Quantum gravity in the asymptotic-safety approach

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22 April 2020

RUPRECHT-KARLS-
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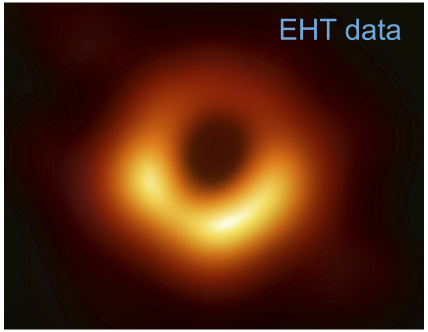
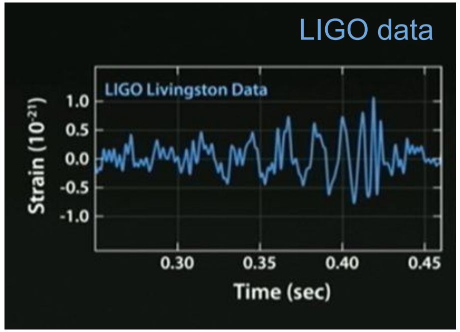
Einstein Gravity, Singularities and Renormalization

Einstein Gravity

$$S_{EH} = \frac{1}{16\pi G} \int d^4x \sqrt{-g}\, (R - 2\Lambda)$$





Very successful in the description of gravitational phenomena, even in strong field regimes.
However:

- **Classical singularities**

  the solutions of the Einstein equations are generally singular ⇒ loss of predictivity

  [Penrose, ‘65; Penrose, Hawking, ‘70;]

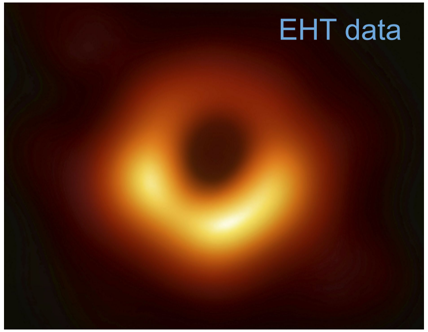
- **Renormalizability issues**

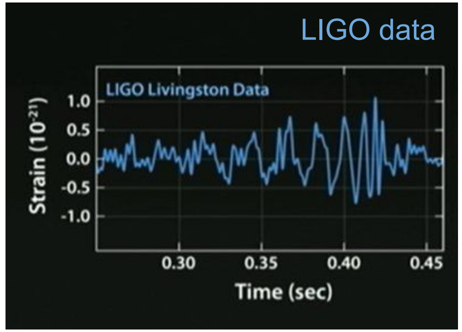
  the Newton’s constant has negative mass dimension ⇒ ultraviolet divergences

  [’t Hooft,Veltman, ‘74; Goroff,Sagnotti, ‘86;]

General Relativity is incomplete and breaks down at high energies

Einstein Gravity, Singularities and Renormalization





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Asymptotically Safe Gravity (Weinberg, 1976)

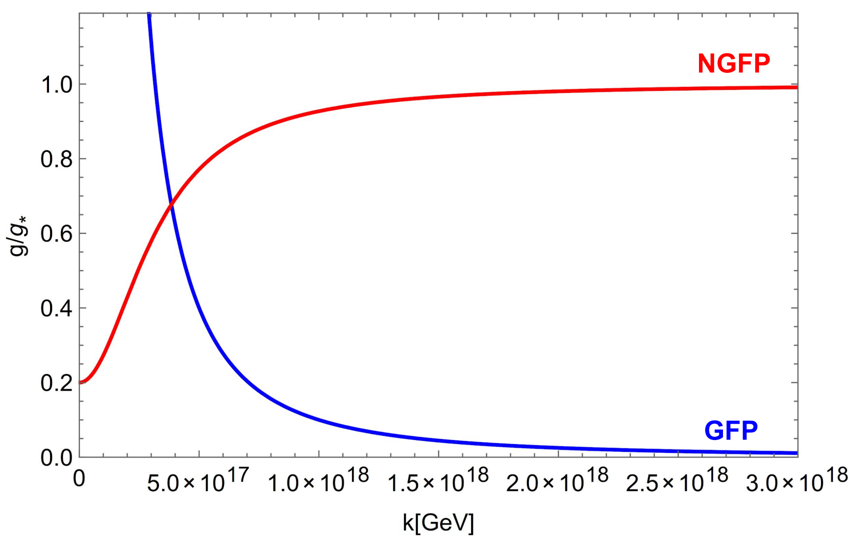
- General Relativity might make sense as a quantum field theory
- Key idea: generalized notion of renormalizability based on the Wilsonian Renormalization Group

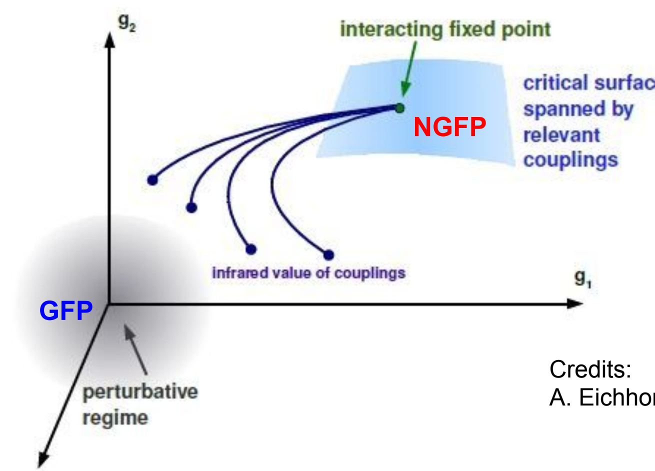
S. Weinberg, Erice Subnucl. Phys.1976:1

RG fixed points and renormalizability

Two types of well-definite **ultraviolet completion** (microscopic/fundamental theory)

