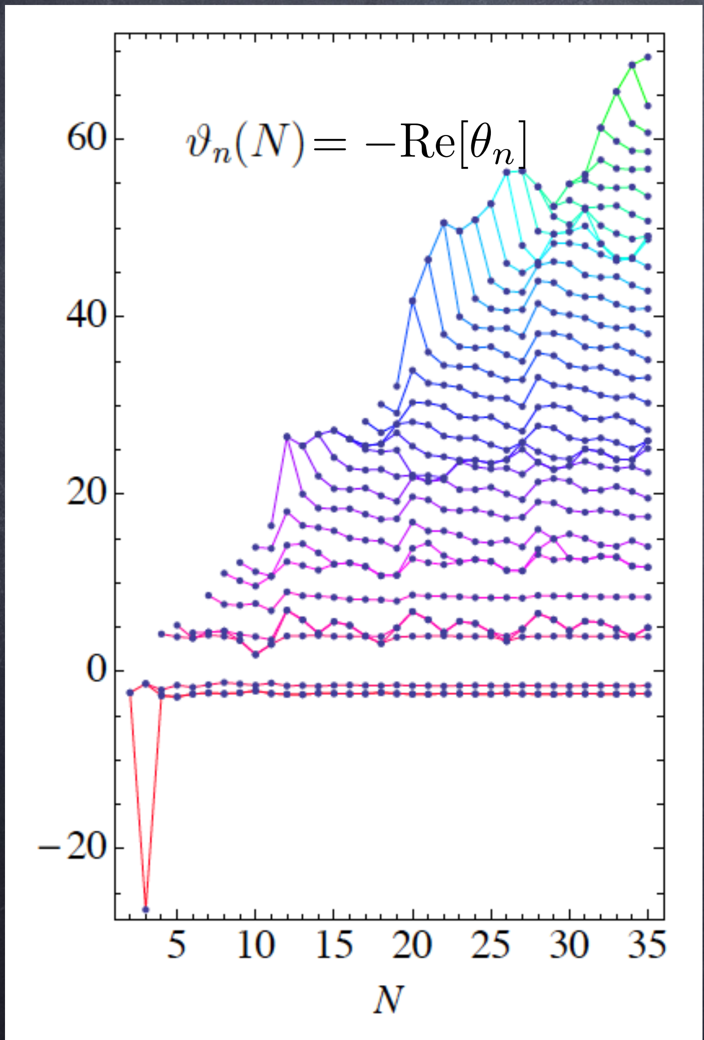
f(R) truncations

$$\Gamma_k = \int d^4x\sqrt{g} f_k(R) = \sum_i a_i(k) \int d^4x \sqrt{g}\, R^i$$



- three relevant directions
- near-Gaussian scaling for irrelevant directions:

$[R^n] = 2\,n \quad \rightarrow d_n = 4 - 2n$

$$\theta_n = 4.06 - 2.17\, n$$

-> canonical dimensionality useful guide for further truncations

[Falls, Litim, Nikolakopoulos, Rahmede '14]

Tensor structures beyond R

$$\Gamma_k = \int d^4x\sqrt{g}\left(u_0 + u_1 R + (u_2 - \frac{2}{3}u_3)R^2 + 2u_3\, R_{\mu\nu}R^{\mu\nu}\right)$$

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[Gies, Knorr, Lippoldt, Saueressig '16]

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Beyond finite-dimensional truncations

truncation $\Gamma_k = \int d^4x \sqrt{g} f(R)$

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Fixed-point equation: $\varphi(r) = k^{-4} f(R/k^2)$

$$\partial_t \varphi(r) - 2r\,\varphi'(r) + 4\varphi = rhs(\varphi, \varphi', \varphi'', \varphi''')$$

$\Gamma_k^{(2)}$ $\partial_t R_k \sim \partial_t \Gamma_k^{(2)} \sim \partial_t f''$

$$32\pi^2(\dot{\varphi} - 2r\varphi' + 4\varphi) = \frac{c_1(\dot{\varphi}' - 2r\varphi'') + c_2\varphi'}{\varphi'[6 + (6\alpha + 1)r]} + \frac{c_3(\dot{\varphi}'' - 2r\varphi''') + c_4\varphi''}{[3 + (3\beta - 1)r]\varphi'' + \varphi'} - \frac{c_5}{4 + (4\gamma - 1)r}$$

[Ohta, Percacci, Vacca '15]

-> Solution has 3 free parameters

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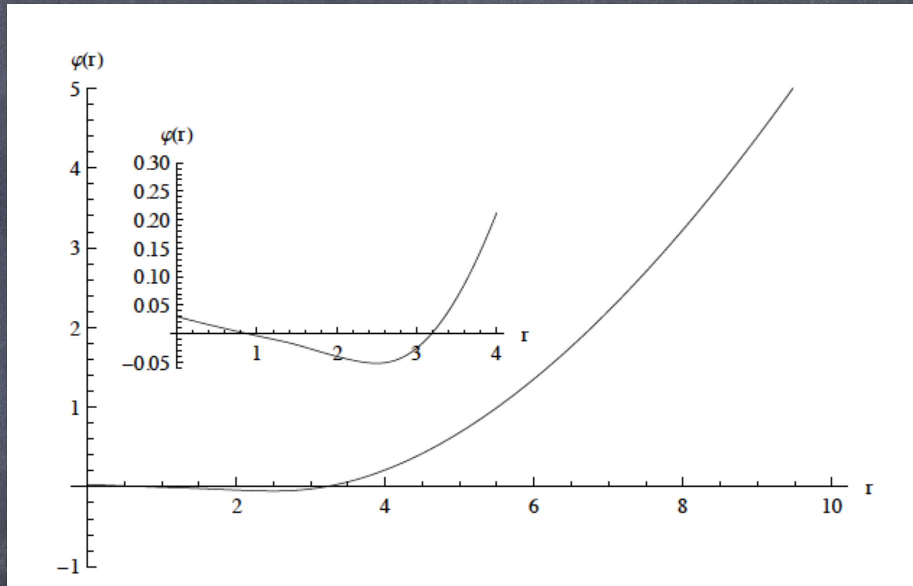
-> Solution has 3 free parameters:

$$\varphi(r) = g_0 + g_1 r + g_2 r^2$$

Fixed singularities: demand continuity of sol'n
-> each singularity "uses up" a free parameter

Beyond finite-dimensional truncations

truncation $\Gamma_k = \int d^4x \sqrt{g} f(R)$



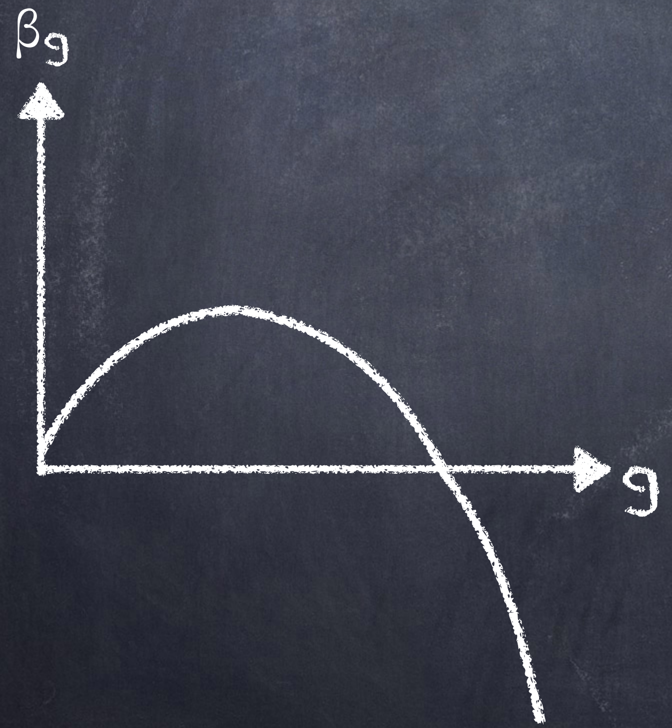
-> Global solutions have been found

[Benedetti, Caravelli '12; Dietz, Morris '12 '13 '15;
Demmel, Saueressig, Zanusso '15; Ohta, Percacci, Vacca '15]

Why d = 4 ?

$[G_N] = 2 - d$

$$\beta_g = (d-2)g + \mathcal{O}(g^2)$$



-> mechanism of balancing of canonical and quantum scaling could/should work beyond d=4

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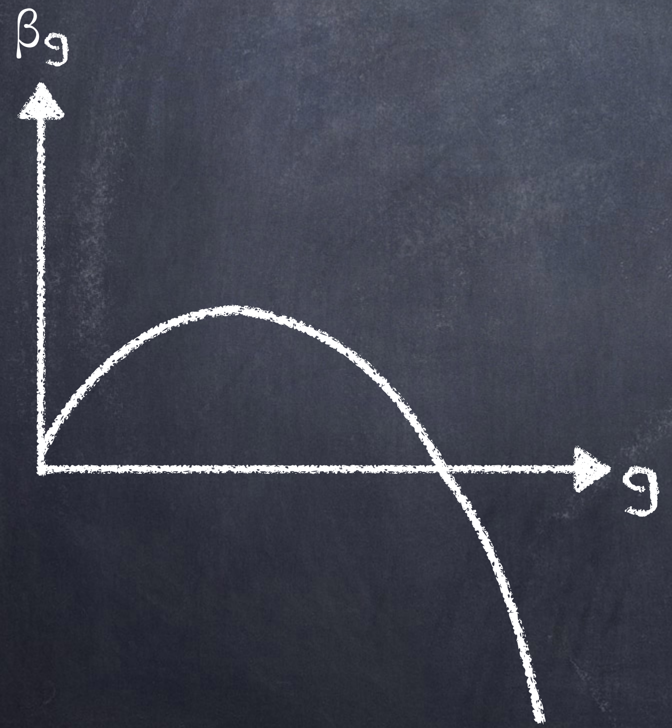

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truncation:	d_{max}	
Einstein-Hilbert	$\gtrsim 11$	[Fischer, Limit '06]
Einstein-Hilbert + quadratic curvature	$\gtrsim 6$	[Ohta, Percacci, 13]
Einstein-Hilbert	≈ 7.7	[Falls '15]

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Phenomenology of quantum gravity

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Experimental tests of quantum gravity:

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Experimental tests of quantum gravity:

Direct (``smoking-gun signals"):

- cosmology/astrophysics
- violation of symmetries -> effects that are usually zero
  Example: Lorentz-symmetry violation searches

Phenomenology of quantum gravity: Searches for Lorentz-symmetry violation

$$c^2\, p^2 = E^2 \left(1 + \sum_i s_i\, \frac{E^i}{M_{\rm Pl}^i} \right)$$

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$$v=\frac{\partial E}{\partial p}\approx c\left(1-s_n\frac{1+n}{2}\left(\frac{E}{M_{\rm Pl}}\right)^n\right)\qquad n=1,2,..$$

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-> Fermi satellite: $s_1 > 1.2$

[Abdo et al., '09]

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Experimental tests of quantum gravity:

Direct ("smoking-gun signals"):

- cosmology/astrophysics
- violation of symmetries -> effects that are usually zero

Indirect (Observational consistency tests):

- Semiclassical regime: Does large spacetime as we know it emerge from microscopic model?
- Can matter with all its properties be accommodated in the microscopic model?

