Title: Shedding light on dark matter in asymptotic safety

Date: Jun 06, 2018 11:15 AM

URL: http://pirsa.org/18060023

Abstract: The nature of dark matter is one of the outstanding riddles of fundamental physics. Here, I will discuss first steps to explore dark matter in the asymptotic safety paradigm. As a first example, I will show indications for an asymptotically safe fixed point in the Higgs portal to fermionic dark matter, leading to a relation between the Higgs portal coupling and the dark matter mass. This model also serves as an example for different mechanisms that generate asymptotic safety.

I will then review some properties of an extended Higgs sector under the coupling to asymptotically safe quantum gravity and discuss how quantum gravity fluctuations flatten the Higgs potential and thus lead to a decoupling of scalar singlets which are subject to experimental searches for dark matter.

Shedding light on dark matter in asymptotic safety

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Asymptotic safety in a dark universe, Perimeter Institute, June 2018

Higgs portals to the dark sector

$\lambda_{h\psi} h^2 \bar{\psi}\psi$ [Lopez-Honorez, Schwetz, Zupan '12…]

dark fermions

$\lambda_{h\chi} h^2 \chi^2$ [Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Velthuis '01…]

dark scalars

- **dark matter relic density from thermal freeze out**
- **possible contribution to Higgs vacuum stability**
- **channel for direct searches (@ LHC, Xenon, Lux…): upper bounds**

[Beniwal, Rajec, Savage, Scott, Weniger, White, Williams '16]

Outline

$\lambda_{h\psi} h^2 \bar{\psi}\psi$ [Lopez-Honorez, Schwetz, Zupan '12…]

dark fermions

- toy model: no SM degrees of freedom, no gravity
- exhibits several mechanisms for AS in truncations
- indication for AS in first truncations

[AE, Held, Vander Griend '18]

$\lambda_{h\chi} h^2 \chi^2$ [Silveira, Zee '85; McDonald '94; Burgess, Pospelov, Velthuis '01…]

dark scalars

- (extended) Higgs sector under impact of asymptotically safe quantum gravity in truncations

[AE, Hamada, Lumma, Yamada '17]

potential examples of predictive power of the asymptotic safety paradigm

- relation between $\lambda_{h\psi}$ and m_ψ

& relic-density constraint: m_ψ fixed

- Higgs mass prediction

[Shaposhnikov, Wetterich '09]

- decoupling of dark scalar

Mechanisms for asymptotic safety

- **one-loop versus two-loop**

  e.g. gauge-Yukawa models $\beta_{\alpha_g} = (-B + C\alpha_g)\,\alpha_g^2 + \mathcal{O}(\alpha_g^4)$ [Litim, Sannino '14]

- **canonical vs. quantum**

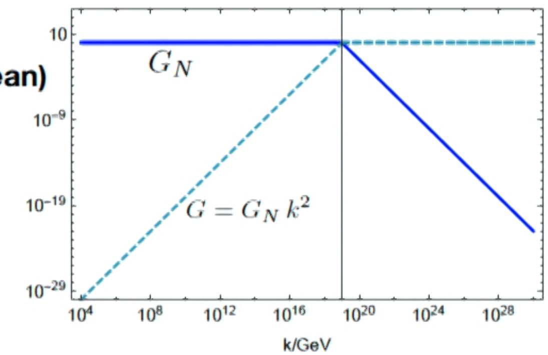
  e.g. gravity in d=2+ε & **d = 4 (Euclidean)**

  [Weinberg '76; Christensen, Duff '78 Gastmans, Kallosh, Truffin '78]

  [Benedetti, AE, Gies, Litim, Morris, Pawlowski, Percacci, Reuter, Saueressig, Wetterich....]

$$\beta_G = \epsilon\, G - \#\, G^2 + \mathcal{O}(G^3)$$

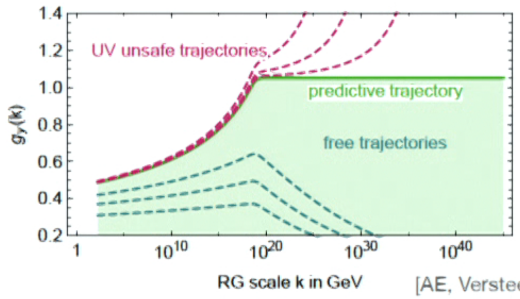
Classical gravity regime **Quantum gravity regime**



