Title: TBA

Speakers: Javier Serra

Series: Particle Physics

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Abstract: TBA

Vacuum Transitions Seeded by Stars

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

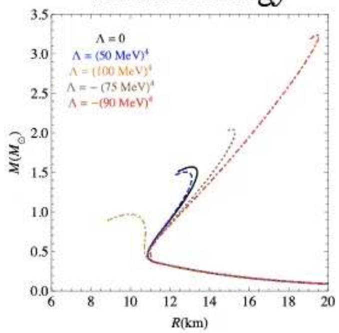
Javi Serra

TUM
Technische Universität München

R.Balkin, JS, K.Springmann, S.Stelzl and A.Weiler
arXiv:2105.13354, 2106.11320

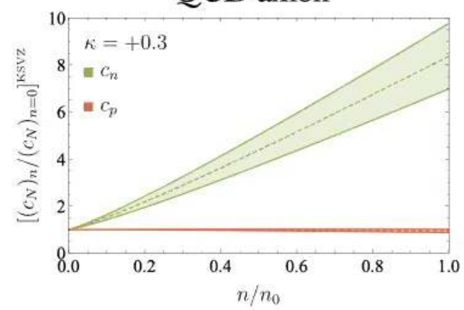
Program to study the physics of well-motivated light scalar fields at finite density.

vacuum energy



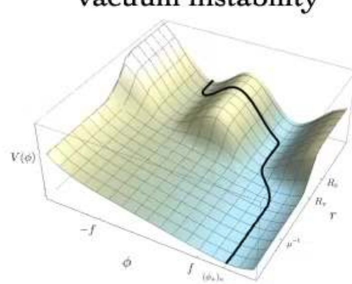
(Bellazzini, Csaki, Hubisz, JS, Terning '15)

QCD axion

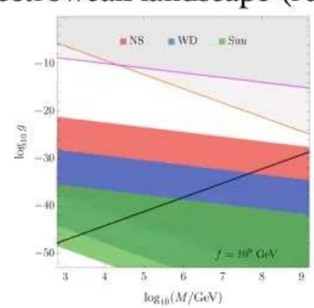


(Balkin, JS, Springmann, Weiler '20)

vacuum instability



electroweak landscape (relaxion)



(Balkin, JS, Springmann, Stelzl, Weiler '21)

2

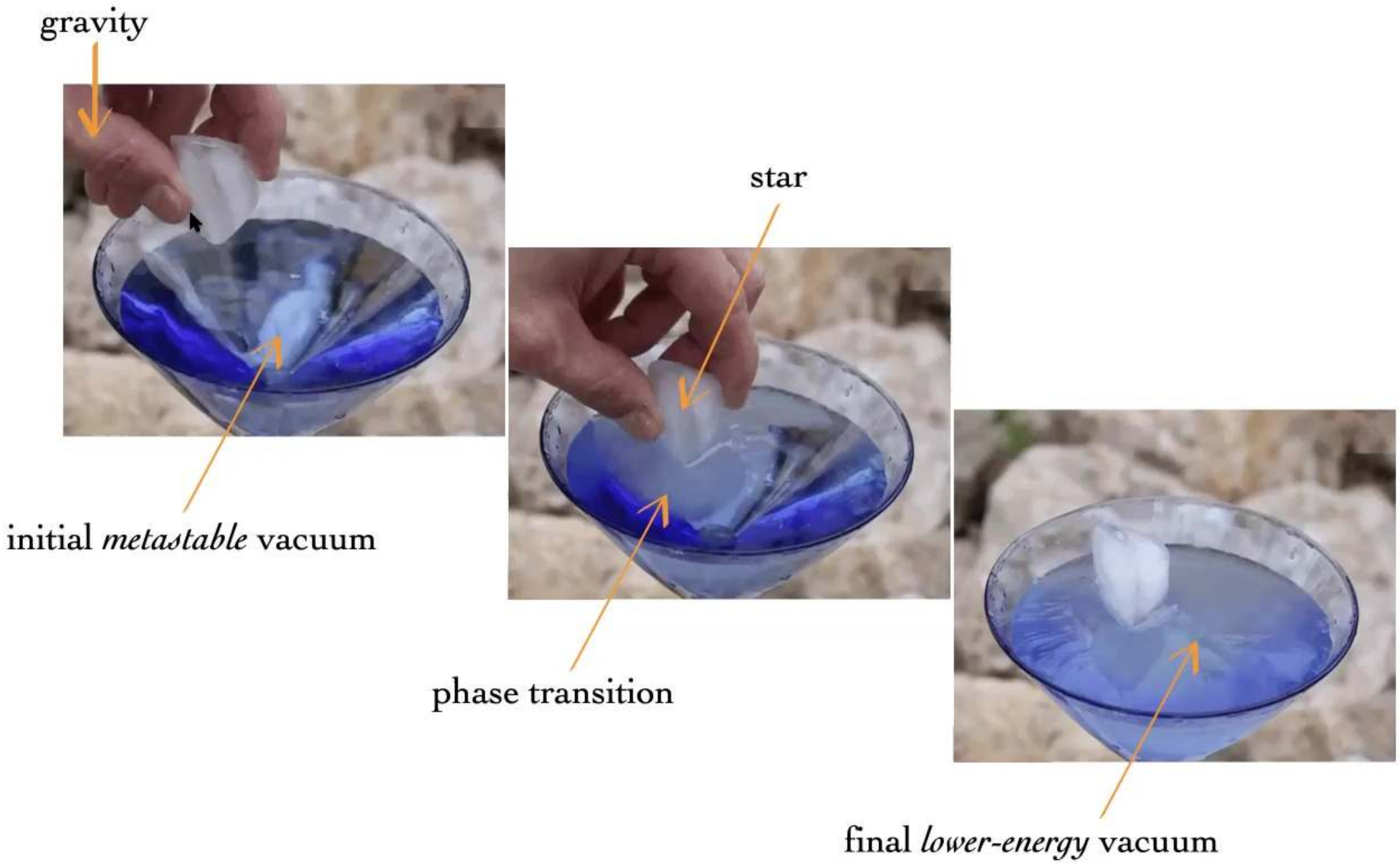
Vacuum Transitions Seeded by Stars

A super-cool water analogy.

3

Vacuum Transitions Seeded by Stars

A super-cool water analogy.



4

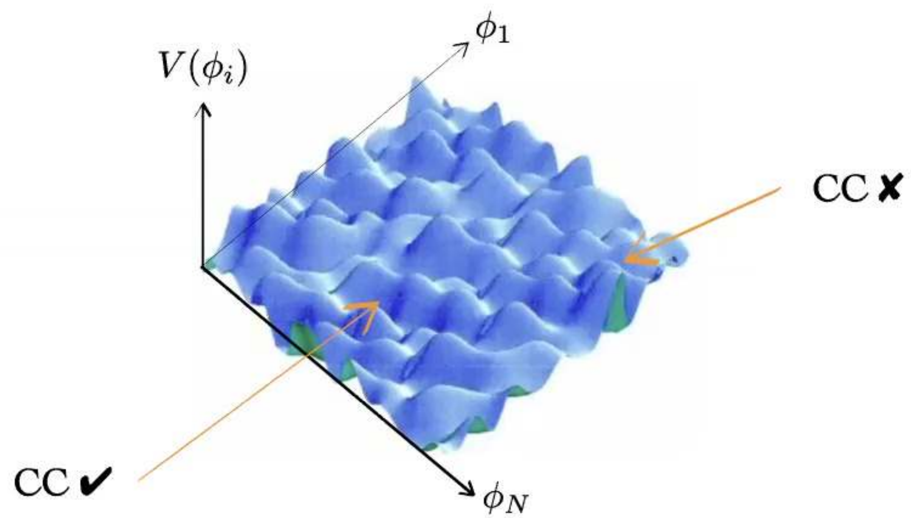
Motivations

Landscapes

Experimental evidence of a vacuum different from ours would be revolutionary.

Cosmological Constant problem

Weinberg '87
Bousso, Polchinski '00
…



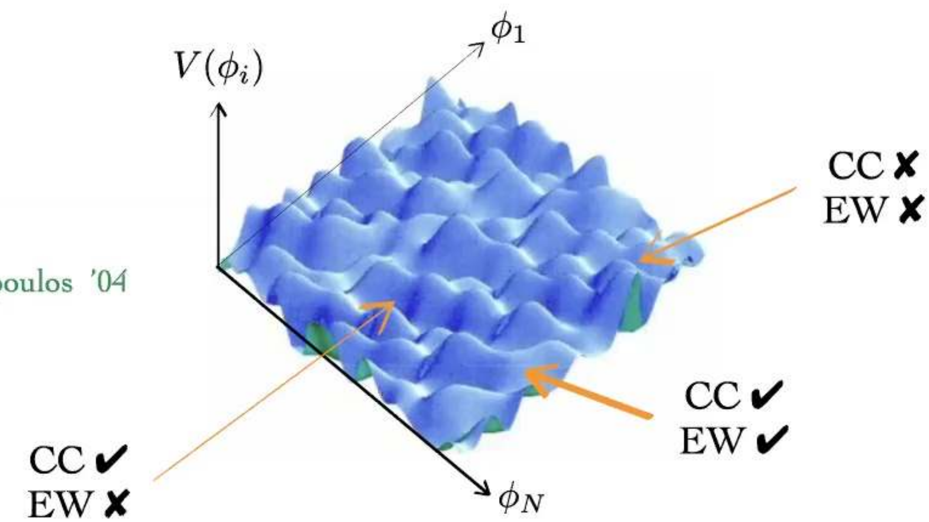
Arguably the best explanation for the tiny size of the cosmological constant.

