Quantum gravity implications for particle physics

Astrid Eichhorn,
CP3-Origins, SDU (Odense) & Heidelberg University

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based on work with Aaron Held, Johannes Lumma, Marc Schiffer and Fleur Versteegen

CP3-Origins

University of Southern Denmark

Die Junge Akademie

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

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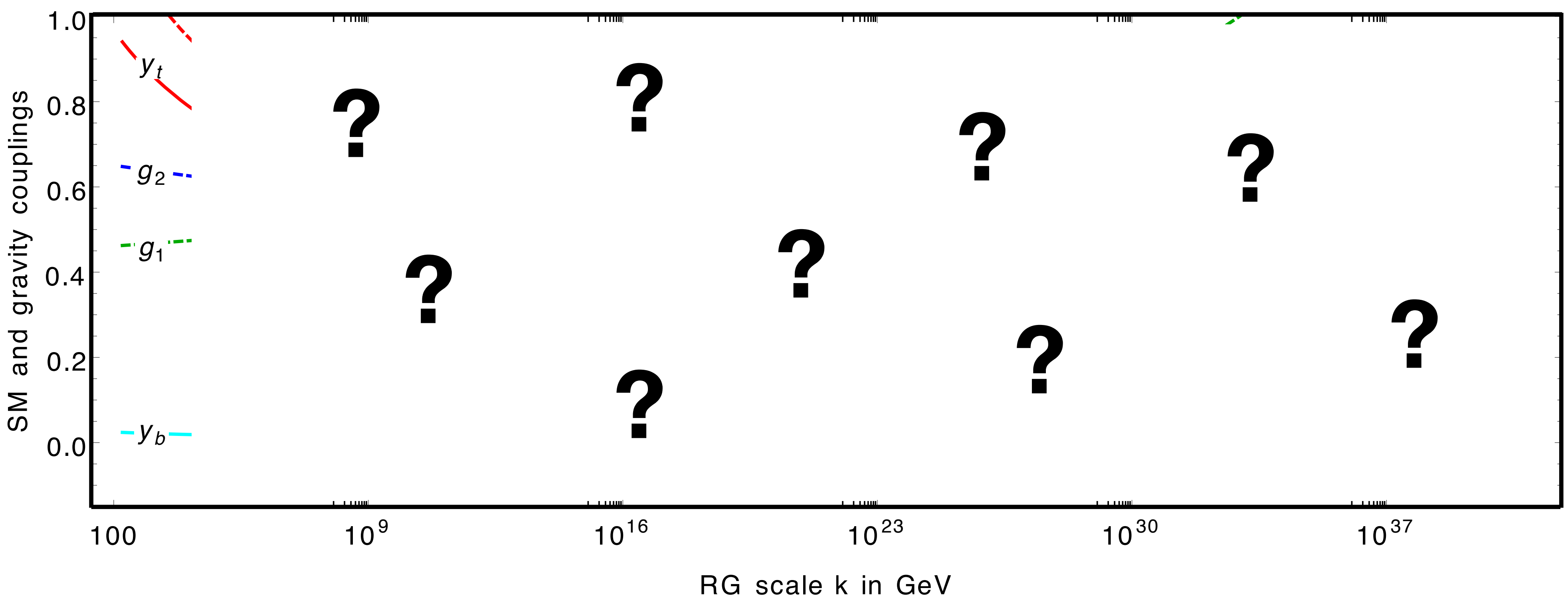
Status of the Standard Model

Before LHC



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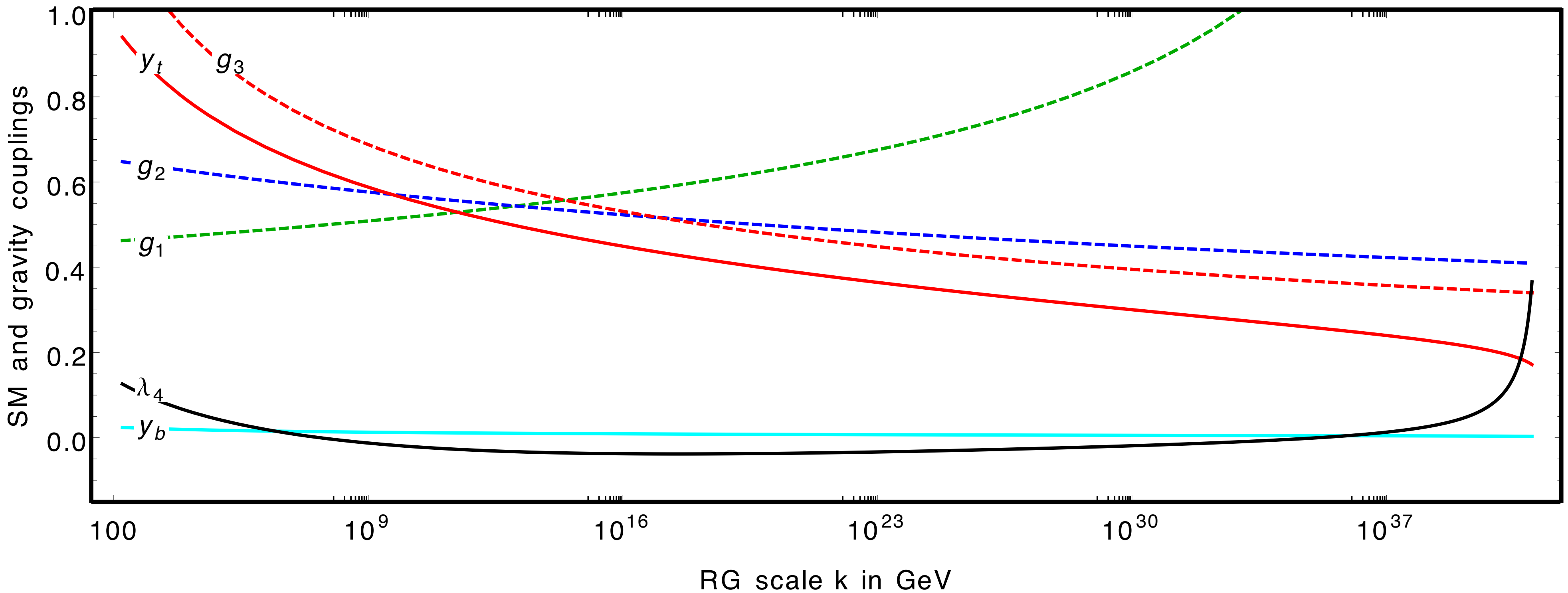
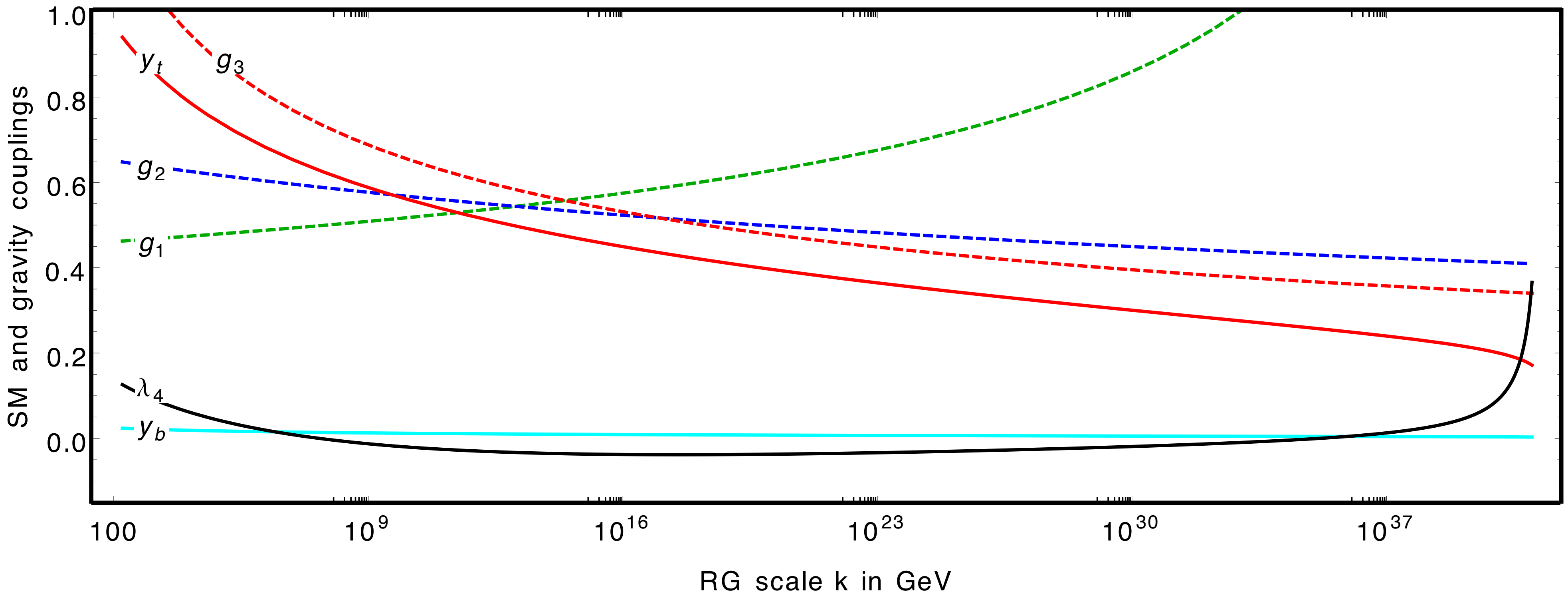


@ M_h = 125 GeV: can extend the Standard Model all the way to the Planck scale

Status of the Standard Model



- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**
- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**
- **gravitational interaction is missing**

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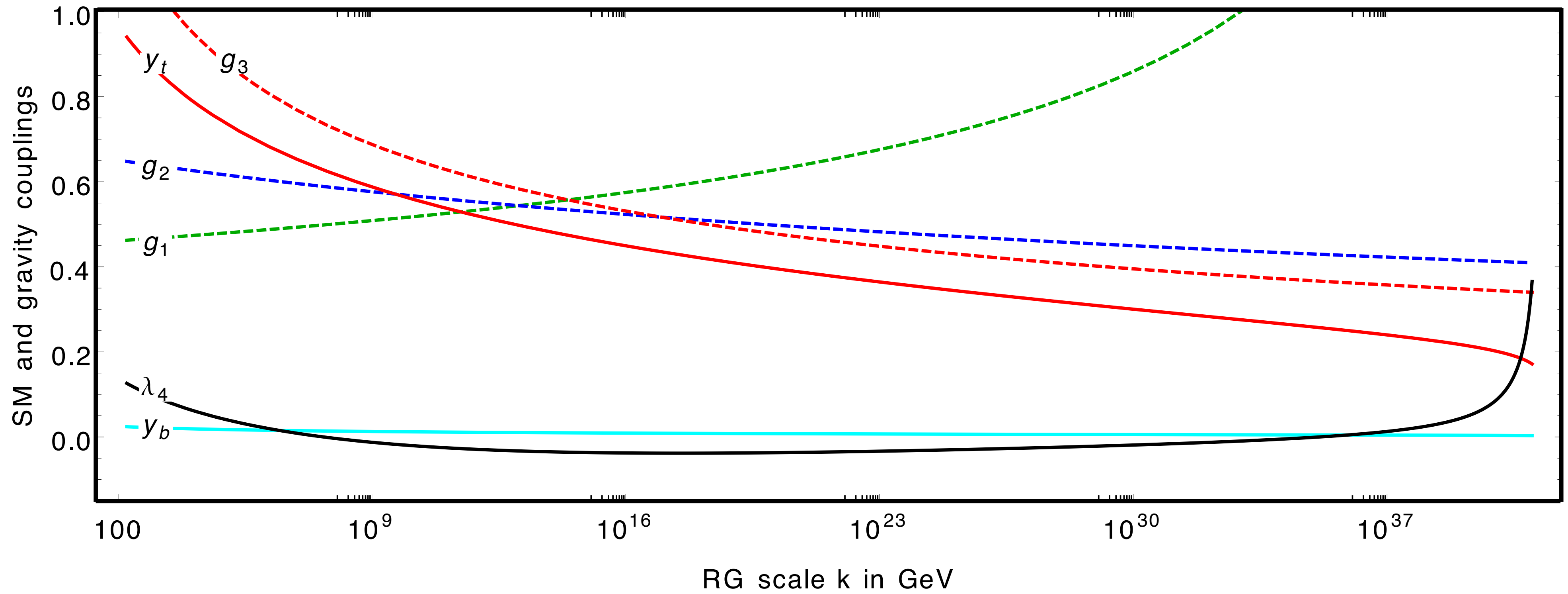

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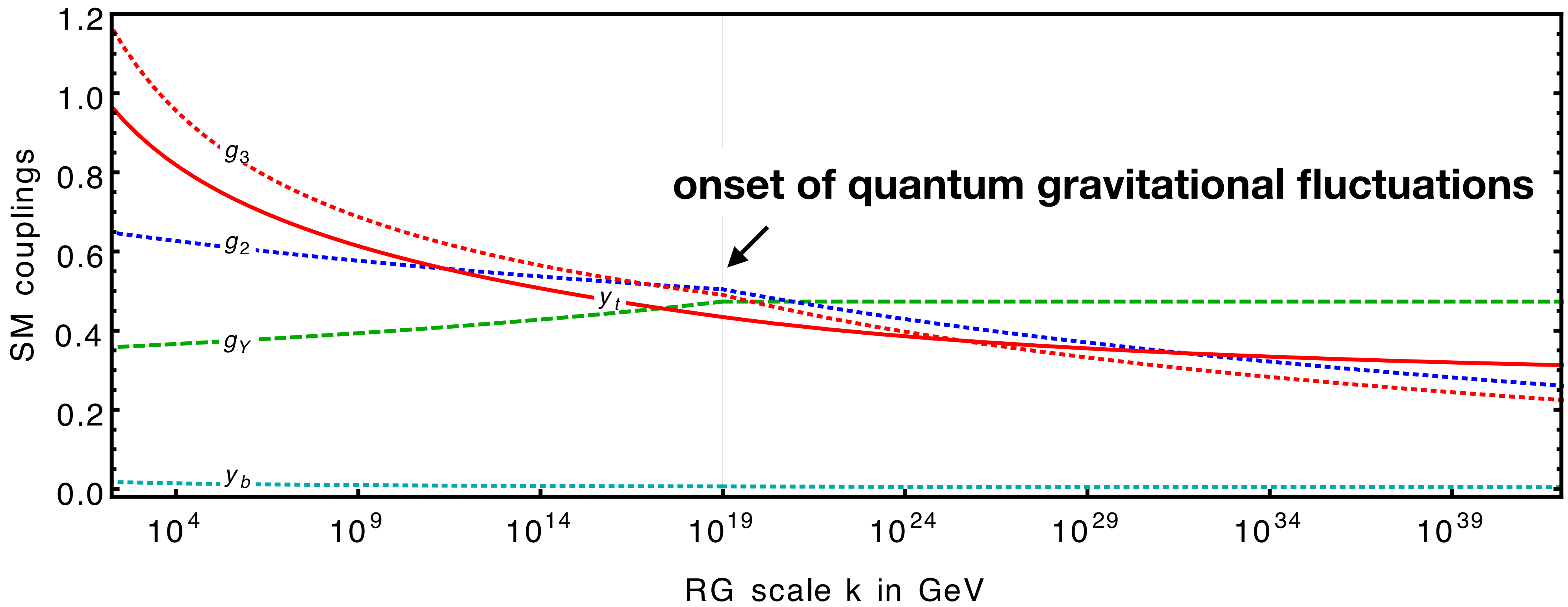
- **gravitational interaction is missing**

$\longrightarrow$ **are these challenges/problems connected?**

Hints for asymptotically safe gravity + Standard Model



- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**

  $\longrightarrow$ quantum-gravity induced ultraviolet completion for Standard Model

- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**

  $\longrightarrow$ potentially calculable from first principles ($\rightarrow$ tests of QG at e/w scale)

Connection to particle physics - a challenge

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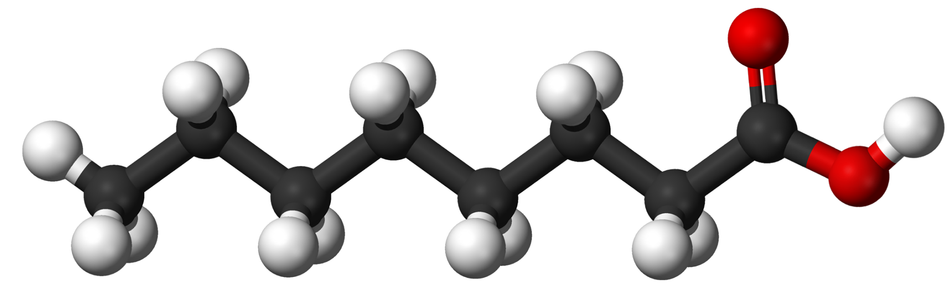
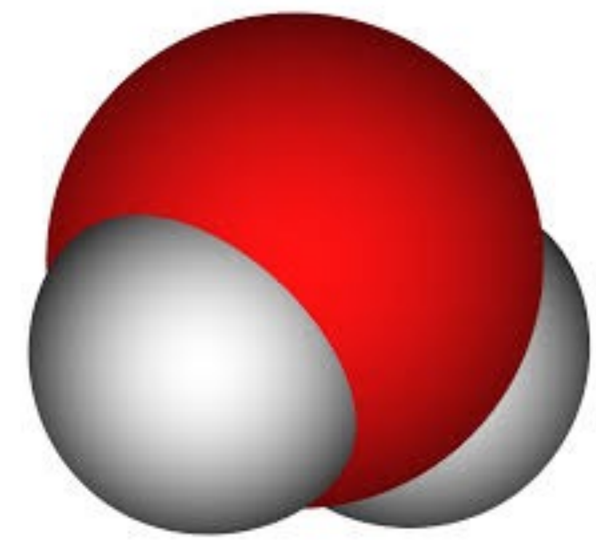


zooming out:
microscopic information gets lost

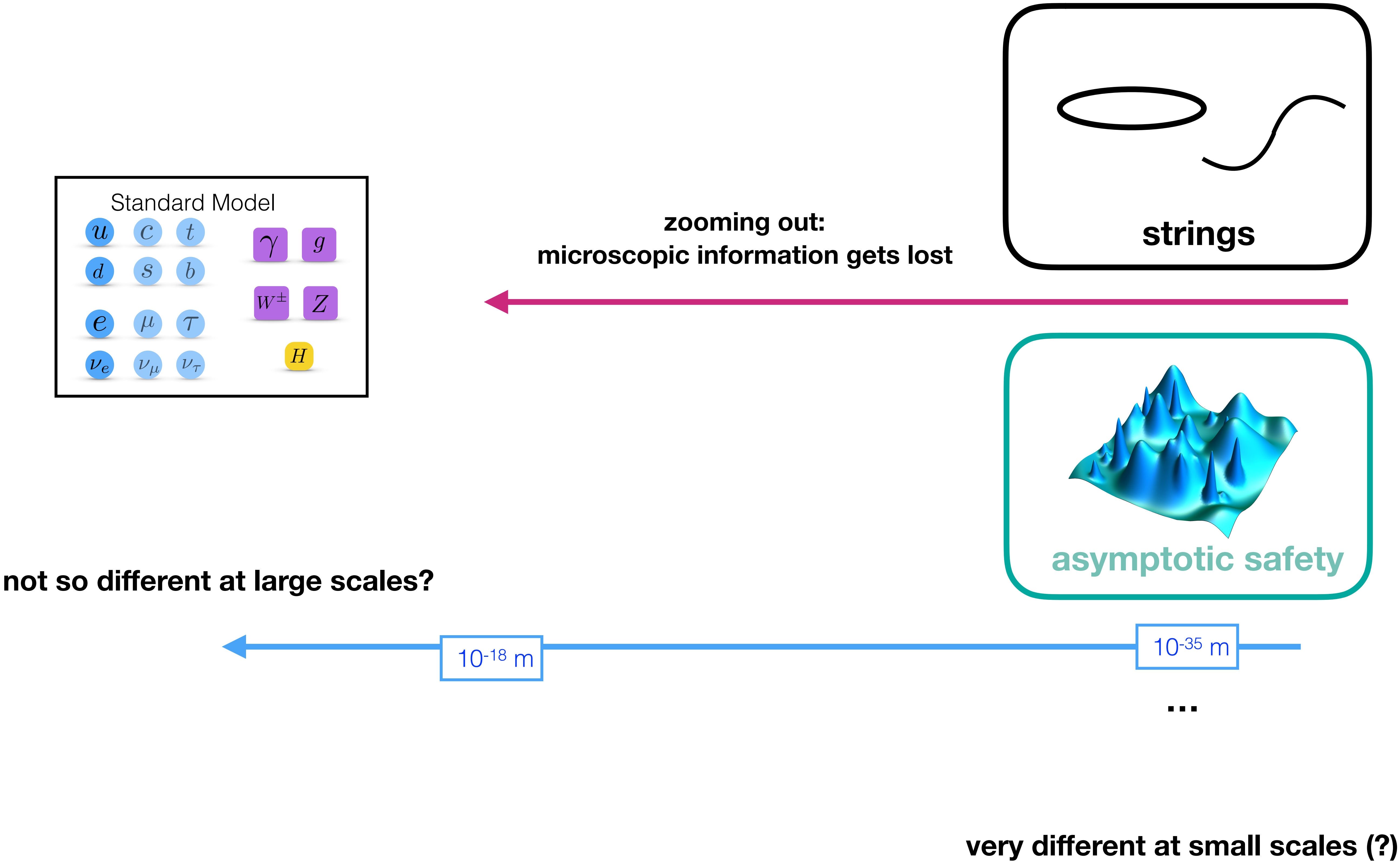


not so different at large scales?

...

very different at small scales

Connection to particle physics - a challenge



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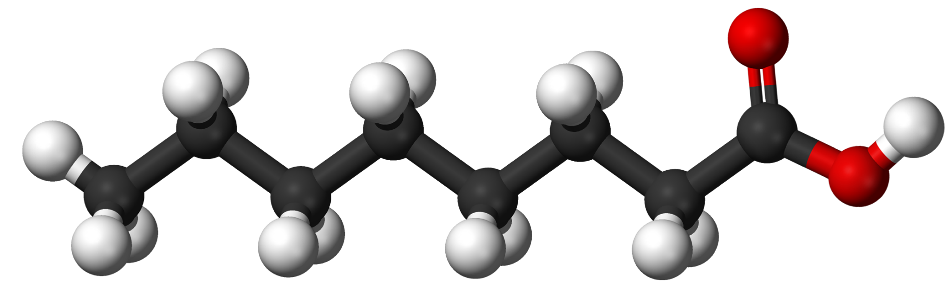

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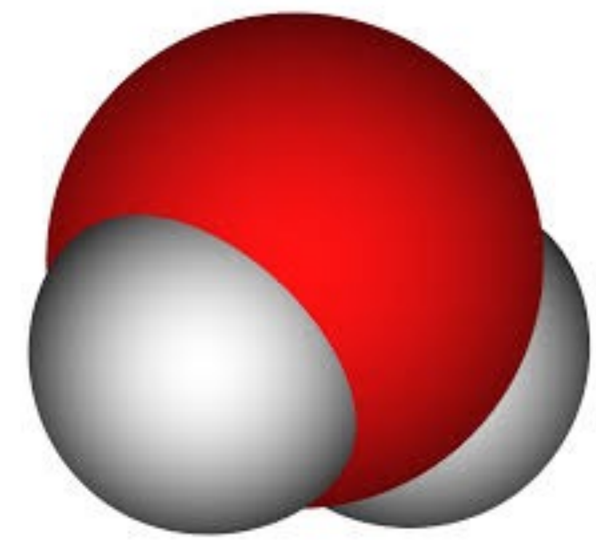

imprints of microscopic physics at macroscopic scales

example/analogy: viscosity vs. molecular scale

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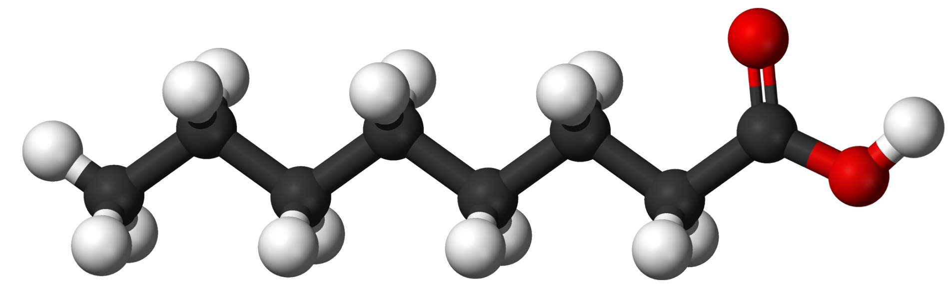
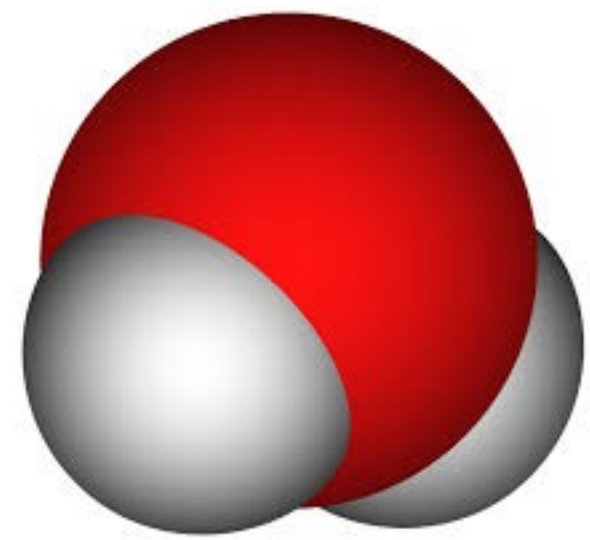




imprints of microscopic physics at macroscopic scales

example/analogy: viscosity vs. molecular scale

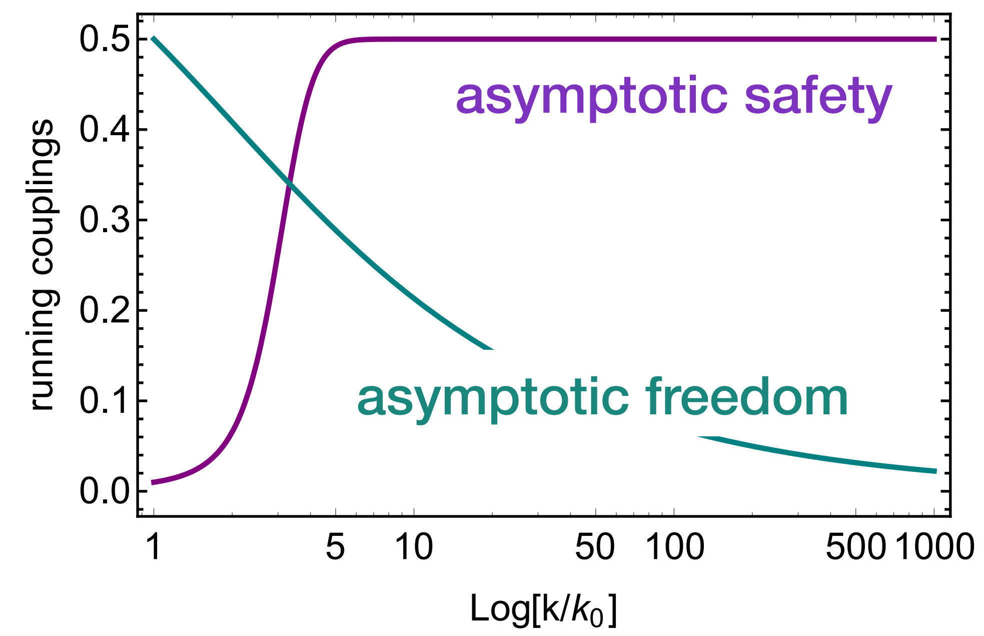
Which parts of macrophysics are sensitive to the underlying QG picture?

some Standard Model couplings could be irrelevant (predicted!) at AS fixed point

What is asymptotic safety?

