Indications for particle physics from asymptotic safety

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in collaboration with E. M. Sessolo
and
A. Chikkaballi, S. Pramanick, D. Rizzo, Y. Yamamoto

Mainly based on:
Eur.Phys.J.C 81 (2021) 4, 272 (arXiv: 2007.03567)
JHEP 08 (2022) 262 (arXiv: 2204.00866)
JHEP 11 (2023) 224 (arXiv: 2308.06114)
and work in progress

Quantum spacetime and the Renormalization Group 2025

National Science Centre Poland

Heidelberg, 31.03.2025

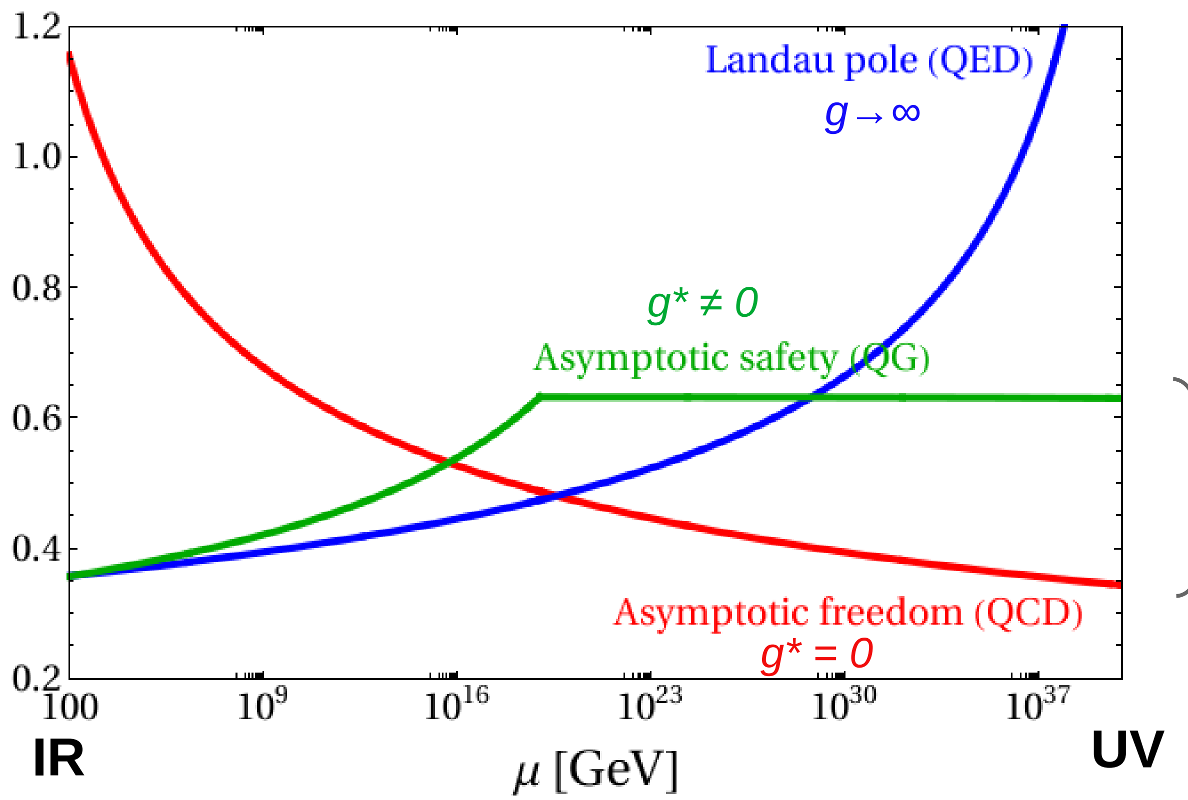
NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

Asymptotic safety

… why we like it

IR
predictive

$$\beta_g = \frac{dg}{dt} = \frac{dg}{d\ln\mu}$$



UV
complete

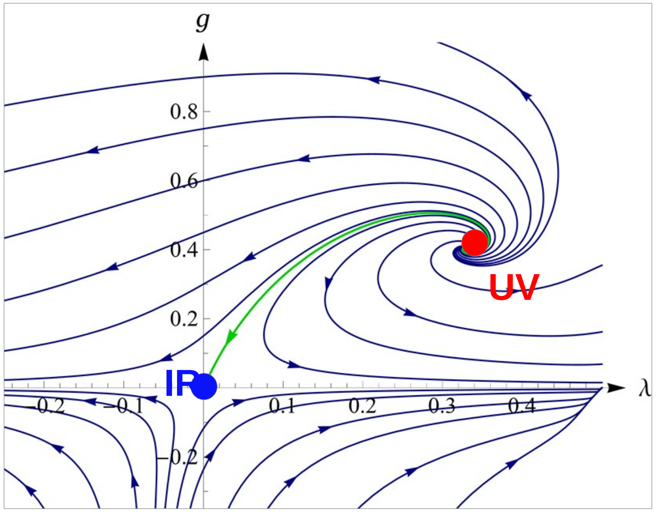
$$\beta_g(g^*) = 0$$

Asymptotic safety

… how we get it

Trans-Planckian fixed point for gravity (FRG)

M. Reuter, F. Saueressig , PRD 65, 065016 (2002)



Other possibility in 4D:

- Gauge-Yukawa (Li-Sa) models
  (Litim, Sannino, JHEP 1412 (2014) 178)

Trans-Planckian corrections to matter RGEs (FRG)

$$k > M_{\rm Pl}$$

$$\beta_g = \beta_g^{\rm SM+NP} - g\, f_g \qquad = 0$$

$$\beta_y = \beta_y^{\rm SM+NP} - y\, f_y \qquad = 0$$

fixed points for matter

parametric description of (universal) gravity contributions

e.g. A. Eichhorn, A. Held, 1707.01107
A. Eichhorn, F. Versteegen, 1709.07252

heuristic approach: confront AS with low-scale pheno

Asymptotic safety

… what we can learn

- **Predictions** for Beyond the Standard Model
- **Consistency** of the IR physics with the AS ansatz
- **Naturally small** parameters (eg. neutrino masses)
- **Forbidding couplings** allowed by symmetries
- Conclusions

