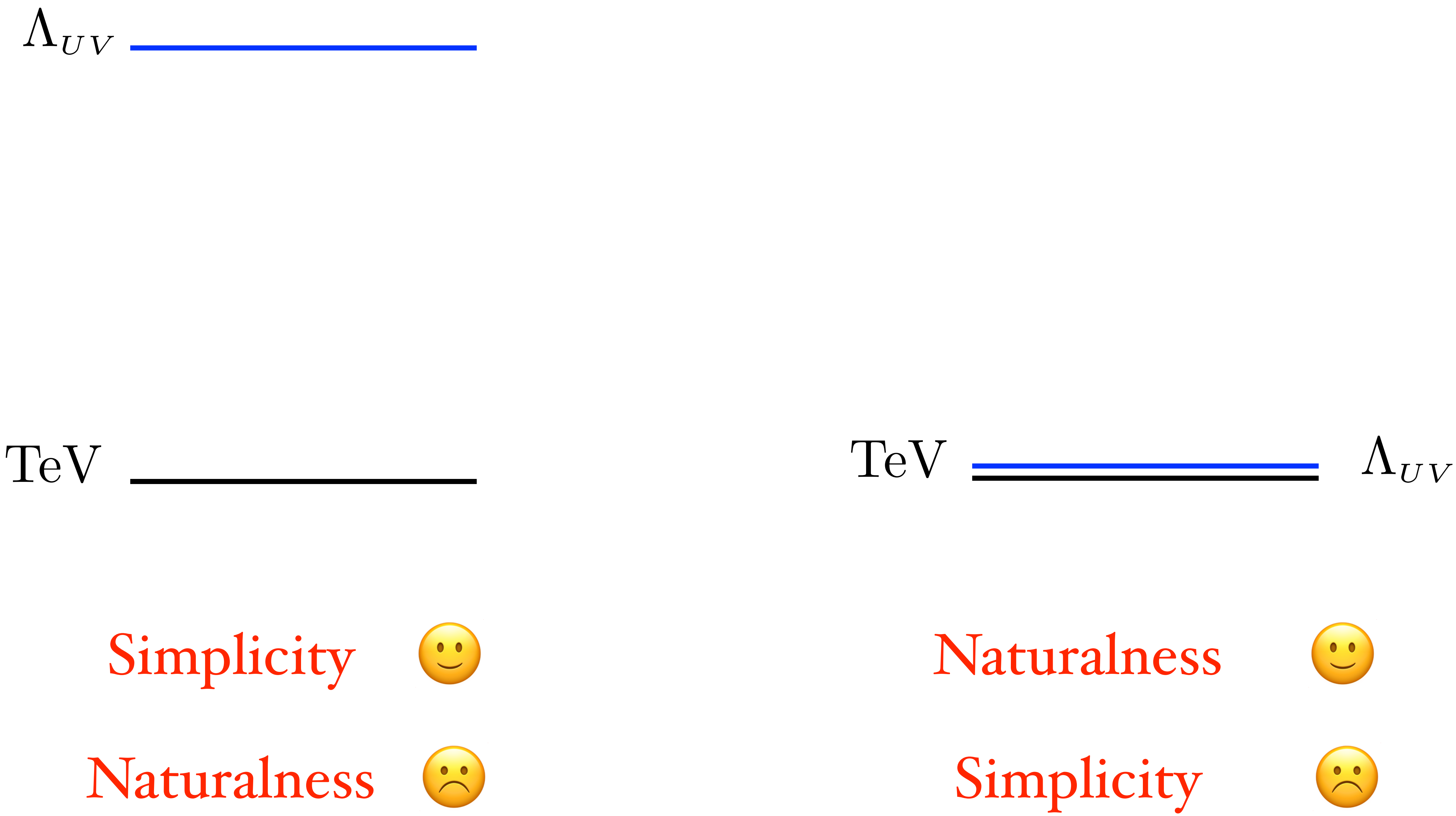
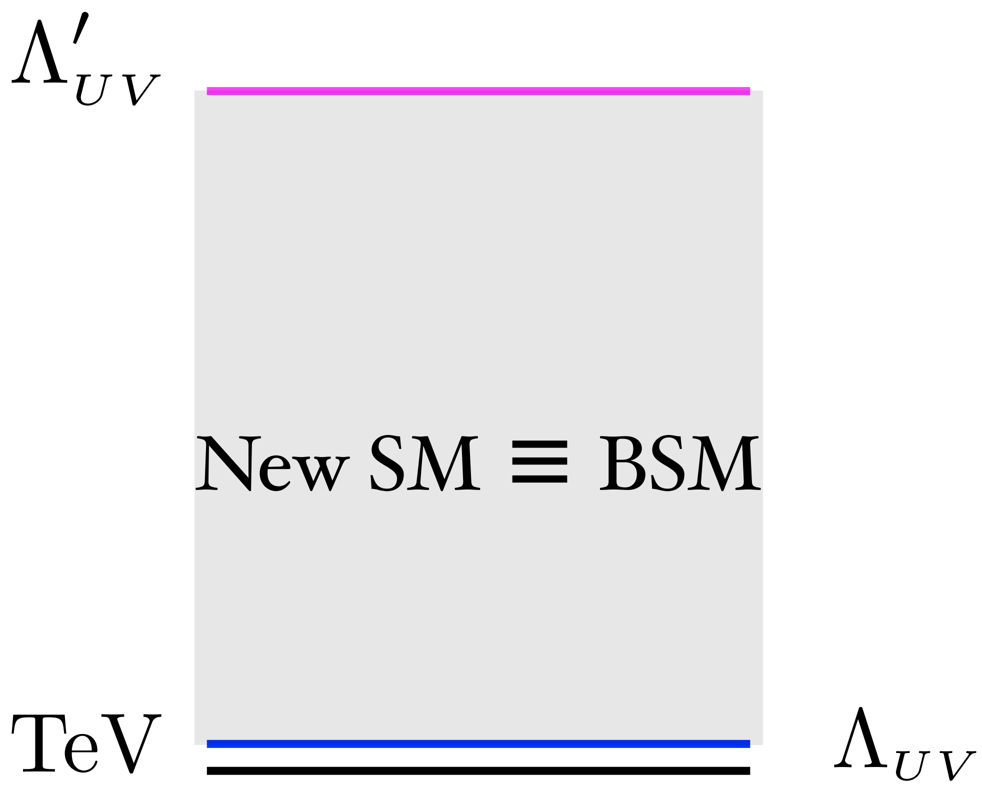
BSM and the Hierarchy Paradox