What is asymptotic safety?

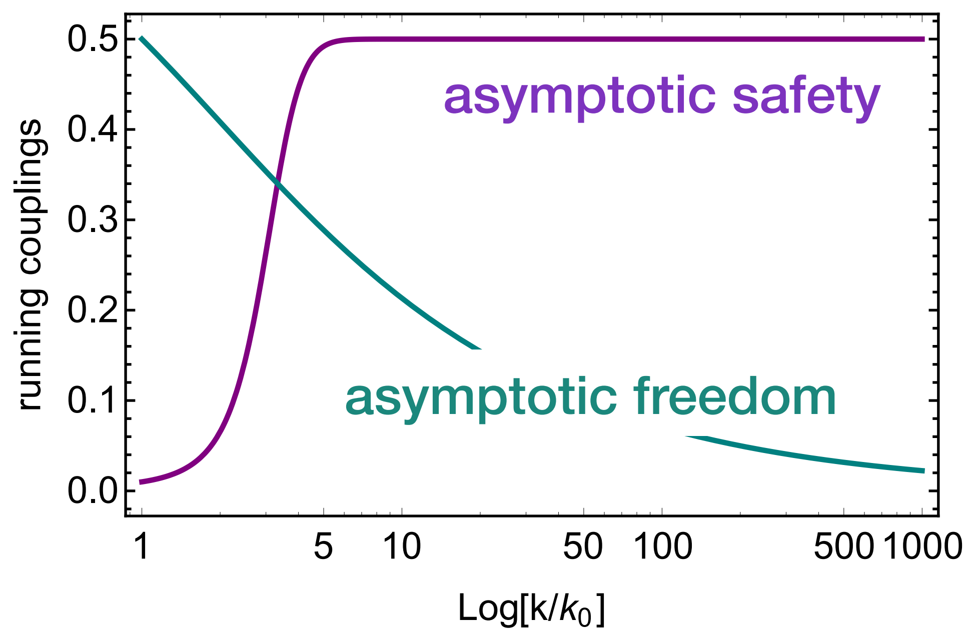
- a generalization of asymptotic freedom



- a scenario for ultraviolet completions of local quantum field theories

What is asymptotic safety?

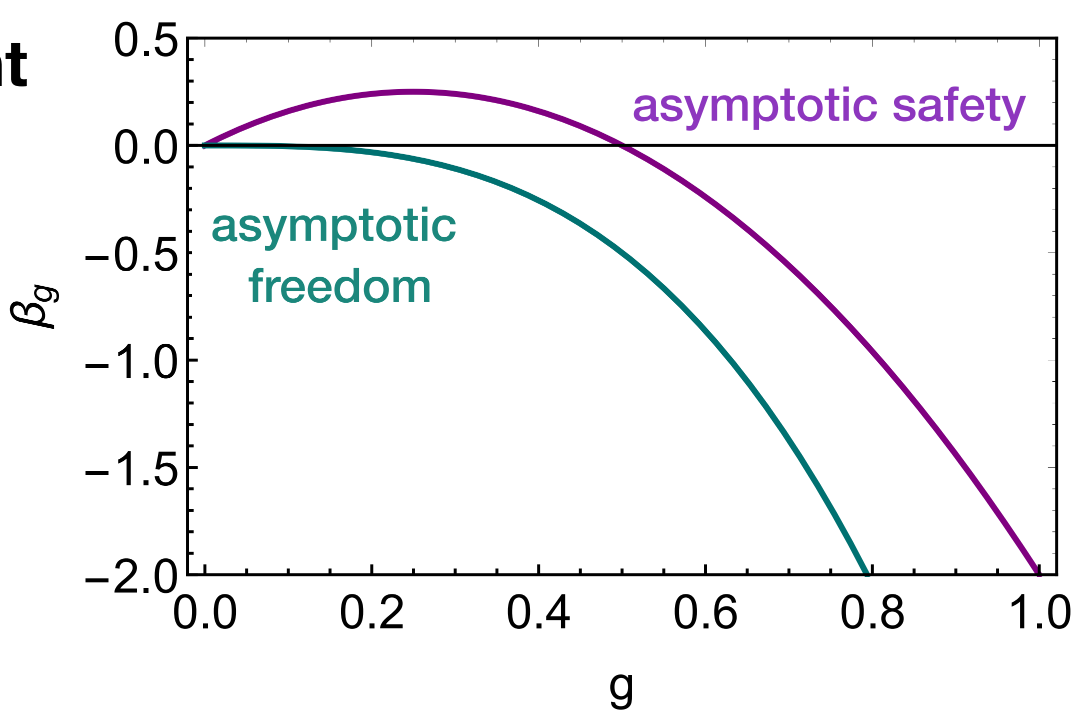
- **a generalization of asymptotic freedom**



- **a scenario for ultraviolet completions of local quantum field theories**
- **an interacting Renormalization Group fixed point**

$$\beta_{g_i} = k\partial_k\, g_i(k) = 0 \quad \textbf{at} \quad g_{i\,*} \neq 0$$

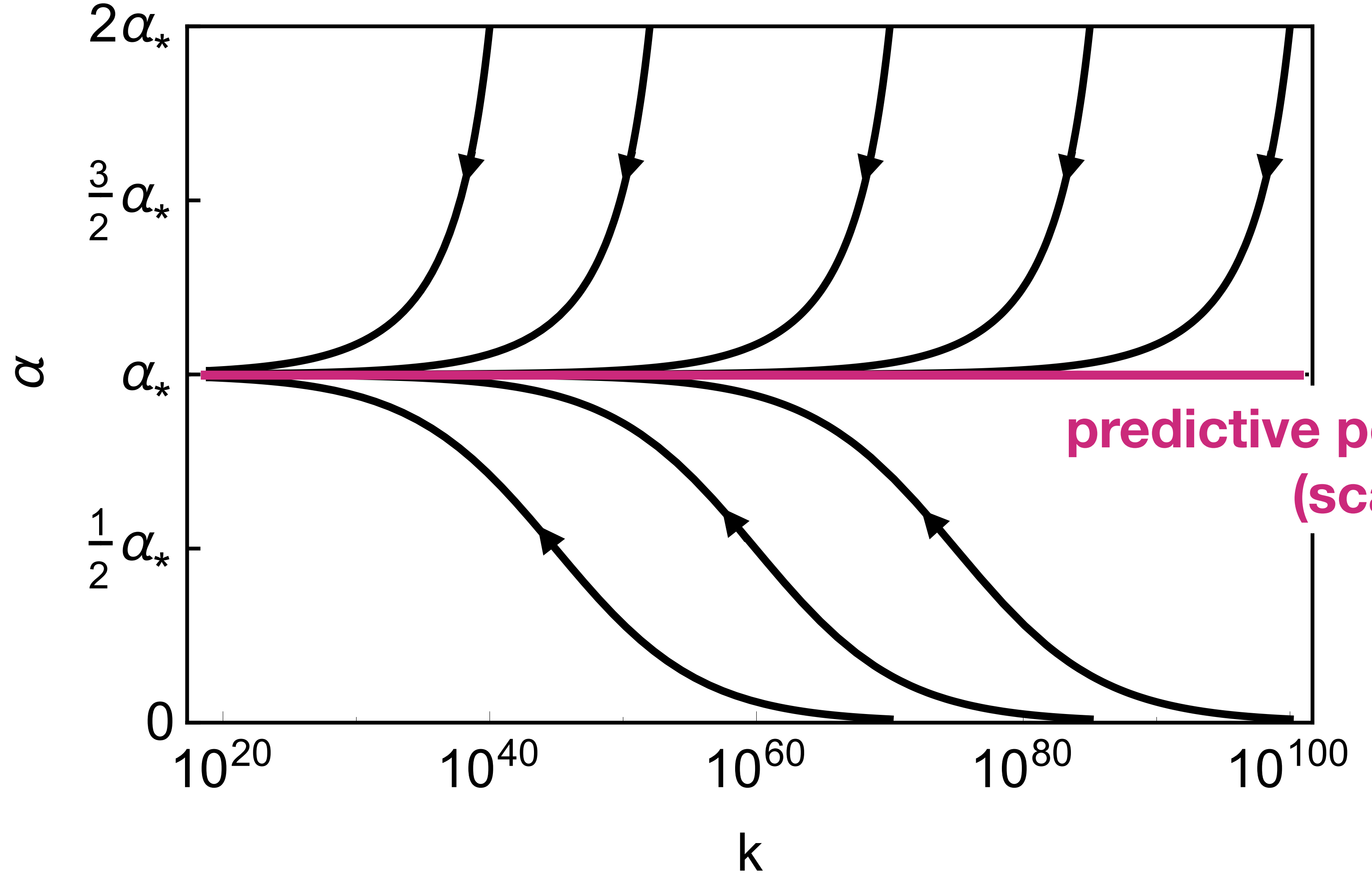
enhanced symmetry:
quantum scale symmetry



- **consequence: universal predictions for a subset of couplings**

Predictions from asymptotic safety

Irrelevant directions: Predictions from asymptotic safety

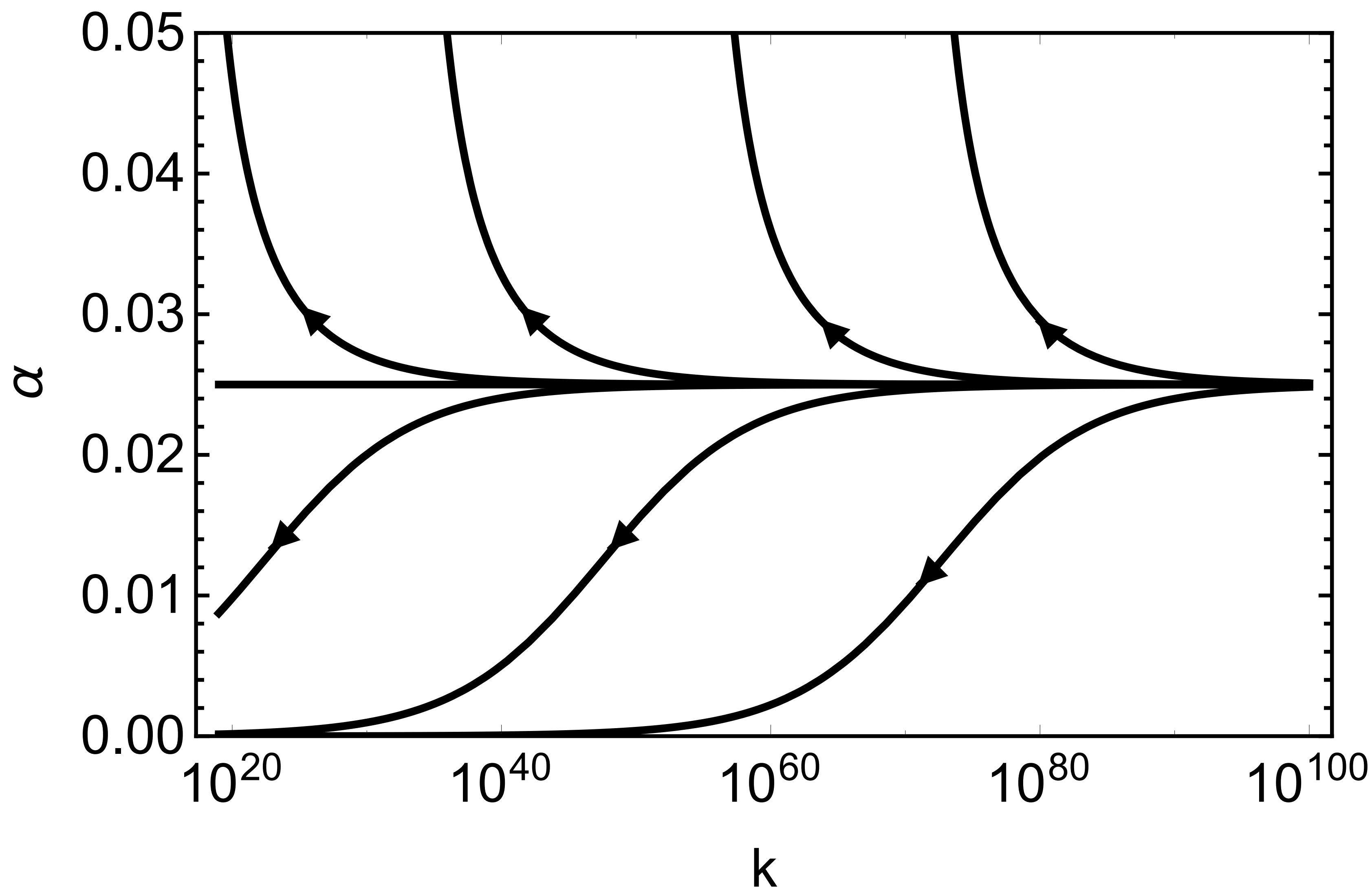


Infrared attractive direction

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

Free parameters of asymptotic safety

Relevant directions: Free parameters (parameterize deviations from scale invariance)



all IR values reachable from fixed point

Infrared repulsive direction

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

Asymptotically safe gravity - key idea

$$Z = \int \mathcal{D}g_{\mu\nu} e^{iS[g_{\mu\nu}]}$$

Quantum gravity:
Quantum fluctuations of spacetime
path integral for metric (cf. Yang-Mills)

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Quantum fluctuations of gravity drive
running gravitational couplings

$$S = -\frac{1}{16\pi G_N} \int d^4x \sqrt{g}\, R + ...$$

Strength of grav. interaction depends
on energy scale at which theory is probed

$$G_N \to G_N(k)$$

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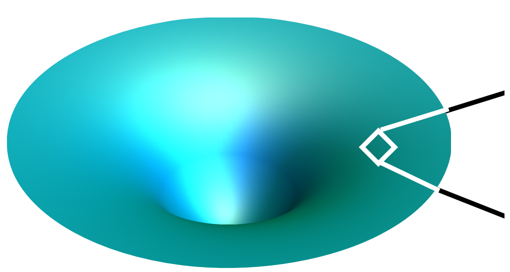

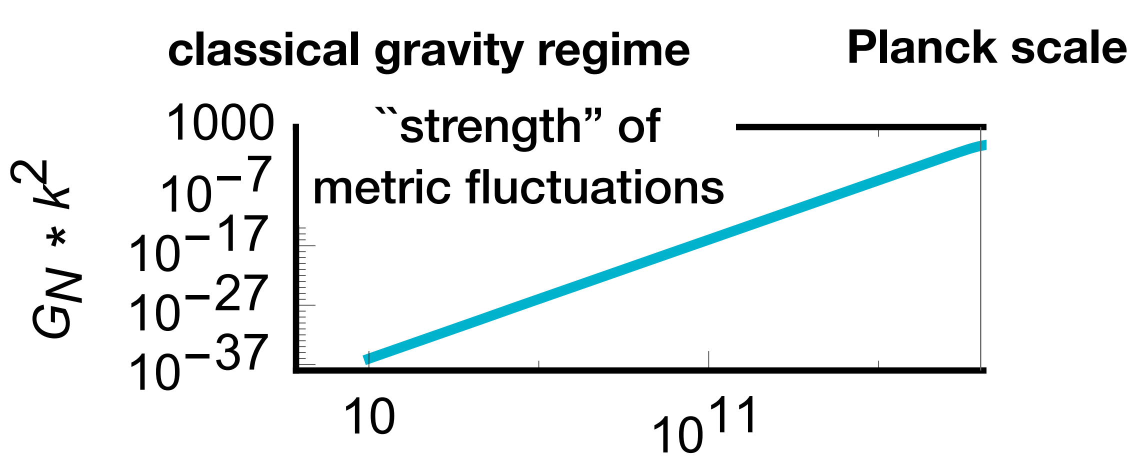

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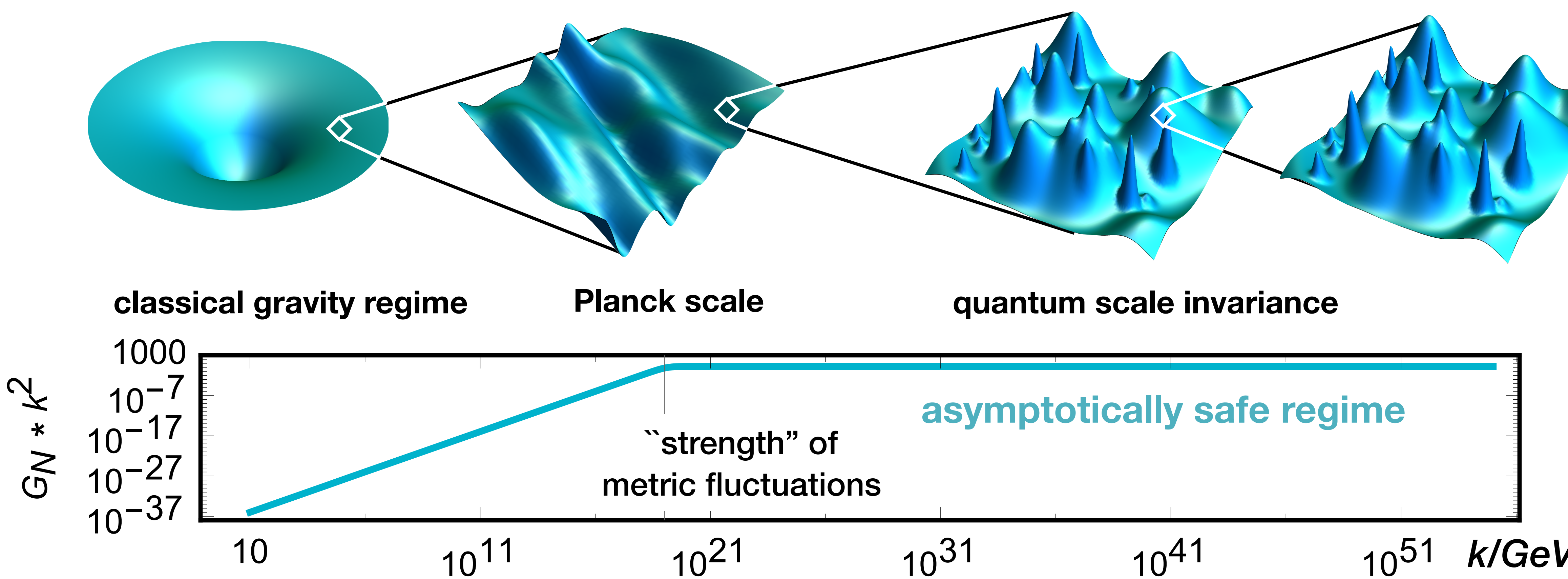
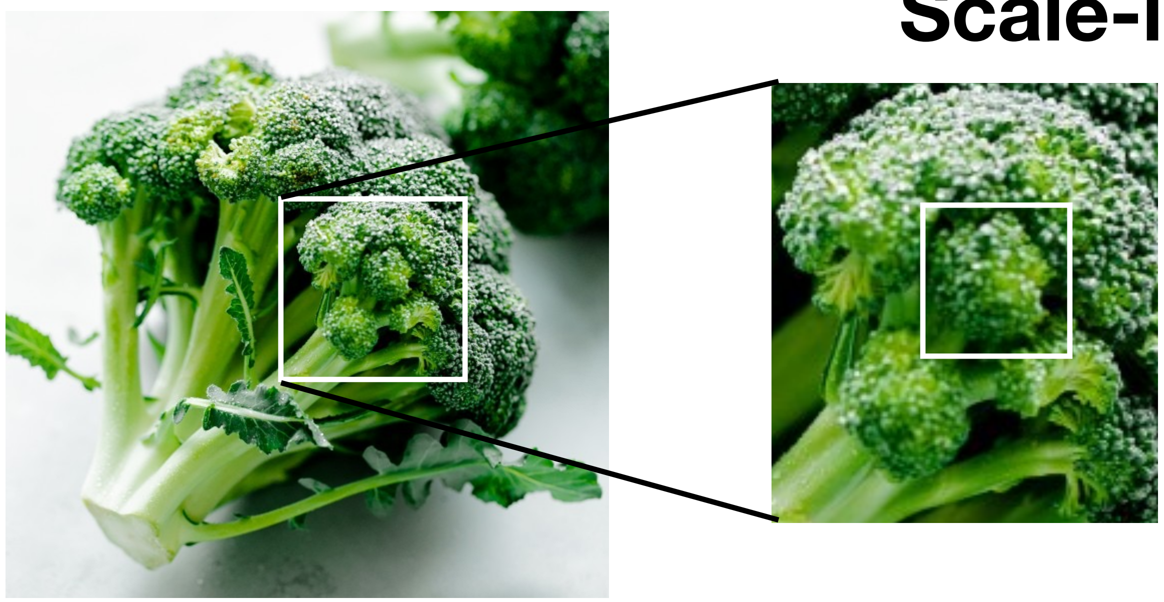
Quantum fluctuations of gravity ``shield” gravitational interaction in the UV



$$\beta_G = 2G - \#\, G^2 + ...$$

Asymptotically safe gravity - key idea

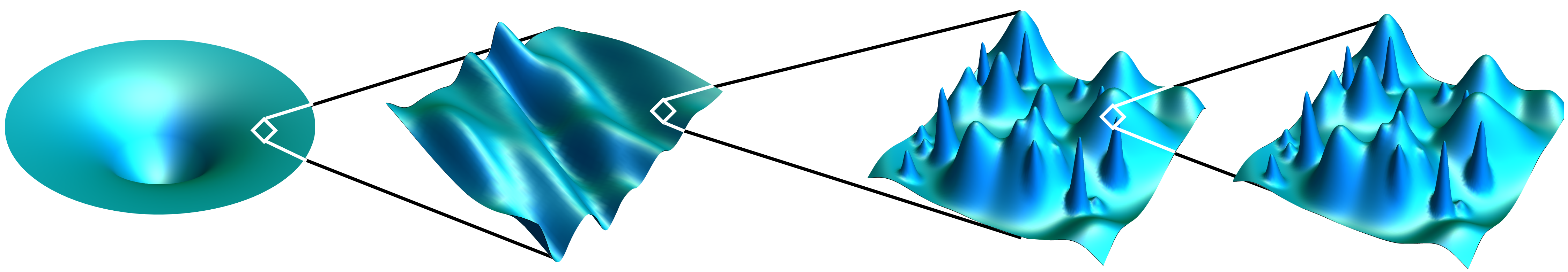
Scale-invariance made intuitive



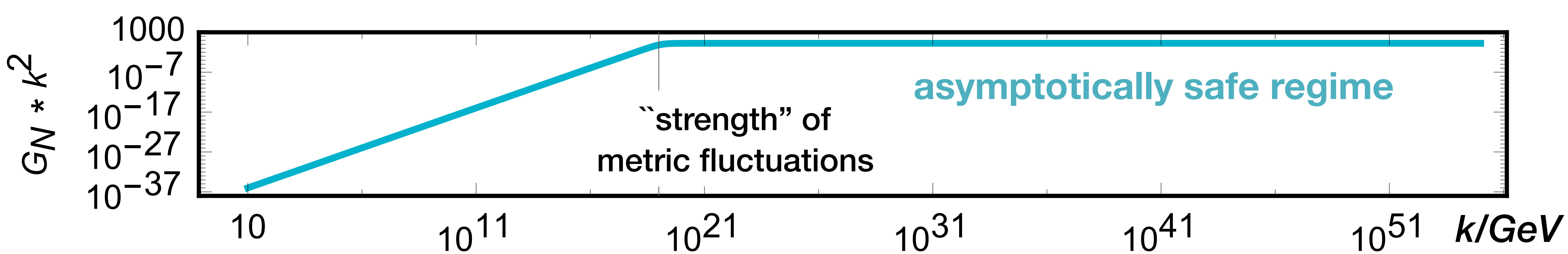
changes of the ``zoom factor" have no effect

fractal-like quantum spacetime

[Lauscher, Reuter '05; Reuter, Saueressig '10; Calcagni, A.E., Saueressig '13]



classical gravity regime   Planck scale   quantum scale invariance



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Asymptotically safe gravity - status and open questions

status:

compelling indications for asymptotically safe fixed point in pure Euclidean gravity from truncated functional RG studies (Wetterich-equation) [Reuter '96]

fixed point	operators	
✓	$\sqrt{g}$	[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Becker, Reuter '14;
✓	$\sqrt{g}R$	Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15]
✓	$\sqrt{g}R^2,\ \sqrt{g}R^{\mu\nu}R_{\mu\nu}$	[Benedetti, Machado, Saueressig '09; Denz, Pawlowski, Reichert '17]
✓	$\sqrt{g}R^3$	[Codello, Percacci, Rahmede '07, '08 Machado, Saueressig '07; A.E. '15]
. . .	. . .	
✓	$\sqrt{g}R^{70}$	[Falls, Litim, Nikolakopoulos, Rahmede '13 '14; Falls, Litim, Schroeder '18] [Christiansen, Falls, Pawlowski, Reichert '17]
✓	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[Gies, Knorr, Lippoldt, Saueressig '16]

open questions/ongoing work:

- **quantitative apparent convergence (in particular with matter)**
- **background independence**
- **Lorentzian signature**
- **unitarity/ghosts (note subtleties in QG case)**

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assumption for rest of this talk: asymptotic safety in gravity -> Consequences for matter?

