# Indications for particle physics from asymptotic safety

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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)

National Science Centre Poland

*12th International Conference on the Exact Renormalization Group*

*Les Diablerets, 23.09.2024*

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

# Outline

- Why do we need asymptotic safety in particle physics?
- Trans-Planckian asymptotic safety
- Predictions for BSM from trans-Planckian AS
- Small neutrino masses from trans-Planckian AS
- Conclusions

# Where do we stand?

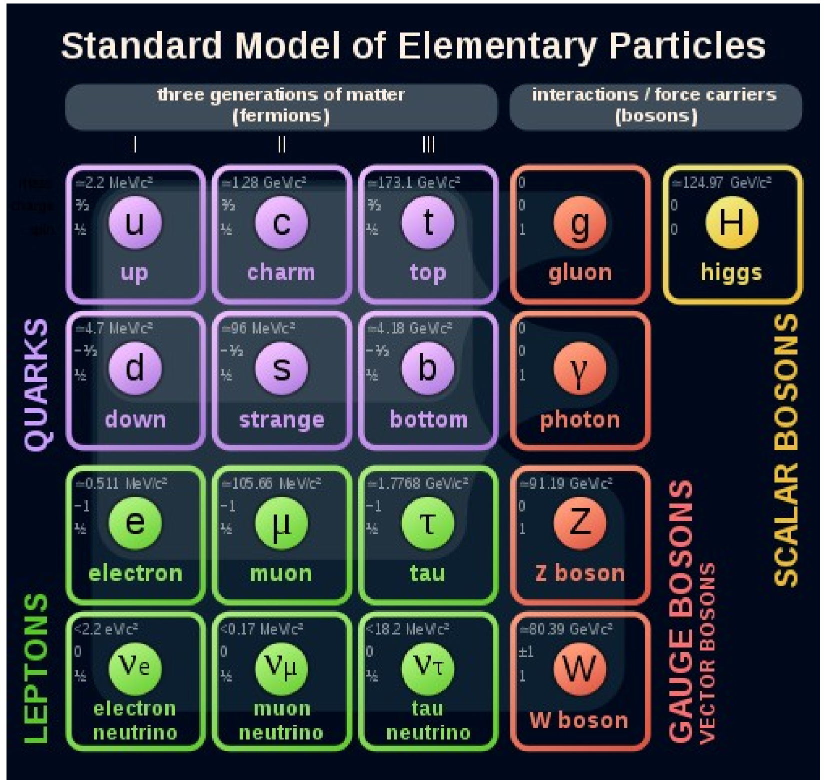
**All particles discovered**

1983: W and Z bosons (CERN)

1995: top quark (Fermilab)

2000: tau neutrino (Fermilab)

2012: Higgs boson (CERN)




$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

**Predictions perfectly agree with experiment**

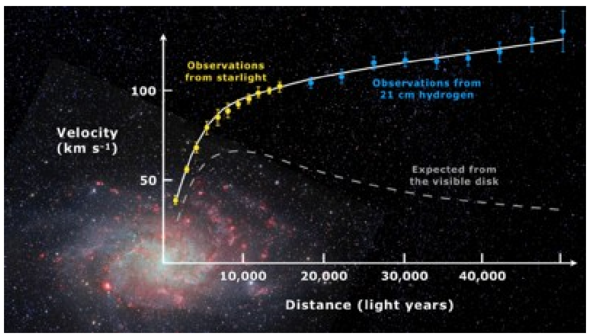
ex.
electron magnetic dipole moment
1 part per 100 billion

## An extremelly successful theory

# Where do we stand?

## Standard Model is an effective theory

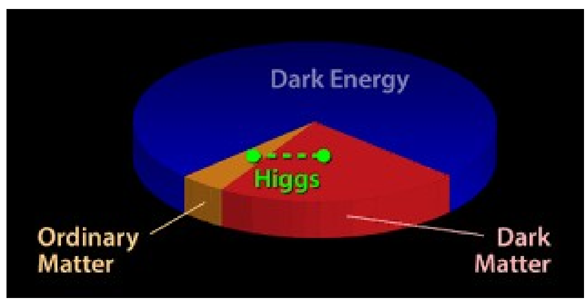
### Empirical puzzles



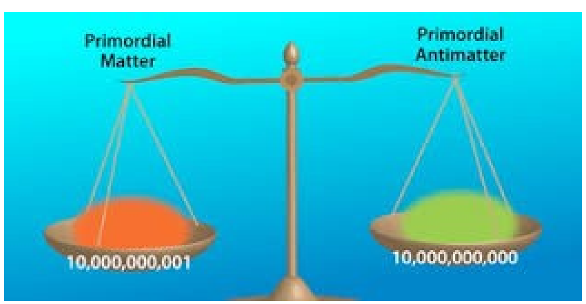
from Wikipedia

dark matter

dark energy



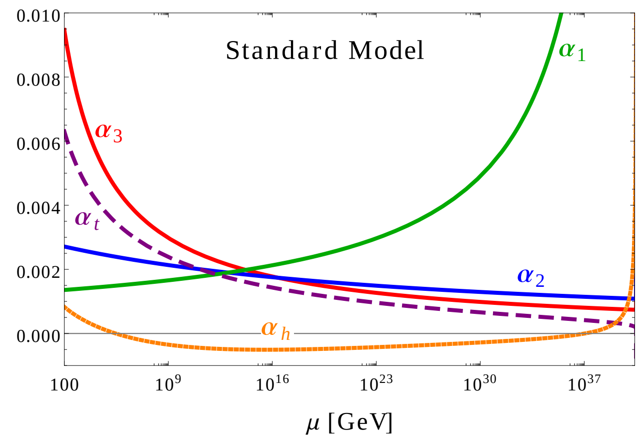
Alan Stonebraker



from M.G.Strauss

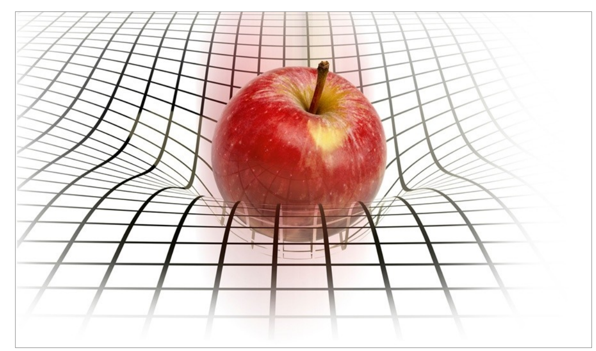
baryon asymmetry

### Theoretical riddles




Landau pole

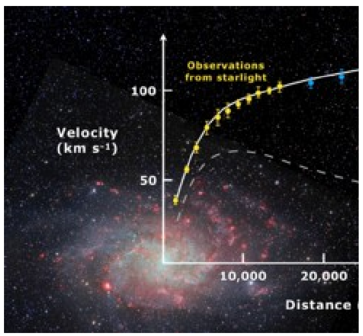
gravity


Credit: Alison Mackey/Discover

# Where do we stand?

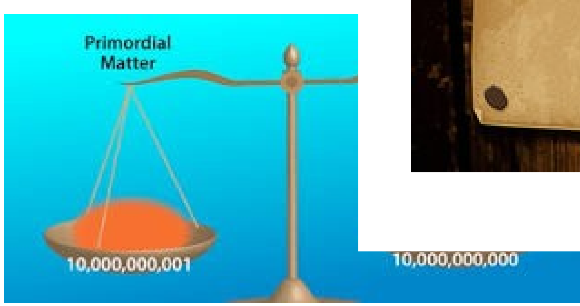
## Standard Model is an <u>effective theory</u>

**<u>Empirical puzzles</u>** **<u>Theoretical riddles</u>**

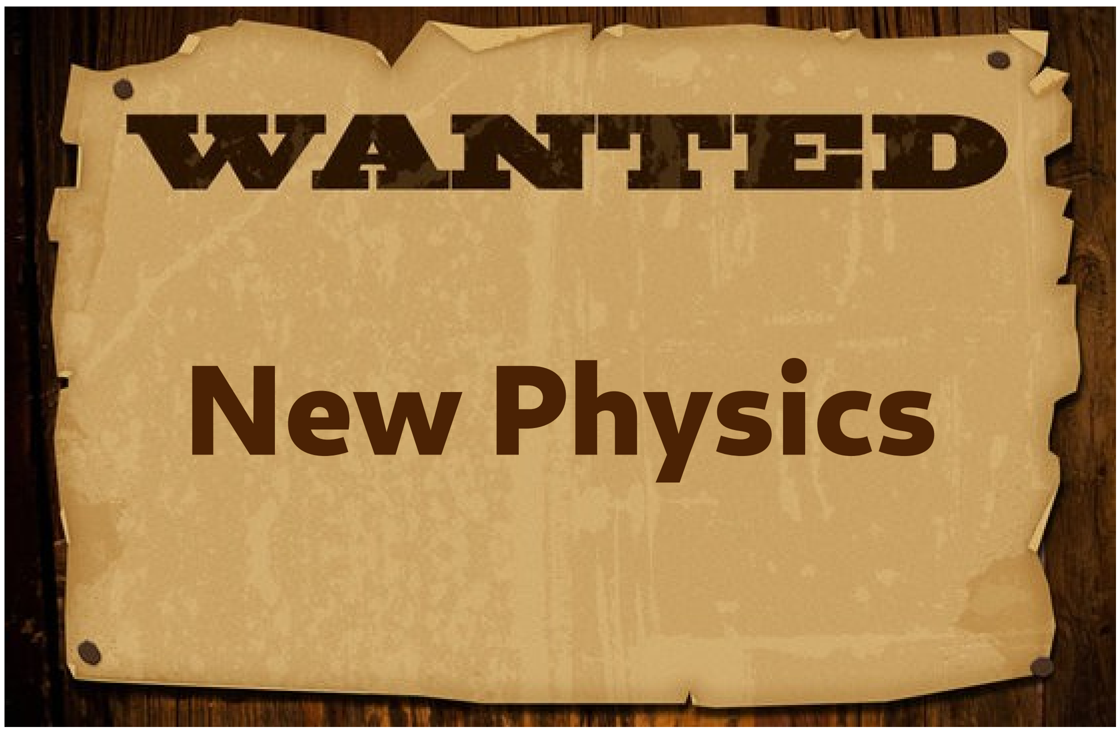


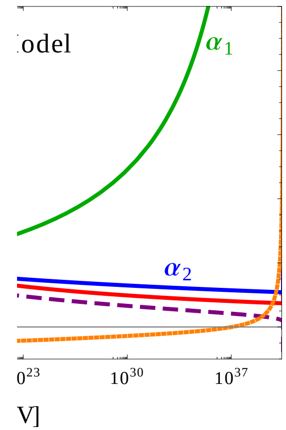
from Wikipedia

**dark**

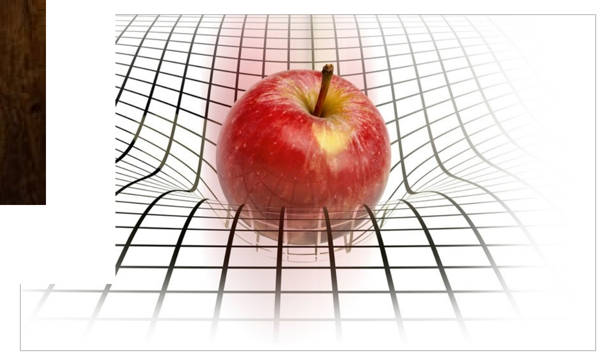


from M.G.Strauss




**Landau pole**


Credit: Alison Mackey/Discover

# Which New Physics?

## BSM Physics

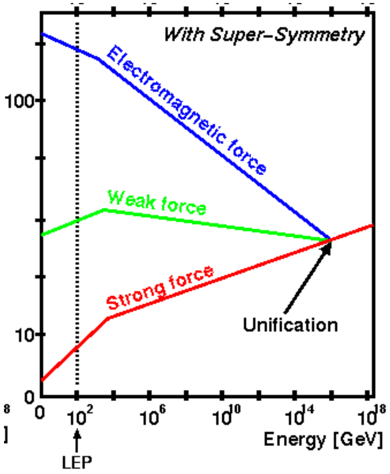
**adds extra IR d.o.f to explain observational phenomena**

- (low-scale) supersymmetry
- vector-like fermions
- extra scalars
- axions
- long-lived particles
- feebly interacting particles
- any many others ...

