Beyond the SM at Finite Density

INVISIBLES24

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Instituto de Física Teórica UAM-CSIC

CSIC Consejo Superior de Investigaciones Científicas

in collaboration w/ R. Balkin, K. Springmann, S. Stelzl, and A. Weiler

Light Scalars Beyond the SM at Finite Density

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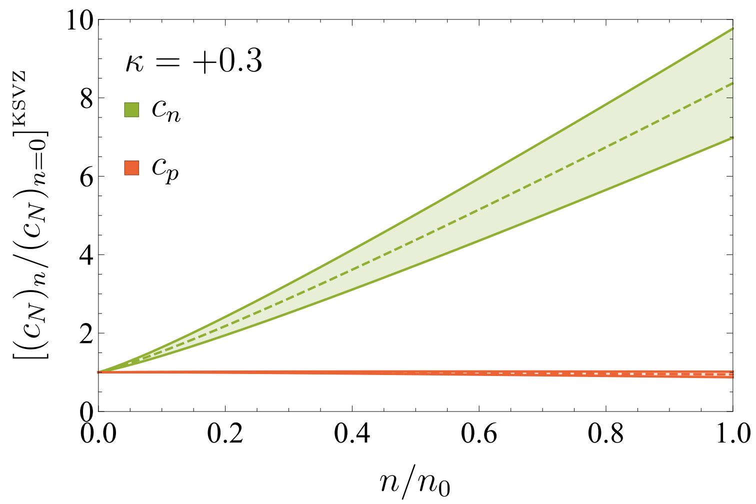
Program to study the physics of well-motivated scalar fields at finite density.

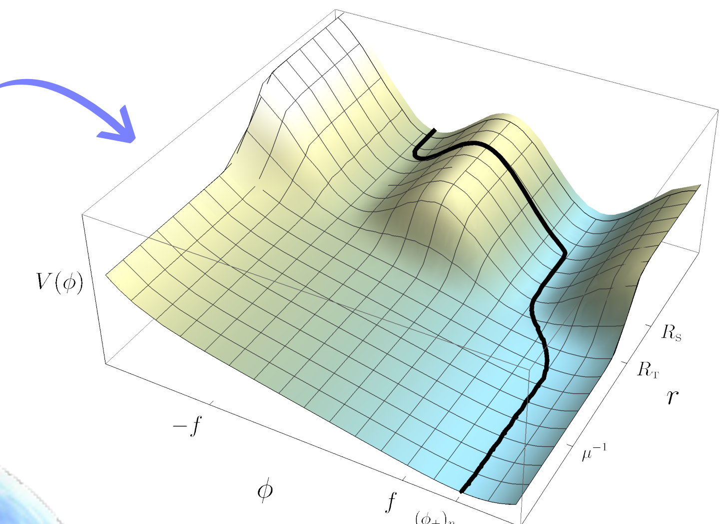
QCD Axion

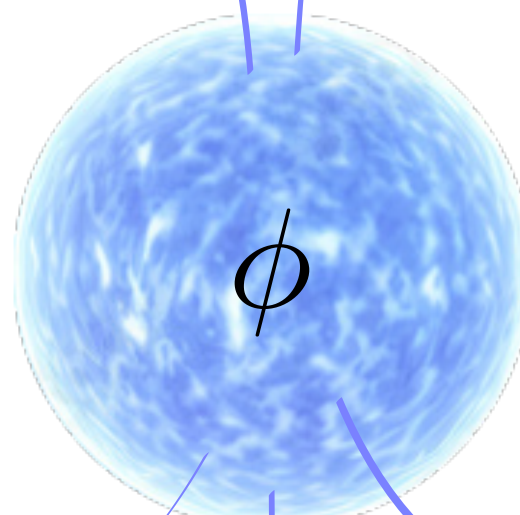
arXiv:2003.04903



Phase Transitions

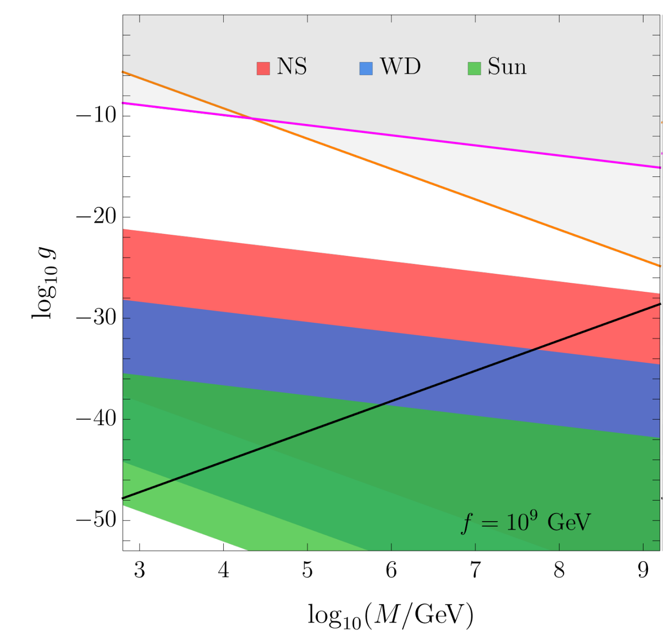
arXiv:2105.13354





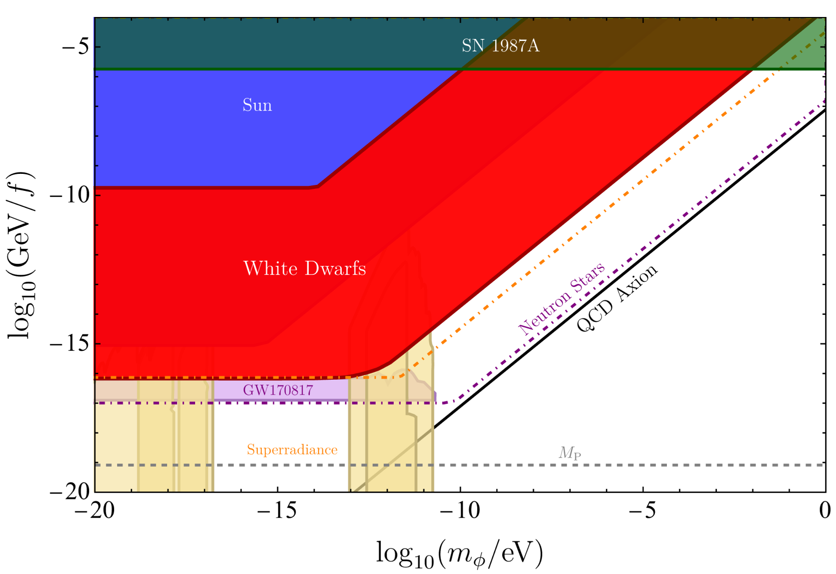
Relaxion

arXiv:2106.11320



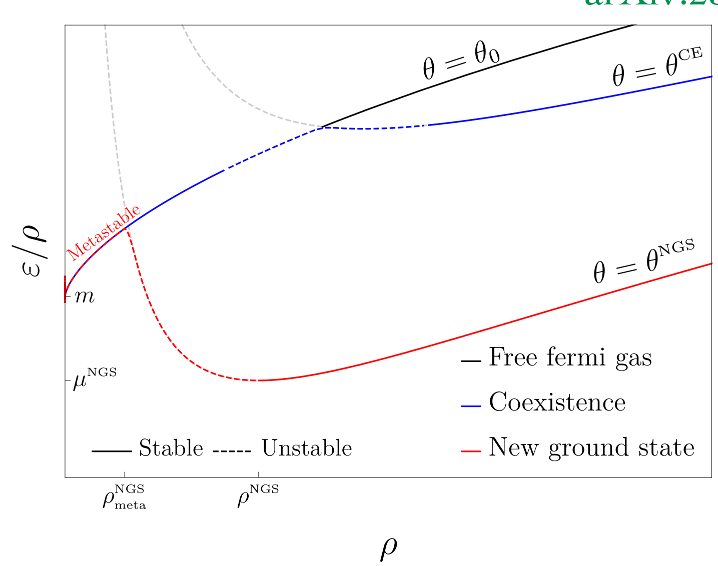
Lighter QCD Axion

arXiv:2211.02661



New Ground State

arXiv:2307.14418



Motivations

Strong-CP Problem

Violation of NDA expectations in the QCD sector.

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_{\mu\nu} \widetilde{G}^{\mu\nu}$$

Theory	Experiment (nEDM)
$\theta = O(1)$	$\theta \lesssim 10^{-10}$

$\delta_{\rm CKM} = O(1)$

The puzzling absence of CP violation in the interactions of hadrons.

see e.g. E. Hardy and C. Tamarit vs A. Ramos talks

Strong-CP Problem

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Peccei, Quinn; Weinberg; Wilczek '77

QCD Axion

Nambu-Goldstone boson of QCD-anomalous $U(1)_{PQ}$ symmetry

$$\mathcal{L}_{\theta+a} = \frac{1}{2}(\partial_\mu a)^2 + \underline{\left(\theta + \frac{a}{f_a}\right)} \frac{g_s^2}{32\pi^2} G_{\mu\nu}\widetilde{G}^{\mu\nu}$$

$$\rightarrow \frac{a}{f_a}$$

$$\downarrow$$

QCD infrared dynamics makes axion solve strong CP-problem.

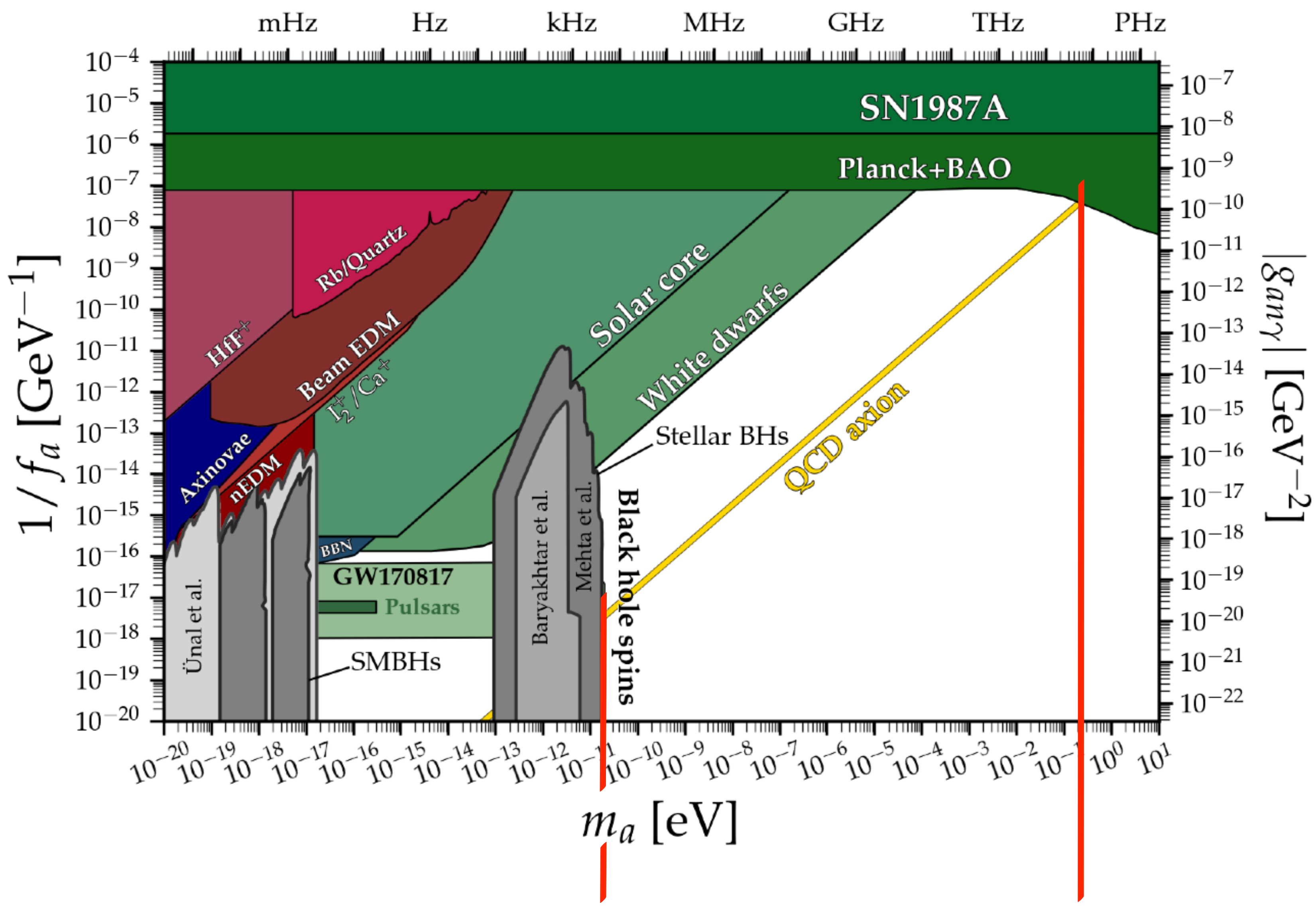
$$V(a) \sim -m_\pi^2 f_\pi^2 \cos\frac{a}{f_a}$$

$$\langle a \rangle = 0 \qquad m_a \sim m_\pi f_\pi / f_a$$

$$m_\pi f_\pi \approx 130\,\mathrm{MeV}$$

QCD Axion

Current status of QCD-axion parameter space.



Superradiance		Hot DM component
Baryakhtar et al. '20	$10^{-11} \lesssim m_a/\text{eV} \lesssim 10^{-1}$	Caloni et al. '22
Mehta et al. '20	$10^{7} \lesssim f_a/\text{GeV} \lesssim 10^{17}$	rev. Caputo, Raffelt '24
...		...

Hook, Huang '17; Hook '18

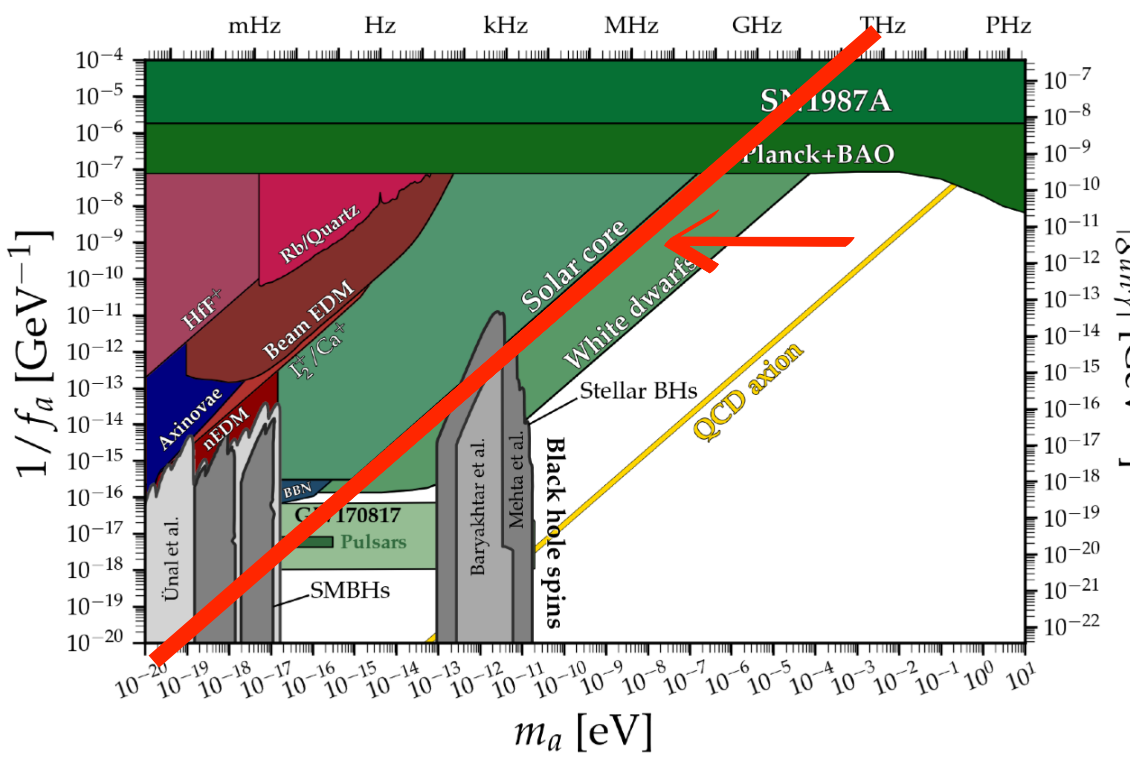
Light QCD Axion

Lighter version of the canonical QCD axion.

$$V_\epsilon(a) = \epsilon V(a) = -\epsilon m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{a}{2 f_a}}$$

$$\langle a \rangle = 0 \qquad m_a^2 = \epsilon \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{m_u m_d}{(m_u + m_d)^2}$$

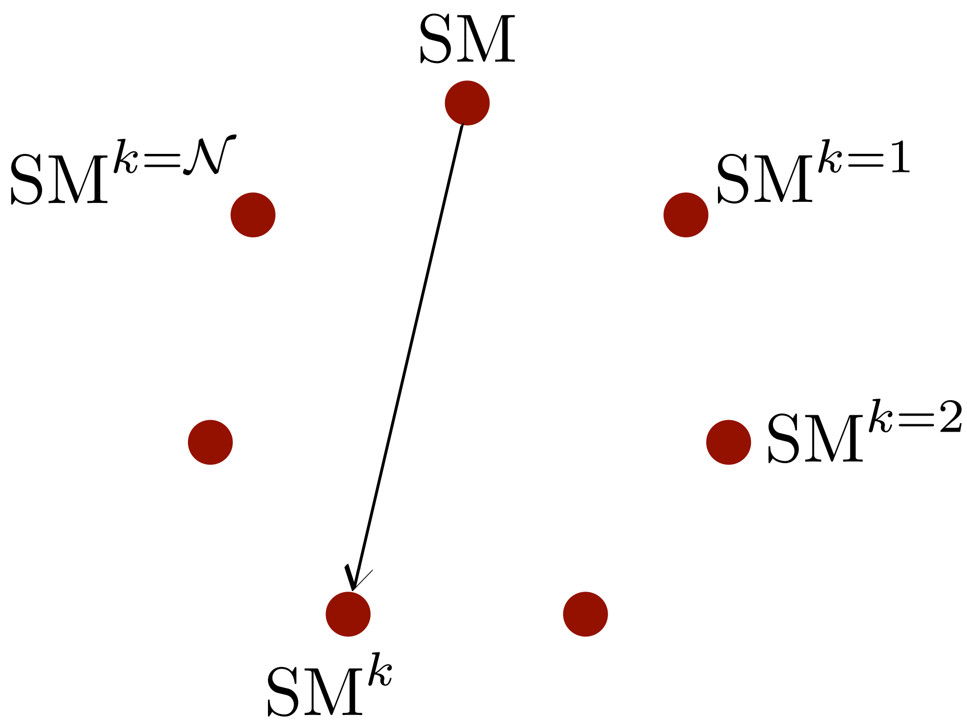
$\epsilon \ll 1$



(Hook '18; di Luzio et al. '21)

$Z_{\mathcal{N}}$ QCD Axion

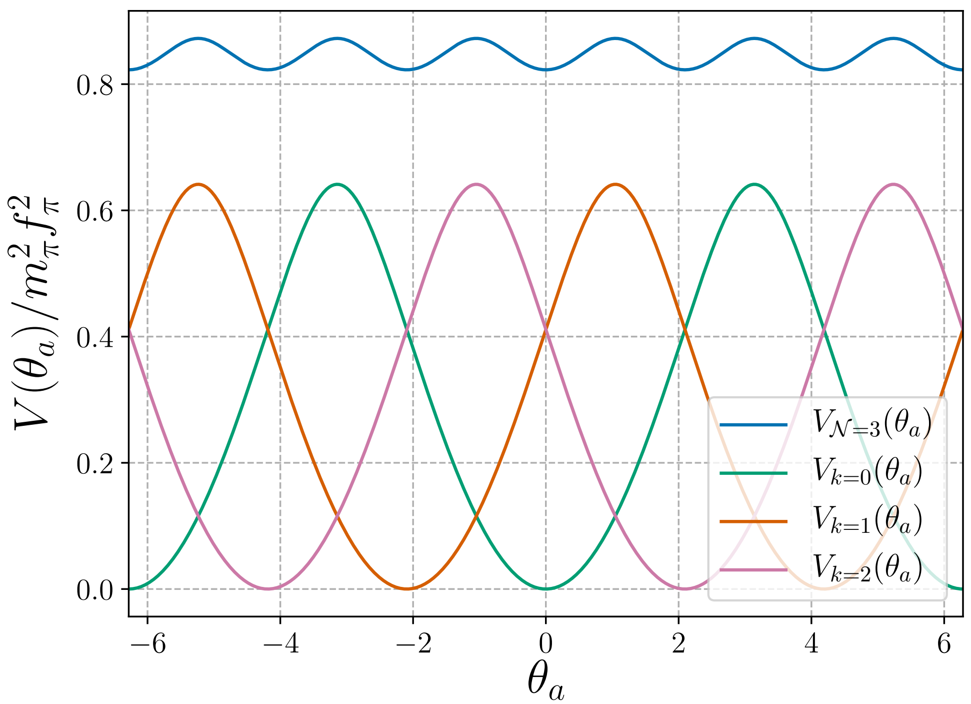
Lighter QCD axion based from discrete $Z_{\mathcal{N}}$ ($\mathcal{N}$ odd) symmetry.



