Indications for BSM from unification, vacuum stability and gravitational waves

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in collaboration with
D. Kumar, D. Rizzo, E. M. Sessolo

JHEP 1912 (2019) 094 (arXiv: 1910.00847)
and work in progress

Workshop on Standard Model and Beyond, Corfu
02.09.2024

National Science Centre Poland

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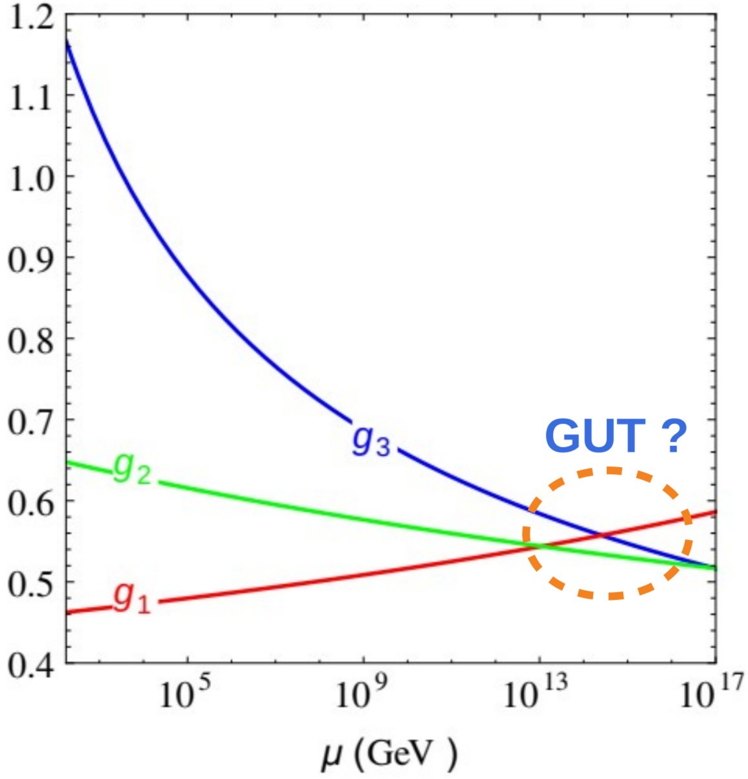
The new old story

Standard Model



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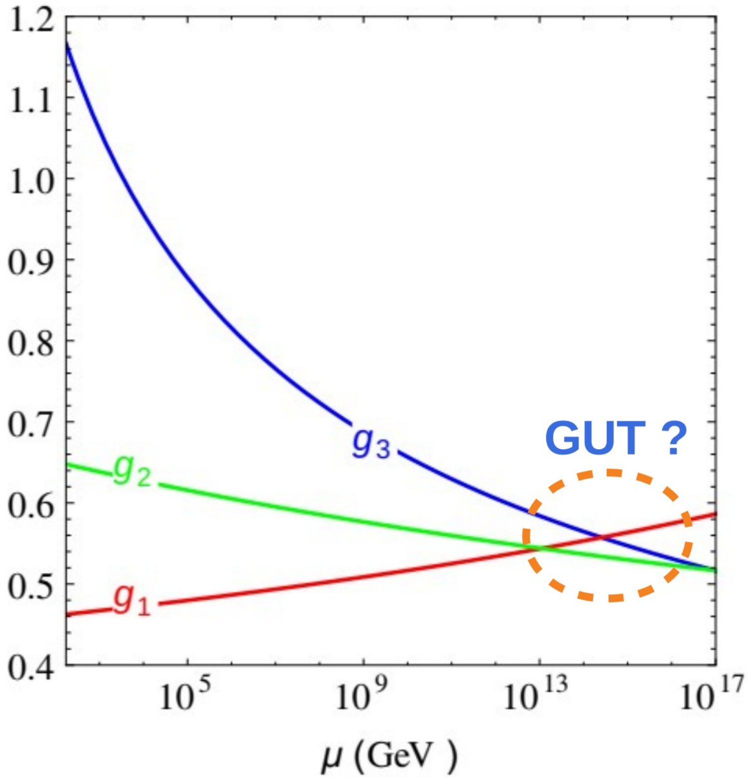
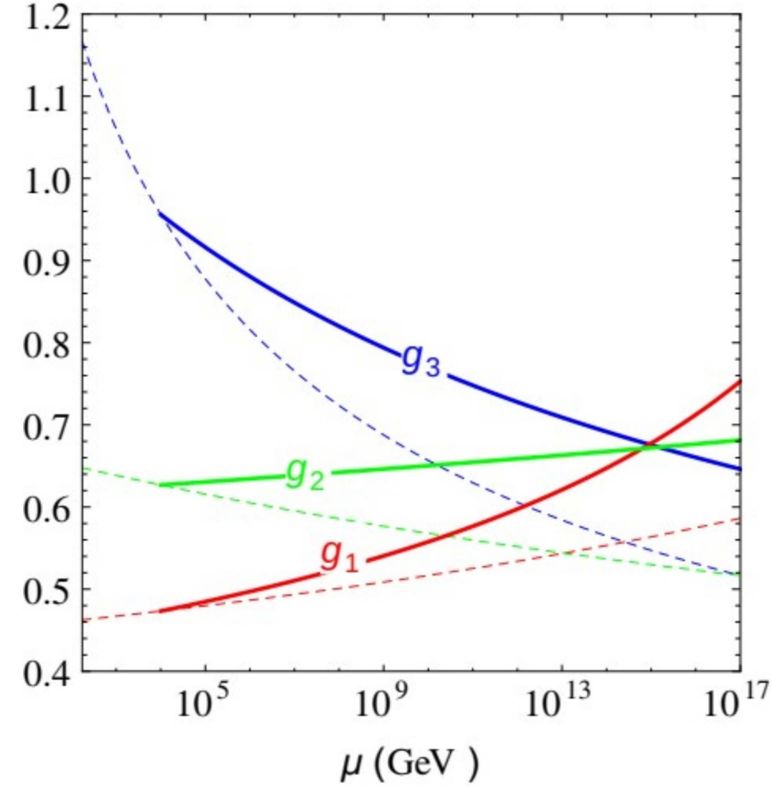