## UV completion

**switches from an effective to a full theory**

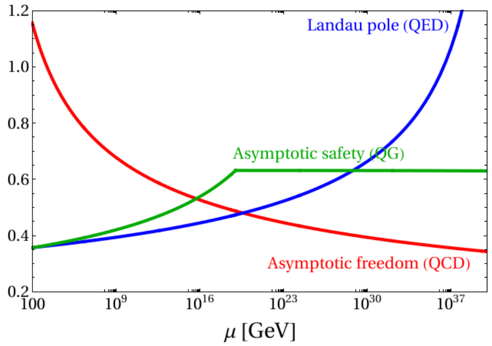
no Landau poles, renormalizable




**Grand Unification**

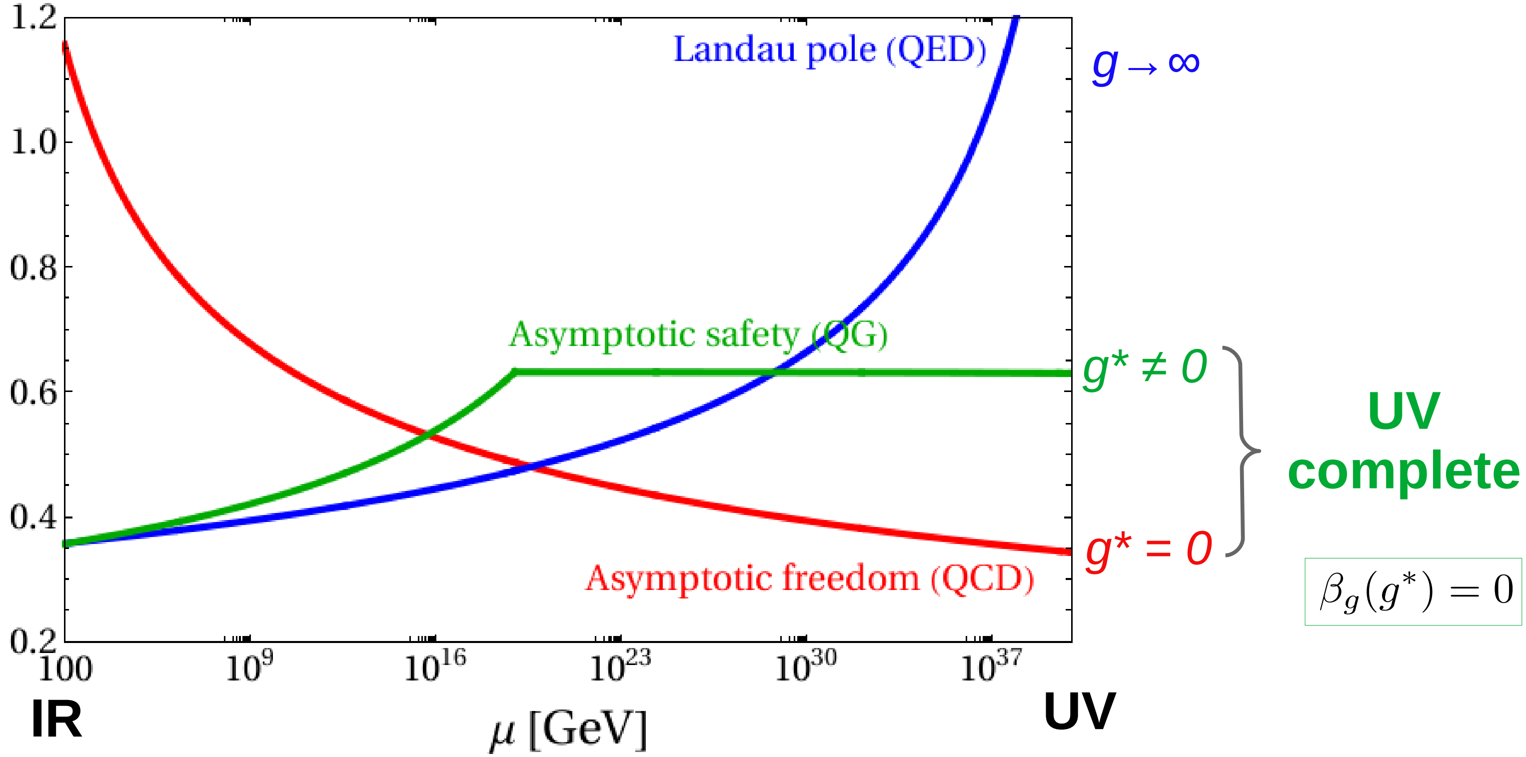
asymptotic freedom

**asymptotic safety**



# Asymptotic safety

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




## Known candidates in 4D:

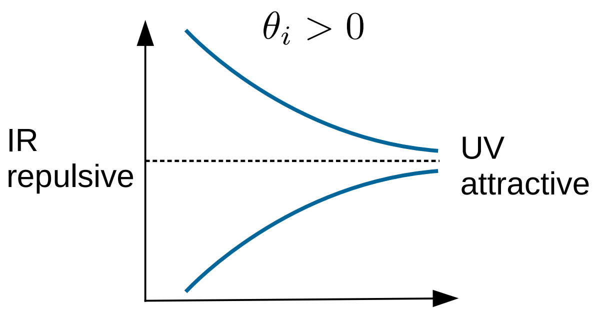
- Gauge-Yukawa (Litim-Sannino) models
  (Litim, Sannino, JHEP 1412 (2014) 178) — talks by T.Steudtner, D.Rizzo, G. Costa, A.Mukhaeva
  - Planck safety
    (Hiller, Hormigos-Feliu, Litim, Steudtner, '19,'20) — talk by G.Hiller
- quantum gravity → **this talk** — also talk by N.Ohta

# Bonus feature - predictivity

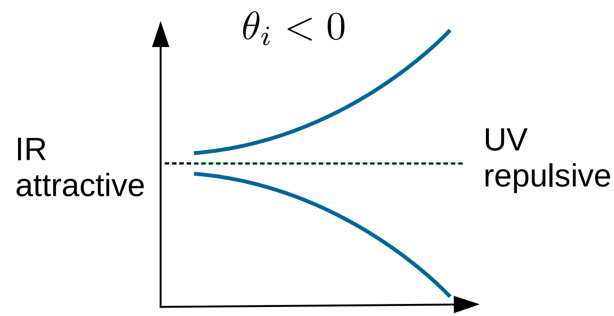
$$\boxed{\beta_i(\{\alpha_j^*\}) = 0} \longrightarrow M_{ij} = \partial\beta_i/\partial\alpha_j|_{\{\alpha_i^*\}} \longrightarrow \{-\theta_i\}$$

stability matrix

critical exponents



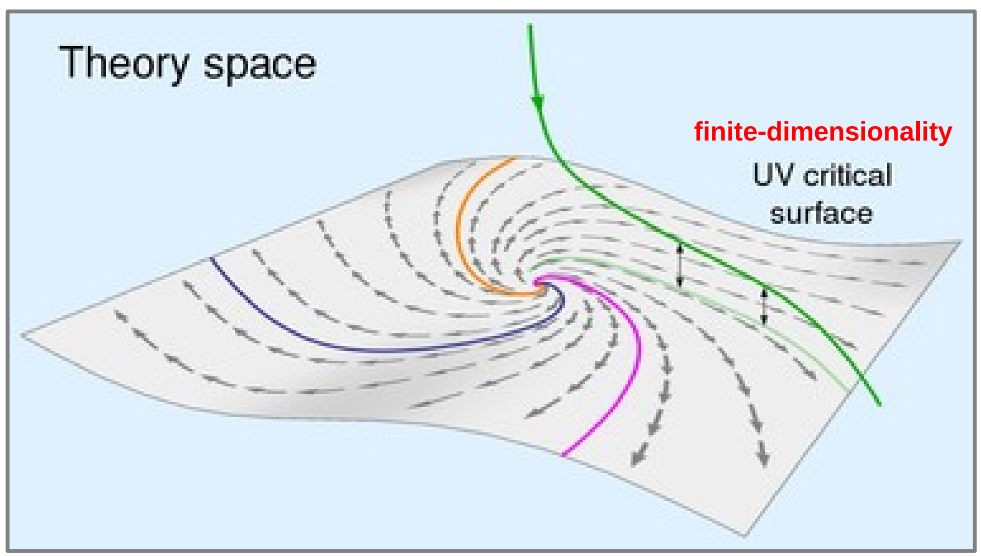

Relevant couplings are
free parameters of the theory




Irrelevant couplings provide
predictions

span the
**UV critical surface**
(define a fundamental QFT)

once determined by the
experiment ...




from Wikipedia

can only deviate from
the FP along the
critical surface

… can be uniquely fixed

**PREDICTIONS**

# Asymptotic safety in quantum gravity

M. Reuter, PRD 57, 971 (1998)

Prototype example: **Einstein-Hilbert gravity**

$$S_{\rm EH}[\tilde{g}_{\mu\nu}] = \frac{1}{16\pi G_N} \int d^4x \sqrt{\tilde{g}}\,(2\Lambda - R)$$

Dimensionless couplings:

$$g = G_N k^2 \qquad \lambda = \Lambda k^{-2}$$

From the FRG (Wetterich equation):

$$k\partial_k g = [2 + \eta_g(g,\lambda)]\, g$$

$$k\partial_k \lambda = -2\lambda + g\eta_\lambda(g,\lambda)$$

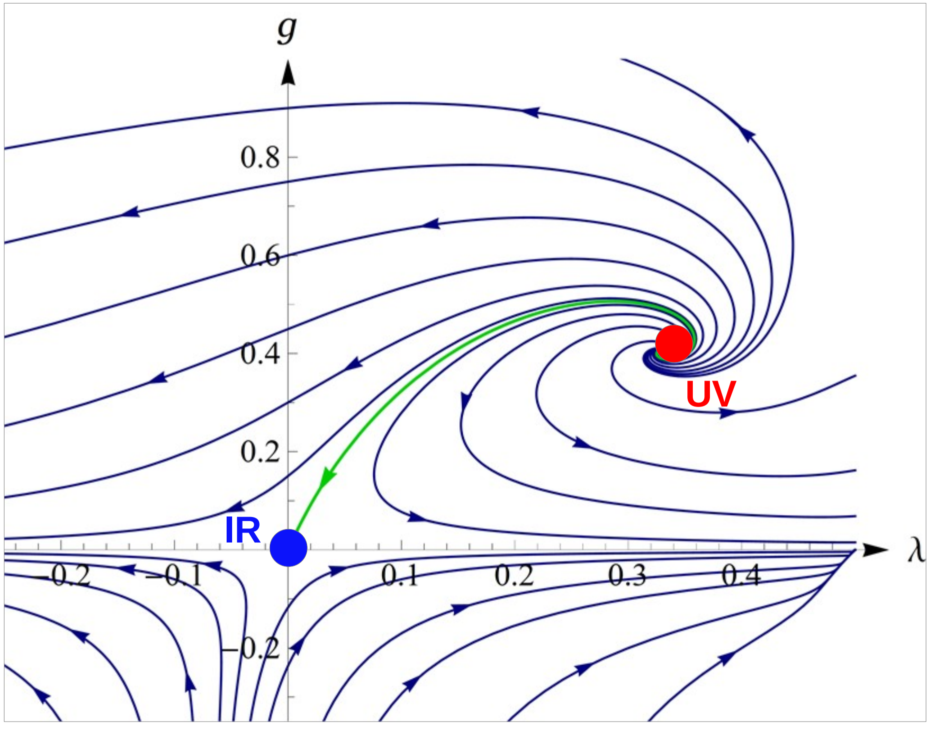
**2 fixed points:**

Gaussian: $g^* = 0 \qquad \lambda^* = 0$

Interactive: $g^* \neq 0 \qquad \lambda^* \neq 0$

## Trans-Planckian fixed point

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




**FP persists when adding new interactions**

[ Litim '04, Codello, Percacci, Rahmede '06, Benedetti, Machado, Saueressig '09, Narain, Percacci '09, Manrique, Rechenberger, Saueressig '11, Falls, Litim, Nikolakopoulos '13, Dona', Eichhorn, Percacci '13, Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16, Pawlowski *et al.* '18 … many more ]

**Critical surface has finite dimension**

[ Denz, Pawlowski, Reichert '16, Falls, Ohta, Percacci '20, Kluth. Litim '20, Knorr '21]

# Asymptotic safety in QG with matter

[Robinson, Wilczek '06, Pietrykowski '07, Toms '08, Rodigast, Schuster '09, Zanusso et al. '09, Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16,Wetterich, Yamada '16, Hamada, Yamada '17, Pawlowski et al. '18, Eichhorn, Versteegen '17, Eichhorn, Held '17-'18 …]

## Trans-Planckian corrections of matter RGEs $k > M_{\rm Pl}$ (functional renormalization group)

Wetterich, Reuter, Saueressig, Percacci, Litim, Pawlowski, Eichhorn ...

SM gauge couplings

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

$$\frac{dg_2}{dt} = -\frac{g_2^3}{16\pi^2}\frac{19}{6} \quad - f_g\, g_2$$

$$\frac{dg_3}{dt} = -\frac{g_3^3}{16\pi^2}7 \quad - f_g\, g_3$$

universal corrections depend on gravity fixed points

$$f_g = \tilde{G}^* \frac{1-4\tilde{\Lambda}^*}{4\pi\left(1-2\tilde{\Lambda}^*\right)^2}, \qquad f_y = -\tilde{G}^* \frac{96+\tilde{\Lambda}^*\left(-235+103\tilde{\Lambda}^*+56\tilde{\Lambda}^{*2}\right)}{12\pi\left(3-10\tilde{\Lambda}^*+8\tilde{\Lambda}^{*2}\right)^2}$$

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

SM Yukawa couplings

$$\frac{dy_t}{dt} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2+\frac{3}{2}y_b^2+3y_s^2+3y_c^2-\frac{9}{4}g_2^2-8g_3^2-\frac{17}{12}g_Y^2+y_e^2+y_\mu^2+y_\tau^2\right) \quad - f_y\, y_t$$

$$\frac{dy_b}{dt} = \frac{y_b}{16\pi^2}\left(\frac{9}{2}y_b^2+\frac{3}{2}y_t^2+3y_s^2+3y_c^2-\frac{9}{4}g_2^2-8g_3^2-\frac{5}{12}g_Y^2+y_e^2+y_\mu^2+y_\tau^2\right) \quad - f_y\, y_b$$

... same for other quarks and leptons

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[Robinson, Wilczek '06, Pietrykowski '07, Toms '08, Rodigast, Schuster '09, Zanusso et al. '09, Daum, Harst, Reuter '09, Folkerst, Litim, Pawlowski '11, Harst, Reuter '11, Christiansen, Eichhorn '17, Eichhorn, Versteegen '17, Zanusso *et al.* '09, Oda, Yamada '15, Eichhorn, Held, Pawlowski '16,Wetterich, Yamada '16, Hamada, Yamada '17, Pawlowski et al. '18, Eichhorn, Versteegen '17, Eichhorn, Held '17-'18 …]

