Stabilizing dark matter
With quantum scale symmetry

Based on 2505.02803 [hep-ph] with A. Chikkaballi, K. Kowalska, E. Sessolo

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16.09.2025 - Matter to the Deepest 2025 - Katowice

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Program

Based on 2505.02803 [hep-ph] with A. Chikkaballi, K. Kowalska, E. Sessolo

- Motivation
  - Quantum scale symmetry: fixed points and scaling behavior
- Our work
  - SU(6) GUT model
  - Using quantum scale symmetry to get dark matter candidates
  - Brief look into the dark matter phenomenology
- Final remarks

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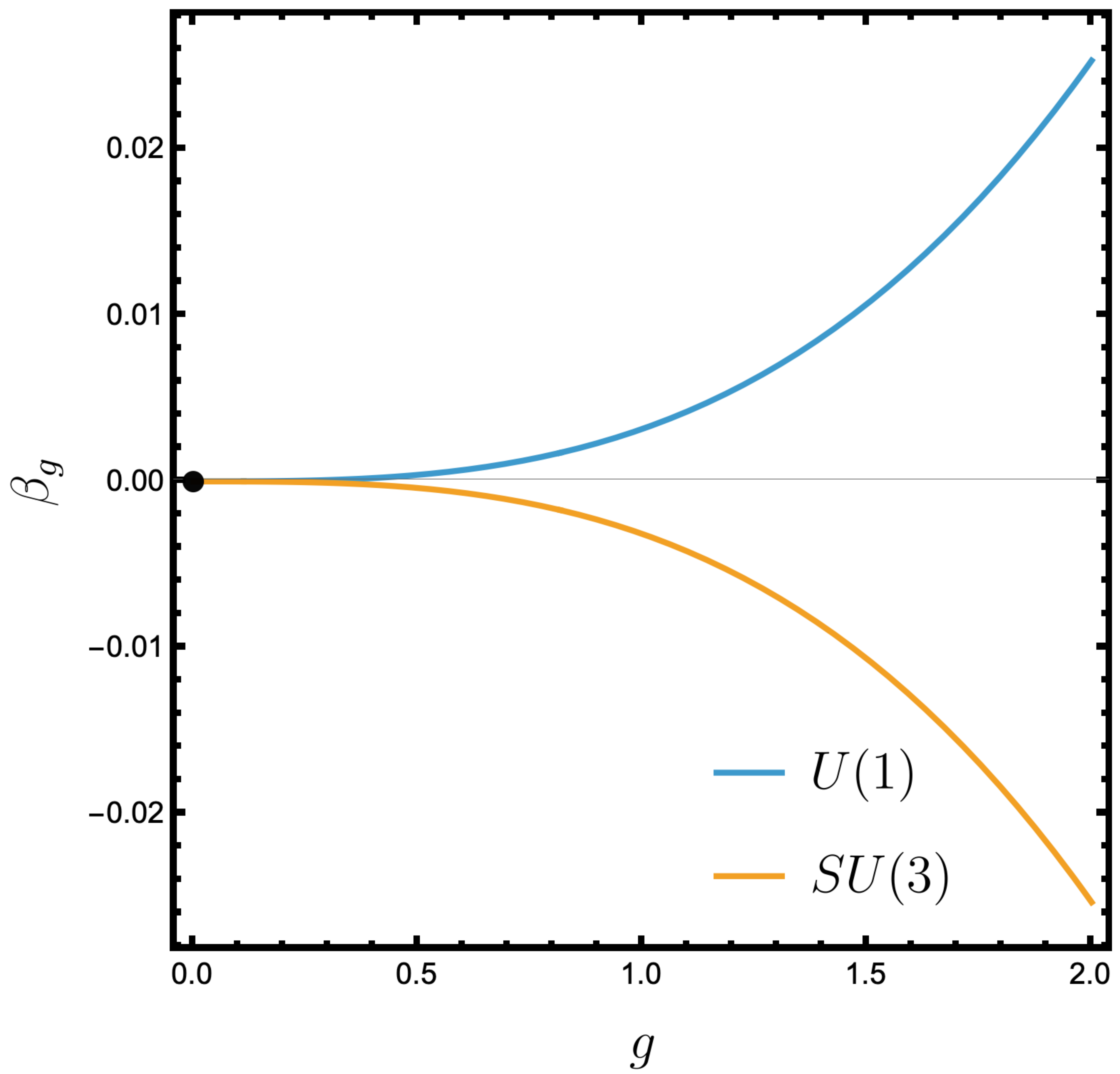
Motivating quantum scale symmetry

Beta functions in Yang-Mills theories

- Want to compute beta functions to see how couplings run with some RG-time $t = \ln(k/k_0)$
- Beta function $\beta_g \equiv \dfrac{dg}{dt}$
- Consider Yang-Mills model $\mathscr{L}_{SU(N)} = -\dfrac{1}{4}F_{\mu\nu}F^{\mu\nu}(A^a)$

$$A \to Z_A^{1/2}A \Rightarrow \eta_A = -\partial_t \ln Z_A$$

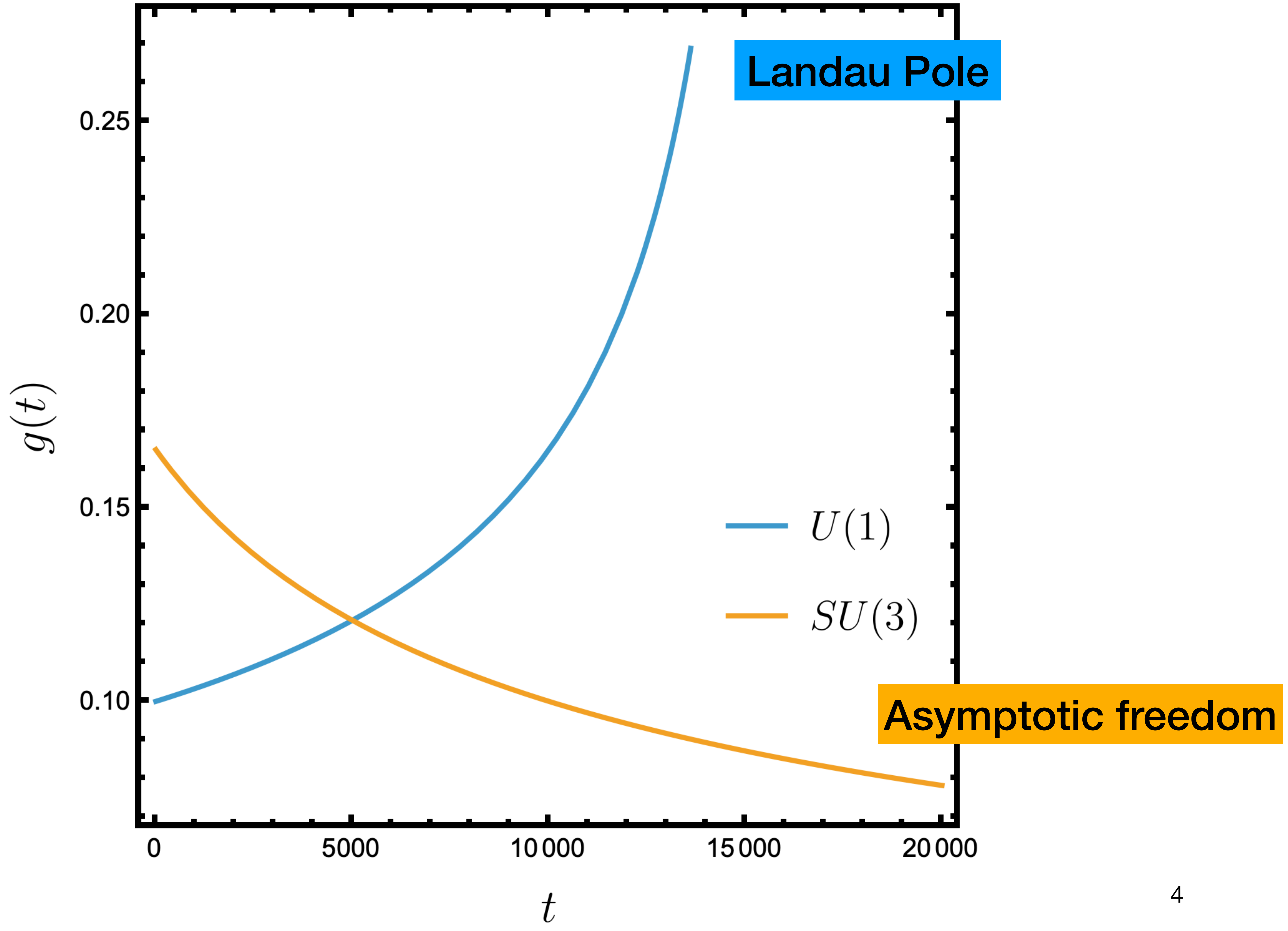
- Use background field formalism: $\beta_g = \dfrac{1}{2}\eta_A\, g$ Abbott 1981
- U(1) (eg. QED): $\eta_A^{U(1)} = +\dfrac{g_1^2}{16\pi^2} > 0$
- SU(3) (eg. QCD): $\eta_A^{SU(3)} = -\dfrac{g_3^2}{16\pi^2} < 0$

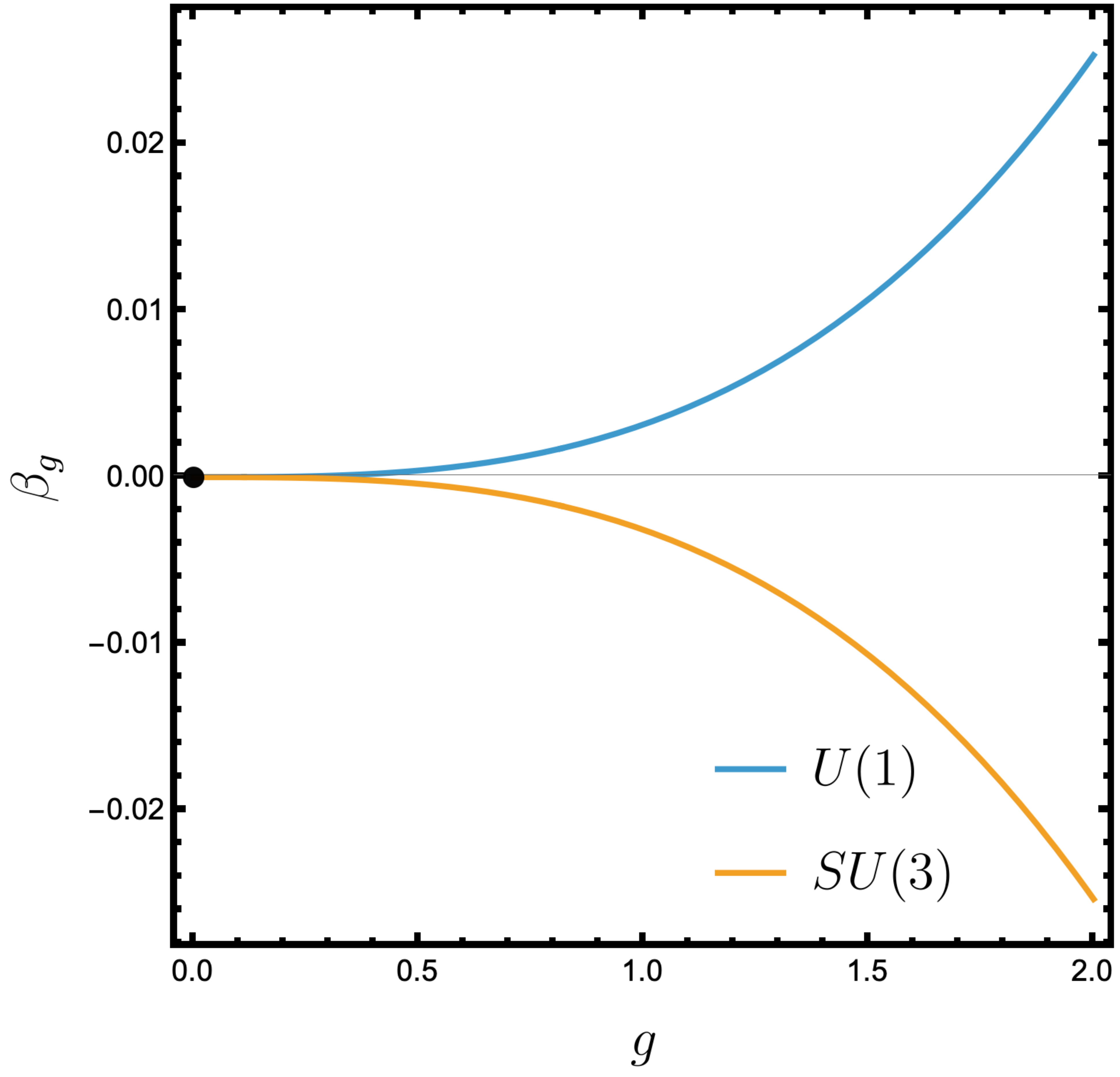


Motivating quantum scale symmetry

Beta functions in Yang-Mills theories

$$\beta_g = \frac{1}{2}\eta_A\, g \qquad \eta_A^{U(1)} = +\frac{g_1^2}{16\pi^2} > 0 \qquad \eta_A^{SU(3)} = -\frac{g_3^2}{16\pi^2} < 0$$





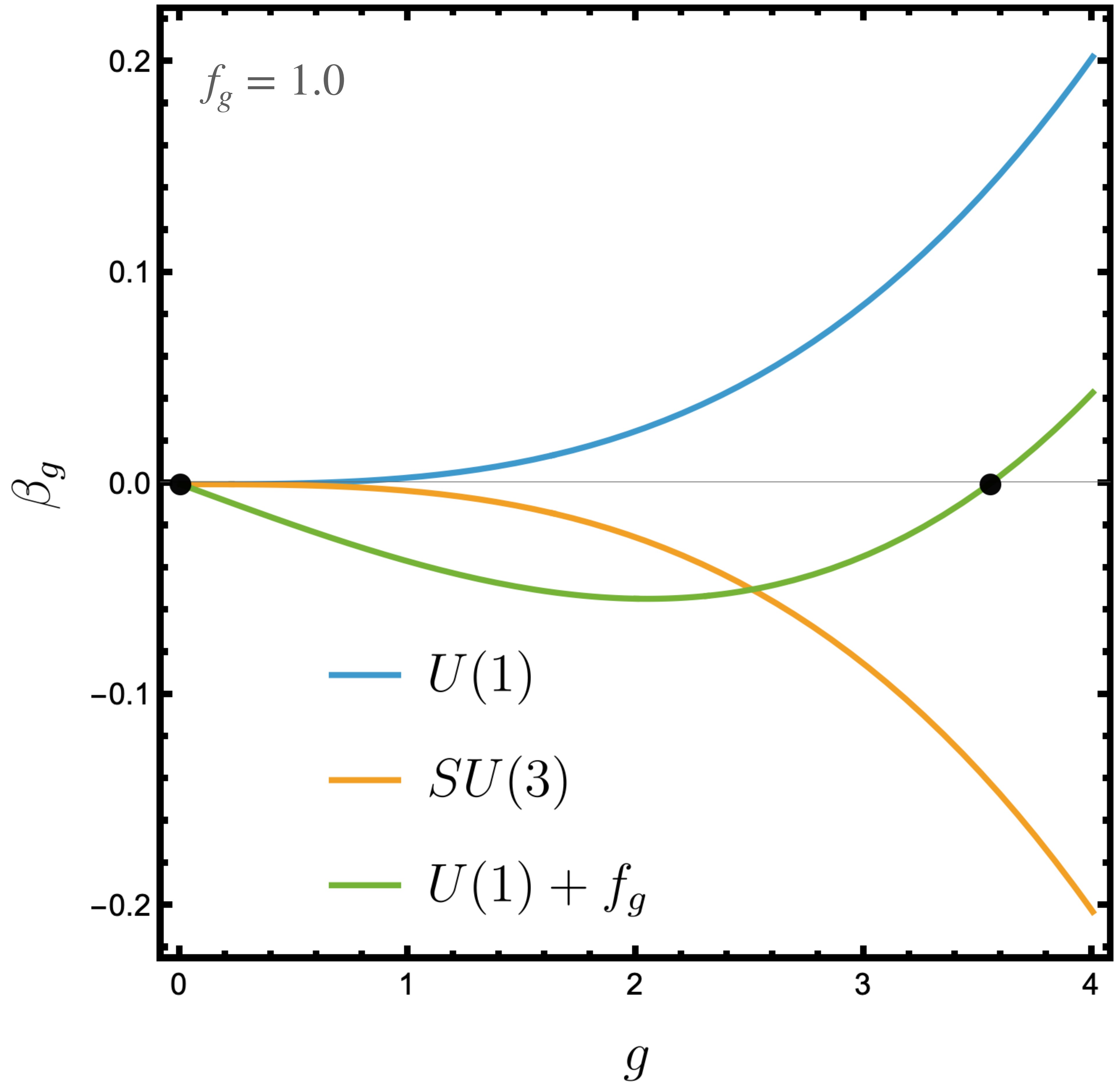
Motivating quantum scale symmetry

Add linear correction to U(1) model

$$\beta_{g_1} = \frac{1}{2}\eta_A\, g_1 - \frac{f_g}{2}\frac{g_1}{4\pi} \qquad \eta_A^{U(1)} = +\frac{g_1^2}{16\pi^2} > 0$$

If $f_g > 0$, new zero of the beta function $\rightarrow$ **new fixed point** $g_* \neq 0$

$$g_*^2 = (4\pi) f_g$$



Motivating quantum scale symmetry

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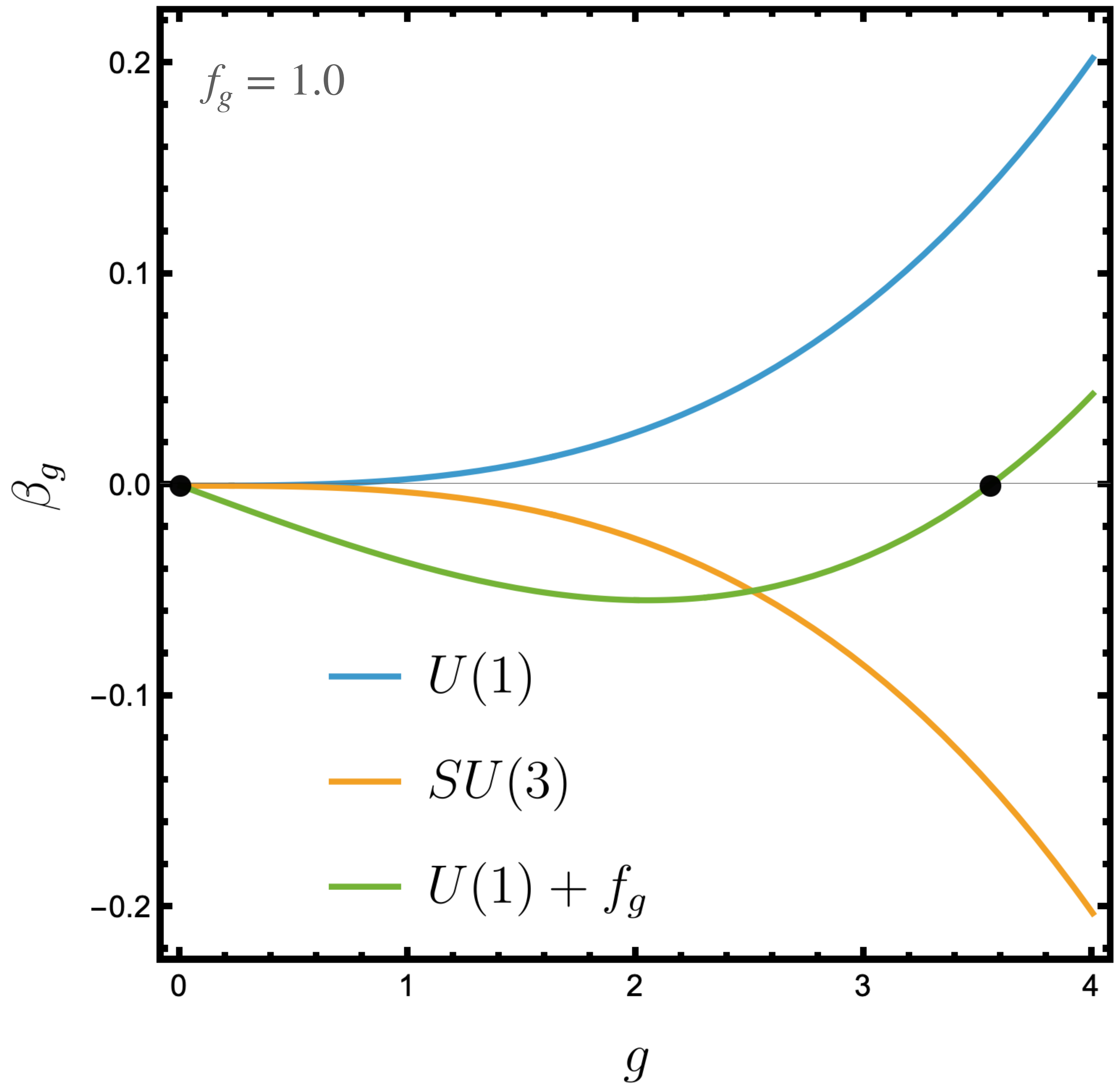
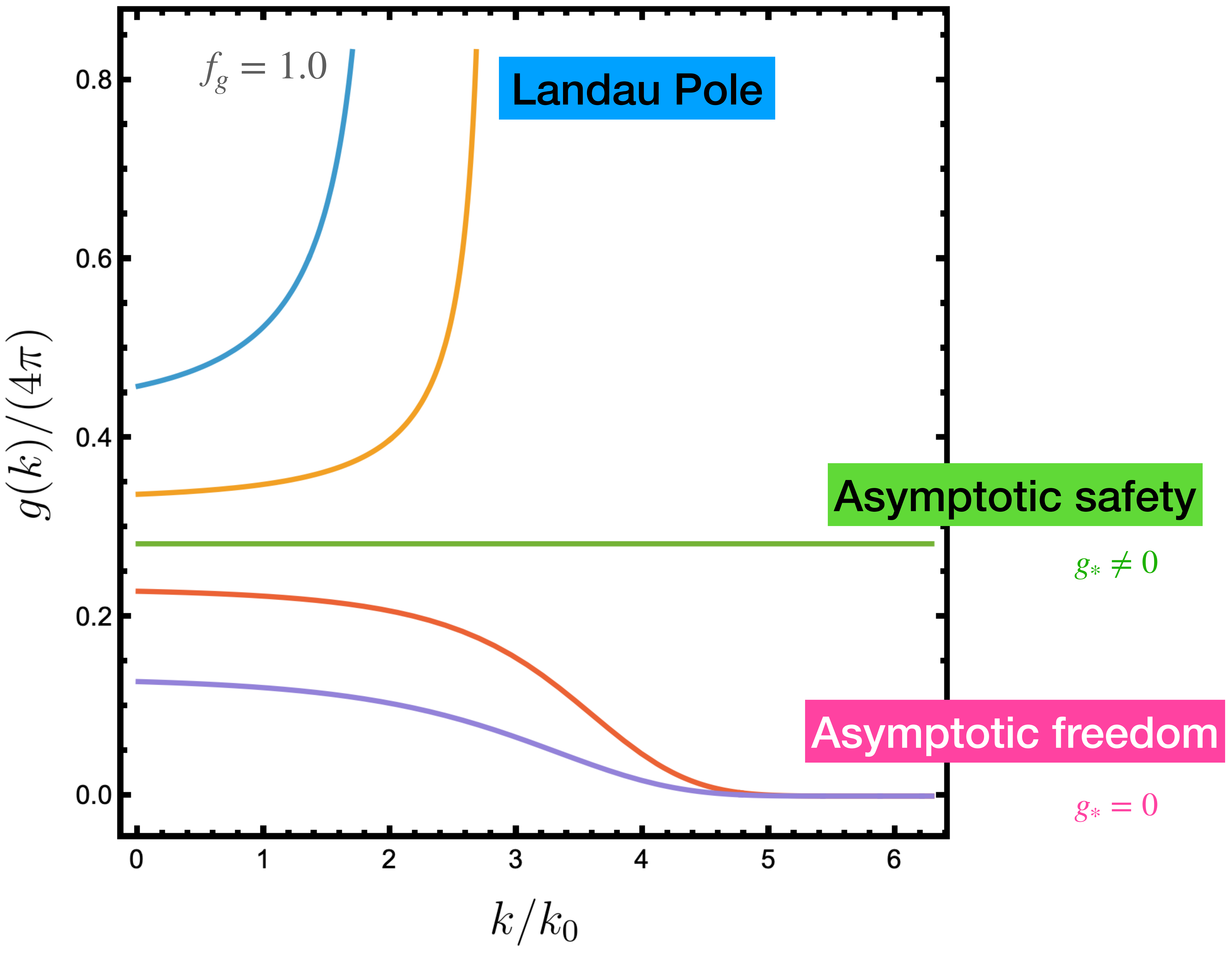


