Asymptotically safe gravity

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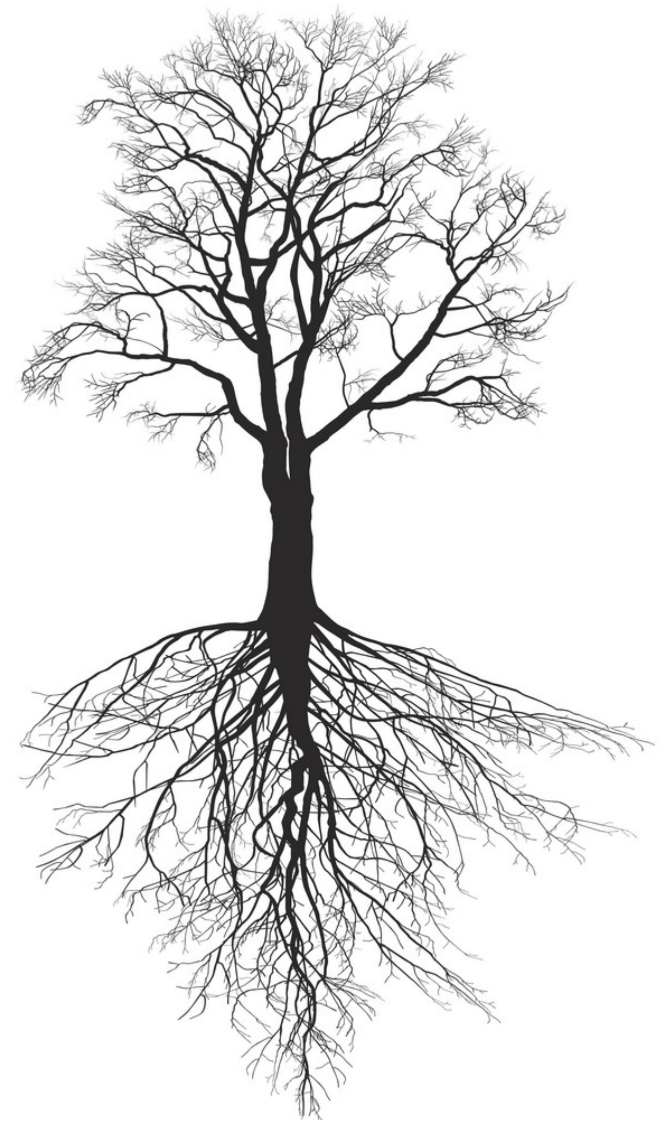
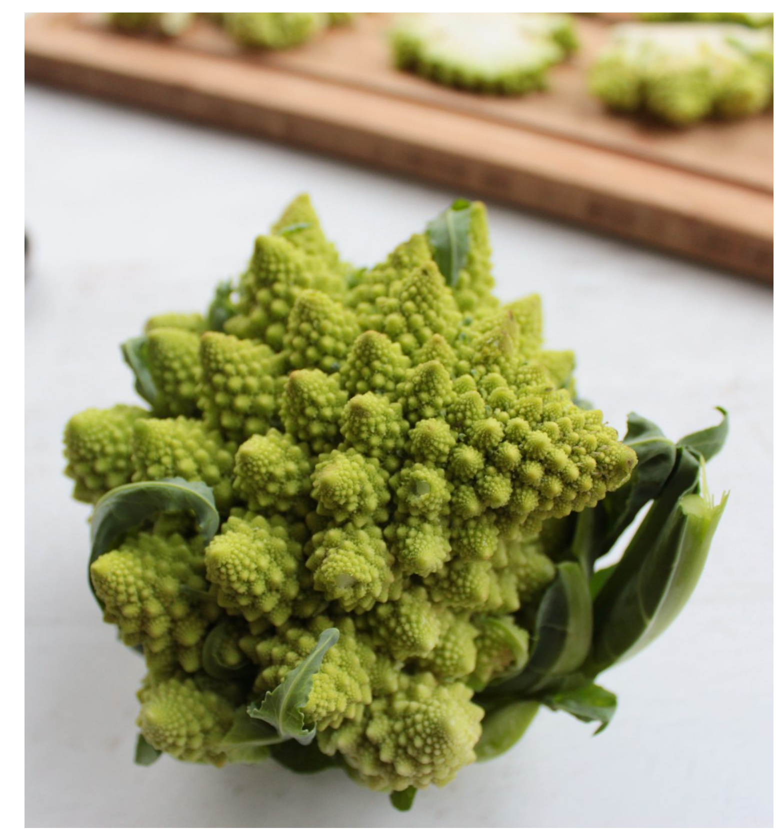
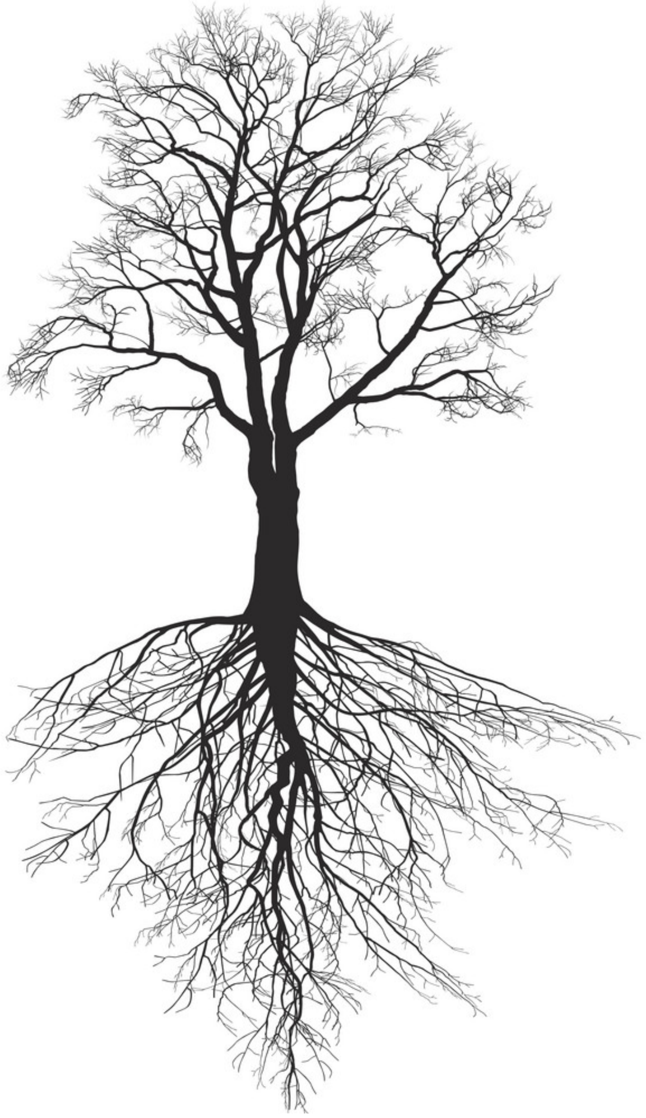
Scale symmetry

Scale symmetry



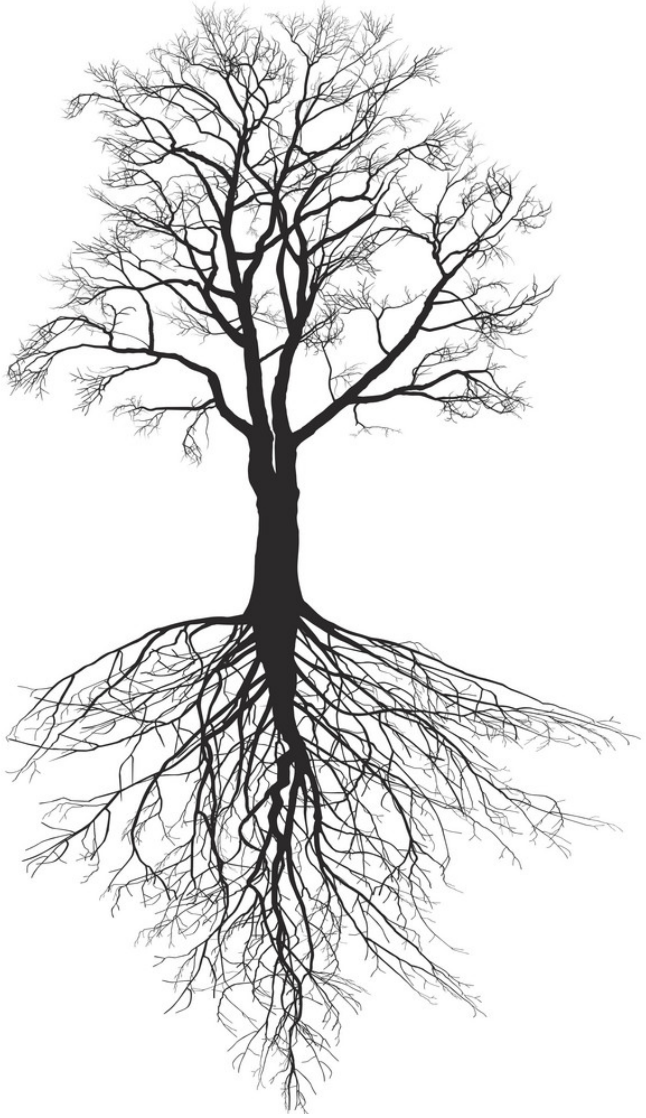


Scale symmetry



Could this be a much deeper principle of nature?

Scale symmetry

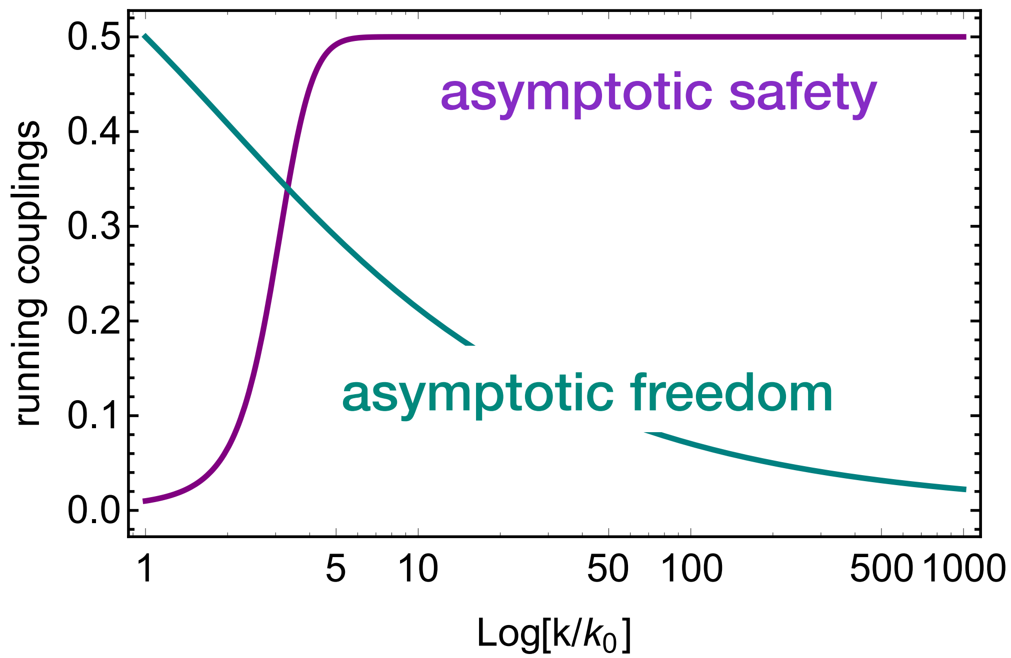


Could this be a much deeper principle of nature?

AdS/CFT, continuum limit in discrete quantum gravity approaches, asymptotically safe quantum gravity…

Scale symmetry in a QFT

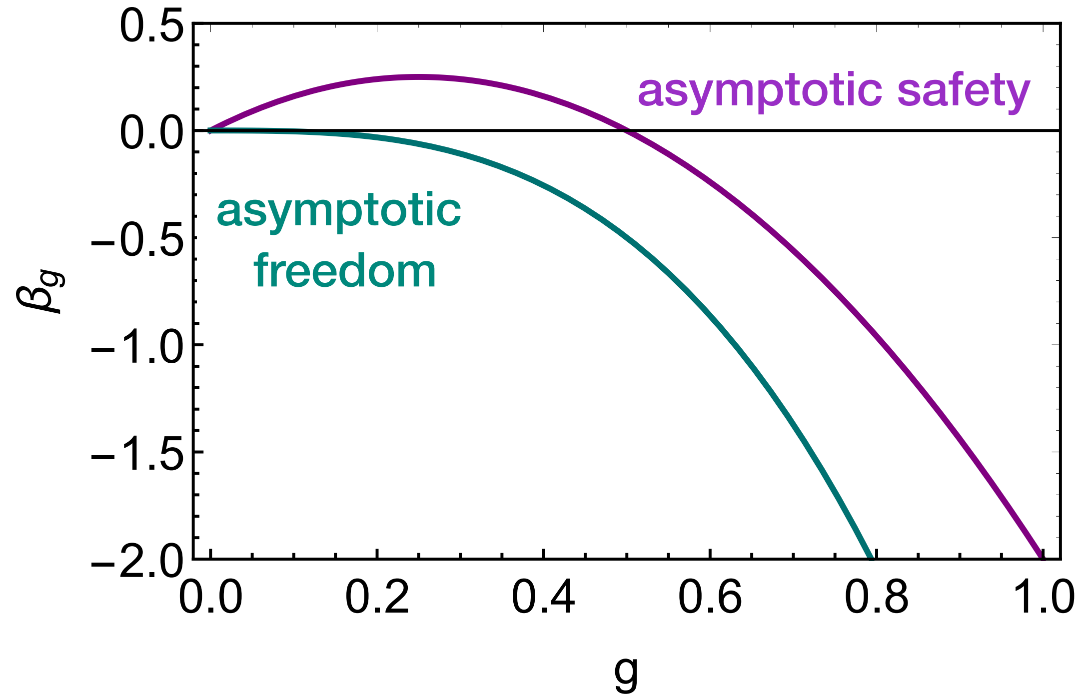
Scale symmetry in a QFT



quantum scale-symmetry *

classical scale-symmetry

$$\beta_g = k\,\partial_k g(k)$$



$\longrightarrow$ **ultraviolet completions of QFTs**

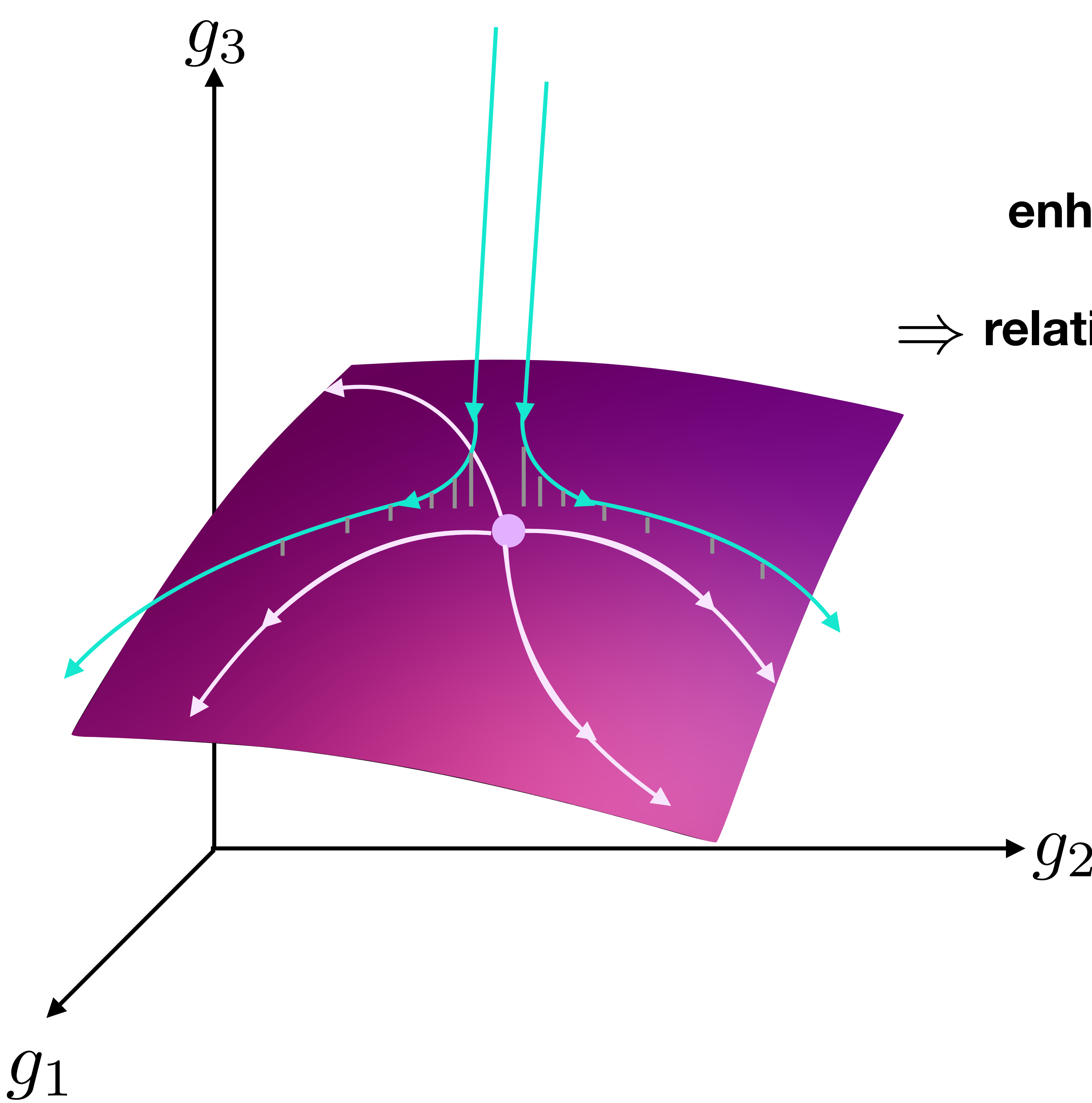
* examples of quantum scale symmetry across various dimensionalities:

- 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

Theory space: infinite-dimensional space of couplings



Predictivity:

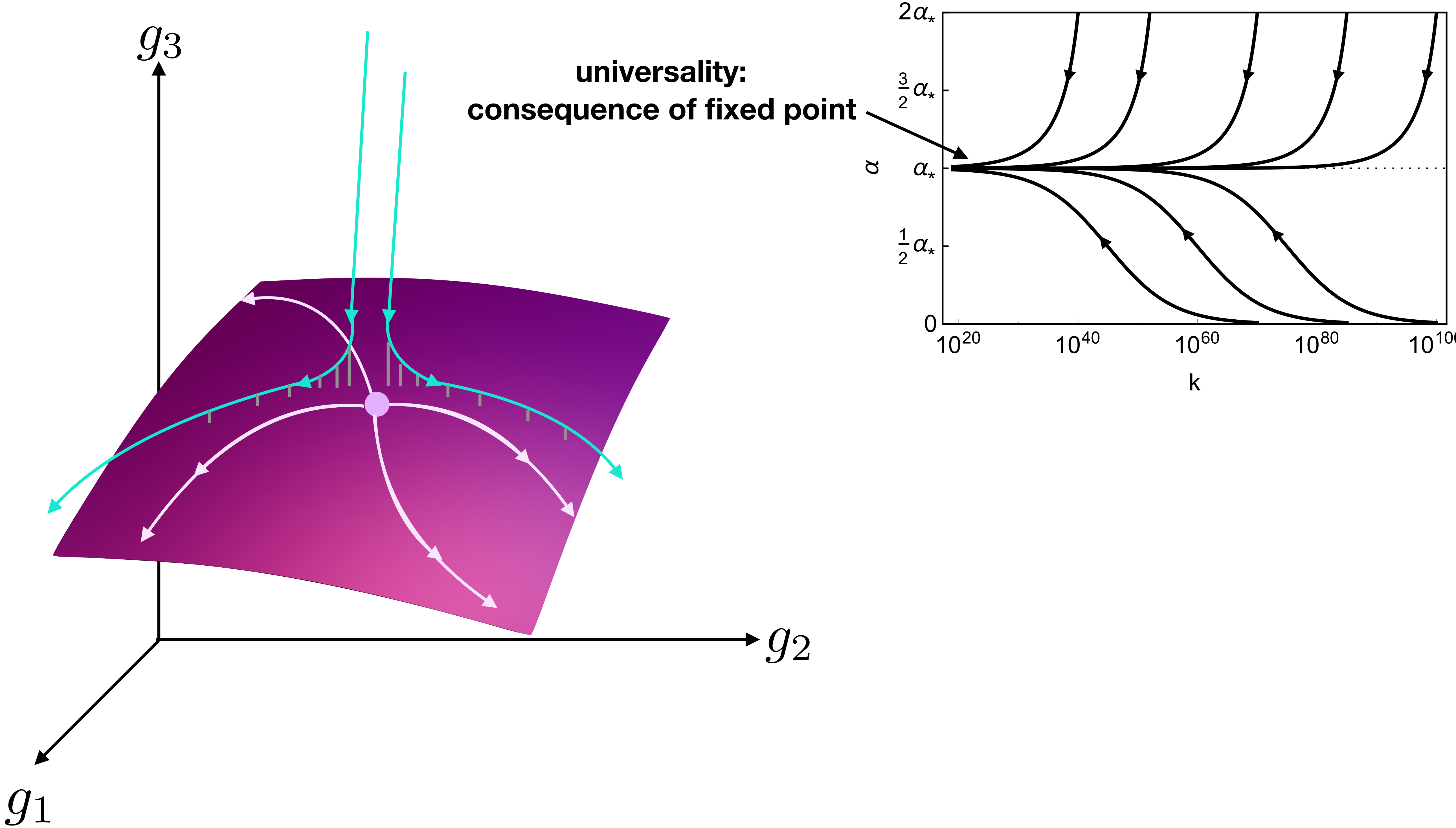
enhanced symmetry in UV

$\Rightarrow$ **relations between couplings**

Scale symmetry in a QFT

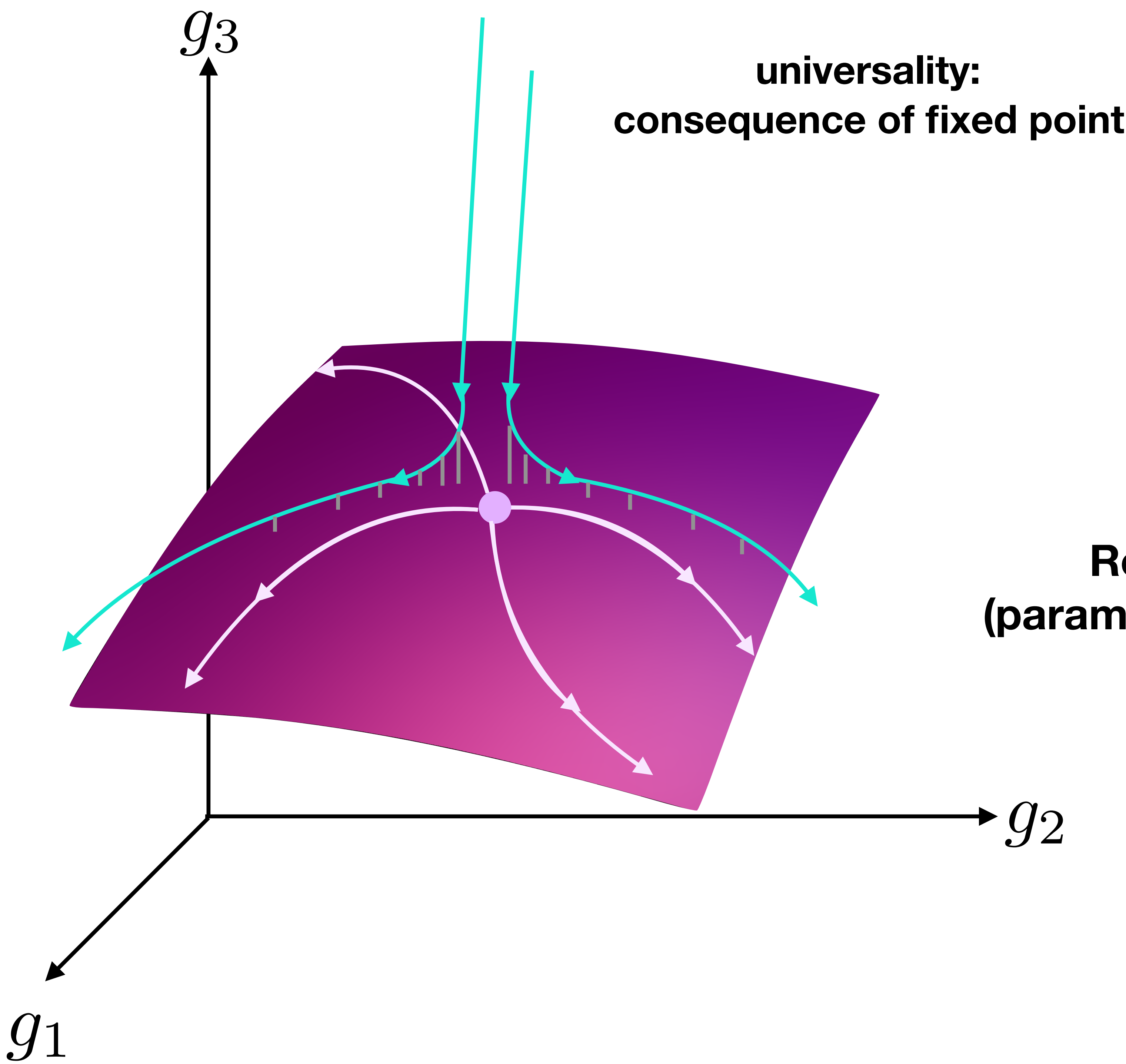
Theory space: infinite-dimensional space of couplings

