

# Particle Physics Phenomenology Today

Non commutative Geometry and Particle Physics 2013

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# Outline

- ▶ Snapshot of the desert from Higgs to Planck:  
Vacuum, scalar fields, hierarchy, unification
- ▶ Filling the desert: new scales and new physics  
supersymmetry and compositeness
- ▶ Role of conformal symmetry
- ▶ Flavour physics and BSM
- ▶ After the LHC

# Disparate Scales



Is the LHC announcing a desert up to the Planck scale?

## It cannot be a desert

Dark energy (the cosmological constant problem)

Dark matter

Baryon Asymmetry

Neutrinos: Majorana and Dirac

Muon  $g-2$

Electric Dipole Moments (EDMs)

...

Cosmology  
& Astronomy

Particle Physics

Can one scalar (Higgs) field and some massive neutrinos  
explain it all ?  
i.e. the evolution of our Universe

Find an answer to the following questions:

Stability of the EW vacuum

Renormalization of scalar masses (naturalness)

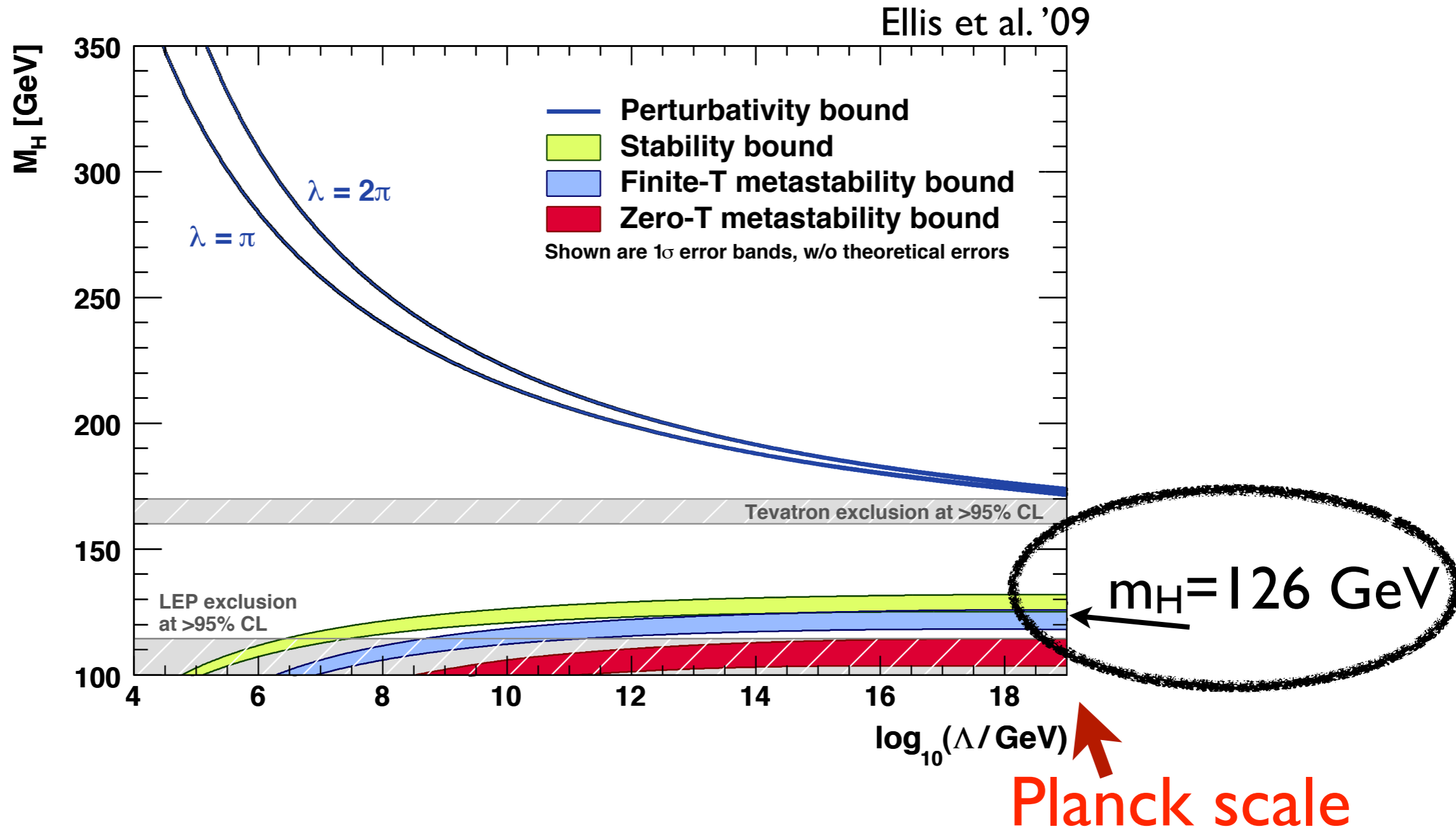
Hierarchy of scales (gauge hierarchy problem)

Unification

# Stability of the EW vacuum

⇒ triviality and radiative corrections Cortese Petronzio EP '92

⇒ vacuum stability Isidori Ridolfi Strumia '01



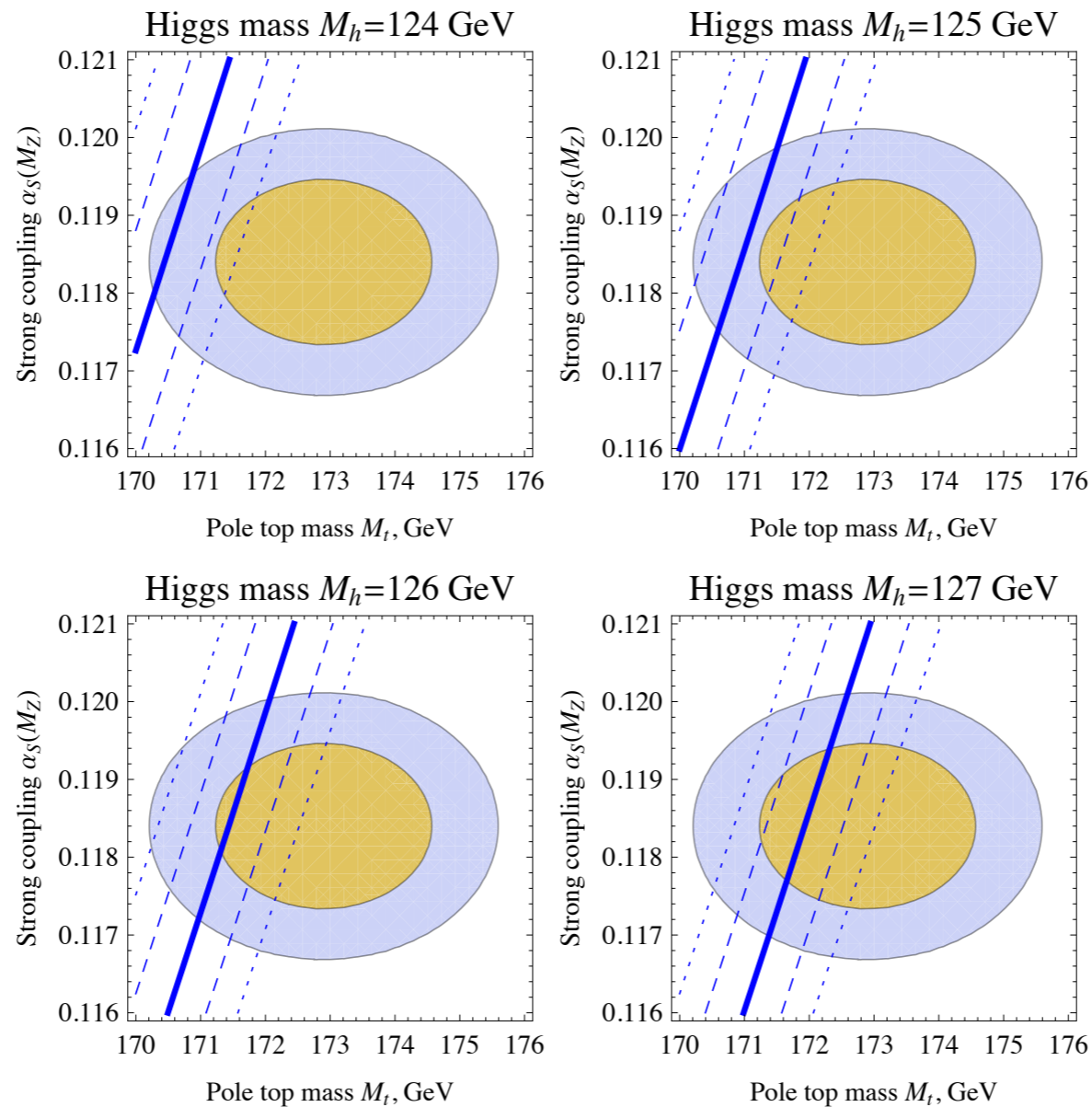
The SM may be a valid EFT up to the Planck scale



# Updated stability bound

Bezrukov, Kalmykov, Kniehl, Shaposhnikov 2012

$$M_{\min} = \left[ 128.95 + \frac{M_t - 172.9 \text{ GeV}}{1.1 \text{ GeV}} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56 \right] \text{ GeV}$$



Present uncertainties do not allow to conclude if  $M_H = 124 - 127$  GeV indicates stability or metastability of the SM vacuum

# Higgs & the Evolving Universe

LEP and LHC tell us that  $M_H > M_{\text{metastability}}$  : we live in a vacuum with lifetime at least larger than the age of the Universe  $\Rightarrow$  NP is not needed to stabilise the SM vacuum

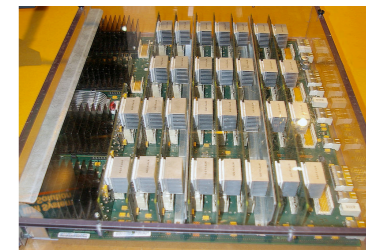
A numerical coincidence ?

UV stability scale predicted by SM parameters is about the Planck scale



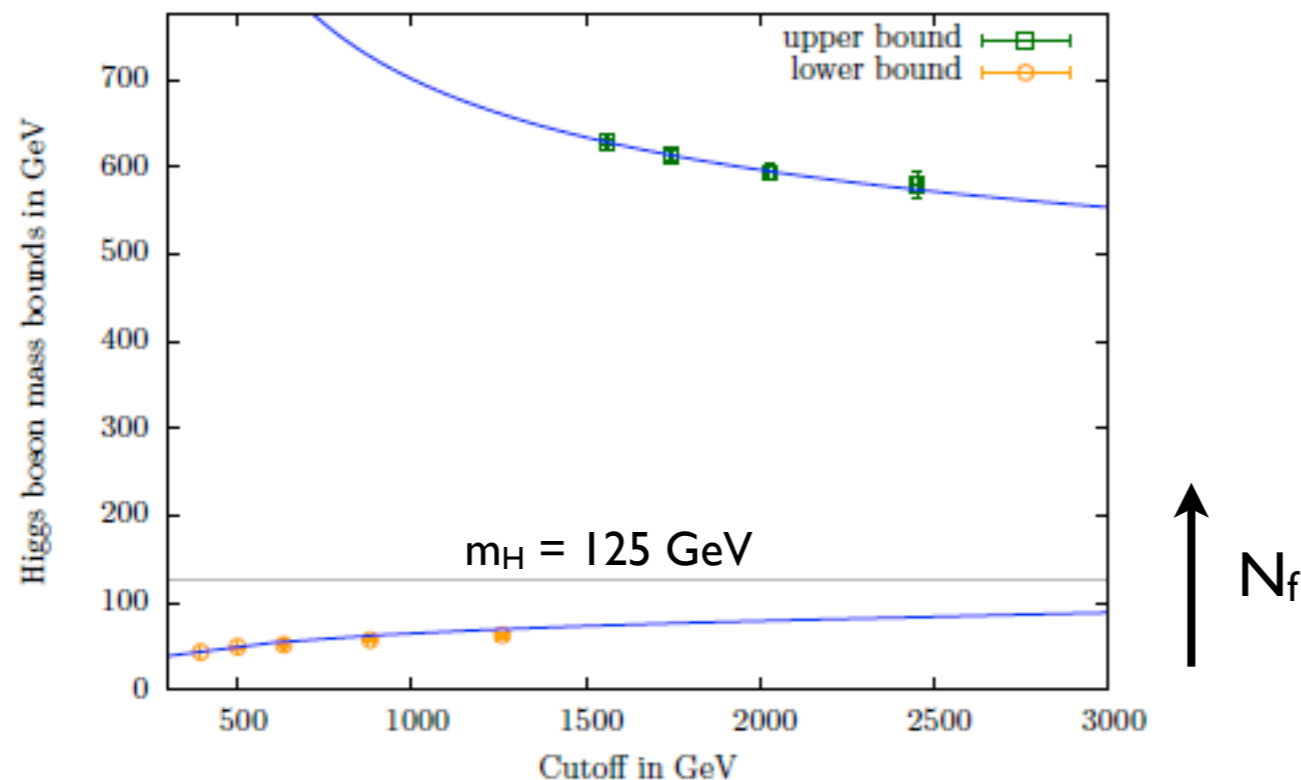
# Lattice stability bound

Hedge et al. Adv. High Energy Phys. 2013 (2013) 875612



$$\mathcal{L}_{F+Y}[\bar{\psi}, \psi, \phi] = \bar{\psi} D_{ov} \psi + y_b (\bar{t}, \bar{b})_L \phi b_R + y_t (\bar{t}, \bar{b})_L \tilde{\phi} t_R + h.c.$$

Overlap fermions with exact  $SU(2)_L \times U(1)_R$  chiral symmetry



$\Lambda = 1/a$   $\Lambda \sim 10^{10}$  GeV inaccessible

4th fermion generation excluded  
( $m_{t'} > 350$  GeV exp. constraint)

# Renormalization of scalar masses (naturalness)

Q: Well posed question or inappropriate use of regularization?



## SM scalar mass

$$\delta m_h^2 = -4 \sum_f m_f^2 \frac{\Lambda^2}{v^2} + (2m_W^2 + m_Z^2 + m_h^2) \frac{\Lambda^2}{v^2}$$

conformal symmetry broken

## SM fermion mass

$$\delta m_f = A m_f \ln \frac{\Lambda}{v} \quad A > 0$$

chiral symmetry protection

# Rescued by scale invariance (conformal symmetry)

$$T_{\mu}^{\mu} \sim \sum_i \beta_i(\{g\}, \{\lambda\}) \cdot O_i^{(d=4)} + \text{mass terms}$$

$$T_{\mu}^{\mu}{}_{\text{classical}} = 2m_h^2 h^{\dagger}h$$

$$T_{\mu}^{\mu}{}_{\text{one loop}} = 2\delta m_h^2 h^{\dagger}h + \sum_i \beta_i(\{g\}, \{\lambda\}) \cdot O_i^{(d=4)}$$

$\delta m_h^2 \sim \Lambda^2$   $\longrightarrow$  explicit breaking of conformal symmetry

$\delta m_h^2 \sim m_h^2$   $\longrightarrow$  spontaneous breaking of conformal symmetry

Introduce a dilaton field

## Exercise: classical scalar theory

[S. Coleman 'Aspects of symmetry']

$$\mathcal{L}_m = -\frac{1}{2}m^2\phi^2 \rightarrow -\frac{1}{2}m^2\phi^2 e^{2f\sigma} \quad \chi(x) = \frac{1}{f}e^{f\sigma(x)}$$

$$\int d^4x \delta\mathcal{L}_m = 0$$

dilaton field  
=  
Goldstone boson of scale  
(conformal) invariance

Realize PCDC by adding a mass term for the dilaton

$$\mathcal{L}_B = -\frac{1}{2}m_\sigma^2\sigma^2 + O(\sigma^3) \Rightarrow \partial_\mu s^\mu = T_\mu^\mu = -\frac{m_\sigma^2}{f}\sigma$$

Extend to the quantized theory

[see e.g. Shaposhnikov, Zenhausern arXiv:0809.3406]

Open questions: unitarity, uniqueness, which SM sectors?