$$a \to a + \frac{2\pi k}{\mathcal{N}} f_a$$

$$V_{\mathcal{N}}(a) \simeq -\frac{m_\pi^2 f_\pi^2}{\mathcal{N}^2} \cos \mathcal{N} \frac{a}{f_a}$$

$$\langle a \rangle = \frac{\pi k}{\mathcal{N}} \qquad m_a^2 = \frac{m_\pi^2 f_\pi^2}{f_a^2} \sqrt{\frac{1-z}{\pi(1+z)}} \mathcal{N}^{3/2} z^{\mathcal{N}}$$



Cosmological Constant / Electroweak Hierarchy Problems

Violation of NDA expectations in the gravitational / Higgs sectors

$$\mathcal{L}_{d<4} = \sqrt{-g}\left(\Lambda_{\rm CC} + m_H^2 |H|^2\right)$$

<u>Theory</u>

$$\frac{\Lambda_{\rm CC}}{M_{\rm Pl}^4} = O(1) \qquad \frac{m_H^2}{M_{\rm Pl}^2} = O(1)$$

<u>Experiment</u>
(LHC, Universe)

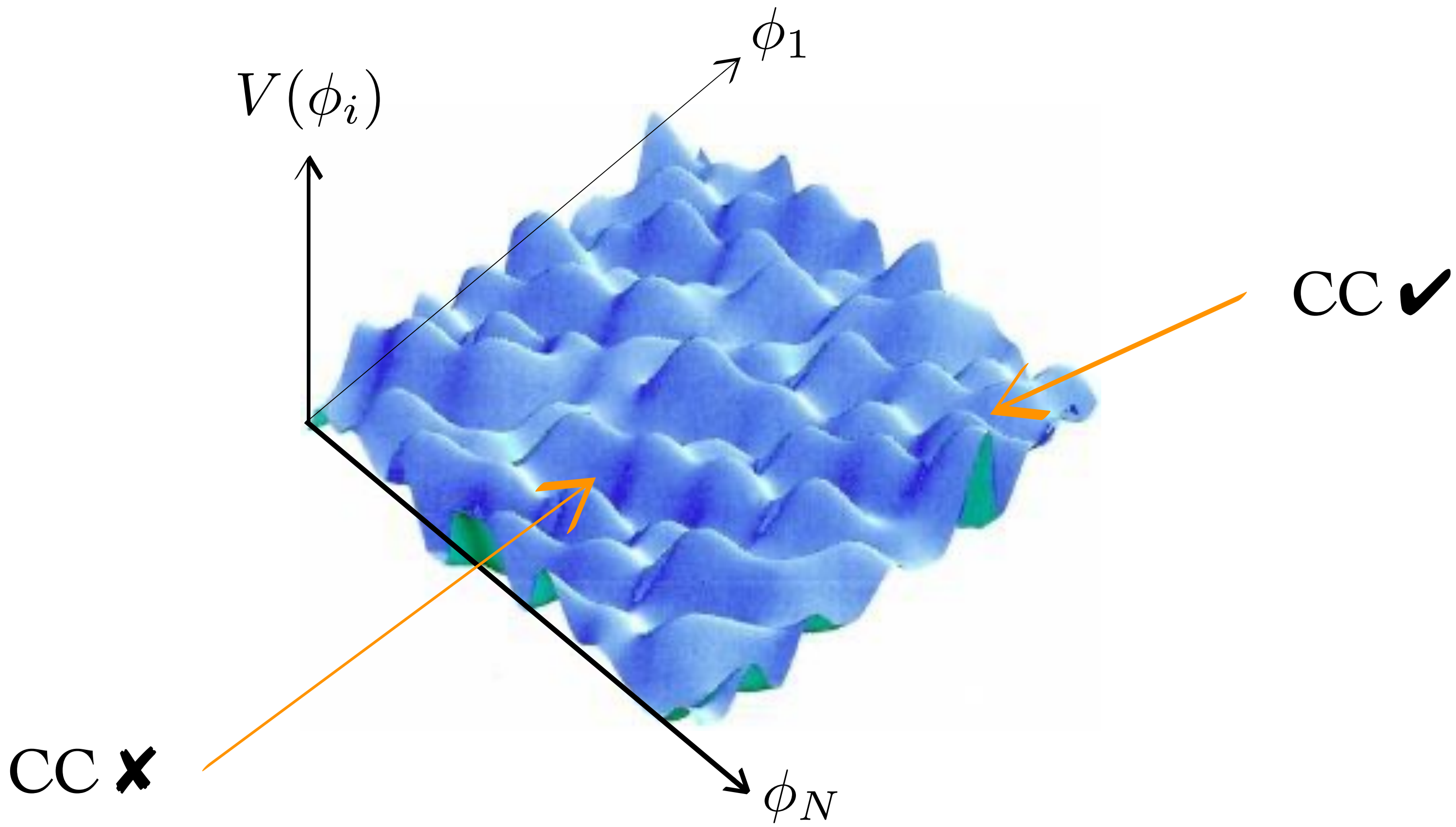
$$\frac{\Lambda_{\rm CC}}{M_{\rm Pl}^4} \sim 10^{-120} \qquad \frac{m_H^2}{M_{\rm Pl}^2} \sim 10^{-30}$$

The perplexing existence of a big universe w/ big things in it.

Weinberg '87; Bousso, Polchinski '00, …

Landscapes

Low-energy dimensionful parameters are not fundamentally calculable by finelly scanned.



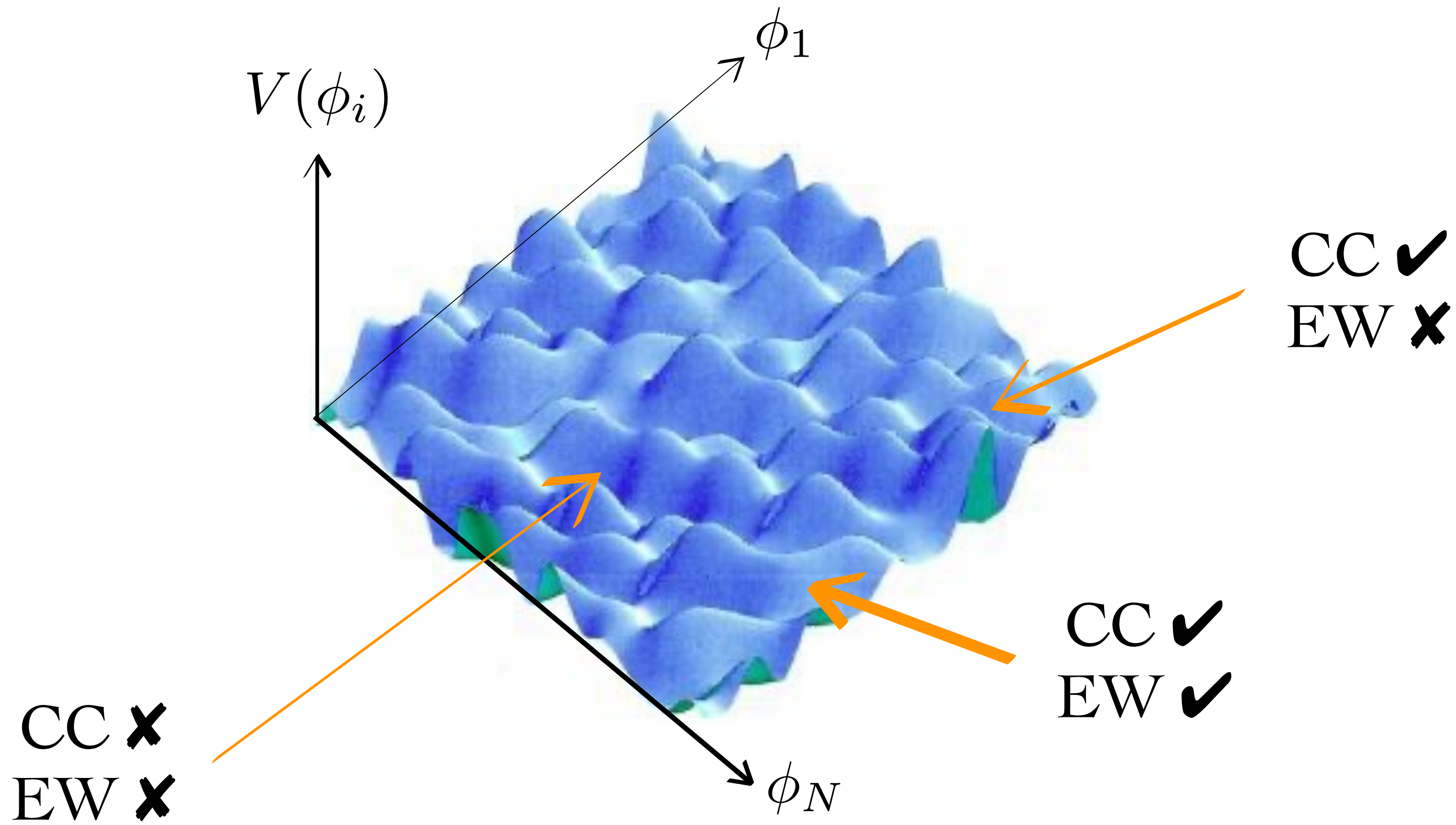
Arguably the best explanation for the tiny size of the cosmological constant.

[along w/ selection mechanism of our vacuum among the multiverse of vacua]

Agrawal et al. '97

Landscapes

Low-energy dimensionful parameters are not fundamentally calculable by finelly scanned.



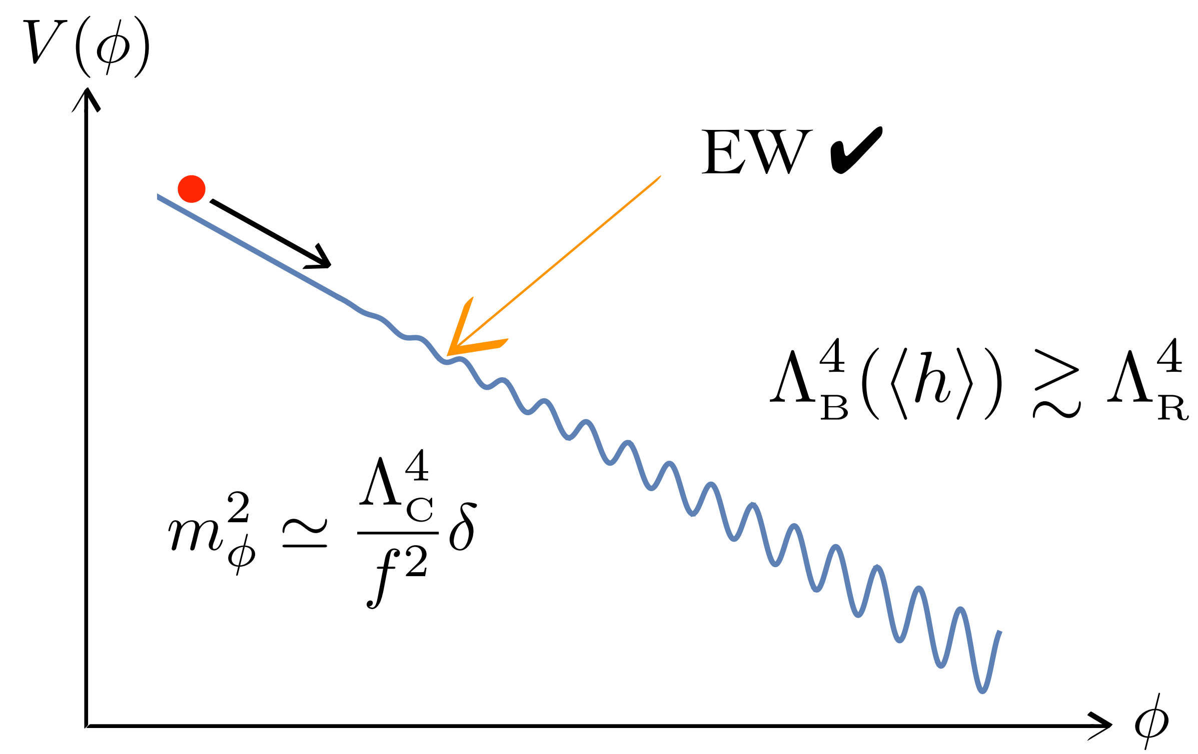
see e.g. O. Matsedonskyi talk

Alternative to standard symmetry approaches: supersymmetry/compositeness.

[along w/ selection mechanism of our vacuum among the multiverse of vacua]

Relaxion

Dynamical selection of small electroweak scale via weakly-coupled light axion-like scalar.



$$V(\phi) = -\Lambda_{\rm R}^4 \frac{\phi}{f} + \underline{\Lambda_{\rm B}^4(h)} \cos\frac{\phi}{f}$$

Non-vanishig Higgs VEV triggers QCD-like* barrier that stops relaxion's evolution.

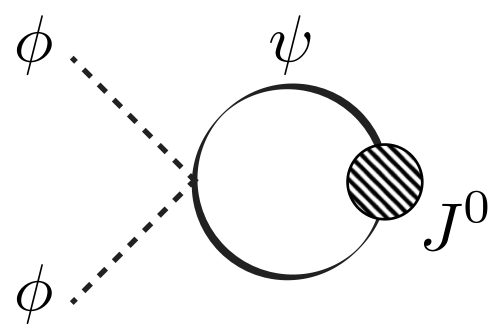
* QCD-axion: $\Lambda_{\rm B}^4(h) \sim m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u+m_d)^2}\frac{h}{v}$

Finite Density

Finite Density Effects

Properties of **scalar** coupled to conserved charge change in **system** w/ non-vanishing density.

$$\mathcal{L} \supset \phi^2 \bar{\psi}\psi - V(\phi)$$



$$n = \langle J^0 \rangle \overset{\text{NR}}{\simeq} \langle \bar{\psi}\psi \rangle \longrightarrow \Delta V(\phi) = n\phi^2$$

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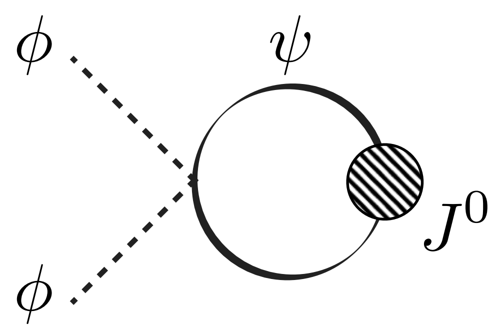

$$n = \langle J^0 \rangle \overset{\text{NR}}{\simeq} \langle \bar{\psi}\psi \rangle \longrightarrow \Delta V(\phi) = n\phi^2$$

Free Fermi gas: $\quad n = 2\int^{k_F} \frac{d^3k}{(2\pi)^3} = \frac{k_F^3}{3\pi^2} \qquad k_F(\mu) = \sqrt{\mu^2 - m^2}\,\Theta(\mu - m)$

Formally, fermion loops evaluated w/ finite density ($T = 0$) propagator:

$$iG(p) = (\not{p} + m)\left[\underbrace{\frac{i}{p^2 - m^2 + i\epsilon}}_{\text{vacuum}} - \underbrace{2\pi\delta(p^2 - m^2)\Theta(p^0)\Theta(k_F - |\vec{p}|)}_{\text{medium (Fermi sea)}}\right]$$

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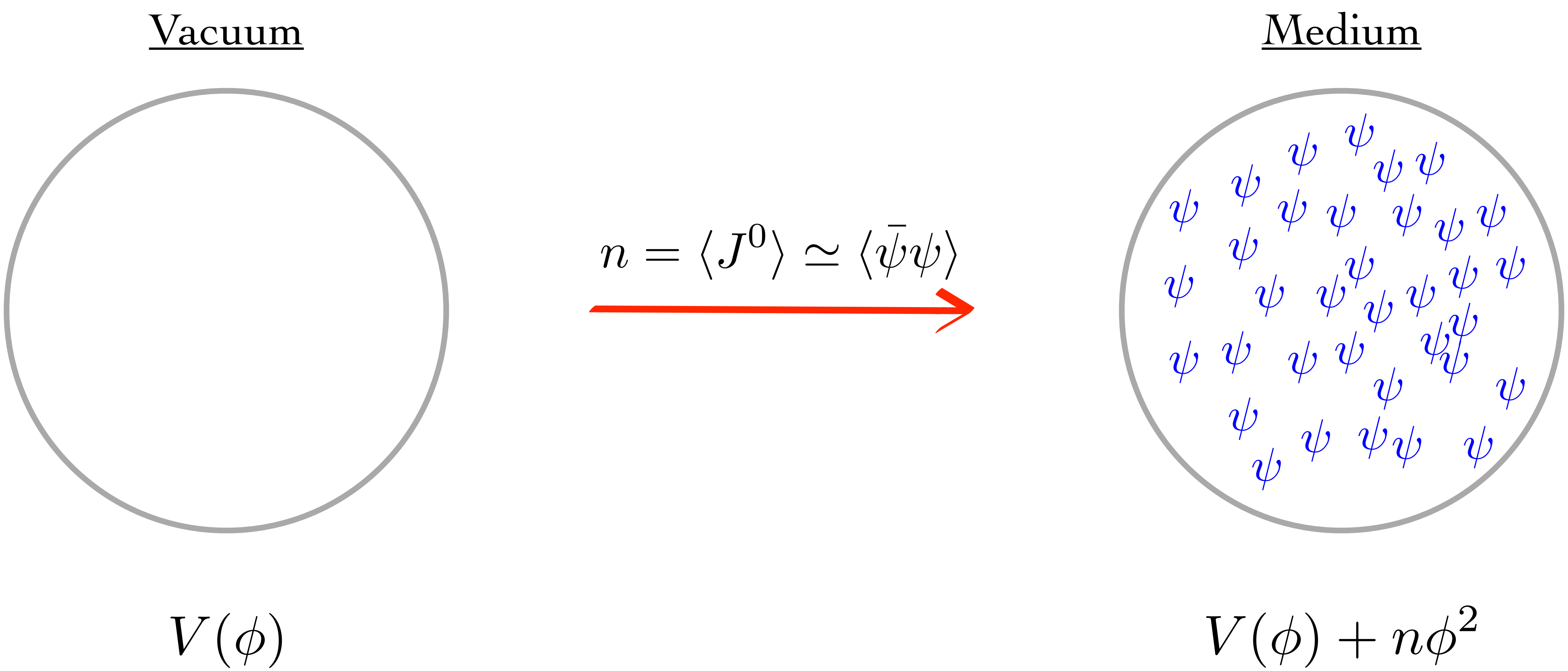
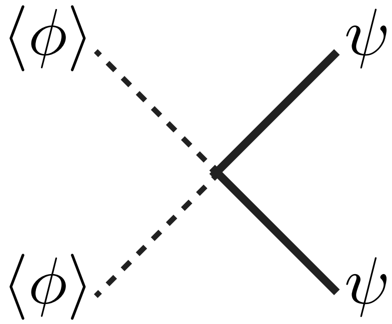


Finite Density Effects

Properties of **system** coupled to **scalar** change if scalarization take place.

$$\mathcal{L} \supset \phi^2 \bar{\psi}\psi - m\bar{\psi}\psi$$



$$\langle\phi\rangle \neq 0 \quad \longrightarrow \quad \Delta m(\phi) = \langle\phi\rangle^2$$

Scalar-dependent grand-canonical potential:

$$\Omega = \Omega(\mu, \phi)$$

$$\left.\frac{\partial \Omega}{\partial \mu}\right|_{\phi} = n \qquad \left.\frac{\partial \Omega}{\partial \phi}\right|_{\mu} = 0$$

Finite Density Effects

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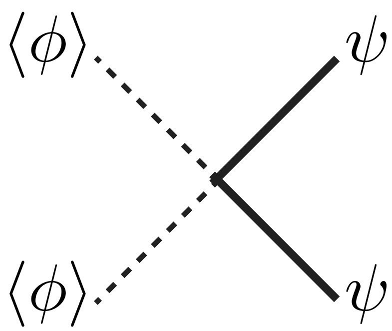


$$\xrightarrow{\langle\phi\rangle \neq 0} \quad \Delta m(\phi) = \langle\phi\rangle^2$$

Scalar-dependent grand-canonical potential:

$$\Omega = \Omega(\mu, \phi)$$

$$\left.\frac{\partial \Omega}{\partial \mu}\right|_{\phi} = n \qquad \left.\frac{\partial \Omega}{\partial \phi}\right|_{\mu} = 0$$

Free Fermi gas: $\Omega(\mu,\phi) = \Omega_\psi(\mu, m(\phi)) + V(\phi) \xrightarrow[\text{NR}]{\partial_\phi|_\mu} \frac{\partial V}{\partial \phi} + n\frac{\partial m}{\partial \phi} = 0$

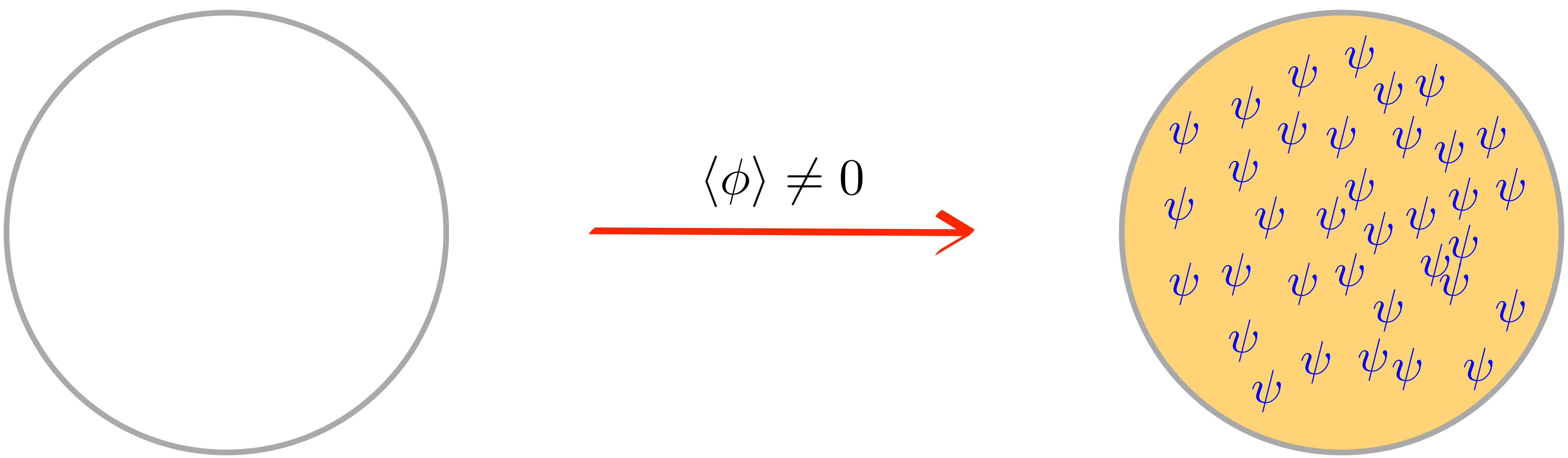
Finite Density Effects

Properties of **system** coupled to **scalar** change if scalarization take place.

$$\mathcal{L} \supset \phi^2 \bar{\psi}\psi - m\bar{\psi}\psi$$

Vacuum

Medium

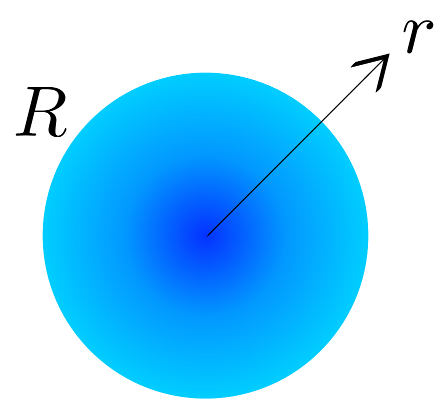


m

$m - \langle \phi \rangle^2$

Stars

Compact stellar objects: finite size, spherically symmetric, dense systems.



