Asymptotic safety in gravity

Astrid Eichhorn

Imperial College, London

Southampton High Energy Physics Seminar, January 16, 2015

The missing corner of Bronstein's cube

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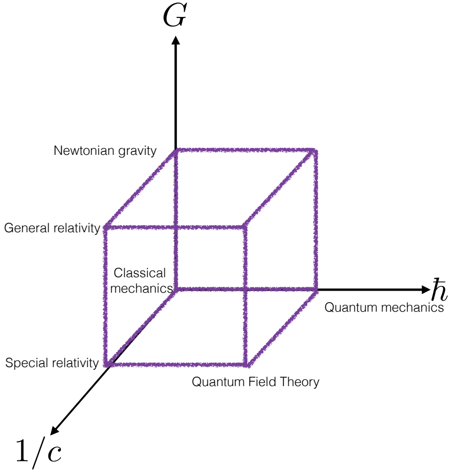

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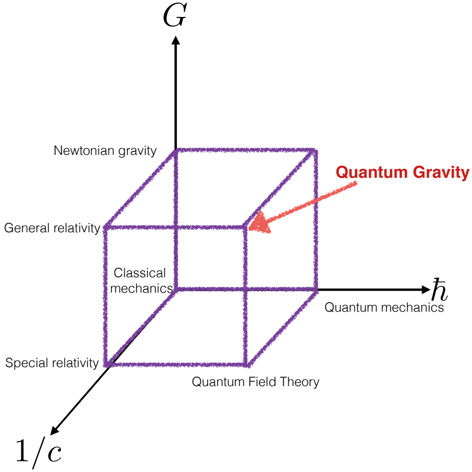
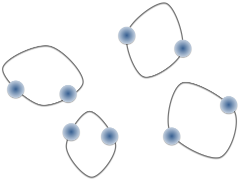


Quantum field theory and gravity

quantum fields:



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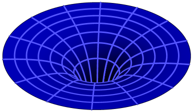

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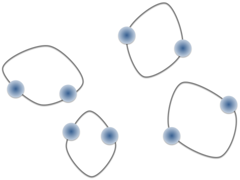

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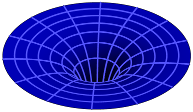
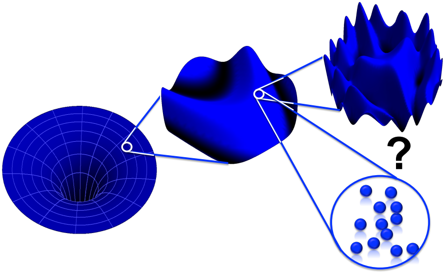


$\rightarrow$ quantum gravity:



spacetime fluctuations

at the Planck scale $M_{\rm Pl} = \sqrt{\frac{\hbar c}{G}}$

quantum field theory of gravity in the path-integral framework:

Goal: $\int \mathcal{D}g_{\mu\nu}\, e^{i\,S[g_{\mu\nu}]}$

Quantum gravity

Goal: $\int \mathcal{D}g\, e^{i\,S[g]} \rightarrow \int \mathcal{D}g\, e^{-S[g]} \rightarrow \int_{p<k} \mathcal{D}g\, e^{-\Gamma_k}$

$1/k$: "resolution" Γ_k : effective dynamics for long-wavelength modes

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works as an effective theory at low energies:

$S_{\text{eff}} = \frac{-1}{16\pi G_N} \int \sqrt{g}\,(R - 2\Lambda) + \dots$

example: quantum gravity contribution to Newtonian potential:

$$V(r) = V_{\text{Newton}} + V_{\text{pN}} + \frac{G m_1 m_2}{r} \frac{41}{10\pi} \frac{G\hbar}{r^2} + ...$$

[Donoghue, 1994]

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10^{-40}

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- leave the continuum and postulate spacetime discreteness? (e.g. Loop Quantum Gravity, causal sets)
- introduce new (unobserved) degrees of freedom? (e.g. Supergravity)
- break fundamental symmetries? (e.g. Horava-Lifshitz gravity)
- introduce non-locality? (e.g. strings)

