Asymptotically Safe Unimodular Gravity

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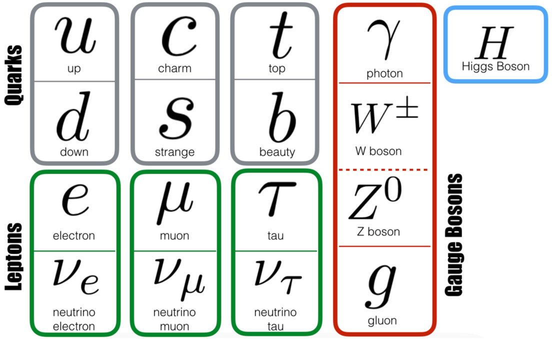
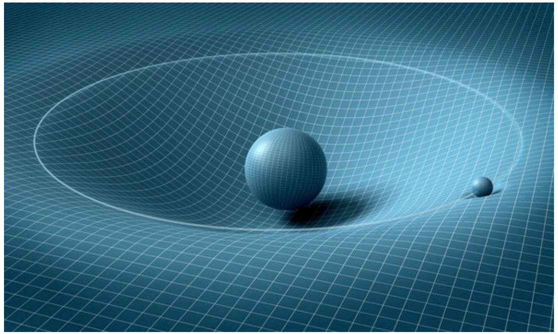
University of Southern Denmark

Cornerstones of fundamental physics

Standard Model



General Relativity



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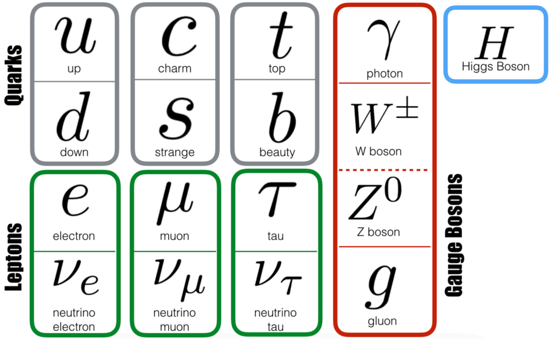

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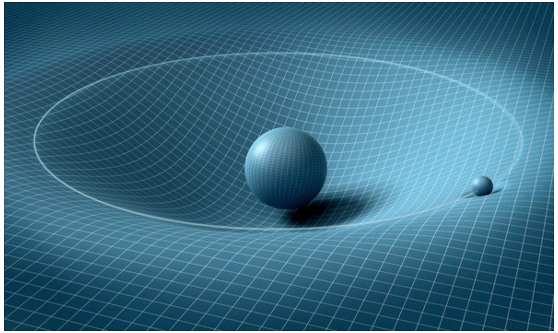

- Very successful in experiments/observations

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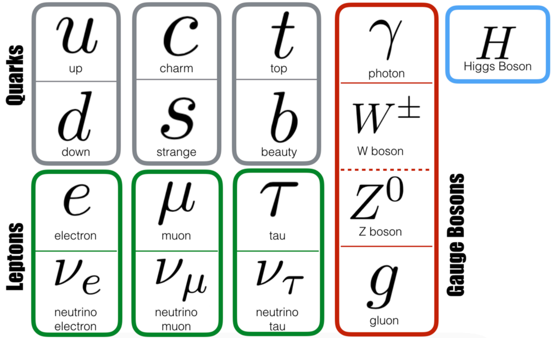

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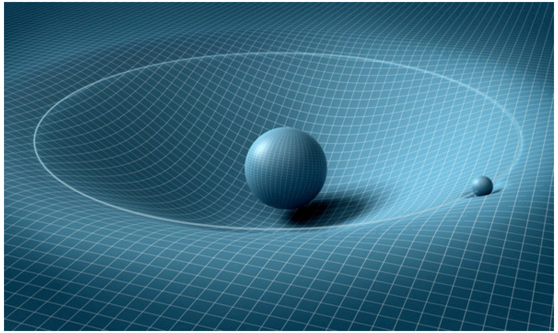

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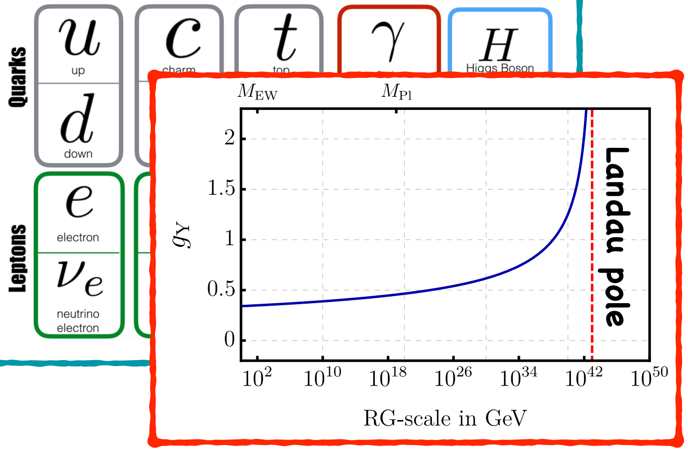

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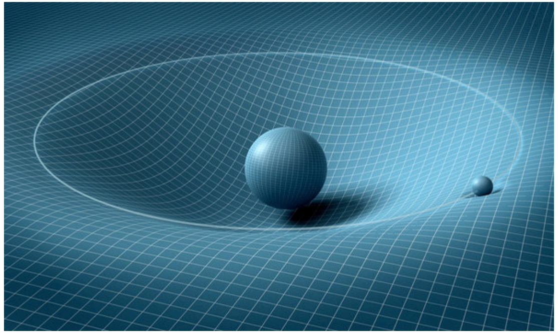

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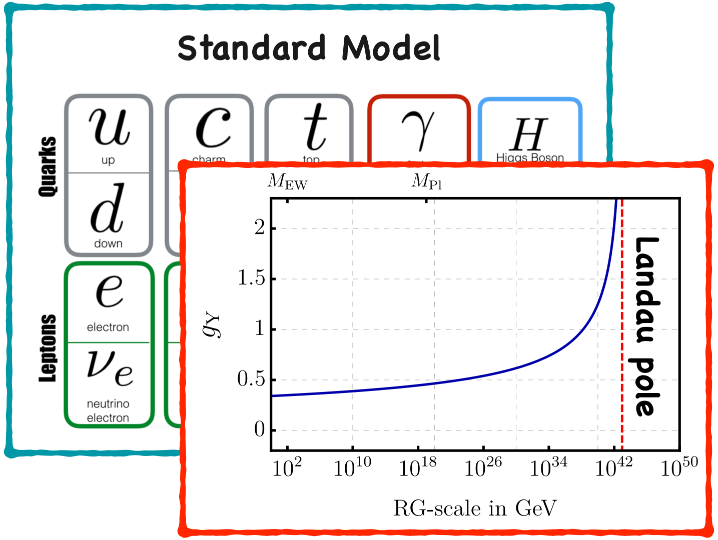

