Universality classes of Quantum Gravity

Frank Saueressig

Research Institute for Mathematics, Astrophysics and Particle Physics

Radboud University Nijmegen

A. Contillo, G. D'Odorico, E. Manrique, S. Rechenberger, M. Schutten

arXiv:1102.5012, arXiv:1212.5114, arXiv:1309.7273, arXiv:1406.4366

ERG2014, Lefkada, September 22, 2014

Quantum Gravity within Quantum Field Theory

Requirements:

a) well-defined behavior at high energy

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- ensures the absence of UV-divergences

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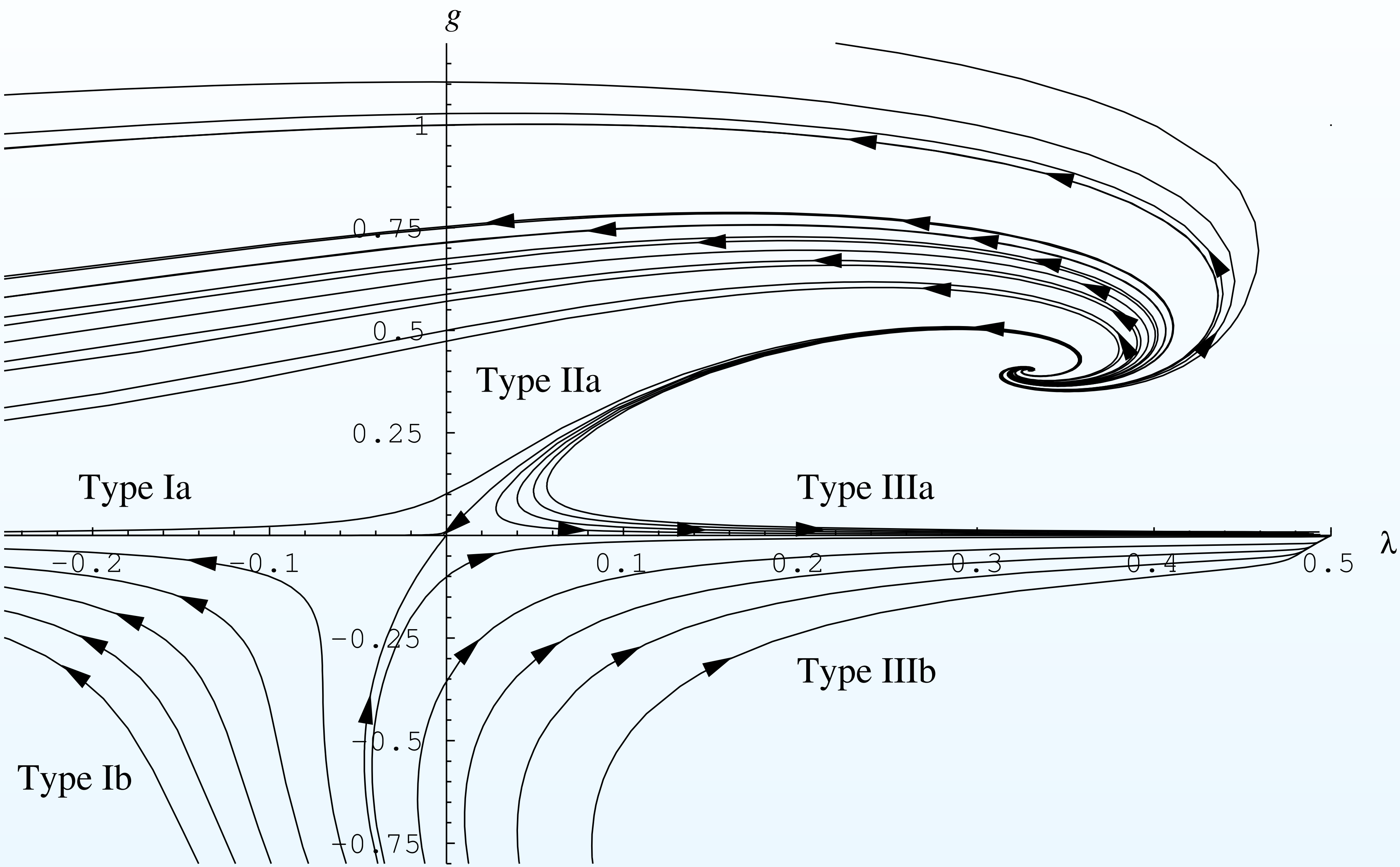
d) question of unitarity

- information loss in black holes?