- **Gaussian Fixed Point (GFP)**: free theory ⇒ *Asymptotic Freedom*
- **Non-gaussian Fixed Point (NGFP)**: interacting theory ⇒ *Asymptotic Safety*



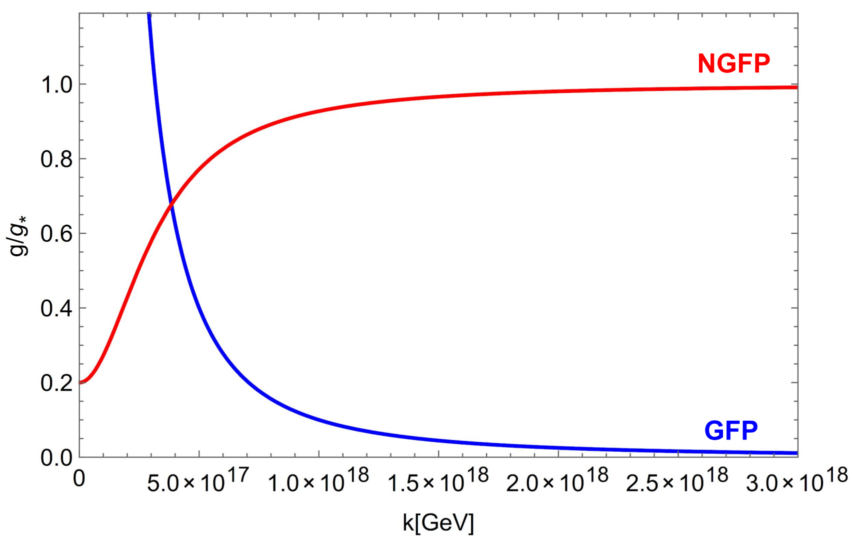


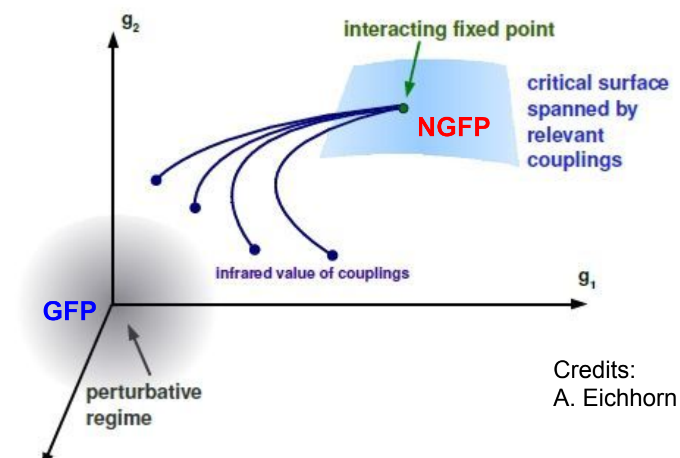
Credits:
A. Eichhorn

RG fixed points and renormalizability

Generalized (non-perturbative) renormalizability

- **Ultraviolet completion** ⇔ UV-attractive **fixed point** (microscopic theory)
  - **Gaussian Fixed Point (GFP)**: free theory ⇒ *Asymptotic Freedom*
  - **Non-gaussian Fixed Point (NGFP)**: interacting theory ⇒ *Asymptotic Safety*
- **Predictivity** ⇔ finite number of relevant directions





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Asymptotic Safety in Quantum Gravity

Einstein-Hilbert truncation

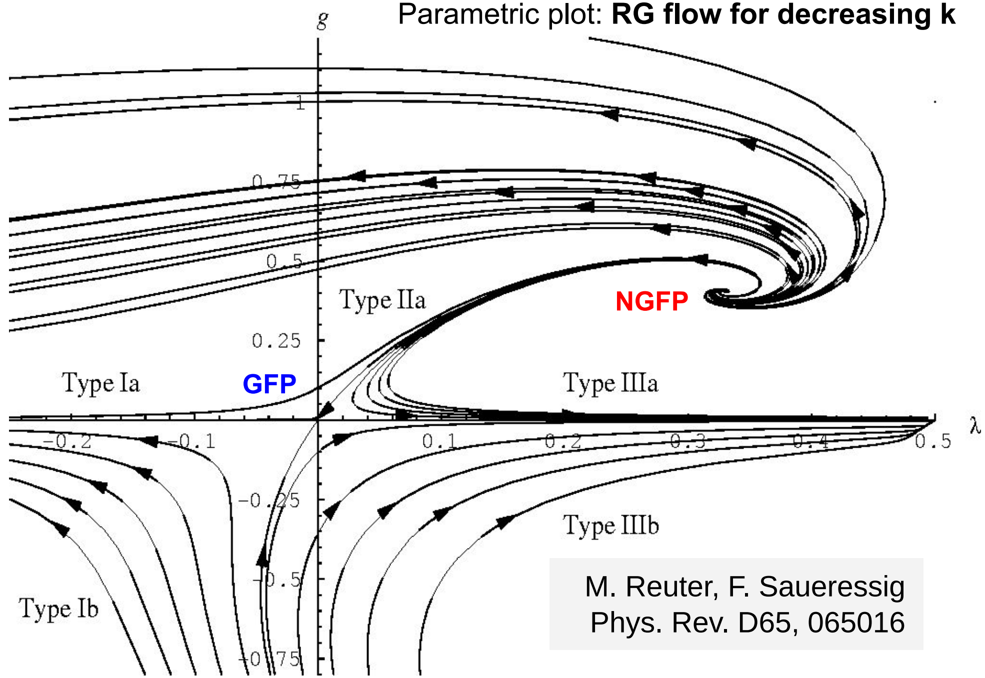
$$S_k = \frac{1}{16\pi G_k} \int d^4x \sqrt{-g}\,(R - 2\Lambda_k)$$

