

Title: UV-complete relativistic field theories and softened gravity

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Abstract: A field theory is fundamental if it features a UV fixed point (either trivial or interacting). Gravity may not change drastically the UV behavior if the Einstein gravitational interactions are softened above a critical sub-Planckian energy scale. A concrete implementation of this softened gravity can be obtained by adding terms quadratic in the curvature to the Einstein-Hilbert action. One way to implement this scenario consists in requiring that all matter couplings flow to zero at infinite energy (total asymptotic freedom). More generally, some of the couplings flow to zero, while others approach interacting fixed points. The requirement of having a fundamental field theory can have important implications for particle physics phenomenology.

The Standard Model (SM) and its needed extensions

The SM is very successful but it has certainly to be extended:

e.g. it does not include gravity and does not (completely) account for

- ▶ Neutrino Oscillations
- ▶ Dark Matter (DM)
- ▶ Baryon Asymmetry of the Universe (BAU)

Many ideas to address these issues have been proposed and it is difficult to find scientific criteria to select the right path

→ Models valid up to infinite energy

One way to ameliorate this situation:

construct models for the largest possible energy range and address the highest number of SM issues (much more selective than considering these issues separately)

This implies that not only collider bounds, but also observational cosmological/astrophysical bounds should be taken into account

Theoretical motivations for UV-complete field theories

Can a relativistic field theory hold up to infinite energy and be phenomenologically viable?

- ▶ Very important to understand nature at a more fundamental level
- ▶ Even if we obtained a negative answer, we would still gain some precious information: excluding a well-motivated and theoretically appealing framework is valuable

Fundamental field theories

We are confident that a field theory is truly fundamental if

- ▶ All couplings flow to zero at infinite energy (total asymptotic freedom, TAF, CAF, FAF, ...):
similarly to what happens in QCD, but extended to *all* fundamental interactions
- ▶ Or all couplings flow to an interacting fixed point: total asymptotic safety (TAS)
- ▶ Or, *more generally*, some couplings flow to zero and others to an interacting fixed point, henceforth total asymptotic freedom/safety (TAFS)

Recently, examples of TAS and TAFS theories were found with perturbation theory or resummation technique: e.g. [Litim, Sannino (2014)], [Mølgaard and Sannino (2016)], [Abel, Sannino (2014)], [Bond, Hiller, Kowalska, Litim (2017)], [Mann, Meffe, Sannino, Steele, Wang, Zhang (2017)], [Pelaggi, Plascencia, Salvio, Sannino, Smirnov, Strumia (2017)]

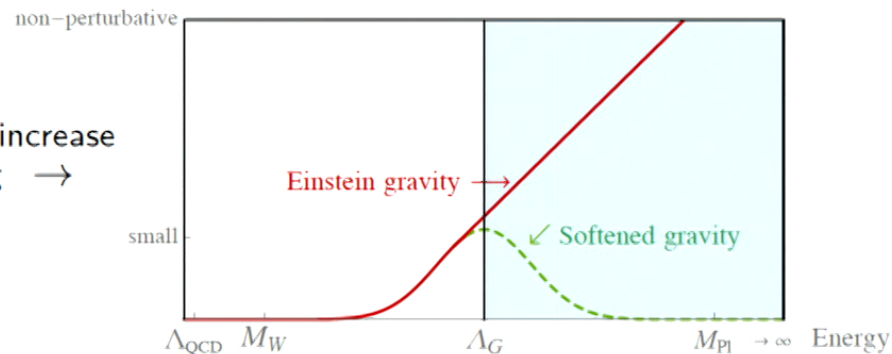
The phenomenology of this new class of theories is a very interesting target for the future

Is the TAFS programme compatible with gravity?

(Einstein) gravitational interactions increase with energy

Idea (*softened gravity*):

consider theories where the increase of the gravitational coupling \rightarrow stops at some $\Lambda_G \ll M_{\text{Pl}}$.