Irrelevant directions:
Predictions from asymptotic safety



Scale symmetry in a QFT

Theory space: infinite-dimensional space of couplings



Irrelevant directions:
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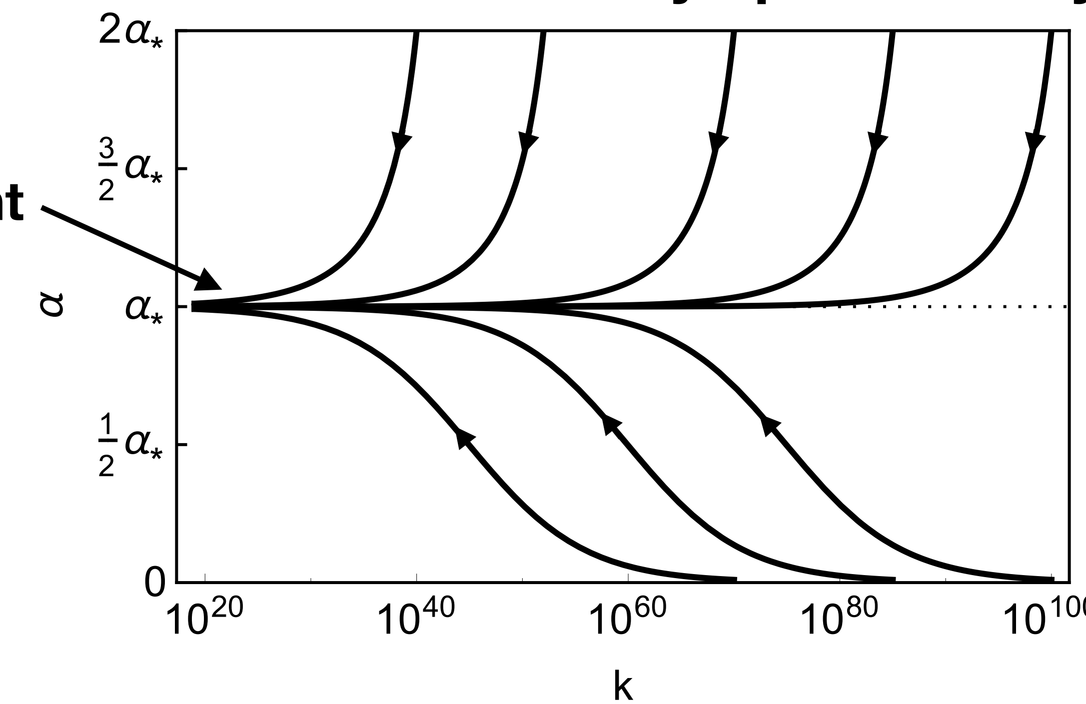
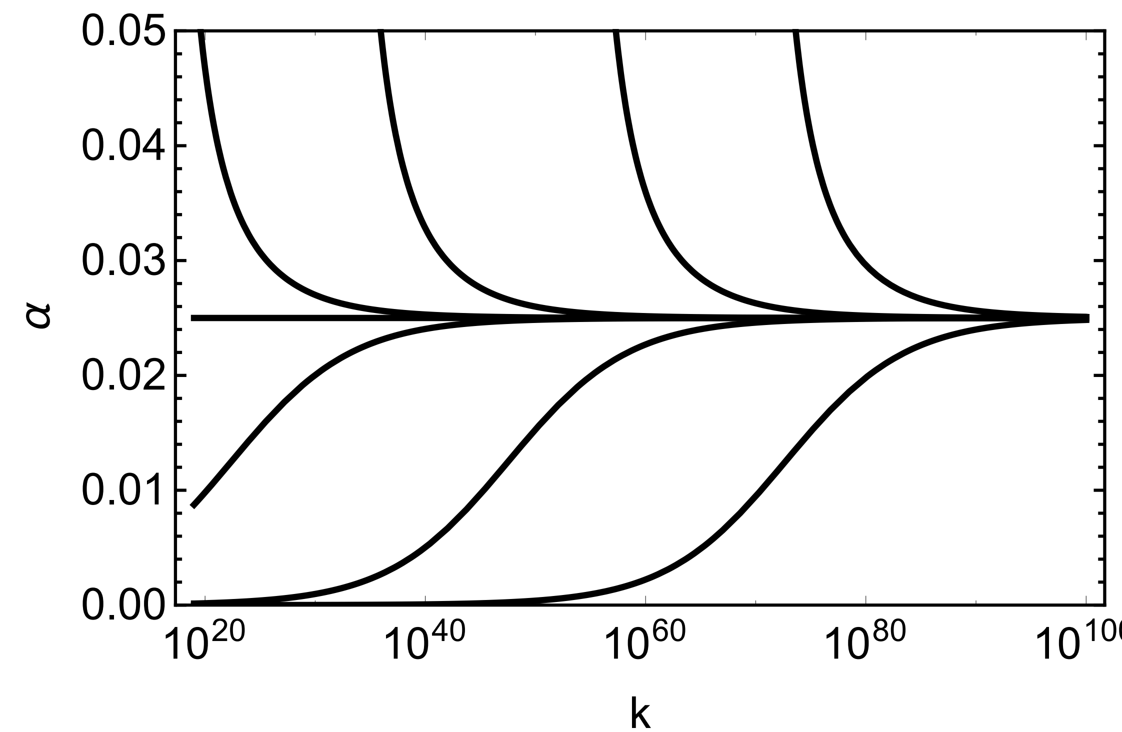
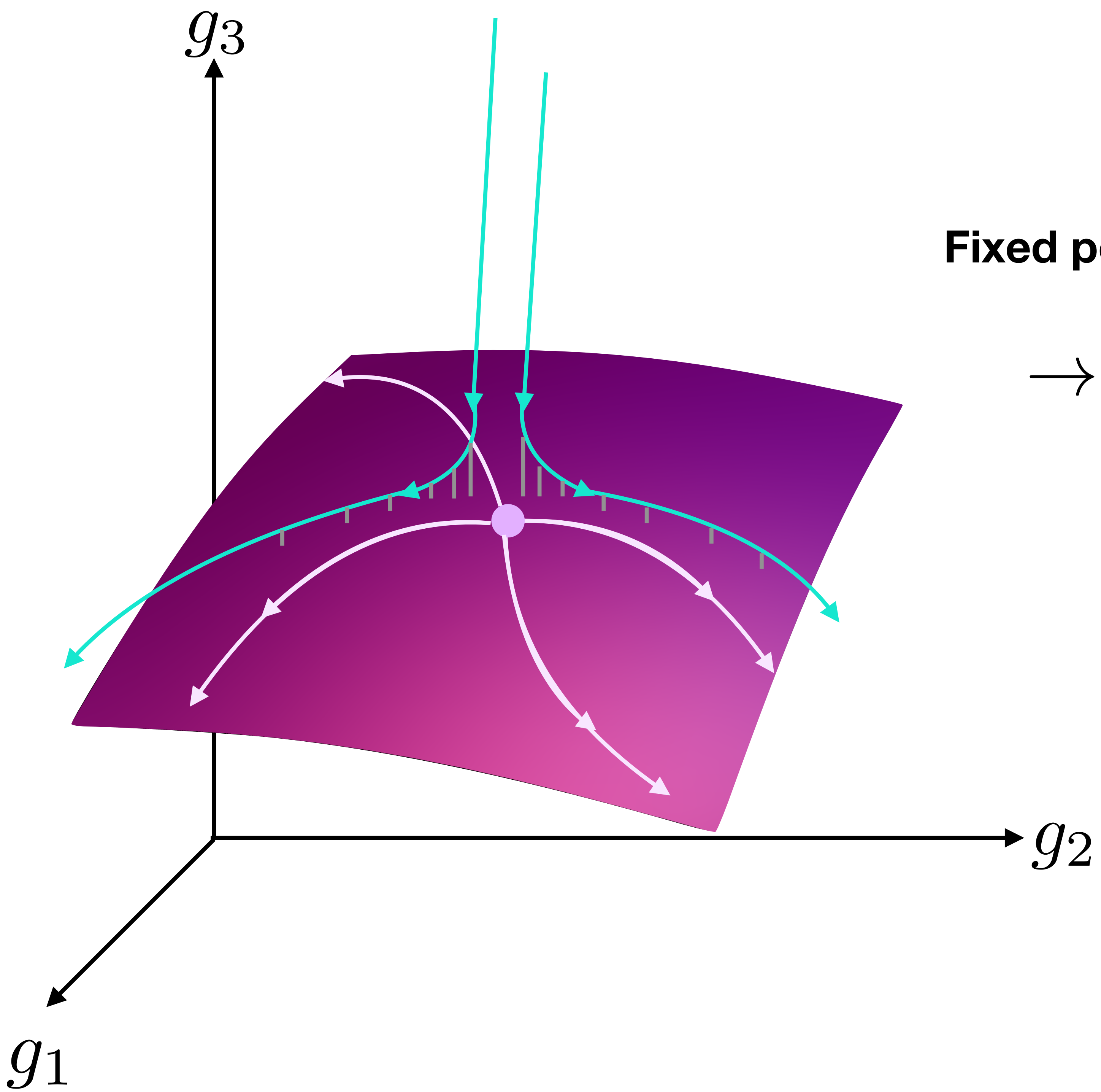


Relevant directions: Free parameters
(parameterize deviations from scale invariance)



Scale symmetry in a QFT

Theory space: infinite-dimensional space of couplings



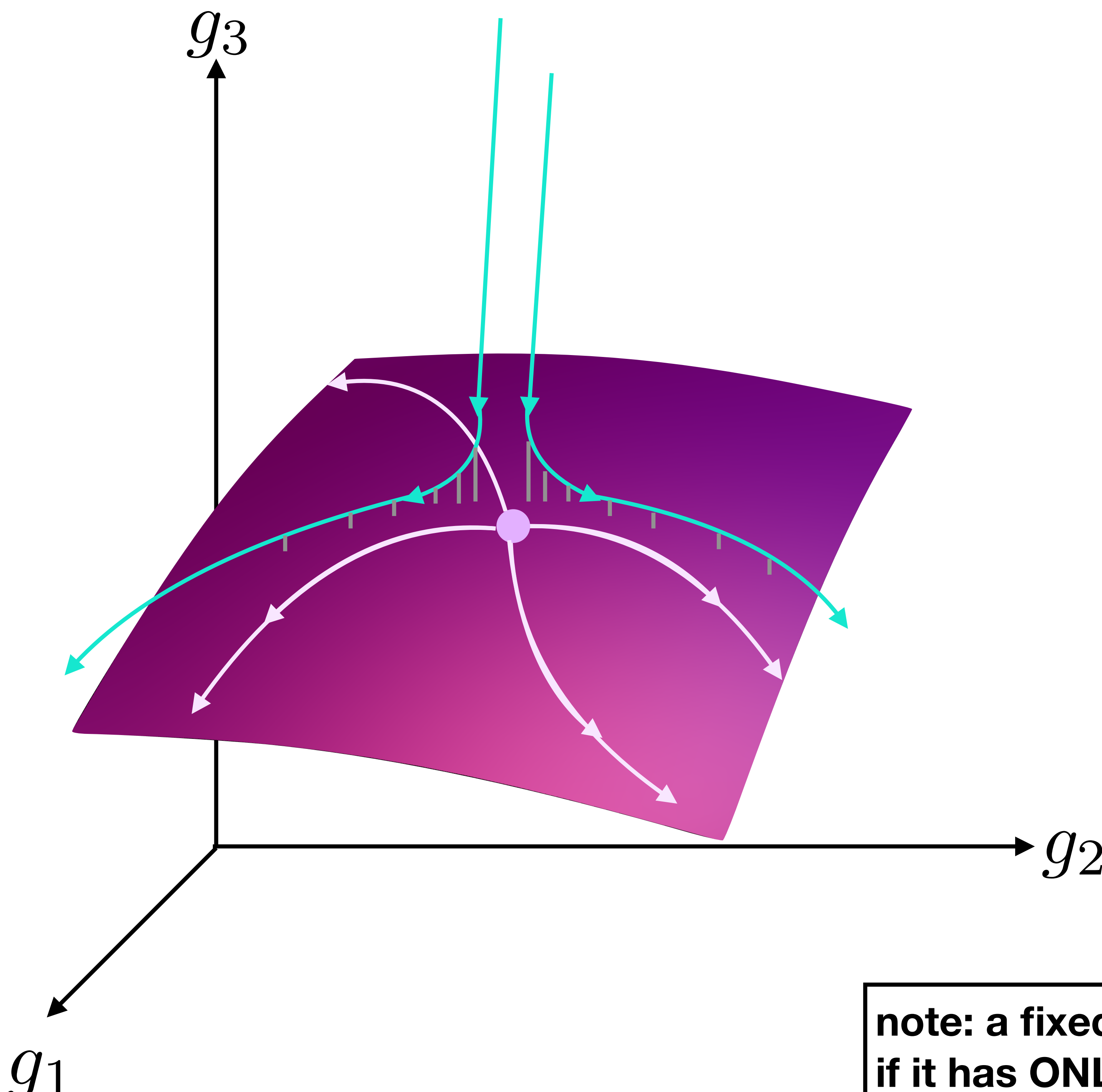
Fundamental asymptotic safety:

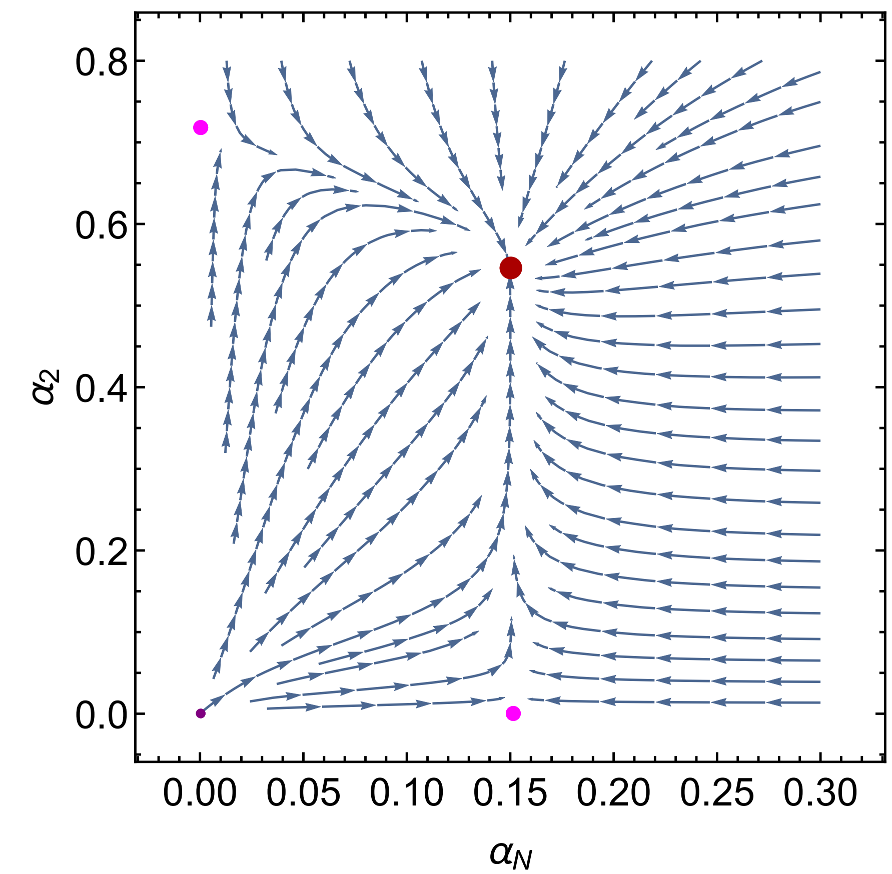
Fixed point with finitely many relevant directions

$\rightarrow$ **Ultraviolet completion**
(non-perturbative) renormalizability

Scale symmetry in a QFT

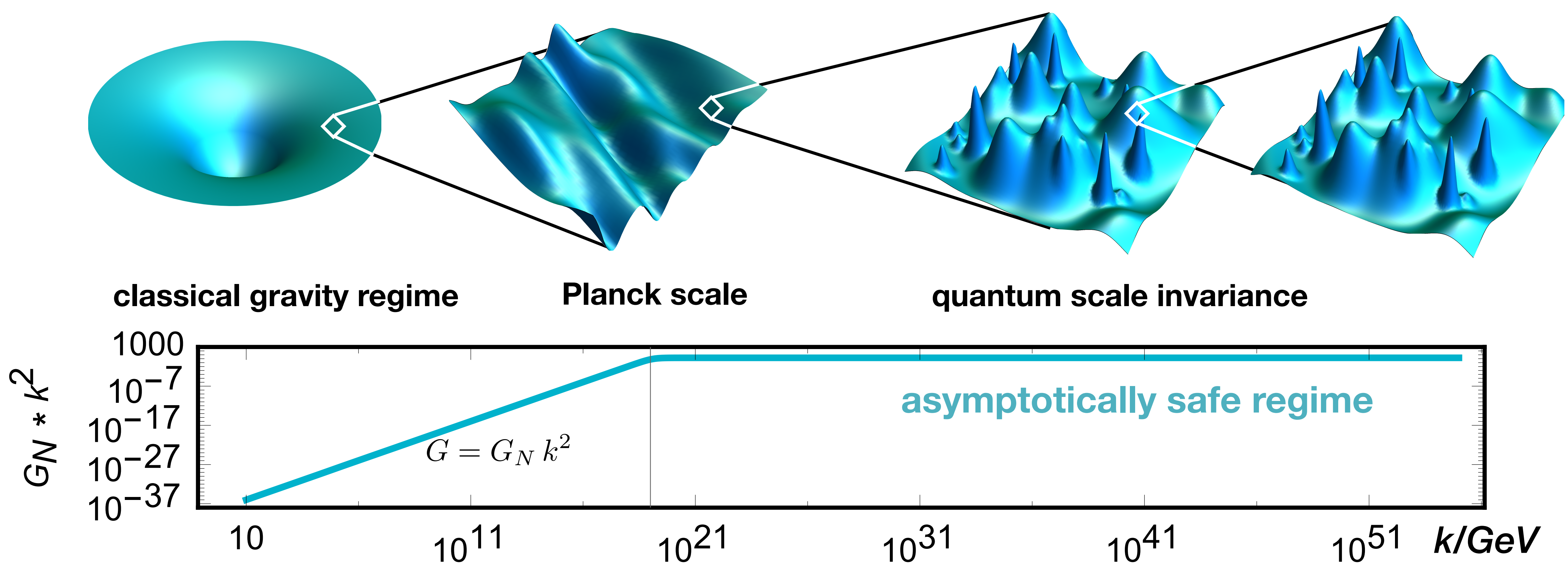
Theory space: infinite-dimensional space of couplings





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?



(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

CDT: [Ambjorn, Jurkiewicz, Loll…]
DT: [Coumbe, Laiho, Unmuth-Yockey, Caterall]

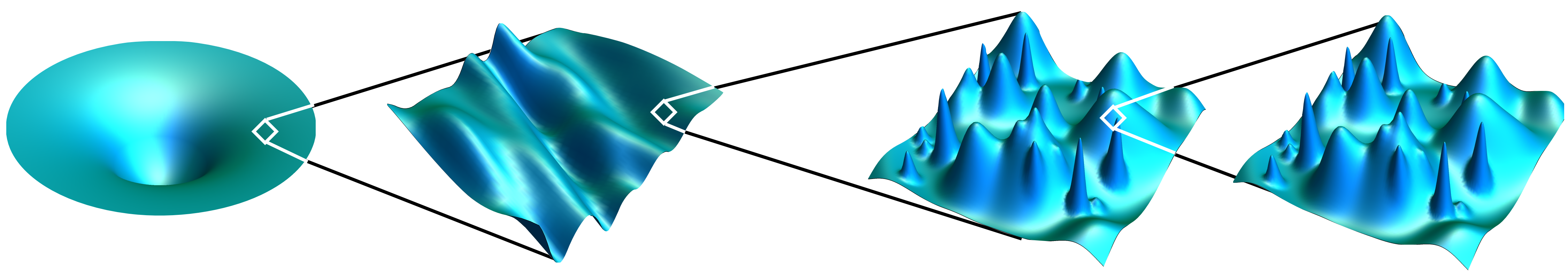
scale invariance: universal continuum limit exists

- **continuum approach**

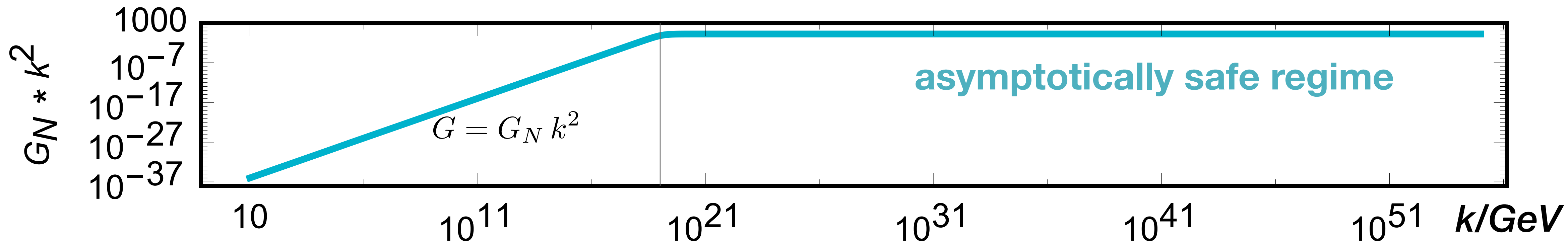
Functional Renormalization Group

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

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



classical gravity regime **Planck scale** **quantum scale invariance**



(similarly for all other couplings)

Asymptotic safety in gravity?

