Title: Black Holes in Asymptotically Safe Gravity

Date: Jul 23, 2013 11:45 AM

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Abstract: <span>In this talk, I will briefly review the main ingredients of the gravitational asymptotic safety program before focusing on the phenomenological consequences originating from the scale-dependent couplings characteristic for the theory. In particular, I will discuss recent unexpected developments in unveiling the structure of microscopic black holes within Asymptotic Safety: in the asymptotic UV the structure of the quantum solutions is universal and given by the classical Schwarzschild-de Sitter solution, entailing a self-similarity between the classical and quantum regime. As a consequence asymptotically safe black holes evaporate completely and no Planck-size remnants are formed. The relation of these results to previous criticism that Asymptotic Safety does not reproduce the state-count of a conformal field theory will be addressed.</span>

# Black Holes in Asymptotically Safe Gravity

**Frank Saueressig**

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*Radboud University Nijmegen*

M. Reuter and F. S., Lect. Notes Phys. 863 (2013) 185, arXiv:1205.5431

B. Koch and F. S., arXiv:1306.1546

Loops 13, Perimeter Institute, July 23rd, 2013

# Outline

- black holes as inspiration for quantum gravity
- Asymptotic Safety in a nutshell
- physics from the effective average action
- black holes in Asymptotic Safety
- the HL-CDT-AS connection
- 3 take-away messages

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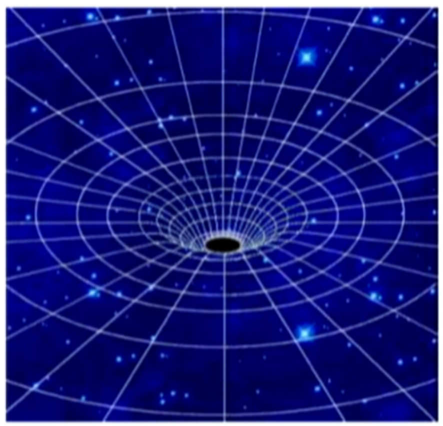
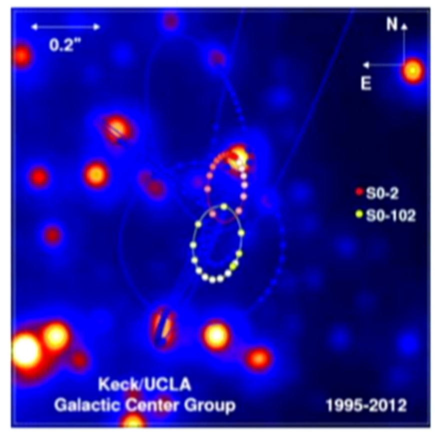
## Classical black holes

vacuum solution of Einstein's equations

$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 d\Omega_2^2$$

- observed in Nature






  - AGN's: power most energetic processes in the universe

## Black holes from a theoretical perspective

- uniqueness theorems:
  - black holes are characterized by small number of parameters $M, J, q$
- curvature singularity at origin
  - General Relativity predicts its own breakdown
- horizons:

$$r_{\mathrm{SH}} = 2 G M$$

- semi-classical: thermodynamics associated with horizon

$$T_{\mathrm{SH}} = \frac{1}{8\pi G M} \quad , \quad S_{\mathrm{SH}} = \frac{A}{4G}$$

  - black holes emit black body radiation
  - origin of the horizon entropy?

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- information-loss problem

particle collision
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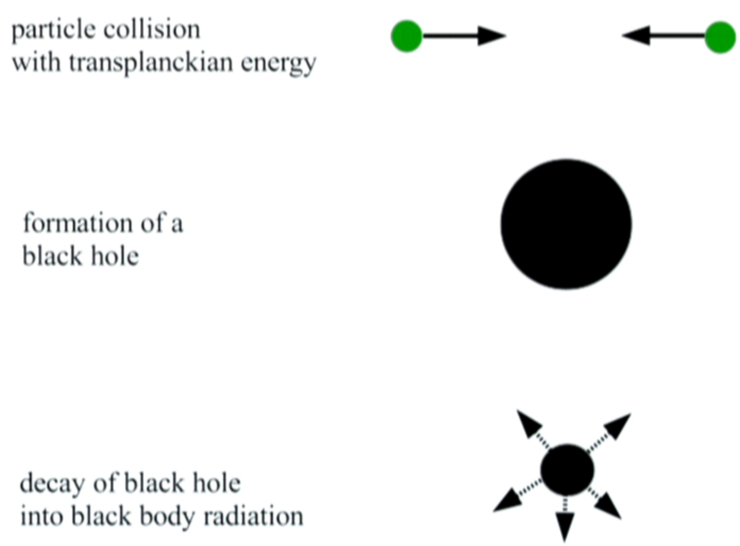


questions should find answers within

Quantum Gravity

## Asymptotic Safety

## in a nutshell

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# Perturbative quantization of General Relativity

Dynamics of General Relativity governed by Einstein-Hilbert action

$$S^{\mathrm{EH}} = \frac{1}{16\pi G_N} \int d^d x \sqrt{g} \, \{-R + 2\Lambda\}$$

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Wilsonian picture of perturbative renormalization:

⇒ dimensionless coupling constant attracted to GFP (free theory) in UV

- introduce dimensionless coupling constants

$$g_k = k^{d-2} G_N \,, \quad \lambda_k \equiv \Lambda k^{-2}$$

- GFP: flow governed by mass-dimension:

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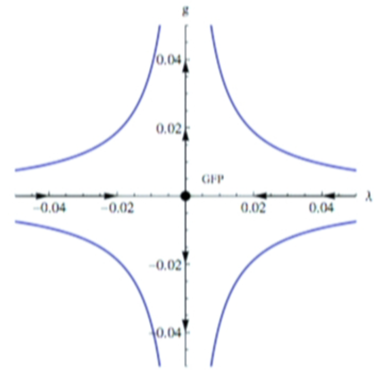

