Title: The power of diversity - or why linking quantum gravity approaches could matter

Speakers: Astrid Eichhorn

Collection: Emmy Noether Workshop: The Structure of Quantum Space Time

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Abstract: Linking quantum gravity approaches could be important to make progress in quantum gravity. In my talk, I will try to make this case using asymptotically safe gravity as an example. I will briefly review the status of the approach and highlight the open questions, and discuss proposed ideas how the link to other approaches could be useful to tackle these. Finally, I will emphasize the need for universality in quantum gravity, and argue that there might be universal features from quantum gravity in black-hole shadows.

The power of diversity

Astrid Eichhorn
CP3-Origins, University of Southern Denmark
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Emmy-Noether workshop on the quantum structure of spacetime
Perimeter Institute, 19.11. 2019

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Die Junge Akademie

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ZUKUNFT SEIT 1386

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

The status of quantum gravity?

- AdS/CFT
- Asymptotically safe gravity
- causal sets
- Dynamical Triangulations
- Group Field Theory
- Loop QG/ Spin foams
- matrix/tensor models
- noncommutative geometry
- String theory
- ...

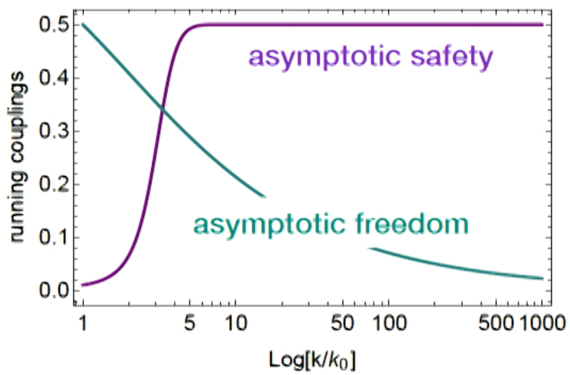
Plan of this talk:

- introduce asymptotically safe quantum gravity
- selectively highlight some open questions
- discuss how input from other approaches might provide answers
- mathematical diversity but physical unity?
  singularity-free black holes as potential example

Scale symmetry

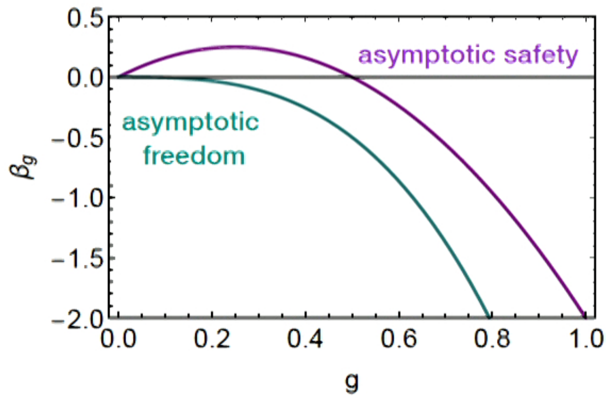
Scale symmetry

Scale symmetry in a QFT



quantum scale-symmetry *

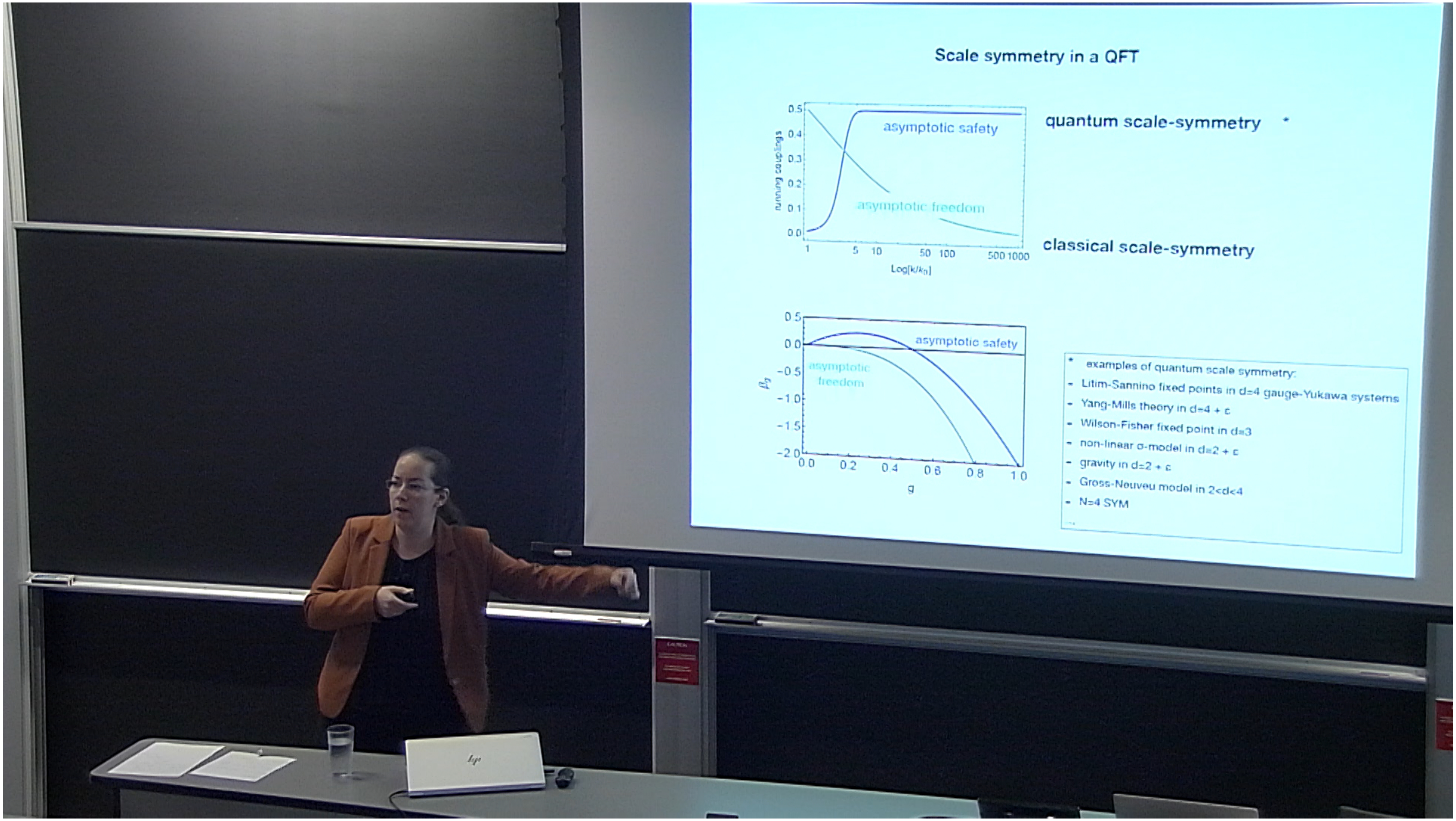
classical scale-symmetry



* examples of quantum scale symmetry:

- Litim-Sannino fixed points in d=4 gauge-Yukawa systems
- Yang-Mills theory in d=4 + ε
- Wilson-Fisher fixed point in d=3
- non-linear σ-model in d=2 + ε
- gravity in d=2 + ε
- Gross-Neuveu model in 2<d<4
- N=4 SYM

...