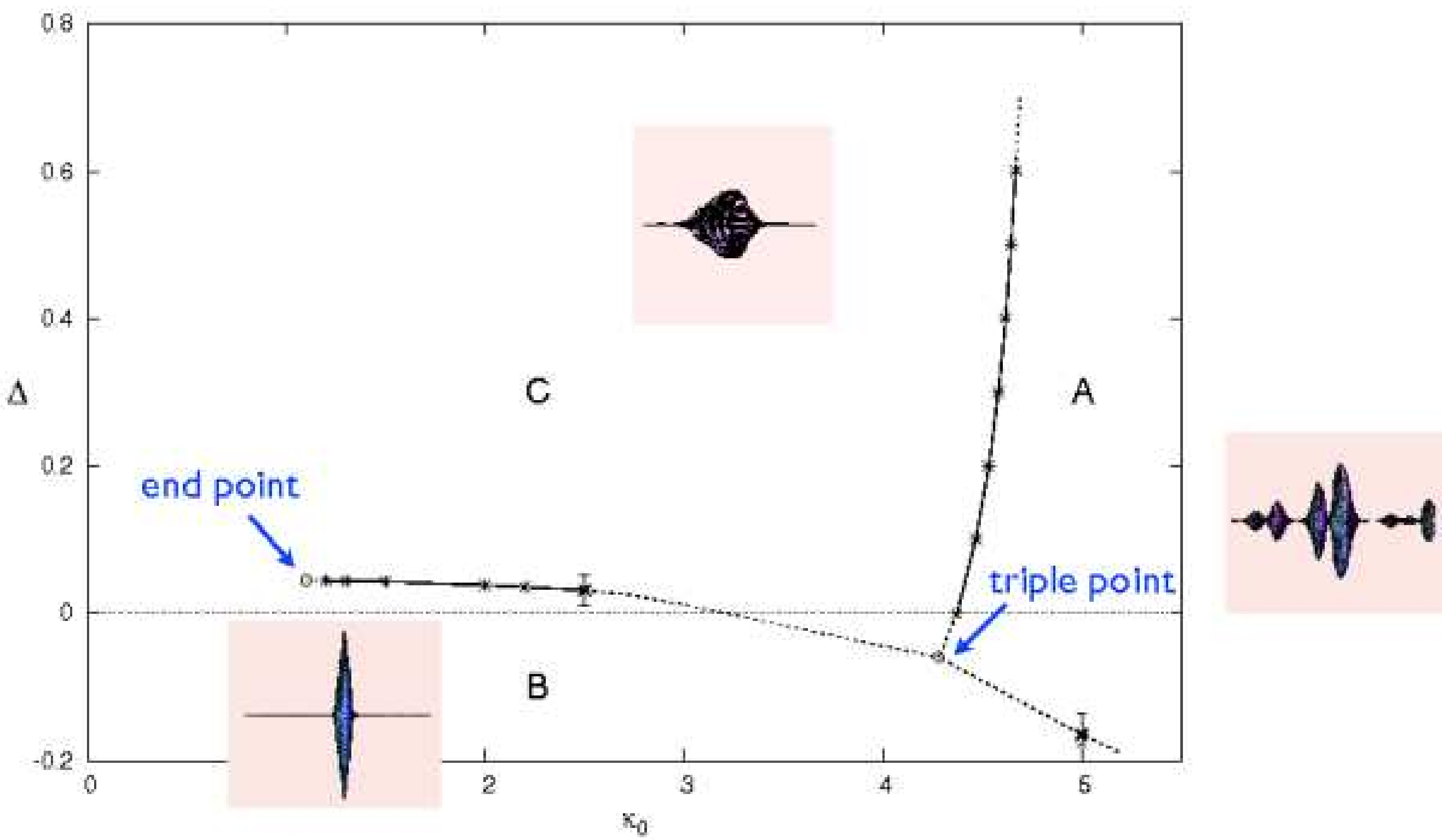
The phase diagram of Asymptotic Safety

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



The phase diagram of Causal Dynamical Triangulations

J. Ambjørn, J. Jurkiewicz, R. Loll; D. Benedetti, J. Cooperman, . . .



Once upon a time there was a . . . puzzle

FRGE and Dynamical Triangulations investigate the same path integral

continuum functional renormalization group (FRGE):

- covariant computation, Euclidean signature
  - non-Gaussian fixed point (NGFP)
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Monte Carlo Simulation of gravitational partition sum

- Causal Dynamical Triangulations (CDT)
  - second order phase transition line
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- Euclidean Dynamical Triangulations (EDT)
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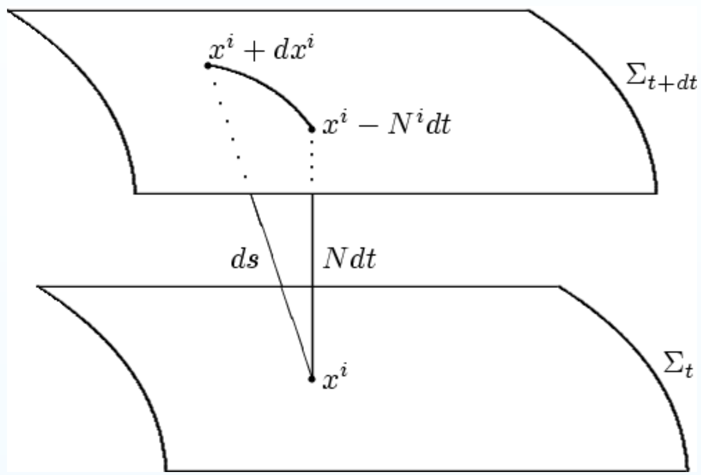
How does a causal structure influence Asymptotic Safety?

