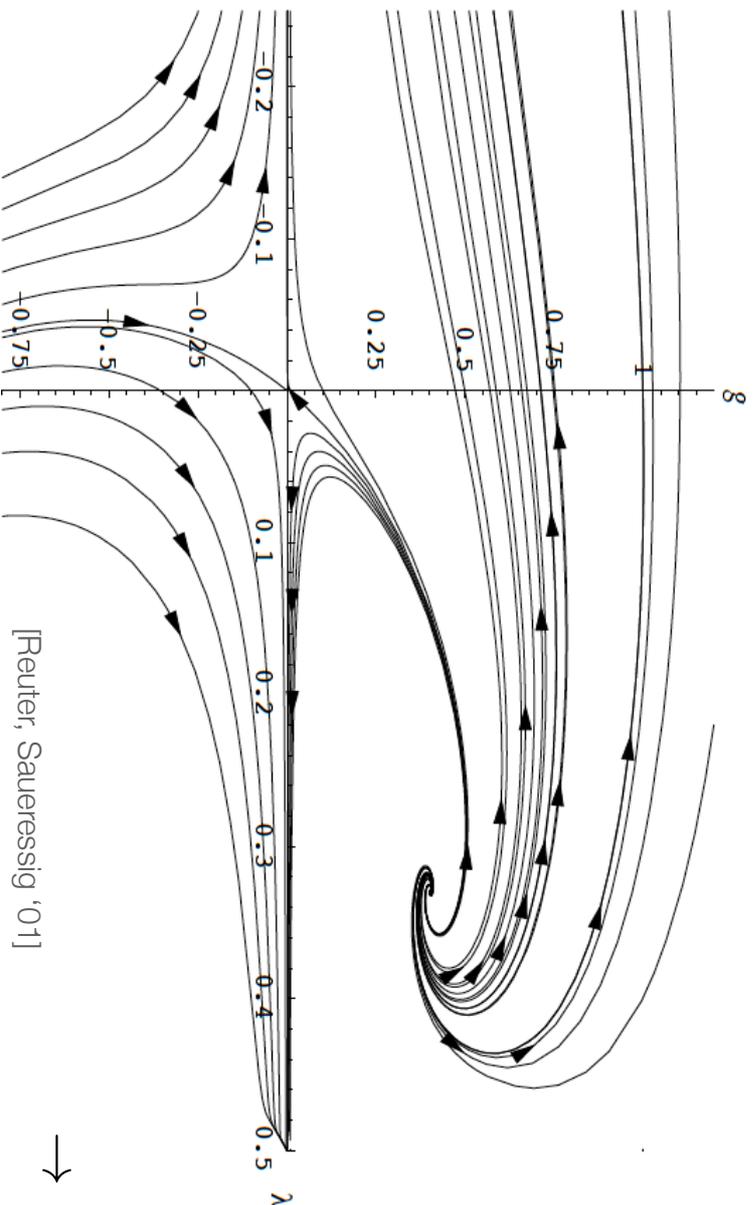


Perturbative nonrenormalizability: FRG viewpoint

$$\Gamma_k = -\frac{1}{16\pi G_N} \int d^4x \sqrt{g} (R - 2\Lambda) + S_{\text{gauge-fixing}}$$



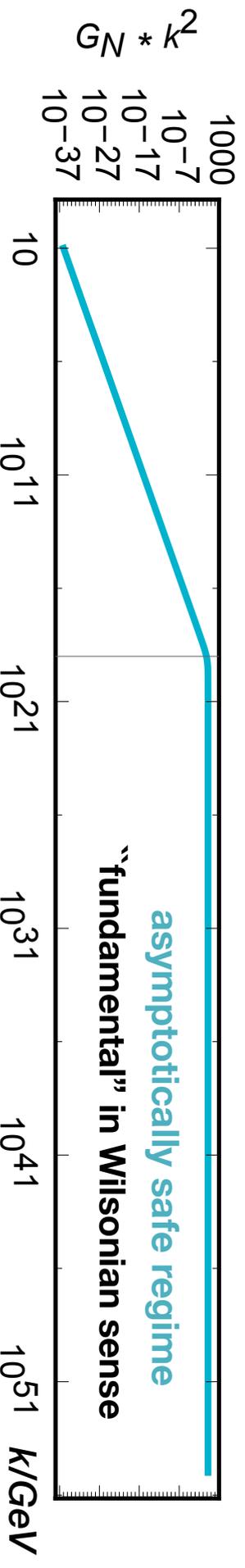
[Reuter, Saueressig '01]

$$\rightarrow \beta_g = 2g + \eta_N(g, \lambda)g$$

$$\lambda(k) = \Lambda(k)k^{-2}$$

$$g(k) = G_N(k)k^2$$

- \Rightarrow higher-order counterterms
- \Rightarrow no asymptotic freedom



theory space

operators

$$\sqrt{g}$$

$$\sqrt{g}R$$

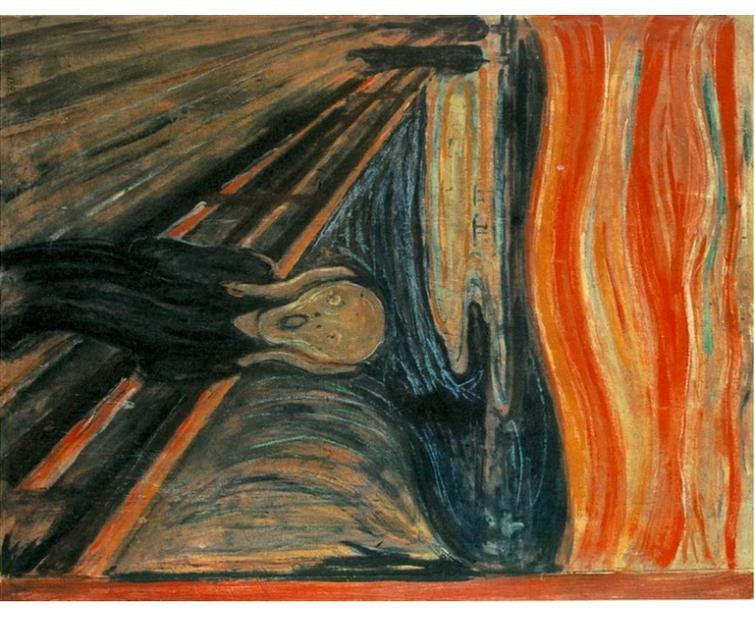
$$\sqrt{g}R \square R$$

$$\sqrt{g}R^{\mu\nu}R_{\mu\nu}$$

$$\sqrt{g}R^{34}$$

$$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$$

$$\sqrt{g}R_{\mu\nu}R^{\nu\kappa}R_{\kappa\lambda}R^{\lambda\mu}$$



Bringing order to theory space

operators

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$$\sqrt{g}R$$

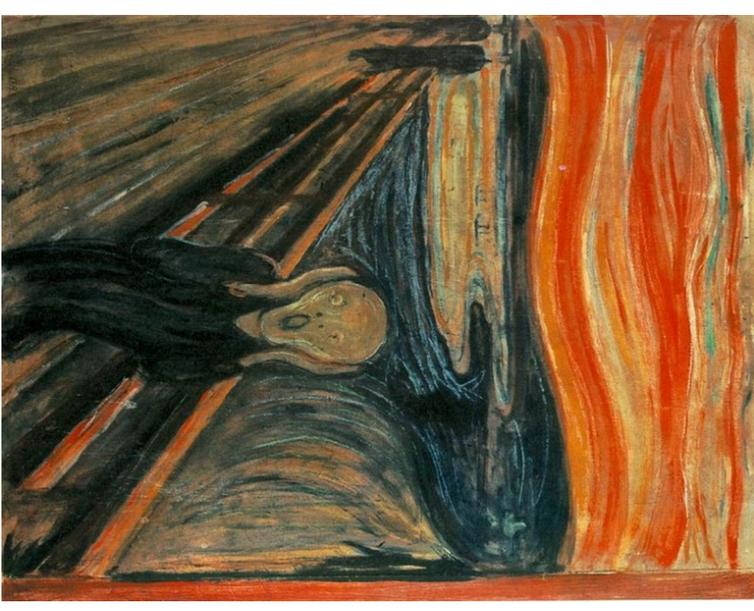
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Which are relevant? How to devise reliable truncations?

Only as non-perturbative as necessary?

fixed point	operators	corresponding couplings:
✓	\sqrt{g}	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Becker, Reuter '14;
✓	$\sqrt{g}R$	Christiansen, Knorr, Meibohm, Pawłowski, Reichert '15]
✓	$\sqrt{g}R^2, \sqrt{g}R^{\mu\nu}R_{\mu\nu}$	[Benedetti, Machado, Saueressig '09; Christiansen '16 Denz, Pawłowski, Reichert '17]
✓	$\sqrt{g}R^3$	[Codello, Percacci, Rahmede '07, '08 Machado, Saueressig '07; A.E. '15; de Brito, Ohta, Pereira, Tomaz, Yamada '18]
•	•	
•	•	
✓	$\sqrt{g}R^{34}$	[Falls, Litim, Nikolakopoulos, Rahmede '13 '14]
•	•	
•	•	
•	•	[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 $f(R)$