NP needed →

Standard Model + NP



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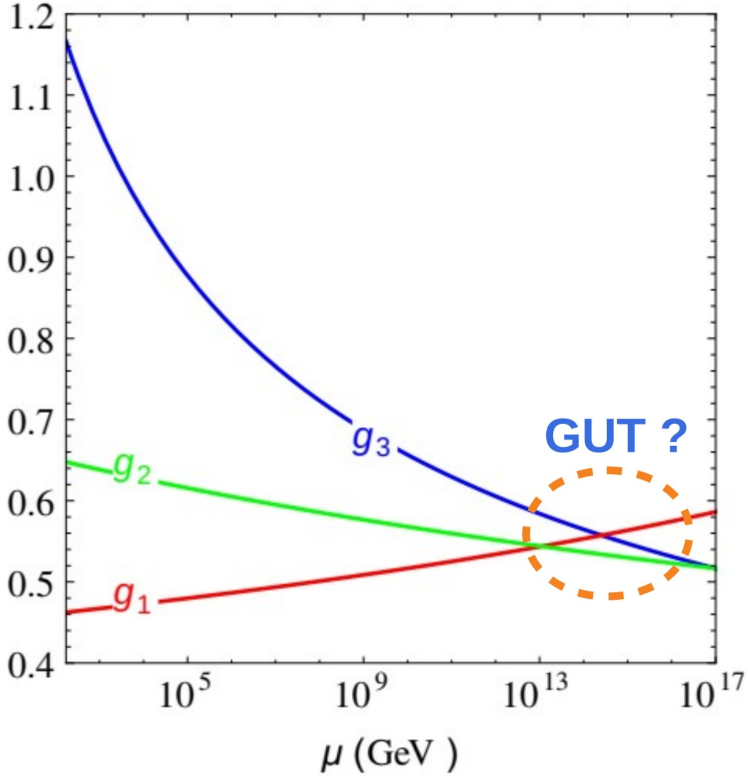

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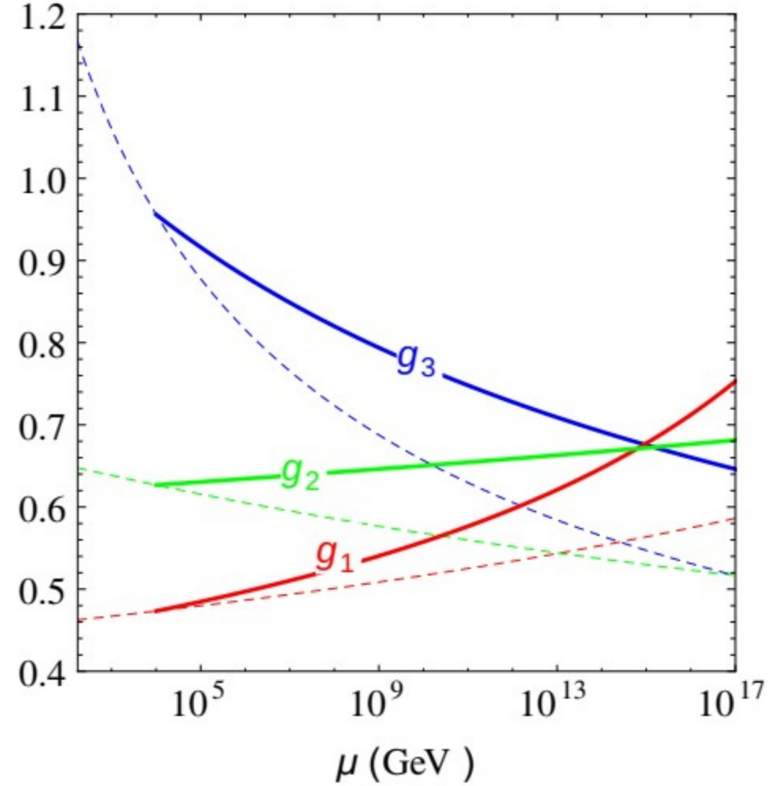

Our goal: classification of the BSM extensions with VL fermions and gauge unification

KK, D.Kumar, arXiv: 1910.00847
JHEP 12 (2019) 094

Analysis strategy

KK, D.Kumar, arXiv: 1910.00847

Some previous work:

T. G. Rizzo, Phys. Rev. D45 (1992) 3903–3905

B. Bhattacherjee, P. Byakti, A. Kushwaha, S. K. Vempati, JHEP 05 (2018) 090

Initial assumptions:

- NP = vector-like fermions (mass < 10 TeV)
- unification scale in the range 10^{15} - 10^{18} GeV
- *SU(5)*-like GUT gauge symmetry
- negligible Yukawa interaction → **long-lived particles**

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↓

24 distinct representations of *SU(3)xSU(2)xU(1)*

$$\begin{aligned}
\text{color singlets :}\quad & (\mathbf{1},\mathbf{1},1)\,,(\mathbf{1},\mathbf{1},-2)\,,\left(\mathbf{1},\mathbf{2},\tfrac{1}{2}\right),\left(\mathbf{1},\mathbf{2},-\tfrac{3}{2}\right),(\mathbf{1},\mathbf{3},0)\,,(\mathbf{1},\mathbf{3},1)\,,\\
& \left(\mathbf{1},\mathbf{4},\tfrac{1}{2}\right),\left(\mathbf{1},\mathbf{4},-\tfrac{3}{2}\right),\\
\text{color triplets :}\quad & \left(\mathbf{3},\mathbf{1},-\tfrac{1}{3}\right),\left(\bar{\mathbf{3}},\mathbf{1},-\tfrac{2}{3}\right),\left(\bar{\mathbf{3}},\mathbf{1},\tfrac{4}{3}\right),\left(\bar{\mathbf{3}},\mathbf{1},-\tfrac{5}{3}\right),\left(\mathbf{3},\mathbf{2},\tfrac{1}{6}\right),\left(\bar{\mathbf{3}},\mathbf{2},\tfrac{5}{6}\right),\\
& \left(\bar{\mathbf{3}},\mathbf{2},-\tfrac{7}{6}\right),\left(\mathbf{3},\mathbf{3},-\tfrac{1}{3}\right),\left(\bar{\mathbf{3}},\mathbf{3},-\tfrac{2}{3}\right),\\
\text{color sextets :}\quad & \left(\bar{\mathbf{6}},\mathbf{1},-\tfrac{1}{3}\right),\left(\mathbf{6},\mathbf{1},-\tfrac{2}{3}\right),\left(\bar{\mathbf{6}},\mathbf{2},\tfrac{1}{6}\right),\left(\mathbf{6},\mathbf{2},\tfrac{5}{6}\right),\\
\text{color octets :}\quad & (\mathbf{8},\mathbf{1},0)\,,(\mathbf{8},\mathbf{1},1)\,,\left(\mathbf{8},\mathbf{2},\tfrac{1}{2}\right).
\end{aligned}$$

