

SUSY now or never



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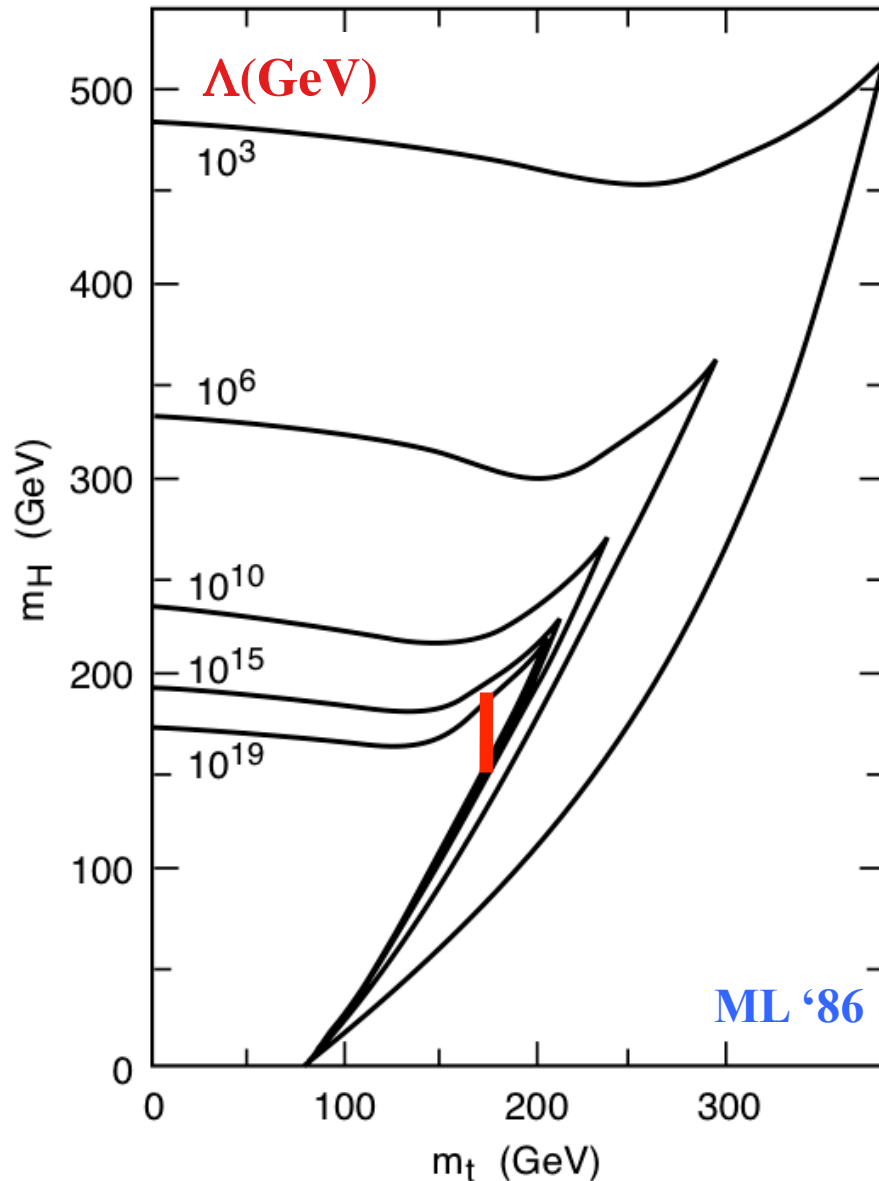


- **J. Kopp, ML, V. Niro, T. Underwood, arxiv:0909.2653**
- **M. Holthausen, ML, M. Schmidt, arxiv:0911.0710**



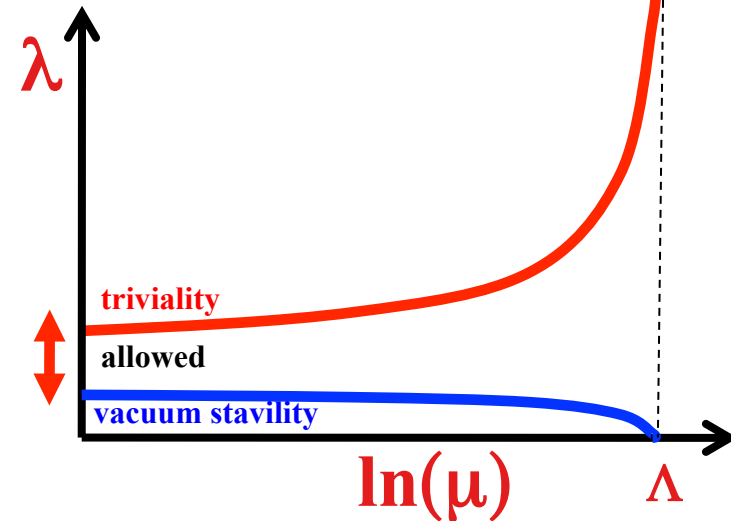
**BEYOND 2010 – 5th Int. Conference on Beyond the Standard Models of Particle Physics,
Cosmology and Astrophysics, Feb- 1-6, 2010 — Cape Town, South Africa**

