The asymptotic-safety paradigm for gravity and matter

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All Things EFT online seminar series

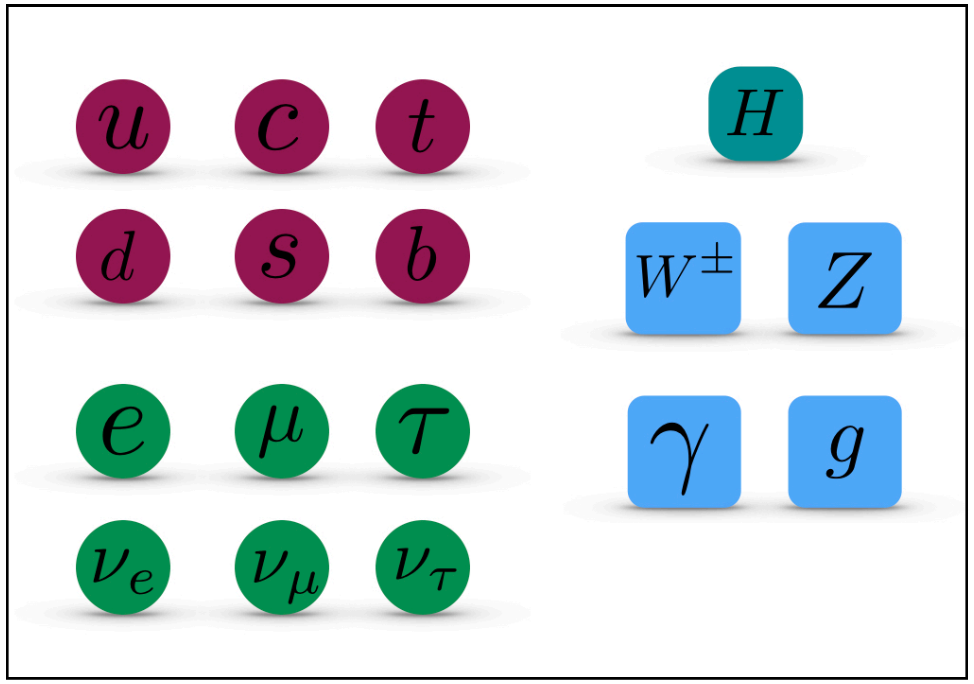
May 19, 2021

CP3-Origins

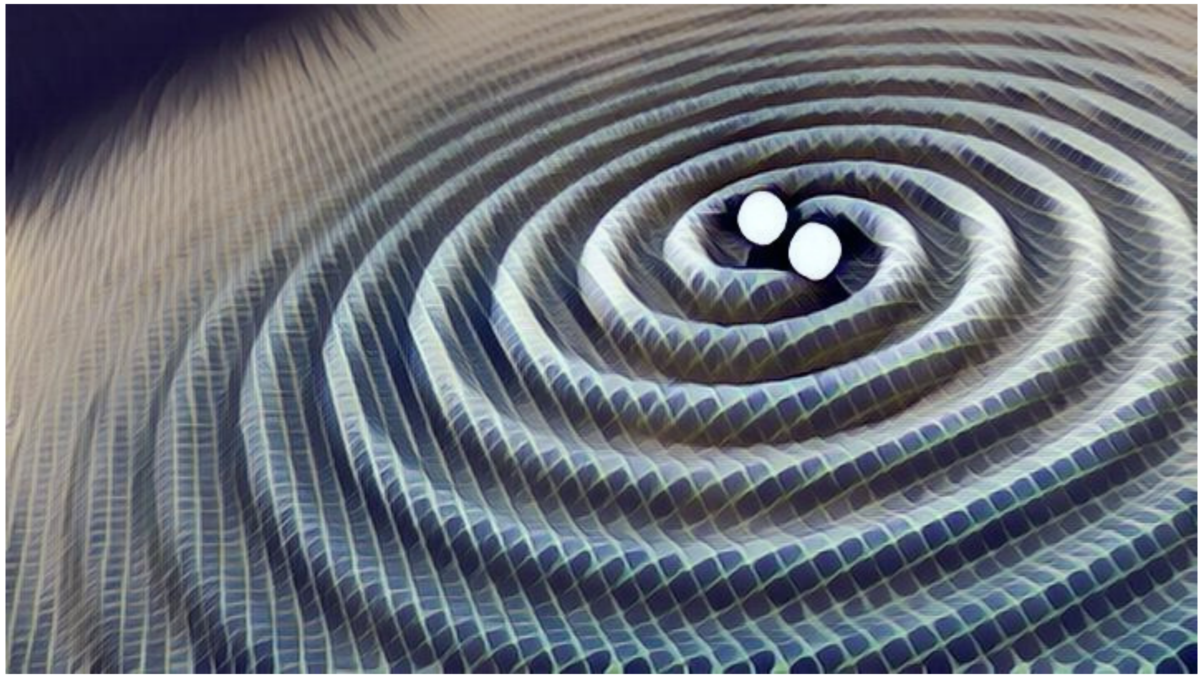
University of Southern Denmark

THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

Effective field theories of nature



Standard Model



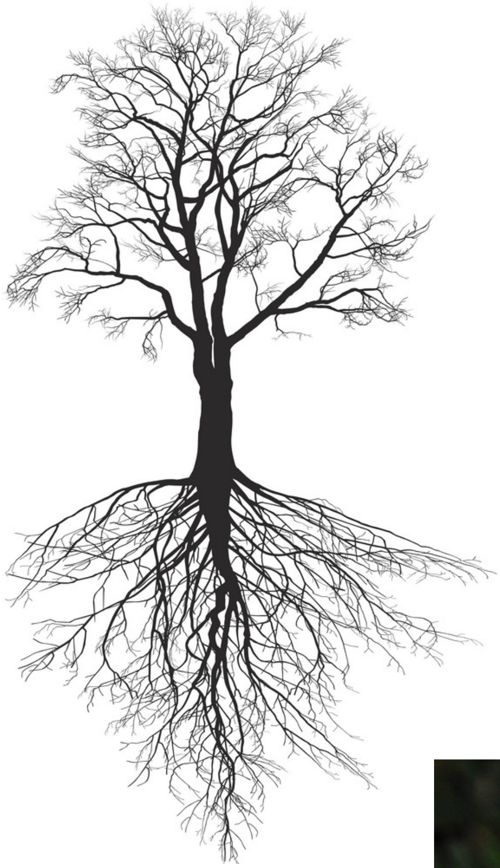
Einstein gravity

→ highly successful in experiments/observations

Can asymptotic safety help?
- → not ultraviolet (UV) complete
- → breakdown of predictivity at high energies/small distances; occurrence of Landau poles
- → unknown how to combine the two beyond EFT regime

Asymptotic safety: a symmetry principle

Could scale symmetry be a deep principle of nature?

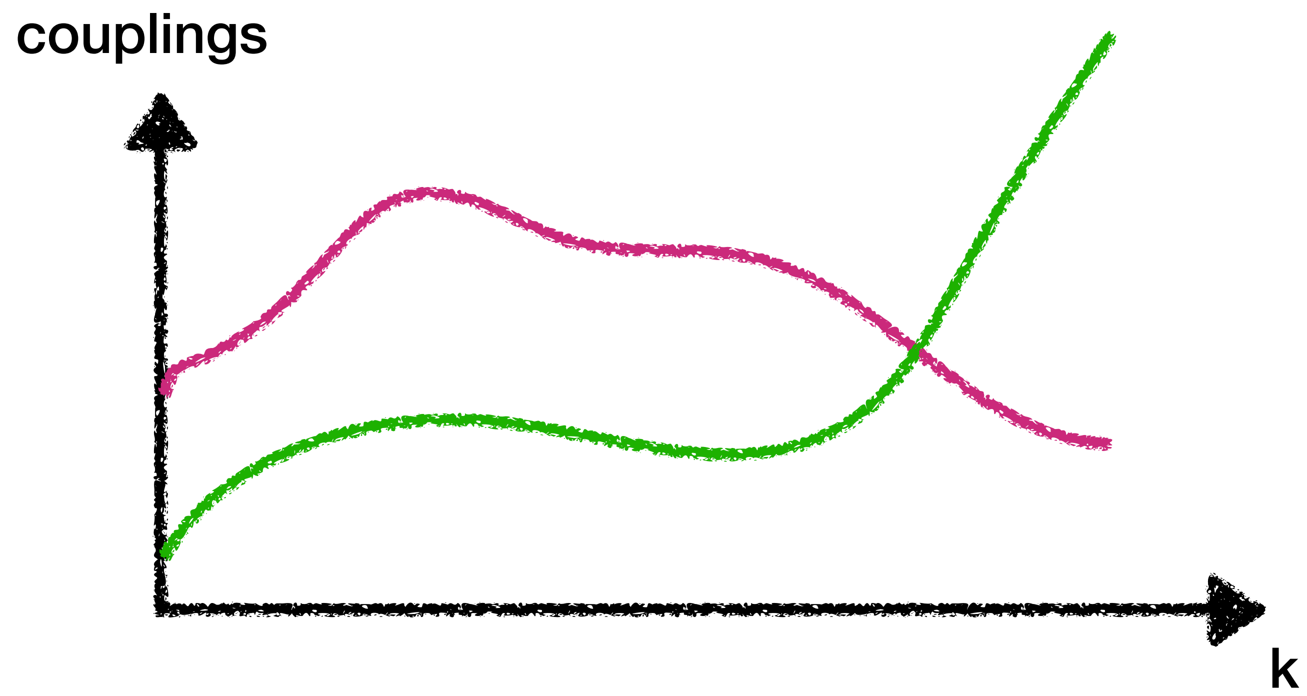


Asymptotic safety

Could scale symmetry be a deep principle of nature?

Presence of quantum fluctuations:

Theory is scale dependent:
Renormalization Group flow



Asymptotic safety

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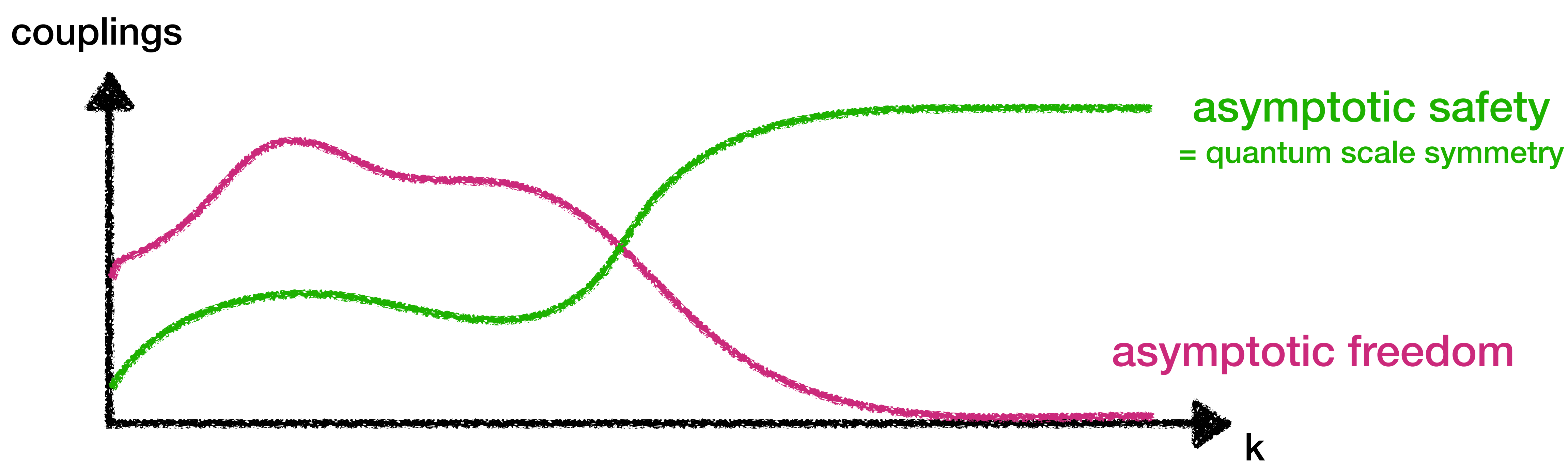
Renormalization Group flow

Scale symmetry:
Renormalization Group fixed point



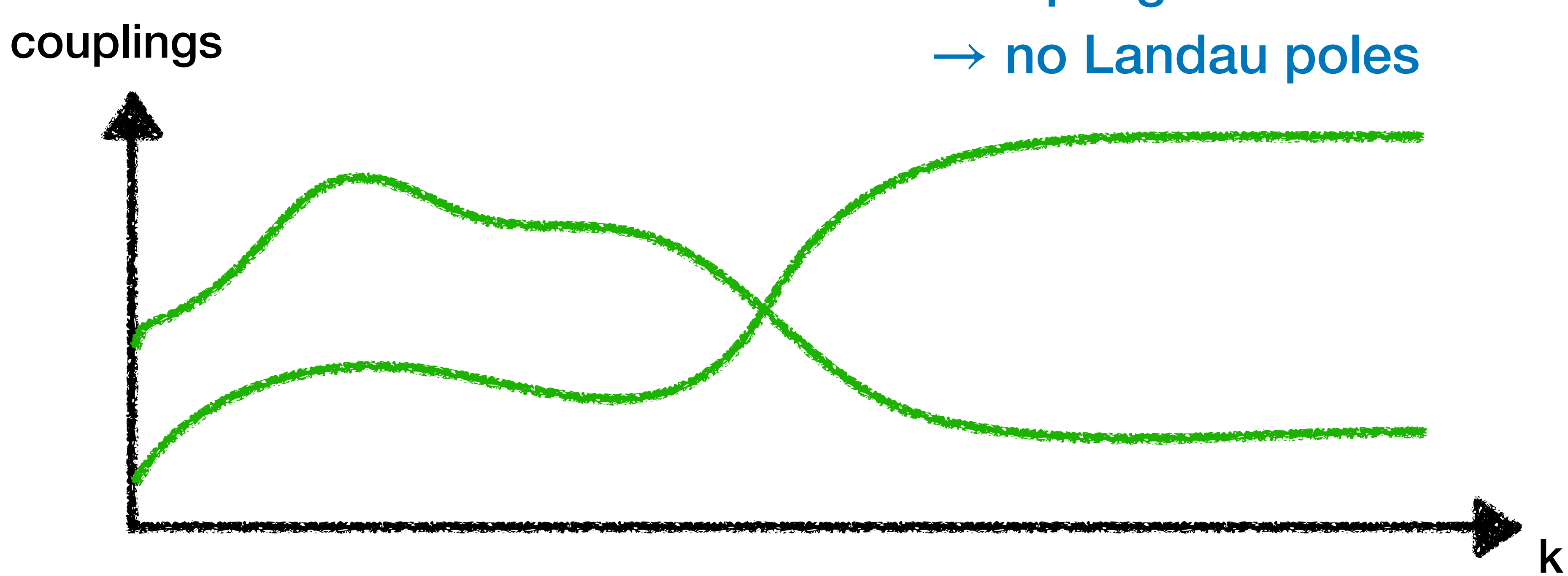
Asymptotic safety

Asymptotic safety = EFT + UV quantum scale symmetry

$\longrightarrow$ UV extensions/completion & predictivity

couplings = const

$\rightarrow$ no Landau poles



$$\Gamma = \int d^4x \left(g_1 \mathcal{O}_1 + g_2 \mathcal{O}_2 + g_3 \mathcal{O}_3 + g_4 \mathcal{O}_4 \dots \right)$$

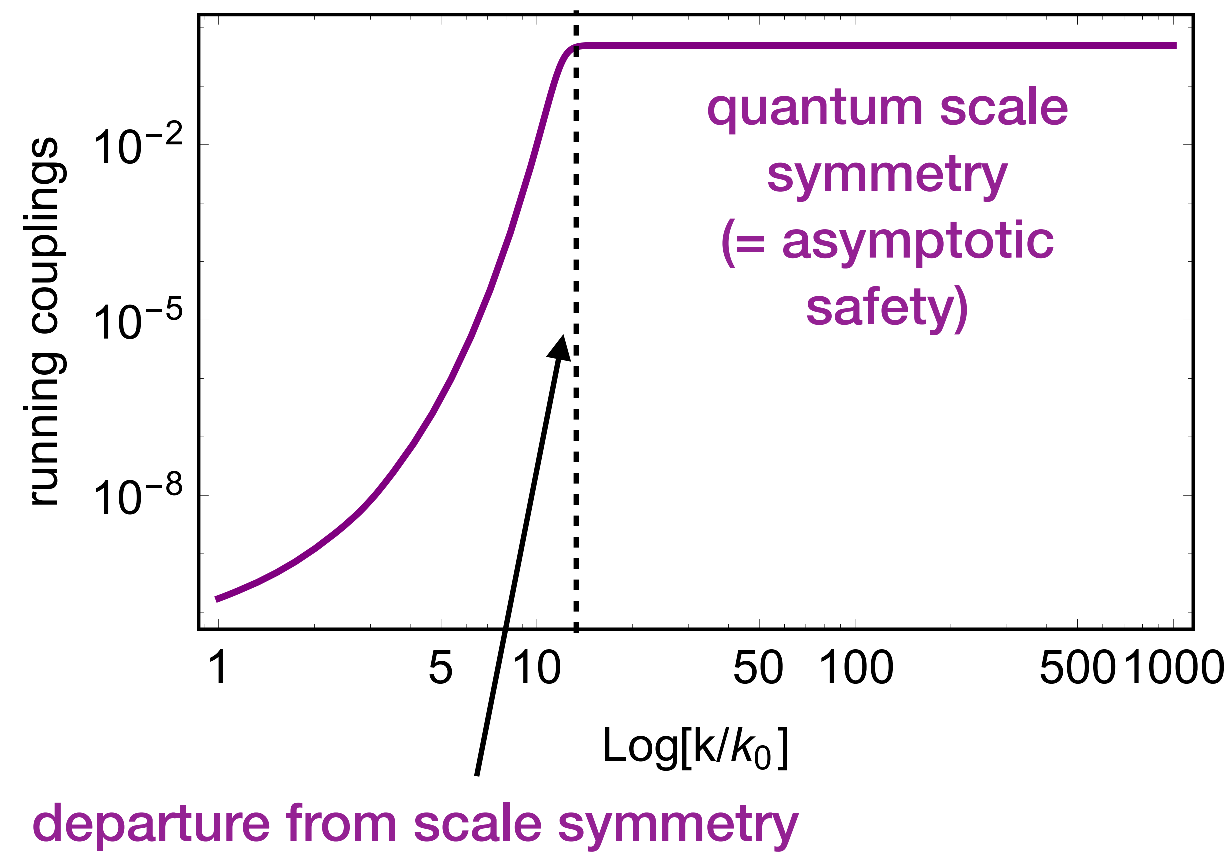
Asymptotic safety:

All g_i start at a fixed point in the UV

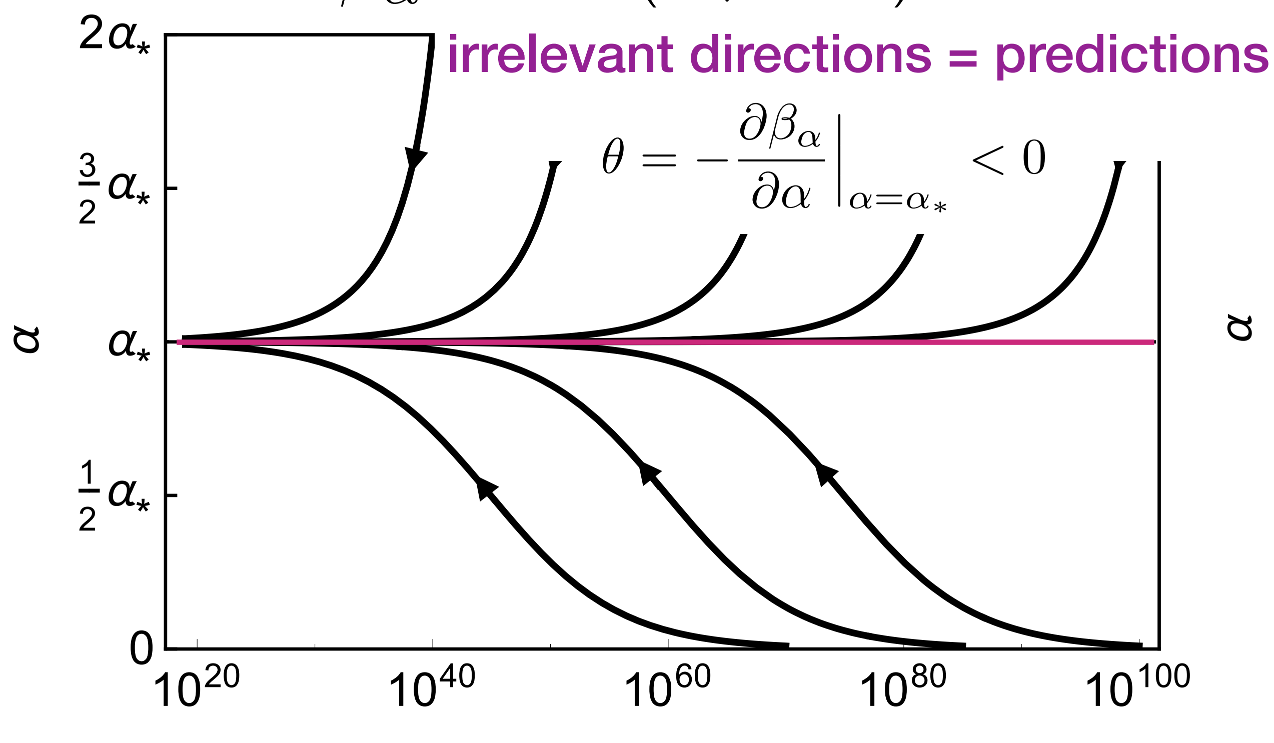
$\Rightarrow$ relations $g_4 = g_4(g_1, g_2, g_3)$

