Title: Interplay of quantum gravity and matter: Role of symmetries

Speakers: Astrid Eichhorn

Series: Quantum Gravity

Date: April 08, 2021 - 2:30 PM

URL: http://pirsa.org/21040018

Abstract: Across different scales, symmetries shape physical systems: for example, in effective theories in condensed matter, various global symmetries are realized; at higher energy scales, the local symmetries of the Standard Model of particle physics take over. But what is the fate of symmetries at the Planck scale, where quantum gravity fluctuations kick in?

In this talk, I will focus on this question mainly from the perspective of asymptotic safety and will highlight a number of results about the role of symmetries in the interplay of asymptotically safe quantum gravity with matter. I will then mainly focus on particular discrete global symmetries, which have the attractive feature of generating mass-hierarchies without extra fine-tuning, and discuss whether or not these could be realized in quantum-gravity-matter models.

Interplay of matter and quantum gravity: Role of symmetries

Astrid Eichhorn

Constraints on discrete global symmetries in quantum gravity

Passant Ali, Astrid Eichhorn, Martin Pauly, Michael M. Scherer

arXiv:2012.07868

Perimeter Institute for Theoretical Physics, Quantum Gravity Seminar

April 7, 2021

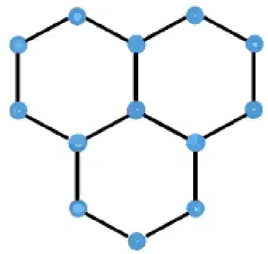
CP3-Origins

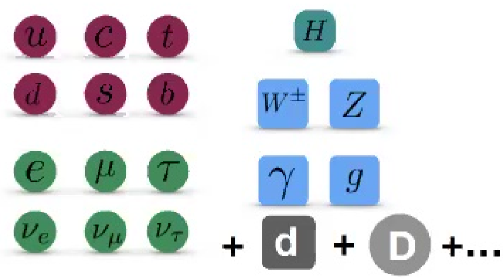
SDU University of Southern Denmark

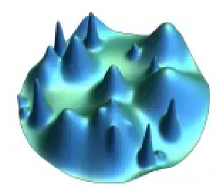
THE VELUX FOUNDATIONS

VILLUM FONDEN VELUX FONDEN

Symmetries across different scales







Condensed Matter

Global symmetries
& their spontaneous
breaking

Particle Physics

Local + global symmetries *
& their spontaneous
breaking

Quantum Gravity

???

Why these symmetries
and not others?

* continuous (e.g., U(1),
SU(N)), not discrete (e.g., $\mathbb{Z}_n$)
symmetries

Symmetries in quantum gravity-matter models

(Currently?) no universal statements across quantum-gravity approaches possible

Example: chiral symmetry for fermions $\longrightarrow$ light fermions

$$\psi_L \xrightarrow{S_L} \psi'_L \qquad \psi_R \xrightarrow{S_R} \psi'_R \qquad m\,\bar{\psi}\psi = m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$$

- Stringy arguments: $\nexists$ any global symmetries

- Loop quantum gravity: chiral symmetry may or may not remain unbroken

  [Gambini, Pullin '15] [Barnett, Smolin '15]

- Euclidean dynamical triangulations: chiral symmetry may remain unbroken

  [Catterall, Laiho, Unmuth-Yockey '18]

- Asymptotically safe gravity:
  - no chiral symmetry breaking by metric fluctuations
    [AE, Gies '11; Meibohm, Pawlowski '16; AE, Held '17]
  - chiral symmetry breaking by curved background may give give rise to upper bound on number of light fermions
    [Gies, Martini '18; Gies, Salek '21]
  - chiral symmetry breaking by Abelian gauge field fluctuations may give rise to lower bound on number of light fermions
    [de Brito, AE, Schiffer '20]

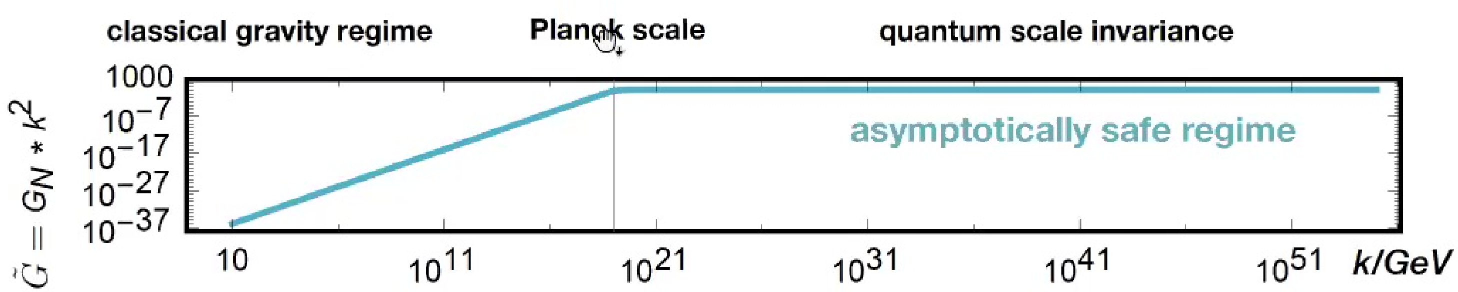
Lightning review of the asymptotic-safety paradigm

Quantum field theories of nature:

- Landau-pole problem:
  Divergences in scale-dependent couplings

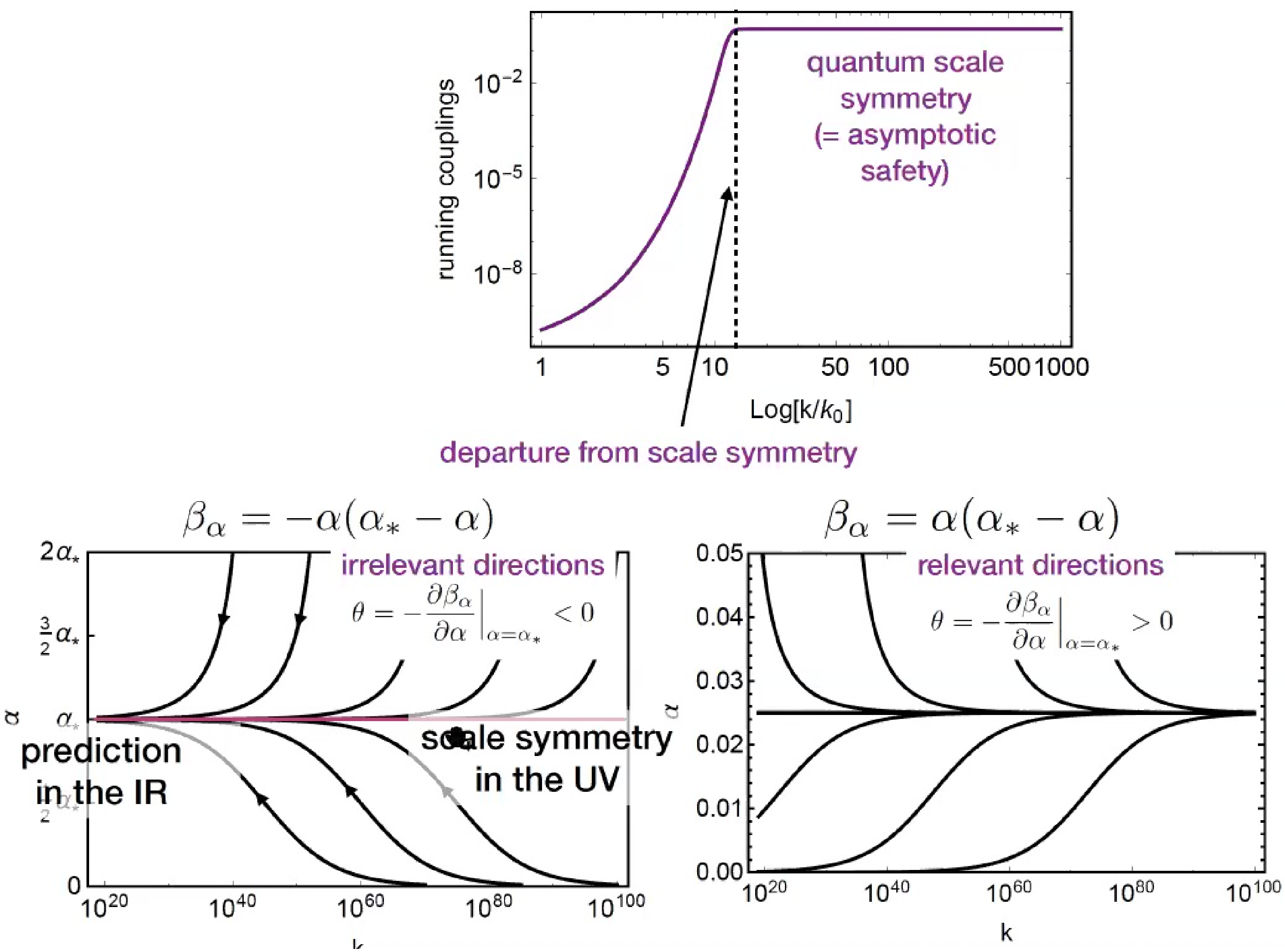
- Predictivity problem:
  Effective field theories feature infinitely many free parameters