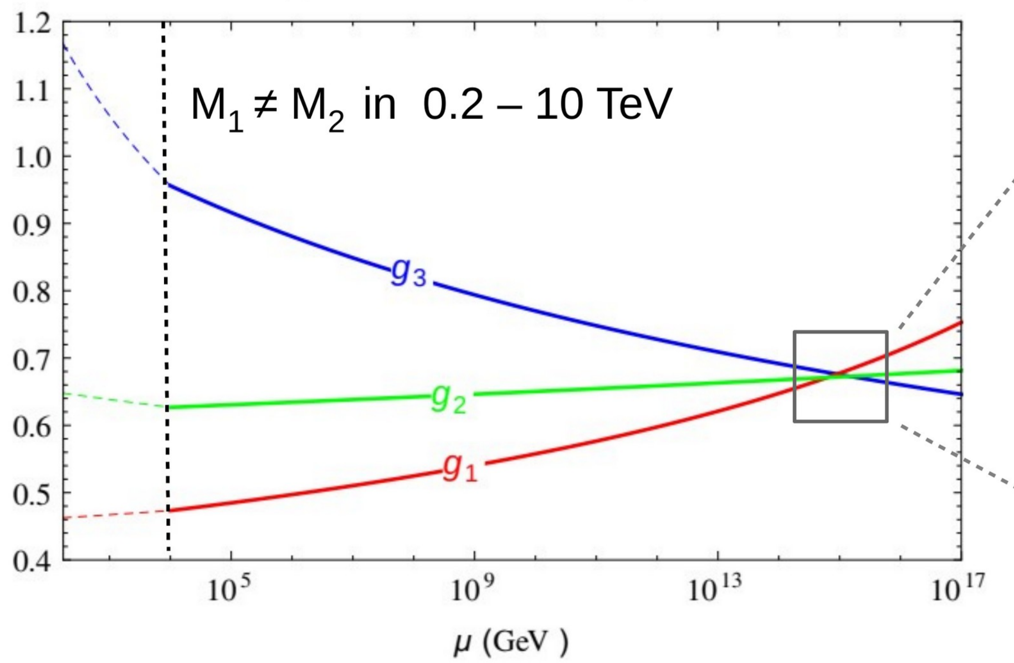
our fundamental building blocks

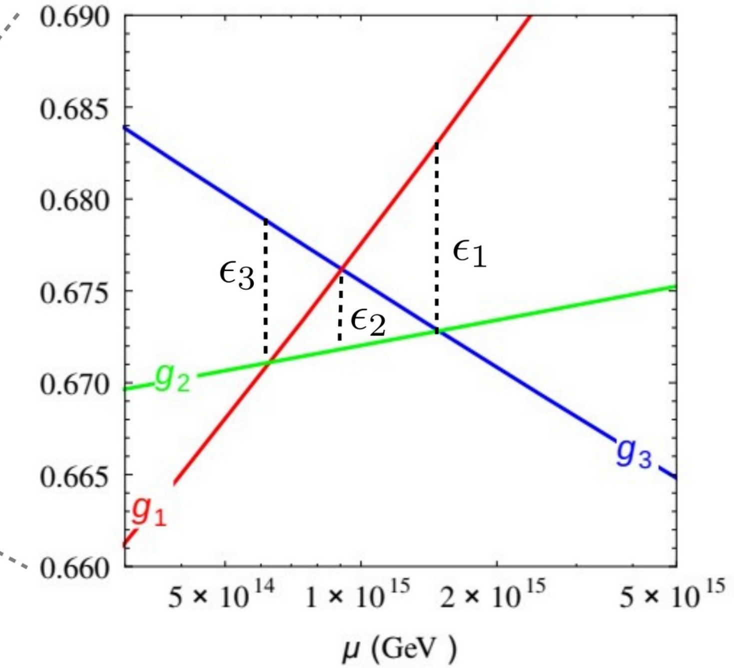
Analysis strategy

note: no unification with 1 VL rep. (see, ex. Bhattacherjee et al. *JHEP 05 (2018) 90)*

KK, D.Kumar, arXiv: 1910.00847

2 VL rep: $SM + N_1 \times VL(R_1) + N_2 \times VL(R_2)$





$$\epsilon_k = \frac{g_k^2(M_{\rm GUT}^{ij}) - g_{ij}^2}{g_{ij}^2}$$

precise gauge unification (PGU)

SM: ε=7%
MSSM: ε=1%

$$\epsilon \leq 1\%$$

$$\epsilon = \min(\epsilon_1, \epsilon_2, \epsilon_3)$$

goodness of unification

Summary of the results

Scenario	$\mathbf{R_{F_1}}$	$\mathbf{R_{F_2}}$	N_1	N_2
F1	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{6},\mathbf{1},\frac{1}{3})$	12	2
F2	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{6},\mathbf{1},\frac{1}{3})$	20	4
F3	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{6},\mathbf{1},\frac{1}{3})$	22	4
F4	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{8},\mathbf{1},0)$	8	1
F5	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{8},\mathbf{1},0)$	12	2
F6	$(\mathbf{1},\mathbf{2},\frac{1}{2})$	$(\mathbf{8},\mathbf{1},0)$	14	2
F7	$(\mathbf{1},\mathbf{3},0)$	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	2	8
F8	$(\mathbf{1},\mathbf{3},0)$	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	3	12
F9	$(\mathbf{1},\mathbf{3},0)$	$(\mathbf{6},\mathbf{1},-\frac{2}{3})$	3	2
F10	$(\mathbf{1},\mathbf{4},\frac{1}{2})$	$(\mathbf{6},\mathbf{1},-\frac{2}{3})$	2	4
F11	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	2	2
F12	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	4	4
F13	$(\mathbf{3},\mathbf{1},\frac{2}{3})$	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	6	6

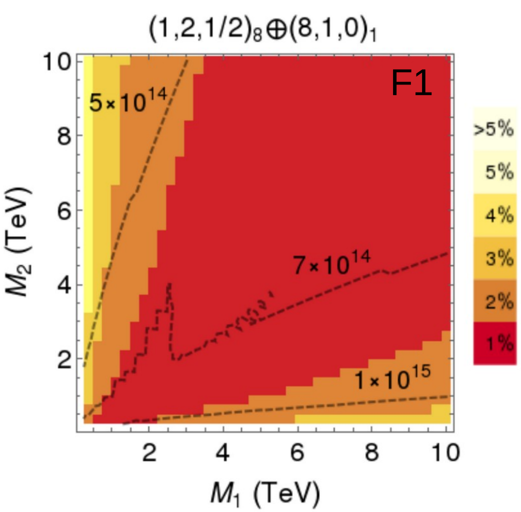
276 initial models

↓

7 PGU models

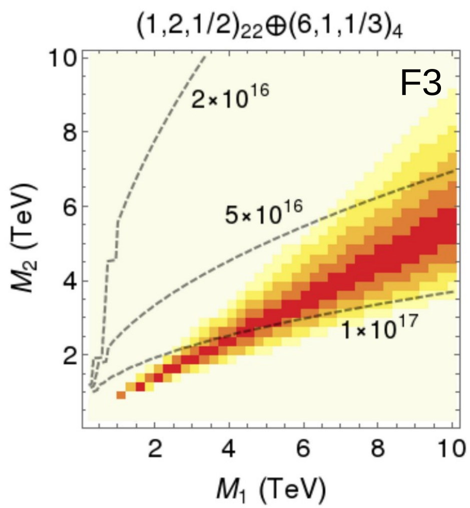
Probing the PGU models

unification scale



low

$$\mathrm{M_{GUT}} \simeq 10^{15}\ \mathrm{GeV}$$



moderate/high

$$\mathrm{M_{GUT}} \sim 10^{16} - 10^{17}\ \mathrm{GeV}$$

Scenario	$\mathbf{R_{F_1}}$	$\mathbf{R_{F_2}}$	N_1	N_2
~~F1~~	~~$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$~~	~~$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$~~	~~12~~	~~2~~
F2	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	20	4
F3	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	22	4
~~F4~~	~~$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$~~	~~$(\mathbf{8}, \mathbf{1}, 0)$~~	~~8~~	~~1~~
F5	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, 0)$	12	2
F6	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$(\mathbf{8}, \mathbf{1}, 0)$	14	2
F7	$(\mathbf{1}, \mathbf{3}, 0)$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	2	8
F8	$(\mathbf{1}, \mathbf{3}, 0)$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	3	12
~~F9~~	~~$(\mathbf{1}, \mathbf{3}, 0)$~~	~~$(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$~~	~~3~~	~~2~~
F10	$(\mathbf{1}, \mathbf{4}, \frac{1}{2})$	$(\mathbf{6}, \mathbf{1}, -\frac{2}{3})$	2	4
F11	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	2	2
F12	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	4	4
F13	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	6	6