All are from U(1) here



Motivating quantum scale symmetry

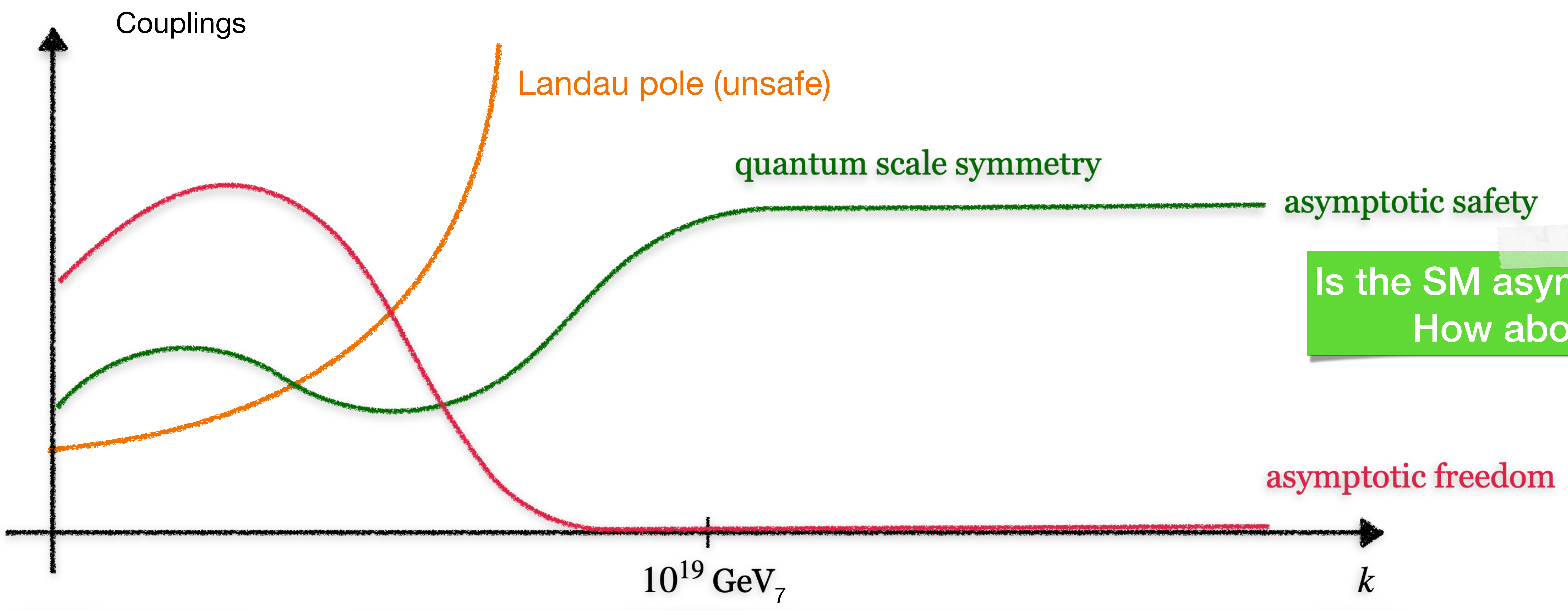
Can heal UV divergences, Landau poles

Weinberg '79

- **Asymptotic safety = quantum scale symmetry**
- Condition: fixed point at UV
- Here UV means, very very large scales, e.g. GUT or Planck scales

U(Y) has Landau pole in the UV (unsafe)

SU(3) is asymptotically free

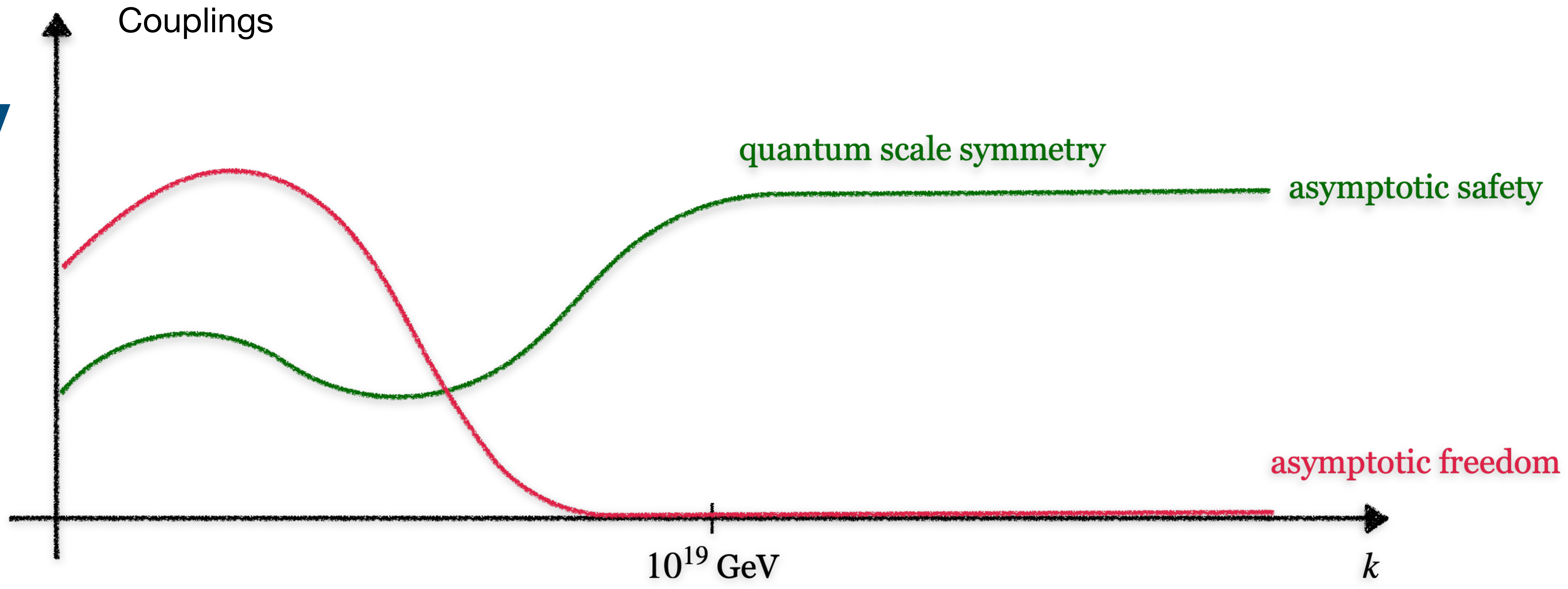


Is the SM asymptotically safe?
How about gravity?

Asymptotic safety

Quantum scale symmetry

$$\beta_{g_i} = \frac{dg_i}{dt}, \qquad t = \ln(k/k_0)$$

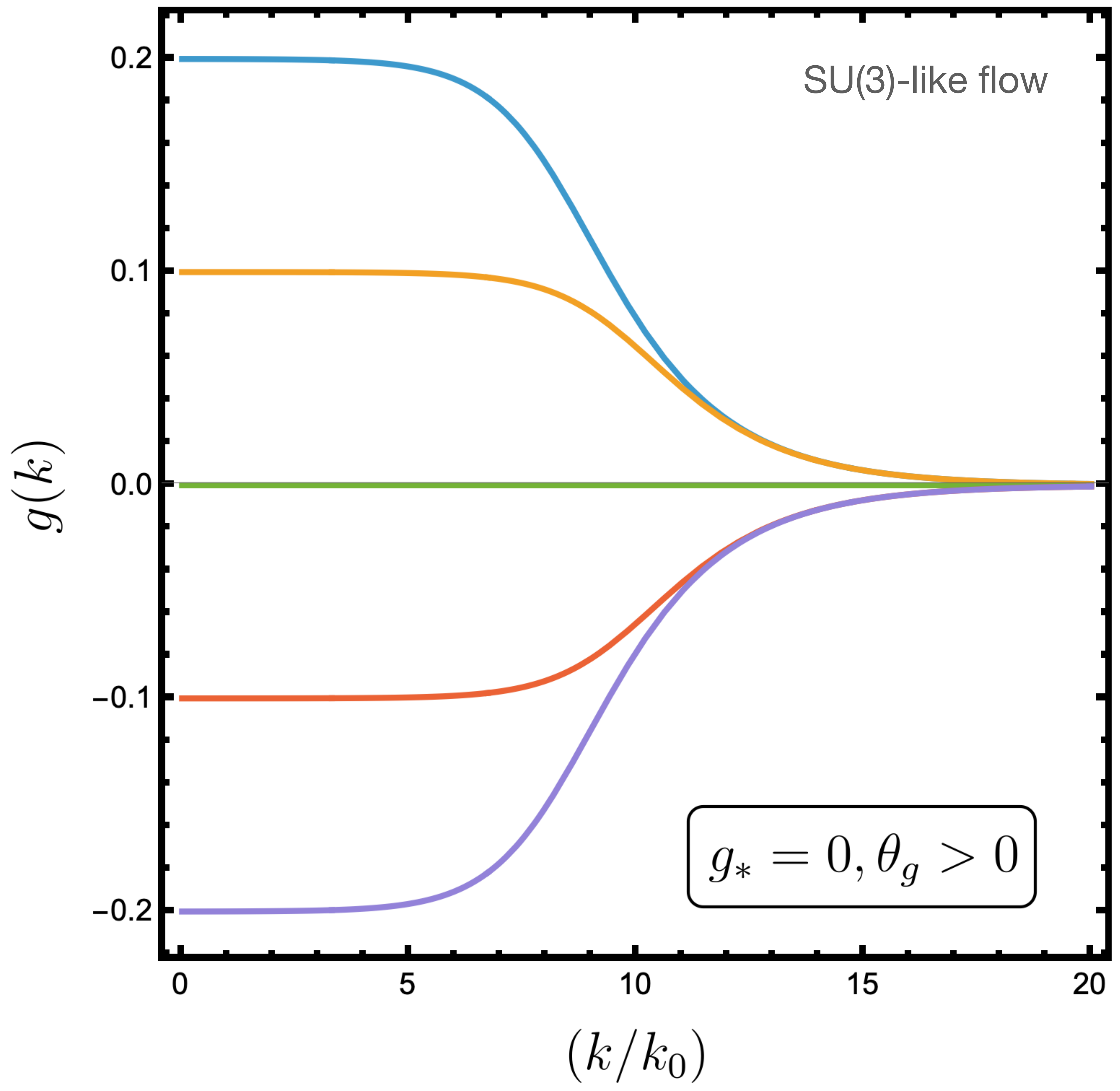


- Asymptotic safety requires
  - interacting fixed point (UV completion).
  - finite number of free parameters (finite number of experiments to fix them).
- All other parameters are predictions.
- Fixed points and critical exponents:
  - Gaussian fixed points: $g_* = 0$
  - Interacting (non-Gaussian) fixed points: $g_* \neq 0$
  - $M_{ij} = \frac{\partial \beta_{g_i}}{\partial g_j}|_{g_*}, \theta_i = -\,\mathrm{eig}(M)\,.$

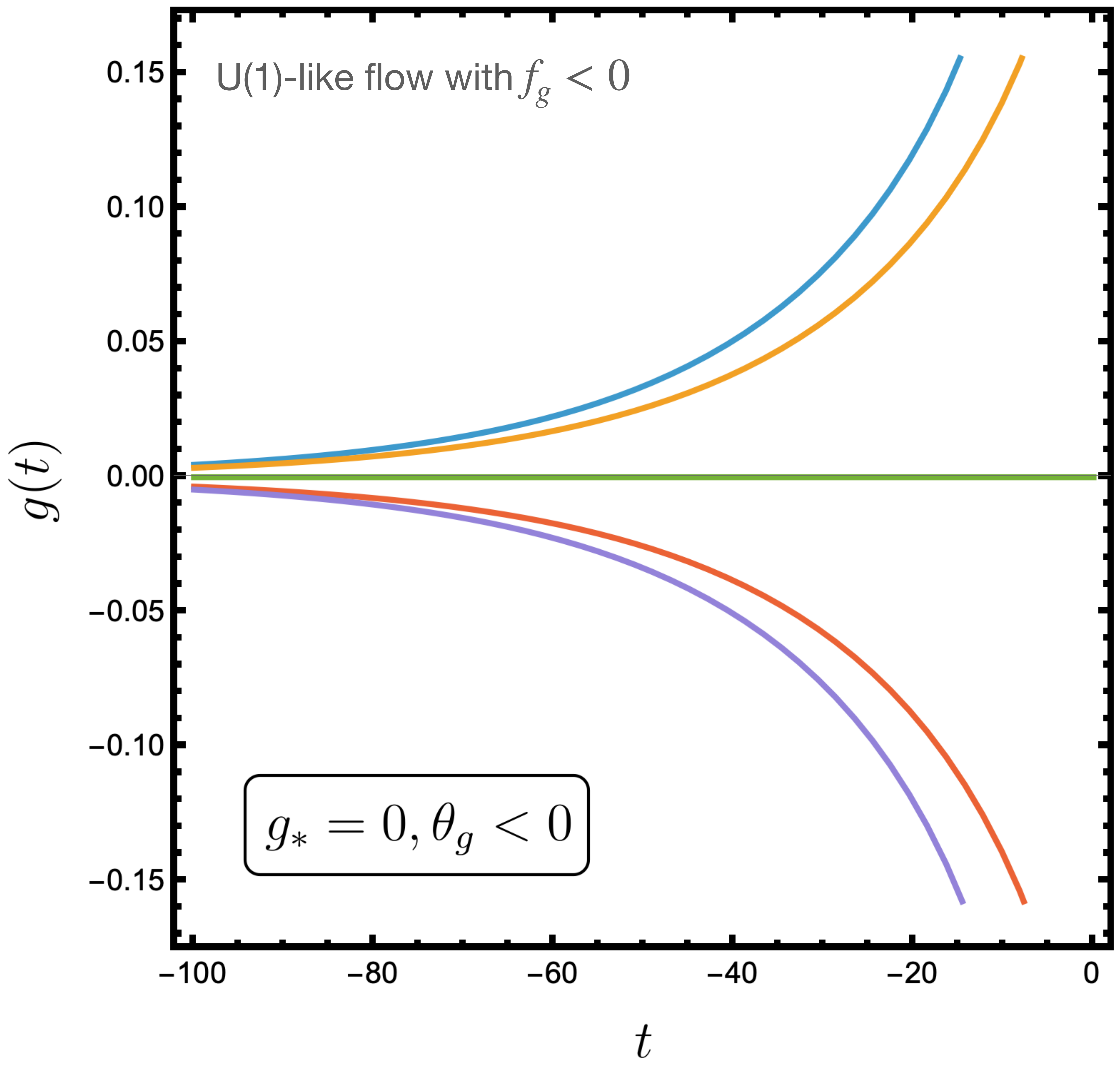
How do we know whether they are free parameters or predictions

Free parameters	$\sim \theta_i > 0$	relevant directions, IR-repulsive
Predictions	$\sim \theta_i < 0$	irrelevant directions, IR-attractive

IR repulsive UV attractive



IR attractive UV repulsive



How do we know whether they are free parameters or predictions

Free parameters ~ $\theta_i > 0$ relevant directions

Predictions ~ $\theta_i < 0$ irrelevant directions

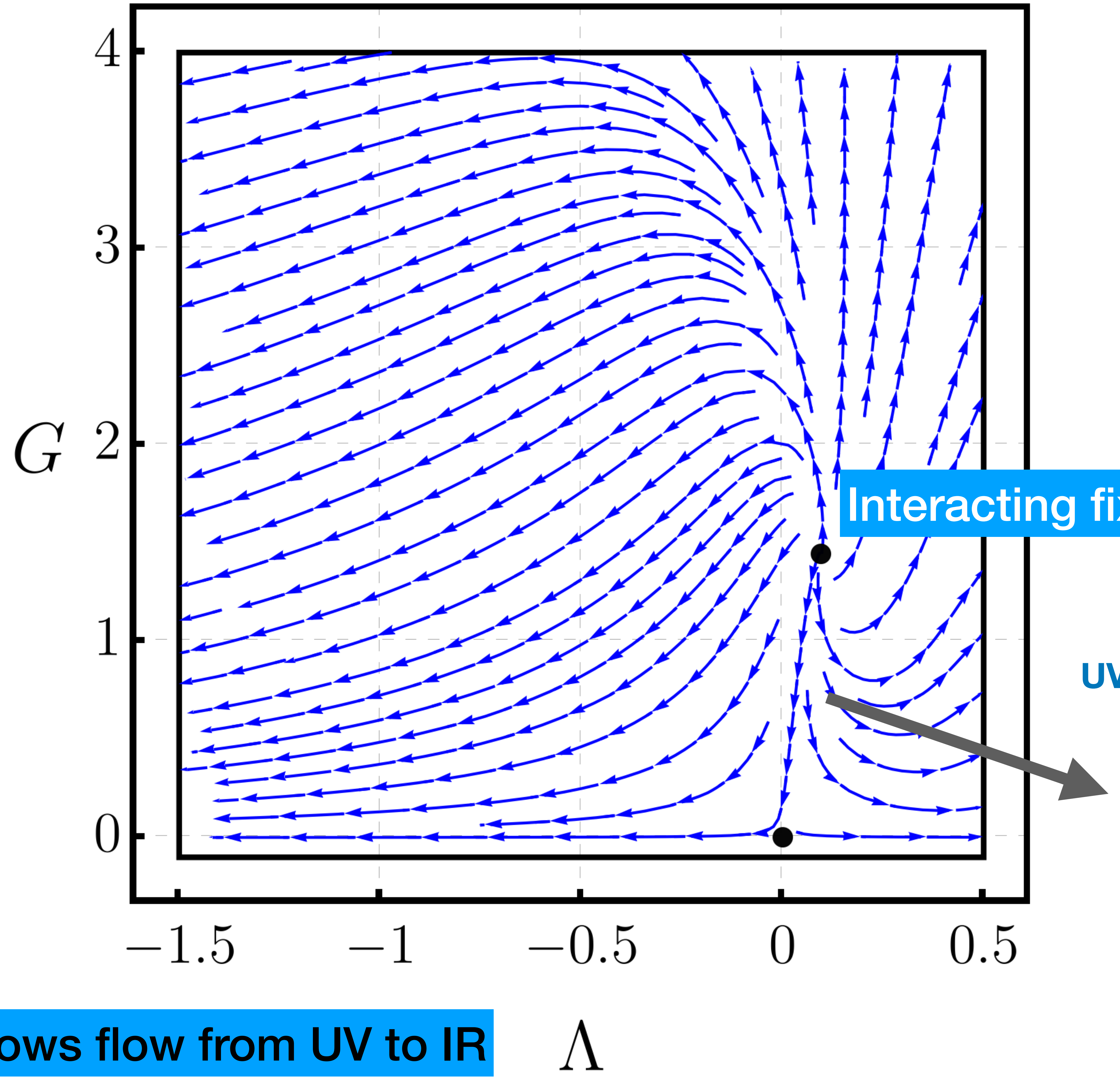
Asymptotic safety

Gravity

Weinberg '79

Seminal work: Reuter, Phys.Rev.D 57 (1998)

Phase space of General Relativity (Einstein-Hilbert truncation)



$$S_{EH} = -\frac{1}{16\pi G_N}\int d^4x\sqrt{g}(R - 2\Lambda_{cc})$$

$$G_N = Gk^{-2}, \Lambda_{cc} = \Lambda k^2$$

@ Transplanckian scale -> UV completion is solved!

UV attractive (Relevant directions) -> free parameters

The flow can bring G_N and Λ_{cc} to small and positive values (Newton constant and de Sitter) at lower scales!

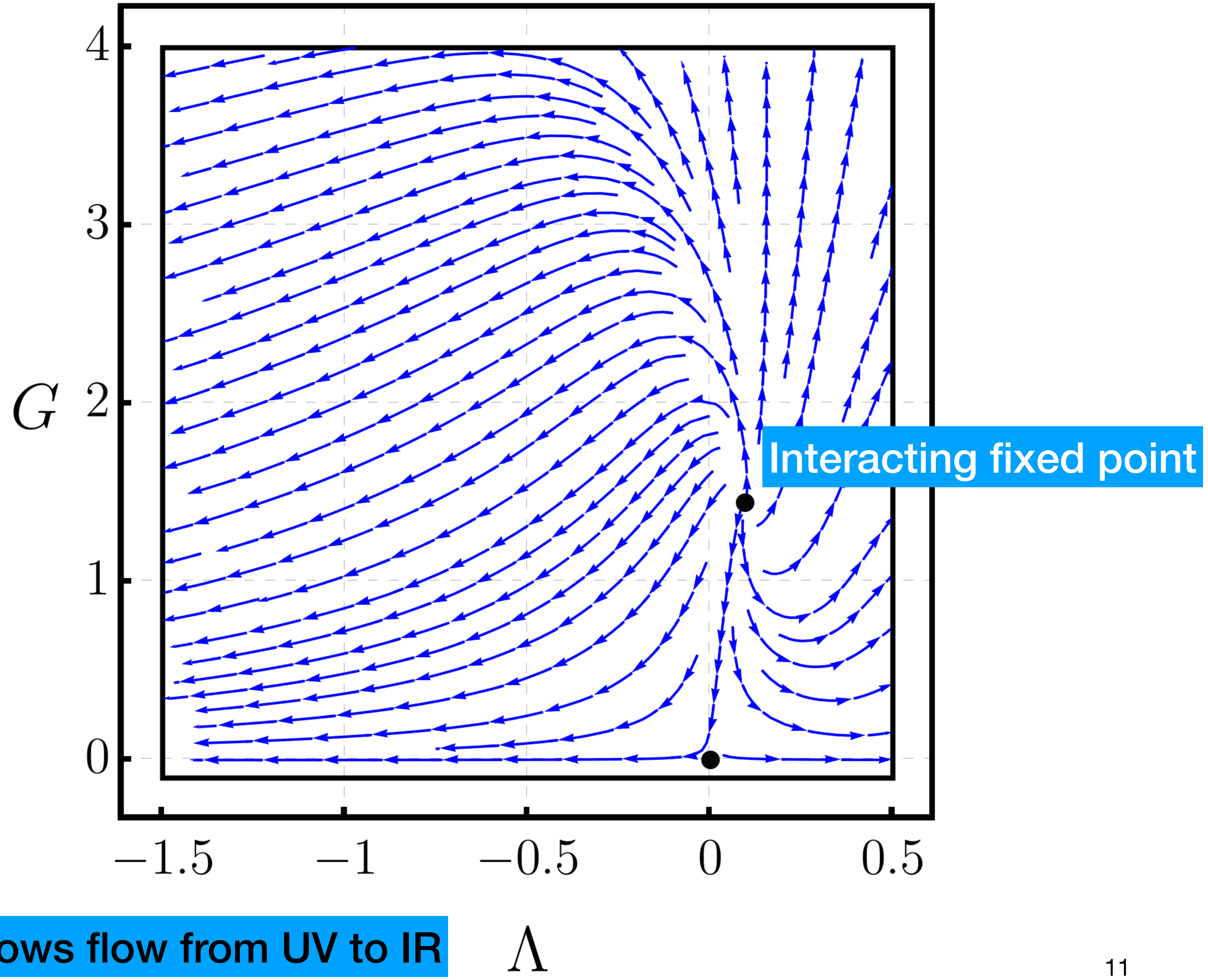
Asymptotic safety

Gravity

Weinberg ‘79

Seminal work: Reuter, Phys.Rev.D 57 (1998)

Phase space of General Relativity (Einstein-Hilbert truncation)



Arrows flow from UV to IR

How does the inclusion of new operators affect the result?

Recent criticism: 2412.14108, 2412.14194, 2506.05100 Branchina et al, 2503.02941 Bonanno et al, 2504.12006 Held et al.

Critical reflections: 1911.02967 Donoghue, 2004.06810 Bonanno et al.

