Title: Why matter matters in quantum gravity

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Abstract: I will argue that a fundamental theory of quantum gravity that is applicable to our universe must include matter degrees of freedom. In my talk I will focus on the option that these are fundamental, in contrast to low-energy effective, degrees of freedom, and must thus be included in the microscopic dynamics of spacetime.
I will present evidence that dynamical Standard Model matter is compatible with asymptotically safe quantum gravity, while several "Beyond Standard Model" scenarios are disfavored. I will also discuss how the coupling to matter opens a window into the observational quantum gravity regime.

Why matter matters in quantum gravity

Astrid Eichhorn

Perimeter Institute, Waterloo

Renormalization Group approaches to quantum gravity, April 25, 2014

Introduction: What matters in quantum gravity

our universe contains gravitational
and matter degrees of freedom

assume: matter & gravity fundamental

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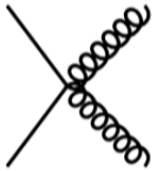
interaction between these cannot be switched off

$$\int d^d x \sqrt{g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \longrightarrow$$



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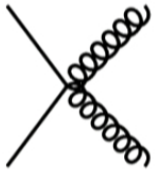

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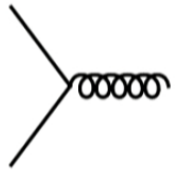

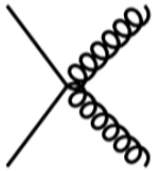

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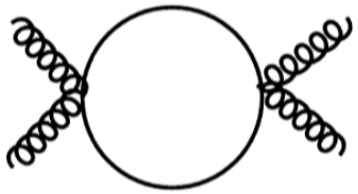
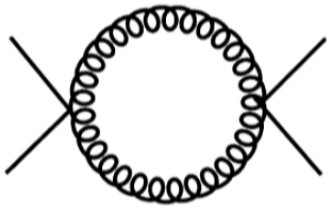


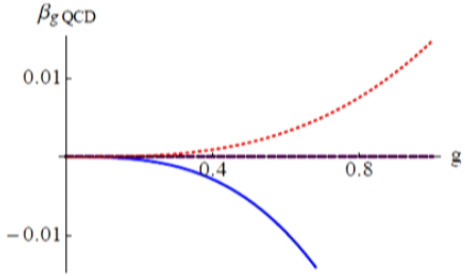


RG flow in gravity and matter sector driven by metric & matter fluctuations $\Rightarrow$ gravity and matter matters!

Learning by example: Possible effects of matter

Towards the UV: Quantum Chromodynamics:

Asymptotic freedom only for $N_f < 16.5$



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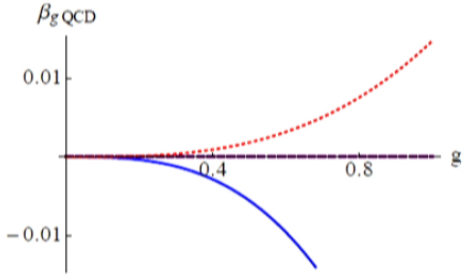

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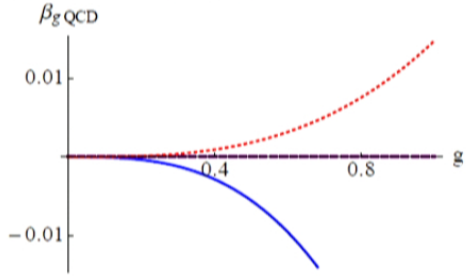

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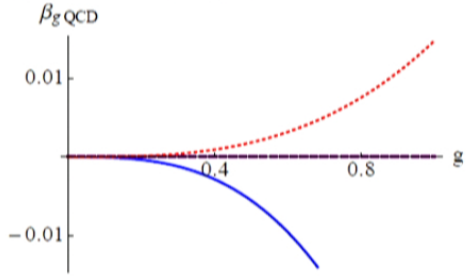

UV completion for gravity compatible with Standard Model?

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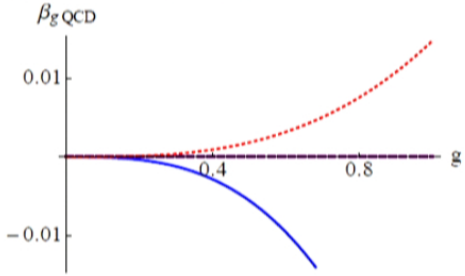

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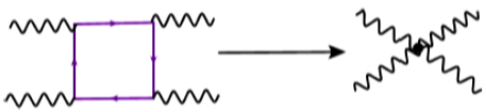
Towards the IR: Quantum Electrodynamics:

microscopic action:
no $\gamma - \gamma$ interaction

low-energy effective action:
fermionic fluctuations:



Euler-Heisenberg effective action ($\int F^2 + F^4$)

