Higgs-driven Cosmology in the Conformally Symmetric Standard Model Coupled to General Relativity

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Outline

- What does the Higgs Field have to do with Cosmology?
  LHC data on metastability $\rightarrow$ a Higgs-Driven Cosmology!
- The theory to investigate this:
  Locally Conformally Invariant Standard Model + Gravity
- Geodesically Complete Universe

  more relevant now with the possible discovery of primordial gravitational waves

Collaborators:

I.B. + S.H. Chen: 1004.0752

I.B.+ S.H. Chen + N. Turok: 1105.3606

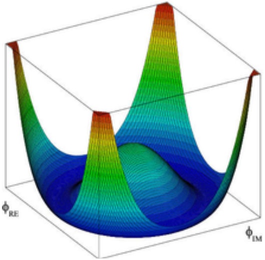
I.B. + S.H. Chen + P. Steinhardt + N. Turok: 1112.2470, 1207.1940

I.B. : 1109.5872, 1209.1068

I.B. + P. Steinhardt + N. Turok: 1307.1848, 1307.8106, 1312.0739, 1407.0992

The Higgs Field and the Universe

- The Higgs field is much more than just a particle! The vacuum state of the Higgs, $h(x) = v$, describes the **entire universe today**.



$$H = \begin{pmatrix} 0 \\ \frac{h(x)}{\sqrt{2}} \end{pmatrix}, \quad V(H) = \lambda \left(H^\dagger H - v^2/2 \right)^2$$

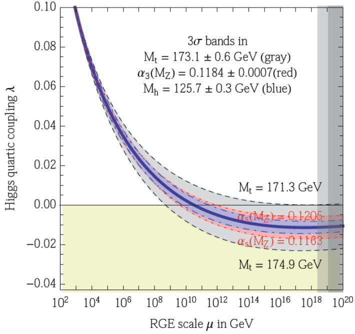
- v is a space-time constant throughout the universe, just like Dark Energy Λ (a relativistic "Ether"). Shouldn't we expect a relation?
- Besides today's state of the universe, the Higgs $h(x)$, as a function of time, could play a very central role in the early universe!

Instability in the Quantum Effective Potential

- The running of $\lambda(h)$ has a long history since late 1970's. For years,

$$\lambda(h) \geq 0$$

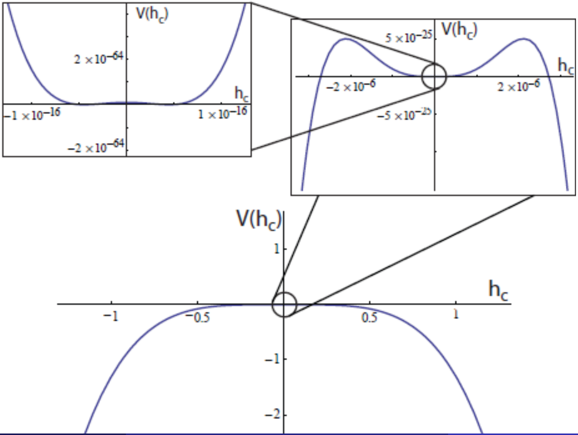
  was assumed to put limits on m_{higgs} before the discovery of the Higgs particle. But the measured value of m_h violates this stability bound!!
- $\lambda(h)$ has big sensitivity to m_{top} versus m_{higgs}. After the discovery of the higgs, 2-loops (G. Degrassi et.al, 2012) + others:



Quantum Effective Higgs Potential

A simplified model of $\lambda(h)$ with the key metastable behavior

$$V_{eff}(h) \equiv \lambda_0 \left(1 - \epsilon \ln\left(\frac{h}{v}\right)^2\right)\left(h^2 - v^2\right)^2, \; v = 246\,\frac{\text{GeV}}{c^2} \simeq \frac{10^{-16}}{4} M_{Pl}$$



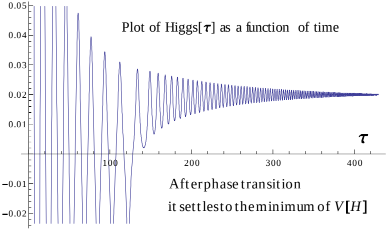
Phase Transitions to Planck Scale and Impact on Cosmos

- After phase transition new value of order $h \sim M_{Planck}$.

