Title: Probing asymptotically safe quantum gravity with matter

Speakers: Marc Schiffer

Series: Quantum Gravity

Date: May 23, 2024 - 2:30 PM

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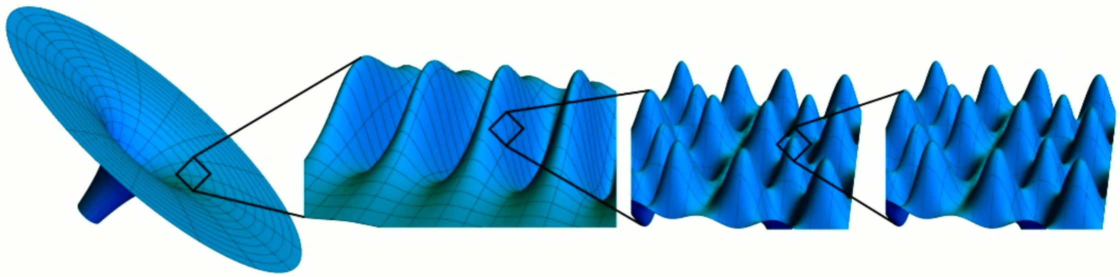
Abstract: Asymptotically safe quantum gravity might provide a unified description of the fundamental dynamics of quantum gravity and matter. The realization of asymptotic safety, i.e., of scale symmetry at high energies, constraints the possible interactions and dynamics of a system. In this talk, I will first introduce the scenario of asymptotic safety for gravity with matter, and explain how it can be explored using functional methods. I will then emphasize, how the constraints on the microscopic dynamics of matter arising from quantum scale symmetry can turn into constraints on the gravitational dynamics, both by exploring the asymptotically safe fixed-point structure, and by exploring resulting infrared physics.

Zoom link

Probing asymptotically safe quantum gravity with matter



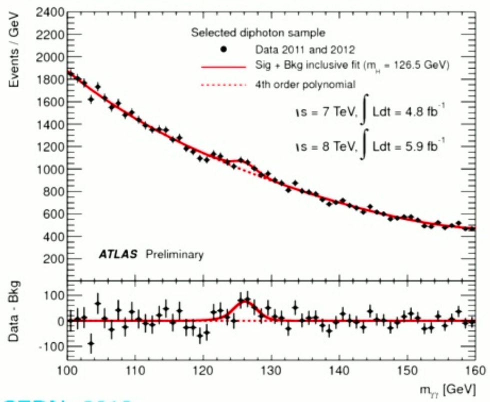
Perimeter Institute, Quantum Gravity Seminar

Marc Schiffer, Perimeter Institute

May 23, 2024

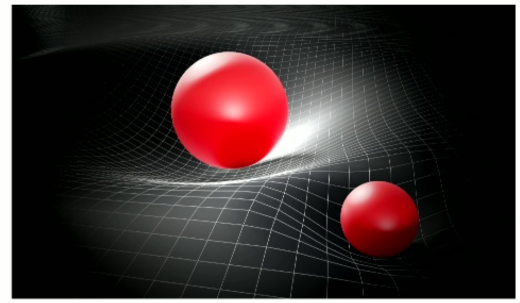
Why Matter in Quantum Gravity?

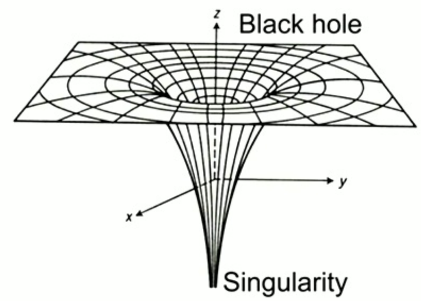
Standard Model



CERN, 2012

General Relativity





Northern Arizona University

Scale of QG: $M_{\rm Pl} = \sqrt{\frac{\hbar\, c}{G_{\rm N}}}$

Why Matter in Quantum Gravity?

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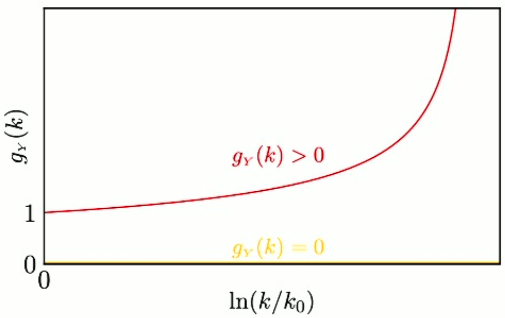
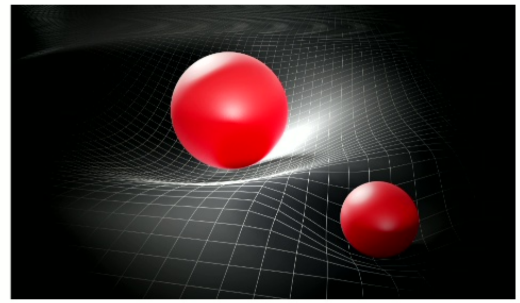
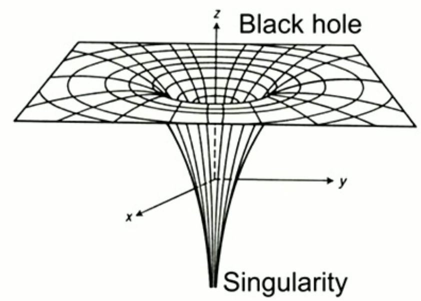


Scale of divergence: $E_{\mathrm{LP}} \gg M_{\mathrm{Pl}}$

General Relativity





Northern Arizona University

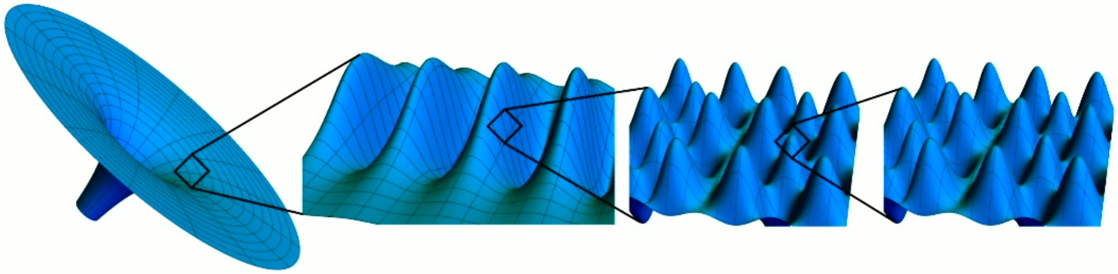
Scale of QG: $M_{\mathrm{Pl}} = \sqrt{\frac{\hbar\, c}{G_{\mathrm{N}}}}$

Quantum nature of spacetime: might provide UV-completion for GR and SM!

