Stabilizing dark matter

With quantum scale symmetry

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

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Stabilizing dark matter

Using quantum scale symmetry

- Consider gauge-invariant Yukawa sector

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

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

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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!

Program

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

- Brief overview of our DM model
  - Doubly charged 2HDM2C from SSB of SU(6) GUT model
- Brief introduction to quantum scale symmetry
- Secluding mechanism

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GUT model - SU(6)

Yukawa couplings

SM | Dark sector

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

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

2505.02803

See talks about 2HDM and 3HDM Scalars 2025

SU(6) model @ EWSB scale

Scalar sector: doubly charged 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 $15^{(S)} + 6_1^{(S)} + 6_2^{(S)} + 21^{(S)} + 35^{(S)}$
- $15^{(S)} \to \left(\mathbf{1}, \mathbf{2}, \frac{1}{2}; -4\right) + \ldots$
- $6_1^{(S)} \to \left(\mathbf{1}, \bar{\mathbf{2}}, -\frac{1}{2}; -1\right) + \ldots$

} **2HDM (H_u, H_d)** — Type-II 2HDM

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

} **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

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

$$\bar{\mathbf{6}}_1^{(F)} \supset \bar{\mathbf{5}}_{-1}^{(\mathrm{SM})} \supset d_1,\, L_1 \qquad \bar{\mathbf{6}}_1^{(F)} \supset \mathbf{1}_5^{(F)} \supset \nu_1$$
$$\bar{\mathbf{6}}_2^{(F)} \supset \bar{\mathbf{5}}_{-1}^{(F)} \supset d_2,\, L_2 \qquad \bar{\mathbf{6}}_2^{(F)} \supset \mathbf{1}_5^{(F)} \supset \nu_2$$
$$\mathbf{15}^{(F)} \supset \mathbf{10}_2^{(\mathrm{SM})} \supset Q,\, u,\, e \qquad \mathbf{15}^{(F)} \supset \mathbf{5}_{-4}^{(F)} \supset d',\, L'\,.$$

- Yukawa Sector

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

- 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

$$\mathscr{L}_{\rm IR} \supset 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1H_dQ + y_e\, eH_dL_1 + y_\nu\, L'H_d^{c\dagger}\nu_1 + y_D\, d_2d's_6 + y_L\, L'L_2s_6 + y_{\nu_1}\, \nu_1\nu_1s_{21} + y_{\nu_2}\, \nu_2\nu_2s_{21}$$
$$+y_d'\, d_2H_dQ + y_e'\, eH_dL_2 + y_\nu'\, L'H_d^{c\dagger}\nu_2 + y_D'\, d_1d's_6 + y_L'\, L'L_1s_6 + 2\tilde{y}_{11}\, \nu_1H_u^{c\dagger}L_1 + 2\tilde{y}_{22}\, \nu_2H_u^{c\dagger}L_2$$
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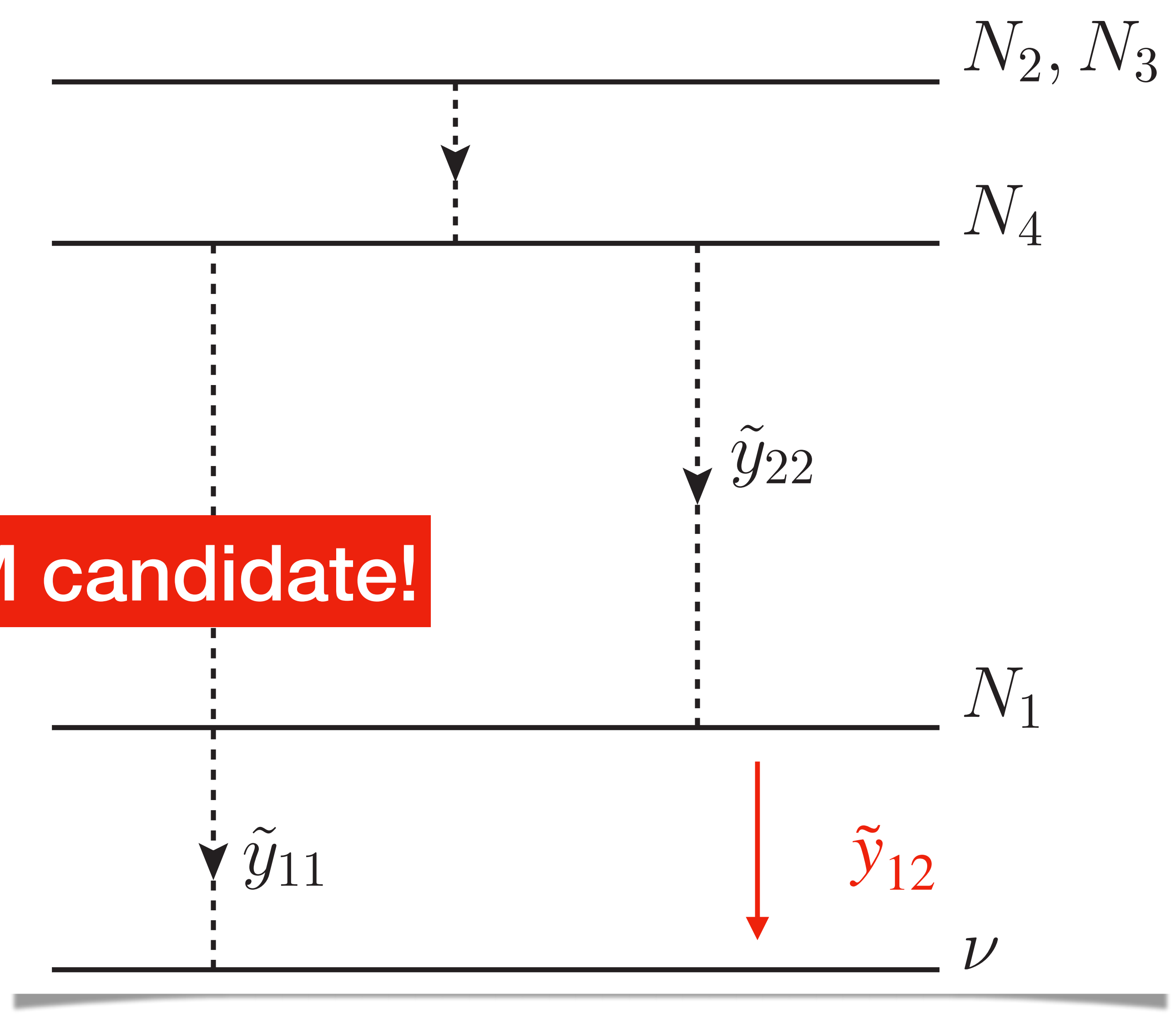
There is no stable DM candidate!

$N_4 \sim \nu_1$

$N_1 \sim \nu_2$

$L_1 \supset \nu$



Stabilizing dark matter

Using quantum scale symmetry

- SU(6) — Yukawa Lagrangian

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

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

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

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

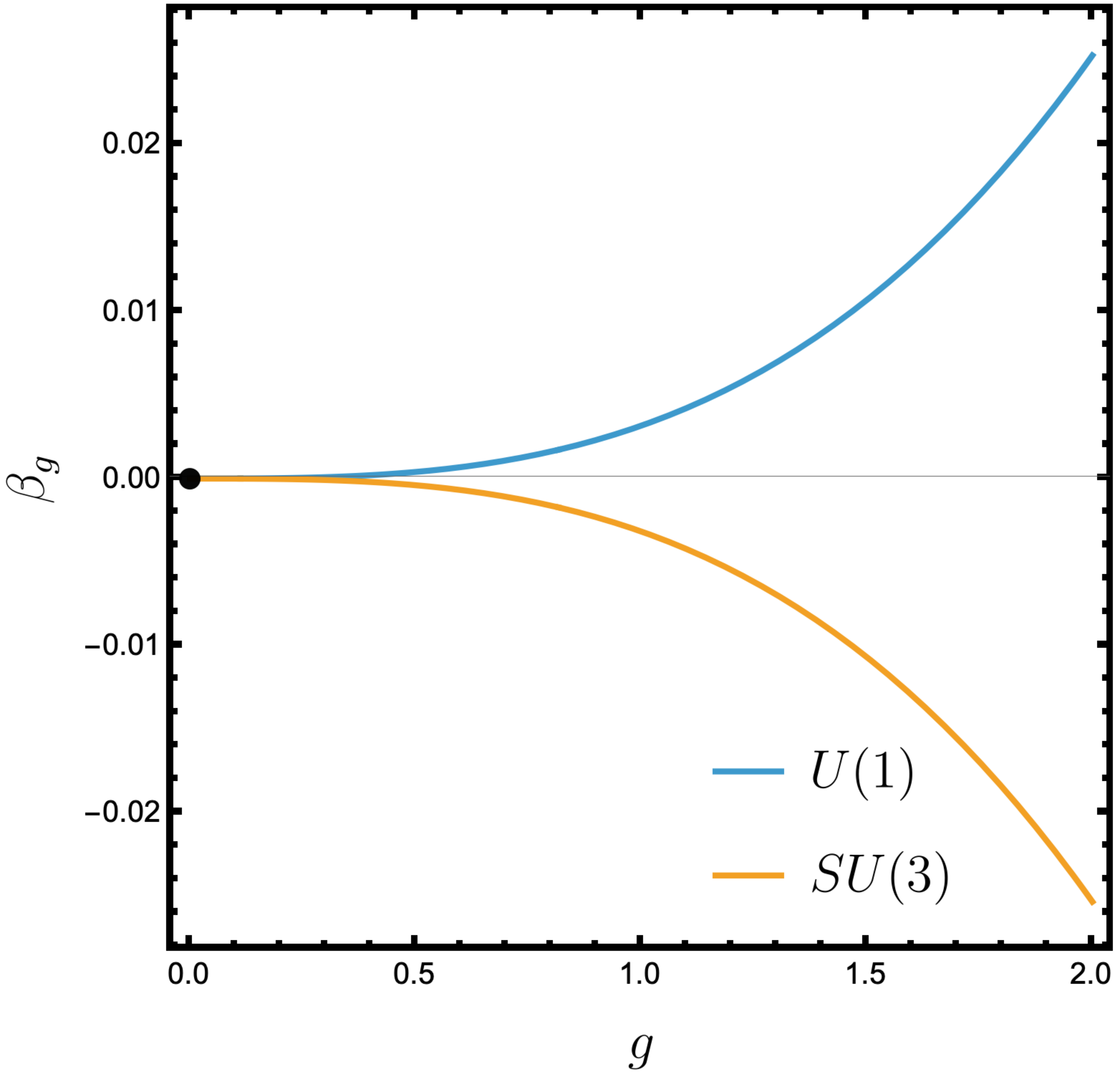
- i) Introduce global or discrete symmetries — Most works in the literature
- ii) secluding mechanism from quantum scale invariance — Our paper!

