Top mass from asymptotic safety

Astrid Eichhorn
University of Heidelberg

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

October 06, 2017
Online VIA lecture

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recent work with:
Aaron Held (1705.02342, to appear in PRD, 1707.01107)
& Jan Pawlowski (1604.02041; Phys.Rev. D94 (2016) no.10, 104027)

Fleur Versteegen (arXiv:1709.07252)

Nic Christiansen (1702.07724; Phys.Lett. B770 (2017) 154-160)

Stefan Lippoldt (1611.05878; Phys.Lett. B767 (2017) 142-146)

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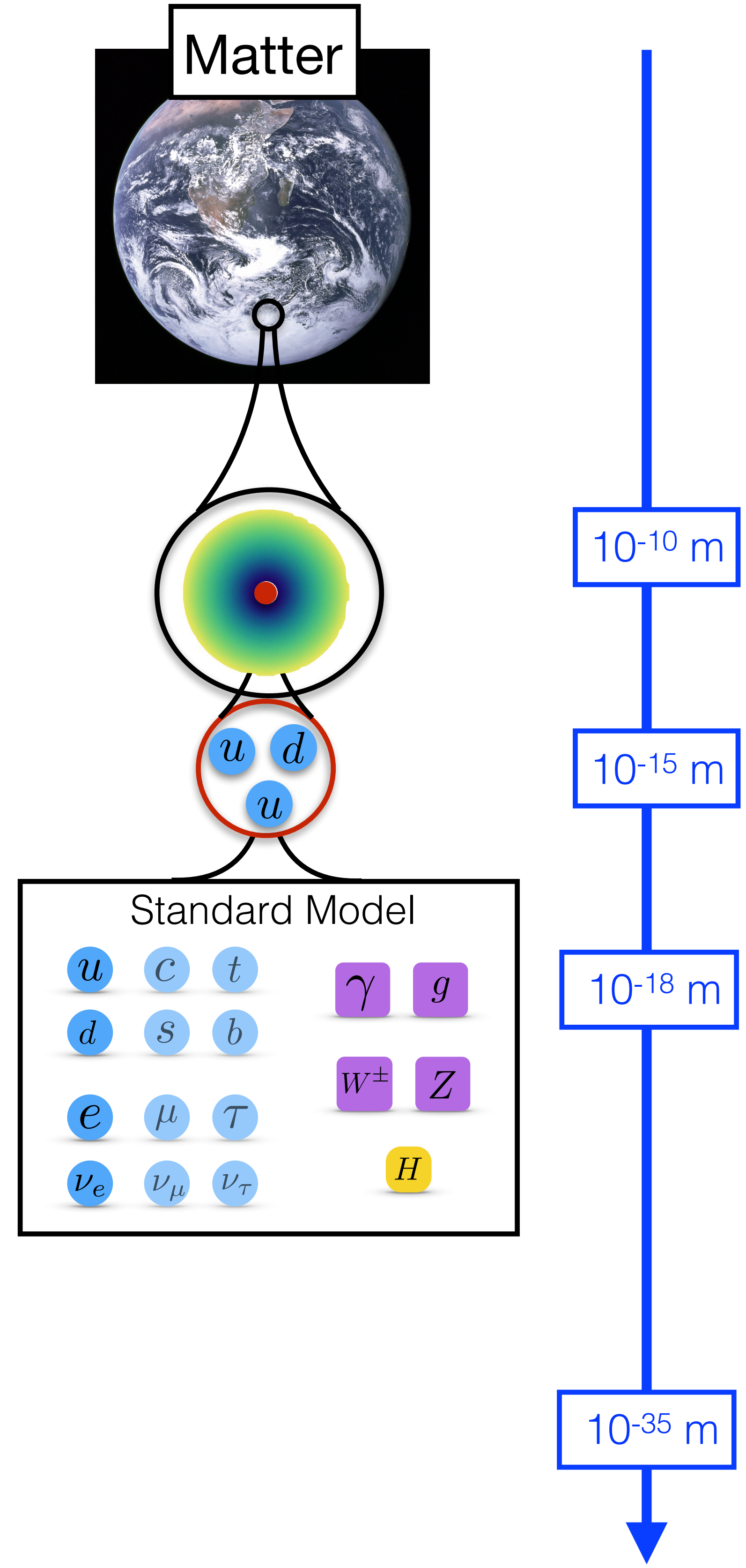
What are the fundamental building blocks of our universe?



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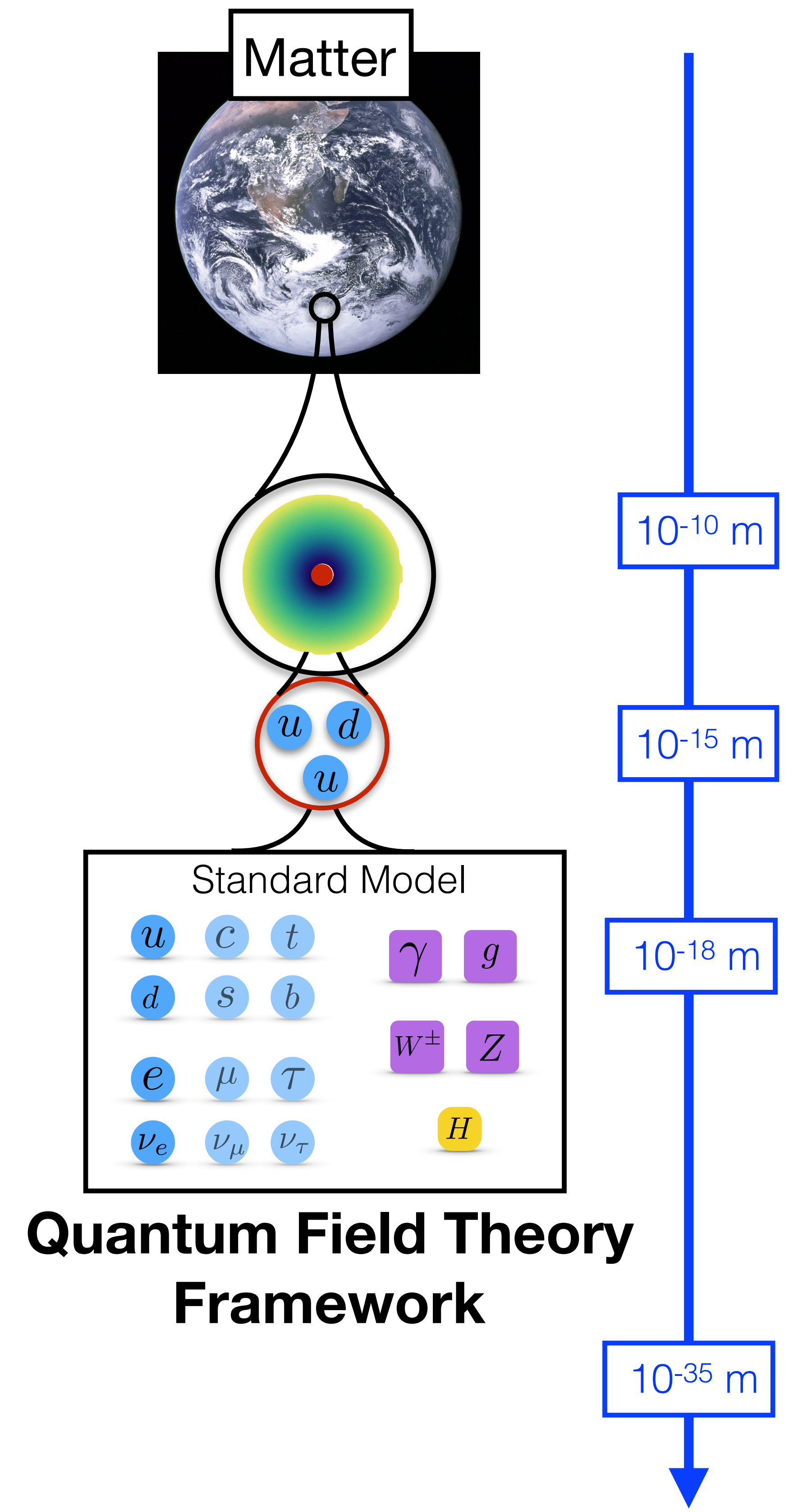
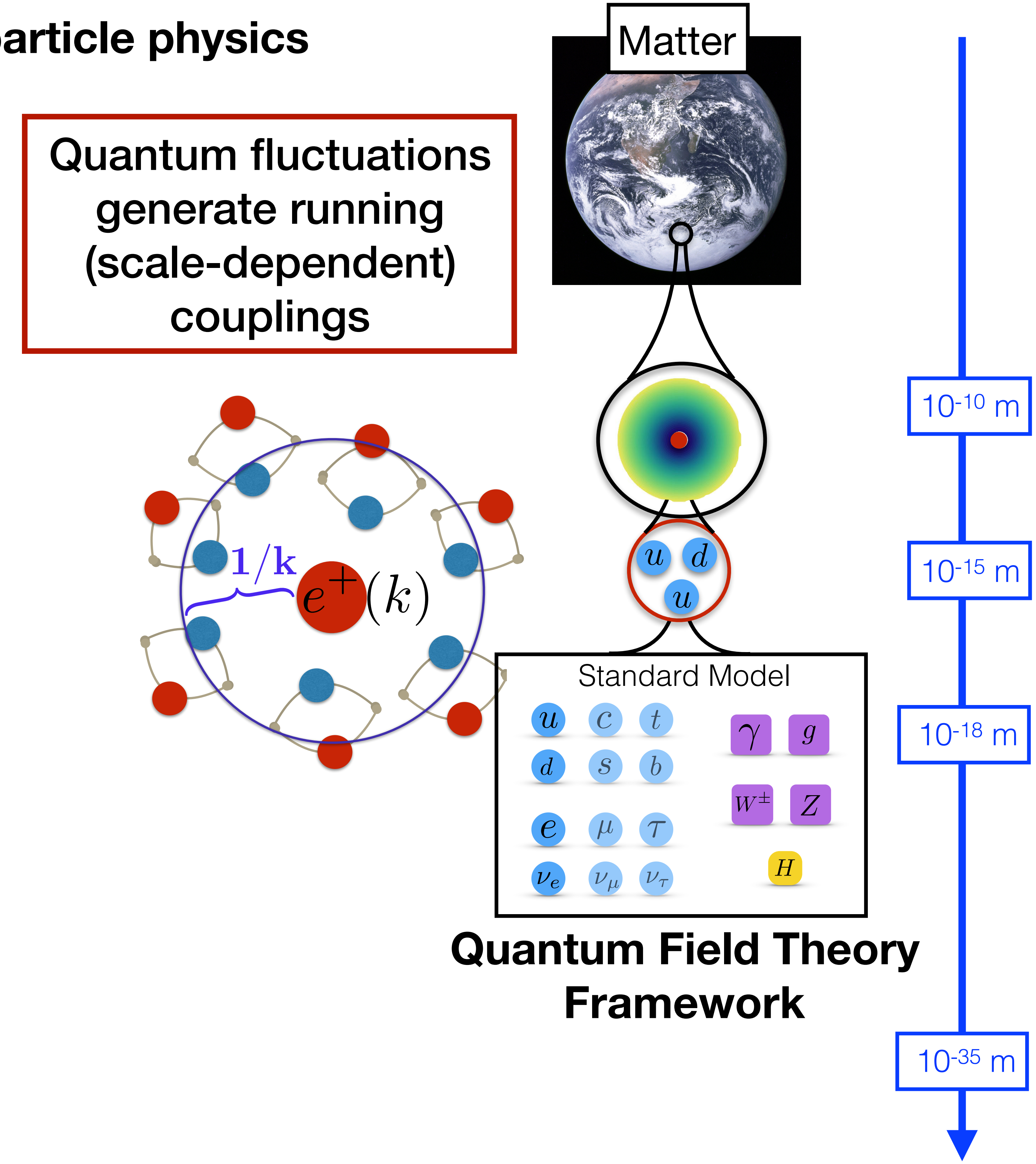


What are the fundamental building blocks of our universe?

Status of the Standard Model of particle physics



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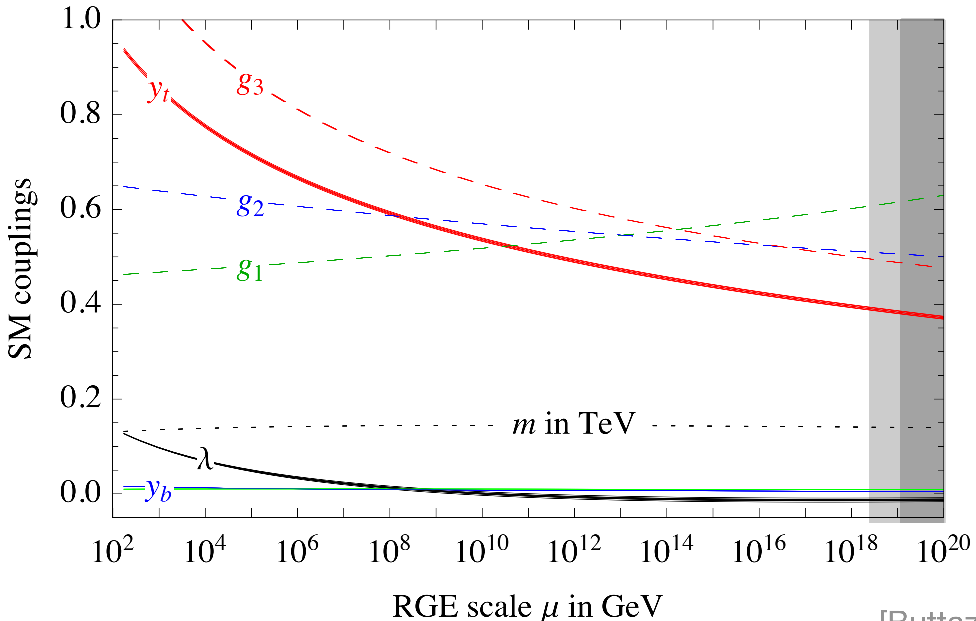
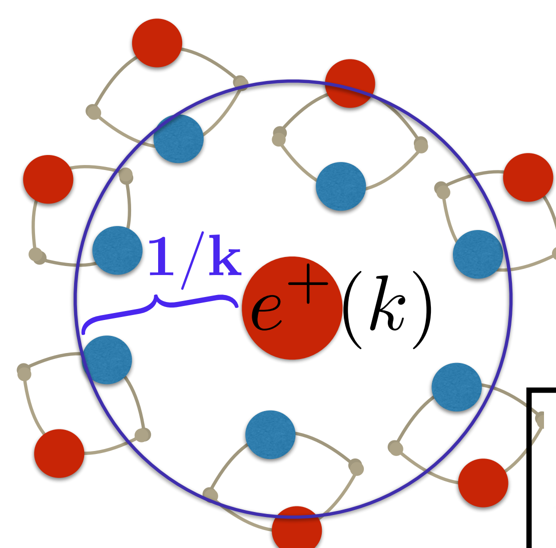
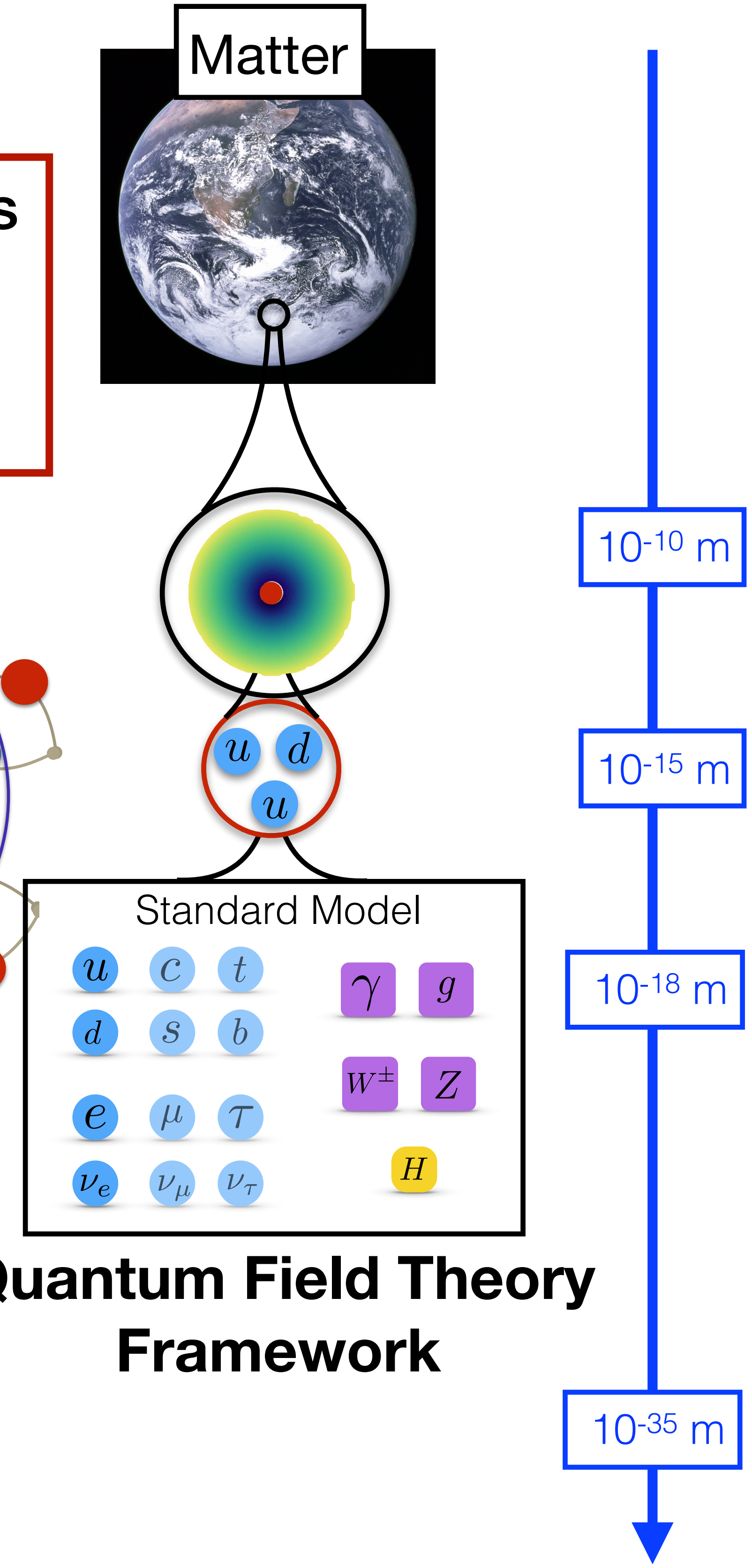


[Buttazzo et al. '13]

Quantum fluctuations generate running (scale-dependent) couplings





Quantum Field Theory Framework

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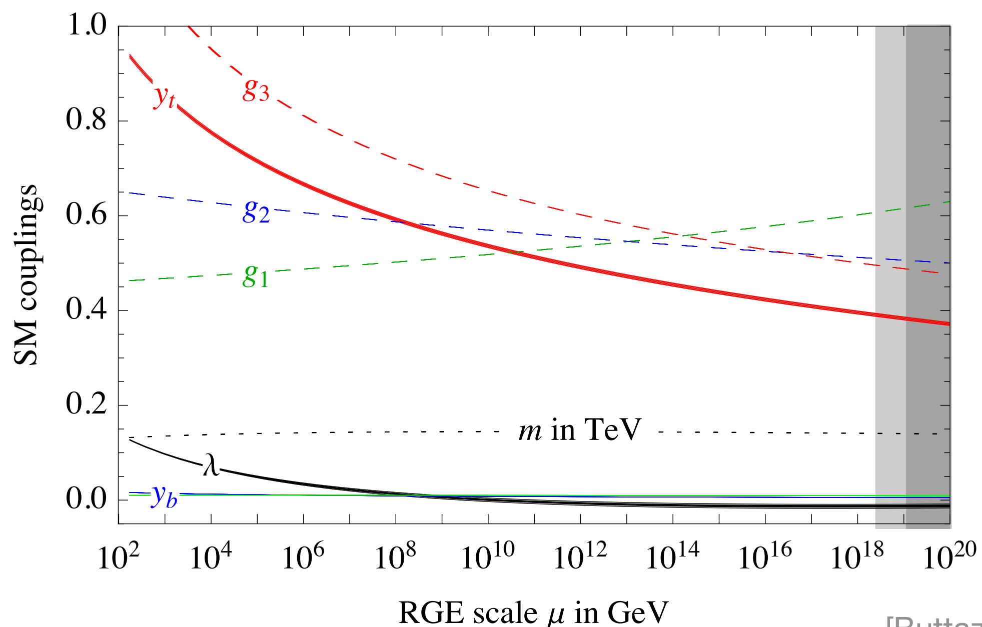

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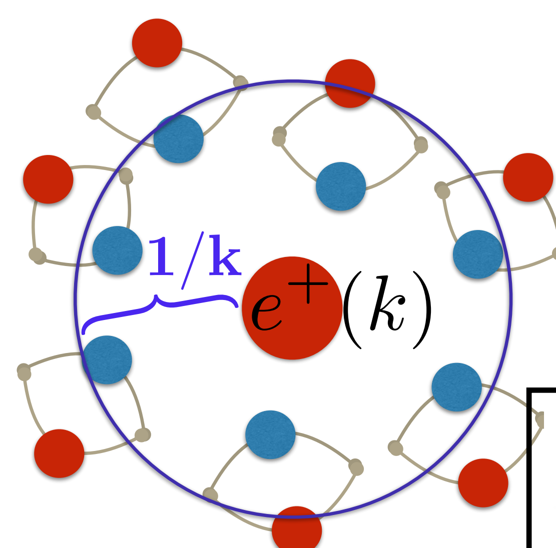

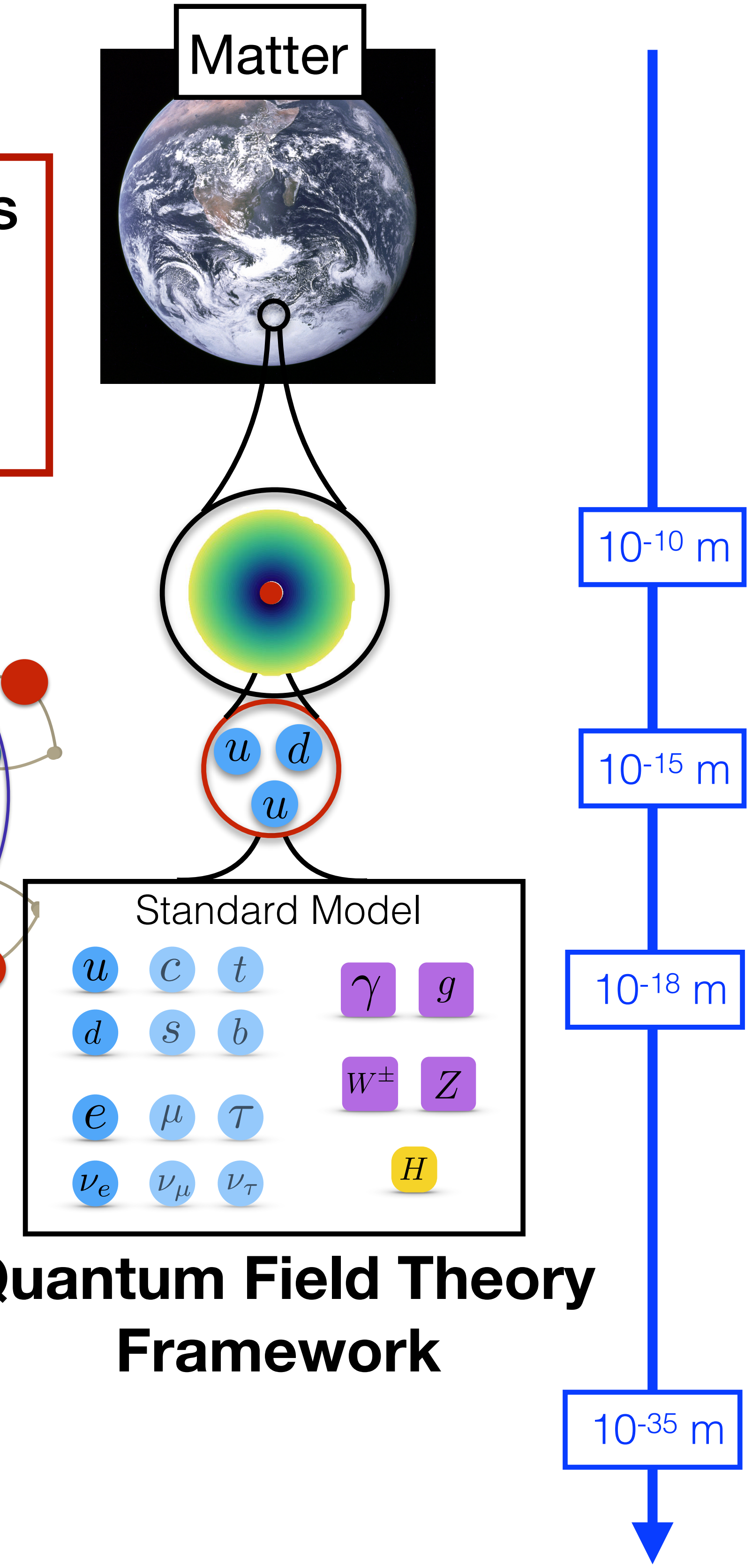

Quantum Field Theory Framework

- **can extend up to M_{Pl} (@ M_h ~ 125 GeV)**
- **breakdown in transplanckian regime (Landau pole/ triviality problem in Abelian hypercharge & Higgs-Yukawa)**

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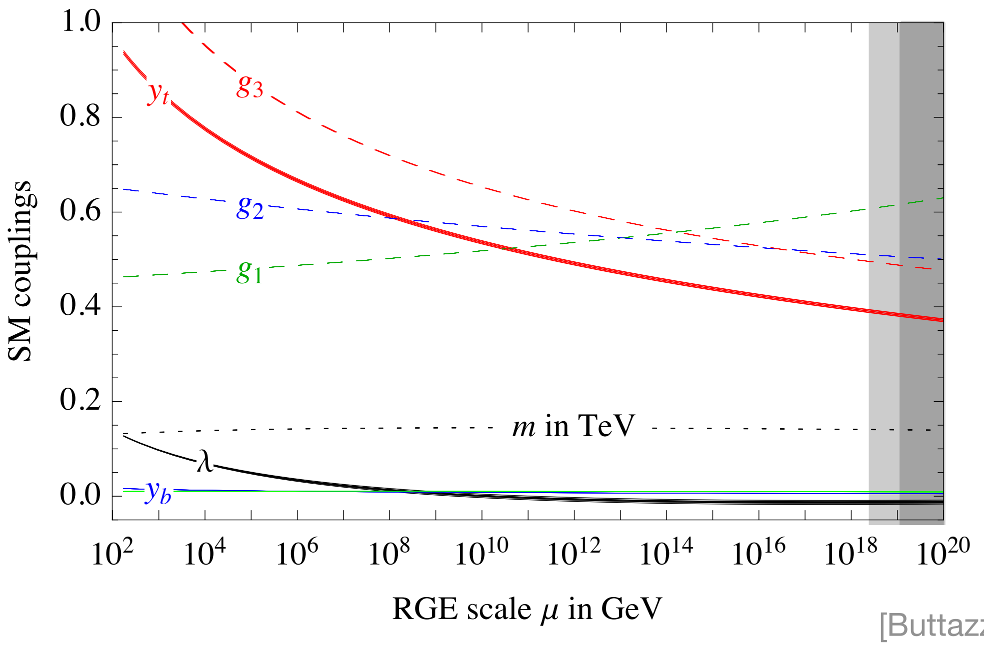

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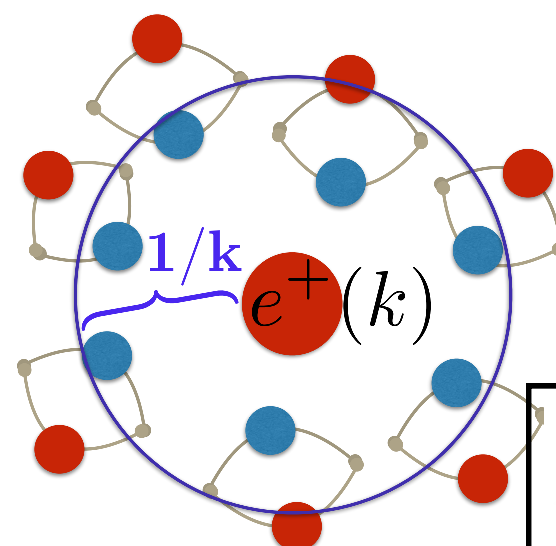

- can extend up to M_{Pl} (@ M_h ~ 125 GeV)
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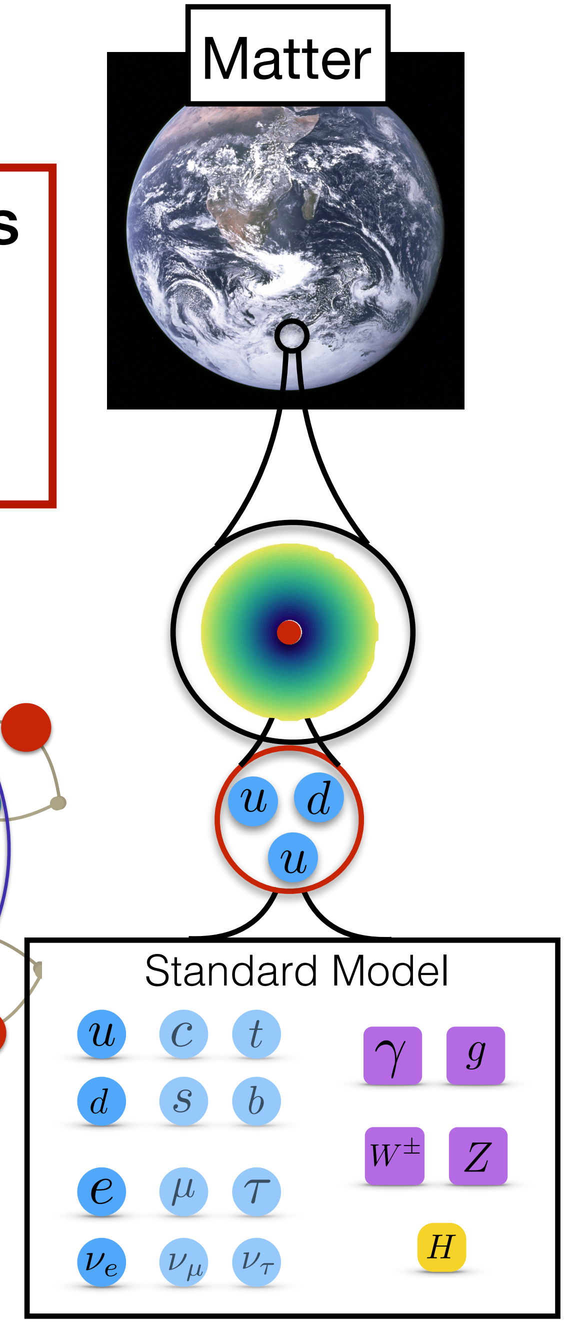
- fails to include quantum gravity
- 19 free parameters



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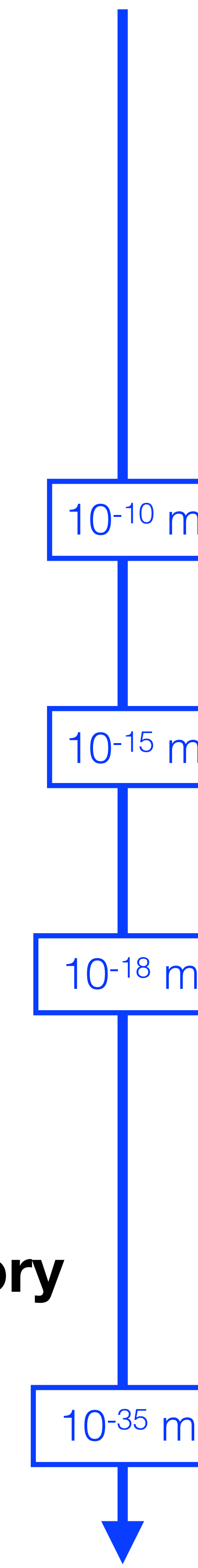