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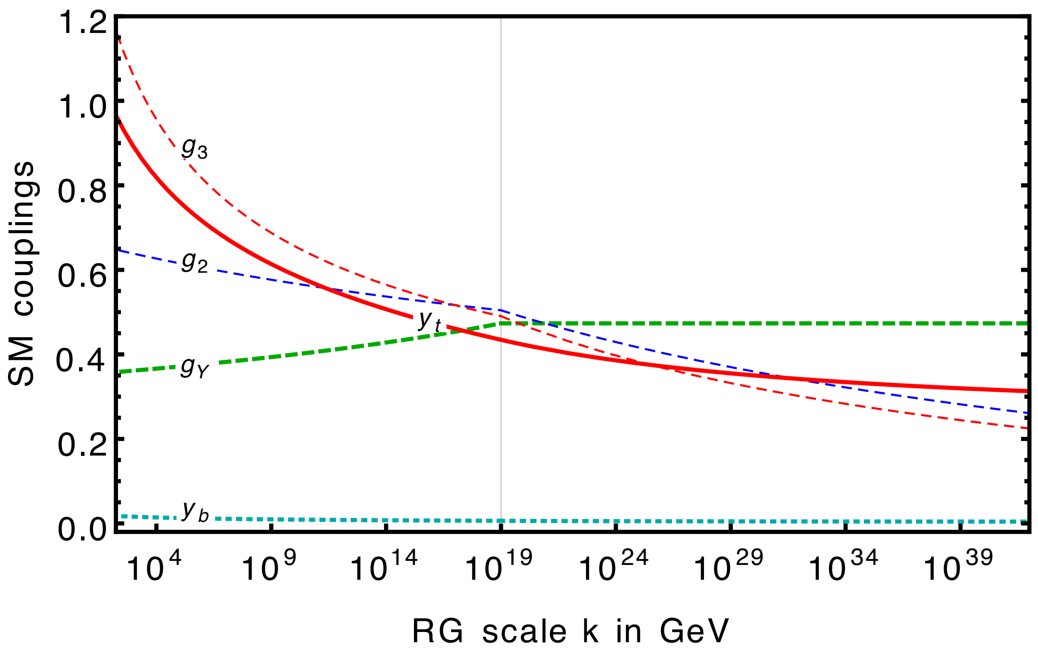
Asymptotically safe guide to the literature on SM + QG:



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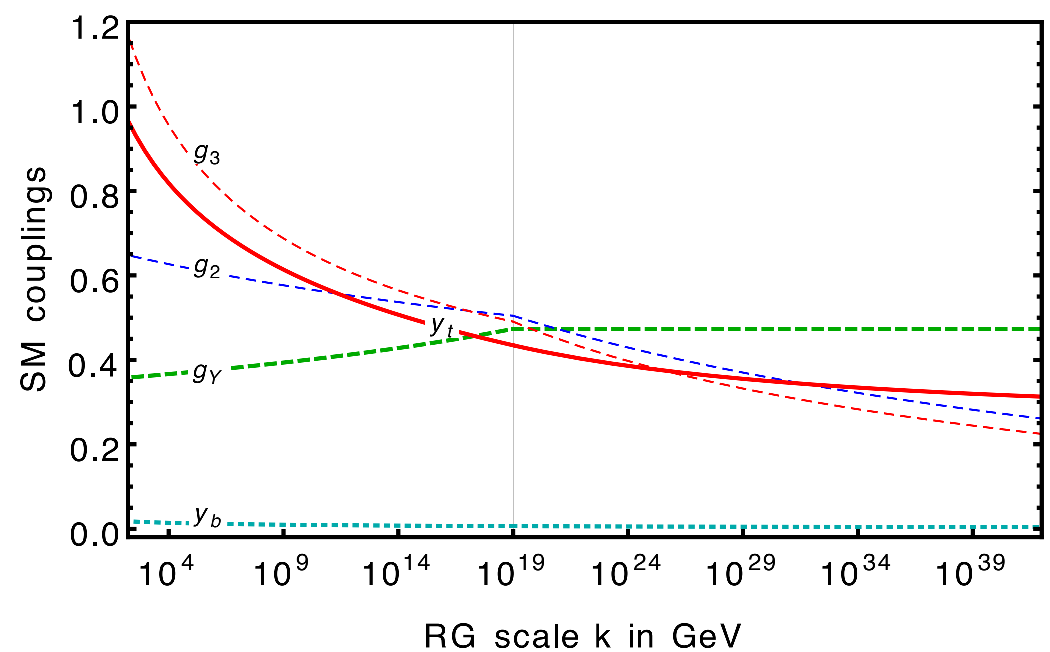

Hints in truncations of RG flow from functional RG techniques that SM could become UV complete by AS quantum gravity fluctuations:

- AF in non-Abelian couplings preserved

[Daum, Harst, Reuter JHEP 1001 (2010) 084; Folkerts, Litim, Pawlowski, Phys.Lett. B709 (2012) 234-241;
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- AF/AS in U(1)

[Harst, Reuter JHEP 1105 (2011) 119; Christiansen, AE, Phys.Lett. B770 (2017) 154-160; AE, Versteegen JHEP 1801 (2018) 030]

- Higgs quartic vanishes (approximately?) at Planck scale

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Pawlowski, Reichert, Wetterich, Yamada arXiv:1811.11706]

- AF/AS in Yukawas

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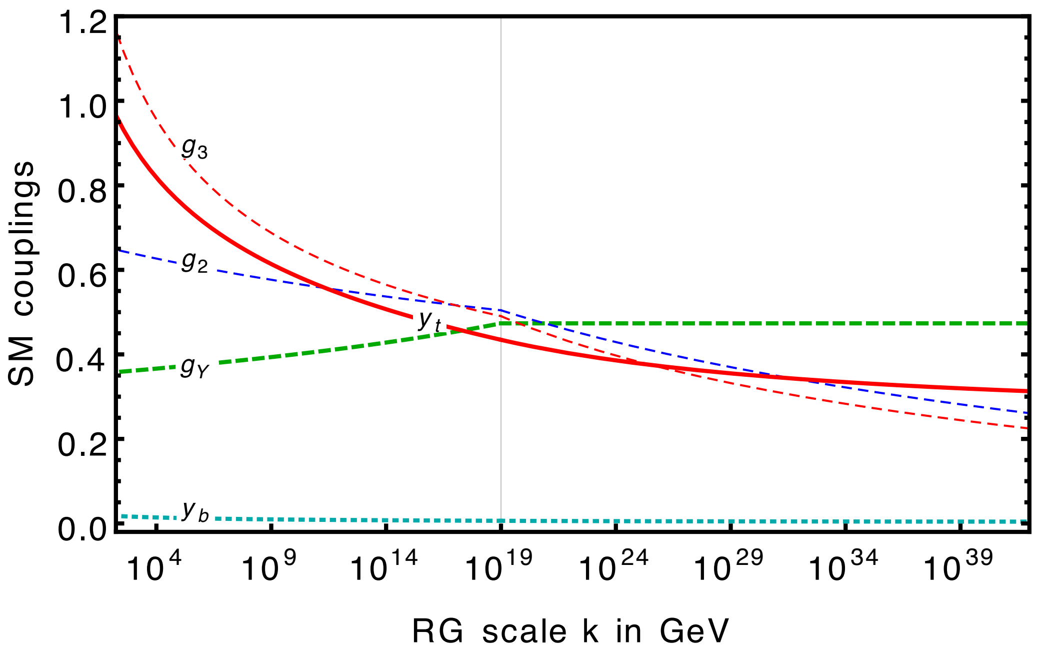

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Predictive power of asymptotic safety - proof of principle: Abelian gauge coupling

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- **Asymptotically safe quantum gravity could act like effective change of dimensionality**

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

metric fluctuations

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

$f_g \to 0$ below M_{pl}

[Daum, Harst, Reuter ’09;
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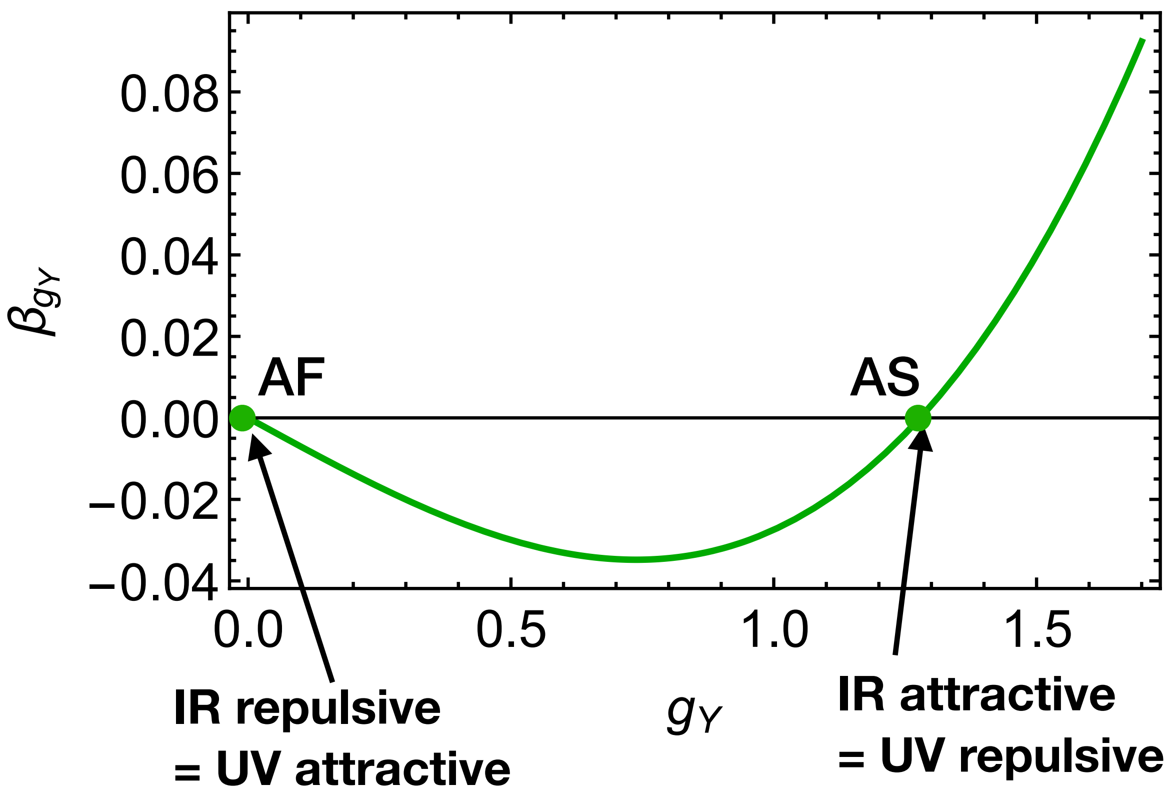

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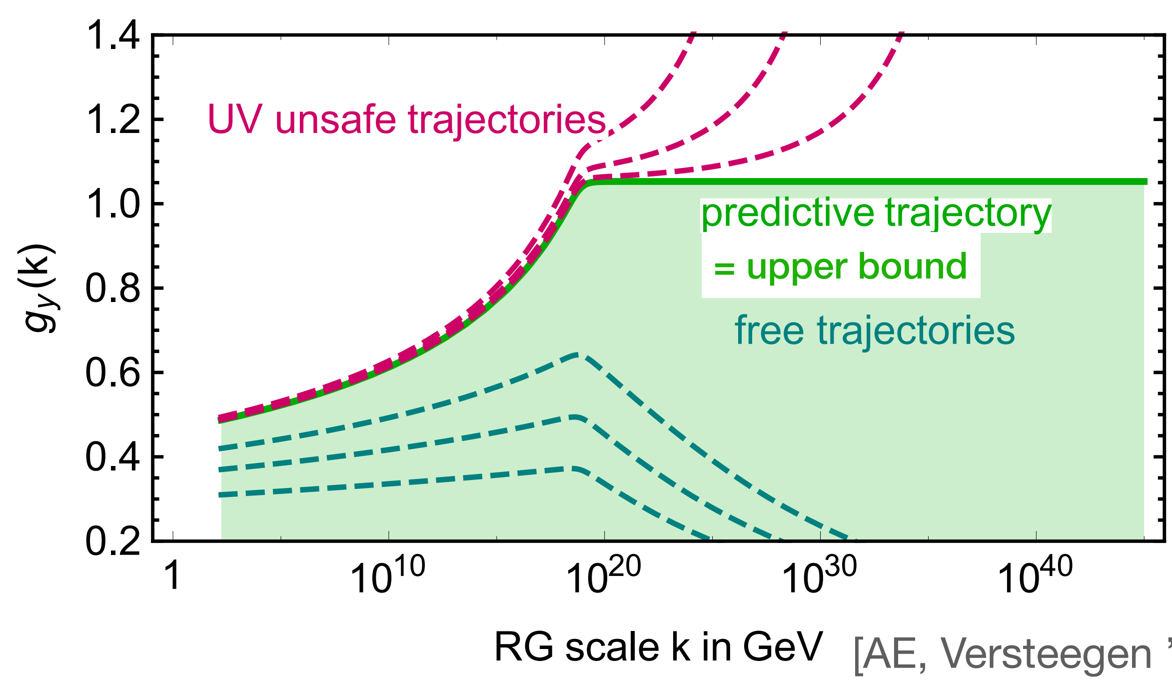
matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting



[AE, Versteegen '17]

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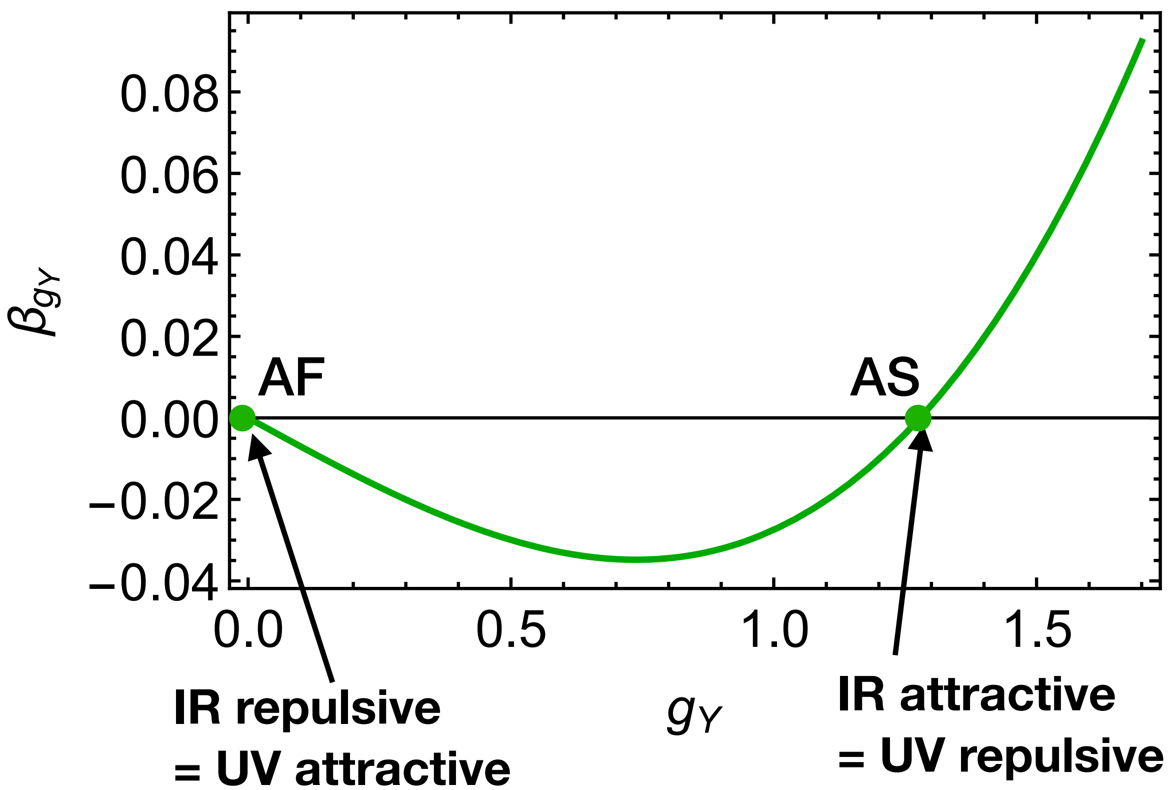

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$\Rightarrow$ **large IR values of g_Y cannot be reached from any fixed point**

$\Rightarrow$ **bound on g_Y is unique value reached from interacting fixed point**

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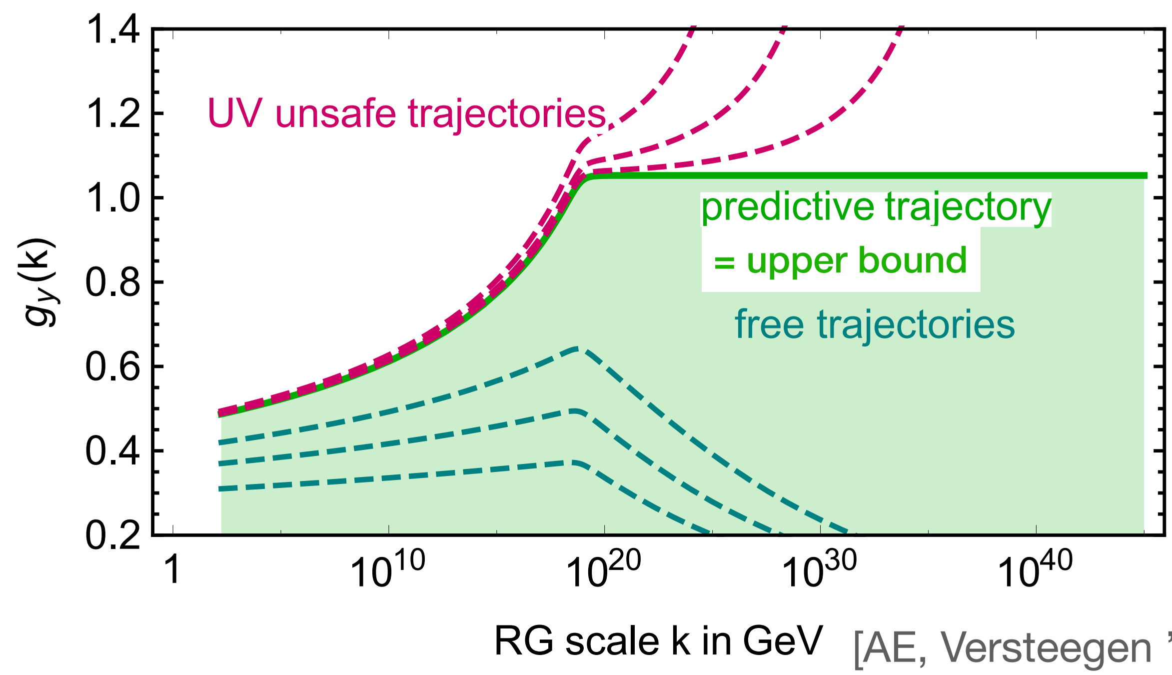

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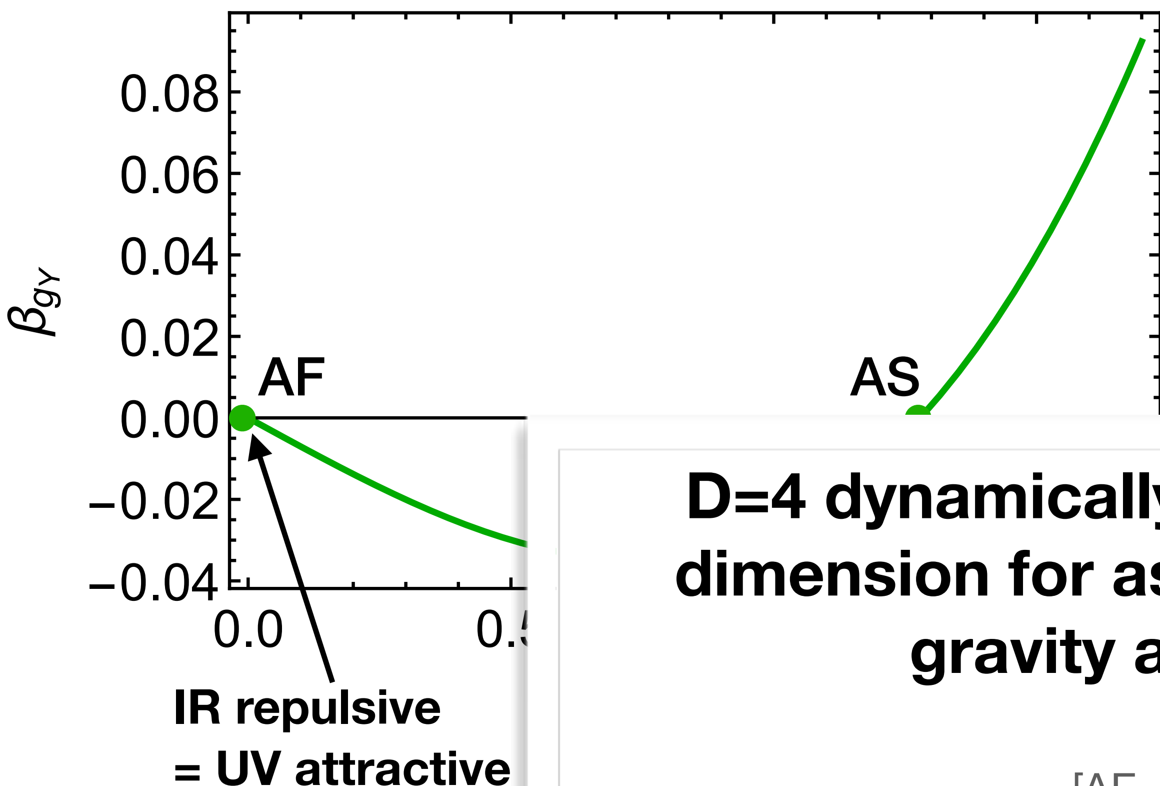

D=4 dynamically selected critical dimension for asymptotically safe gravity and matter

[AE, Schiffer ’19]

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om any fixed point

is unique value
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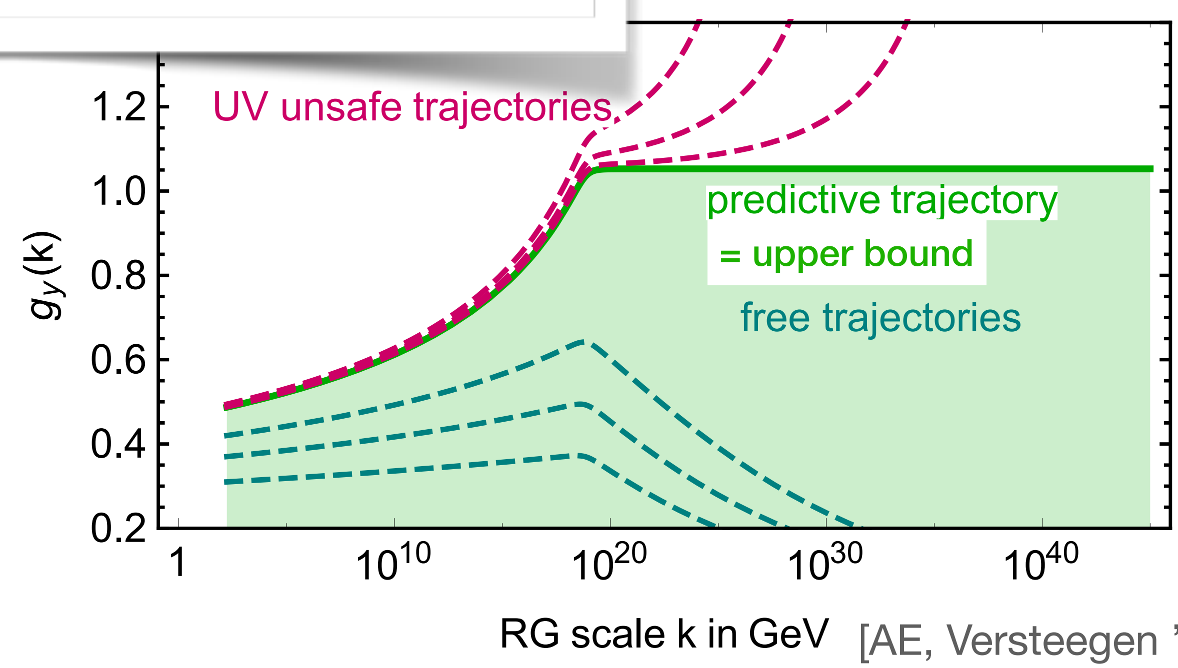

[AE, Versteegen ’17]

Top mass, bottom mass and Abelian gauge coupling from asymptotic safety

[AE, Held 1803.04027 , Phys.Rev.Lett. 121 (2018) no.15, 151302]

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

$$\rightarrow g_{Y\,*} > 0$$

Top & bottom Yukawa: *

$$\beta_{y_{t/b}} = \frac{3}{16\pi^2} y_{t/b}^3 - f_y\, y_{t/b}$$

$$\rightarrow y_{t,b\,*} > 0$$

gravity is ``flavor-blind"

* $f_y > 0$ **restricts viable space of microscopic coupling values** [AE, Held '17]

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Top & bottom Yukawa: *

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

$\rightarrow y_{t,b\,*} > 0$ unequal hypercharge of top, bottom: unequal fixed-point values

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

$\rightarrow$ **unique set** $(M_t, M_b, g_Y(k_{\rm ew}))$

* $f_y > 0$ **restricts viable space of microscopic coupling values** [AE, Held '17]

Top mass, bottom mass and Abelian gauge coupling from asymptotic safety

[AE, Held 1803.04027 , Phys.Rev.Lett. 121 (2018) no.15, 151302]

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

$$\rightarrow g_{Y\,*} > 0$$

Top & bottom Yukawa:

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

$\rightarrow y_{t,b\,*} > 0$ unequal hypercharge of top, bottom: unequal fixed-point values

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Proposed mechanism to explain $M_b \ll M_t$

QG induces finite fixed-point values for $y_{t,b}$

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Is there a point in space of micr. grav. couplings where this works quantitatively?