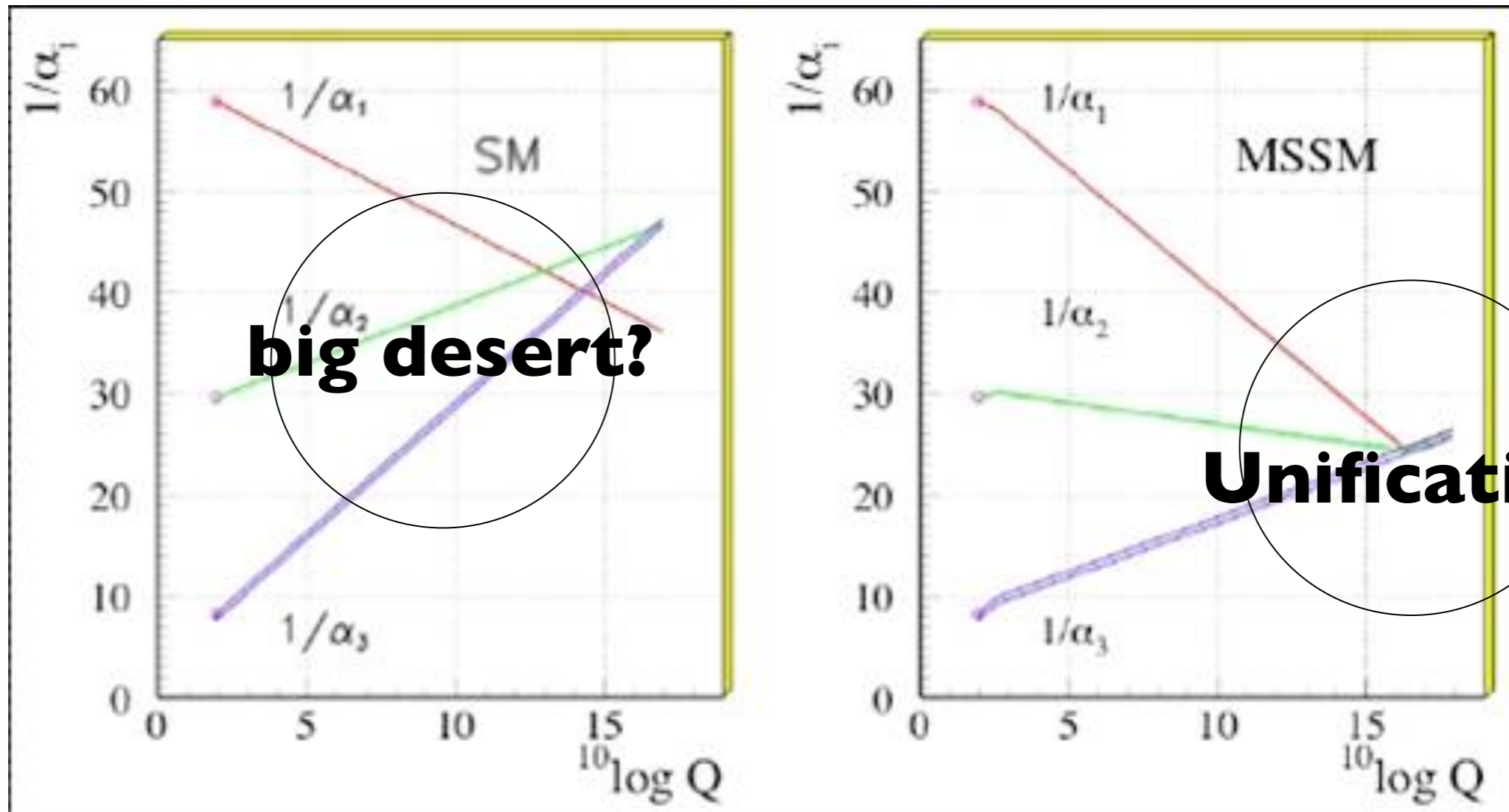
scalar sector:  $\frac{1}{2}m_{Higgs}^2 H^2 \rightarrow \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \lambda(H^2 - \zeta^2\chi^2)^2$

# Hierarchy of scales and unification of forces

Q: Are there new relevant scales between Higgs/Fermi and Planck?



## Two known scenarios



## Two avenues

Add new scales  
 $\Leftrightarrow$  new particles

e.g.  
(weakly coupled) supersymmetry  
(strongly coupled) compositeness

No new scale  
 $\Leftrightarrow$  minimal particle content

e.g.  
Conformal symmetry at Planck  
Need to break it spontaneously

1

$10^3$

$10^{19}$  GeV

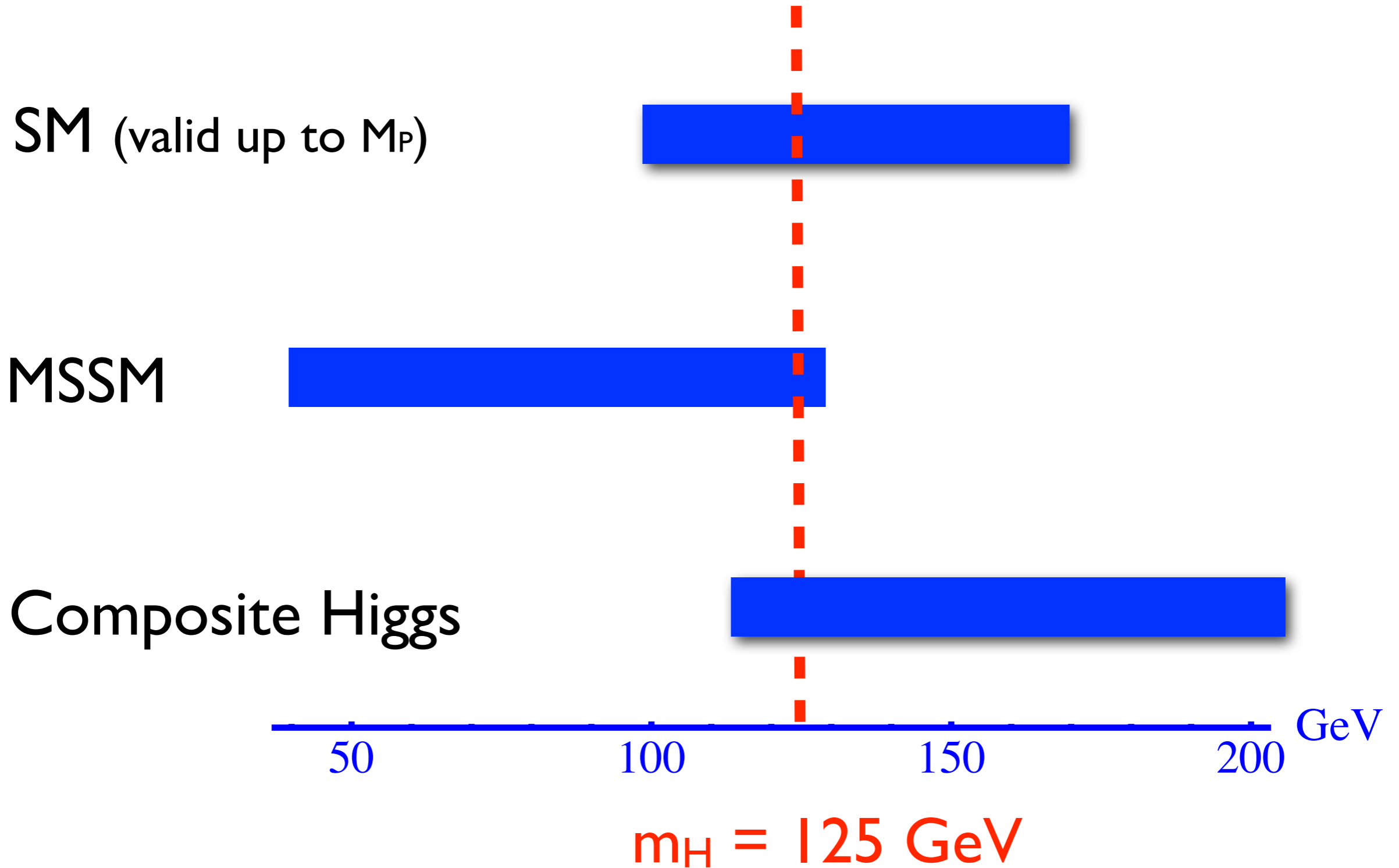


confinement ElectroWeak

Planck

# Higgs mass range

Pomarol @ICHEP12

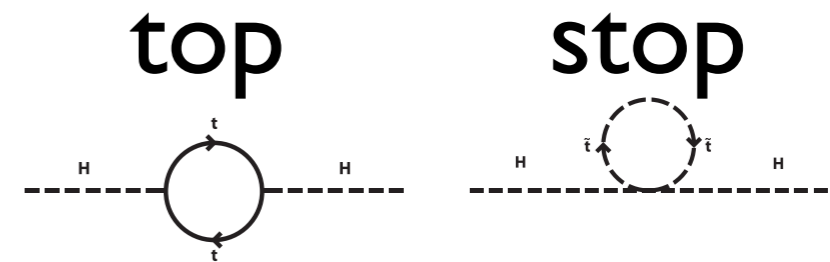




Main stream solutions have invoked the criterion of naturalness (along with unification of gauge forces) for the last 40 years

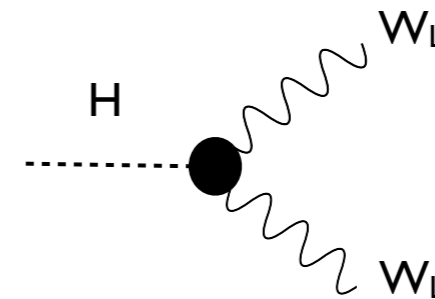
**SUPERSYMMETRY**

Djouadi 08



**COMPOSITENESS**

Bhattacharyya I I



**without or with extra spatial dimensions (RS, ADD, etc)**

# Compositeness

Superconductivity

Cooper pairs  $\langle ee \rangle$   
weakly coupled

Confinement

quark condensate  $\langle qq \rangle$   
strongly coupled

Postulate strong dynamics BSM (no decoupling of h.o. operators)  
→ light composite Higgs

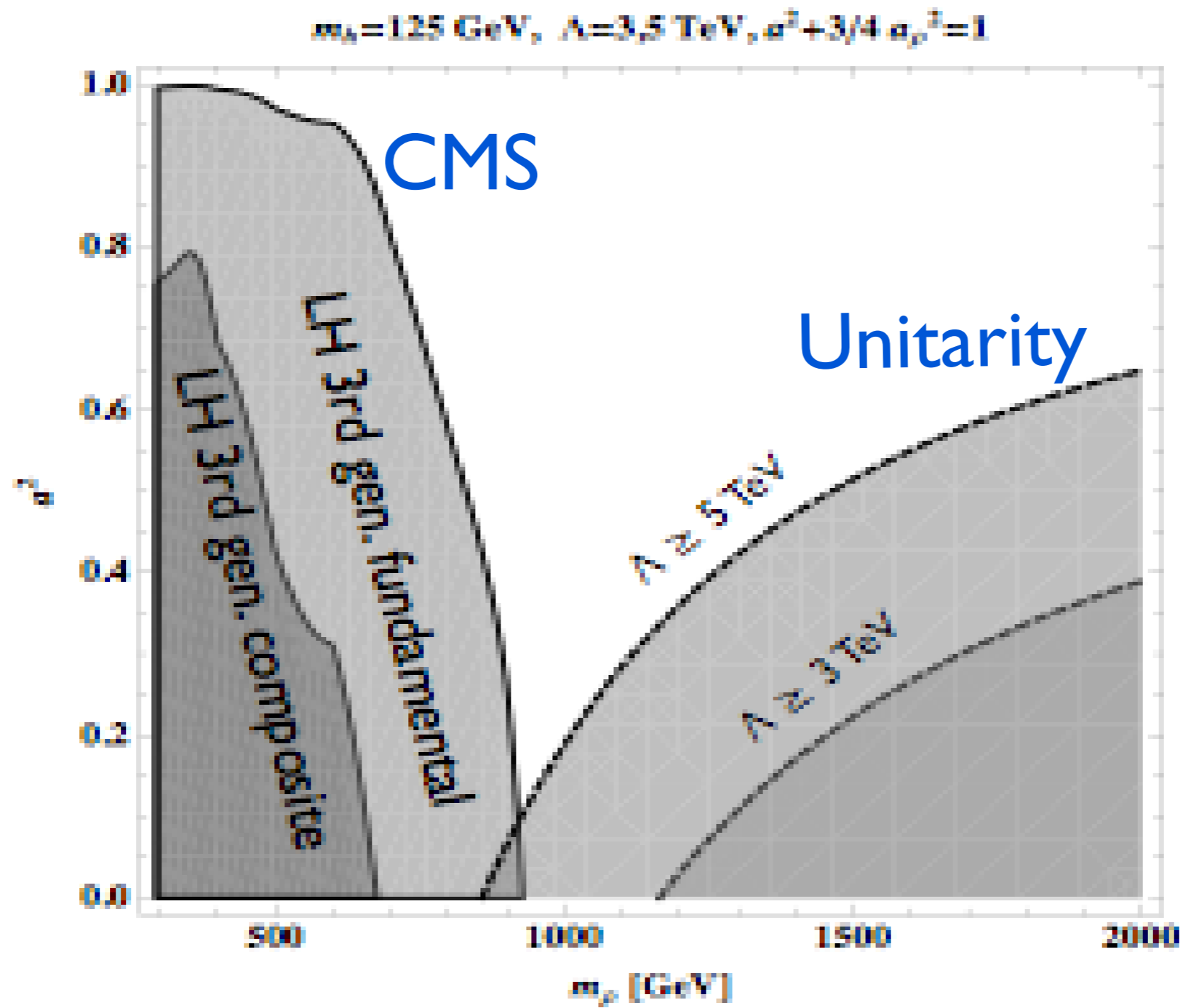
The Higgs boson can be the pNGB of an extended global symmetry or the dilaton of a spontaneously broken CFT  $\Rightarrow$  SM couplings modified

LHC data constrain the compositeness scale and the spectrum

The more the couplings deviate from the SM, the lighter the **new composites** (resonances) must be to ensure unitarity up to the compositeness scale  $\Lambda$