$n(r)$ $\phi(r)$

Tolman-Oppenheimer-Volkoff + scalar equations:

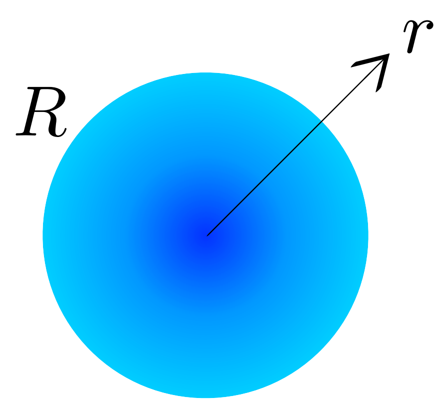
$$M' = 4\pi r^2 \varepsilon \left[1 + O(\tfrac{\phi'^2}{\epsilon})\right]$$

$$p' = -\frac{GM}{r^2}\varepsilon \left[1 + O(\tfrac{GM}{r}, \tfrac{p}{\varepsilon}, \tfrac{\phi'^2}{\epsilon})\right] - \phi' \frac{\partial \Omega}{\partial \phi}$$

$$\left(\phi'' + \tfrac{2}{r}\phi'\right)\left[1 + O(\tfrac{GM}{r})\right] = \frac{\partial \Omega}{\partial \phi}$$

Stars

Compact stellar objects: finite size, spherically symmetric, dense systems.



$n(r) \qquad \phi(r)$

Tolman-Oppenheimer-Volkoff + scalar equations:

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$$p' = -\frac{GM}{r^2}\varepsilon \left[1 + O(\tfrac{GM}{r}, \tfrac{p}{\varepsilon}, \cancel{\tfrac{\phi'^2}{\epsilon}})\right] - \cancel{\phi'}\frac{\partial\Omega}{\partial\phi}$$

$$(\cancel{\phi''} + \tfrac{2}{r}\cancel{\phi'})\left[1 + O(\tfrac{GM}{r})\right] = \frac{\partial\Omega}{\partial\phi}$$

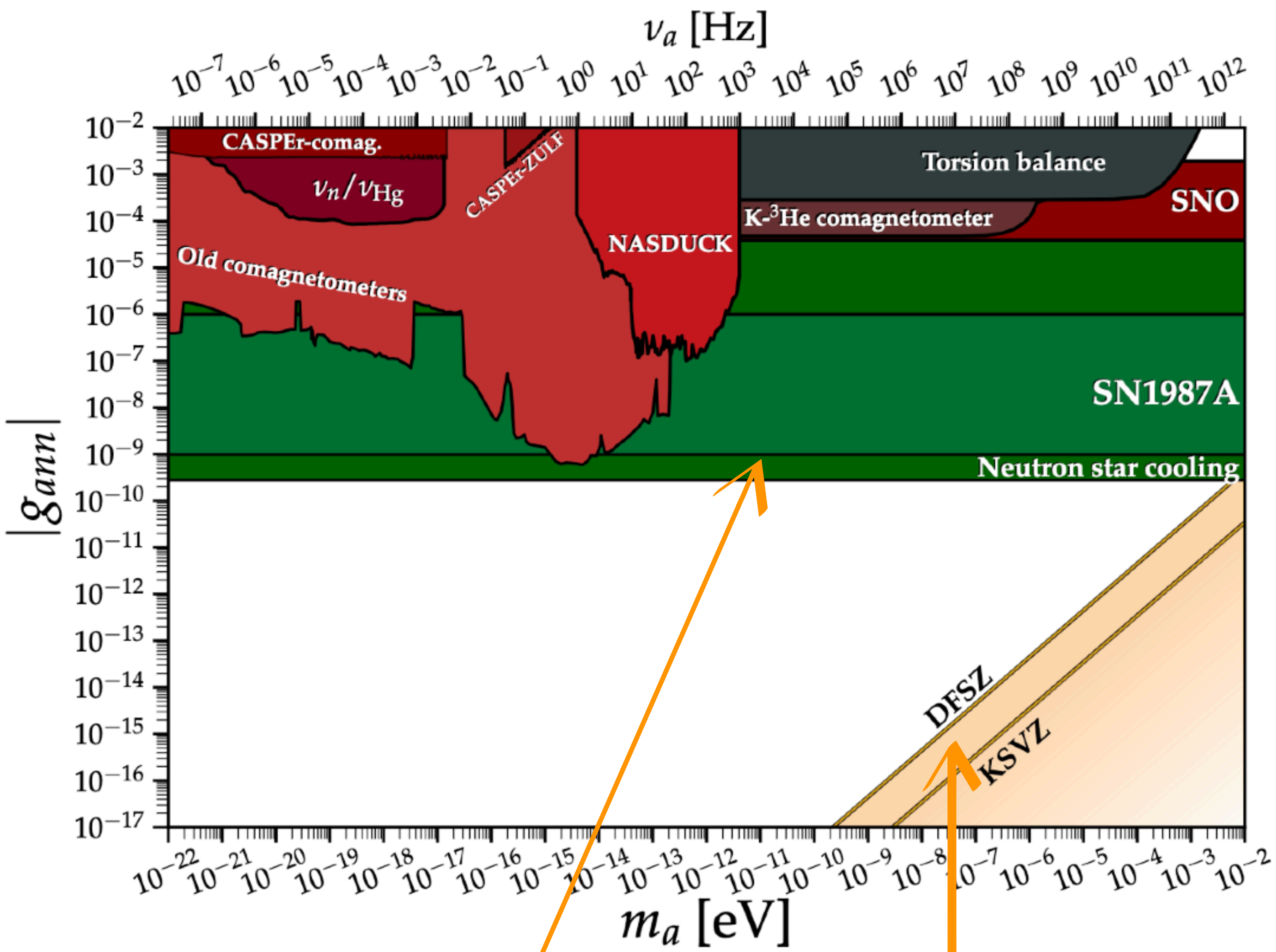
* negligible gradient energy limit: $\dfrac{1}{\bar{m}_\phi(n)} \ll R$

QCD Axion

Carenza et al. '19, Buschmann et al. '21

Stellar Emission: Bounds

Supernova and Neutron star cooling bounds not systematic in finite-density effects.



in medium

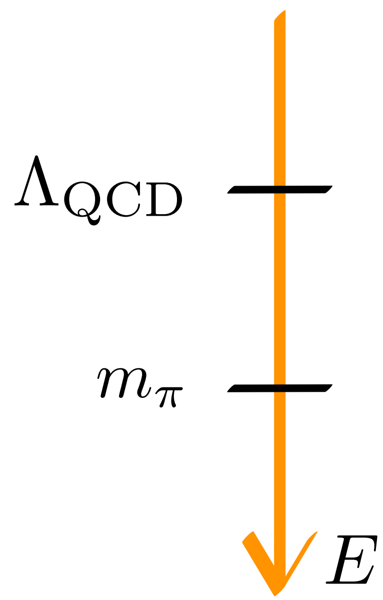
in vacuum

QCD Axion Couplings: in Vacuum

Model-independent low-energy couplings to protons/neutrons from axion-pion mixing.

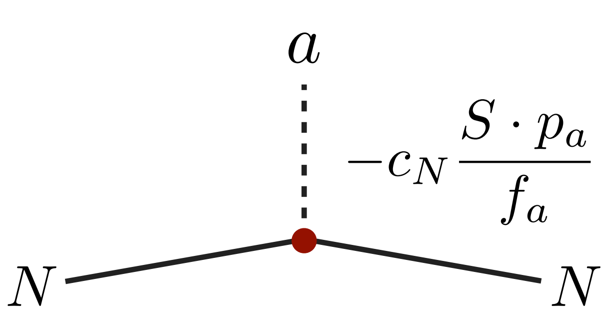
$$\mathcal{L}_a \supset \underbrace{\frac{a}{f_a}\frac{g_s^2}{32\pi^2}G_{\mu\nu}\widetilde{G}^{\mu\nu}}_{\text{model independent}} + \underbrace{\frac{\partial_\mu a}{2f_a}\sum_q c_q^0 \bar{q}\gamma^\mu\gamma_5 q}_{\text{model dependent}}$$

KSVZ axion: $c_q^0 \simeq 0$



Axion derivative coupling to non-relativistic neutrons/protons below pion mass.

$$\frac{\partial_\mu a}{f_a}\bar{N}S^\mu\left(g_A c_{u-d}\sigma_3 + g_0 c_{u+d}\mathbb{I}\right)N \qquad N = \begin{pmatrix} p \\ n \end{pmatrix}$$

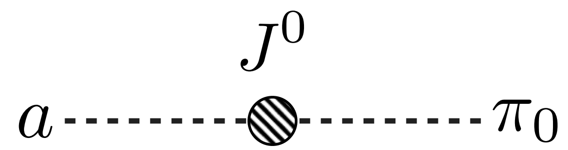


$$c_N^{\mathrm{KSVZ}} = \begin{pmatrix} -0.42(3) \\ +0.02(3) \end{pmatrix}$$

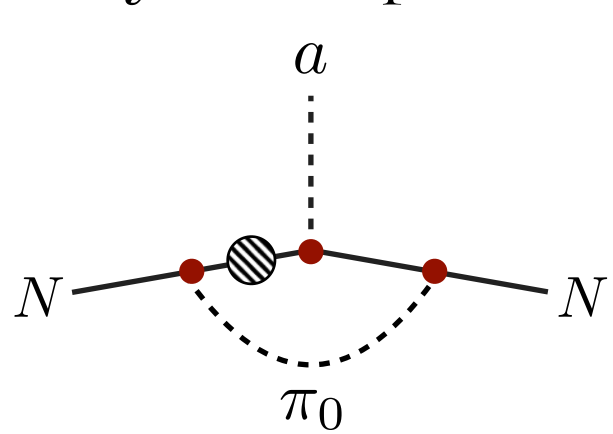
← **accidental cancellation**

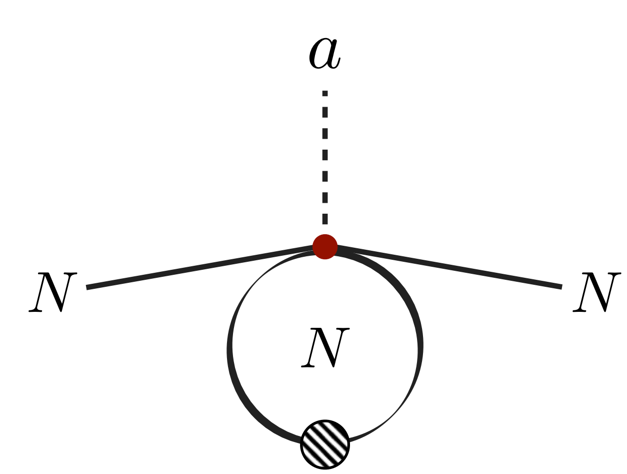
QCD Axion Couplings: in Medium

- Axion-meson mixing angles: $c_{u\pm d}$



- **Nuclear matrix elements:** $g_A,\ g_0$

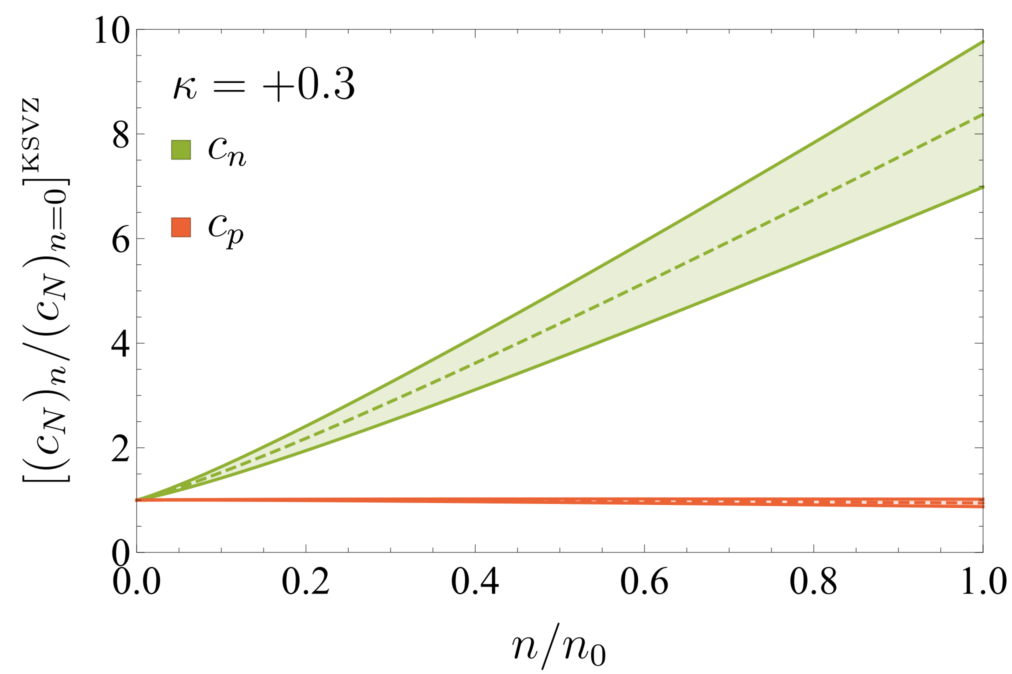




$k_F \simeq 260\,\mathrm{MeV}\,(n/n_0)^{1/3}$

$k_F > m_\pi$

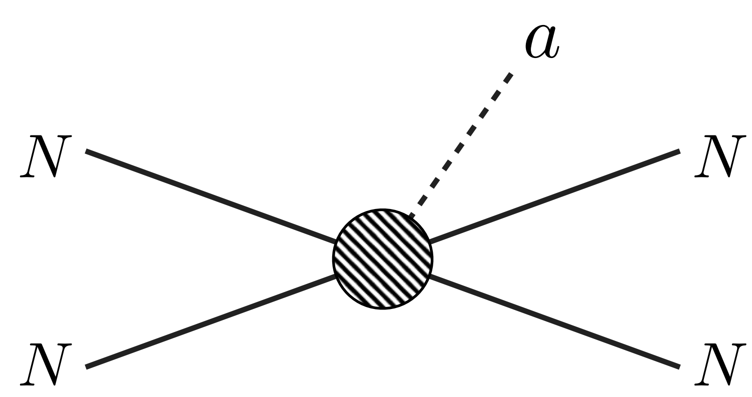
$(k_F/\Lambda_\chi)^2 \simeq 15\%\,(n/n_0)^{2/3}$

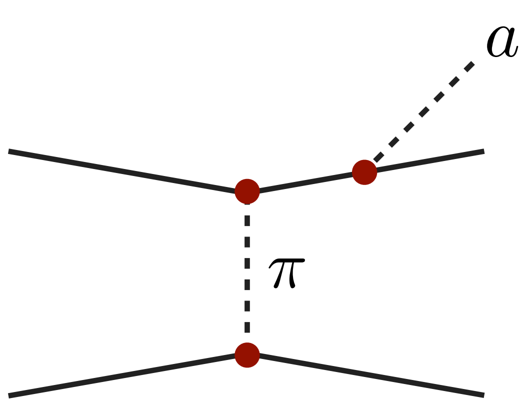


Stadlbauer, Springmann, Stelzl, Weiler to appear

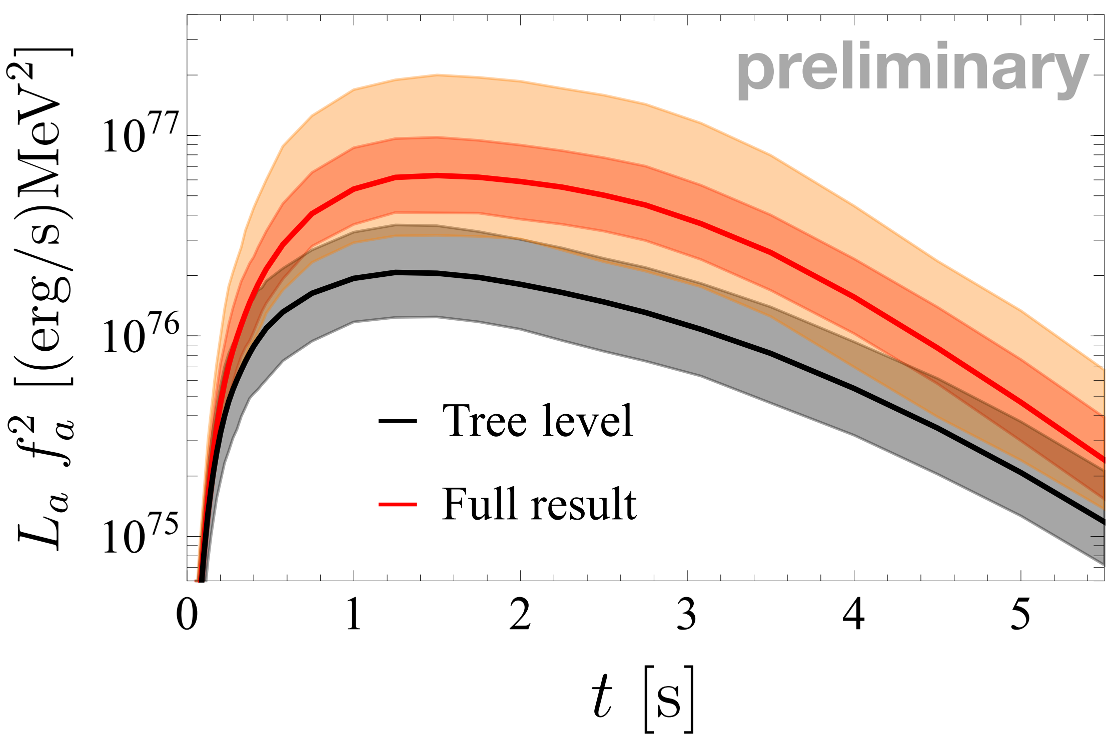
QCD Axion Emission: in Medium

Axion emissivity in Supernova and Neutron star cooling, systematically.





Raffelt, Seckel '88



SN bound meaningful (th. error), NS cooling bound O(1) uncertain; similar for DFSZ/KSVZ.

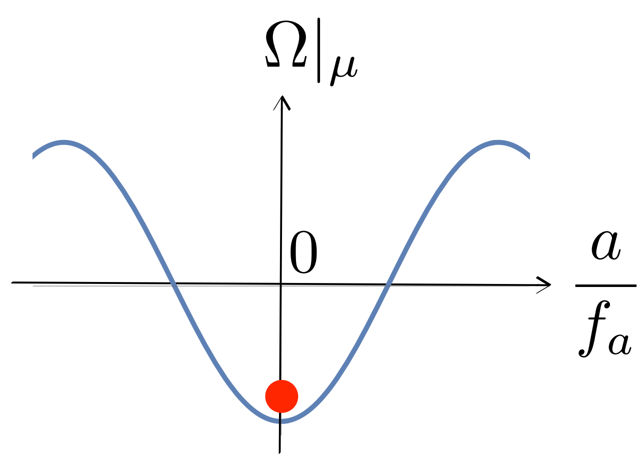
Lighter QCD Axion

Axionalization

Lighter QCD axion developes non-trivial profile in dense enough systems.