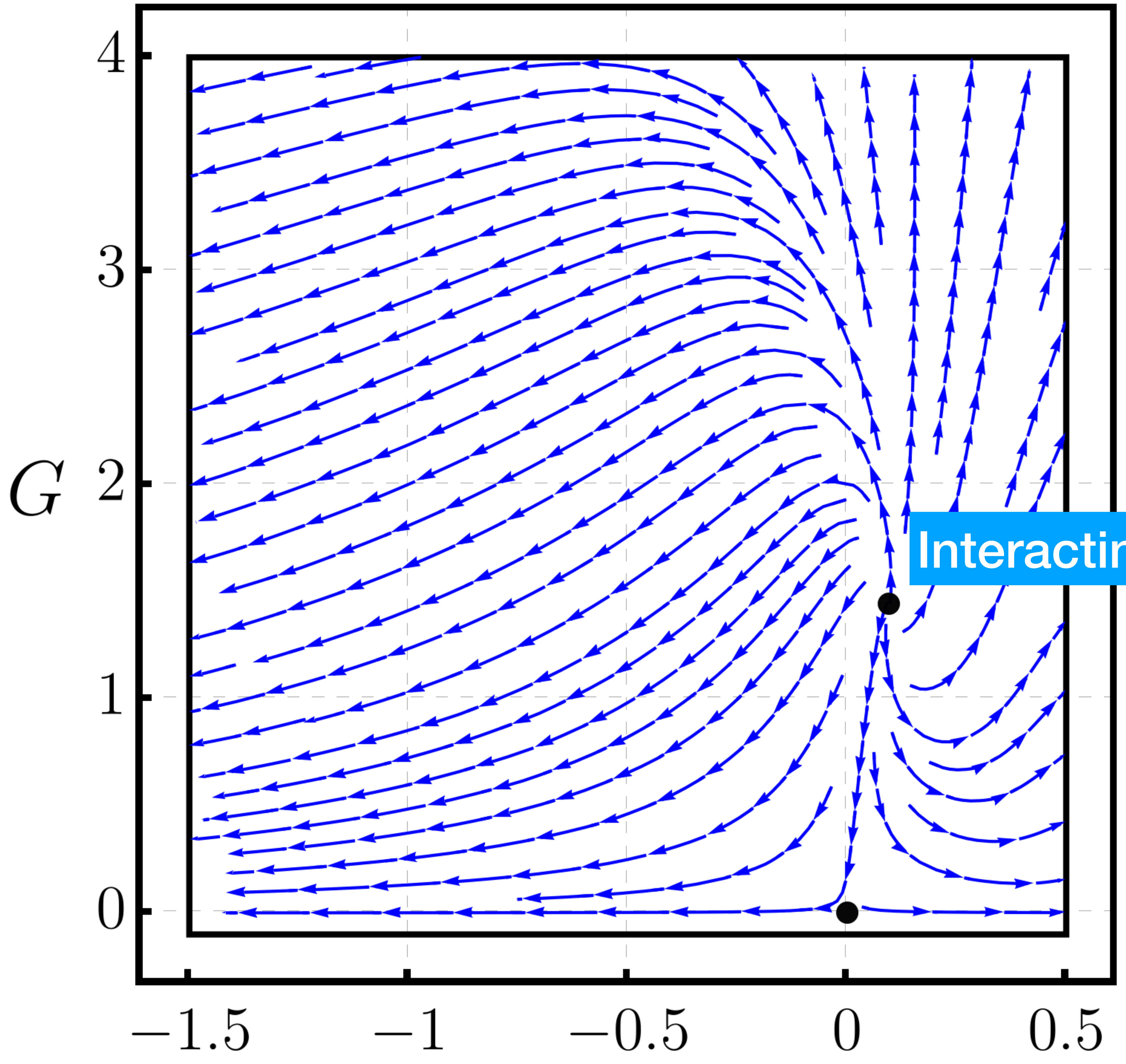
Asymptotic safety

Gravity

Weinberg '79

Seminal work: Reuter, Phys.Rev.D 57 (1998)

Phase space of General Relativity (Einstein-Hilbert truncation)



Arrows flow from UV to IR

How does the inclusion of new operators affect the result?

Evidence for fixed point with only 3 free parameters

operators included beyond Einstein-Hilbert	# rel. dir.	# irrel. dir.	Reθ_1	Reθ_2	Reθ_3
-	2	-	1.94	1.94	-
-	2	-	1.67	1.67	-
$\sqrt{g}R^2$	3	0	28.8	2.15	2.15
$\sqrt{g}R^2, \sqrt{g}R^3$	3	1	2.67	2.67	2.07
$\sqrt{g}R^2, \sqrt{g}R^3$	3	1	2.71	2.71	2.07
$\sqrt{g}R^2, \sqrt{g}R^6$	3	1	2.39	2.39	1.51
$\sqrt{g}R^2, ..., \sqrt{g}R^8$	3	6	2.41	2.41	1.40
$\sqrt{g}R^2, ..., \sqrt{g}R^{34}$	3	32	2.50	2.50	1.59
$\sqrt{g}R^2, \sqrt{g}R_{\mu\nu}R^{\mu\nu}$	3	1	8.40	2.51	1.69
$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda\rho\sigma}C^{\rho\sigma}{}_{\mu\nu}$	2	1	1.48	1.48	-

A. Eichhorn Front.Astron.Space Sci. 5 (2019) 47

See backup slides for more information about calculation and references!

See backup slides for systematic uncertainties

See e.g. review 2212.07456 Eichhorn, Schiffer

Quantum scale symmetry

Interplay between matter and gravity

- Assume the gravitational fixed point exists at transplanckian scales
    - Details of the fundamental physics are unknown
    - But there is <u>quantum scale invariance</u> (fundamental principle)
- How does the gauge couplings run with gravity?

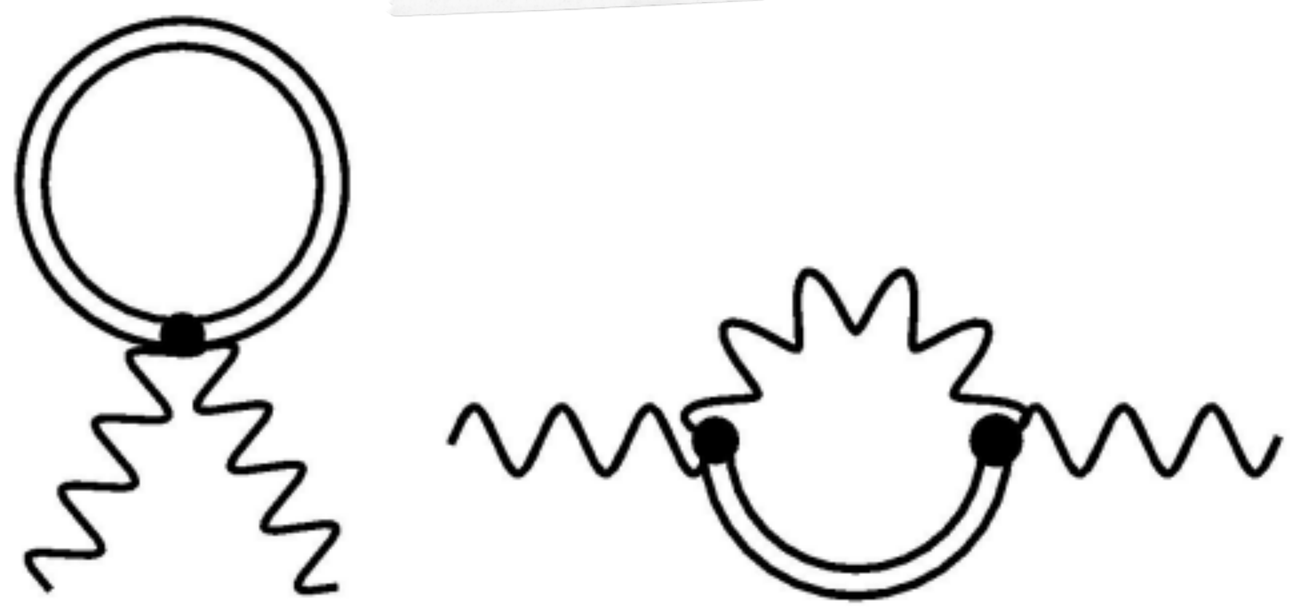
Gravitational correction to matter systems

Interplay between matter gravity - Example

Robinson/Wilczek, Pietrykowski, Toms, Ebert/Plefka/Rodigast ’06-08

- How does the gauge couplings run with gravity?
- Use background field formalism: $\beta_g = \frac{1}{2}\eta_A\, g$
- $\eta_A = \eta_A^{matter}(g) + \underline{\eta_A^{gravity}(G)}$
- Then it is possible to write, at leading order,

$$\beta_{g_i} = \beta_{g_i}^{matter} - f_g\, g_i$$



$$\eta_A^{YM} = \pm \frac{g_{YM}^2}{16\pi^2}$$

Notice: This has the same structure of the beta functions at the beginning of the talk!

$f_g > 0$ gives interacting fixed point for U(1) and preserves asymptotic freedom for SU(3)

See e.g. review 2212.07456 Eichhorn, Schiffer

See some applications in the backup slides

Quantum scale symmetry

Interplay between matter and gravity

- Assume the gravitational fixed point exists at transplanckian scales
    - Details of the fundamental physics are unknown
    - But there is quantum scale invariance (fundamental principle)
- Then, FRG calculations give some $f_g \geq 0$ (gauge) and $f_y > 0$ (Yukawa):
    - $\dfrac{dg_i}{dt} = \beta_{g_i}^{\text{matter}} - \underline{f_g\, g_i}$
    - $\dfrac{dy_i}{dt} = \beta_{y_i}^{\text{matter}} - \underline{f_y\, y_i}$

Corrections are universal, but depend on gravity fixed points

Treat $f_g > 0, f_y > 0$, as free, small coefficients

Use them to match SM particles, pre/pos-dict couplings

For example, use y_t to determine f_y, then predict other y_i

For computations of f_g and f_y in ASQG, see, e.g., 0910.4938 Daum, Harst, Reuter, 1101.5552 Folkerts, Litim, Pawlowski 1707.01107 Eichhorn, Held, 1709.07252 Eichhorn, Versteegen, 2207.09817 Pastor-Gutiérrez, Pawlowski, Reichert

Stabilizing dark matter

Using quantum scale symmetry

Abstract

In the context of gauge-Yukawa theories with trans-Planckian asymptotic safety, quantum scale symmetry can prevent the appearance in the Lagrangian of couplings that would otherwise be allowed by the gauge symmetry. Such couplings correspond to irrelevant Gaussian fixed points of the renormalization group flow. Their absence in the theory implies that different sectors of the gauge-Yukawa theory are secluded from one another, in similar fashion to the effects of a global or a discrete symmetry. As an example, we impose the trans-Planckian scale symmetry on a model of Grand Unification based on the gauge group SU(6), showing that it leads to the emergence of several fermionic WIMP dark matter candidates whose coupling strengths are entirely predicted by the UV completion.

2505.02803 **A. Chikkaballi, K. Kowalska, RRLdS, E. Sessolo**

GUT model - SU(6)

Yukawa couplings

SM

Dark sector

- Minimal anomaly-free fermion content $3 \times \left(\overline{15^{(F)} + \bar{6}_1^{(F)}} + \underline{\bar{6}_2^{(F)}} \right)$
- Scalar content $15^{(S)} + 6_1^{(S)} + 6_2^{(S)} + 21^{(S)} + 35^{(S)}$
- Yukawa Lagrangian

$$\begin{aligned}\mathcal{L} \supset\; & y_{11}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)} + y_{12}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} + y_{21}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)} + y_{22}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} \\ & + \tilde{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)} \\ & + \hat{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{21}^{(S)} + \hat{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)} + \hat{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)} \\ & + y_u\,\mathbf{15}^{(F)}\mathbf{15}^{(F)}\mathbf{15}^{(S)} + \mathrm{H.c.}\end{aligned}$$

SU(6) model @ EWSB scale

Scalar sector: 2HDM + 2 Complex

- $SU(6) \to SU(5) \times U(1)_C \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$
- Scalar sector $15^{(S)} + 6_1^{(S)} + 6_2^{(S)} + 21^{(S)} + 35^{(S)}$
- $15^{(S)} \to \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}; -4\right) + \dots$
- $6_1^{(S)} \to \left(\mathbf{1}, \bar{\mathbf{2}}, -\frac{1}{2}; -1\right) + \dots$

$\Big\}$ 2HDM (H_u, H_d)

- $6_2^{(S)} \to (\mathbf{1}, \mathbf{1}, 0; 5) + \dots$
- $21^{(S)} \to (\mathbf{1}, \mathbf{1}, 0; -10) + \dots$

$\Big\}$ 2C (s_6, s_{21})

vevs break $U(1)_X$ and give mass to a Z'

Spectrum contains SM Higgs + 3 neutral Higgses + 2 Pseudoscalars + 1 charged Higgs

SU(6) model @ EWSB scale

Fermion sector

- $SU(6) \to SU(5) \times U(1)_C \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

$$\bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \supset \bar{\mathbf{5}}_{-1}^{(\mathrm{SM})} \supset d_1,\, L_1 \qquad \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \supset \mathbf{1}_5^{(F)} \supset \nu_1$$
$$\bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \supset \bar{\mathbf{5}}_{-1}^{(F)} \supset d_2,\, L_2 \qquad \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \supset \mathbf{1}_5^{(F)} \supset \nu_2$$
$$\mathbf{15}^{(F)} \supset \mathbf{10}_2^{(\mathrm{SM})} \supset Q,\, u,\, e \qquad \mathbf{15}^{(F)} \supset \mathbf{5}_{-4}^{(F)} \supset d',\, L'\,.$$

- Yukawa Sector

$$\mathscr{L}_{\mathrm{IR}} \supset 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1H_dQ + y_e\, eH_dL_1 + y_\nu\, L'H_d^{c\dagger}\nu_1 + y_D\, d_2d's_6 + y_L\, L'L_2s_6 + y_{\nu_1}\, \nu_1\nu_1s_{21} + y_{\nu_2}\, \nu_2\nu_2s_{21}$$
$$+y_d'\, d_2H_dQ + y_e'\, eH_dL_2 + y_\nu'\, L'H_d^{c\dagger}\nu_2 + y_D'\, d_1d's_6 + y_L'\, L'L_1s_6 + 2\tilde{y}_{11}\, \nu_1H_u^{c\dagger}L_1 + 2\tilde{y}_{22}\, \nu_2H_u^{c\dagger}L_2$$
$$+\tilde{y}_{12}\left(\nu_1H_u^{c\dagger}L_2 + \nu_2H_u^{c\dagger}L_1\right) + \hat{y}_{12}\, \nu_1\nu_2s_{21} + \text{H.c.}$$

- Each generation, 5 neutral massive Majorana fermions

$$Q : \left(\mathbf{3}, \mathbf{2}, \frac{1}{6}; 2\right), \quad u : \left(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3}; 2\right), \quad d_1, d_2 : \left(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}; -1\right), \quad d' : \left(\mathbf{3}, \mathbf{1}, -\frac{1}{3}; -4\right),$$
$$L_1, L_2 : \left(\mathbf{1}, \mathbf{2}, -\frac{1}{2}; -1\right), \quad L' : \left(\mathbf{1}, \bar{\mathbf{2}}, \frac{1}{2}; -4\right), \quad e : (\mathbf{1}, \mathbf{1}, 1; 2), \quad \nu_1, \nu_2 : (\mathbf{1}, \mathbf{1}, 0; 5),$$

$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y_L' v_{s6} & 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u \\ y_L' v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y_\nu' v_d \\ 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u & y_\nu v_d & y_{\nu_1}v_{s21} & \hat{y}_{12}v_{s21} \\ \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u & y_\nu' v_d & \hat{y}_{12}v_{s21} & y_{\nu_2}v_{s21} \end{pmatrix}$$

Spectrum contains SM + 3 ($Q_d' + e' + 4\,N_i$)

Basis: $\langle \nu_{L_1}, \nu_{L_2}, \nu_{L'}, \nu_1, \nu_2 \,|\,, |\, \nu_{L_1}, \nu_{L_2}, \nu_{L'}, \nu_1, \nu_2 \rangle$

SU(6) model @ EWSB scale

Fermion sector

- $SU(6) \to SU(5)\times U(1)_C \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$

- Yukawa Sector

$$\mathscr{L}_{\text{IR}} \supset 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1H_dQ + y_e\, eH_dL_1 + y_\nu\, L'H_d^{c\dagger}\nu_1 + y_D\, d_2d's_6 + y_L\, L'L_2s_6 + y_{\nu_1}\, \nu_1\nu_1s_{21} + y_{\nu_2}\, \nu_2\nu_2s_{21}$$

$$+y'_d\, d_2H_dQ + y'_e\, eH_dL_2 + y'_\nu\, L'H_d^{c\dagger}\nu_2 + y'_D\, d_1d's_6 + y'_L\, L'L_1s_6 + 2\tilde{y}_{11}\, \nu_1H_u^{c\dagger}L_1 + 2\tilde{y}_{22}\, \nu_2H_u^{c\dagger}L_2$$

$$+\tilde{y}_{12}\left(\nu_1H_u^{c\dagger}L_2 + \nu_2H_u^{c\dagger}L_1\right) + \hat{y}_{12}\, \nu_1\nu_2s_{21} + \text{H.c.}$$

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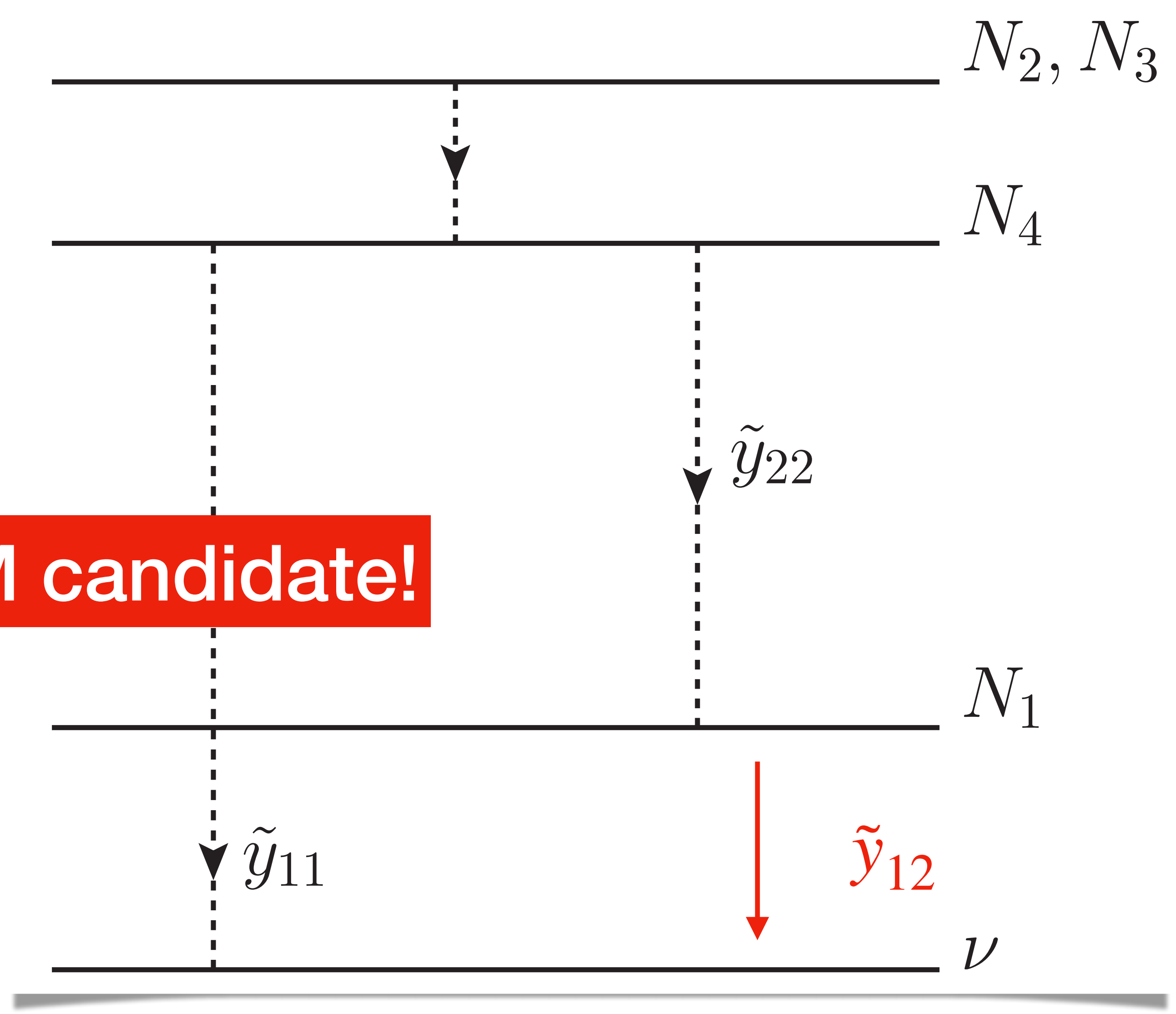
$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y'_L v_{s6} & 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u \\ y'_L v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y'_\nu v_d \\ 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u & y_\nu v_d & y_{\nu_1}v_{s21} & \hat{y}_{12}v_{s21} \\ \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u & y'_\nu v_d & \hat{y}_{12}v_{s21} & y_{\nu_2}v_{s21} \end{pmatrix}$$

There is no stable DM candidate!

$N_4 \sim \nu_1$

$N_1 \sim \nu_2$

$L_1 \supset \nu$



Stabilizing dark matter

Using quantum scale symmetry

- Yukawa Lagrangian

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All operators are invariant under SU(6). But they introduce mixings leading to decays no DM

- i) Introduce global or discrete symmetries — Most works in the literature
- ii) secluding mechanism from quantum scale invariance — Our paper!

For example, SU(6) DM model E. Ma 2011.01398 - 84, instead of $\bar{6}_2$. Mixings are eliminated with Z_2 symmetry.

