Unexpected Role of the Higgs Field in the Evolution of the Universe

Itzhak Bars

USC

March 28, 2014

Lecture at Gunion Fest

Outline

1. Discovery in the LHC Measurements: Metastable Higgs Field

Outline

1. Discovery in the LHC Measurements: Metastable Higgs Field
2. The theory to investigate this:
   Locally Conformally Invariant Standard Model + Gravity

Outline

1. Discovery in the LHC Measurements: Metastable Higgs Field
2. The theory to investigate this:
   Locally Conformally Invariant Standard Model + Gravity
3. New Higgs-Driven Cosmology

Outline

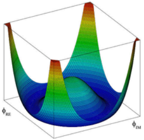
1. Discovery in the LHC Measurements: Metastable Higgs Field
2. The theory to investigate this:
   Locally Conformally Invariant Standard Model + Gravity
3. New Higgs-Driven Cosmology
4. Geodesically Complete Universe

   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

The Higgs Field and the Universe

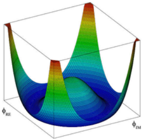
- The Higgs field **fills the entire universe;** much more than just a particle! The vacuum of the classical Higgs potential, $V(H) = \lambda \left(H^{\dagger}H - v^2/2\right)^2$,



describes the current state of the entire universe because it is space-time independent. Just like Dark Energy (a relativistic "Ether"). Should we expect a relation? Beyond explaining the origin of mass, the Higgs could play a more central role in the SM than originally anticipated. What was it in the early universe?

The Higgs Field and the Universe

- The Higgs field **fills the entire universe;** much more than just a particle! The vacuum of the classical Higgs potential, $V(H) = \lambda \left(H^\dagger H - v^2/2\right)^2$,

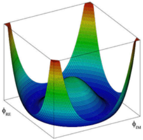


describes the current state of the entire universe because it is space-time independent. Just like Dark Energy (a relativistic "Ether"). Should we expect a relation? Beyond explaining the origin of mass, the Higgs could play a more central role in the SM than originally anticipated. What was it in the early universe?

- The **quantum corrected** effective potential $V_{eff}(H)$ is unexpectedly important: λ is not a constant, $\lambda(H)$ runs with scale and decreases at large H. The question is: how far down does it go?

The Higgs Field and the Universe

- The Higgs field **fills the entire universe;** much more than just a particle! The vacuum of the classical Higgs potential, $V(H) = \lambda \left(H^\dagger H - v^2/2\right)^2$,



describes the current state of the entire universe because it is space-time independent. Just like Dark Energy (a relativistic "Ether"). Should we expect a relation? Beyond explaining the origin of mass, the Higgs could play a more central role in the SM than originally anticipated. What was it in the early universe?
- The **quantum corrected** effective potential $V_{eff}(H)$ is unexpectedly important: λ is not a constant, $\lambda(H)$ runs with scale and decreases at large H. The question is: how far down does it go?
- The real story of H may be strongly **time dependent**: If H becomes large, the SM would not be decoupled from gravity. Large interactions with gravity could alter cosmological history .

Instability in the Effective Potential

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

$$\lambda(H) \geq 0$$

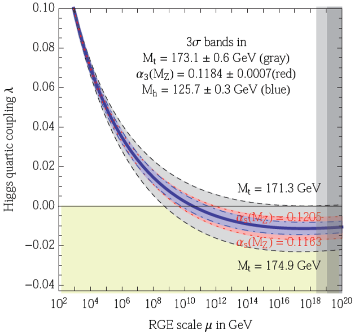
  was assumed to put limits on m_H before the discovery of the Higgs particle. But the measured value of m_H violates this stability bound!!

Instability in the 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_H 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:

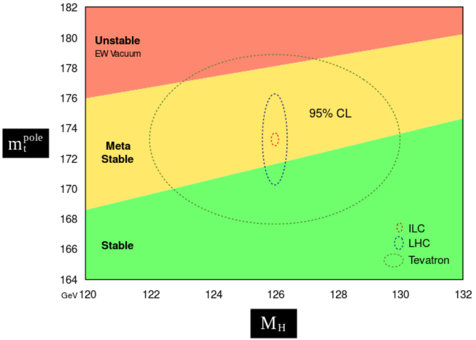


- The stable region (keeping only the most important terms in 2-loops)

$$m_H > 129.4 + 1.4\left(\frac{m_t - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s\left(m_Z\right) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$

- The stable region (keeping only the most important terms in 2-loops)

$$m_H > 129.4 + 1.4 \left(\frac{m_t - 173.1}{0.7} \right) - 0.5 \left(\frac{\alpha_s (m_Z) - 0.1184}{0.0007} \right) \pm 1.0_{th}$$