Matter in quantum gravity

phenomenologically viable model of quantum spacetime must accommodate observed matter

-> expectation: matter will have effect on microscopic dynamics of spacetime

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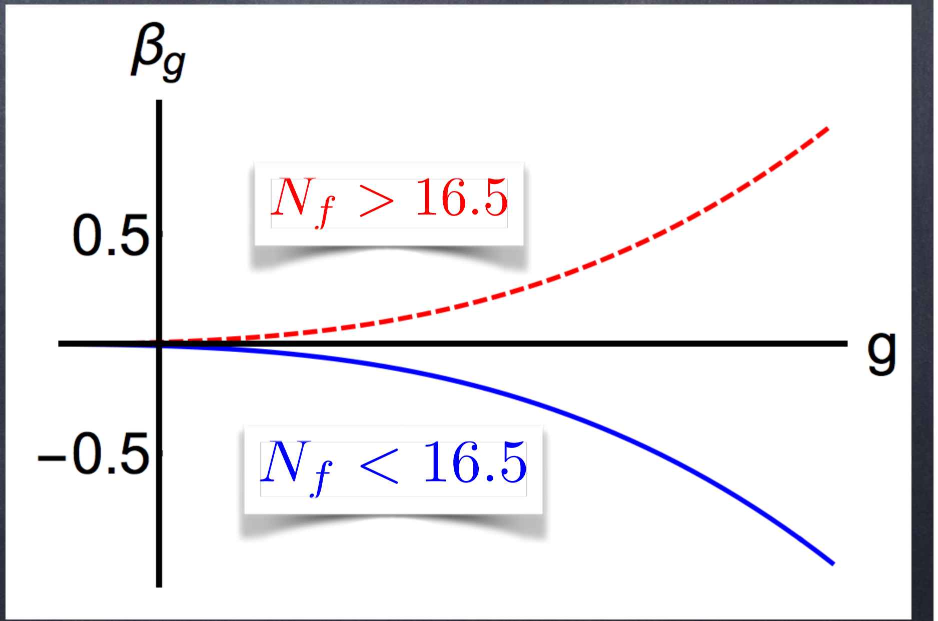
$$\beta_{g^2} = -\left(11 - \frac{2N_f}{3}\right)\frac{g^4}{16\pi^2}$$

-> matter fluctuations can destroy asymptotic freedom in gauge theories



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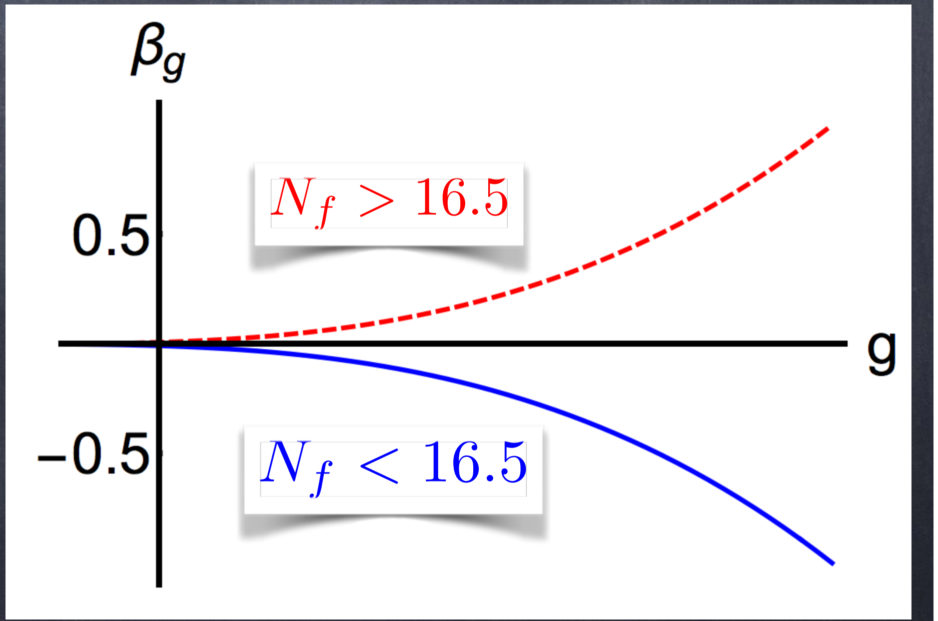

-> matter fluctuations can destroy asymptotic freedom in gauge theories

-> what about asymptotic safety in gravity?

Matter in quantum gravity

effects of minimally coupled matter on background couplings

[Percacci, Perini '02, '03; Codello, Percacci, Rahmede;
Dona, AE, Percacci '13]

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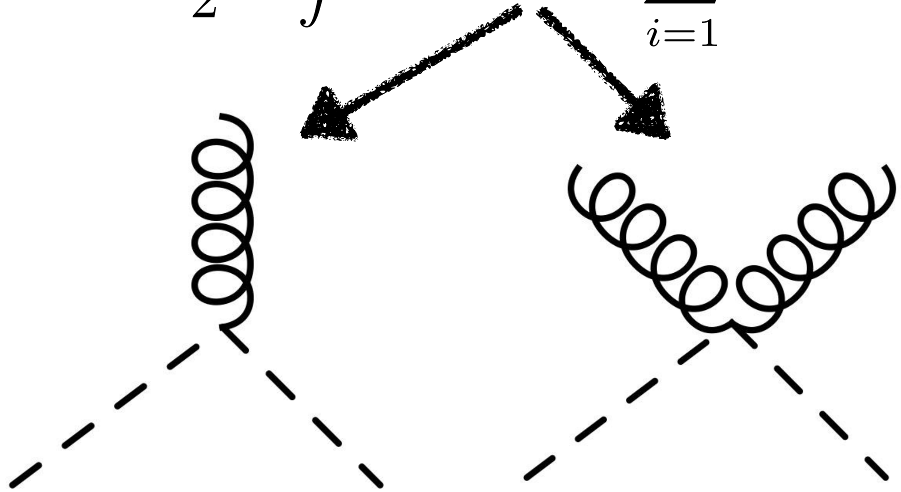

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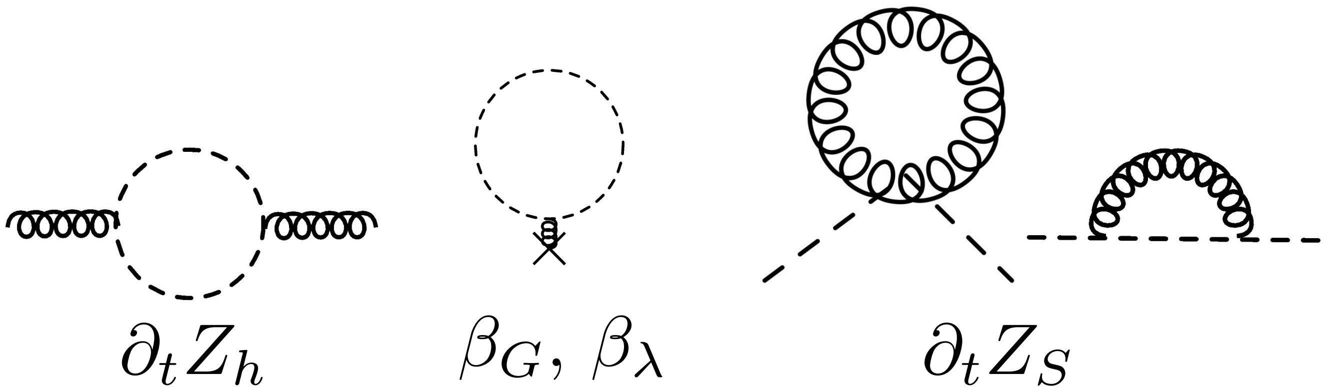

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[Dona, AE, Percacci '13]

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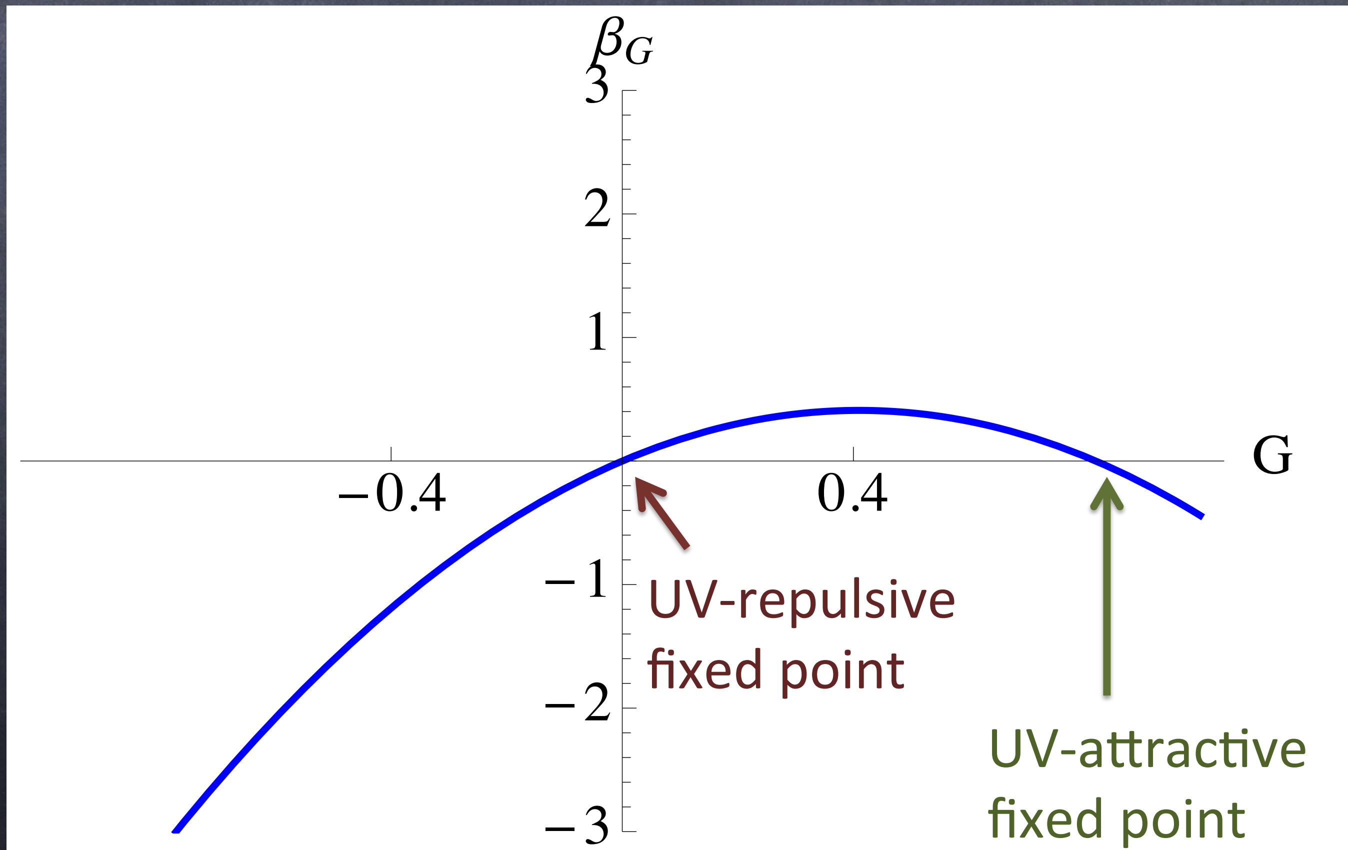

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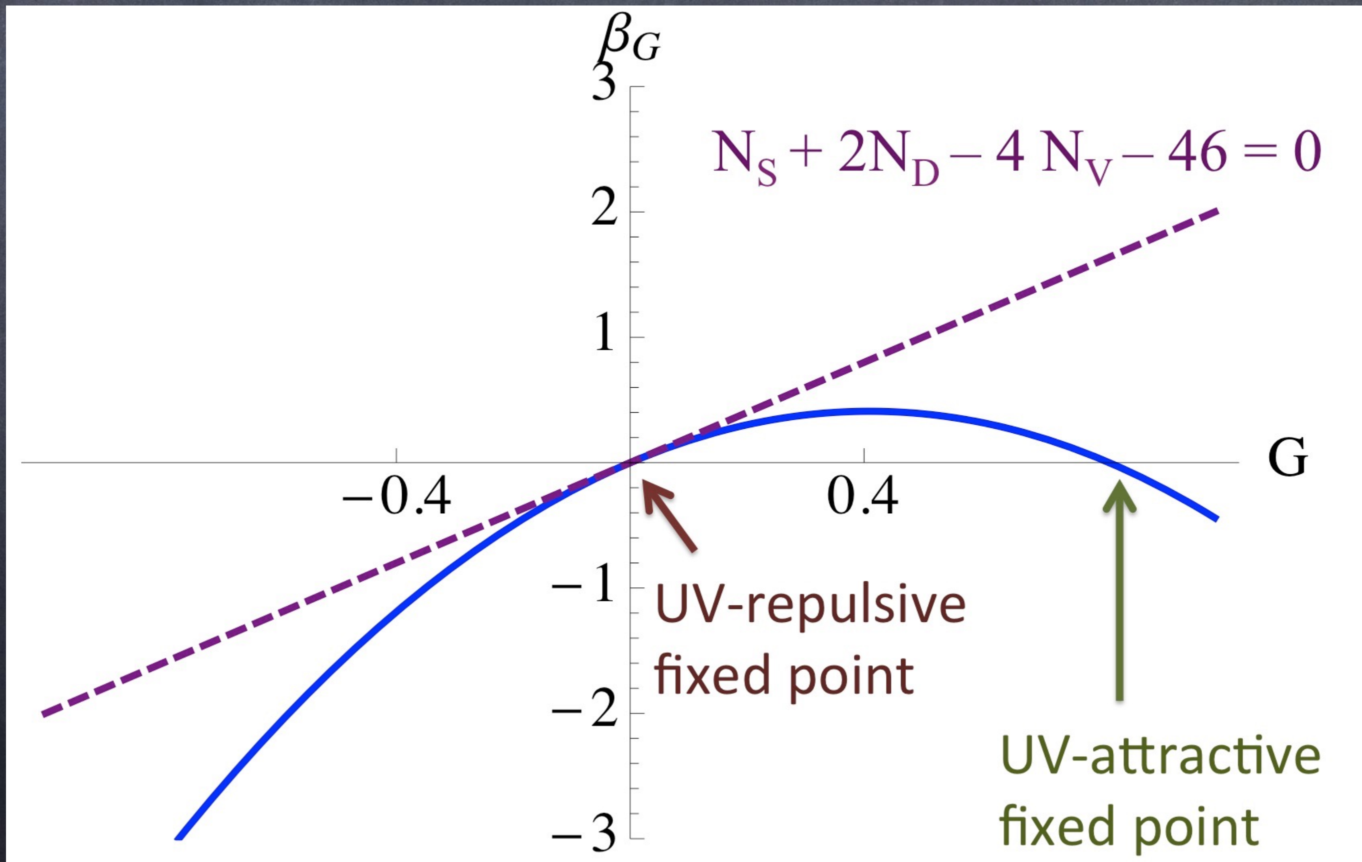

