The Asymptotically Safe Standard Model:

From quantum gravity to dynamical chiral symmetry breaking

Álvaro Pastor Gutiérrez

[2207.09817] APG, Jan M. Pawlowski and Manuel Reichert

MAX-PLANCK-INSTITUT
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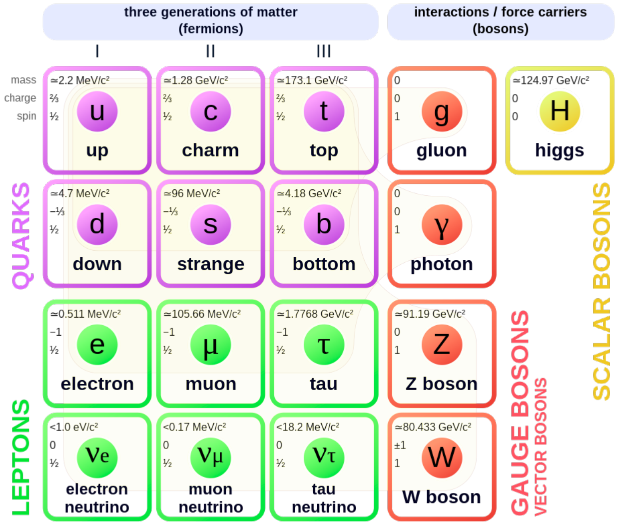
Towards a fundamental theory

<u>Standard Model</u>



Wikipedia

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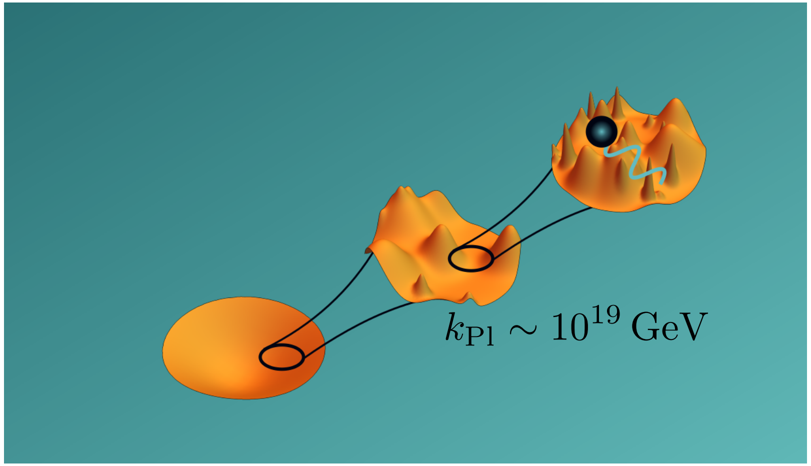
<u>Quantum Gravity</u>



as-seminars.quantum-spacetime.net

The Asymptotically Safe Standard Model

The minimal ASSM: setup

Standard Model

- All SM matter content /symmetries

$$SU(3)_C \times SU(2)_L \times U(1)_Y \qquad \begin{aligned} q &= (d,\, u,\, s,\, c,\, b,\, t) \\ l &= (e,\, \nu_e,\, \mu,\, \nu_\mu,\, \tau,\, \nu_\tau) \end{aligned}$$

- Free parameters:

$$(\vec{g}_{1,k}\,,\ \vec{g}_{2,k}\,,\ \vec{g}_{3,k}\,,\ \vec{y}_{q,k}\,,\ \vec{y}_{l,k}\,,\ \vec{\lambda}_{\Phi,k}\,,\ \vec{G}_k\,,\ \vec{\Lambda}_k)$$

- Higgs sector

$$V_{\Phi,\text{eff}}(\rho) = \sum_{n=1}^{N_{\max}=17} \lambda_{\Phi,2n}\, Z_\Phi^n \rho^n$$

$$\rho = \text{tr}\,\Phi^\dagger\Phi \qquad \Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathcal{G}_1 + i\mathcal{G}_2 \\ v + H + i\mathcal{G}_3 \end{pmatrix}$$

+

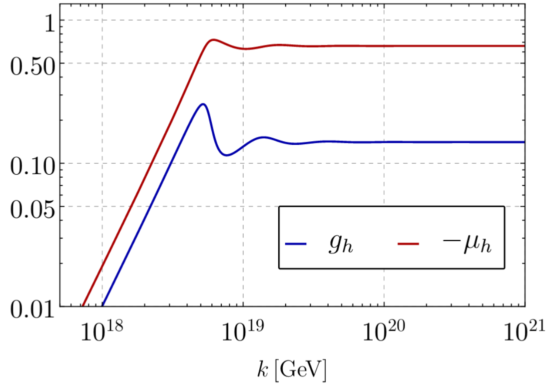
Asymptotically safe quantum gravity

Weinberg‘79, Reuter‘98, Souma‘99

$$S_{\text{EH}} = \frac{1}{16\pi G_{\text{N}}}\int d^4x\sqrt{|g|}\,(2\Lambda - R)$$

