# Electro-Weak Symmetry Breaking in the Light of LHC Data

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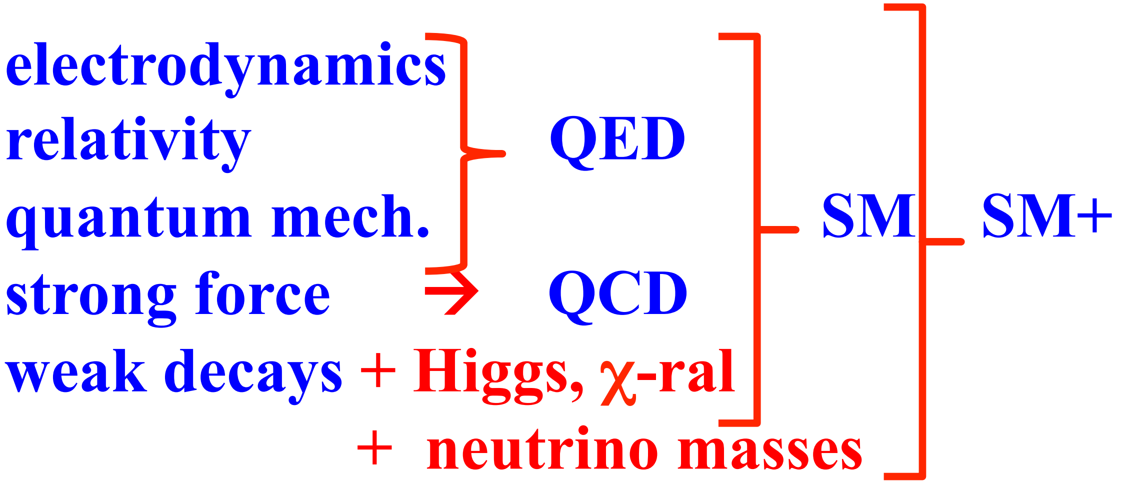
# The Standard Model

= success of renormalizable local quantum field theories in d=4

QED → QCD → SM

$U(1)_{em}$ $SU(3)_C$ $SU(3)_C \times SU(2)_L \times U(1)_Y$



electrodynamics

relativity

quantum mech.

} QED

strong force → QCD

weak decays + Higgs, $\chi$-ral

] SM

+ neutrino masses

] SM+

+ dark matter … → ?

+ … ?

territory of speculations:

LR? TC?

SUSY? GUTs?

extra d.? TOE?

…?

gravity weak scale <<<< $M_{planck}$

Note: GR is non-renormalizable – this is bad…

…maybe good: QFT's cannot explain scales → other concepts → expl. scales

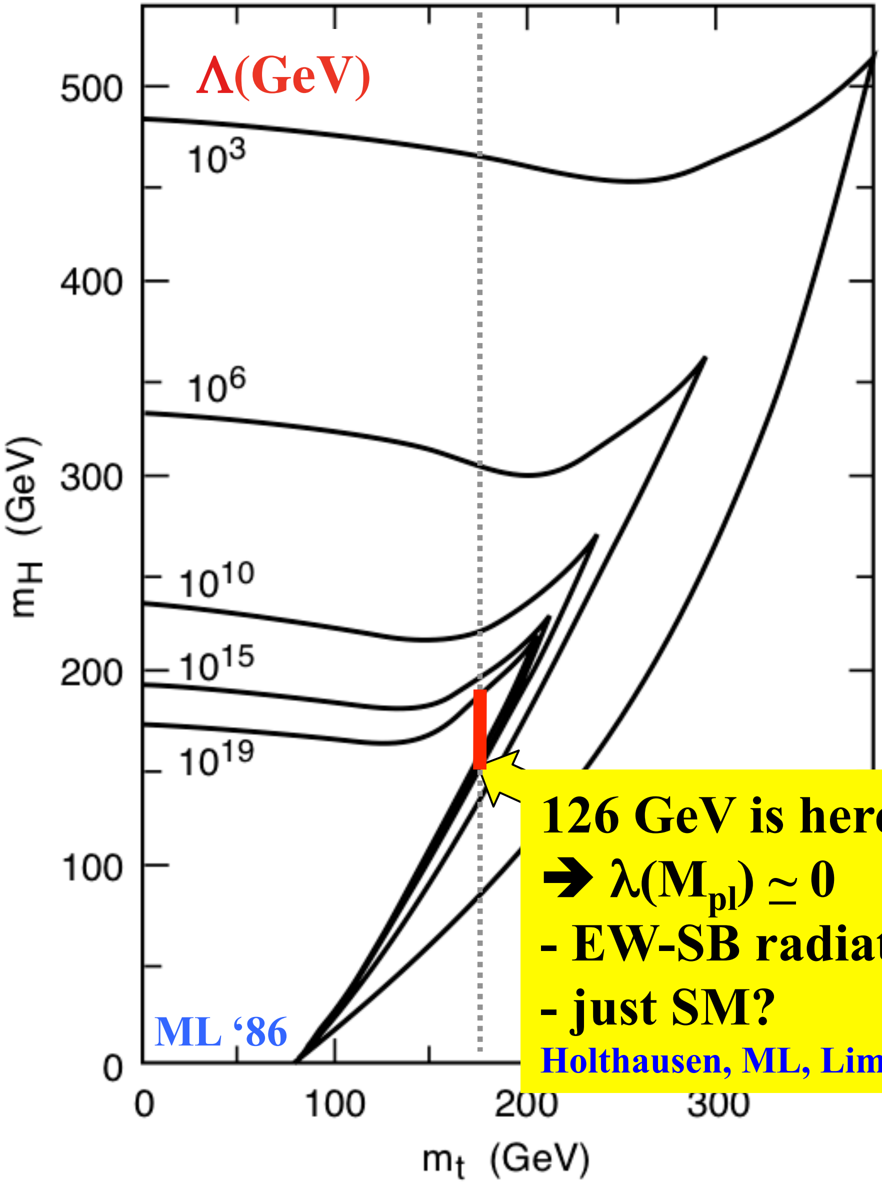
# Look carefully at the SM as a QFT

- **The SM itself (without embedding) is a QFT like QED**
  - infinities, renormalization ➔ only differences are calculable
  - SM itself is perfectly OK ➔ many things unexplained…
- **New or special features**
  - Higgs field (scalar), potential & SSB
  - fermion masses via Yukawa couplings ➔ no explicit fermion masses ←→ reps
  - besides μ no scale ➔ all masses: g*VEV ➔ one scale theory
  - **hierarchy problem ?**

- Renormalizable QFT → no cutoff Λ→ physics of an embedding
- Two scalars φ , Φ ; masses m, M and a mass hierarchy **m << M**
- $\varphi^+\varphi$ and $\Phi^+\Phi$ are singlets ➔ $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ **must exist**
- Quantum corrections $\sim M^2$ drive both masses to the heavy scale
  ➔ **two vastly different scalar scales are generically unstable**

➔ **not a SM problem ←➔ embedding with a 2nd much heavier scalar**

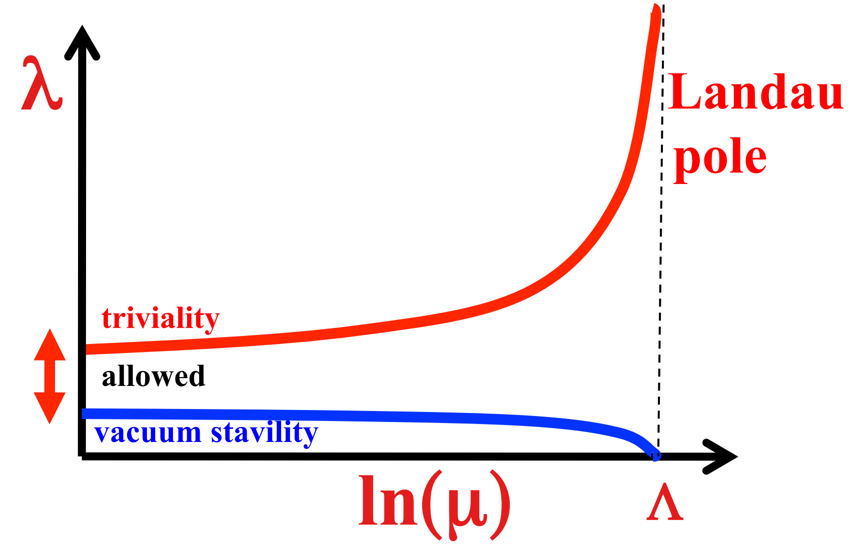
# SM:Triviality and Vacuum Stability



**126 GeV is here!**
**➔ $\lambda(M_{pl}) \simeq 0$**
**- EW-SB radiative**
**- just SM?**
**Holthausen, ML, Lim (2011)**

## 126 GeV < $m_H$ < 174 GeV

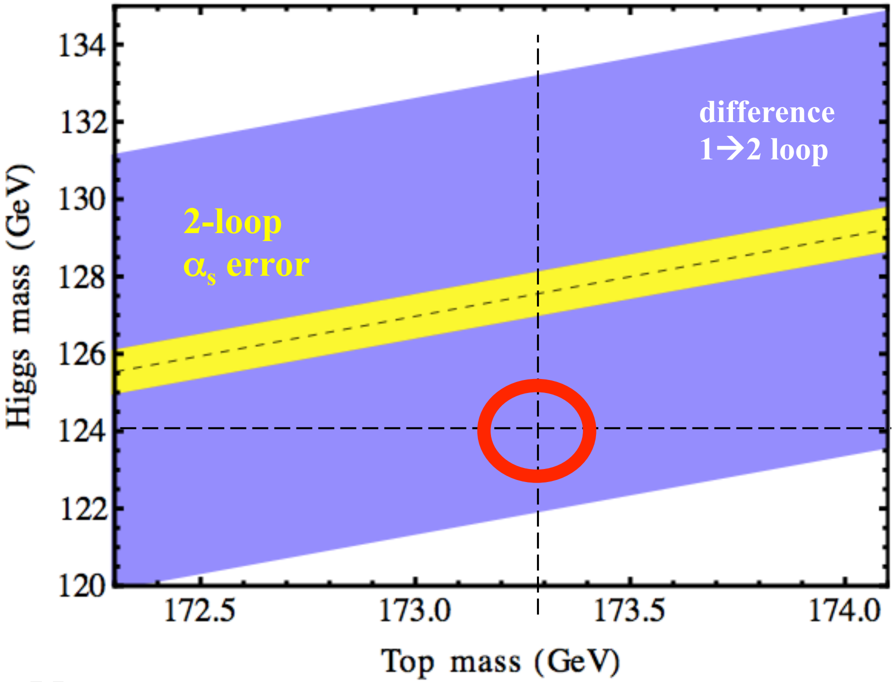
**SM does not exist w/o embeding**
**- U(1) copling , Higgs self-coupling**



