A link that matters: Towards phenomenological constraints on quantum gravity models

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Motivation

Towards Quantum Gravity Phenomenology

How to confront quantum gravity with experiments?

➔ Direct probes seems to be far away from the current technology

➔ Indirect probes might contain some imprints from quantum gravity

- Cosmological observations?
- Astrophysical objects?
- Particle physics experiments?

ASQG and Matter Interactions

A link that matters: From Planck to TeV

Basic idea: Use the RG flow to connect UV fixed points with IR physics

- ➔ UV completion for SM-like couplings?
- ➔ Predicting values at TeV scale?

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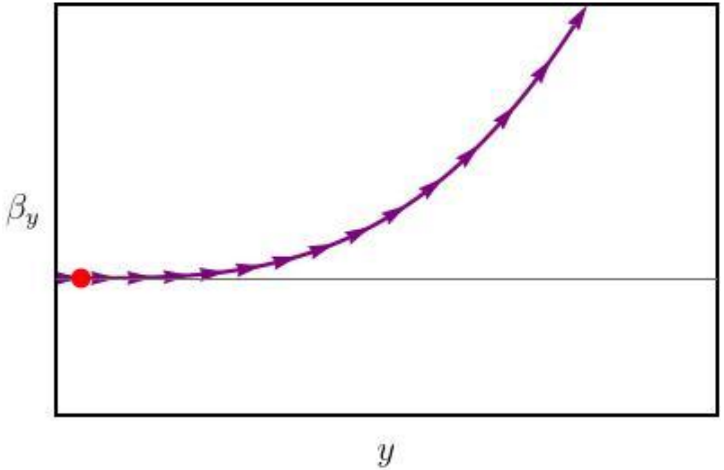
<u>Exemple: Yukawa Interaction</u>

$$\beta_y = \# \, y^3$$



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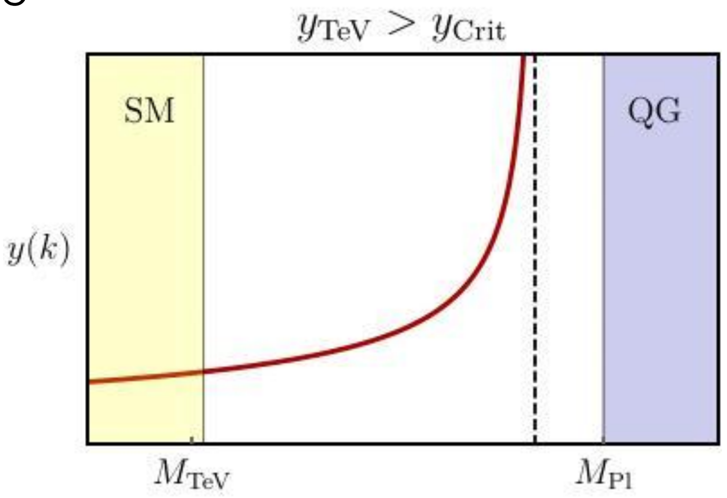
- ➔ New physics below Planck scale?



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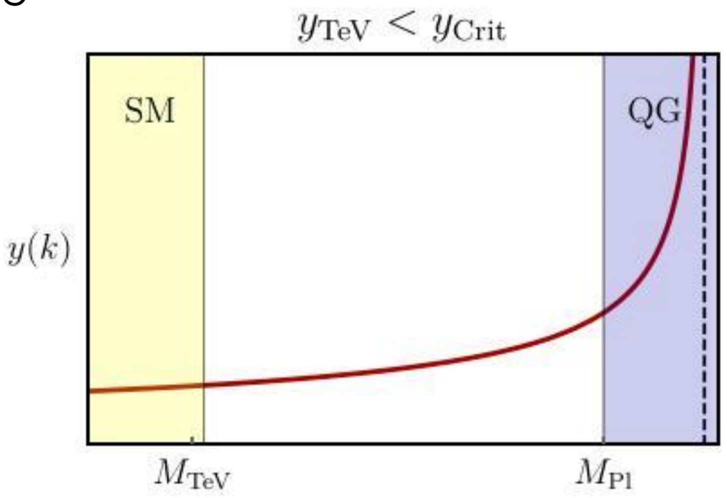