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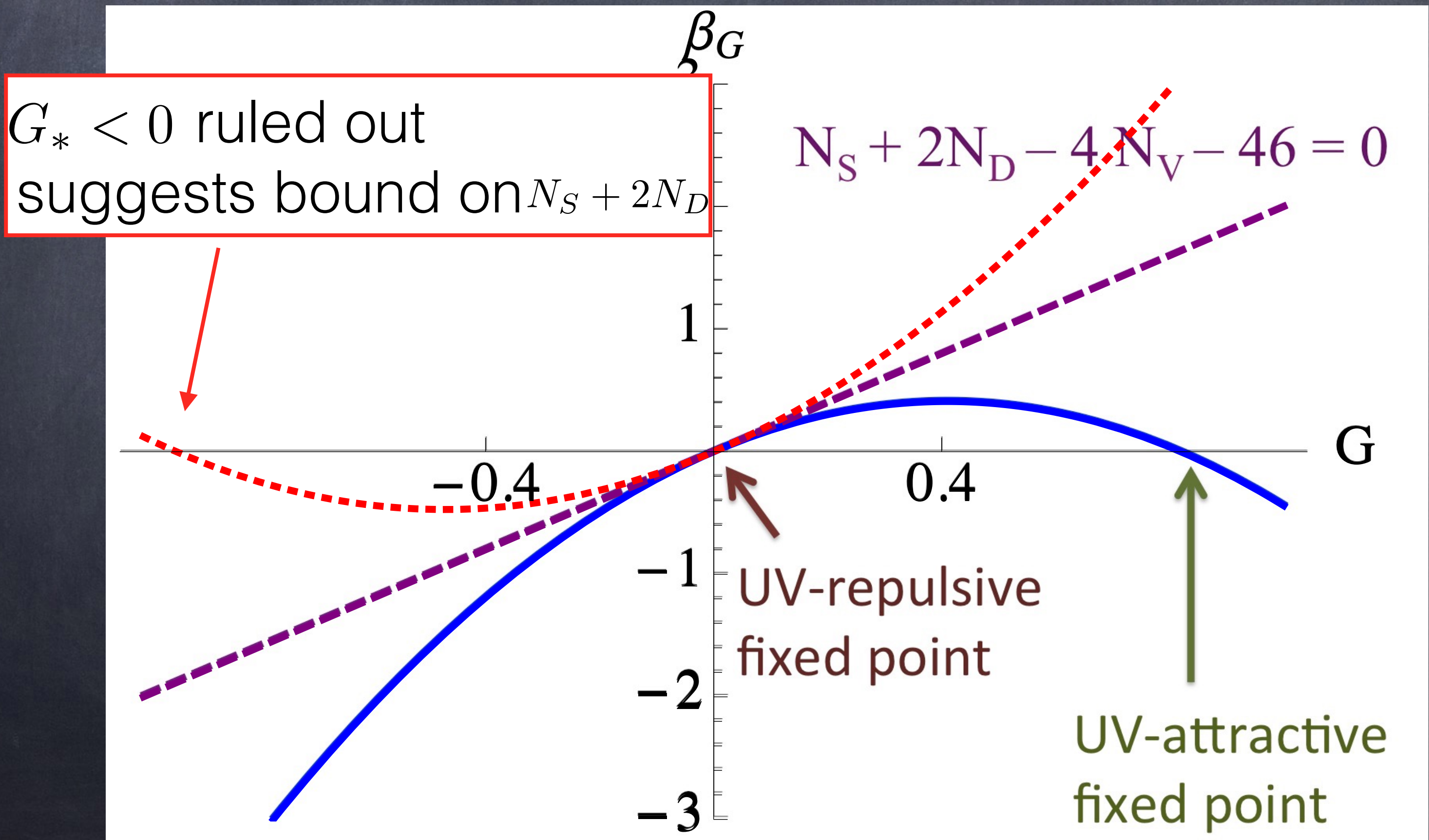

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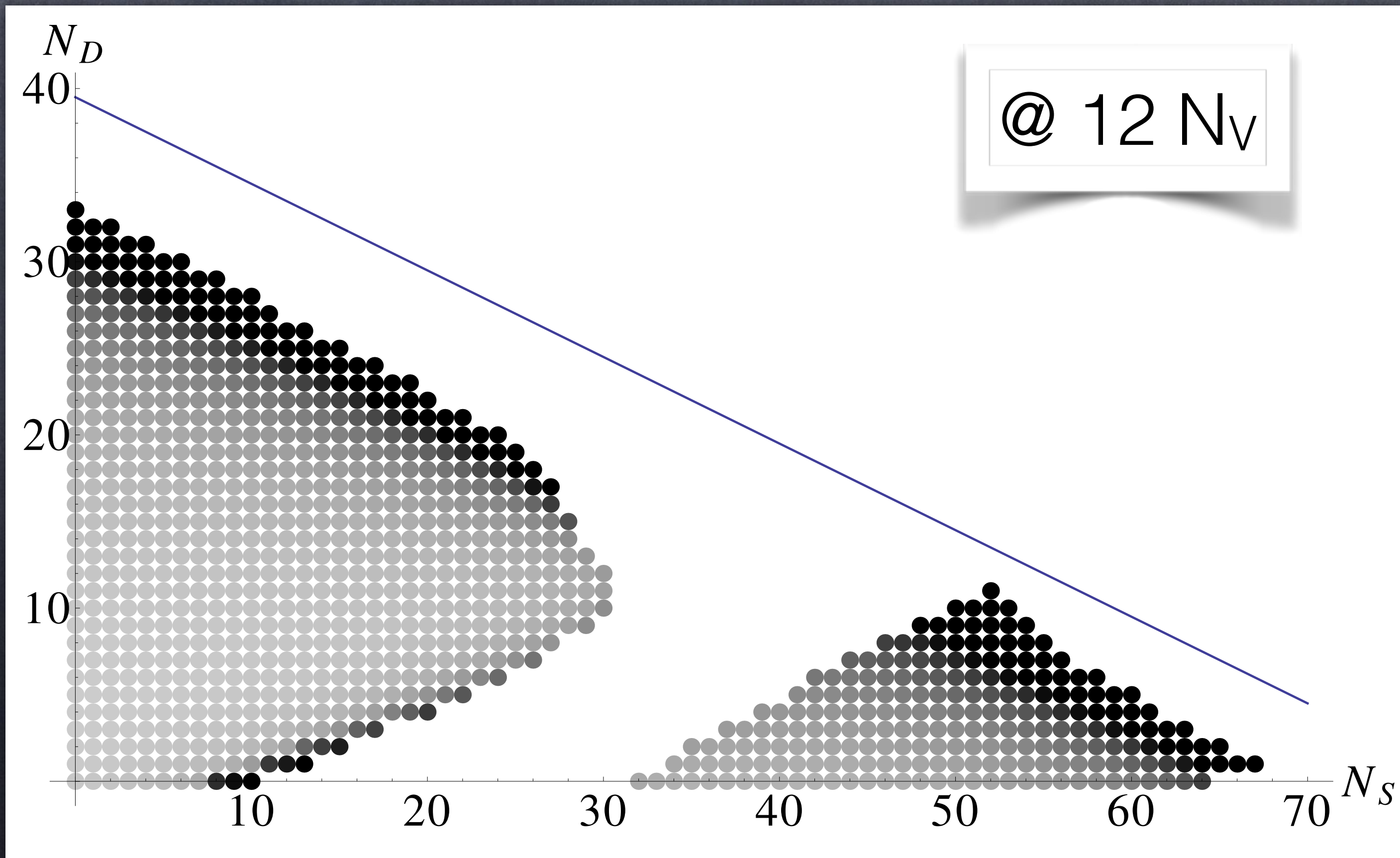

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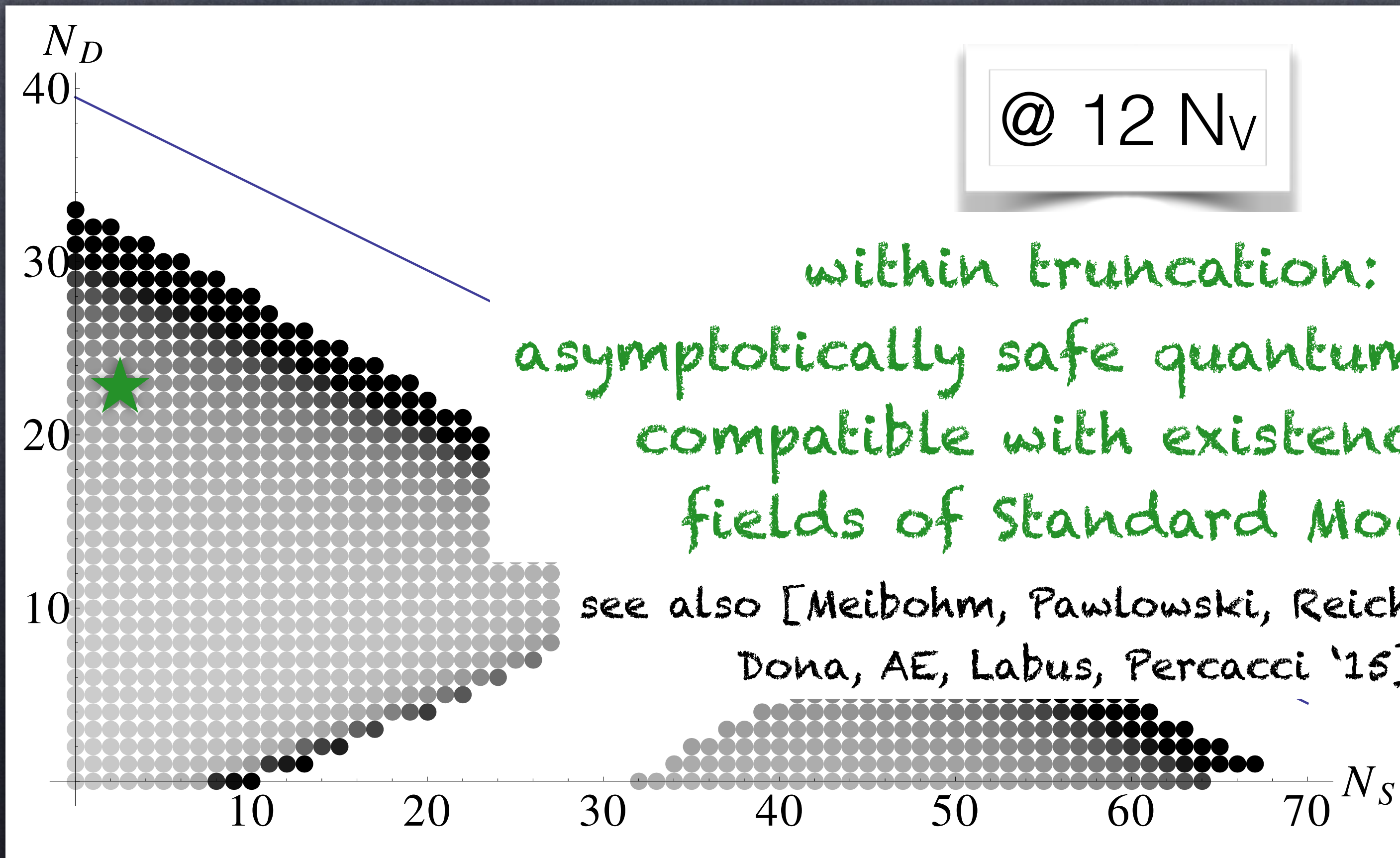

within truncation:
asymptotically safe quantum gravity compatible with existence of fields of Standard Model

see also [Meibohm, Pawlowski, Reichert '15; Dona, AE, Labus, Percacci '15]