$$g_h = G_{\text{N}} k^2$$

$$\mu_h = -2\Lambda/k^2$$



- Minimal gravity-matter coupling

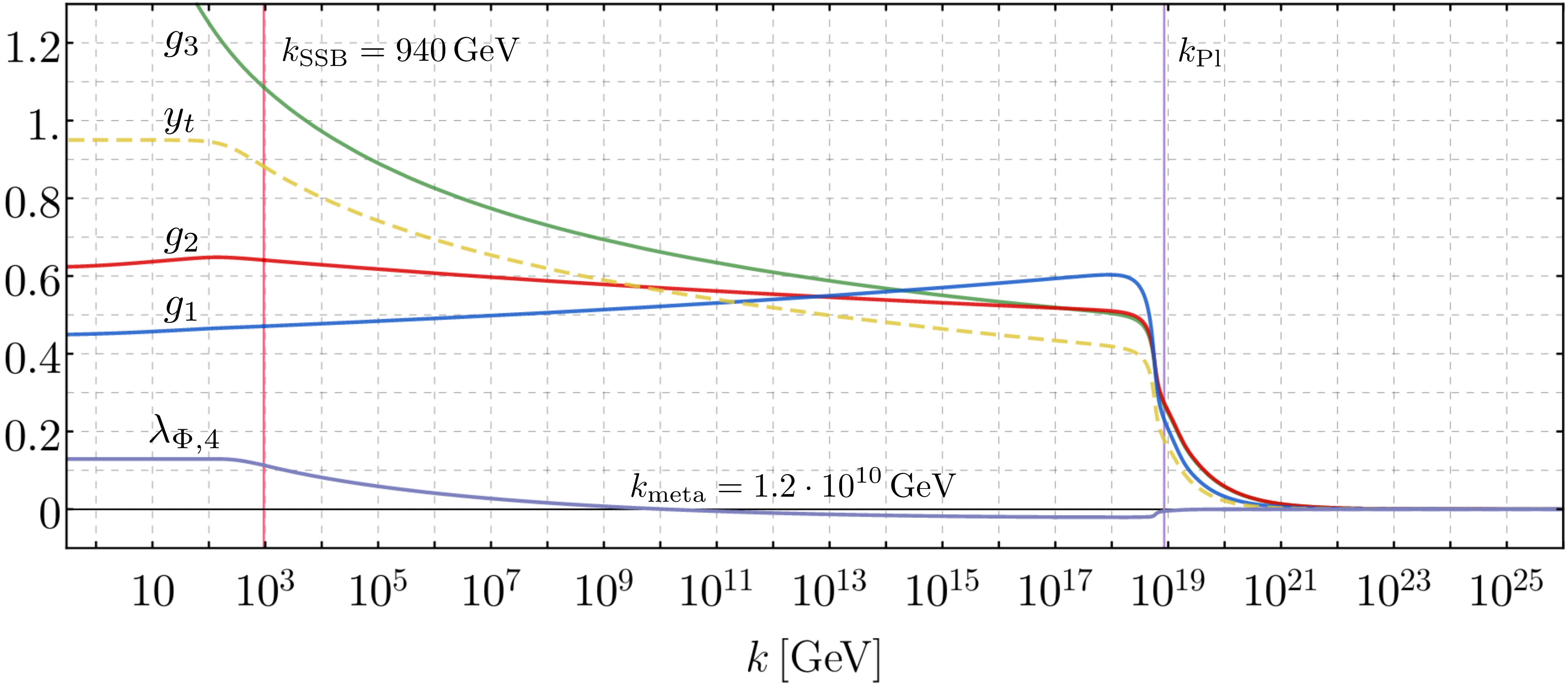
$$g_{\mu\nu} = \delta_{\mu\nu} + \sqrt{16\pi G_{\text{N}}}\, h_{\mu\nu}$$

The Functional Renormalisation Group

Wetterich ‘93

The ASSM trajectory

$SU(3)_C : g_3, \quad SU(2)_L : g_2, \quad U(1)_Y : g_1 = \sqrt{5/3}\, g_Y$



Broken phase and scale setting

- Deep IR QCD: Dynamical chiral symmetry breaking

$$m_q = \frac{y_q\, v}{\sqrt{2}} + \Delta M_q^{\rm const}$$

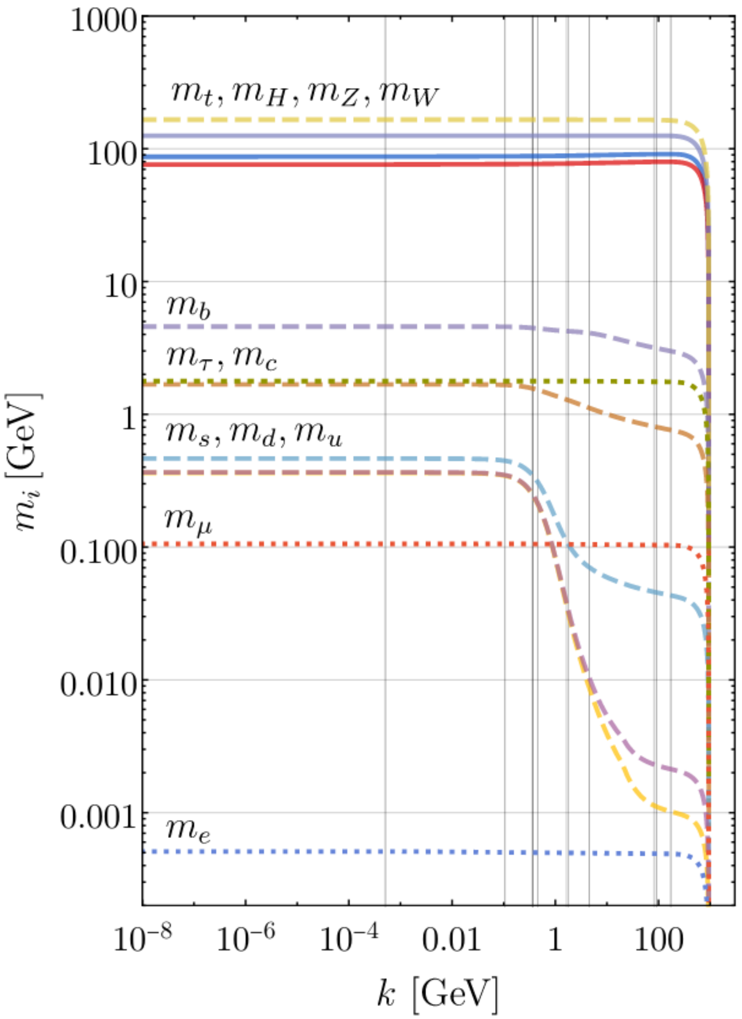
- Top Yukawa $\rightarrow$ Top quark pole mass

