Title: The asymptotic safety paradigm for quantum gravity and matter

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Abstract: <p>In this talk, I will discuss the asymptotic safety paradigm, and will highlight that it can provide a framework for a predictive ultraviolet completion for gravity and matter. Specifically, I will discuss compelling hints that exist for the realization of asymptotic safety in pure gravity, and will then present recent progress on the case of gravity coupled to Standard Model matter. In particular, I will highlight results that show how to forge a link between physics at the Planck scale and physics at the electroweak scale, in order to impose observational constraints on the microscopic quantum gravity dynamics.</p>

The asymptotic safety paradigm for gravity & matter

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University of Heidelberg

based on work with
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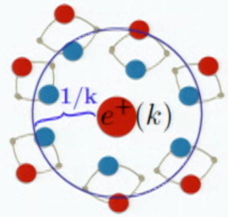
S. Lippoldt, J. Pawlowski

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

March 2, 2017
Quantum Gravity Seminar, Perimeter Institute for Theoretical Physics

The asymptotic safety paradigm

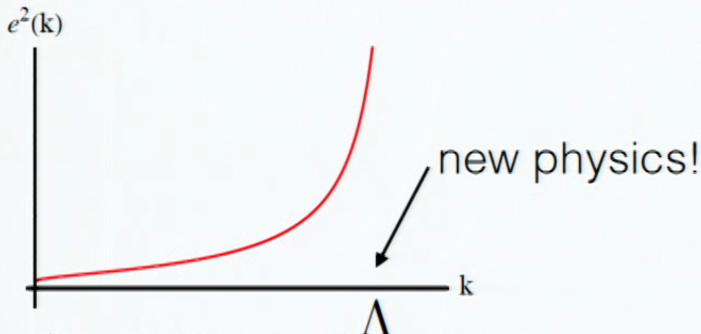
$$\int \mathcal{D}\varphi \, e^{-S[\varphi]}$$



quantum fluctuations generate scale dependent couplings

UV behavior:

effective theory:
Landau pole (triviality problem)

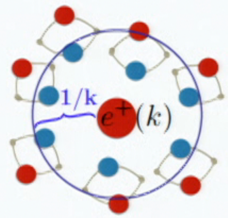


$\lambda\,\varphi^4$ [Aizenmann '81; Frohlich '82, Wolff '09]

U(1) gauge theory [Gell-Mann, Low '54; Gockeler et al. '97; Gies, Jaeckel '04]

The asymptotic safety paradigm

$$\int \mathcal{D}\varphi\, e^{-S[\varphi]}$$

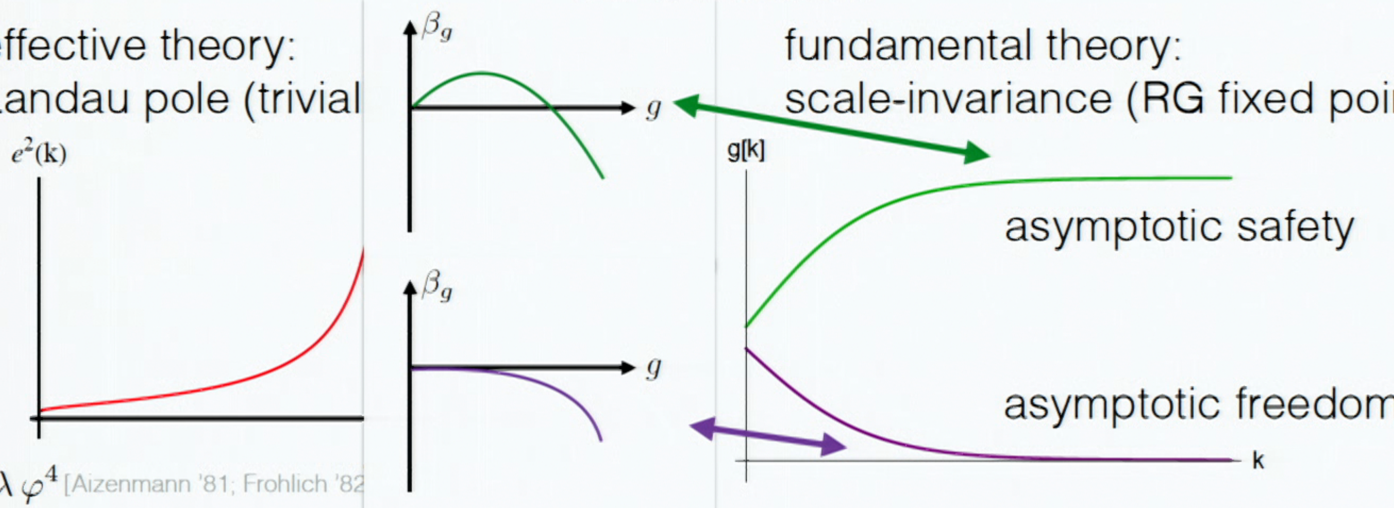


quantum fluctuations generate scale dependent couplings

UV behavior:

effective theory:
Landau pole (trivial

fundamental theory:
scale-invariance (RG fixed point)



$\lambda\,\varphi^4$ [Aizenmann '81; Frohlich '82

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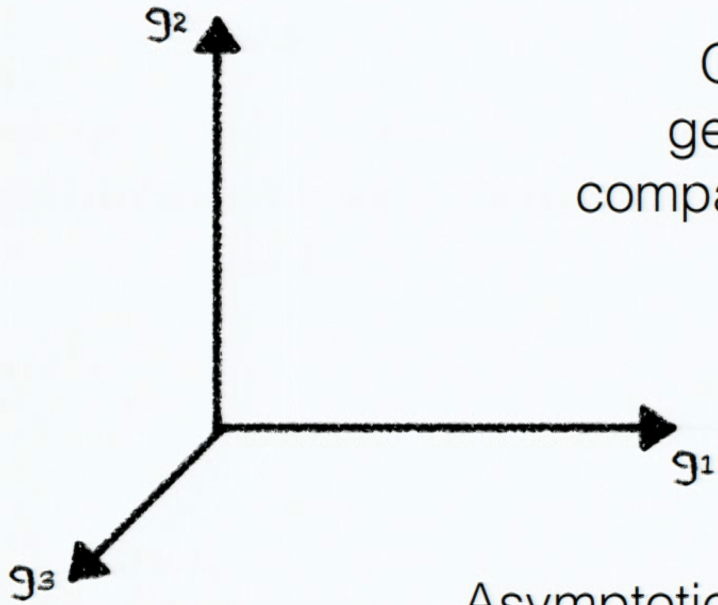
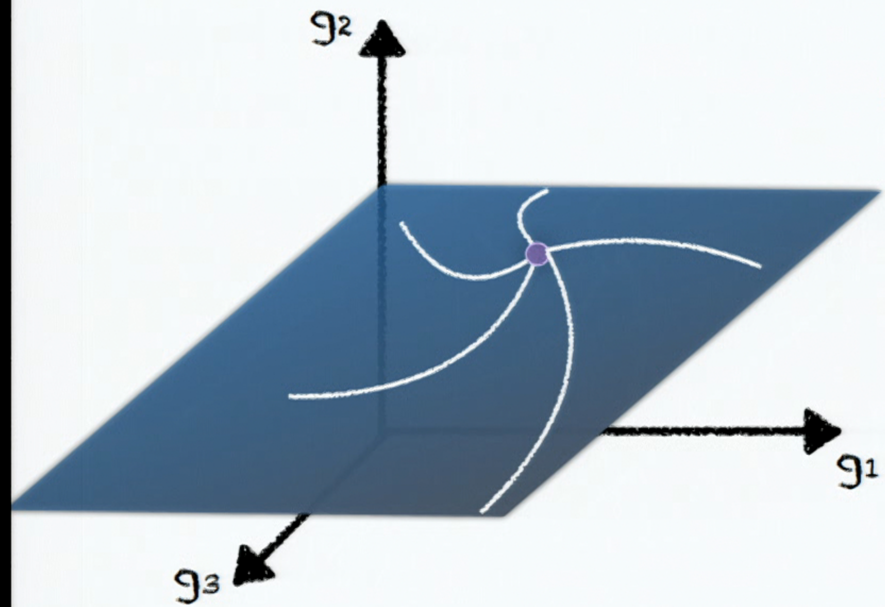
Theory space



Quantum fluctuations
generate all interactions
compatible with the symmetries

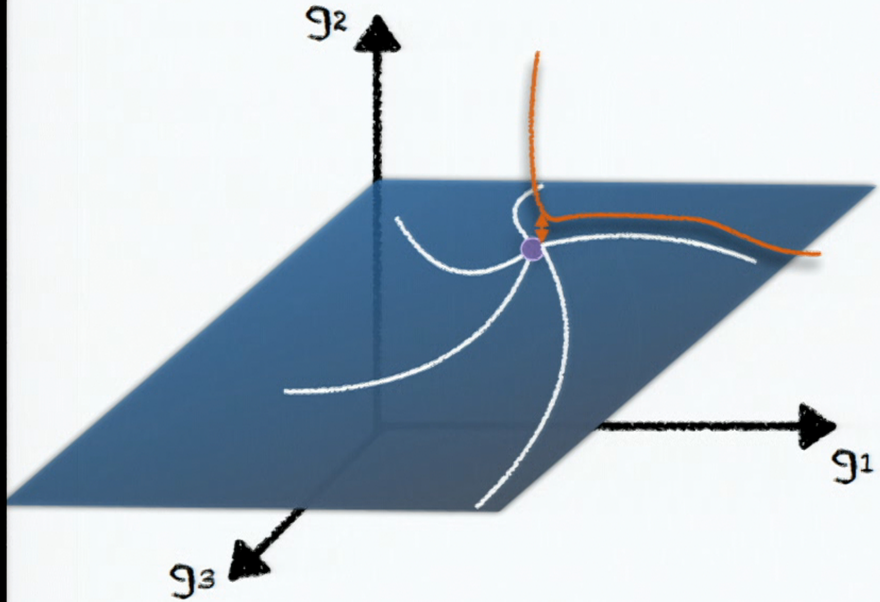
Asymptotic safety/freedom:
Fixed point in infinite-dimensional theory space

Irrelevant directions: Predictions from asymptotic safety



UV-critical surface:
UV-attractive directions
<-> free parameters

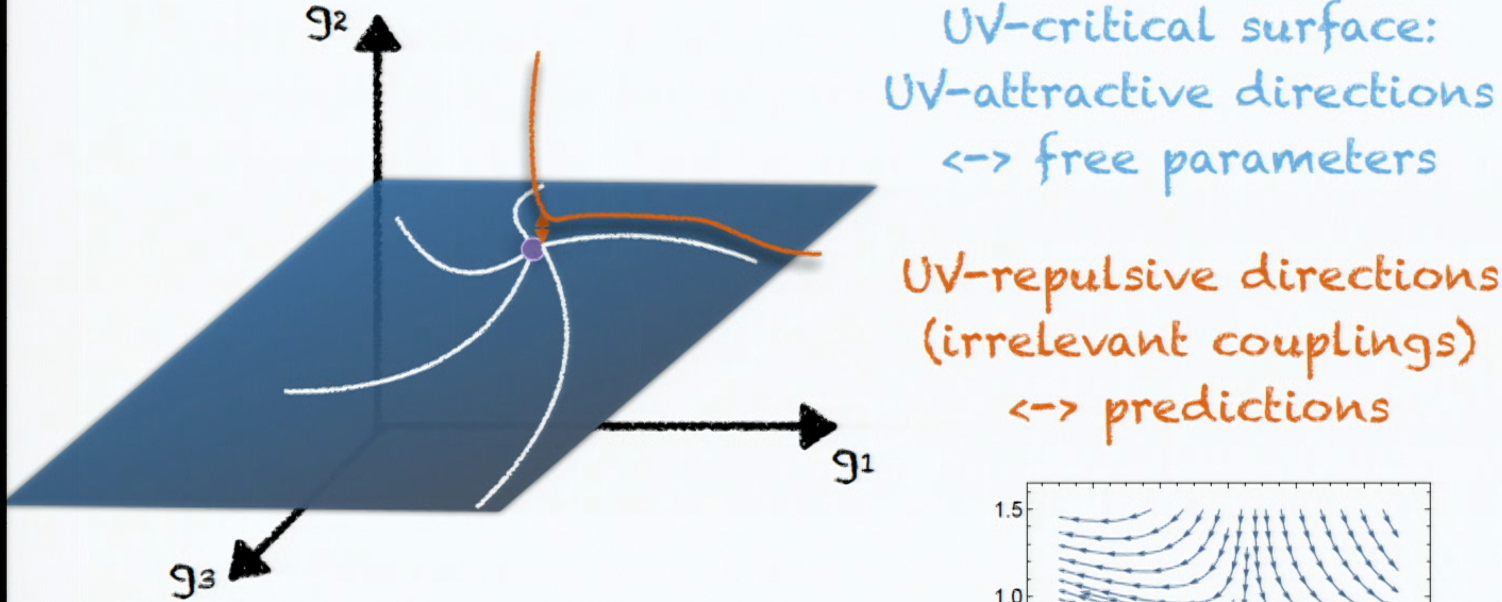
Irrelevant directions: Predictions from asymptotic safety