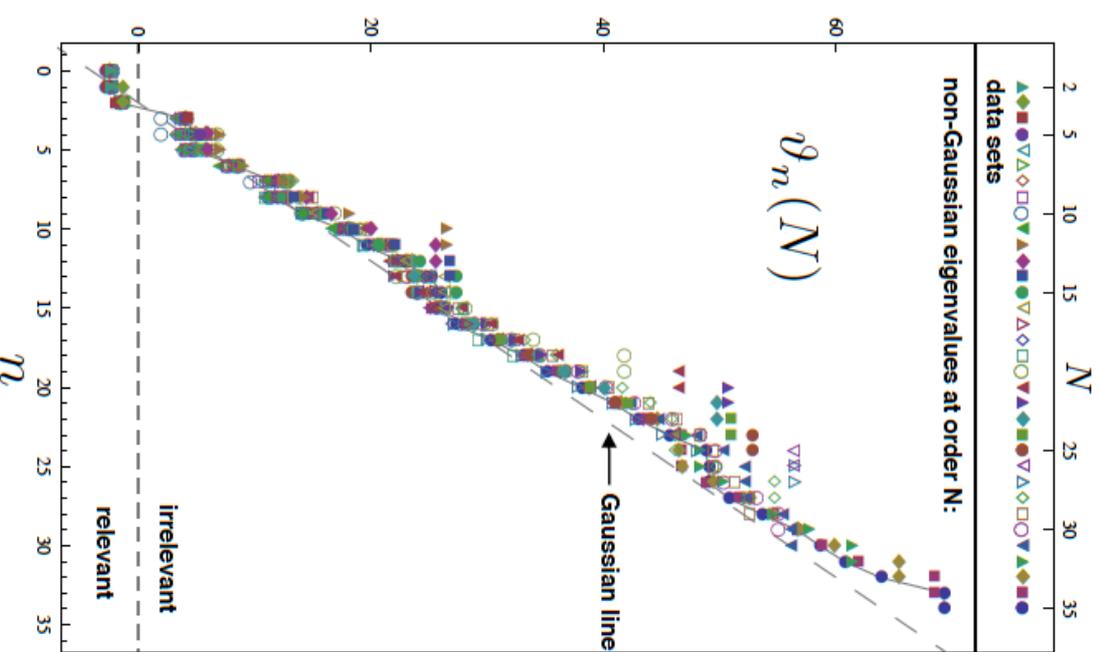
[Benedetti, Caravelli '12; Dietz, Morris '12,
Demmel, Saueressig, Zanusso '14, '15;
Gonzalez-Martin, Morris, Slade '17]

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[Falls, Litim, Nikolakopoulos, Rahmede '13 '14; Falls, Litim, Schröder '18]

also indicated by near-trivial

Slavnov-Taylor-identities

[AE, Labus, Pawłowski, Reichert '18; AE, Lippoldt, Pawłowski, Reichert, Schiffer '18 AE, Lippoldt, Schiffer '18]

Open questions in asymptotically safe quantum gravity

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- **Lorentzian asymptotic safety?**

fixed point persists if configuration space consists of foliatable spacetimes

[Saueressig et al.]

Open questions in asymptotically safe quantum gravity

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- Background independence?

distinguish $g_{\mu\nu}$ and $\bar{g}_{\mu\nu}$

→ “bimetric” flows [Marrique, Reuter '09; & Saueressig '10; Becker, Reuter '14]

→ fluctuation field [Christiansen, Pawłowski, Reichert et al. '15]

[Dona, AE, Labus, Percacci '15]

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- Unitarity?

Ostrogradsky instability: higher-order time derivatives result in instability
(classically), can be traded for non-unitarity in quantum theory

[review: Woodard '15]

But: this applies if time-derivatives to finite order

Unitarity: Propagator $\sim (p^2 f(p^2))^{-1}$ with no zeroes in $f(p^2)$ (cf. eff. action of QED/QCD)

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- phenomenological viability?

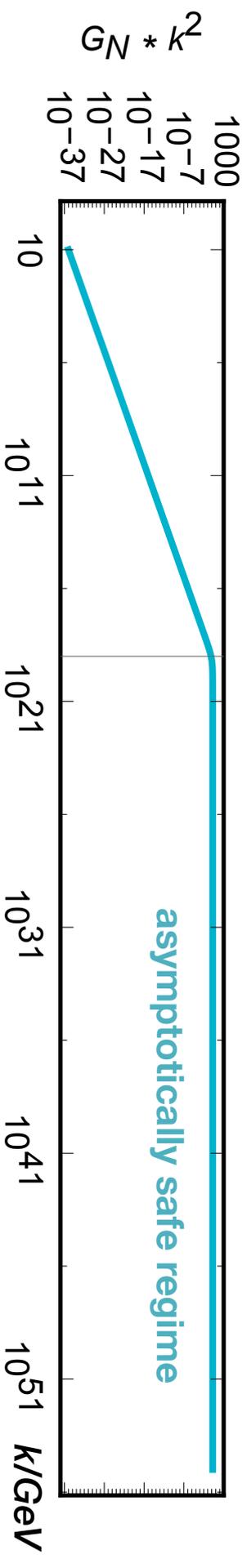
Physics from a fixed point

- **black-hole singularity resolution**
- **properties of quantum geometry**
- **interplay with matter (“matter matters”)**
 - **towards a fundamental Lagrangian theory of everything, that is predictive**
- **early-universe cosmology (asymptotically safe inflation)**

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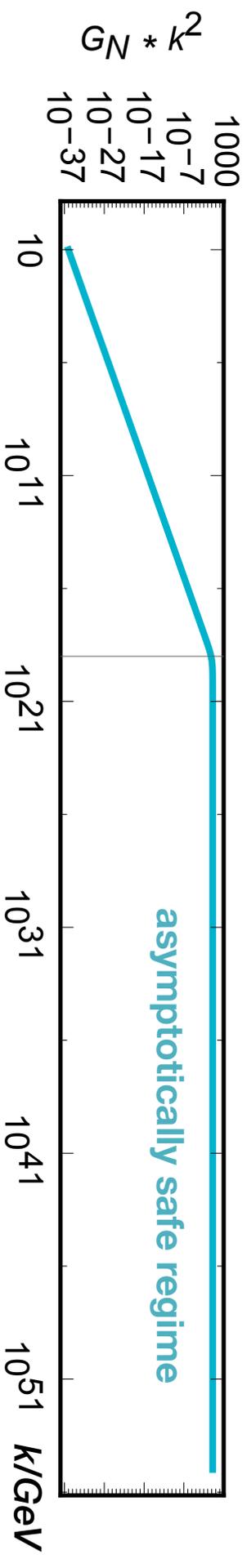
Asymptotically safe black holes



gravity “weaker than classical” in the UV

→ expect resolution of classical spacetime singularities

Asymptotically safe black holes

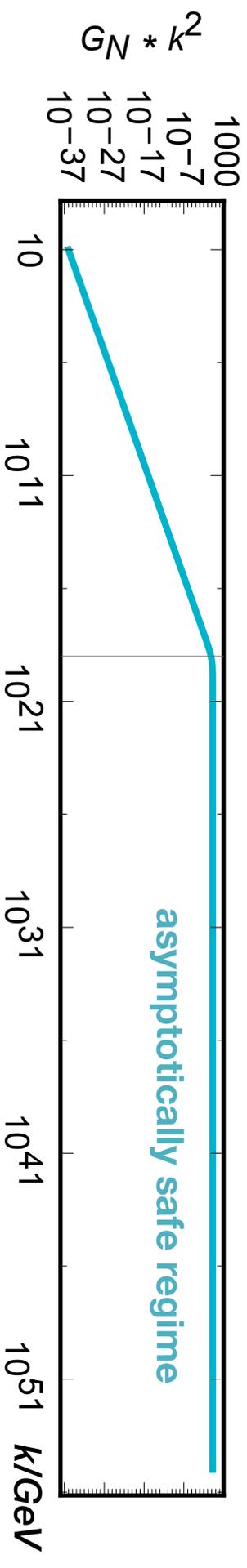


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Schwarzschild singularity $K = R_{\mu\nu\kappa\lambda} R^{\mu\nu\kappa\lambda} \sim \frac{G_N^2}{r^6}$

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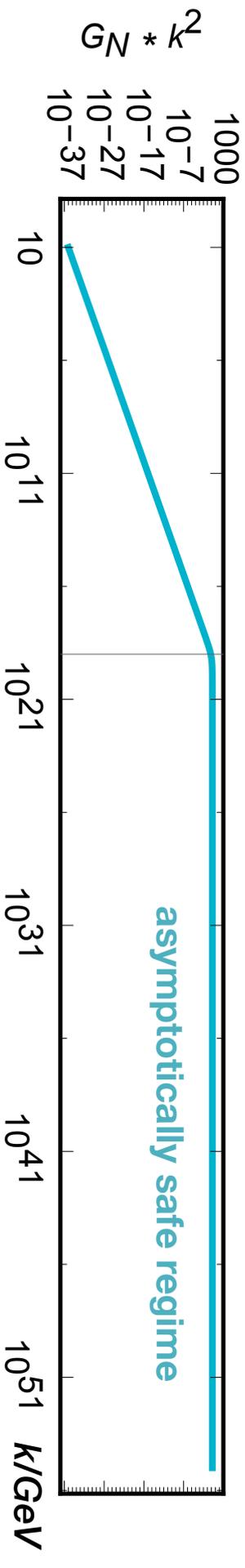
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$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2 \quad f(r) = 1 - \frac{2G_N M}{r} \quad \text{with } G_N = G_N(k)$$

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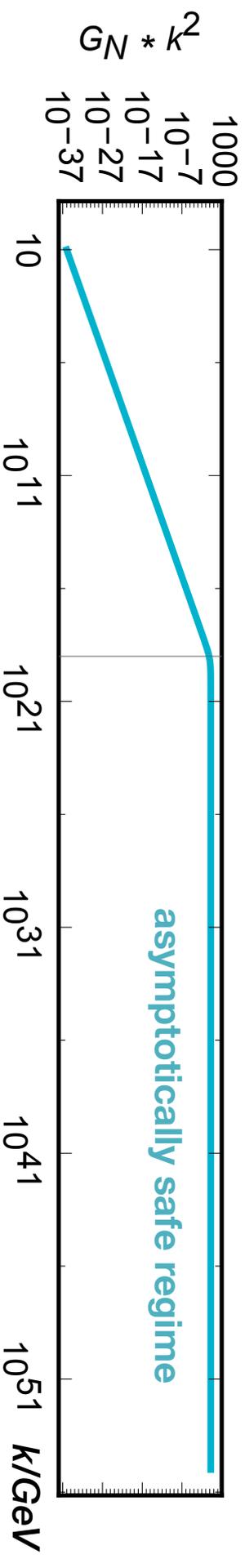
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UV ↔ **large curvature** $k \sim K^{1/4}$

hints for singularity-resolution in ASQG

$$\rightarrow f(r) = 1 - \frac{2M}{r} \frac{M_{\text{Pl}}^2}{M_{\text{Pl}}^2} \frac{1}{1 + \gamma \left(\frac{M}{M_{\text{Pl}}^4} r^3 \right)} \quad K \sim \frac{G_N(k)^2}{r^6} \sim \frac{r^6}{r^6}$$