Stabilizing dark matter

Using quantum scale symmetry

- Yukawa Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset\ & y_{11}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)} + y_{12}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} + y_{21}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)} + y_{22}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} \\
& + \tilde{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)} \\
& + \hat{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{21}^{(S)} + \hat{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)} + \hat{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)} \\
& + y_u\,\mathbf{15}^{(F)}\mathbf{15}^{(F)}\mathbf{15}^{(S)} + \text{H.c.}
\end{aligned}
$$

- Derive beta functions (including gravity contribution) and seek fixed points
  - $\dfrac{dg_i}{dt} = \beta_{g_i}^{\text{matter}} - f_g\, g_i$
  - $\dfrac{dy_i}{dt} = \beta_{y_i}^{\text{matter}} - f_y\, y_i$

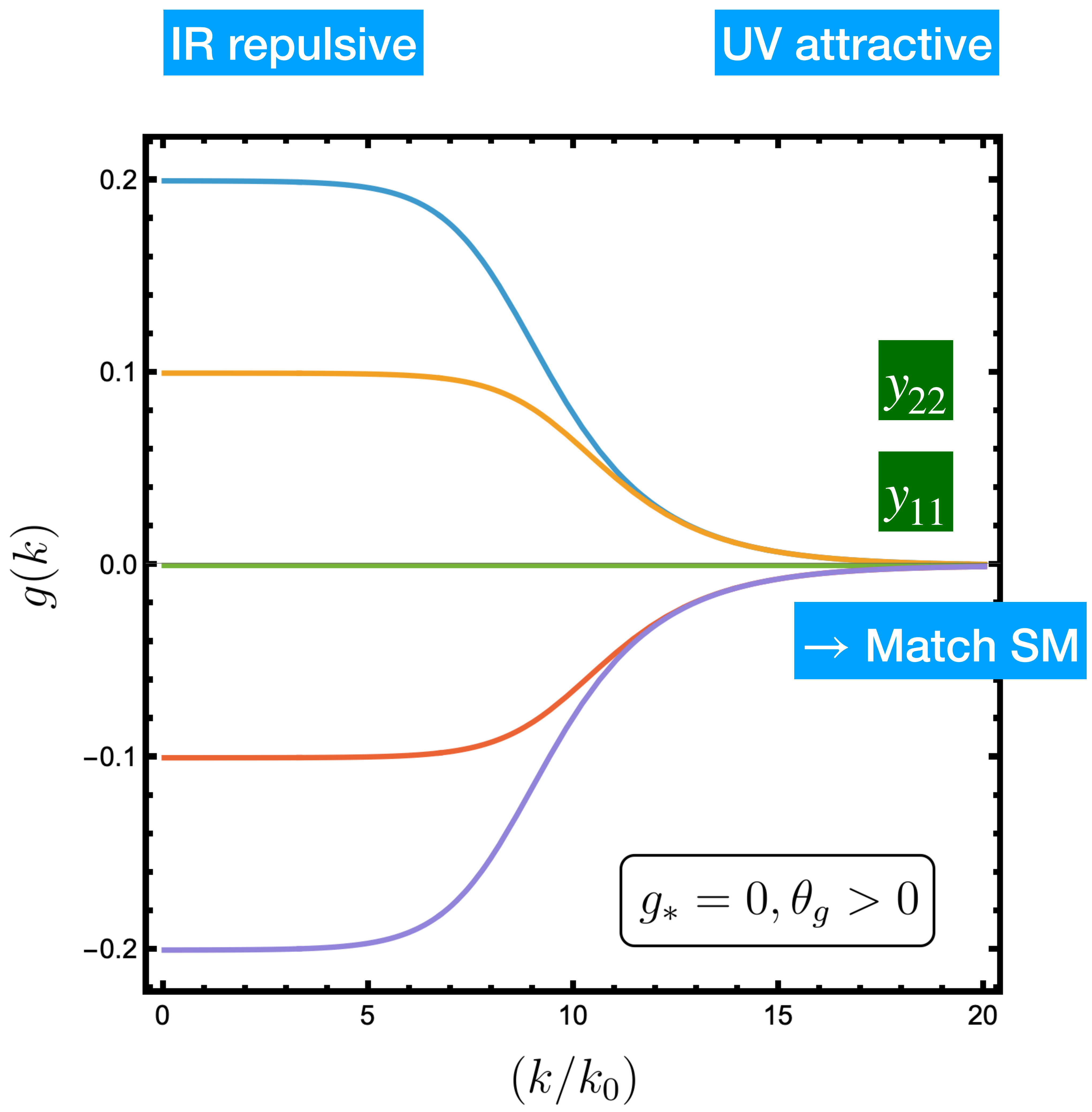
Idea:

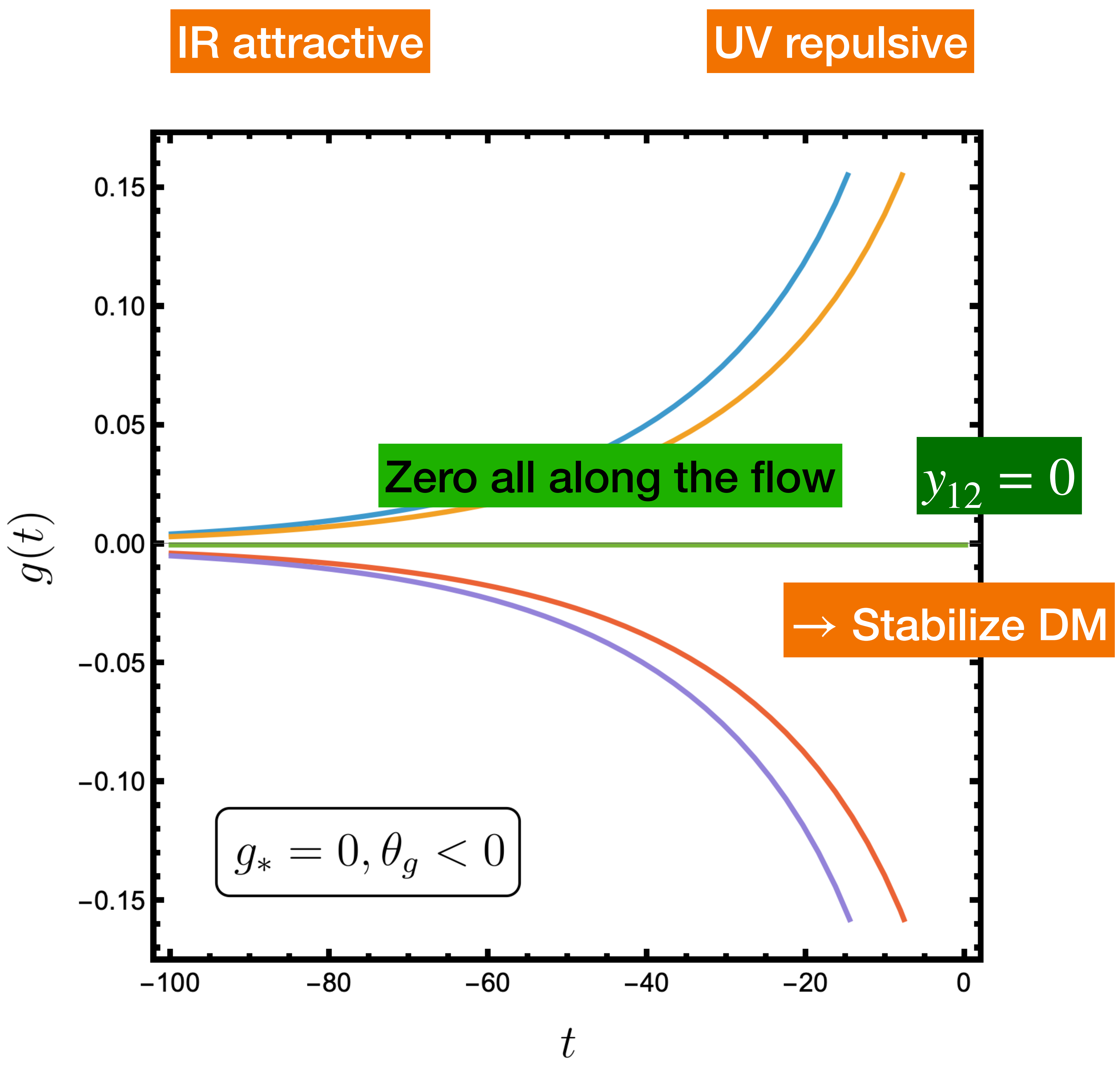
Full system has many fixed points.
Search for a FP solution

$$y_{22}^* \neq 0, y_{11}^* = y_{12}^* = y_{21}^* = 0.$$

$$\theta_{11} > 0, \theta_{12}, \theta_{21} < 0$$

Free parameter **Predictions**





Full system has many fixed points.
Search for a FP solution

$$y^*_{22} \neq 0, y^*_{11} = y^*_{12} = y^*_{21} = 0.$$

$$\theta_{11} > 0, \theta_{12}, \theta_{21} < 0$$

Free parameters	~ $\theta_i > 0$	relevant directions
Predictions	~ $\theta_i < 0$	irrelevant directions

Stabilizing dark matter

Dark matter candidates

- Before SSB

$$\begin{aligned}\mathcal{L} \supset\ & \underline{y_{11} \mathbf{15}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(S)}} + \cancel{y_{12} \mathbf{15}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(S)}} + \cancel{y_{21} \mathbf{15}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(S)}} + \underline{y_{22} \mathbf{15}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(S)}} \\ & \cancel{+ \tilde{y}_{11} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \mathbf{15}^{(S)} + \tilde{y}_{12} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \mathbf{15}^{(S)} + \tilde{y}_{22} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \mathbf{15}^{(S)}} \\ & + \underline{\hat{y}_{11} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \mathbf{21}^{(S)}} + \cancel{\hat{y}_{12} \bar{\mathbf{6}}_{\mathbf{1}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \mathbf{21}^{(S)}} + \underline{\hat{y}_{22} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \bar{\mathbf{6}}_{\mathbf{2}}^{(F)} \mathbf{21}^{(S)}} \\ & + \underline{y_u \mathbf{15}^{(F)} \mathbf{15}^{(F)} \mathbf{15}^{(S)}} + \text{H.c.}\end{aligned}$$

- After SSB

y_u (up quarks): Fix f_y by matching to top quark mass

Free parameters

$$\boxed{\begin{aligned}\mathcal{L}_{\text{IR1}} \supset\ & \underline{2y_u\, u H_u^{c\dagger} Q} + \underline{y_d\, d_1 H_d Q + y_e\, e H_d L_1 + y_\nu\, L' H_d^{c\dagger} \nu_1} \\ & \underline{+ y_D\, d_2 d' s_6 + y_L\, L' L_2 s_6} + \underline{y_{\nu_1}\, \nu_1 \nu_1 s_{21} + y_{\nu_2}\, \nu_2 \nu_2 s_{21}} + \text{H.c.}\,,\end{aligned}}$$

Predictions

DM and neutrino are predictions of the theory

- From RG flow

$\tan\beta = 1$

SU(6)	y_u	y_{22}		$\hat{y}_{11}$	$\hat{y}_{22}$	y_{11}	
	y_u	y_D	y_L	y_{ν_1}	y_{ν_2}	y_d	y_ν
$\mu = 1\,\text{TeV}$	0.69	1.1	0.55	0.57	0.51	0.027	0.014

From gauge coupling unification and RG flow: $g_X = 0.07$

Gives correct SM particle masses

Many decays are forbidden: can have DM candidates!

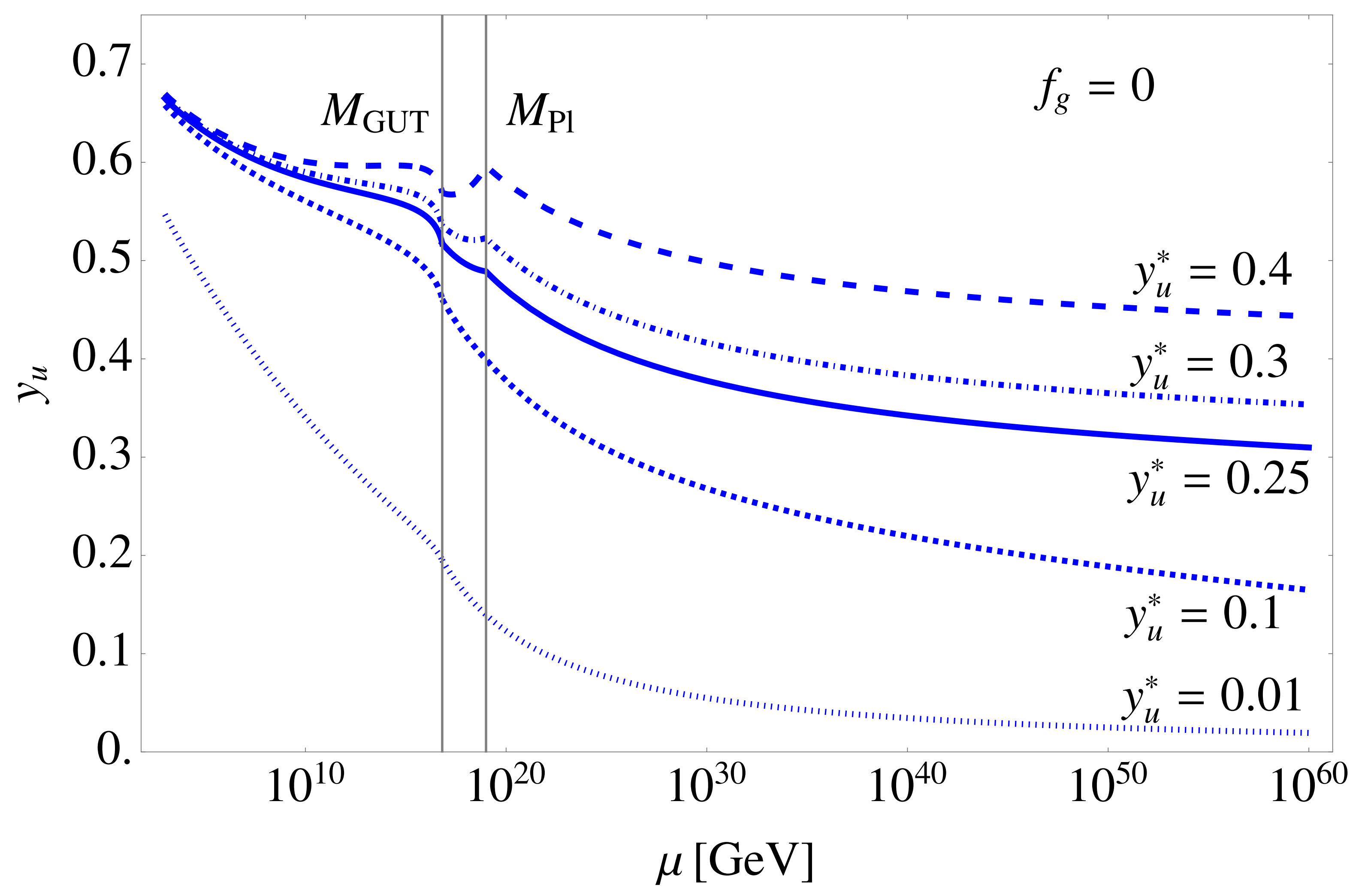
Stabilizing dark matter

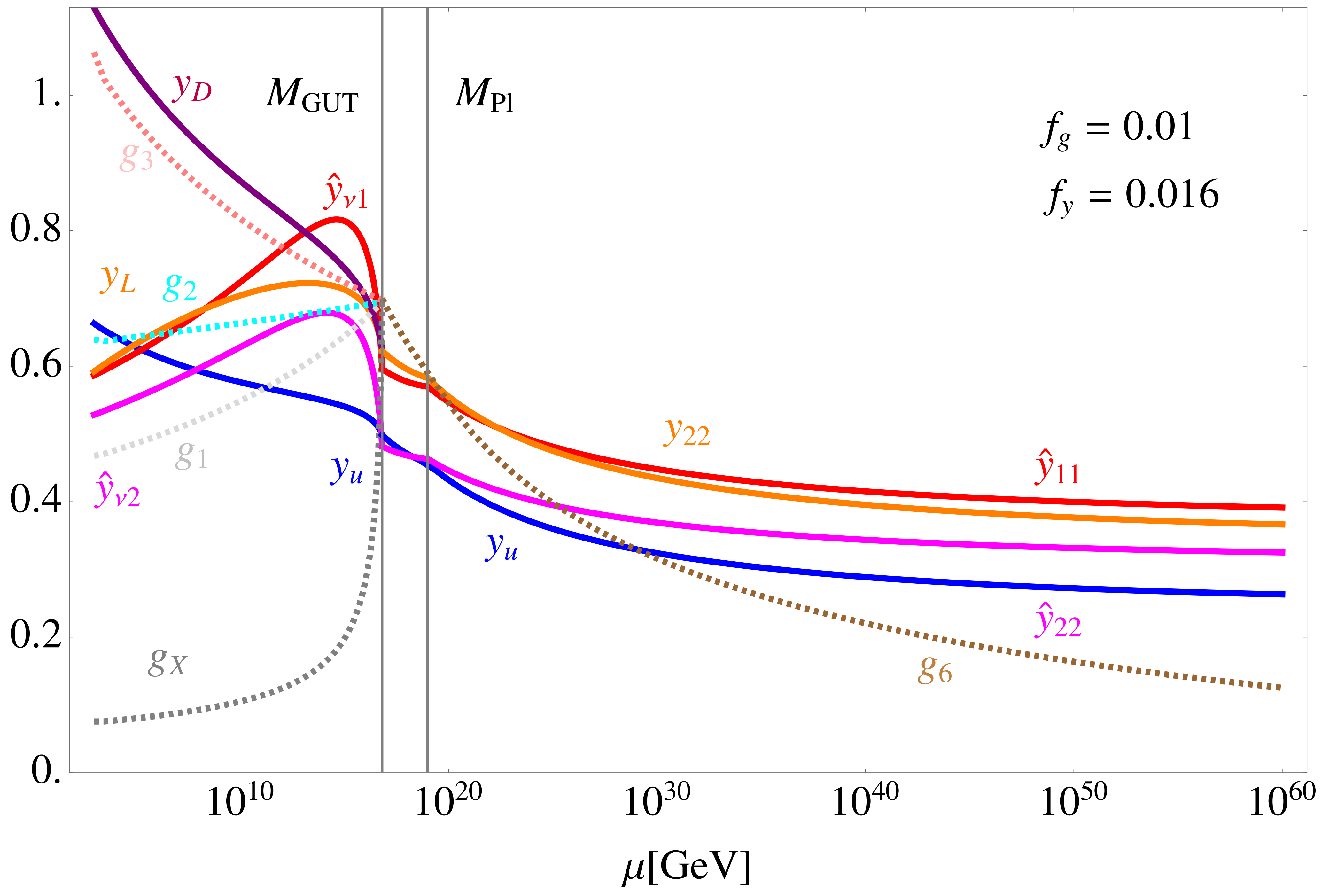
Impact of f_g and f_y in our model

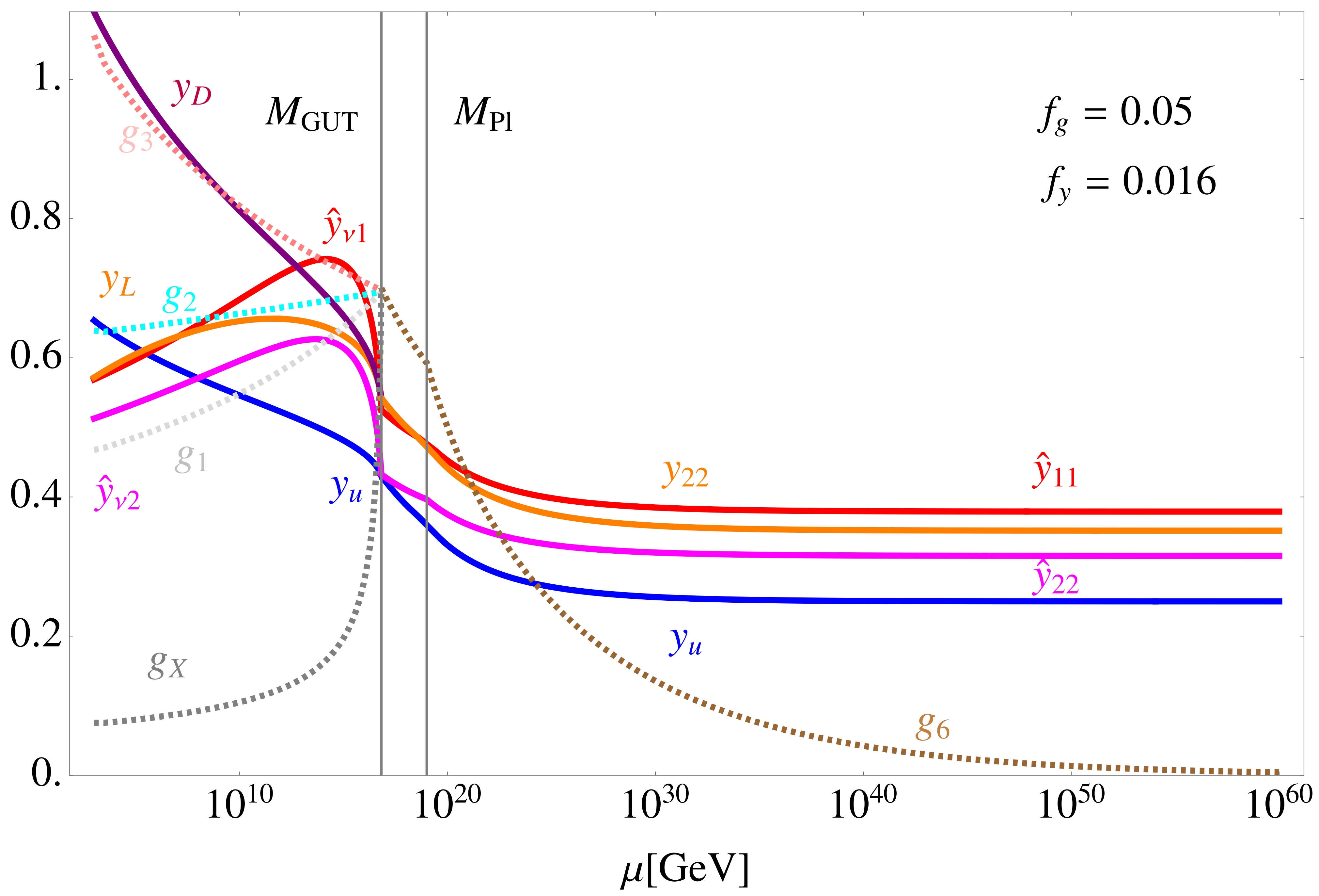
Predictions independent on f_g to a large extent

Needs to be careful with f_y

y_u (up quarks): Fix f_y by matching to top quark mass







$\tan\beta = 1 \quad m_u = m_{top,SM}$

See also Kotlarski, Kowalska, Sessolo 2304.08959

Stabilizing dark matter

Dark matter candidates

$$\boxed{\begin{aligned}\mathcal{L}_{\text{IR1}} \supset\ & 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1 H_d Q + y_e\, eH_d L_1 + y_\nu\, L' H_d^{c\dagger}\nu_1 \\ & + y_D\, d_2 d' s_6 + y_L\, L' L_2 s_6 + y_{\nu_1}\, \nu_1\nu_1 s_{21} + y_{\nu_2}\, \nu_2\nu_2 s_{21} + \text{H.c.}\,,\end{aligned}}$$

$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y'_L v_{s6} & 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u \\ y'_L v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y'_\nu v_d \\ 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u & y_\nu v_d & y_{\nu_1}v_{s21} & \hat{y}_{12}v_{s21} \\ \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u & y'_\nu v_d & \hat{y}_{12}v_{s21} & y_{\nu_2}v_{s21} \end{pmatrix}$$

DM is stable

$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & y_L v_{s6} & 0 & 0 \\ 0 & y_L v_{s6} & 0 & y_\nu v_d & 0 \\ 0 & 0 & y_\nu v_d & y_{\nu_1}v_{s21} & 0 \\ 0 & 0 & 0 & 0 & y_{\nu_2}v_{s21} \end{pmatrix}$$

3rd generation neutrino is massless

Sectors have been secluded: two component dark matter

Stabilizing dark matter

Turning on small couplings

- "Naturally small Yukawa couplings"

  Kowalska, Pramanick, Sessolo 2204.00866

  - Different FP structure (1st and 2nd gens)

- Inverted ordering

  - 3rd generation neutrino is massless

  - 1st and 2nd neutrinos are massive

- Dynamical suppression of couplings

1st and 2nd generations

Notice: new fixed-point structure

Now relevant directions -> free parameters!

y_u^*	y_{22}^*	$\hat{y}_{11}^*$	$\hat{y}_{22}^*$	y_{11}^*	y_{12}^*	y_{21}^*	$\tilde{y}_{11}^*$	$\tilde{y}_{12}^*$	$\tilde{y}_{22}^*$	$\hat{y}_{12}^*$
0.0	0.54	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
θ_t	θ_{22}	$\hat{\theta}_{11}$	$\hat{\theta}_{22}$	θ_{11}	θ_{12}	θ_{21}	$\tilde{\theta}_{11}$	$\tilde{\theta}_{12}$	$\tilde{\theta}_{22}$	$\hat{\theta}_{12}$
1.9	−5.0	2.5	1.0	2.2	0	0	2.5	1.8	1.0	1.8

$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y'_L v_{s6} & 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u \\ y'_L v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y'_\nu v_d \\ \underline{2\tilde{y}_{11}v_u} & \tilde{y}_{12}v_u & y_\nu v_d & y_{\nu_1}v_{s21} & \hat{y}_{12}v_{s21} \\ \underline{\tilde{y}_{12}v_u} & 2\tilde{y}_{22}v_u & y'_\nu v_d & \hat{y}_{12}v_{s21} & y_{\nu_2}v_{s21} \end{pmatrix}$$

Mechanism gives realistic mass to the first and second neutrino generations

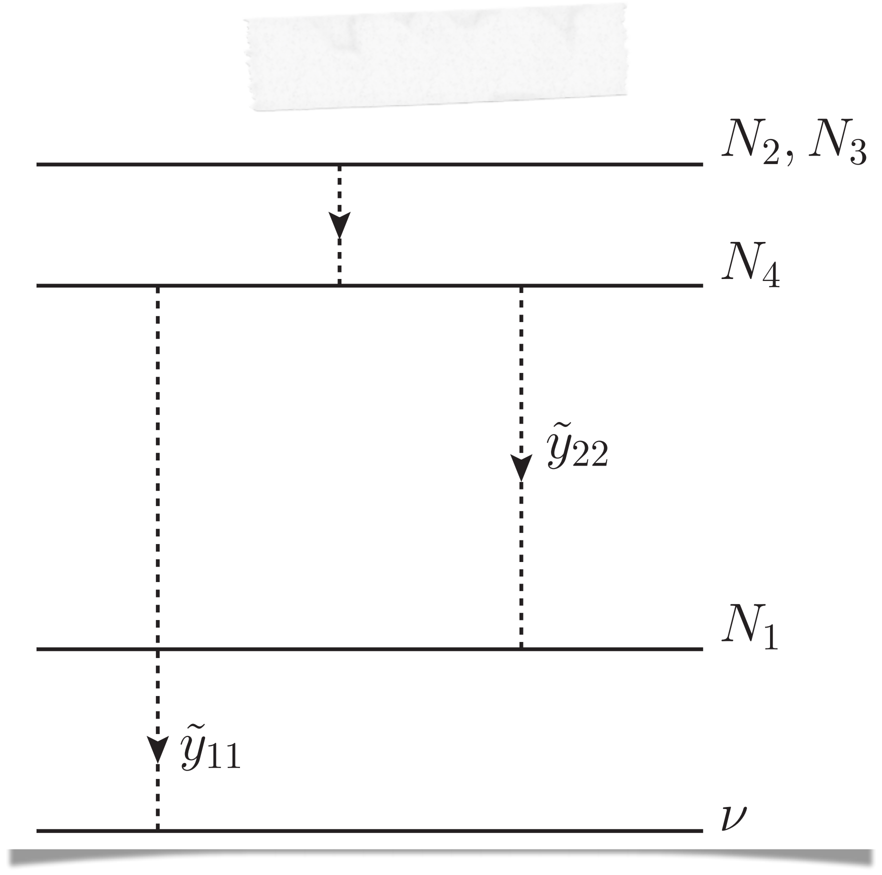
A) Only lightest neutrino is massless.