$\longrightarrow$ quantum scale symmetry $\beta_{\tilde{G}} = k\partial_k \tilde{G} = 0$ as a solution

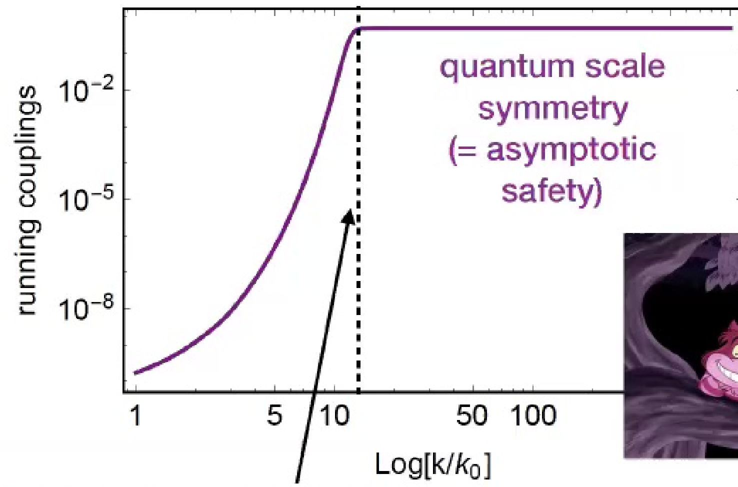


(...and similarly for all other couplings...)

Predictive power of asymptotic safety

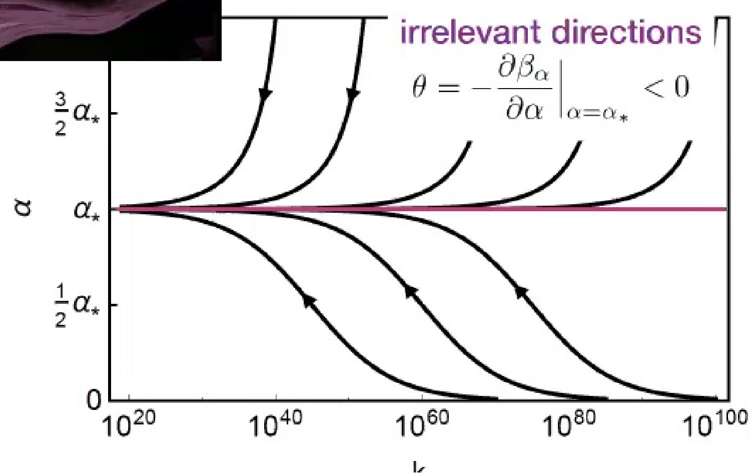


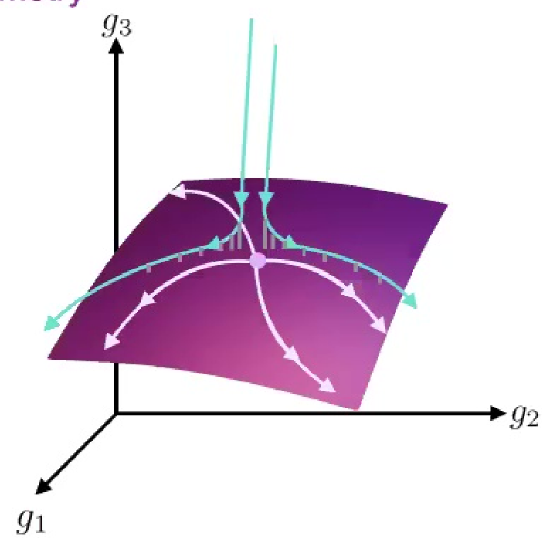
Predictive power of asymptotic safety



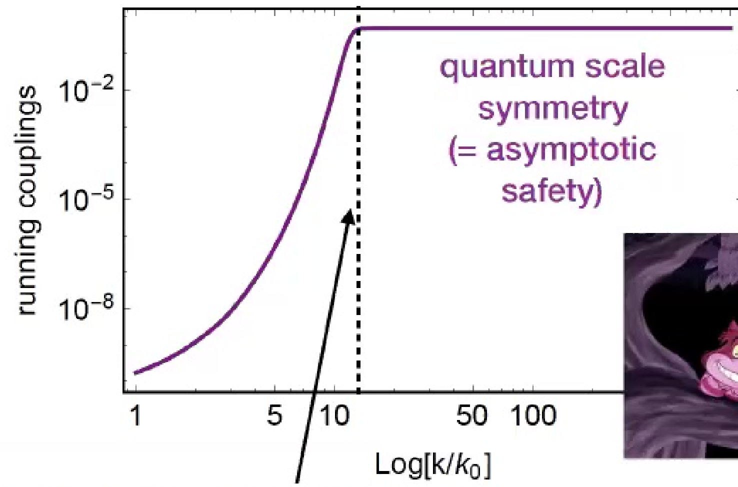
departure from scale symmetry

IR consequences of UV scale symmetry: relations between couplings/predictions of coupling values





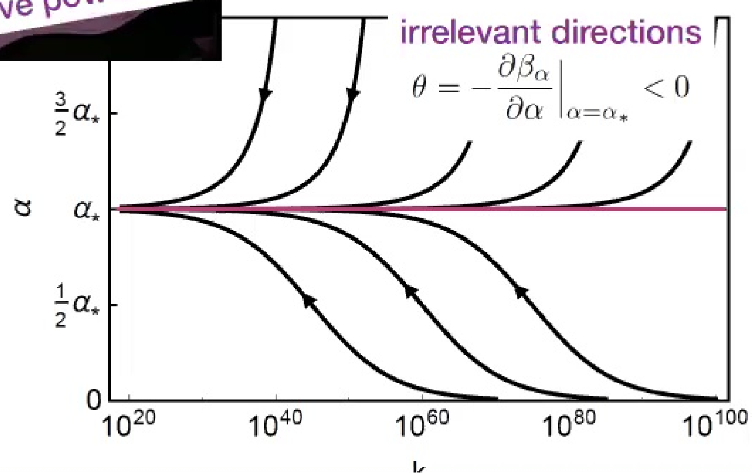
Predictive power of asymptotic safety

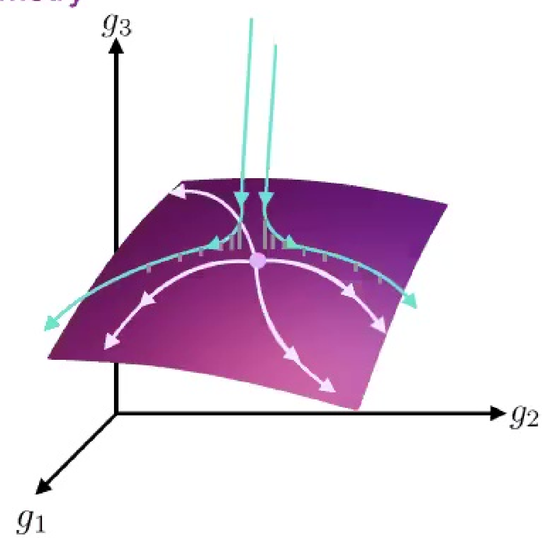


departure from scale symmetry

IR consequences of UV scale symmetry: relations between couplings/predictions of coupling values