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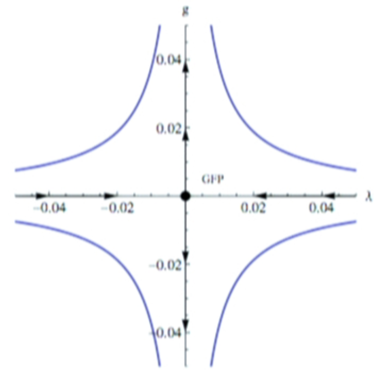


General Relativity is perturbatively non-renormalizable

## Building blocks for Asymptotic Safety

Requirements:

a) non-Gaussian fixed point (NGFP)

- controls the UV-behavior of the RG-trajectory
- ensures the absence of UV-divergences

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- recover gravitational physics captured by General Relativity:
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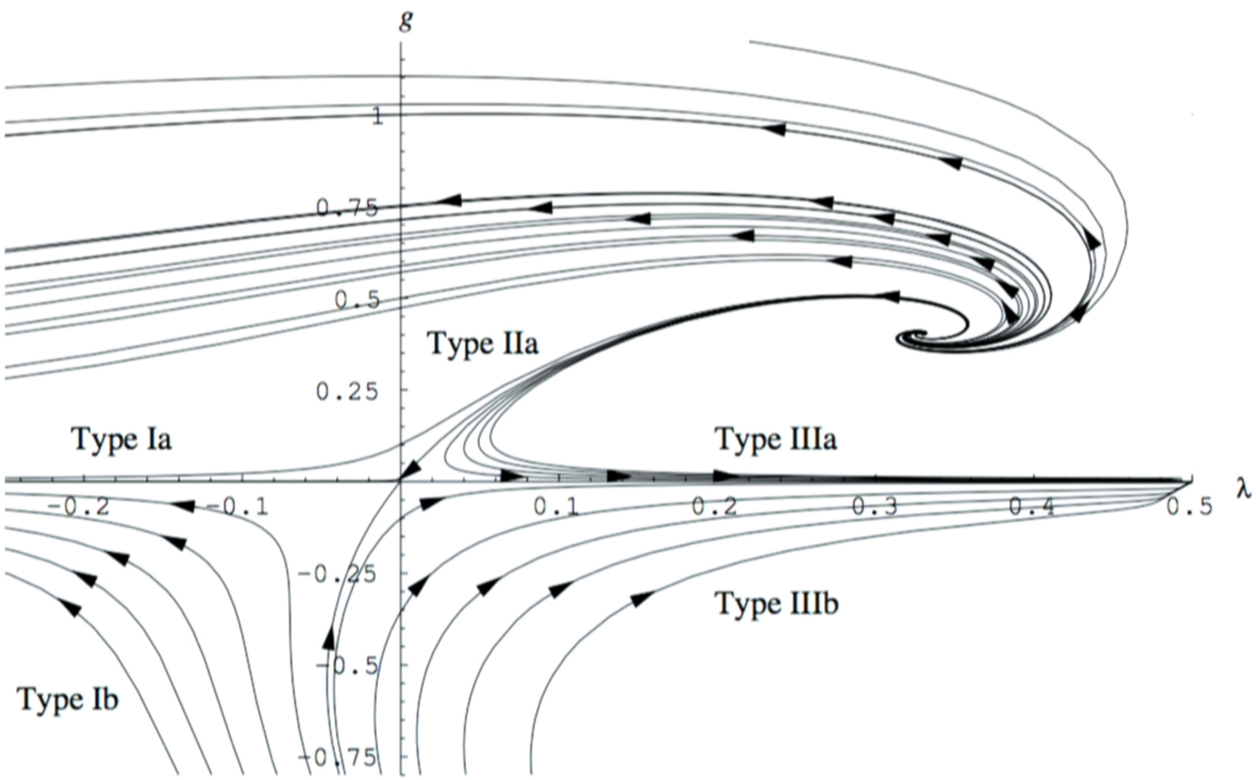
Quantum Einstein Gravity (QEG)

## Einstein-Hilbert-truncation: the phase diagram

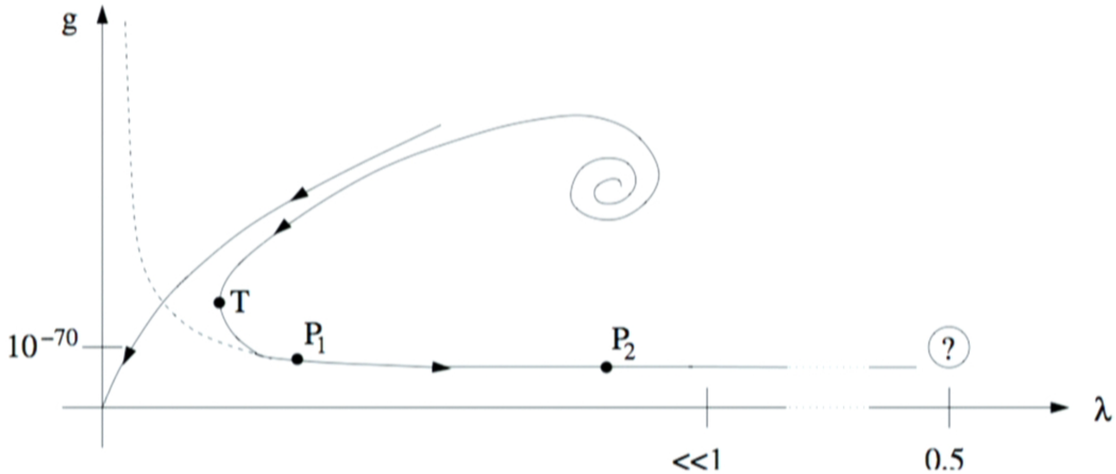
M. Reuter, F. S., Phys. Rev. D **65** (2002) 065016, hep-th/0110054