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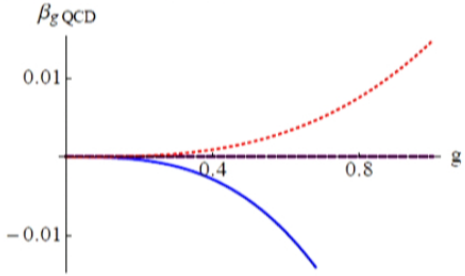

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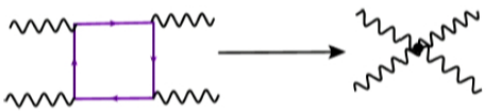

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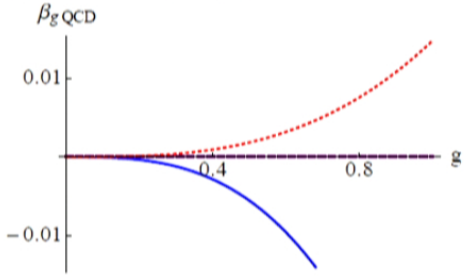

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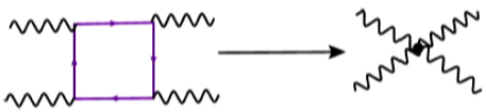


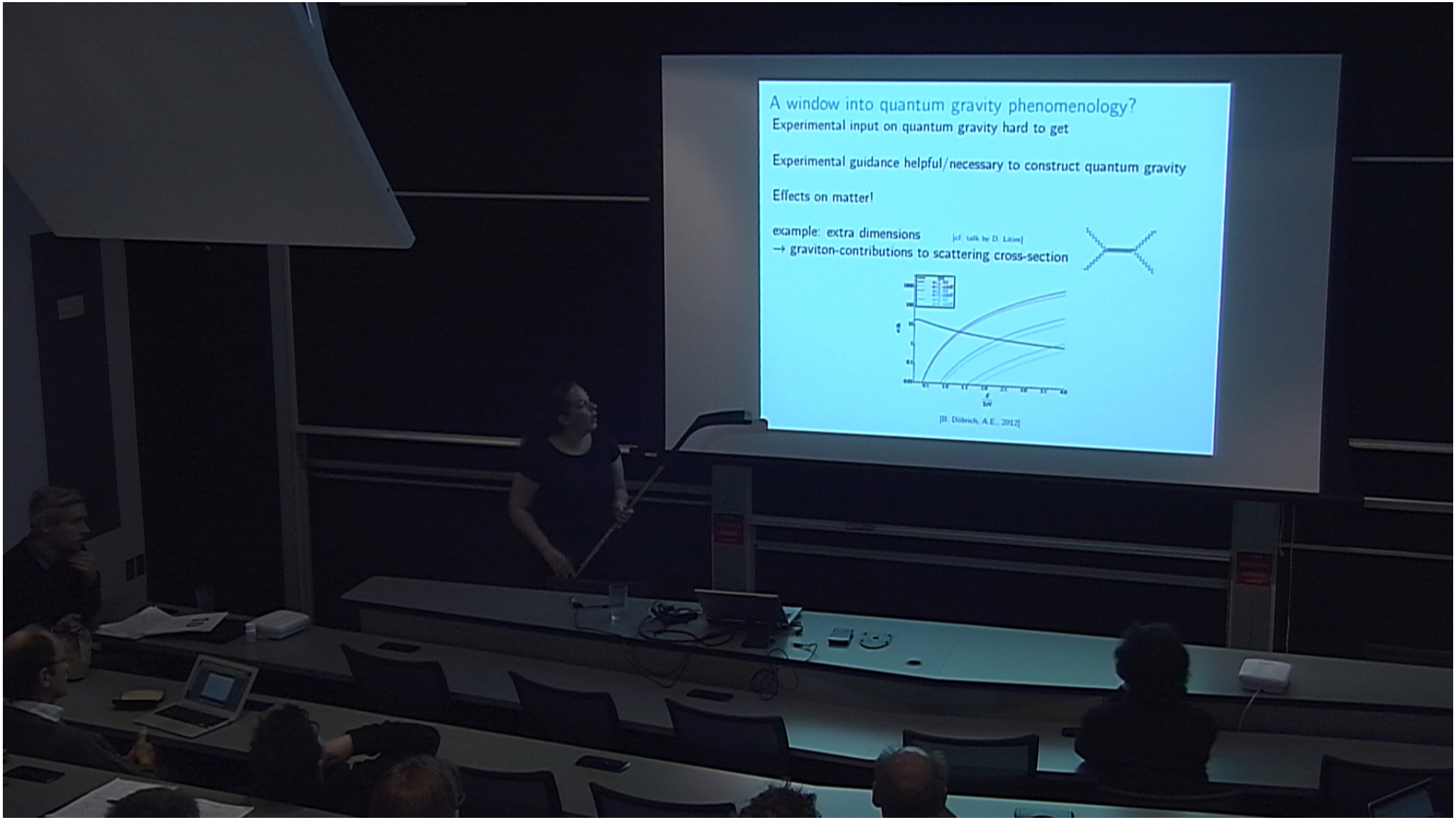
Euler-Heisenberg effective action ($\int F^2 + F^4$)

Low-energy effective action compatible with observations?