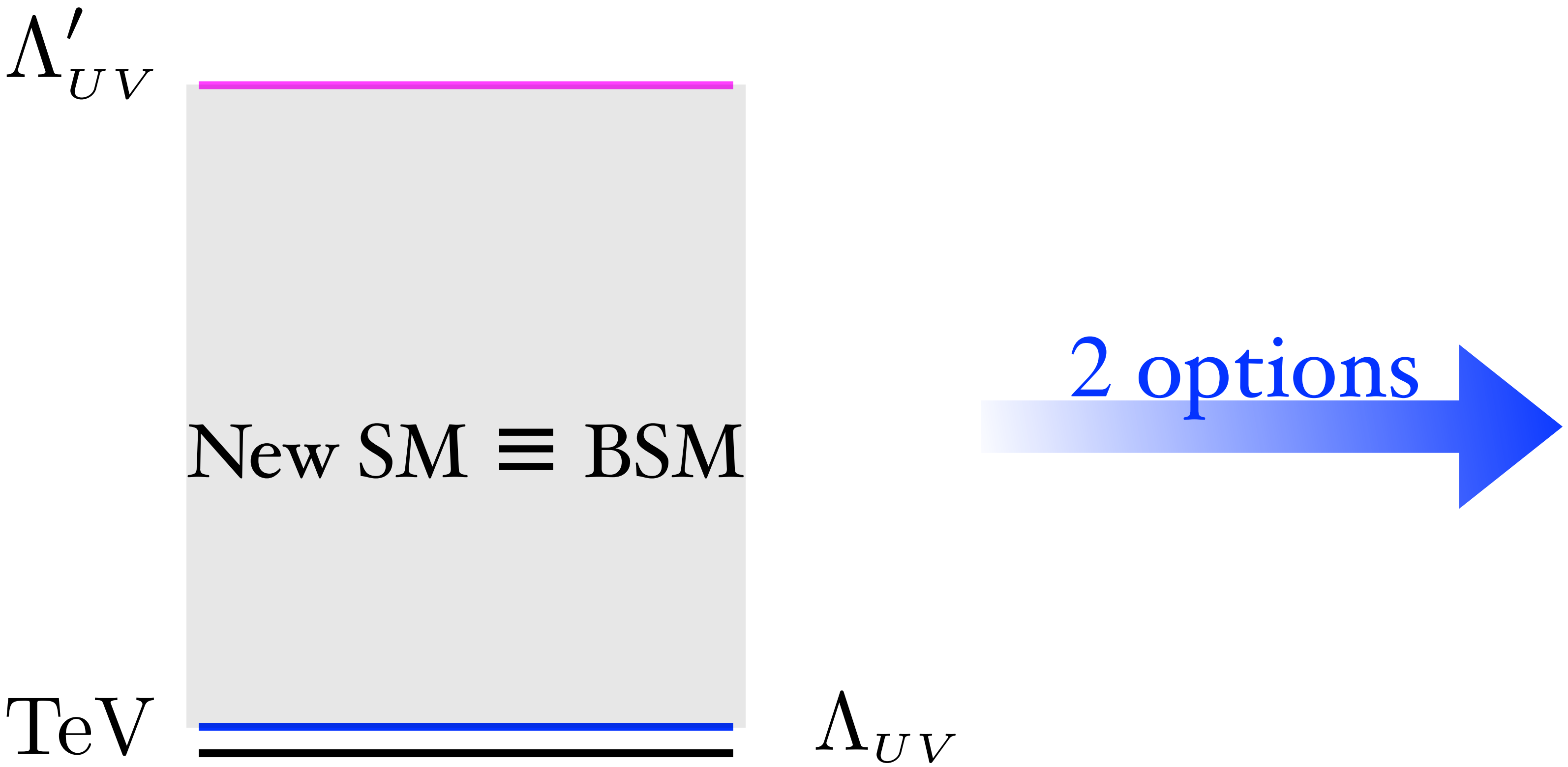

Λ_{UV}
TeV
Simplicity 🙂
Naturalness 🙁
TeV
Λ_{UV}
Naturalness 🙂
Simplicity 🙁

Ideally



- $\Lambda_{UV} \ll \Lambda'_{UV}$ natural in BSM
- $\mathcal{L}_4$ in BSM shares as much magic as possible with $\mathcal{L}_4$ in SM

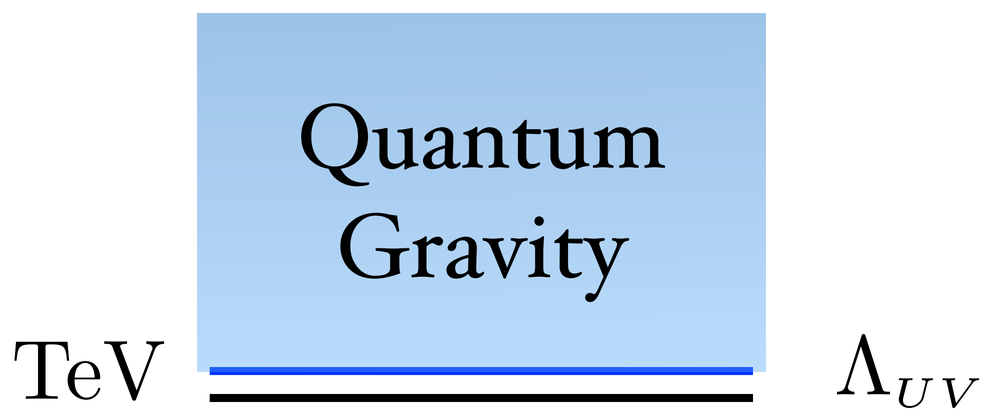
Can this ideal be realized ?



- no elementary scalars: Composite Higgs
- elementary scalars with symmetry protecting their mass: Supersymmetry

A more dramatic 3rd option: Low scale QG with large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali 1998



$$M_P^2 = \Lambda_{UV}^{2+n} R^n$$

- Simplicity seems harder to realize

- However the separation of fields via their localization on 'branes' in the large extra directions can seed Simplicity

- Indeed the only realistic construction of Composite Higgs models rely on extra dimensions through the holographic bulk/boundary correspondence

Making small m_H^2 natural through symmetry

Supersymmetry

Supersymmetry Algebra

$$[J_{\mu\nu}, J_{\rho\sigma}] = i\,(\eta_{\mu\sigma}J_{\nu\rho} + \eta_{\nu\rho}J_{\mu\sigma} - \eta_{\mu\rho}J_{\nu\sigma} - \eta_{\nu\sigma}J_{\mu\rho})$$

$$[J_{\mu\nu}, P_\rho] = i\,(\eta_{\nu\rho}P_\mu - \eta_{\mu\rho}P_\nu) \qquad [P_\mu, P_\nu] = 0$$

Poincaré Algebra

$$[\,Q_\alpha,\, P_\mu\,] \,=\, 0 \qquad [\,Q_\alpha,\, M_{\mu\nu}\,] \,=\, \frac{1}{2}\,(\sigma_{\mu\nu})_\alpha^{\beta}\,Q_\beta$$

$$\{\,Q_\alpha,\, Q_\beta\,\} \,=\, -2(\gamma^\mu C)_{\alpha\beta}P_\mu$$

Supersymmetric Extension

Q_α has spin $\frac{1}{2}$

Q_α relates states whose spins differ by $\frac{1}{2}$

particle (spin = J) **SUSY** super-particle (spin = $J \pm \frac{1}{2}$)

$$[\,Q_\alpha,\, P_\mu\,] = 0 \longrightarrow M_J = M_{J\pm\frac{1}{2}}$$

Super-Multiplets

$\chi_L^\alpha, \quad \varphi$	chiral
$\chi_R^\alpha, \quad \varphi^*$	anti-chiral
$\lambda^\alpha, \quad A_\mu$	vector
$a, \quad \psi_D^\alpha, \quad A_\mu$	massive vector

Super-Multiplets

	χ_L^α,	φ	chiral
	2	2	
	χ_R^α,	φ^*	anti-chiral
	2	2	
	λ^α,	A_μ	vector
	2	2	
a,	ψ_D^α,	A_μ	massive vector
1	2	3	

$$m_\chi \quad \xleftrightarrow{\quad Q \quad} \quad m_\varphi^2 = m_\chi^* m_\chi$$

The scalar mass is controlled by the same chiral symmetry that controls the fermion mass

- m_φ^2 can be naturally $\ll (\Lambda'_{UV})^2$

- that does not yet explain ***how*** m_φ^2 got to be $\ll \Lambda'^{\,2}_{UV}$, but sets the stage for an explanation

Supersymmetric Standard Model

particles				Sparticles			
quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R	d_R	*squarks*	$\begin{pmatrix} \tilde{u}_L \\ \tilde{d}_L \end{pmatrix}$	$\tilde{u}_R$	$\tilde{d}_R$
leptons	$\begin{pmatrix} e_L \\ \nu_L \end{pmatrix}$	e_R		*sleptons*	$\begin{pmatrix} \tilde{e}_L \\ \tilde{\nu}_L \end{pmatrix}$	$\tilde{e}_R$	
Higgs doublets	H_1 (hypercharge $= -1$) H_2 (hypercharge $= +1$)			*Higgsinos*	$\tilde{H}_1$ $\tilde{H}_2$		
	$W_\mu^\pm, W_\mu^3$			*winos*	$\tilde{\omega}^\pm, \tilde{\omega}^3$		
	B_μ			*bino*	$\tilde{b}$		
	G_μ^A	$A = 1, \ldots, 8$		*gluinos*	$\tilde{g}^A$		