Functional Renormalization Group Equation

for foliated spacetimes

Foliation structure via ADM-decomposition

Preferred "time"-direction via foliation of space-time



- foliation structure $\mathcal{M}^{d+1} = S^1 \times \mathcal{M}^d$ with $y^\mu \mapsto (\tau, x^a)$:

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

- fundamental fields: $g_{\mu\nu} \mapsto (N, N_i, \sigma_{ij})$

$$g_{\mu\nu} = \begin{pmatrix} N^2 + N_i N^i & N_j \\ N_i & \sigma_{ij} \end{pmatrix}$$

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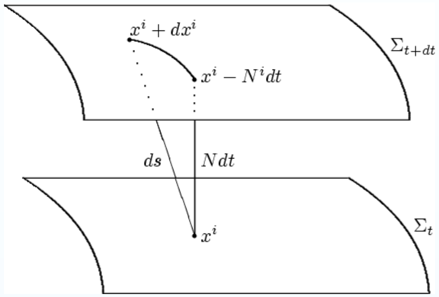

- foliation structure $\mathcal{M}^{d+1} = S^1 \times \mathcal{M}^d$ with $y^\mu \mapsto (\tau, x^a)$:

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Allows to include signature parameter $\epsilon = \pm 1$

Foliated functional renormalization group equation

Flow equation: formally the same as in covariant construction

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

- covariant: $\mathcal{M}^4$

$$\mathrm{STr} \approx \sum_{\text{fields}} \int d^4y \sqrt{\bar{g}}$$

- foliated: $S^1 \times \mathcal{M}^3$

$$\mathrm{STr} \approx \sqrt{\epsilon} \sum_{\text{component fields}} \sum_{\text{KK-modes}} \int d^3x \sqrt{\bar{\sigma}}$$

  - structure resembles: quantum field theory at finite temperature!

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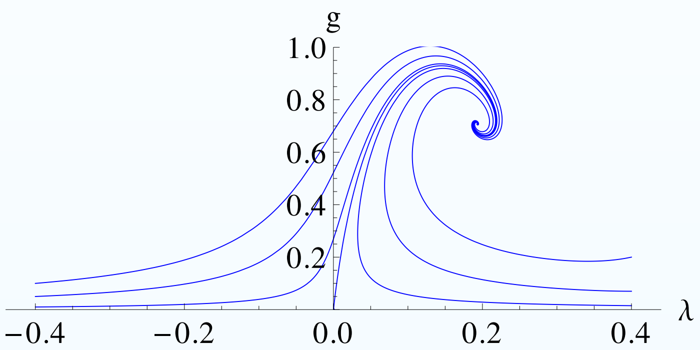
Advantages of the foliated flow equation:

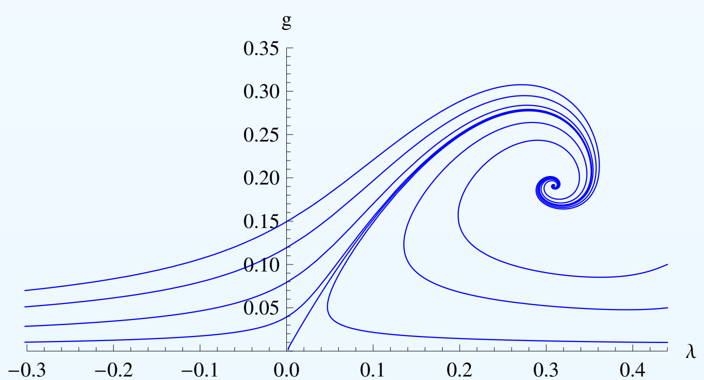
- ϵ-dependence: keep track of signature effects
- structure: same as in Causal Dynamical Triangulations