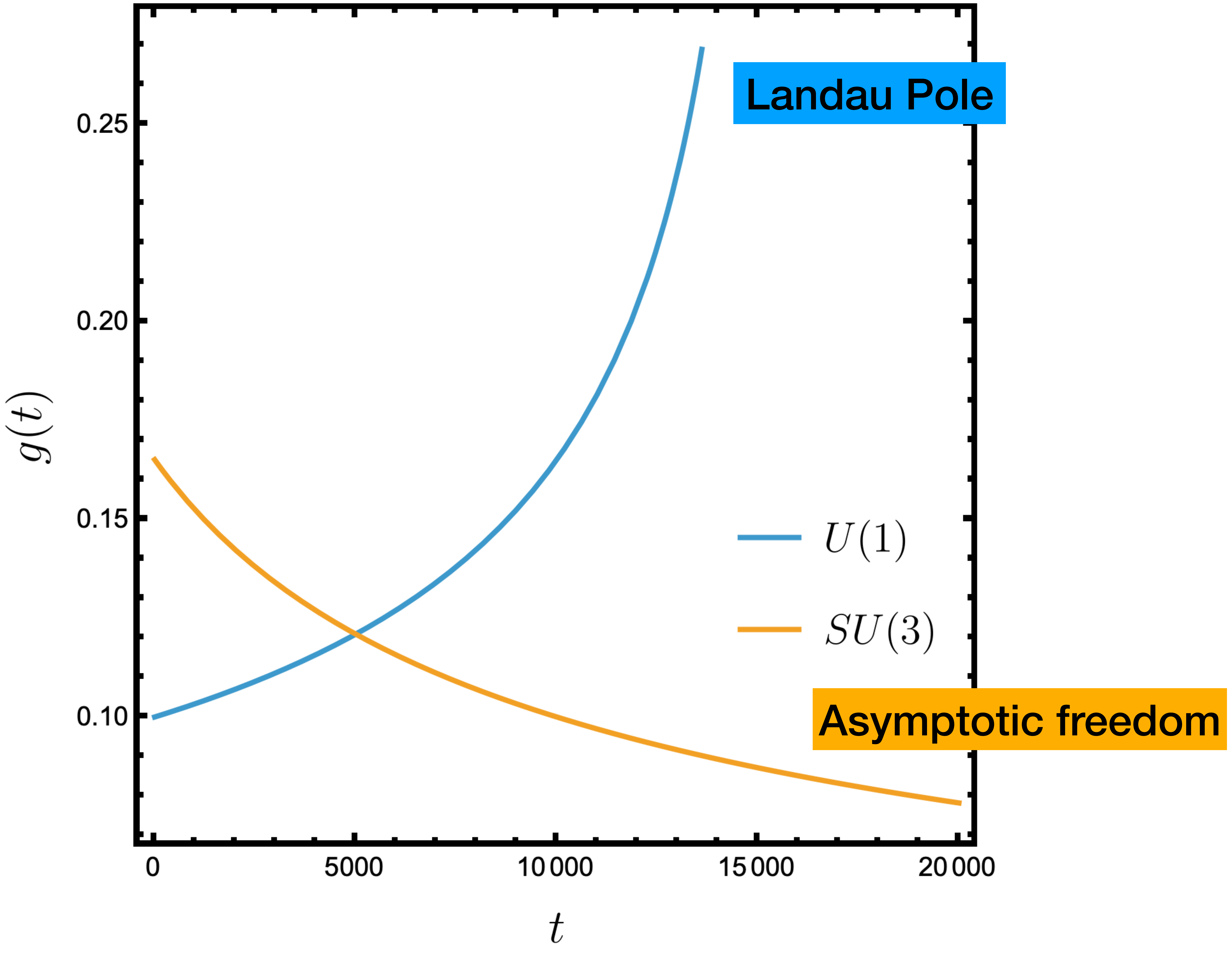
$$\beta_g \equiv \frac{dg}{dt}$$

Motivating quantum scale symmetry

Beta functions in Yang-Mills theories

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





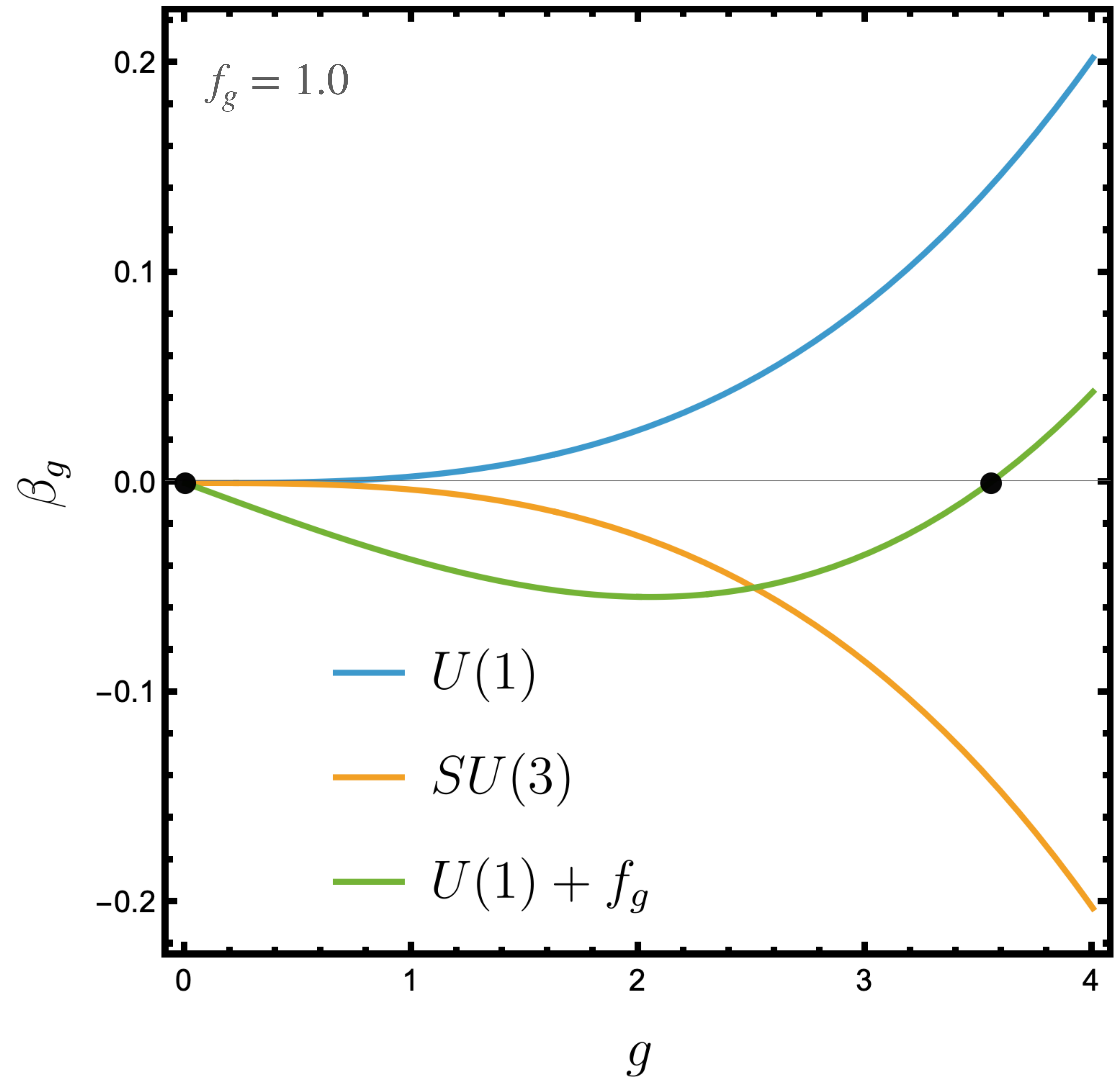
Motivating quantum scale symmetry

Add linear correction

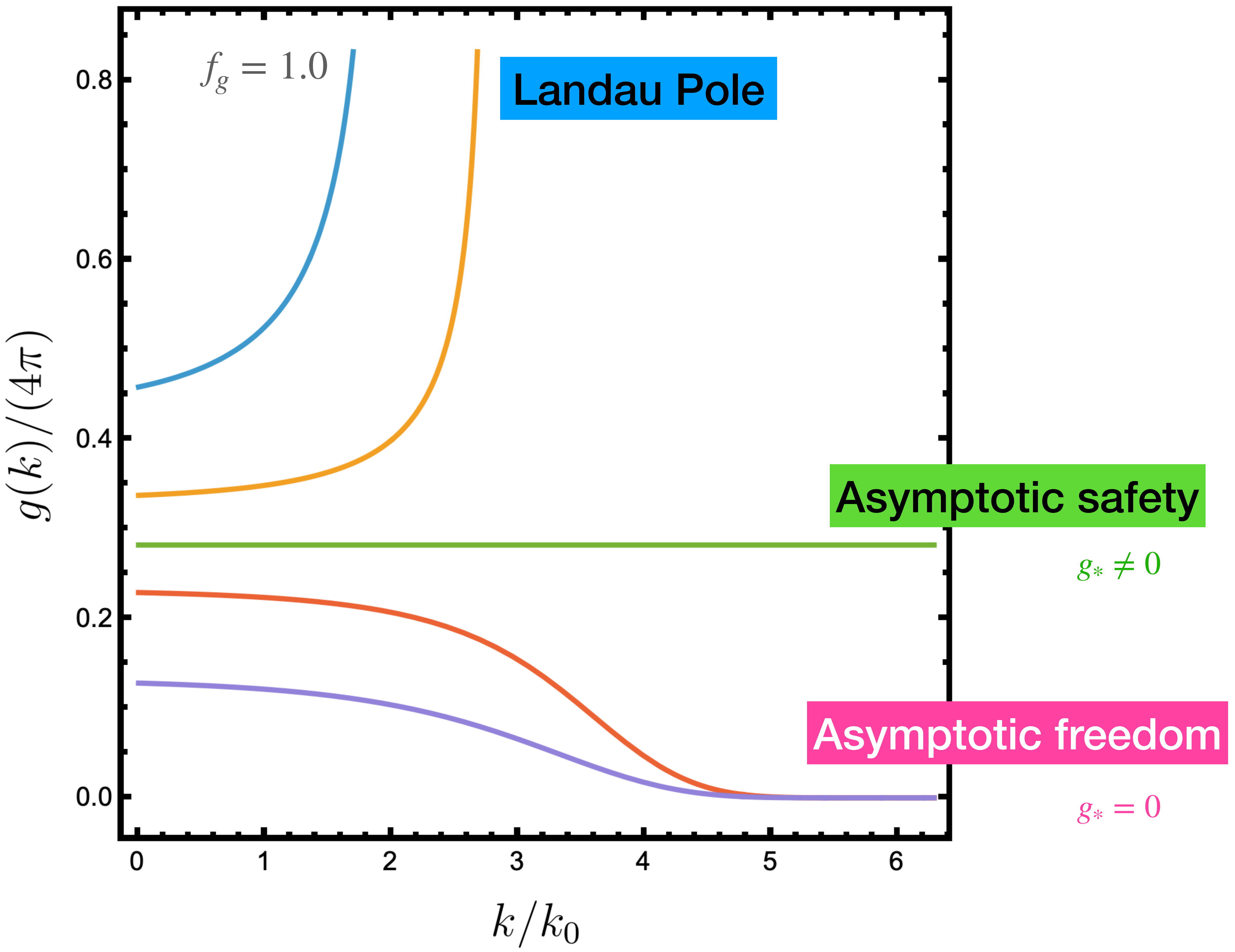
$$\beta_{g_1} = \frac{1}{2}\eta_A\, g_1 - \frac{f_g}{2}\frac{g_1}{4\pi}$$

$$\eta_A^{U(1)} = +\frac{g_1^2}{16\pi^2} > 0$$

If $f_g > 0$, new **zero of the beta function** → new **interacting fixed point** $g_* \neq 0$ $\quad g_*^2 = (4\pi) f_g$



All are from U(1) here



Weinberg '79

Motivating quantum scale symmetry

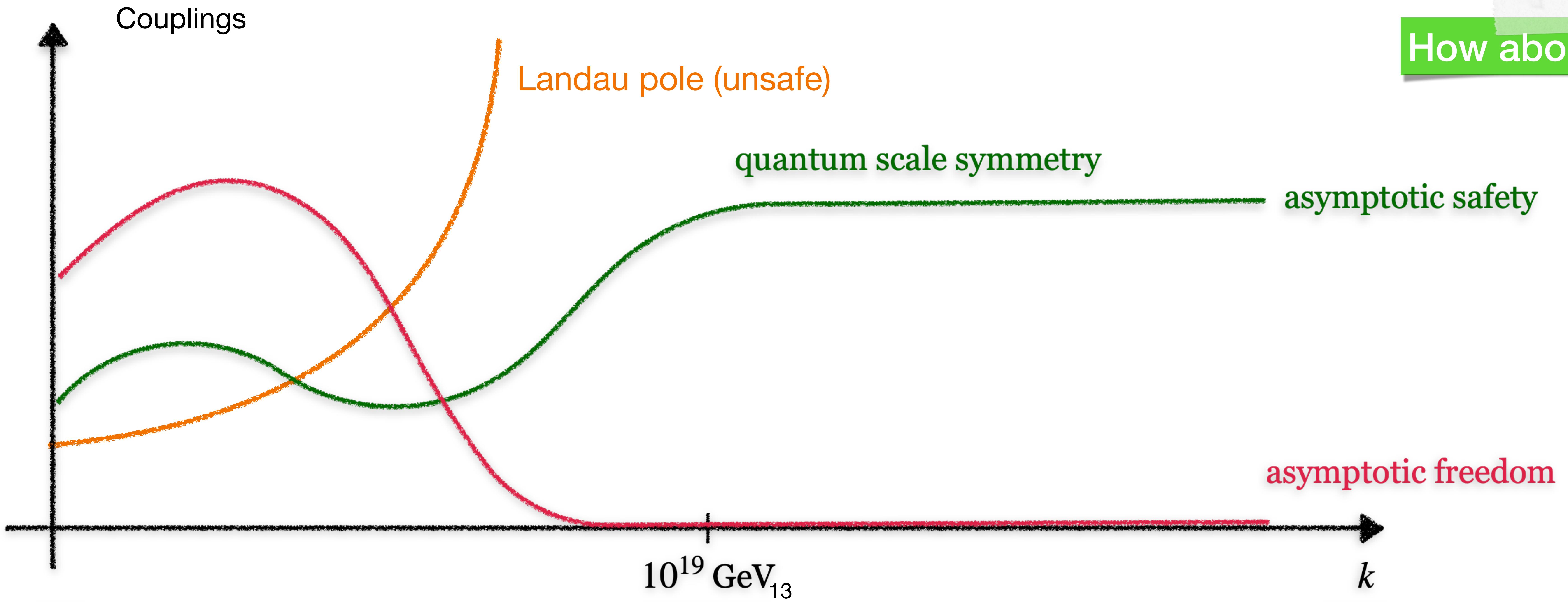
Can heal UV divergences and Landau poles

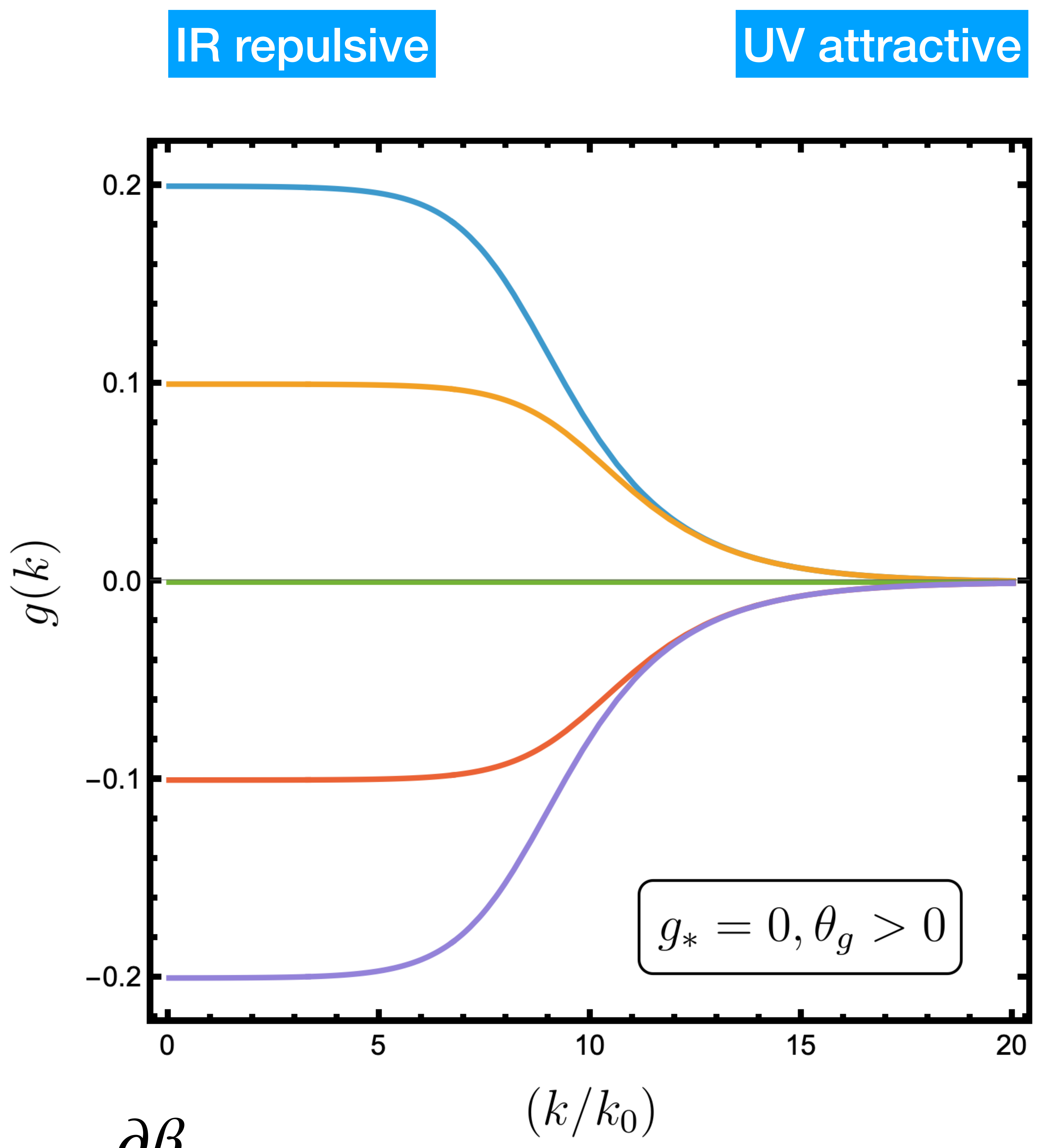
- **Asymptotic safety = quantum scale symmetry**
- Condition: interacting fixed point at UV
- Here UV means, very very large scales, e.g. GUT or Planck scales

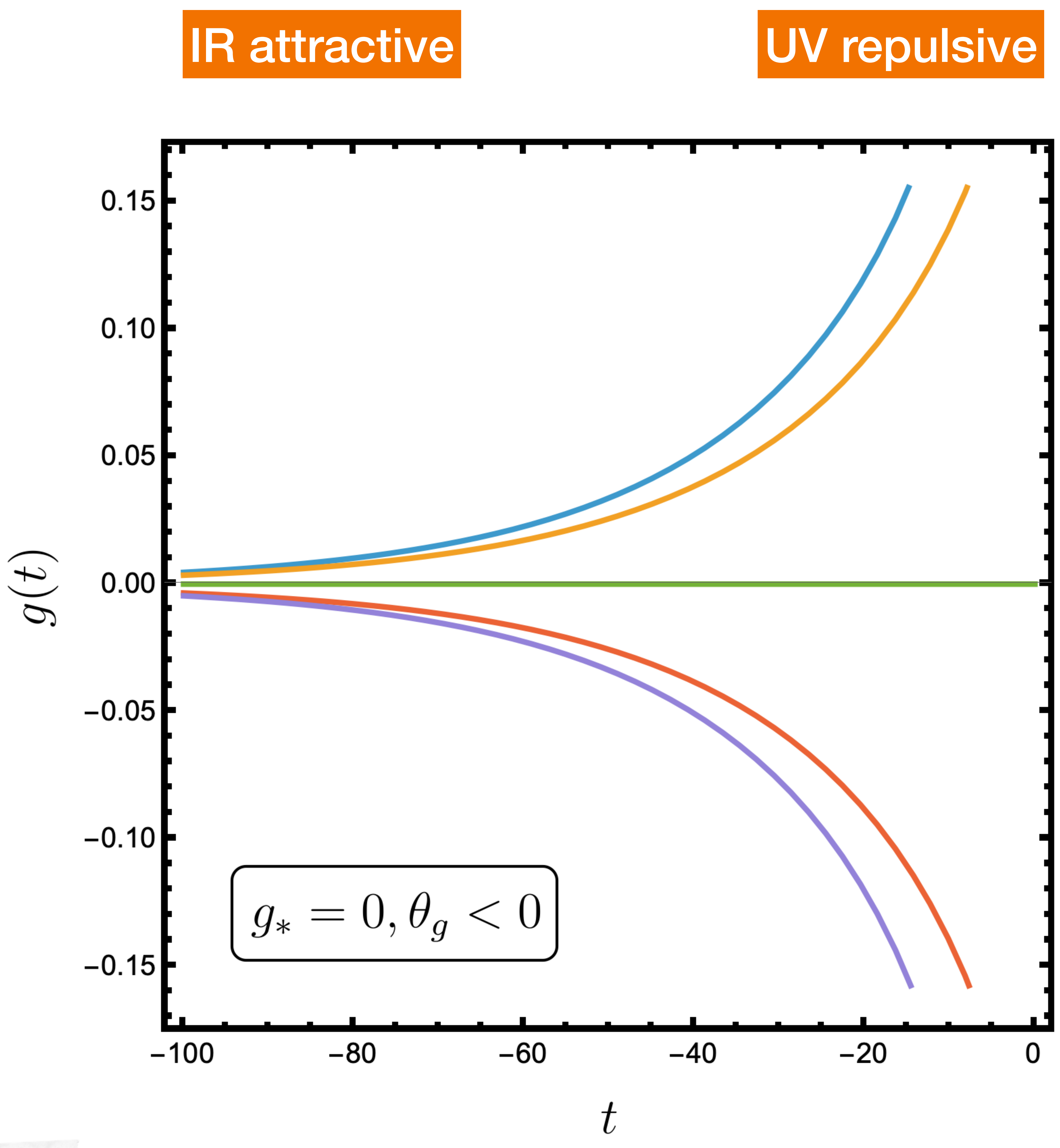
U(Y) has Landau pole in the UV (unsafe)

SU(3) is asymptotically free

How about gravity?







$$M_{ij} = \frac{\partial \beta_{g_i}}{\partial g_j} \Big|_{g_*}$$

$$\theta_i = -\,\text{eig}(M)\,.$$

Parameters can be free parameters or predictions

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

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

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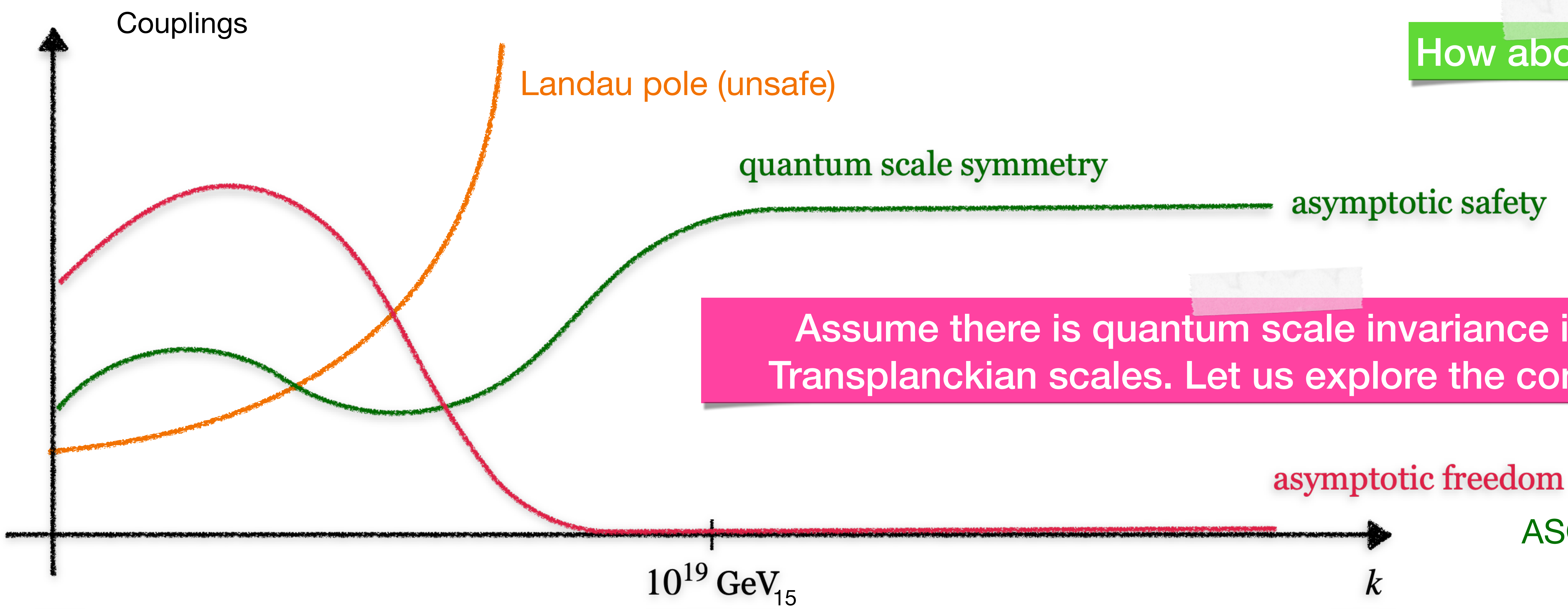

How about gravity?