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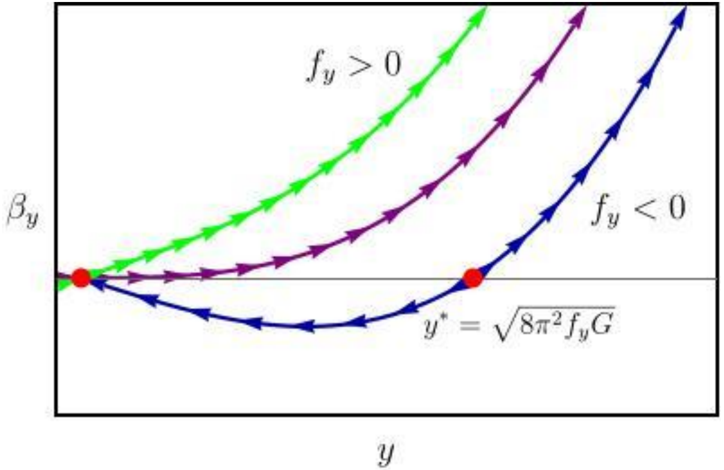

<u>Exemple: Yukawa Interaction</u>

$$\beta_y = \# \, y^3 + f_y \, G \, y$$

- ➔ $f_y > 0$ - screening
- ➔ $f_y < 0$ - anti-screening contribution

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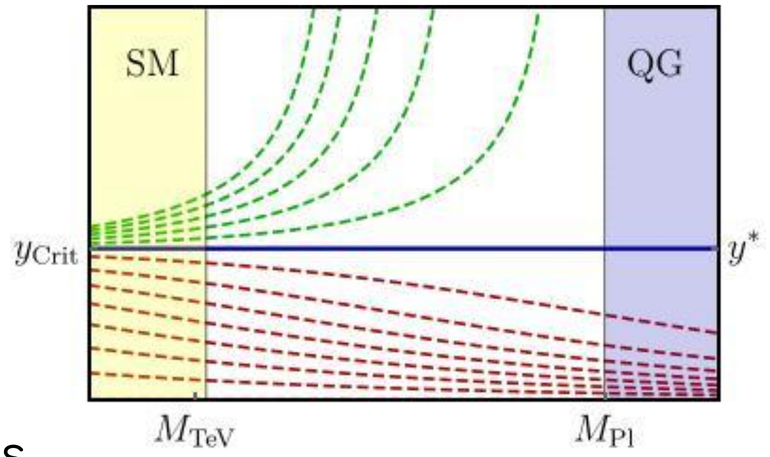

<u>Exemple: Yukawa Interaction</u>

Yukawa flow with $f_y < 0$

➔ $y_{\rm TeV} < y_{\rm Crit}$ - A.F. trajectories

➔ $y_{\rm TeV} = y_{\rm Crit}$ - Safe (predictive) trajectories

➔ $y_{\rm TeV} > y_{\rm Crit}$ - Unsafe trajectories

ASQG and Matter Interactions

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<u>Developments in ASQG + SM</u>

- ➔ Higgs mass predictions — Shaposhnikov and Wetterich, '09
- ➔ UV completion in the hypercharge sector — Christiansen and Eichhorn '17; Eichhorn and Versteegen '17
- ➔ Top-Botton mass difference — Eichhorn and Held '17, '18, '19

ASQG and Matter Interactions

Constraining different candidates for ASQG

Consistency tests for Quantum Gravity candidates:

➔ Resolving the Landau pole problem for SM-like couplings?

➔ Viable “predictions” for SM-like couplings at TeV?

ASQG and Matter Interactions

Constraining different candidates for ASQG

Consistency tests for Quantum Gravity candidates:

- ➔ Resolving the Landau pole problem for SM-like couplings?
- ➔ Viable "predictions" for SM-like couplings at TeV?

Metric based candidates for ASQG

- ➔ "Standard" ASQG (Diff. Symmetry)
- ➔ Quantum Unimodular Gravity (TDiff. Symmetry)
- ➔ Weyl squared gravity (Weyl + Diff. Symmetry)

Unimodular (Quantum) Gravity

Basics of Unimodular Gravity

GR with fixed metric determinant: $\det g_{\mu\nu} = \omega$

$$S_{\rm UG}[g_{\mu\nu}] = -\frac{1}{16\pi G_N}\int d^4x\sqrt{\omega}\,R(g) \implies R_{\mu\nu} - \frac{1}{4}g_{\mu\nu}R = -8\pi G_N\left(T_{\mu\nu} - \frac{1}{4}g_{\mu\nu}T\right)$$