Lot of stuff ...which we do not observe

Supersymmetry must be 'spontaneously' broken

$$m_{\text{sparticles}} \sim M_S \gtrsim \text{weak scale}$$

$$m_H^2 = \mu\mu^* + c_h M_S^2$$

higgsino mass

triggers EWSB

under all circumstances

$$|c_h| \gtrsim \frac{3y_t^2}{8\pi^2} \xrightarrow{\text{naturalness}} M_S \lesssim 500 \text{ GeV}$$

$\mathscr{L}_4$ in the MSSM

superfields

$$q_L \Rightarrow Q \qquad \bar{u}_R \Rightarrow U_c \qquad \bar{e}_R \Rightarrow E_c$$

$$\ell_L \Rightarrow L \qquad \bar{d}_R \Rightarrow D_c$$

Yukawa couplings $\Rightarrow$ superpotential

$$W = Y_u^{ij} Q^i H_2 U_c^j + Y_d^{ij} Q^i H_1 D_c^j + Y_e^{ij} L^i H_1 E_c^j$$

$$+ \lambda_{ijk} L^i L^j E_c^k + \lambda'_{ijk} L^i Q^j D_c^k + \lambda''_{ijk} U_c^i D_c^j D_c^k + \mu_i L_i H_u$$

$\Delta L = 1$ $\Delta L = 1$ $\Delta B = 1$ $\Delta L = 1$

$$\tilde{u}_R \, \tilde{d}_R \, \tilde{q}_L \, \tilde{\ell}_L$$

scalars allow $B + L$ violation at the renormalizable level !

Matter Parity P_M

$$Q,\, U_c,\, D_c,\, L,\, E_c \;\Rightarrow\; -Q,\, -U_c,\, -D_c,\, -L,\, -E_c$$

$$H_{1,2} \;\Rightarrow\; H_{1,2}$$

R-Parity

$$R_P \equiv P_M\,(-1)^{2S}$$

$$W = Y_u^{ij} Q^i H_2 U_c^j + Y_d^{ij} Q^i H_1 D_c^j + Y_e^{ij} L^i H_1 E_c^j$$
$$+ \lambda_{ijk} L^i L^j E_c^k + \lambda'_{ijk} L^i Q^j D_c^k + \lambda''_{ijk} U_c^i D_c^j D_c^k + \mu_i L_i H_u$$

Matter Parity P_M

$$Q,\, U_c,\, D_c,\, L,\, E_c \;\Rightarrow\; -Q,\, -U_c,\, -D_c,\, -L,\, -E_c$$

$$H_{1,2} \;\Rightarrow\; H_{1,2}$$

R-Parity

$$R_P \;\equiv\; P_M\,(-1)^{2S}$$

$$W \;=\; Y_u^{ij} Q^i H_2 U_c^j \,+\, Y_d^{ij} Q^i H_1 D_c^j \,+\, Y_e^{ij} L^i H_1 E_c^j$$

$$+\,\lambda_{ijk} L^i L^j E_c^k \,+\, \lambda'_{ijk} L^i Q^j D_c^k \,+\, \lambda''_{ijk} U_c^i D_c^j D_c^k \,+\, \mu_i L_i H_u$$

Scalar masses and flavor

$$\mathcal{L}_{d=2} \;=\; (m^2_{\tilde{q}})_{ij}\, \tilde{q}^{i*}_{L} \tilde{q}^{j}_{L} + (m^2_{\tilde{u}})_{ij}\, \tilde{u}^{i*}_{R} \tilde{u}^{j}_{R} + (m^2_{\tilde{d}})_{ij}\, \tilde{d}^{i*}_{R} \tilde{d}^{j}_{R} + (m^2_{\tilde{\ell}})_{ij}\, \tilde{\ell}^{i*}_{L} \tilde{\ell}^{j}_{L} + (m^2_{\tilde{e}})_{ij}\, \tilde{e}^{i*}_{R} \tilde{e}^{j}_{R}$$

- In general no correlation with V_{CKM} and no GIM mechanism
- Unacceptably large 1-loop contributions to FCNC, edms, etc
- The solution to this problem requires the implementation of clever and somewhat ad hoc model building mechanisms: *Simplicity bought by Cleverness*

Ex: Approximate Flavor Symmetries

Ex: Gauge Mediated Supersymmetry Breaking

$$(m^2_{\tilde{q}})_{ij} \simeq m^2_{\tilde{q}} \times \mathbf{1}_{ij} \qquad (m^2_{\tilde{u}})_{ij} \simeq m^2_{\tilde{u}} \times \mathbf{1}_{ij} \qquad \text{etc.}$$

- These clever mechanisms in their extreme incarnation allowed flavor constraints to be met with sparticles around the weak scale, fully compatibly with Naturalness

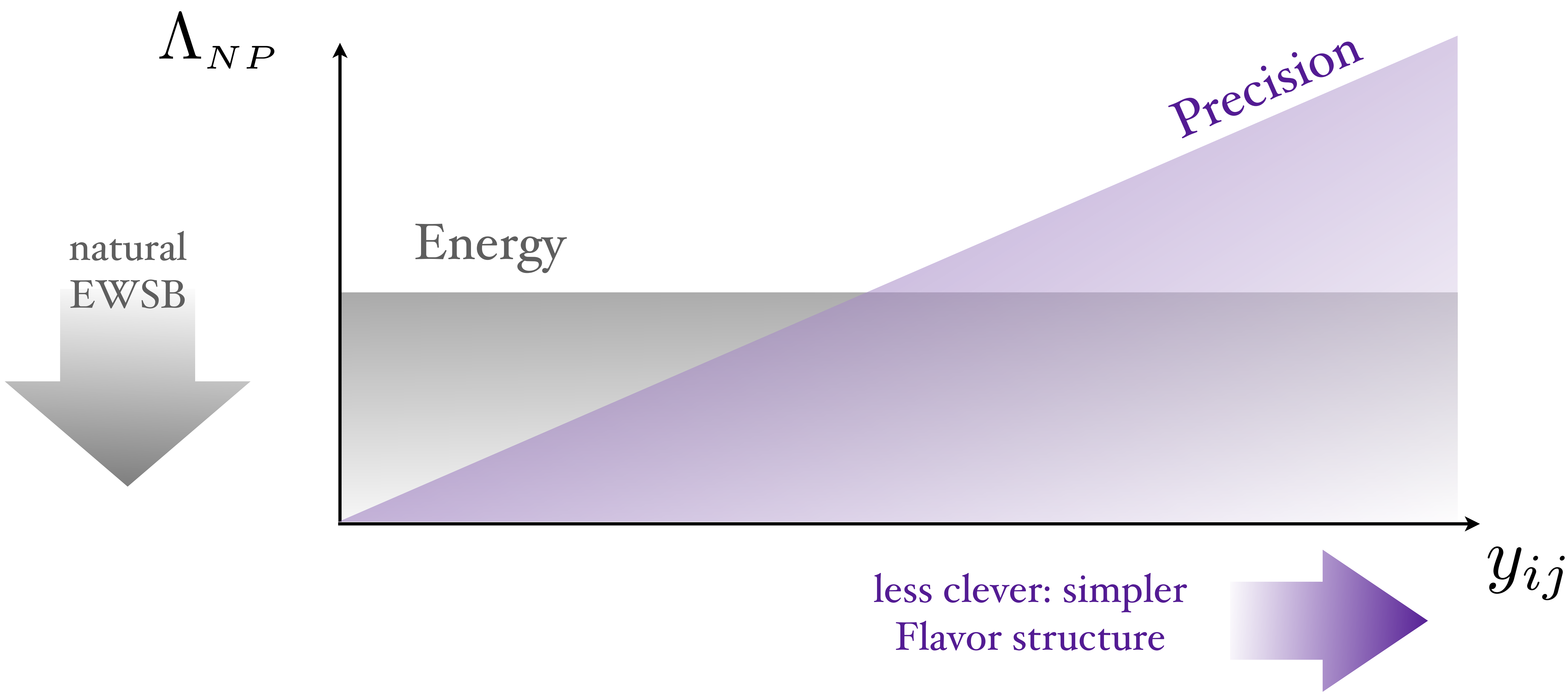
- However LHC data indicate Nature's preference to be simple and her reluctance to be clever