Assume there is quantum scale invariance in nature at Transplanckian scales. Let us explore the consequences.

$G_*, \Lambda_* \neq 0$

ASQG: Finite number of free parameters

Gravitational correction to matter systems

Running of the gauge coupling with gravity

- Use background field formalism: $\beta_g = \frac{1}{2}\eta_A\, g$ $\qquad \eta_A^{YM} = \pm \frac{g_{YM}^2}{16\pi^2}$
- $\eta_A = \eta_A^{matter}(g) + \eta_A^{gravity}(G)$
- Then it is possible to write, at leading order,

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

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

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)

Value of f_g is scheme-dependent.

Gravitational correction to matter systems

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

$$f_g = f_g(G_*, \Lambda_*) \geq 0$$

Assume there is quantum scale invariance in nature at Transplanckian scales. Let us explore the consequences.

Similar for Yukawa sector

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-Gutierrez, Pawlowski, Reichert

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

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

Idea:

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

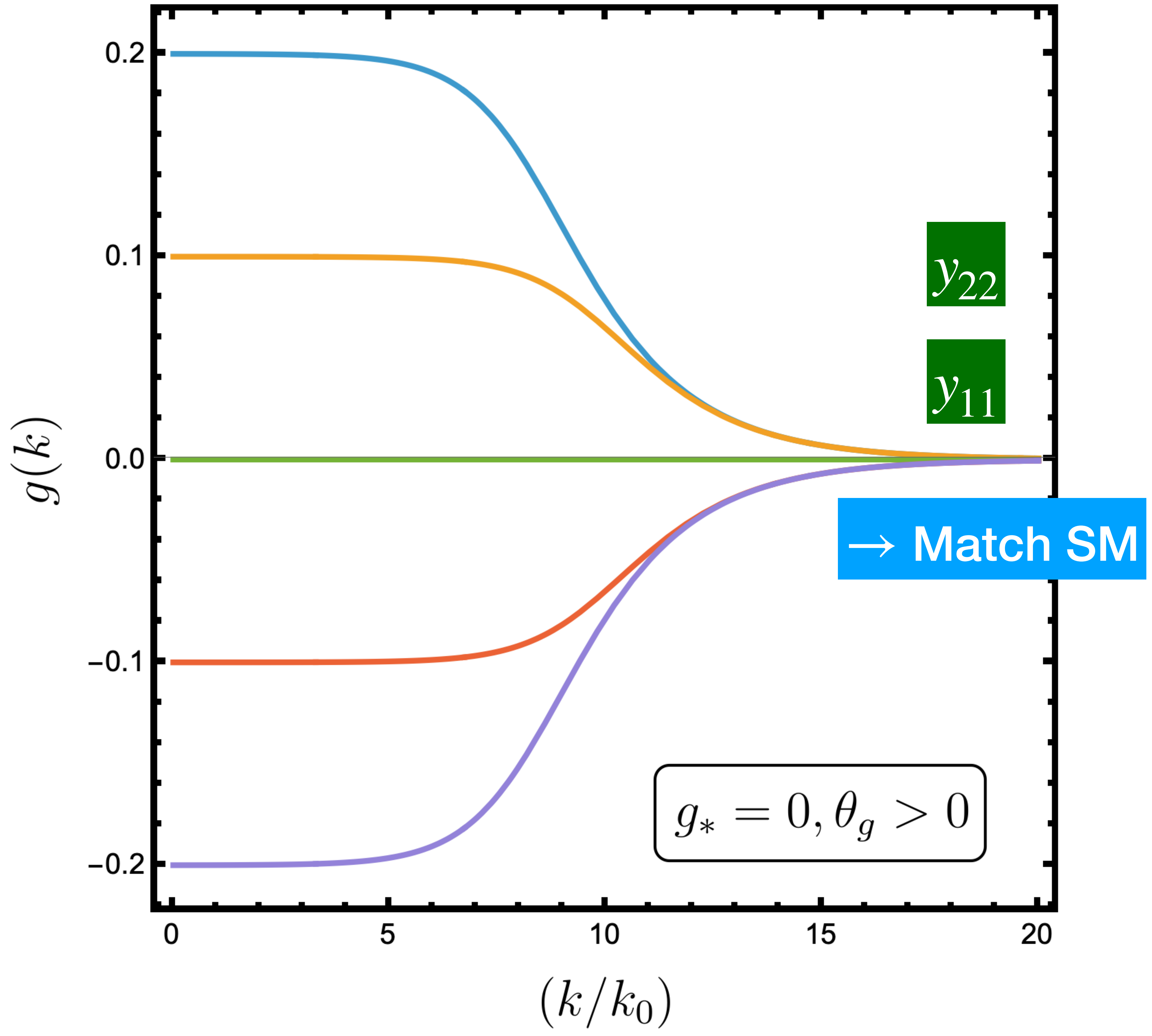
$y_{22}^* \neq 0, y_{11}^* = y_{12}^* = y_{21}^* = 0.$

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

Free parameter **Predictions**

IR repulsive

UV attractive



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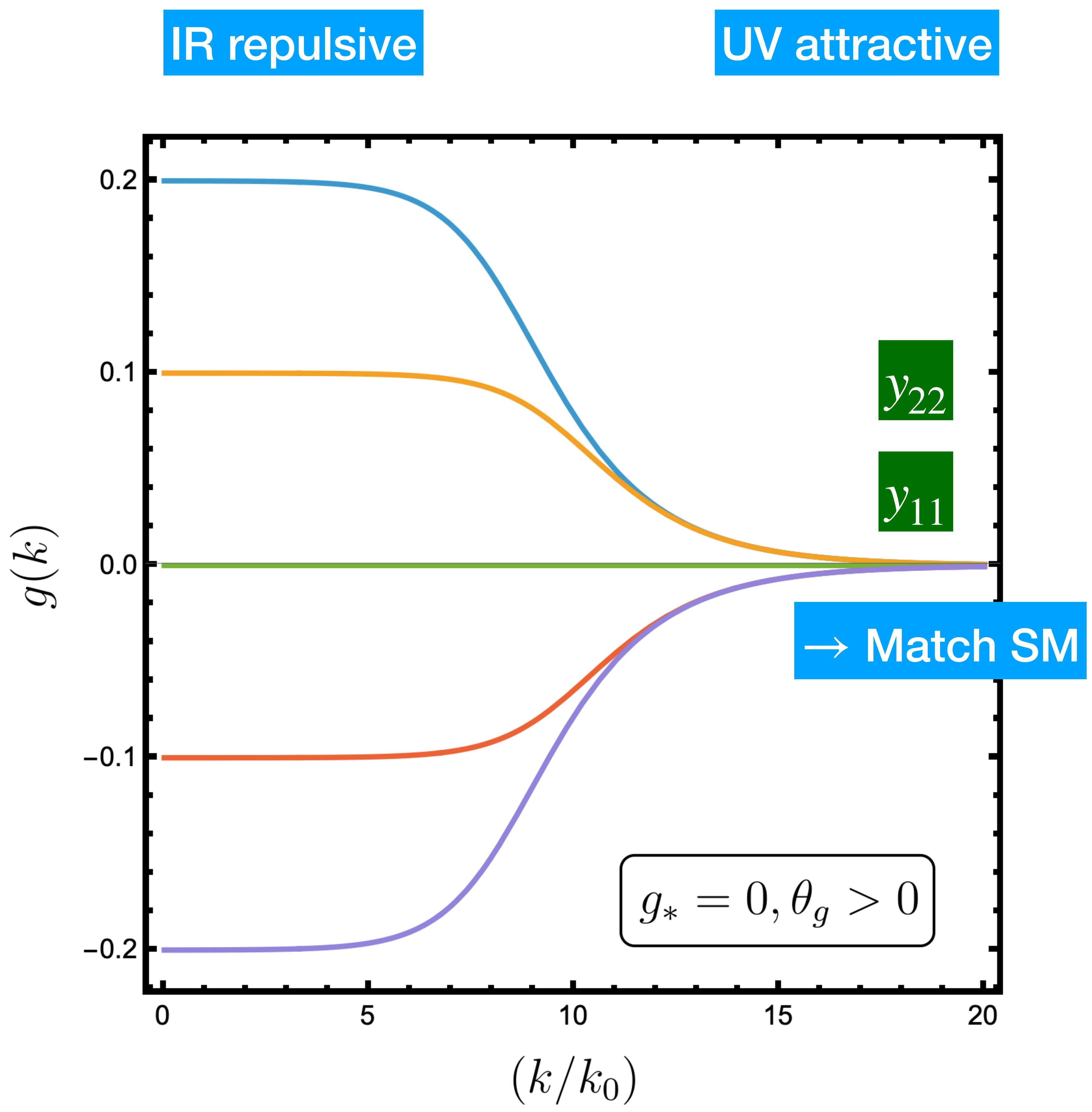
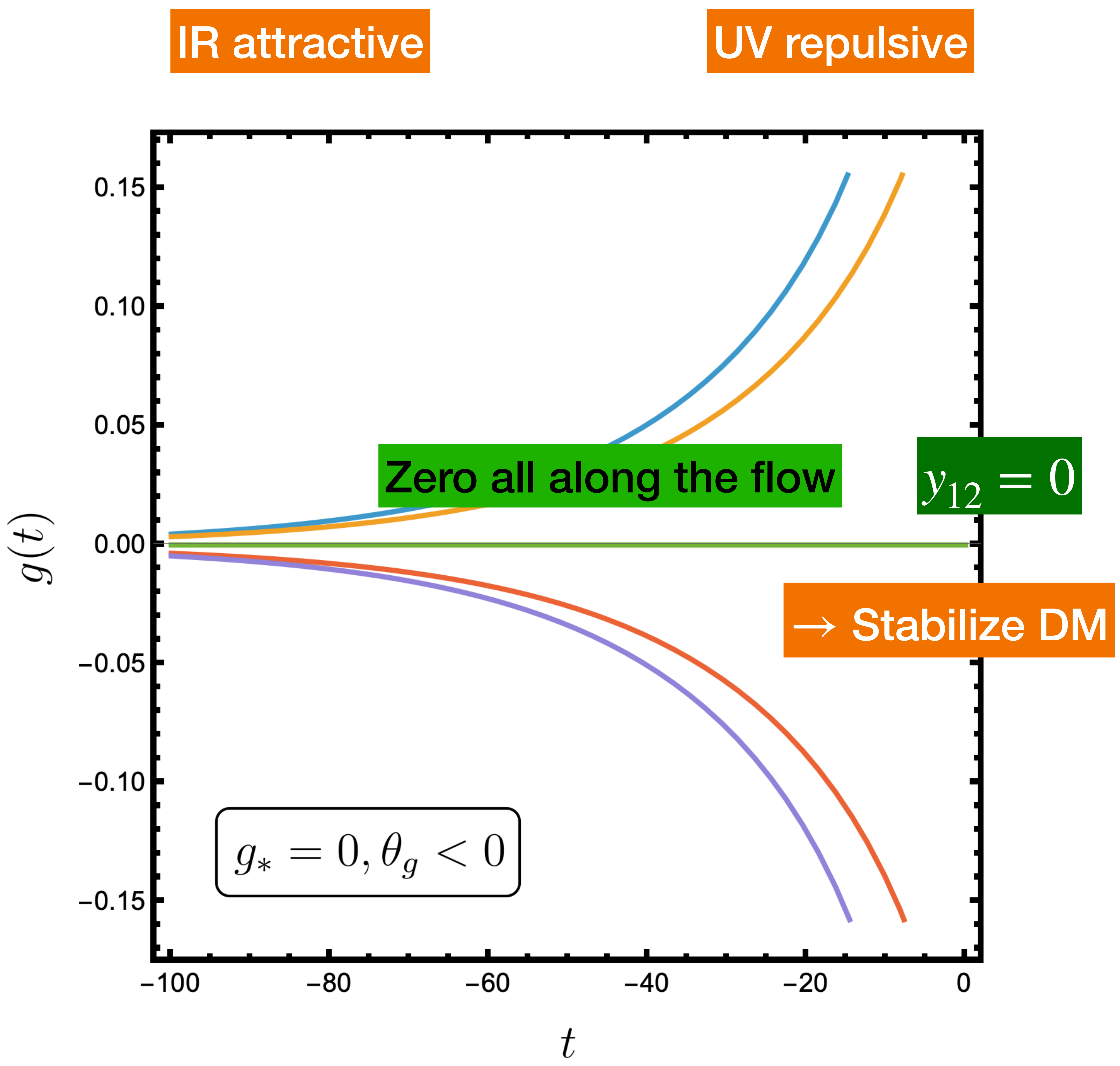




Full system has many fixed points.
Search for a FP solution
$$y_{22}^* \neq 0, y_{11}^* = y_{12}^* = y_{21}^* = 0.$$
$$\theta_{11} > 0, \theta_{12}, \theta_{21} < 0$$

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

Stabilizing dark matter

Dark matter candidates

- Before SSB

$$\mathcal{L} \supset y_{11} \mathbf{15}^{(F)} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_1^{(S)} + y_{12} \mathbf{15}^{(F)} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_2^{(S)} + y_{21} \mathbf{15}^{(F)} \bar{\mathbf{6}}_2^{(F)} \bar{\mathbf{6}}_1^{(S)} + y_{22} \mathbf{15}^{(F)} \bar{\mathbf{6}}_2^{(F)} \bar{\mathbf{6}}_2^{(S)}$$
$$+ \tilde{y}_{11} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_1^{(F)} \mathbf{15}^{(S)} + \tilde{y}_{12} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_2^{(F)} \mathbf{15}^{(S)} + \tilde{y}_{22} \bar{\mathbf{6}}_2^{(F)} \bar{\mathbf{6}}_2^{(F)} \mathbf{15}^{(S)}$$
$$+ \hat{y}_{11} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_1^{(F)} \mathbf{21}^{(S)} + \hat{y}_{12} \bar{\mathbf{6}}_1^{(F)} \bar{\mathbf{6}}_2^{(F)} \mathbf{21}^{(S)} + \hat{y}_{22} \bar{\mathbf{6}}_2^{(F)} \bar{\mathbf{6}}_2^{(F)} \mathbf{21}^{(S)}$$
$$+ y_u \mathbf{15}^{(F)} \mathbf{15}^{(F)} \mathbf{15}^{(S)} + \text{H.c.}$$

- After SSB

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

Free parameters

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

Predictions

DM and neutrino are predictions of the theory

- From RG flow

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

Gives correct SM particle masses

Many decays are forbidden: can have DM candidates!

