Does (asymptotically safe) quantum gravity have to be a TOE?

Workshop on strongly-interacting field theories,
TPI Jena
Nov. 7, 2015

Astrid Eichhorn, Imperial College, London

Quantum spacetime and matter?

Is it “safe” to ignore matter degrees of freedom while exploring the quantum structure of spacetime?

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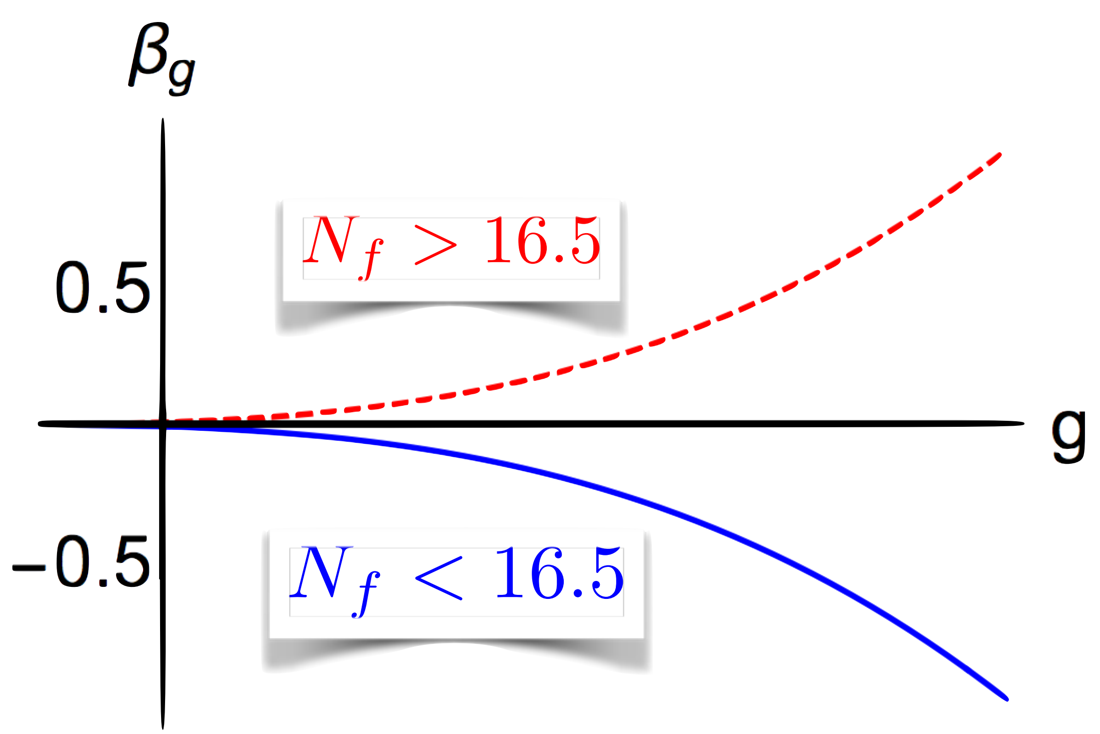

Asymptotic freedom in Yang-Mills theories does not exist for arbitrary number of matter fields

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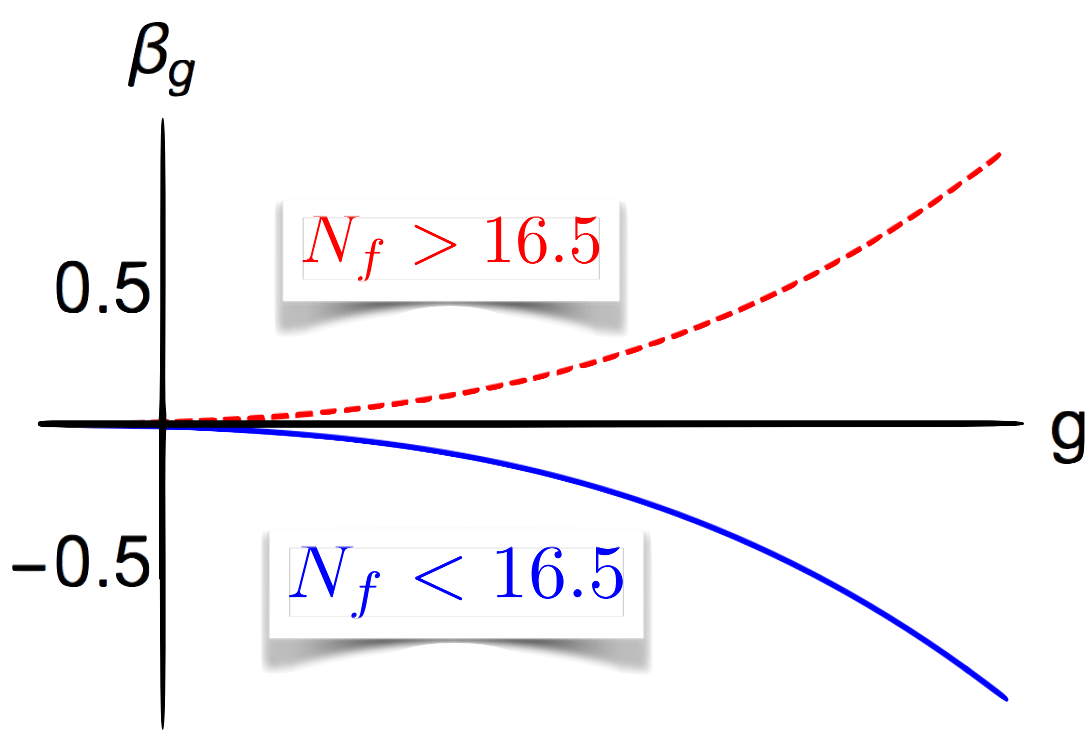

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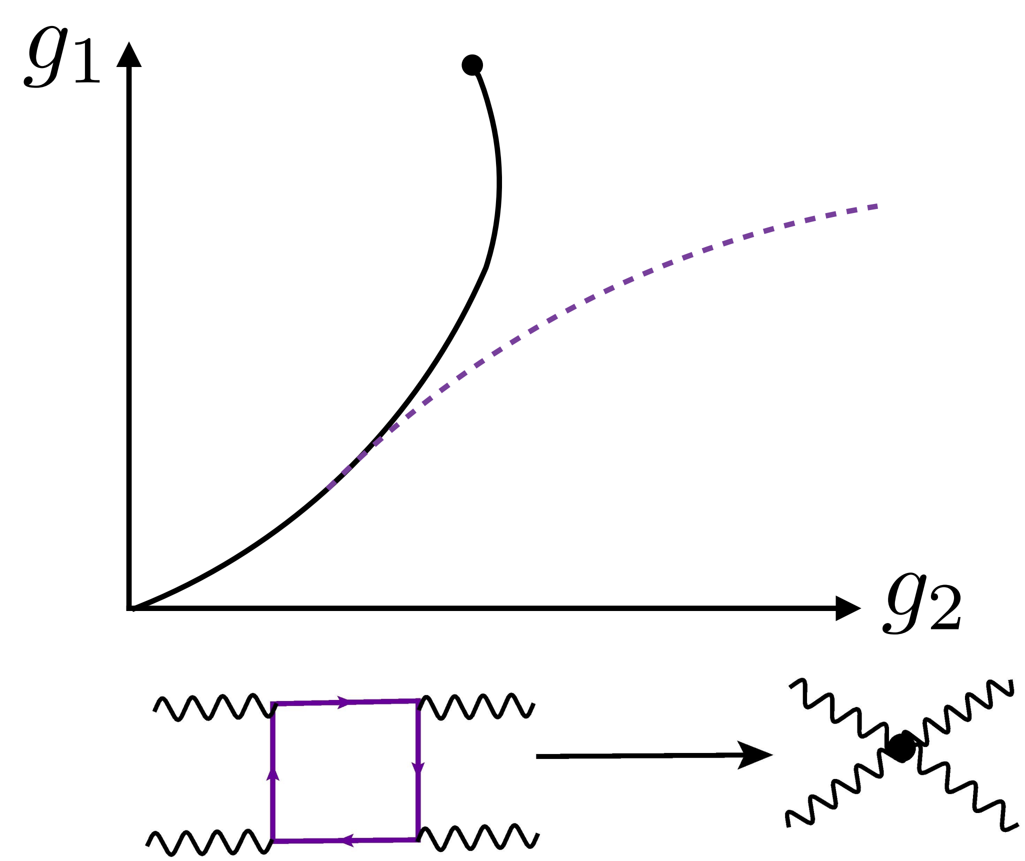

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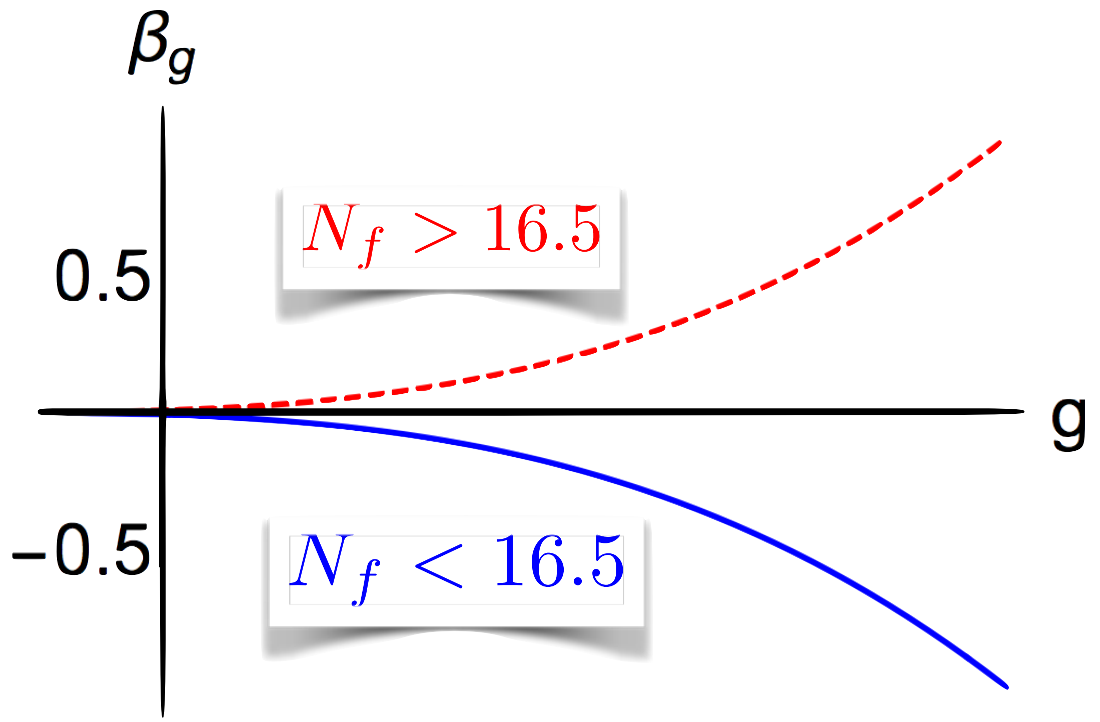

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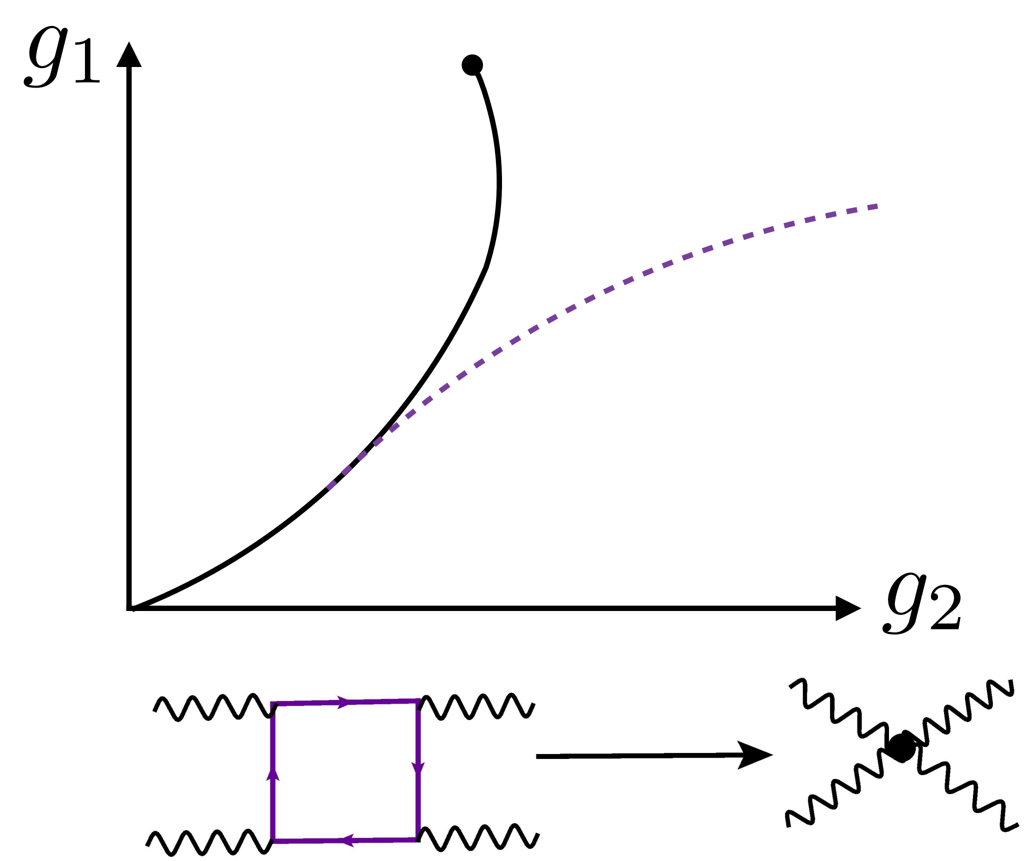
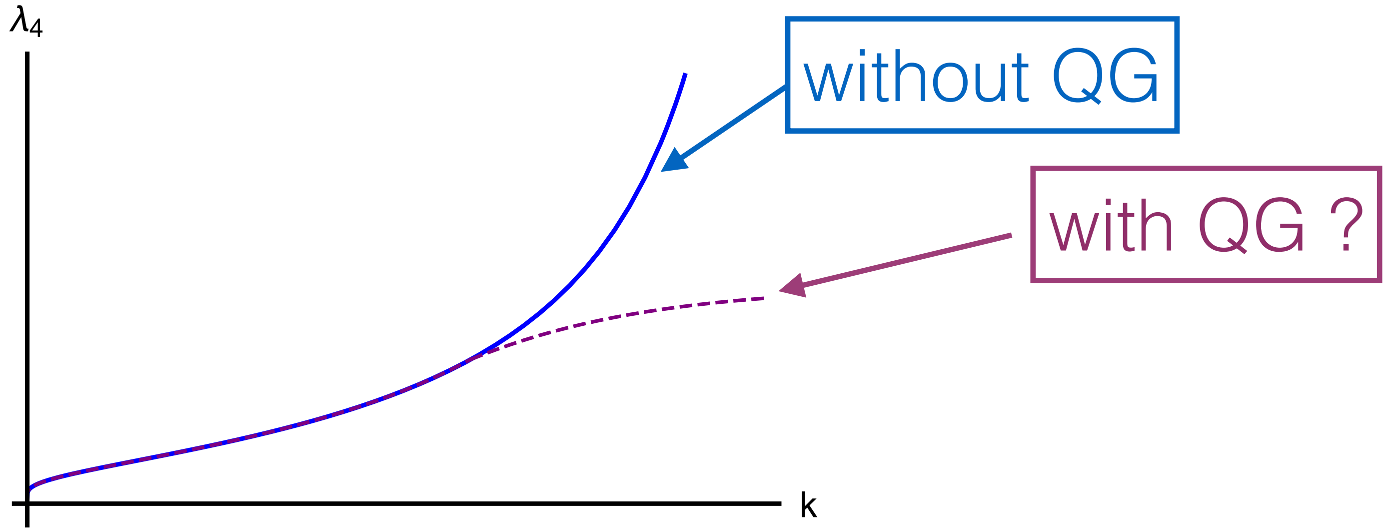


In sum-over-histories setting for QG, matter fluctuations will generically change microscopic gravitational dynamics

Quantum spacetime and matter?