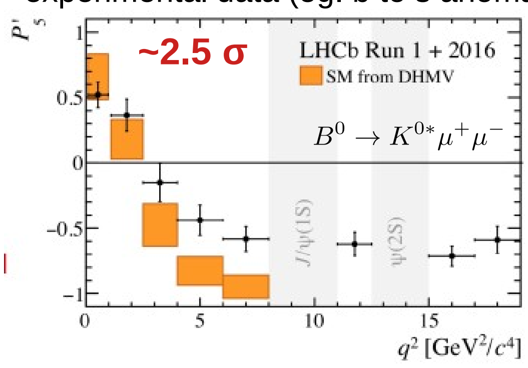
Predictions for BSM

Working assumption:
there is a UV interacting FP for (some) SM couplings

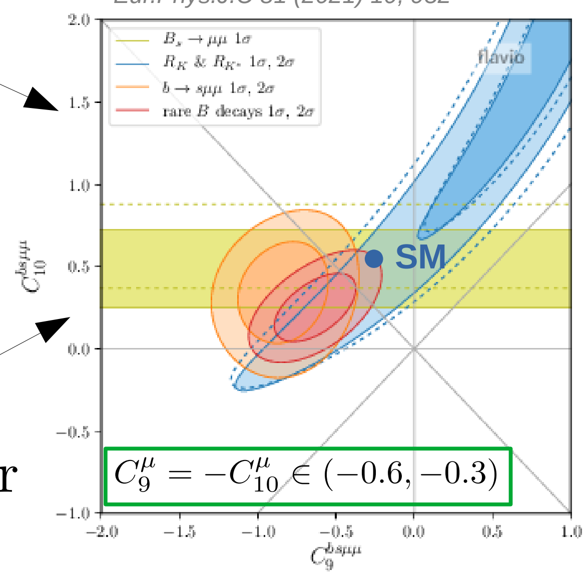
heuristic determination $f_{g,y}$ from matching to SM → universality of $f_{g,y}$ → **predictions for BSM (non-zero couplings)** → **experimental signatures**

Particularly usefull for **experimental anomalies:**

experimental data (eg. b to s anomalies)



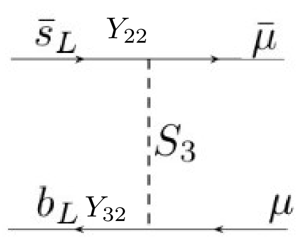
W.Altmannshofer, P.Stangl, Eur.Phys.J.C 81 (2021) 10, 952



(SM)EFT parametrization

$$\frac{\mathcal{C}_{\rm NP}}{\Lambda^n} \approx \frac{c_i c_j}{m_{\rm NP}^n} \times \text{loop factor}$$

BSM model (ex. leptoquarks)



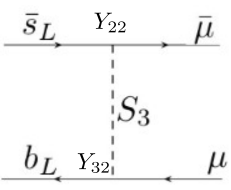
$$C_9^\mu = -C_{10}^\mu = \frac{\pi v_h^2}{V_{33}V_{32}^*\alpha_{\rm em}} \frac{\hat{Y}_{32}^L \hat{Y}_{22}^{L*}}{m_{S_3}^2}$$

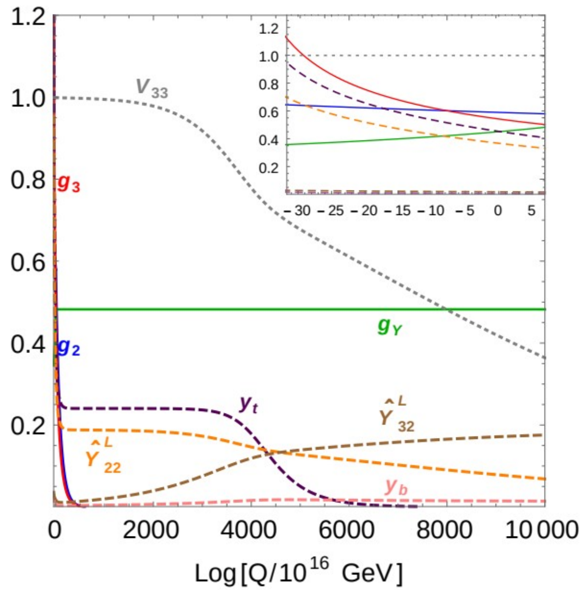
no precise prediction for the BSM mass

Example: leptoquark mass

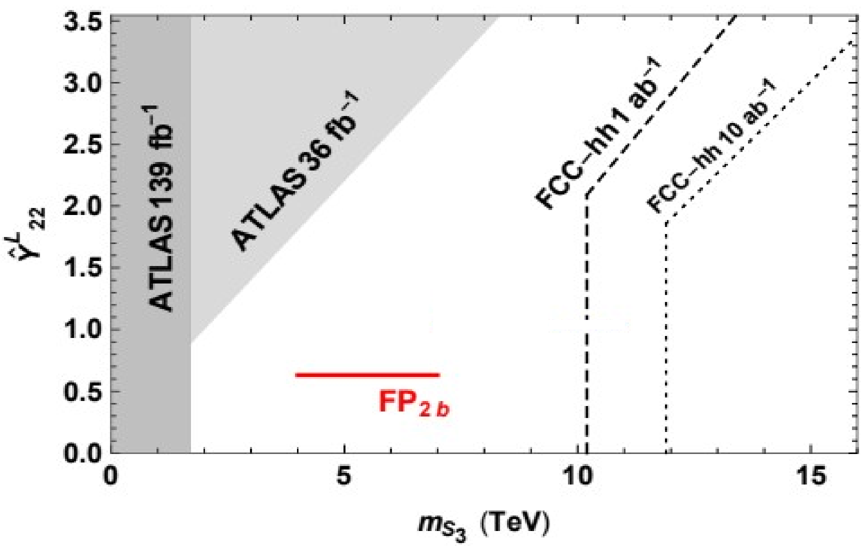
KK, E.M.Sessolo, Y.Yamamoto,
Eur.Phys.J.C 81 (2021) 4, 272

SM + LQ + QG





UV boundary condtitions from irrelevant g_Y and y_t



mass predicted

$$\boxed{M_{S_3} \in (4.5, 7)\ \mathrm{TeV}}$$

In the reach of the FCC!