See more details in backup slides

Stabilizing dark matter

Single Dark Matter candidates

Singlet DM

Upper bound on the Z' mass around 9 TeV

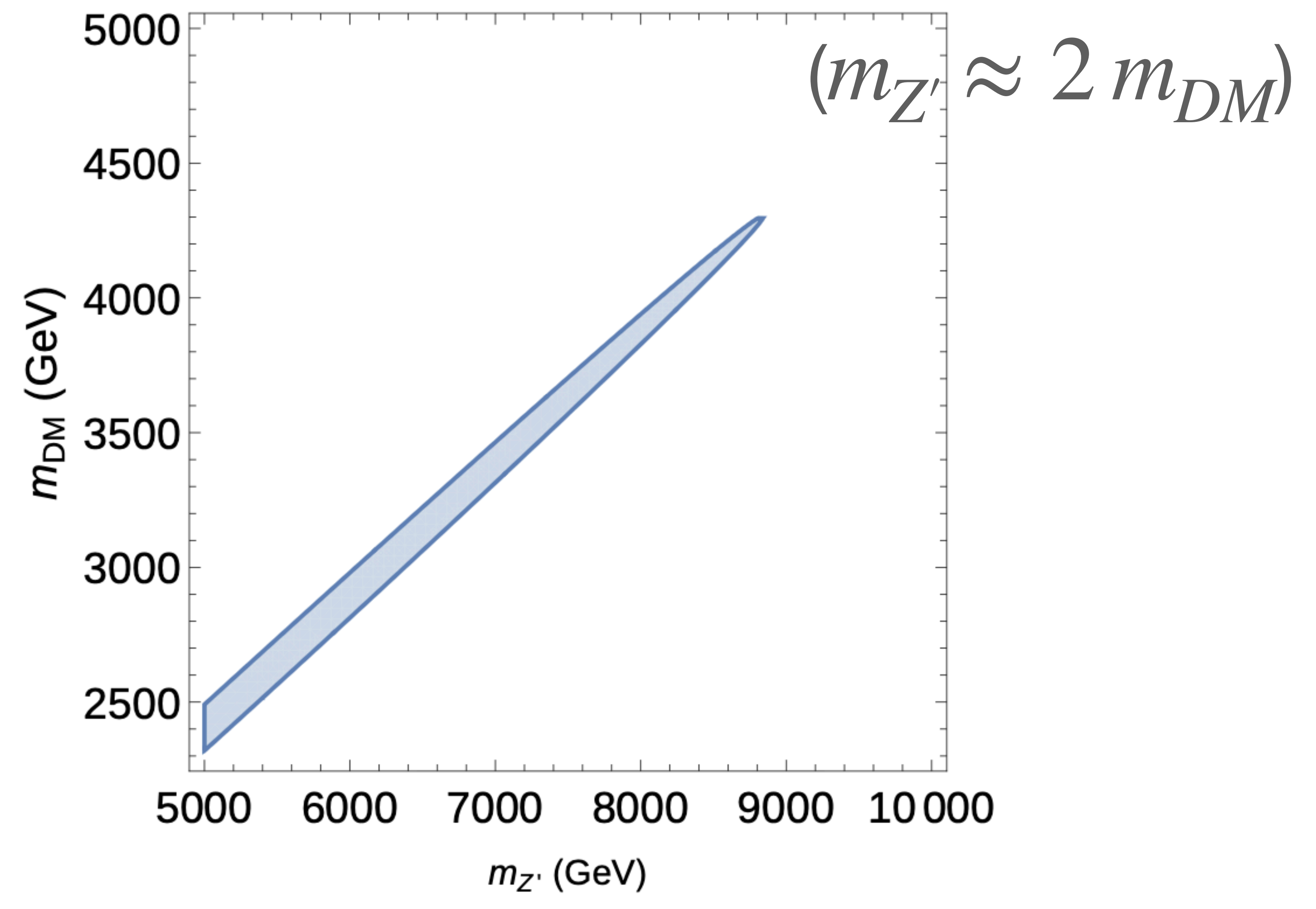
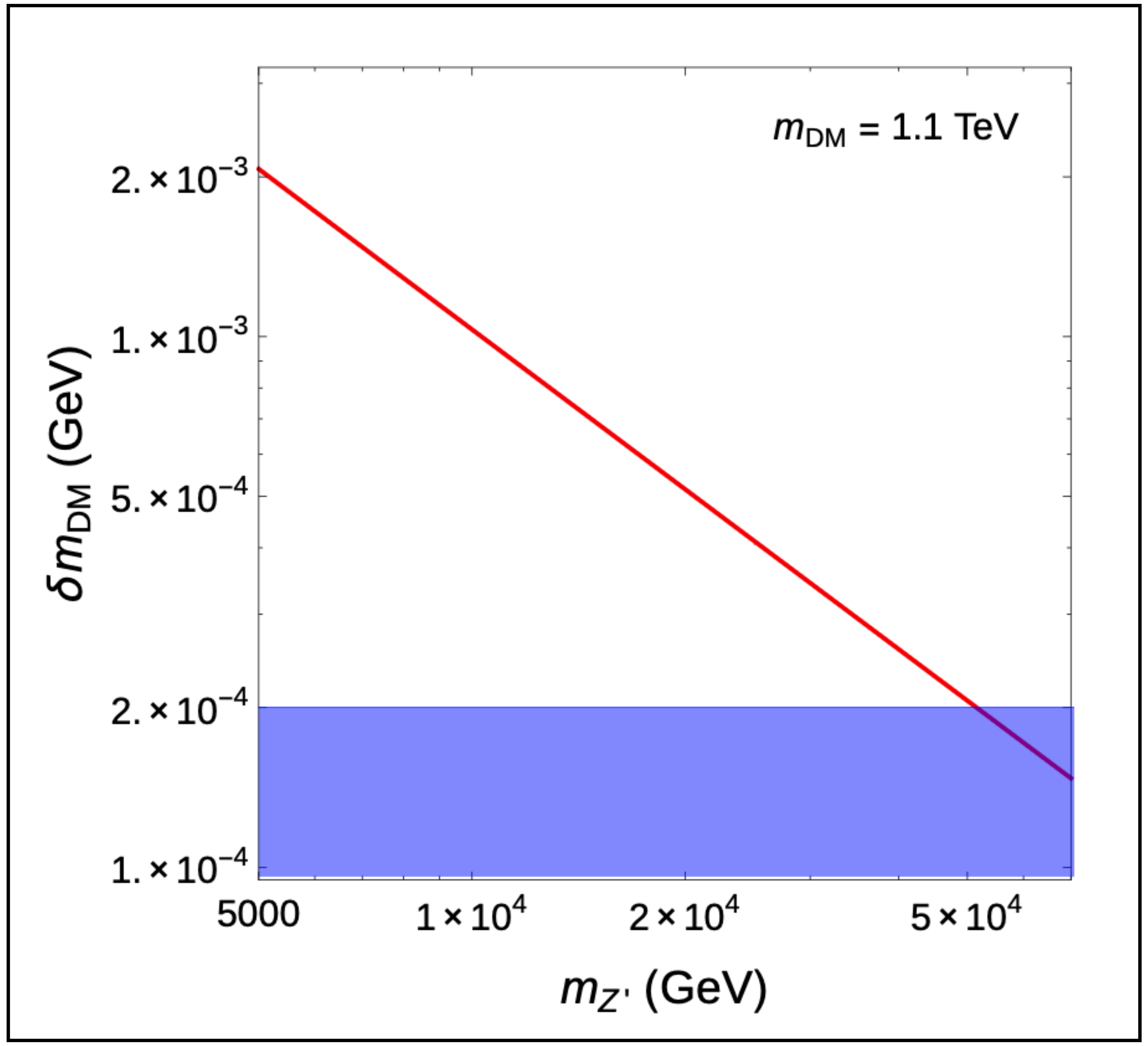


Figure 5: The region of under-abundant relic density (in blue) in the SM-singlet DM case.

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)

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

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Stabilizing dark matter

Using quantum scale symmetry

- Yukawa Lagrangian

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

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!

See backup slides for more details!

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Dziękuję!

Thank you!

rafael.santos@ncbj.gov.pl

Backup slides

Stabilizing dark matter

Fermion sector without quantum scale symmetry

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

- Yukawa Sector

$$\mathscr{L}_{\rm IR} \supset 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1 H_d Q + y_e\, eH_d L_1 + y_\nu\, L'H_d^{c\dagger}\nu_1 + y_D\, d_2 d' s_6 + y_L\, L'L_2 s_6 + y_{\nu_1}\,\nu_1\nu_1 s_{21} + y_{\nu_2}\,\nu_2\nu_2 s_{21}$$

$$+y'_d\, d_2 H_d Q + y'_e\, eH_d L_2 + y'_\nu\, L'H_d^{c\dagger}\nu_2 + y'_D\, d_1 d' s_6 + y'_L\, L'L_1 s_6 + 2\tilde{y}_{11}\,\nu_1 H_u^{c\dagger}L_1 + 2\tilde{y}_{22}\,\nu_2 H_u^{c\dagger}L_2$$

$$+\tilde{y}_{12}\left(\nu_1 H_u^{c\dagger}L_2 + \nu_2 H_u^{c\dagger}L_1\right) + \hat{y}_{12}\,\nu_1\nu_2 s_{21} + \text{H.c.}$$

- Each generation, 5 neutral massive Majorana fermions

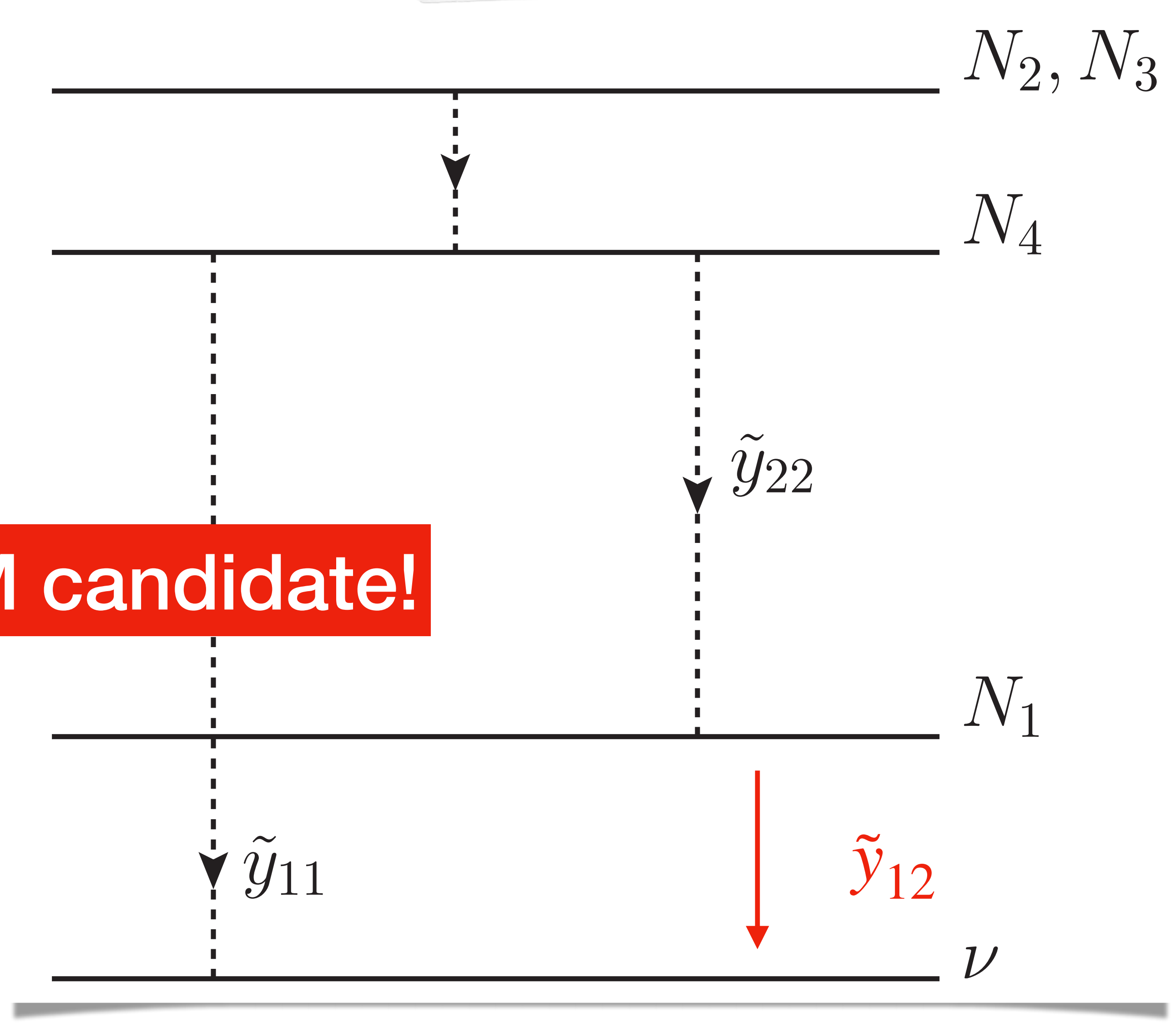
$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y'_L v_{s6} & 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12}v_u & 2\tilde{y}_{22}v_u \\ y'_L v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y'_\nu v_d \\ 2\tilde{y}_{11}v_u & \tilde{y}_{12}v_u & y_\nu v_d & y_{\nu_1}v_{s21}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

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

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

- 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

Compare fermion sector with(out) quantum scale symmetry

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

$$\mathscr{L}_{\text{IR}} \supset 2y_u\, uH_u^{c\dagger}Q + y_d\, d_1 H_d Q + y_e\, eH_d L_1 + y_\nu\, L' H_d^{c\dagger}\nu_1 + y_D\, d_2 d' s_6 + y_L\, L' L_2 s_6 + y_{\nu_1}\, \nu_1\nu_1 s_{21} + y_{\nu_2}\, \nu_2\nu_2 s_{21}$$
$$+ y_d'\, d_2 H_d Q + y_e'\, eH_d L_2 + y_\nu'\, L' H_d^{c\dagger}\nu_2 + y_D'\, d_1 d' s_6 + y_L'\, L' L_1 s_6 + 2\tilde{y}_{11}\, \nu_1 H_u^{c\dagger} L_1 + 2\tilde{y}_{22}\, \nu_2 H_u^{c\dagger} L_2$$
$$+ \tilde{y}_{12}\left(\nu_1 H_u^{c\dagger} L_2 + \nu_2 H_u^{c\dagger} L_1\right) + \hat{y}_{12}\, \nu_1\nu_2 s_{21} + \text{H.c.}$$

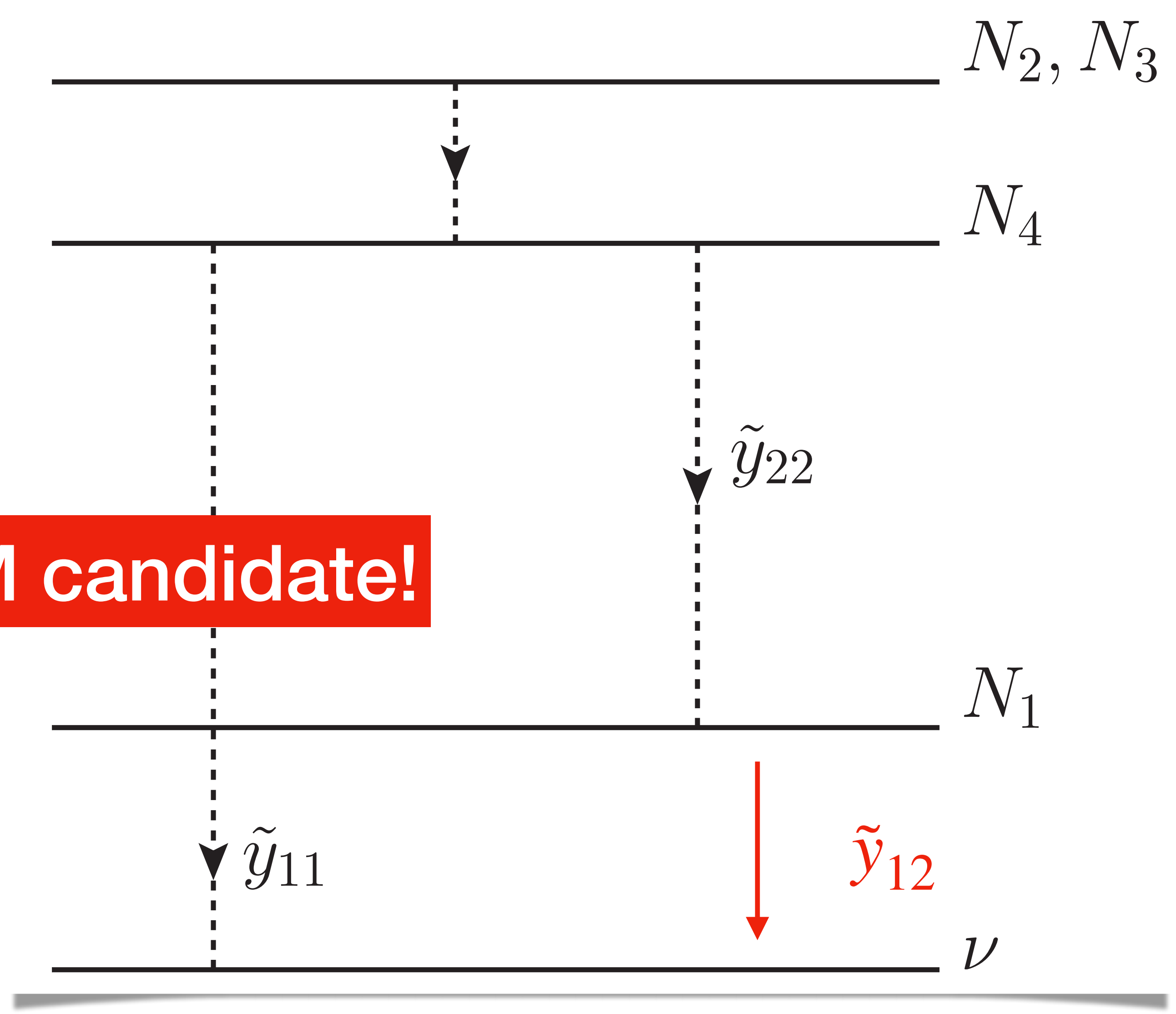
$$\frac{1}{2}M_\nu = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 & y_L' v_{s6} & 2\tilde{y}_{11} v_u & \tilde{y}_{12} v_u \\ 0 & 0 & y_L v_{s6} & \tilde{y}_{12} v_u & 2\tilde{y}_{22} v_u \\ y_L' v_{s6} & y_L v_{s6} & 0 & y_\nu v_d & y_\nu' v_d \\ 2\tilde{y}_{11} v_u & \tilde{y}_{12} v_u & y_\nu v_d & y_{\nu_1}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

There is no stable DM candidate!