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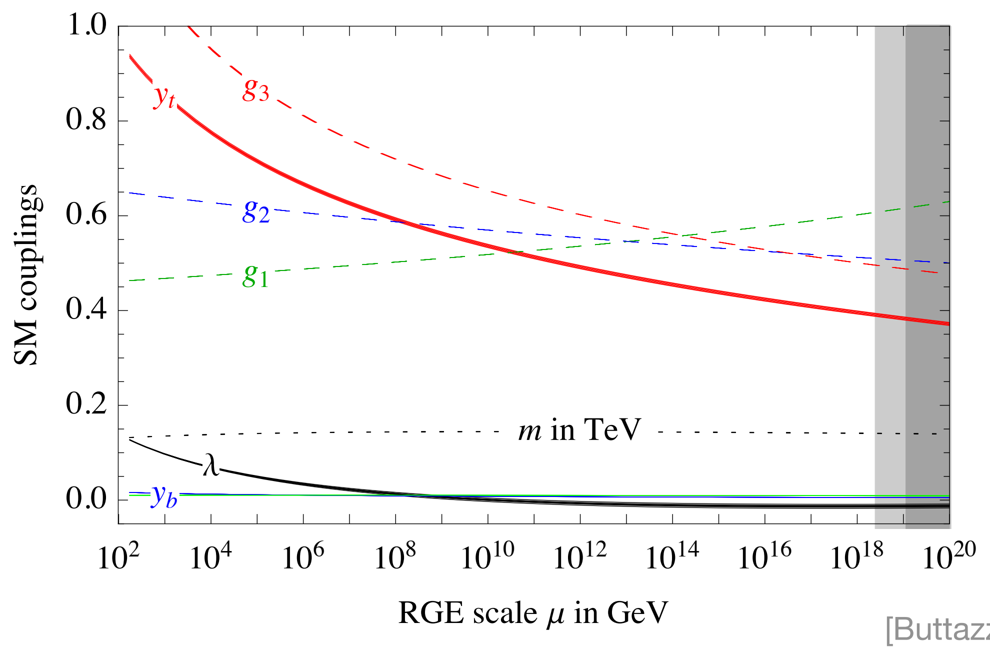

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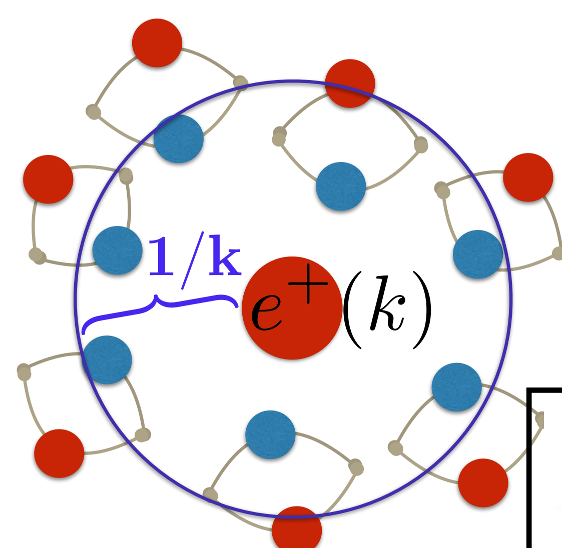

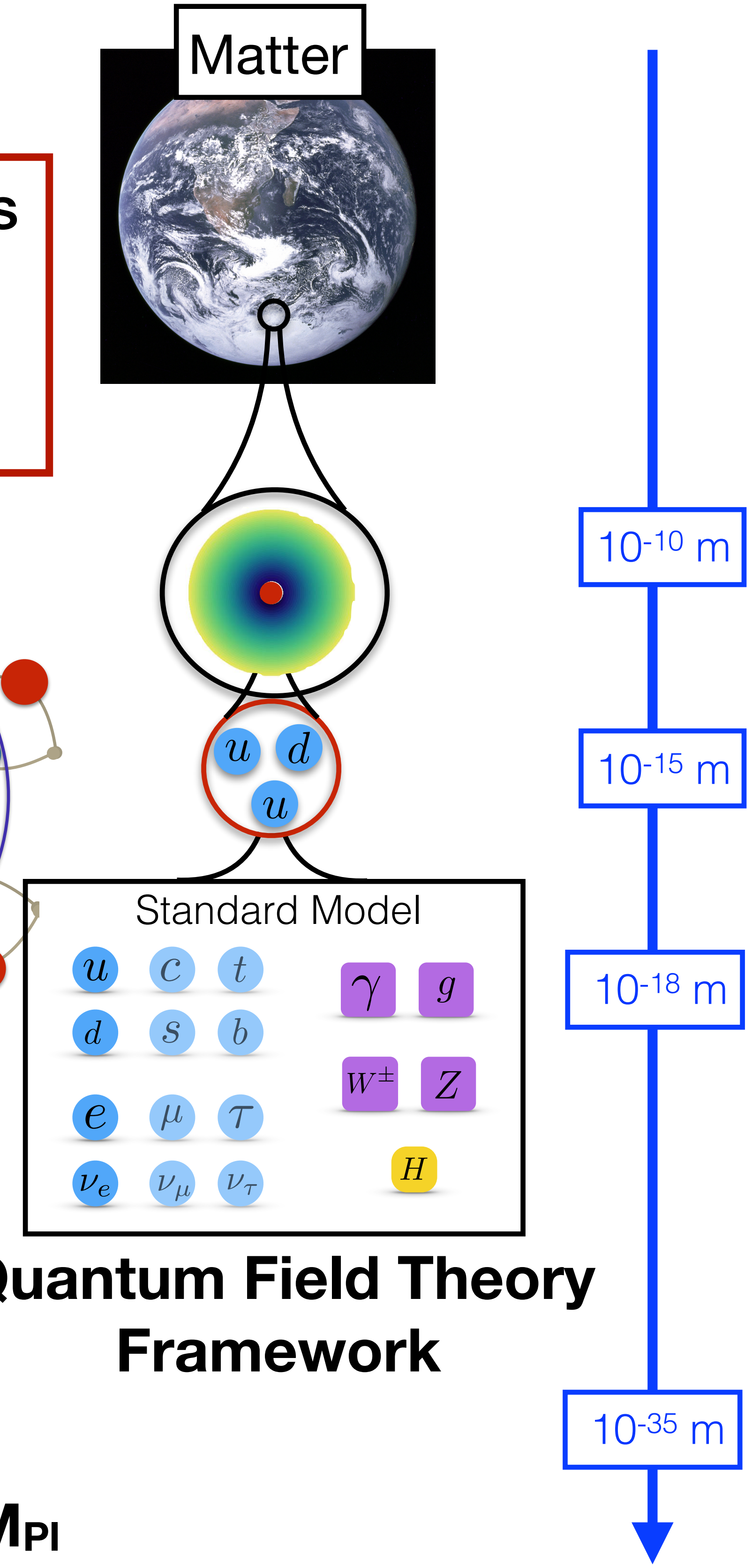

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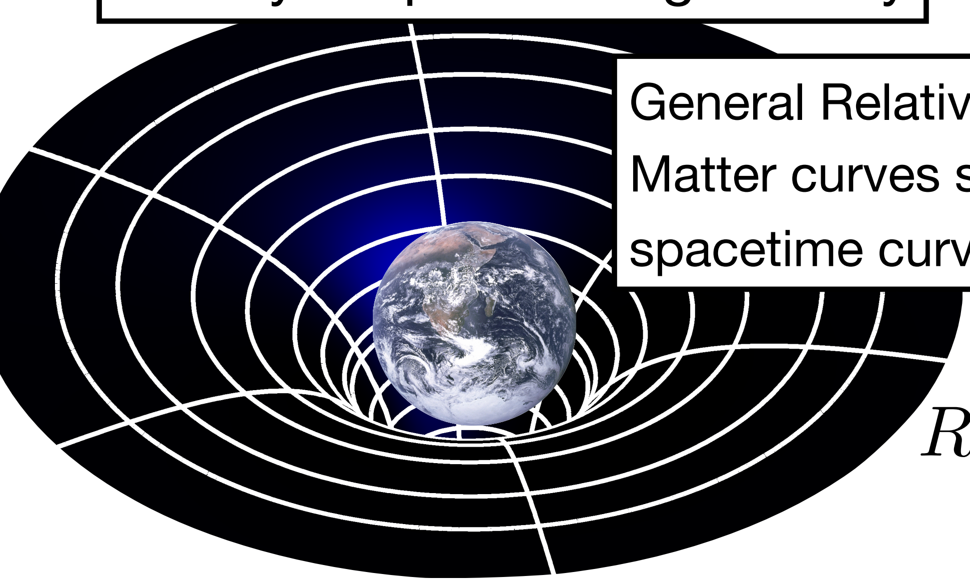
- **fails to include quantum gravity**
- **19 free parameters**

$\rightarrow$ **highly successful effective field theory**

$\rightarrow$ **new physics (quantum gravity?!) required beyond M_{Pl}**

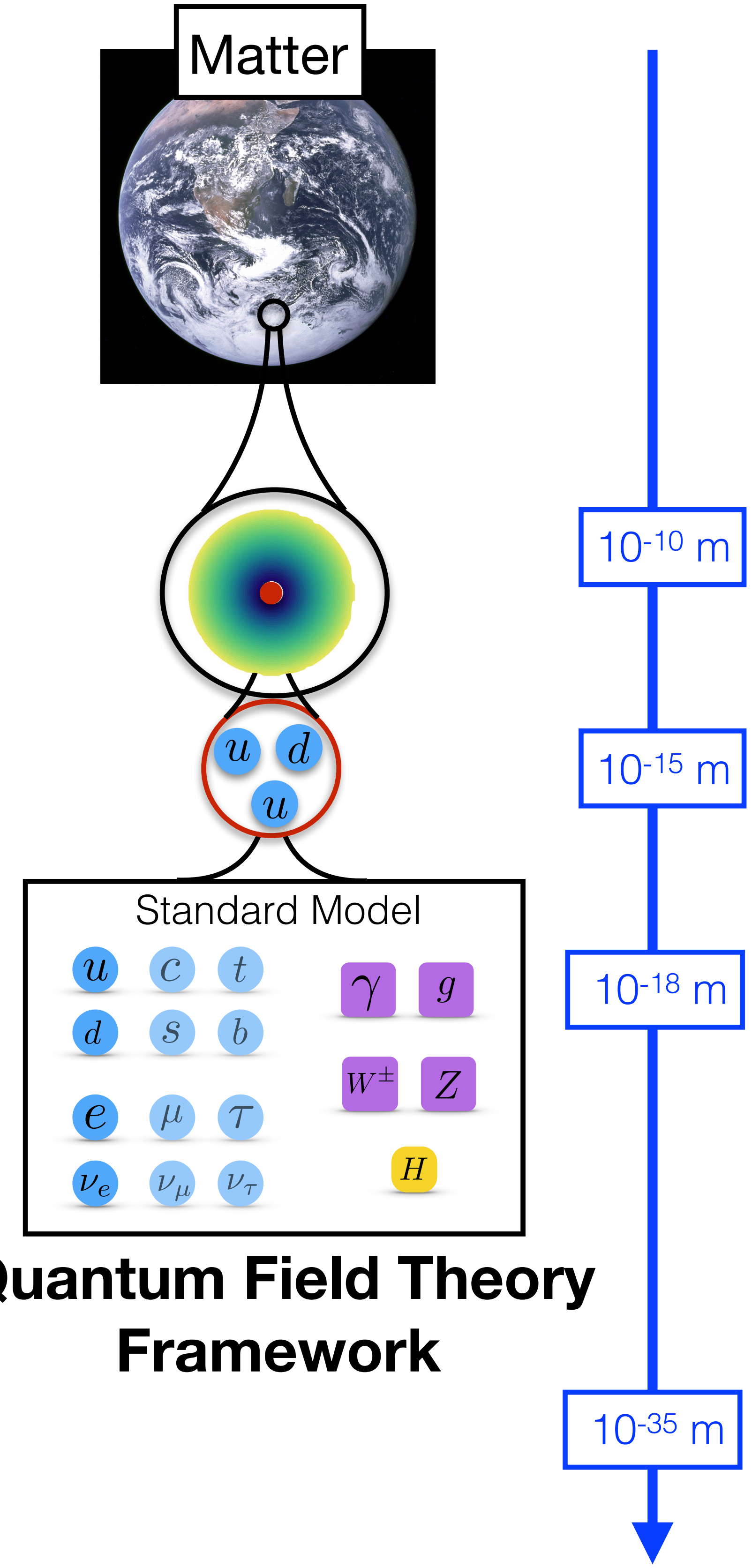
What are the fundamental building blocks of our universe?

Gravity = Spacetime geometry



General Relativity:
Matter curves spacetime &
spacetime curvature tells matter how to move

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N \, T_{\mu\nu}$$



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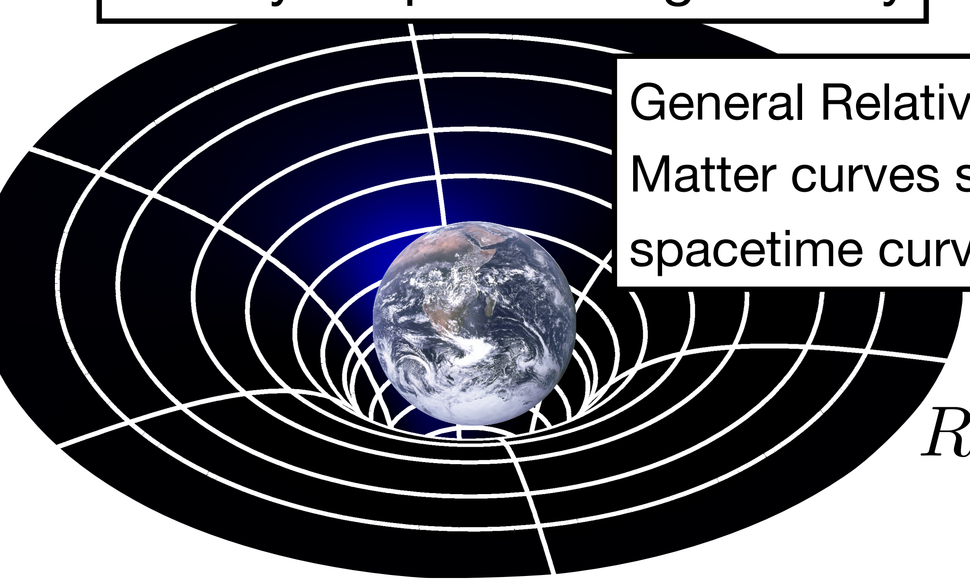

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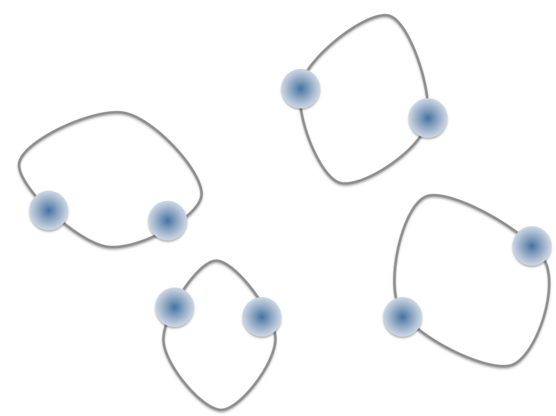

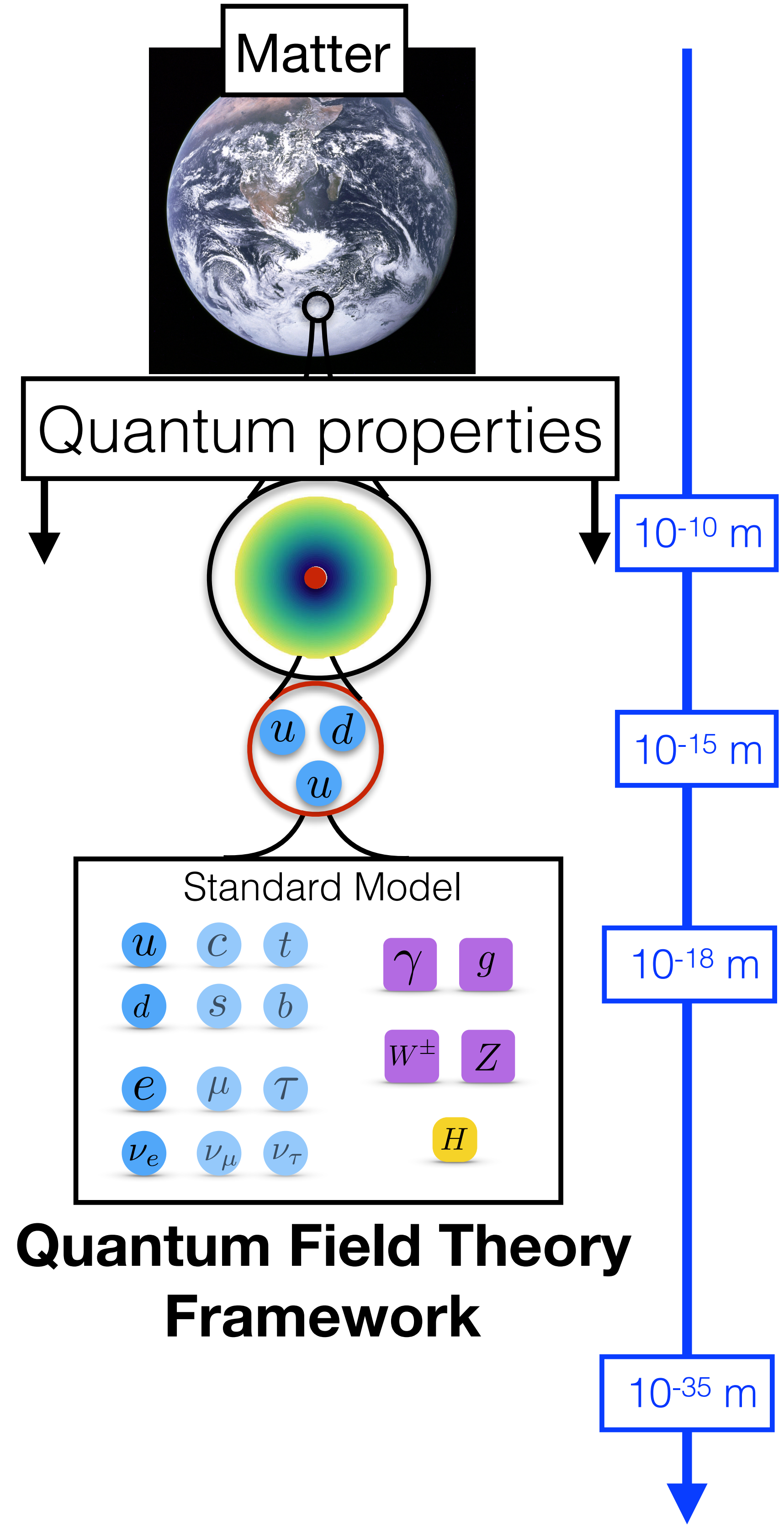

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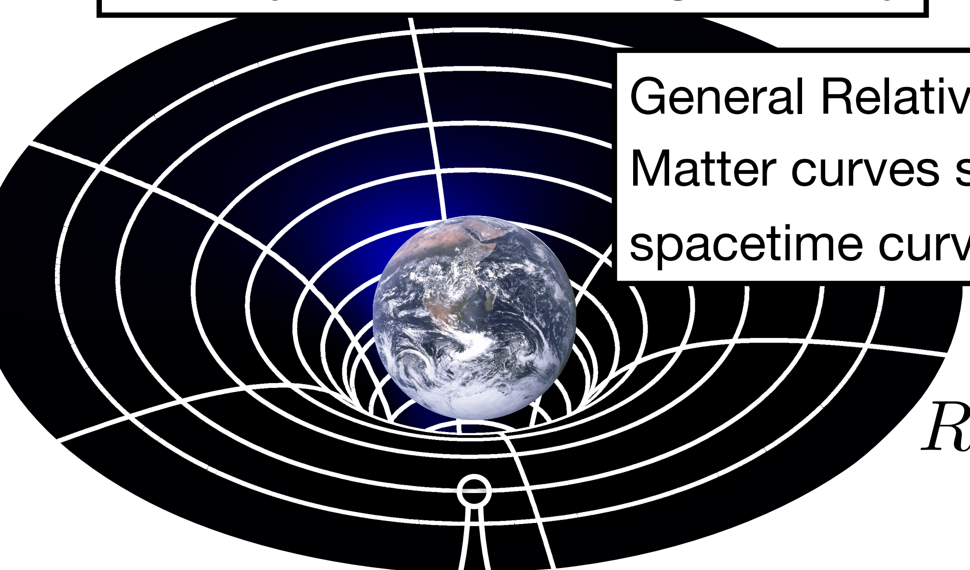

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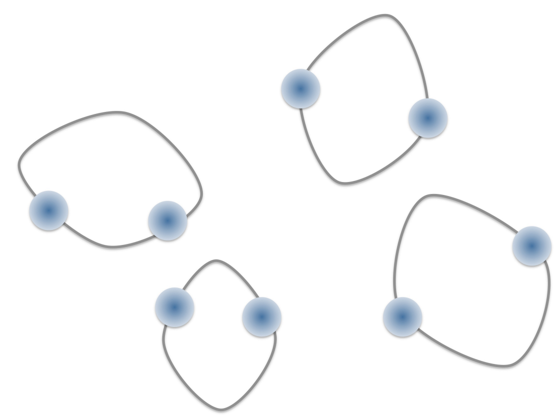
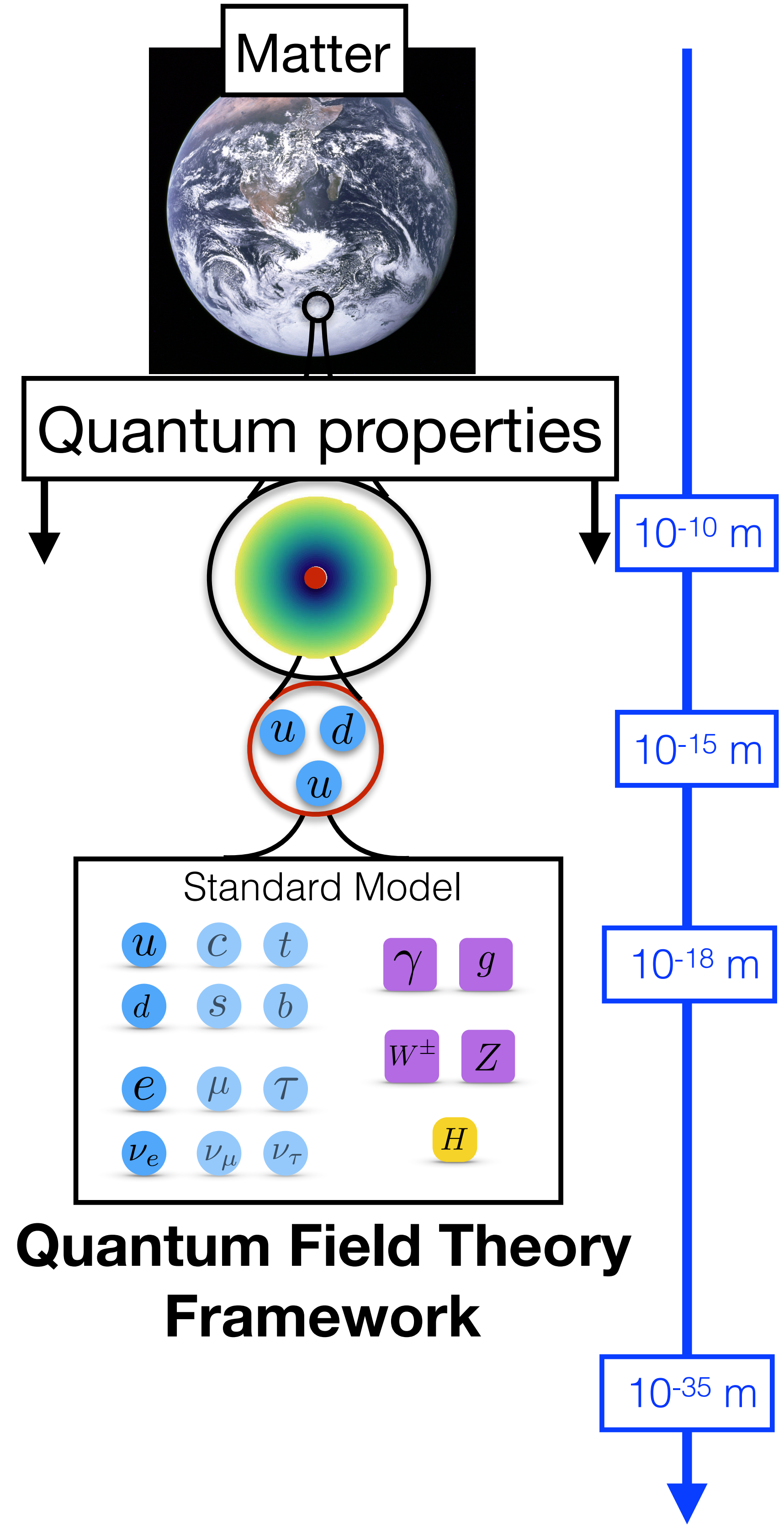
Quantum properties





Quantum Field Theory Framework

→ **asymptotically safe gravity**

- local QFT framework
  - works for all other forces
- degrees of freedom: metric
  - good description of gravity at low energies

→ could induce predictive UV completion of SM

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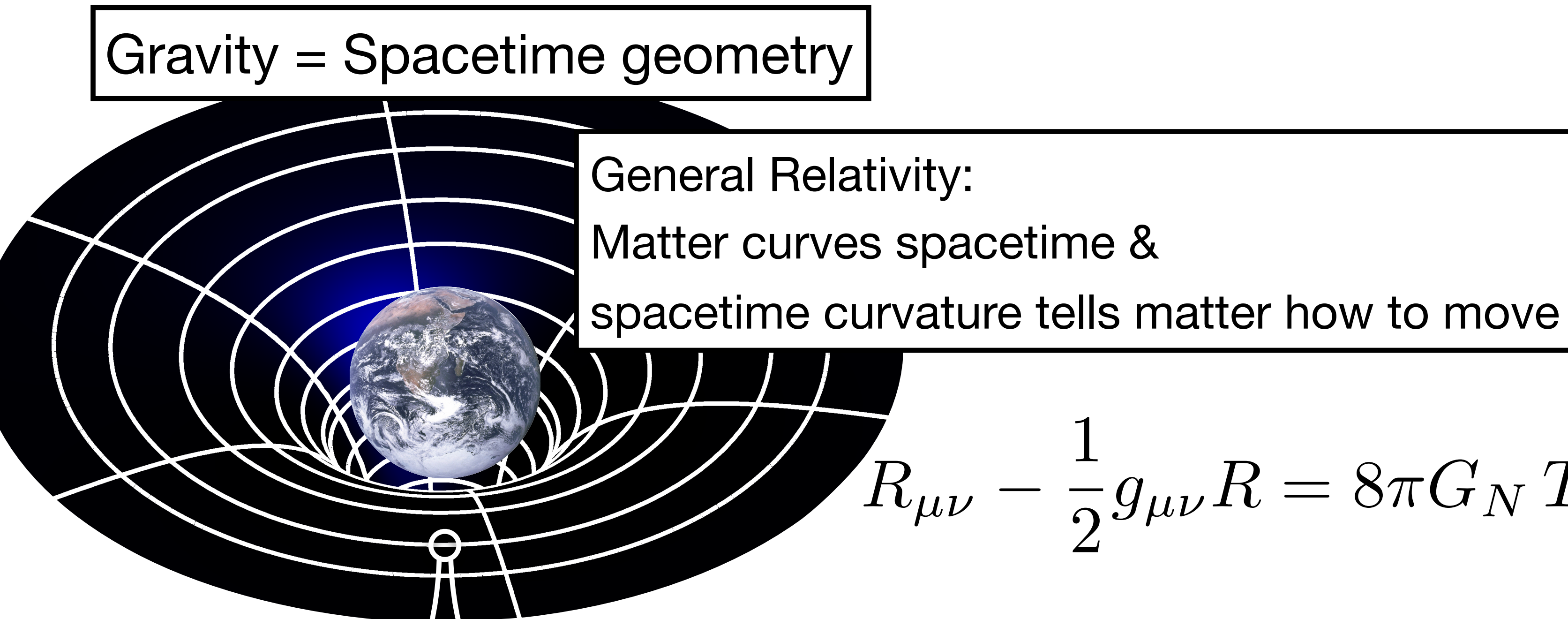

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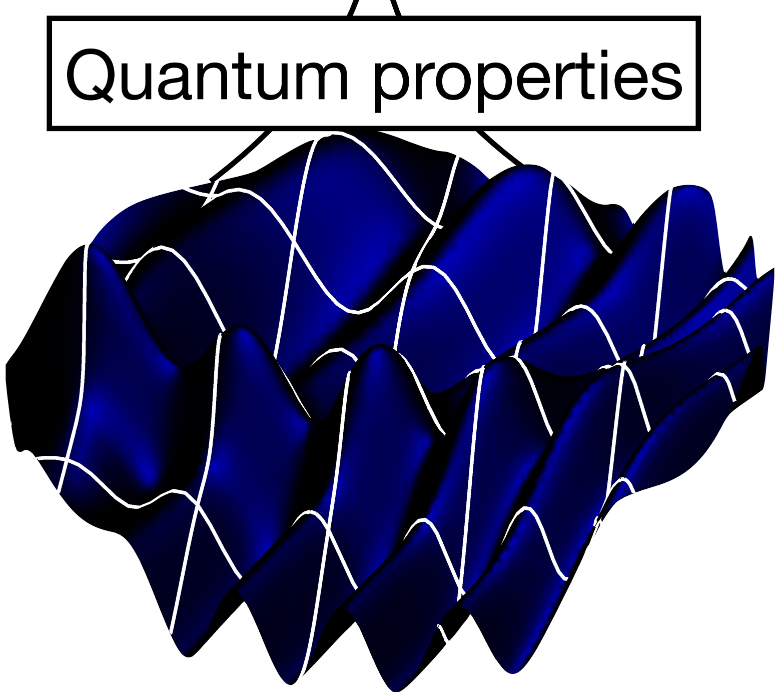
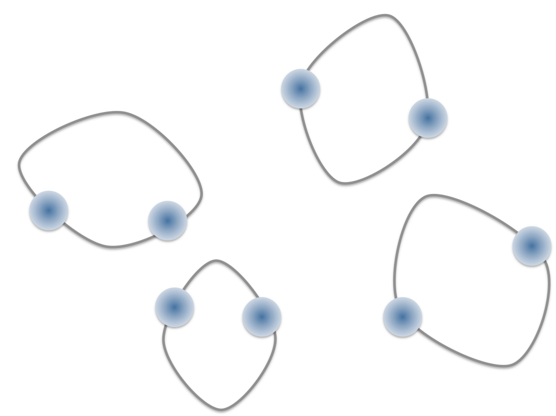
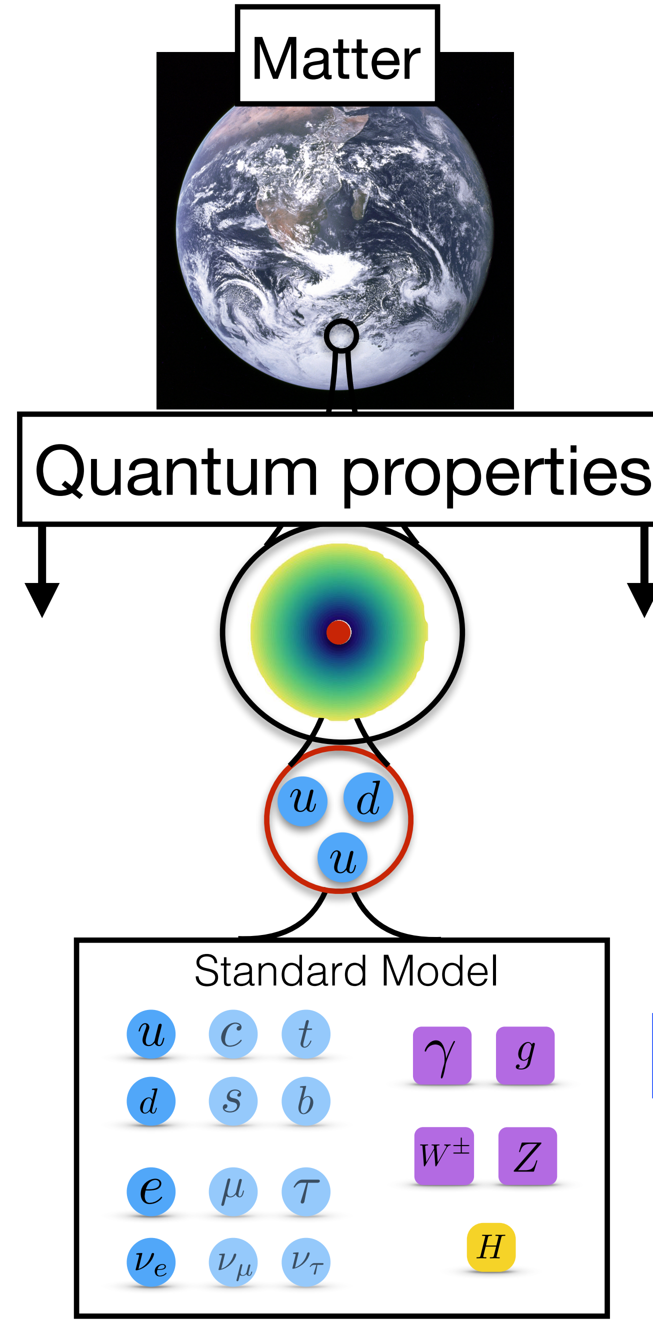




$$Z = \int \mathcal{D} g_{\mu\nu} e^{iS[g_{\mu\nu}]}$$



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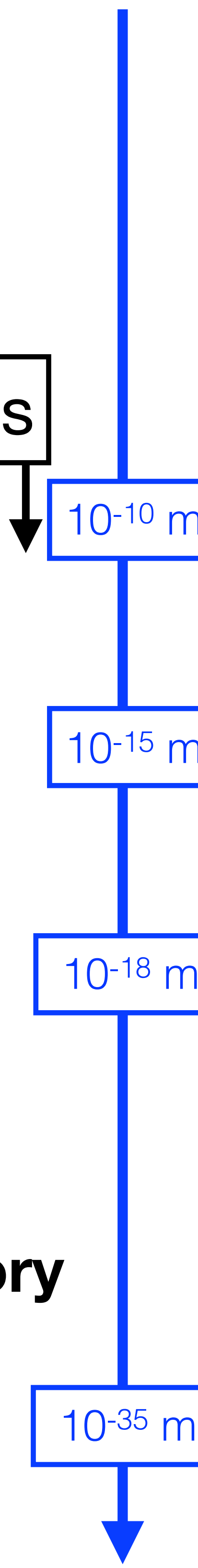

Quantum field theory for gravity

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

Which microscopic action?