- ε-expansion d=2 + ε
- “lattice” approach
- continuum approach

38

(C)DTs

Functional Renormalization Group

[Reuter ’96]
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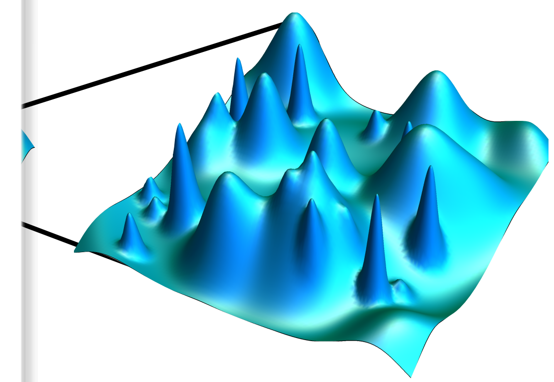


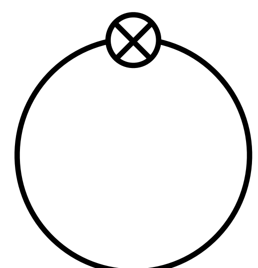
riance

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”

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



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

[Wetterich ’93]

in practise:
truncate to (finite) subset of operators

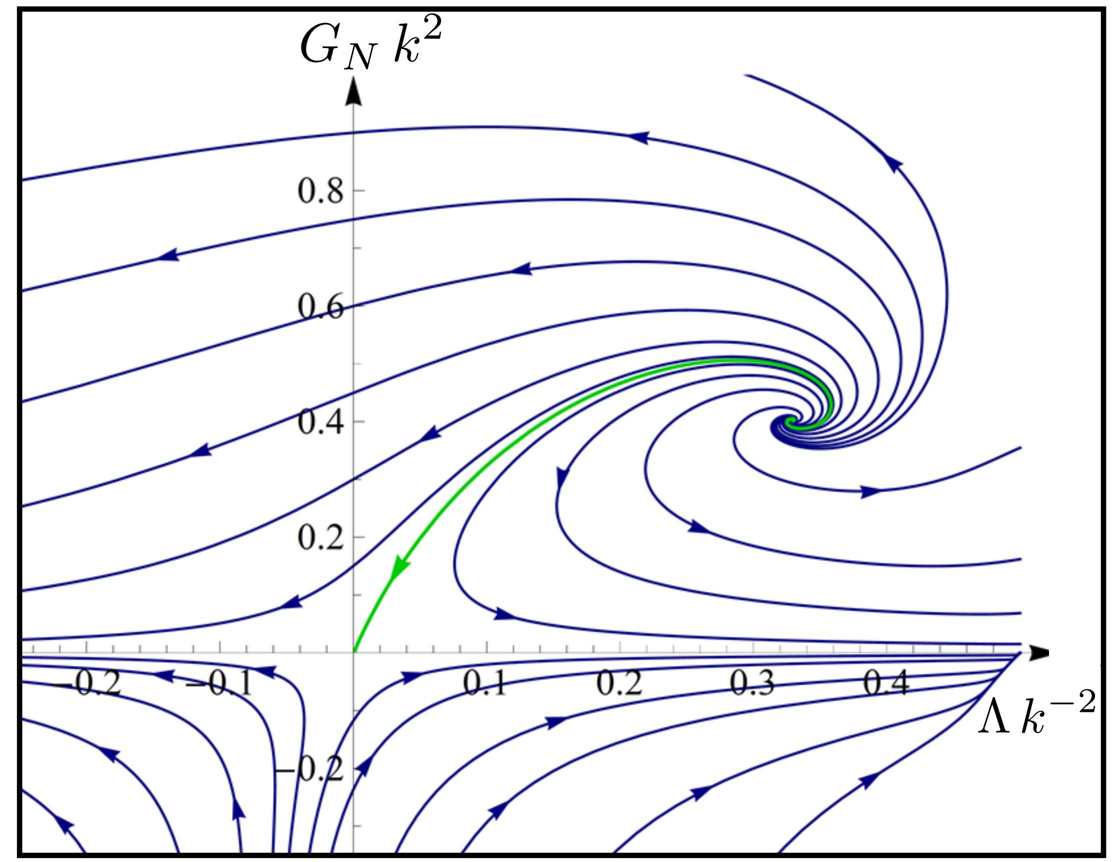
gravity: candidate guiding principle: near-perturbativity

[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]

Indications for (Euclidean) gravitational fixed point

based on truncated Functional Renormalization Group studies, pioneered by M. Reuter ('96):

fixed point	operators	corresponding couplings:
✔	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Litim '03; 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]
. . .	. . .	[Falls, Litim, Nikolakopoulos, Rahmede '13 '14]
✔	$\sqrt{g}R^{34}$	
. . .	. . .	[Falls, Litim, Schröder '18]
✔	$\sqrt{g}R^{70}$	
✔	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[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;
figure: Nink]

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based on truncated Functional Renormalization Group studies, pioneered by M. Reuter ('96):

fixed point	operators	corresponding couplings:	free parameter (relevant)	prediction (irrelevant)	canonically
✓	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Litim '03; 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
. . .	. . .			. . .	⋮
		[Falls, Litim, Nikolakopoulos, Rahmede '13 '14]			
✓	$\sqrt{g}R^{34}$				
. . .	. . .	[Falls, Litim, Schröder '18]		x	irrelevant
✓	$\sqrt{g}R^{70}$				
✓	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[Gies, Knorr, Lippoldt, Saueressig '16]		x	irrelevant

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

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✓	$\sqrt{g}R^2,\ \sqrt{g}R^{\mu\nu}R_{\mu\nu}$	[Benedetti, Machado, Saueressig '09; Christiansen '16 Denz, Pawlowski, Reichert '17]	x	x
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⋮	⋮			⋮
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⋮	⋮			x
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✓	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[Gies, Knorr, Lippoldt, Saueressig '16]		x

predicted…

… but testable?

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

Matter matters

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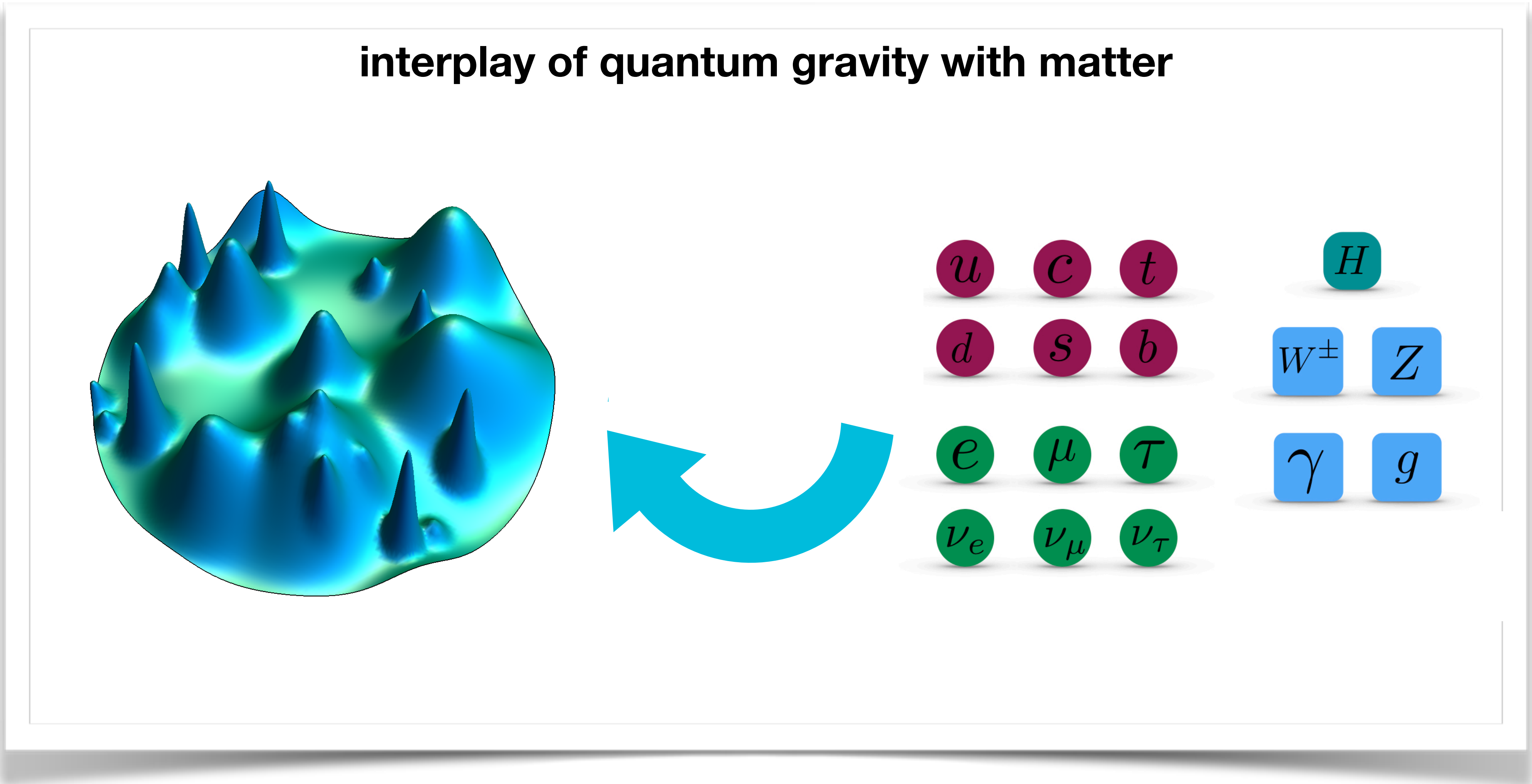
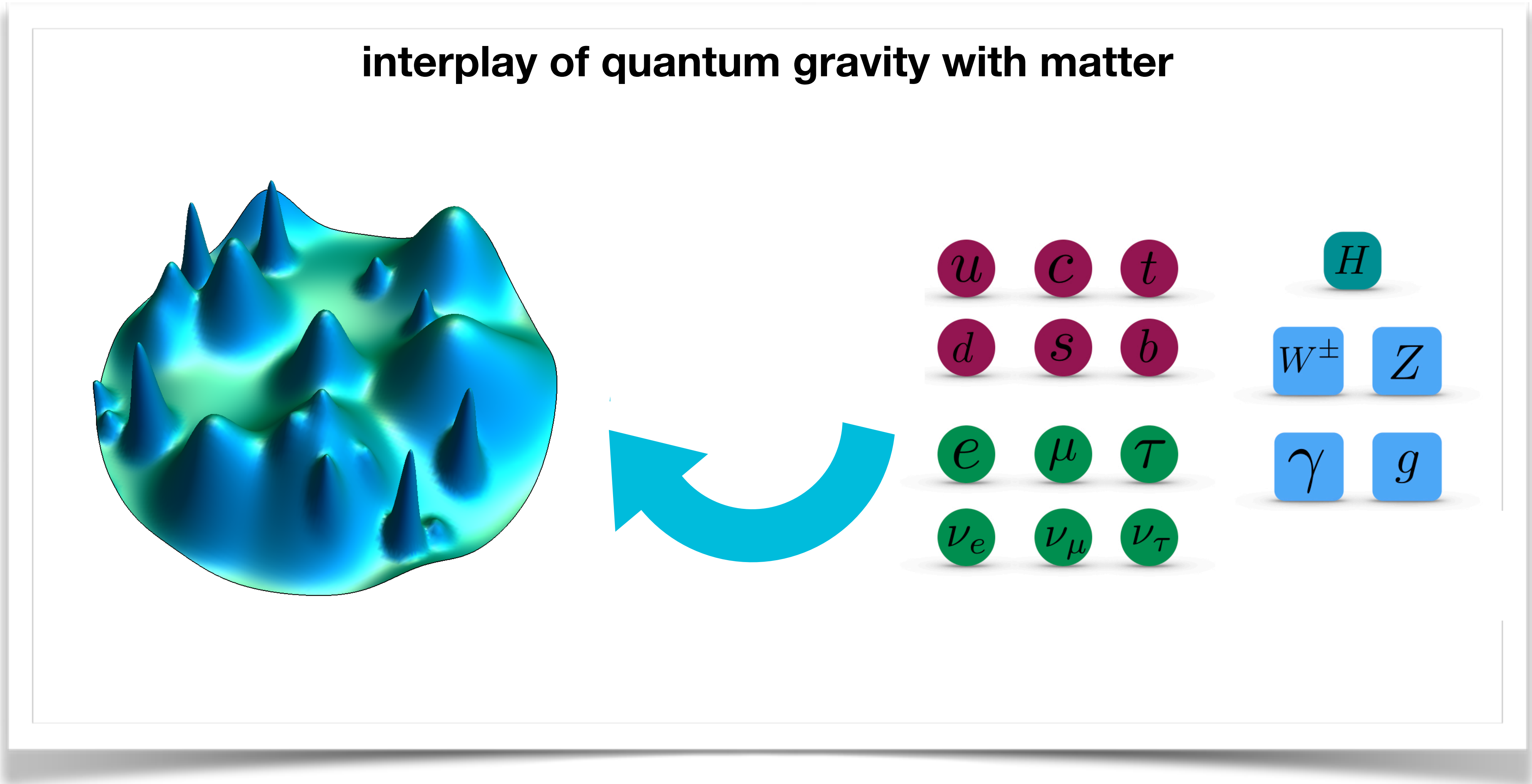


Matter matters



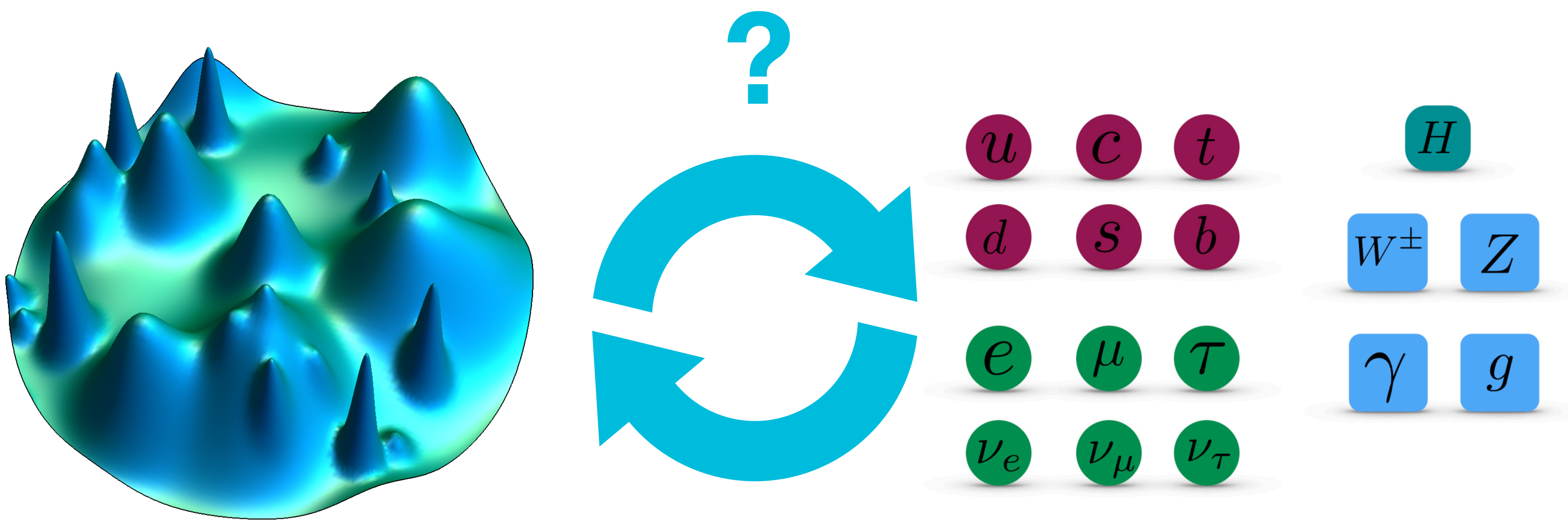
Indications in truncations that can add all Standard Model matter fields without destroying gravitational fixed point

[Dona, AE, Percacci '13;
Meibohm, Pawlowski, Reichert '15;
Dona, AE, Labus, Percacci '15; AE, Lippoldt '16;
Biemans, Platania, Saueressig '17;
Alkofer, Saueressig '18;
AE, Lippoldt, Pawlowski, Reichert, Schiffer '18;
AE, Lippoldt, Schiffer '18;
Yamada, Wetterich '19]

observational consistency test (✓)

Matter matters

interplay of quantum gravity with matter



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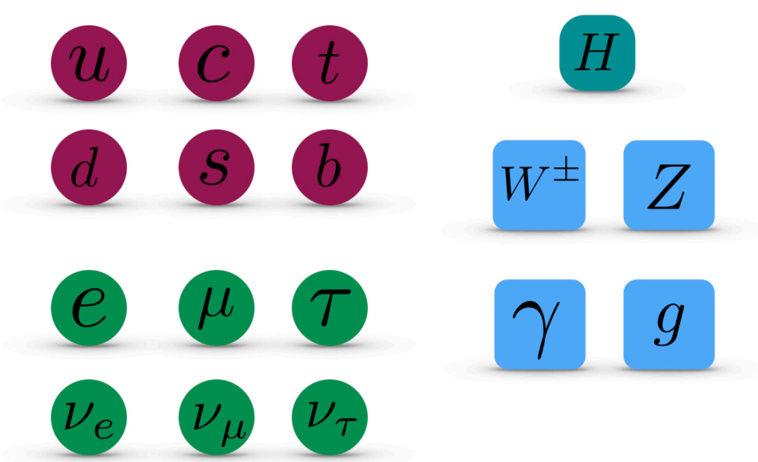
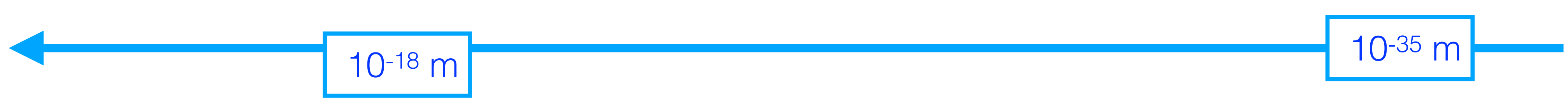
observational consistency test

Observational consistency tests of quantum gravity in particle physics

challenge:
huge gap in scales between
Planck scale & electroweak scale

Standard Model





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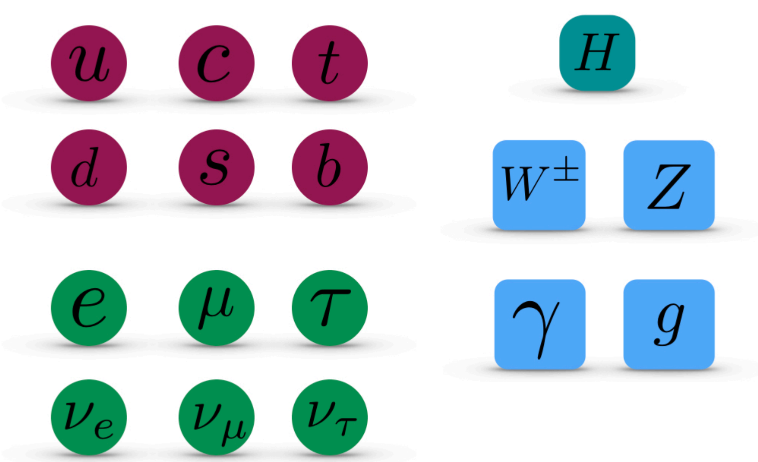
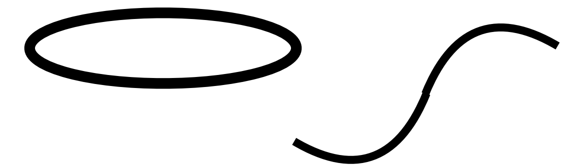
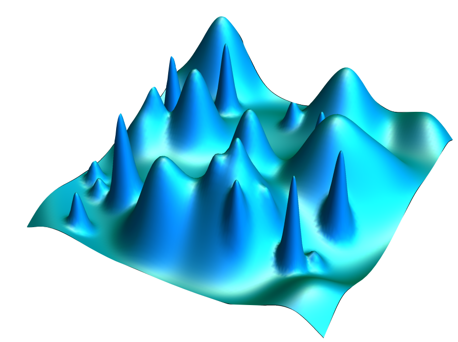


zooming out:
microscopic information gets lost



strings



asymptotic safety

not so different at large scales?

10^{-18} m

10^{-35} m

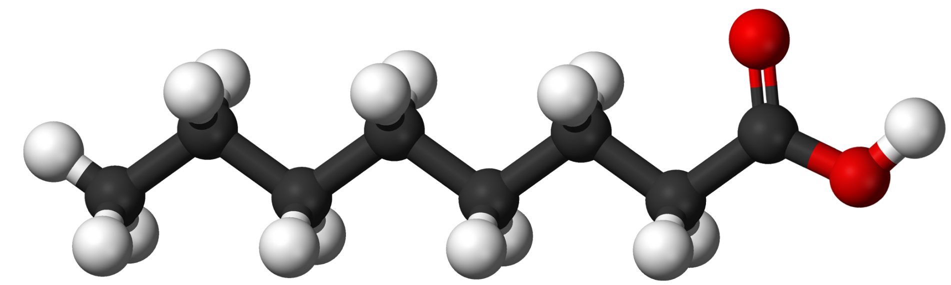
...

very different at small scales *

*** or are they?** [de Alwiss, AE, Held, Pawlowski, Schiffer, Versteegen ‘19]

Observational consistency tests of quantum gravity in particle physics

challenge:
huge gap in scales between
Planck scale & electroweak scale



zooming out:
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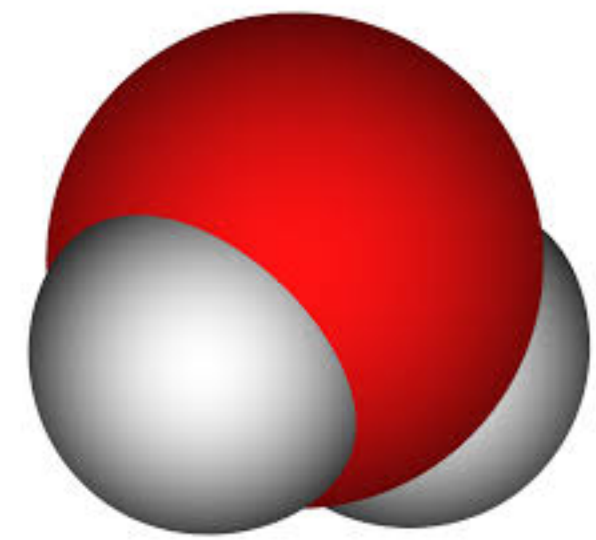

not so different at large scales?

...