Open problems in the Standard Model:

- triviality problem in $U(1)_Y$ and Higgs quartic coupling



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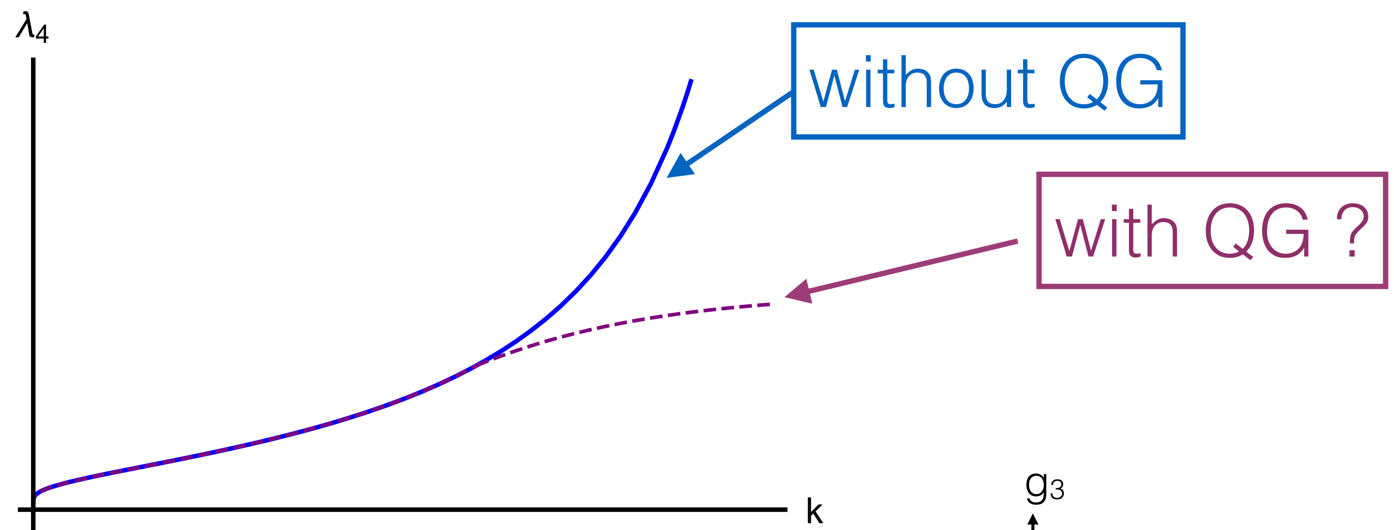
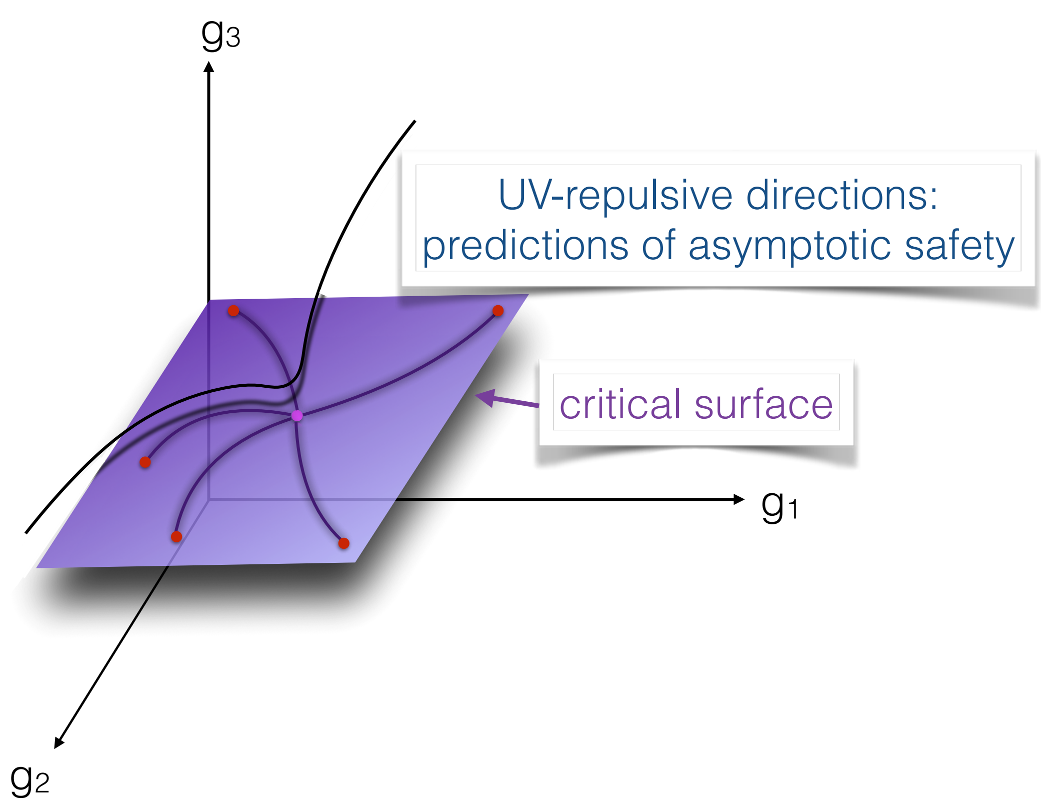
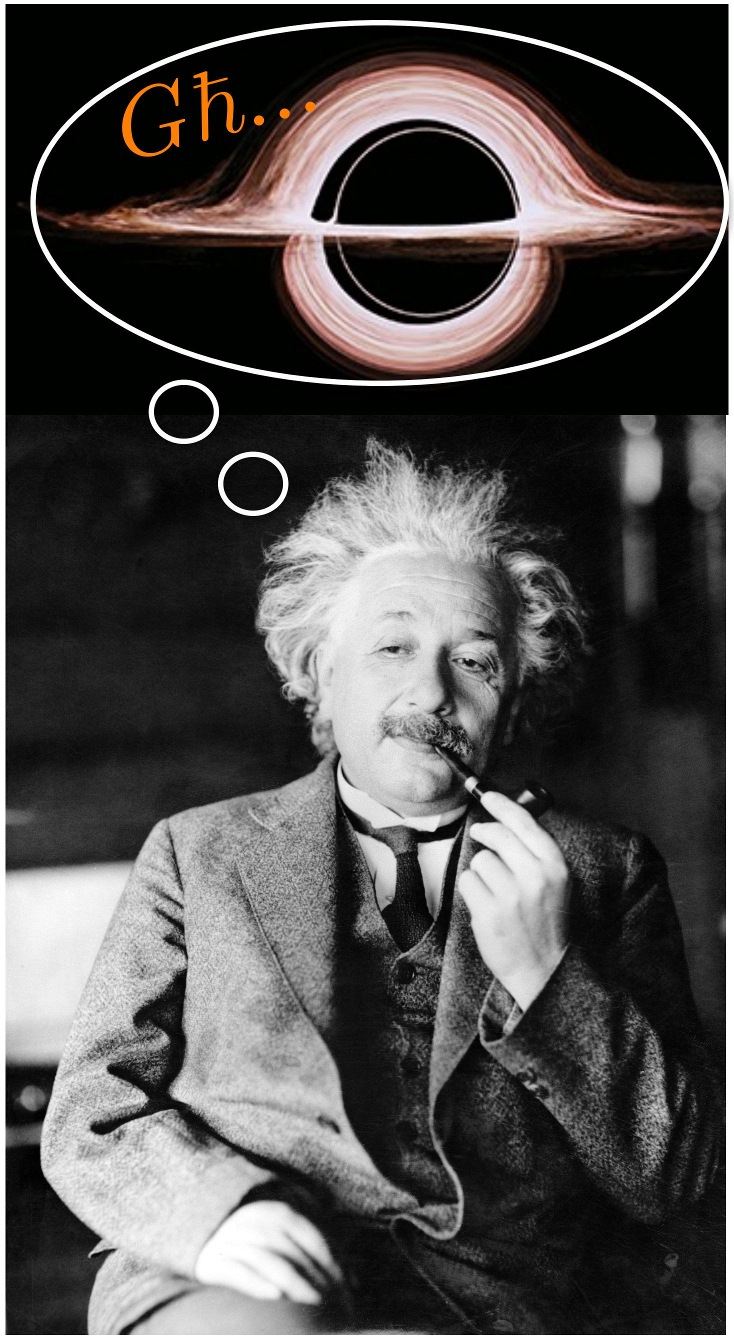


- predictions of free parameters of the Standard Model (e.g. Yukawa couplings) possible?

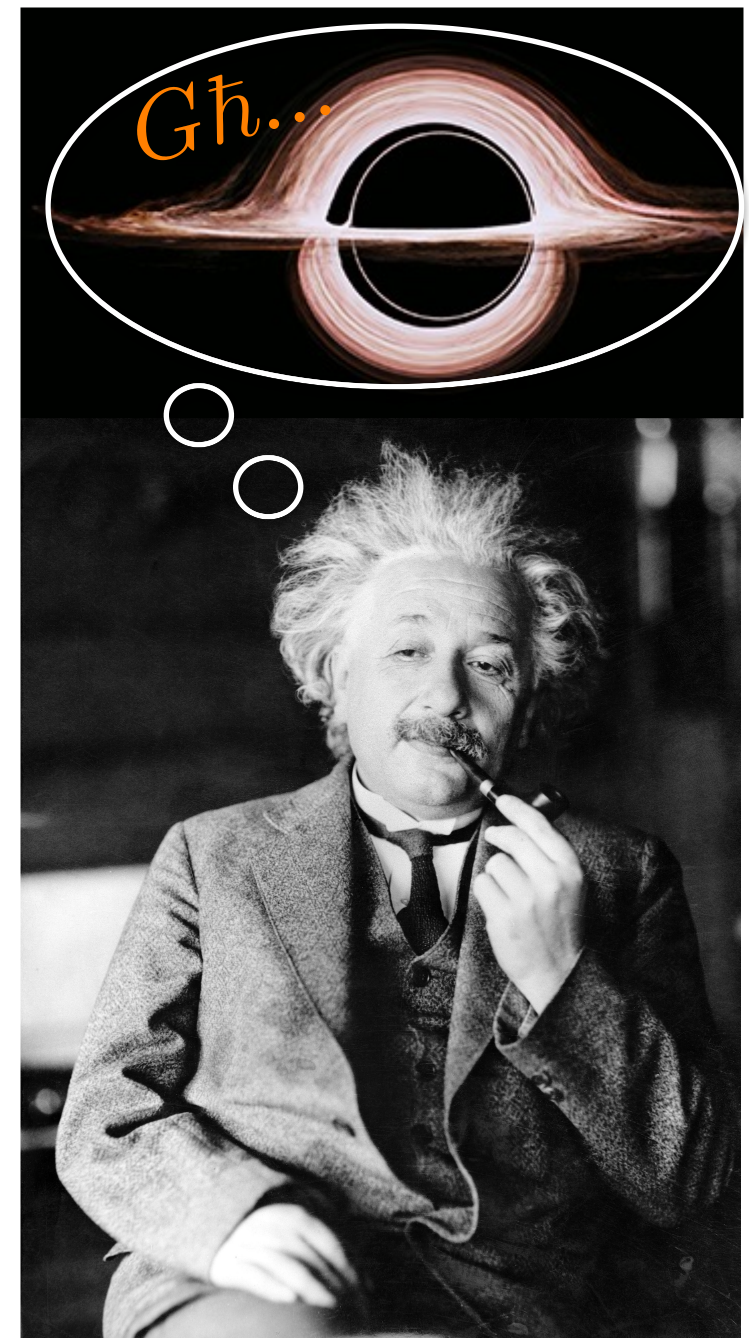


Including matter:
Possibilities to test quantum gravity observationally?