A window into quantum gravity phenomenology?

Experimental input on quantum gravity hard to get

Experimental guidance helpful/necessary to construct quantum gravity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Effects on matter!
example: extra dimensions
[cf. talk by D. Litim]
→ graviton-contributions to scattering cross-section
[B. Dübrich, A.E., 2012]

Matter effects on the gravitational fixed point

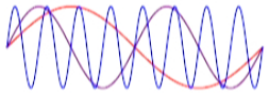
with P. Doná, R. Percacci (2013): Truncation of the effective action:

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

with "bimetric" structure [cf. talks by J. Pawlowski, M. Reuter]

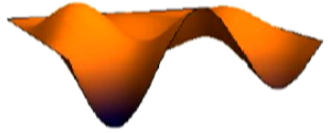
Setting a scale in quantum gravity

RG: sort quantum fluctuations according to momentum

flat background: p^2 

curved background: D^2

fluctuating spacetime?



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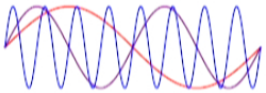
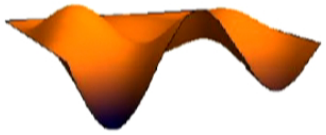
flat background: p^2  curved background: D^2



fluctuating spacetime?

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

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

$\bar{D}^2 \rightarrow$ short/long wavelength quantum fluctuations $\rightarrow h_{\mu\nu}\, R_k(\bar{D}^2)\, h_{\mu\nu}$

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

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

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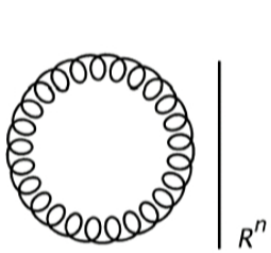
with P. Doná, R. Percacci (2013): Truncation of the effective action:

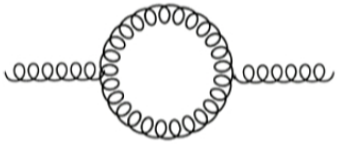
$$\Gamma_k = \Gamma_{k\,\mathrm{Einstein-Hilbert}} + \Gamma_{k\,\mathrm{matter}}$$

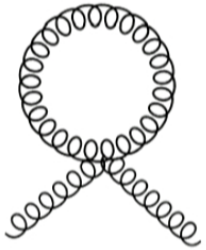
$$\Gamma_{k\,\mathrm{Einstein-Hilbert}} + S_{\mathrm{gf}} = \frac{1}{16\pi G}\int d^d x\sqrt{\bar{g}}\left(-\bar{R} + 2\Lambda\right)$$

$$+\frac{Z_h}{2}\int d^d x\sqrt{\bar{g}}\, h\cdot\left(\left(-\bar{D}^2 - 2\Lambda\right) + W(R)\right)\cdot h$$