Landscapes

Experimental evidence of a vacuum different from ours would be revolutionary.

Electroweak Hierarchy problem

Agrawal et al. '98
Dvali, Vilenkin '03
Arkani-Hamed, Dimopoulos '04
…



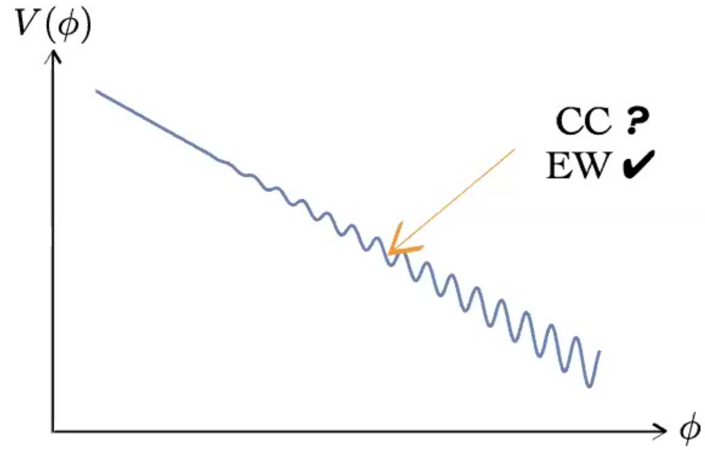
No evidence of standard symmetry approaches and low short-term experimental prospects.

IR Landscapes

Experimental evidence of a vacuum different from ours would be revolutionary.

Cosmological selection of a small electroweak scale

Graham, Kaplan, Rajendran '15



Structured and more predictive landscape.

Many other recent ideas along with novel signatures and bright experimental prospects.

Multi-Vacua at Finite Density

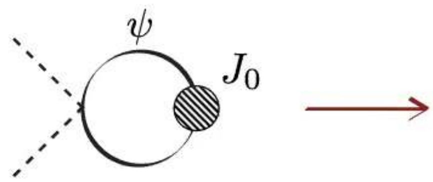
Hook, Huang '19

Finite Density and Size

Coupling to the conserved charge (number density) of the system.

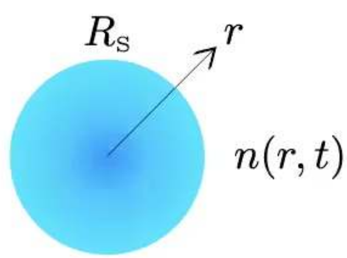
$$n \sim \langle J_{\mu=0} \rangle \sim \langle \bar{\psi}\psi \rangle$$

$$f(\phi)\bar{\psi}\psi$$



$$V(\phi, n) \sim V(\phi) + n f(\phi)$$

Stars: finite size dense systems, non-homogeneous and non-isotropic.



Spatial dependence constitutes main novelty regarding bubble dynamics.

Scalar Potential à la Coleman

Simplest scalar potential to make the physics transparent.

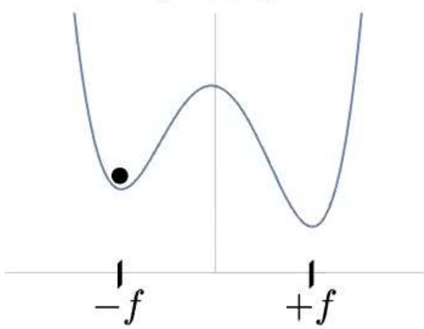
$$V(\phi) \sim -\Lambda_{\mathrm{R}}^4 \frac{\phi}{f} + \Lambda_{\mathrm{B}}^4 \left(\frac{\phi^2}{f^2} - 1 \right)^2$$

$$\delta^2 \equiv 1 - \frac{\Lambda_{\mathrm{R}}^4}{\Lambda_{\mathrm{B}}^4}$$

$\delta^2 > 0$ $\qquad\qquad$ $\delta^2 < 0$

Deep

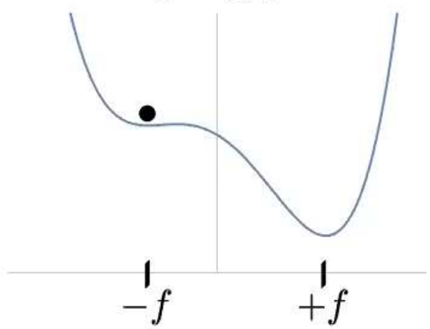
$\delta^2 \approx 1$



$m_\phi^2 \sim \Lambda_{\mathrm{B}}^4 / f^2$

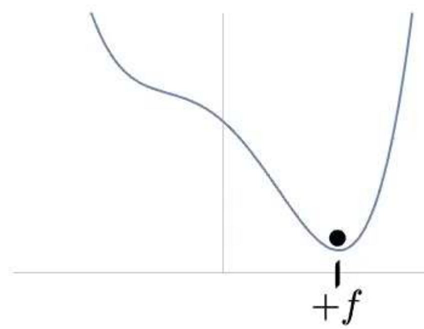
Shallow

$\delta^2 \ll 1$



$m_\phi^2 \sim \delta\, \Lambda_{\mathrm{B}}^4 / f^2$

Single minimum



$\Delta\Lambda \sim -\Lambda_{\mathrm{R}}^4$

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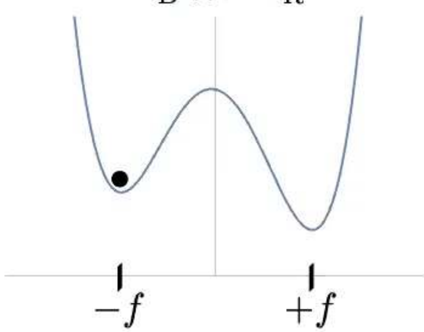
$\Lambda_{\rm B} > \Lambda_{\rm R}$

$\Lambda_{\rm B} < \Lambda_{\rm R}$

Deep

$\Lambda_{\rm B} \gg \Lambda_{\rm R}$



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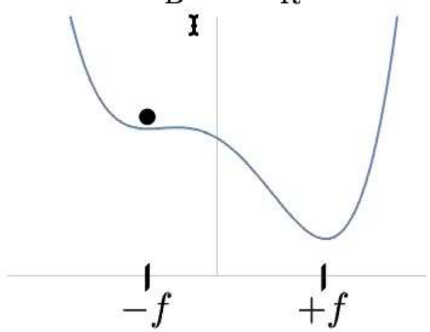
$\Lambda_{\rm B} \approx \Lambda_{\rm R}$



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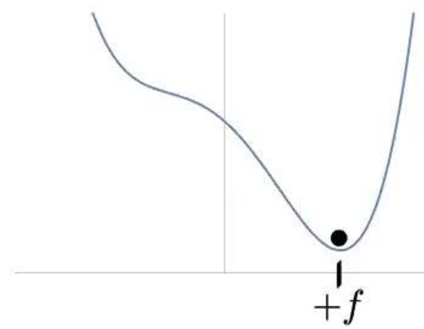

$\Delta\Lambda \sim -\Lambda_{\rm R}^4$

Finite Density Deformation

Motivated and predictive scenario: SM scale as source of the barrier.

$$\Lambda_{\mathrm{B}}^4 \propto \langle \mathcal{O}_{\mathrm{SM}} \rangle$$

$$\downarrow$$

$$\Lambda_{\mathrm{B}}^4(n) < \Lambda_{\mathrm{B}}^4$$

Classical transition between vacua allowed above critical density.

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

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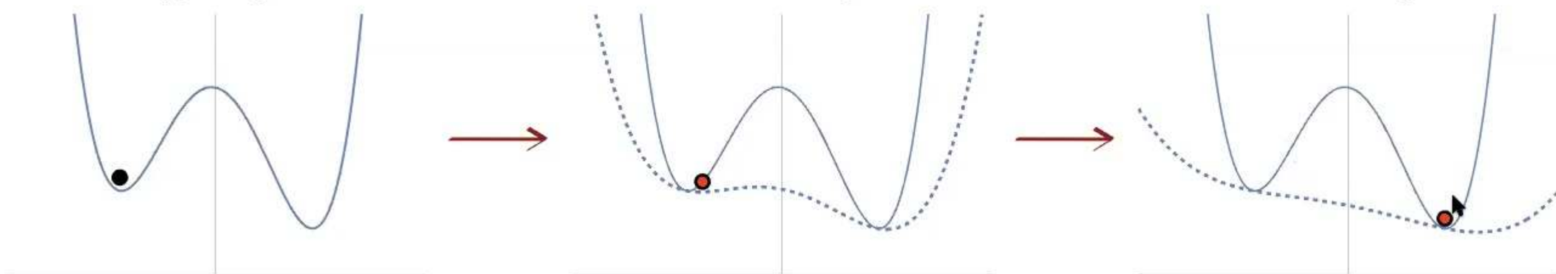
Deep