[Bonanno, Reuter '99 '00, 06 ;

Falls, Litim '11 ; Koch, Saueressig '13,

Pawlowski, Stock '18

Adeifeoba, AE, Platania, '18;

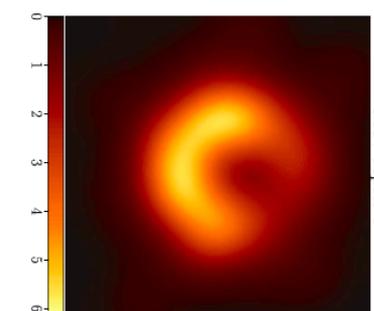
Held, Gold, AE '19]

Asymptotically safe black-hole shadows

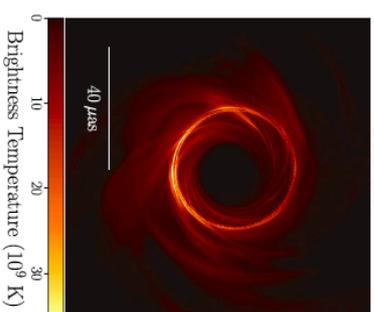
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THE ASTROPHYSICAL JOURNAL LETTERS, 875:L2 (31pp), 2019 April 10

M87 April 6

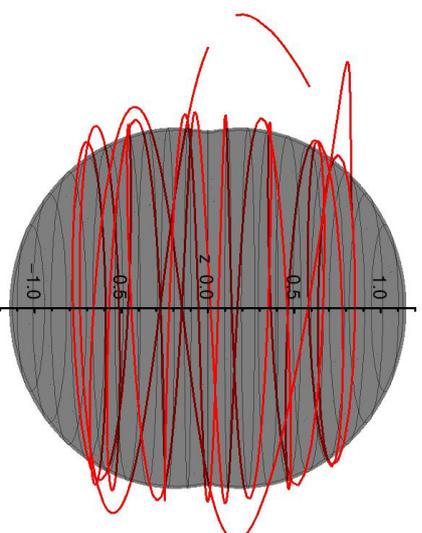
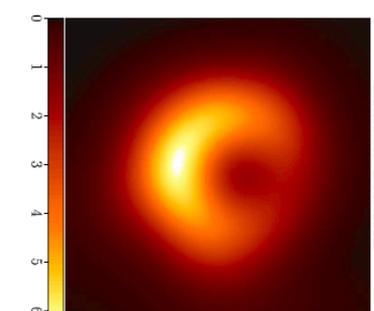


GRMHD



The EHT Collaboration et al.

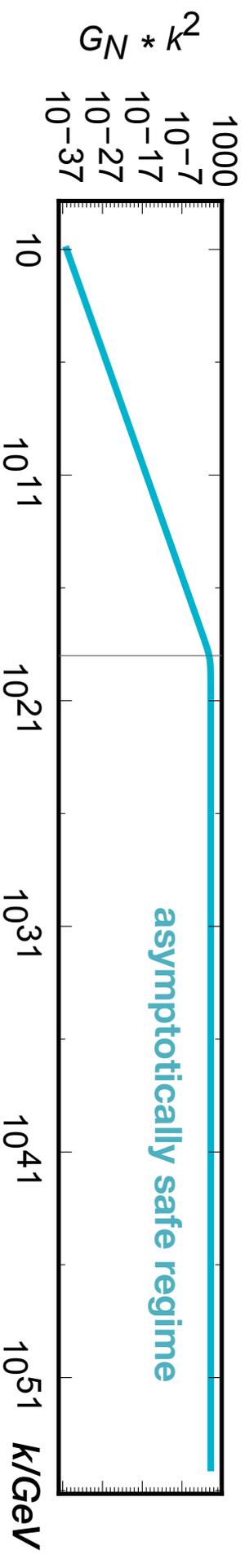
Blurred GRMHD



the light ring comes from null geodesics probing near-horizon geometry

Asymptotically safe black-hole shadows

[Held, Gold, AE '19]



gravity “weaker than classical” in the UV

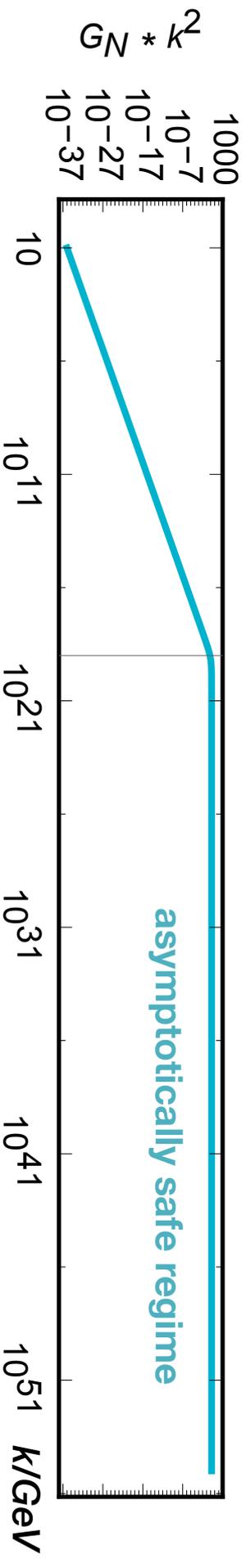
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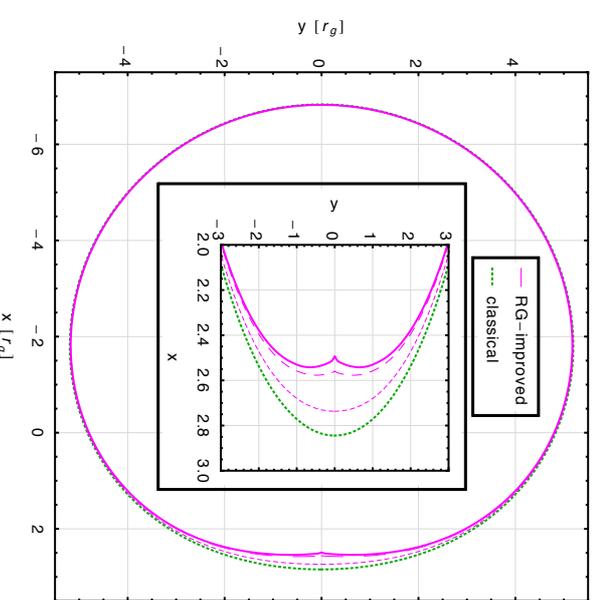


gravity “weaker than classical” in the UV

- expect resolution of classical spacetime singularities
- expect more compact horizon & shadow due to effective “repulsive force” from QG

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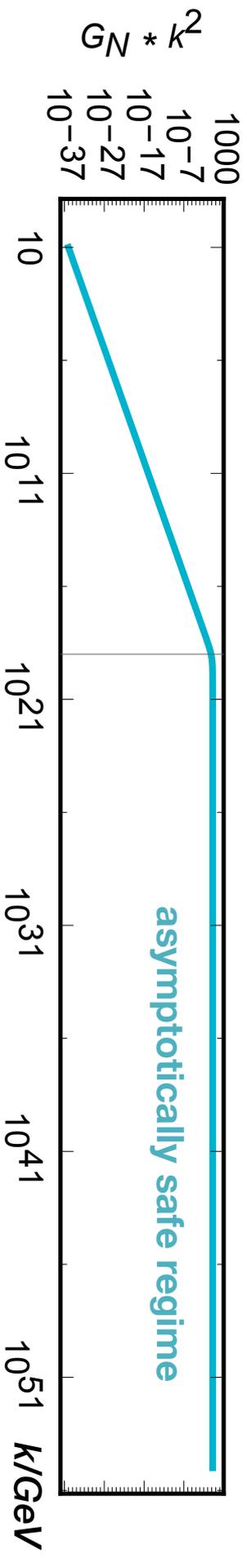
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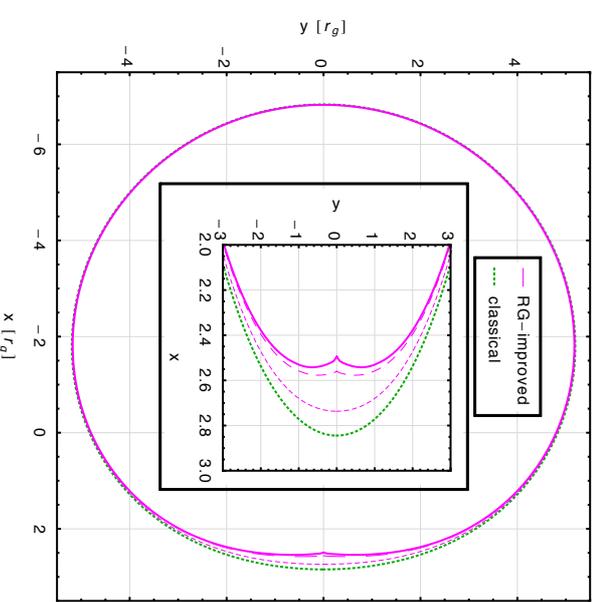
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- unique signature:
- mass-measurements close to horizon & at large r differ

