Title: An asymptotically safe road to quantum gravity with matter

Speakers: Marc Schiffer

Series: Colloquium

Date: February 08, 2023 - 2:00 PM

URL: https://pirsa.org/23020045

Abstract: I will introduce asymptotically safe quantum gravity, which is based on the quantum realization of scale invariance, as one candidate theory to describe nature at all scales. I will discuss the concept of an asymptotically safe fixed point, and how the realization of scale invariance at high energies might provide a predictive and UV-complete description of nature. In particular, I will focus on the interplay of gravity and matter, and highlight mechanisms how this interplay might lead to constraints and predictions of asymptotically safe gravity-matter systems.

Zoom Link: https://pitp.zoom.us/j/99056179498?pwd=SzlXK1R5dExNckFMM1pMS3IvS1VyQT09

Why Quantum Gravity?

Standard Model

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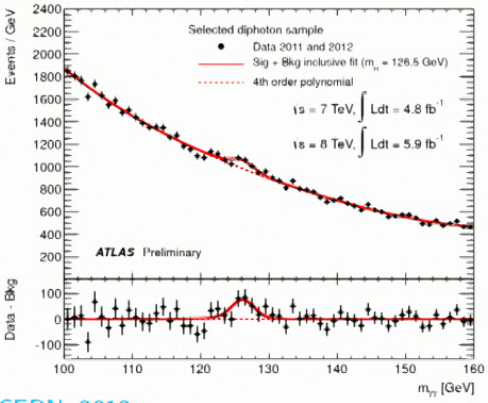
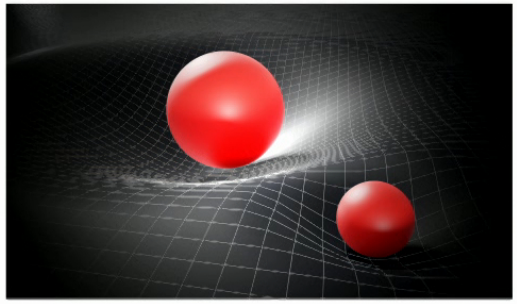


CERN, 2012

General Relativity



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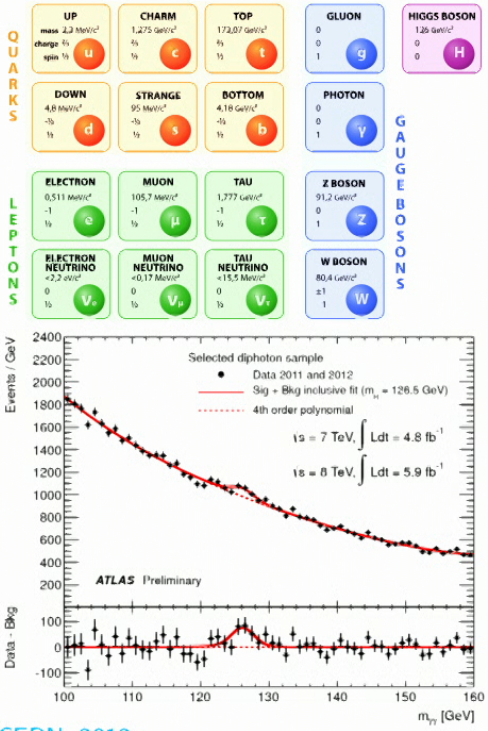

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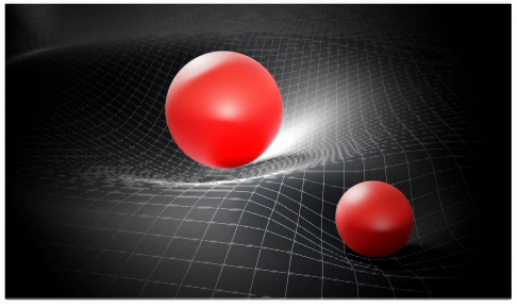

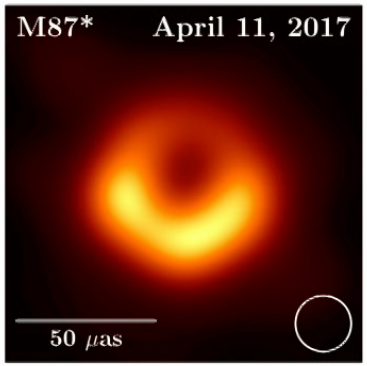

EHT, 2019

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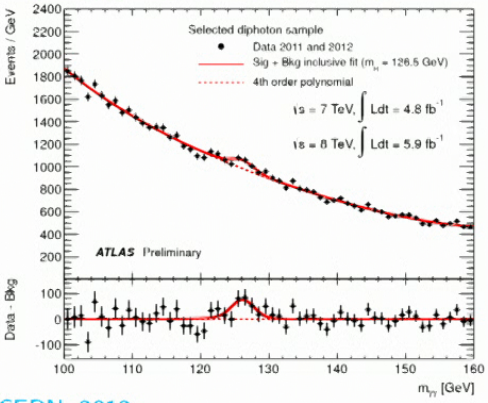

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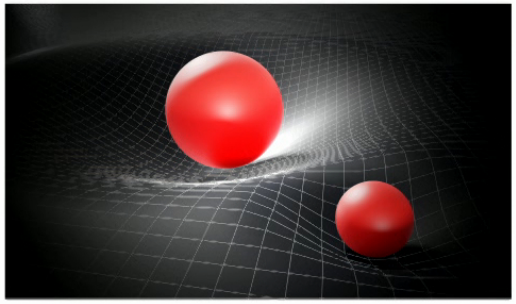

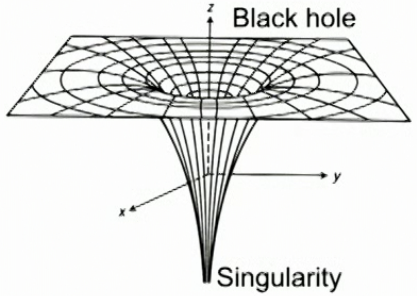

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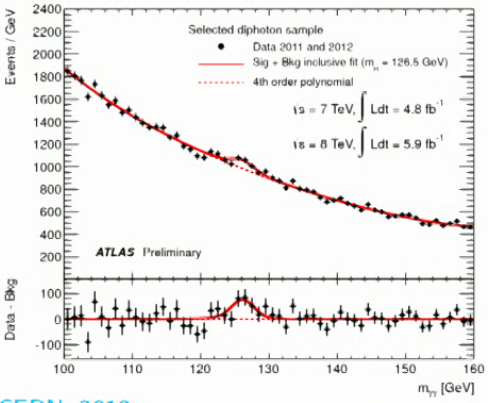

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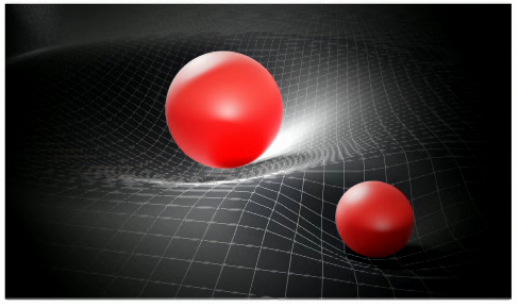

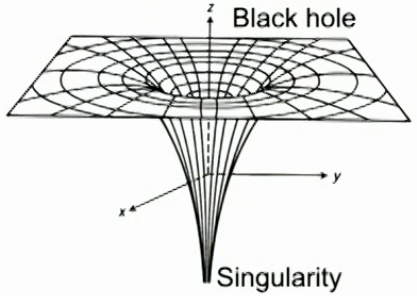

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Scale of QG: $M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G_{\mathrm{N}}}}$

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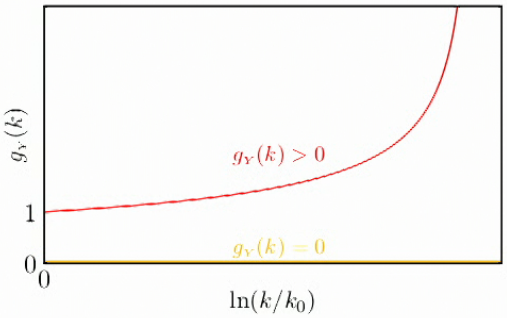