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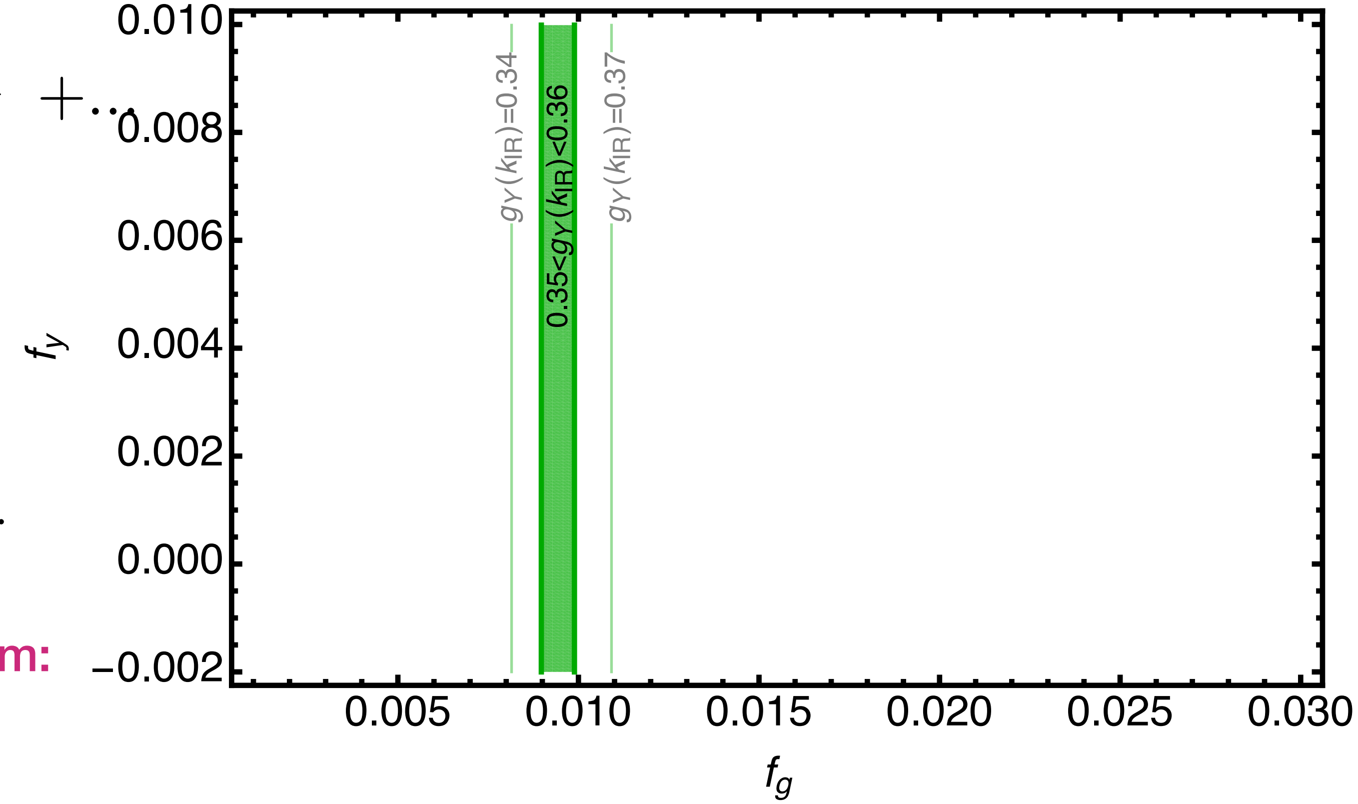

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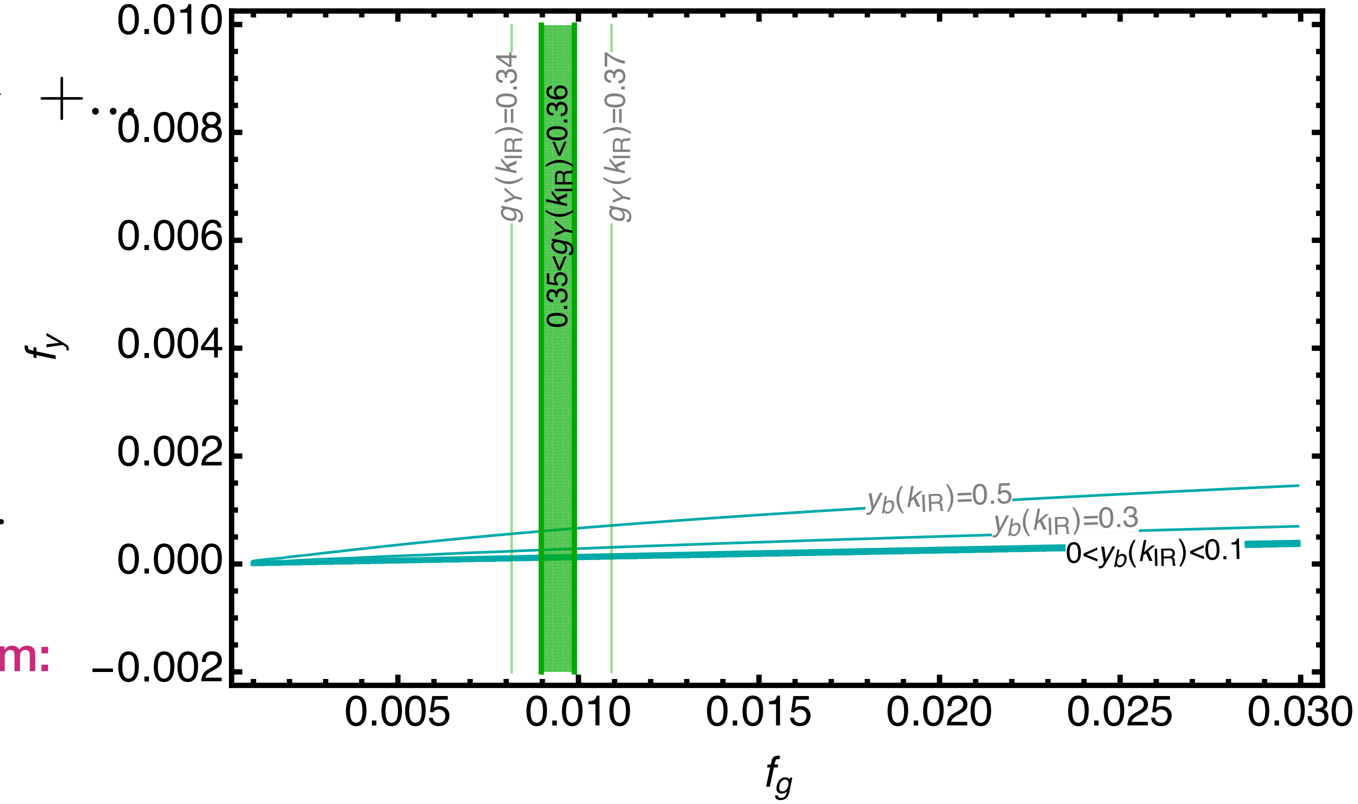

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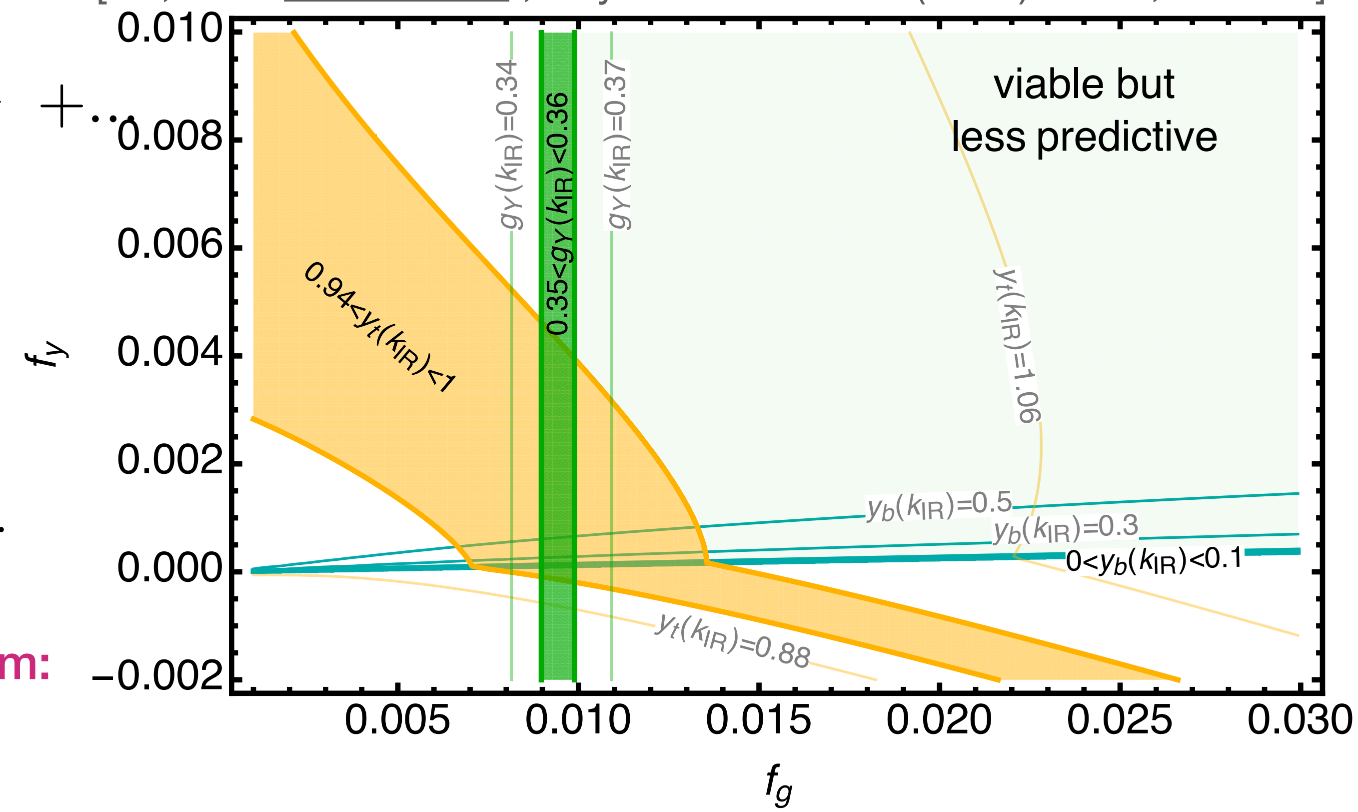

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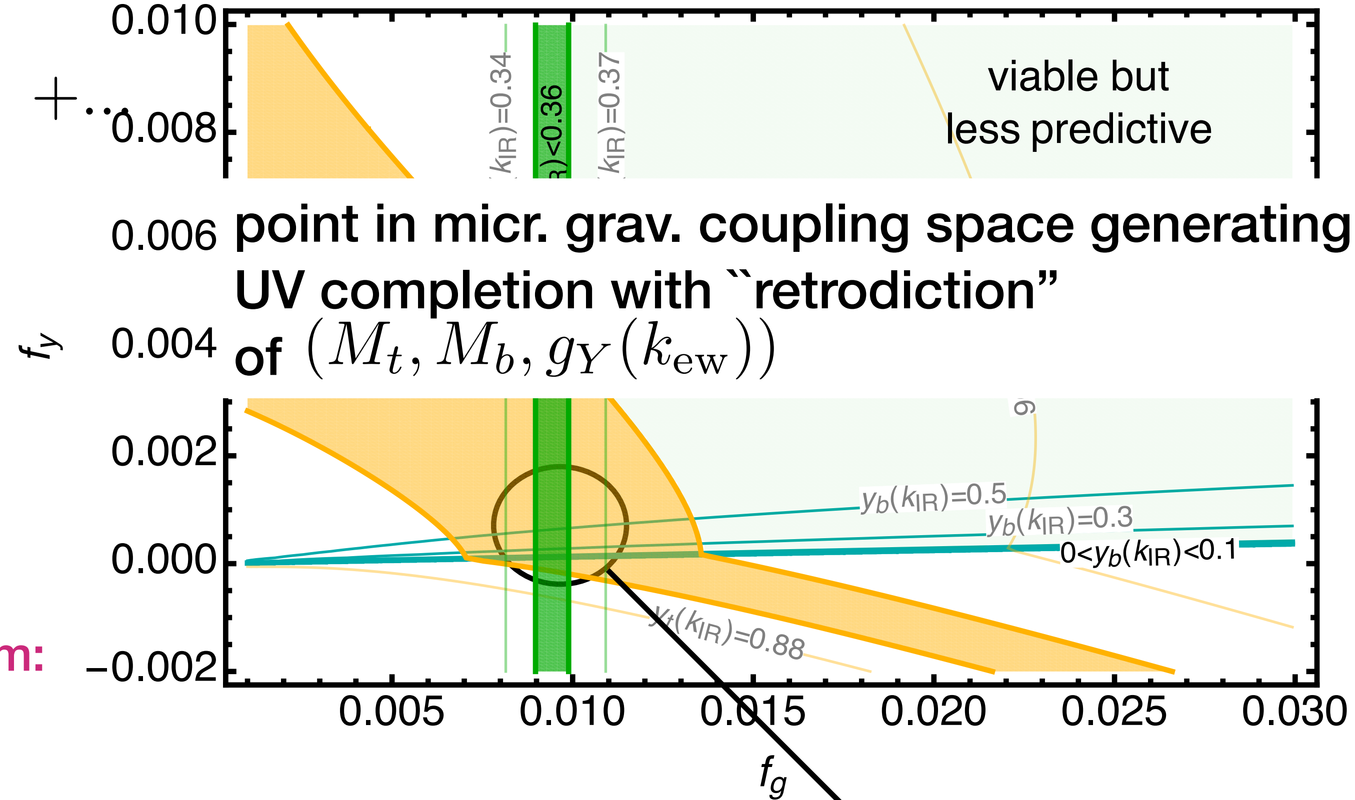

point in micr. grav. coupling space generating UV completion with ``retrodiction" of $(M_t, M_b, g_Y(k_{ew}))$

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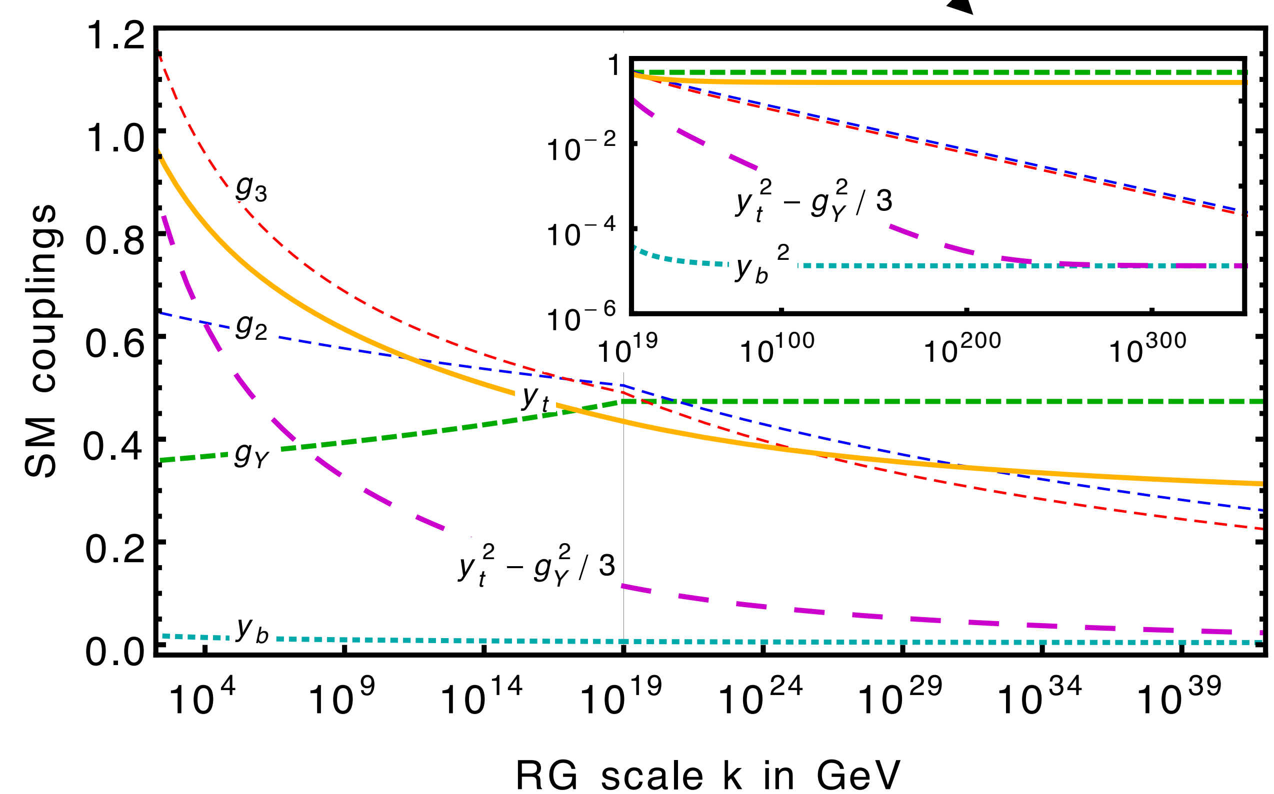

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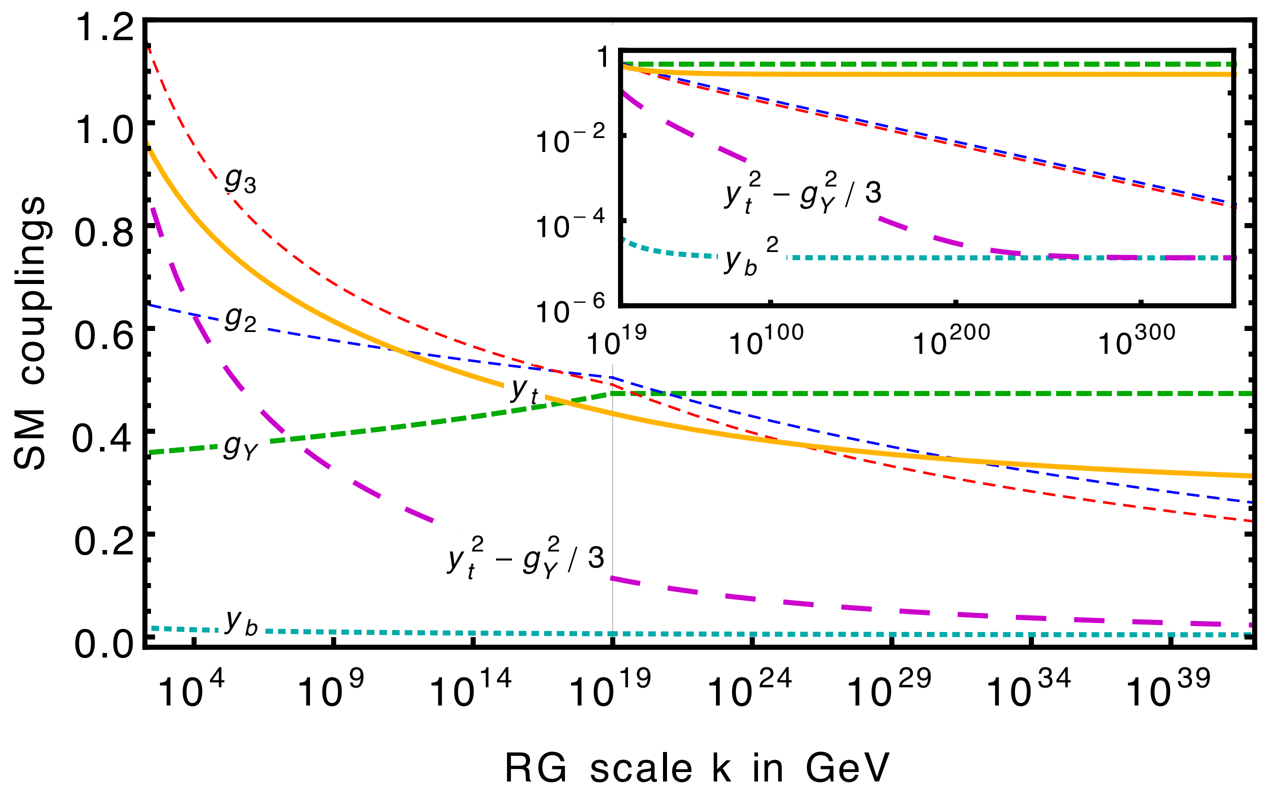
[AE, Held 1803.04027 , Phys.Rev.Lett. 121 (2018) no.15, 151302]



Is this in fact asymptotically safe gravity?

What requirements must new physics satisfy to yield these retrodictions?

Three observations

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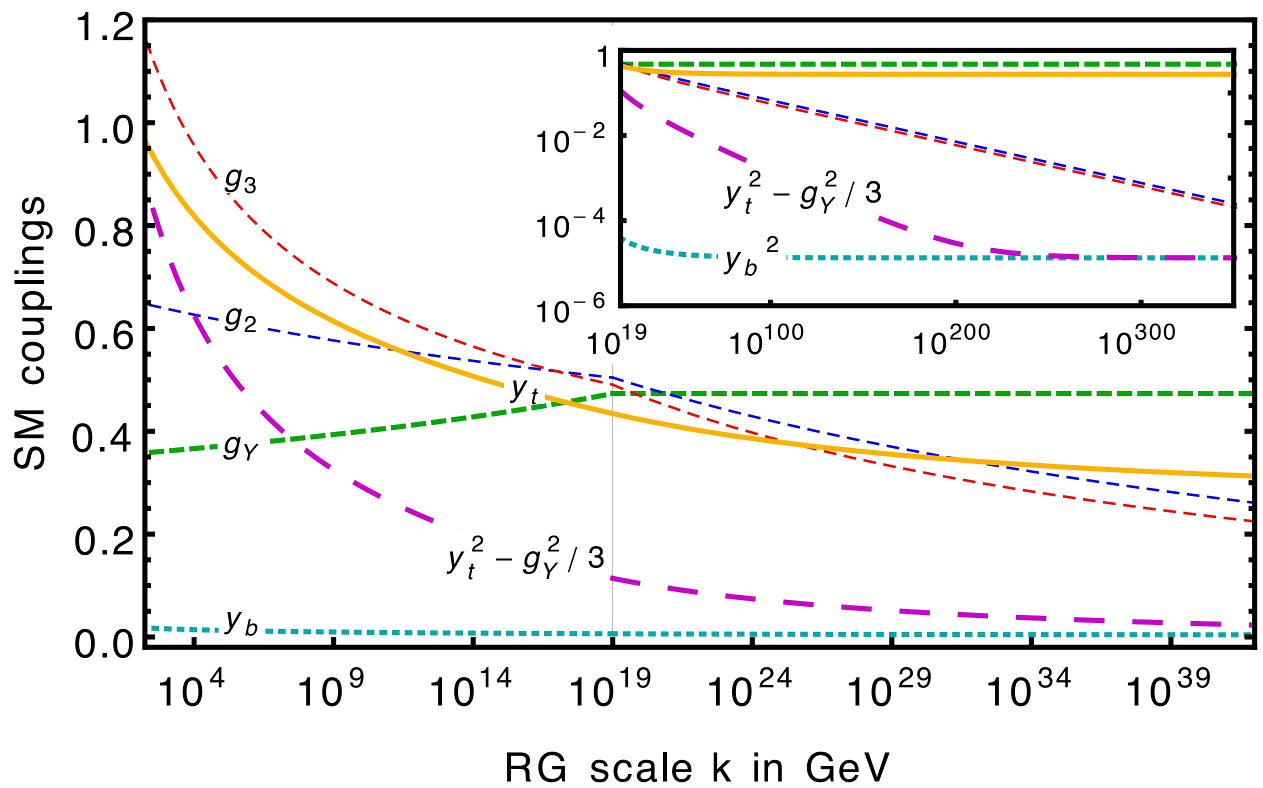


- **transplanckian flow of Yukawas driven by non-Abelian flow away from AF**

  $\longrightarrow$ \`\`speed" of non-Abelian flow impacts retrodictions

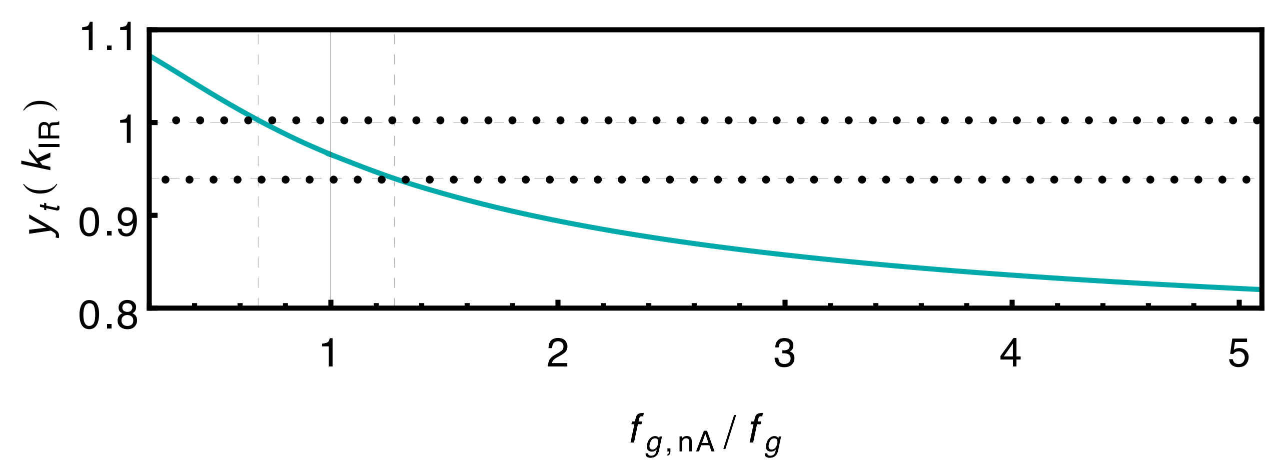
Abelian hypercharge: $\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y$

SU(2): $\beta_{g_2} = \frac{-19 g_2^3}{6\cdot 16\pi^2} - f_{g,\text{nA}}\, g_2$

SU(3): $\beta_{g_3} = \frac{-7 g_3^3}{16\pi^2} - f_{g,\text{nA}}\, g_3$

universality (= blindness to internal symmetries) of QG

test if non-universal (= non-QG) contributions do better:



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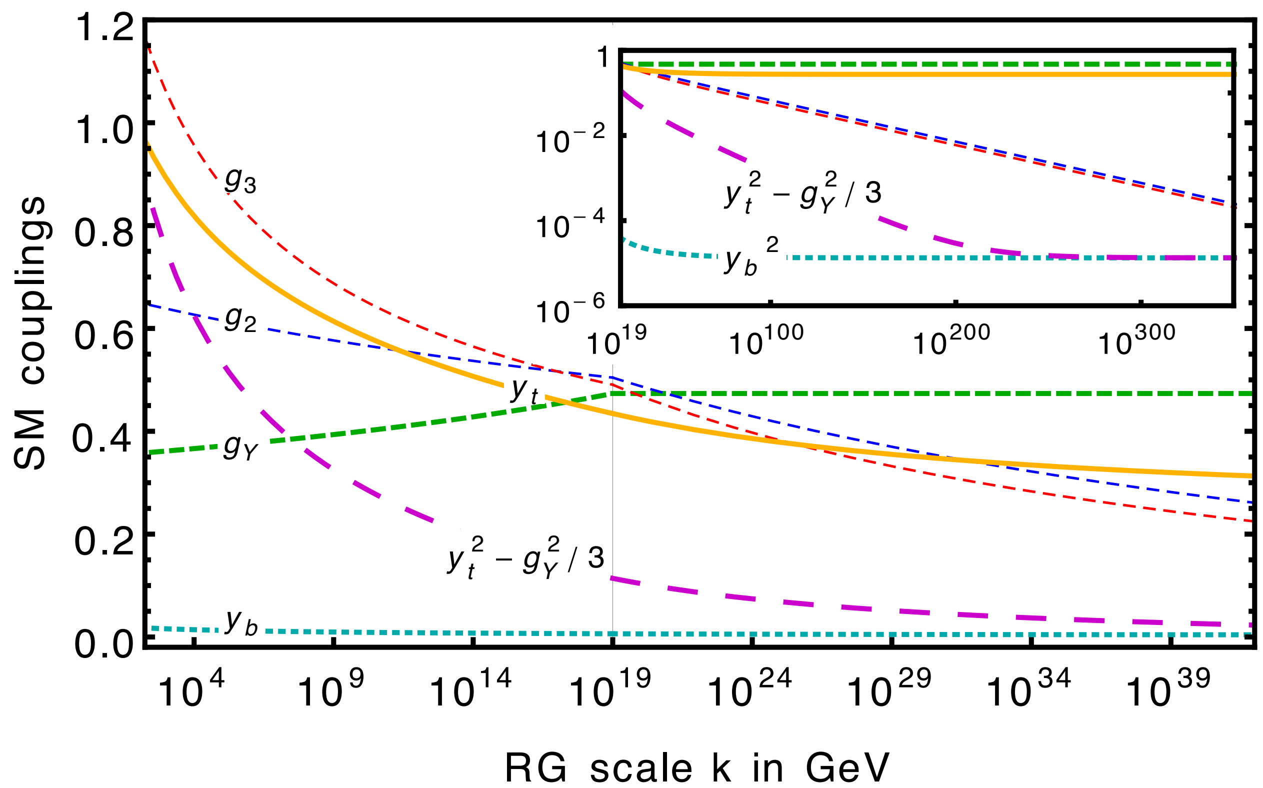
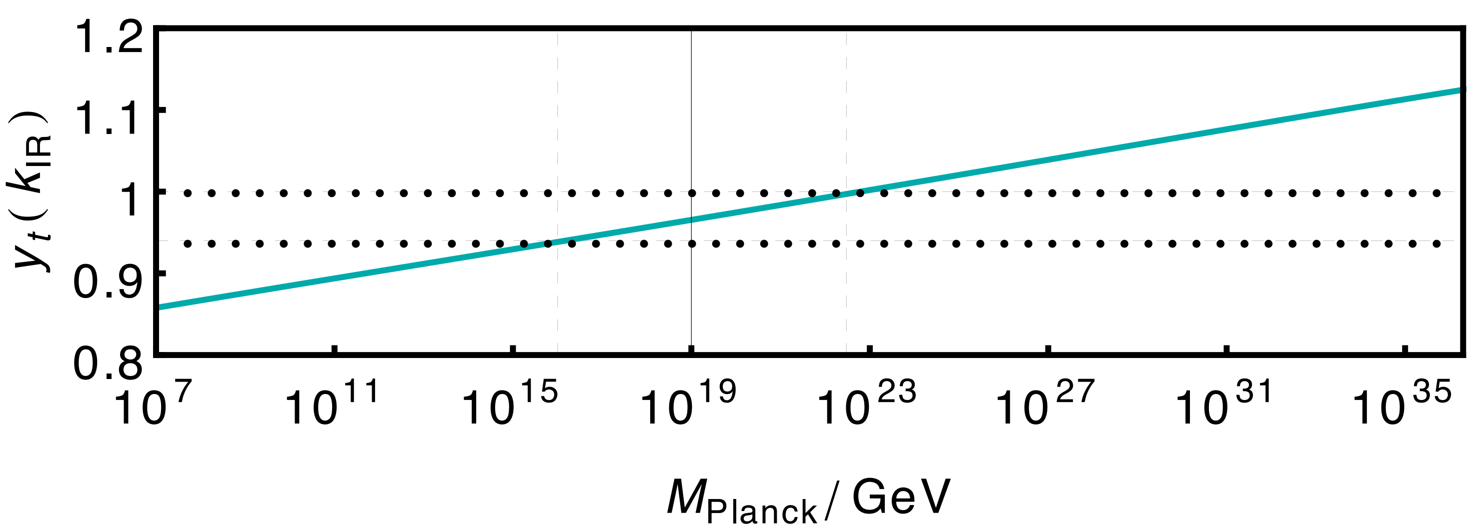


$f_i = \text{const} \geq 0$ **above M_{pl}**

$f_i \to 0$ **below M_{pl}**

input of Planck scale is an assumption - maybe other scales do better?



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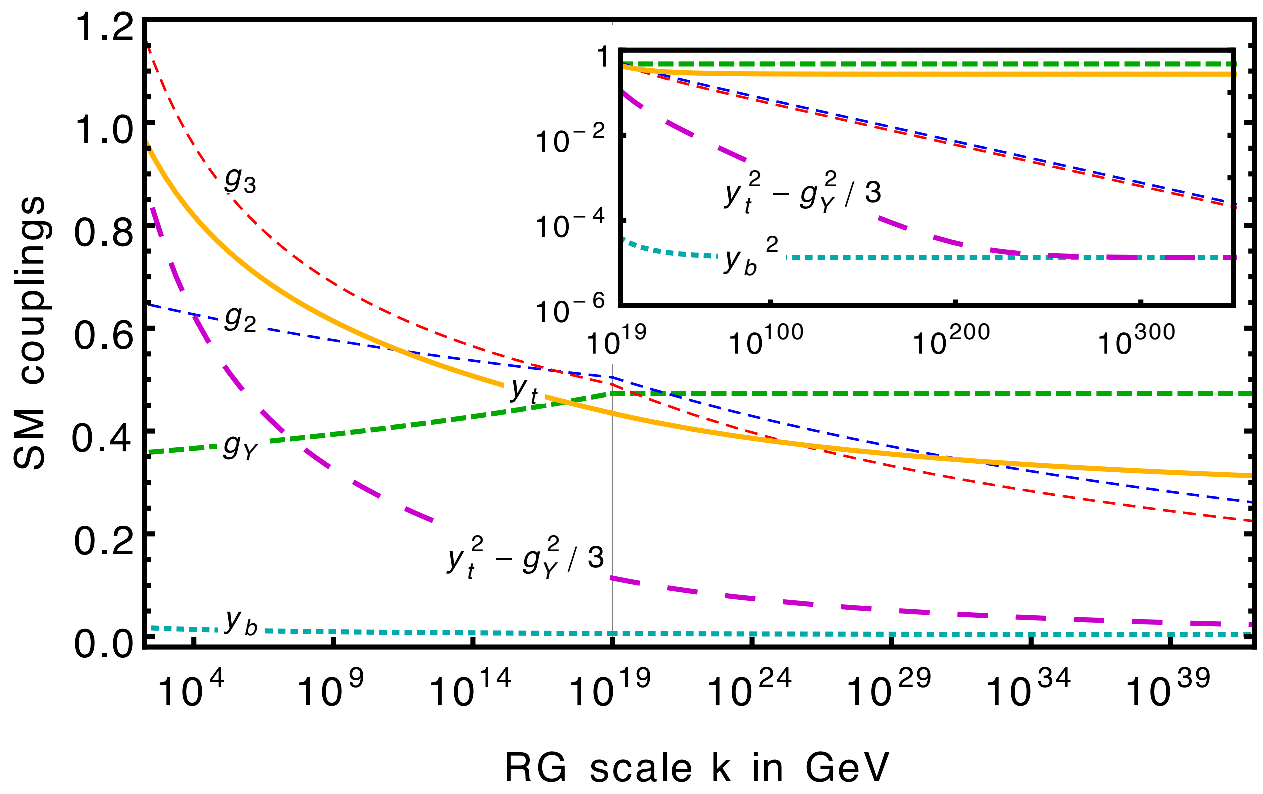

1) **constant linear contributions**

2) **universal contributions**

(indep. of internal symmetries)

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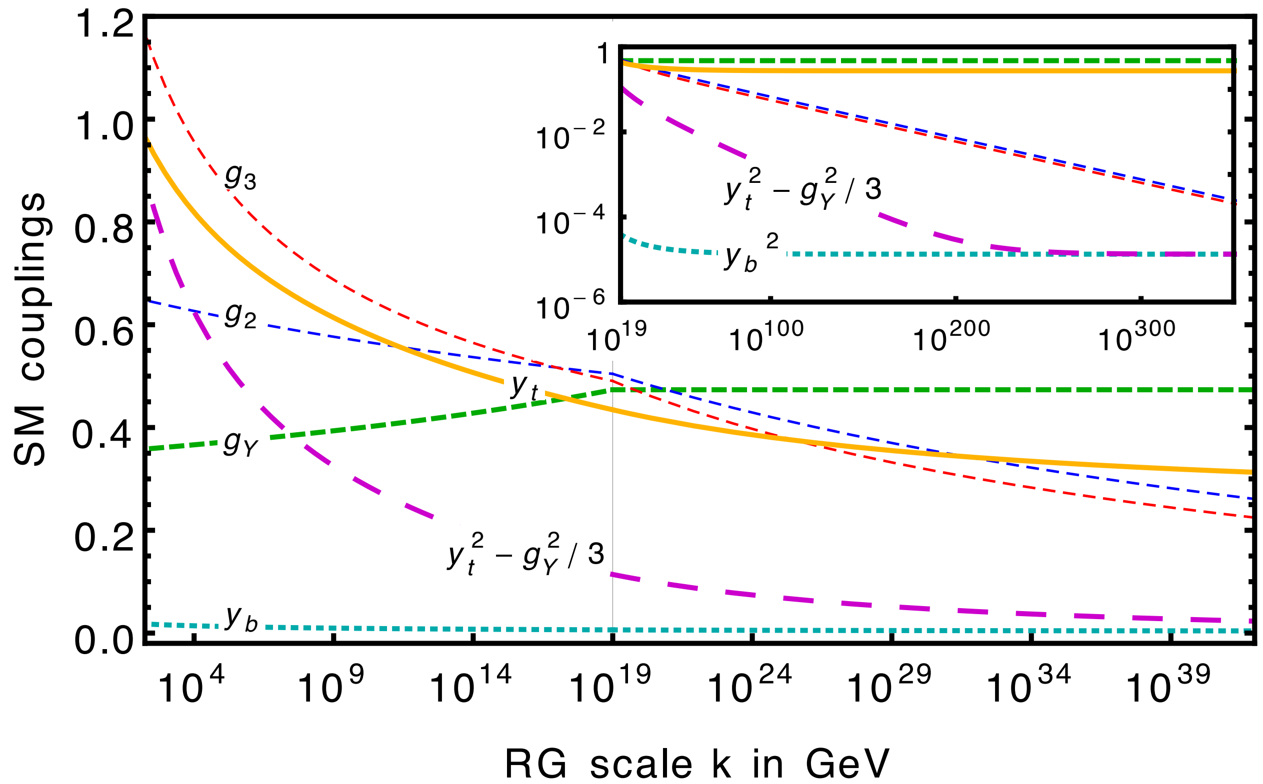

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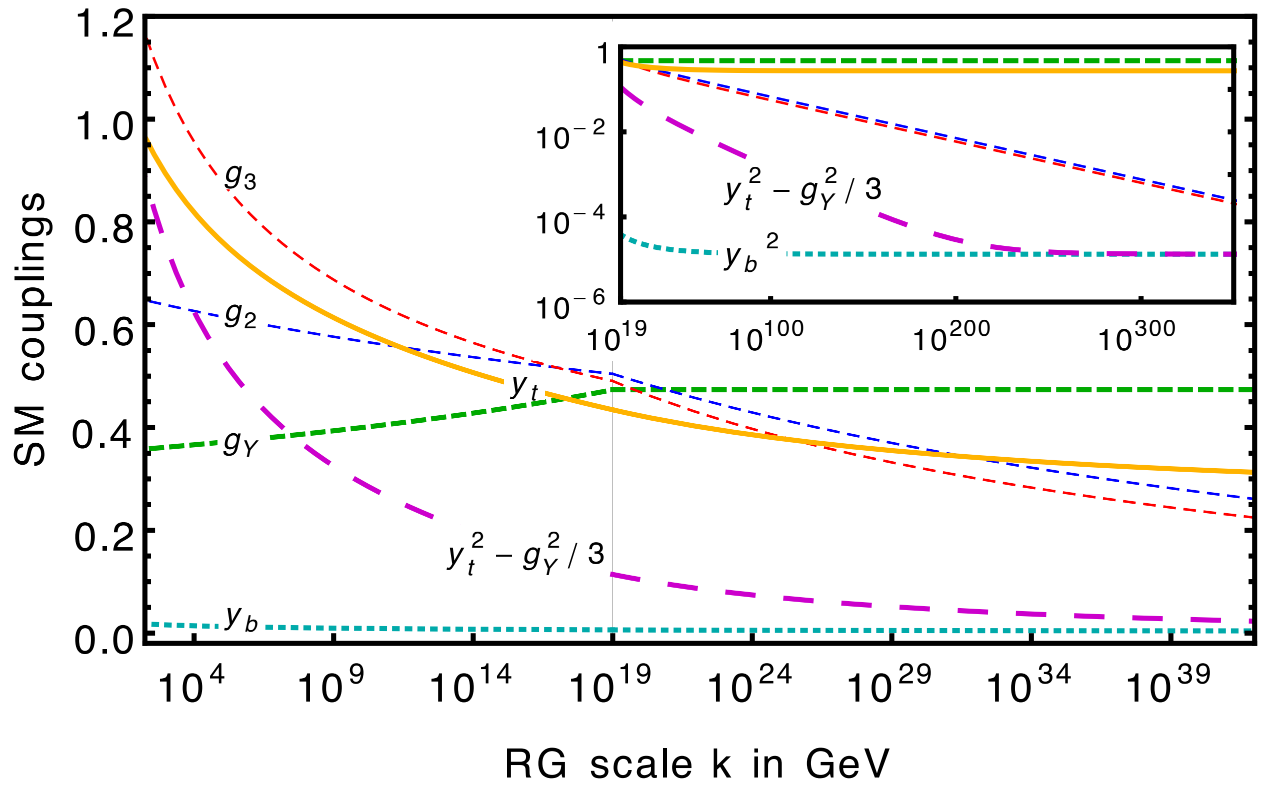

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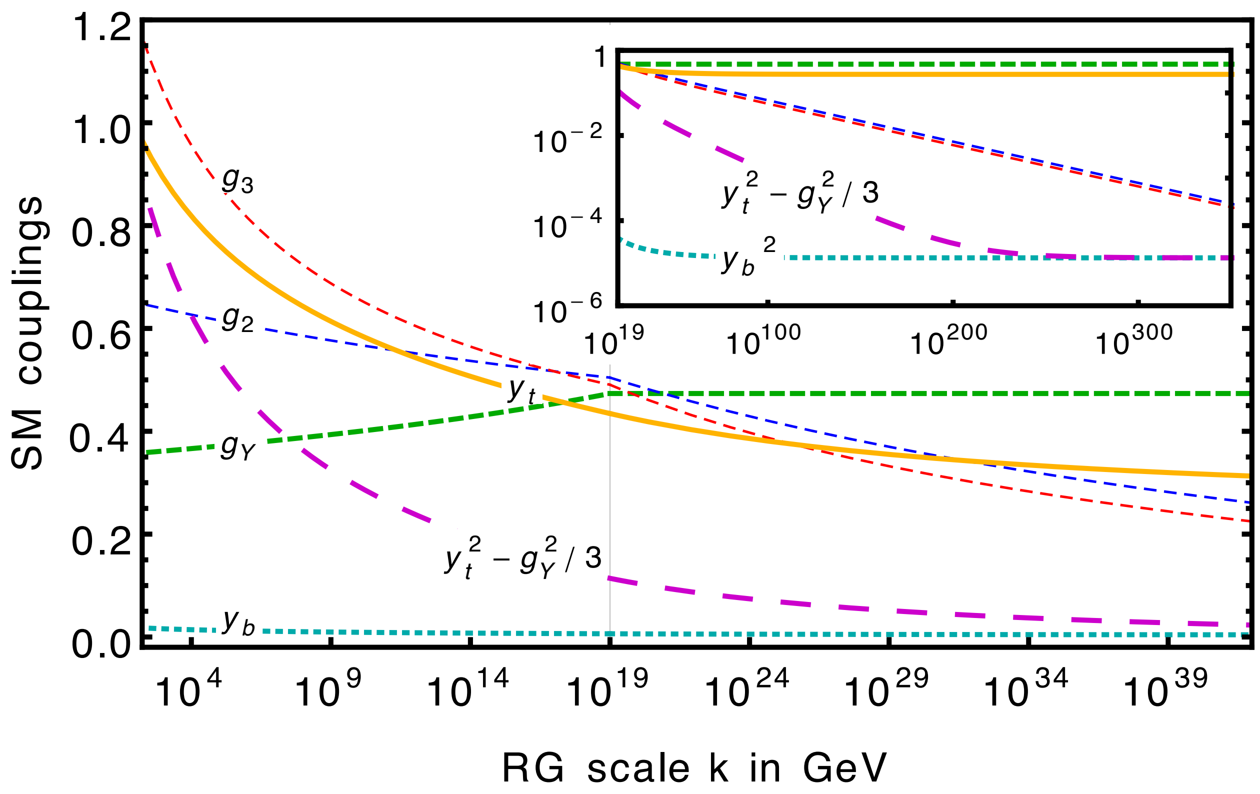
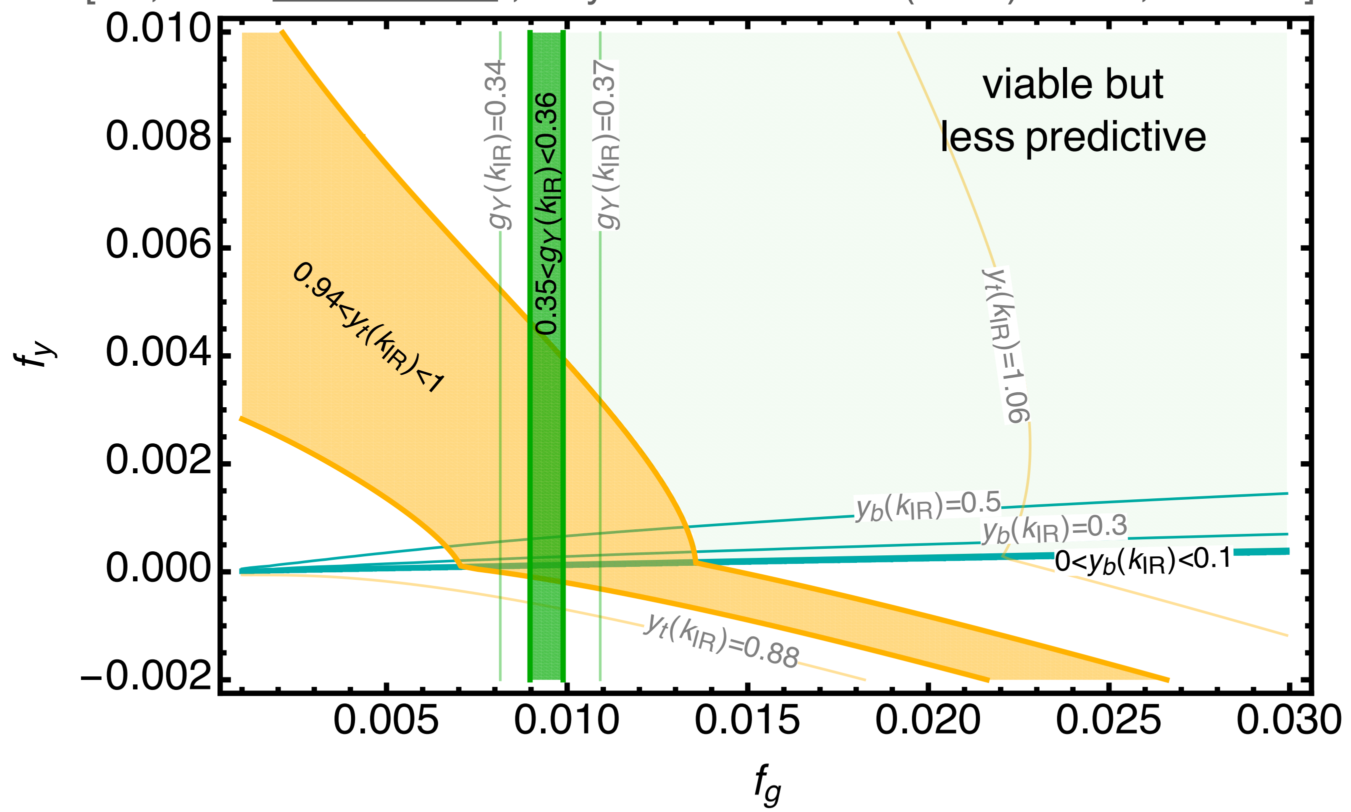
probably asymptotically safe quantum gravity…

…effectively like dimensional reduction

Charges & Masses are linked?

[AE, Held 1803.04027 , Phys.Rev.Lett. 121 (2018) no.15, 151302]





obtained for SM hypercharge values

Can other charge assignments do better?

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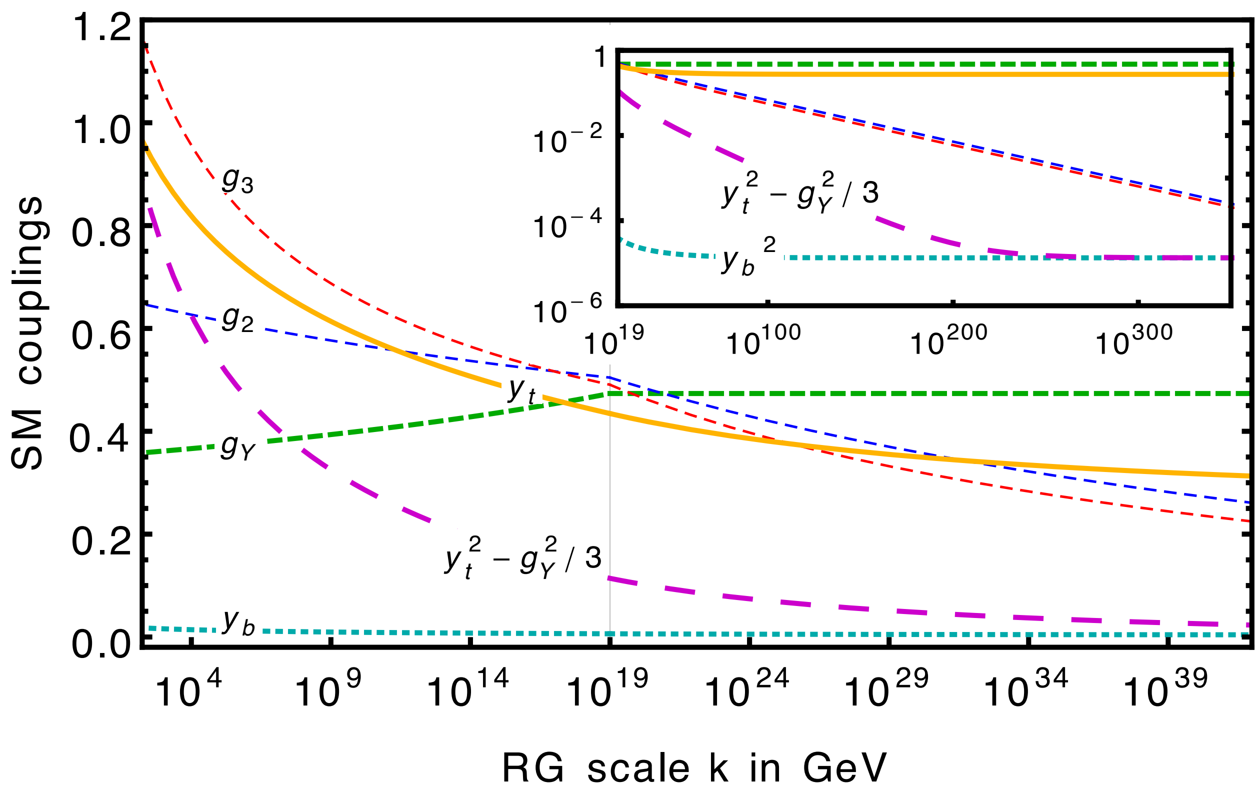

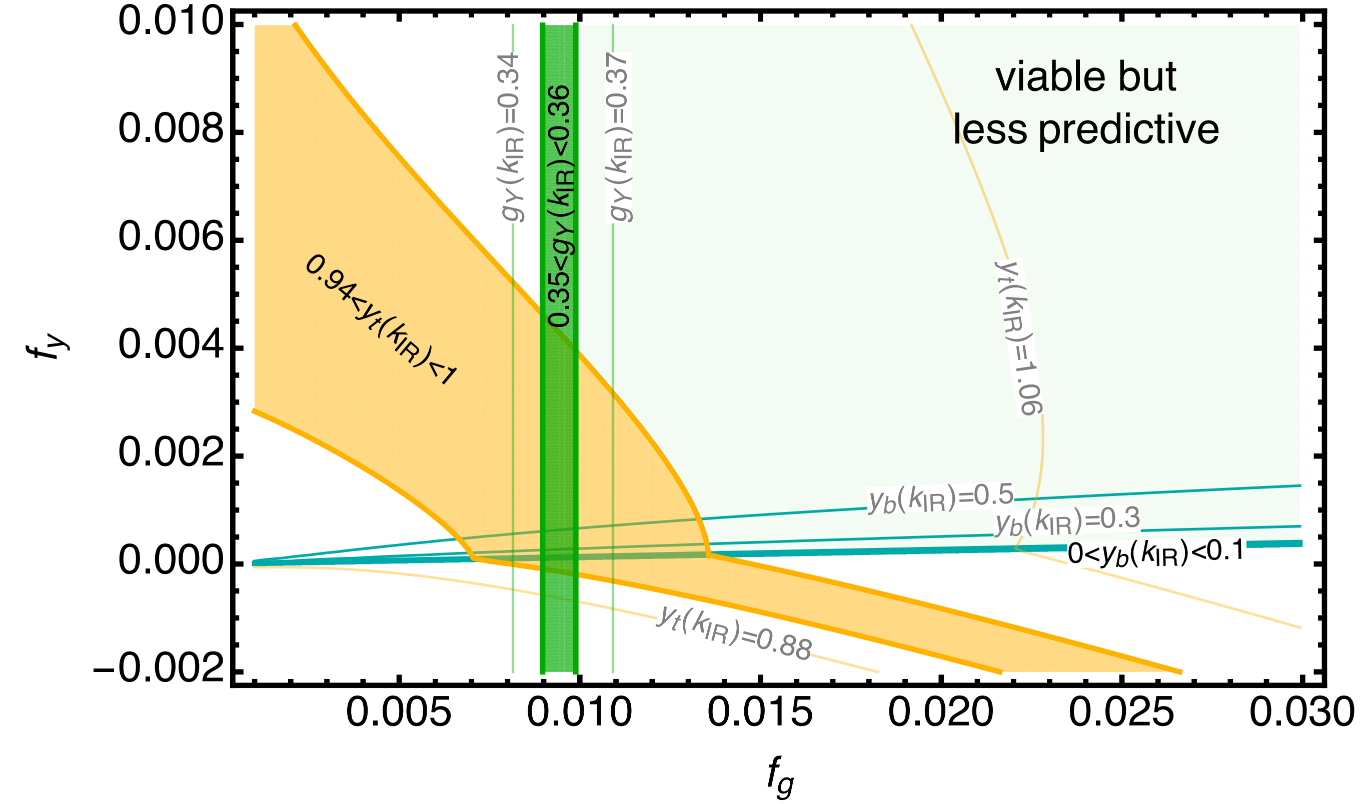

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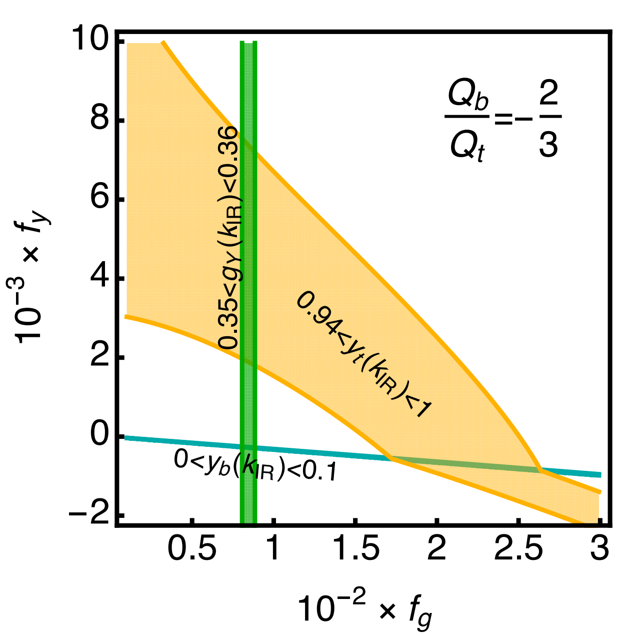