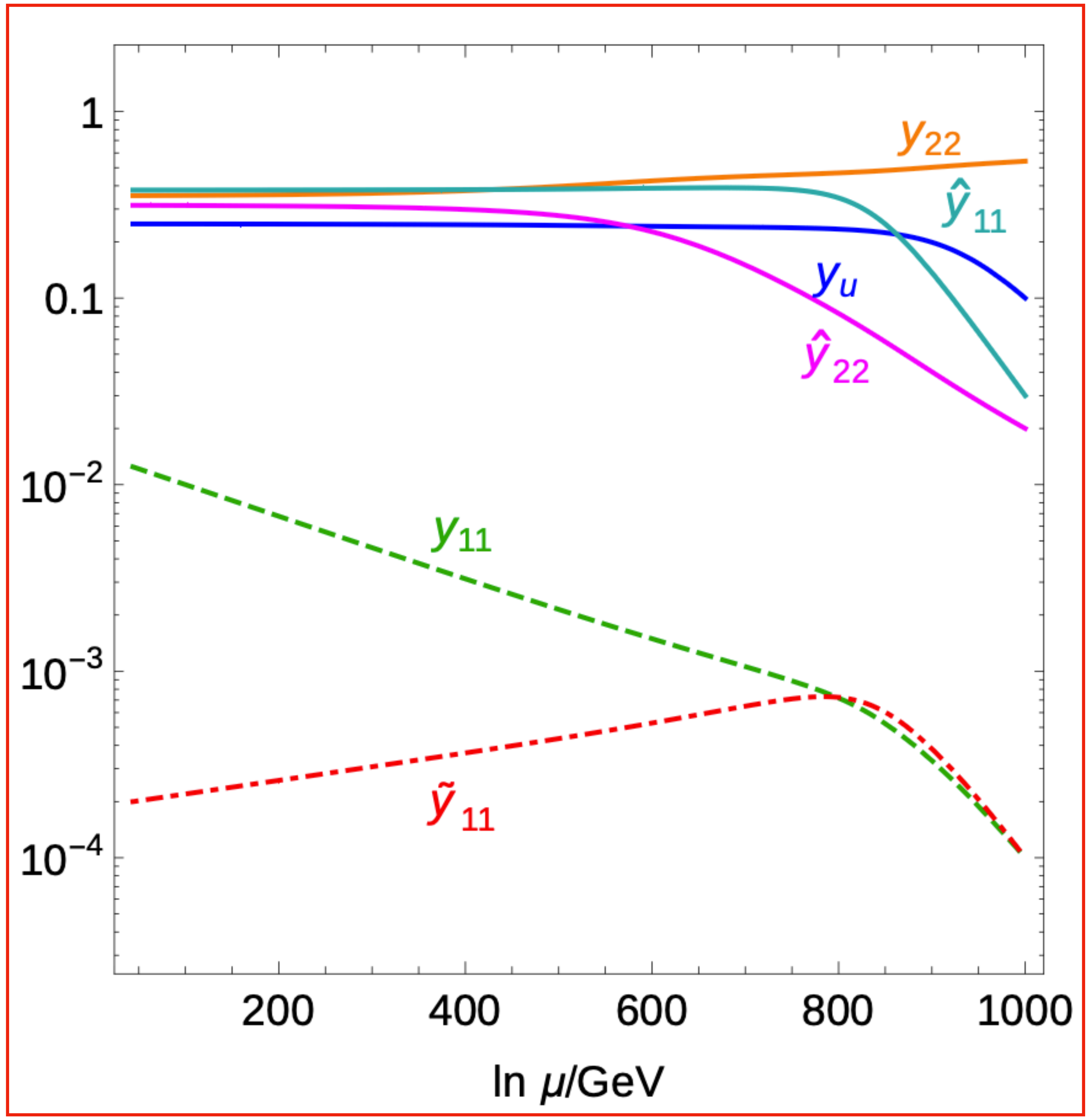
B) Two DM candidates -> Single DM candidate

Stabilizing dark matter

Turning on small couplings

- “Naturally small Yukawa couplings”
    - Different FP structure (1st and 2nd)
- Inverted ordering
- Dynamical suppression of couplings





Kowalska, Pramanick, Sessolo 2204.00866

A) Only lightest neutrino is massless.
B) Two DM candidates -> Single DM candidate

1st and 2nd generations

Also 3rd generation

Stabilizing dark matter

Single Dark Matter candidates

Analytical expressions can be used

See backup slides

$v_{s6} > v_{s21}$ **Singlet DM**

$v_{s6} < v_{s21}$ **Doublet DM (Higgsino-like)**

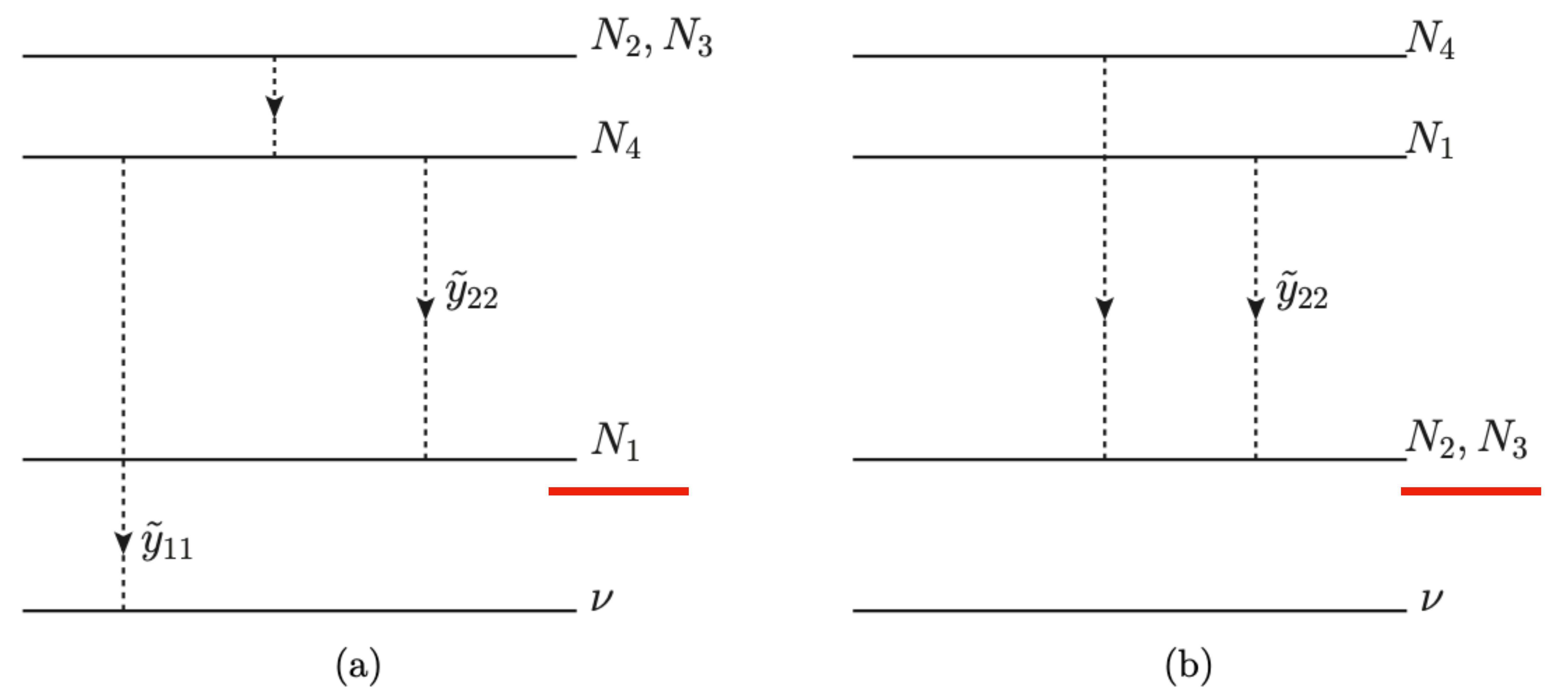


Figure 4: Decay chains of the heavy Majorana fermions N_1, N_2, N_3, and N_4 in the presence of non-zero (yet arbitrarily small) Yukawa couplings $\tilde{y}_{11}$ and $\tilde{y}_{22}$.

$$\delta m_{\rm DM} \equiv m_{N_3} - m_{N_2} = \sqrt{2}\frac{y_\nu^2 v_d^2}{y_{\nu_1} v_{s_{21}}}$$

Two-component dark matter also possible. Work in progress: Numerical analysis 2HDM2CF— WK, KK, RRLdS, EMS

See analytical expressions in backup slides

Stabilizing dark matter

Single Dark Matter candidates

Singlet DM

Upper bound on the Z' mass around 9 TeV

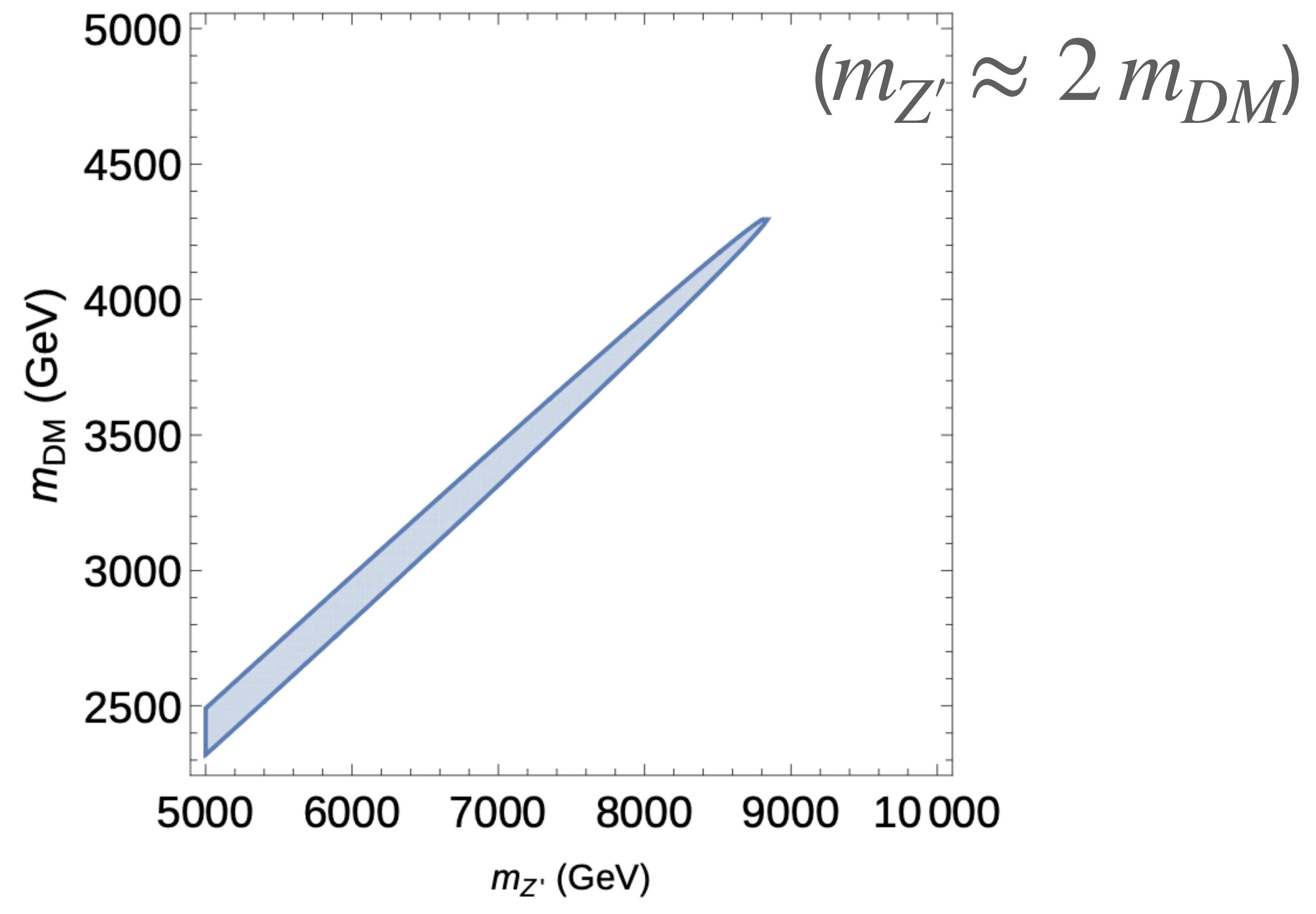
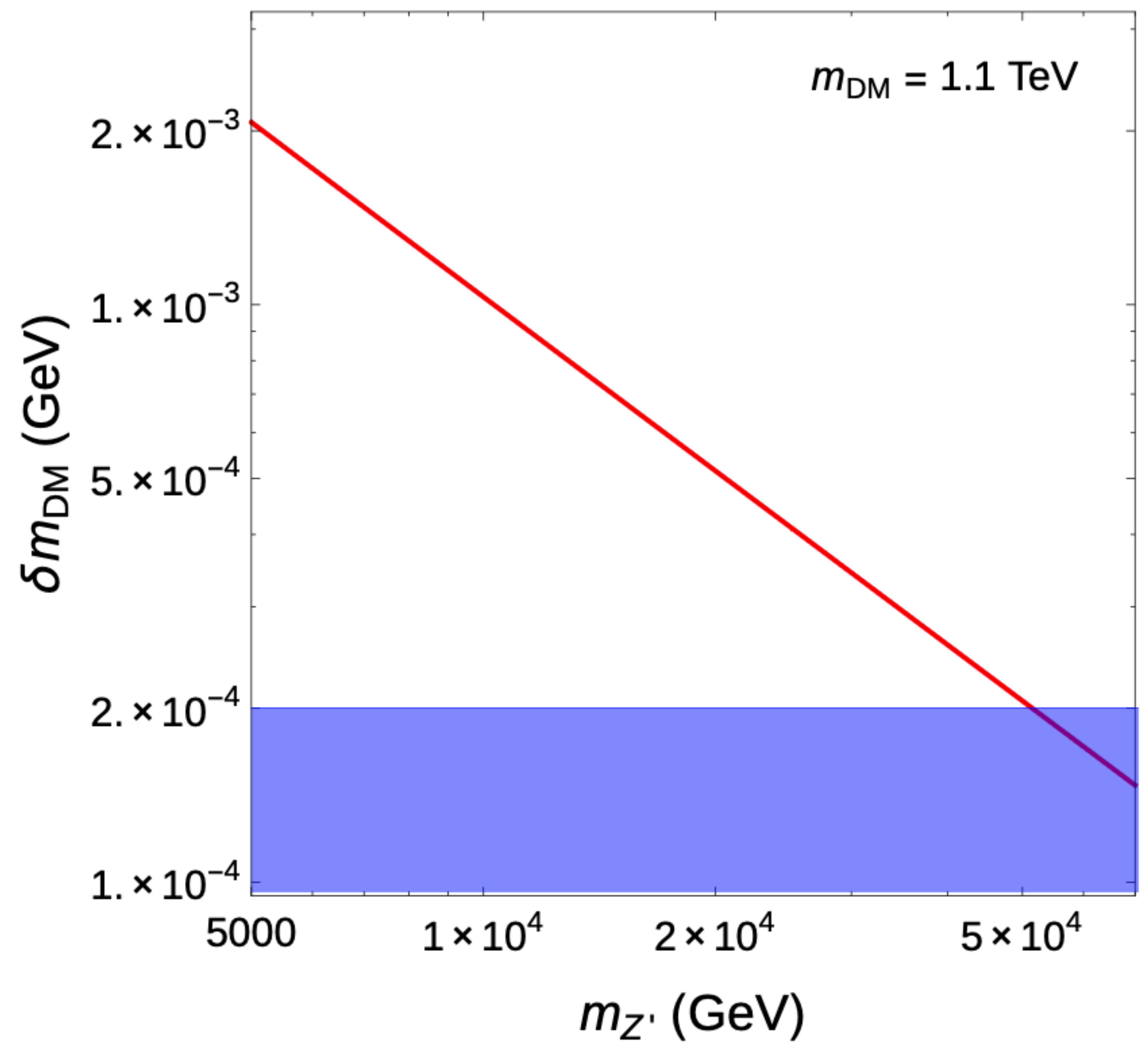


Figure 5: The region of under-abundant relic density (in blue) in the SM-singlet DM case.

Doublet DM (Higgsino-like)

Upper bound on the Z' mass around 50 TeV



Upper bound on $\delta\, m_{DM} \approx 0.2$ MeV comes from inelastic scattering limits (SI DM-nucleon)

See also Dirac DM in ASQG Reichert, Smirnov 1911.00012 (upper bound Z' mass around 100 TeV)

Final remarks

- We assumed quantum scale symmetry as fundamental principle
    - Not concerned with the quantum theory of gravity
- Rather, what are the effects at lower energy scales?
    - Quantum scale symmetry forbids the appearance of couplings/decays
    - Couplings can be made arbitrarily small dynamically
        - DM is stable and decays are controlled
        - No need for extra global, discrete symmetries

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Dziękuję!

Thank you!

rafael.santos@ncbj.gov.pl

2505.02803

Backup slide

Stabilizing dark matter

Using quantum scale symmetry

- Yukawa Lagrangian

$$
\begin{aligned}
\mathcal{L} \supset\ & y_{11}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)} \cancel{+ y_{12}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} + y_{21}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(S)}} + y_{22}\mathbf{15}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(S)} \\
& \cancel{+ \tilde{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)} + \tilde{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{15}^{(S)}} \\
& + \hat{y}_{11}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\mathbf{21}^{(S)} \cancel{+ \hat{y}_{12}\,\bar{\mathbf{6}}_{\mathbf{1}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)}} + \hat{y}_{22}\,\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\bar{\mathbf{6}}_{\mathbf{2}}^{(F)}\mathbf{21}^{(S)} \\
& + y_u\,\mathbf{15}^{(F)}\mathbf{15}^{(F)}\mathbf{15}^{(S)} + \mathrm{H.c.}
\end{aligned}
$$

- Derive beta functions (including gravity contribution) and seek fixed points

y_u (up quarks): Fix f_y by matching to top quark mass

DM and neutrino are predictions of the theory

y_u^*	y_{22}^*	$\hat{y}_{11}^*$	$\hat{y}_{22}^*$	y_{11}^*	y_{12}^*	y_{21}^*	$\tilde{y}_{11}^*$	$\tilde{y}_{12}^*$	$\tilde{y}_{22}^*$	$\hat{y}_{12}^*$
0.25	0.35	0.38	0.32	0.0	0.0	0.0	0.0	0.0	0.0	0.0
θ_u	θ_{22}	$\hat{\theta}_{11}$	$\hat{\theta}_{22}$	θ_{11}	θ_{12}	θ_{21}	$\tilde{\theta}_{11}$	$\tilde{\theta}_{12}$	$\tilde{\theta}_{22}$	$\hat{\theta}_{12}$
-4.5	-2.1	-4.6	-3.2	0.62	-0.31	0	-0.26	-0.26	-0.26	-3.4

Table 1: Upper line: Trans-Planckian fixed points of the SU(6) Yukawa couplings for an arbitrary choice of $f_y = 0.016$. Lower line: The corresponding critical exponents times $16\pi^2$.

Notice the y_{ij} satisfy the conditions we considered before

Irrelevant parameters remaining zero along the flow

$g_{6,*} = 0$

Stabilizing dark matter

Singlet Dark Matter candidate

- Relic density
- Mediated channels through resonant Z' $(m_{Z'} = 2\, m_{DM})$
  - Focus on the gauge-Yukawa sector (asymptotic safety)
- Singlet DM analysis U(1)-extension SM

Gondolo, Gelmini Nucl. Phys. B 360 (1991) 145-179
Okada, Okada, Raut 1811.11927

$$\langle \sigma v \rangle = \frac{1}{16\pi^4} \left(\frac{m_{\rm DM}}{x_f} \right) \frac{1}{n_{\rm eq}^2} \int_{4m_{\rm DM}^2}^{\infty} ds\, \hat{\sigma}(s) \sqrt{s} K_1 \left(\frac{x_f \sqrt{s}}{m_{\rm DM}} \right),$$

$$\hat{\sigma}(s) = 2 \left(s - 4m_{\rm DM}^2 \right) \sigma_{\rm SM}(s)\,, \qquad \sigma_{\rm SM}(s) = \frac{25 \cdot 135\,\pi}{3} \frac{g_X^4}{16\pi^2} \frac{\sqrt{s\,(s - 4m_{\rm DM}^2)}}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2}\,,$$

Requires BSM Higgs heavy enough.

