Dimensional Transmutation in Particle Physics and Cosmology

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Theory Institute on Scale Invariance in Particle Physics and Cosmology

Università di Roma Tor Vergata

CERN

Goals of the talk

Give an overview of models where *all* masses are generated by quantum effects, through dimensional transmutation

(these models have classical scale invariance (CSI), broken by quantum effects)

Both applications to particle physics and cosmology will be discussed

Some motivations for models with CSI

Motivation 1: inflation (one can have naturally flat potentials)

Consider a no-scale Lagrangian $\mathscr{L}_\varphi$ for the inflaton φ:

$$\mathscr{L}_\varphi = (\partial\varphi)^2 - \lambda_\varphi \varphi^4 - \xi_\varphi \varphi^2 R,$$

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The potential is flat at tree-level, but at quantum level λ_φ and ξ_φ depend on φ.

The RGEs give some slope, which is small if the couplings are perturbative.

$\rightarrow$ **inflation!**

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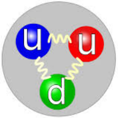
Motivation 2: origin of mass and EW symmetry breaking

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

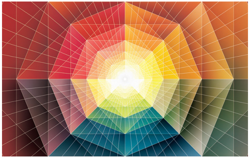
Example: the proton mass $\longrightarrow$



Is it possible to generate all the mass dynamically? If yes, with $M_{\rm EW} \ll M_{\rm Pl}$?

Classical Scale Invariance in the press

For an outreach article on CSI see
[Natalie Wolchover
for Quanta Magazine (2014)]



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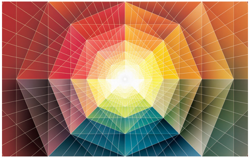

For Quanta Magazine (Simons Foundation)

Many contributed to CSI: many participants to this workshop plus

...Adler, Alexander-Nunneley, Blas, Carone, Chang, Chun, Englert, Fatelo, Foot, Garcia-Bellido, Gastmans, Gerard, Hambye, Hempfling, Henz, Hur, Jaeckel, Jung, Khoze, Meissner, McDonald, Ng, Okada, Orikasa, Pawlowski, Pilaftsis, Quiros, Raidal, Racioppi, Ramos, Rodigast, Spannowsky, Spethmann, Tkachov, Truffin, Tuominen, Volkas, Weyers, Wu, Zenhausern ...

The quantum breaking of scale invariance we need is similar to the Coleman-Weinberg (CW) mechanism, but here we need a gravitational generalization

The Coleman-Weinberg mechanism

- The *Coleman-Weinberg (CW) mechanism (1973)* is a perturbative way to generate a mass through quantum corrections in the absence of gravity

- These effects can be captured by the effective potential $V_{\rm eff}$

- One requires the existence of an (approximately) flat direction in the tree-level potential: if such direction did not exist we would expect the radiative corrections to be negligible with respect to the slope of the tree-level potential

- Essentially this means that a combination $\lambda_{\rm CW}$ of the quartic couplings has to vanish at some scale $\mu_{\rm CW}$: then there is an (approximately) flat direction parameterized by some scalar, $\varphi_{\rm CW}$:

$$V_{\rm eff}^{\rm CW} = \lambda_{\rm CW}(\varphi_{\rm CW})\varphi_{\rm CW}^4 + \text{constant} \simeq \text{constant} \quad \text{for} \quad \varphi_{\rm CW} \approx \mu_{\rm CW}$$

Gravitational generalizations of the CW mechanism

The general Lagrangian including gravity, the Standard Model (SM) and a beyond the Standard Model (BSM) sector is (we call this theory *agravity*)

$$\mathscr{L} = \frac{R^2}{6f_0^2} + \frac{\frac{1}{3}R^2 - R_{\mu\nu}^2}{f_2^2} + \mathscr{L}_4^{\rm SM} + \mathscr{L}_4^{\rm BSM}$$

These gravitational terms should be added:
If not added to the classical Lagrangian they are generated by quantum effects.

Once they are added the gravitational sector is also renormalizable

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Non-gravitational sector

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$\langle s\rangle$ generates the EW scale
$\nearrow$

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$\swarrow$

Agravity sector

$\langle s\rangle$ generates $\bar{M}_{\rm Pl}$: $\quad \xi_S s^2 R \rightarrow \bar{M}_{\rm Pl}^2 = \xi_S\langle s\rangle^2$

Conditions for the gravitational CW mechanism

Agravity successfully generates the Planck scale if

$$\begin{cases} \lambda_s(s) & \simeq & 0 & \leftrightarrow & \text{nearly vanishing cosmological constant (dark energy)} \\ \lambda'_s(s) & = & 0 & \leftrightarrow & \text{minimum condition} \\ \xi_s(s) & > & 0 & & \text{then we identify} \quad \xi_s(s) s^2 = \bar{M}_{\rm Pl}^2 \end{cases}$$

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[Salvio, Strumia (2014)]

