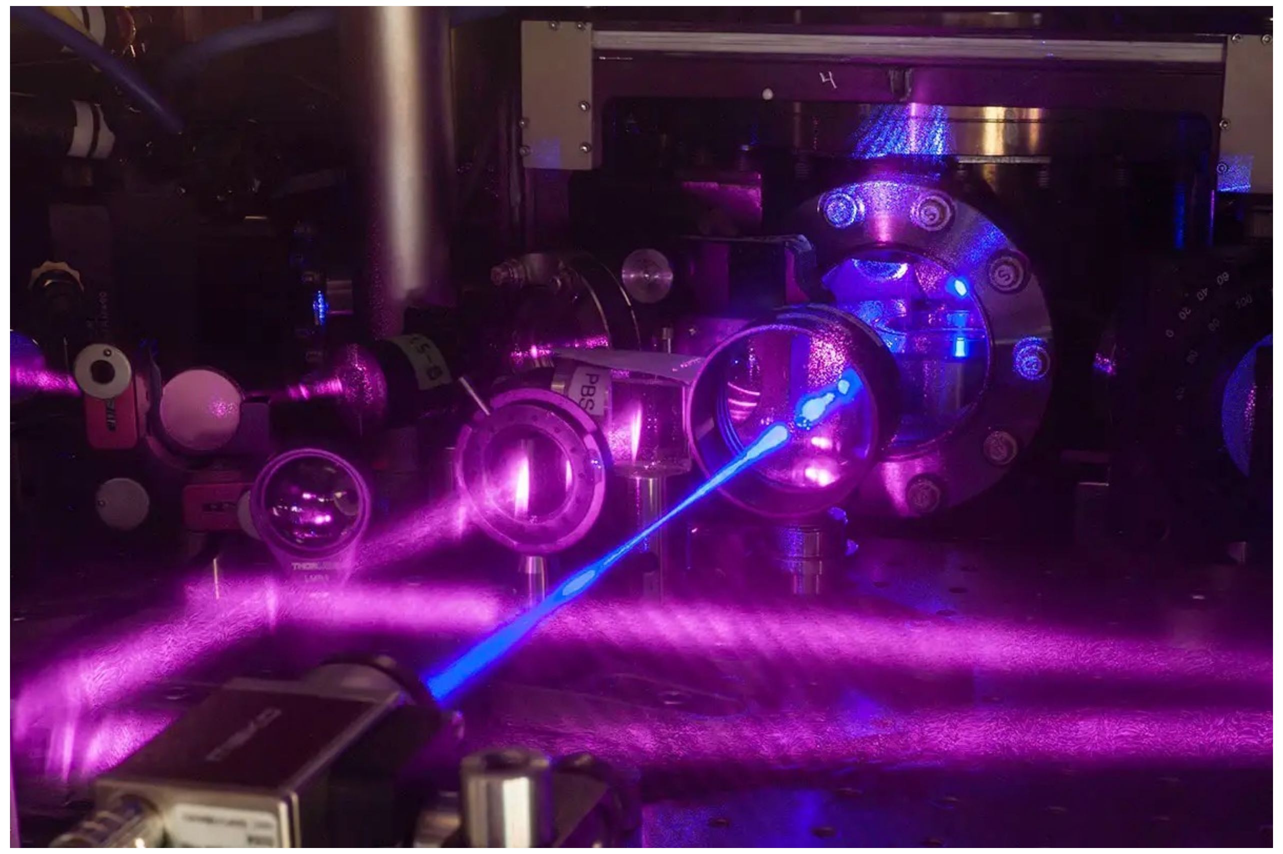
Axion parameter space

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



https://github.com/cajohare/AxionLimits

[Bartnick, Springmann, Stelzl, Weiler: To appear]