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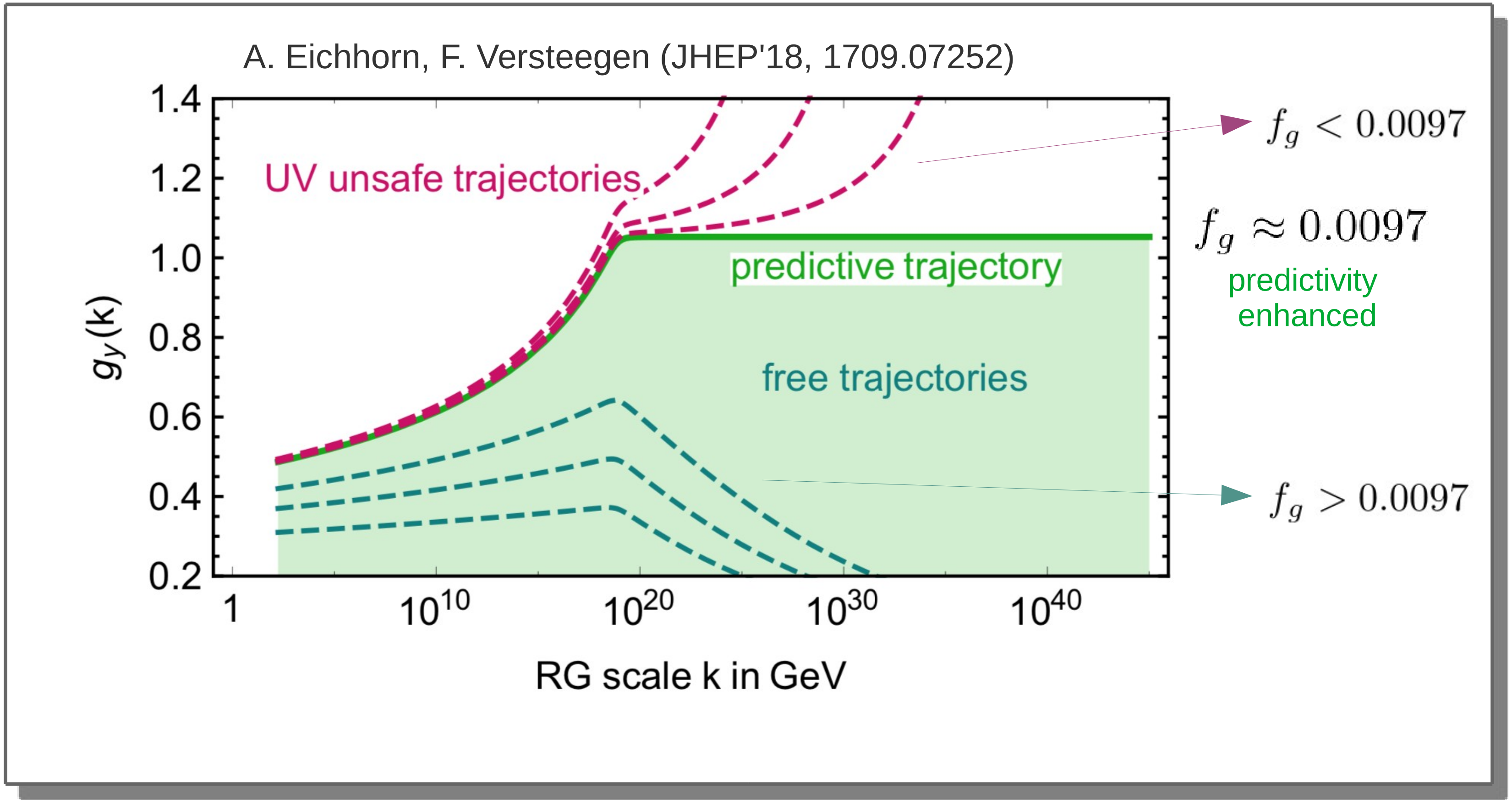
$$\frac{dy_b}{dt} = \frac{y_b}{16\pi^2}\left(\frac{9}{2}y_b^2 + \frac{3}{2}y_t^2 + 3y_s^2 + 3y_c^2 - \frac{9}{4}g_2^2 - 8g_3^2 - \frac{5}{12}g_Y^2 + y_e^2 + y_\mu^2 + y_\tau^2\right) - f_y\, y_b = 0$$

... same for other quarks and leptons

**get fixed points for matter**

# Predictions – heuristic approach

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



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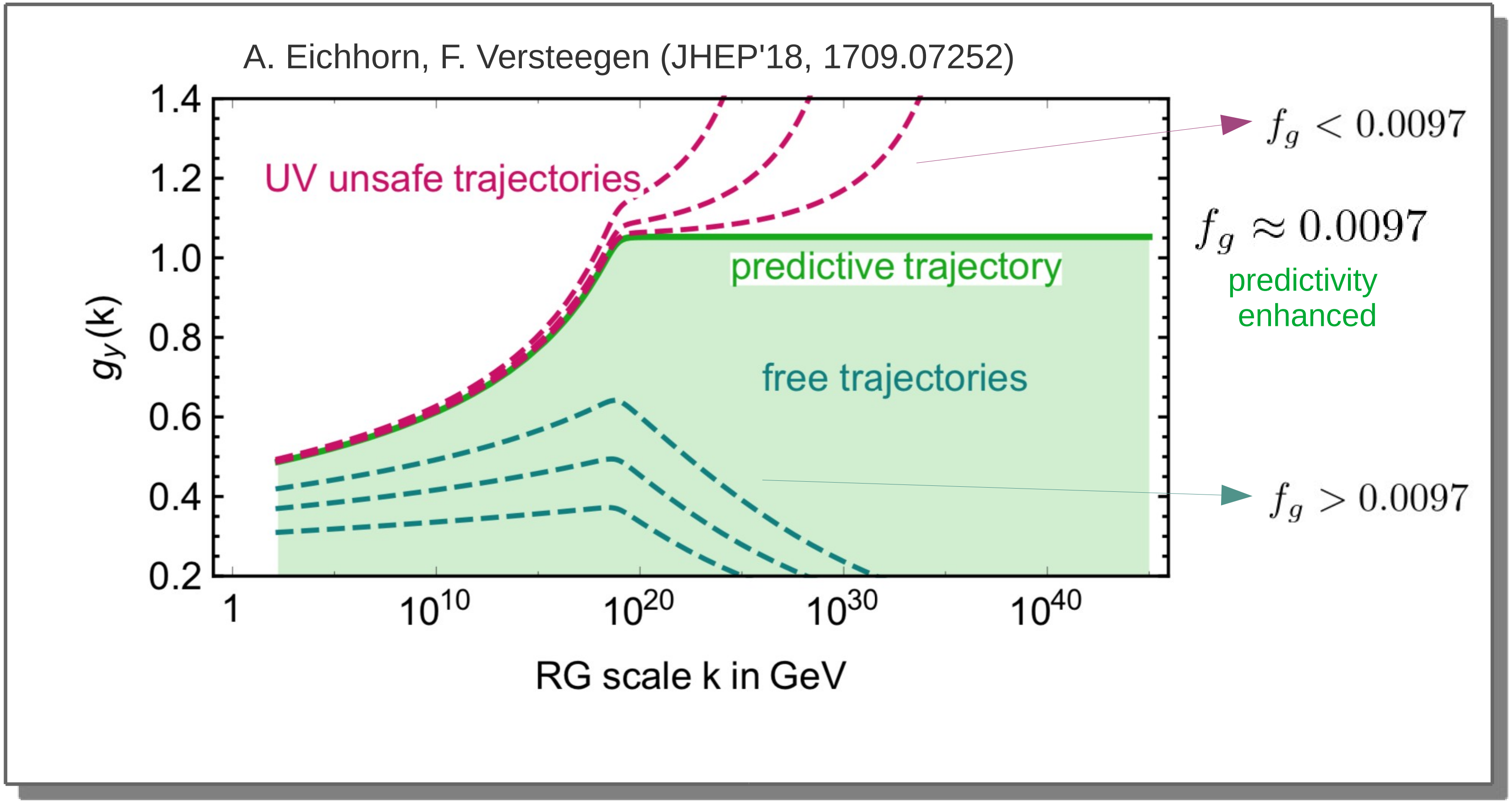



**UV fixed point** → heuristic determination $f_{g,y}$ → universality of $f_{g,y}$ → **predictions for (B)SM**

# Postdictions for the SM

## Top/bottom mass splitting

A. Eichhorn, A. Held (Phys.Rev.Lett. 121 (2018) 15)

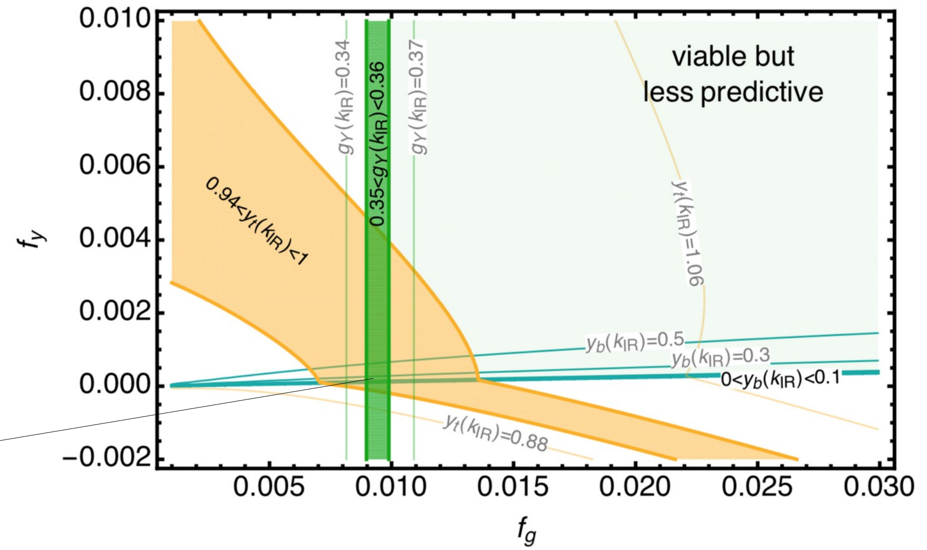
… *irrelevant* fixed points for top and bottom Yukawas feature a nice relation ...

$$y_t^{*2} - y_b^{*2} = \frac{1}{3} g_Y^{*2}$$

… IR values can be matched to the SM if ...

$$f_g = 9.7 \times 10^{-3} \qquad f_y \approx 1.2 \times 10^{-4}$$

to be verified with the FRG
(but not far off the existing caluclations)




## The full hadronic sector (masses and mixings)

R. Alkofer, A. Eichhorn, A. Held, C. M. Nieto, R. Percacci (Annals Phys. 421 (2020) 168282)

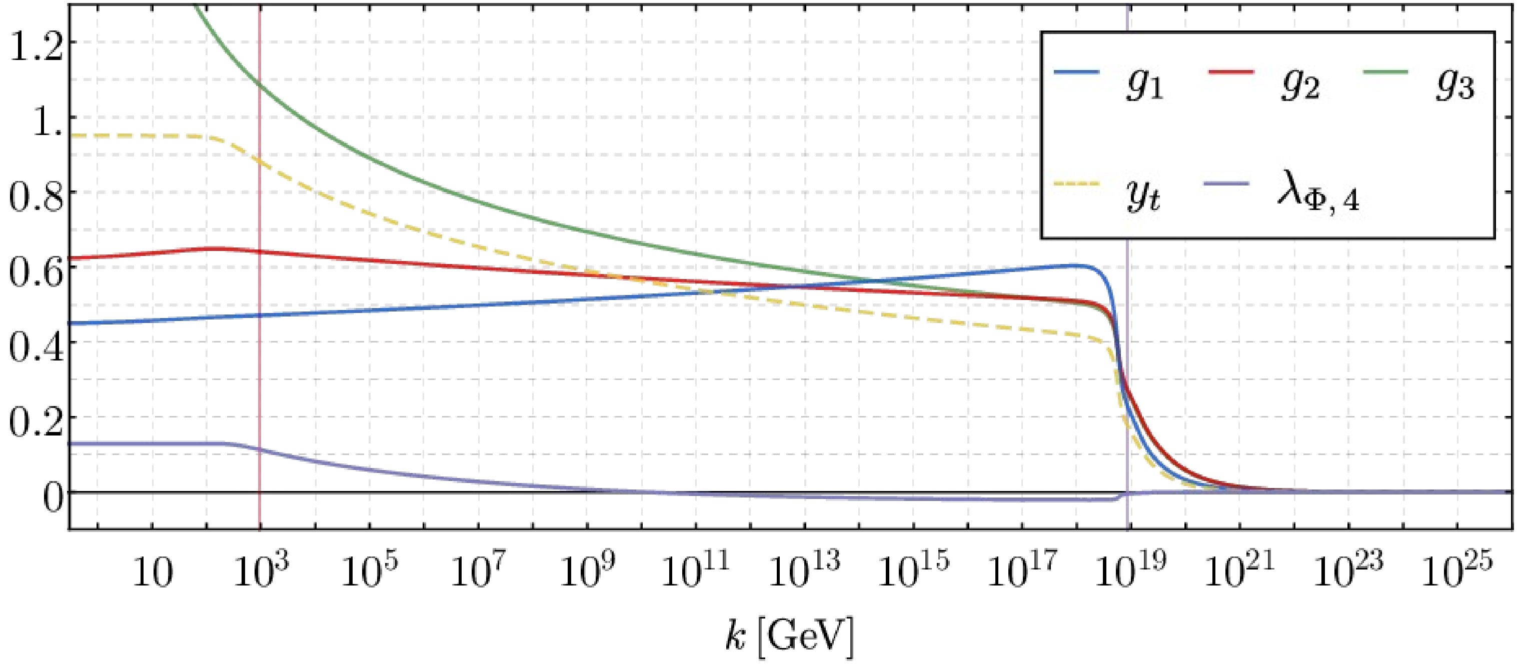
- *Irrelevant* directions of the CKM matrix do not match the IR values
- Most predictive solution overshoots the top mass by 10% (because relevant Gaussian CKM matrix elements alter the top/bottom relation $y_t^{*\,2} - y_b^2 = 2/3 g_Y^{*\,2}$)
- **Asymptotically free** Yukawa couplings are favored $f_g = 9.7 \times 10^{-3}$ $\quad f_y > -2.2 \times 10^{-4}$

