Matter matters in Asymptotically Safe gravity

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Trieste, Italy

21$^{\text{st}}$ January 2014

based on
arXiv: 1311.2898 [hep-th]
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Outline of the talk:

- Motivation
- Brief introduction to Asymptotic Safety
- Does Matter matter in Asymptotic Safety?
- Conclusions

Motivation

Matter in Quantum Gravity

- usually ignored or not dynamical
- the addition of matter d.o.f. could alter the properties of the theory

  e.g. Yang-Mills theory with too many fermions

Matter in the AS scenario

- straightforward inclusion of matter d.o.f.
- quantum gravity fluctuations generate matter interaction
- compatibility with particle physics models?
- a test for quantum gravity!

Introduction to Asymptotic Safety I

Perturbative Quantum Gravity is non renormalizable

- at one loop level with matter ['t Hooft and Veltman, 1974]
- at two loops level pure gravity [Goroff and Sagnotti, 1986]

Maybe gravity is Asymptotically Safe! [Weinberg, 1976]

- A nontrivial fixed point exists for the underlying renormalization group (RG) flow of gravity

Fixed Points

- Definition

  - a point (g_i^*) in theory space where all couplings stop running ($\beta_i(g_i^*) \equiv 0$)

  - the usual definition to dimensionful coupling is extended

- Properties

  - well defined (no divergences)

  - finite dimensional UV critical surface

- Recover GR in the IR Limit

  - RG-trajectories have intervals where GR is a good approximation

Introduction to Asymptotic Safety II

Perturbative Quantum Gravity is non renormalizable

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Maybe gravity is Asymptotically Safe! [Weinberg, 1976]

- A nontrivial fixed point exists for the underlying renormalization group (RG) flow of gravity
- Calculability improved in the early '90s with the use of *effective average action* [Reuter and Wetterich, 1994]

Functional Renormalization Group Approach

- The main ingredient is the Effective Average Action Γ_k
  - *$k \to 0$: usual effective action*
- Addition of regulator or cutoff R_k term
  - *implement the coarse grain*
  - *suppression factor for the fluctuations with momenta lower than k*
- The Effective Average Action satisfies the Wetterich equation:

$$\partial_t \Gamma_k = \frac{1}{2} \mathrm{STr} \frac{\partial_t \mathcal{R}_k}{\Gamma_k^{(2)} + \mathcal{R}_k}$$

Introduction to Asymptotic Safety III

Perturbative Quantum Gravity is non renormalizable

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- A nontrivial fixed point exists for the underlying renormalization group (RG) flow of gravity
- Calculability improved in the early '90s with the use of *effective average action* [Reuter and Wetterich, 1994]
- More than two decades of work contributed to find evidence of the existence of a non-Gaussian FP with different truncations.

Which truncations?

Einstein-Hilbert truncation

$R^2 C^2$ truncation

$f(R)$ truncation

$\vdots$ $\qquad \dots$

$R^3 \qquad C_{\mu\nu}^{\rho\sigma} C_{\rho\sigma}^{\gamma\delta} C_{\gamma\delta}^{\mu\nu} \qquad R\Box R \qquad +7$ more

$R^2 \qquad C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} \qquad R_{\mu\nu} R^{\mu\nu}$

R

1

Does Matter matter in AS?

Our truncation is given by

$$\Gamma_k = \Gamma_{\rm EH} + S_{\rm gf} + S_{\rm gh} + \Gamma_{\rm matter}$$

- Einstein-Hilbert Action with the standard gauge fixing and ghosts
- Massless minimally coupled matter and gauge fields (N_S, N_D, N_V)

  fermions $\longrightarrow$ *tetrads formulation, symmetric gauge fixing, no* $O(4)$ *ghosts*

  gauge fields $\longrightarrow$ *belian, no mixing between gauge and diffeo ghosts*
- For a consistent closure of the β-functions graviton and matter anomalous dimensions are needed

The method

FRG techniques

- Background Field Method

  - *gauge invariance of the Effective Action* Γ

  - *meaningful distinction between high and low momentum quantum fluctuations*

  - *background independence achieved by keeping the background field general*

The main novelty

- Computation of anomalous dimensions
  $\eta_\Phi = -\partial_t \ln Z_\Phi \qquad \Phi = (h, c, S, D, V)$
- two points functionals on a flat background

Combined with the computation for $\partial_t \tilde{G}$ and $\partial_t \tilde{\Lambda}$