Einstein-Hilbert action & perturbative quantisation: $$S = -\frac{1}{16\pi G_N}\int d^4x \sqrt{g}\, R$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \sqrt{16\pi G_N} h_{\mu\nu}$$

spin-2-field on flat background

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counterterms:

1-loop: $R^2,\ R_{\mu\nu}R^{\mu\nu}$ 't Hooft, Veltman '74; Deser, Nieuwenhuizen '74

2-loop: $C_{\mu\nu\kappa\lambda}C^{\kappa\lambda\rho\sigma}C_{\rho\sigma}{}^{\mu\nu}$ Goroff, Sagnotti '86; Van de Ven '92

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breakdown of predictivity

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consistent choice of S with finite number of free parameters?

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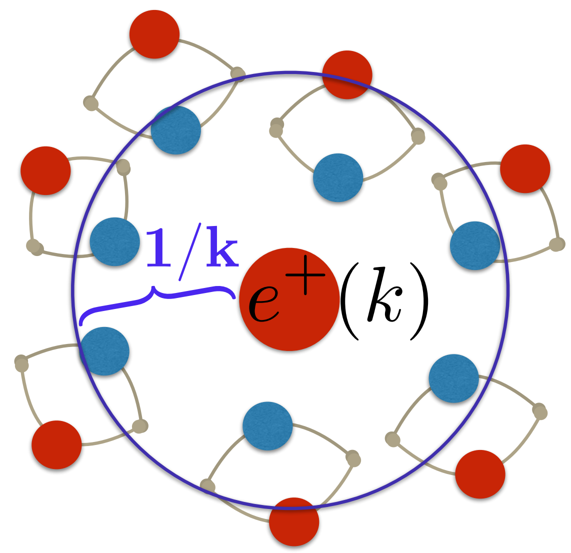

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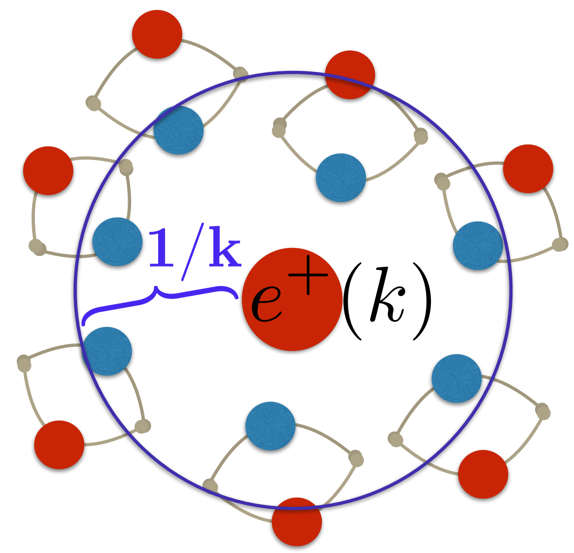

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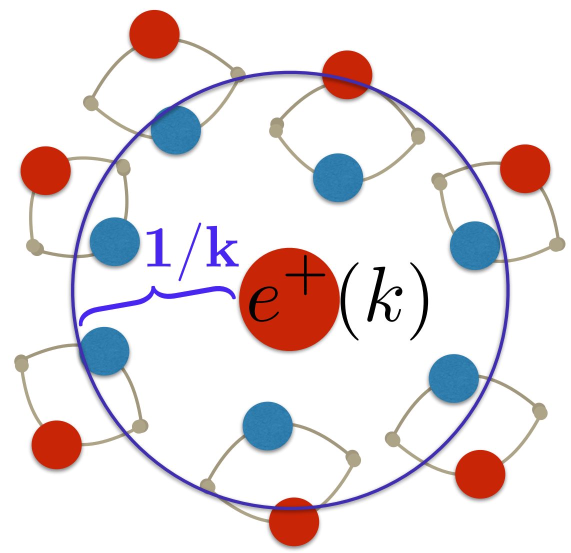

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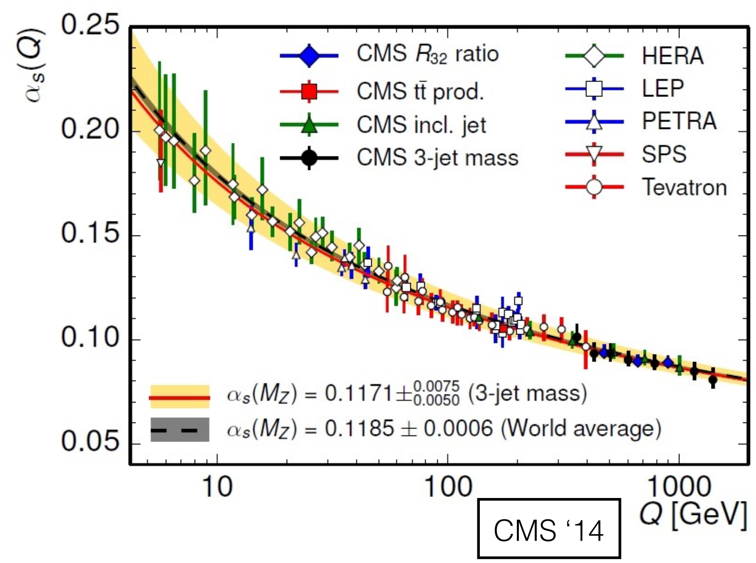

Asymptotic freedom in non- Abelian gauge theories

[Gross, Wilczek '73; Politzer '73]

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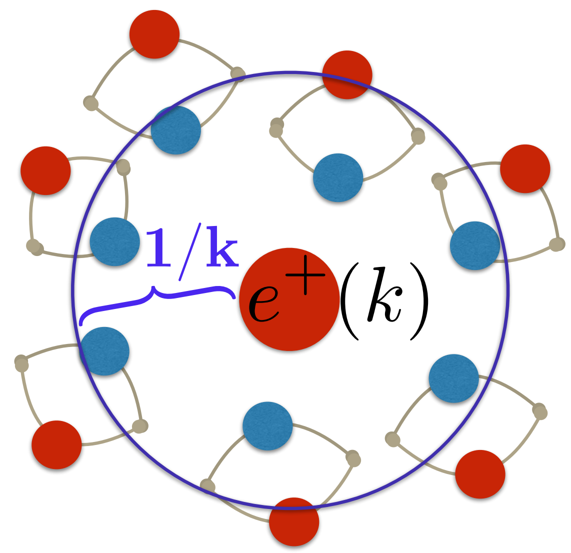
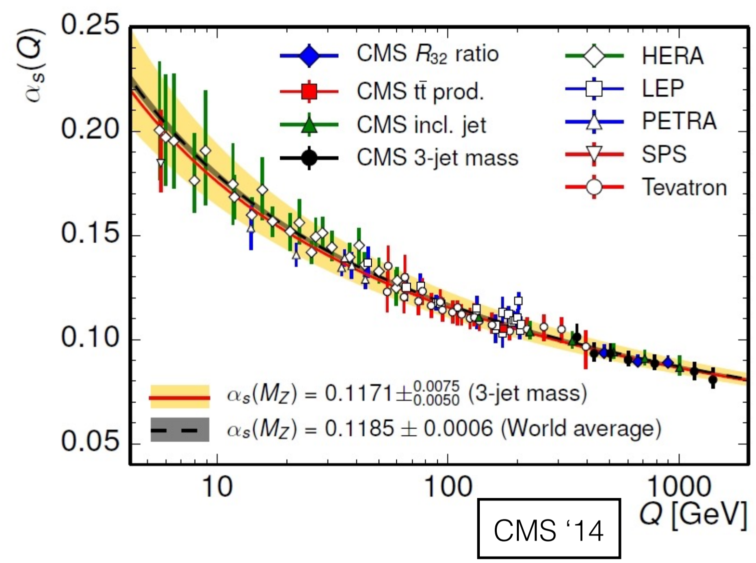


microscopic regime in fundamental theory (viable w/o ``new physics”): scale- invariance



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quark+ gluon fluctuations (universal @ 1loop)

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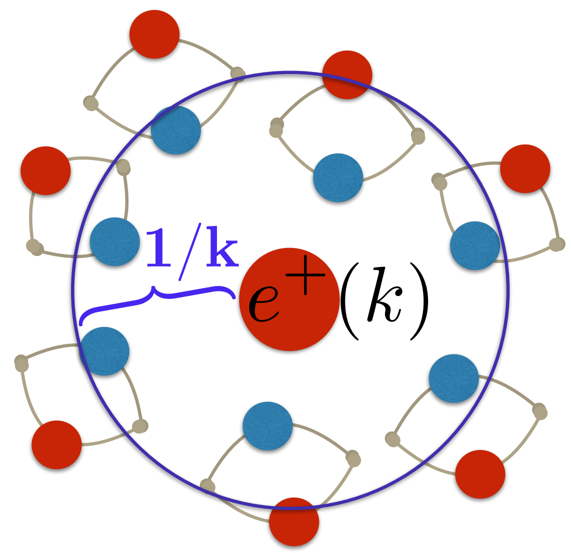

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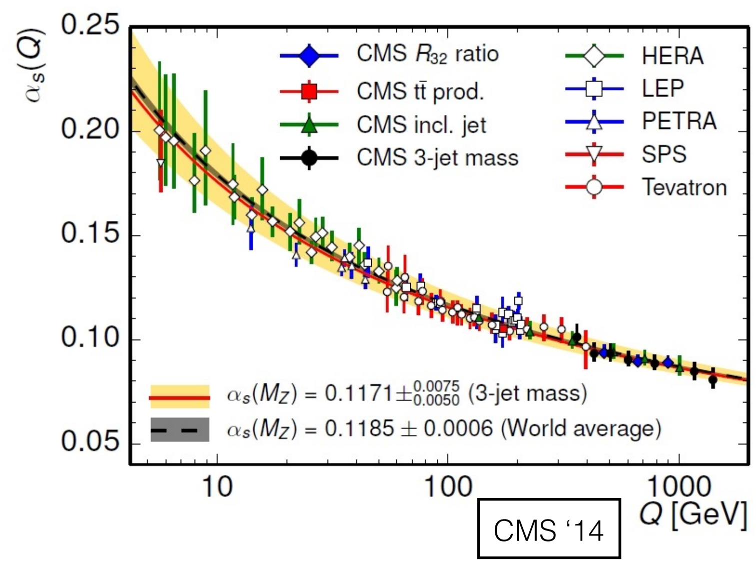

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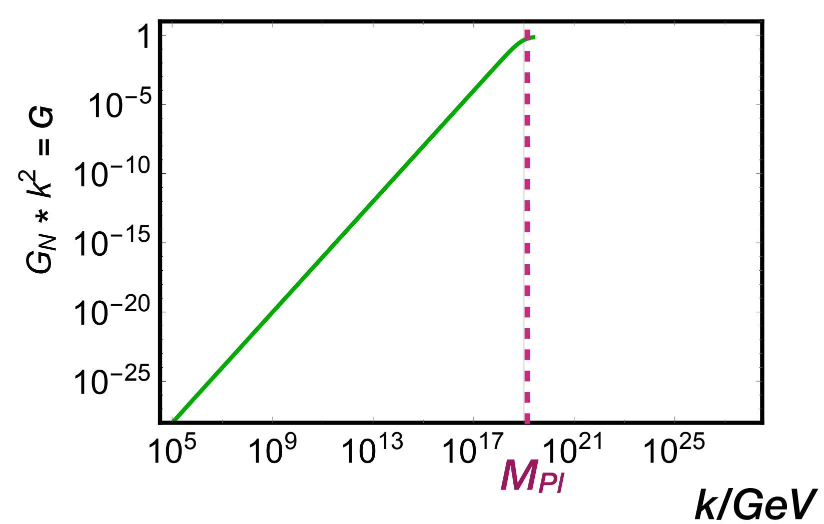

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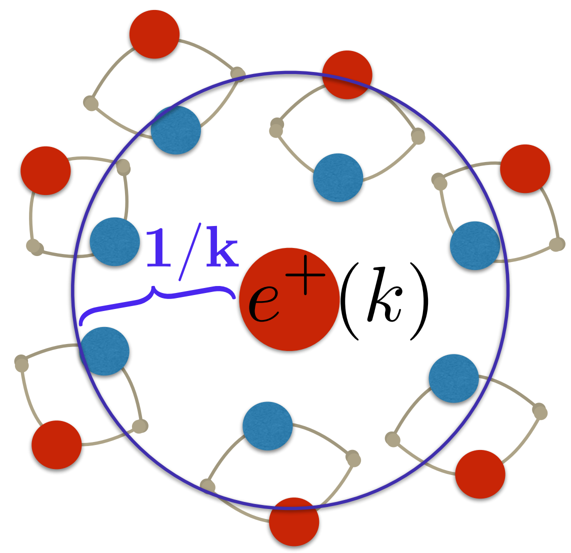

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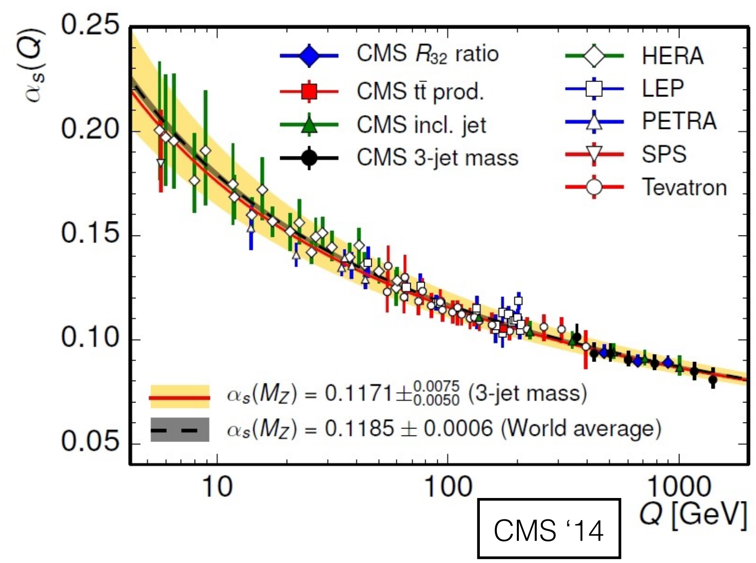

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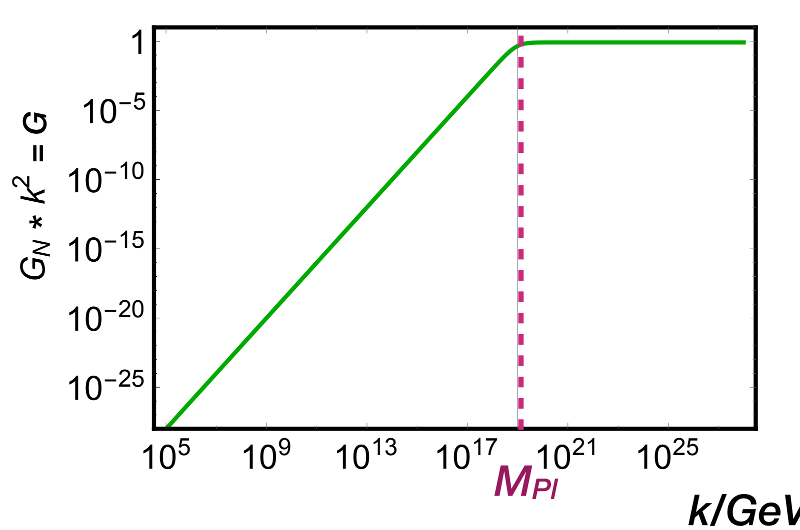

$$\beta_G = 2G - \frac{23\, G^2}{3\pi} + \dots$$

metric fluctuations

$$G^* = \frac{6\pi}{23}$$

[Codello, Percacci, Rahmede ’08]

Asymptotic safety

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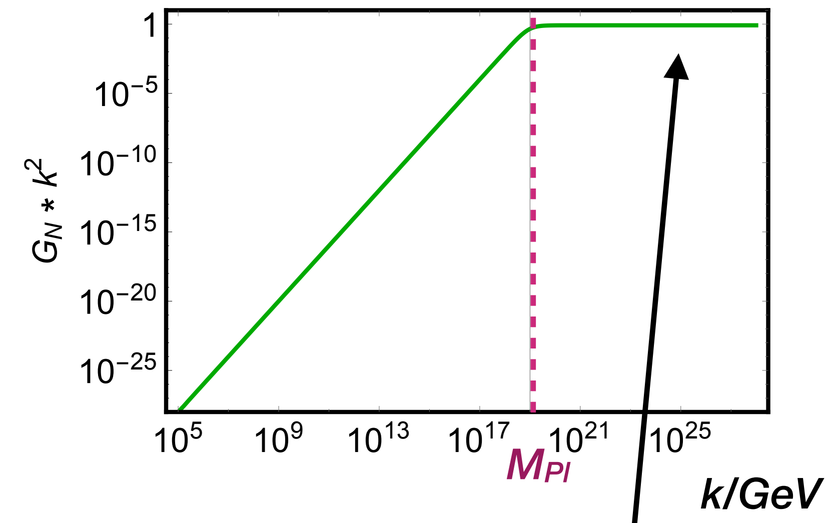

scale invariant
fixed-point regime
(microscopic dynamics @$k \to \infty$)

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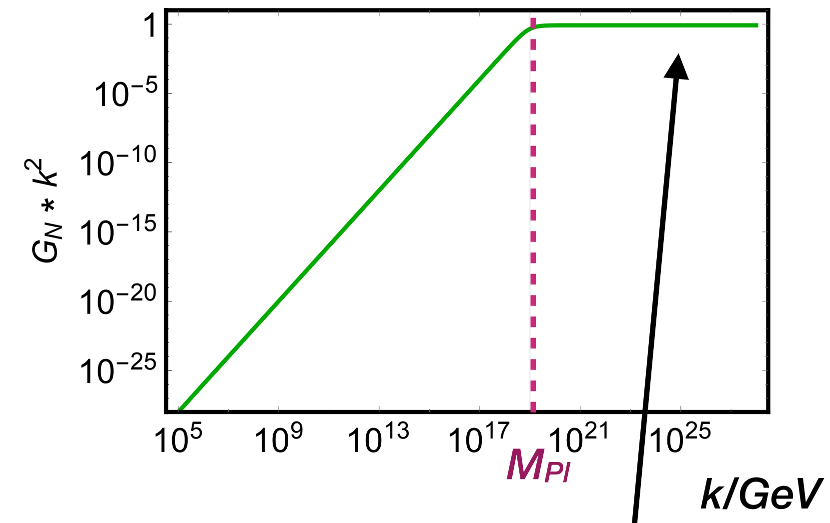

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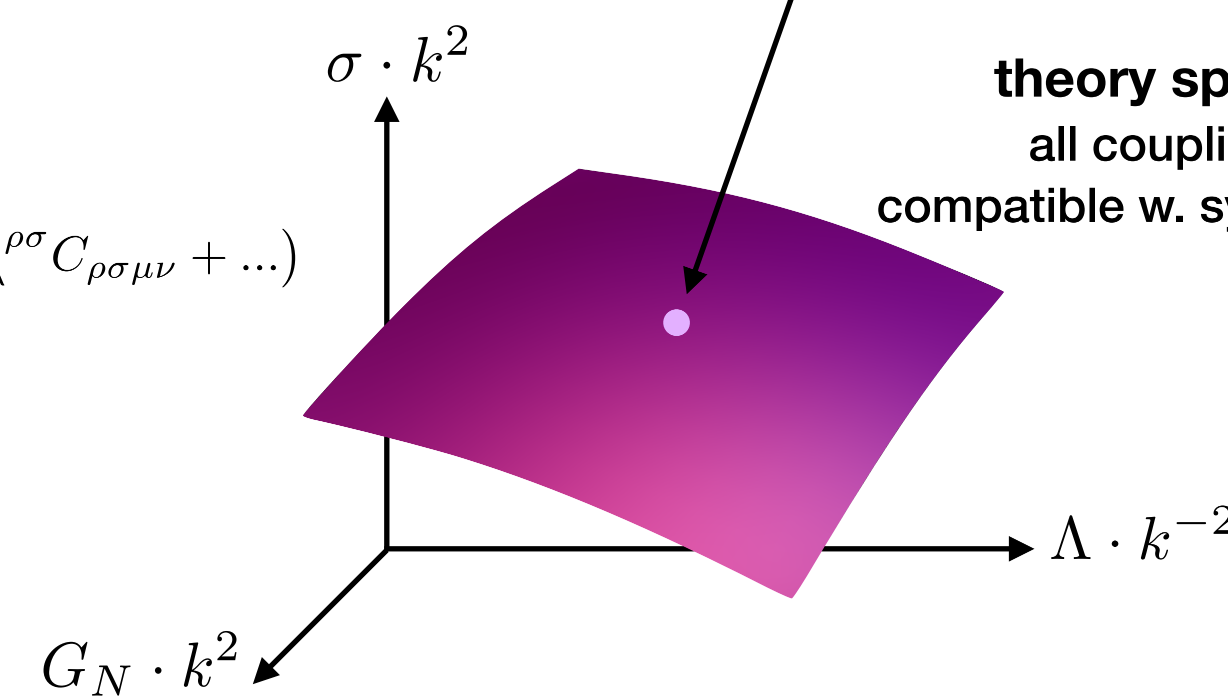

theory space:
all couplings
compatible w. symmetries

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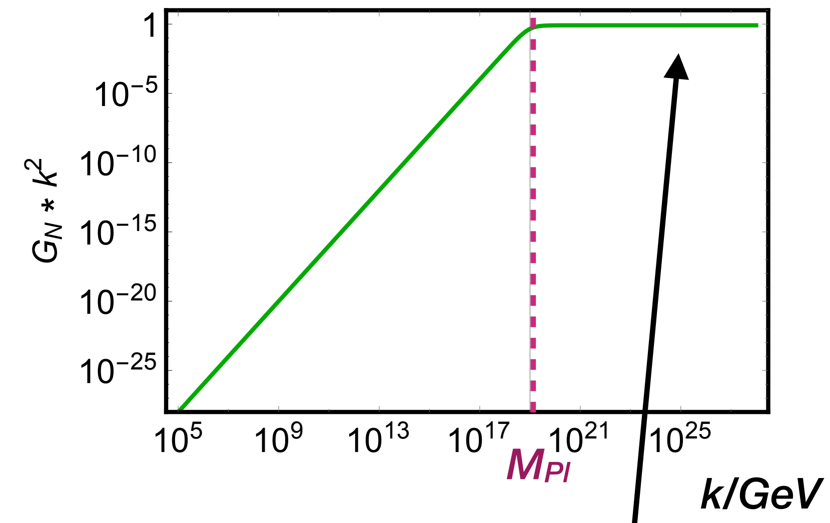

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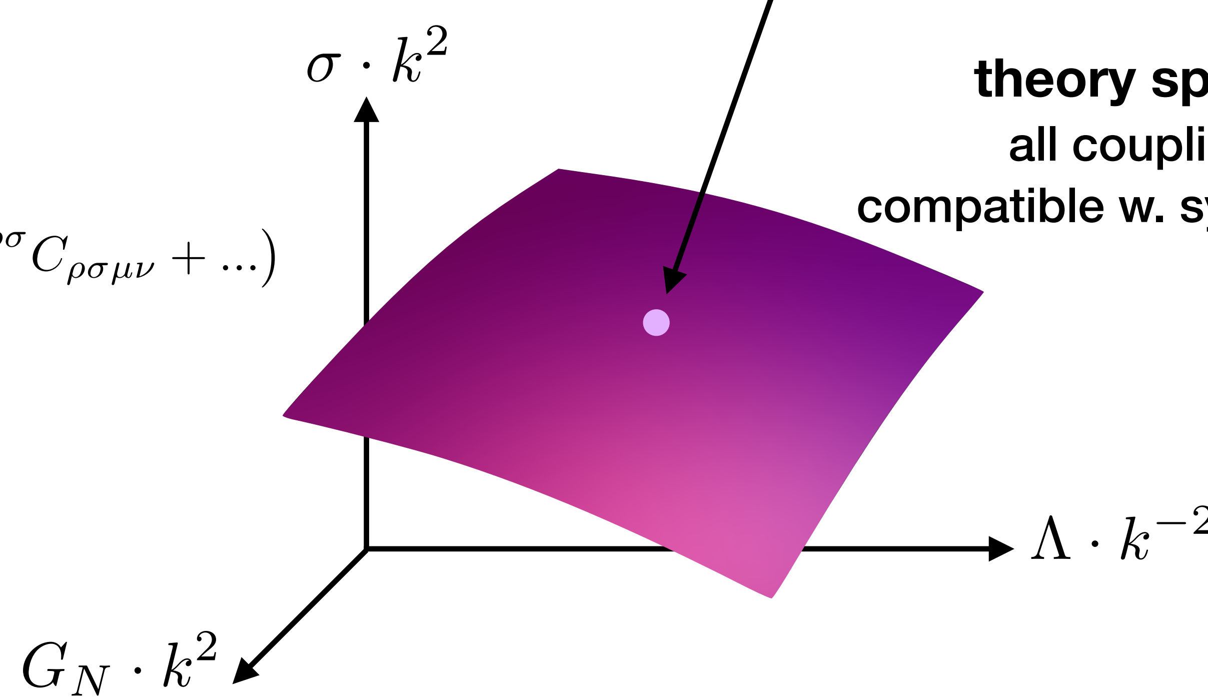
But at large scales our world
is clearly not scale-invariant?!



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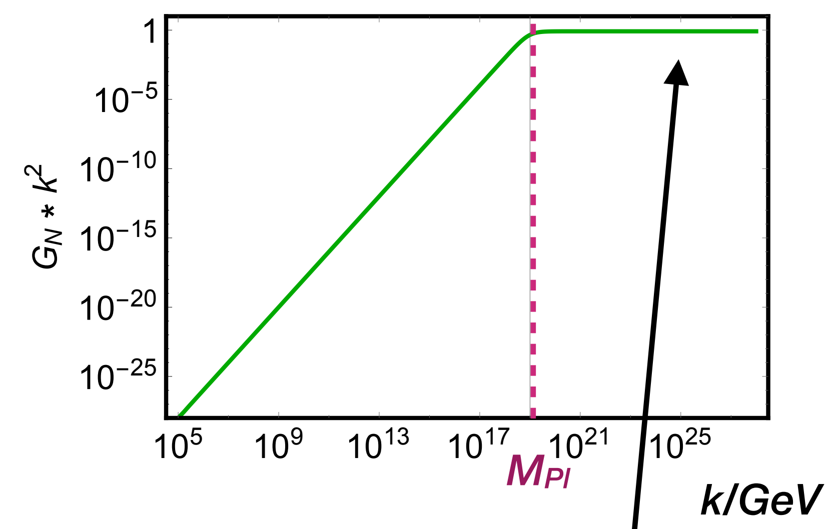

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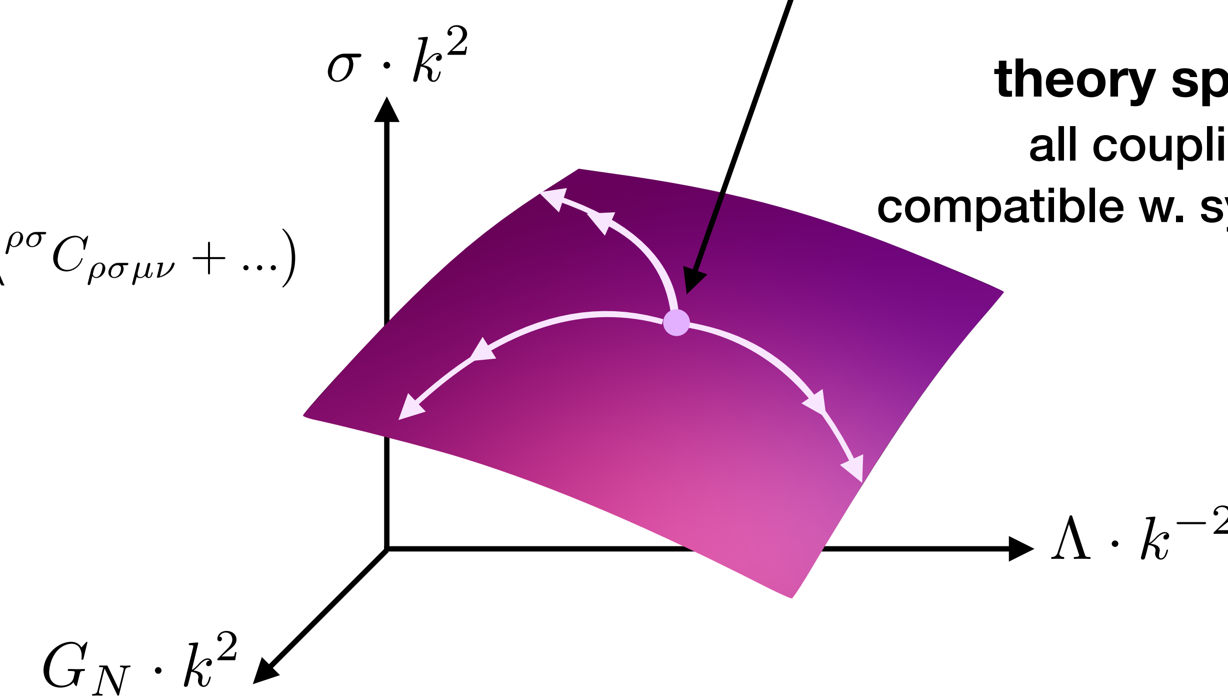
$\longrightarrow$ Flow away from fixed point



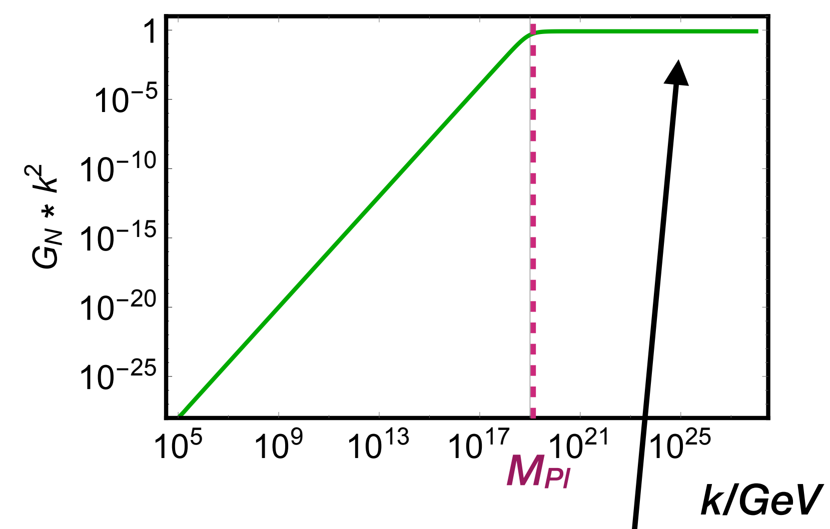
theory space:
all couplings
compatible w. symmetries

Asymptotic safety

Quantum gravity:
Newton coupling grows towards UV

asymptotically safe beyond M_{Pl}

[Weinberg '76, '79; Reuter '96]