SK (F1, F4)

HK (F9)

EXCLUDED

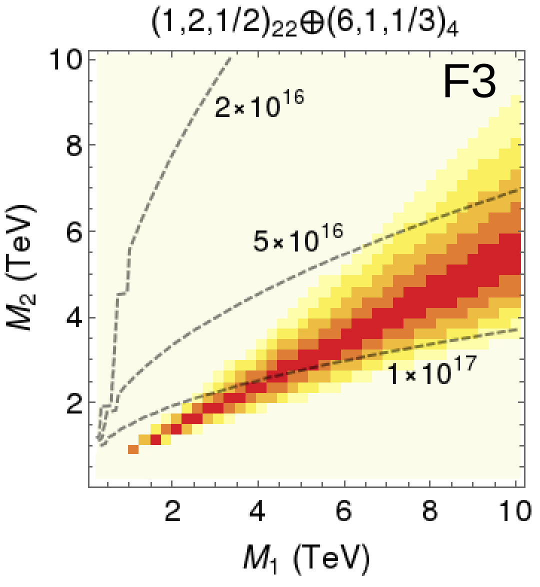
- unification possible for a wide range of masses
- excluded or to be excluded by the **proton decay** measurements at SK/HK

- compressed / hierarchical spectrum

$$\tau_p^{\mathrm{SK}} > 1.6 \times 10^{34}\ \mathrm{years} \qquad \tau_p^{\mathrm{HK}} > 2 \times 10^{35}\ \mathrm{years}$$

Probing the PGU models

unification scale



unification scale decreases when VL mass increases →

Model	Proton decay $M_1^{\max}$	$M_2^{\max}$
F1	Excluded	
F2	25	180
F3	350	200
F4	Excluded	
F5	10	50
F6	500	50
F7	20	100
F8	2×10^5	5×10^5
F9	Excluded HK	
F10	250	1000
F11	600	200
F12	6×10^4	400
F13	-	2×10^6

masses in TeV

$$\tau_p = \left(\frac{4\pi}{g_{\rm GUT}^2}\right)^2 \left(\frac{M_{\rm GUT}}{\rm GeV}\right)^4 \times 2.0 \times 10^{-32}$$

for g_{GUT}=0.7

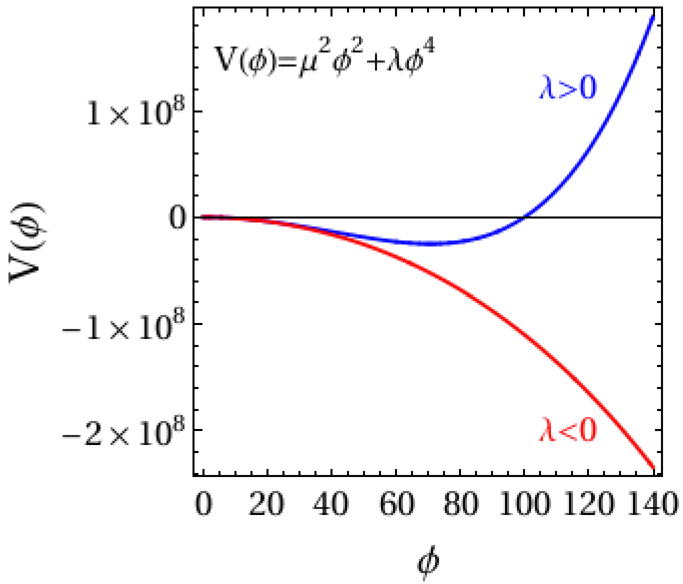
$$M_{\rm GUT} = 10^{15}\,{\rm GeV} \to \tau_p = 1.3 \times 10^{31}\ {\rm years}$$

$$M_{\rm GUT} = 10^{16}\,{\rm GeV} \to \tau_p = 1.3 \times 10^{35}\ {\rm years}$$

model-independent upper bounds on VL mass

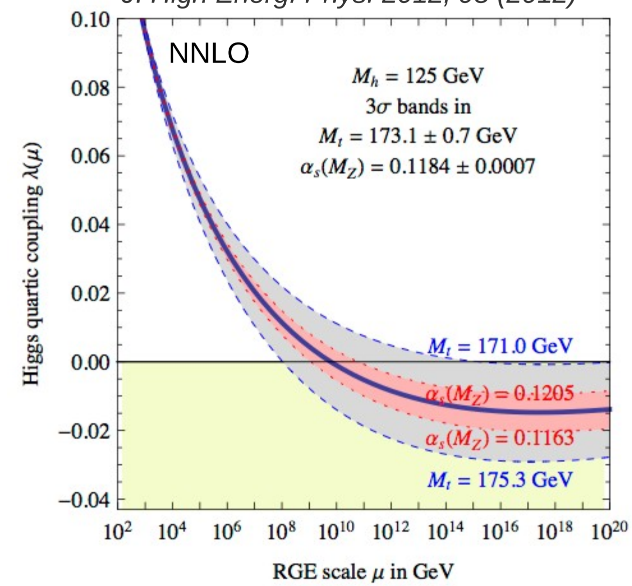
Vacuum stability

scalar potential must be bounded from below



In the Standard Model vacuum metastable

G. Degrassi, S. Di Vita, J. Elias-Miró, J. Espinosa, G. Giudice, G. Isidori, A. Strumia
J. High Energ. Phys. 2012, 98 (2012)



stability can be restored in BSM

ex. with VL fermions

Gopalakrishna, Velusamy, *PRD 99 (2019)*, Arsenault *et al. PRD 107 (2023)*, Hiller *et al. arXiv: 2401.08811, Adhikary et al. arXiv: 2406.16050…*
many more