- spherical background
- keeping into account all the anomalous dimensions

One loop analysis

- Neglect anomalous dimensions
- Expand β-functions to first order in $\tilde{\Lambda}$

$$\begin{aligned} \beta_{\tilde{G}} &= 2\tilde{G} + \frac{\tilde{G}^2}{6\pi}\left(N_S + 2N_D - 4N_V - 22\right), \\ \beta_{\tilde{\Lambda}} &= -2\tilde{\Lambda} + \frac{\tilde{G}}{4\pi}\left(N_S - 4N_D + 2N_V + 2\right) \\ &\quad + \frac{\tilde{G}\tilde{\Lambda}}{6\pi}\left(N_S + 2N_D - 4N_V + 8\right). \end{aligned}$$

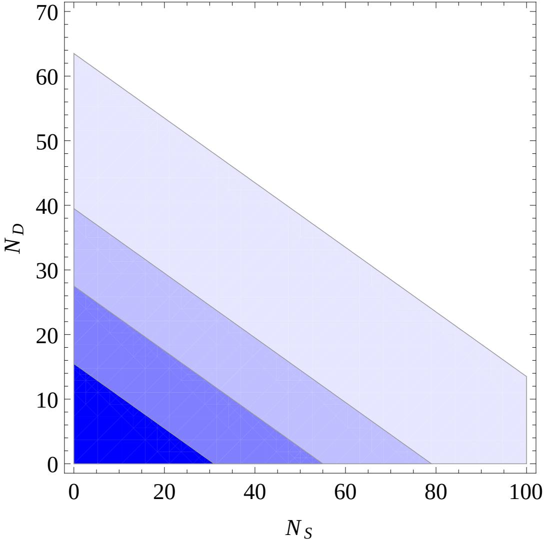
- red numberanalyzes encode the effect of gravitons and ghosts
- we can study the problem analytically
- we analyze the effect of matter in this approximation

There is a non-Gaussian fixed point

$$
\begin{aligned}
\tilde{\Lambda}_* &= -\frac{3}{4}\frac{N_S - 4N_D + 2N_V + 2}{N_S + 2N_D - 4N_V - 7}\,, \\
\tilde{G}_* &= -\frac{12\pi}{N_S + 2N_D - 4N_V - 22}\,.
\end{aligned}
$$

- We require the positivity of $\tilde{G}_*$

  $N_S + 2N_D - 4N_V - 22 < 0$
- There are divergences. We consider the region of fixed points connected with the "no matter" one.
- The critical exponents are both positive in the allowed region



Allowed region with 0, 6, 12, 24 gauge fields

Results for the full system

Selection criteria (continuous deformation of the fixed point without matter)

- we require $\tilde{G}_* > 0$
- discard fixed points with less than two relevant directions
- rule out "too large" critical exponents (≈ 20 - optional)

Anomalous dimension and predictivity (critical exponents at the FP and anomalous dimension)

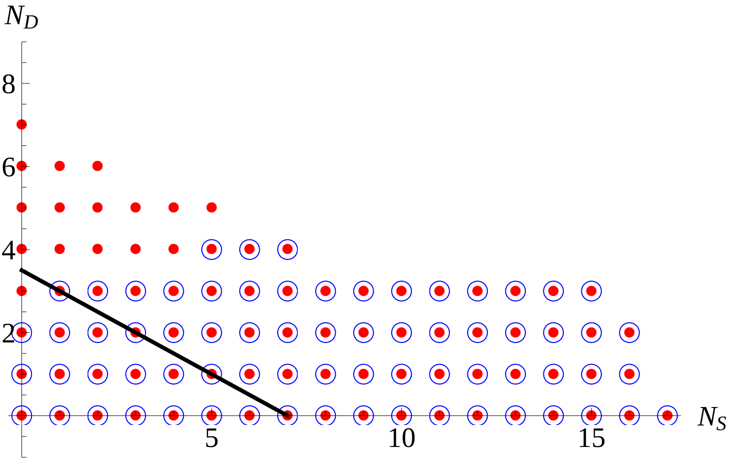
For a term $\mathcal{O} \equiv g_{\mathcal{O}} \Phi^n$

$$\theta_{\mathcal{O}} = -\left(-d + n d_\Phi + \frac{n}{2}\eta_\Phi\right) + \ldots \to \eta_\Phi > -2d_\Phi$$

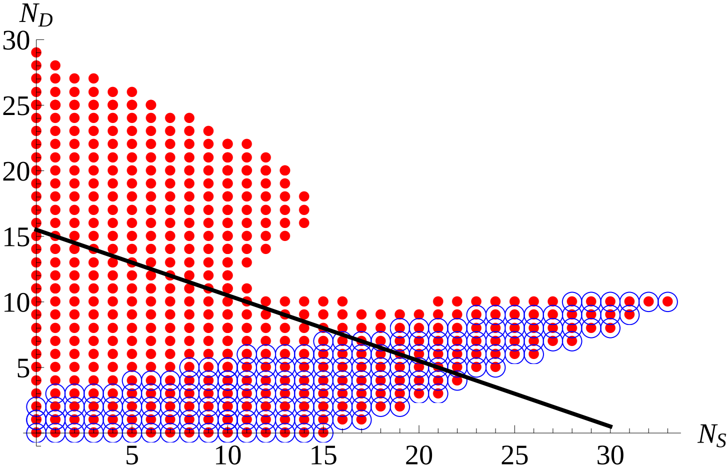
For the graviton $\eta_h > -\frac{d+2}{2}$ is an additional requirement on the fixed point!