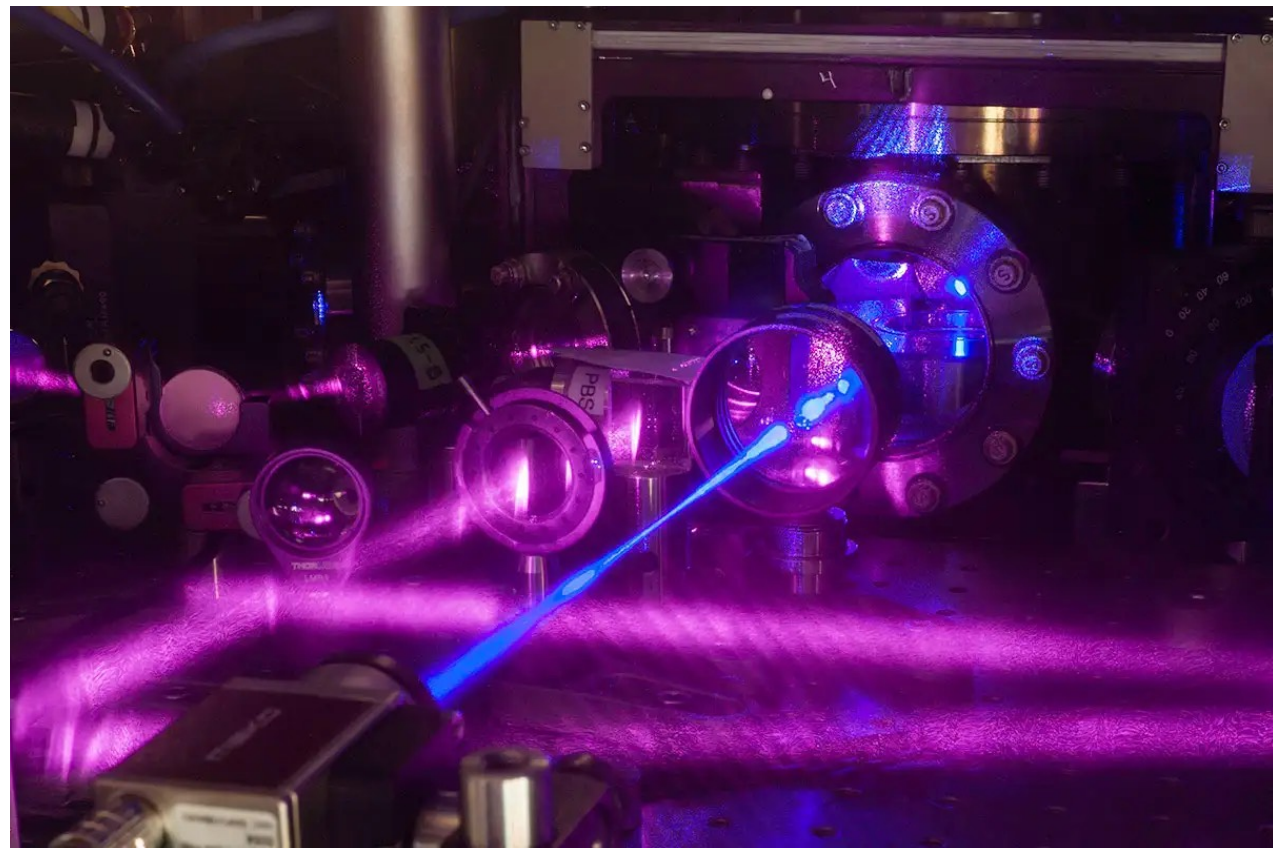
vs.

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

[Bartnick, Springmann, Stelzl, Weiler: To appear]



vs.