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Observational consistency tests of quantum gravity in particle physics

challenge:
huge gap in scales between
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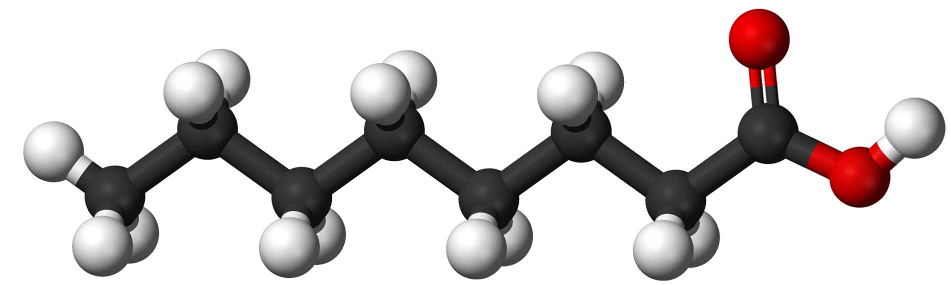
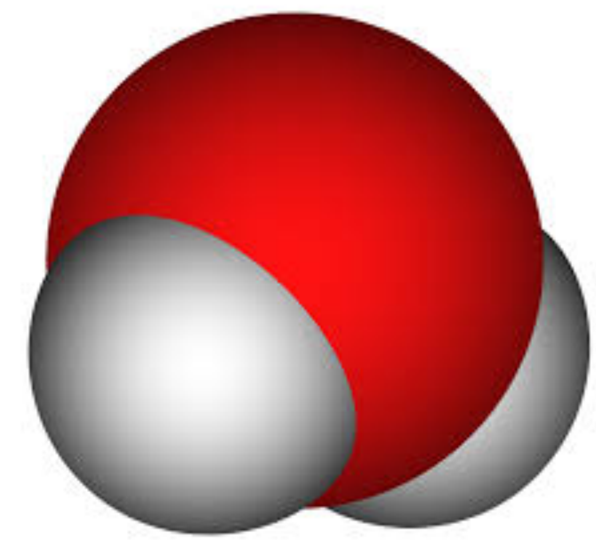


zooming out:
most microscopic information gets lost



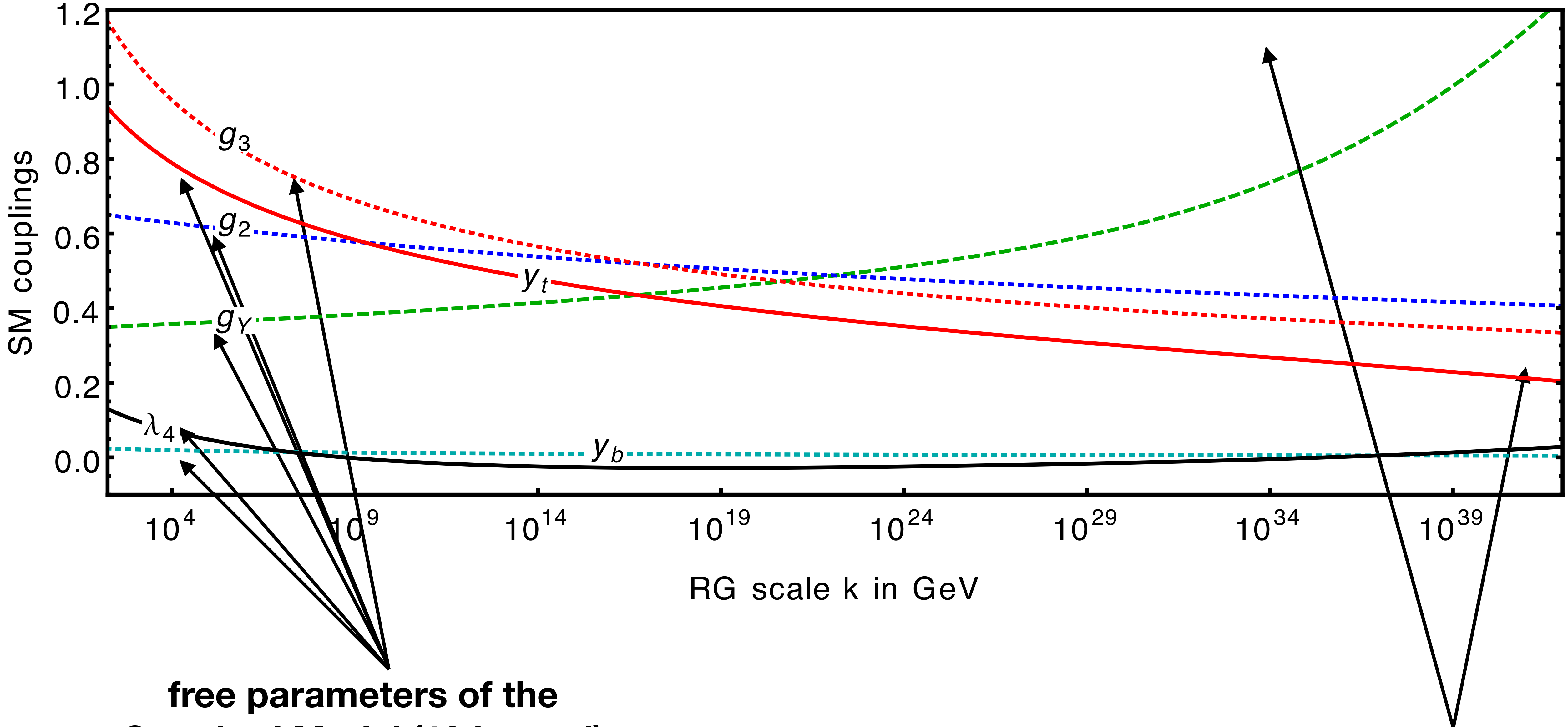
imprints of microscopic physics at macroscopic scales

example: viscosity

Microscopic scale symmetry could have consequences at macroscopic scales

Which parts of macrophysics are sensitive to the underlying gravitational microphysics?

Standard Model of particles

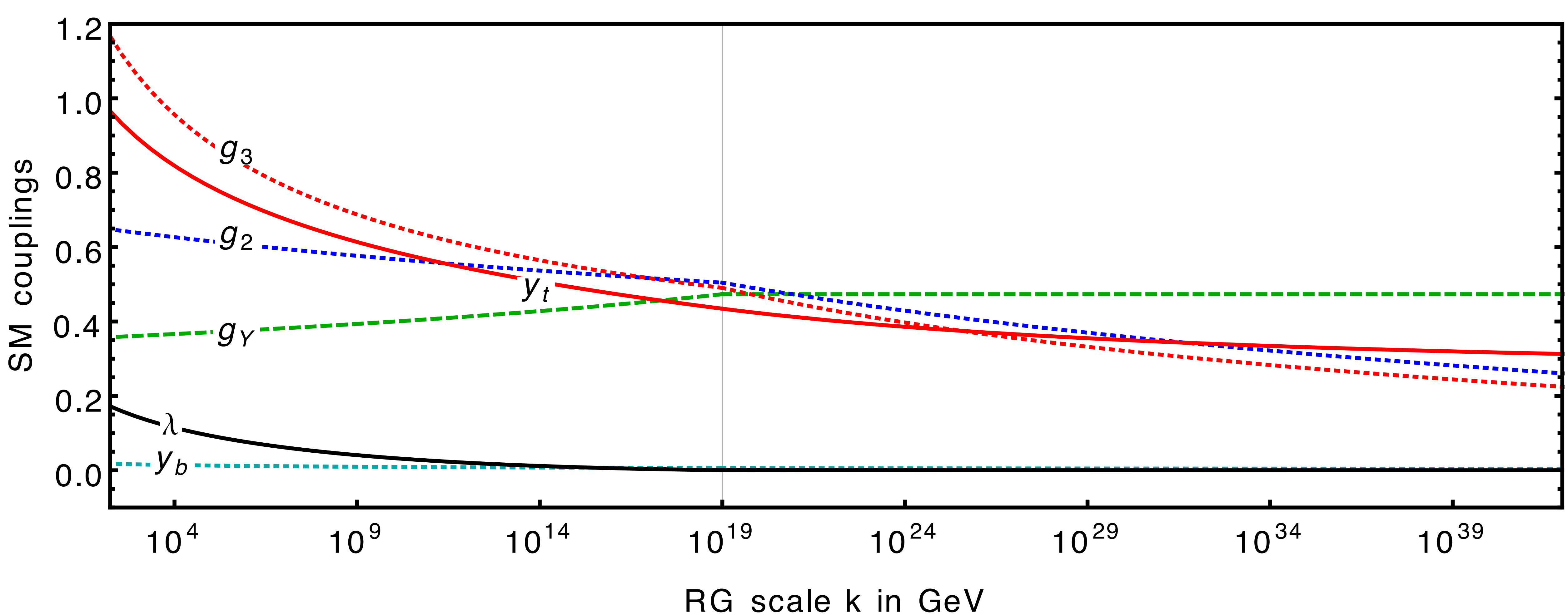


free parameters of the Standard Model (19 in total)

Landau poles = singularities

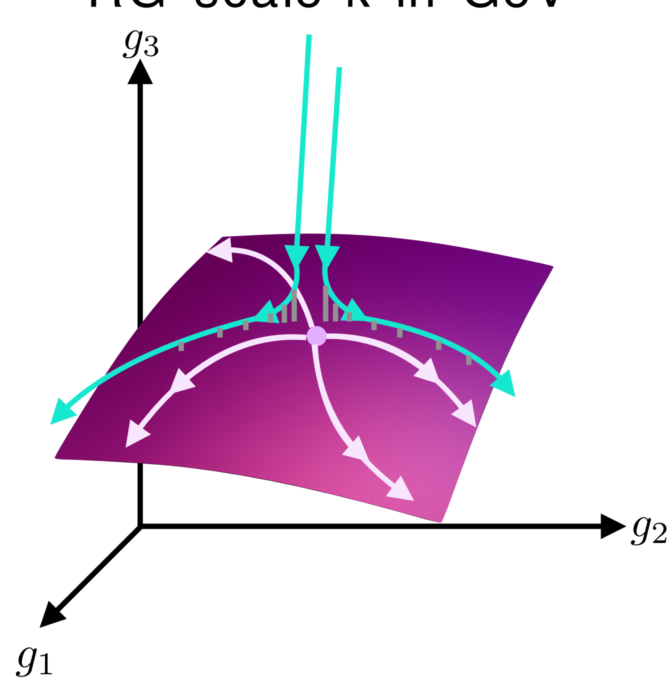
- **breakdown of SM**
- **need for “new physics”**

Asymptotically safe Standard Model of particles?



free parameters of the Standard Model (19 in total)

→ **scale symmetry: enhanced symmetry fixes free parameters?**

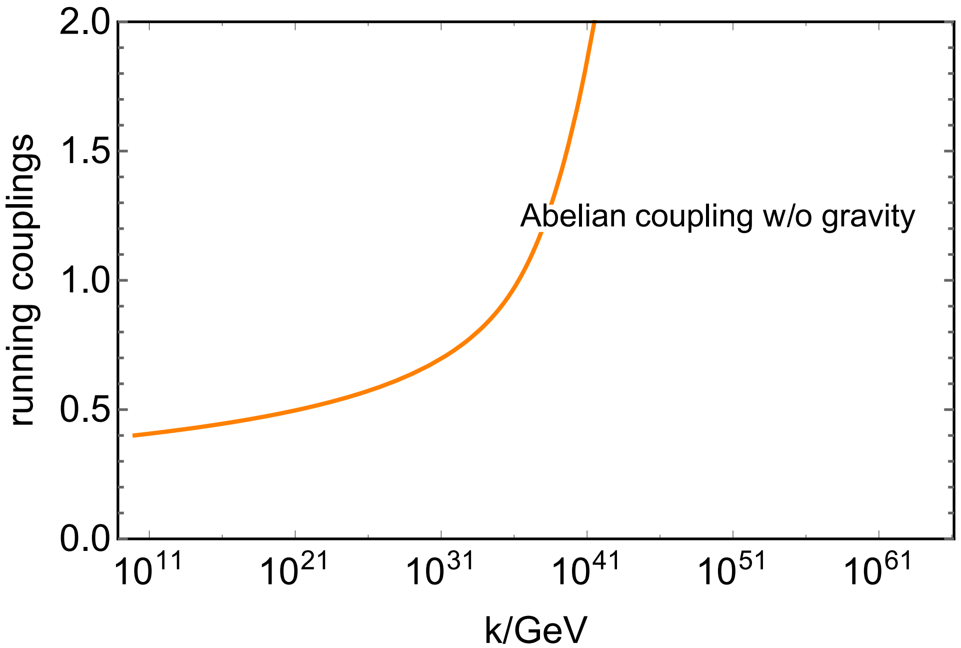


Landau poles = singularities

- **breakdown of SM**
- **need for "new physics"**

→ **beyond M_{Planck}: "just" gravity?**

Predictive power of asymptotic safety: Abelian gauge coupling

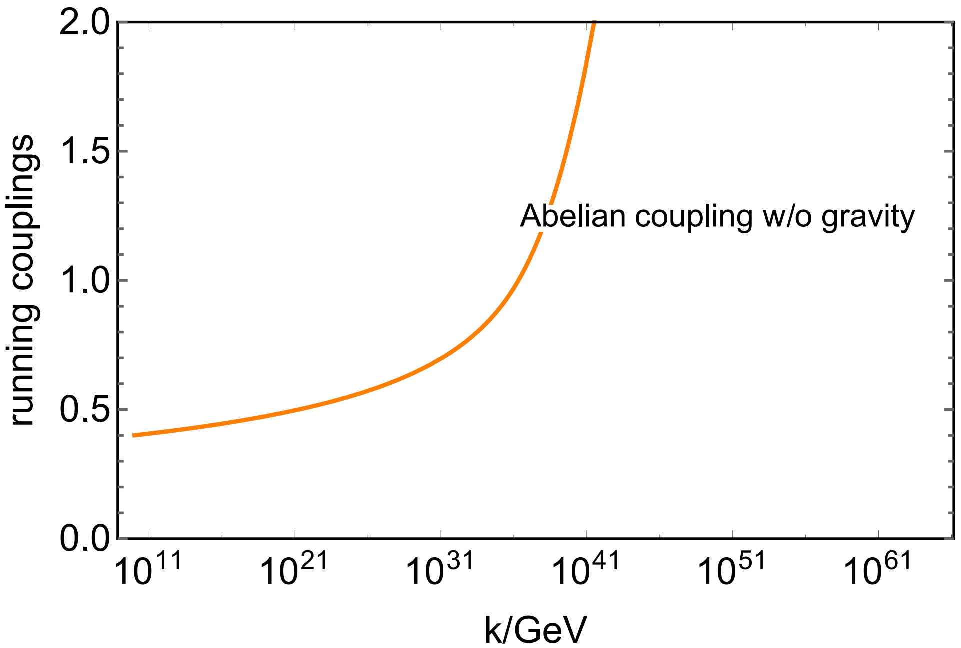


$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} + \ \dots$$

triviality problem

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

Predictive power of asymptotic safety: Abelian gauge coupling



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

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]

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

[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**

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

metric fluctuations

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

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

$f_g \rightarrow 0$ below M_{pl}

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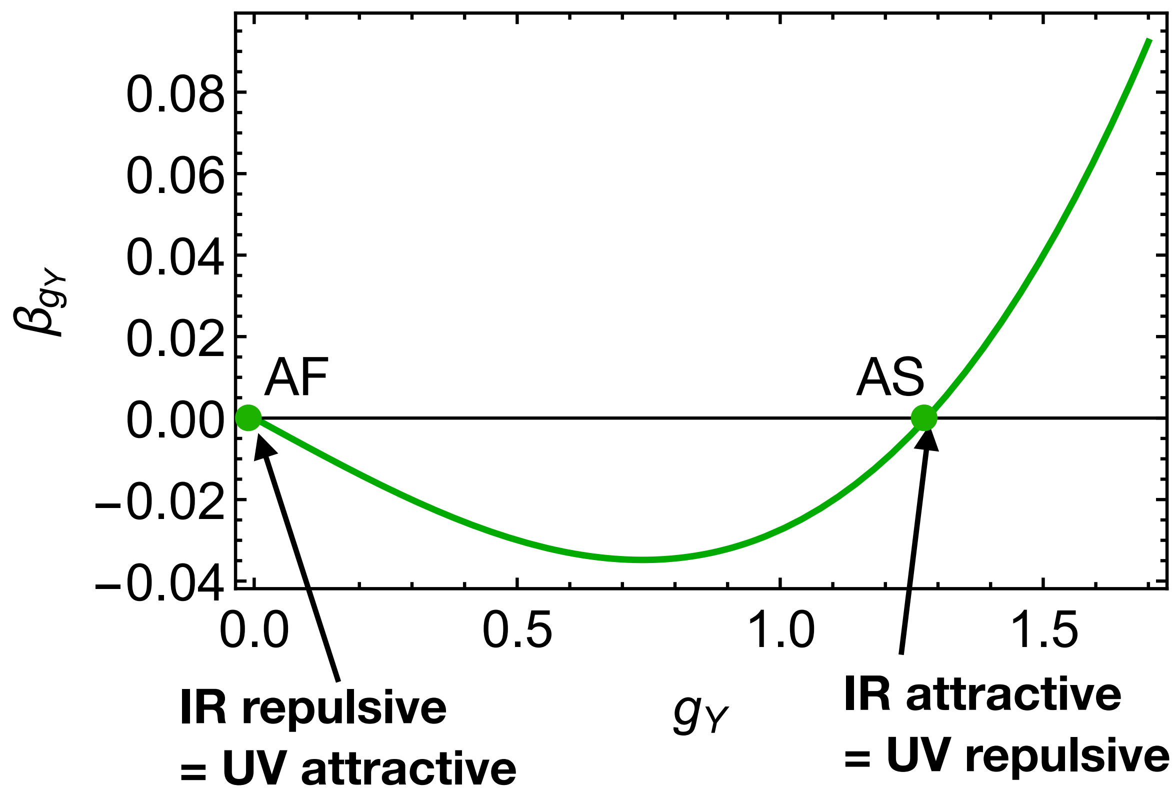

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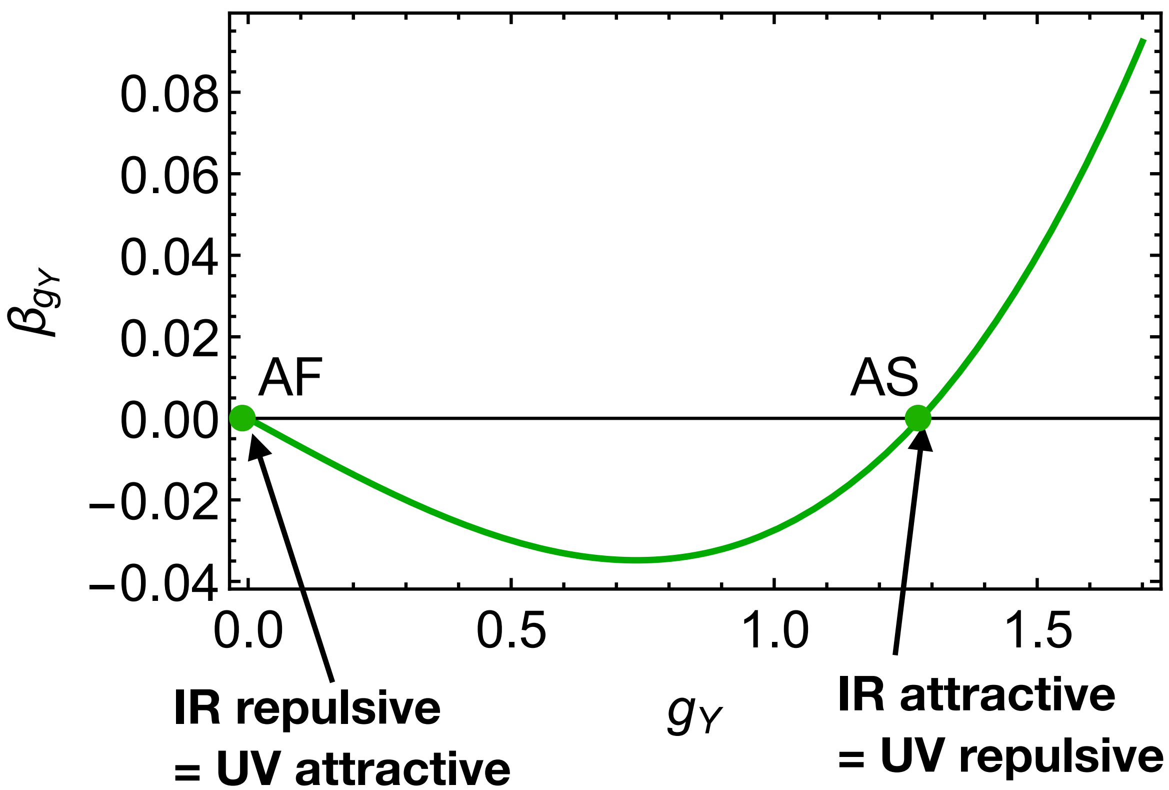

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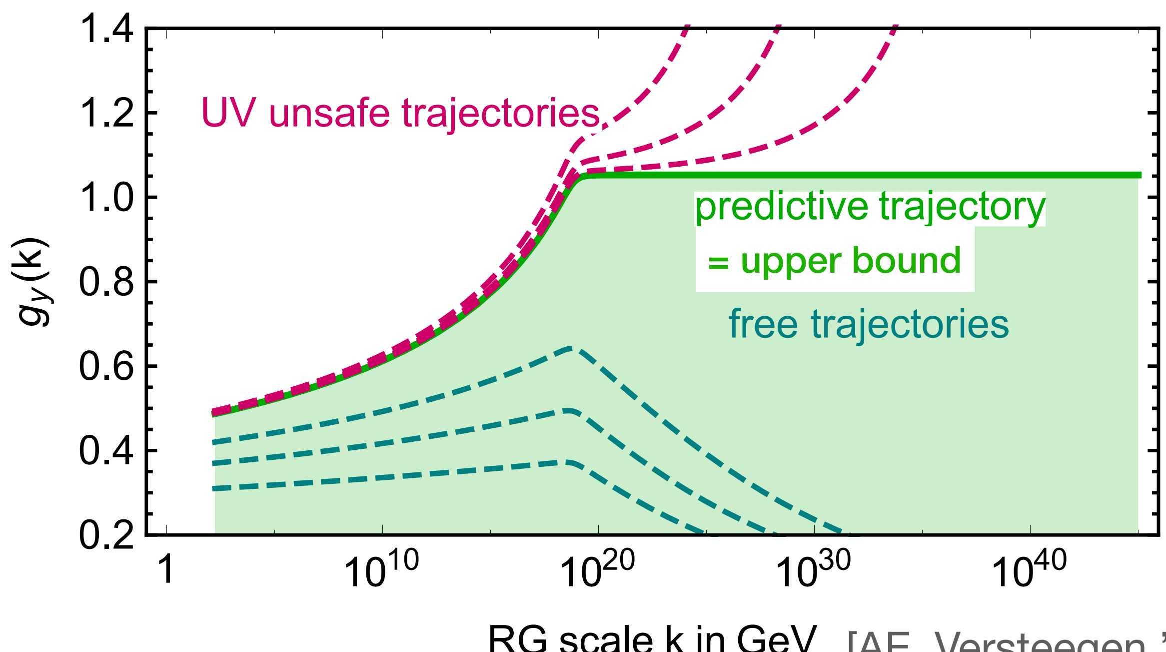
matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting



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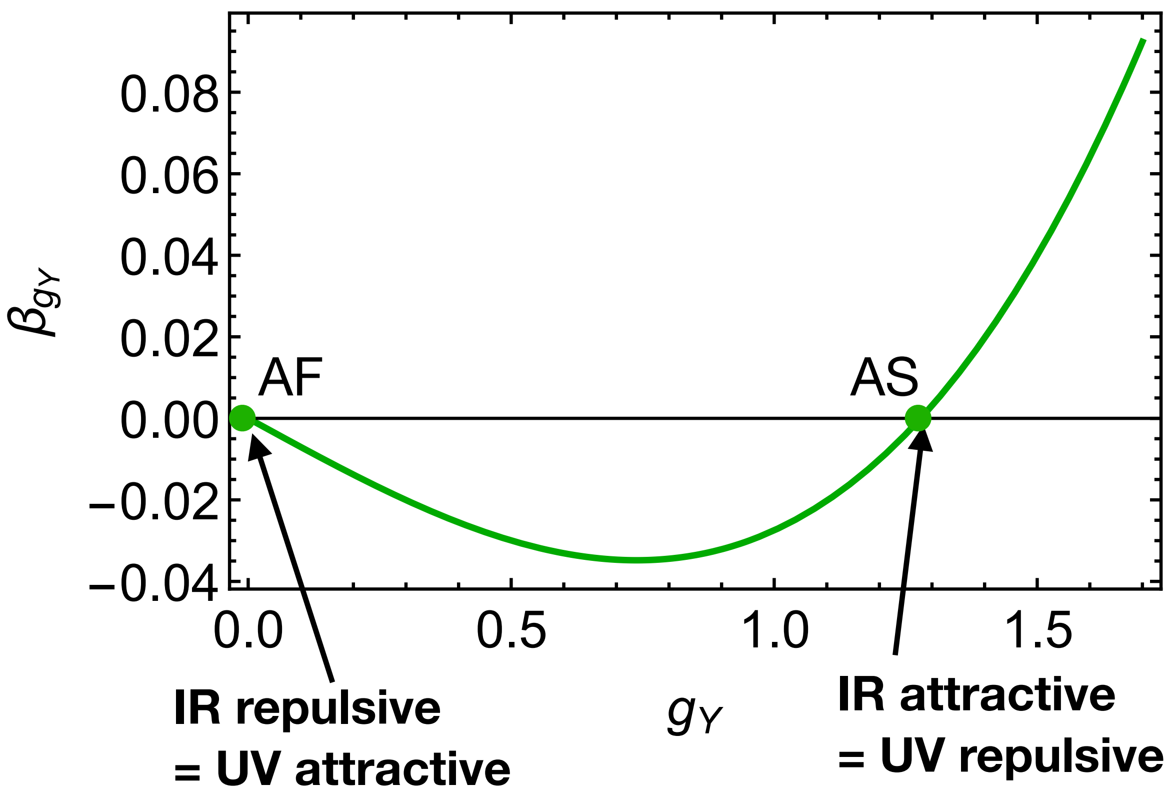