- ➔ Classically equivalent to GR
- ➔ C.C. arises as an integration constant
  - Different perspective on the C.C. problem
- ➔ UG is symmetric under TDiff. rather than Diff.
  - Symmetry group in the bottom-up approach

Weinberg '89
Percacci '18

Van Der Bij, Van Dam and Yee Jack Ng '82

Unimodular (Quantum) Gravity

Quantum Unimodular Gravity

Quantizing Unimodular Gravity:

$$S_{\mathrm{UG}}[g_{\mu\nu}] = -\frac{1}{16\pi G_N}\int d^4x\sqrt{\omega}\,R(g) \quad \Longrightarrow \quad Z_{\mathrm{UG}} \sim \int_{\mathrm{UG}} \mathcal{D}g_{\mu\nu}\, e^{iS_{\mathrm{UG}}[g_{\mu\nu}]}$$

- ➔ Quantum (in)equivalence with GR?
- ➔ How to implement unimodularity in the path integral?
  - Field redefinition?
  - Lagrange multipliers?
- ➔ <u>Our approach:</u>

$$g_{\mu\nu} = \bar{g}_{\mu\alpha}(e^h)^\alpha{}_\nu$$

with unimodular background and traceless fluctuations

Gravity-Matter Systems in Unimodular Setting

Truncation:

$$\Gamma_k = \Gamma_k^{\text{UG}} + \Gamma_k^{\text{SM-like}}$$

➔ (Unimodular) Gravitational Setor

$$\Gamma_k^{\text{UG}} = \frac{1}{16\pi G_N} \int_x \sqrt{\omega}\left(-R + \bar{a}R^2 + \bar{b}R_{\mu\nu}^2\right) + \Gamma_k^{\text{g.f.}}$$

➔ SM-like sector

$$\Gamma_k^{\text{SM-like}} = \frac{Z_A}{4} \int_x \sqrt{\omega} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta} + \Gamma_k^{\text{g.f.}}$$
$$+ \frac{1}{2} \int_x \sqrt{\omega}\left(Z_{k,\phi} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + 2V_k(\phi)\right) + \int_x \sqrt{\omega}\left(Z_{k,\psi}\, i\bar{\psi}\,\gamma\cdot D\,\psi + i y_k\, \phi\, \bar{\psi}\psi\right)$$

Gravity-Matter Systems in Unimodular Setting

Yukawa and abelian gauge couplings:

$$\beta_y\big|_{\mathrm{grav}} = f_y\, G\, y \quad \Longrightarrow \quad f_y = \frac{1}{160\pi}\left(\frac{75\,(2+3b)}{(1+b)^2} + \frac{2\,(9-42a-14b)}{(1-6a-2b)^2}\right)$$

$$\beta_{g_Y^2}\big|_{\mathrm{grav}} = f_{g_Y^2}\, G\, g_Y^2 \quad \Longrightarrow \quad f_{g_Y^2} = -\frac{1}{90\pi}\left(\frac{5\,(10+7b)}{(1+b)^2} - \frac{4\,(5-21a-7b)}{(1-6a-2b)^2}\right)$$

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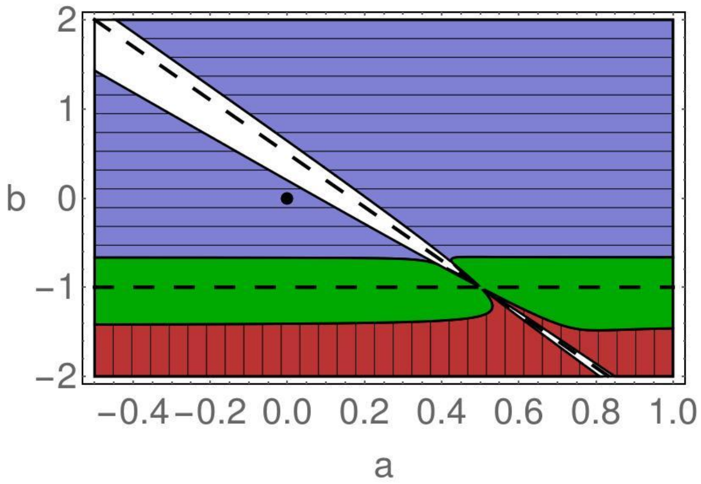
Quantum gravity anti-screening contributions:

- ➔ $f_y < 0$ and $f_{g_Y^2} < 0$
- ➔ Regions for UV completion and predictivity are available!