Why we must extend the SM: Triviality



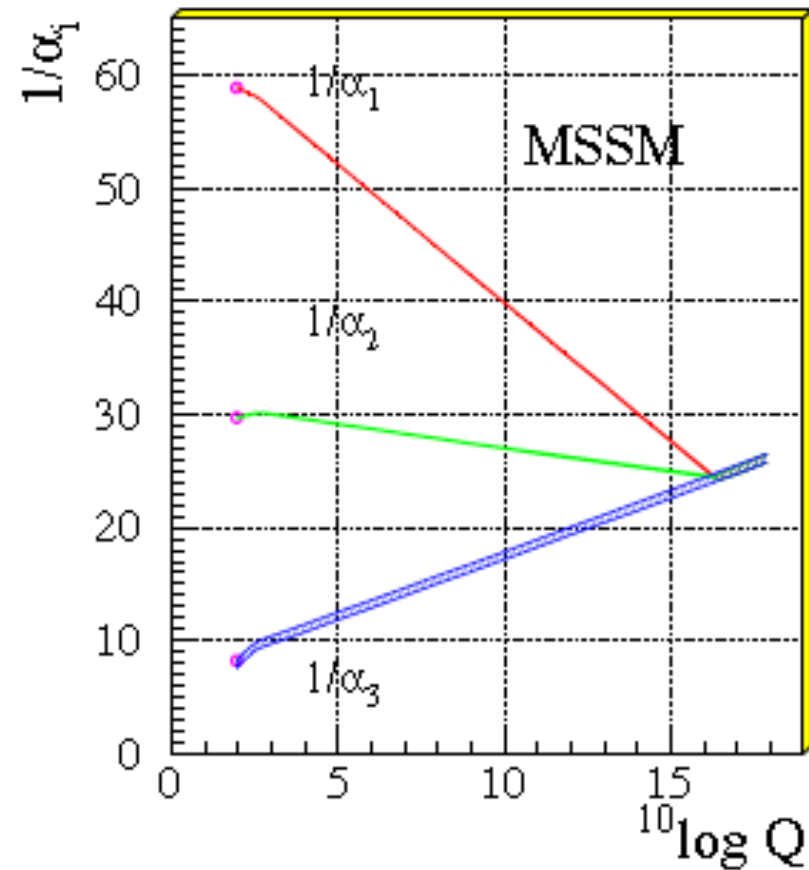
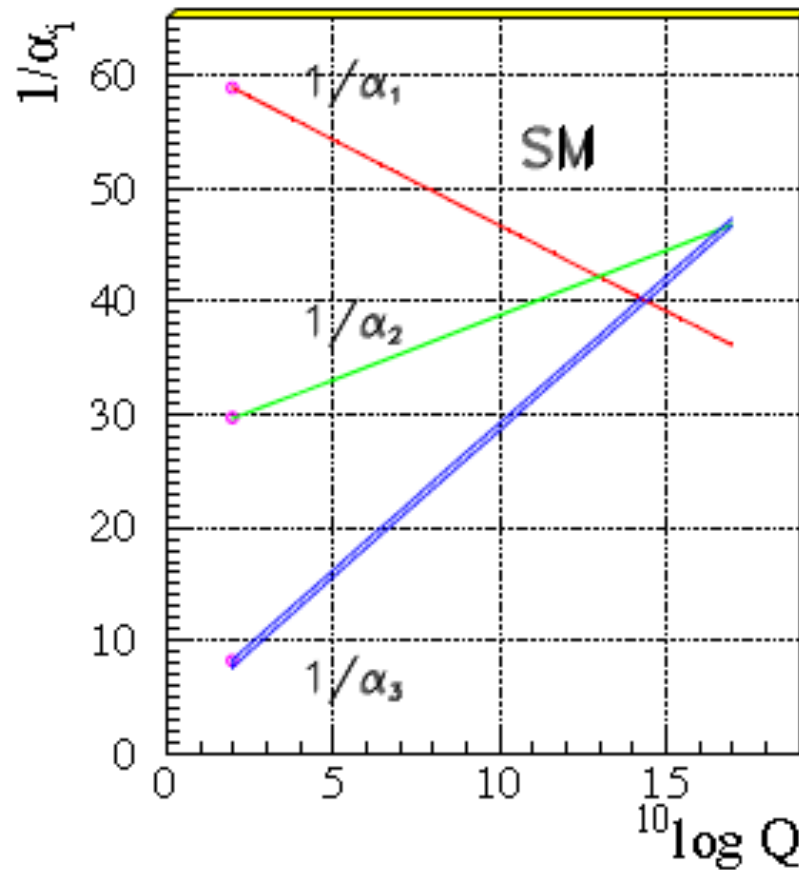
$$125 \text{ GeV} < m_H < 174 \text{ GeV}$$

SM does not exist w/o embedding
 - U(1) coupling, Higgs self-coupling



→ RGE arguments seem to work
 → we need an embedding

Weak Scale SUSY works very good



SM: couplings do not unify

MSSM: perfect! → luck? → other models?

EW Symmetry Breaking Options

EW symmetry breaking scenarios:

- **Just SM up to high scale** → **hierarchy problems unsolved**
 - a) why is $v = 246 \text{ GeV} \ll M_{\text{Planck}} = 10^{19} \text{ GeV}$?
 - b) how can $v \ll M_{\text{planck}}$ be stabilized ?
- **Dynamical symmetry breaking** → **~ effective Higgs**
- **Protective symmetry** → **Supersymmetry**

→ new Physics in TeV range...
→ LHC will see new physics
... but what if not?

alternative scenarios:
→ SUSY later
→ other protective symmetry

Alternative Routes

- What the LHC could find beyond what is known...
 - nothing \rightarrow unitarity violation! \leftrightarrow hidden stuff
 - just a SM Higgs!
 - extension w/o immediate solution of the hierarchy problem
 - ...
- \rightarrow gauge extensions which are super-symmetrized later
 - e.g. left-right symmetric extensions
 - add SUSY at Λ_{LR} or close by \rightarrow ... to avoid hierarchies...
 - scenarios where one scalar (=SM Higgs) is lighter
 - unification should occur
 - \rightarrow above proton decay scale $\tau_p \sim \frac{M_{GUT}^4}{m_p^5}$
 - \rightarrow below or at M_{Pl} – unification at M_{Pl} would be even nice...

Left-Right Extensions

all quarks
and leptons
fit nicely into
L, R doublets

$$Q(3, 2, 1, \frac{1}{3}) = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$Q^c(3^*, 1, 2, -\frac{1}{3}) = \begin{pmatrix} d^c \\ -u^c \end{pmatrix}$$

$$L(1, 2, 1, -1) = \begin{pmatrix} \nu_e \\ e \end{pmatrix}$$

$$L^c(1, 1, 2, 1) = \begin{pmatrix} e \\ -\nu_e \end{pmatrix}$$

symmetry breaking $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{LR}} U(1)_Y$

nice: U(1) carries B-L charge

scalars for SB: $\Delta(1, 3, 1, 2)$ and $\Delta^c(1, 1, 3, -2)$

$$\Phi(1, 2, 2, 0)$$

→ non-SUSY LR model with triplets

add SUSY

$$\bar{\Delta}(1, 3, 1, -2)$$

$$\text{and } \bar{\Delta}^c(1, 1, 3, 2)$$

→ superfields

$$\Phi_1 \text{ and } \Phi_2$$

R-parity cons.

$$S(1, 1, 1, 0)$$

→ minimal SUSY LR model

Other Models

**S replaced
by triplets**

$$\Omega(1, 3, 1, 0) \quad \text{and} \quad \Omega^c(1, 1, 3, 0)$$

→ non-minimal SUSY LR model with triplets

→ staged SB $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{LR}} U(1)_R \times U(1)_{B-L} \xrightarrow{M_{B-L}} U(1)_Y$

Pati-Salam group

$$SU(2)_L \times SU(2)_R \times SU(4)$$

→ SUSY Pati-Salam model

$$\xrightarrow{M_{PS}} SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$\xrightarrow{M_{LR}} SU(3)_c \times SU(2)_L \times U(1)_Y,$$

**matter
Higgses**

$$\begin{array}{ll} \psi(2, 1, 4) & \text{and} \quad \psi^c(1, 2, 4^*) \\ \Phi(2, 2, 1) & \text{and} \quad \Phi(2, 2, 15) \end{array}$$