$N_4 \sim \nu_1$

$N_1 \sim \nu_2$

$L_1 \supset \nu$



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Backup slide

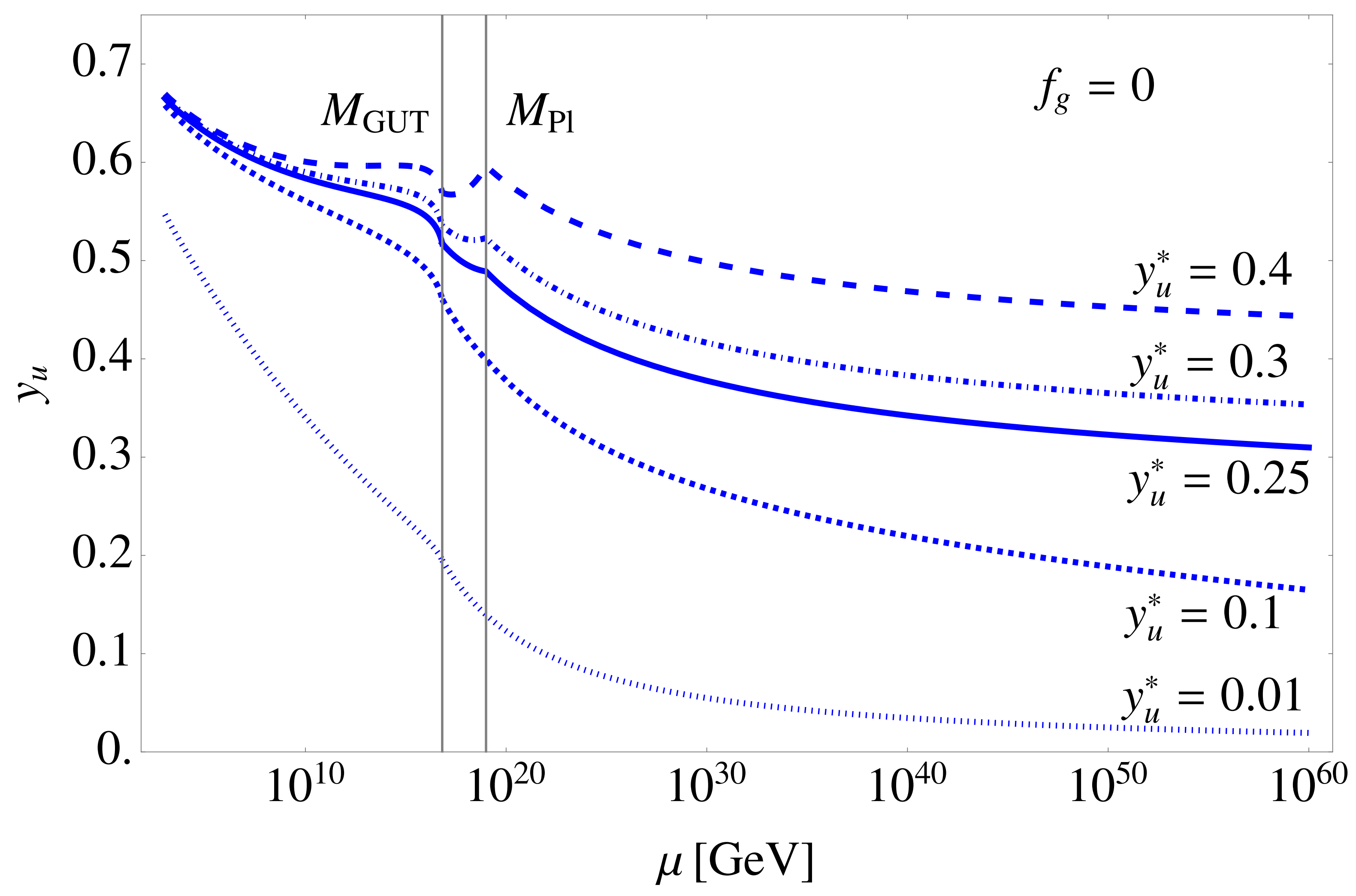
Stabilizing dark matter

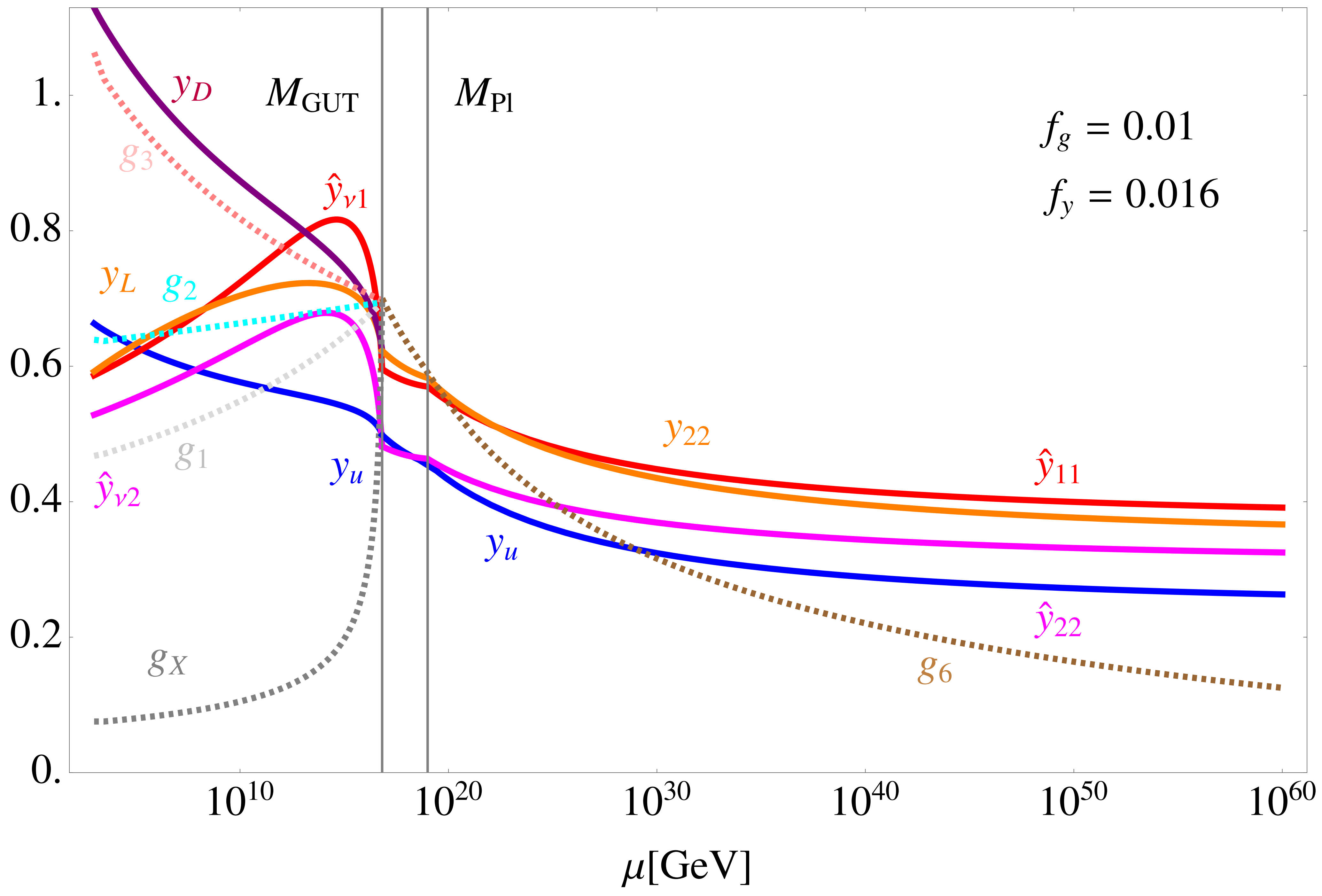
Impact of f_g and f_y in our model

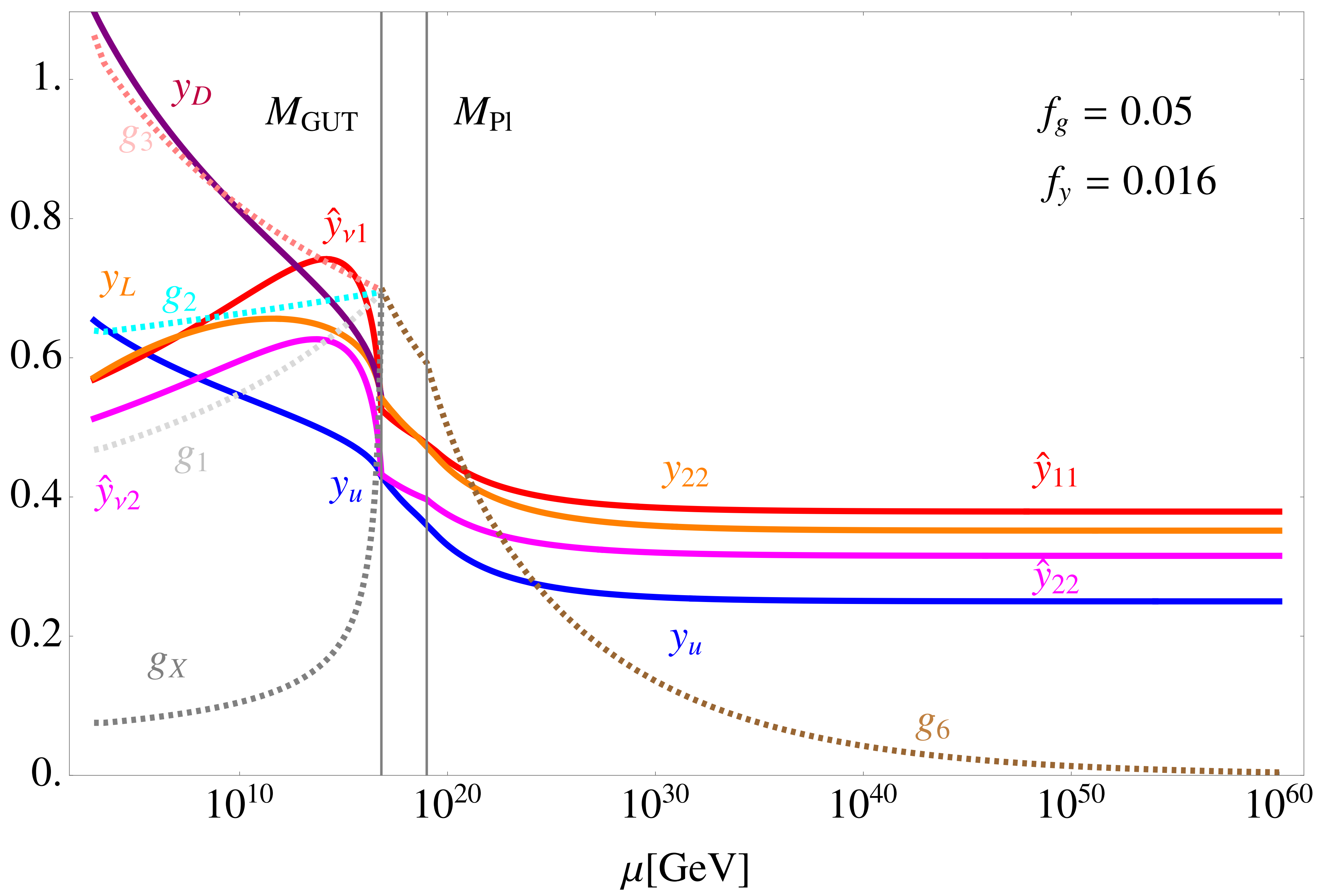
Predictions independent on f_g to a large extent

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

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

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

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

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Backup slide

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

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

Mechanism gives realistic mass to the first and second neutrino generations

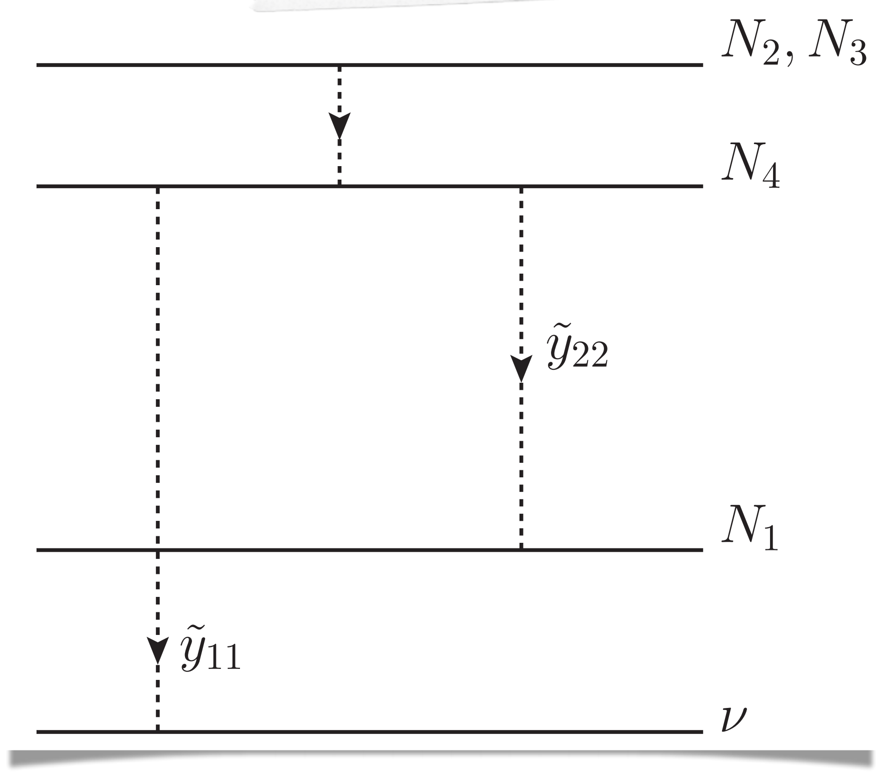
A) Only lightest neutrino is massless.

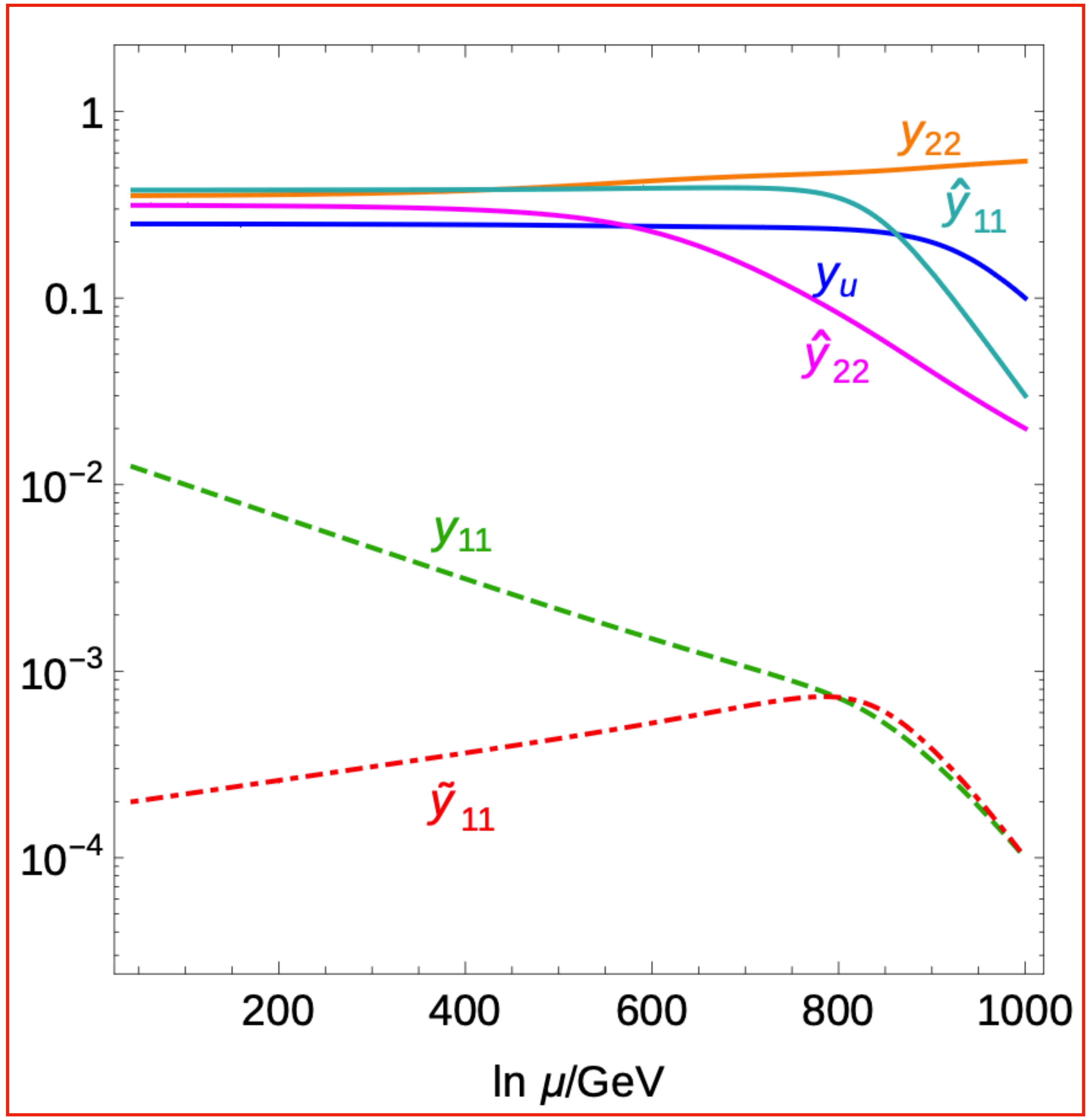
B) Two DM candidates -> Single DM candidate