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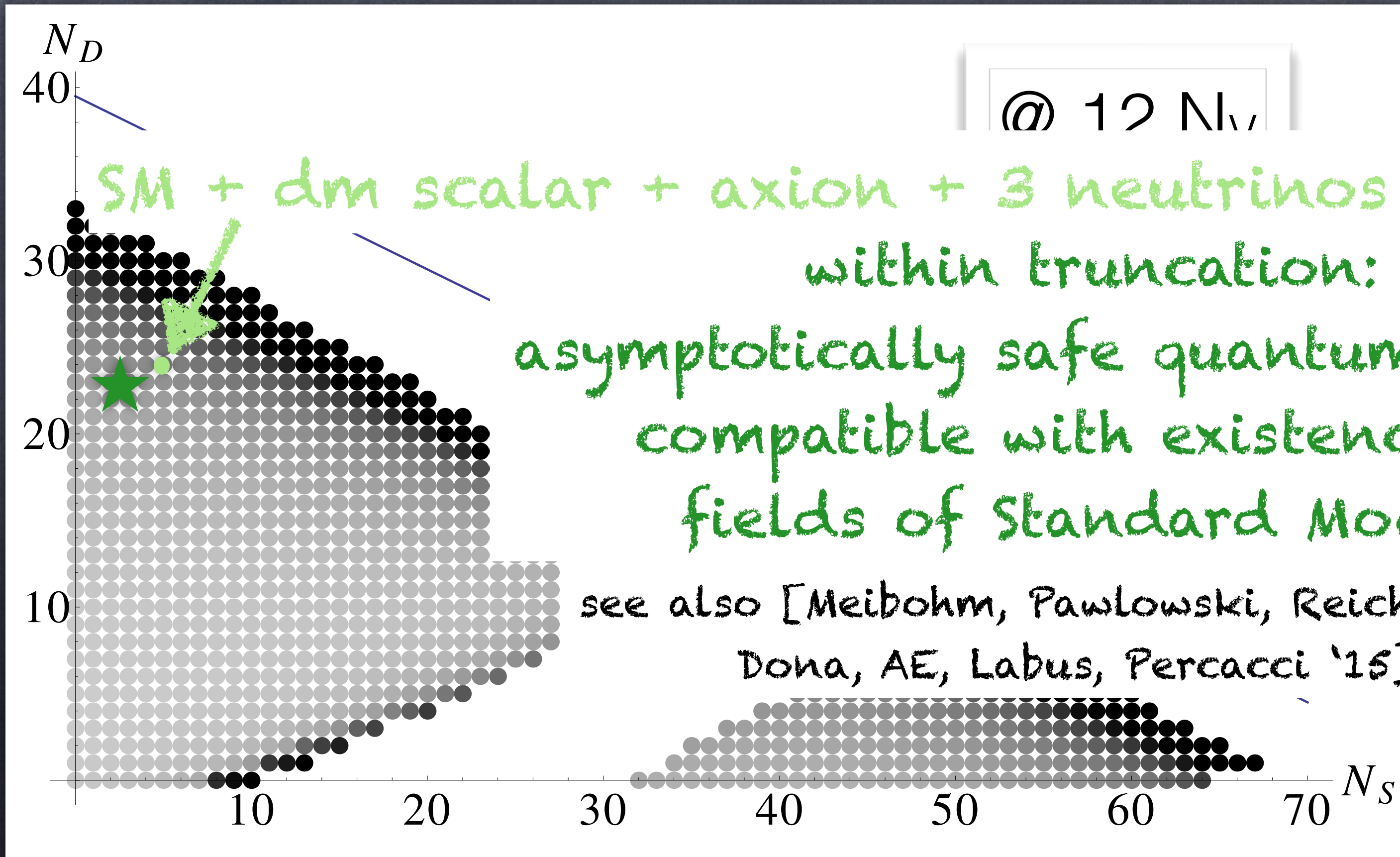

SM + dm scalar + axion + 3 neutrinos

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Standard Model

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Could induce a joint gravity-matter fixed point?

Quantum gravity effects on matter

$SU(3) \times SU(2)_L \times U(1)_Y$ + fermions (chiral symmetry) + Higgs

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Quantum-gravity induced fixed points
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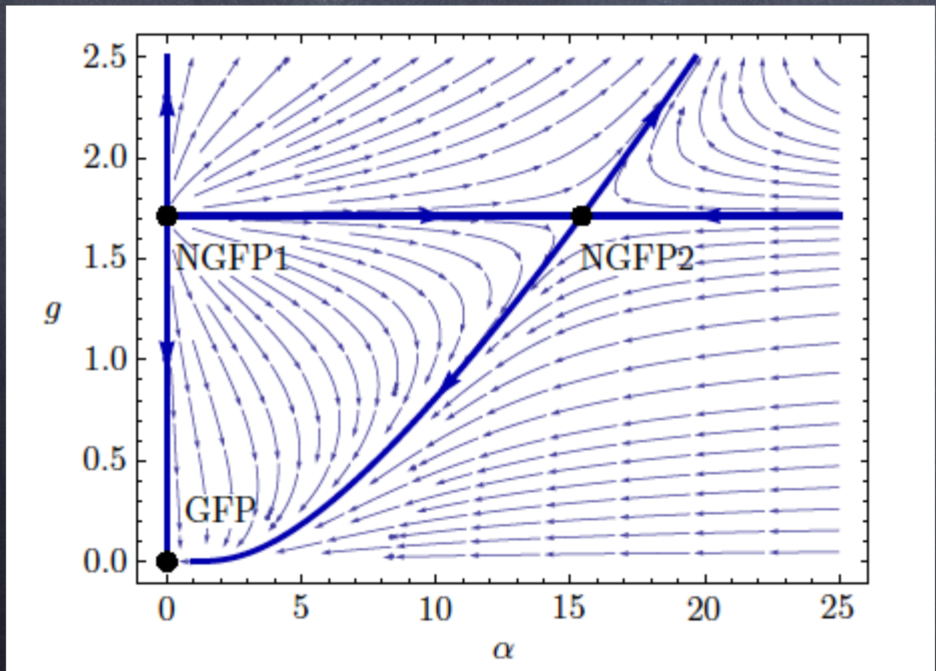

[Harst, Reuter '11]

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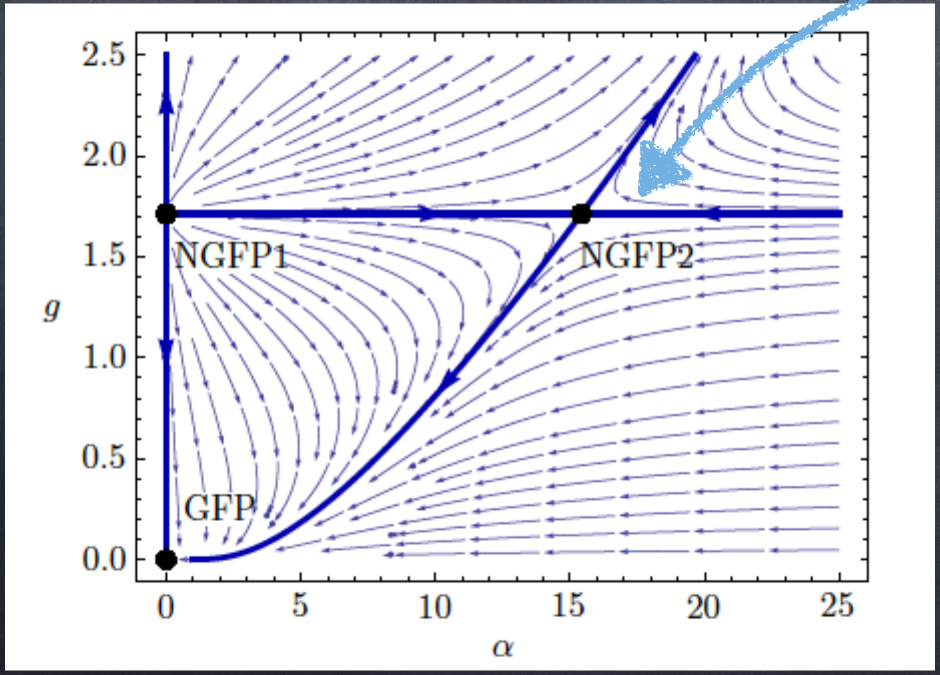

U(1) coupling irrelevant

$$\alpha_{\mathrm{em\,IR}} \approx \frac{1}{11}$$

[Harst, Reuter '11]

Quantum gravity effects on matter

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↓

Asymptotic freedom in gauge theories persists in asymptotically safe gravity (truncation: Einstein-Hilbert + F^2)

[Daum, Harst, Reuter '10; Folkerts, Litim, Pawlowski '11]

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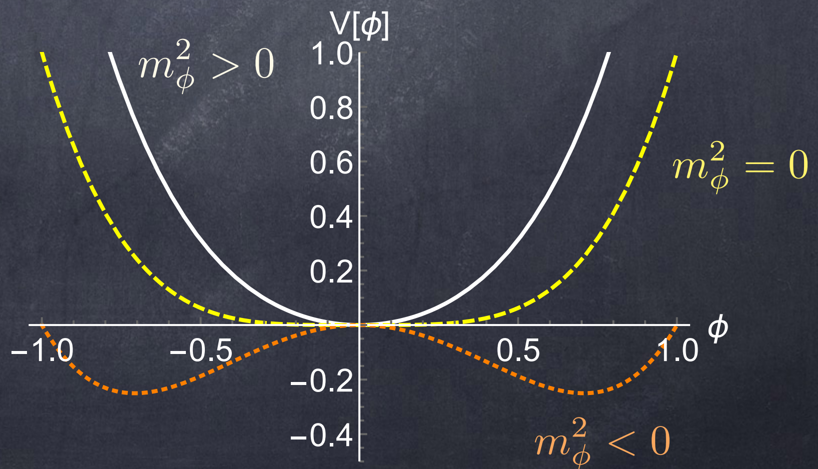

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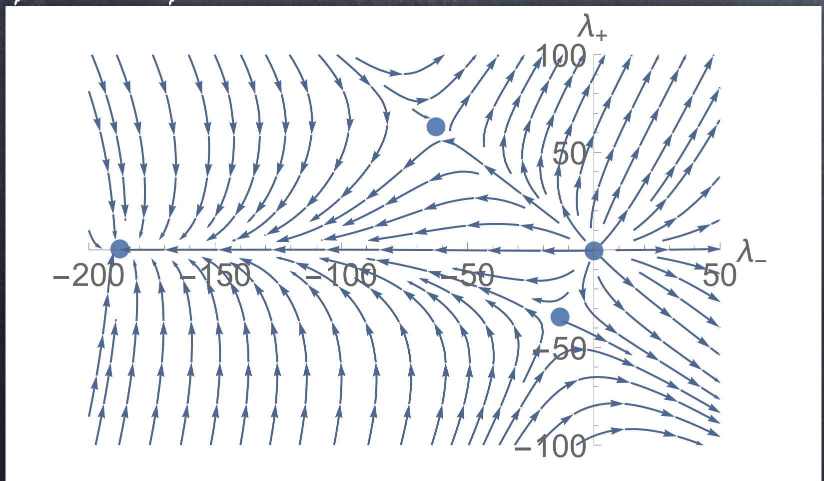
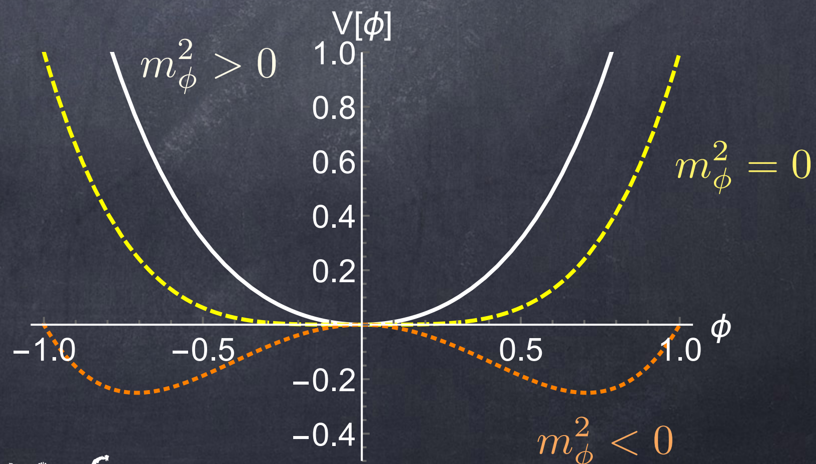
-> four-fermion interactions λ_i

$\bar{\psi}\psi \sim \phi$ with $m_\phi^2 \sim \dfrac{1}{\lambda_i}$



[AE, Gies '09; Meibohm, Pawlowski '16]



-> asymptotic safety compatible with light fermions

Quantum gravity effects on matter

$SU(3) \times SU(2)_L \times U(1)_Y$ + fermions (chiral symmetry) + Higgs

Fixed point in matter sector at vanishing couplings

truncation: Einstein-Hilbert + $V[\phi] + f(\phi)R$

[Percacci, Narain '09; Percacci, Vacca '15; Oda, Yamada '15]

-> could lead to M_H = 126 GeV [Shaposhnikov, Wetterich '09]

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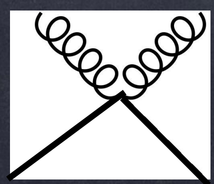
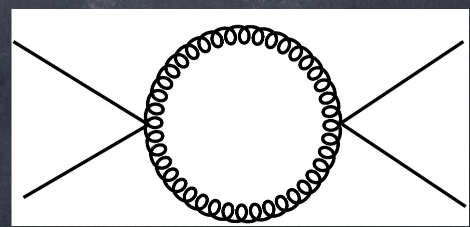
truncation is not closed:
momentum-dependent matter
self-interactions induced
at interacting fixed point

[AE '12]

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





$c_1\,(\partial_\mu\phi\partial^\mu\phi)^2$

$c_{1\,*} \neq 0$

Quantum gravity effects on matter

SU(3) x SU(2)$_L$ x U(1)$_Y$ + fermions (chiral symmetry) + Higgs

-> expected fixed-point structure for gravity + matter:
fully interacting

truncation is not closed:
momentum-dependent matter
self-interactions induced
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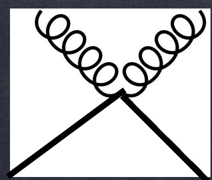
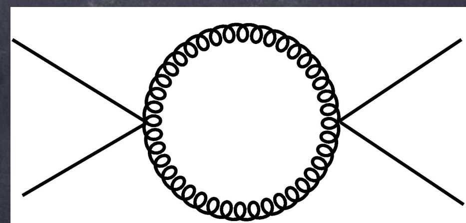
[AE '12]

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





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Quantum gravity effects on matter

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-> hints for asymptotic safety in SM + gravity

open questions:

- Is there a joint fixed point beyond simple truncations?
- What are the (ir)relevant directions?
- Can some of the SM parameters be predicted correctly from AS?