EHT & measurements of Keplerian orbits of stars constrain

$$\gamma < 10^{95}$$



[Held, Gold, AE '19]

Asymptotically safe shadows as a blueprint for QG effects

[Held, Gold, AE '19]

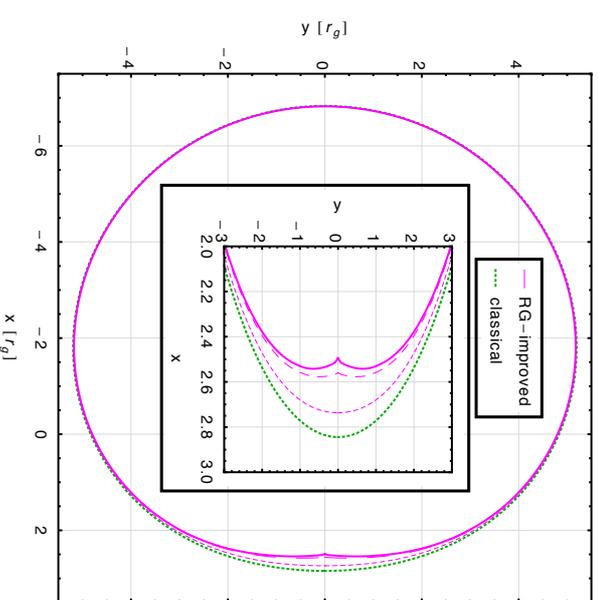
generic mechanism for singularity resolution: gravity weaker in the UV

→ effective “repulsive force” from QG

→ effectively like reduced mass close to horizon

Expectation for many QG models:

- more compact shadow than classically
- observational signature: mass-measurements at different radii differ



[Held, Gold, AE '19]

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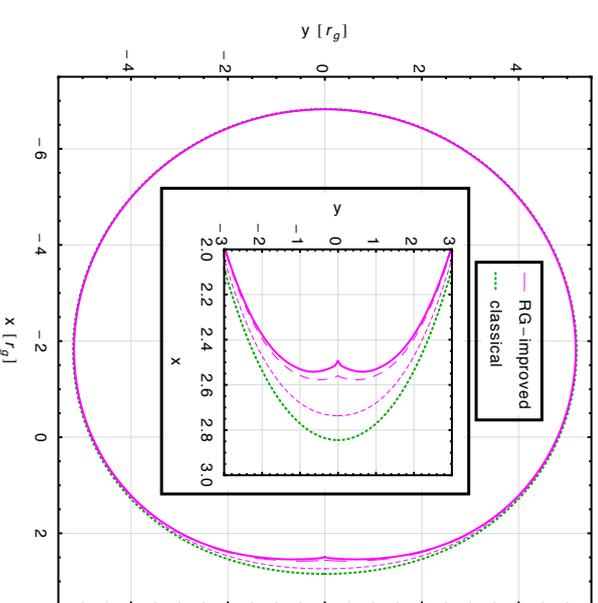
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examples with “improved” metrics with these characteristics:

Loop Quantum Gravity

Non-commutative spacetime

stringy corrections

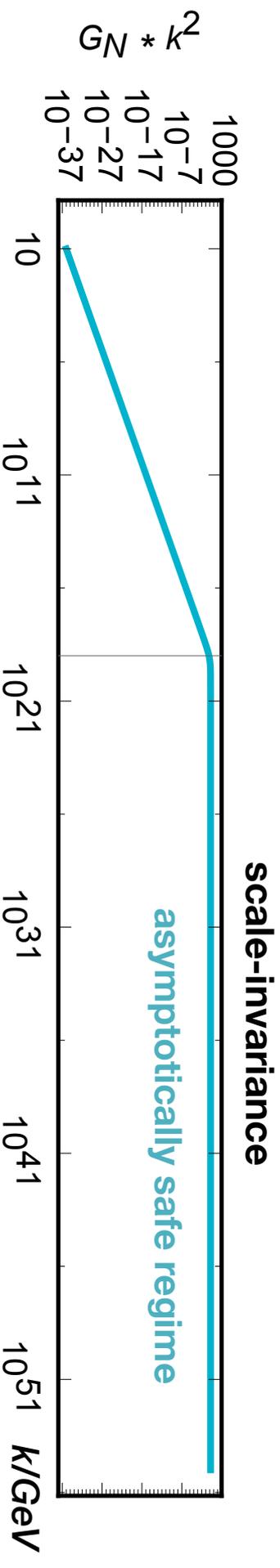


[Held, Gold, AE '19]

Physics from a fixed point

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- interplay with matter (“matter matters”)
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Properties of spacetime geometry



- **dynamical dimensional reduction (as “measured” by random walker)**

[Lauscher, Reuter '05; Reuter, Saueressig '11, Calcagni, AE, Saueressig '13]

- **difference between different measures of dimensionality**

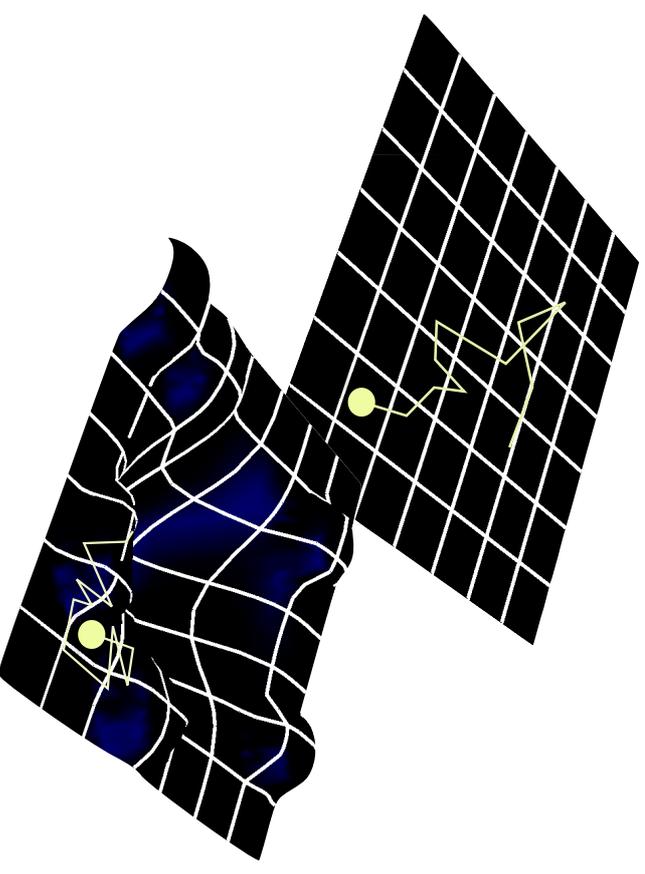
[Reuter, Saueressig '11]

$$(\partial_\sigma - \nabla^2) P(x, x', \sigma) = 0$$

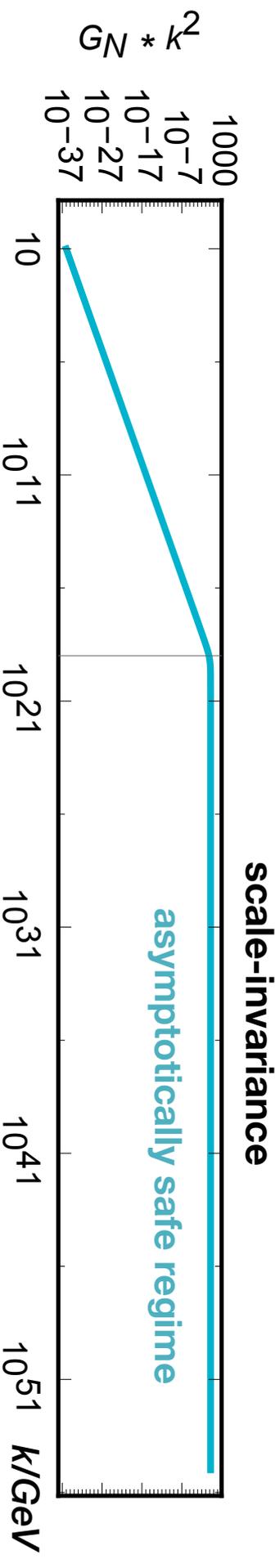
$$\rightarrow (\partial_\sigma - \langle \nabla^2 \rangle_k) P(x, x', \sigma) = 0$$

$$k \sim \frac{1}{\sigma^{1/4}}$$

$$\rightarrow \left(\frac{\partial}{\partial \sigma^{1/2}} - \nabla^2 \right) P(x, x', \sigma) = 0$$