$n = 0$ $\qquad$ $n \approx n_c$ $\qquad$ $n > n_c$



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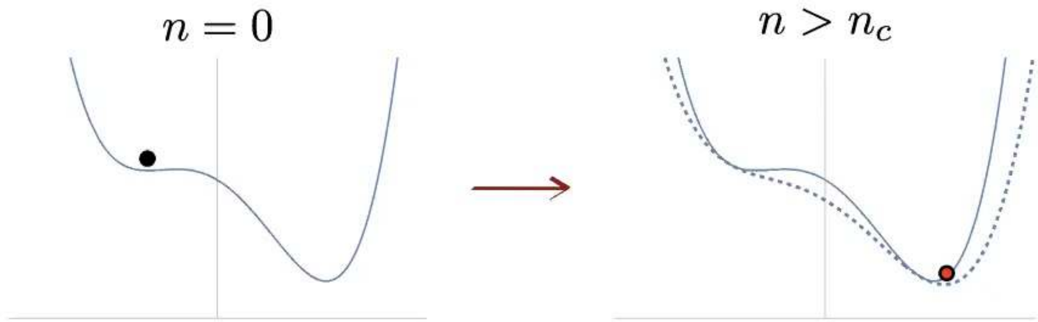


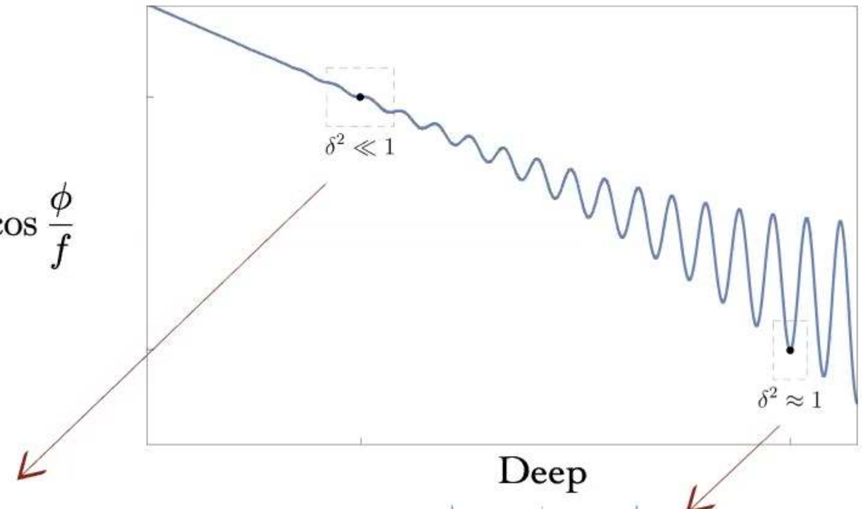
15

Electroweak Scale Relaxation

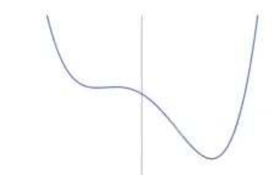
Relaxion potential as paradigmatic case.

$$\mathcal{O}_{\rm SM} = \bar{q}Hq \qquad\qquad \mathcal{O}_{\rm SM} = |H|^2$$

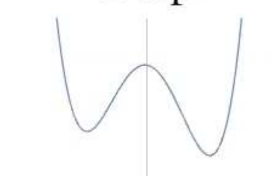
$$V(\phi) \sim -\Lambda_{\rm R}^4 \frac{\phi}{f} + \Lambda_{\rm B}^4(\phi)\cos\frac{\phi}{f}$$



Shallow



Deep



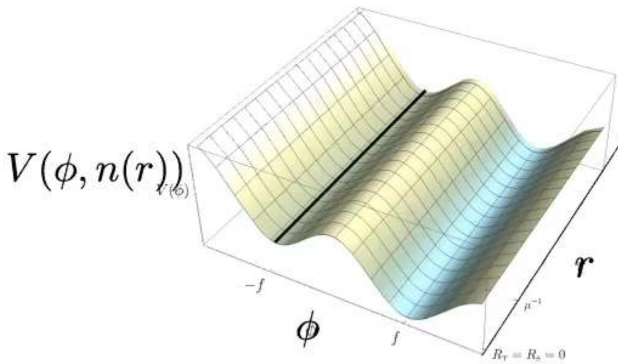
Fate of metastable minimum at finite density independent of how we got to such minimum.

Bubble Dynamics

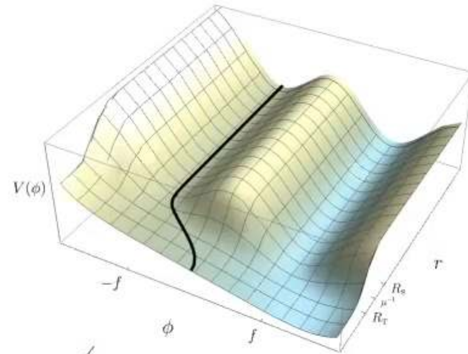
17

Formation and Expansion

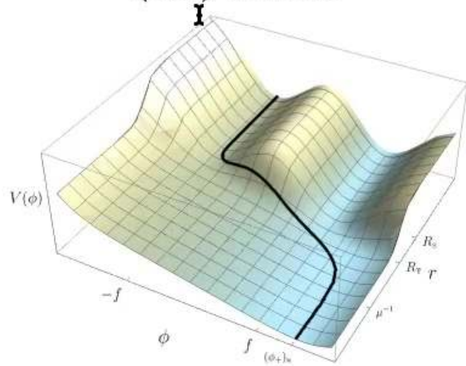
no bubble



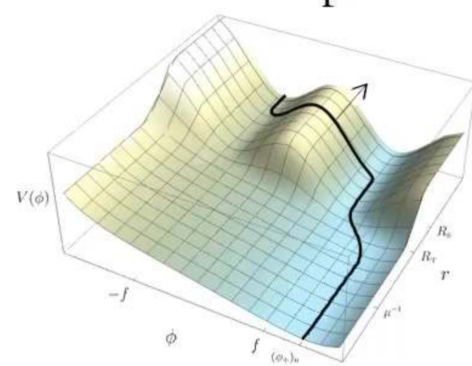
proto-bubble



(full) bubble



bubble escape

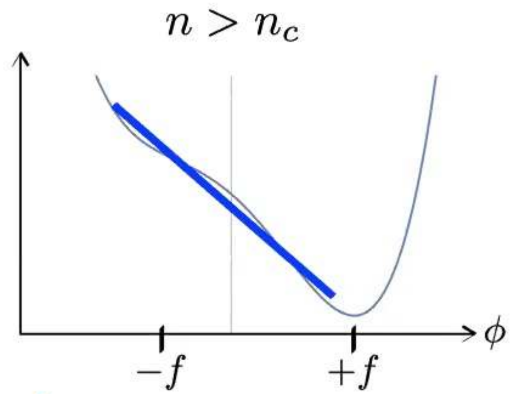


Verified with numerical solutions of scalar EOM.

Time and Length Scales

$$\ddot{\phi} - \phi'' - \frac{2}{r}\phi' = -V_{,\phi}$$

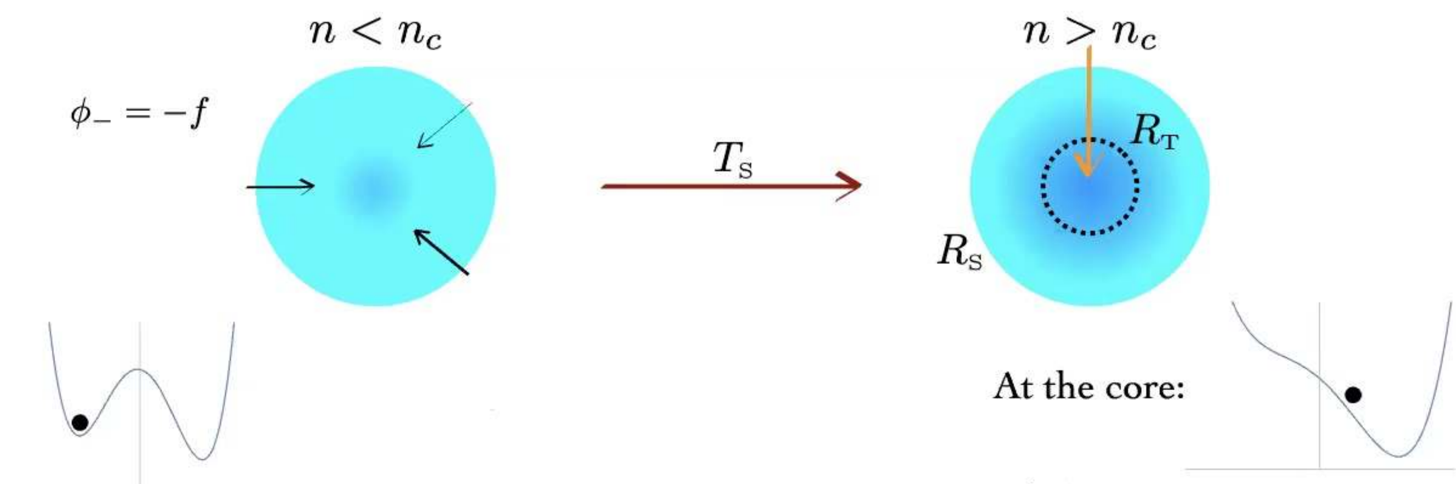
$$V(\phi, n > n_c) \simeq -\Lambda_{\mathrm{R}}^4 \frac{\phi}{f}$$



$$\mu^2 \equiv \frac{\Lambda_{\mathrm{R}}^4}{f^2}$$

Typical time and length scales of a star to be compared with $1/\mu$.