Within softened gravity one can also have the gravitational contribution to the Higgs mass under control:

$$\delta M_h^2 \approx \frac{G_N \Lambda_G^4}{(4\pi)^2}$$

Requiring naturalness $\rightarrow \Lambda_G \lesssim 10^{11} \text{ GeV}$

[Giudice, Isidori, Salvio, Strumia (2014)]

▶ An example of softened gravity can be obtained by adding terms quadratic in the curvature to the Einstein-Hilbert action (*quadratic gravity*) [Salvio, Strumia (2014)]

Quadratic gravity scenario

The general quadratic gravity Lagrangian:

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

where

- ▶ \mathcal{L}^{EH} is the Einstein-Hilbert piece
- ▶ \mathcal{L}^{SM} is the SM \mathcal{L} (plus $-\xi_H |H|^2 R$):
- ▶ \mathcal{L}^{BSM} describes BSM physics.

In general $\mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{BSM}}$ includes $-\xi_{ab}\phi_a\phi_b R/2$ involving the scalars ϕ_a

Gravitational RGEs

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

\Rightarrow - f_2^2 is asymptotically free for $f_2^2 > 0$ (no problem with $f_2^2 > 0$)
- f_0^2 is asymptotically free only for $f_0^2 < 0$
(corresponds to a tachyonic scalar with squared mass $M_0^2 = f_0^2 \bar{M}_{\text{Pl}}^2$)

Asymptotic safety can save us

[*Salvio, Strumia (2017)*] showed that, when f_0 grows up to infinity in the infinite energy limit, f_0 does not hit any Landau pole, provided that

- ▶ All scalars have asymptotically Weyl-invariant ($\xi_{ab} = -\delta_{ab}/6$) couplings
- ▶ All other couplings approach fixed points

Then, quadratic gravity can flow to a Weyl-invariant theory, a.k.a. conformal gravity, at infinite energy.

Ghost issues

The fluctuations around the Minkowski vacuum includes a spin-2 ghost with mass

$$M_2 \equiv \frac{f_2 \bar{M}_{\text{Pl}}}{\sqrt{2}}$$

It is a manifestation of the Ostrogradsky theorem for Lagrangians that depend non-degenerately on the second derivatives: the classical Hamiltonian is not bounded from below

▶ The quantum Hamiltonian can be bounded from below if an **indefinite** metric on the Hilbert space is introduced, with probabilistic issues

Two possible solutions

- ▶ *[Lee-Wick idea (1969)]*: the ghost, being unstable, does not appear as an asymptotic state. *[Anselmi, Piva (2017)]* claimed that the theory is unitary if the ghost propagator is prescribed appropriately:

$$\text{Euclidean propagator} = \lim_{\substack{\varepsilon \rightarrow 0 \\ \text{done at the end}}} \frac{p^2 + M_2^2}{(p^2 + M_2^2)^2 + \varepsilon^4}$$

- ▶ The existence of an indefinite metric does not preclude the existence of positive metrics too. For any self-adjoint operator with a complete set of eigenstates one can always define a positive metric (there can be different metrics for observables that do not commute with each other): see e.g. *[Salvio (2018)]*

Introduction: why field theories valid up to infinite energy

What about gravity?

Particle Phenomenology of UV-complete field theories

Conclusions

TAFS phenomenology

In order to eliminate the Landau poles or run into a non-perturbative regime so far we needed to avoid U(1) gauge factors (obvious in the TAF case)

→ explanation of the electric charge quantization

(we will discuss the more general TAFS case later)

We find 2 options: $SU(4)_{PS} \times SU(2)_L \times SU(2)_R$, $SU(3)_C \times SU(3)_L \times SU(3)_R$

that, unlike SU(5) and SO(10), are not severely constrained by proton decay

→ $M_{NP} \sim \text{TeV}$ (compatibly with naturalness)

▶ TAFS natural models that predict new physics at the LHC and/or future colliders have been found!

W_R , Z' , H' , etc

[Giudice, Isidori, Salvio, Strumia (2014); Pelaggi, Strumia, Vignali (2015)]

A Pati-Salam TAF model

| | 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 |

How to realize the more general TAFS scenario?