UV-critical surface:
UV-attractive directions
<-> free parameters

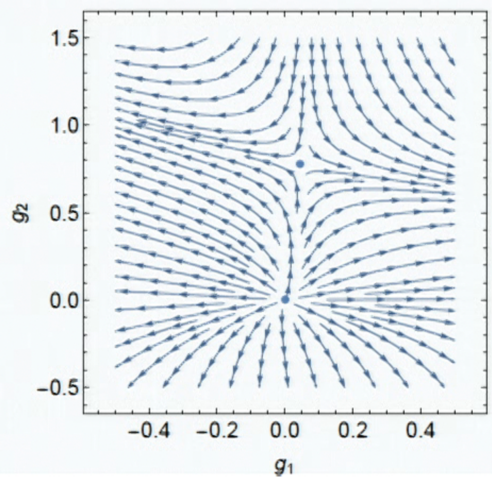
UV-repulsive directions
(irrelevant couplings)
<-> predictions

Irrelevant directions: Predictions from asymptotic safety



towards infrared:
irrelevant couplings determined
(QG fluctuations force irrelevant couplings to specific values)

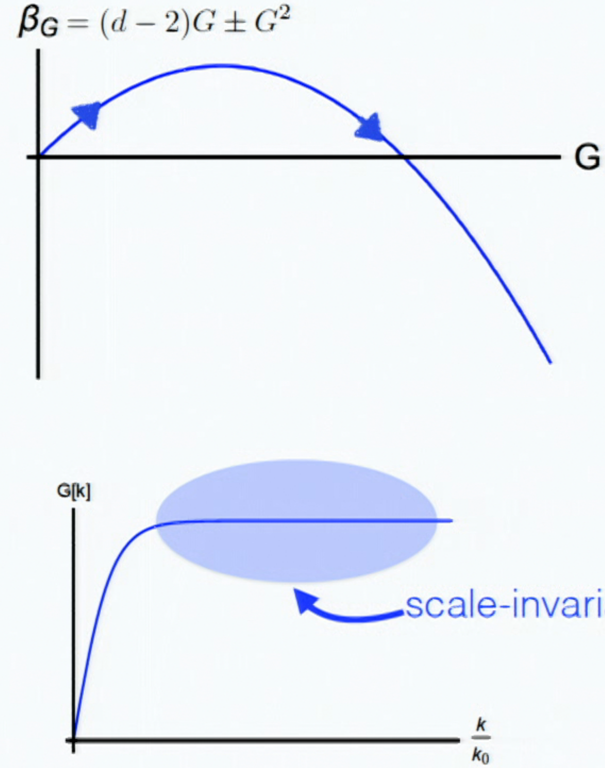
asymptotically free models:
couplings with negative canonical dimension



Mechanism for asymptotic safety

$[G_N] = 2 - d \;\longrightarrow$ dim'less: $G = G_N k^{d-2}$

Balancing canonical and quantum scaling:



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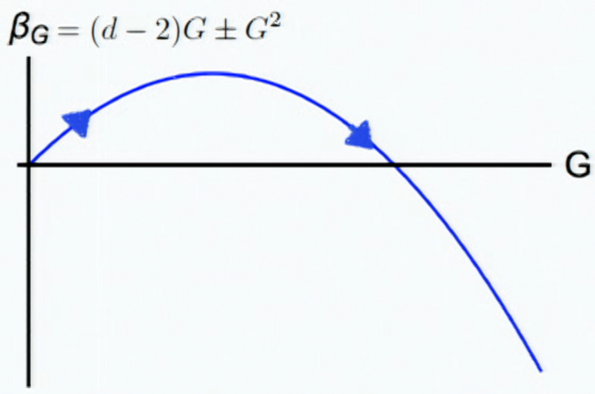
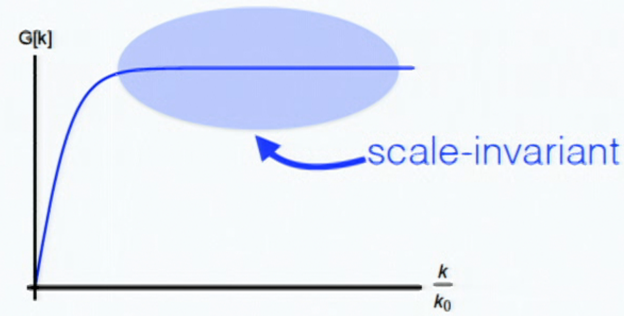


ϵ expansion in $d = 2 + \epsilon$

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

Weinberg '76; Christensen, Duff '78
Gastmans, Kallosh, Truffin '78



Goal: extension to d=4 ?

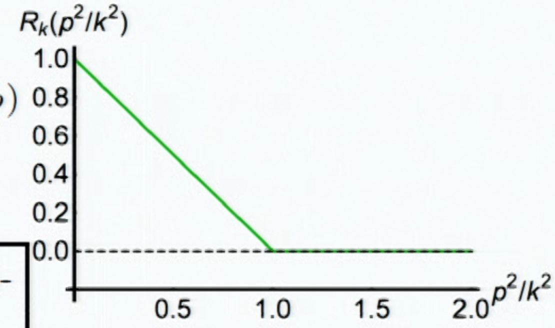
Functional Renormalization Group

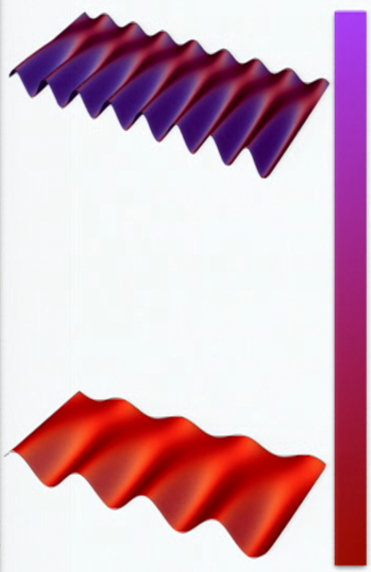
probe scale dependence of QFT

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

Wetterich '93; Morris, '94

scale- and momentum-dependent ``mass”





S

Γ_k contains effect of quantum fluctuations above k

$$\Gamma_k = \sum_i g_i(k) \int d^d x\, \mathcal{O}^i$$

$\Gamma_{k\to 0}$

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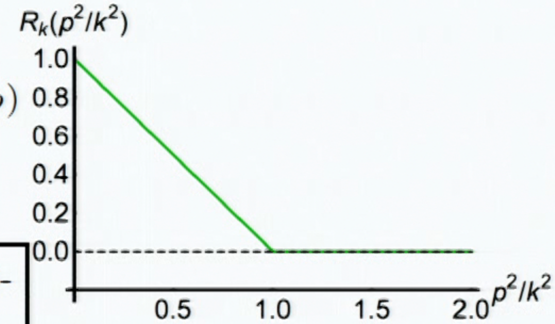

S ← prediction of asymptotic safety

Γ_k contains effect of quantum fluctuations above k

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$$\rightarrow k\partial_k \Gamma_k = \sum_i \beta_{g_i} \int d^d x \mathcal{O}^i$$

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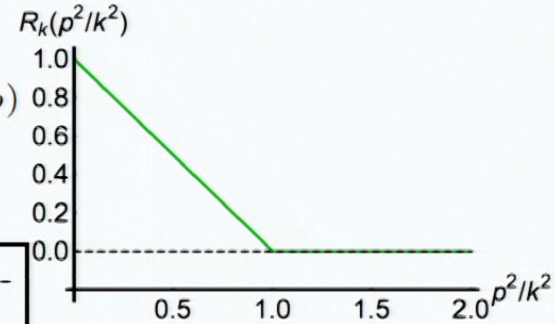

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Wetterich equation:

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

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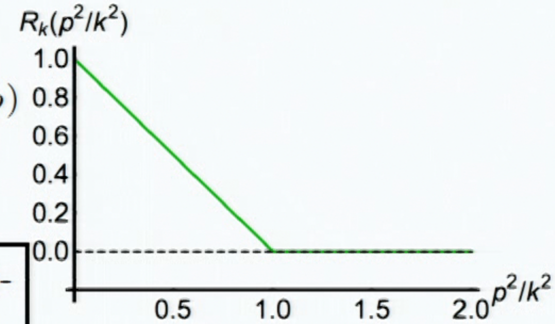

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practical calculations: truncation

$$\Gamma_k = \sum_i g_i(k) \int d^d x \, \mathcal{O}^i$$

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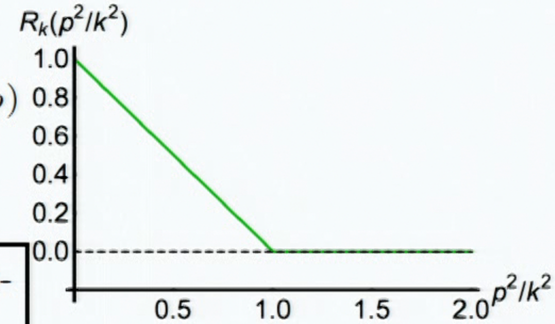

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Asymptotically Safe Gravity: Reuter, '96

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

$$\int \mathcal{D}g_{\mu\nu} \to \int \mathcal{D}h_{\mu\nu}$$

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

$\longrightarrow$ shift symmetry: $(\bar{g}_{\mu\nu} + \epsilon_{\mu\nu}) + (h_{\mu\nu} - \epsilon_{\mu\nu}) = g_{\mu\nu}$

$\longrightarrow$ distinction between background & fluctuation couplings

Manrique, Reuter '09; Manrique, Reuter, Saueressig '10, '11; Christiansen, Litim, Pawlowski, Rodigast '12; Becker, Reuter '14; Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15; Denz, Pawlowski, Reichert '16

shift Ward identity Dietz, Morris '15; Morris '16; Percacci, Vacca '16

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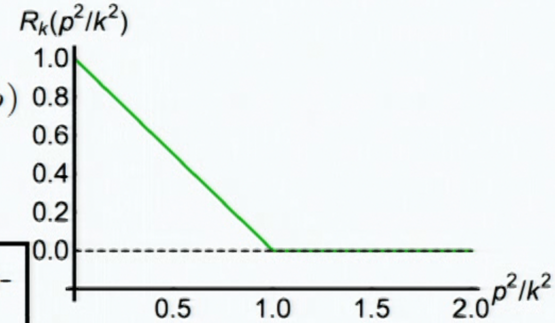

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matrix/tensor models: A.E., Koslowski '13, '14, '17

group field theories: Benedetti, Ben Geloun, Oriti '14; Benedetti, Lahoche '15; Ben Geloun, Martini, Oriti '15, '16; Ben Geloun, Koslowski '16; Carrozza, Lahoche '16

Functional Renormalization Group & ϵ - expansion

perturbative evidence for asymptotic safety:

expansion in $d = 2 + \epsilon$

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

Weinberg '76; Christensen, Duff '78
Gastmans, Kallosh, Truffin '78

Goal: Match onto d >2 results
and extend to d=4

FRG suitable tool:
extend pert. controlled FP away from crit. dim.
$\rightarrow$ see non-gravity models

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PHYSICAL REVIEW D **90**, 025018 (2014)

Critical $O(N)$ models in $6-\epsilon$ dimensions

Lin Fei,[1] Simone Giombi,[1] and Igor R. Klebanov[1,2]

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- **unitary UV completion of O(N) models in *d*>4**

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi_i)^2 + \frac{1}{2}(\partial_\mu z)^2 + \frac{1}{2} g z \phi_i \phi_i + \frac{1}{6}\lambda z^3$$