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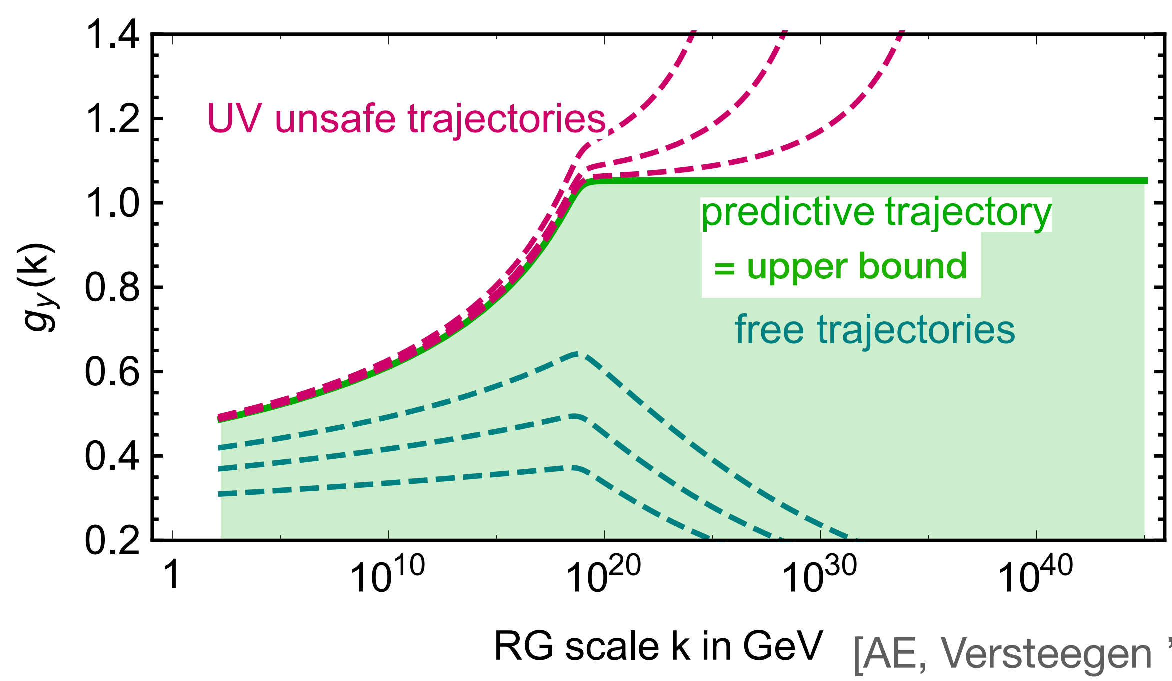
hint for:

- **gravity-induced UV completion**
- **enhanced predictive power: fixing free parameter of the EFT**



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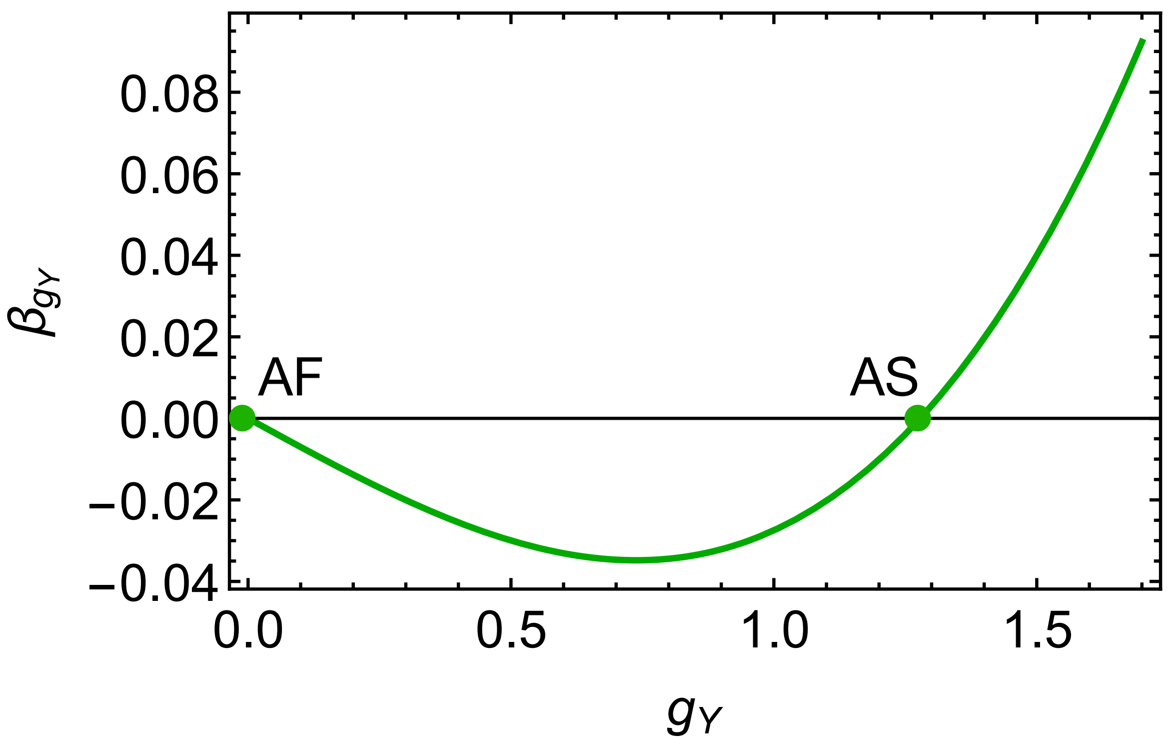

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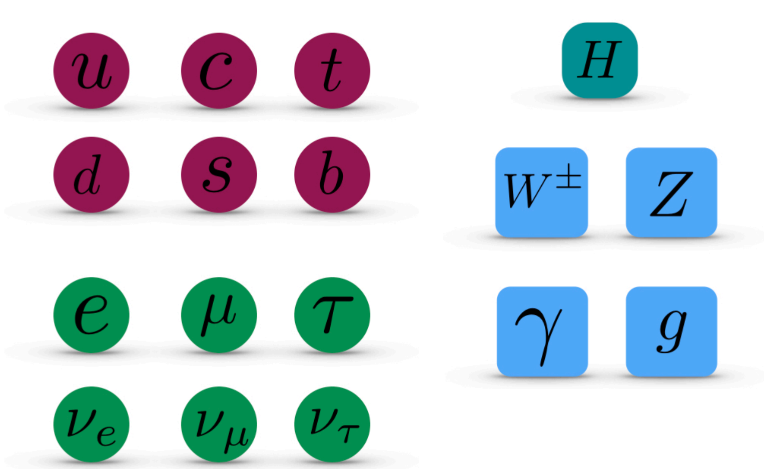
prediction $\Leftarrow$ **microscopic scale symmetry**

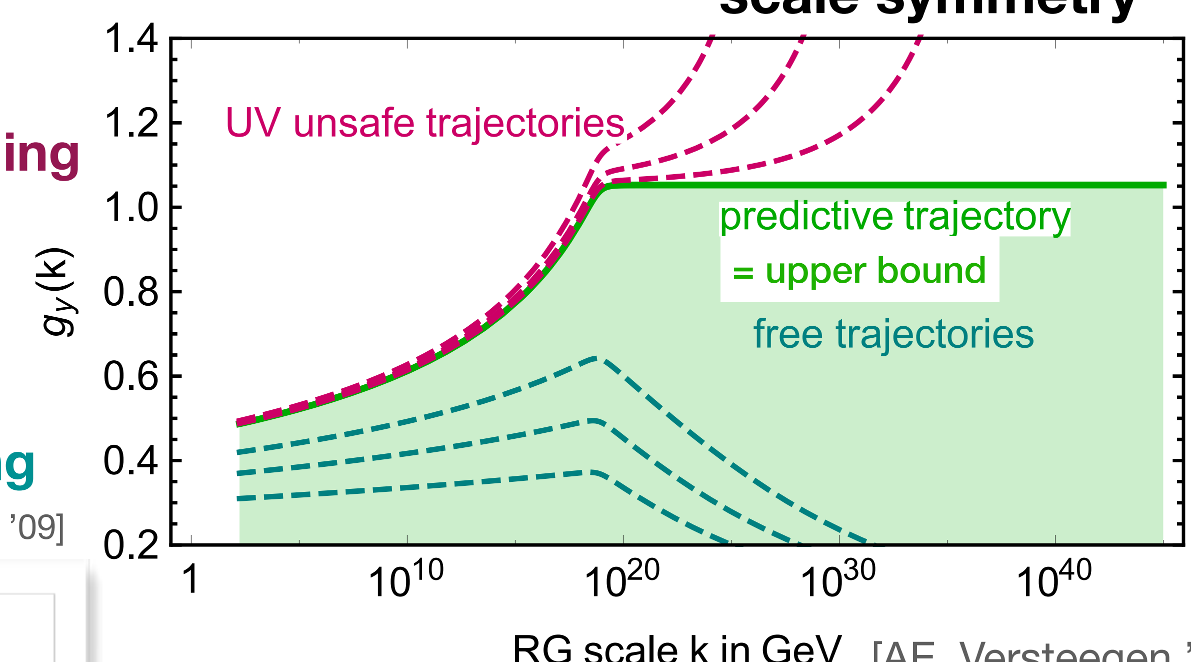
first hints for similar mechanism:



top-Yukawa coupling
[AE, Held '17]

top-bottom- U(1)
[AE, Held '18]

Higgs self-coupling
[Shaposhnikov, Wetterich '09]



[AE, Versteegen '17]

observational consistency tests
(currently subject to theoretical syst. uncertainties)

Predictive power of asymptotic safety: d=4

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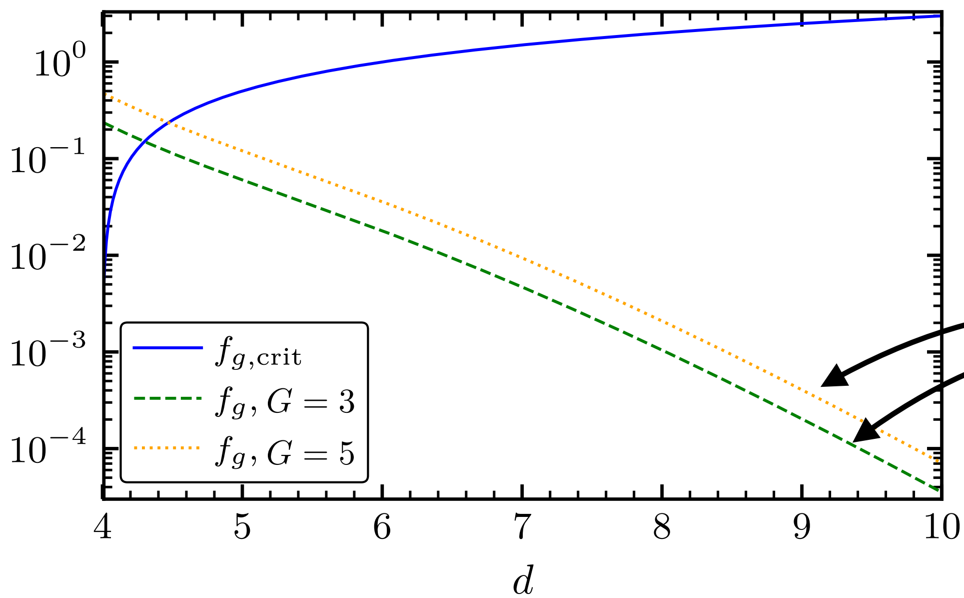

truncation of grav. dynamics to Einstein-Hilbert

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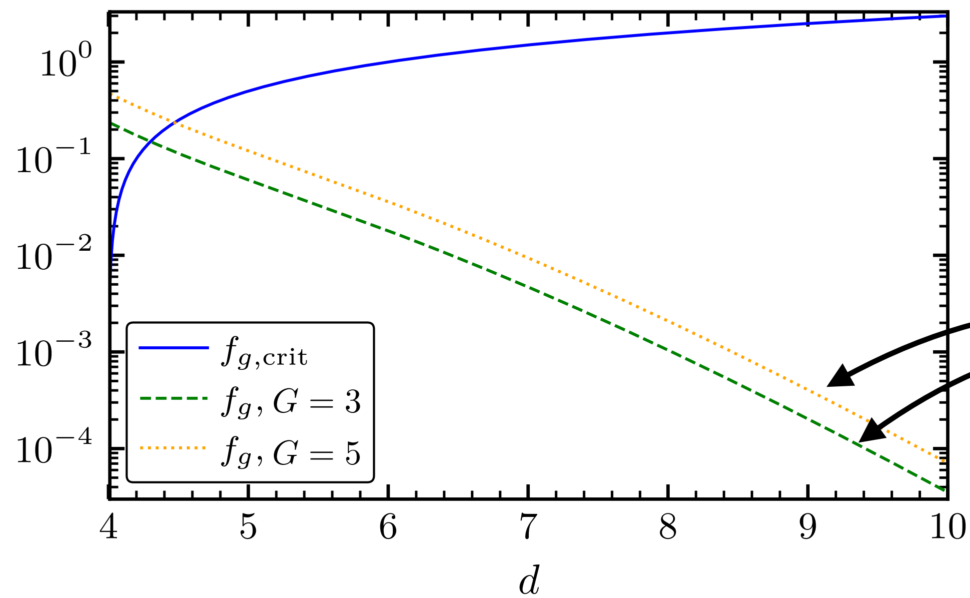

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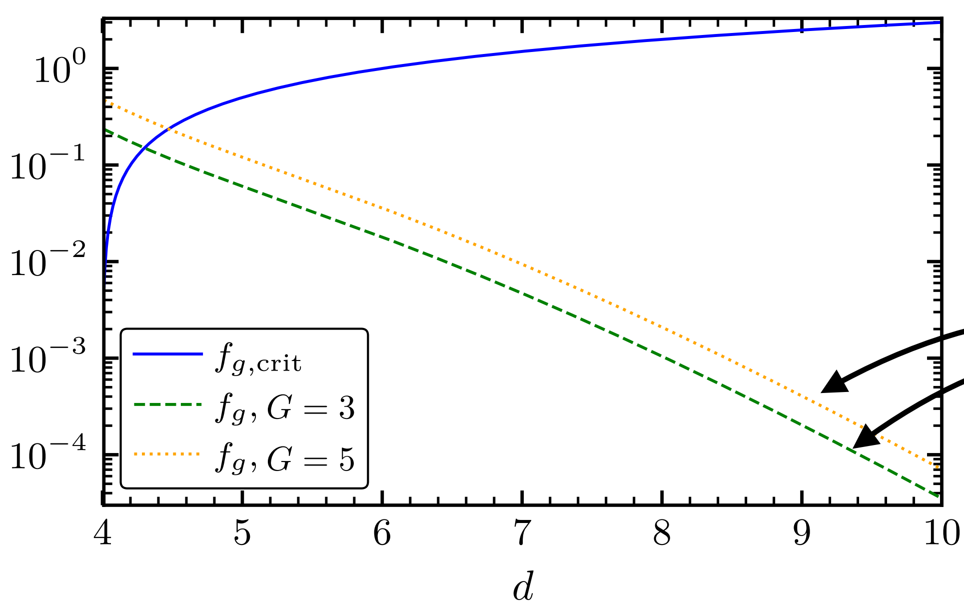


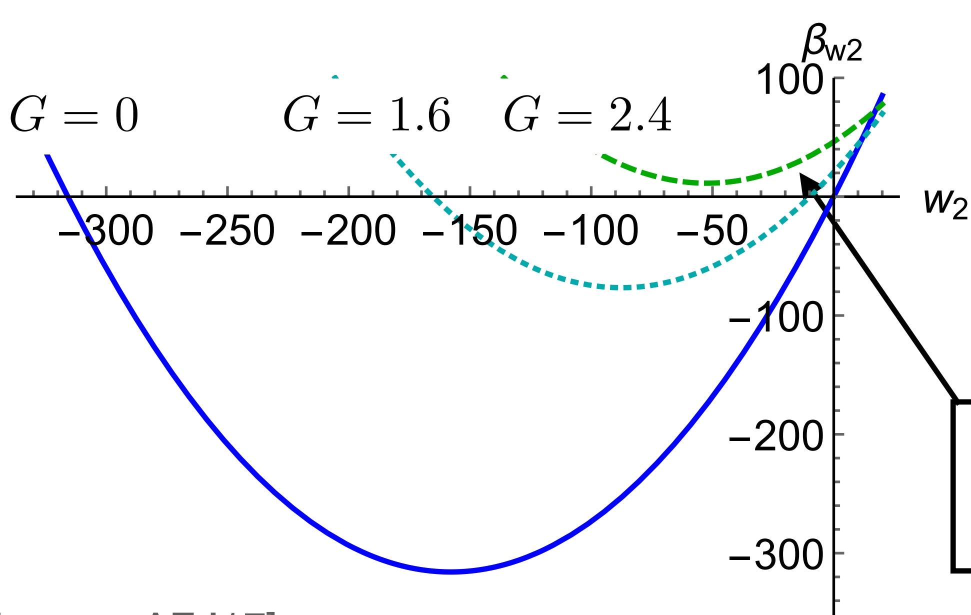
truncation of grav. dynamics to Einstein-Hilbert

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

but: weak-gravity bound:

large G triggers new divergences in higher-order matter self interactions, e.g., $w_2 \left(F^2\right)^2$

[AE, Held, Pawlowski '16; AE, Held '17]



no fixed point for h/o interactions in the presence of gravity @ large G

[Christiansen, AE '17]

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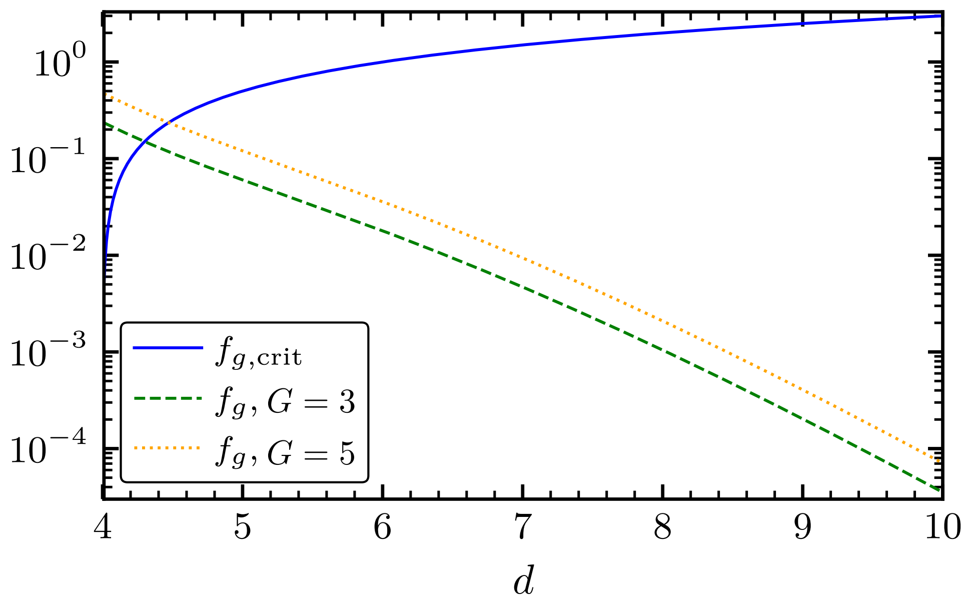

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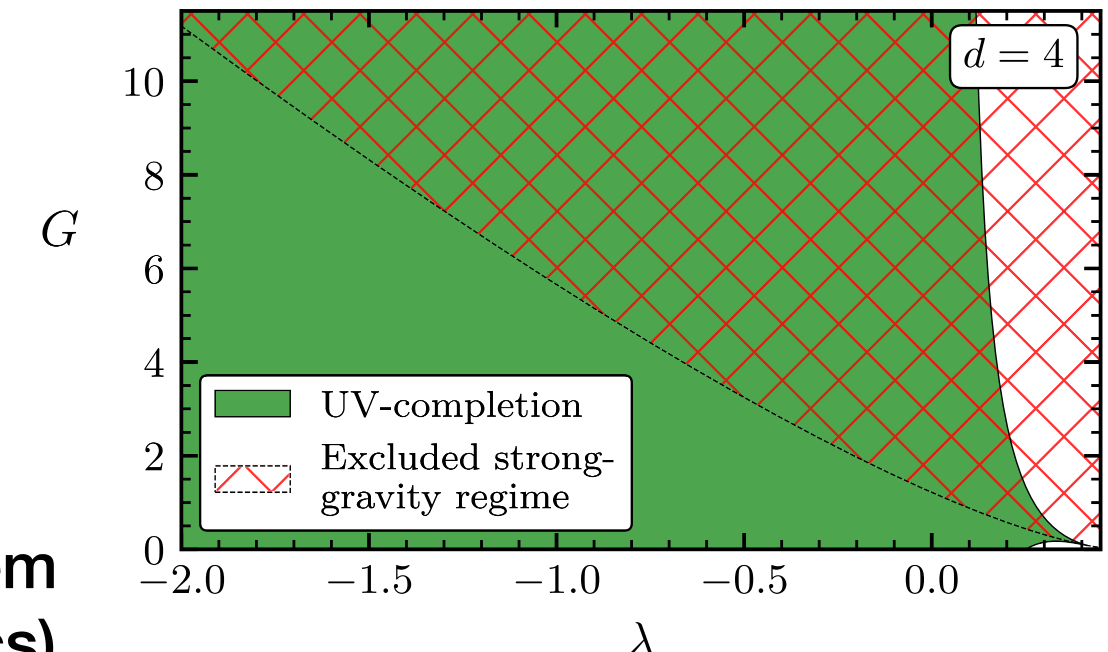

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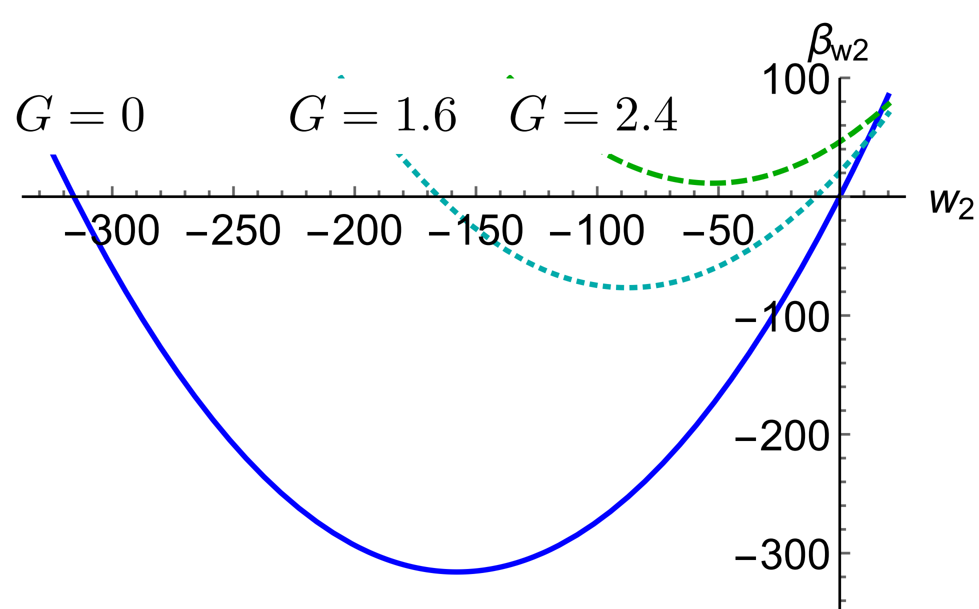