Comparison: phase diagrams for ADM-variables

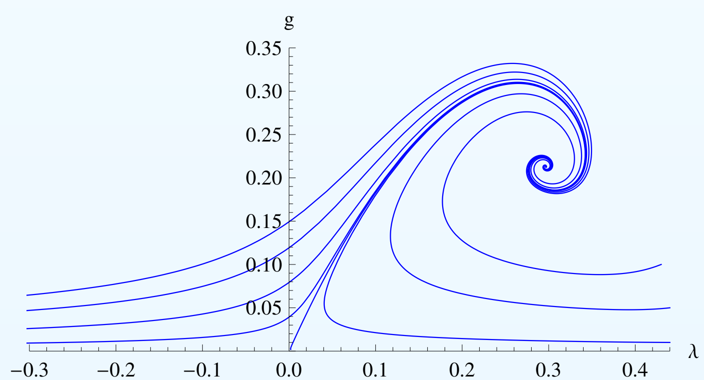
$$\Gamma_k^{\rm ADM} = \frac{\sqrt{\epsilon}}{16\pi G_k} \int d\tau d^3x N\sqrt{\sigma} \left[\epsilon^{-1} \left(K_{ij}K^{ij} - K^2 \right) - R^{(3)} + 2\Lambda_k \right] + S^{\rm gf} + S^{\rm gh}$$



covariant computation



Euclidean $\epsilon = 1$



Lorentzian: $\epsilon = -1$

It's all about choosing a gauge:

covariant formulation:

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$$

perform covariant gauge-fixing (e.g., harmonic gauge)

$$F_\mu = \bar{D}^\nu h_{\mu\nu} - \tfrac{1}{2}\bar{D}_\mu h_\nu{}^\nu = 0\,.$$

foliated formulation with ADM-fields $g_{\mu\nu} \mapsto \{N, N_i, \sigma_{ij}\}$

$$N = \bar{N} + h\,, \qquad N_i = \bar{N}_i + h_i\,, \qquad \sigma_{ij} = \bar{\sigma}_{ij} + h_{ij}$$

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- fluctuations in the metric on the spatial slice only

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> ADM fields in temporal gauge
>
> No fluctuations in stacking spatial slices!

Symmetries conserved by the foliated FRGE

fundamental fields: $\left\{\tilde{N}(\tau,x), \tilde{N}_i(\tau,x), \tilde{\sigma}_{ij}(\tau,x)\right\}$

symmetry: general coordinate invariance inherited from $\gamma_{\mu\nu}$:

$$\delta\gamma_{\mu\nu} = \mathcal{L}_v(\gamma_{\mu\nu})\,, \qquad v^\alpha = (f(\tau,x)\,,\,\zeta^a(\tau,x))$$

induces

$$\delta\tilde{N} = f\partial_\tau\tilde{N} + \zeta^k\partial_k\tilde{N} + \tilde{N}\partial_\tau f - \tilde{N}\tilde{N}^i\partial_i f\,,$$

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- Non-linearity of ADM-decomposition: symmetry realized non-linearly
- in ADM it is impossible to combine:
  - linear background field method
  - regulator $\Delta_k S$ quadratic in fluctuation fields
  - background Diff($\mathcal{M}$)-symmetry

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background symmetry respected by FRGE:

- subgroup of linear transformations

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symmetry group of Hořava-Lifshitz gravity

Wetterich Equation

for projectable Hořava-Lifshitz gravity

[E. Manrique, S. Rechenberger, F.S., arXiv:1102.5012]
[S. Rechenberger, F.S., arXiv:1212.5114]
[A. Contillo, S. Rechenberger, F.S., arXiv:1309.7273]
[G. D'Odorico, M. Schutten, F.S., arXiv:1406.4366]

[M. Baggio, J. de Boer and K. Holsheimer, arXiv:1112.6416]
[D. Benedetti, F. Guarnieri, arXiv:1311.6253]

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

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Can construct the effective average action for projectable HL-gravity