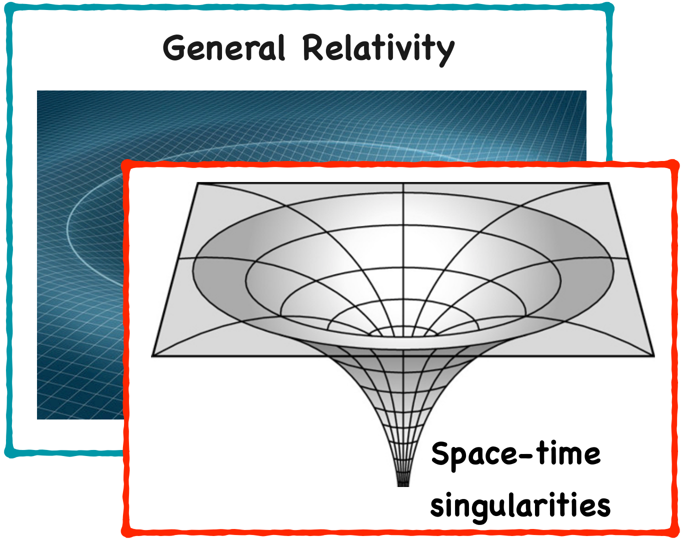

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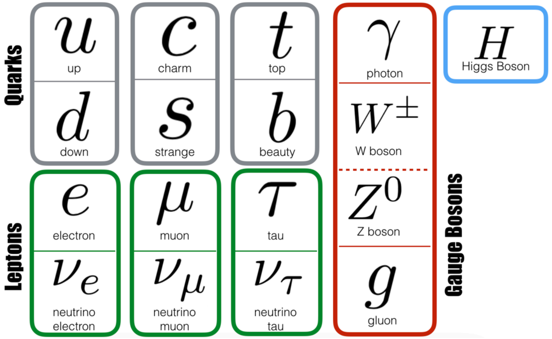

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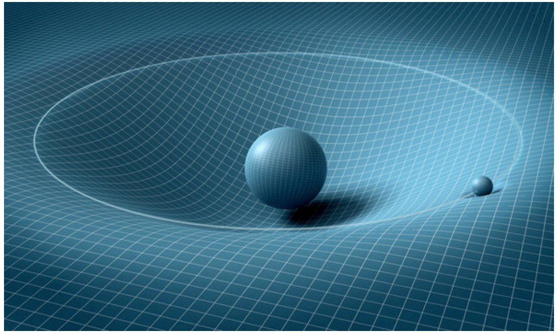

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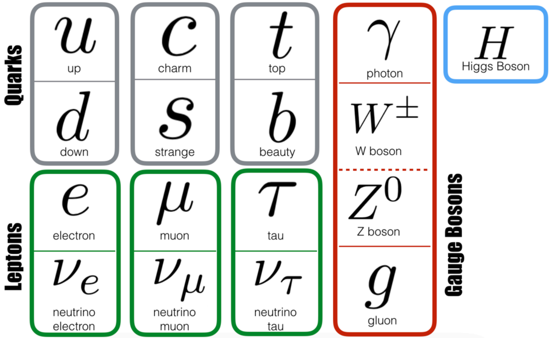

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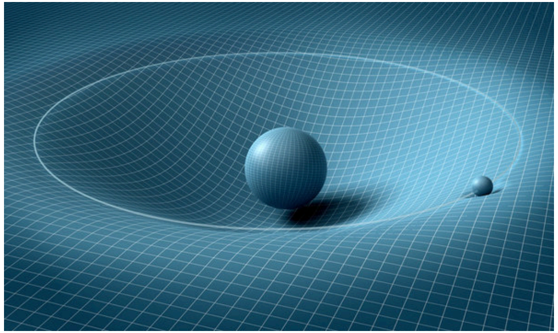

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This talk:

The asymptotic safety paradigm may help with these challenges!

Asymptotically Safe Quantum Gravity

Gravity as a quantum field theory

$$S_{\mathrm{EH}}[g_{\mu\nu}] = \frac{1}{16\pi G_{\mathrm{N}}} \int_x \sqrt{|g|}\left(2\Lambda - R\right)$$

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✳ **Perturbatively non-renormalizable!** 't Hooft and Veltman 1974
Goroff and Sagnotti 1986

➡ **Loss of predictivity!**

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✳ Still works as an Effective Field Theory (below the Planck scale)

Donoghue 1994

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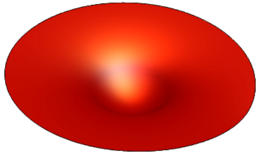

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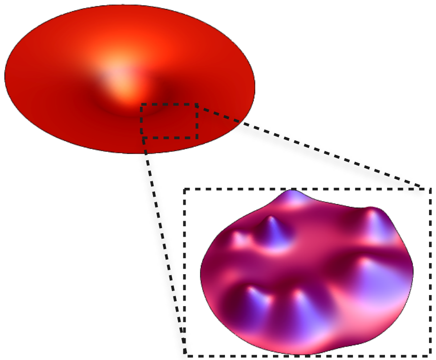

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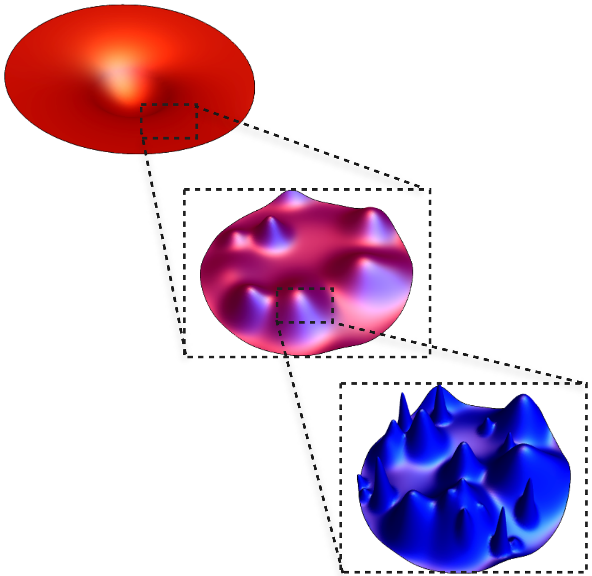