Scale symmetry in a QFT
asymptotic safety
asymptotic freedom
running couplings
Log[k/k0]
quantum scale-symmetry *
classical scale-symmetry
asymptotic safety
asymptotic freedom
g
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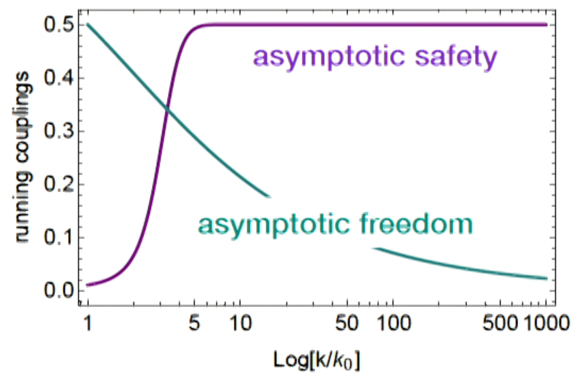
Scale symmetry in a QFT



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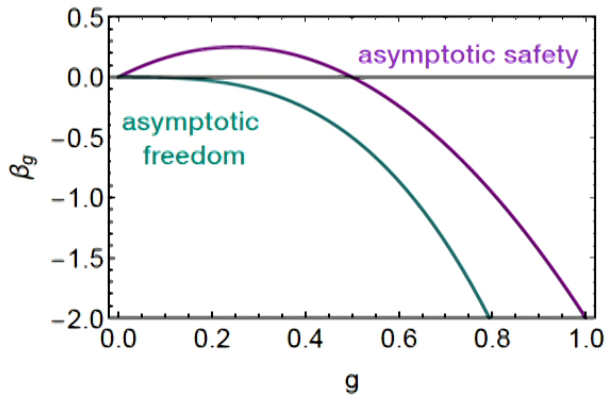
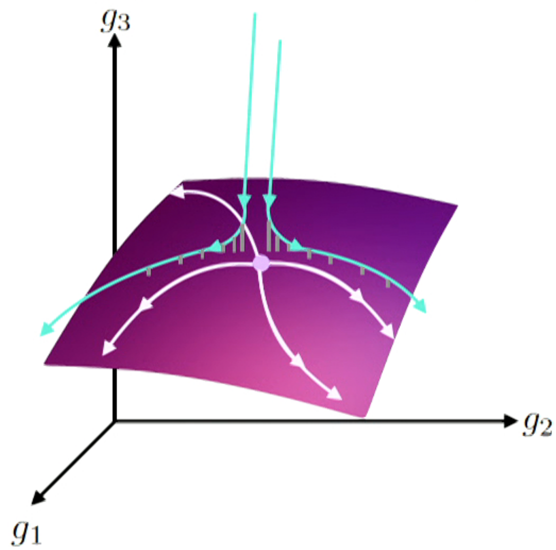
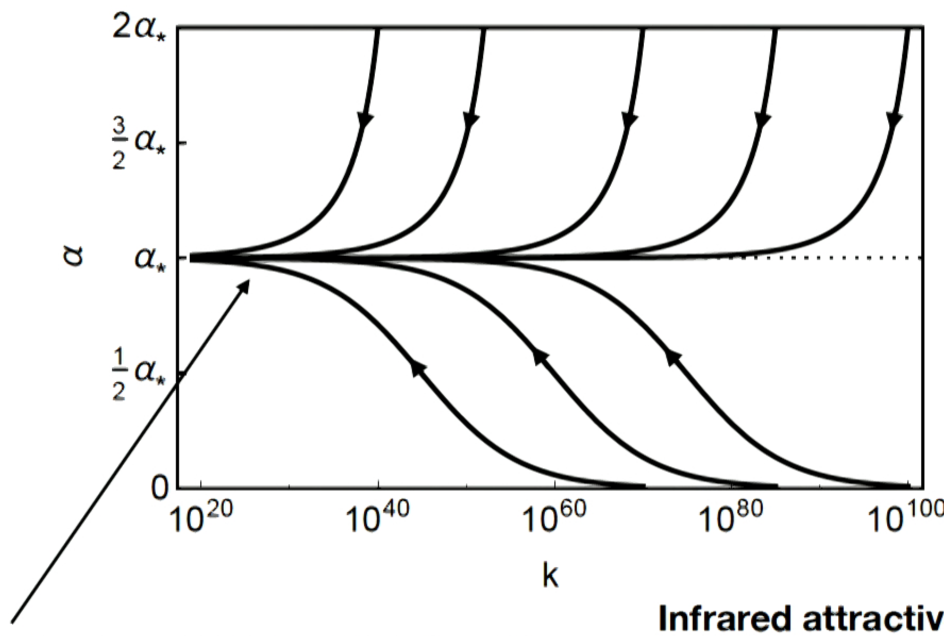


theory space: infinite-dimensional space of couplings



Universal predictions from scale symmetry

Irrelevant directions: Predictions from asymptotic safety



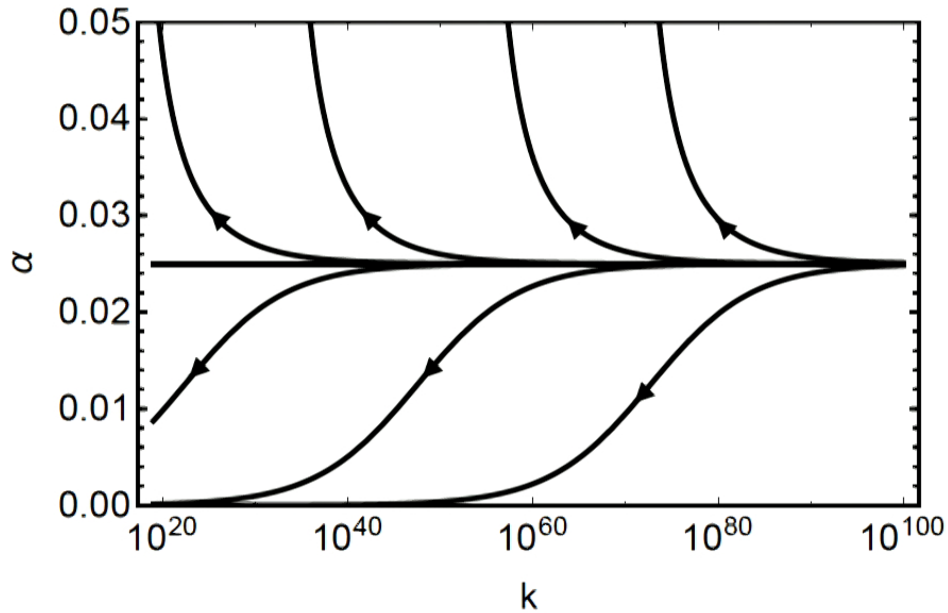
universality: consequence of fixed point

Infrared attractive direction

$$\beta_\alpha = -\alpha(\alpha_* - \alpha)$$

Universal predictions from scale symmetry

Relevant directions: Free parameters (parameterize deviations from scale invariance)