EFT: independent free parameters

Predictive power of asymptotic safety



$$\beta_\alpha = -\alpha(\alpha_* - \alpha)$$



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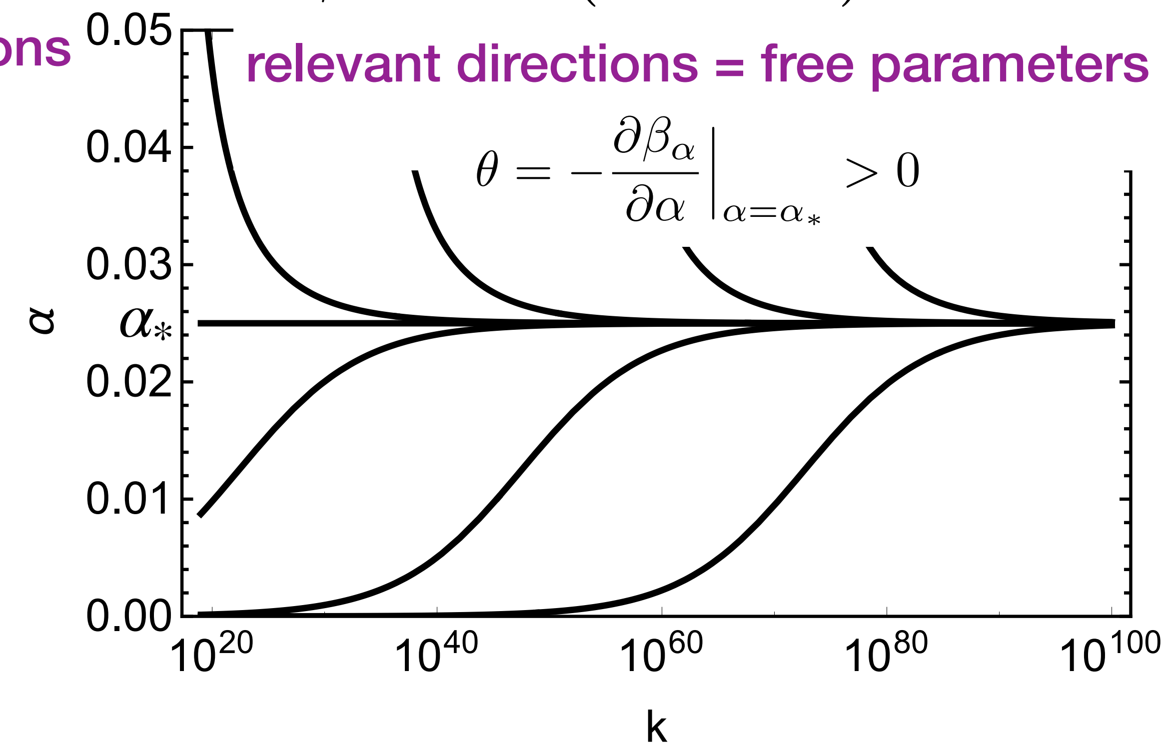

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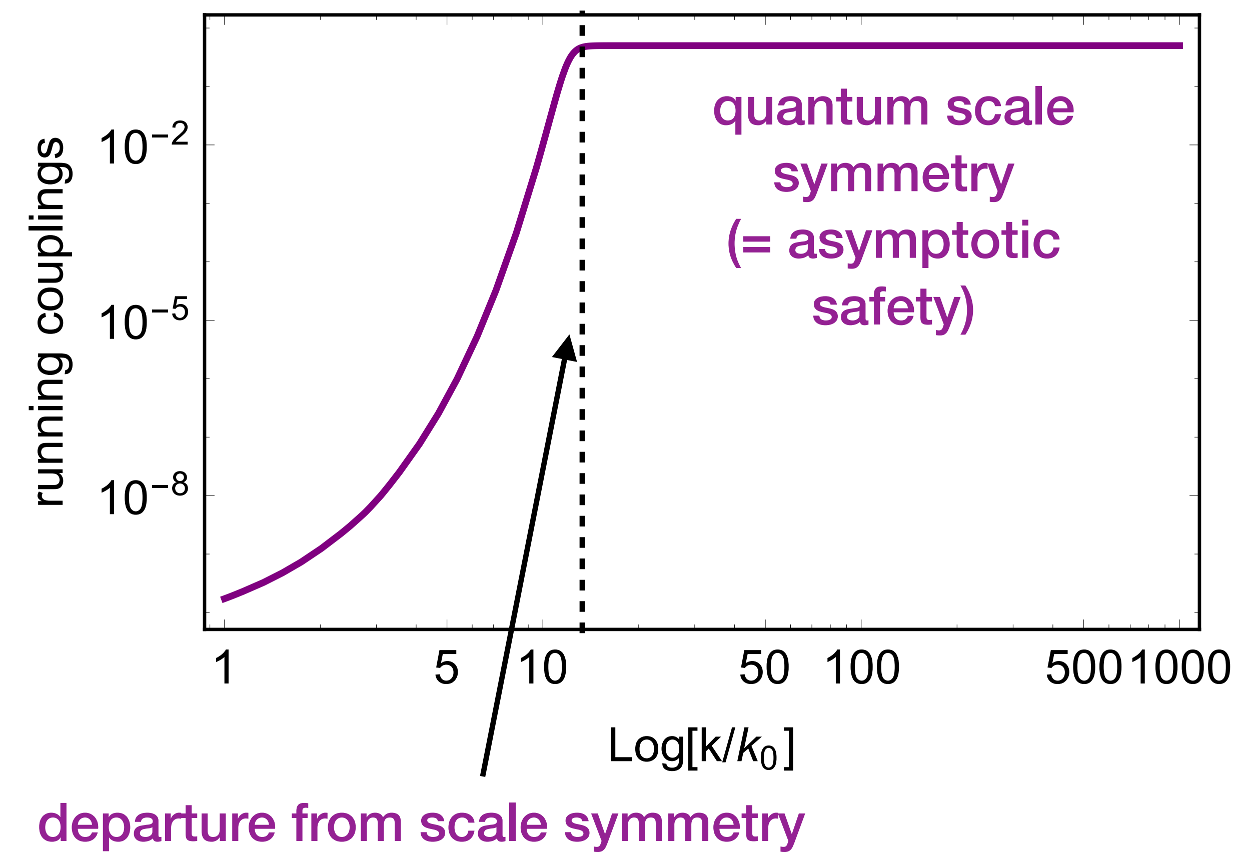

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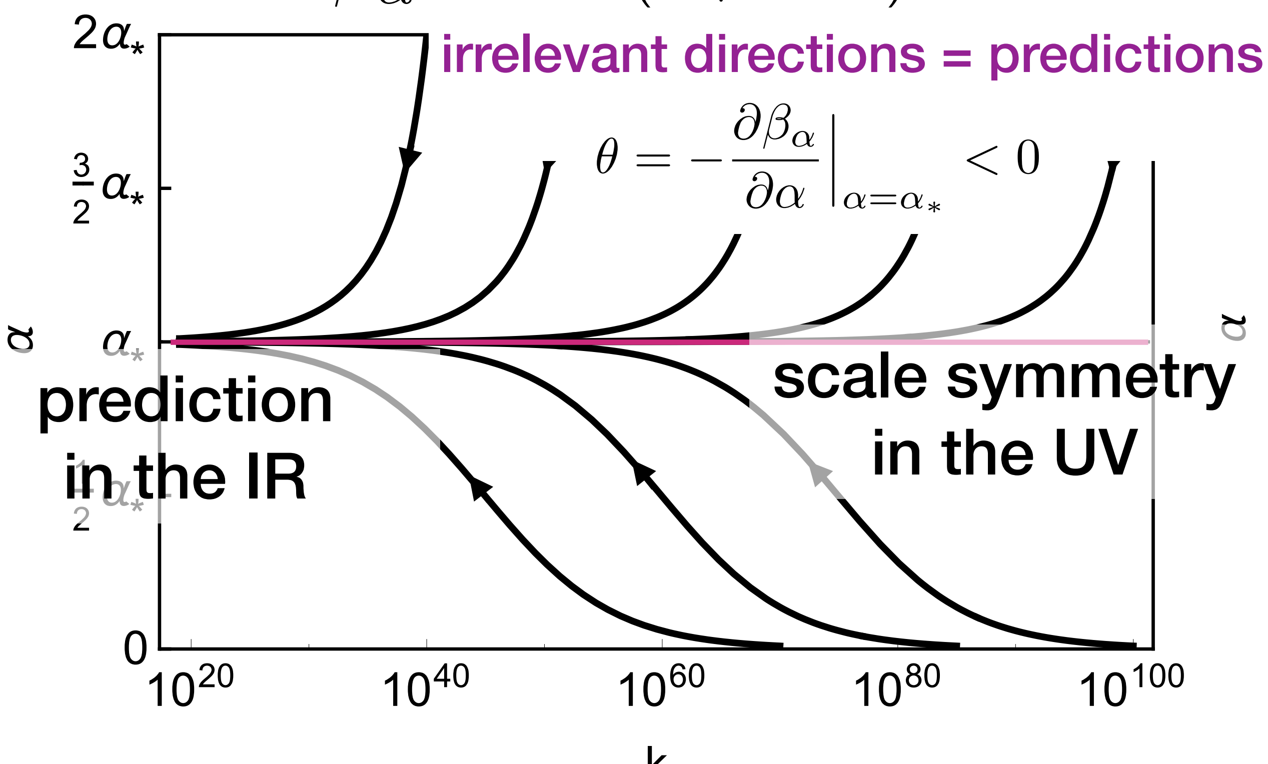

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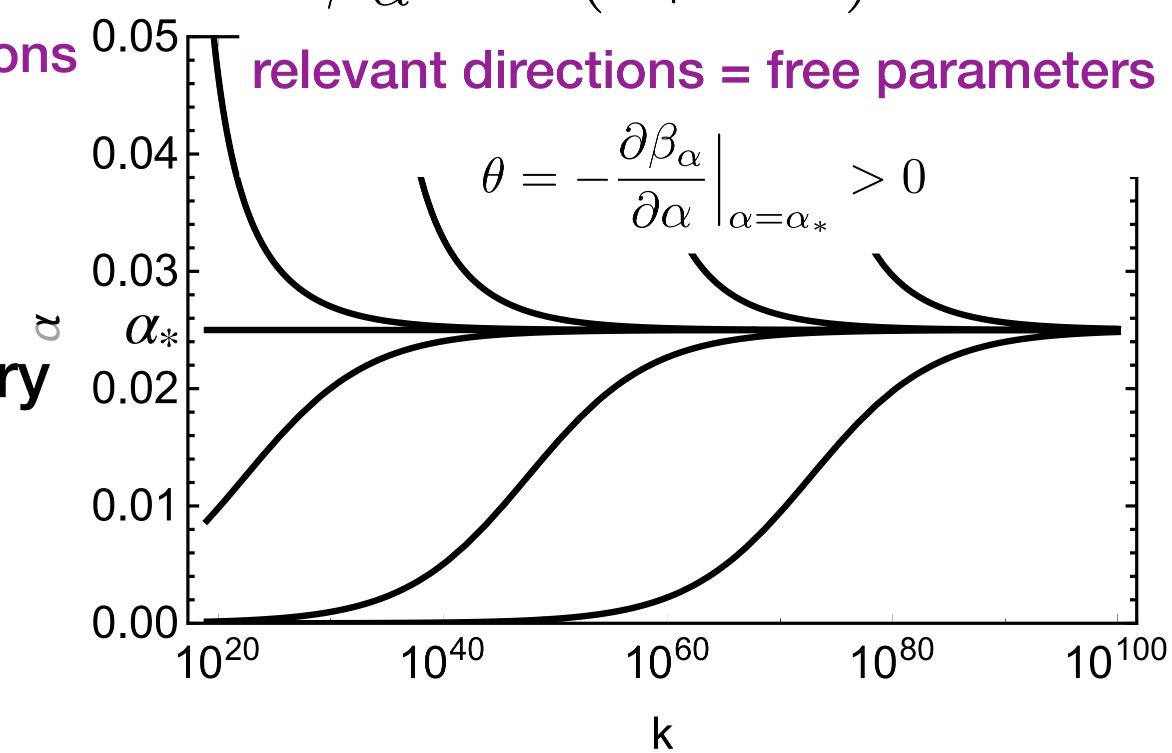
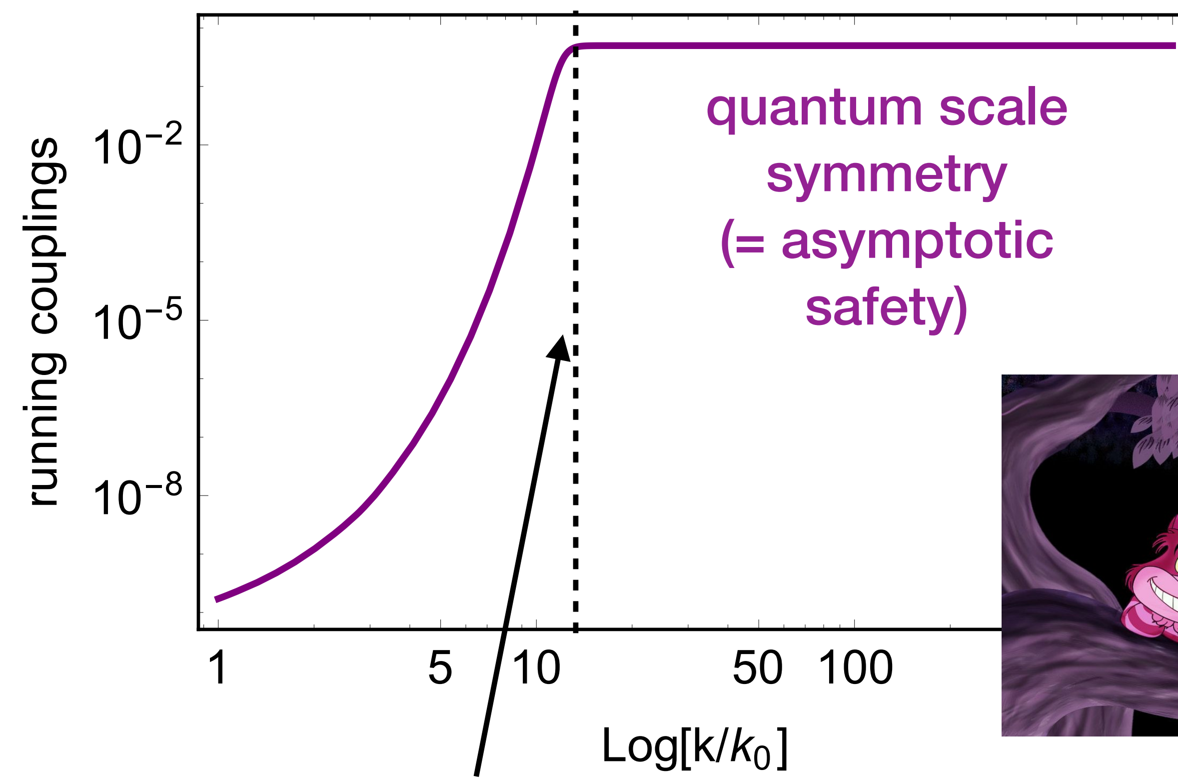


Predictive power of asymptotic safety

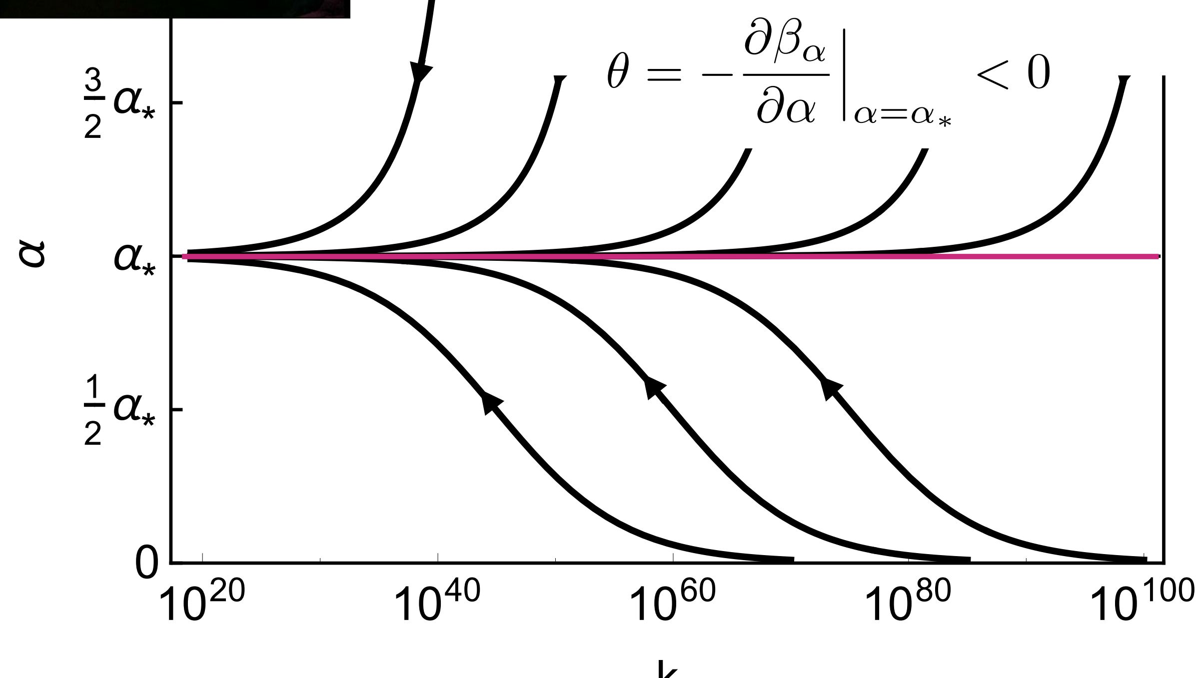


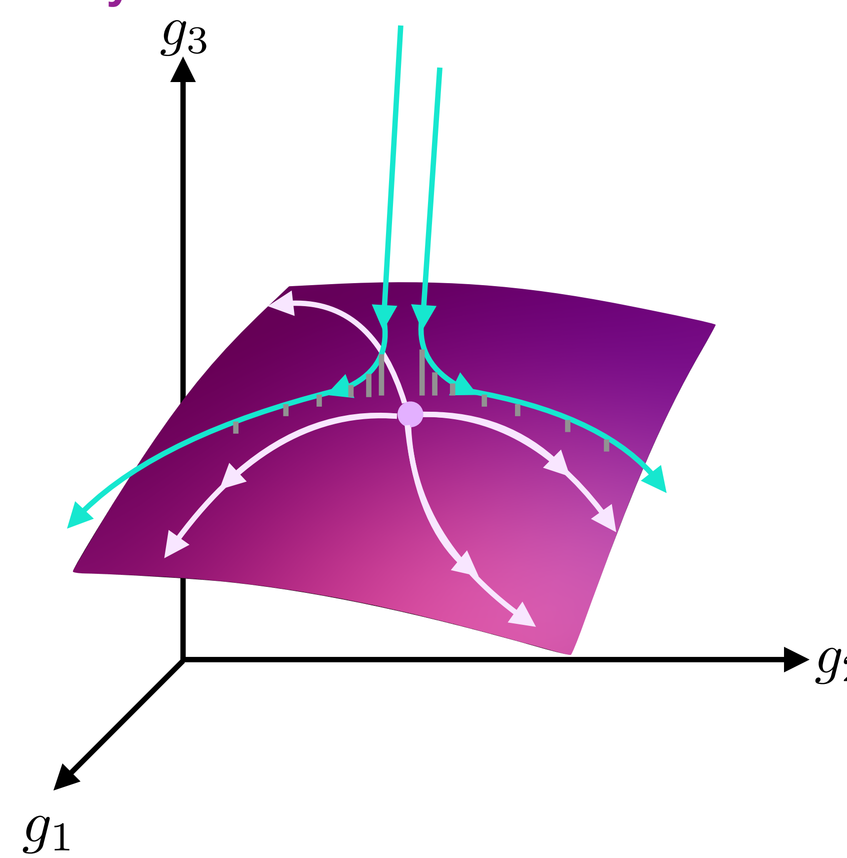
departure from scale symmetry

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

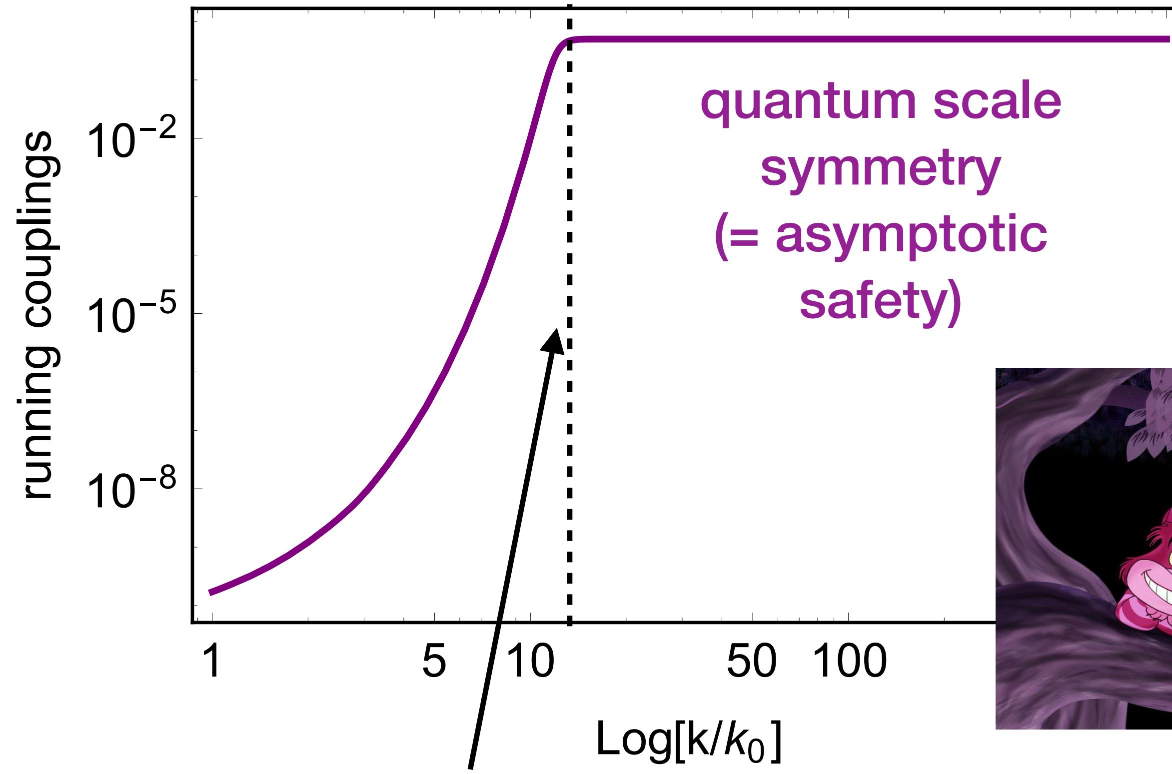
irrelevant directions = predictions

$$\theta = -\frac{\partial \beta_\alpha}{\partial \alpha}\Big|_{\alpha=\alpha_*} < 0$$