Effects of matter

- Scalar fields $\rightarrow \tilde{G}_*$ to smaller values and $\tilde{\Lambda}_*$ to larger positive values
  - *critical number of scalar fields*
  - *strong increase on the critical exponents*
- Fermion fields $\rightarrow \tilde{G}_*$ to larger values and $\tilde{\Lambda}_*$ to larger negative values
  - *critical number of fermion fields*
  - *small effect on the critical exponents*
- Vector fields $\rightarrow \tilde{G}_*$ to smaller values and $\tilde{\Lambda}_*$ to larger positive values
  - *no maximal number of vector fields but predictivity might not be preserved*



Allowed region with 0 gauge fields



Allowed region with 12 gauge fields

Specific matter models

Disclaimer:

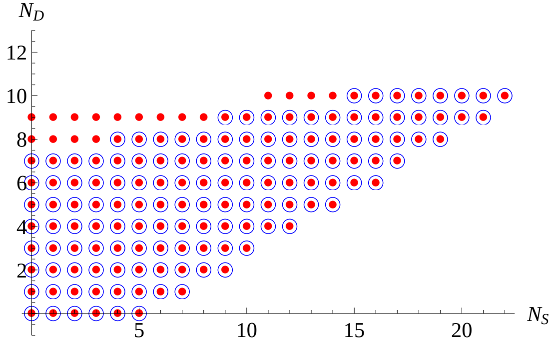
1. particular truncation
2. neglecting matter self interaction
3. all the gauge fields are abelian

Model	N_S	N_D	N_V	$\tilde{G}_*$	$\tilde{\Lambda}_*$	θ_1	θ_2	η_h
no matter	0	0	0	1.45	-0.008	3.08	1.55	0.07
SM	4	45/2	12	5.34	-7.03	3.90	1.95	-34.90
SM +dm scalar	5	45/2	12	6.32	-8.19	3.90	1.95	-40.87
SM+ 3 ν's	4	24	12	8.26	-11.90	3.90	1.98	-53.33
SM+3ν's + axion+dm	6	24	12	15.38	-21.57	3.90	1.99	-97.33
MSSM	49	61/2	12	-	-	-	-	-
SU(5) GUT	124	24	24	-	-	-	-	-
SO(10) GUT	97	24	45	-	-	-	-	-

- SM and extensions are compatible with a Gravitational FP
- large η_h means predictivity needs to be examined carefully

Higher dimension

- Extra dimensions are not required in Asymptotic Safety scenario of pure gravity but compatible
- For $d = 5$, 6 the Standard Model matter d.o.f. are incompatible with a viable gravitational fixed point



F.P. in $d = 5$ and 12 gauge fields.

Dynamical Quantum Gravity scale

- In QCD quantum fluctuations lead to the dynamical generation of Λ_{QCD}
- A quantum-gravity scale will emerge dynamically

  - transition scale to the fixed-point regime

  - the dimensionful Newton coupling passes from being constant to a scale-free regime in which $G(k^2) \sim \frac{1}{k^2}$

  - was found to be close to the Planck scale in previous studies with the Einstein-Hilbert truncation[1]
- Matter fluctuations change the scale:

  - scalars seem to have little effect on the transition scale

  - fermions shift this scale towards larger values

[1] M. Reuter and H. Weyer, JCAP **0412**, 001 (2004)

Conclusions

- Compatibility of matter degrees of freedom with the Asymptotic Safety scenario for gravity

  - effect of scalar, fermionic and abelian gauge field fluctuations on the existence of an interacting fixed point

  - anomalous dimensions of the quantum fluctuations were included

  - a new criterion on the anomalous dimensions relying on predictivity of the theory

  - upper limits on the allowed number of scalar, fermionic and vector degrees of freedom

- Focusing on particular models
  - *Standard Model matter content is compatible with the existence of a NGFP*
  - *observationally motivated extensions are compatible too*
  - *the other models are not*
- Going to larger dimension
  - *the allowed region shrinks*
  - *no more compatibility with the SM*
- Effect of matter degrees of freedom on the quantum gravity scale
  - *the quantum gravity scale may be farther than we expect*

Thank you!