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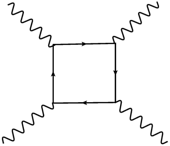
Asymptotic safety: Continuum quantum field theory of the metric

Fundamental quantum field theories



$\int_{p<k} \mathcal{D} g_{\mu\nu}(p)\, e^{-\Gamma_k[g_{\mu\nu}(p); g_i]}$ with $\Gamma_k[g_{\mu\nu}] = \int_x \Sigma_i g_i(k) \mathcal{O}_i(g_{\mu\nu})$

effective: $k < \Lambda_{UV}$, fundamental: $k \to \infty$

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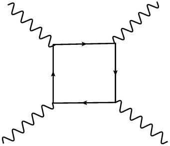

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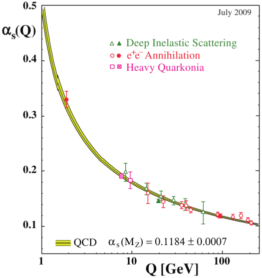

[S. Bethke, 2009]

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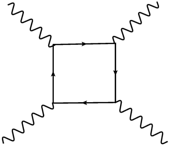

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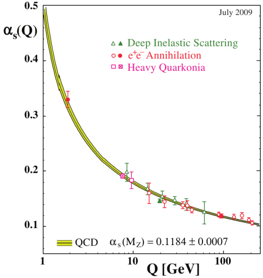

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$$\beta_g = k\, \partial_k g(k)$$

Asymptotic freedom:

non-interacting fixed point

[Gross, Wilczek; Politzer (1973)]

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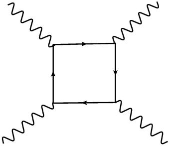

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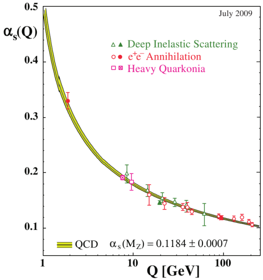

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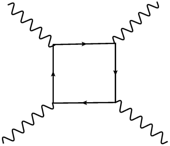

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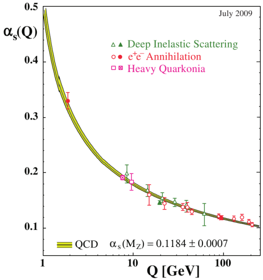

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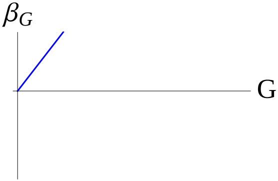

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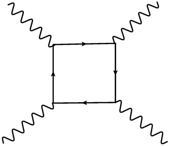

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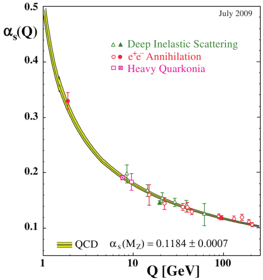

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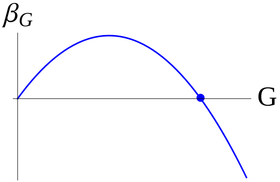
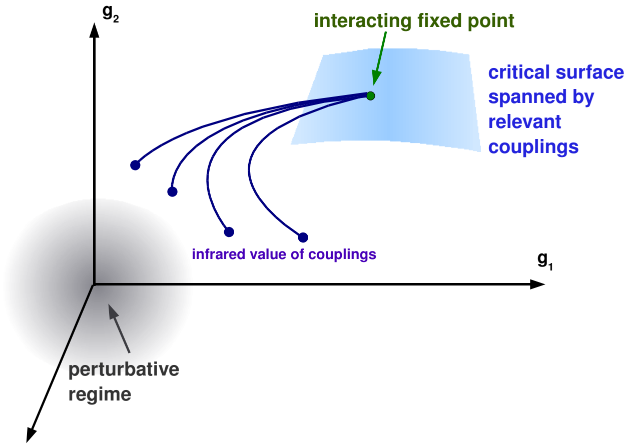