Gravity-Matter Systems in Unimodular Setting

Higgs mass predictivity:

In UG, the gravitational contribution to the scalar potential flow comes exclusively from the scalar anomalous dimension

$$V_k(\phi) = \sum_n k^{4-2n} \lambda_n \, \phi^{2n} \quad \Longrightarrow \quad \beta_{\lambda_n}\big|_{\text{grav}} = n \, \eta_\phi\big|_{\text{grav}} \lambda_n$$

$$\eta_\phi\big|_{\text{grav}} = \frac{1}{40\pi}\left(\frac{25\,(2+3\,b)}{(1+b)^2} + \frac{4(5-33a-11b)}{(1-6a-2b)^2}\right)$$

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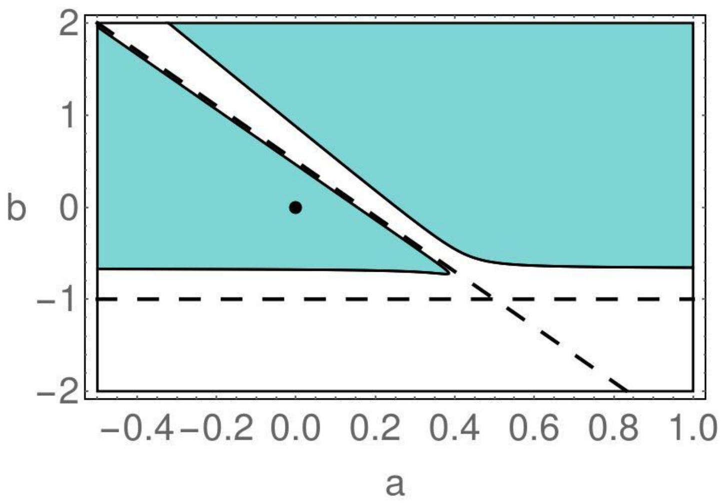
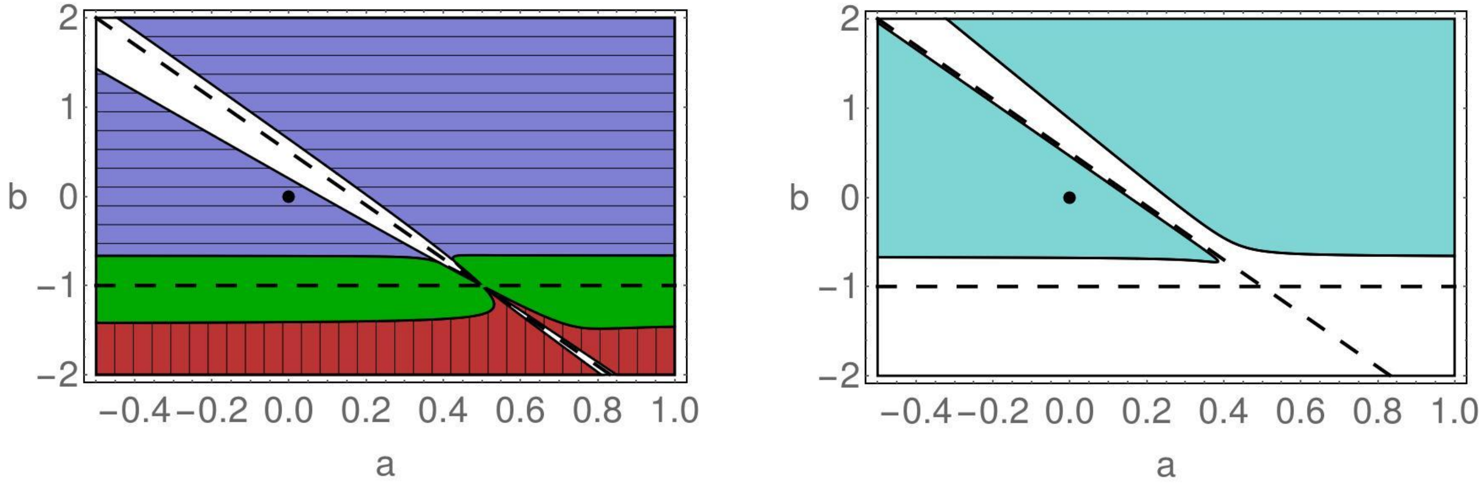
Predictivity of the Higgs mass requires positive contribution to the anomalous dimension



Gravity-Matter Systems in Unimodular Setting

Combined SM-like couplings:

Simultaneous UV completion and Higgs mass predictivity?