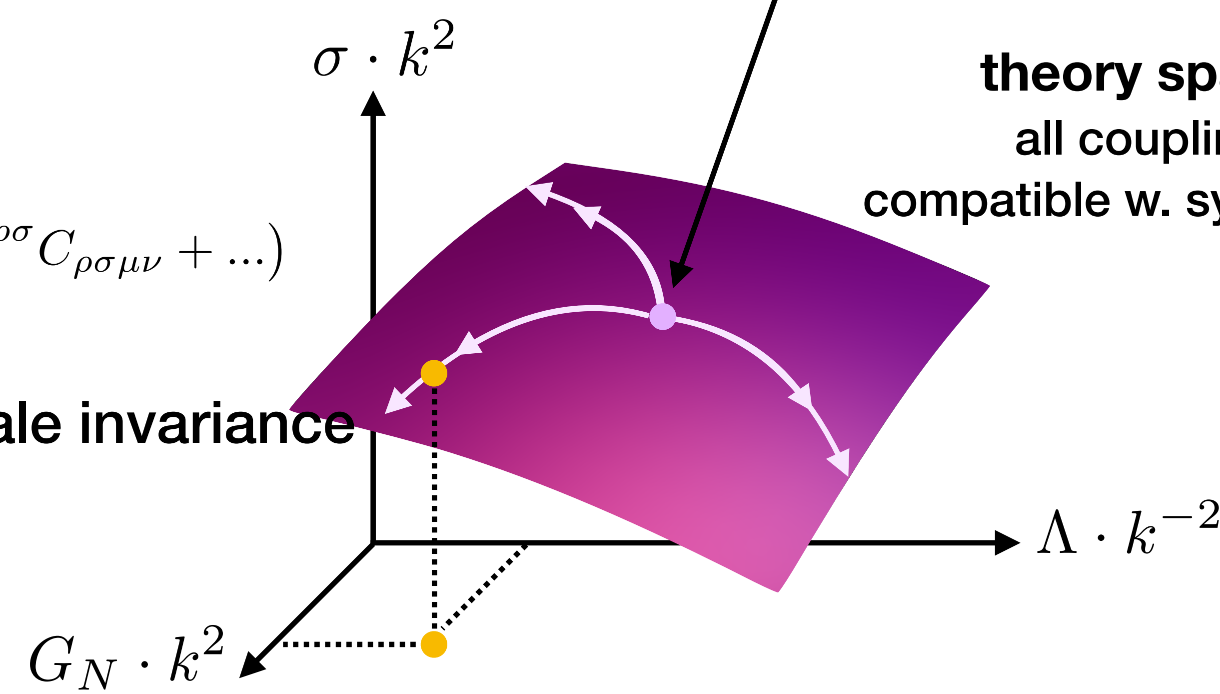


scale invariant
fixed-point regime
(microscopic dynamics @$k \to \infty$)

higher-order interactions generated by quantum fluctuations:

$$\Gamma_k = -\frac{1}{16\pi G_N}\int d^4x\,\sqrt{g}\,(R-2\Lambda)$$

$$+\int d^4x\,\sqrt{g}\,(a_1\,R^2 + a_2 R^{\mu\nu}R_{\mu\nu} + \sigma\, C^{\mu\nu\kappa\lambda}C_{\kappa\lambda}{}^{\rho\sigma}C_{\rho\sigma\mu\nu} + ...)$$



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low-energy dynamics:
- free parameters encode deviation from scale invariance (relevant couplings)

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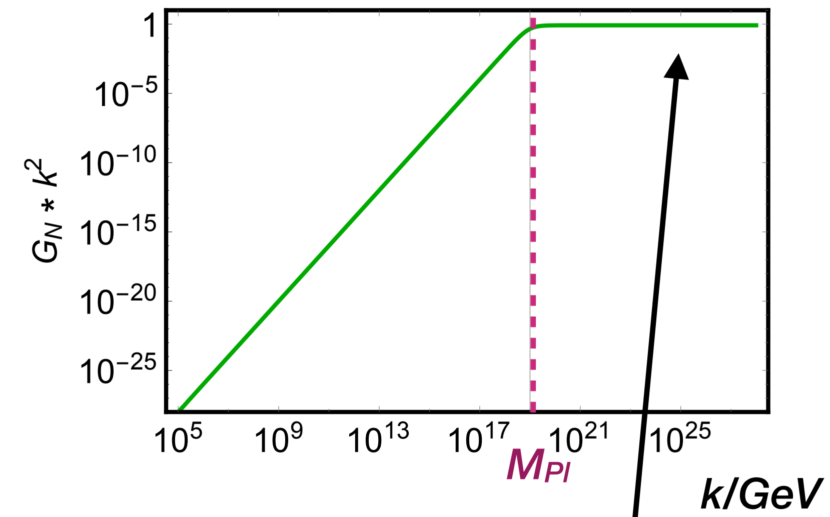

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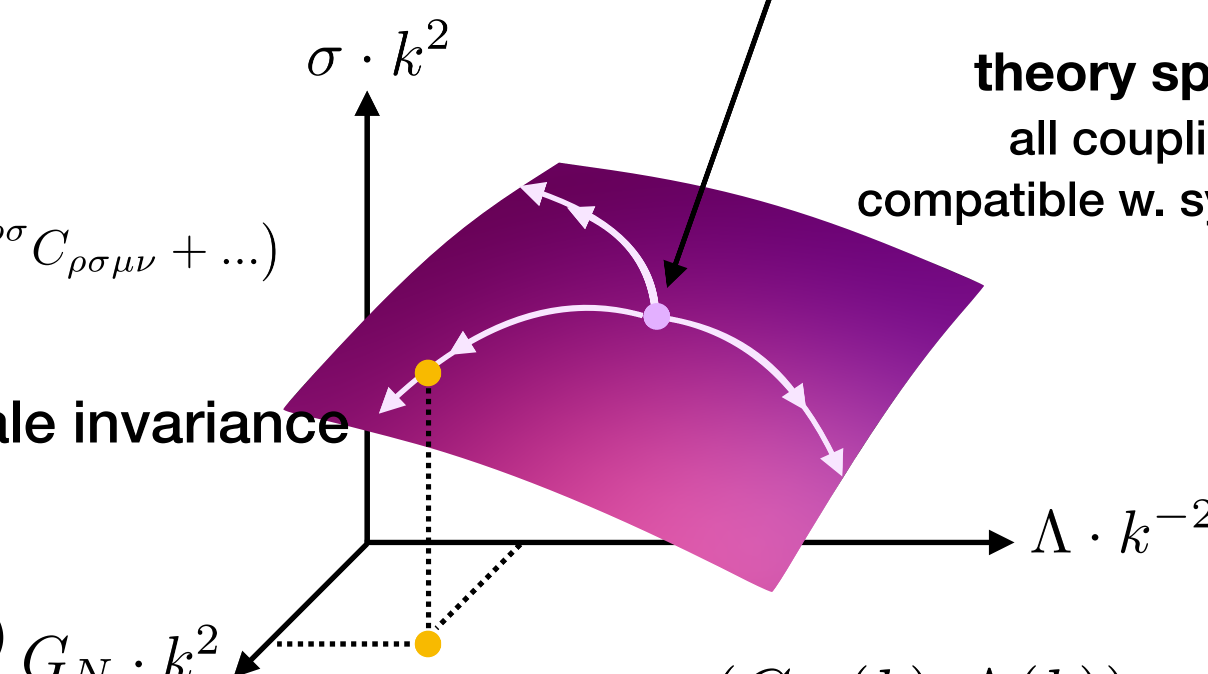

$$\to \sigma = \sigma(G_N(k), \Lambda(k))$$

low-energy dynamics:

- free parameters encode deviation from scale invariance
  (relevant couplings)
- irrelevant couplings ***predicted***
  (qm fluc’s force flow to stick to critical hypersurface)

Asymptotic safety in a nutshell

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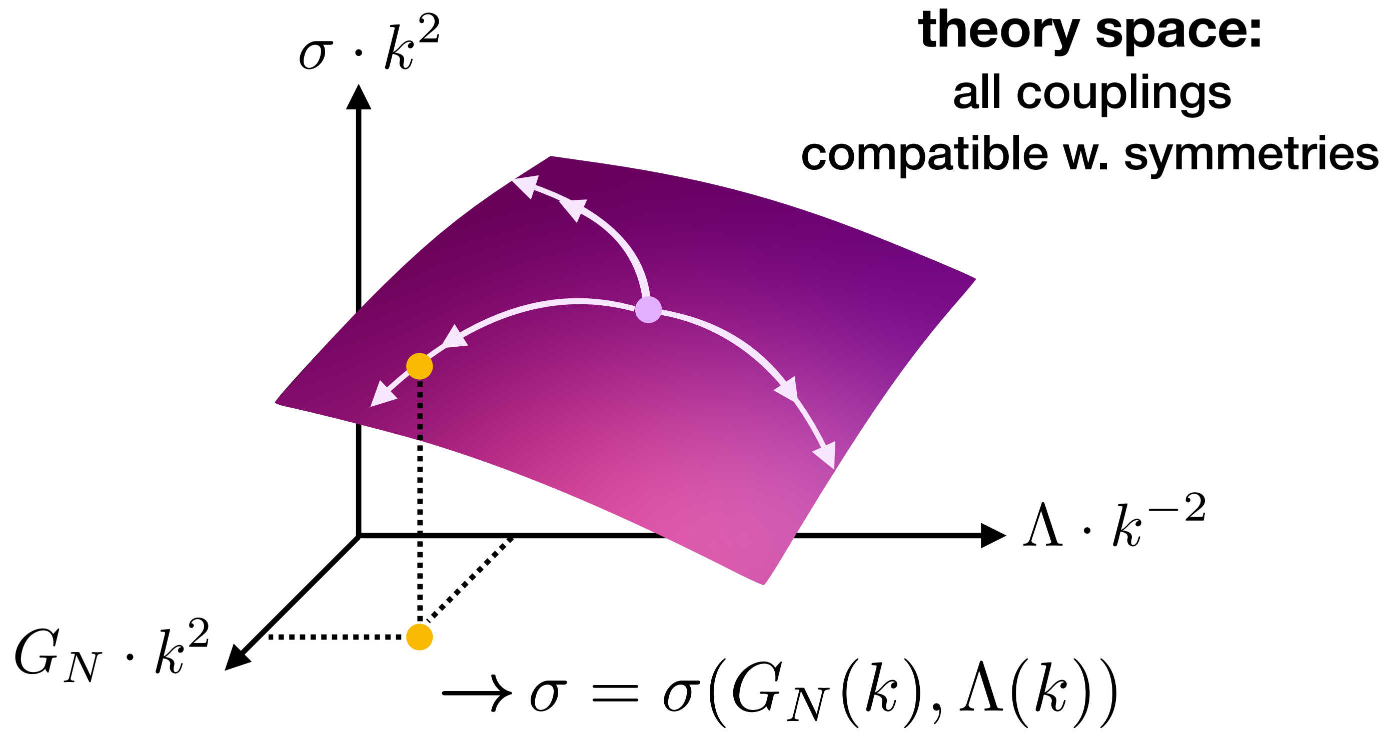

Theory space features an interacting fixed point $\rightarrow$ UV complete

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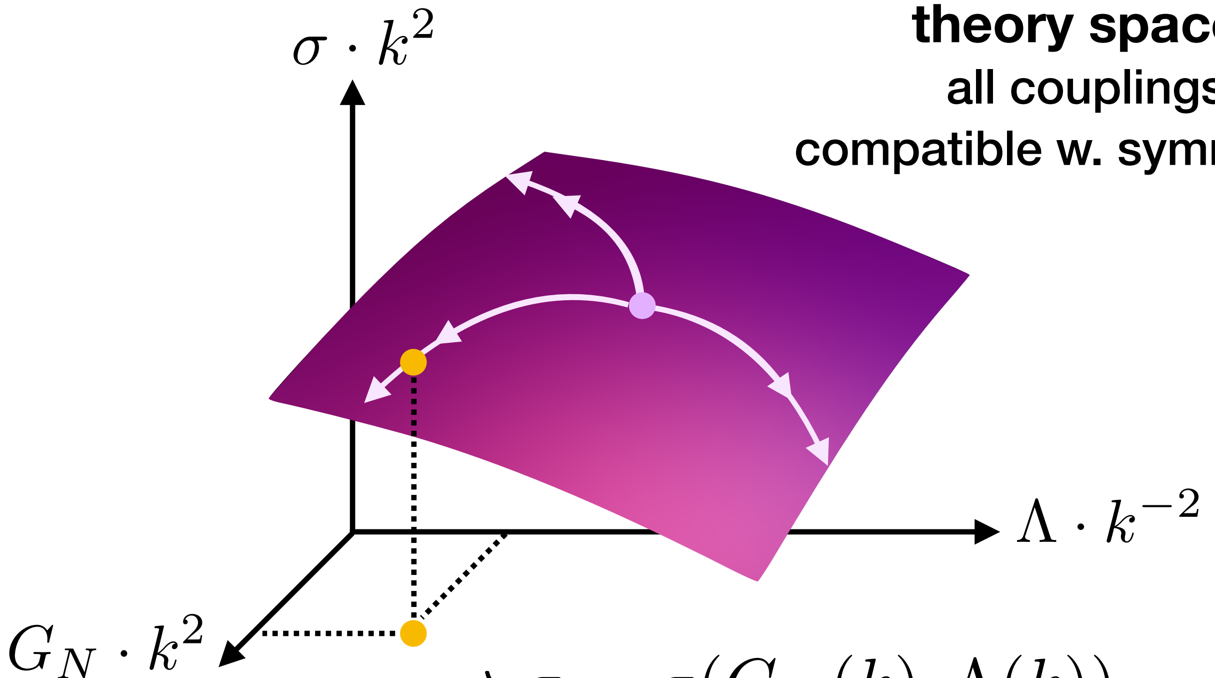

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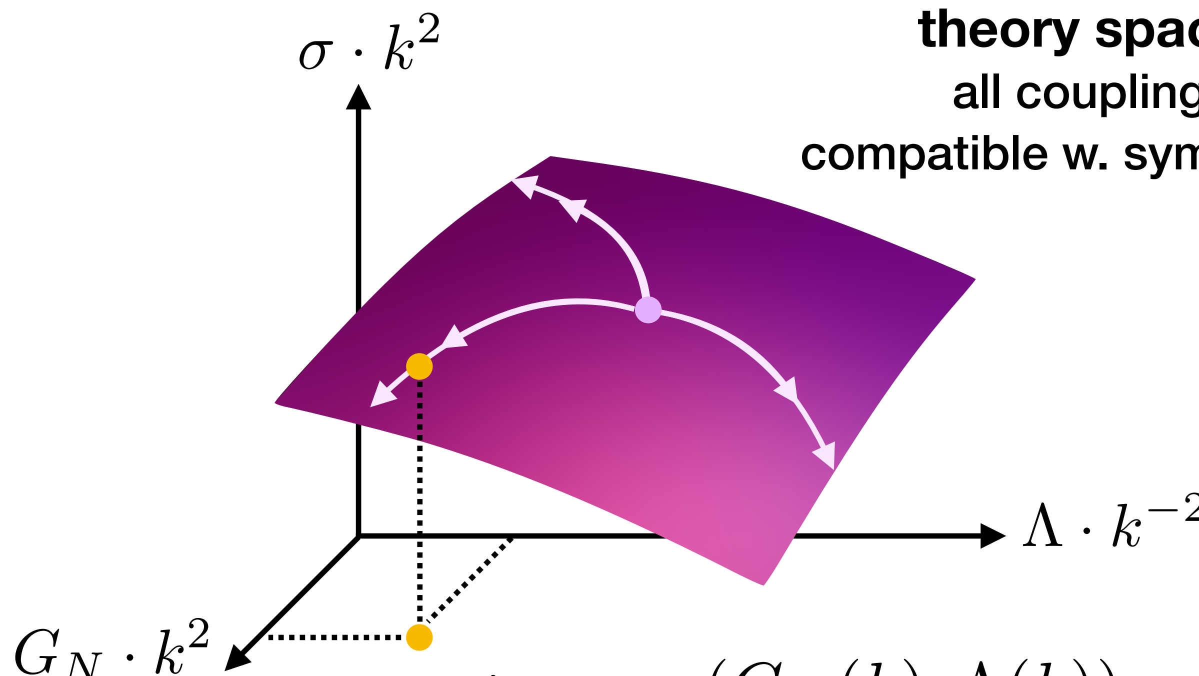

theory space:
all couplings
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$$\to \sigma = \sigma(G_N(k), \Lambda(k))$$

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.

$\to$ UV complete

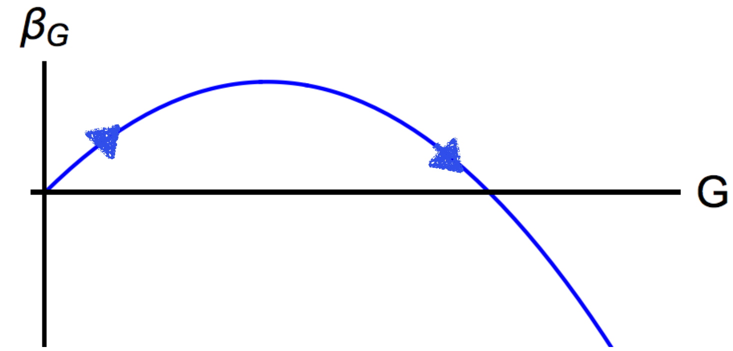
$\to$ predictive
(finite # free parameters)

$\to$ predictions for irrelevant couplings match observations

Hints for asymptotic safety of 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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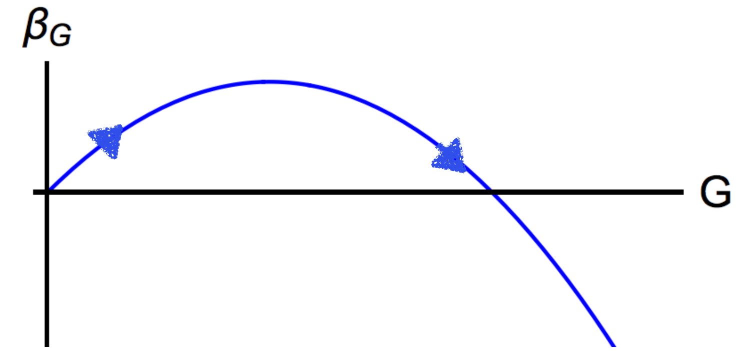

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- **lattice simulations (Euclidean/Causal Dynamical Triangulations)**
  continuum limit not conclusively established

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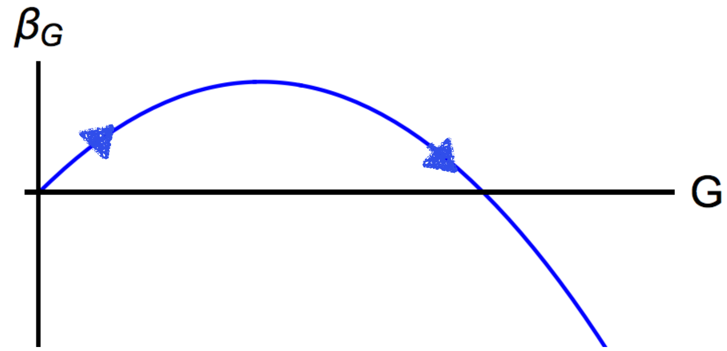

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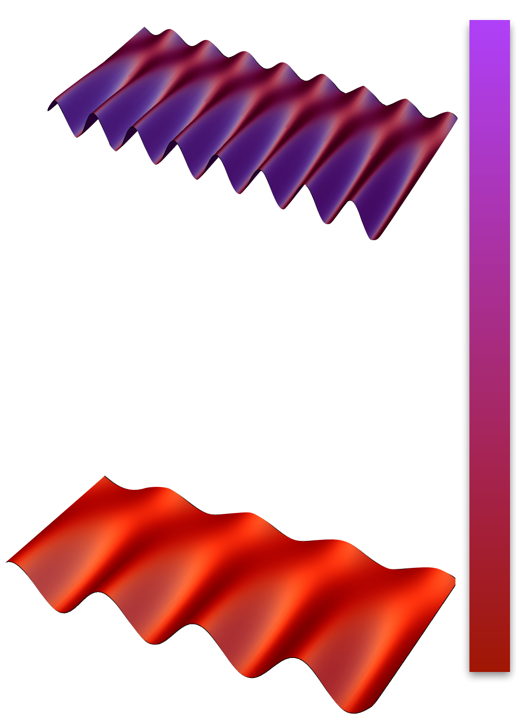
$$e^{-\Gamma_k[\phi]} = \int \mathcal{D}\varphi \, e^{-S[\varphi] - \frac{1}{2}\int \varphi(-p) R_k(p) \varphi(p)}$$

scale- and momentum-dependent ``mass"

probe scale dependence of QFT

Wetterich '93, Reuter '96



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Γ_k contains effect of quantum fluctuations above k

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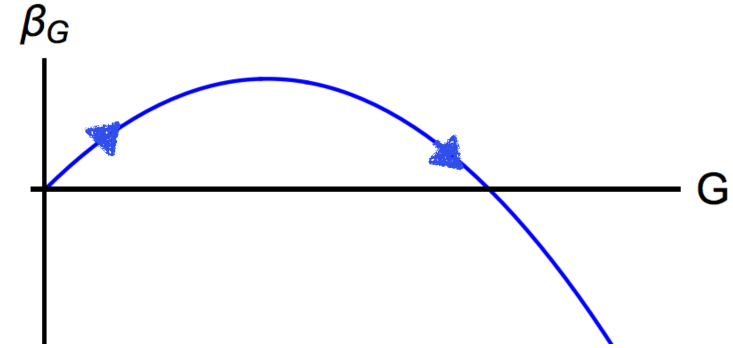

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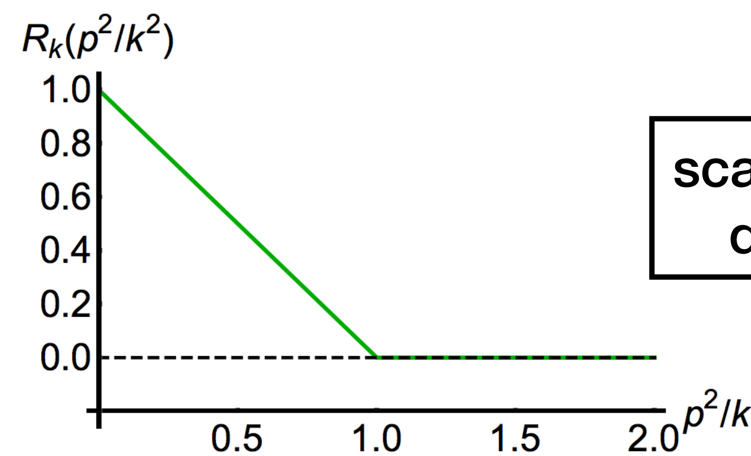

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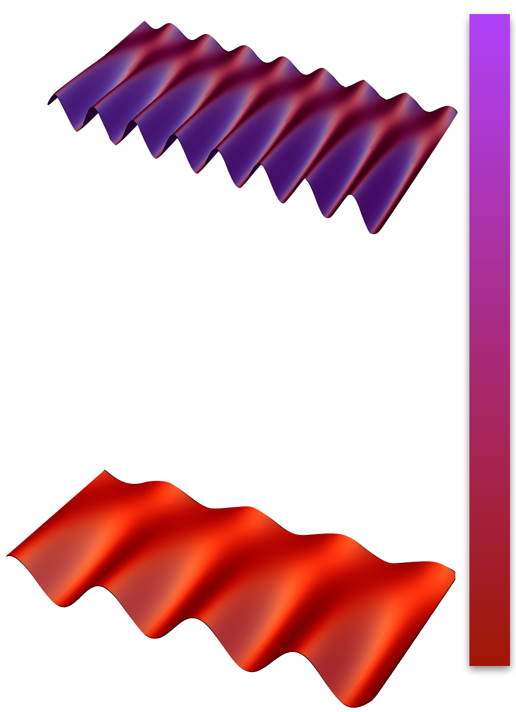

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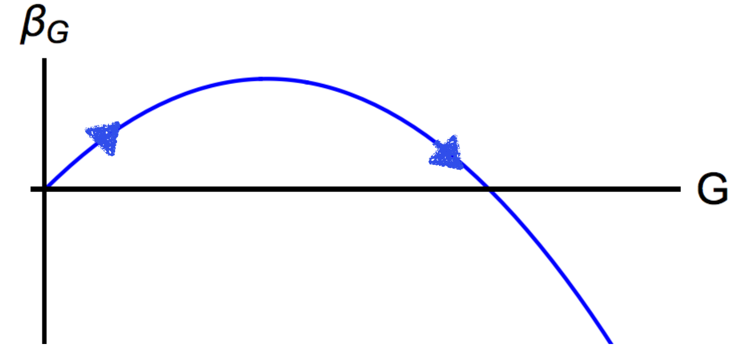

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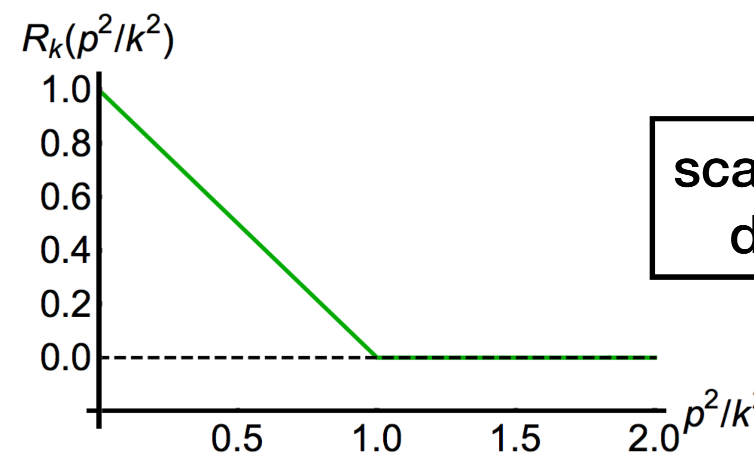

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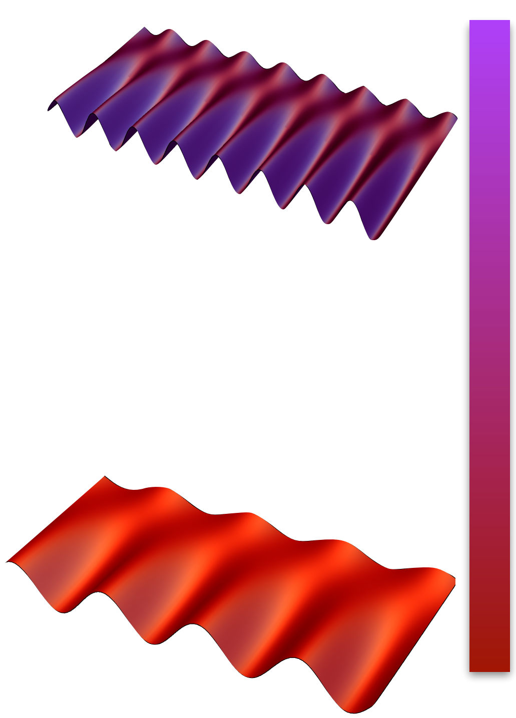

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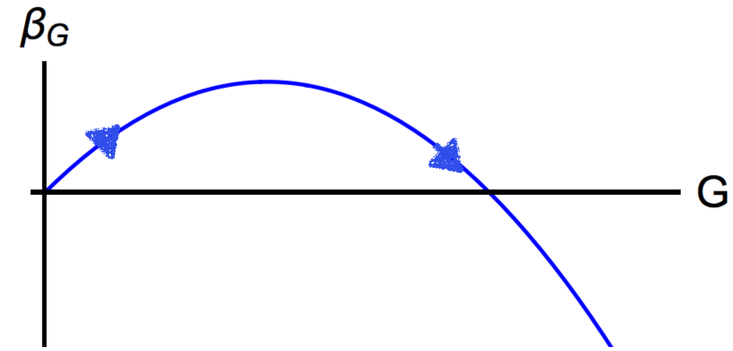

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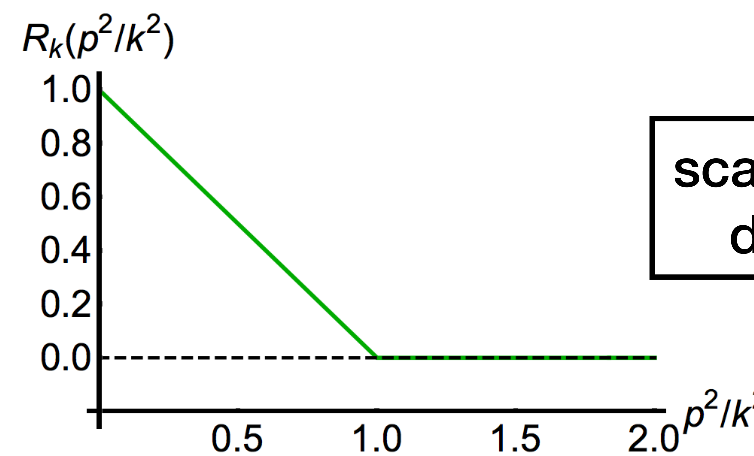

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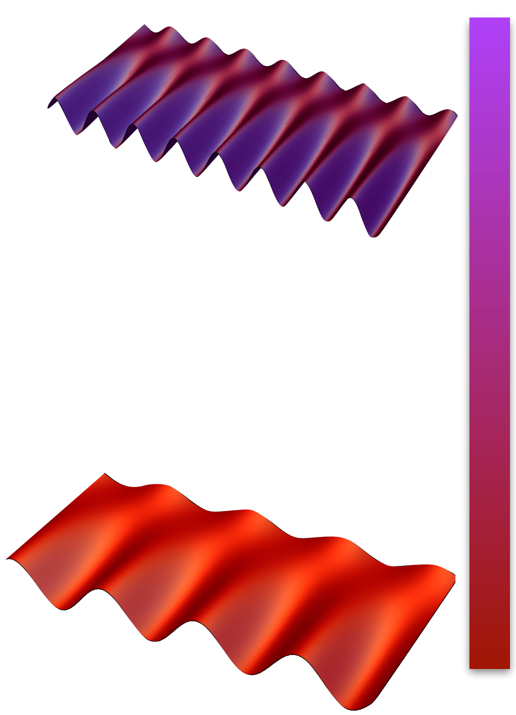

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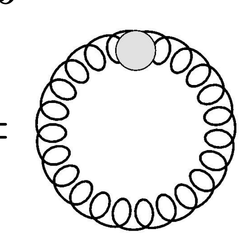
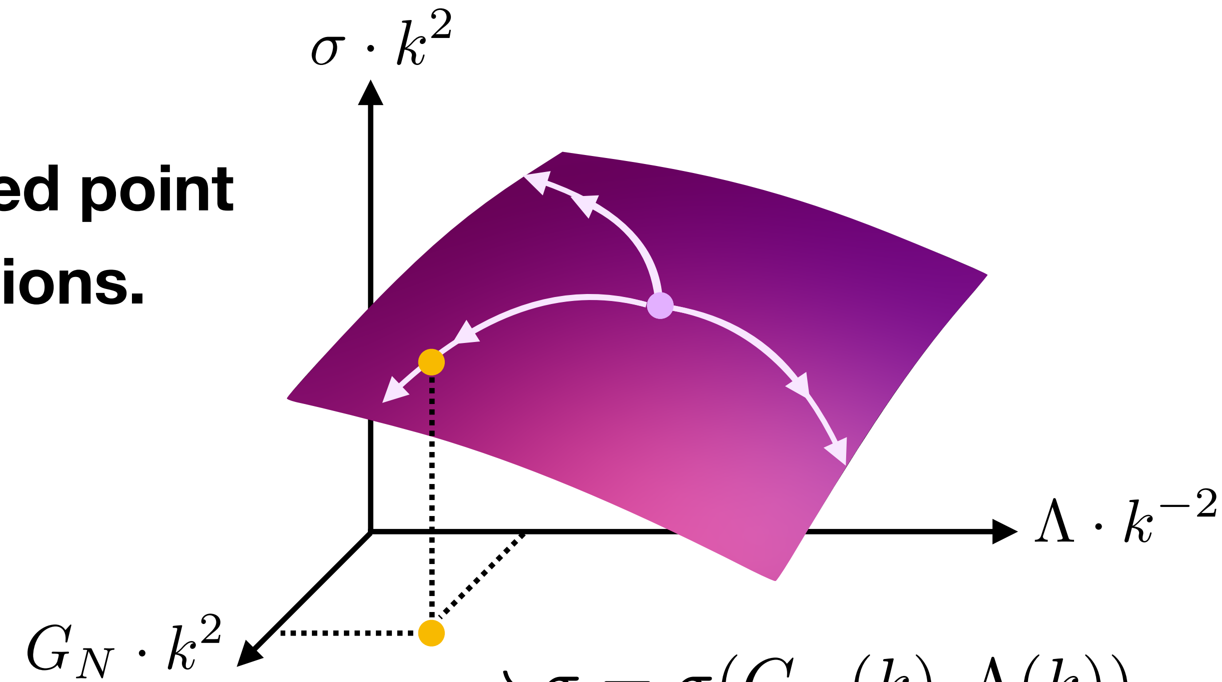
Wetterich equation: $\partial_k \Gamma_k = \frac{1}{2} \mathrm{STr} \left(\Gamma_k^{(2)} + R_k\right)^{-1} \partial_k R_k =$ 

Hints for asymptotic safety of gravity

Theory space features an interacting fixed point with a finite number of relevant directions.