Towards asymptotically safe phenomenology?

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Expect quantum gravity to play important role in early universe

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(e.g. external momenta in scattering processes; curvature scales in early universe)

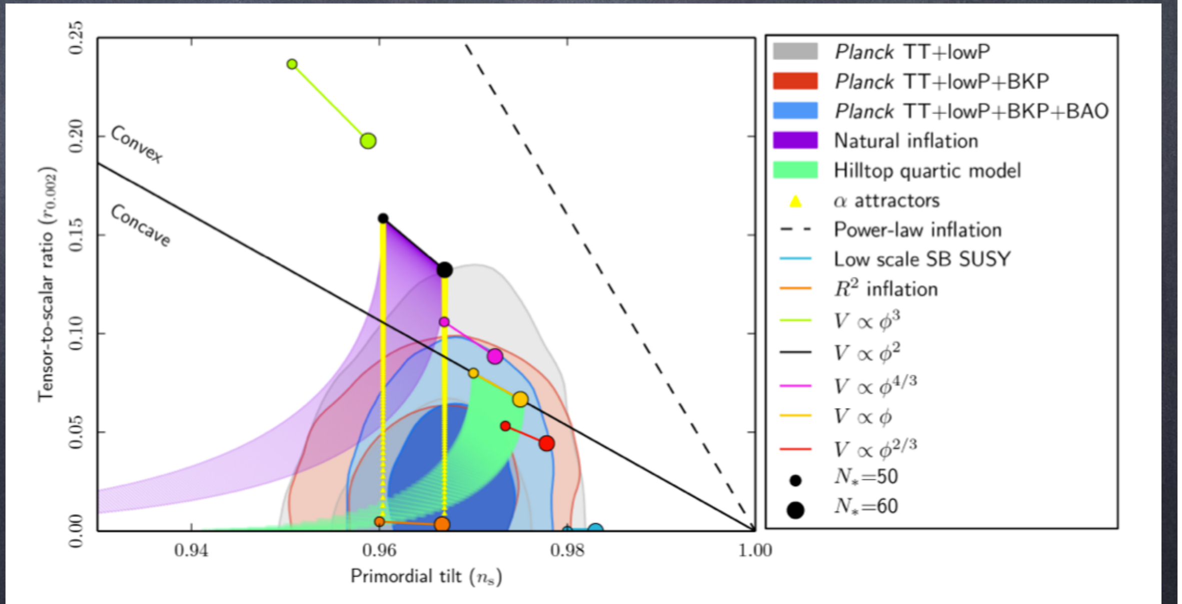
Extract hints about phenomenology from $\Gamma_{k^2\sim R}$

-> inflationary model compatible with observational data?

[Bonanno, Reuter '01, '02; Reuter, Saueressig '05; Bonanno, Reuter '07; Contillo '10; Bonanno, Contillo, Percacci '11; Contillo, Hindmarsh, Rahmede '12; Bonanno, Platania '15]

Towards asymptotically safe phenomenology?

"RG improved" action $\Gamma_{k^2\sim R} = \int d^4x\sqrt{-g}f(R)$



[Planck collaboration '15]

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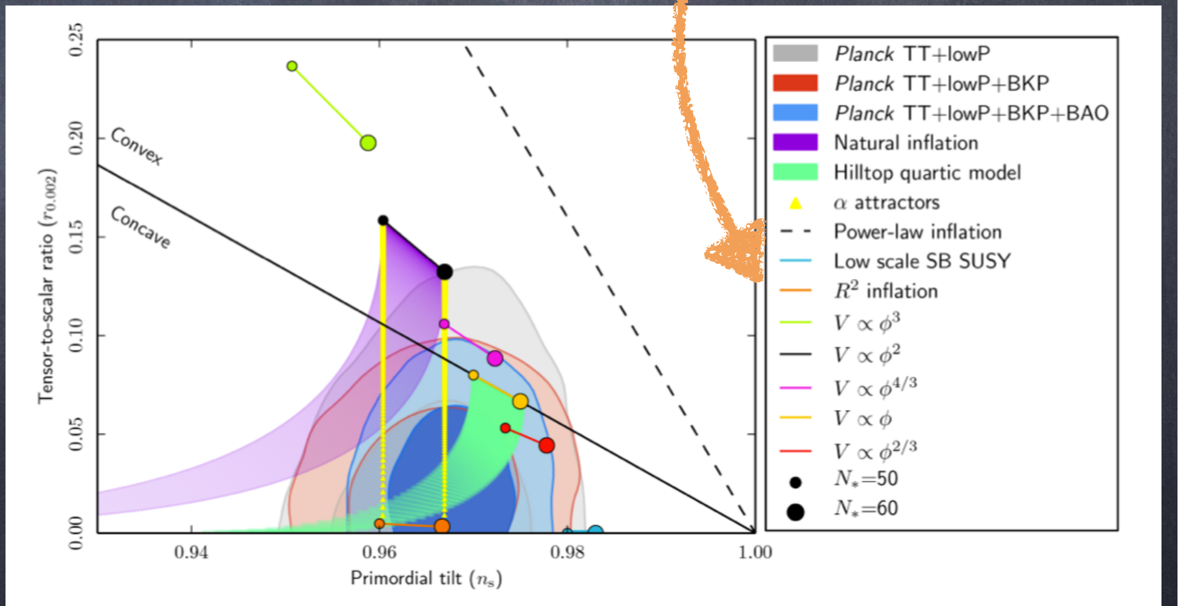

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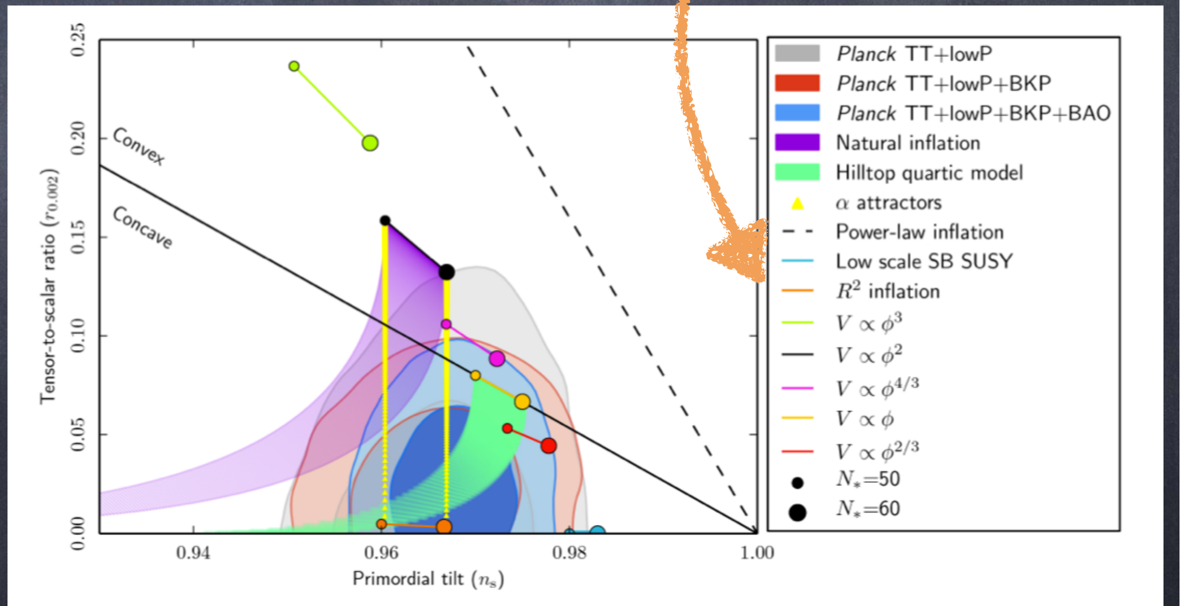

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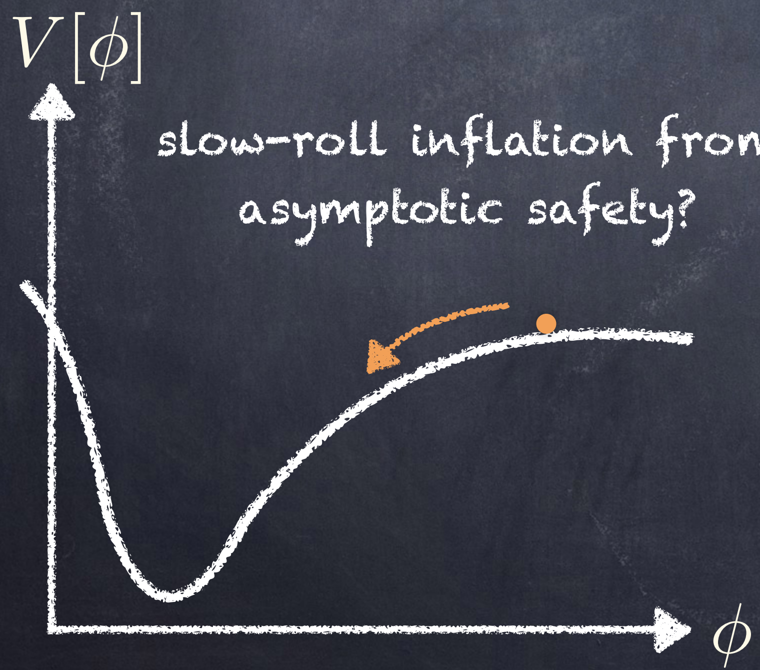

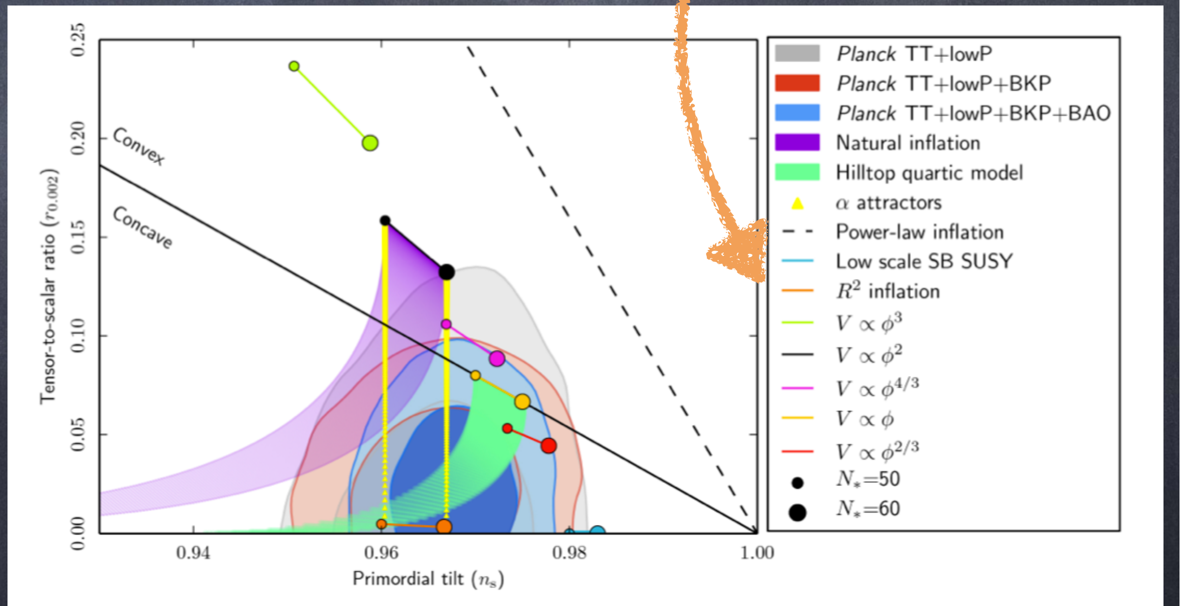

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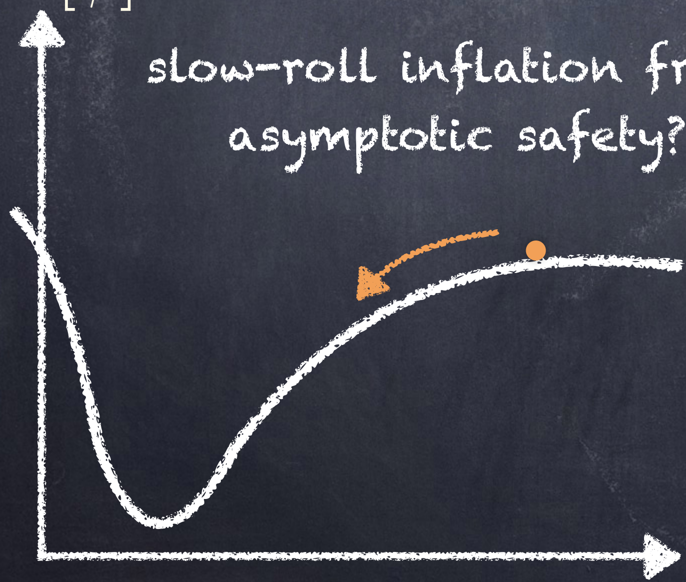