- Notice that cleverness could be significantly spared at the price of some tuning by having the sparticles in the 10 – 100 TeV range

- The exploration of the energy and precision frontiers provides complementary constraints on Naturalness and Simplicity

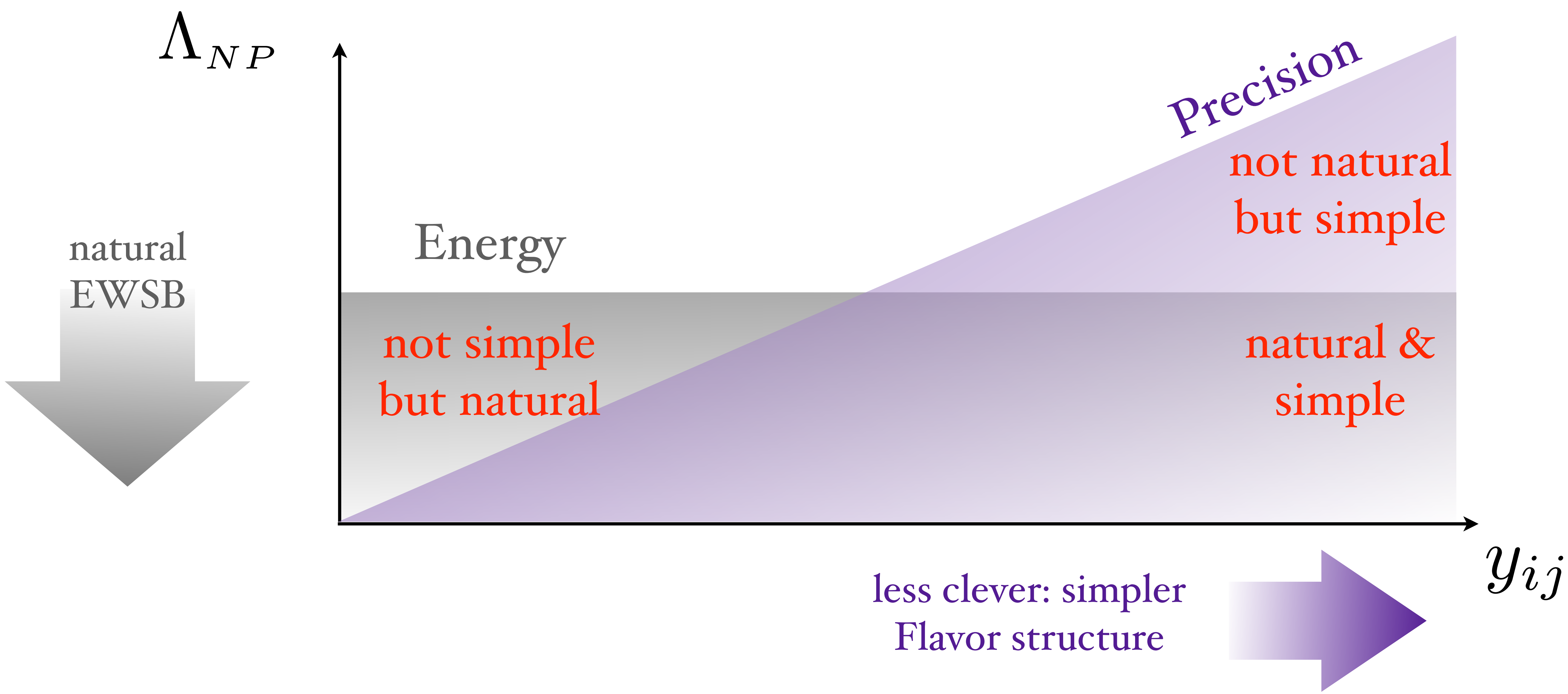
Complementarity of Energy and Precision

$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda_{NP}^2}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda_{NP}^2}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$