Including matter: Possibilities to test quantum gravity observationally?

quantum gravity model has to admit existence and properties of observed matter



Example: chiral (i.e. light) fermions

within truncation: compatible with asymptotically safe gravity

A.E., H. Gies,'11

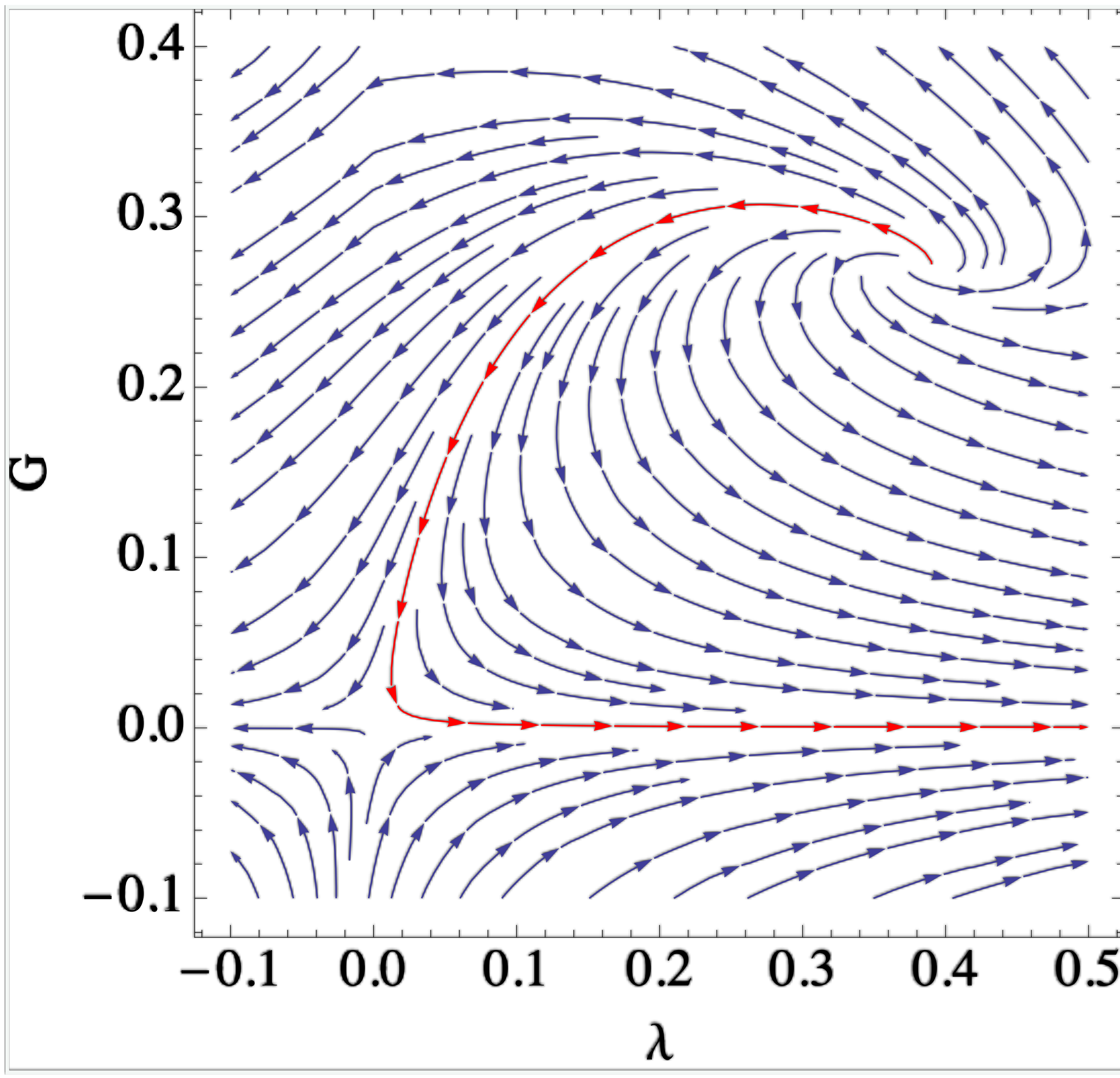
no clear indications in Loop Quantum Gravity

Barnett, Smolin, '15; Gambini, Pullin, '15

Evidence for asymptotic safety in gravity

$$\Gamma_k = -\frac{1}{16\pi G_N(k)} \int d^4x \sqrt{g}\,(R - 2\bar{\lambda}(k))$$

$$G(k) = G_N\,k^2, \qquad \lambda(k) = \bar{\lambda}(k)/k^2$$



Reuter, '96; Reuter, Saueressig '01, Litim, '03

interacting fixed point
with ~ 3 (?) relevant directions

extended truncations:

- gauge fixing & ghosts

Groh, Saueressig, '10; Eichhorn, Gies, '10; Eichhorn, '13

- distinction of background & fluctuation couplings

Manrique, Reuter, Saueressig, '11;
Christiansen, Litim, Pawlowski, Rodigast, '14;
Codello, D'Odorico, Pagani, '14; Becker, Reuter, '14, '15;
Christiansen, Knorr, Meibohm, Pawlowski, Reichert, '15

- higher curvature terms

$f(R)$ Reuter, Lauscher, '02; Codello, Percacci, Rahmede, '09;
Benedetti, Caravelli, '12; Dietz, Morris, '12;
Demmel, Saueressig, Zanusso, '15

$R^2, \quad R_{\mu\nu}R^{\mu\nu}$ Benedetti, Machado, Saueressig, '09

Matter degrees of freedom

fundamental
$\longrightarrow$ need to
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‘’matter from spacetime”:
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in asymptotic safety:
standard QFT framework, so matter fields ‘simple’

Possible structure of a fixed point for gravity + matter

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use simple(r) example of interacting fixed point:
Wilson-Fisher fixed point & generalisations in $O(N)$ symmetric 3d scalar model

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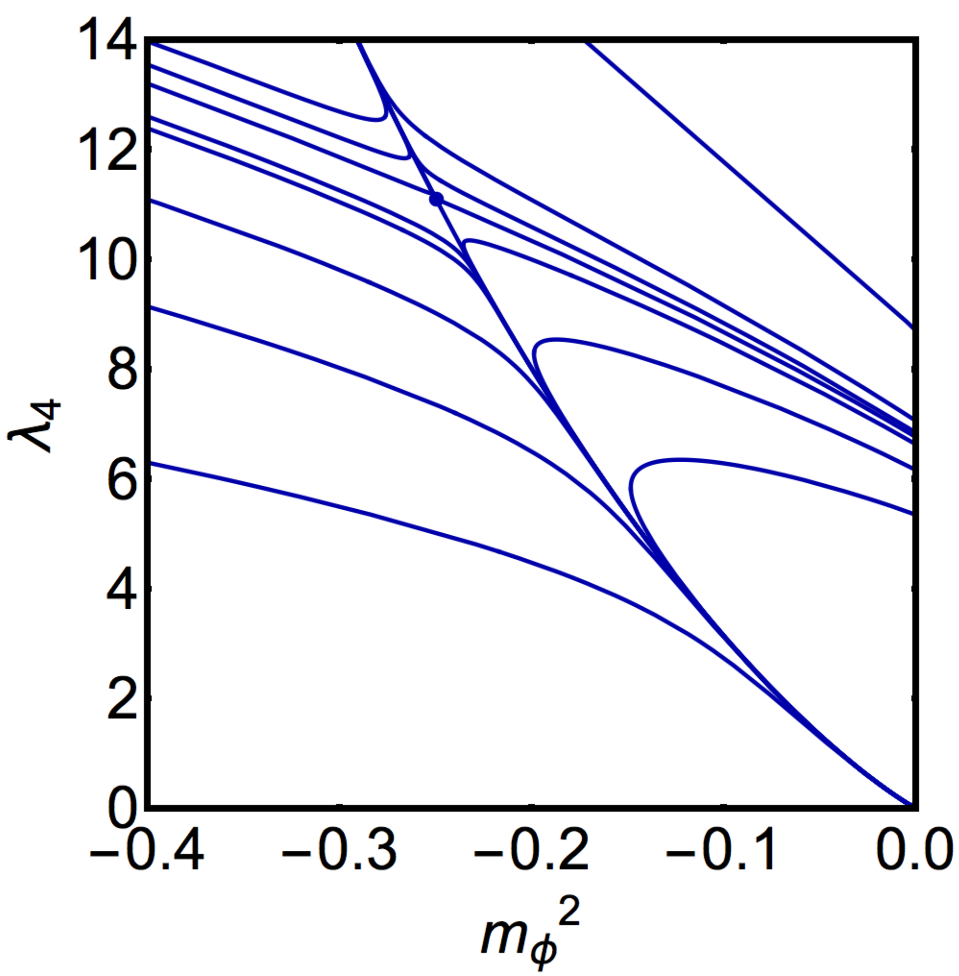
$$V(\phi^2) = \frac{m_\phi^2}{2}\phi_i\phi^i + \frac{\lambda_4}{8}(\phi_i\phi^i)^2 \qquad i = 1, ..., N$$



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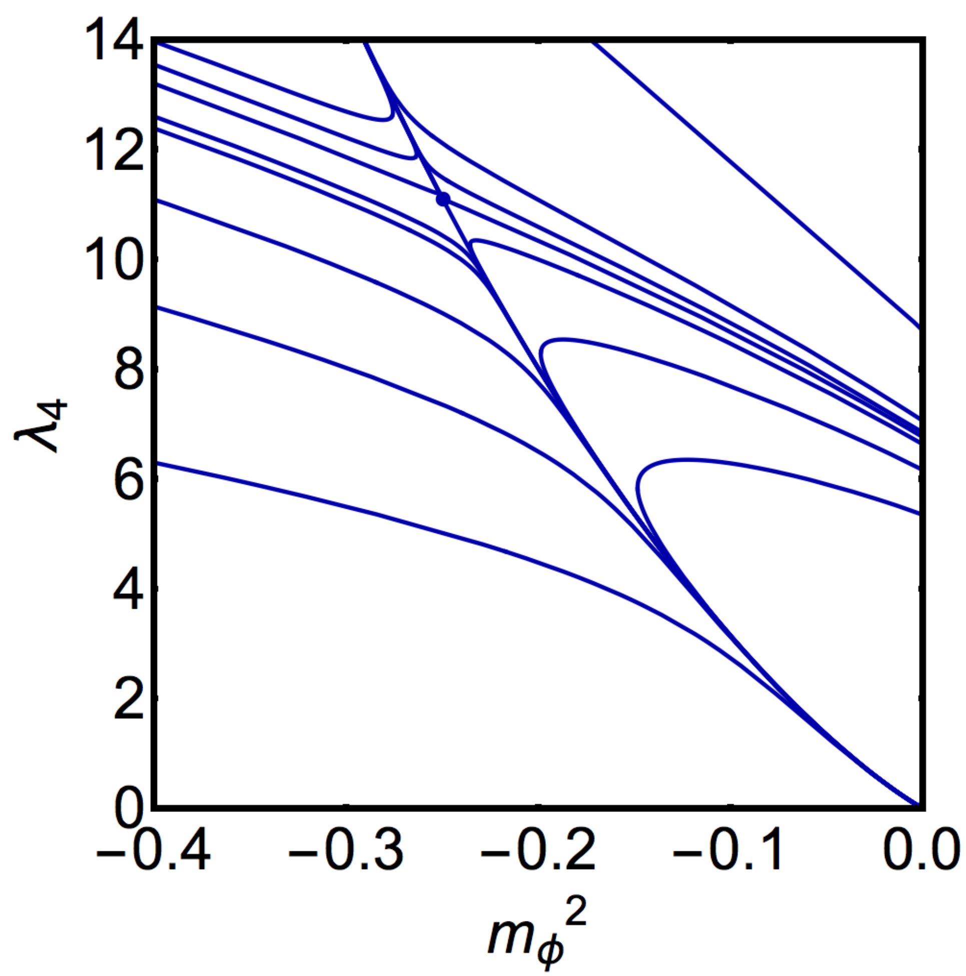

add a second O(M) scalar:

$$V_{\text{int}} = \frac{\lambda_{2,2}}{4}\phi_i\phi^i\chi_j\chi^j$$

What are possible fixed points?

A.E., D. Mesterházy, M. Scherer, ’13, ’14
A.E., T. Helfer, D. Mesterházy, M. Scherer, ‘15

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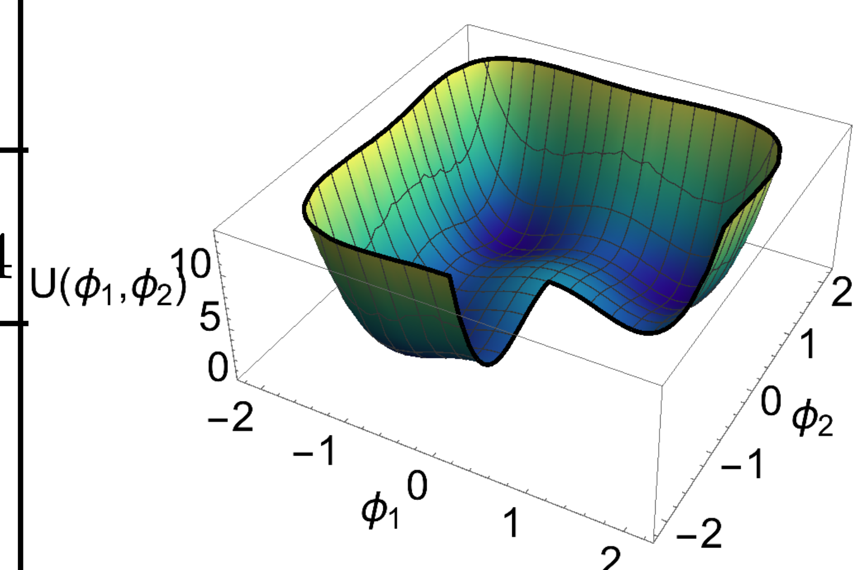

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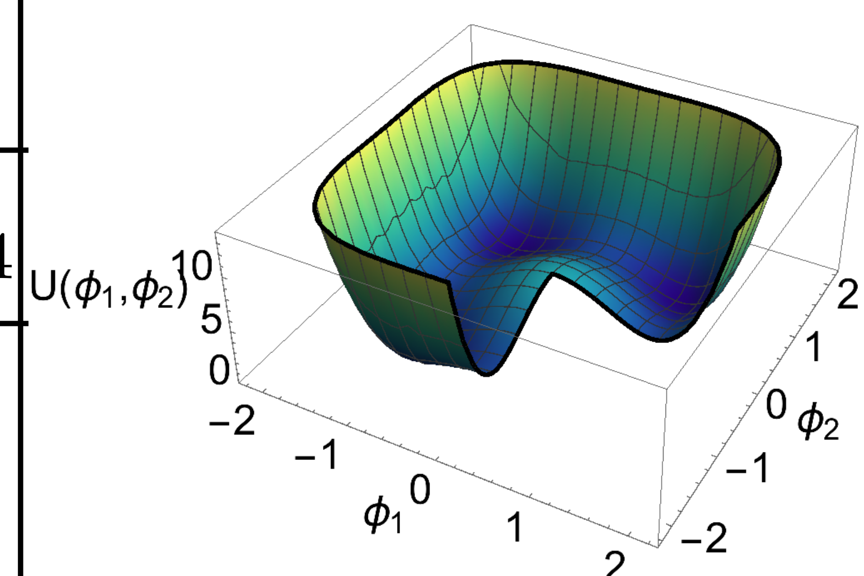

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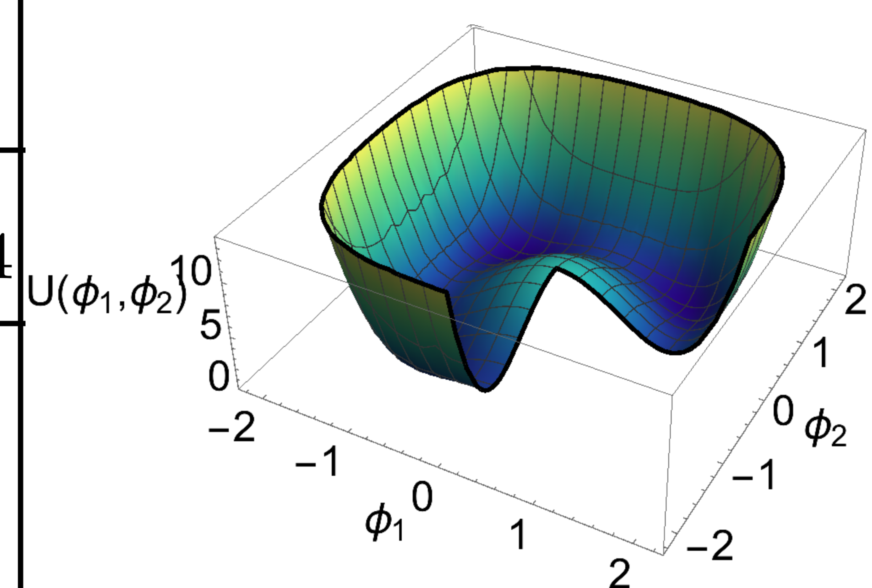