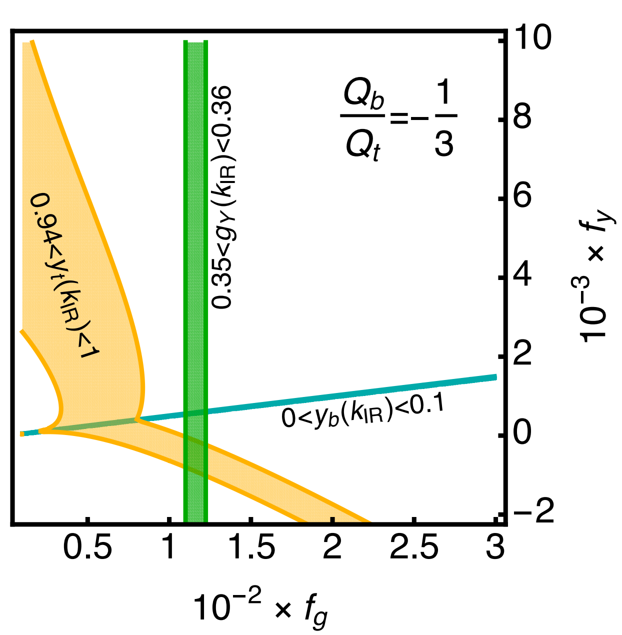

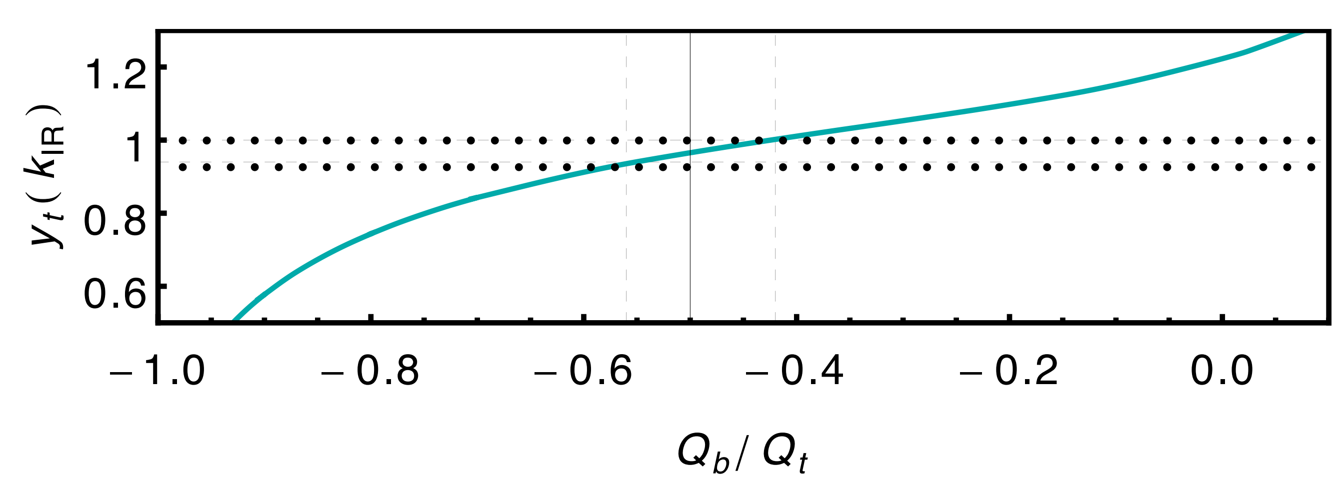

masses of top & bottom select SM top/bottom charge ratio

Asymptotic safety
- a new paradigm for model building at and beyond the LHC?

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Mechanisms for asymptotic safety

@ Planck scale

Asymptotically safe BSM physics

- **``effective dimensional reduction" from QG**

$\longrightarrow$ **vanishing Higgs portal coupling to uncharged scalar dark matter**

[AE, Hamada, Lumma, Yamada Phys.Rev. D97 (2018) no.8, 086004]

$\longrightarrow$ **unified gauge coupling calculable & viable breaking chains restricted in GUT settings**

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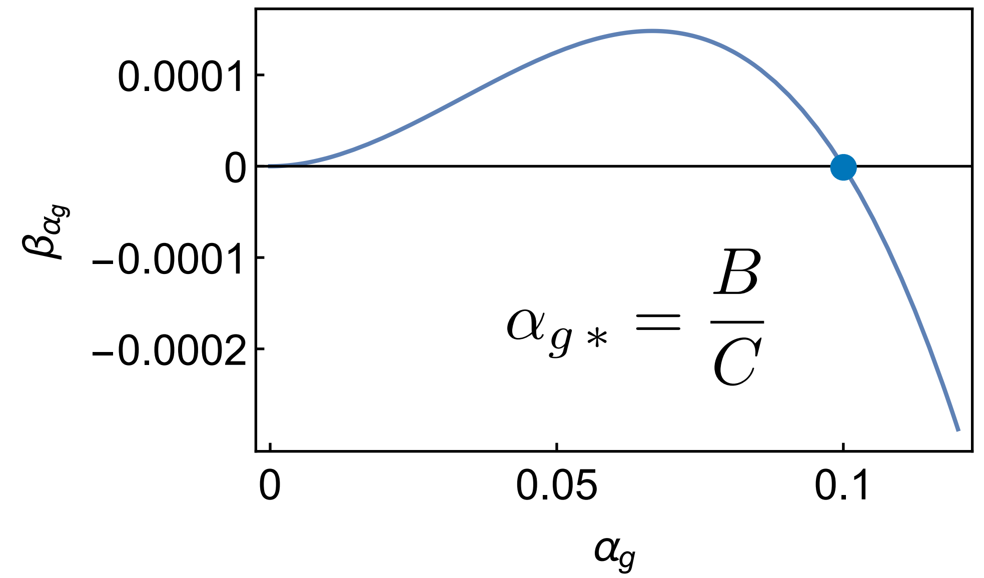

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- **competing degrees of freedom**

$$\beta_\lambda = \beta^{(\text{bosonic})} - \beta^{(\text{fermionic})}$$

first tentative hints in fermionic Higgs portal

[AE, Held, Vander Griend HEP 1808 (2018) 147]

analysis of Higgs stability:

[Held, Sondenheimer arXiv:1811.07898]

…in a nutshell

- asymptotic safety = UV completion for QFTs through scale-invariant fixed-point regime

- compelling indications for fixed point in pure gravity (open questions: Lorentzian, background-independent, unitary?)

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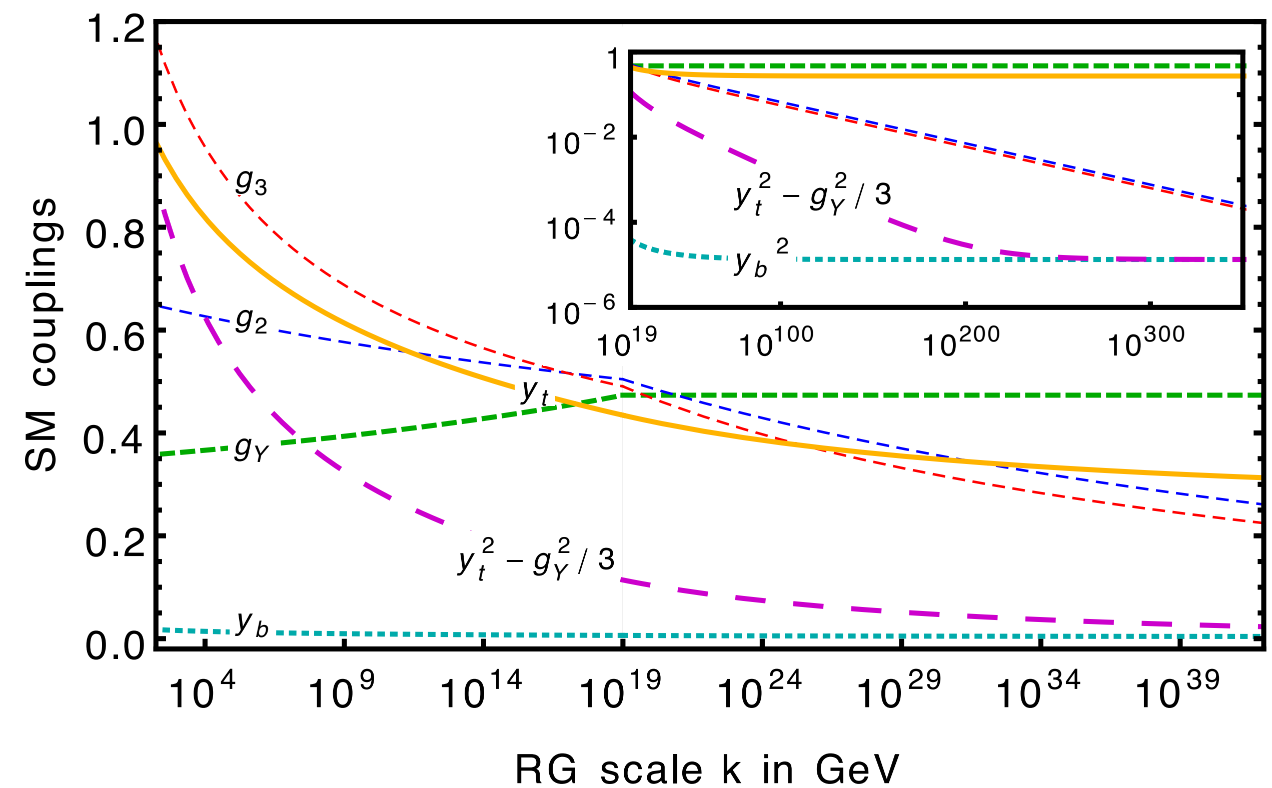
  - **become subject to observational consistency tests**

Example:
Different masses of top and bottom generated from different charges through fixed-point structure



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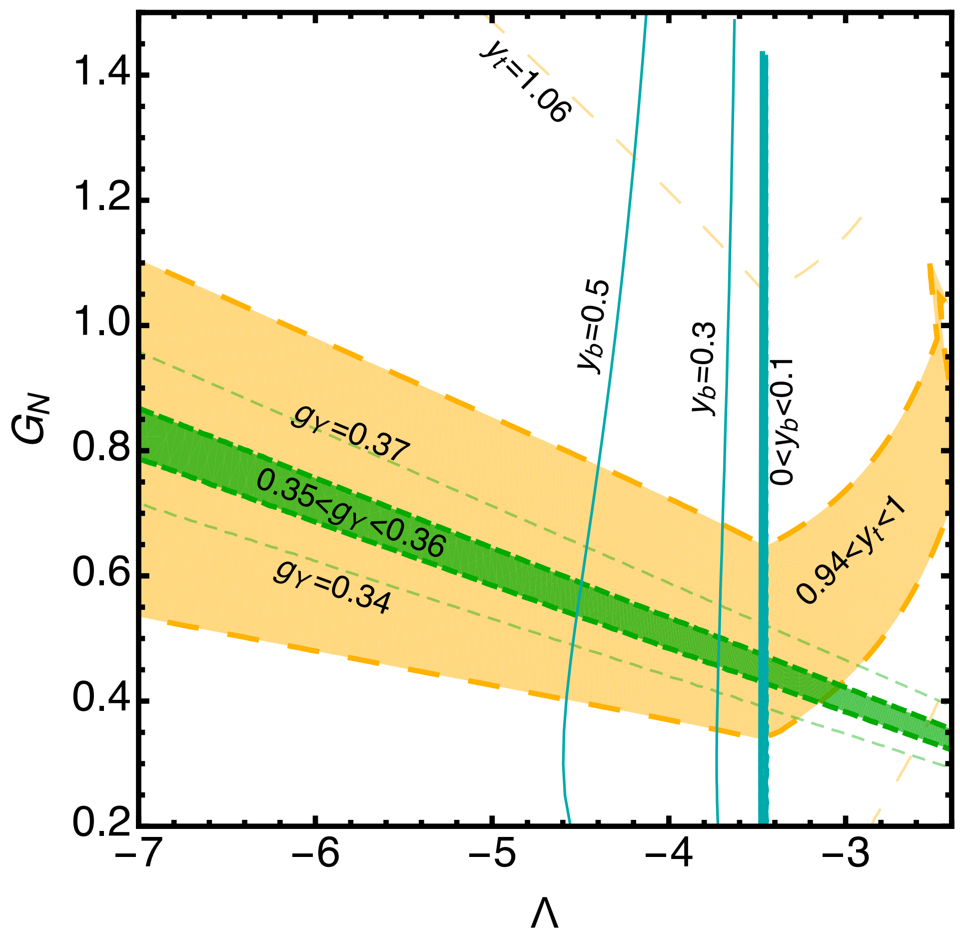
Asymptotically, particle physics might be safe - stay tuned…!

Thank you for your attention.

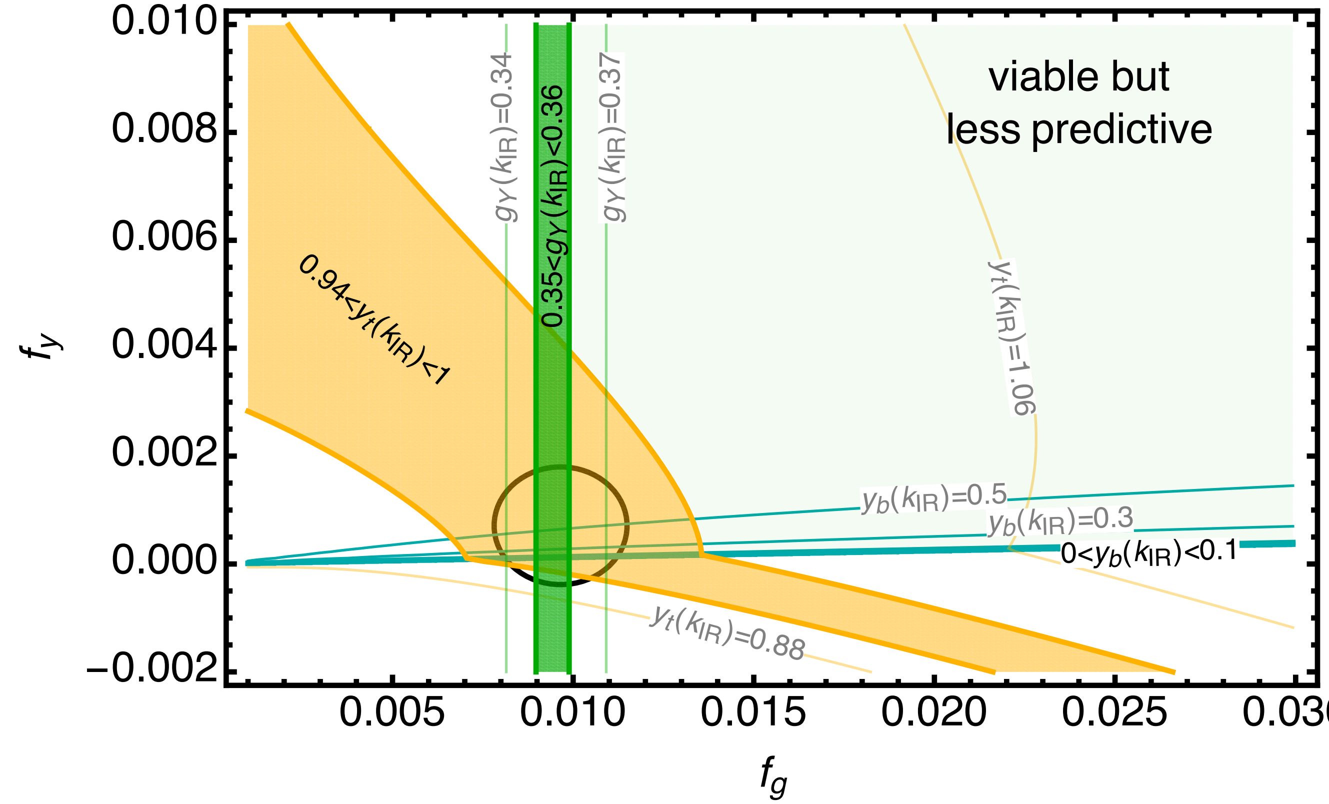
Switch gears: add gravitational fixed-point values from truncated flows

observational consistency constraint on microscopic grav. coupling space

[AE, Held 1803.04027 , Phys.Rev.Lett. 121 (2018) no.15, 151302]



(Einstein-Hilbert truncation)



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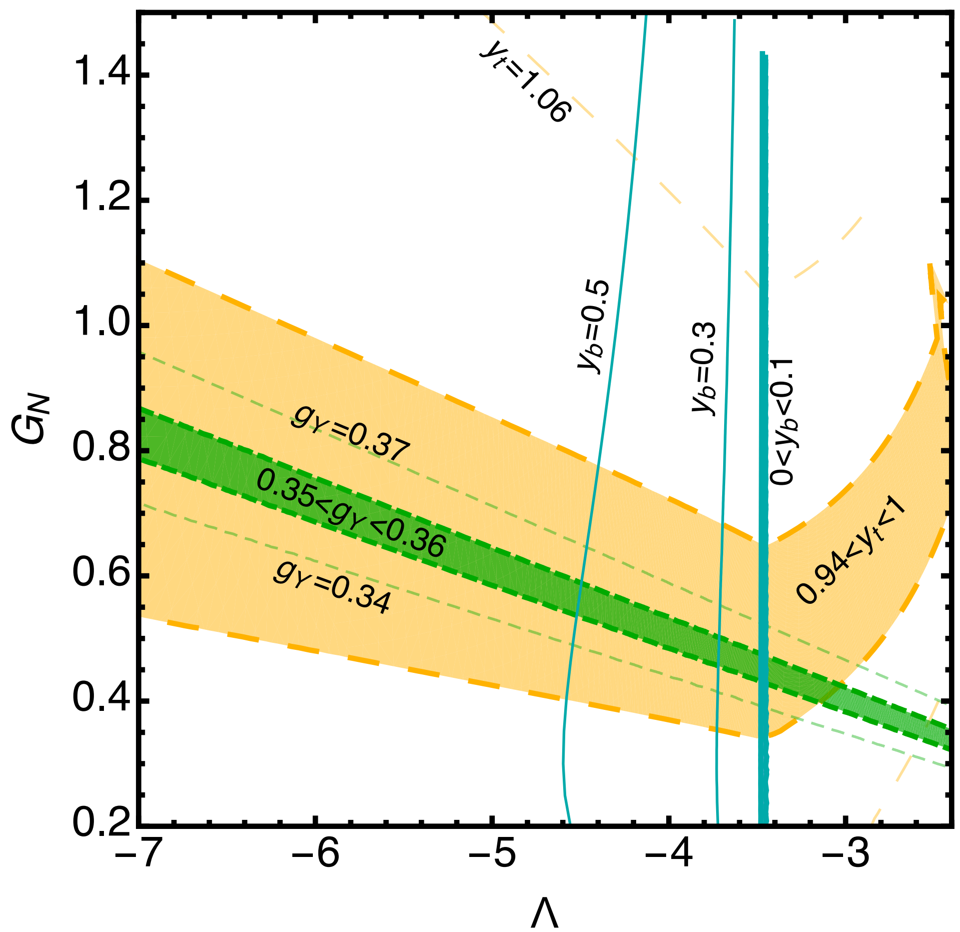

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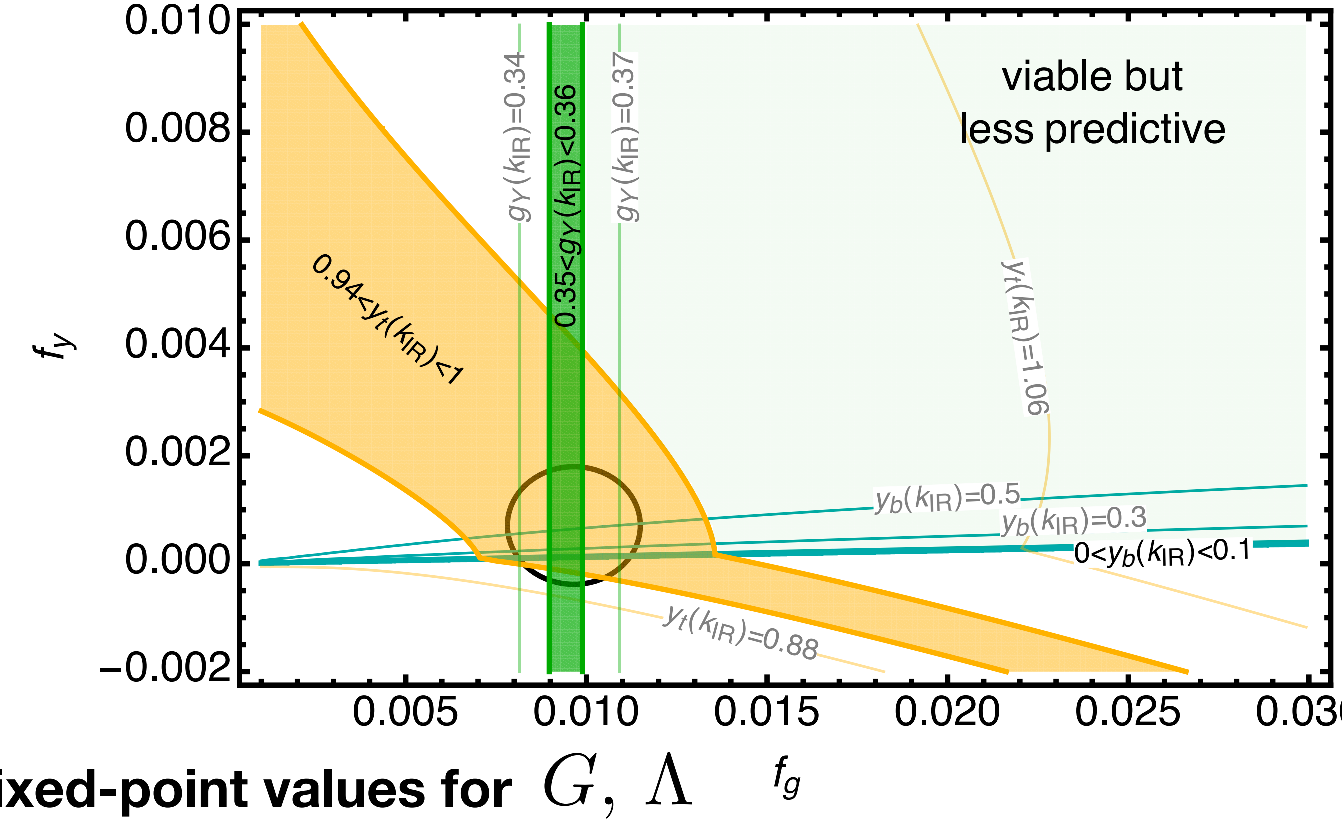

fixed-point values for $G,\ \Lambda$

depend on matter content:
"backreaction matters"

[Dona, AE, Percacci '13]

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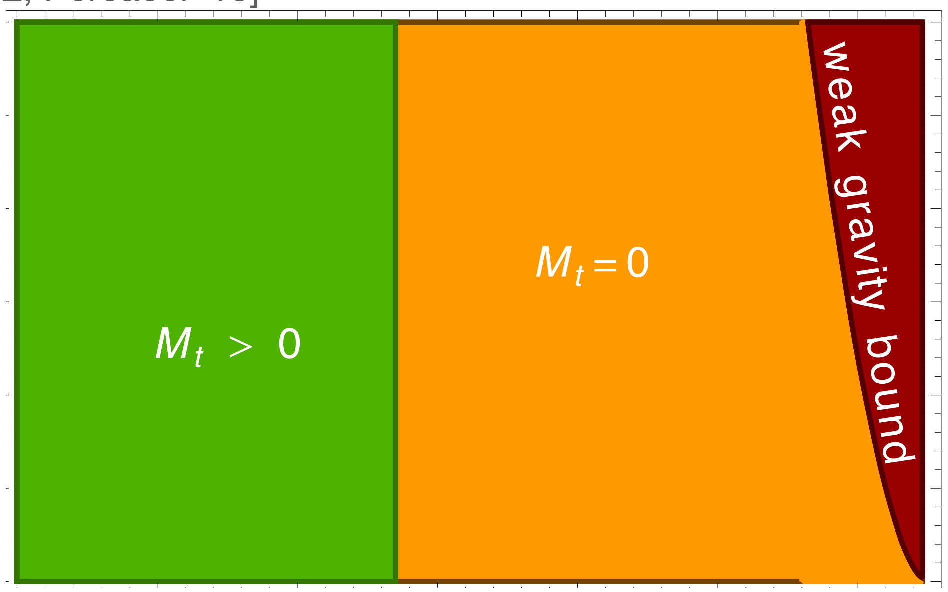