$$M_{t,\rm pole}^{(\rm exp)} = 172.5 \pm 0.7\,\text{GeV}, \qquad \Gamma_{t,\rm pole}^{(\rm exp)} = 1.42^{+0.19}_{-0.15}\,\text{GeV}$$

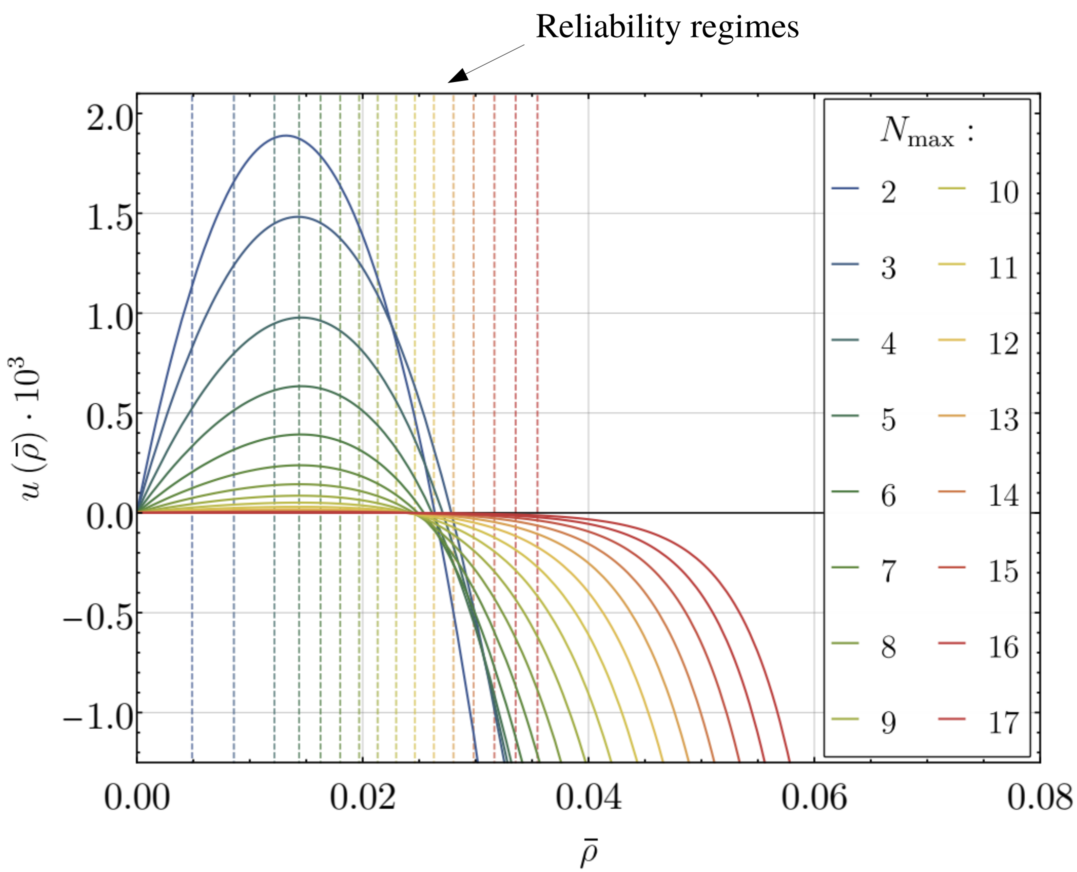
  - Top pole width prediction:

$$m_t = 165.4^{+0.9}_{-0.2}\,\text{GeV}$$
$$y_t = 0.950^{+0.005}_{-0.001}$$

$$\Gamma_{t,\rm pole}^{(\rm theo)} = 1.72^{+0.09}_{-0.41}\,\text{GeV}$$



UV-Higgs potential

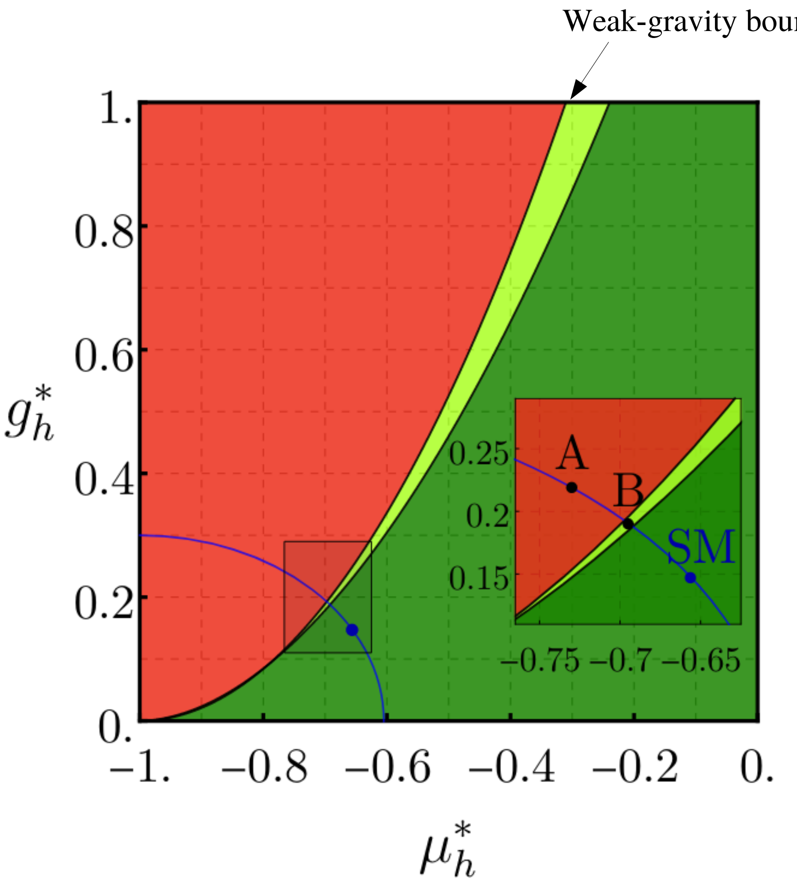


$$V_{\Phi,\text{eff}}(\rho) = \sum_{n=1}^{N_{\max}=17} \lambda_{\Phi,2n}\, Z_\Phi^n \rho^n$$
$$= \mu_\Phi \bar{\rho} + \lambda_{\Phi,4}\, \bar{\rho}^2 + \lambda_{\Phi,6}\, \bar{\rho}^3 + \lambda_{\Phi,8}\, \bar{\rho}^4 + \dots$$

$$\rho = \text{tr}\, \Phi^\dagger \Phi \qquad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathcal{G}_1 + i\mathcal{G}_2 \\ v + H + i\mathcal{G}_3 \end{pmatrix}$$

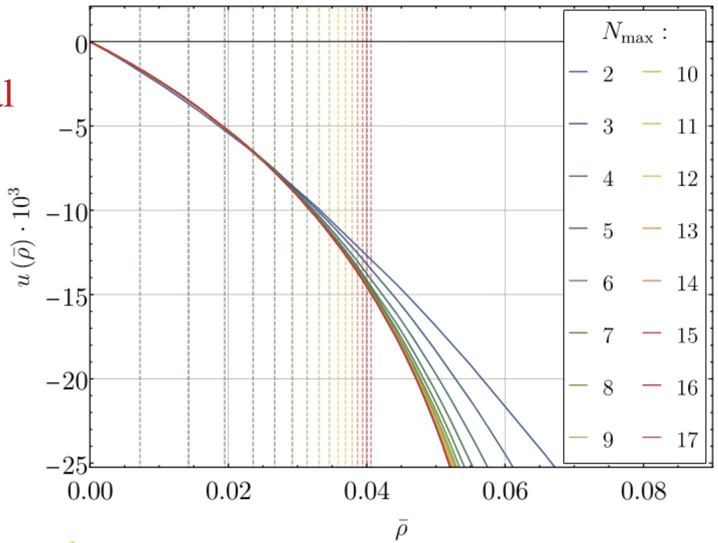
- Converged **flat potential**
- As many free parameters as the SM Higgs potential (two relevant directions)
- Recently discussed in [2207.06749] Laporte et al.

UV-Higgs landscape



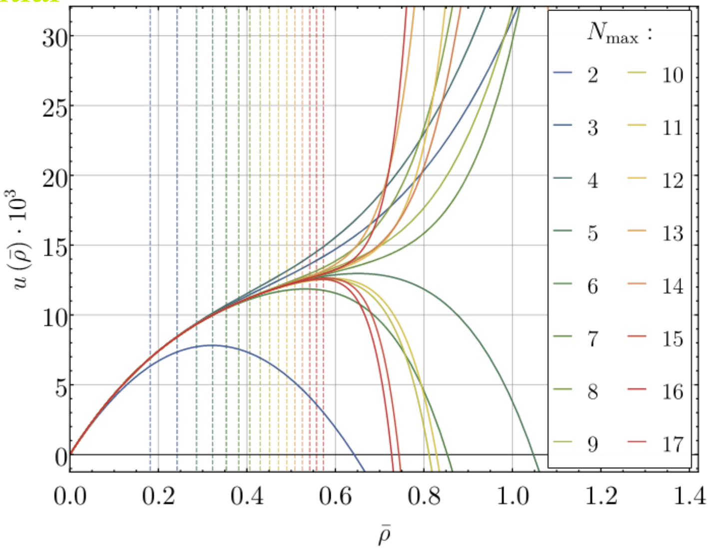
(A)