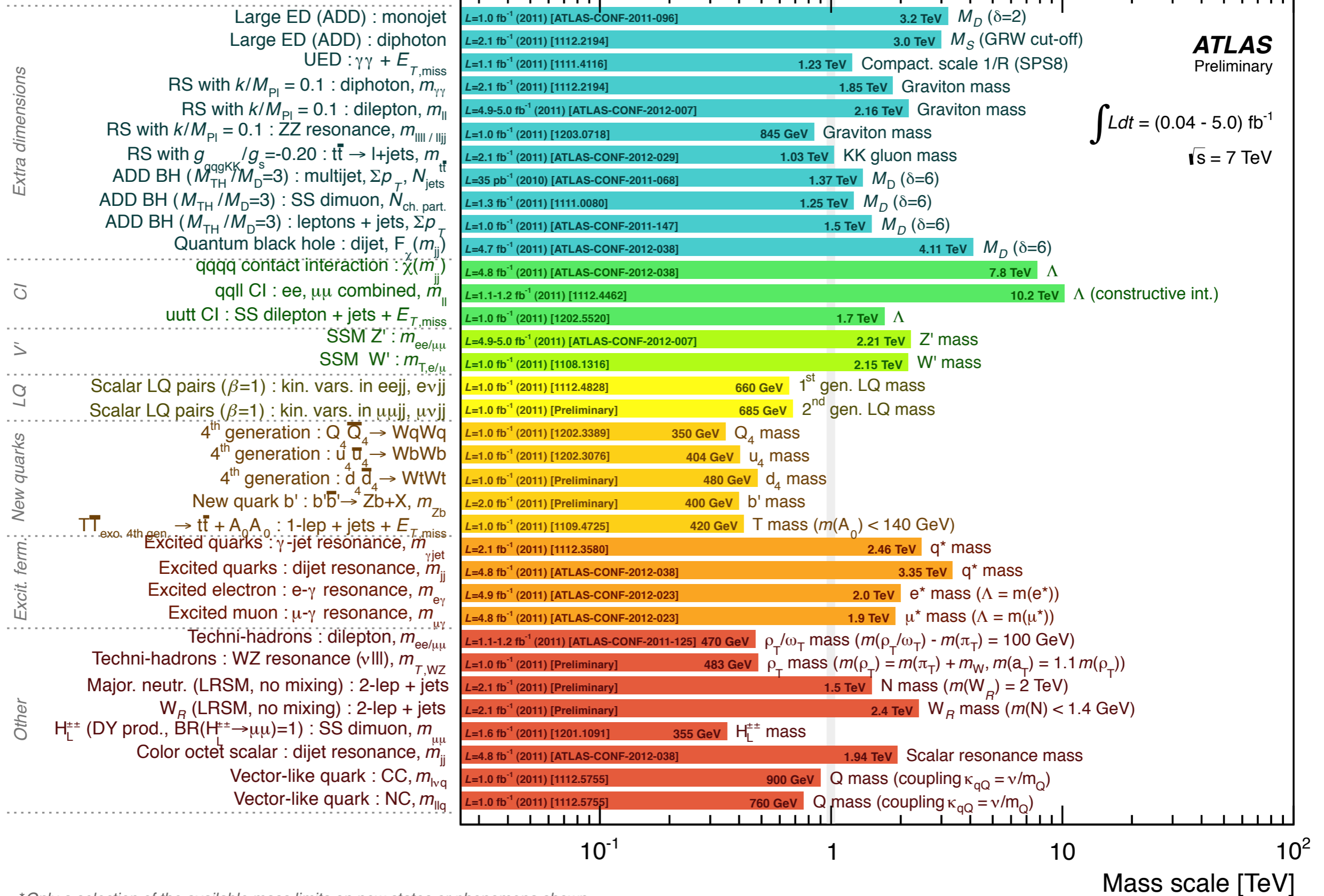
The Higgs postpones the onset of the vector resonance to higher masses w.r.t. to Higgsless models  $\Rightarrow$  improve compatibility with LHC constraints

Strongest direct constraints on the  $\rho$  come from di-boson searches at LHC  
 $\rho^\pm \rightarrow W^\pm Z \rightarrow 3 l + \nu$ .



From CMS results the interesting range  $700 \text{ GeV} < m_\rho < 2 \text{ TeV}$  is allowed

# ATLAS Exotics Searches\* - 95% CL Lower Limits (Status: March 2012)



\*Only a selection of the available mass limits on new states or phenomena shown

# ATLAS SUSY Searches\* - 95% CL Lower Limits (Status: ICHEP 2012)

**Inclusive searches**

MSUGRA/CMSSM : 0 lep + j's +  $E_{T,miss}$

MSUGRA/CMSSM : 1 lep + j's +  $E_{T,miss}$

MSUGRA/CMSSM : 0 lep + multijets +  $E_{T,miss}$

Pheno model : 0 lep + j's +  $E_{T,miss}$

Pheno model : 0 lep + j's +  $E_{T,miss}$

Glauino med.  $\tilde{\chi}^\pm$  ( $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}^\pm$ ) : 1 lep + j's +  $E_{T,miss}$

GMSB : 2 lep OSSF +  $E_{T,miss}$

GMSB : 1- $\tau$  + j's +  $E_{T,miss}$

GMSB : 2- $\tau$  + j's +  $E_{T,miss}$

GGM :  $\gamma\gamma$  +  $E_{T,miss}$

**3rd gen. squarks gluino mediated**

$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  (virtual  $\tilde{b}$ ) : 0 lep + 1/2 b-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  (virtual  $\tilde{b}$ ) : 0 lep + 3 b-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$  (real  $\tilde{b}$ ) : 0 lep + 3 b-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (virtual  $\tilde{t}$ ) : 1 lep + 1/2 b-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (virtual  $\tilde{t}$ ) : 2 lep (SS) + j's +  $E_{T,miss}$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (virtual  $\tilde{t}$ ) : 0 lep + multi-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (virtual  $\tilde{t}$ ) : 0 lep + 3 b-j's +  $E_{T,miss}$

$\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$  (real  $\tilde{t}$ ) : 0 lep + 3 b-j's +  $E_{T,miss}$

**3rd gen. squarks direct production**

$b\bar{b}, b_1 \rightarrow b\tilde{\chi}_1^0$  : 0 lep + 2-b-jets +  $E_{T,miss}$

$t\bar{t}$  (very light),  $\tilde{t} \rightarrow b\tilde{\chi}_1^+$  : 2 lep +  $E_{T,miss}$

$t\bar{t}$  (light),  $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$  : 1/2 lep + b-jet +  $E_{T,miss}$

$t\bar{t}$  (heavy),  $\tilde{t} \rightarrow t\tilde{\chi}_1^0$  : 0 lep + b-jet +  $E_{T,miss}$

$t\bar{t}$  (heavy),  $\tilde{t} \rightarrow t\tilde{\chi}_1^0$  : 1 lep + b-jet +  $E_{T,miss}$

$t\bar{t}$  (heavy),  $\tilde{t} \rightarrow t\tilde{\chi}_1^0$  : 2 lep + b-jet +  $E_{T,miss}$

$t\bar{t}$  (GMSB) :  $Z(\rightarrow ll)$  + b-jet +  $E_{T,miss}$

**EW direct**

$\tilde{l}_L, \tilde{l} \rightarrow l\tilde{\chi}_1^0$  : 2 lep +  $E_{T,miss}$

$\tilde{\chi}_1^+, \tilde{\chi}_1^0, \tilde{\chi}_1^- \rightarrow l\nu(\bar{\nu}) \rightarrow l\nu\tilde{\chi}_1^0$  : 2 lep +  $E_{T,miss}$

$\tilde{\chi}_1^\pm, \tilde{\chi}_2^0 \rightarrow 3l(l\nu\nu) + \nu + 2\tilde{\chi}_1^0$  : 3 lep +  $E_{T,miss}$

AMSB : long-lived  $\tilde{\chi}_1^\pm$

**Long-lived particles**

Stable  $\tilde{g}$  R-hadrons : Full detector

Stable  $\tilde{b}$  R-hadrons : Full detector

Stable  $\tilde{t}$  R-hadrons : Full detector

Metastable  $\tilde{g}$  R-hadrons : Pixel det. only

GMSB : stable  $\tilde{\tau}$

**RPV**

RPV : high-mass  $e\mu$

Bilinear RPV : 1 lep + j's +  $E_{T,miss}$

BC1 RPV : 4 lep +  $E_{T,miss}$

**Other**

Hypercolour scalar gluons : 4 jets,  $m_{ij} \approx m_{kl}$

Spin dep. WIMP interaction : monojet +  $E_{T,miss}$

Spin indep. WIMP interaction : monojet +  $E_{T,miss}$

|  |             |   |
|--|-------------|---|
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-033] | 1.40 TeV    | $\tilde{q} = \tilde{g}$ mass  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-041] | 1.20 TeV    | $\tilde{q} = \tilde{g}$ mass  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [1206.1760]           | 840 GeV     | $\tilde{g}$ mass (large $m_0$ )   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-033] | 1.38 TeV    | $\tilde{q}$ mass ( $m(\tilde{g}) < 2$ TeV, light $\tilde{\chi}_1^0$ )   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-033] | 940 GeV     | $\tilde{g}$ mass ( $m(\tilde{q}) < 2$ TeV, light $\tilde{\chi}_1^0$ )   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-041] | 900 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^\pm) = \frac{1}{2}(m(\tilde{\chi}_1^0) + m(\tilde{g}))$ )                 |
| L=1.0 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2011-156] | 810 GeV     | $\tilde{g}$ mass ( $\tan\beta < 35$ )   |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1204.3852]           | 920 GeV     | $\tilde{g}$ mass ( $\tan\beta > 20$ )   |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1203.6580]           | 990 GeV     | $\tilde{g}$ mass ( $\tan\beta > 20$ )   |
| L=4.8 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-072] | 1.07 TeV    | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) > 50$ GeV)  |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1203.6193]           | 900 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 300$ GeV)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-058] | 1.02 TeV    | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 400$ GeV)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-058] | 1.00 TeV    | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) = 60$ GeV)  |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1203.6193]           | 710 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 150$ GeV)   |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1203.5763]           | 650 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 210$ GeV)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [1206.1760]           | 870 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 100$ GeV)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-058] | 940 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) < 50$ GeV)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-058] | 820 GeV     | $\tilde{g}$ mass ( $m(\tilde{\chi}_1^0) = 60$ GeV)  |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1112.3832]           | 390 GeV     | $\tilde{b}$ mass ( $m(\tilde{\chi}_1^0) < 60$ GeV)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-059]       | 135 GeV     | $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 45$ GeV)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-070]       | 120-173 GeV | $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 45$ GeV)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-074]       | 380-465 GeV | $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-073]       | 230-440 GeV | $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-071]       | 298-305 GeV | $\tilde{t}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )  |
| L=2.1 fb <sup>-1</sup> , 7 TeV [1204.6736]           | 310 GeV     | $\tilde{t}$ mass ( $115 < m(\tilde{\chi}_1^0) < 230$ GeV)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-076]       | 93-180 GeV  | $\tilde{l}$ mass ( $m(\tilde{\chi}_1^0) = 0$ )  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-076]       | 120-330 GeV | $\tilde{\chi}_1^\pm$ mass ( $m(\tilde{\chi}_1^0) = 0, m(\tilde{l}, \tilde{\nu}) = \frac{1}{2}(m(\tilde{\chi}_1^\pm) + m(\tilde{\chi}_1^0))$ ) |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-077]       | 60-500 GeV  | $\tilde{\chi}_1^\pm$ mass ( $m(\tilde{\chi}_1^0) = m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0) = 0, m(\tilde{l}, \tilde{\nu})$ as above)         |
| L=4.7 fb <sup>-1</sup> , 7 TeV [CONF-2012-034]       | 118 GeV     | $\tilde{\chi}_1^\pm$ mass ( $1 < \tau(\tilde{\chi}_1^\pm) < 2$ ns, 90 GeV limit in [0.2, 90] ns)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075] | 985 GeV     | $\tilde{g}$ mass  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075] | 612 GeV     | $\tilde{b}$ mass  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075] | 683 GeV     | $\tilde{t}$ mass  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075] | 910 GeV     | $\tilde{g}$ mass ( $\tau(\tilde{g}) > 10$ ns)   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-075] | 310 GeV     | $\tilde{\tau}$ mass ( $5 < \tan\beta < 20$ )  |
| L=1.1 fb <sup>-1</sup> , 7 TeV [1109.3089]           | 1.32 TeV    | $\tilde{\nu}_\tau$ mass ( $\lambda'_{311}=0.10, \lambda'_{312}=0.05$ )  |
| L=1.0 fb <sup>-1</sup> , 7 TeV [1109.6606]           | 760 GeV     | $\tilde{q} = \tilde{g}$ mass ( $c\tau_{LSP} < 15$ mm)   |
| L=2.1 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-035] | 1.77 TeV    | $\tilde{g}$ mass  |
| L=34 pb <sup>-1</sup> , 7 TeV [1110.2693]            | 100-185 GeV | sgluon mass (not excluded: $m_{sg} \approx 140 \pm 3$ GeV)  |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-084] | 709 GeV     | $M^*$ scale ( $m_\chi < 100$ GeV, vector D5, Dirac $\chi$ )   |
| L=4.7 fb <sup>-1</sup> , 7 TeV [ATLAS-CONF-2012-084] | 548 GeV     | $M^*$ scale ( $m_\chi < 100$ GeV, tensor D9, Dirac $\chi$ )   |

$\int L dt = (0.03 - 4.8) \text{ fb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$

**ATLAS**  
Preliminary

10<sup>-1</sup> 1 10  
Mass scale [TeV]

\* Only a selection of the available mass limits on new states or phenomena shown