also: complementary predictions in flavor: ex. D-meson decays

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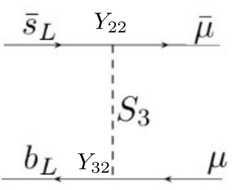

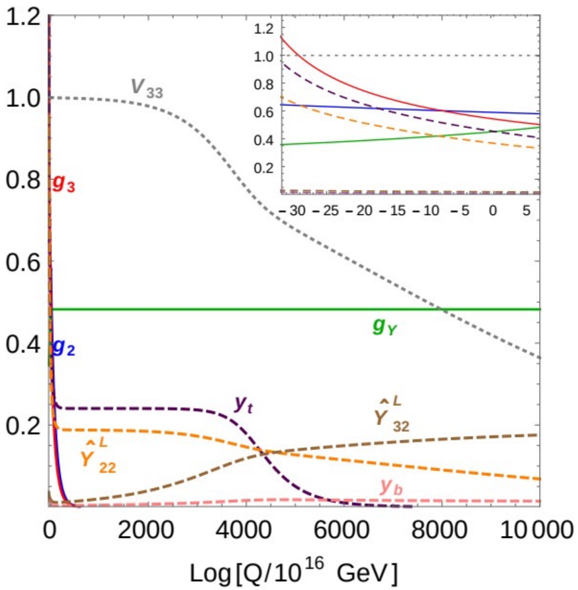

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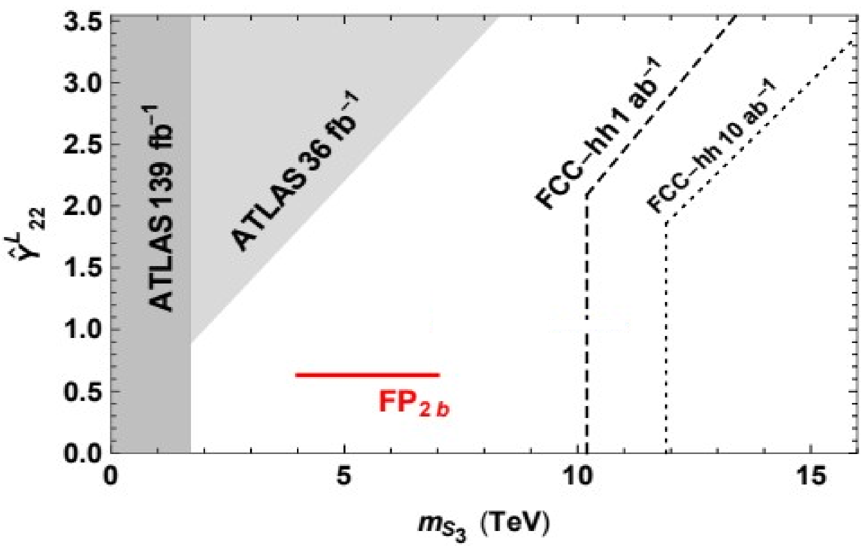

also: complementary predictions in flavor: ex. D-meson decays

Some other works along this lines...

- **anomalies in *b* → *s***

A.Chikkaballi, W. Kotlarski, KK, D.Rizzo, E.M.Sessolo, JHEP 01 (2023) 164

- **anomalies in *b* → *c***

KK, E.M.Sessolo, Y.Yamamoto, Eur.Phys.J.C 81 (2021) 4, 272

- **muon *g-2***

KK, E.M.Sessolo, Phys. Rev. D 103, (2021)

Other AS predictions for BSM

Reichert, Smirnov, 1803.04027; Grabowski, Kwapisz, Meissner, 1810.08461; Hamada, Tsumura, Yamada, 2002.03666, Eichhorn, Pauly, 2005.03661; de Brito, Eichhorn, Lino dos Santos, 2112.08972, Boos, Carone, Donald, Musser, 2206.02686, 2209.14268, Eichhorn, dos Santos, Miqueleto, 2306.17718

mass predicted

$$\boxed{M_{S_3} \in (4.5, 7)\ \mathrm{TeV}}$$

In the reach of the FCC!

Predictions for BSM

PROS:

- UV constraints on BSM (a priori free) couplings
- Allows to pinpoint BSM masses when confronted with data
- Predictions are (very) robust W.Kotlarski, KK, D.Rizzo, E.M.Sessolo EPJC ’23, arXiv: 2304.08959

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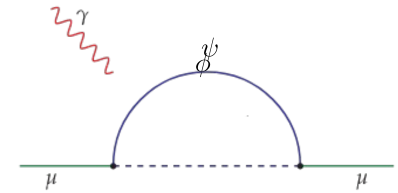
CONS:

- Interactive fixed point in the SM needed $\xrightarrow{\text{but...}}$ A. Pastor-Gutiérrez, J. M. Pawlowski, M. Reichert SciPost Phys. 15 (2023) 3, 105
- Very specific values of f_g, f_y required $\longrightarrow$ What about FRG?
- Only useful when there is experimental data
- No clear way of checking consitency with AS (case by case analysis needed)

Consistency between AS and pheno

VL fermions:

$$\mathcal{L}_{\rm NP} \supset \left(Y_R\, \mu_R E' S + Y_L\, F' S^\dagger l_\mu + Y_1\, E\, h^\dagger F + Y_2\, F' h\, E' + \text{H.c.} \right)$$



in the context of g-2

$$\boxed{Y_R^* \neq 0,\, Y_L^* \neq 0,\, Y_1^* \neq 0,\, Y_2^* = 0}$$

to explain g-2

$$\frac{dy_\mu}{dt} = \frac{1}{16\pi^2}\left\{ \left[3y_t^2 + C_1 \left(Y_1^2 + Y_2^2 + \frac{1}{2} Y_L^2 + \frac{1}{2} Y_R^2 \right) - \frac{15}{4} g_Y^2 - \frac{9}{4} g_2^2 \right] y_\mu + \cancel{C_2\, Y_2\, Y_R\, Y_L} \right\} - f_y\, y_\mu$$

allows for $y_\mu^* = 0$ muon mass correct

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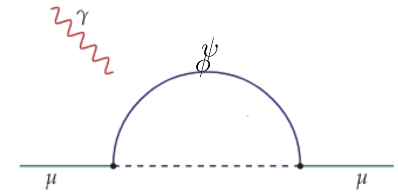

