Agravity

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Based on

Alberto Salvio and Alessandro Strumia, JHEP **1406** *(2014) 080, arXiv:1403.4226*

Outline

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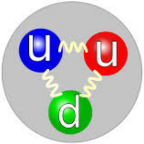
Motivation 1: origin of matter

Most of the mass of the matter we see has a dynamical origin

example: only few percents of the mass of the proton is due to the quark masses which comes from an ad hoc minus sign in the Higgs mechanism



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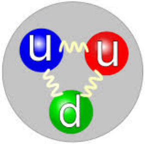

Is it possible to generate all the mass dynamically?

→ Dimensionless theories, or "agravity", when gravity is included

Inflation *[Guth (1981); Linde (1982); Albrecht and Steinhardt (1982)]*




Inflation is the (conjectured) nearly exponential expansion of the early universe ...

What it can solve: horizon, flatness, monopole problems.

To solve these problems inflation should last enough → lower bounds on

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How it is implemented (slow-roll inflation):

- we assume a scalar field φ ($\equiv$ the inflaton)
- at some early time $U(\varphi)$ is large, but quite flat
- → the scalar field rolls slowly at first down $U(\varphi)$, so that the Hubble constant changes slowly, and the universe undergoes a nearly exponential expansion.

The inflaton rolls slowly if

$$\epsilon \equiv \frac{M_P^2}{2}\left(\frac{1}{U}\frac{dU}{d\varphi}\right)^2 \ll 1, \quad \eta \equiv \frac{M_P^2}{U}\frac{d^2U}{d\varphi^2} \ll 1$$

... from which we can compute observable inflationary parameters:
the scalar amplitude A_s, its spectral index n_s and the tensor-to-scalar ratio $r = \frac{A_t}{A_s}$

$$n_s = 1 - 6\epsilon + 2\eta, \qquad A_s = \frac{U/\epsilon}{24\pi^2 M_P^4}, \qquad r = 16\epsilon \qquad \text{computed at } \varphi = \varphi_{in}$$

Motivation 2: inflation

Cosmological observations suggest inflation

However, this is a quite unusual outcome of quantum field theory: it requires special models with flat potentials. What is the reason for this flatness?

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$$-\xi_S |S|^2 R$$

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- By going to the Einstein frame ...

$$V_E = M_P^4 \frac{\lambda_S |S|^4}{(\xi_S |S|^2)^2} = M_P^4 \frac{\lambda_S}{\xi_S^2}$$

The potential is flat at tree-level, but at quantum level λ_S and ξ_S run ...

the beta-functions of the theory give the slow-roll parameters ...,
so they are small if couplings are perturbative

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what we need to have inflation!

Agravity scenario

The most general agravity action compatible with general relativistic invariance ... :

$$S = \int d^4x \sqrt{|\det g|} \left[\frac{R^2}{6f_0^2} + \frac{\frac{1}{3}R^2 - R_{\mu\nu}^2}{f_2^2} + \mathcal{L}_{\rm SM}^{\rm adim} + \mathcal{L}_{\rm BSM}^{\rm adim} \right]$$

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$\mathcal{L}_{\rm SM}^{\rm adim}$, is the no-scale part of the Standard Model (SM) Lagrangian:

$$\mathcal{L}_{\rm SM}^{\rm adim} = -\frac{F_{\mu\nu}^2}{4g^2} + \bar{\psi} i \not{D} \psi + |D_\mu H|^2 - (yH\psi\psi + \text{h.c.}) - \lambda_H |H|^4 - \xi_H |H|^2 R$$

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Example: adding a scalar singlet S one would have

$$\mathcal{L}_{\rm BSM}^{\rm adim} = |D_\mu S|^2 - \lambda_S |S|^4 + \lambda_{HS} |S|^2 |H|^2 - \xi_S |S|^2 R.$$

M_P can be generated dynamically:
if, at quantum level, S gets a vacuum expectation value (VEV) ...

$$M_P^2 = 2\xi_S |\langle S \rangle|^2 \simeq 2.4 \times 10^{18} \text{GeV} \quad \text{(the reduced Planck mass)}$$

Scale invariance

Scale invariance is an accidental symmetry in agravity due to the absence of scales

It is broken by quantum corrections

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Previous literature on scale invariant theories ... standing on the shoulder of giants!