[Weinberg, 1979]

Asymptotic safety



Fundamental theory:

Running dimensionless couplings approach fixed point towards UV

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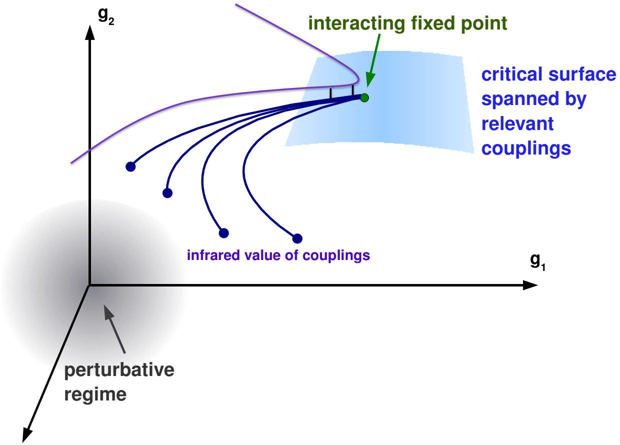

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Predictive theory:

Finite number of relevant (UV-attractive) couplings:

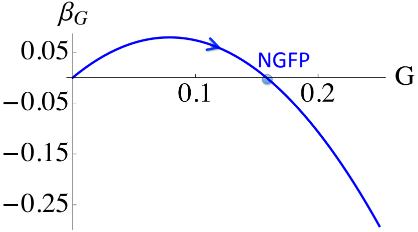
$$g_i(k) = g_* + c\ \left(\frac{k}{k_0}\right)^{-\theta_i} \qquad \theta_i = d_i + \eta_i$$

Asymptotically Safe Quantum Gravity: Evidence

search for scale-free point: $G(k) = G_N k^2$

- epsilon-expansion $d = 2 + \epsilon$ [Weinberg, 1979]

$$\beta_G = \epsilon G - \frac{38}{3} G^2$$



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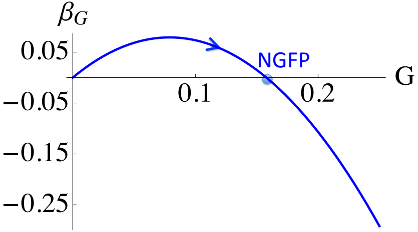
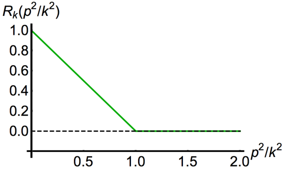


- Causal Dynamical Triangulations (?) [Ambjorn, Jurkiewicz, Loll, 2000]
- symmetry-reduced setting [Niedermaier, 2009]
- functional Renormalization Group equation [Wetterich, 1993; Reuter, 1996]

Functional Renormalization Group

include high- energy quantum fluctuations first:

$$e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \, e^{-S[\varphi]-\frac{1}{2}\int_p \varphi(p)\, R_k(p)\, \varphi(-p)}$$



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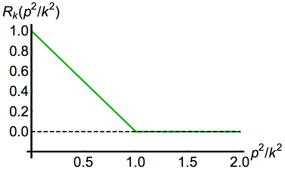

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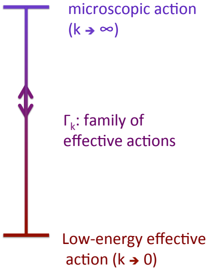
scale-dependent action:

$\mathbf{\Gamma}_k$ contains effect of quantum fluctuations above momentum scale k

$\Gamma_{k\to 0} = \Gamma \qquad \Gamma_{k\to\Lambda\to\infty} \to S$

$\Gamma = \Gamma_{\mathrm{EH}} \qquad S$: prediction!