Time and Length Scales



$$\mu R_T \sim 1 \longrightarrow \frac{\Delta\phi}{f} \sim 1$$

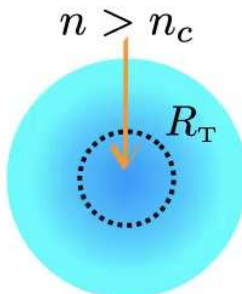
For typical stellar processes: $\mu T_S \gg 1$

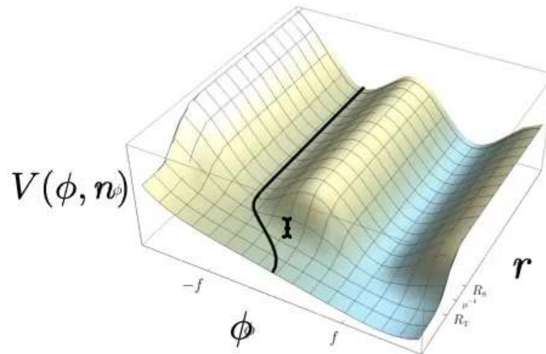
↓

Scalar EOM can be *initially* solved in time steps; in each step time is frozen.

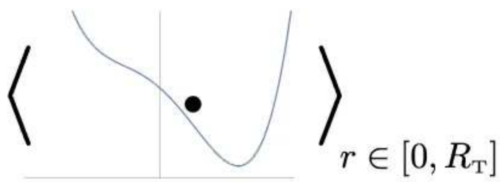
Bubble Formation

$\phi_- = -f$





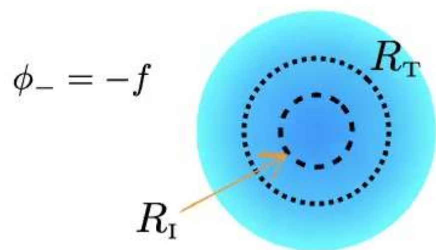
Balance between field gradient and energy-density gain.

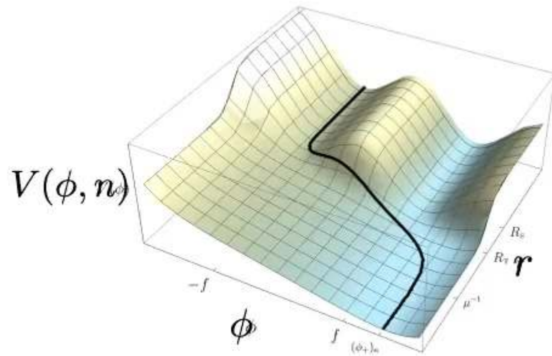


$\longrightarrow \quad \langle \phi'^2 \rangle \sim \langle \Delta\Lambda \rangle$

$$\frac{\phi(r) - \phi_-}{f} \simeq \mu^2 (R_{\mathrm{T}}^2 - r^2)$$

Bubble Formation





$$\phi(r < R_I) = \phi_+ \sim +f$$

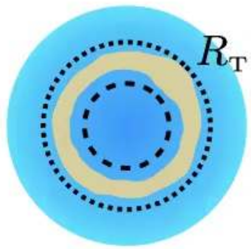
Complete bubble is formed when the core is large enough.

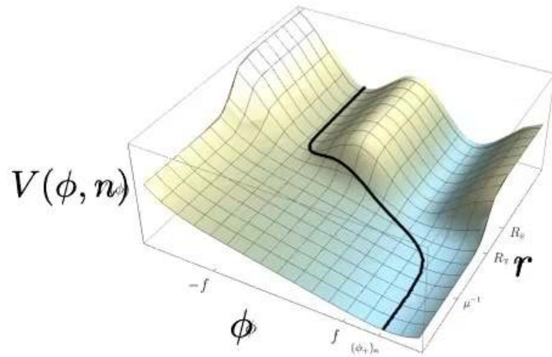
<u>Formation condition</u>

$$R_T \gtrsim \frac{1}{\mu} = \frac{f}{\Lambda_R^2}$$

Bubble Formation

$\phi_{-} = -f$





$$\phi(r < R_{\mathrm{I}}) = \phi_{+} \sim +f$$

Complete bubble is formed when the core is large enough.

$$x = \frac{R_{\mathrm{T}} - R_{\mathrm{I}}}{R_{\mathrm{T}}} \sim \frac{1}{\mu R_{\mathrm{T}}} < 1$$

Bubbles becomes relatively thiner if the core keep growing, until equilibrium is lost!

Bubble Expansion

Once the bubble is fully formed (and thin) we can easily understand its dynamics.

$$E(R) \sim -\frac{4\pi}{3}R^3\epsilon + 4\pi R^2\sigma(R)$$

volume potential energy
$\epsilon \sim -\Delta\Lambda \sim \Lambda_{\mathrm{R}}^4$

surface tension energy.

Minimization of the energy of the scalar field configuration points to instability.

$$R = R_{\mathrm{T}} \to R(t)$$

$$\sigma\ddot{R} = \epsilon - \frac{2\sigma}{R} - \sigma' \qquad \sigma' = \frac{d\sigma}{dR}$$

Radius dependent tension leads to additional contracting force.

Bubble Expansion

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volume potential energy
$\epsilon \sim -\Delta\Lambda \sim \Lambda_{\rm R}^4$

surface tension energy.

Additional contracting force from R-dependent tension does not decay with R.

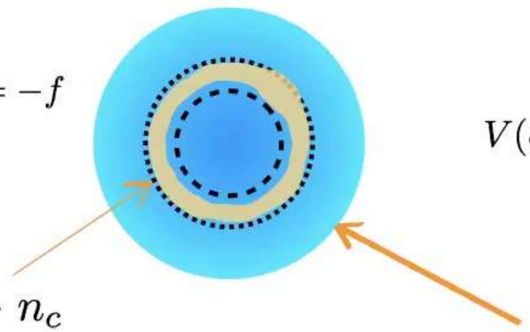
$$\sigma \ddot{R} \sim \epsilon - \sigma'$$

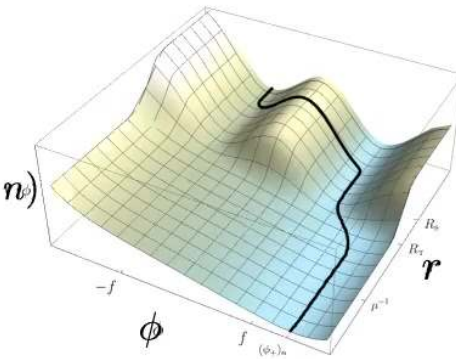
Escape condition

$$\epsilon \gtrsim \sigma' \sim \frac{\sigma(R_{\rm S}) - \sigma(R_{\rm T})}{R_{\rm S} - R_{\rm T}}$$

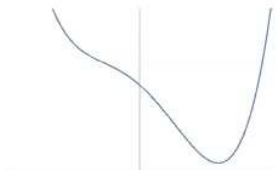
Bubble Expansion

$\phi_- = -f$





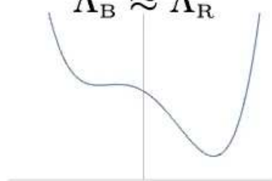
$n > n_c$



$\sigma(R_{\mathrm{T}}) \sim \Lambda_{\mathrm{R}}^2 f$

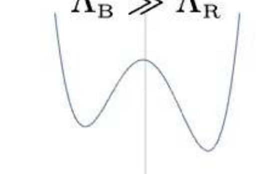
$n = 0$

Shallow
$\Lambda_{\mathrm{B}} \approx \Lambda_{\mathrm{R}}$



$\sigma(R_{\mathrm{S}}) \approx \sigma(R_{\mathrm{T}})$

Deep
$\Lambda_{\mathrm{B}} \gg \Lambda_{\mathrm{R}}$



$\sigma(R_{\mathrm{S}}) \sim \Lambda_{\mathrm{B}}^2 f \gg \sigma(R_{\mathrm{T}})$

<u>Escape condition</u>

Shallow

$$\left(R_{\mathrm{T}} \gtrsim \frac{f}{\Lambda_{\mathrm{R}}^2} \right)$$

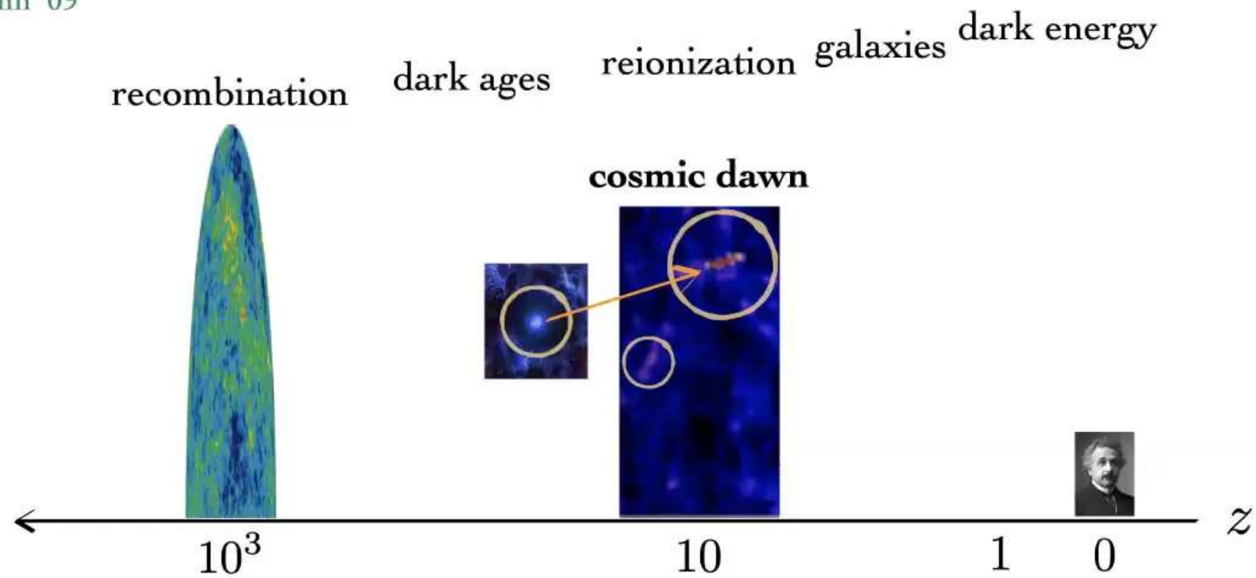
Deep

$$R_{\mathrm{S}} - R_{\mathrm{T}} \gtrsim \frac{f \Lambda_{\mathrm{B}}^2}{\Lambda_{\mathrm{R}}^4}$$