## The RG trajectory realized in Nature

M. Reuter, H. Weyer, JCAP 0412 (2004) 001, hep-th/0410119

measurement of $G_N, \Lambda$ in classical regime:



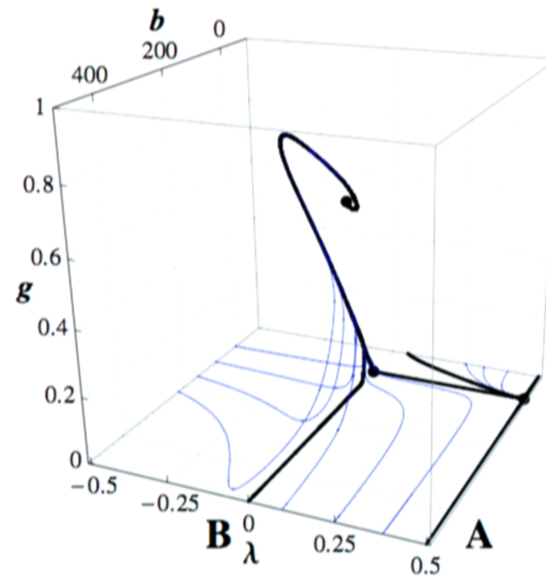

- originates at NGFP (quantum regime: $G(k) = k^{2-d} g_*, \Lambda(k) = k^2 \lambda_*$)
- passing *extremely* close to the GFP
- long classical GR regime (classical regime: $G(k) = \mathrm{const}, \Lambda(k) = \mathrm{const}$)
- $\lambda \lesssim 1/2$: IR fixed point?

## Charting the RG-flow of the $R^2$-truncation

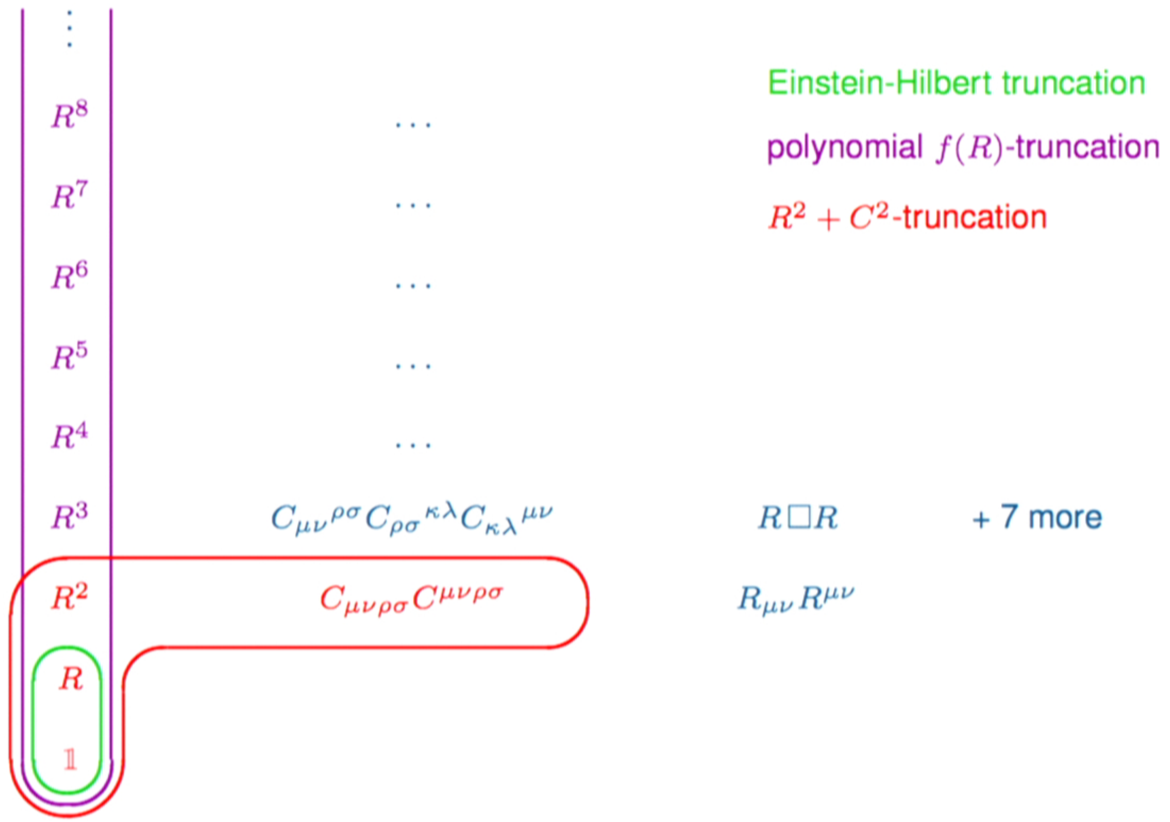
O. Lauscher, M. Reuter, Phys. Rev. D66 (2002) 025026, hep-th/0205062
S. Rechenberger, F.S., Phys. Rev. D86 (2012) 024018, arXiv:1206.0657

Extending Einstein-Hilbert truncation with higher-derivative couplings

$$\Gamma_k^{\text{grav}}[g] = \int d^4x \sqrt{g} \left[ \frac{1}{16\pi G_k} (-R + 2\Lambda_k) + \frac{1}{b_k} R^2 \right]$$



## Charting the theory space spanned by $\Gamma_k^{\mathrm{grav}}[g]$



## Exploring the gravitational theory space

Some key results:

- evidence for asymptotic safety
  - $\Rightarrow$ non-Gaussian fixed point provides UV completion of gravity
- low number of relevant parameter:
  - $\Rightarrow$ dimensionality of UV-critical surface $\simeq 3$
- perturbative counterterms:
  - gravity + matter: asymptotic safety survives 1-loop counterterm

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Study black holes within Asymptotic Safety?