Properties of spacetime geometry

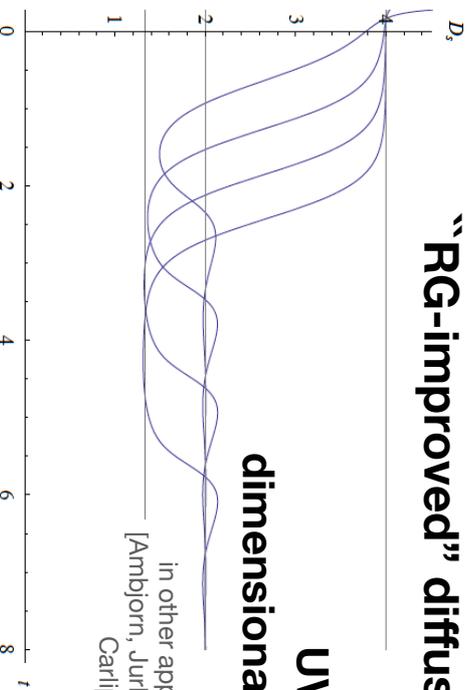


- dynamical dimensional reduction (as “measured” by random walker)
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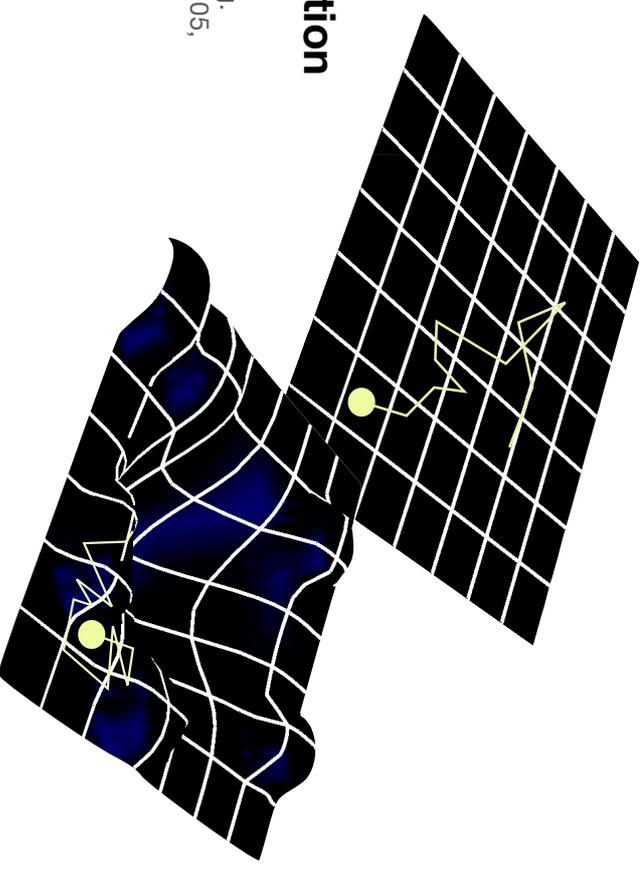
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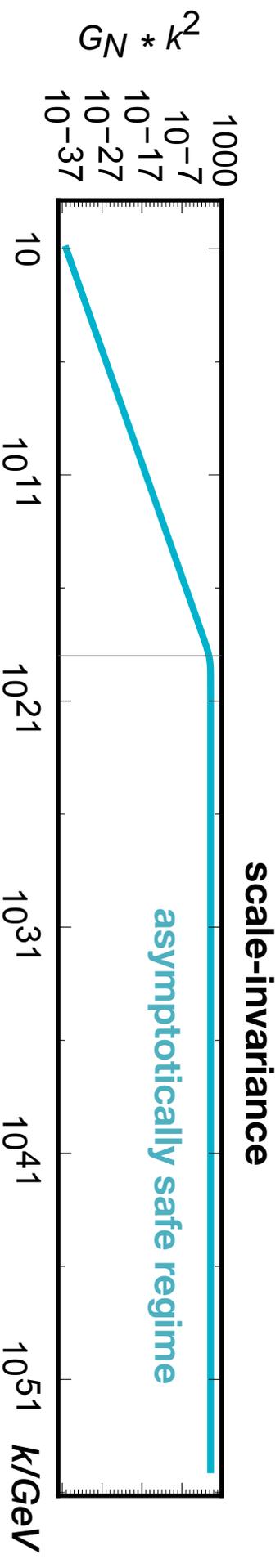
classical spacetime “RG-improved” diffusion



in other approaches, e.g.
[Ambjorn, Jurkiewicz, Loll '05,
Carlip '09...]



Properties of spacetime geometry



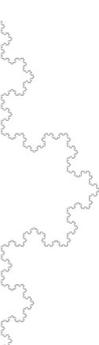
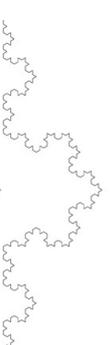
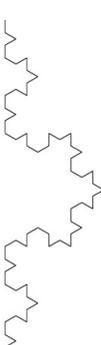
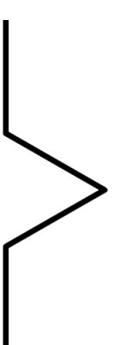
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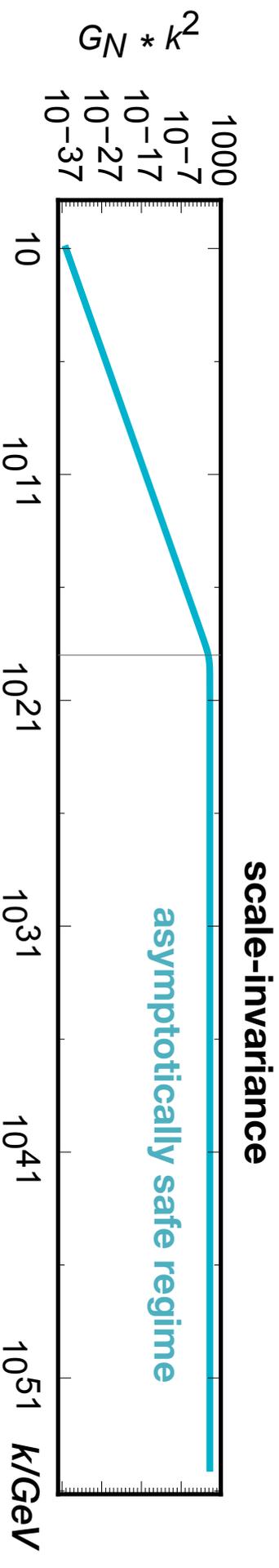
fractal-like spacetime



[Ambjorn, Jurkiewicz, Loll '05, Carlip '09...]

Koch curve

Properties of spacetime geometry



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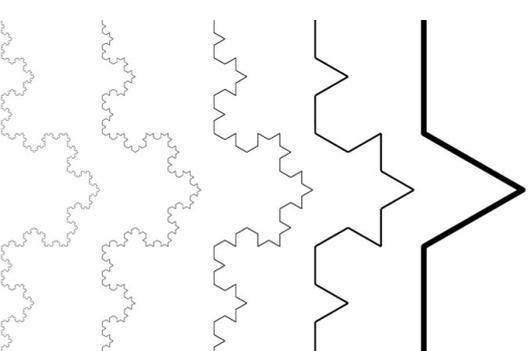
[Reuter, Saueressig '11]

fractal-like spacetime



[analogy: M. Reuter “Quantum spacetime and the Renormalization Group” 2018]

[Ambjorn, Jurkiewicz, Loll '05, Carlip '09...]



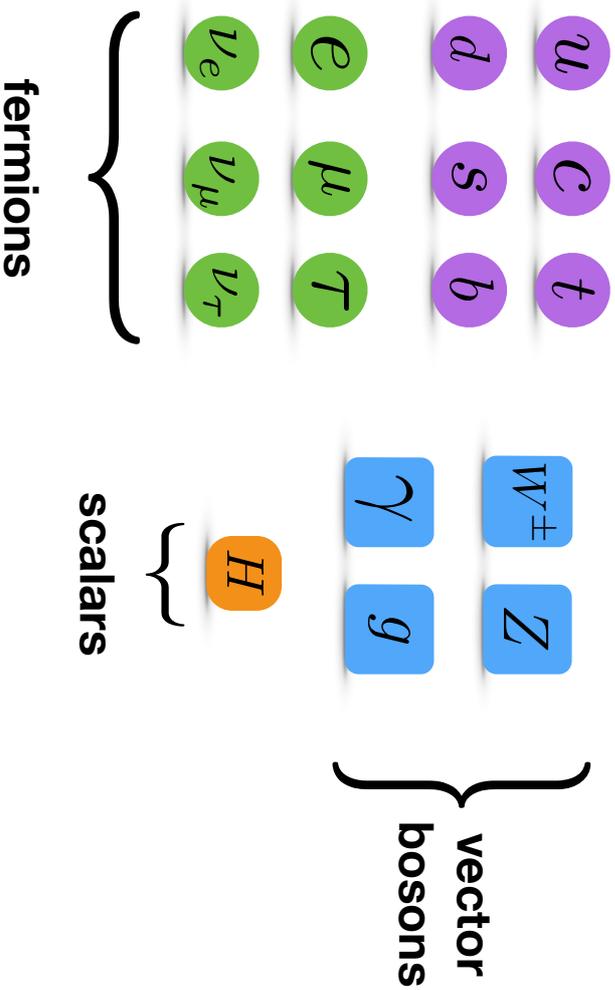
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Impact of matter on quantum structure of spacetime

Standard Model of particle physics



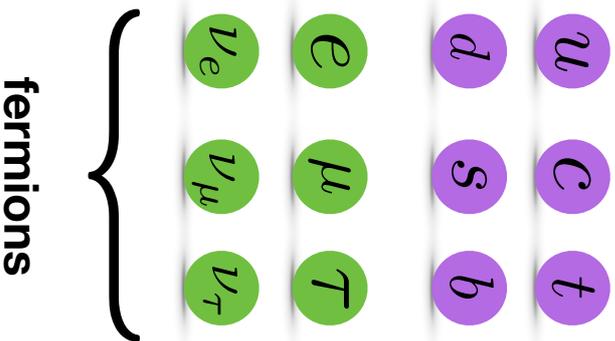
$$\beta_G = 2G - \frac{G^2}{6\pi} \left(\underbrace{N_s + 2N_f}_{\text{screening}} - \underbrace{4N_v - 46}_{\text{antiscreening}} \right) + \dots$$