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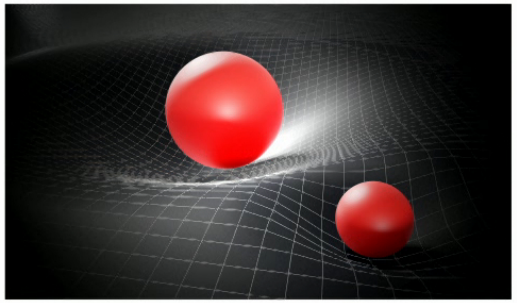

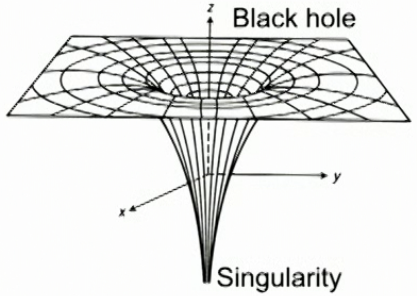

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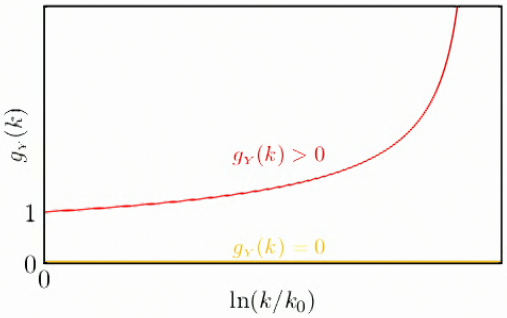

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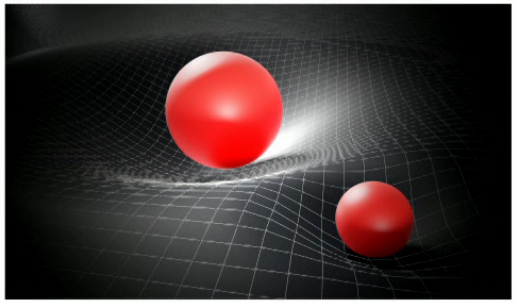

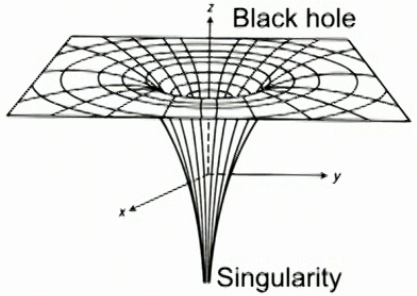

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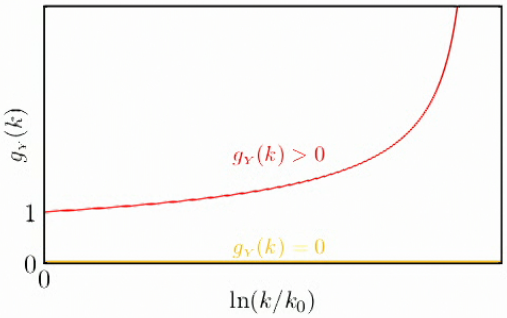

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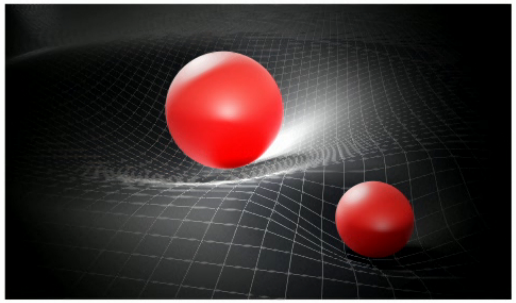

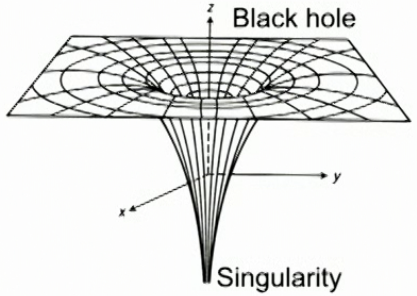

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Scale of QG: $M_{\rm Pl} = \sqrt{\frac{\hbar c}{G_{\rm N}}}$

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

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- Perturbative QG:
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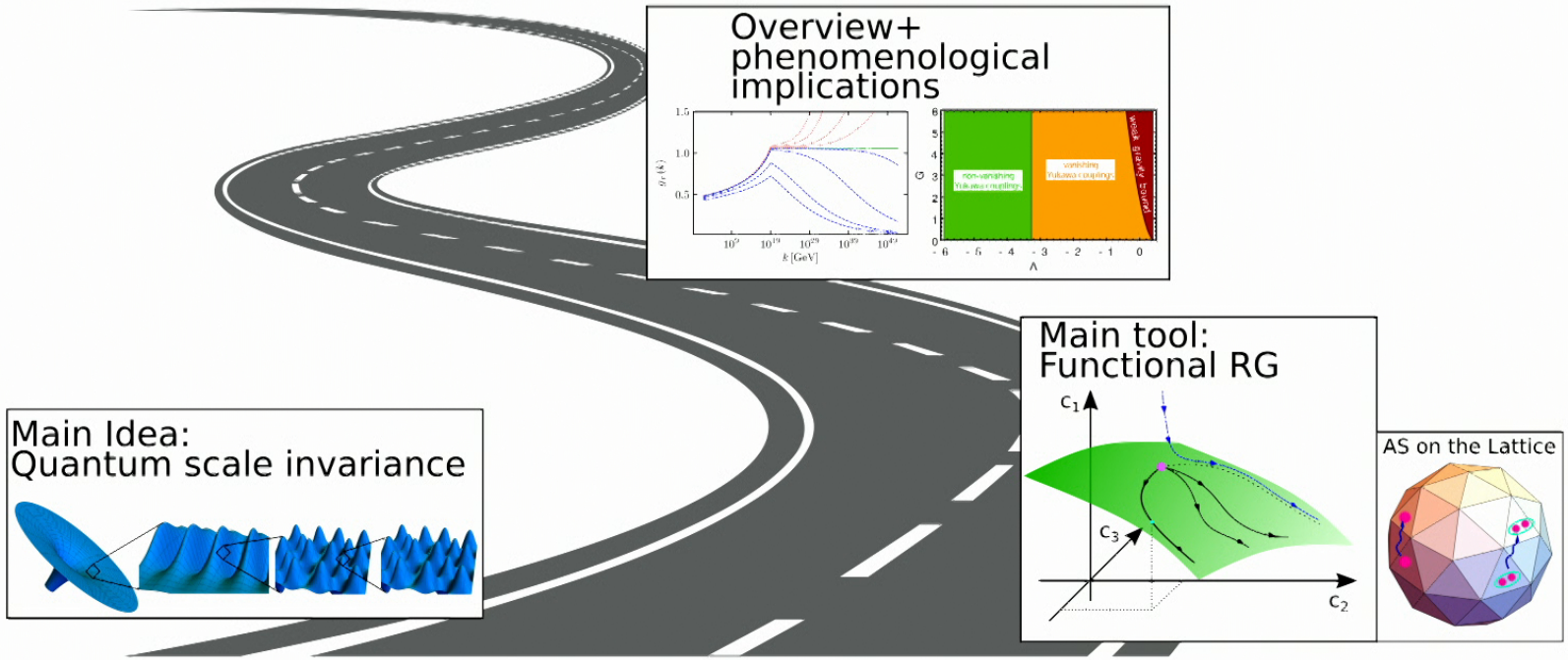
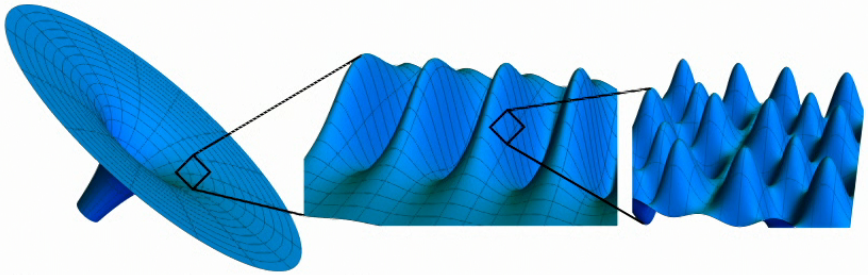
Perturbative quantization of GR fails due to loss of predictivity!