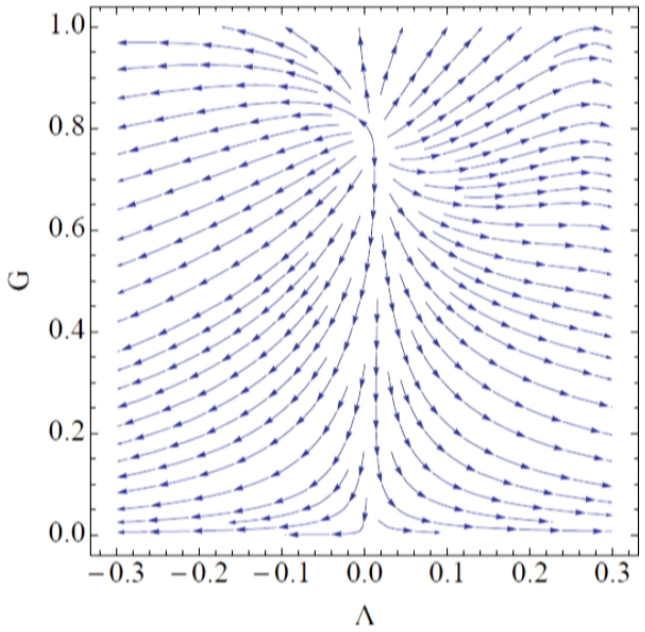
$\beta_G,\ \beta_\Lambda$





$\partial_t Z_h$

Results: Graviton wave function renormalization



fixed point persists

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

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

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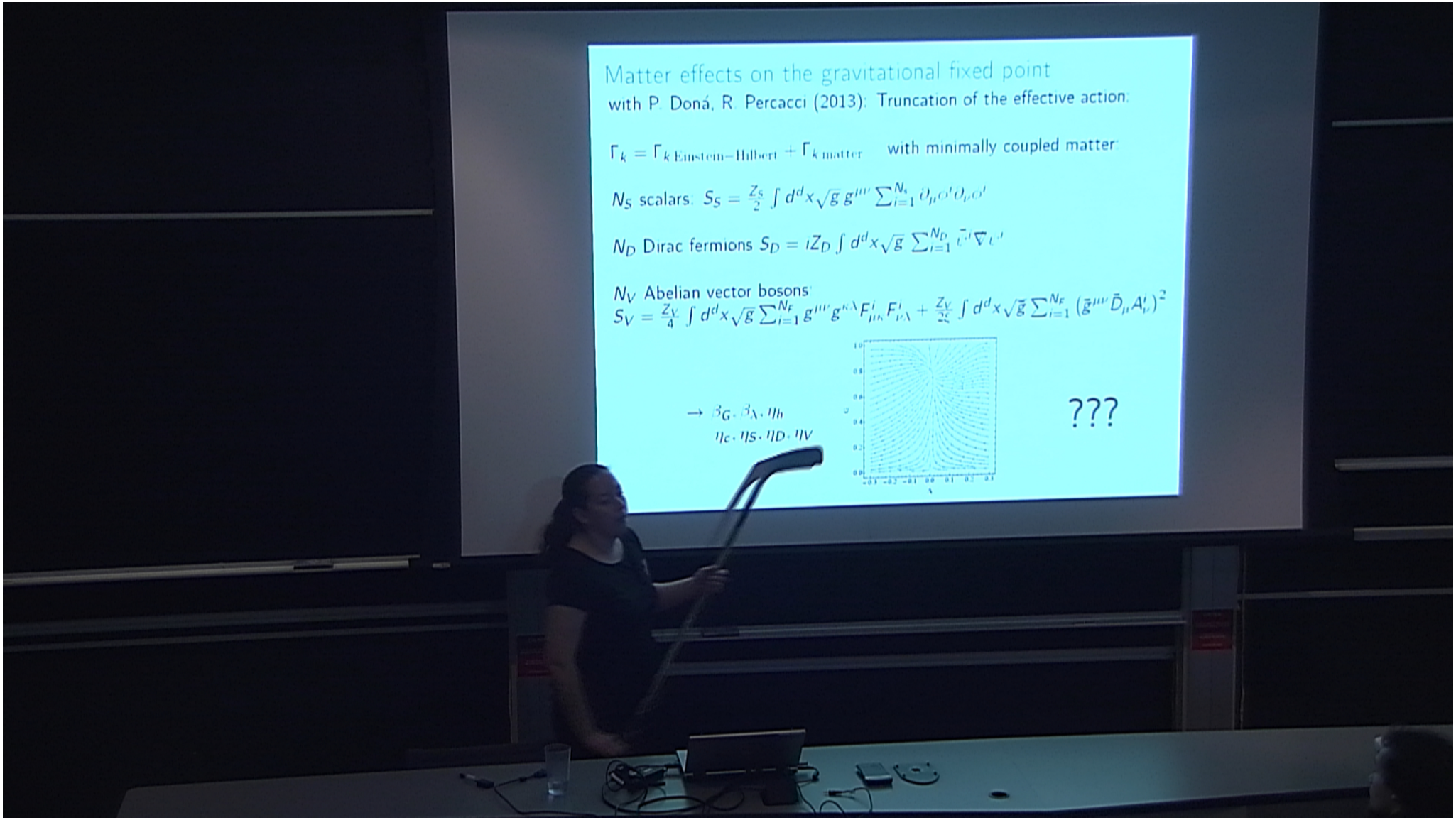
with P. Doná, R. Percacci (2013): Truncation of the effective action:

$\Gamma_k = \Gamma_{k\,\mathrm{Einstein-Hilbert}} + \Gamma_{k\,\mathrm{matter}}$ with minimally coupled matter:

N_S scalars: $S_S = \frac{Z_S}{2} \int d^d x \sqrt{g}\, g^{\mu\nu} \sum_{i=1}^{N_s} \partial_\mu \phi^i \partial_\nu \phi^i$

N_D Dirac fermions $S_D = i Z_D \int d^d x \sqrt{g} \sum_{i=1}^{N_D} \bar{\psi}^i \not{\nabla} \psi^i$