screening

antiscreening

Impact of matter on quantum structure of spacetime

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vector bosons



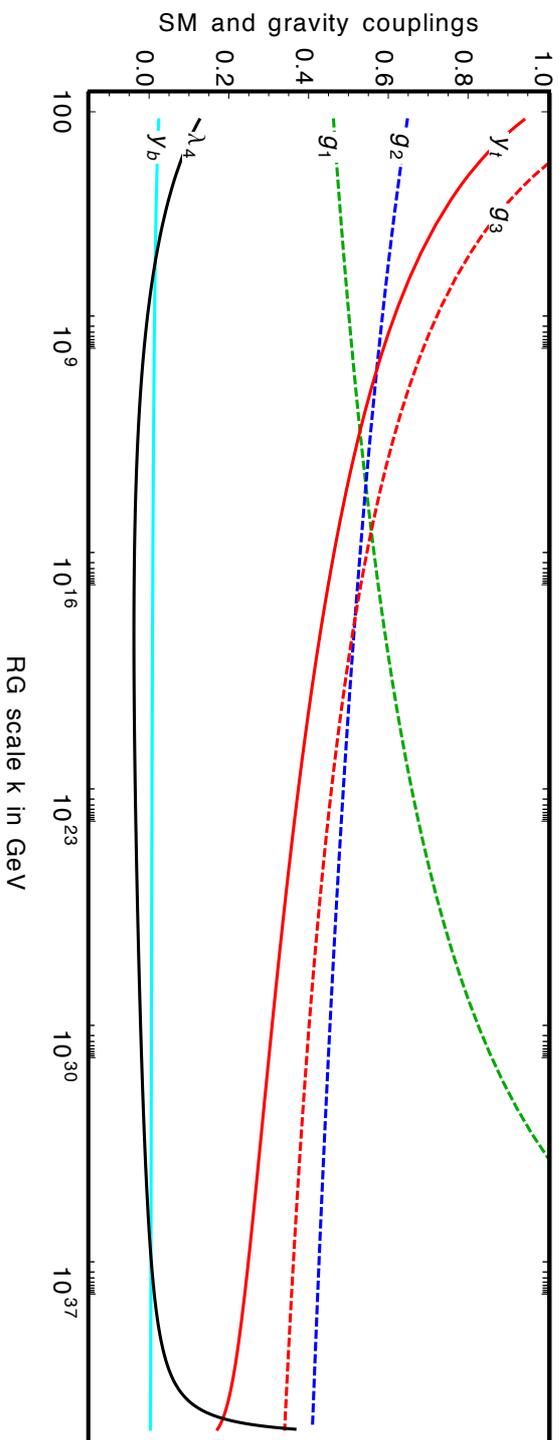
compatible with asymptotically safe fixed point in gravity (in truncations) (observational consistency test passed)

antiscreening

$$\beta_G = 2G - \frac{G^2}{6\pi} \left(\underbrace{N_s + 2N_f}_{\text{screening}} - \underbrace{4N_v - 46}_{\text{antiscreening}} \right) + \dots$$

Status of the Standard Model

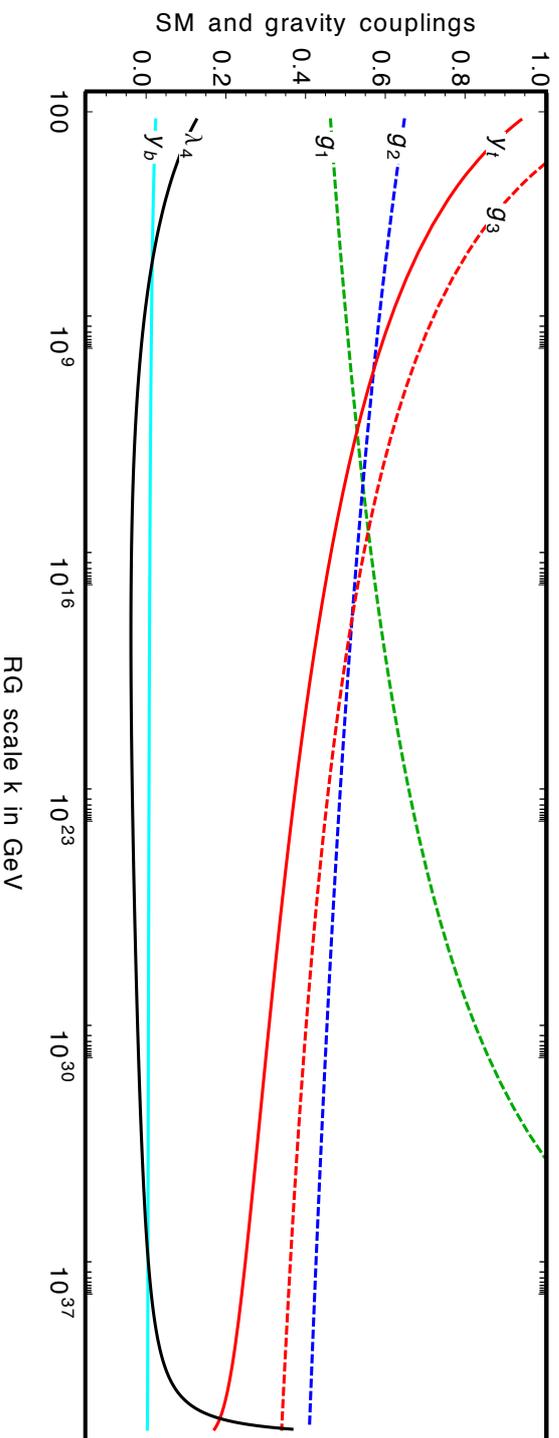
After LHC



@ $M_h = 125$ GeV: can extend the Standard Model all the way to the Planck scale

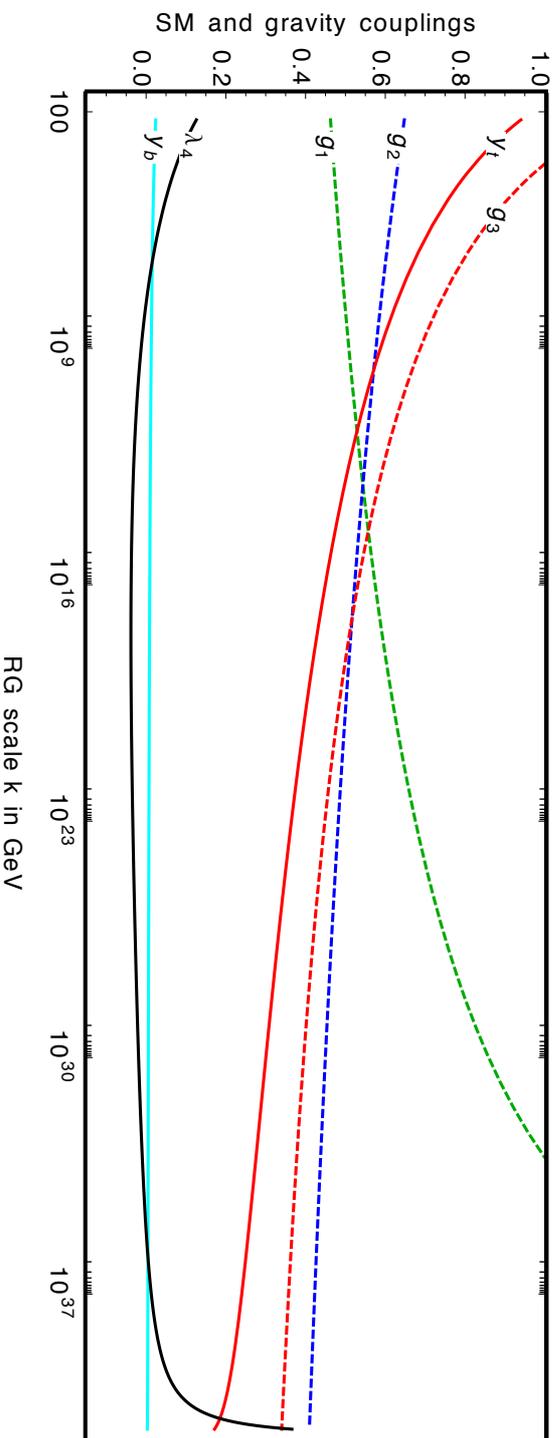


Status of the Standard Model



- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**
- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**
- **gravitational interaction is missing**

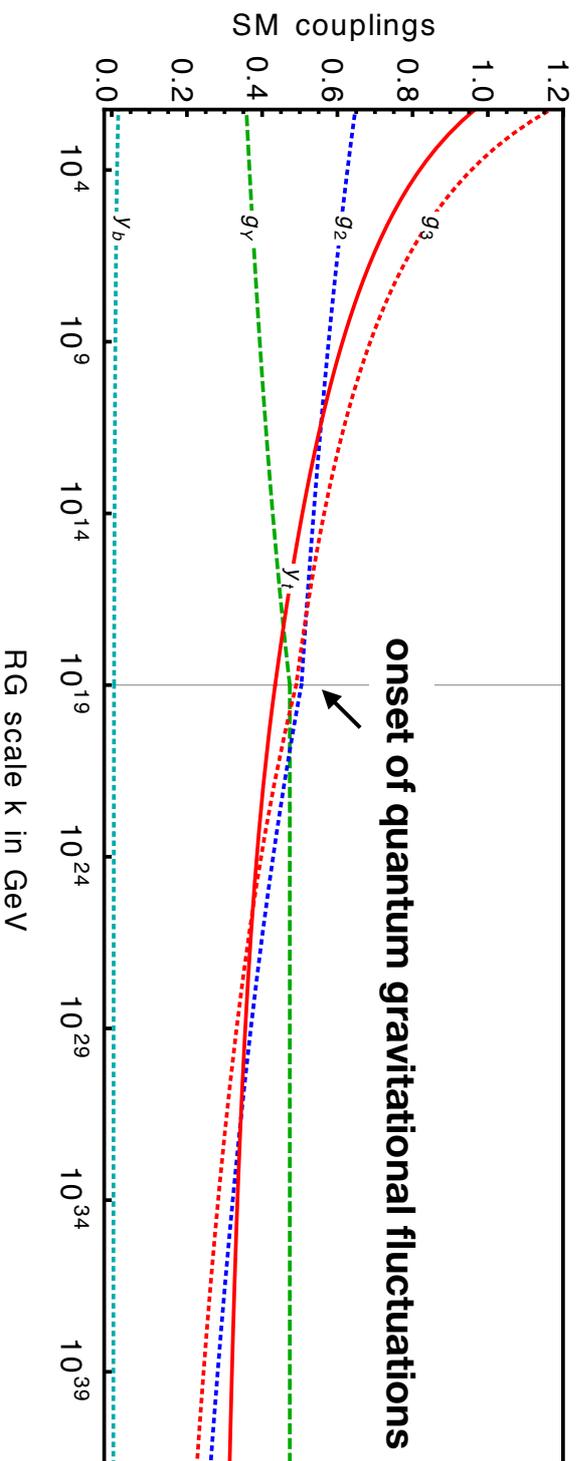
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→ **are these challenges/problems connected?**

Hints for asymptotically safe gravity + Standard Model



- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**
 - **quantum-gravity induced ultraviolet completion for Standard Model**
- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**
 - **potentially calculable from first principles (→ tests of QG at e/w scale)**

Observational tests of asymptotically safe quantum gravity?

