On the Origin of Scales and Inflation

Models of all interactions in the absence of fundamental scales (agravity)

Alberto Salvio

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March ..., 2015

Based on

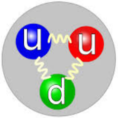
- Salvio, Strumia, arXiv:1403.4226 (JHEP)
- Kannike, Hütsi, Pizza, Racioppi, Raidal, Salvio, Strumia, arXiv:1502.01334
- Giudice, Isidori, Salvio, Strumia arXiv:1412.2769

Main motivations for agravity

Motivation 1: naturalness

Agravity provides an alternative solution of the hierarchy problem: there are no Λ^2 *contributions because there are no masses. This in turn leads to dynamical generation of masses*

Like for the proton: its mass is mostly dynamical generated



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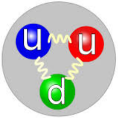

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Cosmological observations suggest inflation. However, it requires flat potentials.
What is the reason for this flatness? *Agravity gives us an explanation*:
The Einstein frame potential of a scalar s in agravity is

$$U(s) = \frac{\lambda_S s^4}{(2\xi_S s^2)^2} \bar{M}_{\rm Pl}^4 = \frac{\lambda_S}{4\xi_S^2} \bar{M}_{\rm Pl}^4$$

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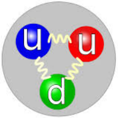

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what we need to have inflation!

Agravity scenario

The *most general* agravity Lagrangian:

$$\mathcal{L} = \frac{R^2}{6f_0^2} + \frac{\frac{1}{3}R^2 - R_{\mu\nu}^2}{f_2^2} + \mathcal{L}_{\rm SM}^{\rm adim} + \mathcal{L}_{\rm BSM}^{\rm adim}$$

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Non-gravitational sectors

- $\mathscr{L}_{\rm SM}^{\rm adim}$ is the no-scale part of the SM Lagrangian (without $m^2|H|^2/2$):
$$\mathscr{L}_{\rm SM}^{\rm adim} = -\frac{F_{\mu\nu}^2}{4} + \bar{\psi}i\not{D}\psi + |D_\mu H|^2 - (yH\psi\psi + \text{h.c.}) - \lambda_H|H|^4 - \xi_H|H|^2 R$$
- $\mathscr{L}_{\rm BSM}^{\rm adim}$ describes physics beyond the SM (BSM). It generates the weak scale

adding a scalar s $\rightarrow \mathscr{L}_{\rm BSM}^{\rm adim} = ... + \lambda_{HS}s^2|H|^2/2 - \xi_S s^2 R/2$

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Gravity sector

- $\langle s \rangle$ generates $\bar{M}_{\rm Pl}$: $\xi_S s^2 R \rightarrow \bar{M}_{\rm Pl}^2 = \xi_S |\langle s \rangle|^2$
- *Agravity is renormalizable*, however, looking at the spectrum:

  (i) massless graviton

  (ii) scalar z with mass $M_0^2 \sim \frac{1}{2} f_0^2 \bar{M}_{\rm Pl}^2$

  (iii) massive graviton with mass $M_2^2 = \frac{1}{2} f_2^2 \bar{M}_{\rm Pl}^2$ and negative norm, but with energy bounded from below

▸ The literature is controversial

Quantum corrections

They are mostly encoded in the RGEs

They are important to obtain n_s and r and to dynamically generate $\bar{M}_{\rm Pl}$ and m

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- We computed the 1-loop RGEs for all couplings of the most general agravity

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

Without gravity this was done before
[Machacek and Vaughn (1983,1984,1985)]