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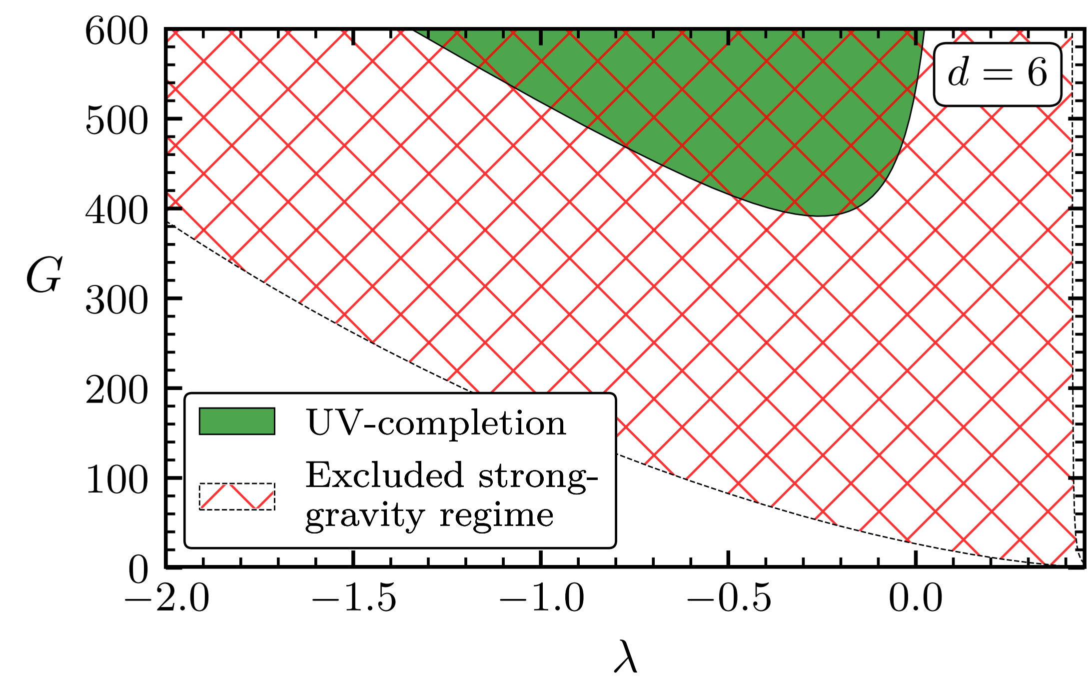

Key open question in asymptotic safety: Unitarity?

fixed point	operators	corresponding couplings:
✔	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Litim '03; Becker, Reuter '14;
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✔	$\sqrt{g}R^{34}$	
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	full $f(R)$	[Benedetti, Caravelli '12; Dietz, Morris '12, Demmel, Saueressig, Zanusso '14, '15; Gonzalez-Martin, Morris, Slade '17]

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[however, see also, e.g., Anselmi, Piva '17, '18 Donoghue '19]

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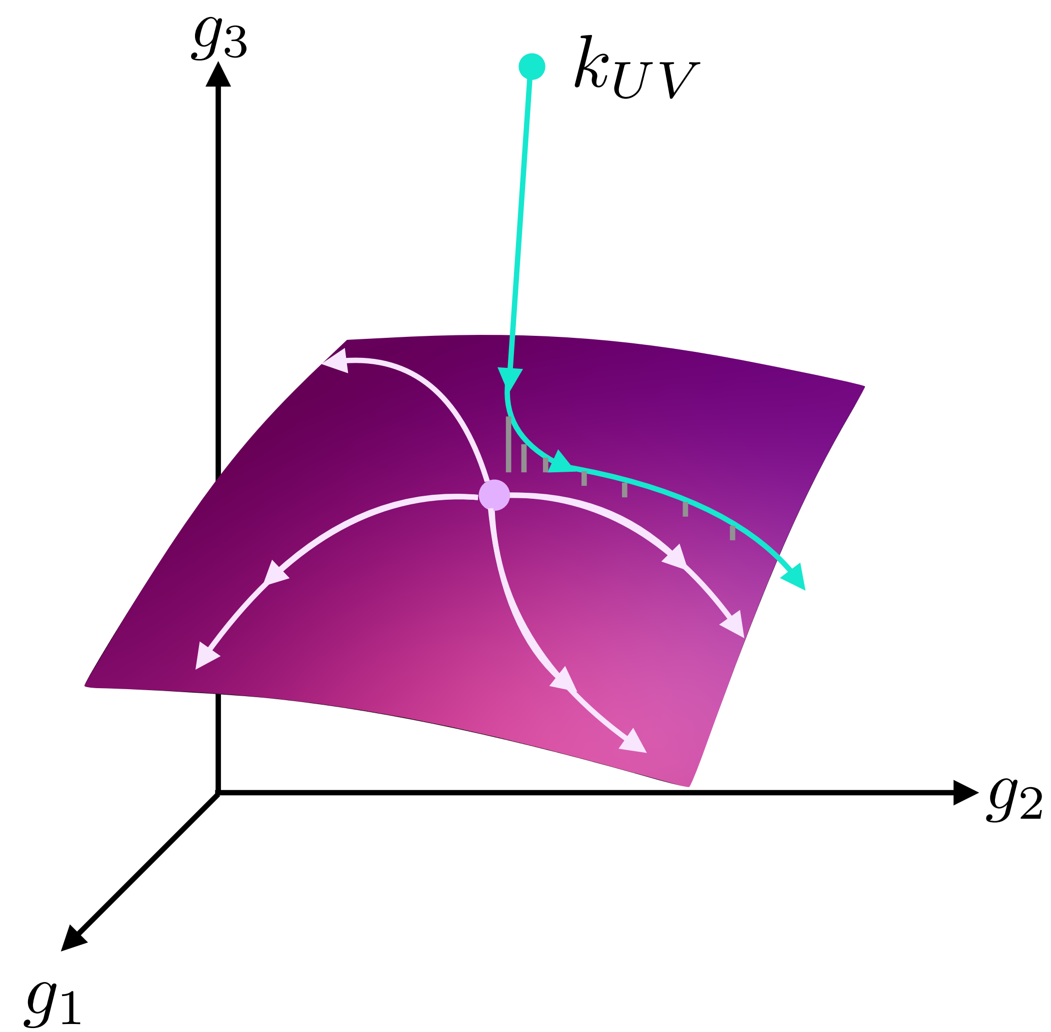
$\rightarrow$ motivates "non-fundamental" asymptotic safety

Key open question 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]



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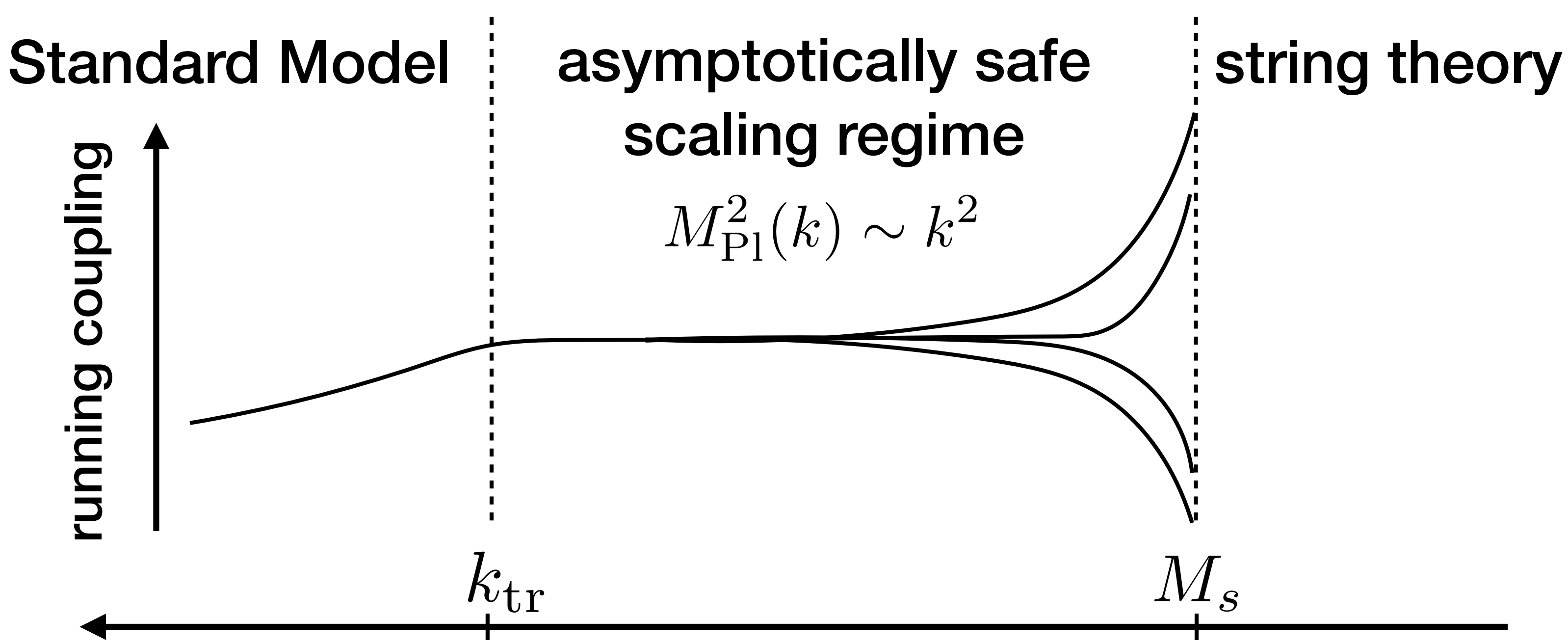
- unitarity "inherited" from microscopic theory

weak-gravity conjecture in asymptotic safety:

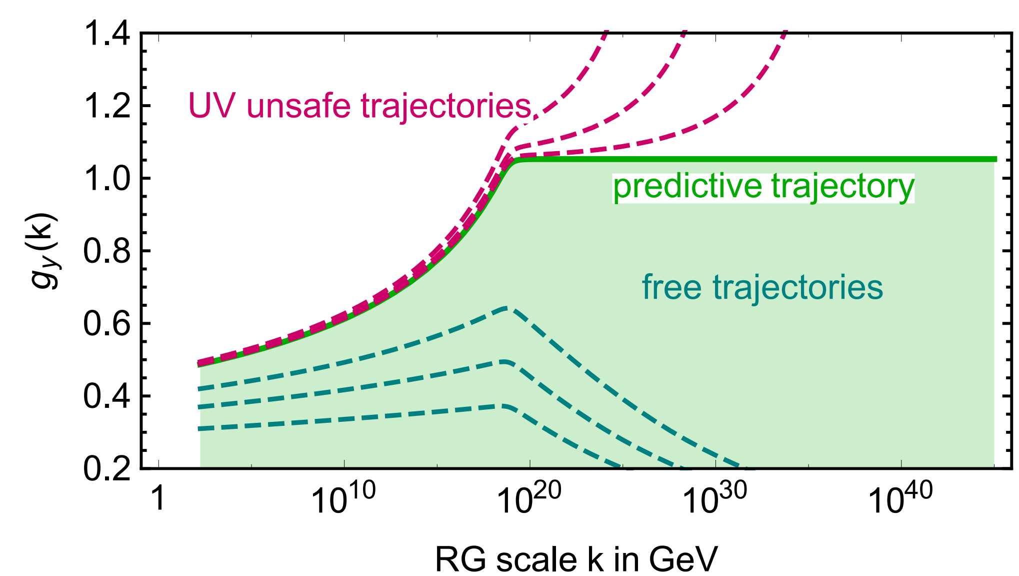
$$\frac{g_*}{8\pi G_*} > m_{\mathrm{WGC}\,*}$$

might hold at fixed point with finite gauge coupling, but: conditions on fixed-point values

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



$$\frac{\mathcal{V}^{4/3}}{\sqrt{g_s}} < \frac{1}{4\pi G_*}$$



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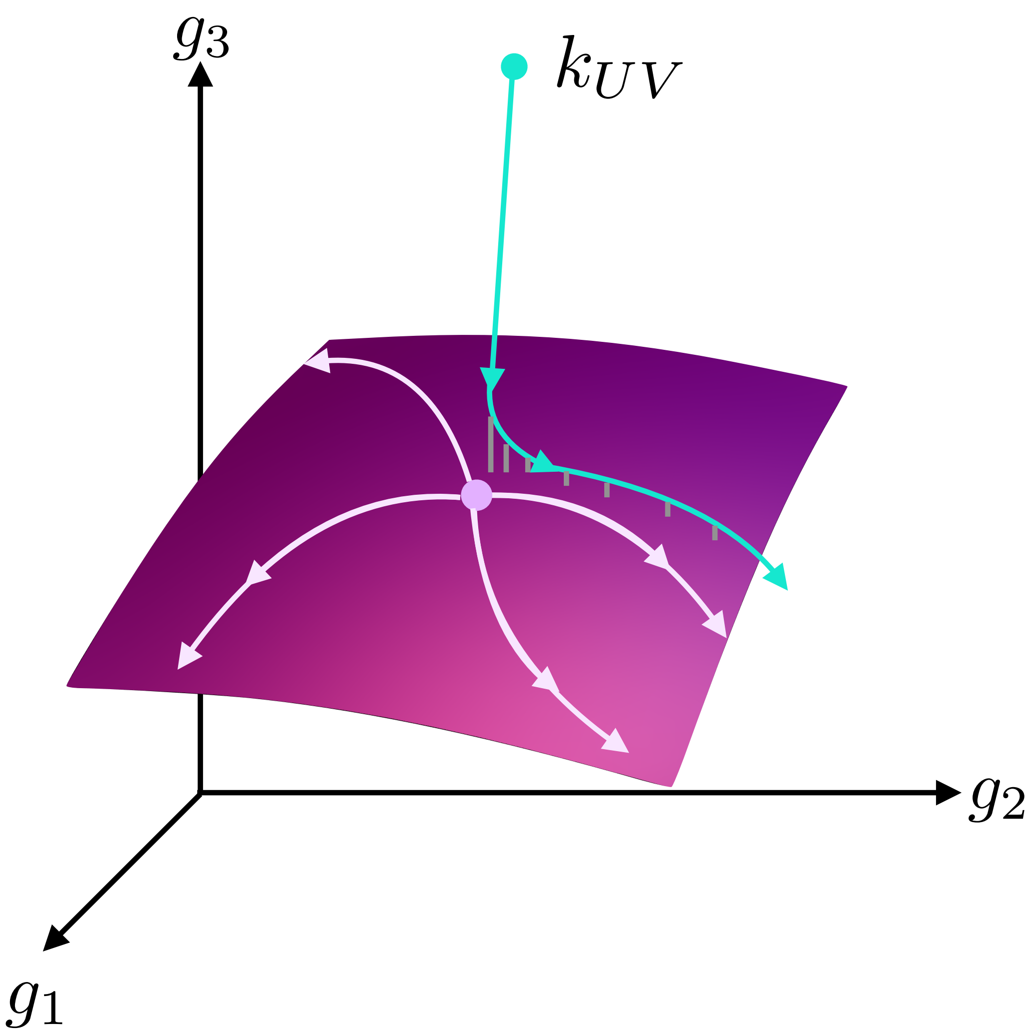

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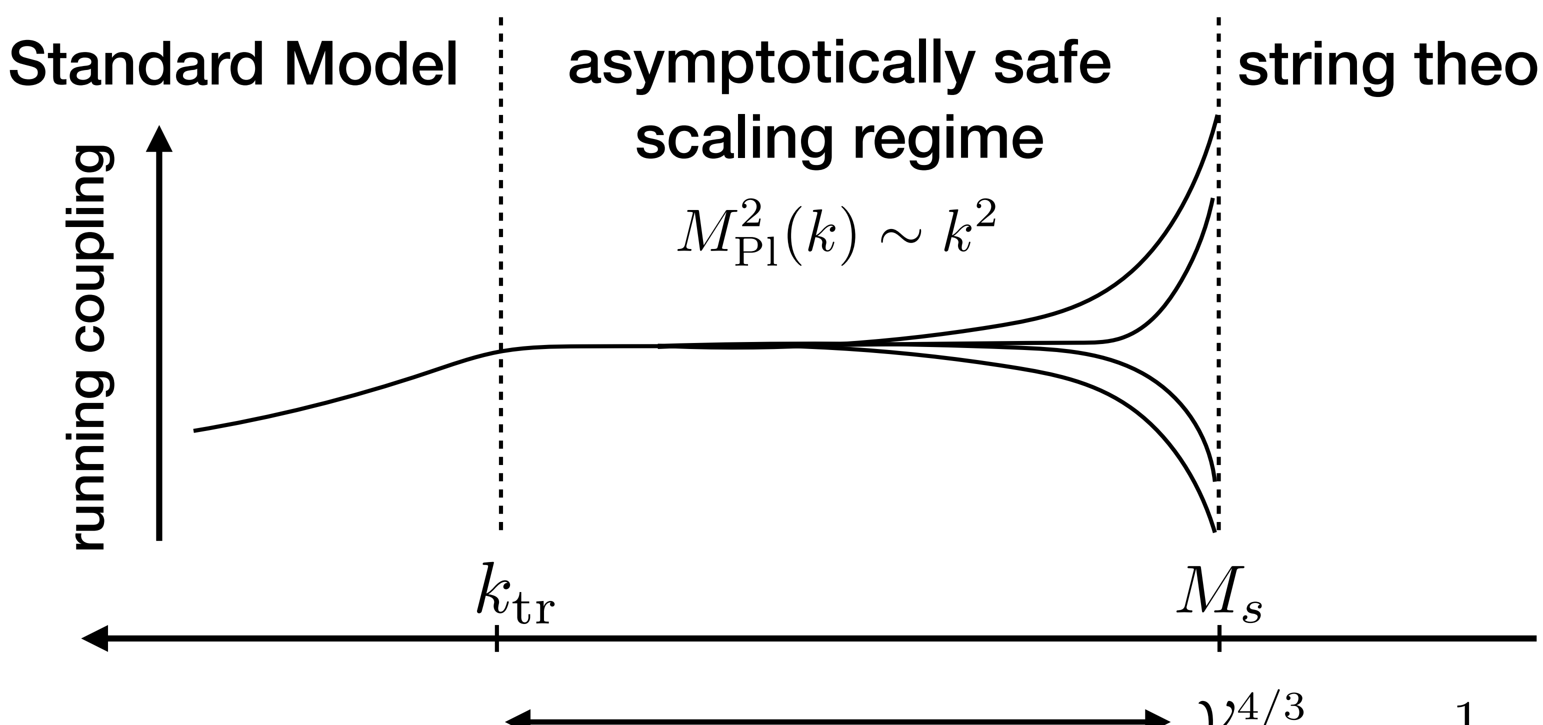

separation of scales $\frac{\mathcal{V}^{4/3}}{\sqrt{g_s}} < \frac{1}{4\pi G_*}$

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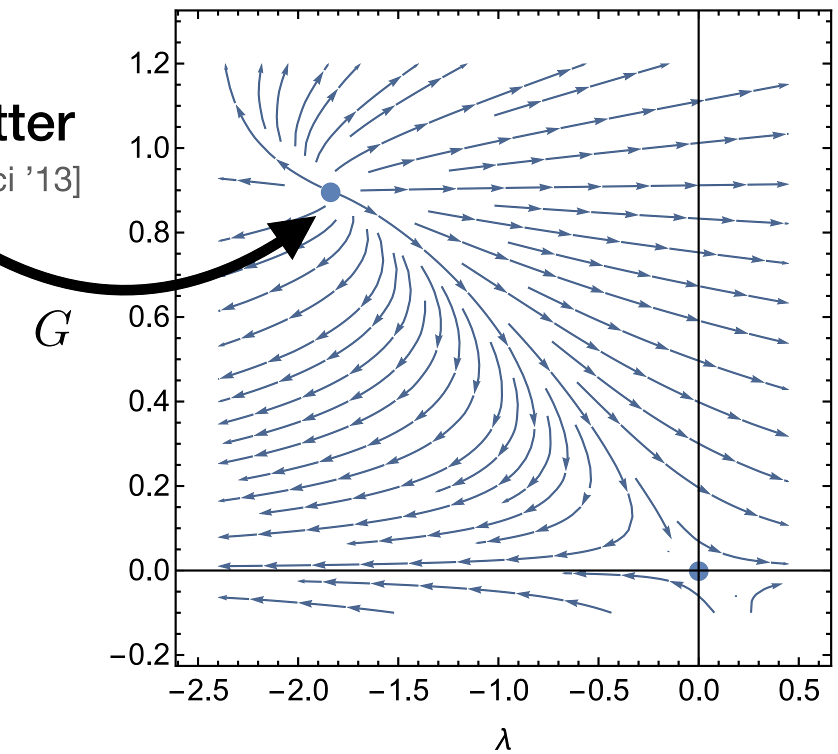
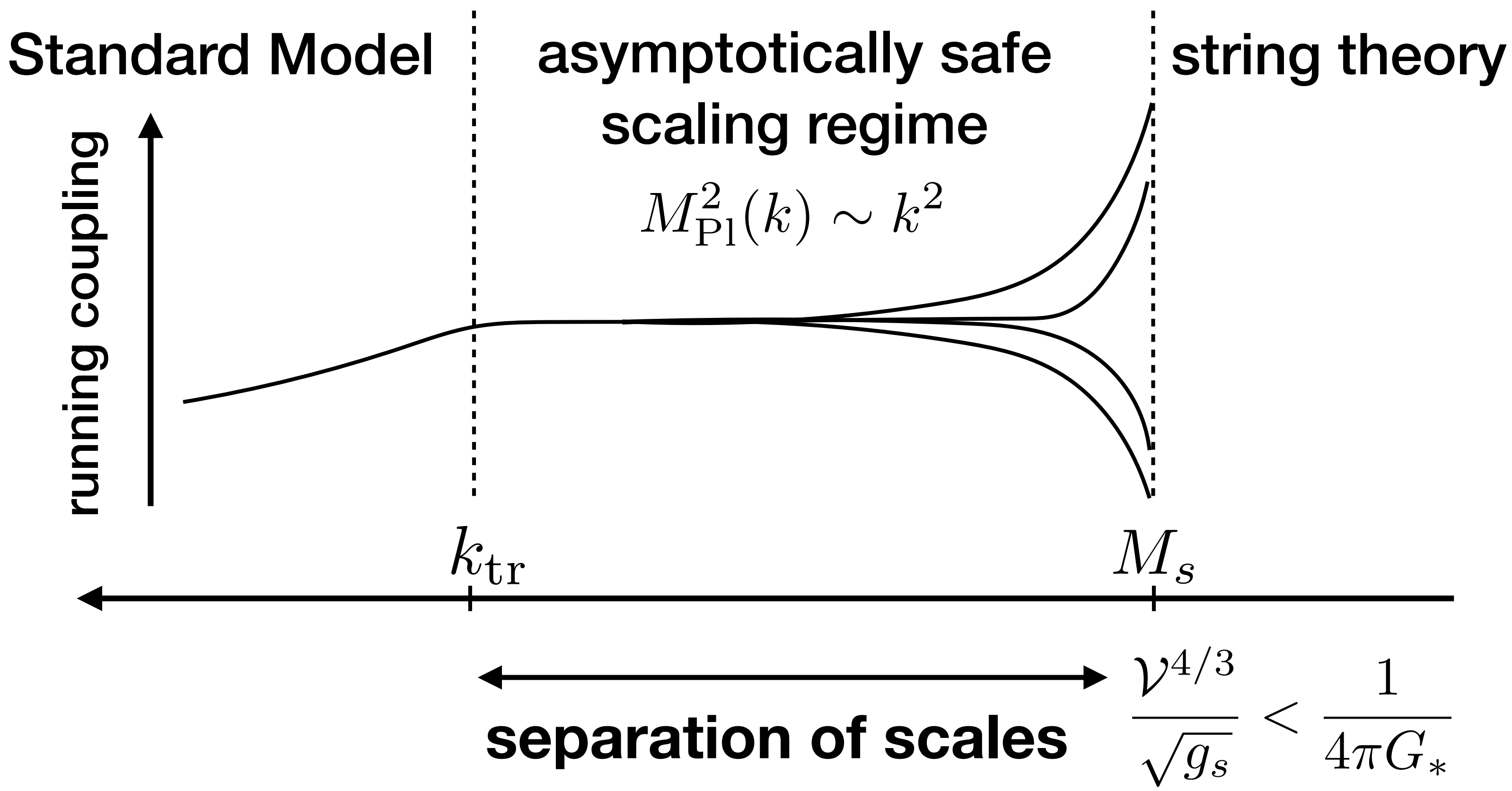
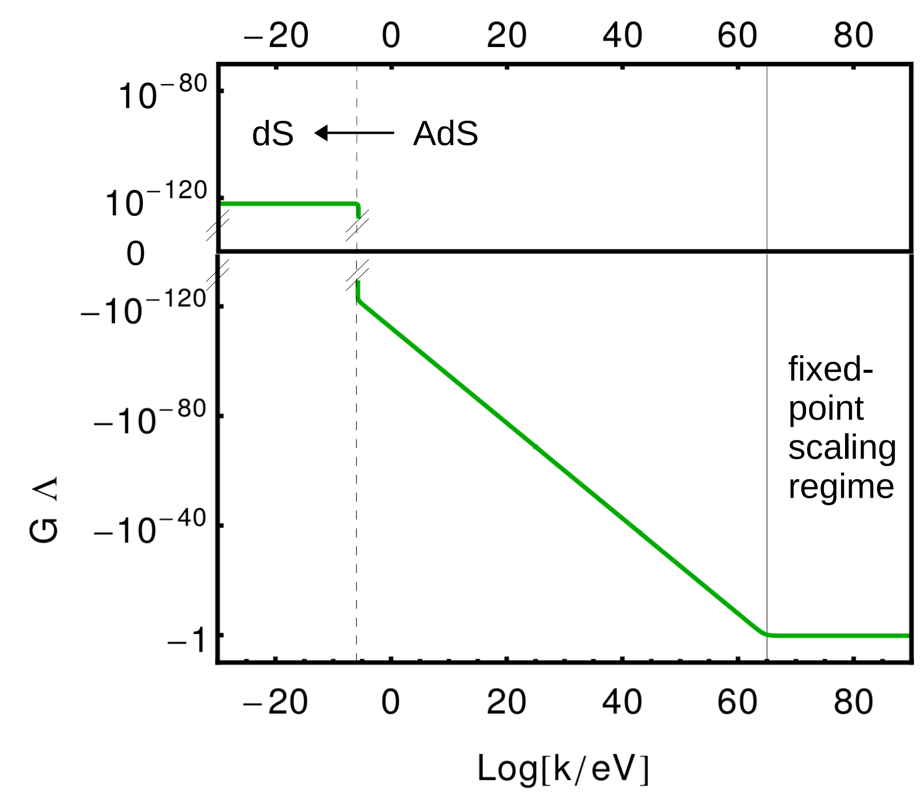
transition from microscopic AdS to macroscopic dS?