Outline

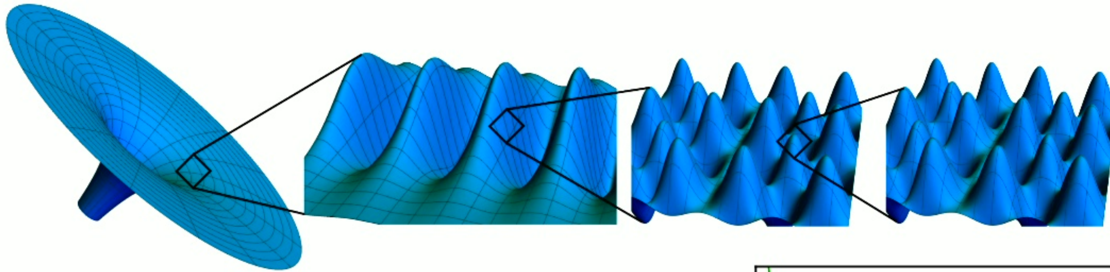
- Asymptotically safe quantum gravity
  - FRG studies
    - Constraints from the $U(1)$ sector
    - Constraints from scalar fields?
  - EDT studies
    - Newtonian Binding
    - de Sitter Volume profile

Asymptotically Safe Quantum Gravity

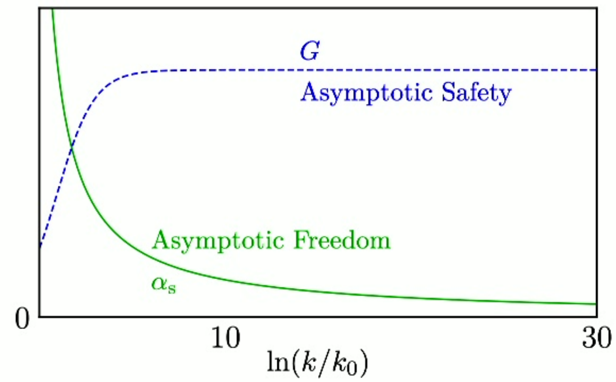


- Perturbative quantum gravity:
  loss of predictivity
- Key idea of asymptotic safety:
  Quantum realization of
  scale symmetry
  - imposes infinitely many conditions on theory

Asymptotically Safe Quantum Gravity



- Perturbative quantum gravity:
  loss of predictivity
- Key idea of asymptotic safety:
  Quantum realization of
  scale symmetry
  - imposes infinitely many conditions on theory
  - Examples for AS:
    gauge-Yukawa systems (perturbative)
    [Litim, Sannino; 2014]
    Gross-Neveu, Wilson-Fisher, etc.
    [Braun, Gies, Scherer; 2010], see also review [Eichhorn, 2019]



Asymptotic freedom:
free fixed point, $\alpha_{s,*} = 0$

Asymptotic safety:
interacting fixed point, $G_* \neq 0$

Tools to discover asymptotic safety in gravity

- Perturbative methods
  [Christensen, Duff; 1978], [Gastmans, Kallosh, Truffin; 1978], [Martini, Ugolotti, Zanusso; 2021]
  [M. Niedermaier, 2006]
- Lattice methods (EDT/CDT)
  [Ambjorn, Jurkiewicz; 1991], [Ambjorn, R. Loll; 1998]
- Functional Renormalization Group
  [Wetterich; 1993], [Ellwanger; 1993], [Morris; 1994], [Reuter; 1996]

Comparison: functional and Lattice methods

- Functional methods:
  - extract scale dependence of couplings
  - AS: $k\partial_k \vec{g} = 0$
  - need truncations, artificial background, ...

- Lattice methods:
  - extract lattice correlators, order parameters, ...
  - AS: continuous phase transition
  - finite size effects, extrapolations, "guessing" of relevant parameters, ...

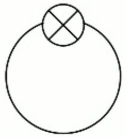
Tool: Functional Renormalization Group

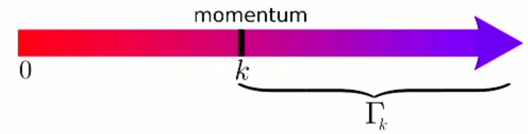
Main idea:
include quantum fluctuations step by step

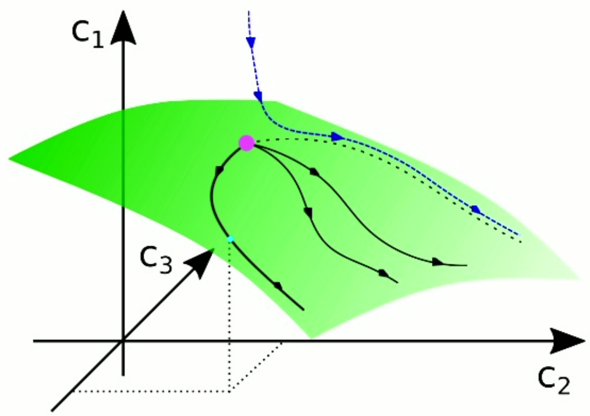
$$e^{-\Gamma_k[\phi]} \sim \int \mathcal{D}\varphi \; e^{-S[\varphi]-\frac{1}{2}\int_p \varphi(-p)R_k(p^2)\varphi(p)}\,, \qquad R_k(p^2)\begin{cases} > 0 \,\text{if}\, p^2 < k^2 \,(\text{supression}) \\ = 0 \,\text{if}\, p^2 > k^2 \,(\text{no}\,\text{supression}) \end{cases}$$