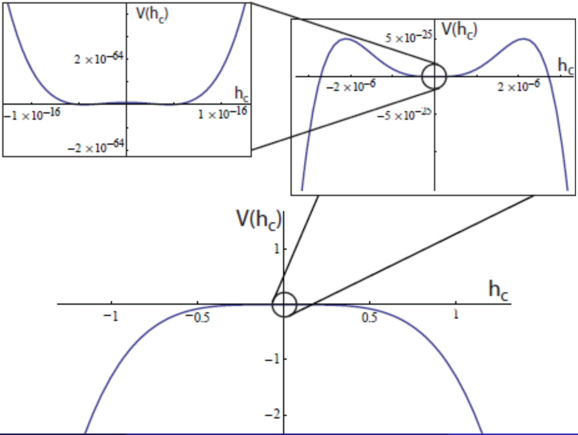
- Most recent values (2014) are in the metastable region

$$m_H = [125.9 \pm 0.4] \ \ \text{GeV}/c^2; \ \ m_t = [173.34 \pm 0.76] \ \ \ \text{GeV}/c^2$$

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 influences the evolution of the universe significantly, then makes a phase transition to the current vacuum.
- Can the Higgs alone drive all cosmology? Or participate strongly?

  How does this behavior alter our overall understanding of cosmological events?

  Requires a fresh start of theoretical investigation with new tools.
- New tools were already available: **complete set of analytic cosmological solutions** (BCST).

  This is an application of new duality methods in 1T physics generated by 2T-physics.

  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...

  (Tell at the end if you ask, or see local expert Andrew Waldrom)

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 influences the evolution of the universe significantly, then makes a phase transition to the current vacuum.
- Can the Higgs alone drive all cosmology? Or participate strongly?
  How does this behavior alter our overall understanding of cosmological events?
  Requires a fresh start of theoretical investigation with new tools.
- New tools were already available: **complete set of analytic cosmological solutions** (BCST).
  This is an application of new duality methods in 1T physics generated by 2T-physics.
  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...

(Tell at the end if you ask, or see local expert Andrew Waldrom)

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 influences the evolution of the universe significantly, then makes a phase transition to the current vacuum.
- Can the Higgs alone drive all cosmology? Or participate strongly?
  How does this behavior alter our overall understanding of cosmological events?
  Requires a fresh start of theoretical investigation with new tools.
- New tools were already available: **complete set of analytic cosmological solutions** (BCST).
  This is an application of new duality methods in 1T physics generated by 2T-physics.
  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...

  (Tell at the end if you ask, or see local expert Andrew Waldrom)

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 influences the evolution of the universe significantly, then makes a phase transition to the current vacuum.
- Can the Higgs alone drive all cosmology? Or participate strongly?
  How does this behavior alter our overall understanding of cosmological events?
  Requires a fresh start of theoretical investigation with new tools.
- New tools were already available: **complete set of analytic cosmological solutions** (BCST).
  This is an application of new duality methods in 1T physics generated by 2T-physics.
  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...

  (Tell at the end if you ask, or see local expert Andrew Waldrom)

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 influences the evolution of the universe significantly, then makes a phase transition to the current vacuum.
- Can the Higgs alone drive all cosmology? Or participate strongly?
  How does this behavior alter our overall understanding of cosmological events?
  Requires a fresh start of theoretical investigation with new tools.
- New tools were already available: **complete set of analytic cosmological solutions** (BCST).
  This is an application of new duality methods in 1T physics generated by 2T-physics.
  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...
  (Tell at the end if you ask, or see local expert Andrew Waldrom)

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

- Scaling symmetry (classical) $\left\{ \begin{array}{l} \text{at smallest scales SM is symmetric if quadratic Higgs } =0 \\ \text{at largest scales, observe} \simeq \text{scale inv. primordial fluctuations} \end{array} \right.$

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

- Scaling symmetry (classical) $\left\{\begin{array}{l}\text{at smallest scales SM is symmetric if quadratic Higgs }=0\\ \text{at largest scales, observe}\simeq\text{scale inv. primordial fluctuations}\end{array}\right.$
- Must avoid massless dilaton, therefore local scale symmetry (Weyl)

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

H=electroweak Higgs doublet
ϕ=dilaton, relative $-$ required, ghost } **conformal scalars** (generalizations, 1307.1848 / functions U,G,V; +scalars; SUSY)