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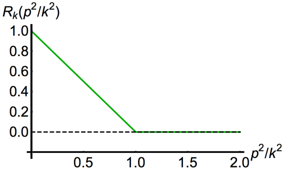

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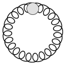
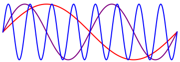
Wetterich equation [1993]:

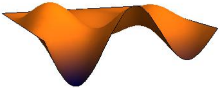
$$\partial_k \Gamma_k = \frac{1}{2}\mathrm{STr}\left(\Gamma_k^{(2)} + R_k\right)^{-1} \partial_k R_k =$$ 

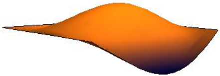
$\to$ non-perturbative $\beta_g = k\partial_k g(k) \to$ Quantum Gravity [Reuter, 1996]

Setting a scale in quantum gravity

RG: sort quantum fluctuations according to momentum

flat background: p^2  curved background: D^2





fluctuating spacetime?

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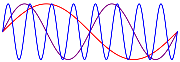

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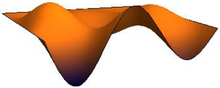
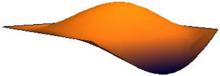
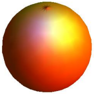


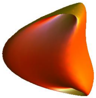


fluctuating spacetime?

background field method: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$

$$\int \mathcal{D}g_{\mu\nu} e^{-S[g_{\mu\nu}]} = \int \mathcal{D}h_{\mu\nu} e^{-S[\bar{g}_{\mu\nu}+h_{\mu\nu}]}$$





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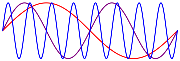
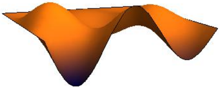
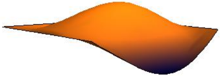
flat background: p^2  curved background: D^2





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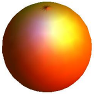

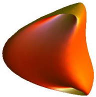

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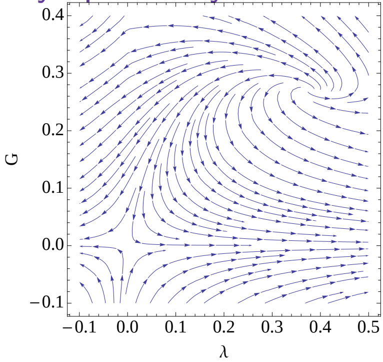
action symmetric under $\bar{g}_{\mu\nu} \rightarrow \bar{g}_{\mu\nu} + \gamma_{\mu\nu}$, $h_{\mu\nu} \rightarrow h_{\mu\nu} - \gamma_{\mu\nu}$

broken by regulator! $\Rightarrow$ background couplings $\neq$ fluctuation couplings

Asymptotically Safe Quantum Gravity: Evidence

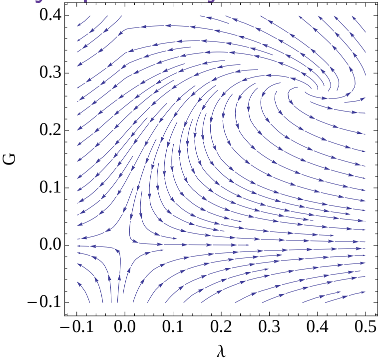


$$\Gamma_{k\,\mathrm{EH}} = \frac{-1}{16\pi G_N(k)} \int (R - 2\bar{\lambda}(k))$$

[Reuter ('96); Reuter, Saueressig ('01); Litim ('03)]

fixed-point action: *prediction*

Asymptotically Safe Quantum Gravity: Evidence



$$\Gamma_{k\,\mathrm{EH}} = \frac{-1}{16\pi G_N(k)} \int (R - 2\bar{\lambda}(k))$$

[Reuter ('96); Reuter, Saueressig ('01); Litim ('03)]

fixed-point action: *prediction*

$$\Gamma_k = \Gamma_{k\,\mathrm{EH}} + \Gamma_{\mathrm{gauge-fixing}} + \Gamma_{\mathrm{ghost}} + \int d^4x \sqrt{g}\,(f(R) + R_{\mu\nu}R^{\mu\nu} + ...)$$