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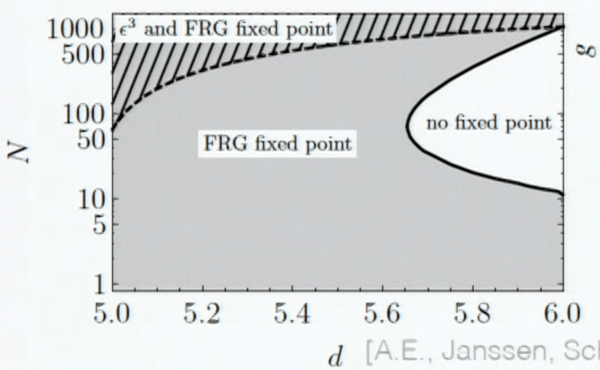
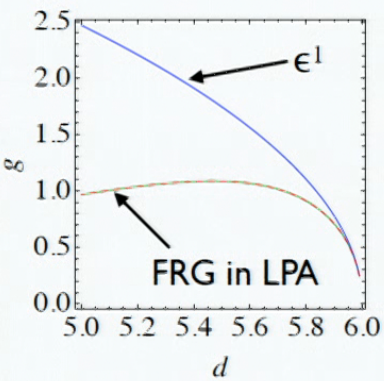
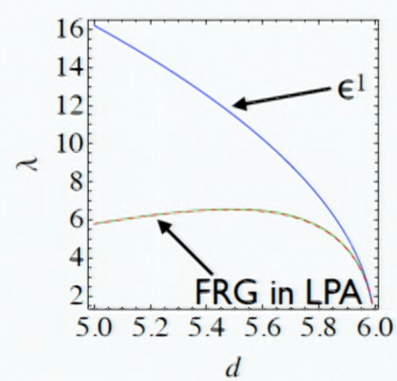


[A.E., Janssen, Scherer '16]





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interacting fixed point
for gravity:
well-controlled limit for d -> 2

FRG in $d = 2 + \epsilon$

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

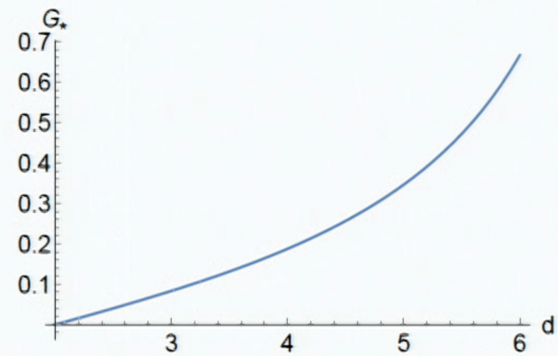
Nink '15, Falls '15, '17

(regulator- independent)

continuation of fixed point towards d=4?

$$\beta_G = (d-2)G - \frac{2}{3}\left(18 - \frac{d(d-3)}{2}\right) G^2$$

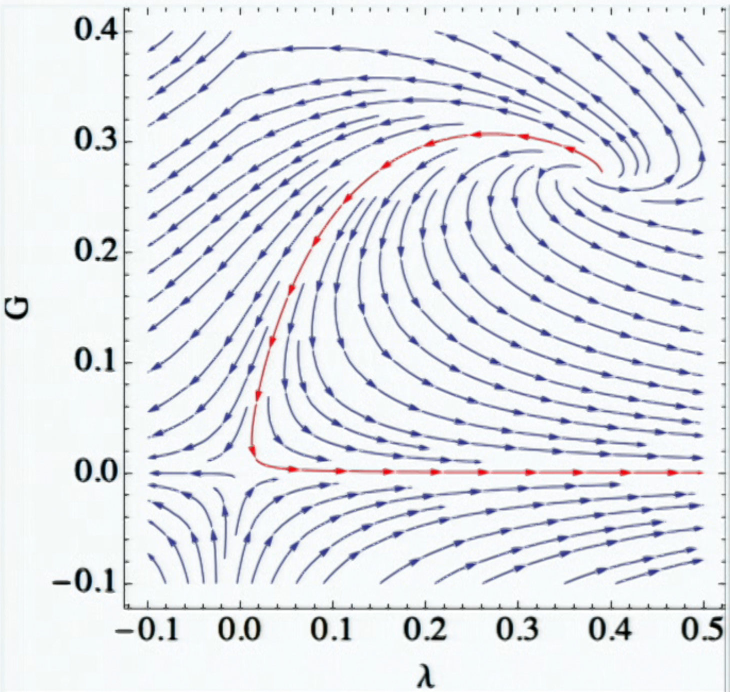
Falls '15



The case for asymptotic safety in gravity

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

interacting fixed point
with ~ 3 (?) relevant directions



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

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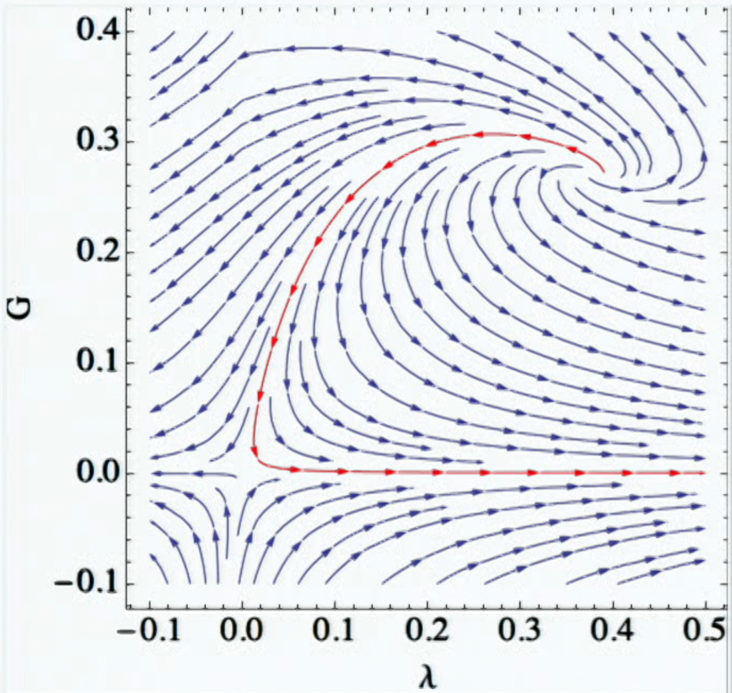

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$$f(R)=\sum_{n=0}^{N} a_n R^n$$

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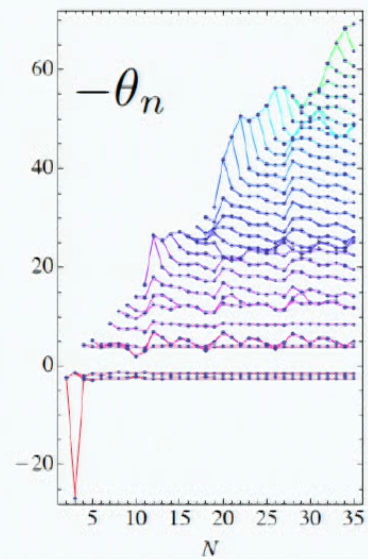

- towards convergence in extensions of the truncation
- near-canonical scaling: guidance for well-controlled truncations

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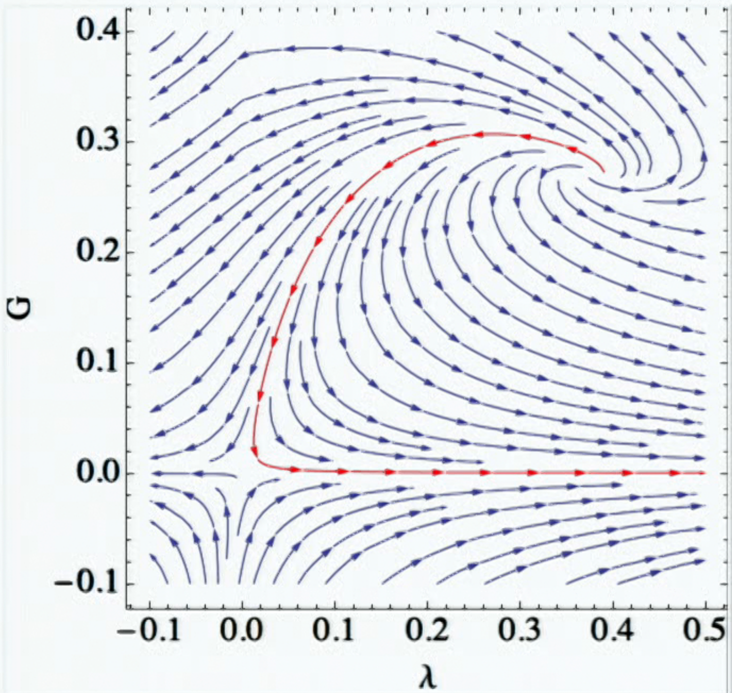

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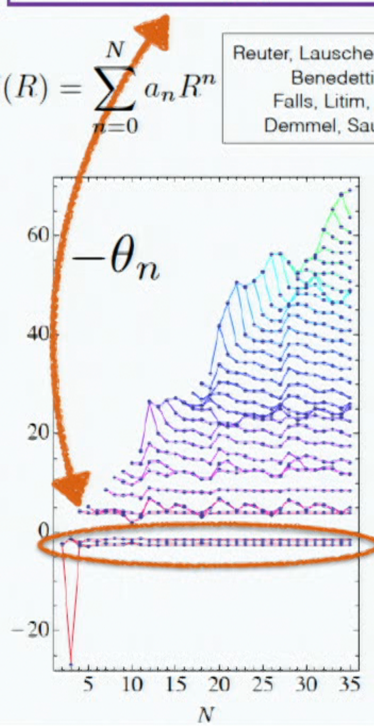

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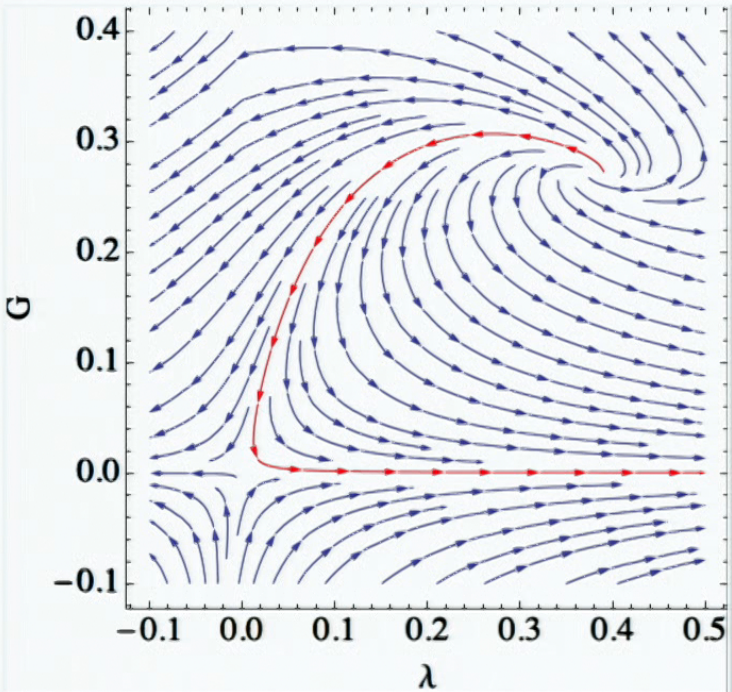

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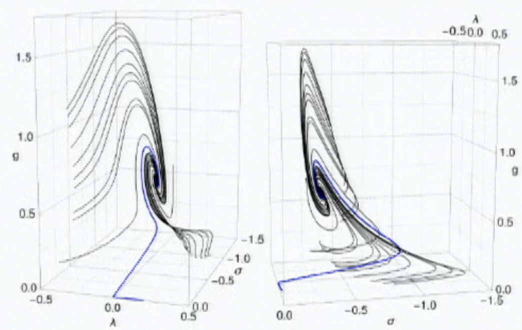
$R^2, \quad R_{\mu\nu}R^{\mu\nu}$ — Benedetti, Machado, Saueressig, '09

Christiansen, '16

$C_{\mu\nu}{}^{\kappa\lambda} C_{\kappa\lambda}{}^{\rho\sigma} C_{\rho\sigma}{}^{\mu\nu}$ — Gies, Knorr, Lippoldt, Saueressig '16



perturbative counterterms: asymptotic safety

A link that matters

$M_{\rm obs} \approx M_{\rm ew}$

$10^4\,\mathrm{GeV}$

observable
(physics)

$M_{\rm Planck}$

$10^{19}\,\mathrm{GeV}$

not currently observable

A link that matters

$M_{\rm obs} \approx M_{\rm ew}$ — $10^4\,{\rm GeV}$

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$M_{\rm Planck}$ — $10^{19}\,{\rm GeV}$

not currently observable
(physics?) *

* "In any region of physics where very little is known, one must keep to the experimental basis if one is not to indulge in wild speculation that is almost certain to be wrong. "
(P.A.M. Dirac)

A link that matters

$M_{\mathrm{obs}} \approx M_{\mathrm{ew}}$

$10^4\,\mathrm{GeV}$

observable
(physics)

M_{Planck}

$10^{19}\,\mathrm{GeV}$

not currently observable
(physics?) *

constrains viable
microscopic models

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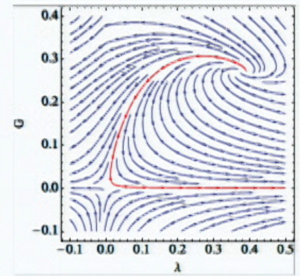
Asymptotic safety for quantum gravity and matter

quantum gravity dynamics

matter dynamics

Asymptotic safety for quantum gravity and matter

Can quantum fluctuations
of matter destroy
consistent quantum gravity model?



quantum gravity dynamics

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Can quantum fluctuations
of gravity generate
a viable UV completion for matter?