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

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

- Scaling symmetry (classical) $\left\{ \begin{array}{l} \text{at smallest scales SM is symmetric if quadratic Higgs } =0 \\ \text{at largest scales, observe} \simeq \text{scale inv. primordial fluctuations} \end{array} \right.$
- Must avoid massless dilaton, therefore local scale symmetry (Weyl)

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

$\left.\begin{array}{l} H = \text{electroweak Higgs doublet} \\ \phi = \text{dilaton, relative} - \text{required, ghost} \end{array}\right\}$ **conformal scalars** (generalizations, 1307.1848 functions U,G,V; +scalars; SUSY)

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

- **No dimensionful constants**: no G_{grav}, no m_{Higgs}, no $m_{q,l,W,Z}$, no Λ_{cosm}

They emerge in **c-gauge**, $\phi(x) \to \phi_0$, useful at low energy $2H^\dagger H \ll \phi_0^2$

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

same constant source fills entire universe with a scale

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

Higgs Driven Cosmology (BST) - details, arXiv:1307.8106

- Relevant cosmological degrees of freedom $\left(\text{only time dependent homogeneous fields}\right)$

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

scale factor	anisotropy	Higgs	dilaton
$a(\tau)$	$\alpha_{1,2}(\tau)$	$h(\tau)$	$\phi(\tau)$

radiation density	fields that couple to Higgs	
$\frac{\rho_r}{a^4(\tau)}$	$\frac{\rho_m}{a^2(\tau)}h^2(\tau)$	scale invariant

$$, \quad H = \begin{pmatrix} 0 \\ \frac{h(\tau)}{\sqrt{2}} \end{pmatrix}$$

Higgs Driven Cosmology (BST) - details, arXiv:1307.8106

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

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

scale factor $a(\tau)$ — anisotropy $\alpha_{1,2}(\tau)$ — Higgs $h(\tau)$ — dilaton $\phi(\tau)$

radiation density $\frac{\rho_r}{a^4(\tau)}$ — fields that couple to Higgs $\frac{\rho_m}{a^2(\tau)}h^2(\tau)$ — scale invariant, $H = \begin{pmatrix} 0 \\ \frac{h(\tau)}{\sqrt{2}} \end{pmatrix}$

- Weyl symmetric action: $(a,h,\phi) \to \left(\Omega^{-1}a, \Omega h, \Omega\phi\right)$, **invariants** ah, $a\phi$, $\frac{h}{\phi}$

$$L = \left\{ \begin{array}{c} \frac{1}{2}\left(\phi^2 - h^2\right)a^2\left[\left(\dot\alpha_1^2+\dot\alpha_2^2\right)+\mathcal{K}\left(\alpha_1,\alpha_2\right)\right] \\ -\frac{1}{2}\left(\partial_\tau(a\phi)\right)^2 + \frac{1}{2}\left(\partial_\tau(ah)\right)^2 - \rho_r - \rho_m a^2 h^2 \\ -a^4\left[\frac{\lambda}{4}\left(1-\epsilon\ln\frac{h^2}{\omega^2\phi^2}\right)\left(h^2-\omega^2\phi^2\right)^2 + \frac{\lambda'}{4}\phi^4\right] \end{array} \right\}, \begin{array}{c}\text{Hamiltonian} \\ \text{constraint}=0 \\ (G_{00}=T_{00})\end{array}$$

$$\mathcal{K}(\alpha_1,\alpha_2) = \frac{\text{k}}{1-4\text{sign(k)}}\left[\begin{array}{c} e^{-8\alpha_1} + 4e^{4\alpha_1}\sinh^2\left(2\sqrt{3}\alpha_2\right) \\ -4\text{sign(k)}\; e^{-2\alpha_1}\cosh\left(2\sqrt{3}\alpha_2\right)\end{array}\right]$$

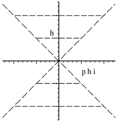
$\mathcal{K}$=k, if isotropic, $\alpha_{1,2}=0$

$\mathcal{K}=0$ if flat (k=0), any $\alpha_{1,2}$

Useful Gauges: c-gauge, gamma-gauge, Einstein frame

E-gauge for GR interpretation +patch incomplete	$\phi_E^2 - h_E^2 = \pm 1 \; (= \pm 6 M_{Pl}^2)$, $\phi_E^{(+)} = \cosh\sigma$, $h_E^{(+)} = \sinh\sigma$ $\pm$ patches, degrees of freedom: $a_E(\tau), \sigma(\tau)$
c-gauge for low energy interpretation	$\phi_c(\tau) = \phi_0 = 1$ (using $M_{Pl} = \frac{1}{\sqrt{6}}$) degrees of freedom: $a_c(\tau)$, $h_c(\tau)$ Higgs
γ-gauge for computation	$a_\gamma(\tau) = 1$, geodesically complete, all patches degrees of freedom: $\phi_\gamma(\tau)$, $h_\gamma(\tau)$