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$\boxed{Y_R^* \neq 0,\; Y_L^* \neq 0,\; Y_1^* \neq 0,\; Y_2^* = 0}$ *to explain g-2*

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Leptoquark: 

$$\mathcal{L}_{NP} \supset Y_{ij}^L Q_i^T(-i\sigma_2)L_j S_1 + Y_{ij}^R u_{R\,i}^* e_{R\,j}^* S_1 + \text{H.c.}$$

$\boxed{Y_{32}^{R*} \neq 0,\; Y_{32}^{L*} \neq 0}$ *to explain g-2*

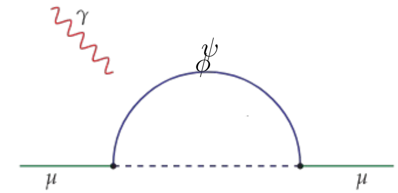
$$\frac{dy_\mu}{dt} \sim -6\, y_t Y_{33}^R Y_{23}^L$$

does not allow for $y_\mu^* = 0$ muon mass incorrect ~ top mass

Consistency between AS and pheno

VL fermions:

$$\mathcal{L}_{\rm NP} \supset \left(Y_R\, \mu_R E' S + Y_L\, F' S^\dagger l_\mu + Y_1\, E\, h^\dagger F + Y_2\, F' h\, E' + \text{H.c.}\right)$$



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$\boxed{Y_R^* \neq 0,\ Y_L^* \neq 0,\ Y_1^* \neq 0,\ Y_2^* = 0}$ *to explain g-2*

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NOT CONSISTENT WITH AS

$$\frac{dy_\mu}{dt} \sim -6\, y_t Y_{33}^R Y_{23}^L$$

does not allow for $y_\mu^* = 0$ muon mass incorrect ~ top mass

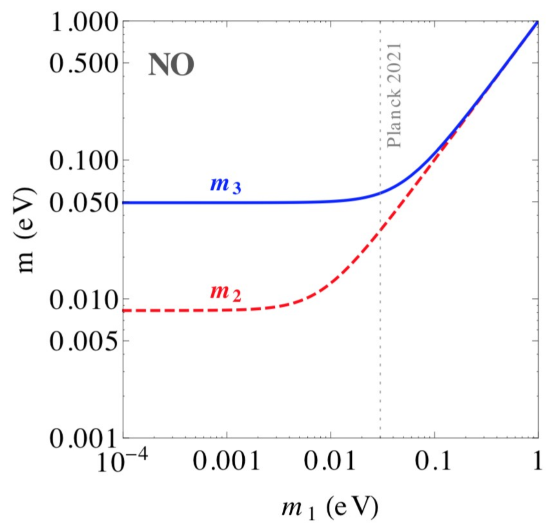
Naturally small neutrino masses

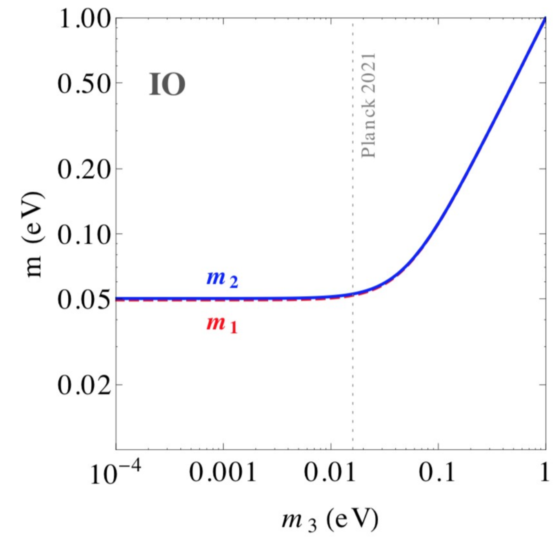
NuFIT5.1 (2021) 2007.14792

$$\Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2,$$
$$\text{NO:} \quad \Delta m^2_{31} = 2.515^{+0.028}_{-0.028} \times 10^{-3}\,\mathrm{eV}^2,$$
$$\text{IO:} \quad \Delta m^2_{32} = -2.498^{+0.028}_{-0.029} \times 10^{-3}\,\mathrm{eV}^2,$$

Planck (2021) 1807.06209

$$\sum_{i=1,2,3} m_i < 0.12\,\mathrm{eV}$$





either Dirac neutrino ...

$$\mathcal{L}_D = -y_\nu^{ij}\,\nu_{R,i}\,(H^c)^\dagger L_j + \mathrm{H.c.}$$

$$m_\nu = \frac{y_\nu v_H}{\sqrt{2}}$$

- 10^{-13} Yukawa coupling
- Lepton number is conserved

… or Majorana neutrino

e.g. Type 1 see-saw

$$\mathcal{L}_M = \mathcal{L}_D - \frac{1}{2} M_N^{ij} \nu_{R,i}\nu_{R,j} + \mathrm{H.c.}$$

$$m_\nu = \begin{pmatrix} 0 & m_D^T \\ m_D & M_N \end{pmatrix} \qquad m_\nu = y_\nu^2 v_h^2/(\sqrt{2}M_N)$$

- $O(1)$ Yukawa coupling
- Lepton number is violated

Naturally small neutrino masses

KK, S.Pramanick, E.Sessolo, JHEP 08 (2022) 262

SM + RHN:

$$\frac{dg_Y}{dt} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y = 0$$ get f_g

$$\frac{dy_t}{dt} = \frac{y_t}{16\pi^2}\left[\frac{9}{2}y_t^2 + y_\nu^2 - \frac{17}{12}g_Y^2\right] - f_y\, y_t = 0$$ get f_y

$$\frac{dy_\nu}{dt} = \frac{y_\nu}{16\pi^2}\left[3y_t^2 + \frac{5}{2}y_\nu^2 - \frac{3}{4}g_Y^2\right] - f_y\, y_\nu = 0$$ predict

$\Longrightarrow$ $g_Y^*, y_t^* \sim \mathcal{O}(1)$

$\beta_\nu \equiv \frac{dy_\nu}{dt} = 0 \;\rightarrow$ two IRR solutions for neutrino FP:

1. $$y_\nu^{*2} = \frac{32\pi^2}{5}f_y + \frac{3}{10}g_Y^{*2} - \frac{6}{5}y_t^{*2}$$ (interactive)

2. $$y_\nu^* = 0$$ (Gaussian)

Naturally small neutrino masses

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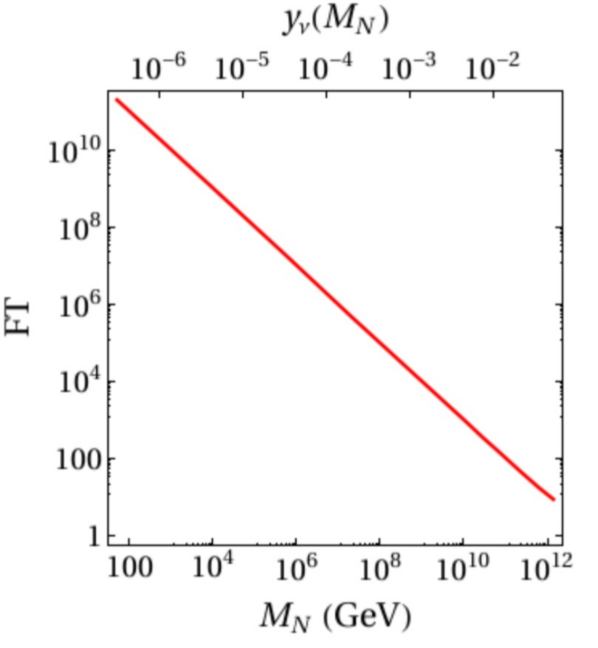
large fine tuning of f_y to get small Yukawa

large Yukawa coupling → Majorana neutrino

$$m_\nu = y_\nu^2 v_h^2/(\sqrt{2}M_N)$$

AS prediction for the Majorana mass



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$\Rightarrow$ $g_Y^*, y_t^* \sim \mathcal{O}(1)$

$\beta_\nu \equiv \frac{dy_\nu}{dt} = 0 \;\rightarrow$ two IRR solutions for neutrino FP:

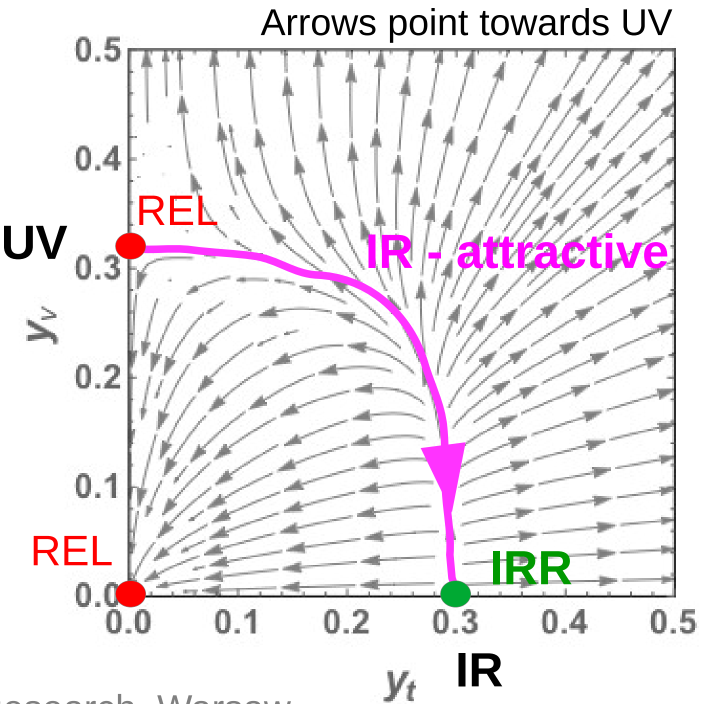
2. $y_\nu^* = 0$ (Gaussian)

<u>Irrelevant</u> if *fy* is small enough!

$f_y < f_{\nu,tY}^{\text{crit}} \approx 0.0008$ $\quad 16\pi^2\theta_\nu \approx \underline{-\frac{2}{3}g_Y^{*2}} + \frac{3}{2}y_t^{*2} < 0$

small Yukawa coupling → Dirac neutrino

Relevant FPs provide a UV completion



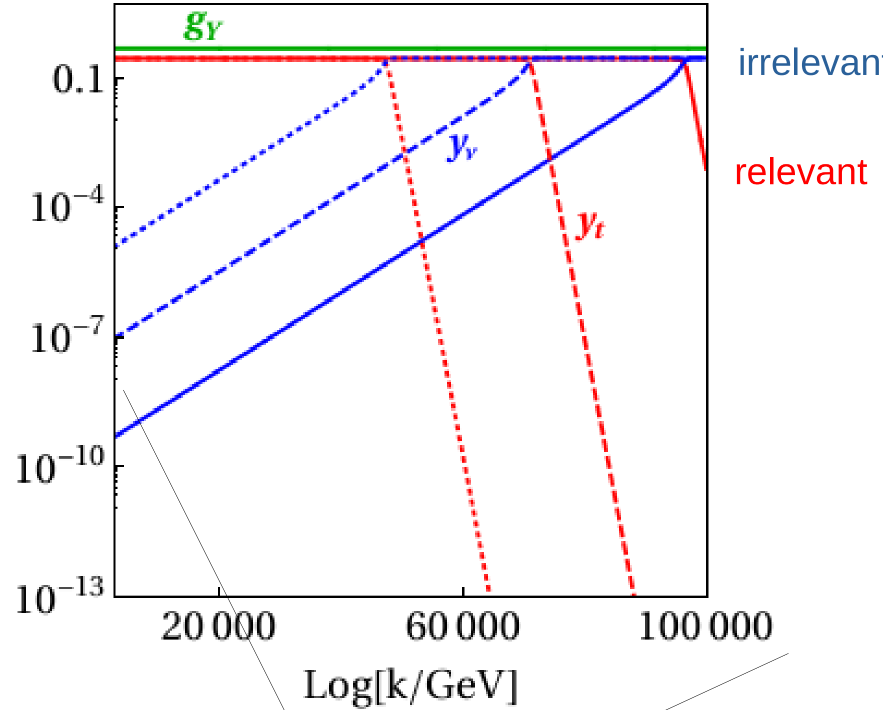
Naturally small neutrino masses

Integrated curve in blue :

$$y_\nu(t;\kappa) \approx \left(\frac{16\pi^2 f_y}{e^{f_y(\kappa-t)}+5/2}\right)^{1/2}$$