Higgs-mediated channels also possible. Work in progress: Numerical analysis 2HDM2CF— WK, KK, RRLdS, EMS

Stabilizing dark matter

Doublet Dark Matter candidate

- Small mass difference of components to avoid tight constraints on elastic scattering (pure Dirac particle)

$$\boxed{\delta m_{\mathrm{DM}} \equiv m_{N_3} - m_{N_2} = \sqrt{2}\frac{y_\nu^2 v_d^2}{y_{\nu_1} v_{s_{21}}}}$$

- Relic density (Higgsino-like candidate)

Assuming BSM Higgs are heavy enough.

$$\boxed{\langle \sigma v \rangle_{\tilde{H}}^{(\mathrm{eff})} \approx \frac{21\, g_2^4 + 3\, g_2^2 g_Y^2 + 11\, g_Y^2}{512\, \pi\, m_{\mathrm{DM}}^2}\,,}$$

See “The well-tempered neutralino”
Arkani-Hamed, Delgado, Giudice hep-ph/0601041

- Requires DM mass around 1.1 TeV

Interaction with heavy Higgs can after result. Work in progress: Numerical analysis 2HDM2CF— WK, KK, RRLdS, EMS

Stabilizing dark matter

Secluding mechanism

Find solutions with more interacting fixed points, keeping this behavior for the critical exponents

- From AS, $f_y > 0$
- If $\theta_{11} > 0$, y_{11} is relevant
- If $\theta_{12} < 0$, y_{12} is irrelevant -> vanishes

Relevant direction —> free parameter

From the transplanckian fixed point at zero, y_{11} will flow towards different values at lower energies. “Can be tuned to what we need”

Irrelevant, interacting fixed points are predictions

Relevant, Gaussian fixed points are free parameters and run to non-vanishing values

Irrelevant direction —> prediction

From the transplanckian fixed point at zero, y_{12} will stay at zero throughout the flow. “Coupling is always off”

$$\boxed{M_f = \frac{1}{\sqrt{2}} \begin{pmatrix} y_{11}v_1 & y_{12}v_2 \\ y_{21}v_1 & y_{22}v_2 \end{pmatrix}}$$

$y_{12} = 0 = y_{21}$ Mixing is forbidden

y_{11} is relevant

y_{22} is prediction

Secluding mechanism: portal $y_{12}\psi F_1 S_2$ is allowed by gauge symmetry, But quantum scale symmetry secludes this sector (gravity-matter)

Use this to close decay channels (instead of imposing global symmetry)

Functional Renormalization Group

Machinery

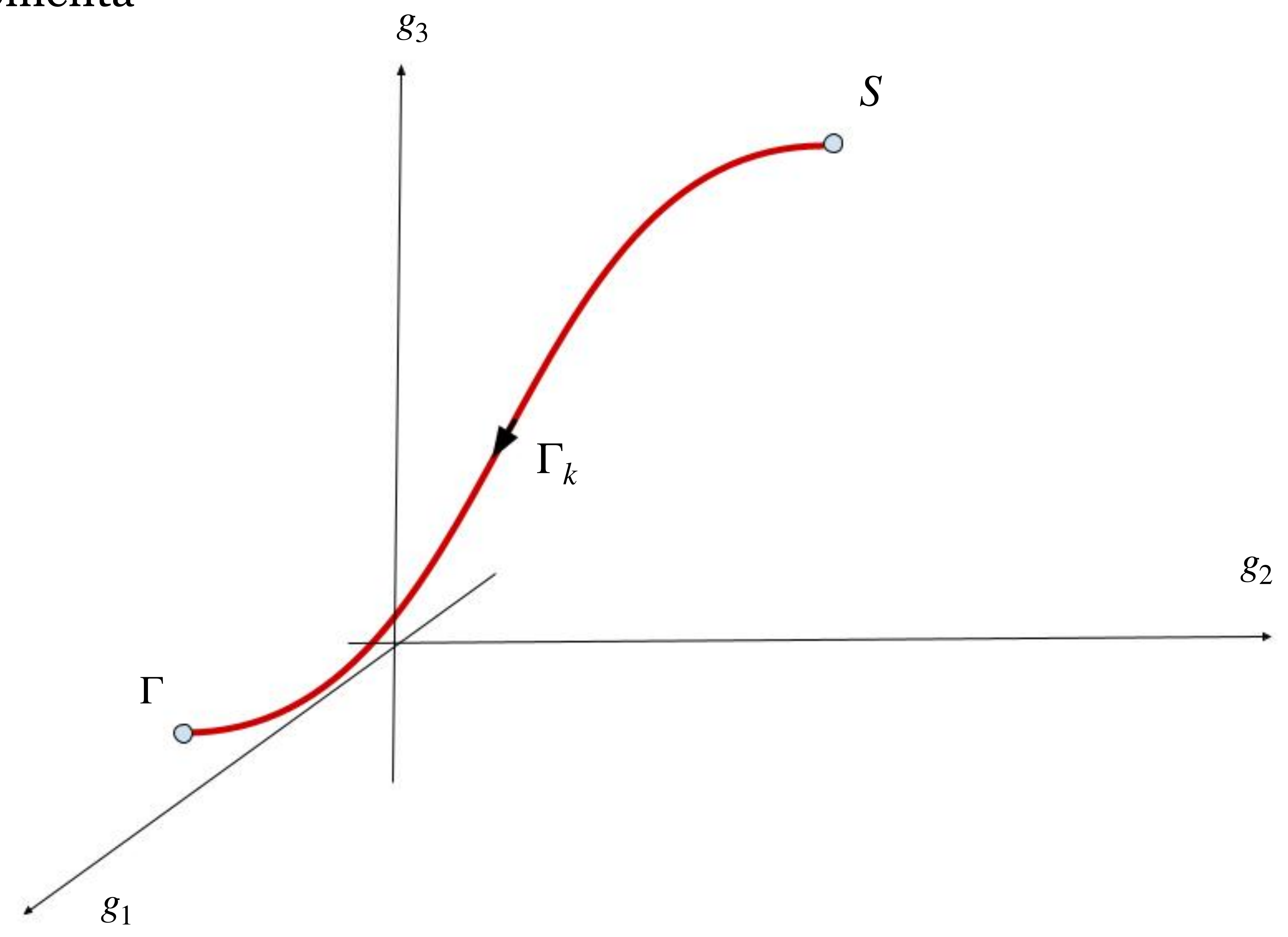
- Inspired by Wilsonian approach to path integrals: integrating out quantum fluctuations as a function of the **RG-scale** k**;**
- **Average effective action** Γ_k**:** only quantum fluctuations with large momenta $(p^2 > k^2)$ are integrated out;
- **IR regulator** R_k **(cutoff):** suppression of small momenta $(p^2 < k^2)$;
- The mass-like IR regulator term

$$\Delta S_k[\phi] = \frac{1}{2}\int_p \phi(-p)R_k(p^2)\phi(p)$$

defines the generating functional and the effective action

$$Z_k[J] = \int_\Lambda D\varphi \exp\left(-S_k[\varphi] + \int J\cdot\varphi - \Delta S_k[\varphi]\right),$$

$$\Gamma_k[\phi] = \int J\cdot\phi - \log Z_k[J] - \Delta S_k[\phi].$$



Interpolation between the bare action $S(k\to\infty)$ and the full effective action $\Gamma(k\to 0)$

Pedagogical reviews: Gies 12', Reichert 20'

FRG applications, Dupuis et al. 20'

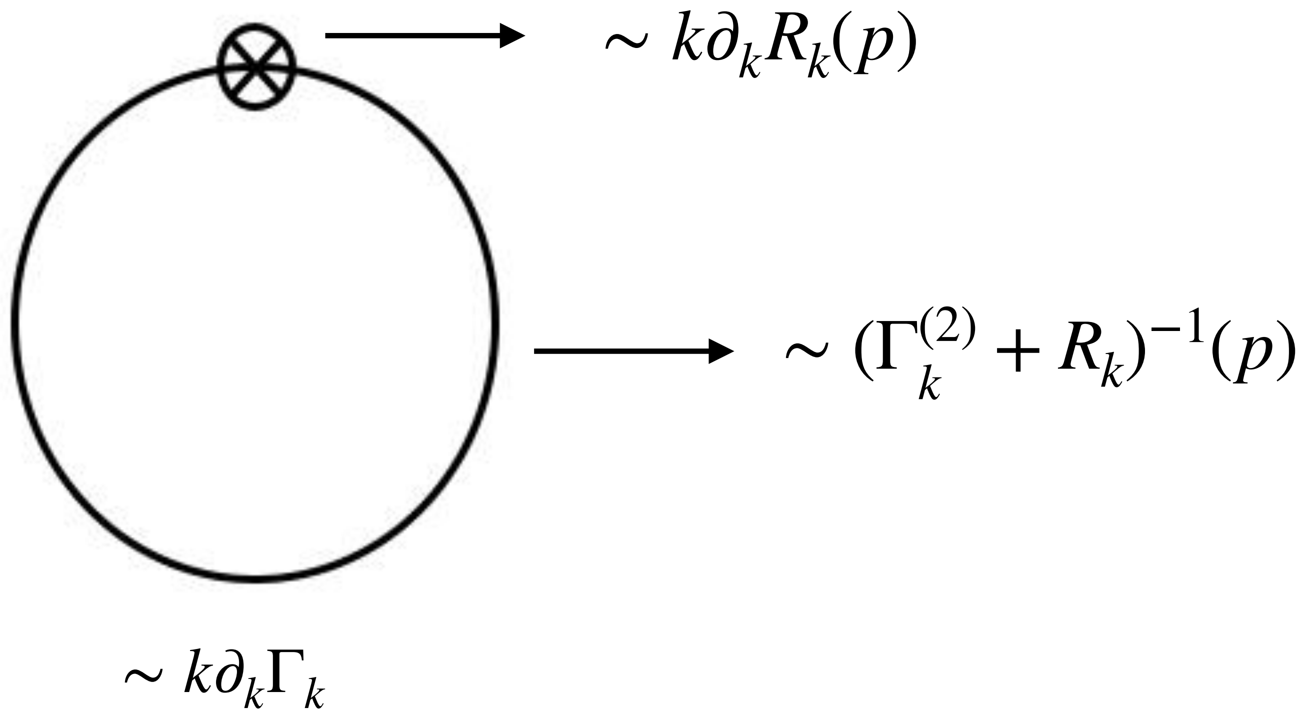
Functional Renormalization Group

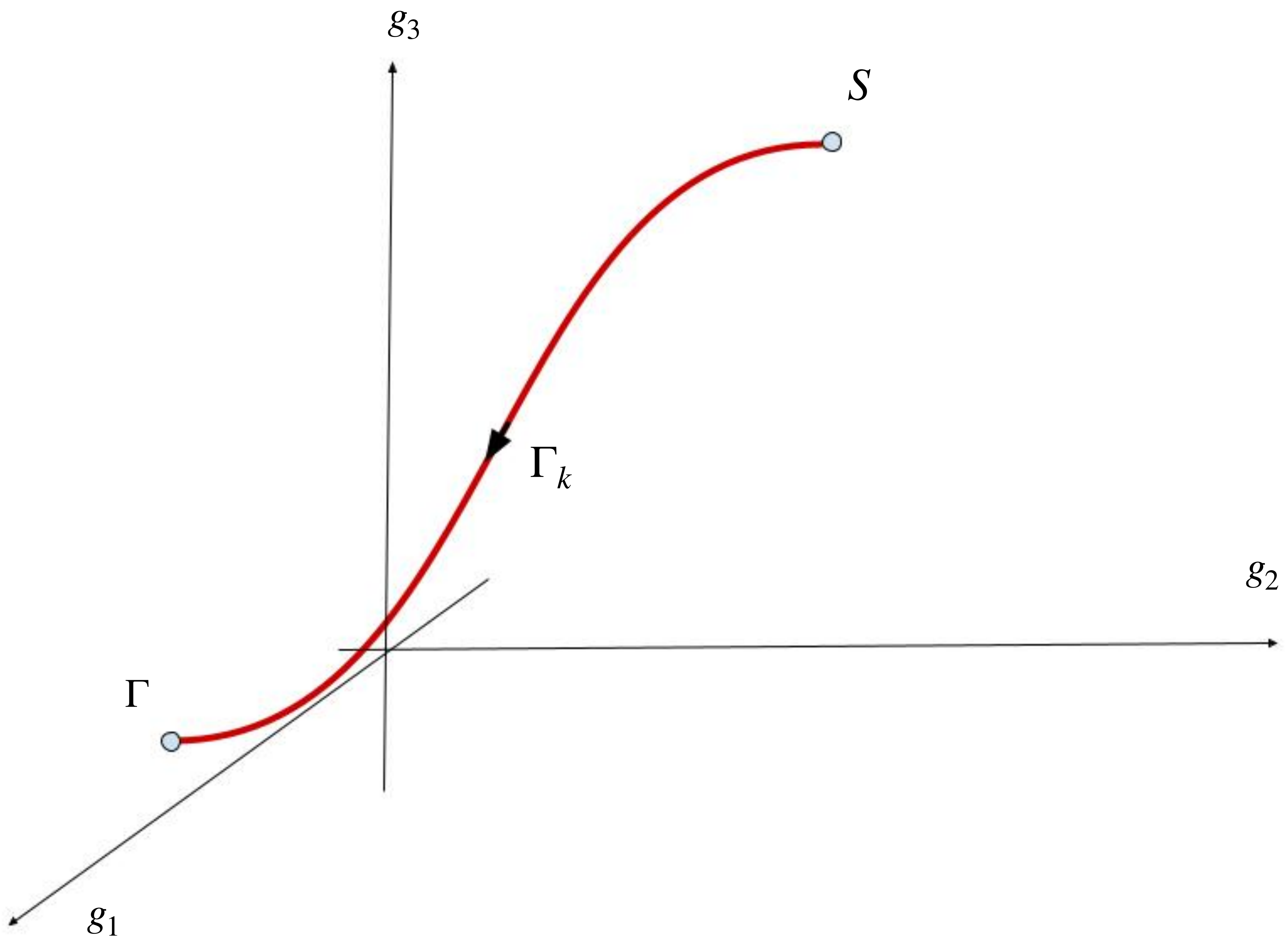
- $\Gamma_k[\phi] = \int J \cdot \phi - \log Z_k[J] - \Delta S_k[\phi]$
- Flow equation:

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

[Wetterich 93', Morris 94', Reuter 98']

- Exact 1-loop equation





Interpolation between the bare action $S\,(k \to \infty)$ and the full effective action $\Gamma\,(k \to 0)$

Pedagogical reviews: Gies 12', Reichert 20'

FRG applications, Dupuis et al. 20'

Backup slide: systematic uncertainties

Function Renormalization Group

Euclidean signature:

- $(k^2 > p^2)$ requires Euclidean signature!
- Wick rotation not well defined for non-perturbative calculations!

Gauge and parametrization:

- Dependence on gauge, regulator, and parametrization choices

Infinite dimensional theory space:

- It requires truncation.
- Check convergence of expansion schemes.
- universal quantities may depend on gauge choice and/or scheme.

Gauge invariance:

- Regulator can break gauge invariance.
- Work out modified Ward-Takahashi identities.
- Background approximation vs fluctuation approach

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

Warning: Results dependent on truncation and systematical uncertainties!

Asymptotically-safe Quantum Gravity

Einstein-Hilbert term

- $\Lambda = 0$:

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

$$G_N = Gk^{-2}$$

$$\beta_G = 2G - C\,G^2, \qquad C > 0$$

Canonical   Quantum fluctuations

$$M_{ij} = \frac{\partial \beta_{g_i}}{\partial g_j}\Big|_{g_*}, \qquad \theta_i = -\,\mathrm{eig}(M),$$

Critical exponents

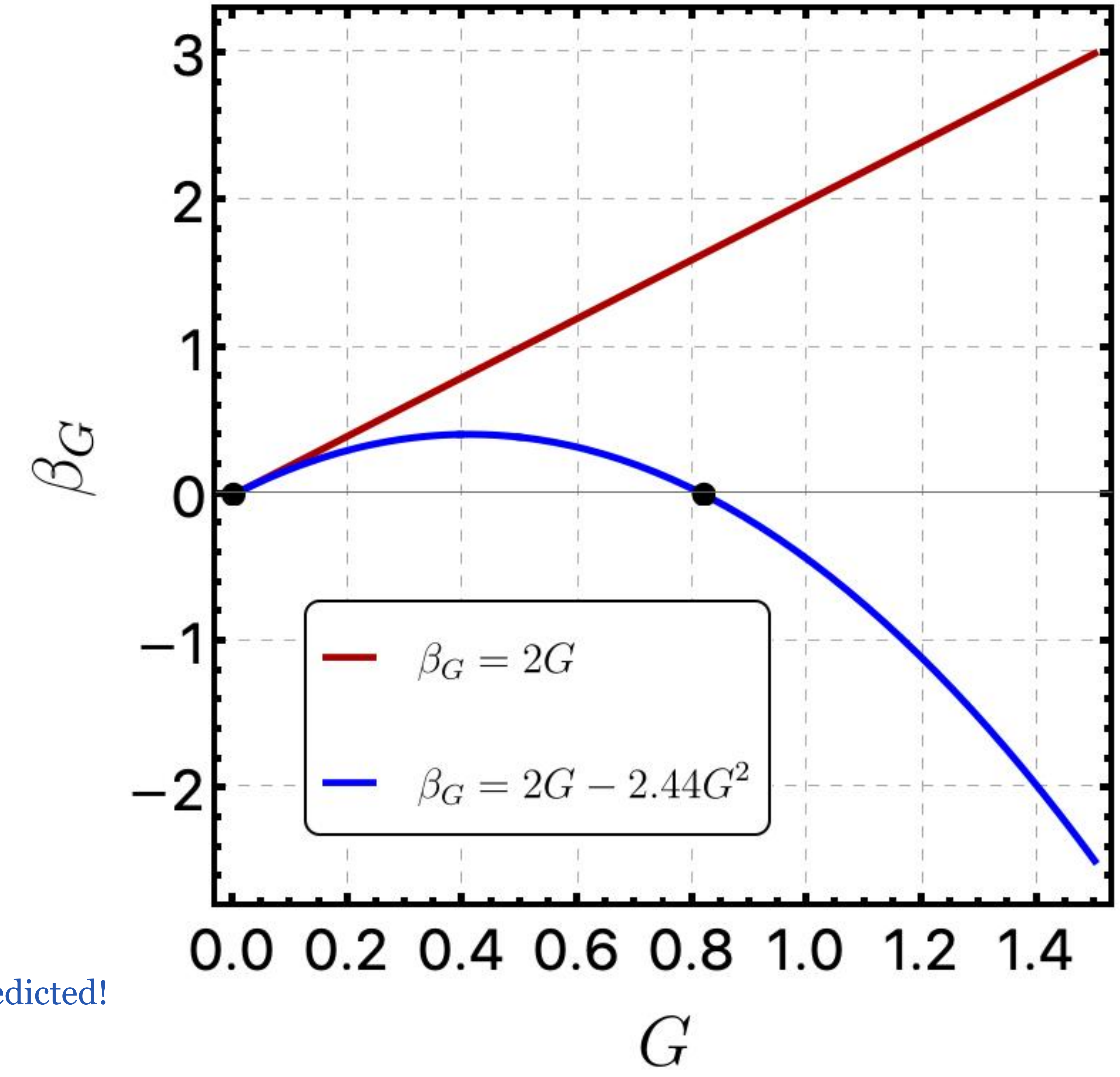
$$\theta_G\,|_{G_*=0} = -\,2$$

Free fixed point
Irrelevant direction (prediction)

$$\theta_G\,|_{G_*=2/C} = +\,2$$

Interacting fixed point
Relevant direction (free parameter)

$\Rightarrow G_N$ cannot be predicted!



Backup slide

Asymptotic safety
Gravity

$$S_{EH} = -\frac{1}{16\pi G_N}\int d^4x\sqrt{g}(R - 2\Lambda_{cc})$$

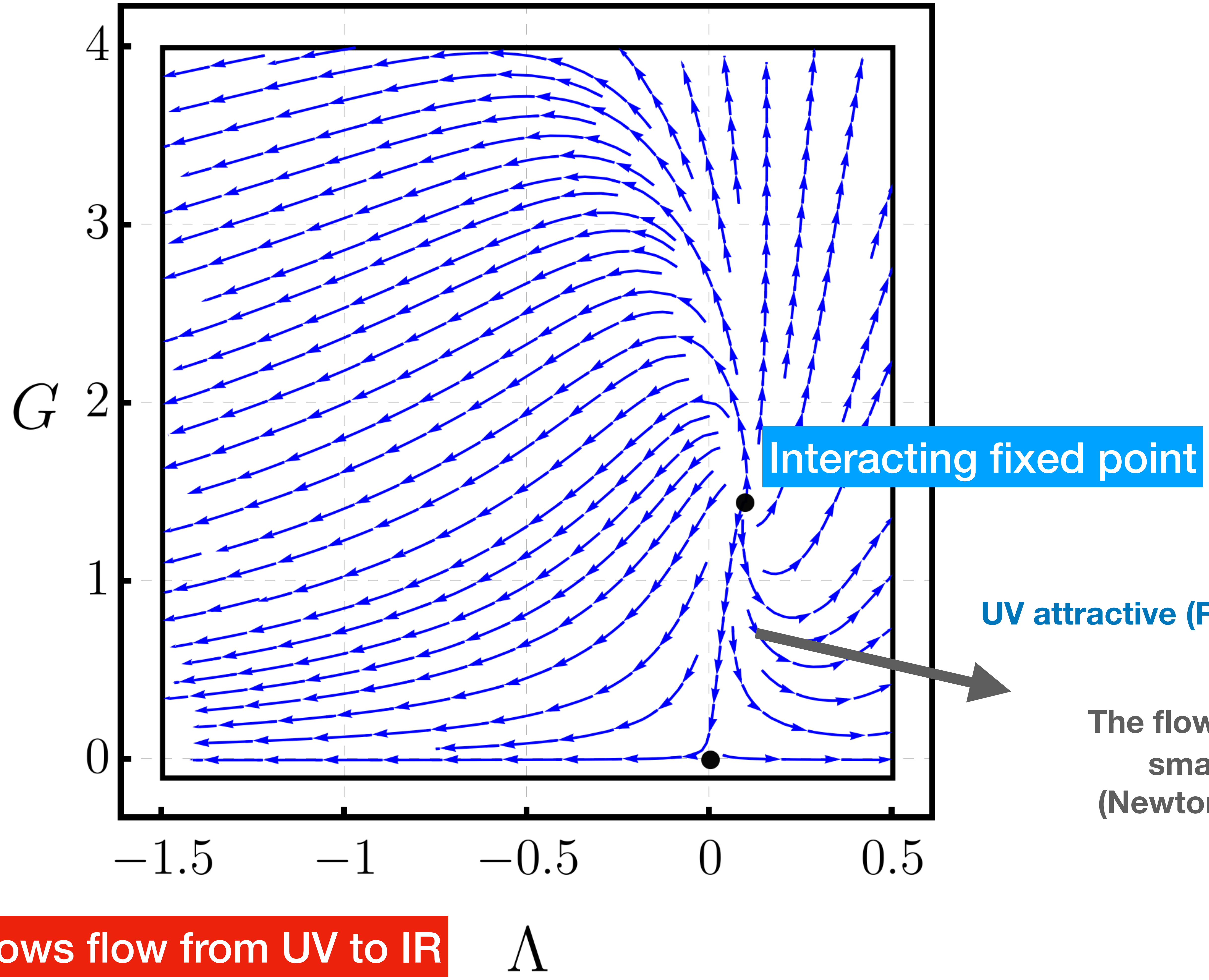
$$G_N = Gk^{-2},\ \Lambda_{cc} = \Lambda k^2$$

$$\beta_G = 2G - C\,G^2, \qquad C > 0$$

Canonical Quantum fluctuations

Relevant direction

Phase space of General Relativity (Einstein-Hilbert truncation)



@ Transplanckian scale -> UV completion is solved!

UV attractive (Relevant directions) -> free parameters

The flow can bring G_N and Λ_{cc} to small and positive values (Newton constant and de Sitter) at lower scales!