## Effective average action $\Gamma_k$ for gravity

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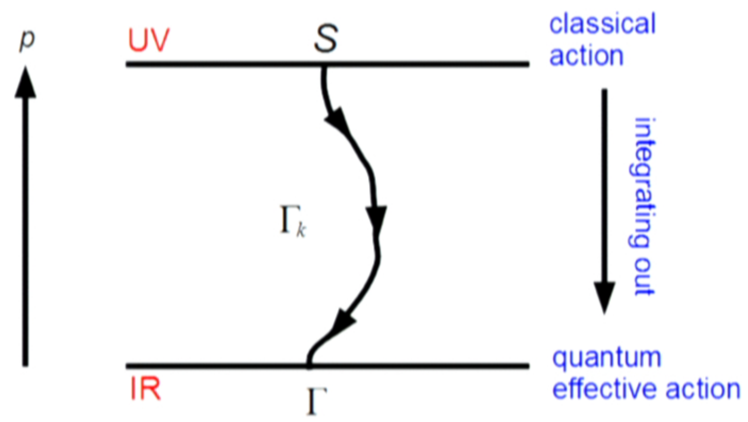
central idea: integrate out quantum fluctuations shell-by-shell in momentum-space



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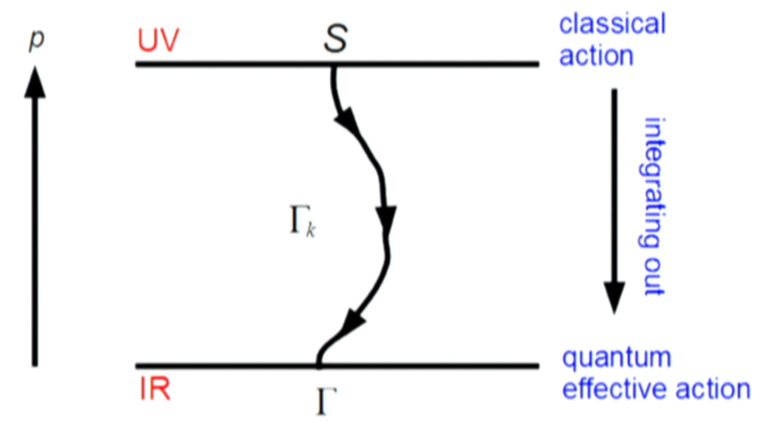


- scale-dependence governed by functional renormalization group equation

$$k\partial_k \Gamma_k[\phi, \bar{\phi}] = \frac{1}{2} \mathrm{STr} \left[ \left( \Gamma_k^{(2)} + \mathcal{R}_k \right)^{-1} k\partial_k \mathcal{R}_k \right]$$

  - effective vertices in encorporate quantum-corrections with $p^2 > k^2$

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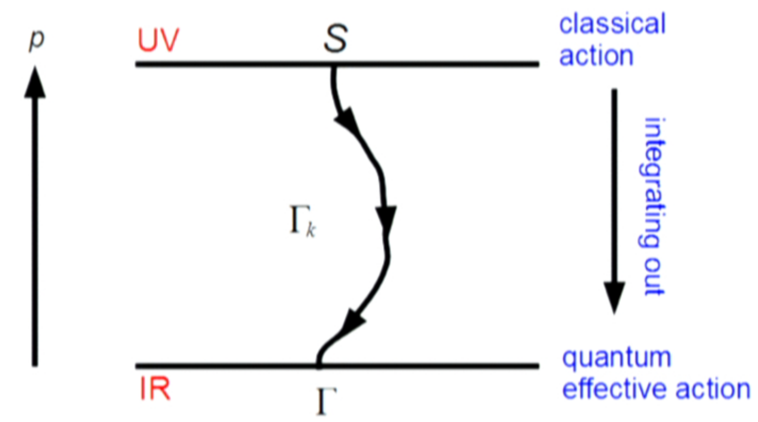


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classical space-times from general relativity

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$$R_{\mu\nu} = \frac{2}{2-d}\,\Lambda\, g_{\mu\nu}$$

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quantum theory: compute observables

$$\langle \mathcal{O} \rangle \equiv \int \mathcal{D}\gamma \mathcal{D}C \mathcal{D}\bar{C} \, \mathcal{O}[\gamma] \, e^{-S_{\mathrm{bare}}[\gamma, C, \bar{C}]}$$

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**Very hard!**

## Quantum physics from average action $\Gamma_k$

A. Bonanno, M. Reuter, Phys. Rev. D 60 (1999) 084011, gr-qc/9811026

essential: $\Gamma_k$ provides effective description of physics at scale $k$:

- capture quantum effects by “RG-improvement” scheme:
  - exploit information contained in running couplings

1. transition: classical $S^{\mathrm{EH}} \to$ average action $\Gamma_k[g]$
   - one-parameter family of effective actions valid at different scales
2. single-scale problem may allow for “cutoff-identification”
   - express RG-scale $k$ through physical cutoff $\xi$
     - requires: physical intuition
3. obtain: modification of classical system by quantum effects

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EXIT

## Practical RG-improvement schemes

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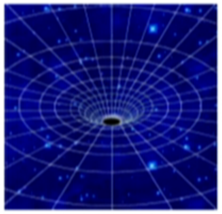
3. improved average action
   - $\Gamma_k$: replace $G_N \longrightarrow G(k(\xi))$

     $k^2 \propto R \longrightarrow$ Einstein-Hilbert action $\mapsto f(R)$-gravity theory
   - compute modified equations of motion
   - solve modified equations of motion

## Black holes in Asymptotic Safety



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## Everybody knows: Asymptotic Safety is wrong ...