RGEs

$$16\pi^2 \frac{dg_i(t)}{dt} = b_i [g_i(t)]^3 \rightarrow \alpha_i^{-1}(t) = \alpha_i^{-1}(t_0) - \frac{1}{2\pi} b_i (t - t_0)$$

$$b_i = \sum_R s(R) T_i(R) - \frac{11}{3} C_{2i}. \quad (\text{non-SUSY models})$$

$$b_i = \sum_R T_i(R) - 3 C_{2i}. \quad (\text{SUSY models})$$

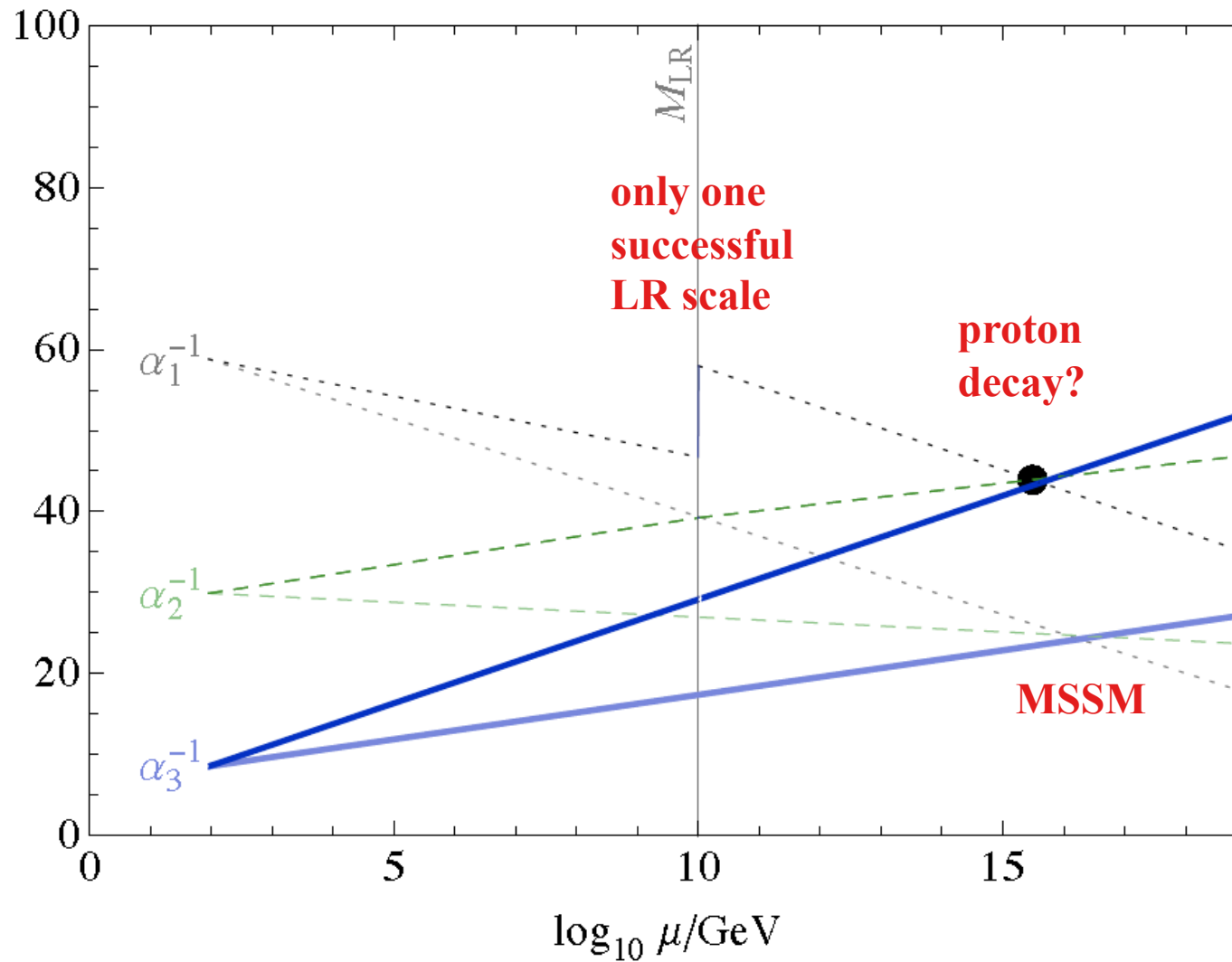
1-loop, no thresholds, no detailed spectrum