Flow Equation
[Wetterich, 1993], [Ellwanger, 1993], [Morris, 1994], [Reuter, 1996]

$$k\,\partial_k \Gamma_k = \frac{1}{2}\,\mathsf{STr}\left(\left(\Gamma_k^{(2)} + R_k\right)^{-1} k\,\partial_k R_k\right)$$

$$= \frac{1}{2}$$ 





→ search for fixed points $k\,\partial_k g_i = 0$

→ describe RG-flow in theory-space

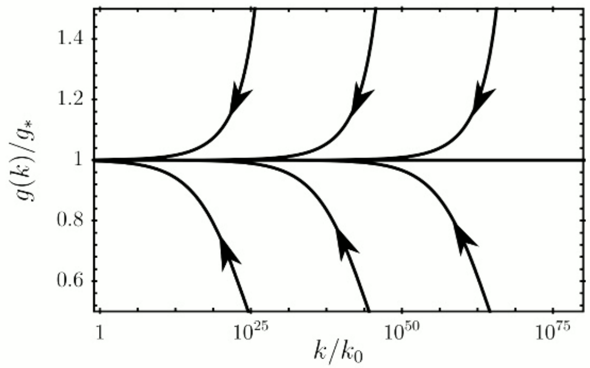
Γ_k : requires truncation

Predictivity in asymptotic safety

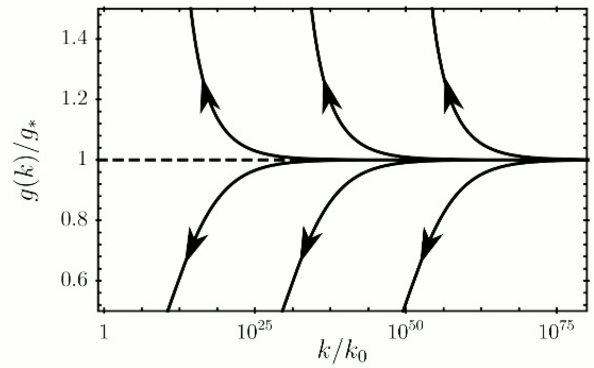
scale invariance

our universe at low energies

→ departure from scale invariance is necessary



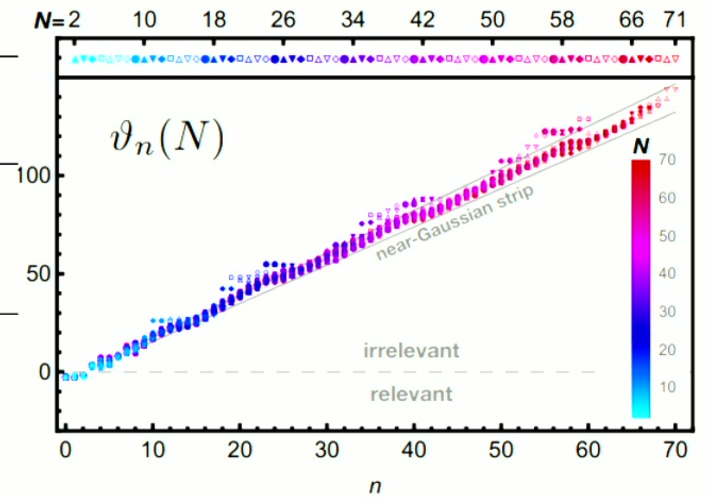
Irrelevant direction:
prediction in IR



Relevant direction:
free parameter

AS in pure gravity

Fixed point	Invariants	Rel.	Irrel.
✓	$\Lambda + R$ [Reuter; 1996]	✓	
✓	$R^2 + R_{\mu\nu}R^{\mu\nu}$ [Benedetti, Machado, Saueressig; 2009]	✓	✓
✓	$C_{\mu\nu}^{\ \ \rho\sigma}\, C_{\rho\sigma}^{\ \ \kappa\lambda}\, C_{\kappa\lambda}^{\ \ \mu\nu}$ [Gies, Knorr, Lippoldt, Saueressig; 2016] [Baldazzi, Falls, Kluth, Knorr; 2023]		✓
✓ ⋮ ✓	R^3 [Reuter, Lauscher, 2002] ⋮ $R^{70},\ R^{\mu\nu\,34},\dots$ [Codello, Percacci, Rahmede; 2007, 2008] [Machado, Saueressig; 2007] [Falls, Litim, et. al; '13, '14, '17, '18] [Litim, Kluth; 2020, 2022]		✓ ⋮ ✓



[Falls, Litim, Schröder; 2018]

Relevant: $\vartheta_n < 0$, free parameter

Irrelevant: $\vartheta_n > 0$, prediction

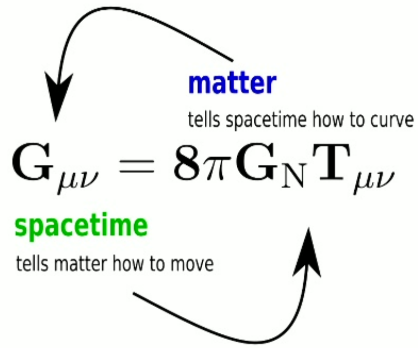
Fluctuation approach: review: [Reichert, Pawlowski; 2020], ...

Form-factor expansion: [Knorr, Ripken, Saueressig; 2019], ...

Current 'hot topics'

- Key questions for asymptotically safe quantum gravity (FRG):
  [Bonnano, Eichhorn, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca; 2020]
  - Convergence
    [Falls, Litim, et al., 2013, 2014, 2017, 2018], [Litim, Kluth, 2020, 2022], [Denz, Pawlowski, Reichert, 2018]
    [Baldazzi, Falls, Kluth, Knorr; 2023], . . .
  - Lorentzian signature
    [Manrique, Rechenberger, Saueressig, 2011], [Bonnano, Denz, Pawlowski, Reichert, 2020]
    [Knorr, 2018], [Eichhorn, Platania, MS, 2019]
    [Fehre, Litim, Pawlowski, Reichert, 2021], [D'Angelo, Drago, Pinamonto, Rejzner, 2022], [D'Angelo; 2023]
  - Unitarity and scattering amplitudes
    [Bonnano, Denz, Pawlowski, Reichert, 2020], [Fehre, Litim, Pawlowski, Reichert, 2021]
    [Draper, Knorr, Ripken, Saueressig, 2020], [Knorr, MS, 2021]
    [Platania, Wetterich, 2020], [Platania, 2021], . . .
  - **Interplay of gravity and matter**
    review: [Eichhorn, MS; 2022]