Predictive power of asymptotic safety

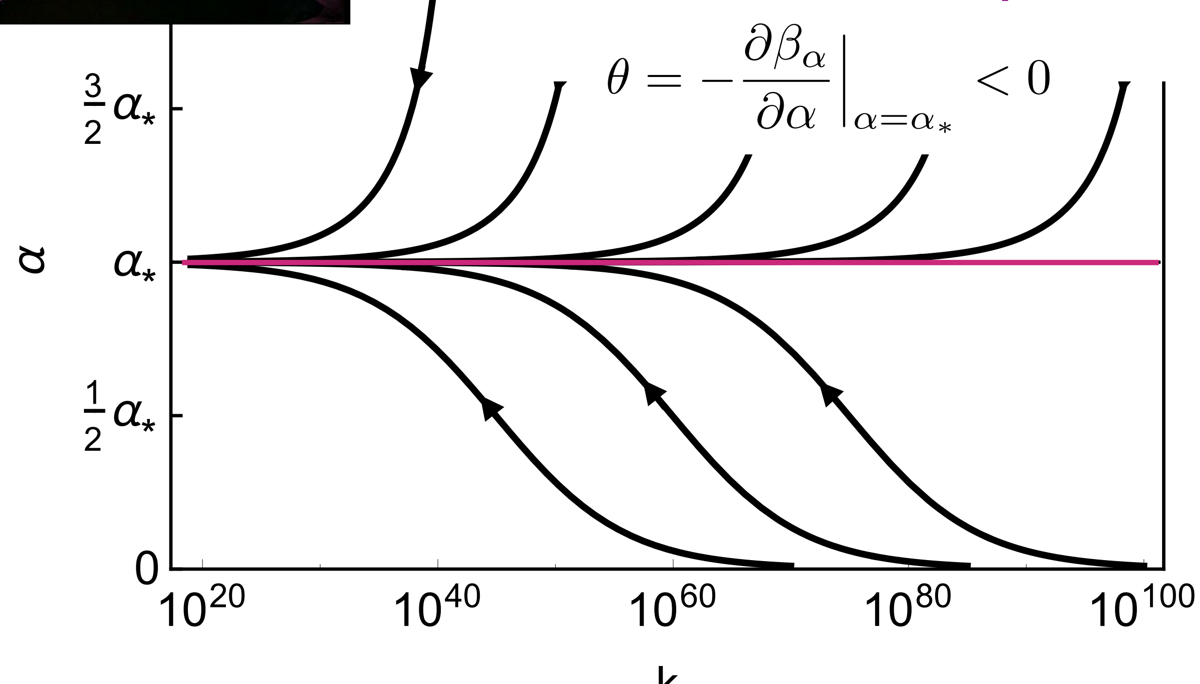


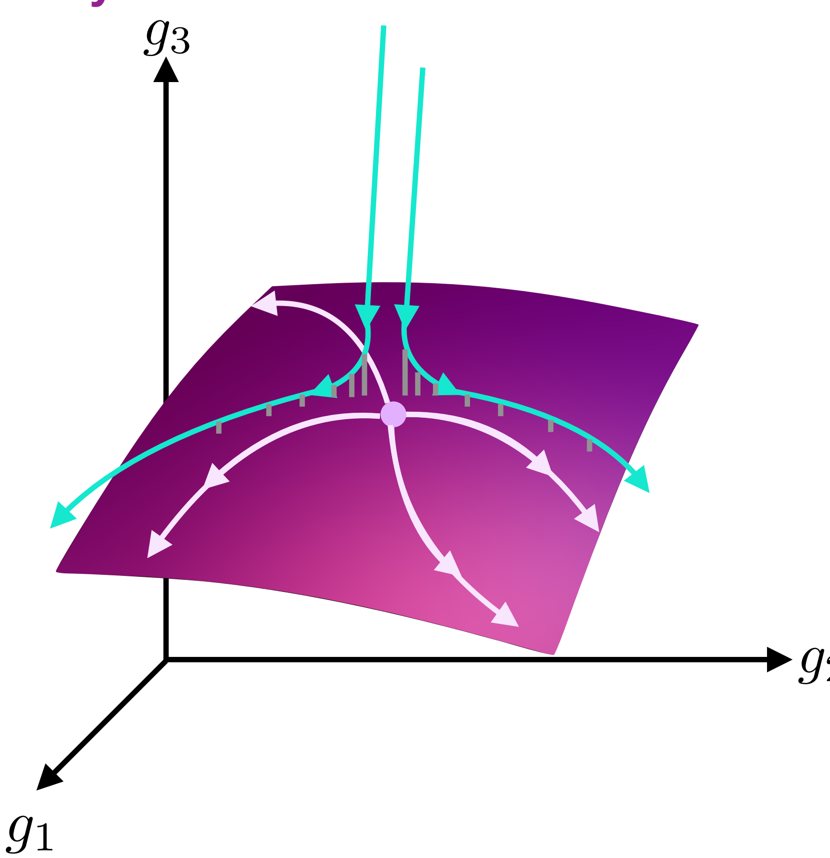
departure from scale symmetry

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

predictive power of new symmetry

irrelevant directions = predictions



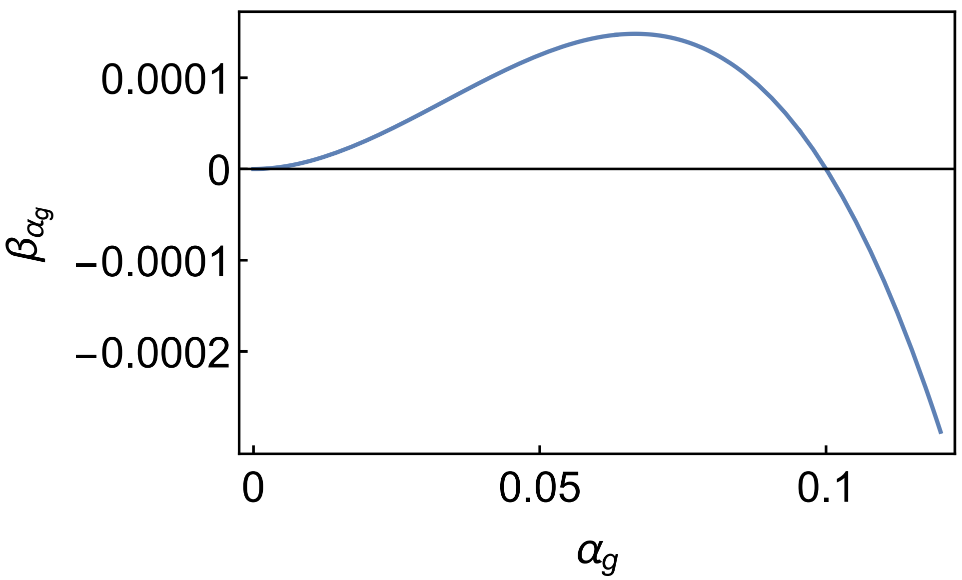


Asymptotic safety - an example in 4d perturbative QFT

Gauge-Yukawa theory:

Litim, Sannino '14

$$\beta_{\alpha_g} = (-B + C\alpha_g - D\alpha_y)\,\alpha_g^2 + \mathcal{O}(\alpha_i^4)$$



$$\beta_{\alpha_y} = (E\,\alpha_y - F\,\alpha_g)\,\alpha_y + \mathcal{O}(\alpha_i^3)$$

B, C, D, E, F depend on number of charged fermions and scalars

Asymptotic safety - an example in 4d perturbative QFT

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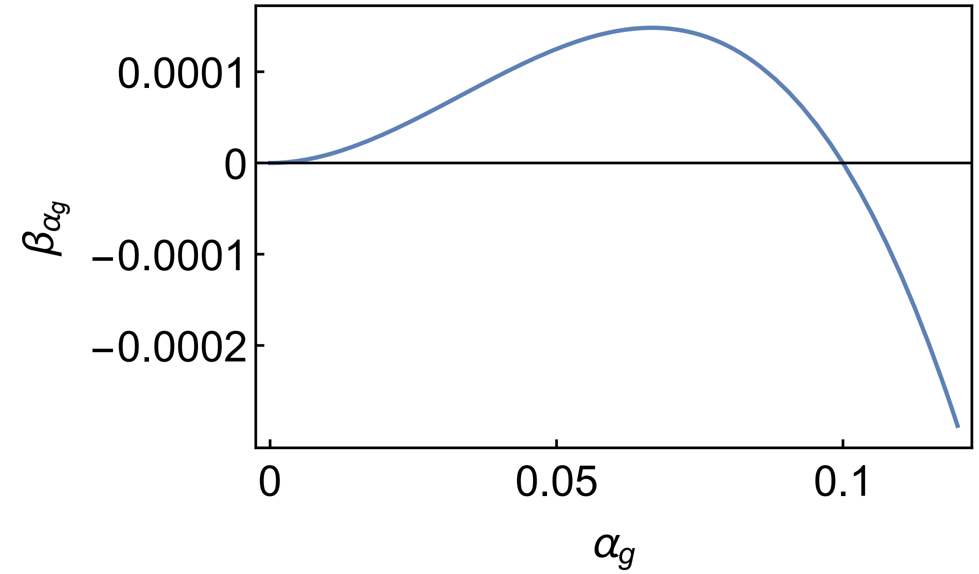

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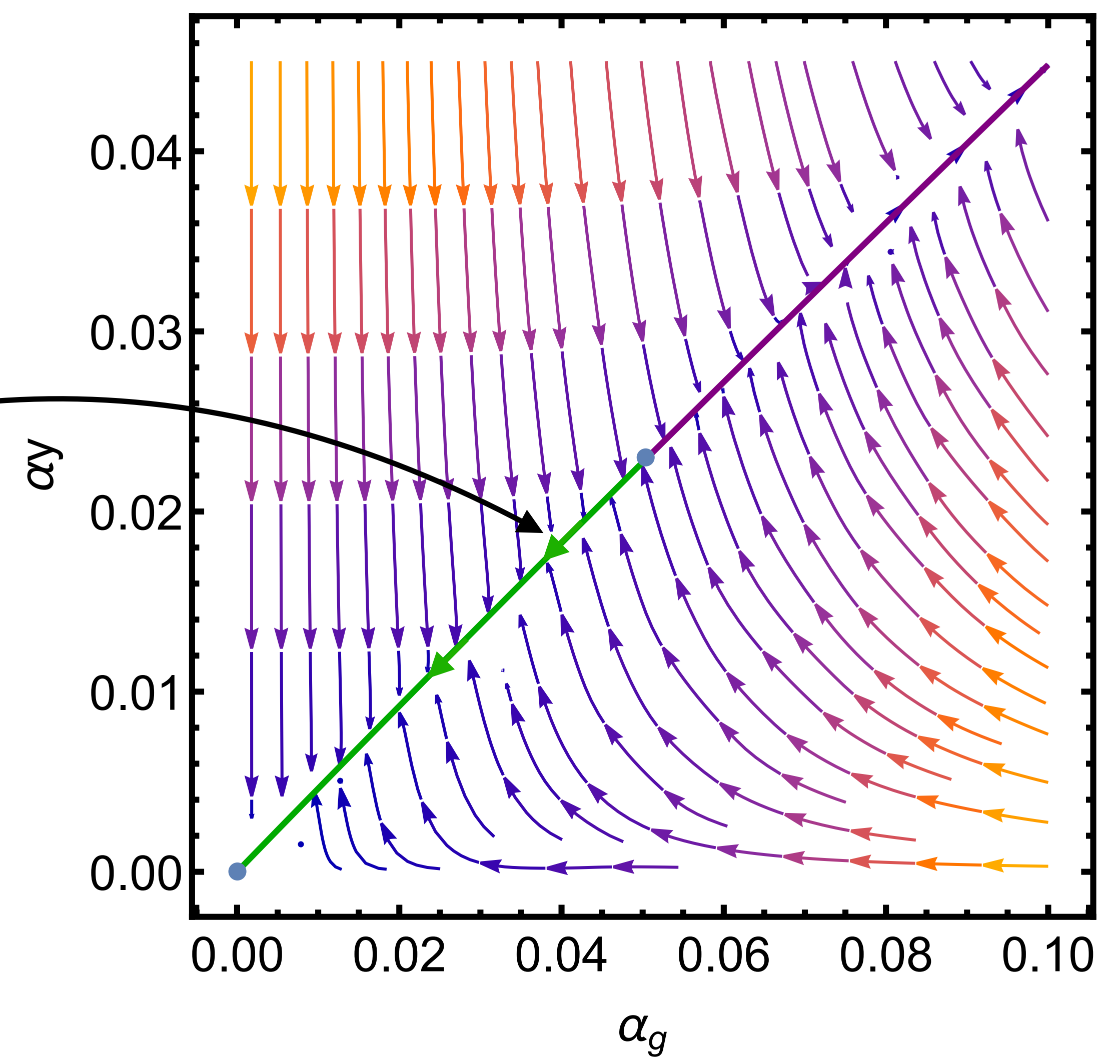
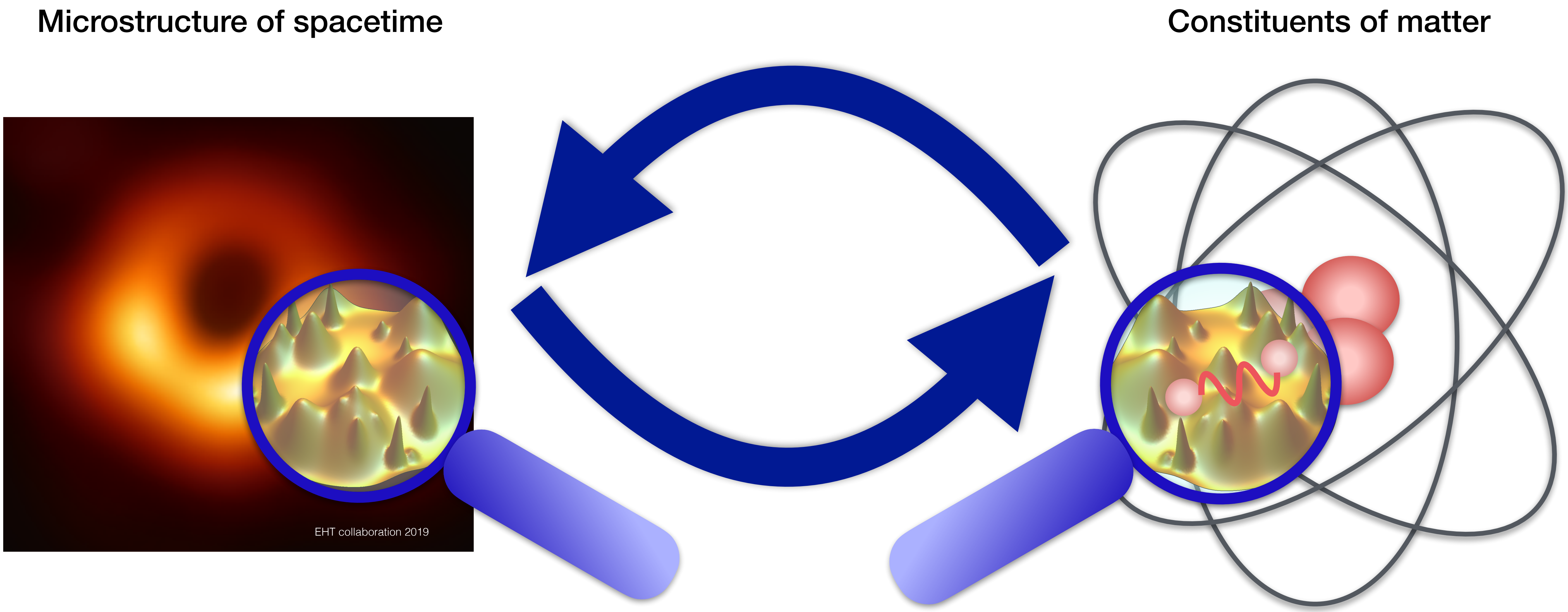
B, C, D, E, F depend on number of charged fermions and scalars

α_y calculable as function of α_g



The search for asymptotic safety in gravity-matter systems

Motivation:



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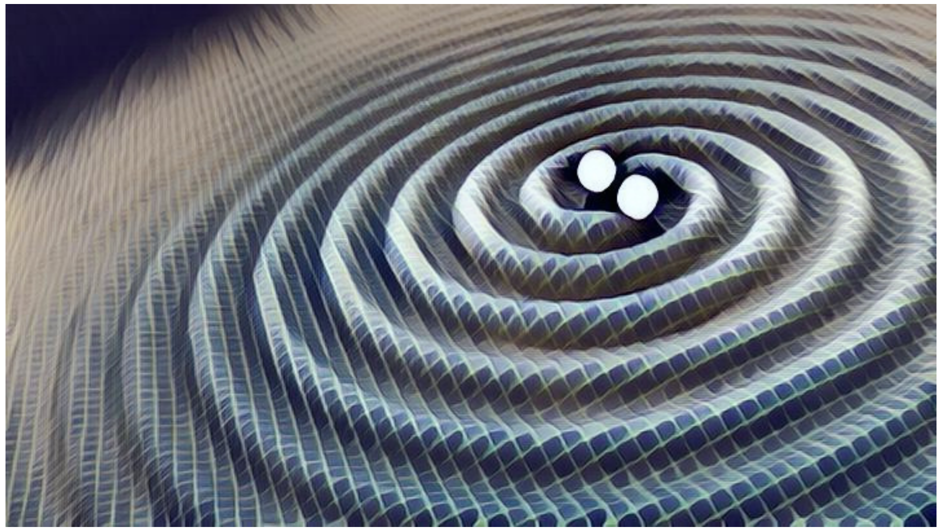
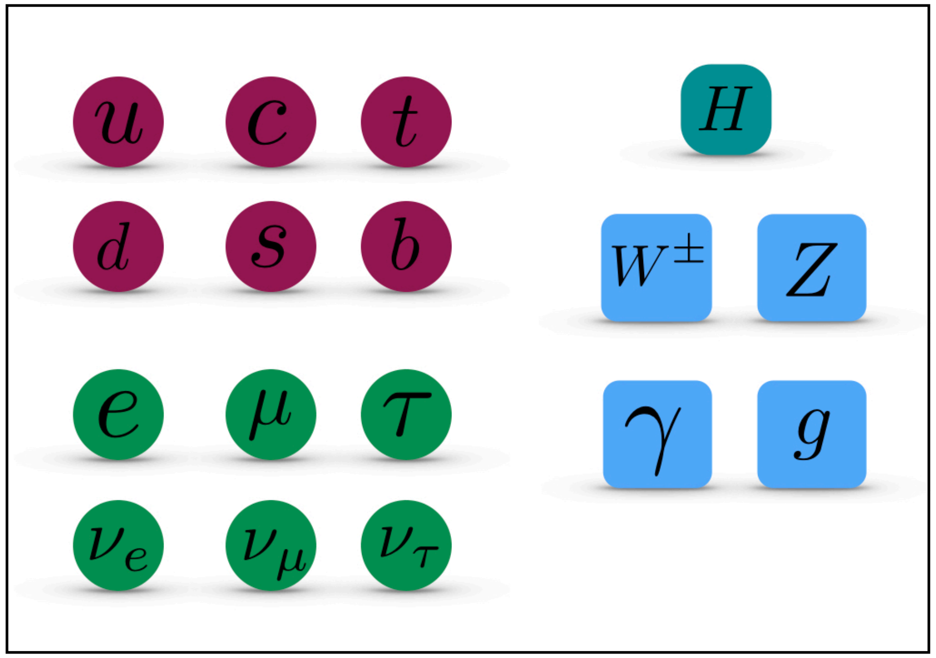
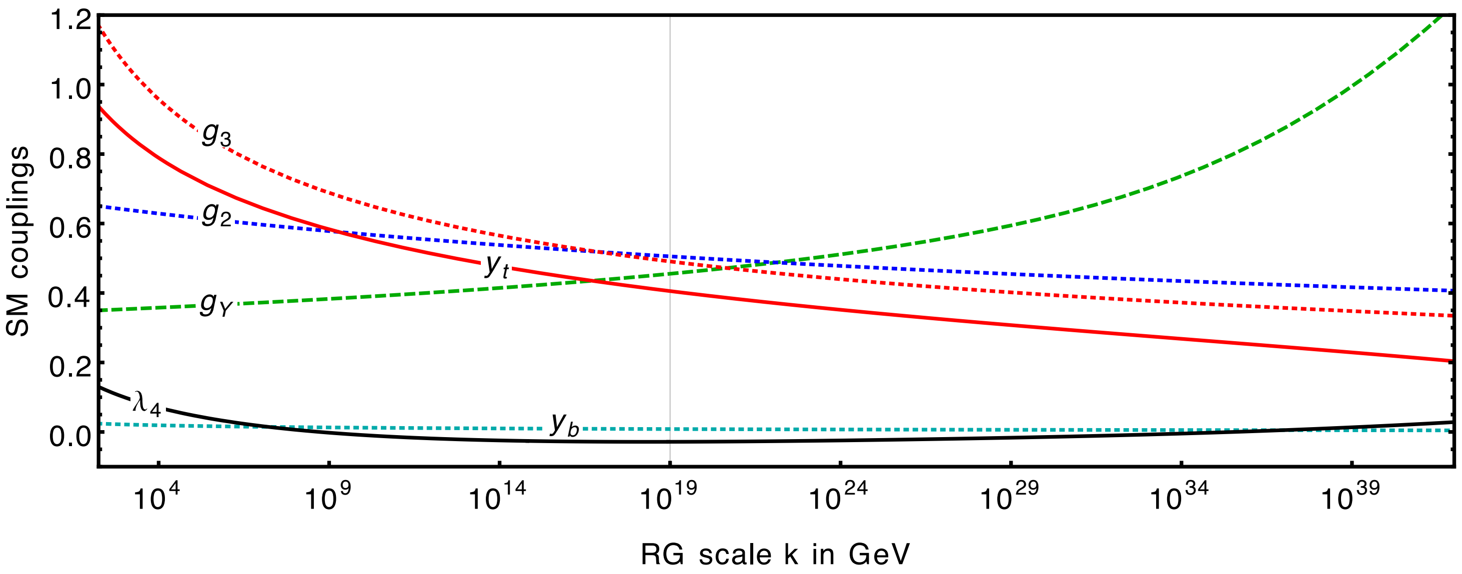


Einstein gravity:
perturbatively non-renormalizable

$$\Gamma = \int d^4x \sqrt{-g} \left(\Lambda(k) + \frac{1}{16\pi G_N(k)} R + a_1(k) R^2 + b(k) R_{\mu\nu} R^{\mu\nu} + a_2(k) R^3 + \ldots \right)$$

$\longrightarrow$ loss of predictivity at Planck scale





$\longrightarrow$ transplanckian Landau poles

$\longrightarrow$ 19 free parameters

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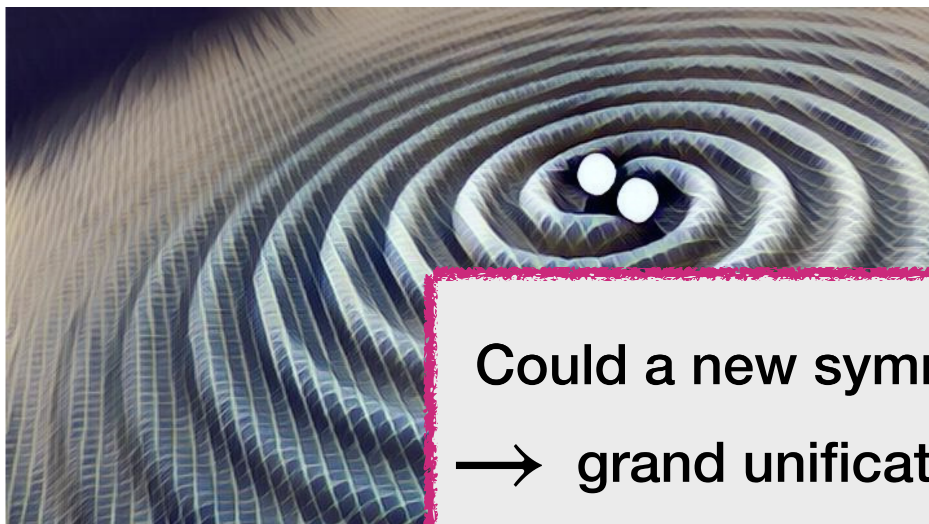


