How perturbative is quantum gravity?

Asymptotic Safety Online Seminar

November 5th 2018

Marc Schiffer, Heidelberg University

with A. Eichhorn, S. Lippoldt, J. M. Pawlowski and M. Reichert arXiv 1810.02828

Emmy Noether-Programm

DFG Deutsche Forschungsgemeinschaft

Near-Perturbativeness of Quantum Gravity

Technical implications

- Guideline for future truncations
- A posteriori justification of previous truncations
- Application of perturbative methods in transplanckian regime
  $\rightarrow$ provide indications for existence of fixed point
  [M. R. Niedermaier, 2009]

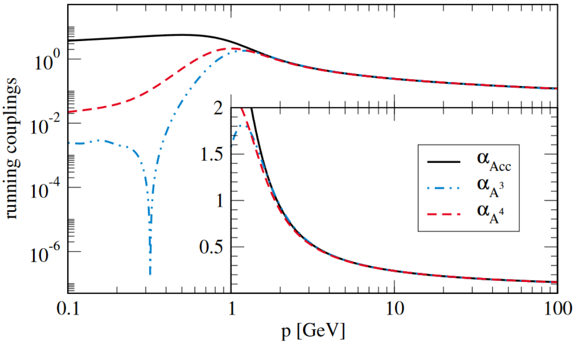
Physical implications

- Asymptotically safe Standard Model favors perturbative nature of fixed point
- Appealing scenario: interactions at high energies
  $\rightarrow$ strong enough to induce asymptotic safety
  $\rightarrow$ near canonical scaling for higher order operators
  [Falls, Litim, Nikolakopolous and Rahmede, 2013]
  [Falls, Litim, Nikolakopolous and Rahmede, 2014]
  [Falls, Litim and Schröder, 2018]

Avatars of a gauge coupling

Non-abelian gauge theories: different incarnations of the gauge coupling!

QCD



[A. K. Cyrol, L. Fister, M. Mitter, J.M. Pawlowski and N. Strodthoff, 2016]

Gravity + Matter

?

$\Downarrow$

Effective Universality at UV fixed point

Avatars of the Newton coupling (I)

Classical level:

$$S = \int d^4x \left[\frac{\sqrt{g}}{G} R + \sqrt{g}\, \bar{\psi} \not{\nabla} \psi \right] \to \Gamma \sim \int d^4x \Big[\Big(h\partial^2 h + \sqrt{G}\; h(\partial h)(\partial h) + \dots \Big) + \Big(\bar{\psi}\partial\psi + \sqrt{G}\; h\bar{\psi}\partial\psi + \dots \Big) \Big]$$

- Linear split: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$
  $\to \sqrt{g}\, R \approx \partial^2 h + h\partial^2 h + h(\partial h)(\partial h) + \mathcal{O}(h^4)$
  $\to \sqrt{g}\, \bar{\psi} \not{\nabla} \psi \approx \bar{\psi} \not{\partial} \psi + h\bar{\psi}\partial\gamma\psi + \mathcal{O}(h^2)$
- Rescale: $h_{\mu\nu} \to \sqrt{G}\, h_{\mu\nu}$

Avatars of the Newton coupling (II)

Quantum level:

$$S = \int \mathrm{d}^4x \left[\frac{\sqrt{g}}{G} R + \sqrt{g}\,\bar{\psi}\nabla\!\!\!/\,\psi\right] \to \Gamma \sim \int \mathrm{d}^4x \Bigg[\left(h\partial^2 h + \sqrt{G_h}\, h(\partial h)(\partial h) + \dots\right)$$

$$+ S_{\text{gf}}(\bar{g}, h) \qquad + \left(\bar{\psi}\partial\psi + \sqrt{G_\psi}\, h\bar{\psi}\partial\psi + \dots\right)\Bigg]$$