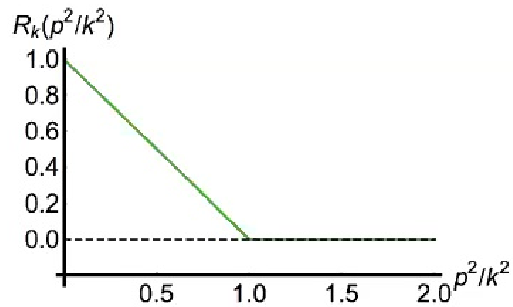
predictive power of new symmetry





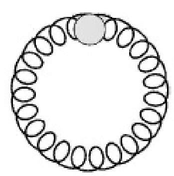
Functional Renormalization Group

$$e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \, e^{-S[\varphi] - \frac{1}{2}\int \varphi(-p) R_k(p) \varphi(p)}$$



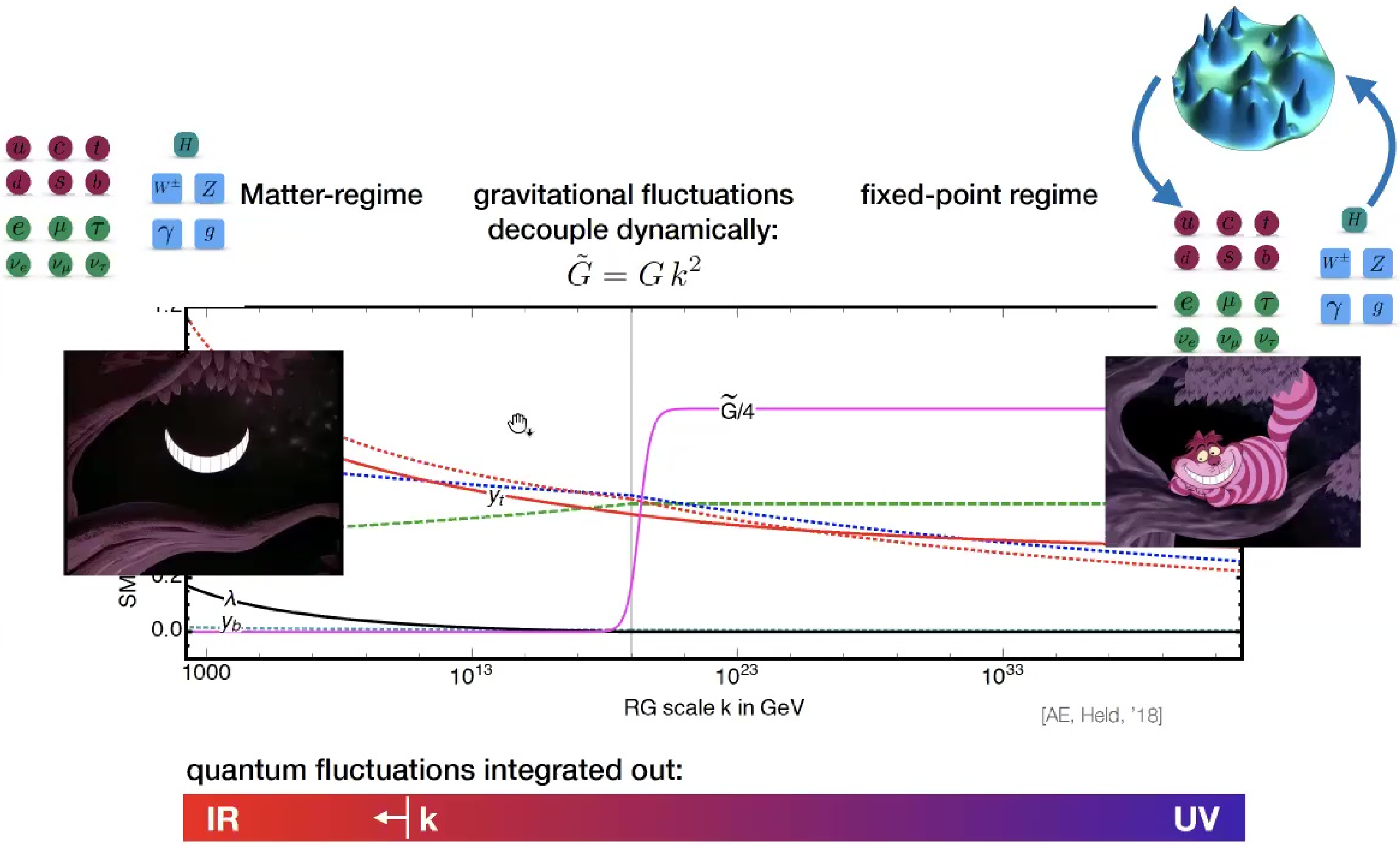
quantum fluctuations integrated out:

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



1) find fixed points (aka quantum scale symmetry) by solving $\partial_k \Gamma_k = 0$
2) integrate to $k = 0$ from fixed point as initial condition

Three regimes of the gravity-matter functional RG flow



Status of asymptotically safe gravity-matter models

Effect of gravity on Standard Model:

Non-Abelian gauge sector:

[Daum, Harst, Reuter '10; Folkerts, Litim, Pawlowski '12; Christiansen, Litim, Pawlowski, Reichert '18]

Abelian gauge sector:

[Harst, Reuter '11; Christiansen, AE, '17; AE, Versteegen '18; AE, Schiffer '19; de Brito, AE, Pereira '19]

Yukawa sector

[Oda, Yamada '16; AE, Held, Pawlowski '16; AE, Held '17; AE, Held '18; Alkofer, AE, Held, Percacci, Nieto, Schröfl '20]

Higgs potential

[Narain, Percacci '10; Shaposhnikov, Wetterich '10, Oda, Yamada, '16; Hamada, Yamada '17; AE, Hamada, Lumma, Yamada '18; Pawlowski, Reichert, Wetterich, Yamada '18; AE, Pauly '20]

Induced matter interactions

[AE '12 '14; AE, Held, Pawlowski '16; AE, Held '17; Christiansen, AE '17; AE, Schiffer '19]

Beyond SM:

Grand Unified Theories [AE, Held, Wetterich '17 '19]

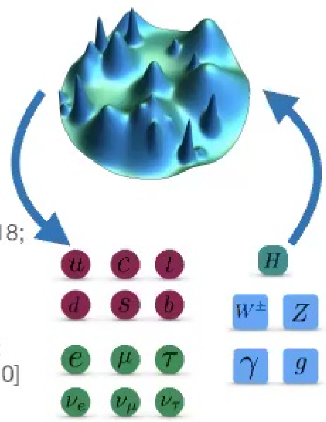
Dark sector [AE, Hamada, Lumma, Yamada, '17; AE, Pauly '20]

U(1) extensions [Hamada, Tsumura, Yamada '19; Reichert, Smirnov '19; Kwapisz '19]

Majorana masses [Brito, Hamada, Pereira, Yamada '19]

Flavor structure [Kowalska, Sessolo '20]

Muon g-2 [Kowalska, Sessolo '20]



Effect of scalars, fermions and vectors on gravitational fixed point:

- **Einstein-Hilbert truncation & minimal coupling:**
  [Dona, AE, Percacci '13; Meibohm, Pawlowski, Reichert '15; Dona, AE, Labus, Percacci '15; Biemans, Platania, Saueressig '17; AE, Lippoldt, Pawlowski, Reichert, Schiffer '18; Yamada, Wetterich '19]
- **Beyond minimal coupling:**
  [AE, Lippoldt '16; AE, Lippoldt, Skrinjar '17; AE, Lippoldt, Schiffer '18]
- **Beyond Einstein-Hilbert truncation:**
  [Alkofer, Saueressig '18; Bürger, Pawlowski, Schäfer, Reichert '18]

Symmetries for scalar fields in effective field theories

$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + \ldots}_{} + \bar{z}_n\underbrace{(\phi^n + (\phi^*)^n)}_{}\right)$$