# Asymptotically safe SM

## First self-consistent FRG approach

A. Pastor-Gutiérrez, J. M. Pawlowski, M. Reichert
(SciPost Phys. 15 (2023) 3, 105)

**all SM couplings are asymptotically free**



# Predictions for BSM

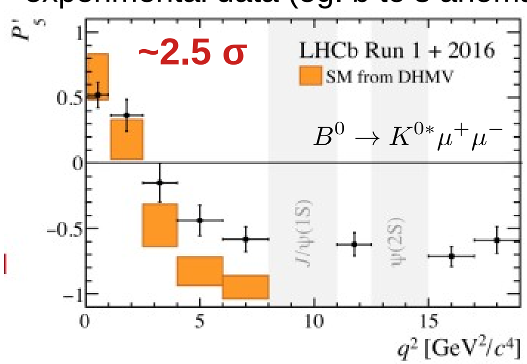
**Working assumption:**
**there is a UV interacting FP for (some) SM couplings**

to be confirmed by the FRG caluclation in a given BSM

heuristic determination $f_{g,y}$ → universality of $f_{g,y}$ → **predictions for (B)SM** → **experimental signatures**

Particularly usefull for **experimental anomalies:**

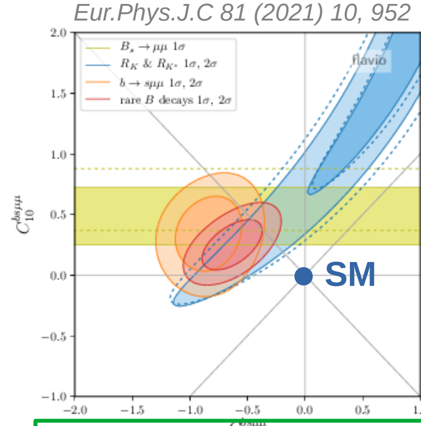
experimental data (eg. b to s anomalies)




(SM)EFT parametrization

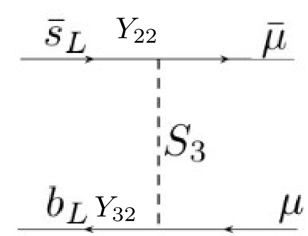
$$\frac{\mathcal{C}_{\rm NP}}{\Lambda^n} \approx \frac{c_i c_j}{m_{\rm NP}^n} \times \text{loop factor}$$

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




$$C_9^\mu = -C_{10}^\mu \in (-0.6, -0.3)$$

**BSM model (ex. leptoquarks)**



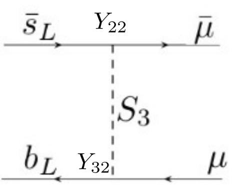

$$C_9^\mu = -C_{10}^\mu = \frac{\pi v_h^2}{V_{33}V_{32}^*\alpha_{\rm em}} \frac{\hat{Y}_{32}^L \hat{Y}_{22}^{L*}}{m_{S_3}^2}$$

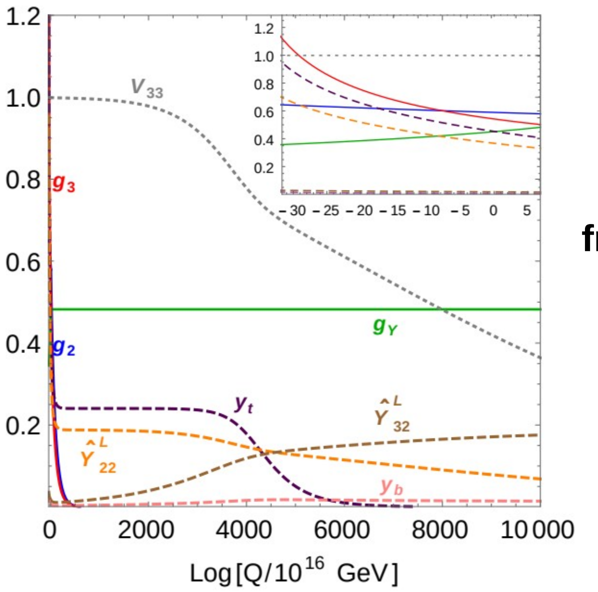
no precise prediction for the BSM mass

# Example: leptoquark mass

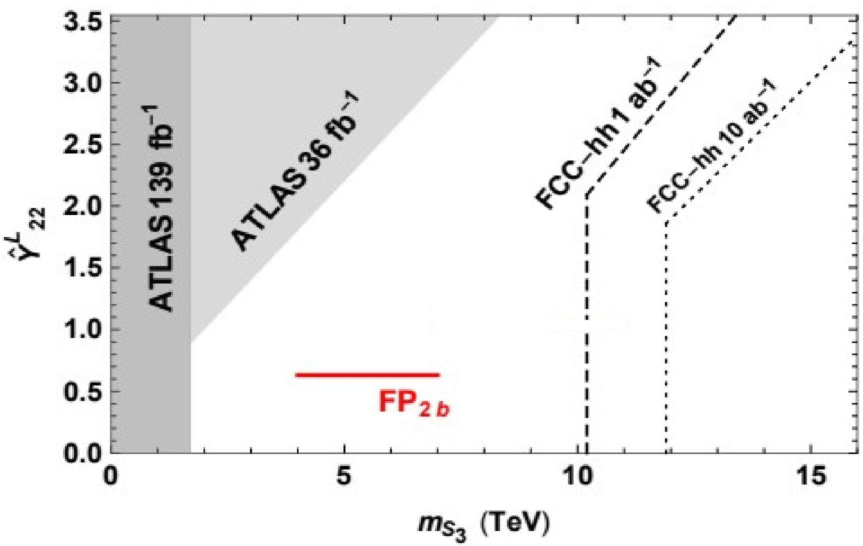
KK, E.M.Sessolo, Y.Yamamoto,
Eur.Phys.J.C 81 (2021) 4, 272

SM + LQ + QG




**UV boundary condtitions from irrelevant $g_Y$ and $y_t$**




**mass predicted**

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

**In the reach of the FCC!**

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

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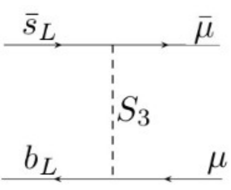


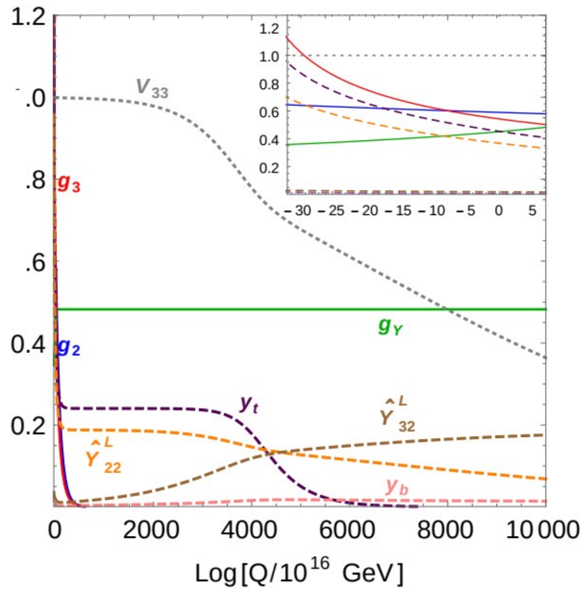


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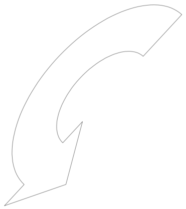
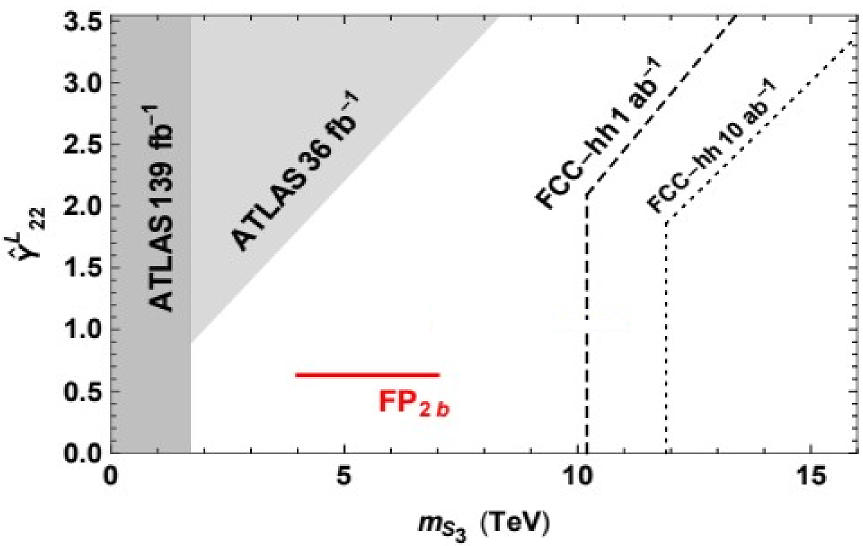





## Some other works along this lines...

- **anomalies in $b \to s$**

  A.Chikkaballi, W. Kotlarski, KK, D.Rizzo, E.M.Sessolo, JHEP 01 (2023) 164
- **anomalies in $b \to c$**