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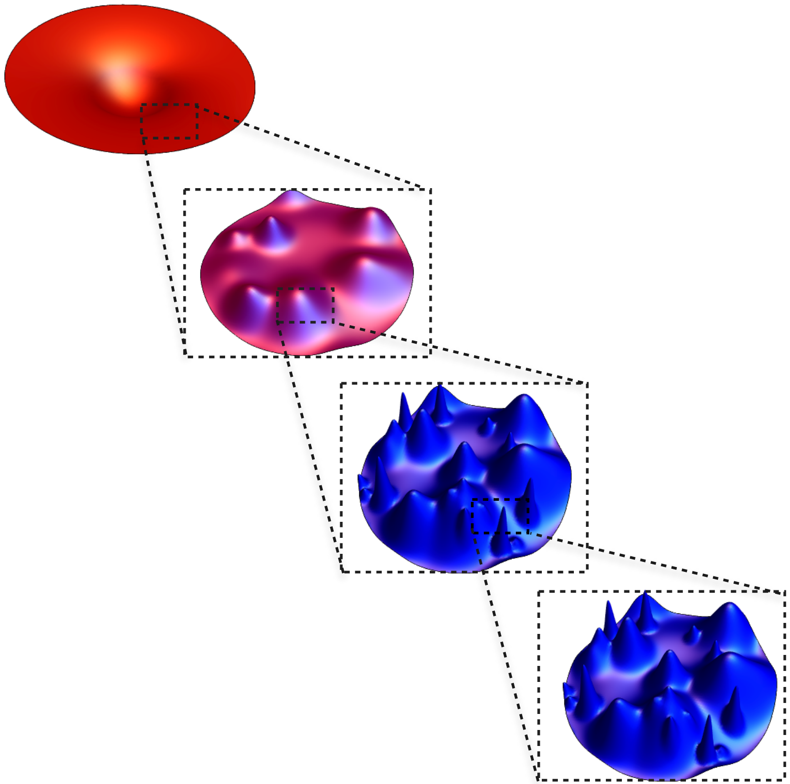

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Quantum scale symmetry and fixed points

- Quantum scale symmetry corresponds to fixed points in the renormalization group flow

$$k\partial_k g_i(k) = \beta_{g_i}(g_1, g_2, \cdots)$$

$$\beta_{g_i}(g_1^*, g_2^*, \cdots) = 0\,, \quad \forall \beta_{g_i}$$

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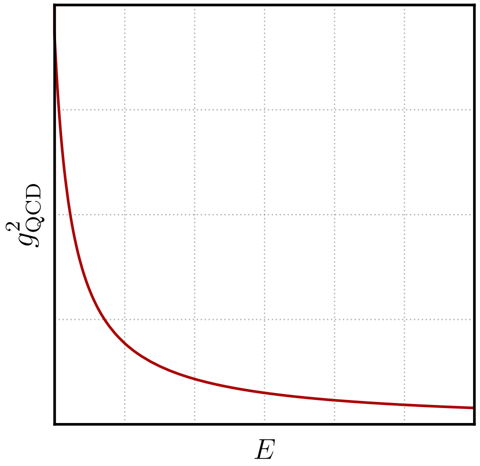
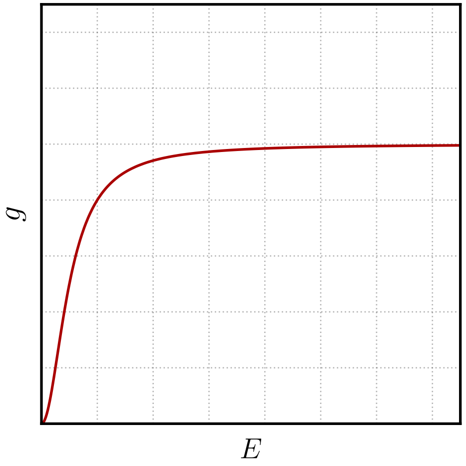
Asymptotic freedom



Asymptotic safety



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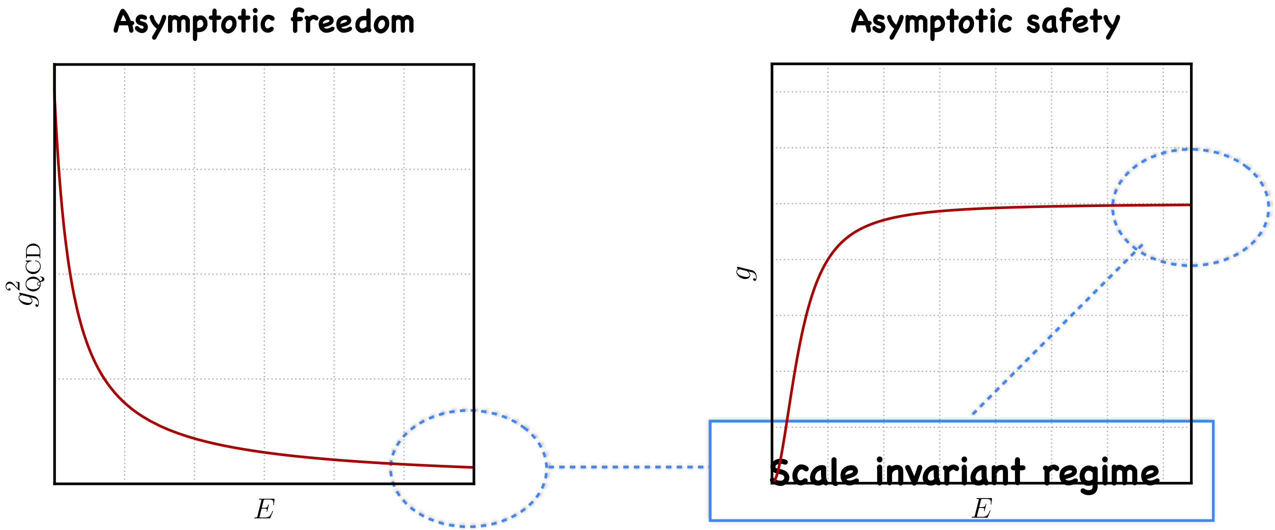

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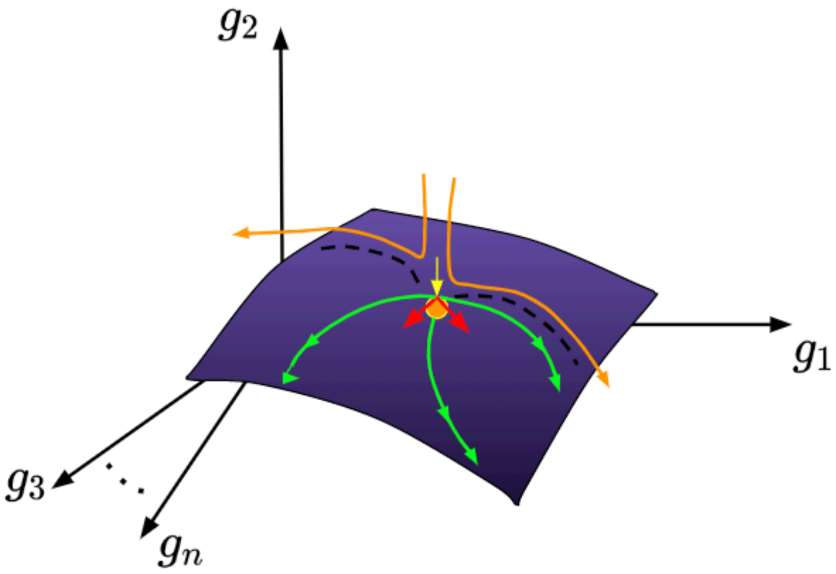