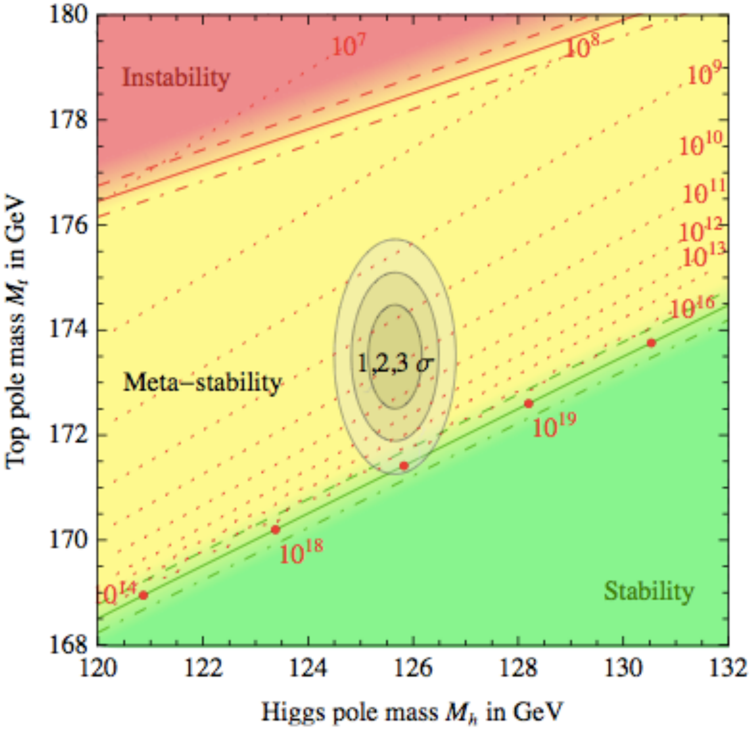
**➔ RGE arguments seem to work**
**➔ we need some embeding**
**⇔ no BSM physics observed!**
**➔ just a SM Higgs**

# Is the Higgs Potential at $M_{Planck}$ flat?

**Holthausen, ML, Lim**



**Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia**



**Notes:**

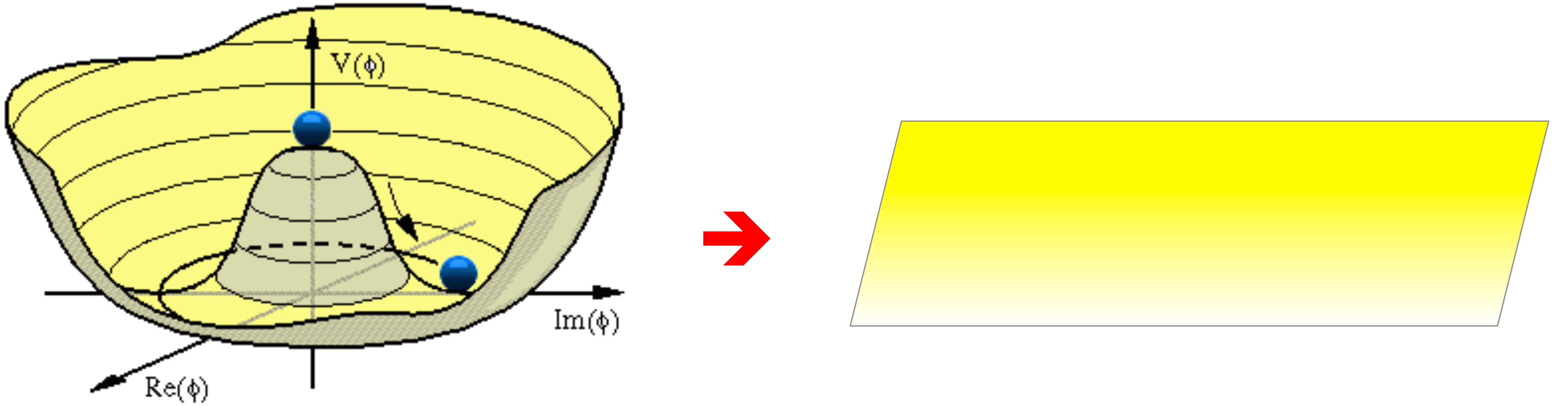
- remarkable relation between weak scale, $m_t$, couplings and $M_{Planck}$ ↔ precision
- strong cancellations between Higgs and top loops
  → very sensitive to exact value and error of $m_H$, $m_t$, $\alpha_s = 0.1184(7)$ → currently 1.8σ in $m_t$
- other physics: DM, $m_\nu$ … axions, …Planck scale thresholds… SM+ ↔ $\lambda = 0$

→ top mass errors: data ↔ LO-MC → translation of $m_{pole}$ → MS bar

→ be cautious about claiming that metastability is established

# Is there a Message?

- $\lambda(M_{Planck}) \simeq 0$? ➔ flat potential at $M_{planck}$
  ➔ flat Mexcican hat at the Planck scale



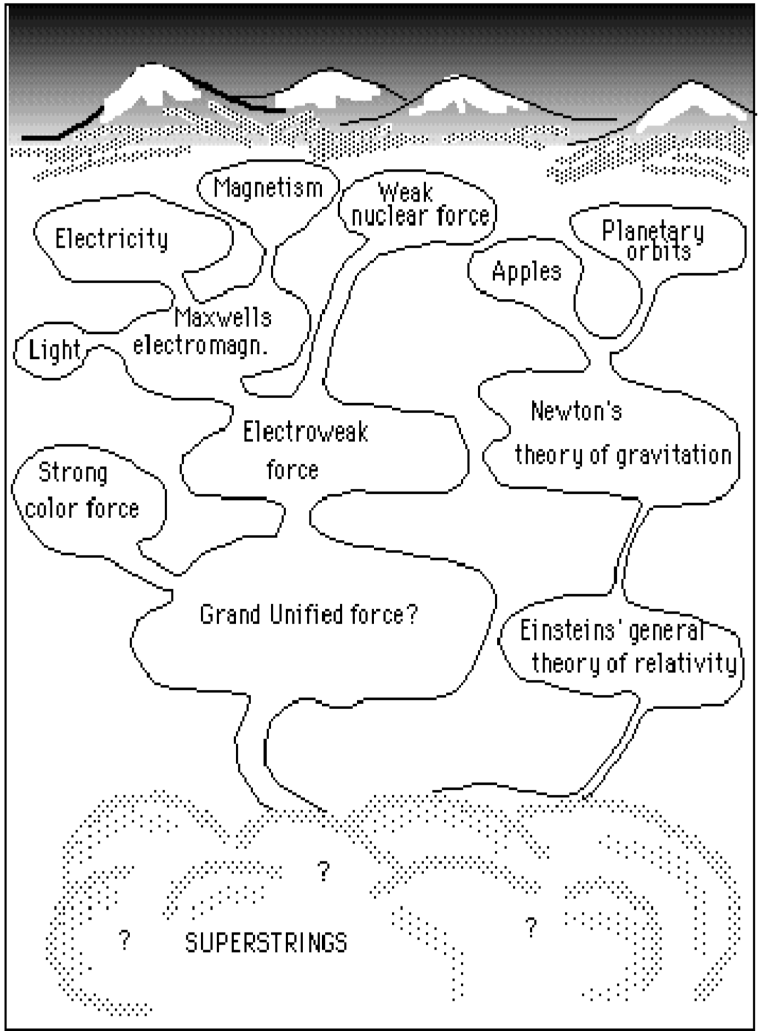
- if in addition $\mu^2 = 0$ ➔ $V(M_{Planck}) \simeq 0$?

(Remember: $\mu$ is the only single scale of the SM)

➔ **conformal symmetry as potential solution to the HP**

- **Conceptual aspects**
- **Realizations & implications for neutrino masses**

# Reasons to go Beyond the Standard Model



## Theoretical:

SM does not exist without cutoff
(triviality, vacuum stability)