..., Alexander-Nunneley, Bezrukov, Blas, Carone, Chang, Chun, Englert, Fatelo, Foot, Garcia-Bellido, Gastmans, Gerard, Hambye, Heikinheimo, Hempfling, Henz, Hill, Hur, Iso, Jaeckel, Jung, Karananas, Khoze, Ko, Kobakhidze, Lee, Meissner, McDonald, Nicolai, Ng, Okada, Orikasa, Pawlowski, Pilaftsis, Quiros, Raidal, Racioppi, Ramos, Rodigast, Rubio, Shaposhnikov, Spannowsky, Spethmann, Strumia, Tkachov, Truffin, Tuominen, Volkas, Wetterich, Weyers, Wu, Zenhausern ...

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The most general dimensionless actions compatible with general relativistic invariance:

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$\rightarrow$ the gravity kinetic terms have 4 derivatives, and the graviton propagator is $\propto 1/p^4$

$\rightarrow$ gravity becomes renormalizable *[Stelle (1977)]*

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Linearizing around the flat space:

- A massless graviton
- $1/f_0$ leads to an effective scalar with mass $M_0^2 = \frac{1}{2} f_0^2 M_P^2 + \cdots$.
- $1/f_2$ leads to a massive graviton with mass $M_2^2 = \frac{1}{2} f_2^2 M_P^2$ and negative norm (a ghost), however with energy bounded from below ...

positive literature: Lee-Wick, Hawking-Hertog, Mannheim, ...

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We adopt the "shut up and calculate" strategy!

Quantum agravity

The quantum corrections to a renormalizable theory are mostly encoded in the renormalization group equations (RGEs) for its parameters ...

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The most general agravity can be parameterized by the following $\mathcal{L}/\sqrt{|\det g|}$

$$\frac{R^2}{6f_0^2}+\frac{\frac{1}{3}R^2-R_{\mu\nu}^2}{f_2^2}-\frac{1}{4}(F_{\mu\nu}^A)^2+\frac{(D_\mu\phi_a)^2}{2}-\frac{\xi_{ab}}{2}\phi_a\phi_b R-\frac{\lambda_{abcd}}{4!}\phi_a\phi_b\phi_c\phi_d+\bar{\psi}_j i\not{D}\psi_j-Y_{ij}^a\psi_i\psi_j\phi_a+\text{h.c.}$$

We can obtain the RGEs of this renormalizable quantum field theory: the β functions

$$\beta_p \equiv \frac{dp}{d\ln\bar{\mu}} \qquad \text{(of all parameters } p\text{)}$$

defined conventionally in the modified minimal subtraction ($\overline{\mathrm{MS}}$) scheme ...

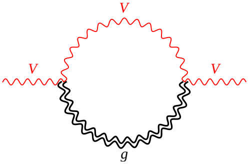
In the absence of gravity this was done before even at two-loop level
[Machacek and Vaughn (1983,1984,1985)]

We extend it to include gravity and use the one-loop approximation

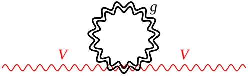
$$\text{for} \quad \bar{\mu} > M_P \quad \text{(dimensionless case)}$$

RGEs for the gauge couplings

The possible new gravity contributions are



(Rainbow)



(Seagull)

but their contributions to the RGEs exactly cancel!
This was previously noticed in *[Narain and Anishetty (2013)]*

A possible explanation: the graviton is not charged

RGE for the Yukawa couplings

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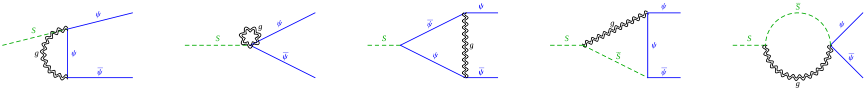

We find the one-loop RGE:

$$(4\pi)^2 \frac{dY^a}{d\ln\bar\mu} = \frac{1}{2}(Y^{\dagger b}Y^bY^a + Y^aY^{\dagger b}Y^b) + 2Y^bY^{\dagger a}Y^b + Y^b\mathrm{Tr}(Y^{\dagger b}Y^a) - 3\{C_{2F}, Y^a\} + \frac{15}{8}f_2^2Y^a$$

where $C_{2F} = t^At^A$ and t^A are the fermion gauge generators

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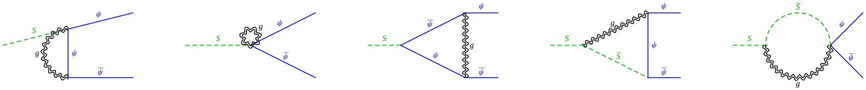