➡ Predictivity: Finite dimensional critical surface

Functional Renormalization Group

Functional RG is a stepwise implementation of a path-integral

Wetterich 1993
Ellwanger 1993
Morris 1994

$$e^{-\Gamma_k[\varphi]} \sim \int \mathcal{D}\phi \, e^{-S[\phi+\varphi]-\frac{1}{2}\phi\cdot\mathbf{R}_k\cdot\phi}$$

✳ Euclidean QFT

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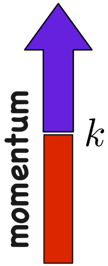

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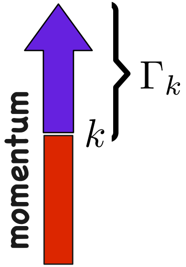

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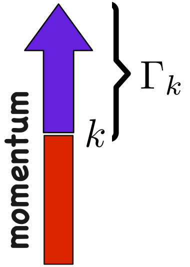

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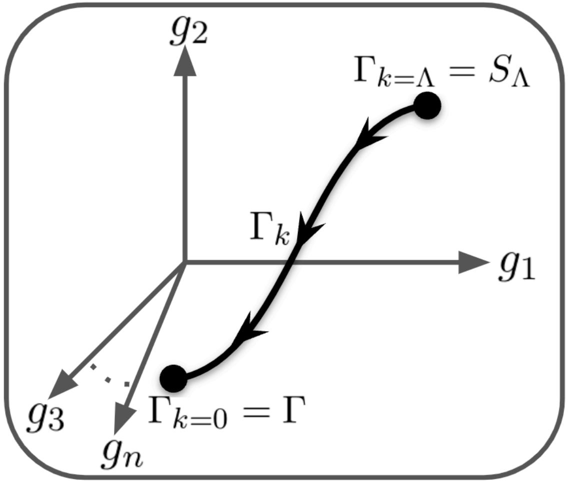
➡ RG Flow - Wetterich equation

$$k\partial_k\Gamma_k = \frac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)}+\mathbf{R}_k\right)^{-1} k\partial_k\mathbf{R}_k\right]$$

➡ Theory space:

$$\Gamma_k[\varphi] = \sum_n k^{-\Delta_n} g_n(k)\mathcal{O}_n[\varphi]$$



Functional RG and Asymptotically Safe Quantum Gravity

Functional RG as a tool to explore Asymptotic Safety

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➡ **The Einstein-Hilbert truncation** Reuter 1998

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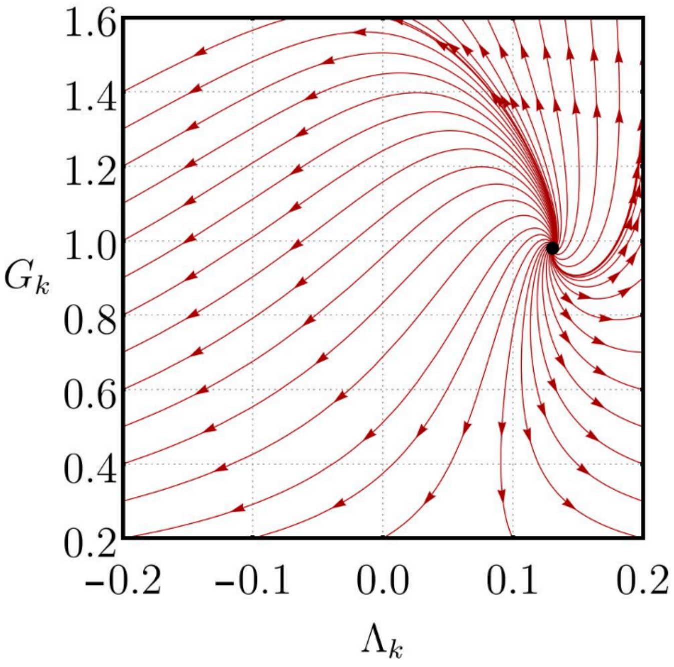

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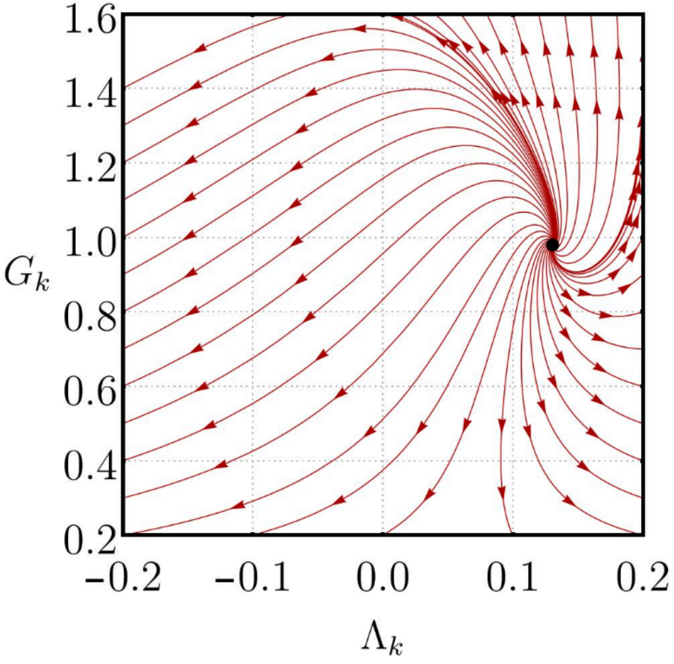

➡ **There are further indications from more sophisticated truncations**

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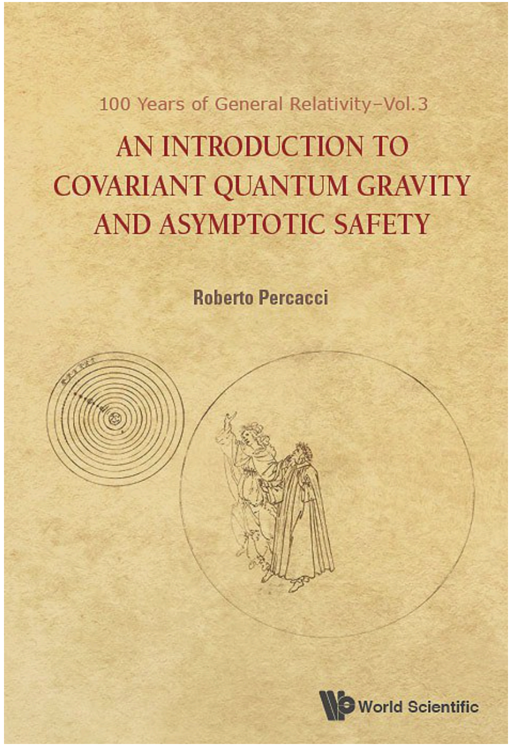
For more details on ASQG, see:

- Roberto Percacci's mini-course on Quantum Gravity



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- Asymptotically Safe Quantum Gravity at GravBR (Youtube channel) [GPB and A. Tomaz]

Unimodular (Quantum) Gravity

Basics of Unimodular Gravity

** For a recent review, see:
Carballo-Rubio, Garay, García-Moreno 2022

GR with fixed metric determinant: $\det(g_{\mu\nu}) = \omega^2(x)$

$$S_{\mathrm{UG}} = -\frac{1}{16\pi G_{\mathrm{N}}} \int_x \omega(x)\, R(g) \longrightarrow R_{\mu\nu} - \frac{1}{4} g_{\mu\nu} R = 8\pi G_{\mathrm{N}} \left(T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} T \right)$$

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- UG is classically equivalent to GR (for conserved energy-momentum tensor)

See:
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- Cosmological constant arises as an integration constant

Weinberg 1989
Percacci 2018

➡ Different perspective on the C.C. problem

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➡ Different perspective on the C.C. problem

- UG is symmetric under TDiff. rather than Diff. $\longrightarrow \nabla_\mu \epsilon^\mu = 0$

➡ Symmetry group in the bottom-up approach

Van Der Bij, Van Dam and Yee Jack Ng 1982
Barceló, Carballo-Rubio, Garay 2014

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Quantizing Unimodular Gravity

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- Quantum (in)equivalence with RG? GPB, Melichev, Percacci and Pereira 2021
- How to implement the unimodularity in the path integral?
  - ➡ Field redefinition?
  - ➡ Lagrange multipliers?

Unimodular (Quantum) Gravity

Basics of Unimodular Quantum Gravity

Quantizing Unimodular Gravity

$$S_{\rm UG} = -\frac{1}{16\pi G_{\rm N}} \int_x \omega(x)\, R(g) \quad \longrightarrow \quad Z_{\rm UG} \sim \int [\mathcal{D}g_{\mu\nu}]_{\rm UG}\, e^{iS_{\rm UG}[g_{\mu\nu}]}$$

- Quantum (in)equivalence with RG? GPB, Melichev, Percacci and Pereira 2021
- How to implement the unimodularity in the path integral?
  - ➡ Field redefinition?
  - ➡ Lagrange multipliers?
- <u>Our approach:</u>

$$g_{\mu\nu} = \bar{g}_{\mu\alpha}\left(e^h\right)^\alpha{}_\nu \qquad \text{with}$$

➡ $\det(\bar{g}_{\mu\nu}) = \omega^2(x)$

➡ $h^\mu{}_\mu = 0$

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- Unimodular quantum gravity is also perturbatively non-renormalizable!

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- Unimodular quantum gravity is also perturbatively non-renormalizable!
- Can we achieve UV completion via asymptotic safety?
- Can we distinguish asymptotically safe unimodular gravity from the standard scenario based on GR?

Novel indications for asymptotic safety in unimodular gravity

Unimodular $f(R)$-truncation

Earlier works on unimodular ASQG:
Eichhorn 2013; Saltas 2014; Benedetti 2015

$$\Gamma_k = \frac{1}{16\pi k^{-2} G_k} \int_x \omega f_k(R)$$

Eichhorn 2015
GPB, Pereira and Vieira 2020

$$f_k(R) = -R + \alpha_{k,2} R^2 + \cdots + \alpha_{k,N} R^N$$

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Flow equation in Unimodular Gravity

Ardón, Ohta, Percacci 2017
Percacci 2018

$$k\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)} + \mathbf{R}_k\right)^{-1} k\partial_k \mathbf{R}_k\right] \overbrace{- \frac{1}{2}\mathrm{Tr}\left[\left(\Delta + \mathbf{R}_k\right)^{-1} k\partial_k \mathbf{R}_k\right]}^{\text{Measure contribution}}$$

GPB, Pereira 2020

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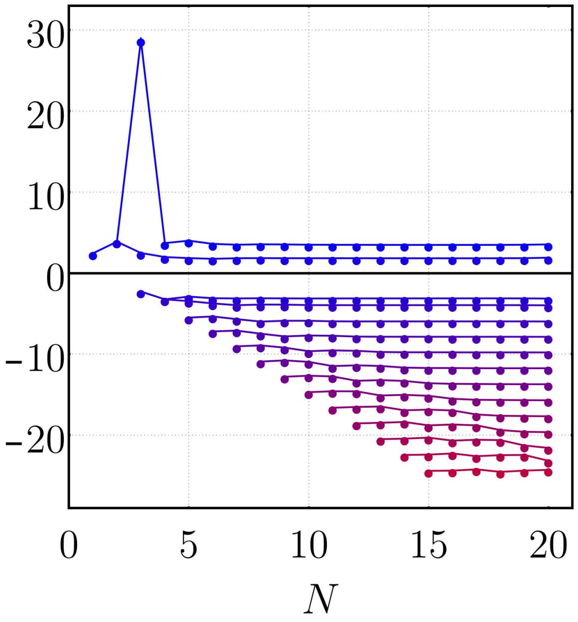
$$f_k(R) = -R + \alpha_{k,2} R^2 + \cdots + \alpha_{k,N} R^N$$

- Number of relevant directions stabilizes at two
- Near-canonical scaling (for negative crit. exp)

$$\theta_n \sim 4 - 2n\,, \quad n = 3, 4, \cdots$$

Critical exponents



Novel indications for asymptotic safety in unimodular gravity

Unimodular truncations beyond Ricci scalar

$$\Gamma_k = \frac{1}{16\pi k^{-2} G_k} \int_x \omega \left(F_k(R^2_{\mu\nu}) + R\, Z_k(R^2_{\mu\nu}) \right)$$

Falls, King, Litim, Nikolakopoulos, Rahmede 2017 in standard ASQG
GPB, Pereira and Vieira 2020 in unimodular ASQG

$$F_k(R^2_{\mu\nu}) = \rho_{k,2} R^2_{\mu\nu} + \cdots + \rho_{k,2N_{\mathrm{F}}} \left(R^2_{\mu\nu}\right)^{N_{\mathrm{F}}}$$

$$Z_k(R^2_{\mu\nu}) = -1 + \rho_{k,3} R^2_{\mu\nu} + \cdots + \rho_{k,2N_{\mathrm{Z}}+1} \left(R^2_{\mu\nu}\right)^{N_{\mathrm{Z}}}$$