gravity/antigravity

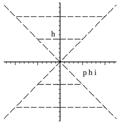


$|\phi| = |h|$ at 45^o
$a_E = 0$, $h_c = 1$

Useful Gauges: c-gauge, gamma-gauge, Einstein frame

E-gauge for GR interpretation +patch incomplete	$\phi_E^2 - h_E^2 = \pm 1 \; (= \pm 6\text{M}_{\text{Pl}}^2)$, $\phi_E^{(+)} = \cosh\sigma$, $h_E^{(+)} = \sinh\sigma$ $\pm$ patches, degrees of freedom: $a_E(\tau), \sigma(\tau)$
c-gauge for low energy interpretation	$\phi_c(\tau) = \phi_0 = 1$ (using $\text{M}_{\text{Pl}} = \frac{1}{\sqrt{6}}$) degrees of freedom: $a_c(\tau)$, $h_c(\tau)$ Higgs
γ-gauge for computation	$a_\gamma(\tau) = 1$, geodesically complete, all patches degrees of freedom: $\phi_\gamma(\tau)$, $h_\gamma(\tau)$

gravity/antigravity



$|\phi| = |h|$ *at* 45^o
$a_E = 0$, $h_c = 1$

Relations: obtained by using gauge invariants, $a^2\left(\phi^2 - h^2\right)$, $\frac{h}{\phi}$, and $a\phi$

E-frame: $a_E^2 = |\phi_\gamma^2 - h_\gamma^2|$, $\sigma = \tanh^{-1}\left(\frac{h_\gamma}{\phi_\gamma}\right)$ $\left(\sigma \approx \frac{h_\gamma}{\phi_\gamma} \text{ when } |\phi_\gamma| \gg |h_\gamma|\right)$

c-frame: $h_c = \frac{h_\gamma}{\phi_\gamma}$ (Higgs), $a_c = \phi_\gamma$ $\left(\approx a_E \text{ when } |\phi_\gamma| \gg |h_\gamma|\right)$

Useful Gauges: c-gauge, gamma-gauge, Einstein frame

E-gauge for GR interpretation +patch incomplete: $\phi_E^2 - h_E^2 = \pm 1 \; (= \pm 6 M_{Pl}^2)$, $\phi_E^{(+)} = \cosh\sigma$, $h_E^{(+)} = \sinh\sigma$

$\pm$ patches, degrees of freedom: $a_E(\tau), \sigma(\tau)$

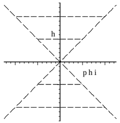
c-gauge for low energy interpretation: $\phi_c(\tau) = \phi_0 = 1$ (using $M_{Pl} = \frac{1}{\sqrt{6}}$)

degrees of freedom: $a_c(\tau)$, $h_c(\tau)$ Higgs

γ-gauge for computation: $a_\gamma(\tau) = 1$, geodesically complete, all patches

degrees of freedom: $\phi_\gamma(\tau)$, $h_\gamma(\tau)$

gravity/antigravity



$|\phi| = |h|$ *at* 45^o

$a_E = 0$, $h_c = 1$

Relations: obtained by using gauge invariants, $a^2(\phi^2 - h^2)$, $\frac{h}{\phi}$, and $a\phi$

E-frame: $a_E^2 = |\phi_\gamma^2 - h_\gamma^2|$, $\sigma = \tanh^{-1}\left(\frac{h_\gamma}{\phi_\gamma}\right)$ $\left(\sigma \approx \frac{h_\gamma}{\phi_\gamma} \text{ when } |\phi_\gamma| \gg |h_\gamma|\right)$

c-frame: $h_c = \frac{h_\gamma}{\phi_\gamma}$ (Higgs), $a_c = \phi_\gamma$ ($\approx a_E$ when $|\phi_\gamma| \gg |h_\gamma|$)