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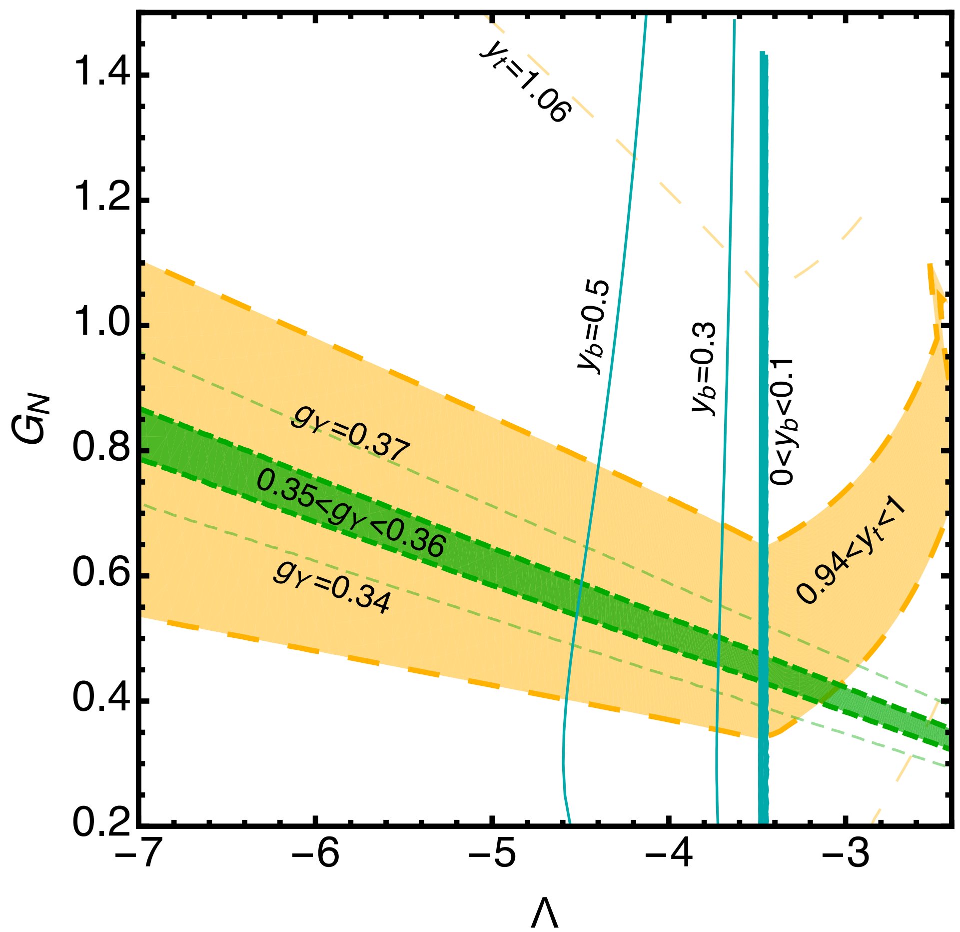

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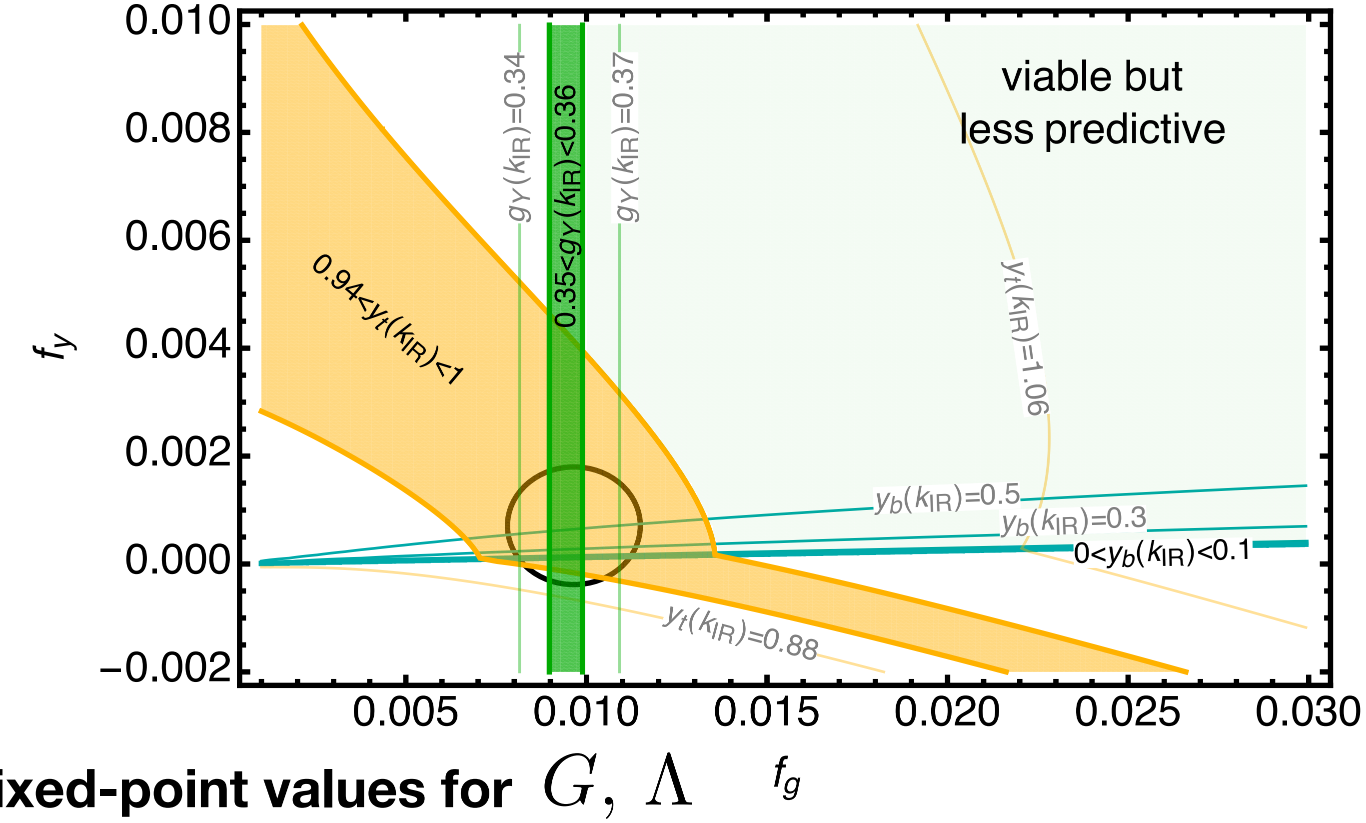

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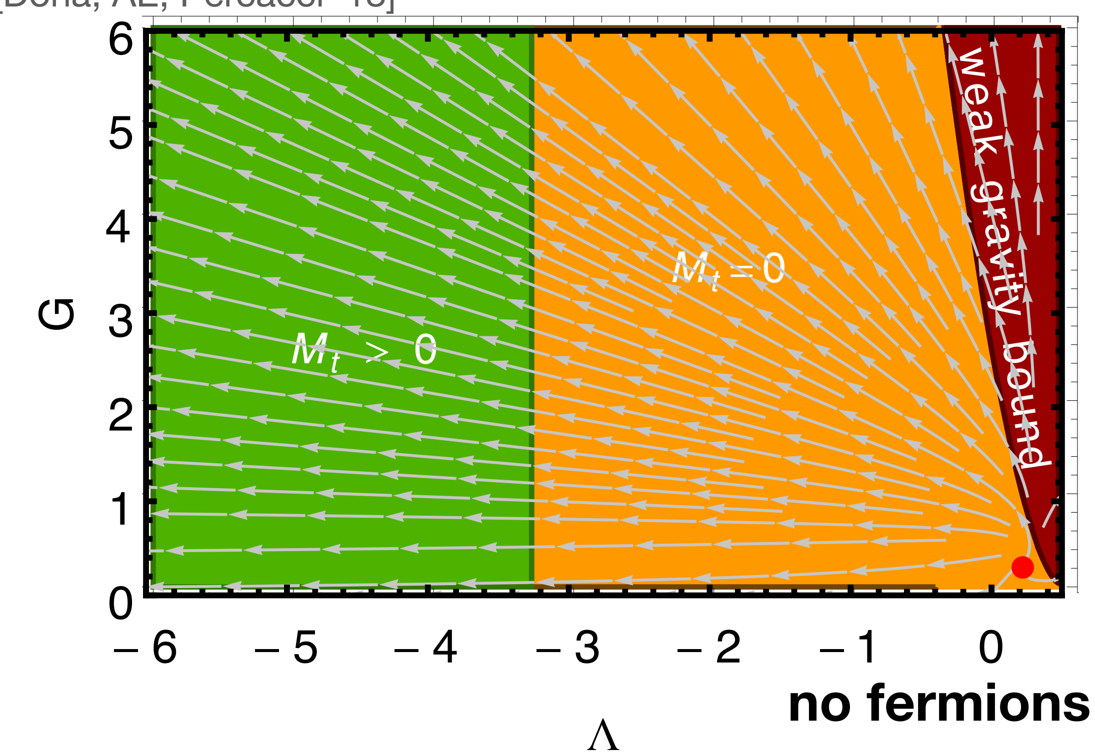

no fermions

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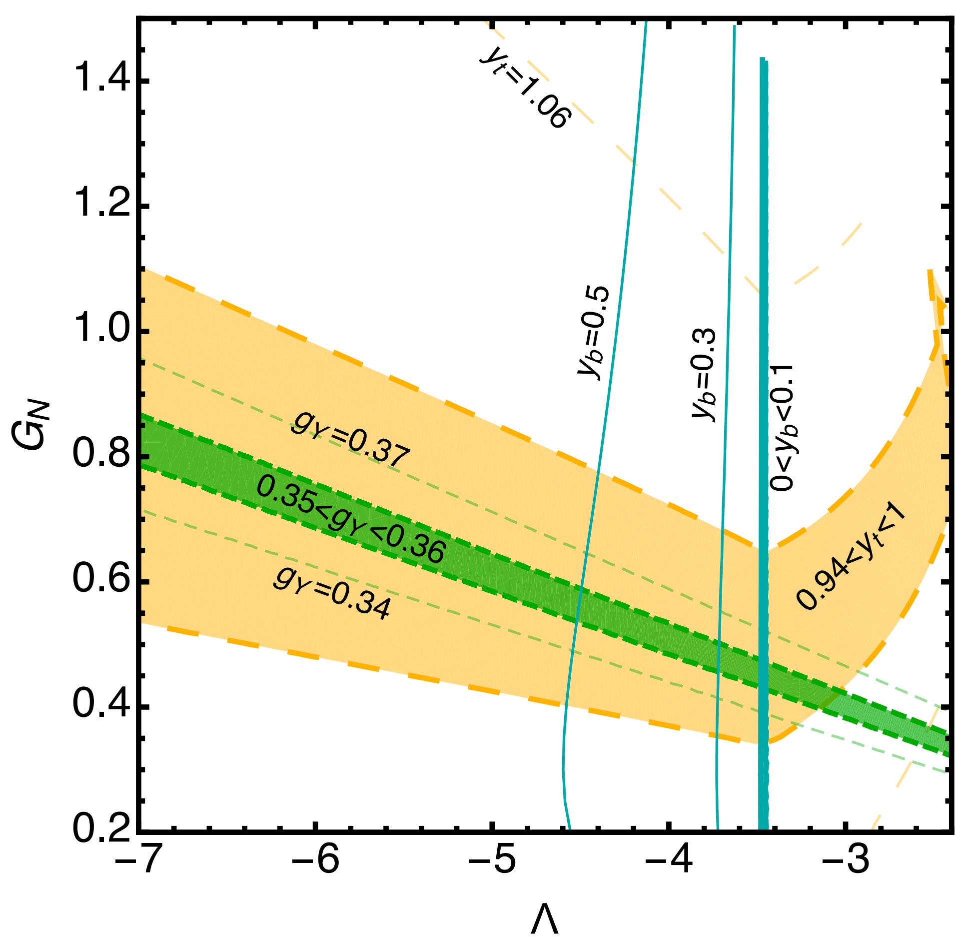

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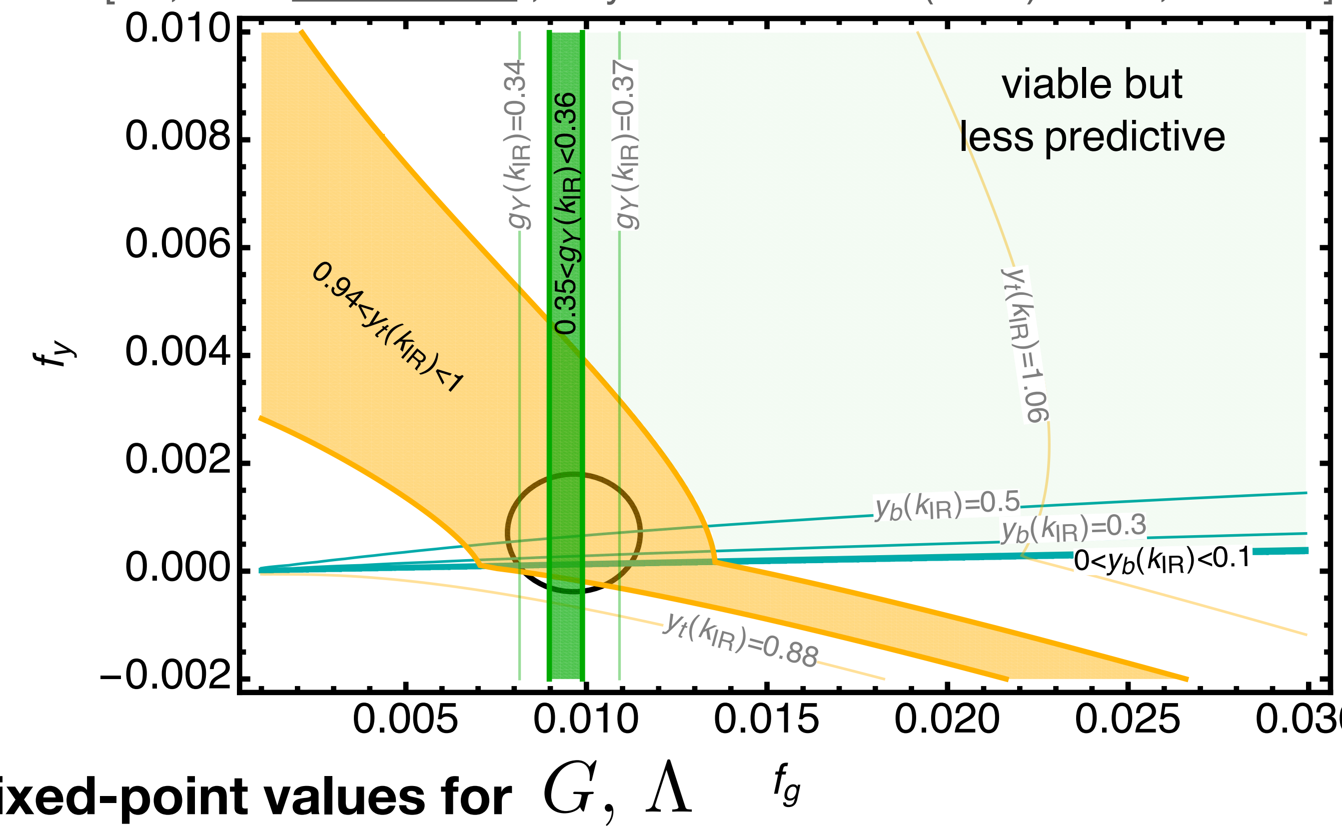

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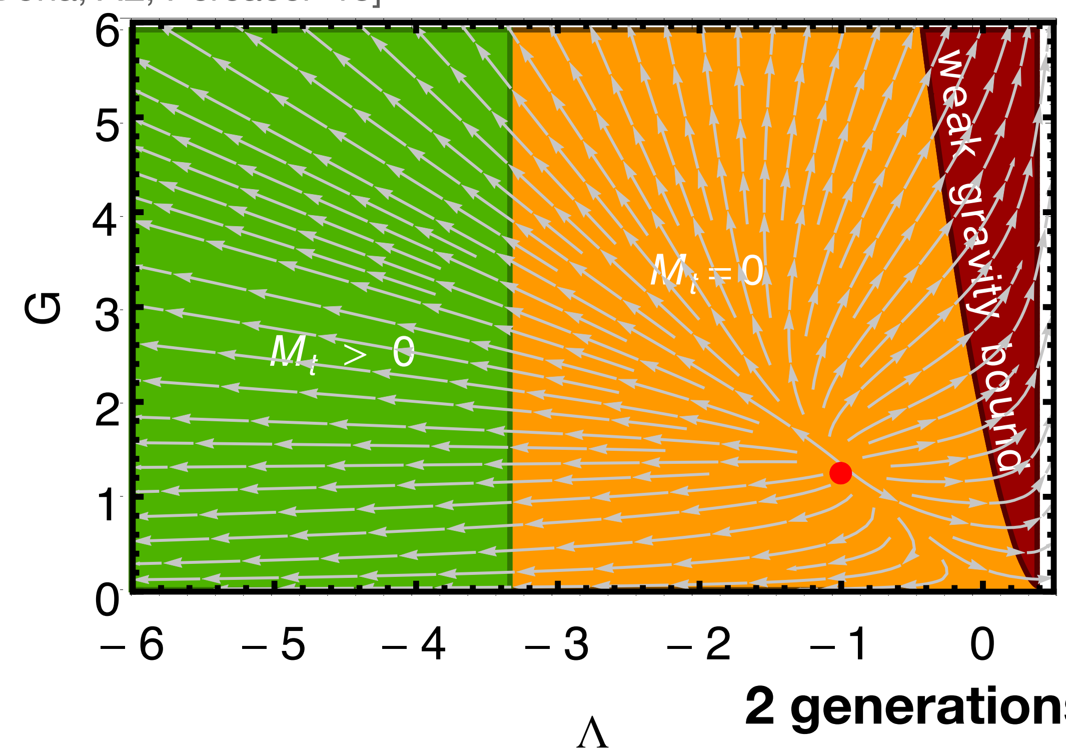

2 generations

Switch gears: add gravitational fixed-point values from truncated flows

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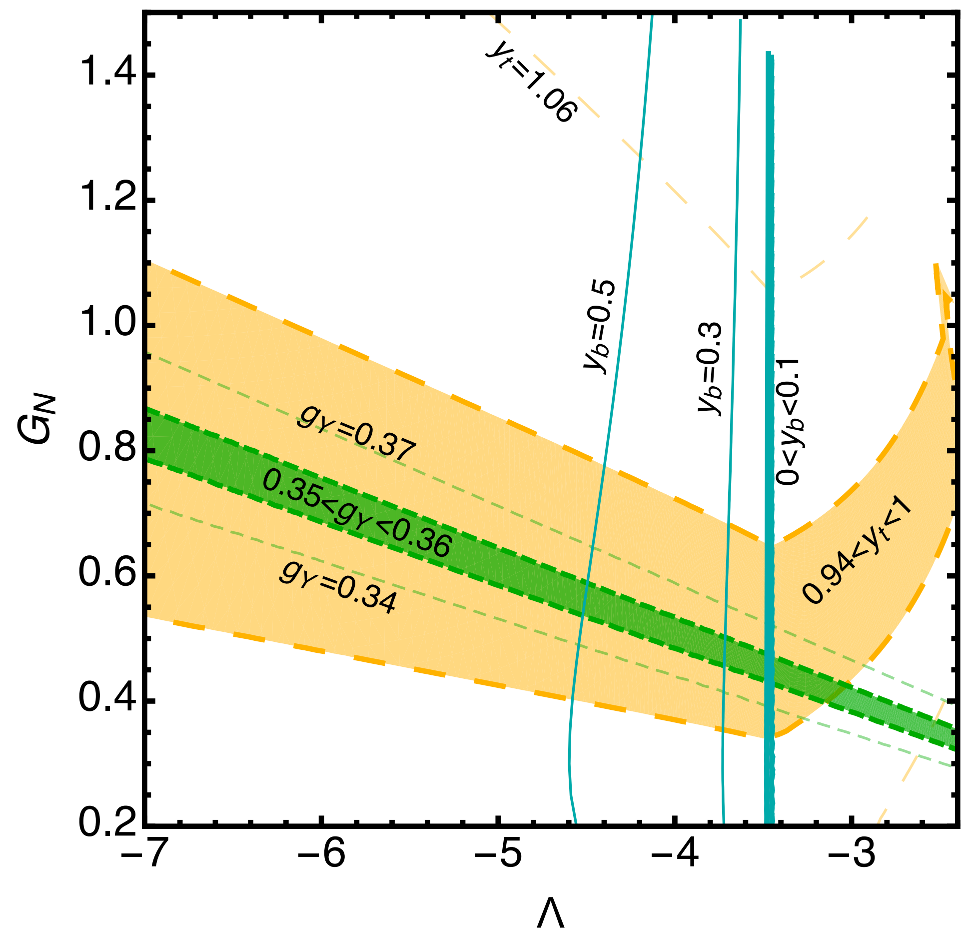
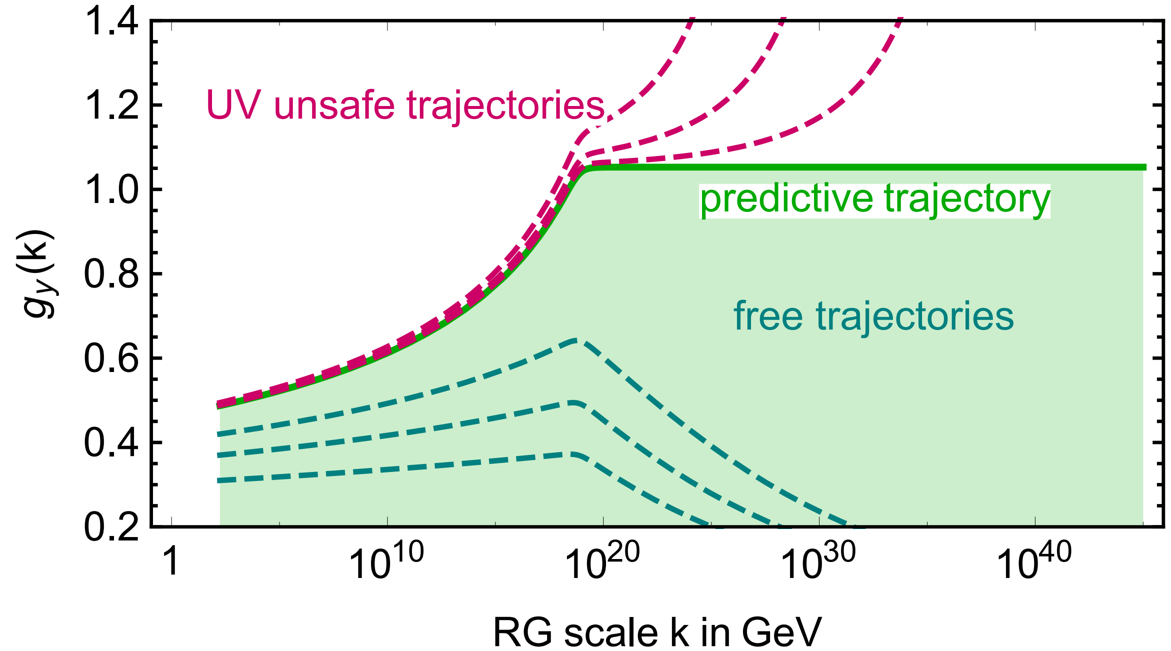
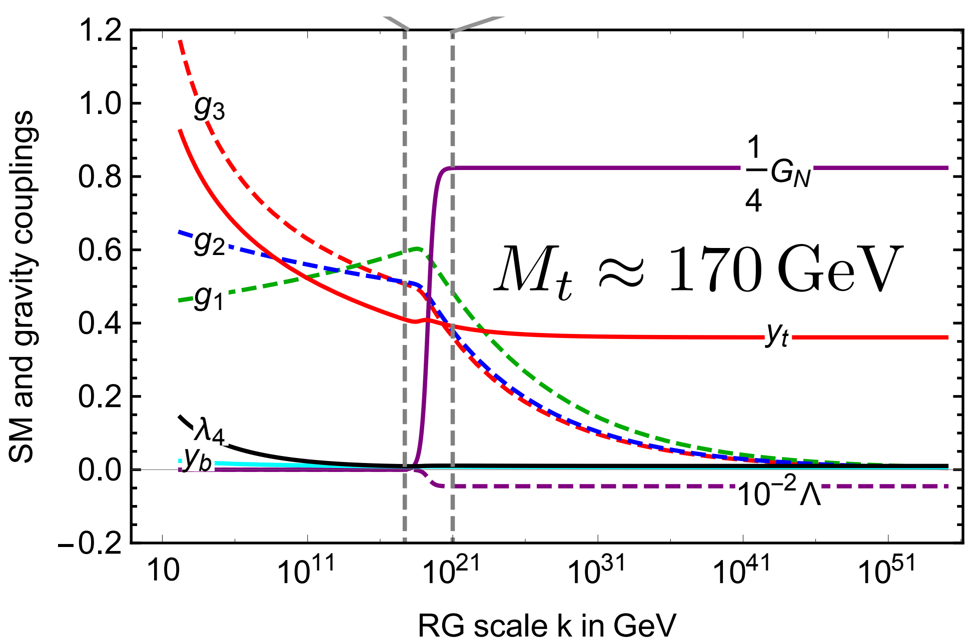






[AE, Held, arXiv:1707.01107 , Phys.Lett. B777 (2018) 217-221]