Einstein gravity:
perturbatively non-renormalizable

$k)R_{\mu\nu}R^{\mu\nu} + a_2(k)R^3 + \dots \Big)$

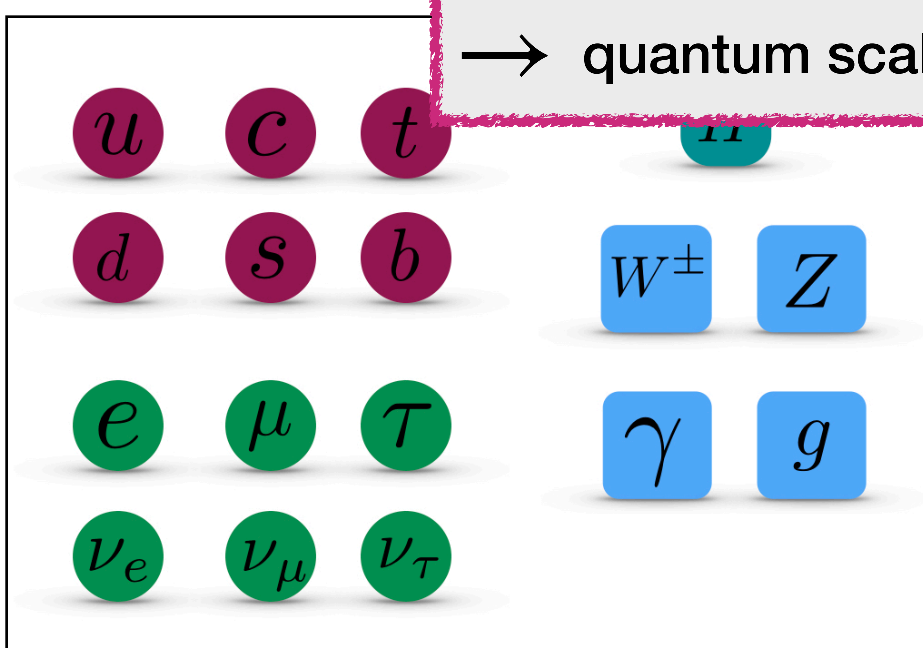
cale

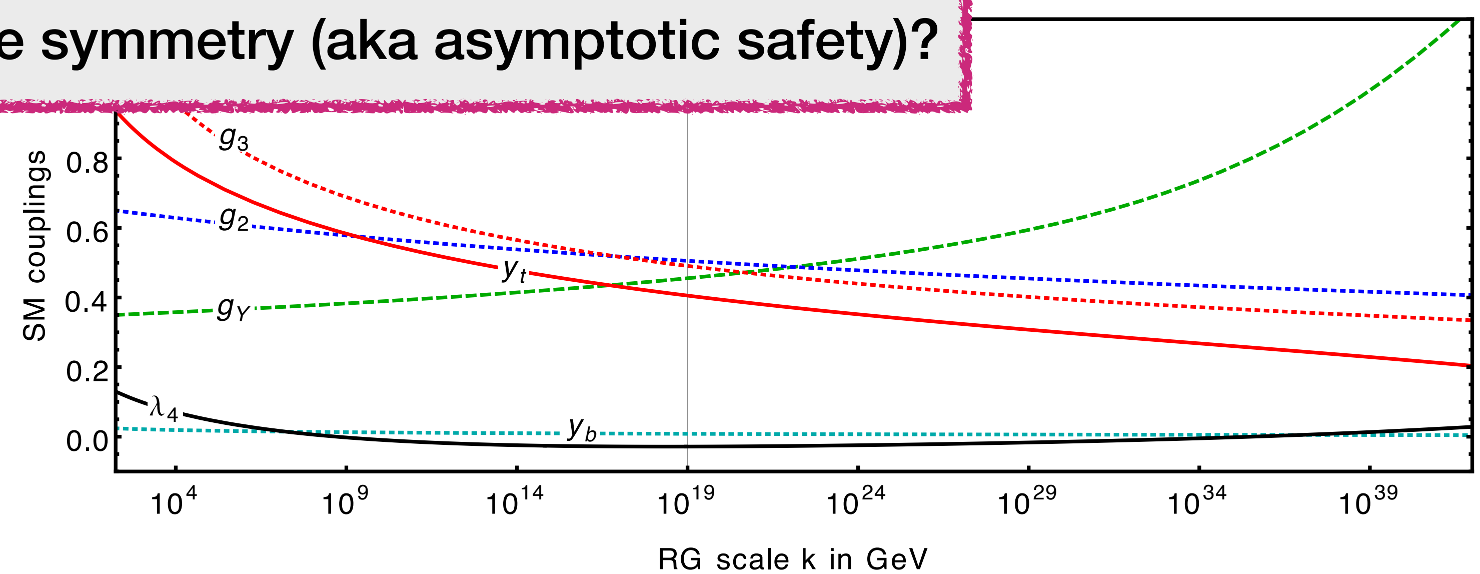
Could a new symmetry help?

$\longrightarrow$ grand unification?

$\longrightarrow$ supersymmetry?

$\longrightarrow$ quantum scale symmetry (aka asymptotic safety)?





$\longrightarrow$ transplanckian Landau poles

$\longrightarrow$ 19 free parameters

The search for asymptotic safety in gravity-matter systems

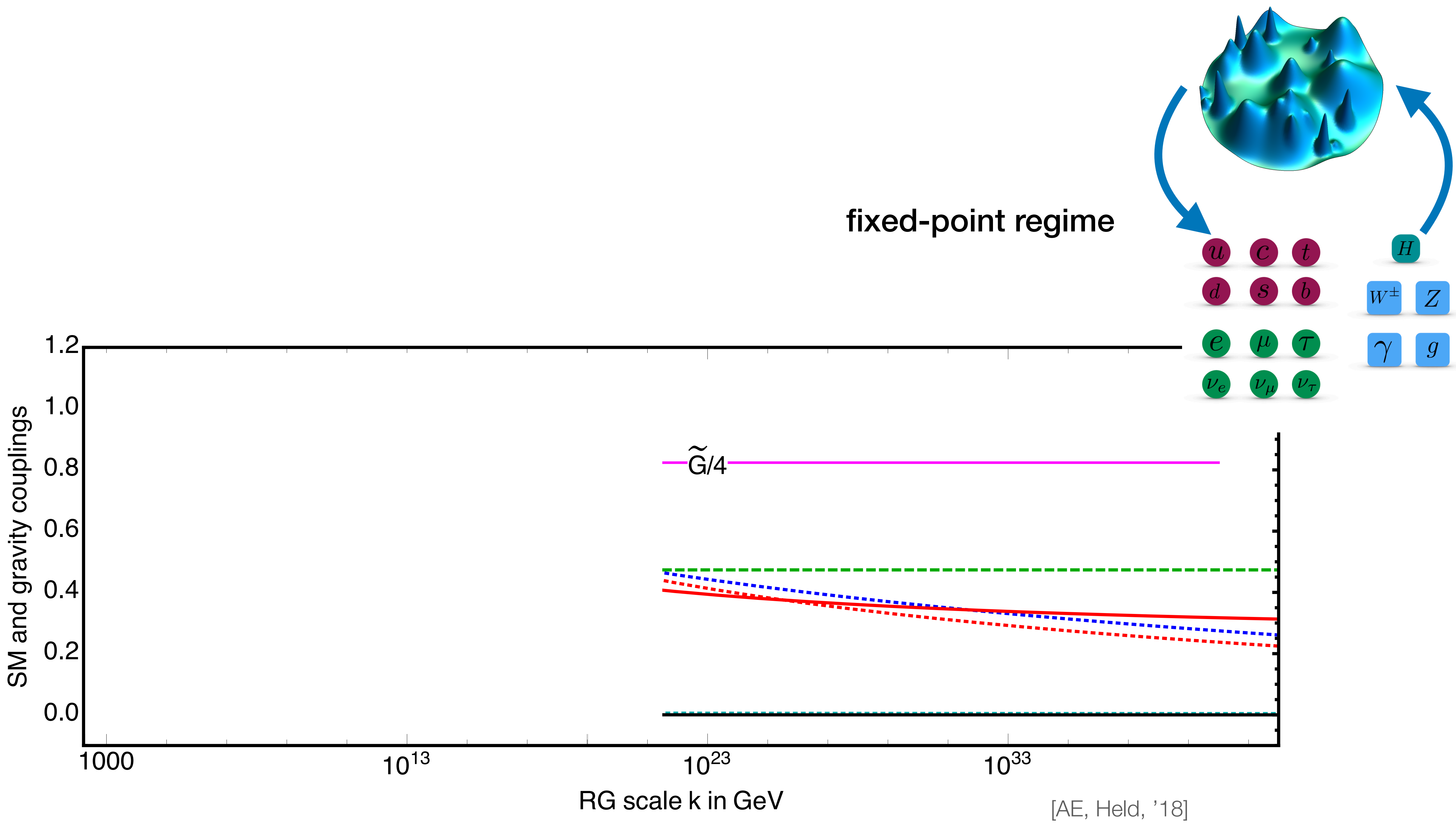
- brief introduction to the technical setup

- status of asymptotic safety in gravity-matter systems

  & open questions

- predictive power of asymptotic safety
  - Abelian gauge coupling
  - Yukawa sector
  - dark sectors

Three regimes of the gravity-matter functional RG flow



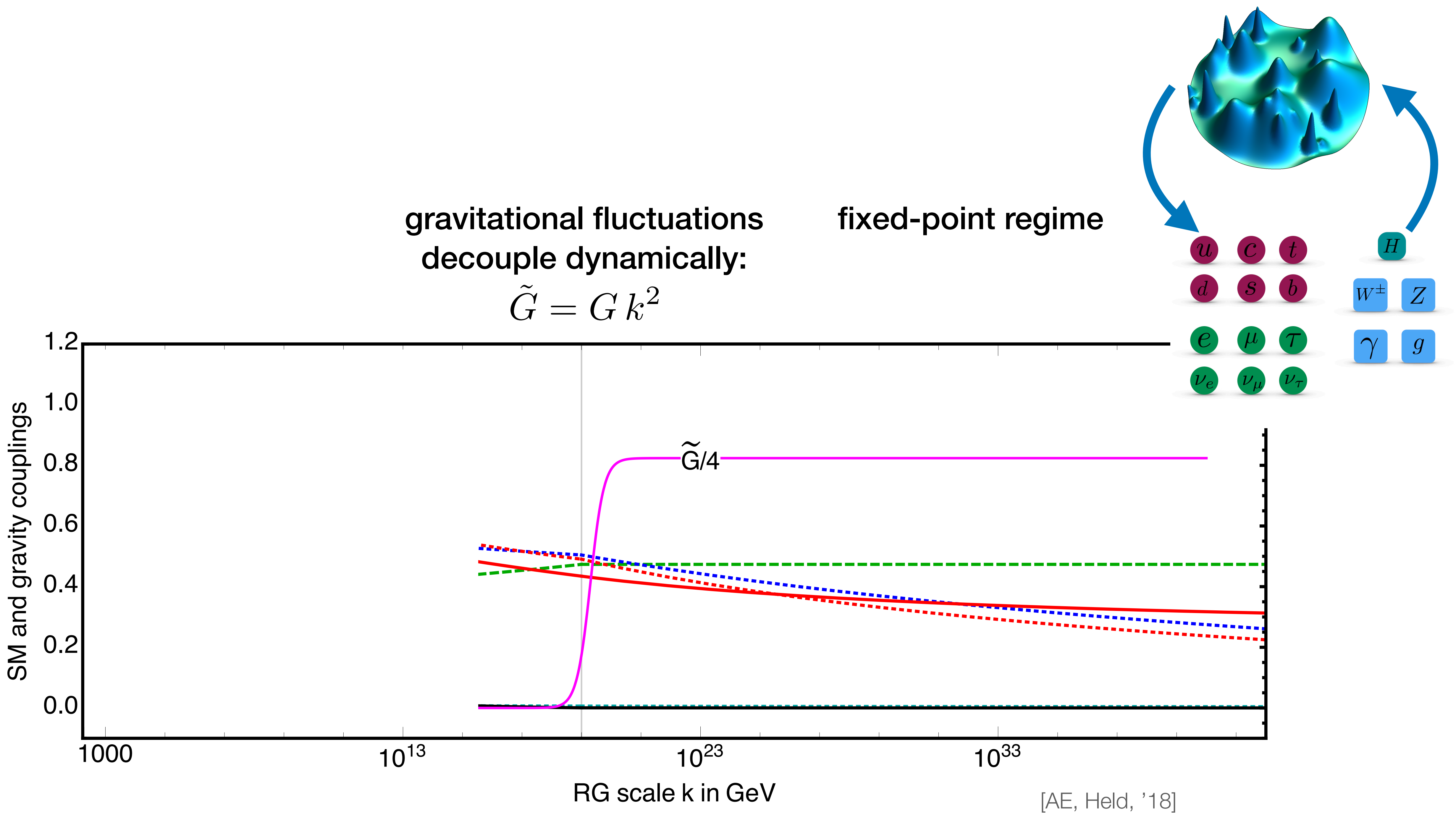
quantum fluctuations integrated out:

Three regimes of the gravity-matter functional RG flow

gravitational fluctuations decouple dynamically:

$\tilde{G} = G\,k^2$

fixed-point regime



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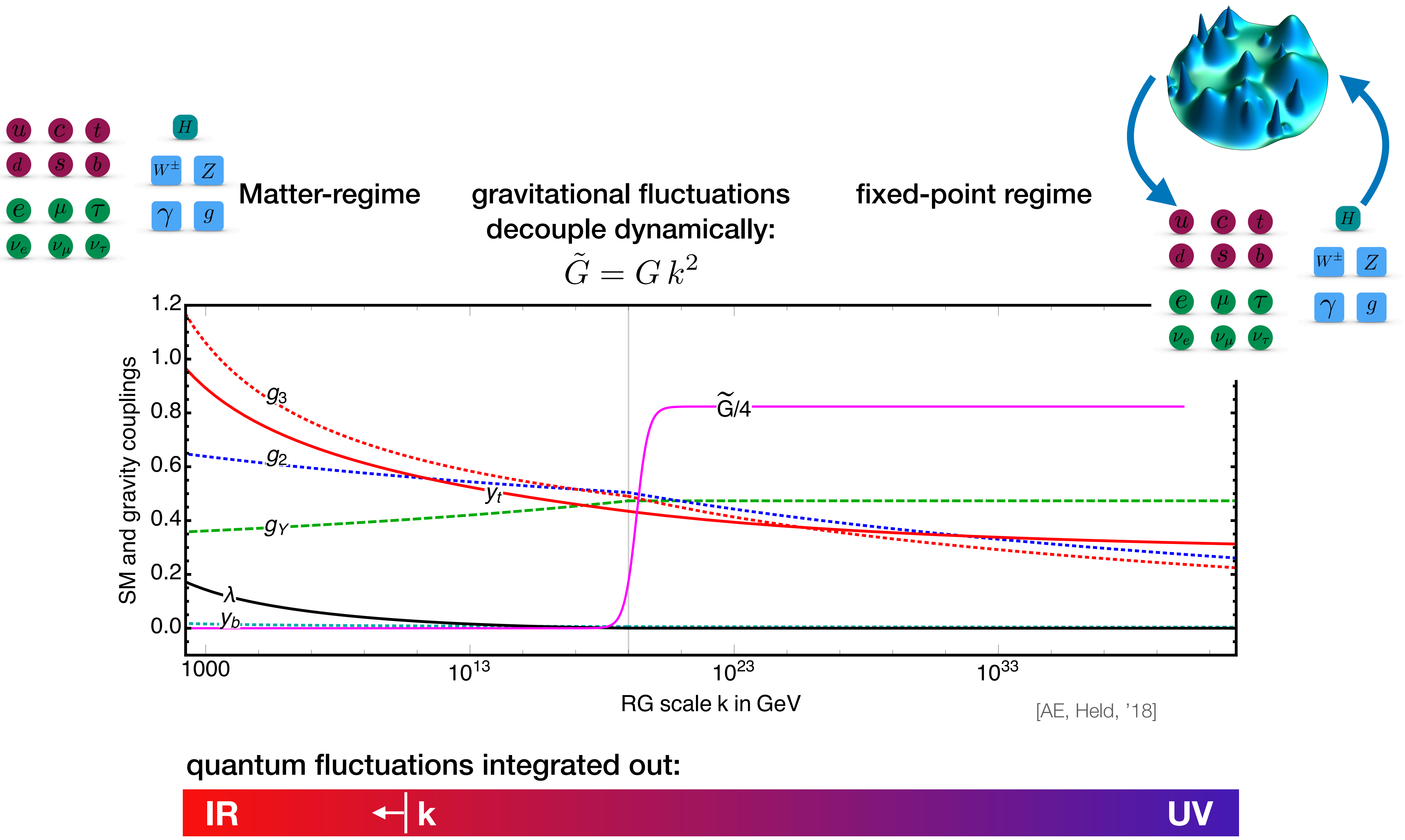
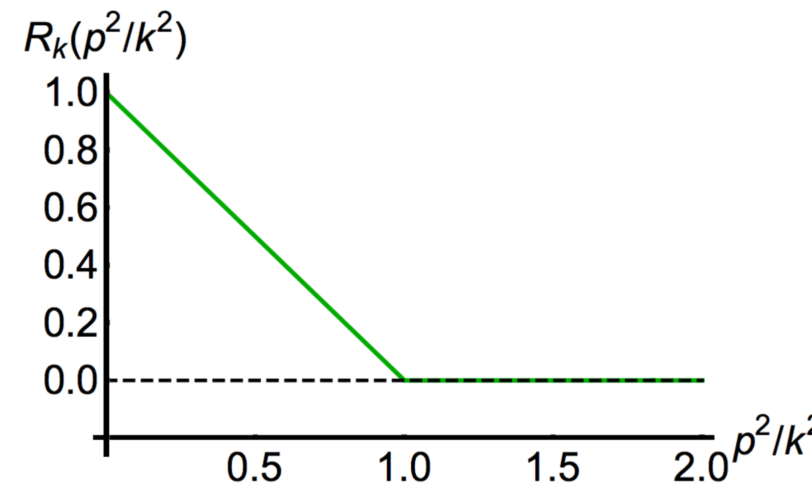


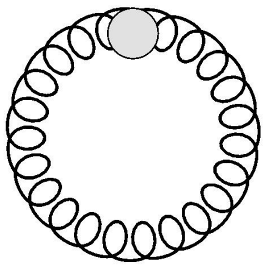
Functional Renormalization Group

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



quantum fluctuations integrated out:

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



Wetterich '92

used from in- and out-of-equilibrium statistical physics to quantum many-particle systems, high-energy physics to quantum gravity

recent review: Dupuis, Canet, AE et al. '20

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

in practise: beta functions for couplings in truncations of Γ_k

Status of asymptotic safety

- existence of Reuter fixed point

  [Weinberg '76; Reuter '96]

  - for pure gravity ✓

    selected examples:

    Einstein-Hilbert $+R^2 + R^2_{\mu\nu} + E$

    Falls, Ohta, Percacci, '20

    Einstein-Hilbert $+R^2 + \ldots + R^{70}$

    Falls, Litim Schröder '18

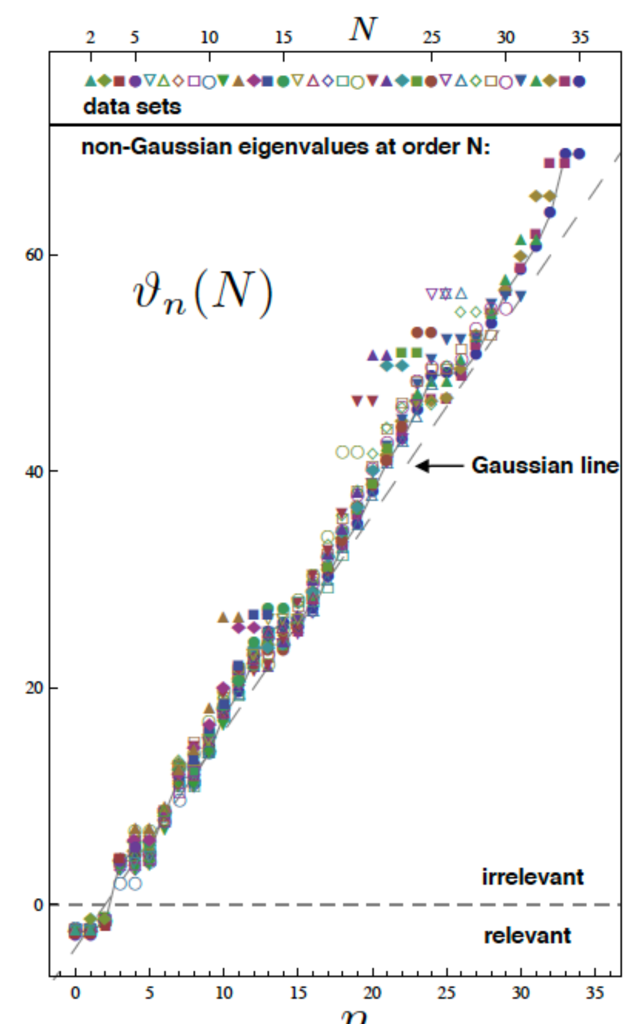
    Einstein-Hilbert $+R_{\mu\nu\kappa\lambda}R^{\kappa\lambda\rho\sigma}R_{\rho\sigma}{}^{\mu\nu}$

    Gies, Knorr, Lippoldt, Saueressig '16

critical exponents:

near-canonical scaling
(guiding principle for robust truncations)

Falls, Litim, Nikolakopoulos, Rahmede, '13, '14
Falls, Litim Schröder '18



also indicated by near-trivial
symmetry identities

[AE, Labus, Pawlowski, Reichert '18;
AE, Lippoldt, Pawlowski, Reichert, Schiffer '18
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    Einstein-Hilbert $+R_{\mu\nu\kappa\lambda}R^{\kappa\lambda\rho\sigma}R_{\rho\sigma}{}^{\mu\nu}$

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critical exponents:

Open questions:

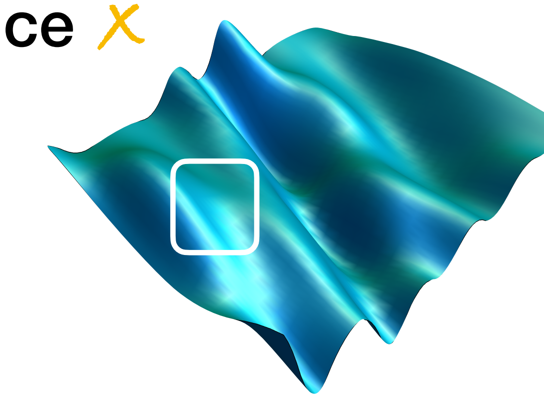
see "Critical reflections on asymptotically safe gravity" Bonanno, AE, Gies, Pawlowski, Percacci, Reuter, Saueressig, Vacca '20 for further details

- background independence ✗

  Morris '16

  Becker, Reuter '14

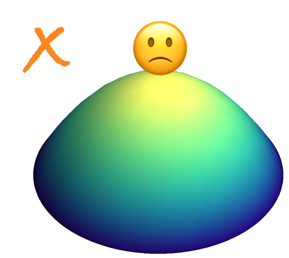
  Denz, Pawlowski, Reichert '16



- Lorentzian signature ✗

  Manrique, Rechenberger, Saueressig '11

- propagating modes/instabilities ✗



  Draper, Knorr, Ripken, Saueressig '20

  Platania, Wetterich '20

  Bonanno, Denz, Pawlowski, Reichert '21

- Phenomenological viability?

  Matter matters!

