Asymptotic safety for the Standard Model (with gravity)

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Lattice for Beyond the Standard Model Physics 2019, Syracuse University, May 3, 2019

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

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University of Southern Denmark

Die Junge Akademie

RUPRECHT-KARLS-UNIVERSITÄT HEIDELBERG
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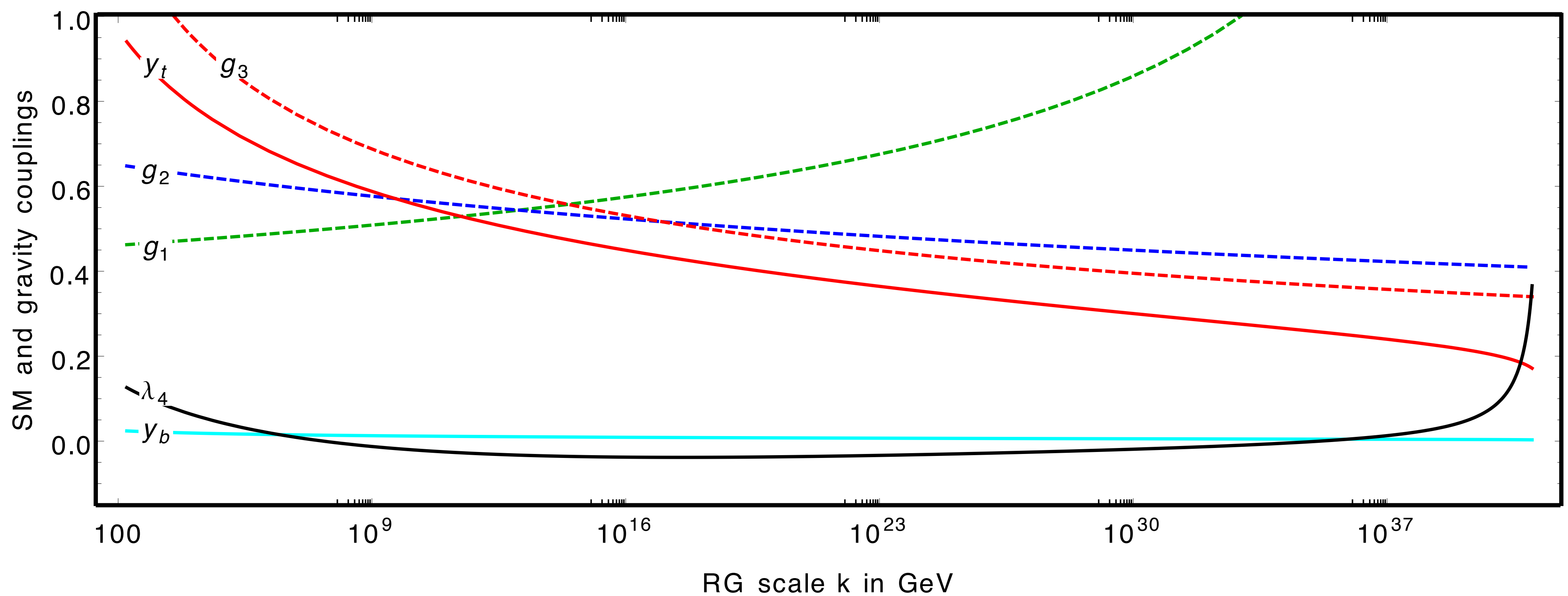
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Status of the Standard Model

After LHC



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

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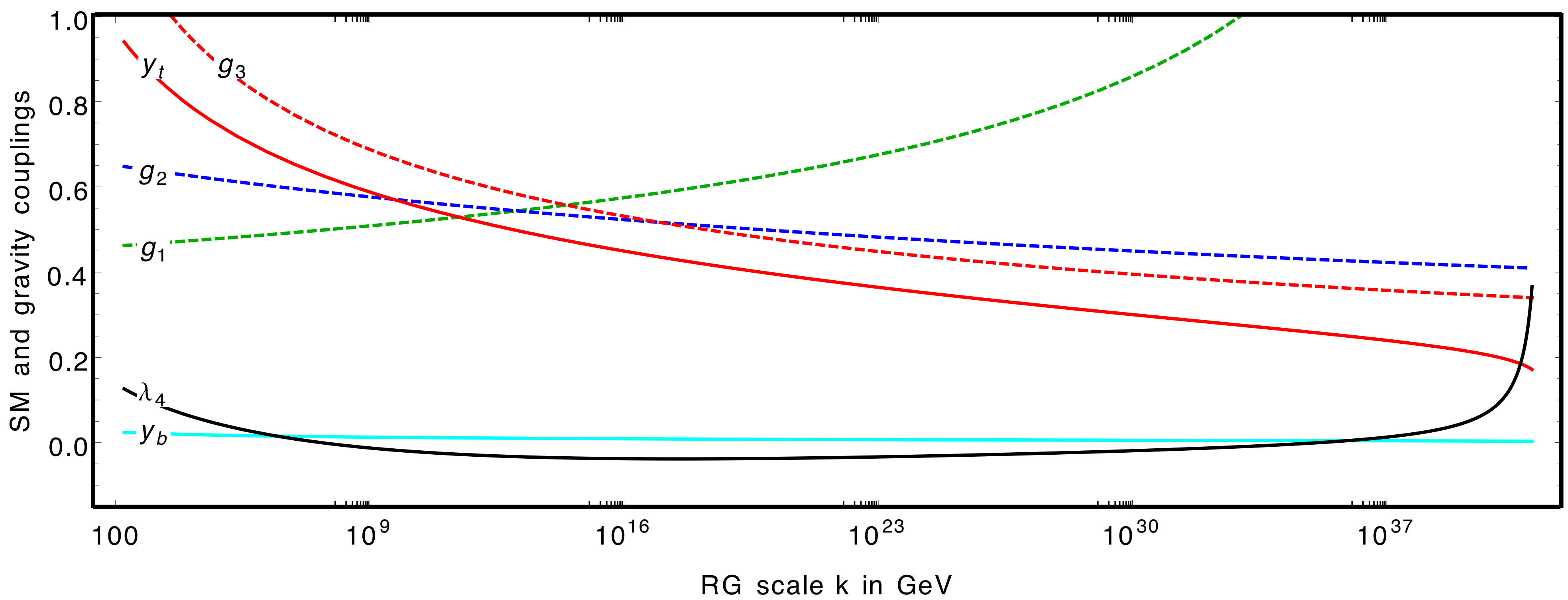

- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**
- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**
- **gravitational interaction is missing**

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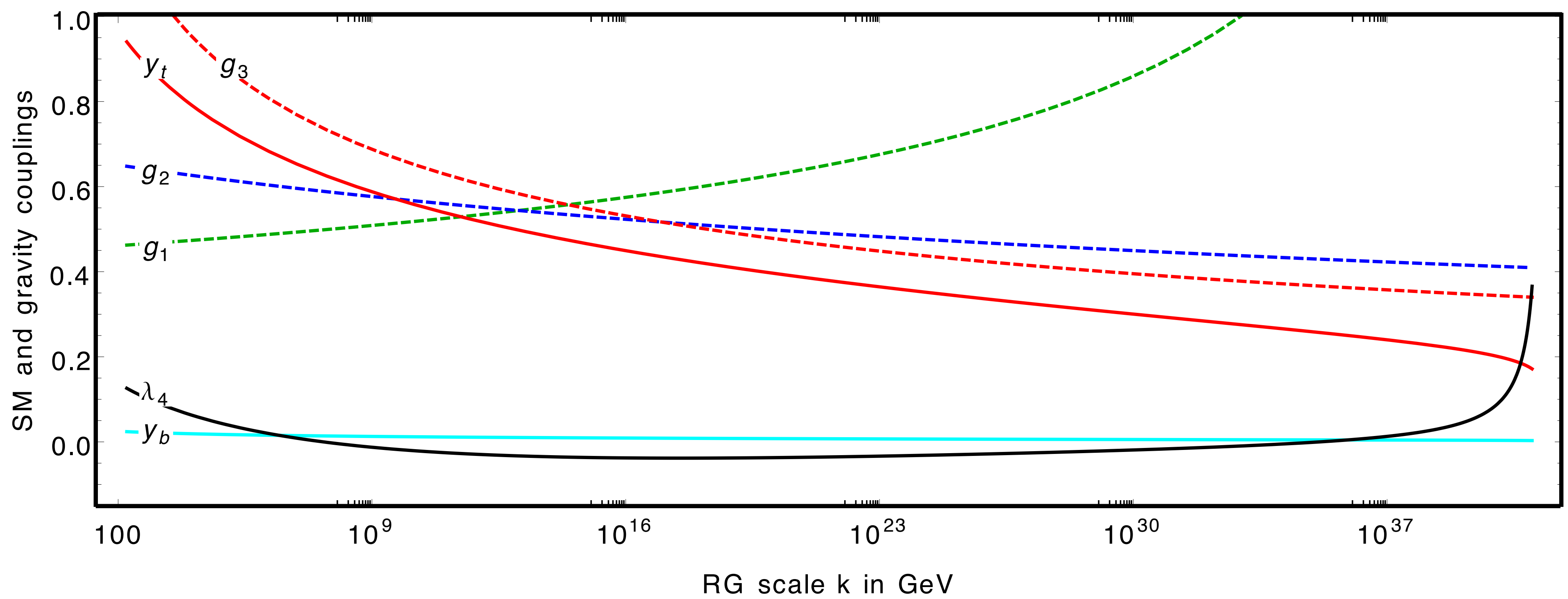

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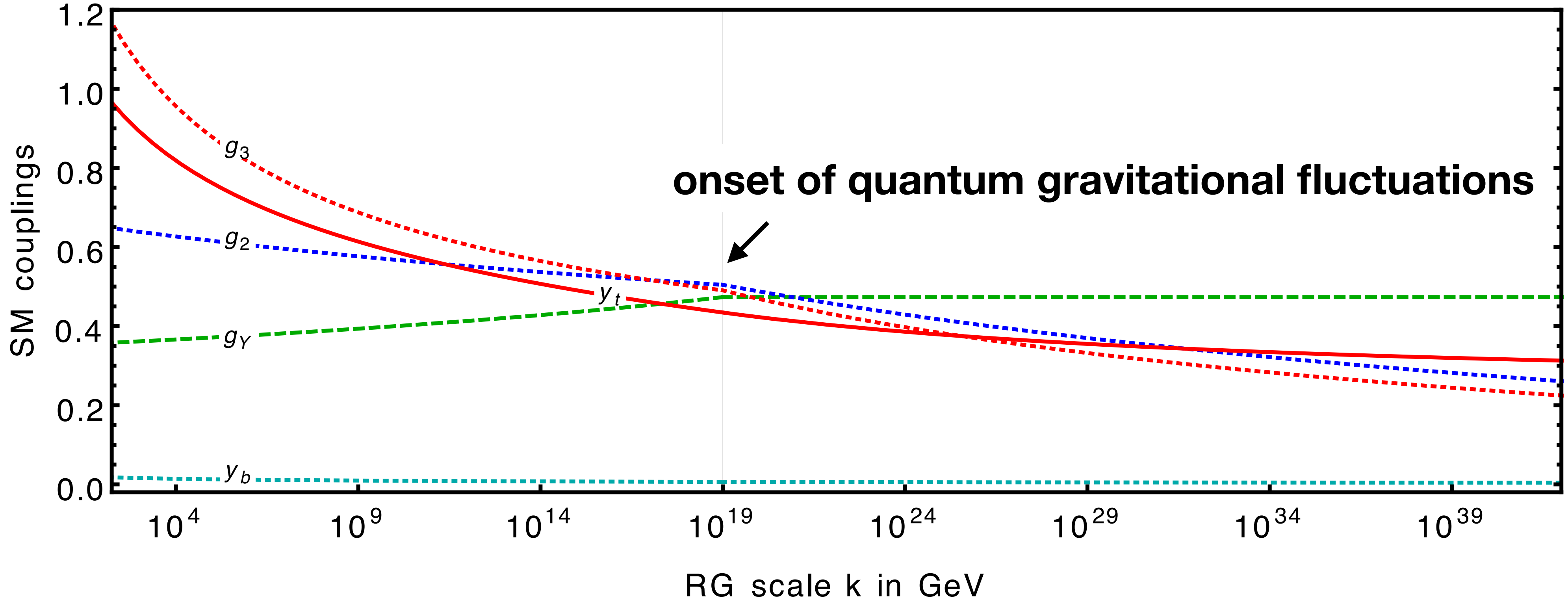
- **low-energy values of all couplings are free parameters (e.g. hierarchy problem)**
- **gravitational interaction is missing**

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

Hints for asymptotically safe gravity + Standard Model



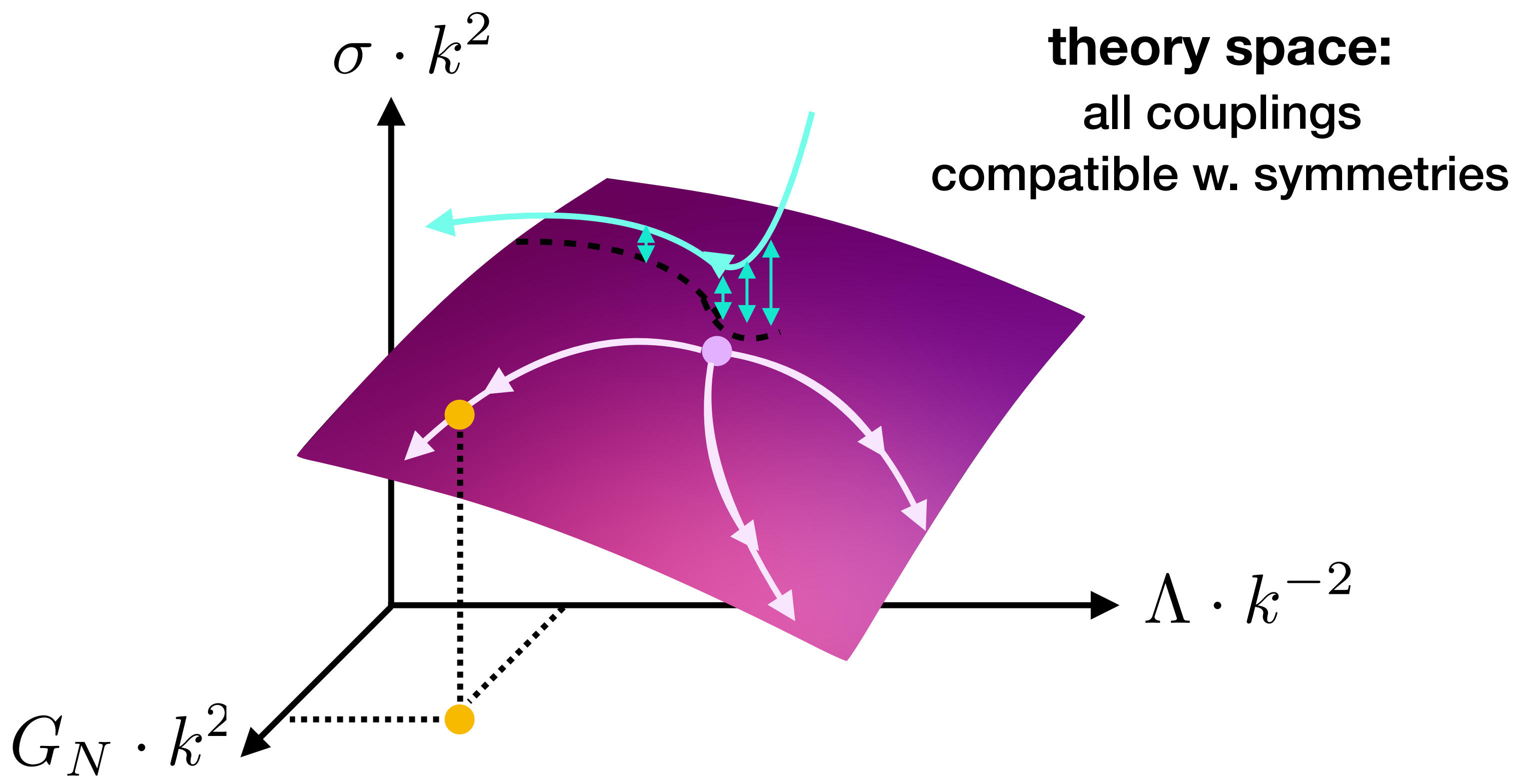
- **Landau poles/ triviality problem in U(1) hypercharge and Higgs-Yukawa sector**

  $\longrightarrow$ 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 ($\longrightarrow$ tests of QG at e/w scale)

Asymptotic safety in a nutshell



Theory space features an interacting fixed point $\longrightarrow$ UV complete $\beta_i = 0 \,\forall\, i$

$\longrightarrow$ lattice: universal continuum limit

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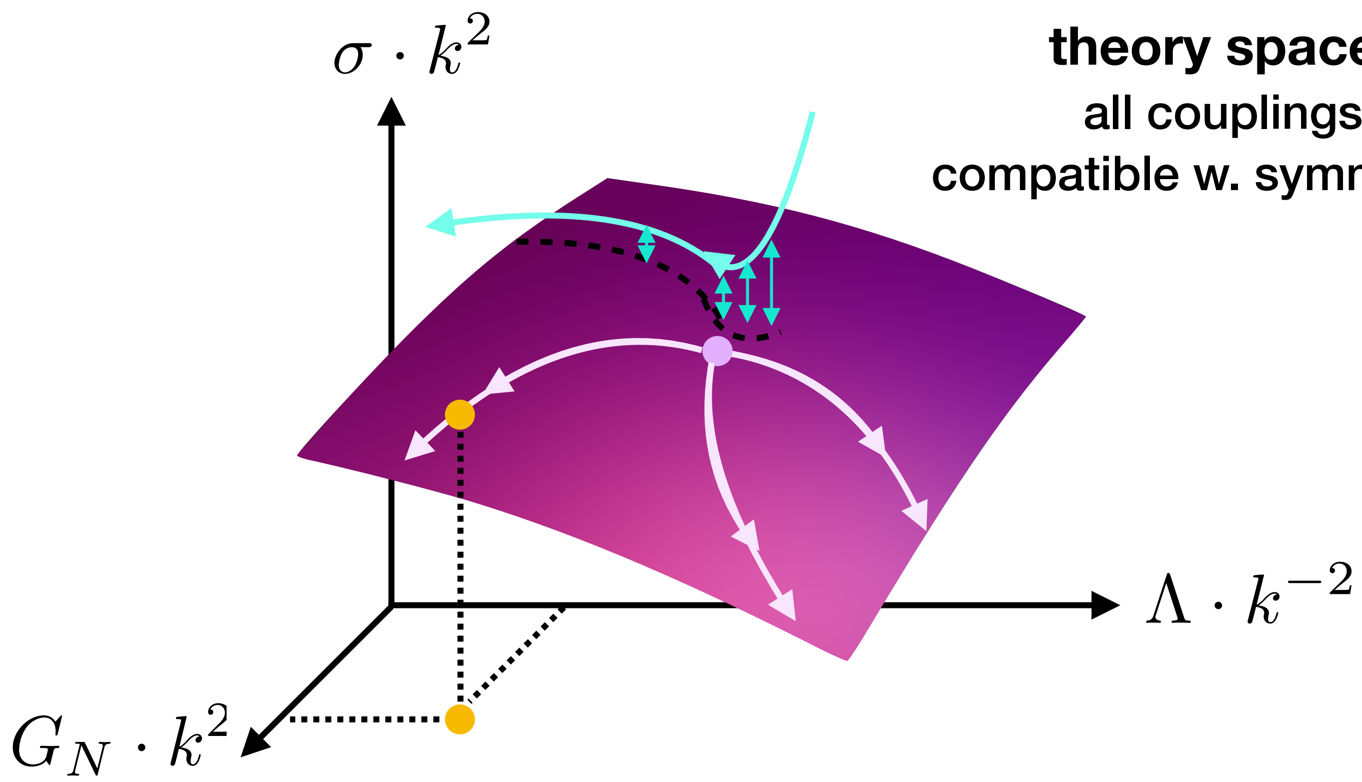
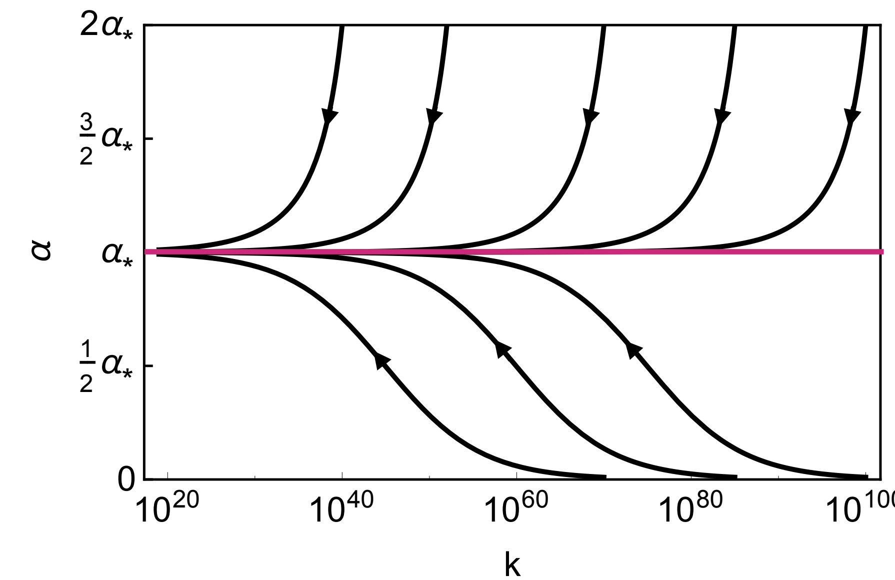


theory space:
all couplings
compatible w. symmetries

Irrelevant directions:
Predictions from asymptotic safety



predictive power of new symmetry (scale symmetry)

Theory space features an interacting fixed point

with a finite number of relevant directions.

$\rightarrow$ UV complete $\quad \beta_i = 0 \, \forall \, i$

$\rightarrow$ lattice: universal continuum limit

$\rightarrow$ predictive
(finite # free parameters)

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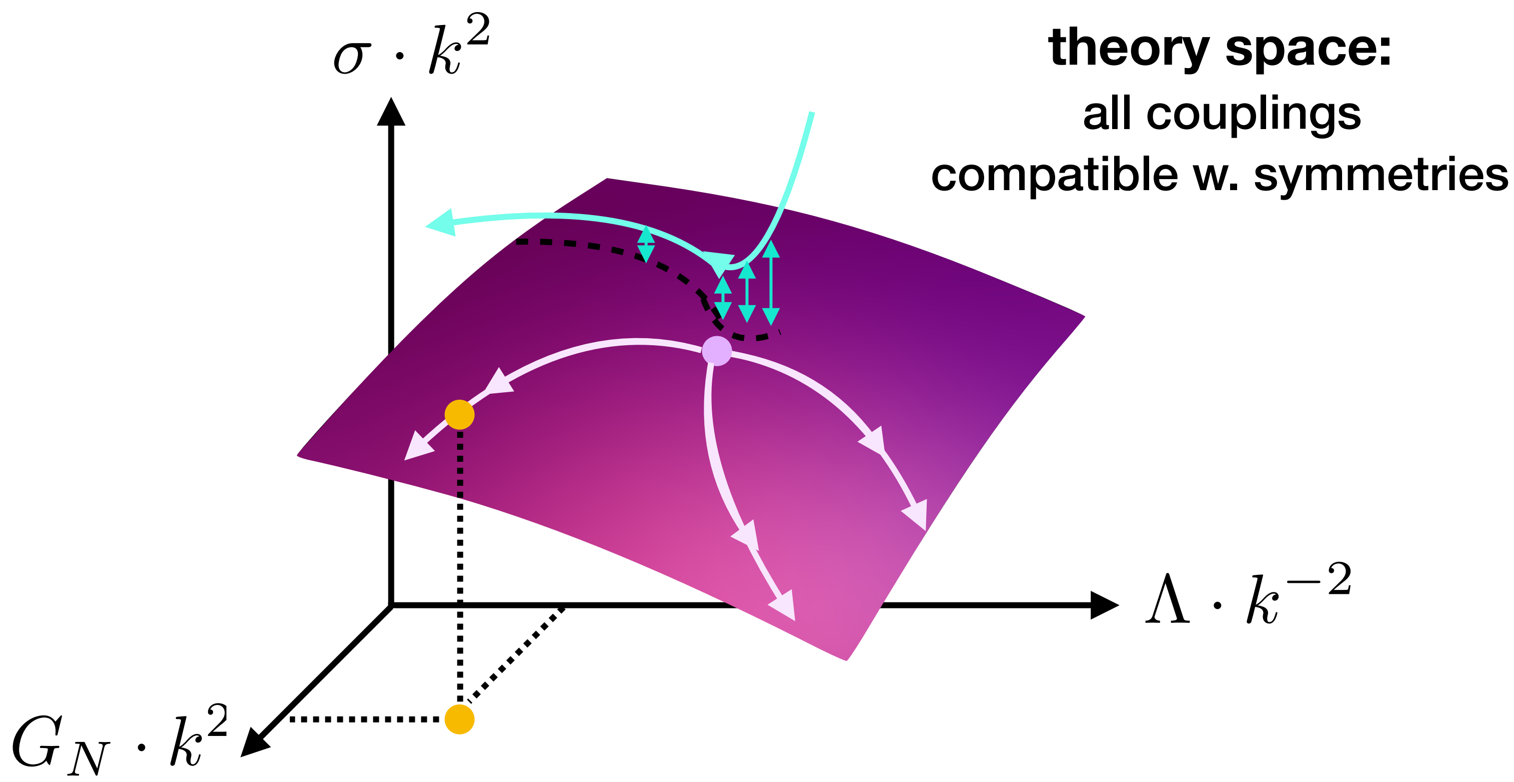

Irrelevant directions:
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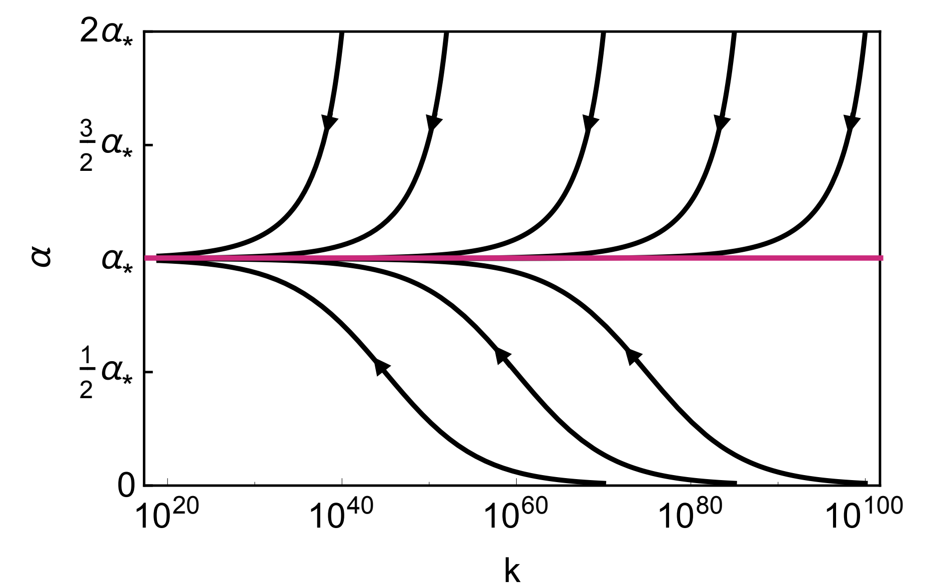

predictive power of new symmetry (scale symmetry)

Theory space features an interacting fixed point

with a finite number of relevant directions.
(At least) one trajectory emanating from the fixed point reaches a phenomenologically viable IR regime.