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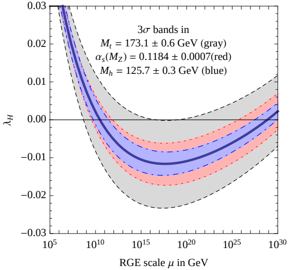
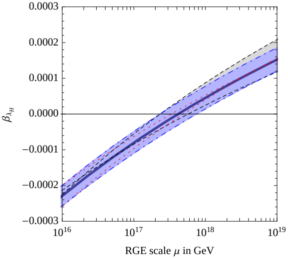
It is possible to satisfy these conditions as they are realized in the physics we know (the SM)!
↘

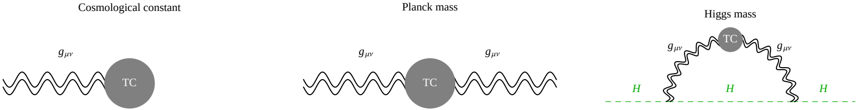




[Salvio, Strumia (2014)]

Non-perturbative generations of scales

Alternatively all scales can be induced by a new gauge group G_{TC} that becomes non-perturbative around the Planck scale, such that condensates are generated.
[Adler (1982)], *[Salvio, Strumia (2017)]*, *[Donoghue, Menezes (2017)]*, *[Kubo. Lindner, Schmitz, Yamada (2018)]*



This option will be discussed in *Donoghue*'s and *Yamada*'s talks

- Agravity is renormalizable (clear from the absence of fundamental scales) and rigorously proved by *Stelle (1977, and his talk)* in the presence of $\bar{M}_{\rm Pl}$ (see also a more recent proof of *Barvinsky, Blas, Herrero-Valea, Sibiryakov and Steinwachs (2017)*)
- Furthermore, it can be extended up to infinite energy if there is a UV fixed point *[Salvio, Strumia (2017)]*, predicting transplanckian physics *[Salvio, Strumia, Veermae (2018)]*.

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However, looking at the classical spectrum *[Stelle (1977)]*:

(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 spin-2 ghost with mass $M_2^2 = \frac{1}{2} f_2^2 \bar{M}_{\rm Pl}^2$

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However, there exist *quantizations* with Hamiltonians bounded from below, that preserve the unitarity of the theory.

See the talks by *Anselmi* and *Mannheim*.

Natural dynamical generation of the weak scale

1) *Low energies* ($\mu < M_{0,2}$): agravity can be neglected and we recover the SM
$\rightarrow m$ is the only mass parameter and we do not see any large corrections to it

[Salvio, Strumia (2014)], *[Kannike, Pizza, Racioppi, Raidal, Salvio, Strumia (2015)]*

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

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

$m^2 \sim \bar{M}_{\rm Pl}^2 g^2$, naturalness $\rightarrow$ $f_2, f_0(1+6\xi_H)^{1/4} \sim \sqrt{\frac{4\pi m}{M_{\rm Pl}}} \sim 10^{-8}$

These *ultraweak couplings* are preserved by the RGE even for $f_0 \gtrsim 10^{-5}$
by staying close to the conformal value $\xi_H = -1/6$

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3) *Large energies* ($\mu > \bar{M}_{\rm Pl}$): in the perturbative CW-like mechanism we have

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

$$\to \quad \lambda_{HS} \sim 10^{-32}$$

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

[Salvio, Strumia (2014)], *[Kannike, Pizza, Racioppi, Raidal, Salvio, Strumia (2015)]*

Natural dynamical generation of the weak scale

Note that the Higgs naturalness ($f_2 \ll 1$) implies a subplanckian ghost
$\rightarrow$ there could be observable predictions from inflation

Black holes

Once $\bar{M}_{\rm Pl}$ is generated we have a gravity Lagrangian

$$\mathscr{L}_{\rm gravity} = \frac{R^2}{6f_0^2} + \frac{\frac{1}{3}R^2 - R_{\mu\nu}^2}{f_2^2} - \frac{\bar{M}_{\rm Pl}^2}{2}R$$

which predicts other black holes solutions besides those of Einstein gravity

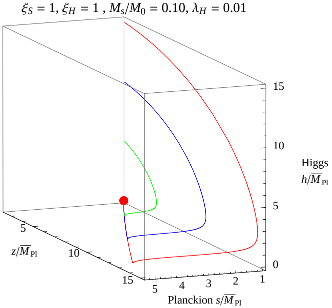
(see Stelle's talk)

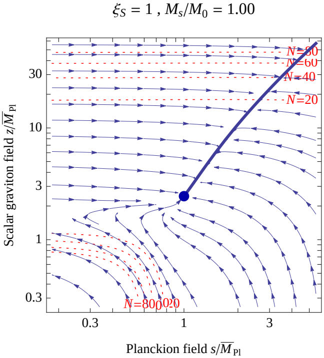
and other horizonless solutions

(see Holdoms talk)