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

scalar-electron coupling

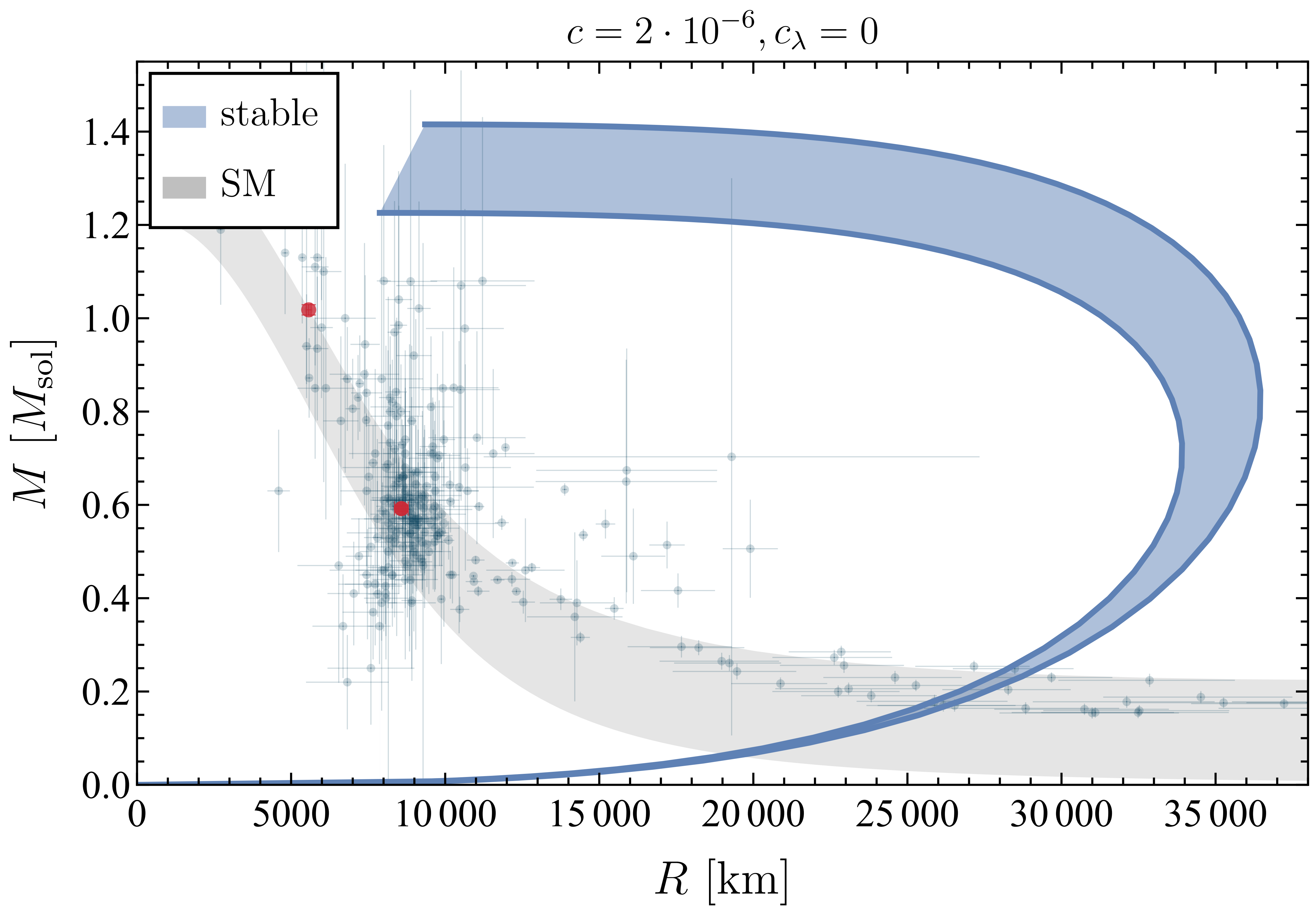
$$\mathcal{L}_{\rm int} \approx \frac{d_{m_N}^{(2)}}{2M_p^2} m_N \phi^2 \bar{\psi}_N \psi_N$$

scalar-nucleon coupling

Observing New Ground States (general couplings)

[Bartnick, Springmann, Stelzl, Weiler: To appear]