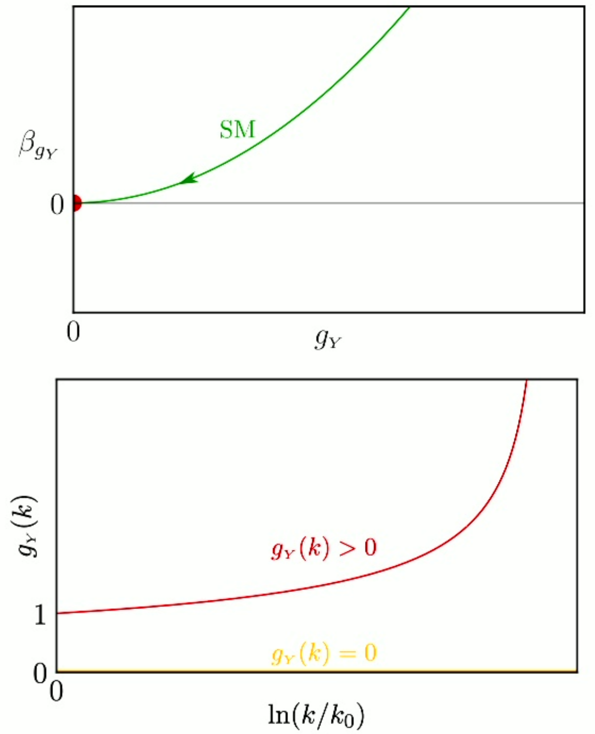
AS in gravity-matter systems



- Key questions for gravity-matter systems:
  - Does the gravity fixed-point allow for the inclusion of SM-matter?
    [Doná, Eichhorn, Percacci; 2013], [Meibohm, Pawlowski, Reichert; 2016], [Biemanns, Platania, Saueressig; 2017]
    [Pastor-Gutierrez, Pawlowski, Reichert, 2022], · · ·
  - **Does ASQG support a UV-complete matter sector?**
    Does a UV-complete matter sector pose constraints on gravity?
    [Harst, Reuter; 2011], [Eichhorn, Held, Pawlowski; 2016], [Christiansen, Eichhorn; 2017], · · ·
  - Is there a viable phenomenology?
    [Shaposhnikov, Wetterich; 2009], [Harst, Reuter; 2011], [Eichhorn, Held; 2017, 2018], [Eichhorn, Versteegen; 2017], · · ·
    [Draper, Knorr, Ripken, Saueressig; 2020], [Knorr, Pirlo, Ripken, Saueressig; 2022]
    [Reichert, Smirnov; 2019], [Kowalska, Sessolo; 2020], [Eichhorn, Pauly; 2020]
    [Pastor-Gutierrez, Pawlowski, Reichert, 2022], · · ·
    [Platania, Knorr; 2024], [Eichhorn, Odgaard Pedersen, MS, 2024]

The $U(1)$ sector of the Standard Model

$$\beta_{g_Y} = \frac{1}{16\pi^2}\frac{41}{6}g_Y^3 + \mathcal{O}(g_Y^4)$$

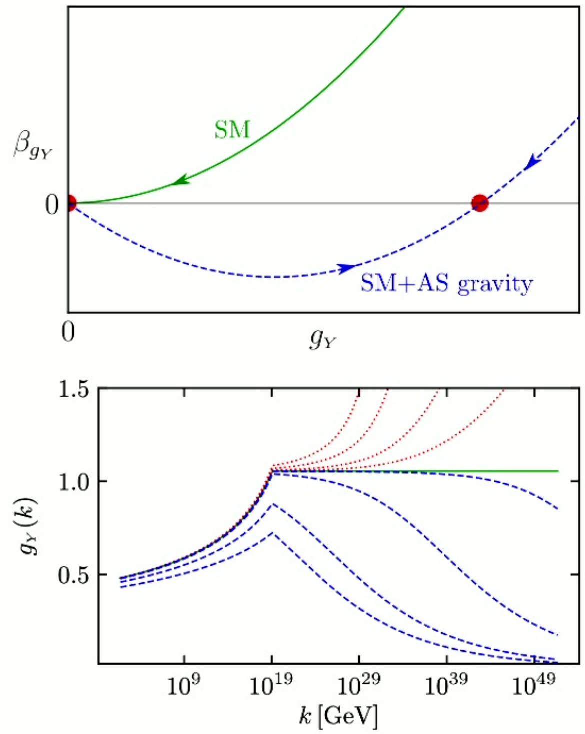


The $U(1)$ sector of the Standard Model

$$\beta_{g_Y} = -f_g\, g_Y + \frac{1}{16\pi^2}\frac{41}{6} g_Y^3 + \mathcal{O}(g_Y^4)$$

$$f_g \begin{cases} = \text{const.} \geq 0\,, & \text{for } k > M_{\text{Pl}} \\ \approx 0\,, & \text{for } k < M_{\text{Pl}} \end{cases}$$

[Daum, Harst, Reuter; 2009], [Harst, Reuter; 2011], [Folkerts, Litim, Pawlowski; 2011], [Christiansen, Eichhorn; 2017], [Eichhorn, Versteegen; 2017], [Christiansen, Litim, Pawlowski, Reichert; 2017] [de Brito, Eichhorn; 2022]



Metric fluctuations might induce a UV completion of the $U(1)$-sector.
$\Rightarrow$ Upper bound on $g_Y(k)$ (i.e., constraints on gravity) [Eichhorn, Versteegen; 2017]

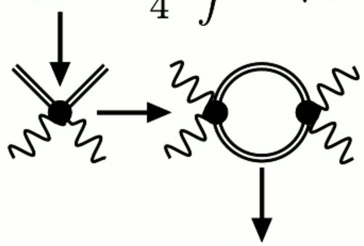
Induced interaction

- Example: Abelian gauge field A_μ

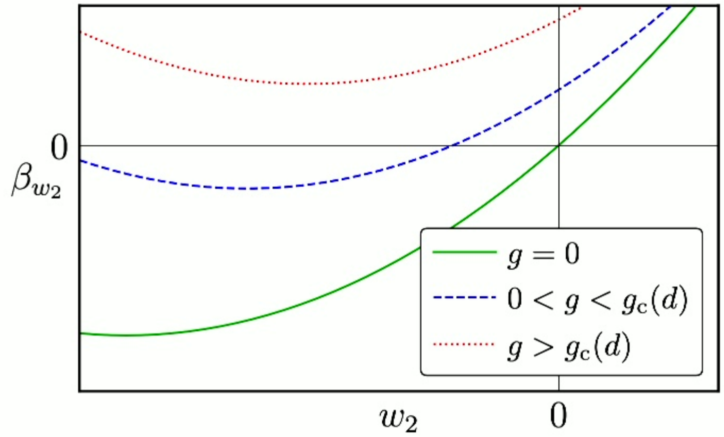
  $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