Predictions for inflation: inflationary classical path

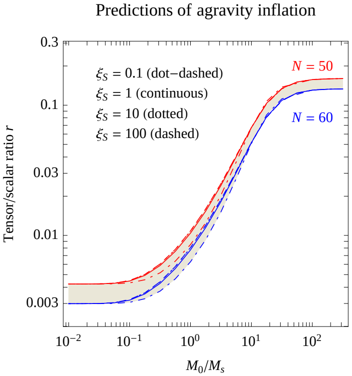
Take 3 scalars: h, s and "a graviscalar" z (from R^2-term)

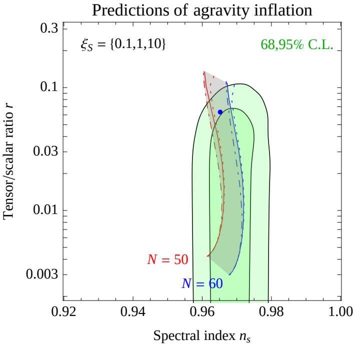




[Kannike, Pizza, Racioppi, Raidal, Salvio, Strumia (2015)]

Predictions for inflation ($M_2 > H$)





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

[Kannike, Pizza, Racioppi, Raidal, Salvio, Strumia (2015)]

Predictions for inflation ($M_2 < H$, compatibly with Higgs naturalness)

The only modifications:

- r gets suppressed

$$r \to \frac{r}{1 + \frac{2H^2}{M_2^2}}$$

  models that are excluded because have large r (e.g. quadratic inflation) can then become allowed
- There is an isocurvature mode (which fullfils the observational bounds) corresponding to the scalar component of the spin-2 ghost (the vector components and the other tensor component decay with time)

Indeed,

- $P_{\mathcal{R}}$ is not changed by the ghost (so n_s is not changed either)
- while the tensor power spectrum is modified:

$$P_t \to \frac{P_t}{1 + \frac{2H^2}{M_2^2}}$$

- The isocurvature power spectrum P_B is the same as the tensor power spectrum in Einstein's gravity, except that it is smaller by a factor of $3/16 \approx 1/5$:

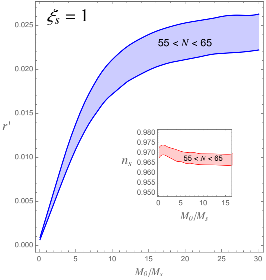
$$P_B = \frac{3}{2\bar{M}_{\rm Pl}^2}\left(\frac{H}{2\pi}\right)^2$$

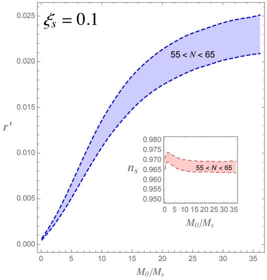
  and the correlation $P_{\mathcal{R}B}$ is highly suppressed

[Ivanov, Tokareva (2016)], *[Salvio (2017)]*

Ghost-isocurvature power spectrum ($M_2 < H$)

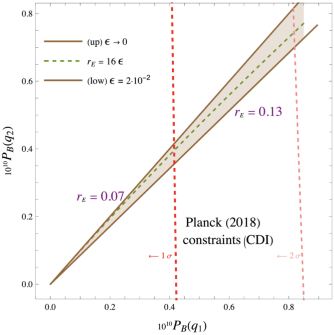
Defining $r' \equiv \dfrac{P_B}{P_{\mathcal{R}}}$





$q_1 = 0.002\ \text{Mpc}^{-1}$ and $q_2 = 0.1\ \text{Mpc}^{-1}$.

The strongest constraints from *Planck (2018)* have been taken



[Salvio (2017) + work in progress]

CSI, Dark Matter (DM) and neutrinos

In one way or another a dark sector is introduced. e.g.

Perturbatively one adds a scalar s whose quartic should decrease with energy somewhere $\rightarrow$ extra fermions,
The lightest fermion can be DM: fermions ψ have an associated $\psi \rightarrow -\psi$ symmetry that keeps the lightest fermion stable.

CSI and DM will be discussed e.g. in the talks by *Iso and Teresi*

Right-handed neutrinos in CSI will be discussed in the talks by *Brdar and Helmboldt*

Summary of the overview

- CSI provides
  1. a dynamical origin for all masses via dimensional transmutation
  2. naturally flat inflationary potentials if the theory is perturbative (we have seen a gravitational extension of the CW mechanism)
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- Right-handed neutrinos can be included and DM can be explained
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- However, there are quantizations that render the Hamiltonian bounded from below and preserve unitarity

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- However, there are quantizations that render the Hamiltonian bounded from below and preserve unitarity
- Naturalness imply that the ghost is below 10^{12} GeV and can, therefore, be tested with inflationary data
- The theory is in good agreement with data and predict **a new (gravitational) isocurvature mode which can be tested**.

Thank you very much for your attention!