Roadmap


Overview+
phenomenological
implications
Main tool:
Functional RG
AS on the Lattice
Main Idea:
Quantum scale invariance

Asymptotically Safe Quantum Gravity



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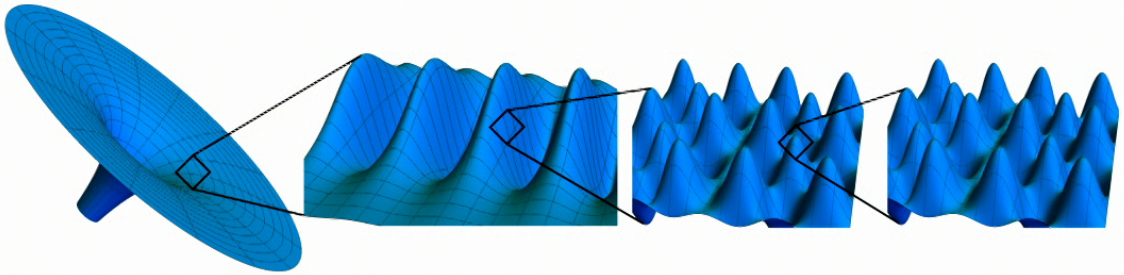
Asymptotically Safe Quantum Gravity



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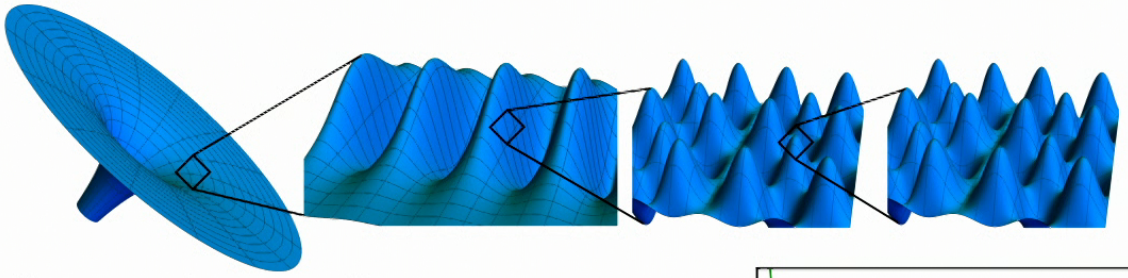

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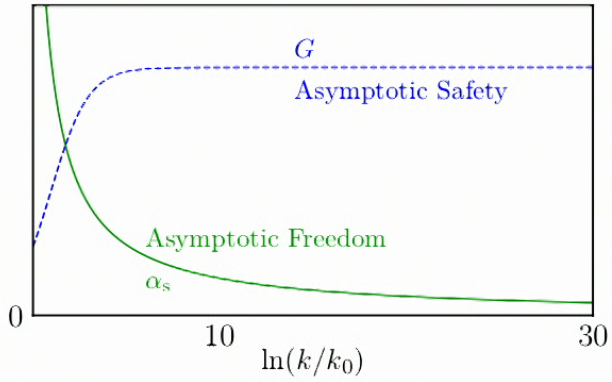

Asymptotic freedom:
free fixed point, $\alpha_{s,*} = 0$
Asymptotic safety:
interacting fixed point, $G_* \neq 0$

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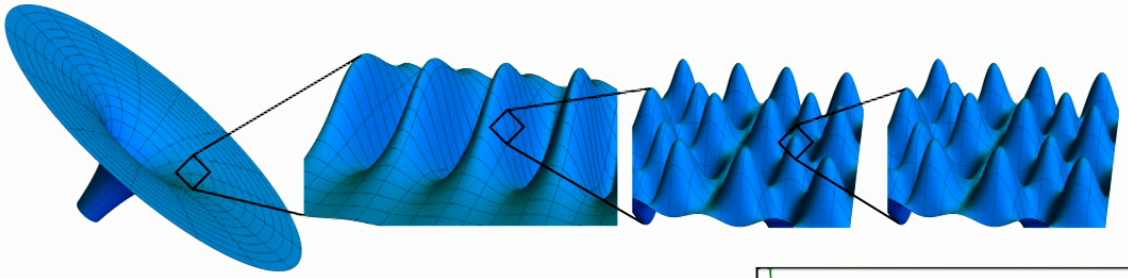

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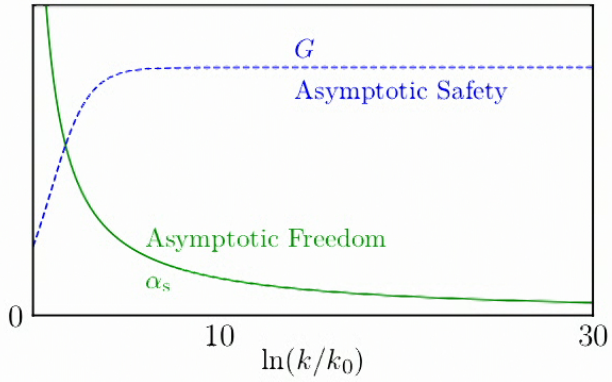

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Tools to discover asymptotic safety in gravity

- Perturbative methods

  [Christensen, Duff; 1978], [Gastmans, Kallosh, Truffin; 1978], [Martini, Ugolotti, Zanusso; 2021]

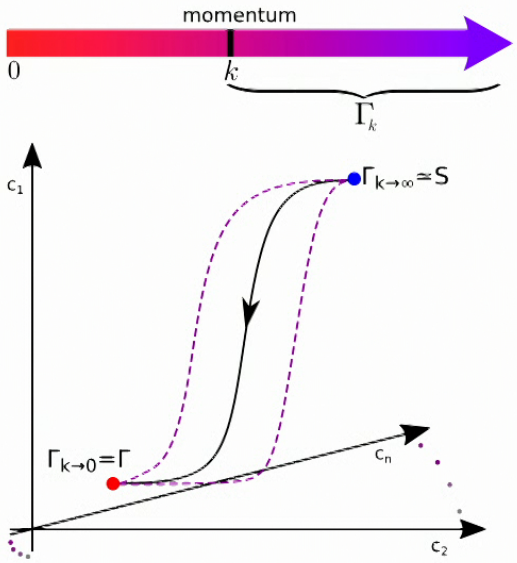
  [M. Niedermaier, 2006]
- Lattice methods (EDT/CDT)

  [Ambjorn, Jurkiewicz; 1991], [Ambjorn, R. Loll; 1998]
- Functional Renormalization Group

  [Wetterich; 1993], [Ellwanger; 1993], [Morris; 1994], [Reuter; 1996]

Tool: Functional Renormalization Group

Main idea:
include quantum fluctuations step by step



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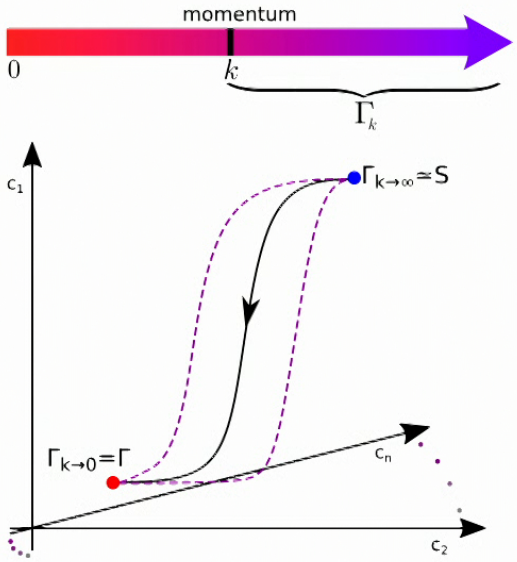

