Towards predictivity in asymptotically safe quantum gravity with matter

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Marc Schiffer, Heidelberg University

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Motivation

- No direct experimental tests of fundamental properties of our universe
- Only consistency tests/retrodictions are possible
- E.g., in String theory: $d = 10$ is the critical dimension of the superstring
- Asymptotic Safety:
  [Weinberg, 1979]
  Quantum properties of spacetime in terms of quantum fluctuations of the metric

Standard Model matter + Asymptotically safe quantum gravity

$\Downarrow$

pre/retrodictions of SM couplings

phenomenological consistency tests

AS: quantum realization of scale symmetry

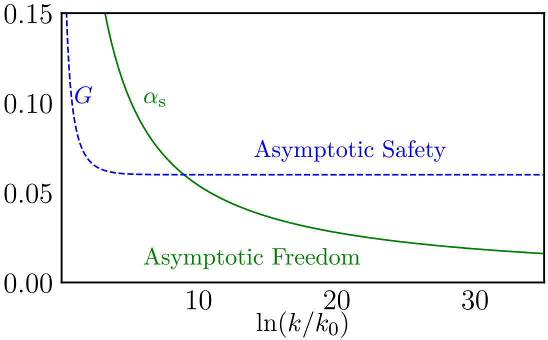
- Classical scale invariance: broken by quantum fluctuations
  - couplings are scale dependent
  - consistency of theory up to arbitrary energies not guaranteed
- Restoration of scale symmetry: inconsistencies are avoided

- Quantum fluctuations vanish asymptotically

$$\beta_{\alpha_s} = -\frac{11}{2\pi}\alpha_s + \mathcal{O}(\alpha_s^3)$$

- Quantum fluctuations balance

$$\beta_G = \varepsilon G - \frac{50}{3}G^2 + \mathcal{O}(G^3)$$

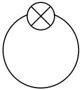


Tool: Functional Renormalization Group

Non-Perturbative Renormalisation Group Equation

[Wetterich, 1993], [Ellwanger, 1993], [Morris, 1994], [Reuter, 1996]

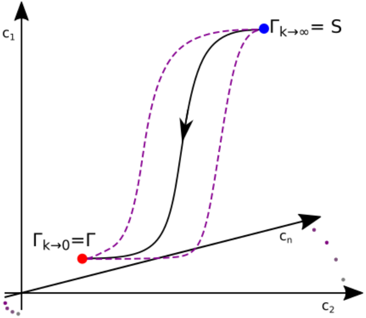
$$k\,\partial_k \Gamma_k = \frac{1}{2}\,\mathrm{STr}\left(\left(\Gamma_k^{(2)} + R_k\right)^{-1} k\,\partial_k R_k\right) = \frac{1}{2}$$



Γ_k = scale dependent effective action

R_k = IR regulator

- exact 1-loop equation
- extract β-functions via projection
- truncation needed $\rightarrow$ not closed
- Euclidean



Critical Exponents

- Linearized β-functions

$$\beta_{g_j} = \beta_{g_j}\Big|_{\mathbf{g}=\mathbf{g}^*} + \sum_i \left(\frac{\partial \beta_{g_j}}{\partial g_i}\right)\Big|_{\mathbf{g}=\mathbf{g}^*} (g_i - g_i^*) + \mathcal{O}\left((g_i - g_i^*)^2\right)$$

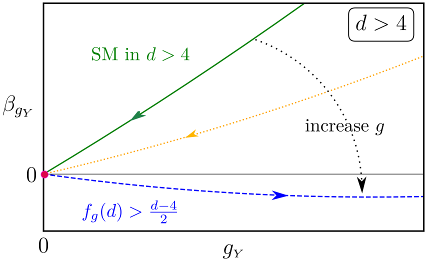
- Solution to linearized flow equations

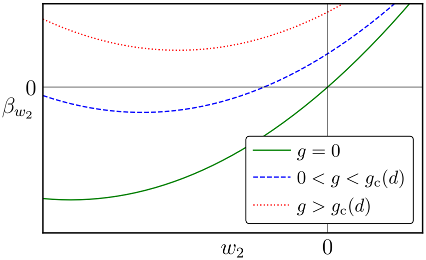
$$g_j(k) = g_j^* + \sum_I c_I V_j^I \left(\frac{k}{k_0}\right)^{-\Theta_I} \quad \text{with} \quad -\operatorname{eig}(M) = \Theta_I\,.$$

$\mathrm{Re}(\Theta_I) < 0$	$\mathrm{Re}(\Theta_I) > 0$
• irrelevant direction	• relevant direction
• c_I drop out for $\frac{k}{k_0} \to 0$	• c_I remain
• **no** free parameter for each irrelevant direction	• **one** free parameter for each relevant direction