Asymptotic safety for quantum gravity and matter

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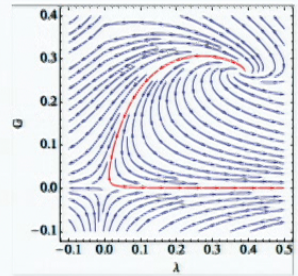

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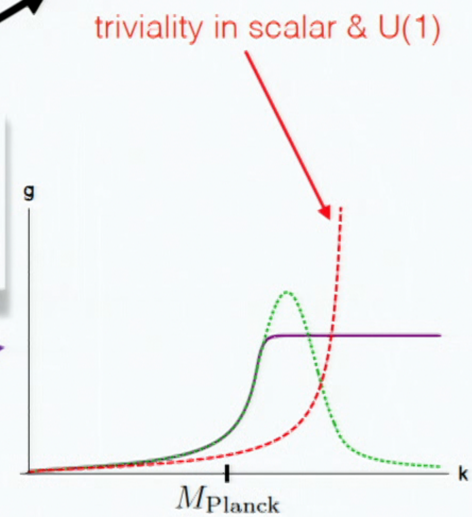
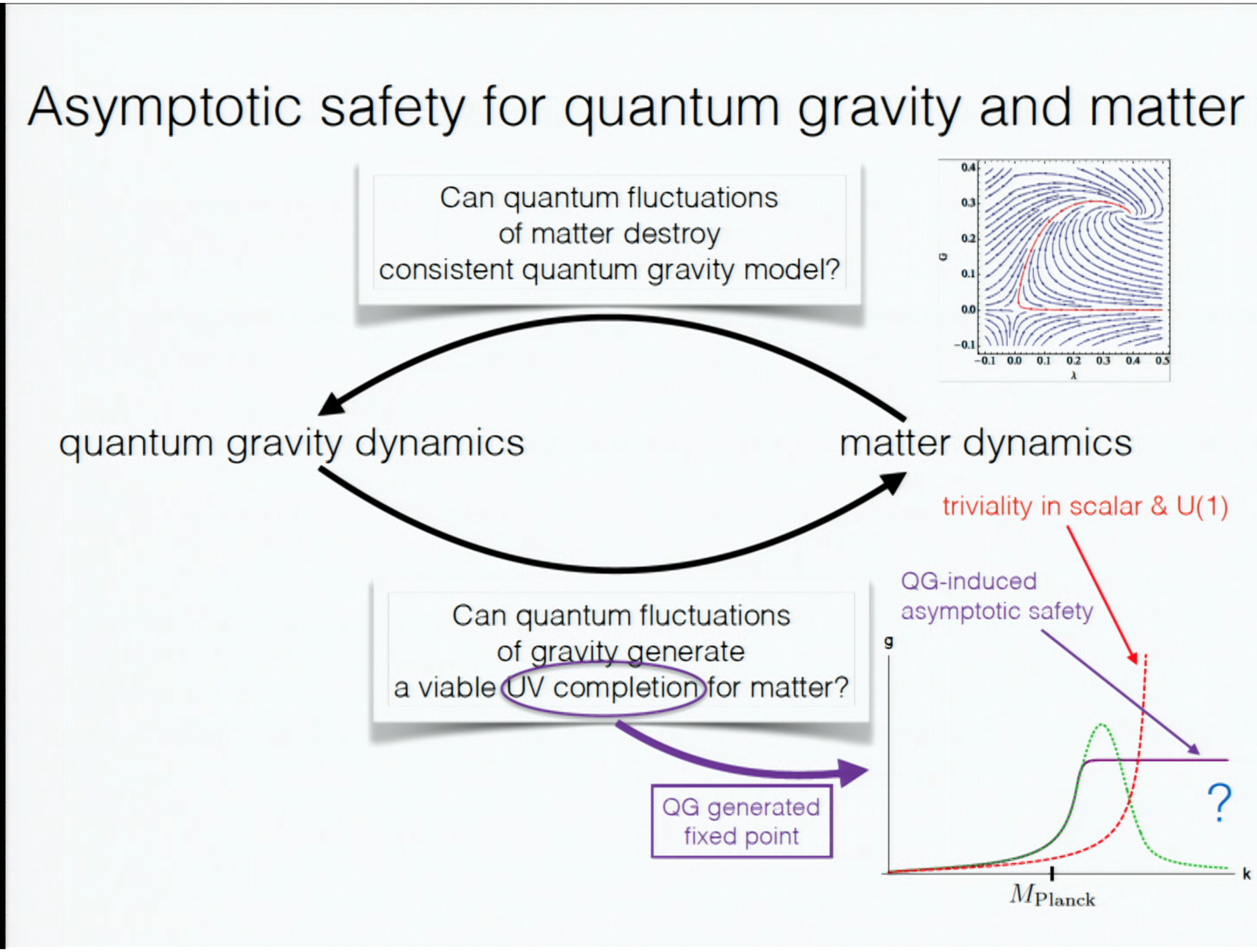
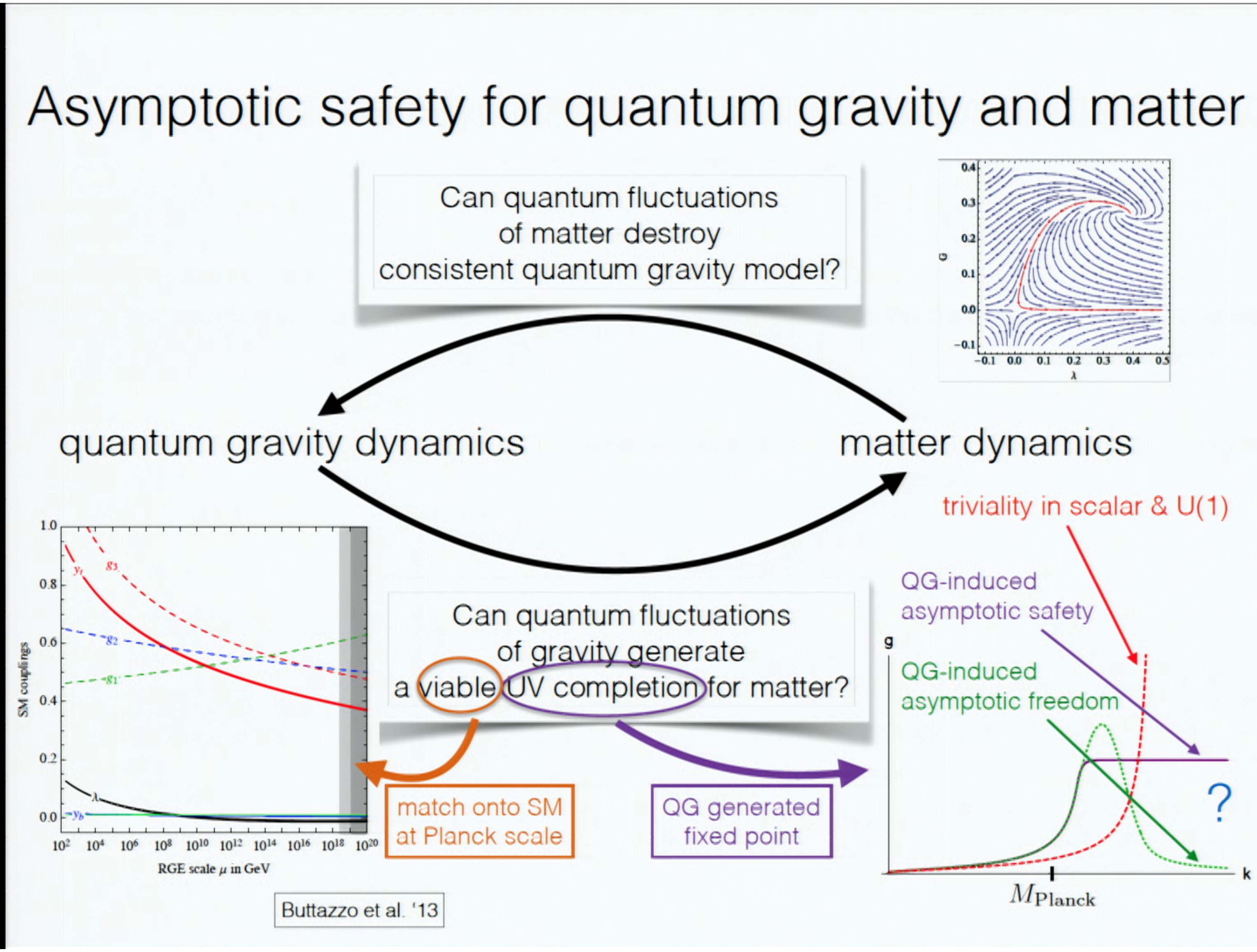
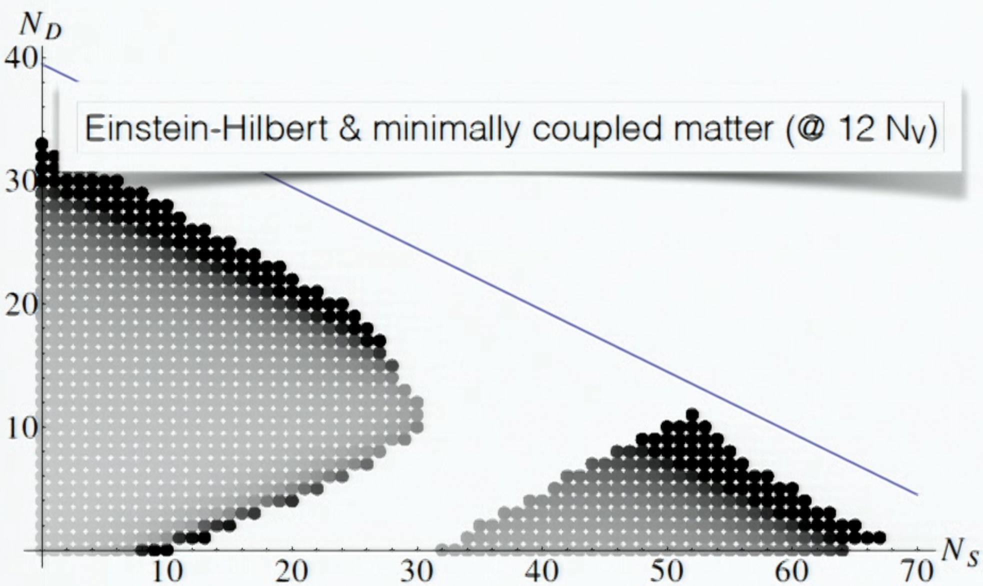



Asymptotic safety for quantum gravity and matter
Can quantum fluctuations of matter destroy consistent quantum gravity model?
quantum gravity dynamics
matter dynamics
triviality in scalar & U(1)
QG-induced asymptotic safety
Can quantum fluctuations of gravity generate a viable UV completion for matter?
QG generated fixed point
g
k
?
M_{Planck}
G
λ

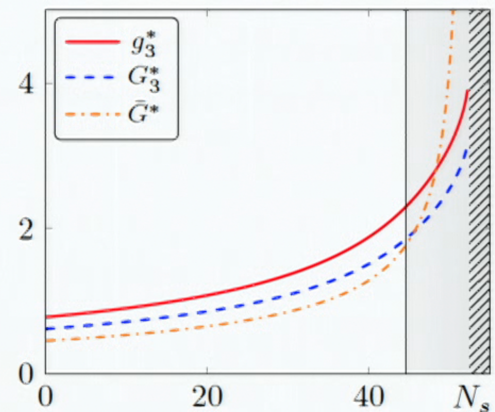

Asymptotic safety for quantum gravity and matter
Can quantum fluctuations of matter destroy consistent quantum gravity model?
quantum gravity dynamics
matter dynamics
Can quantum fluctuations of gravity generate a viable UV completion for matter?
match onto SM at Planck scale
QG generated fixed point
triviality in scalar & U(1)
QG-induced asymptotic safety
QG-induced asymptotic freedom
?
g
k
M_{Planck}
SM couplings
RGE scale μ in GeV
Buttazzo et al. '13

Matter matters

Quantum fluctuations of matter alter the UV dynamics for gravity



[Dona, AE, Percacci '13, '14]



