Black Holes within Asymptotic Safety

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B. Koch and F. Saueressig, Class. Quant. Grav. 31 (2014) 015006

B. Koch and F. Saueressig, Int. J. Mod. Phys. A29 (2014) 8, 1430011

FFP14, Marseille, July 16, 2014

Outline

- Why quantum gravity?
- Asymptotic Safety in a nutshell
- Black holes within Asymptotic Safety
- Summary

Motivations for Quantum Gravity

1. internal consistency

$$\underbrace{R_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu}\, R + \Lambda\, g_{\mu\nu}}_{\text{classical}} \quad = \quad 8\,\pi\, G_N \quad \underbrace{T_{\mu\nu}}_{\text{quantum}}$$

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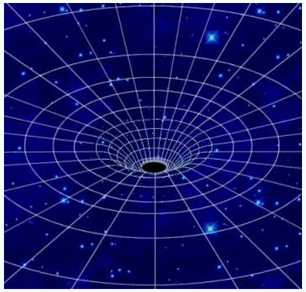
   - black hole singularities
   - Big Bang singularity



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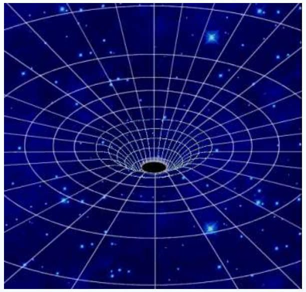
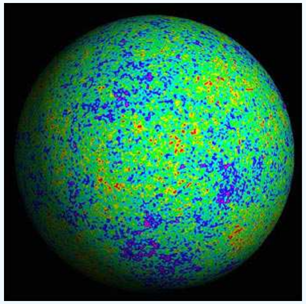


3. cosmological observations:
   - small positive cosmological constant
   - initial conditions for structure formation



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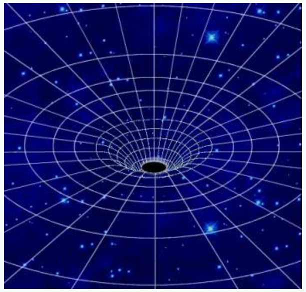

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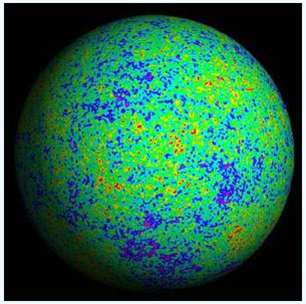

General Relativity is incomplete

Quantum Gravity may give better answers to these puzzles

The quantum gravity landscape

a) Treat gravity as effective field theory: [J. Donoghue, gr-qc/9405057]

- compute corrections in $E^2/M_{\rm Pl}^2 \ll 1$ (independent of UV-completion)
- breaks down at $E^2 \approx M_{\rm Pl}^2$

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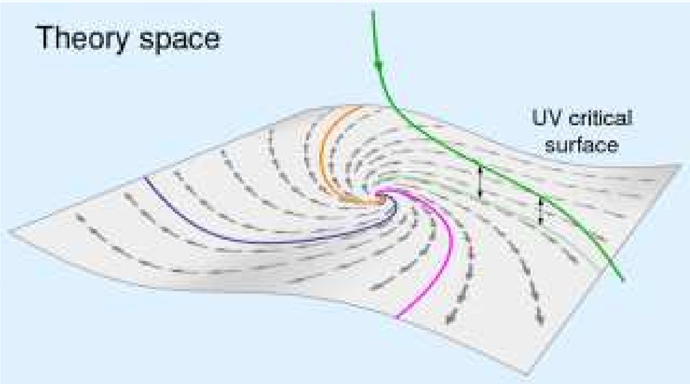
UV-completion of gravity within QFT

Central ingredient: fixed point of renormalization group flow

β-functions vanish at fixed point $\{g_i^*\}$:

- RG flow can "end" at a fixed point keeping $\lim_{k\to\infty} g_k = g^*$ finite!
  - trajectory has no unphysical UV divergences
  - well-defined continuum limit
- 2 classes of RG trajectories:
  - relevant $=$ end at FP in UV
  - irrelevant $=$ go somewhere else...
- predictive power:
  - number of relevant directions
    $=$ free parameters (determine experimentally)



[scholarpedia '13]

Proposals for UV fixed points

- isotropic Gaussian Fixed Point (GFP)
  - fundamental theory: Einstein-Hilbert action
  - perturbation theory in G_N

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  $\Longleftrightarrow$ experimental determination of relevant parameters
- guarantees predictive power

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c) classical limit:

- RG-trajectories have part where GR is good approximation
- recover gravitational physics captured by General Relativity:
  (perihelion shift, gravitational lensing, nucleo-synthesis, . . .)