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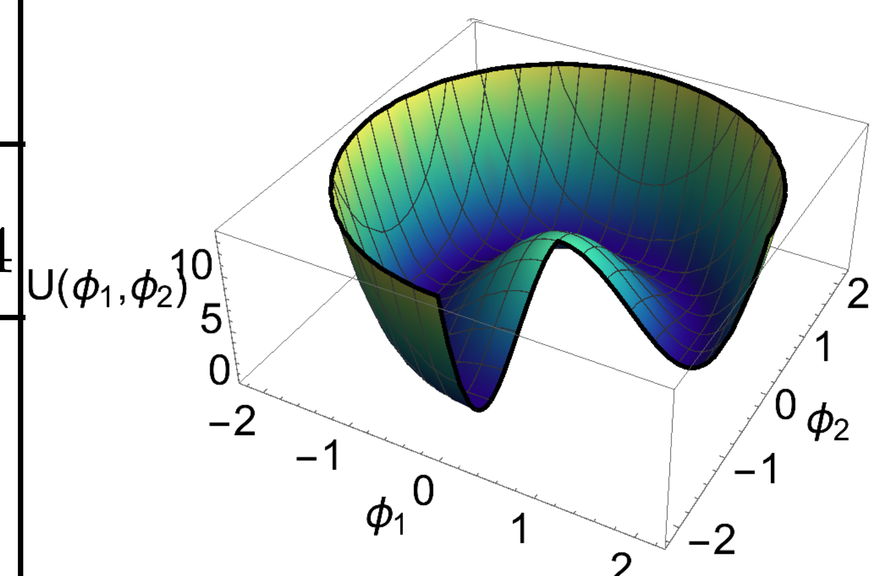

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→ follows from single-field WF fixed point

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biconical	$\neq 0$	$\neq 0$	$\neq 0$	→ induced by nontrivial interactions between both sectors

Nelson, Kosterlitz, Fisher '74;
Calabrese, Pelissetto, Vicari '03;
Folk, Holovatch, Moser ' 08;
Eichhorn, Mesterházy, Scherer '13

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→ Standard Model (most probably) not UV complete by itself

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→ supergravity?

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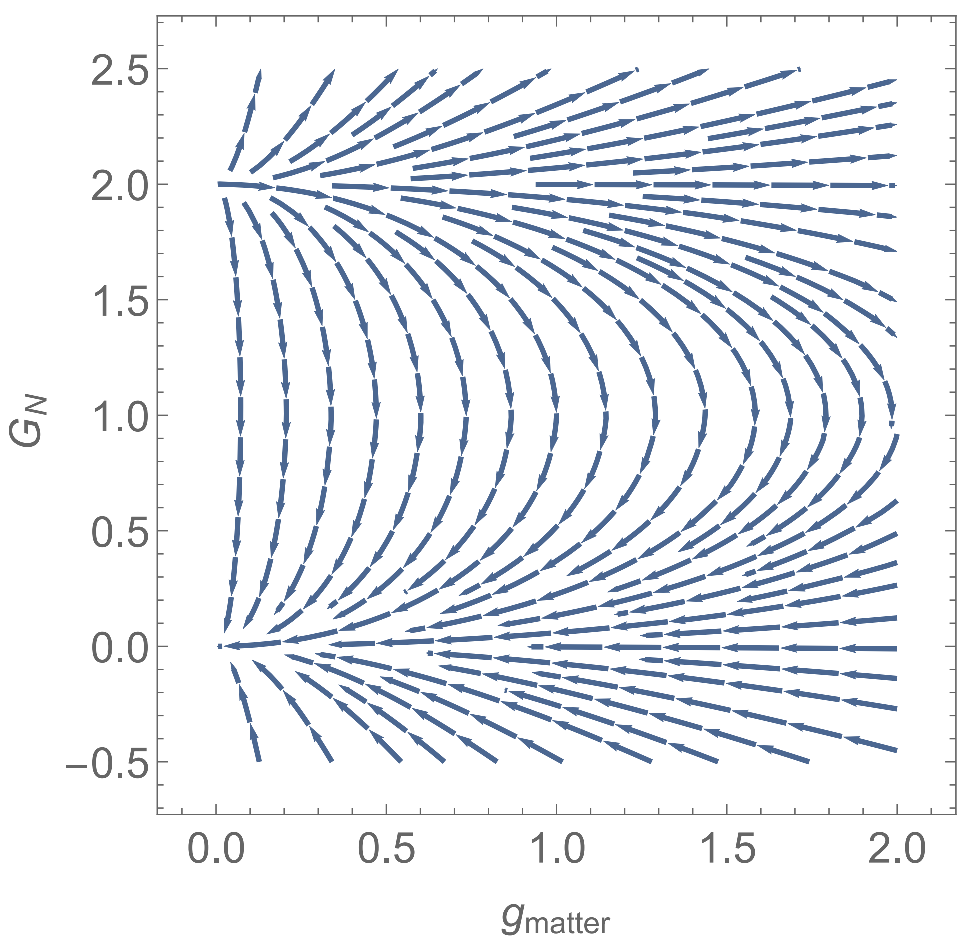
Gaussian matter fixed point:
Gravitational couplings finite; matter couplings vanish

$$\int d^dx\,\sqrt{g}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

$$i\int d^dx\,\sqrt{g}\bar{\psi}\not{\nabla}\psi$$



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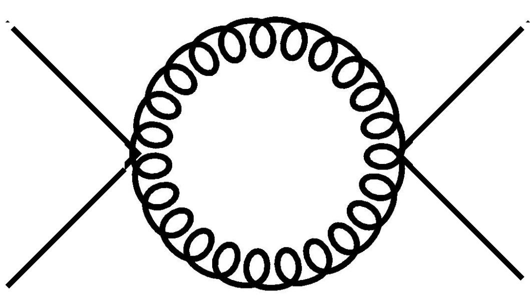

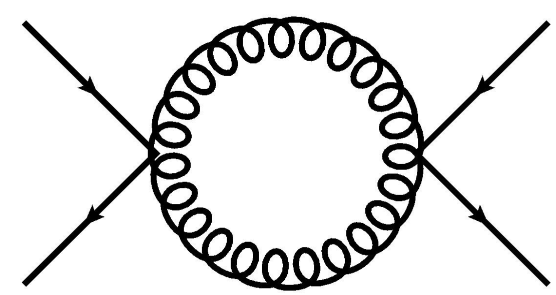

$$\rho\int d^4\sqrt{g}\,g^{\mu\nu}(\partial_\mu\phi\partial_\nu\phi)g^{\kappa\lambda}(\partial_\kappa\phi\partial_\lambda\phi)$$

$$\lambda_\pm\int d^4\sqrt{g}\,\left(\bar{\psi}\gamma_\mu\psi\bar{\psi}\gamma^\mu\psi\pm\bar{\psi}\gamma_\mu\gamma_5\psi\bar{\psi}\gamma^\mu\gamma_5\psi\right)$$

Structure of a fixed point for gravity + matter

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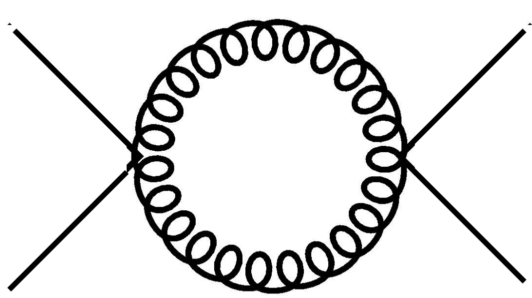

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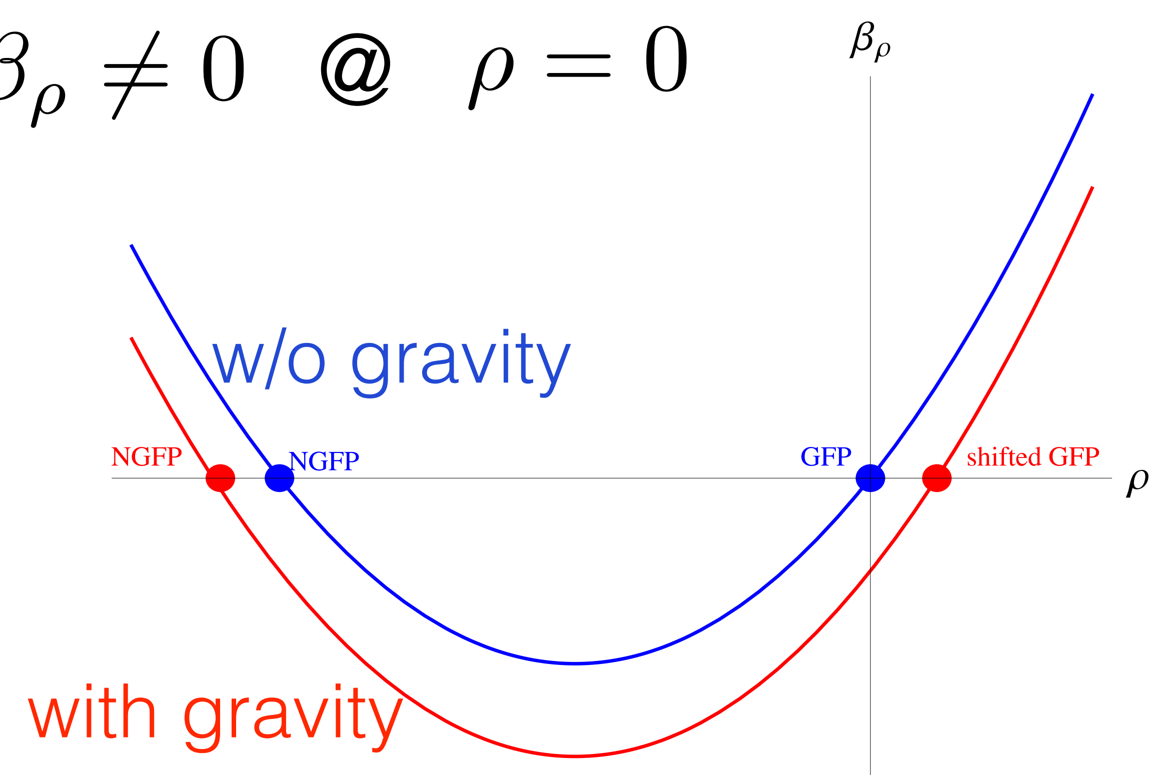
A.E., '12

$$\beta_\rho = ... + \# G^2$$

$$\Rightarrow \beta_\rho \neq 0 \quad @ \quad \rho = 0$$



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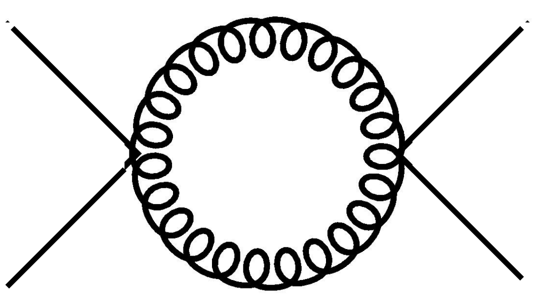

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$$\beta_\rho = ... + \# G^2$$

$$\Rightarrow \beta_\rho \neq 0 \quad @ \quad \rho = 0$$

$$\Rightarrow \lambda_{\phi\,4\,*} \neq 0$$

Gaussian matter fixed point
appears to be truncation artefact

truncations beyond LPA required

Structure of a fixed point for gravity + matter

Gaussian matter fixed point:
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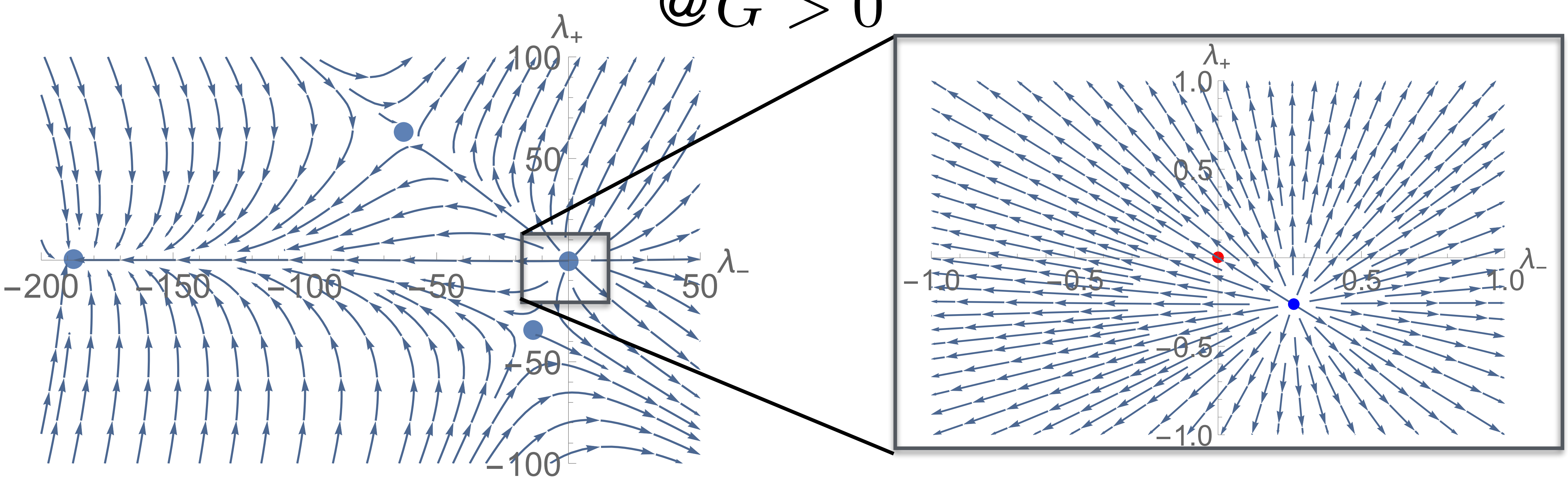
$$i\int d^dx\,\sqrt{g}\bar{\psi}\nabla\!\!\!/\,\psi \quad \rightarrow \quad \lambda_{\pm}\int d^4\sqrt{g}\,\left(\bar{\psi}\gamma_\mu\psi\bar{\psi}\gamma^\mu\psi \pm \bar{\psi}\gamma_\mu\gamma_5\psi\bar{\psi}\gamma^\mu\gamma_5\psi\right)$$