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

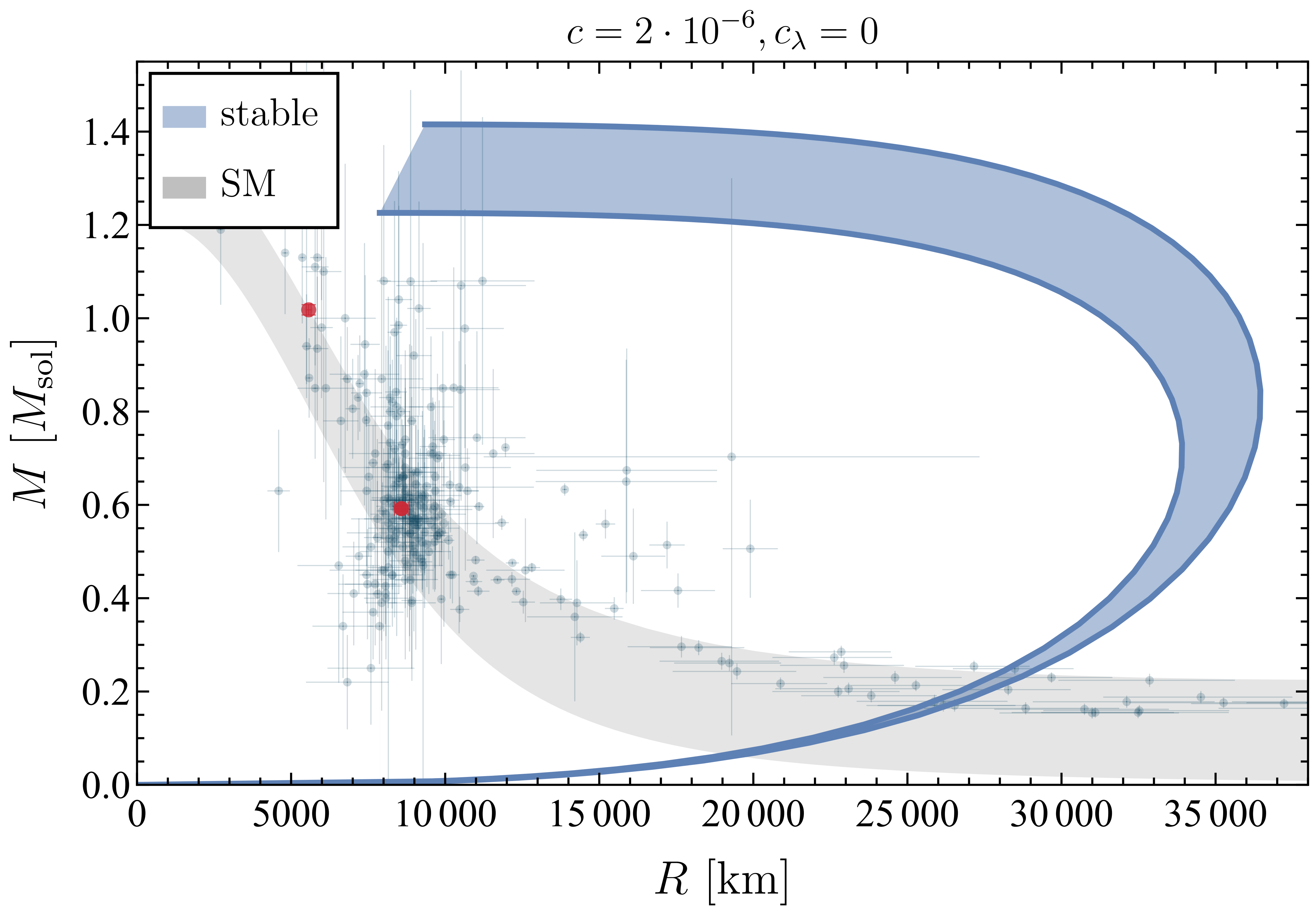


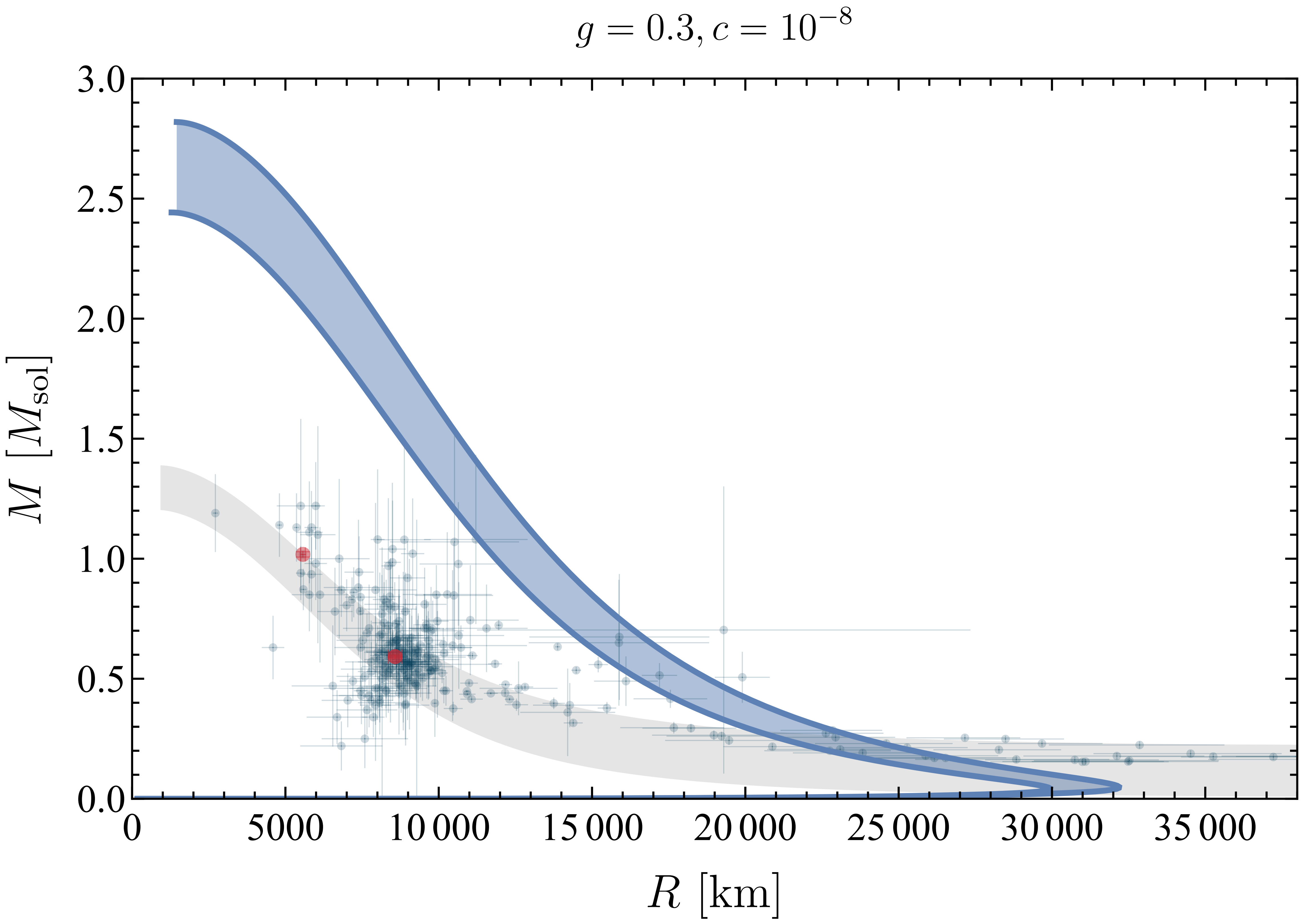
Observing New Ground States (general couplings)

[Bartnick, Springmann, Stelzl, Weiler: To appear]