E-gauge H constraint Friedmann Eq

$$\left(\frac{\dot a_E}{a_E^2}\right)^2 = \frac{\pi_1^2 + \pi_2^2 + \pi_\sigma^2}{a_E^6} + \frac{\rho_r}{a_E^4} + \frac{\rho_m \sinh^2\sigma}{a_E^2} + V(\sigma),$$

for $a_E \to$ small (45^o) dominant terms KE($\pi_{1,2,\sigma}$), then ρ_r

γ-gauge H constraint only ϕ, h, **all patches** decouple in certain cases

$$H = \begin{pmatrix} -\frac{1}{2}\pi_\phi^2 + \frac{1}{2}\pi_h^2 + \frac{\pi_1^2 + \pi_2^2}{2(\phi_\gamma^2 - h_\gamma^2)} + \rho_r + \rho_m h_\gamma^2 \\ + \frac{\lambda}{4}\left(1 - \epsilon \ln \frac{h_\gamma^2}{\omega^2 \phi_\gamma^2}\right)\left(h_\gamma^2 - \omega^2\phi_\gamma^2\right)^2 + \frac{\lambda' \phi_\gamma^4}{4} \end{pmatrix} = 0$$

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). This guided numerical analysis of $V_{eff}(H,\phi)$ for the SM, including **anisotropy**.

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). This guided numerical analysis of $V_{eff}(H, \phi)$ for the SM, including **anisotropy**.
- All solutions are generically cyclic, and $\ni$ stable band of metastable initial conditions

Bang	$\longrightarrow$	Metastable phase (long time)
$\uparrow$	$\nwarrow$ rarely	$\downarrow$
Antigravity phase (short time)	$\longleftarrow$	Crunch

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). This guided numerical analysis of $V_{eff}(H,\phi)$ for the SM, including **anisotropy**.
- All solutions are generically cyclic, and $\ni$ stable band of metastable initial conditions

$$\begin{array}{ccc} \text{Bang} & \longrightarrow & \text{Metastable phase (long time)} \\ \uparrow & \nwarrow & \downarrow \\ & \text{rarely} & \\ \text{Antigravity phase (short time)} & \longleftarrow & \text{Crunch} \end{array}$$

- 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).

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). This guided numerical analysis of $V_{eff}(H,\phi)$ for the SM, including **anisotropy**.
- All solutions are generically cyclic, and $\ni$ stable band of metastable initial conditions

Bang	$\longrightarrow$	Metastable phase (long time)
$\uparrow$	$\nwarrow$ rarely	$\downarrow$
Antigravity phase (short time)	$\longleftarrow$	Crunch

- 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** at the classical physics level; discovered a generic **antigravity phase** in between Crunch/Bang transition.

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). This guided numerical analysis of $V_{eff}(H,\phi)$ for the SM, including **anisotropy**.
- All solutions are generically cyclic, and $\ni$ stable band of metastable initial conditions

$$
\begin{array}{ccc}
\text{Bang} & \longrightarrow & \text{Metastable phase (long time)} \\
\uparrow & \nwarrow & \downarrow \\
 & \text{rarely} & \\
\text{Antigravity phase (short time)} & \longleftarrow & \text{Crunch}
\end{array}
$$

- 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** at the classical physics level; discovered a generic **antigravity phase** in between Crunch/Bang transition.
- Obtained analytically **geodesically complete** global space-time, with all patches in field space, and learned that all solutions sail through smoothly despite singularities.

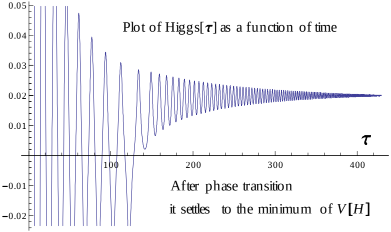
HiggsCosmo(BST)– analytic solutions, generic behavior

- For special potentials $V(H, \phi)$, obtained **analytically** all cosmological solutions, including **radiation** and **curvature**, with **all initial conditions** (identified 25 regions). This guided numerical analysis of $V_{eff}(H, \phi)$ for the SM, including **anisotropy**.
- All solutions are generically cyclic, and $\ni$ stable band of metastable initial conditions

Bang	$\longrightarrow$	Metastable phase (long time)
$\uparrow$	$\nwarrow$ rarely	$\downarrow$
Antigravity phase (short time)	$\longleftarrow$	Crunch

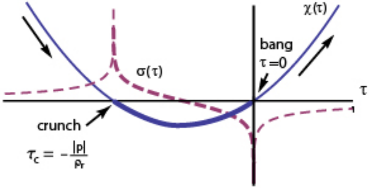
- Generic **analytic** solution near the singularity is controlled by an attractor driven by [anisotropy + Higgs kinetic energy + radiation], all else is subleading (space curvature, inhomogeneities, $V_{eff}(H, \phi)$, cosmological constant).
- **Resolved cosmological singularities** at the classical physics level; discovered a generic **antigravity phase** in between Crunch/Bang transition.
- Obtained analytically **geodesically complete** global space-time, with all patches in field space, and learned that all solutions sail through smoothly despite singularities.
- **The SM Higgs field alone drives the entire cycle, no additional scalars needed.**