Manrique, Reuter, Saueressig ('09, '10);

Donkin, Pawlowski ('12); Codello, D'Odorico, Pagani ('13);

Christiansen, Litim, Pawlowski, Rodigast ('12); Christiansen, Knorr, Pawlowski, Rodigast ('14);

Doná, A.E., Percacci ('14); Becker, Reuter ('14)

A.E., Gies, Scherer ('09); A.E., Gies ('10);

Groh, Saueressig ('10); A.E. ('13)

Machado, Saueressig ('07);

Codello, Percacci, Rahmede ('08);

Benedetti, Caravelli ('12);

Falls, Litim, Nikolakopoulos ('13);

Dietz, Morris ('12, '13); Demmel, Saueressig, Zanusso ('14)

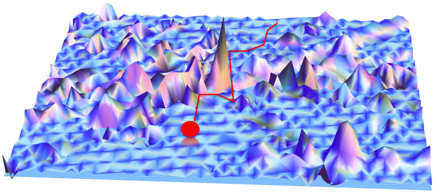
Benedetti, Machado, Saueressig ('09)

- What are the properties of quantum spacetime?
- What is the status of the cosmological constant problem in asymptotic safety?
- Does matter matter in asymptotically safe gravity?

Nature of quantum spacetime

Nature of quantum spacetime

Probe the quantum regime by a (fictitious) diffusing particle:



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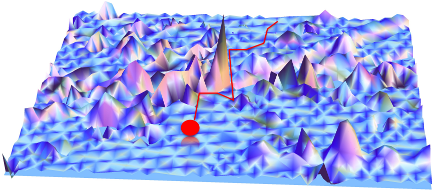

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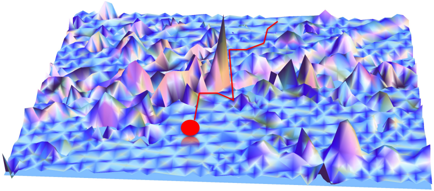

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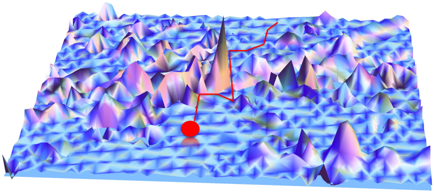

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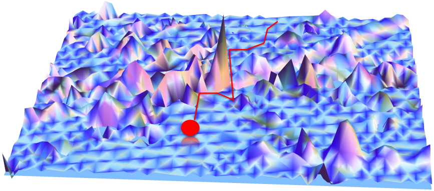

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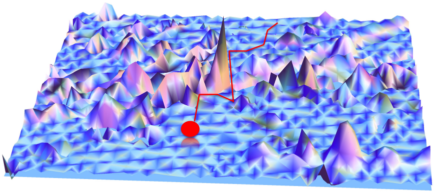

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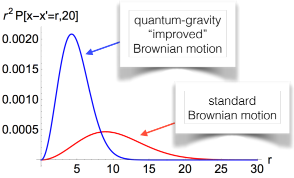

[Calcagni, A.E., Saueressig, 2013]

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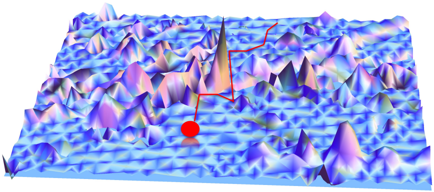

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spectral dimension: $d_s = 4$ at large length scales, $d_s = 2$ at small scales

[Lauscher, Reuter (2005); Reuter, Saueressig (2011); Calcagni, A.E., Saueressig (2013)]

quantum spacetime undergoes dynamical dimensional reduction

The cosmological constant in asymptotic safety

'natural': $\Lambda \sim M^2_{\rm Planck}$ measured: $\Lambda_{\rm meas} \sim 10^{-122} \Lambda_{\rm expect}$

$\rightarrow$ fine-tuning of bare c.c.