Phase Transition at Cosmic Dawn

(successful) Phase Transition

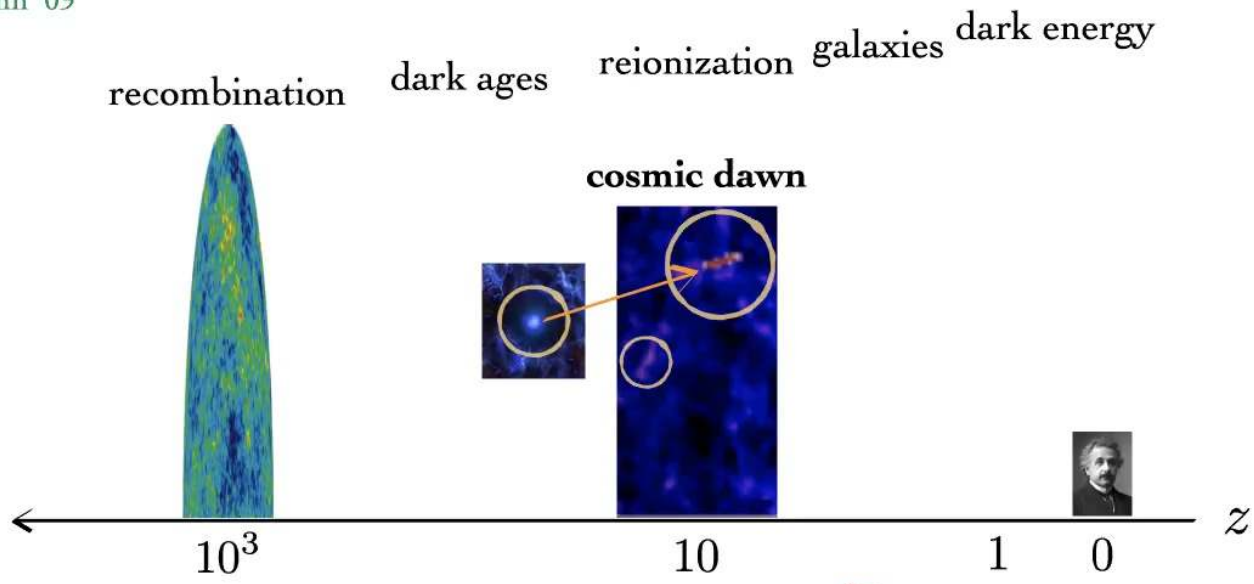
Baumann '09



28

(successful) Phase Transition

Baumann '09



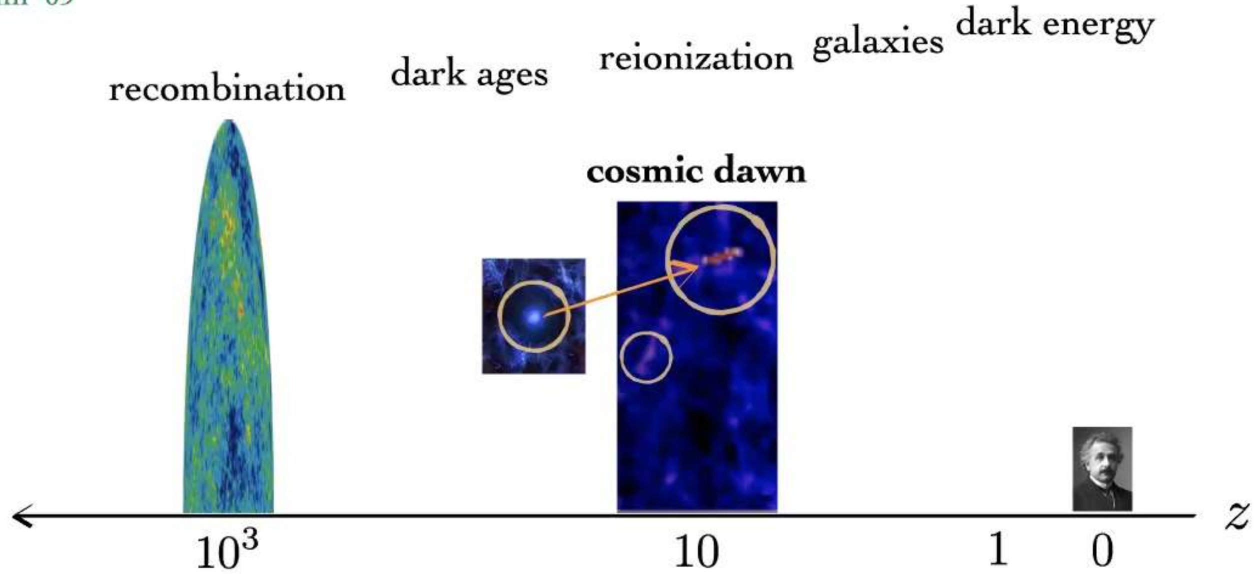
If the universe within our horizon completely transitions to lower-energy minimum:

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

For (dense enough) small stars, change in DE (cosmological constant) way too large.

(successful) Phase Transition

Baumann '09



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

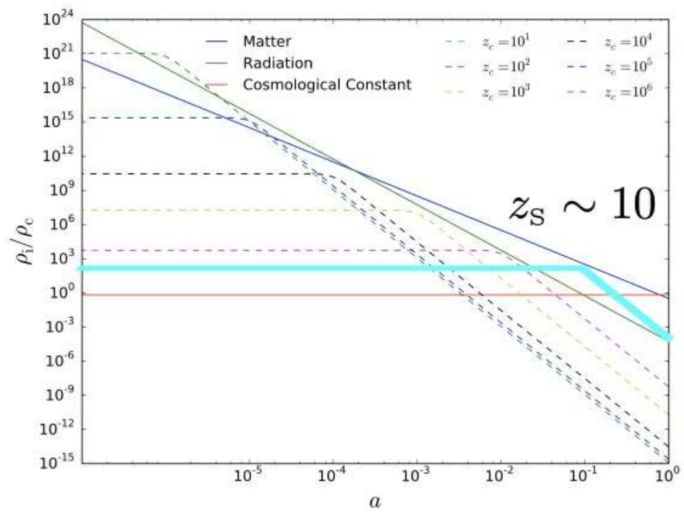
$$\sim R_{\mathrm{S}}^{\mathrm{max}} \sim 10^3\, \mathrm{R}_\odot$$

$$-\Delta\Lambda \sim \Lambda_{\mathrm{R}}^4 \gtrsim \left(\frac{f}{R_{\mathrm{S}}}\right)^2 \approx \Lambda_0 \left(\frac{f}{10\,\mathrm{TeV}}\right)^2 \left(\frac{10^9\,\mathrm{km}}{R_{\mathrm{S}}}\right)^2$$

For the largest stars, change in DE (cosmological constant) same order as ΛCDM.

Cosmological Bounds

Constraints on early DE component recently studied in the context of Hubble tension.



Karwall, Kamionkowski '16

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

Very conservative bound on vacuum energy change, yet generically violated.