- $\rightarrow$ UV complete $\quad \beta_i = 0 \, \forall \, i$
- $\longrightarrow$ lattice: universal continuum limit
- $\rightarrow$ predictive (finite # free parameters)
- $\rightarrow$ predictions for irrelevant couplings (= IR attractive) match observations

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)

Asymptotically safe gravity - key idea

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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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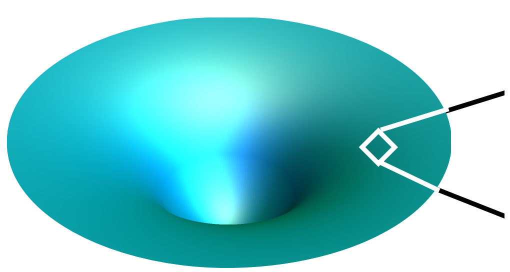

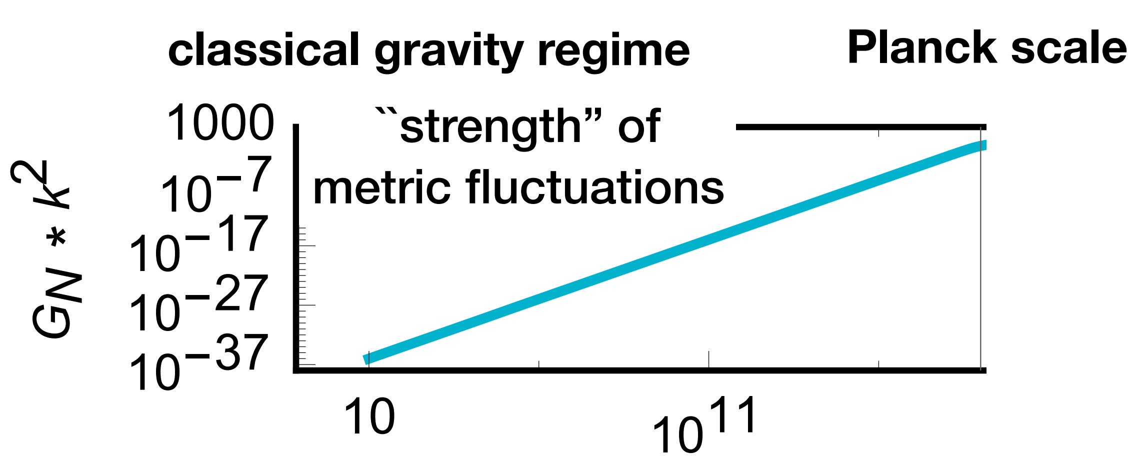

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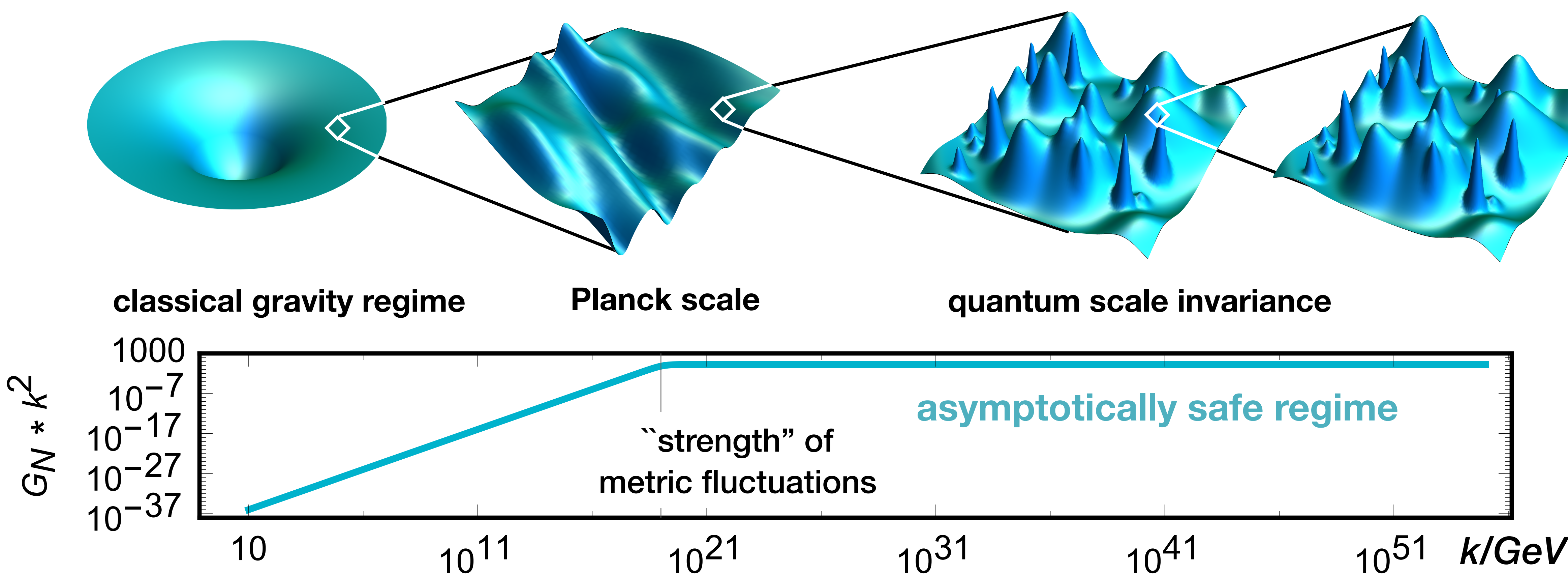
Quantum fluctuations of gravity ``shield" gravitational interaction in the UV



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

Asymptotically safe gravity - key idea

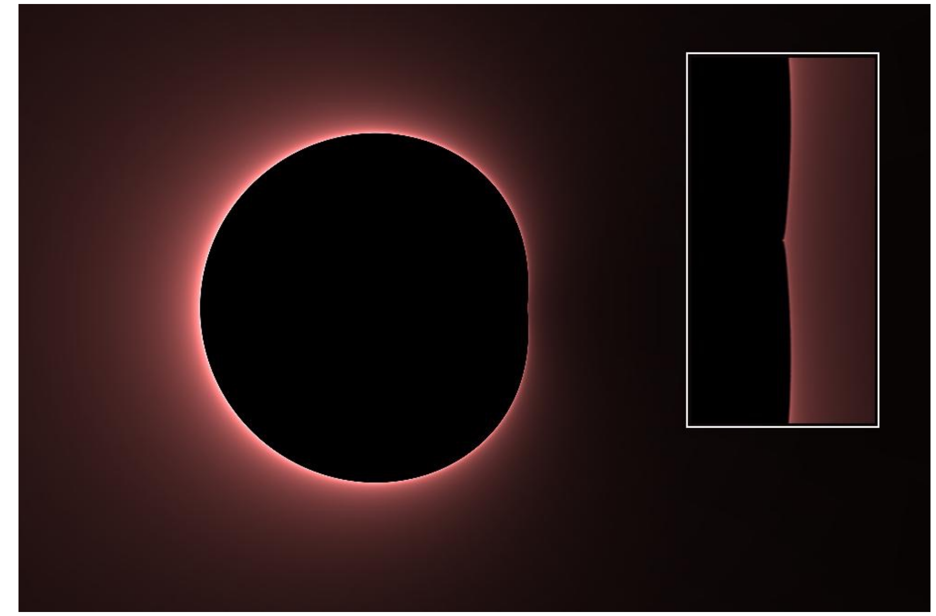
“weaker” gravity in the UV

$\longrightarrow$ singularity resolution in black holes

[Bonanno, Reuter ’99; Falls, Litim ’12; Adeifeoboa, AE, Platania ’18…]

$\longrightarrow$ singularity-resolving physics: imprints in black-hole shadows (EHT)

[Held, Gold, AE ‘19]



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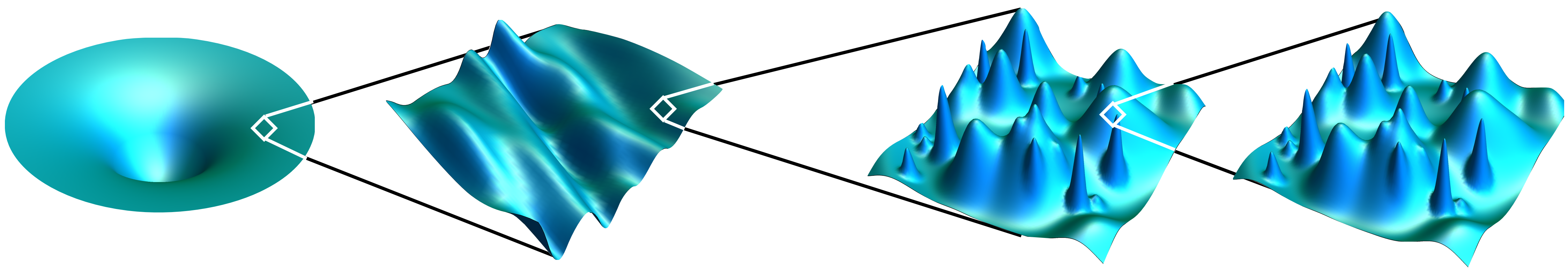
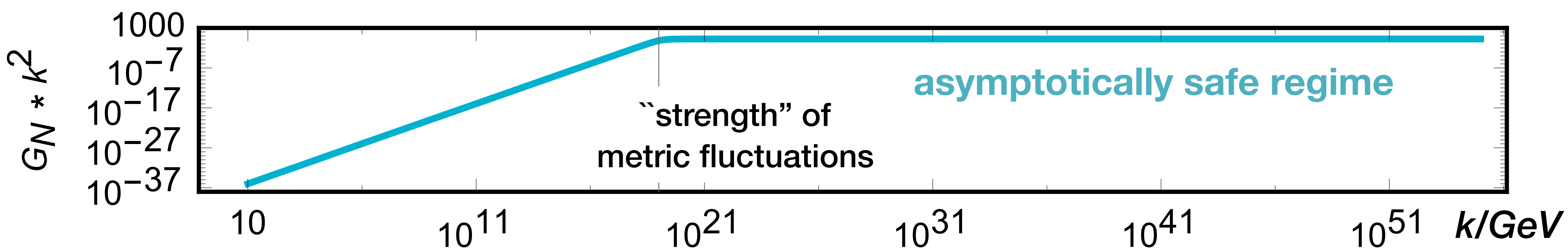


classical gravity regime **Planck scale** **quantum scale invariance**



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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;
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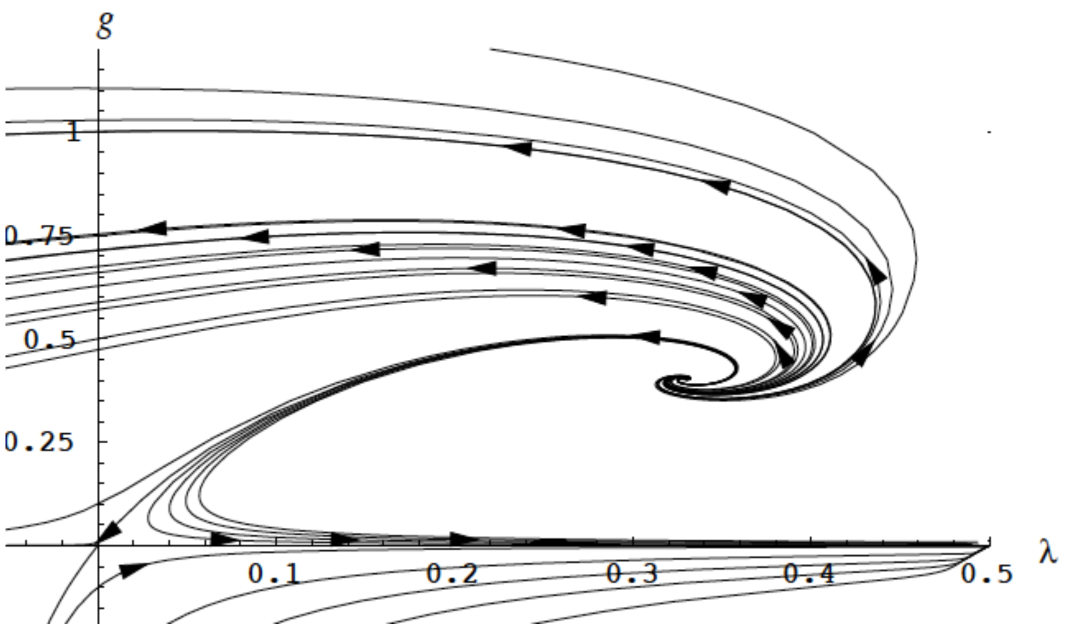

[Reuter, Saueressig '02]

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✓	$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu}$	[Gies, Knorr, Lippoldt, Saueressig '16]

systematic expansion scheme based on near-Gaussianity

[Falls, Litim, Nikolakopoulos, Rahmede '13 '14 '19;
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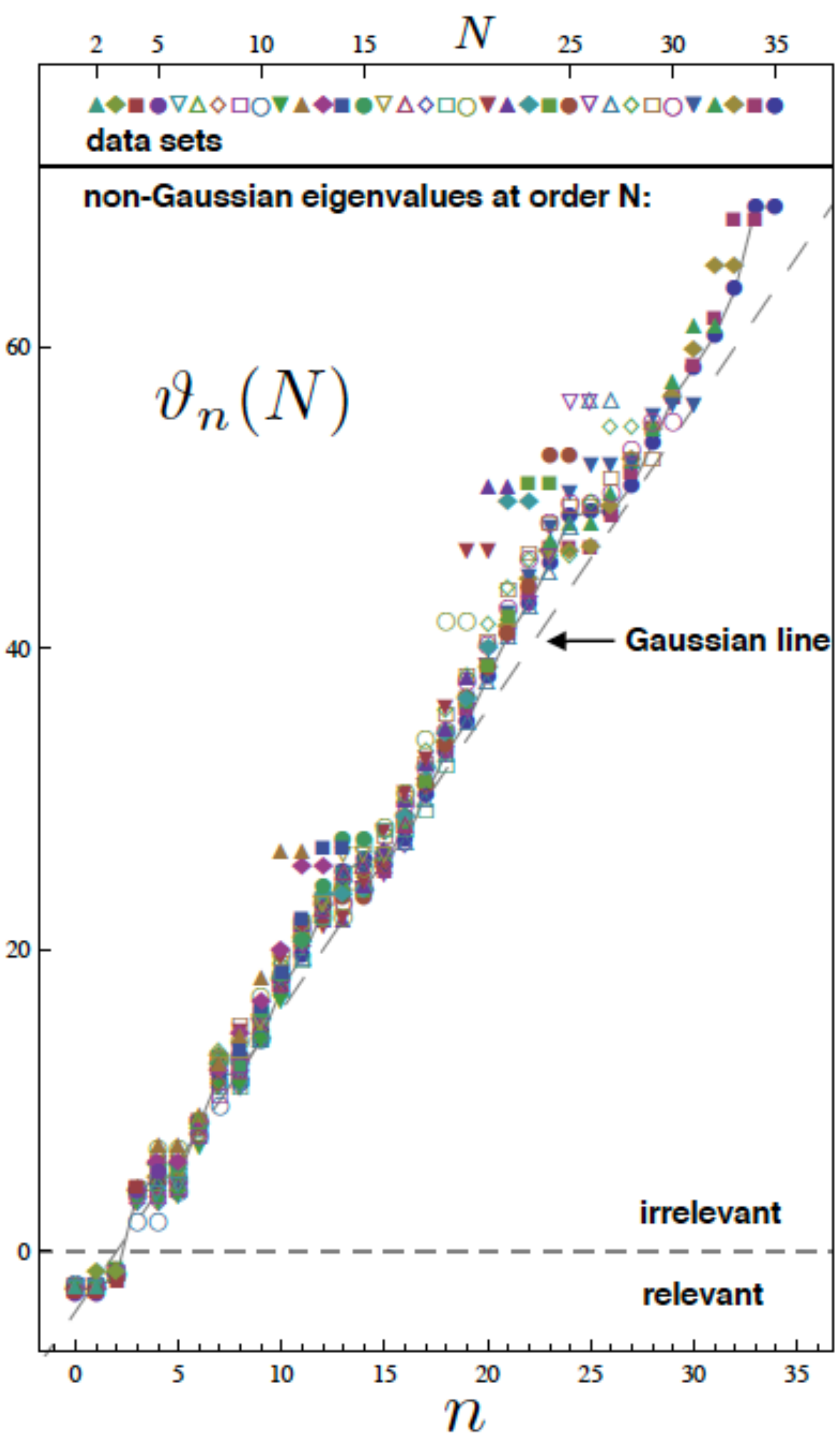

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open questions/ongoing work:

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

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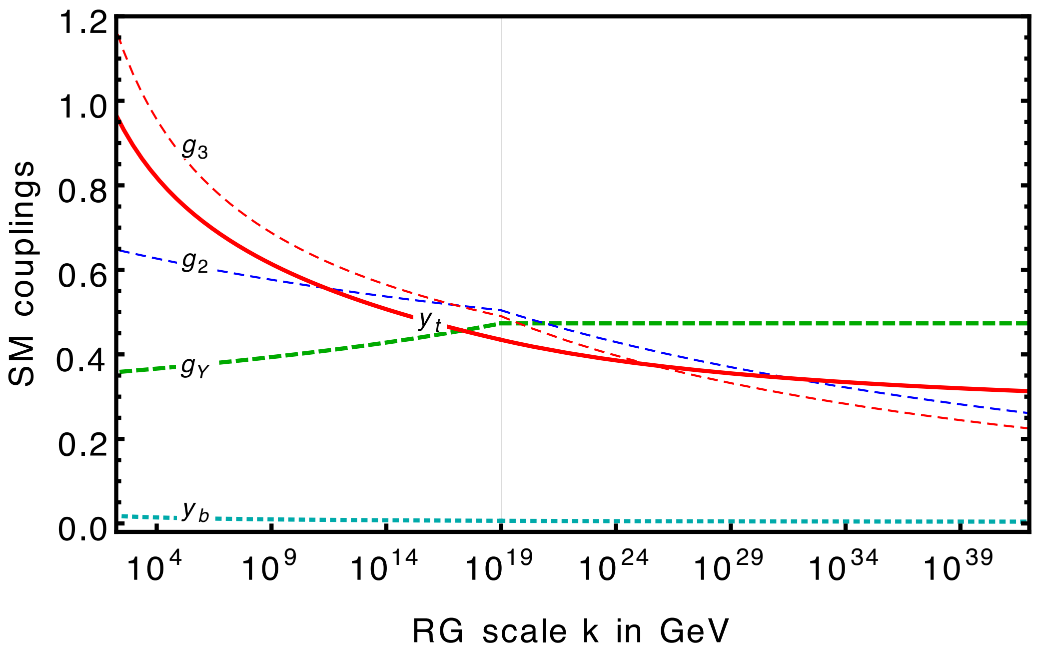
assumption for rest of this talk:
asymptotic safety in gravity
-> Consequences for matter?

Asymptotically safe guide to the literature on SM + QG:

required:

- extended truncations
- confirmation from other methods (lattice!)