- scale-dependence governed by functional renormalization group equation

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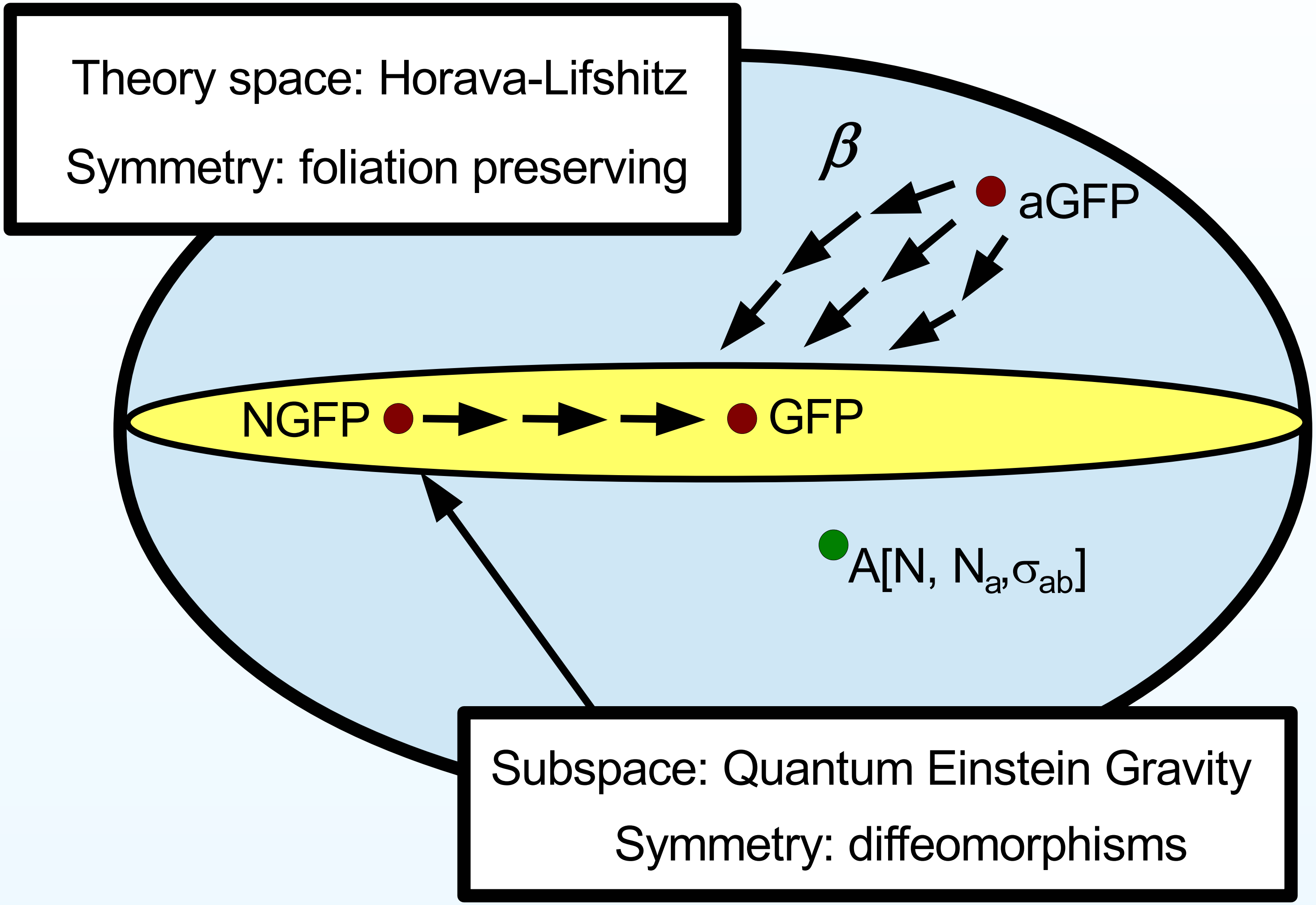
  - Complication: anisotropic models have two correlation lengths

Relation between Asymptotic Safety and Hořava-Lifshitz gravity



also see: talk by G. D'Odorico tomorrow

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  - fundamental theory: Einstein-Hilbert action
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Gravity

RG-flows of Hořava-Lifshitz gravity in the IR

A. Contillo, S. Rechenberger, F.S., JHEP 1312 (2013) 017

RG-flow of anisotropic λ-R truncation

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

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Fixed points of the beta functions:

- Wheeler-de Witt metric $\Rightarrow$ line of GFPs

$$\tilde{G}_* = 0\,, \qquad \tilde{\Lambda}_* = 0\,, \qquad \lambda = \lambda_*$$

  - one IR attractive, one IR repulsive, one marginal direction

- NGFP:

$$\tilde{G}_* = 0.49\,, \qquad \tilde{\Lambda}_* = 0.17\,, \qquad \lambda_* = 0.44$$