Guide to the literature on 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 ’17a ’17b ‘18; Alkofer, AE, Held, Percacci, Nieto, Schröfl ’20]

Higgs potential

[Narain, Percacci ’09; Shaposhnikov, Wetterich ’10, Hamada, Yamada ’17; AE, Hamada, Lumma, Yamada ‘17; Pawlowski, Reichert, Wetterich, Yamada ’18; AE, Pauly ‘20]

Induced matter interactions

[AE ’11 ’12; AE, Held, Pawlowski ‘16; AE, Held ’17; Christiansen, AE ’17; AE, Schiffer ’19]

Beyond SM:

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

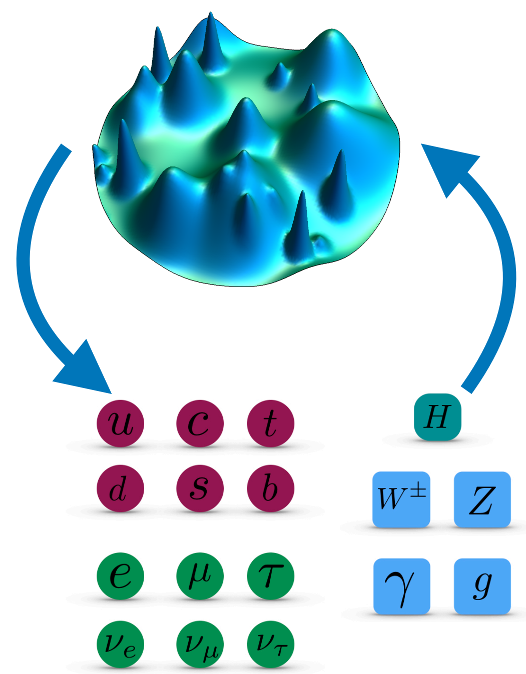
Dark sector

[AE, Hamada, Lumma, Yamada, ‘17; Hamada, Tsumura, Yamada ’19; Reichert, Smirnov ’19; Kwapisz ’19; AE, Pauly ’20]

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

Flavor structure [Kowalska, Sessolo ’20]

Muon g-2 [Kowalska, Sessolo ’20]



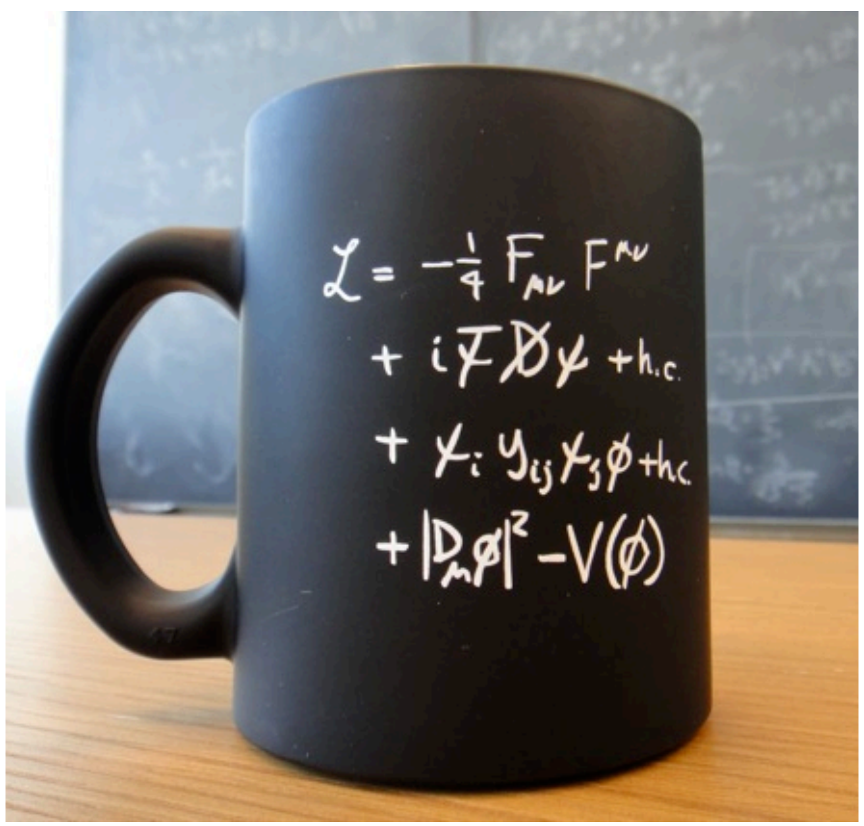
Effect of scalars, fermions and vectors on gravitational fixed point:

- **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]

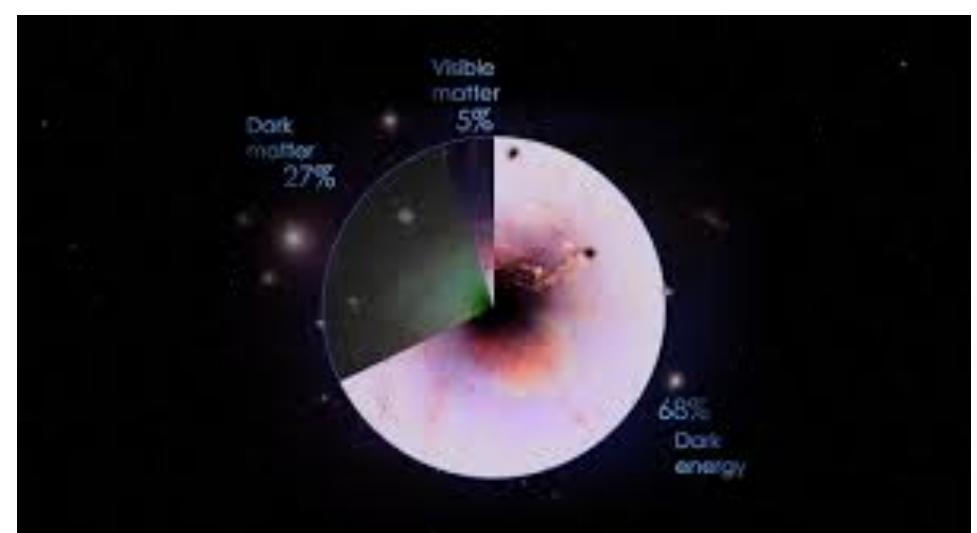
Predictive power of asymptotic safety

3 examples with gravity in

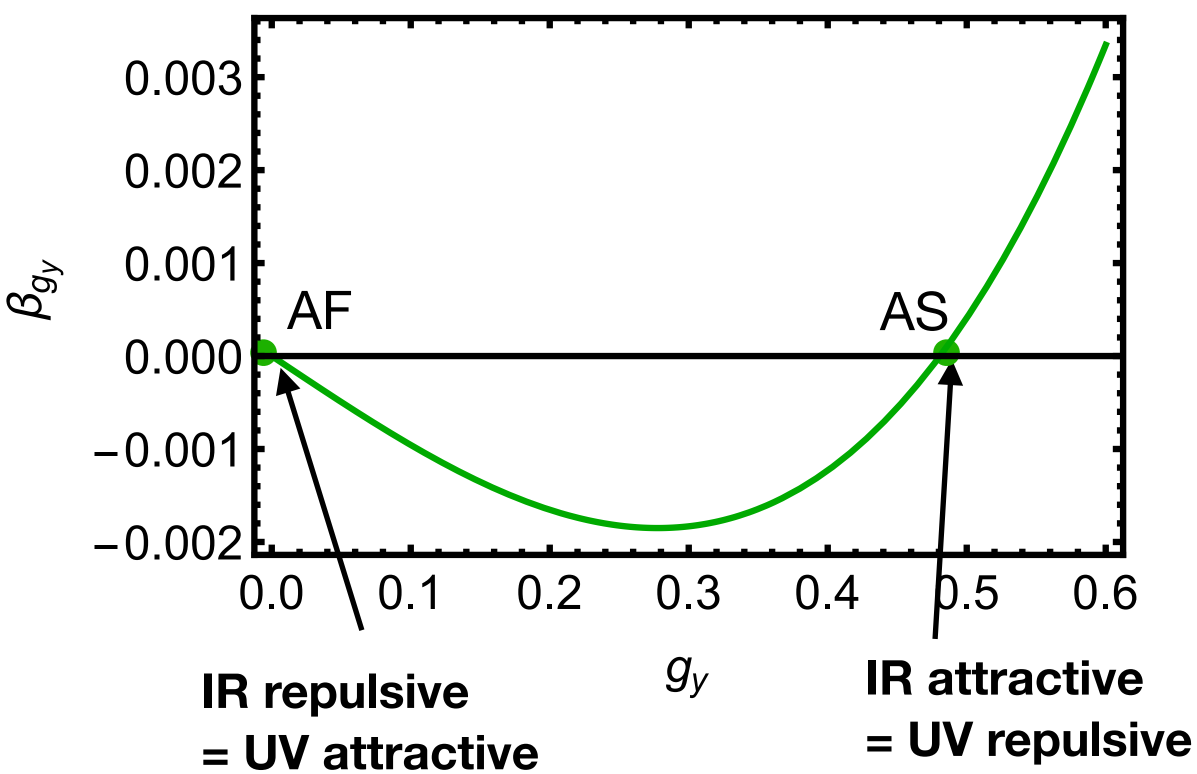
Standard-Model like systems



& beyond



Upper bound on the Abelian gauge coupling



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

metric fluctuations

$$f_g = G\frac{5}{36\pi}\left(\frac{8}{1-2\Lambda} + \frac{8}{(1-2\Lambda)^2}\right)$$

$f_g = \text{const} \geq 0$ above M_{pl}

$f_g \to 0$ below M_{pl}

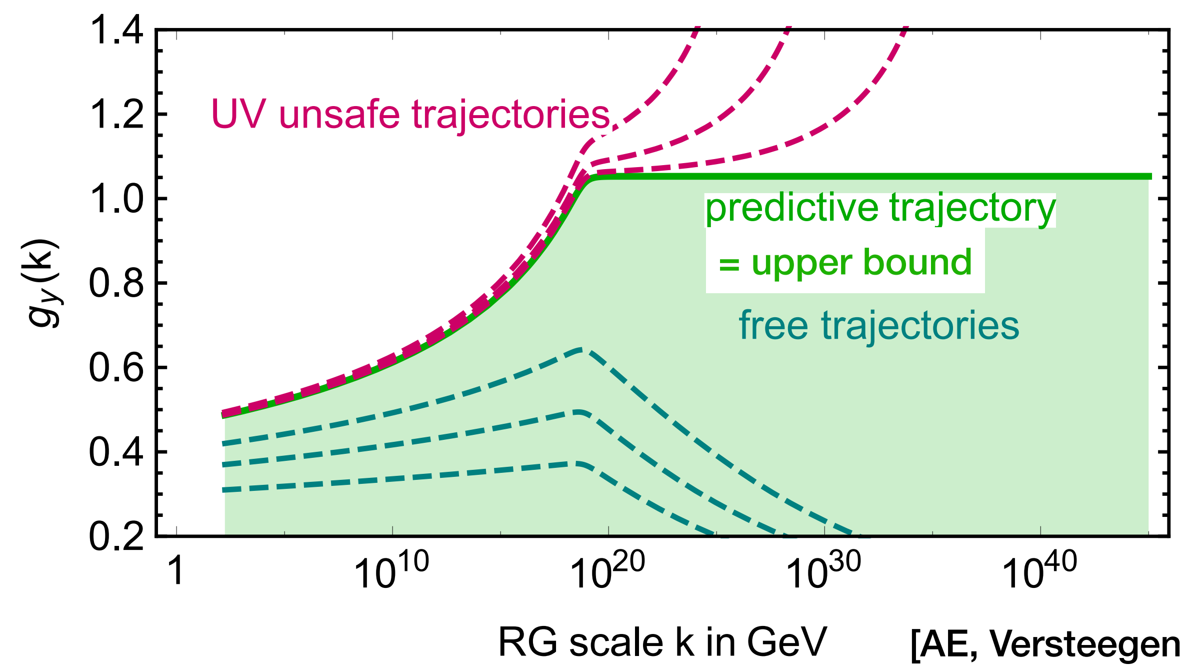
[Daum, Harst, Reuter '10; Harst, Reuter '11; Folkerts, Litim, Pawlowski '12; Christiansen, Litim, Pawlowski, Reichert '18; Christiansen, AE '17; AE, Versteegen '18; AE, Schiffer '19; de Brito, AE, Pereira '19]

matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting



[AE, Versteegen '18]

Gauge-Yukawa systems with gravity

Motivation: Where does the difference between top and bottom quark mass come from?

Quark masses ~ Yukawa couplings

Step 1:
Implications of asymptotic safety for a single Yukawa coupling (top quark)

[AE, Held '17a '17b]

Step 2:
Generalization to two Yukawa couplings (top-bottom system)

[AE, Held '18]

Step 3:
Generalization to three generations of quarks with mixing

[Alkofer, AE, Held, Percacci, Nieto, Schröfl '20]

Step 4:
Generalization to three generations of quarks and leptons

work in progress

Asymptotic safety and the top quark

$$\beta_{y_t} = \frac{9}{32\pi^2} y_t^3 - f_y y_t + \ldots$$

metric fluctuations

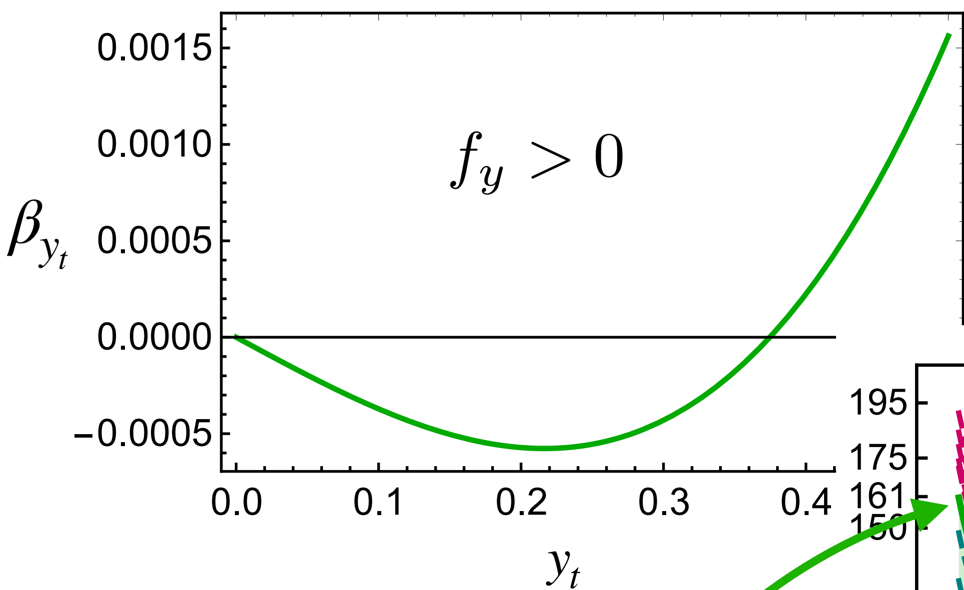
Einstein-Hilbert truncation:

[Oda, Yamada '16;
AE, Held, Pawlowski '16]

+ higher-order interactions

[Hamada, Yamada '17;
AE, Held '17a]

Asymptotic safety and the top quark



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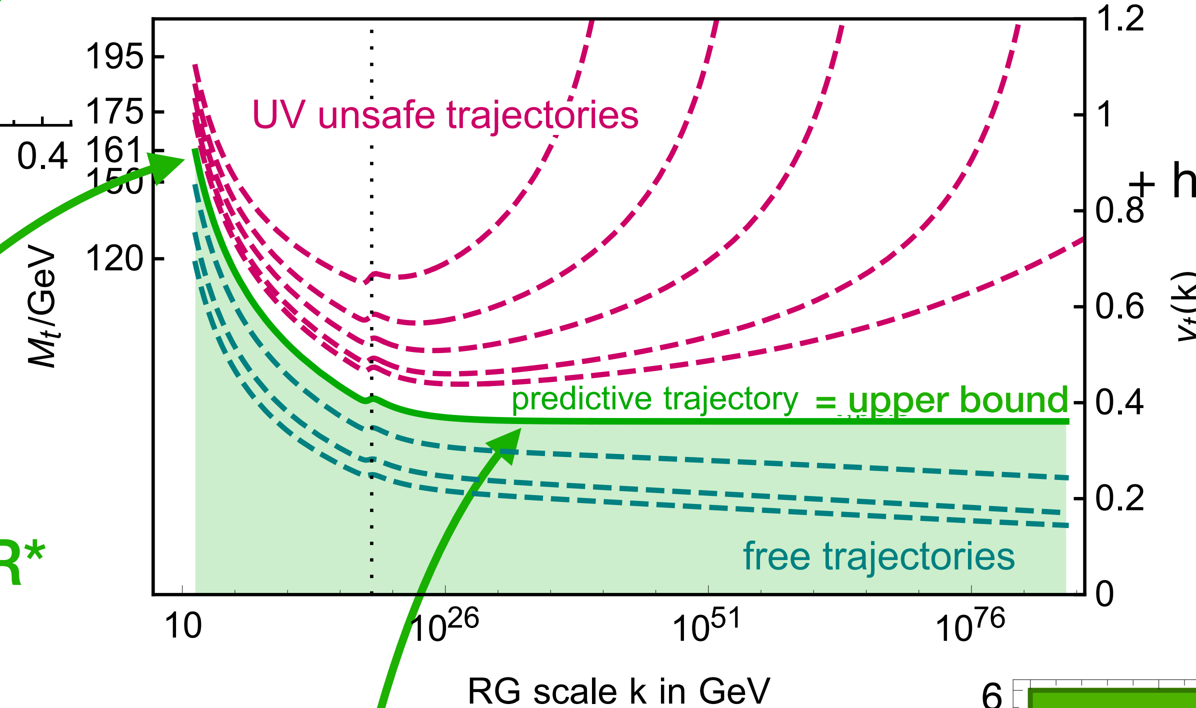
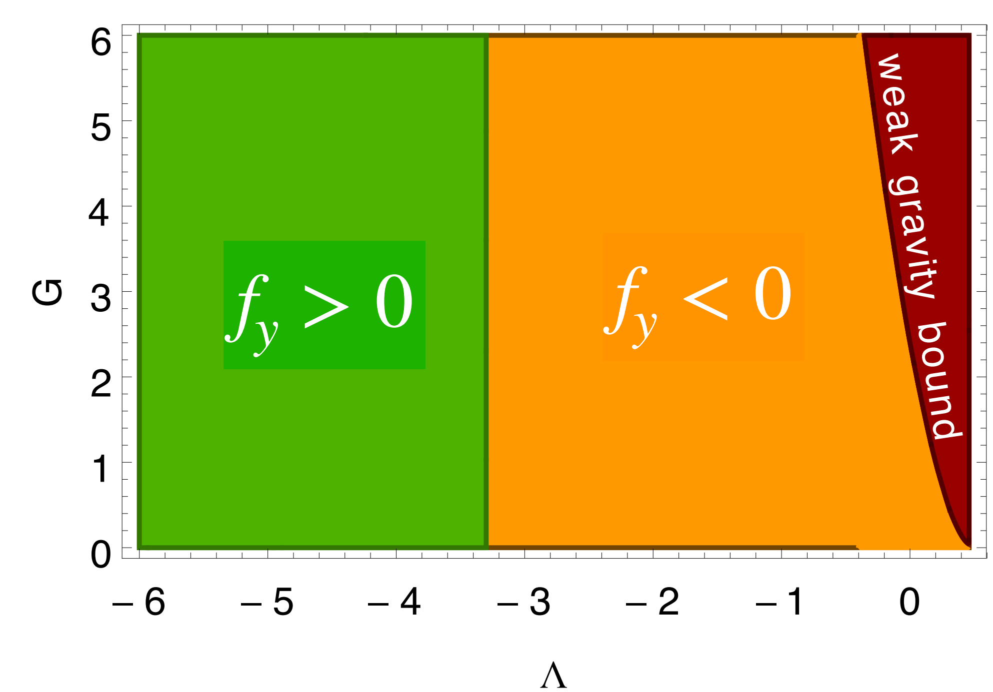


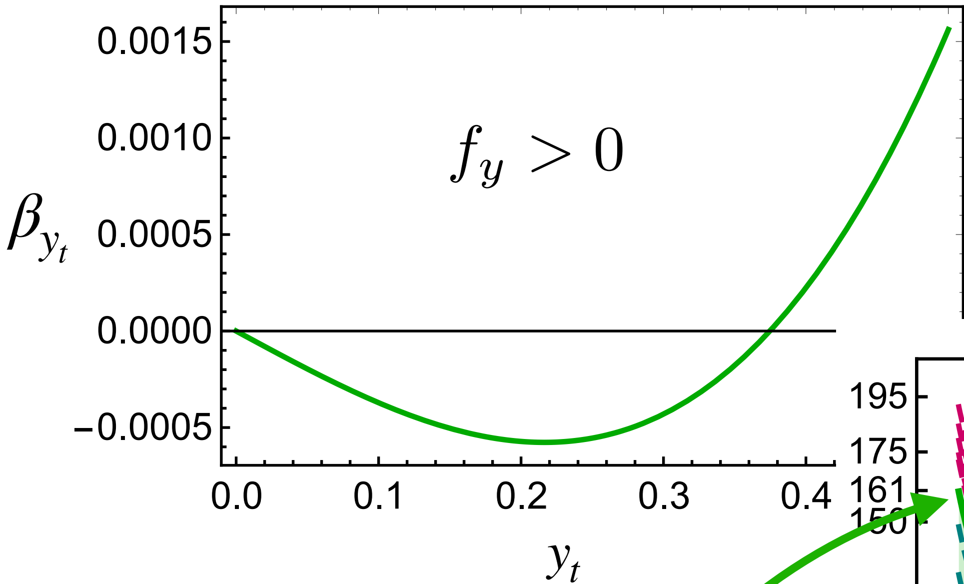
unique value in IR*

quantum scale-symmetry in UV



*systematic uncertainty due to truncation

Asymptotic safety and the top quark



$$\beta_{y_t} = \frac{9}{32\pi^2} y_t^3 - f_y\, y_t + \ldots$$

metric fluctuations

Einstein-Hilbert truncation:

[Oda, Yamada '16;
AE, Held, Pawlowski '16]