  - From kinetic term:

$$S_{\text{kin}} = \frac{Z_A}{4}\int \mathrm{d}^d x\sqrt{g}F_{\mu\nu}F^{\mu\nu}$$



$$S_{\text{int}} = \frac{w_2 k^{-d}}{8}\int \mathrm{d}^d x\sqrt{g}\,(F_{\mu\nu}F^{\mu\nu})^2$$



- Schematically:

$$\beta_{w_2} = B_0(G) + w_2\, B_1(G) + w_2^2 B_2$$

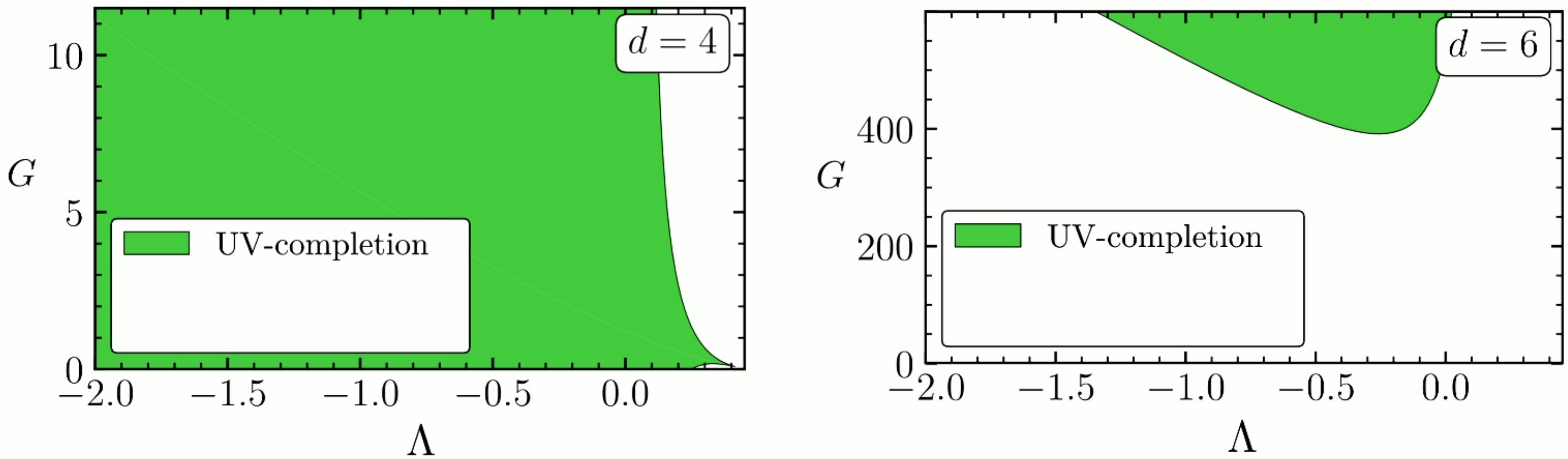
- $\exists$ real FP only for $B_0 \leq \frac{B_1^2(G)}{4B_2}$

UV-completion of induced interactions: might impose constraints on gravity

[Eichhorn; 2012], [de Brito, Eichhorn, Linos dos Santos; 2021], [Laporte, Pereira, Saueressig, Wang, 2021], [Knorr, 2022], [de Brito, Knorr, MS; 2023] [Eichhorn, Gies; 2011], [Eichhorn, Lippoldt, MS; 2018], [Christiansen, Eichhorn; 2017], [Eichhorn, MS; 2019], [Eichhorn, Kwapisz, MS; 2021]

The $U(1)$ sector in $d > 4$

- $\beta_{g_Y} = g_Y\left(\frac{d-4}{2} - f_g(d)\right) + \mathcal{O}(g_Y^3)$
  $\Rightarrow$ UV-completion shifts into more strongly coupled regime



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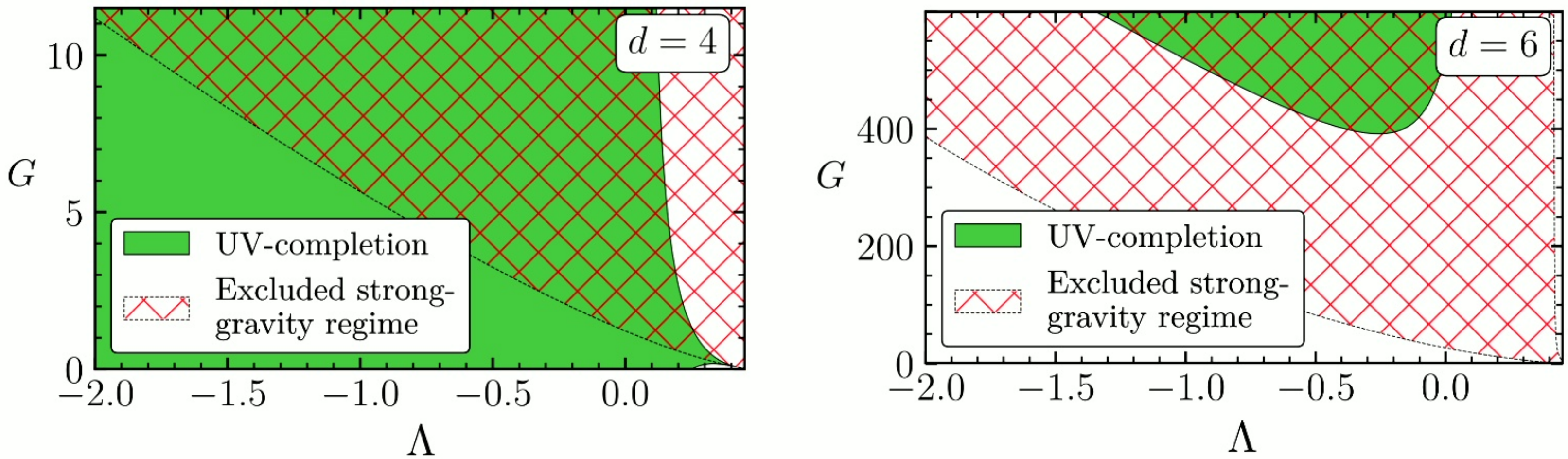
- Strongly coupled regime: might feature new divergences in matter sector



$U(1)$ gauge sector might remain UV-incomplete in $d \geq 6$, even in the presence of gravity.
[Eichhorn, MS; 2019], [Eichhorn, Kwapisz, MS; 2021]