Typically an interacting fixed point occurs for non-perturbative couplings

To have perturbative control we added a very large number N_F of extra fermions and expanded in $1/N_F$ (for a fixed value of $N_F \times (\text{gauge coupling})^2$)

An infinite number of Feynman diagrams contribute in this case and one needs to resum them

However, the lattice should allow us to check and extend these results

Resummation for the gauge β -functions

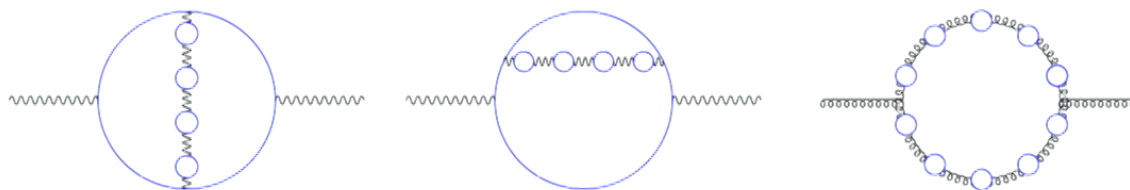
If the N_F fermions are in a non-trivial representation R_i of the gauge group factor G_i

$$\frac{\partial \alpha_i}{\partial \ln \mu} = \beta_{\alpha_i} = \beta_{\alpha_i}^{\text{SM}} + \beta_{\alpha_i}^{\text{extra}}$$

$$\beta_{\alpha_i}^{\text{extra}} = \frac{\alpha_i^2}{2\pi} \Delta b_i + \frac{\alpha_i^2}{3\pi} F_i(\Delta b_i \frac{\alpha_i}{4\pi}) + \mathcal{O}(1/N_F), \quad \text{with} \quad \Delta b_i = \frac{4}{3} N_F S_{R_i},$$

where S_{R_i} is the Dynkin index of R_i and F_i were computed in

[Palanques-Mestre, Pascual (1984)]



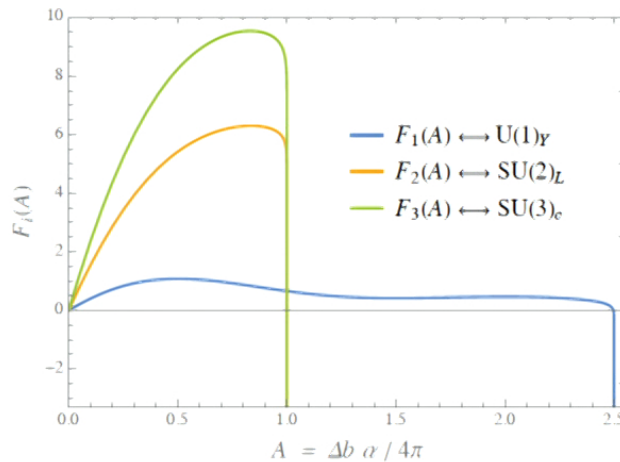
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where S_{R_i} is the Dynkin index of R_i



$$F_1(A) \xrightarrow{A \rightarrow 5/2} \frac{14}{15\pi^2} \ln \left(1 - \frac{2A}{5} \right) + 0.611 + \dots,$$

$$F_n(A) \xrightarrow{A \rightarrow 1} \frac{n}{8} \ln(1 - A) + \dots \quad (n = 2, 3)$$

Resummation for Yukawa β -functions

[Kowalska, Sessolo (2017)]

[Pelaggi, Plascencia, Salvio, Sannino, Smirnov, Strumia (2018)]

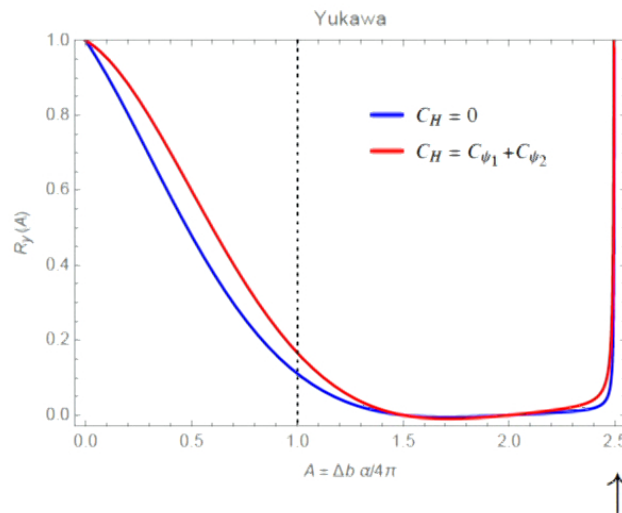
Consider $y \psi_1 \psi_2 H + \text{h.c.}$, where $\psi_{1,2}$ are Weyl fermions and H is a scalar

$$\frac{\partial y}{\partial \ln \mu} = \beta_y = -3 \frac{y}{4\pi} \sum_i (C_{\psi_1 i} + C_{\psi_2 i}) \alpha_i \times R_y(A_i) + \mathcal{O}(y^3)$$

where $C_{\varphi i}$ is the quadratic Casimir of φ under G_i .