Gauge hierarchy problem

Gauge unification, charge quantization

Strong CP problem

Unification with gravity

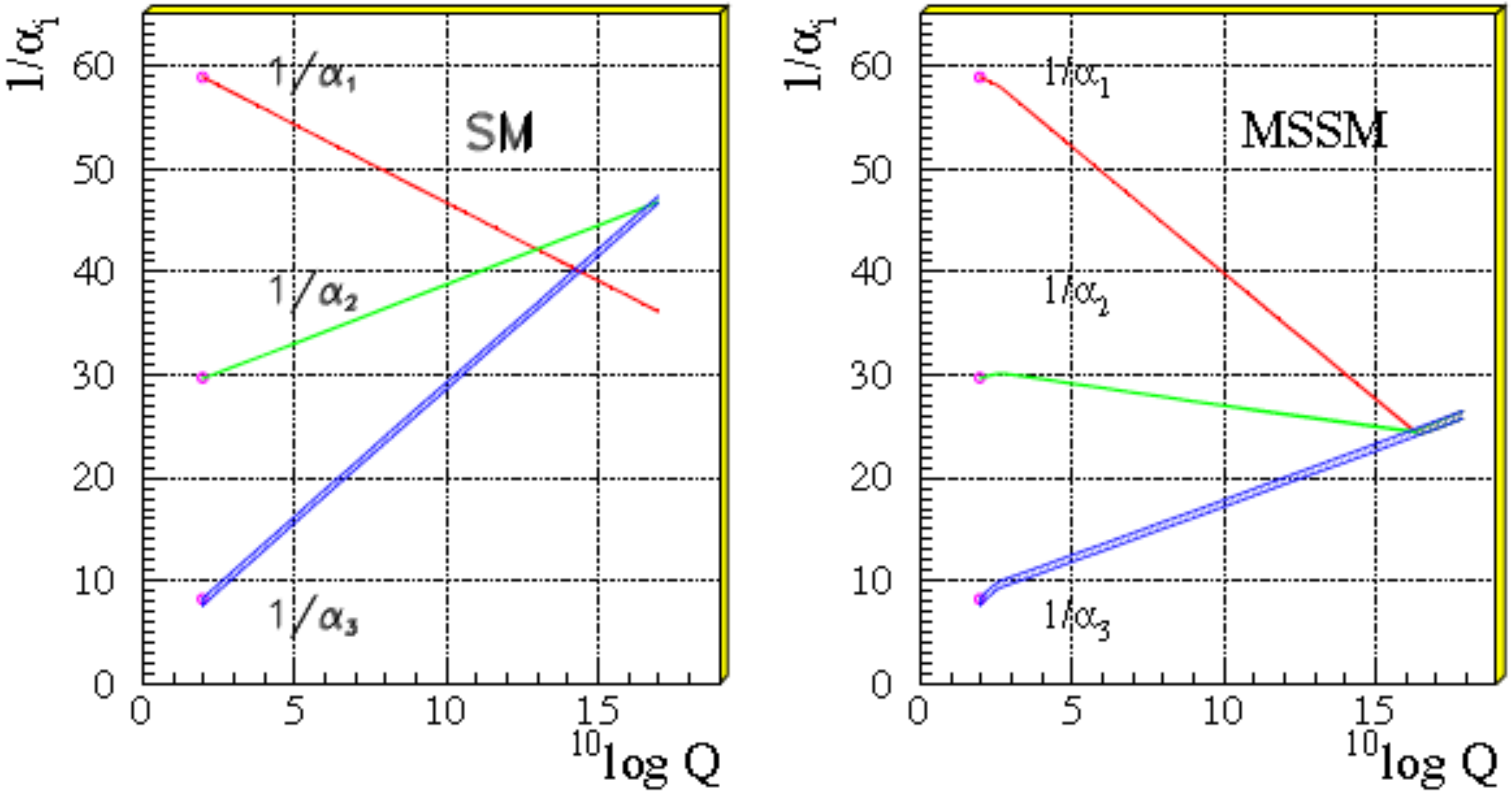
Global symmetries & GR anomalies

Why: 3 generations, representations,
d=4, many parameters

## Experimental facts:

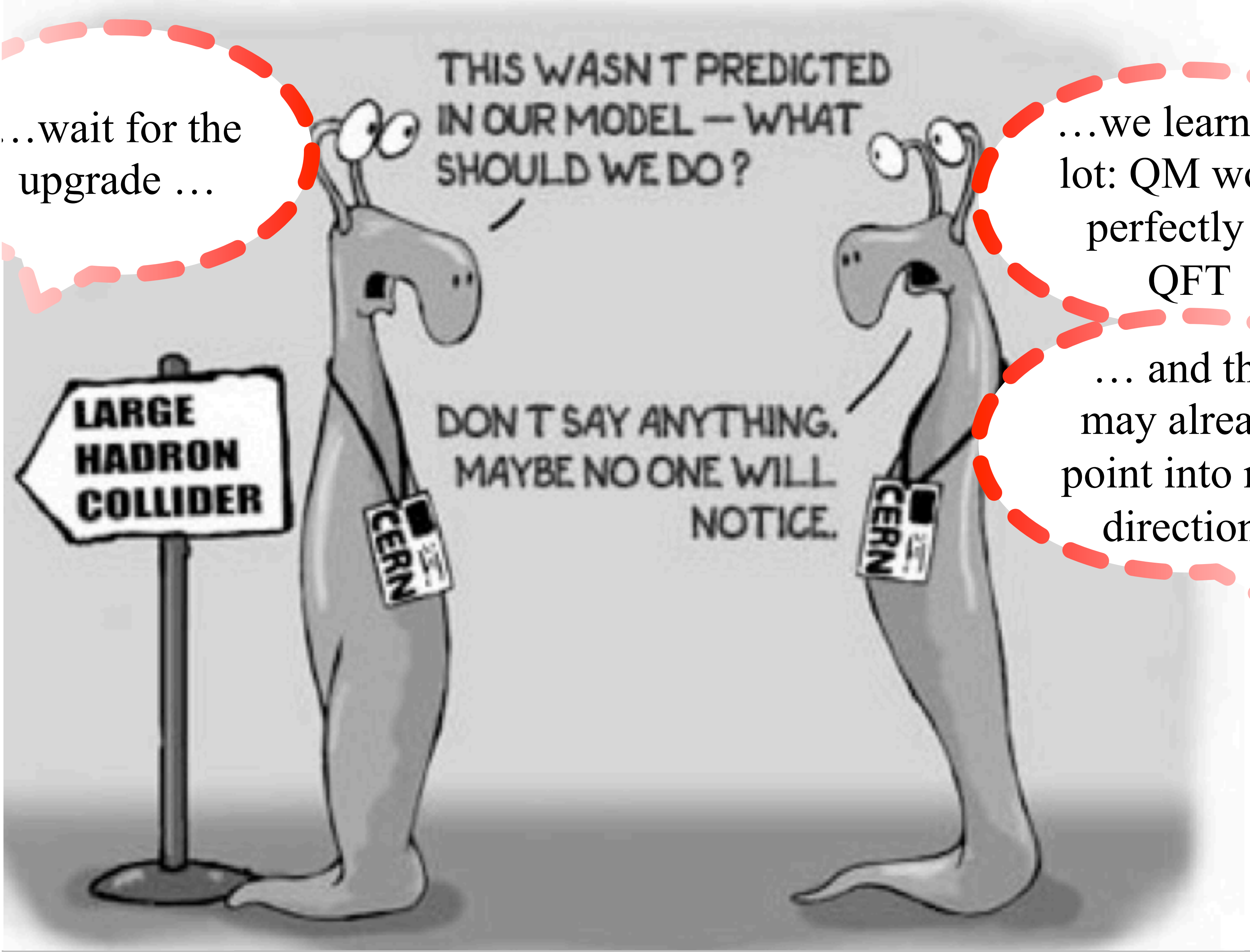
- Electro weak scale << Planck scale
- Gauge couplings almost unify
- Neutrino masses & large mixings
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Inflation
- Dark Energy

# Weak Scale SUSY works very good



SM: couplings do not unify

MSSM: perfect! ➔ turn the LHC an and let's see…



…wait for the upgrade …

…we learned a lot: QM works perfectly as QFT

… and this may already point into new directions

# Why not extend the SM and add SUSY later?

➔Think of extensions which are super-symmetrized or extended later + a reason why the EW scale is (somewhat) lower

- e.g. left-right symmetric extensions of SM
- add SUSY at $\Lambda_{LR}$
- scenarios where one scalar (=SM Higgs) is lighter
- unification should occur
  ➔ above proton decay scale $\tau_p \sim \frac{M_{\text{GUT}}^4}{m_p^5}$
  ➔ below Planck scale – or at $M_{Pl}$ would be even nice…

# RGEs

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

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

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

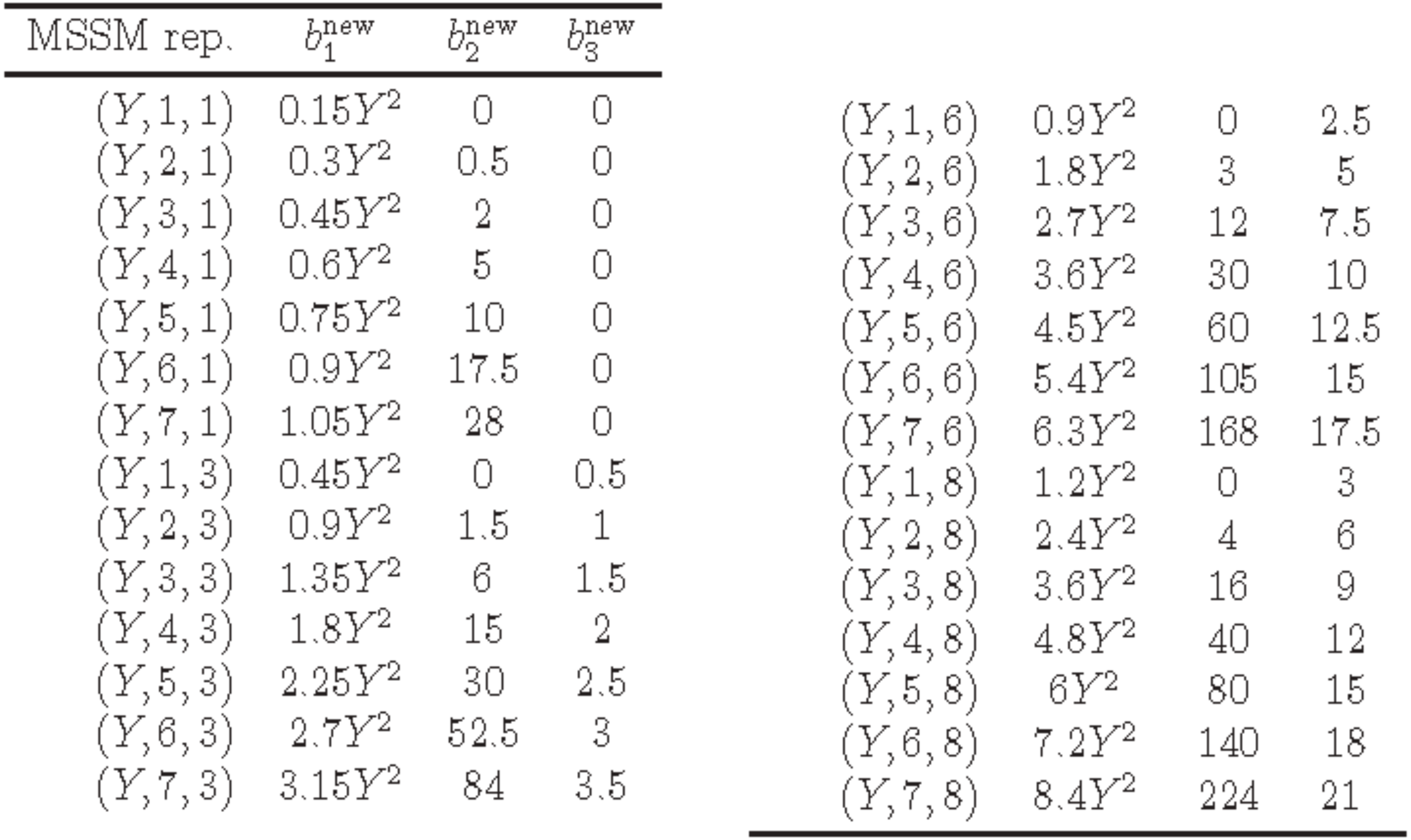
**1-loop, no thresholds, no detailed spectrum**