N_V Abelian vector bosons:
$S_V = \frac{Z_V}{4} \int d^d x \sqrt{g} \sum_{i=1}^{N_F} g^{\mu\nu} g^{\kappa\lambda} F^i_{\mu\kappa} F^i_{\nu\lambda} + \frac{Z_V}{2\xi} \int d^d x \sqrt{\bar{g}} \sum_{i=1}^{N_F} \left(\bar{g}^{\mu\nu} \bar{D}_\mu A^i_\nu\right)^2$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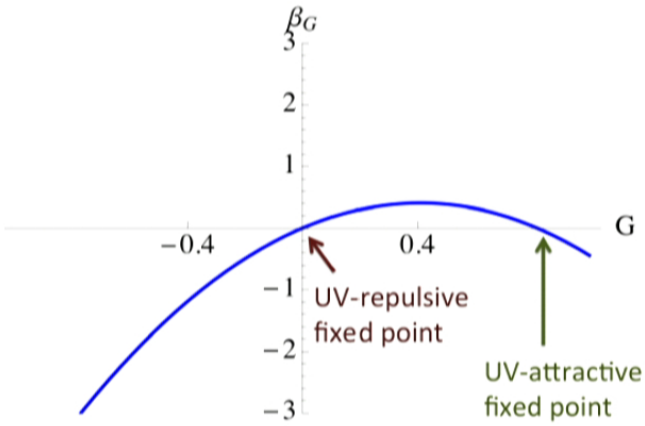
$\rightarrow \beta_G, \beta_\Lambda, \eta_h$
$\eta_c, \eta_S, \eta_D, \eta_V$
???

Perturbative analysis

(neglect graviton and matter wave function renormalizations)

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



Perturbative analysis

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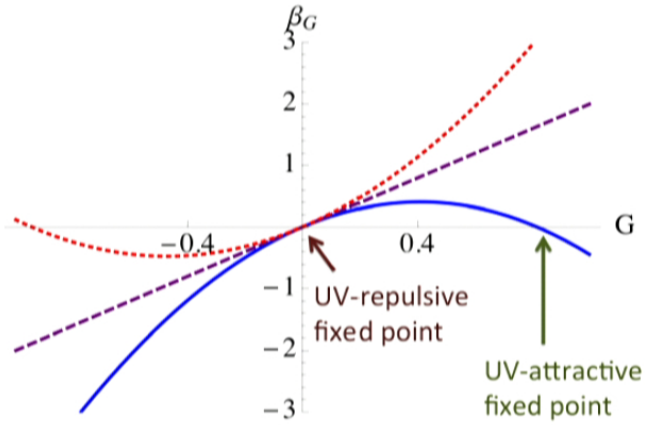
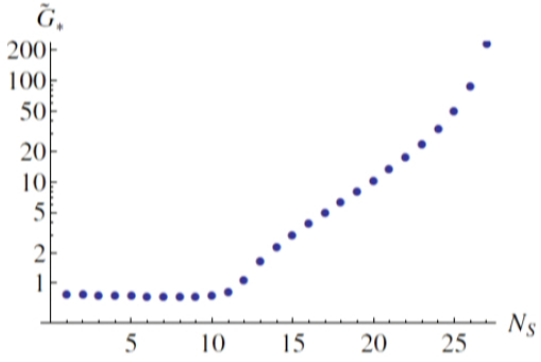
$$\beta_G = 2G + \frac{G^2}{6\pi}\left(N_S + 2N_D - 4N_V - 46\right),$$

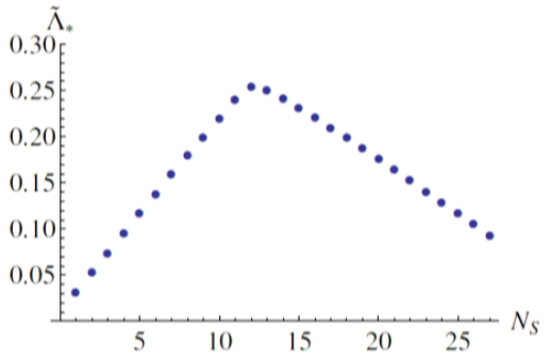


$\rightarrow$ for a given number of vectors N_V, there is an upper limit on the number of scalars N_S and Dirac fermions N_D!

Matter matters in asymptotically safe quantum gravity!