Dynamical generation of the Planck scale

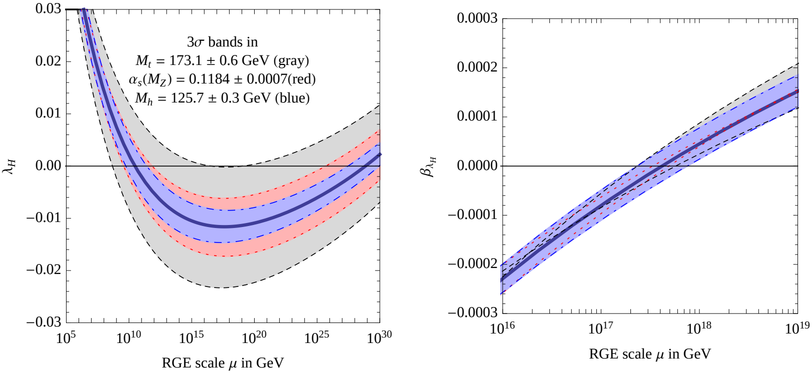
Agravity successfully generates the Planck scale if

$$\begin{cases} \lambda_S(s) & \simeq & 0 & \leftrightarrow & \text{nearly vanishing cosmological constant (dark energy)} \\ \frac{d\lambda_S}{ds}(s) & = & 0 & \leftrightarrow & \text{minimum condition} \\ \xi_S(s)s^2 & = & \bar{M}_{\rm Pl}^2 & \leftrightarrow & \text{observed Planck mass} \end{cases}$$

Is the dynamical generation of the Planck scale possible?

Are these conditions realized in the physics we know (the SM)?

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



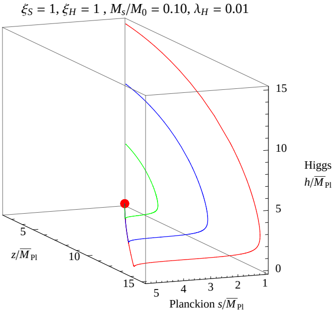
Thus the dynamical generation of the Planck scale is possible!

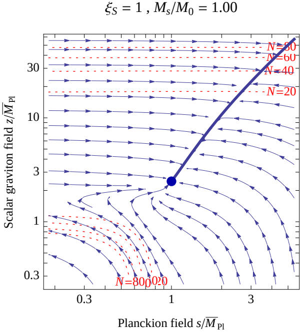
Predictions for inflation (generically a multifield inflation)

The minimal realistic model has at least 3 scalars:

the SM scalar h
the Planckion s
the graviscalar z

M_s = mass of s
M_0 = mass of z





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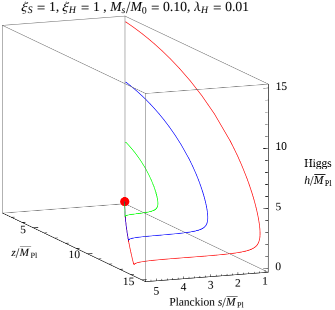
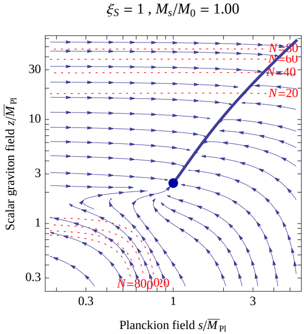
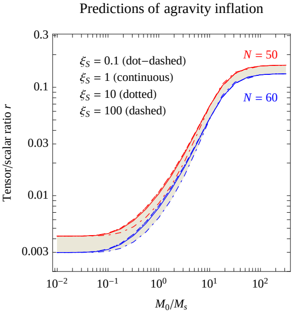
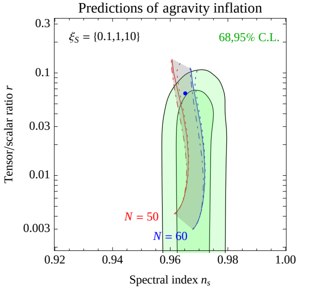
- **left:** when $M_s \ll (\gg) M_0$, the inflaton is s (z)
- **right:** comparison with a global fit of PLANCK and BICEP2/KECK









Natural dynamical generation of the weak scale

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

$$(4\pi)^2 \frac{dm^2}{d\ln\mu} = m^2 \beta_m^{\rm SM}, \qquad \beta_m^{\rm SM} = 12\lambda_H + 6y_t^2 - \frac{9g_2^2}{2} - \frac{9g_1^2}{10}$$

