Title: TBA
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Abstract: TBA
Vacuum Transitions Seeded by Stars

Javi Serra

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.

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

(Balkin, JS, Springmann, Weiler '20)

(Balkin, JS, Springmann, Stelzl, Weiler '21)
Vacuum Transitions Seeded by Stars

A super-cool water analogy.
Vacuum Transitions Seeded by Stars

A super-cool water analogy.

gravity

initial metastable vacuum

phase transition

star

final lower-energy vacuum
Motivations
Landscapes

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

Cosmological Constant problem

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

Weinberg '87
Bousso, Polchinski '00
...
Landscapes

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

Electroweak Hierarchy problem

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

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.

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

\[ f(\phi)\bar{\psi}\psi \quad J_0 \quad V(\phi, n) \sim V(\phi) + nf(\phi) \]

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

\[ R_S \quad r \quad n(r, t) \]

Spatial dependence constitutes main novelty regarding bubble dynamics.
Scalar Potential à la Coleman

Simplest scalar potential to make the physics transparent.

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4 \left( \frac{\phi^2}{f^2} - 1 \right)^2 \]

\[ \delta^2 > 0 \quad \delta^2 \equiv 1 - \frac{\Lambda_R^4}{\Lambda_B^4} \quad \delta^2 < 0 \]

Deep \quad \delta^2 \approx 1

Shallow \quad \delta^2 \ll 1

Single minimum

\[ m^2_\phi \sim \Lambda_B^4 / f^2 \]

\[ m^2_\phi \sim \delta \Lambda_B^4 / f^2 \]

\[ \Delta \Lambda \sim -\Lambda_R^4 \]
Scalar Potential à la Coleman

Simplest scalar potential to make the physics transparent.

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4 \left( \frac{\phi^2}{f^2} - 1 \right)^2 \]

\[ \Lambda_B > \Lambda_R \]
\[ \Lambda_B < \Lambda_R \]

\[ \delta^2 \equiv 1 - \frac{\Lambda_R^4}{\Lambda_B^4} \]

**Deep**
\[ \Lambda_B \gg \Lambda_R \]

**Shallow**
\[ \Lambda_B \approx \Lambda_R \]

**Single minimum**

\[ m^2_\phi \sim \Lambda_B^4 / f^2 \]
\[ m^2_\phi \sim \delta \Lambda_B^4 / f^2 \]
\[ \Delta \Lambda \sim -\Lambda_R^4 \]
Finite Density Deformation

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

\[ \Lambda_B^4 \propto \langle \mathcal{O}_{\text{SM}} \rangle \]

\[ \Lambda_B^4(n) < \Lambda_B^4 \]

Classical transition between vacua allowed above critical density.

\[ \Lambda_B^4(n_c) = \Lambda_R^4 \]
Finite Density Deformation

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Diagram:

- \( n = 0 \) (Deep)
- \( n \approx n_c \)
- \( n > n_c \)
Finite Density Deformation

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\[ \Lambda_B^4(n) < \Lambda_B^4 \]

Classical transition between vacua allowed above critical density.

\[ \Lambda_B^4(n_c) = \Lambda_R^4 \]

Shallow

\[ n = 0 \]

\[ n > n_c \]
Electroweak Scale Relaxation

Relaxion potential as paradigmatic case.

\[ \mathcal{O}_{\text{SM}} = \bar{q} H q \quad \mathcal{O}_{\text{SM}} = |H|^2 \]

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4(\phi) \cos \frac{\phi}{f} \]

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

no bubble

\[ V(\phi, n(r)) \]

(r) proto-bubble

\[ \phi \]

(full) bubble

Verified with numerical solutions of scalar EOM.
Time and Length Scales

\[ \ddot{\phi} - \phi'' - \frac{2}{r} \phi' = -V,\phi \]

\[ V(\phi, n > n_c) \approx -\frac{1}{\Lambda_R^4} \frac{\phi}{f} \]

\[ \mu^2 \equiv \frac{\Lambda_R^4}{f^2} \]