Quantum gravity as quantum field theory: Asymptotic Safety

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Quantum Einstein Gravity (QEG)

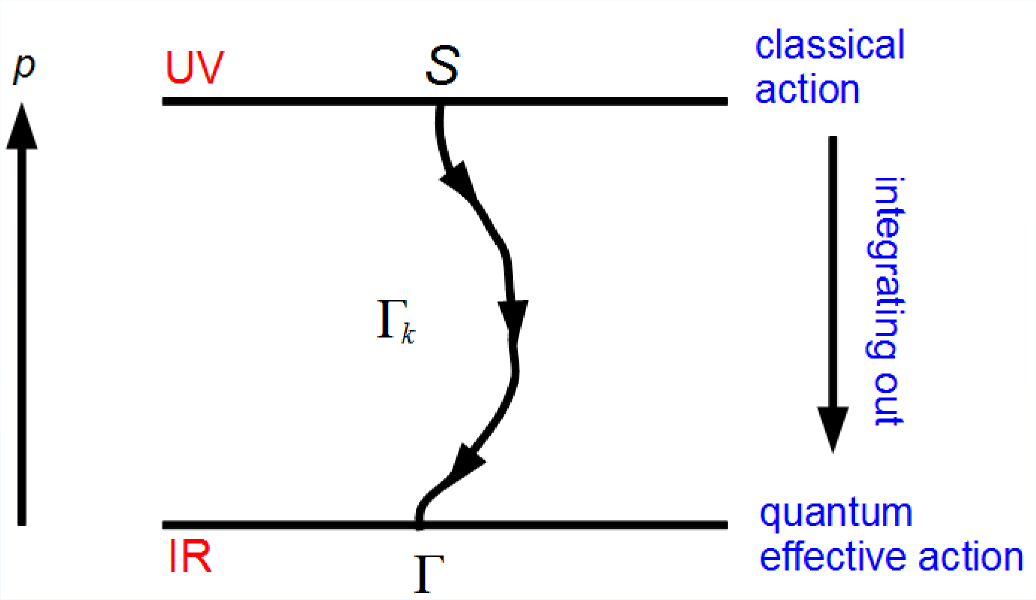
Asymptotic Safety

in a nutshell

Effective average action Γ_k for gravity

C. Wetterich, Phys. Lett. **B301** (1993) 90
M. Reuter, Phys. Rev. D **57** (1998) 971

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



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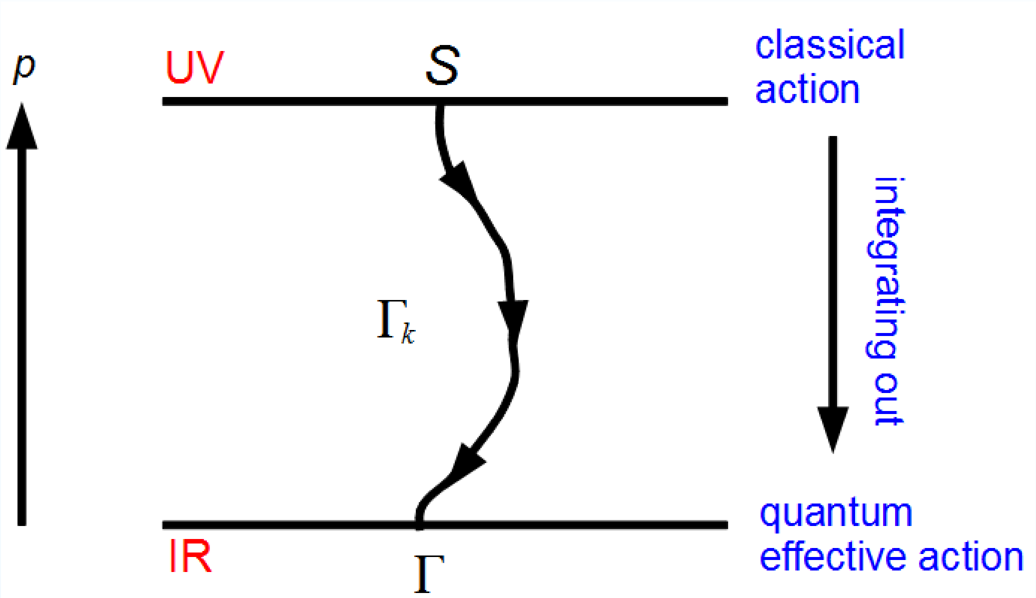

- scale-dependence governed by functional renormalization group equation

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

  - vertices of Γ_k incorporate quantum-corrections with $p^2 \gtrsim k^2$

Approximate solutions of the flow equation

approximate Γ_k by scale-dependent Einstein-Hilbert action:

$$\Gamma_k \approx \frac{1}{16\pi G(k)} \int d^4x \sqrt{g}\,[-R + 2\Lambda(k)] + S^{\mathrm{gf}} + S^{\mathrm{gh}}$$