  Huge influence on the the universe through strong interaction with gravity. The universe reacts roughly as if there is a huge negative cosmological constant; bubbles of the new vacuum rapidly fill the universe $\longrightarrow$ **Big Crunch**.
- Estimated lifetime of metastable vacuum: many billions of years.

  Currently we are safe, but collapse will happen eventually: Very significant cosmologically.
- By time reversal, the same behavior will happen at the Big Bang.

  The Higgs that starts out in the order of the Planck scale can influence the evolution of the universe significantly, and then make a phase transition to the current vacuum.



Simplest theory:Locally Conformal SM+GR, (1307.1848)

- Can a large Higgs alone drive all cosmology? Or participate strongly?
  New tools based on conformal symmetry: **complete set of analytic cosmological solutions and geodesic completeness through cosmological singularities** (Bars, Chen, Steinhardt, Turok).
- We see **scaling symmetry at small and large scales**: SM without Higgs mass, and cosmological primordial fluctuations. Therefore build-in scaling as a fundamental symmetry.
- To avoid massless dilaton $\rightarrow$ local scale symmetry (Weyl)

$$\mathcal{L}(x) = \sqrt{-g}\left[\begin{array}{c} \frac{1}{12}\left(\phi^2 - 2H^\dagger H\right) R(g) \\ +g^{\mu\nu}\left(\frac{1}{2}\partial_\mu\phi\partial_\nu\phi - D_\mu H^\dagger D_\nu H\right) \\ -\left(\frac{\lambda}{4}\left(H^\dagger H - \omega^2\phi^2\right)^2 + \frac{\lambda'}{4}\phi^4\right) \\ +L_{\text{SM}}\left(\begin{array}{c}\text{quarks,leptons,gauge bosons,darkmatter,}\nu_R \\ \text{Yukawa couplings to H,not to }\phi\text{ except for }\nu_R\end{array}\right)\end{array}\right]$$

- conformally coupled scalars: $\left\{\begin{array}{l} H\text{=electroweak Higgs doublet} \\ \phi\text{=“dilaton”, relative }(-)\text{ sign is required, ghost}\end{array}\right.$

$$g_{\mu\nu} \rightarrow \Omega^{-2} g_{\mu\nu},\ \begin{array}{c}\phi \rightarrow \Omega\phi \\ H \rightarrow \Omega H\end{array},\ \psi_{q,l} \rightarrow \Omega^{3/2}\psi_{q,l},\ A_\mu^{\gamma,W,Z,g}\ \text{unchanged}$$

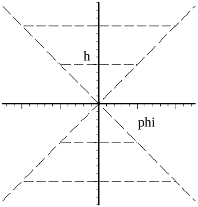
- **No dimensionful constants**: G_{grav}, m_{Higgs}, $m_{q,l,W,Z}$, Λ_{cosm}
- They emerge in c-gauge, $\phi(x) \longrightarrow \phi_0$, from

$$\frac{1}{12}\left(\phi^2 - 2H^\dagger H\right) R(g) - \left(\frac{\lambda}{4}\left(H^\dagger H - \omega^2\phi^2\right)^2 + \frac{\lambda'}{4}\phi^4\right)$$

$$\frac{M_{Pl}^2}{2} = \frac{\phi_0^2}{12}, \quad \overset{246\text{ GeV}/c^2}{v_{Higgs}} = \sqrt{2}\omega\phi_0, \quad \frac{M_{Pl}^2\Lambda}{2} = \frac{\lambda'\phi_0^4}{4}$$

same source ϕ_0 fills entire universe with dimensionful parameters

- Can effective grav. const $\frac{1}{12}\left(\phi_0^2 - 2H^\dagger H\right)$ change sign during cosmological evolution $\longrightarrow$ gravity/antigravity?