Unstable potential

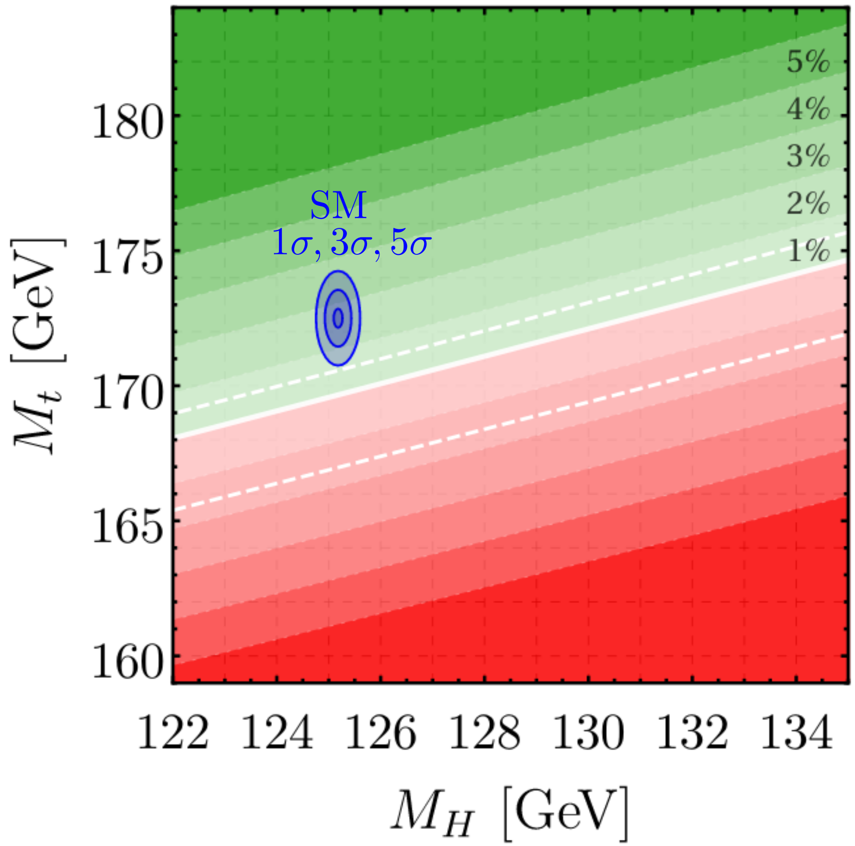


Hyper-predictive potential

(B)



Quantitative for *qualitative*



New flat UV-Higgs potential

Gaussian FP trajectory

Higgs instability

<u>Sources of systematics:</u>

- Strong coupling: $\alpha_{s,k=M_Z} \in [\alpha_s^{\overline{\text{MS}}},\, 1.10\, \alpha_s^{\overline{\text{MS}}}]$
- Top pole mass: $^{+0.9}_{-0.2}$ GeV
- Gravity FP: $\ll 1\text{GeV}$
- FRG truncation
- …

Conclusions and outlook

- **Novel UV-Higgs potential**
- **Unified** and **UV-complete picture** of the SM + QG
- Consistent non-perturbative UV-IR renormalisation, from trans-planckian to sub-Fermi scales

➔ **Versatile framework** for **non-perturbative new physics**

- Thorough **systematic analysis**

On the gravity side...

- Studied **viability** of gravity-matter systems accounting for **momentum dependencies**
- **Consistent RG-scheme** results with inclusion of **mass-thresholds** at all scales
- Found a **kinematic identity** for gravity- gauge-fermion/Yukawa systems

Beyond the ASSM...

- Non-perturbative BSM (CH, …) + ASSM
- UV complete extensions
- Implementation of flavour
- Finite temperature SM: EWPT
- Expanded Higgs potential at ~EW scale
- …

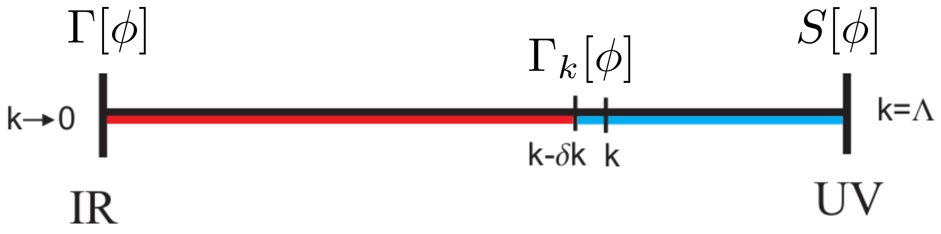
Thank you for your attention!

Additional slides

The functional Renormalisation Group

$$\Gamma_k[\phi] = \int_x J(x)\phi(x) - \mathcal{W}_k[J] - \Delta S_k[\phi]$$

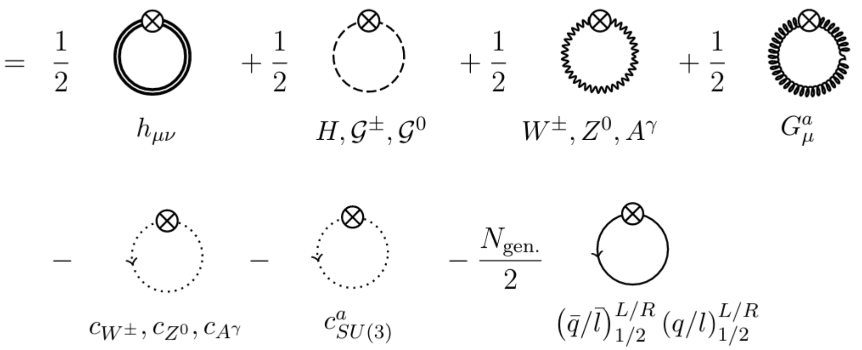
$$\Delta S_k[\phi] = \int_p \phi(p) R_k^{(\phi)} \phi(-p)$$



$$\partial_t \Gamma_k[\phi] = \frac{1}{2}\mathrm{Tr}\left[\frac{1}{\Gamma_k^{(2)} + R_k}\partial_t R_k\right]$$

$\partial_t = k\partial_k$

Wetterich‘93



- One-loop exact
- Non-perturbative
- Mass-thresholds accounted
- Analytic regulators