- **competing degrees of freedom**

  e.g. gravity and matter (?)

$$\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\,\frac{41}{6} - f_g\, g_Y$$



[AE, Versteegen '17]

Mechanisms for asymptotic safety in the Higgs portal to dark fermions

$$\Gamma_k = \int d^4x \left(\text{kin} + \bar{m}_\psi \bar{\psi}\psi + \bar{\lambda}_{h\psi} h^2 \bar{\psi}\psi + V[h]\right) \qquad V[h] = \frac{1}{2} m^2 h^2 + \frac{\lambda_h}{8} h^4$$

potential mechanisms: canonical vs. quantum competing d.o.f.

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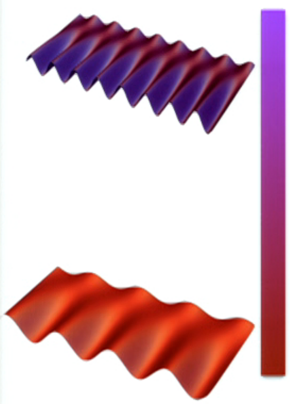
tool: Functional RG

probe scale dependence of QFT

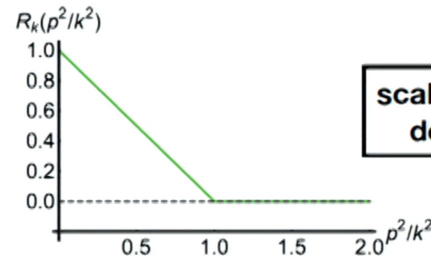


S [Wetterich '93]

Γ_k **contains effect of qm fluctuations above k**

$\Gamma_{k\to 0}$

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



scale- and momentum-dependent ``mass"

$$\Gamma_k = \sum_i g_i(k) \int d^dx\, \mathcal{O}^i \;\to k\partial_k \Gamma_k = \sum_i \beta_{g_i} \int d^dx \mathcal{O}^i$$

Wetterich equation:

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

$=$ 

strategy:

(Ising model [Litim, Zappala '10]**,**
Gross-Neveu (Yukawa) [Knorr '16, Gies et al. '17, Classen, Herbut, Scherer '17]**,**
multicritical points [AE, Mesterhazy, Scherer '14]**...)**

- **truncate eff. dynamics (e.g., guided by canonical relevance)**
- **apparent convergence**

Mechanisms for asymptotic safety in the Higgs portal to dark fermions

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tool: Functional RG

[AE, Held, Vander Griend '18]

- **canonical vs. quantum**

$$\beta_{\lambda_{h\psi}} = \underbrace{\lambda_{h\psi}}_{\text{canonical}} + \underbrace{\frac{3\lambda_4\,\lambda_{h\psi}}{16\pi^2(1+m_\phi^2)^3} + \frac{m_\psi\,\lambda_{h\psi}^2(2+m_\psi^2+m_\phi^2)}{8\pi^2(1+m_\phi^2)^2(1+m_\psi^2)^2}}_{\text{quantum}}$$

potential contribution to stabilization of electroweak vacuum if mass-term subdominant

- **competing degrees of freedom**

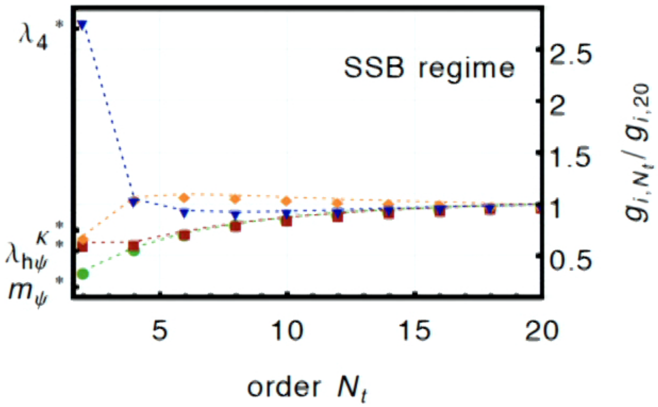
$$\beta_{\lambda_4} = \underbrace{\frac{9\lambda_4^2}{16\pi^2(1+m_\phi^2)^3}}_{\text{bosons}} + \underbrace{\frac{\lambda_{h\psi}^2}{4\pi^2(1+m_\psi^2)^2} - \frac{m_\psi^2\,\lambda_{h\psi}^2}{\pi^2(1+m_\psi^2)^3}}_{\text{fermions}}$$

