Simplicity + Symmetry

Some Cosmological Consequences of Conformally Invariant SM and GR

Itzhak Bars

USC

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Lecture at "Looking for Simplicity" Workshop

Princeton University

Outline

- Locally Conformally Invariant Standard Model + Gravity

Collaborators & References:

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

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  - General formulation of Weyl invariant effective theory and Weyl invariant renormalized theory.

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    Analytic/numerical complete set of cosmological solutions (25 regions of parameter space)

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- 2T-physics behind the scenes

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

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

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- Must avoid massless dilaton, therefore local scale symmetry (Weyl) when coupled to GR

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

conformal scalars: H =electroweak Higgs doublet, ϕ =dilaton, *ghost* − required

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

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- **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 $2H^\dagger H \ll \phi_0^2$

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

same constant source fills entire universe with a scale hierarchy by hand, but stable

Cosmology: can effective grav. const $\frac{1}{12}\left(\phi_0^2 - 2H^\dagger H\right)$ change sign (antigravity)? **geodesically complete**!

General theory of Weyl Invariant SM+GR (1307.1848)

- Effective non-renormalizable field th., or Weyl invariant regularization & renormalization
  Many scalars: $\left[\frac{1}{12}U\left(\phi^i\right)R\left(g\right)+g^{\mu\nu}G_{ij}\left(\phi\right)\frac{1}{2}\partial_\mu\phi^i\partial_\nu\phi^j-V\left(\phi^i\right)\right]$
  Weyl.Symm: Homegeous: $U\left(t\phi^i\right)=t^2U\left(\phi^i\right)$, $V\left(t\phi^i\right)=t^4V\left(\phi^i\right)$, with homothety conditions $\partial_iU=-2G_{ij}\phi^j$, $G_{ij}\phi^i\phi^j=-U$. general solutions for U,G,V (1008.1540) ,(1307.1848)

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- Only two scalars, H (doublet) and ϕ (no new degree of freedom)

$$\frac{\mathcal{L}(x)}{\sqrt{-g}}=\left[\begin{array}{c}\frac{1}{12}\phi^2u\left(z\right)R\left(g\right)-\phi^4f\left(z\right)-G\left(z\right)\left|D_\mu H\right|^2\\+\frac{1}{2}\left(u\left(z\right)-zu'\left(z\right)-z^2G\left(z\right)\right)\left(\partial_\mu\phi\right)^2\\+\frac{1}{2}\left(\frac{\partial u}{\partial H}+2G\left(z\right)\frac{H^\dagger}{\phi}\right)\partial\phi\cdot DH+h.c.\\+L_{\text{SM}}\left(\begin{array}{c}\text{quarks,leptons,gauge bosons,darkmatter,}\nu_R\\\text{Yukawa couplings to H,not to }\phi\text{ except for }\nu_R\end{array}\right)\end{array}+\cdots\right]$$

$u\left(z\right),\ G\left(z\right),\ f\left(z\right)$ general functions of $z=\frac{\sqrt{2}|H|}{\phi}$, $\left[\cdots\ \text{higher derivatives}\right]$

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$$\begin{array}{c}\text{Only}\\ 2\\ \text{scalars}\\ H,\phi\end{array}\ \frac{\mathcal{L}(x)}{\sqrt{-g}}=\left[\begin{array}{c}\frac{1}{12}\phi^2u\left(z\right)R\left(g\right)-\phi^4f\left(z\right)-G\left(z\right)\left|D_\mu H\right|^2\\ +\frac{1}{2}\left(u\left(z\right)-zu'\left(z\right)-z^2G\left(z\right)\right)\left(\partial_\mu\phi\right)^2\\ +\frac{1}{2}\left(\frac{\partial u}{\partial H}+2G\left(z\right)\frac{H^\dagger}{\phi}\right)\partial\phi\cdot DH+h.c.\\ +L_{\text{SM}}\left(\begin{array}{c}\text{quarks,leptons,gauge bosons,darkmatter,}\nu_R\\ \text{Yukawa couplings to H,not to }\phi\text{ except for }\nu_R\end{array}\right)\end{array}+\cdots\right]$$