Outline: Conditions for UV complete matter sector

- UV completion for marginal couplings
  - Effective dimensionality has to be lowered to below four
  - Strong enough metric fluctuations necessary
  - might lead to pre/retrodictions of SM couplings
- UV completion for induced interactions
  - Strong metric fluctuations trigger new divergences
  - Weak enough metric fluctuations necessary
  - excludes region in gravitational parameter space





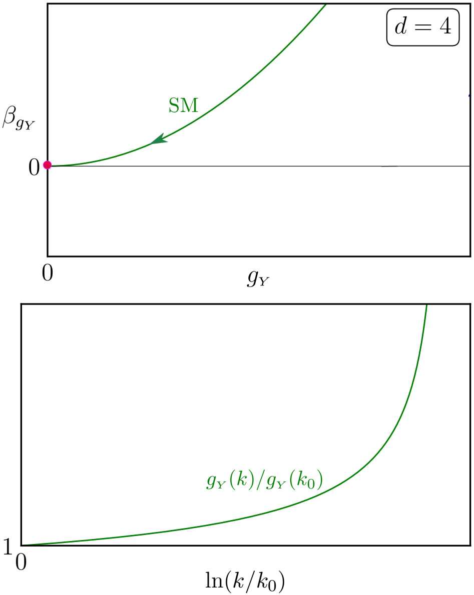
The $U(1)$ sector of the Standard Model

- Quantum fluctuations:
  vacuum is screening

$$k\partial_k g_Y(k) = \beta_{g_Y}\big|_{\mathrm{SM}} = \frac{1}{16\pi^2}\frac{41}{6}g_Y^3 + \mathcal{O}(g_Y^4)$$

- Landau Pole: UV-completion
  requires new physics
  [Gell-Mann and Low, 1954], [Gockeler, Horsley, Linke, Rakow, Schierholz and Stuben, 1998], [Gies and Jaeckel, 2004]

$$g_Y^2(k) = \frac{g_Y^2(k_0)}{1 - \frac{1}{8\pi^2}\frac{41}{6}g_Y^2(k_0)\ln\left(\frac{k}{k_0}\right)}$$

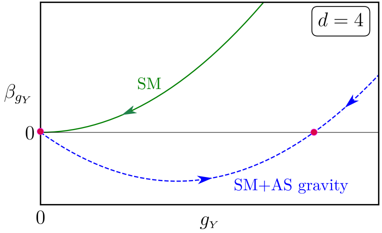


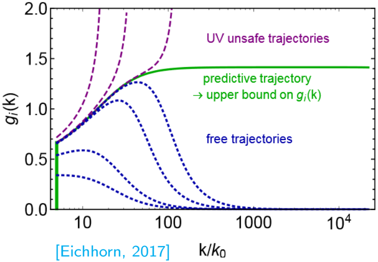
The $U(1)$ sector of the Standard Model with AS quantum gravity

- Under inclusion of AS gravity:

$$\beta_{g_Y} = -f_g g_Y + \frac{1}{16\pi^2}\frac{41}{6} g_Y^3 + \mathcal{O}(g_Y^4)$$

- FRG studies: $f_g \geq 0$ for $g > 0$ (in $d = 4$)
  [Daum, Harst and Reuter, 2009], [Harst and Reuter, 2011], [Folkerts, Litim and Pawlowski, 2011], [Christiansen and Eichhorn, 2017], [Eichhorn and Versteegen, 2017], [Christiansen, Litim, Pawlowski and Reichert, 2017]
  - Antiscreening effect of metric fluctuations
  - Abelian gauge coupling becomes asymptotically free





[Eichhorn, 2017]

In $d = 4$, metric fluctuations might induce a (predictive) UV completion of the SM matter sector. [Shaposhnikov, Wetterich, 2009], [Harst, Reuter, 2011], [Eichhorn, Versteegen, 2017], [Eichhorn, Held, 2017; 2018]

Outline: Conditions for UV complete matter sector

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- UV completion for induced interactions
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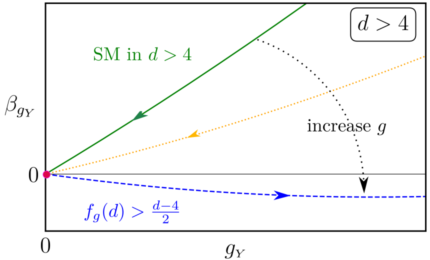
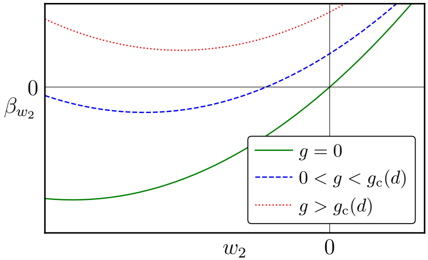