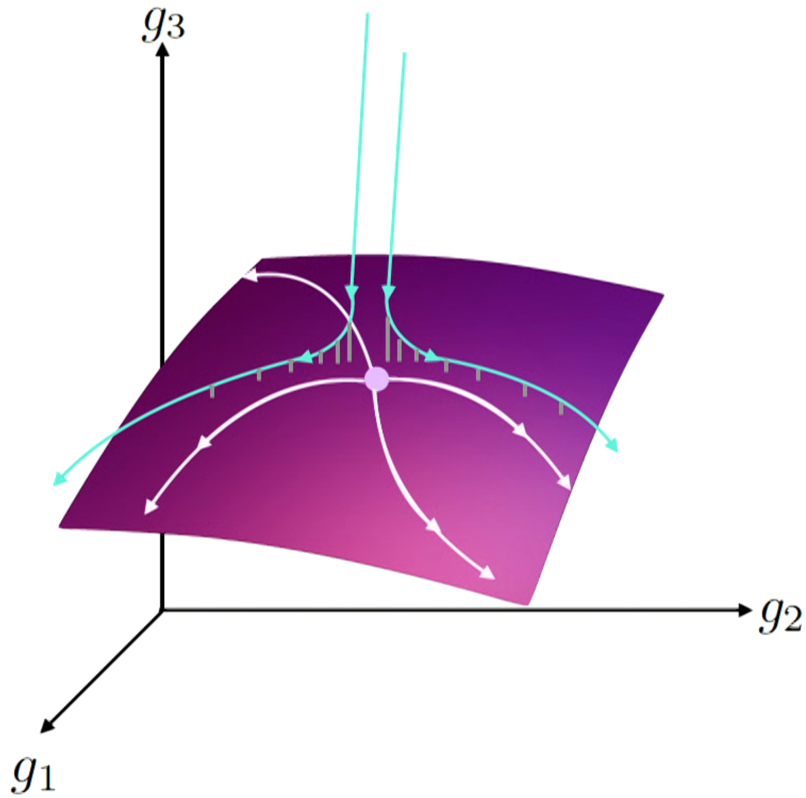


all IR values reachable from fixed point

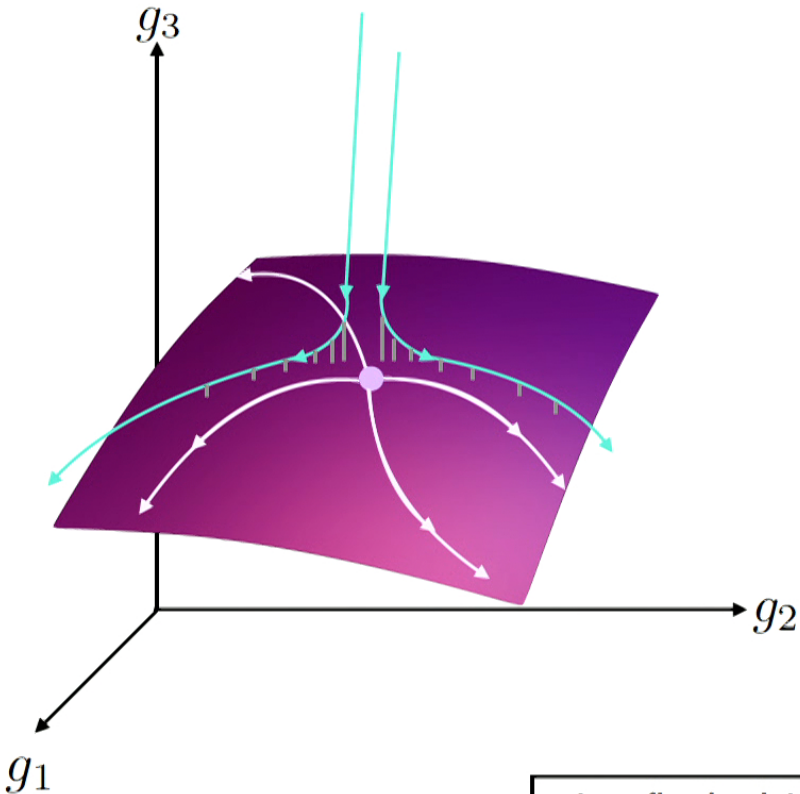
Infrared repulsive direction

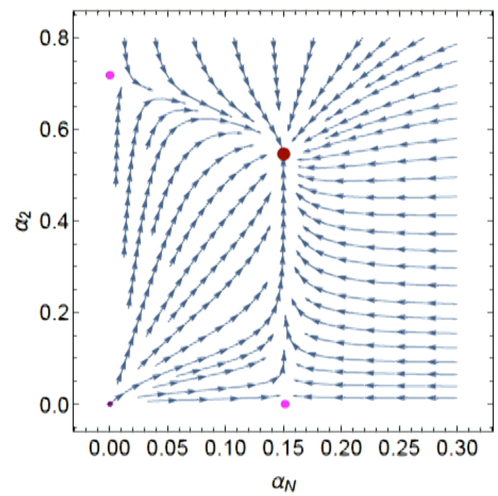
$$\beta_\alpha = \alpha(\alpha_* - \alpha)$$

Universal predictions from scale symmetry



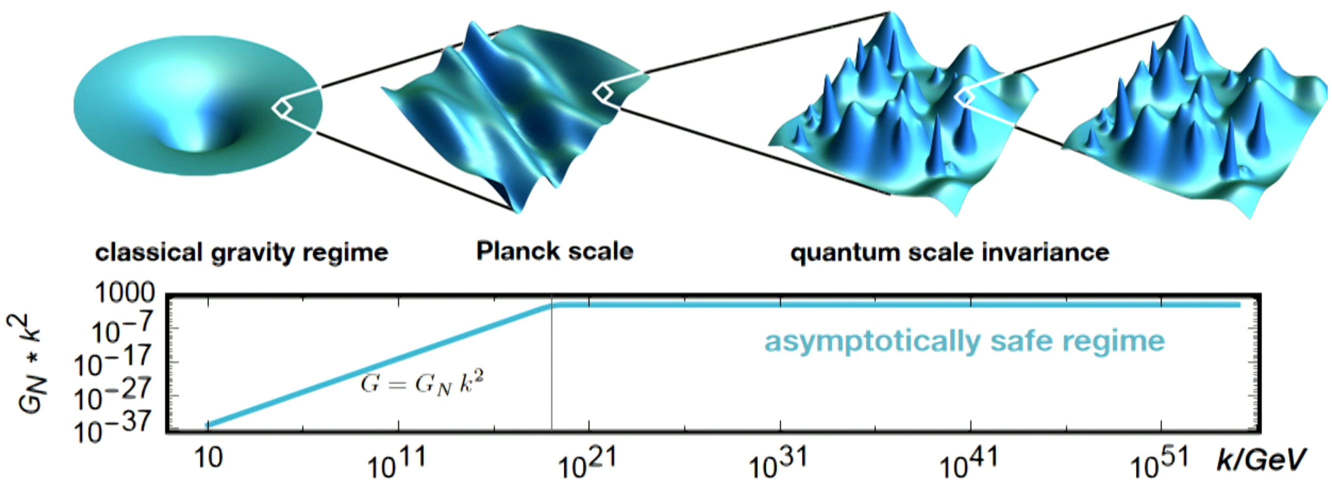
Universal predictions from scale symmetry





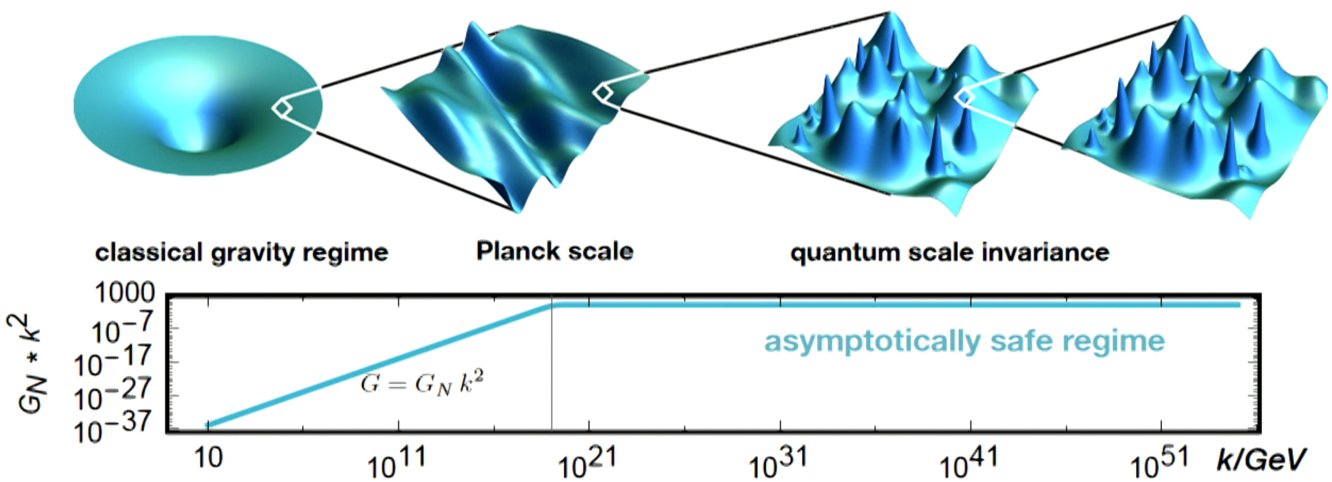
note: a fixed point is only unambiguously UV or IR, if it has ONLY IR repulsive or ONLY IR attractive directions

Asymptotic safety in gravity?