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

**→ matching at LR-scale**

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

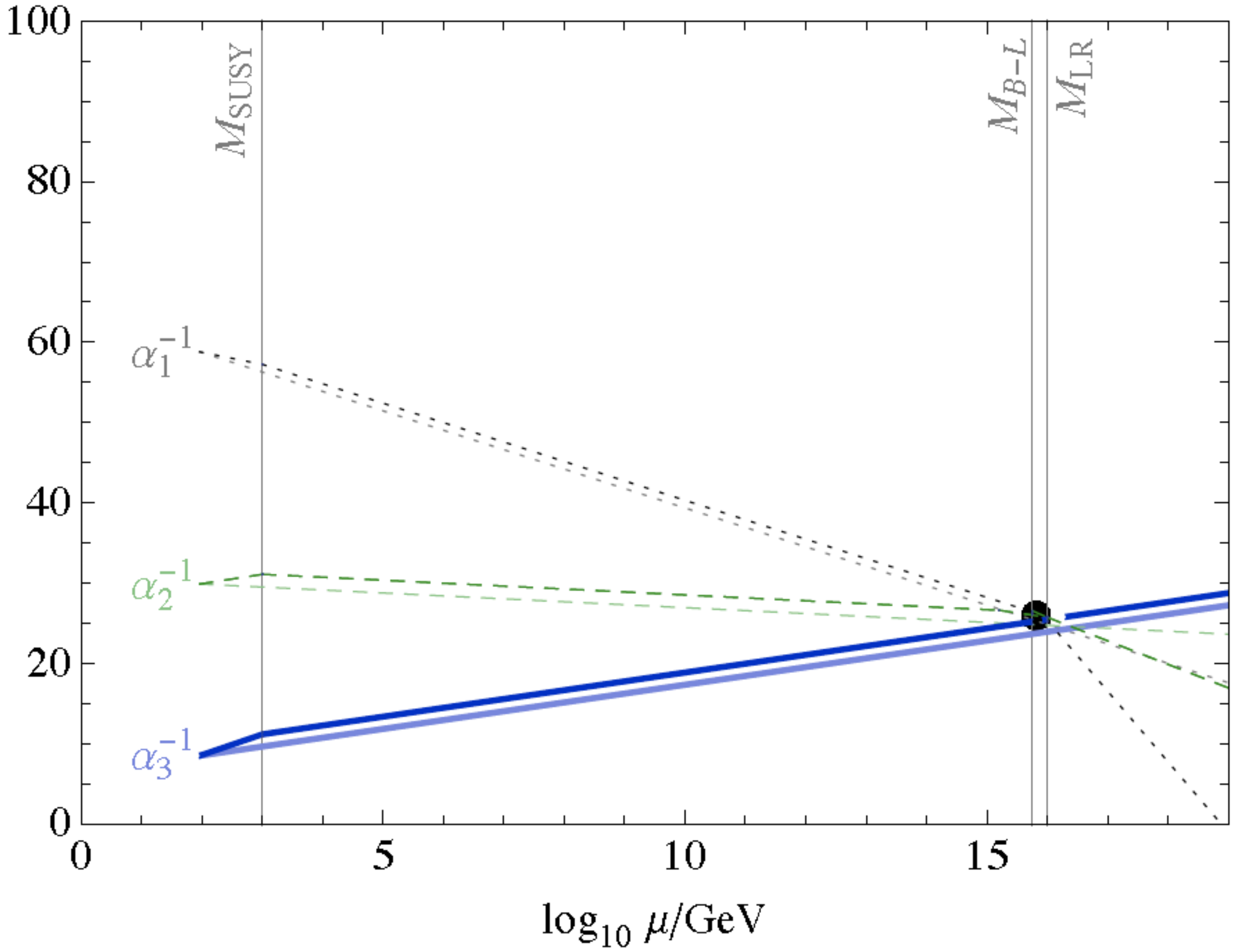
# Add arbitrary new Particles → RGE’s



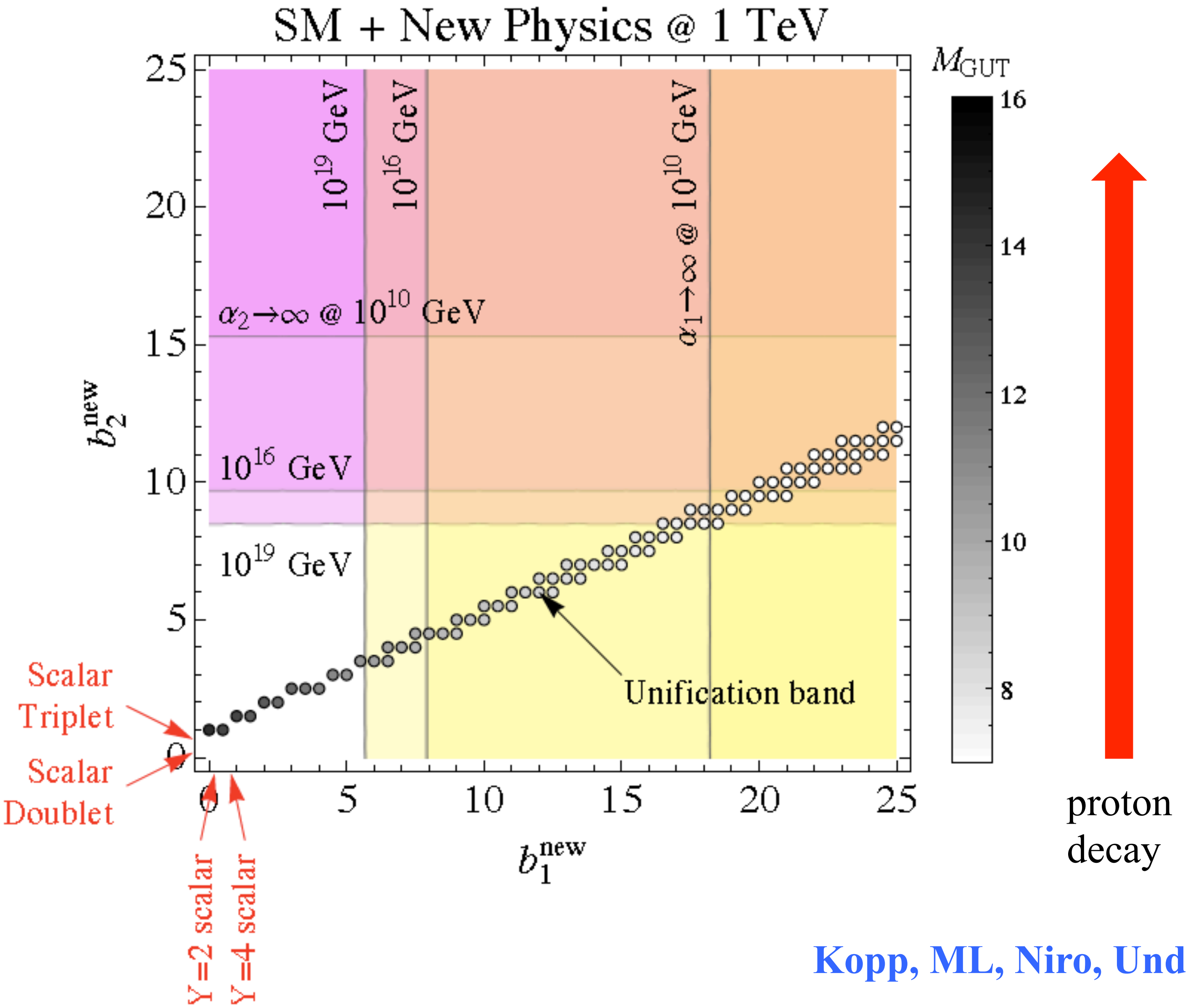
| MSSM rep. | $b_1^{\text{new}}$ | $b_2^{\text{new}}$ | $b_3^{\text{new}}$ |
|---|---|---|---|
| $(Y,1,1)$ | $0.15Y^2$ | 0 | 0 |
| $(Y,2,1)$ | $0.3Y^2$ | 0.5 | 0 |
| $(Y,3,1)$ | $0.45Y^2$ | 2 | 0 |
| $(Y,4,1)$ | $0.6Y^2$ | 5 | 0 |
| $(Y,5,1)$ | $0.75Y^2$ | 10 | 0 |
| $(Y,6,1)$ | $0.9Y^2$ | 17.5 | 0 |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

# SUSY-LR Model with intermediate B-L



# Perturbativity & Unification w/o SUSY



Scalar Triplet

Scalar Doublet

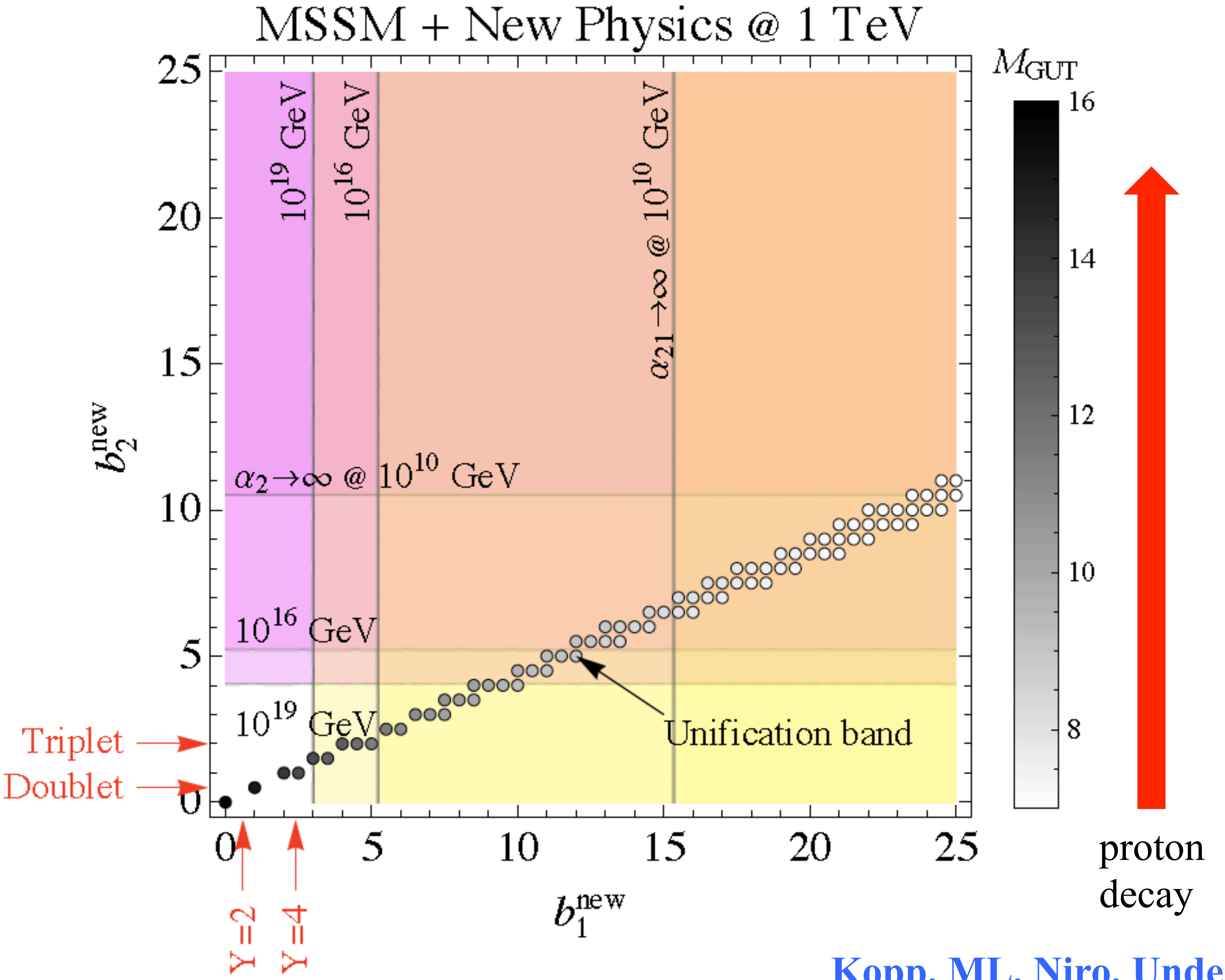
Y=2 scalar

Y=4 scalar

proton decay

**Kopp, ML, Niro, Underwood**

# Perturbativity & Unification with SUSY



**Kopp, ML, Niro, Underwood**

# Lessons

- **Extensions of the SM require corresponding scalar degrees of freedom required to break these extra symmetries ➔ problems: Landau poles, no unification, proton decay, Planck scale…**
- **Does not improve with SUSY: # of bosons vs. fermions SUSY balances $\Lambda^2$ terms, but not ln $\Lambda$ terms**
  - E.g. LR-SUSY → bi-doublet, triplets, superpartners and duplication to avoid anomalies
    ➔ many fields where $\Lambda^2$, but not ln($\Lambda$) terms cancel
- **Low lying SUSY in its minimal form works best**

**➔ look for it! ... But what if it would not show up?**

# Conformal Symmetry & EW Symmetry Breaking

# Conformal Symmetry as Protective Symmetry

**- Exact (unbroken) CS**

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

➔ no preferred scale and therefore no scale problems

**- Conformal Anomaly (CA): Quantum effects explicitly break CS**

existence of CA → CS preserving regularization does not exist

- dimensional regularization is close to CS and gives only ln($\Lambda$)
- cutoff reg. ➔ $\Lambda^2$ terms; violates CS badly → Ward Identity

**Bardeen:** maybe CS still forbids $\Lambda^2$ divergences

➔ CS breaking ←→ β-functions ←→ ln($\Lambda$) divergences

➔ anomaly induced spontaneous EWSB

NOTE: asymmetric logic! The fact the dimensional regularization kills a $\Lambda^2$ dependence is well known. Argument goes the other way!