Fermions, scalars and the fixed point





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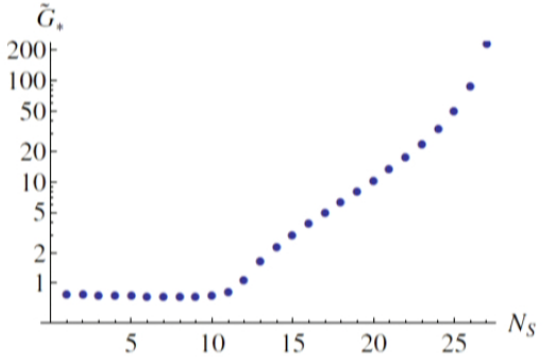
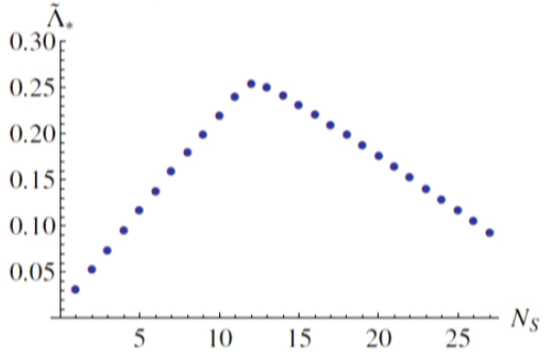
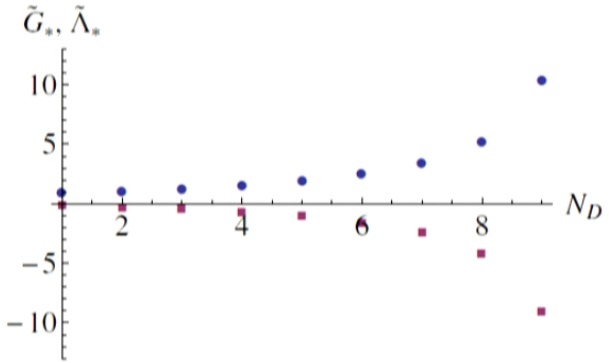
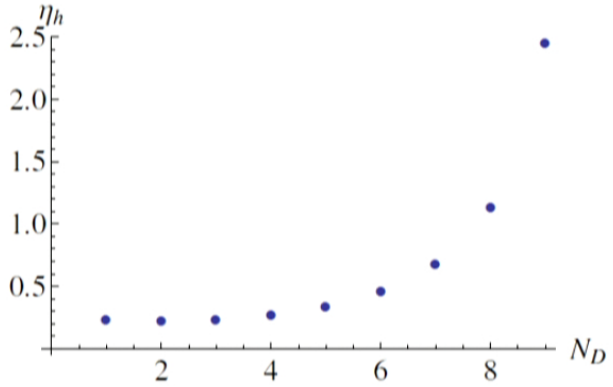