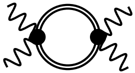


The "weak gravity bound"

- Specifically in asymptotically safe gravity:
  - There exist indications that metric fluctuations must not be too strong.
  - Interacting nature of gravity induces novel interactions in the matter sector.
    [Eichhorn and Gies, 2011], [Eichhorn, 2012], [Meibohm and Pawlowski, 2016], [Eichhorn, Held and Pawlowski, 2016], [Christiansen and Eichhorn, 2017], [Eichhorn and Held, 2017], [Eichhorn, Lippoldt and Skinjar, 2017] [Eichhorn, Lippoldt and MS, 2018], [Eichhorn, Platania and MS, 2019]
  - Beyond the weak-gravity regime, metric fluctuations can induce novel divergences in these interactions.

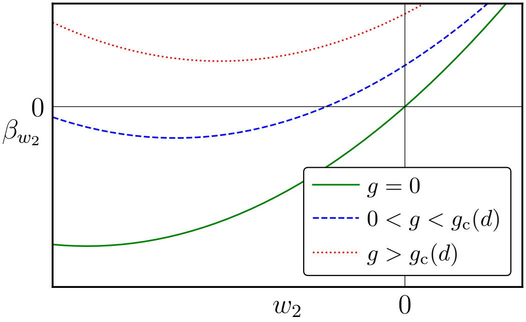
Induced interaction

- Higher order couplings are induced
- Example: Abelian gauge field
  ↳$w_2 F^4$ term is induced



- Schematically:

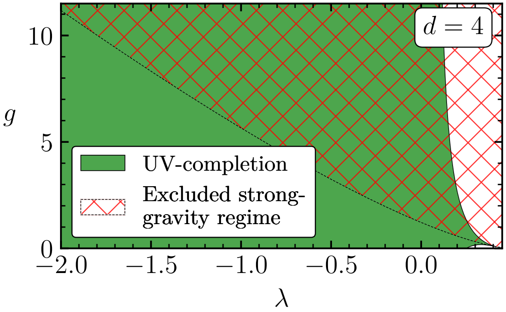
$$\beta_{w_2} = B_0(g) + w_2\, B_1(g) + w_2^2 B_2$$

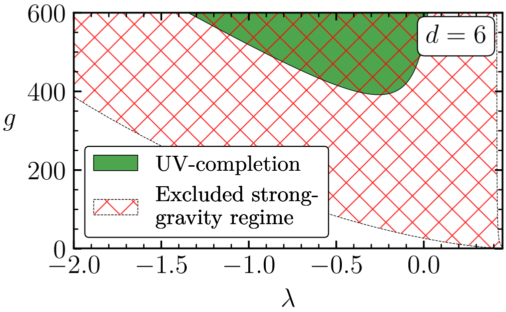


- $\exists$ real FP only for $B_0 \leq \frac{B_1^2(g)}{4B_2}$
- gives rise to *Weak gravity bound*
  [Eichhorn and Gies, 2011], [Eichhorn, 2012]
  [Eichhorn, Held and Pawlowski, 2016],
  [Christiansen and Eichhorn, 2017], [Eichhorn and Held, 2017]

Excluded strong gravity regime

- Evaluate $f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$ and "weak gravity bound" (FRG computations)
- Study explicitly conditions: $f_g(d) > \frac{d-4}{2}$ in weak-gravity regime



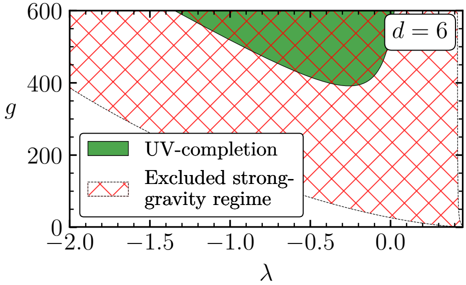


Key Result

$U(1)$ gauge sector remains UV incomplete in $d \geq 6$, even in the presence of gravity.

Summary

- Strong enough metric fluctuations for gravitational solution of Landau pole.
  ↳ Effective dimensionality lowered below four.
- Gravitational fluctuations should remain near-perturbative.
  ↳ Explicitly: Possible new divergences in matter sector.



The predictive power of the asymptotic-safety paradigm covers SM couplings and could extend to fundamental parameters of the geometry.

Thank you for your attention!