  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**

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

**In the reach of the FCC!**

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

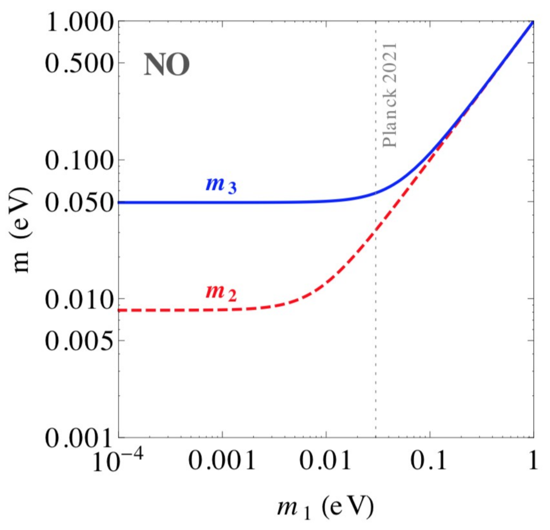
# Neutrino mass – how to make it small

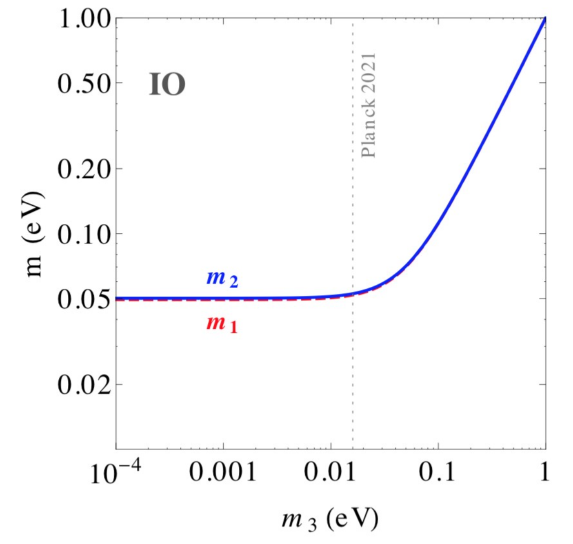
NuFIT5.1 (2021) 2007.14792

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

Planck (2021) 1807.06209

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



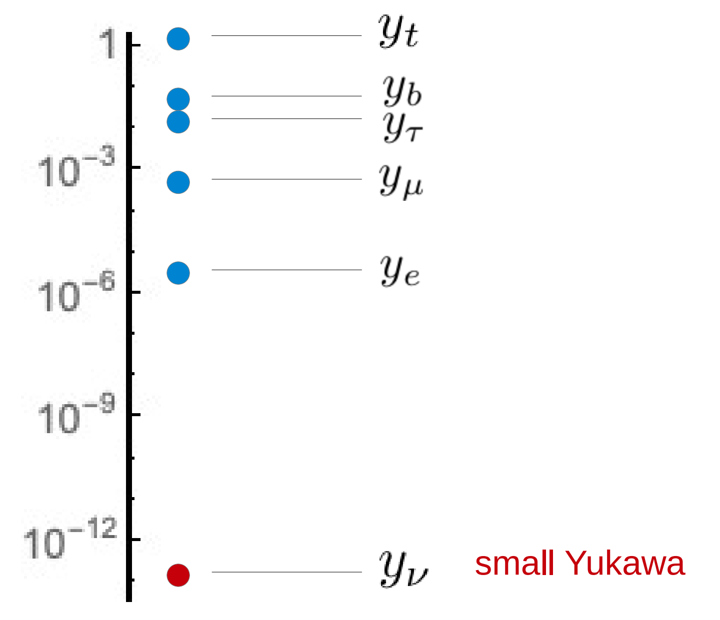




**either Dirac neutrino ...**

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

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

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



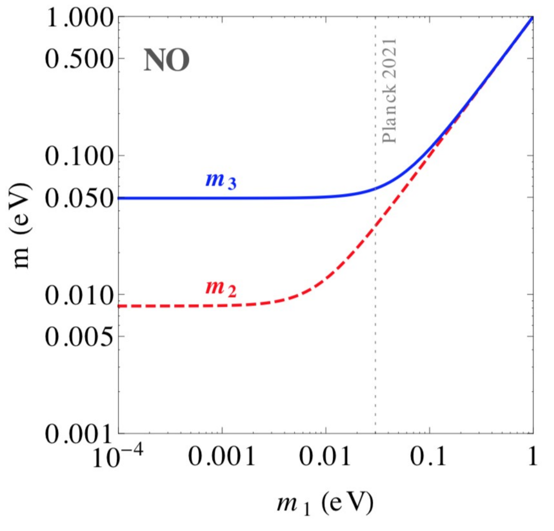
# Neutrino mass – how to make it small

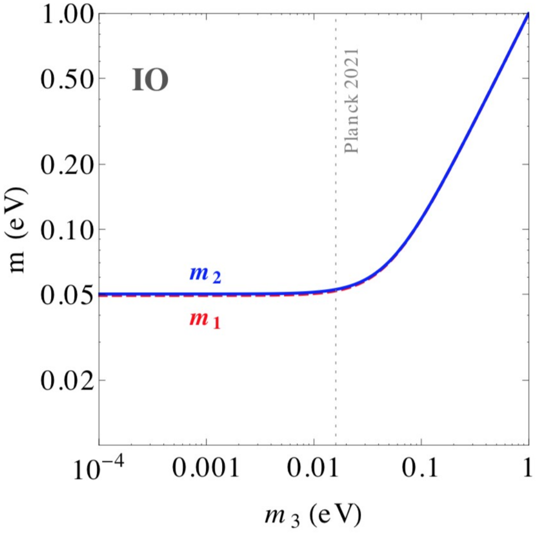
NuFIT5.1 (2021) 2007.14792

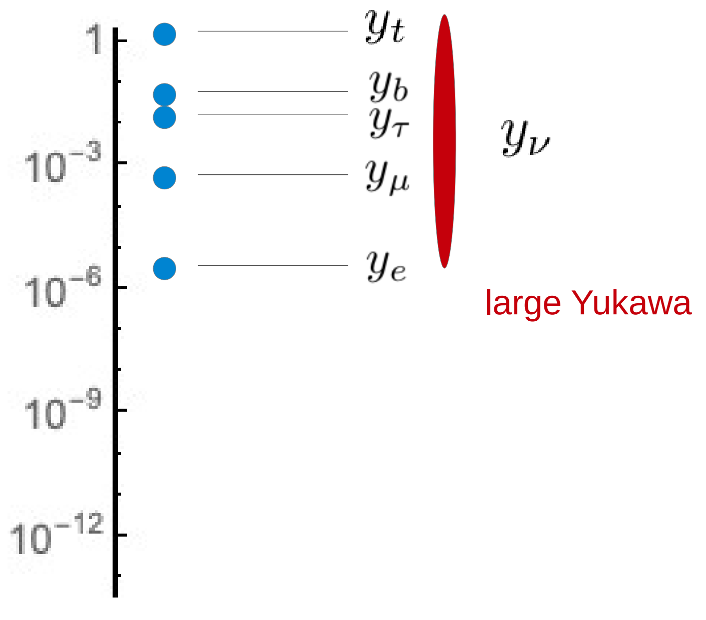
$$\begin{aligned} &\Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2, \\ \text{NO:}\quad &\Delta m^2_{31} = 2.515^{+0.028}_{-0.028} \times 10^{-3}\,\mathrm{eV}^2, \\ \text{IO:}\quad &\Delta m^2_{32} = -2.498^{+0.028}_{-0.029} \times 10^{-3}\,\mathrm{eV}^2, \end{aligned}$$

Planck (2021) 1807.06209

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




## … 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

# Neutrino – top system

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

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

$\beta_\nu \equiv \frac{dy_\nu}{dt} = 0$ $\rightarrow$ 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)

# Neutrino – top system

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

**SM + RHN:**

$$\frac{dg_Y}{dt} = \frac{g_Y^3}{16\pi^2}\frac{41}{6} - f_g\, g_Y$$
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$$\frac{dy_\nu}{dt} = \frac{y_\nu}{16\pi^2}\left[3y_t^2 + \frac{5}{2}y_\nu^2 - \frac{3}{4}g_Y^2\right] - f_y\, y_\nu$$

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

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

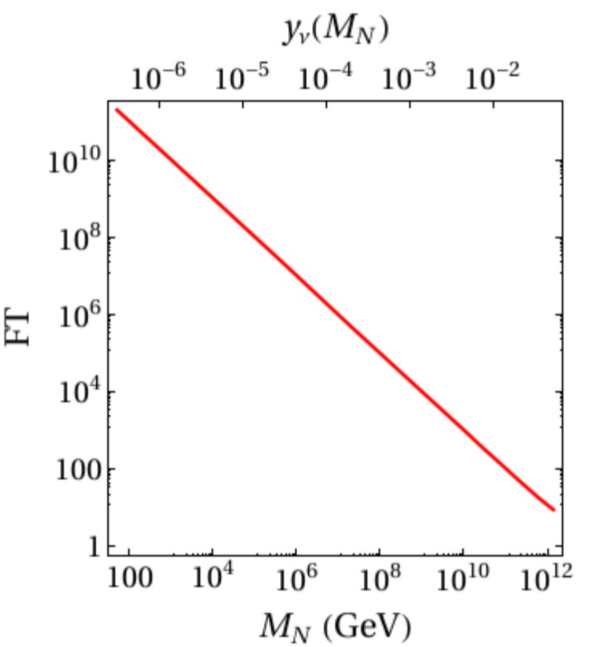
**1.** $$y_\nu^{*2} = \frac{32\pi^2}{5}f_y + \frac{3}{10}g_Y^{*2} - \frac{6}{5}y_t^{*2}$$ (interactive)

**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**



# Neutrino – top system

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

**SM + RHN:**

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

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

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

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

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

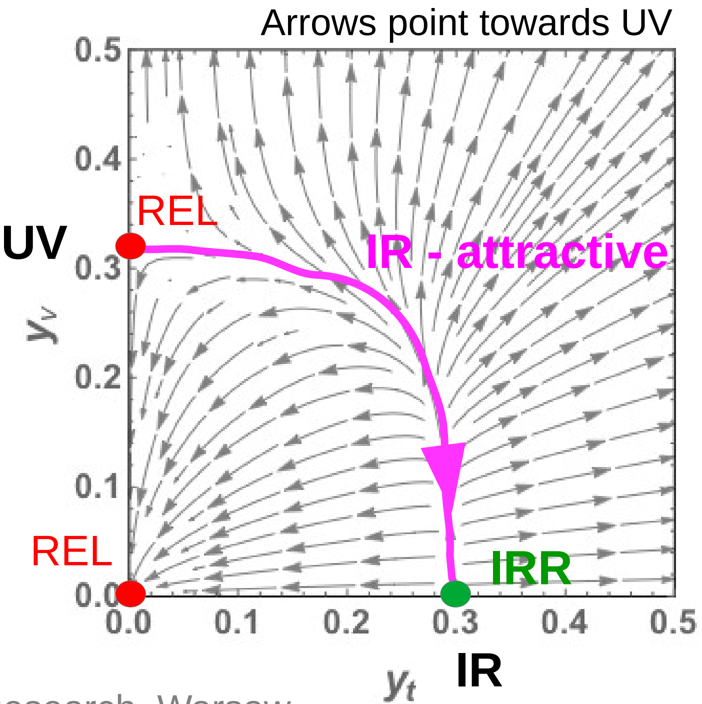
**2.** $y_\nu^* = 0$ (Gaussian)

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

$$f_y < f_{\nu,tY}^{\text{crit}} \approx 0.0008$$

**small Yukawa coupling → Dirac neutrino**

**Relevant FPs provide a UV completion**



# A dynamical mechanism!

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

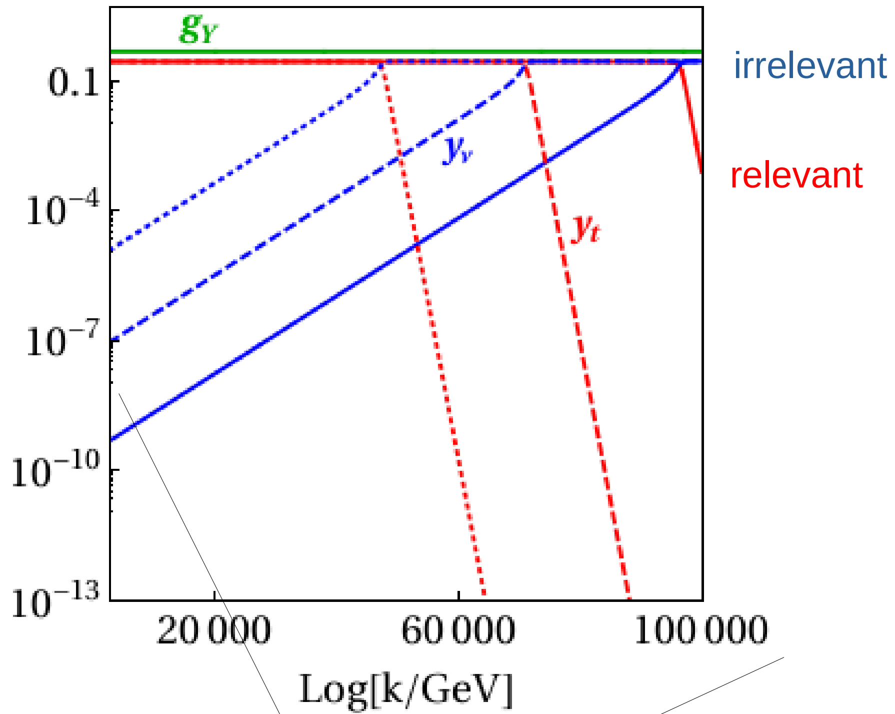
**No fine tuning:**

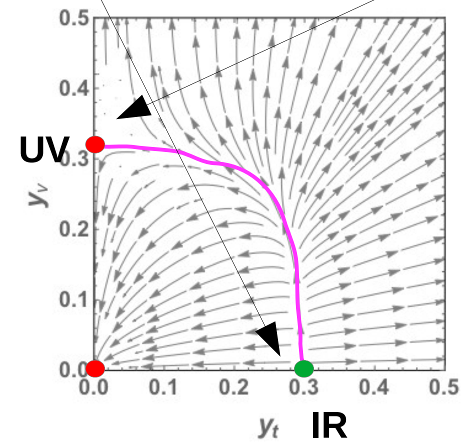
Smallness of the neutrino Yukawa due to the "distance" of the Planck scale from infinity

**Neutrinos can be Dirac naturally**

**Alternative to the see-saw mechanism**

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



# The mechanism is more generic...

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

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

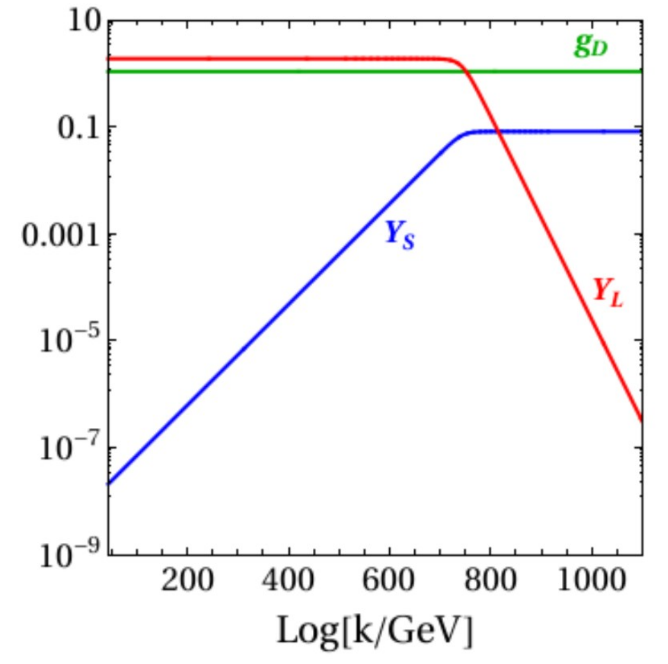
Recall that...

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

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

… thus we want ...

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



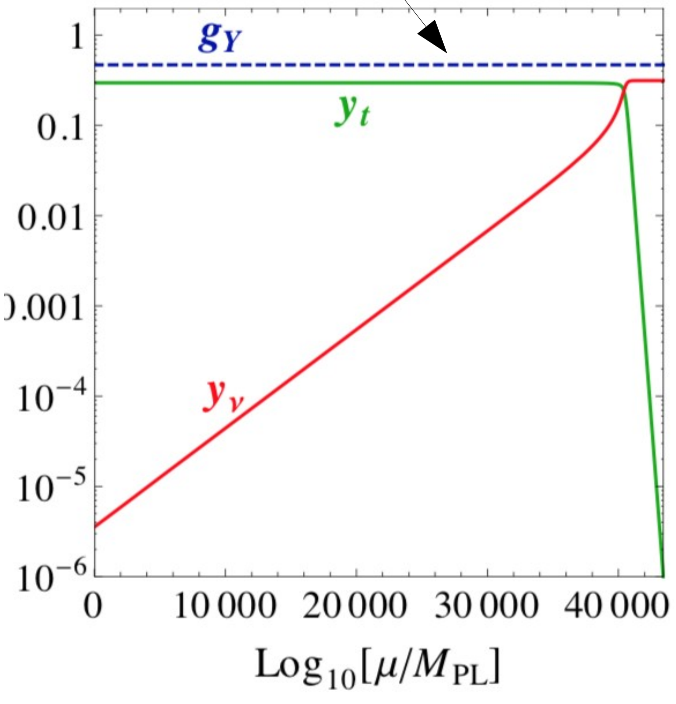

… it happens often (but not always) if $Q_\psi \gg Q_\chi$ (gauge charge)

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

# Connections to FRG

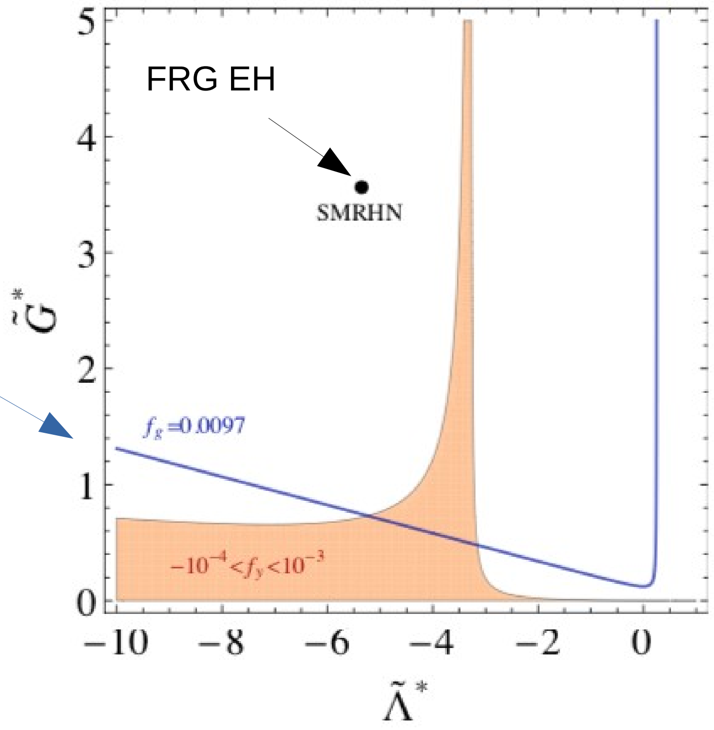
## SM + QG:

$$16\pi^2\theta_\nu \approx -\frac{2}{3}g_Y^{*2} + \frac{3}{2}y_t^{*2} < 0$$ for the mechanism to work