$$@G>0$$



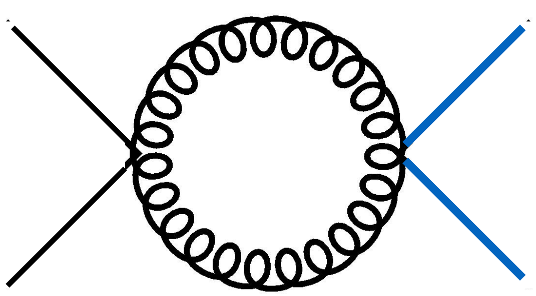
A.E., H. Gies,'11

gravity-fermion fixed point is interacting

Structure of a fixed point for gravity + matter

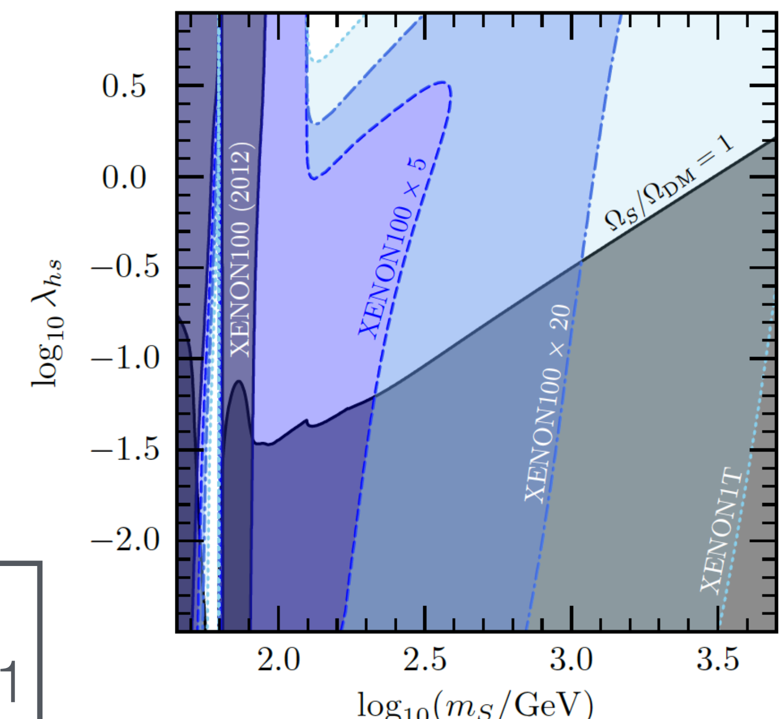
Phenomenological consequence:
If dark matter is scalar, Higgs portal coupling in asymptotic safety is finite

$$\int d^dx \sqrt{g}\, g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi \quad + \quad \int d^dx \sqrt{g}\, g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi$$



$$\rightarrow \lambda_{2,2}\phi^2\chi^2 \neq 0$$

Silveira, Zee '85; McDonald '94; Burgess, Pospelov, ter Veldhuis '01



Cline, Scott, Kainulainen, Weniger, '13

Open question: Can we predict Higgs-portal coupling from asymptotic safety?

Gravitational effects on the Yukawa sector

$$\int d^d x \sqrt{g} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi \qquad\qquad i \int d^d x \sqrt{g} \bar{\psi} \not{\nabla} \psi$$

$$X \int d^d x \sqrt{g} \left(\bar{\psi} \gamma^\mu \psi \right) \left(D_\mu g^{\kappa\lambda} \partial_\kappa \phi \partial_\lambda \phi \right)$$

Poster: A. Held

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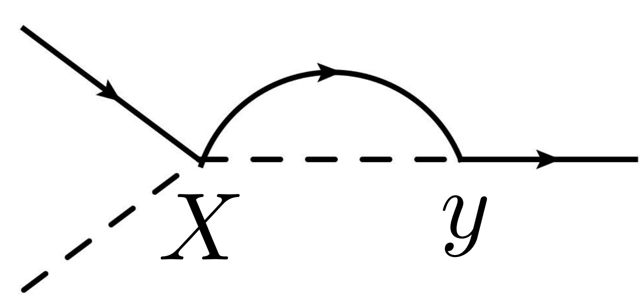
$$X_* \neq 0$$

$$y\int d^dx\sqrt{x}\bar{\psi}\psi\phi$$



$\Rightarrow$ additional contribution to critical exponent from

[Zanusso, Zambelli, Vacca, Percacci, ’09; Zanusso, Vacca, ’10]

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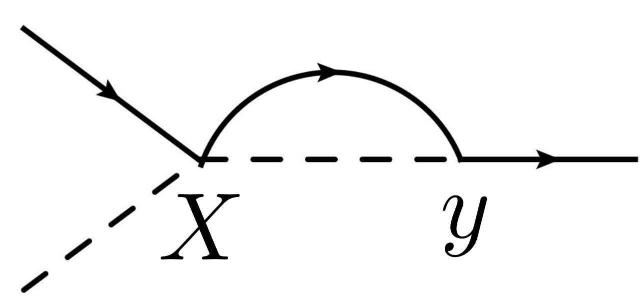

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Can asymptotic safety predict the structure of the Yukawa sector? …stay tuned…

Setting a scale in quantum gravity?

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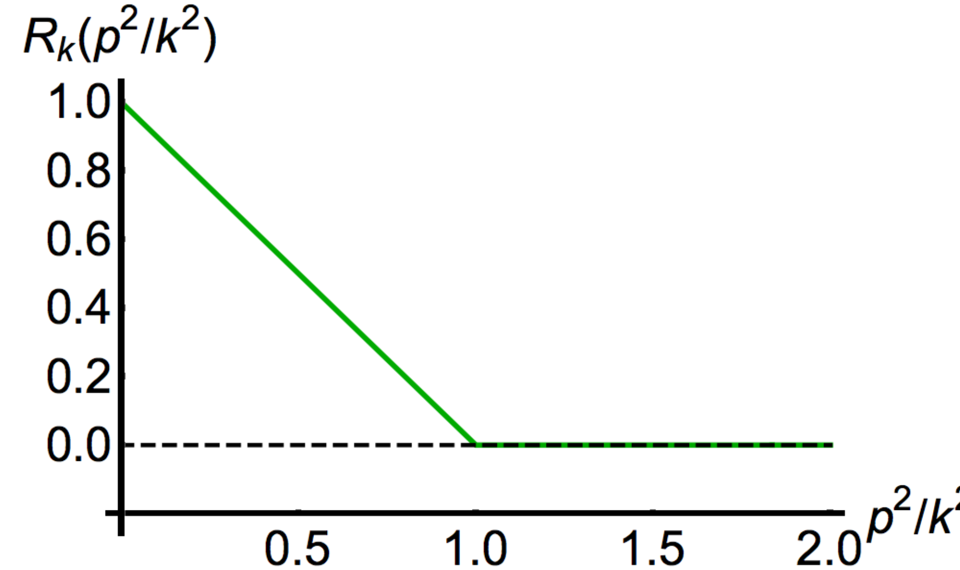
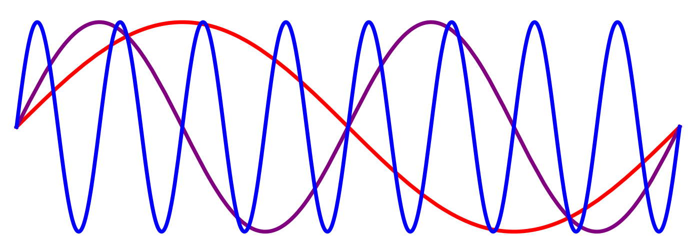
$$\int \mathcal{D}\varphi \, e^{-S[\varphi]-\int_p \varphi(p) R_k(p^2)\varphi(-p)}$$



Wetterich ’93; Morris ‘94

on a flat background: $\varphi(x) = \int_p \tilde{\varphi}(p) e^{ip\cdot x}$



on a curved background $\bar{g}_{\mu\nu}$: $p^2 \to -\bar{D}^2$

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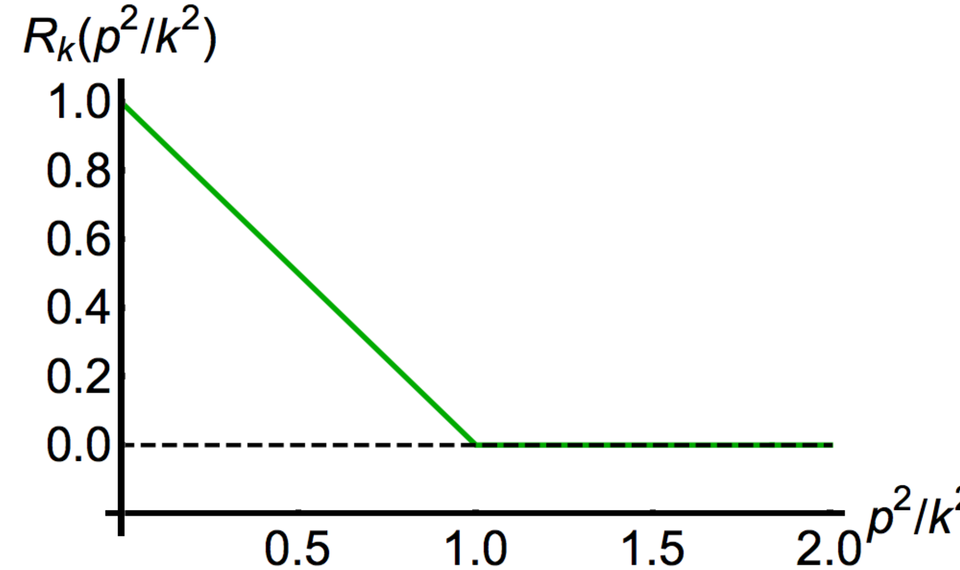

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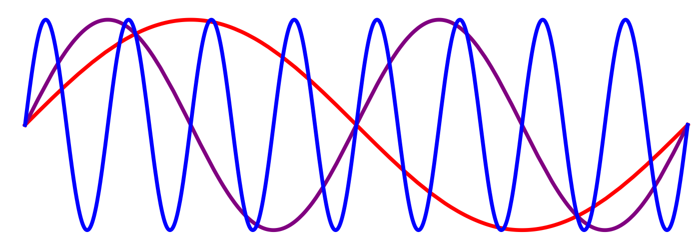

on a curved background $\bar{g}_{\mu\nu}$: $p^2 \to -\bar{D}^2$

in quantum gravity: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$ or $g_{\mu\nu} = \bar{g}_{\mu\kappa} \left(e^{h^{\cdot}{}_{\cdot}}\right)^{\kappa}{}_{\nu}$

path integral:

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

scale setting:

$$h_{\mu\nu} R_k^{\mu\nu\kappa\lambda}(-\bar{D}^2) h_{\kappa\lambda}$$

Setting a scale in quantum gravity?

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scale setting:

$$h_{\mu\nu} R_k^{\mu\nu\kappa\lambda}(-\bar{D}^2) h_{\kappa\lambda}$$

$$S[g_{\mu\nu}] = -\frac{1}{16\pi G_N}\int d^4x \sqrt{g}\, R$$

$$= -\frac{1}{16\pi \bar{G}_N}\int d^4x \sqrt{\bar{g}}\, \bar{R}$$

$$-\frac{1}{16\pi G_1}\int d^4x \sqrt{\bar{g}}\, h_{\mu\nu} K^{\mu\nu}[\bar{g}] + \frac{1}{16\pi G_2}\int d^4x \sqrt{\bar{g}} h_{\mu\nu} h_{\kappa\lambda} K^{\mu\nu\kappa\lambda}[\bar{g}] + \dots$$

$$\beta_{\bar{G}_N} \neq \beta_{G_1} \neq \beta_{G_2} \dots$$

Matter matters

$$\beta_{\bar{G}} = 2\bar{G} - \frac{\bar{G}^2}{48\pi}\left(26(4-\eta_h) + 20(4-\eta_c) - N_S(4-\eta_S) - N_D(4-\eta_D) + 2N_V(8-\eta_V)\right)$$

Donà, A.E., Percacci ’13, ‘14

destabilizing effect

one-loop result: Standard Model degrees of freedom compatible with grav. fixed point

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Donà, A.E., Percacci ’13, ‘14

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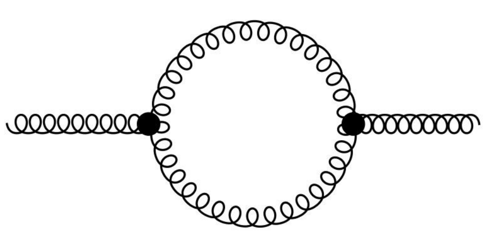
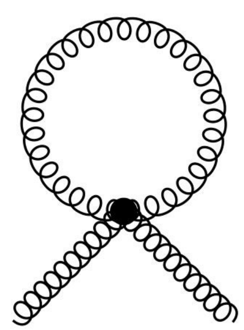
Where do fluctuation couplings enter?