GUT - U(1) normalization: SM, MSSM \rightarrow GUT = 20/3 LR=8/3

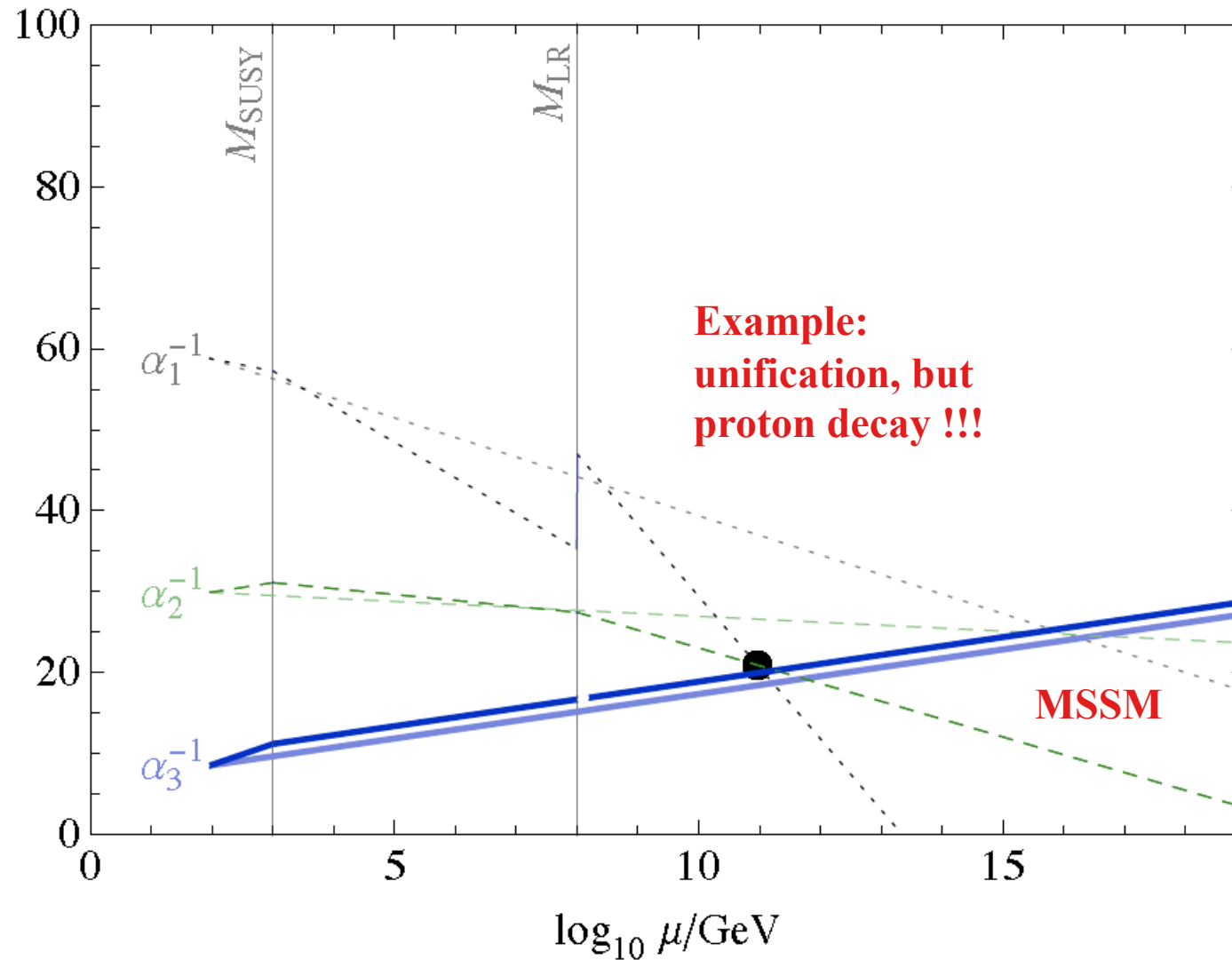
\rightarrow matching at LR-scale

$$\alpha_{1,\text{LR}}(M_{\text{LR}}) = \frac{2}{5} \frac{\alpha_{1,\text{SM}}(M_{\text{LR}}) \alpha_2(M_{\text{LR}})}{\alpha_2(M_{\text{LR}}) - \frac{3}{5} \alpha_{1,\text{SM}}(M_{\text{LR}})}$$