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

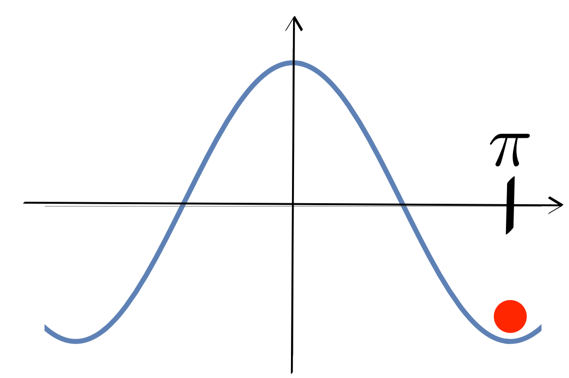
$$m_N(a) - m_N \simeq +g m_N \left(\cos\frac{a}{f_a} - 1\right) \qquad g \simeq \sigma_N / m_N$$



$$\left.\frac{\partial\Omega}{\partial\phi}\right|_\mu = 0$$

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

$$n_c$$



$$\Delta m_N \simeq -32\,\text{MeV}\left(\frac{\sigma_N}{50\,\text{MeV}}\right)$$

Axionalization

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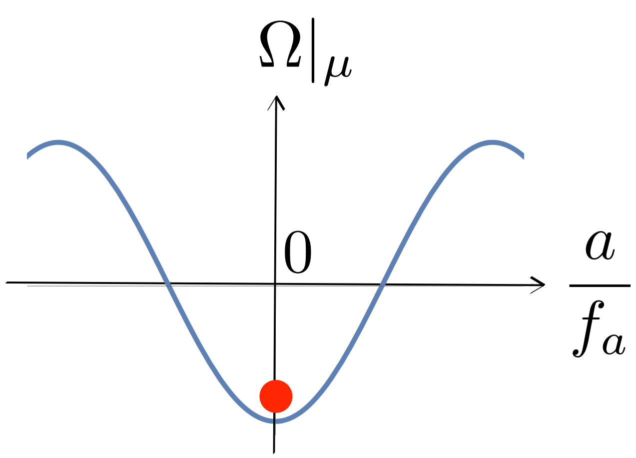

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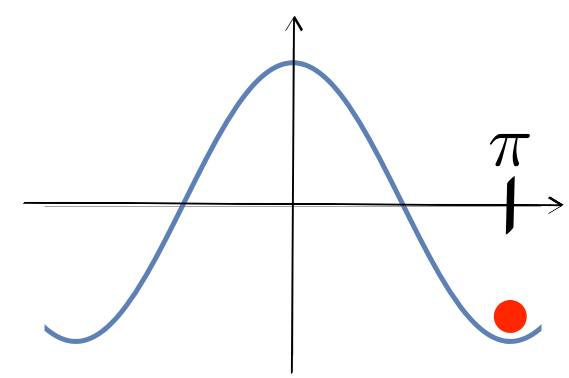
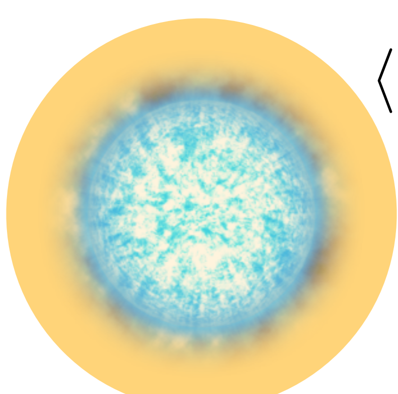


$$\Delta m_N \simeq -32\,\mathrm{MeV} \left(\frac{\sigma_N}{50\,\mathrm{MeV}} \right)$$

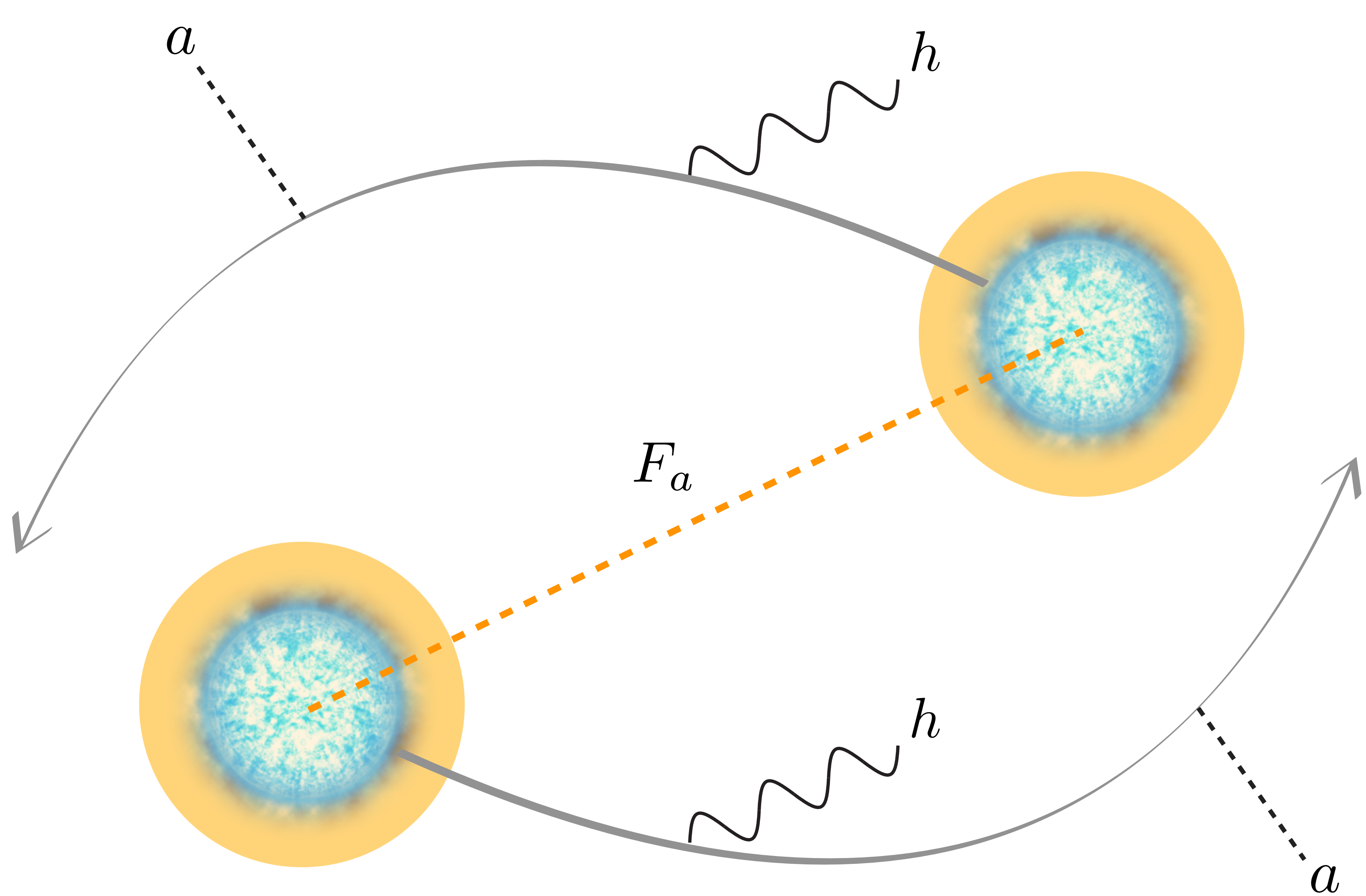


$$\langle a \rangle = \pi f_a$$

$$R \gtrsim \frac{1}{\bar{m}_\phi(n)} = 10^4\,\mathrm{km} \left(\frac{f}{10^{16}\,\mathrm{GeV}} \right) \left(\frac{10^{-4}\,\mathrm{MeV}^3}{n_{\mathrm{WD}}} \right)^{1/2}$$

Neutron Star Mergers

Lighter QCD axion mediates long-range force between axionalized neutron stars.



Merger dynamics affected for Planck-scale decay constants.

New Ground State

Lighter QCD axion leads to new scalarized ground state of (free) matter.

$$\varepsilon(n,\phi) = \varepsilon_\psi(n,\phi) + V(\phi)$$
$$p(n,\phi) = p_\psi(n,\phi) - V(\phi)$$

$\psi = n,\ e+p,\ e+p+n$

$\langle\phi\rangle \neq 0$ → **Instability**

$p_\psi(n_c, \langle\phi\rangle) < V(\langle\phi\rangle)$

New Ground State

Lighter QCD axion leads to new scalarized ground state of (free) matter.

$$\varepsilon(n,\phi) = \varepsilon_\psi(n,\phi) + V(\phi)$$
$$p(n,\phi) = p_\psi(n,\phi) - V(\phi)$$

$\psi = n,\ e+p,\ e+p+n$

$\langle\phi\rangle \neq 0$ → **Instability**

$p_\psi(n_c, \langle\phi\rangle) < V(\langle\phi\rangle)$

$\theta = \langle \phi / f \rangle$

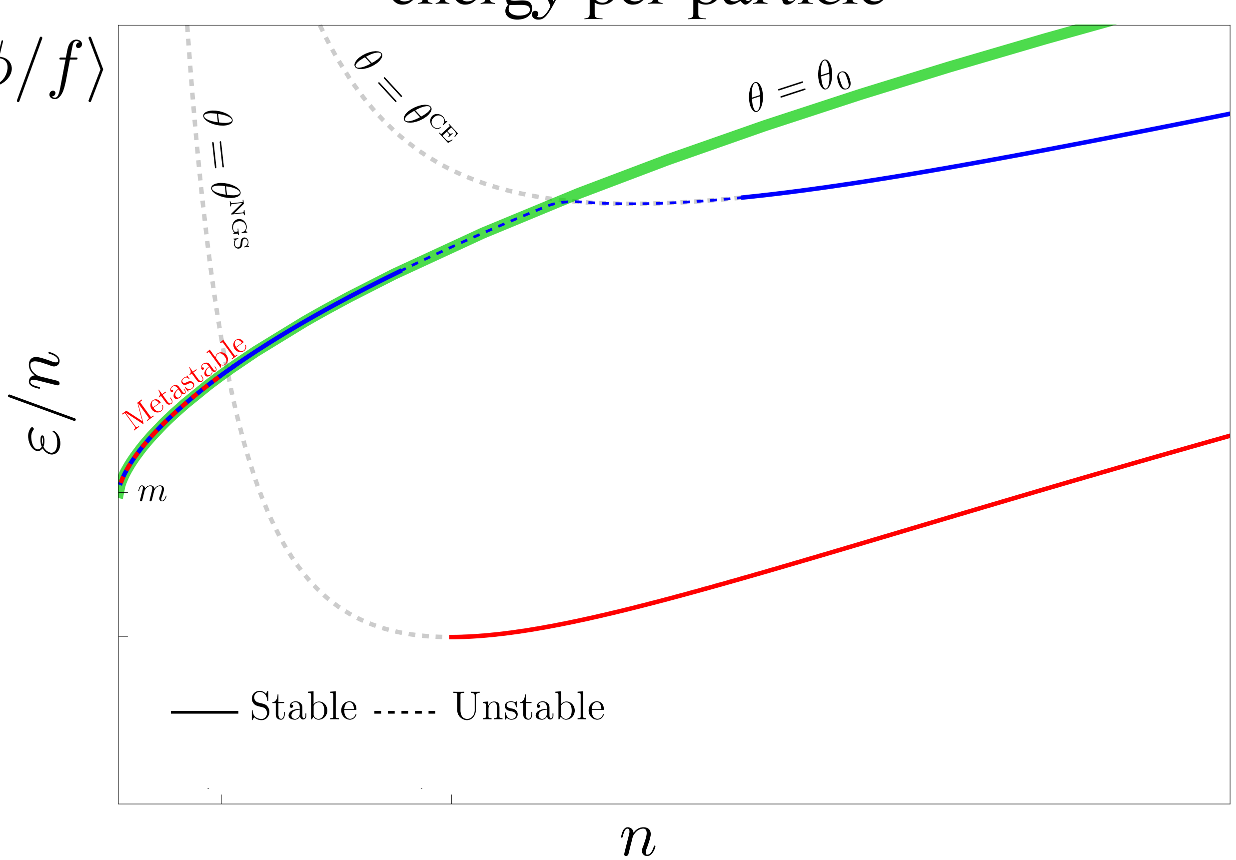
$$p = n^2 \frac{\partial(\varepsilon/n)}{\partial n}$$

NR free Fermi gas

$p \sim k_F^5/m$

$\varepsilon \sim m k_F^3$

energy per particle



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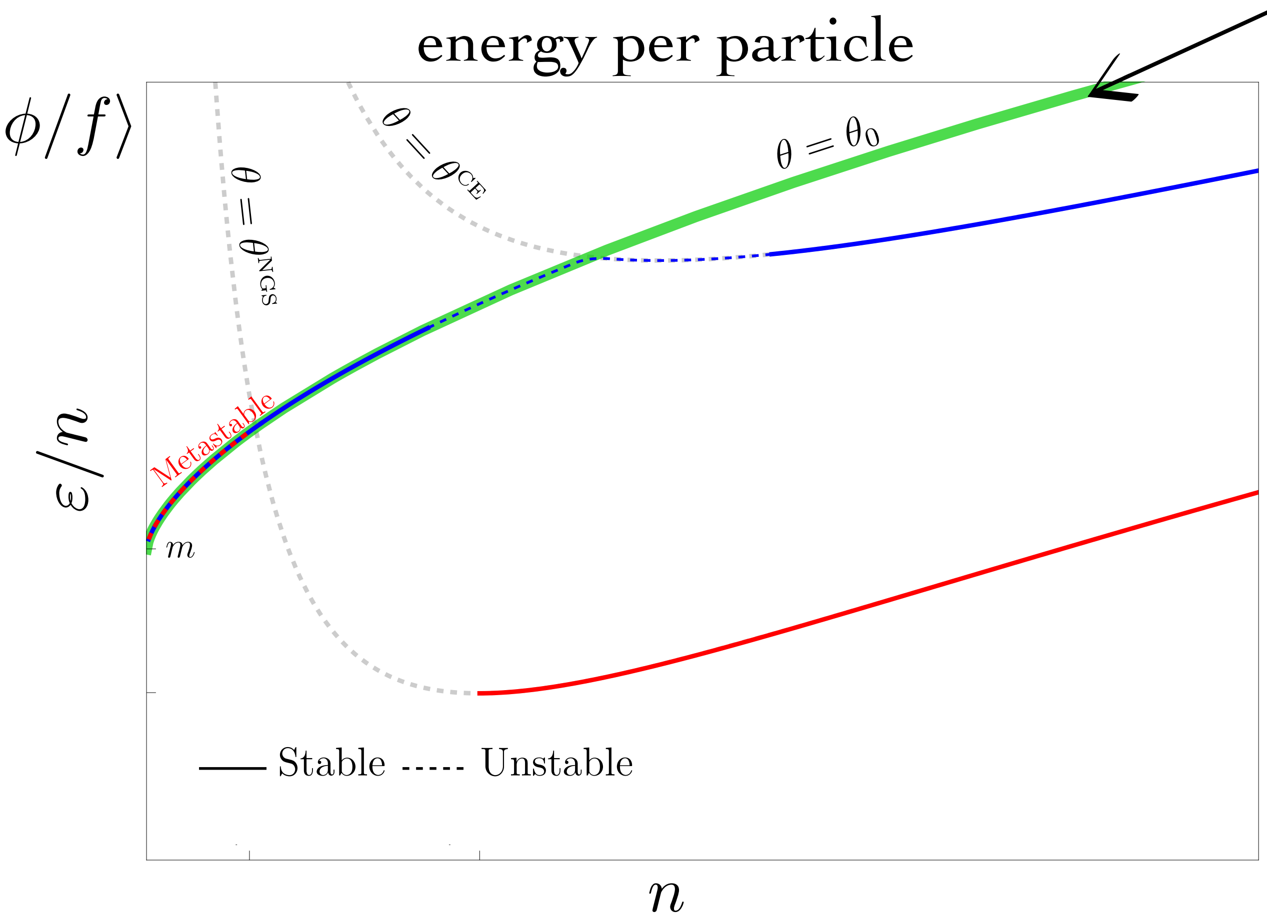

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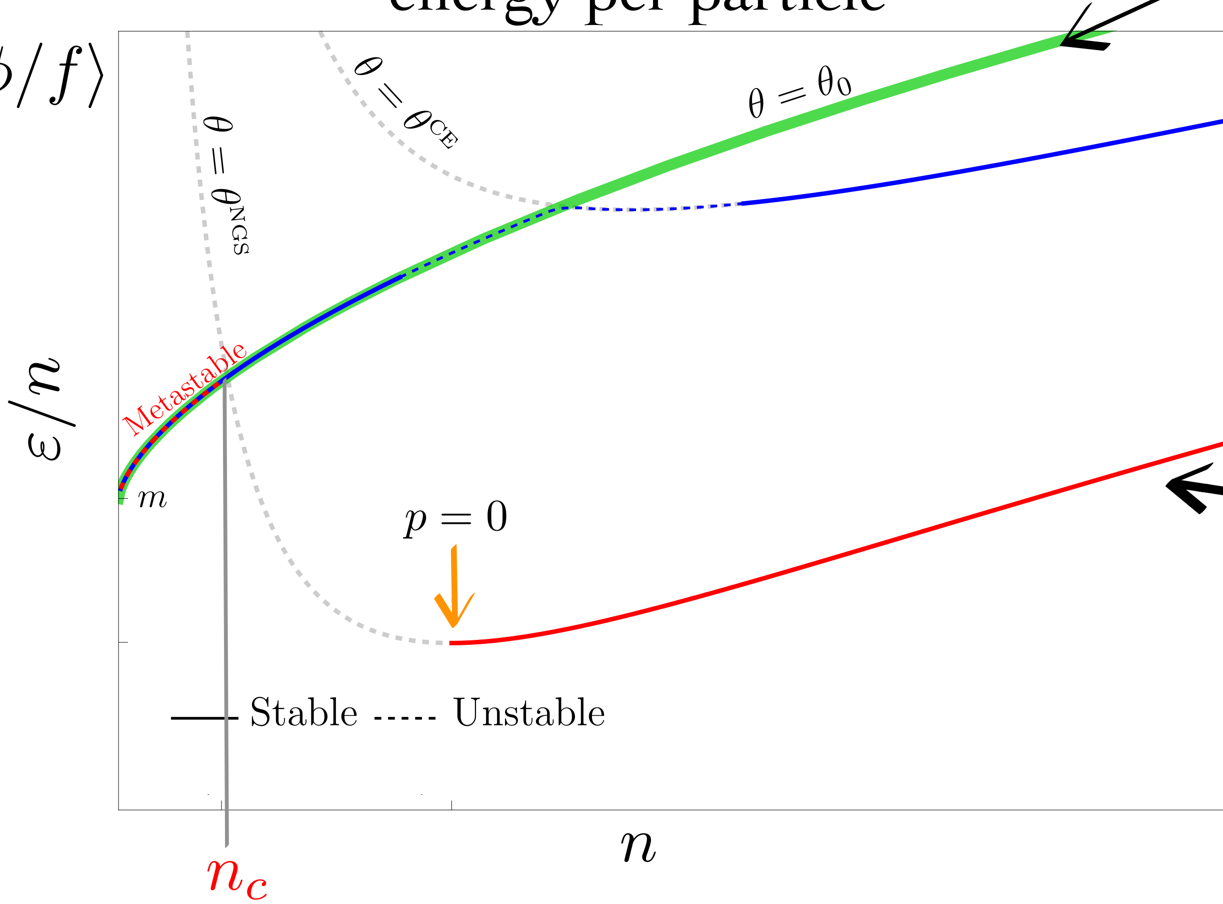