$$\boxed{G_k = k^{-2} g_k \qquad \Lambda_k = k^2 \lambda_k}$$

Fixed points of the RG flow:

- **GFP** $\rightarrow$ saddle point
- **NGFP** $\rightarrow$ UV-attractor

Parametric plot: **RG flow for decreasing k**



M. Reuter, F. Saueressig
Phys. Rev. D65, 065016

Looking for Asymptotic Safety

Functional RG equations for different ansatz of S allow to verify the existence of the NGFP

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

C. Wetterich. *Phys. Lett. B* 301:90 (1993)
M. Reuter. *Phys. Rev*. D. **57** (2): 971 (1998)

→ **NGFP + 3 relevant directions**

$$f(R) \simeq \sum_{n=0}^{N} a_n R^n$$

Polynomial up to N=71:
Reuter, Lauscher, '02; Codello, Percacci, Rahmede '09; Benedetti, Caravelli, '12; Dietz, Morris, '12; Falls, Litim, Nikolakopoulos, Rahmede, '13, '14 Demmel, Saueressig, Zanusso, '15; Falls, Litim, Schoeder, '18
Beyond polynomial:
Benedetti, Caravelli, '12; Demmel, Saueressig, Zanusso, '12; Dietz, Morris, '13

$$R, \quad R^2, \quad R_{\mu\nu}R^{\mu\nu}$$

Benedetti, Machado, Saueressig, '09. Christiansen, '16, Oda, Yamada '17

$$R, \quad C_{\mu\nu}^{\kappa\lambda}C_{\kappa\lambda}^{\rho\sigma}C_{\rho\sigma}^{\mu\nu}$$

Gies, Knorr, Lippoldt, Saueressig '16

→ Canonical power counting is still a good guideline

Eichhorn, Lippoldt, Pawlowski, Reichert, Schiffer. Phys.Lett. B792 (2019) 310-314

Asymptotically Safe Gravity: problems and open questions

Main problems related with the Functional RG:

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

- **Truncation**
  - Solving the FRG equations requires **truncation**
  - Within truncation: **regulator, gauge and parametrization dependence**

  Form factors, RG flow of generic entire functions: Knorr, Ripken, Saueressig - *Class.Quant.Grav.* 36 (2019) 23, 234001

- **Causal structure and Lorentzian signature**

  Lorentzian EH truncation, Matsubara formalism: Manrique, Rechenberger, Saueressig - *Phys.Rev.Lett.* 106 (2011) 25130
  Euclidean EH truncation, ADM formalism: Biemans, AP, Saueressig - *Phys.Rev.D* 95 (2017) 8, 086013
  Euclidean EH truncation + matter, ADM formalism: Biemans, AP, Saueressig - *JHEP* 05 (2017) 093
  Euclidean EH truncation, generic foliation, lorentz-violation: Knorr *Phys.Lett.B* 792 (2019) 142-148
  Euclidean EH truncation + matter, generic foliation, lorentz-violation: Eichhorn, AP, Schiffer. Arxiv:1911.10066

More open questions on asymptotically safe gravity:

- **Unitarity**

  Eichhorn, AP, Wetterich - *to appear soon*

- **Phenomenology / signatures of asymptotic safety**

  Literature on RG-improved models: A. Bonanno, A. Eichhorn, K. Falls, A. Held, D. Litim, AP, M. Reuter, F. Saueressig etc.

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Asymptotic Safety on foliated spacetimes

- Functional Renormalization Group is based on a *Euclidean* path integral

- The nature of our universe is *Lorentzian*

- QFTs on fixed Minkowski background:
  Wick rotation to restore a *Lorentzian* signature

- **Gravity**: integration over all possible geometries

$$\int D[g_{\mu\nu}]\, e^{-S[g_{\mu\nu}]} \longrightarrow$$

Metric formulation:
no well-distinguished time direction

- The **causal structure** of the spacetime might be important to determine the quantum properties of gravity

- Comparison of FRG results with causal dynamical triangulations (CDT) program

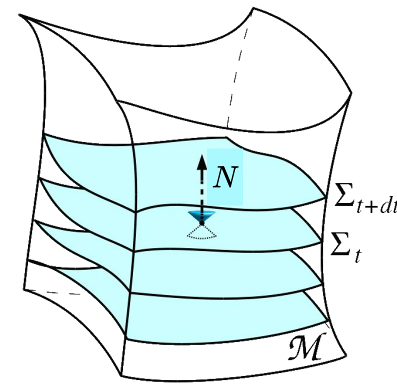
R. Loll. Nucl.Phys.Proc.Suppl. 94 (2001) 96-107