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2) *Intermediate energies* ($M_{0,2} < \mu < \bar{M}_{\rm Pl}$): Both m and $\bar{M}_{\rm Pl}$ appear and we find

$$(4\pi)^2 \frac{d}{d\ln\mu}\frac{m^2}{\bar{M}_{\rm Pl}^2} = -\xi_H[5f_2^4 + f_0^4(1+6\xi_H)] + \dots$$

The red term is a non-multiplicative potentially dangerous correction to m

$$m^2 \sim \bar{M}_{\rm Pl}^2 f_{0,2}^4, \quad \text{naturalness} \rightarrow f_0, f_2 \sim \sqrt{\frac{4\pi m}{M_{\rm Pl}}} \sim 10^{-8}$$

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3) *Large energies* ($\mu > \bar{M}_{\rm Pl}$):

$$\lambda_{HS}|H|^2 s^2 \quad \rightarrow \quad m^2 = \lambda_{HS}\langle s\rangle^2$$

λ_{HS} can be naturally small (looking at the RGE of λ_{HS}):

$$\rightarrow \quad \lambda_{HS} \sim f_{0,2}^4$$

Natural weak scale and unification

It is possible to preserve a natural weak scale if

- a semi-simple gauge group is used: e.g. the Pati-Salam $SU(4) \times SU(2) \times SU(2)$
- all SM Landau poles are removed (we require this as we want to go up to infinite energy and in the SM the experiments tell us that e.g. g_Y diverges at 10^{42} GeV)

Models of this type have been found
and predict a lot of new physics not far above the weak scale
(In the SM the elimination of such poles requires unrealistic conditions: $g_Y = 0$, ...)

Conclusions

- *Naturalness and a rationale for inflation can be achieved in no-scale theories of all interactions (including gravity): agravity*

- *Inflation: the minimal realistic model predicts* $n_s \approx 0.967, \quad 0.003 < r < 0.13,$ *in agreement with* PLANCK *and* BICEP2/KECK. KECK/BICEP3 *may give us more constraints on this scenario.*

- *Naturalness is also compatible with unification.* *SM Landau poles can also be eliminated.* *In this case there is new physics not far above the weak scale (e.g.* W'*).*

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THANK YOU VERY MUCH
FOR YOUR ATTENTION!

Extra slides

Ghosts

Negative literature *[Ostrogradski (1850), Smilga (2009), ...]*

- *Classically* the energy is not bounded from below (Ostrogradski instability)
- *At quantum level* creation of negative energy $\sim$ destruction of positive energy: the Hamiltonian becomes positive, but some states ("ghosts") have negative norm

Positive literature

- *[Lee, Wick (1969)]* the introduction of negative norms can lead to a unitary S-matrix, provided that all stable particle states have positive norm
- *[Hawking, Hertog (2001)]* at least in a simple scalar field ϕ theory, the problem comes from regarding ϕ and $\Box\phi$ as independent and can be overcome by using the path integral, where they are dependent.

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Results for RGEs

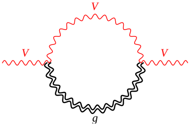
Gauge couplings

Possible new gravity contributions

Their contributions to the RGEs cancel!

This was previously noticed in *[Narain, Anishetty (2013)]*

Possible explanation:
the graviton is not charged



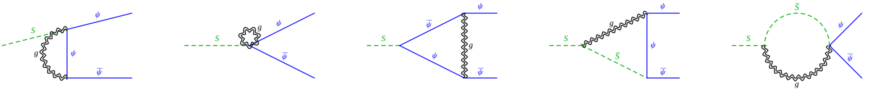
(Rainbow)

(Seagull)

Yukawa couplings

We find the one-loop RGE (where $C_{2F} \equiv t^A t^A$ and $t^A \equiv$ "fermion gauge generators"):

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



All remaining RGEs

We also computed the RGEs for ‣ λ_{abcd} ‣ ξ_{ab} ‣ f_0 and f_2

RGEs for the quartic couplings

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

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

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)

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RGEs for the quartic couplings: SM case

For the SM H plus the complex scalar singlet S the RGEs become:

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

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RGEs for the scalar/graviton couplings

Complicated calculation (but computer algebra helps!)