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quantum fluctuations of spacetime at $M_{\text{pl}} = \sqrt{\frac{\hbar c}{G_N}} = 10^{19} \text{ GeV} = 10^{15} \text{ ELHC}$

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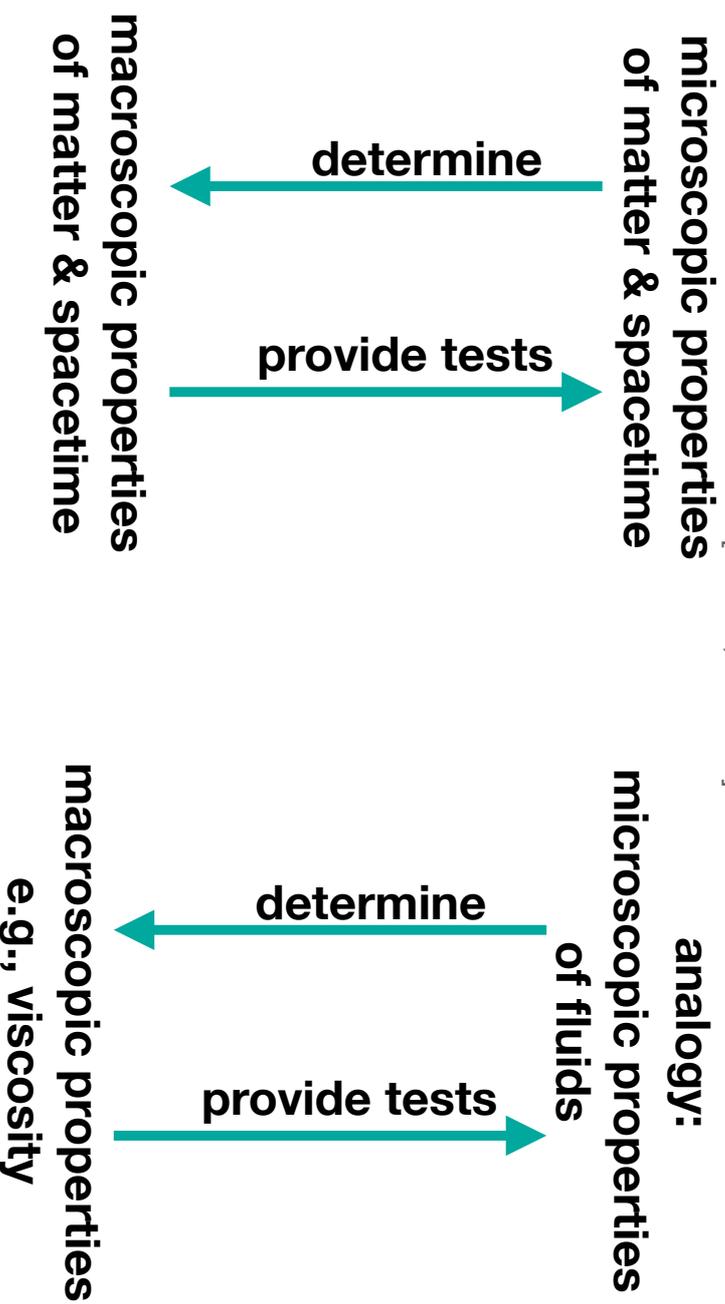
[see AE, Gies '11]

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Predictive power of asymptotic safety - proof of principle: Abelian gauge coupling

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- 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

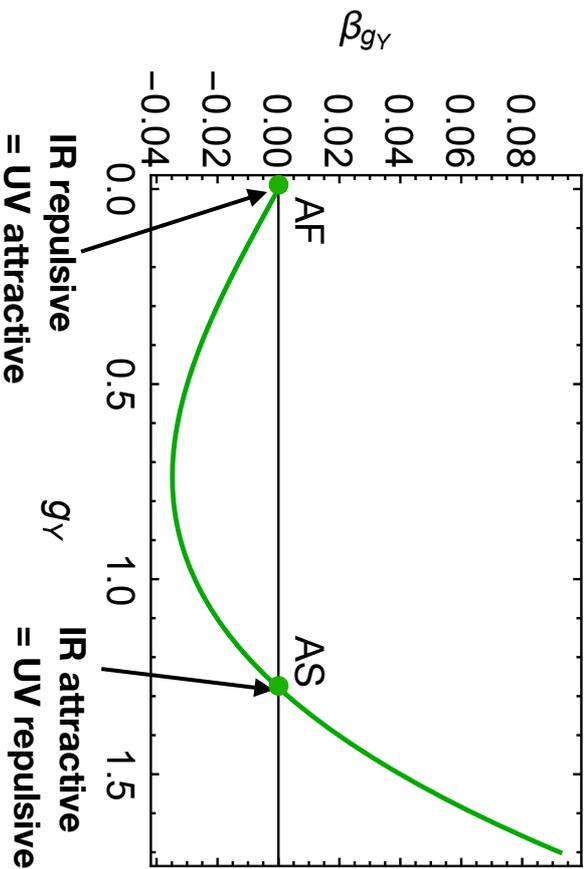
$f_g = \text{const} \geq 0$ above M_{pl}

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[Daum, Harst, Reuter '09;
Folkerts, Litm, Pawłowski '09;
Harst, Reuter '11;
Christiansen, AE '17;
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Predictive power of asymptotic safety - proof of principle: Abelian gauge coupling

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matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting

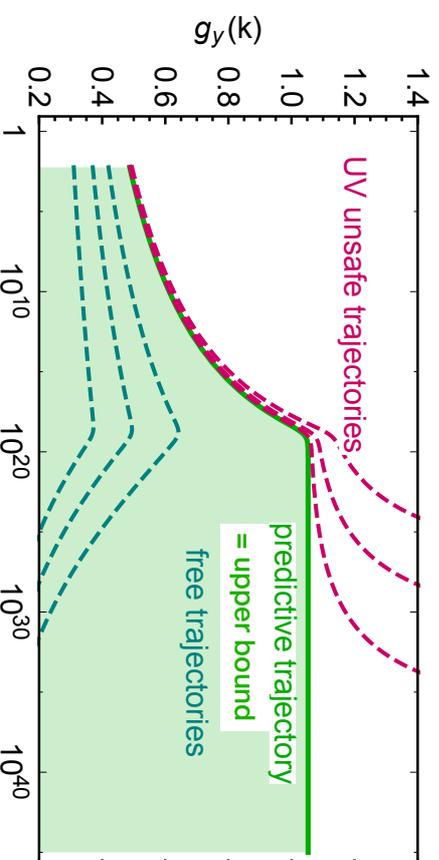
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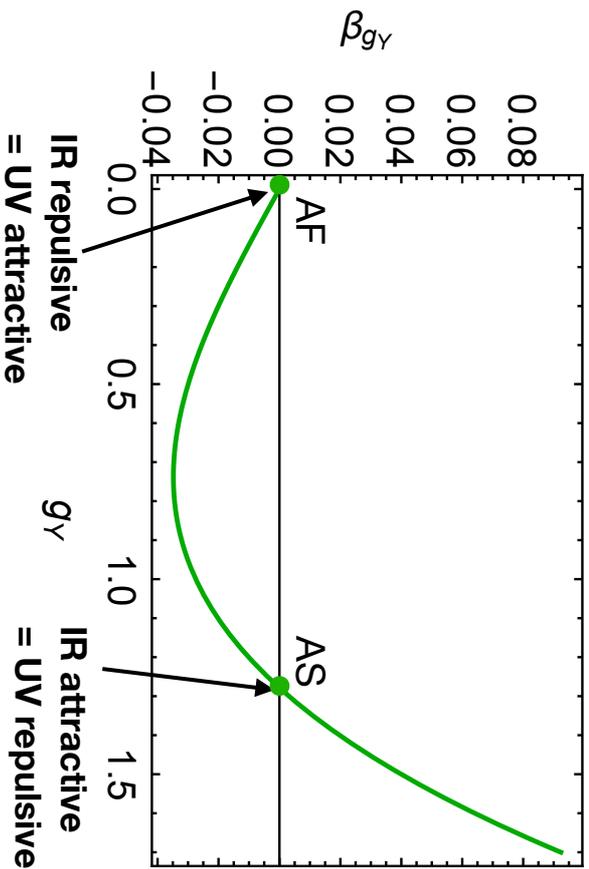
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RG scale k in GeV [AE, Versteegen '17]

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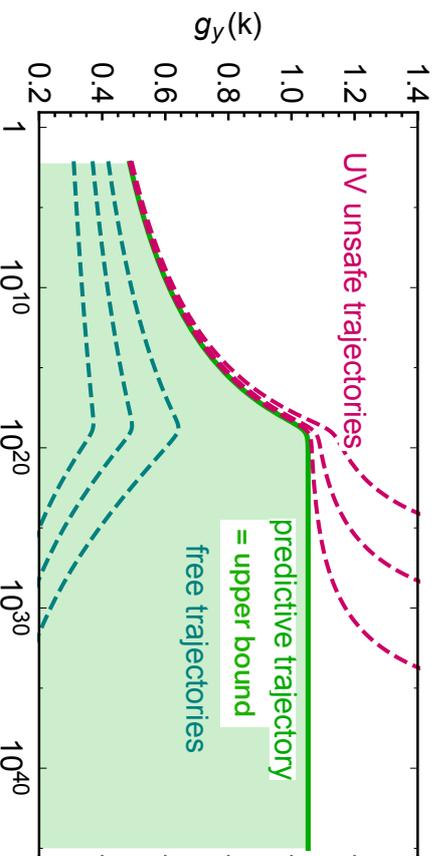
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⇒ large IR values of g_Y cannot be reached from any fixed point