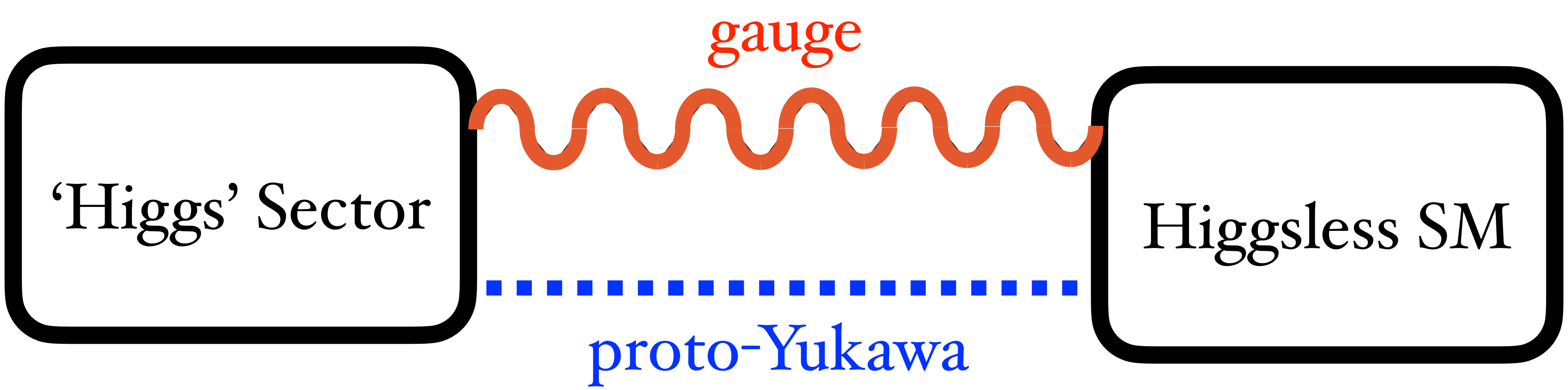


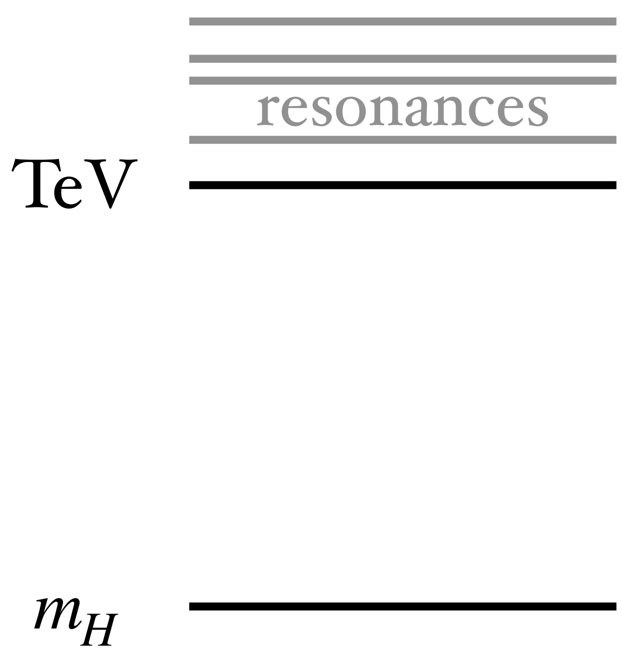
Complementarity of Energy and Precision

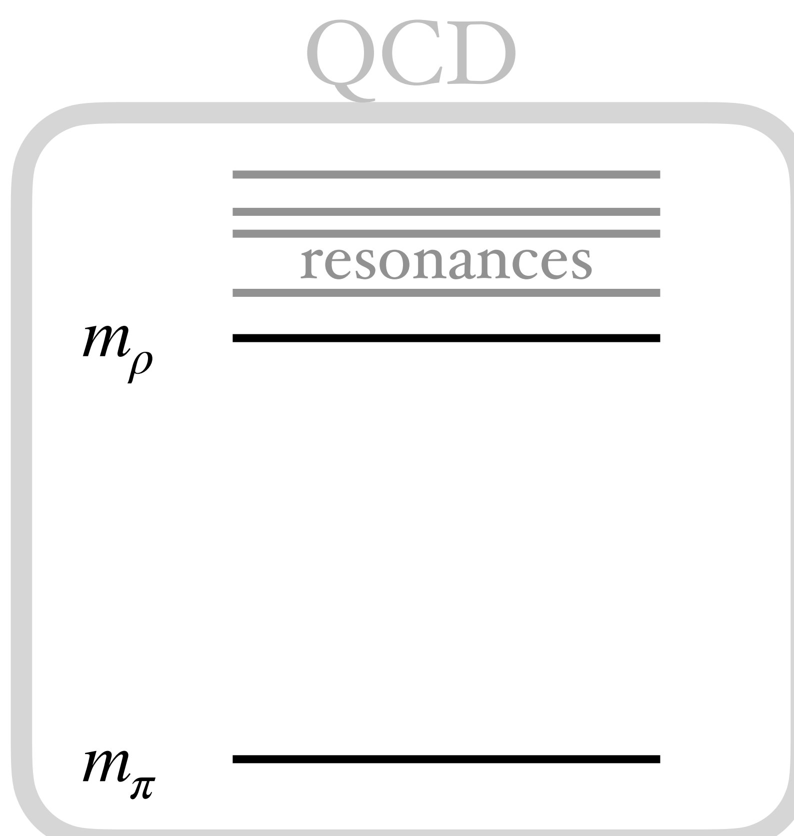
$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda^2_{NP}}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda^2_{NP}}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$



Higgs Compositeness

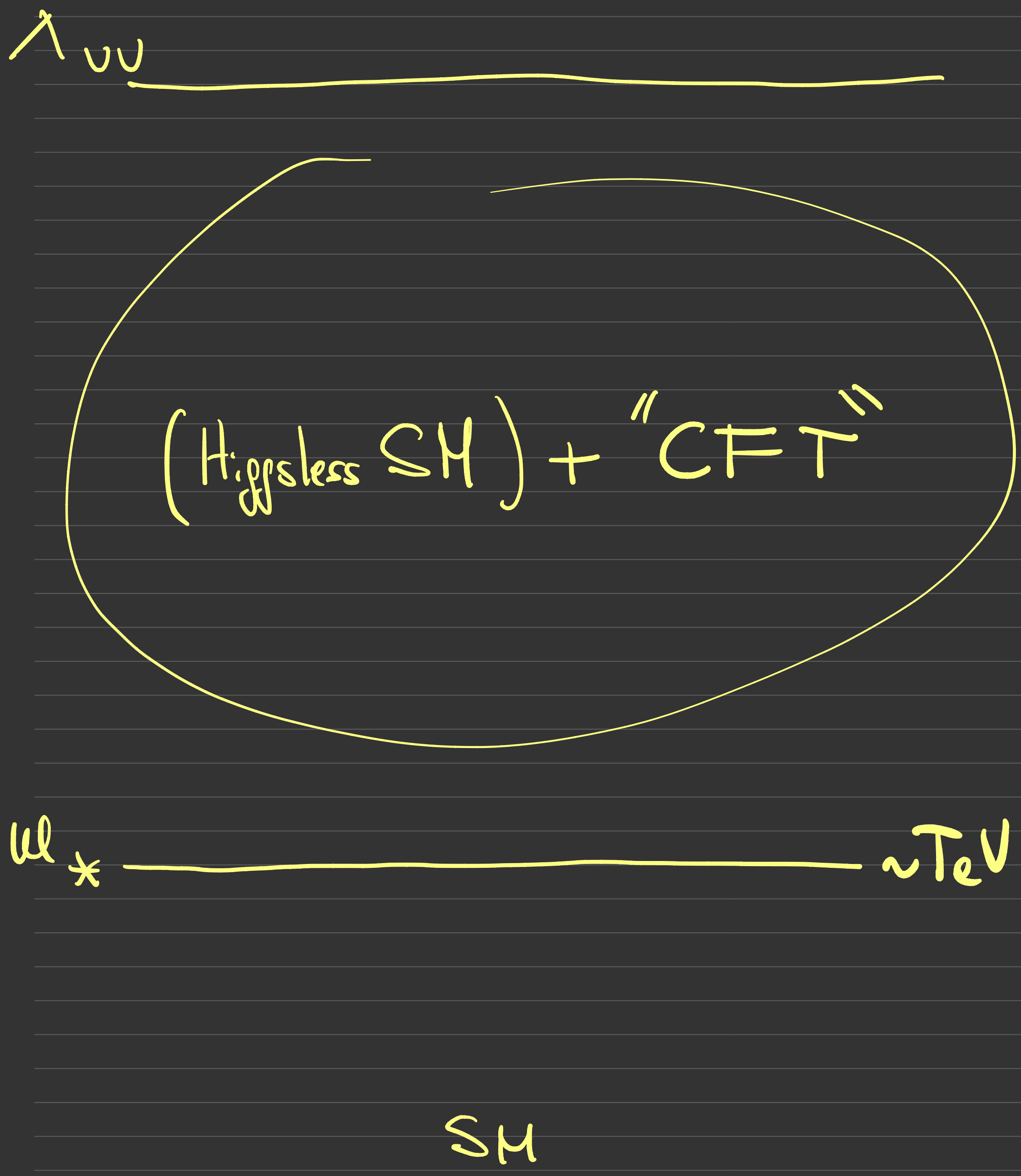






best option:
H is a pseudoGoldstone

simplest option: $H = SO(5)/SO(4)$



$$S = S_{SM'} + S_{CFT} + S_{mix} + S_{mass}$$

Ex of S_{mass}

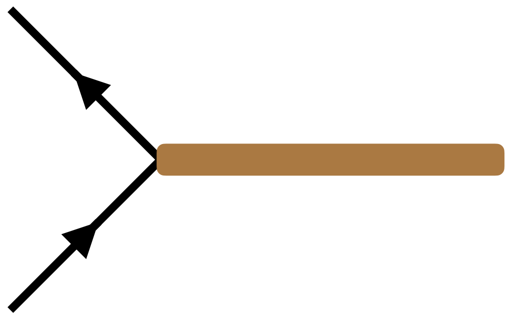
$$S_{mass} = \int d^4x \; g \, \Lambda_{UV}^{\varepsilon} \, \mathcal{O}_{4-\varepsilon}$$

$$\bar{g}(E) = \frac{g \Lambda_{UV}^{\varepsilon}}{E^{\varepsilon}}$$

$$\bar{g}(m_*) \equiv 1 \Rightarrow m_* = g^{1/\varepsilon} \Lambda_{UV}$$

Proto Yukawas: two options

✦ bilinear



$$\frac{1}{\Lambda'^{d_{\mathcal{O}}-1}_{UV}} \bar{f} f \mathcal{O}_H \qquad d_{\mathcal{O}} > 1$$

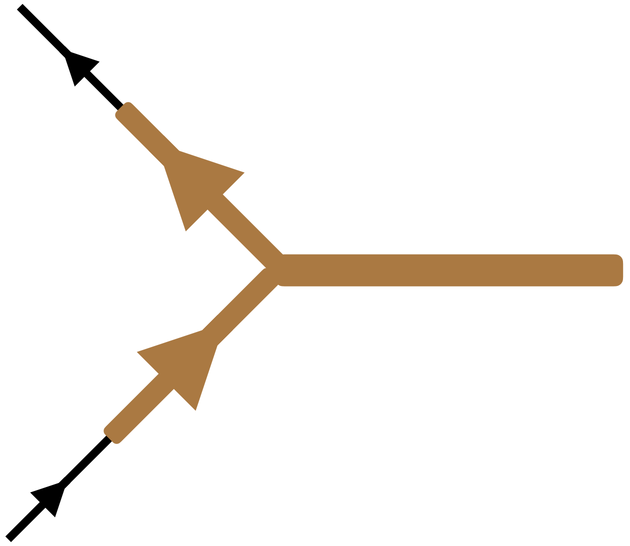
charged fermion masses come from $\mathscr{L}_{d>4}$ like unwanted FCNC