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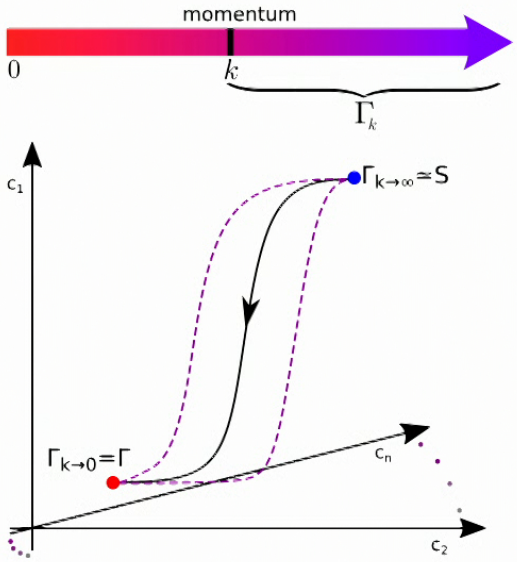

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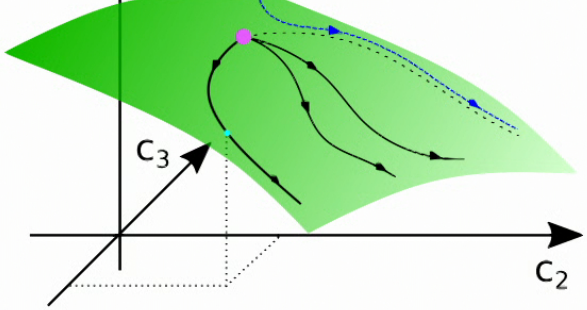
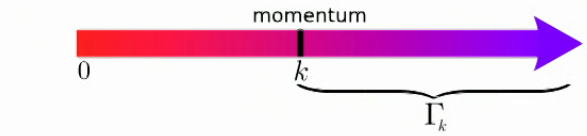
Flow Equation

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

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

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





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

$\rightarrow$ describe RG-flow in theory-space

Γ_k : requires truncation

Predictivity in asymptotic safety

scale invariance

our universe at low energies

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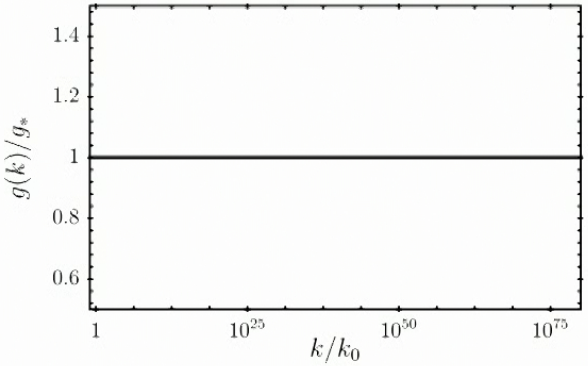

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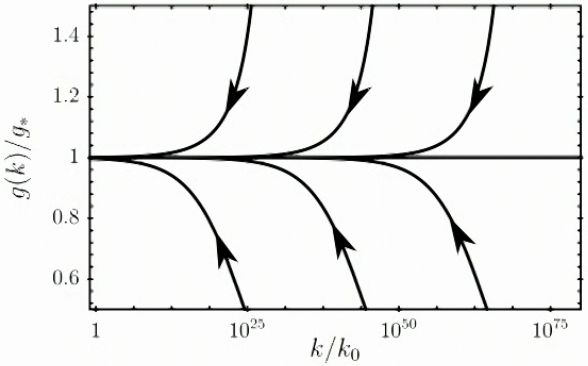

Irrelevant direction:
prediction in IR

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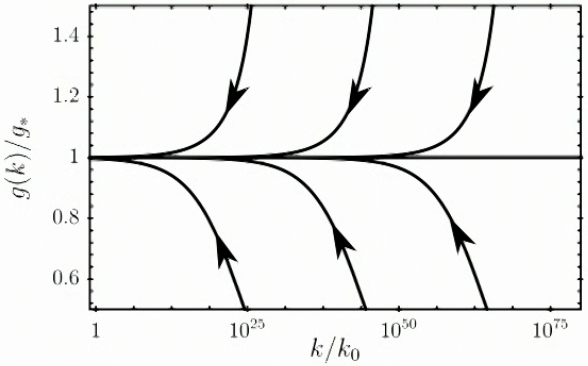

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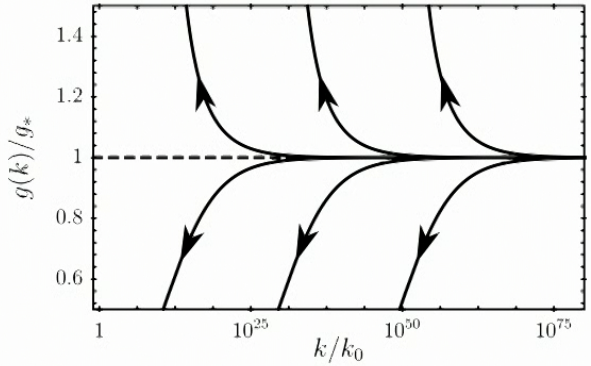
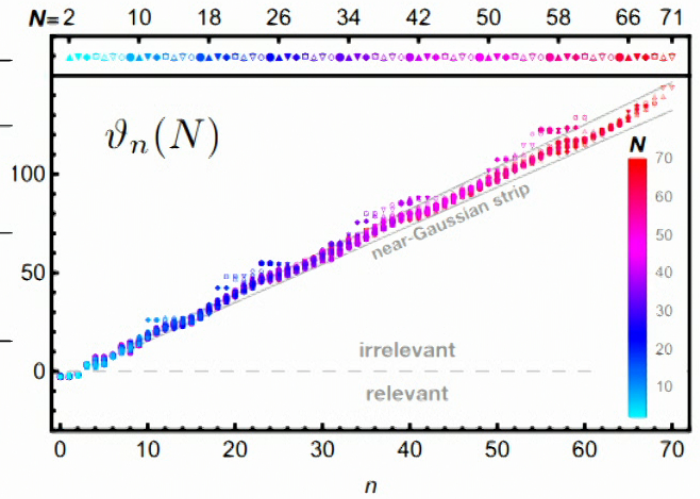


Relevant direction:
free parameter

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]	✓	✓
✓	$C^{\rho\sigma}_{\mu\nu}\, C^{\kappa\lambda}_{\rho\sigma}\, C^{\mu\nu}_{\kappa\lambda}$ [Gies, Knorr, Lippoldt, Saueressig; 2016]		✓
✓	R^3 [Reuter, Lauscher, 2002]		✓
⋮	⋮		⋮
✓	R^{70}, $R^{\mu\nu\,34}$, ... [Codello, Percacci, Rahmede; 2007, 2008] [Machado, Saueressig; 2007] [K. Falls et. al; 2013,2018] [Litim, Kluth; 2020]		✓



[Falls, Litim, Schröder; 2018]

Relevant: $\vartheta_n < 0$, free parameter

Irrelevant: $\vartheta_n > 0$, prediction

AS in pure gravity

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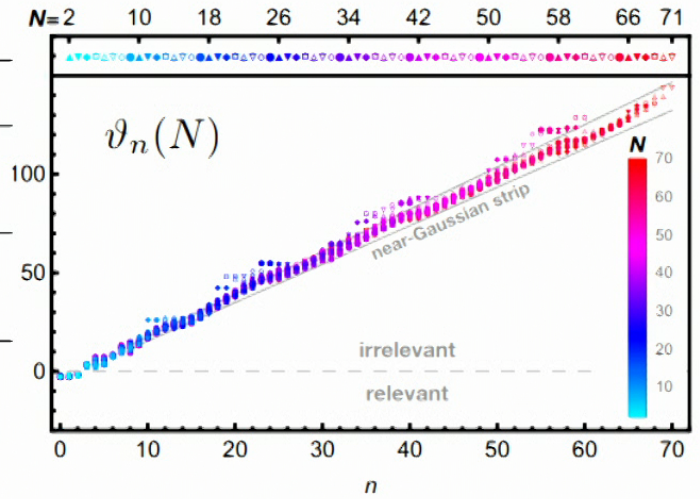