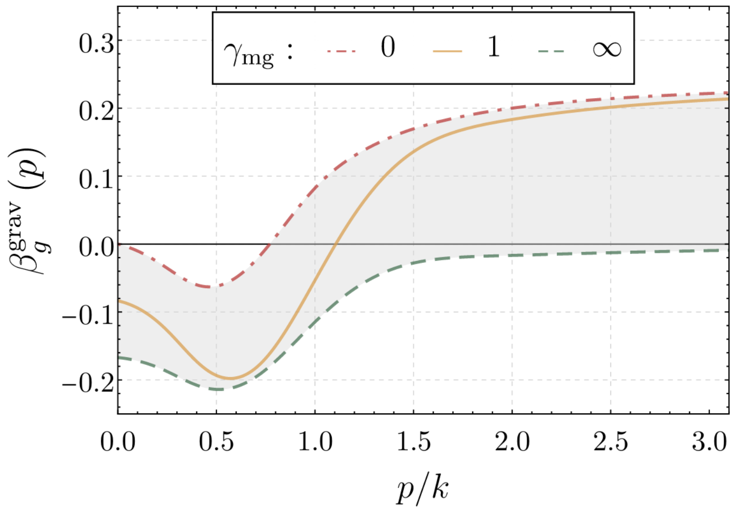
Existence of the ASSM

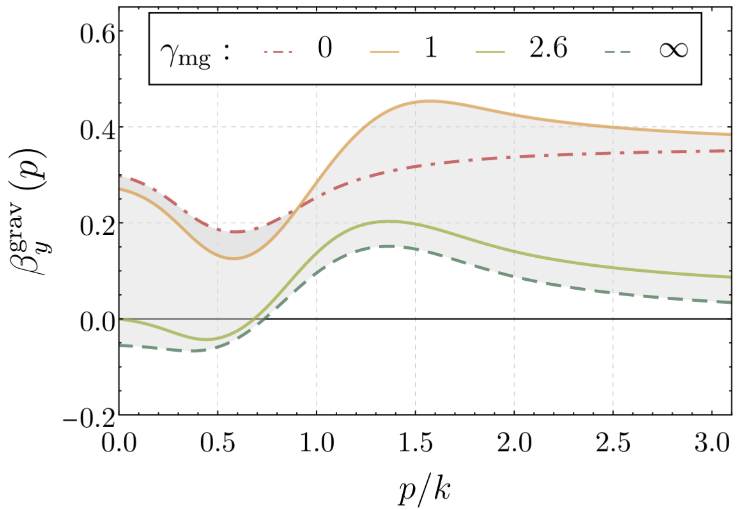
$$r_{\text{flat}}(x) = \left(\frac{1}{x} - 1\right)\,\Theta(1-x) \qquad\qquad x = \frac{p^2}{k^2}$$

$$r_{\text{mat}}(x) = r_{\text{flat}}\left(\frac{1}{\gamma_{\text{mg}}^2}x\right)$$

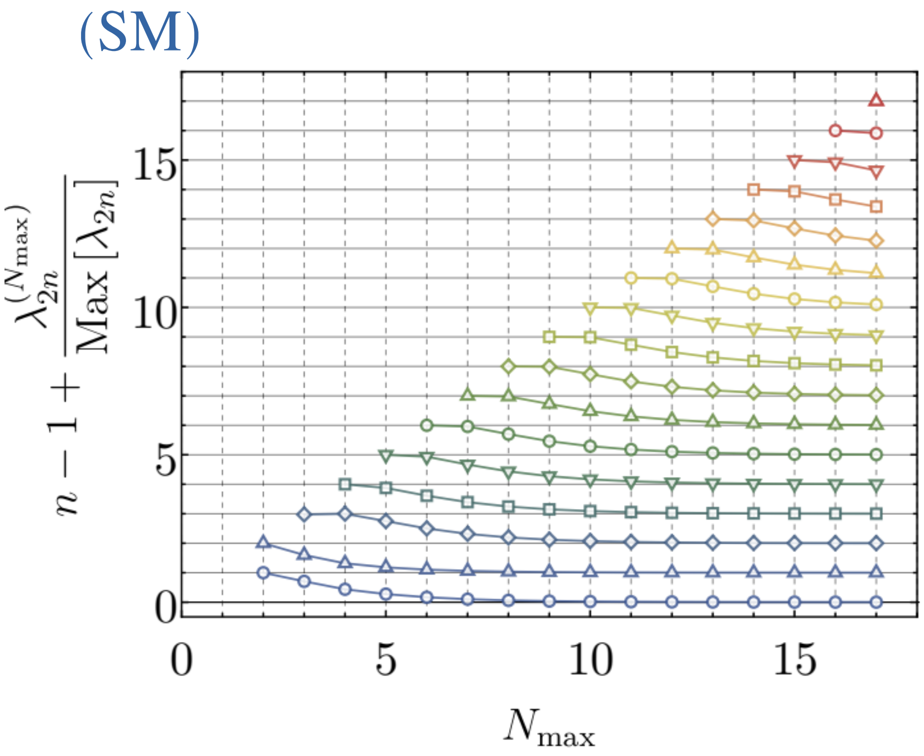
- *Matter matters:* $\gamma_{\text{mg}} \to 0$
  - The matter propagators lack the IR mass introduced by the regulator and hence are enhanced relative to the graviton propagator
- *Gravity rules:* $\gamma_{\text{mg}} \to \infty$
  - The graviton propagator lacks the IR mass introduced by the regulator and hence are enhanced relative to the matter propagators