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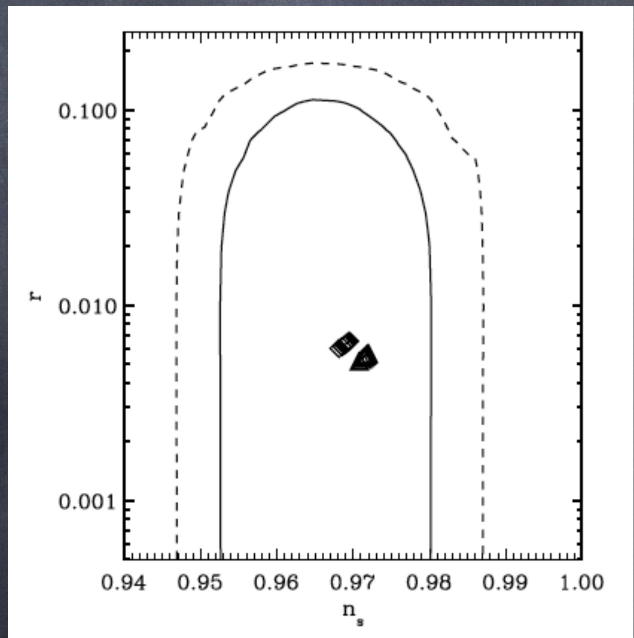

[Bonanno, Platania '15]

The cosmological constant problem in asymptotic safety

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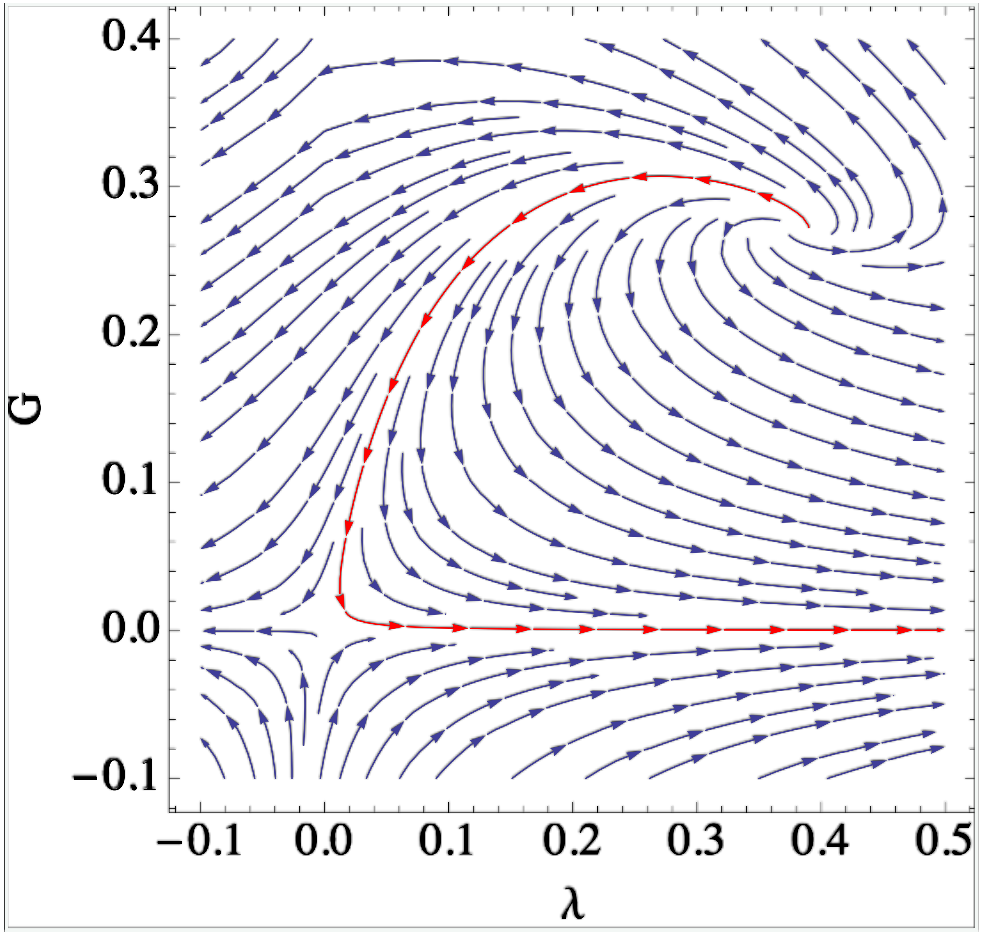
$$\Gamma_k = -\frac{1}{16\pi G_N}\int d^4x\,\sqrt{g}\,(R-2\Lambda) \qquad G = G_N k^2, \quad \lambda = \Lambda k^{-2}$$



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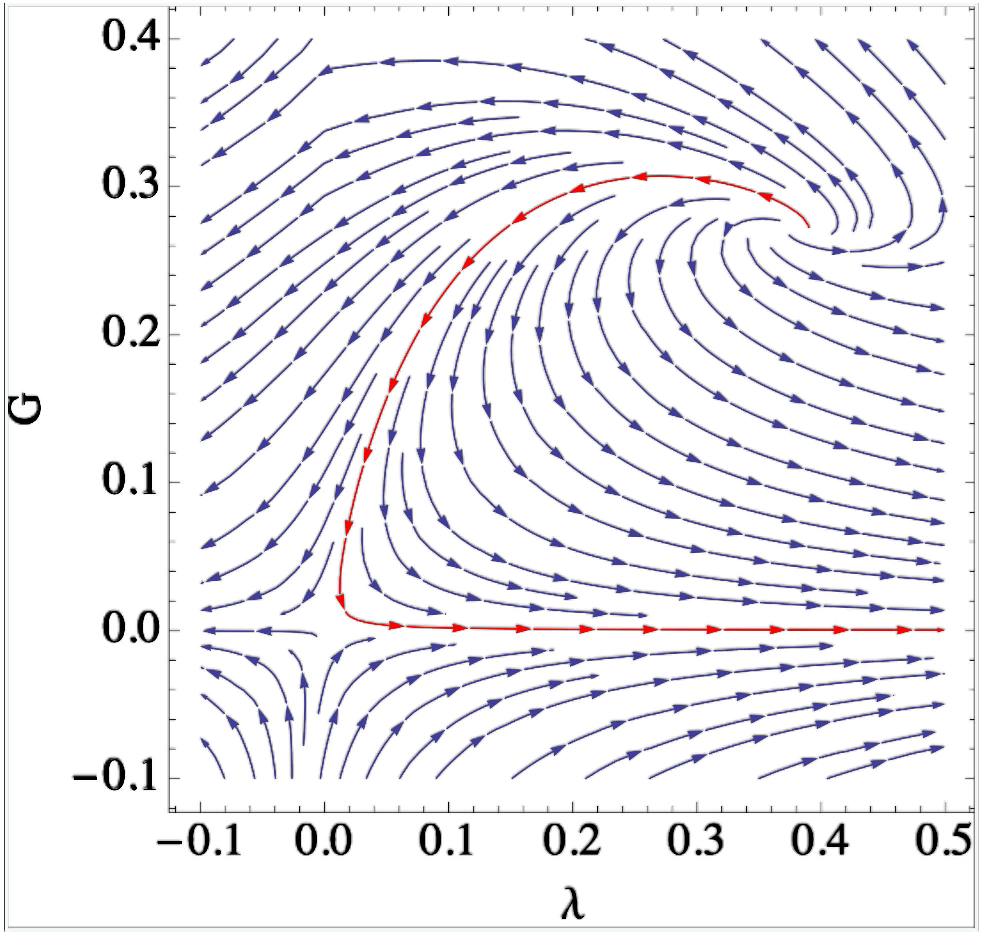

Effective field theory argument:

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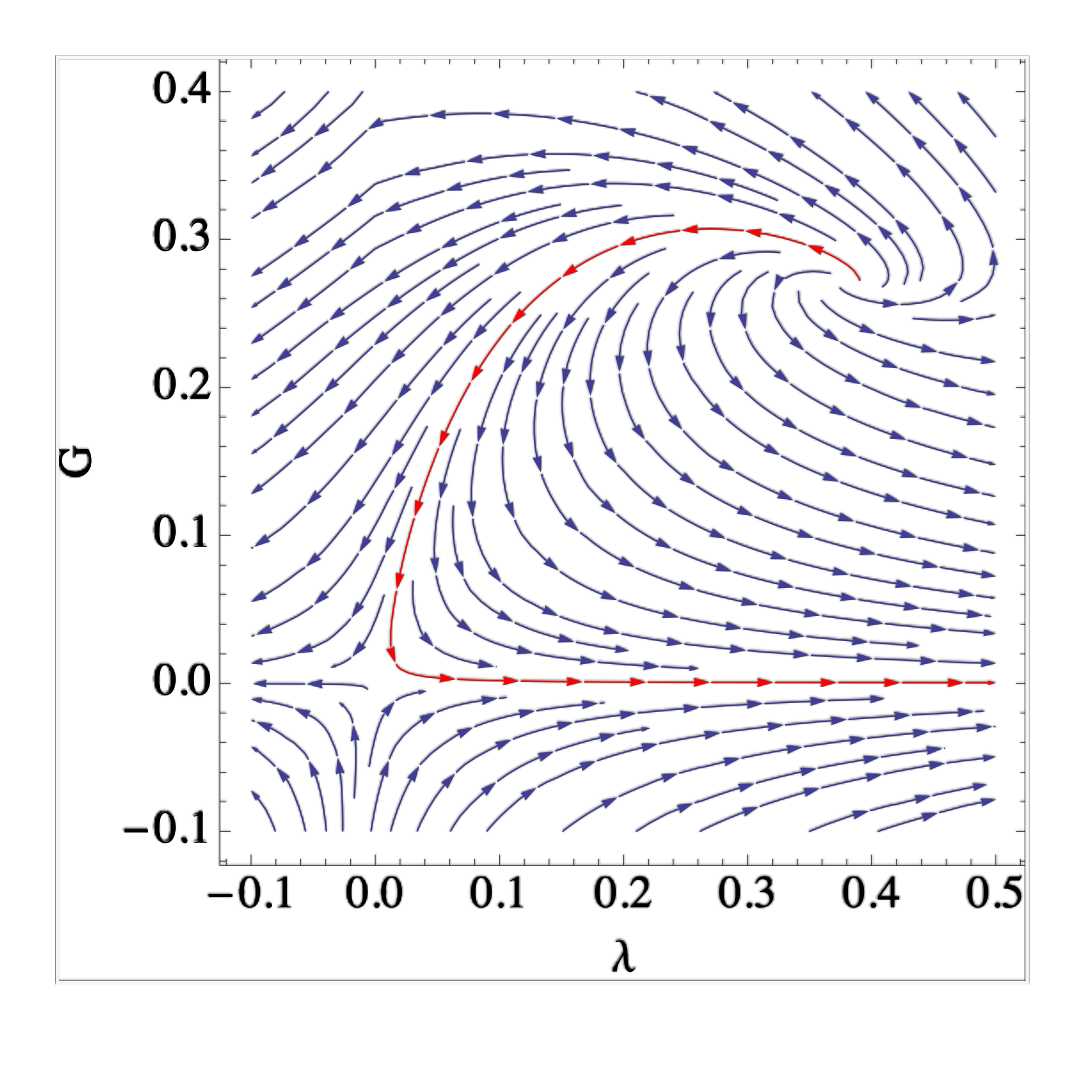