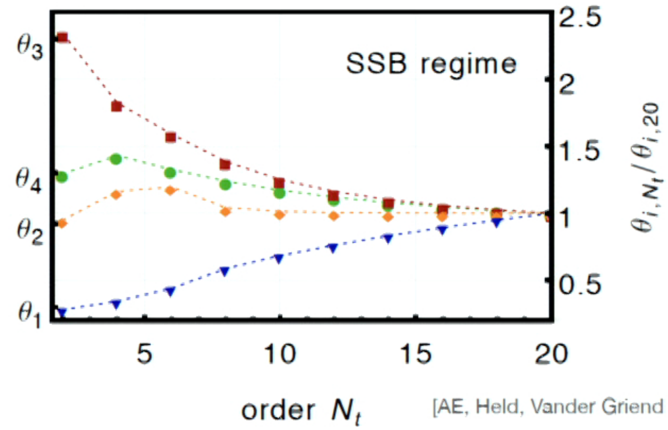
[cf. mechanism in simple Higgs-Yukawa models: Gies, Scherer '09]

Asymptotic safety in fermionic Higgs portal - status

- towards apparent convergence in extended truncations?

$$V[h] = \sum_{i=1}^{N_t} \frac{\lambda_{2i}}{i!} \left(\frac{h^2}{2} - \kappa \right)^i$$





[AE, Held, Vander Griend '18]

$\theta_1 = 12.5,\ \theta_2 = 3.7,\ \theta_3 = 1.7,\ \theta_4 = -1.9$ **@ N_t=20**

note: difference to SYM

$\longrightarrow$ **further extensions required (specifically: fermion selfinteractions)**

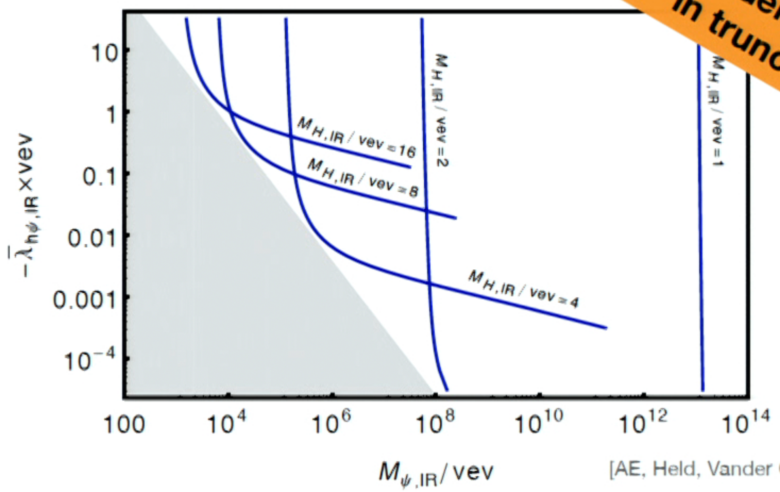
Asymptotic safety in fermionic Higgs portal - potential consequences

EFT setting: $\lambda_h,\, m_h,\, \lambda_{h\psi},\, m_\psi$ **free parameters**

Asymptotically safe setting: 3 relevant, 1 irrelevant direction (in truncation)

$$\rightarrow \lambda_{h\psi} = \lambda_{h\psi}(\lambda_h,\, m_h,\, m_\psi)$$

toy model constraint in truncation



[AE, Held, Vander Griend '18]

relic density in WIMP paradigm: $\lambda_{h\psi} = \lambda_{h\psi}(m_\psi)$

Higgs portal to scalar dark matter $\lambda_{h\chi} h^2 \chi^2$

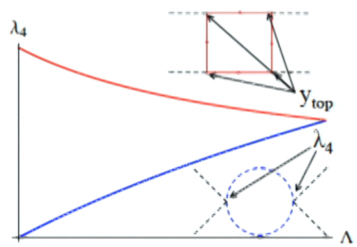
attractive model that might

- explain dark matter relic density
- reconcile Higgs vacuum stability with M_h=126 GeV