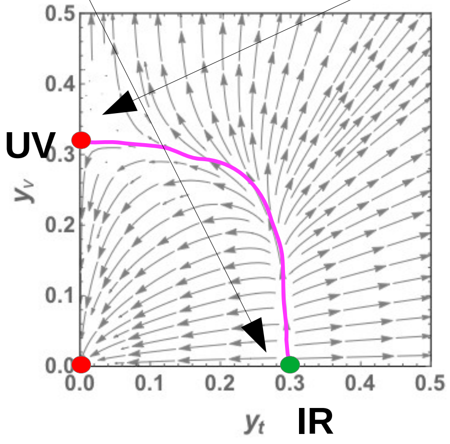
κ = “distance” in e-folds

KK, S.Pramanick, E.Sessolo, JHEP 08 (2022) 262



No fine tuning:

Smallness of the neutrino Yukawa due to the “distance” of the Planck scale from infinity



Neutrinos can be Dirac naturally

Alternative to the see-saw mechanism

The mechanism is more generic...

In pairs of Yukawa interactions one can use the "large" Y_L to drive down the "small" Y_S...

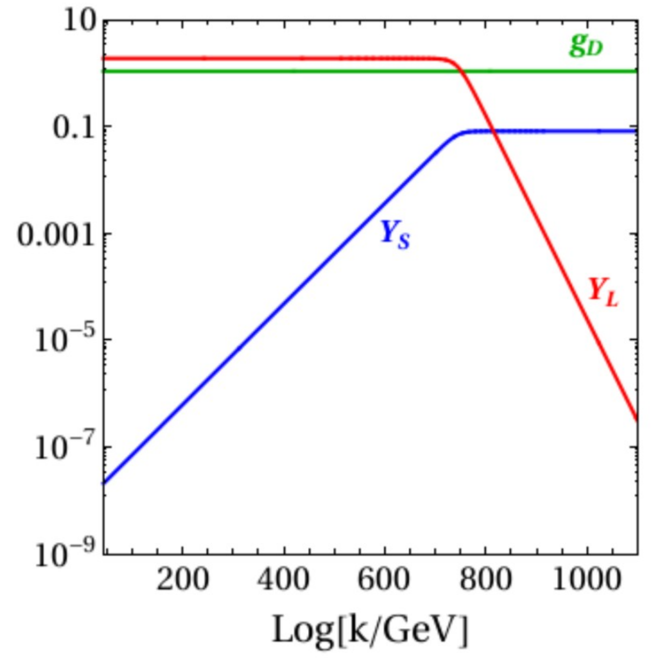
$$\mathcal{L} \supset Y_S\, \chi_R \Phi \chi_L + Y_L\, \psi_R \Phi \psi_L + \mathrm{H.c.}$$

Recall that...

$$\frac{dy_X}{dt} = \frac{y_X}{16\pi^2}\left[\alpha_X\, y_X^2 + \alpha_Z y_Z^2 - \alpha_Y\, g_Y^2\right] - f_y\, y_X$$
$$\frac{dy_Z}{dt} = \frac{y_Z}{16\pi^2}\left[\alpha'_X\, y_X^2 + \alpha'_Z y_Z^2 - \alpha'_Y\, g_Y^2\right] - f_y\, y_Z$$

… thus we want ...

$$f_{Z,XY}^{\mathrm{crit}} = \frac{g_Y^{*2}}{16\pi^2}\,\frac{\alpha'_X\alpha_Y - \alpha'_Y\alpha_X}{\alpha_X - \alpha'_X} > f_y\,(\text{from UV})$$



… it happens often (but not always) if $Q_\psi \gg Q_\chi$ (gauge charge)

Can use it to justify freeze-in, feebly interacting models, etc...

Connections to FRG

A. Chikkaballi, KK, E. Sessolo, 2308.06114

SM + gauged U(1)$_{B-L}$ + QG:

$$\boxed{g_Y^* = 0\ldots}$$

… but its role played by

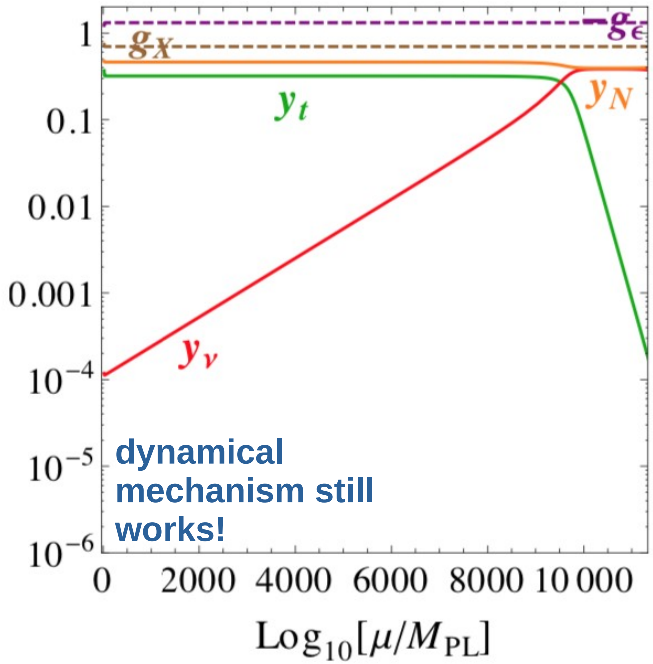
$$g_X^* \neq 0, \quad g_\epsilon^* \neq 0$$