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

\[ \phi_- = -f \]

\[ n < n_c \]

\[ T_s \]

\[ n > n_c \]

At the core:

\[ R_T \]

\[ R_S \]

\[ \mu R_T \sim 1 \quad \Rightarrow \quad \frac{\Delta \phi}{f} \sim 1 \]

For typical stellar processes:

\[ \mu T_s \gg 1 \]

Scalar EOM can be \textit{initially} solved in time steps; in each step time is frozen.
Balance between field gradient and energy-density gain.

\[ \langle \phi'^2 \rangle \sim \langle \Delta \Delta \rangle \]

\[ \frac{\phi(r) - \phi_-}{f} \simeq \mu^2 (R_T^2 - r^2) \]
Bubble Formation

\[ \phi_- = -f \]

\[ \phi(r < R_1) = \phi_+ \sim +f \]

Complete bubble is formed when the core is large enough.

**Formation condition**

\[ R_T \gtrsim \frac{1}{\mu} = \frac{f}{\Lambda_R^2} \]
Bubble Formation

\[ \phi_- = -f \]

\[ V(\phi, n) \]

\[ \phi(r < R_1) = \phi_+ \sim +f \]

Complete bubble is formed when the core is large enough.

\[ x = \frac{R_T - R_1}{R_T} \sim \frac{1}{\mu R_T} < 1 \]

Bubbles becomes relatively thinner 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.

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

volume potential energy
$$\varepsilon \sim -\Delta \Lambda \sim \Lambda_R^4$$

surface tension energy.

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

$$R = R_T \to R(t)$$

$$\sigma \ddot{R} = \varepsilon - \frac{2\sigma}{R} - \sigma'$$

$$\sigma' = \frac{d\sigma}{dR}$$

Radius dependent tension leads to additional contracting force.
Bubble Expansion

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

Volume potential energy

\[ \epsilon \sim -\Delta \Lambda \sim \Lambda^4_R \]

Surface tension energy.

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

\[ \sigma \ddot{R} \sim \epsilon - \sigma' \]

Escape condition

\[ \epsilon \gtrsim \sigma' \sim \frac{\sigma(R_S) - \sigma(R_T)}{R_S - R_T} \]
**Bubble Expansion**

\[ \phi_- = -f \]

\[ n > n_c \]

\[ \sigma(R_T) \sim \Lambda_R^2 f \]

- **Shallow**
  \[ \Lambda_B \approx \Lambda_R \]
  \[ \sigma(R_S) \approx \sigma(R_T) \]

- **Deep**
  \[ \Lambda_B \gg \Lambda_R \]
  \[ \sigma(R_S) \sim \Lambda_B^2 f \gg \sigma(R_T) \]

**Escape condition**

- **Shallow**
  \[ R_T \gtrsim \frac{f}{\Lambda_R^2} \]

- **Deep**
  \[ R_S - R_T \gtrsim \frac{f \Lambda_B^2}{\Lambda_R^4} \]
Phase Transition at Cosmic Dawn
(successful) Phase Transition

recombination  dark ages  reionization  galaxies  dark energy

cosmic dawn

$10^3$  $10$  $1$  $0$

$z$
(successful) Phase Transition

Baumann '09

recombination  dark ages  reionization  galaxies  dark energy

cosmic dawn

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

\[-\Delta \Lambda \sim \Lambda_R^4 \gtrsim \left( \frac{f}{R_S} \right)^2 \approx \Lambda_0 \times 10^{15} \left( \frac{f}{10 \text{ TeV}} \right)^2 \left( \frac{10 \text{ km}}{R_S} \right)^2 \sim R_N^4\]

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

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

\[ -\Delta \Lambda \sim \Lambda_R^4 \gtrsim \left( \frac{f}{R_s} \right)^2 \approx \Lambda_0 \left( \frac{f}{10 \text{ TeV}} \right)^2 \left( \frac{10^9 \text{ km}}{R_s} \right)^2 \]