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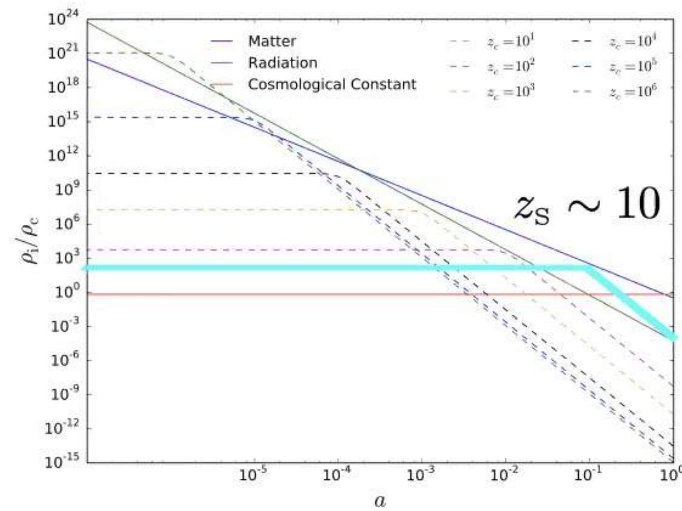

Karwall, Kamionkowski '16

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Relaxion

Electroweak Scale Relaxation

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$$\mathcal{O}_{\rm SM} = \bar{q} H q \qquad\qquad \mathcal{O}_{\rm SM} = |H|^2$$

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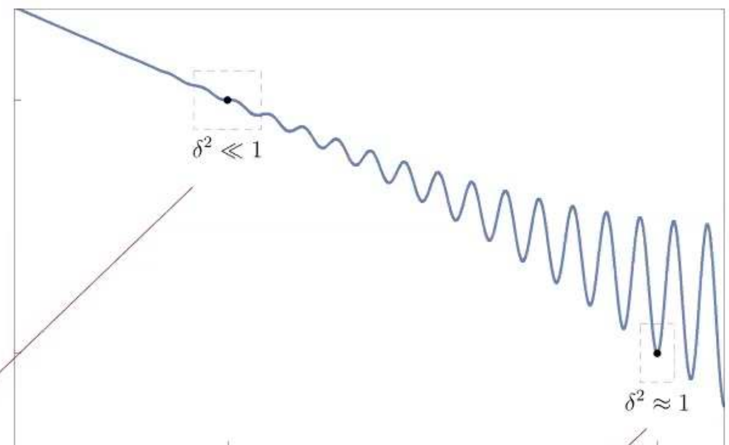
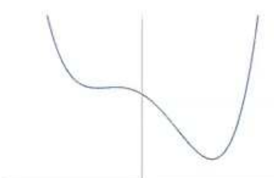
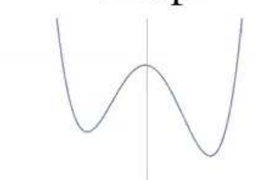


Shallow



Deep



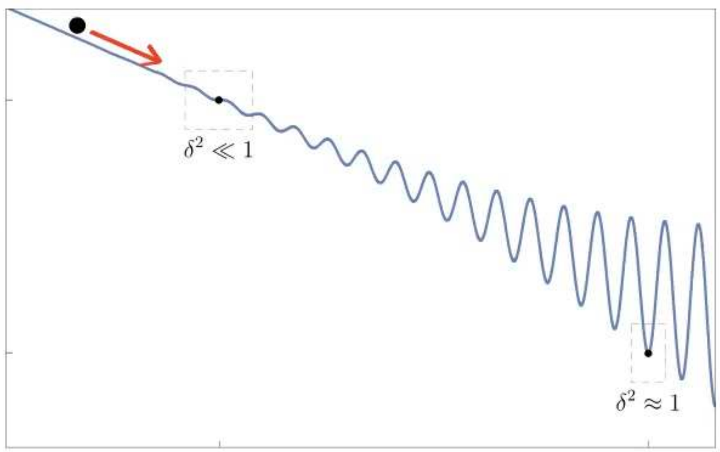
Fate of metastable minimum at finite density independent of how we got to such minimum.

Electroweak Scale Relaxation

The size of the potential barriers increases with field value because the Higgs VEV does.

$$V(h) \sim (M^2 - g\phi M)h^2 + \lambda h^4$$

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



QCD relaxion

$$\Lambda_{\rm B}^4(\phi) \sim \Lambda_{\rm QCD}^4 \frac{h(\phi)}{v}$$

non-QCD relaxion

$$\Lambda_{\rm B}^4(\phi) \sim \Lambda_{\rm C}^4 \frac{h^2(\phi)}{v^2}$$

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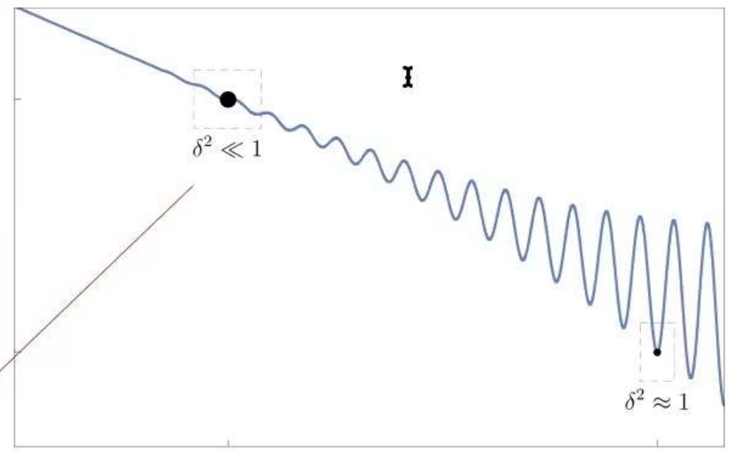
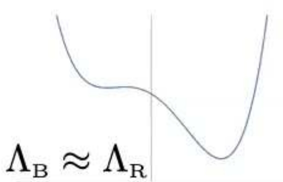


$$V(\phi) \sim -\Lambda_{\rm R}^4 \frac{\phi}{f} + \Lambda_{\rm B}^4(\phi) \cos\frac{\phi}{f}$$

Shallow

$$\delta^2 \equiv 1 - \frac{\Lambda_{\rm R}^4}{\Lambda_{\rm B}^4}$$



$$\delta^2_{\ell_*=1} \simeq \frac{\Lambda^4_{\rm QCD,C}}{v^2 M^2}$$

Banerjee et al. '20

Shallow minima are always present since cutoff above TeV.

QCD Relaxion at Finite Density

$$\Lambda_{\rm B}^4 \sim \Lambda_{\rm QCD}^4 \sim m_q \langle \bar{q} q \rangle$$

$$\downarrow \quad \langle \bar{q} q \rangle \to \langle \bar{q} q \rangle (n)$$

$$\frac{\Lambda_{\rm B}^4(n)}{\Lambda_{\rm B}^4} \simeq 1 - \frac{\sigma_{\pi N} n_b}{m_\pi^2 f_\pi^2}$$

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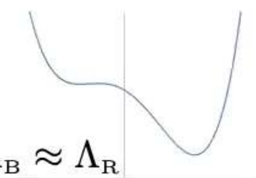
Shallow

(escape condition irrelevant)



$\Lambda_{\rm B} \approx \Lambda_{\rm R}$

dense enough
$\Lambda_{\rm B}^4(n) < \Lambda_{\rm R}^4$

$$n_b \gtrsim \frac{1}{M^2} \frac{\pi \Lambda_{\rm QCD}^8}{\sigma_{\pi N} v^2}$$

large enough
$R_{\rm S} \sim R_{\rm T} \gtrsim f/\Lambda_{\rm R}^2$

$$R_{\rm S} \gtrsim \frac{f}{\Lambda_{\rm QCD}^2}$$

QCD Relaxion at Finite Density

Both these conditions are easily satisfied by Neutron Stars and White Dwarfs,

$$n_{\rm NS} \sim 10^6\,{\rm MeV}^3 \qquad R_{\rm NS} \sim 10\,{\rm km}$$

$$n_{\rm WD} \sim 0.1\,{\rm MeV}^3 \qquad R_{\rm WD} \sim 10^3\,{\rm km}$$

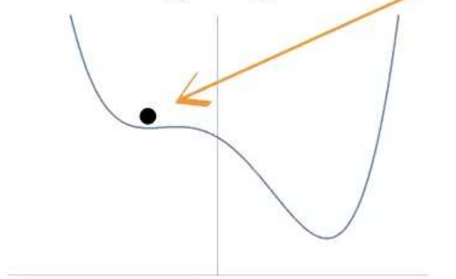
for any reasonable values of the cutoff and decay constant:

$$M \gtrsim 1\,{\rm TeV} \qquad f \lesssim M_{\rm P}$$

Shallow

$n = 0$

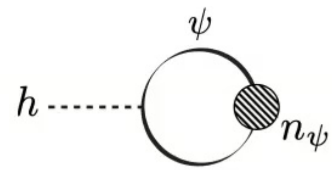
$\theta_{\rm QCD} \approx \pi/2$



Non-QCD Relaxion at Finite Density

$$\Lambda_{\mathrm{B}}^4 \sim \Lambda_{\mathrm{C}}^4 \frac{h^2}{v^2}$$

$$h^2 \to h^2(n)$$



$$\frac{\Lambda_{\mathrm{B}}^4(n)}{\Lambda_{\mathrm{B}}^4} \simeq 1 - \frac{\sigma_{\pi N} n_b}{m_h^2 v^2}$$

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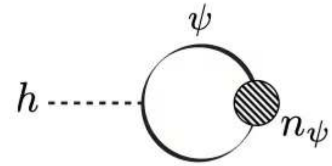
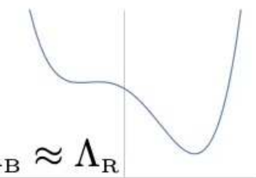


$$\frac{\Lambda_{\rm B}^4(n)}{\Lambda_{\rm B}^4} \simeq 1 - \frac{\sigma_{\pi N} n_b}{m_h^2 v^2}$$

Shallow (escape condition irrelevant)



$\Lambda_{\rm B} \approx \Lambda_{\rm R}$

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large enough
$R_{\rm S} \sim R_{\rm T} \gtrsim f/\Lambda_{\rm R}^2$

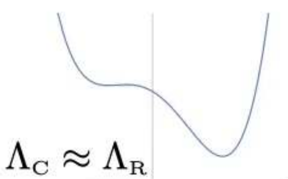
$$n_b \gtrsim \frac{\Lambda_{\rm C}^4}{M^2} \frac{v^2}{\sigma_{\pi N}}$$