Positivity bounds for photon-gravity systems

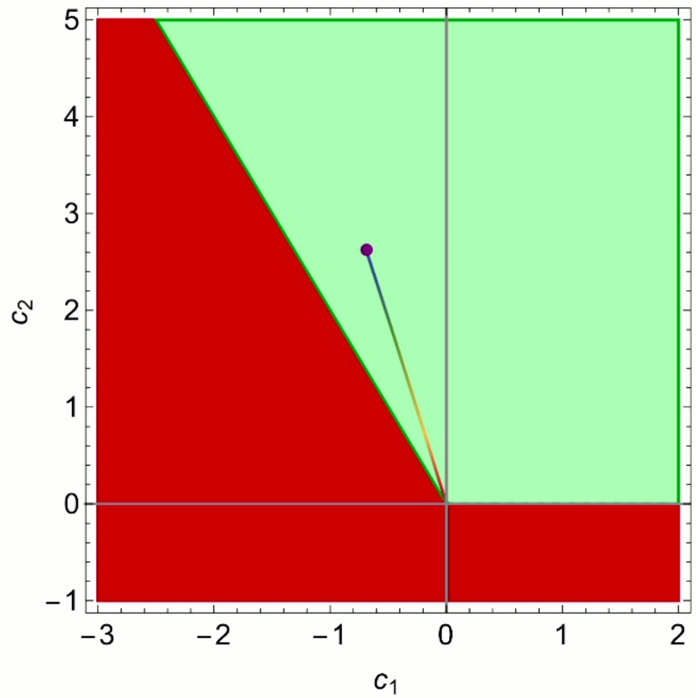
- Based on [Eichhorn, Odgaard Pedersen, MS, 2024] , see also [Platania, Knorr; 2024]
- Photon-gravity system:

$$\mathcal{L} = \frac{Z_A}{4} F^2 + \frac{c_1}{k^4} \left(F^2\right)^2 + \frac{c_2}{k^4} F^4$$

- Positivity bounds:
  constraints on Wilson coefficients;
  derived demanding unitarity, locality,
  microcausality, and Lorentz invariance
  [e.g., Carillo Gonzalez, de Rham, Jaitly, Pozsgay, Tokareva; 2023]
  More subtle in gravity: massless graviton
  [Alberte, de Rham, Jaitly, Tolley; 2020]
- (Standard) bounds:

$$4c_1 > -3c_2\,, \quad \frac{4c_1 + 3c_2}{|4c_1 + c_2|} > 1$$

- Under some assumptions: (Wick-rotation, scale dependence of $G, \Lambda, \ldots$)



[Eichhorn, Odgaard Pedersen, MS; 2024]

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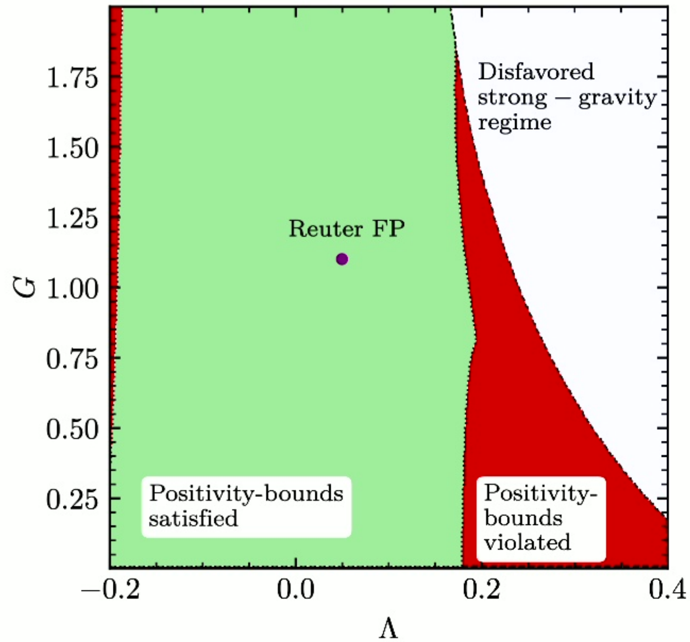
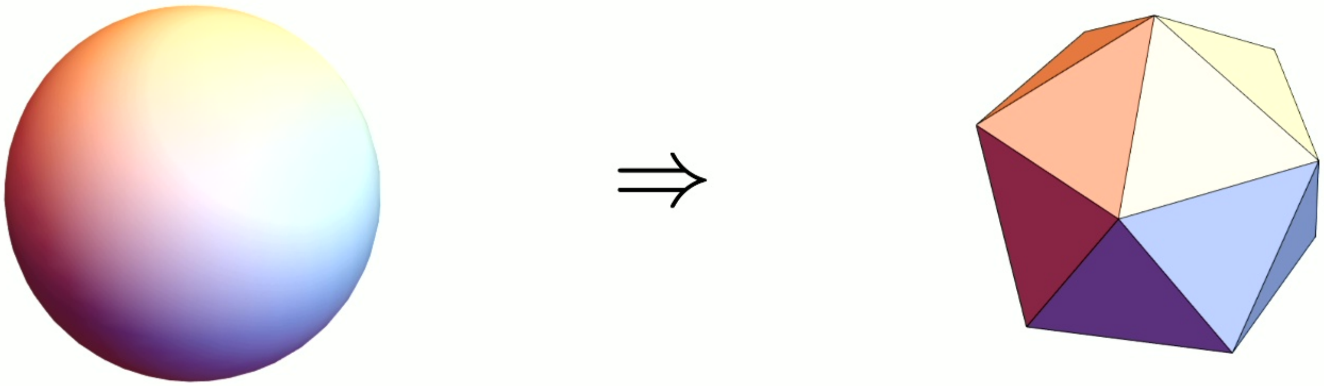


[Eichhorn, Odgaard Pedersen, MS; 2024]