- two running couplings: $G(k), \Lambda(k)$

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explicit β-functions for dimensionless couplings $g_k := k^2 G(k)\,,\ \lambda_k := \Lambda(k) k^{-2}$

- Particular choice of $\mathcal{R}_k$ (Litim cutoff)

$$k\partial_k g_k = (\eta_N + 2) g_k\,,$$

$$k\partial_k \lambda_k = -\,(2 - \eta_N)\,\lambda_k - \tfrac{g_k}{2\pi}\left[5\,\tfrac{1}{1-2\,\lambda_k} - 4 - \tfrac{5}{6}\,\tfrac{1}{1-2\lambda_k}\eta_N\right]$$

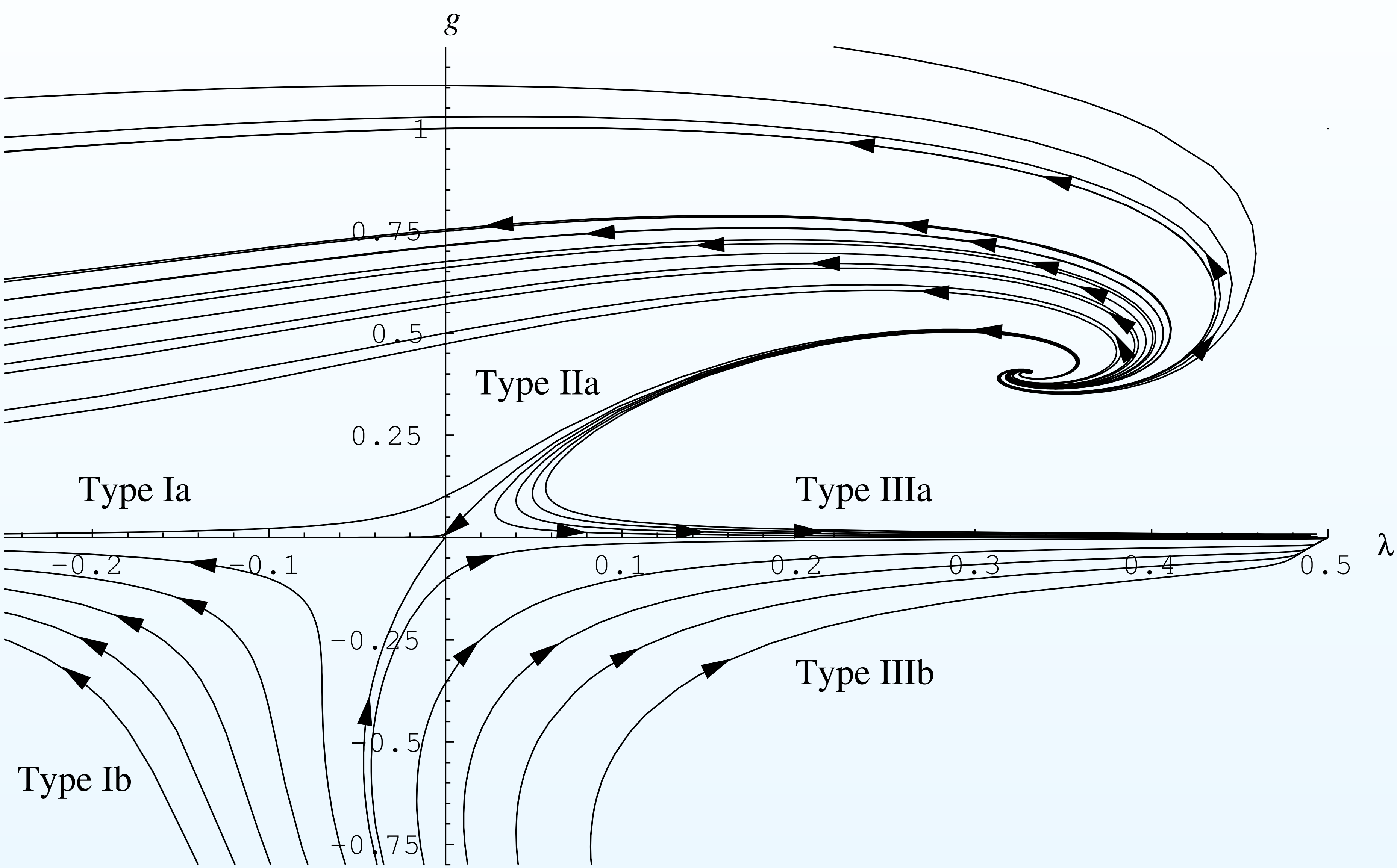
- anomalous dimension of Newton's constant:

$$\eta_N = \frac{g B_1}{1 - g B_2}$$

$$B_1 = \tfrac{1}{3\pi}\left[5\,\tfrac{1}{1-2\lambda} - 9\,\tfrac{1}{(1-2\lambda)^2} - 7\right]\,,\ B_2 = -\tfrac{1}{12\pi}\left[5\,\tfrac{1}{1-2\lambda} + 6\,\tfrac{1}{(1-2\lambda)^2}\right]$$