A. Shomer, arXiv:0709.3555

- state-count of a $d$-dimensional CFT implies

$$\frac{S}{R^{d-1}} \propto \left(\frac{E}{R^{d-1}}\right)^{\nu_{\rm CFT}} \quad , \quad \nu_{\rm CFT} = \frac{d-1}{d}$$

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- "everybody knows": grav. dof at high energies are black holes

$$S \propto G_N^{-1} R^{d-2} \quad , \quad E \propto G_N^{-1} R^{d-3}$$

implies

$$S \propto G_N^{1/d-3} E^{\nu_{\mathrm{BH}}} \quad , \quad \nu_{\mathrm{BH}} = \frac{d-2}{d-3}$$

thus gravity has the wrong state-count for a CFT

$$\nu_{\mathrm{BH}} \neq \nu_{\mathrm{CFT}}$$

## Classical black hole solutions with cosmological constant

spherical symmetric, static solutions of Einstein's equations

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega_2^2$$

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horizons

- $\Lambda \leq 0$ : black hole horizon $r_{\mathrm{bh}}$
- $\Lambda > 0, M < (3G\sqrt{\Lambda})^{-1}$ : black hole + cosmological horizon $r_{\mathrm{bh}} < r_{\mathrm{cosmo}}$

  $\Lambda > 0, M \geq (3G\sqrt{\Lambda})^{-1}$ : naked singularity

horizon temperature

$$T = \frac{1}{4\pi} \left. \frac{\partial f(r)}{\partial r} \right|_{r=r_{\mathrm{horizon}}}$$

## Cutoff identification for black holes

[A. Bonanno, M. Reuter, gr-qc/9811026]
[A. Bonanno, M. Reuter, hep-th/0002196]
[K. Falls, D. F. Litim, A. Raghuraman, arXiv:1002.0260]

requirements for cutoff-identification $k = k(\text{physical scale})$

- invariance under coordinate transformations
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proposal

$$k(P) = \frac{\xi}{d(P)}\,, \qquad d(P) = \int_{\mathcal{C}_r} \sqrt{|ds^2|}$$

- results compatible with improved e.o.m and action scheme

short distance behavior

$$k(r) = \frac{3\xi}{2}\,\sqrt{2GM}\,r^{-3/2}\,(1 + \mathcal{O}(r))$$

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## High-energy behavior of RG-improved black holes

- classical line element

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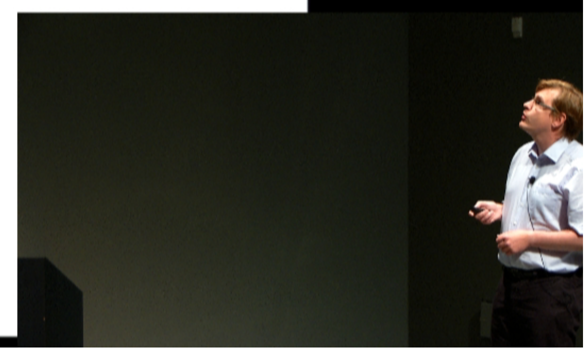

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- Quantum-improved black hole at NGFP:

$$\boxed{f_*(r) = 1 - \frac{2\,M\,G_0}{r}\left(\frac{3}{4}\lambda_*\xi^2\right) - \frac{1}{3}\left(\frac{4g_*}{3G_0\xi^2}\right)r^2}$$

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Consequences from including a running cosmological constant $\lambda_* \neq 0$:

- RG-improved line-element: Schwarzschild-de Sitter black hole
- counterintuitive: short-distance behavior determined by $\Lambda_k$
- horizon entropy fulfills Cardy-Verlinde formula
- maximal black hole: entropy agrees with state-counting property of $\Gamma_k$

$$\tilde{S}_{\rm max} = \frac{\pi}{g_*\lambda_*}$$

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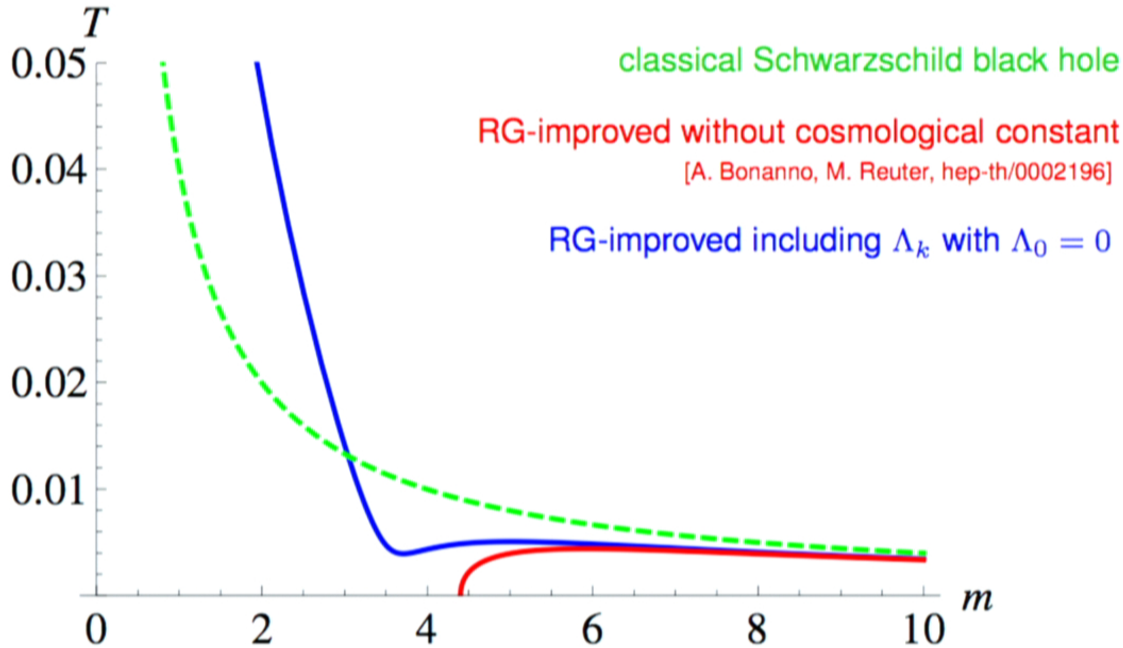
$$\tilde{S}_{\rm max} = \frac{\pi}{g_*\lambda_*}$$