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)**

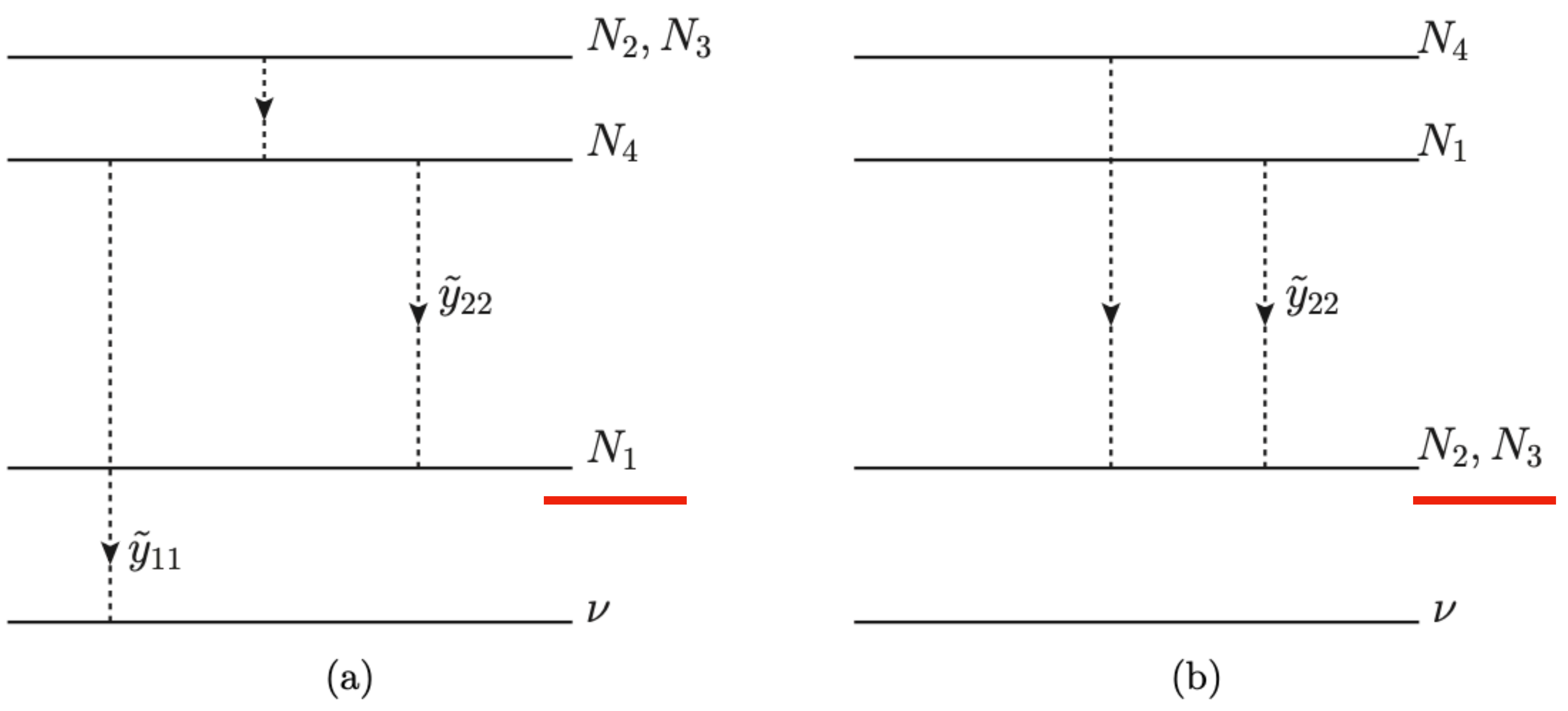


Figure 4: Decay chains of the heavy Majorana fermions N_1, N_2, N_3, and N_4 in the presence of non-zero (yet arbitrarily small) Yukawa couplings $\tilde{y}_{11}$ and $\tilde{y}_{22}$.

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

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

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)

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

- Relic density (Higgsino-like candidate)

Assuming BSM Higgs are heavy enough.

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

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

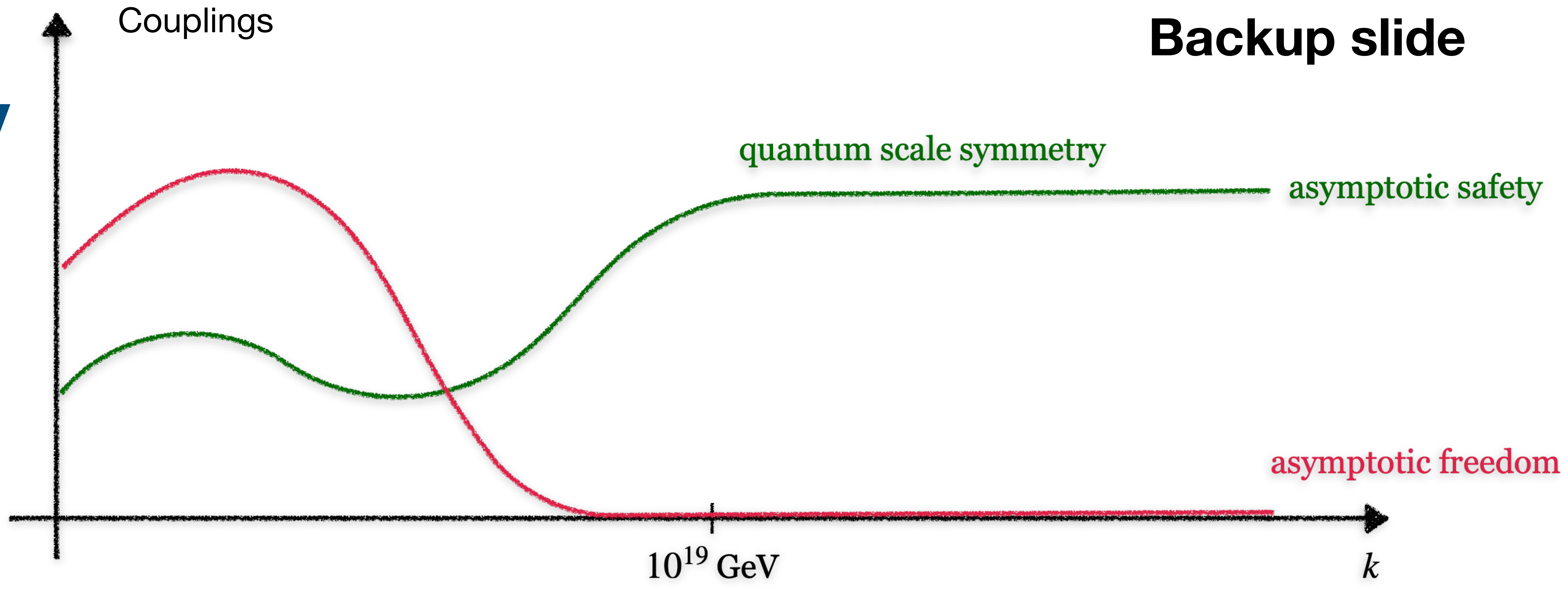
- Requires DM mass around 1.1 TeV

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

Backup slide

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: $g_* \neq 0$
  - $M_{ij} = \frac{\partial \beta_{g_i}}{\partial g_j}|_{g_*}, \theta_i = -\,\text{eig}(M)\,.$

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

See e.g. review 2212.07456 Eichhorn, Schiffer

Backup slide

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

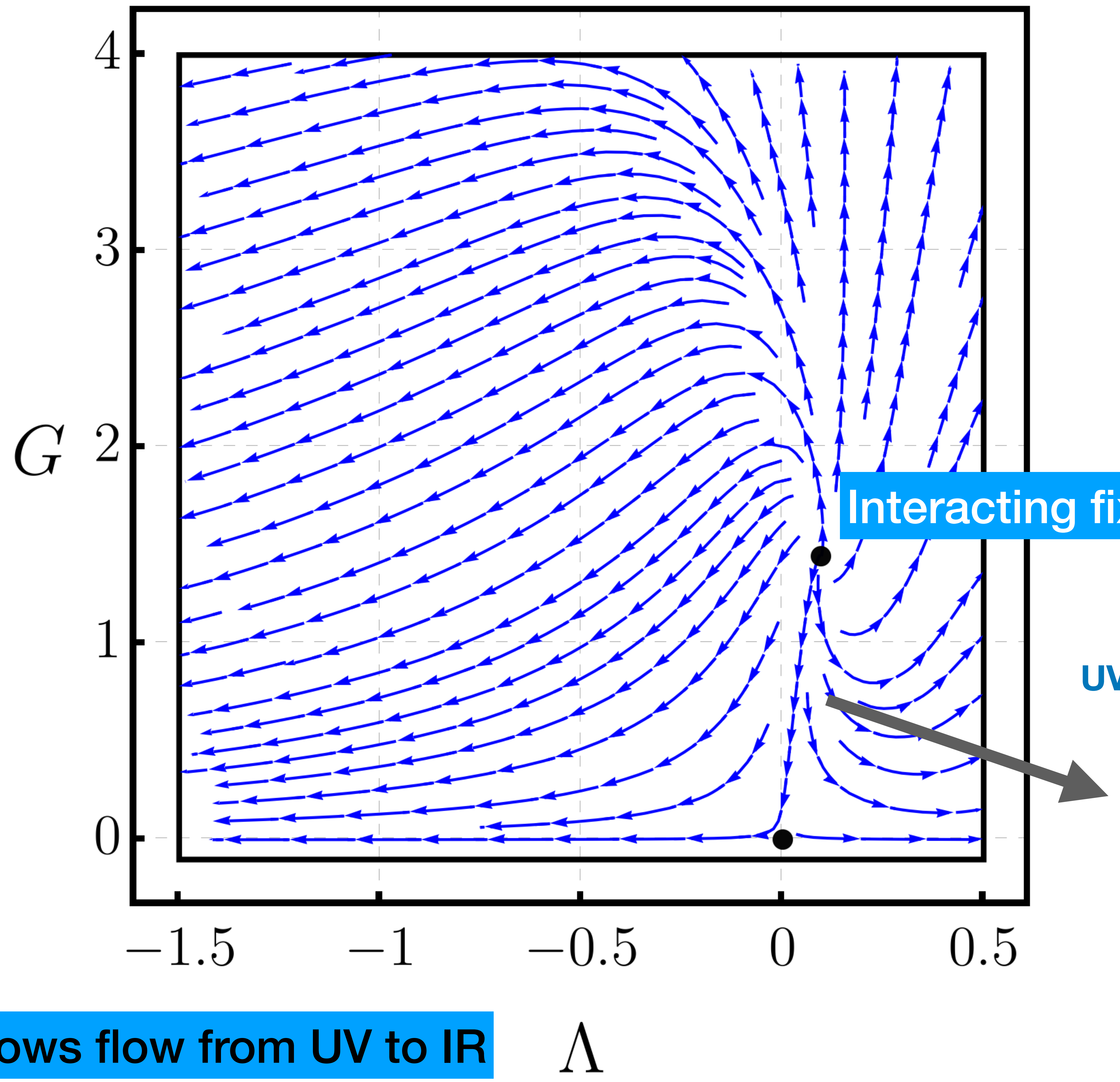
Asymptotic safety

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

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

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

@ 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!