$\phi^{(*)} \to \phi^{(*)} + a$

$\phi^{(*)} \to e^{(-)i\,\alpha}\phi^{(*)}$

shift symmetry & U(1) symmetry

$\phi^{(*)} \to e^{(-)i\,\alpha}\phi^{(*)}$

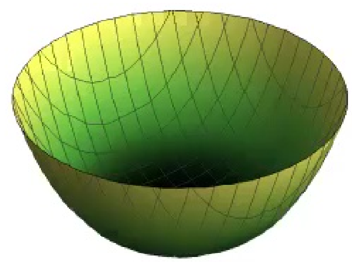
U(1) symmetry

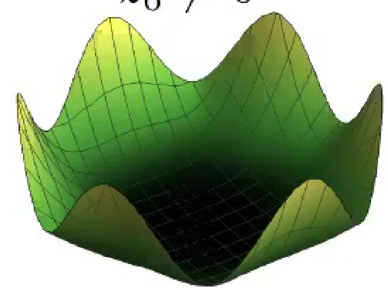
$\phi^{(*)} \to e^{(-)i\,\frac{2\pi}{n}}\phi^{(*)}$

$\mathbb{Z}_n$ symmetry

$\bar{z}_6 \neq 0$

$m^2 > 0$

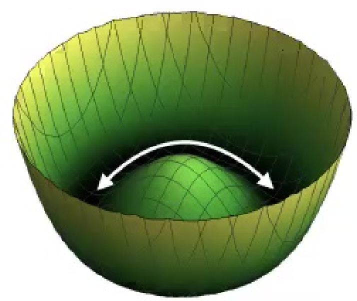


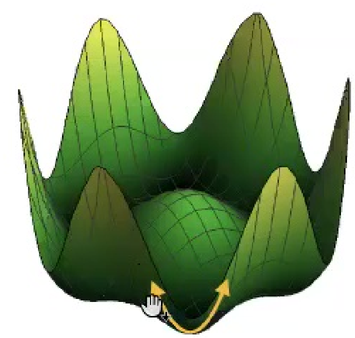


Goldstone's theorem: transverse mode is massless, when U(1) is broken spontaneously

Explizit U(1) breaking by $\mathbb{Z}_n$ symmetric term yields a transverse mass

$m^2 < 0$





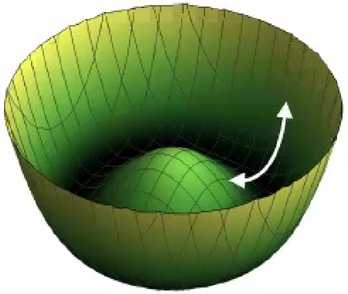
Mass-hierarchies without extra finetuning

Goldstone's theorem: transverse mode is massless, when U(1) is broken spontaneously

$$V_{\mathrm{U}(1)} = \frac{\lambda_4}{2}\left(\phi^*\phi - \bar{\kappa}\right)^2$$

Explizit U(1) breaking by $\mathbb{Z}_n$ symmetric term yields a transverse mass

$$V_{\mathbb{Z}_n} = -\bar{z}_n\left(\phi^n + (\phi^*)^n + 2(-1)^n(\phi\phi^*)^{\frac{n}{2}}\right)$$

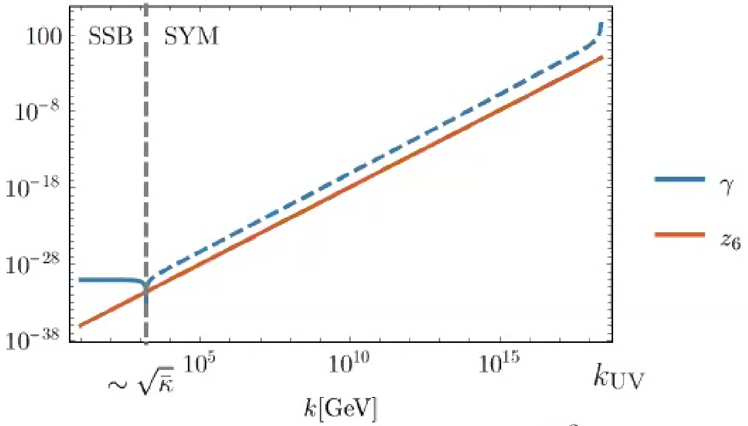


$$M^2_{\mathrm{long}} = 2\bar{\kappa}\lambda_4$$

$$M^2_{\mathrm{trans}} = n^2\bar{z}_n\,\bar{\kappa}^{\frac{n}{2}-1}$$

$$\gamma = \frac{M^2_{\mathrm{trans}}}{M^2_{\mathrm{long}}} = \frac{n^2\,z_n\,\kappa^{\frac{n}{2}-2}}{2\lambda_4}$$

$$\beta_{z_n} = (4-n)z_n + \mathcal{O}(\mathrm{couplings}^2)$$



$$\Rightarrow\ z_n \sim \left(\frac{k}{k_{\mathrm{UV}}}\right)^{n-4}$$

- one fine-tuning required ($\kappa(k_{\mathrm{UV}})$) to obtain $\frac{M^2_{\mathrm{long}}}{k^2_{\mathrm{UV}}} \ll 1$
- NO second fine-tuning required to obtain $\gamma \ll 1$ [Leonard, Delamotte, Wschebor '18; Ali, AE, Pauly, Scherer '20]

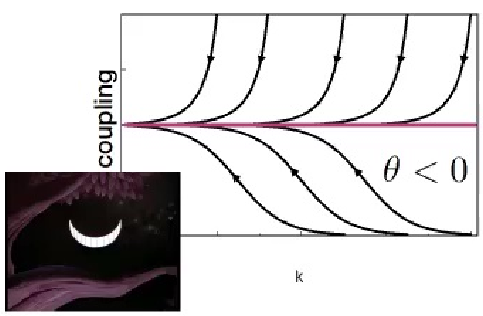
Symmetries for scalar fields in asymptotically safe gravity-matter theories

$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + ...}_{\text{U(1) symmetry}} + \bar{z}_n\underbrace{\left(\phi^n + (\phi^*)^n\right)}_{\mathbb{Z}_n\text{ symmetry}}\right)$$

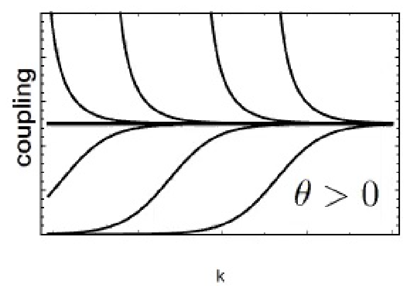
metric fluctuations preserve the symmetries of the kinetic term $\Rightarrow$ **fixed-point values under the impact of ASQG: (** $m = \frac{\bar{m}}{k},\ z_n = \frac{\bar{z}_n}{k^{n-4}}$ **)**

[AE '12; AE, Held '17]

$$m_*^2 = 0,\ \lambda_{4\,*} = 0,\ z_{n\,*} = 0$$ [Ali, AE, Pauly, Scherer '20]



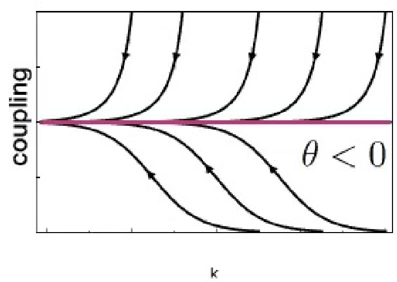
?