Einstein-Hilbert-truncation: the phase diagram

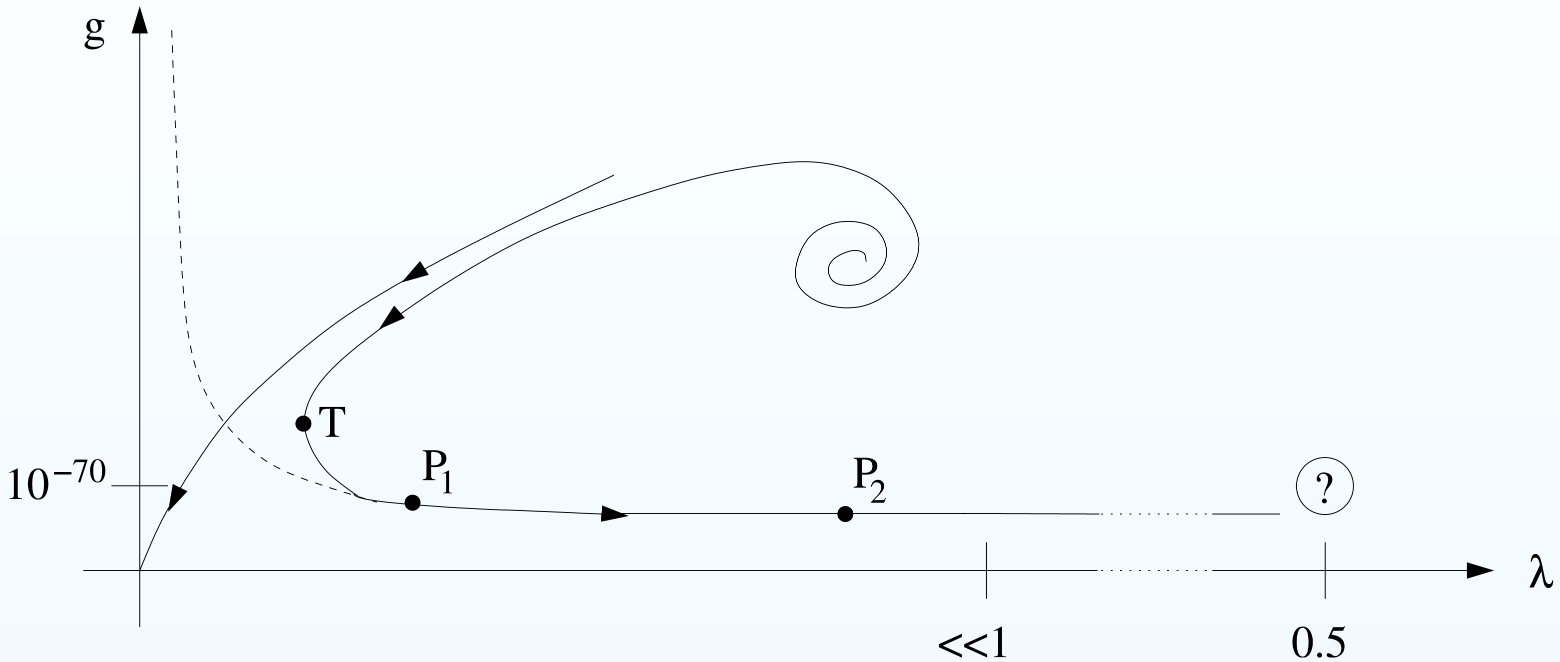
M. Reuter and F. Saueressig, Phys. Rev. D **65** (2002) 065016 [hep-th/0110054]



Connecting the quantum and classical regimes

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

identify RG trajectory realized in Nature by measurement of G_N, Λ



- NGFP: quantum regime ($G(k) = k^{-2} g_*, \Lambda(k) = k^2 \lambda_*$)
- T: flow passes extremely close to GFP
- $\mathrm{P}_1 \to \mathrm{P}_2$: classical regime ($G(k) = \mathrm{const}, \Lambda(k) = \mathrm{const}$)
- $\lambda \lesssim 1/2$: IR fixed point?