- Linear split: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$
  $\to \sqrt{g}\, R \approx \partial^2 h + h\partial^2 h + h(\partial h)(\partial h) + \mathcal{O}(h^4)$
  $\to \sqrt{g}\,\bar{\psi}\nabla\!\!\!/\,\psi \approx \bar{\psi}\partial\!\!\!/\,\psi + h\bar{\psi}\partial\gamma\psi + \mathcal{O}(h^2)$
- Rescale: $h_{\mu\nu} \to \sqrt{G}\, h_{\mu\nu}$
- Quantum level: Introduce gauge fixing $S_{\text{gf}}(\bar{g}, h)$ and Regularization

- analogously for

  ghosts $\to G_c$

  scalars $\to G_\varphi$

  vectors $\to G_A$

(Effective) Universality

- QCD:
  $[\alpha_\mathsf{s}] = 0$
  $\rightarrow$ 2-loop universality
  $\rightarrow$ perturbative regime:
  one gauge coupling

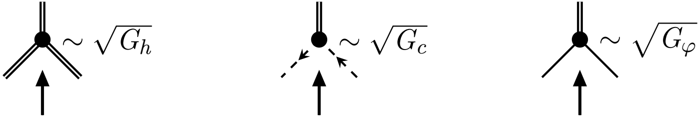
- Gravity:
  $[G_\mathsf{N}] = -2$
  $\rightarrow$ no universality
  $\rightarrow$ gauge symmetry encoded in
  relations for avatars

- **Effective Universality**: semi-quantitative agreement of β-functions
  [A. Eichhorn, P. Labus, J. M. Pawlowski and M. Reichert, 2018]

- Quantify deviation from effective universality:

$$\varepsilon_{ij}(G, \mu, \lambda_3) \sim \left|\beta_{G_i} - \beta_{G_j}\right|_{G_i = G_j = G}$$

- Computation of β-functions: Functional Renormalization Group



$$S = \frac{1}{16\pi G_{\mathrm{N}}} \int \mathrm{d}^4x \sqrt{g}\,(2\Lambda - R) + S_{\textsf{gf,grav}} + S_{\textsf{gh,grav}} + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g} g^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi$$

$$+ \int \mathrm{d}^4x \sqrt{g}\, \bar{\psi} \not{\nabla} \psi + \frac{1}{2} \int \mathrm{d}^4x \sqrt{g}\, g^{\mu\nu} g^{\rho\sigma}\, \mathrm{tr} F_{\mu\rho} F_{\nu\sigma} + S_{\textsf{gf,gauge}} + S_{\textsf{gh,gauge}}$$

Flow equations

- Regularization and gauge fixing:

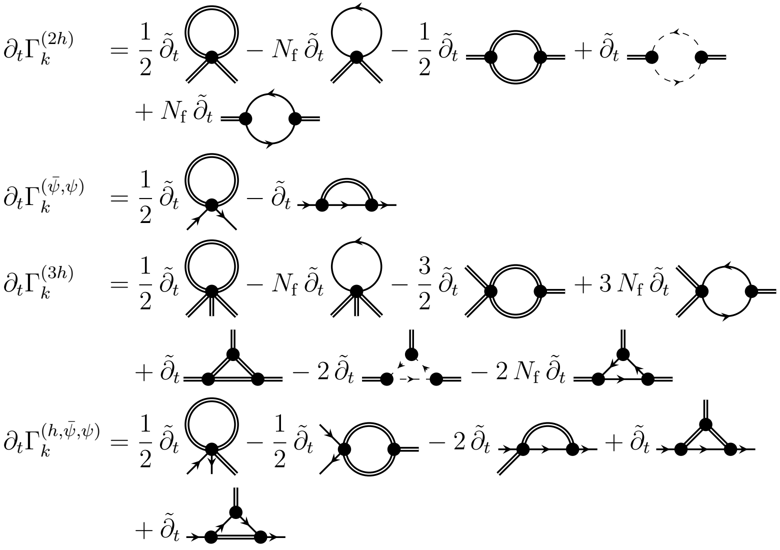
$$\Gamma_k = \Gamma_k[\bar{g}, h, \Phi]$$

- Vertices depend on momentum configuration

$$\Gamma_k^{(n,l)} = \frac{\delta^{n+l}\Gamma_k[\bar{g}, h, \Phi]}{\delta h^n(p_{h_1}, \dots, p_{h_n})\delta\Phi^l(p_{\Phi_1}, \dots, p_{\Phi_1})}$$