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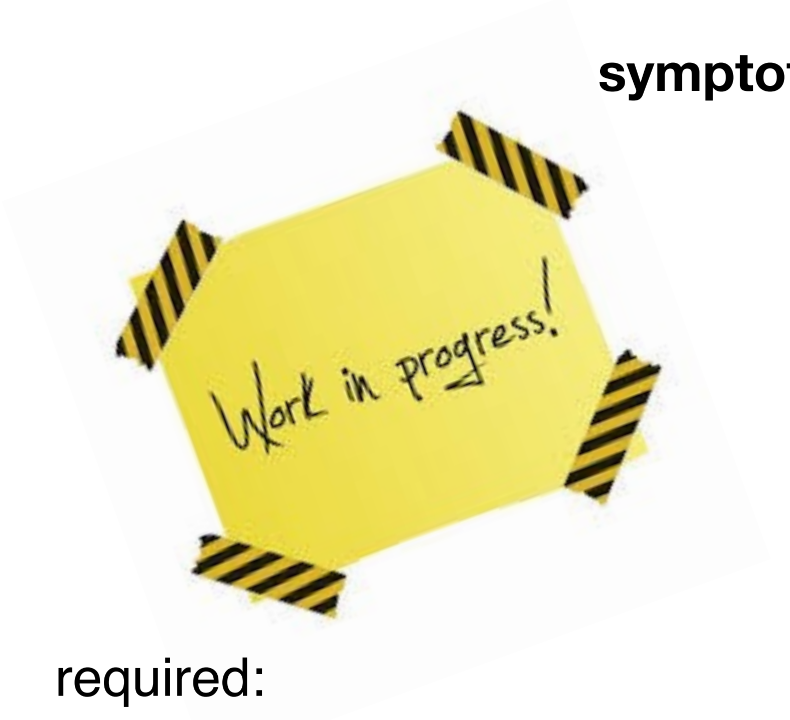

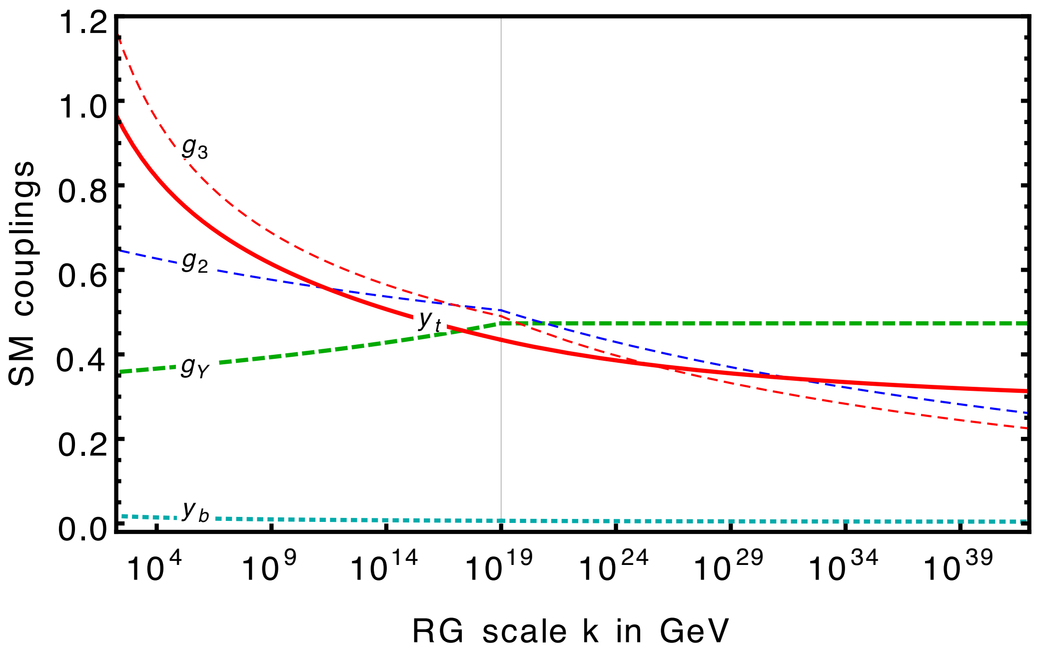

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Hints in truncations of RG flow from functional RG techniques that SM could become UV complete by AS quantum gravity fluctuations:

- AF in non-Abelian couplings preserved

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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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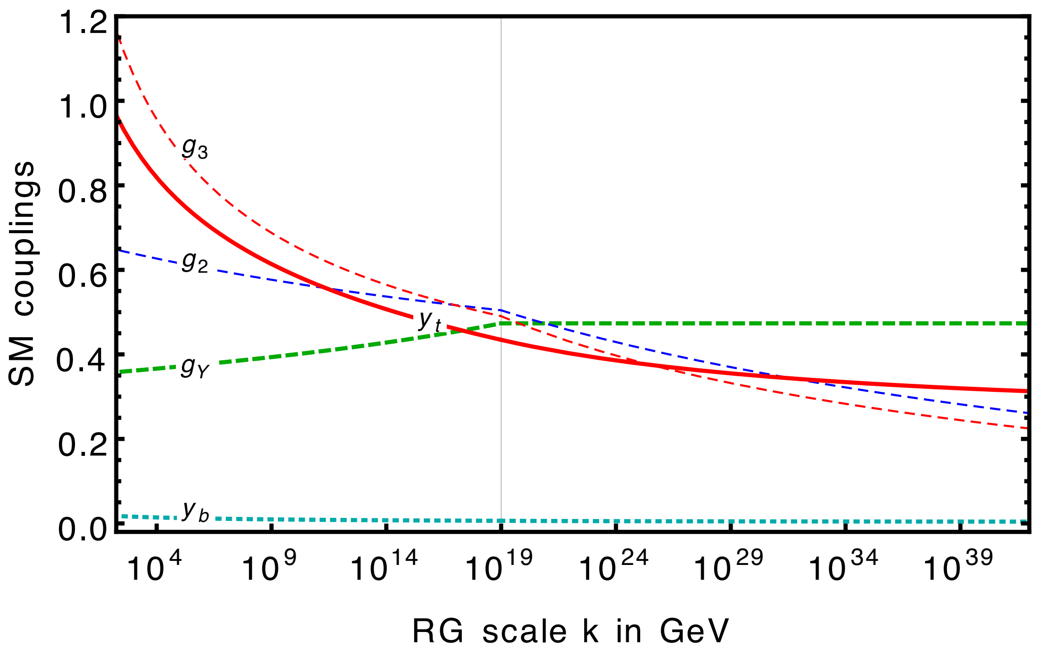

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Predictive power of asymptotic safety - proof of principle: Abelian gauge coupling

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

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

metric fluctuations

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

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[Daum, Harst, Reuter ’09; Folkerts, Litim, Pawlowski ’09; Harst, Reuter ’11; Christiansen, AE ’17; AE, Versteegen ’17; Christiansen et al. ’17]

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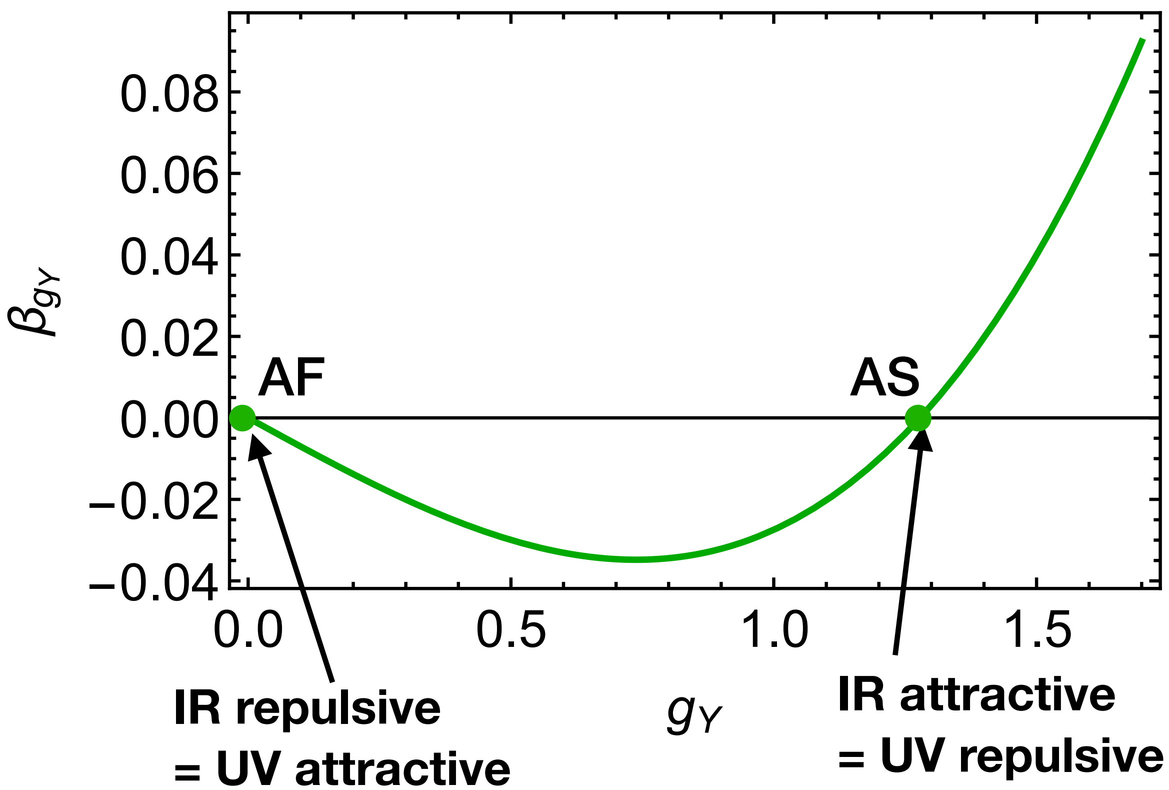

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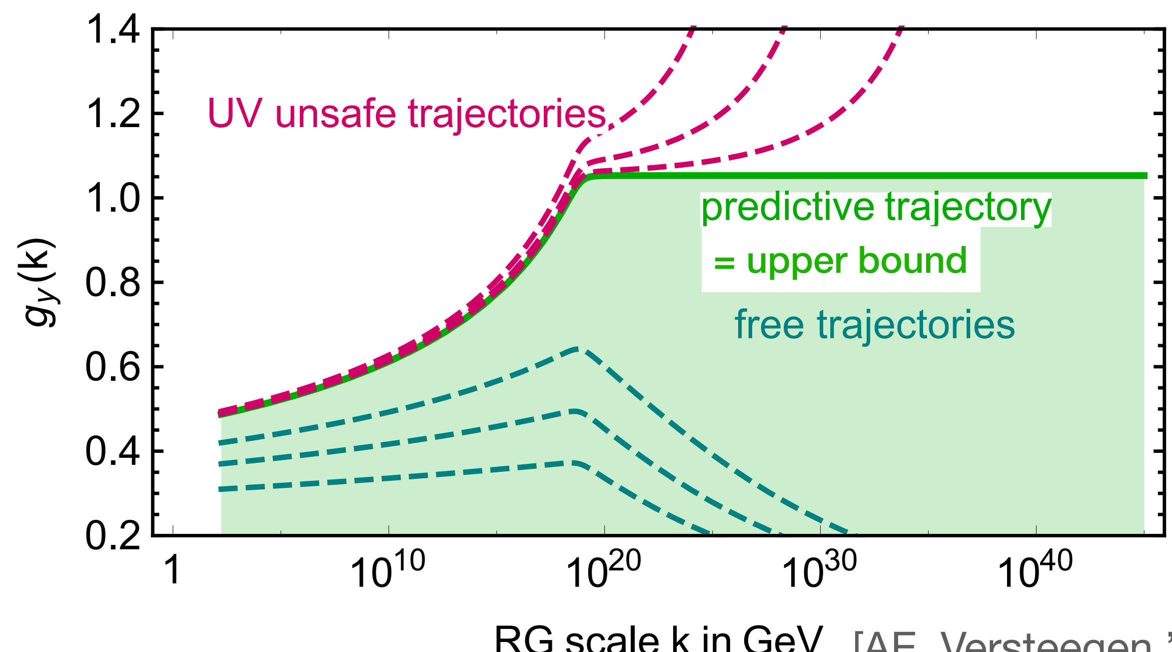
matter & gravity fluctuations compete:

strong gravity: asymptotically free

strong matter: UV unsafe

balance: UV safe & interacting



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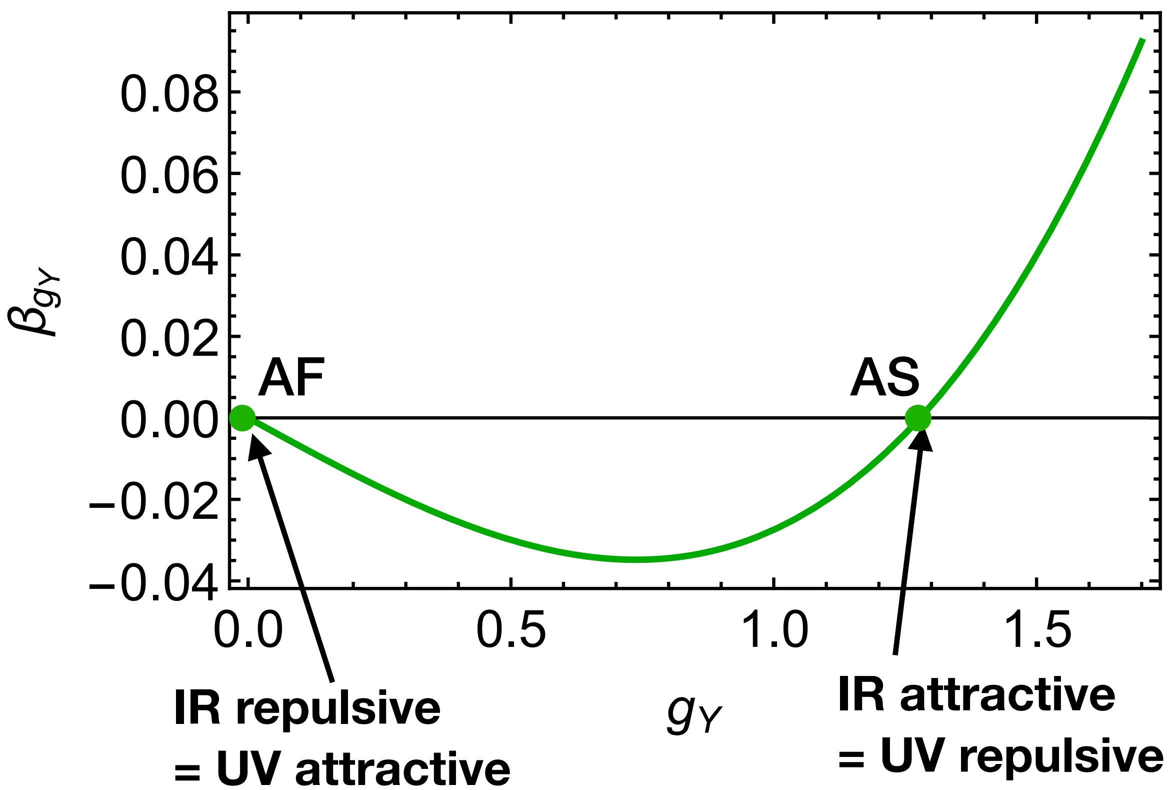

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$\Rightarrow$ **large IR values of g_Y cannot be reached from any fixed point**

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

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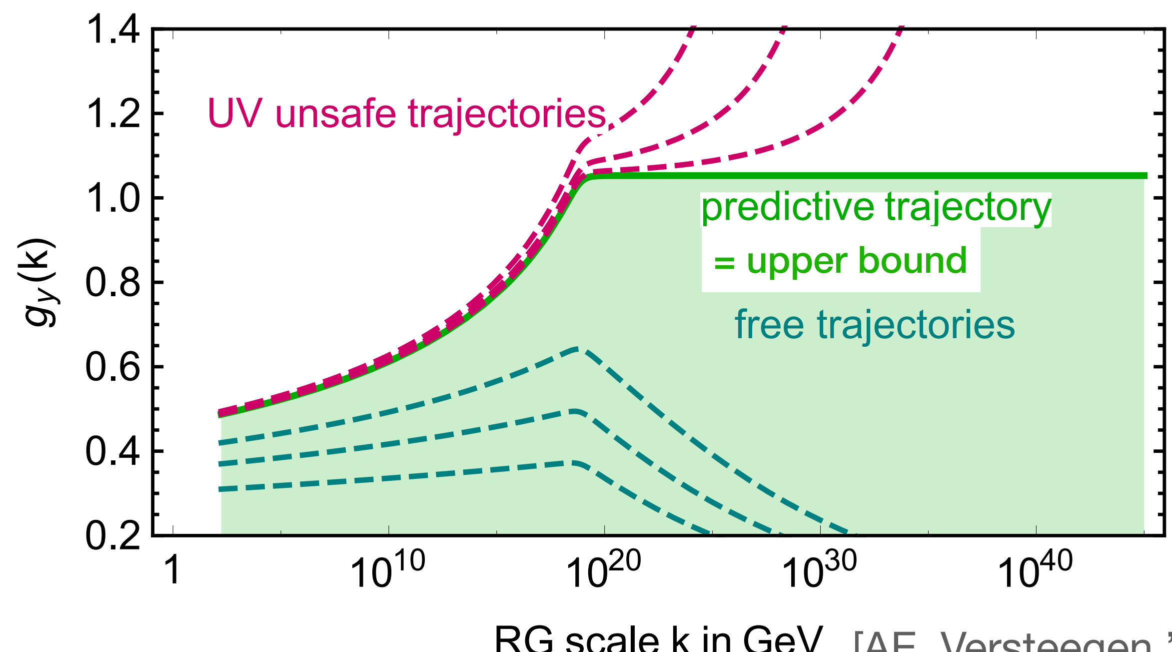

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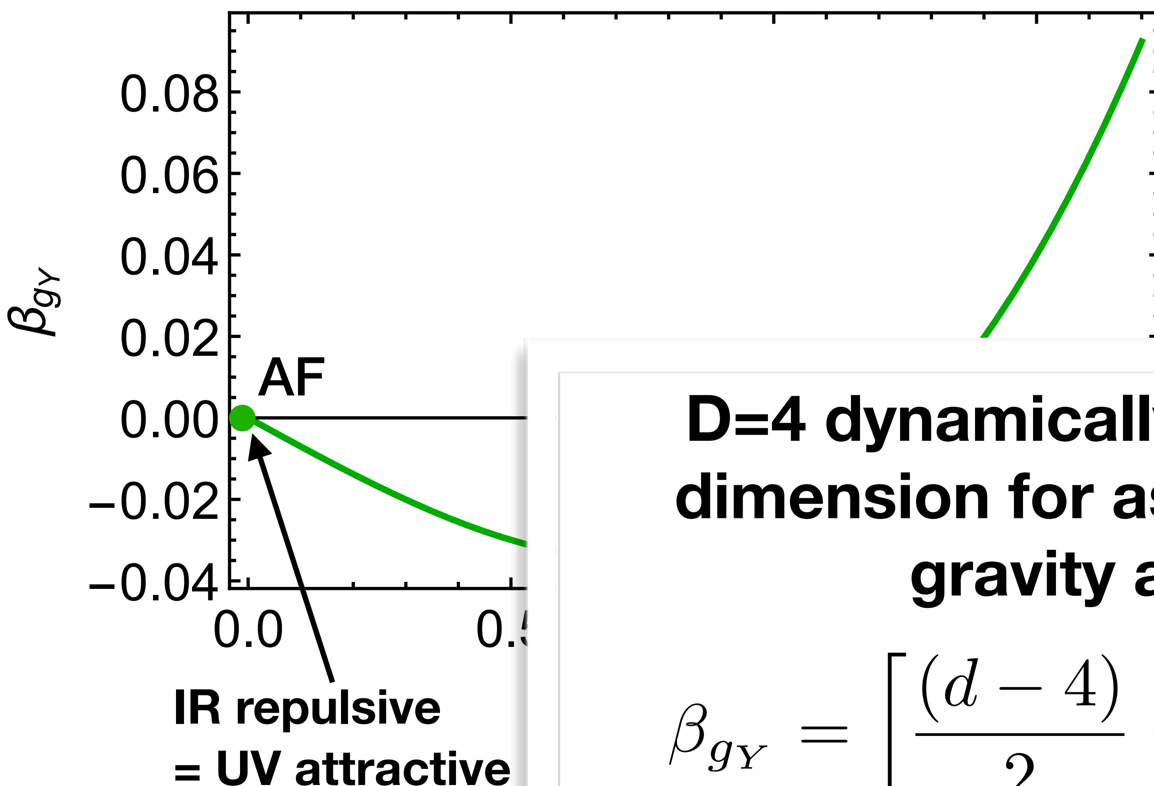

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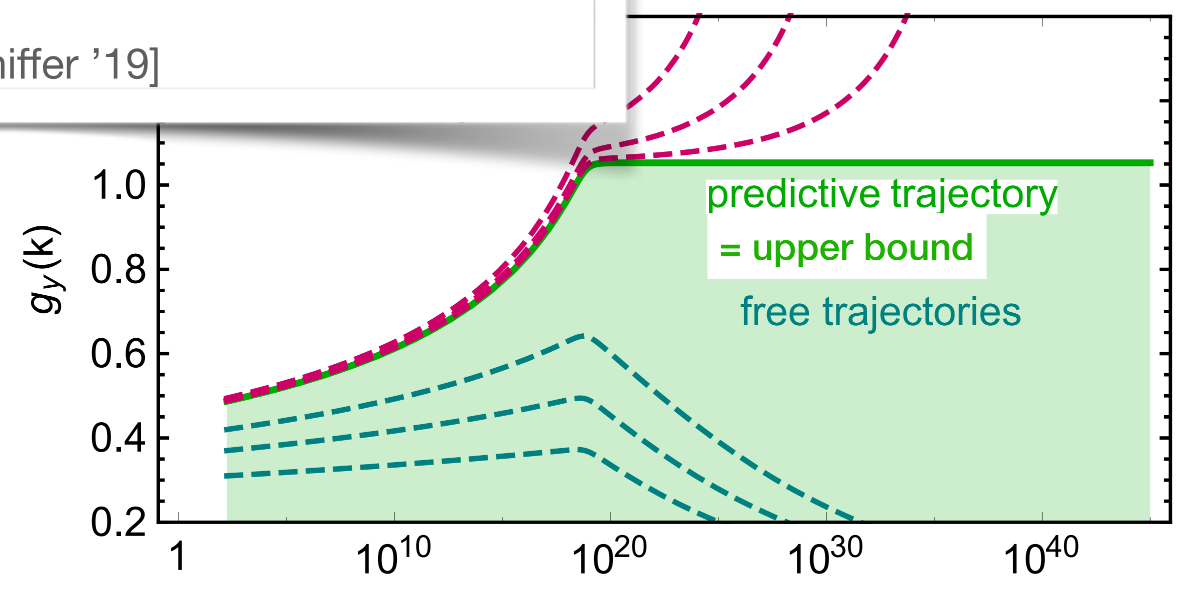
D=4 dynamically selected critical dimension for asymptotically safe gravity and matter

$$\beta_{g_Y} = \left[\frac{(d-4)}{2} - f_g(d)\right] g_Y + \ldots$$

[AE, Schiffer ’19]

...s of g_Y cannot ...om any fixed point

...is unique value ...interacting fixed point



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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 gravitational coupling values** [AE, Held ’17]

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

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

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

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

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

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

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

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Prerequisite:
no spontaneous or explicit chiral symmetry through quantum gravity effects

[AE, Gies ’11; AE, Lippoldt ‘16]

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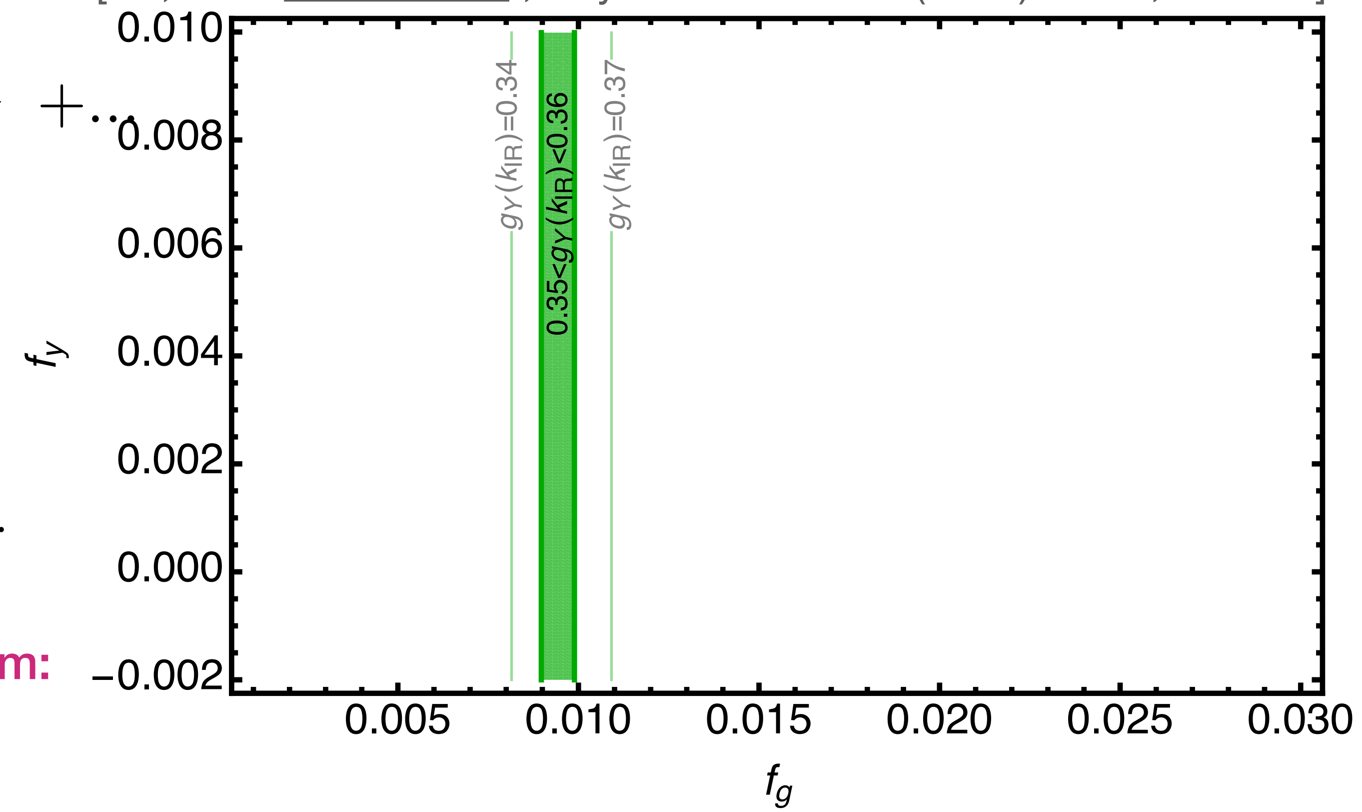