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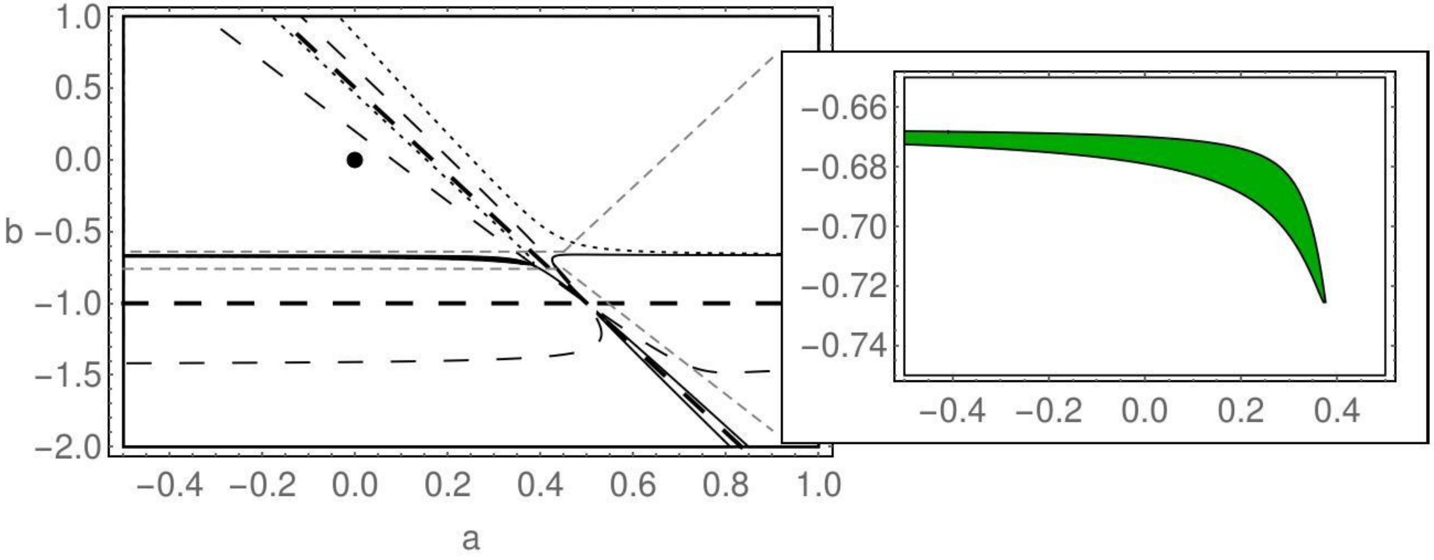
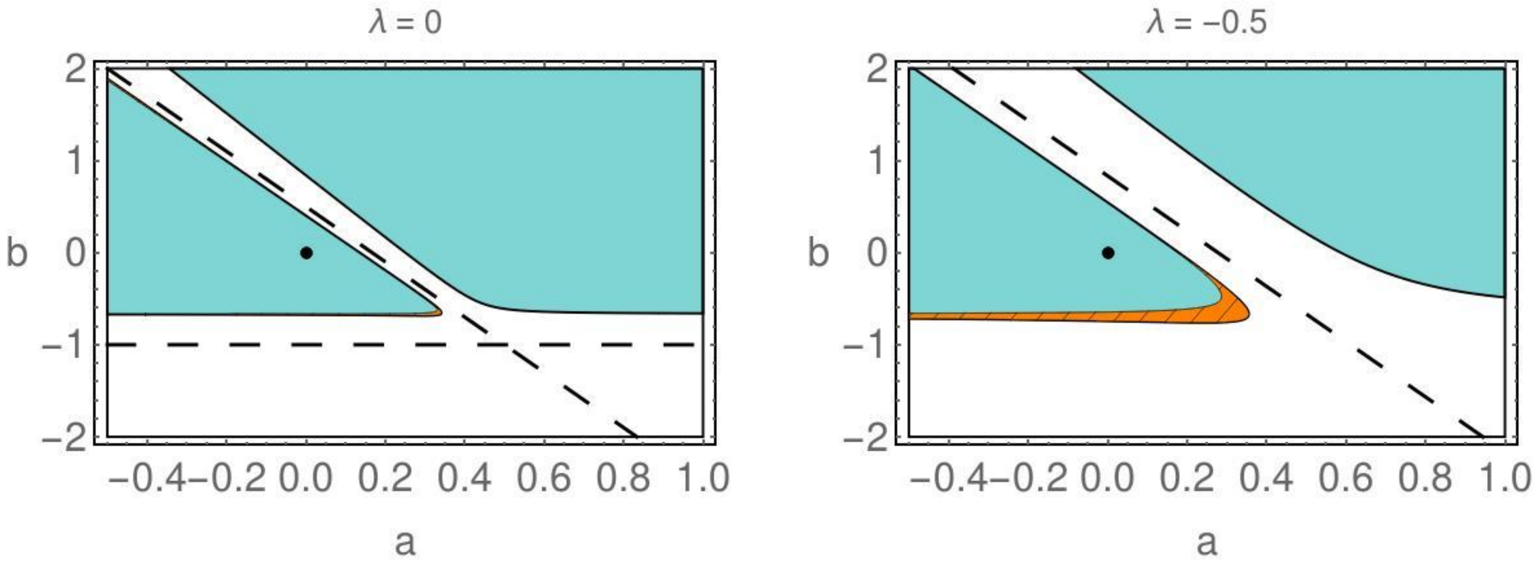