$\Rightarrow \eta_h = \eta_h(G_3, G_4)$ $\longrightarrow$ talk by J. Pawlowski

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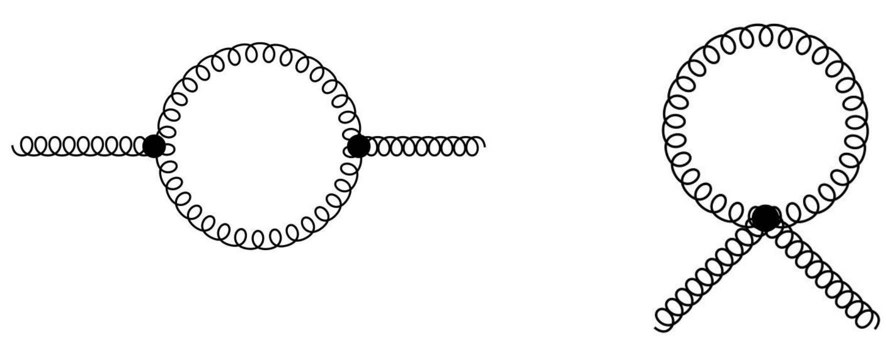

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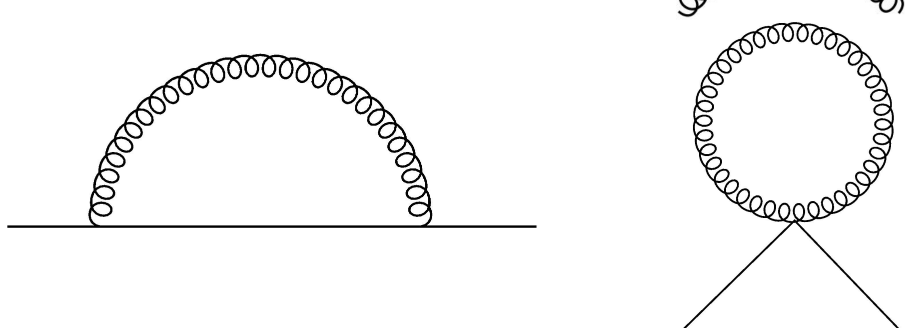
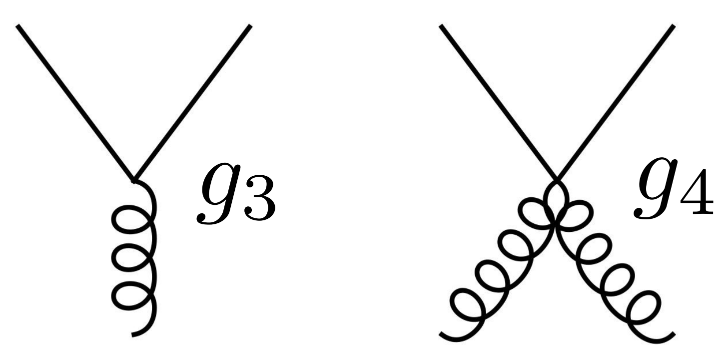


$\Rightarrow$

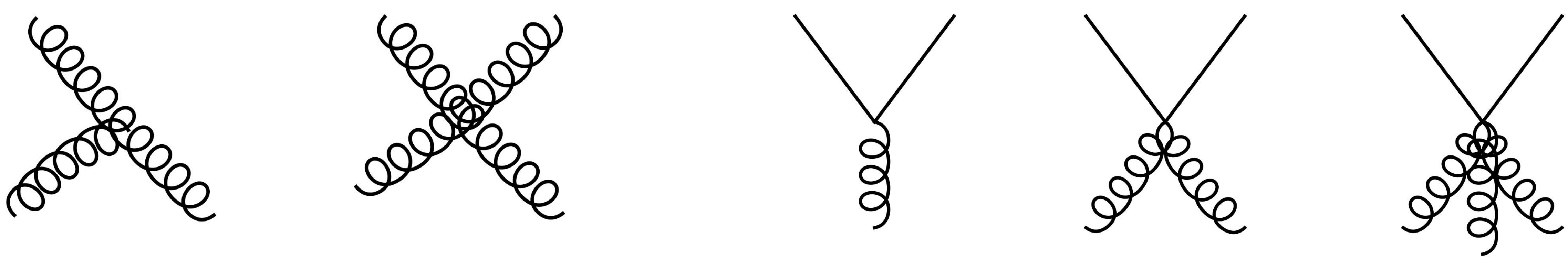


“Newton couplings” in gravity-matter systems

$$\hat{\Gamma} = -\frac{1}{16\pi G}\int d^4x\sqrt{g}R \; + S_{\rm gf} + \frac{1}{2}\int d^4x\sqrt{g}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

$$g_{\mu\nu} = \bar{g}_{\mu\kappa}\left(e^{h^{\cdot}{}_{\cdot}}\right)^{\kappa}{}_{\nu}$$

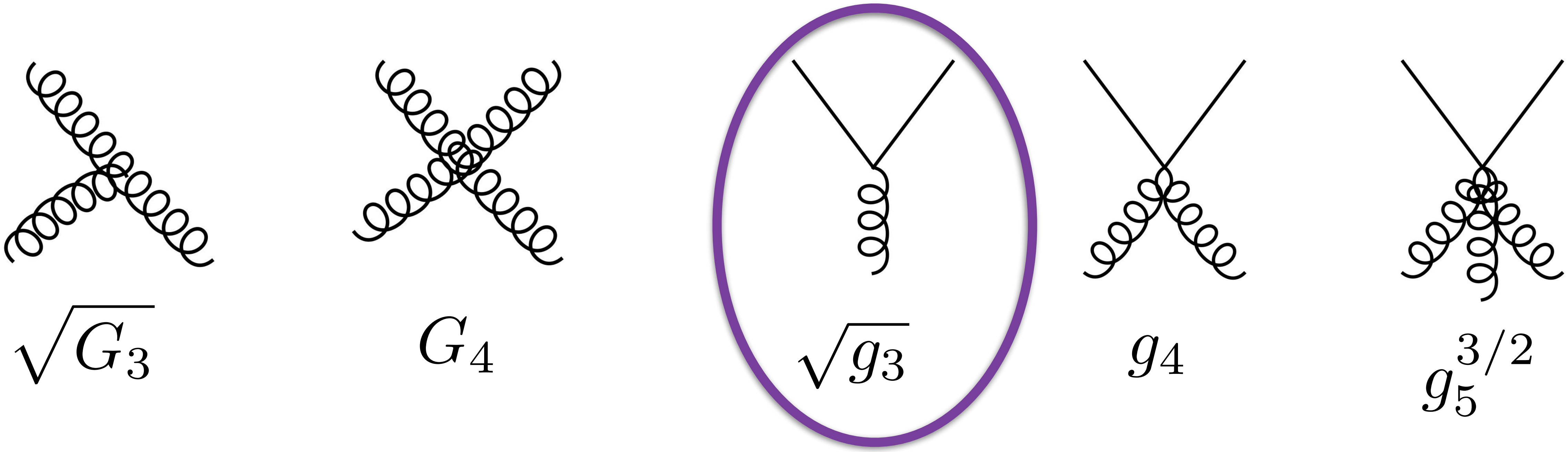
(unimodular gauge)



$\sqrt{G_3}$ G_4 $\sqrt{g_3}$ g_4 $g_5^{3/2}$

work in progress with P. Labus, P. Donà and R. Percacci

“Newton couplings” in gravity-matter systems



$$\beta_{g_3} = (2 + \eta_{\mathrm{TT}} + 2\eta_S)\, g_3 + \frac{3}{2\pi} g_3^2 + \frac{3}{2\pi} g_3^{3/2} \sqrt{G_3} - \frac{4}{\pi} g_3 g_4 - \frac{5}{18\pi} g_5^{3/2} \sqrt{g_3}$$
$$+ \left(-\frac{5}{54\pi} g_4 \sqrt{G_3} + \frac{23}{108\pi} g_5^{3/2} \right) \sqrt{g_3}\eta_{\mathrm{TT}} + \left(\frac{-1}{20\pi} g_3^{3/2} - \frac{1}{10\pi} g_3 \sqrt{G_3} + \frac{1}{4\pi} \sqrt{g_3} g_4 + \frac{5}{54\pi} g_4 \sqrt{G_3} - \frac{1}{6\pi} g_5^{3/2} \right) \sqrt{g_3}\eta_\sigma$$
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work in progress with P. Labus, P. Donà and R. Percacci

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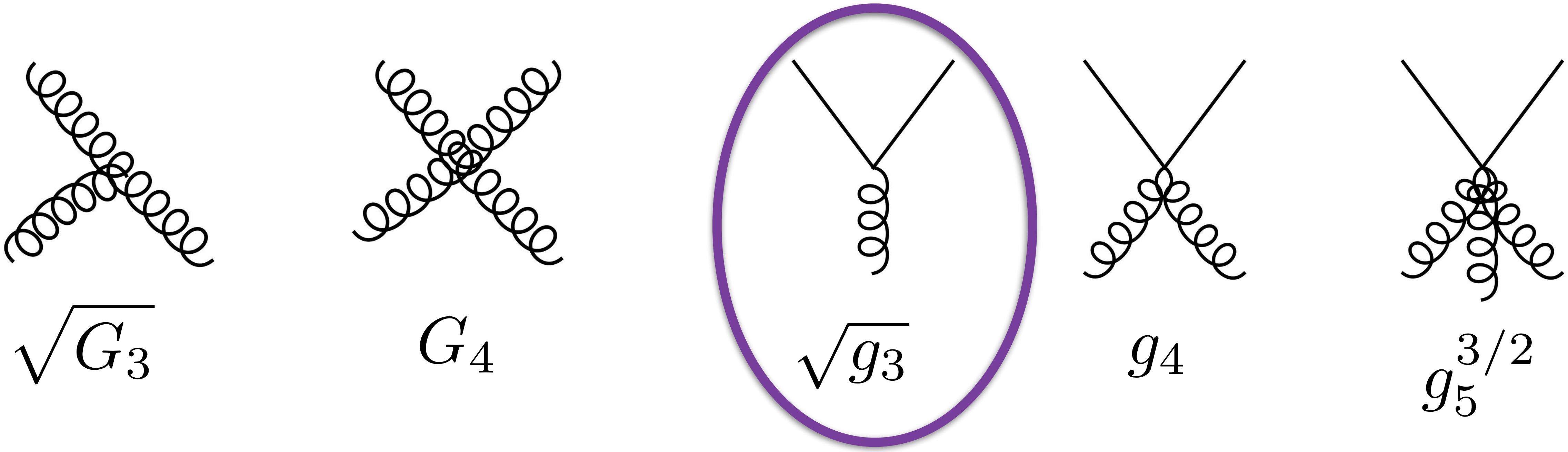

$$\beta_{g_3} = (2+\eta_{\mathrm{TT}}+2\eta_S)\,g_3 + \frac{3}{2\pi}g_3^2 + \frac{3}{2\pi}g_3^{3/2}\sqrt{G_3} - \frac{4}{\pi}g_3 g_4 - \frac{5}{18\pi}g_5^{3/2}\sqrt{g_3}$$

$$+\left(-\frac{5}{54\pi}g_4\sqrt{G_3}+\frac{23}{108\pi}g_5^{3/2}\right)\sqrt{g_3}\eta_{\mathrm{TT}} + \left(\frac{-1}{20\pi}g_3^{3/2}-\frac{1}{10\pi}g_3\sqrt{G_3}+\frac{1}{4\pi}\sqrt{g_3}g_4+\frac{5}{54\pi}g_4\sqrt{G_3}-\frac{1}{6\pi}g_5^{3/2}\right)\sqrt{g_3}\eta_\sigma$$

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$$h_{\mu\nu} = h_{\mu\nu}^{TT} + \ldots + \bar{D}^{-2}\bar{D}_\mu\bar{D}_\nu\sigma - \frac{1}{4}\bar{g}_{\mu\nu}\sigma$$

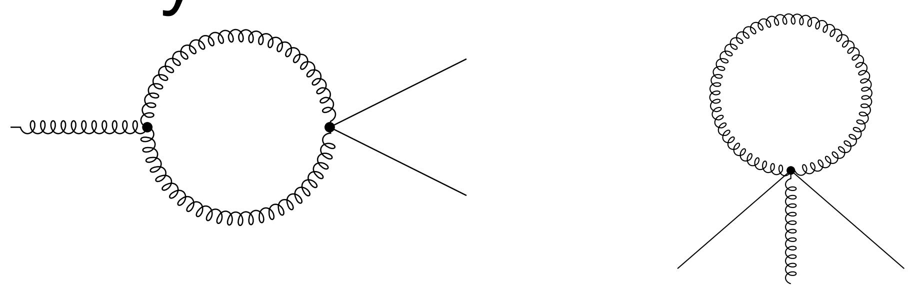
⟶ distinguish anomalous dimensions for graviton modes $\eta_{\mathrm{TT}}, \eta_\sigma$

work in progress with P. Labus, P. Donà and R. Percacci

“Newton couplings” in gravity-matter systems

pure-gravity limit: no scalar fluctuations (only external lines)

β_{g_3} :



$$g_5 = g_4 = G_3 = G_4 = g_3$$

$g_{3\,*} = 4.58 \qquad \theta = 2.27$

$\eta_{\mathrm{TT}} = -1.24 \qquad \eta_\sigma = 1.32$

cf. background results:

$\bar{G}_* = 3.68 \qquad \theta = 2$

[Vacca, Percacci, ‘15]

“Newton couplings” in gravity-matter systems

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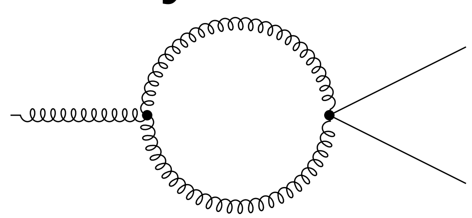
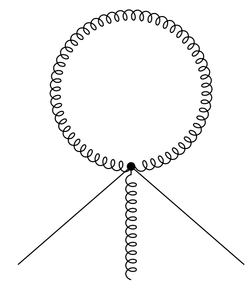

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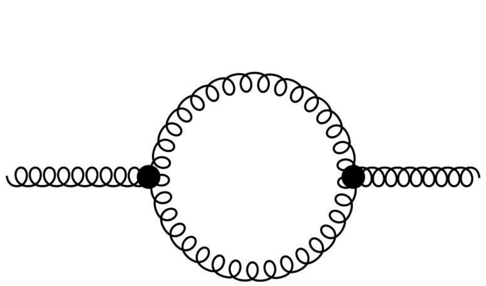
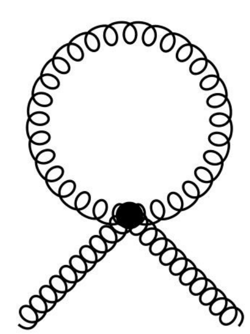
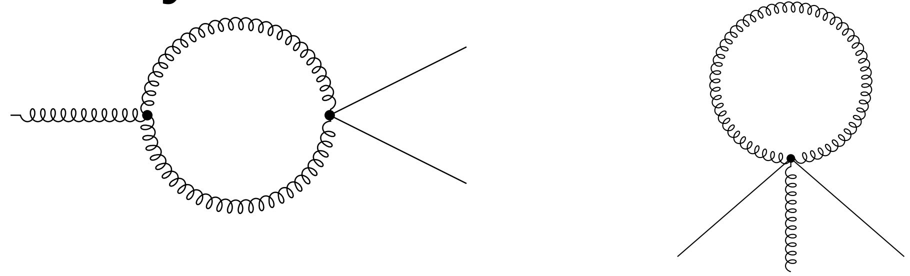
cf. $\eta_h = 0.54$ (linear parameterisation) [Donà, Eichhorn, Percacci, ‘13]

$$\Rightarrow \eta \sim G$$

“Newton couplings” in gravity-matter systems

pure-gravity limit: no scalar fluctuations (only external lines)



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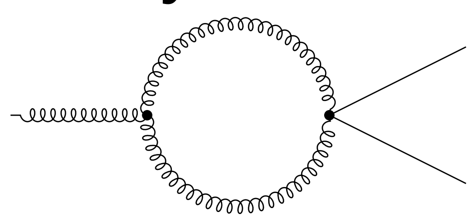
[Vacca, Percacci, ‘15]

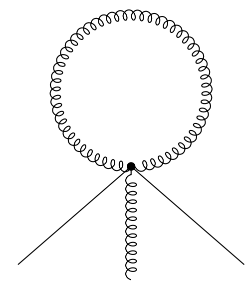
``dimensional reduction” of spacetime?

direction for the future:
distinguish tensor structures also in the vertices?