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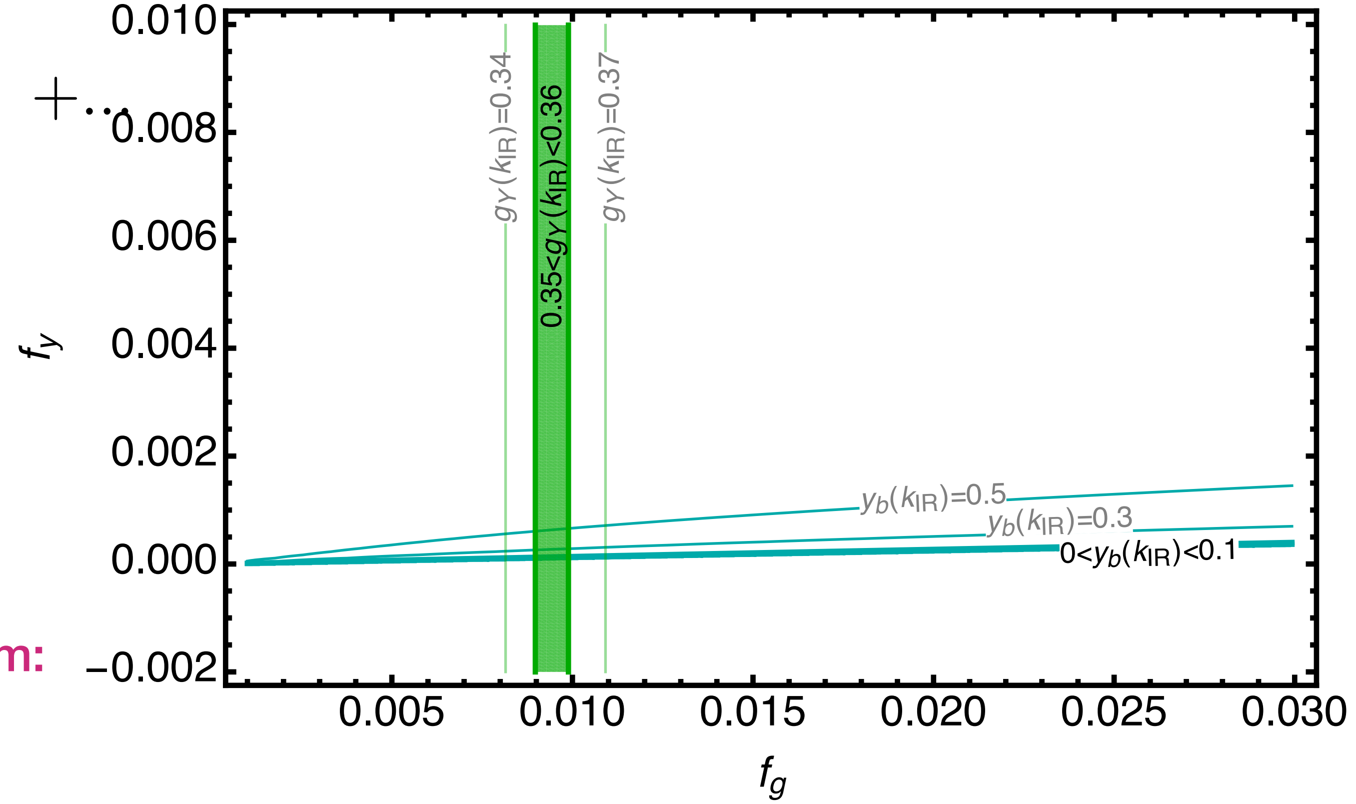

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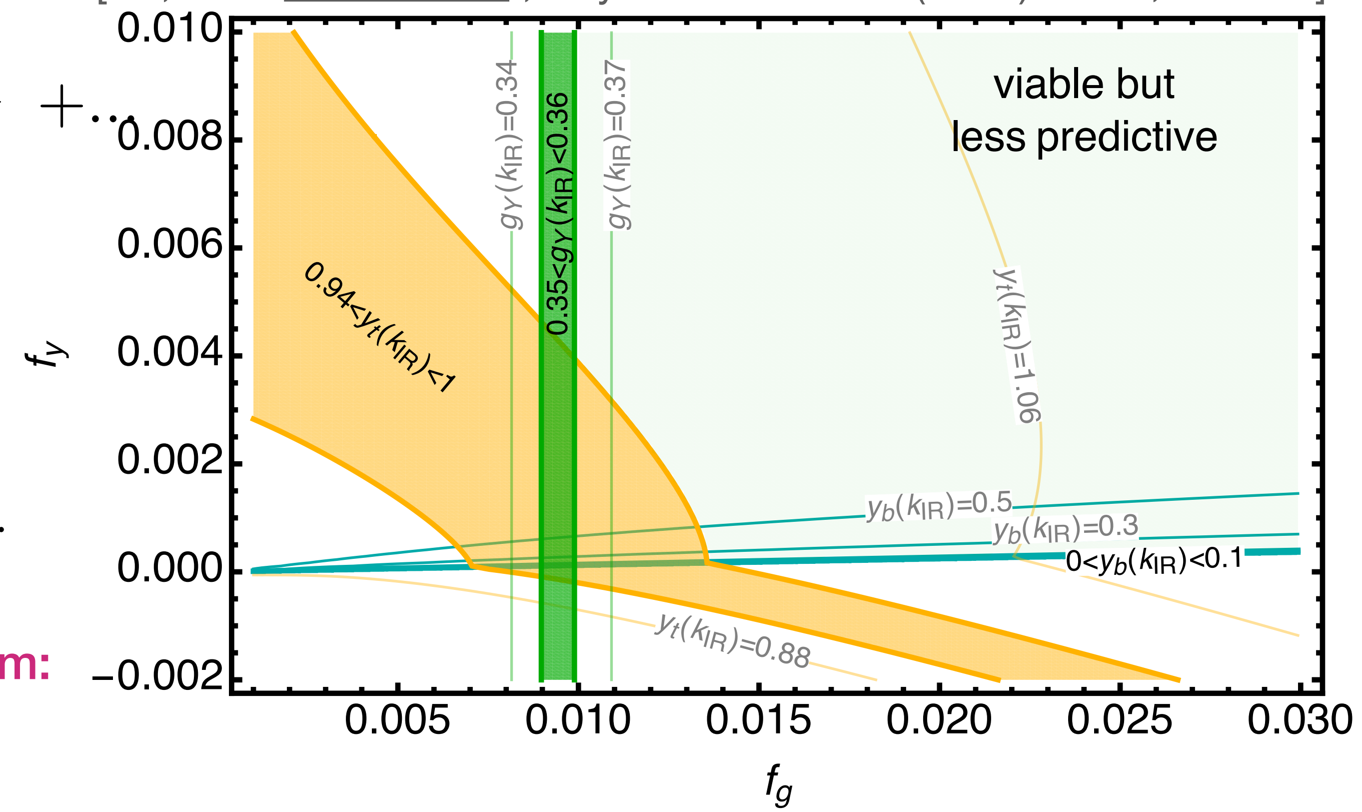

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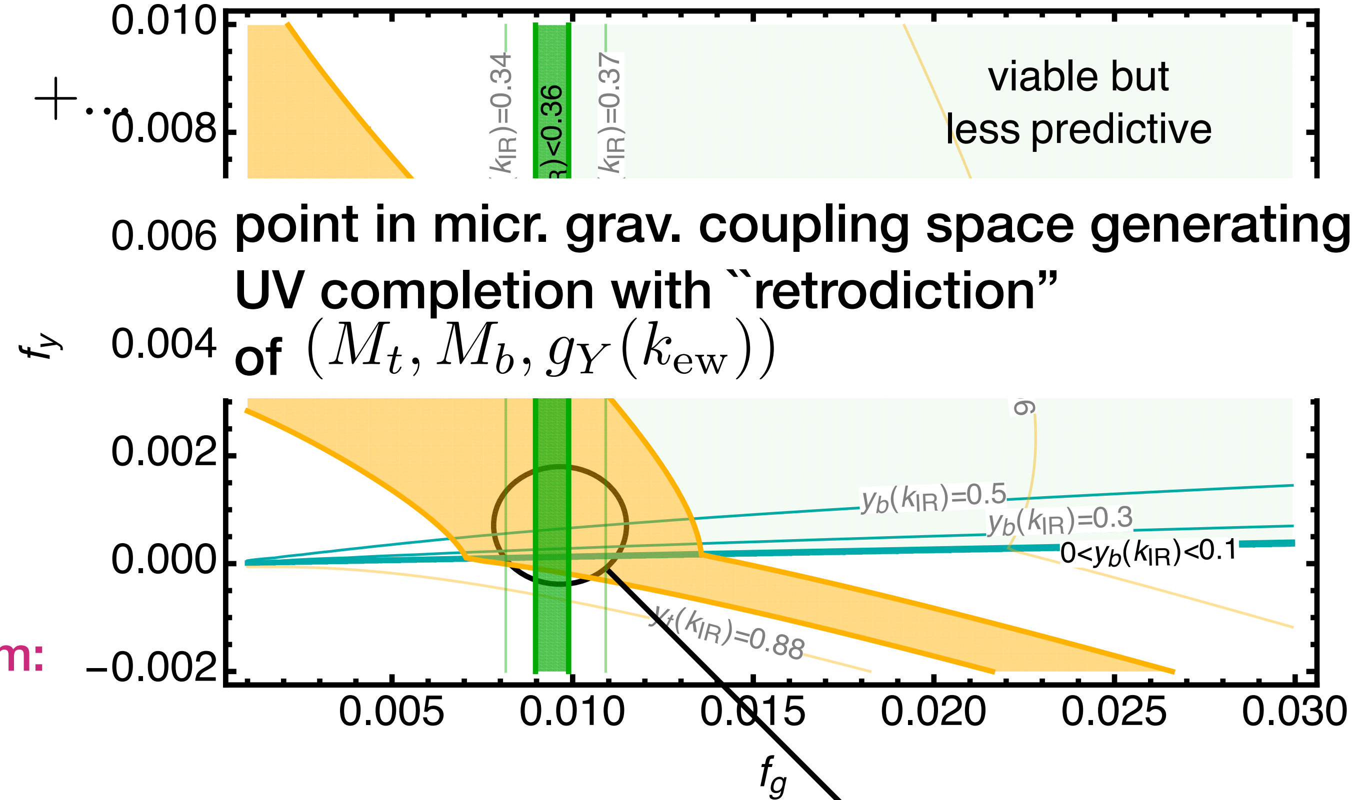

point in micr. grav. coupling space generating UV completion with ``retrodiction" of $(M_t, M_b, g_Y(k_{\rm ew}))$

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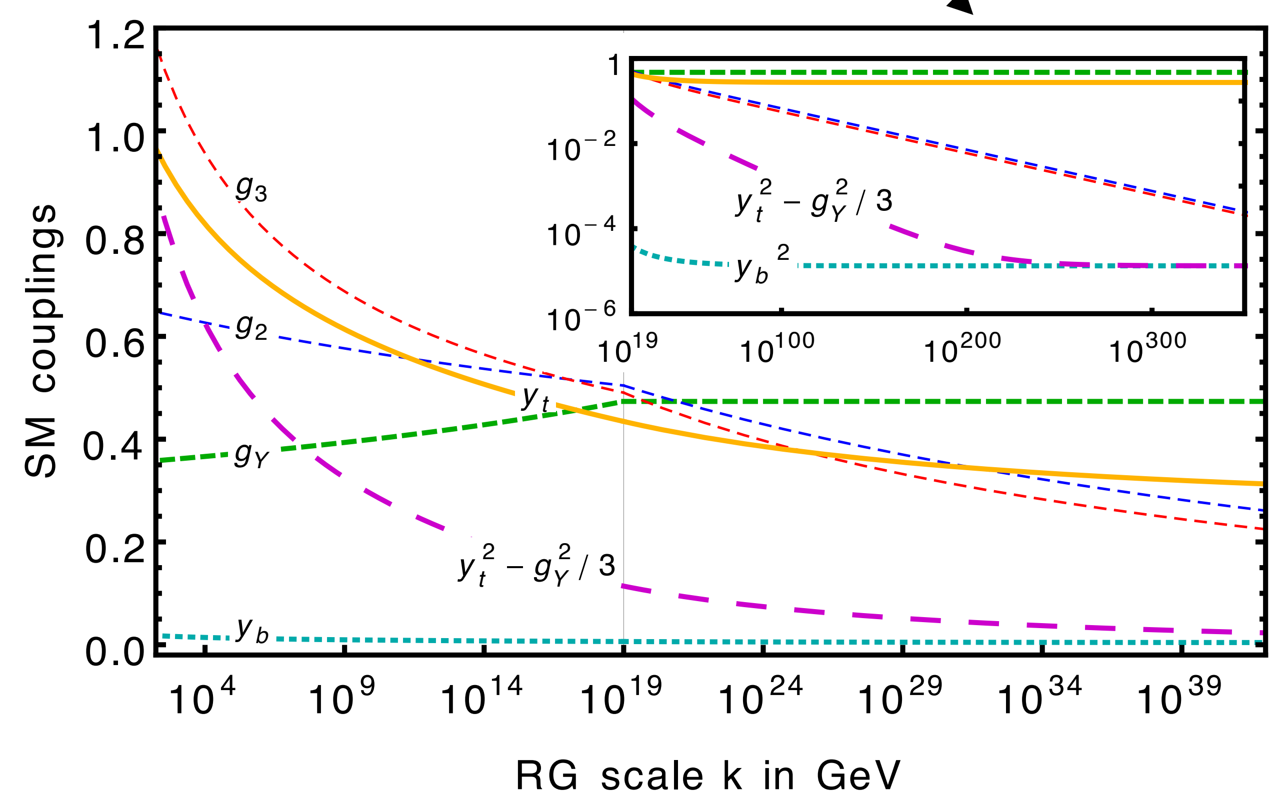
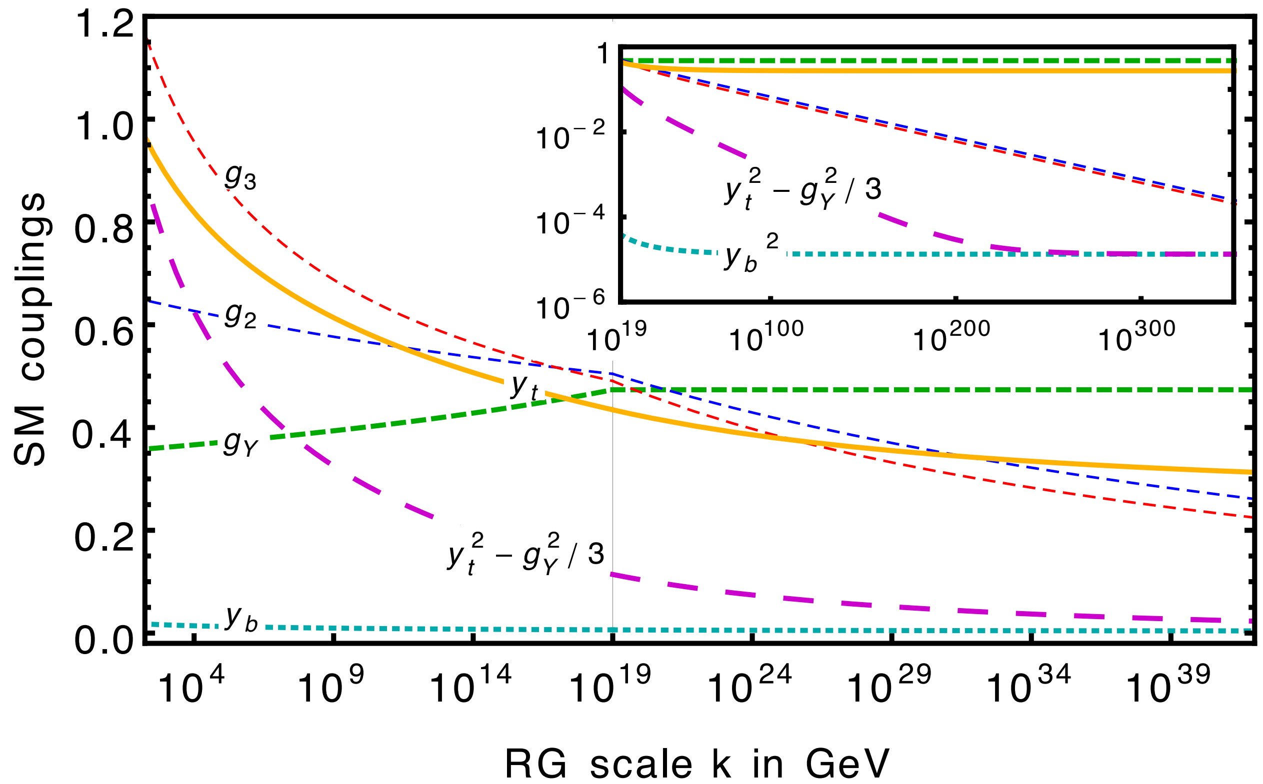


Three observations

[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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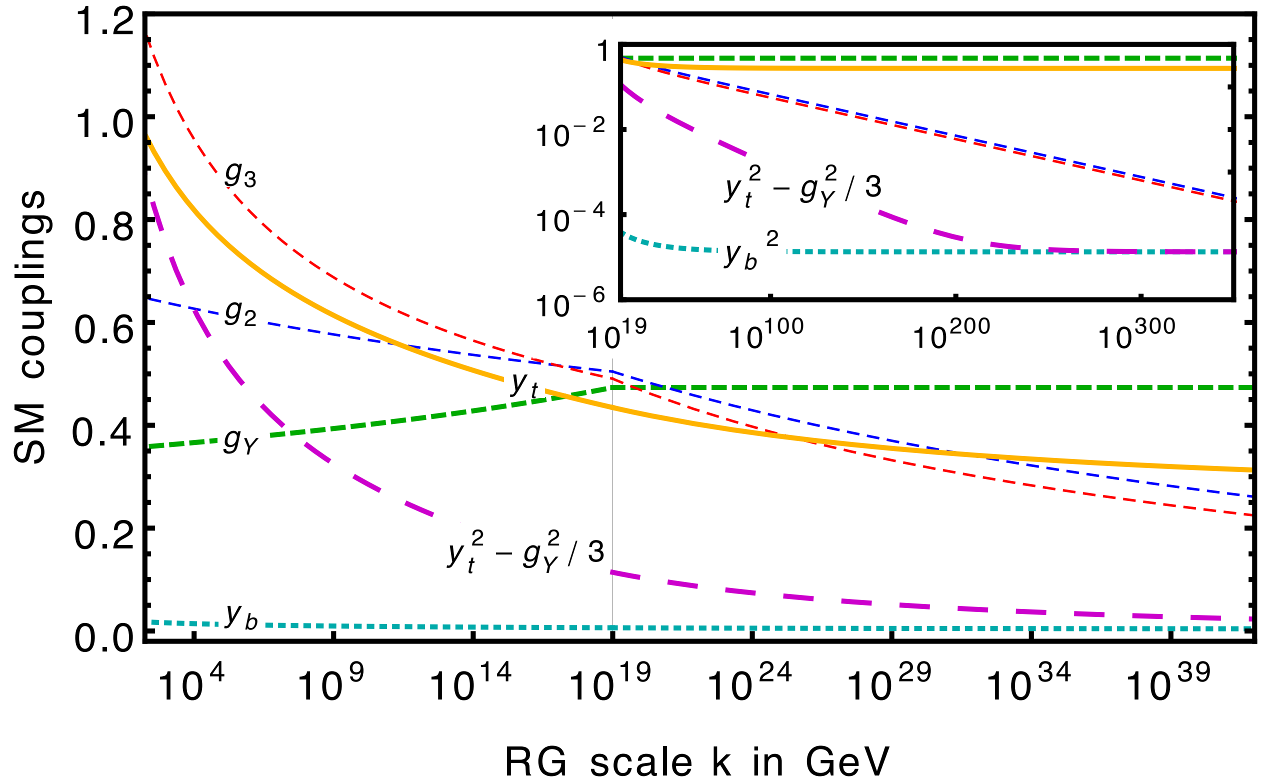


- **transplanckian flow of Yukawas driven by non-Abelian flow away from AF**

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

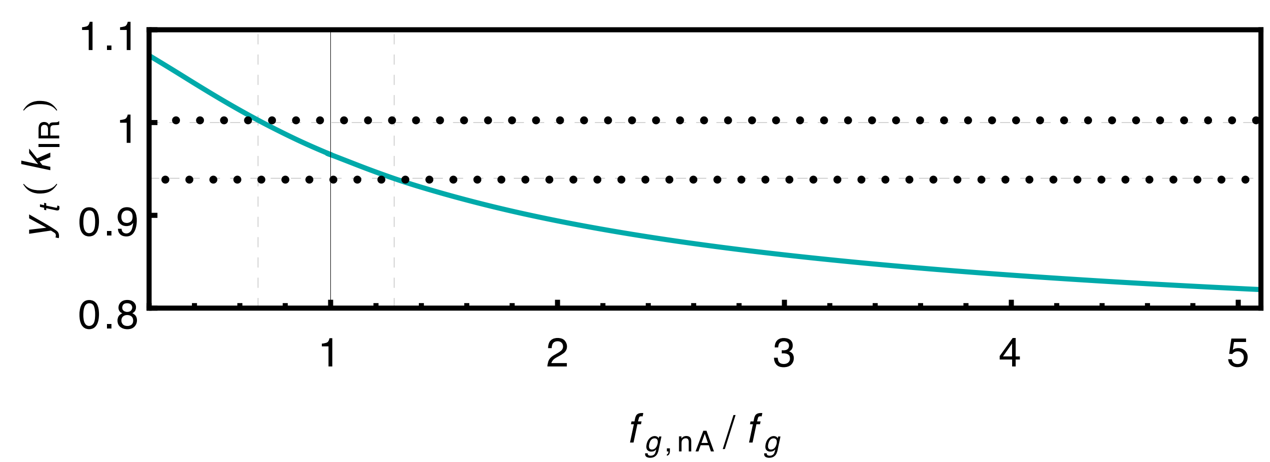
Abelian hypercharge: $\beta_{g_Y} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y$

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

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

universality (= blindness to internal symmetries) of QG

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



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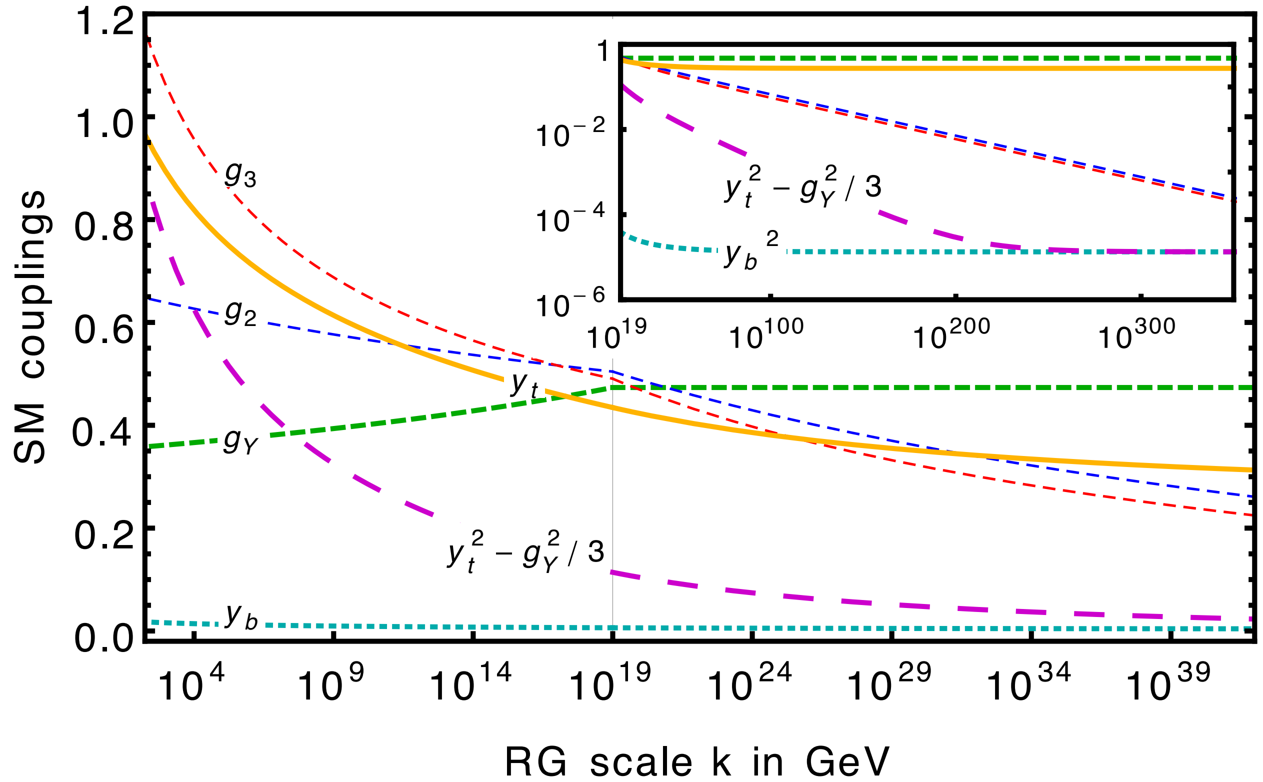
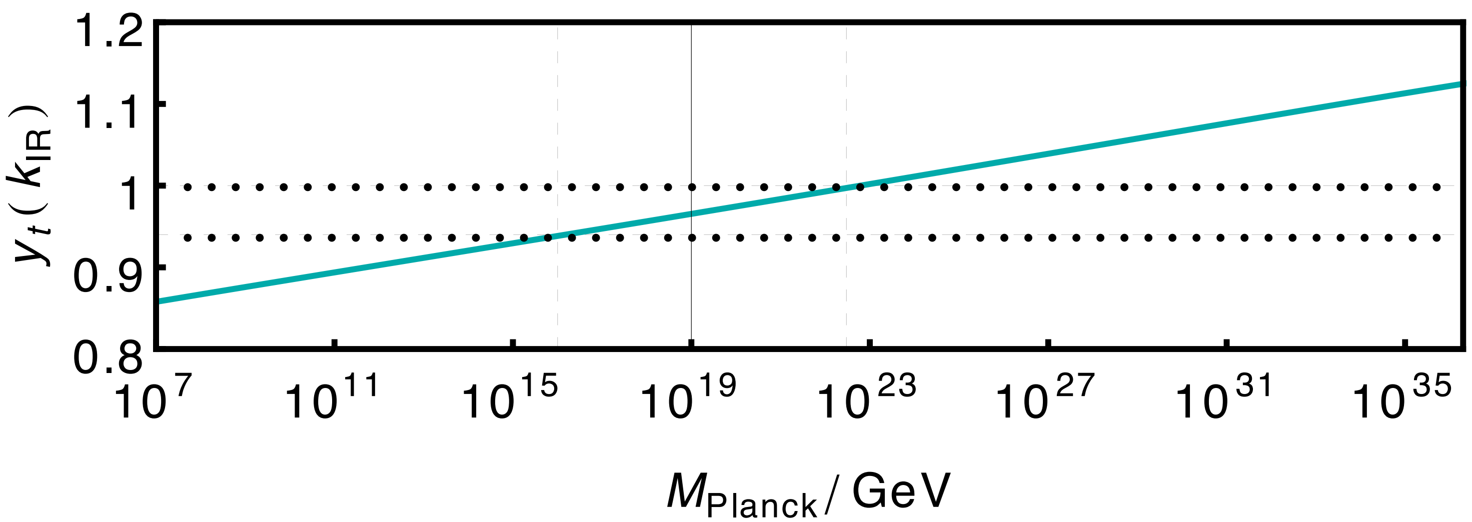