[Gonderinger, et al. '10]

FRG study with h/o effects: [AE, Scherer '14]

Higgs vacuum stability:
bosons vs. fermions

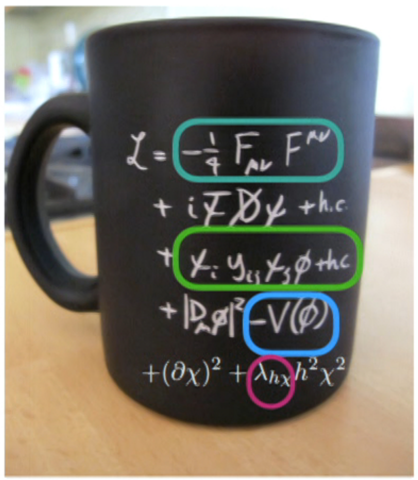


Impact of asymptotically safe quantum gravity on
(extended) Higgs sector?

Asymptotically safe quantum gravity: effects on matter

QG contribution to Standard Model matter couplings (@ 1 loop)

truncations of gravity dynamics $f_i = f_i(G, ...)$



gauge couplings $\beta_{g_i} = f_g\, g_i + \#_i g_i^3 \dots$

Yukawa couplings $\beta_y = f_y y + \#_y y^3 \dots$

Higgs quartic $\beta_{\lambda_H} = f_\lambda \lambda_H + \#_H \lambda_H^2 \dots$

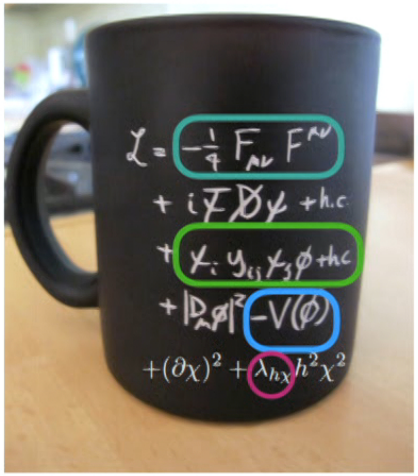
Higgs portal $\beta_{\lambda_{h\chi}} = f_\lambda \lambda_{h\chi} + \#_{h\chi} \lambda_{h\chi}^2 \dots$

QG effect:
like change in canonical dimension:
triggers asymptotic freedom for $f_i < 0$

same structure for gauge-Yukawa systems

[Christiansen, A.E., Held '17]

Asymptotically safe quantum gravity: effects on matter



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$f_g \leqslant 0$

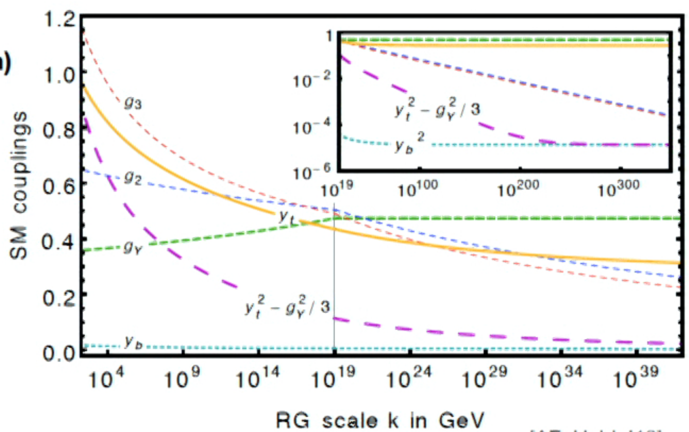
(Einstein-Hilbert truncation)

[Daum, Harst, Reuter '10; Folkerts, Litim, Pawlowski '11; Harst, Reuter '11, Christiansen, AE '17, AE, Versteegen '17, Christiansen et al. '17]

$f_y < 0$

restricts micr. grav. parameter space

[AE, Held, Pawlowski '16; AE, Held, '17, '18]