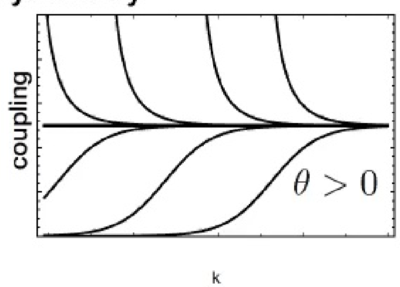
$$\theta = -\frac{\partial\beta_{m^2(\lambda_4,z_n)}}{\partial m^2(\lambda_4,z_n)}\Big|_{FP}$$

Symmetries for scalar fields in asymptotically safe gravity-matter theories

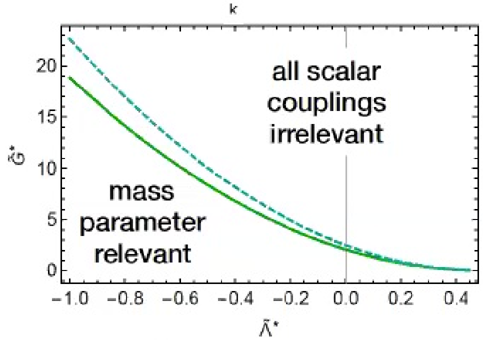
$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + \dots}_{\text{U(1) symmetry}} + \bar{z}_n\underbrace{(\phi^n + (\phi^*)^n)}_{\mathbb{Z}_n\text{ symmetry}}\right)$$



?



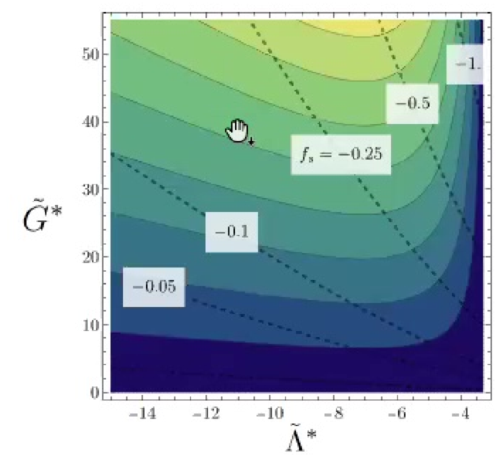
$$\theta = -\frac{\partial\beta_{m^2(\lambda_4,z_n)}}{\partial m^2(\lambda_4,z_n)}\Big|_{FP} = \begin{cases} 2 + f_s(\text{grav. coup.}) & \text{for } m^2 \\ f_s(\text{grav. coup.}) & \text{for } \lambda_4 \\ (4-n) + \underbrace{f_s(\text{grav. coup.})}_{<0} & \text{for } z_n \end{cases}$$



[AE, Hamada, Lumma, Yamada '17]

example:
Einstein-Hilbert truncation *:

$$\Gamma_k = \frac{1}{16\pi\tilde{G}k^{-2}}\int d^4x\sqrt{g}\left(R - 2\tilde{\Lambda}k^2\right)$$



* beyond Einstein-Hilbert: [de Brito, AE, Pereira '19]

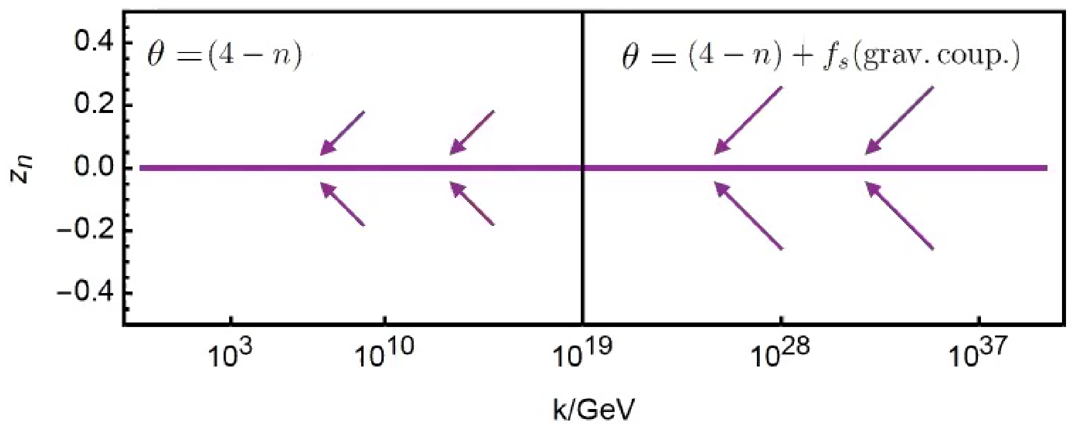
Symmetries for scalar fields in asymptotically safe gravity-matter theories

$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + ...}_{\text{U(1) symmetry}} + \bar{z}_n\underbrace{(\phi^n + (\phi^*)^n)}_{\mathbb{Z}_n \text{ symmetry}}\right)$$

Matter-regime

gravitational fluctuations decouple dynamically: $\tilde{G} = G\,k^2$

fixed-point regime



quantum fluctuations integrated out:

Symmetries for scalar fields in asymptotically safe gravity-matter theories

$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + \ldots}_{\text{U(1) symmetry}} + \bar{z}_n \underbrace{\left(\phi^n + (\phi^*)^n\right)}_{\mathbb{Z}_n \text{ symmetry}}\right)$$

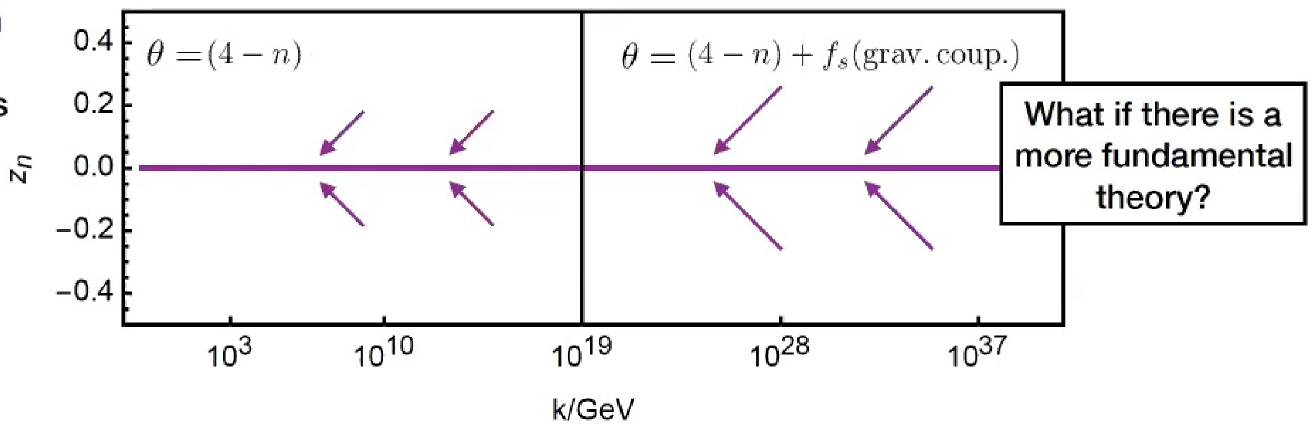
Matter-regime

gravitational fluctuations decouple dynamically: $\tilde{G} = G\,k^2$

fixed-point regime

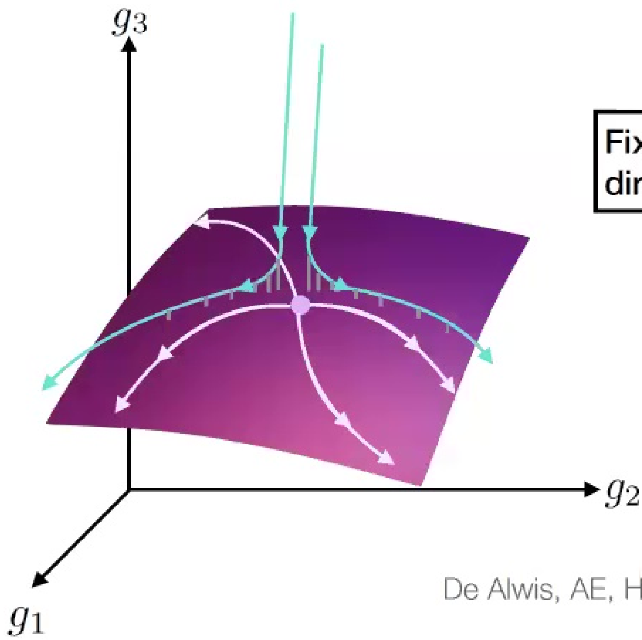
No discrete $\mathbb{Z}_n,\, n > 4$ symmetry realized in asymptotically safe scalar-gravity models