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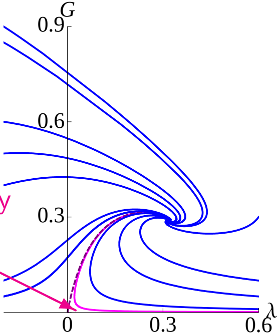
fine-tuning
of RG trajectory



$G = G_N k^2$, $\lambda = \Lambda / k^2$

Motivation: Why unimodular quantum gravity?

unimodular: $\sqrt{g} = \bar{\epsilon} = const$ [Einstein, 1919; van Dam, van der Bij, Ng (1982); Unruh (1989)...]

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Can unimodular gravity be asymptotically safe?

$\sqrt{g} = \mathrm{const}$ $\rightarrow$ spectrum of quantum fluctuations differs to standard case
$\sqrt{g} = \mathrm{const}$ $\rightarrow$ symmetry: transverse diffeomorphisms

$\Rightarrow$ Renormalization Group flow differs from standard case

Unimodular asymptotic safety

Einstein-Hilbert truncation: G features UV-attractive fixed point [A.E., 2013]

$f(R)$ truncation [A.E., to appear]:

(regulator as in [Benedetti, Caravelli, 2012])

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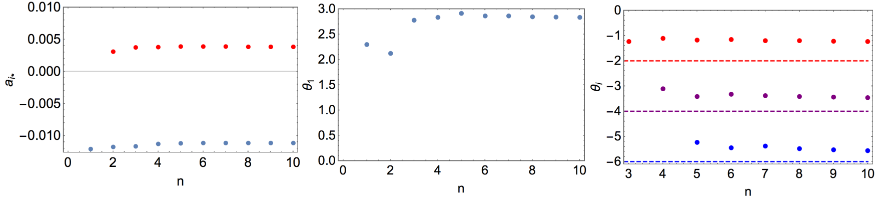

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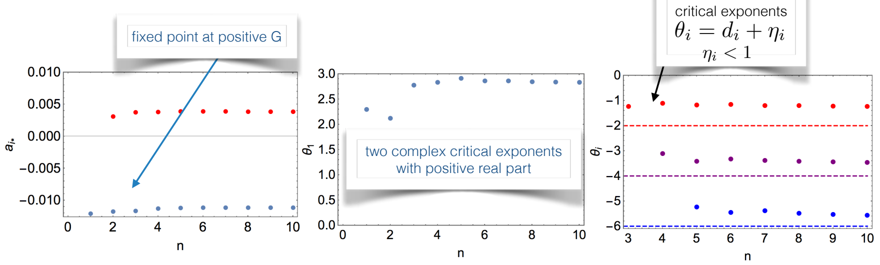

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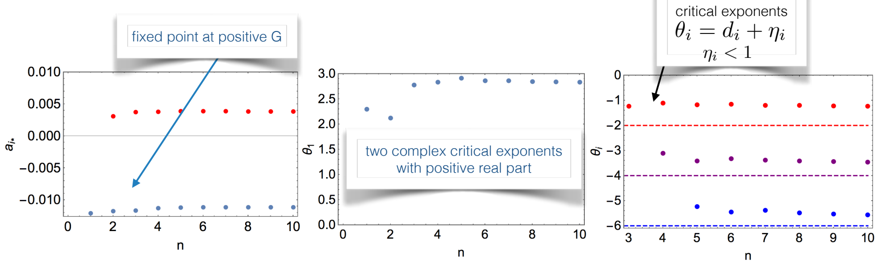

unimodular asymptotic safety seems viable!

Does matter matter in quantum gravity?

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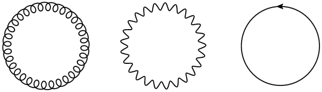
quantum fluctuations of all fields drive Renormalization Group flow:



Quantum gravity and matter

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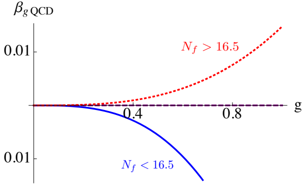
Matter will have an effect on quantum gravity

analogy: Quantum Chromodynamics:



Asymptotic freedom only for $N_f < 16.5$

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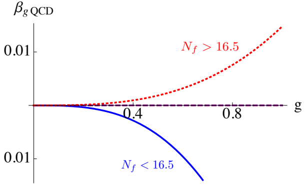

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Is Asymptotically Safe Gravity compatible with Standard Model matter?