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. **Backup slide**

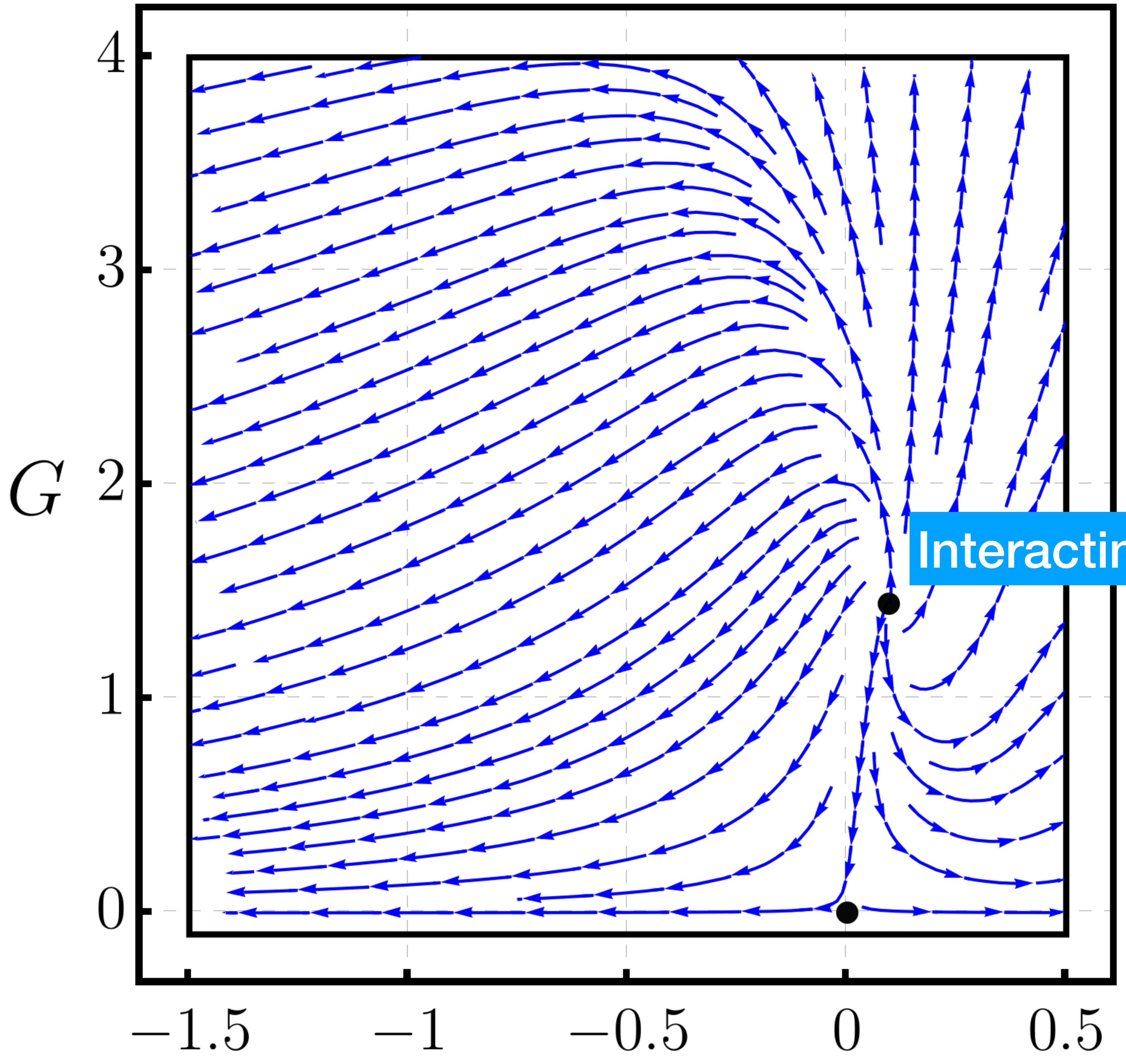
Asymptotic safety

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

Backup slide

Interplay with matter and landscape

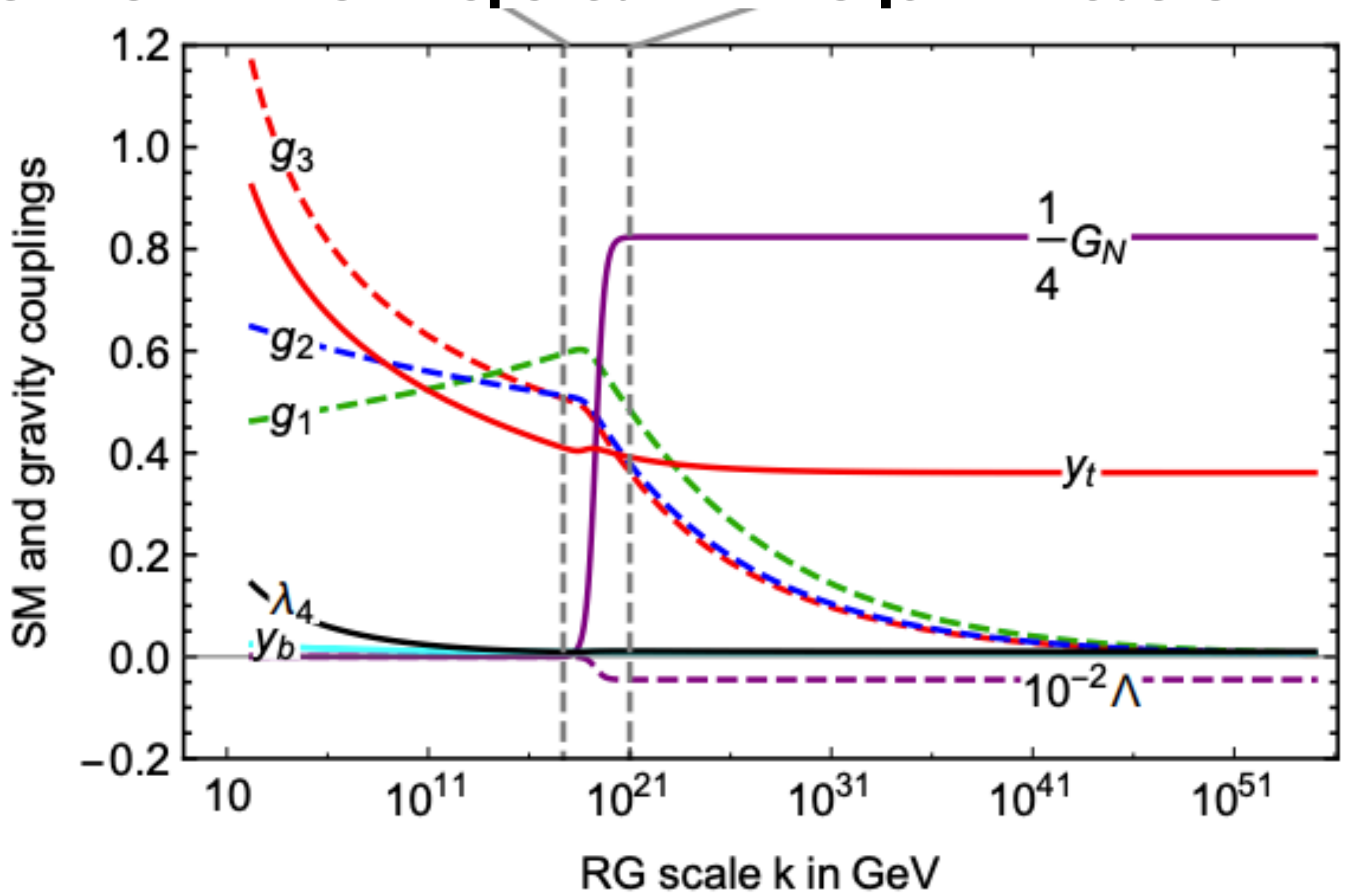
A few applications

- Prediction of Higgs mass Shaposhnikov/Wetterich 0912.0208

Abstract

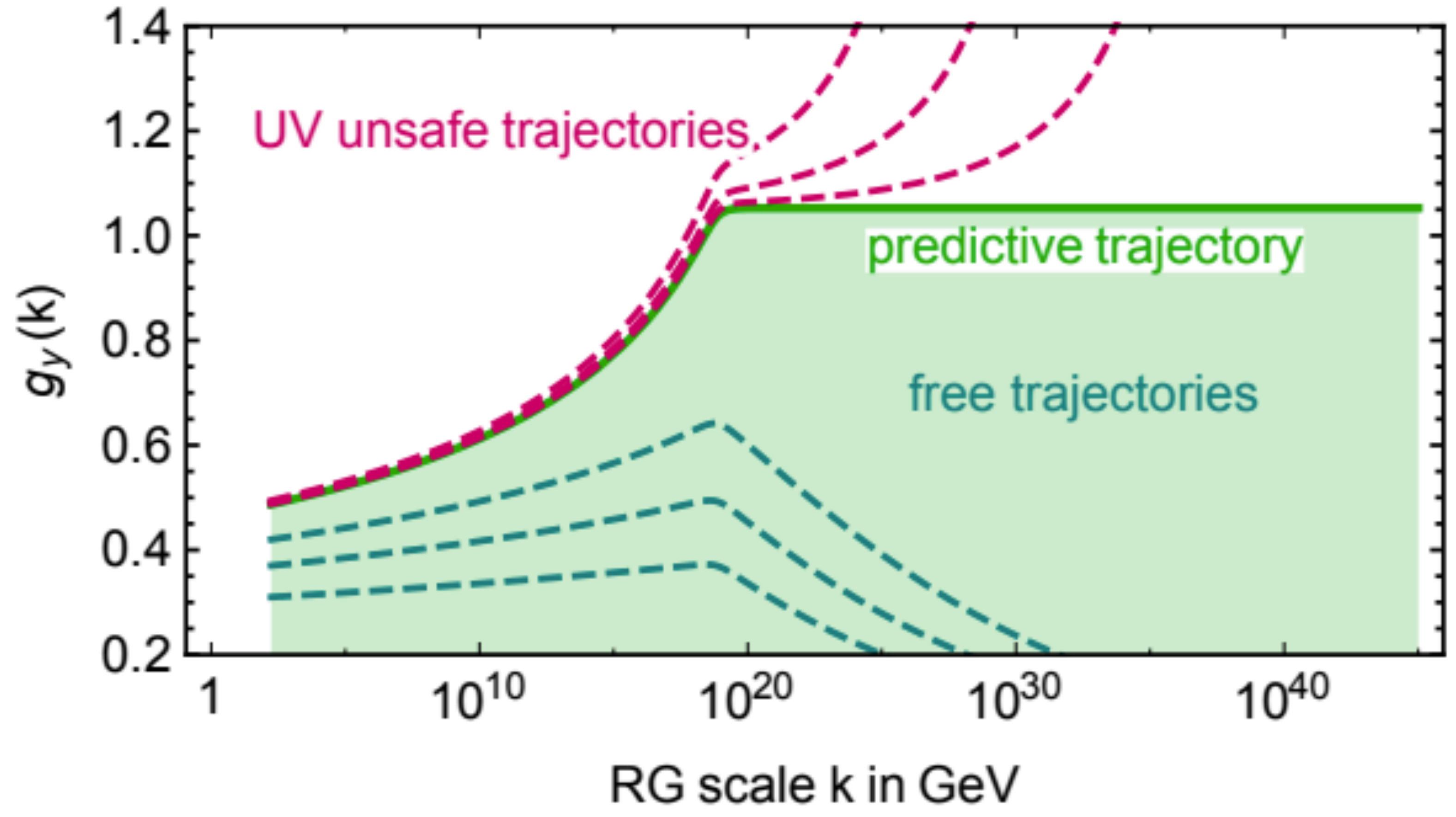
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question 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 $m_H = m_{\rm min} = 126$ 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 $m_{\rm min} < m_H < m_{\rm max} \simeq 174$ 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

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

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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

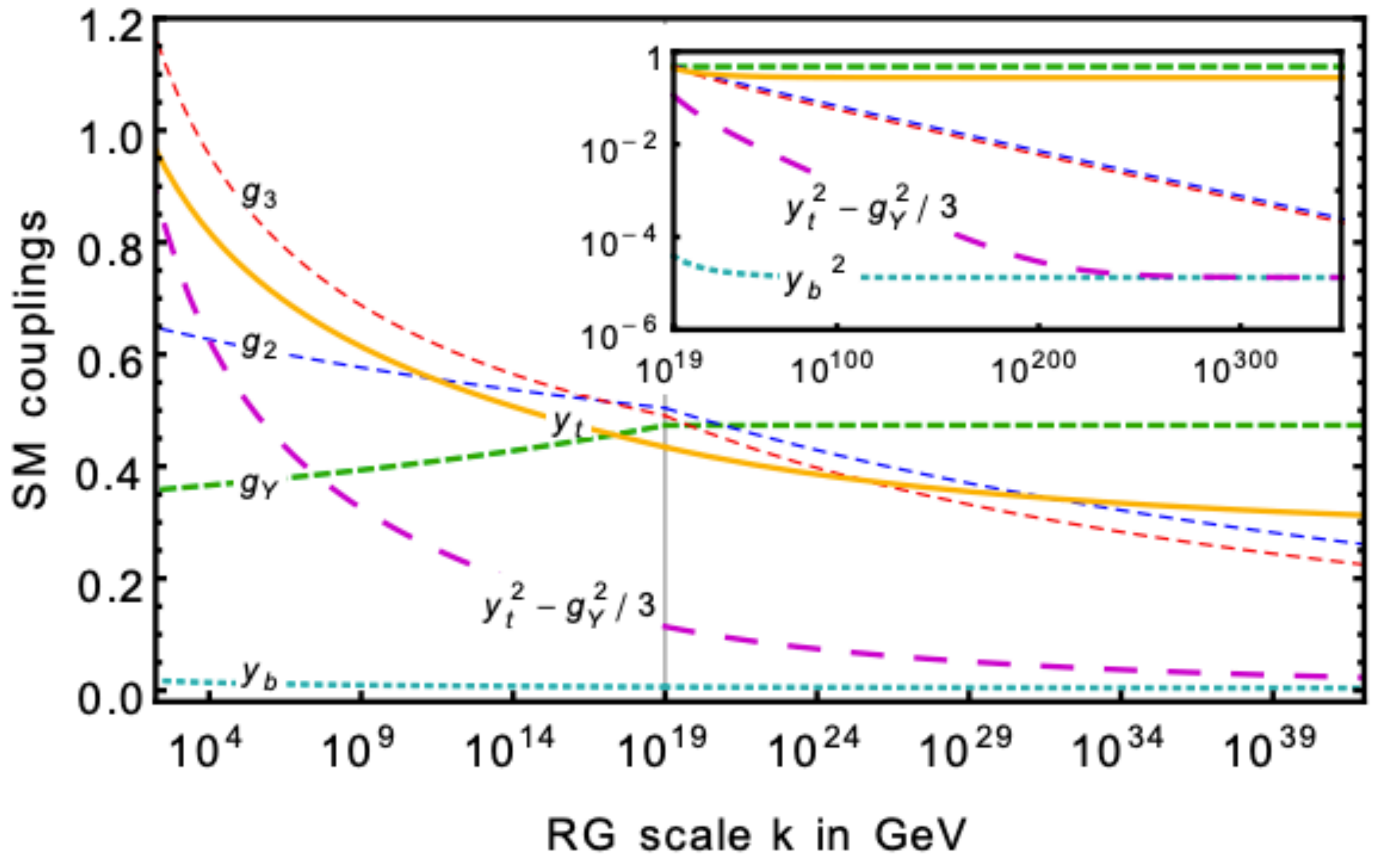

FIG. 1. RG trajectory of Standard-Model couplings for $f_g = 9.7 \times 10^{-3}$ and $f_y = 1.188 \times 10^{-4}$, reaching $g(k_{\mathrm{IR}}) = 0.358$, $y_t(k_{\mathrm{IR}}) = 0.965$, and $y_b(k_{\mathrm{IR}}) = 0.018$ at $k_{\mathrm{IR}} = 173\,\mathrm{GeV}$. We also plot $y_t^2 - g_Y^2/3$ (pink,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

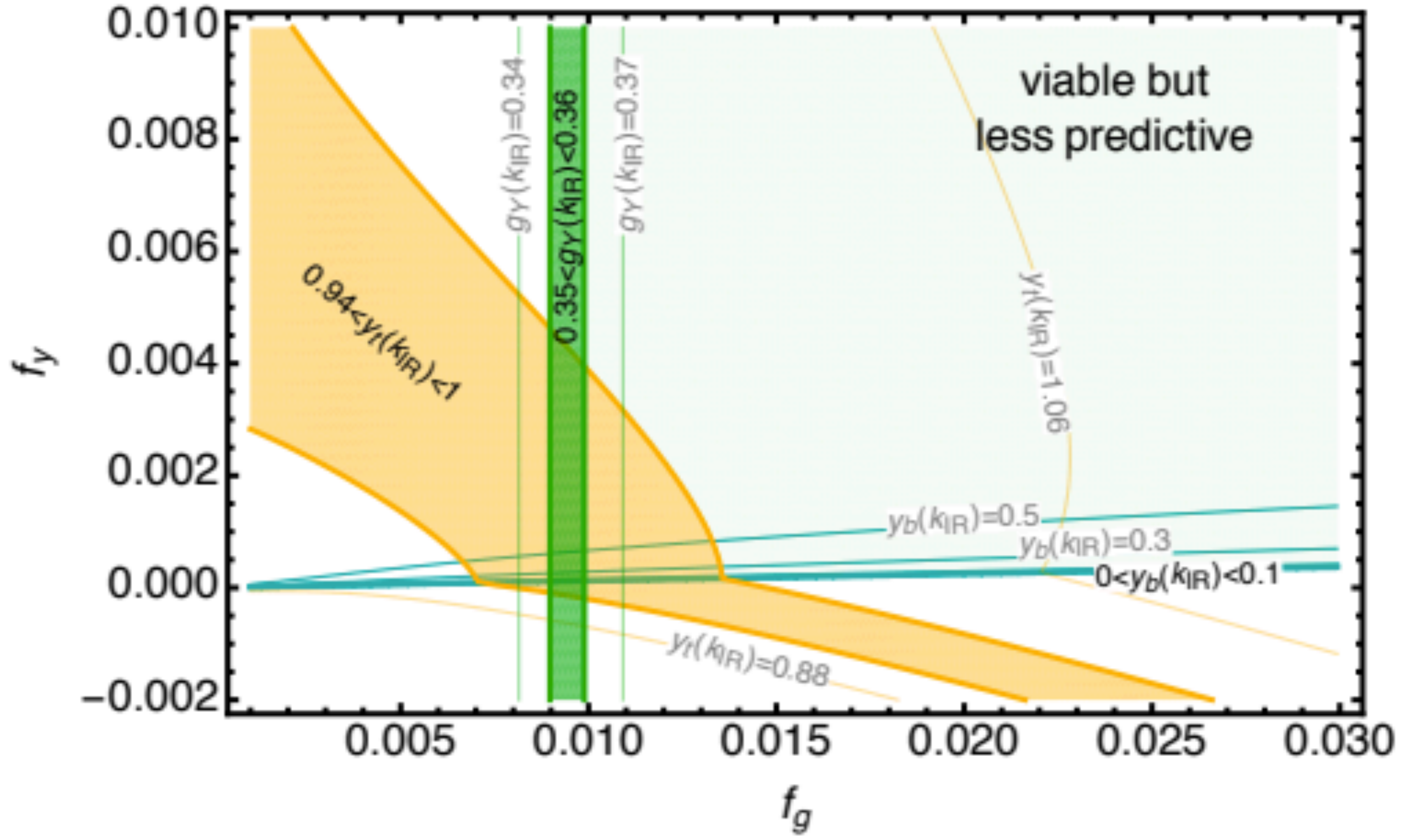

FIG. 2. IR values of retrodicted couplings $g_Y(k_{\mathrm{IR}})$, $y_t(k_{\mathrm{IR}})$ and $y_b(k_{\mathrm{IR}})$ at $k_{\mathrm{IR}} = 173$ GeV as a function of the two independent quantum-gravity contributions f_g and f_y.

Eichhorn/Held 1803.04027

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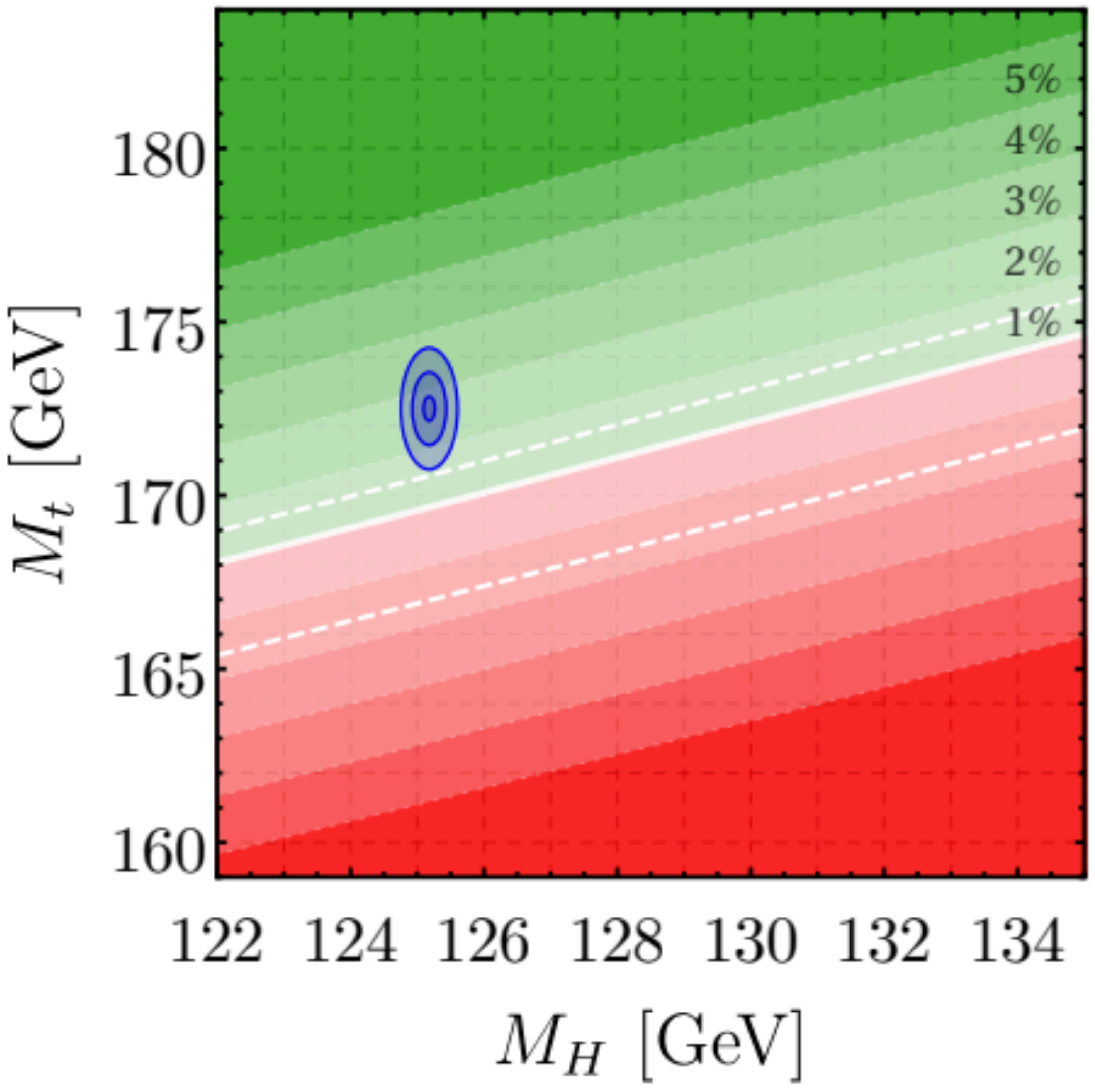
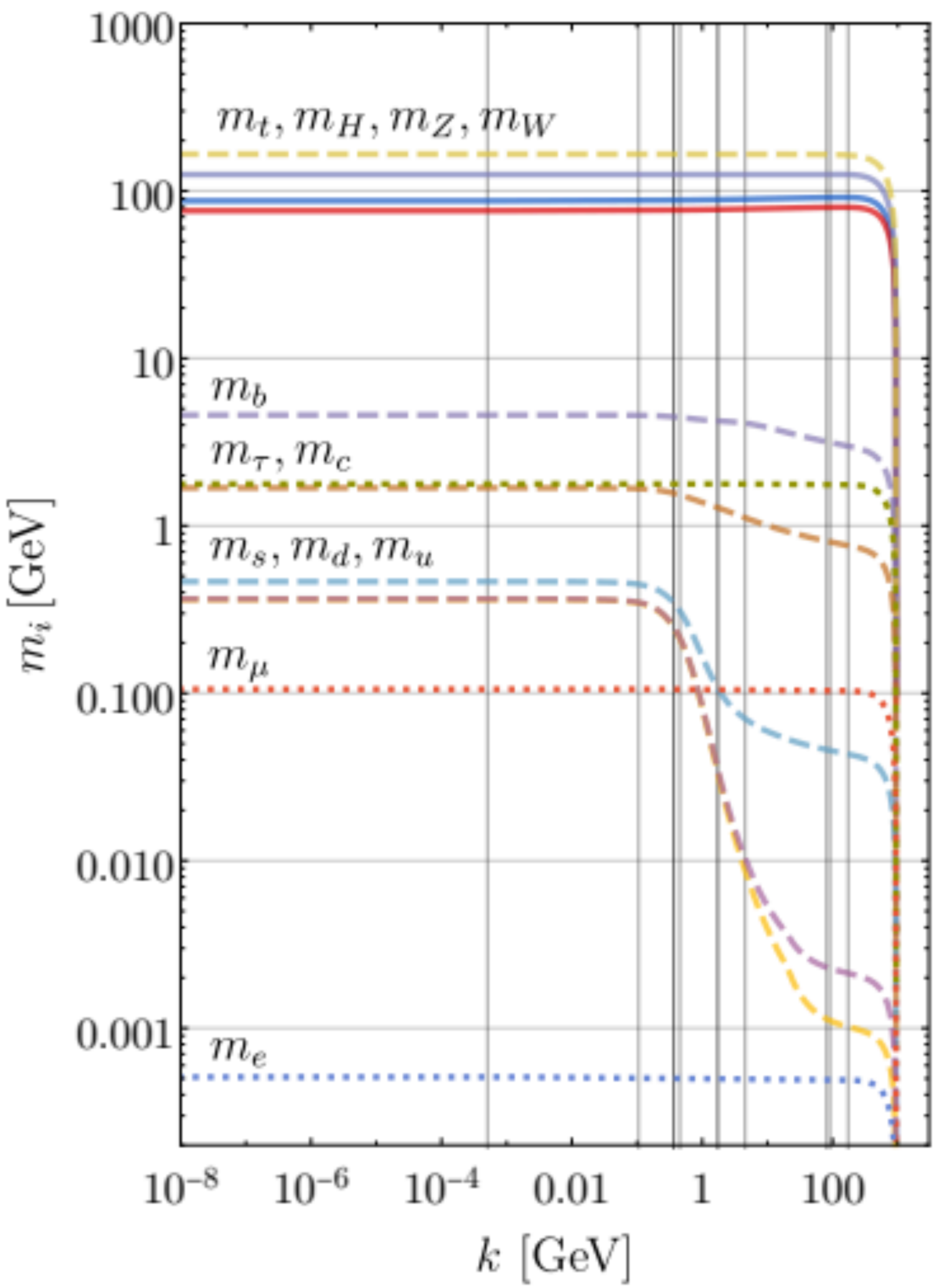
Interplay with matter and landscape