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"bare" value

from qm fluc's

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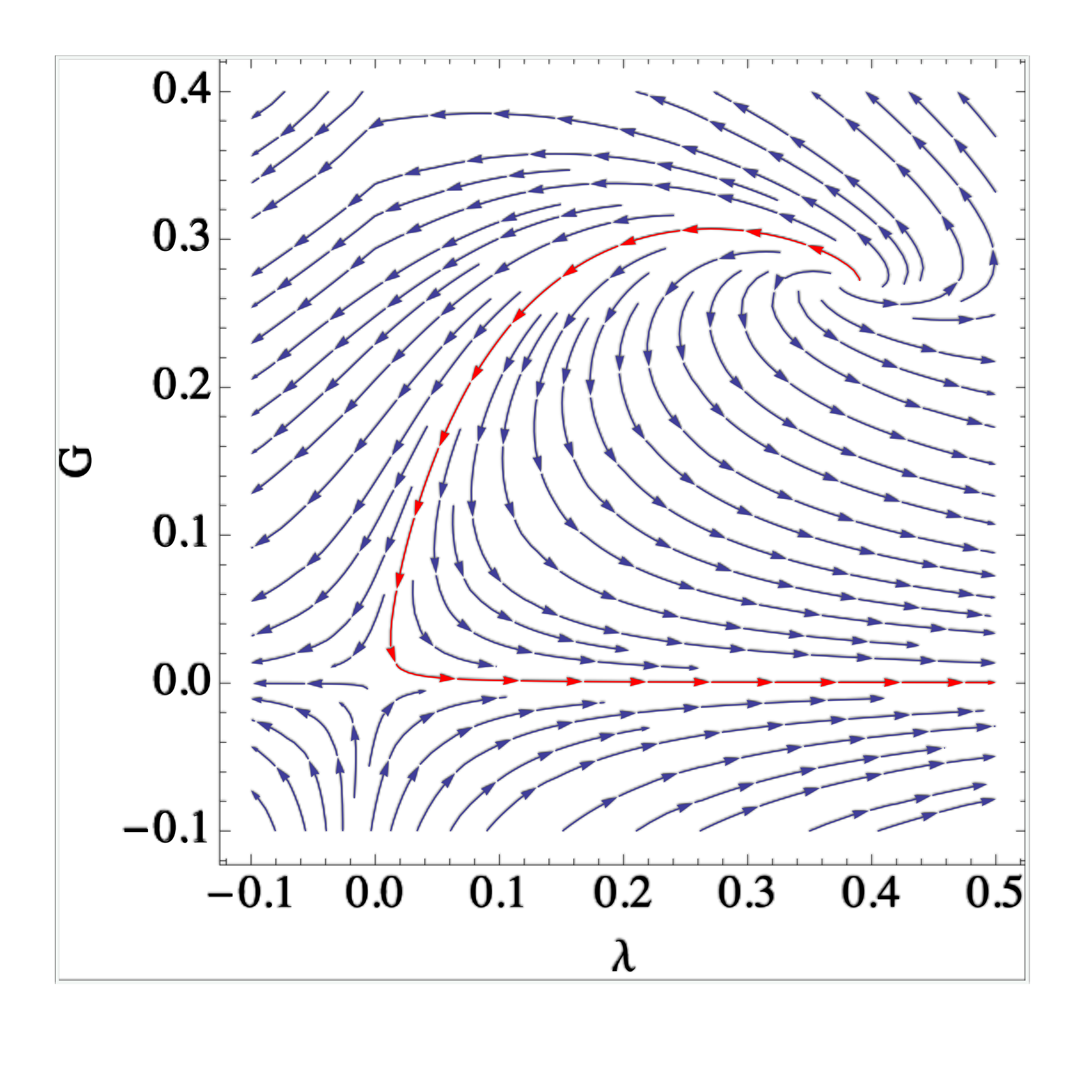

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"bare" value (Λ_0) from qm fluc's ($\delta\Lambda$)

$$\Lambda_{\text{measured}} \approx 10^{-122} M_{\text{Pl}}^2$$

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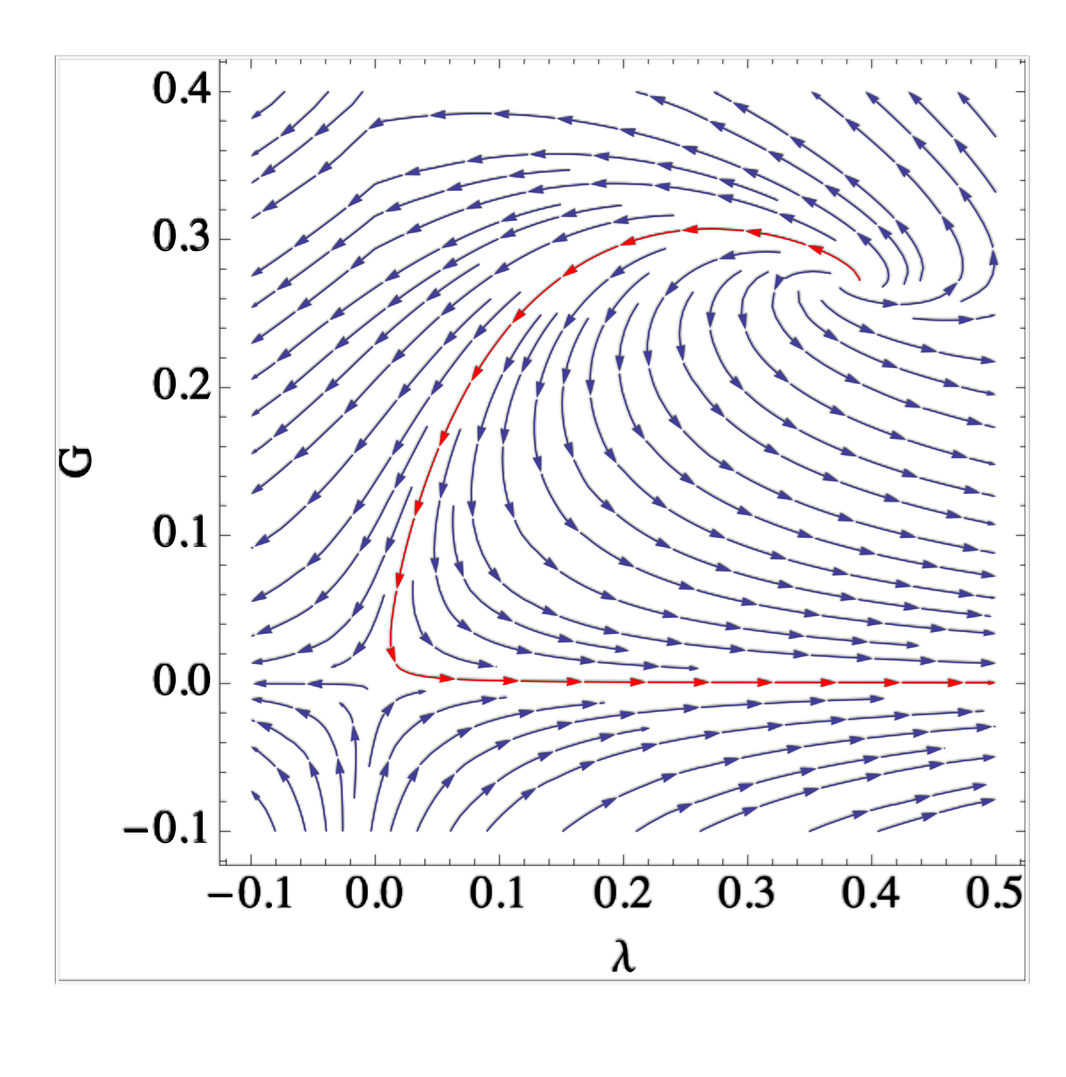

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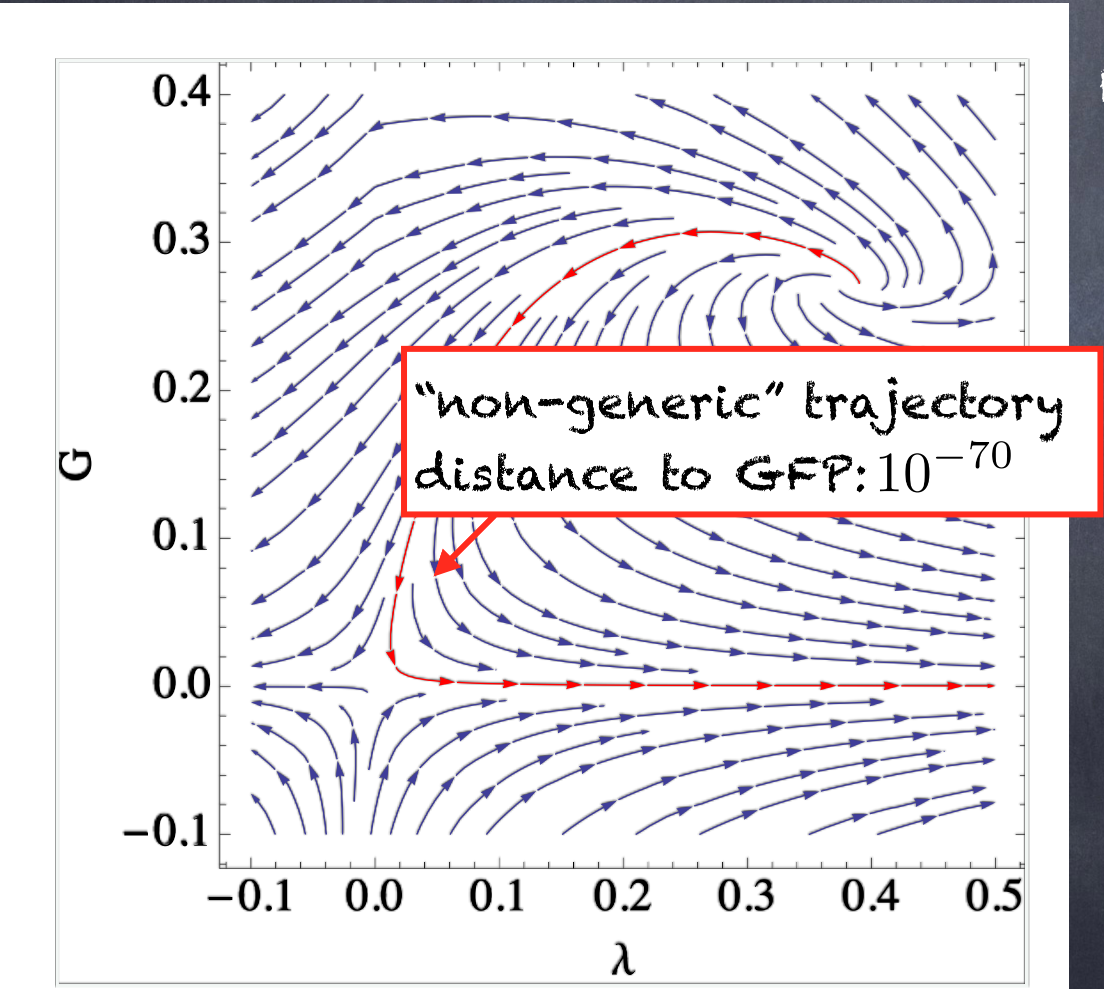

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Cosmological constant in unimodular gravity

fundamental variable of gravity: $g_{\mu\nu}$ with $\sqrt{g} = \text{const} = \epsilon$

[Einstein (1919); Ng, van Dam, van der Bij (1982); Unruh (1989); Weinberg (1989), Henneaux, Teitelboim (1989); Alvarez (2005), Smolin (2009)]

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$\Lambda \int d^4x \sqrt{g} = \Lambda \cdot \mathrm{const}$ -> not part of the action

not a running coupling

quantum fluctuations do not contribute

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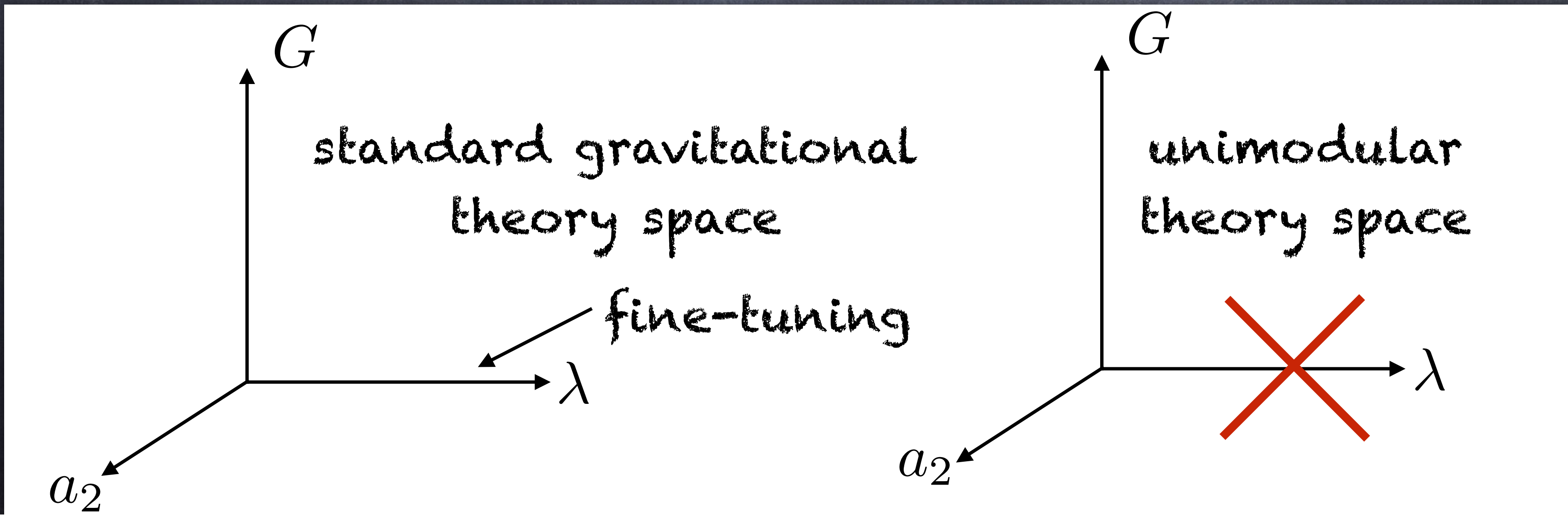

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...vity?

fu... ...onst $= \epsilon$

-> ...1982); Unruh (198...