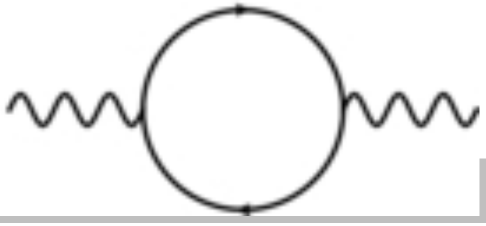
# Looking at it in different Ways…

- Basics of QFT: Renormalization ←→ commutator
  - $[\Phi(X),\Pi(y)] \sim \delta^3(x-y)$ → ~~delta funtion~~ → distribution
  - freedom to define δ*δ → renormalization ←→ counterterms
  - along come technicalities: lattice, Λ, Pauli-Villars, MS-bar, …
- Reminder: Technicalities do not establish physical existence!
- Conceptiully most clear → BPHZ-renormalization
- Symmetries are essential!

<u>Question:</u> Is gauge symmetry spoiled by discovering massive gauge bosons? → NO ←→ Higgs mechanism

→ non-linear realization of the underlying symmetry

→ important consequence: naïve power counting is wrong



Gauge invariance → only log sensitivity

# Versions of QCD…

- **QCD with massless (chrial) fermions**
  - ➔ gauge + conformal symmetry
  - ➔ dimensional transmutation ➔ $\Lambda_{QCD}$ (2 scales: $<\bar{q}q>$ , $<GG>$)
  - ➔ reference scale ; everything else is scale ratios
  - ➔ no $\Lambda^2$ sensitivity – there is no other physical scale!
  - ➔ **no hierarchy problem**

**Question:Do fundamental theories require absolute scales?**

Why not everything in relative terms?

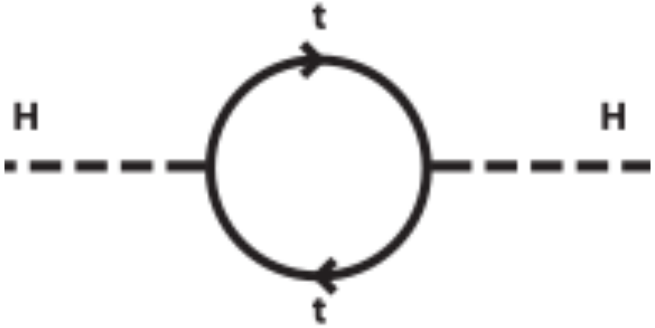
Don't blame a theory forthe scale problems which you invented in your head (a lattice, a cutoff, …)

**Important: The conformal anomaly**

**⬅➔ dimensional transmutation⬅➔ $\beta$-fcts. ⬅➔ logs**

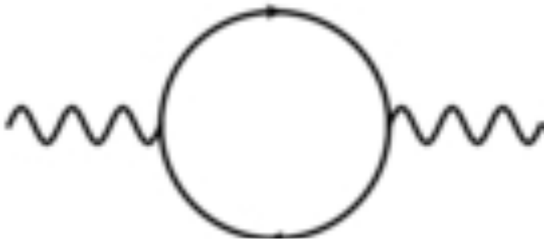
# Now massless scalar QCD…

- Massless scalar field instead of chiral fermions
- Gauge and conformal symmetry
- Technically there seems to be a $\Lambda^2$ divergence
  ➔ but this has no meaning since (if) there is no other explicit physical reference scale
- Dimensional transmutation ➔ $\Lambda_{QCD}$
  ➔ reference scale ; everything else is scale ratios
  ➔ conformal anomaly ➔ β-functions ➔ only logs

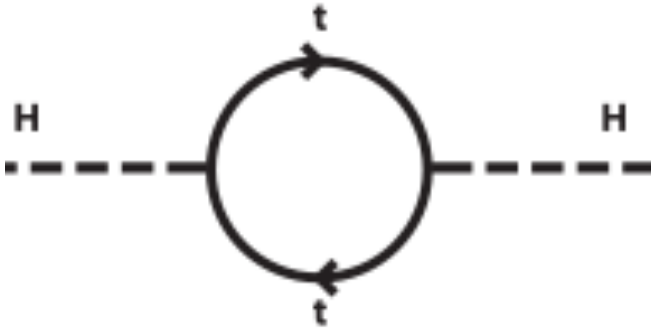


**Relict of conformal symmetry**
**➔ only log sensitivity**

# Implications



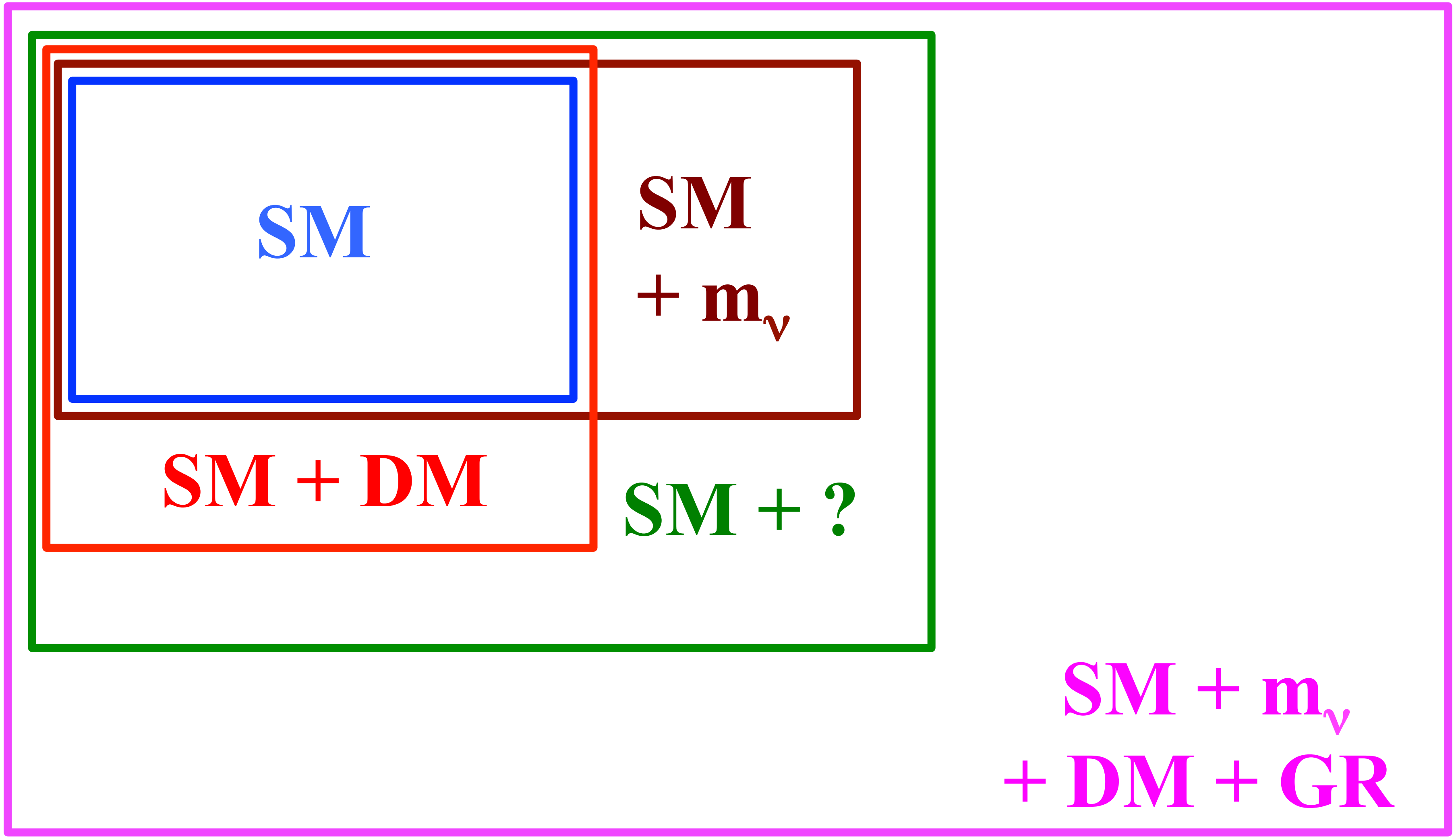
Gauge invariance → only log sensitivity



If conformal symmetry is realized in a non-linear way → protective relic of conformal symmetry → only log sensitivity

- No hierarchy problem, even though there is the the conformal anomaly = logs ←→ $\beta$-functions
- Dimensional transmutation due to log running like in QCD
  → scalars can condense and set scales like fermions
  → use this in Coleman Weinberg effective potential calculations
  ←→ most attractive channels (MAC) ←→ $\beta$-functions

# Implementing the Ideas at different Levels



SM

SM
+ $m_\nu$

SM + DM

SM + ?

SM + $m_\nu$
+ DM + GR

➔ at all levels: non-linear realization of conformal symmetry

# Further general Comments

- New (hidden) sector ↔ DM, neutrino masses, …
- Question: Isn't the Planck-Scale spoiling things?
  → non-linear realization… → conformal gravity…
  ideas: see e.g. 1403.4226 by A. Salvio and A. Strumia …
  K. Hamada, 1109.6109, 0811.1647, 0907.3969, …
- Question: What about inflation?
  see e.g. 1405.3987 by K. Kannike, A. Racioppi, M. Raidal
  or 1308.6338 by V. Khoze
- Unification …
- UV stability: ultimate solution should be asymptotically safe (have UV-FPs) … → U(1) from non-abelian group
- Justifying classical scale invariance
  → cancel the conformal anomaly
  → nature of space time & observables…

# Let’s try to implement the idea…

# Why the minimalistic SM does not work

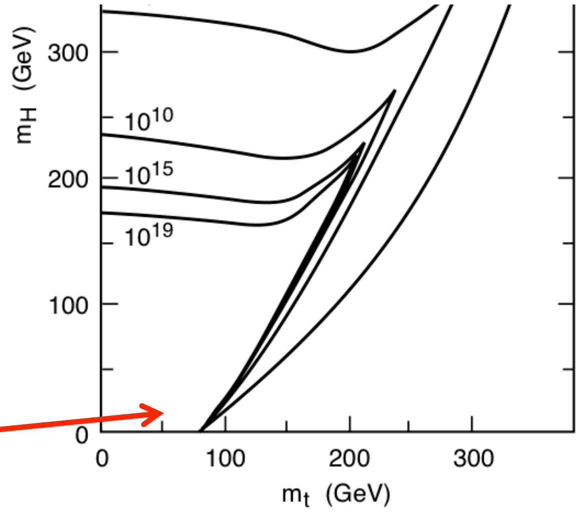
**Minimalistic:**

SM + choose $\mu = 0$ ←→ CS

Coleman Weinberg: effective potential

➔ CS breaking (dimensional transmutation)

➔ induces for $m_t < 79$ GeV
a Higgs mass $m_H = 8.9$ GeV

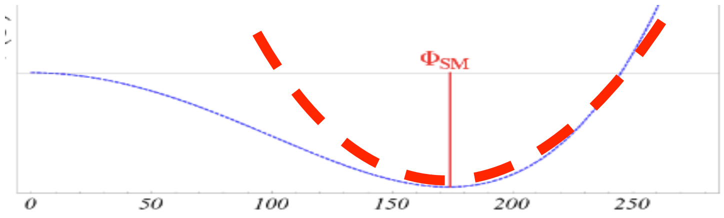


This would conceptually realize the idea, but:

Higgs too light and the idea does not work for $m_t > 79$ GeV

**Reason for $m_H \ll v$: $V_{eff}$ flat around minimum**

**←→ $m_H \sim$ loop factor $\sim 1/16\pi^2$**



AND: We need neutrino masses, dark matter, …

# Realizing the Idea via Higgs Portals

- SM scalar $\Phi$ plus some new scalar $\varphi$ (or more scalars)
- CS → no scalar mass terms
- the scalars interact → $\lambda_{mix}(\varphi^+\varphi)(\Phi^+\Phi)$ must exist

→ a condensate of $\langle\varphi^+\varphi\rangle$ produces $\lambda_{mix}\langle\varphi^+\varphi\rangle(\Phi^+\Phi) = \mu^2(\Phi^+\Phi)$
→ effective mass term for $\Phi$

- CS anomalous … → breaking → only $\ln(\Lambda)$

→ implies a TeV-ish condensate for $\varphi$ to obtain $\langle\Phi\rangle = 246$ GeV

- Model building possibilities / phenomenological aspects:
  - $\varphi$ could be an effective field of some hidden sector DSB
  - further particles could exist in hidden sector; e.g. confining…
  - extra hidden U(1) potentially problematic ←→ U(1) mixing
  - avoid Yukawas which couple visible and hidden sector

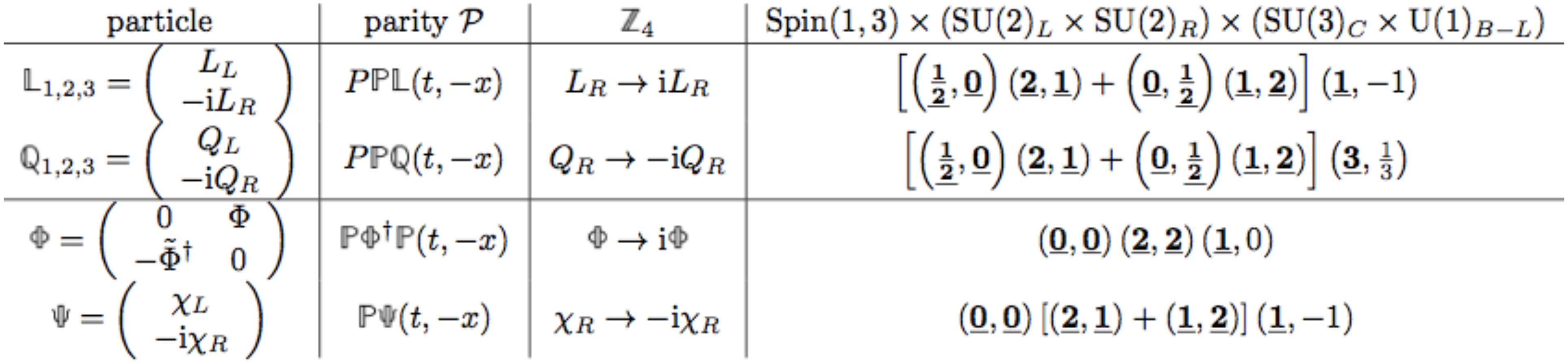
  → phenomenology safe due to Higgs portal, but there is TeV-ish new physics!

# Realizing this Idea: Left-Right Extension

**M. Holthausen, ML, M. Schmidt**

## Radiative SB in conformal LR-extension of SM

(use isomorphism SU(2) × SU(2) $\simeq$ Spin(4) → representations)



| particle | parity $\mathcal{P}$ | $\mathbb{Z}_4$ | $\text{Spin}(1,3) \times (\text{SU}(2)_L \times \text{SU}(2)_R) \times (\text{SU}(3)_C \times \text{U}(1)_{B-L})$ |
|---|---|---|---|
| $\mathbb{L}_{1,2,3} = \begin{pmatrix} L_L \\ -\mathrm{i} L_R \end{pmatrix}$ | $P\mathbb{P}\mathbb{L}(t,-x)$ | $L_R \to \mathrm{i} L_R$ | $\left[\left(\underline{\tfrac{\mathbf{1}}{\mathbf{2}}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\tfrac{\mathbf{1}}{\mathbf{2}}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{1}},-1)$ |
| $\mathbb{Q}_{1,2,3} = \begin{pmatrix} Q_L \\ -\mathrm{i} Q_R \end{pmatrix}$ | $P\mathbb{P}\mathbb{Q}(t,-x)$ | $Q_R \to -\mathrm{i} Q_R$ | $\left[\left(\underline{\tfrac{\mathbf{1}}{\mathbf{2}}},\underline{\mathbf{0}}\right)(\underline{\mathbf{2}},\underline{\mathbf{1}}) + \left(\underline{\mathbf{0}},\underline{\tfrac{\mathbf{1}}{\mathbf{2}}}\right)(\underline{\mathbf{1}},\underline{\mathbf{2}})\right](\underline{\mathbf{3}},\tfrac{1}{3})$ |
| $\Phi = \begin{pmatrix} 0 & \Phi \\ -\tilde{\Phi}^\dagger & 0 \end{pmatrix}$ | $\mathbb{P}\Phi^\dagger\mathbb{P}(t,-x)$ | $\Phi \to \mathrm{i}\Phi$ | $(\underline{\mathbf{0}},\underline{\mathbf{0}})(\underline{\mathbf{2}},\underline{\mathbf{2}})(\underline{\mathbf{1}},0)$ |
| $\Psi = \begin{pmatrix} \chi_L \\ -\mathrm{i}\chi_R \end{pmatrix}$ | $\mathbb{P}\Psi(t,-x)$ | $\chi_R \to -\mathrm{i}\chi_R$ | $(\underline{\mathbf{0}},\underline{\mathbf{0}})[(\underline{\mathbf{2}},\underline{\mathbf{1}}) + (\underline{\mathbf{1}},\underline{\mathbf{2}})](\underline{\mathbf{1}},-1)$ |

- → **the usual fermions, one bi-doublet, two doublets**
- → **a $Z_4$ symmetry**
- → **no scalar mass terms ←→ CS**

# ➔ Most general gauge and scale invariant potential respecting Z4

$$\mathcal{V}(\Phi,\Psi)=\frac{\kappa_1}{2}\left(\overline{\Psi}\Psi\right)^2+\frac{\kappa_2}{2}\left(\overline{\Psi}\Gamma\Psi\right)^2+\lambda_1\left(\mathrm{tr}\Phi^\dagger\Phi\right)^2+\lambda_2\left(\mathrm{tr}\Phi\Phi+\mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2+\lambda_3\left(\mathrm{tr}\Phi\Phi-\mathrm{tr}\Phi^\dagger\Phi^\dagger\right)^2$$
$$+\beta_1\,\overline{\Psi}\Psi\mathrm{tr}\Phi^\dagger\Phi+f_1\,\overline{\Psi}\Gamma[\Phi^\dagger,\Phi]\Psi\ ,$$

➔ calculate $V_{\mathrm{eff}}$

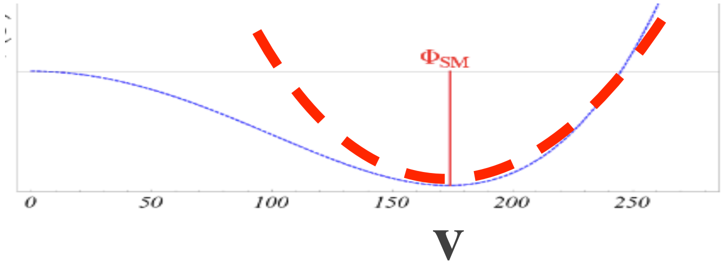
➔ Gildner-Weinberg formalism (RG improvement of flat directions)

- anomaly breaks CS
- spontaneous breaking of parity, $Z_4$, LR and EW symmetry
- $m_H \ll v$ ; typically suppressed by 1-2 orders of magnitude

  Reason: $V_{\mathrm{eff}}$ flat around minimum

  ←→ $m_H \sim$ loop factor $\sim 1/16\pi^2$

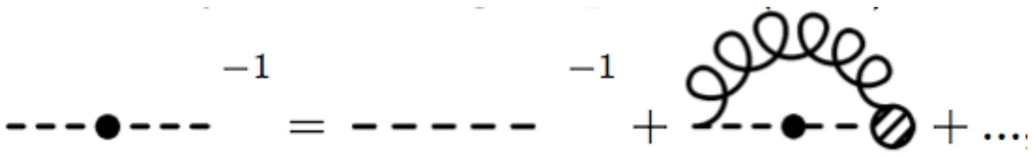
  → generic feature → predictions
- everything works nicely…



➔ requires moderate parameter adjustment for the separation of the LR and EW scale… PGB…?

# Rather minimalistic: SM + QCD Scalar S

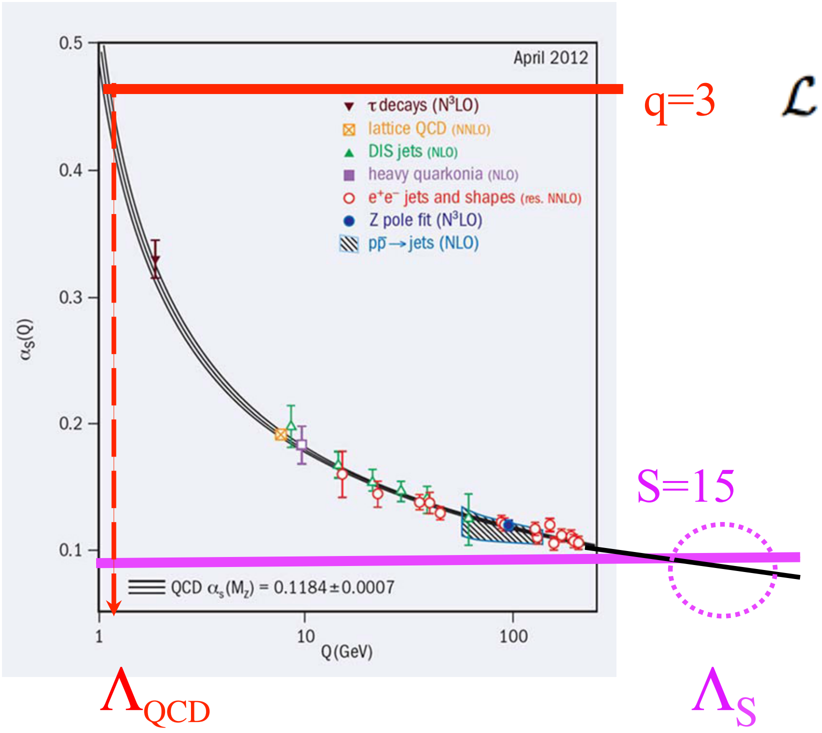
**J. Kubo, K.S. Lim, ML** New scalar representation S → QCD gap equation:



→ $C_2(S)\alpha(\Lambda) \gtrsim X$

$C_2(\Lambda)$ increases with larger representations

←→ condensation for smaller values of running α



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM},m^2\to 0} + (D_{\mu,ij}S_j)^\dagger (D^\mu_{ik} S_k) + \lambda_{HS} H^\dagger H S^\dagger S - \lambda_{1_i}\left[\bar{\boldsymbol{S}}\times \boldsymbol{S} \times \bar{\boldsymbol{S}}\times \boldsymbol{S}\right]_{\boldsymbol{1}_i}$$

$$\lambda_{HS}\langle S^\dagger S\rangle H^\dagger H \to \lambda_{HS}\Lambda^2 H^\dagger H$$

$$m_h^2 = 2\lambda_{HS}\Lambda^2 \qquad \frac{\lambda_h}{\lambda_{HS}} = \frac{\Lambda^2}{v^2}$$