Matter matters

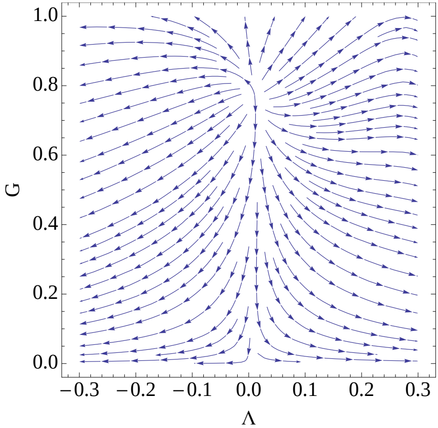
with P. Doná, R. Percacci (2013, 2014):

$$\Gamma_k = \Gamma_{k\,\mathrm{Einstein-Hilbert}} + \Gamma_{k\,\mathrm{matter}}$$

$$\Gamma_{k\,\mathrm{Einstein-Hilbert}} =$$
$$\int d^dx\sqrt{\bar{g}}\left(\frac{1}{16\pi G}\left(-\bar{R}+2\Lambda\right)+\frac{Z_h}{2}\,h\cdot((-\bar{D}^2-2\Lambda)+W(R))\cdot h\right)$$

[see also Christiansen, Litim, Pawlowski, Rodigast (2012); Codello, D'Odorico, Pagani (2013)]

Results: Graviton wave function renormalization



fixed point persists

critical exponents purely real ($\theta_1 = 3.3$, $\theta_2 = 1.9$)

$\eta_h = \partial_t \ln Z_h = 0.27$ $G_* = 0.77$ $\Lambda_* = 0.01$

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N_V Abelian vector bosons:
$S_V = \frac{Z_V}{4}\int d^dx\sqrt{g}\sum_{i=1}^{N_F}g^{\mu\nu}g^{\kappa\lambda}F^i_{\mu\kappa}F^i_{\nu\lambda}+\frac{Z_V}{2\xi}\int d^dx\sqrt{\bar{g}}\sum_{i=1}^{N_F}\left(\bar{g}^{\mu\nu}\bar{D}_\mu A^i_\nu\right)^2$

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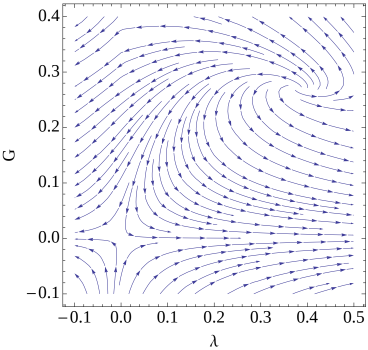
N_{RS} spin 3/2 fields: $S_{RS} = \frac{1}{2}\int d^dx\sqrt{g}\sum_{i=1}^{N_{RS}}\epsilon^{\mu\nu\rho\sigma}\bar{\Psi}_\mu\gamma_\nu\gamma_5\nabla_\rho\Psi_\sigma$

Matter matters

$\rightarrow \beta_G, \beta_\lambda$



???