Vacuum stability in PGUs

no BSM Yukawa interactions

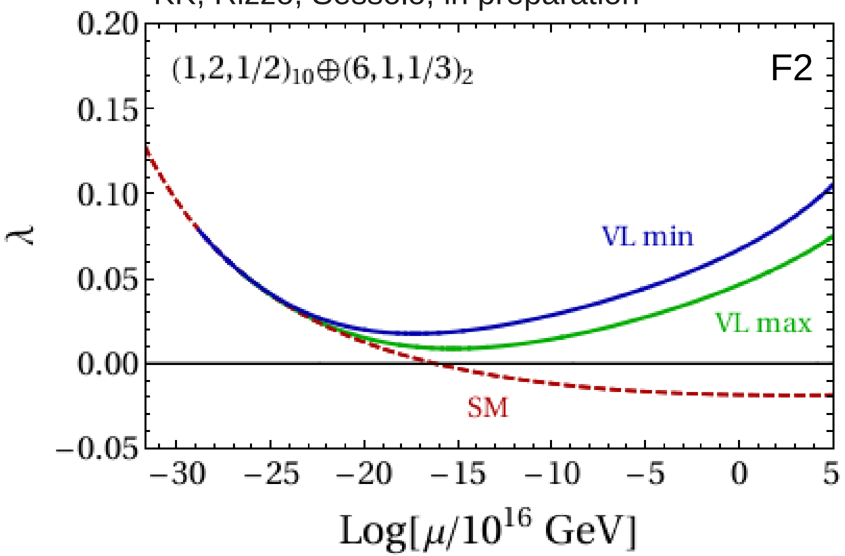
$$16\pi^2\,\beta(g_3) = g_3^3\left(-7+\frac{2}{3}N_F\,S_2(R_{F3})\,d(R_{F2})\right) \quad\rightarrow g_3 \nearrow$$

$$16\pi^2\,\beta(y_t) = y_t\left(\frac{9}{2}y_t^2-8g_3^2-\frac{9}{4}g_2^2-\frac{17}{12}g_Y^2\right) \quad\rightarrow y_t \searrow$$

$$16\pi^2\,\beta(\lambda) = 24\lambda^2+12\lambda\,y_t^2-6y_t^4+f(g_Y,g_2,\lambda) \quad\rightarrow \lambda \nearrow$$

vacuum gets stabilized

KK, Rizzo, Sessolo, in preparation



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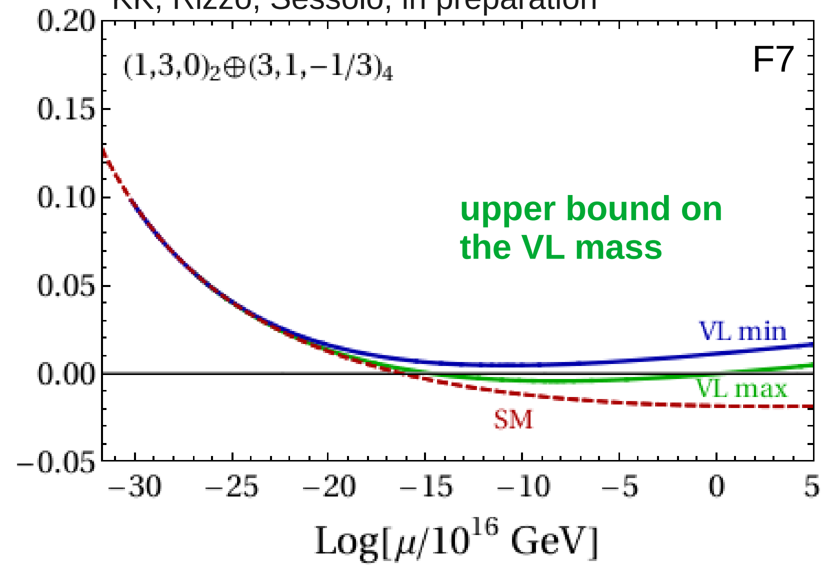

Vacuum stability in PGUs

with BSM Yukawa interactions

$$16\pi^2\,\beta(g_3) = g_3^3\left(-7+\frac{2}{3}N_F\,S_2(R_{F3})\,d(R_{F2})\right) \quad \rightarrow g_3 \nearrow$$

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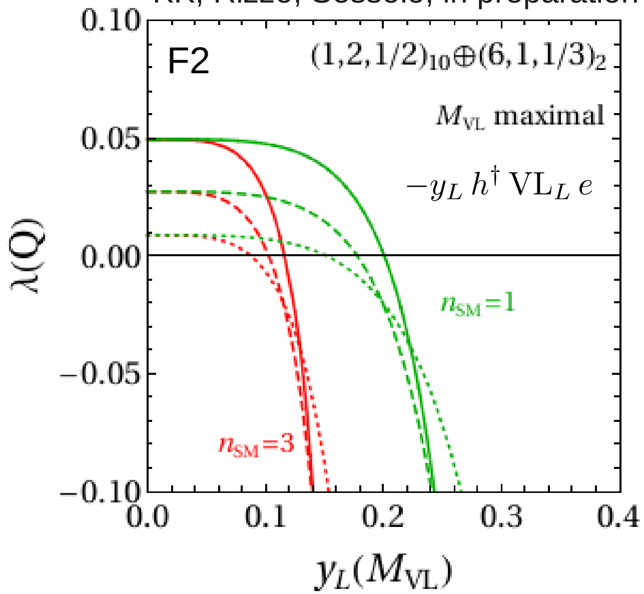
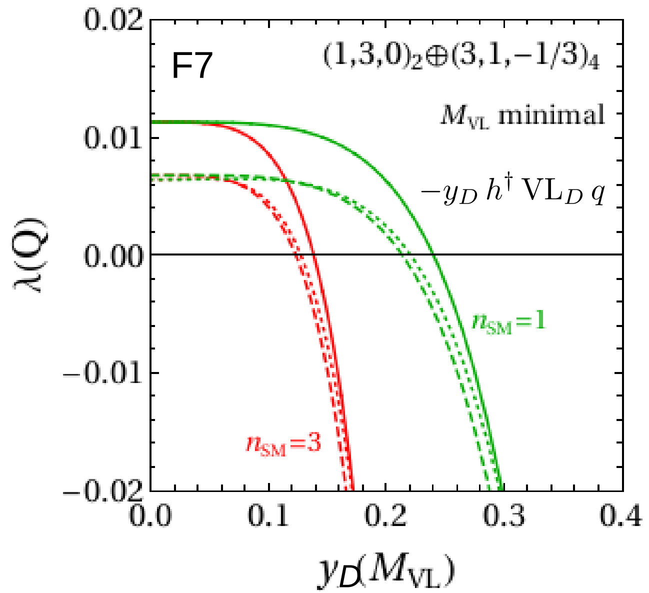
$$16\pi^2\,\beta(\lambda) = 24\lambda^2 + \frac{3}{8}g_Y^4 + C\,\lambda\,y_{\rm BSM}^2 - 6y_t^4 - B\,y_{\rm BSM}^4 + f(g_Y, g_2, \lambda) \quad \rightarrow \lambda \searrow$$

vacuum gets destabilized

KK, Rizzo, Sessolo, in preparation





Upper bound on the BSM Yukawa couplings

~ 0.1 - 0.3

cf. also Adhikary et al. *arXiv: 2406.16050*

Other scalars?

In SU(5): $\mathcal{L}_{\rm Yuk} = Y_d\, \mathbf{\bar{5}} \times \mathbf{10} \times \mathbf{\bar{5}_H} + Y_u\, \mathbf{10} \times \mathbf{10} \times \mathbf{5_H}$ { Higgs doublet, color triplet }

Scalars can emerge naturally in GUTs

see also
M. Malinsky talk

- **SU(5)**

$\mathbf{24},\ \mathbf{75} \supset (\mathbf{1},\mathbf{1})_\mathbf{0}$ → **singlet S**

- **SU(6)** **(and larger)**

$\mathcal{L}_{\rm Yuk} = Y_{15}\, \mathbf{15} \times \mathbf{15} \times \mathbf{15}^{H_1} + Y_6\, \mathbf{15} \times \mathbf{\bar{6}} \times \mathbf{\bar{6}}^{H_2}$ → **2HDM**

$SU(6) \to SU(5) \times U(1)_5$

$\mathbf{6} = \mathbf{1}_{-\mathbf{5}} + \mathbf{5}_\mathbf{1}$ → **singlet S + U(1)’**

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Complementary signals with scalars?