[AE, Labus, Pawlowski, Reichert, to appear]

$$\beta_G = 2G - G^2\left(\#_{\text{grav}} - N_S \#_{\text{scalar}}\right), \quad \#_{\text{grav}} > 0, \quad \#_{\text{scalar}} > 0$$

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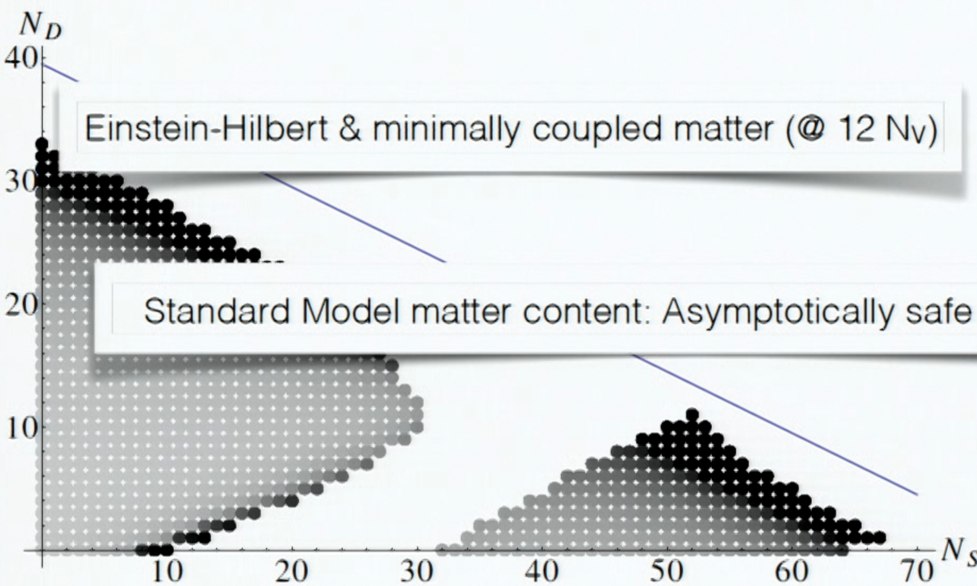

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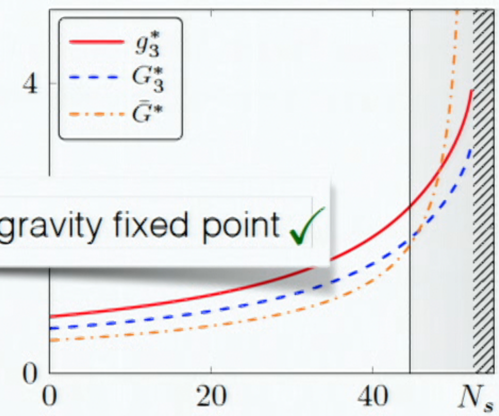

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Asymptotically safe solution to the U(1) triviality problem

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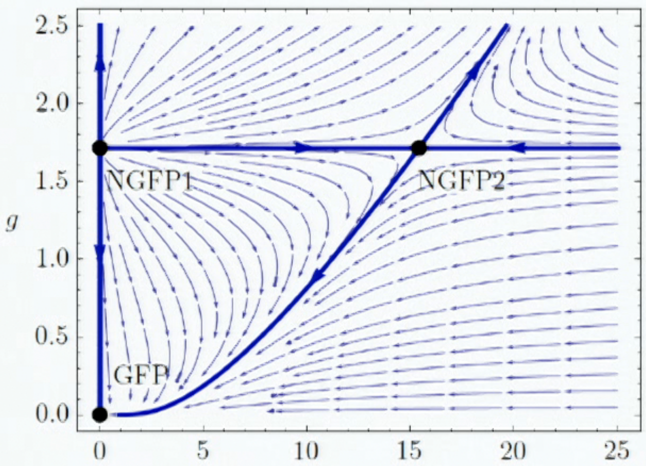
$$\Gamma_k = \Gamma_{k\,\mathrm{EH}} + \frac{1}{4 g_{U(1)}^2} \int d^4x \sqrt{g}\, F^2$$



[Harst, Reuter '11]

Newton coupling

$$\partial_t g_{U(1)}^2 = \left(\frac{2}{3\pi} N_f g_{U(1)}^2 - \frac{6}{\pi} g \Phi_1(0) \right) g_{U(1)}^2$$

[Harst, Reuter '11]

non- Abelian case:
[Daum, Harst, Reuter '10; Folkerts, Litim, Pawlowski '11]

QG-induced asymptotic freedom?

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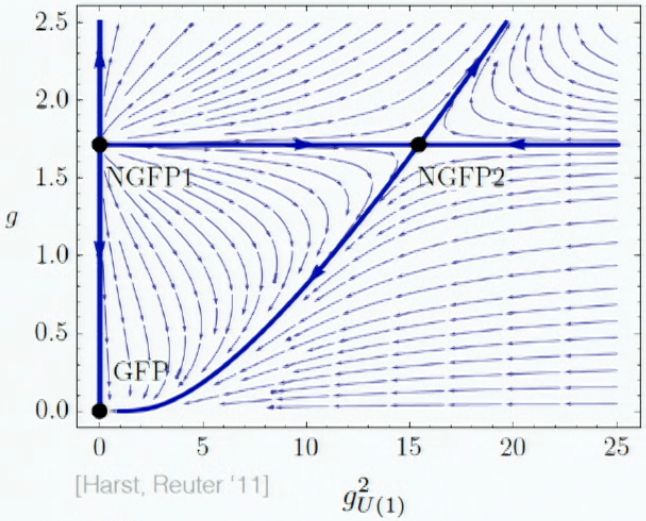

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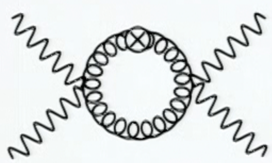
$$\sqrt{g}\,g^{\mu\nu}g^{\kappa\lambda}F_{\mu\kappa}F_{\nu\lambda}$$

QG-induced photon-interactions



$$\beta_{w_2} = 4w_2 + 40g^2 - \frac{7}{2\pi}g\,w_2 + \frac{1}{8\pi^2}w_2^2$$

$w_2\,(F^2)^2$

shift free to interacting fixed point

[Christiansen, AE, 2017]

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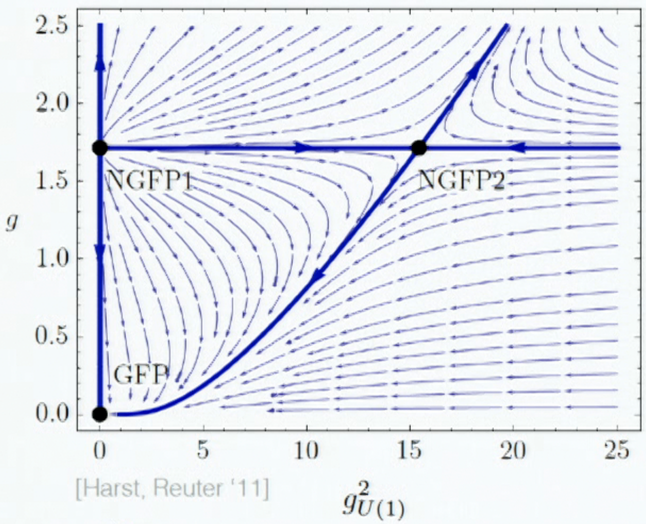

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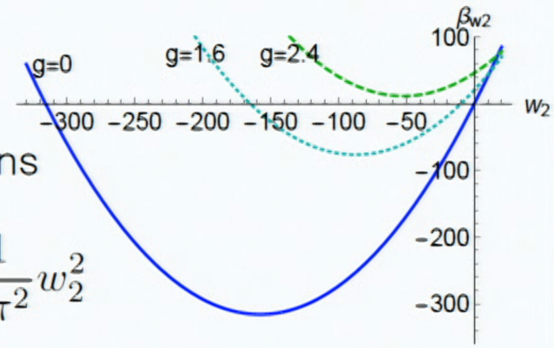

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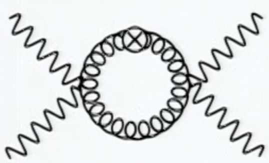

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[Christiansen, AE, 2017]

Asymptotically safe solution to the U(1) triviality problem

gravity must remain ``weak''
for a real fixed point in
U(1) gauge theory

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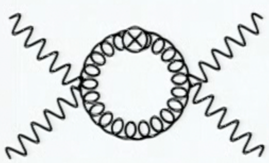
QG-induced photon-interactions



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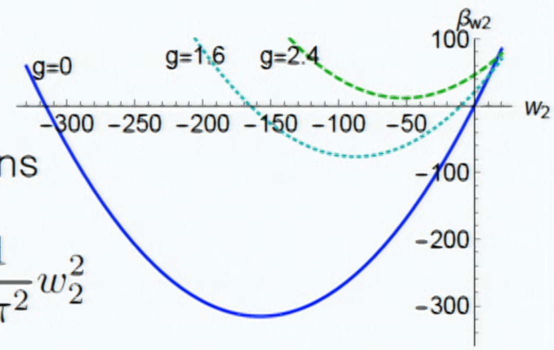

Asymptotically safe solution to the U(1) triviality problem

interaction structure in gauge sector:

$$\frac{1}{4g_{U(1)}^2} F^2 + w_2 F^4$$

interacting fixed point

asymptotically free fixed point?

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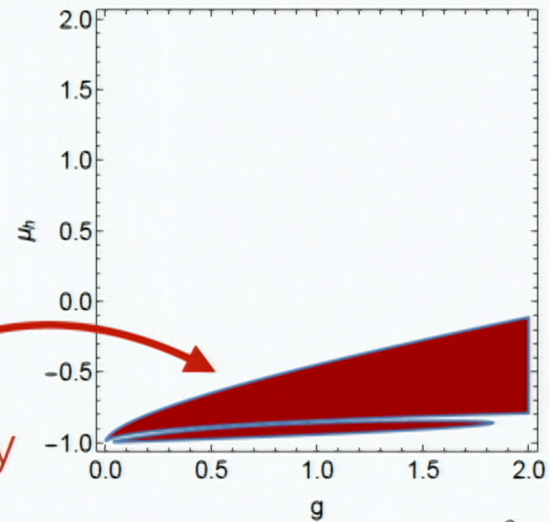
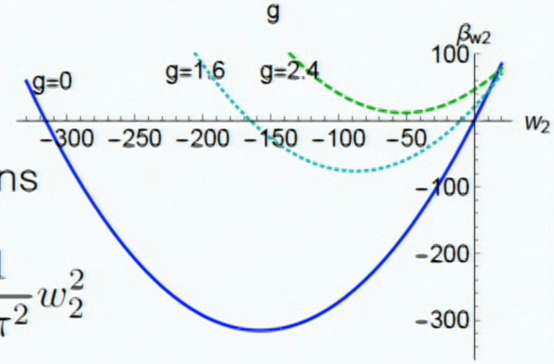


effective gravity coupling $\frac{g}{1+\mu_h}$

strong gravity excluded



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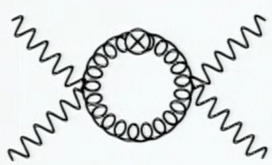

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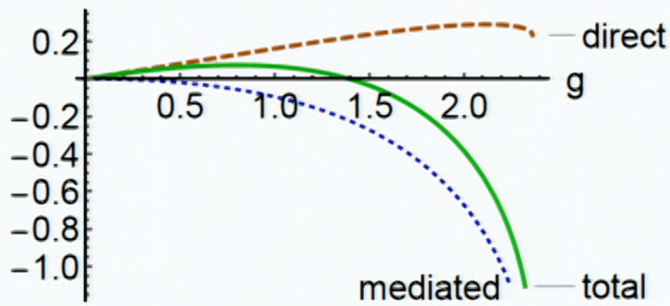
asymptotic freedom in $g_{U(1)}$: $\theta_{g^2_{U(1)}} = \theta_{g^2_{U(1)}}\Big|_{\rm grav} + \theta_{g^2_{U(1)}}\Big|_{w_2} > 0$

contributions to $\theta_{g_{U(1)}{}^2}$



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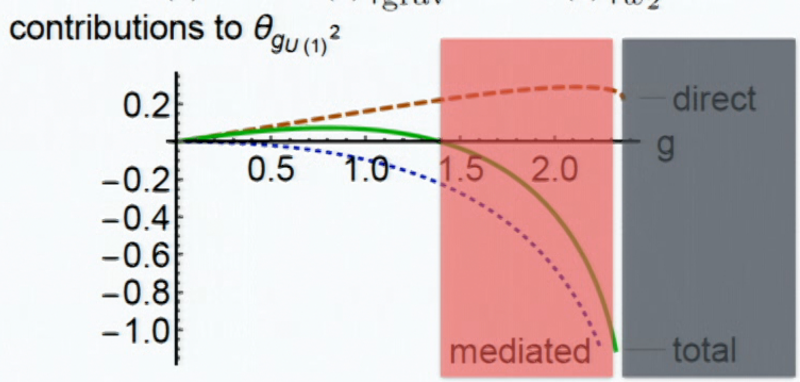

gravity-induced interactions destroy asymptotic freedom

gravity too strong to support fixed point in gauge sector

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interacting fixed point $g_{U(1)^2}(k) = \left(\frac{k}{k_0}\right)^{-\theta_{g^2_{U(1)}}} \Rightarrow g_{U(1)^2}(M_{\rm Planck}) \approx 0$