Comparison with "Standard" ASQG

UV completion and Higgs mass predictivity?



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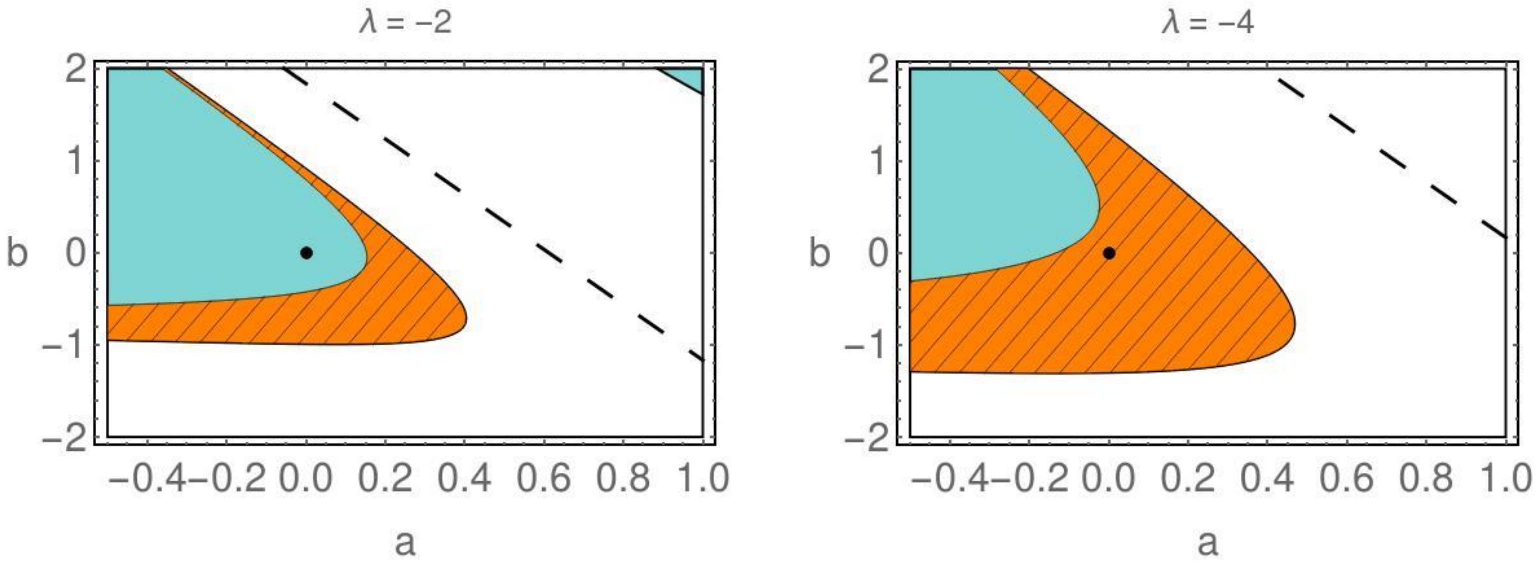

➔ The overlap viable region for UV completion/pedictivity of SM-like couplings is enlarged by negative values of C.C.