  - three UV-attractive eigen-directions
  - imprint of Asymptotic Safety

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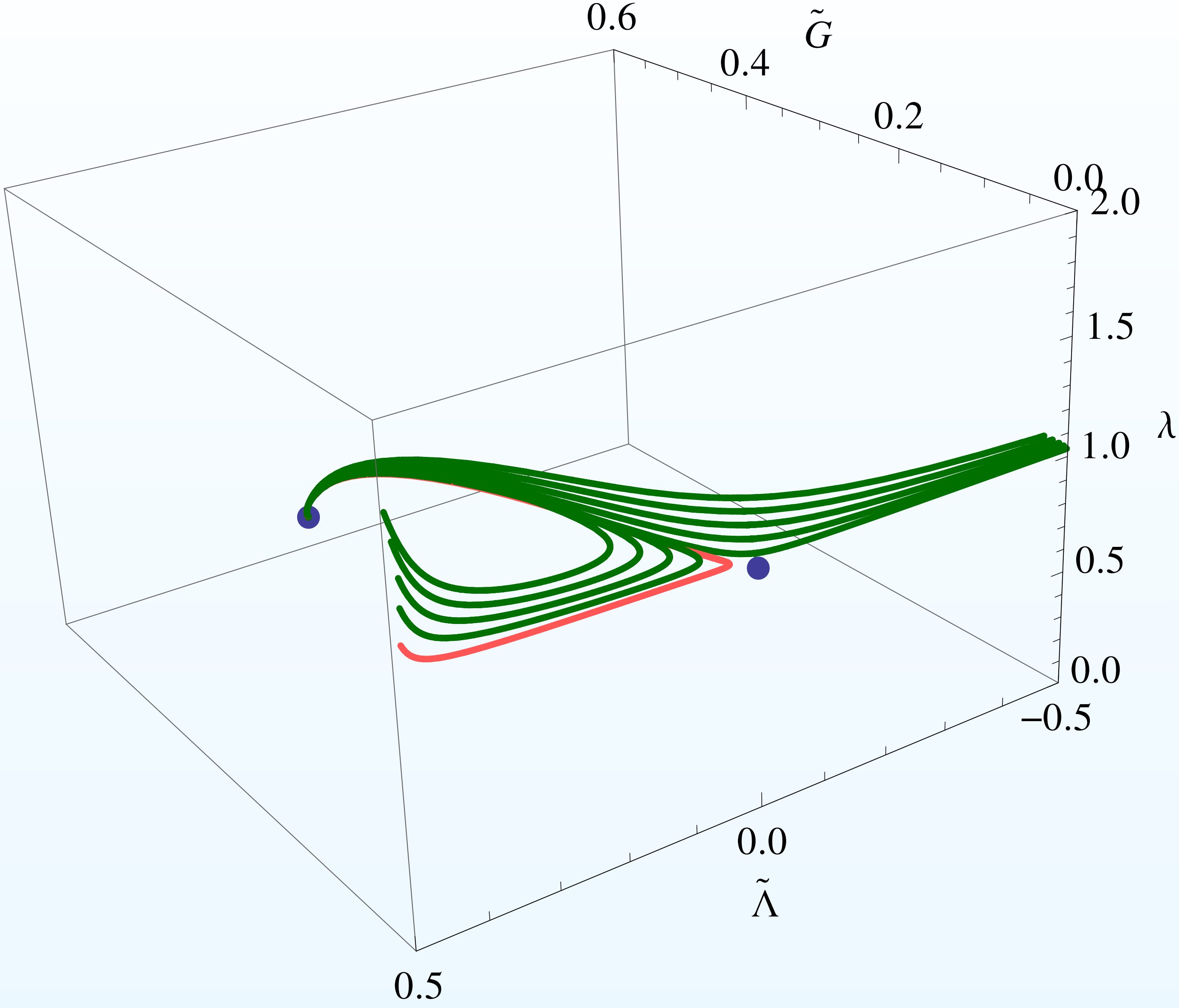
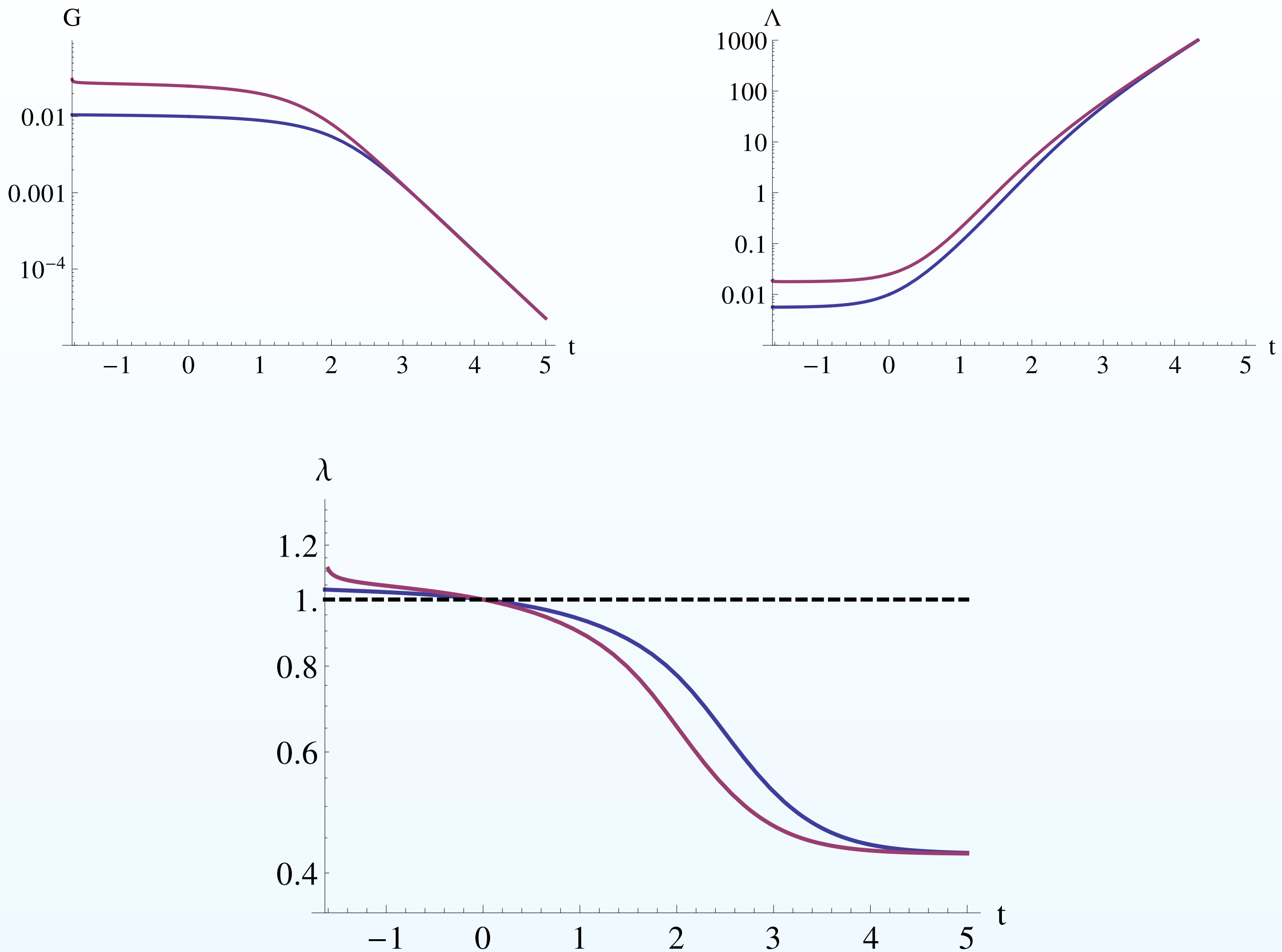
anisotropic GFP providing UV-limit of HL-gravity not in truncation