“Newton couplings” in gravity-matter systems

pure-gravity limit: no scalar fluctuations (only external lines)





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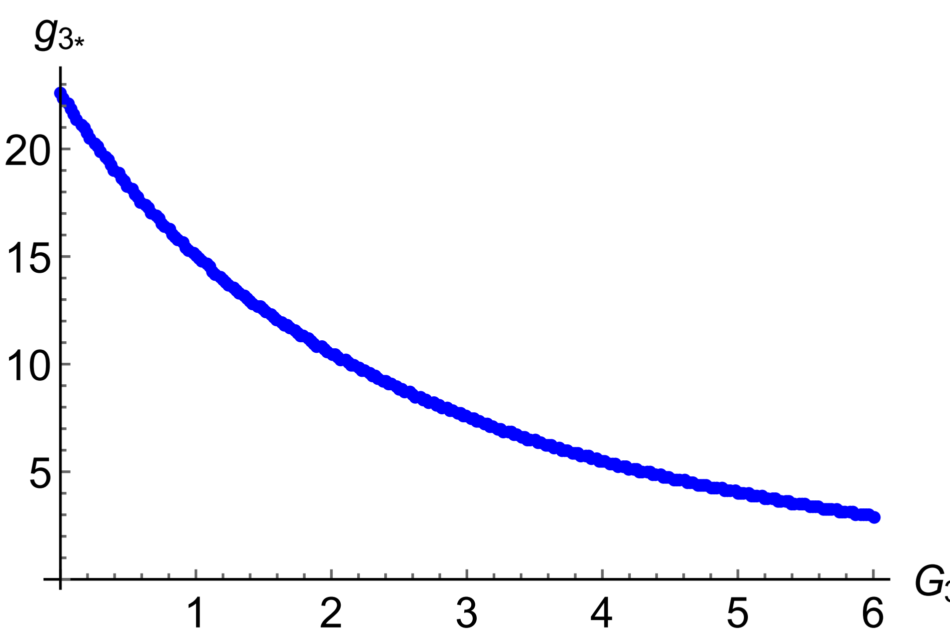
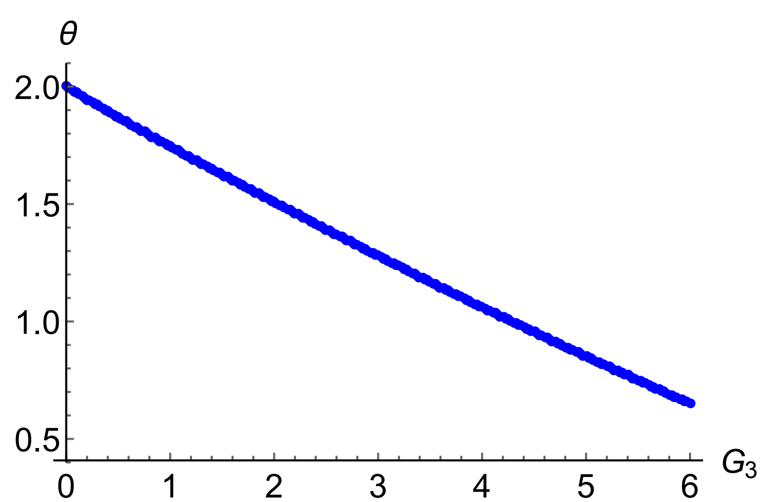
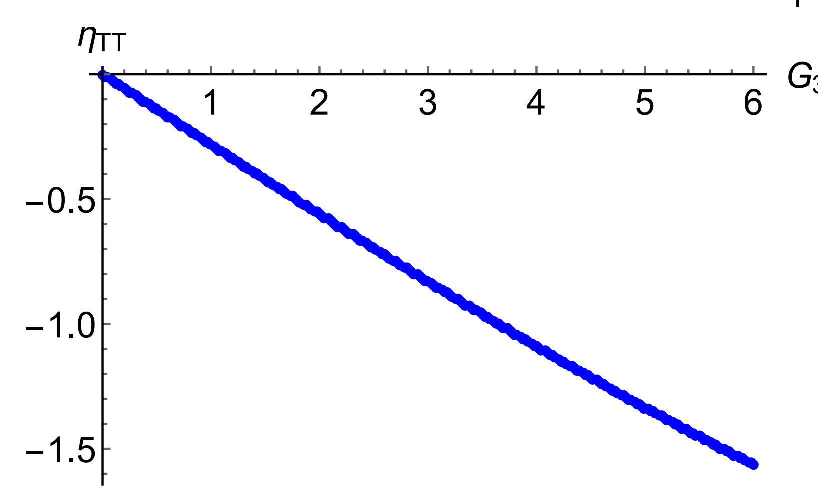


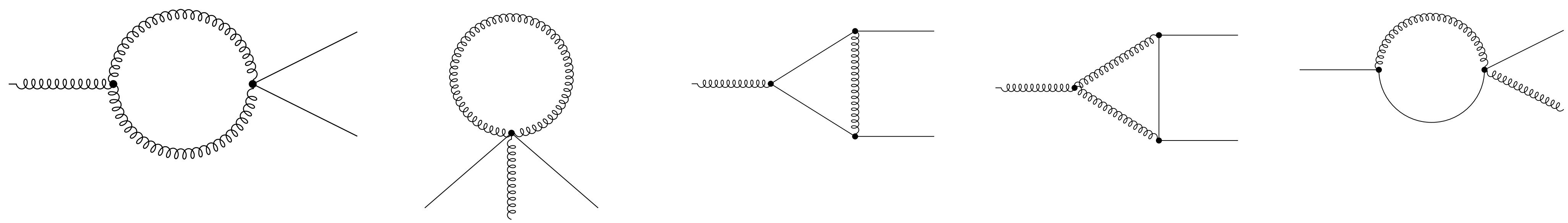




confirmation of asymptotic safety in fluctuation couplings

“Newton couplings” in gravity-matter systems

include scalar fluctuations (prelim. results)

β_{g_3} 

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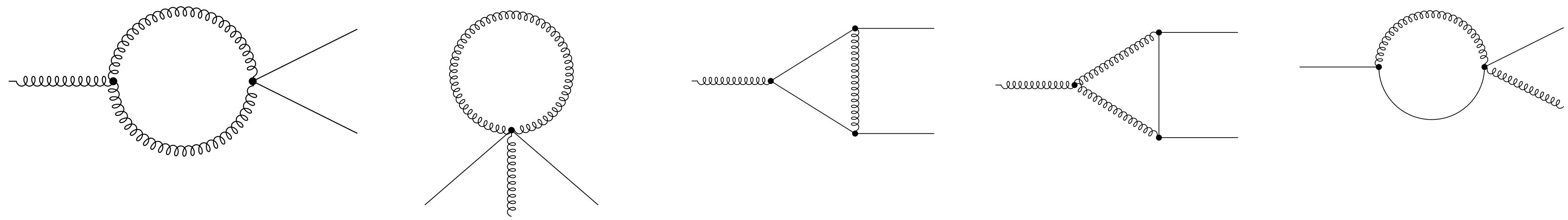
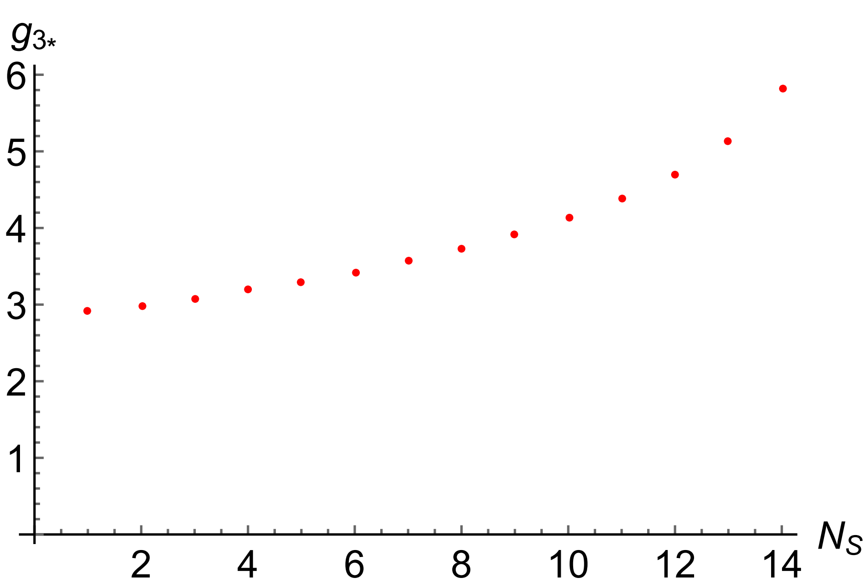
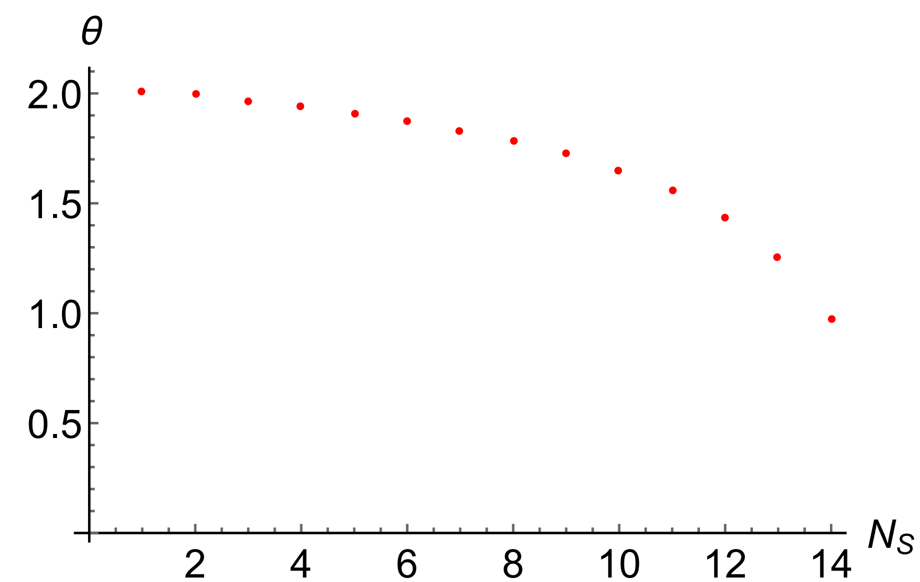


$$\eta_s = 0$$

$$\beta_{g_3} = 2g_3 - \frac{g_3^2}{6\pi}\left(13 - \frac{N_S}{4}\right) + \ldots$$





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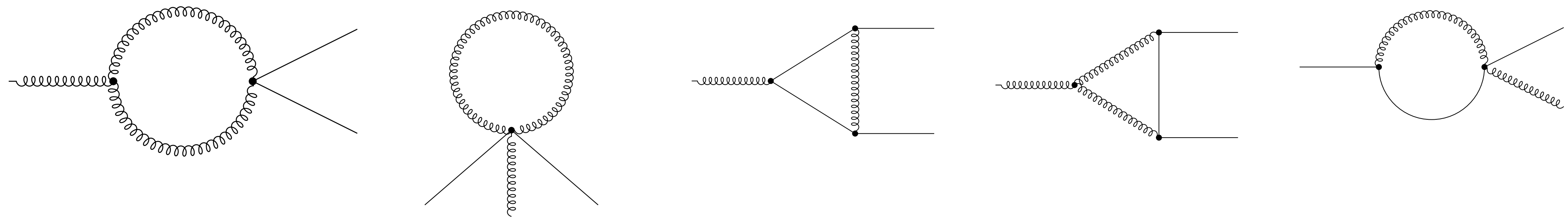

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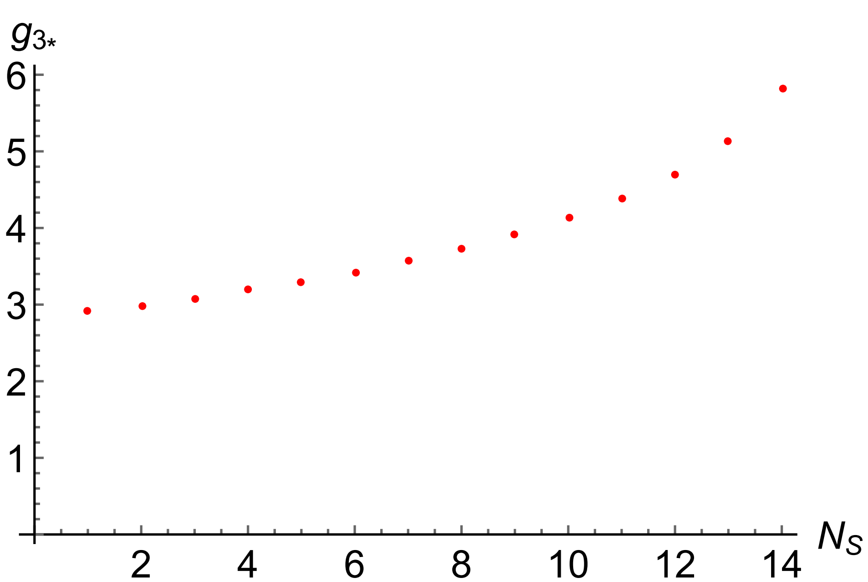
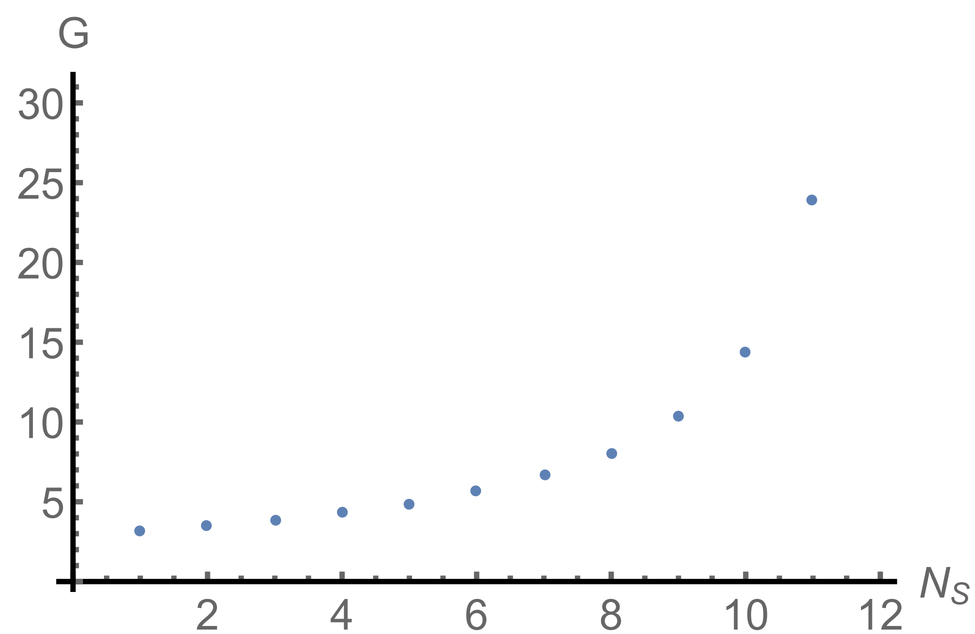
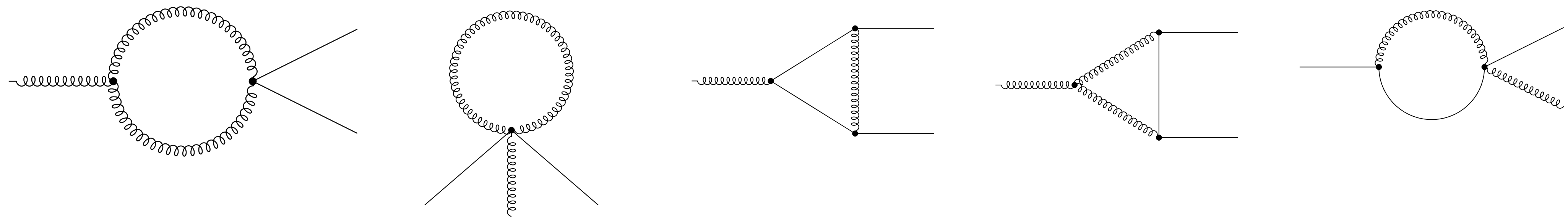




background coupling and fluctuation coupling similar

“Newton couplings” in gravity-matter systems

include scalar fluctuations (prelim. results)