[Falls, Litim, Schröder; 2018]

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Current 'hot topics'

- Key questions for asymptotically safe quantum gravity (FRG):
  [Bonnano, Eichhorn, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca; 2020]
  - Convergence
    [Falls et al., 2013, 2018], [Litim, Kluth, 2020], [Denz, Pawlowski, Reichert, 2018], . . .
  - 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]
  - Unitarity and scattering amplitudes
    [Bonnano, Denz, Pawlowski, Reichert, 2020], [Fehre, Litim, Pawlowski, Reichert, 2021]
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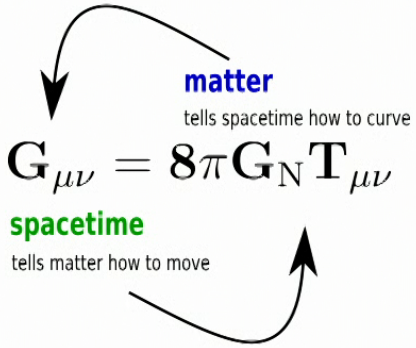
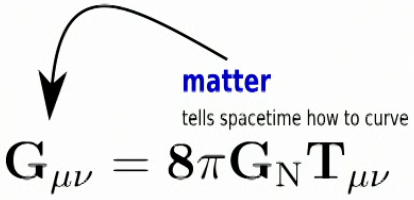
AS in gravity-matter systems



- Key questions for gravity-matter systems:

AS in gravity-matter systems



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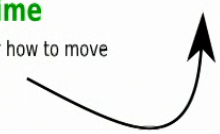
AS in gravity-matter systems

$$\mathbf{G}_{\mu\nu} = 8\pi \mathbf{G}_{\mathrm{N}} \mathbf{T}_{\mu\nu}$$

spacetime

tells matter how to move



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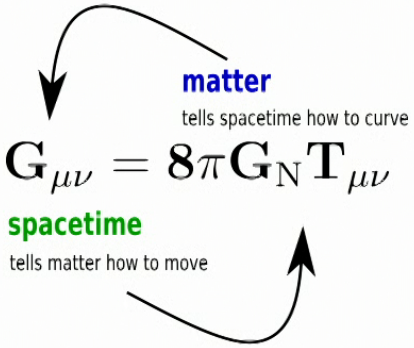

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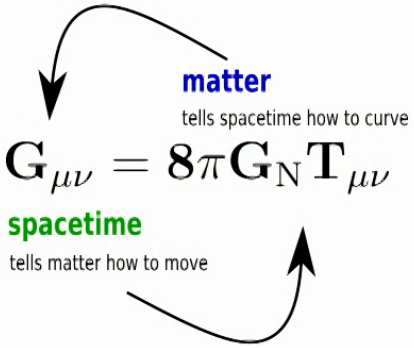

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Effect of matter on gravity

- Schematically:

$$\beta_G = 2G - G^2 \left(b_{\rm grav} + a_{\rm S}\, N_{\rm S} + a_{\rm F}\, N_{\rm F} + a_{\rm V}\, N_{\rm V} \right) + \mathcal{O}(G^3)\,.$$

- FP in pure gravity (with $G_* > 0$): $b_{\rm grav} > 0$

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All computations so far: AS fixed point supports SM-matter!

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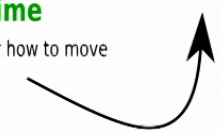

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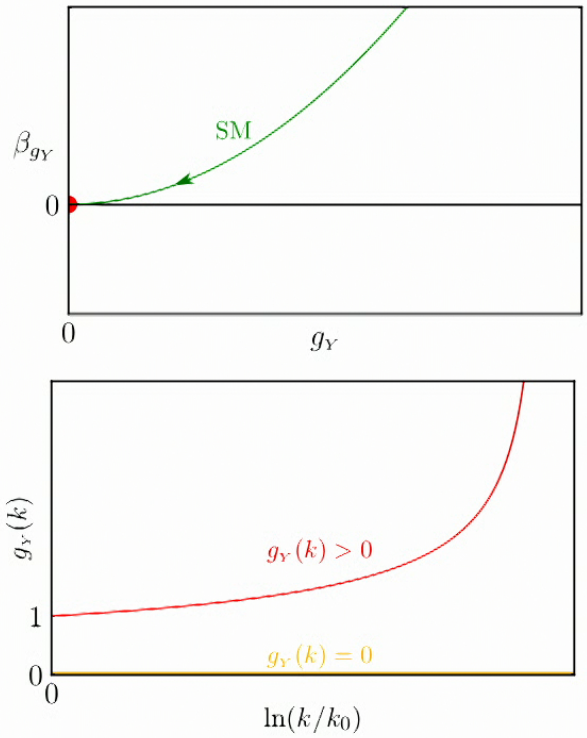
The $U(1)$ sector of the Standard Model

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



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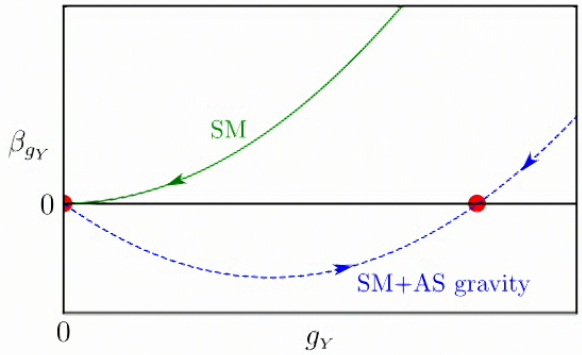
$$f_g \begin{cases} = \text{const.} \geq 0\,, & \text{for } k > M_{\text{Pl}} \\ \approx 0\,, & \text{for } k < M_{\text{Pl}} \end{cases}$$



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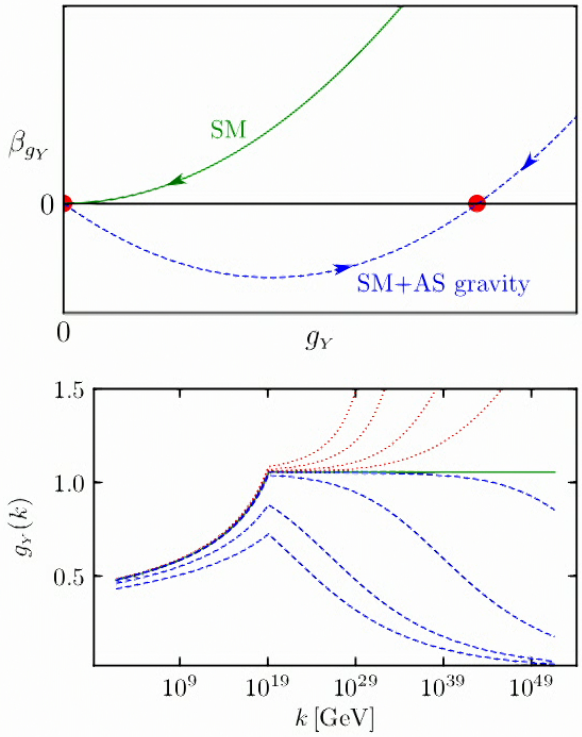