$f_g \approx 0.0097$
to match SM value

A. Chikkaballi, KK, E. Sessolo, 2308.06114




FRG calculation following
A.Eichhorn, F.Versteegen, 1709.07252

**FRG calculation should eventually match the blue line**

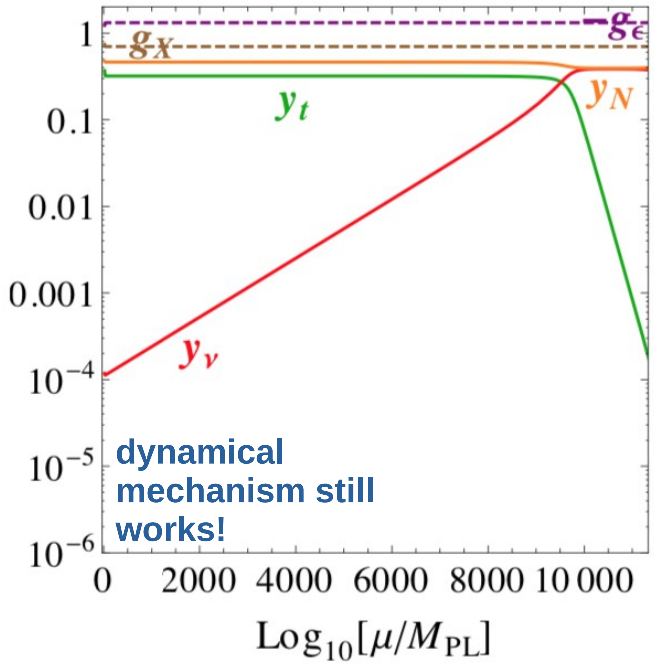
# Connections to FRG

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

$g_Y = 0$ …

… but its role played by

$$g_X = \frac{g_{B-L}}{\sqrt{1-\epsilon^2}}\,, \quad g_\epsilon = -\frac{\epsilon\, g_Y}{\sqrt{1-\epsilon^2}}$$



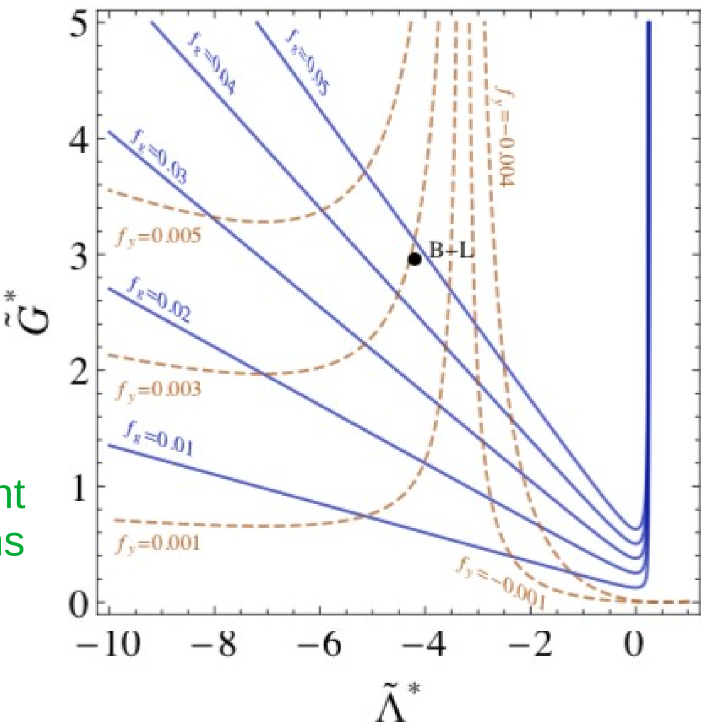

$f_g =$ **any**

easier to make consistent with the FRG calculations

extended gauge sector

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

A. Chikkaballi, KK, E. Sessolo, 2308.06114




FRG calculation following
A.Eichhorn, F.Versteegen, 1709.07252

<u>Extra info</u>: FP analysis provides **predictions for $g_X$, $g_\varepsilon$**

# Predictions for B-L model

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

extended scalar sector

$$\mathcal{L}_M = -y_N^{ij} S\, \nu_{R,i}\, \nu_{R,j} + \text{H.c.}$$ → **Majorana mass term**

$f_g$, $f_y$ lead to *predictive* (irrel.) fixed points for $g_X$, $g_\epsilon$, $y_N$ :

(all BPs have $y_\nu^* = 0$ irrel.)

A. Chikkaballi, KK, E. Sessolo, 2308.06114

| | $f_g$ | $f_y$ | $g_X^*$ | $g_\epsilon^*$ | $y_N^*$ | $g_X$ ($10^{5,7,9}$ GeV) | $g_\epsilon$ ($10^{5,7,9}$ GeV) | $y_N$ ($10^{5,7,9}$ GeV) | |
|---|---|---|---|---|---|---|---|---|---|
| BP1 | 0.01 | 0.0005 | 0.10 | −0.55 | 0.12 | 0.29, 0.29, 0.30 | −0.26, −0.27, −0.28 | 0.16, 0.16, 0.16 | **Majorana** |
| BP2 | 0.05 | −0.005 | 0.70 | −1.32 | 0.47 | 0.40, 0.41, 0.44 | −0.52, −0.56, −0.61 | 0.42, 0.44, 0.45 | **Majorana** |
| BP3 | 0.02 | −0.0015 | 0.10 | −0.75 | 0.0 | 0.12, 0.12, 0.12 | −0.33, −0.35, −0.37 | 0.0 | **Dirac** |
| BP4 | 0.03 | −0.004 | 0.10 | 0.75 | 0.0 | 0.09, 0.09, 0.09 | 0.23, 0.25, 0.28 | 0.0 | **Dirac** |

**Note**: large kinetic mixing

strong LHC bounds on Z' production ⇒ implies $v_S >> v_H$

# Predictions for B-L model

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

extended scalar sector

$$\mathcal{L}_M = -y_N^{ij} S\, \nu_{R,i}\, \nu_{R,j} + \text{H.c.}$$ → **Majorana mass term**

$f_g$, $f_y$ lead to *predictive* (irrel.) fixed points for $g_X$, $g_\epsilon$, $y_N$ :

(all BPs have $y_\nu^* = 0$ irrel.)

A. Chikkaballi, KK, E. Sessolo, 2308.06114

| | $f_g$ | $f_y$ | $g_X^*$ | $g_\epsilon^*$ | $y_N^*$ | $g_X$ $(10^{5,7,9}$ GeV) | $g_\epsilon$ $(10^{5,7,9}$ GeV) | $y_N$ $(10^{5,7,9}$ GeV) | |
|---|---|---|---|---|---|---|---|---|---|
| BP1 | 0.01 | 0.0005 | 0.10 | −0.55 | 0.12 | 0.29, 0.29, 0.30 | −0.26, −0.27, −0.28 | 0.16, 0.16, 0.16 | **Majorana** |
| BP2 | 0.05 | −0.005 | 0.70 | −1.32 | 0.47 | 0.40, 0.41, 0.44 | −0.52, −0.56, −0.61 | 0.42, 0.44, 0.45 | **Majorana** |
| BP3 | 0.02 | −0.0015 | 0.10 | −0.75 | 0.0 | 0.12, 0.12, 0.12 | −0.33, −0.35, −0.37 | 0.0 | **Dirac** |
| BP4 | 0.03 | −0.004 | 0.10 | 0.75 | 0.0 | 0.09, 0.09, 0.09 | 0.23, 0.25, 0.28 | 0.0 | **Dirac** |

**Note**: large kinetic mixing

strong LHC bounds on Z' production

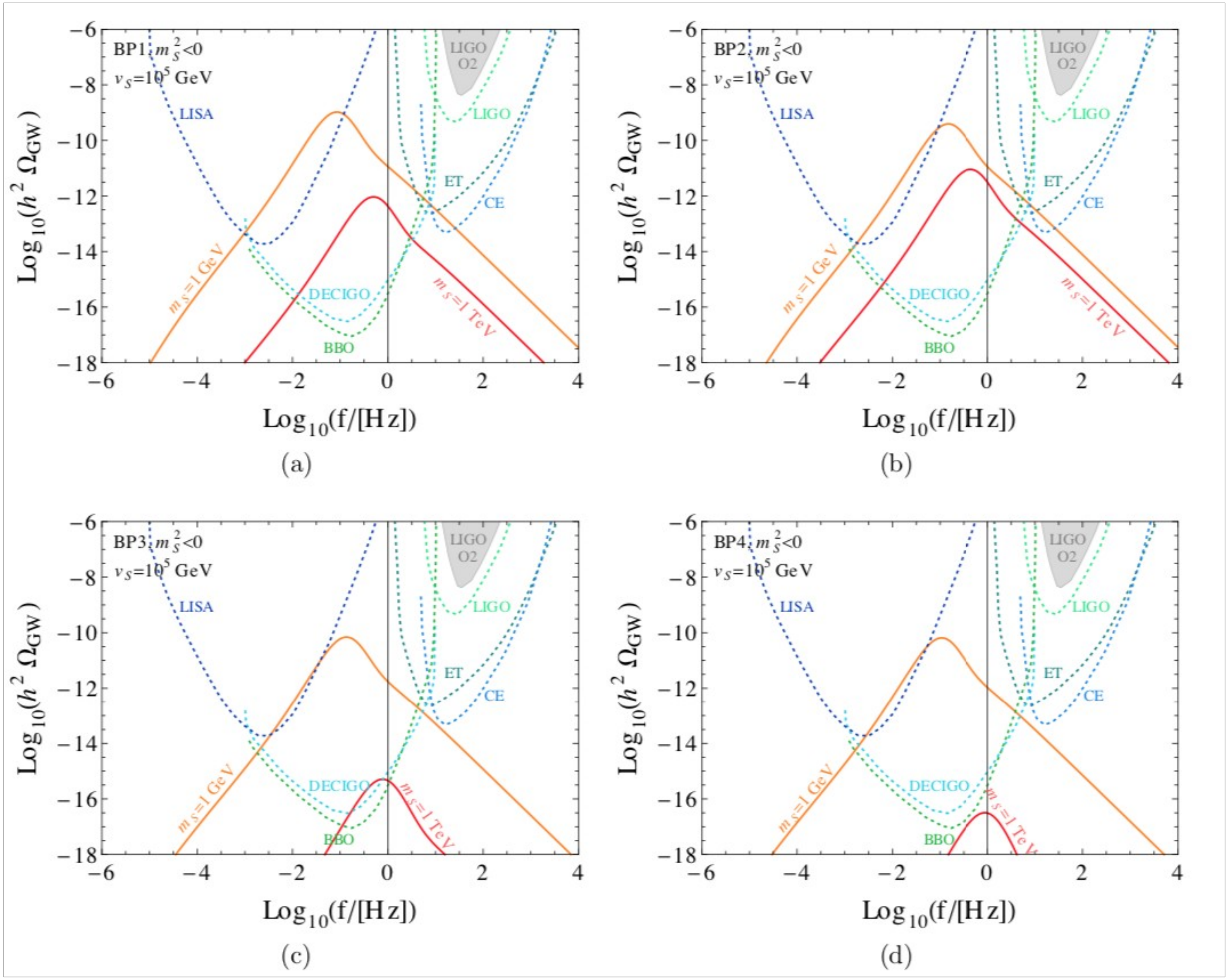
⇒ implies $v_S \gg v_H$

**Gravitational waves from FOPT?**

# Gravitational waves

**Signal is now visible...**

A. Chikkaballi, KK, E. Sessolo, 2308.06114




**… but discriminating features washed-out by the scalar masses**

# Conclusions

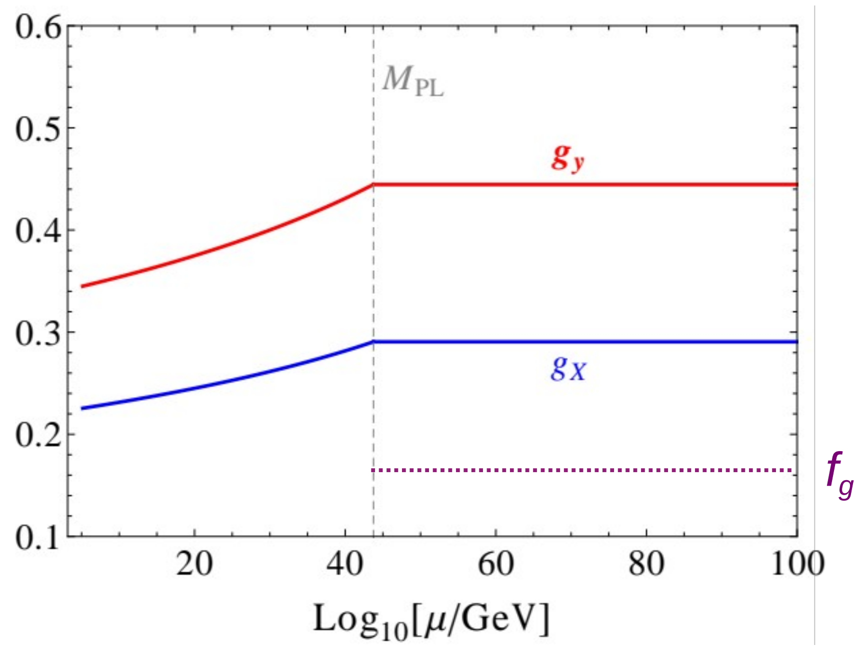
- AS based on quantum gravity offers a **predictive UV completion**
- Via UV irr. fixed point, AS can lead to **specific and testable predictions** for BSM
- AS can be used to make the neutrino (or other) Yukawa coupling **arbitrarily small dynamically**
- Mechanism relies on an **irrelevant Gaussian fixed point** of the trans-Planckian RG flow of Yukawa coupling
- In the SM + QG **some tension** between the FRG results and phenomenology, but perhaps not so in gauged *B-L*