$f_i = \text{const} \geq 0$ **above M_{pl}**

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

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



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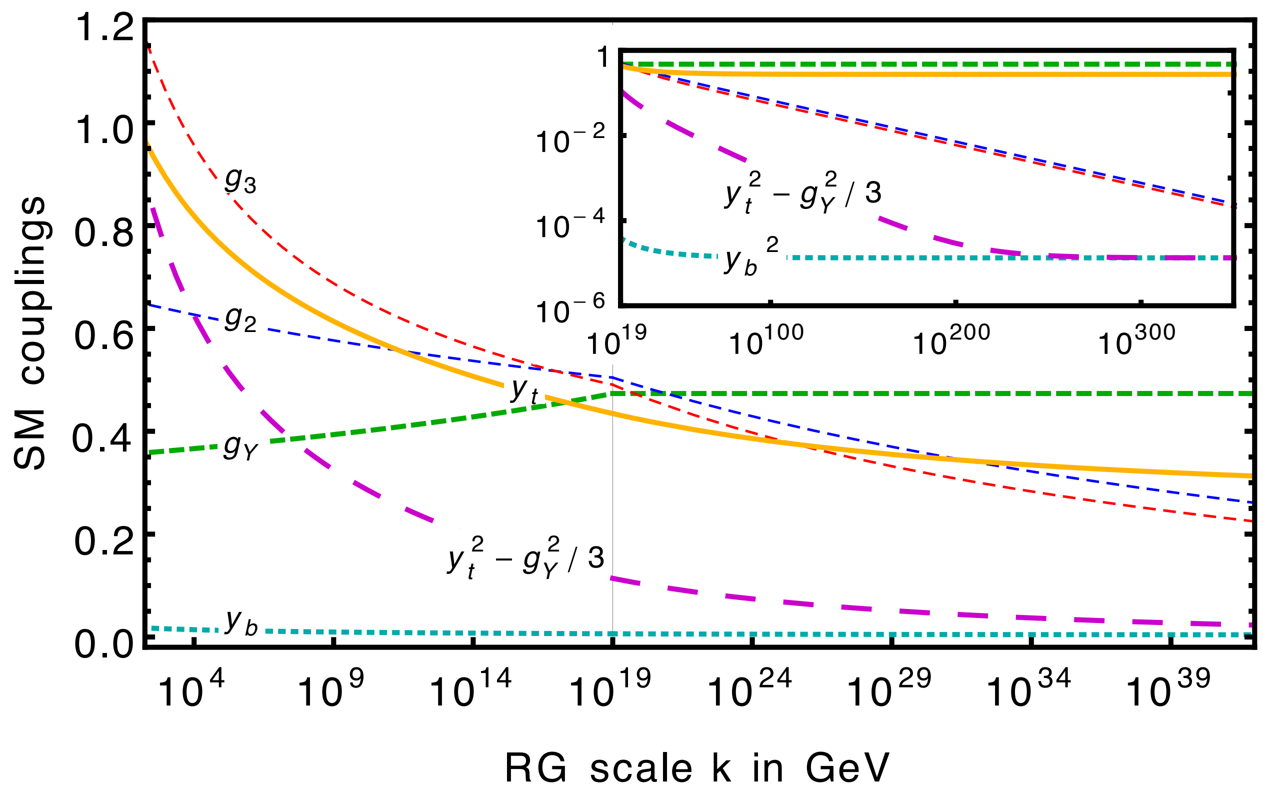

1) **constant linear contributions**
2) **universal contributions**
   (indep. of internal symmetries)
3) **at (very roughly) Planck scale**

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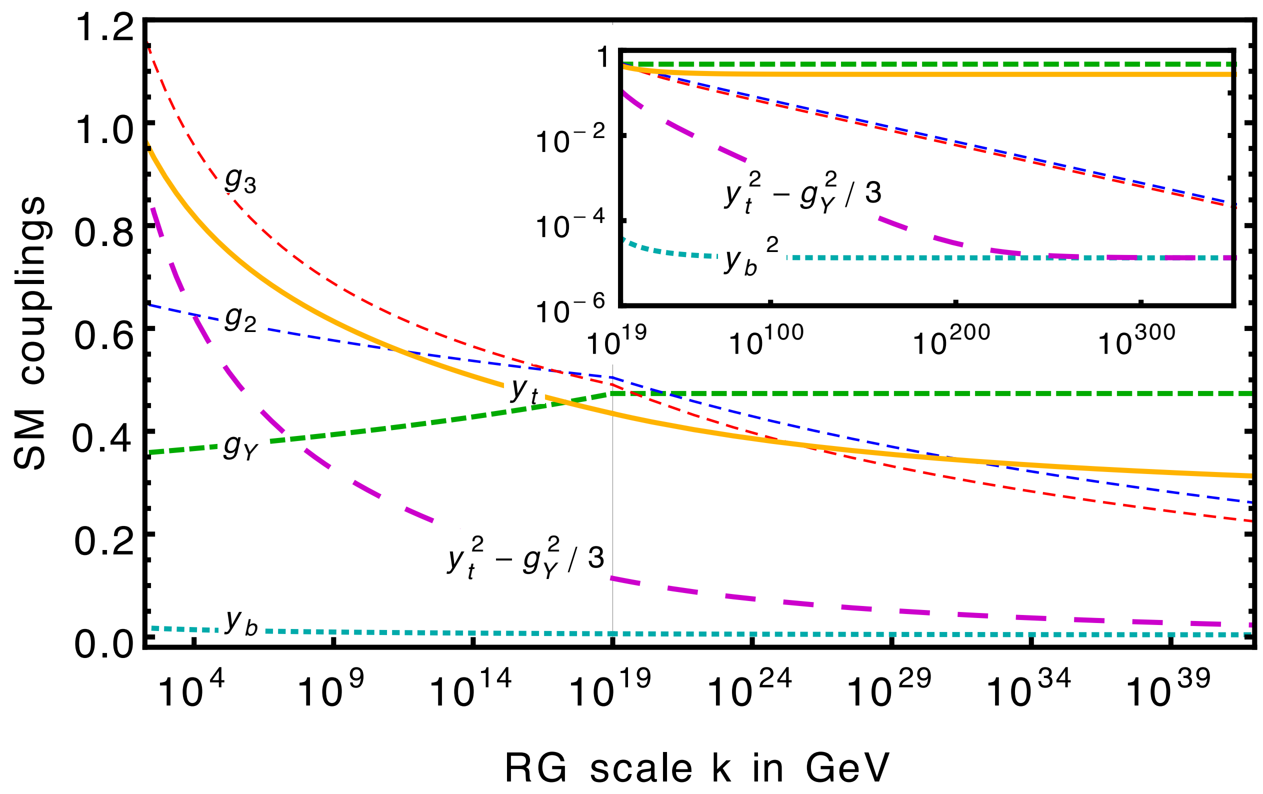

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If **it looks** ***like a duck*****, swims** ***like a duck*****, and** ***quacks like a duck…***

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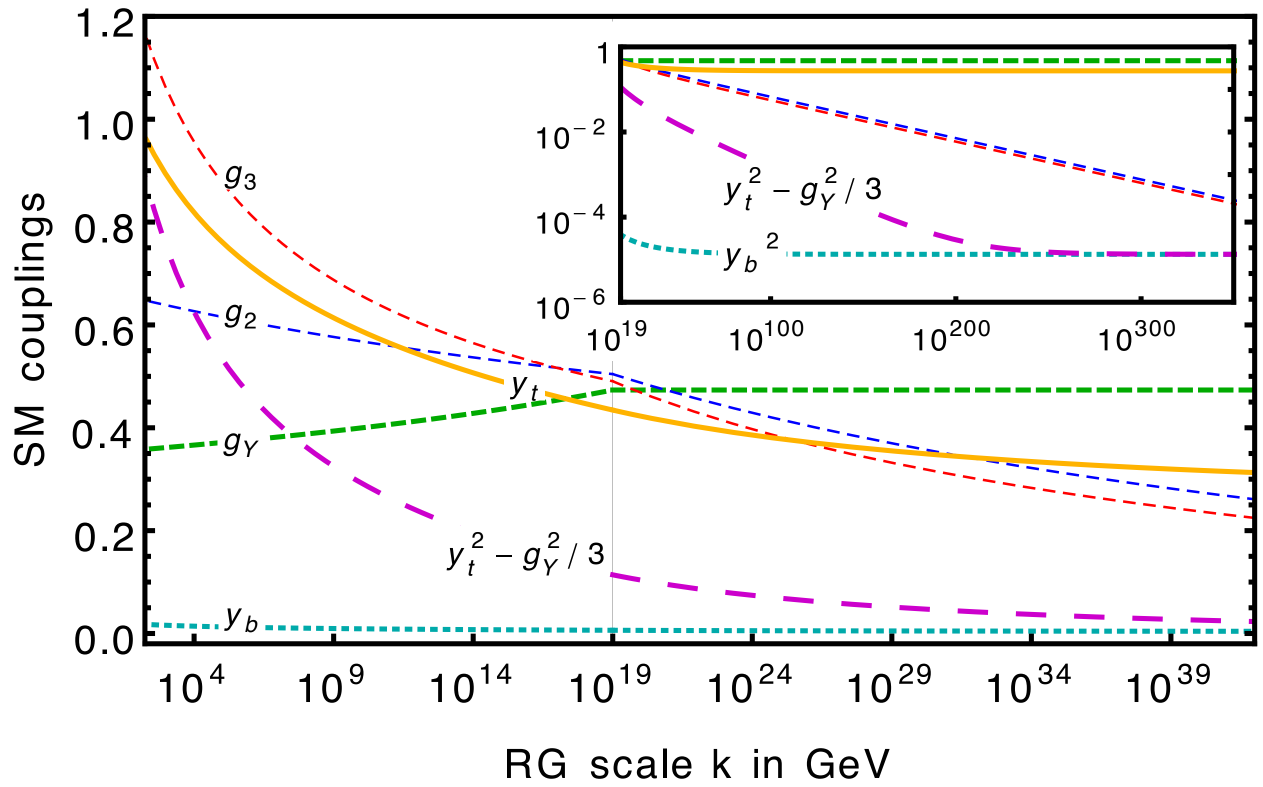

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probably asymptotically safe quantum gravity…

…effectively like dimensional reduction

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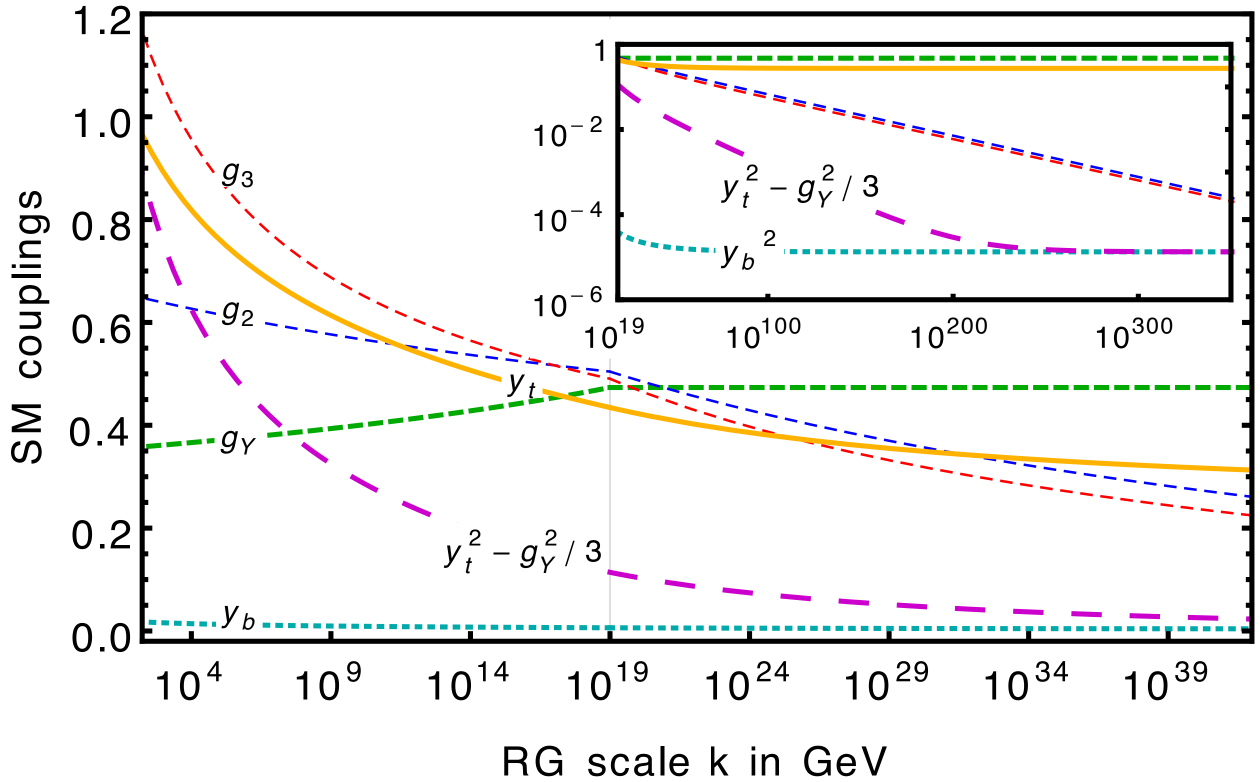
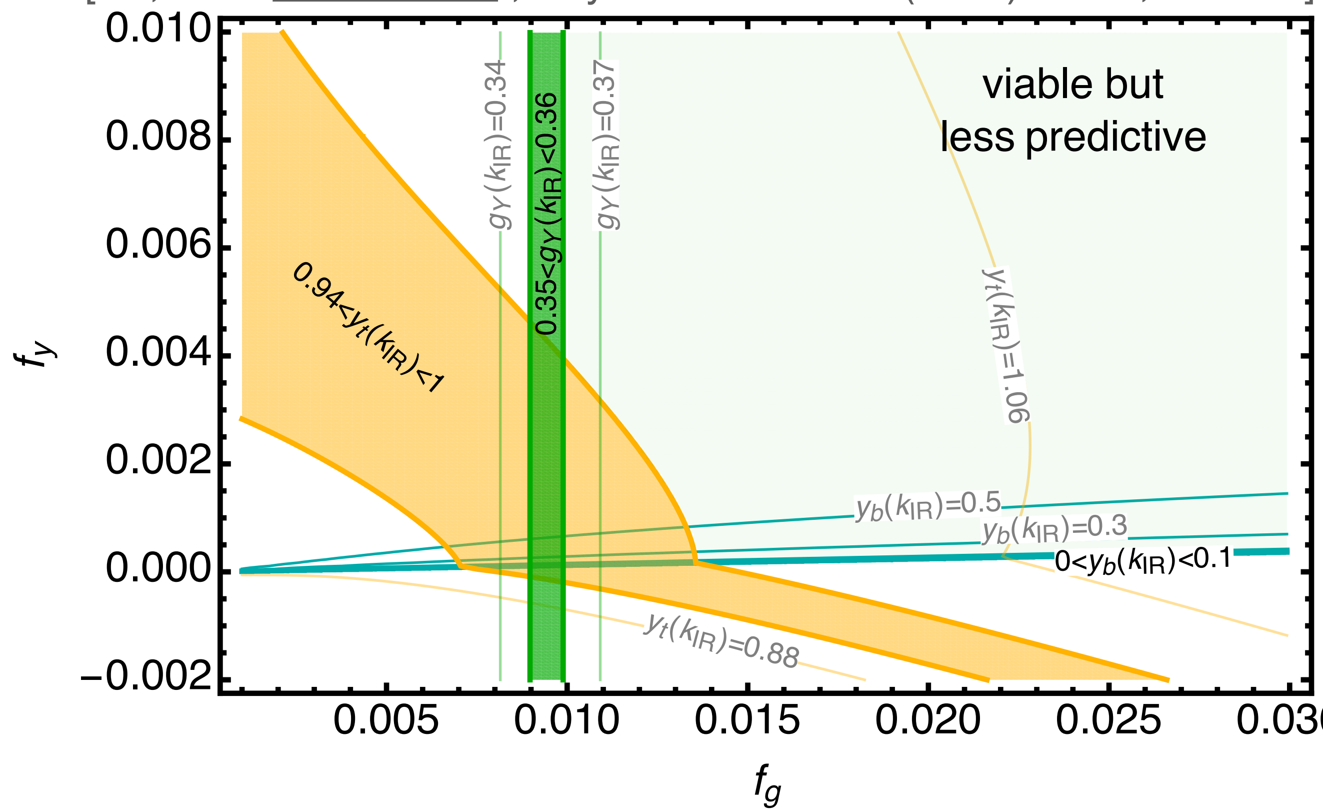
Charges & Masses are linked?

[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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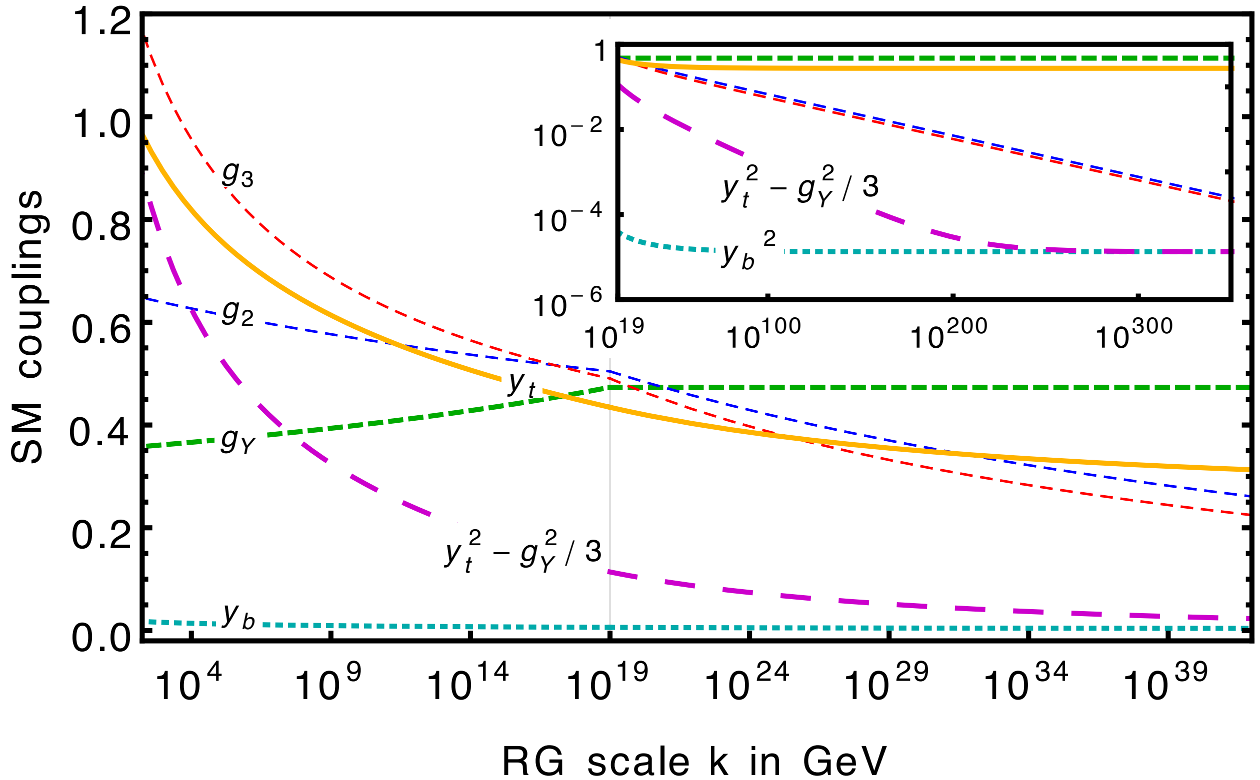

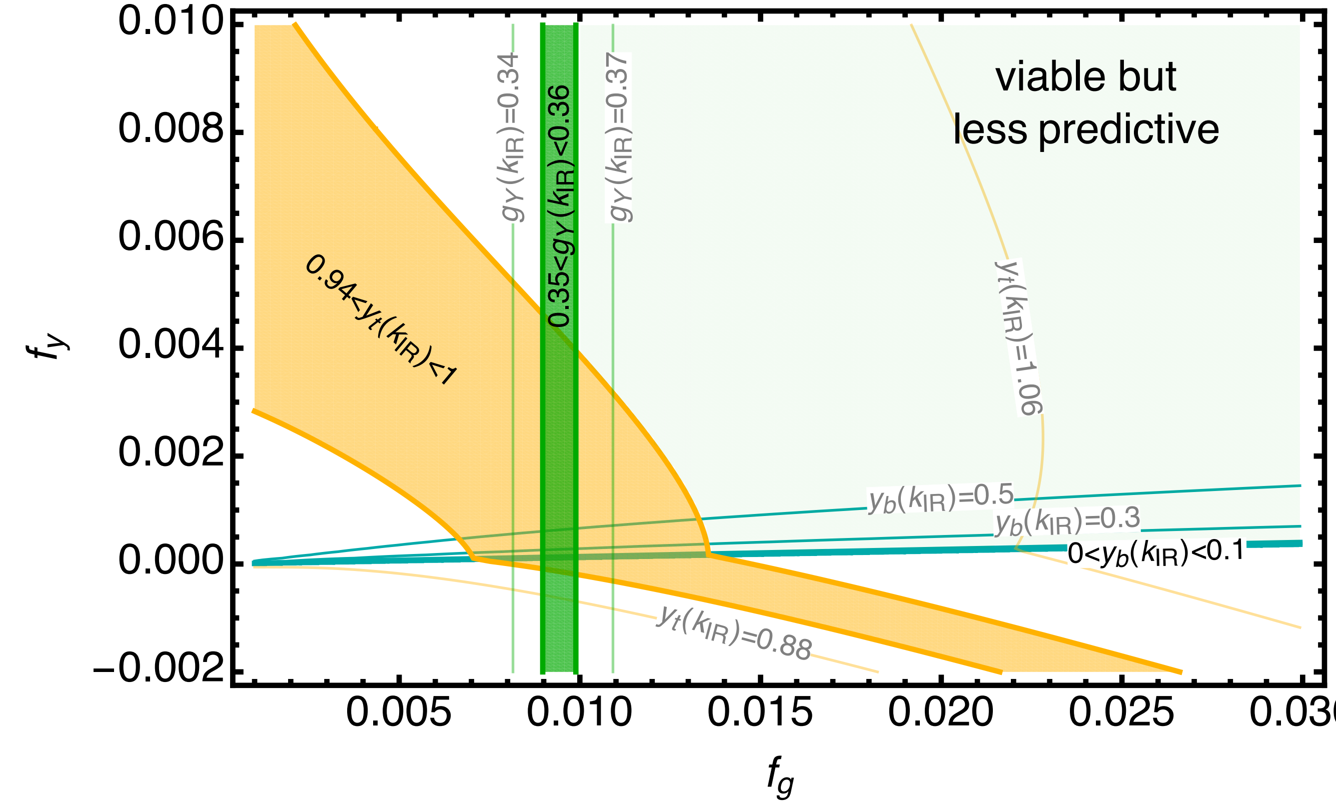

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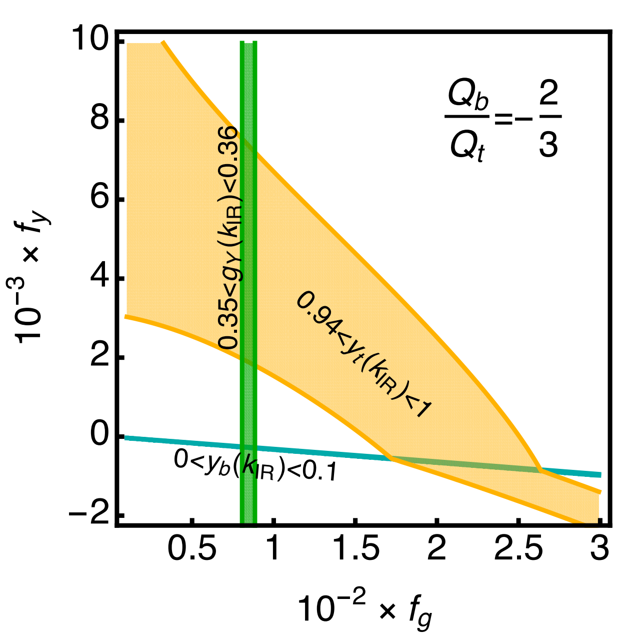