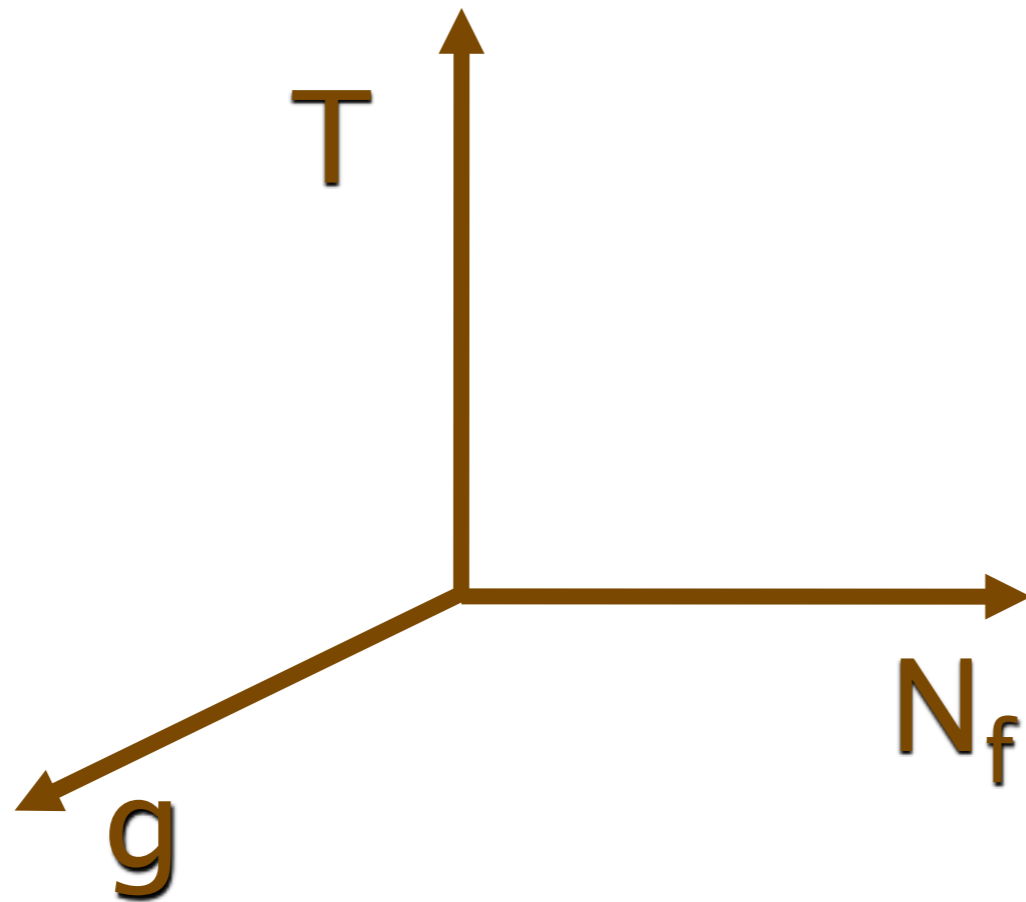


# More on the role of Conformal Symmetry

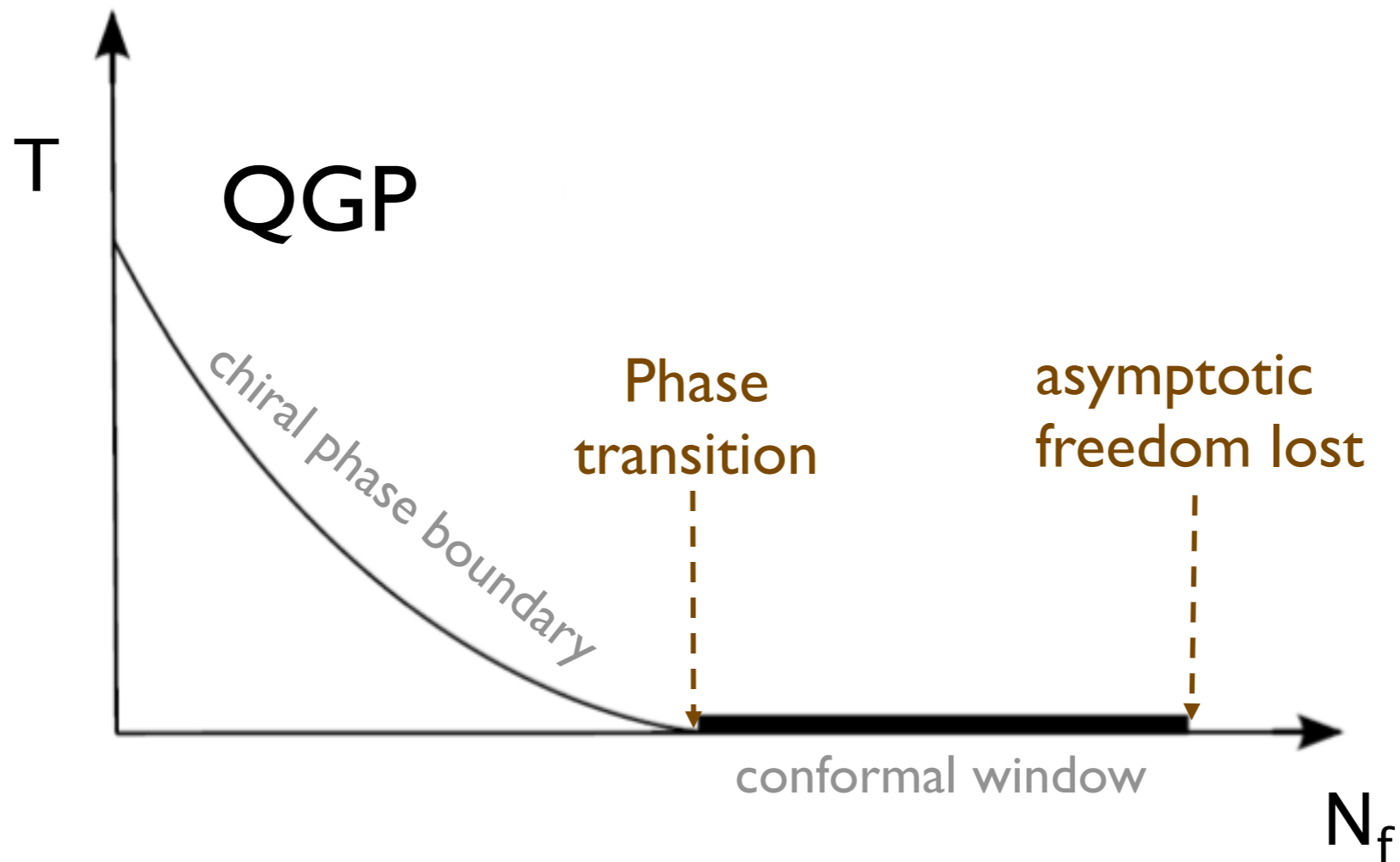
A pedagogical example

What is the fixed point structure of fundamental forces?

# The phase diagram of $SU(N)$ gauge theories



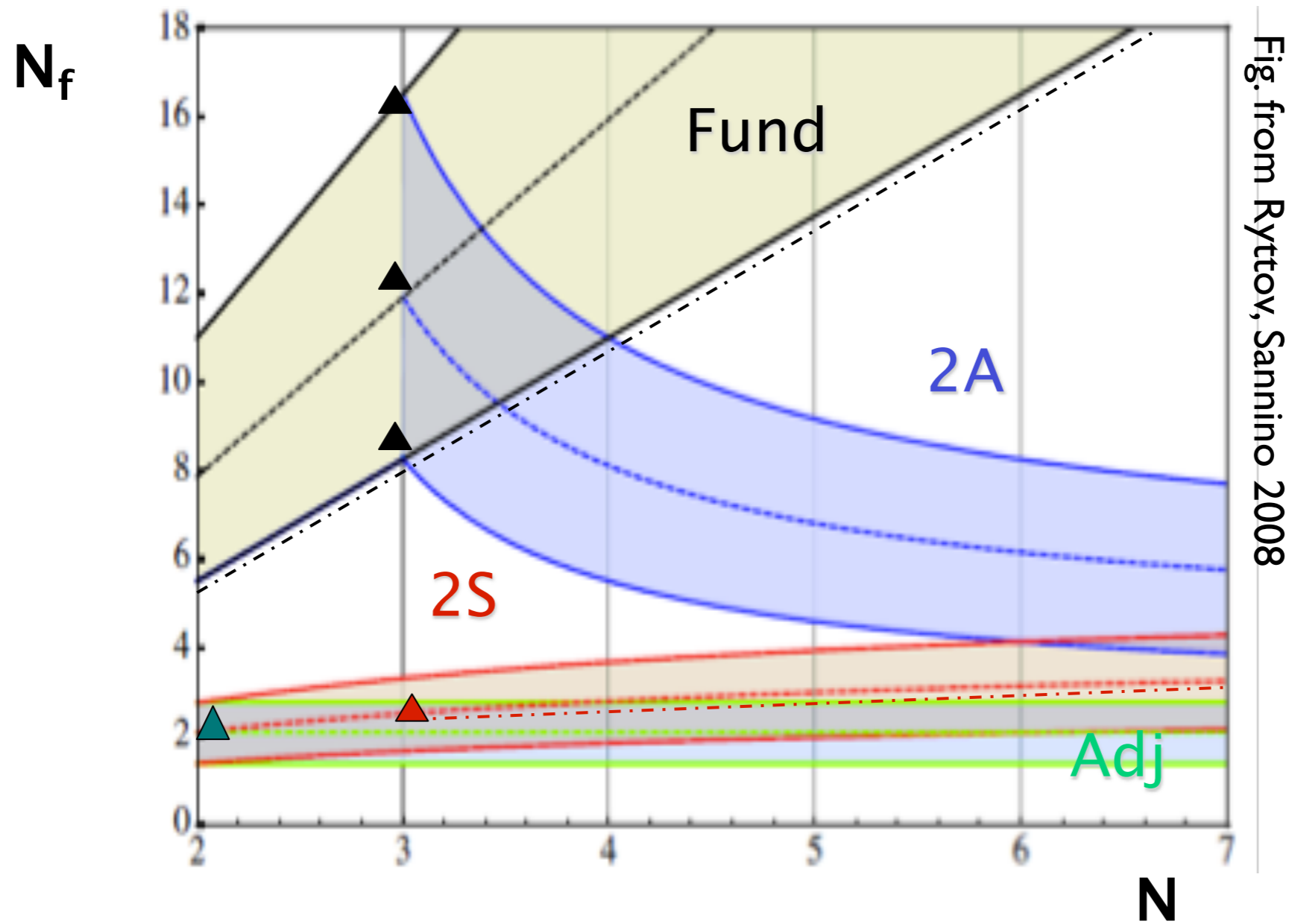
# QCD: fundamental fermions



Physics of:

- ✓ quark gluon plasma (QGP): high  $T$  - low  $N_f$
- ✓ preconformal regime ( $T=0$ , low  $T$  - high  $N_f$ )
- ✓ conformal regime ( $T=0$ )

# Less flavour for larger Casimir



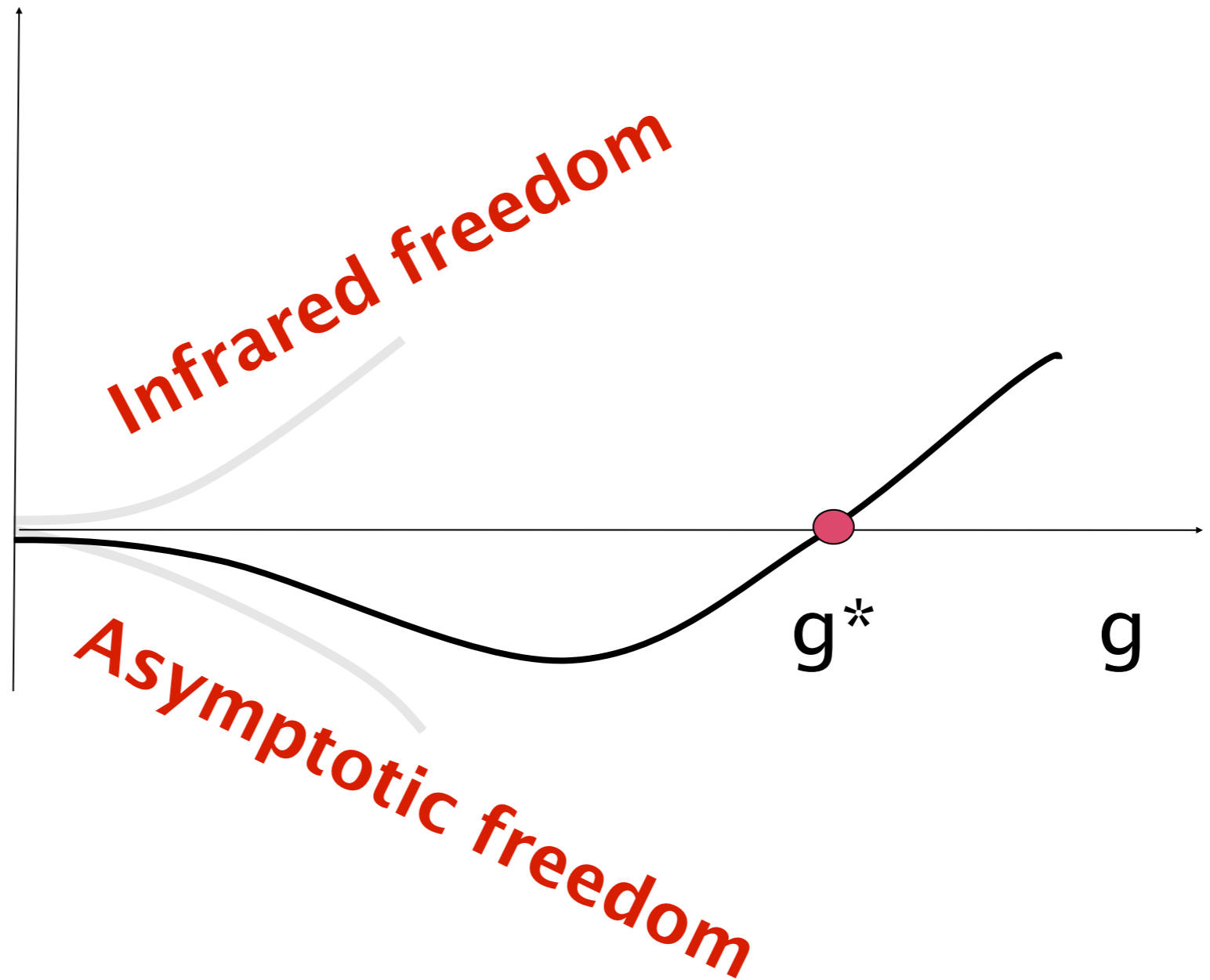
$$\beta(g) = -b_0 g^3 - b_1 g^5 + \dots$$

The first two (universal) coefficients  
change sign by varying flavours

Caswell 1974  
Banks,Zaks 1982

$$b_0 = \frac{1}{16\pi^2} \left( \underset{\substack{\uparrow \\ N=3}}{11} - \frac{2}{3} N_f \right) \quad b_1 = \frac{1}{(16\pi^2)^2} \left( \underset{\substack{\uparrow \\ N=3}}{102} - \frac{38}{3} N_f \right)$$