# Backup slides

# Predictions for NP - assumptions

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC ’23, arXiv: 2304.08959

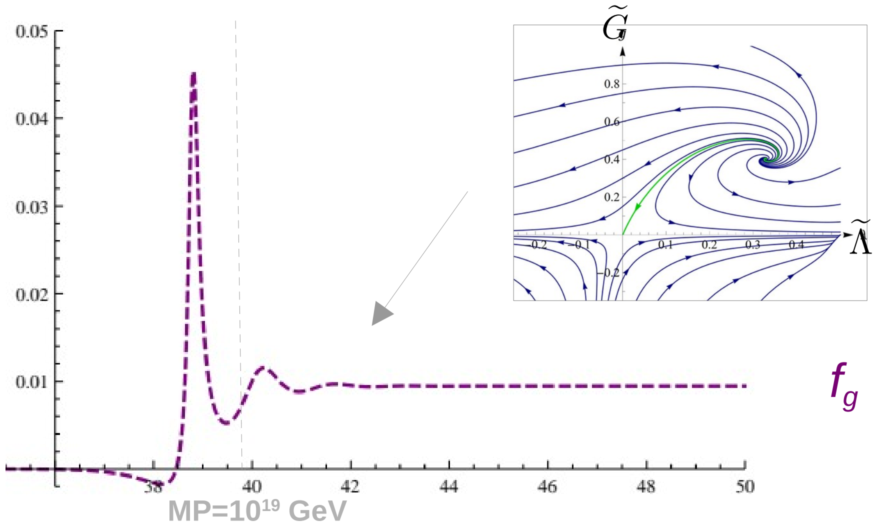
- 1-loop matter RGEs
- Planck scale set at $10^{19}$ GeV
- Gravity parameters *f* are constant
- Gravity decouples instantaneously




**But in FRG:**

eg. EH truncation, α=0, β=1 g.f
A. Eichhorn, F. Versteegen, JHEP 01 (2018) 030

$$f_g(t) = \tilde{G}(t)\frac{1-4\tilde{\Lambda}(t)}{4\pi\left(1-2\tilde{\Lambda}(t)\right)^2}$$




**Let’s drop the assumptions...**

# Uncertainties – gauge sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

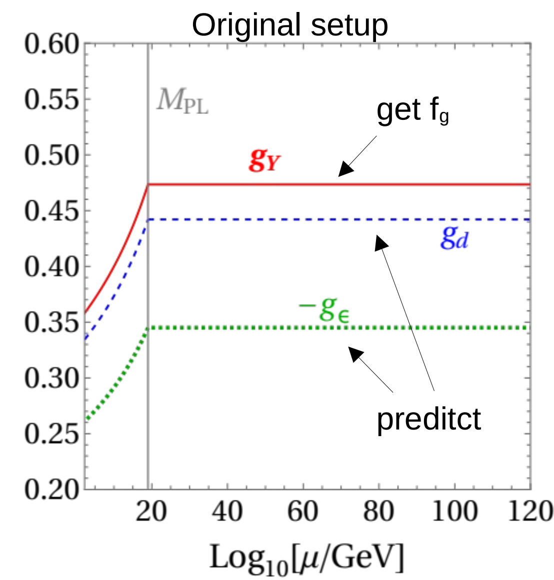
eg. $U(1)_Y \times U(1)_D$

Recall B-L from E.Sessolo's talk

$$\frac{dg_Y}{dt} = \frac{1}{16\pi^2}\overbrace{\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right)}^{\tilde{b}_Y} g_Y^3 - g_Y\, f_g(t)$$

$$\frac{dg_d}{dt} = \frac{1}{16\pi^2}\left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right) g_d g_\epsilon^2 + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^3 + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right) g_d^2 g_\epsilon\right] - g_d\, f_g(t)$$

$$\frac{dg_\epsilon}{dt} = \frac{1}{16\pi^2}\left[\left(b_Y + \Pi^{(Y)}_{n\geq 2}\right)\left(g_\epsilon^3 + 2 g_Y^2 g_\epsilon\right) + \left(b_d + \Pi^{(d)}_{n\geq 2}\right) g_d^2 g_\epsilon + \left(b_\epsilon + \Pi^{(\epsilon)}_{n\geq 2}\right)\left(g_Y^2 g_d + g_d g_\epsilon^2\right)\right] - g_\epsilon\, f_g(t)$$




## The coupling ratios do not depend on $f_g$

(due to the universality of QG)

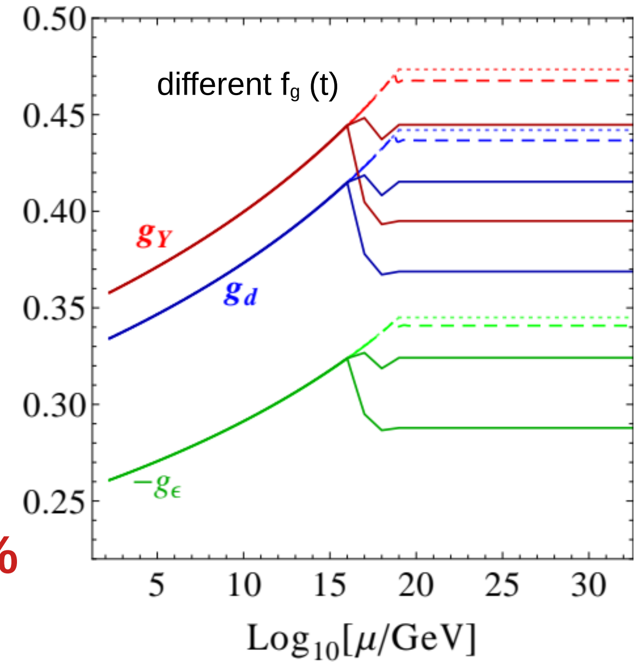
$$\frac{g_d^*}{g_Y^*}(n \text{ loops}) \approx \frac{2\tilde{b}_Y}{\sqrt{4\tilde{b}_Y\tilde{b}_d - \tilde{b}_\epsilon^2}}$$

$$\frac{g_\epsilon^*}{g_Y^*}(n \text{ loops}) \approx -\frac{\tilde{b}_\epsilon}{\sqrt{4\tilde{b}_Y\tilde{b}_d - \tilde{b}_\epsilon^2}}$$

Invariant of the RGE flow

**PREDICTIONS VERY STABLE**

**δg ≤ 0.1%**



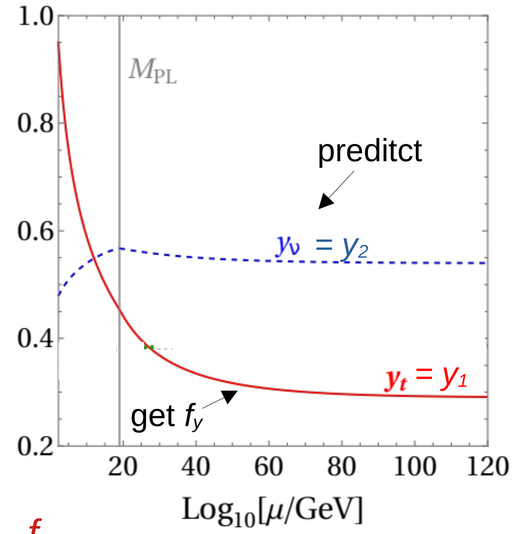
# Uncertainties – Yukawa sector

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
EPJC '23, arXiv: 2304.08959

<u>2-Yukawa system</u>

$$\frac{dy_1}{dt} = \frac{y_1}{16\pi^2}\left(a_1^{(1)} y_1^2 + a_2^{(1)} y_2^2 - a'^{(1)} g_1^2 + \sum_{n\geq 2} \Pi_n^{(1)}\right) - y_1 f_y(t)$$

$$\frac{dy_2}{dt} = \frac{y_2}{16\pi^2}\left(a_1^{(2)} y_1^2 + a_2^{(2)} y_2^2 - a'^{(2)} g_1^2 + \sum_{n\geq 2} \Pi_n^{(2)}\right) - y_2 f_y(t)$$




**The FP ratio $y_2$ to $y_1$ depends on FP of other couplings**

fixed $f_g$ and $f_y$ — shift due to the running $f_g$, $f_y$

$$\frac{y_2^*}{y_1^*}(1\ \text{loop}) \approx \left[\frac{\left(a_1^{(2)} - a_1^{(1)}\right) + \left(a'^{(1)} - a'^{(2)}\right) g_1^{*2}/y_1^{*2}}{a_2^{(1)} - a_2^{(2)}} + \frac{\left(a_1^{(2)} - a_1^{(1)}\right)\delta y_1^{*2} + \left(a'^{(1)} - a'^{(2)}\right)\delta g_1^{*2}}{y_1^{*2}\left(a_2^{(1)} - a_2^{(2)}\right)}\right]^{1/2}$$

<u>eg. LQ $S_3$ model:</u>

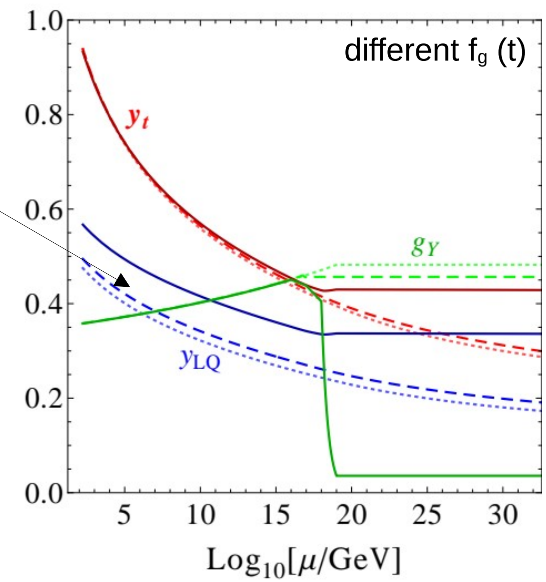
$$\mathcal{L} \supset -Y_{LQ}\, Q^T \tilde{\epsilon} S_3\, L + \text{H.c.}$$

**... but not so much in FRG**

**... IR focusing helps**

**PREDICTION UNSTABLE ...**

**$\delta y \leq 20\%$**



# Does it work in the full SM?

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

PMNS parametrization

$$U_2 = |U_{\alpha i}|^2 = \begin{bmatrix} X & Y & 1-X-Y \\ Z & W & 1-Z-W \\ 1-X-Z & 1-Y-W & X+Y+Z+W-1 \end{bmatrix}$$

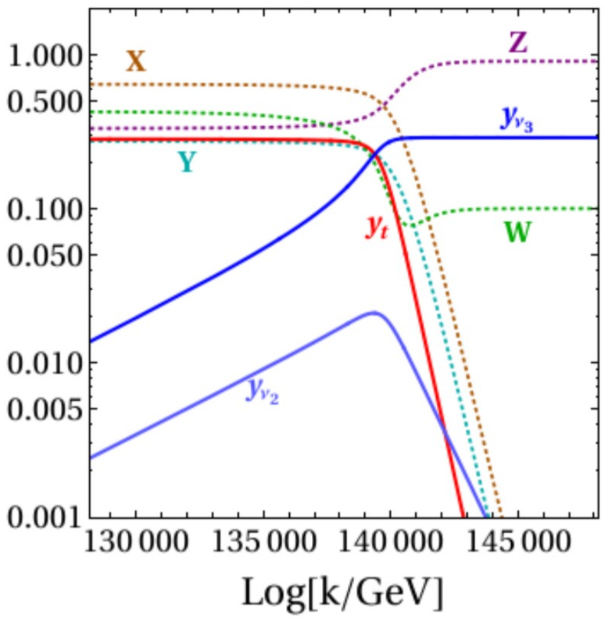
$$\theta_{12} = \arctan\sqrt{\frac{Y}{X}}$$
$$\theta_{13} = \arccos\sqrt{X+Y}$$
$$\theta_{23} = \arcsin\sqrt{\frac{1-W-Z}{X+Y}}$$

$$\delta = \arccos\frac{(X+Y)^2 Z - Y(X+Y+Z+W-1) - X(1-W-Z)(1-X-Y)}{2\sqrt{XY(1-X-Y)(1-Z-W)(X+Y+Z+W-1)}}$$

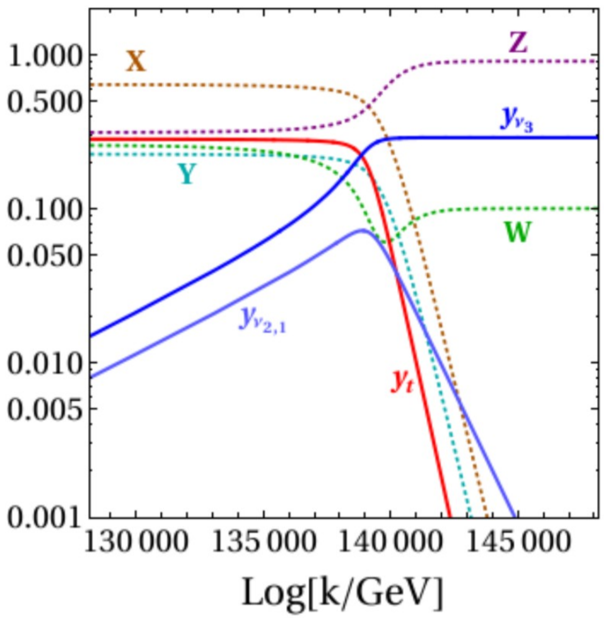
PMNS fit $X \in [0.64 - 0.71]$ $Y \in [0.26 - 0.34]$ $Z \in [0.05 - 0.26]$ $W \in [0.21 - 0.48]$