HiggsCosmo(BST) - Generic behavior (pictures)

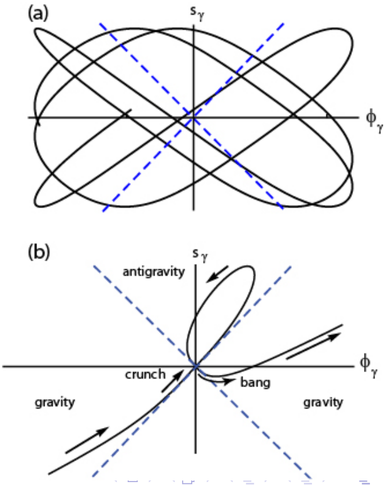


Higgs settling to vacuum while universe expands

Crunch/Antigravity/Bang : $\chi = \phi_\gamma^2 - h_\gamma^2$, $a_E^2 = |\chi|$

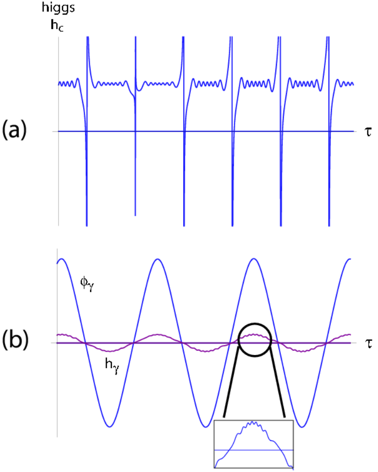


(a) Generic cyclic behavior, gravity/antigravity.
(b) With anisotropy: both ϕ_γ, h_γ must pass simultaneously through origin, and antigravity



HiggsCosmo(BST)-Narrow band of stable initial conds

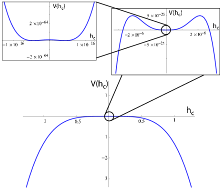
Higgs recaptures metastable state after each Bang



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

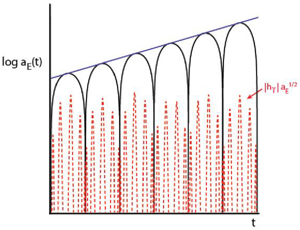
tiny negative λ' imitates tunnelling

Infinite oscillations in effective potential



∞cycles,entropy produced during antigravit

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

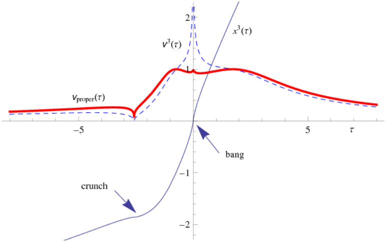


Geodesically Complete Universe: Info goes through singul.

All geodesics $x^\mu(\lambda)$ in **all SM** cosmologies: $g_{\mu\nu}(x)\,,\, h(x)\,,\; m(x) = g_p h(x)\,,$

$$\mathcal{S}_{\text{particle}} = -\int d\lambda\;\; m(x)\sqrt{-\dot{x}^\mu \dot{x}^\nu g_{\mu\nu}(x)},\;\;\Rightarrow\;\; x^i(\tau) = q^i + \int^\tau d\tau' \frac{g_3^{ij}(\tau')k_j}{\sqrt{g_3^{kl}(\tau')k_k k_l + m^2(\tau')a^2(\tau')}}$$

including anisotropy in 3D metric $g_3^{ij}(x(\tau))$



, $m \to 0$ included

- $x(\tau)$ for both massive & massless geodesics is finite and continuous throughout
- The coordinate velocity $v = \dot{x}$ goes to 0 (or ∞) at crunch and ∞ (or 0) at bang.
- The proper speed $v_{proper} = \sqrt{g_{3ij}\dot{x}^i\dot{x}^j} / \sqrt{g_{3ij}\dot{x}^i\dot{x}^j + m^2 a^2}$, never exceeds unity.
- Information goes through despite singularity in **all SM** complete geometries

Summary and Outlook

- Obtained all solutions of SM+GR, all initial conditions. Included all geometries and all geodesics in geodesically complete universe - New progress with new methods and new concepts in cosmology. All at the classical and semi-classical levels.

Summary and Outlook

- Obtained all solutions of SM+GR, all initial conditions. Included all geometries and all geodesics in geodesically complete universe - New progress with new methods and new concepts in cosmology. All at the classical and semi-classical levels.
- So far understood firmly the generic behavior: Generic universe is cyclic. Repeated cycles of (Bang $\longrightarrow$ settle to metastable for a long time $\longrightarrow$ crunch $\longrightarrow$ antigravity for a short time $\longrightarrow$ Bang etc) Each cycle lasts a finite amount of conformal time; but in cosmic time (observer dependent) some cycles may be infinitely long (depends on signs of parameters in $V(\phi, h)$).