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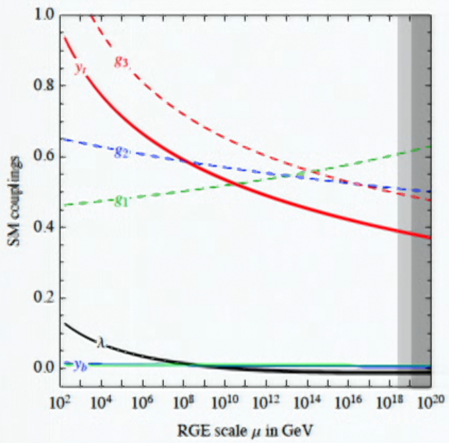

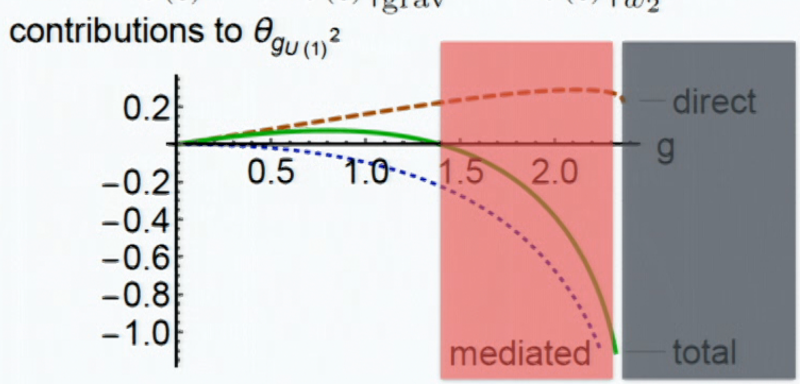

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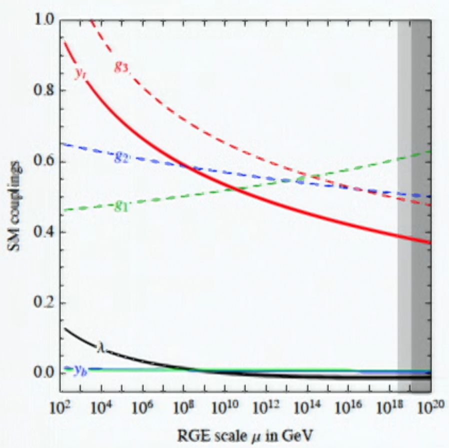

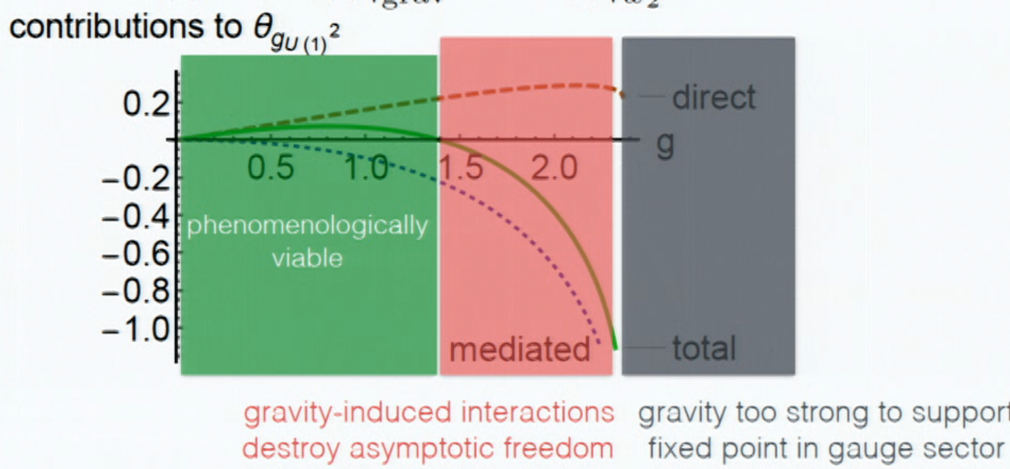

QG-induced fixed-point structure

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interacting fixed point

free fixed point

QG-induced fixed-point structure

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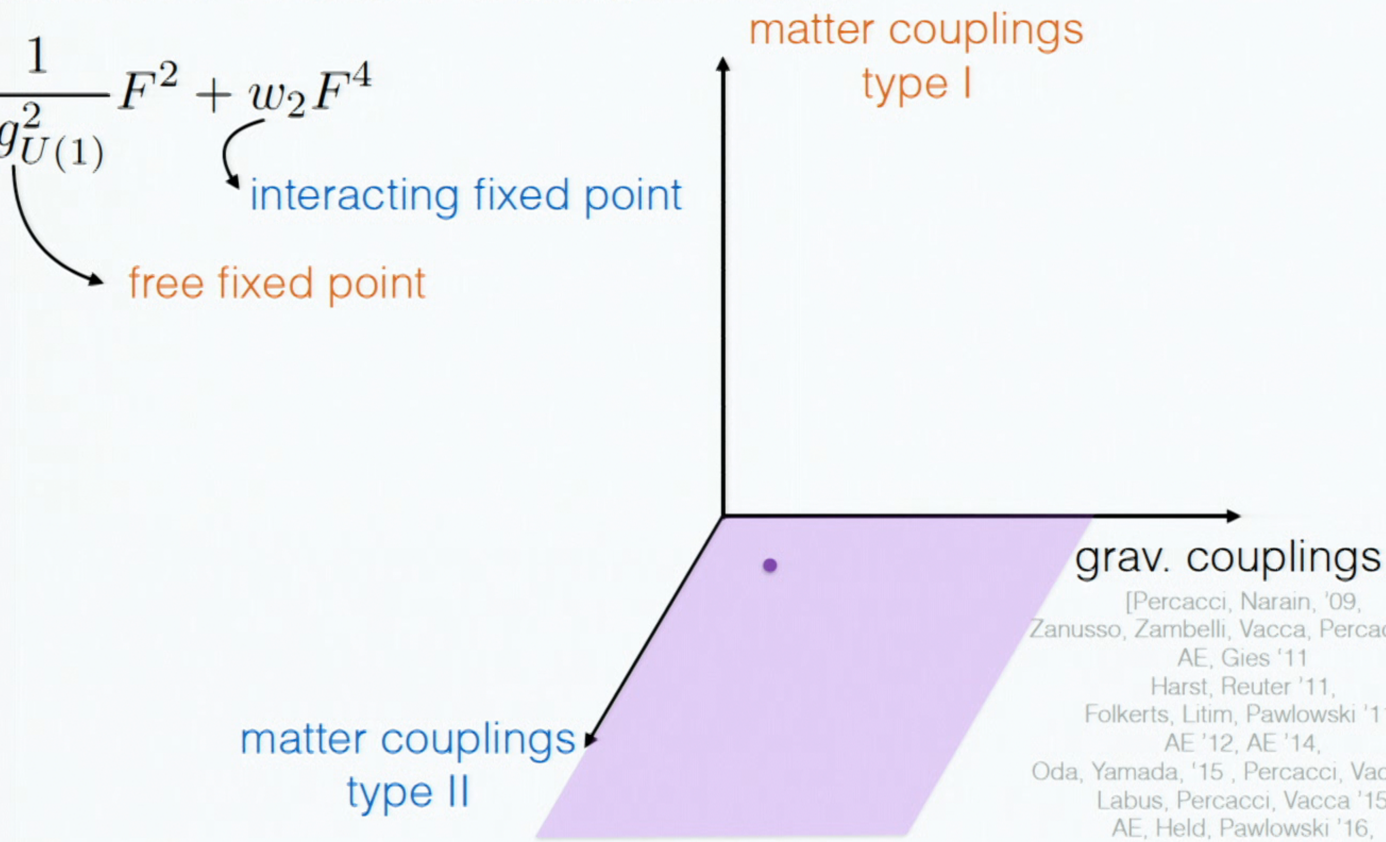


[Percacci, Narain, '09,
Zanusso, Zambelli, Vacca, Percacci '09;
AE, Gies '11
Harst, Reuter '11,
Folkerts, Litim, Pawlowski '11,
AE '12, AE '14,
Oda, Yamada, '15 , Percacci, Vacca '15,
Labus, Percacci, Vacca '15
AE, Held, Pawlowski '16,
Christiansen, AE '17]...

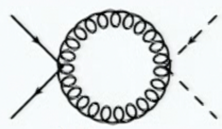
Symmetries dictate fixed-point structure

$iZ_\psi \int d^4x \sqrt{g}\bar{\psi}\nabla\!\!\!/\,\psi \qquad \frac{Z_\phi}{2}\int d^4x \sqrt{g}\, g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$

$\psi \to e^{i\,\alpha\gamma_5}\psi \qquad \phi \to -\phi$

$\bar{\psi} \to \bar{\psi}e^{i\,\alpha\gamma_5}$ shift symm. $\phi \to \phi + a$

induced interactions (non-free)



fermions & scalars $\chi\,(\partial_\mu\phi\partial^\mu\phi)\,\bar{\psi}\nabla\!\!\!/\,\psi \to \chi_* \neq 0$ [AE, Held, Pawlowski '16]

$\rightarrow$ fixed point in matter sector cannot be completely free

nonzero interactions: symmetry of kinetic term

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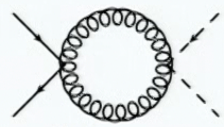
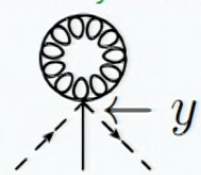


QG flucs: global symmetries ✓



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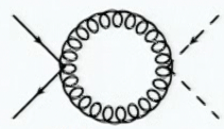

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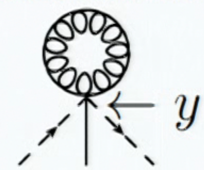

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$$\beta_y|_{\rm grav} = \#\,y\,g$$

minimally interacting FP: free in couplings with reduced symmetry, interacting in couplings with full symmetry of kin. terms

Symmetries dictate fixed-point structure

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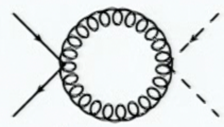

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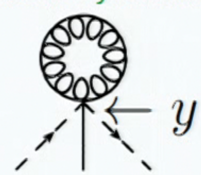

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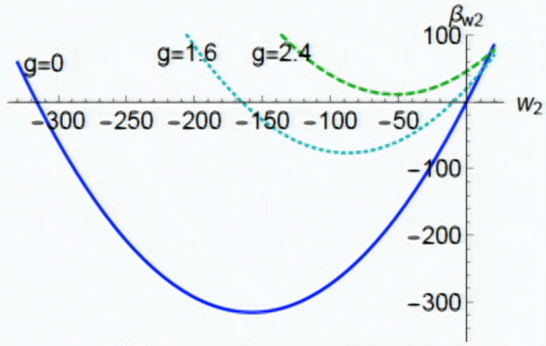
- Real couplings at induced fixed point?
- (Ir)relevant interactions?