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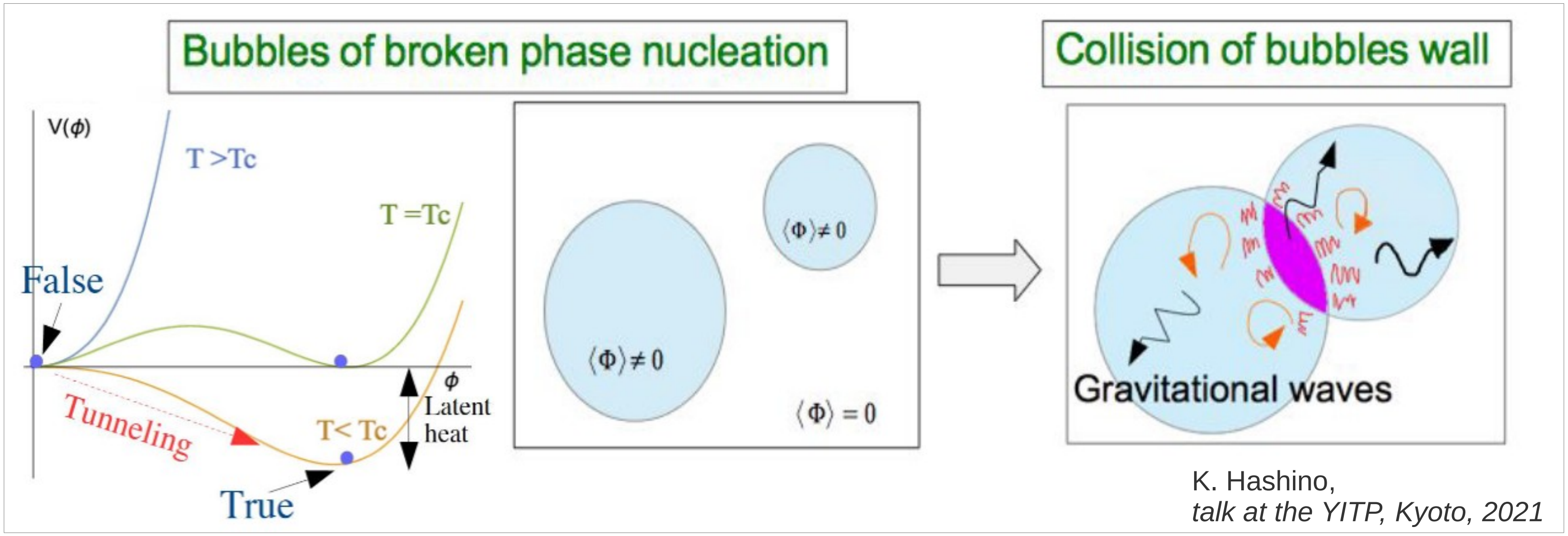
Complementary signals with scalars?

First order phase transition... Gravitational waves...

Gravitational waves from FOPT



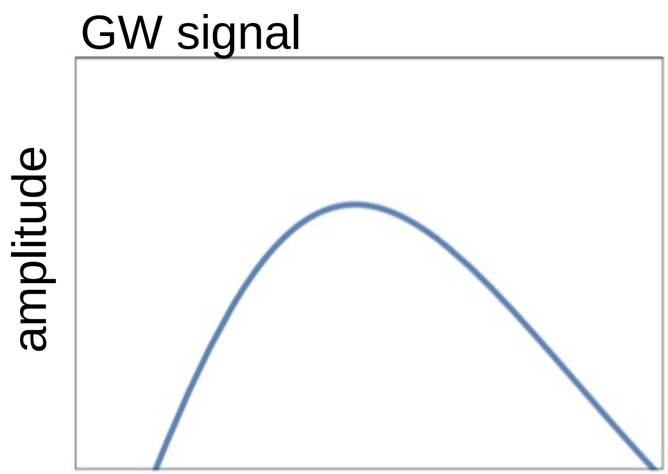
K. Hashino,
talk at the YITP, Kyoto, 2021

see talk by
M. Merchand

later today:
talks by Z.Wang,
J.Kersten, S.King

Latent heat α

Nucleation speed β/H*



← < ϕ vev > →

Linde '81, '83, Turner *et al.* '92-'94; Guth *et al.* '80, '81, Caprini *et al.* '07-'09, Hindmarsh *et al.* '13-'17, Ellis *et al.* '18 … many more

Gravitational waves from FOPT

Singlet scalar + $U(1)_X$

Ellis *et al. JCAP 06 (2019),* Jinno, Takimoto *PRD 95 (2017),* Okada, Seto *PRD 98 (2018),* Marzo *et al. EPJC 79 (2019),* Hasegawa *et al. PRD 99 (2019),* Haba, Yamada *PRD 101 (2020)…* many more

known example: clasically scale inv. SM + $U(1)_{B-L}$

$$V(H,S) = \lambda_1 \left(H^\dagger H\right)^2 + \lambda_2 \left(S^\dagger S\right)^2 + \lambda_3 \left(H^\dagger H\right)\left(S^\dagger S\right)$$

symmetry breaking through CW:

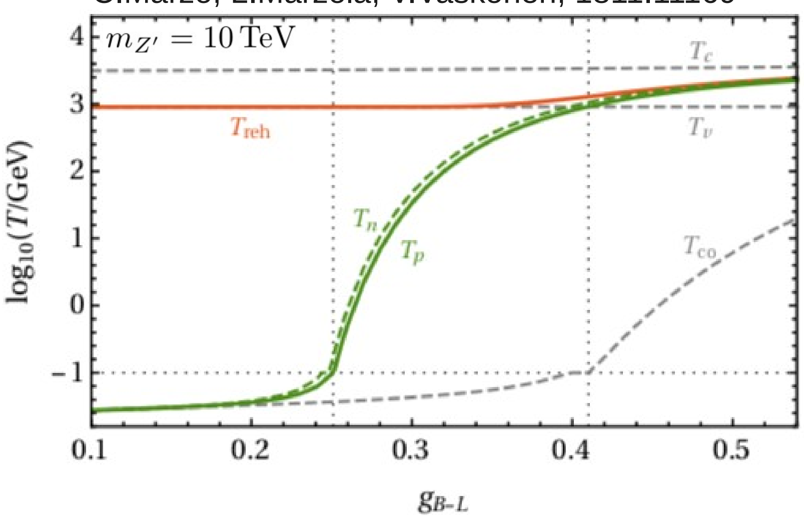
$$V(\phi) = \frac{1}{4}\lambda_2(t)\,\phi^4 + \frac{1}{128\,\pi^2}\left[20\lambda_2^2(t) + 96\,g_X^4(t)\right]\phi^4\left(-\frac{25}{6} + \ln\frac{\phi^2}{\mu^2}\right)$$

$$Q_S = 2, \quad \phi = \sqrt{2}Re(S)$$

strenght of the GW signal given by g_X …

(simplified model)