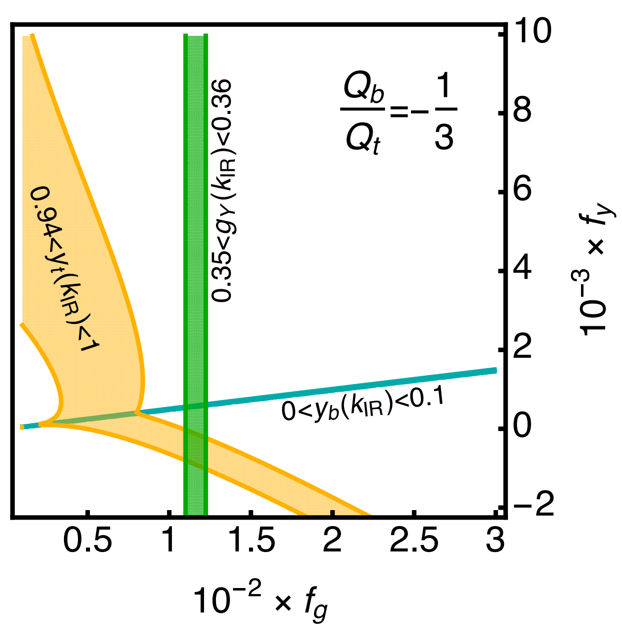

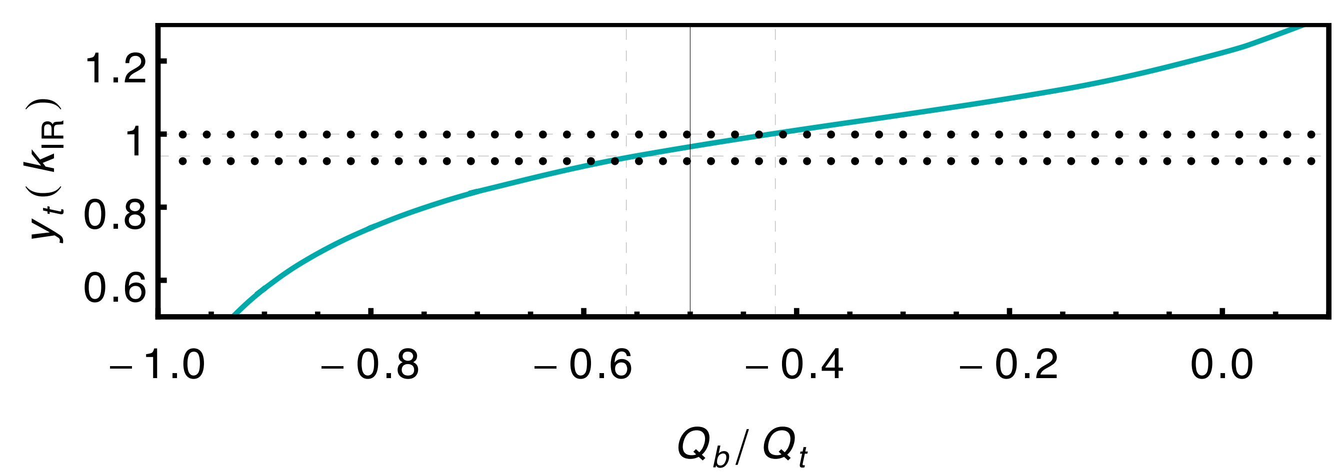

masses of top & bottom select SM top/bottom charge ratio

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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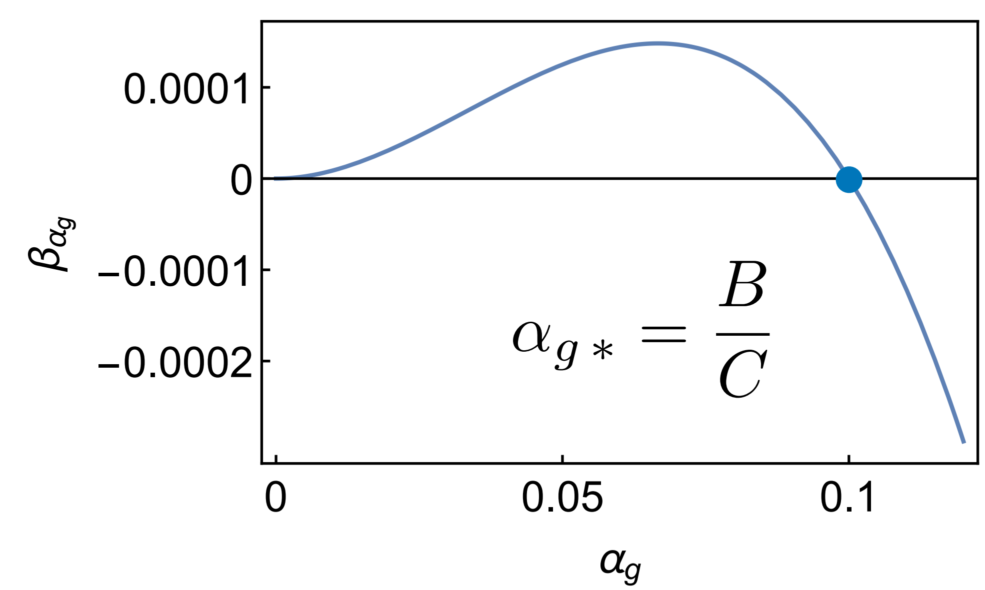
blueprint for gauge-Yukawa models in d=4 dimensions: [Litim, Sannino '14]

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



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- **competing degrees of freedom**

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

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

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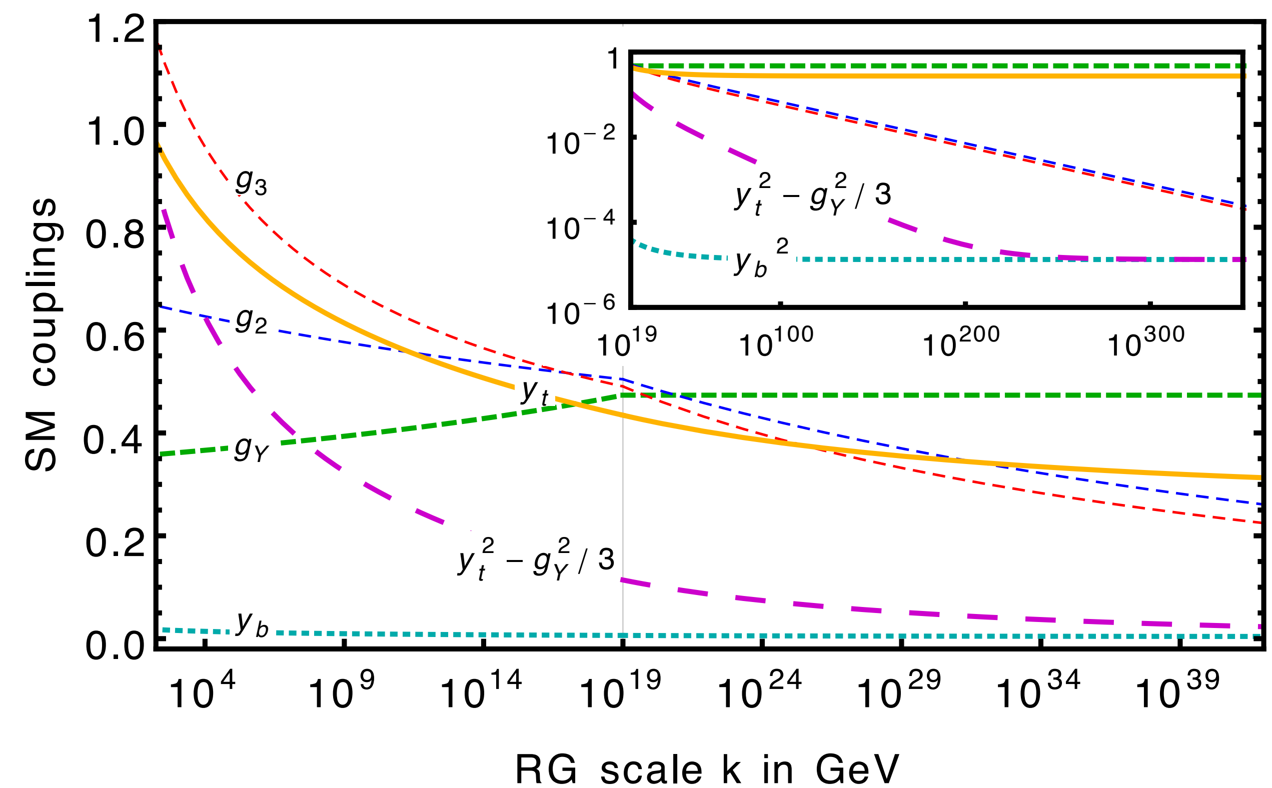
  - increase predictivity
  - become subject to observational consistency tests

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



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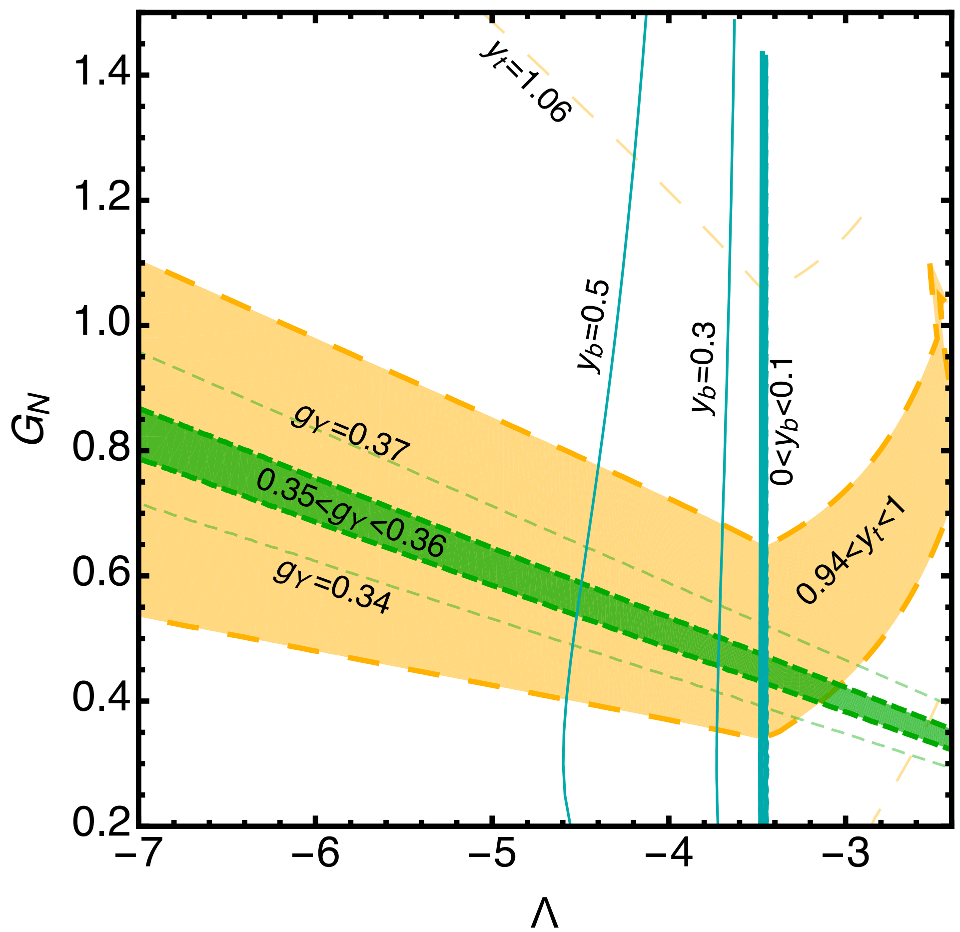
Asymptotically, particle physics might be safe - stay tuned…!

Thank you for your attention.

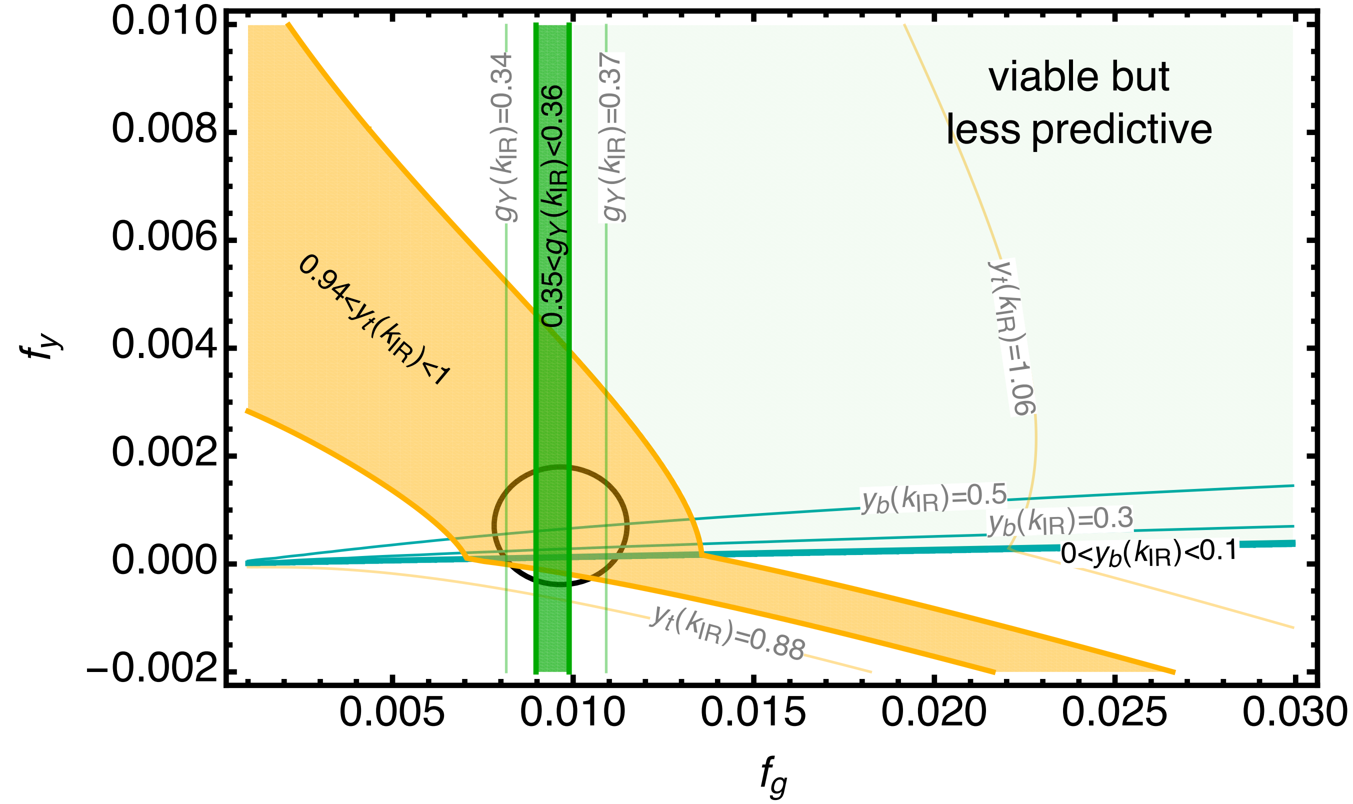
Switch gears: add gravitational fixed-point values from truncated flows

observational consistency constraint on microscopic grav. coupling space



(Einstein-Hilbert truncation)

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



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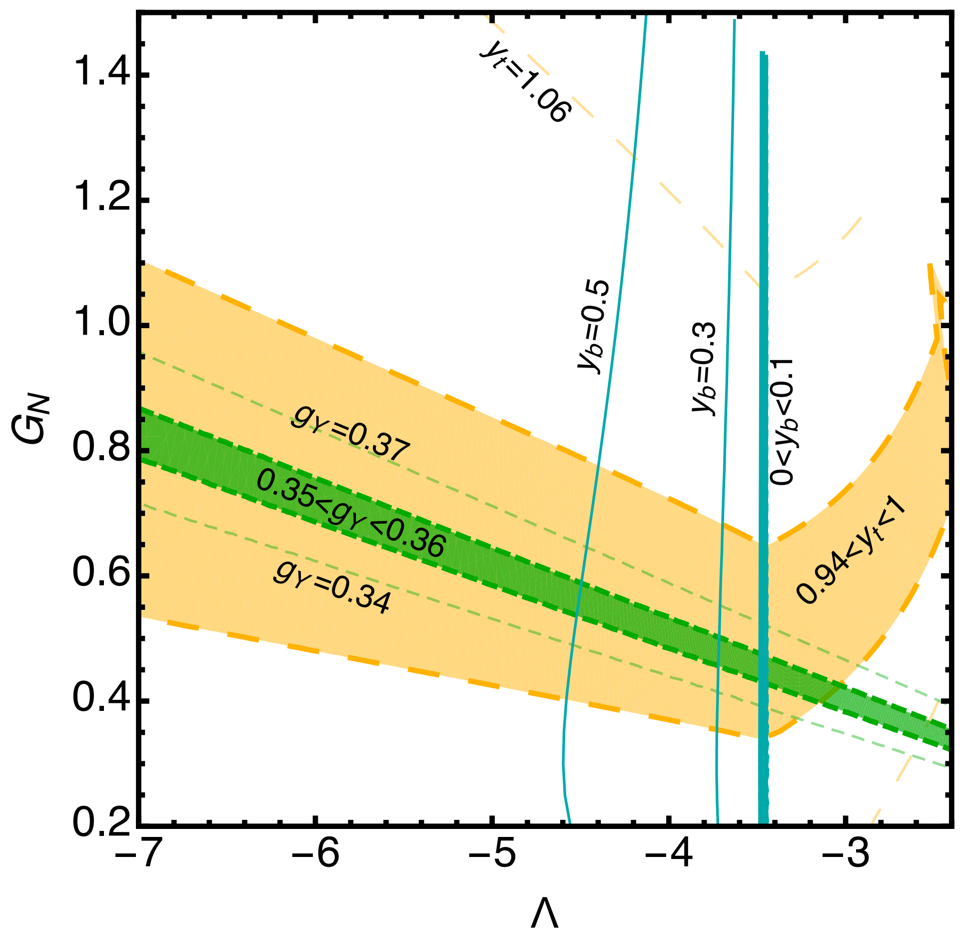

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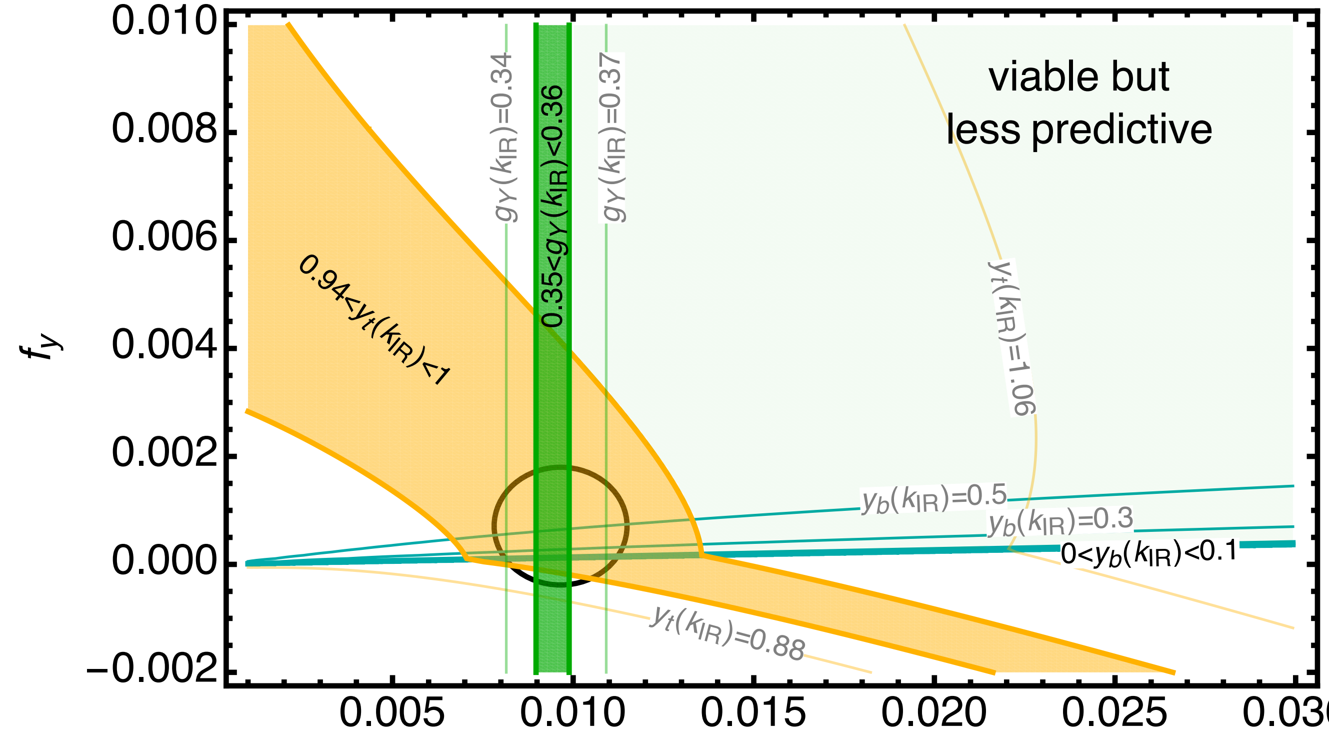

fixed-point values for $G,\ \Lambda$ f_g

depend on matter content: "backreaction matters"

[Dona, AE, Percacci '13]

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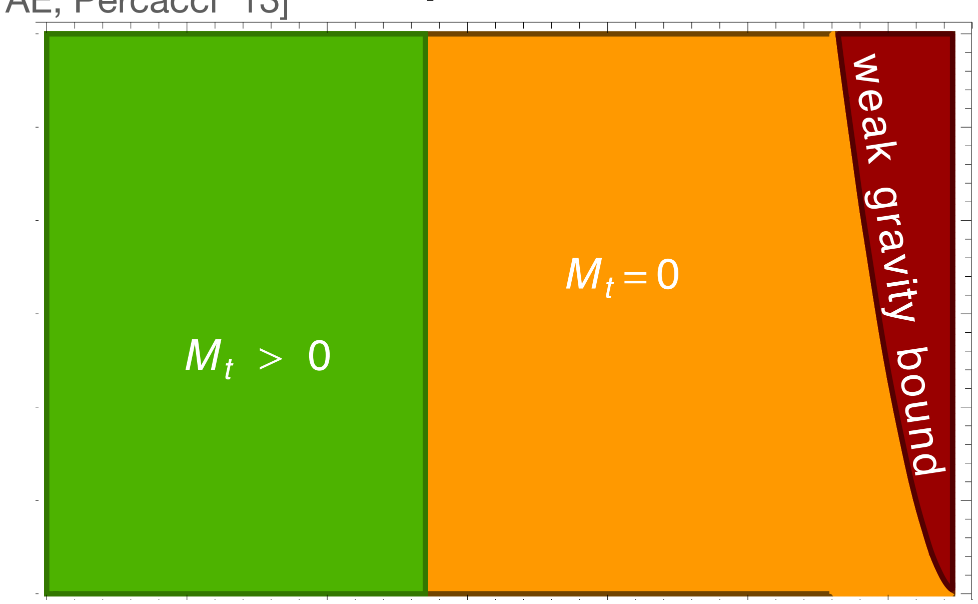

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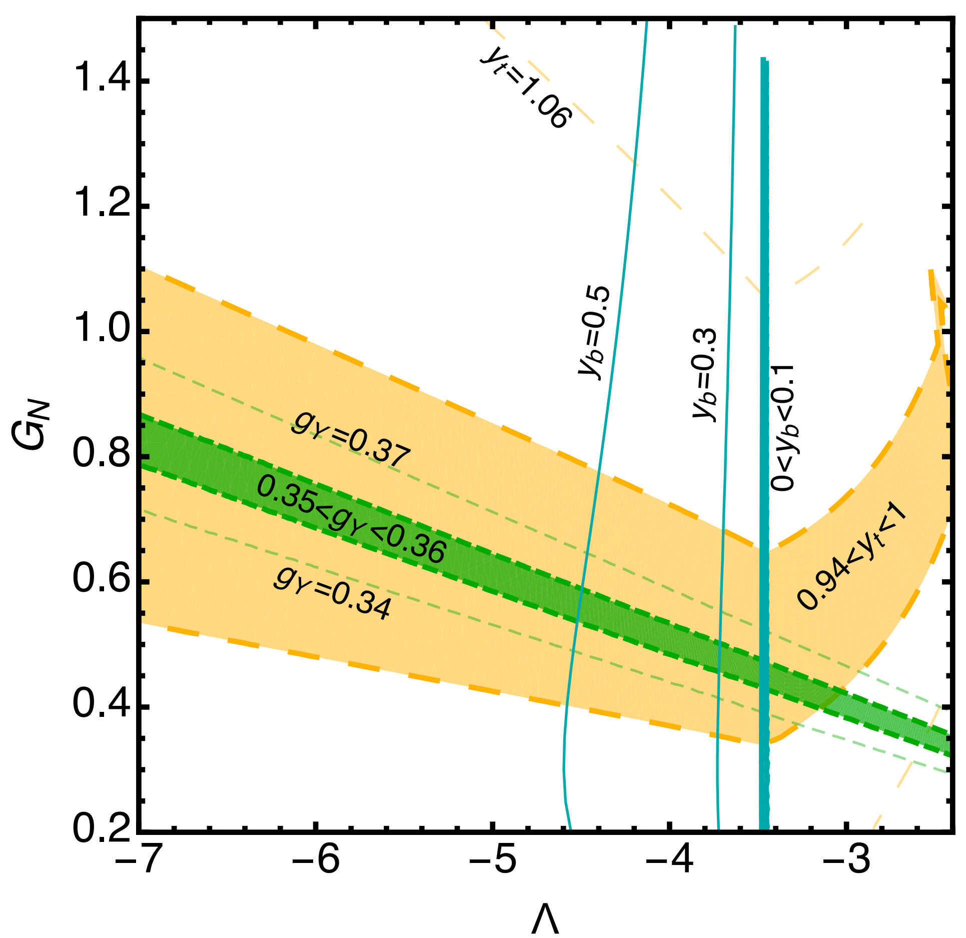