$\longrightarrow$ UV complete

$\longrightarrow$ predictive



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tool: functional RG equation in truncations of theory space
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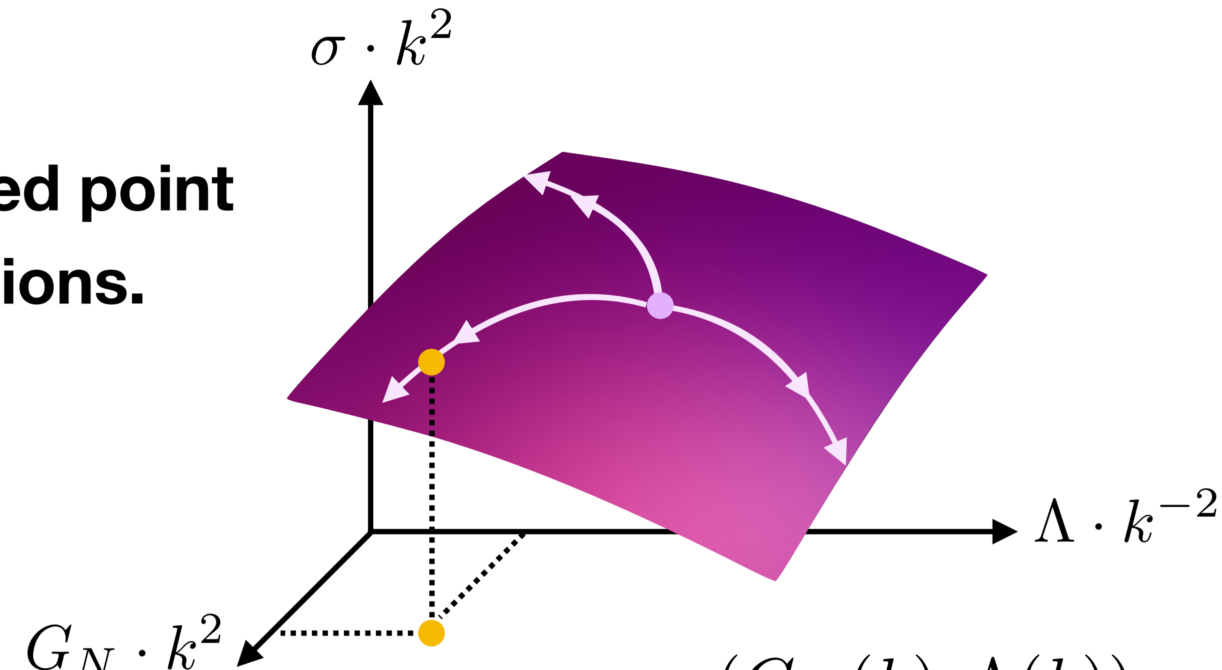

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fixed point	operators	relevant	irrelevant
✓	$\sqrt{g}$	x	
✓	$\sqrt{g}R$	x	

[Reuter '96, Lauscher, Reuter '01; Reuter, Saueressig '02; Becker, Reuter '14; Christiansen, Knorr, Meibohm, Pawlowski, Reichert '15]

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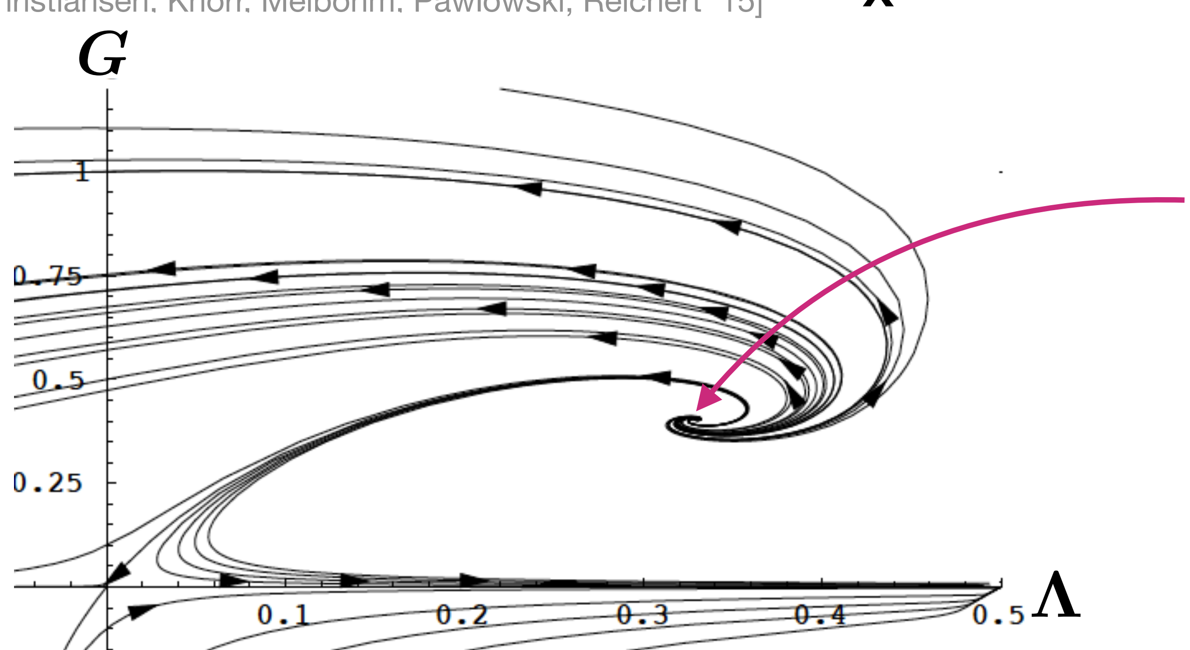

UV fixed point

[Reuter, Saueressig '01]

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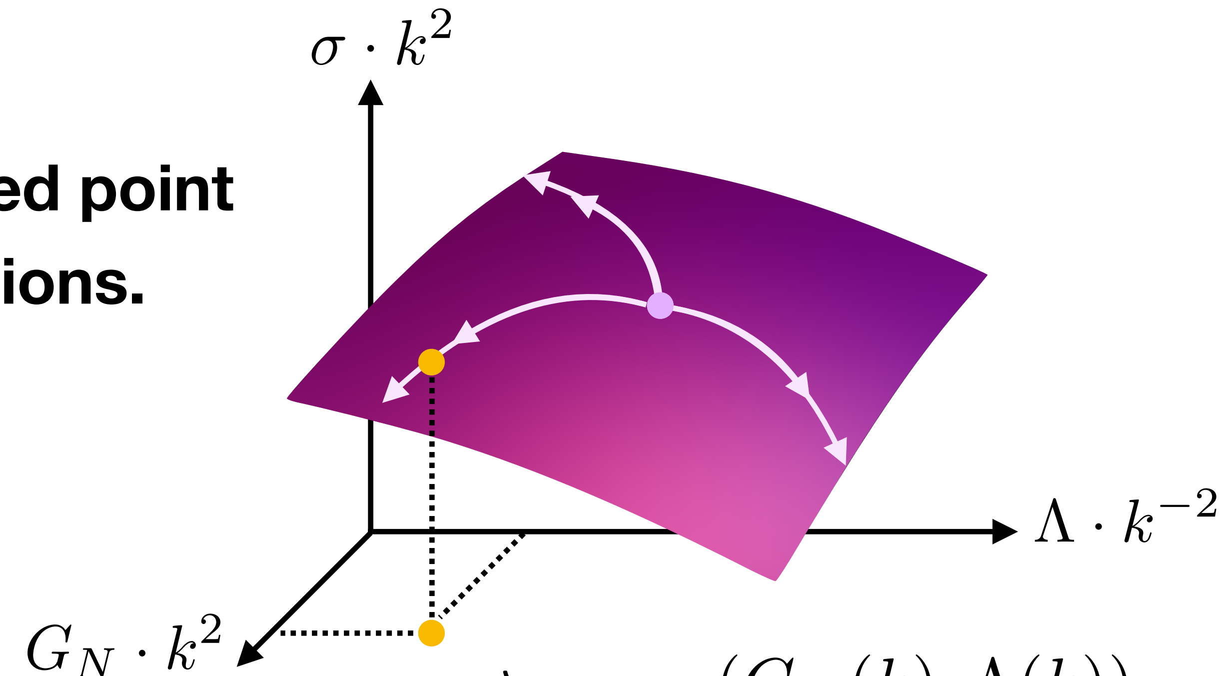

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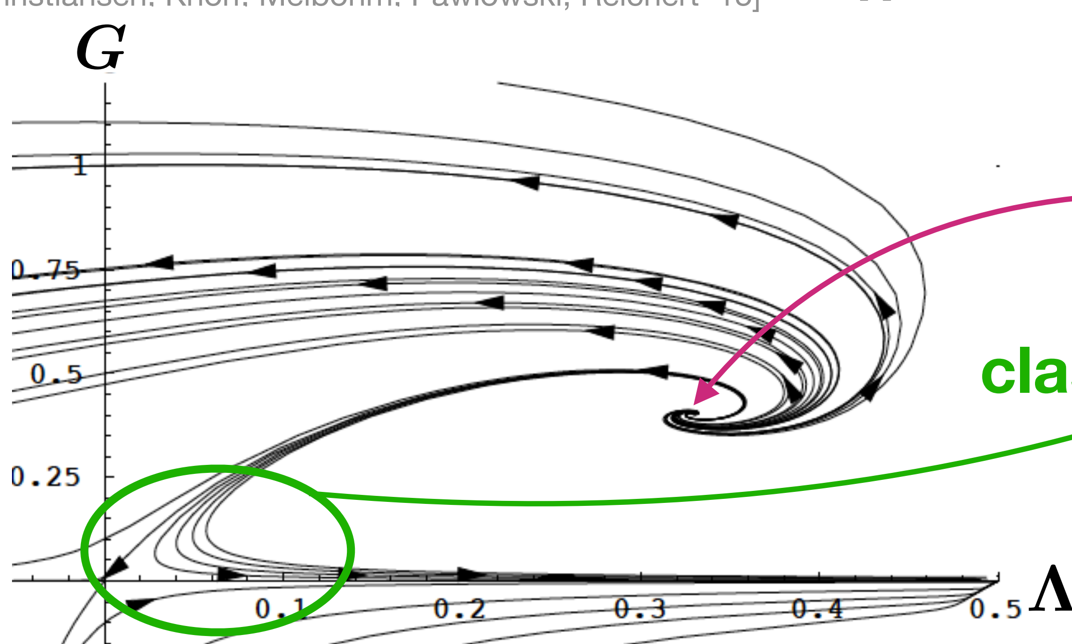

UV fixed point

classical gravity regime

[Reuter, Saueressig '01]

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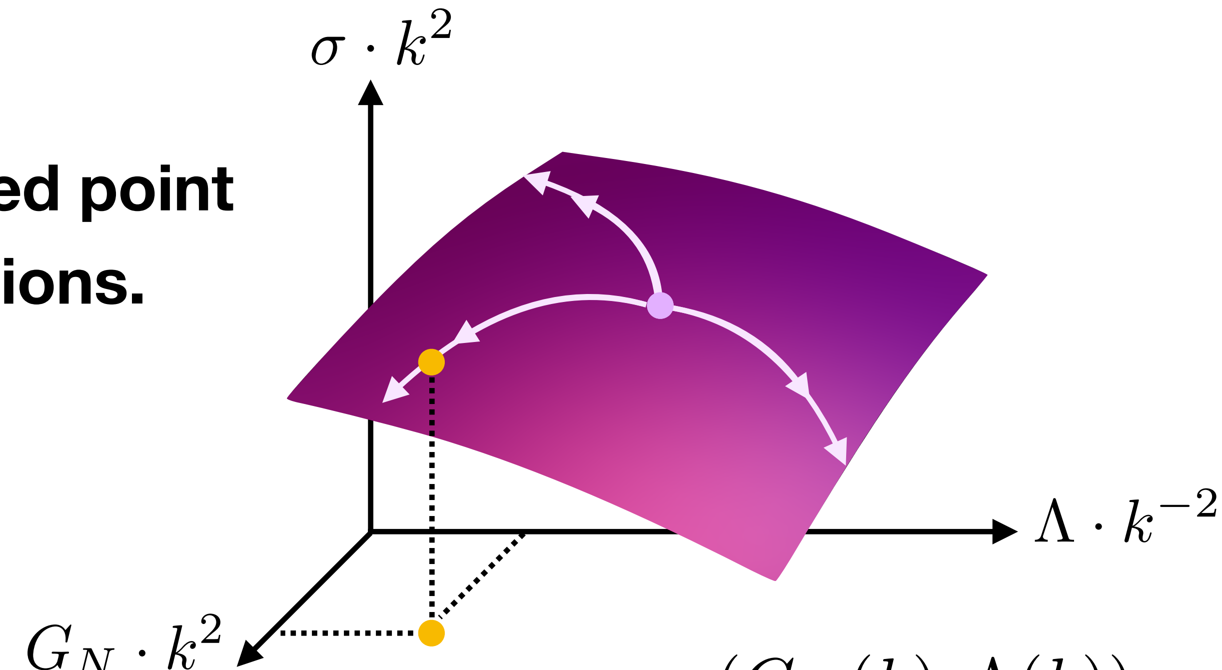

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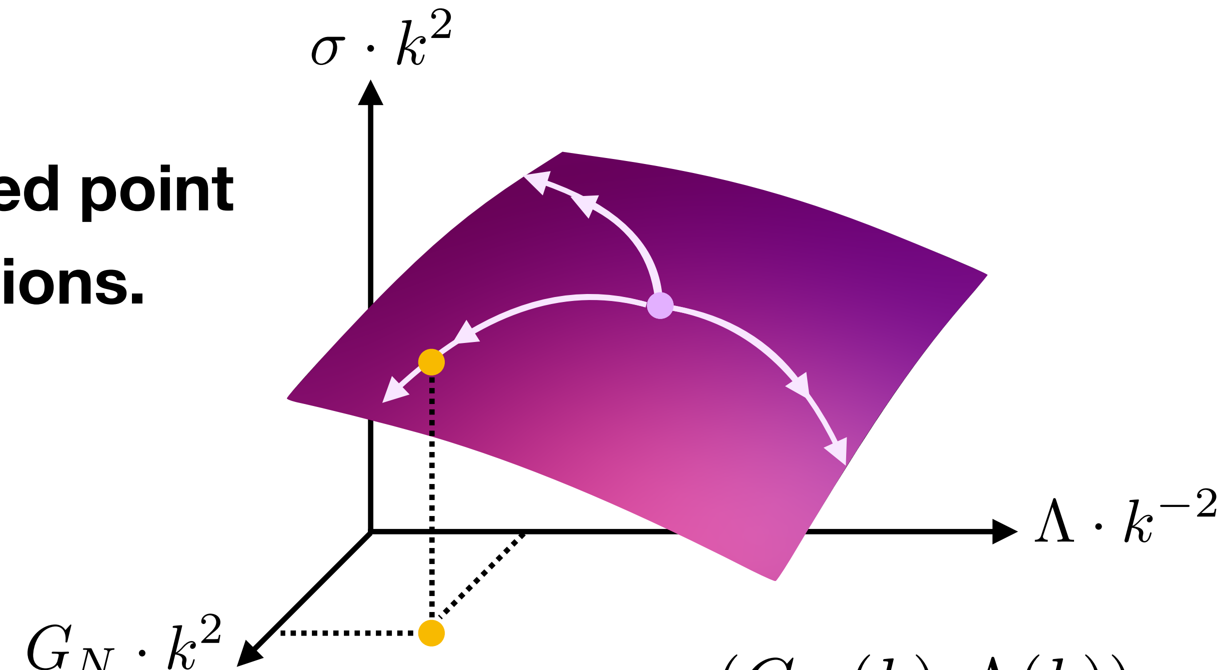

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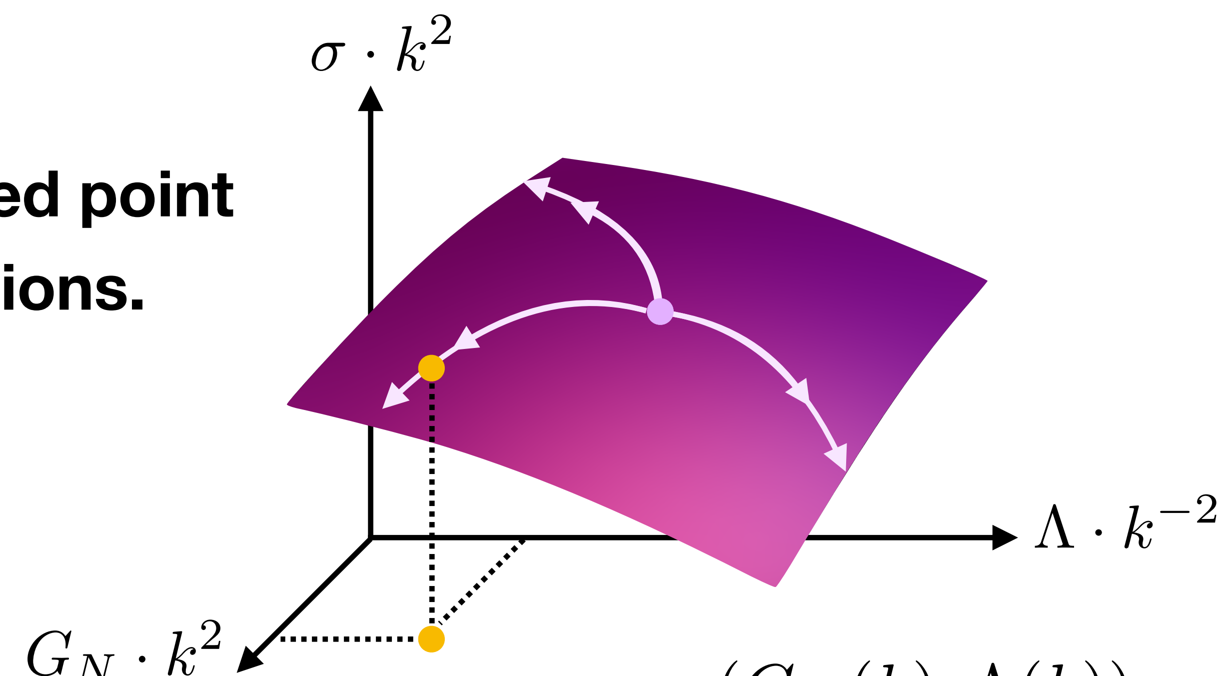

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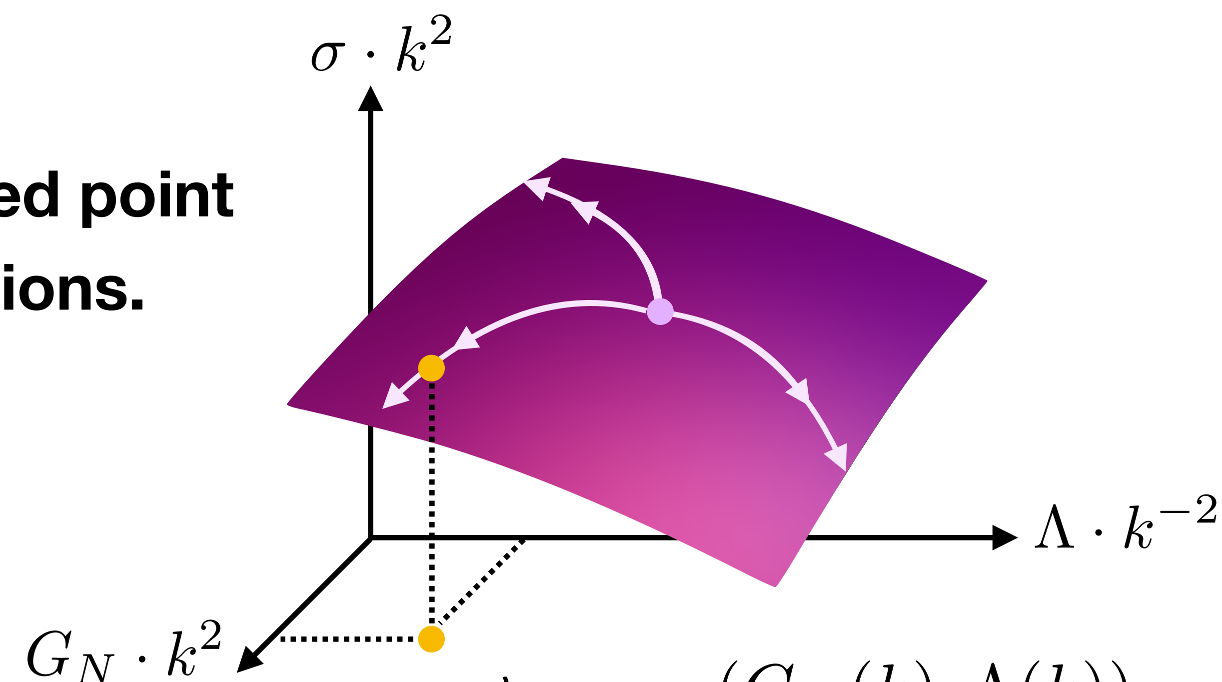

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ordering principle:
canonical mass dimension of couplings

$\longrightarrow$ **control over approximations with finitely many couplings**

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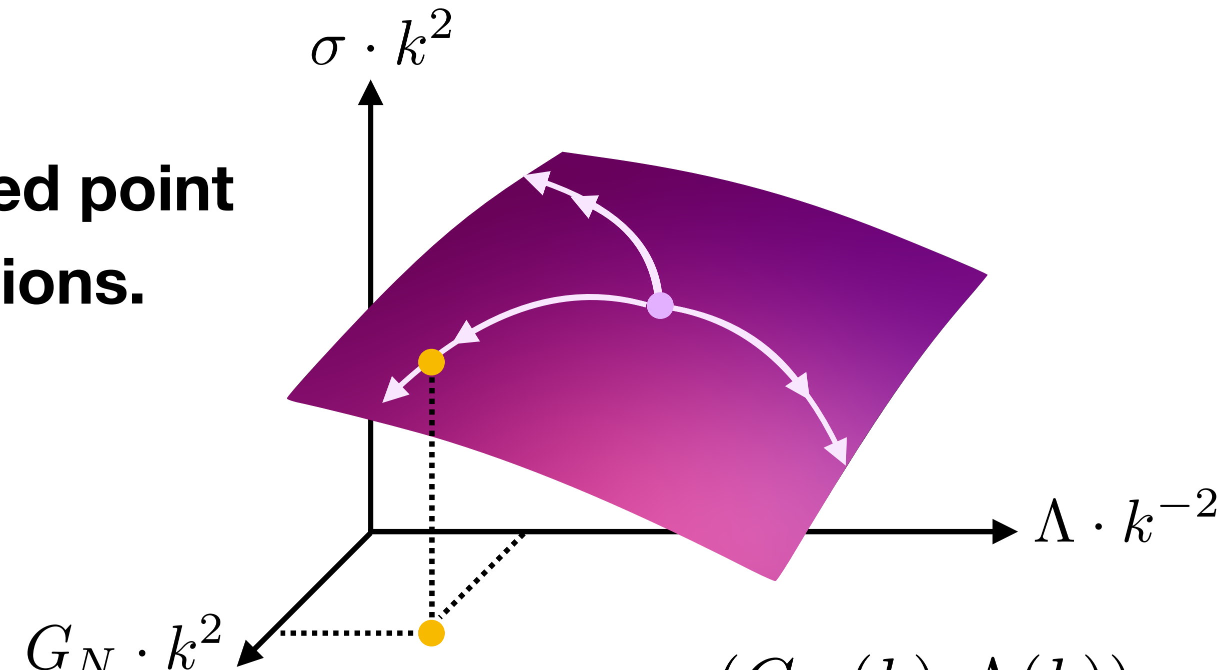

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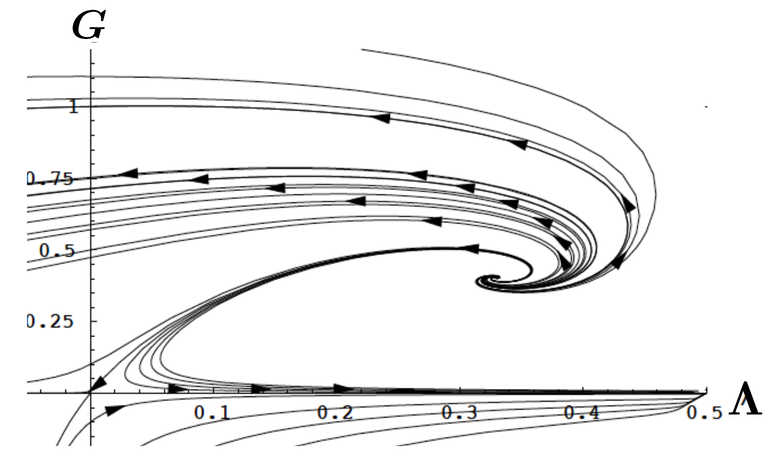
status: compelling hints for asymptotic safety in pure gravity

$\longrightarrow$ **what about matter?**

Asymptotic safety for gravity & matter

Asymptotic safety for gravity & matter

Can quantum fluctuations
of matter destroy a
consistent quantum gravity model?



quantum gravity dynamics

matter dynamics

Asymptotic safety for gravity & matter

Can quantum fluctuations
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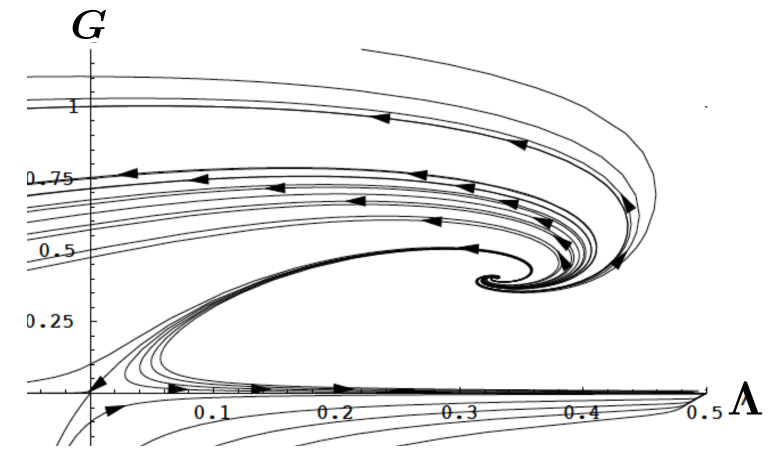

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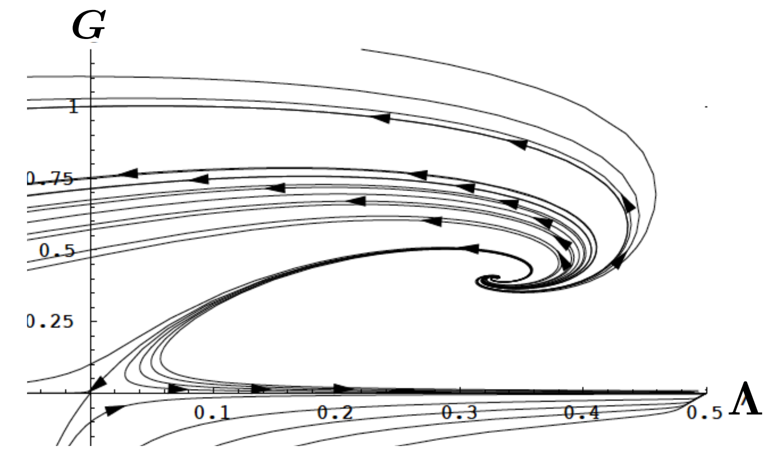

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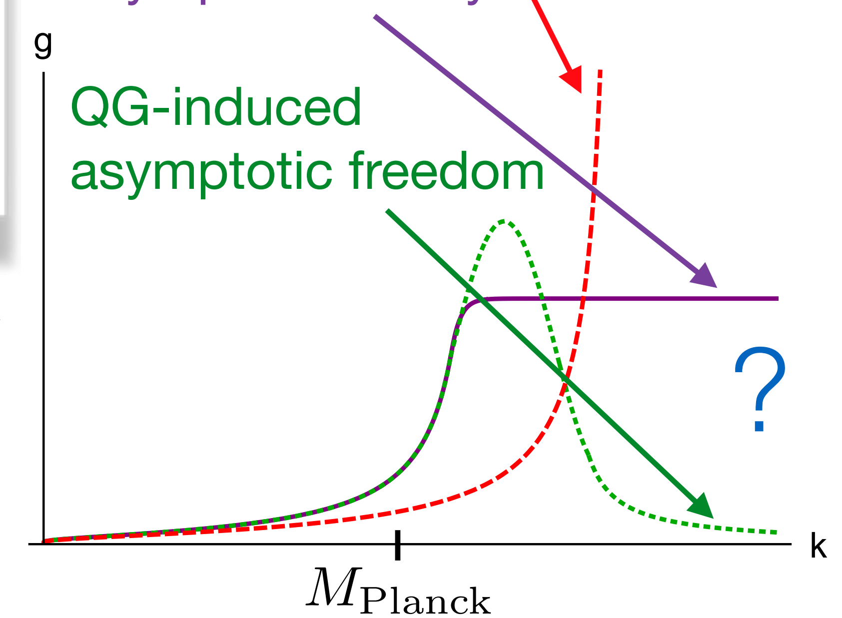

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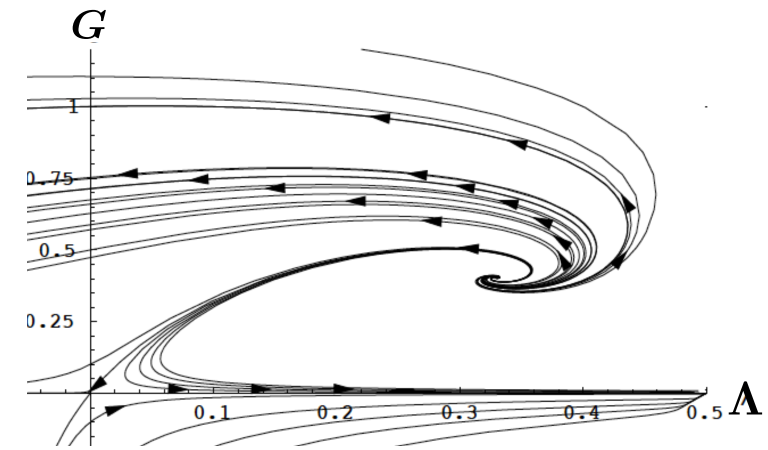

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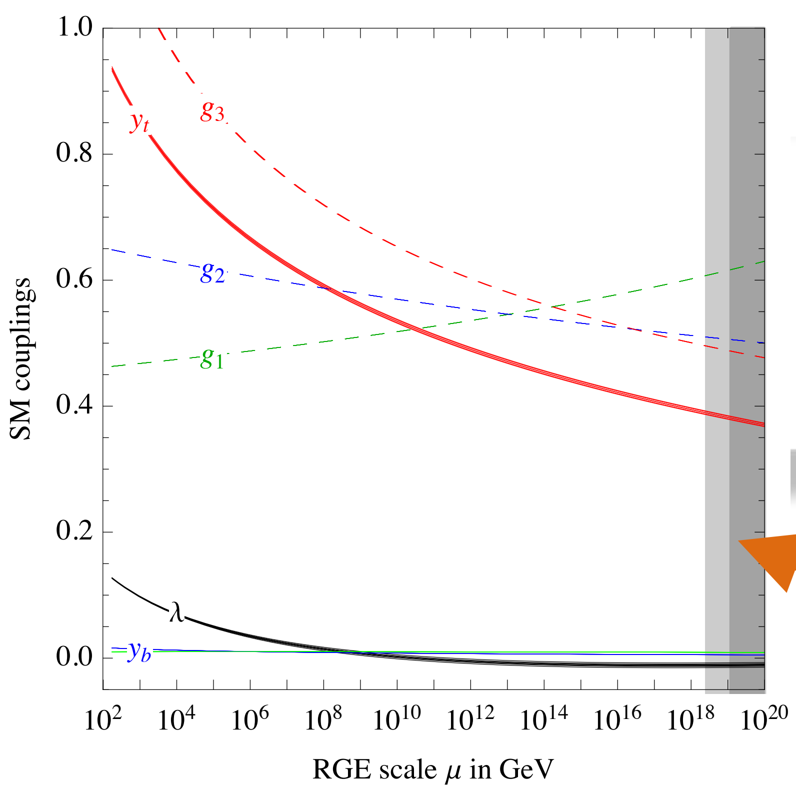

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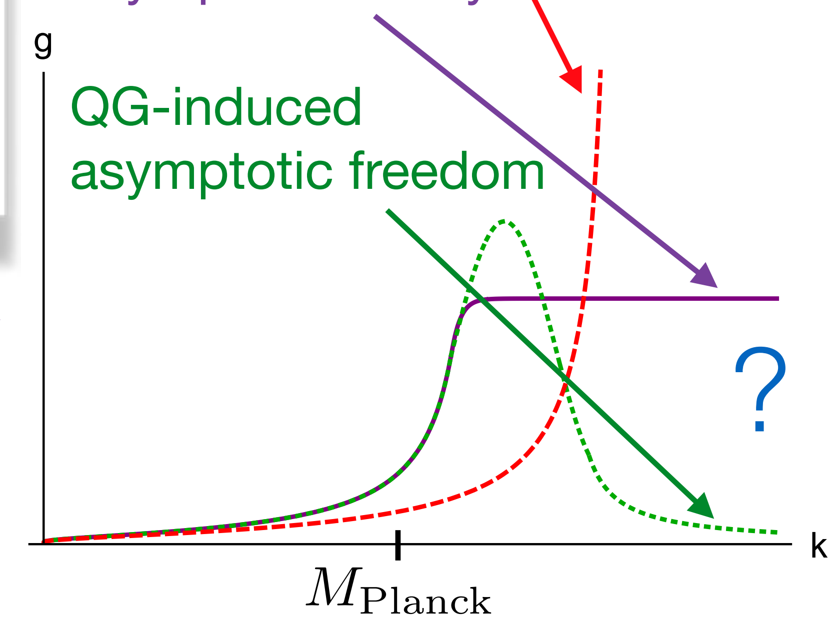