impact of fermionic matter

[Dona, AE, Percacci '13]







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:

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

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

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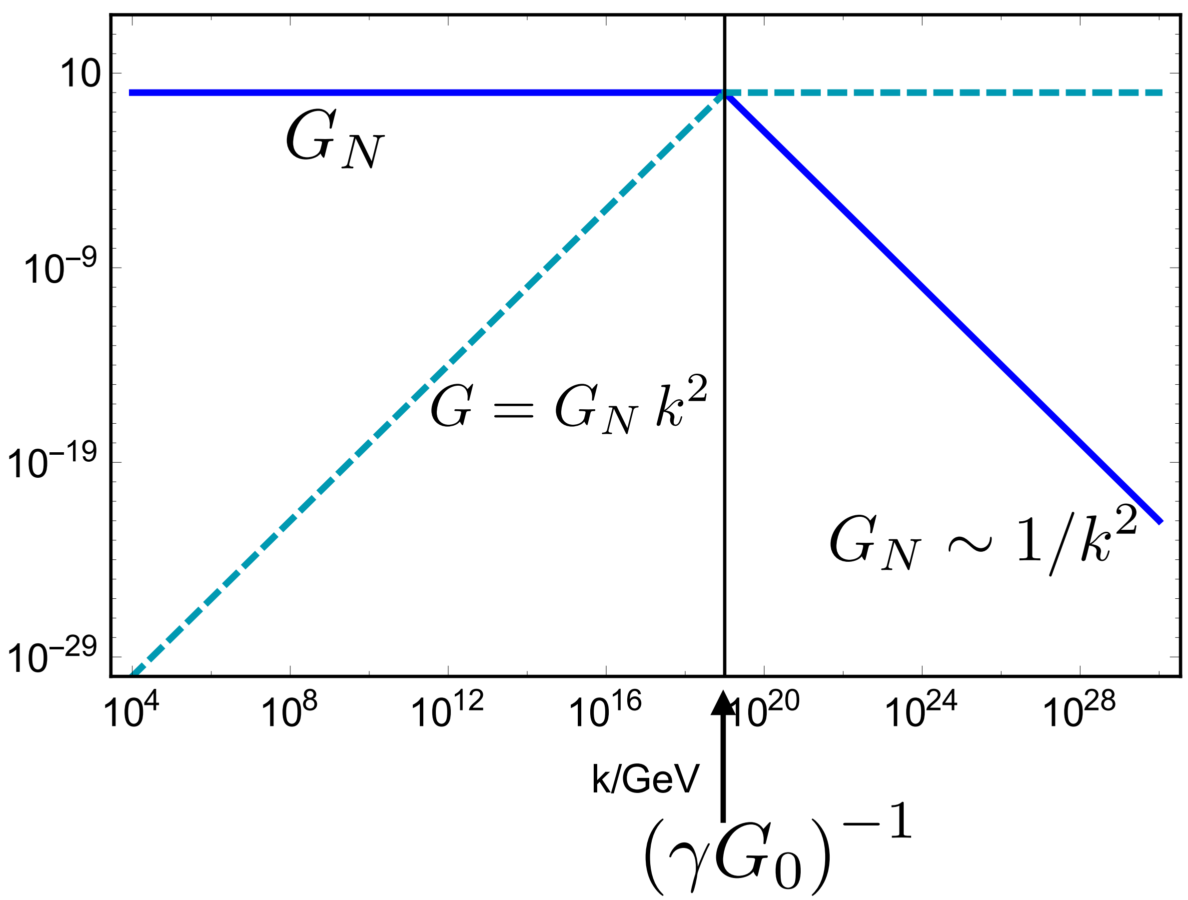
note:
heuristic argument!

Mathematical diversity, physical unity?

Classical gravity regime **Quantum gravity regime**



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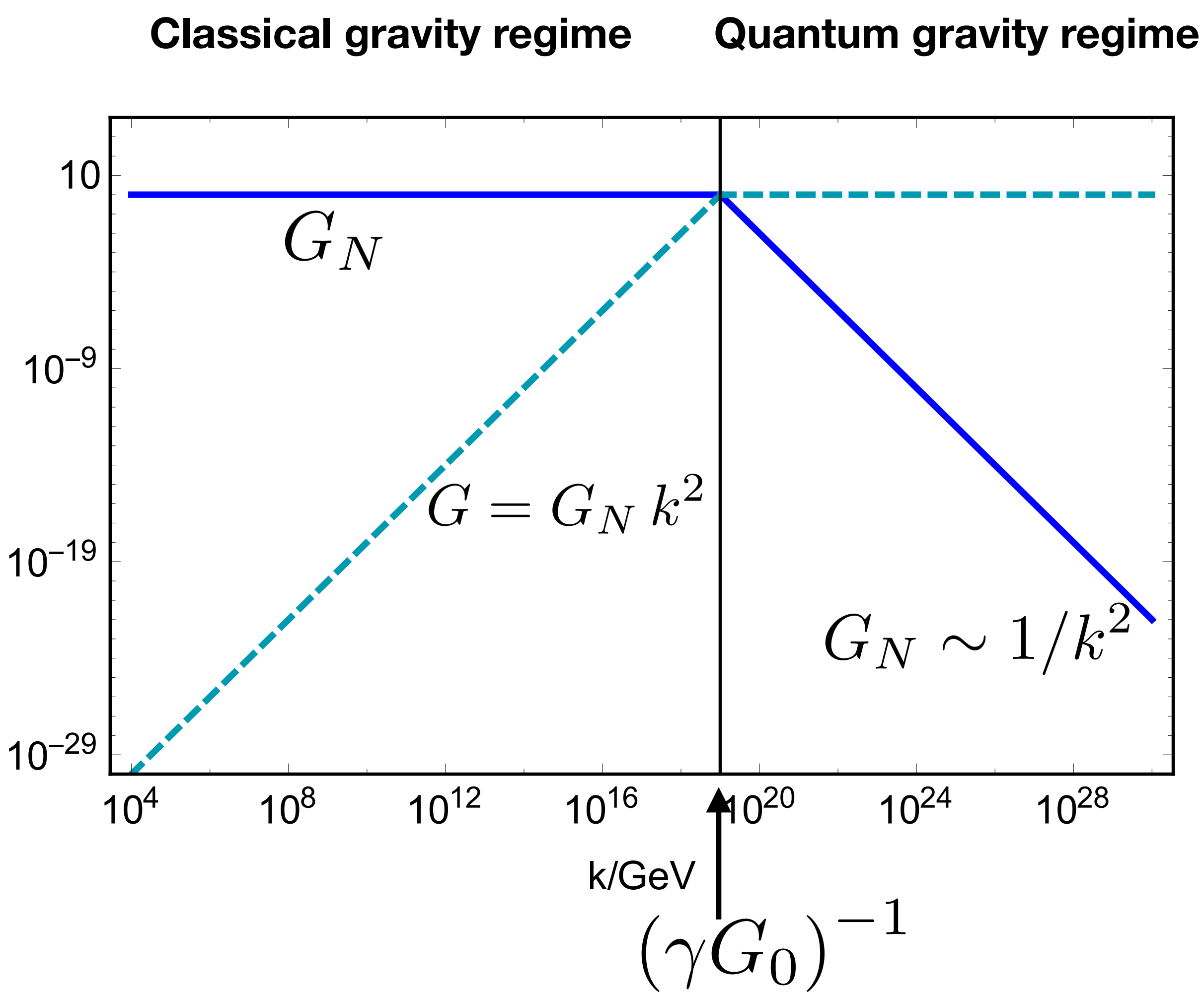
$$G_N \to G_N(k)$$

note: heuristic argument!

Mathematical diversity, physical unity?



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- **spherically symmetric case:**

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

Schwarzschild black hole:

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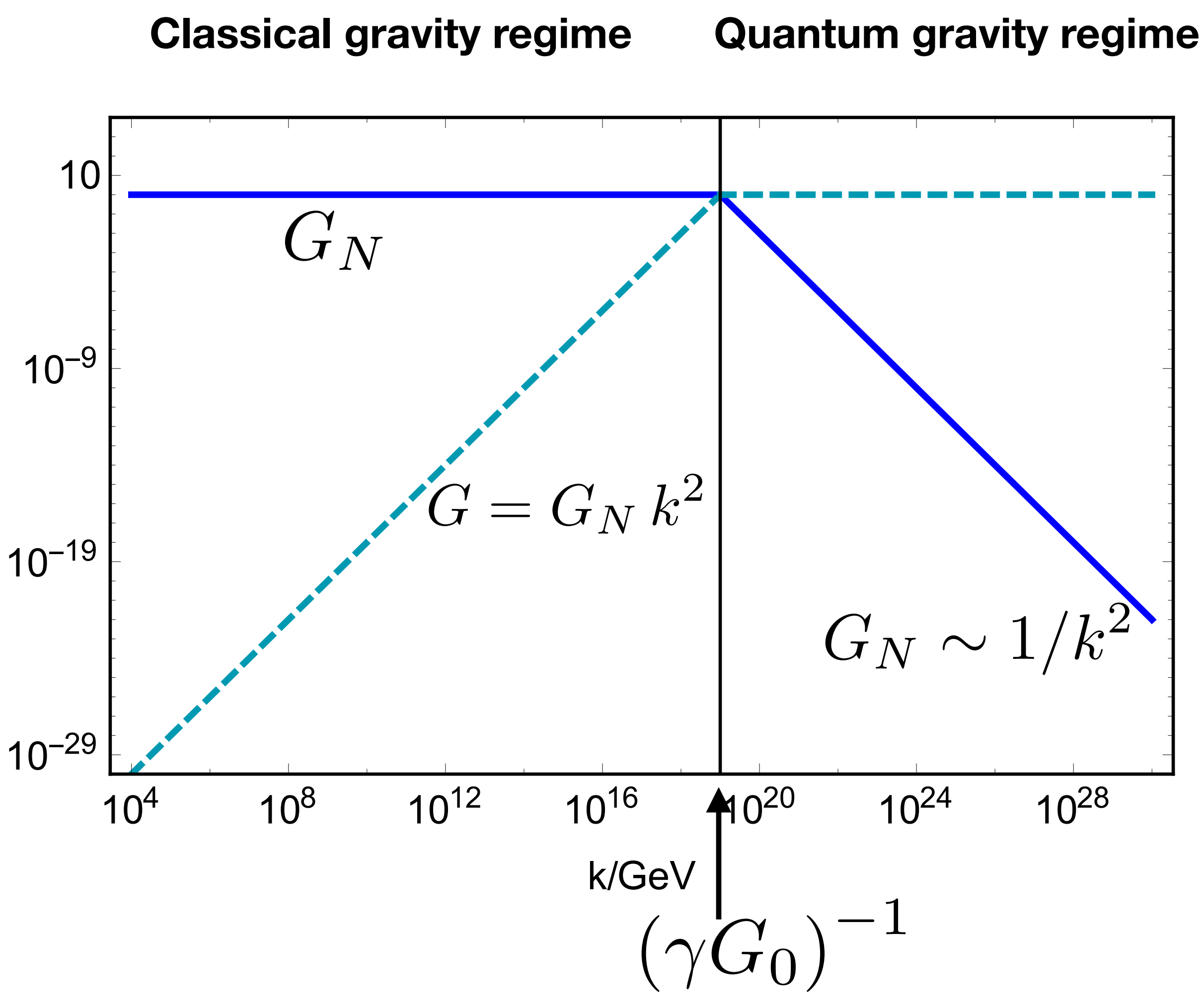

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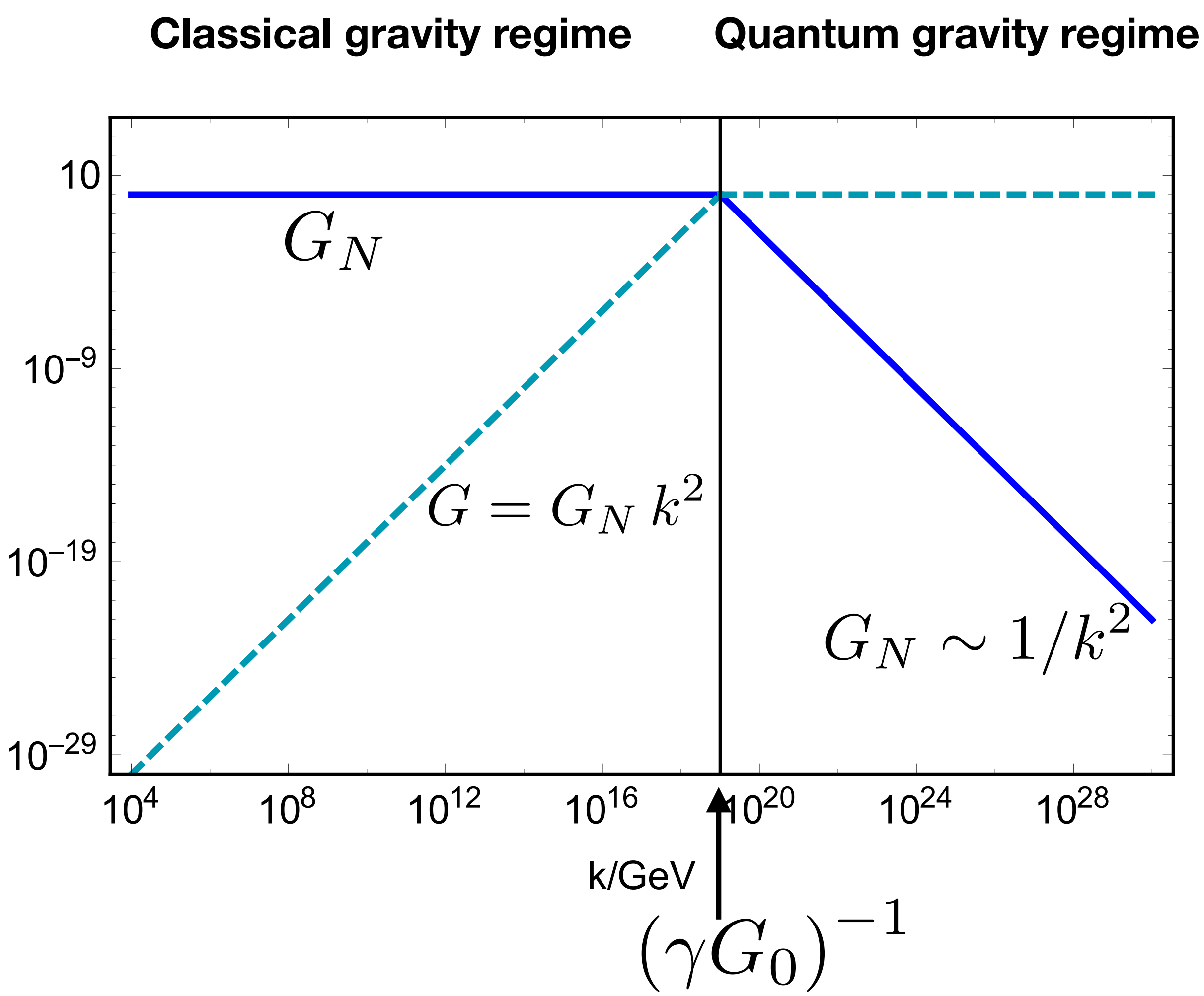

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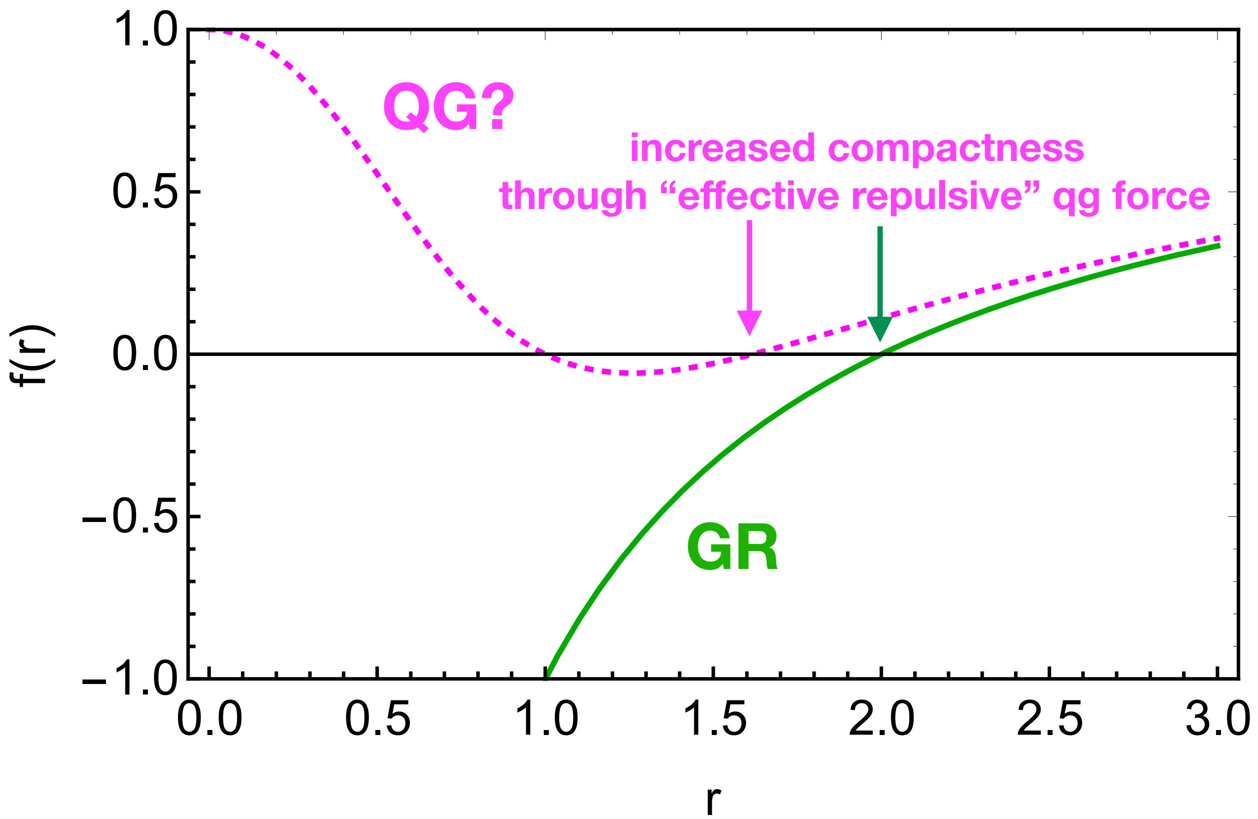
- **RG-improved line element:**

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

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

[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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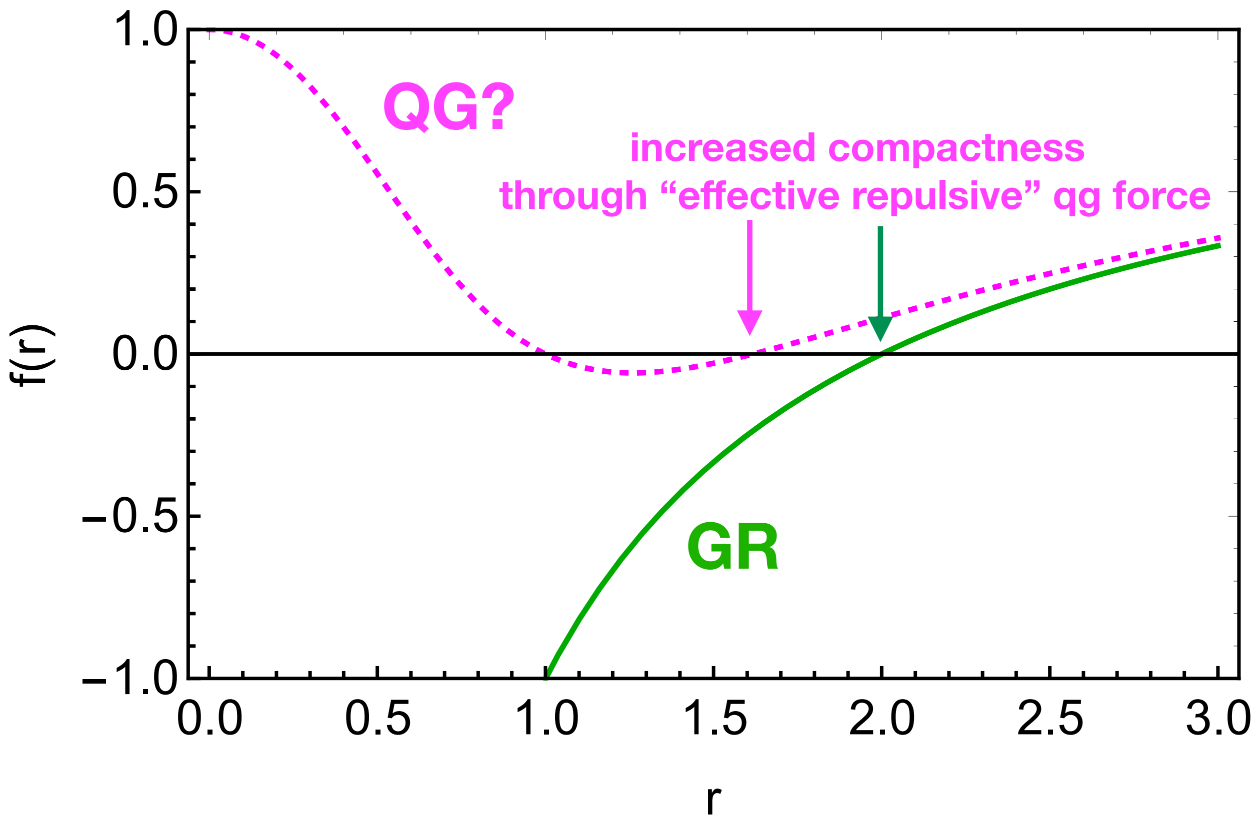

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[Hayward '06]

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]

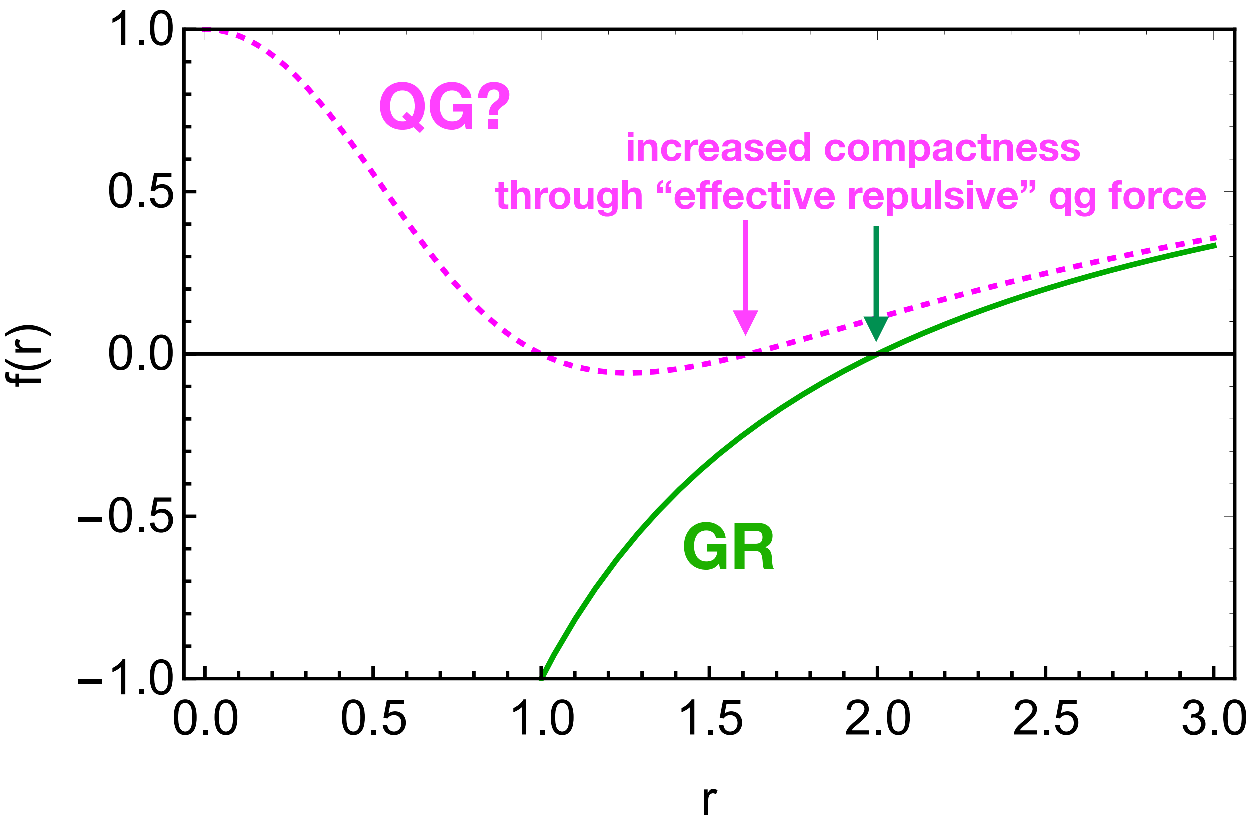
noncommutative geometry

[Nicolini '06]

String theory

[Nicolini '19]

Mathematical diversity, physical unity?