# Phenomenology

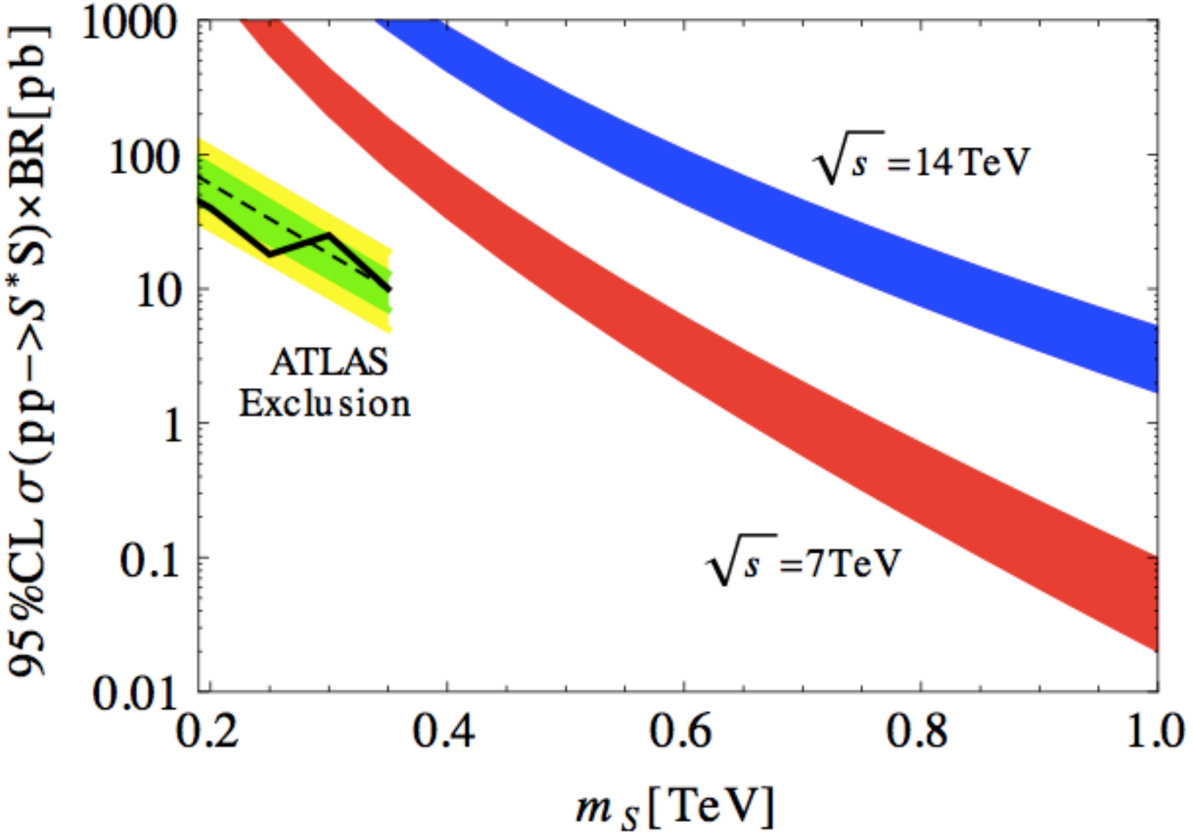


Figure 3. The $S$ pair production cross section from gluon fusion channel is calculated for different value of $m_S$. The 95% confidence level exclusion limit on $\sigma \times$BR for $\sqrt{s} = 7$ TeV by ATLAS is plotted. We assume 100% BR of $\langle S^\dagger S\rangle$ into two jets.

# Realizing the Idea: Examples for other Directions

**SM + extra singlet: Φ, φ**

Nicolai, Meissner, Farzinnia, He, Ren, Foot, Kobakhidze, Volkas, …

**SM + extra SU(N) with new N-plet in a hidden sector**

Ko, Carone, Ramos, Holthausen, Kubo, Lim, ML, (Hambye, Strumia) , …

**SM embedded into larger symmetry** (CW-type LR)

Holthausen, ML, M. Schmidt

**SM + colored scalar which condenses at TeV scale**

Kubo, Lim, ML

Since the SM-only version does not work → observable effects:
- Higgs coupling to other scalars (singlet, hidden sector, …)
- dark matter candidates ←→ hidden sectors & Higgs portals
- consequences for neutrino masses

# Conformal Symmetry & Neutrino Masses

ML, S. Schmidt and J.Smirnov

- No explicit scale ➔ no explicit (Dirac or Majorana) mass term → only Yukawa couplings ⊗ generic scales
- Enlarge the Standard Model field spectrum
  like in 0706.1829 - R. Foot, A. Kobakhidze, K.L. McDonald, R. Volkas
- Consider direct product groups: SM ⊗ HS
- Two scales: CS breaking scale at O(TeV) + induced EW scale

Important consequence for fermion mass terms:
➔ spectrum of Yukawa couplings ⊗ TeV or EW scale
➔ interesting consequences ←→ Majorana mass terms are no longer expected at the generic L-breaking scale → anywhere

# Examples

$$\mathcal{M} = \begin{pmatrix} 0 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & y_M\langle\phi\rangle \end{pmatrix}$$

**Yukawa seesaw:**

SM + $\nu_R$ + singlet

$$\langle\phi\rangle \approx \text{TeV}$$

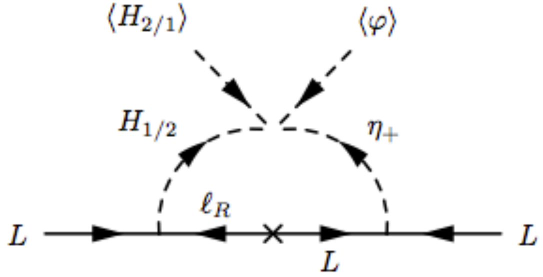
$$\langle H\rangle \approx 1/4\,\text{TeV}$$

➔ generically expect a TeV seesaw

BUT: $y_M$ might be tiny

➔ wide range of sterile masses ➔ includes pseudo-Dirac case

**Radiative masses**



$$\mathcal{M} = m_L \qquad \text{or}$$

$$\mathcal{M} = \begin{pmatrix} \mu_1 & y_D\langle H\rangle \\ y_D^T\langle H\rangle & \mu_2 \end{pmatrix}$$

➔pseudo-Dirac case

**The punch line:**
**all usual neutrino mass terms can be generated**

**→ suitable scalars**
**→ no explicit masses**
**all via Yukawa couplings**
**→ different numerical expectations**

# A Fresh Example: Inverse Seesaw

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

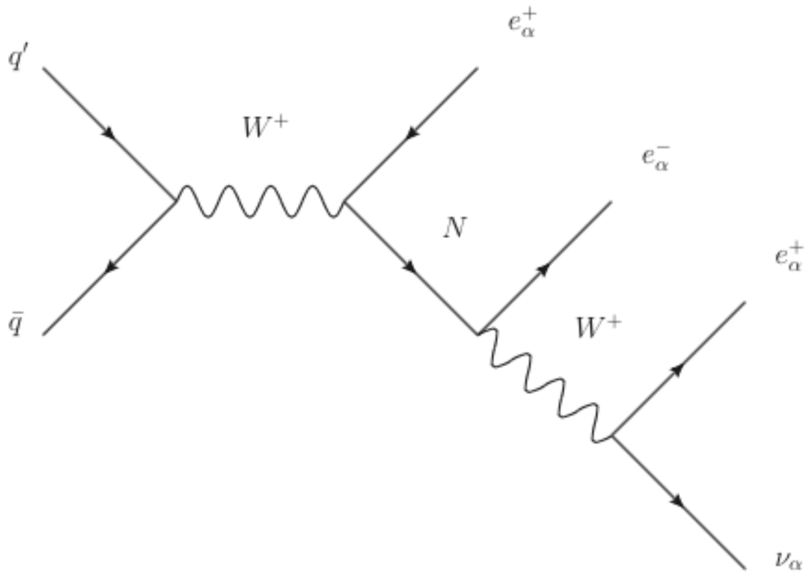
**1503.03066 P. Humbert, ML, J. Smirnov**

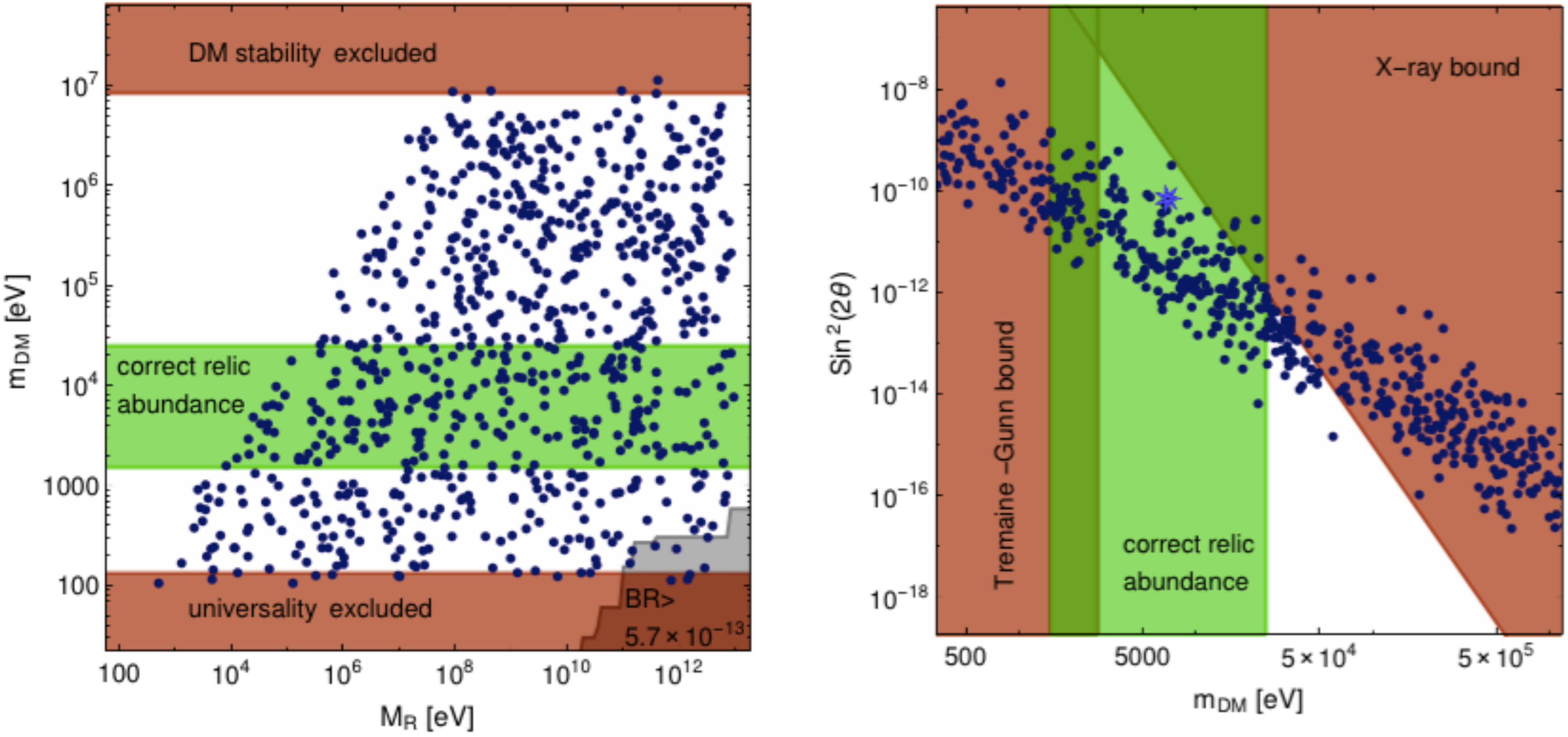
| | $H$ | $\phi_1$ | $\phi_2$ | $L$ | $\nu_R$ | $N_R$ | $N_L$ |
|---|---|---|---|---|---|---|---|
| $U(1)_X$ | 0 | 1 | 2 | 0 | 0 | 1 | 1 |
| Lepton Number | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| $U(1)_Y$ | 1 | 0 | 0 | -1 | 0 | 0 | 0 |
| $SU(2)_L$ | 2 | 1 | 1 | 2 | 1 | 1 | 1 |

$$\mathcal{M} = \begin{pmatrix} 0 & y_D \langle H \rangle & 0 & 0 \\ y_D \langle H \rangle & 0 & y_1 \langle \phi_1 \rangle & \tilde{y}_1 \langle \phi_1 \rangle \\ 0 & y_1 \langle \phi_1 \rangle & y_2 \langle \phi_2 \rangle & 0 \\ 0 & \tilde{y}_1 \langle \phi_1 \rangle & 0 & \tilde{y}_2 \langle \phi_2 \rangle \end{pmatrix}$$