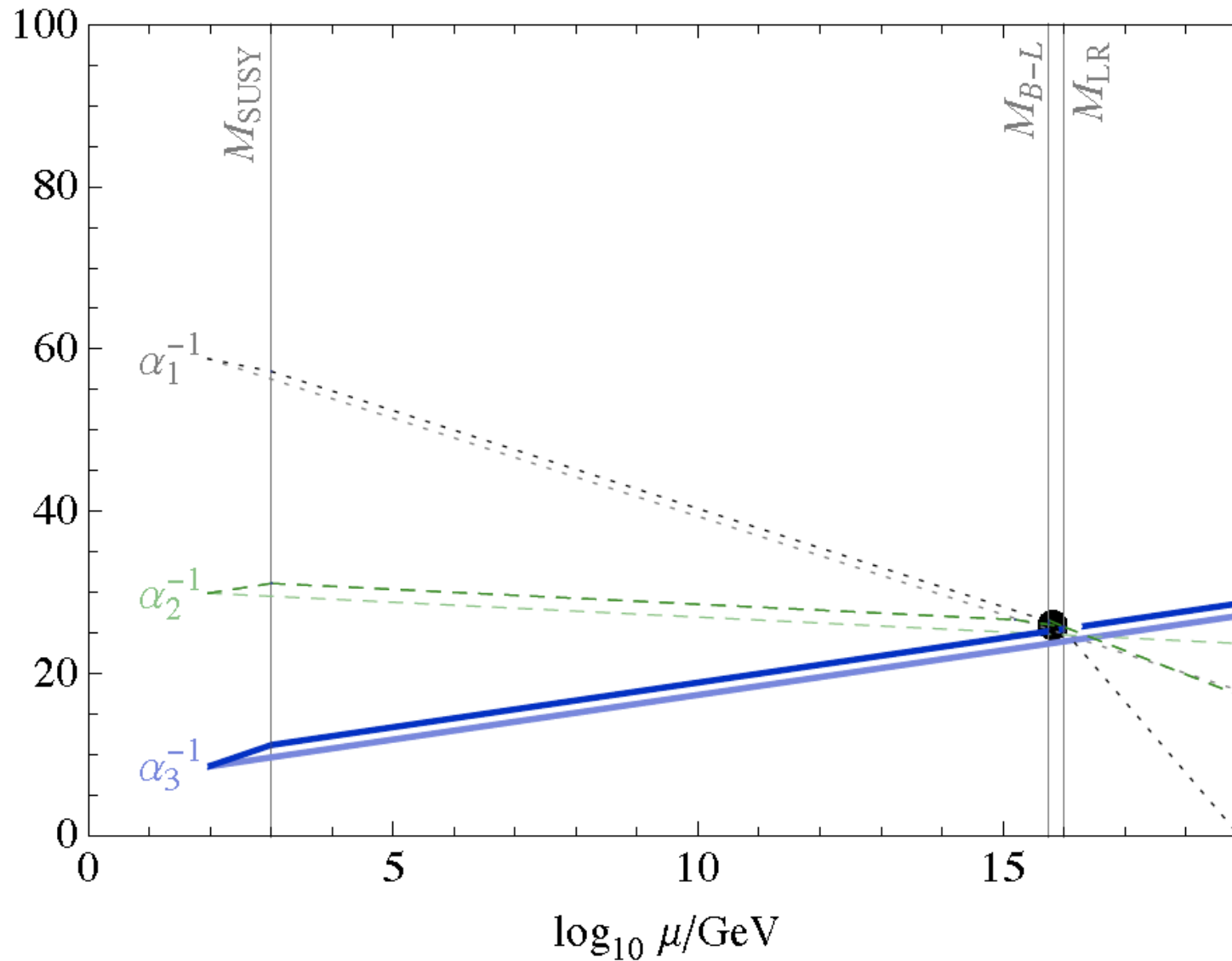
Non-SUSY LR model with Higgs Triplets



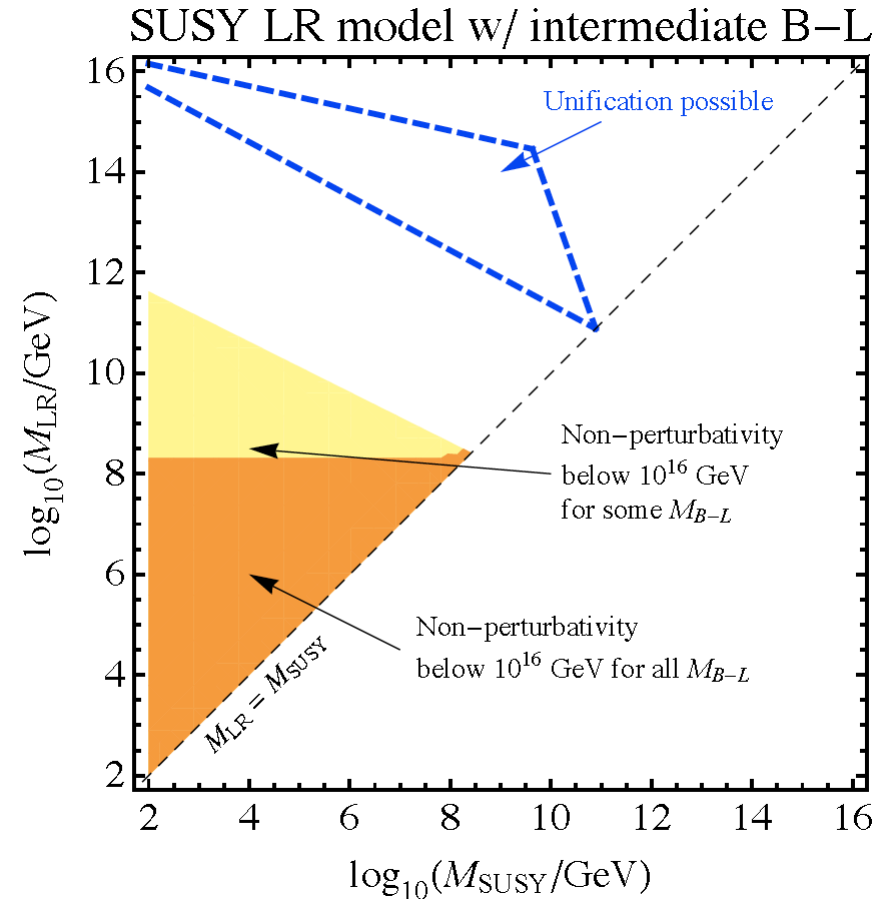
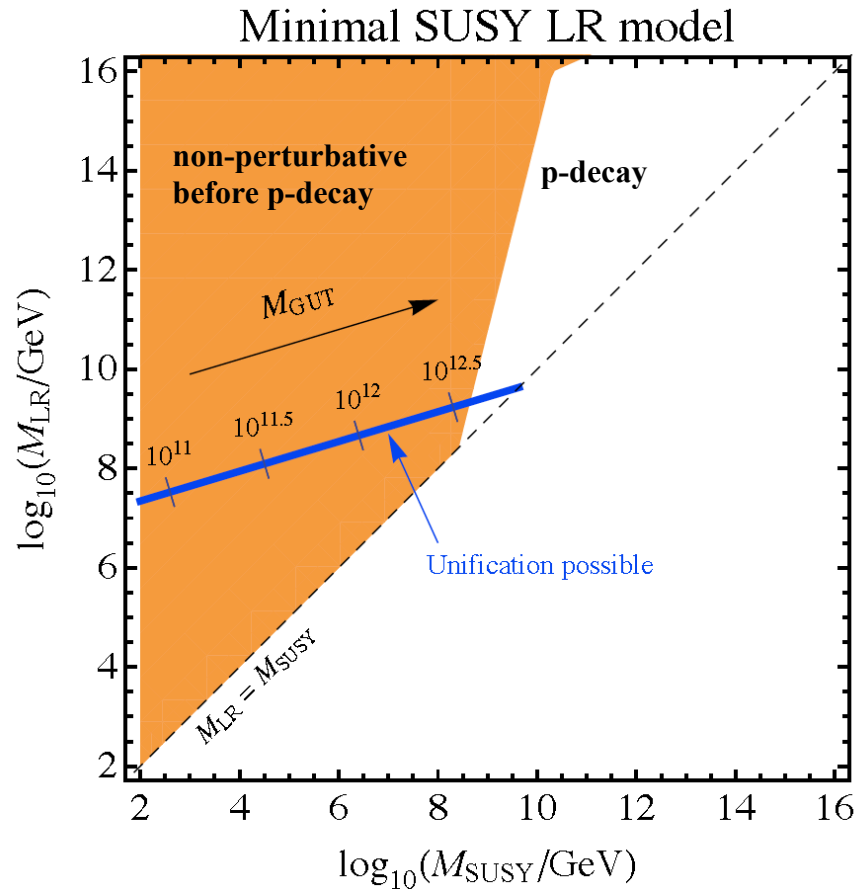
Minimal SUSY-LR MModel