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effectively:
reduced radius-dependent mass parameter

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

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

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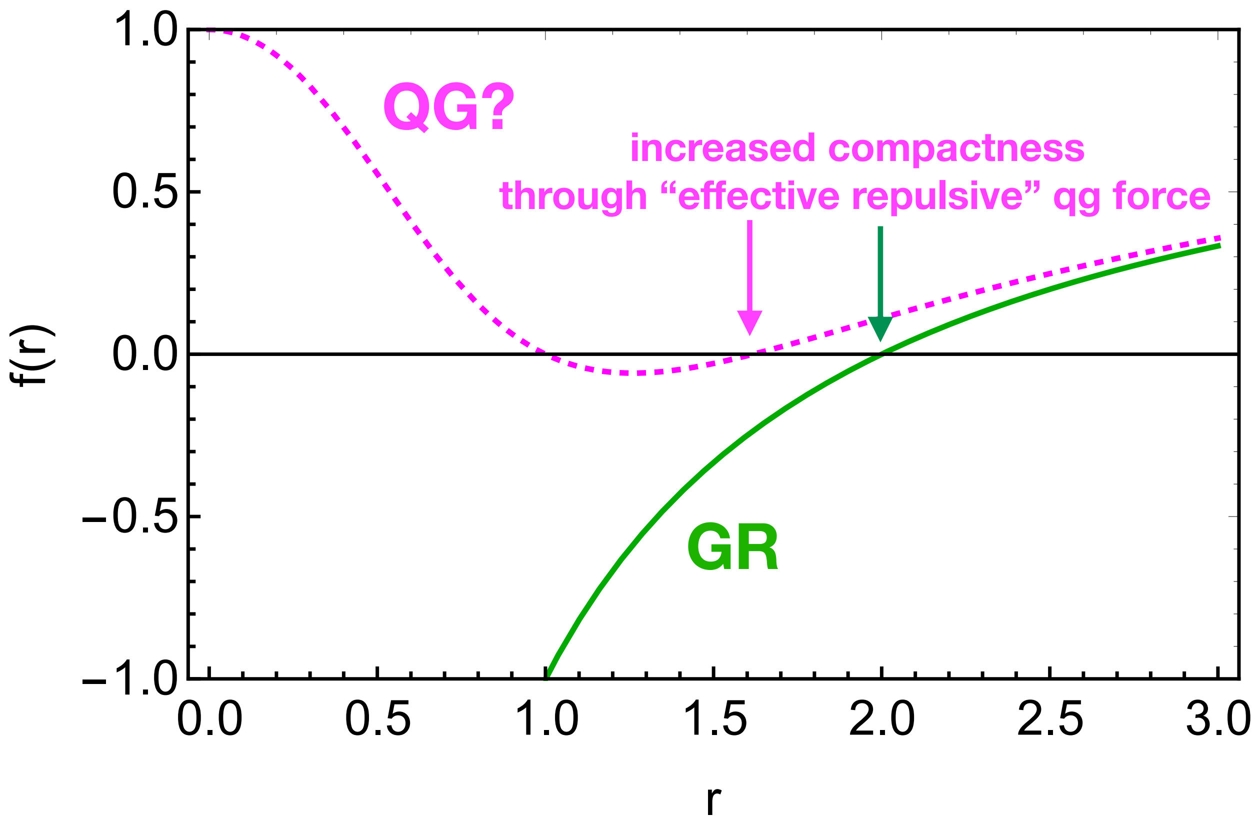

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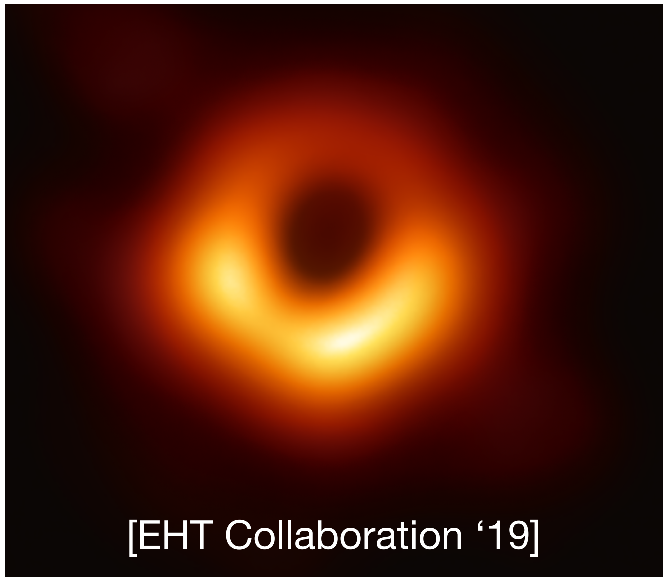
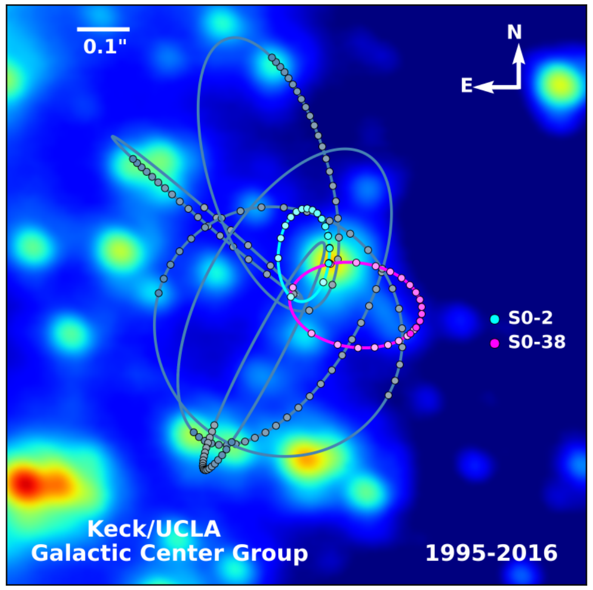
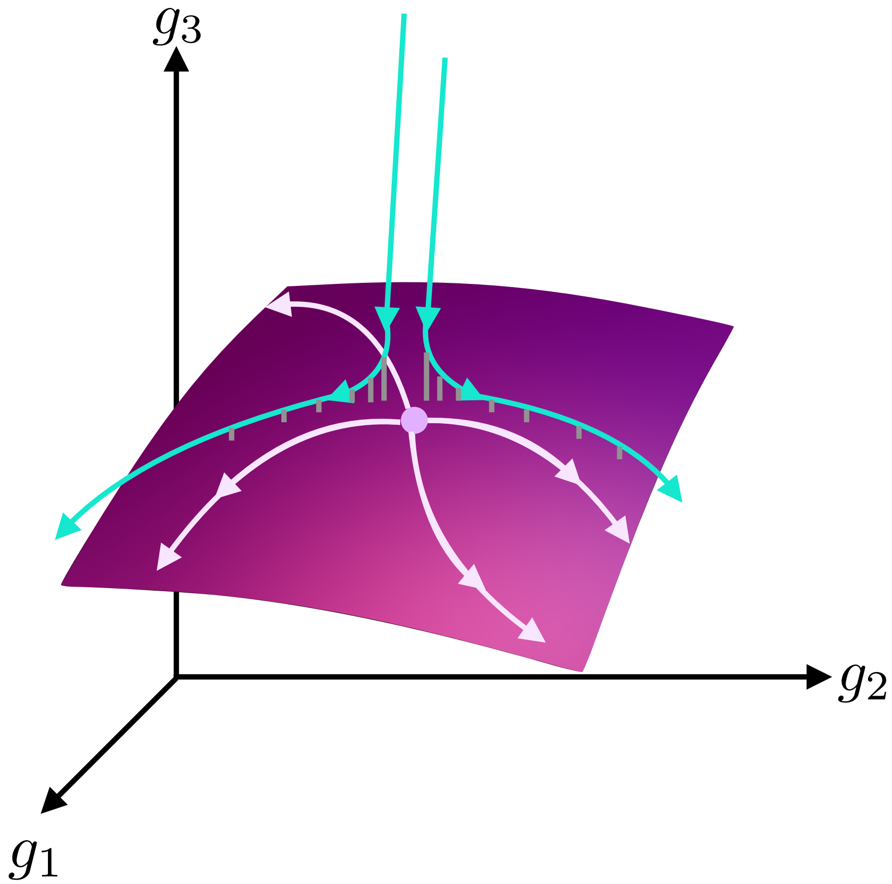




constraint on γ
see
[Held, Gold, AE '19]

Summary



Status of asymptotic safety in gravity:

- strong indications for fixed point in Euclidean gravity
- tentative hints for enhanced predictive power in matter sector
- first hint that predictive power could extend to parameters of the geometry (d=4)
- heuristic argument results in regular black-hole metric similar to several other approaches, with "effective mass" M(r)
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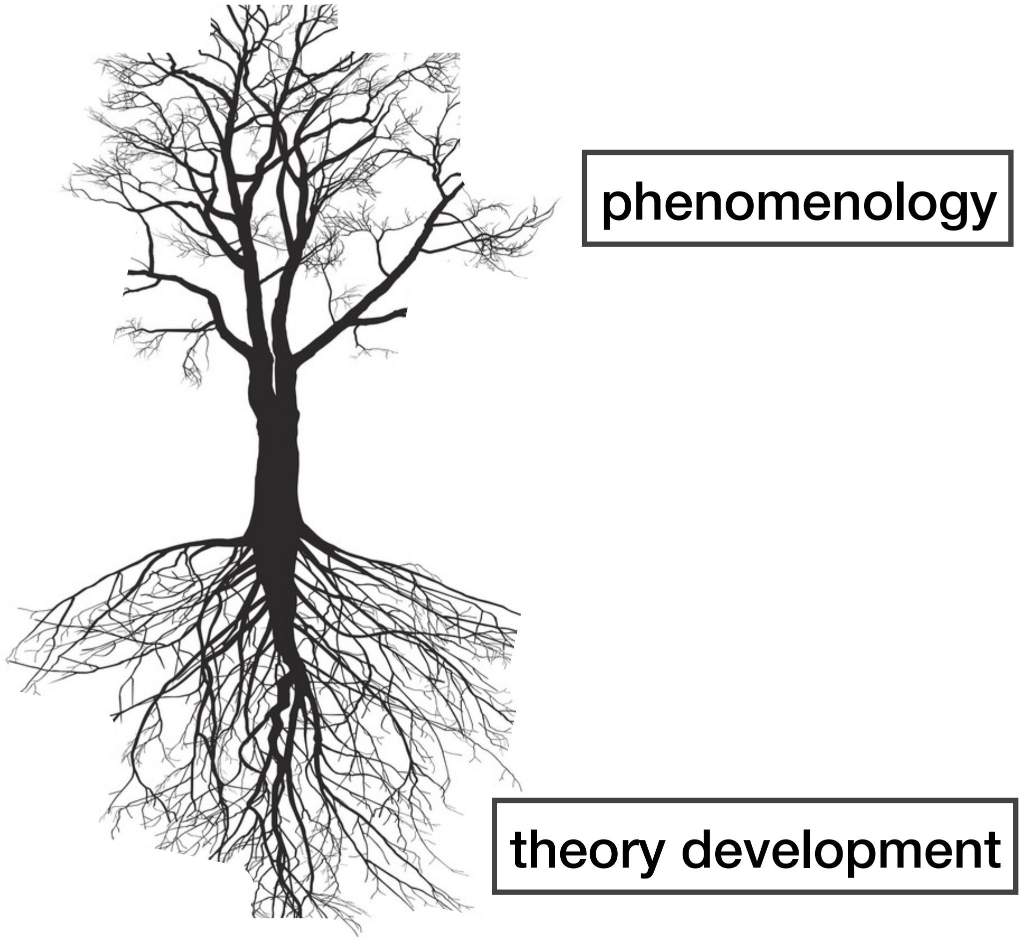

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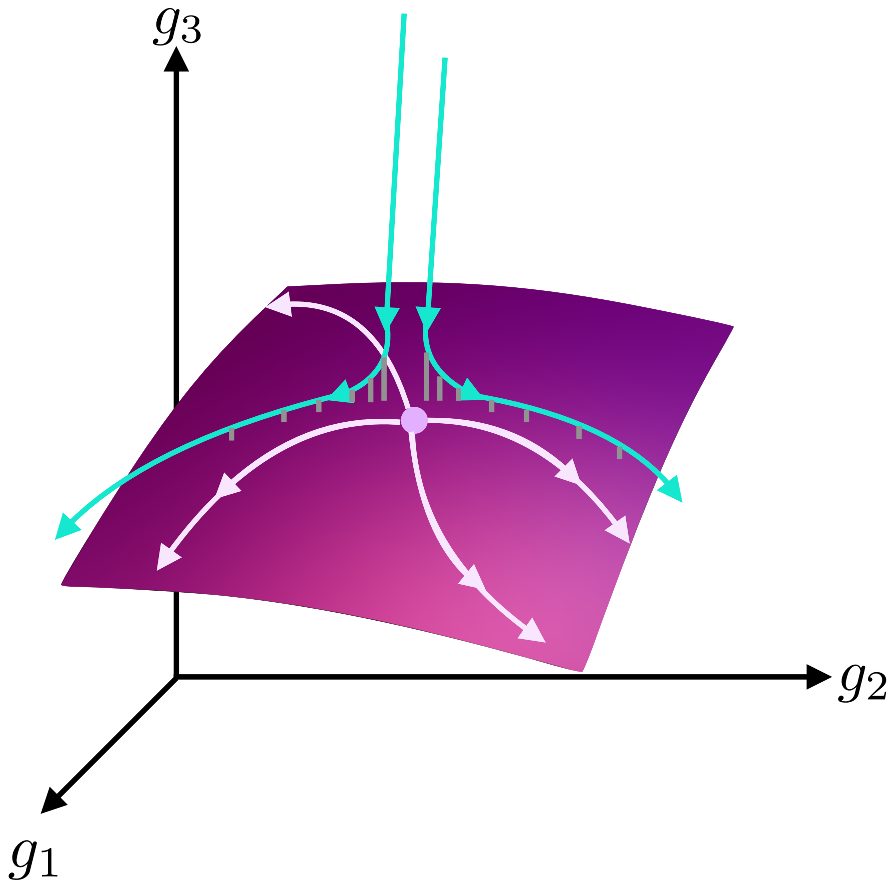

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Key challenges:

- Lorentzian nature of spacetime
- Unitarity
  - higher-order terms only lead to extra poles in truncations?
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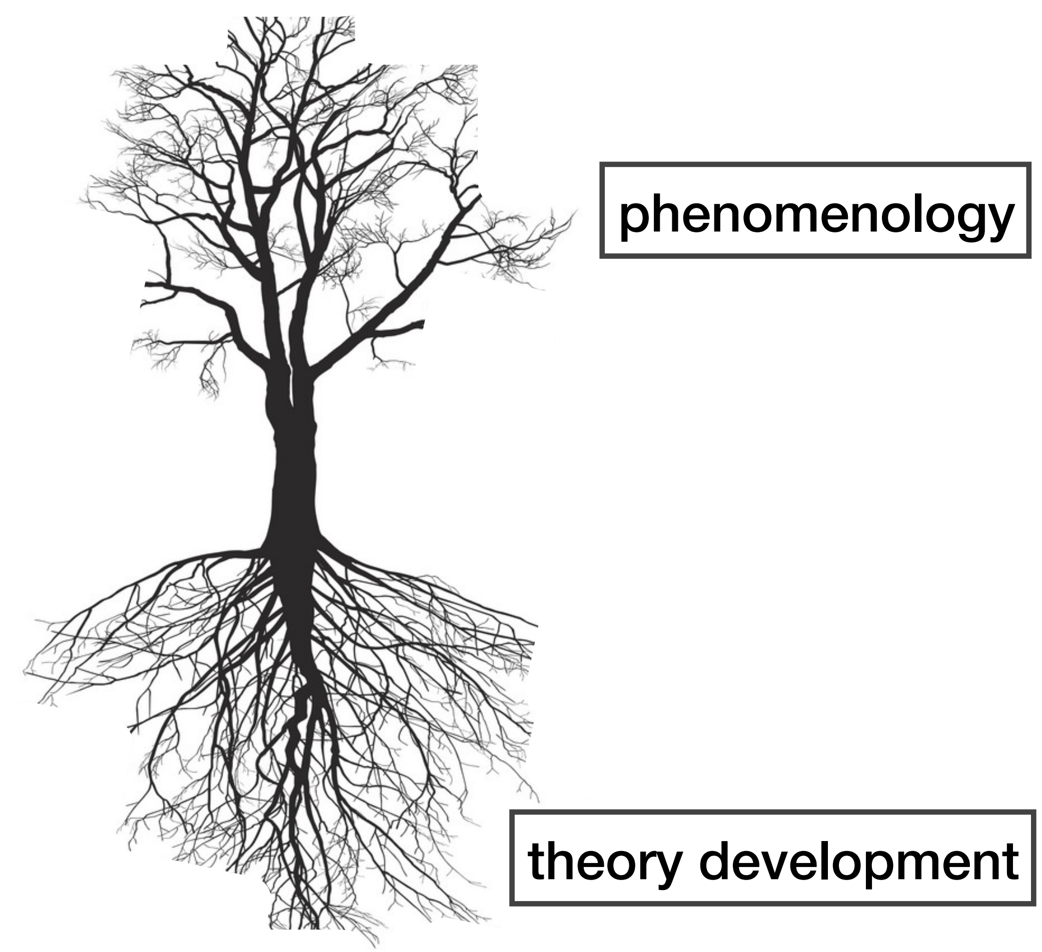
- observational consistency tests



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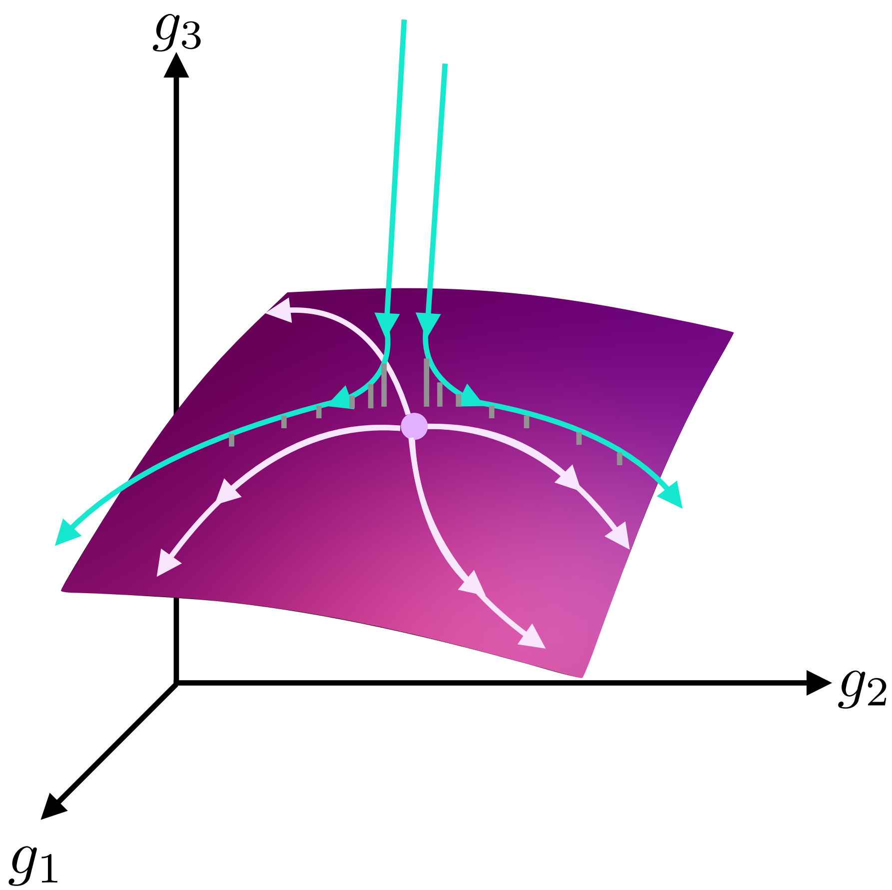

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phenomenology

Stay tuned for growth at both ends!

theory development

Quantitative characterization of universality classes from the FRG

example: Ising model

local potential approximation (LPA N): $$\Gamma_k = \int \left(Z_k \partial_\mu \phi \partial^\mu \phi + V_k(\phi^2) \right) .$$

$$V_k = \sum_{i=1}^{N} \lambda_i \, \phi^{2i}$$

truncation	$\nu = 1/\theta_1$	$\omega = -\theta_2$	η
LPA 2	1/2	1/3	0
LPA 3	0.729	1.07	0
LPA 4	0.651	0.599	0
LPA 5	0.645	0.644	0
LPA 6	0.65	0.661	0
LPA 7	0.65	0.656	0
LPA 8	0.65	0.654	0
LPA' 2	0.526	0.505	0.0546
LPA ' 3	0.684	1.33	0.0387
LPA' 4	0.64	0.703	0.0433
LPA '5	0.634	0.719	0.0445
LPA' 6	0.637	0.728	0.0443
LPA ' 7	0.637	0.727	0.0443
LPA '8	0.637	0.726	0.0443.

fourth order derivative expansion:

$$\nu = 0.632, \quad \eta = 0.033$$

[Canet et al, '04; Litim, Zappala '10]

cf. 7-loop pert. theory

$$\nu = 0.6304, \quad \eta = 0.0335$$

[Guida, Zinn-Justin '98]

…similar for other universality classes
(with fermions, scalars, vectors, in arbitrary dimension)