Novel indications for asymptotic safety in unimodular gravity

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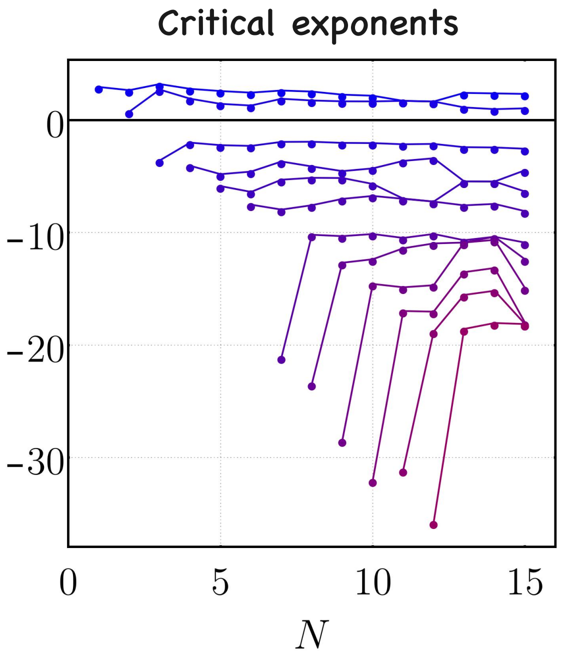

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- Number of relevant directions stabilizes at two
- We also observe sear-canonical scaling, but only for high order truncations

Novel indications for asymptotic safety in unimodular gravity

Steps Beyond Background Field Approximation

GPB, Pereira 2020

$$\Gamma_k^{\mathrm{UG}} = -\frac{1}{16\pi G_{\mathrm{N}}} \int_x \omega\, R(g(\bar{g}, h)) + \frac{1}{2} m_{k,h}^2 \int_x \omega\, h_{\mu\nu}^2$$

Motivated by

mSTIs and mNIs

Novel indications for asymptotic safety in unimodular gravity

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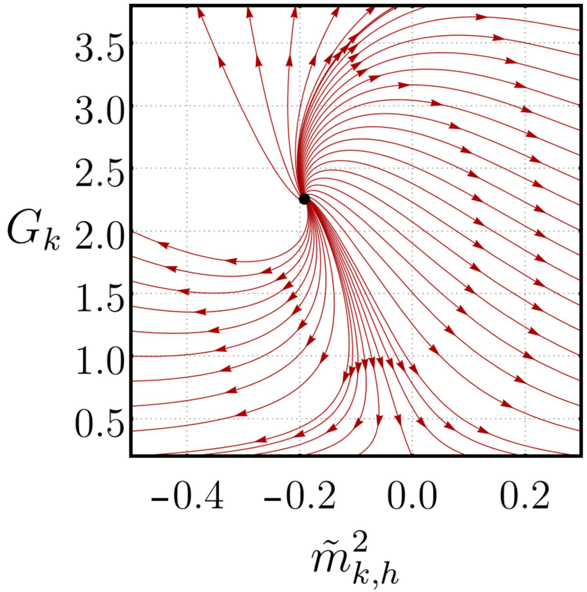
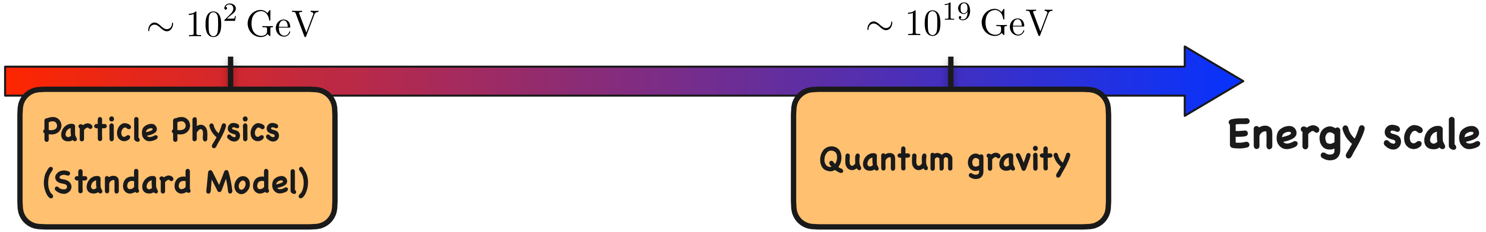
Motivated by mSTIs and mNIs



- The RG-flow resembles the picture from standard ASQG
- The mass parameter should not be confused with the cosmological constant

Connecting quantum gravity to particle physics



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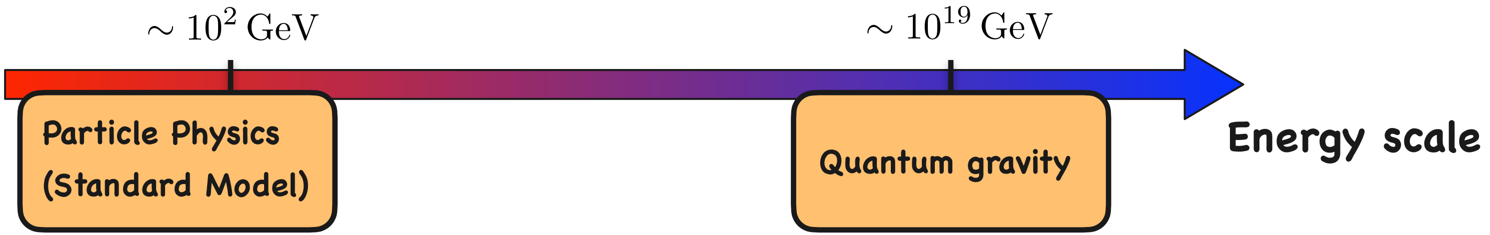

➡ Matter can impact the structure of (or even destroy) the gravitational fixed point: “Matter Matters in QG”

Donà, Eichhorn, Percacci 2013
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** See also Eichhorn, Schiffer 2022 for an overview on gravity+matter in AS

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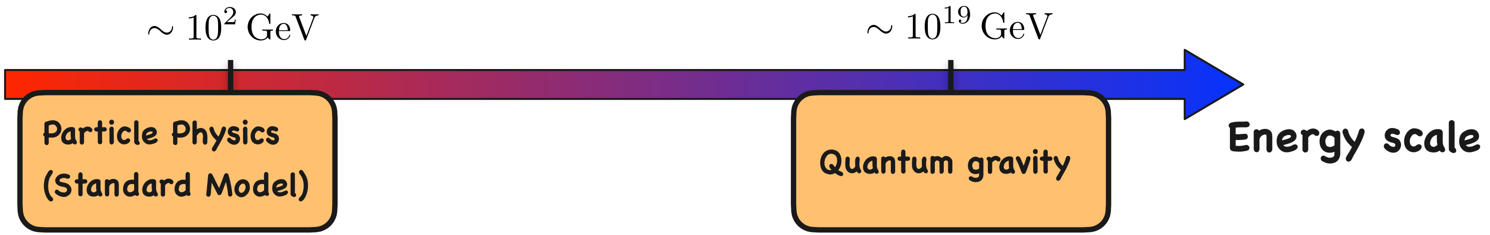

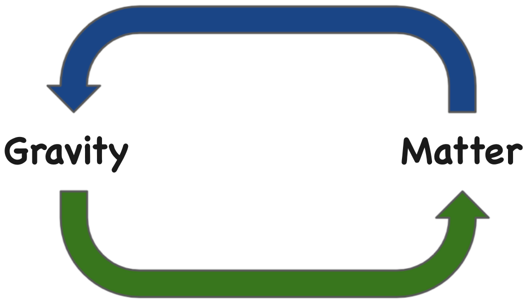

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➡ Gravity can impose non-trivial constraints in the RG flow of matter couplings