Asymptotic Safety on foliated spacetimes

Spacetime foliation $\mathcal{M}^D \longrightarrow \mathcal{M}^{D-1} \times \mathbb{R}$

Spacelike surfaces

Time Direction



The **covariant metric** is written in terms of the **ADM fields**

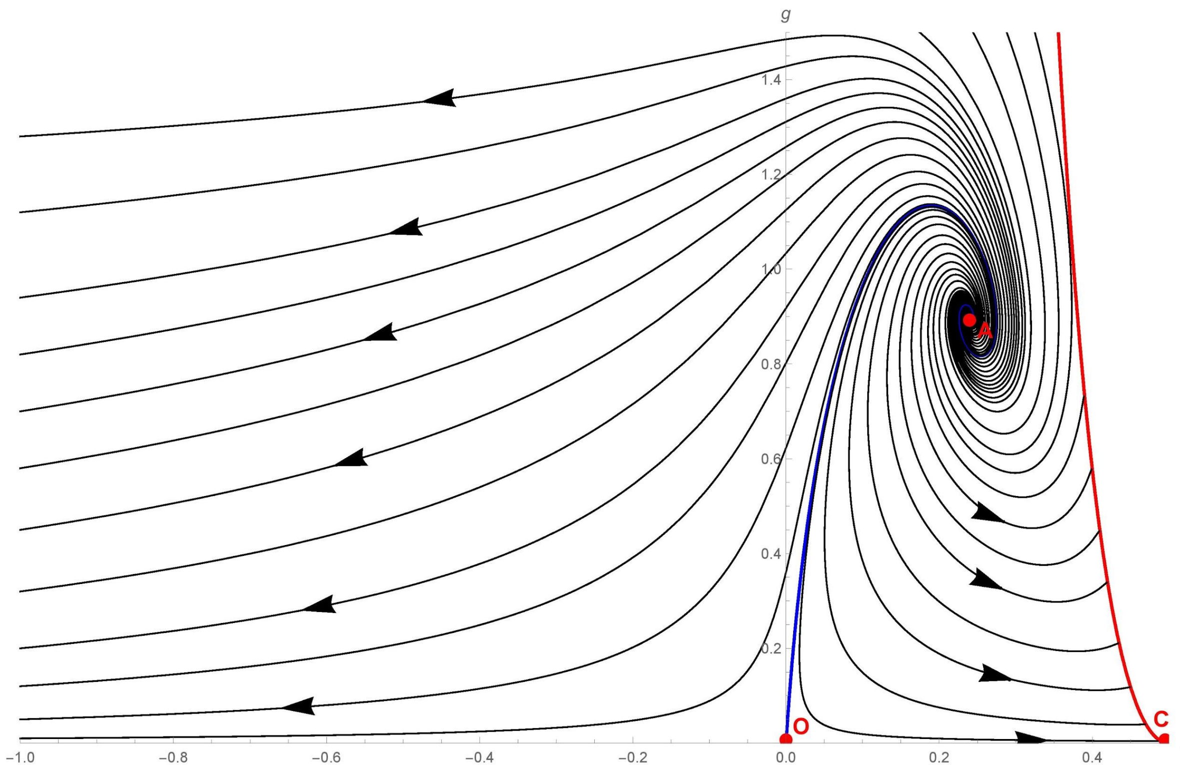
$$g_{\mu\nu} \longrightarrow \{N, N_i, \sigma_{ij}\}$$

$$ds^2 = N^2 dt^2 + \sigma_{ij}\,(dx^i + N^i dt)(dx^j + N^j dt)$$

Functional integral over the ADM-fields

$$\mathcal{Z} = \int D[N]\, D[N^i]\, D[\sigma_{ij}]\, e^{-S[N, N_i, \sigma_{ij}]} \quad \Longrightarrow \quad \Gamma_k = \Gamma_k[N, N_i, \sigma_{ij}]$$

Properties of the gravitational RG flow: phase diagram in (3+1)-dimensions



The RG-flows obtained in the covariant and foliated approaches share similar properties:

- **UV-attractive NGFP**
- **Complex critical exponents**

J. Biemans, AP, F. Saueressig
Phys. Rev. D 95, 086013 (2017)

RG-flow: Gravity-matter systems

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

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$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$S_k = S_k^{\text{grav}} + S_k^{\text{matter}}$$

RG-flow: Gravity-matter systems

$$\underbrace{R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu}}_{\downarrow} = \underbrace{8\pi G\, T_{\mu\nu}}_{\downarrow}$$

$$S_k = S_k^{\text{grav}} + {\color{red} S_k^{\text{matter}}}$$

Is the gravitational RG flow influenced by the presence of matter fields?

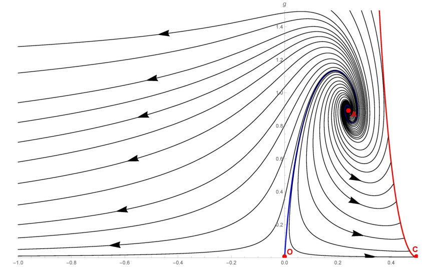
Matter...matters!