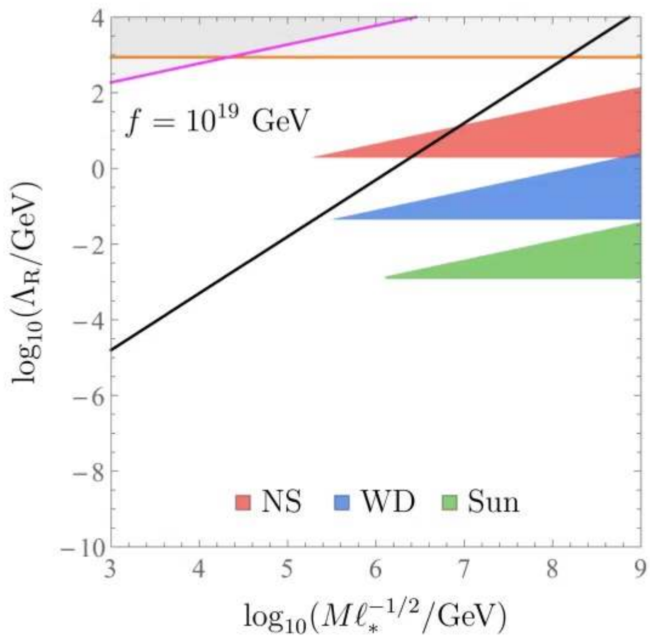
$$R_{\rm S} \gtrsim \frac{f}{\Lambda_{\rm C}^2}$$

Non-QCD Relaxion at Finite Density

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

Shallow





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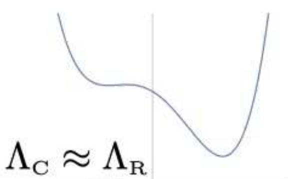

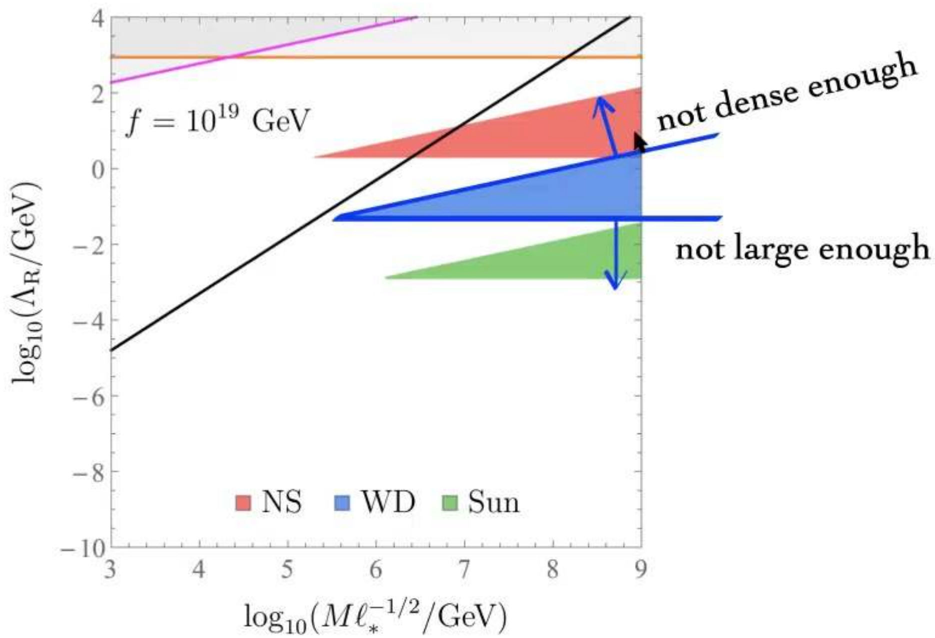

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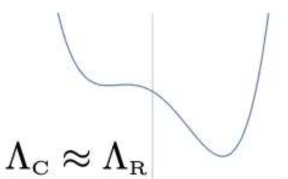

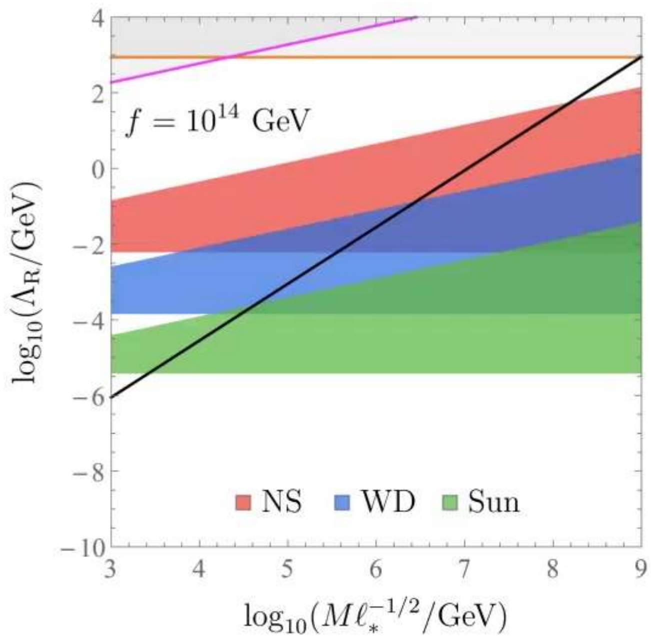

Non-QCD Relaxion at Finite Density

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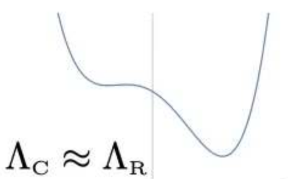
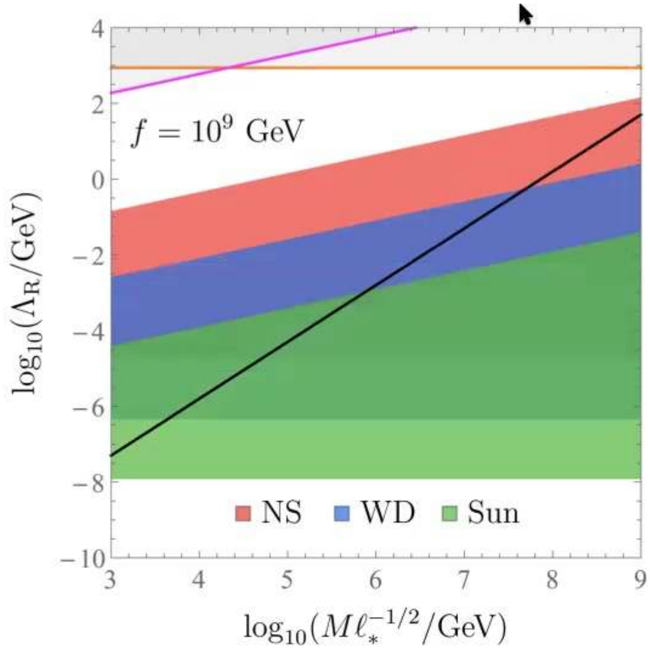




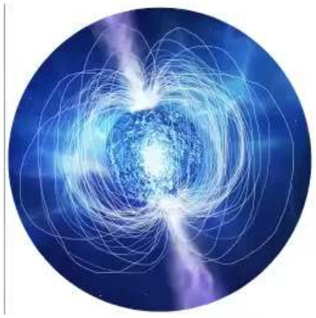
Considering super-giant stars would require reassessment of DE bound.

Vacuum Instability Triggered by EM Fields

Example of generalization beyond matter density effects: rotating NSs.

$\Omega_{\rm NS} \sim 10\,\mathrm{Hz}$

$B_{\rm NS} \sim 10^{10}\,\mathrm{T}$

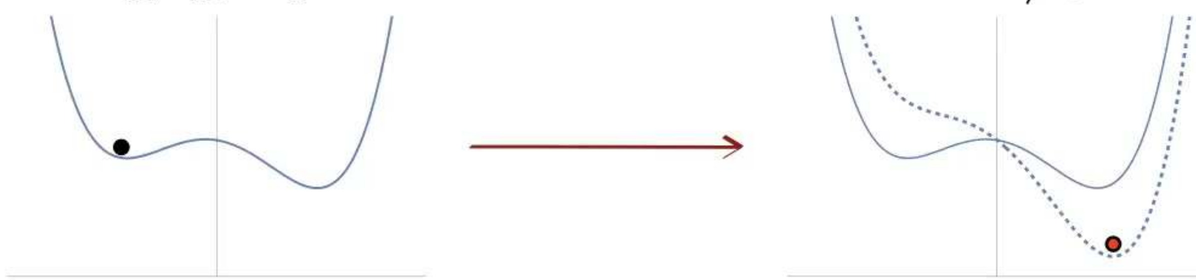


$$\vec{E}\cdot\vec{B}(r) = \left(\frac{B_{\rm S}^2 R_{\rm S}^6 \Omega_{\rm S}^2}{4r^4}\right)\Theta(r - R_{\rm S})$$

$$g_{\phi\gamma\gamma}\frac{\phi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\Lambda_{\rm R}^4(\vec{E}\cdot\vec{B}) > \Lambda_{\rm R}^4$$

$\vec{E}\cdot\vec{B} = 0$ $\qquad\qquad$ $\vec{E}\cdot\vec{B} \neq 0$



45

Vacuum Instability Triggered by EM Fields

Similar analysis to the case of finite matter density.