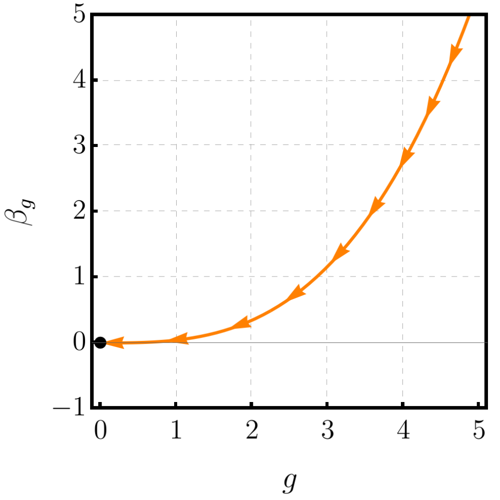
** See also Eichhorn, Schiffer 2022 for an overview on gravity+matter in AS

The interplay between quantum gravity and particle physics

The interplay between quantum gravity and particle physics

Asymptotic safety connecting quantum gravity to particle physics

Ex: flow of Abelian-gauge couplings



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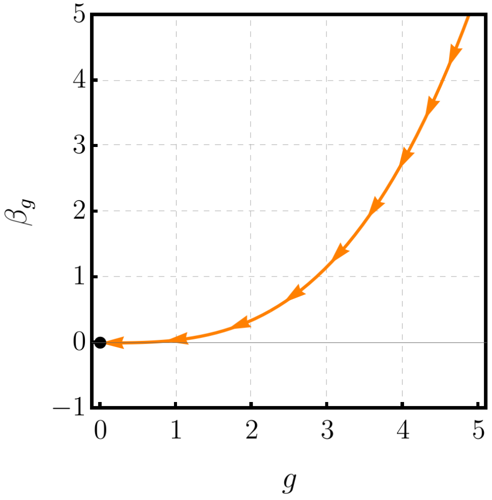
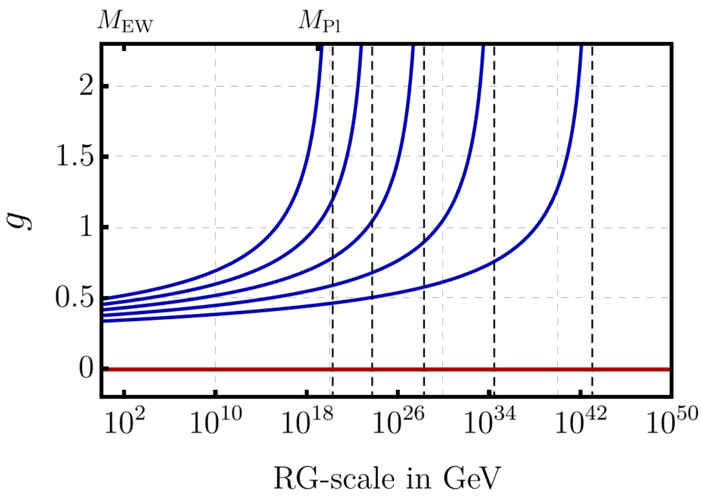


Landau-pole



Triviality problem

The interplay between quantum gravity and particle physics

Asymptotic safety connecting quantum gravity to particle physics

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Ex: flow of Abelian-gauge couplings + Gravity - Gravity acts with anti-screening effects

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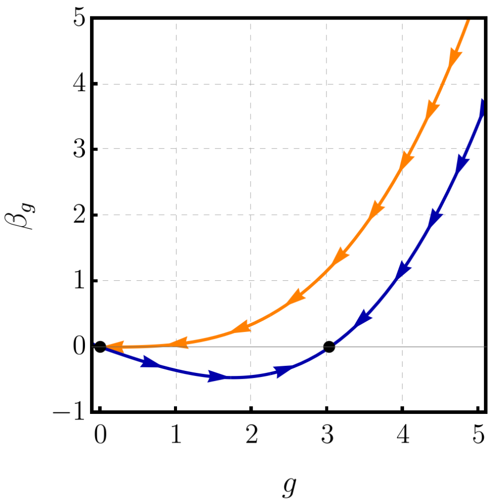

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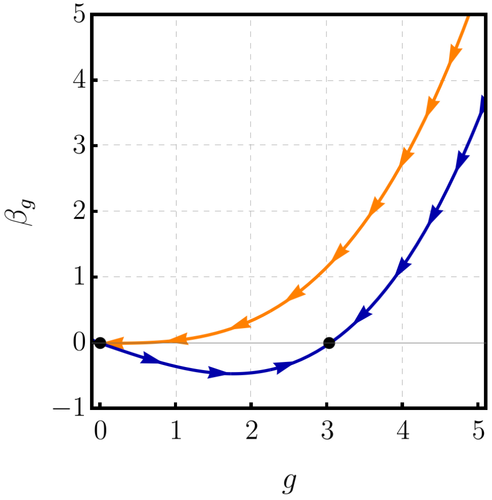

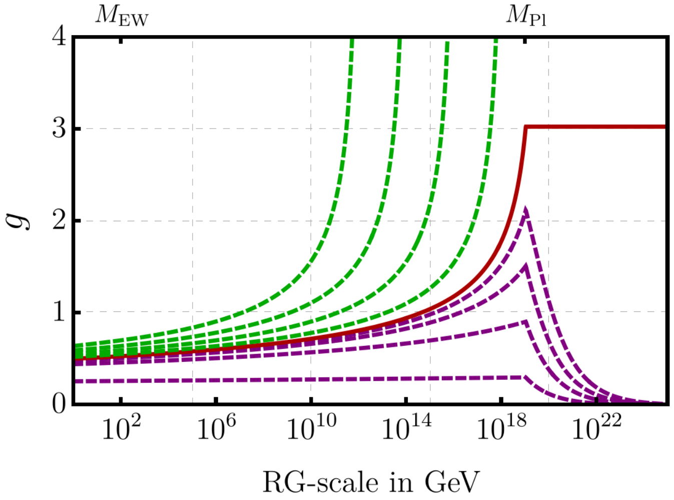

The interplay between quantum gravity and particle physics

Very exciting results in the last 15 years:

The interplay between quantum gravity and particle physics

Very exciting results in the last 15 years:

- Quantum gravity effects on the Higgs potential

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  - Flattening of the the Higgs potential
  - Higgs mass from asymptotically safe gravity Shaposhnikov, Wetterich 2009

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  - Possible solution of the hypercharge triviality problem

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GPB, Eichhorn, Pereira 2019
GPB, Eichhorn 2022