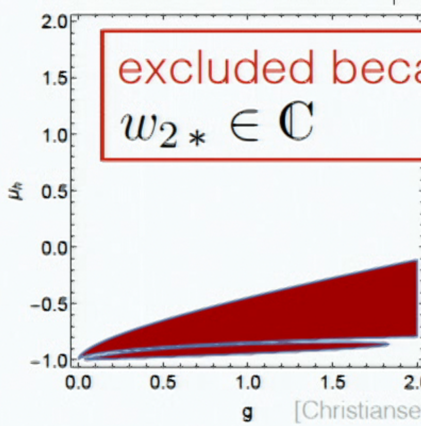
minimally interacting FP:
free in couplings with
reduced symmetry,
interacting in couplings with
full symmetry of kin. terms

Asymptotic safety for matter requires ``weakly interacting" gravity

gauge fields

induced interactions $w_2 \, (F^2)^2 \to w_{2\,*} \neq 0$





[Christiansen, AE, 2017]

Asymptotic safety for matter requires ``weakly interacting" gravity

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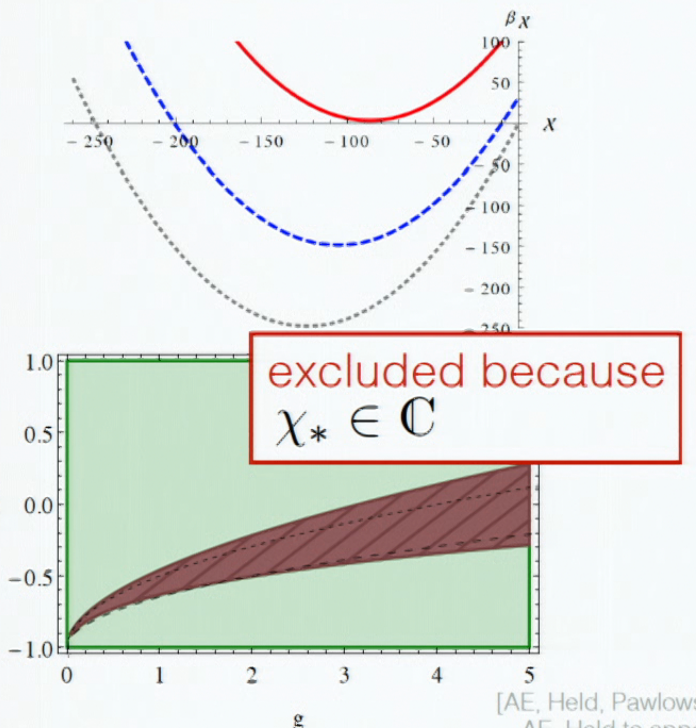

[AE, Held, Pawlowski '16
AE, Held to appear]

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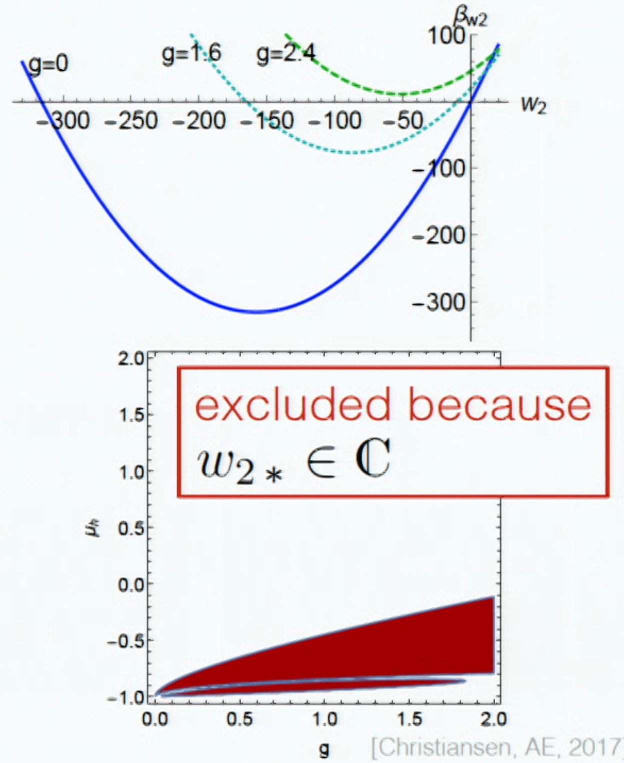

[Christiansen, AE, 2017]

Asymptotic safety for matter requires ``weakly interacting” gravity

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induced interactions
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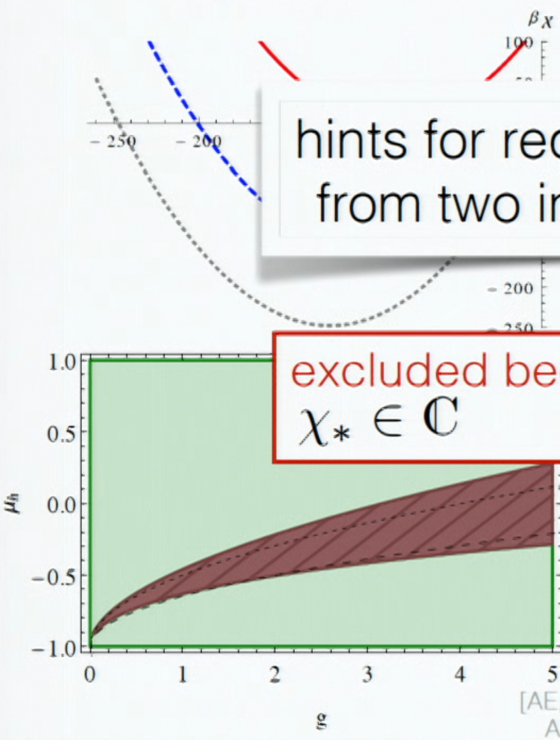
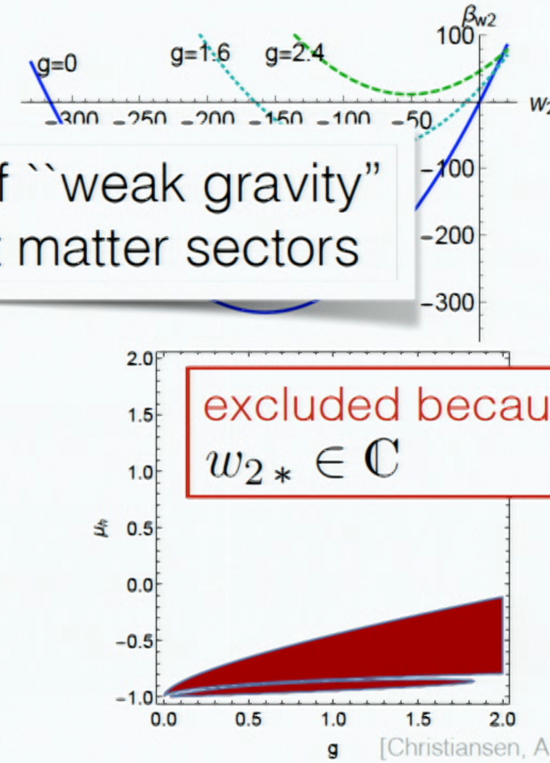




hints for requirement of ``weak gravity”
from two independent matter sectors

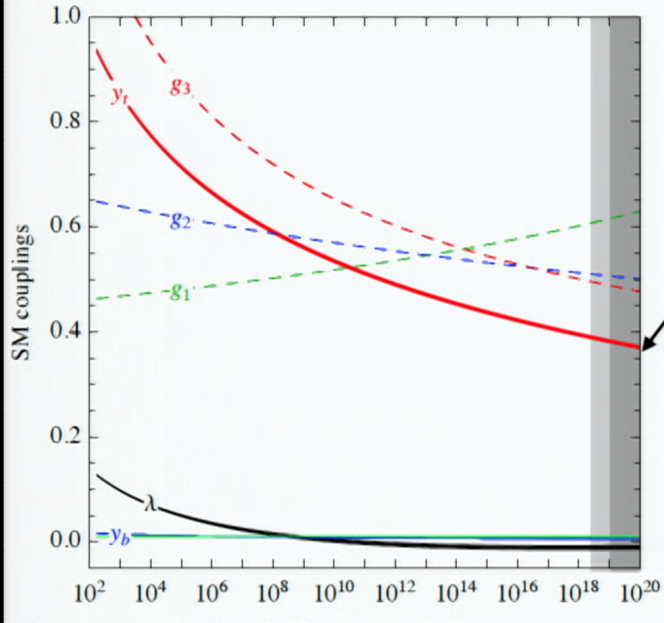
excluded because
$\chi_* \in \mathbb{C}$

excluded because
$w_{2\,*} \in \mathbb{C}$

[AE, Held, Pawlowski '16
AE, Held to appear]

[Christiansen, AE, 2017]

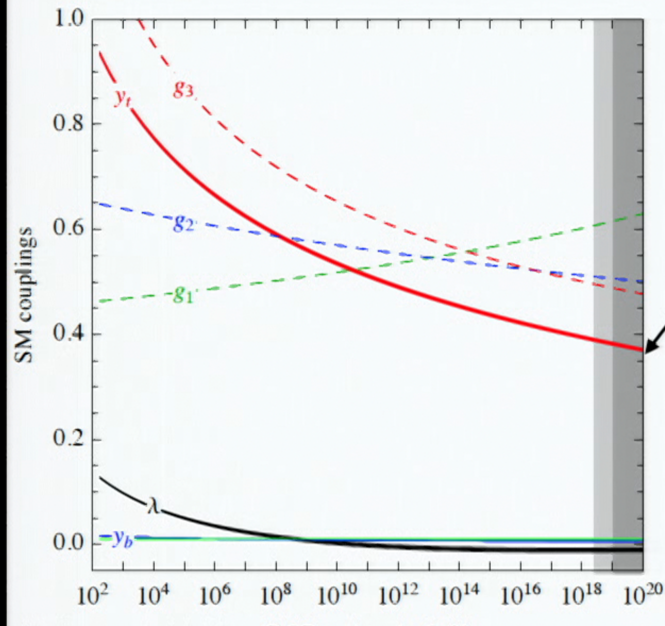
Linking ASQG to the electroweak scale



[Buttazzo et al. '13]

Connection to viable UV fixed point?

Linking ASQG to the electroweak scale



[Buttazzo et al. '13]

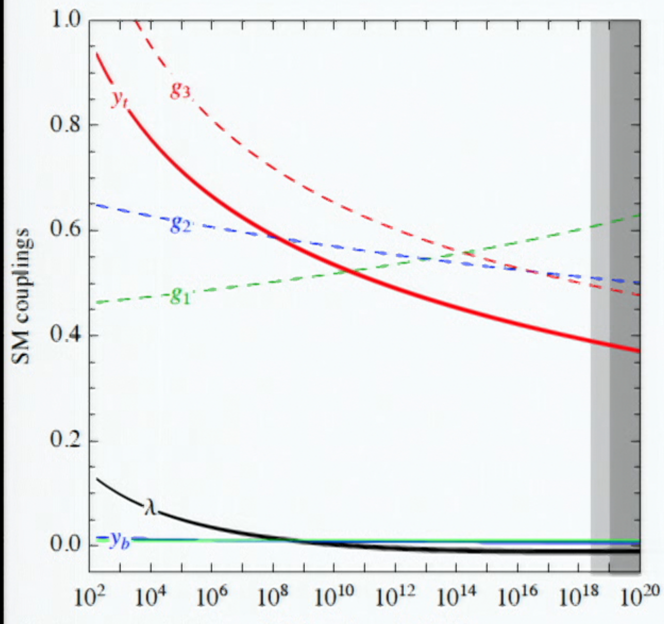
Connection to viable UV fixed point?

toy model: simple Higgs-Yukawa model:

$$\Gamma_k = \frac{Z_\phi}{2}\int d^4x\sqrt{g}\, g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + i\, Z_\psi \int d^4x\sqrt{g}\bar{\psi}\nabla\!\!\!\!/\,\psi + i\, y\int d^4x\sqrt{g}\phi\bar{\psi}\psi$$

[AE, Held, Pawlowski '16; AE, Held, to appear]

Linking ASQG to the electroweak scale



$$\beta_y = -\theta_y\Big|_{\text{grav}}\, y\, g + \frac{y^3}{8\pi^2} \rightarrow y_* = 0$$

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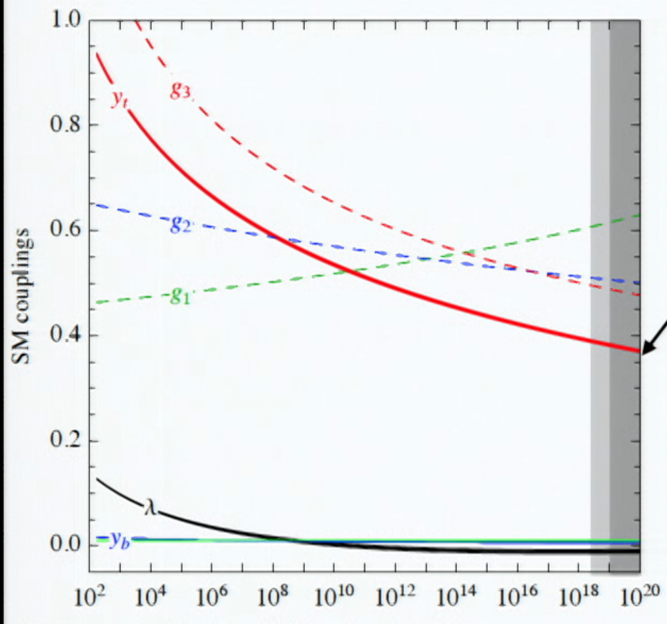

[Buttazzo et al. '13]

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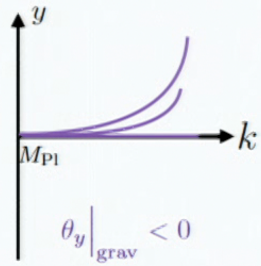
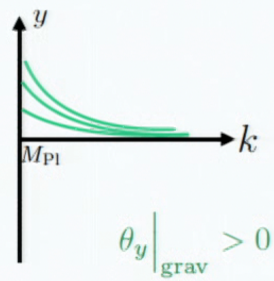
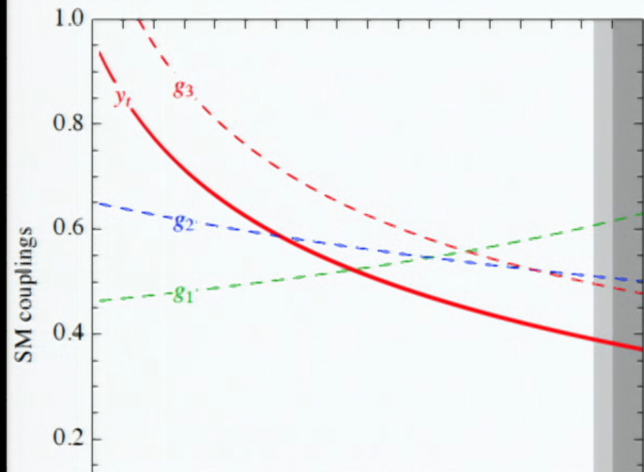
When can this fixed point be connected to viable Planck-scale physics?