SUSY-LR Model with intermediate B-L



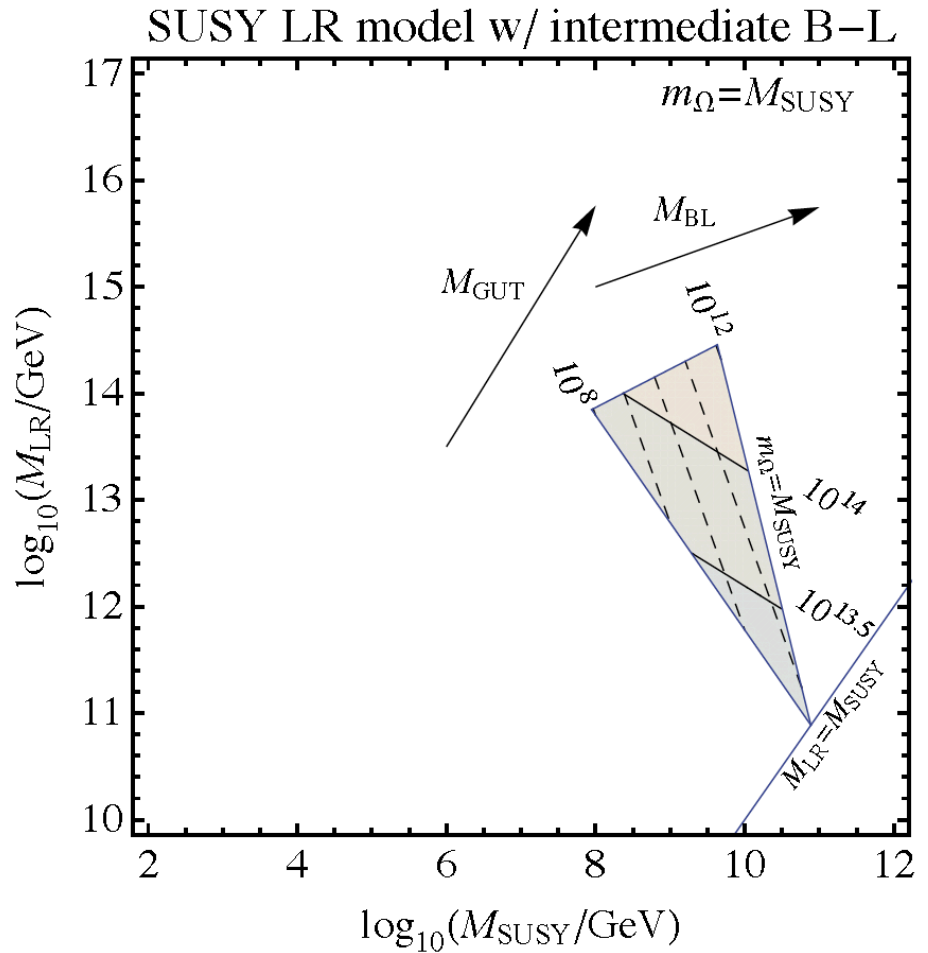
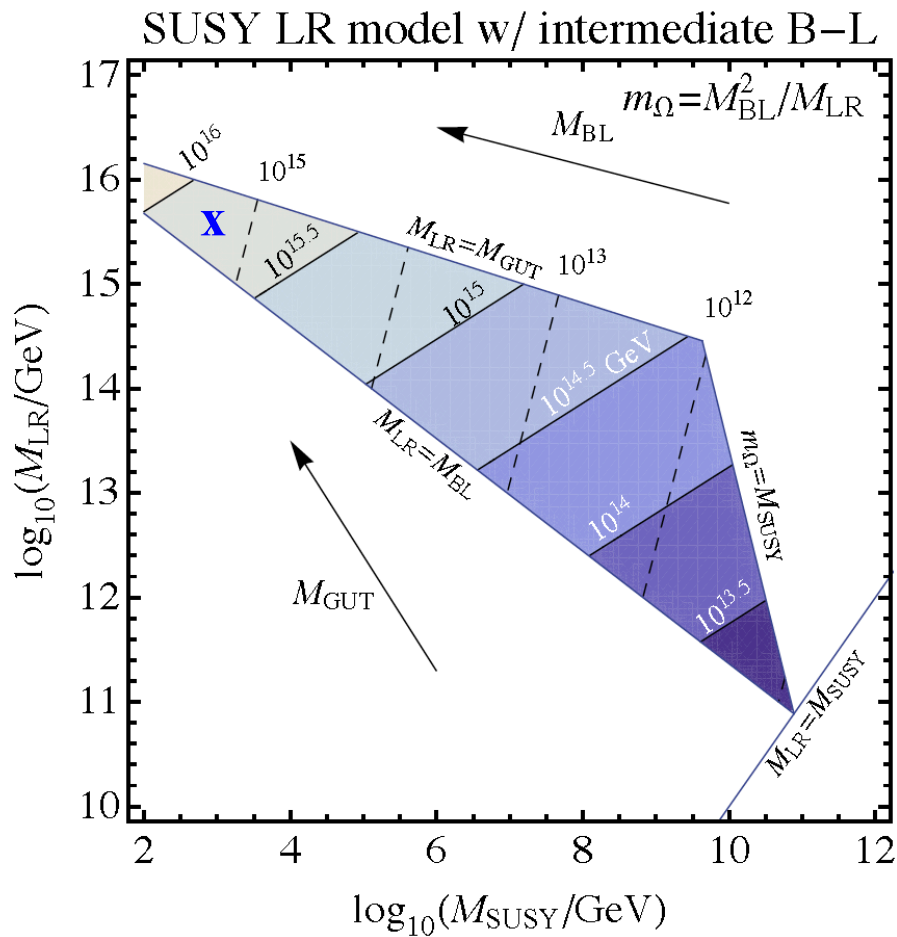
Coupling Unification & Perturbativity



➔ no low scale solutions

➔ solutions: MSSM + intermediate B-L + late LR extension

GUT scale (solid lines) and B-L breaking scale (dashed)



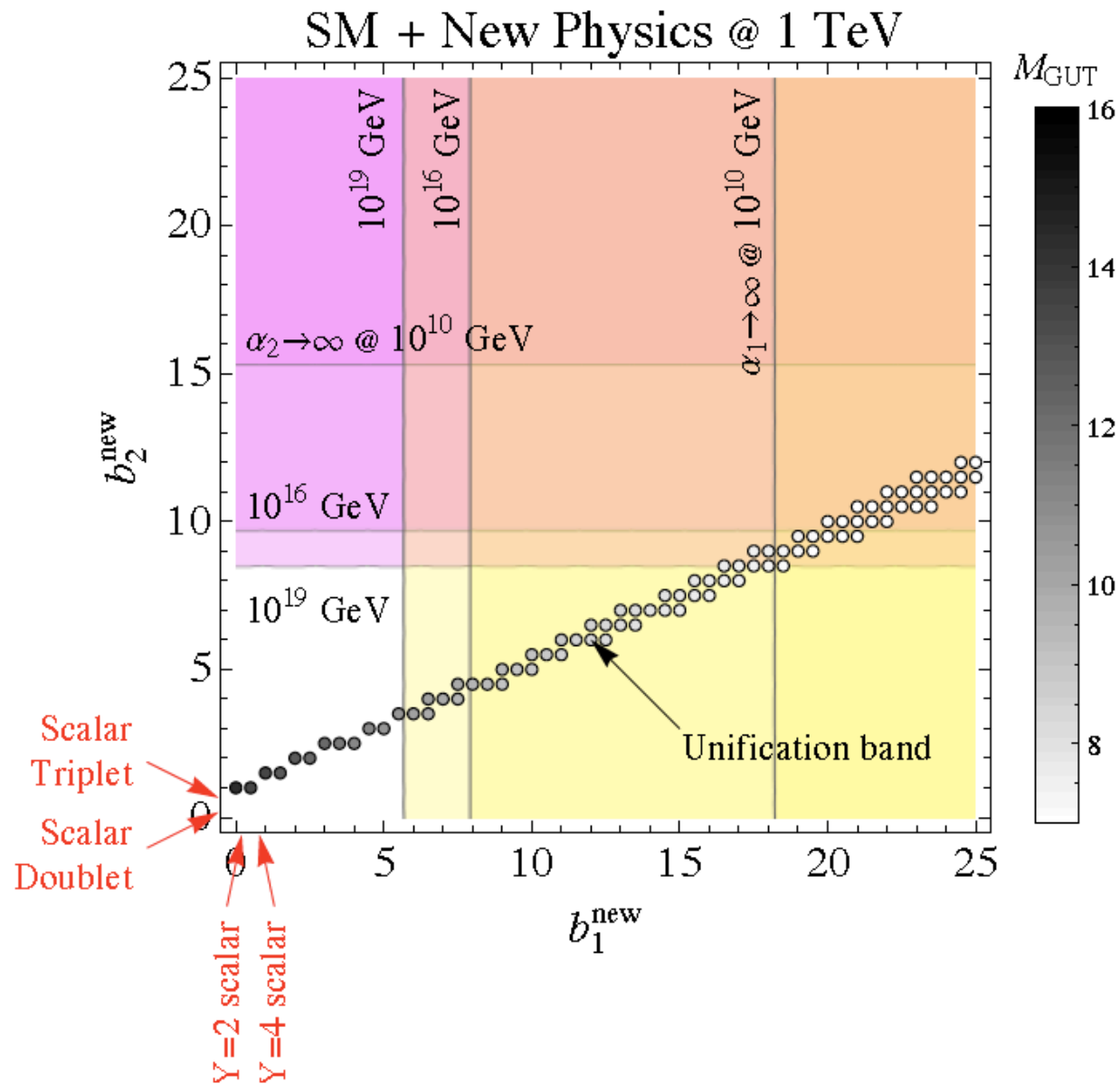
proton decay \rightarrow only high scales \rightarrow low SUSY scale and high LR scale