Hořava-Lifshitz gravity: recovering general relativity in the IR



Scale-dependence of dimensionful couplings



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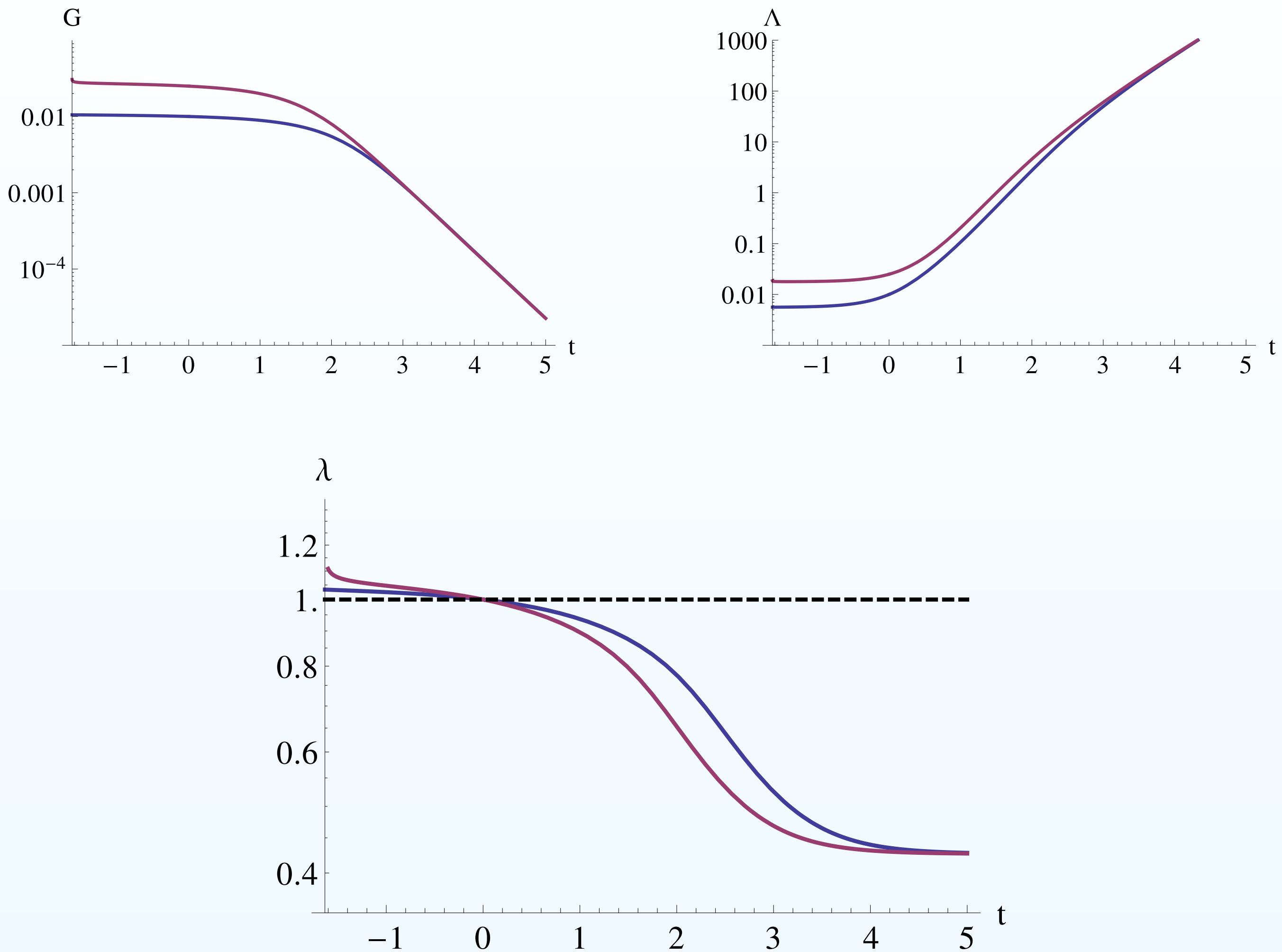