[Ali, AE, Pauly, Scherer '20]

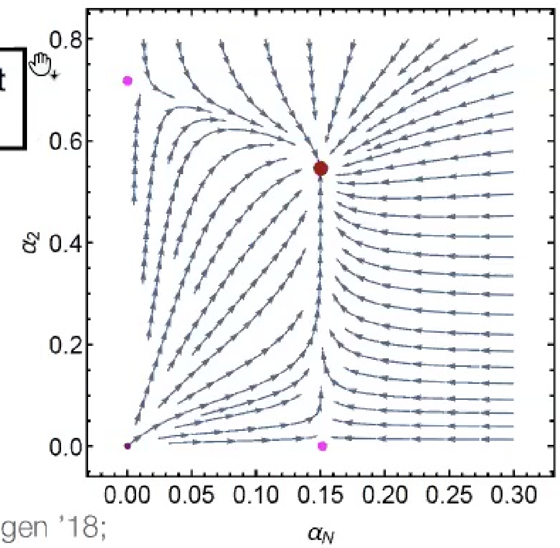


quantum fluctuations integrated out:

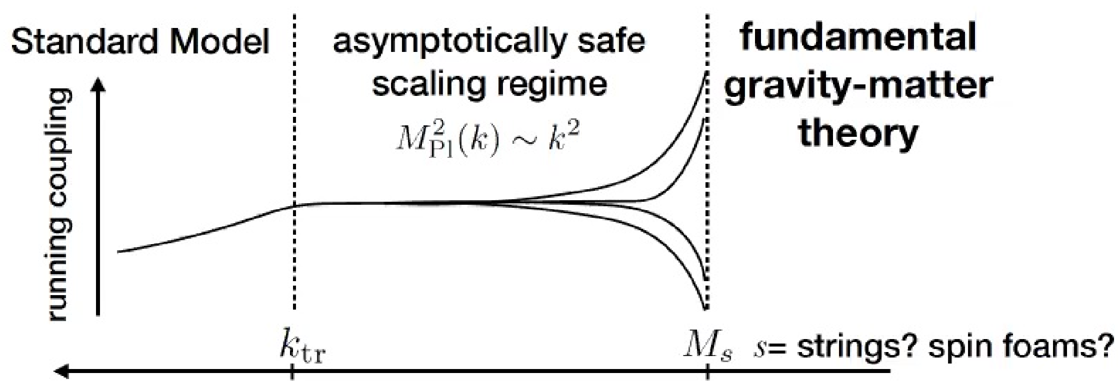
Effective asymptotic safety



Fixed points with ≥ 1 relevant direction can be UV ***or*** IR

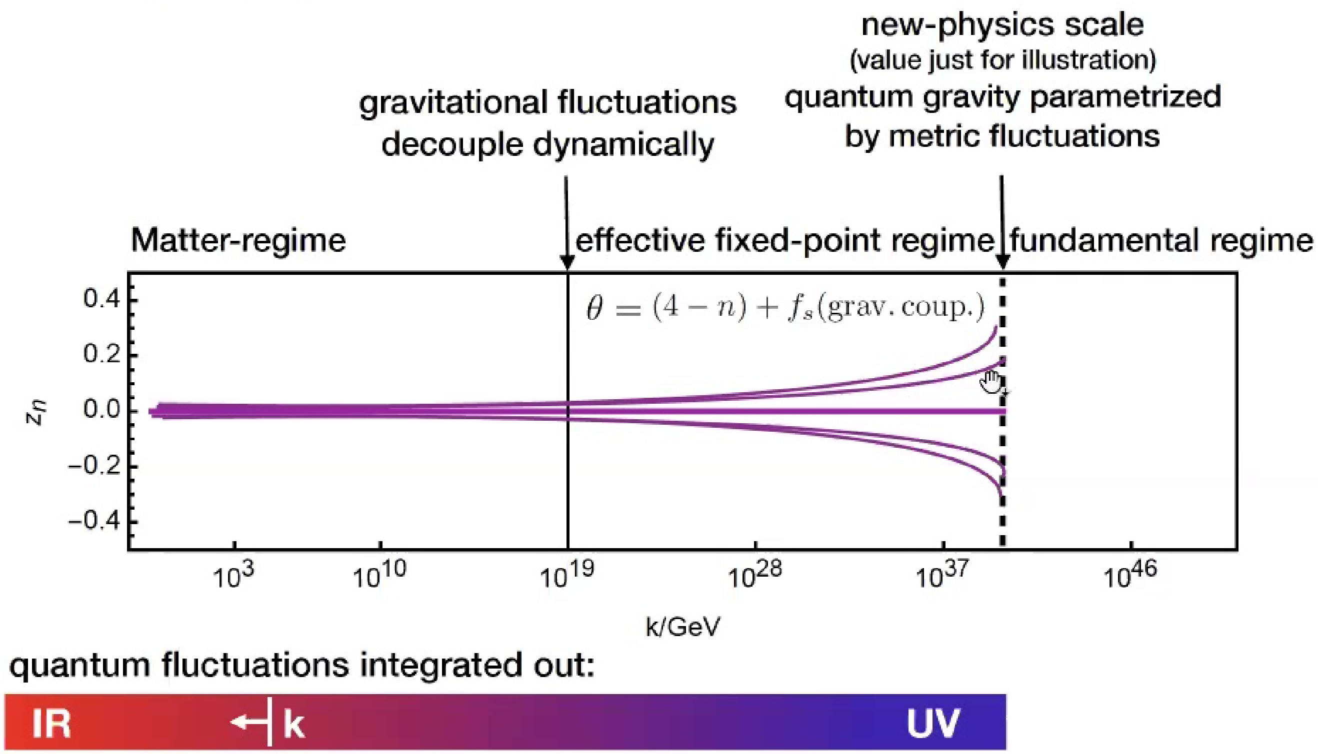


[Percacci, Vacca '10;
De Alwis, AE, Held, Pawlowski, Schiffer, Versteegen '18;
Held '20]



Symmetries for scalar fields in effective asymptotic safety

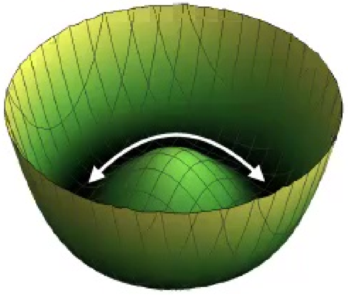
$$\Gamma_k = \int d^4x\sqrt{g}\left(\underbrace{g^{\mu\nu}\partial_\mu\phi^*\partial_\nu\phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2\phi^*\phi + \frac{\lambda_4}{2}(\phi^*\phi)^2 + \ldots}_{\text{U(1) symmetry}} + \bar{z}_n\underbrace{\left(\phi^n + (\phi^*)^n\right)}_{\mathbb{Z}_n\text{ symmetry}}\right)$$



Gravitational enhancement of mass hierarchies in effective asymptotic safety

Goldstone's theorem: transverse mode is massless, when U(1) is broken spontaneously

$$V_{\mathrm{U}(1)} = \frac{\lambda_4}{2}\left(\phi^*\phi - \bar{\kappa}\right)^2$$



$$M^2_{\mathrm{long}} = 2\bar{\kappa}\lambda_4$$

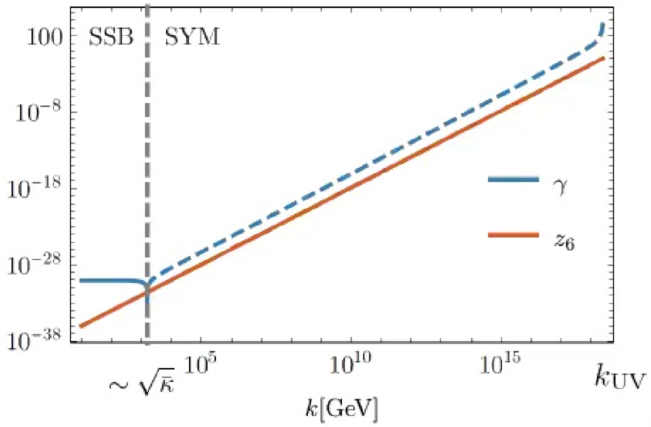
$$M^2_{\mathrm{trans}} = n^2 \bar{z}_n\, \bar{\kappa}^{\frac{n}{2}-1}$$