$$\beta(g) = \mu \frac{dg}{d\mu}$$



The 4D theory is conformal at  $g^*$  with anomalous dimensions

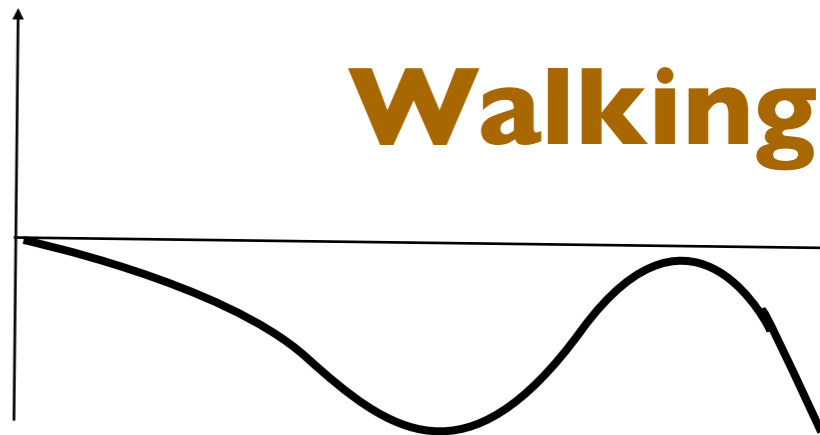
$\beta(g)$

$N_f < N_f^c$

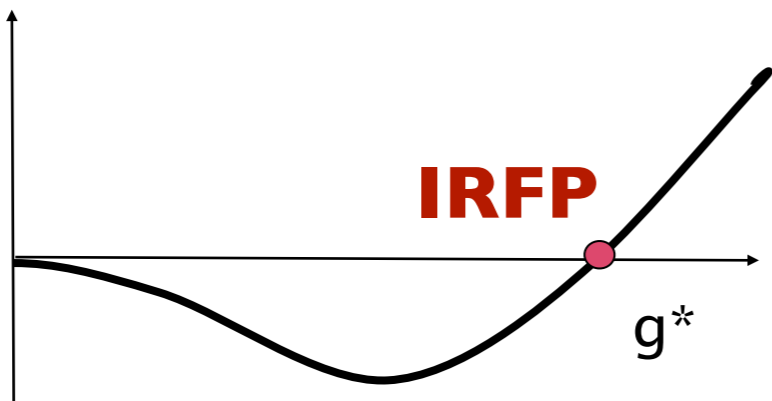


$N_f \approx N_f^c$

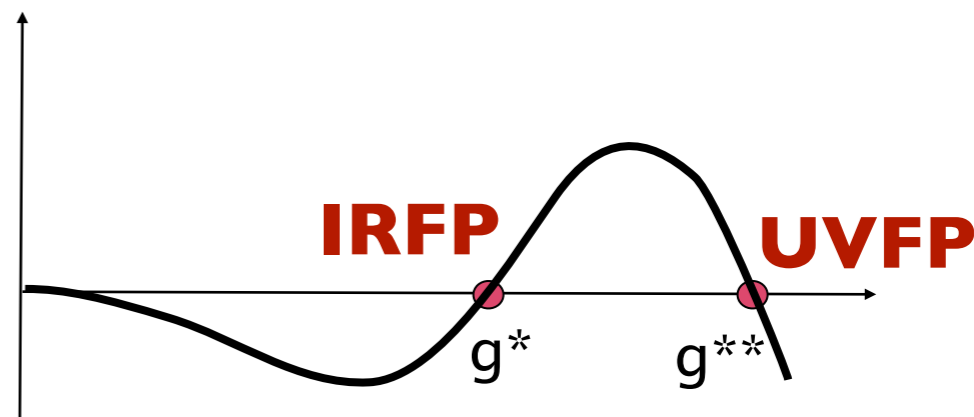
**Walking ?**



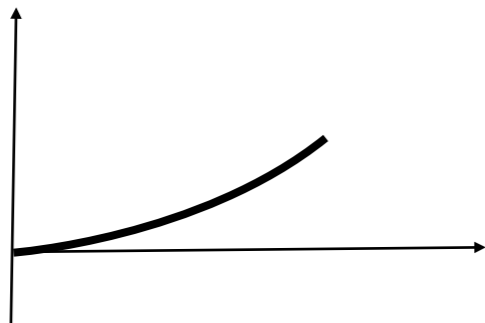
$N_f^{AF} > N_f > N_f^c$



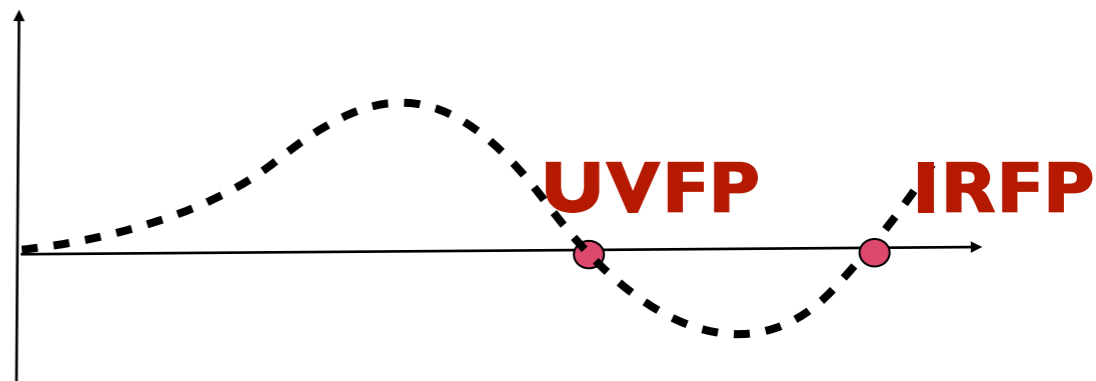
or



$N_f > N_f^{AF}$

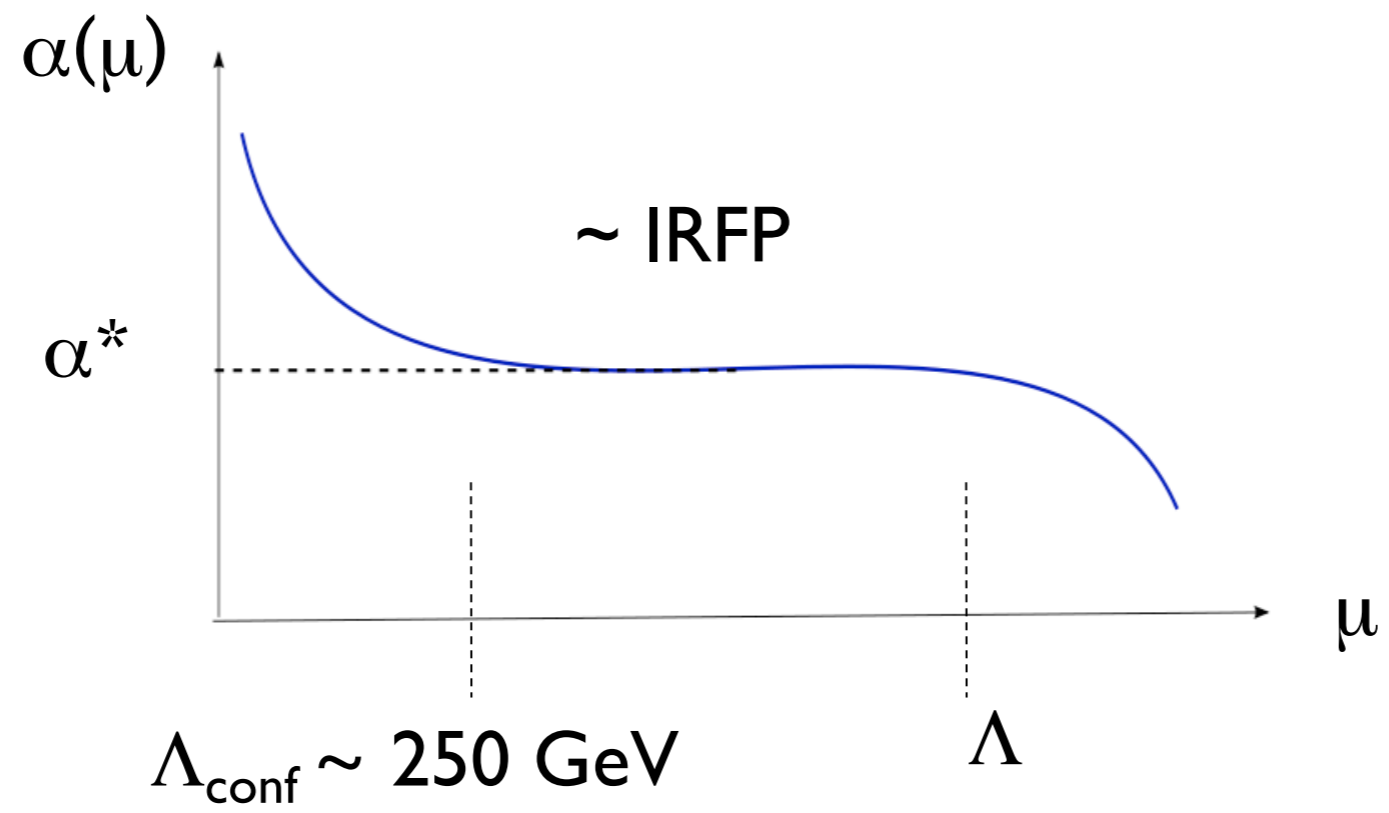


or





# Walking regime

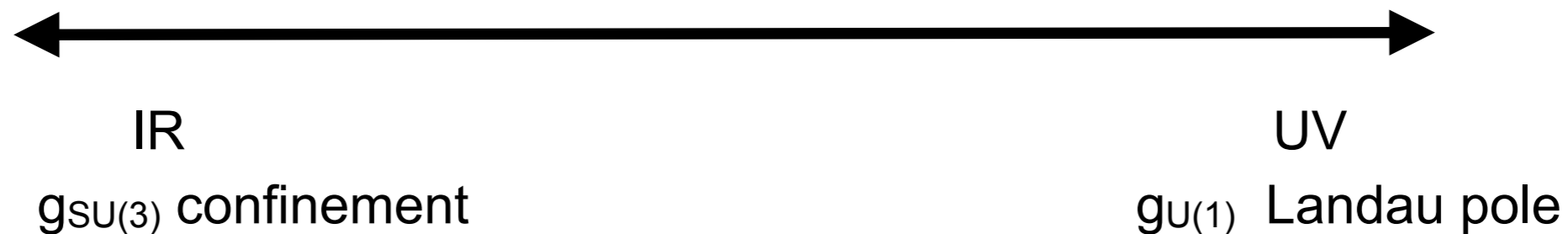


Large and slowly running anomalous dimensions

$$\langle \bar{\psi}\psi \rangle_{\Lambda'} = \langle \bar{\psi}\psi \rangle_{\Lambda} e^{\int_{\Lambda}^{\Lambda'} \frac{d\mu}{\mu} \gamma(\mu)} \simeq \langle \bar{\psi}\psi \rangle_{\Lambda} \left( \frac{\Lambda'}{\Lambda} \right)^{\gamma}$$

produce a large hierarchy of condensates

# The ultraviolet fate of the Standard Model



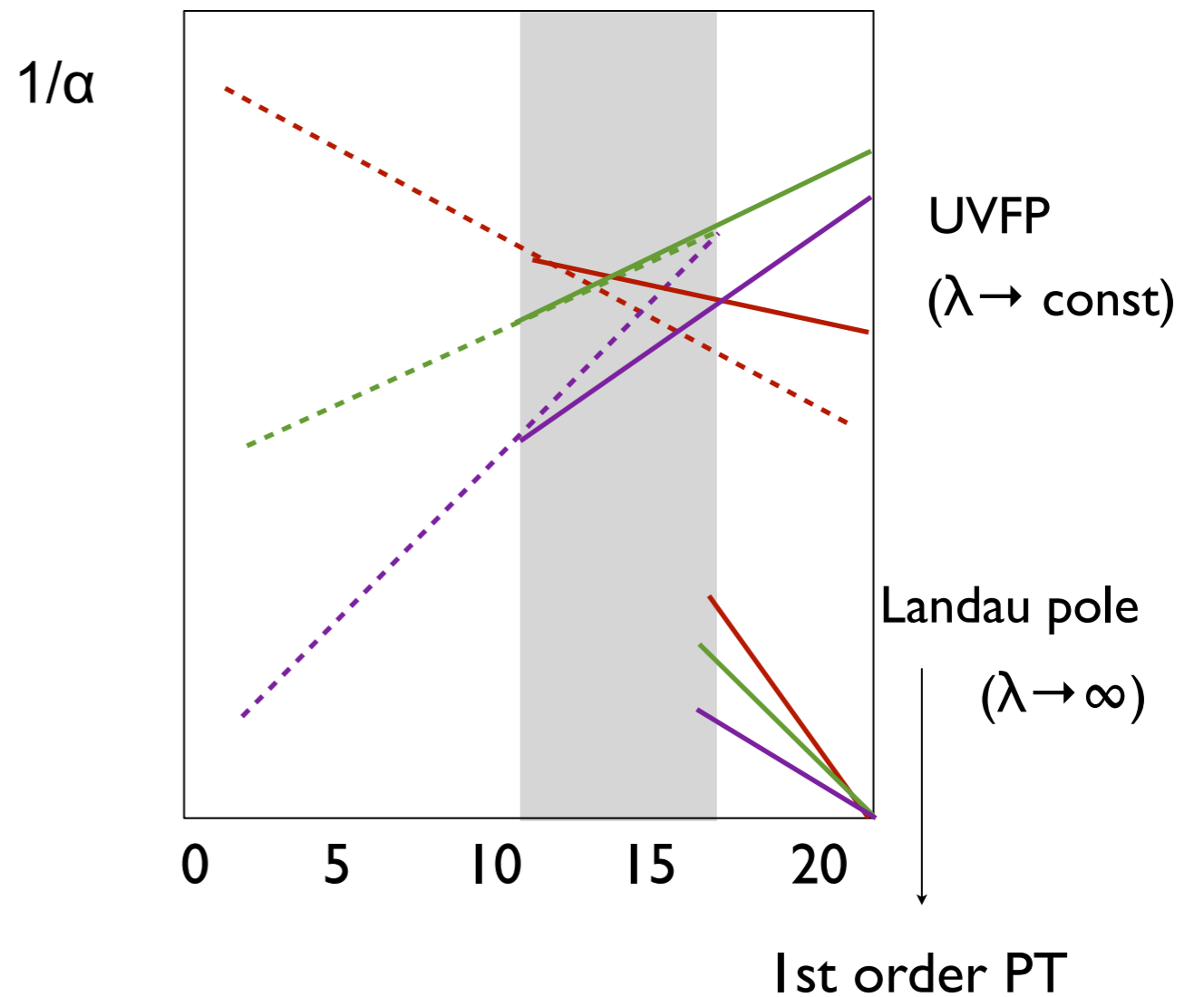
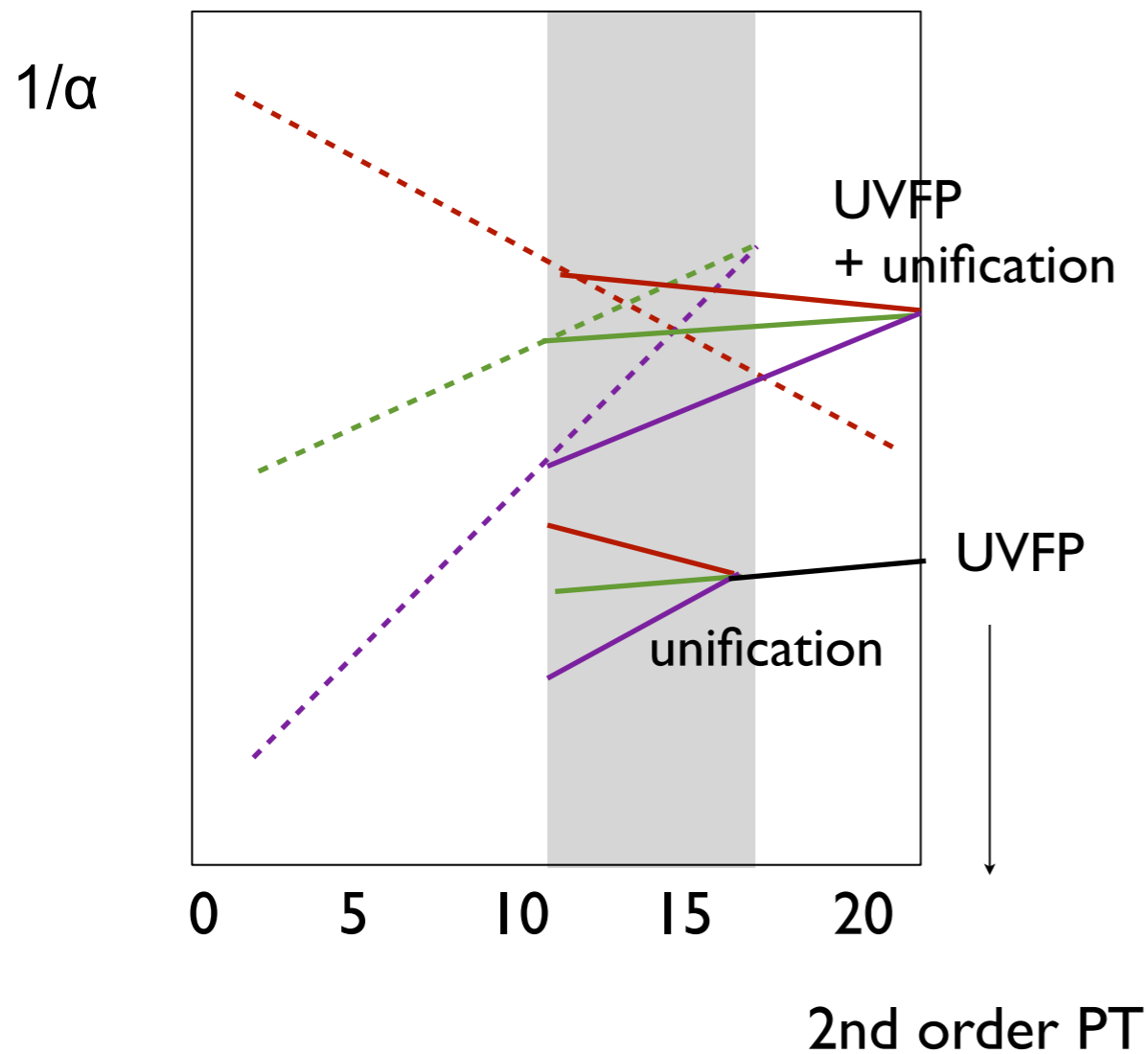
Before the top discovery [Pendleton, Ross 1981]