GFP governs IR-behavior of HL-gravity

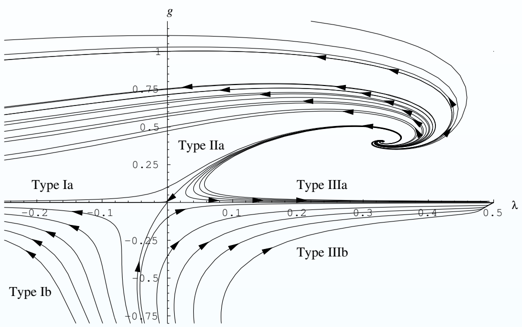
small value of cosmological constant makes λ compatible with experiments

Summary and Outlook

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



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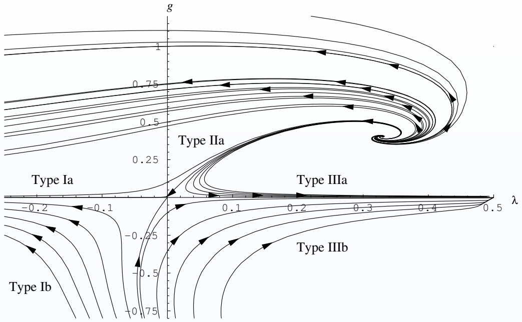
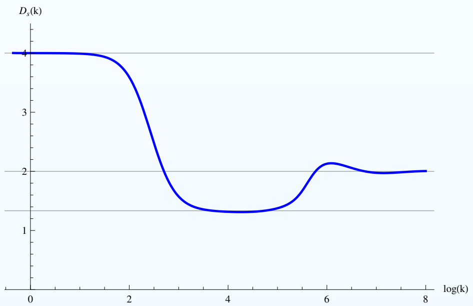


Connecting the FRG to CDT

- Constructed FRG probing CDT theory space
- prospects of comparing RG flows



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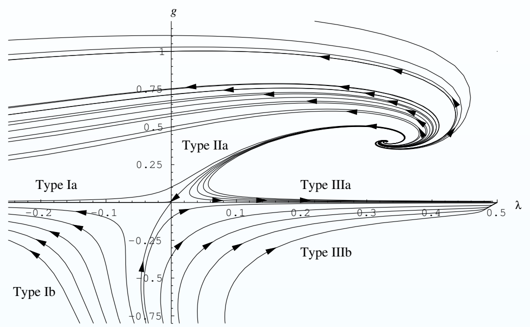

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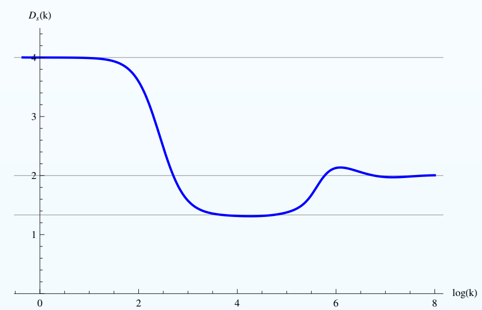
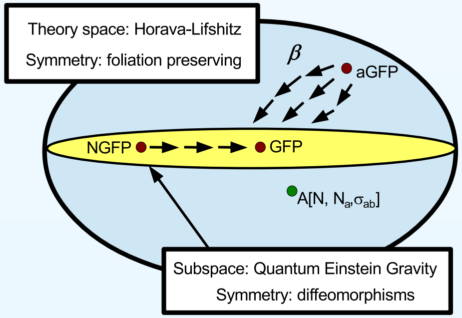


Connection to Hořava-Lifshitz gravity

- use different RG fixed points for continuum limit
- FRGE: key tool for establishing renormalizability



Outlook

many proposals for quantum gravity within QFT:

- Asymptotic Safety
- (Causal) Dynamical Triangulations
- Hořava-Lifshitz gravity
- first order formalism
- shape dynamics

differences:

- field content (metric, vielbein, ADM-variables, . . .)
- symmetry group (diffeomorphisms, foliation preserving diff.)

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RG techniques crucial in all models!