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For the SM, we find the one-loop RGE for the top quark Yukawa coupling:

$$(4\pi)^2 \frac{dy_t}{d\ln\bar{\mu}} = \frac{9}{2}y_t^3 + y_t\left(\frac{15}{8}f_2^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right)$$

RGEs for the quartic couplings

Tens of Feynman diagrams contribute to these RGEs ... we obtain

$$
\begin{aligned}
(4\pi)^2 \frac{d\lambda_{abcd}}{d\ln\bar{\mu}} \quad = \quad & \sum_{\text{perms}} \left[\frac{1}{8}\lambda_{abef}\lambda_{efcd} + \frac{3}{8}\{\theta^A, \theta^B\}_{ab}\{\theta^A, \theta^B\}_{cd} - \mathrm{Tr}\, Y^a Y^{\dagger b} Y^c Y^{\dagger d} + \right. \\
& + \frac{5}{8} f_2^4 \xi_{ab}\xi_{cd} + \frac{f_0^4}{8}\xi_{ae}\xi_{cf}(\delta_{eb} + 6\xi_{eb})(\delta_{fd} + 6\xi_{fd}) \\
& \left. + \frac{f_0^2}{4!}(\delta_{ae} + 6\xi_{ae})(\delta_{bf} + 6\xi_{bf})\lambda_{efcd} \right] + \lambda_{abcd}\left[\sum_k (Y_2^k - 3C_{2S}^k) + 5f_2^2 \right],
\end{aligned}
$$

where the first sum runs over the 4! permutations of *abcd* and the second sum over $k = \{a, b, c, d\}$, with Y_2^k and C_2^k defined by

$$
\mathrm{Tr}(Y^{\dagger a} Y^b) = Y_2^a \delta^{ab}, \quad \theta^A_{ac}\theta^A_{cb} = C_{2S}^a \delta_{ab}
$$

(θ^A are the scalar gauge generators)

RGEs for the quartic couplings: SM case

For the SM Higgs doublet plus the complex scalar singlet S the RGEs become:

$$
\begin{aligned}
(4\pi)^2 \frac{d\lambda_S}{d\ln\bar{\mu}} &= 20\lambda_S^2 + 2\lambda_{HS}^2 + \frac{\xi_S^2}{2}\left[5f_2^4 + f_0^4(1+6\xi_S)^2\right] + \lambda_S\left[5f_2^2 + f_0^2(1+6\xi_S)^2\right] \\
(4\pi)^2 \frac{d\lambda_{HS}}{d\ln\bar{\mu}} &= -\xi_H\xi_S\left[5f_2^4 + f_0^4(6\xi_S+1)(6\xi_H+1)\right] - 4\lambda_{HS}^2 + \lambda_{HS}\Big\{8\lambda_S + 12\lambda_H + 6y_t^2 \\
&\quad +5f_2^2 + \frac{f_0^2}{6}\left[(6\xi_S+1)^2 + (6\xi_H+1)^2 + 4(6\xi_S+1)(6\xi_H+1)\right]\Big\} \\
(4\pi)^2 \frac{d\lambda_H}{d\ln\bar{\mu}} &= \frac{9}{8}g_2^4 + \frac{9}{20}g_1^2g_2^2 + \frac{27}{200}g_1^4 - 6y_t^4 + 24\lambda_H^2 + \lambda_{HS}^2 + \frac{\xi_H^2}{2}\left[5f_2^4 + f_0^4(1+6\xi_H)^2\right] \\
&\quad +\lambda_H\left(5f_2^2 + f_0^2(1+6\xi_H)^2 + 12y_t^2 - 9g_2^2 - \frac{9}{5}g_1^2\right).
\end{aligned}
$$

RGEs for the scalar/graviton couplings

Complicated calculation (but computer algebra helps!)

$$(4\pi)^2 \frac{d\xi_{ab}}{d\ln\bar{\mu}} = \frac{1}{6}\lambda_{abcd}\,(6\xi_{cd}+\delta_{cd}) + (6\xi_{ab}+\delta_{ab})\sum_k \left[\frac{Y_2^k}{3} - \frac{C_{2S}^k}{2}\right] + \\ -\frac{5f_2^4}{3f_0^2}\xi_{ab} + f_0^2\xi_{ac}\left(\xi_{cd}+\frac{2}{3}\delta_{cd}\right)(6\xi_{db}+\delta_{db})$$