(...and similarly for all other couplings...)

Asymptotic safety in gravity?



(...and similarly for all other couplings...)

Asymptotic safety in gravity?

- **ε-expansion d=2 + ε**

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

[Weinberg '86; Gastmans, Kallosh, Truffin '78; Christensen, Duff '78…]

- **1-loop perturbation theory in d=4**

[Niedermaier '04 '05…]

- **"lattice" approach**

(C)DTs

C: [Ambjorn, Jurkiewicz, Loll…]
no C: [Coumbe, Laiho, Unmuth-Yockey, Caterall]

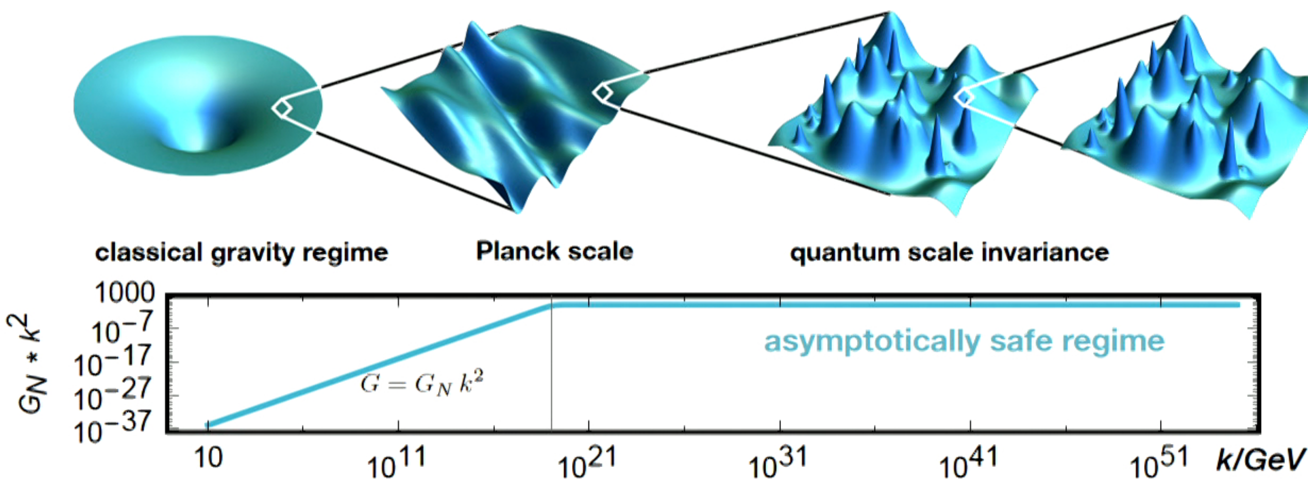
scale invariance:
universal continuum limit exists

- **continuum approach**

Functional Renormalization Group

[Reuter '96]
[Benedetti, Bonanno, Codello, AE, Falls, Gies, Held, Knorr, Litim, Pagani, Pawlowski, Percacci, Pereira, Platania, Reichert, Saueressig, Yamada, Wetterich…]

scale invariance:
universal k $\longrightarrow \infty$ limit exists



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Asymptotic safety in gravity?

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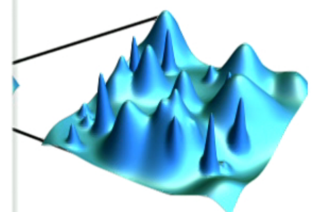

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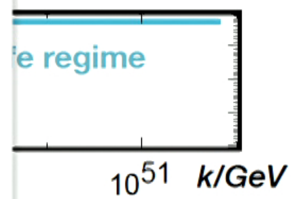
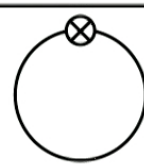


FRG in brief:

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

scale- and momentum-dependent "mass"

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

in practise:
truncate to (finite) subset of operators

gravity: candidate guiding principle near-perturbativeness

[Falls, Litim, Nikolakopoulos, Rahmede '13 '14; AE, Labus, Pawlowski, Reichert '18;
Falls, Litim, Schröder '18; AE, Lippoldt, Pawlowski, Reichert, Schiffer '18
AE, Lippoldt, Schiffer '18]

(…and similarly for all other couplings…)

Indications for (Euclidean) gravitational fixed point in d=4

based on truncated FRG studies:

fixed point	operators	corresponding couplings:
✓	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Becker, Reuter '14;
✓	$\sqrt{g}R$	Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15]
✓	$\sqrt{g}R^2$, $\sqrt{g}R^{\mu\nu}R_{\mu\nu}$	[Benedetti, Machado, Saueressig '09; Christiansen '16 Denz, Pawlowski, Reichert '17]
✓	$\sqrt{g}R^3$	[Codello, Percacci, Rahmede '07, '08 Machado, Saueressig '07; A.E. '15; de Brito, Ohta, Pereira, Tomaz, Yamada '18]
.	.	
.	.	
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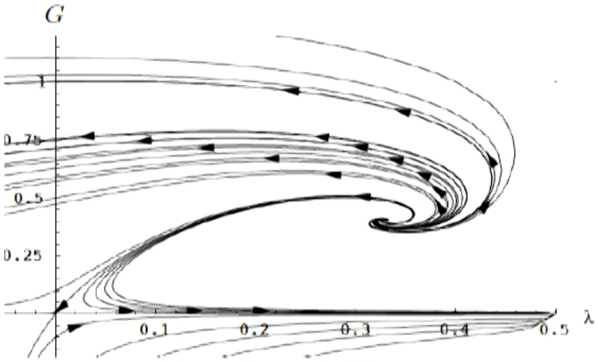
.	.	
✓	$\sqrt{g}R^{70}$	
✓	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[Gies, Knorr, Lippoldt, Saueressig '16]

full $f(R)$ [Benedetti, Caravelli '12; Dietz, Morris '12, Demmel, Saueressig, Zanusso '14, '15; Gonzalez-Martin, Morris, Slade '17]



[Reuter, Saueressig '02]

Indications for (Euclidean) gravitational fixed point in d=4

based on truncated FRG studies:

fixed point	operators	corresponding couplings:	free parameter (relevant)	prediction (irrelevant)	canonically
✓	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Becker, Reuter '14;	x		relevant
✓	$\sqrt{g}R$	Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15]	x		relevant
✓	$\sqrt{g}R^2,\ \sqrt{g}R^{\mu\nu}R_{\mu\nu}$	[Benedetti, Machado, Saueressig '09; Christiansen '16 Denz, Pawlowski, Reichert '17]	x	x	marginal
✓	$\sqrt{g}R^3$	[Codello, Percacci, Rahmede '07, '08 Machado, Saueressig '07; A.E. '15; de Brito, Ohta, Pereira, Tomaz, Yamada '18]		x	irrelevant
⋮	⋮			⋮	⋮
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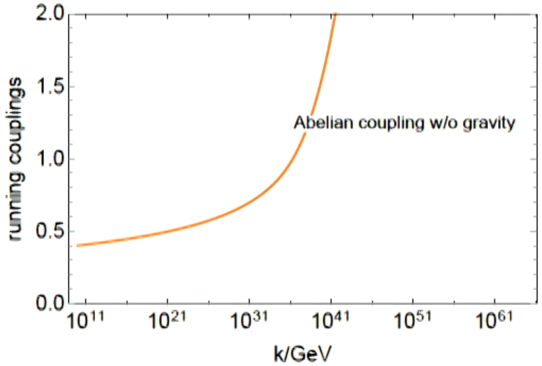
Predictive power of asymptotic safety: Abelian gauge coupling