Linking ASQG to the electroweak scale



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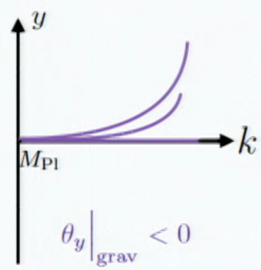
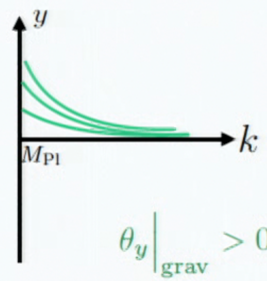
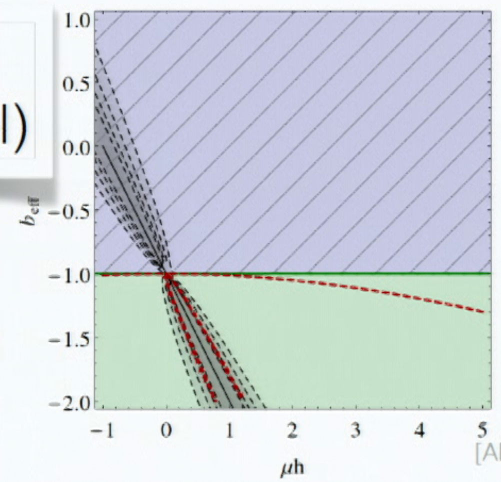




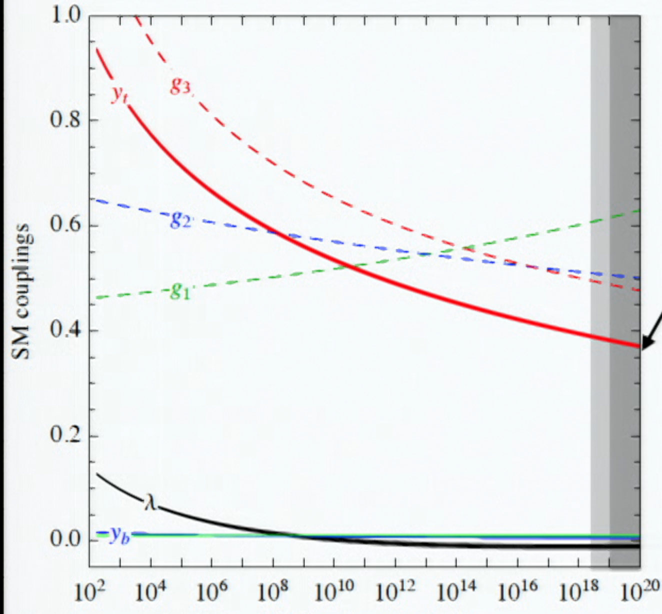
constraint on fixed-point values
(outlook: Higgs-top-bottom model)

$$\Gamma_{k\,\rm grav} = \frac{-1}{16\pi G} Z_h \int d^4x\,\sqrt{g}\,(R-2\Lambda)$$
$$+ \frac{1}{16\pi} Z_h \int d^4x\,\sqrt{g}\Big(aR^2 + bR_{\mu\nu}R^{\mu\nu}$$
$$+ cR\Box R + dR_{\mu\nu}\Box R^{\mu\nu}\Big)$$



[AE, Held, to appear]

Linking QG to the electroweak scale



[Buttazzo et al. '13]

determines entire top mass at e/w scale

$$y\bar{t}t\,\phi \to (y\cdot\langle\phi\rangle)\bar{t}t$$

chiral symmetry:

no microscopic fermion masses

$$m_\psi\bar{\psi}\psi = \frac{m_\psi}{2}\left(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R\right)$$

in the Standard Model

$\rightarrow$ guaranteed automatically below $M_{\rm Pl}$ or nontrivial constraint on fundamental model?

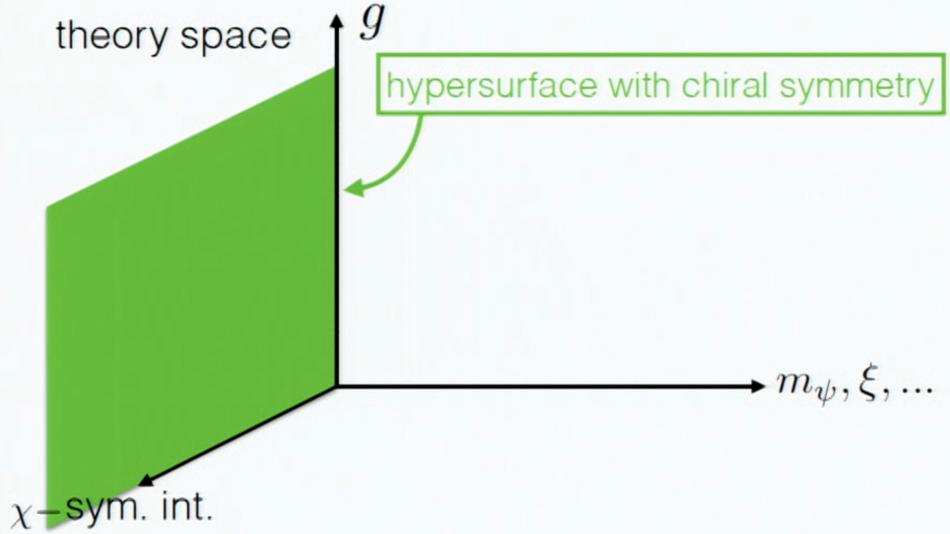
Chiral fermions

chiral symmetry: no microscopic fermion masses $m_\psi \bar{\psi}\psi$ in the Standard Model

$\longrightarrow$ guaranteed automatically below $M_{\rm Pl}$ or nontrivial constraint on fundamental model?

$$\Gamma_k = \Gamma_{\rm grav} + iZ_\psi \int d^4x\, \sqrt{g}\, \bar{\psi}^i \nabla\!\!\!/\, \psi^i + i\bar{m}_\psi \int d^4x \sqrt{g} \bar{\psi}^i \psi^i$$
$$+ i\bar{\xi} \int d^4x \sqrt{g} R \bar{\psi}^i \psi^i + i\bar{\zeta} \int d^4x \sqrt{g} \bar{\psi}^i \nabla^2 \psi^i$$

[AE, Lippoldt '16]



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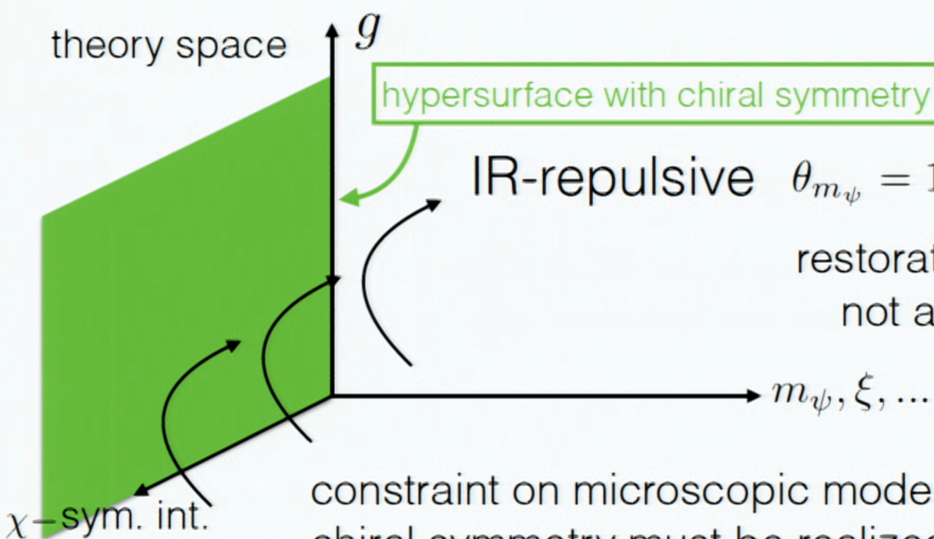


$\theta_{m_\psi} = 1 + \theta_{m_\psi}\Big|_{\rm grav} > 0$

restoration of chiral symmetry
not automatic towards IR

constraint on microscopic models:
chiral symmetry must be realized microscopically

Chiral fermions in asymptotic safety

$$\Gamma_k = \Gamma_{\text{grav}} + iZ_\psi \int d^4x\,\sqrt{g}\,\bar{\psi}^i \nabla\!\!\!/\, \psi^i + i\bar{m}_\psi \int d^4x \sqrt{g}\bar{\psi}^i\psi^i$$
$$+ i\bar{\xi}\int d^4x\sqrt{g}R\bar{\psi}^i\psi^i + i\bar{\zeta}\int d^4x\sqrt{g}\bar{\psi}^i\nabla^2\psi^i$$

[AE, Lippoldt '16]

fixed point	symmetry for fermions	g_*	λ_*	$m_{\psi\,*}$	ξ_*	ζ_*	η_ψ	θ_1	θ_2	θ_3	θ_4	θ_5
chiral non-Gaußian	chiral	2.52	-0.42	0	0	0	-0.17	3.54	1.34	0.84	-0.73	-1.27
chiral non-Gaußian	chiral	2.52	-0.42	0	–	–	-0.17	3.54	1.34	0.84	–	–
chiral non-Gaußian	chiral	2.52	-0.42	–	0	–	-0.17	3.54	1.34	–	-0.69	–
chiral non-Gaußian	chiral	2.52	-0.42	–	–	0	-0.17	3.54	1.34	–	–	-1.30
non-Gaußian	none	1.00	-0.27	1.01	1.10	-2.49	-0.56	3.65	1.66	0.59	-2.50 ± i 1.60	
non-Gaußian	none	2.52	-0.41	–	0.74	–	-0.15	3.54	1.37 ± i 0.04		–	–

chirally symmetric interacting fixed point:
realization of chiral symmetry on all scales

Conclusions & Outlook

quantum gravity might provide a UV completion for the Standard Model

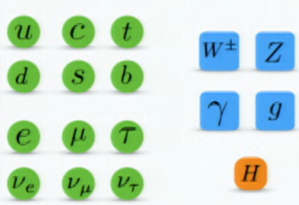
→ asymptotically safe solution to the U(1) triviality problem

→ existence of matter fixed point requires weak gravity

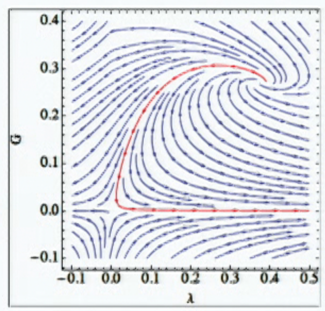
→ (phenomenologically) viable matter fixed point constrains gravitational parameter space

→ existence of chiral fermions accommodated in ASQG (chiral symmetry not IR attractive)

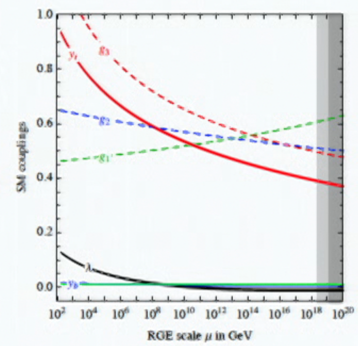
Outlook:



+ gravity =



+



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