**Normal ordering works!** (no solution found with IO)

Hierarchical NO

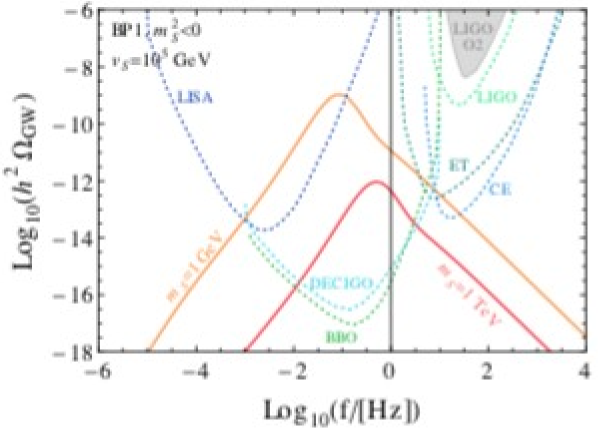



Degenerate NO



# Details of BP1 and BP2

BP1



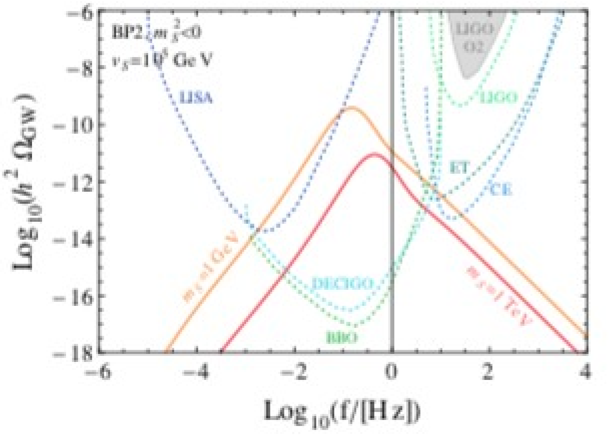

$m_S = 1\ GeV : \alpha = 10^{10}\ ,\ \beta = 49.8$

$T_p = 14.6\ GeV$

$m_S = 1\ TeV : \alpha = 0.27\ ,\ \beta = 185$

$T_p$ ~ 10 TeV

BP2




$m_S = 1\ GeV : \alpha = 10^{11}\ ,\ \beta = 78.9$

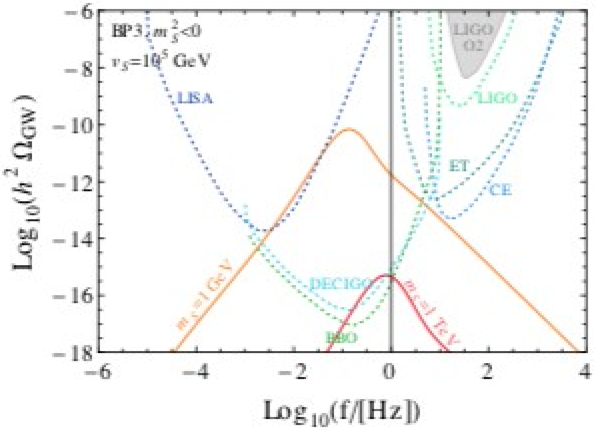
$T_p = 8\ GeV$

$m_S = 1\ TeV : \alpha = 0.88\ ,\ \beta = 187$

$T_p$ ~ 10 TeV

# Details of BP3 and BP4

BP3



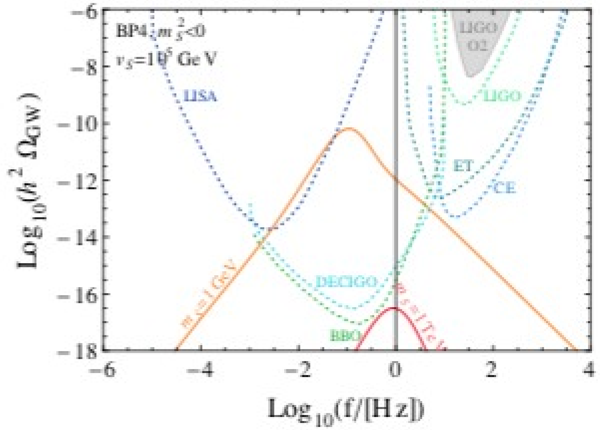

$m_S = 1\ GeV : \alpha = 10^9\ ,\ \beta = 189$

$T_p = 10.04\ GeV$

$m_S = 1\ TeV : \alpha = 0.02\ ,\ \beta = 227$

$T_p$ ~ 10 TeV

BP4




$m_S = 1\ GeV : \alpha = 10^8\ ,\ \beta = 201$

$T_p = 11.5\ GeV$

$m_S = 1\ TeV : \alpha = 0.01\ ,\ \beta = 229$

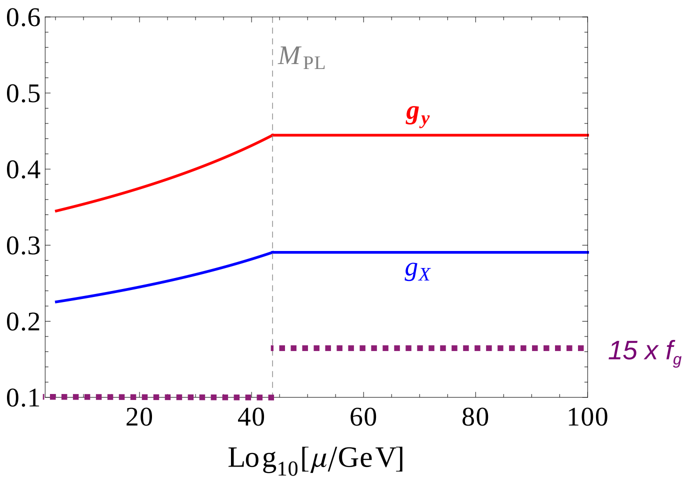
$T_p =$ ~ 10 TeV

# How robust are low-scale predictions?

W.Kotlarski, KK, D.Rizzo, E.M.Sessolo
Eur. Phys. J. C, 83 (2023) 644

**assumptions:**

- 1-loop matter RGEs
- Planck scale set at $10^{19}$ GeV
- Gravity parameters *f* are constant
- Gravity decouples instantaneously



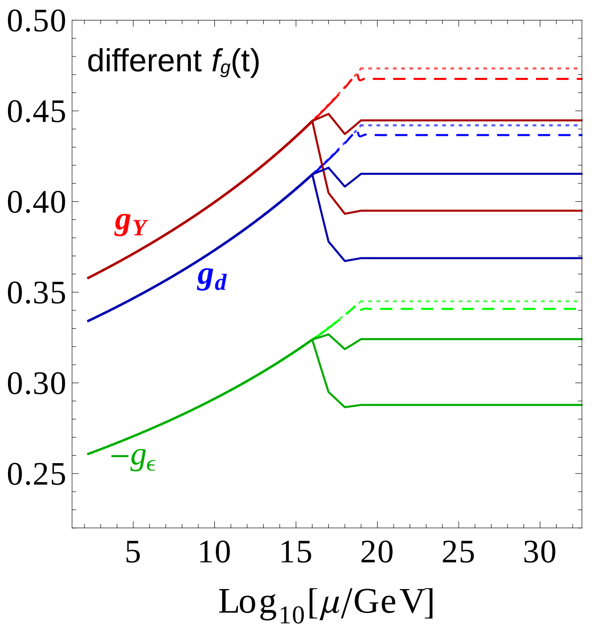

**The gauge coupling ratios do not depend on $f_g$**
(due to the universality of QG)

**Invariant under the RGE flow**

⇩

**PREDICTIONS VERY STABLE**

$$\delta g \lesssim 0.1\%$$



# How robust are low-scale predictions?

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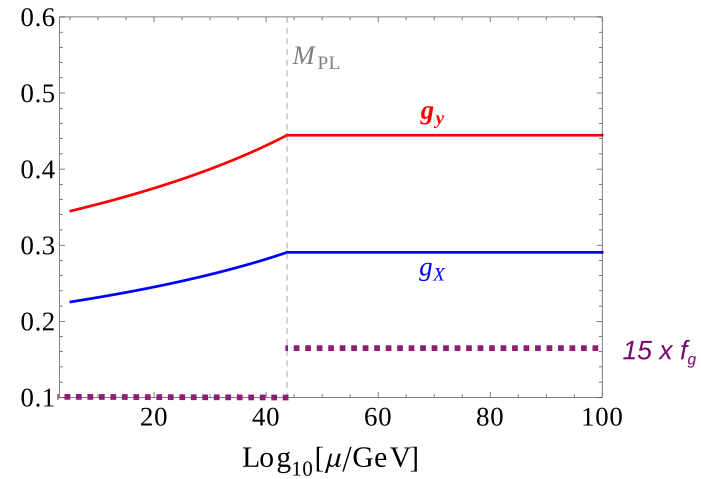



**The Yukawa ratios depend on the other FPs**

fixed $f_g$ and $f_y$

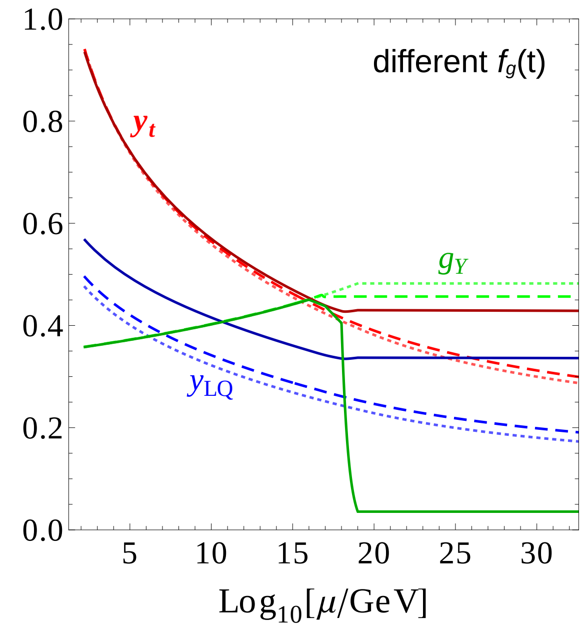
shift due to the running $f_g$, $f_y$

$$\left(\frac{y^*_{LQ}}{y^*_t}\right)^2 (1\ \text{loop}) \approx A + B g_Y^{*2}/y_t^{*2} + C\delta(y_t^*, g_Y^*)$$

$y_2^* \ll y_1^*$ **PREDICTIONS UNSTABLE**

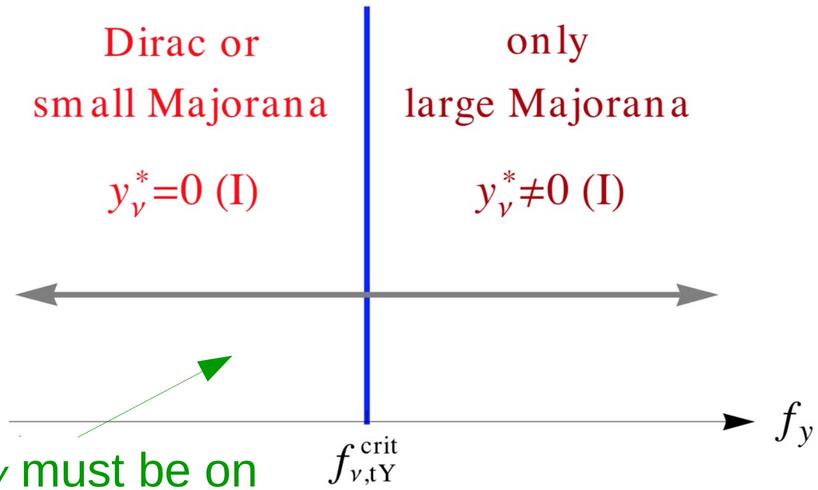
$y_2^* \approx y_1^*$ $\delta y \lesssim 20\%$

**+ fousing, realistic UV running**



# Is neutrino special?

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




*fy* must be on this side of *f*crit ...

… and there's an *f*crit for each fermion ...

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

$$f_{Z,XY}^{\mathrm{crit}} = \frac{g_Y^{*2}}{16\pi^2}\,\frac{\alpha'_X\alpha_Y - \alpha'_Y\alpha_X}{\alpha_X - \alpha'_X}$$

… but top mass is good only if... $-1\times 10^{-4} \lesssim f_y \lesssim 1\times 10^{-3}$

| $Z$ | $\alpha'_{X=t}$ | $\alpha'_Y$ | $f_{Z,tY}^{\mathrm{crit}}$ | |
|---|---|---|---|---|
| $u, c$ | 3 | $\frac{17}{12}$ | $-20.0\times 10^{-4}$ | TOP BAD |
| $b$ | $\frac{3}{2}$ | $\frac{5}{12}$ | $1.17\times 10^{-4}$ | TOP OKAY |
| $d, s$ | 3 | $\frac{5}{12}$ | $22.3\times 10^{-4}$ | TOP GOOD |
| $\nu_i$ | 3 | $\frac{3}{4}$ | $8.22\times 10^{-4}$ | TOP GOOD |
| $e, \mu, \tau$ | 3 | $\frac{15}{4}$ | $-119\times 10^{-4}$ | TOP BAD |

# Is neutrino special?

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

**… running CKM makes $f_{crit}$ smaller**

No CKM:

Running CKM:

$$16\pi^2\theta_{d,s} \approx 16\pi^2 f_y - 3y_t^{*2} + \frac{5}{12}g_Y^{*2} \quad \Rightarrow \quad 16\pi^2\theta_{d,s} \approx 16\pi^2 f_y - \frac{3}{2}\left(1+|V_{tb}|^2\right)y_t^{*2} + \frac{5}{12}g_Y^{*2}$$

FP = 0

R. Alkofer *et al.* (2003.08401)

… but top mass is good only if... $-1 \times 10^{-4} \lesssim f_y \lesssim 1 \times 10^{-3}$

| $Z$ | $\alpha'_{X=t}$ | $\alpha'_Y$ | $f^{\text{crit}}_{Z,tY}$ | |
|---|---|---|---|---|
| $u, c$ | 3 | $\frac{17}{12}$ | $-20.0 \times 10^{-4}$ | TOP BAD |
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| $e, \mu, \tau$ | 3 | $\frac{15}{4}$ | $-119 \times 10^{-4}$ | TOP BAD |

**… perhaps the neutrino is special after all**