- i)  $y_t$  and  $\lambda$  share AF and develop an IRFP if only gauge coupling  $g_{SU(3)}$
- ii) running of light quark masses and charged leptons unaffected by  $y_t$ , light down quark masses receive small contributions
- iii) RG running of  $m_b/m_\tau$  dominated by  $y_t$
- iv) gauge couplings unaffected by  $y_t$  at one loop
- v) CKM mixing angles and phase seem to slowly approach an IRFP at zero

# Scenarios at the Planck scale

|   |   |
|---|---|
| <p><b>Ingredients</b></p> <ul style="list-style-type: none"> <li>New particle thresholds</li> <li>New symmetries</li> <li>Walking (near-conformal)</li> </ul> | <p><b>Caveats</b></p> <ul style="list-style-type: none"> <li>Failure of e.g. SU(5)</li> <li><math>g_{1,2,3}</math> enter strong coupling <math>\Rightarrow</math> no pert theory</li> </ul> |
|---|---|

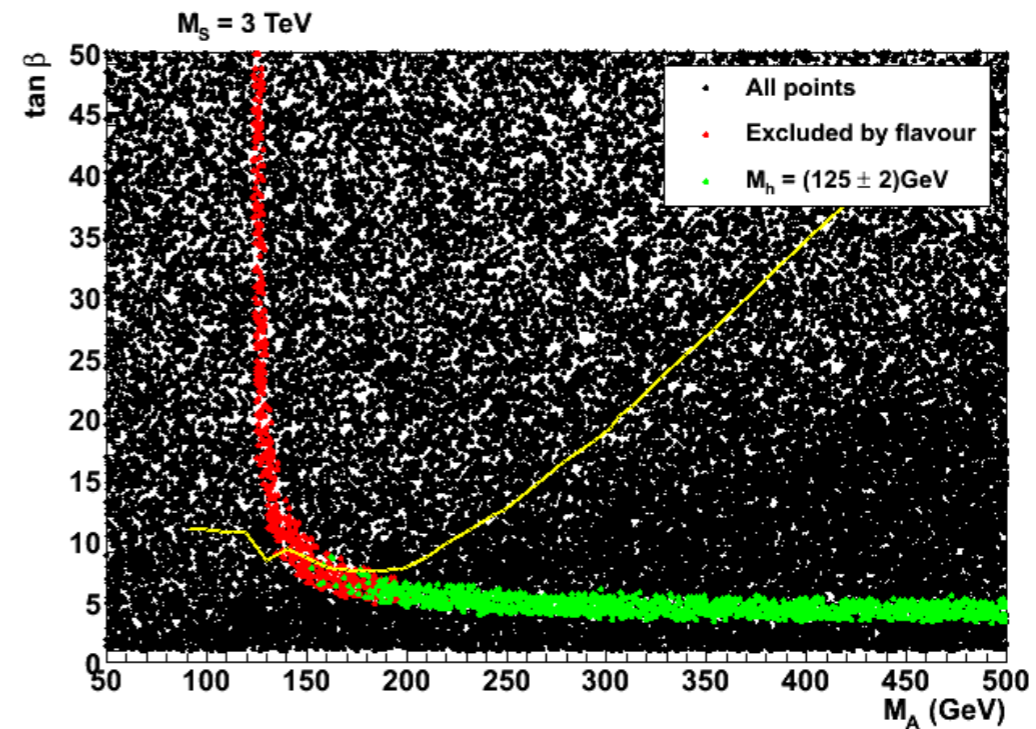
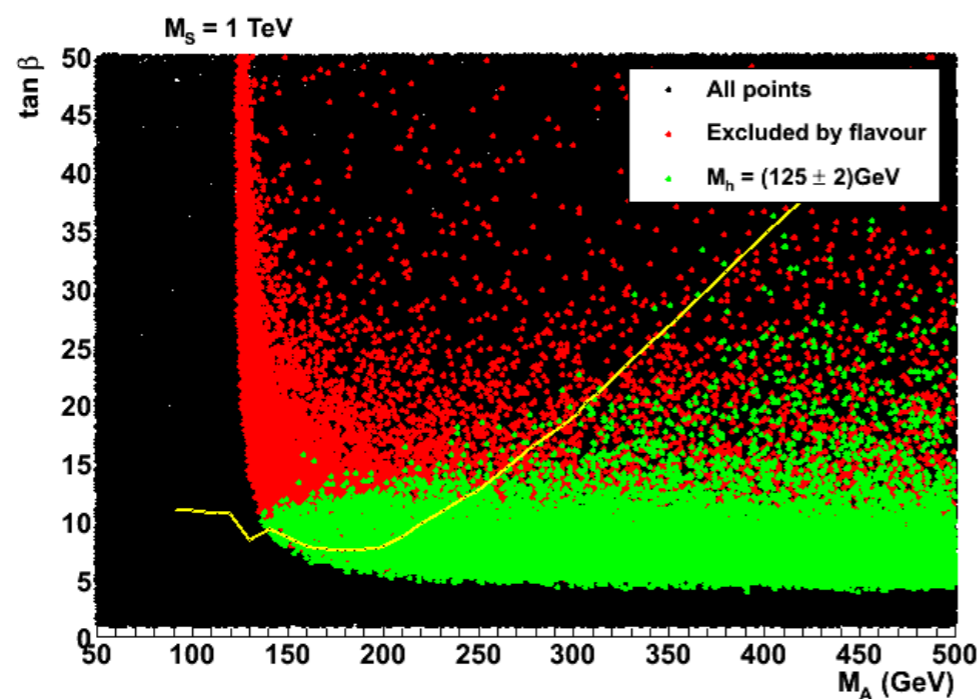
$y_t \rightarrow 0$  for  $\Lambda \rightarrow \Lambda_{\text{Planck}}$  plausible?  
 $\lambda \rightarrow 0$  or  $\lambda \rightarrow \infty$  or  $\lambda \rightarrow \text{const}$  (asymptotic safety)



# Flavour physics

# Flavor@LHC and new physics

SUSY example: pMSSM maximal mixing scenario (N. Mahmoudi, Moriond 2012)



yellow line: CMS limit with 4.6/fb

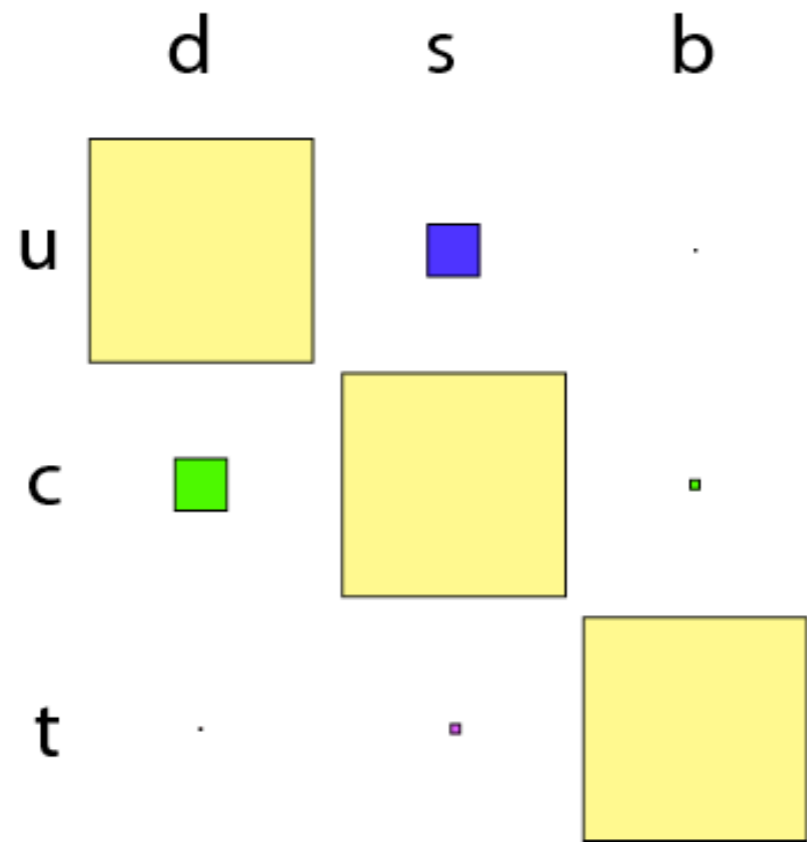
Flavor constraints from:  $b \rightarrow s\gamma$ ,  $B \rightarrow \tau\nu$  and new LHCb limit on  $B_s \rightarrow \mu^+\mu^-$

Assumed discovery of Higgs at  $(125 \pm 2) \text{ GeV}$

# Mass & mixing patterns for quarks and leptons



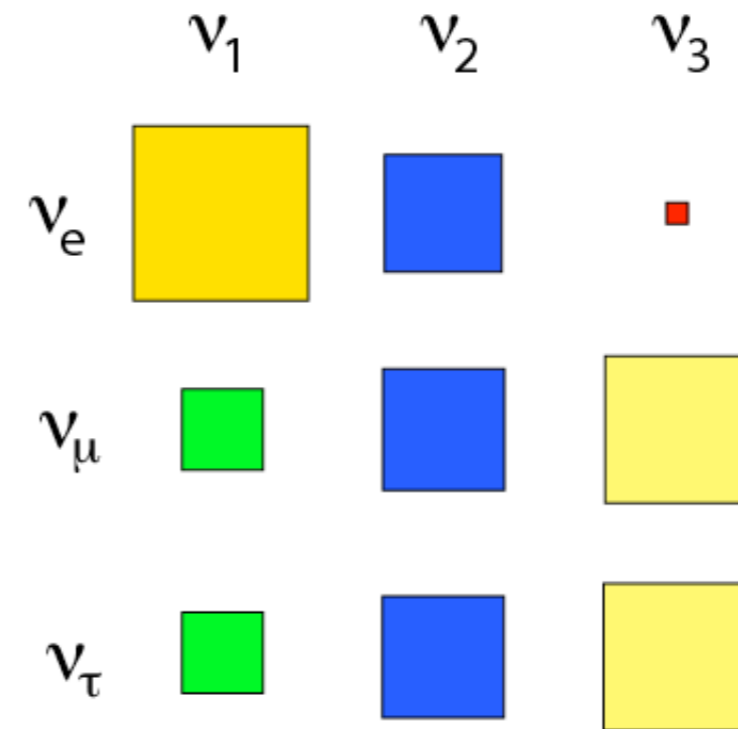
# Experimental mixing patterns



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \dots$$

CKM matrix almost unity



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|V_{PMNS}|^2 = \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix} + \dots$$

PMNS matrix almost tribimaximal

# Neutrinos

## A pedagogical mystery

Mass & mixing matrices

DOUBLE-CHOOZ, DAYA-BAY, RENO

$$7.15 \times 10^{-5} \text{ eV}^2 \leq \Delta m_{solar}^2 \leq 8.00 \times 10^{-5} \text{ eV}^2$$

$$2.27 \times 10^{-3} \text{ eV}^2 \leq \Delta m_{atm}^2 \leq 2.55 \times 10^{-3} \text{ eV}^2$$

$$r = \frac{\Delta m_{solar}^2}{\Delta m_{atm}^2} \simeq \frac{1}{30}$$

$$0.275 \leq \sin^2 \theta_{12} \leq 0.342$$

$$0.348 \leq \sin^2 \theta_{23} \leq 0.448$$

$$0.0193 \leq \sin^2 \theta_{13} \leq 0.0290$$

Pattern of mixing angles

$$\sin^2 \theta_{12} \simeq \frac{1}{3}$$

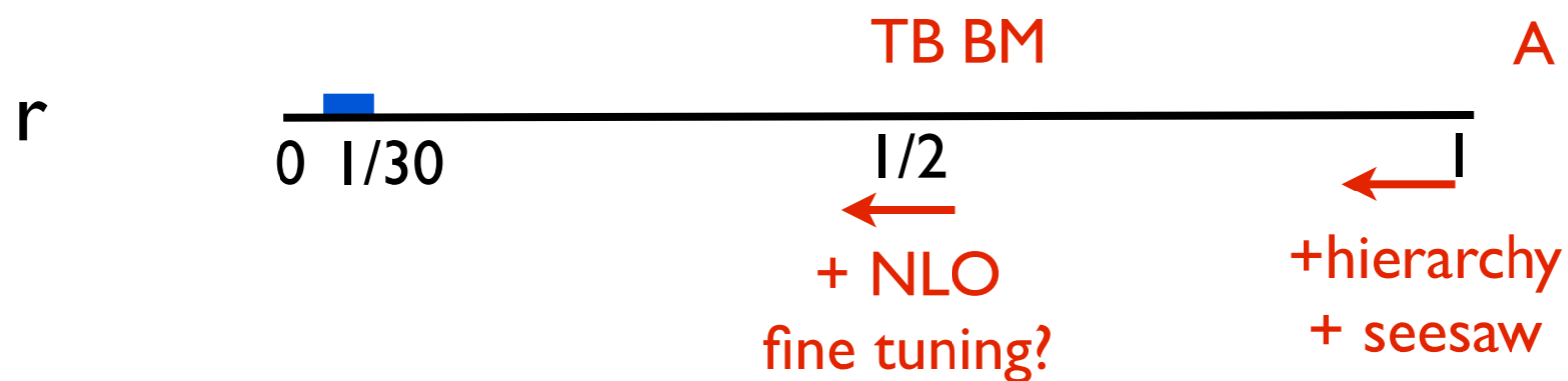
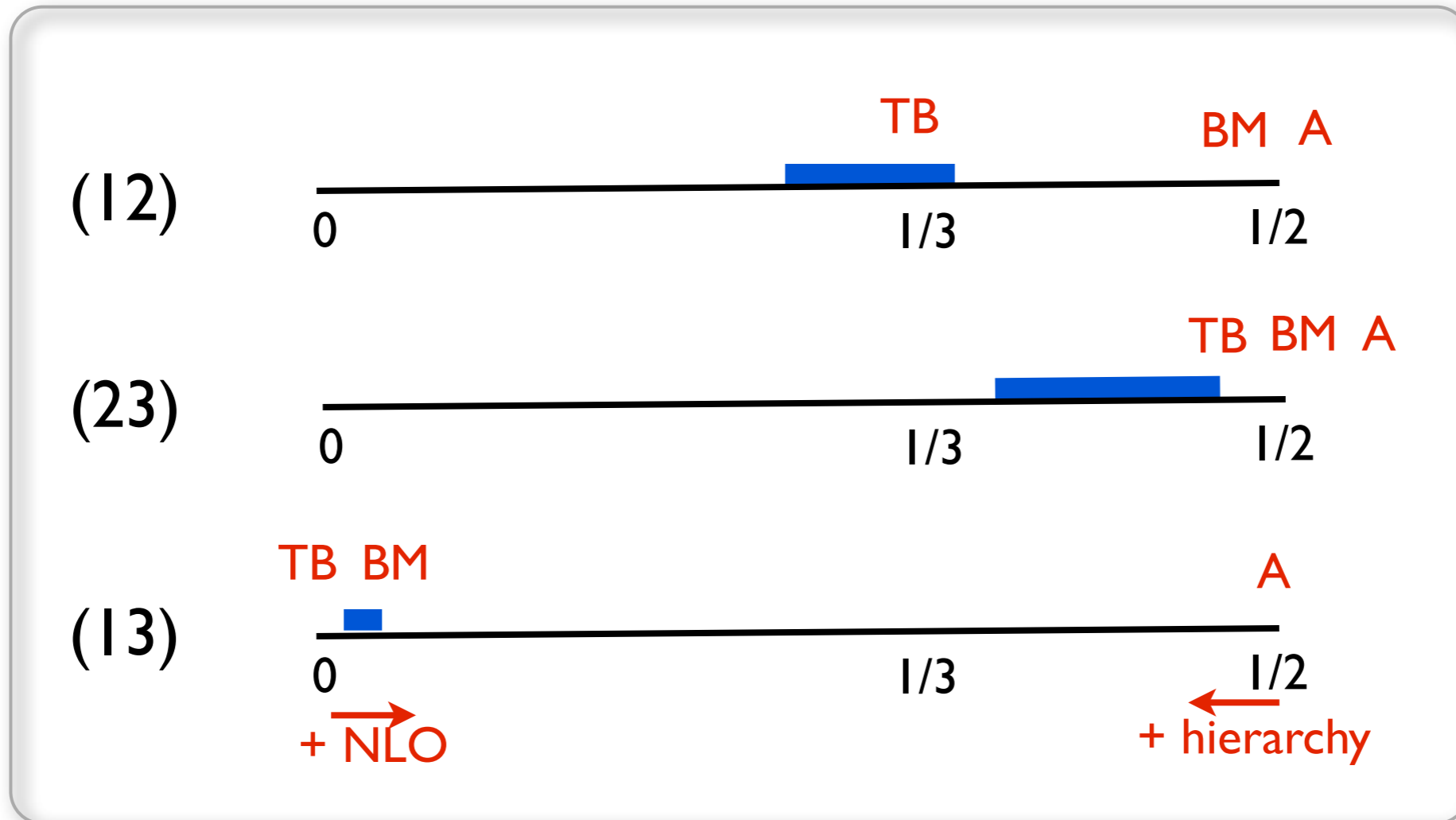
$$\sin^2 \theta_{23} \simeq \frac{1}{2}$$