- Adding a minimal coupling to matter fields modifies *universal properties* of the gravitational RG flow

P. Dona, A. Eichhorn, R. Percacci
Phys. Rev. D **89**, 084035 (2014)

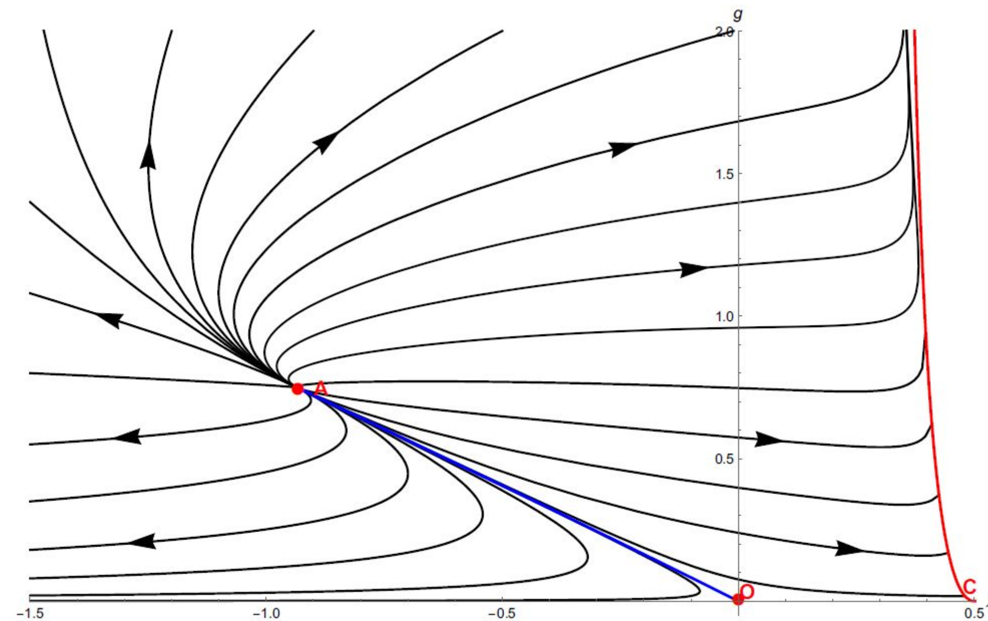
- Vice versa, gravity influences the running of the matter couplings and could induce a viable UV completion of the SM

Daum, Harst, Reuter '09; Harst, Reuter '11; Folkerts, Litim, Pawlowski '11; Christiansen, Eichhorn '17; Eichhorn, Held, Pawlowski '16; Eichhorn, Held '17



+

Matter fields of the Standard Model minimally coupled to gravity (non-interacting)



J. Biemans, AP, F. Saueressig
JHEP 05 (2017) 093 (2017)

Astrophysical and cosmological implications of Asymptotically Safe Gravity

Quantum spacetime in Asymptotically Safe Gravity

Goal: understand how *quantum fluctuations* modify the classical solutions of GR at high energies

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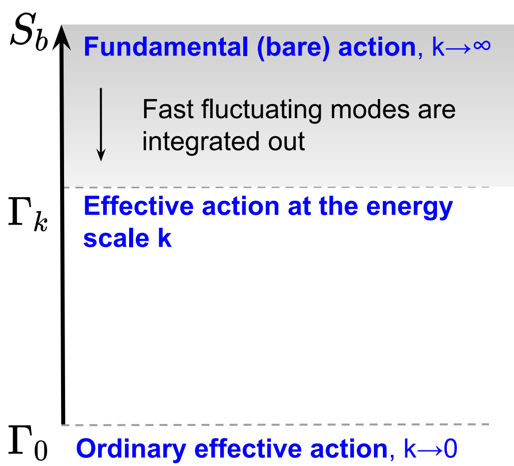
Derivation of quantum solutions from the functional renormalization group:



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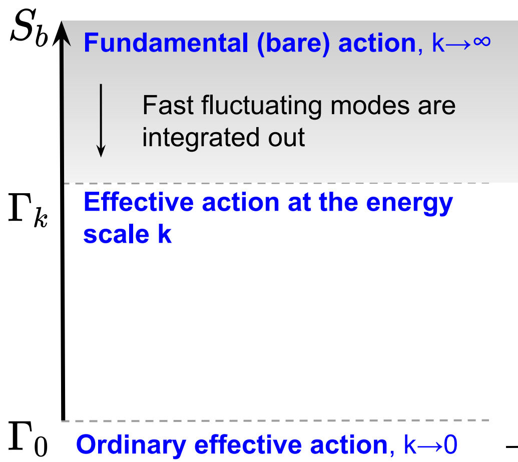

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All quantum fluctuations are integrated out (non-localities)
Incorporates all quantum effects → fully-dressed quantities
Quantum solutions from effective field equations:

$$\frac{\delta \Gamma_0}{\delta g_{\mu\nu}} = 0$$

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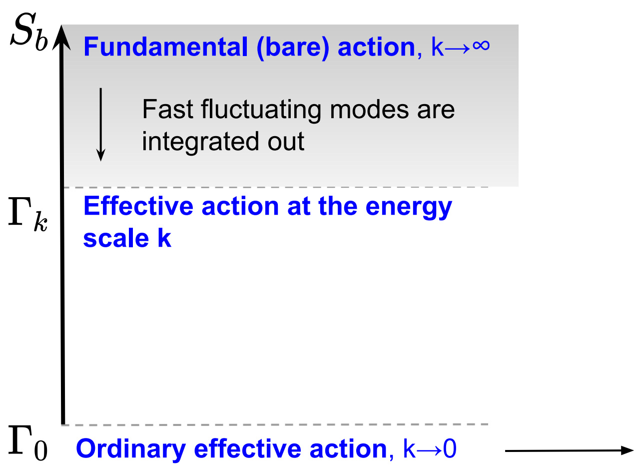