Weyl-Squared Gravity

Exploring larger symmetries in Quantum Gravity

Weyl-squared gravity is characterized by an enhanced symmetry corresponding to Weyl transformations:

For a review see: Scholz '18

$$g_{\mu\nu}(x) \mapsto g'_{\mu\nu}(x) = \Omega^2(x)\, g_{\mu\nu}(x)$$

➔ Strong restrictions on the allowed (local) interactions:

$$S_{\text{Weyl}} = \frac{1}{2w} \int_x \sqrt{g}\, C^2_{\mu\nu\alpha\beta}$$

➔ Power-counting renormalizable and asymptotically-free
- Natural candidate for UV completion Fradkin and Tseytlin '82

➔ Issues related with unitarity to be understood

Weyl-Squared Gravity

The interplay gravity-matter in Weyl-Squared setting

- ➔ UV completion/predictivity of SM-like couplings?
- ➔ Universality of quantum-gravity contributions due to dimensionless couplings in the gravitational sector?

FRG truncation

$$\Gamma_k^{\mathrm{WG}} = \int_x \sqrt{g}\left(\frac{1}{2w}C^2_{\mu\nu\alpha\beta} + \frac{Z_{k,\phi}}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + \frac{\lambda_{k,4}}{4!}\phi^4 + \frac{\chi}{6}\phi^2 R \right.$$
$$\left. + \frac{Z_{k,A}}{4}g^{\mu\alpha}g^{\nu\beta}F_{\mu\nu}F_{\alpha\beta} + Z_{k,\psi}i\bar{\psi}\gamma\cdot D\psi + i\,y_k\phi\bar{\psi}\psi\right) + \Gamma_k^{\mathrm{g.f.}}$$

Weyl-Squared Gravity

UV completion/predictivity of SM-like couplings?

Yukawa and abelian gauge sectors:

$$\beta_y|_{\mathrm{WG}} = f_y\, w\, y \quad \Longrightarrow \quad f_y = \frac{15}{64\pi^2}\Phi_2^3$$

$$\beta_{e_Y^2}|_{\mathrm{WG}} = f_{e_Y^2}\, w\, e_Y^2 \quad \Longrightarrow \quad f_{e_Y^2} = \frac{5}{12\pi^2}\left(\Phi_2^3 - 3\Phi_3^4\right)$$

Threshold integrals: $\Phi_n^p = \dfrac{1}{\Gamma(n)} \displaystyle\int_0^\infty dy\, y^{n-1} \frac{r(r) - y r'(y)}{(y + r(y))^p}$

Weyl-Squared Gravity

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$$\beta_y|_{\mathrm{WG}} = f_y\, w\, y \quad \Rightarrow \quad f_y = \frac{15}{64\pi^2}\Phi_2^3 = \frac{15}{128\pi^2}$$

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Threshold integrals: $\Phi_n^p = \frac{1}{\Gamma(n)}\int_0^\infty dy\, y^{n-1}\frac{r(r) - yr'(y)}{(y + r(y))^p}$

➔ Universal result: $\Phi_n^{n+1} = \frac{1}{\Gamma(n+1)}$

➔ The results are also universal with respect to field parametrization

Ohta and Percacci '16

Weyl-Squared Gravity

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UV completion/predictivity?

- ➔ UV completion in the Yukawa sector depend on the sign of w
- ➔ No UV completion induced in the abelian gauge sector

Concluding Remarks

- The interplay between gravity and matter might help to pave some way to perform phenomenological tests in quantum gravity
  - UV completion/predictivity of SM-like couplings as viability tests
- Unimodular gravity-matter systems
  - Quite similar results in comparison with standard ASQG with vanishing C.C.
  - Quantum UG seems to be less predictive than standard ASQG with C.C.
    - Possible to mimic in UG with the introductions of "graviton mass parameters" motivated by mSTI's
  - Further analysis is necessary in order to get quantitative "predictions" in UG
- Weyl-squared gravity
  - No UV completion in the abelian gauge sector
  - Universal results with respect to the choice of regulator and field parametrization

Acknowledgements

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- ITP - Heidelberg University for the hospitality

Thank you for your attention!