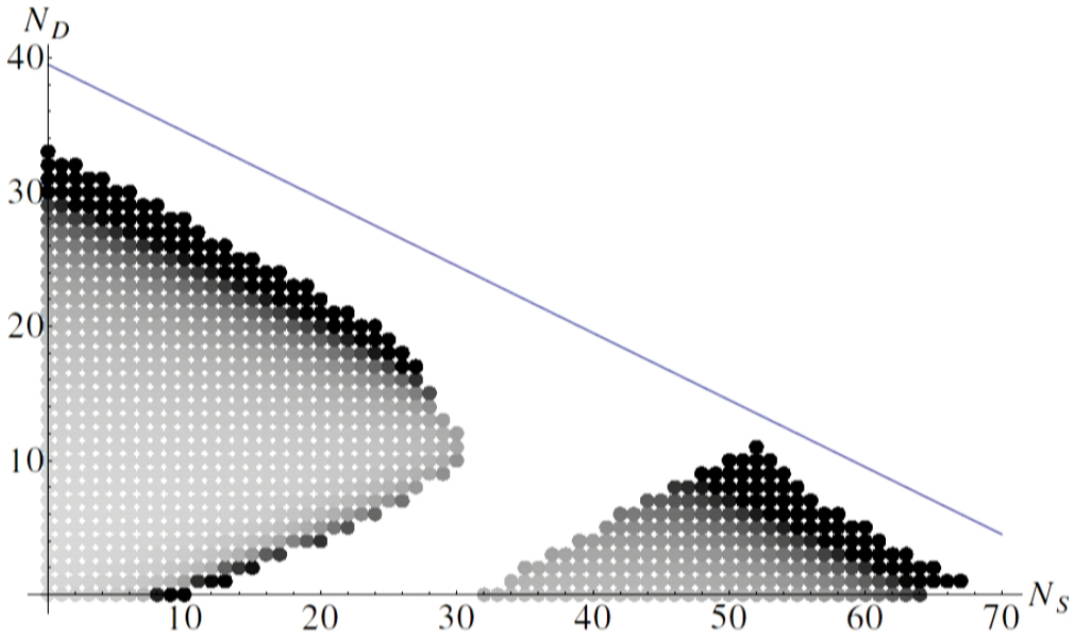






scalars & fermions drive G_* to divergence $\Rightarrow$ upper limit on N_S, N_D

Full analysis for $N_V = 12$



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

Specific matter models

Standard Model: $(N_S = 4, N_D = 45/2, N_V = 12)$ ✓

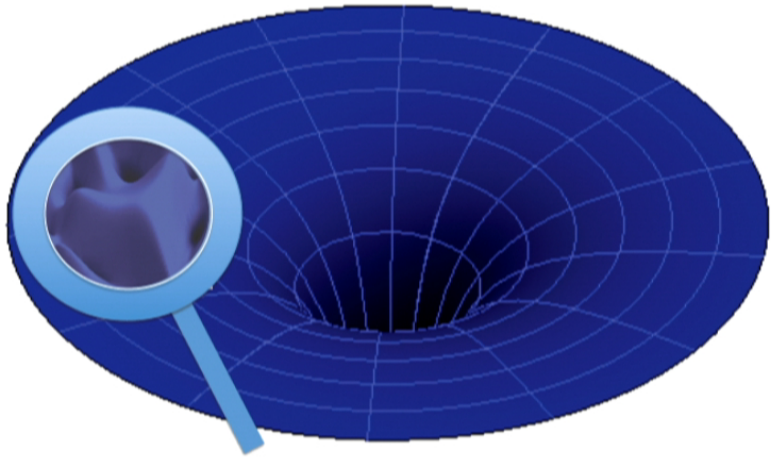
→ right-handed neutrinos? ✓

→ dark matter scalar? ✓ [see also 1404.5962 [hep-ph] w. M. Scherer]

→ axion? ✓

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

Tests of quantum gravity

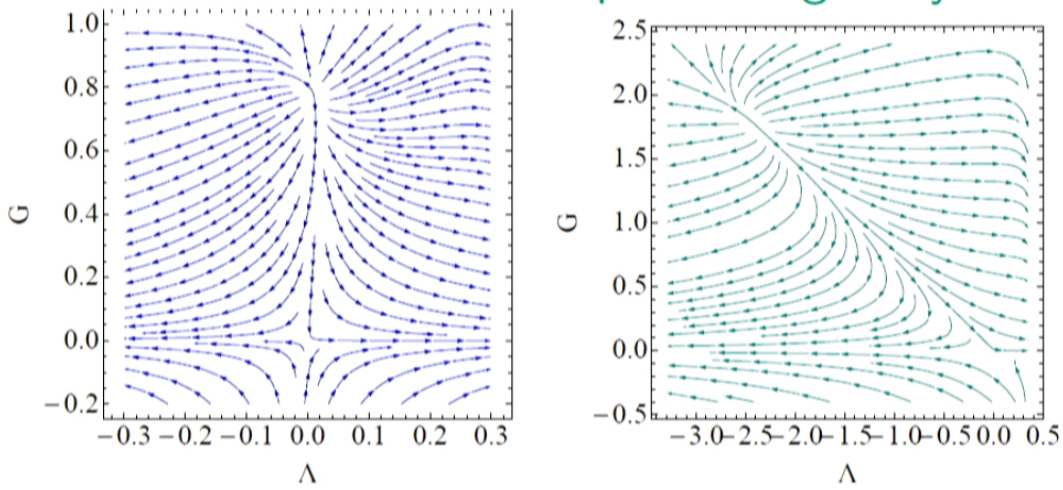


Does testing quantum gravity require galaxy-size accelerators?

Possibly could test Asymptotically Safe Quantum Gravity at LHC, 14 TeV: Look for Beyond-Standard-Model particle physics

experimental searches for weakly-coupled low-mass particles (dark matter) might also test quantum gravity

Matter and "the scale of quantum gravity"



- $G \sim O(1)$: quantum gravity effects "visible"

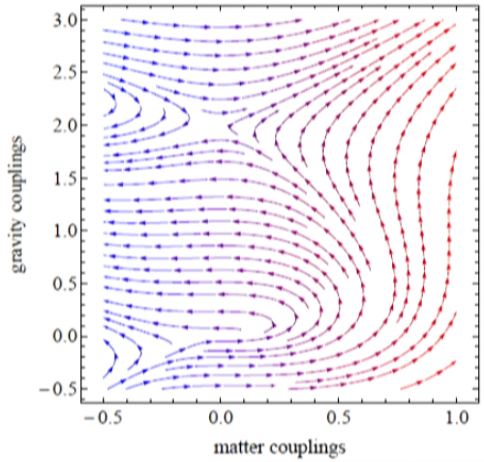
$$\beta_G = 2G + \frac{G^2}{6\pi}\left(N_S + 2N_D - 4N_V\right)$$
$$\Rightarrow \frac{k_1^2}{M_{\rm Pl}^2} = 1 - \frac{1}{12\pi}(N_S + 2N_D - 4N_V)$$ [cf. X. Calmet, T.-C. Yang, 2011]

- fixed-point scale: $G_N = \frac{G}{k^2} \to \frac{G_*}{k^2}$:
  $M_{*\,\rm SM} \approx 10 M_*$

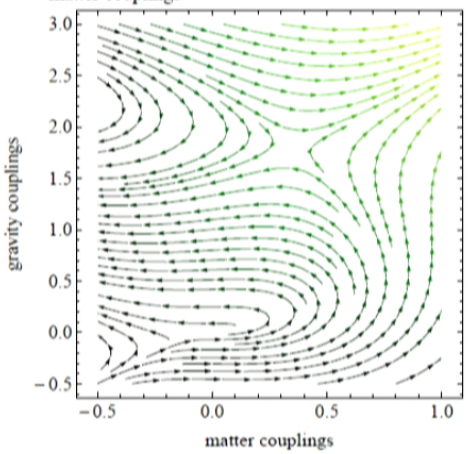
Asymptotic safety: Matter-gravity fixed point structure