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Problem: Fully-quantum effective action is currently unknown

Phenomenology of AS:

- Fully-quantum effective action is unknown
- Semi-classical models that capture key features / hallmarks of asymptotic safety

Hallmarks of asymptotically safe gravity:

- **Scale invariance** of the theory at high energies
- **Gravitational antiscreening**
  (weakening of the gravitational interaction at high energies / short distances)

Idea:

⇒ Construct *semi-classical models* that have these features

⇒ In the context of quantum field theory: **renormalization-group improvement**
(expected to provide qualitative understanding of the effect of quantum fluctuations)

The Renormalization Group improvement

- Asymptotically Safe Gravity is based on **Quantum Field Theory**

- In the context of QFT, the **RG-improvement** is widely used to study the effect of leading order quantum corrections

  - Start from a well-known classical system

  - Replace characteristic constants with running couplings

  - Close the system by identifying the RG-scale with a characteristic energy scale of the system

EXAMPLE 1: RG-improvement of the **electric potential** in ***Quantum Electrodynamics***

$$V(r) = -\frac{e^2}{r} \quad \to \quad V_k(r) = -\frac{e_k^2}{r} \quad \xrightarrow[k \sim 1/r]{} \quad V_1(r) \sim -\frac{e^2(r_0^{-1})}{4\pi r}\left(1 + b\log(r_0/r)\right)$$

1-loop Uehling potential

Uehling, E. A. (1935). "Polarization Effects in the Positron Theory". *Physical Review*. **48**: 55–63

The Renormalization Group improvement

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EXAMPLE 2: RG-improvement of the **action** in ***Scalar Electrodynamics***

Radiative corrections included by identifying the RG-scale with the **field strength**

$$S_{\text{cl}}[\phi] \longrightarrow S_k[\phi] \qquad k \sim \phi \qquad \Rightarrow \quad \text{Coleman-Weinberg effective potential}$$

R. Coleman, E.J. Weinberg
Phys.Rev. D7 (1973) 1888-1910

⇒ **Phenomenology of AS**:
Semi-classical models that capture key features / hallmarks of asymptotic safety
Models in the literature based on RG-improvement procedure

Hallmarks of asymptotically safe gravity:

- **Scale invariance** of the theory at high energies

- **Gravitational antiscreening**
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⇒ **Phenomenology of AS**:
Semi-classical models that capture key features / hallmarks of asymptotic safety
Models in the literature based on RG-improvement procedure

Hallmarks of asymptotically safe gravity:

- **Scale invariance** of the theory at high energies → Explanation for the nearly-scale invariant power spectrum of temperature fluctuations in the CMB?

- **Gravitational antiscreening** (weakening of the gravitational interaction at high energies / short distances) → Weakening / resolution of classical spacetime singularities?

Modeling the gravitational antiscreening with the RG-improvement

- Renormalization group equations ⇒ **running Newton's coupling**

$$G_k = \frac{G_0}{1 + G_0\, g_*^{-1} k^2}$$

A. Bonanno, M. Reuter
Phys. Rev. D 62, 043008 (2000)

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- If the Asymptotic Safety conjecture holds, there exists a scale-invariant regime at high energies where the Newton coupling scales as

$$G_k = g_* k^{-2} \qquad \text{for} \quad k \gg M_{Pl}$$

⇒ *the RG-scale-dependent Newton coupling vanishes at high energies*

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⇒ *the RG-scale-dependent Newton coupling vanishes at high energies*

- The RG-scale-dependence of the Newton's constant can be used to model the **weakening of the gravitational interaction at high energies**

⇒ weakening of the *singularities* typically appearing in the classical theory

A. Bonanno, M. Reuter. PRD 62 (2000) 043008
A. Bonanno, B. Koch, AP CQG 34 (2017) 095012
A. Bonanno, G. Gionti, AP, CQG 35 (2018) 6, 065004
AP. EPJC 79 (2019) 470

Asymptotically Safe Inflation and CMB power spectrum

- Let us assume that **inflation** occurs in the presence of gravity (EH approximation), minimally coupled to matter fields

- In a first approximation, we assume that matter does not contribute to the inflationary dynamics, i.e. inflation is driven by QG fluctuations only

1) Running couplings induce a **scale-dependent Lagrangian**

$$\mathcal{L}_k = \frac{1}{16\pi G_k}\{R - 2\Lambda_k\} - \beta_k R^2 + \dots$$

2) In the fixed-point regime diffeomorphism-invariance (contracted Bianchi identities) implies

$$R\left(\frac{1}{G_k}\right)' - 2\left(\frac{\Lambda_k}{G_k}\right)' = 0 \qquad \Rightarrow \qquad k^2 \sim R$$

M. Reuter, H. Weyer, JCAP 0412, 001 (2004)
B. Koch, I. Ramirez, CQG 28 (2011) 055008
S. Domazet, H. Stefancic, CQG 29 (2012) 235005

$\Rightarrow$ **Effective f(R) action**

Asymptotically Safe Inflation and CMB power spectrum

- The **critical scaling around the NGFP** depends on the matter content of the theory
- Gravity+matter → **positive and real critical exponents**