A few applications

- Asymptotically safe Standard Model

Pastor-Gutiérrez, Pawlowski, Reichert 2207.09817





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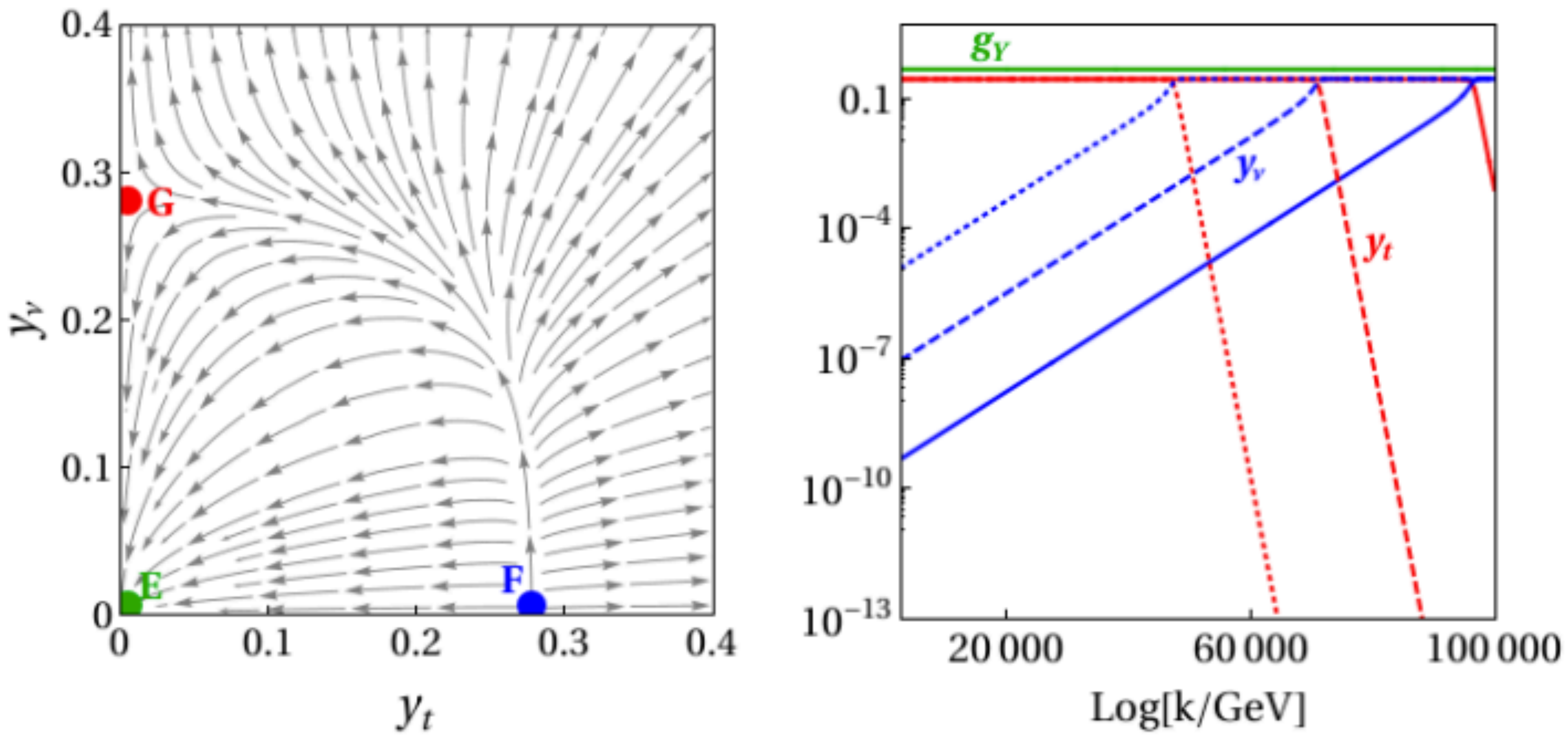
A few applications

- Naturally small Yukawa couplings

Kowalska, Pramanick, Sessolo 2204.00866

$f_g = 0.0096, f_y = 0.0002$

One SM generation

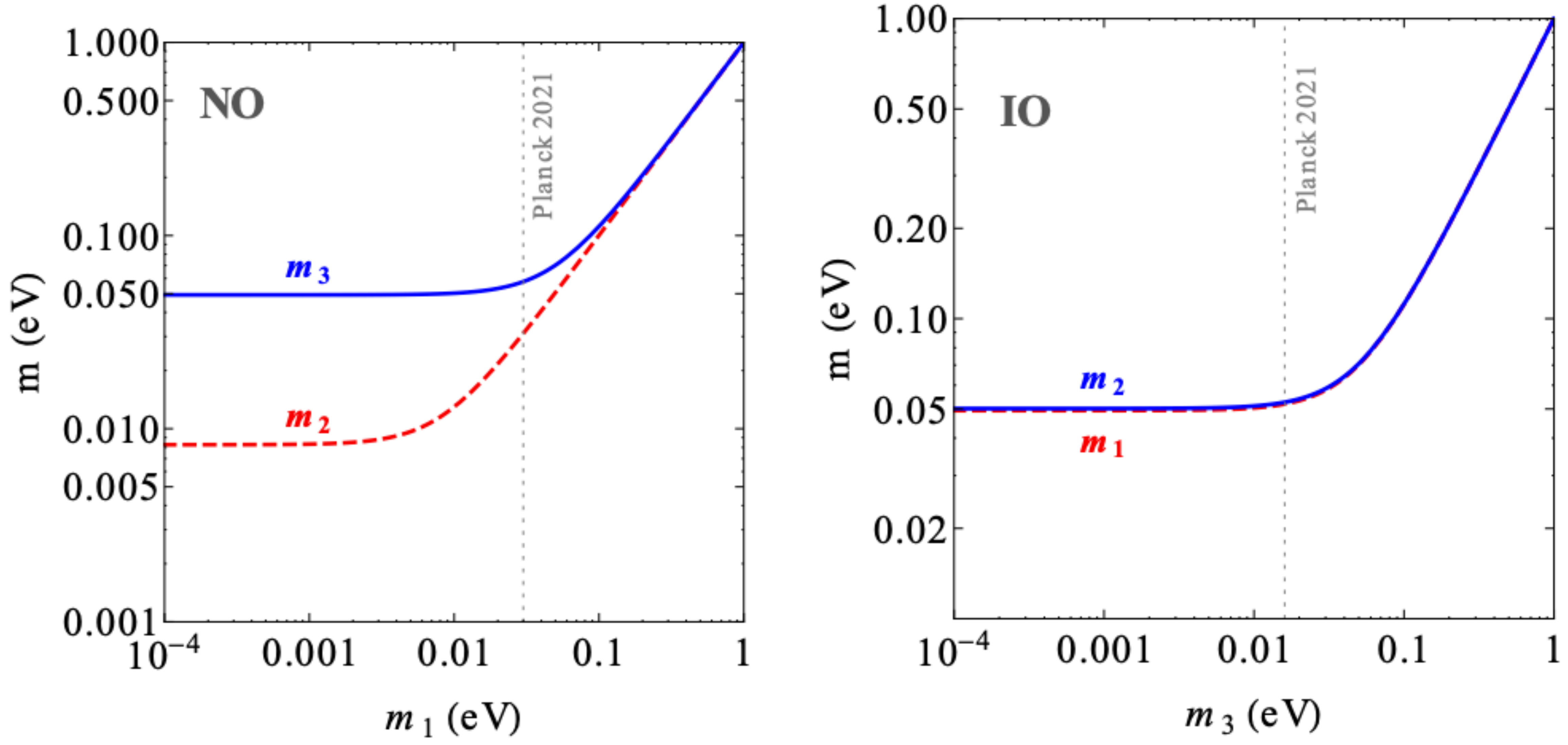


There is fully IR-attractive interacting FP for top Yukawa coupling $y_{t,*} \neq 0$

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

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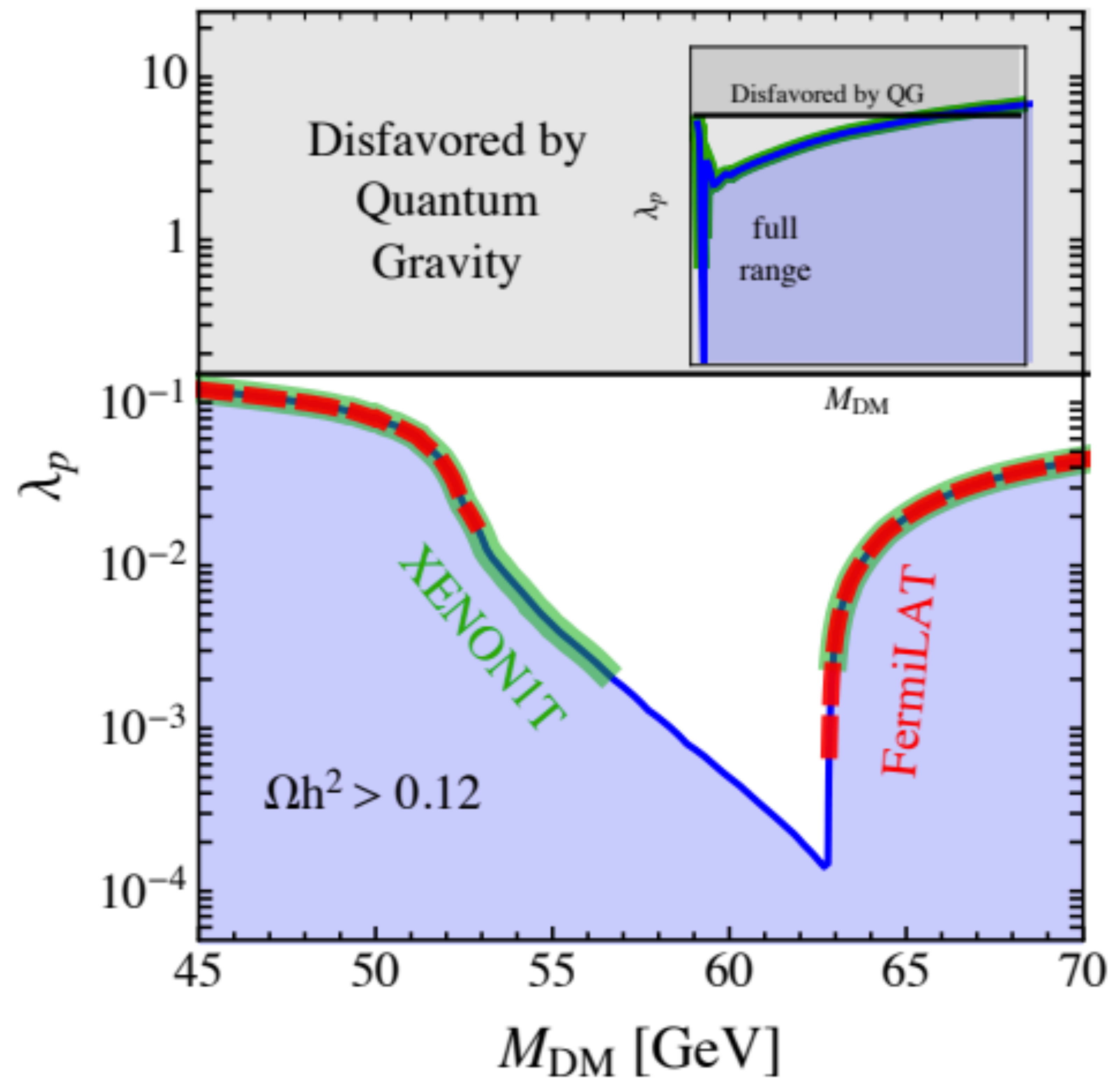
Interplay with matter and landscape

A few applications

- Dark matter

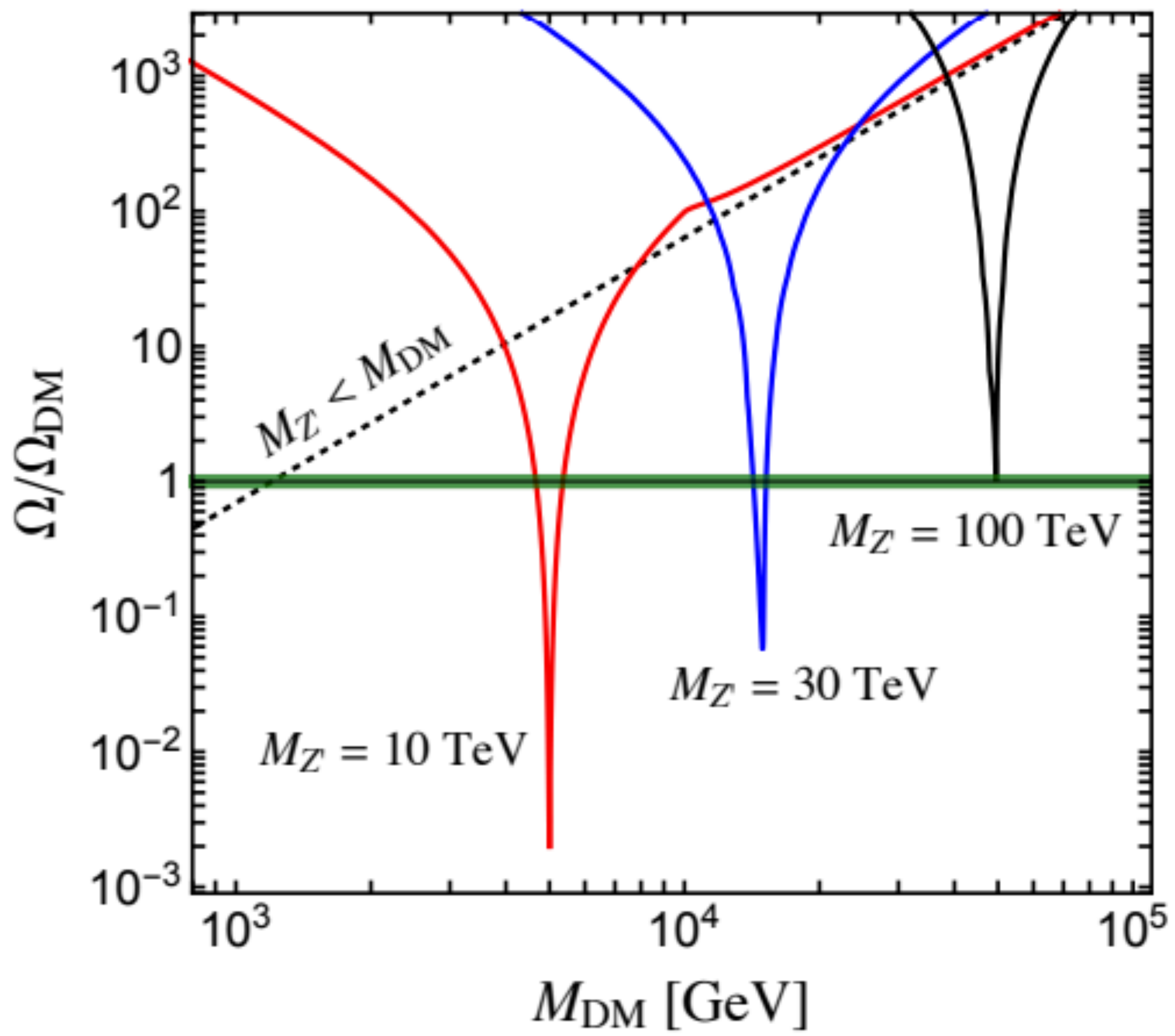
Reichert/Smirnov 1911.00012

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

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



Fermionic dark matter: resonance with Z'

Bound for DM mass: 50 TeV