- Perform Vertex expansion of $\Gamma_k[\bar{g}, h, \Phi]$ up to three-point level

Diagrammatic representation of vertex flows



Bilocal flow equations

- Flow of graviton-fermion three-point vertex (at momentum symmetric point)

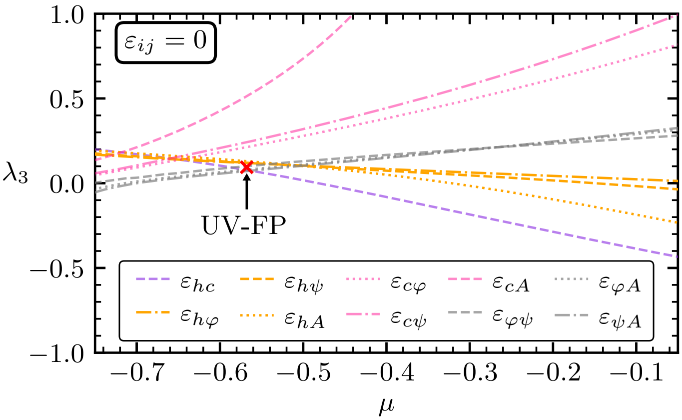
$$\partial_t \left[\sqrt{Z_h(p^2)}\, Z_\psi(p^2) \sqrt{G_\psi(p^2)\, k^{-2}}\, p^2 \right] = \sqrt{Z_h(p^2)}\, Z_\psi(p^2)\, \underbrace{\partial_t \Gamma_k^{(h,\bar\psi,\psi)}(p^2) \Big|_{G_\psi}}_{\text{Flow}^{(h,\bar\psi,\psi)}(p^2)}$$

- Evaluate vertex flows at $p^2 = 0$ and $p^2 = k^2$
- Bilocal flow equation:

$$\beta_{G_\psi} = \left(2 + \frac{1}{2}\eta_h(k^2) + \eta_\psi(k^2) \right) G_\psi + 2\sqrt{G_\psi}\, \text{Flow}^{(h,\bar\psi,\psi)}(k^2)$$

- Analogously for G_h, G_c, G_φ, G_A

Effective Universality



- Pairwise comparison of β-functions
- $\varepsilon_{ij} \sim \left|\beta_{G_i} - \beta_{G_j}\right|$
- $\varepsilon_{ij} = 0$ lines
- Red cross: UV-FP

Key Result

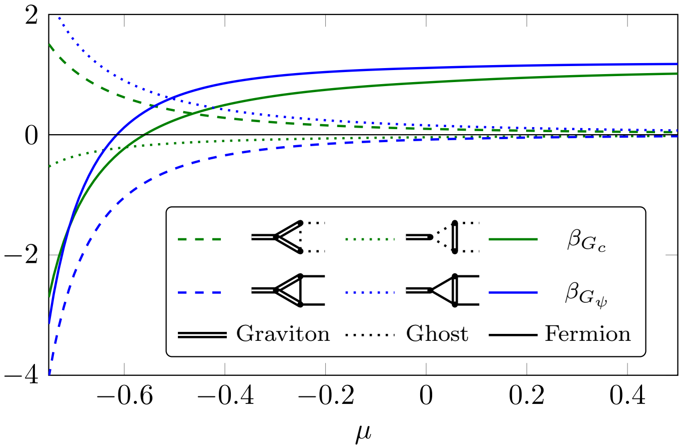
UV-FP lies in symmetry preferred region.

Key Result

$\varepsilon_{ij} = 0$ lines exist for all avatars of the Newton coupling.