For the largest stars, change in DE (cosmological constant) same order as \( \Lambda_{CDM} \).
Cosmological Bounds

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

Karwall, Kamionkowski ’16

\[ z_S \sim 10 \]

\[-\Delta \Lambda \lesssim \Lambda_0 \times 10^2 \]

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

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

\[ z_\text{S} \sim 10 \]

\[ -\Delta \Lambda \lesssim \Lambda_0 \times 10^2 \]

Very conservative bound on vacuum energy change, yet generically violated.
Relaxion
Electroweak Scale Relaxation

Relaxion potential as paradigmatic case.

\[ \mathcal{O}_{\text{SM}} = \bar{q} H q \quad \mathcal{O}_{\text{SM}} = |H|^2 \]

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4(\phi) \cos \frac{\phi}{f} \]

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.

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

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4(\phi) \cos \frac{\phi}{f} \]

**QCD relaxation**

\[ \Lambda_B^4(\phi) \sim \Lambda_{QCD}^4 \frac{h(\phi)}{v} \]

**non-QCD relaxation**

\[ \Lambda_B^4(\phi) \sim \Lambda_C^4 \frac{h^2(\phi)}{v^2} \]
Electroweak Scale Relaxation

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

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

\[ V(\phi) \sim -\Lambda_R^4 \frac{\phi}{f} + \Lambda_B^4(\phi) \cos \frac{\phi}{f} \]

\[ \delta^2 \equiv 1 - \frac{\Lambda_R^4}{\Lambda_B^4} \]

\[ \Lambda_B \approx \Lambda_R \]

\[ \delta_{\ell_*}^2 = 1 \sim \frac{\Lambda_{QCD,C}^4}{v^2 M^2} \]

Shallow minima are always present since cutoff above TeV.

Banerjee et al. '20
QCD Relaxion at Finite Density

\[ \Lambda_B^4 \sim \Lambda_{\text{QCD}}^4 \sim m_q \langle \bar{q}q \rangle \]

\[ \langle \bar{q}q \rangle \rightarrow \langle \bar{q}q \rangle(n) \]

\[ \frac{\Lambda_B^4(n)}{\Lambda_B^4} \approx 1 - \frac{\sigma_{\pi N} n_b}{m_\pi^2 f_\pi^2} \]
QCD Relaxation at Finite Density

\[ \Lambda_B^4 \sim \Lambda_{QCD}^4 \sim m_q \langle \bar{q}q \rangle \]

\[ \langle \bar{q}q \rangle \rightarrow \langle \bar{q}q \rangle (n) \]

\[ \frac{\Lambda_B^4 (n)}{\Lambda_B^4} \approx 1 - \frac{\sigma_{\pi N} n_b}{m_{\pi}^2 f_\pi^2} \]

**Shallow** (escape condition irrelevant)

- dense enough
  \[ \Lambda_B^4 (n) < \Lambda_R^4 \]
- \[ n_b \gtrsim \frac{\pi \Lambda_{QCD}^8}{M^2 \sigma_{\pi N} v^2} \]

- large enough
  \[ R_s \sim R_T \gtrsim f/\Lambda_R^2 \]
  \[ R_s \gtrsim \frac{f}{\Lambda_{QCD}^2} \]
QCD Relaxion at Finite Density

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

\[ n_{NS} \sim 10^6 \text{ MeV}^3 \quad R_{NS} \sim 10 \text{ km} \]
\[ n_{WD} \sim 0.1 \text{ MeV}^3 \quad R_{WD} \sim 10^3 \text{ km} \]

for any reasonable values of the cutoff and decay constant:

\[ M \gtrsim 1 \text{ TeV} \quad f \lesssim M_p \]

\[ \text{Shallow} \quad n = 0 \quad \theta_{QCD} \approx \pi/2 \]