NR free Fermi gas

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new ground state

$m(\langle\phi\rangle) < \mu < m$

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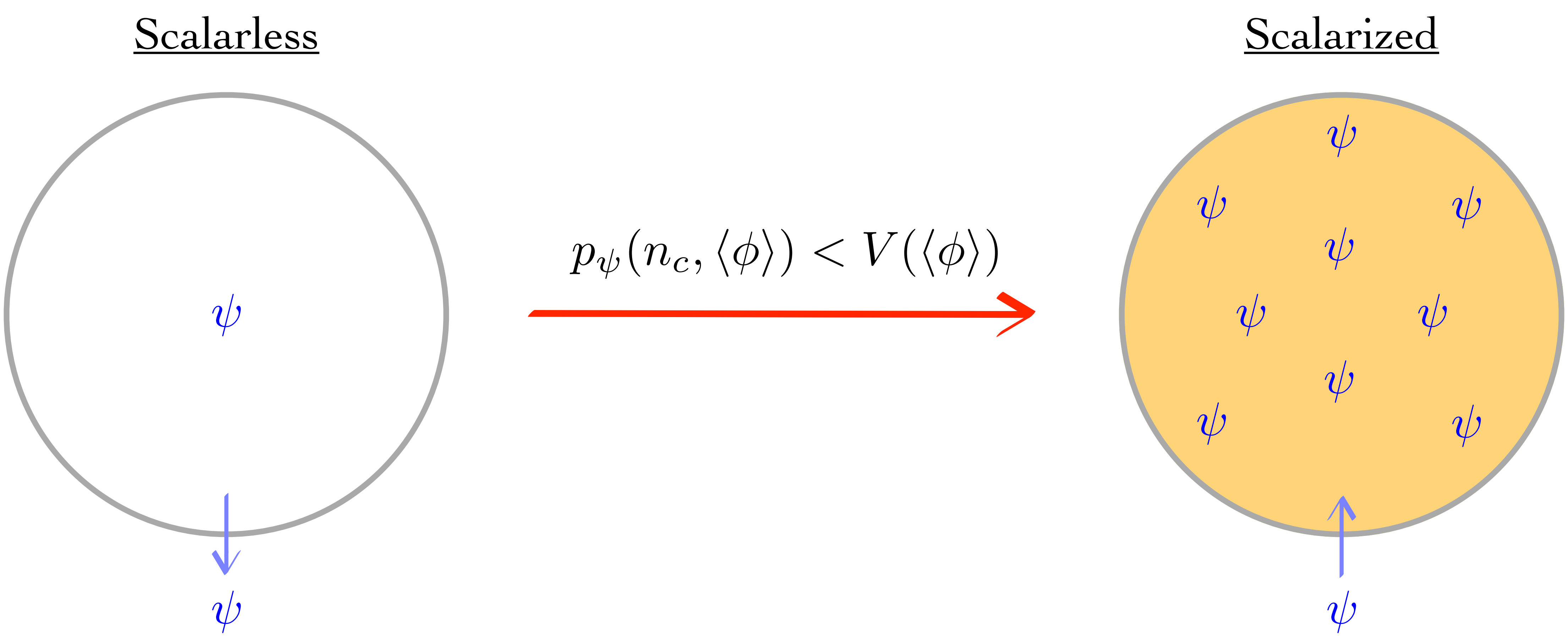
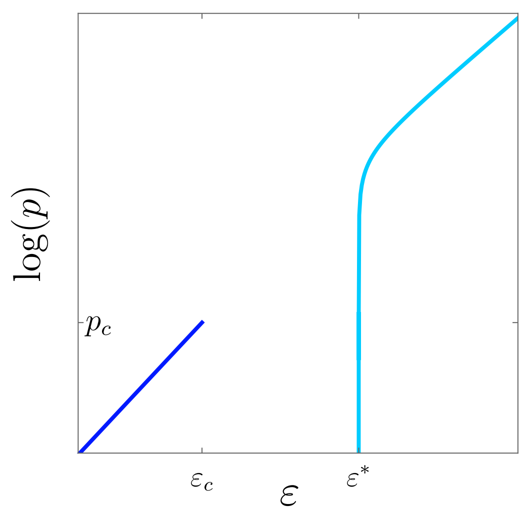


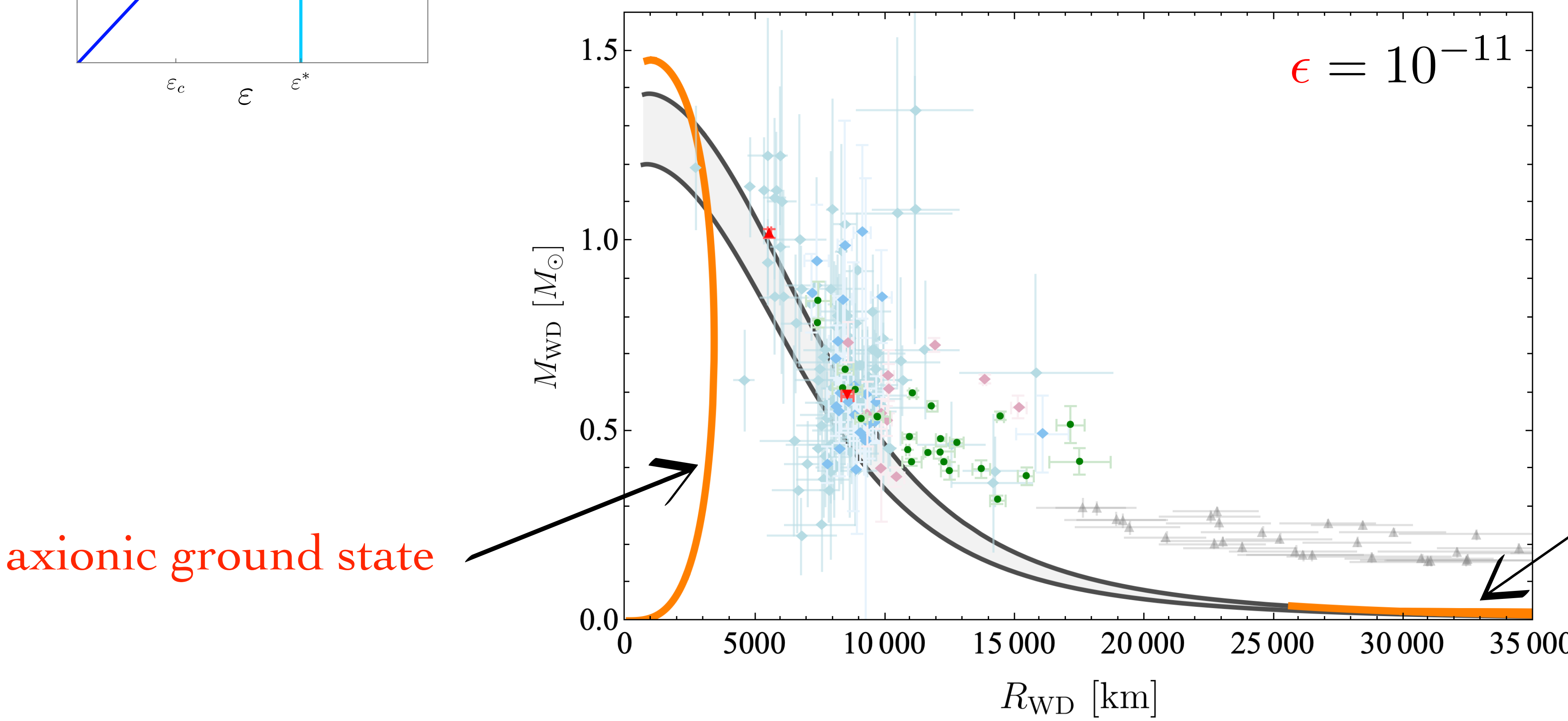
White-Dwarf Mass-Radius Gap

Discontinuity in Equation of State leads to a gap in M-R plane of WDs.

$$p \simeq p_e \qquad \varepsilon \simeq 2 m_N n \qquad n = n_e = n_p$$



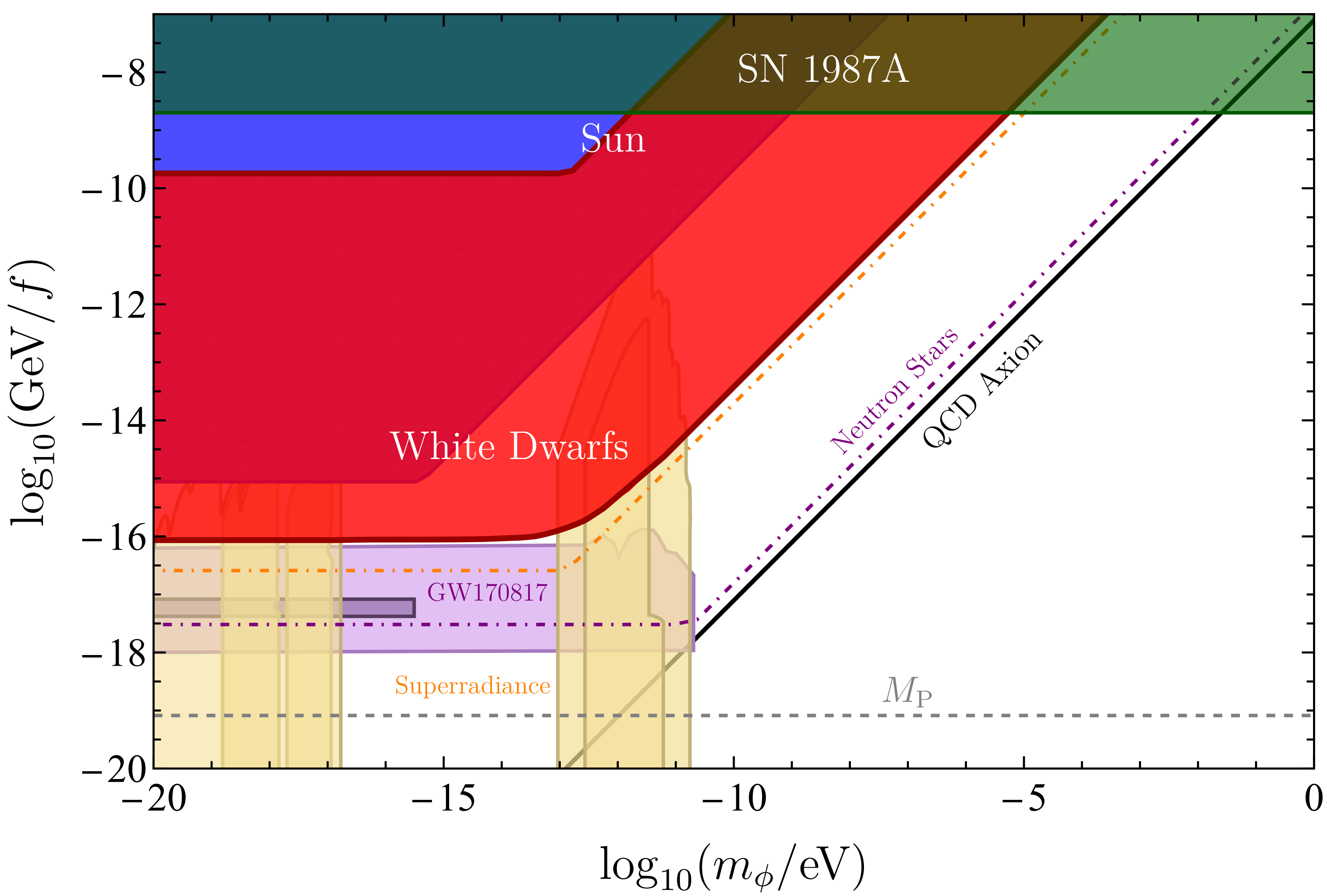
$$m_N(\pi f_a) < \mu \simeq m_N$$



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

Experimental Bounds

Strong bounds on lighter QCD axion from absence of observed gap.



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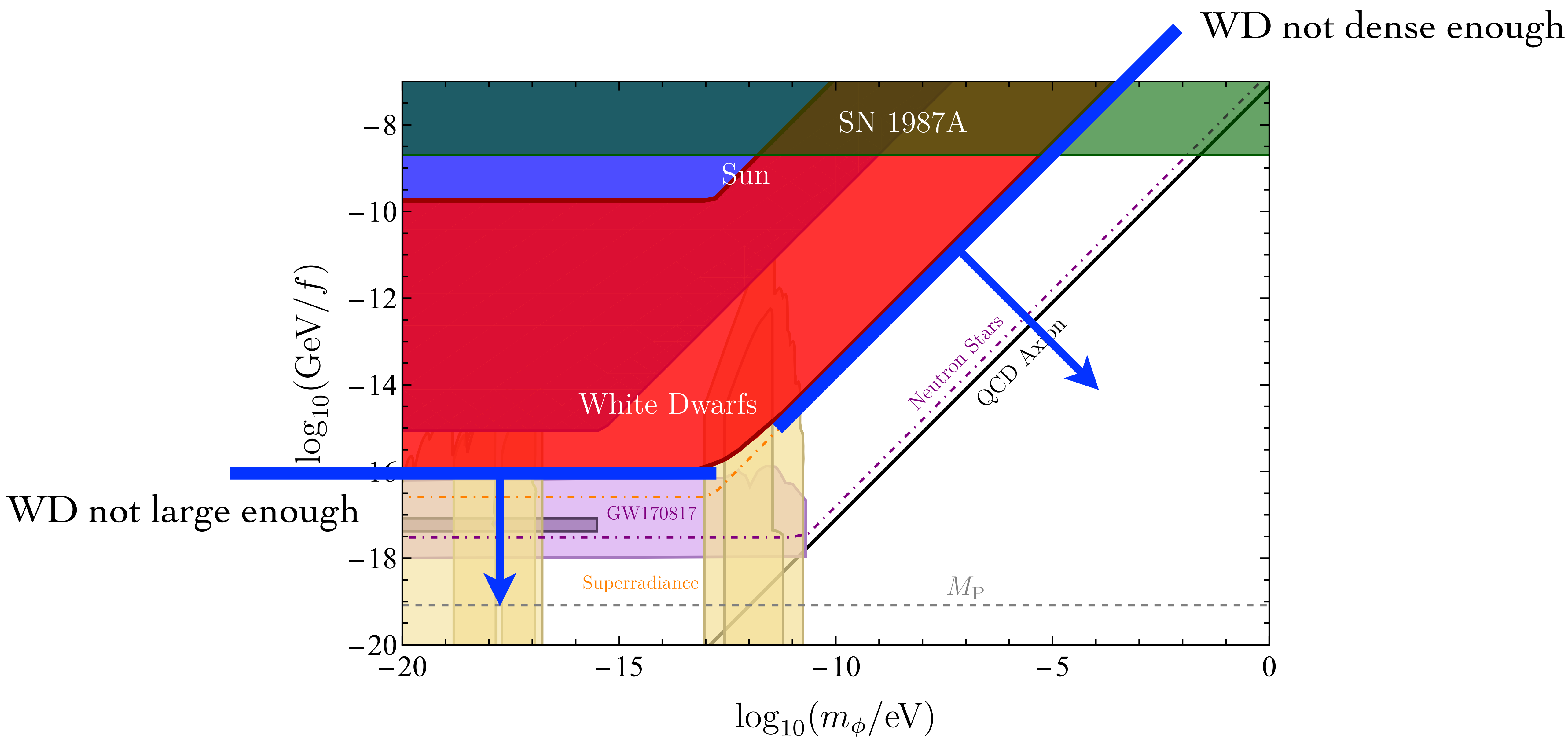


[Almost identical bounds hold for the Z_N realization.]

QCD Scalars

Heavier (and larger) Neutron Stars

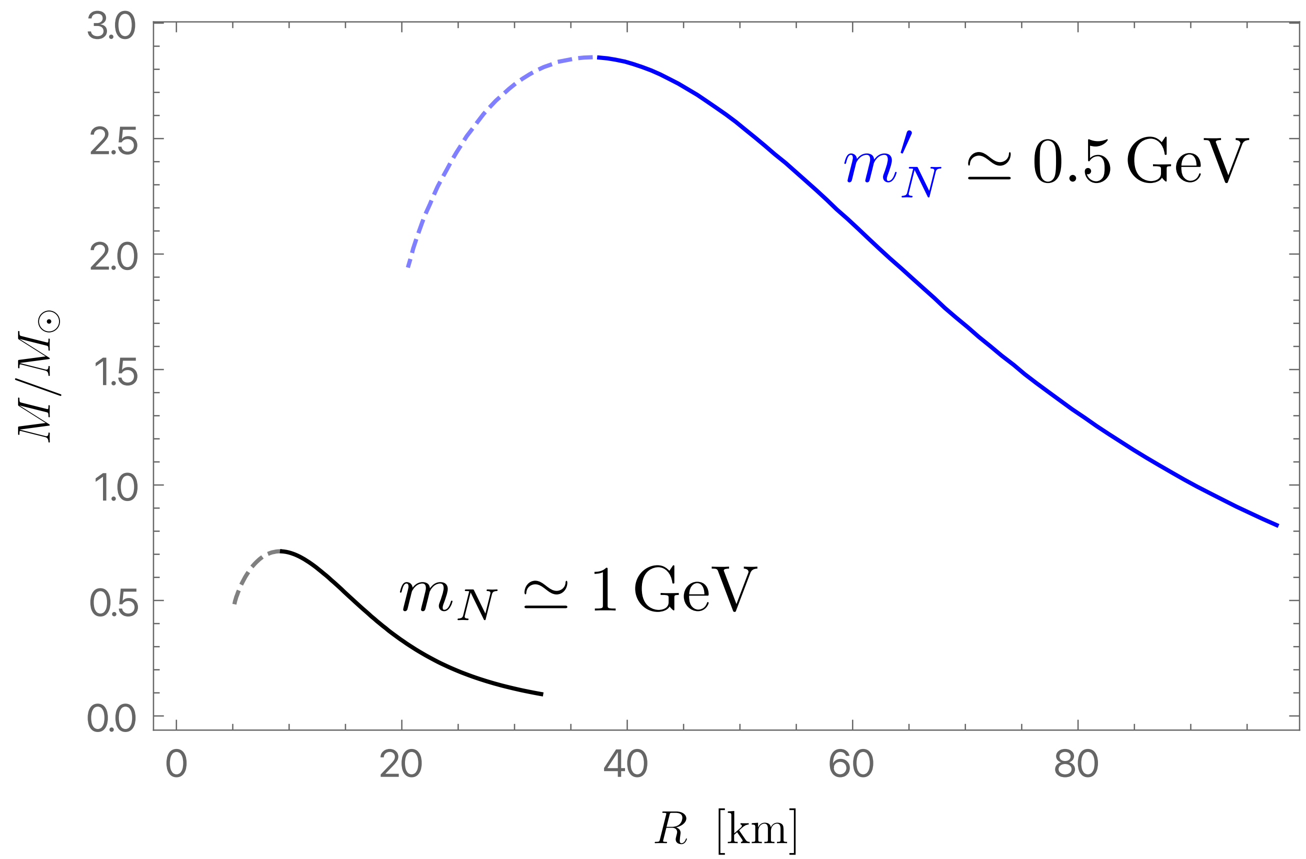
Mass (and radius) of NS made of a free Fermi gas neutrons increases w/ its mass.

$$\frac{M_{\rm max}(m_N)}{M_{\rm max}(m'_N)} \simeq \left(\frac{m'_N}{m_N}\right)^2$$

$$m(r) \sim m_N n_N r^3$$

$$\varepsilon_N \sim m_N n_N \sim m_N^4$$

$$\varepsilon_g \sim m(r) m_N n_N / M_{\rm Pl}^2 r$$



Active QCD-coupled scalars realize this.