Buttazzo et al. ‘13

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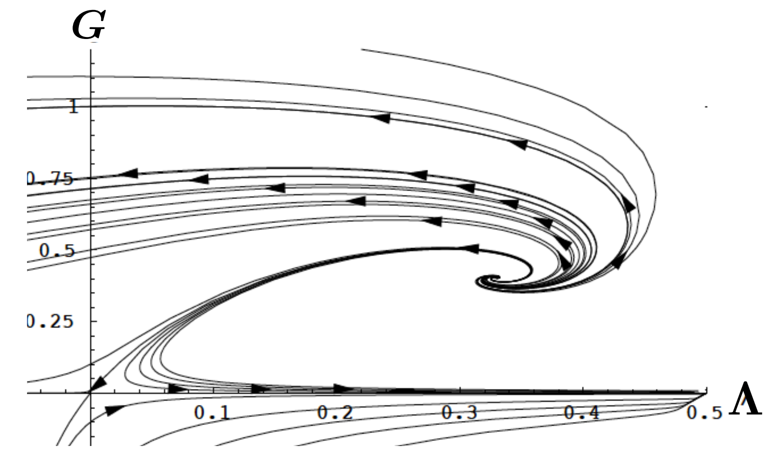

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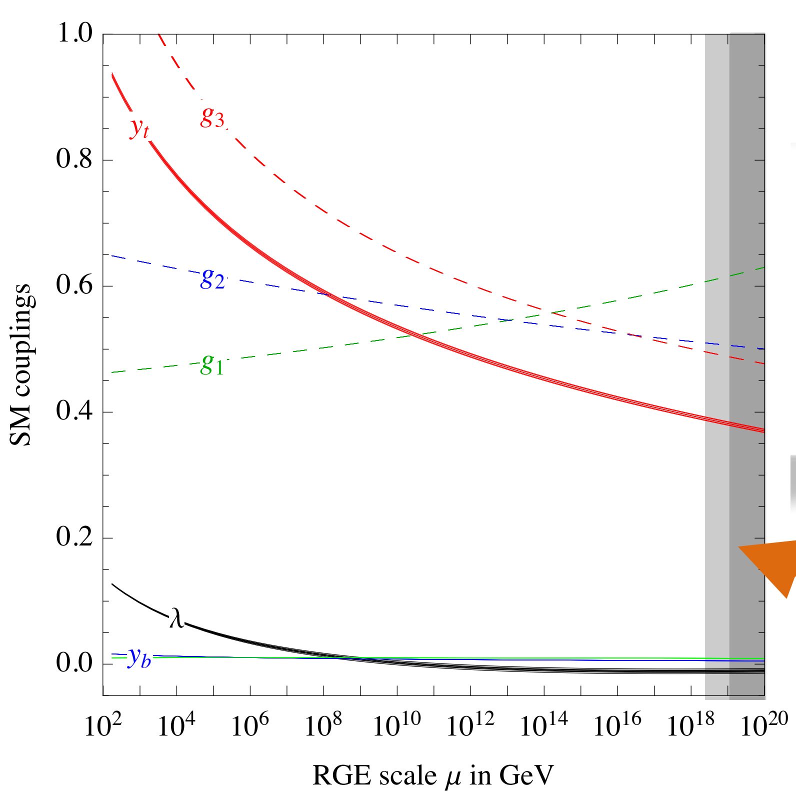

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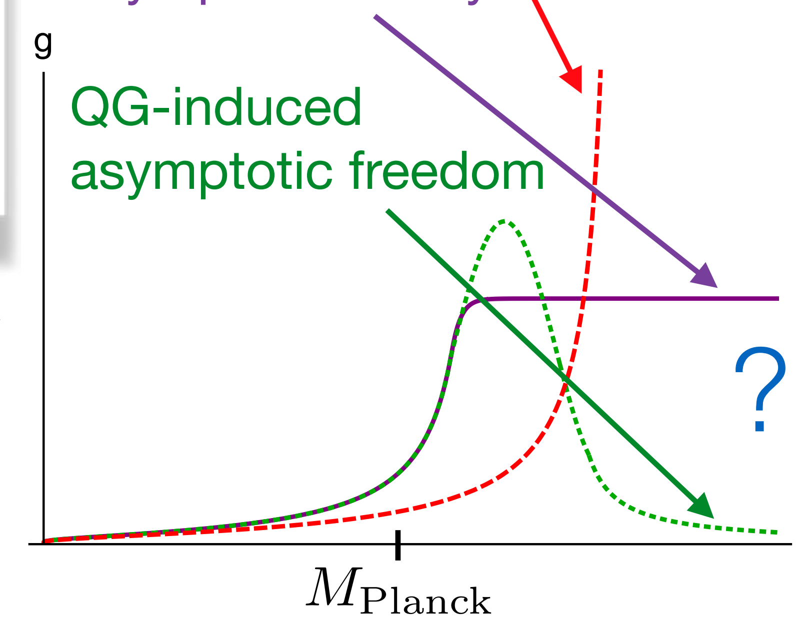

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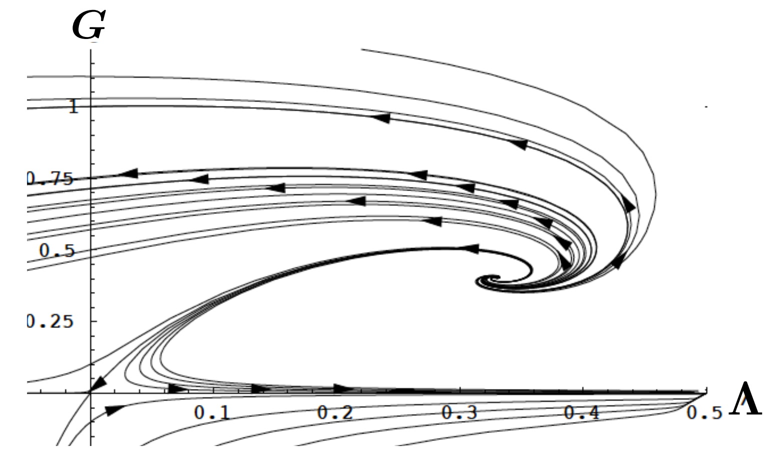
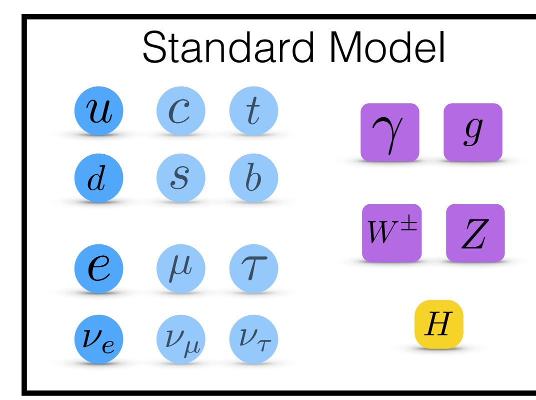


minimally coupled SM fields



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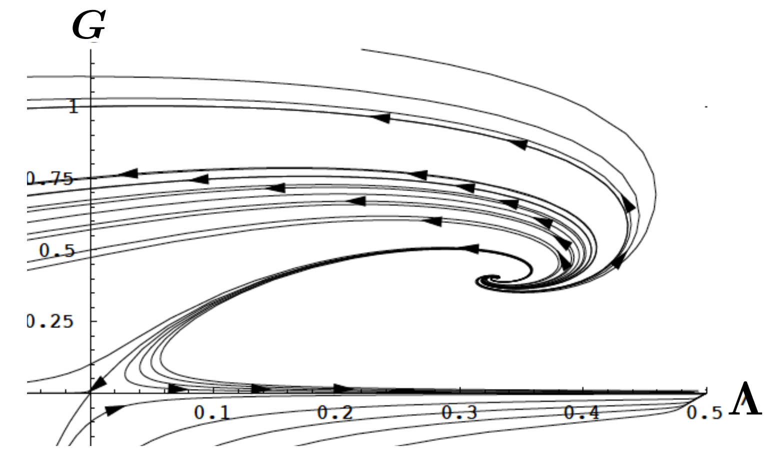

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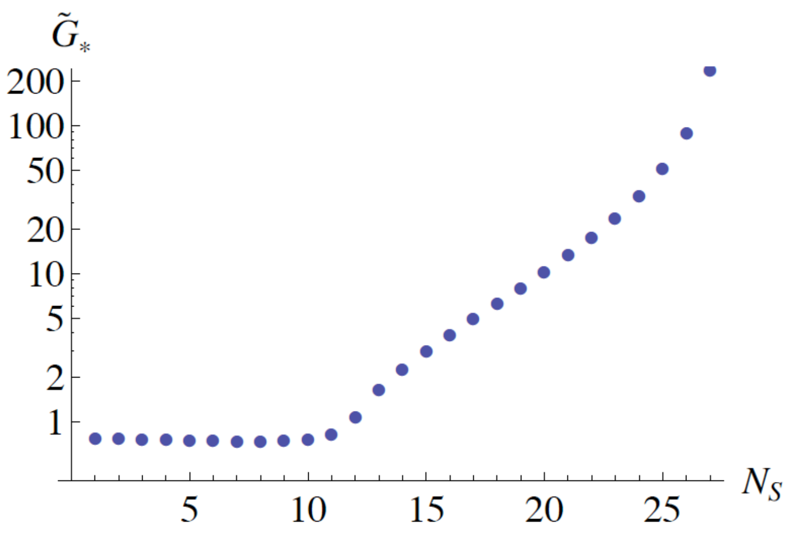
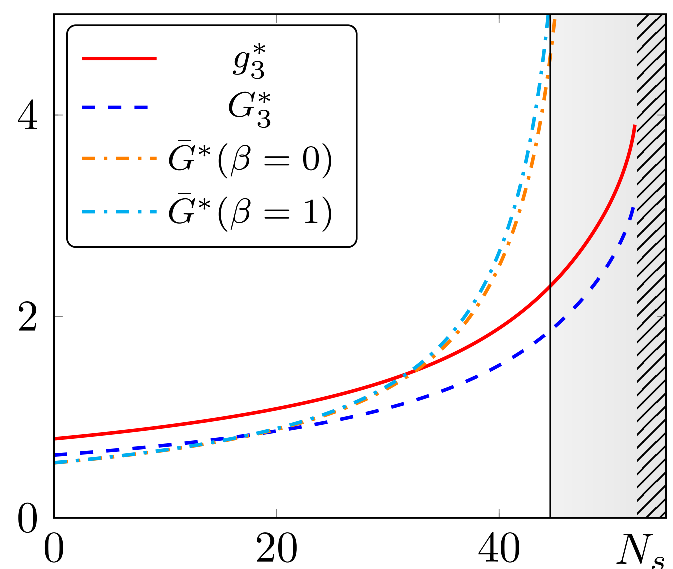


[Dona, AE, Percacci '13]



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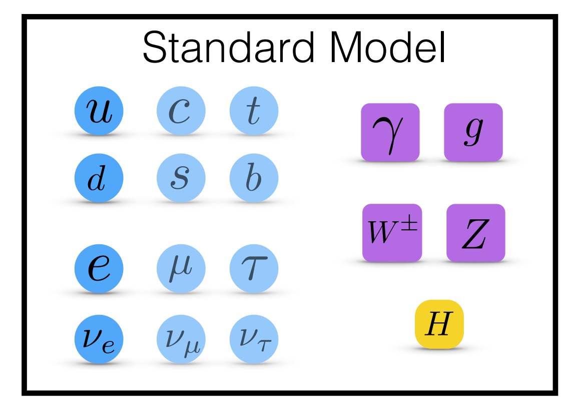

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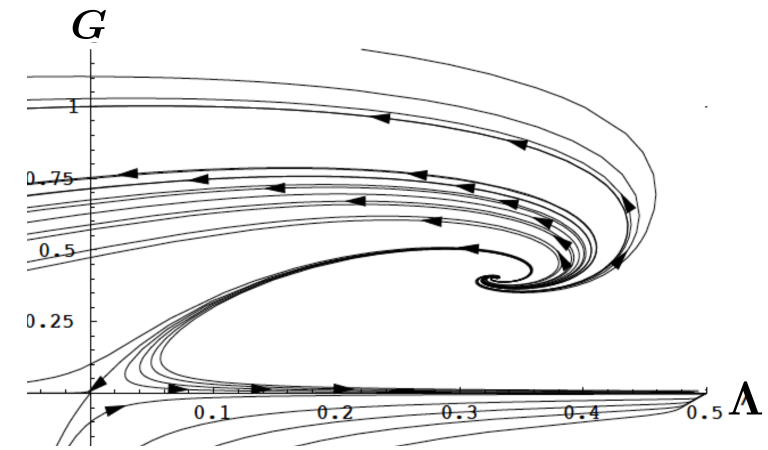

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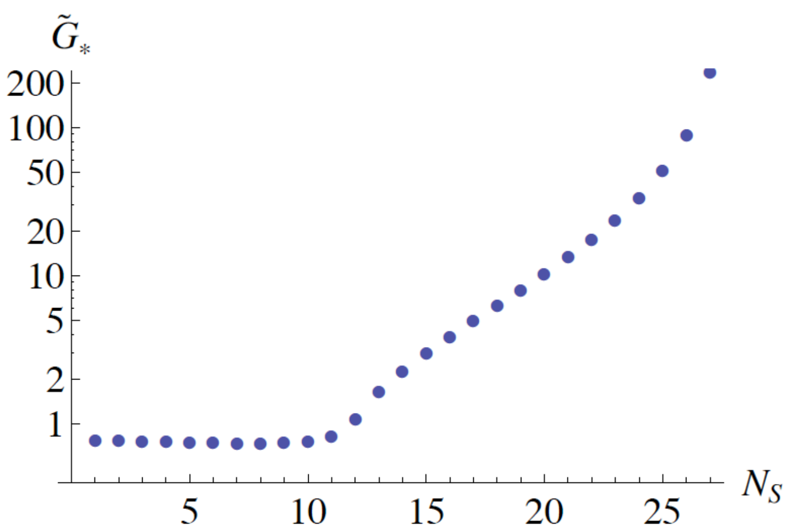

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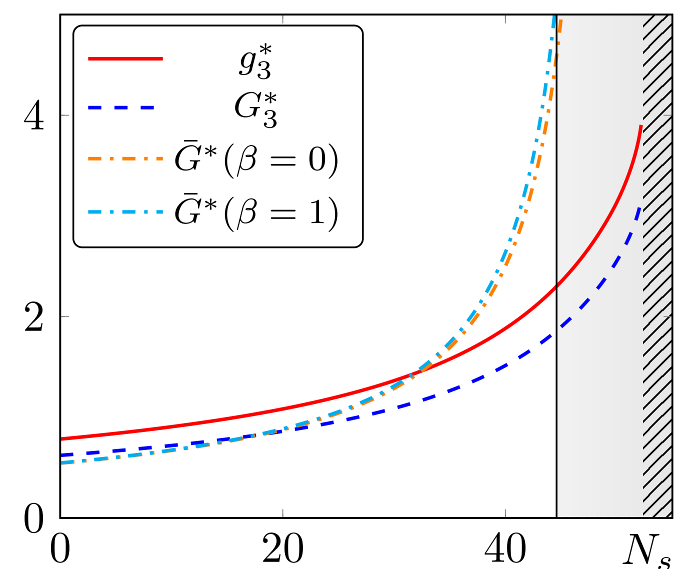

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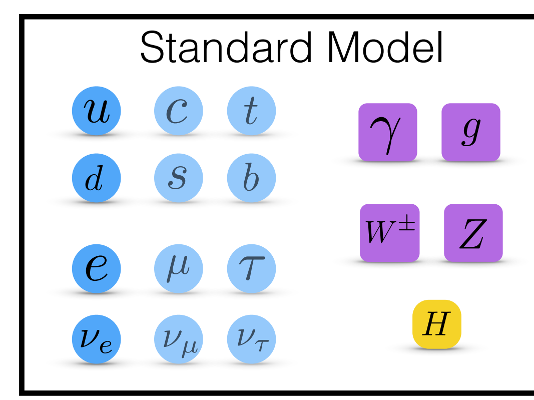

matter content of SM (& small extensions)
admits a gravity fixed point in Einstein-Hilbert truncation

[Dona, AE, Percacci ’13, ’14]

[Meibohm, Pawlowski, Reichert ’15
Dona, AE, Labus, Percacci ’15
Biemans, Platania, Saueressig ’17]

strong hint: asymptotically safe gravity could pass a critical observational consistency test

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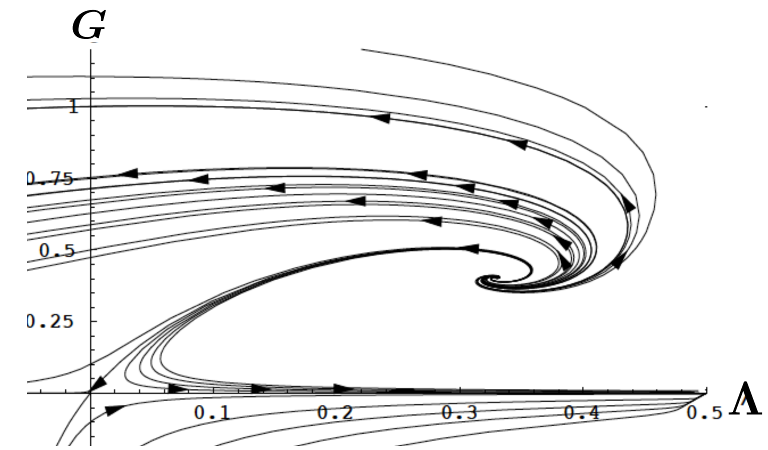

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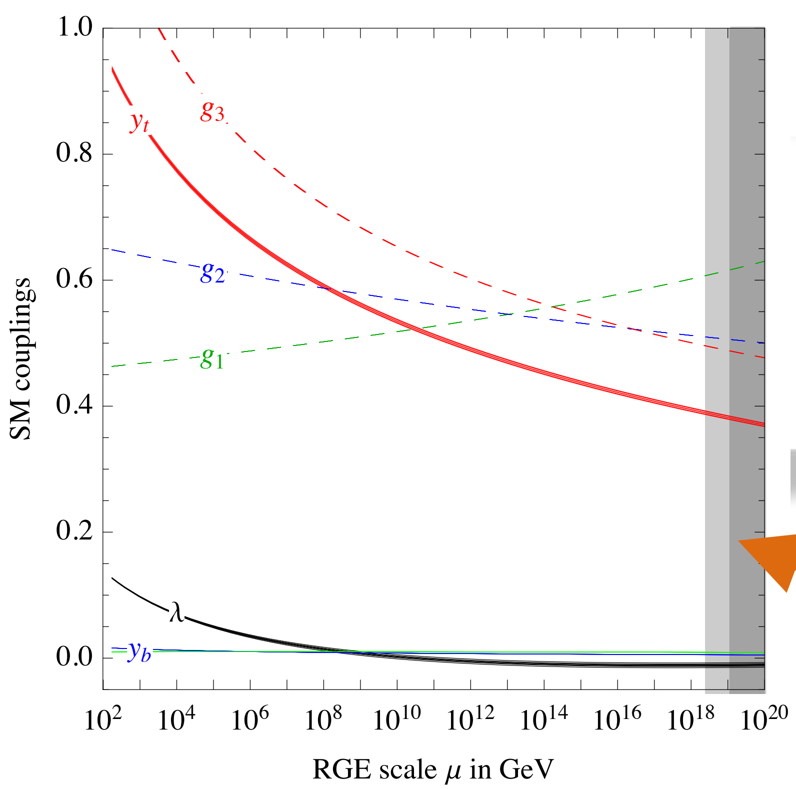

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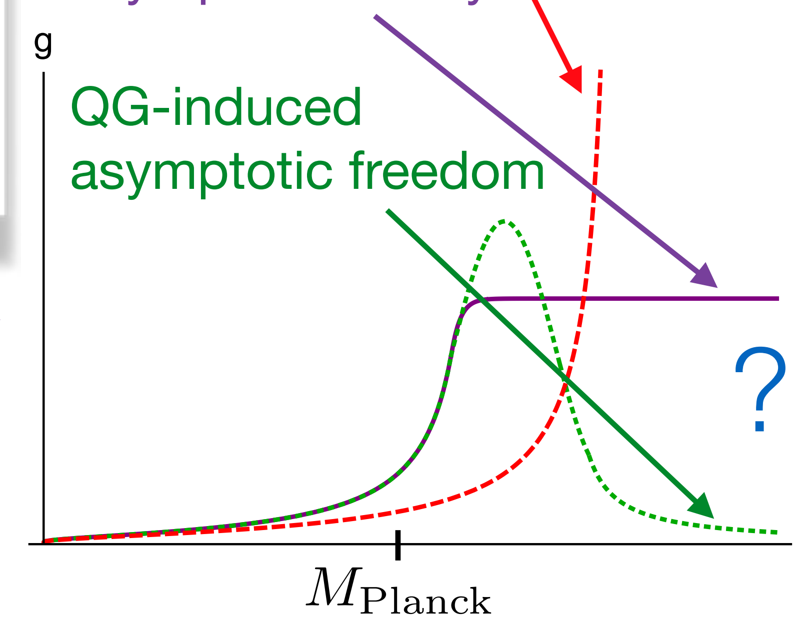
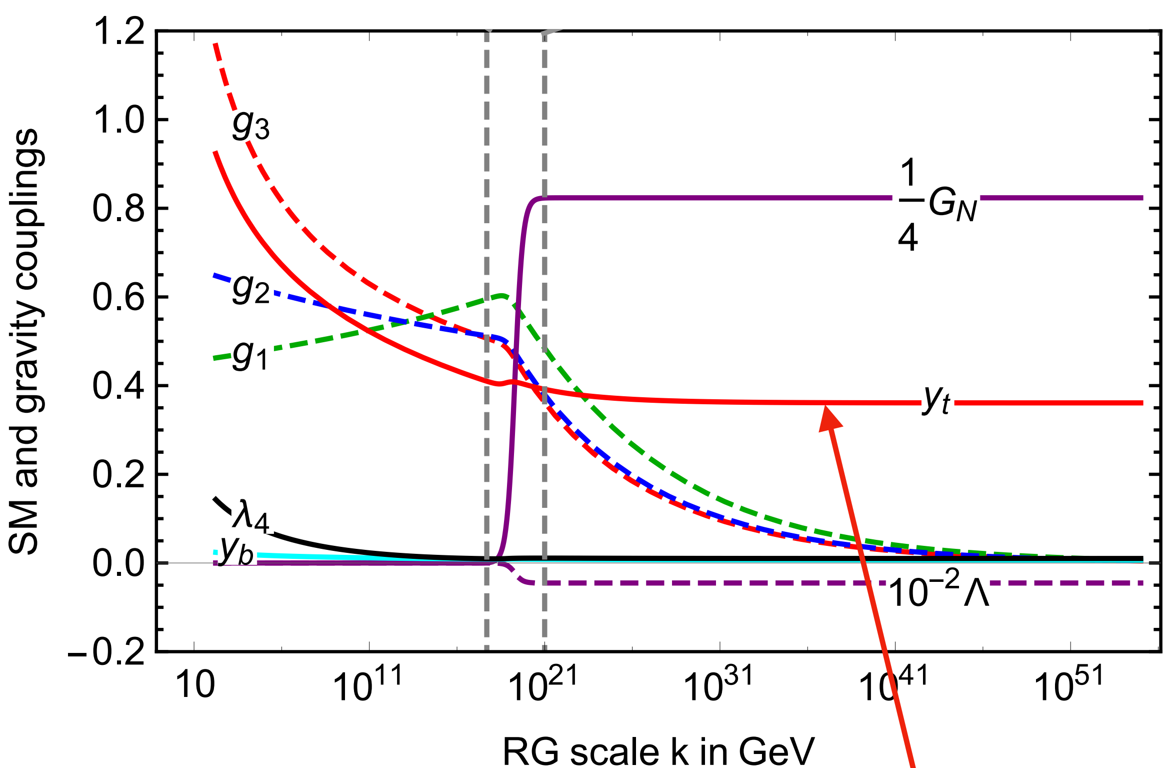


Quantum-gravity induced UV completion for the SM

results within simple truncations

$\rightarrow$ **convergence of results in extended truncations: stay tuned…**

Quantum-gravity induced UV completion for the SM



within simple truncations:

- **asymptotic freedom in all gauge couplings (incl. Abelian hypercharge)**

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

- **asymptotic safety in top Yukawa coupling with $M_t >> M_b$ fixed uniquely**

[AE, Held, Pawlowski '16; AE, Held 05/17, 07/17]

$\mathrm{M_t} \approx 170\,\mathrm{GeV}$ **fixed uniquely**

Standard Model: $\mathrm{M_t}$ **is a free parameter**

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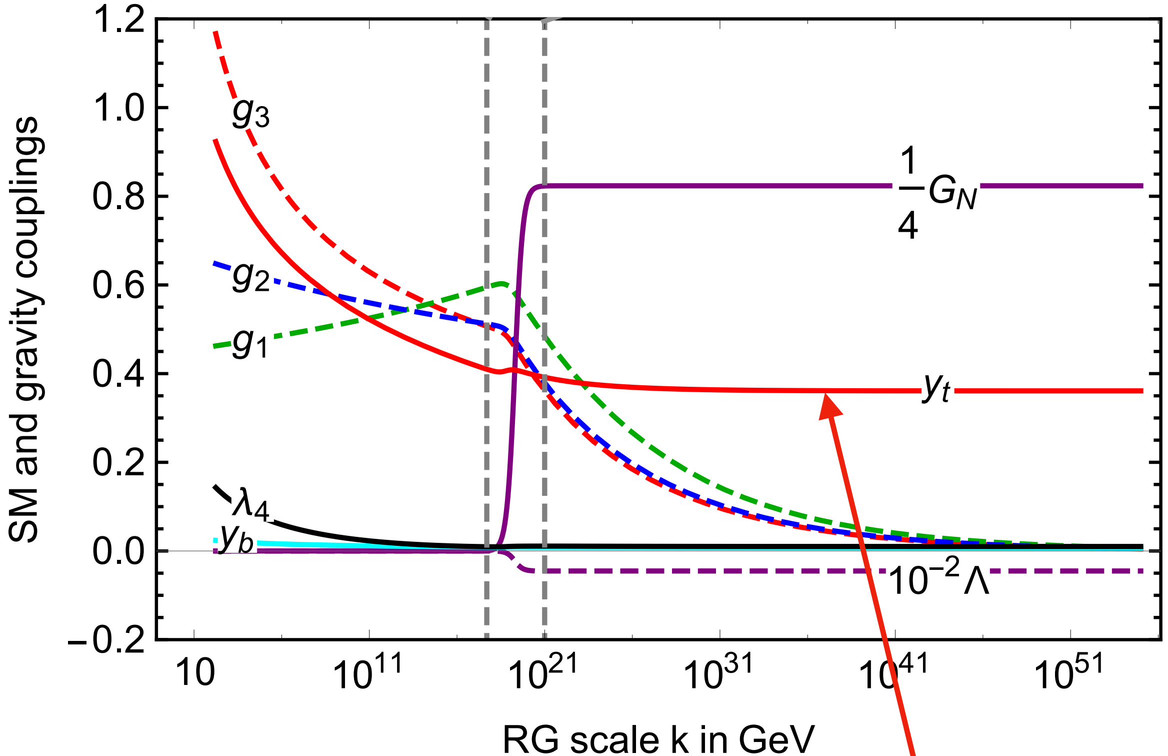

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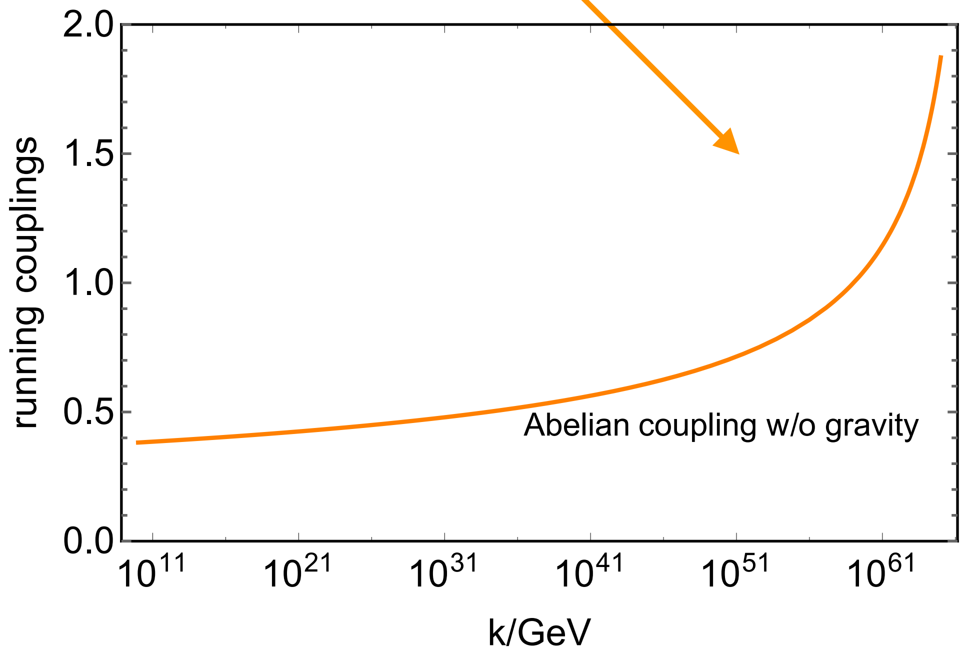
Gauge-gravity interplay

Abelian gauge theory:

$$\beta_{g_1} = \frac{g_1^3}{16\pi^2}\frac{41}{10}$$

screening

-> triviality problem



Non- Abelian gauge theory:

$$\beta_{g_3} = -\frac{g_3^3}{16\pi^2}7$$

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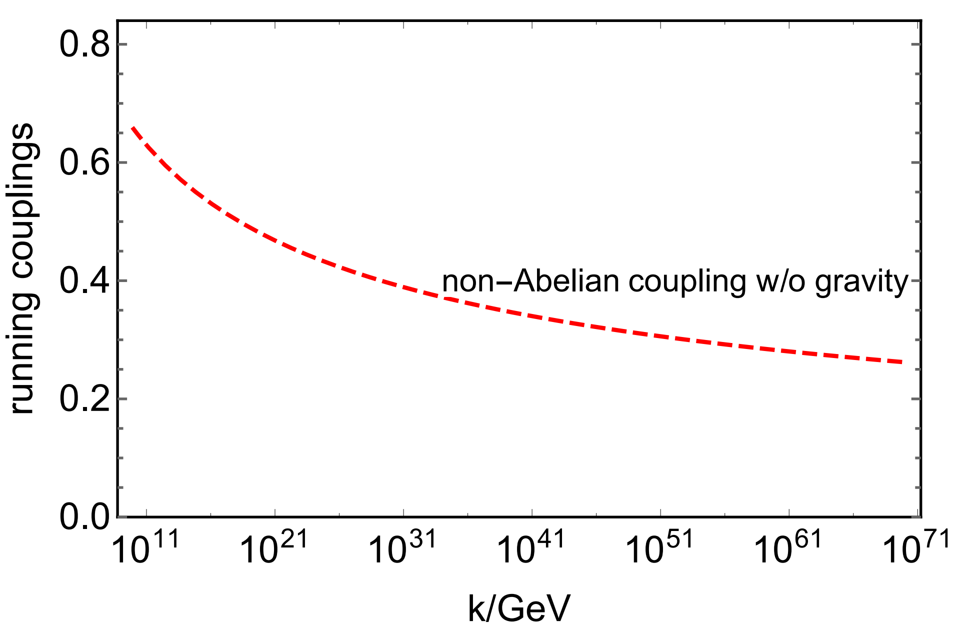

Gauge-gravity interplay

switch on gravity:
metric fluctuations in Einstein-Hilbert approximation: parameterized by $G,\ \Lambda$

Abelian gauge theory:

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gauge-group-independent contribution

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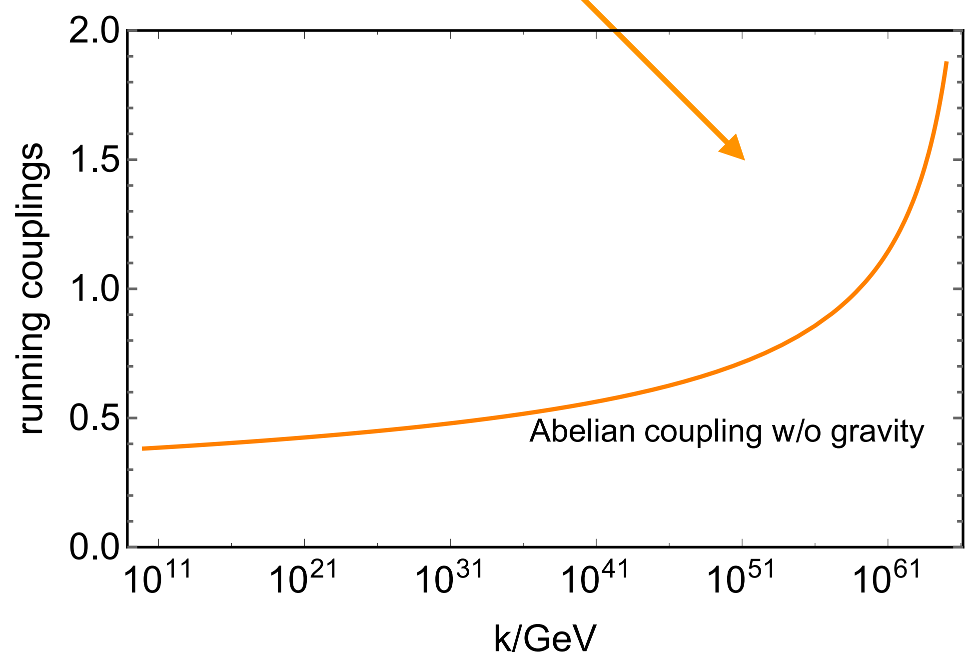