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- Field redefinitions: always possible basis for 2 fields with diagonal KE,
  $ds^2=A^2\left(z\right)\left(\frac{1}{2}d\phi^2-dH^\dagger dH\right)$. Two constraints on $u\left(z\right),G\left(z\right)$, solution:
  $G=Z_{ren}(\rightarrow 1)$ and $\phi^2u\left(z\right)=Z_{ren}\left(\phi^2-2H^\dagger H\right)\Rightarrow$ **Simplest version is unique (and geodesically complete!!)**. Only effect, renormalized potential $\phi^4f\left(z\right)$.

Cosmological Conformal Dynamics (BST), arXiv:1307.1848

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

radiation density $\frac{\rho_r}{a^4(\tau)}$

fields that couple to Higgs $\frac{\rho_{m_2} h^2(\tau)}{a^2(\tau)}$, $\frac{\rho_{m_1}|h(\tau)|}{a^3(\tau)}$ scale invariant

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

$$L = \left\{ \begin{array}{c} \frac{1}{2}\left(\phi^2 - h^2\right) a^2 \left[\left(\dot{\alpha}_1^2 + \dot{\alpha}_2^2 \right) + \mathcal{K}(\alpha_1, \alpha_2) \right] - \rho_r \\ -\frac{1}{2} \left(\partial_\tau (a\phi) \right)^2 + \frac{1}{2} \left(\partial_\tau (ah) \right)^2 - \rho_{m_1} a |h| - \rho_{m_2} a^2 h^2 \\ -a^4 \left[\frac{\lambda}{4} \left(1 - \varepsilon \ln \frac{h^2}{\omega^2 \phi^2} \right) \left(h^2 - \omega^2 \phi^2 \right)^2 + \frac{\lambda'}{4} \phi^4 \right] \end{array} \right\}$$

Hamilt=0 constraint $(G_{00} = T_{00})$

NOTE WEYL INV. RENORMALIZATION AT SCALE DEFINED BY FIELD

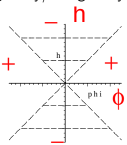
$$\mathcal{K}(\alpha_1,\alpha_2) = \frac{\text{k}}{1 - 4\text{sign(k)}} \left[\begin{array}{c} e^{-8\alpha_1} + 4e^{4\alpha_1} \sinh^2\left(2\sqrt{3}\alpha_2\right) \\ -4\text{sign(k)}\ e^{-2\alpha_1} \cosh\left(2\sqrt{3}\alpha_2\right) \end{array} \right]$$

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

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

Gauges: In gamma-gauge (almost) decoupled dynamics

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



at 45^o, $|h/\phi| = 1$ invariant
$a_E = 0,\ h_c = \frac{h}{\phi} \to \pm 1$

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for GR interpretation

$$\phi_E^2 - h_E^2 = \pm 1 \ (= \pm 6 M_{Pl}^2),$$

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+ patch
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c-gauge dofs
$a_c(\tau), \ h_c(\tau)$=Higgs
for low energy interpretation

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Geodesically complete, all patches

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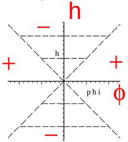
gravity/antigravity



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E-gauge±
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$$\left(\frac{\dot{a}_E}{a_E^2}\right)^2 = \frac{p_1^2 + p_2^2 + p_\sigma^2}{a_E^6} \pm \frac{\rho_r}{a_E^4} \pm \frac{\rho_{m_1} \frac{|\sinh\sigma|}{|\cosh\sigma|}}{a_E^3} \pm \frac{\rho_{m_2} \frac{\sinh^2\sigma}{\cosh^2\sigma}}{a_E^2} - \frac{K(\alpha_1, \alpha_2)}{a_E^2} \pm V(\sigma)$$