Summary and Outlook

- Obtained all solutions of SM+GR, all initial conditions. Included all geometries and all geodesics in geodesically complete universe - New progress with new methods and new concepts in cosmology. All at the classical and semi-classical levels.
- So far understood firmly the generic behavior: Generic universe is cyclic. Repeated cycles of (Bang $\longrightarrow$ settle to metastable for a long time $\longrightarrow$ crunch $\longrightarrow$ antigravity for a short time $\longrightarrow$ Bang etc) Each cycle lasts a finite amount of conformal time; but in cosmic time (observer dependent) some cycles may be infinitely long (depends on signs of parameters in $V(\phi, h)$).
- Crunch/Antigravity and Antigravity/Bang transitions understood analytically and independent of the model (attractor, conserved quantities). Information goes through singularities.

Summary and Outlook

- Obtained all solutions of SM+GR, all initial conditions. Included all geometries and all geodesics in geodesically complete universe - New progress with new methods and new concepts in cosmology. All at the classical and semi-classical levels.
- So far understood firmly the generic behavior: Generic universe is cyclic. Repeated cycles of (Bang $\longrightarrow$ settle to metastable for a long time $\longrightarrow$ crunch $\longrightarrow$ antigravity for a short time $\longrightarrow$ Bang etc) Each cycle lasts a finite amount of conformal time; but in cosmic time (observer dependent) some cycles may be infinitely long (depends on signs of parameters in $V(\phi, h)$).
- Crunch/Antigravity and Antigravity/Bang transitions understood analytically and independent of the model (attractor, conserved quantities). Information goes through singularities.
- Cosmic perturbations, data fitting, not well developed yet. We want to insist on generic behavior rather than wishful thinking. Mulling over exciting ideas, different than available scenarios (inflation/ekpyrotic), truth somewhere in between. Not difficult since little data to fit, but theory has several available parameters plus initial conditions.

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,
  1. expect softer, not harsher, behavior due to expected singularity resolution in QG

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,
  1. expect softer, not harsher, behavior due to expected singularity resolution in QG
  2. String theory may be attempted using our geodesically complete solutions as the cosmological string background consistent with conformal symmetry on the worldsheet. This is something new in string theory.

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,
    1. expect softer, not harsher, behavior due to expected singularity resolution in QG
    2. String theory may be attempted using our geodesically complete solutions as the cosmological string background consistent with conformal symmetry on the worldsheet. This is something new in string theory.
- While waiting for QG, classical results are useful for physics

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,
  1. expect softer, not harsher, behavior due to expected singularity resolution in QG
  2. String theory may be attempted using our geodesically complete solutions as the cosmological string background consistent with conformal symmetry on the worldsheet. This is something new in string theory.
- While waiting for QG, classical results are useful for physics
  1. Think of the Klein Paradox in classical field theory (e.g. electron around a big nucleus). Correct interpretation of the paradox captures the essence of the physics in QFT (particle creation/annihilation). Used as a tool in the case of Graphite. Similar notions would be useful here too, to interpret physics of geodesically complete classical gravity.

How about quantum gravity effects?

- Wheeler deWitt equation is no problem; same behavior, only "fuzzy".
- Possible strong quantum effects near singularities; unfortunately nobody knows how? But,
  1. expect softer, not harsher, behavior due to expected singularity resolution in QG
  2. String theory may be attempted using our geodesically complete solutions as the cosmological string background consistent with conformal symmetry on the worldsheet. This is something new in string theory.
- While waiting for QG, classical results are useful for physics
  1. Think of the Klein Paradox in classical field theory (e.g. electron around a big nucleus). Correct interpretation of the paradox captures the essence of the physics in QFT (particle creation/annihilation). Used as a tool in the case of Graphite. Similar notions would be useful here too, to interpret physics of geodesically complete classical gravity.
  2. Investigated analytic continuation in complex τ plane. Avoid Planck scale and antigravity region at large contours, so avoid QG. Found complex solution, without cuts in τ, gives the same physically relevant results of geodesically complete classical solutions, by analytic continuation before Crunch and after Bang.

2T-physics and its relation to 1T-physics

Behind BST cosmology there is a deeper theory: 2T SM+GR in 4+2 dims. Concepts and techniques of computation used for analytic results in cosmology originated in studies of 2T gravity and 2T standard model in 4+2 dimensions.