Approximative analysis

(neglect graviton and matter wave function renormalizations)

$$\beta_G = 2G + \frac{G^2}{6\pi}\left(\qquad - 46 \right),$$

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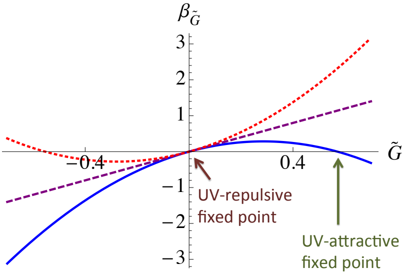
$$\beta_G = 2G + \frac{G^2}{6\pi}\left(N_S + 2N_D - 4N_V - N_{RS} - 46\right)$$ [P.Doná, A.E., R. Percacci, 2013, 2014]

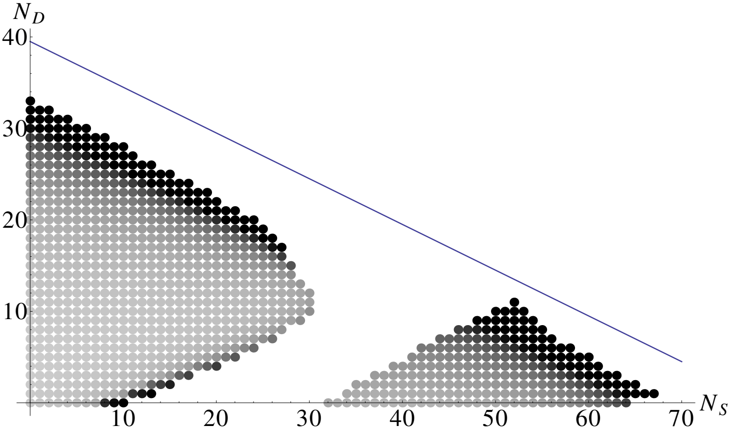


→ for a given number of vectors N_V (and $N_{RS} = 0$), there is an upper limit on the number of scalars N_S and Dirac fermions N_D!

Matter matters in asymptotically safe quantum gravity!

Full analysis

$N_V = 12$, $N_{RS} = 0$



upper limit on N_D and N_S

Standard Model: $N_V = 12$, $N_D = 45/2$, $N_S = 4$: compatible with gravitational fixed point (disclaimer: truncated RG flow)

Specific matter models

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supergravity $(N_{RS} = 1^*)$ ✓

supersymmetric extension (MSSM*: $N_S = 49, N_D = 61/2, N_V = 12$) ✗

$*$ Interactions and regulator not supersymmetric

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GUT (SO(10): $N_S = 97, N_D = 24, N_V = 45$) ✗

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Prediction:
Only specific models with restricted matter content are compatible with Asymptotically Safe Quantum Gravity!

Unimodular case

(neglect graviton and matter wave function renormalizations)

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$$\beta_G = 2G + \frac{G^2}{6\pi}\left(N_S + 2N_D - 4N_V - N_{RS} - 20\right),$$ [A.E., to appear]

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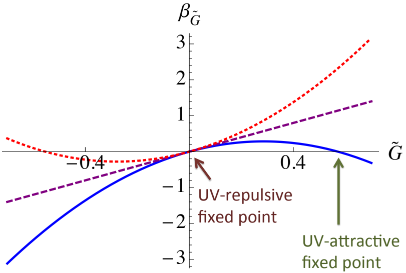
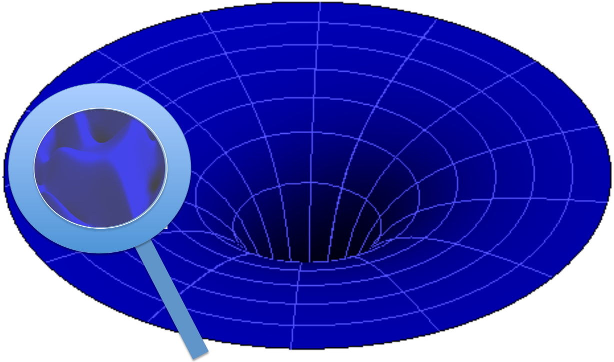


Standard Model compatible

critical number of fermions and scalars changes slightly
⇒ BSM discoveries could distinguish QG models!

Tests of quantum gravity



Does testing quantum gravity require galaxy-size accelerators?

No! Can test Asymptotically Safe Quantum Gravity at LHC, 14 TeV:
Look for Beyond-Standard-Model particle physics

Summary

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Thank you for your attention!