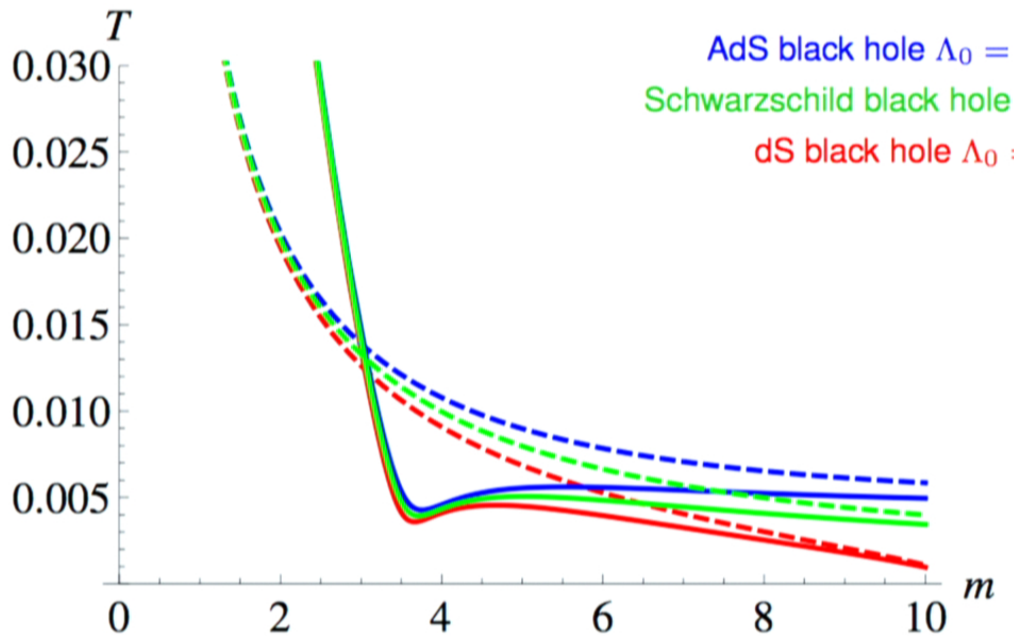
## Temperature of RG-improved Schwarzschild black holes




- $\Lambda_k$ crucially influences structure of light black holes

Inclusion of $\Lambda_k$ prevents remnant formation

## Temperature of asymptotic (Anti-) de Sitter black holes




- non-Gaussian fixed point guarantees universal short-distance properties
- black holes evaporate completely

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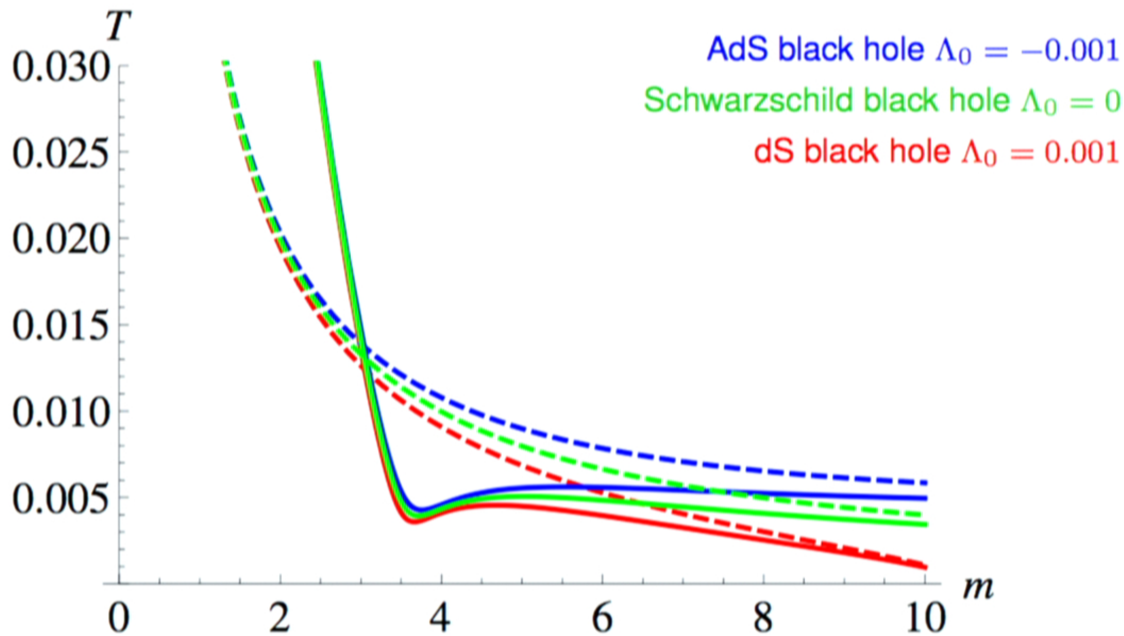


- non-Gaussian fixed point guarantees universal short-distance properties
- black holes evaporate completely

Hořava-Lifshitz Gravity

Causal Dynamical Triangulations

Asymptotic Safety

and its connections

# Hořava-Lifshitz gravity in a nutshell

P. Hořava, Phys. Rev. D79 (2009) 084008, arXiv:0901.3775

central idea: find a perturbatively renormalizable quantum theory of gravity

fundamental fields: $\{N(\tau), N_i(\tau, x), \sigma_{ij}(\tau, x)\}$

symmetry: Diff($\mathcal{M}, \Sigma$) $\subset$ Diff($\mathcal{M}$)