- ➔light eV “active” neutrino(s)
- ➔two pseudo-Dirac neutrinos; m$\gtrsim$TeV
- ➔sterile state with μ ≈ keV

- ➔Tiny non-unitarty of PMNS matrix
- ➔Tiny lepton universality violation
- ➔Suppressed 0νββ decay
- ➔Lepton flavour violation
- ➔Tri-lepton production at LHC
- ➔keV neutrinos as warm dark matter ➔




DM stability excluded
correct relic abundance
universality excluded
BR> $5.7\times10^{-13}$
$m_{DM}$ [eV]
$10^7$
$10^6$
$10^5$
$10^4$
1000
100
100
$10^4$
$10^6$
$10^8$
$10^{10}$
$10^{12}$
$M_R$ [eV]
X-ray bound
Tremaine -Gunn bound
correct relic abundance
$\sin^2(2\theta)$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$
$10^{-18}$
500
5000
$5\times10^4$
$5\times10^5$
$m_{DM}$ [eV]

# General Implications of CISS

- The usual expectation that sterile mass terms are automatically very heavy is no longer fulfilled
- VEVs heavy, but Yukawa couplings may be anything

➔ any sterile spectrum natural

➔eV-evidences may or may not be correct

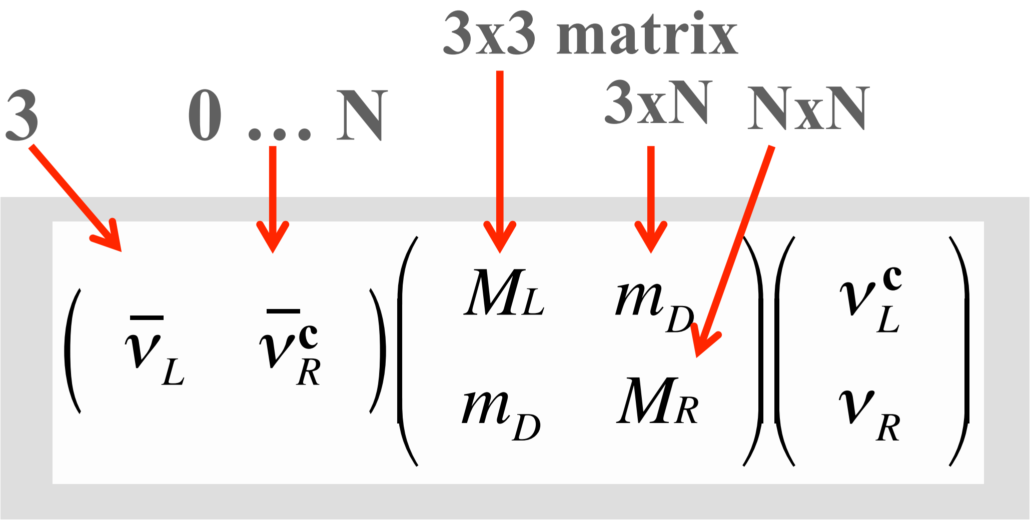
➔ any sterile mass natural: eV, keV, MeV, GeV, TeV, …

➔ cosmology: avoid thermalization and HDM

➔interesting theoretical and phenomenological options:
-TeV improved EW fits (Z-width, NuTeV, $A_{LR}$, …
Akhmedov, Kartavtsev, ML, Michels, J. Smirnov ; Antusch, Fischer

➔- keV ➔ warm dark matter

# Implications 2: Options for Neutrino Mass Spectra



$$\begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} M_L & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

**Usually:**

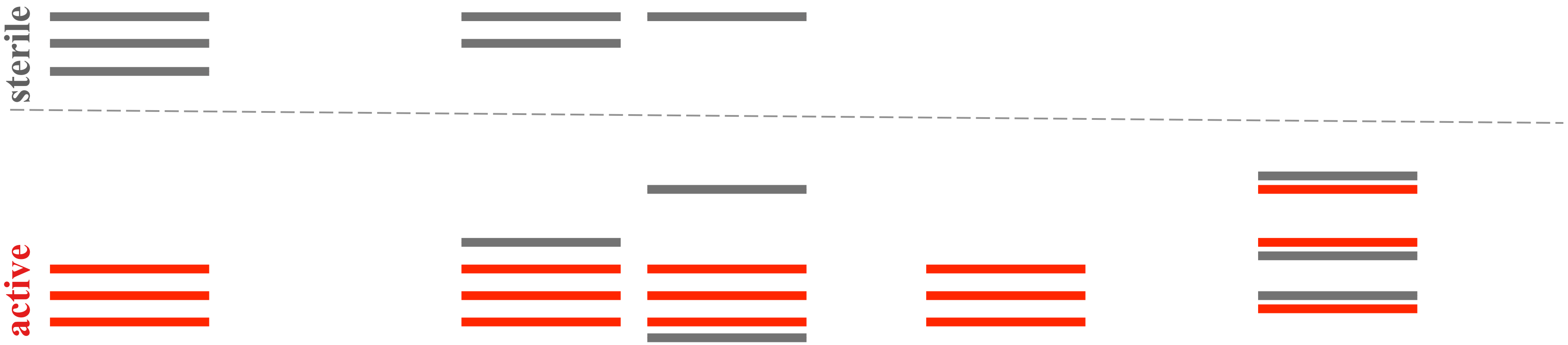
$M_L$ tiny or 0, $M_R$ heavy
→ see-saw & variants
light sterile: F-symmetries...

**Now:**

**$M_L$, $M_R$ may have any value:**

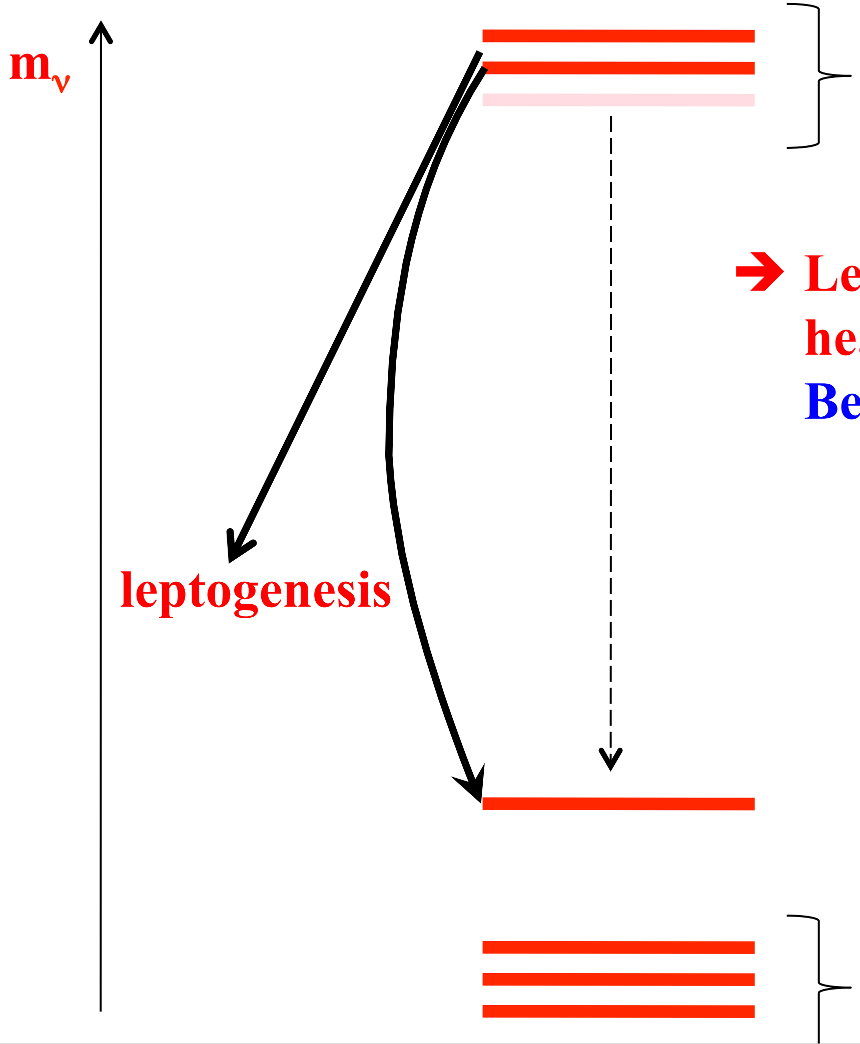
- ➔ diagonalization: 3+N EV
- ➔ 3x3 active almost unitary

| | | | |
|---|---|---|---|
| $M_L$=0, $m_D$ = $M_W$,<br>$M_R$=high: see-saw | $M_R$ singular<br>singular-SS | $M_L$ = $M_R$ = 0<br>Dirac | $M_L$ = $M_R$ = ε<br>pseudo Dirac |



# 3) Most minimalistic Sterile Neutrino Scenarios…

**…see-saw spectrum may be rather different than usual. E.g. …**



**heavy sterile neutrinos typ. $\geq 10^{13}$ GeV**

**➔ Leptogenesis from the decay of two remaining heavy sterile neutrinos works perfectly!**
**Bezrukov, Kartavtsev, ML**

**one light sterile neutrino $\simeq$ keV = DM**

**light active neutrinos < eV**

# Summary

- **SM (+$m_\nu$+DM) works perfectly**
- **no other signs of new physics**
- **The standard hierarchy problem suggests TeV scale physics … which did (so far…) not show up**

- **Revisit how the hierarchy problem may be solved**
  Embeddings into QFTs with classical conformal symmetry
  - SM: Coleman Weinberg effective potential – excluded
  - extended versions → work!

  **➔ testable consequences @ LHC, DM search, neutrinos**
  **➔ important to measure Higgs self-coupling**

- **Next LHC run will in any case be exciting!**