extended gauge sector

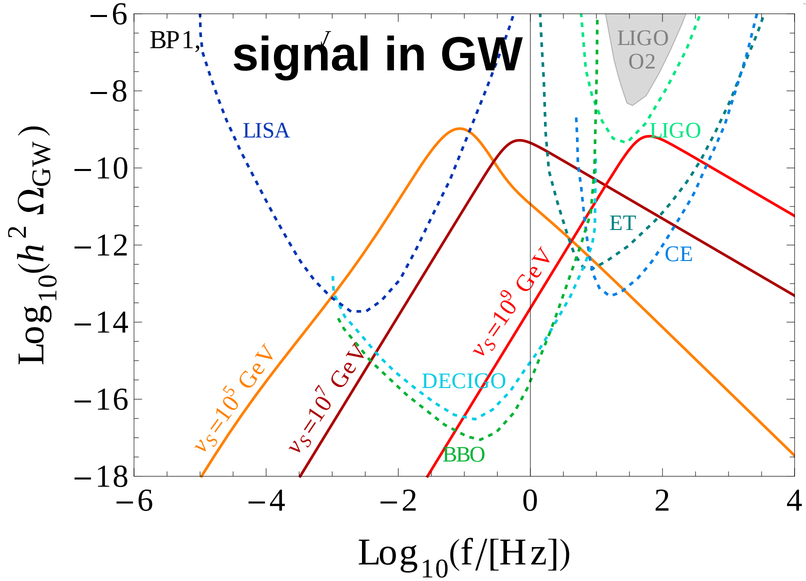
$$\mathcal{L} \supset -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\epsilon}{2}B_{\mu\nu}X^{\mu\nu}$$
$$+i\bar{f}\left(\partial^\mu - ig_Y Q_Y \tilde{B}^\mu - ig_{B-L}Q_{B-L}\tilde{X}^\mu\right)\gamma_\mu f$$

$$f_g > 0.0097$$

easier to make consistent with the FRG calculations



	f_g	f_y	g_X^*	g_ϵ^*	g_X ($10^{5,7,9}$ GeV)
BP1	0.01	0.0005	0.10	−0.55	0.29, 0.29, 0.30
BP2	0.05	−0.005	0.70	−1.32	0.40, 0.41, 0.44
BP3	0.02	−0.0015	0.10	−0.75	0.12, 0.12, 0.12
BP4	0.03	−0.004	0.10	0.75	0.09, 0.09, 0.09



<u>Extra info</u>: FP analysis provides **predictions for g_X, g_ϵ**

Forbidding (allowed) couplings

A. Chikkaballi, KK, R. Lino dos Santos, E. Sessolo,
work in progress

Motivation: stability of the dark matter particle

SU(N) dark matter: stabilizing Z_2 added "by hand" ex. E. Ma, Phys. Rev. D 103, 051704 (2021)

ex. SU(6) minimal anomaly free setup: $\underbrace{15_Q,\, \bar{6}_D}_{\text{SM}},\, \underbrace{\bar{6}_P}_{\text{dark sector}}$ $\quad \bar{6}_P = \bar{5}_P + 1_P$ DM

$$\begin{aligned}\mathcal{L} \supset\ & Y_D \mathbf{15}_Q \bar{\mathbf{6}}_D \bar{\mathbf{6}}_{H_1} + Y_{\text{mix}} \mathbf{15}_Q \bar{\mathbf{6}}_P \bar{\mathbf{6}}_{H_1} + Y'_D \mathbf{15}_Q \bar{\mathbf{6}}_D \bar{\mathbf{6}}_{H_3} + Y'_{\text{mix}} \mathbf{15}_Q \bar{\mathbf{6}}_P \bar{\mathbf{6}}_{H_3} \\ & + Y_U \mathbf{15}_Q \mathbf{15}_Q \mathbf{15}_{H_2} + Y_1\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_D \mathbf{15}_{H_2} + Y_2\, \bar{\mathbf{6}}_P \bar{\mathbf{6}}_P \mathbf{15}_{H_2} + Y_{12}\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_P \mathbf{15}_{H_2} \\ & + Y_3\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_D \mathbf{21}_{H_4} + Y_4\, \bar{\mathbf{6}}_P \bar{\mathbf{6}}_P \mathbf{21}_{H_4} + Y_{34}\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_P \mathbf{21}_{H_4} + \text{H.c.}\end{aligned}$$

Forbidding (allowed) couplings

A. Chikkaballi, KK, R. Lino dos Santos, E. Sessolo,
work in progress

Motivation: stability of the dark matter particle

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Z_2 symmetry forbids the dark-SM mixing

Y_1 small to forbid decay $\text{DM} \to h\, \nu_L$

(META) STABLE DM

Forbidding (allowed) couplings

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$$\mathcal{L} \supset Y_D \mathbf{15}_Q \bar{\mathbf{6}}_D \bar{\mathbf{6}}_{H_1} + \cancel{Y_{\rm mix} \mathbf{15}_Q \bar{\mathbf{6}}_P \bar{\mathbf{6}}_{H_1}} + \cancel{Y'_D \mathbf{15}_Q \bar{\mathbf{6}}_D \bar{\mathbf{6}}_{H_3}} + Y'_{\rm mix} \mathbf{15}_Q \bar{\mathbf{6}}_P \bar{\mathbf{6}}_{H_3}$$
$$+ Y_U \mathbf{15}_Q \mathbf{15}_Q \mathbf{15}_{H_2} + \cancel{Y_1\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_D \mathbf{15}_{H_2}} + Y_2\, \bar{\mathbf{6}}_P \bar{\mathbf{6}}_P \mathbf{15}_{H_2} + \cancel{Y_{12}\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_P \mathbf{15}_{H_2}}$$
$$+ Y_3\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_D \mathbf{21}_{H_4} + Y_4\, \bar{\mathbf{6}}_P \bar{\mathbf{6}}_P \mathbf{21}_{H_4} + \cancel{Y_{34}\, \bar{\mathbf{6}}_D \bar{\mathbf{6}}_P \mathbf{21}_{H_4}} + \text{H.c.}$$

Allowed FP:

$g_6^* = 0\,(\text{R})$ compatibile with AF

$Y_D^{\prime *} = 0\,(\text{IR}),\ Y^*_{mix} = 0\,(\text{IR})$ no SM-dark mixing in the quark sector