- breaks Lorentz-invariance at high energies

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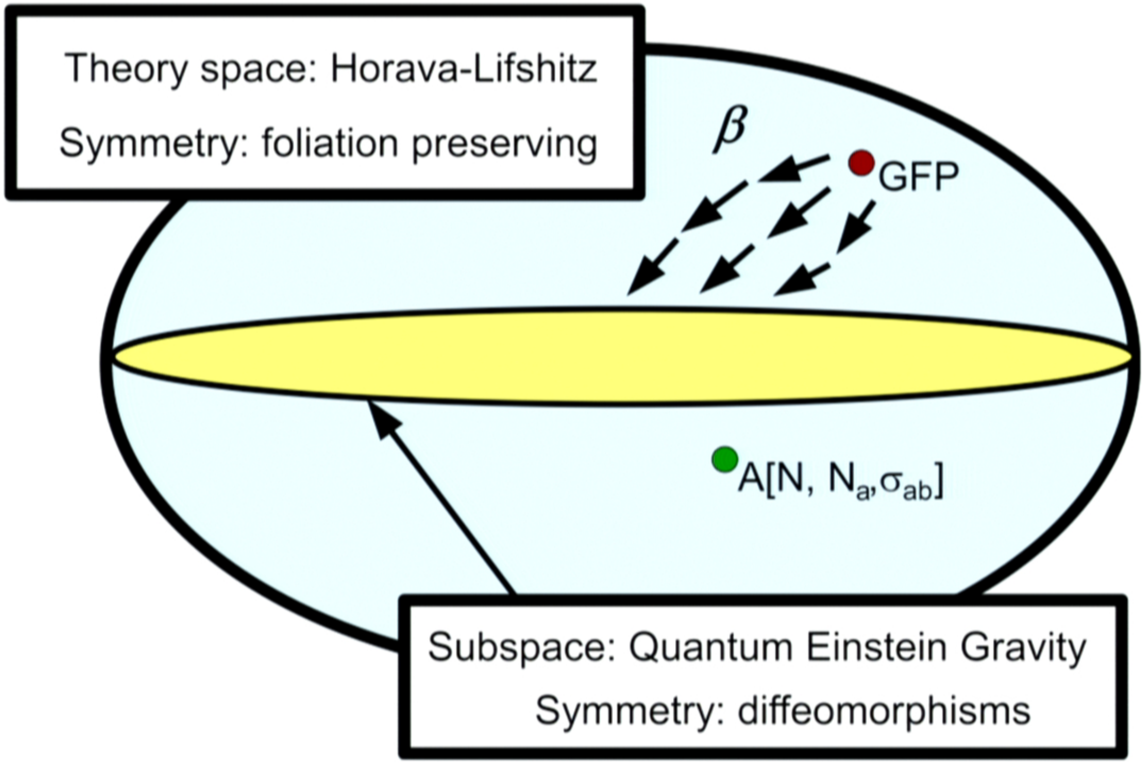
Can construct the effective average action for projective HL-gravity

S. Rechenberger and F.S., JHEP 03 (2013) 010, arXiv:1212.5114

- scale-dependence governed by functional renormalization group equation

$$k\partial_k \Gamma_k[\phi, \bar{\phi}] = \frac{1}{2}\mathrm{STr}\left[\left(\Gamma_k^{(2)} + \mathcal{R}_k\right)^{-1} k\partial_k \mathcal{R}_k\right]$$