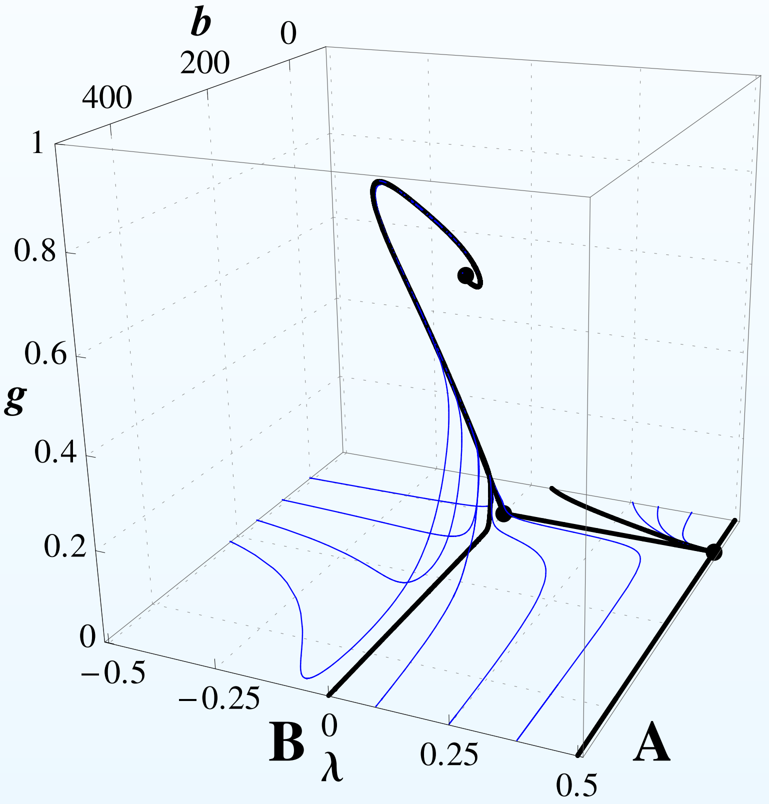
Charting the RG-flow of the R^2-truncation

O. Lauscher, M. Reuter, Phys. Rev. D66 (2002) 025026, hep-th/0205062

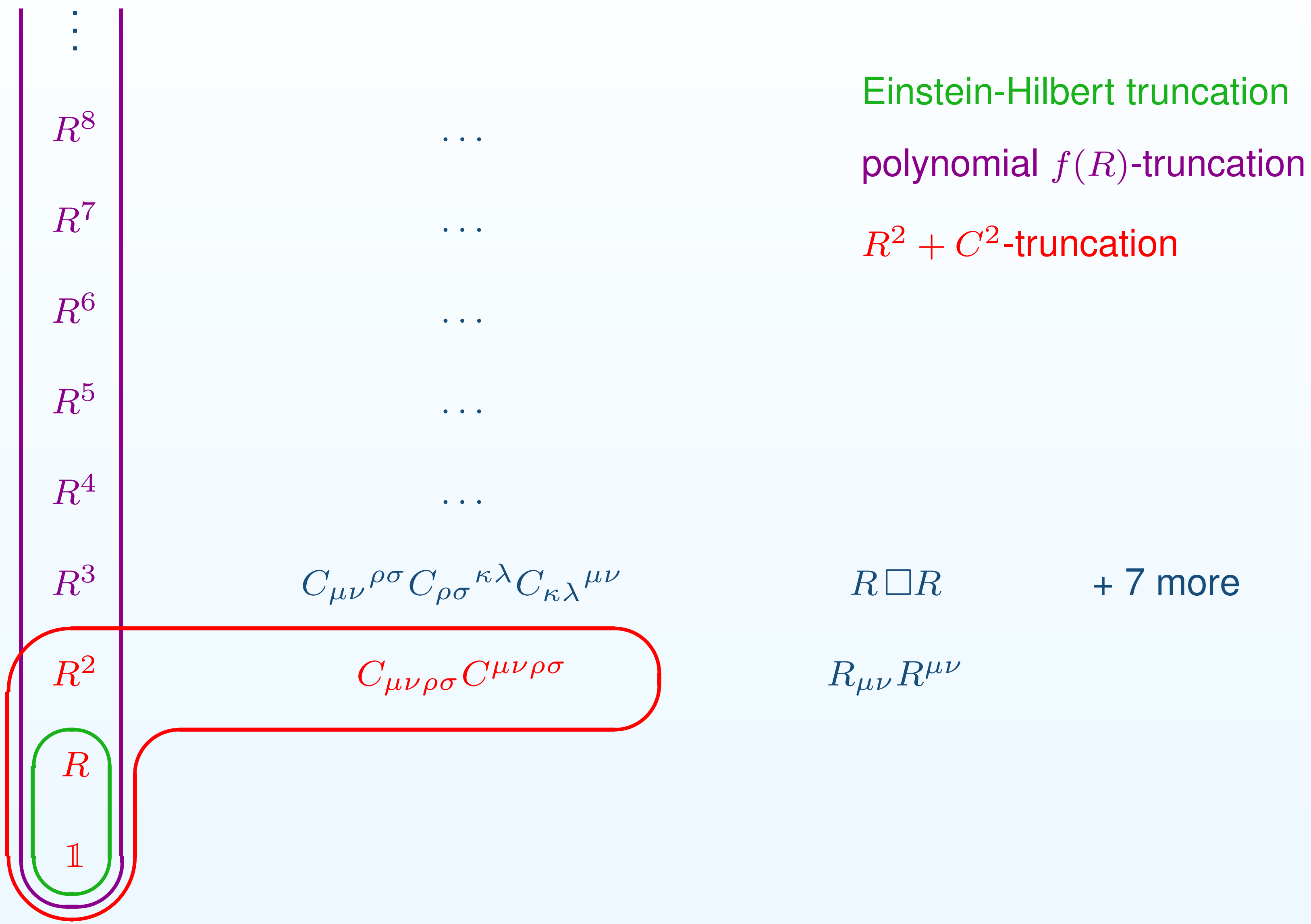
S. Rechenberger, F.S., Phys. Rev. D86 (2012) 024018, arXiv:1206.0657