Two possible scenarios:

- Gravity-dominated
  (Gaussian matter fixed point)



- Fully interacting gravity-matter fixed point



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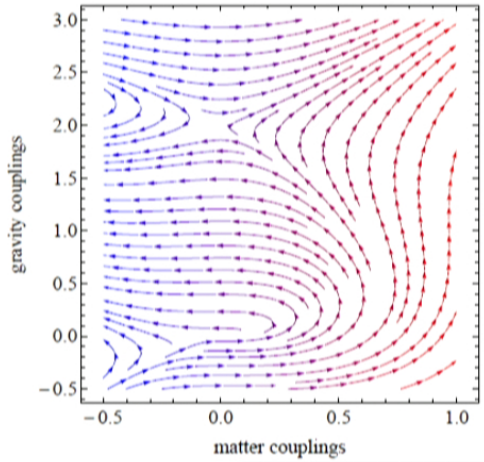
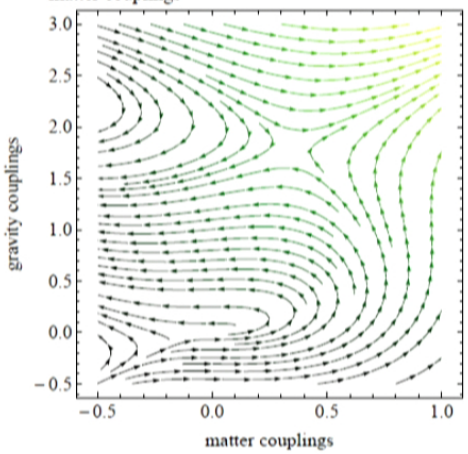
  (Gaussian matter fixed point)



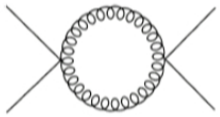
- Fully interacting gravity-matter fixed point



Gravity-induced matter self-interactions

QG fluctuations induce matter self-interactions:

Example: scalar field: [A.E., 2012]



$$Z_k \int d^4x \sqrt{g}\, g^{\mu\nu}\, \partial_\mu\phi\partial_\nu\phi \;\rightarrow\; \rho(k) \int d^4x \sqrt{g}\, \left(g^{\mu\nu}\, \partial_\mu\phi\partial_\nu\phi\right)^2$$

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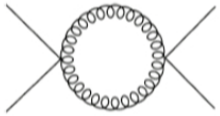

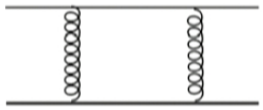

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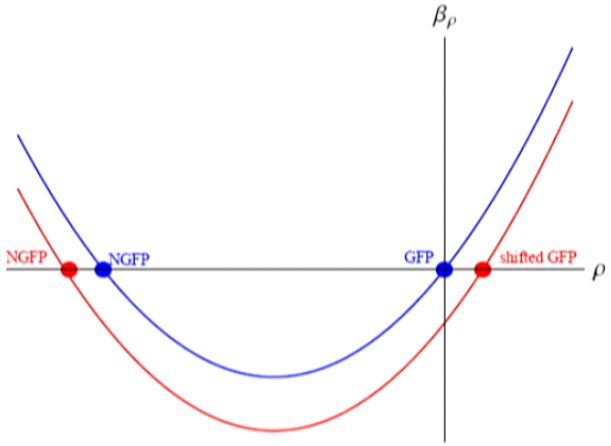


no coupling to gravity: Gaußian fixed point exists

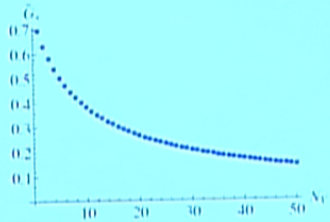
metric fluctuations induce non-vanishing interactions

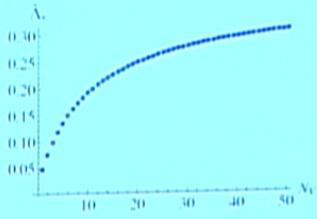
for details & fixed-point values: [A.E. 2012]

Summary & Outlook

- Matter matters in (asymptotically safe) quantum gravity
- Experimental tests of quantum gravity possible (search for Beyond-Standard-Model physics at LHC and low-mass particle search experiments)
- Matter-gravity fixed point interacting $\rightarrow$ full structure remains to be explored and (experimental) implications to be studied!

Vectors and the fixed point





	$\tilde{G}_*$	$\tilde{\Lambda}_*$	θ_1	θ_2	η_h	η_c	η_V
$\lim_{N_V \to \infty}$	0	3/8	4	2	9/10	0	0

vector degrees of freedom unrestricted by fixed-point requirement