$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} + \dots$$

triviality problem

[Gell-Mann, Low '54; Gockeler et al. '98; Gies, Jaeckel '04]

Add gravity

Disclaimers:

- truncation of operator basis

(truncation scheme based on indications for near-perturbative nature of fixed point)

[Falls, Litim, Nikolakopoulos, Rahmede '13 '14; AE, Labus, Pawlowski, Reichert '18; Falls, Litim, Schröder '18; AE, Lippoldt, Pawlowski, Reichert, Schiffer '18 AE, Lippoldt, Schiffer '18]

- gravity-contributions to β functions are not universal (scheme-independent)

(β functions are not physical quantities; Standard Model (marginal couplings): non-universality @ 3 loops & beyond)

[Toms '08, '10; Ellis, Mavromatos '10…]

Predictive power of asymptotic safety: Abelian gauge coupling

- **Asymptotically safe quantum gravity could act like effective change of dimensionality**

$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - \boxed{f_g\, g_Y} + \dots$$

metric fluctuations

Functional RG calculations in truncation of full dynamics (systematic uncertainties!):

$f_g = \text{const} \geq 0$ above M_{pl}

$f_g \to 0$ below M_{pl}

[Daum, Harst, Reuter '09; Folkerts, Litim, Pawlowski '09; Harst, Reuter '11; Christiansen, AE '17; AE, Versteegen '17; Christiansen et al. '17; AE, Schiffer '19; de Brito, AE, Pereira '19]

$$f_g(d) = G\frac{2^{1-d}\pi^{1-\frac{d}{2}}\left(16+(d-2)d\left(12+(d-9)d\right)\right)}{(d-2)d\,\Gamma\left[2+\frac{d}{2}\right](1-2\lambda)^2}(2+d)$$
$$+ G\frac{2^{3-d}((d-2)d-2)\pi^{1-\frac{d}{2}}}{(d-2)\Gamma\left[3+\frac{d}{2}\right](1-2\lambda)}\left((4+d)+\frac{(4+d)}{1-2\lambda}\right)$$
$$- w_{2*}(4+d)\frac{4+d(d-1)}{2^{d+1}\pi^{\frac{d}{2}}\Gamma\left[3+\frac{d}{2}\right]}$$

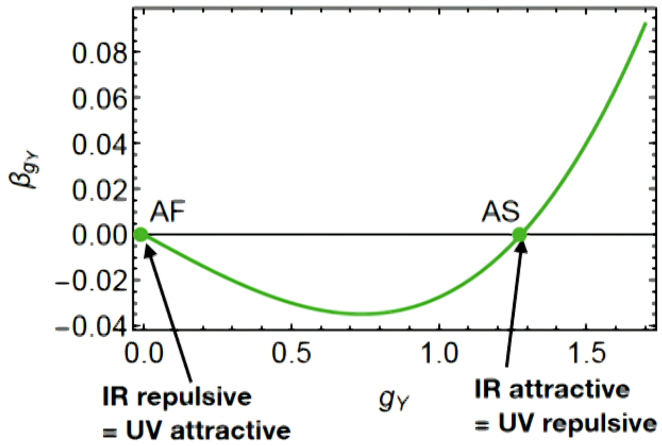
[AE, Schiffer '19]

for inclusion of curvature-squared couplings:

[de Brito, AE, Pereira '19]

Predictive power of asymptotic safety: Abelian gauge coupling

- **Asymptotically safe quantum gravity could act like effective change of dimensionality**



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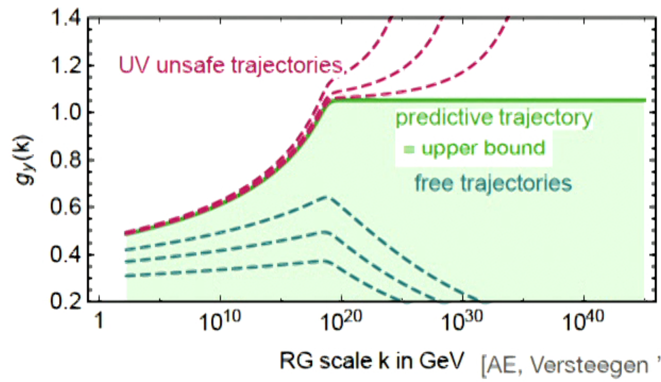
matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting



[AE, Versteegen '17]

Predictive power of asymptotic safety: d=4

- **Asymptotically safe quantum gravity could act like effective change of dimensionality**

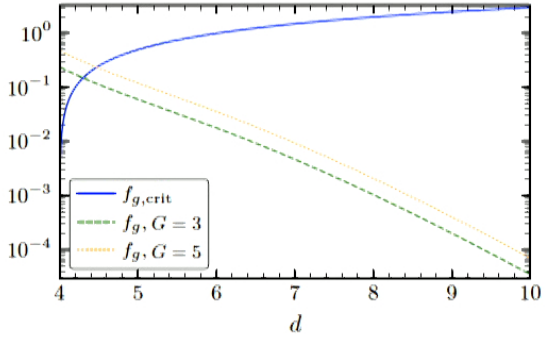
$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y \;+ \ldots$$

[AE, Marc Schiffer, PLB 793, 383, '19]

Predictive power of asymptotic safety: d=4

- **Asymptotically safe quantum gravity could act like effective change of dimensionality**

$$\beta_{g_Y} = \left[\frac{(d-4)}{2} - f_g(d)\right] g_Y + \dots$$



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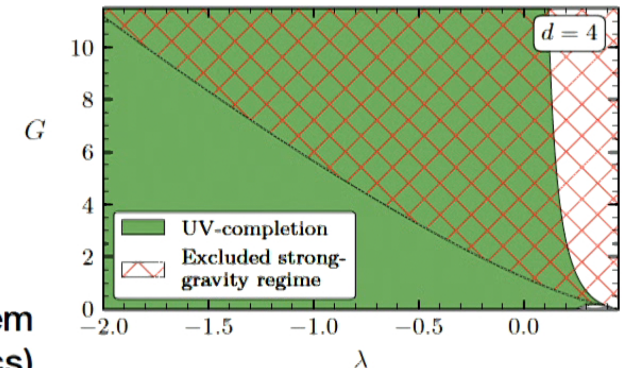
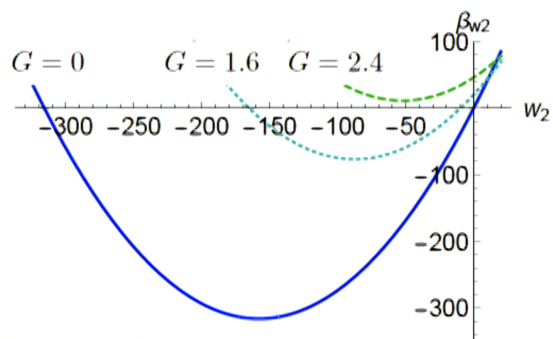
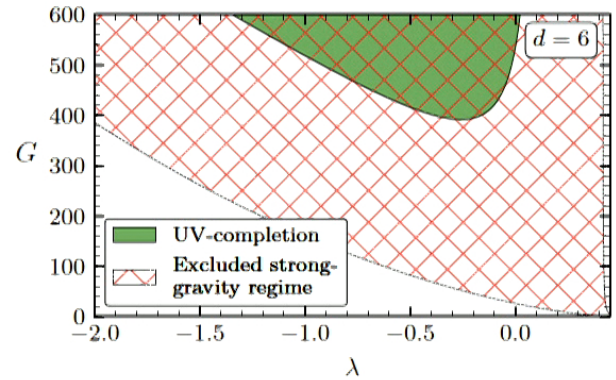