Explizit U(1) breaking by $\mathbb{Z}_n$ symmetric term yields a transverse mass

$$\gamma = \frac{M^2_{\mathrm{trans}}}{M^2_{\mathrm{long}}} = \frac{n^2\, z_n\, \kappa^{\frac{n}{2}-2}}{2\lambda_4}$$

$$\beta_{z_n} = (4-n) z_n + f_s\, z_n + \mathcal{O}(\mathrm{couplings}^2)$$

$$\Rightarrow z_n \sim \left(\frac{k}{k_{\mathrm{UV}}}\right)^{n-4-f_s}$$



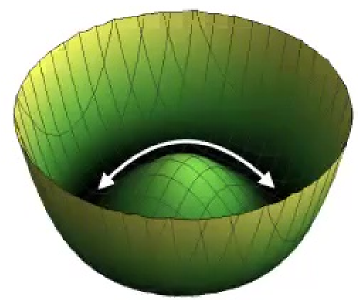
- one fine-tuning required ($\kappa(k_{\mathrm{UV}})$) to obtain $\frac{M^2_{\mathrm{long}}}{k^2_{\mathrm{UV}}} \ll 1$
- NO second fine-tuning required to obtain $\gamma \ll 1$

[Leonard, Delamotte, Wschebor '18; Ali, AE, Pauly, Scherer '20]

Gravitational enhancement of mass hierarchies in effective asymptotic safety

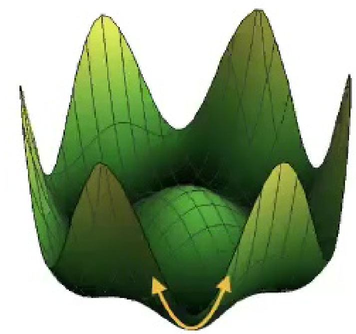
Goldstone's theorem: transverse mode is massless, when U(1) is broken spontaneously

$$V_{\mathrm{U}(1)} = \frac{\lambda_4}{2} (\phi^* \phi - \bar{\kappa})^2$$



$$M^2_{\mathrm{long}} = 2\bar{\kappa}\lambda_4$$

Explizit U(1) breaking by $\mathbb{Z}_n$ symmetric term yields a transverse mass

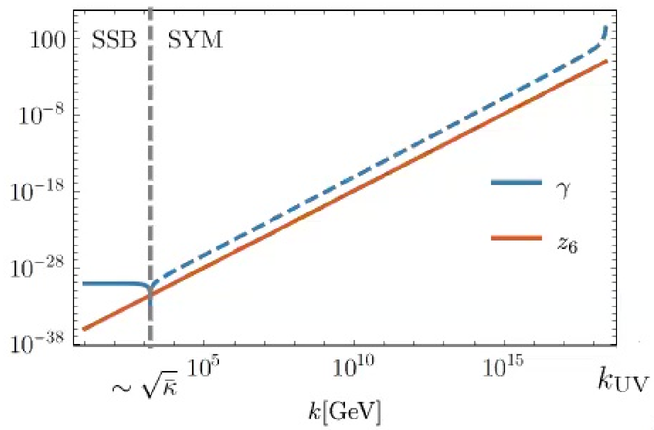


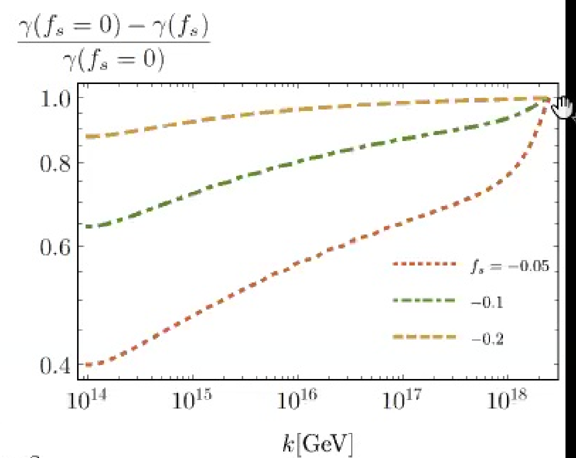
$$M^2_{\mathrm{trans}} = n^2 \bar{z}_n \, \bar{\kappa}^{\frac{n}{2}-1}$$

$$\gamma = \frac{M^2_{\mathrm{trans}}}{M^2_{\mathrm{long}}} = \frac{n^2 \, z_n \, \kappa^{\frac{n}{2}-2}}{2\lambda_4}$$

$$\beta_{z_n} = (4-n) z_n + f_s \, z_n + \mathcal{O}(\mathrm{couplings}^2)$$

$$\Rightarrow z_n \sim \left(\frac{k}{k_{\mathrm{UV}}}\right)^{n-4-f_s}$$



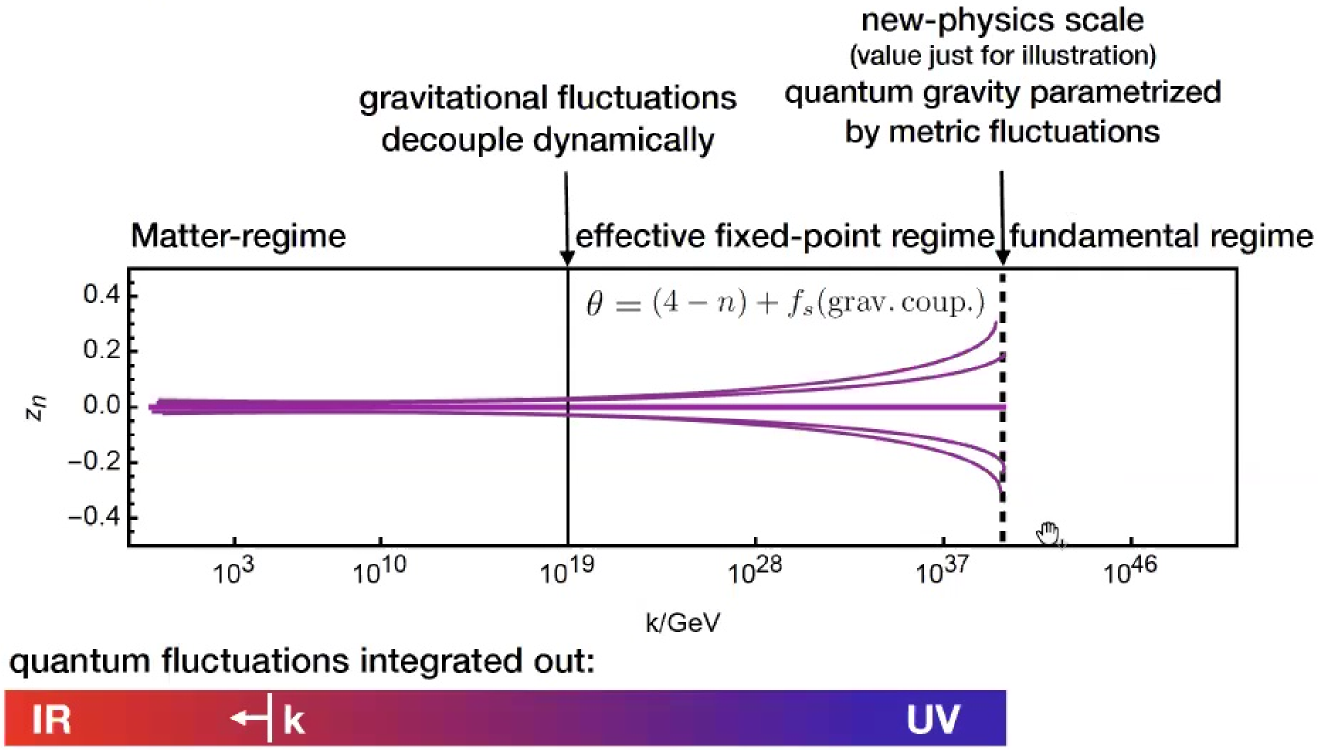


- one fine-tuning required ($\kappa(k_{\mathrm{UV}})$) to obtain $\frac{M^2_{\mathrm{long}}}{k^2_{\mathrm{UV}}} \ll 1$
- NO second fine-tuning required to obtain $\gamma \ll 1$