Contributions of arbitrary new Particles

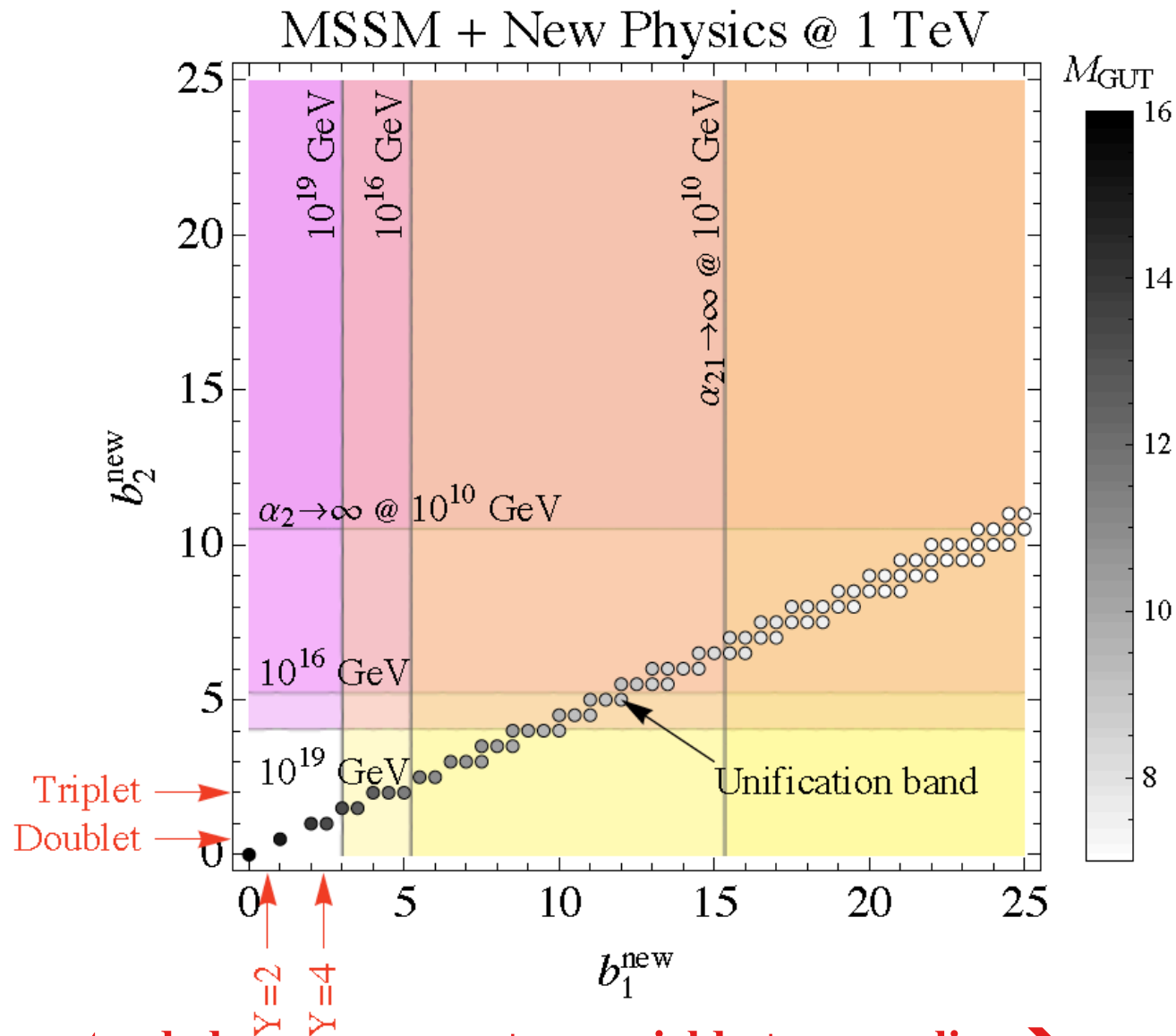
MSSM rep.	b_1^{new}	b_2^{new}	b_3^{new}				
(Y, 1, 1)	$0.15Y^2$	0	0	(Y, 1, 6)	$0.9Y^2$	0	2.5
(Y, 2, 1)	$0.3Y^2$	0.5	0	(Y, 2, 6)	$1.8Y^2$	3	5
(Y, 3, 1)	$0.45Y^2$	2	0	(Y, 3, 6)	$2.7Y^2$	12	7.5
(Y, 4, 1)	$0.6Y^2$	5	0	(Y, 4, 6)	$3.6Y^2$	30	10
(Y, 5, 1)	$0.75Y^2$	10	0	(Y, 5, 6)	$4.5Y^2$	60	12.5
(Y, 6, 1)	$0.9Y^2$	17.5	0	(Y, 6, 6)	$5.4Y^2$	105	15
(Y, 7, 1)	$1.05Y^2$	28	0	(Y, 7, 6)	$6.3Y^2$	168	17.5
(Y, 1, 3)	$0.45Y^2$	0	0.5	(Y, 1, 8)	$1.2Y^2$	0	3
(Y, 2, 3)	$0.9Y^2$	1.5	1	(Y, 2, 8)	$2.4Y^2$	4	6
(Y, 3, 3)	$1.35Y^2$	6	1.5	(Y, 3, 8)	$3.6Y^2$	16	9
(Y, 4, 3)	$1.8Y^2$	15	2	(Y, 4, 8)	$4.8Y^2$	40	12
(Y, 5, 3)	$2.25Y^2$	30	2.5	(Y, 5, 8)	$6Y^2$	80	15
(Y, 6, 3)	$2.7Y^2$	52.5	3	(Y, 6, 8)	$7.2Y^2$	140	18
(Y, 7, 3)	$3.15Y^2$	84	3.5	(Y, 7, 8)	$8.4Y^2$	224	21

- numbers for chiral super fields → non-SUSY x1/3 or x2/3 for scalars/fermions
- b_1 includes GUT normalization factor 3/20
- new physics at 1 TeV