→ @ larger d: solution to the triviality problem requires large G (non-perturbative physics)





[Christiansen, AE '17]

Open questions in asymptotic safety

Unitarity?

based on truncated FRG studies:

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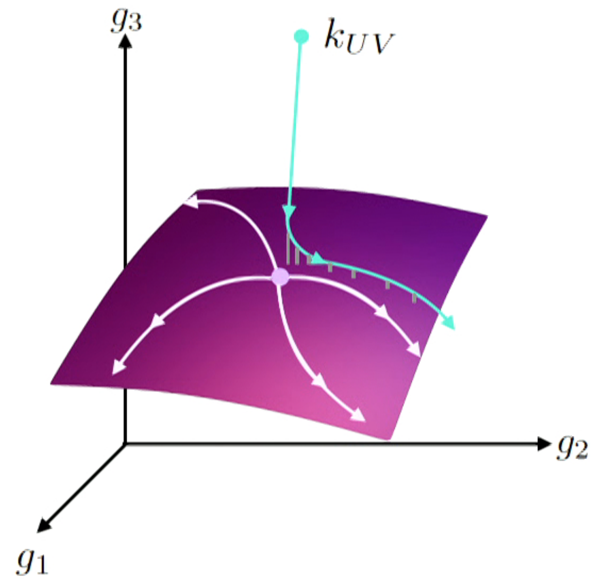
Open questions in asymptotic safety

Unitarity?

Non-fundamental asymptotic safety:

- QFT description of metric + matter holds up to k_{UV}
- a “more fundamental” description sets initial conditions for RG flow at k_{UV}

[Percacci, Vacca '10]



Open questions in asymptotic safety

Unitarity?

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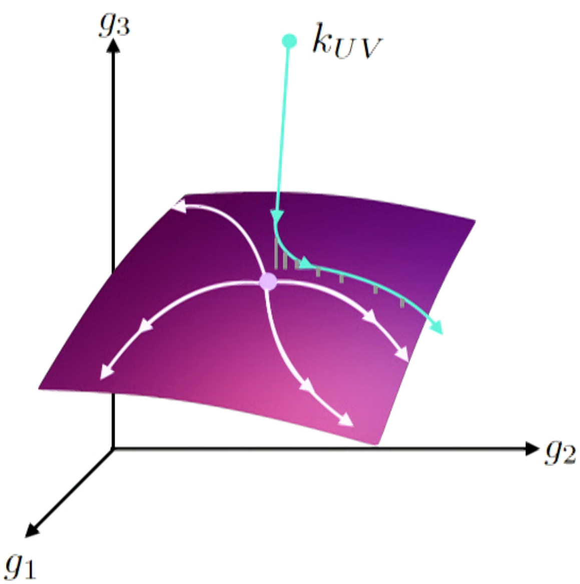
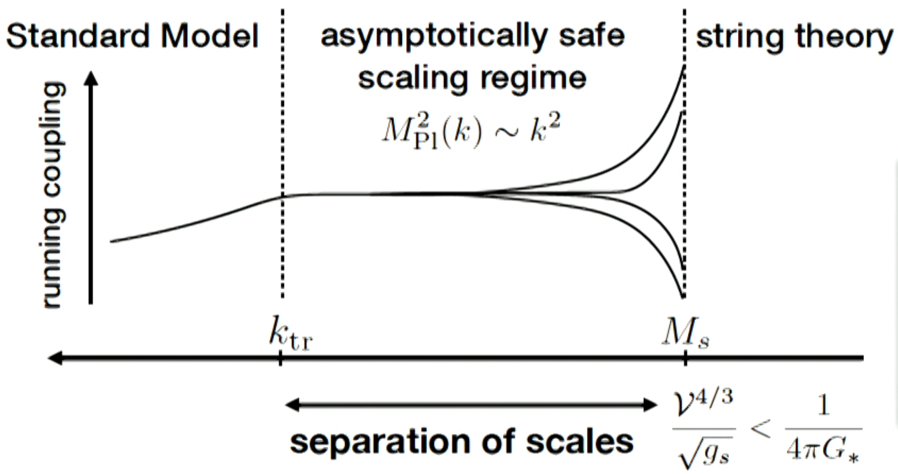
[de Alwiss, AE, Held, Pawlowski, Schiffer, Versteegen '19]





weak-gravity conjecture in asymptotic safety:
might hold at fixed point with finite gauge coupling, but:
conditions on fixed-point values

Open questions in asymptotic safety

Unitarity?

Lorentzian signature?

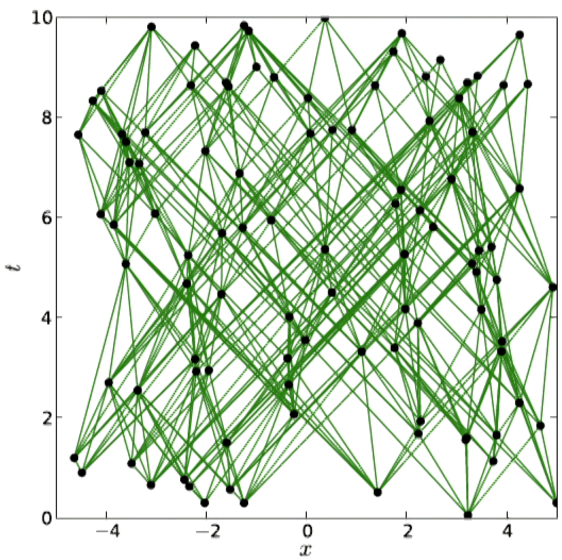
Open questions in asymptotic safety

Lorentzian signature?

scale-invariance: universal continuum limit exists in discrete setting

$\longrightarrow$ re-interpret causal sets!

[AE '17, '19]



spacetime = set of spacetime elements e_i

with order relation $\prec$ (precedes)

local finiteness: $|\{e_k : e_i \prec e_k \prec e_j\}| < \infty$

- fundamental discreteness of spacetime

OR

- Lorentzian regularization of spacetime

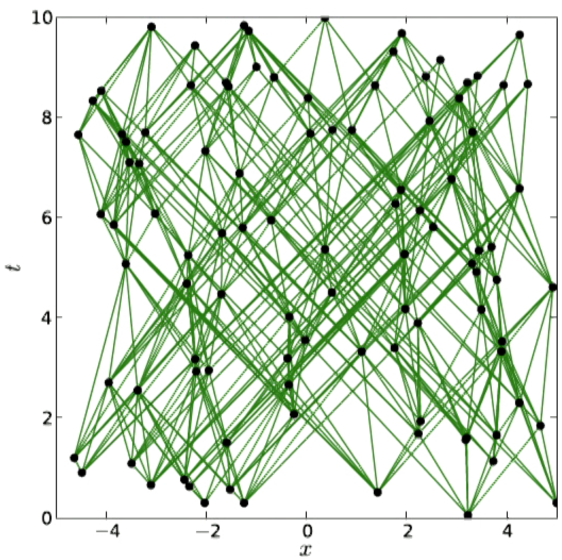
Open questions in asymptotic safety

Lorentzian signature?

scale-invariance: universal continuum limit exists in discrete setting

$\longrightarrow$ re-interpret causal sets!