+ higher-order interactions

[Hamada, Yamada '17;
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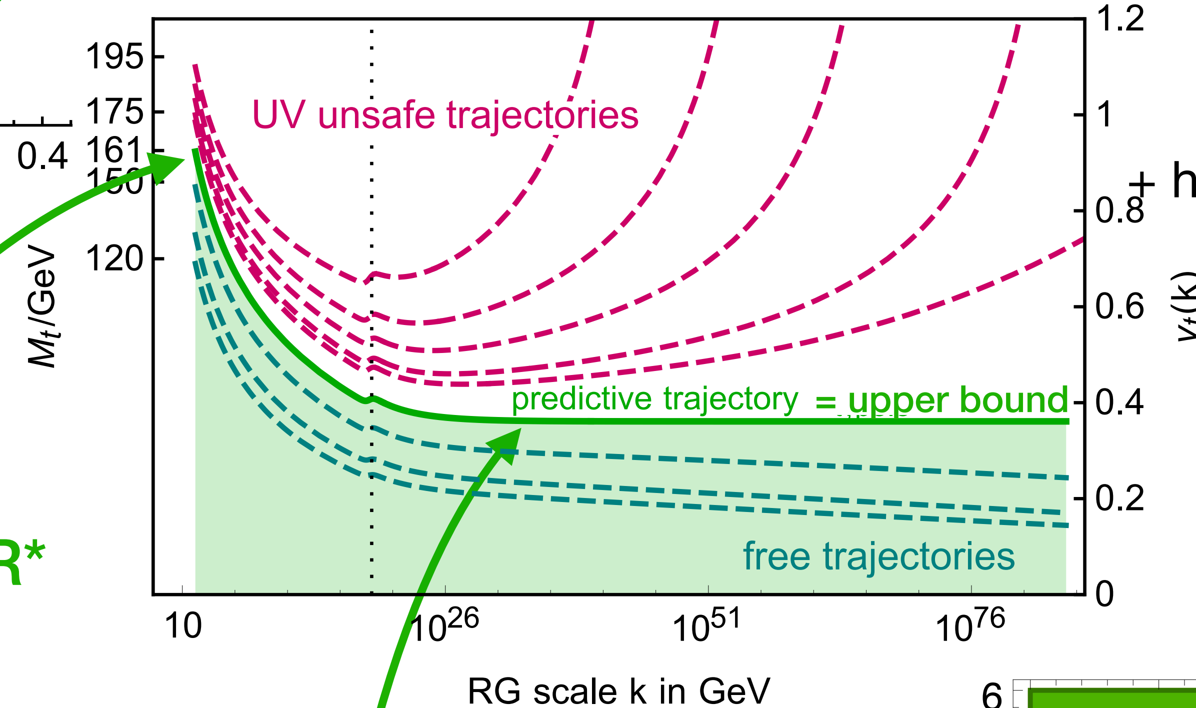
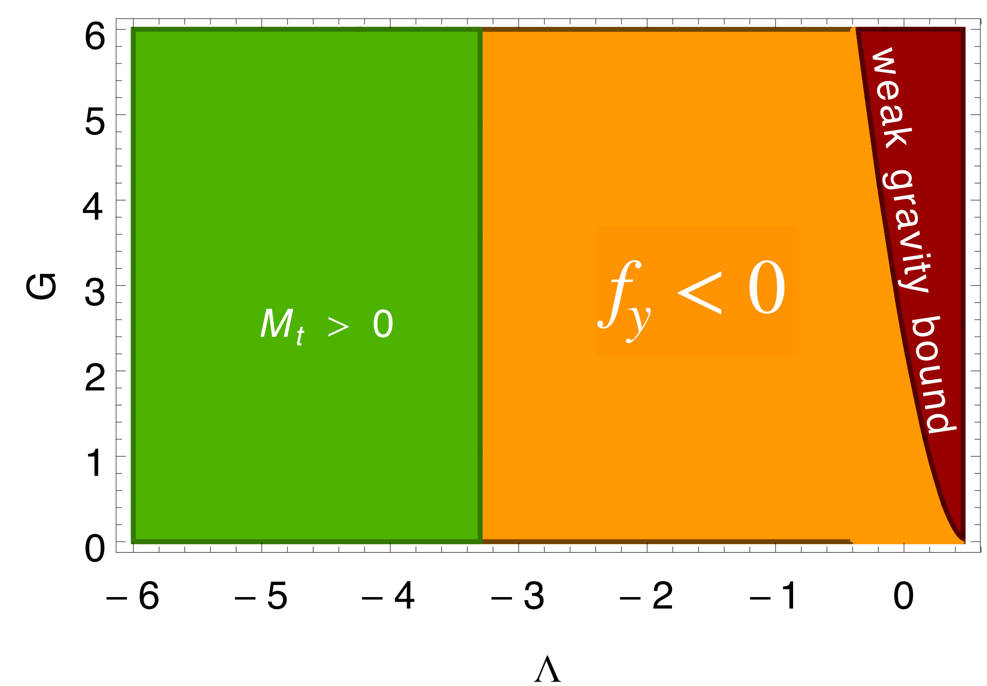


unique value in IR*

quantum scale-symmetry in UV



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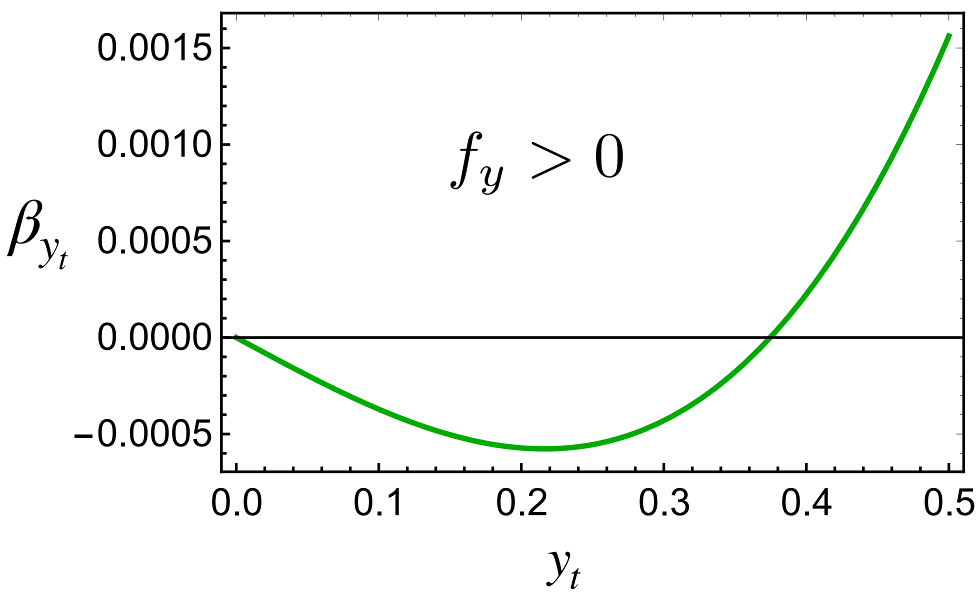
Asymptotic safety and the top quark



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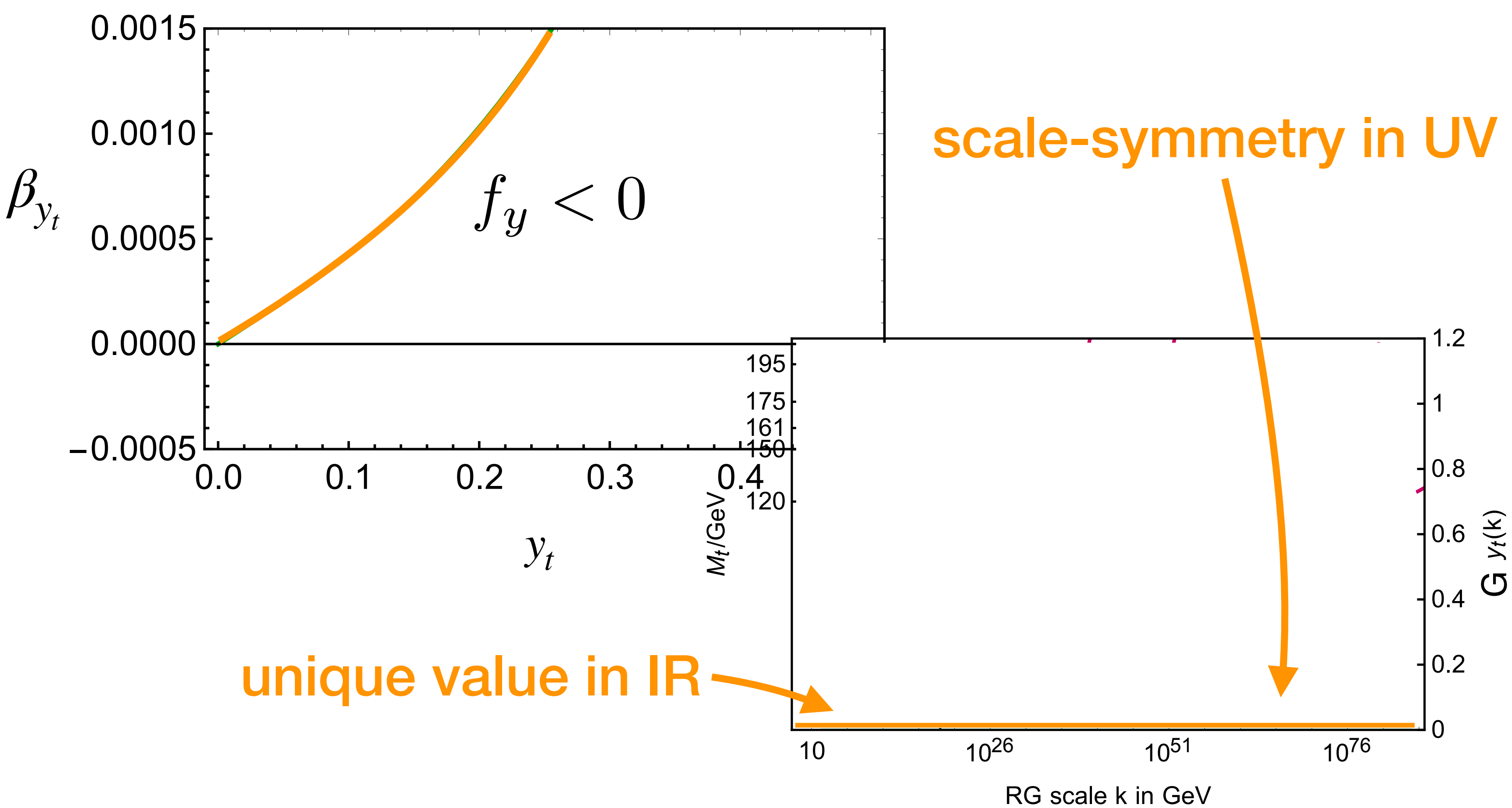
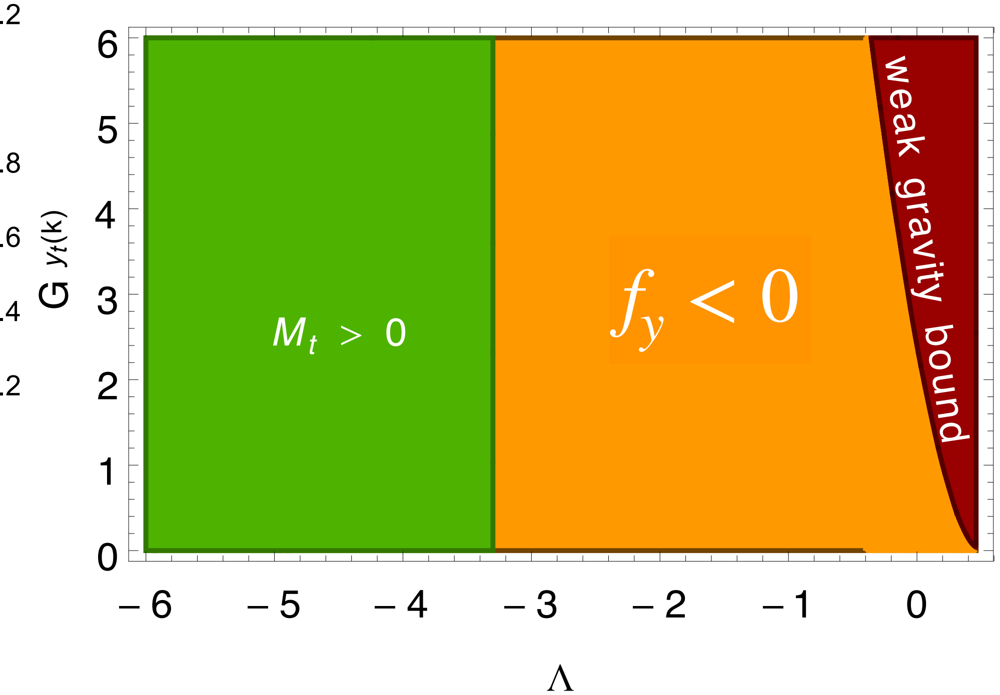
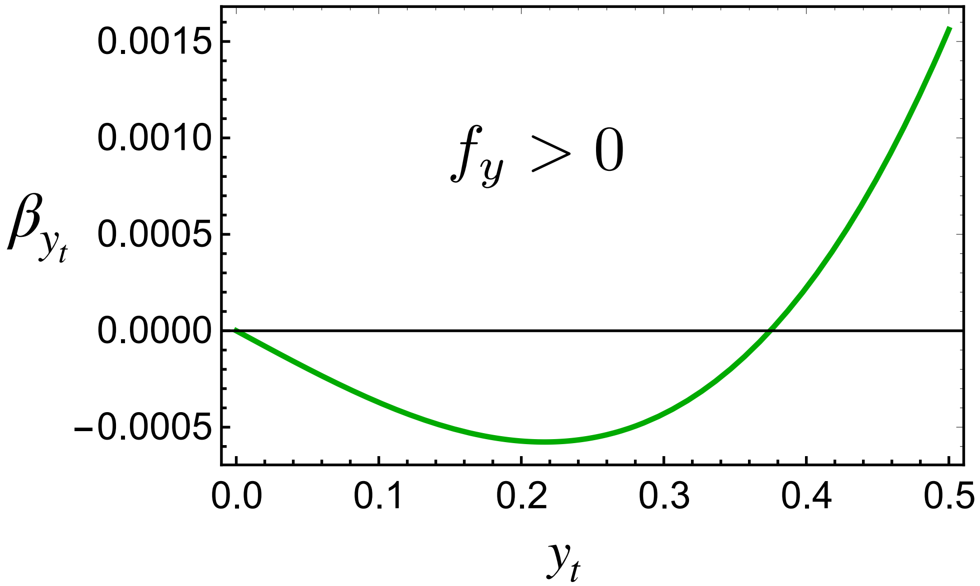




Asymptotic safety and the top quark



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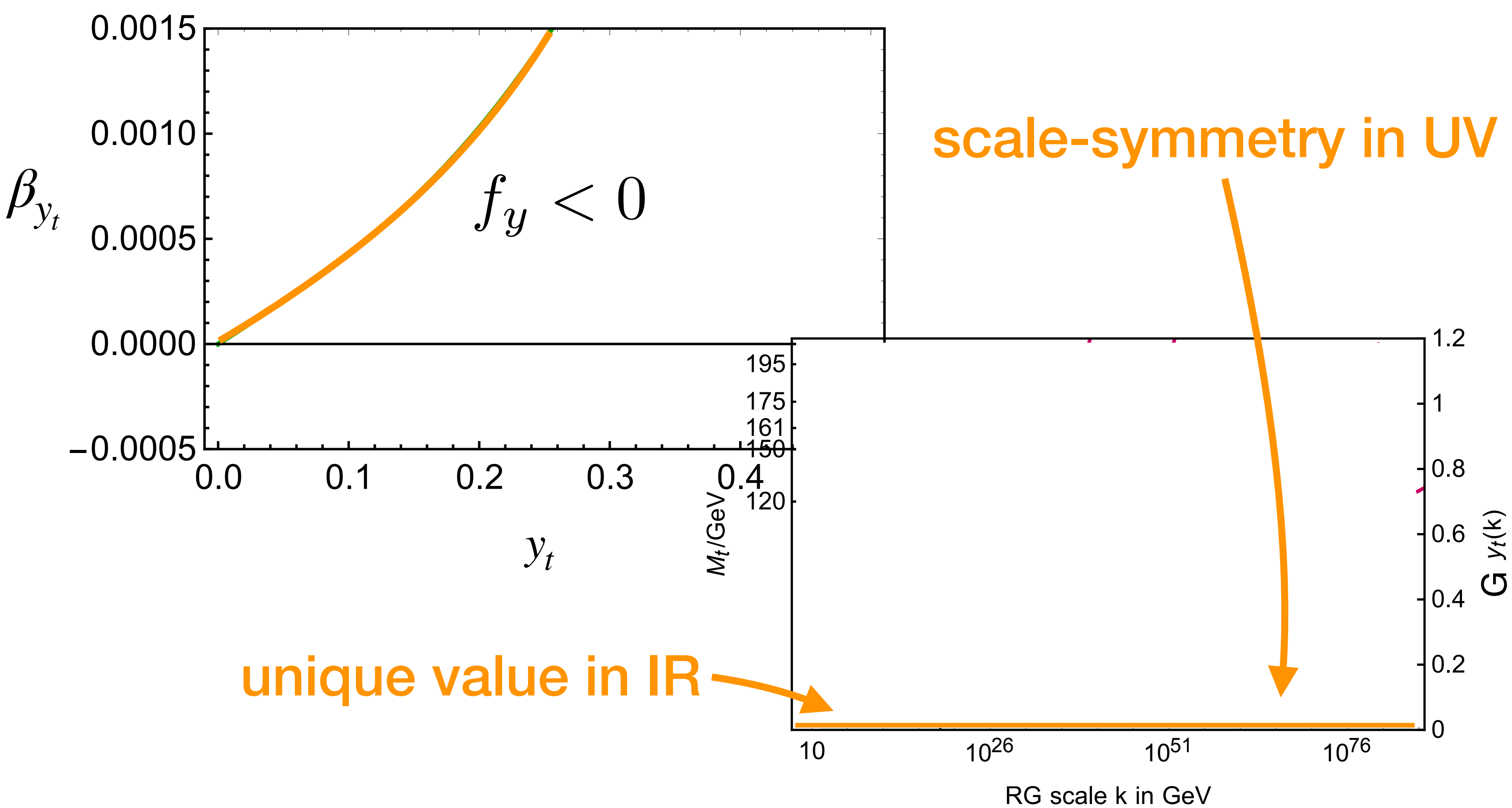
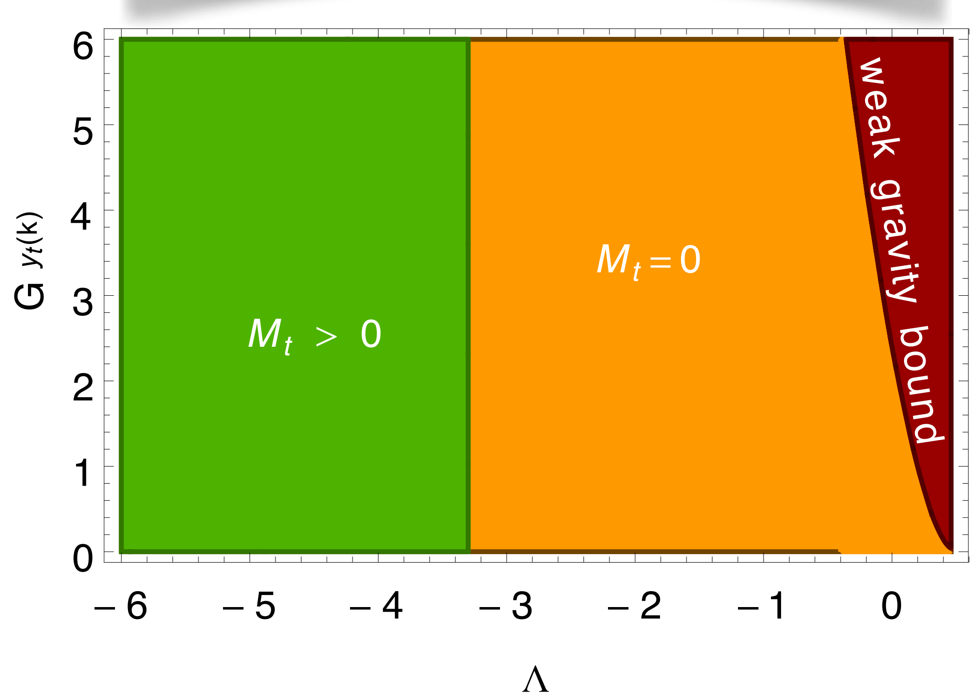
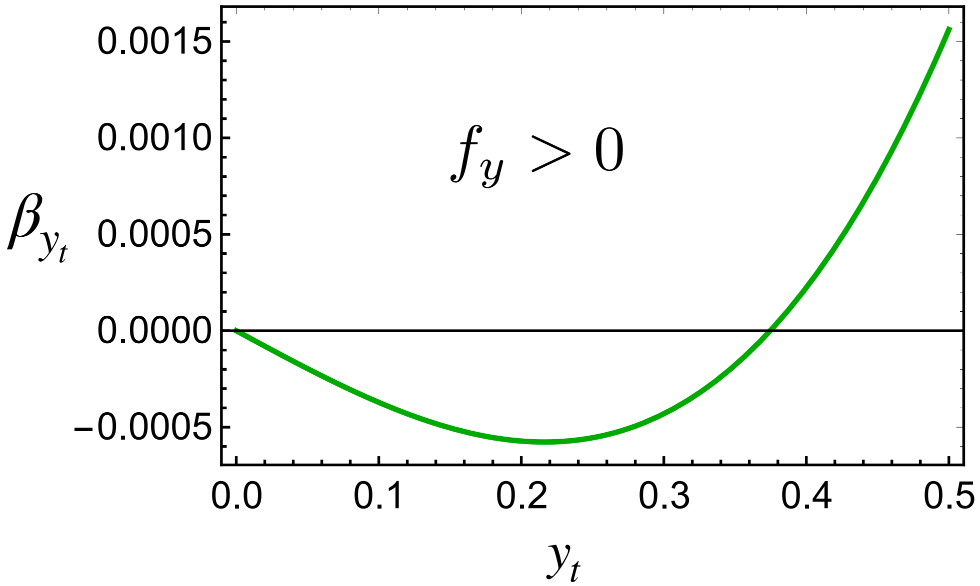
LHC: top-quark Yukawa nonzero

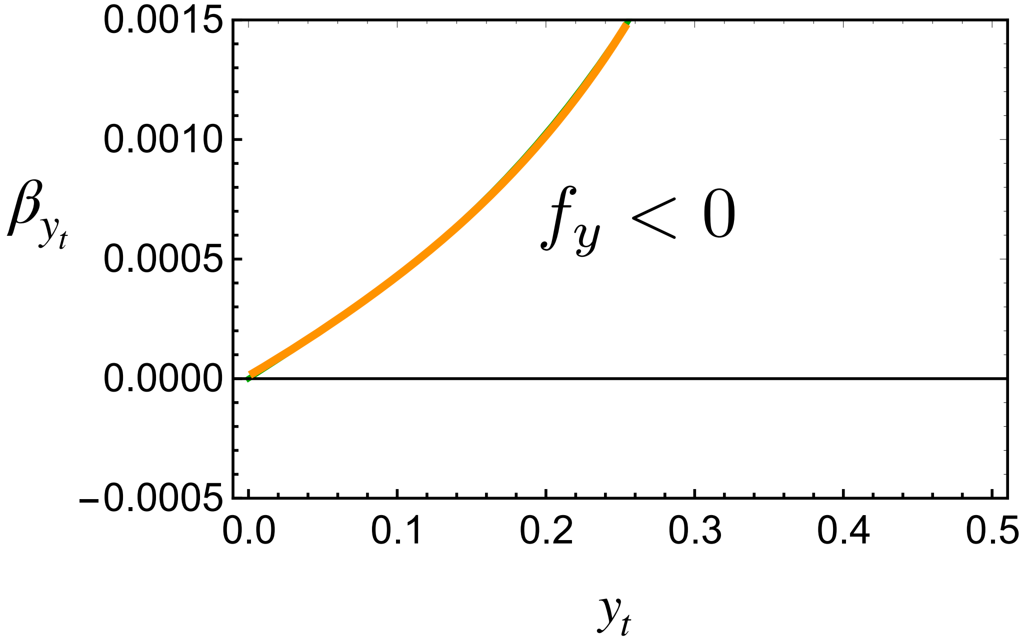
[CMS '20; ATLAS '18]





Asymptotic safety and the top quark





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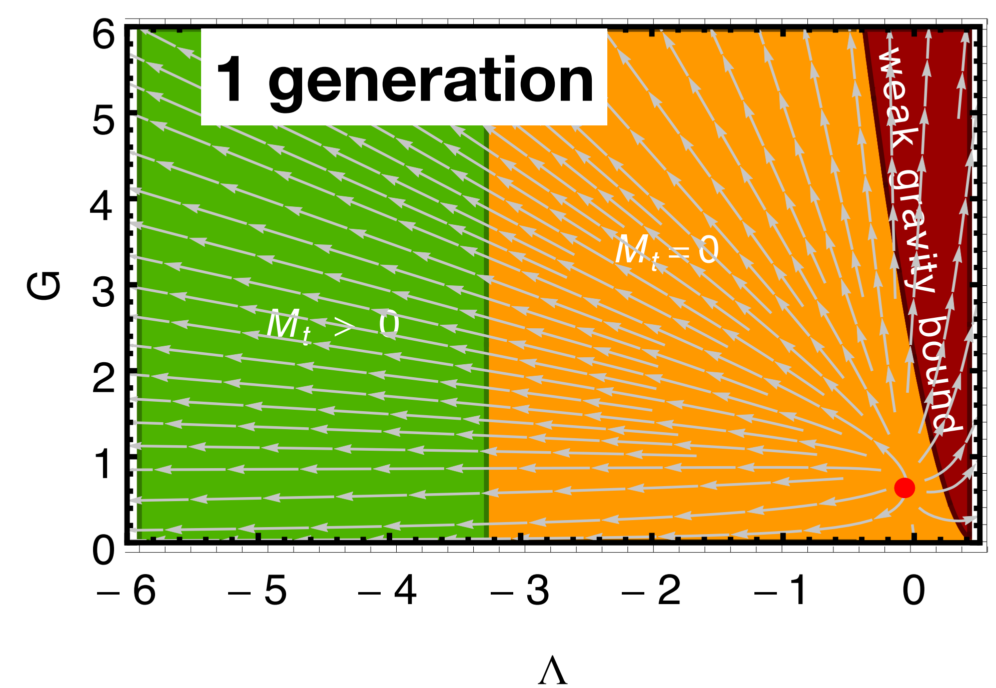
Gravitational fixed-point values?