For a $U(1)$ one has $C_\varphi = q_\varphi^2$, where q_φ is the charge of φ

The well known $\mathcal{O}(y^3)$ terms are not affected by the resummation



$$R_y(1) = \frac{1}{18} \left(2 + \frac{C_H}{C_{\psi_1} + C_{\psi_2}} \right),$$

$$R_y(A) \stackrel{A \rightarrow 5/2}{\simeq} \frac{9 + 10 q_{\psi_1} q_{\psi_2} / (q_{\psi_1}^2 + q_{\psi_2}^2)}{270 \pi^2 (5/2 - A)}$$

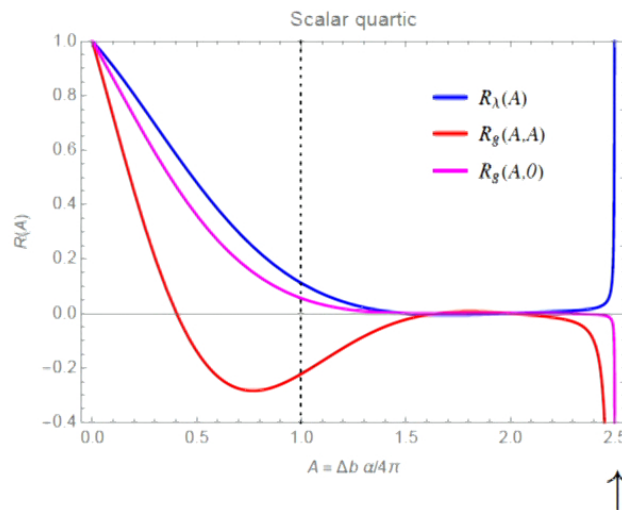
*pole for the Yukawa β -function (coincides with the Abelian gauge fixed point);
 y is then driven to zero*

Resummation for the β -functions of scalar quartic couplings λ

[Pelaggi, Plascencia, Salvio, Sannino, Smirnov, Strumia (2018)]

$$\frac{\partial \lambda}{\partial \ln \mu} = \beta_\lambda = -\frac{\lambda}{4\pi} \sum_i C_i \alpha_i R_\lambda(A_i) + \sum_{ij} C_{ij} \alpha_i \alpha_j R_g(A_i, A_j) + \mathcal{O}(\lambda^2, \lambda y^2, y^4),$$

where C_i and C_{ij} are the well known one-loop β -function coefficients and $\mathcal{O}(\lambda^2, \lambda y^2, y^4)$ is not changed by the resummation if the y s are not many



location of poles (coincides with the Abelian gauge fixed point)

$$R_\lambda(A) \simeq -\frac{2}{135\pi^2 (A - 5/2)} + \dots,$$

$$R_g(A, 0) \simeq \frac{1}{270\pi^2 (A - 5/2)} + \dots$$

$$R_g(A, A) \simeq -\frac{1}{108\pi^2 (A - 5/2)^2} + \dots$$

λ is driven to non-perturbatively large values in the presence of U(1) gauge factors

Conclusions and summary

- ▶ SM extensions valid up to infinite energy allow us
 - ▶ to reduce the arbitrariness we often encounter in model building
 - ▶ to address one of the more fundamental questions: can a relativistic field theory hold up to infinite energy?

- ▶ One of the major obstacles is gravity
 - ▶ One can *assume* generically that gravity gets softened above a subplanckian energy scale
 - ▶ An explicit relativistic field theoretic example of such a softened gravity is quadratic gravity

- ▶ Given that relativistic field theories with UV fixed points (TAFS) are theoretically appealing the study of their phenomenology is interesting
 1. TAF models
 2. TAFS models (more general)

THANK YOU VERY MUCH FOR YOUR ATTENTION!