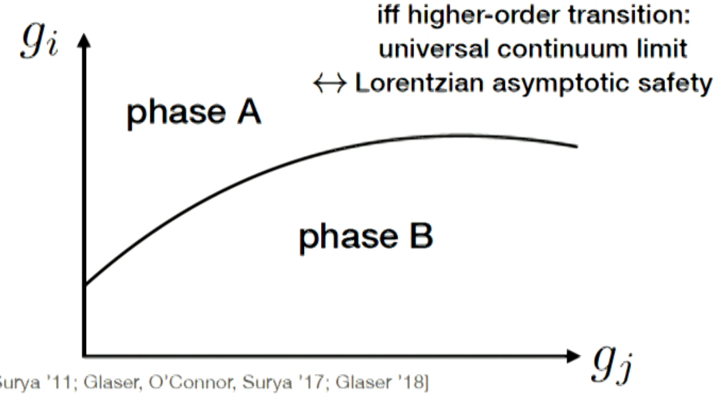
[AE '17, '19]



$$Z_{\rm grav} = \int \mathcal{D}C e^{iS[C]}$$

$$S[C] = g_1 N + \sum_i g_i N_i$$

phase diagram:



[cf. Surya '11; Glaser, O'Connor, Surya '17; Glaser '18]

Open questions in asymptotic safety

Lorentzian signature?

scale-invariance: universal continuum limit exists in discrete setting

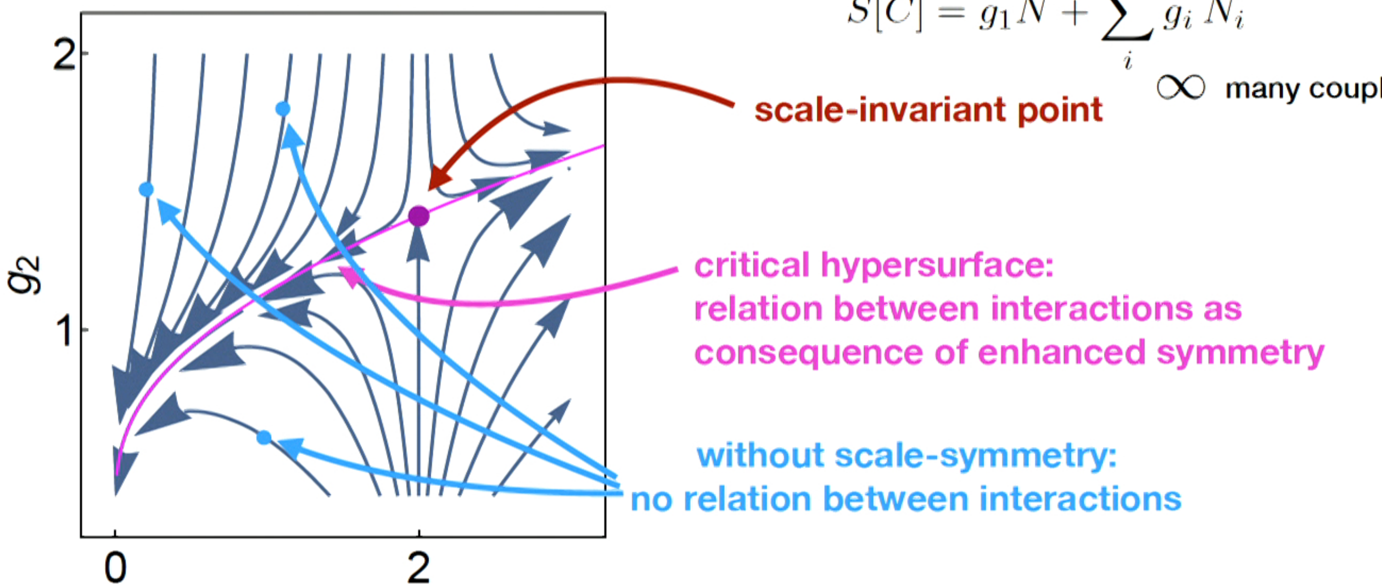
$\longrightarrow$ re-interpret causal sets!
[AE '17, '19]

$$Z_{\text{grav}} = \int \mathcal{D}C e^{iS[C]}$$

causal sets: predictivity

$$S[C] = g_1 N + \sum_i g_i N_i$$

∞ many couplings



Mathematical diversity, physical unity?

AdS/CFT

Asymptotically safe gravity

causal sets

Dynamical Triangulations

Group Field Theory

Loop QG/ Spin foams

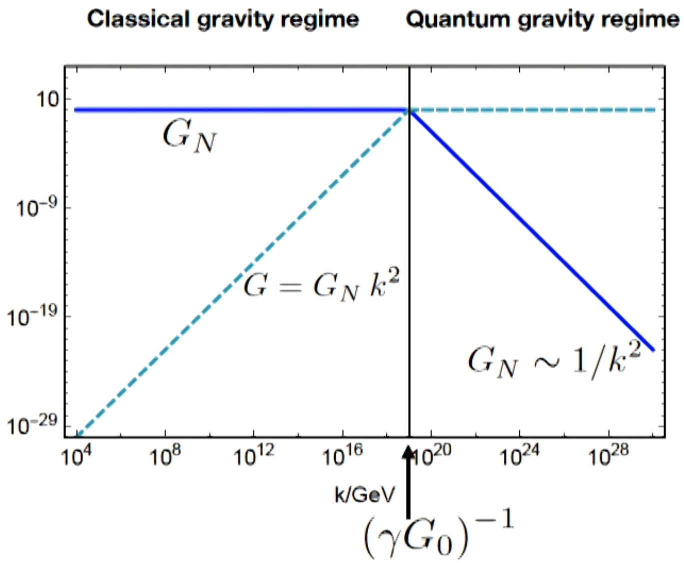
matrix/tensor models

noncommutative geometry

String theory

...

Mathematical diversity, physical unity?

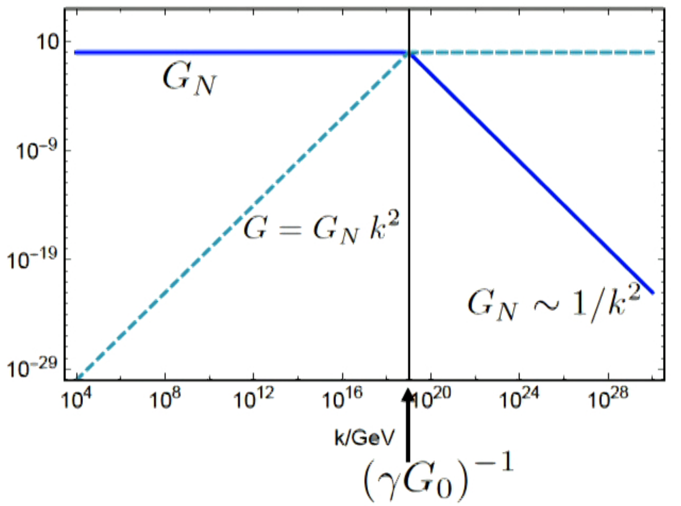


Schwarzschild black hole:

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2\, d\Omega^2$$

$$f(r) = 1 - \frac{2G_N\, M}{r}$$

Mathematical diversity, physical unity?



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- **spherically symmetric case:**

$$K = R_{\mu\nu\kappa\lambda}R^{\mu\nu\kappa\lambda} \sim \frac{G_0^2 M^2}{r^6}$$

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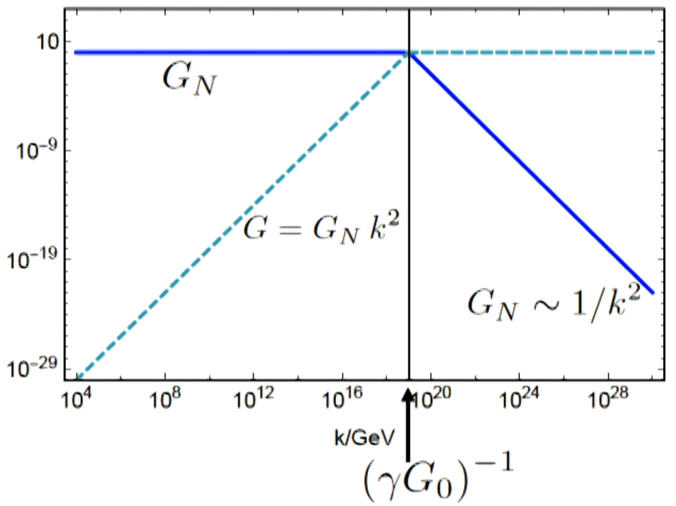
Mathematical diversity, physical unity?