β_{g_3} 

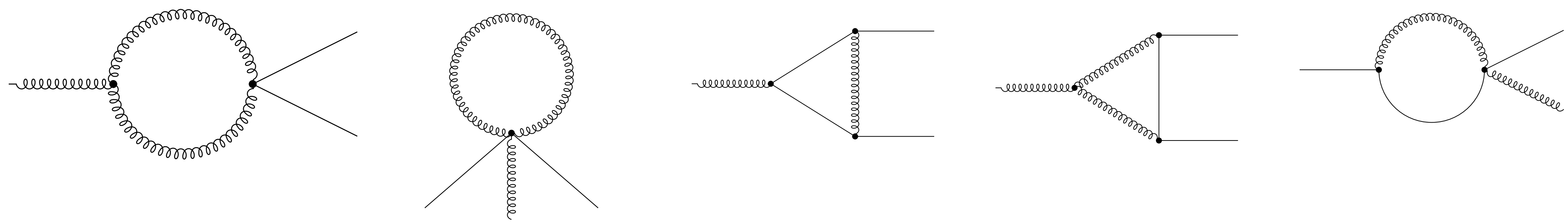
include η_s

$$\beta_{g_3} = 2g_3 - \frac{13}{6\pi}g_3^2 + \frac{g_3^2}{24\pi}N_S + 2g_3\eta_s + ... \qquad \eta_s = \frac{7}{4\pi}g_3$$

“Newton couplings” in gravity-matter systems

include scalar fluctuations (prelim. results)

β_{g_3}



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$$g_i = G_i \qquad \eta_{\mathrm{TT}} = 1.88 \quad \eta_\sigma = -0.76 \quad \eta_s = -3.67$$

$\longrightarrow$ significant effects of scalar matter

"Newton couplings" in gravity-matter systems

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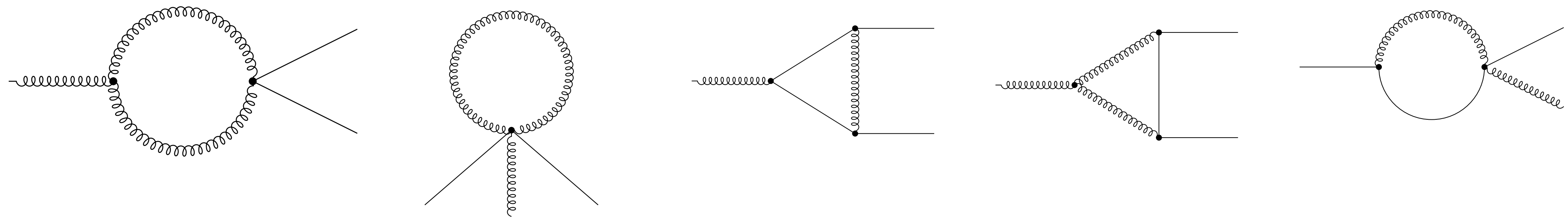
β_{g_3} 

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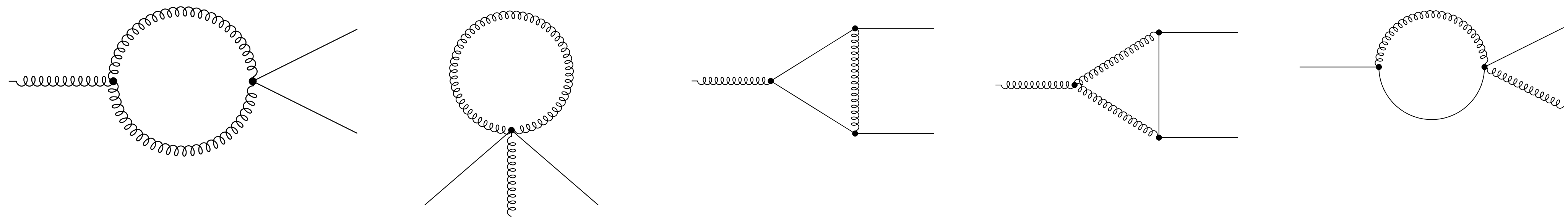
$N_S = 1.8:$ fixed-point annihilation

“Newton couplings” in gravity-matter systems

include scalar fluctuations (prelim. results)

β_{g_3} 

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Future direction: Better truncation for η_s

$$\longrightarrow (\partial_\mu \phi \partial^\mu \phi)^2 \to \eta_s$$

Gravity-induced matter self-interactions could play a role

“Newton couplings” in gravity-matter systems

include scalar fluctuations (prelim. results)

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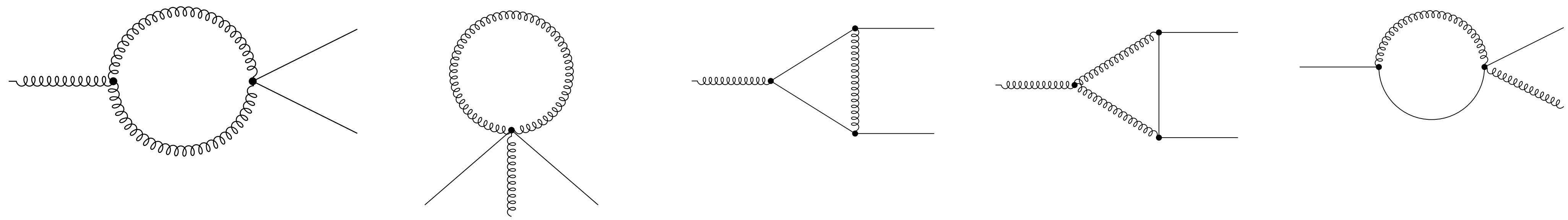

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Gravity-induced matter self-interactions could play a role

Is there a difference between exponential and linear parameterization?

Summary

- asymptotic safety: joint model of gravity and matter

Summary

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- fixed point is fully non-Gaussian

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Summary

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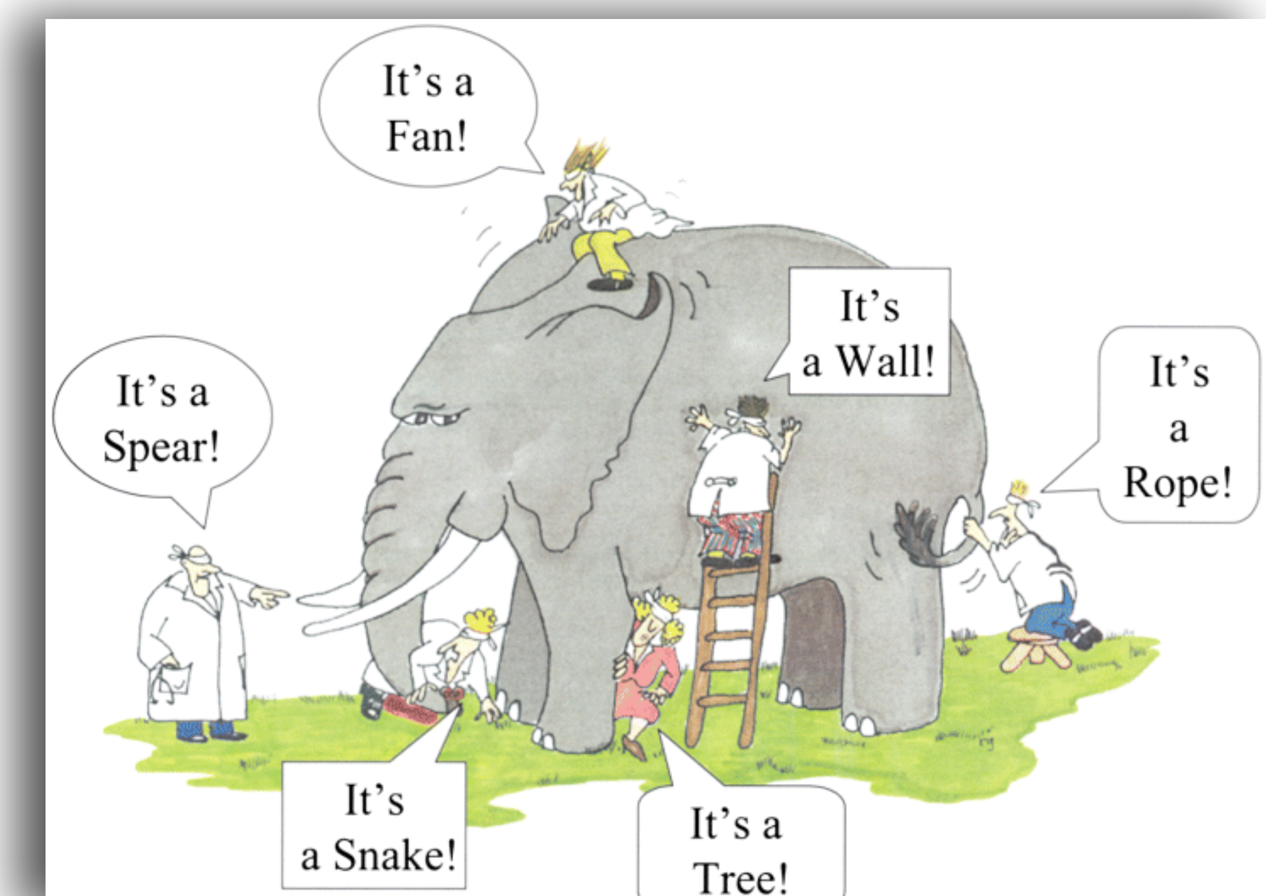
What is the gravity-matter dynamics in the UV?



Summary

- asymptotic safety: joint model of gravity and matter
- fixed point is fully non-Gaussian
- Newton coupling defined from gravity-matter vertex exhibits asymptotic safety in pure-gravity case and in certain approximation also for small number of scalars

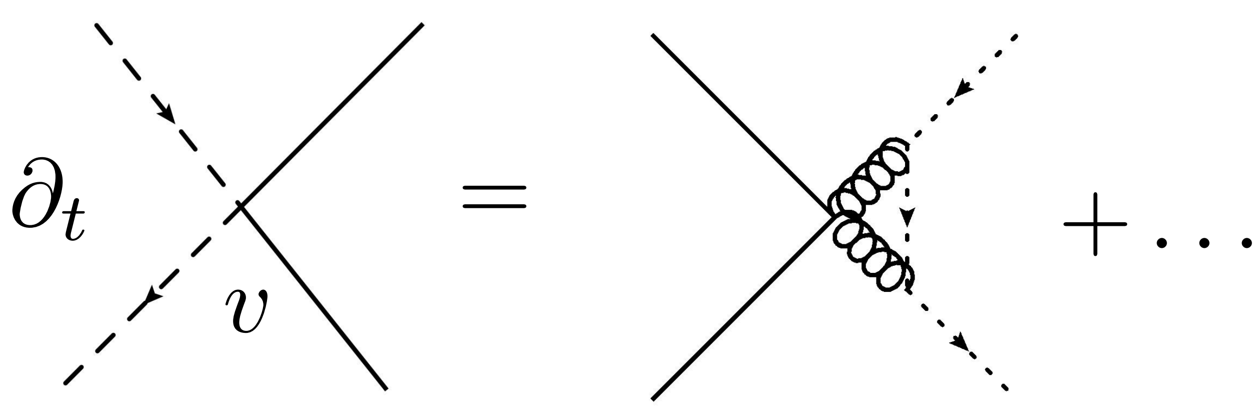
Future directions

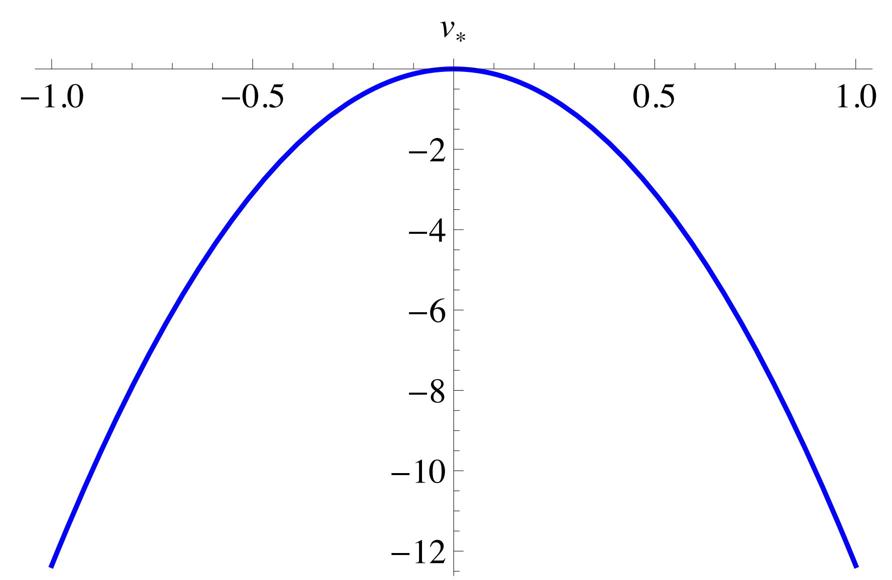
- Explore matter-gravity vertices in larger truncations, linear parameterisation
- Which marginal SM couplings are irrelevant at an interacting fixed point?
- What about asymptotic freedom in gauge theories coupled to asymptotically safe gravity?

Structure of a fixed point for gravity + matter

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

$$\Gamma_{\mathrm{Faddeev-Popov}} = -\sqrt{2} \int \bar{c}_\mu \left(\bar{D}^\rho \bar{g}^{\mu\kappa} g_{\kappa\nu} D_\rho + ... \right) c^\nu$$





A.E., ‘13

no “simple” FP ghost sector at fixed point