## Embedding of QEG in Hořava-Lifshitz gravity

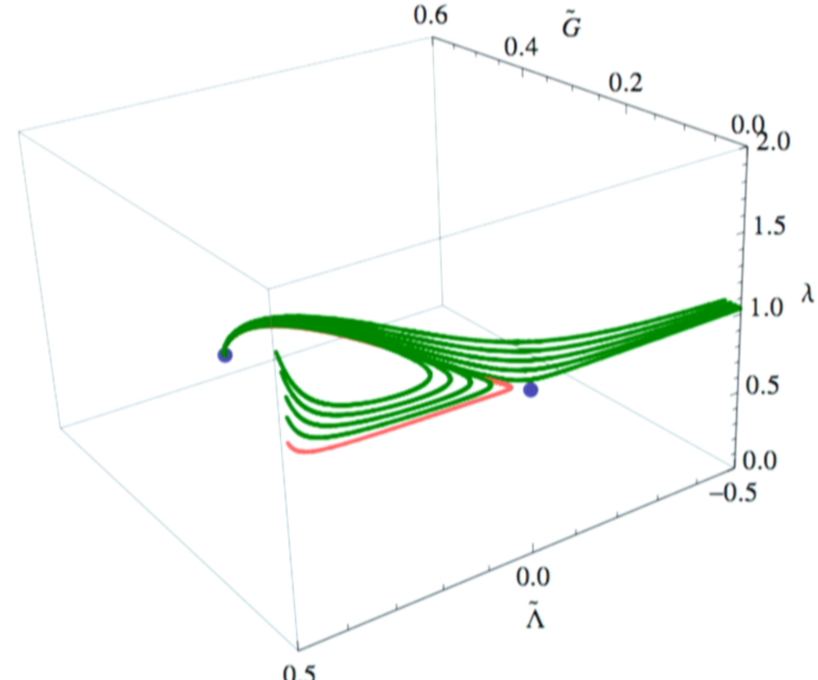


## RG-flows of HL-gravity in the IR

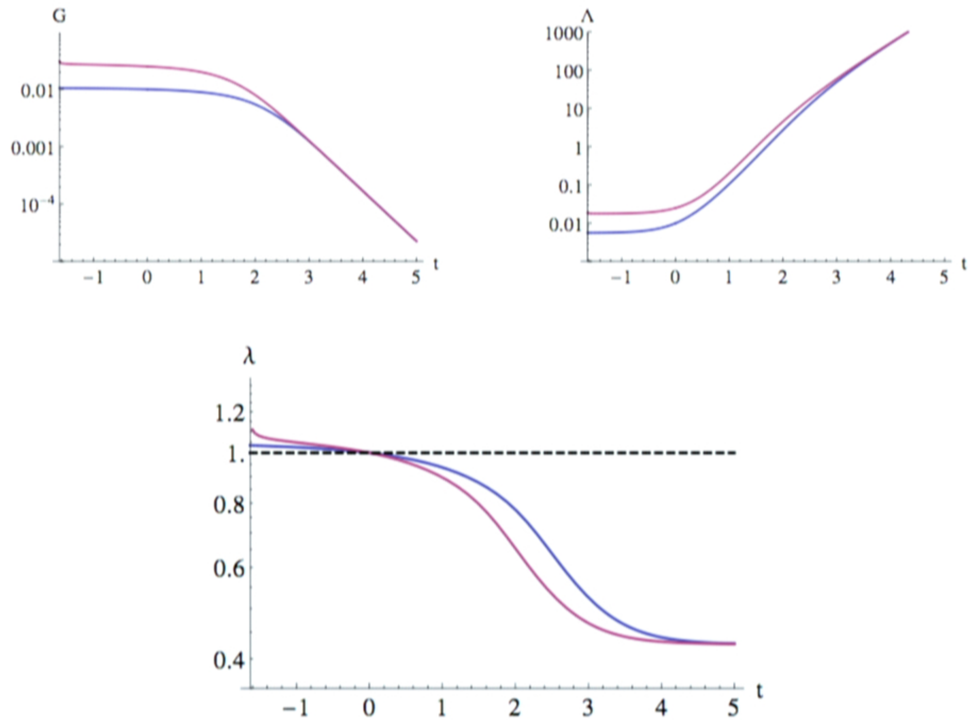
A. Contillo, S. Rechenberger, F.S., to appear

RG-flow of anisotropic Einstein-Hilbert truncation

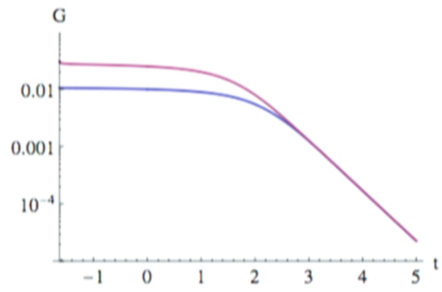
$$\Gamma_k^{\rm grav}[N, N_i, \sigma_{ij}] = \frac{1}{16\pi G_k} \int d\tau d^3x N\sqrt{g} \left[K_{ij}K^{ij} - \lambda_k K^2 -^{(3)} R + 2\Lambda_k\right]$$

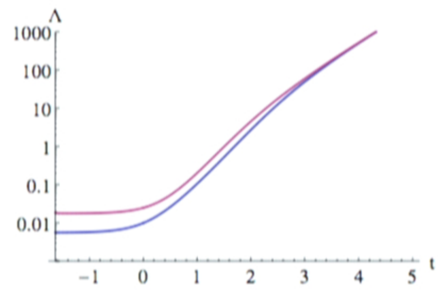


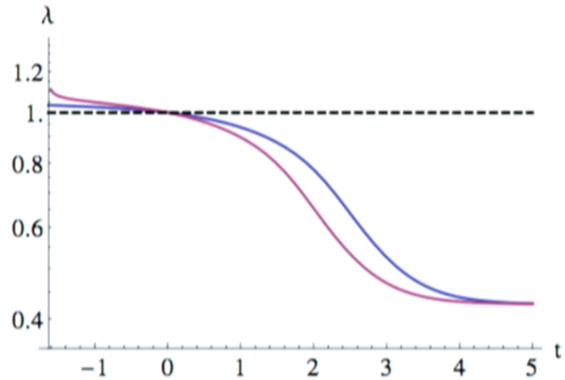
# Scale-dependence of dimensionful couplings



## Scale-dependence of dimensionful couplings




GFP governs IR-behavior of HL-gravity

small value of cosmological constant makes $\lambda$ compatible with experiments three

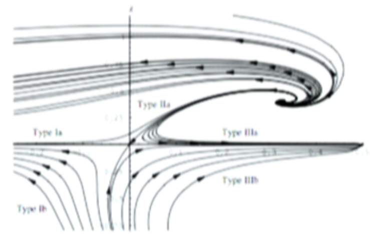
take-away messages

– p. 33/35

## Summay

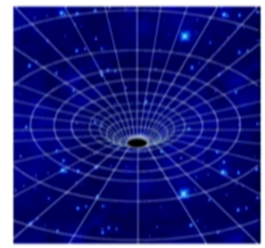
### Asymptotic Safety Program

- strong evidence for a non-Gaussian fixed point:
  - predictive: finite number of relevant parameters
  - connected to classical general relativity in the IR




### Asymptotically Safe black holes

- microscopic black holes are Schwarzschild-de Sitter
  - no formation of black hole remnants
  - entropy compatible with CFT



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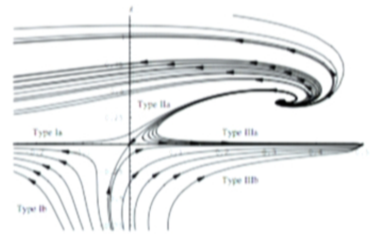

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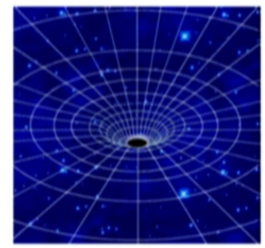
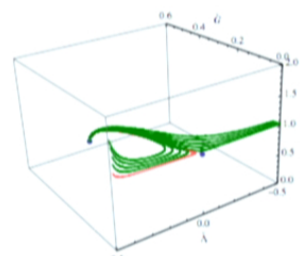


Why is General Relativity so successful?

- emerges as a cross-over phenomenon
- holds for Asymptotic Safety and Hořava-Lifshitz gravity



## More on Asymptotic Safety: parallel sessions

From fixed points to fixed functionals:

- RG-flows of $f(R)$-gravity

  D. Benedetti, T. Morris, K. Falls

- scale-dependent vertex functions

  A. Codello, M. Amber

- momentum-dependence of propagators

  A. Rodigast

phenomenological applications

- quantifying the structure of spacetime

  A. Eichhorn

- cosmology

  A. Contillo