Evidence for asymptotic safety from Euclidean Dynamical Triangulations



- Discretization of spacetime in terms of triangulations

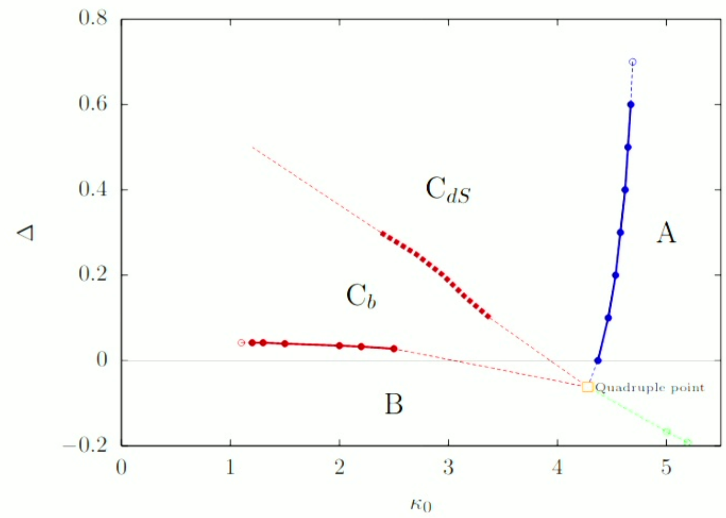
Lattice quantum gravity in $d = 4$

- Discretization of spacetime in terms of triangulations

$$\int \mathcal{D}g \, e^{-S[g]} \to \sum_{\mathcal{T}} \frac{1}{C_{\mathcal{T}}} \qquad e^{-S_{\mathrm{ER}}}$$

- in $d = 4$: no physical phase, no indications for higher-order transition in κ_2-κ_4 - space
  [Ambjørn, Jain, Jurkiewicz, Kristjansen, 1993], [Bakker, Smit, 1994]
  [Ambjørn, Jurkiewicz, 1995], [Bialas, Burda, Krzywicki, Petersson, 1996]
  . . .

- CDT: impose causal structure
  [Ambjørn, Loll, 1998], [Ambjørn, Jurkiewicz, Loll, 2000], . . .



Taken from [Loll, 2020]

Lattice quantum gravity in $d = 4$

- Discretization of spacetime in terms of triangulations

$$\int \mathcal{D}g\, e^{-S[g]} \rightarrow \sum_{\mathcal{T}} \frac{1}{C_{\mathcal{T}}} \left[\prod_{j=1}^{N_2} \mathcal{O}(t_j)^{\beta} \right] e^{-S_{\mathrm{ER}}}$$

- in $d = 4$: no physical phase, no indications for higher-order transition in κ_2-κ_4 - space

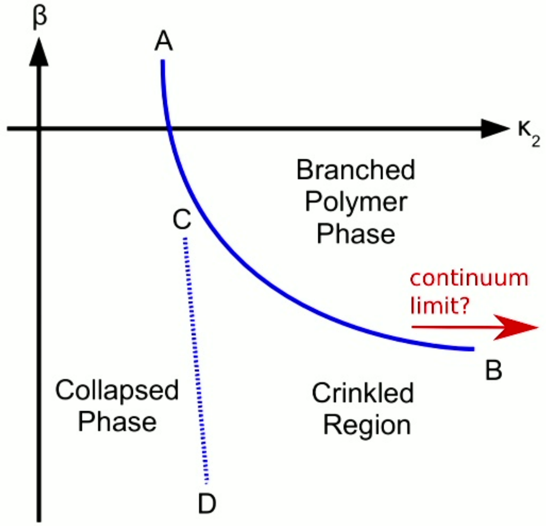
  [Ambjørn, Jain, Jurkiewicz, Kristjansen, 1993], [Bakker, Smit, 1994]
  [Ambjørn, Jurkiewicz, 1995], [Bialas, Burda, Krzywicki, Petersson, 1996]
  . . .

- CDT: impose causal structure

  [Ambjørn, Loll, 1998], [Ambjørn, Jurkiewicz, Loll, 2000], . . .

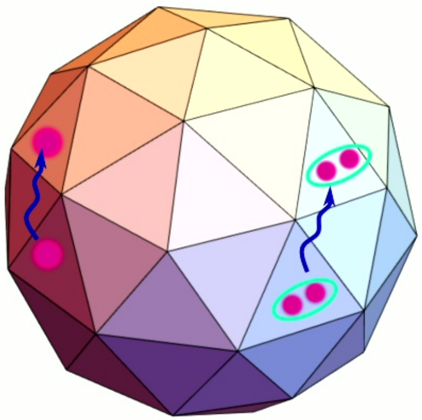
- EDT: include measure term

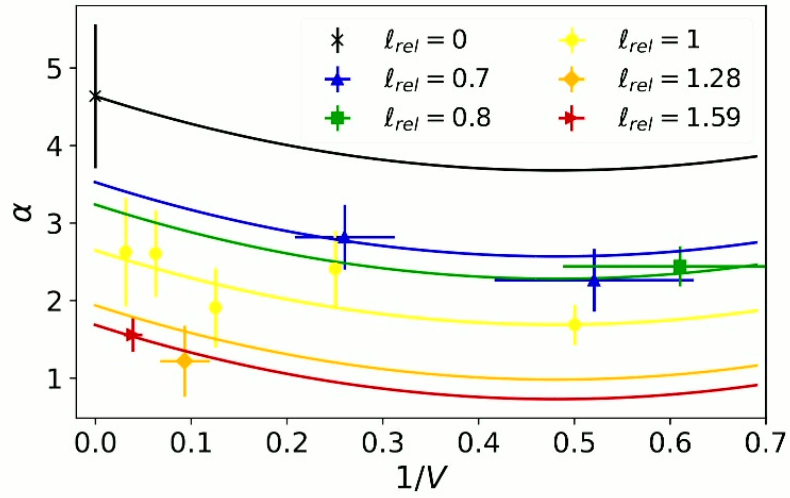
  [Bruegmann, Marinari, 1993], . . .
  [Laiho, Coumbe, 2011], [Ambjørn, Glaser, Goerlich, Jurkiewicz, 2013]
  . . .