Extending Einstein-Hilbert truncation with higher-derivative couplings

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



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



key results: Asymptotic Safety

pure gravity:

- 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 $\simeq 3$

[R. Percacci and A. Codello, arXiv:0705.1769]
[P.F. Machado and F. Saueressig, arXiv:0712.0445]
[D. Benedetti, P.F. Machado and F. Saueressig, arXiv:0901.2984]

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gravity coupled to matter:

- gravity + scalars: asymptotic safety survives 1-loop counterterm

[D. Benedetti, P.F. Machado and F. Saueressig, arXiv:0902.4630]

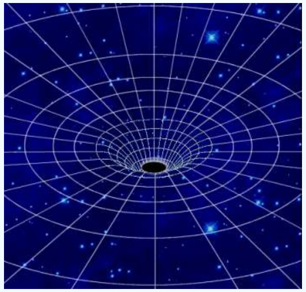
- non-Gaussian fixed point compatible with standard-model matter

[R. Percacci and D. Perini, hep-th/0207033]
[P. Dona, A. Eichhorn and R. Percacci, arXiv:1311.2898]

- prediction of the Higgs mass $m_H \simeq 126$ GeV

[M. Shaposhnikov and C. Wetterich, arXiv:0912.0208]

Black holes in Asymptotic Safety



Classical black hole solutions with cosmological constant

Einstein's equations in vacuum

$$R_{\mu\nu} - \tfrac{1}{2}\, g_{\mu\nu}\, R + \Lambda\, g_{\mu\nu} = 0$$

black holes: spherical symmetric, static solutions

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

$$f(r) = 1 - \frac{2GM}{r} - \frac{1}{3}\Lambda r^2$$

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horizons

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

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

horizon temperature:

$$T = \frac{1}{4\pi}\, \frac{\partial f(r)}{\partial r}\bigg|_{r=r_{\rm horizon}}$$

Quantum physics from average action Γ_k

Γ_k provides effective description of physics at scale k

capture quantum effects by “RG-improvement” scheme:

- transition: classical $S^{\mathrm{EH}} \to$ average action $\Gamma_k[g]$
  - one-parameter family of effective actions valid at different scales
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extracting physics information from Γ_k:

- single-scale problem may allow for "cutoff-identification":
    - based on physical intuition:
      express RG-scale k through physical cutoff ξ

$\Rightarrow$ modification of classical system by quantum effects

Practical RG-improvement schemes

given: physically motivated cutoff-identification $k = k(\xi)$

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   - solve classical equations of motion
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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 $k = k(\mathrm{physical\ scale})$

- invariance under coordinate transformations
- respect symmetries of solution
- “reasonable” asymptotic behavior

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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

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

- full function $k(r)$ can be found numerically

High-energy behavior of RG-improved Schwarzschild black holes

- classical line element

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

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- substitute the cutoff-identification $k^2 \propto r^{-3}$:

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

RG improvement resolves black hole singularity

Asymptotically Safe black holes and Planck stars

S. Hayward, gr-qc/0506126

C. Rovelli and F. Vidotto, arXiv:1401.6562

Loop quantum gravity: modifications of $f(r)$ due to quantum gravitational repulsion:

$$f(r) = 1 - \frac{2mr^2}{r^3 + 2\alpha^2 m}$$

- α: constant determined from fundamental theory

Asymptotics of solution:

$$f(r) = \begin{cases} 1 - \alpha^{-2} r^2 \, , & r \ll 2\alpha^2 m \\ 1 - \frac{2m}{r} + \ldots & r \gg 2\alpha^2 m \end{cases}$$

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Same behavior has RG improved black hole!