[Dona, AE, Percacci '13]



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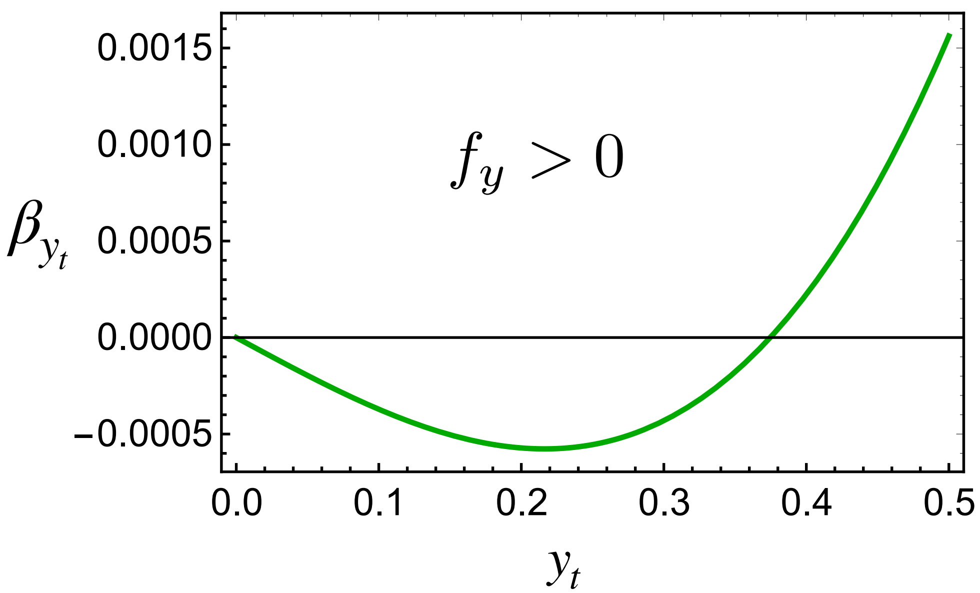

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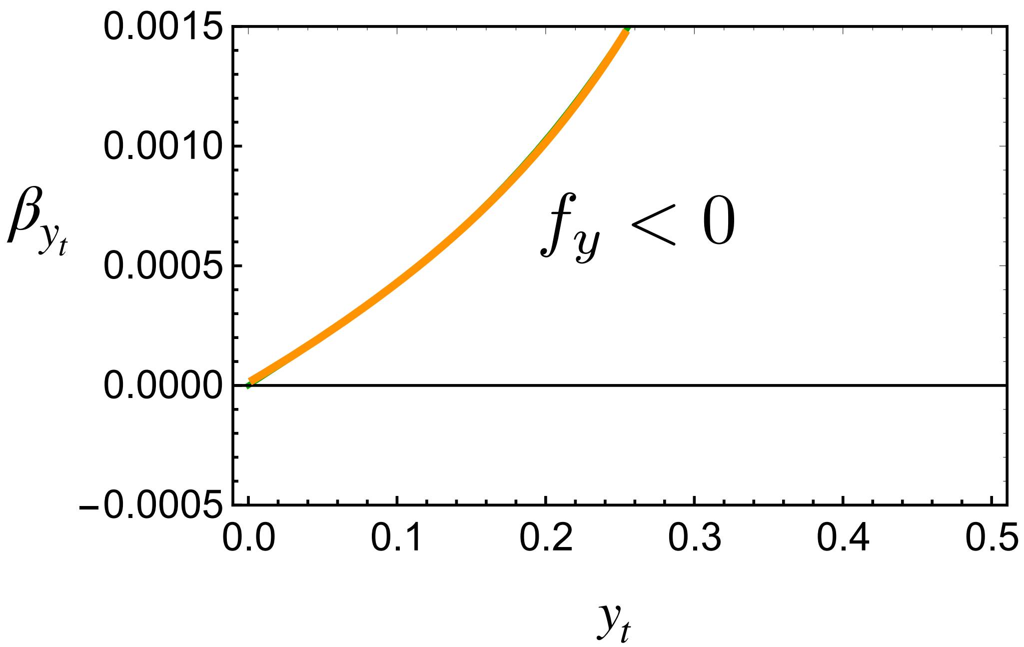

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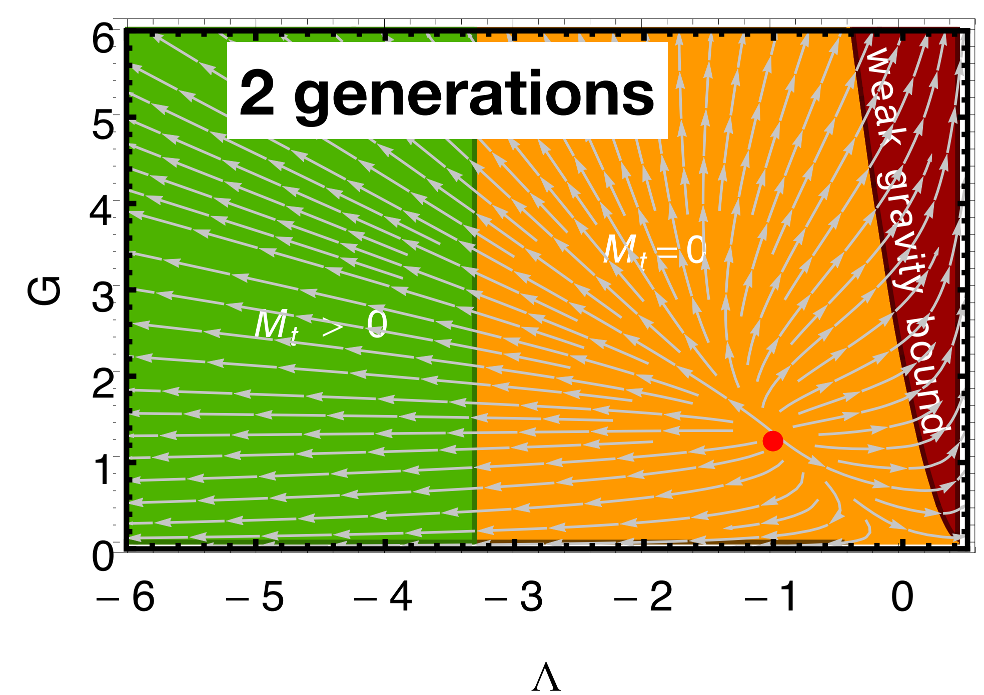

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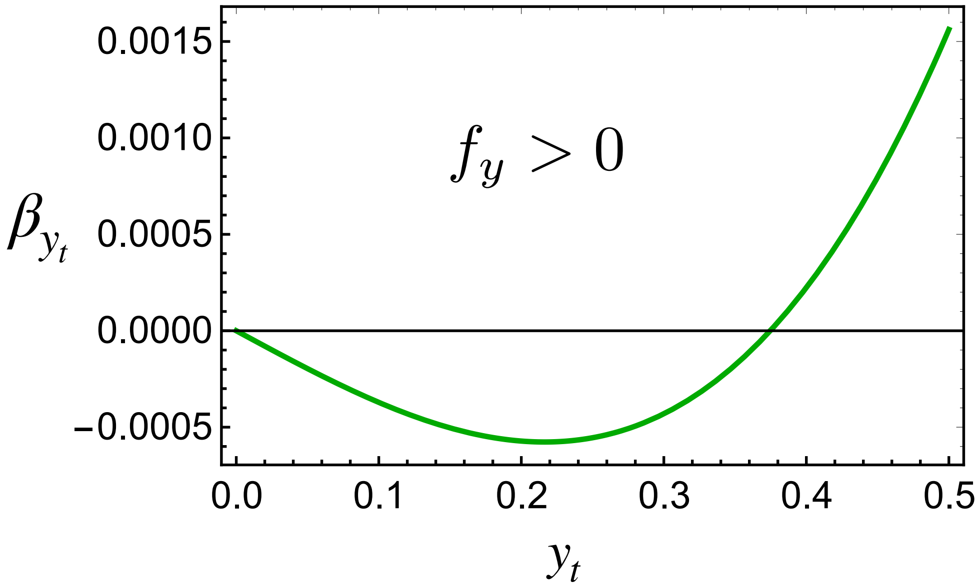

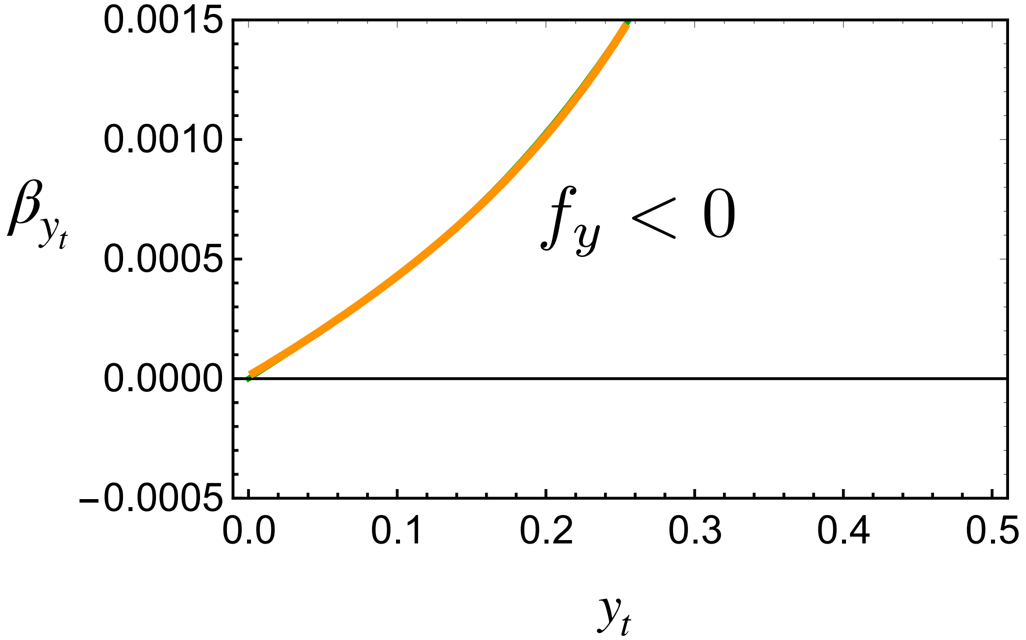

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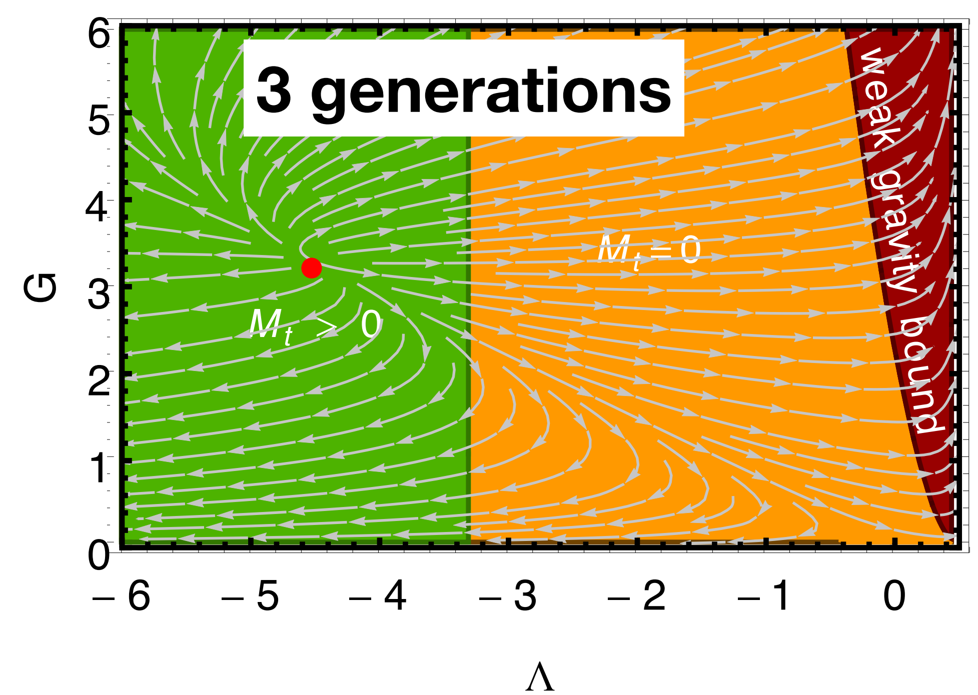


Gauge-Yukawa systems with gravity

Predictive power: Finite fermion masses from Yukawa interactions

Top-bottom system: [AE, Held '18]

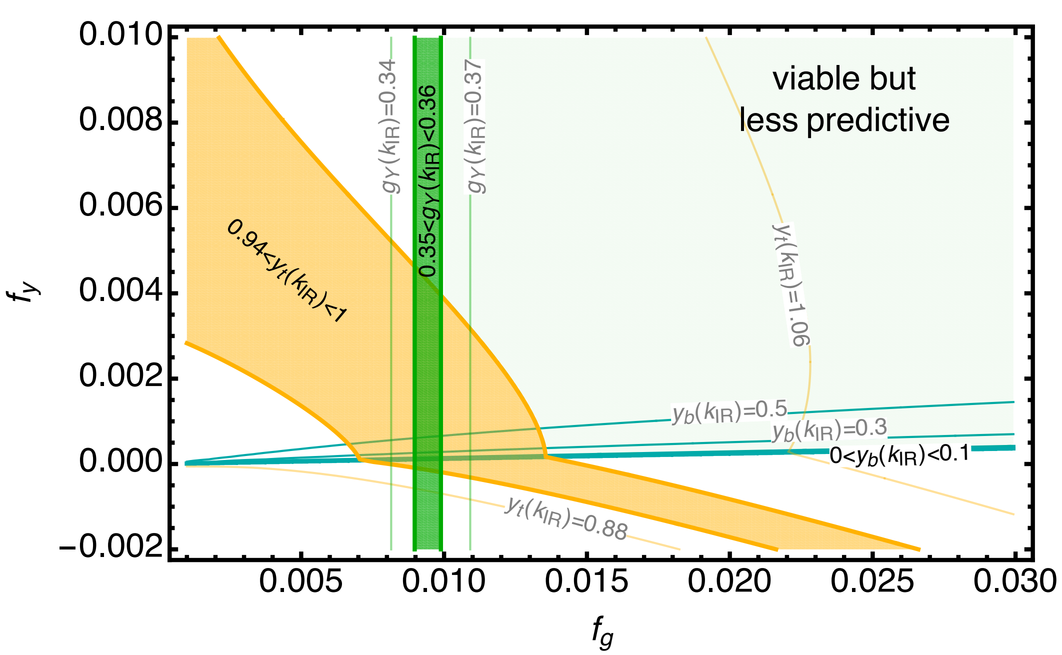
generalization to 3 generations: Alkofer, AE, Held, Percacci, Nieto, Schröfl '20

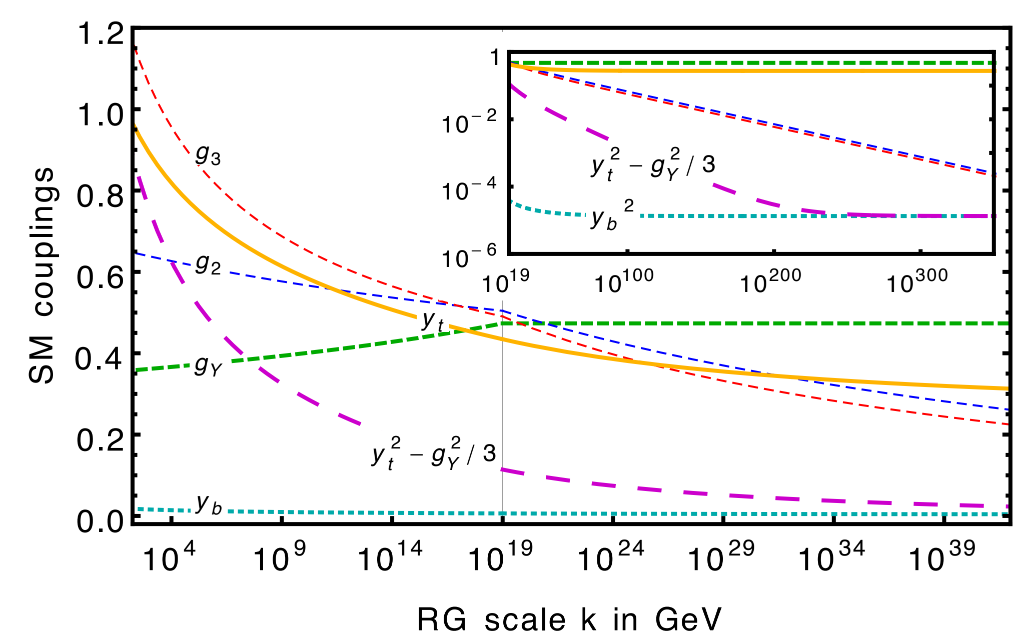
fixed-point relation: $y_{t\,*}^2 - y_{b\,*}^2 = \frac{1}{3} g_{Y\,*}^2$

$$\beta_{y_{t/b}} = \frac{3}{16\pi^2} y_{t/b}^3 - f_y\, y_{t/b} - \frac{3 y_{t/b}}{16\pi^2}\left(1/36 + Y_{t/b}^2\right) g_Y^2 + \ldots$$

unequal hypercharge of top, bottom:
unequal fixed-point values

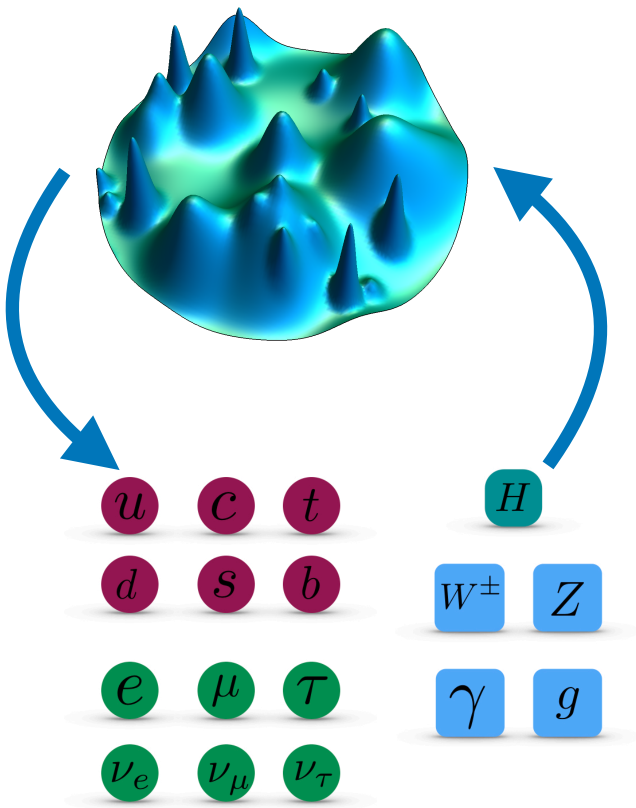
Abelian hypercharge: $\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y$





Top-bottom mass ratio as a consequence of gravity-induced scale symmetry in the UV

Shining a light onto dark sectors:
The asymptotically safe perspective



Standard Model + gravity:

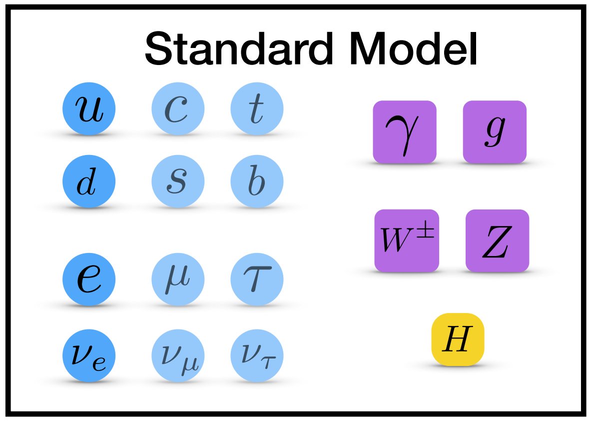
probably not sufficient to describe all observations

How many fields and which interactions?

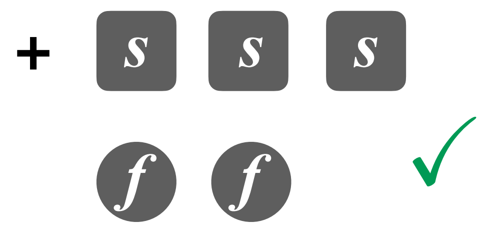
Bold interpretation of lack of discovery to date:
Time for a new theoretical paradigm!