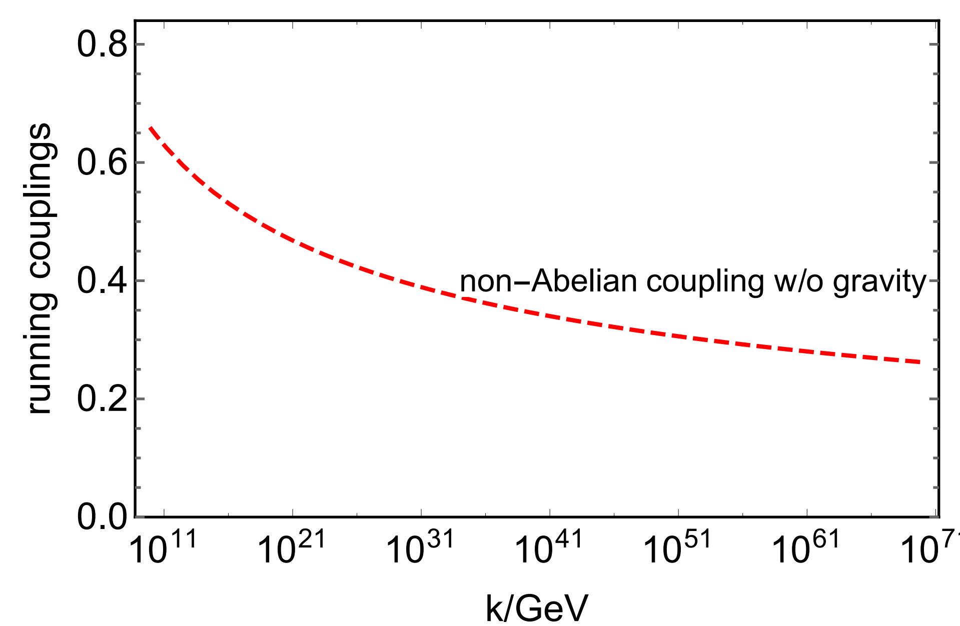

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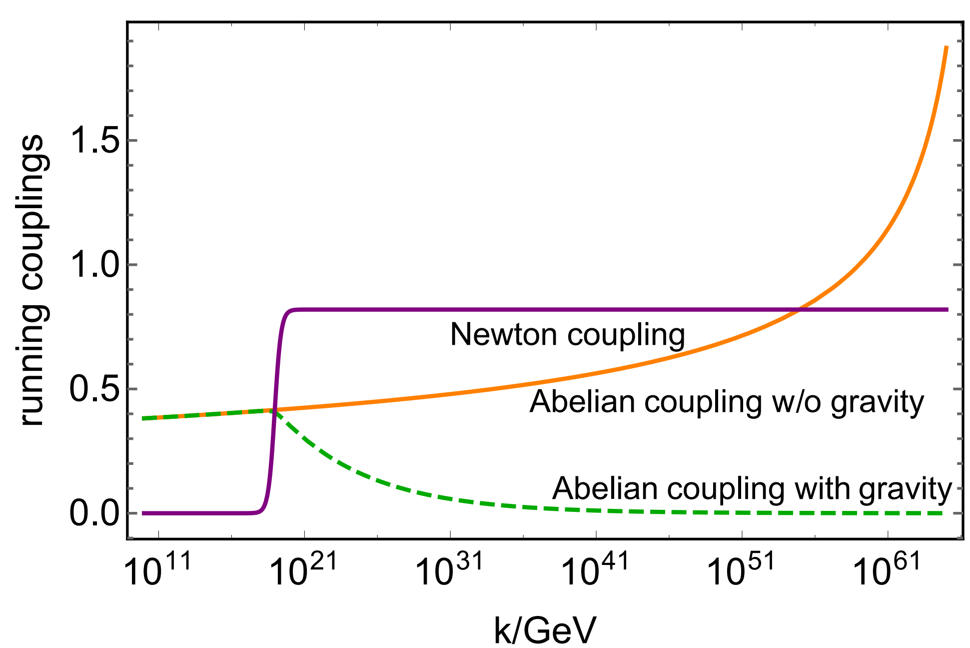
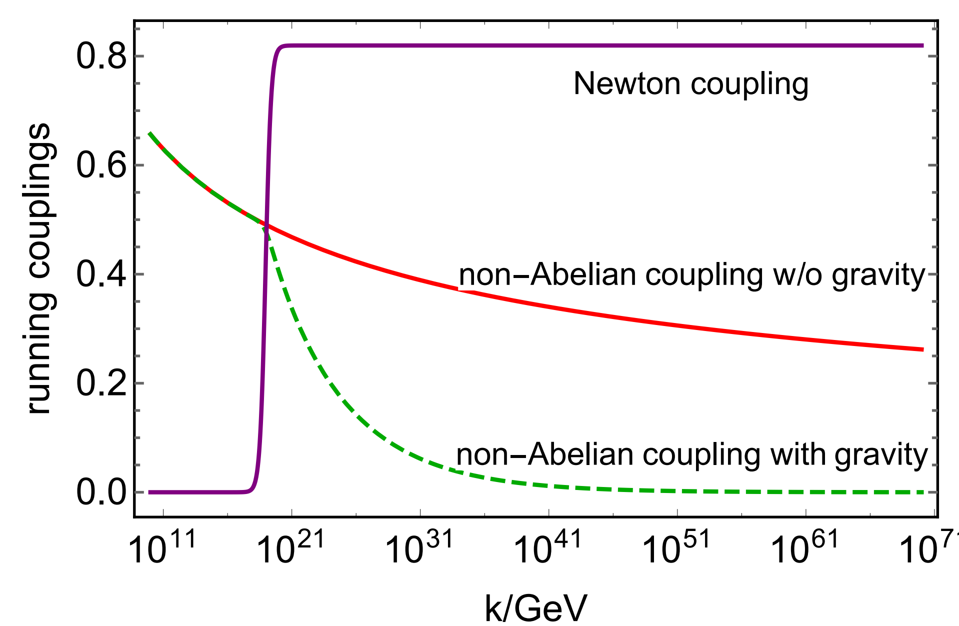
beyond the Planck scale:
power-law running towards asymptotic freedom





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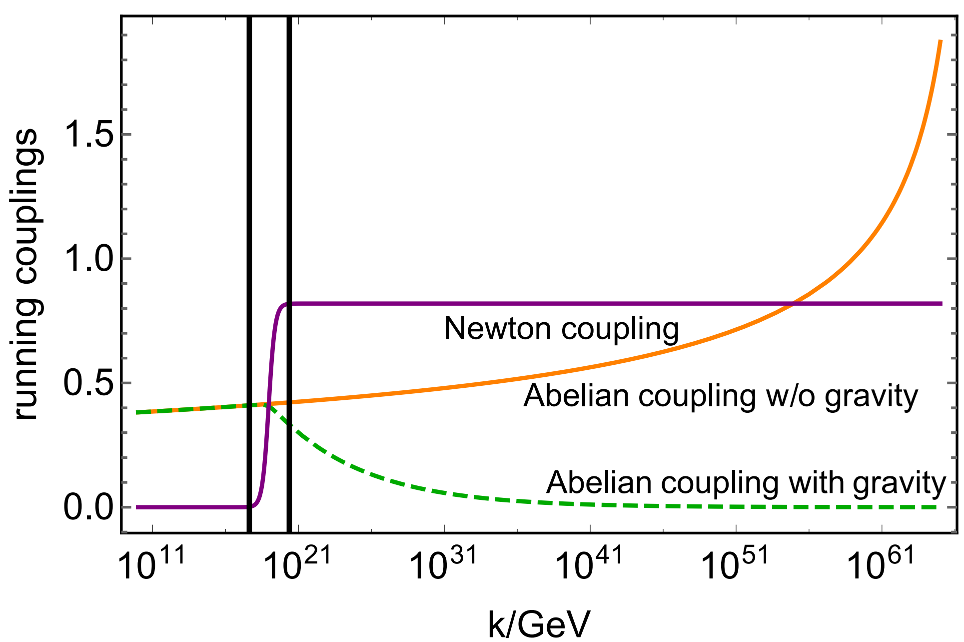

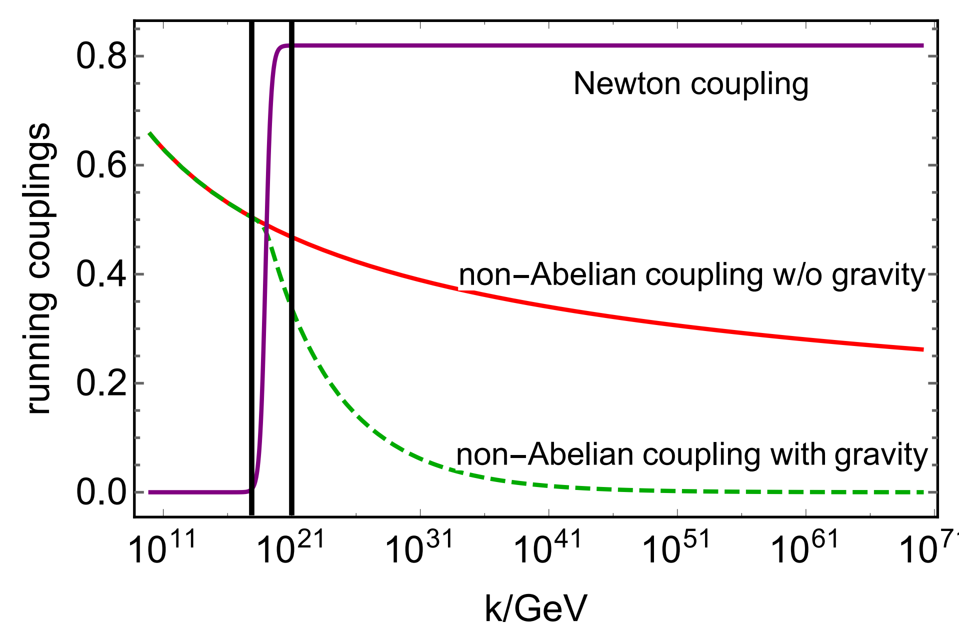

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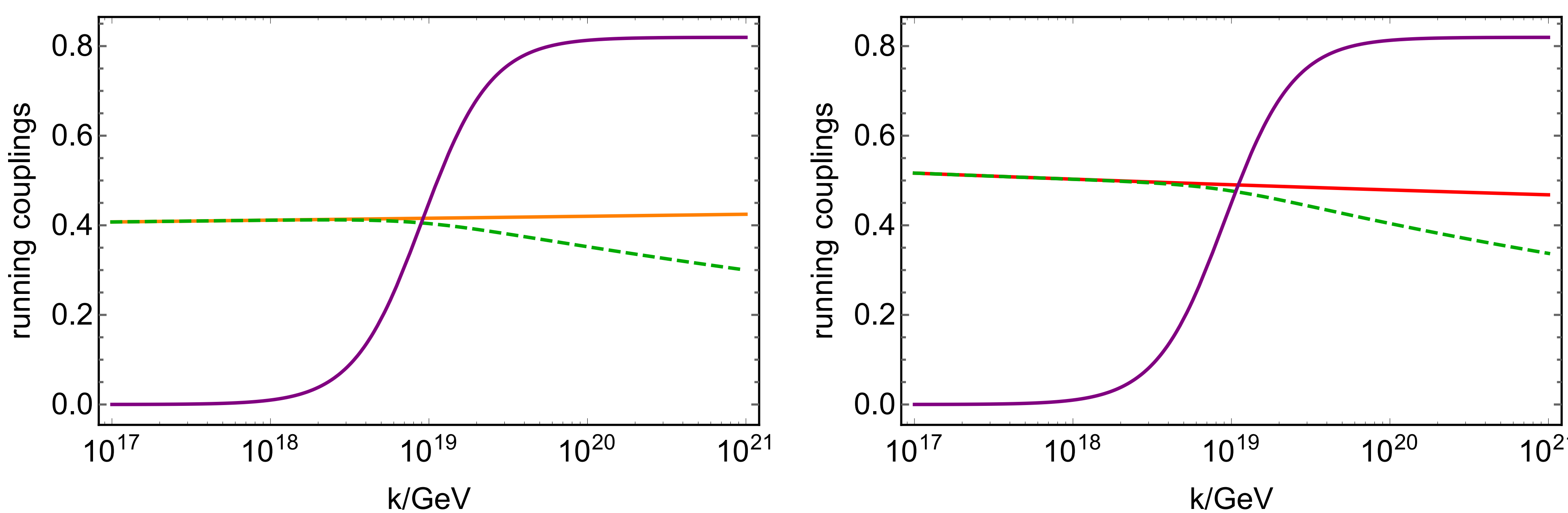

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Top mass from asymptotic safety

reminder: y_t **= free parameter in SM** $M_t \approx 172.4\,\mathrm{GeV}$ [CMS '16]

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vanish in UV

two regimes in gravitational coupling space:

$f_y(\Lambda) > 0$

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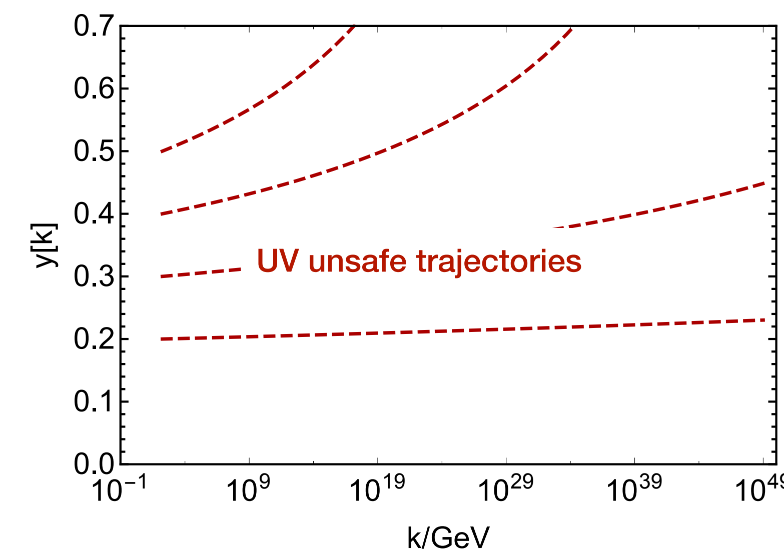
UV safe only for $M_t = 0$



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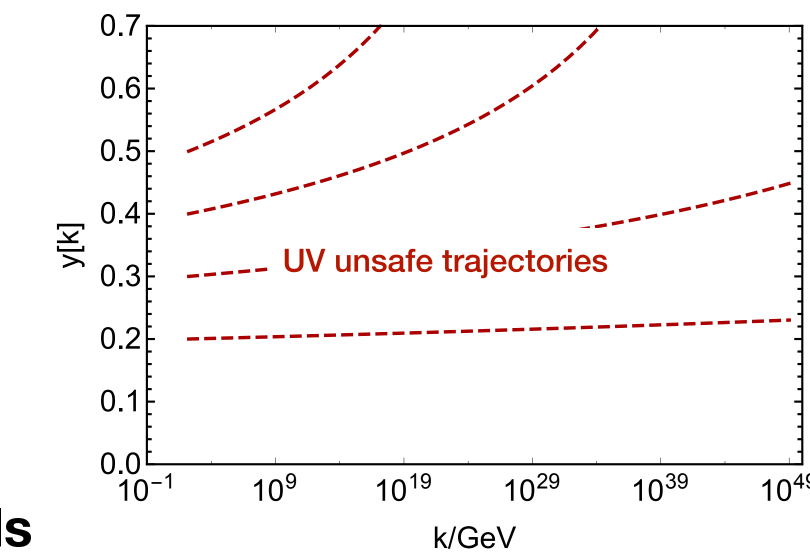

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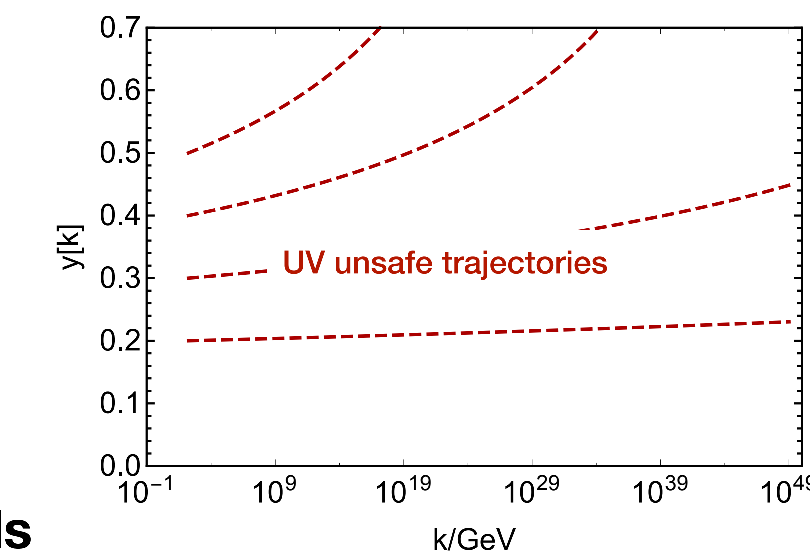

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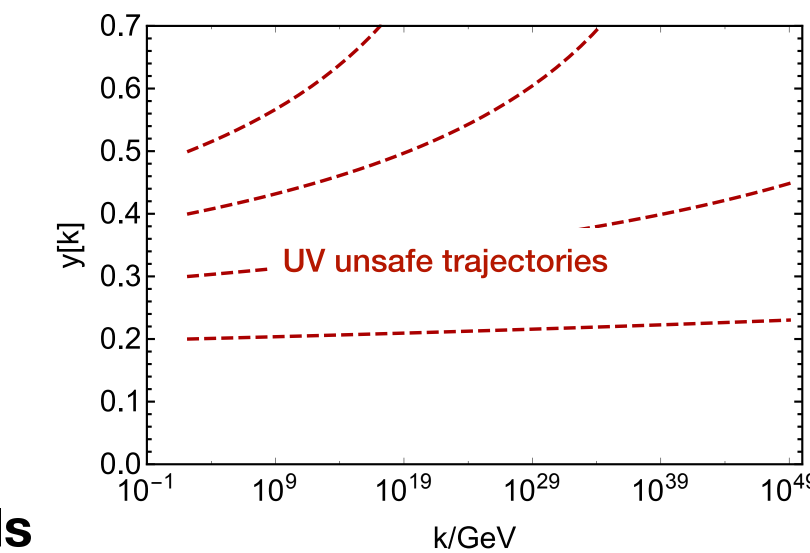

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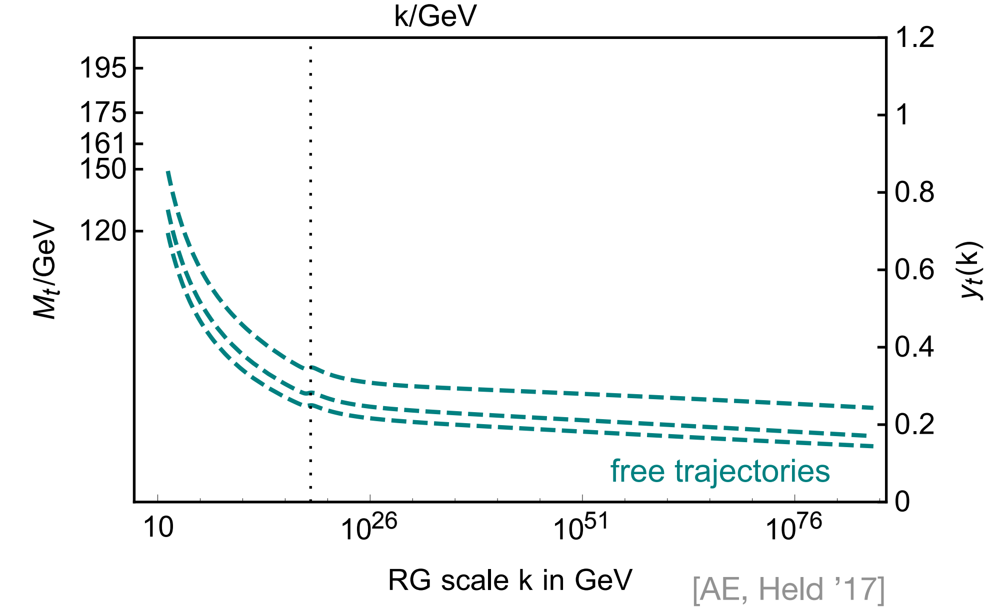

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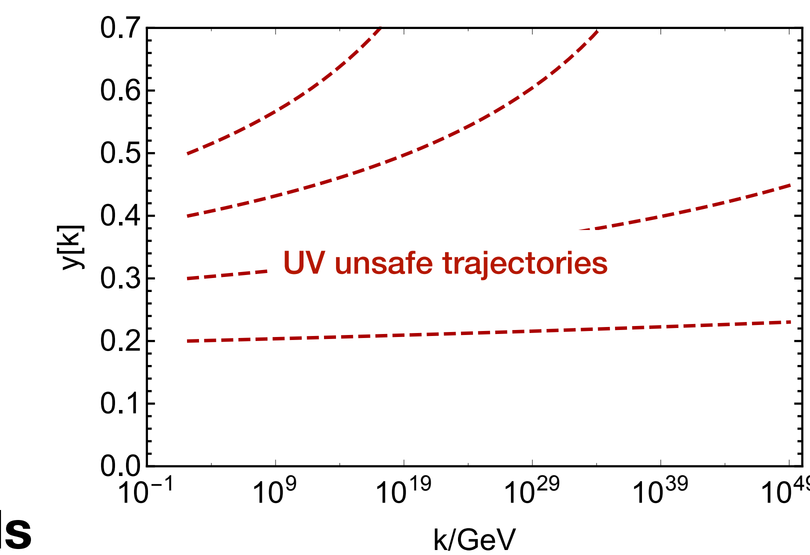

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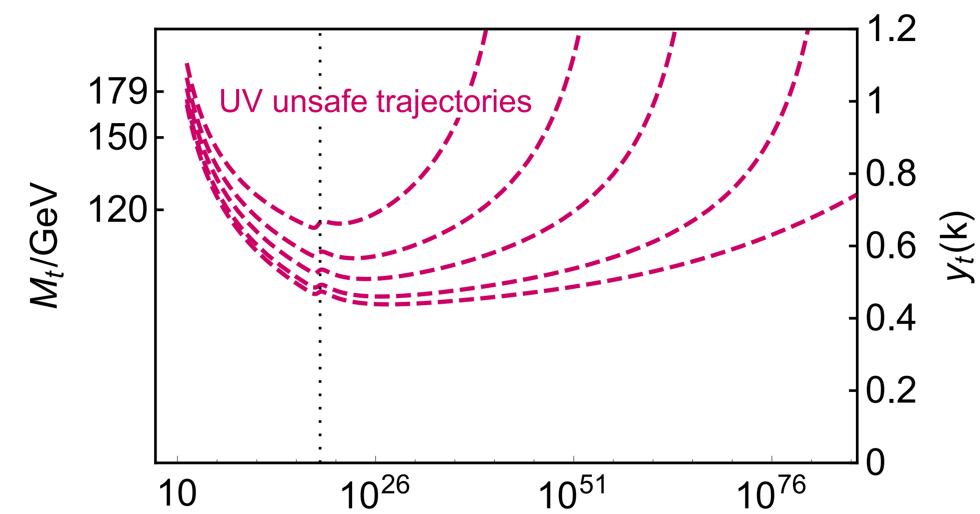

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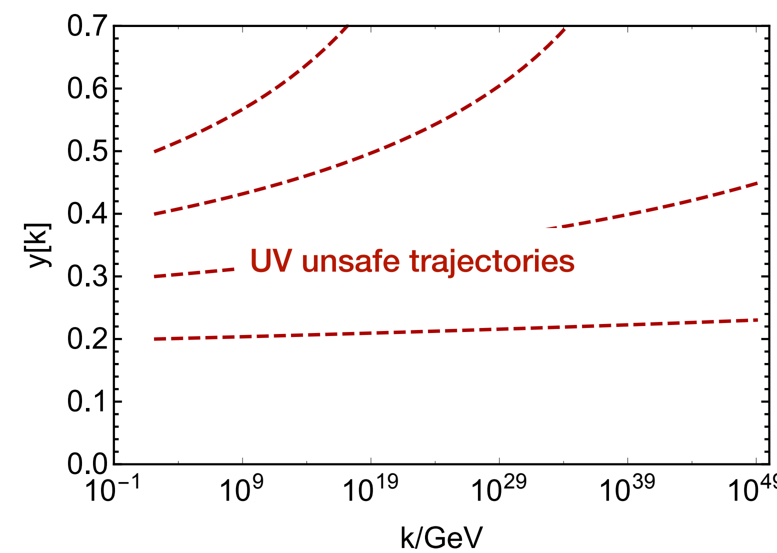

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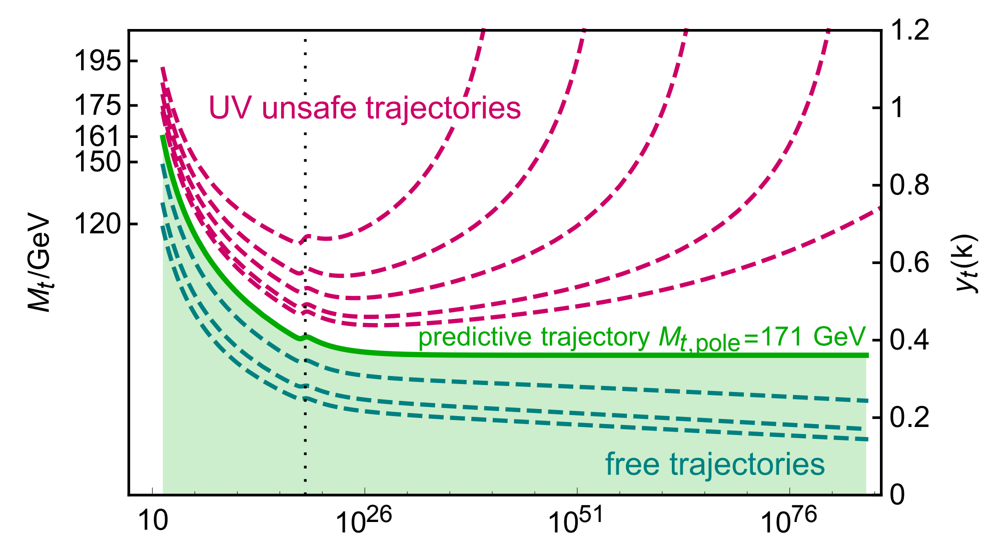
strong gravity: asymptotically free
strong Yukawa: UV unsafe
balance: UV safe



[AE, Held '17]

Top-bottom mass difference from asymptotic safety

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reminder: y_t = free parameter in SM $M_t \approx 172.4\,\mathrm{GeV}$ [CMS '16]

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

vanish in UV

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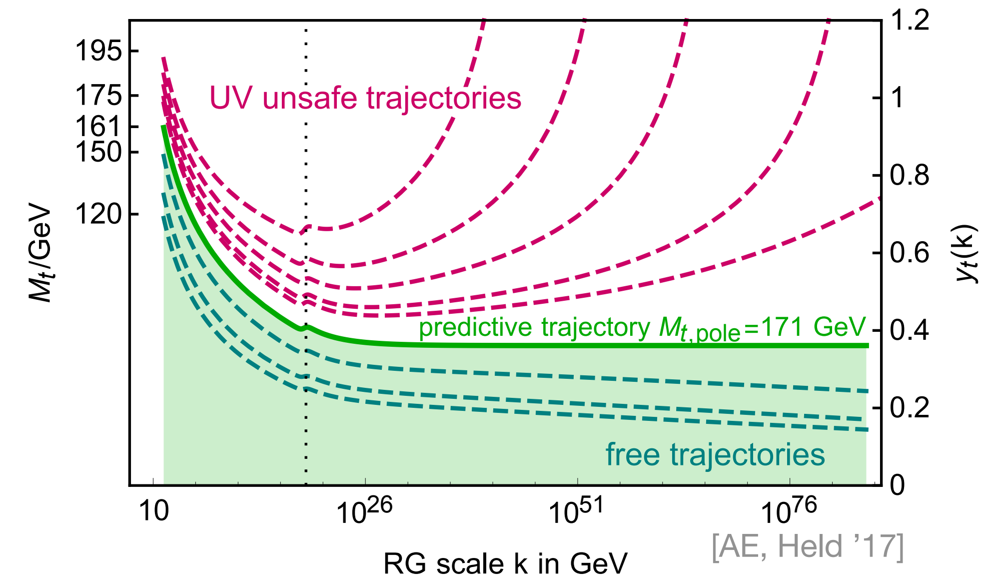

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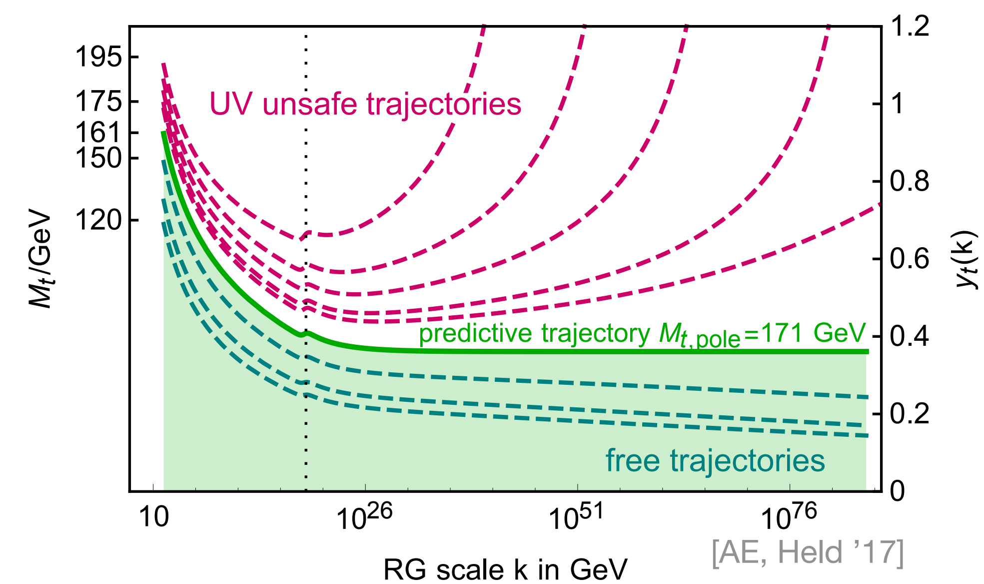
y_b **becomes asymptotically free**

$\longrightarrow M_b < M_t$

y_t **becomes asymptotically safe**



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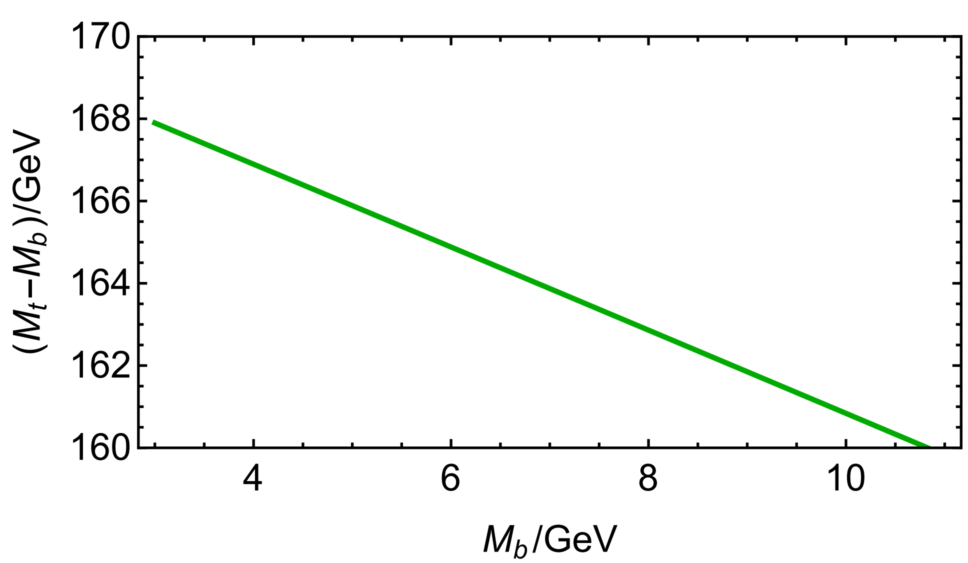

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two regimes in gravitational coupling space:

$f_y(\Lambda) > 0$

Which regime do the microscopic gravitational couplings fall into?