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The RG-improved Lagrangian at the fixed point is an effective f(R) theory:

$$f_*(R) \sim R^2$$

Consistent with quadratic fixed-point solution from the RG flow of f(R)-gravity

J. A. Dietz, T. R. Morris - JHEP01(2013)108
M. Demmel, F. Saueressig, O. Zanusso - JHEP08(2015)113

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Scaling in the vicinity of the NGFP

$$\lambda_k = \lambda_* + c_1\, e_1^1 \left(\frac{k}{k_0}\right)^{-\theta_1} + c_2\, e_2^1 \left(\frac{k}{k_0}\right)^{-\theta_2}$$
$$g_k = g_* + c_1\, e_1^2 \left(\frac{k}{k_0}\right)^{-\theta_1} + c_2\, e_2^2 \left(\frac{k}{k_0}\right)^{-\theta_2}$$

⇒ The effective Lagrangian depends on **universal properties on the RG flow**

Asymptotically Safe Inflation and CMB power spectrum

- Gravity+matter → **positive and real critical exponents**
- The effective Lagrangian depends on the critical exponents

$$\mathcal{L}_{\rm eff} = a_0\, R^2 + b_1\, R^{\frac{4-\theta_1-\theta_2}{2}} + b_2\, R^{\frac{4-\theta_1}{2}} + b_3\, R^{\frac{4-\theta_2}{2}} + b_4\, R^{2-\theta_1} + b_5\, R^{2-\theta_2}$$

Asymptotically Safe Inflation and CMB power spectrum

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- The effective Lagrangian depends on the critical exponents

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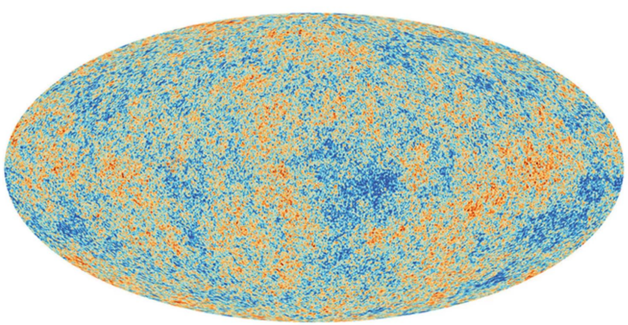


Map of the anisotropies in the CMB as observed by the Planck satellite

Power spectrum of scalar and tensorial perturbations

$$\mathcal{P}_s(k) \sim A_s \left(\frac{k}{k_0}\right)^{n_s - 1} \qquad k_0 \sim 0.05\,\text{Mpc}^{-1}$$

$$\mathcal{P}_t(k) \sim A_t \left(\frac{k}{k_0}\right)^{n_t} \qquad r \equiv \frac{A_t}{A_s}$$

From observations

$$n_s = 0.968 \pm 0.006 \qquad r < 0.11$$

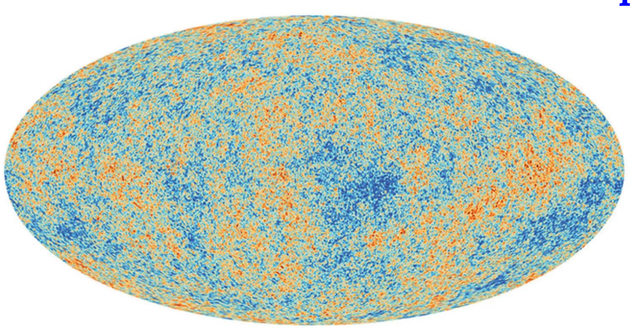
Planck Collaboration, A&A 594, A13 (2016)

Asymptotically Safe Inflation and CMB power spectrum

- Gravity+matter → **positive and real critical exponents**
- The effective Lagrangian depends on the critical exponents

$$\mathcal{L}_{\text{eff}} = \boxed{a_0\, R^2} + b_1\, R^{\frac{4-\theta_1-\theta_2}{2}} + b_2\, R^{\frac{4-\theta_1}{2}} + b_3\, R^{\frac{4-\theta_2}{2}} + b_4\, R^{2-\theta_1} + b_5\, R^{2-\theta_2}$$

Perfectly scale-invariant power spectrum



Map of the anisotropies in the CMB as observed by the Planck satellite

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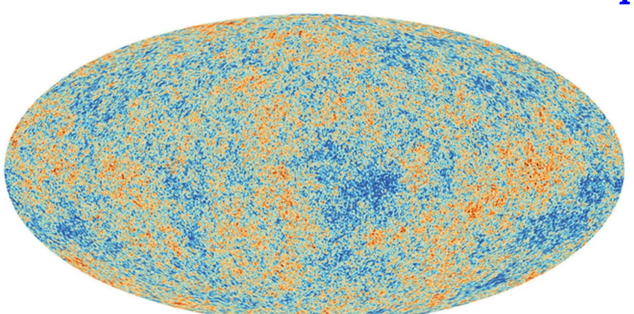