C.Marzo, L.Marzola, V.Vaskonen, 1811.11169



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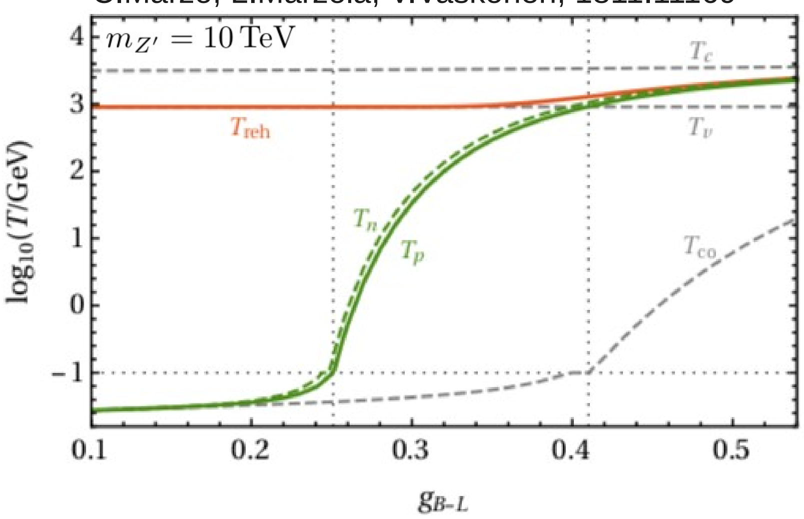

pros: may be washed out by the Yukawas

- nucleation/percolation temp. below QCD
- FOPT stop conition not satisfied

→ **upper bound on Yukawas**

cons: may be difficult to get in a UV-complete model

- too small g$_X$ predicted

ex. QG driven asymptotic safety

A. Chikkaballi, KK. E. Sessolo *JHEP 11 (2023) 224*

Gravitational waves from FOPT

Singlet scalar + U(1)$_X$

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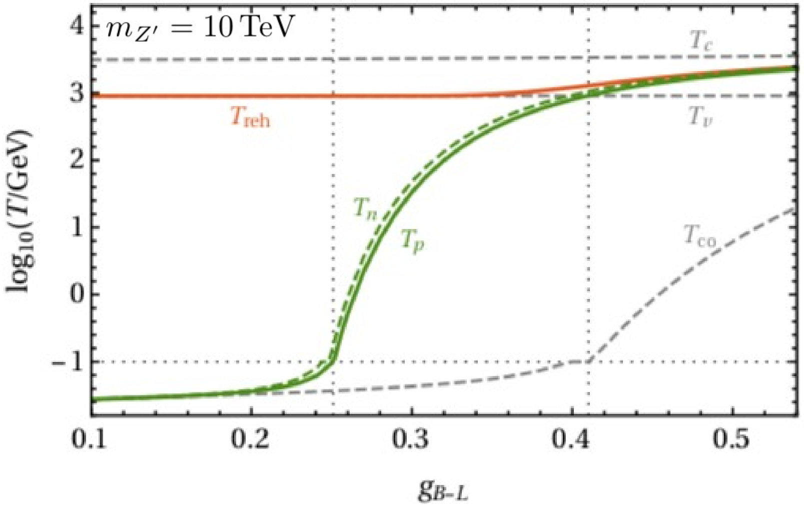
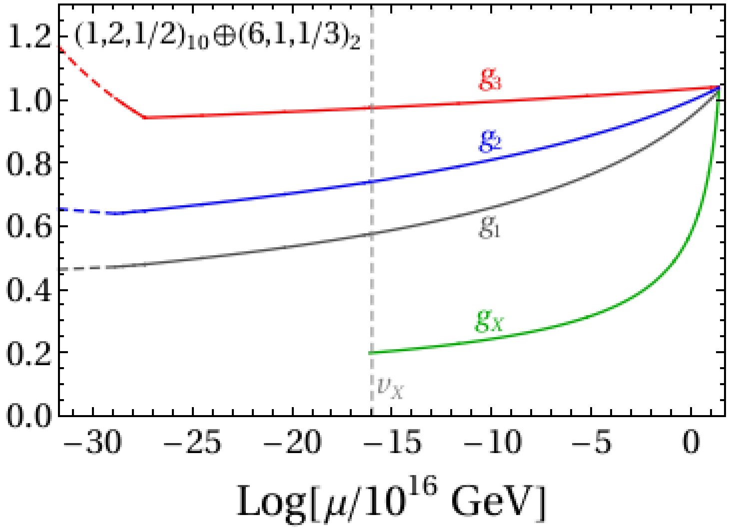


What about our GUT-inspired models?

PGU models with an extra U(1)

$$\sim y_{BSM}\, S\, F_{\rm VL}\, F_{\rm SM}$$

KK, Rizzo, Sessolo, in preparation



unification condition fixes g_X at every scale…

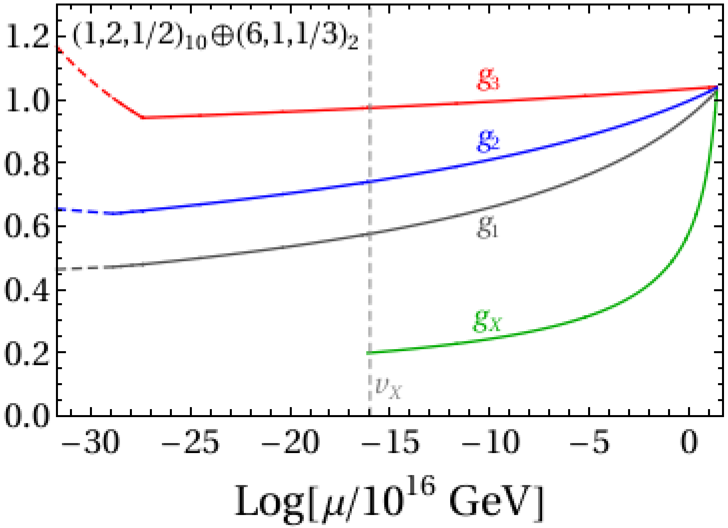
… too small for the FOPT to proceed

unlike the simplified model, no FOPT here

PGU models with an extra U(1)