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- RG-improvement: couplings become scale-dependent

$$f(r) = 1 - \frac{2\,G(k)\,M}{r} - \frac{1}{3}\,\Lambda(k)\,r^2$$

- substitute UV-scaling: $G(k) = g_*\,k^{-2}, \Lambda(k) = \lambda_*\,k^2$

$$f_*(r) = 1 - \frac{2\,g_*\,k^{-2}\,M}{r} - \frac{1}{3}\,\lambda_*\,k^2\,r^2$$

RG-improved black holes including a cosmological constant

- classical line element

$$f(r) = 1 - \frac{2\,G_0\,M}{r} - \frac{1}{3}\,\Lambda_0\,r^2$$

- RG-improvement: couplings become scale-dependent

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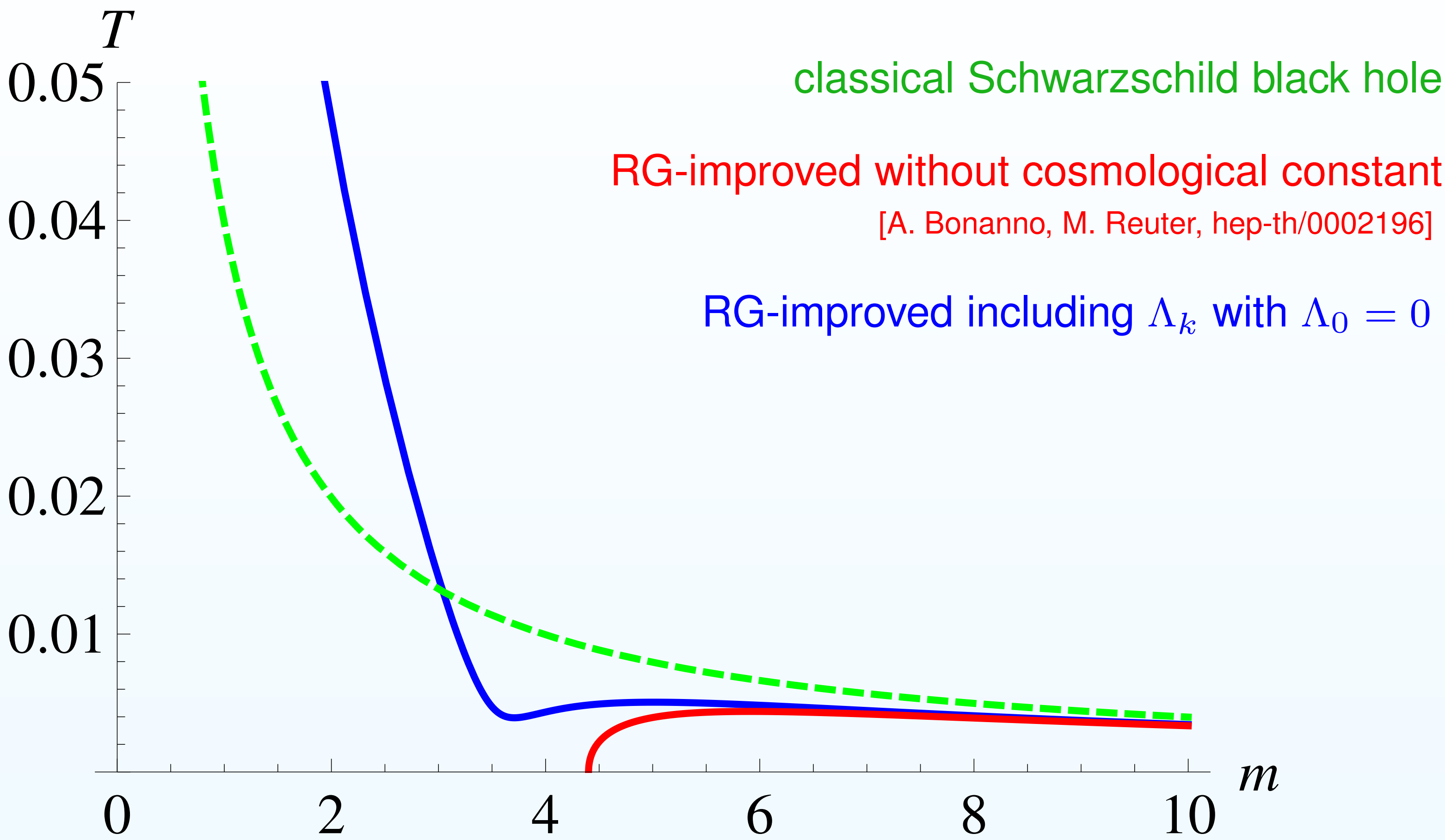
$$f_*(r) = 1 - \frac{2\,g_*\,k^{-2}\,M}{r} - \frac{1}{3}\,\lambda_*\,k^2\,r^2$$

- substitute the cutoff-identification $k^2 \propto r^{-3}$:

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

Microscopic black hole is classical Schwarzschild de Sitter solution

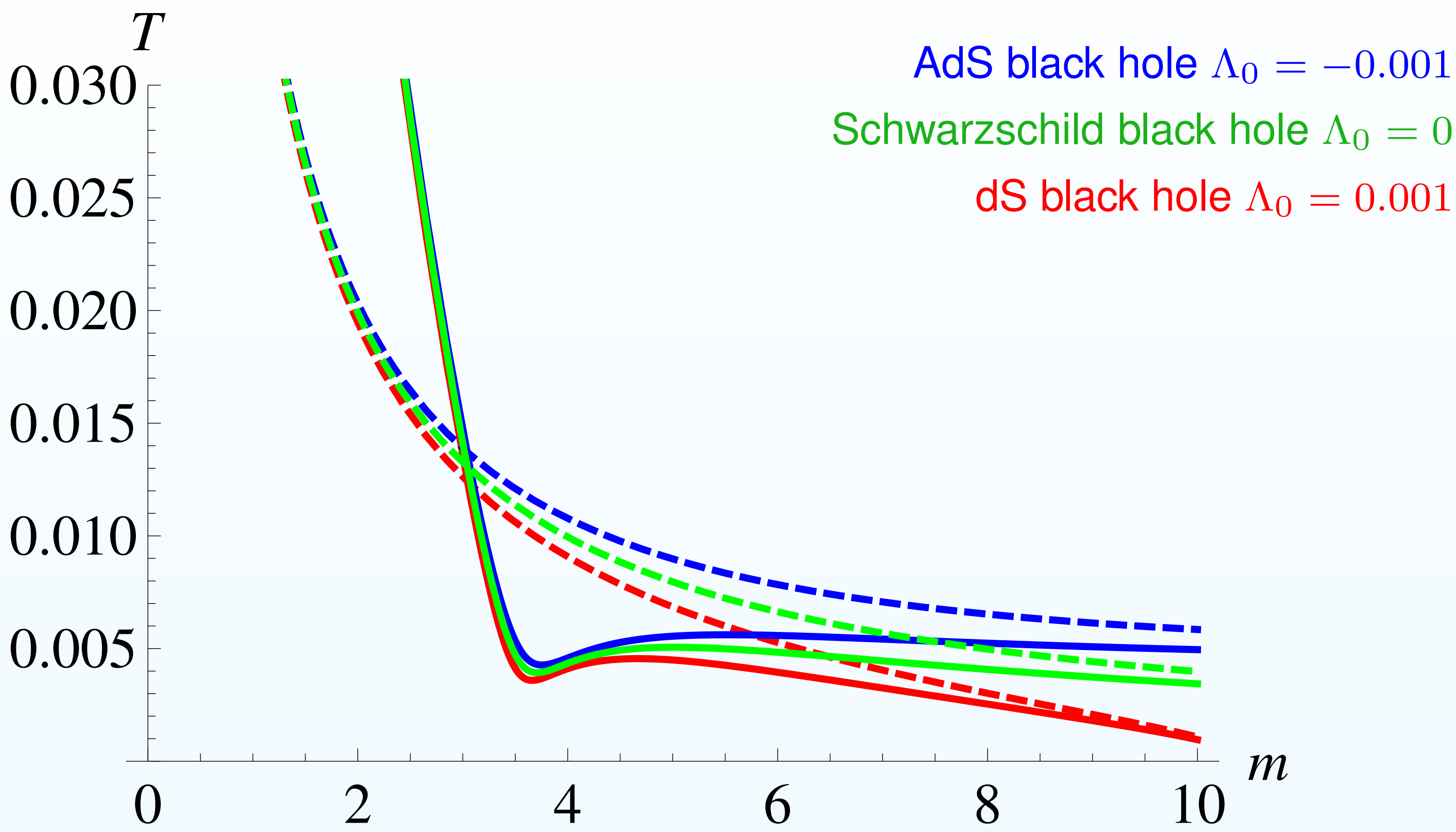
Temperature of RG-improved Schwarzschild black holes



- Λ_k crucially influences structure of light black holes

Inclusion of Λ_k prevents remnant formation

Temperature of asymptotic (Anti-) de Sitter black holes



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

Summary

Asymptotic Safety Program

Gravitational RG flows:

- strong evidence for a non-Gaussian fixed point:
  - predictive: finite number of relevant parameters
  - connected to classical gravity

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Asymptotically Safe black holes:

- RG improved Schwarzschild black holes
  - black hole singularity replaced by de Sitter patch
  - formation of black hole remnants
- RG improved black holes including cosmological constant
  - microscopic structure: Schwarzschild-de Sitter black hole
  - no formation of black hole remnants
  - quantum singularity related to dynamical dimensional reduction?