Ex.: in technicolor models $\mathcal{O}_H = \bar{T}T$

$$\frac{1}{\Lambda'^{d_2}_{UV}} \bar{f} f \mathcal{O}_H + \frac{1}{\Lambda'^{d_2}_{UV}} (\bar{f} f)(\bar{f} f)$$

seen not seen

✦ linear  $y_{iA}\,\bar{f}_i\,\Psi_A$



y_{iA} represent a much 'bigger' set of sources than just the SM Yukawas: no $\mathscr{L}_4$ magic guaranteed

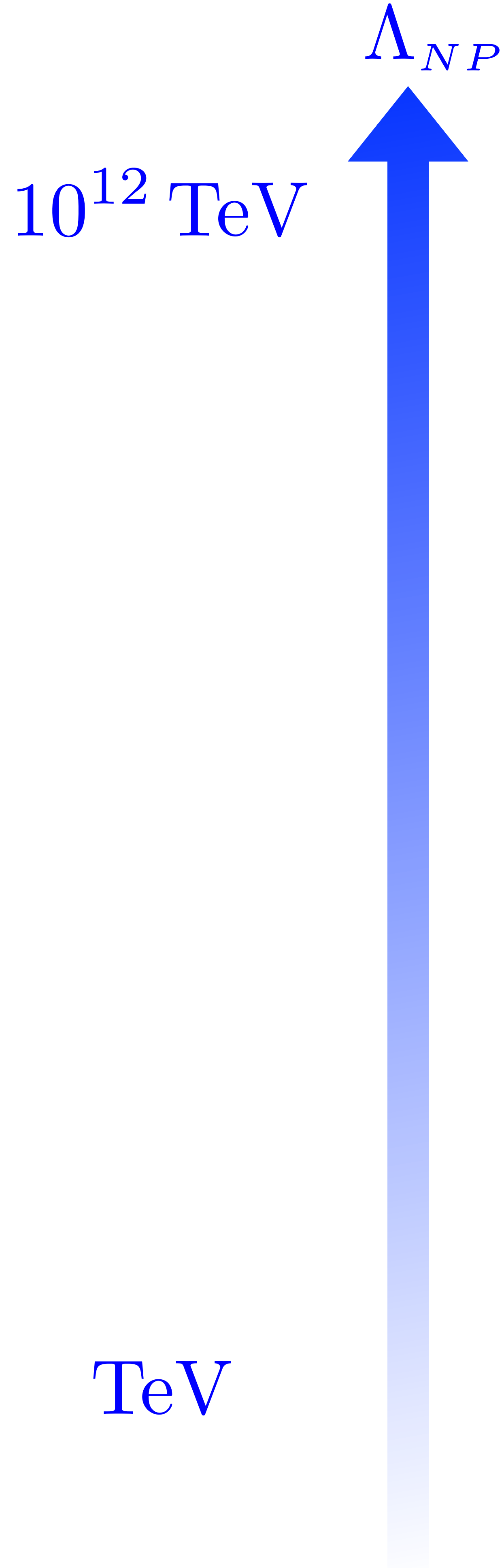
Alas!

It seems there is no free lunch

- $\Lambda_{UV} \gg m_H$ beautifully accounts for the observed structural simplicity of particle physics, but is un-natural

- All natural extensions of the SM need to be retrofitted with some ad hoc mechanism in order to reproduce the simplicity of observations