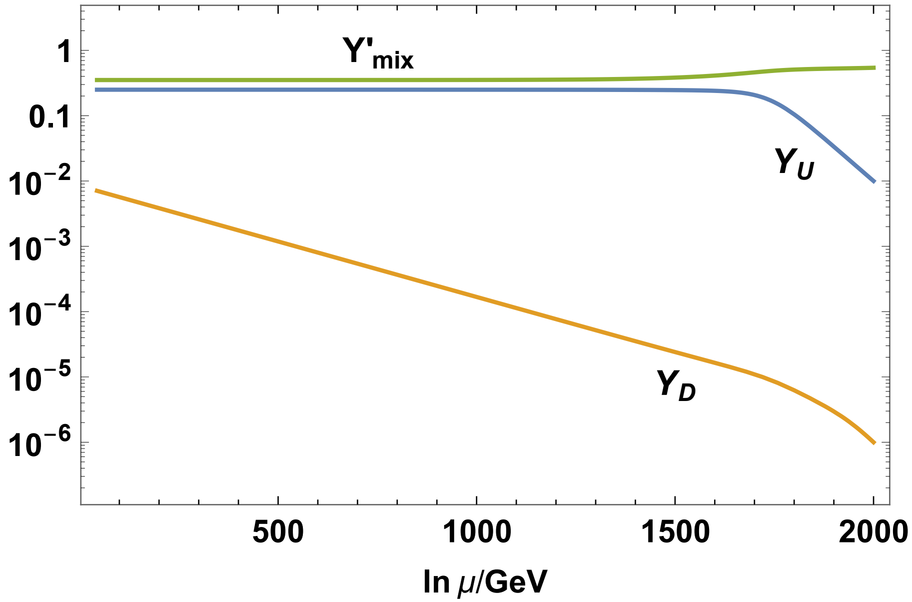
$Y^*_{12} = 0\,(\text{IR}),\ Y^*_{34} = 0\,(\text{IR})$ no SM-dark mixing in the neutrino sector

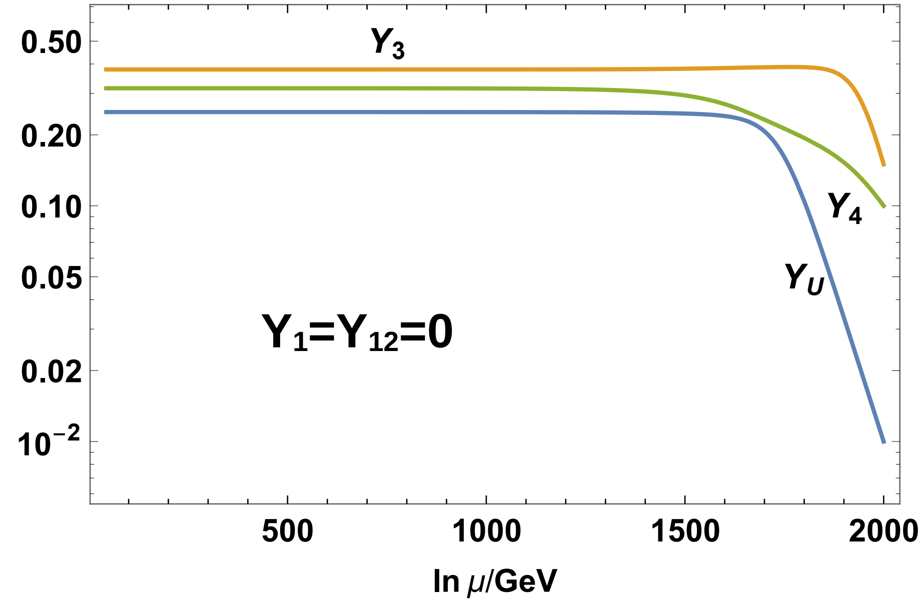
$Y^*_1 = 0\,(\text{IR})$ no decay into the SM neutrino

STABLE DM

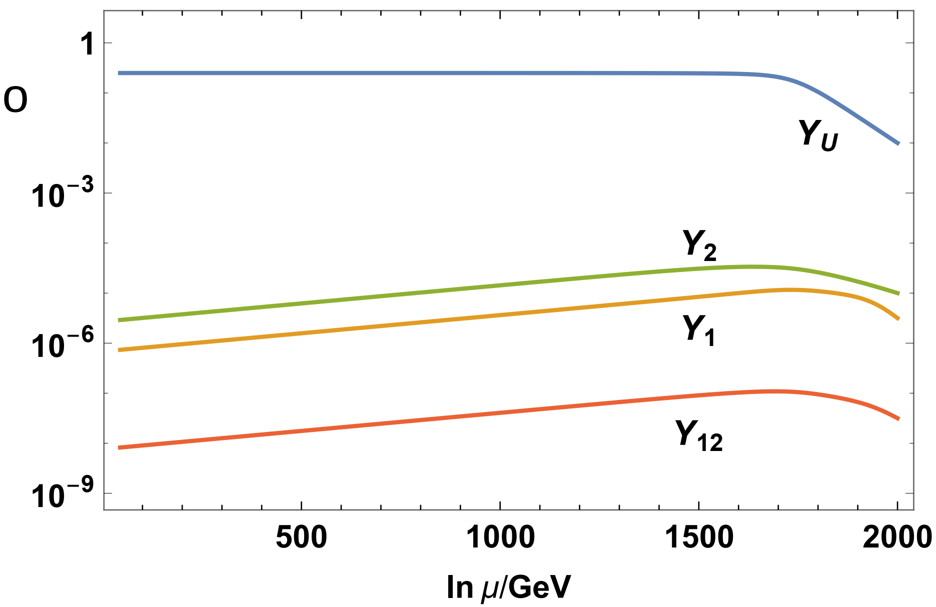
Forbidding (allowed) couplings

A. Chikkaballi, KK, R. Lino dos Santos, E. Sessolo, preliminary





Y_1=0: massless neutrino



(META) STABLE DM

Conclusions

- ASQG-inspired boundary conditions allow for specific predictions for the BSM physics.

- The bottleneck of the heuristic approach: UV interactive FPs for the SM couplig(s).

- In the realizations pertinent to naturalness, AF of the SM gauge couplings can be accommodated.

- Question for the future: can the identified mechanisms be applied in different settings (ex. slow-walk instead of a fixed point).