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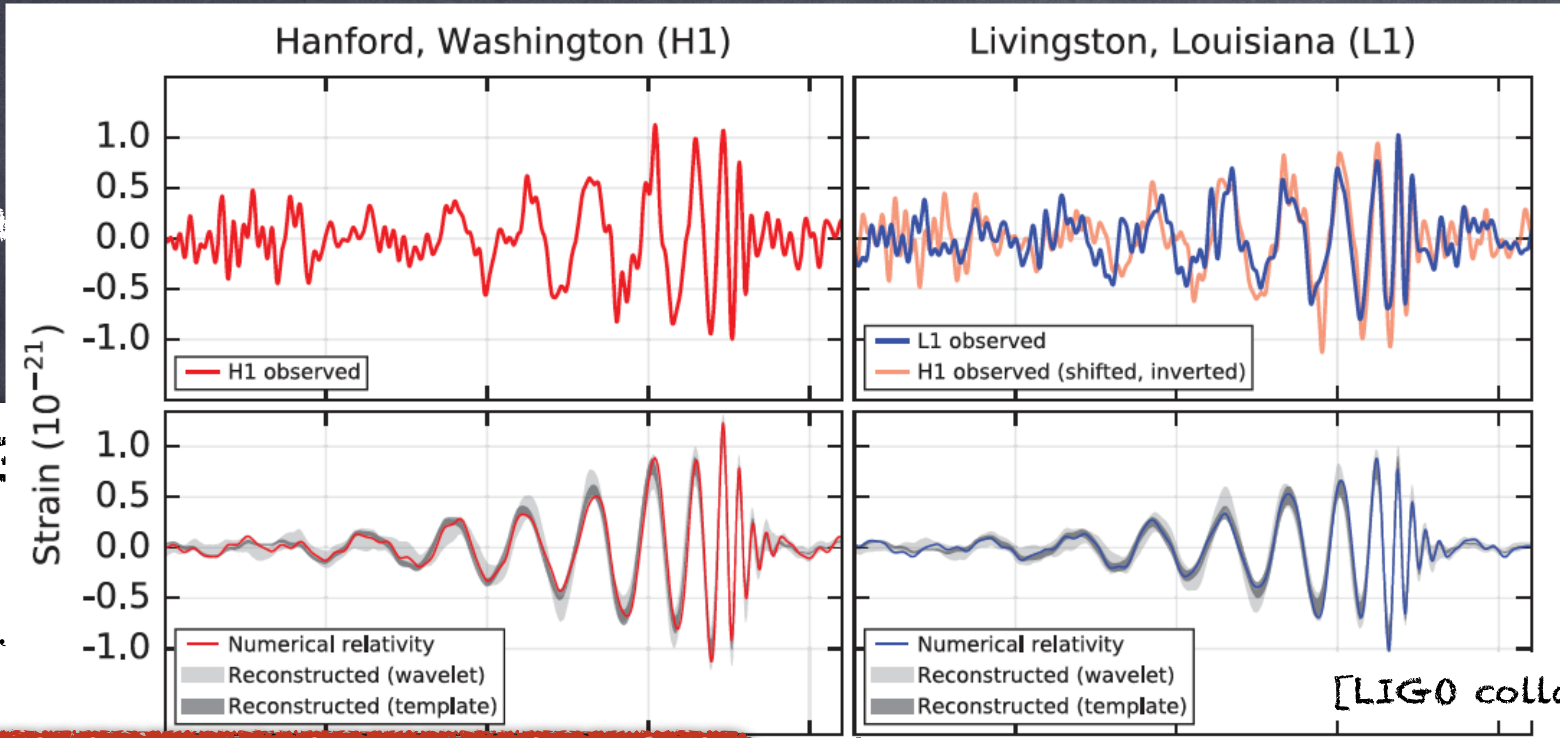

[LIGO collaboration '16]

$S =$ ...

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$$D_\mu \underbrace{\left(R - 8\pi G_N T^{\lambda}_{\lambda}\right)}_{\text{const} = 4\Lambda} = 0$$

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T_{\mu\nu}$$

Unimodular quantum gravity

fundamental variable of gravity: $g_{\mu\nu}$ with $\sqrt{g} = \mathrm{const} = \epsilon$

-> no conformal mode [Einstein (1919); Ng, van Dam, van der Bij (1982); Unruh (198
Henneaux, Teitelboim (1989); Alvarez (2005), Smolin (2009)]

$$\int \mathcal{D}g_{\mu\nu} e^{-S[g_{\mu\nu}]} \quad \text{with} \quad \sqrt{g} = \mathrm{const} = \epsilon$$

-> exponential parameterisation

$g_{\mu\nu} = \bar{g}_{\mu\kappa} \exp[h^{\cdot}_{\cdot}]^{\kappa}{}_{\nu}$ with h= const

-> fewer metric modes contribute to RG flow

-> gauge-fixing sector differs: "TDiff"

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different quantum theory than "standard" asymptotically safe gravity

-> Is unimodular gravity asymptotically safe?

Unimodular asymptotic safety

$$\Gamma_k = \int d^4x \epsilon \, f(R) \qquad f(R) = \sum_{i=1}^{10} a_i \, R^i$$

fixed point exists and stable under extensions of truncation

a_{1*}	a_{2*}	a_{3*}	a_{4*}	a_{5*}	a_{6*}	a_{7*}	a_{8*}	a_{9*}	a_{10*}
-0.0121									
-0.0118	0.0031								
-0.0117	0.0037	0.00025							
-0.0113	0.0038	0.00017	$-5.40 \cdot 10^{-5}$						
-0.0112	0.0039	0.00020	$-5.81 \cdot 10^{-5}$	$6.25 \cdot 10^{-6}$					
-0.0111	0.0039	0.00018	$-6.68 \cdot 10^{-5}$	$5.11 \cdot 10^{-6}$	$-2.59 \cdot 10^{-6}$				
-0.0112	0.0039	0.00018	$-6.67 \cdot 10^{-5}$	$4.77 \cdot 10^{-6}$	$-2.63 \cdot 10^{-6}$	$-1.09 \cdot 10^{-7}$			
-0.0111	0.0039	0.00018	$-6.82 \cdot 10^{-5}$	$4.15 \cdot 10^{-6}$	$-3.12 \cdot 10^{-6}$	$-2.34 \cdot 10^{-7}$	$-1.89 \cdot 10^{-7}$		
-0.0111	0.0038	0.00017	$-6.85 \cdot 10^{-5}$	$3.72 \cdot 10^{-6}$	$-3.26 \cdot 10^{-6}$	$-3.54 \cdot 10^{-7}$	$-2.24 \cdot 10^{-7}$	$-4.91 \cdot 10^{-8}$	
-0.0111	0.0038	0.00017	$-6.90 \cdot 10^{-5}$	$3.37 \cdot 10^{-6}$	$-3.44 \cdot 10^{-6}$	$-4.37 \cdot 10^{-7}$	$-2.85 \cdot 10^{-7}$	$-6.96 \cdot 10^{-8}$	$-2.62 \cdot 10^{-8}$

$\rightarrow$ $G_* \approx 1.8$

[AE, '15]

Unimodular asymptotic safety

$$\Gamma_k = \int d^4x \epsilon\, f(R) \qquad\qquad f(R) = \sum_{i=1}^{10} a_i\, R^i$$

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two relevant directions

$\theta_{1,2}$	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}
2.295								
2.122 ± i 1.232								
2.778 ± i 1.232	-1.233							
2.832 ± i 0.781	-1.113	-3.111						
2.912 ± i 0.687	-1.172	-3.415	-5.235					
2.863 ± i 0.654	-1.155	-3.328	-5.447	-6.997				
2.862 ± i 0.671	-1.197	-3.382	-5.380	-7.464	-8.863			
2.847 ± i 0.673	-1.204	-3.418	-5.483	-7.325	-9.398	-10.708		
2.841± i 0.678	-1.221	-3.440	-5.530	-7.534	-9.236	-11.324	-12.698	
2.834 ± i 0.681	-1.228	-3.462	-5.569	-7.585	-9.545	-11.093	-13.224	-14.514

[AE, '15]

Unimodular asymptotic safety

fixed point in unimodular f(R)

-> step towards solution of c.c. problem in asymptotic safety

-> similarity to fixed point in "standard" gravity: further evidence for asymptotic safety in gravity

Background independence

Background and fluctuation

background independence: central in quantum gravity

$$\int \mathcal{D}g_{\mu\nu} e^{-S[g_{\mu\nu}]}$$

→ no preferred configuration!

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seems at odds with Renormalisation Group:

need to separate "high-momentum" and "low-momentum" modes!

->Need to pick some $\bar{g}_{\mu\nu}$: p^2 -> $-\bar{D}^2$

Breaking of background independence?

Background and fluctuation

Quantum gravity: Need to pick some $\bar{g}_{\mu\nu}$: $p^2 \to -\bar{D}^2$

Background field method: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$ (linear split)

$$\Gamma_k = \Gamma_k[\bar{g}_{\mu\nu}; h_{\mu\nu}]$$

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regulator: $h_{\mu\nu} {R_k}^{\mu\nu\kappa\lambda}(-\bar{D}^2) h_{\kappa\lambda}$ → break Shift symmetry

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[Reuter, Wetterich '94; Litim, Pawlowski '99 '02; Manrique, Reuter '10; Bridle, Dietz, Morris, '13]

-> modified shift Ward-identity

-> distinction between background and fluctuation couplings necessary

Background and fluctuation

Background field method: $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$ (linear split)

Which field enters where?

Physics extracted from $\Gamma_{k\to 0}[g_{\mu\nu} = \bar{g}_{\mu\nu\,\mathrm{phys.}}]$

$$\Gamma_k^{(2)} = \frac{\delta}{\delta g_{\mu\nu}} \frac{\delta}{\delta g_{\kappa\lambda}} \Gamma_k \to \frac{\delta}{\delta h_{\mu\nu}} \frac{\delta}{\delta h_{\kappa\lambda}} \Gamma_k$$

need fluctuation field propagator!

-> need flow of fluctuation field vertices

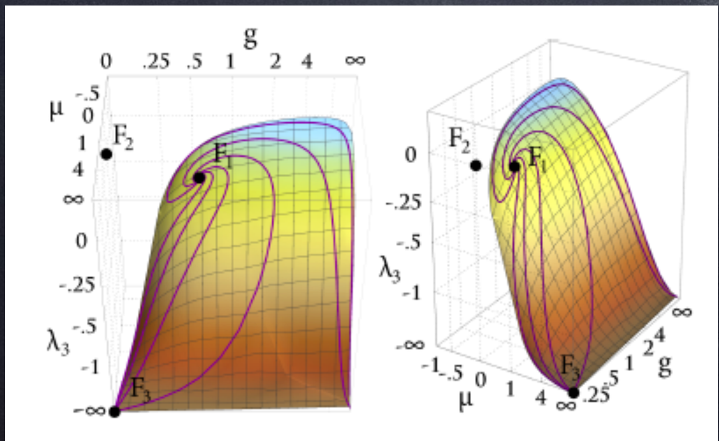
Background and fluctuation

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

$$= -\frac{1}{16\pi G_N}\int d^4x\sqrt{\bar g}\,(\bar R - 2\Lambda)\ +\mathcal{O}(h)$$

$$+\frac{Z_h}{2}\int d^4x\sqrt{\bar g} h_{\mu\nu}K^{\mu\nu\kappa\lambda}(-\bar D^2)h_{\kappa\lambda}$$

$$+G_3\int d^4x\sqrt{\bar g} h_{\mu\nu}h_{\kappa\lambda}h_{\rho\sigma}V^{(3)\,\mu\nu\kappa\lambda\rho\sigma}(-\bar D^2)+\dots$$



g^*	0.66
μ_h^*	-0.59
λ_3^*	0.11
$\lambda_1^*/\sqrt{g_1}^*$	0.39
EVs	$-1.4\pm 4.1i$
	14

[Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15]

“Bi-metric” truncations

$$\Gamma_k[\bar{g}_{\mu\nu}, h_{\mu\nu}] \to \Gamma_k[\bar{g}_{\mu\nu}; g_{\mu\nu}]$$

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"Bi-metric" Einstein-Hilbert truncation:

$\Gamma_{\mathrm{EH}}[\bar{g}_{\mu\nu}]$ $\quad$ $\Gamma_{\mathrm{EH}}[g_{\mu\nu}]$

$\bar{G}_N, \bar{\Lambda}$ $\quad$ G_N, Λ

-> flow only depends on G_N, Λ

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g_*	λ_*	θ_1	θ_2	$\bar{g}_*$	$\bar{\lambda}_*$	$\bar{\theta}_1$	$\bar{\theta}_2$	
0.71	0.19	1.5 + 3i	1.5 - 3i					[Codello, Percacci, Rahmede '09]
0.70	0.21	3.6+4.3i	3.6-4.3i	8.18	-0.01	2	4	[Becker, Reuter '14]

Matter in quantum gravity

effects of minimally coupled matter on fluctuation couplings

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three- "graviton" coupling:

$$\beta_{G_3} = 2G_3 + \beta_{G_3}|_{\text{gravity}} - \frac{G_3^2}{570\pi} 43 N_S - \frac{G_3^2}{11400\pi} 3599 N_D$$

[Meibohm, Pawlowski, Reichert '15]

"graviton"-two-scalar coupling:

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

[Dona, AE, Labus, Percacci '15]

background coupling:

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

[Dona, AE, Percacci '13]

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Standard model matter compatible with gravitational fixed point

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The gravity-matter-puzzle:
How many matter fields
can asymptotically safe
quantum gravity
accommodate?

Asymptotically safe quantum gravity

- compelling evidence for viability in pure gravity
- tantalising hints for phenomenological viability: gravity + SM matter asymptotically safe

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