Arrows flow from UV to IR

Seminal work: Reuter, Phys.Rev.D 57 (1998)

Review: A. Eichhorn Front.Astron.Space Sci. 5 (2019) 47

Backup slide

Asymptotic safety

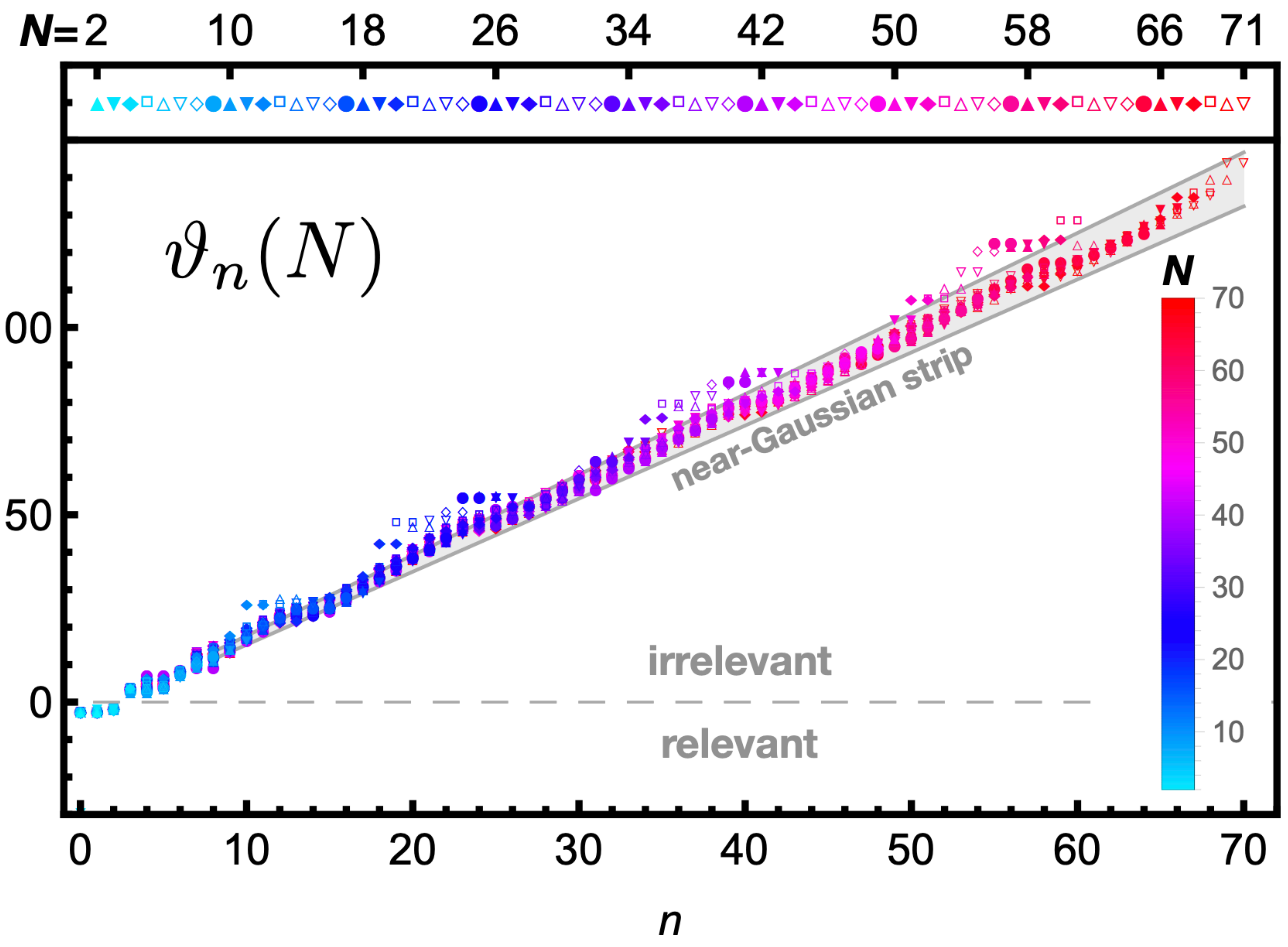
Compelling evidence for ASQG

A. Eichhorn Front.Astron.Space Sci. 5 (2019) 47

operators included beyond Einstein-Hilbert	# rel. dir.	# irrel. dir.	Reθ_1	Reθ_2	Reθ_3
-	2	-	1.94	1.94	-
-	2	-	1.67	1.67	-
$\sqrt{g}R^2$	3	0	28.8	2.15	2.15
$\sqrt{g}R^2, \sqrt{g}R^3$	3	1	2.67	2.67	2.07
$\sqrt{g}R^2, \sqrt{g}R^3$	3	1	2.71	2.71	2.07
$\sqrt{g}R^2, \sqrt{g}R^6$	3	1	2.39	2.39	1.51
$\sqrt{g}R^2, ..., \sqrt{g}R^8$	3	6	2.41	2.41	1.40
$\sqrt{g}R^2, ..., \sqrt{g}R^{34}$	3	32	2.50	2.50	1.59
$\sqrt{g}R^2, \sqrt{g}R_{\mu\nu}R^{\mu\nu}$	3	1	8.40	2.51	1.69
$\sqrt{g}C^{\mu\nu\kappa\lambda}C_{\kappa\lambda\rho\sigma}C^{\rho\sigma}{}_{\mu\nu}$	2	1	1.48	1.48	-

Evidence for fixed point with only 3 free parameters

K. Falls, D. Litim, J. Schröder Phys.Rev.D 99 (2019) 12, 126015



Near-canonical scaling behaviour

Backup slide

Asymptotic safety

Gravity and matter

See, for eg. Eichhorn, Schiffer for a review 2212.07456

Critical reflections: 1911.02967 Donoghue, 2004.06810 Bonanno et al.

Recent criticism: 2412.14108, 2412.14194, 2506.05100 Branchina et al, 2503.02941 Bonanno et al, 2504.12006 Held et al.

- There are many systematic uncertainties in the exact value of (G_*, Λ_*)
- Assume fixed point exists in the matter sector
- Add matter sector
  - Does the fixed point structure in the gravity sector persist? Matter sector?
- Which models belong to the landscape (swampland) of ASQG?
  - What are the effects at lower energy scales?
  - Are them measurable?

UV completion + good phenomenology

Gravitational correction to matter systems

Yang-Mills theories with gravity

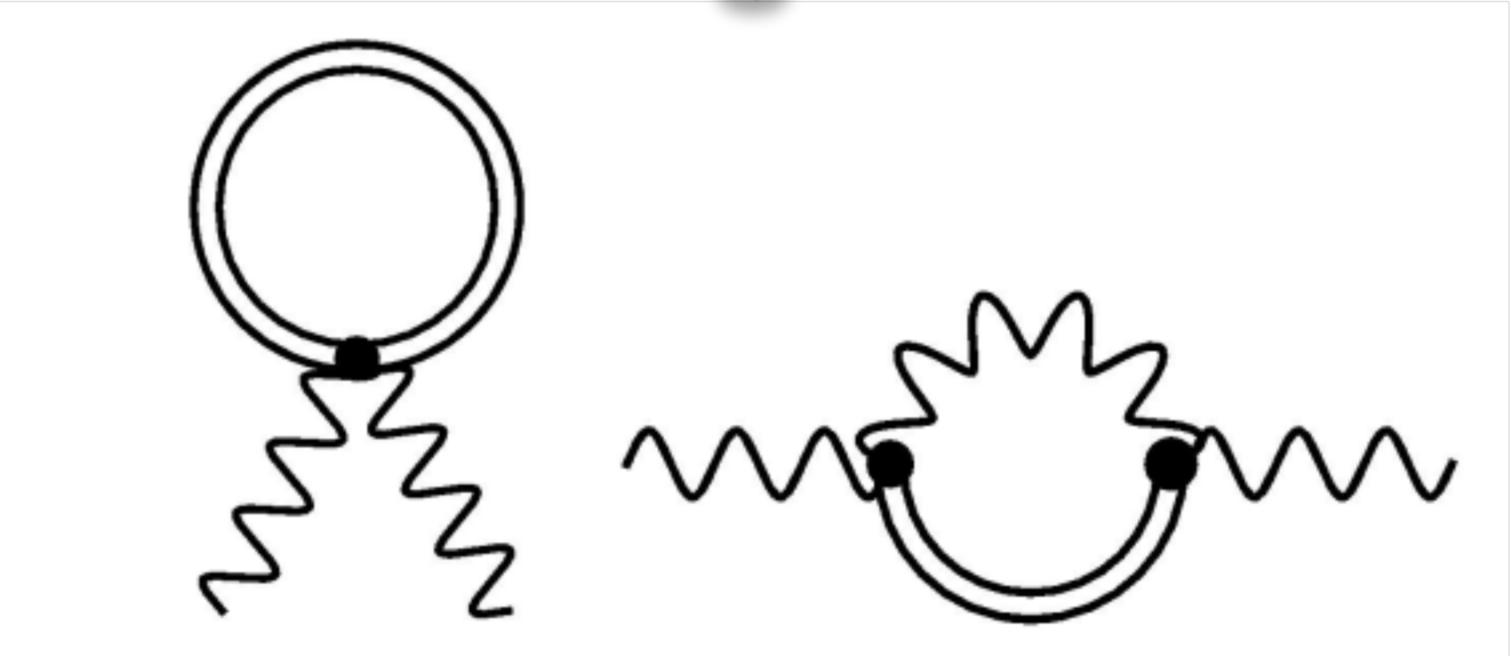
- How does the gauge couplings run?
- Continue using background field formalism: $\beta_g = \frac{1}{2}\eta_A\, g$
- $\eta_A = \eta_A^{matter}(g) + \eta_A^{gravity}(G)$
- Then it is possible to write, at leading order,

$$\beta_{g_i} = \beta_{g_i}^{matter} - f_g\, g_i$$

- In particular, if $\beta_i = A g_i^3 - f_g\, g$, Sign of “A” depends on gauge group!

then we can have new, interacting fixed point at $g_* = \sqrt{\frac{f_g}{A}}$

And critical exponents $\theta_{g,g_*=0} = + f_g,\ \theta_{g,g_*\neq 0} = -2f_g$



$\theta_i > 0$ (UV-attractive fixed point)
$\theta_i < 0$ (IR-attractive fixed-point)

$f_g > 0$ cures the Landau pole (new UV fixed point U(1))

$f_g < 0$ spoils asymptotic freedom (Yang-Mills)

Important question: Is $f_g \neq 0$?

Interplay with matter and landscape

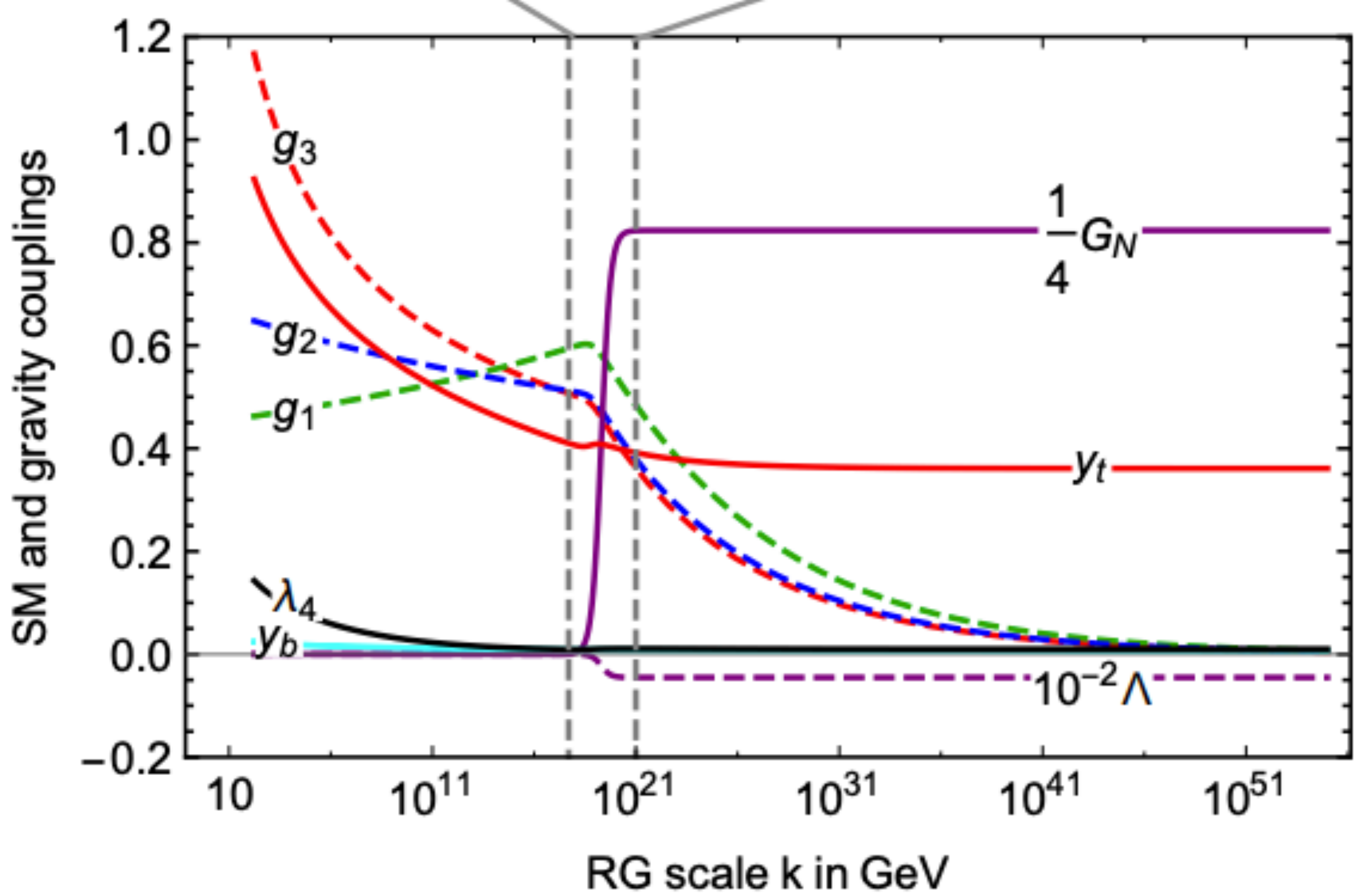
A few applications

- Prediction of Higgs mass Shaposhnikov/Wetterich 0912.0208

Abstract

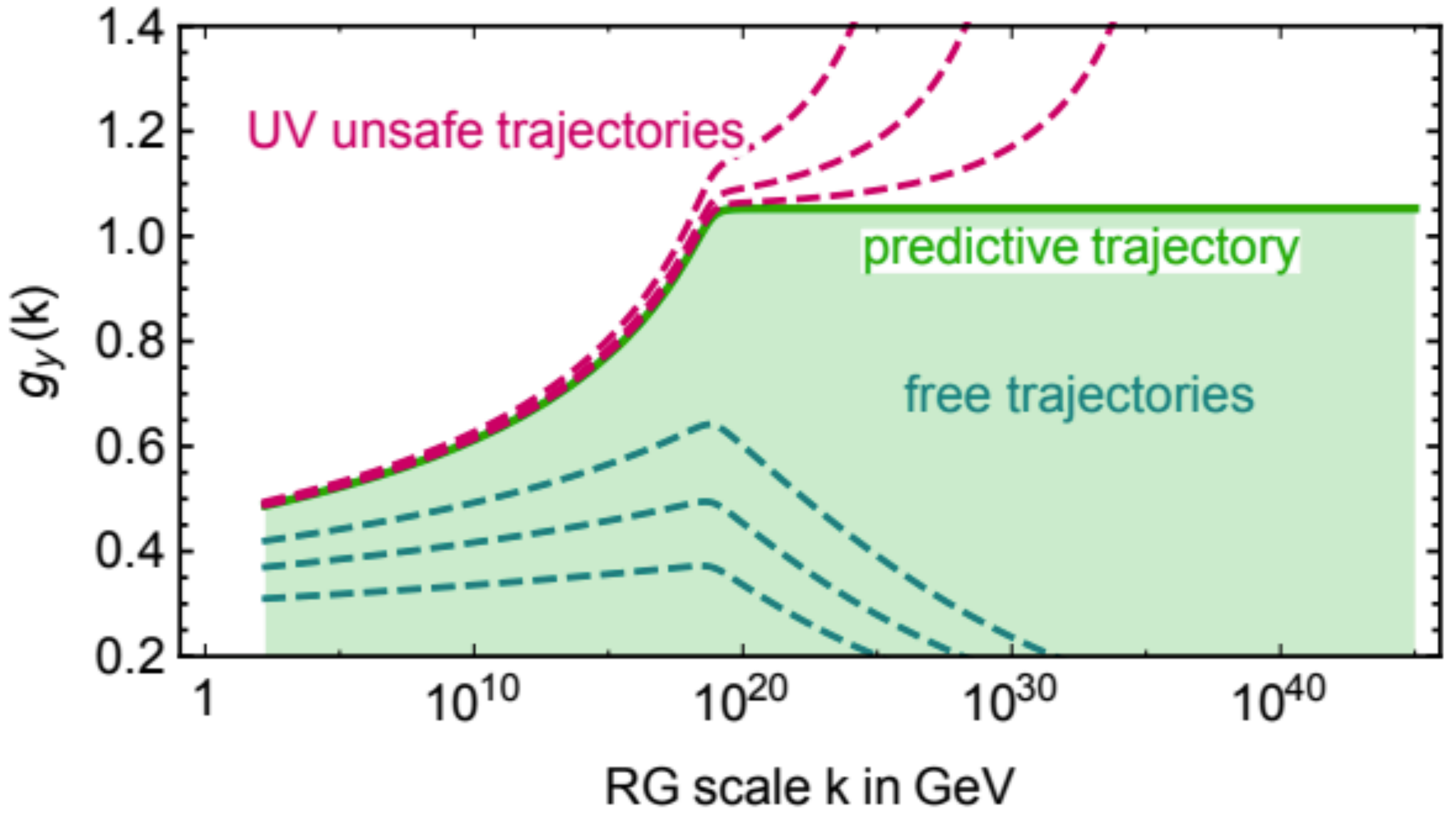
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well. For $A_\lambda < 0$ one finds m_H in the interval $m_{\min} < m_H < m_{\max} \simeq 174$ GeV, now sensitive to A_λ and other properties of the short distance running. The case $A_\lambda > 0$ is favored by explicit computations existing in the literature.

- "Post-diction" of quark-top mass Eichhorn/Held 1707.01107



- Upper bound on the Abelian gauge coupling

Eichhorn/Versteegen 1709.07252



There is UV interacting fixed point for U(Y) if $f_g > 0$

$$f_g = (41/6)(g^2_{Y,*}/16\pi^2)$$

And critical exponents

$$\theta_{g,g_*=0} = +f_g,$$
$$\theta_{g,g_*\neq 0} = -2f_g$$

Interplay with matter and landscape

A few applications

- Prediction of SM top/bottom mass ratio

Reminder: There is UV fixed point for U(Y) if $f_g > 0$

Similar mechanism for the Yukawa couplings

UV fixed points $y_{t*}^2 - y_{b*}^2 = \frac{1}{3} g_{Y*}^2$

Can use the SM to constrain f_y and f_g

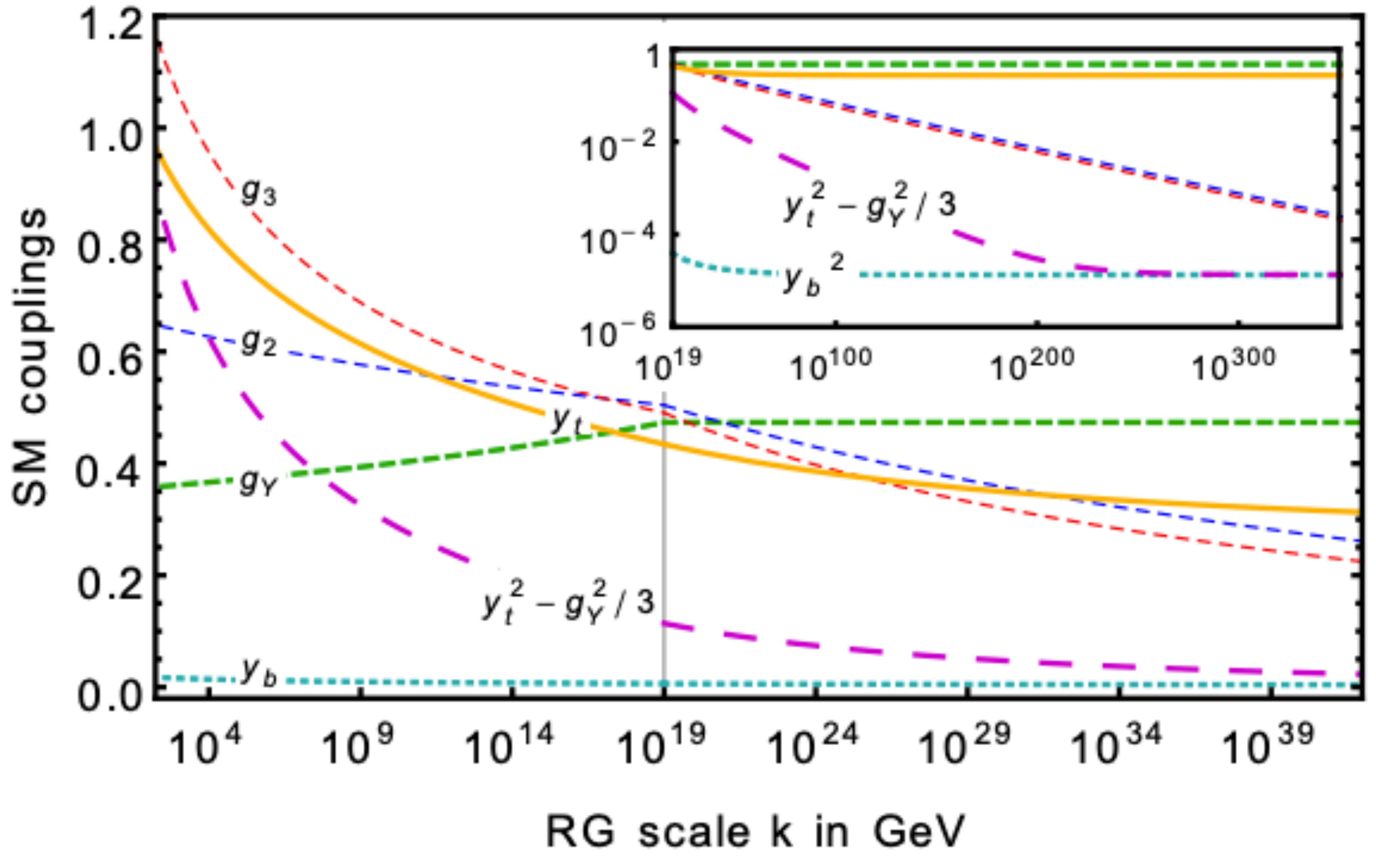


FIG. 1. RG trajectory of Standard-Model couplings for $f_g = 9.7 \times 10^{-3}$ and $f_y = 1.188 \times 10^{-4}$, reaching $g(k_{\mathrm{IR}}) = 0.358$, $y_t(k_{\mathrm{IR}}) = 0.965$, and $y_b(k_{\mathrm{IR}}) = 0.018$ at $k_{\mathrm{IR}} = 173\,\mathrm{GeV}$. We also plot $y_t^2 - g_Y^2/3$ (pink, wide-dashed), which approaches y_{b*}^2 (dotted) in the far UV, cf. Eq. (5).

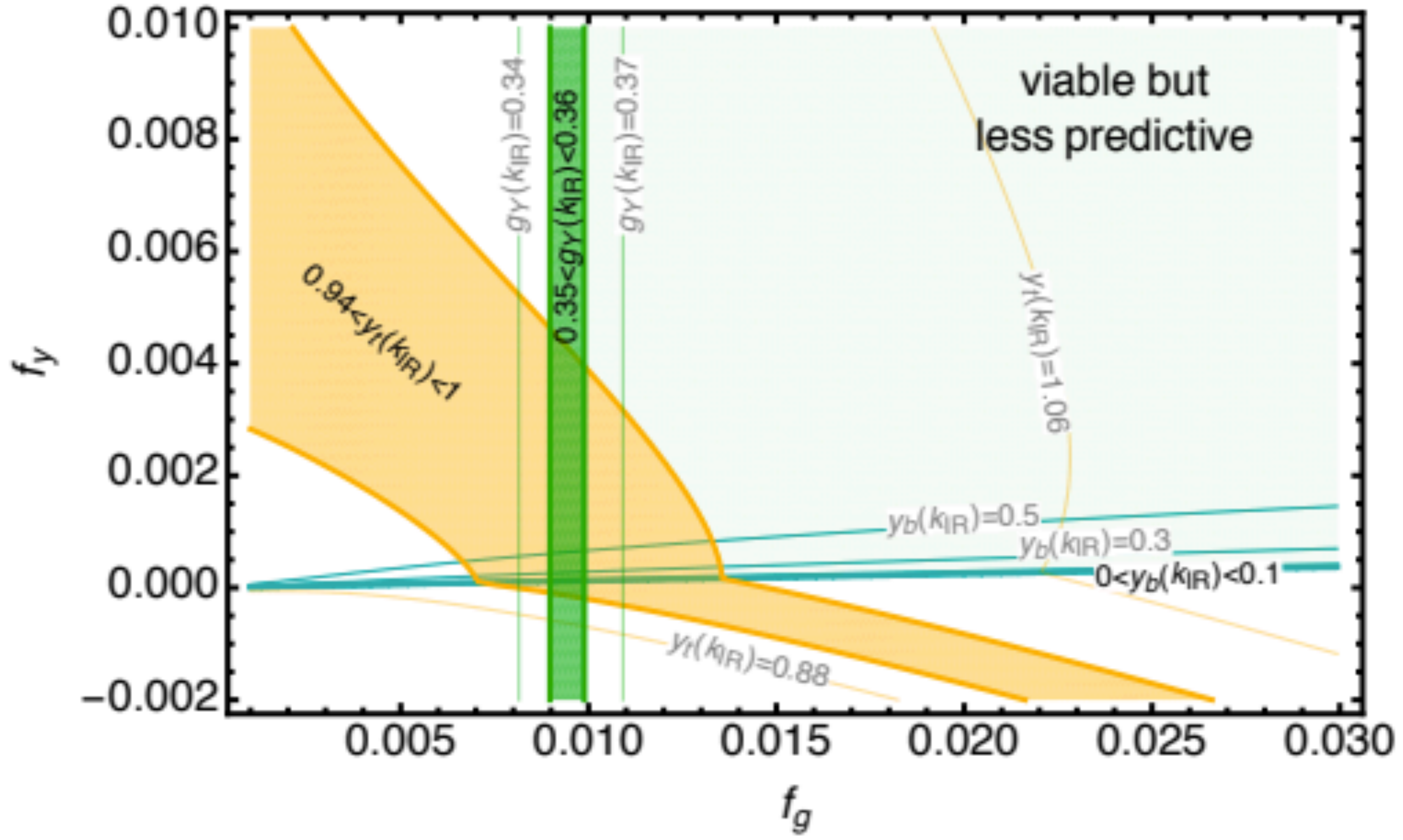


FIG. 2. IR values of retrodicted couplings $g_Y(k_{\mathrm{IR}})$, $y_t(k_{\mathrm{IR}})$ and $y_b(k_{\mathrm{IR}})$ at $k_{\mathrm{IR}} = 173$ GeV as a function of the two independent quantum-gravity contributions f_g and f_y.