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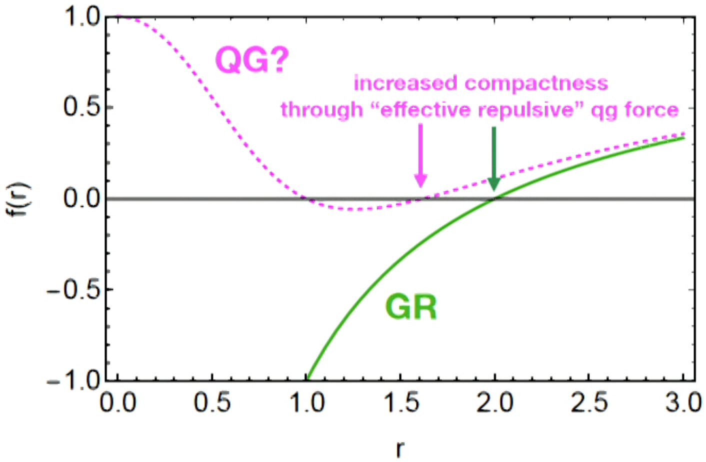
- **RG-improved line element:**

$$f(r) = 1 - \frac{2G_0\, M}{r}\frac{1}{1+\gamma\frac{G_0^2\, M}{r^3}}$$

$$= 1 + \# r^2 + \dots$$

[Bonanno, Reuter '99 '00, 06 ; Falls, Litim '11; Koch, Saueressig '13, Pawlowski, Stock '18 Adeifeoba, AE, Platania, '18, Platania '19, Held, Gold, AE '19]

Mathematical diversity, physical unity?



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[Hayward '06]

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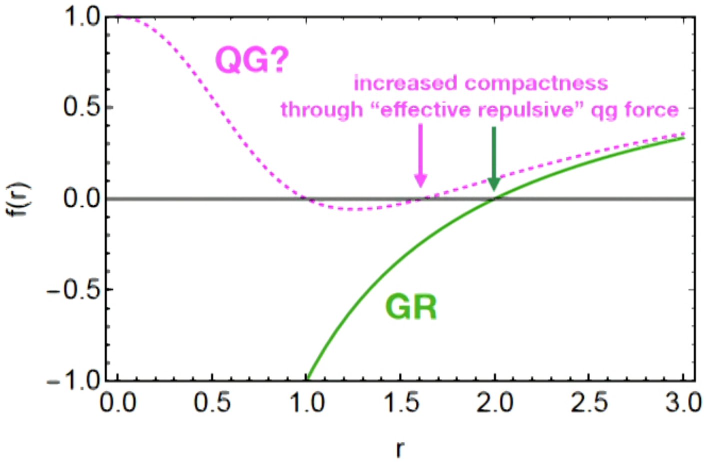

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[Hayward '06]

inspired by quantum gravity:

Asymptotically safe gravity

[Bonanno, Reuter '99 '00, 06 ;
Falls, Litim '11;
Koch, Saueressig '13,
Pawlowski, Stock '18
Adeifeoba, AE, Platania, '18,
Platania '19,
Held, Gold, AE '19]

Loop QG/ Spin foams

[Gambini, Pullin '08, '13;
Rovelli, Vidotto '14]

noncommutative geometry

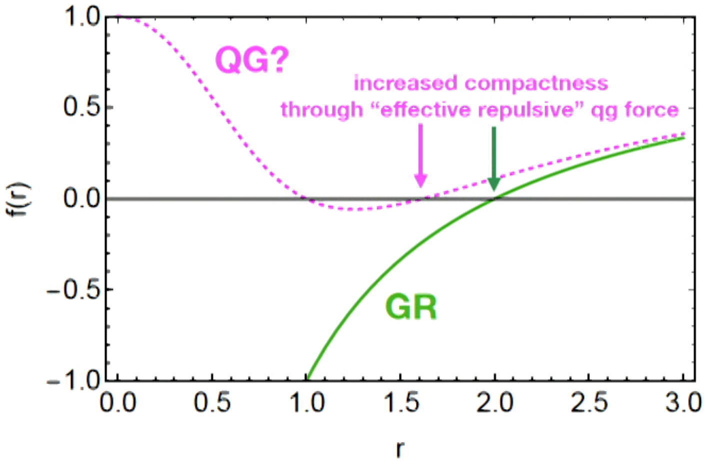
[Nicolini '06]

String theory

[Nicolini '19]

...either one of them!

Mathematical diversity, physical unity?



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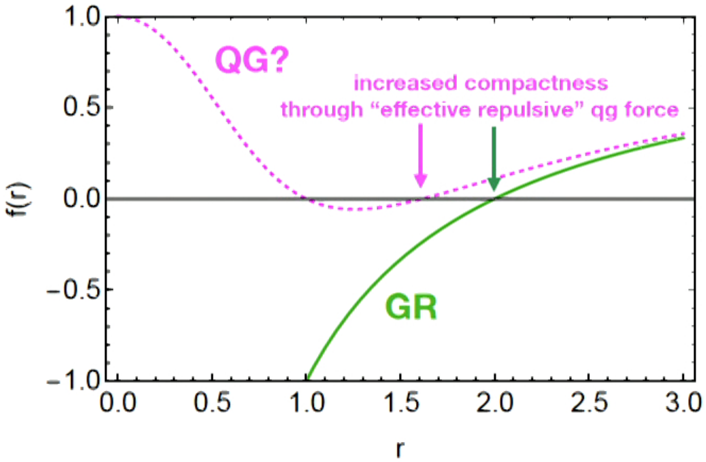
effectively:
reduced radius-dependent mass parameter

$$M_{\mathrm{eff}} = M - \gamma\frac{G_0^2 M^2}{r^3} + \ldots$$

$$M_{\mathrm{eff}}(r \approx r_{\mathrm{horizon}}) \quad < \quad M_{\mathrm{eff}}(r \approx 1000\, r_{\mathrm{horizon}})$$

Mathematical diversity, physical unity?



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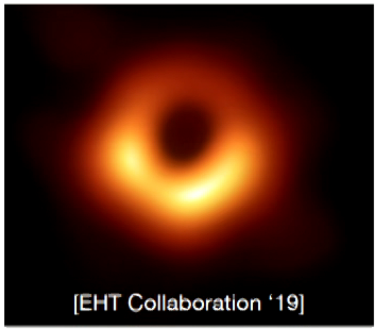

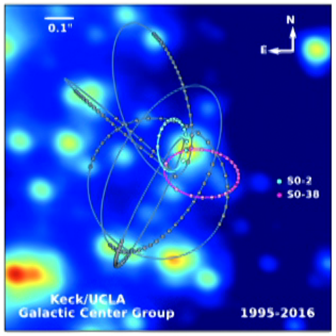

constraint on γ
see
[Held, Gold, AE '19]

Diversity of ideas matters

Open questions in asymptotic safety

Unitarity?

transition from microscopic AdS to macroscopic dS?

Non-fundamental asymptotic safety:

- QFT description of metric + matter holds up to k_{UV}
- a "more fundamental" description sets initial conditions for RG flow at k_{UV}

[de Alwiss, AE, Held, Pawlowski, Schiffer, Versteegen '19]