Perturbativity & Unification w/o SUSY



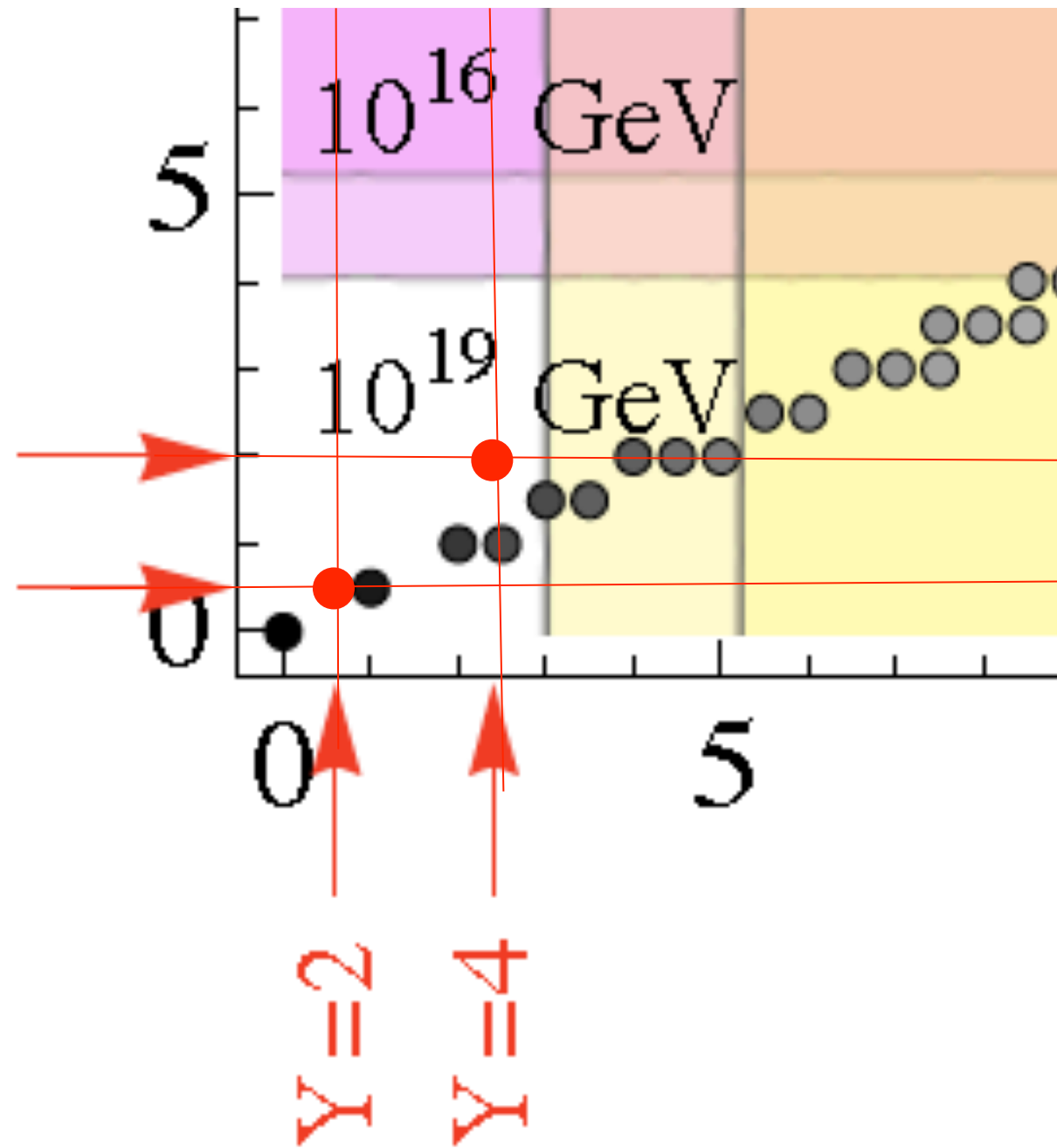
Perturbativity & Unification with SUSY



→ problem: extended gauge group + superfields + anomalies → many particles

adding a single
doublet or triplet

Triplet
Doublet



Conformal Symmetry & Hierarchy Problem

Are there other protective symmetries...?

→ conformal symmetry

Exact (unbroken) CS

→ absence of Λ^2 and $\ln(\Lambda)$ divergences

→ no preferred scale

Conformal anomaly

→ explicit breaking of CS!

→ breaking \leftrightarrow β -functions \leftrightarrow $\ln(\Lambda)$ divergences

→ **BUT: Maybe CS still forbids Λ^2 divergences** Bardeen, ...

Simplest Realization (under this assumption):

→ Coleman-Weinberg effective potential of SM for $\mu^2=0$

$$V_{\text{eff}} = (\mu^2=0)\Phi^2 + \lambda\Phi^4 + C \Phi^4 \ln(\Phi^2/\Lambda^2)$$

with $C \leftrightarrow \beta$ -functions $\leftrightarrow \ln(\Lambda)$

Realizing this Idea

Standard Model

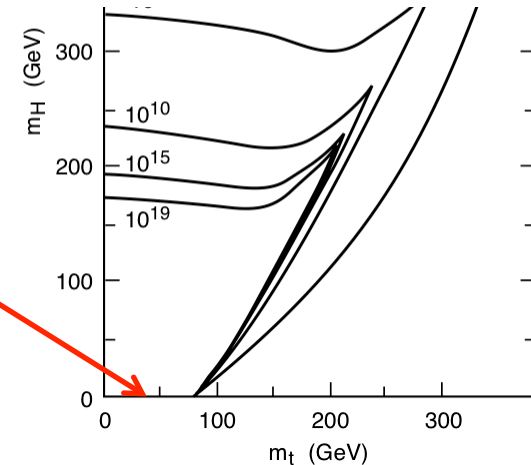
→ does not work: m_H too light and does not exist for $m_t > 80$ GeV

Other realizations

R. Foot, A. Kobakhidze, R. Volkas, 0704.1165

Nicolai, Meissner, 0803.2814

→ M. Holthausen, ML, M. Schmidt, 0911.0710



Conformal LR-extension of SM

→ choose suitable particle content \leftrightarrow breaking of V_{eff}

→ use Gildner Weinberg formalism

→ symmetry breaking $SU(2)_R \times U(1)_{B-L} \xrightarrow{M_{LR}} U(1)_Y$

→ works, but requires some parameter adjustments

Λ_{LR} & FCNC \leftrightarrow Λ_{LR} high enough & SM Higgs must be chosen

Summary

SM extensions with larger gauge groups and low lying SUSY

- breaking of extended symmetries \rightarrow additional scalars
- SUSY \rightarrow superpartners of new particles
- anomaly cancellation of superpartners of new scalars \rightarrow more fields

\rightarrow many new fields \rightarrow generic feature for many extensions

- drives running couplings bigger (destroys asymptotic freedom)
- often leads to divergent couplings
- especially U(1)

\rightarrow extended models with low lying SUSY \leftrightarrow hierarchy problem

- systematically problems with perturbativity
- gauge unification
- proton decay

\rightarrow low lying SUSY in its minimal form works best

\rightarrow argument in favour of weak scale SUSY

\rightarrow or something else \rightarrow conformal symmetry?