Non-trivial cancellations

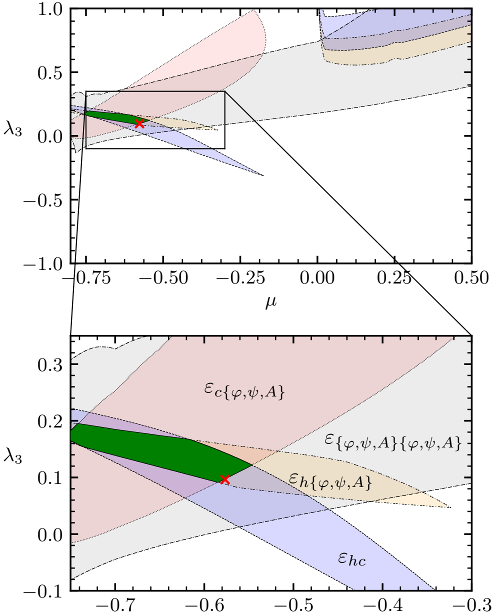
- Compare e.g. β_{G_c} and β_{G_ψ}
- Specific diagrams do not agree
- Full β-functions are similar



Key Result

Only non-trivial cancellations between diagrams lead to effective universality.

Effective Universality at UV Fixed Point



- At UV-FP present:
  - Higher curvature couplings
    [Benedetti, Machado and Saueressig, 2009]
    [Falls, Litim, Nikolakopolous and Rahmede, 2013]
    [Falls, Litim, Nikolakopolous and Rahmede, 2014]
    [Gies, Knorr, Lippoldt and Saueressig, 2016]
    [Christiansen, Falls, Pawlowski, Reichert, 2017]
    [De Brito, Otha, Pereira, Tomaz, Yamada, 2018]
    [Falls, Litim and Schröder, 2018]
  - Non-minimal matter gravity couplings
    [Narain and Percacci, 2009]
    [Percacci and Vacca, 2015]
    [Eichhorn, Lippoldt and Skrinjar, 2017]
  - Matter self-interactions
    [Eichhorn and Gies, 2011], [Eichhorn, 2012]
    [Meibohm and Pawlowski, 2015]
    [Eichhorn, Held and Pawlowski, 2016]
    [Eichhorn and Held, 2017]
    [Christiansen and Eichhorn, 2017]

  $\rightarrow$ systematic error $\delta\varepsilon$
- Lower bound: $\delta\varepsilon \approx 0.2$
  [Meibohm, Pawlowski and Reichert, 2015]
  [Denz, Pawlowski and Reichert, 2016]

Near-Perturbative Quantum Gravity

- Gauge-fixing and regularization:
  fluctuation couplings are related by Slavnov Taylor identities (STIs)
- STIs: sourced by quantum effects
  perturbative limit $\rightarrow$ trivial STIs
  non-perturbative limit $\rightarrow$ non-trivial STIs, e.g. QCD
  [A. K. Cyrol, L. Fister, M. Mitter, J.M. Pawlowski and N. Strodthoff, 2016]
- $\varepsilon_{ij} \approx 0.2 \rightarrow \frac{G_i^*}{G_j^*} \approx 0.7$

  $(G_h^*,\ G_c^*,\ G_\varphi^*,\ G_\psi^*,\ G_A^*) = (0.58,\ 0.55,\ 0.74,\ 0.75,\ 0.84)$

  especially: $\frac{G^*_{\text{min}}}{G^*_{\text{max}}} \approx 0.65$

Key Result

Hint towards near-perturbative nature of asymptotically safe fixed point.

Supression of higher-order operators

- Right-hand side of flow equation: overlap with all operators allowed by symmetry
- E.g. on level of three-graviton coupling: $\sqrt{g}R$ and $\sqrt{g}R_{\mu\nu}R^{\mu\nu}$
- Breaking of diffeomorphism-invariance: difficult to disentangle different contributions
- Assume contamination $\delta\beta_{\mathsf{Ric}}$ to β_{G_h}

$\Rightarrow \varepsilon_{hi} \gtrsim 0.3$

Key Result

$\varepsilon_{ij} \lesssim 0.2$ provides hint for subleading nature of higher order operators.

Summary & Outlook

- Effective universality:
  - hint for physical nature of asymptotically safe fixed point
  - hint for geometric origin of $h_{\mu\nu}$
  - indication for small impact of higher-order operators
  - indication for near-perturbative nature of quantum gravity
- Extend analysis to phenomenologically relevant numbers of scalars, fermions and vector fields