For the SM Higgs doublet plus the complex scalar singlet S the RGEs become:

$$(4\pi)^2 \frac{d\xi_S}{d\ln\bar{\mu}} = (1+6\xi_S)\frac{4}{3}\lambda_S - \frac{2\lambda_{HS}}{3}(1+6\xi_H) + \frac{f_0^2}{3}\xi_S(1+6\xi_S)(2+3\xi_S) - \frac{5}{3}\frac{f_2^4}{f_0^2}\xi_S$$

$$(4\pi)^2 \frac{d\xi_H}{d\ln\bar{\mu}} = (1+6\xi_H)(2y_t^2 - \frac{3}{4}g_2^2 - \frac{3}{20}g_1^2 + 2\lambda_H) - \frac{\lambda_{HS}}{3}(1+6\xi_S) + \\ +\frac{f_0^2}{3}\xi_H(1+6\xi_H)(2+3\xi_H) - \frac{5}{3}\frac{f_2^4}{f_0^2}\xi_H$$

RGE for the agravitational couplings

Huge calculation ... (computer algebra practically needed!!)

$$
\begin{aligned}
(4\pi)^2 \frac{df_2^2}{d\ln\bar{\mu}} &= -f_2^4\left(\frac{133}{10}+\frac{N_V}{5}+\frac{N_f}{20}+\frac{N_s}{60}\right)\\
(4\pi)^2 \frac{df_0^2}{d\ln\bar{\mu}} &= \frac{5}{3}f_2^4+5f_2^2f_0^2+\frac{5}{6}f_0^4+\frac{f_0^4}{12}(\delta_{ab}+6\xi_{ab})(\delta_{ab}+6\xi_{ab})
\end{aligned}
$$

Here N_V, N_f, N_s are the number of vectors, Weyl fermions and real scalars.

In the SM $N_V = 12$, $N_f = 45$, $N_s = 4$.

We confirmed the calculations of *[Avramidi (1995)]*

rather than those of *[Fradkin and Tseytlin (1981,1982)]*

Generic argument

There must be a real scalar s (e.g. the modulus of the complex scalar S)

Agravity generates the Planck scale while keeping the vacuum energy small if

$$\left\{ \begin{array}{rcll} \lambda_S(s) & \simeq & 0 & \text{(vanishing cosmological constant)}, \\ \beta_{\lambda_S}(s) & = & 0 & \text{(minimum condition)}, \\ \xi_S(s)s^2 & = & M_P^2 & \text{(observed Planck mass)}. \end{array} \right.$$

We call s the "Higgs of gravity" as it generates the Planck mass

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Are these conditions realized in the physics we know?

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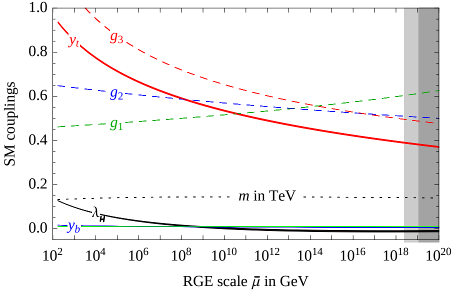

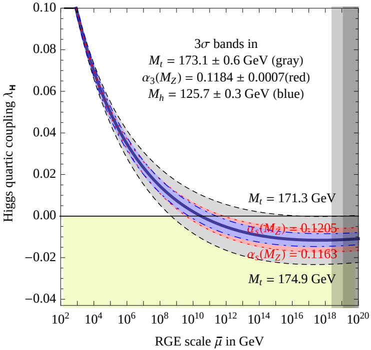

Running of the SM gauge couplings $g_1 = \sqrt{5/3}g_Y$, g_2, g_3, of the top and bottom (y_t, y_b), of the Higgs quartic coupling λ_H and of the Higgs mass parameter m. The thickness indicates the $\pm 1\sigma$ uncertainties in M_t, M_h, α_3. [Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (2013)]

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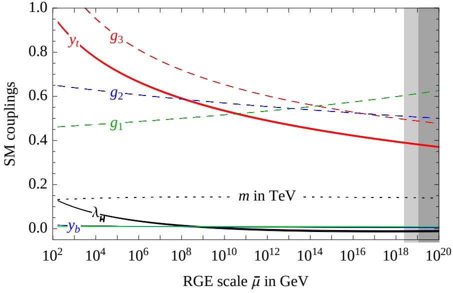