γ-gauge, ϕ, h,
all patches
Ham=0 $\leftrightarrow$Friedmann
decoupling $\varepsilon, \omega, p_{1,2} \to 0$

$$\begin{pmatrix} \frac{p_1^2 + p_2^2}{2(\phi_\gamma^2 - h_\gamma^2)} + \frac{1}{2} K(\alpha_1, \alpha_2) \left(h_\gamma^2 - \phi_\gamma^2\right) \\ + \frac{1}{2} p_h^2 + \rho_r + \rho_{m_1} |h_\gamma| + \rho_{m_2} h_\gamma^2 - \frac{1}{2} p_\phi^2 + \frac{\lambda' \phi_\gamma^4}{4} \\ + \frac{\lambda}{4} \left(1 - \varepsilon \ln \frac{h_\gamma^2}{\omega^2 \phi_\gamma^2}\right) \left(h_\gamma^2 - \omega^2 \phi_\gamma^2\right)^2 \end{pmatrix} = 0$$

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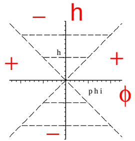

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E-gauge± Ham=0, Friedmann

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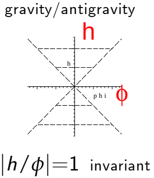
Conversions: obtained by using gauge invariants, $a^2\left(\phi^2 - h^2\right)$, $\frac{h}{\phi}$, and $a\phi$

$(E \leftrightarrow \gamma)$: $a_E^2 = |\phi_\gamma^2 - h_\gamma^2|$, $\left. \begin{smallmatrix} \tanh\sigma \\ \coth\sigma \end{smallmatrix} \right\} = \frac{h_\gamma}{\phi_\gamma} = h_c$ $\left(\sigma \approx \frac{h_\gamma}{\phi_\gamma} \text{ when } |h_\gamma| \ll |\phi_\gamma|\right)$

Gauges: In gamma-gauge (almost) decoupled dynamics

Decoupling limit: neglect anisotropy & $K(\alpha_1, \alpha_2) \longrightarrow k$; neglect ε, ω



$$,0=\left(\begin{array}{c} \frac{p_1^2+p_2^2}{2\left(\phi_\gamma^2-h_\gamma^2\right)} + \frac{1}{2}K(\alpha_1,\alpha_2)\left(h_\gamma^2-\phi_\gamma^2\right) - \frac{1}{2}p_\phi^2 + \frac{\lambda'\phi_\gamma^4}{4} \\ +\frac{1}{2}p_h^2 + \rho_r + \rho_{m_1}\left|h_\gamma\right| + \rho_{m_2}h_\gamma^2 \\ +\frac{\lambda}{4}\left(1-\varepsilon\ln\frac{h_\gamma^2}{\omega^2\phi_\gamma^2}\right)\left(h_\gamma^2-\omega^2\phi_\gamma^2\right)^2 \end{array}\right)$$

Constraint becomes decoupled Hamiltonians $H(h_\gamma) + \rho_r - H(\phi_\gamma) = 0$

$$H(\phi_\gamma) = \frac{1}{2}p_\phi^2 + \frac{1}{2}k\phi_\gamma^2 - \frac{\lambda'\phi_\gamma^4}{4},\quad H(h_\gamma) = \frac{1}{2}p_h^2 + \rho_{m_1}\left|h_\gamma\right| + \rho_{m_2}h_\gamma^2 + \frac{\lambda}{4}h_\gamma^4$$

All solutions: at constant conserved energies $E(\phi_\gamma) = E(h_\gamma) + \rho_r$

Two "particles" each oscillating independently at fixed energies $E(\phi_\gamma)$, $E(h_\gamma)$ in their own potentials with ANY initial conditions. ALL solutions are CYCLIC!!!

$\left(\phi_\gamma^2 - h_\gamma^2\right)$ keeps changing sign!!!! MUST INCLUDE ALL PATCHES!

Analytic (& numerical) 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**.