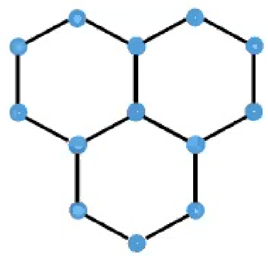
[Leonard, Delamotte, Wschebor '18; Ali, AE, Pauly, Scherer '20]

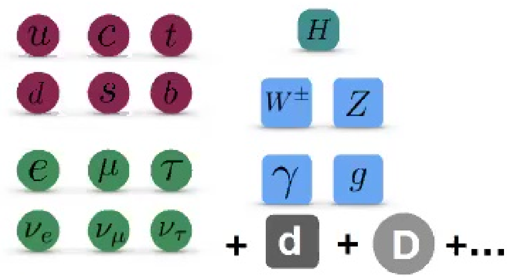
Symmetries for scalar fields in effective asymptotic safety

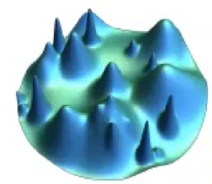
$$\Gamma_k = \int d^4x \sqrt{g} \left(\underbrace{g^{\mu\nu} \partial_\mu \phi^* \partial_\nu \phi}_{\text{shift symmetry \& U(1) symmetry}} + \underbrace{\overline{m}^2 \phi^* \phi + \frac{\lambda_4}{2} (\phi^* \phi)^2 + ...}_{\text{U(1) symmetry}} + \bar{z}_n \underbrace{(\phi^n + (\phi^*)^n)}_{\mathbb{Z}_n \text{ symmetry}} \right)$$



Summary







Condensed Matter

Global symmetries & their spontaneous breaking

Particle Physics

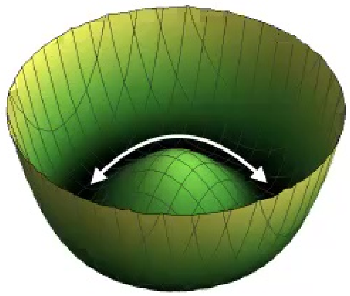
Local + global symmetries & their spontaneous breaking

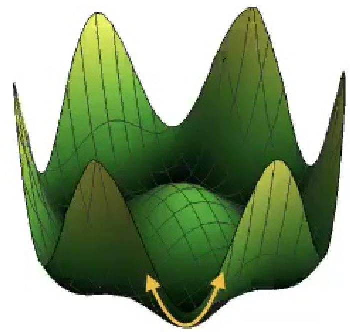
Quantum Gravity

???

No discrete $\mathbb{Z}_n$ symmetries if quantum gravity is (fundamentally) asymptotically safe

Summary

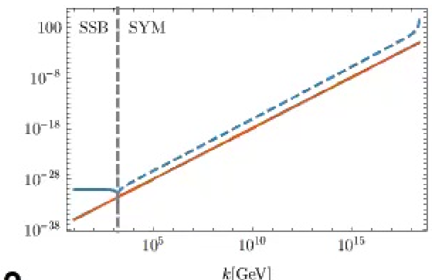




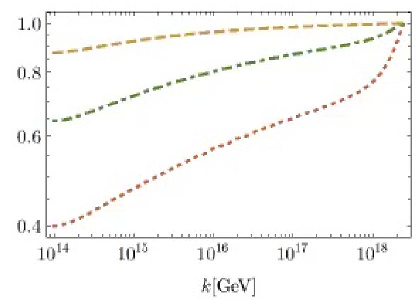
$$M^2_{\text{long}} = 2\bar{\kappa}\lambda_4$$

$$M^2_{\text{trans}} = n^2\,\bar{z}_n\,\bar{\kappa}^{\frac{n}{2}-1}$$

Gravitational enhancement of mass hierarchies in effective asymptotic safety



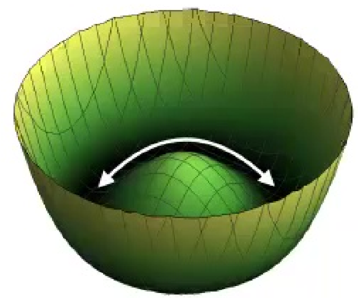
&



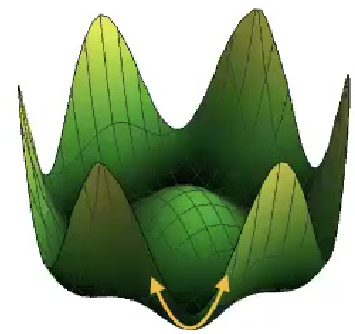
Gravitational enhancement of mass hierarchies in effective asymptotic safety

Goldstone's theorem:
transverse mode is massless,
when U(1) is broken
spontaneously

$$V_{\mathrm{U}(1)} = \frac{\lambda_4}{2}\left(\phi^*\phi - \bar{\kappa}\right)^2$$



$$M^2_{\mathrm{long}} = 2\bar{\kappa}\lambda_4$$



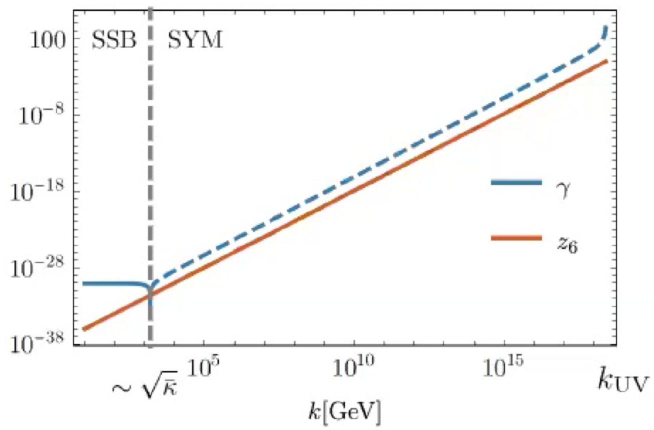
$$M^2_{\mathrm{trans}} = n^2 \bar{z}_n\, \bar{\kappa}^{\frac{n}{2}-1}$$

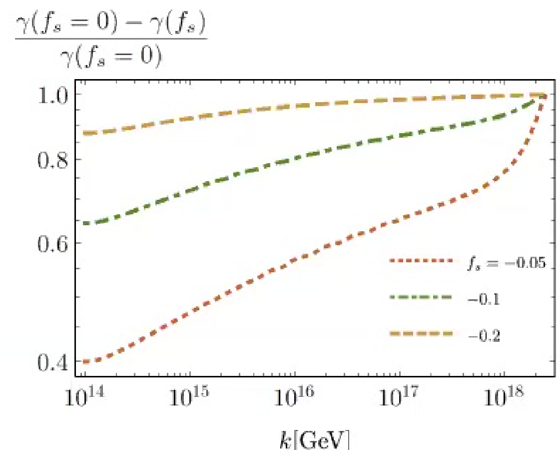
Explizit U(1) breaking by $\mathbb{Z}_n$ symmetric term yields a transverse mass

$$\gamma = \frac{M^2_{\mathrm{trans}}}{M^2_{\mathrm{long}}} = \frac{n^2\, z_n\, \kappa^{\frac{n}{2}-2}}{2\lambda_4}$$

$$\beta_{z_n} = (4-n)z_n + f_s\, z_n + \mathcal{O}(\mathrm{couplings}^2)$$

$$\Rightarrow z_n \sim \left(\frac{k}{k_{\mathrm{UV}}}\right)^{n-4-f_s}$$





- one fine-tuning required ($\kappa(k_{\mathrm{UV}})$) to obtain $\frac{M^2_{\mathrm{long}}}{k^2_{\mathrm{UV}}} \ll 1$
- NO second fine-tuning required to obtain $\gamma \ll 1$

[Leonard, Delamotte, Wschebor '18; Ali, AE, Pauly, Scherer '20]