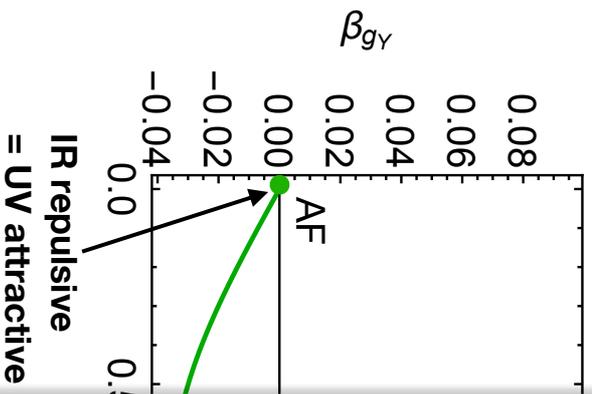
⇒ bound on g_Y is unique value reached from interacting fixed point



RG scale k in GeV [AE, Versteegen '17]

Predictive power of asymptotic safety - proof of principle: Abelian gauge coupling

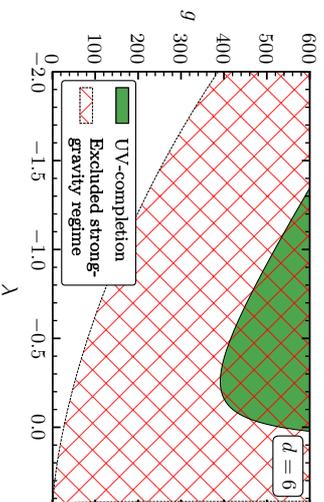
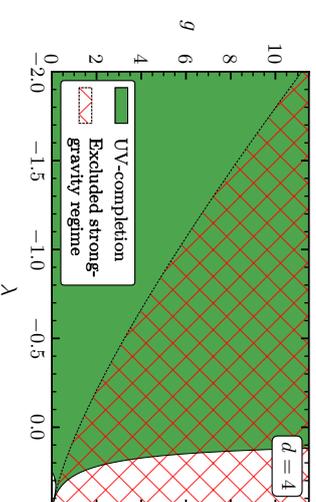
- Asymptotically safe quantum gravity could act like effective change of dimensionality



matter & gravity:
strong gravity: as
strong matter: UV
balance: UV safe

D=4 dynamically selected critical dimension for asymptotically safe gravity and matter

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

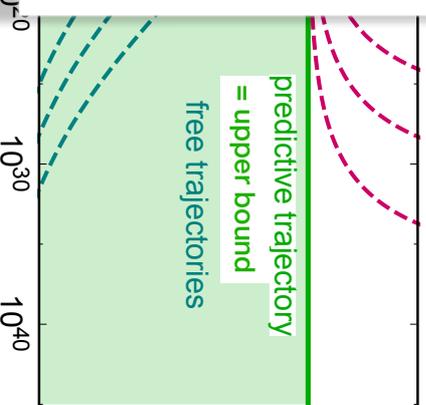


[AE, Schiffer, PLB 793, 383, '19]

\dots
 metric fluctuations

[Daum, Harst, Reuter '09;
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of g_Y cannot
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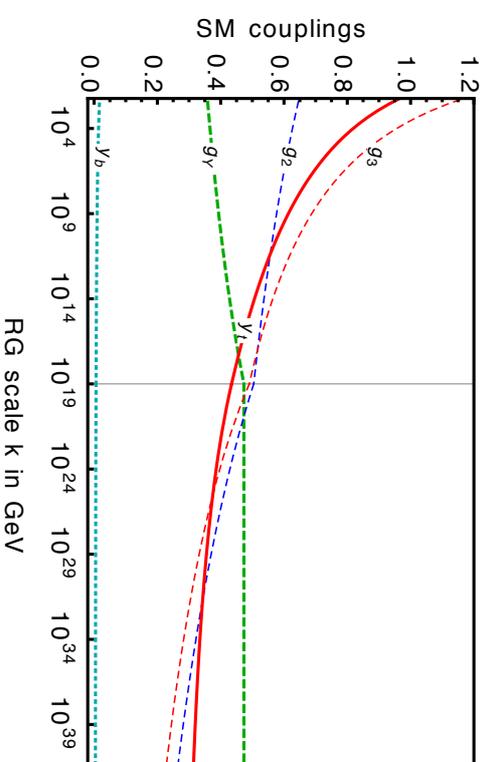
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Asymptotically safe guide to the literature on SM + QG



required:

- extended truncations
- confirmation from other methods

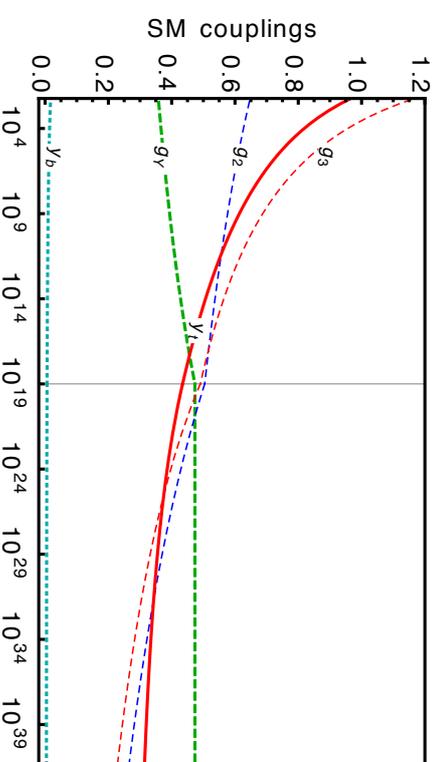


Asymptotically safe guide to the literature on SM + QG



required:

- extended truncations
- confirmation from other methods



Hints in truncations of RG flow from functional RG techniques
that SM could become UV complete by AS quantum gravity fluctuations:

- AF in non-Abelian couplings preserved

[Daum, Harst, Reuter JHEP 1001 (2010) 084; Folkerts, Litim, Pawłowski, Phys.Lett. B709 (2012) 234-241; Christiansen, Litim, Pawłowski, Reichert Phys.Rev. D97 (2018) no.10, 106012]

- AF/AS in U(1)

[Harst, Reuter JHEP 1105 (2011) 119; Christiansen, AE, Phys.Lett. B770 (2017) 154-160; AE, Versteegen JHEP 1801 (2018) 030]

- Higgs quartic vanishes (approximately?) at Planck scale

[Narain, Percacci Class.Quant.Grav. 27 (2010) 075001; Shaposhnikov, Wetterich Phys.Lett. B683 (2010) 196-200, Oda, Yamada, Class.Quant.Grav. 33 (2016) no.12, 125011; Hamada, Yamada JHEP 1708 (2017) 070; AE, Hamada, Lumma, Yamada Phys.Rev. D97 (2018) no.8, 086004; Pawłowski, Reichert, Wetterich, Yamada arXiv:1811.11706]

- AF/AS in Yukawas

[AE, Held, Pawłowski Phys.Rev. D94 (2016) no.10, 104027; AE, Held, Phys.Lett. B777 (2018) 217-221; AE, Held arXiv:1803.04027, Phys.Rev.Lett. 121 (2018) no.15, 151302]

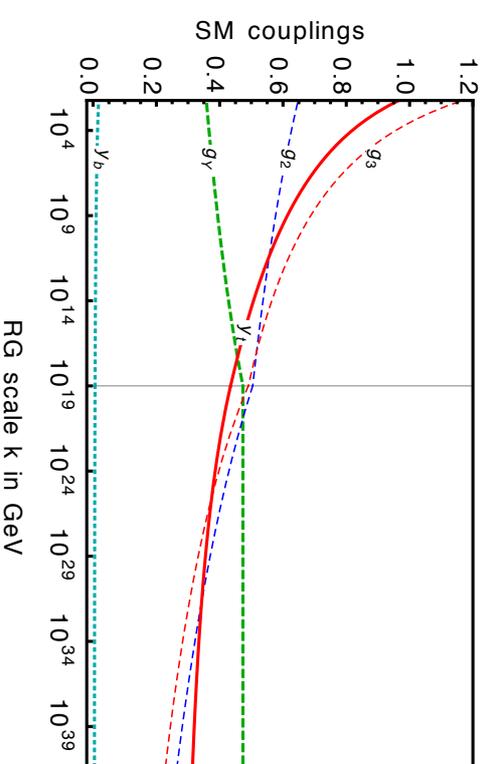
- chiral symmetry unbroken (light fermions)

[AE, Gies, New J.Phys. 13 (2011) 125012; Meibohm, Pawłowski, Eur.Phys.J. C76 (2016) no.5, 285; AE, Lippoldt, hys.Lett. B767 (2017) 142-146; Gies, Martini, Phys.Rev. D97 (2018) no.8, 085017]

Asymptotically safe guide to the literature on BSM + QG



- required:
- extended truncations
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Hints in truncations of RG flow from functional RG techniques
that some BSM models could become UV complete by AS quantum gravity fluctuations:

- AS in GUTs with prediction of gauge coupling & Higgs quartics

[AE, Held, Wetterich, Phys.Lett. B782 (2018) 198-201, & to appear]

- Higgs portal to uncharged scalar dark matter vanishes

[AE, Hamada, Lumma, Yamada, Phys.Rev. D97 (2018) no.8, 086004]

... lots more to do - join the effort!