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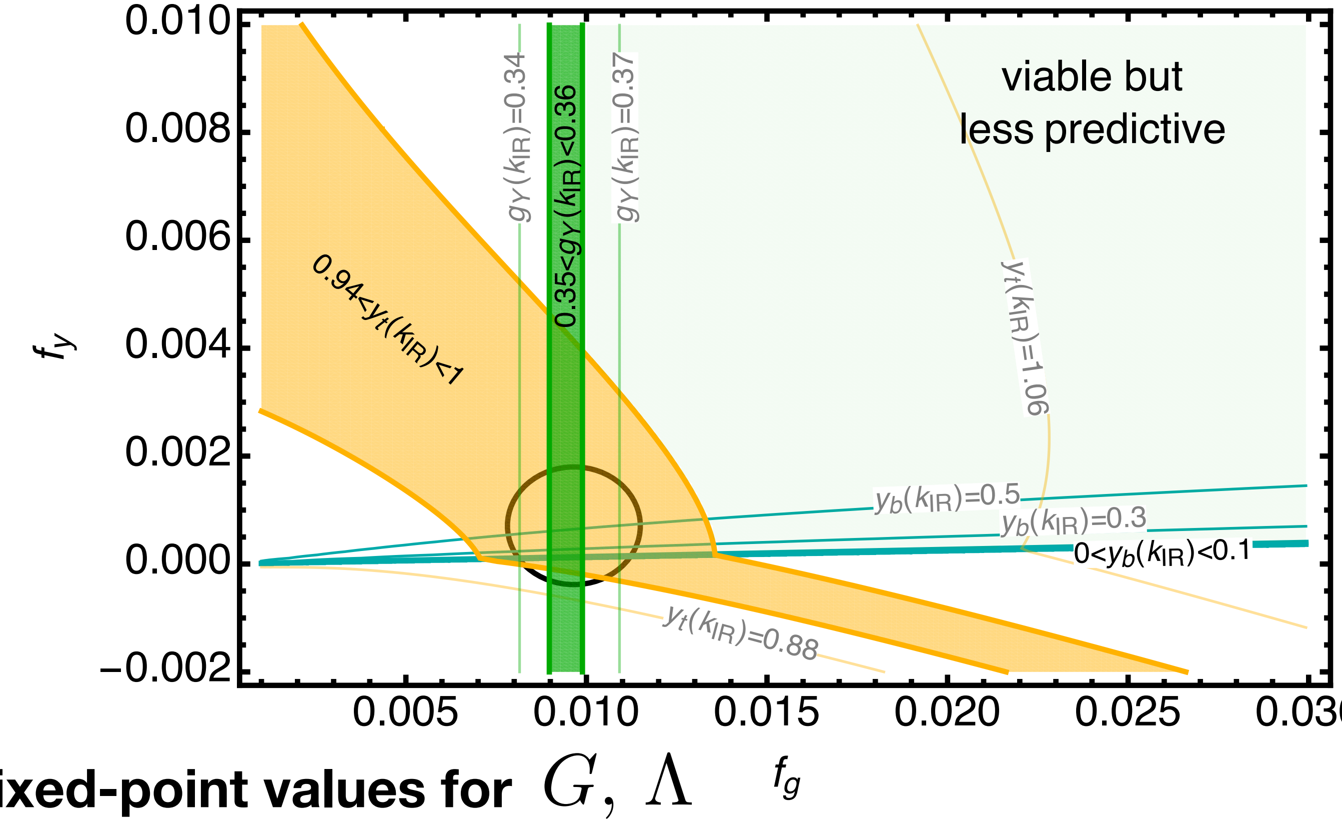

fixed-point values for $G,\ \Lambda$ depend on matter content: “backreaction matters”

[Dona, AE, Percacci '13]

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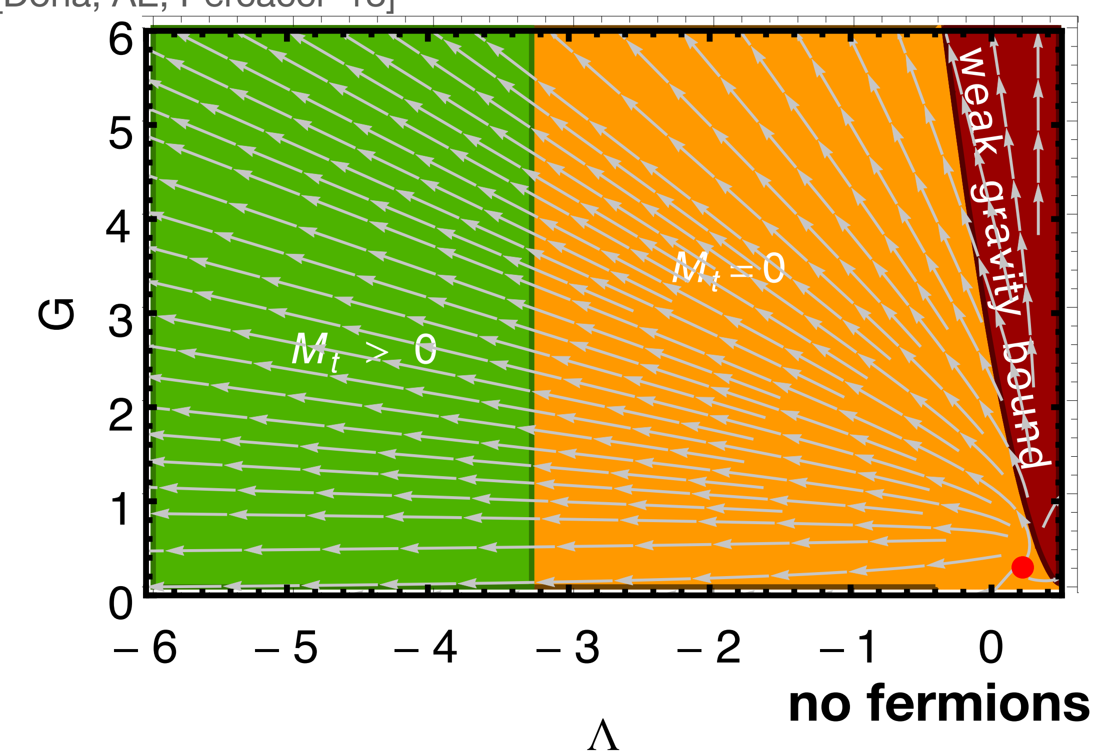
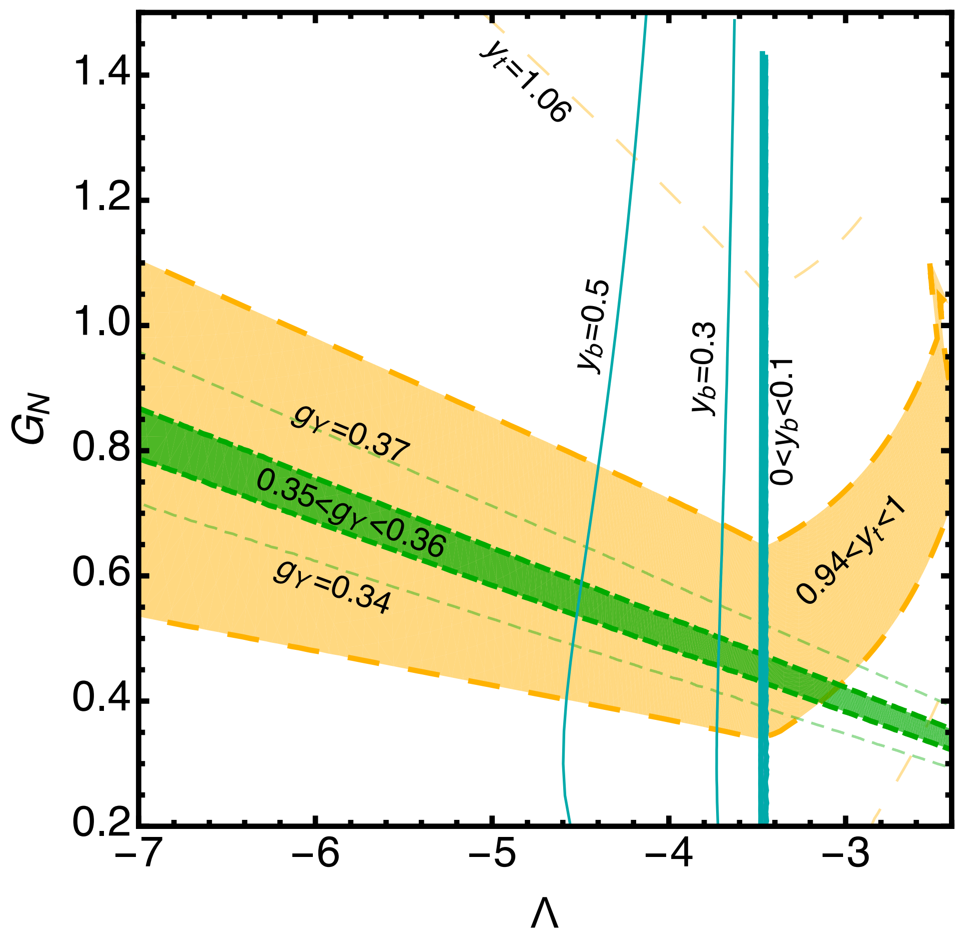


no fermions

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

observational consistency constraint on microscopic grav. coupling space



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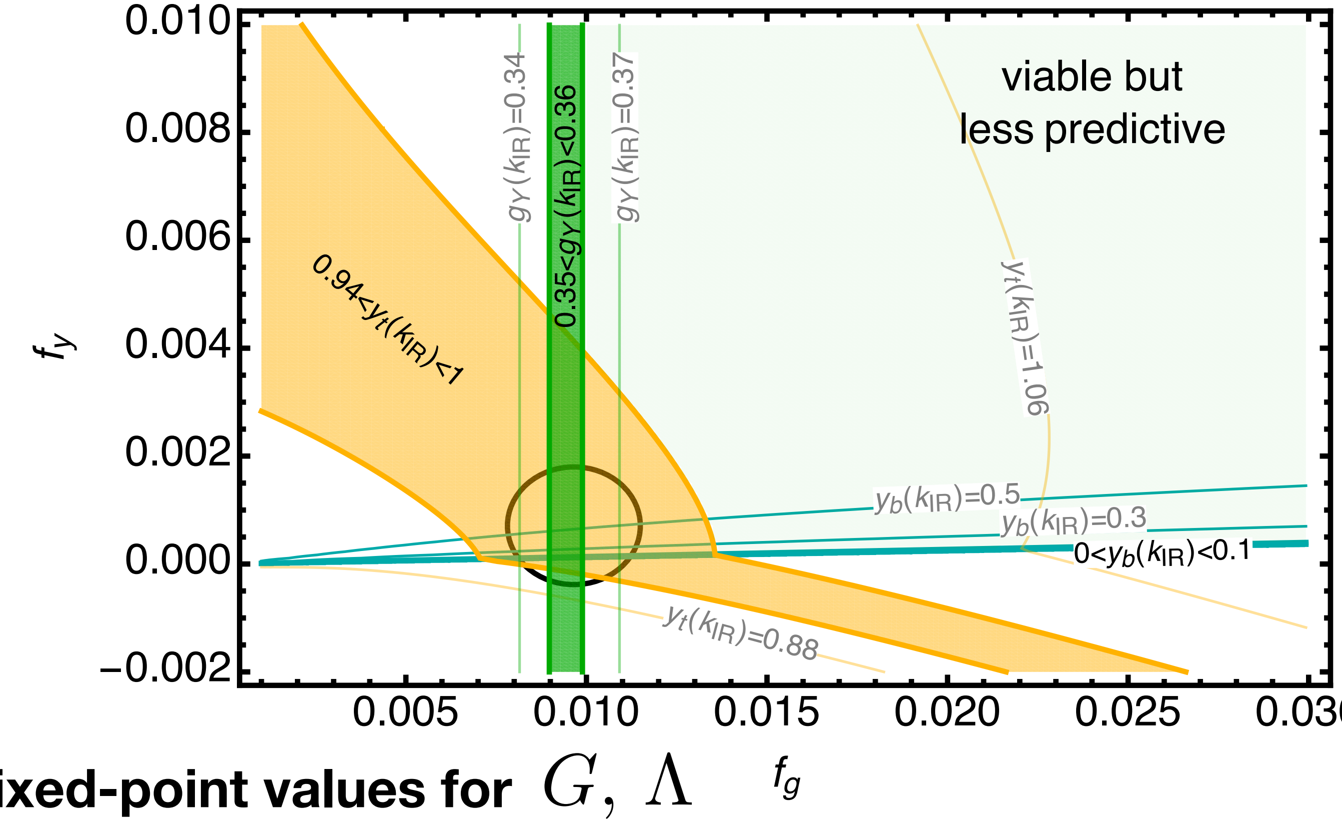

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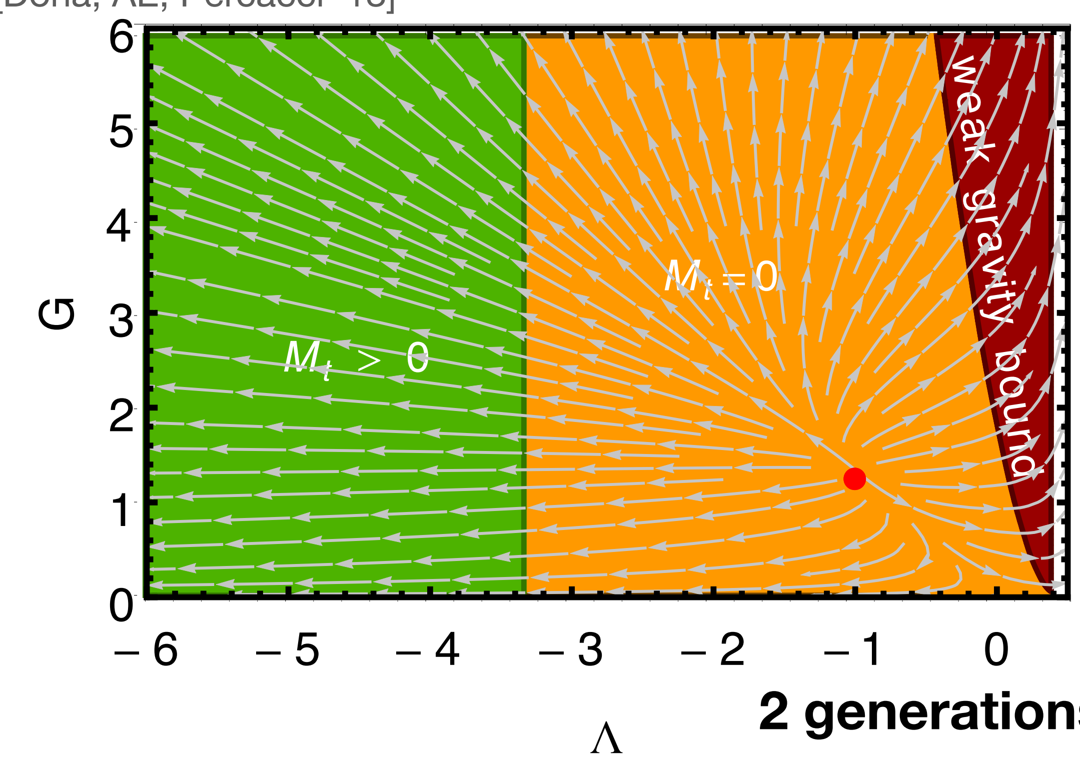

2 generations

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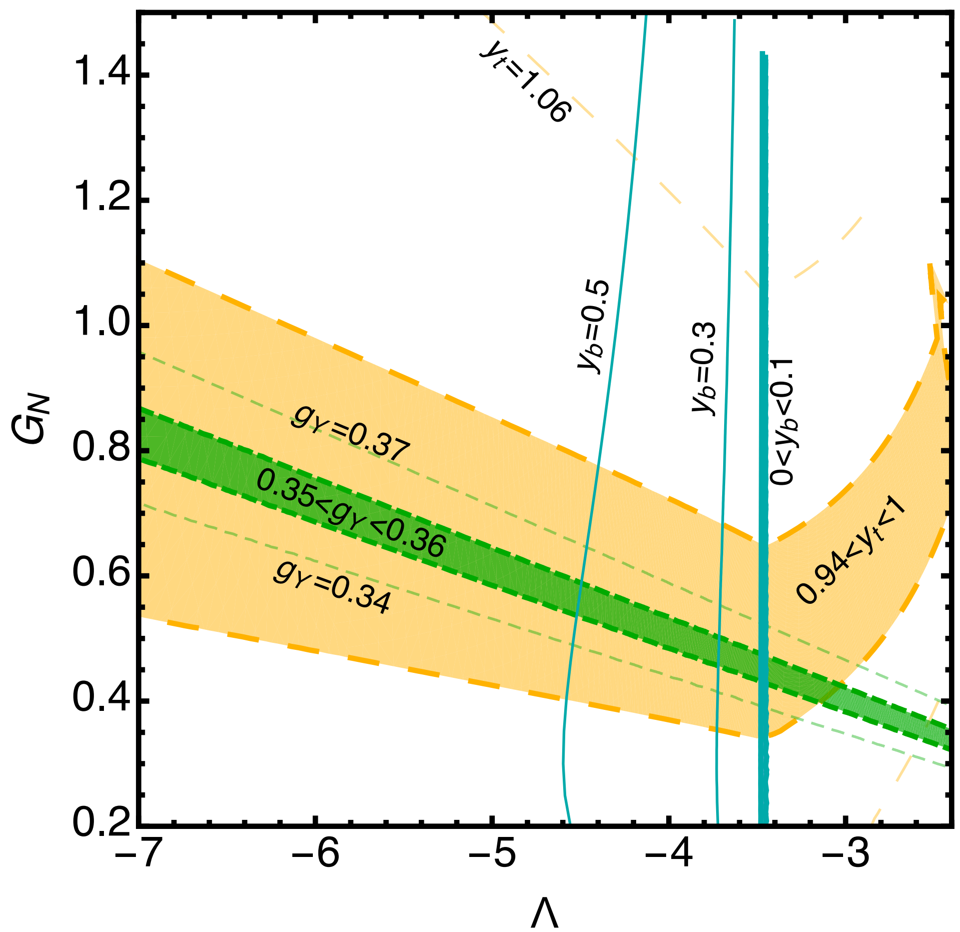

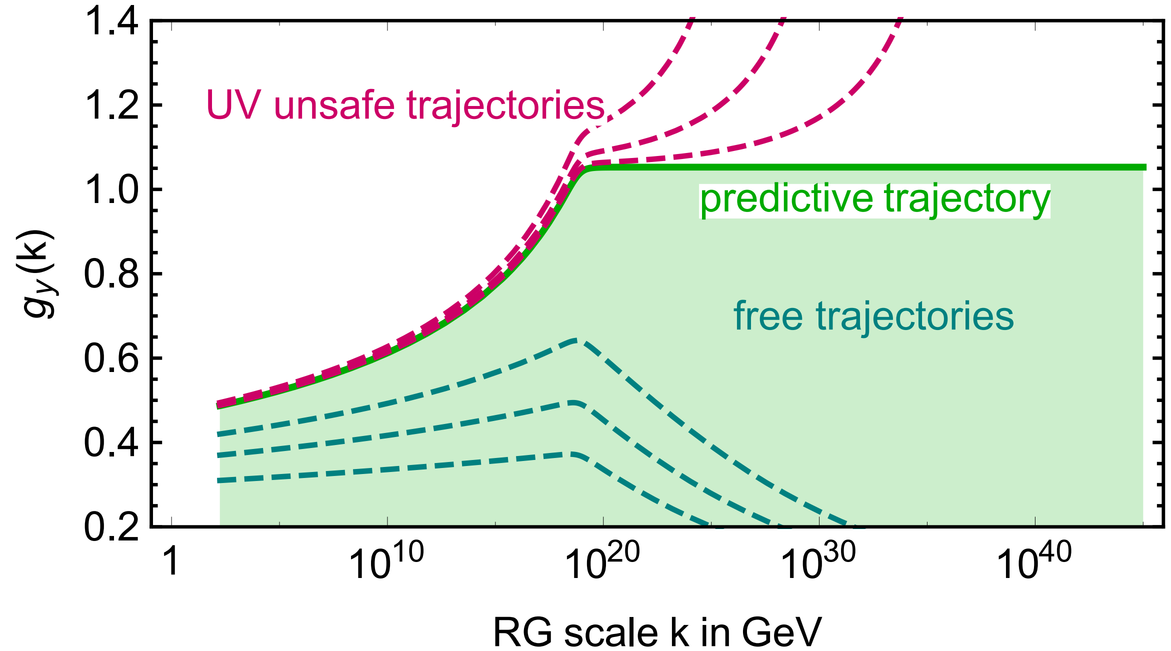

fixed-point values for G, Λ

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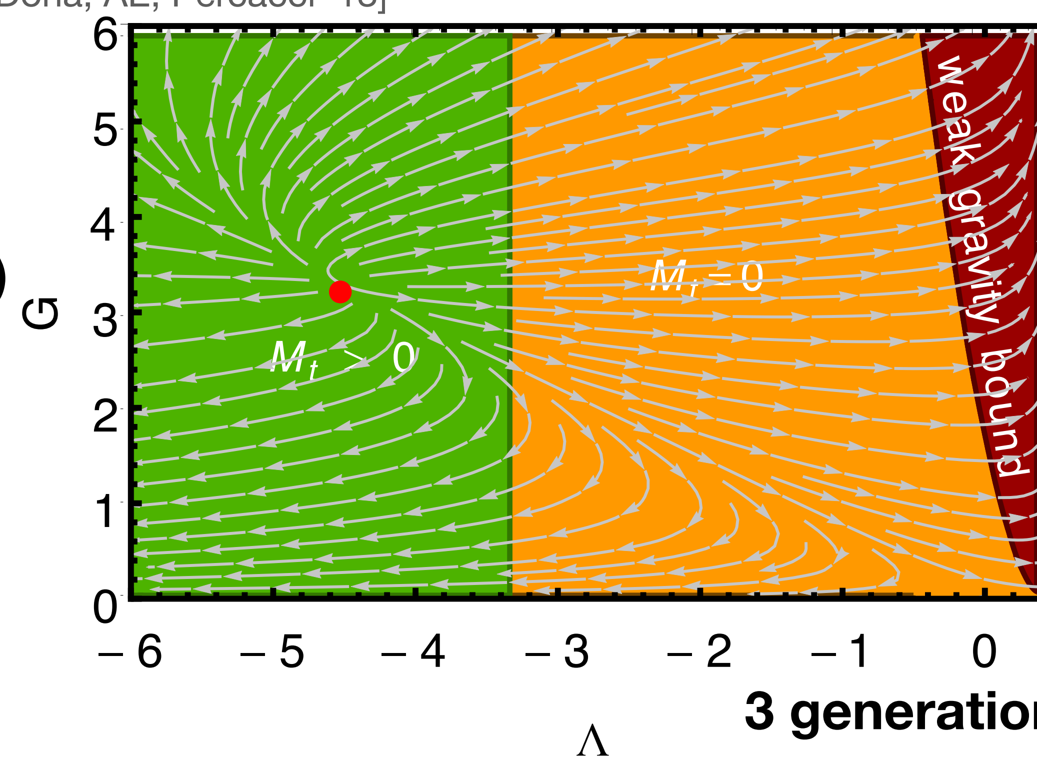
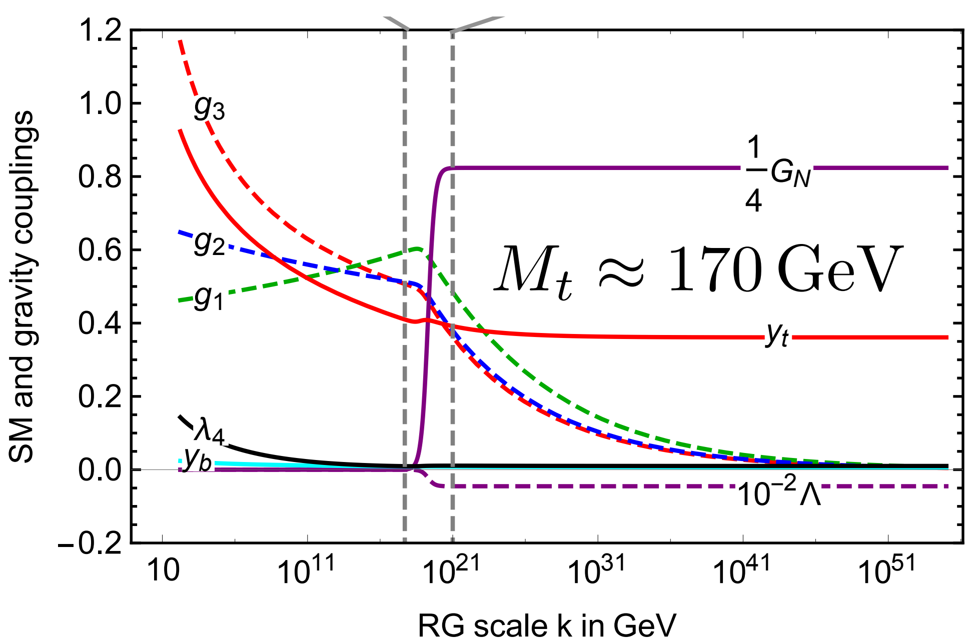