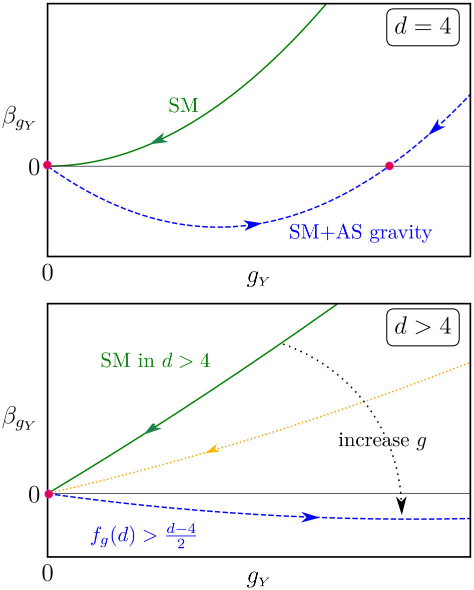
Solution to the triviality problem in $d > 4$

- $[\bar{g}_Y] = \frac{4-d}{2}$

$$\beta_{g_Y} = g_Y \left(\frac{d-4}{2} - f_g(d) \right) + \mathcal{O}(g_Y^3)$$

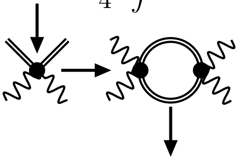
- Competition of $f_g(d)$ with canonical mass term.
- Necessary condition for UV completion:
  Effective dimensionality below four,

$$f_g(d) > \frac{d-4}{2}$$

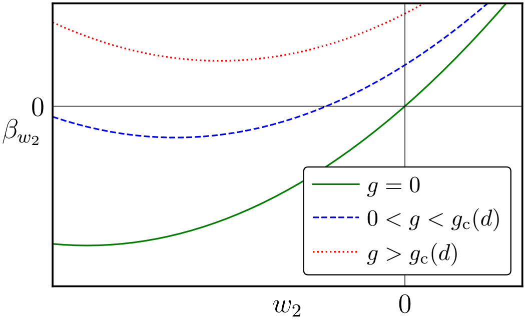


- Example: Abelian gauge field A_μ
  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
  - From kinetic term:

$$S_{\text{kin}} = \frac{Z_A}{4} \int \mathrm{d}^d x \sqrt{g} F_{\mu\nu} F^{\mu\nu}$$



$$S_{\text{int}} = \frac{w_2 k^{-d}}{8} \int \mathrm{d}^d x \sqrt{g} (F_{\mu\nu} F^{\mu\nu})^2$$



- Schematically:

$$\beta_{w_2} = B_0(g) + w_2\, B_1(g) + w_2^2 B_2$$

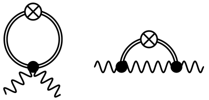
- $\exists$ real FP only for $B_0 \leq \frac{B_1^2(g)}{4B_2}$

Comparison of $f_g(d)$ with $f_{g,\text{crit}}(d)$

- Direct gravitational contribution:

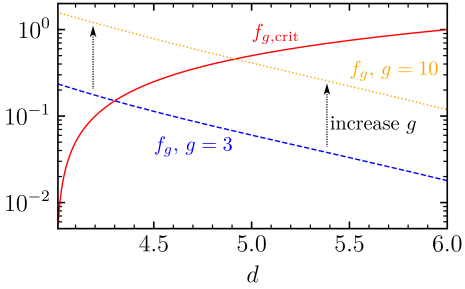
$$f_g = -\frac{\eta_A\big|_{\text{grav}}}{2}$$

- Diagrammatically:



Reminder (with $f_{g,\text{crit}} = \frac{d-4}{2}$):

$$\beta_{g_Y} = g_Y \left(f_{g,\text{crit}} - f_g(d)\right) + \mathcal{O}(g_Y^3)$$



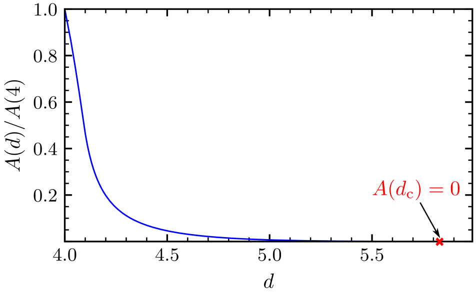
- Opposite behavior of $f_{g,\text{crit}}(d)$ and $f_g(d)$
- Decrease of $f_g(d)$ has to be compensated by increasing g

Key Result

Solution to the triviality problem shifts to more strongly coupled regime for $d > 4$.

UV complete matter sector beyond $d = 4$?

- Area of allowed region for $g \in (0, 1000)$ and $\lambda \in (-1500, 0.5)$.
- Area shrinks to zero at $d_c \approx 5.8$.



- Calculation leading to green and red area: Subject to systematic errors due to truncation.
- Very large deformations necessary to make $d \geq 6$ viable (in explored range).
- Qualitative aspects of the scenario remain unchanged.