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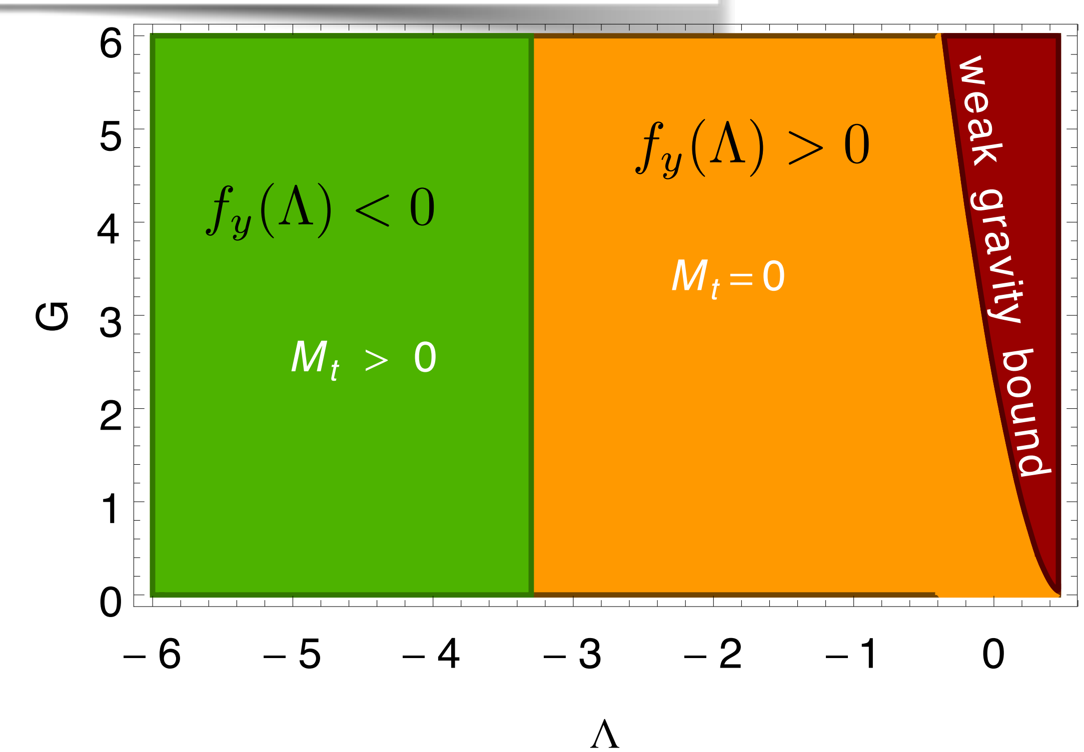

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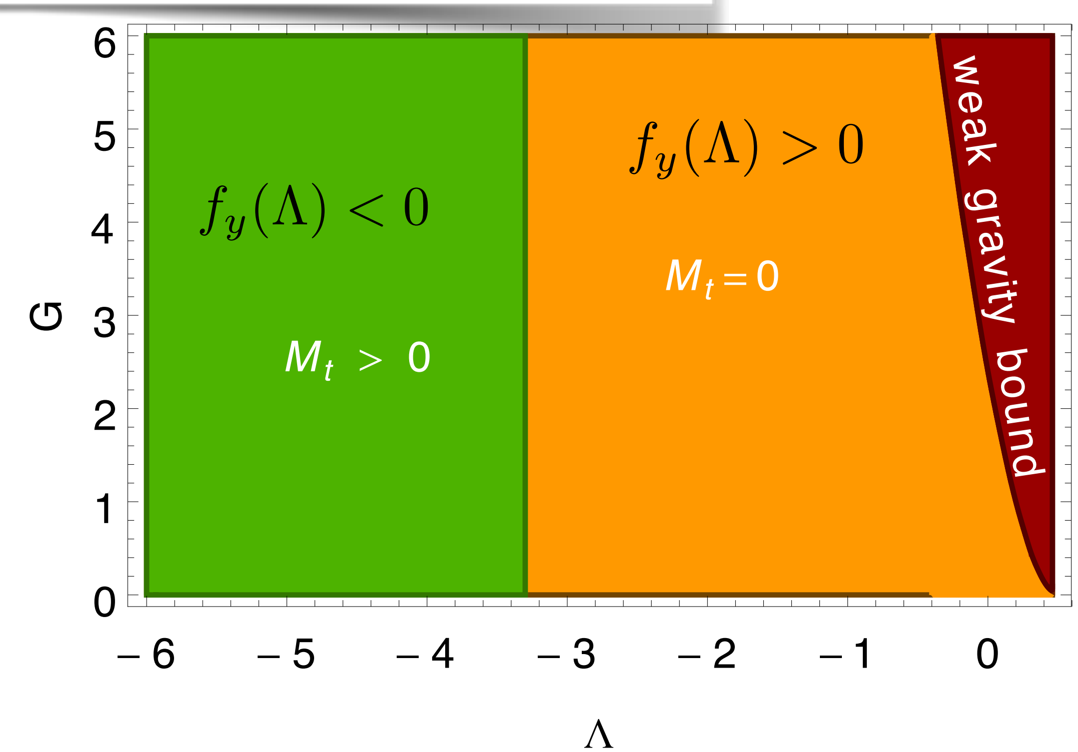

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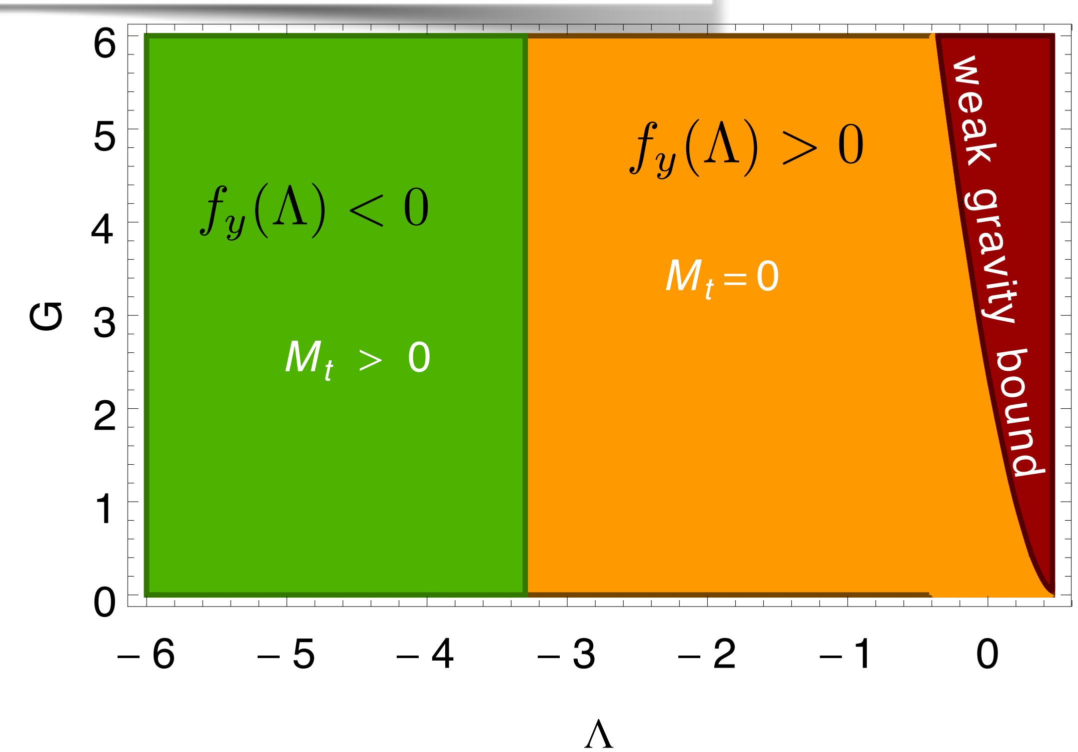
warning: simple approximation convergence to be checked!



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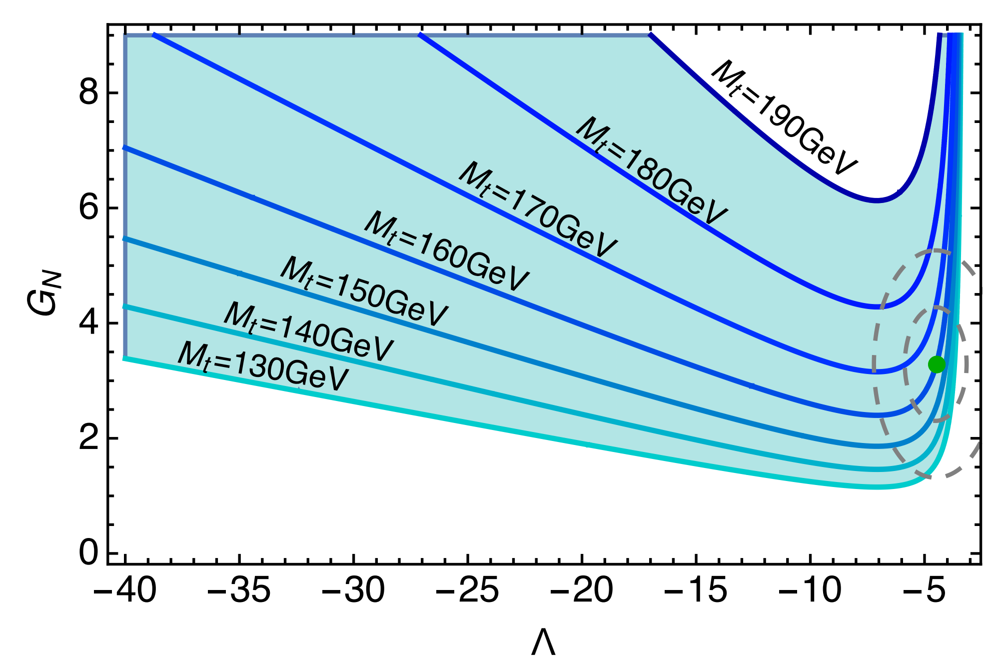
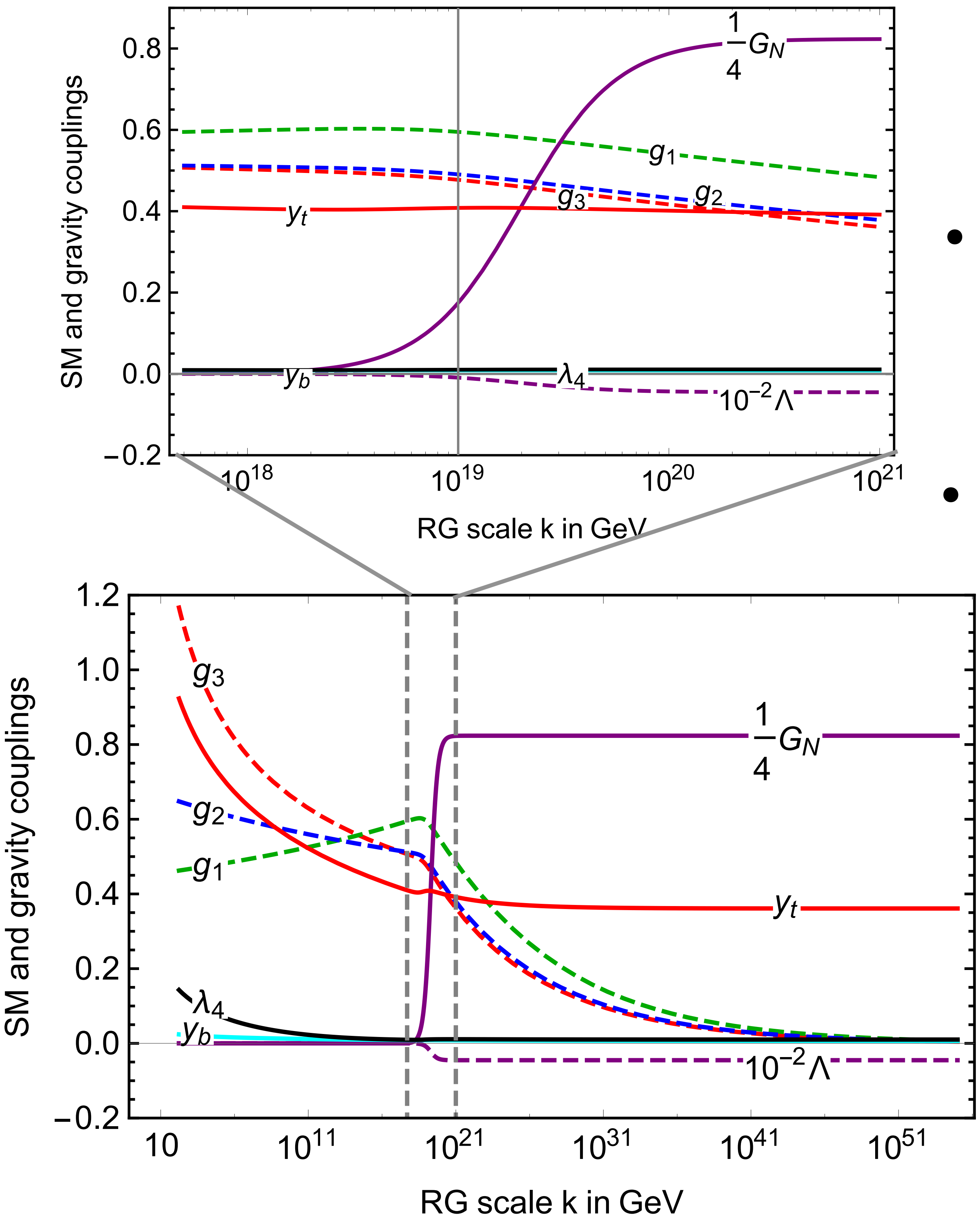


Top mass from asymptotic safety - the full picture



within simple truncations:

- **asymptotic freedom in all gauge couplings (incl. Abelian hypercharge)**

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

- **asymptotic safety in top Yukawa coupling with M_t >> M_b fixed uniquely:** $\mathrm{M_t} \approx 170\,\mathrm{GeV}$

[AE, Held, Pawlowski '16; AE, Held 05/17, 07/17]

- **Higgs mass:**

fixed uniquely [Shaposhnikov, Wetterich '09]

here: simple truncation w. stable vacuum

$$\mathrm{M_h} \gtrsim 130\,\mathrm{GeV}$$

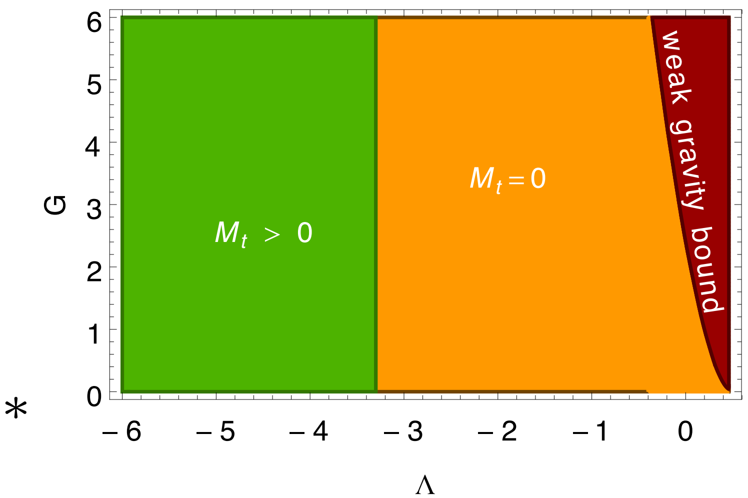
outlook: vacuum stability from asymptotic safety?

Learning about the dark sector from asymptotic safety

dark sector might only couple gravitationally

$\longrightarrow$ **direct detection very challenging**

Learning about the dark sector from asymptotic safety



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$\longrightarrow$ **direct detection very challenging**

asymptotic safety: ALL degrees of freedom affect $G^*,\ \Lambda^*$

$\longrightarrow$ **top-mass value depends on dark sector!**

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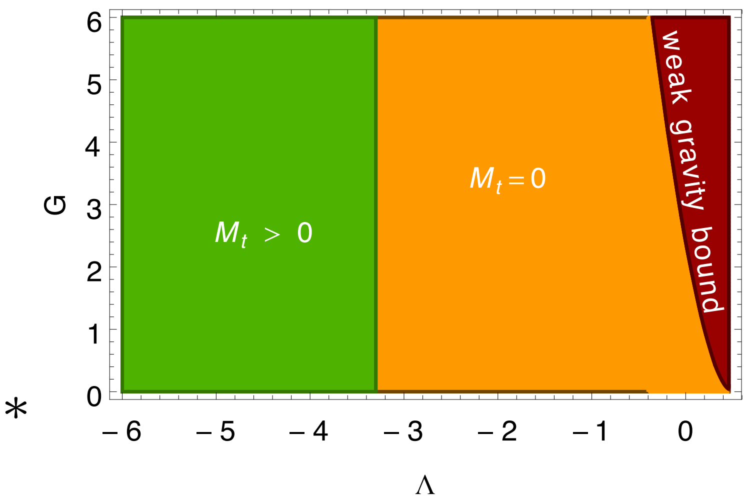
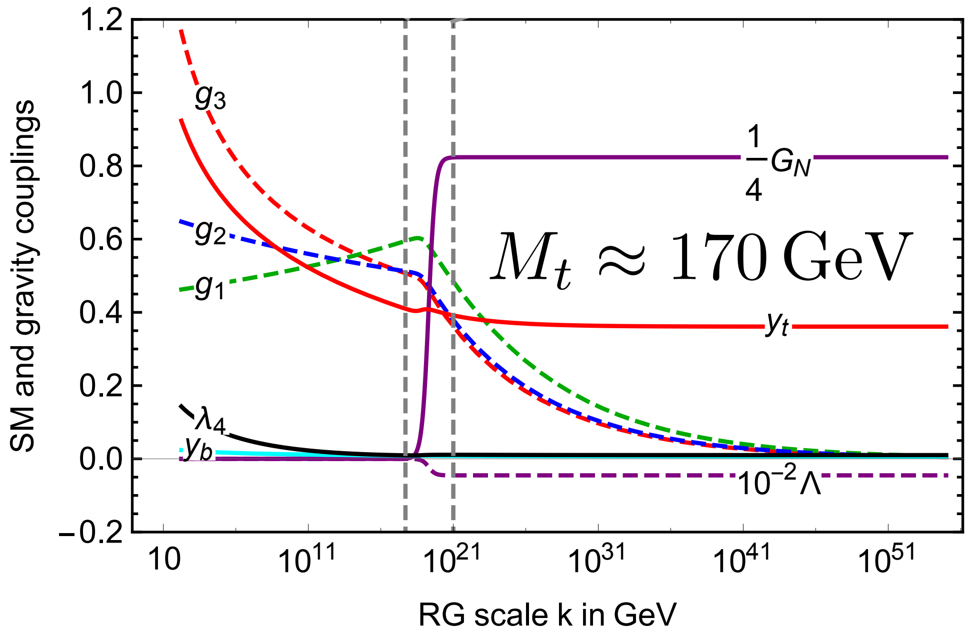


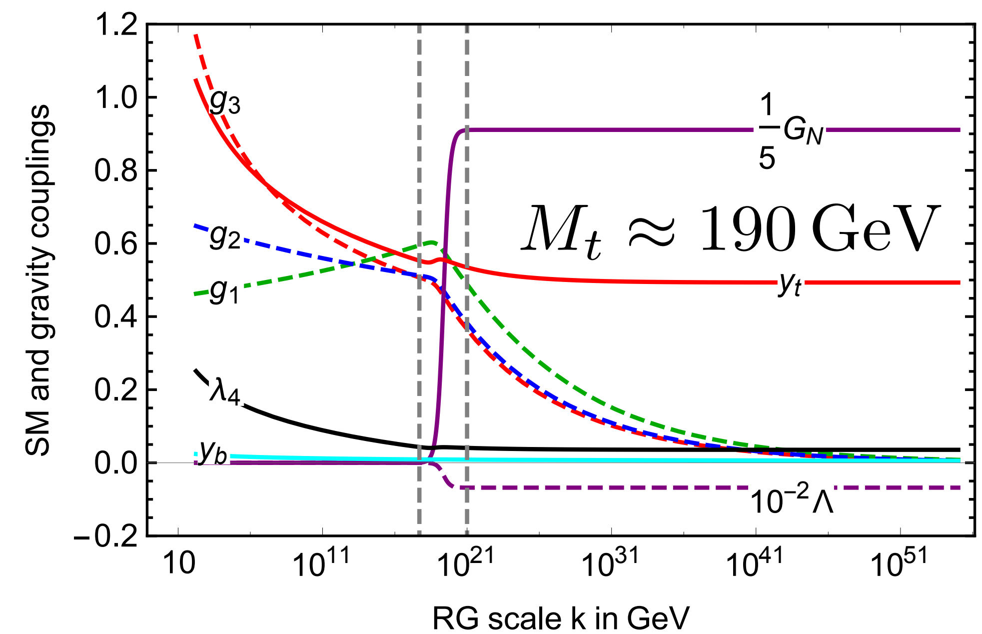
$\longrightarrow$ **direct detection very challenging**

asymptotic safety: ALL degrees of freedom affect $G^*,\ \Lambda^*$

$\longrightarrow$ **top-mass value depends on dark sector!** only gravitationally coupled

toy examples: convergence in fixed-point results: to be tested! SM + 3 Weyl fermions + 1 scalar





outlook: constrain dark sector by matching top-mass value from AS to measured value…

Conclusions

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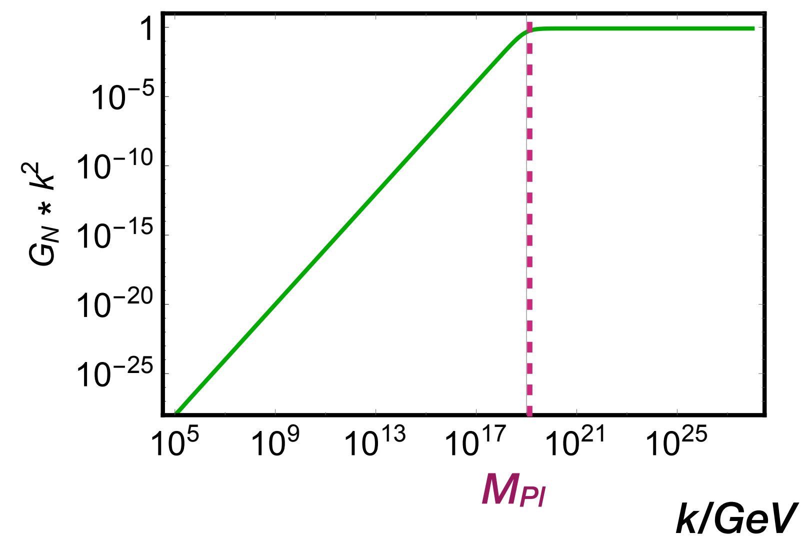
Asymptotic safety:
Quantum field theory for gravity & matter on all scales



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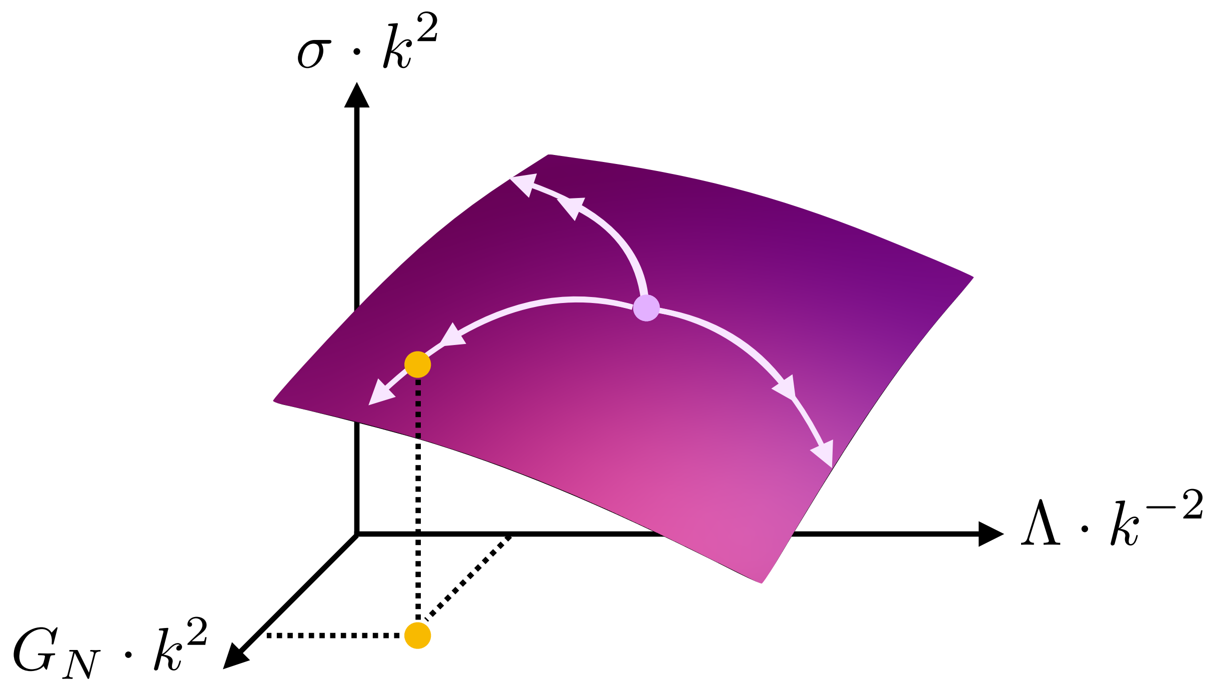

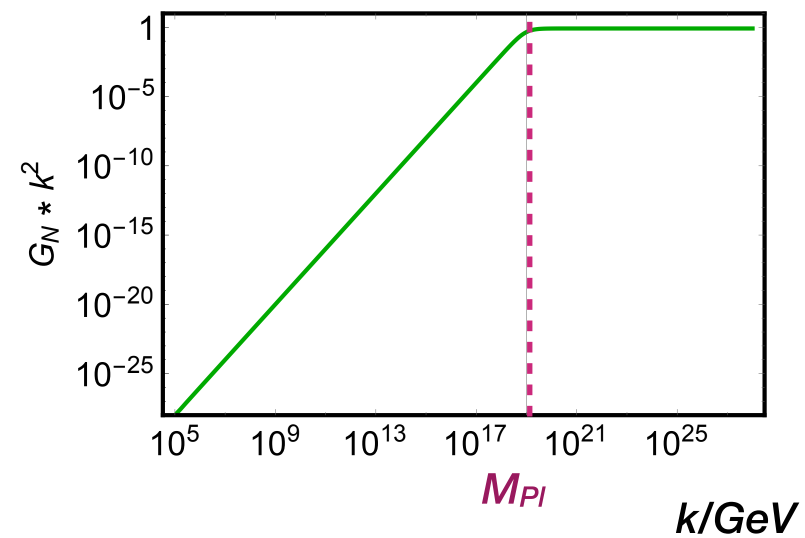

microscopically:
quantum scale- invariance

macroscopically:
predictions for irrelevant couplings

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Asymptotic safety:
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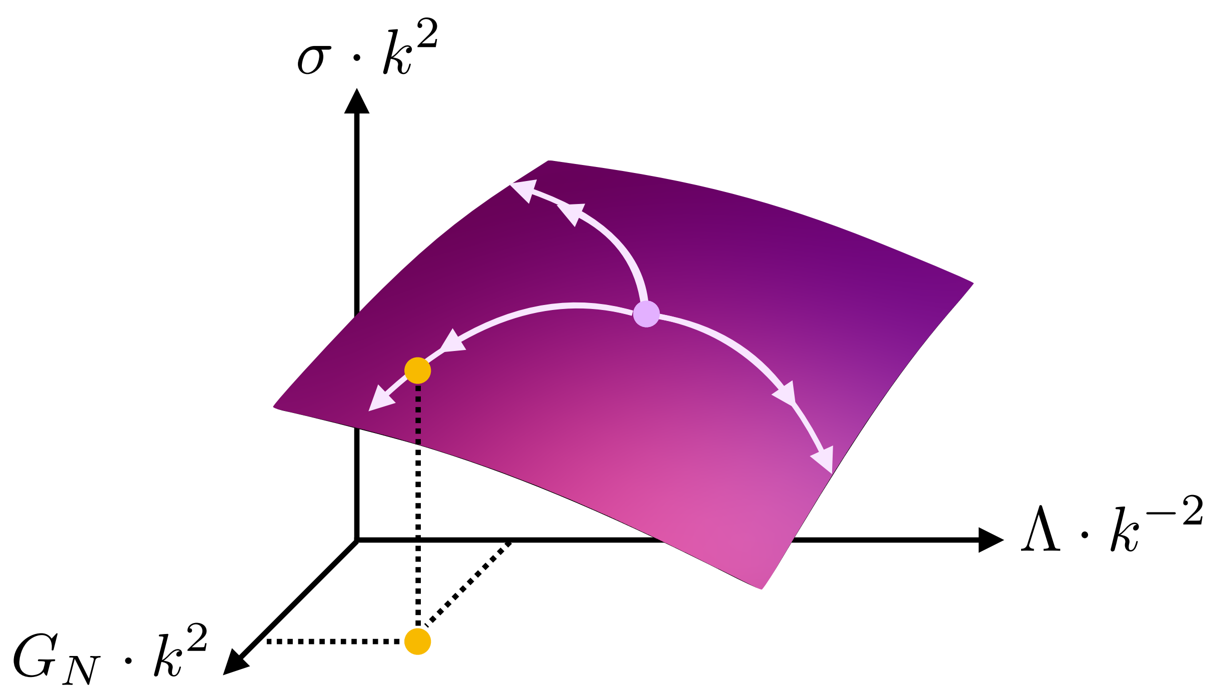

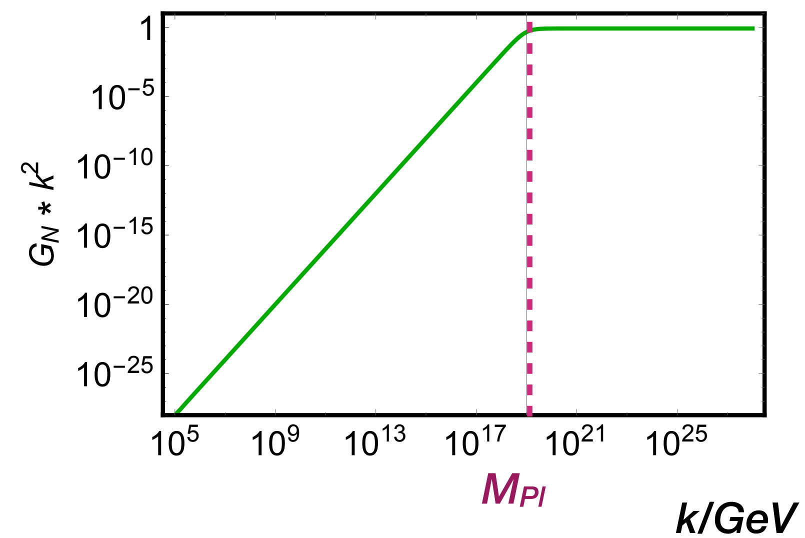

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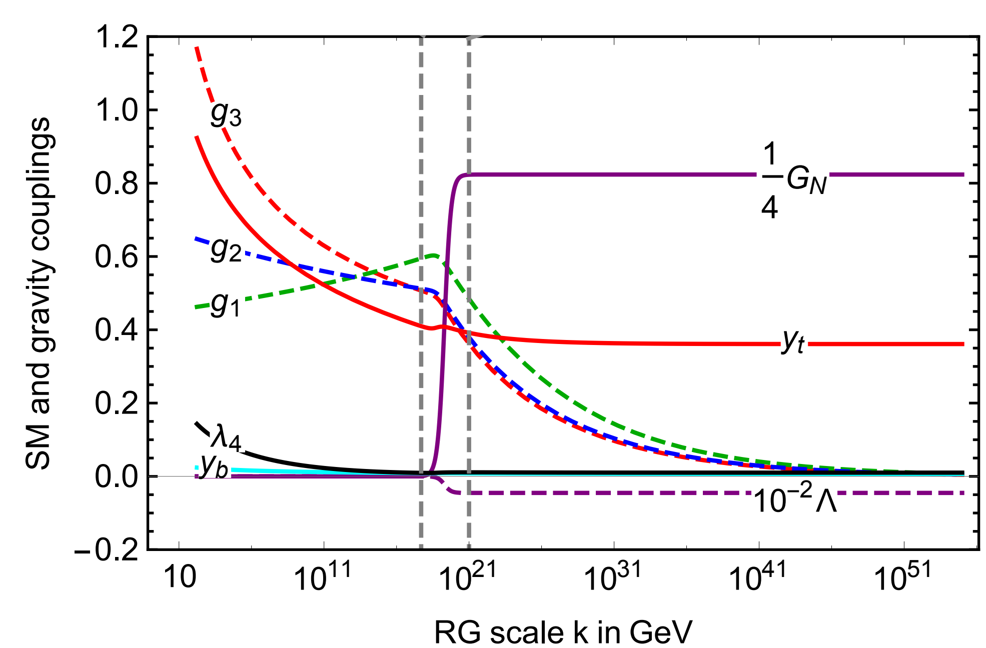

potential consequences:
UV completion for Standard Model with fewer free parameters:
top-mass value explained,
mass-difference to bottom generated

outlook:
- **quantitative convergence**
- **what about the other parameters of the SM?**
- **global stability of Higgs potential & link to Higgs inflation**