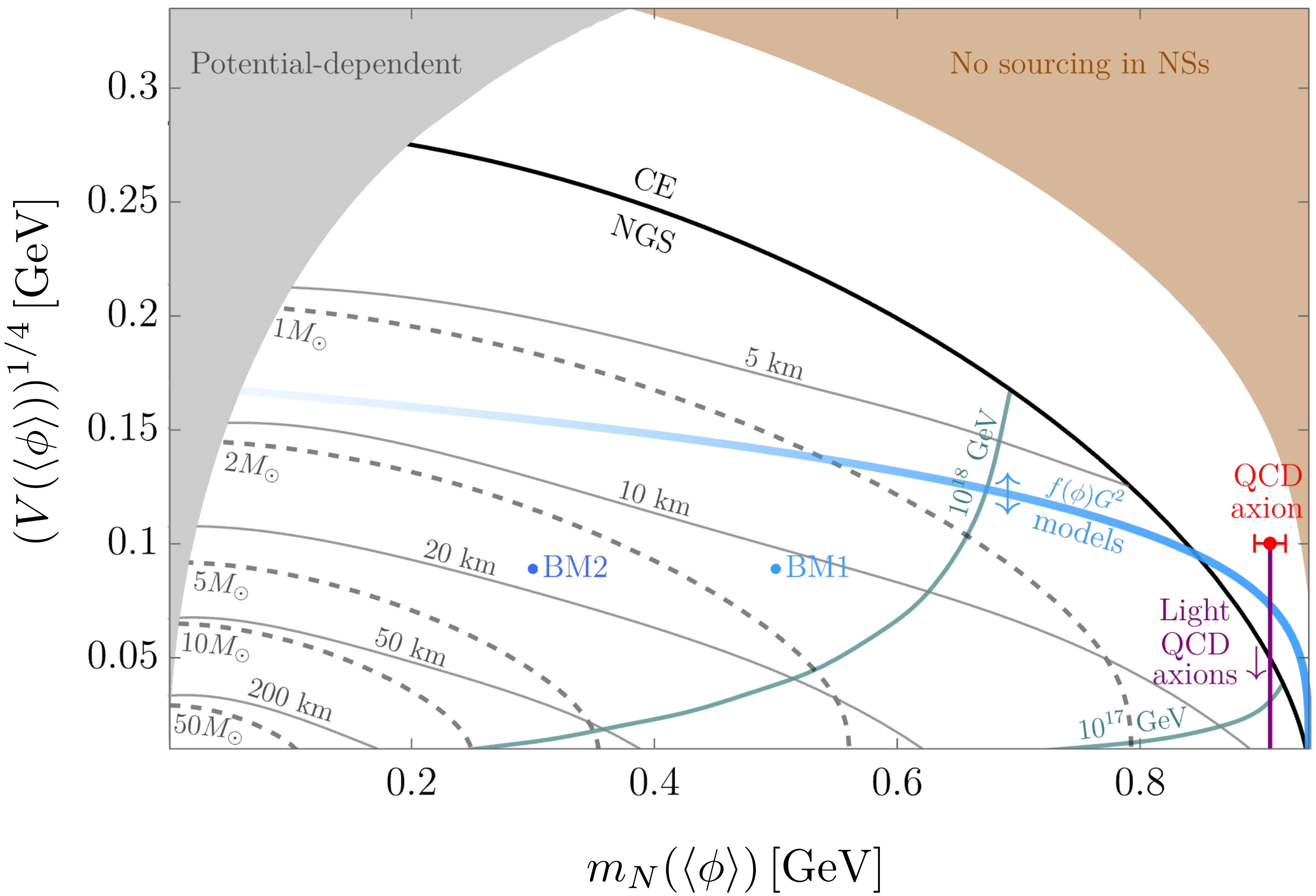
$$m'_N \equiv m_N(\langle\phi\rangle)$$

Scalarized Stellar Landscape

Mass and radius of (free-)neutron stars expand a much larger range than in the "SM".

$$\varepsilon(n,\phi) = \varepsilon_N(n, m_N(\phi)) + V(\phi)$$
$$p(n,\phi) = p_N(n, m_N(\phi)) - V(\phi)$$

more tuned potentials



stronger couplings

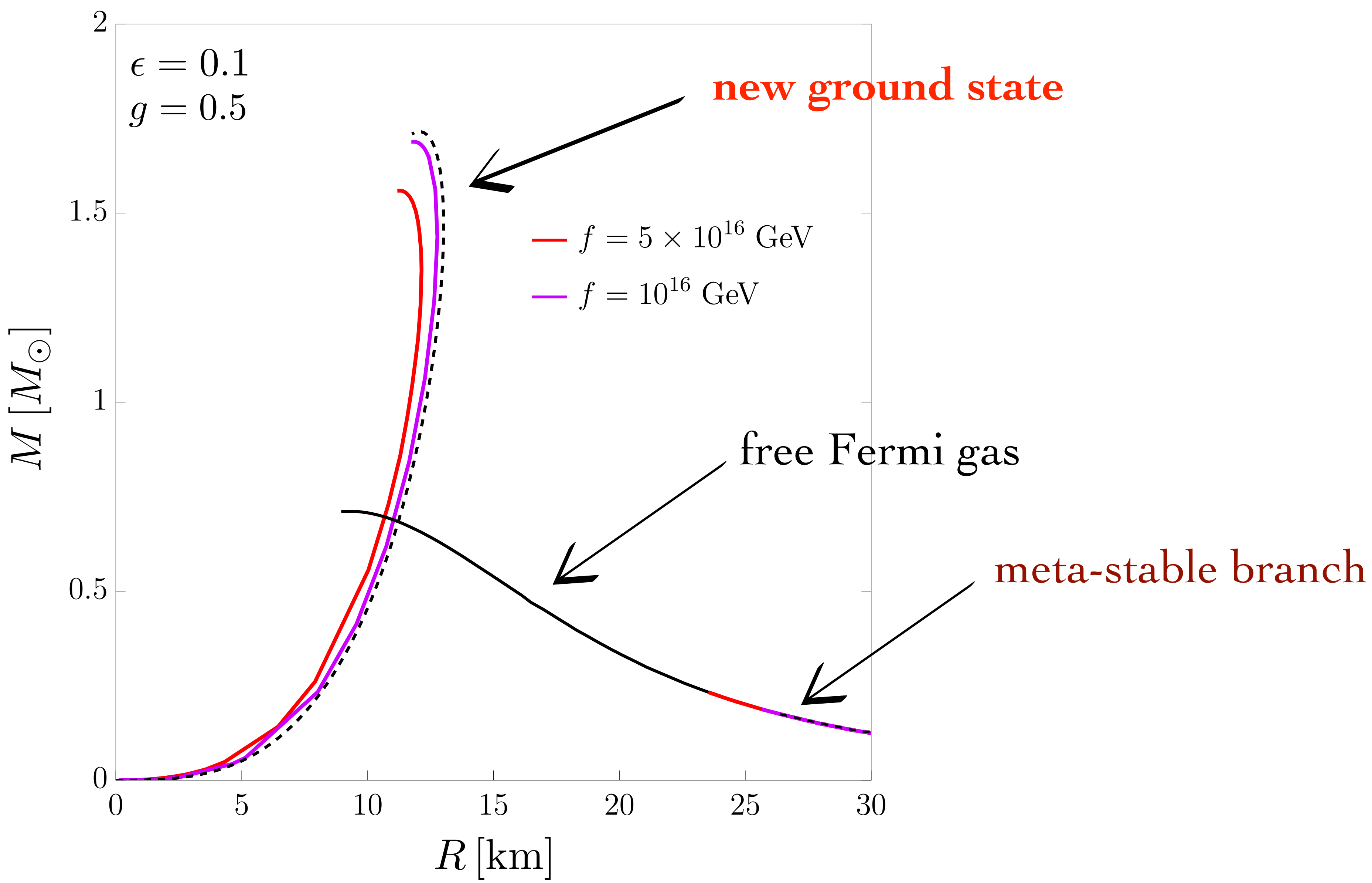
$$\frac{M_{\max}}{M'_{\max}} \simeq \left(\frac{m'_N}{m_N}\right)^2$$

$$\frac{M_{\max}}{M'_{\max}} \simeq \left(\frac{V(\langle\phi\rangle')}{V(\langle\phi\rangle)}\right)^{1/2}$$

Heavy Neutron Stars from ALPs

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

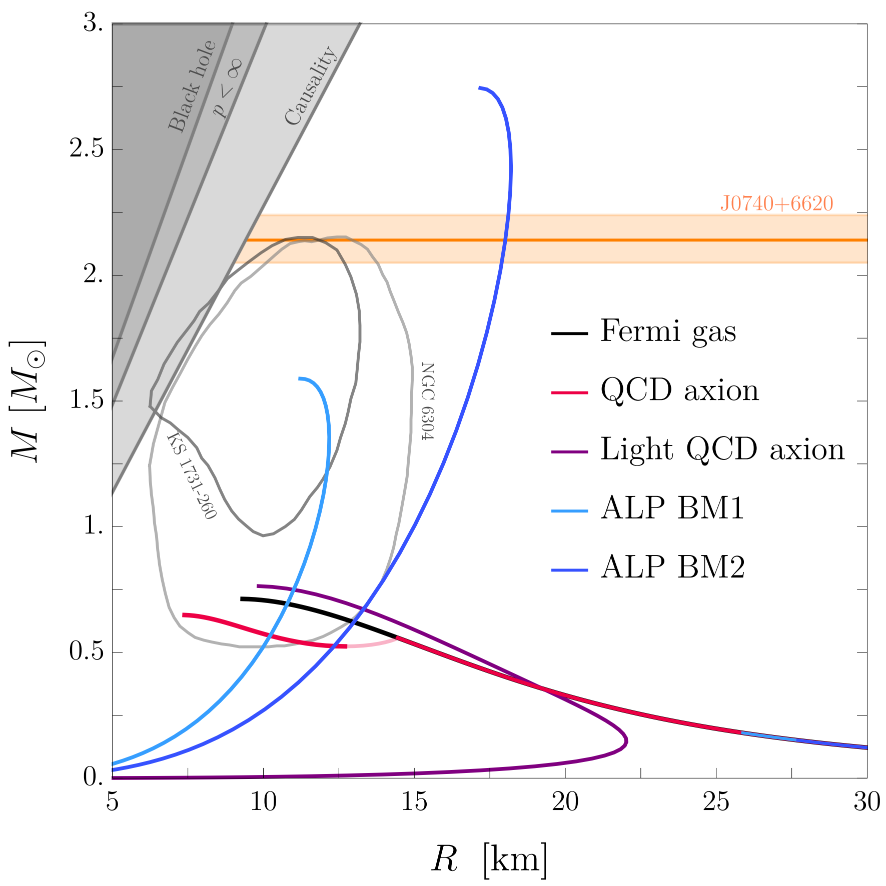
$$m_N(\phi) - m_N = +g m_N \left(\cos\frac{\phi}{f} - 1\right)$$



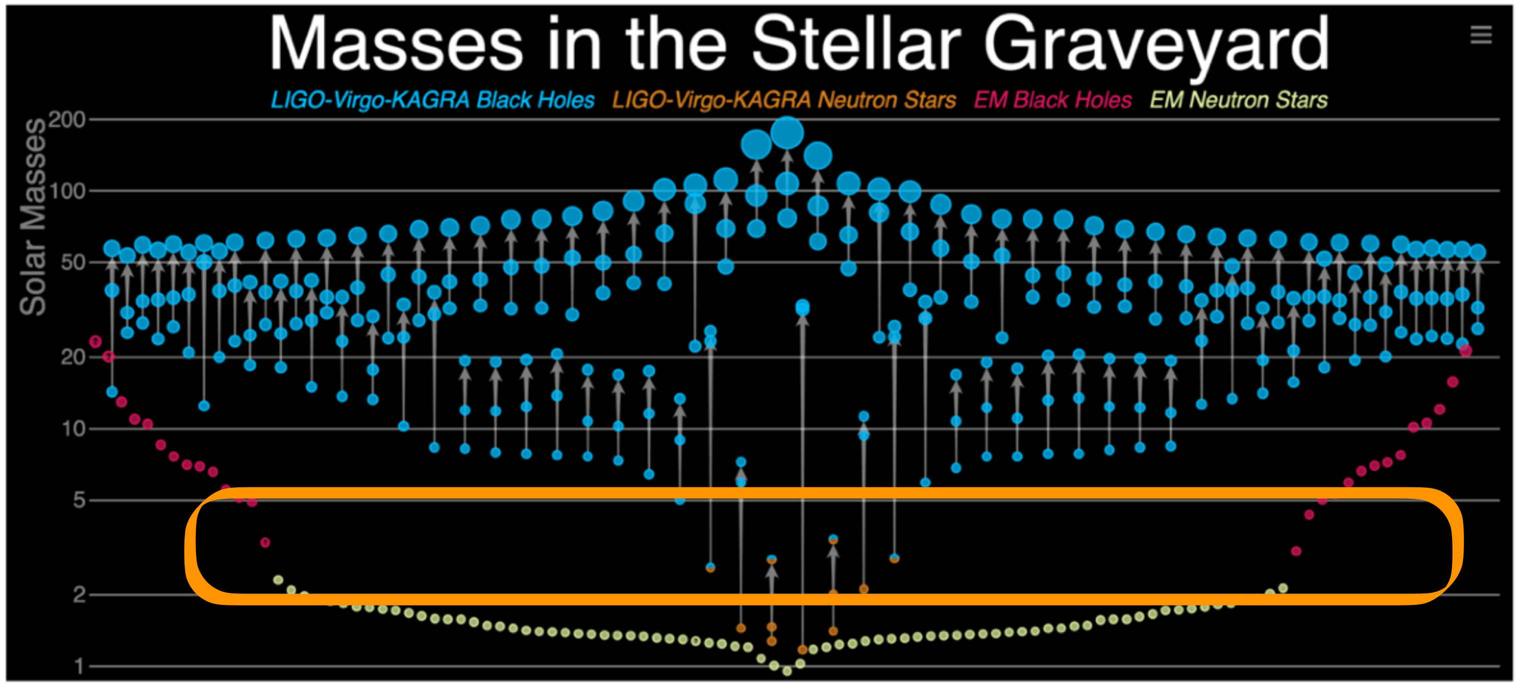
Experimental Observations

Simplified yet physically transparent analysis provides new benchmarks to compare w/ data.

X-ray obs.



Gravitationa wave obs.



Much more data to come in the future from NICER and LIGO-Vigro-KAGRA.

[$M_{\max}$ causal bounds do not generically hold for scalarized NSs.]

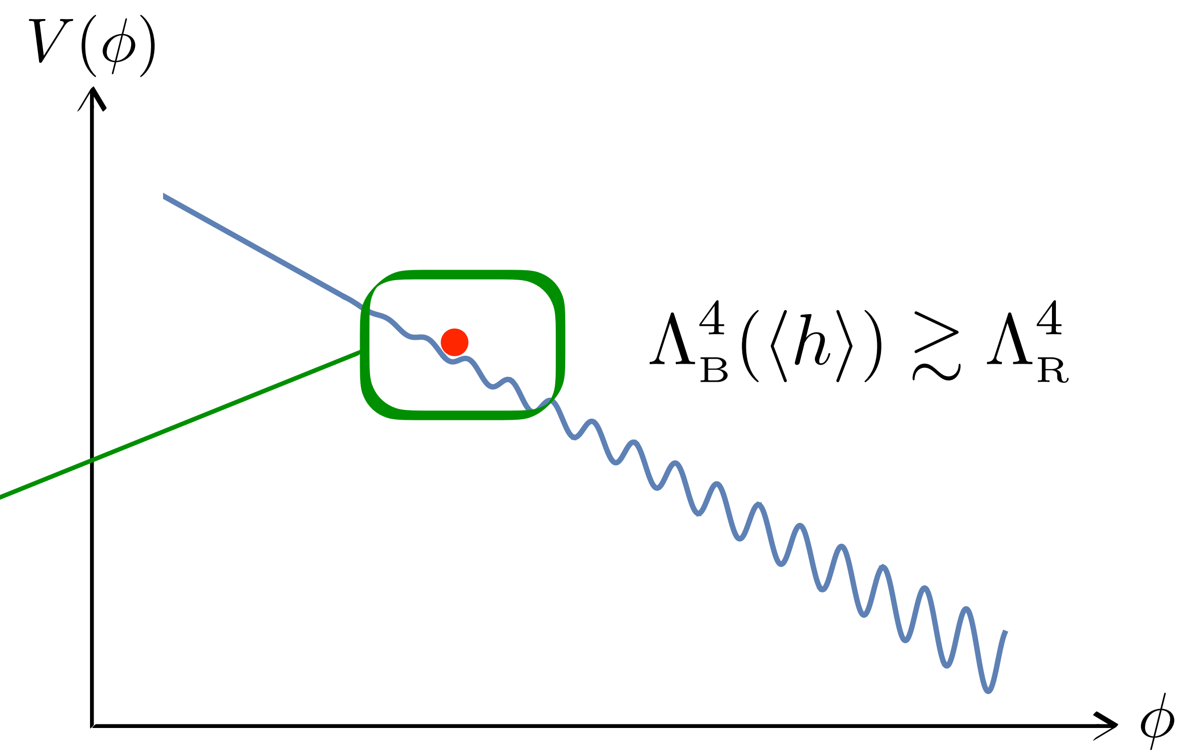
Relaxion

Relaxion at Finite Density

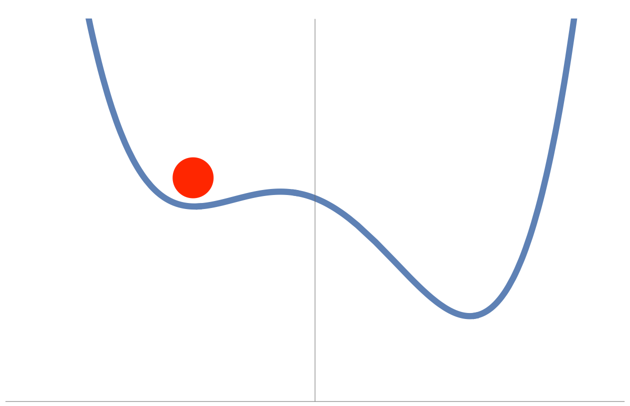
Vacua of (non-QCD) relaxion change in medium, due to Higgs dependence.

$$V(\phi) = -\Lambda_{\rm R}^4 \frac{\phi}{f} + \Lambda_{\rm B}^4(h) \cos\frac{\phi}{f}$$

$$\Lambda_{\rm B}^4(h) = \Lambda_{\rm C}^4 h^2/v^2$$



$\underline{n = 0}$



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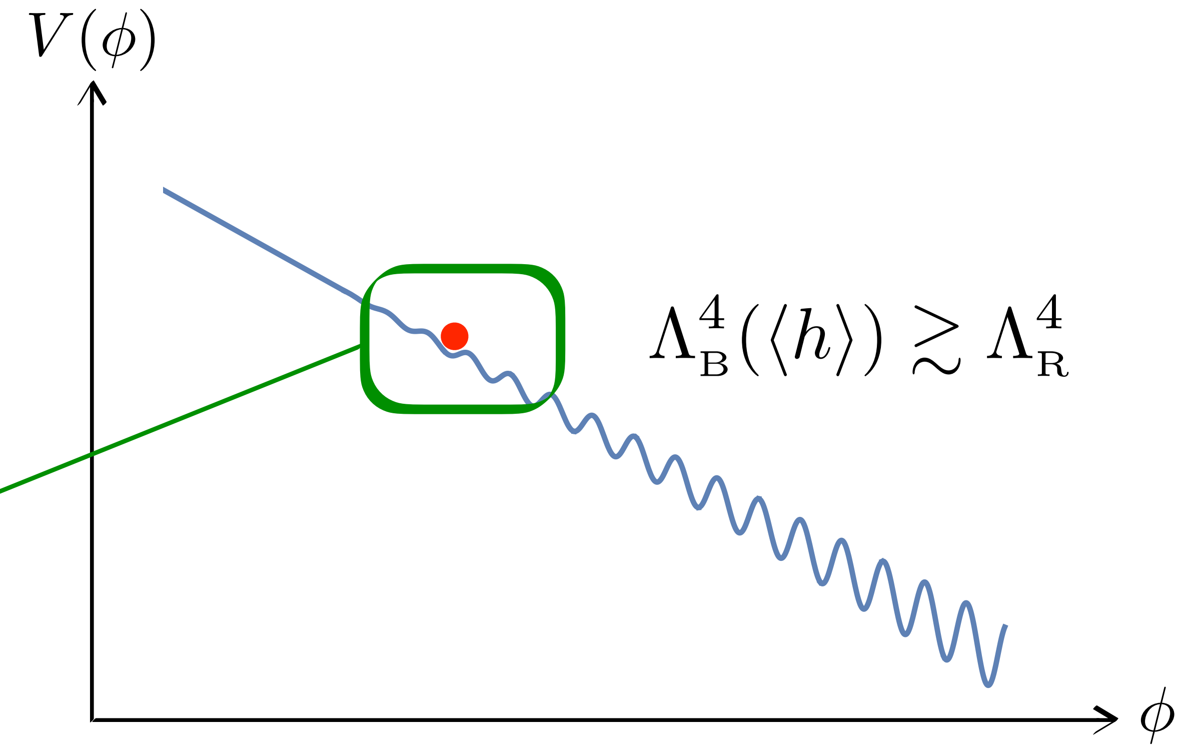
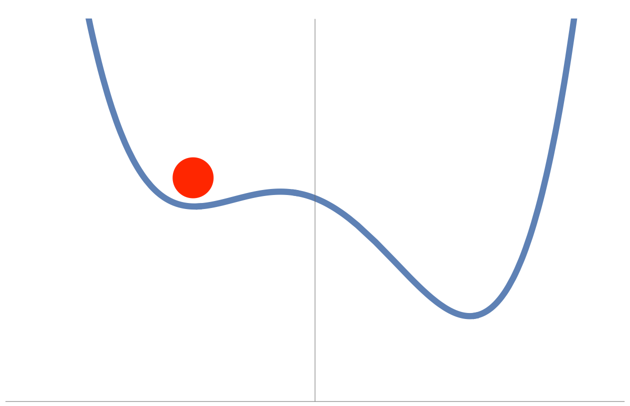


$$\Lambda_{\rm B}^4(\langle h \rangle) \gtrsim \Lambda_{\rm R}^4$$

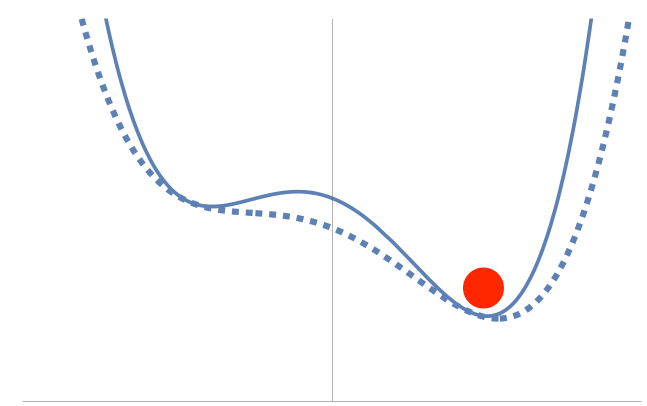
$\underline{n = 0}$



$$\delta h^2 \sim \frac{\sigma_N}{v} \frac{n}{\lambda_H v^3}$$

$$\Lambda_{\rm B}^4(n_c) \equiv \Lambda_{\rm R}^4$$

$\underline{n > n_c}$



Classical transition between vacua allowed above critical density.