Cosmological Conformal Dynamics (BST), arXiv:1307.1848

- Relevant cosmological degrees of freedom (only time dependent fields)

$$ds^2_{B_{7,9,10}} = a^2\left[-d\tau^2 + e^{2\left(\alpha_1+\sqrt{3}\alpha_2\right)}d\sigma_1^2 + e^{2\left(\alpha_1-\sqrt{3}\alpha_2\right)}d\sigma_2^2 + e^{-4\alpha_1}d\sigma_3^2\right]$$

$$H = \begin{pmatrix} 0 \\ \frac{h(\tau)}{\sqrt{2}} \end{pmatrix} \text{ and } \phi(\tau)\,; \quad \begin{matrix} \text{scale factor} \\ a(\tau) \end{matrix} \quad \begin{matrix} \text{anisotropy} \\ \alpha_{1,2}(\tau) \end{matrix} \quad \begin{matrix} \text{Higgs} \\ h(\tau) \end{matrix} \quad \begin{matrix} \text{"dilaton"} \\ \phi(\tau) \end{matrix}$$

Matter, including DM: conformally invariant couplings

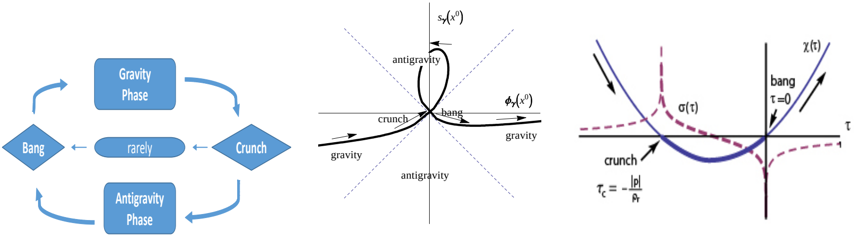
radiation: KE all massless fields $\frac{\rho_r}{a^4(\tau)}$

coupling of matter to Higgs, $W, Z, q, l,$ DM $\frac{h^2(\tau)\rho_{m_2}}{a^2(\tau)}, \frac{|h(\tau)|\rho_{m_1}}{a^3(\tau)}$ scale invariant

- Friedmann Eq.: Near singularity dominant terms are **KE of scalar and anisotropy**, next to leading term is **radiation** ρ_r. The rest is negligible (quadratic or linear h terms $\rho_{m1,2}$, curvature (k), potential energy $V(h)$, DE)

HiggsCosmo(BST)– analytic solutions, generic behavior

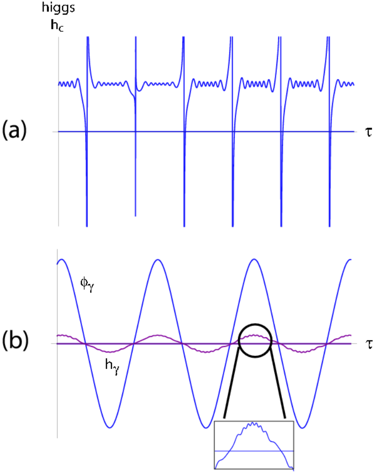
- For special potentials $V(H,\phi)$, obtained **analytically** all cosmological solutions, including **radiation** and **curvature**, with **all initial conditions** (identified 25 regions).
- All solutions are generically cyclic.
- Generic **analytic** solution near the singularity is controlled by an attractor driven by : anisotropy + Higgs kinetic energy + radiation. All else is subleading (space curvature, inhomogeneities, $V_{eff}(H,\phi)$, cosmological constant).



- **Resolved cosmological singularities:** generic **antigravity phase** between Crunch/Bang.
- **geodesically complete** global space-time: all solutions sail through despite singularities.
- **The SM Higgs field alone drives the entire cycle, no additional scalars needed.**

HiggsCosmo(BST)-Narrow band of stable initial conds

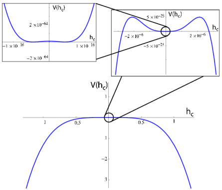
Higgs recaptures metastable state after each Bang



$$\frac{\lambda}{4}\left(1-\epsilon\ \ln\frac{h^2}{\omega^2\phi^2}\right)\left(h^2-\omega^2\phi^2\right)^2+\frac{\lambda'}{4}\phi^4$$

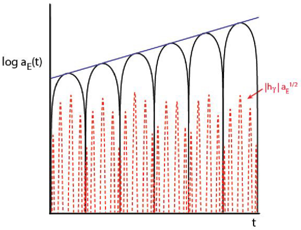
tiny negative λ' imitates tunnelling

Infinite oscillations in effective potential



∞cycles,entropy produced during antigravit

∞ time to $a_E \to 0$, **no beginning**



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- Cosmic perturbations, data fitting, not well developed yet.
- To understand quantum gravity effects, string theory lifted to new space-time Weyl invariant version with a **dynamical tension**: 1407.0992