$$\sin^2 \theta_{13} > 0$$

$$O(\lambda_C^2) < \sin \theta_{13} < O(\lambda_C) \quad \lambda_C = \sin \theta_C$$

→ quark mixing

# Anarchy versus Hierarchy chaos and order

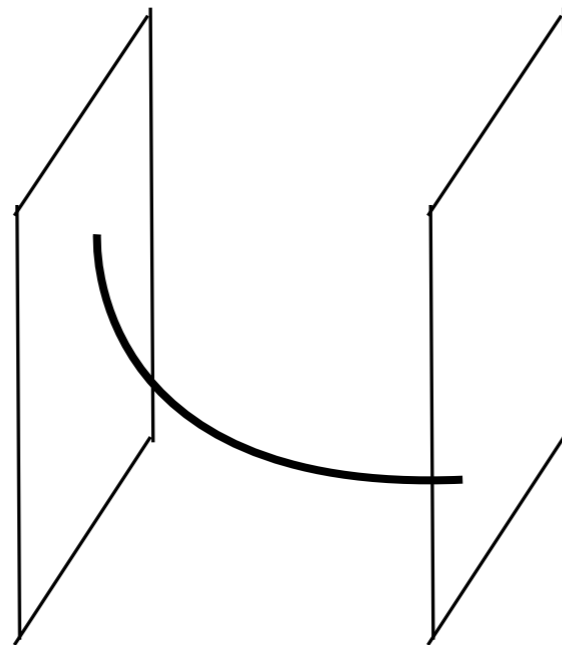


see e.g. Altarelli, Feruglio, Merlo, Stamou 2012

Is there a unified description for quarks & leptons?

Many attempts to a unified description: w and w/o extra dimensions

[e.g. RS-A4 Kadosh EP 2011]



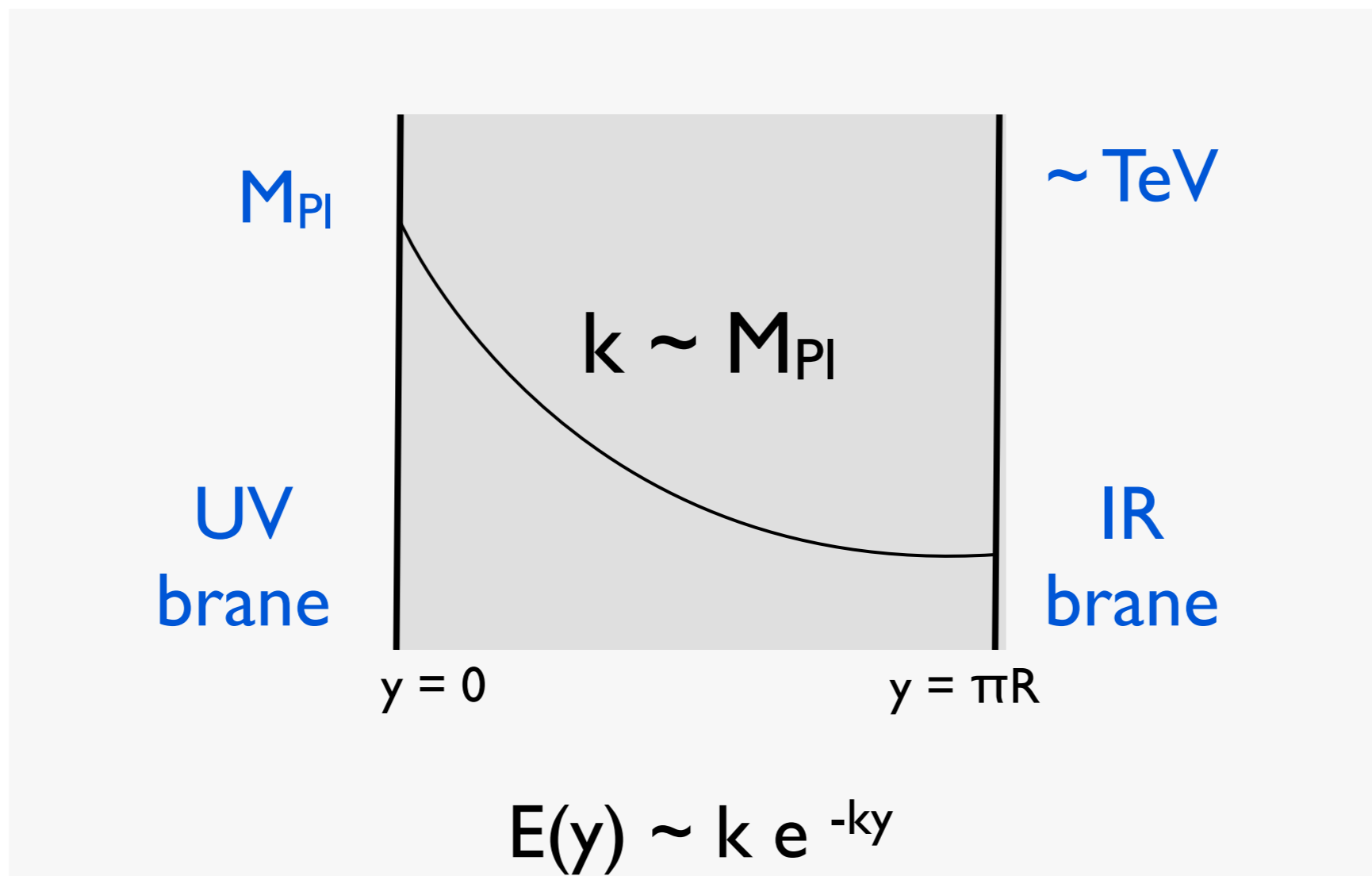
partial compositeness is natural

Powerful discriminators:

EWP parameters  $S, T$  - FCNC processes - CP violation - EDMs - LFV

⇒ High precision flavour physics

# AdS<sub>5</sub> (S<sub>1</sub>/Z<sub>2</sub>)



Two scales:  $k_{\text{UV}} \equiv k \sim M_{\text{Pl}}$

$k_{\text{IR}} \equiv k e^{-\pi k R} \quad k R \cong 1 \quad [\text{KK scale}]$

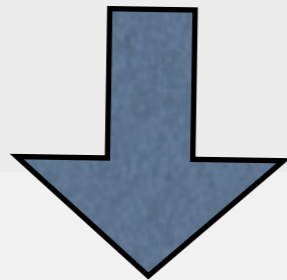
All particles in the bulk  $\Rightarrow$  play with particle localization and symmetries

Zero mode fermions peaked at different points in the bulk  $\Rightarrow$  exponential hierarchy of quarks and charged lepton masses explained by tiny hierarchy of bulk masses and  $O(1)$  5D Yukawas

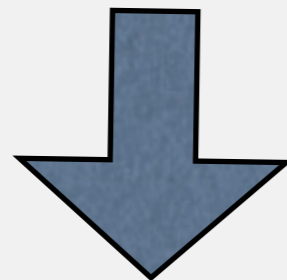


# Anarchy ? or Hierarchy ?

No underlying flavor symmetry to constrain the pattern of 5D Yukawa couplings and bulk mass parameters (non-degeneracy)

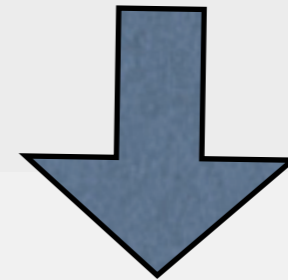


Large FCNC and CP violation  
(little CP problem)