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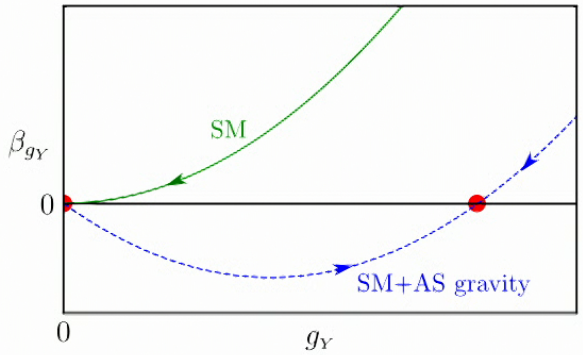
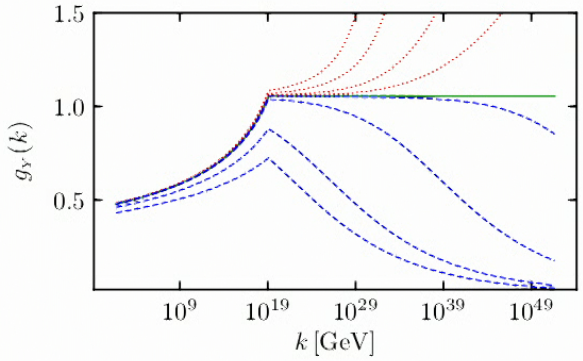


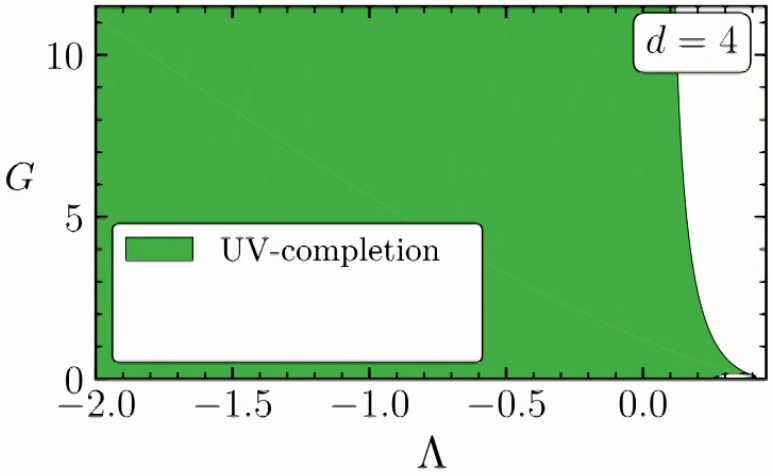


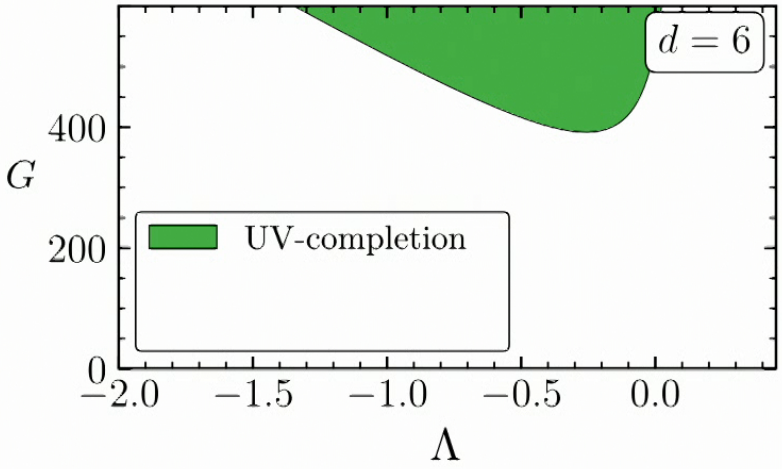
Metric fluctuations might induce a UV completion of the $U(1)$-sector.

$\Rightarrow$ Upper bound on $g_Y(k)$ (i.e., constraints on gravity) [Eichhorn, Versteegen; 2017]

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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  [Eichhorn; 2012], [de Brito, Eichhorn, Robson Linos dos Santos; 2021], [Laporte, Pereira, Saueressig, Wang; 2021], [Knorr; 2022]
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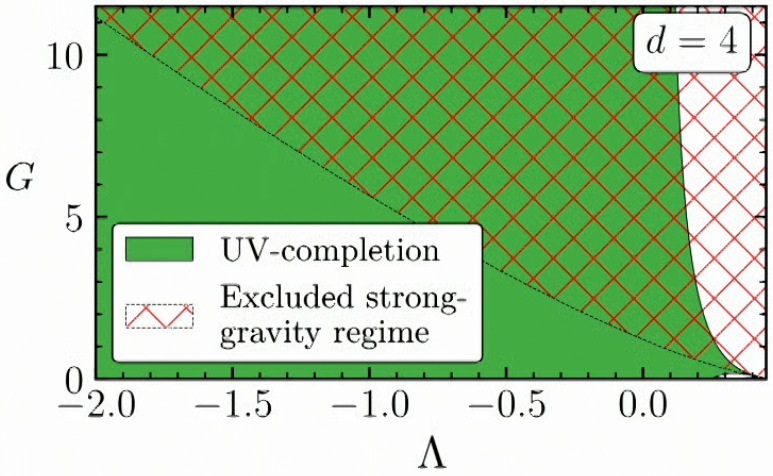

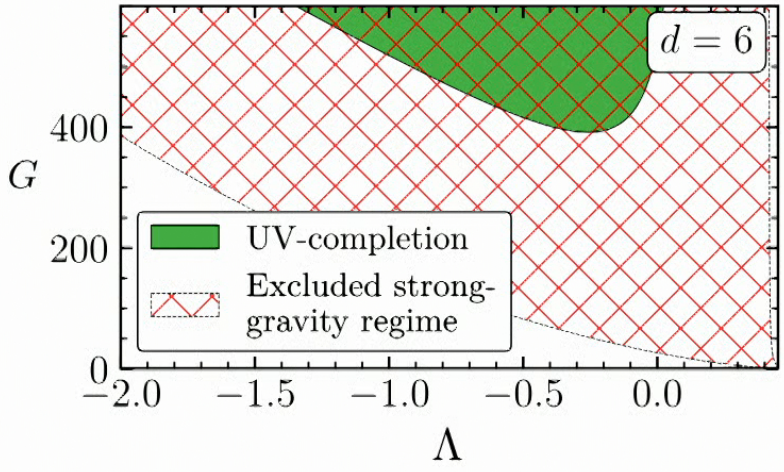

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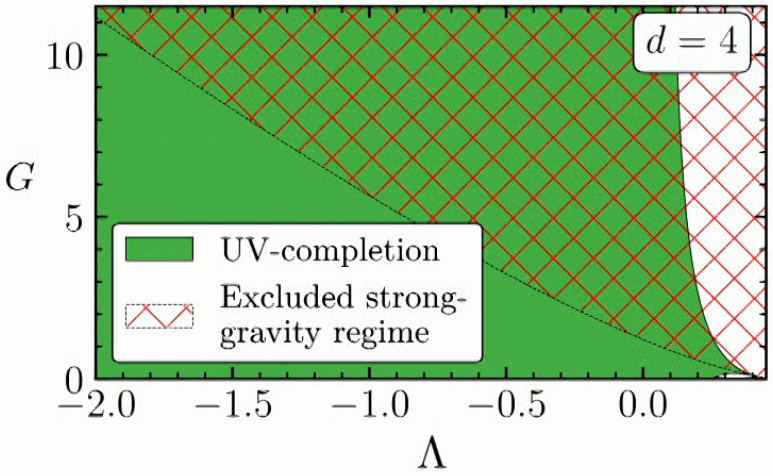
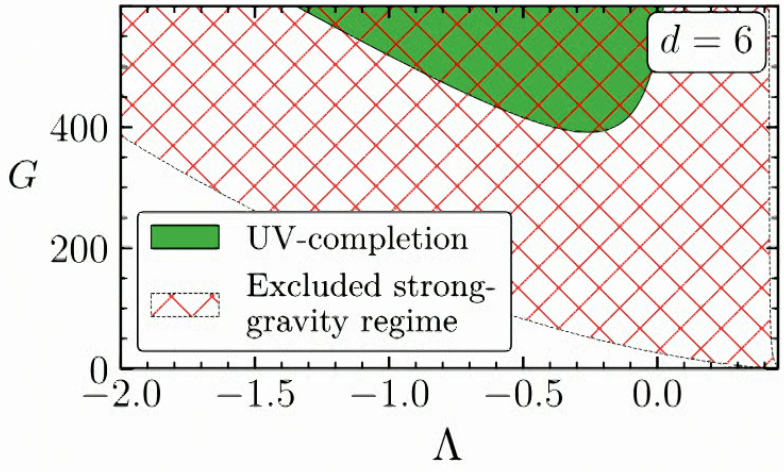