$\sim y_{BSM}\, S\, F_{\rm VL}\, F_{\rm SM}$

KK, Rizzo, Sessolo, in preparation

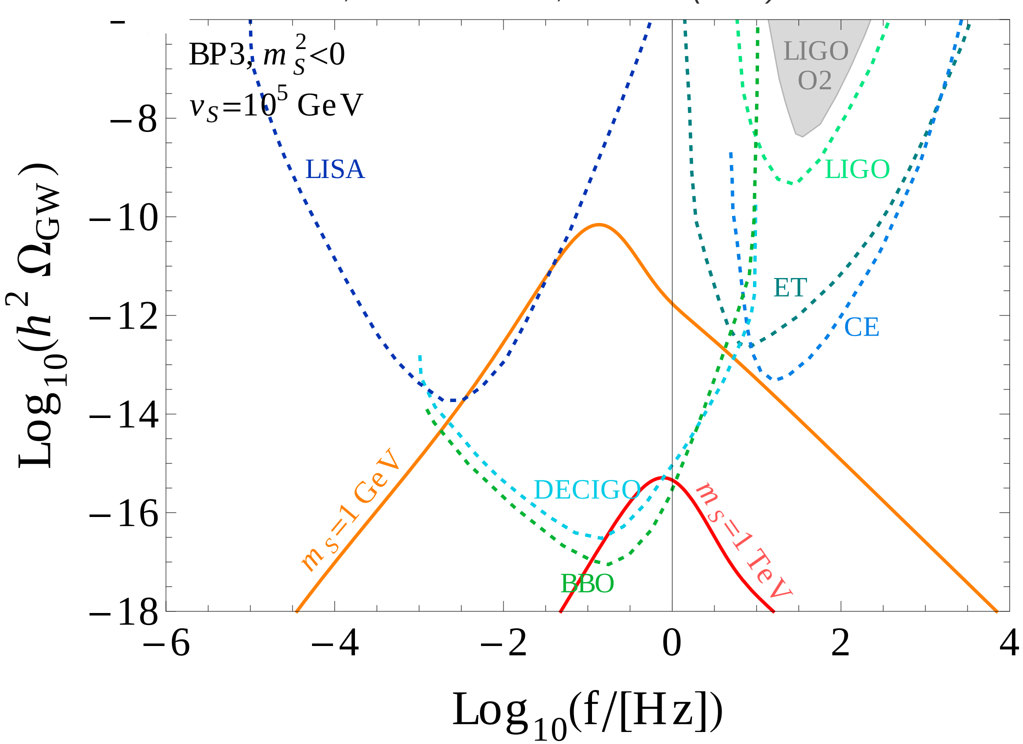


unification condition fixes g_X at every scale…

… too small for the FOPT to proceed

… unless mass term is allowed

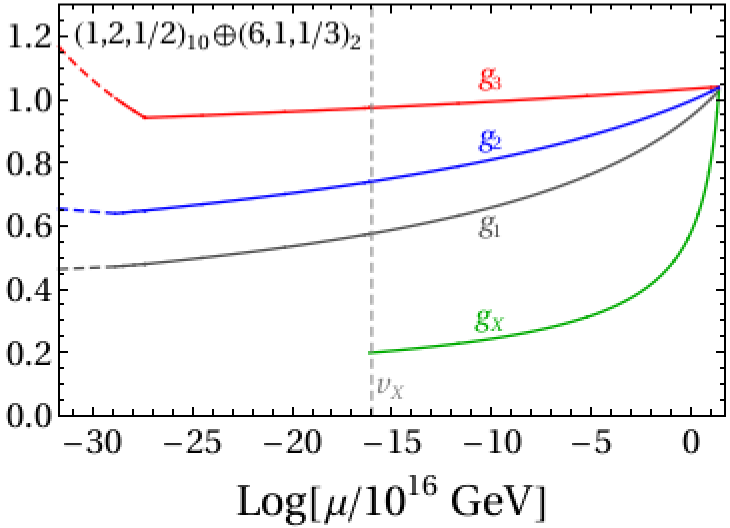
A. Chikkaballi, KK. E. Sessolo, *JHEP 11 (2023) 224*



PGU models with an extra U(1)

$\sim y_{BSM}\, S\, F_{\mathrm{VL}}\, F_{\mathrm{SM}}$

KK, Rizzo, Sessolo, in preparation



unification condition fixes g_X at every scale…

… too small for the FOPT to proceed

… unless mass term is allowed

OTHER SCALARS

2HDM

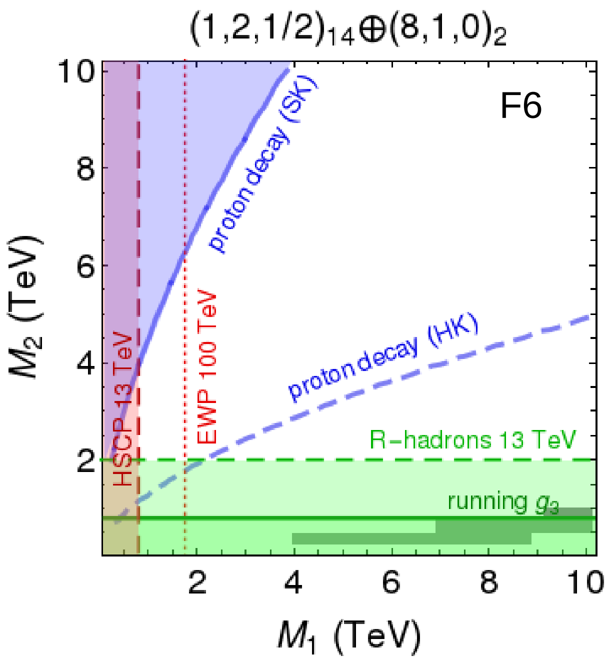
P. Basler, M.Krause, M.Mühlleitner, J.Wittbrodt, A.Wlotzka, *JHEP 02 (2017) 121*

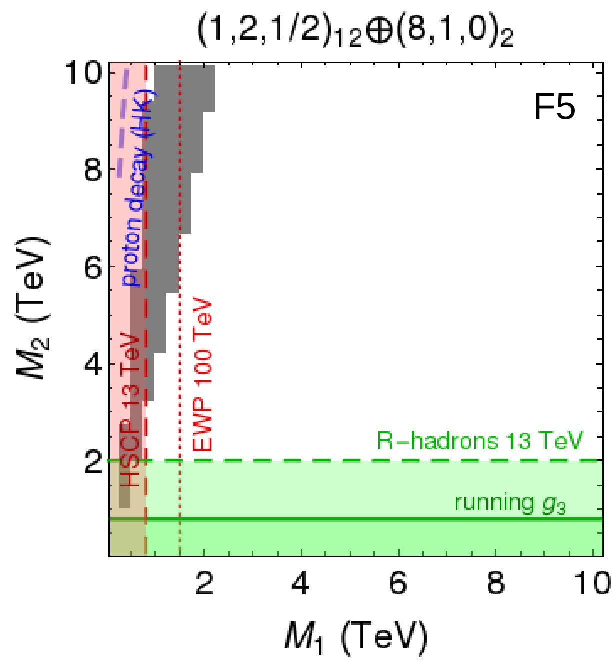
DOES UV GUTs ALSO HAVE A GW SIGNAL?

Conclusions

- Only a few models with VL fermions allow for precise gauge coupling unifcation.
- Upper bounds on VL masses from proton decay.
- Upper bounds on the BSM Yukawa couplings from the EW vacuum stability.
- Gravitational wave signal in scenarios with a singlet scalar and extra gauge $U(1)_X$ with mass only.
- Things to do: FOPTs and GWs in the scenarios with non-singlet scalar representations.

Backup





- almost exluded by running coupling
- to be probed by R-hadrons

- to be probed by the EWP tests
- to be probed by the HSCP searches