3 generations



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

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

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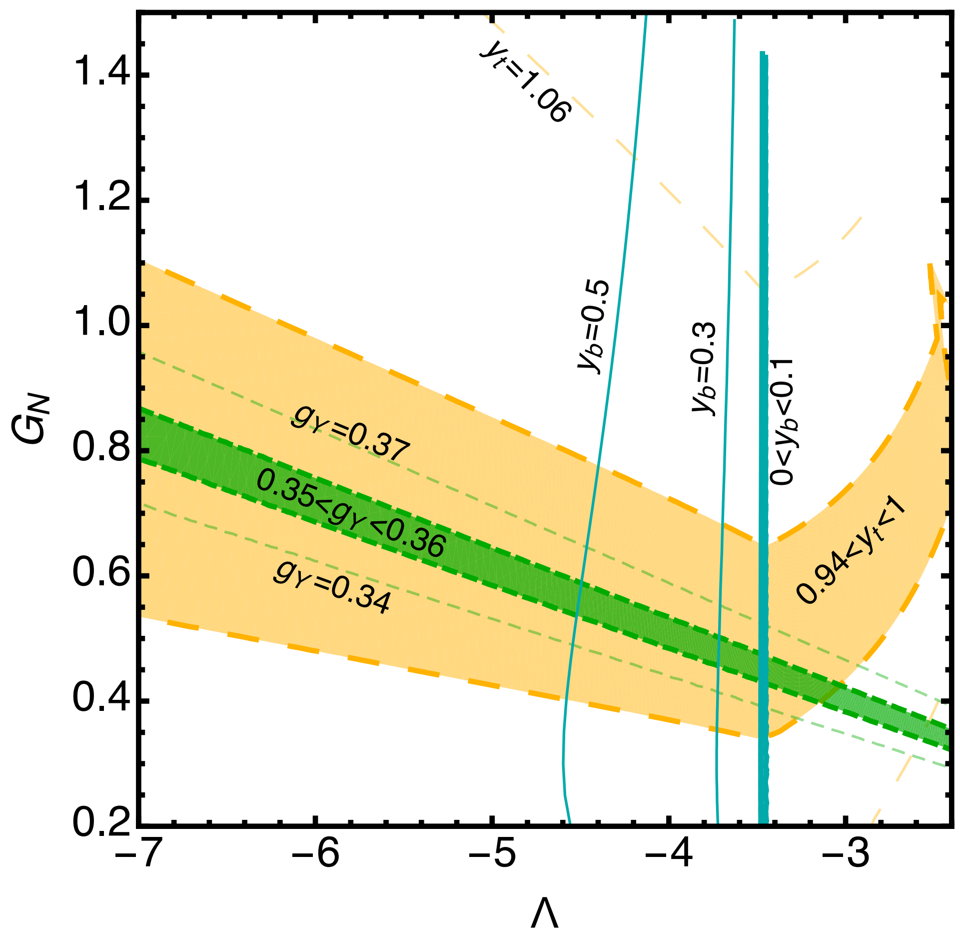

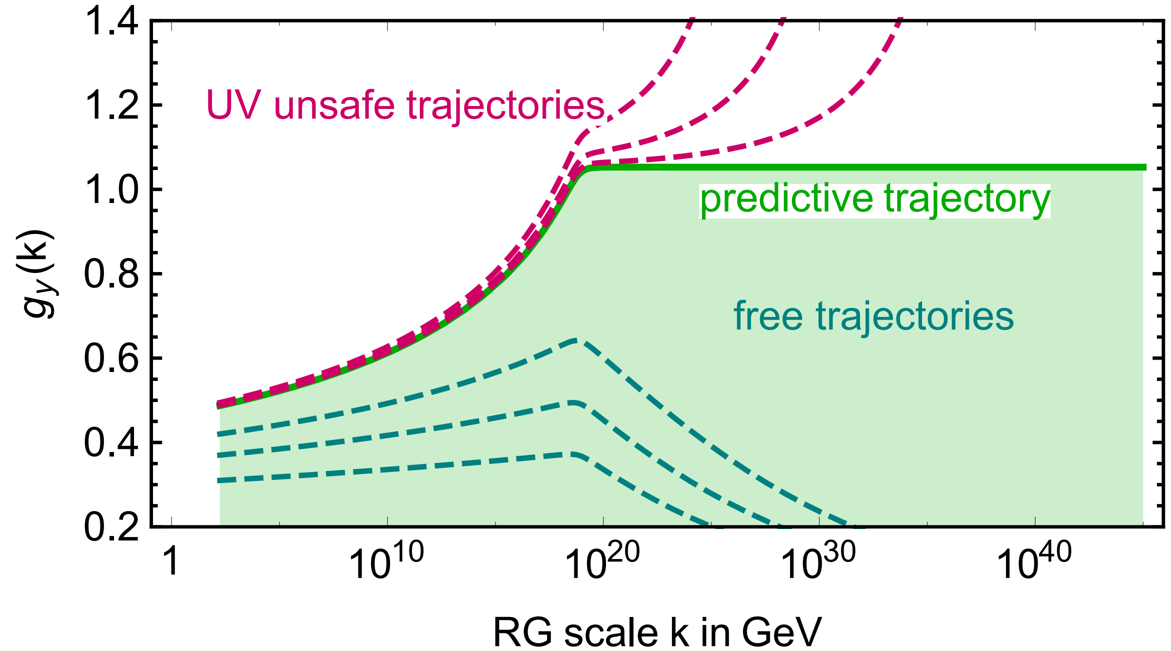

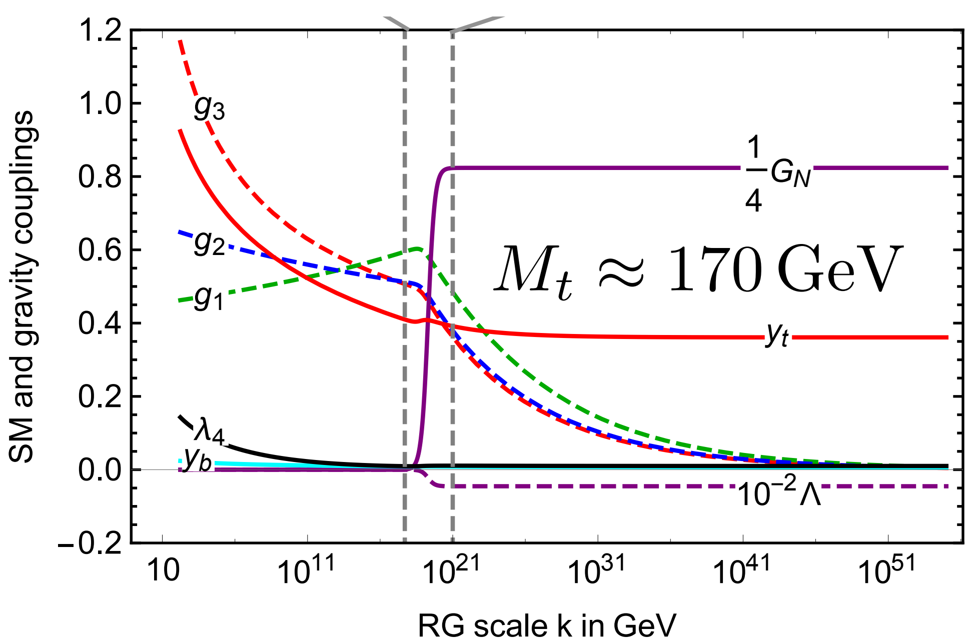

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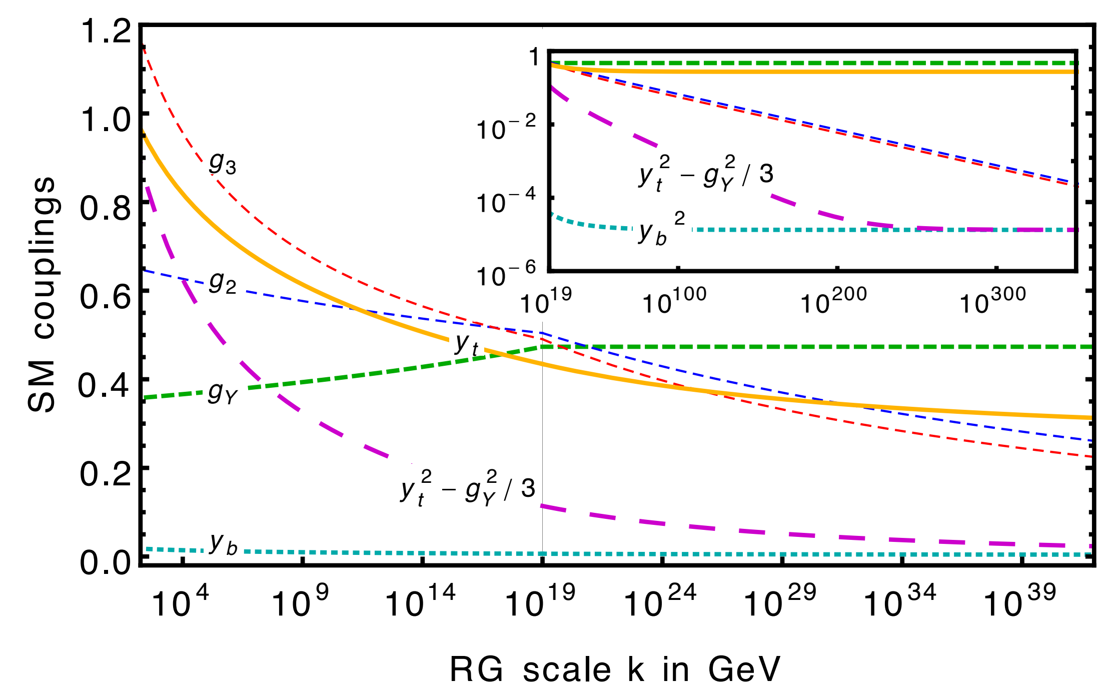
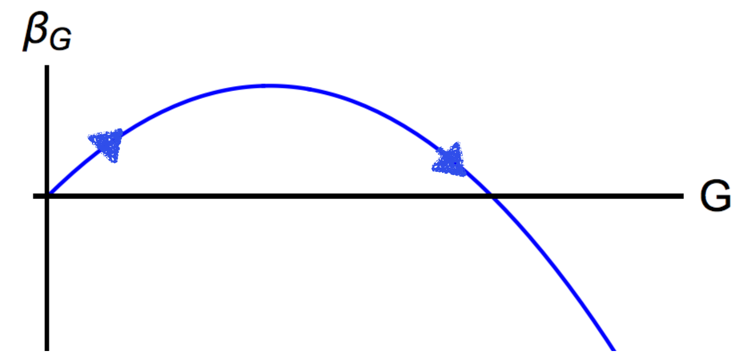
estimate of systematic error: 3 retrodictions are roughly 1.5 δ away



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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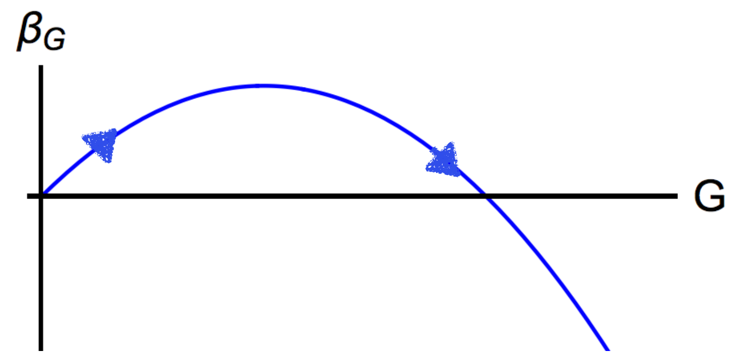
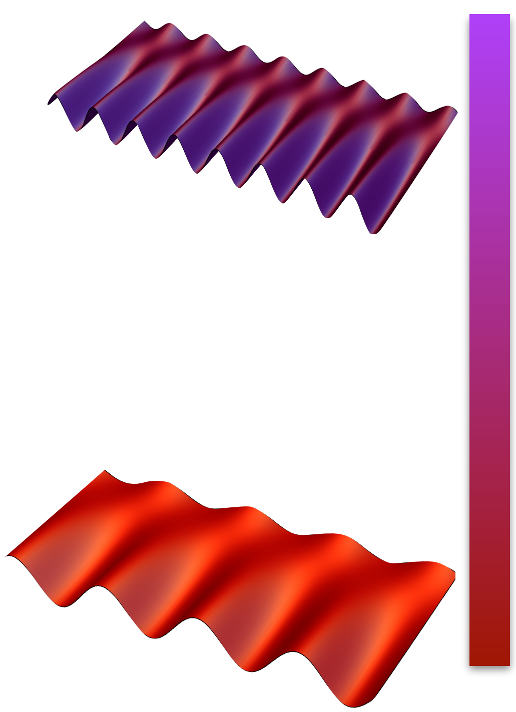


- **Functional Renormalization Group** $e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \, e^{-S[\varphi] - \frac{1}{2}\int \varphi(-p) R_k(p) \varphi(p)}$

  probe scale dependence of QFT

  Wetterich ’93, Reuter ‘96

scale- and momentum-dependent ``mass”



S

Γ_k contains effect of quantum fluctuations above k

$\Gamma_{k\to 0}$

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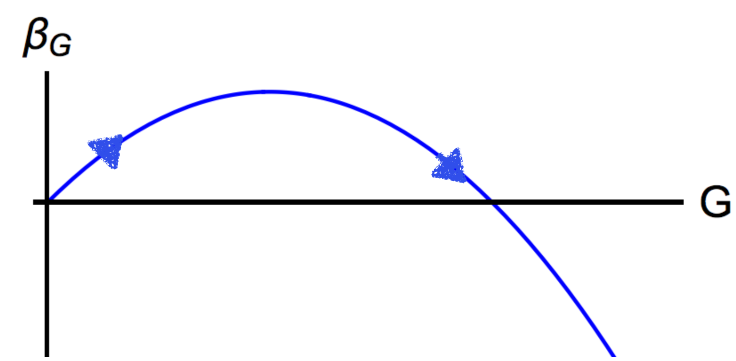

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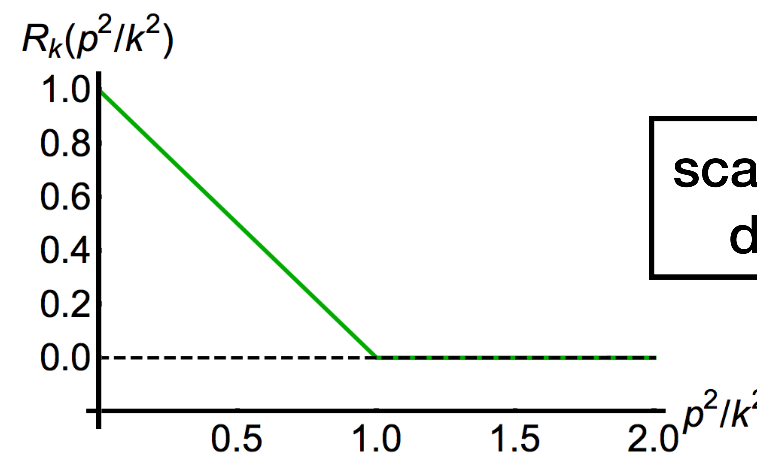

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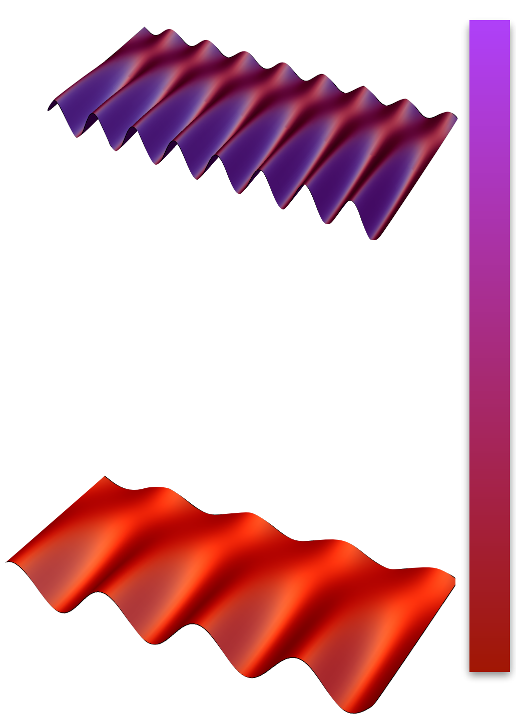

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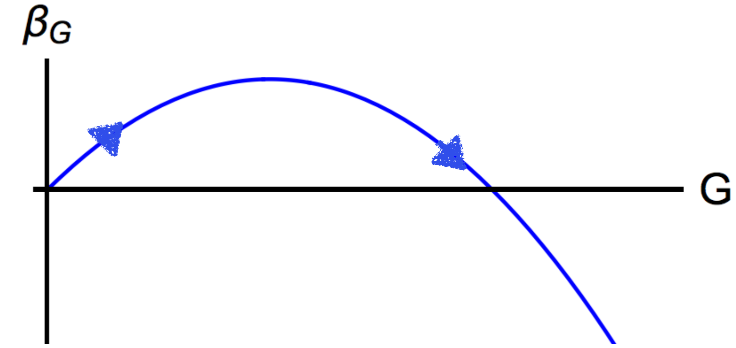

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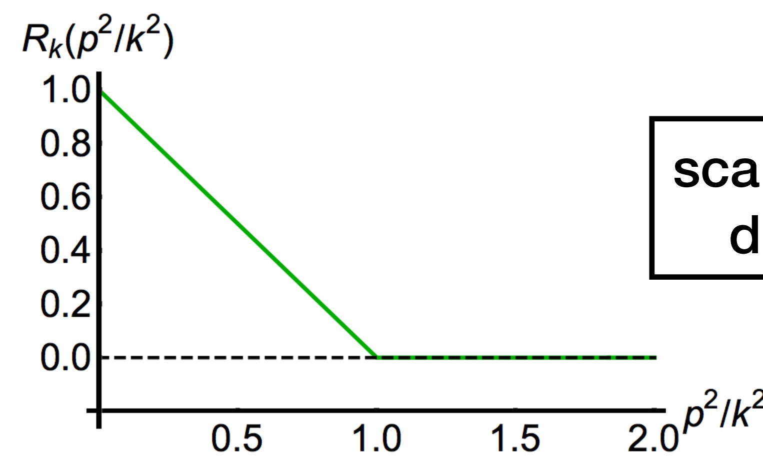

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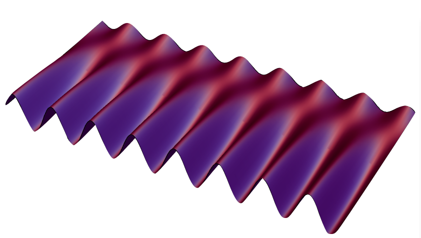

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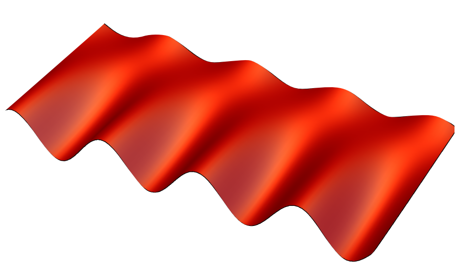
$$\Gamma_k = \sum_i g_i(k) \int d^dx \, \mathcal{O}^i \;\; \rightarrow k\partial_k \Gamma_k = \sum_i \beta_{g_i} \int d^dx \mathcal{O}^i$$



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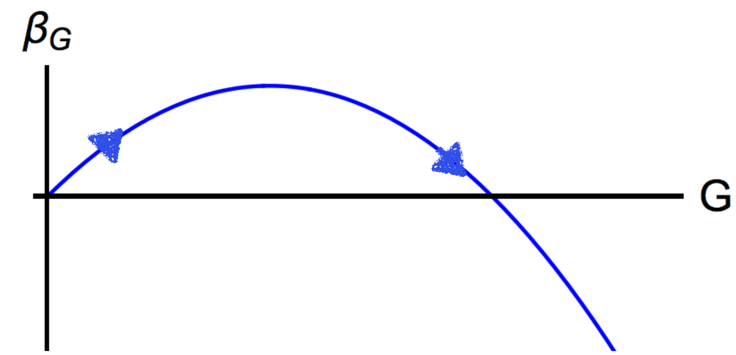

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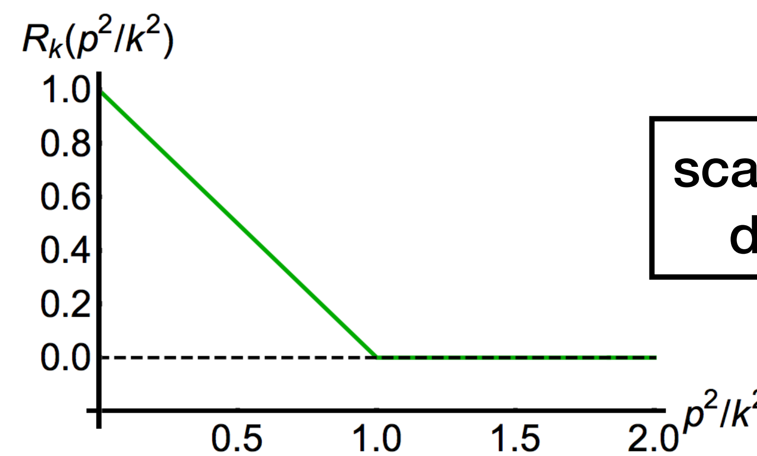

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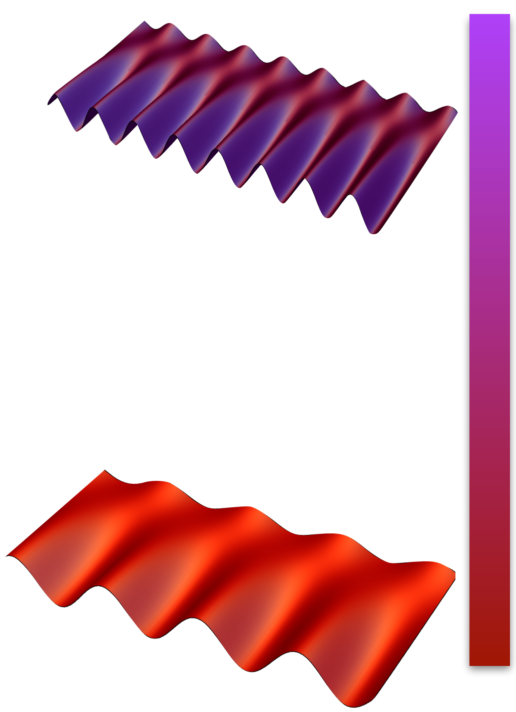

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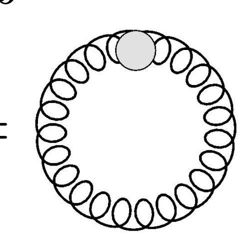
$\Gamma_{k\to 0}$

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

Functional Renormalisation Group

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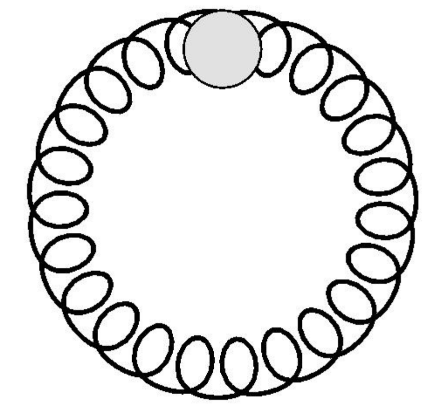

exact one-loop equation

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

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]