Map of the anisotropies in the CMB as observed by the Planck satellite

⇒ Requiring the theory to be compatible with a nearly-scale invariant CMB power spectrum put **constraints on the critical exponents**

$$\min\{\theta_1, \theta_2\} < 4$$

A. Bonanno, AP, F. Saueressig
Phys.Lett. B784 (2018) 229-236

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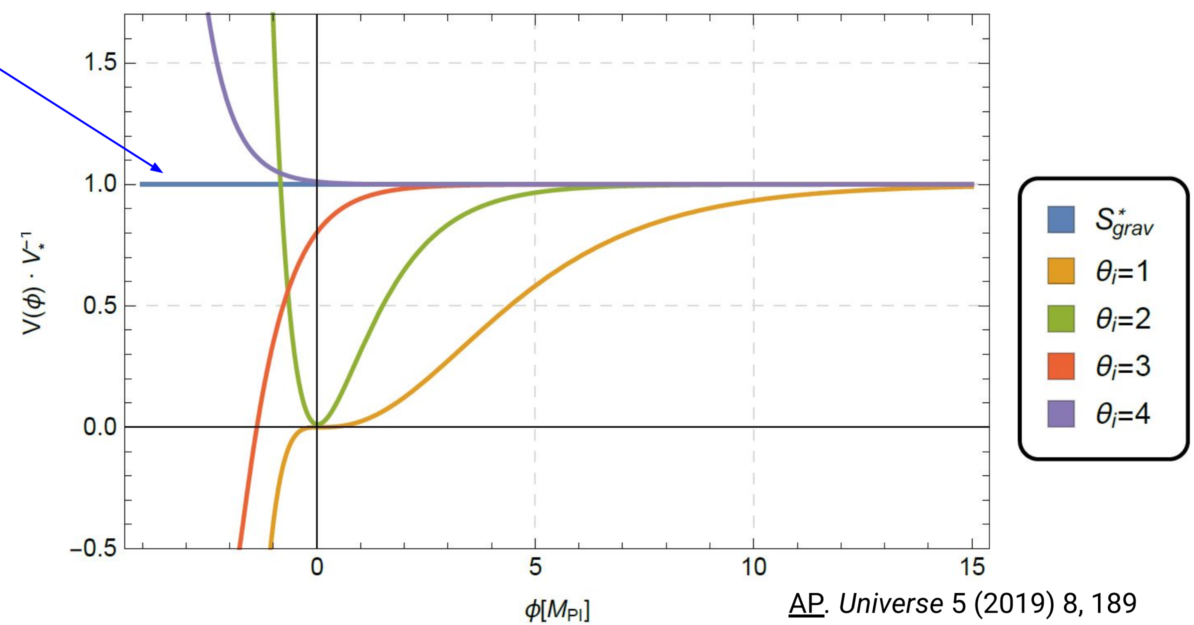

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Asymptotically Safe Inflation: the role of matter fields

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Effective action from AS-gravity coupled to SM-like matter fields

$$\mathcal{L}_{\rm eff} = \frac{1}{16\pi G_N}\left(R + \frac{1}{6m^2}R^2 - 2\Lambda_{\rm eff}\right)$$

Effective couplings

$$G = \frac{g_*^2}{c_2\,(2g_*\xi + 2\lambda_*\xi - 1)\,M_{\rm Pl}^2} \qquad m^2 = \frac{g_*}{6\,\xi\,(1-2\lambda_*\xi)\,G} \qquad \Lambda_{\rm eff} = \frac{M_{\rm Pl}^4\,(c_2^2 + c_1 g_*)\,G}{g_*^2}$$

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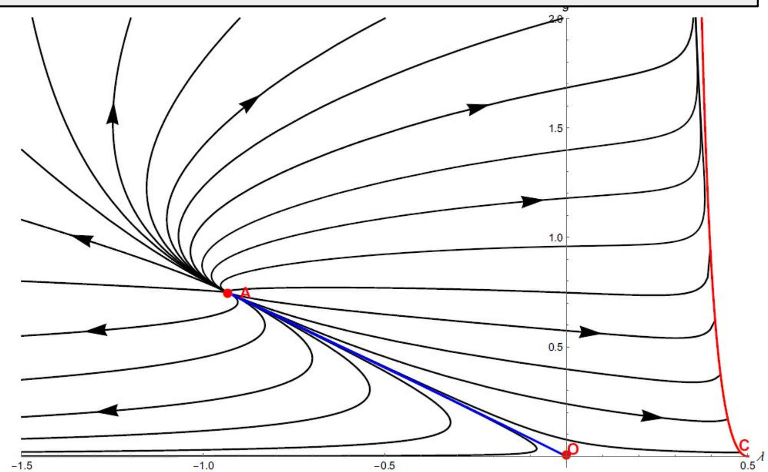
Phase diagram: Einstein-Hilbert truncation + minimally-coupled matter fields of the Standard Model

⇒ The existence of an inflaton field requires the cosmological constant to be negative at the NGFP



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This condition is compatible with similar constraints obtained in
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A. Eichhorn, A. Held. Phys. Lett. B777 (2018), pp. 217–221
A. Bonanno, G. Gionti, AP. Class. Quantum Grav. 35 (2018) 065004

Summary

- **<u>AS-gravity</u>:** aims at constructing quantum gravity in a QFT framework
  Key ingredient: <u>NGFP</u> providing a well defined UV-completion for the gravitational interaction

- <u>Computations with matter</u>: matter fields influence the gravitational RG flow, and vice versa.

- <u>Computations on foliated spacetimes</u>: in the EH truncation qualitatively same phase diagram as in the standard case
  Open questions: Wick rotation / Lorentzian-signature computation?

- Phenomenology of asymptotically safe gravity: **RG-improved models of spacetimes**

- Hallmarks of asymptotically safe gravity:
  - **Scale invariance** of the theory at high energies (⇒ nearly-scale invariant power spectrum?)
  - **Gravitational antiscreening** (⇒ resolution of classical spacetime singularities?)

- More open questions and problems to be addressed
  - **Truncation issue**
  - **Unitarity**