This is the Hierarchy Paradox



High Scale SM:
super simple & super un-natural

TeV Scale New Physics:
not simple & almost natural

See also talk by R. Sundrum HEFT 2016

Λ_{NP}

10^{12} TeV

High Scale SM:
super simple & super un-natural

perfect Flavor and CP — 10^{4} TeV

Middle Options?
just simpler and not yet
super un-natural

better Flavor and
perfect EW — 10^{2} TeV

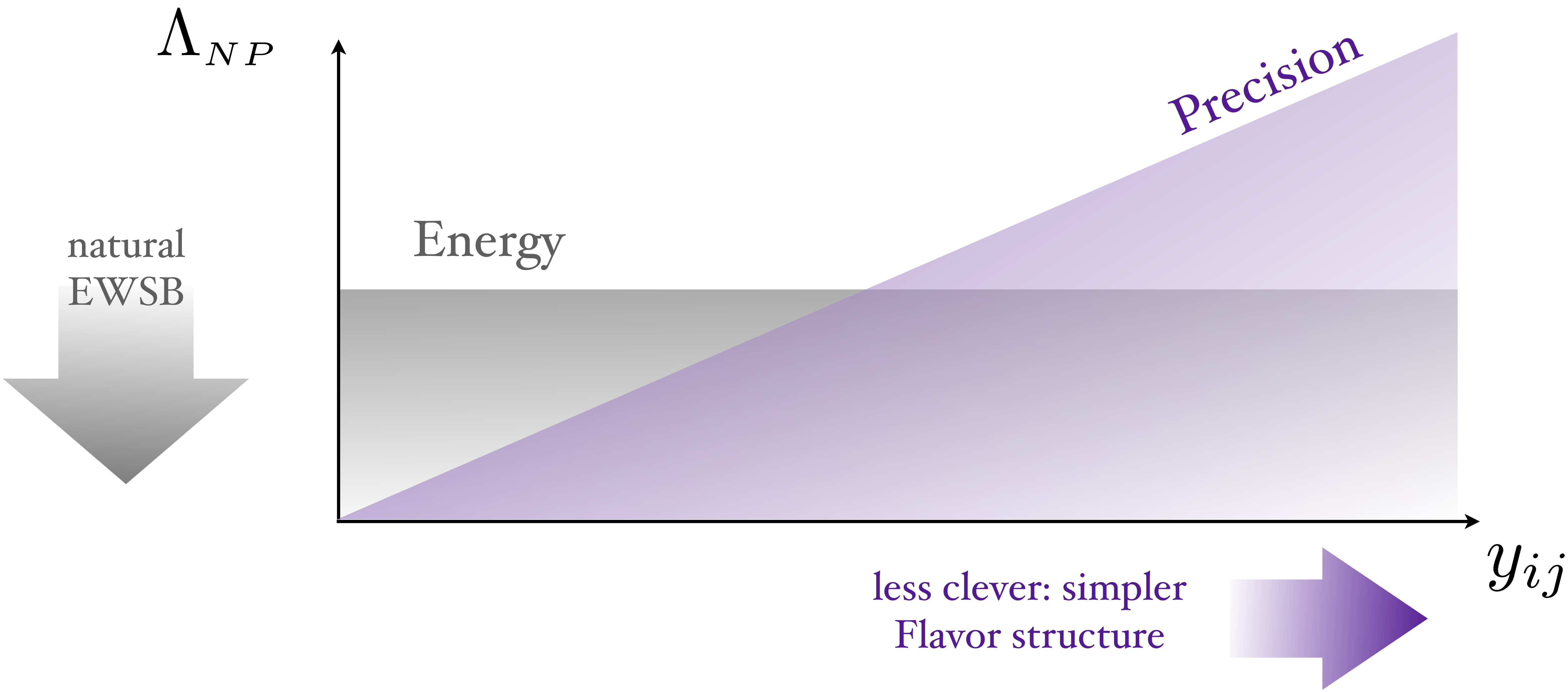
TeV

TeV Scale New Physics:
not simple & almost natural

See also talk by R. Sundrum HEFT 2016

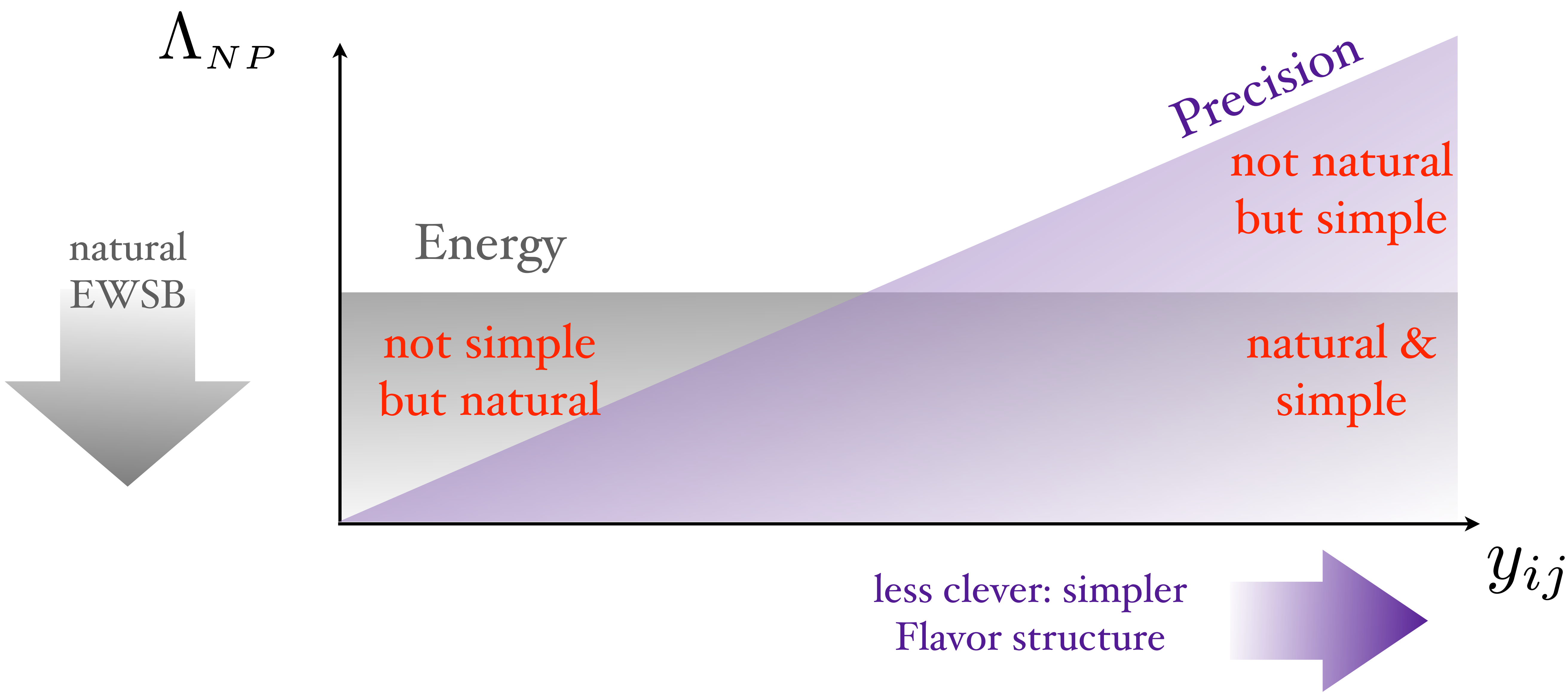
Complementarity of Energy and Precision

$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda_{NP}^2}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda_{NP}^2}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$



Complementarity of Energy and Precision

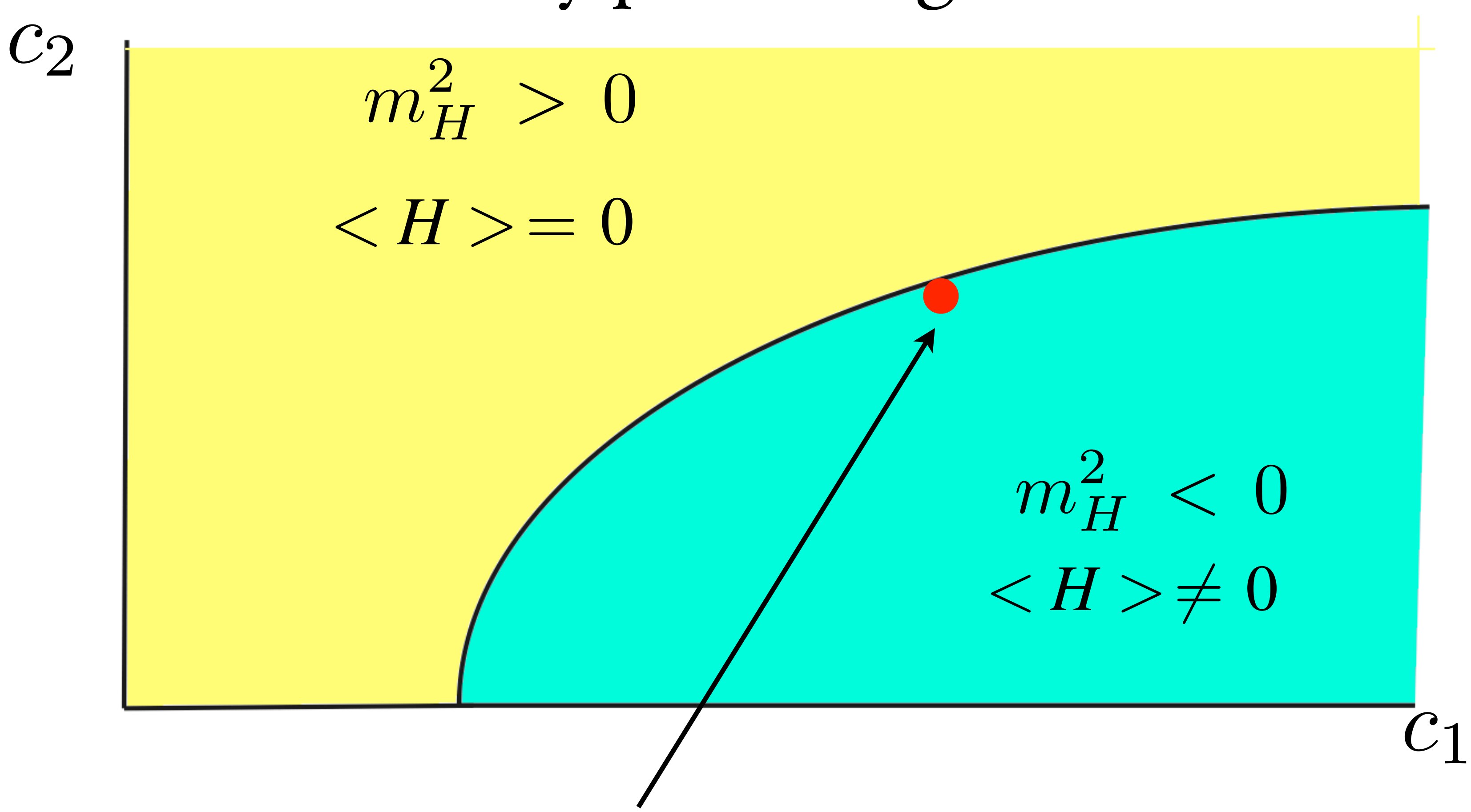
$$\mathcal{L}_{eff} = \frac{y_{ijk\ell}}{\Lambda_{NP}^2}\,\bar{q}_i q_j \bar{q}_k q_\ell + m_i \frac{y_{ij}}{\Lambda_{NP}^2}\,\bar{q}_i \sigma_{\mu\nu} q_j F^{\mu\nu} + \ldots$$



And if it were just a big tuning?