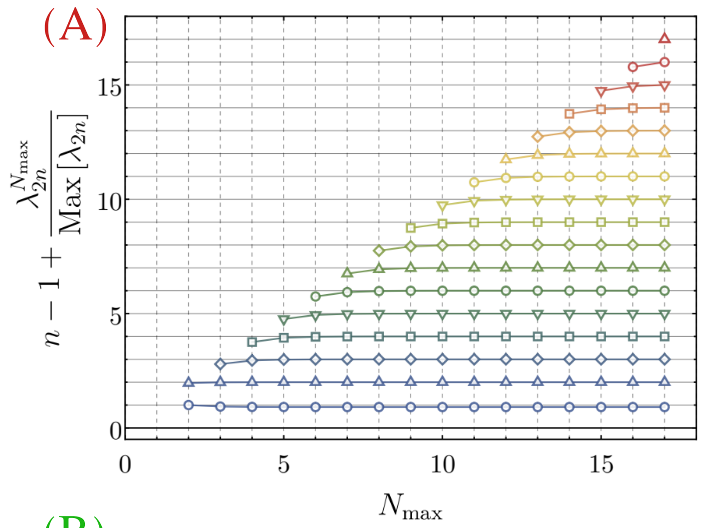
Similar effect achievable through tweaking of cosmological and Newton's constant