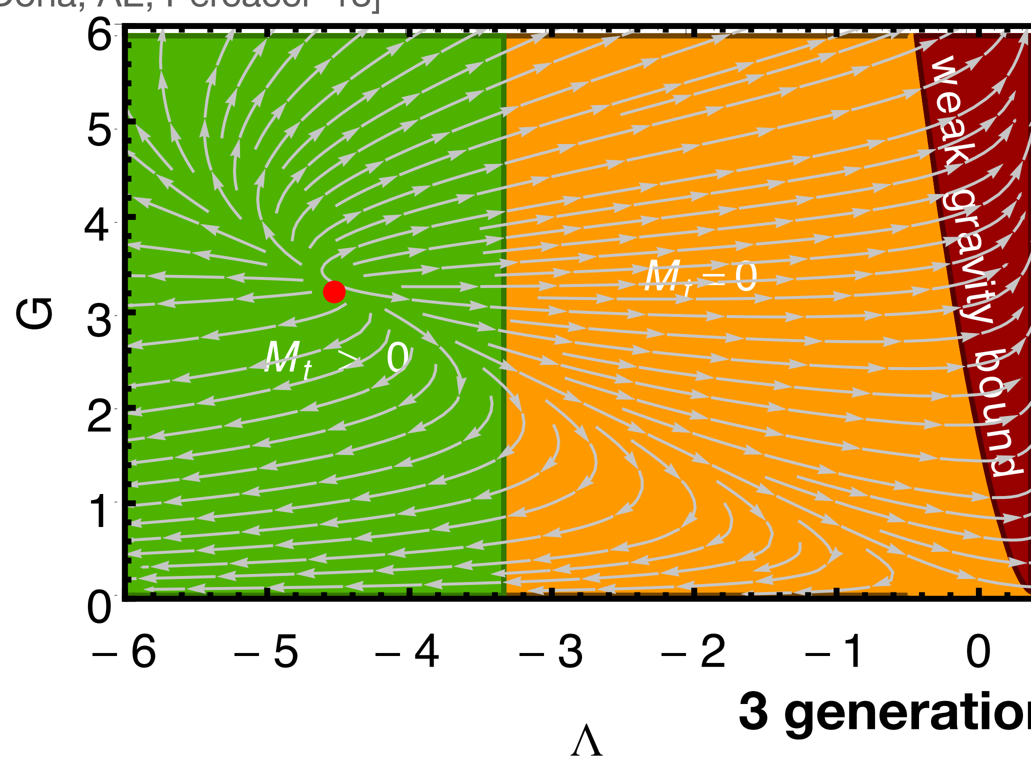
- **y_b AF**
- **g_y AF**
- **y_t AS (predicted)**

fixed-point values for $G,\ \Lambda$

depend on matter content:
"backreaction matters"

[Dona, AE, Percacci '13]

(Einstein-Hilbert truncation)



3 generations

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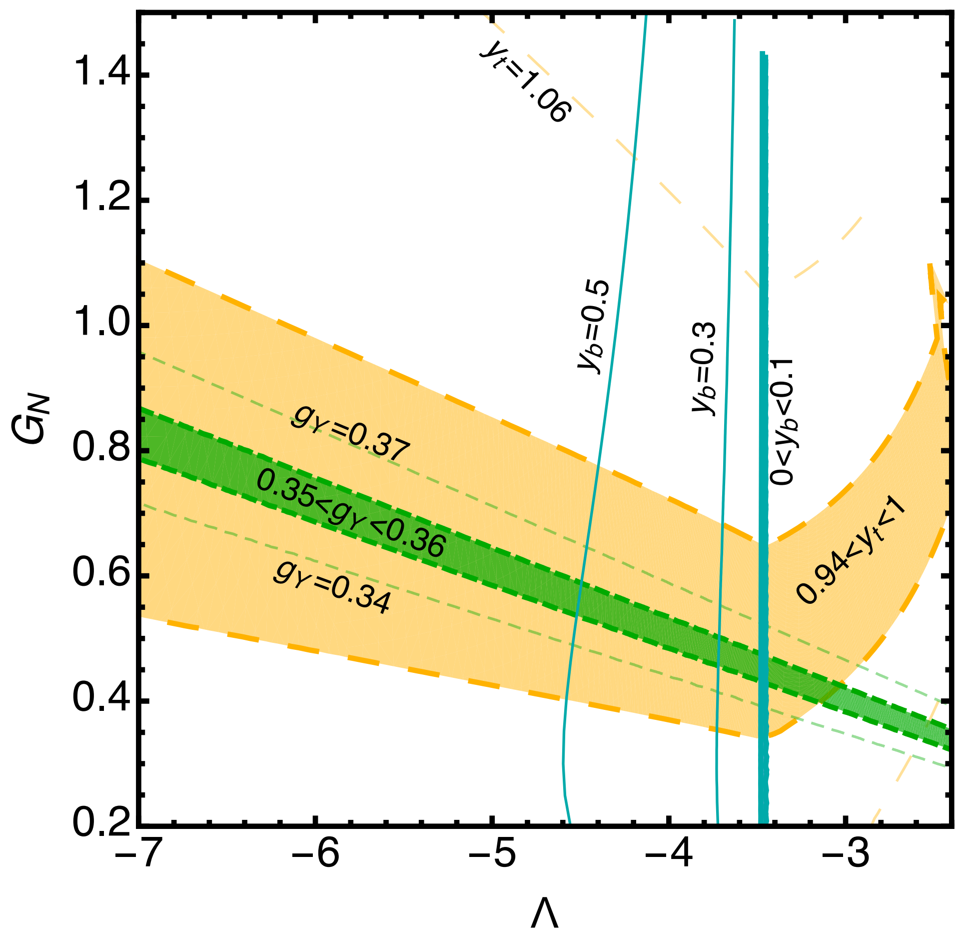
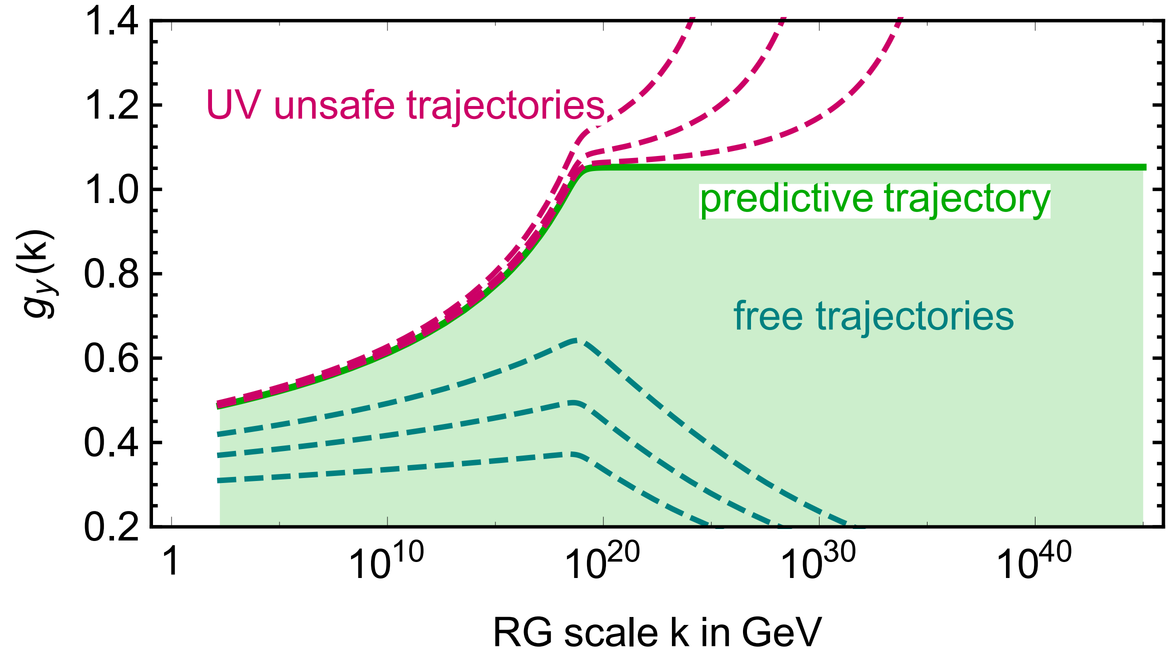
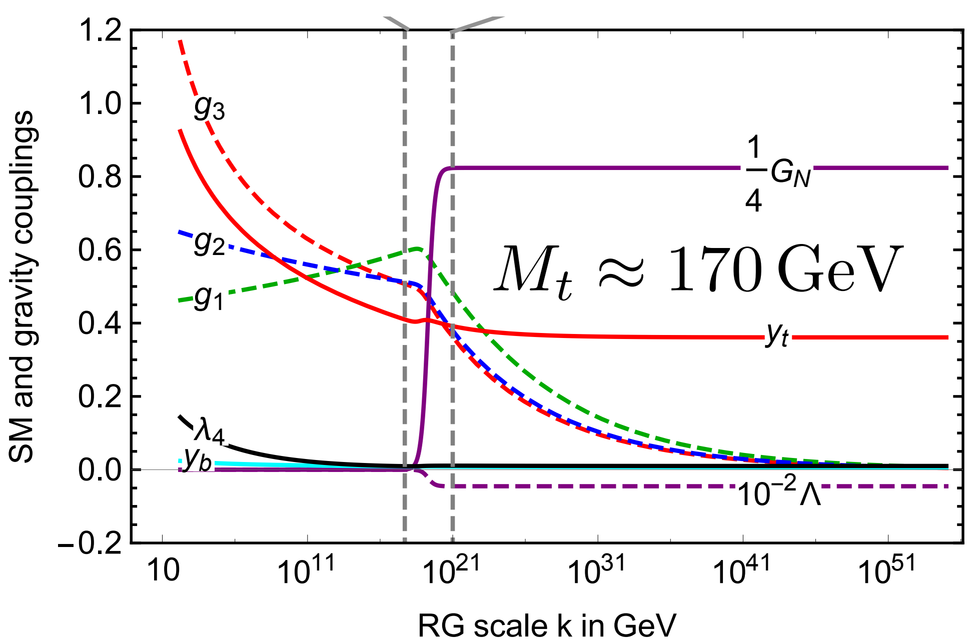




estimate of systematic error: 3 retrodictions are roughly 1.5 δ away



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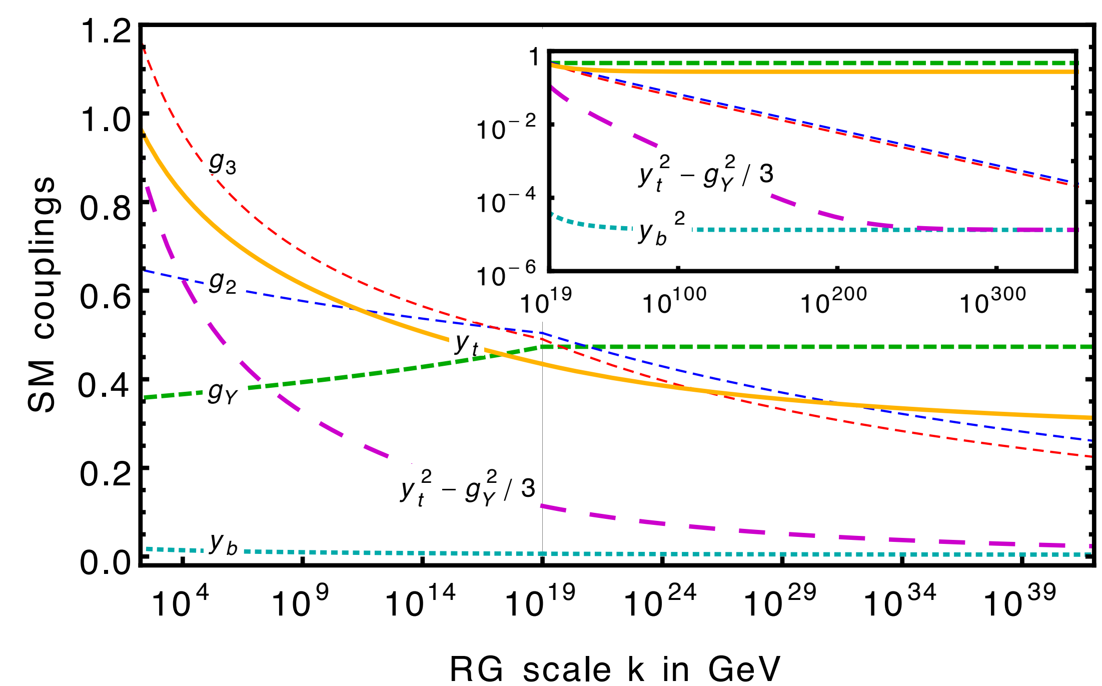

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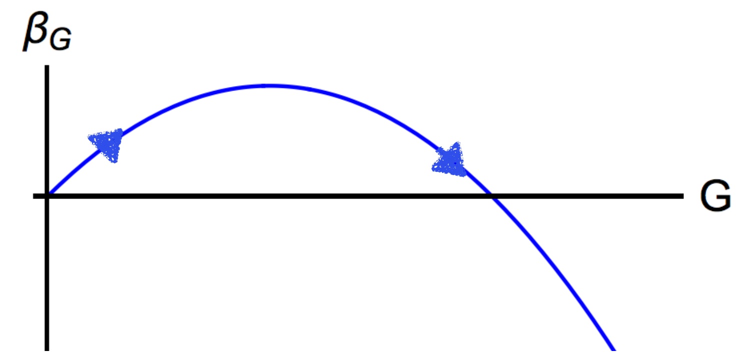
Methods to search for asymptotic safety in gravity

- **ϵ expansion in d=2+ϵ** $\beta_G = \epsilon G - \frac{38}{3} G^2$

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



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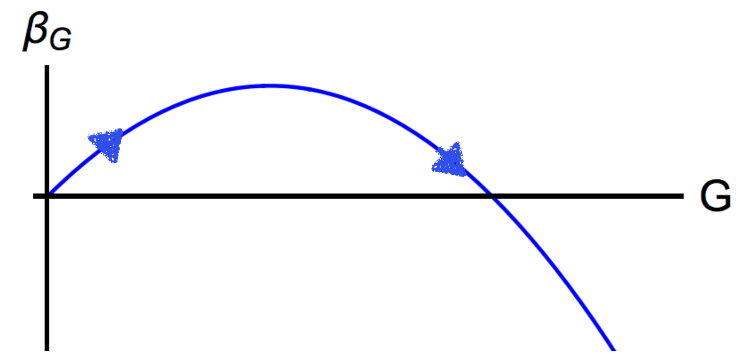
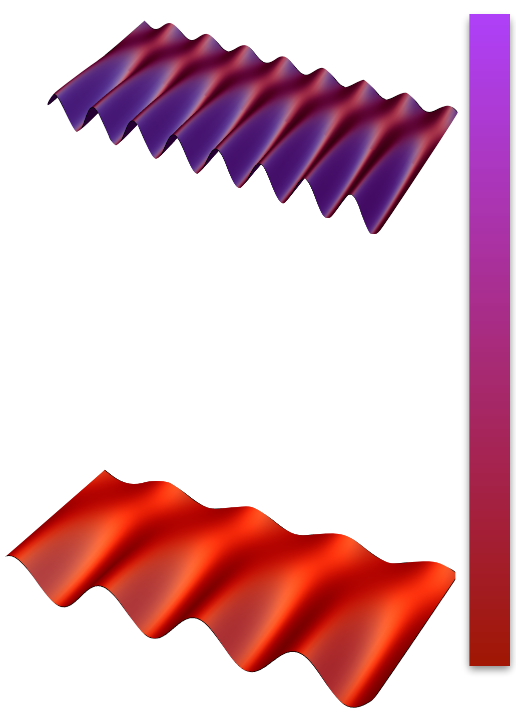


- **Functional Renormalization Group** $e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi\, e^{-S[\varphi] - \frac{1}{2}\int \varphi(-p) R_k(p) \varphi(p)}$

probe scale dependence of QFT

Wetterich '93, Reuter '96

scale- and momentum-dependent ``mass"



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Γ_k contains effect of quantum fluctuations above k

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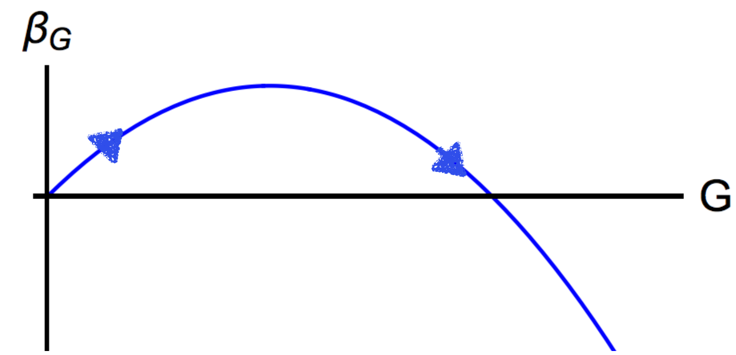

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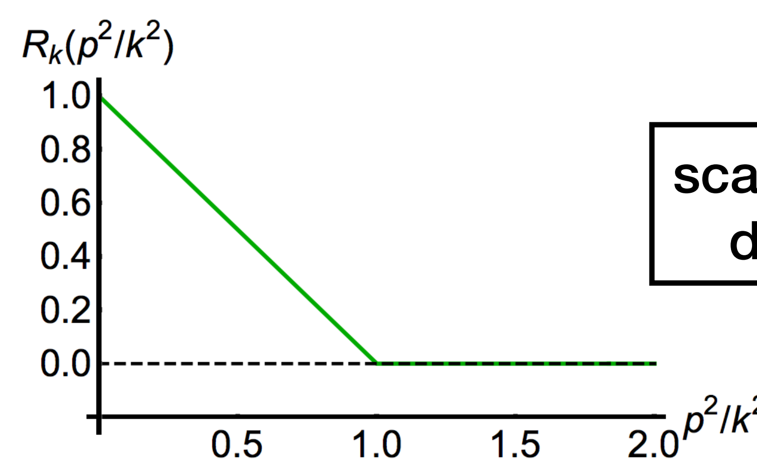

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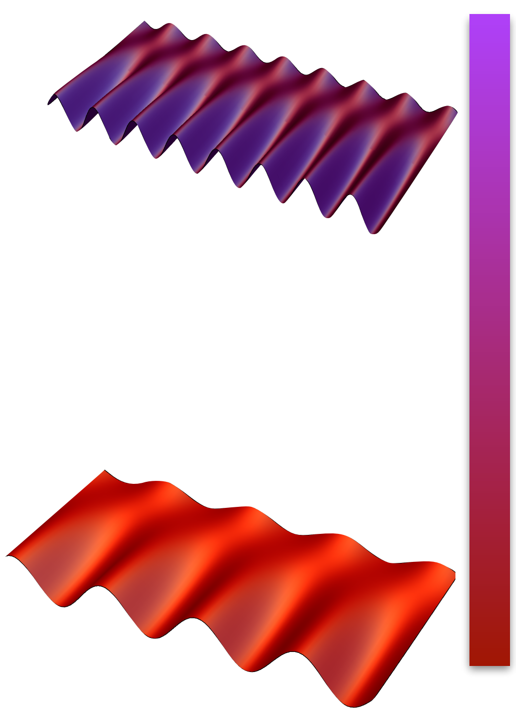

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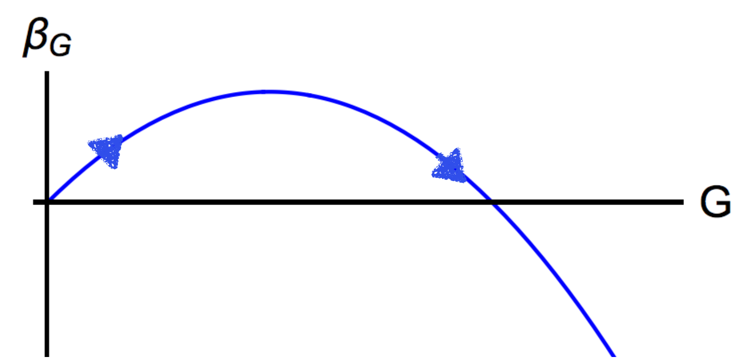

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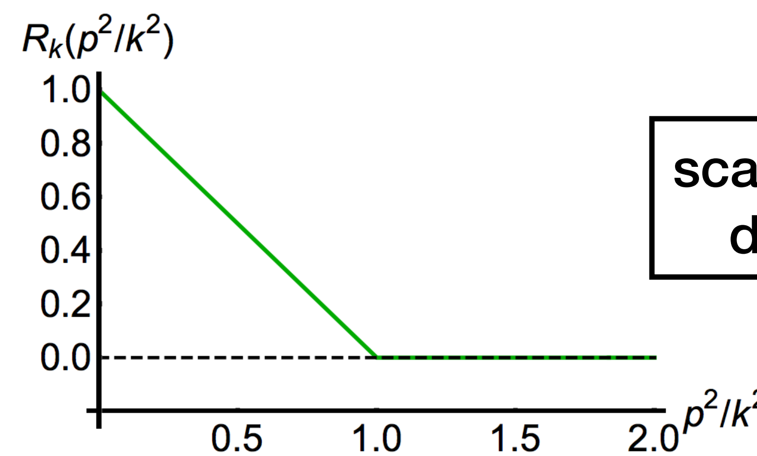

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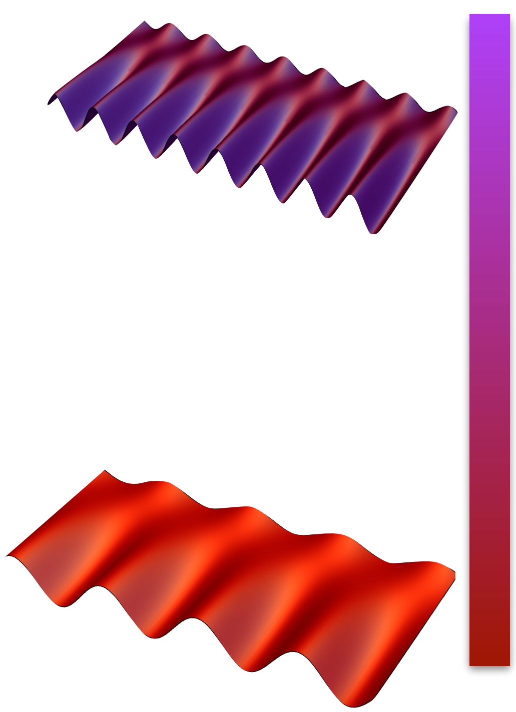

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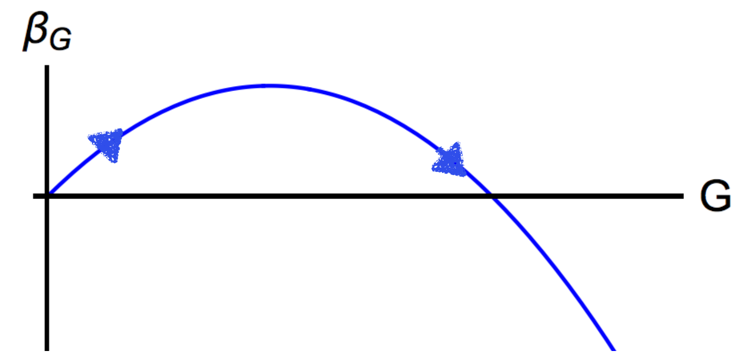

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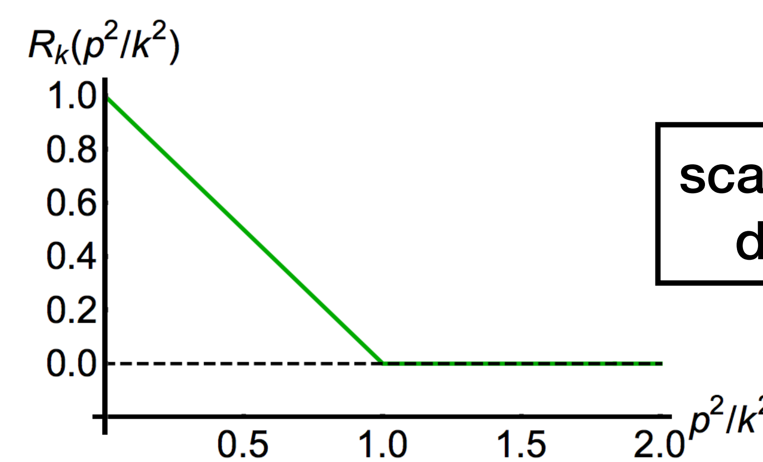

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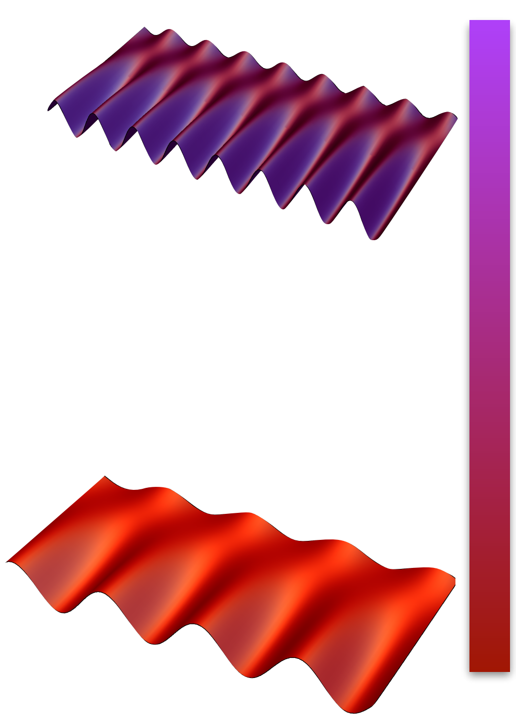

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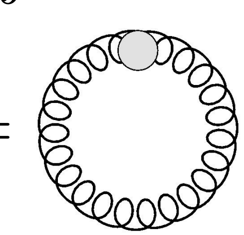
Wetterich equation: $\partial_k \Gamma_k = \frac{1}{2} \mathrm{STr} \left(\Gamma_k^{(2)} + R_k \right)^{-1} \partial_k R_k =$ 

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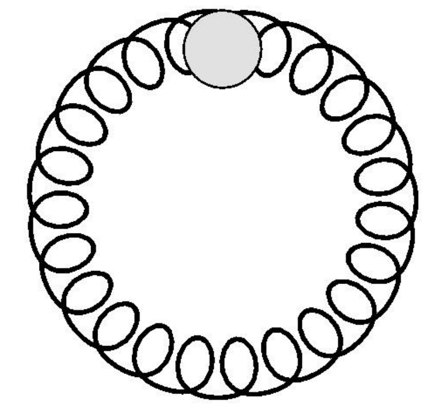

exact one-loop equation

$$\Gamma_k = \sum_i g_i(k) \int d^d x\, \mathcal{O}_i \longrightarrow$$ (infinite) tower of coupled equations β_{g_i}

strategy

- truncate to (finite) set of equations
- search for fixed point solutions
- enlarge truncation
- convergent results?

successfully used in Quantum Chromodynamics, BEC-BCS-crossover,
strongly-correlated fermions in condensed matter,
Wilson-Fisher universality classes & beyond, …..

Functional Renormalisation Group

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example: Ising universality class

scaling exponent of the correlation length: $\xi \sim |T - T_c|^{-\nu}$

$\nu = 0.62999(5)$ conformal bootstrap [Showk et al. '14]

$\nu = 0.63002(10)$ MC [Hasenbusch '10]

$\nu = 0.643$ FRG: LPA [Berges, Tetradis, Wetterich '00]

$\nu = 0.6307$ FRG: $\mathcal{O}(\partial^2)$ [Canet, Delamotte, Mouhanna, Vidal '03]