$$m_H^2 = \sum_a C_{ia} M_a^2 \qquad\qquad M_a^2 \sim \Lambda_{UV}^2$$

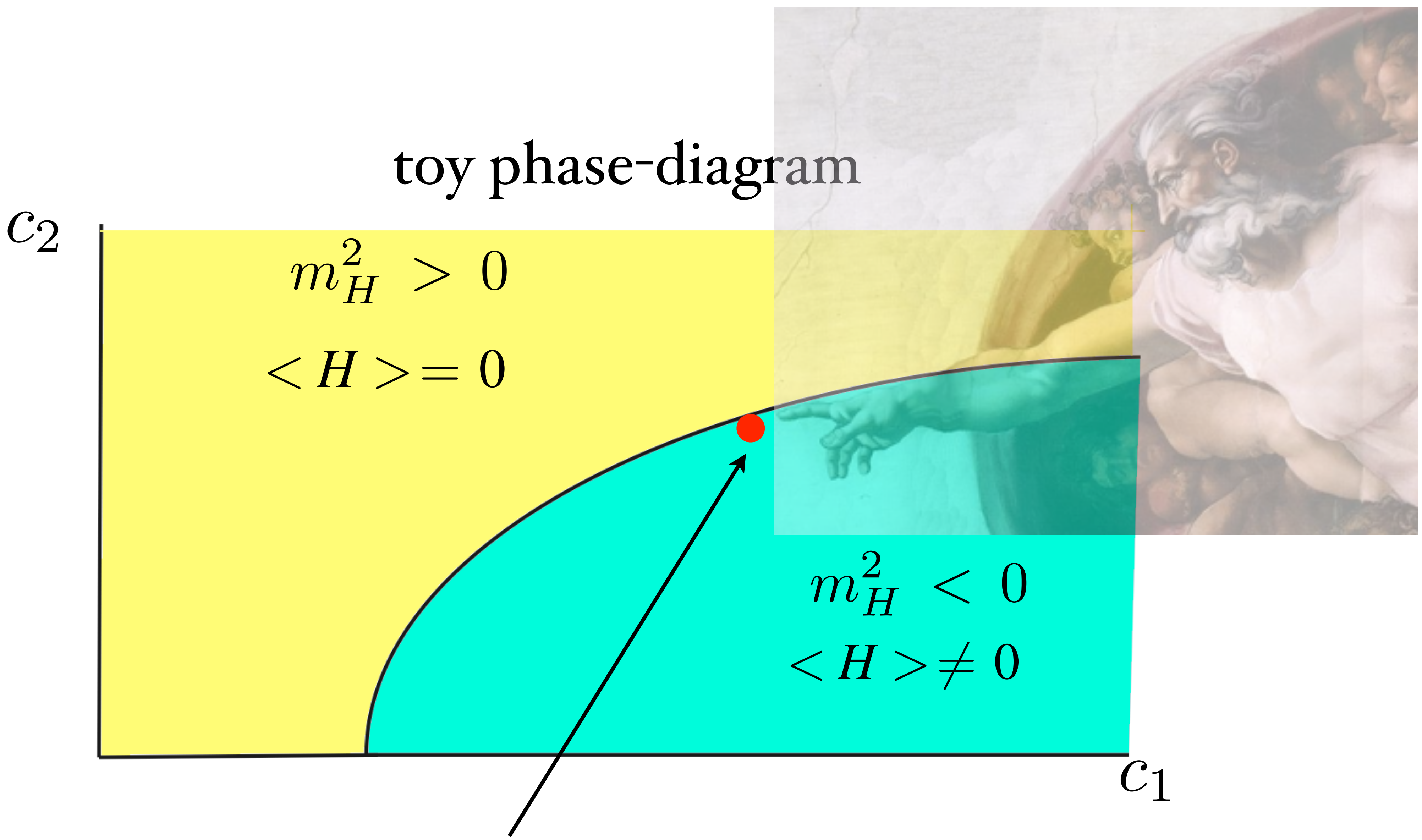
toy phase-diagram



SM lives on critical line

And if it were just a big tuning?

$$m_H^2 = \sum_a C_{ia} M_a^2 \qquad\qquad M_a^2 \sim \Lambda_{UV}^2$$

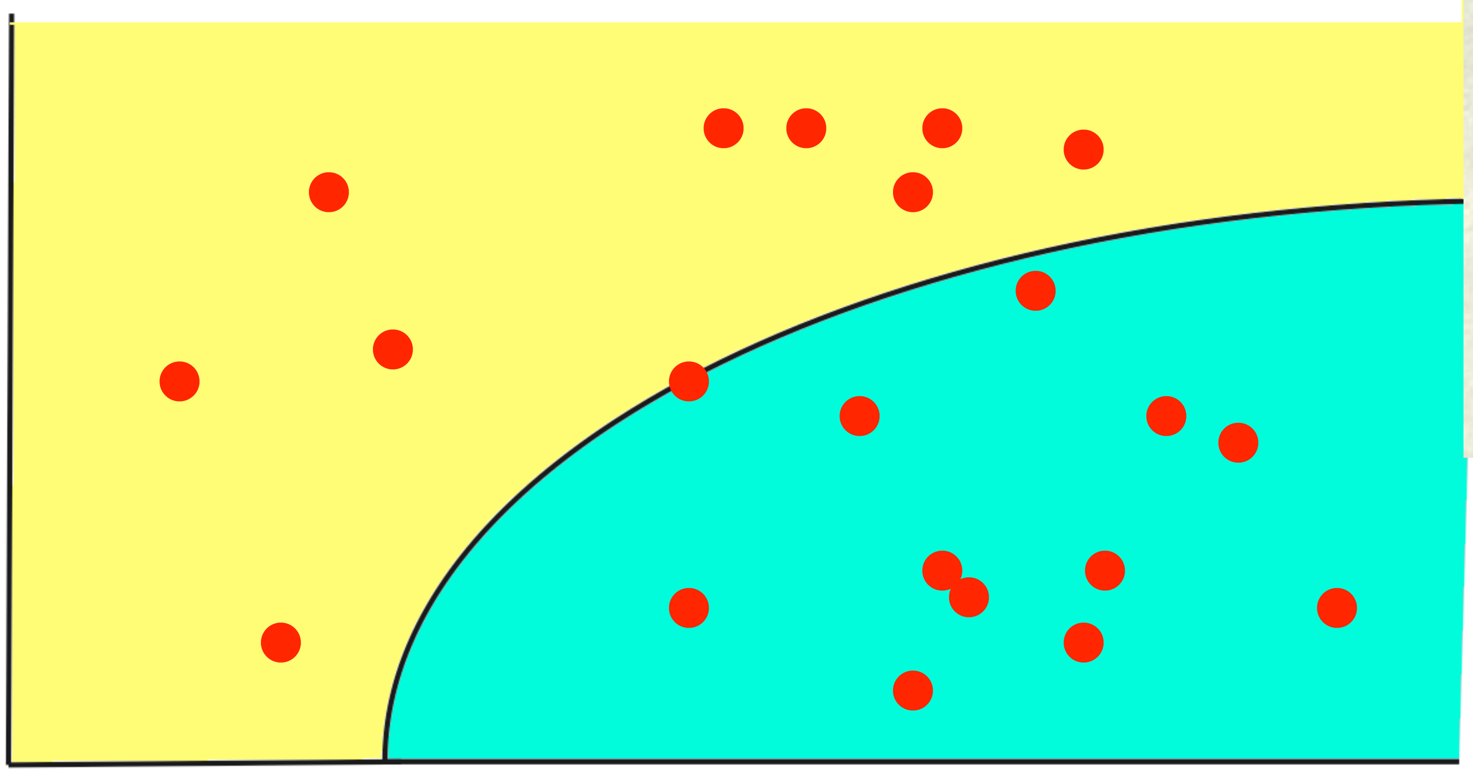


SM lives on critical line

The Lanscape and Anthropic Selection

IDEA

- the fundamental theory possesses a huge landscape of vacua each corresponding to a different choice of parameters
- quantum fluctuations in the early universe dynamics populated all vacua...each in a different patch of the universe (the Multiverse)



Why are we sitting on the critical line?

Because that apparently maximizes complexity: the existence of richly structured nuclear and atomic physics