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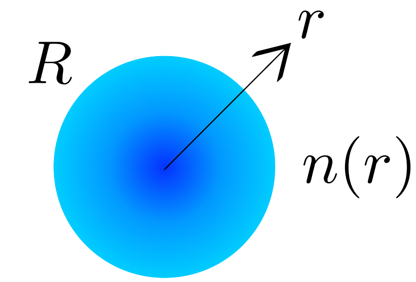
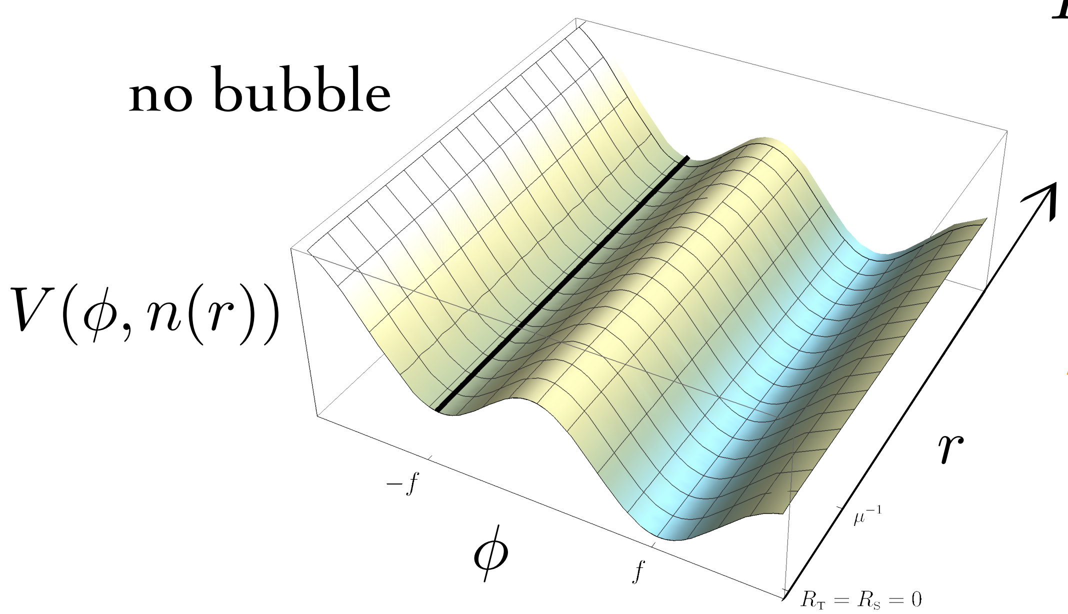
Bubble Formation and Expansion

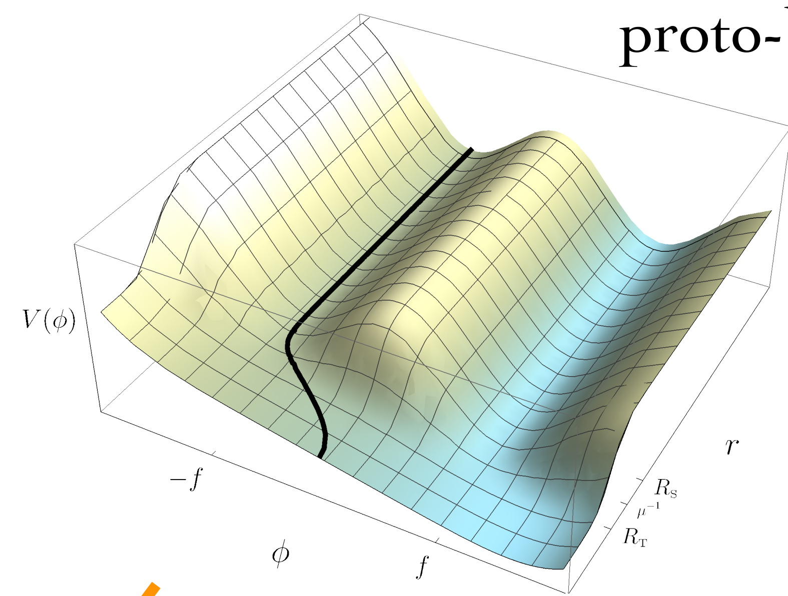
$$R \gtrsim \frac{1}{\bar{m}_\phi(n)} \simeq \frac{f}{\Lambda_{\mathrm{R}}^2}$$



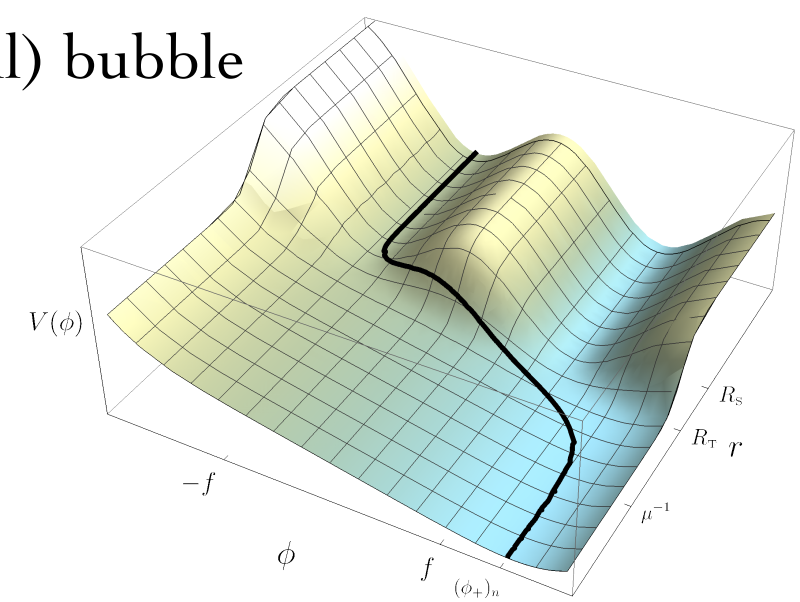
no bubble



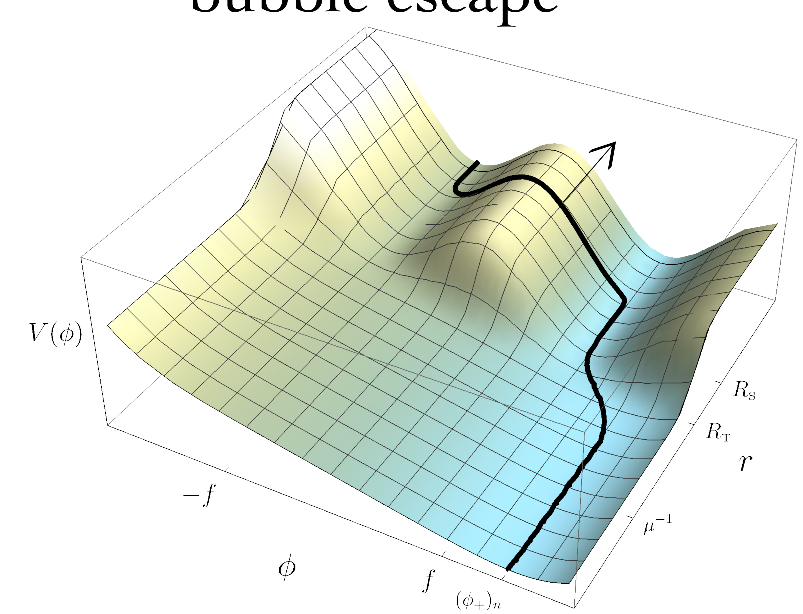
proto-bubble



(full) bubble



bubble escape



[Verified w/ numerical solutions of scalar EoM.]

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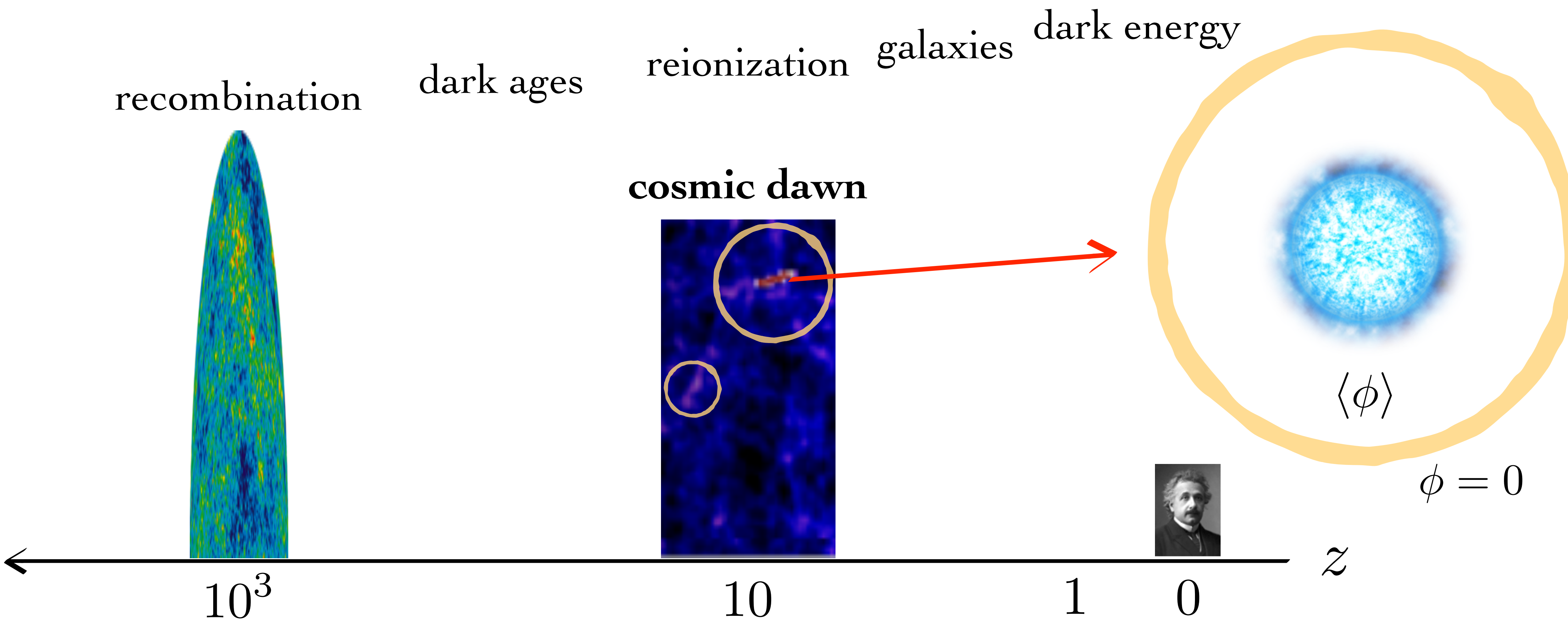
Phase Transition at Cosmic Dawn



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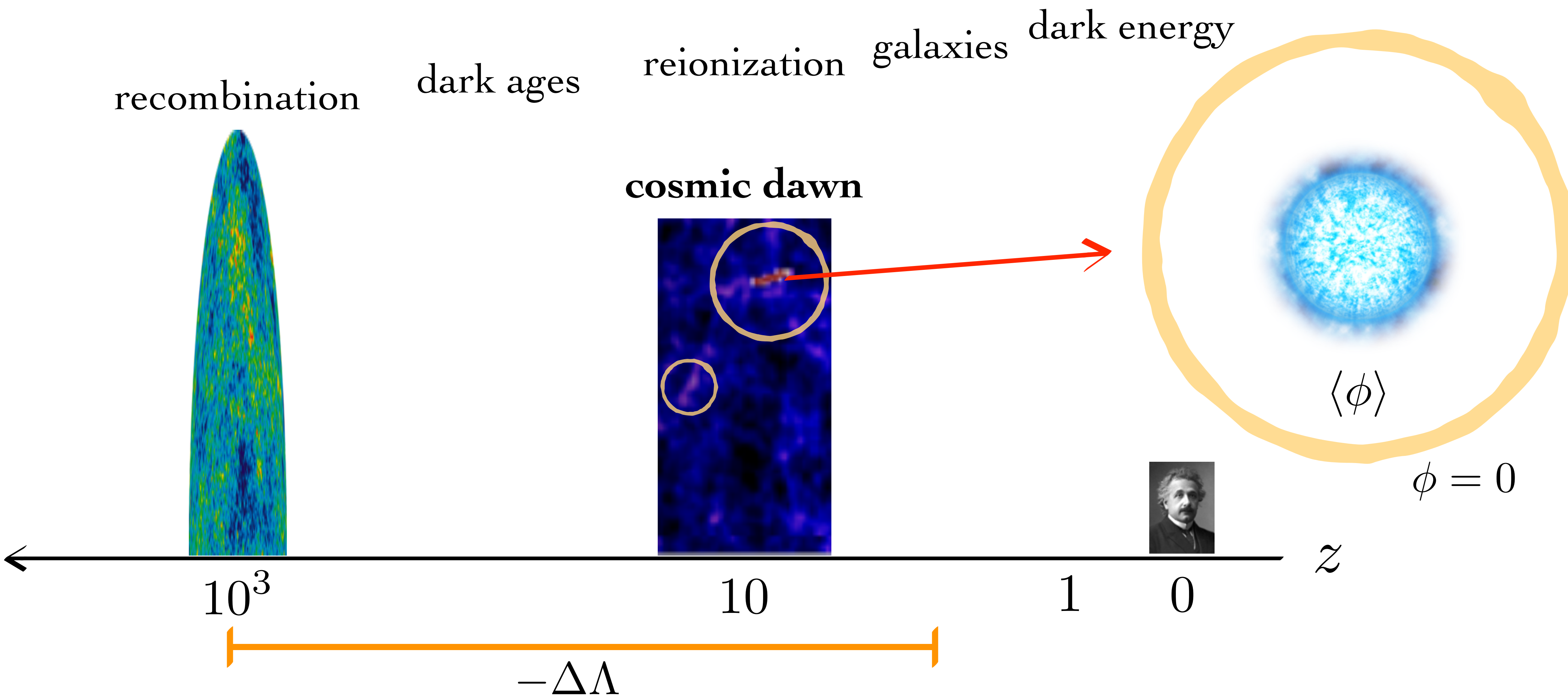

If our universe (within horizon) completely transitions to lower-energy minimum:

$$-\Delta\Lambda \sim \Lambda_{\rm R}^4 \gtrsim \left(\frac{f}{R}\right)^2 \approx \Lambda_0 \times 10^{15} \left(\frac{f}{10\,\text{TeV}}\right)^2 \left(\frac{10\,\text{km}}{R}\right)^2$$

For dense enough small stars, change in dark energy (CC) way too large.

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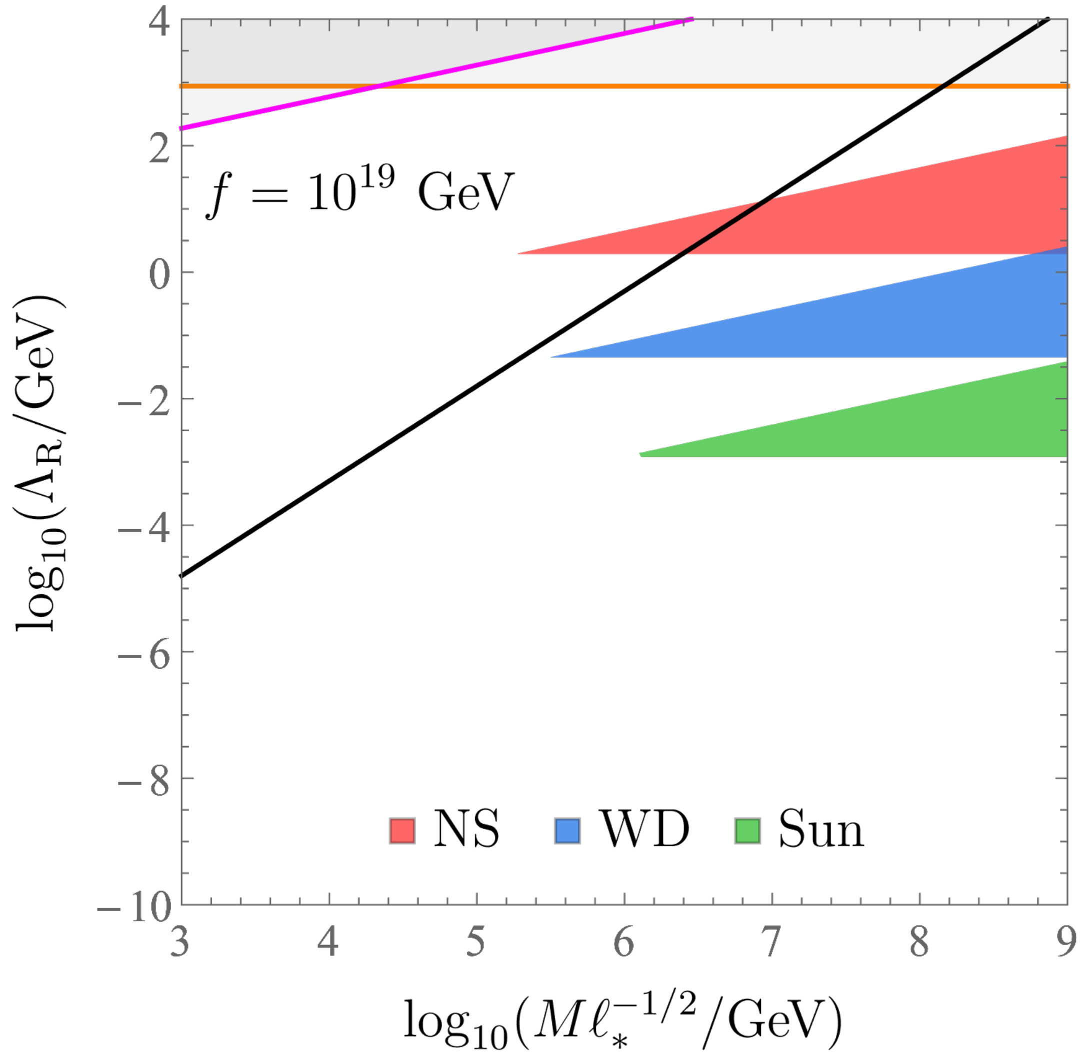
Experimental Bounds

Large fraction of relaxion parameter space would have led to too large change in CC.



$-\Delta\Lambda \lesssim \Lambda_0 \times 10^2$

Karwall, Kamionkowski '16

M = cutoff

ℓ_* = position minimum

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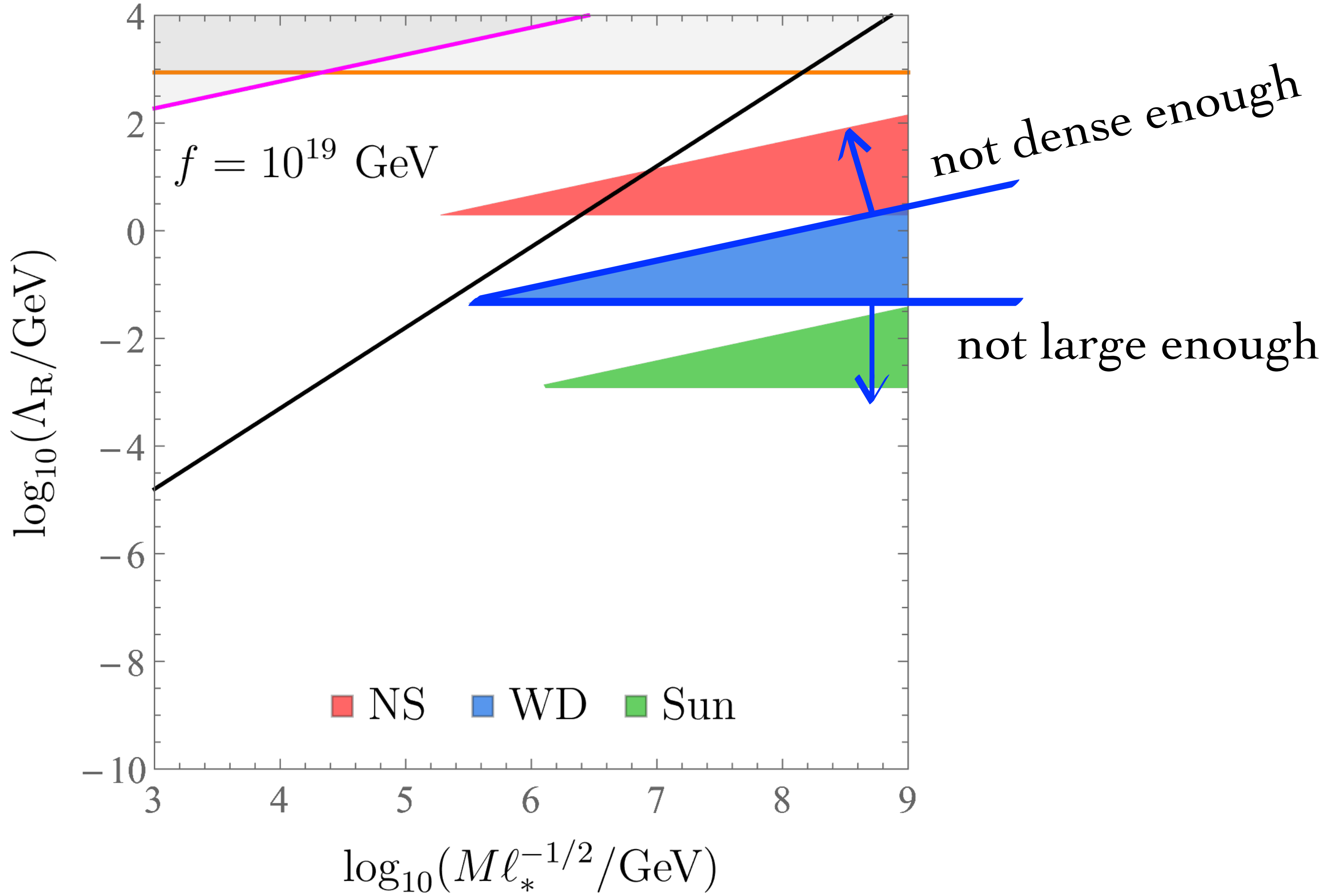