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

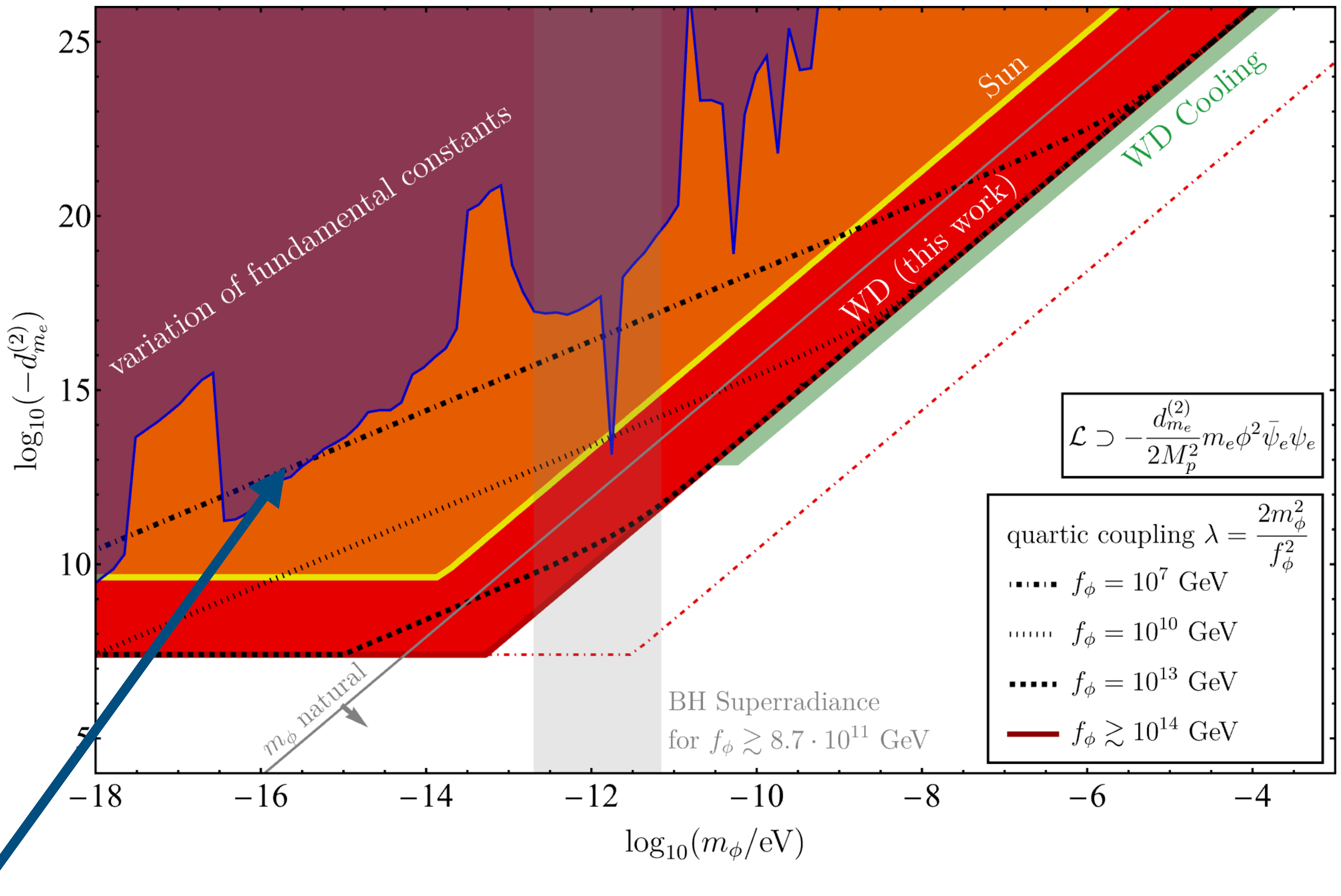
$$\mathcal{L}_{\text{int}} \approx \frac{d_{m_N}^{(2)}}{2M_p^2} m_N \phi^2 \bar{\psi}_N \psi_N$$





Powerful probe: stronger than lab-based

[Bartnick, Springmann, Stelzl, Weiler: To appear]



atomic and nuclear clock bounds are much weaker
(& only work if scalar is significant fraction of DM)

work in collaboration with:

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

Kai Bartnick (Oxford-> TUM),
Michael Stadlbauer (TUM->EPFL)

Conclusions

- Is the Standard Model completion natural? What is it?
- How do we go beyond? energy? intensity? precision?
- Dead stars are precision laboratories for probing new physics beyond the Standard Model.
- Neutron stars are less precise but probe higher scales (I didn’t have time to talk about them.)
- Density effects dramatically reshape both stellar structure and particle emission processes. Much more to do.