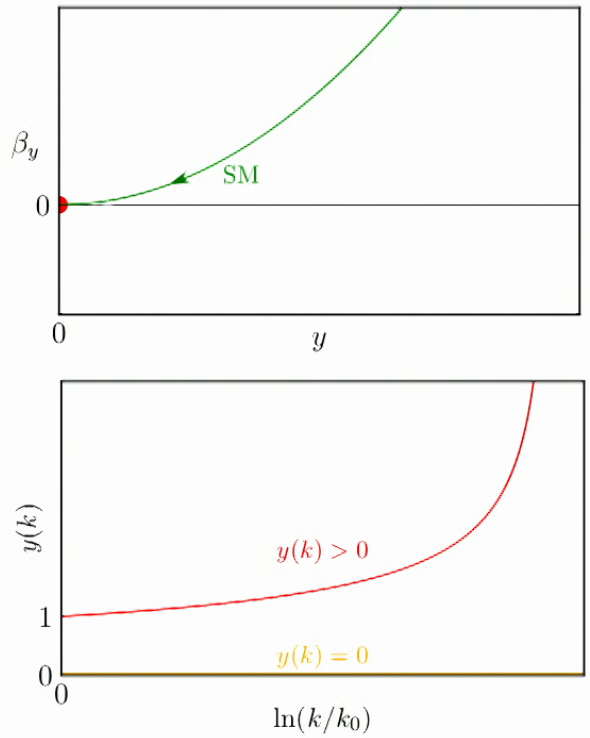


$U(1)$ gauge sector might remain UV-incomplete in $d \geq 6$, even in the presence of gravity.
[Eichhorn, MS; 2019]

Towards the Yukawa sector of the Standard Model

Single Yukawa coupling y:

$$\beta_y = \qquad \#_{\mathrm{SM}}\, y^3 + \mathcal{O}(y^4)$$



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$$\beta_y = -f_y\, y + \#_{\mathrm{SM}}\, y^3 + \mathcal{O}(y^4)$$

$$f_y \begin{cases} = \text{const.} > 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \Lambda < \Lambda_{\mathrm{crit}} \\ = \text{const.} < 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \text{for } \Lambda > \Lambda_{\mathrm{crit}} \\ \approx 0\,, & \text{for } k < M_{\mathrm{Pl}} \end{cases}$$

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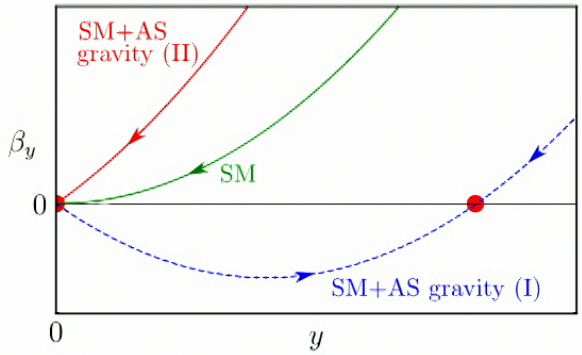

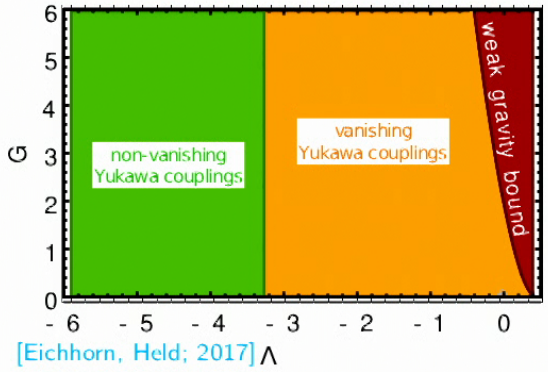

[Eichhorn, Held; 2017]

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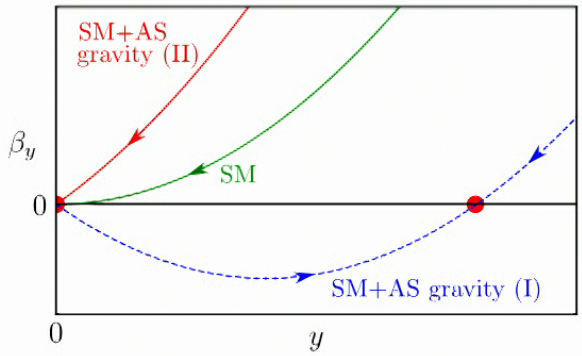
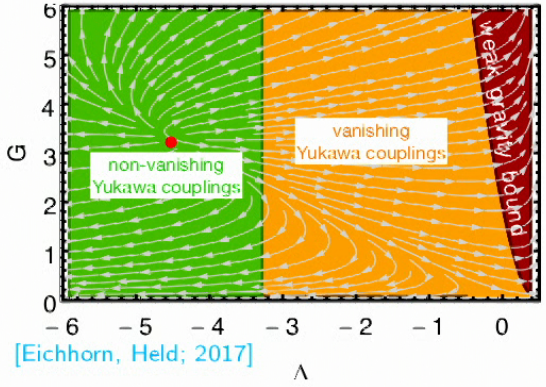
$$f_y \begin{cases} = \text{const.} > 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \Lambda < \Lambda_{\mathrm{crit}} \\ = \text{const.} < 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \text{for } \Lambda > \Lambda_{\mathrm{crit}} \\ \approx 0\,, & \text{for } k < M_{\mathrm{Pl}} \end{cases}$$

[Oda, Yamada; 2015], [Eichhorn, Held, Pawlowski; 2016], [Eichhorn, Held; 2017]





[Eichhorn, Held; 2017]

UV completion of the simple Yukawa system: constraints on gravitational dynamics

Additionally: top mass might be retro-dicted [Eichhorn, Held, 2017]

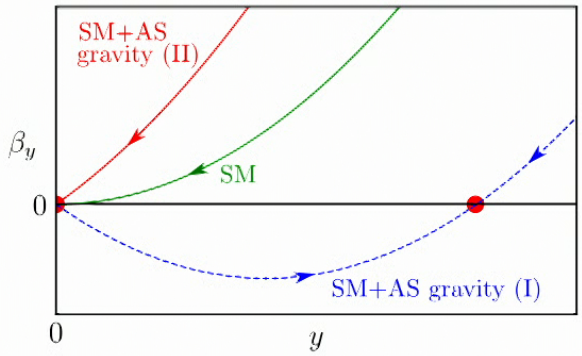
Towards the Yukawa sector of the Standard Model

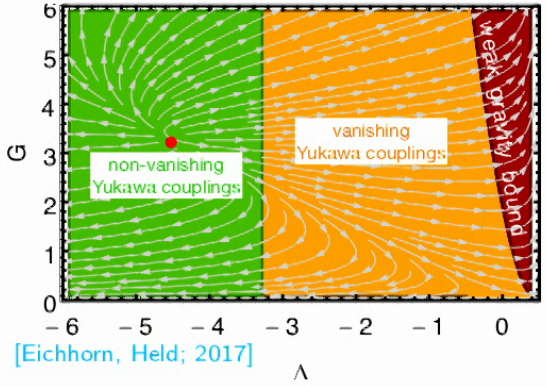
Single Yukawa coupling y:

$$\beta_y = -f_y\, y + \#_{\mathrm{SM}}\, y^3 + \mathcal{O}(y^4)$$

$$f_y \begin{cases} = \text{const.} > 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \Lambda < \Lambda_{\mathrm{crit}} \\ = \text{const.} < 0\,, & \text{for } k > M_{\mathrm{Pl}} \wedge \text{for } \Lambda > \Lambda_{\mathrm{crit}} \\ \approx 0\,, & \text{for } k < M_{\mathrm{Pl}} \end{cases}$$