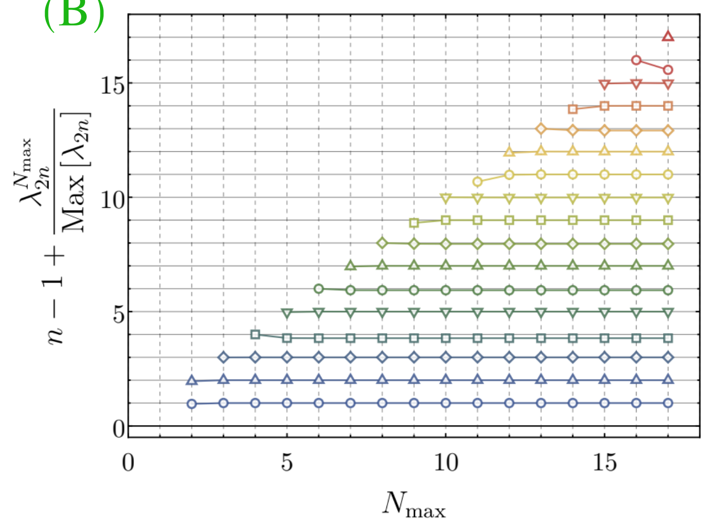


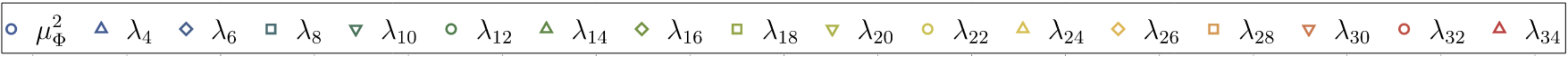


Flattening of the potential

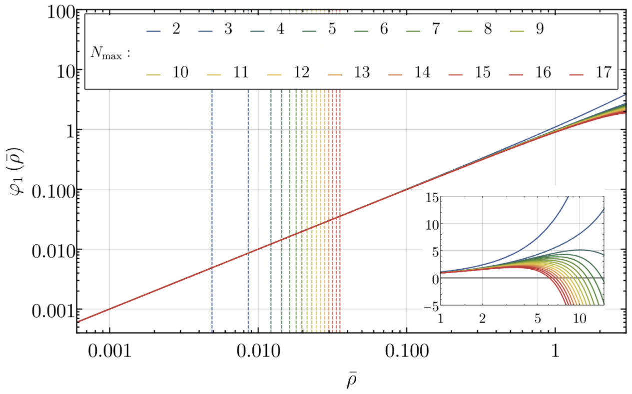


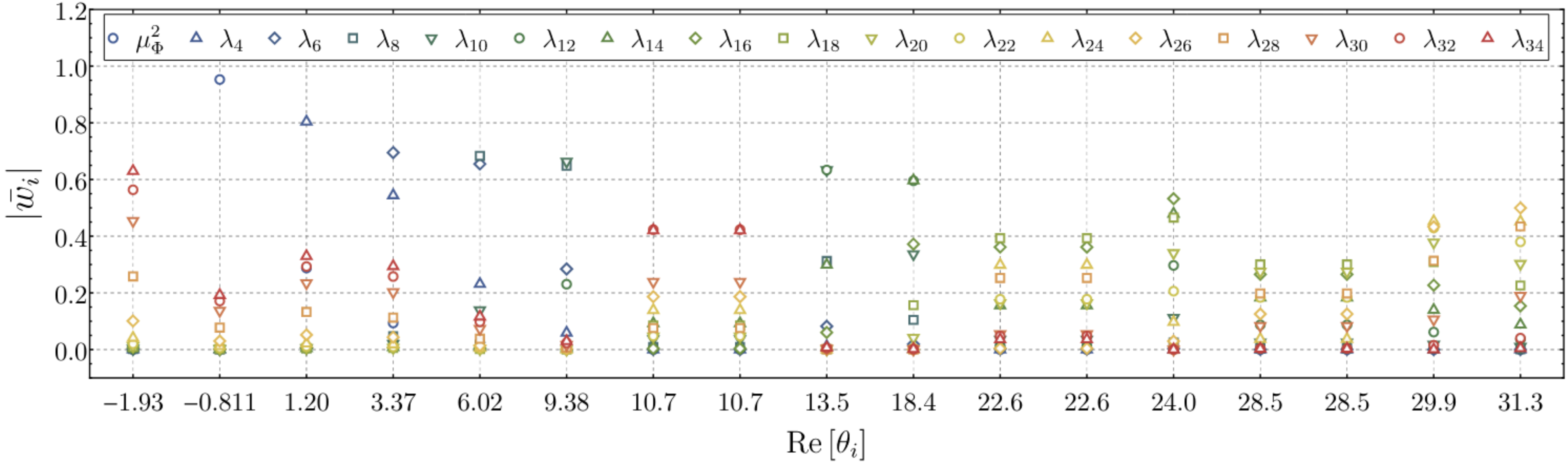






Eigenvectors and eigenfunctions





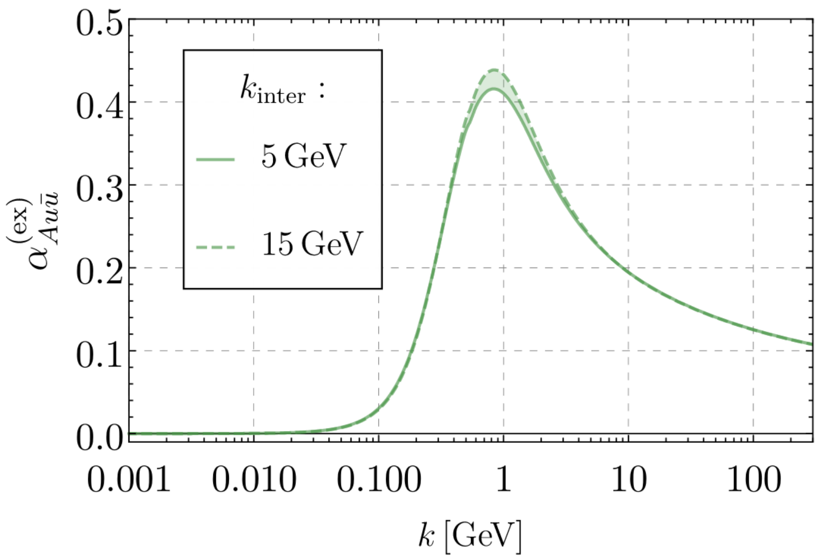
Strong QCD

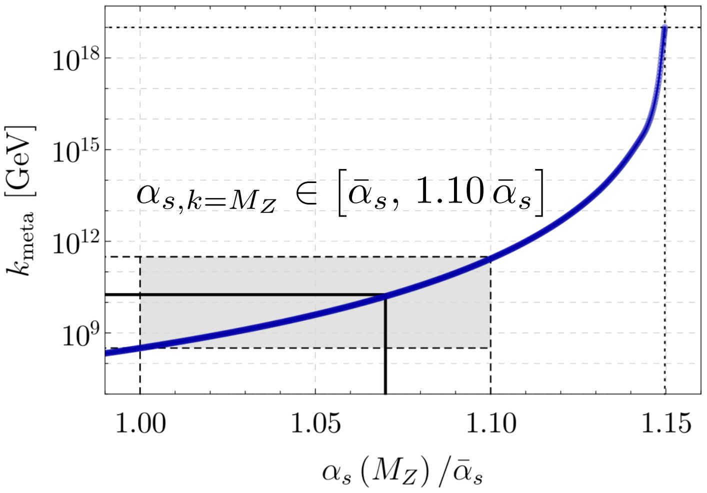
- Implementation of FRG results from 2+1 flavor QCD.
- QCD mass-gap accounted
- Dynamical chiral symmetry breaking
- Scale setting:

$$g_{3,k=M_Z}^{\overline{\mathrm{MS}}} \approx 1.22$$

$$\bar{\alpha}_s := \frac{\left(g_{3,k=M_Z}^{\overline{\mathrm{MS}}}\right)^2}{4\pi} \approx 0.118$$

$$g_{3,k=M_Z} = \sqrt{1.07\,(4\pi\bar{\alpha}_s)} = 1.26$$





The top pole mass determination

$$\left[p^2 + M_t(p)^2\right]_{p^2=-\left[M_t^{(\mathrm{pole})}\right]^2} = 0 \qquad \partial_t[Z_t(p)M_t(p)] = \frac{1}{4}\mathrm{tr}_D\,\partial_t\Gamma^{(2)}_{t\bar{t}}(p)$$

$$[Z_t M_t]^{\mathrm{1loop}}\,(p \lesssim k_{\mathrm{SSB}}) = Z_t m_t + \Delta\,[Z_t M_t]\,(p)$$

$$\Delta[Z_t(p)M_t(p)]$$

$$= \frac{m_{\mathrm{t}}}{16\,\pi^2}\left[4\,g_3^2\,\mathcal{I}(p^2) + 3\,\left(\frac{2\,g_2\sin\theta_W}{3}\right)^2\mathcal{I}(p^2)\right.$$

$$-\frac{h_t^2}{2}\,\mathcal{I}(p^2, m_H) + \frac{h_t^2}{2}\,\mathcal{I}(p^2, m_Z) + h_b^2\,\mathcal{I}(p^2, m_W)$$

$$\left.-\frac{g_Y^2\,(1+2\cos 2\theta_W)}{9}\,\mathcal{I}(p^2, m_Z)\right]$$

$$M_{t,\mathrm{pole}}^{(\mathrm{exp})} = 172.5 \pm 0.7\,\mathrm{GeV} \qquad m_t = 165.4^{+0.9}_{-0.2}\,\mathrm{GeV}$$

$$\Gamma_{t,\mathrm{pole}}^{(\mathrm{exp})} = 1.42^{+0.19}_{-0.15}\,\mathrm{GeV} \qquad \Gamma_{t,\mathrm{pole}}^{(\mathrm{theo})} = 1.72^{+0.09}_{-0.41}\,\mathrm{GeV}$$