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

For the SM H plus the complex scalar singlet S the RGEs become:

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

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

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RGE for the gravitational couplings

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

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

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)]*

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Agravity inflation

All scalar fields in agravity are inflaton candidates

Agravity inflation

All scalar fields in agravity are inflaton candidates

example (the minimal model): h, the Planckion s, the scalar σ in $g_{\mu\nu}$

To see σ

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

By redefining $g^E_{\mu\nu} = g_{\mu\nu} \times f/\bar{M}^2_{\rm Pl}$ with $f = \xi_S s^2 + \xi_H h^2 + \sigma$ one obtains ...

$$\sqrt{|\det g_E|}\left\{\frac{\bar{M}^2_{\rm Pl}}{2}R_E + \bar{M}^2_{\rm Pl}\left[\frac{(\partial_\mu s)^2 + (\partial_\mu h)^2}{2f} + \frac{3(\partial_\mu f)^2}{4f^2}\right] - U\right\} + \cdots$$

as well as their effective potential:

$$U = \frac{\bar{M}^4_{\rm Pl}}{f^2}\left(V + \frac{3f_0^2}{8}\sigma^2\right)$$

Agravity inflation: a simple single field case

We identify inflaton = s by taking the other scalar fields heavy ...

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

$$\epsilon \equiv \frac{\bar{M}_{\rm Pl}^2}{2}\left(\frac{1}{U}\frac{\partial U}{\partial s_E}\right)^2 = \frac{1}{2}\frac{\xi_S}{1+6\xi_S}\left(\frac{\beta_{\lambda_S}}{\lambda_S} - 2\frac{\beta_{\xi_S}}{\xi_S}\right)^2$$

$$\eta \equiv \bar{M}_{\rm Pl}^2 \frac{1}{U}\frac{\partial^2 U}{\partial s_E^2} = \frac{\xi_S}{1+6\xi_S}\left(\frac{\beta(\beta_{\lambda_S})}{\lambda_S} - 2\frac{\beta(\beta_{\xi_S})}{\xi_S} + \frac{5+36\xi_S}{1+6\xi_S}\frac{\beta_{\xi_S}^2}{\xi_S^2} - \frac{7+48\xi_S}{1+6\xi_S}\frac{\beta_{\lambda_S}\beta_{\xi_S}}{2\lambda_S\xi_S}\right)$$

The slow-roll parameters are given by the β-functions ...

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We can insert them in the formulae for the observable parameters A_s, n_s and $r = \frac{A_t}{A_s}$:

$$n_s = 1 - 6\epsilon + 2\eta, \qquad A_s = \frac{U/\epsilon}{24\pi^2\bar{M}_{\rm Pl}^4}, \qquad r = 16\epsilon$$

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

$$N = \frac{1}{\bar{M}_{\rm Pl}^2}\int_0^{s_E(N)} \frac{U(s_E)}{U'(s_E)}\,ds_E$$

A Pati-Salam model without Landau poles

	Fields	spin	generations	$SU(2)_L$	$SU(2)_R$	$SU(4)_{PS}$
skeleton model	$\psi_L = \begin{pmatrix} \nu_L & e_L \\ u_L & d_L \end{pmatrix}$	1/2	3	$\bar{2}$	1	4
	$\psi_R = \begin{pmatrix} \nu_R & u_R \\ e_R & d_R \end{pmatrix}$	1/2	3	1	2	$\bar{4}$
	ϕ_R	0	1	1	2	$\bar{4}$
	$\phi = \begin{pmatrix} H_U^0 & H_D^+ \\ H_U^- & H_D^0 \end{pmatrix}$	0	1	2	$\bar{2}$	1
extra fields	ψ	1/2	$N_\psi \leq 3$	2	$\bar{2}$	1
	Q_L	1/2	2	1	1	10
	Q_R	1/2	2	1	1	$\overline{10}$
	Σ	0	1	1	1	15