[Oda, Yamada; 2015], [Eichhorn, Held, Pawlowski; 2016], [Eichhorn, Held; 2017]



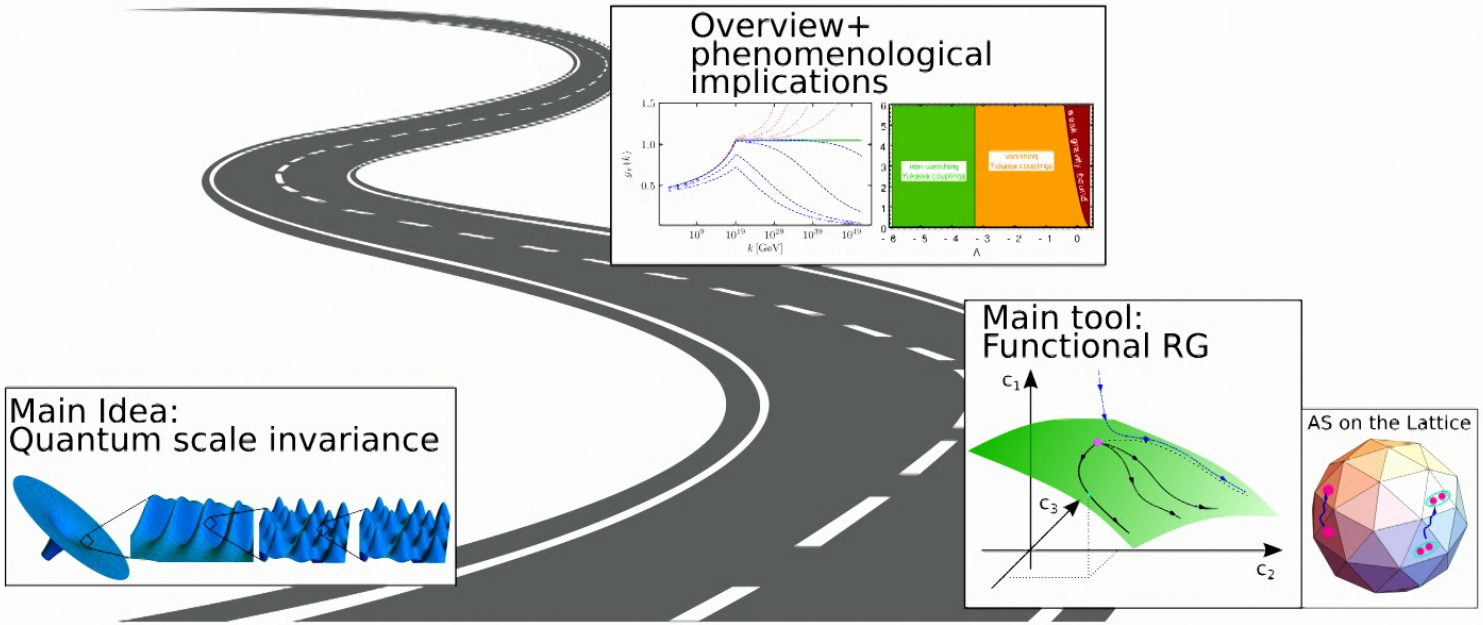


[Eichhorn, Held; 2017]

UV completion of the simple Yukawa system: constraints on gravitational dynamics

Additionally: top mass might be retro-dicted [Eichhorn, Held, 2017]

Roadmap

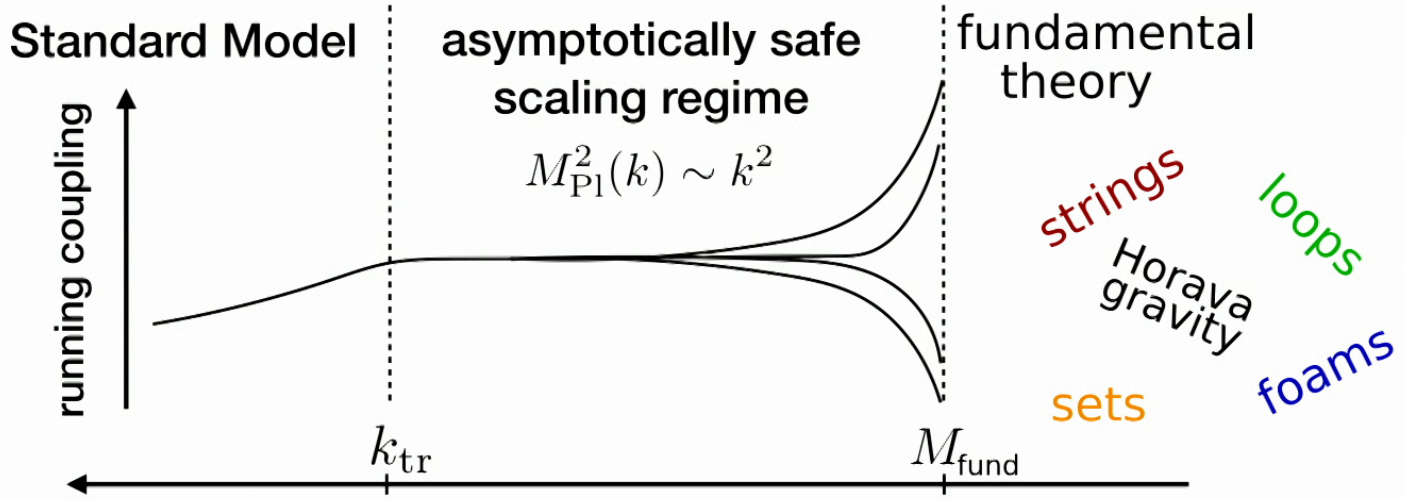

Overview+
phenomenological
implications
Main tool:
Functional RG
AS on the Lattice
Main Idea:
Quantum scale invariance

An asymptotically safe bridge to other approaches

- Effective vs. fundamental asymptotic safety
  [Percacci, Vacca; 2010]
- Applied to:

  Lorentz invariance violations [Eichhorn, Platania, MS; 2019]

  String theory/ swampland
  [de Alwis, Eichhorn, Held, Pawlowski, MS, Versteegen; 2019], [Basile, Platania; 2021]

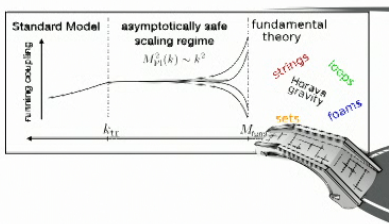


[de Alwis, Eichhorn, Held, Pawlowski, MS, Versteegen; 2019]

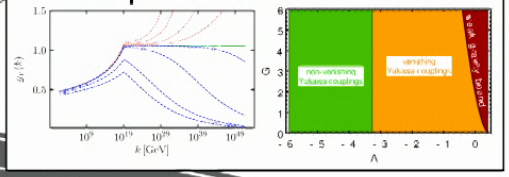
Summary & Outlook

Lorentzian signature
Convergence
Unitarity

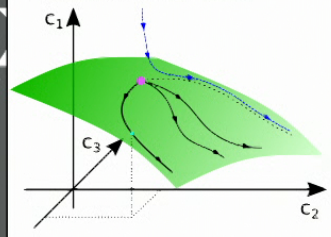
More realistic models for SM sectors
Dark matter / neutrino physics



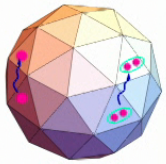
Overview+ phenomenological implications



Main tool: Functional RG



AS on the Lattice



Main Idea:
Quantum scale invariance