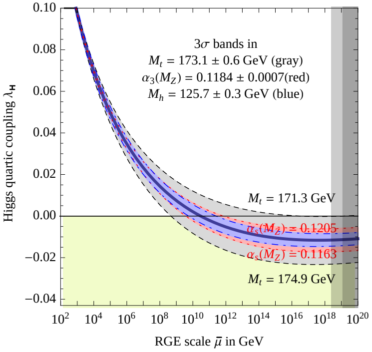

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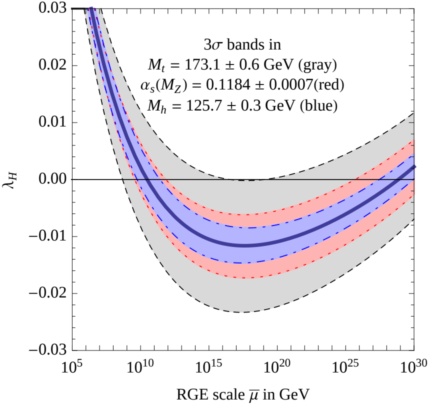
What happens above?

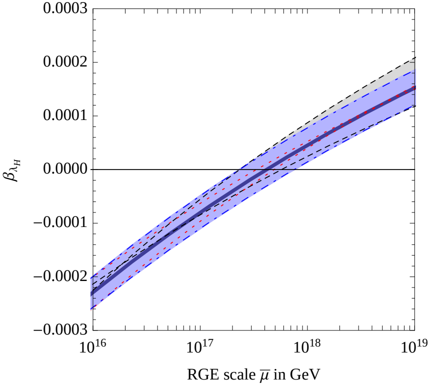
Models

arriving at the Planck scale region and going above

example: λ_H in the SM for $M_h \simeq 125$ GeV and $M_t \simeq 171$ GeV

RGE running of the $\overline{\mathrm{MS}}$ quartic Higgs coupling in the SM





... These conditions are technically possible!

Models

RGEs of agravity $\rightarrow$ in the pure gravitational limit these conditions cannot be satisfied

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A predictive model (no extra parameters): take a 2^{nd} copy of the SM and impose a Z_2 symmetry, spontaneously broken by the fact that the mirror Higgs field (S) has

$$\langle S \rangle \sim M_P \quad \text{while} \quad \langle H \rangle \sim M_W$$

- The mirror photon would be massless
- Mirror SM particles (e.g. a mirror neutrino or electron) may be *Dark Matter ...*
  Interactions between these candidates and the SM are suppressed by λ_{HS} ...
  it would be interesting to explore this possibility!

Agravity inflation

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Agravity inflation

All scalar fields in agravity are inflaton candidates

<u>**example (the minimal model)**</u>: the Higgs h, the Higgs of gravity s, the scalar χ in $g_{\mu\nu}$

To see χ

$$\frac{R^2}{6f_0^2} \to \frac{R^2}{6f_0^2} - \underbrace{\frac{(R + 3f_0^2\chi/2)^2}{6f_0^2}}_{\text{zero on-shell}}$$

By redefining $g^E_{\mu\nu} = g_{\mu\nu} \times f/M_P^2$ with $f = \xi_S s^2 + \xi_H h^2 + \chi$ one obtains ...

$$\sqrt{|\det g_E|}\left\{ -\frac{M_P^2}{2}R_E + M_P^2\left[\frac{(\partial_\mu s)^2 + (\partial_\mu h)^2}{2f} + \frac{3(\partial_\mu f)^2}{4f^2}\right] - V_E\right\} + \cdots$$

as well as their effective potential:

$$V_E = \frac{M_P^4}{f^2}\left(V + \frac{3f_0^2}{8}\chi^2\right)$$

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Then we can easily convert s into a scalar s_E with canonical kinetic term and find

$$\begin{aligned}
\epsilon &\equiv \frac{M_P^2}{2}\left(\frac{1}{V_E}\frac{\partial V_E}{\partial s_E}\right)^2 = \frac{1}{2}\frac{\xi_S}{1+6\xi_S}\left(\frac{\beta_{\lambda_S}}{\lambda_S} - 2\frac{\beta_{\xi_S}}{\xi_S}\right)^2 \\
\eta &\equiv M_P^2\frac{1}{V_E}\frac{\partial^2 V_E}{\partial s_E^2} = \frac{\xi_S}{1+6\xi_S}\left(\frac{\beta(\beta_{\lambda_S})}{\lambda_S} - 2\frac{\beta(\beta_{\xi_S})}{\xi_S} + \frac{5+36\xi_S}{1+6\xi_S}\frac{\beta_{\xi_S}^2}{\xi_S^2} - \frac{7+48\xi_S}{1+6\xi_S}\frac{\beta_{\lambda_S}\beta_{\xi_S}}{2\lambda_S\xi_S}\right)
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We can insert them in the formulae for the observable parameters A_s, n_s and $r = \frac{A_t}{A_s}$:

$$n_s = 1 - 6\epsilon + 2\eta, \qquad A_s = \frac{V_E/\epsilon}{24\pi^2 M_P^4}, \qquad r = 16\epsilon$$

where everything is evaluated at about $N \approx 60$ e-foldings when the inflaton $s_E(N)$ was

$$N = \frac{1}{M_P^2}\int_0^{s_E(N)} \frac{V_E(s_E)}{V_E'(s_E)}\,ds_E$$

Agravity inflation: analytic approximation

$$\left\{\begin{array}{rcl} \lambda_S(s) & \simeq & 0 \\ \beta_{\lambda_S}(s) & = & 0 \\ \xi_S(s)s^2 & = & M_P^2 \end{array}\right. \qquad \to \qquad \lambda_S(\bar\mu \approx s) \approx \frac{b}{2}\ln^2\frac{s}{\langle s\rangle}\,, \qquad \underbrace{\xi_S(\bar\mu) \approx \xi_S}_{\text{for simplicity}}$$

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$$\to \quad \epsilon \approx \eta \approx \frac{2\xi_S}{1+6\xi_S}\frac{1}{\ln^2 s/\langle s\rangle} = \frac{2M_P^2}{s_E^2}$$

The Einstein-frame potential is nearly quadratic around its minimum:

$$V_E = \frac{M_P^4}{4}\frac{\lambda_S}{\xi_S^2} \approx \frac{M_s^2}{2}s_E^2 \qquad \text{with} \qquad M_s = \frac{g^2 M_P}{2(4\pi)^2}\frac{1}{\sqrt{\xi_S(1+6\xi_S)}}$$

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Inserting s_E at $N \approx 60$ e-foldings, $s_E(N) \approx 2\sqrt{N}M_P$, ... **we obtain the predictions**

$$n_s \approx 1 - \frac{2}{N} \approx 0.967, \qquad r \approx \frac{8}{N} \approx 0.13, \qquad A_s \approx \frac{g^4 N^2}{24\pi^2\xi_S(1+6\xi_S)}$$

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VEVs above M_P, $s_E \approx 2\sqrt{N} M_P$, are needed for a quadratic potential

Agravity predicts physics above M_P, and a quadratic potential is a good approximation, even at $s_E > M_P$, because coefficients of higher order terms are dynamically suppressed by extra powers of the loop expansion parameters, which are small at weak coupling

Natural dynamical generation of the weak scale

1) *Low energies* : $\bar{\mu} < M_{0,2} \to$ agravity can be neglected and the SM RGE apply:

$$(4\pi)^2 \frac{dM_h^2}{d\ln\bar{\mu}} \quad = \quad M_h^2 \beta_{M_h}^{\rm SM}, \qquad \beta_{M_h}^{\rm SM} = 12\lambda_H + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10}$$

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The first term is a non-multiplicative potentially dangerous correction to M_h

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3) *Large energies* : $\bar\mu > M_P$: the theory is no-scale and the previous RGEs apply ...

$$\lambda_{HS}|H|^2|S|^2 \quad\to\quad M_h^2 = \lambda_{HS}\langle s\rangle^2$$

Ignoring gravity, λ_{HS} can be naturally arbitrarily small, because it is the only interaction that couples the SM sector with the S sector. Within agravity

$$(4\pi)^2\frac{d\lambda_{HS}}{d\ln\bar\mu} = -\xi_H\xi_S[5f_2^4 + f_0^4(6\xi_S+1)(6\xi_H+1)] + \cdots \quad\to\quad \lambda_{HS} \sim f_{0,2}^4$$

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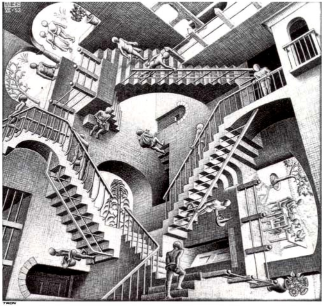
- *Bonus: one can have a natural electroweak scale*

Thank you!



Relativity, 1953; M. C. Escher