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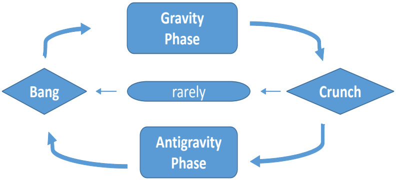

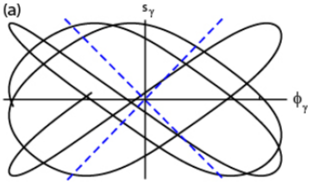

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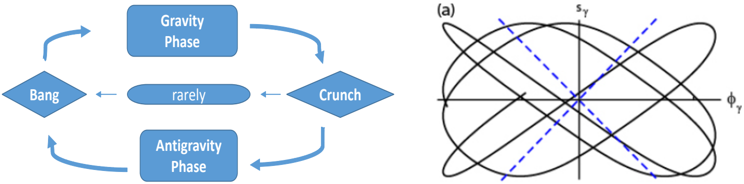

- All field solutions, ϕ_γ, h_γ (equivalently a_E, σ),α_1, α_2, continue through singularities. Massless & massive geodesics (information) sail through crunch/bang. Curvature singularities $R_{\mu\nu\lambda\sigma}$ do not stop particle geodesics, even with anisotropy!!.

- Generic **analytic** solution $\left(\phi_\gamma, h_\gamma, \alpha_{1,2}\right)$ 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$\big)$

$$\left(\frac{\partial_\tau a_E}{a_E^2}\right)^2 = \frac{p_1^2+p_2^2+p_\sigma^2}{a_E^6} \pm \frac{\rho_r}{a_E^4} \pm \frac{\rho_{m_1}|\sinh\sigma|}{a_E^3} \pm \frac{\rho_{m_2}\sinh^2\sigma}{a_E^2} - \frac{K(\alpha_1,\alpha_2)}{a_E^2} \pm V(\sigma), \quad \partial_\tau p_\sigma = \mp a_E^4 V'(\sigma)$$

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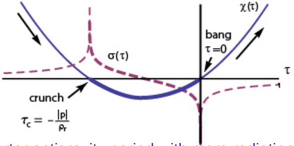
- Singularity resolution: pay attention to conserved quantities, an effective SO(4,2) with 15 conserved charges

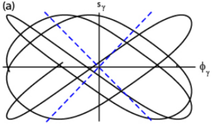
Crunch/**Antigravity**/Bang : $\chi = \phi_\gamma^2 - h_\gamma^2$

$a_E^2 = |\chi|$



shorter antigravity period with more radiation

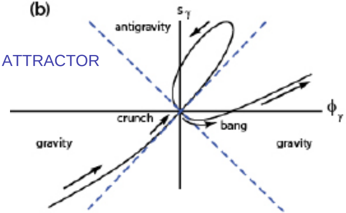
antigravity phase *between*
Crunch/Bang, unavoidable,
Resolves **classical**
cosmological singularities



(a)
Generic cyclic gravity / antigravity

(b) With anisotropy: both ϕ_γ, h_γ must pass simultaneously through origin, and antigravity

ATTRACTOR

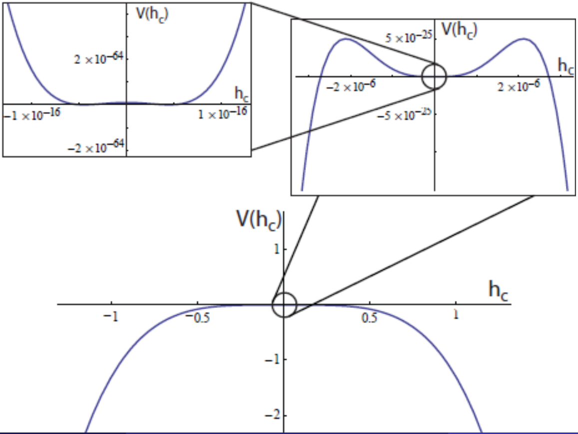


This forces unique initial conditions at each bang !!