Asymptotically safe constraints on dark sectors

How many new fields? “asymptotically safe island”

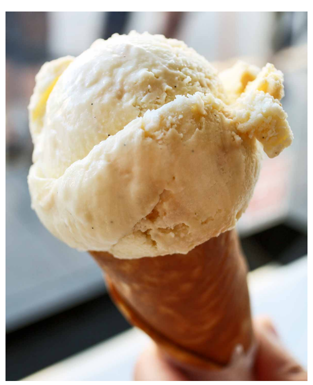


few

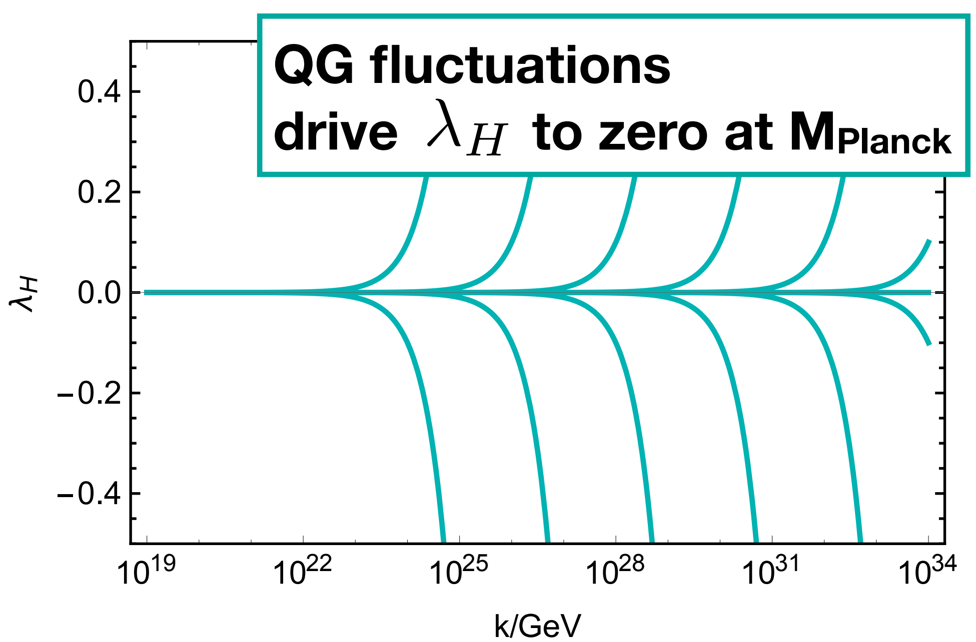


[Dona, AE, Percacci ’13;
Meibohm, Pawlowski, Reichert ’15;
Dona, AE, Labus, Percacci ’15;
Biemans, Platania, Saueressig ’17;
AE, Lippoldt, Pawlowski, Reichert, Schiffer ’18;
Yamada, Wetterich ’19]

The vanilla model:



Higgs portal to one singlet scalar $\lambda_H\, H^2\, s^2$ AE, Hamada, Lumma, Yamada ‘17



→ generically:
quantum gravity flattens scalar potentials

Higgs prediction [Shaposhnikov, Wetterich ’10]

cosmo consequences: AE, Pauly ‘20

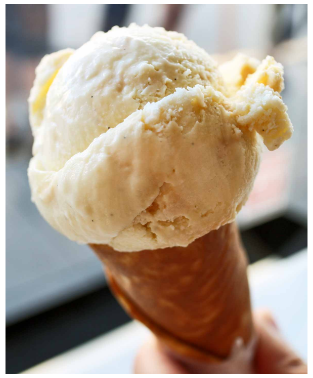
→ decoupling of dark matter;
cannot be produced as thermal relic

→ single, uncharged dark scalar with Higgs portal incompatible with asymptotic safety

Asymptotically safe constraints on dark sectors

Proof of principle: Upgrade and exploit the predictive power

see also:
Hamada, Tsumura, Yamada '19;
Reichert, Smirnov '19



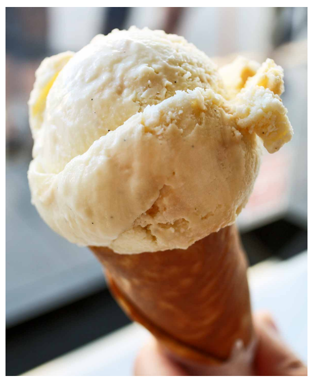
$\rightarrow$

toy model SM Higgs portal to singlet scalar + dark fermion

AE, Pauly '20

Asymptotically safe constraints on dark sectors

Proof of principle: Upgrade and exploit the predictive power

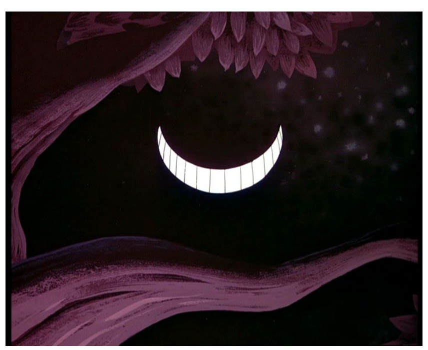


→

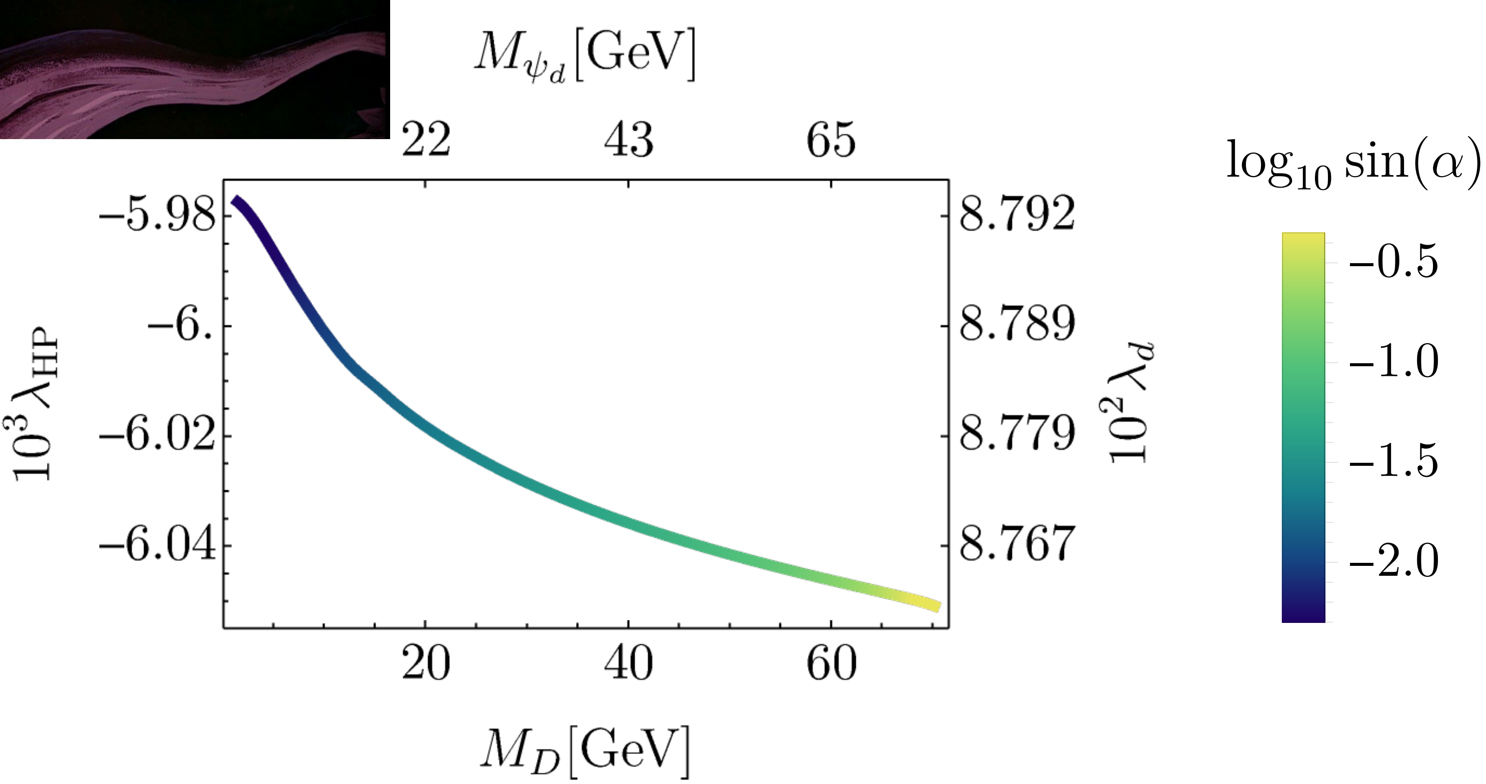
toy model SM Higgs portal to singlet scalar + dark fermion

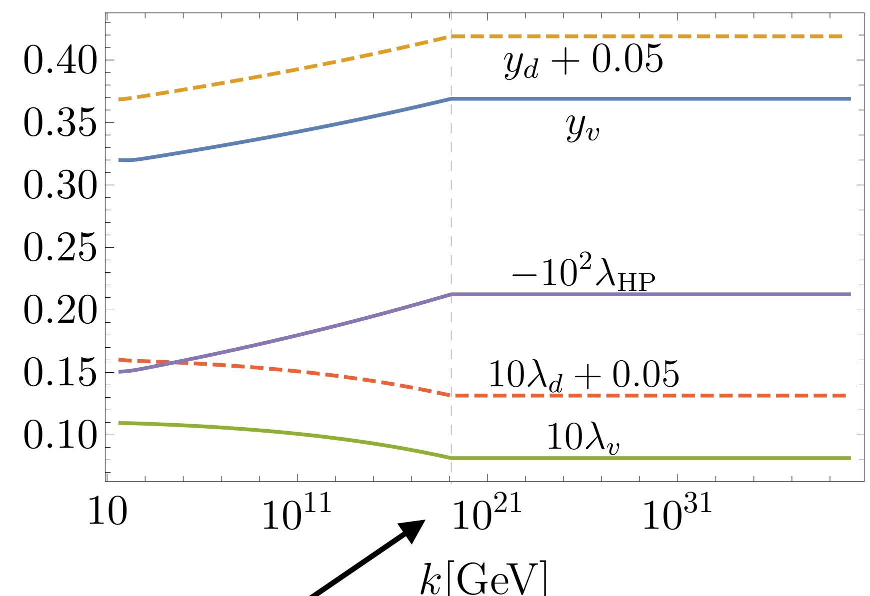
AE, Pauly '20

$$\Gamma_k = \int d^4x\sqrt{g}\,\frac{\lambda_{\rm HP}}{4}\phi_v^2\phi_d^2 + \Gamma_k^{\rm visible} + \Gamma_k^{\rm visible\to dark} + \Gamma_k^{\rm Einstein-Hilbert}$$



$$\Gamma_k^{\rm visible} = \int d^4x\sqrt{g}\left(\frac{Z_{\phi_v}}{2}g^{\mu\nu}\partial_\mu\phi_v\partial_\nu\phi_v + \frac{\bar{m}_v^2}{2}\phi_v^2 + \frac{\lambda_v}{8}\phi_v^4 + \xi_v\phi_v^2 R + iZ_{\psi_v}\bar{\psi}_v\nabla\!\!\!/\,\psi_v + iy_v\,\phi_v\bar{\psi}_v\psi_v\right)$$



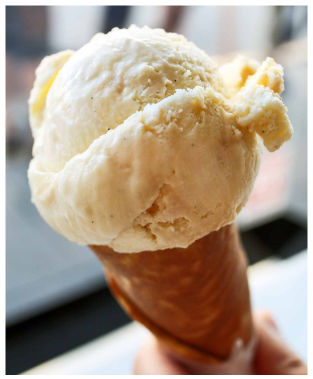


QG fluctuations turn off dynamically

predictive relations from quantum gravity

Asymptotically safe constraints on dark sectors

Proof of principle: Upgrade and exploit the predictive power

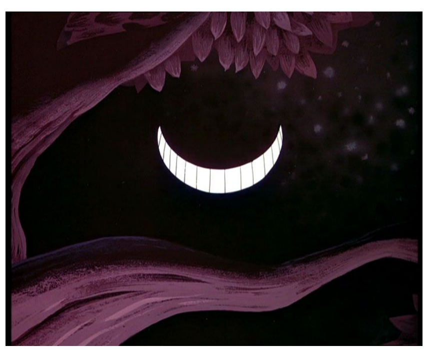


$\rightarrow$

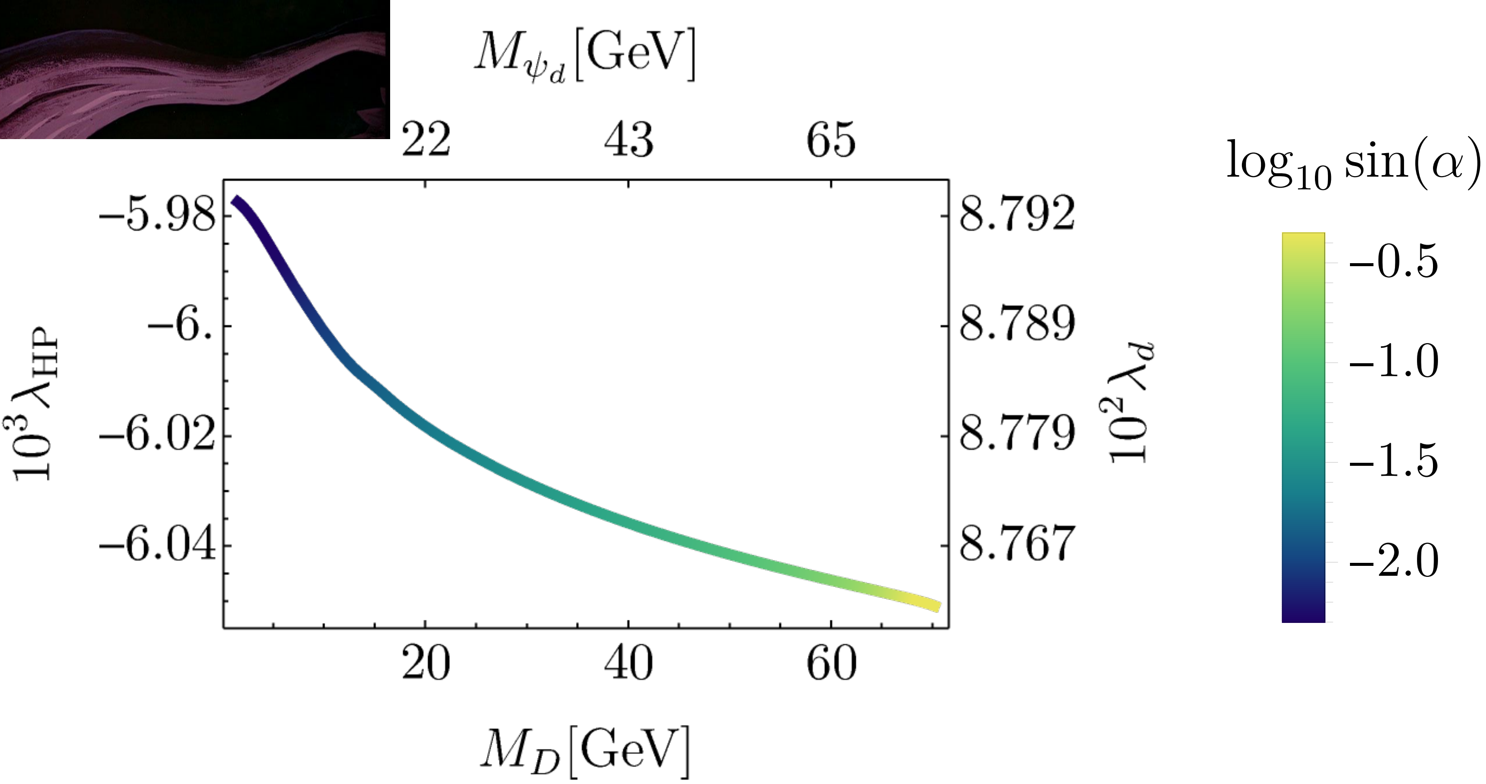
toy model SM Higgs portal to singlet scalar + dark fermion

AE, Pauly '20

$$\Gamma_k = \int d^4x \sqrt{g}\, \frac{\lambda_{\mathrm{HP}}}{4} \phi_v^2 \phi_d^2 + \Gamma_k^{\mathrm{visible}} + \Gamma_k^{\mathrm{visible} \rightarrow \mathrm{dark}} + \Gamma_k^{\mathrm{Einstein-Hilbert}}$$



$$\Gamma_k^{\mathrm{visible}} = \int d^4x \sqrt{g} \left(\frac{Z_{\phi_v}}{2} g^{\mu\nu} \partial_\mu \phi_v \partial_\nu \phi_v + \frac{\bar{m}_v^2}{2} \phi_v^2 + \frac{\lambda_v}{8} \phi_v^4 + \xi_v \phi_v^2 R + i Z_{\psi_v} \bar{\psi}_v \nabla\!\!\!\!/\, \psi_v + i y_v\, \phi_v \bar{\psi}_v \psi_v \right)$$



predictive relations from quantum gravity

Upshot of dark- sector explorations so far:

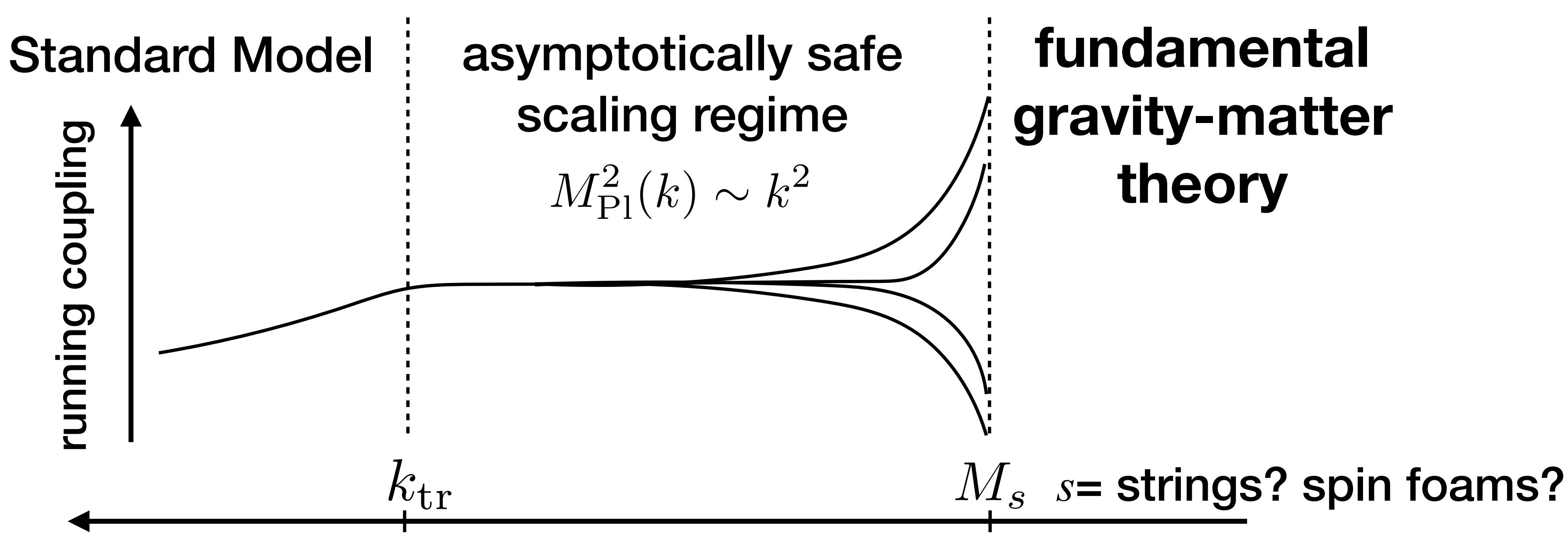
- predictive power of asymptotic safety:
  - simplest dark sector model excluded
  - extended dark sector much more constrained than in effective-field theory setting

Future perspectives: Links

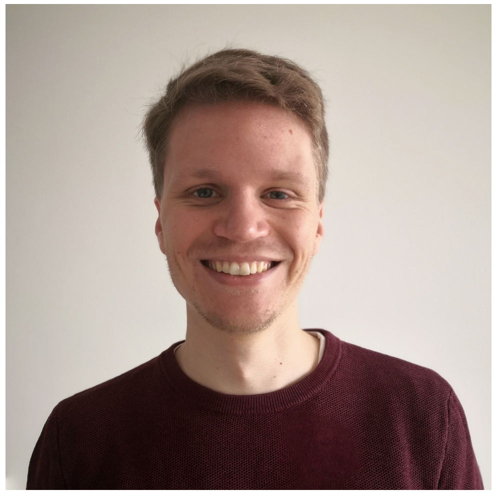
Phenomenology: Links to Standard Model + dark sector

Open theoretical questions (e.g., background independence, Lorentzian signature): link to lattice approaches

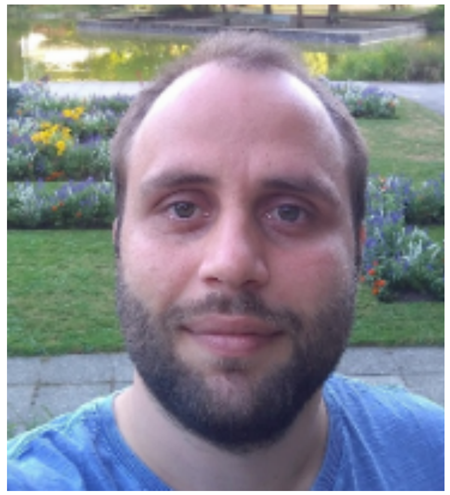
Link to other settings: Effective asymptotic safety



Thanks to the team!



Aaron Held
(now at Imperial College)

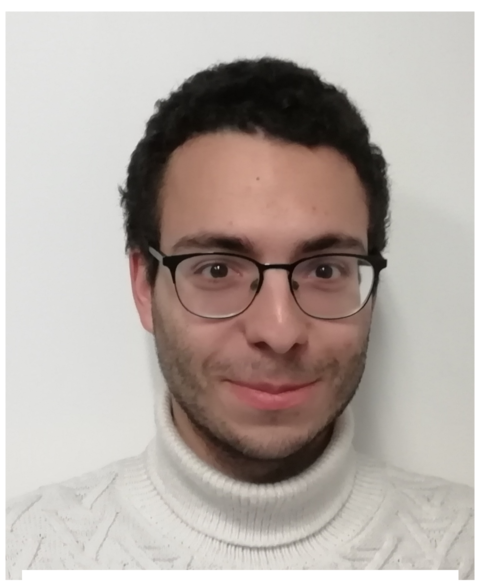


Antonio Pereira
(now at Fluminense Federal & Radboud-University)

Alessia Platania
(now at Perimeter Institute)

Andreas Pithis
(now at LMU)

Fleur Versteegen
(now ASML, Netherlands)



Johannes Lumma
(now at Ecole Polytechnique)

Gustavo Brito
(current member)

Marc Schiffer
(current member; soon at Perimeter Institute)

Martin Pauly
(current member)

Rafael Robson Lino dos Santos
(current member)

as well as bachelor students Johanna Borissova and Philipp Johannsen, master students Jan Engelhardt, Artiom Zaitev, Ademola Adeifeoba, Giovanni Biondo, Peter Vander Griend,
visiting PhD students Jan Kwapisz, João Miqueleto, Carlos Nieto, Shouryya Ray, Arslan Sikandar, Vedran Skrinjar,
as well as former postdoc Nicolai Christiansen