- The Weyl symmetry is a bridge to 4+2 dims, it amounts to coordinate reparametrizations in the extra 1+1 dimensions.

2T-physics and its relation to 1T-physics

Behind BST cosmology there is a deeper theory: 2T SM+GR in 4+2 dims. Concepts and techniques of computation used for analytic results in cosmology originated in studies of 2T gravity and 2T standard model in 4+2 dimensions.

- The Weyl symmetry is a bridge to 4+2 dims, it amounts to coordinate reparametrizations in the extra 1+1 dimensions.
- 2T Physics is an approach with a lot more gauge symmetry, but gauge invariant sector has same physical content as 1T physics (i.e. no exotic stuff)

2T-physics and its relation to 1T-physics

Behind BST cosmology there is a deeper theory: 2T SM+GR in 4+2 dims. Concepts and techniques of computation used for analytic results in cosmology originated in studies of 2T gravity and 2T standard model in 4+2 dimensions.

- The Weyl symmetry is a bridge to 4+2 dims, it amounts to coordinate reparametrizations in the extra 1+1 dimensions.
- 2T Physics is an approach with a lot more gauge symmetry, but gauge invariant sector has same physical content as 1T physics (i.e. no exotic stuff)
- 2T physics makes many more predictions in the form of hidden symmetries (e.g. conformal symm) and dualities that 1T-physics cannot predict, but are true

2T-physics and its relation to 1T-physics

Behind BST cosmology there is a deeper theory: 2T SM+GR in 4+2 dims. Concepts and techniques of computation used for analytic results in cosmology originated in studies of 2T gravity and 2T standard model in 4+2 dimensions.

- The Weyl symmetry is a bridge to 4+2 dims, it amounts to coordinate reparametrizations in the extra 1+1 dimensions.
- 2T Physics is an approach with a lot more gauge symmetry, but gauge invariant sector has same physical content as 1T physics (i.e. no exotic stuff)
- 2T physics makes many more predictions in the form of hidden symmetries (e.g. conformal symm) and dualities that 1T-physics cannot predict, but are true
- Duality is the tool used to solve the cosmological equations analytically (amounts to Weyl gauge transformations in the present example)

Other proposals for Higgs cosmology

Other proposals different than BST: e.g. Bezrukov + Shapashnikov.

- Theoretically their model is an example of our larger class of conformally invariant models, taken in a particular fixed Weyl gauge. But our physical and mathematical analysis is very different.
- They have a specially crafted potential $V_{eff}\left(h\right)$. Unjustified assumptions to solve eqs or fit data with an approximate expression for $h\left(\tau\right)$ (slow roll), ignoring the existence of all other solutions of the same theory.
- Contrasting to our analytic approach with all solutions, shows that their hand-picked "solution" is a minuscule corner of solution space (serious measure problem of all inflationary scenarios: hard to digest guessing approach that ignores the equations.). .

Criticism unfounded

Answer to misleading, careless, criticism by Stanford group:

- We solved the equations analytically near and at the singularity, despite the singularity, and **completed the geometry on both sides of the singularity**. Not true that we were not aware of the curvature singularity with anisotropy. On the contrary, we dealt with it very carefully.
- The curvature singularity is not relevant for our claim of complete geometry and geodesics.
- The misguided critics played old tunes. They made no effort to understand our discovery in the context of classical GR: The cosmological singularity in the conformal SM+GR does not prevent information from traveling smoothly through BigBang/BigCrunch transition!
- This is important in its own right to address questions about cyclic cosmology and the physics very close to singularities (e.g.pre inflation physics even if inflation is right)
- How about quantum gravity?

First, Wheeler deWit equation is no problem; same behavior, only "fuzzy".

Second, we may expect strong quantum corrections; unfortunately nobody knows how? But,

(1) expect softer, not harsher, behavior due to expected singularity resolution in QG

(2) String theory may be attempted using our solutions as the pert. conformal string background

(3) Think of the Klein Paradox, it still captures the physics. We believe here too. Analytic continuation in τ plane avoids Planck scale at large contours.

Data on the Higgs Particle and the Top Quark

- $m_H = [125.9 \pm 0.4]$ GeV$/c^2$; particle data group, 2014 update.

Data on the Higgs Particle and the Top Quark

- $m_H = [125.9 \pm 0.4]$ GeV$/c^2$; particle data group, 2014 update.
- $m_{top} = [173.34 \pm 0.76]$ GeV$/c^2$; 1403.4427v1,
  Combination of Tevatron and LHC measurements of the top-quark mass