...I think I saw it still moving...
Non-QCD Relaxion at Finite Density

\[ \Lambda_B^4 \sim \Lambda_C^4 \frac{h^2}{v^2} \]

\[ h^2 \rightarrow h^2(n) \]

\[ \frac{\Lambda_B^4(n)}{\Lambda_B^4} \simeq 1 - \frac{\sigma_{\pi N} n_b}{m_h^2 v^2} \]
Non-QCD Relaxion at Finite Density

\[ \Lambda_B^4 \sim \Lambda_C^4 \frac{h^2}{v^2} \]

\[ h^2 \rightarrow h^2(n) \]

\[ \frac{\Lambda_B^4(n)}{\Lambda_B^4} \approx 1 - \frac{\sigma_{\pi N} n_b}{m_h v^2} \]

Shallow

dense enough
\[ \Lambda_B^4(n) < \Lambda_R^4 \]

large enough
\[ R_S \sim R_T \gtrsim \frac{f}{\Lambda_R^2} \]

\[ \Lambda_B \approx \Lambda_R \]

\[ n_b \gtrsim \frac{\Lambda_C^4}{M^2} \frac{v^2}{\sigma_{\pi N}} \]

(escape condition irrelevant)

\[ R_S \gtrsim \frac{f}{\Lambda_C^2} \]
Non-QCD Relaxion at Finite Density

Large fraction of parameter space would have led to too large change in DE.
Non-QCD Relaxion at Finite Density

Large fraction of parameter space would have led to too large change in DE.
Non-QCD Relaxion at Finite Density

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

![Graph showing non-QCD relaxion at finite density](image)
Non-QCD Relaxion at Finite Density

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

Shallow

$\Lambda_c \approx \Lambda_R$

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.

\[ \Omega_{NS} \sim 10 \text{ Hz} \]
\[ B_{NS} \sim 10^{10} \text{ T} \]

\[ \tilde{E} \cdot \tilde{B}(r) = \left( \frac{B_s^2 R_s^6 \Omega_s^2}{4 r^4} \right) \Theta(r - R_s) \]

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

\[ \Lambda_R^4 (\tilde{E} \cdot \tilde{B}) > \Lambda_R^4 \]

\[ \tilde{E} \cdot \tilde{B} = 0 \]
\[ \tilde{E} \cdot \tilde{B} \neq 0 \]
Vacuum Instability Triggered by EM Fields

Similar analysis to the case of finite matter density.

**Escape condition**

\[ R_T^\text{EM} - R_S \gtrsim \frac{f \Lambda_B^2}{\Lambda_R^4} \]

\[ R_T^\text{EM} \sim \left( \frac{g \phi \gamma B_S^2 R_S^6 \Omega_S^2}{\delta^2 \Lambda_B^4} \right)^{1/4} \]

\[ \Lambda_B \equiv \Lambda_{TC} \]
Better Cosmological Bounds — Signatures

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.

\[ n < n_c \quad \Rightarrow \quad R_T = 0 \]

**Deep**

\[ S_B \approx 27\sqrt{3}\pi^2 f^4 \frac{\Lambda_B^8}{\Lambda_R^{12}} \]

\[ \frac{S_B(n < n_c)}{S_B} \approx \left( \frac{\Lambda_B(n)}{\Lambda_B} \right)^8 \ll 1 \]

Possibility of a latent phase transition.
Dark Compact Objects

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

\[ n_\tilde{b} \sim m_\tilde{b}^3 \]

\[ R_\tilde{\Sigma} \sim \sqrt{8\pi} \frac{M_P}{m_\tilde{b}^2} \]

\[ \frac{\Lambda_B^4(n)}{\Lambda_B^4} \sim 1 - \frac{\tilde{\sigma} n_\tilde{b}}{\Lambda_C^4} \]

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.
  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.
  (Hook, Huang ’19)

- 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.
  - ...