Quantum Effective Higgs Potential

A simplified model of $\lambda(h)$ (with the key metastable behavior) in c-gauge $(\omega\phi_0 = v)$

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



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**.

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- 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.

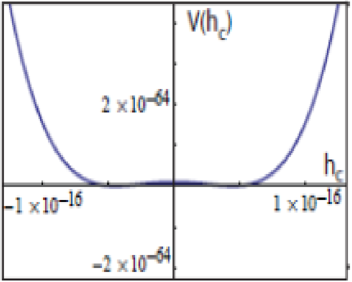
  2T-physics is at the bottom of 1T-physics conformal symmetry SO(4,2), and much more...

  (Tell at the end if you ask)

Generic solution in stable vacuum

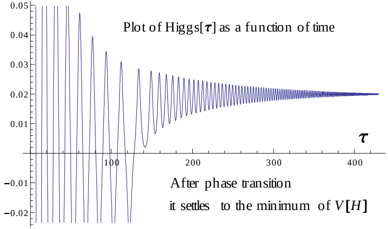
- If stable Higgs vacuum, there is a single cycle (unless there are more scalars, inflaton etc)

If stable vacuum

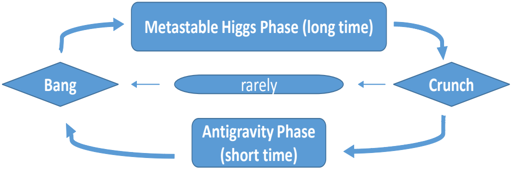


Higgs $h_c = \frac{h_\gamma}{\phi_\gamma} = 1$ emerge **large** at bang

settles to vacuum while universe expands. No cycles.



- Cycles possible only if driven by another scalar field



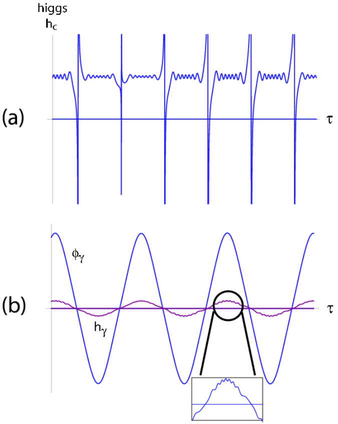
Unstable Vacuum-Narrow band of stable initial conds

The SM Higgs field alone can drive the entire cycle, no additional scalars needed.

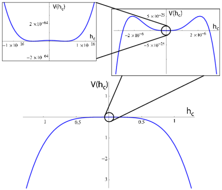
Higgs recaptures metastable state after each Bang

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

tiny negative λ' imitates tunnelling

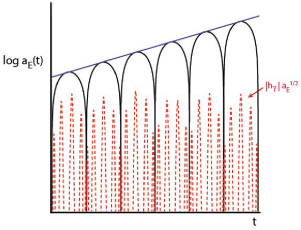


Infinite oscillations in effective potential



∞ cycles, entropy produced during antigravity

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



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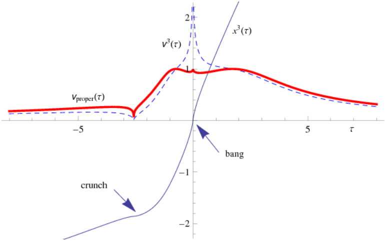
Geodesically Complete Universe: Info goes through singul.

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 $g_3^{ij}(x(\tau))$



, $m \longrightarrow 0$ 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

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  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.

This may be interpreted as semi-classical approximation of the quantum path integral, avoiding singularities

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

For an outline of 2T-physics, mostly in classical mechanics, with a summary of field theoretic formulation, see arXiv:1004.0688

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. arXiv:0811.2510
- 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) arXiv:1004.0688
- 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)

more general examples of dualities
in CM or QM: 1311.4205
in Field Theory: 0705.2834