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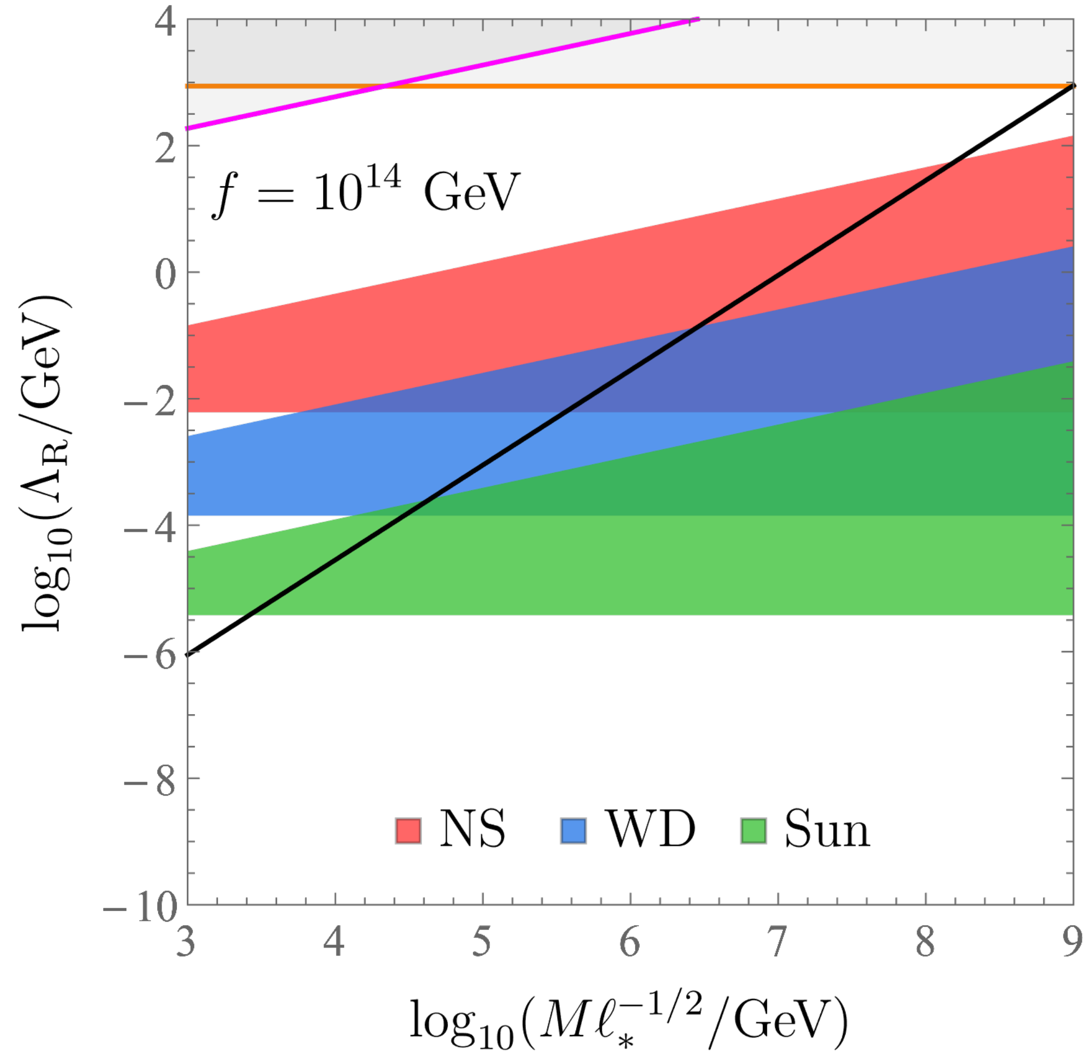

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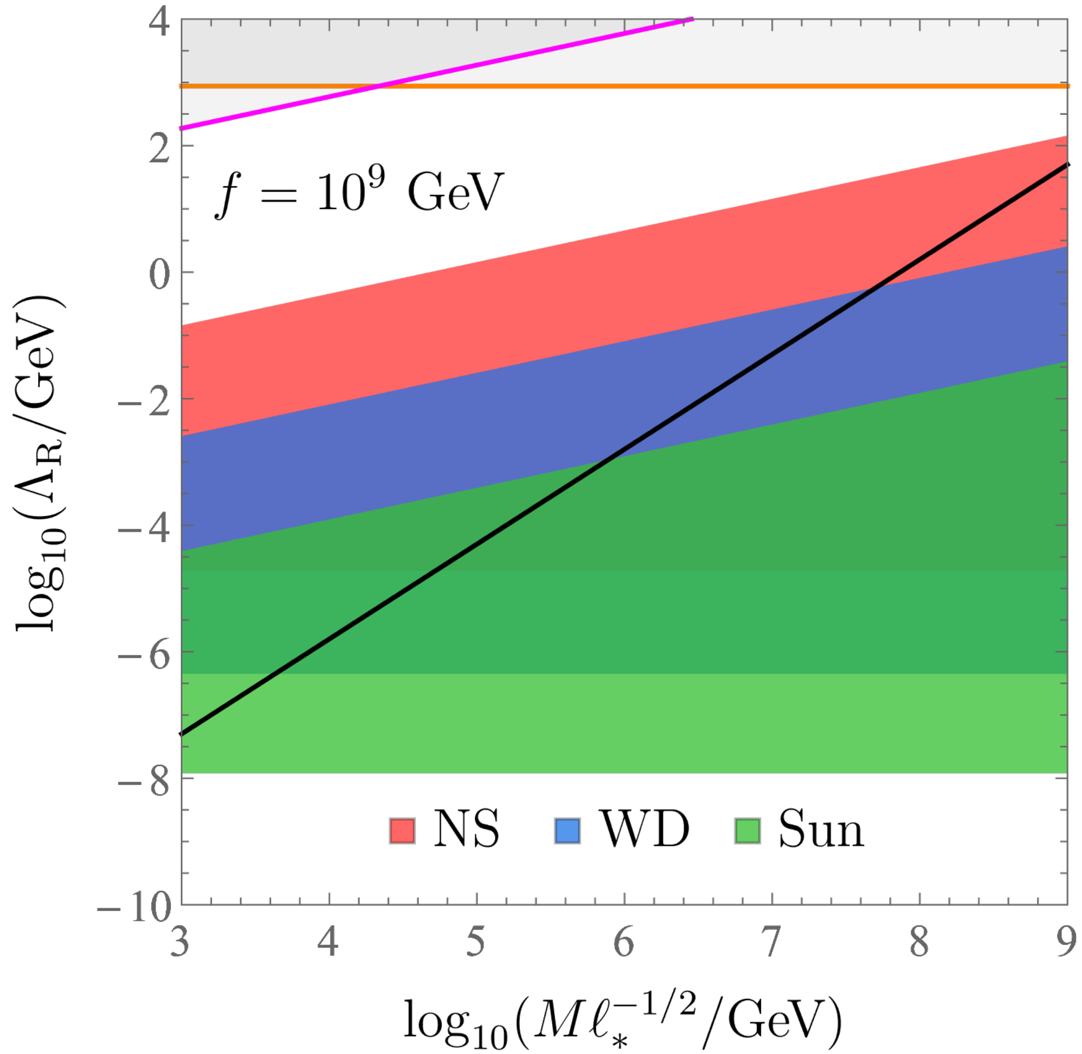

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Karwall, Kamionkowski '16

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Conclusions

Rich interplay between light, weakly-coupled BSM physics and finite density systems:

- QCD-axion emission in supernovae and neutron stars.
- Lighter QCD-axion bounds from M-R relation of white dwarfs.
- Heavy neutron stars in new ground state from QCD-coupled scalars.
- Relaxion bounds from absence of phase transitions at cosmic dawn.
- …

To probe solutions to the main naturalness problems of the SM.

Thank you.

Finite Density Field Theory

Grand-canonical potential density:

$$\hat{\Omega} = \mathcal{H} - \mu J^0$$

Chemical potential as temporal component of gauge field associated w/ conserved charge:

$$\partial_0 \to \partial_0 + i\mu q$$

Ensemble averages w/ density matrix (path) integration:

$$\langle \mathcal{O} \rangle = \frac{\mathrm{Tr}\, \mathcal{O}\hat{\rho}}{\mathrm{Tr}\, \hat{\rho}} \qquad \hat{\rho} = e^{-\frac{1}{T}(H - \mu Q)} \qquad Z(T, \mu, \mathcal{V}) = \mathrm{Tr}\, \hat{\rho}$$

$$\downarrow$$

$$\Omega(T, \mu) = -\frac{T \ln Z}{\mathcal{V}} = \varepsilon - \mu n = -p$$

Light Scalars

Scalar fields of interest are light in contrast to the star's density or temperature.

$$m_\phi \ll n^{1/3} = 1/\ell$$

coherently coupled

$$n \gtrsim \frac{\partial V/\partial\phi}{-\partial m/\partial\phi} \sim \frac{m_\phi^2 f^2}{g_\psi m}$$

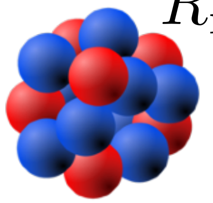
density-sensitive V

$$m_\phi \lesssim T$$

stellar emission

[Energy gradients too large to be source by single nuclei.]

$$m_\phi \ll \frac{1}{R_{\text{nuclei}}}$$



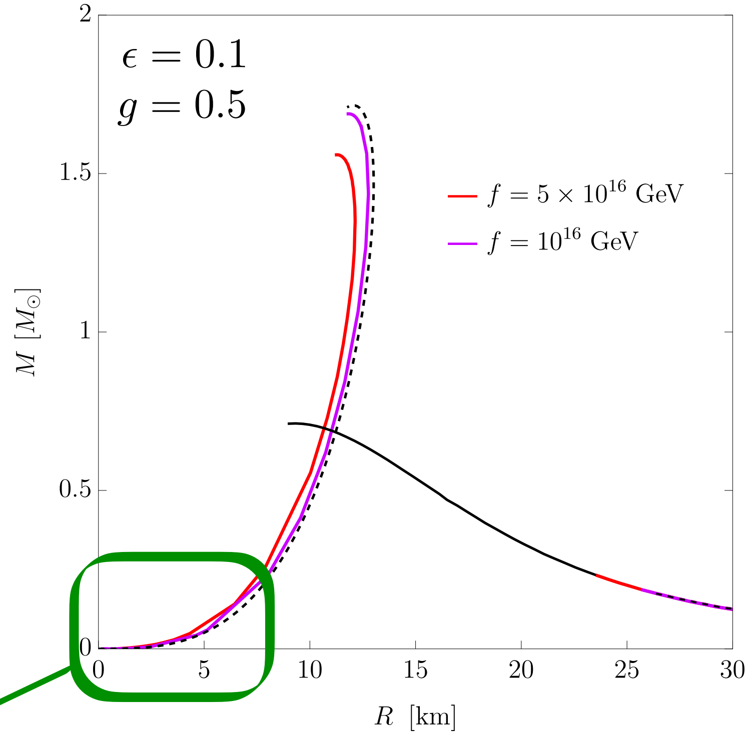
Self-Bound Objects

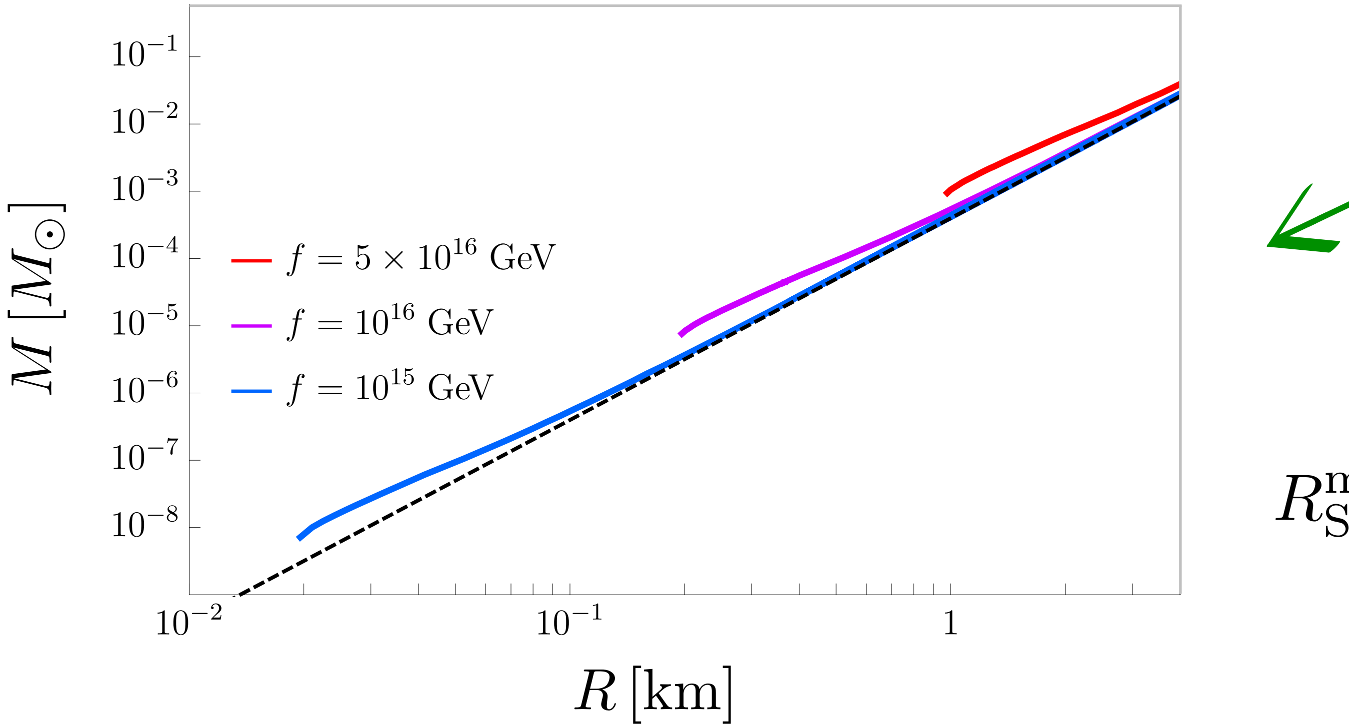
NGS implies stable objects held together by gradient pressure (i.e. no gravity).

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

$$p' = -\phi' \frac{\partial \Omega}{\partial \phi}$$

$$\phi'' + \frac{2}{r}\phi' = \frac{\partial \Omega}{\partial \phi}$$





$$R_{\mathrm{SBO}}^{\mathrm{min}} \sim \frac{1}{m_\phi}$$

Dark Compact Objects

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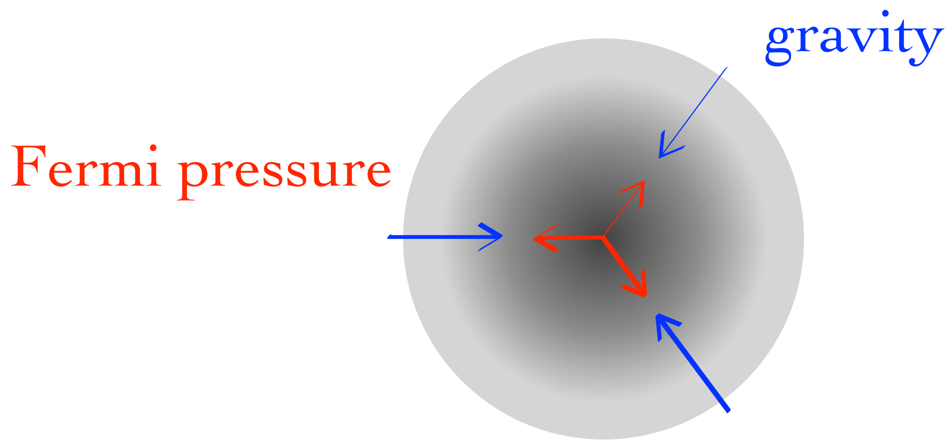
Dark Stars

Classical vacuum transitions seeded by dark-baryon stars.



$$\tilde{n} \sim m_{\tilde{N}}^3$$

$$\tilde{R} \sim \frac{M_{\rm Pl}}{m_{\tilde{N}}^2}$$

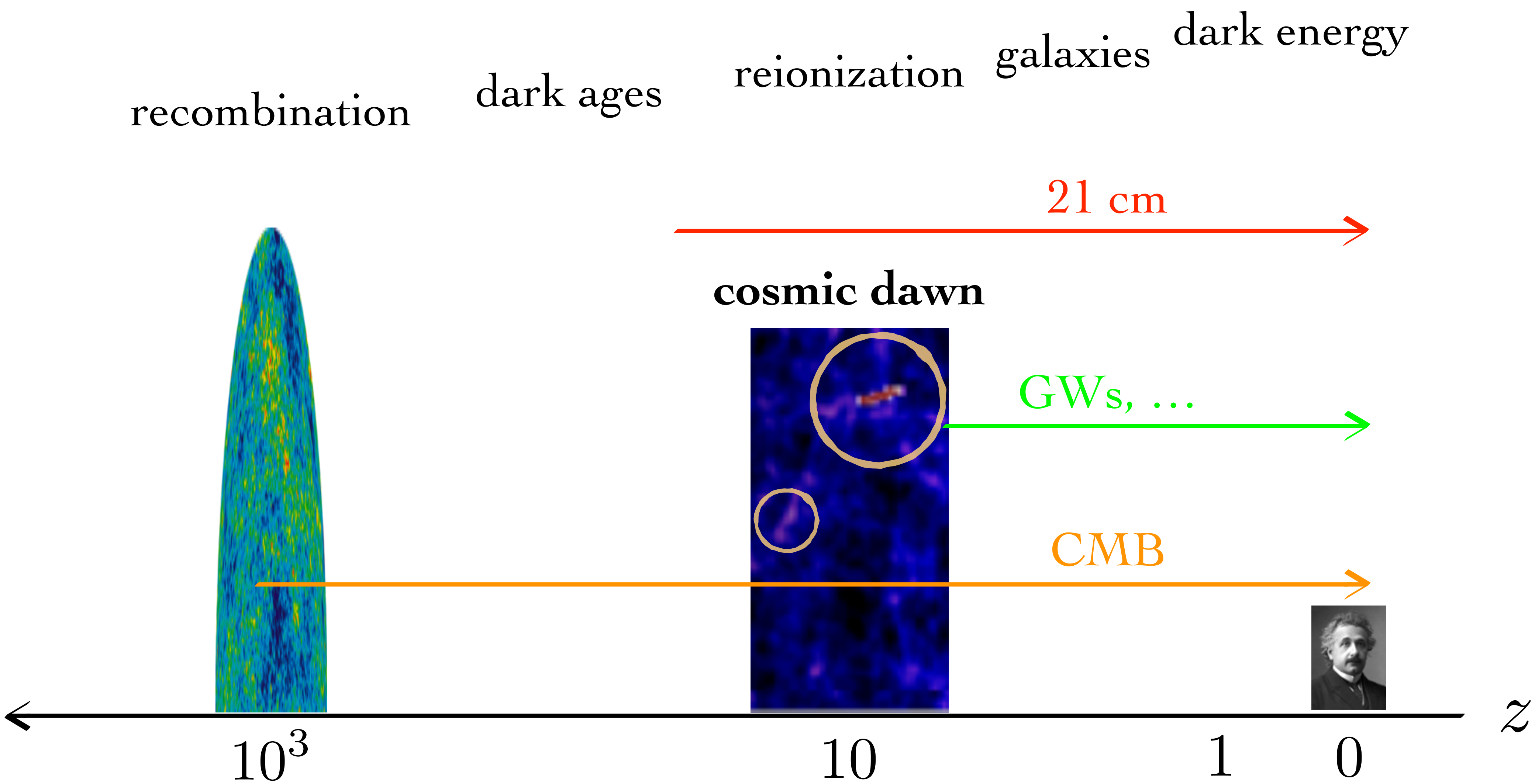
$$\frac{\Lambda_{\rm B}^4(\tilde{n})}{\Lambda_{\rm B}^4} \simeq 1 - \frac{\sigma_{\tilde{N}}\tilde{n}}{\Lambda_{\rm C}^4}$$

dense enough: $\Lambda_{\rm B}^4(\tilde{n}) < \Lambda_{\rm R}^4$ large enough: $m_{\tilde{N}} \lesssim \Lambda_{\rm C}\sqrt{\frac{M_{\rm Pl}}{f}}$

$$-\Delta\Lambda \gtrsim m_{\tilde{N}}^4 \left(\frac{f}{M_{\rm Pl}}\right)^2 \approx \Lambda_0 \times 10^{-2} \left(\frac{m_{\tilde{N}}}{10\,\mathrm{keV}}\right)^4 \left(\frac{f}{10\,\mathrm{TeV}}\right)^2$$

Dark stars could seed phase transitions a priori consistent w/ change in dark energy.

Experimental Probes



Many potential probes of a phase transition at cosmic dawn.