[Ambjorn, Glaser, Goerlich, Jurkiewicz, 2013]
[Coumbe, Laiho, 2014]

Newtonian binding energy from EDT





[Dai, Laiho, MS, Unmuth-Yockey; 2021]

- Use matter as probe for geometry [de Bakker, Smit, 1996]
- Binding energy and renormalized mass from lattice correlators
- Fit binding energy $E_\mathrm{b} = A\, m^\alpha$

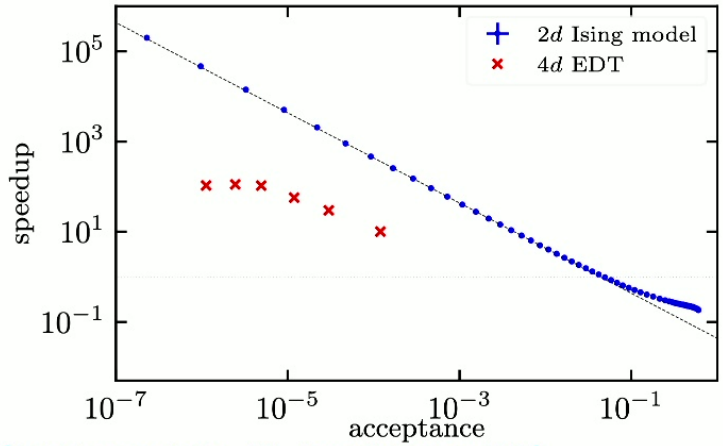
- Continuum, non-relativistic limit: $E_\mathrm{b} = \frac{G\, m^5}{4}$ (in $d = 4$)
- EDT fit: $\alpha = 4.6 \pm 0.9$ $\Rightarrow\ d = 3.9 \pm 0.2$

Rejection free algorithm for EDT

- Challenge:
  acceptance rate p drops:

$$\kappa_2 = 3.0\,, \quad p \sim 3 \cdot 10^{-5};$$
$$\kappa_2 = 3.8\,, \quad p \sim 5 \cdot 10^{-6};$$
$$\kappa_2 = 4.5\,, \quad p \sim 1 \cdot 10^{-6};$$

- Generalize algorithms used in studies of dynamical systems (e.g., growth of crystals)
  [Norman, Cannon, 1972], [Bortz, Kalos, Lebowitz, 1975]
  [Gillespie, 1976], [Schulze, 2004], . . .



[Dai, Freeman, Laiho, MS, Unmuth-Yockey; 2023]

- Proof of principle: 2d Ising model

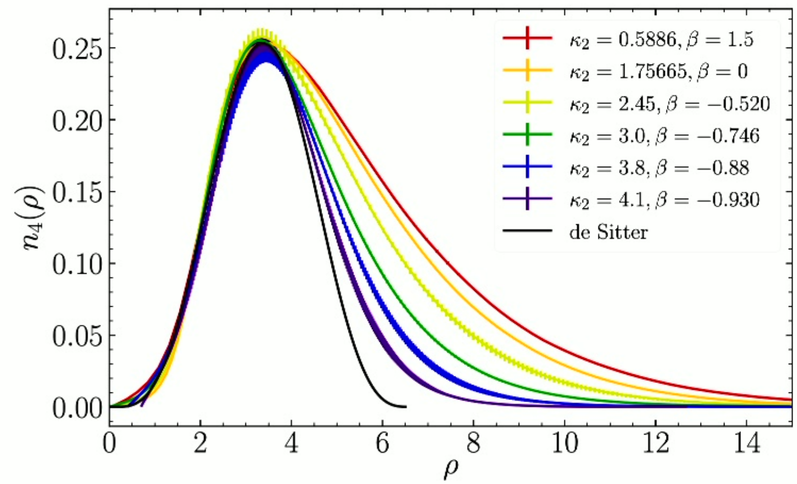
Significant speedup: allows to simulate efficiently at larger κ_2 (finer lattices)

Towards a de Sitter universe in EDT?

- Shelling function $n_4(\tau)$: counts number of four-simplices at geodesic distance τ away from source-simplex.
- For de Sitter with $d_H = 4$:

$$n_4(\tau) \sim \cos^3(\tau)$$

- Peak-height: order parameter of AB-transition



[Dai, Freeman, Laiho, MS, Unmuth-Yockey; 2023]
[Dai, Laiho, MS, Unmuth-Yockey; to appear]

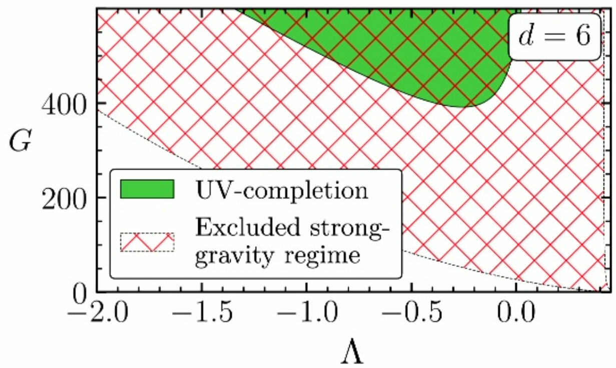
Extract relative lattice spacings via semi-classical analysis [Ambjorn, Goerlich, Jurkiewicz, Loll; 2012] (match with continuum saddle-point approximation)
[Bassler, Laiho, MS, Unmuth-Yockey; 2021], [Dai, Laiho, MS, Unmuth-Yockey; to appear]

$$\ell_{\text{rel}}(\kappa_2 = 2.45) = 1.524(53)\,, \quad \ell_{\text{rel}}(\kappa_2 = 3.4) = 0.860(33)\,, \quad \ell_{\text{rel}}(\kappa_2 = 3.8) = 0.780(91)$$

Lattices become finer for larger κ_2

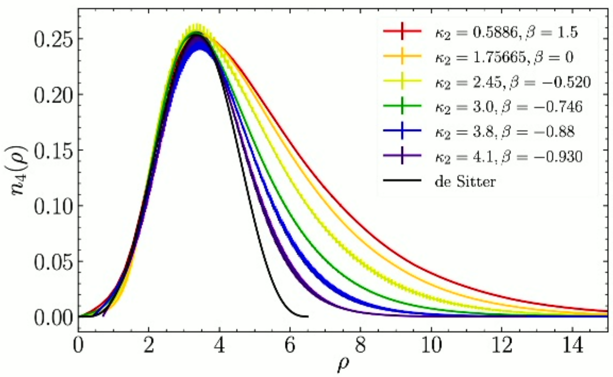
Summary

- Asymptotic safety: quantum realization of scale invariance
- FRG studies:
  - Gravity-matter interplay: might constrain gravitational dynamics from UV considerations



Summary

- Asymptotic safety: quantum realization of scale invariance
- FRG studies:
  - Gravity-matter interplay:
    might constrain gravitational dynamics
    from UV considerations
    and IR constraints
  - Outlook:
    Investigate induced interactions for $g_Y \neq 0$
    [MS; to appear]
- EDT studies:
  - Might feature well behaved non-relativistic limit
  - Might approach de Sitter shape of universe
  - Outlook:
    Combine new algorithm with dynamical matter



Thank you for your attention!