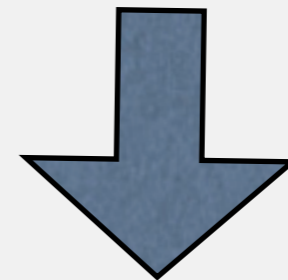


Custodial symmetry augmented with PLR  
to bring down the KK scale to a few TeV

Underlying bulk flavor symmetry  
5D MFV

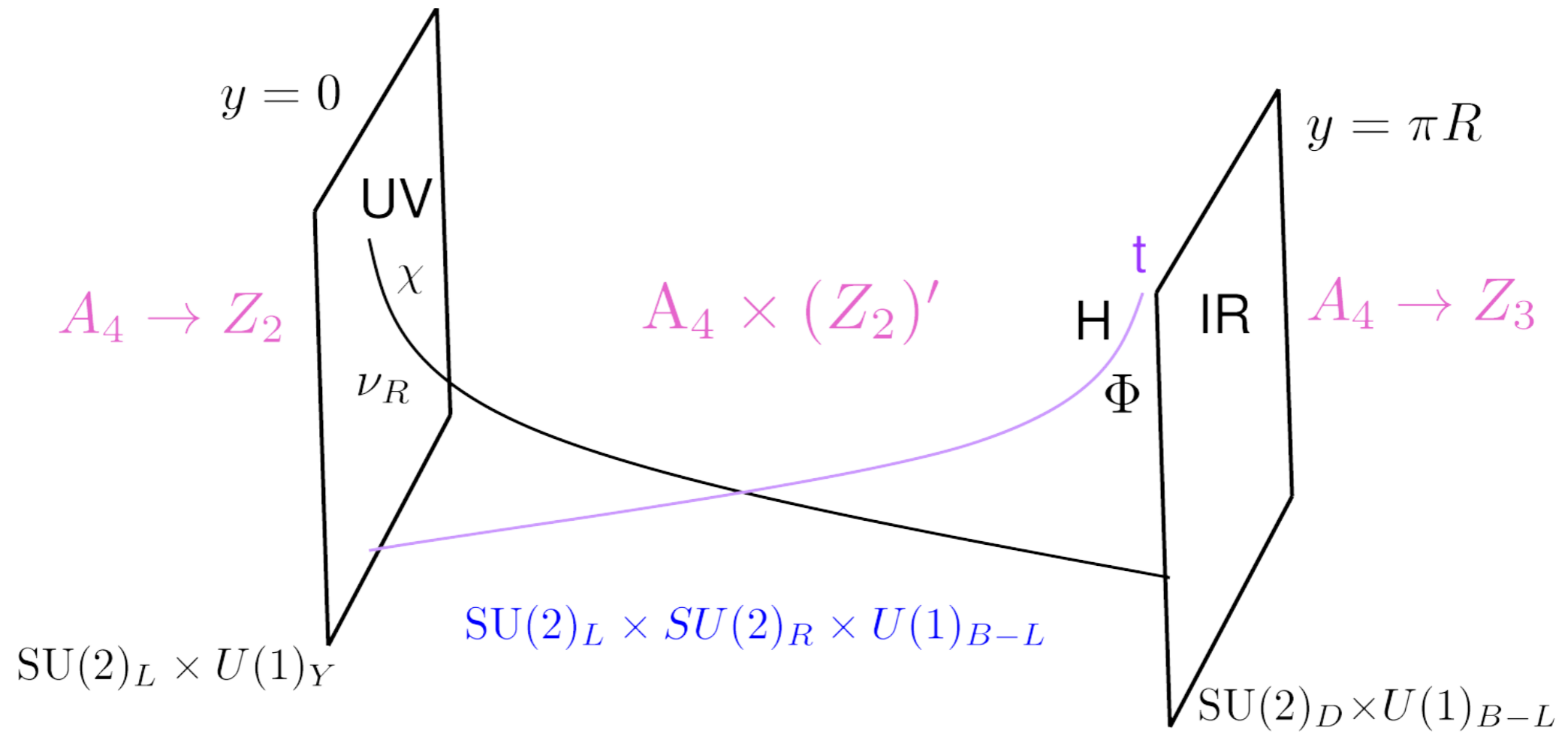


Alignment of Yukawas and masses  
Absence of tree level FCNC

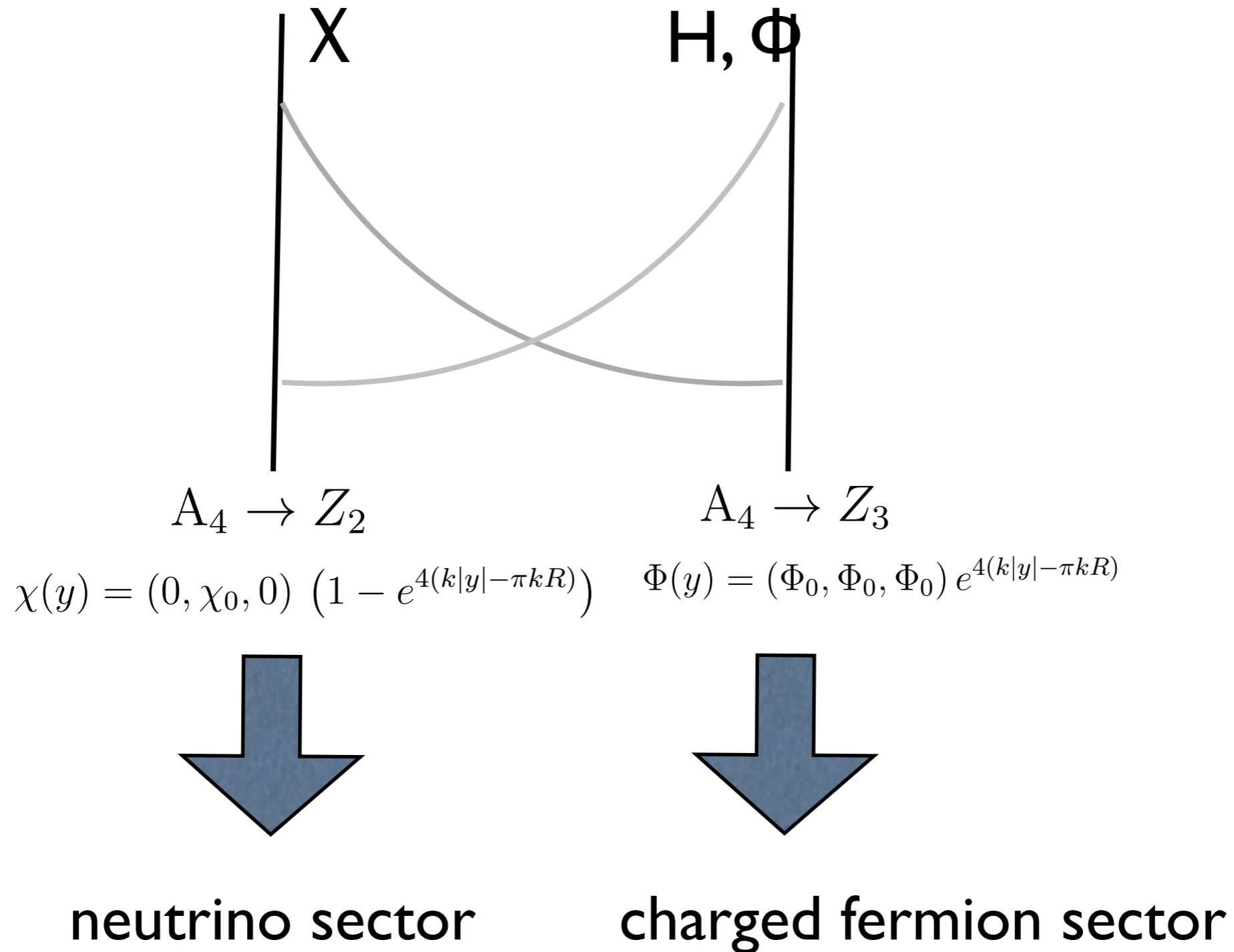


Naturally low KK scale and milder  
little CP problem

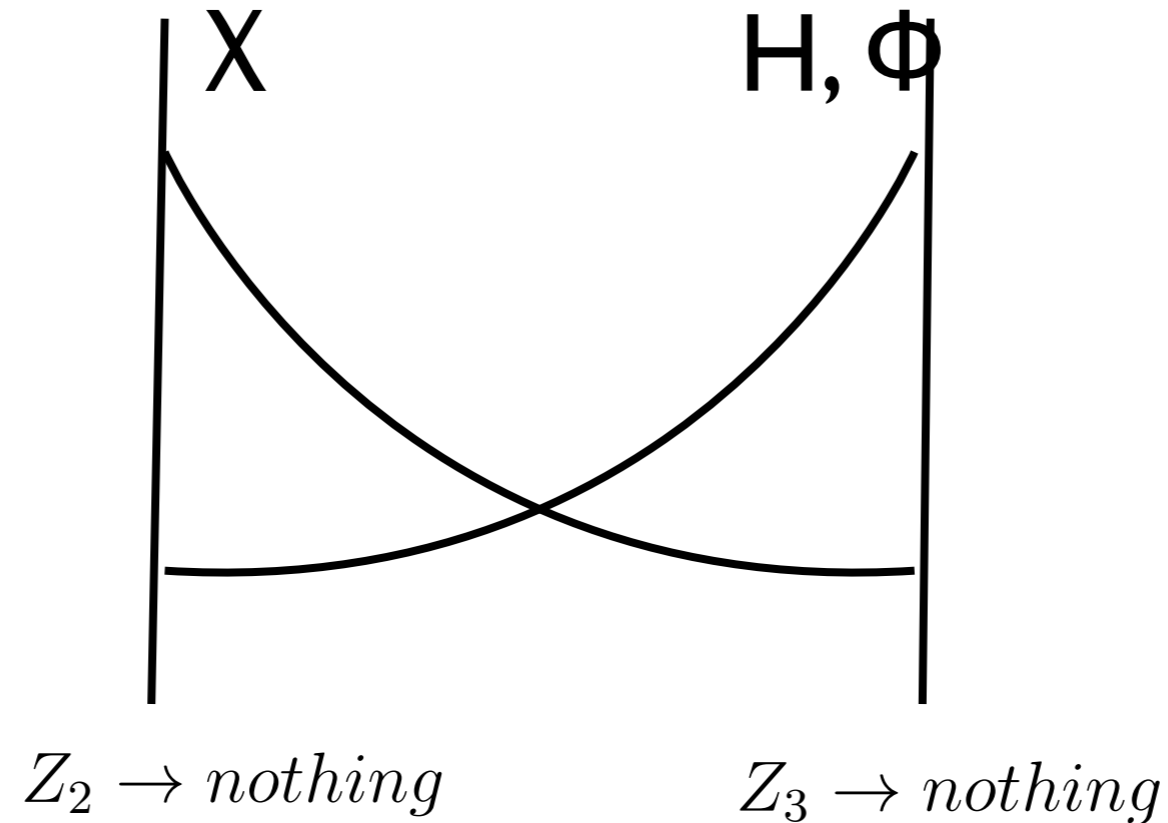
# The RS-A4 model



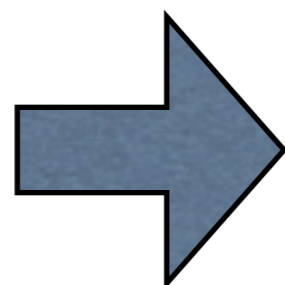
# Masses and mixings at Leading Order



# CKM from cross-talk



cross-brane flavon interactions induce cross-talk  
between neutrino and charged sector



CKM  $\neq$  I  
and deviations from tribimaximal form

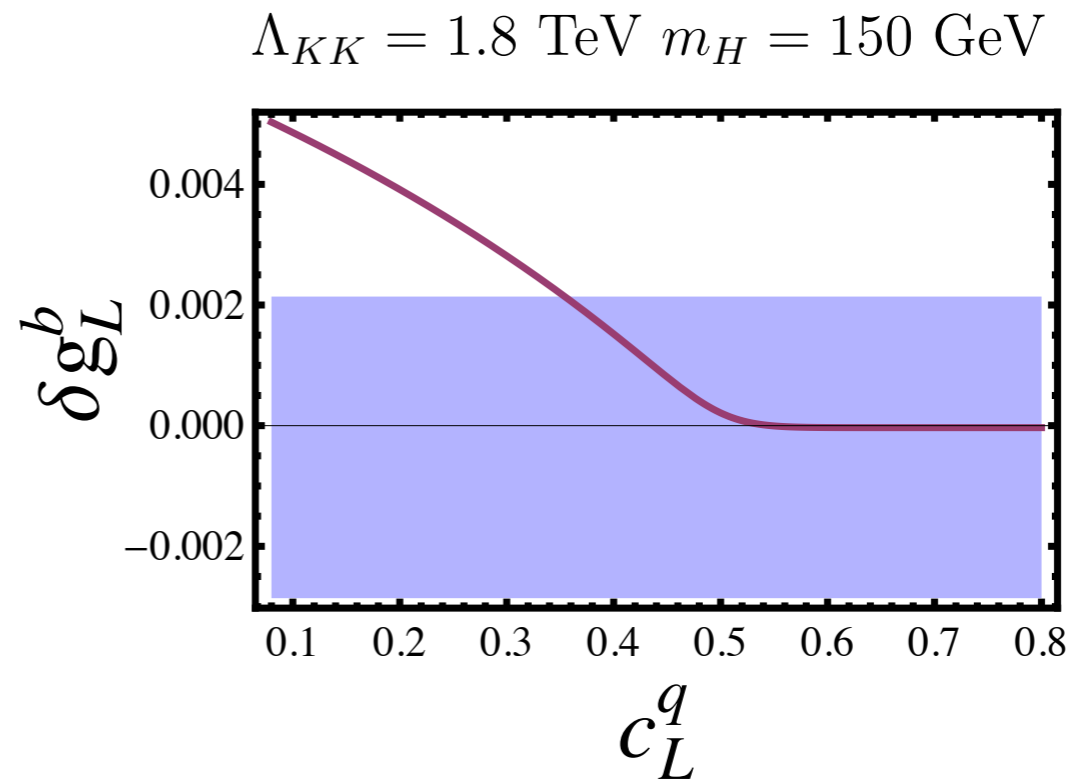
# Phenomenology of RS-A4

Degenerate  $c_L$

Zbb constraint

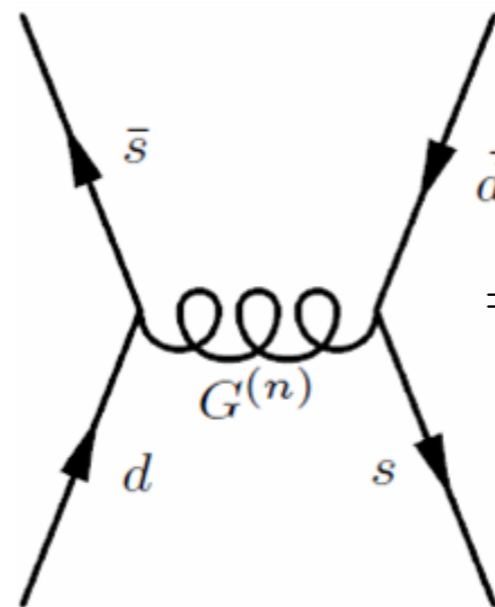
Lower  $c_L \leftrightarrow$  higher  $\Lambda_{KK}$

Reduced window for lighter Higgs



Absence of tree level FCNC

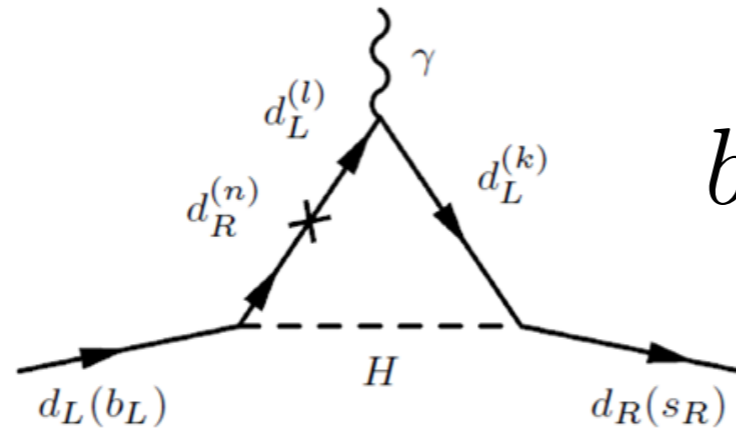
e.g.  $\epsilon_K^{NP} = 0$



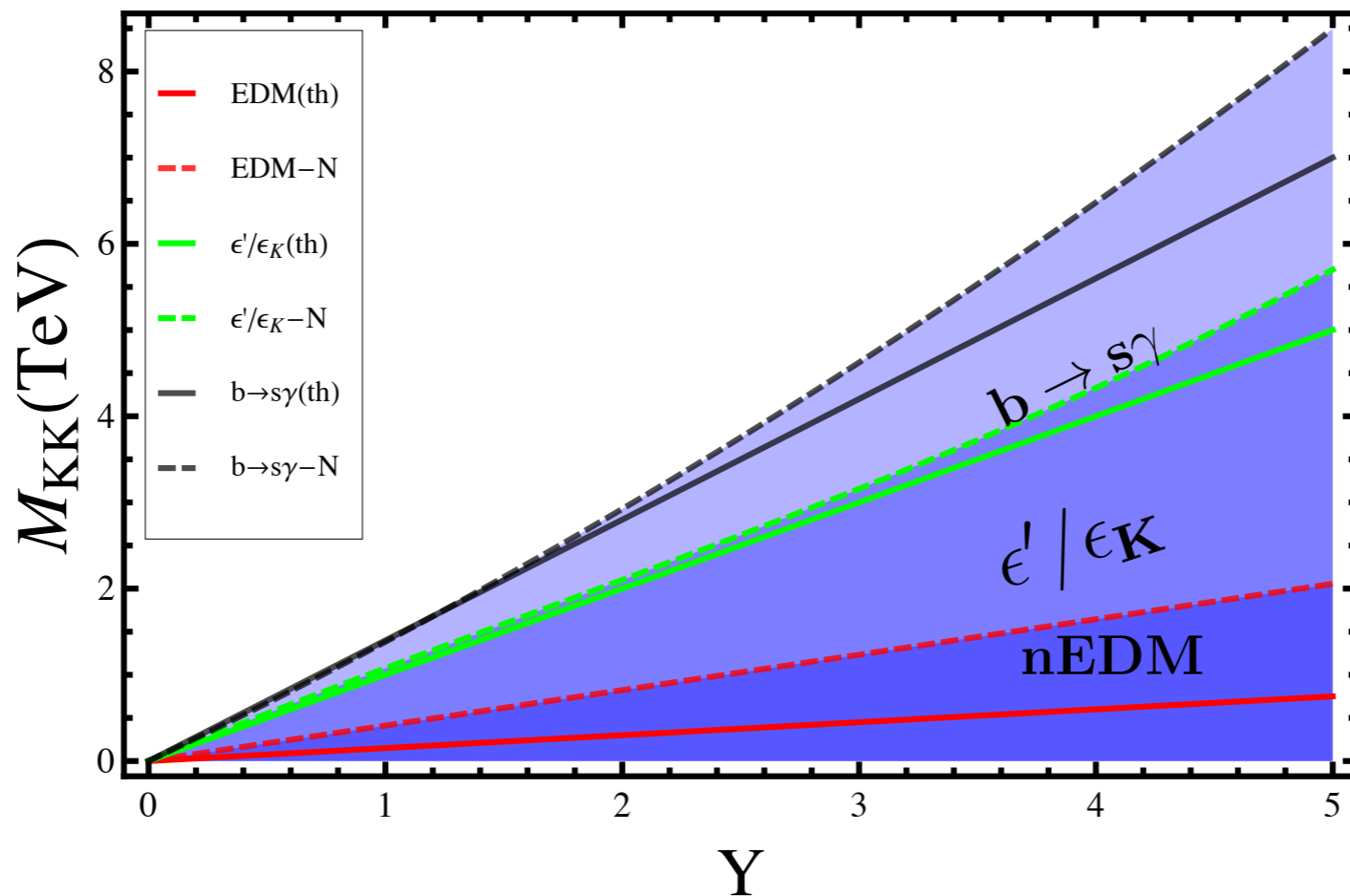
$\Rightarrow \Lambda_{KK} \gtrsim 10 \text{ TeV} \text{ (no } P_{LR})$

(Flavor anarchy)

# Dipole operators for FCNC



$$b \rightarrow s\gamma, \epsilon'/\epsilon_K, \text{nEDM}$$



$d_n \sim 40 \times d_n^{\text{exp}}$  !  
 flavor anarchy

# After the LHC

## Higgs

**But no new particles**

Rely on flavour physics bounds  
CKM matrix elements  
B, D mesons rare decays  
CP violation

## New particles

strongly coupled  
Compositeness

weakly coupled  
Supersymmetry

## Low energy frontier

Sterile neutrinos below the LHC energy ?  
Electric Dipole Moments (EDMs)  
Higher precision muon ( $g-2$ )

## High energy frontier

Higgs, t-quark factory ?  
Planck scale physics (CMB)