Eichhorn/Held 1803.04027

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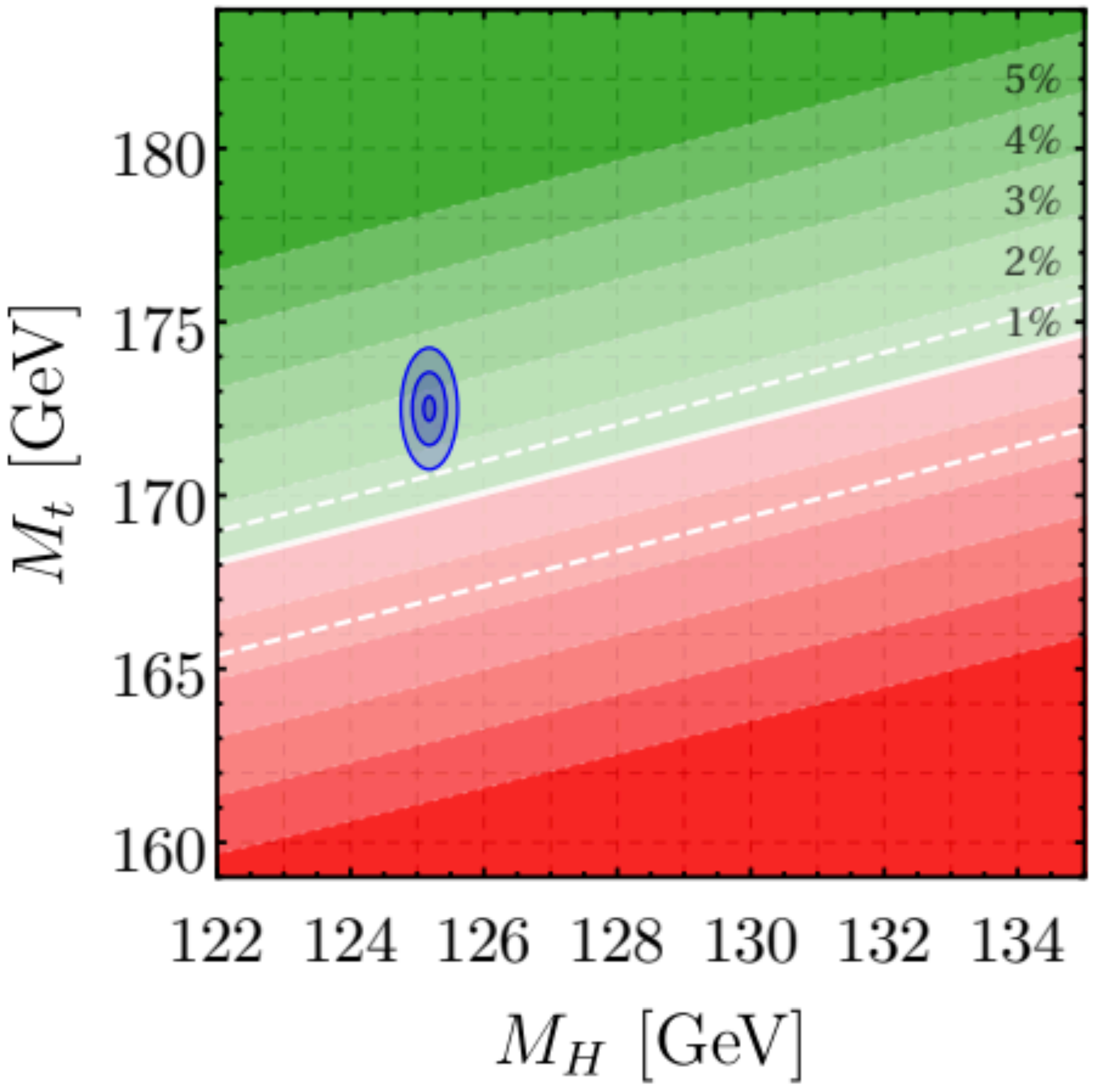
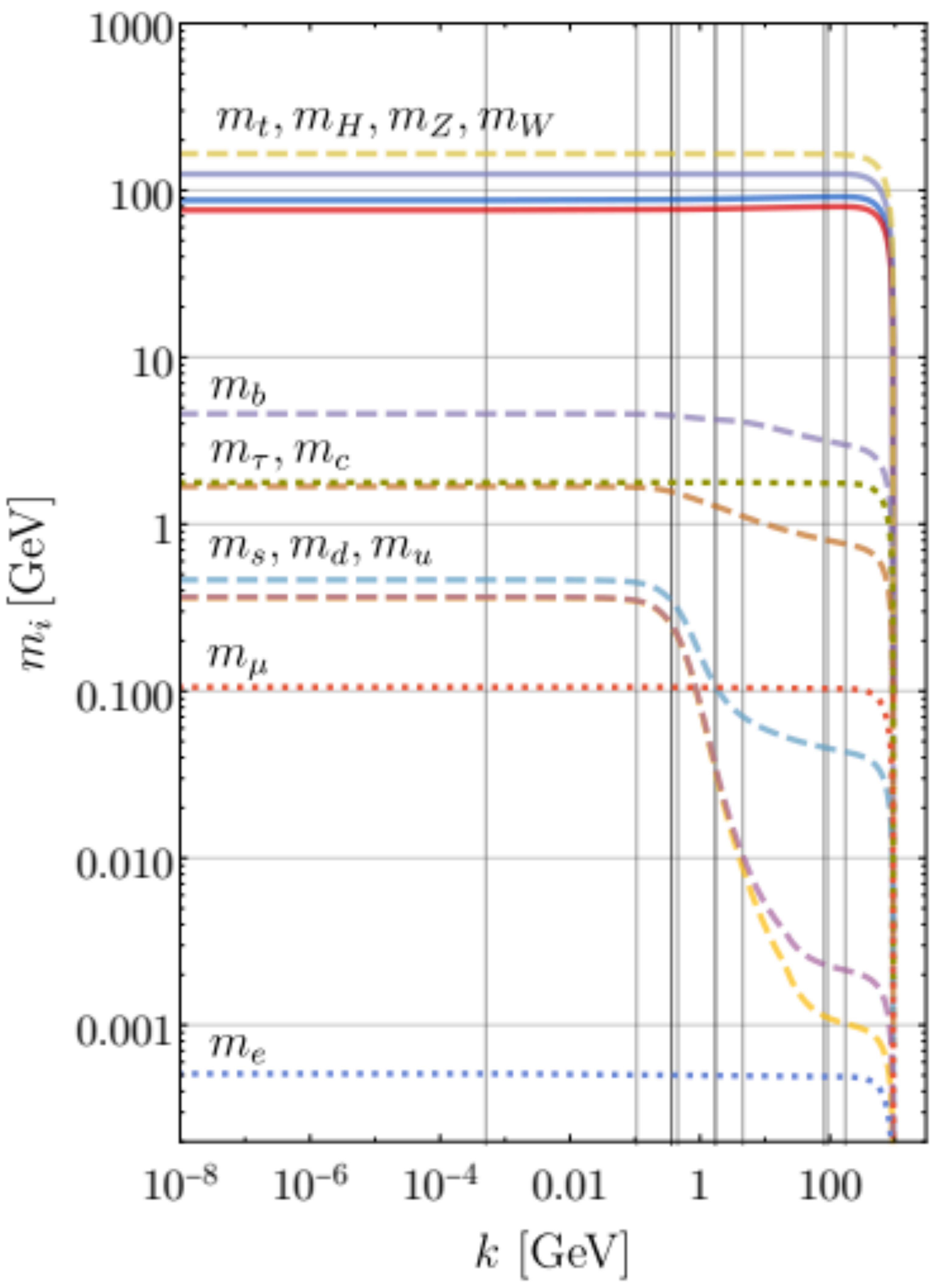
Interplay with matter and landscape

A few applications

- Asymptotically safe Standard Model

Pastor-Gutiérrez, Pawlowski, Reichert 2207.09817





Interplay with matter and landscape

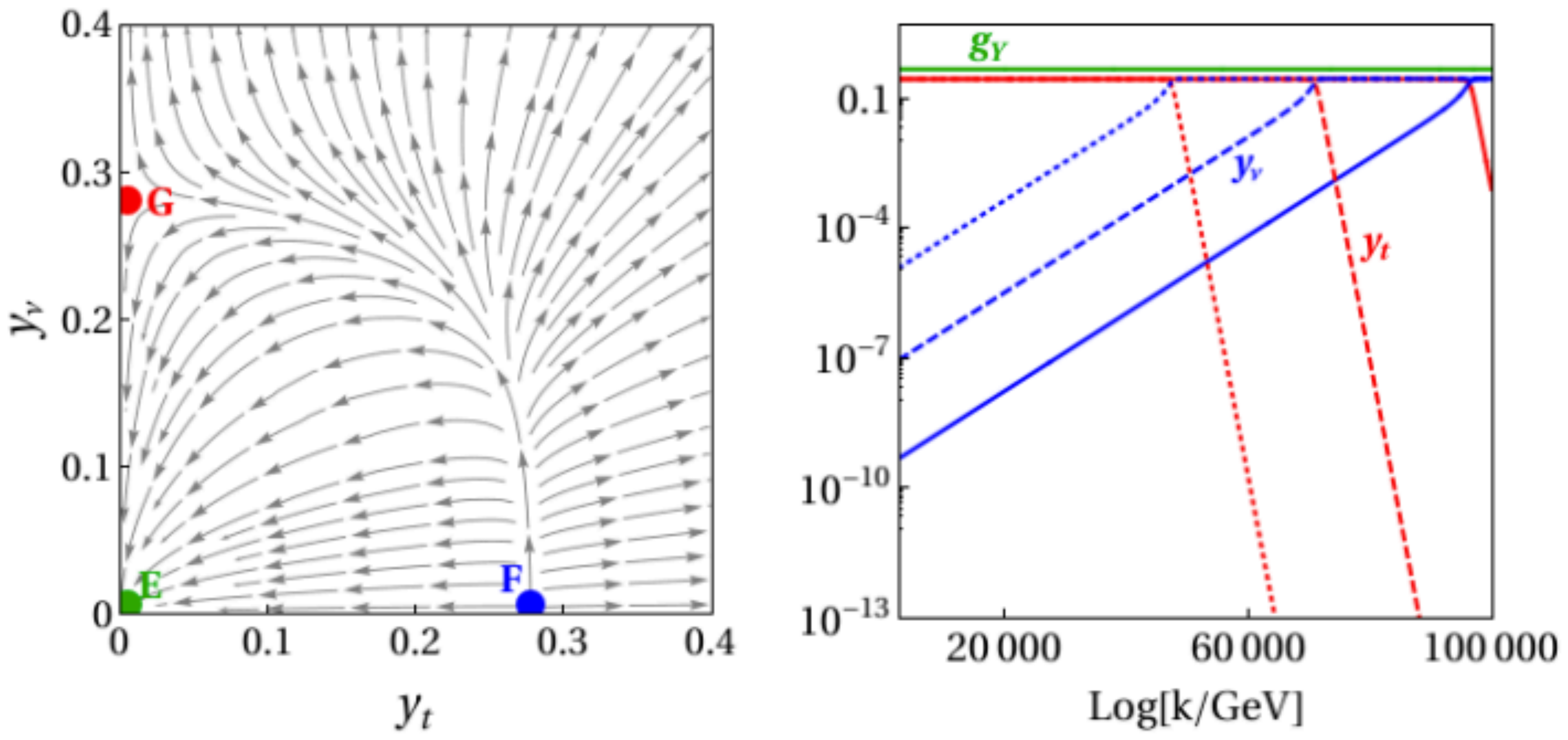
A few applications

- Naturally small Yukawa couplings

Kowalska, Pramanick, Sessolo 2204.00866

$f_g = 0.0096, f_y = 0.0002$

One SM generation

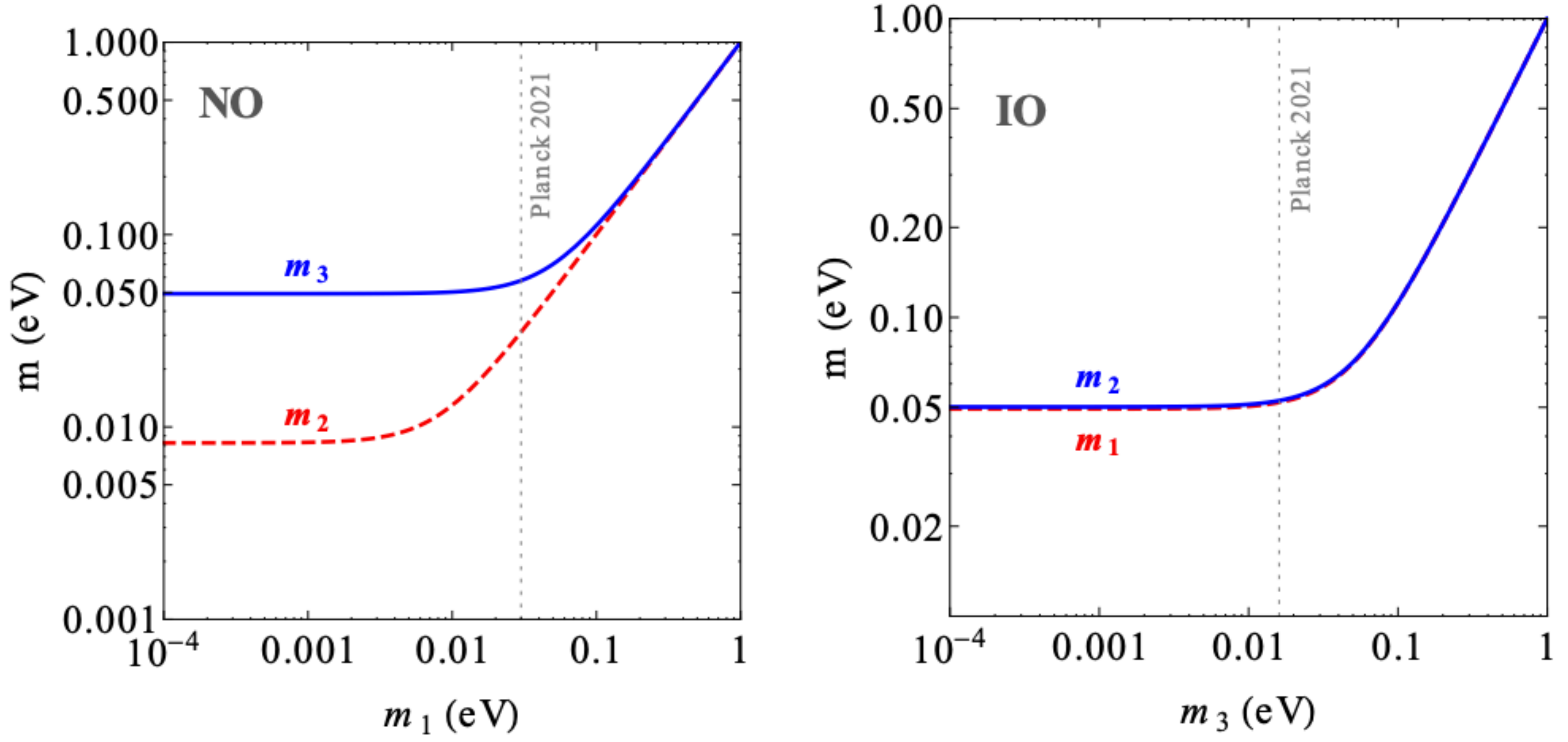


There is fully IR-attractive interacting FP for top Yukawa coupling $y_{t,*} \neq 0$

Also, UV-attractive with relevant $y_{t,*} = 0$, but with irrelevant $y_{\nu_i,*} \neq 0$

Neutrino masses (Type-I see-saw mechanism) $m_\nu = y_\nu^2 v^2/(\sqrt{2}M_N)$

Heavy Majorana neutrino mass M_N, 3 SM generations



(a) (b)

Neutrino masses consistent with global fits

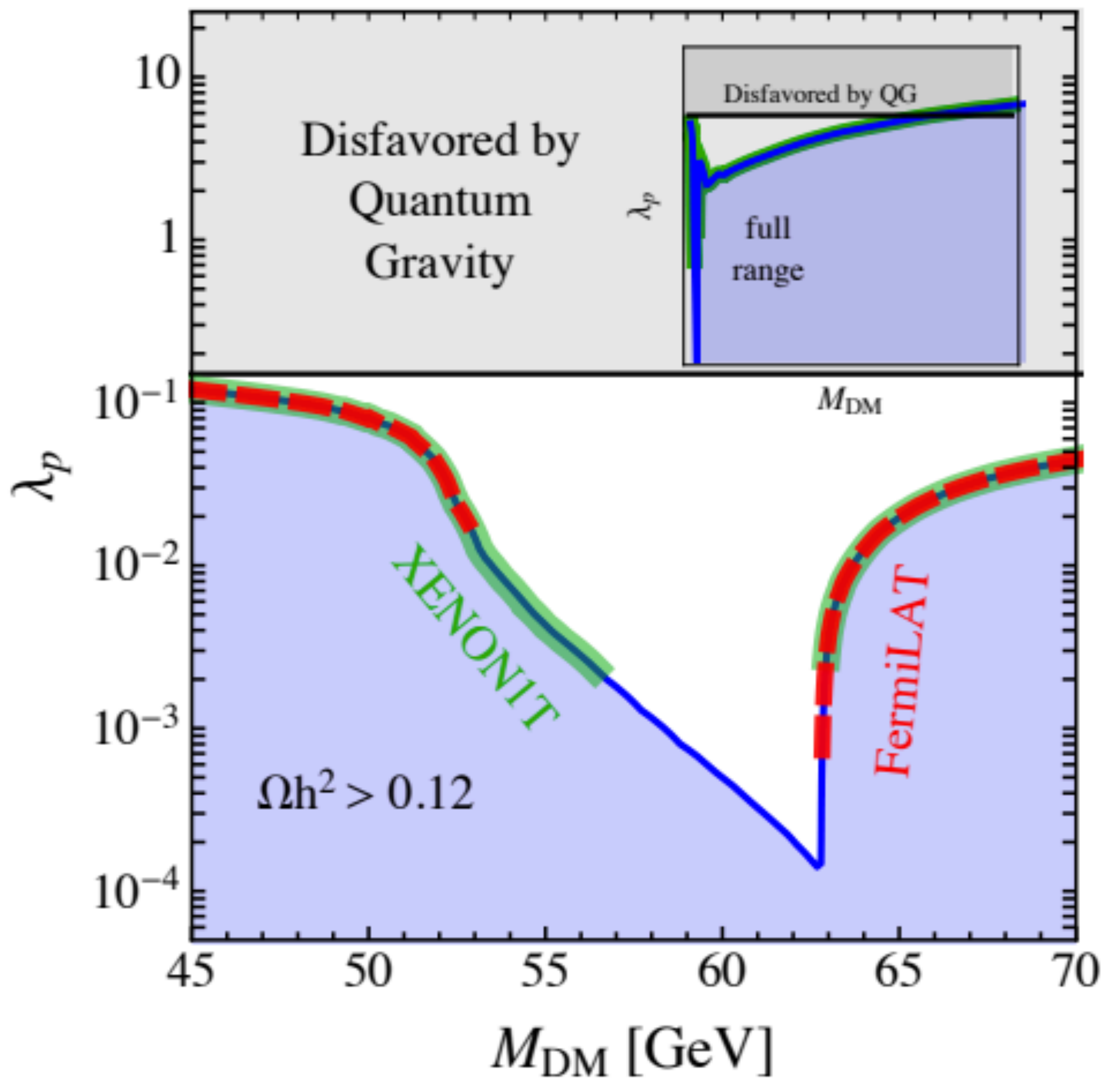
Interplay with matter and landscape

A few applications

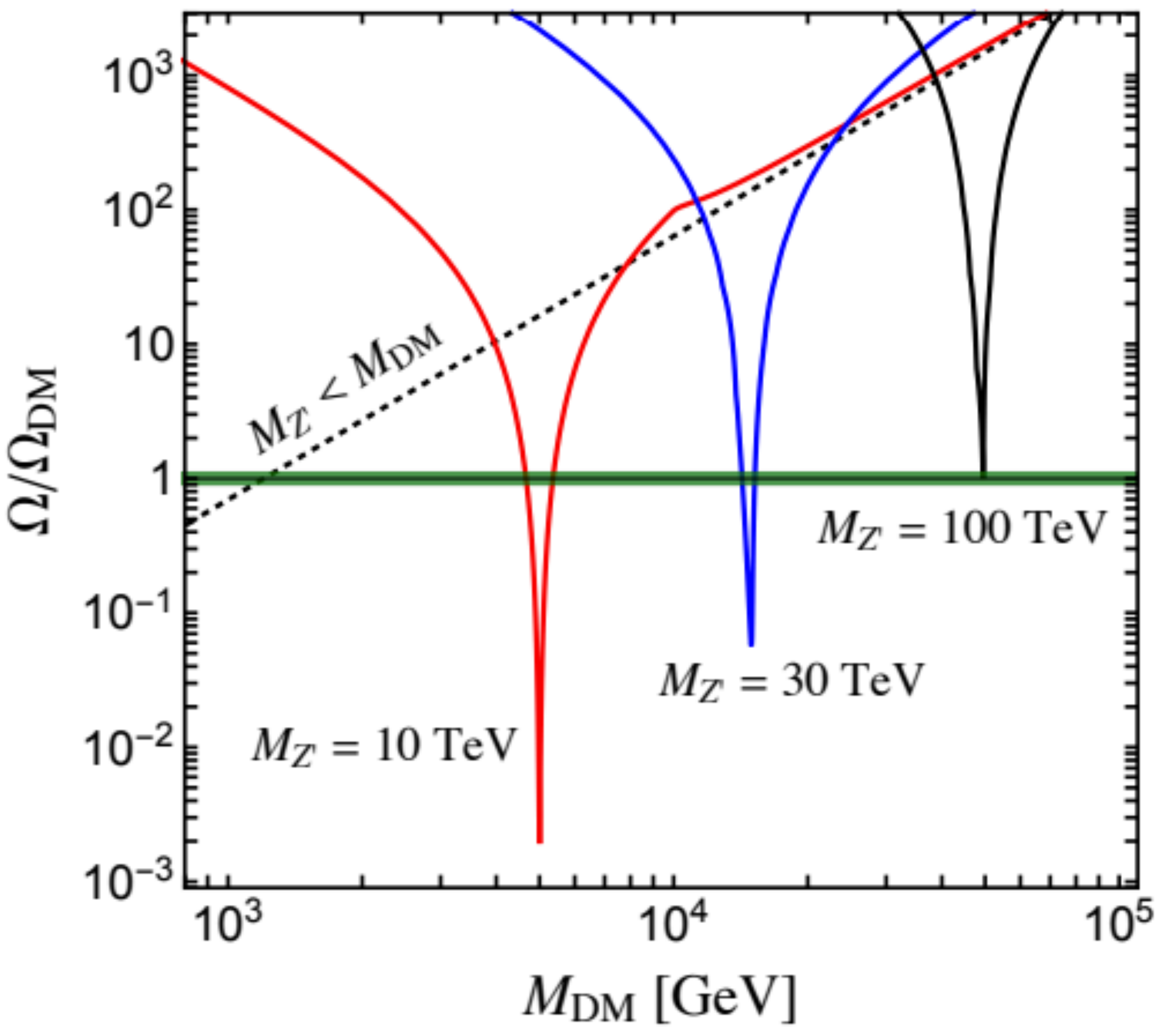
- Dark matter

Reichert/Smirnov 1911.00012

Dark sector contains extra complex scalar field S charged under new U(1) group, portal coupling (λ_p) to SM Higgs H, vector-like fermion, kinetic mixing



Scalar dark matter: resonance with SM Higgs



Fermionic dark matter: resonance with Z'

Bound for DM mass: 50 TeV

Running of quartic couplings quite constrained to be small, to give correct Higgs mass