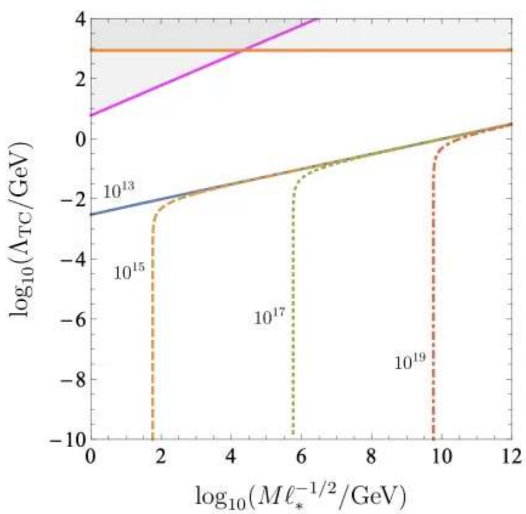
Escape condition

$$R_{\rm T}^{\rm EM} - R_{\rm S} \gtrsim \frac{f\Lambda_{\rm B}^2}{\Lambda_{\rm R}^4}$$

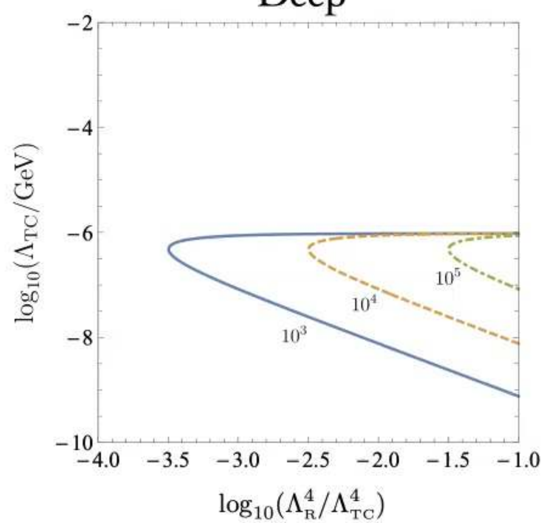
$$R_{\rm T}^{\rm EM} \sim \left(\frac{g_{\phi\gamma\gamma} B_{\rm S}^2 R_{\rm S}^6 \Omega_{\rm S}^2}{\delta^2 \Lambda_{\rm B}^4}\right)^{1/4}$$

$$\Lambda_{\rm B} \equiv \Lambda_{\rm TC}$$

Shallow



Deep

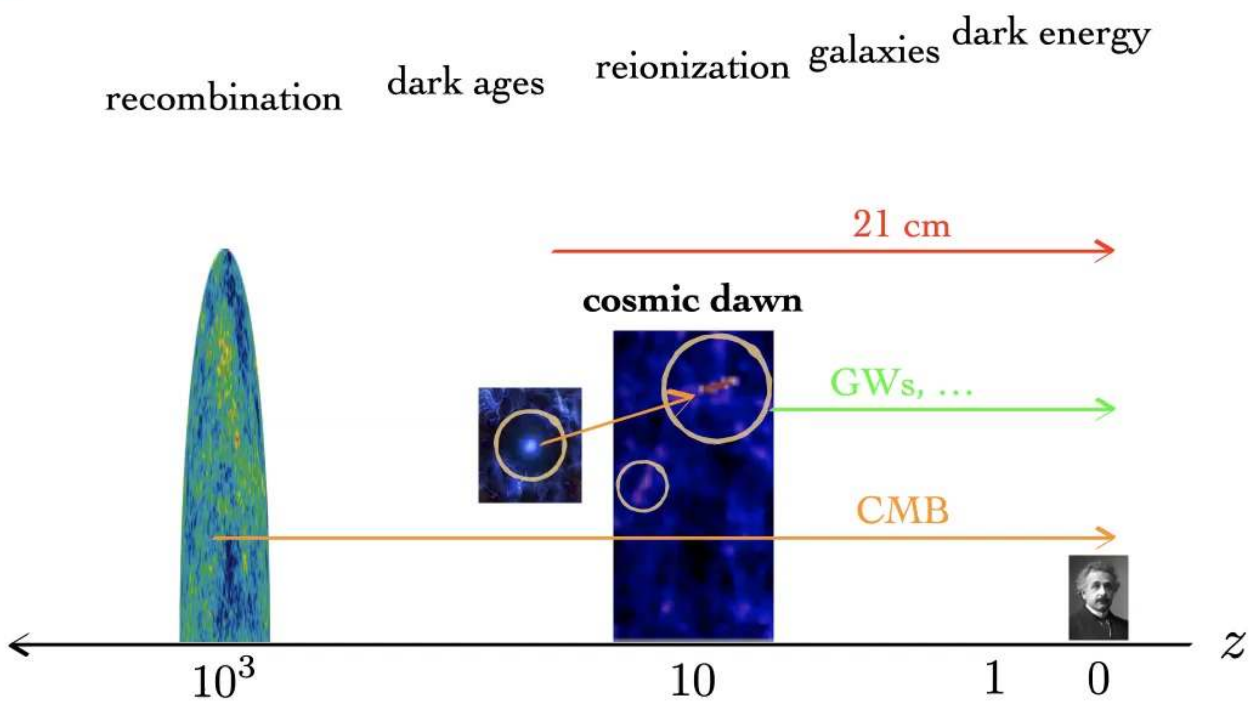


Outlook

47

Better Cosmological Bounds — Signatures

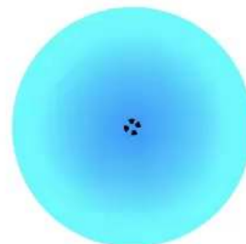
Baumann '09



Many different potential probes of a phase transition at cosmic dawn.

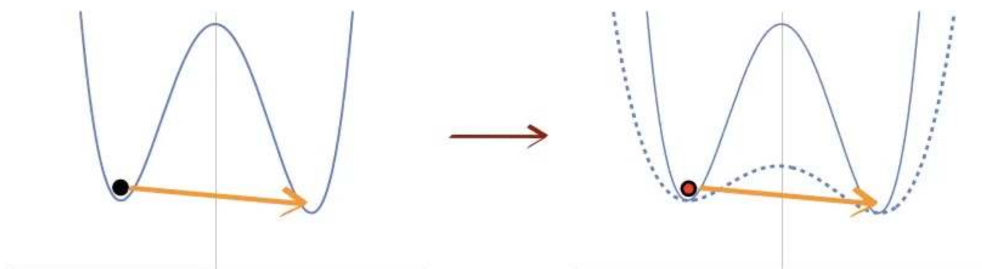
Density Induced Vacuum Decay

While critical densities might never be reached, barrier can get much smaller.

$n < n_c$  $R_{\mathrm{T}} = 0$

Deep

$n = 0$ $\qquad\qquad$ $n < n_c$

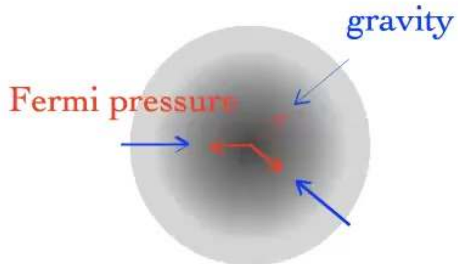


$$S_{\mathrm{B}} \simeq 27\sqrt{3}\pi^2 \frac{f^4 \Lambda_{\mathrm{B}}^8}{\Lambda_{\mathrm{R}}^{12}} \qquad\qquad \frac{S_{\mathrm{B}}(n < n_c)}{S_{\mathrm{B}}} \simeq \left(\frac{\Lambda_{\mathrm{B}}(n)}{\Lambda_{\mathrm{B}}}\right)^8 \ll 1$$

Possibility of a latent phase transition.

Dark Compact Objects

Vacuum transitions seeded by dark neutron stars (from e.g. non-QCD relaxion).



$$n_{\tilde{b}} \sim m_{\tilde{b}}^3$$

$$R_{\tilde{S}} \sim \sqrt{8\pi}\frac{M_P}{m_{\tilde{b}}^2}$$

$$\frac{\Lambda_B^4(n)}{\Lambda_B^4} \simeq 1 - \frac{\tilde{\sigma} n_{\tilde{b}}}{\Lambda_C^4}, \quad n_{\tilde{b}} \sim m_{\tilde{b}}^3$$

dense enough: $\Lambda_B^4(n) < \Lambda_R^4$ | large enough (escape condition): $m_{\tilde{b}} \lesssim \Lambda_C \sqrt{\frac{M_P}{f}}$

$$-\Delta\Lambda \gtrsim m_{\tilde{b}}^4 \left(\frac{f}{M_P}\right)^2 \approx \Lambda_0 \times 10^{-2} \left(\frac{m_{\tilde{b}}}{10\,\text{keV}}\right)^4 \left(\frac{f}{10\text{TeV}}\right)^2$$

Conclusions

- Landscape approach to fine-tuning problems brings novel phenomenology.

  Much needed, e.g. for the electroweak hierarchy in view of LHC critical results.

- Transitions between vacua can be triggered by finite density, e.g. in stars.

  (Hook, Huang '19)

  Phenomenon realizable in models of relaxation of electroweak scale.

  Potential phase transition at cosmic dawn.

  Any experimental signature of a different vacua would be revolutionary.

- Much remains to be explored within the realm of light scalar fields at finite density.

  - induced vacuum decay.
  - early universe matter domination.
  - neutron star equation of state.
  - …