- Quantum gravity effects on Yukawa couplings
  - Possible anti-screening contributions from graviton fluctuations
  - Quantum-gravity induced UV completion in the Yukawa sector
  - Top-bottom mass difference from asymptotically safe gravity

Oda, Yamada 2015
Eichhorn, Held Pawlowski 2016
Eichhorn, Held 2017

Eichhorn, Held 2017
Eichhorn, Held 2018

Gravity-Matter Systems in Unimodular Setting

Setup:

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

- (Unimodular) Gravitational Setor

$$\Gamma_k^{\rm UG} = \frac{1}{16\pi G_{\rm N,k}} \int_x \omega \left(- R + \bar{a}_k R^2 + \bar{w}_k C^2_{\mu\nu\alpha\beta} \right)$$

- SM-like sector

$$\Gamma_k^{\text{SM-like}} = \int_x \left(\frac{Z_A}{4} F^2_{\mu\nu} + \frac{Z_\phi}{2} (\partial\phi)^2 + V_k(\phi^2) + i Z_\psi \bar{\psi} \not{D} \psi + i \bar{y}_k \phi \bar{\psi} \psi \right)$$

Gravity-Matter Systems in Unimodular Setting

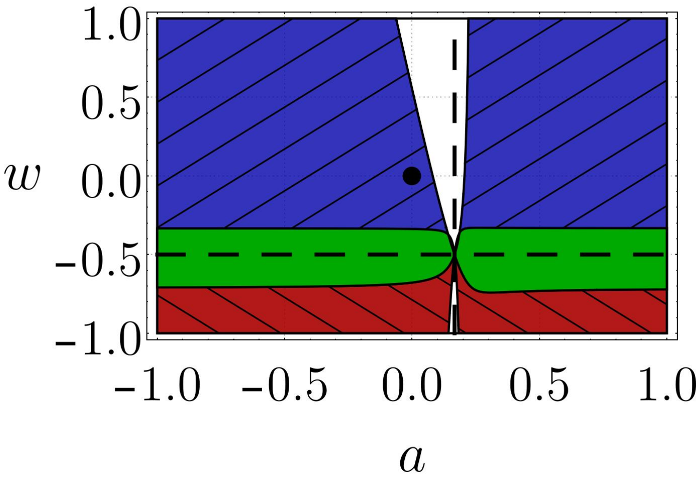
Yukawa and abelian gauge couplings:

$$\beta_y\big|_{\rm grav} = \frac{3\,G\,y}{80\pi}\left(\frac{25(1+3w)}{(1+2w)^2} + \frac{3-14a}{(1-6a)^2}\right)$$

$$\beta_{g^2}\big|_{\rm grav} = -\frac{G\,g^2}{45\pi}\left(\frac{5\,(5+7w)}{(1+2w)^2} + \frac{2\,(5-21a)}{(1-6a)^2}\right)$$

Quantum gravity anti-screening contributions:

- $\beta_y\big|_{\rm grav} < 0$ and $\beta_{g^2}\big|_{\rm grav} < 0$
- Regions for UV completion and predictivity are available!



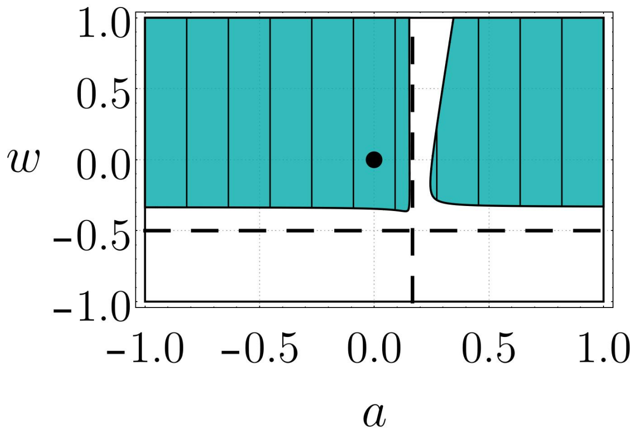
Gravity-Matter Systems in Unimodular Setting

Scalar sector

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

$$V_k(\phi) = \sum_n k^{4-2n} Z_{k,\phi}^n \lambda_{2n} \phi^{2n} \quad \Rightarrow \quad \beta_{\lambda_n}|_{\rm grav} = n\, \eta_\phi|_{\rm grav} \lambda_n$$

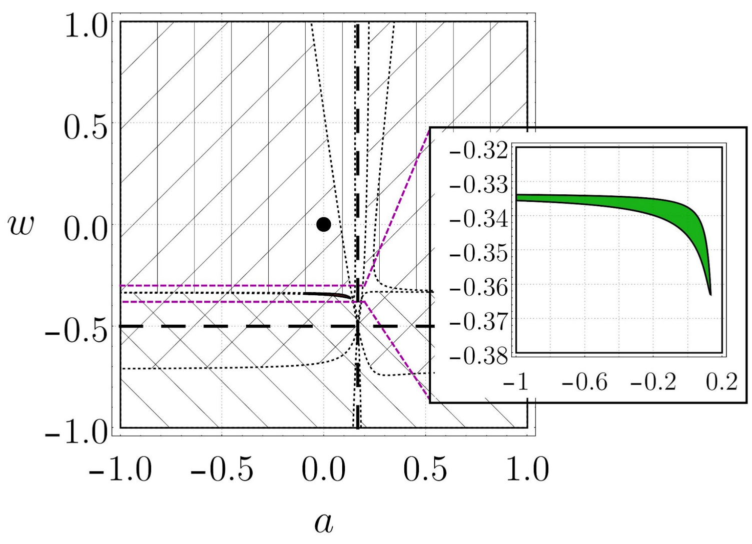
$$\eta_\phi|_{\rm grav} = \frac{G}{20\pi}\left(\frac{25(1+3w)}{(1+2w)^2} + \frac{2(5-33a)}{(1-6a)^2}\right)$$



An RG-predictive scalar potential requires a positive contribution to the anomalous dimension

Gravity-Matter Systems in Unimodular Setting

Combined SM-like couplings



- Small overlap region
- The results are quite similar in comparison with the standard case (with vanishing C.C.)
- Non-vanishing C.C. increases the overlap region in the standard case
- Symmetry-breaking masses can increase the overlap region for UG

Final remarks

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- Asymptotic safety as a road to quantum gravity
  - ➡ UV completion via quantum scale symmetry
  - ➡ Compelling evidences from FRG methods for the viability of ASQG
  - ➡ Many challenges on the way
    (Lorentzian, unitarity, control of non-pert. results, observables, etc…)

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- Asymptotic safety also seems to provide a viable scenario for UV completion in unimodular quantum gravity

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- Asymptotic safety also seems to provide a viable scenario for UV completion in unimodular quantum gravity

- Unimodular gravity-matter systems
  - ➡ Phenomenological selection of different candidates for ASQG?
  - ➡ Quite similar results in comparison with standard ASQG with vanishing C.C.
  - ➡ Quantum UG seems less predictive than standard ASQG with C.C.

Thank you!