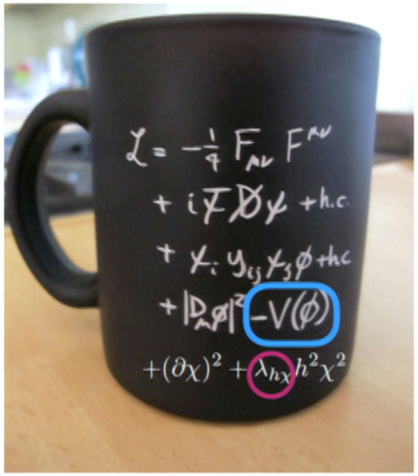
[AE, Held, '18]

in above approximation can find f_g and f_y such that

- **Abelian hypercharge ✓**
- **top & bottom Yukawa ✓**

mass difference of top & bottom explained from charge difference

Quantum gravity fluctuations flatten the Planck-scale Higgs potential



Higgs quartic $\beta_{\lambda_H} = \boxed{f_\lambda \lambda_H} + \#_H \lambda_H^2 \cdots$

Higgs portal $\beta_{\lambda_{h\chi}} = \boxed{f_\lambda \lambda_{h\chi}} + \#_{h\chi} \lambda_{h\chi}^2 \cdots$

shift-symmetry
$h \to h + c \qquad \chi \to \chi + b$

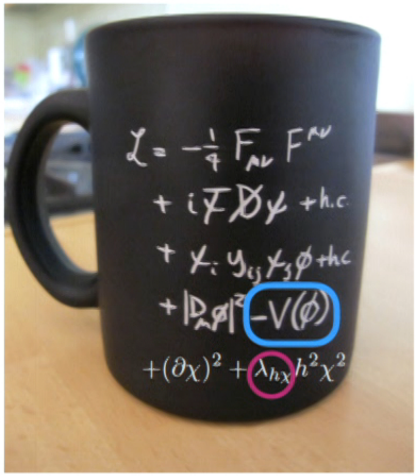
respected by ASQG (all QG+matter truncations to date)

[AE, Held '17]

UV fixed point @ V[h,χ]=0

IR or UV attractive?

Quantum gravity fluctuations flatten the Planck-scale Higgs potential



Higgs quartic $\beta_{\lambda_H} = \boxed{f_\lambda \lambda_H} + \#_H \lambda_H^2 \cdots$ $f_\lambda > 0$

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[Narain, Percacci '09, Zanusso, et al. '10; AE '12, Oda, Yamada '15]

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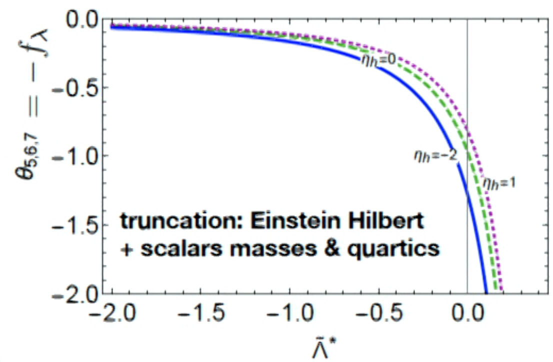
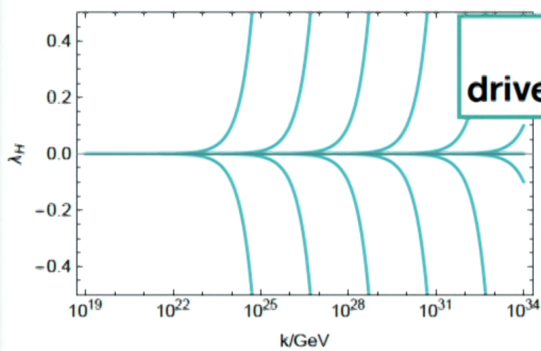


[AE, Hamada, Lumma, Yamada '17]



QG fluctuations drive λ_H to zero at MPlanck

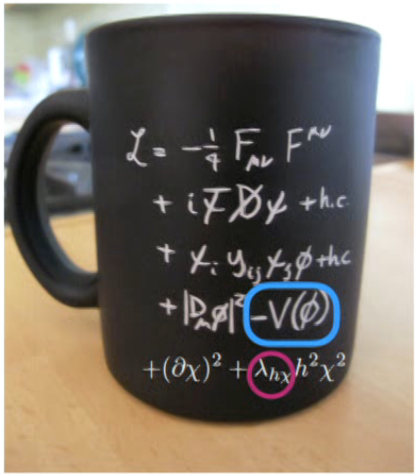
λ_H **regenerated below MPl by top and gauge fluc's**

prediction:

$\longrightarrow M_h \approx 129\,\mathrm{GeV}$ **(top-mass dependence)**

[Shaposhnikov, Wetterich '09; Bezrukov, Kalmykov, Kniehl, Shaposhnikov '12]

Quantum gravity fluctuations flatten the Planck-scale Higgs potential



Higgs quartic $\beta_{\lambda_H} = \boxed{f_\lambda \lambda_H} + \#_H \lambda_H^2 \cdots$ $f_\lambda > 0$

Higgs portal $\beta_{\lambda_{h\chi}} = \boxed{f_\lambda \lambda_{h\chi}} + \#_{h\chi} \lambda_{h\chi}^2 \cdots$

[Narain, Percacci '09, Zanusso, et al. '10; AE '12, Oda, Yamada '15]

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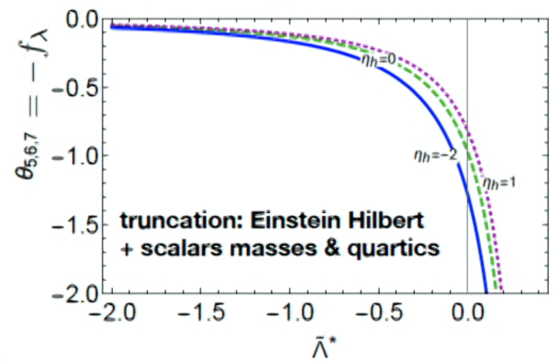

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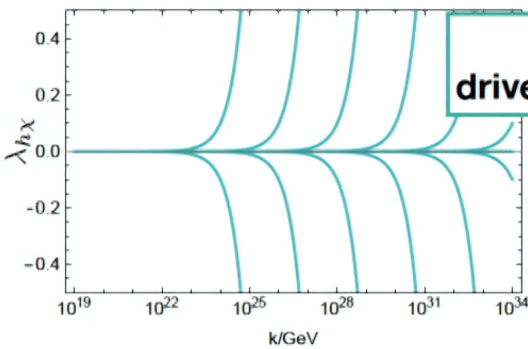


QG fluctuations drive $\lambda_{h\chi}$ to zero at M_{Planck}

χ **uncharged under SM gauge groups**

$\longrightarrow$ **not regenerated below M_{Pl} by top and gauge fluc's**

$\longrightarrow$ **scalar dark matter decouples from SM at all scales (at level of marginal couplings; momentum-dependent interactions expected** [AE, '12]**)**

$\longrightarrow$ **indications against uncharged scalars as thermal relic in AS**

Summary

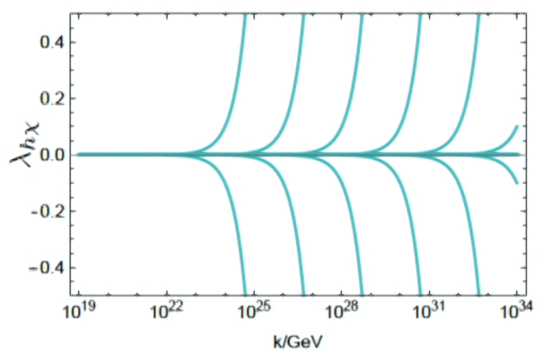
Asymptotic safety paradigm: UV completion for EFTs also with h/o couplings possible

first search in Higgs portal to dark fermions

asymptotic-safety relation: $\rightarrow \lambda_{h\psi} = \lambda_{h\psi}(\lambda_h,\, m_h,\, m_\psi)$

extended truncations/ lattice studies… necessary!

First hints for UV completion of visible universe including gravity in asymptotic safety paradigm (enhanced predictive power?)



Quantum gravity fluctuations flatten the Planck-scale Higgs potential in Einstein-Hilbert truncation

extended truncations/ lattice studies… necessary!

$\longrightarrow$ **vanishing marginal interaction channel for uncharged scalar**

Nature of dark matter in asymptotic safety?