Relevant Standard Model

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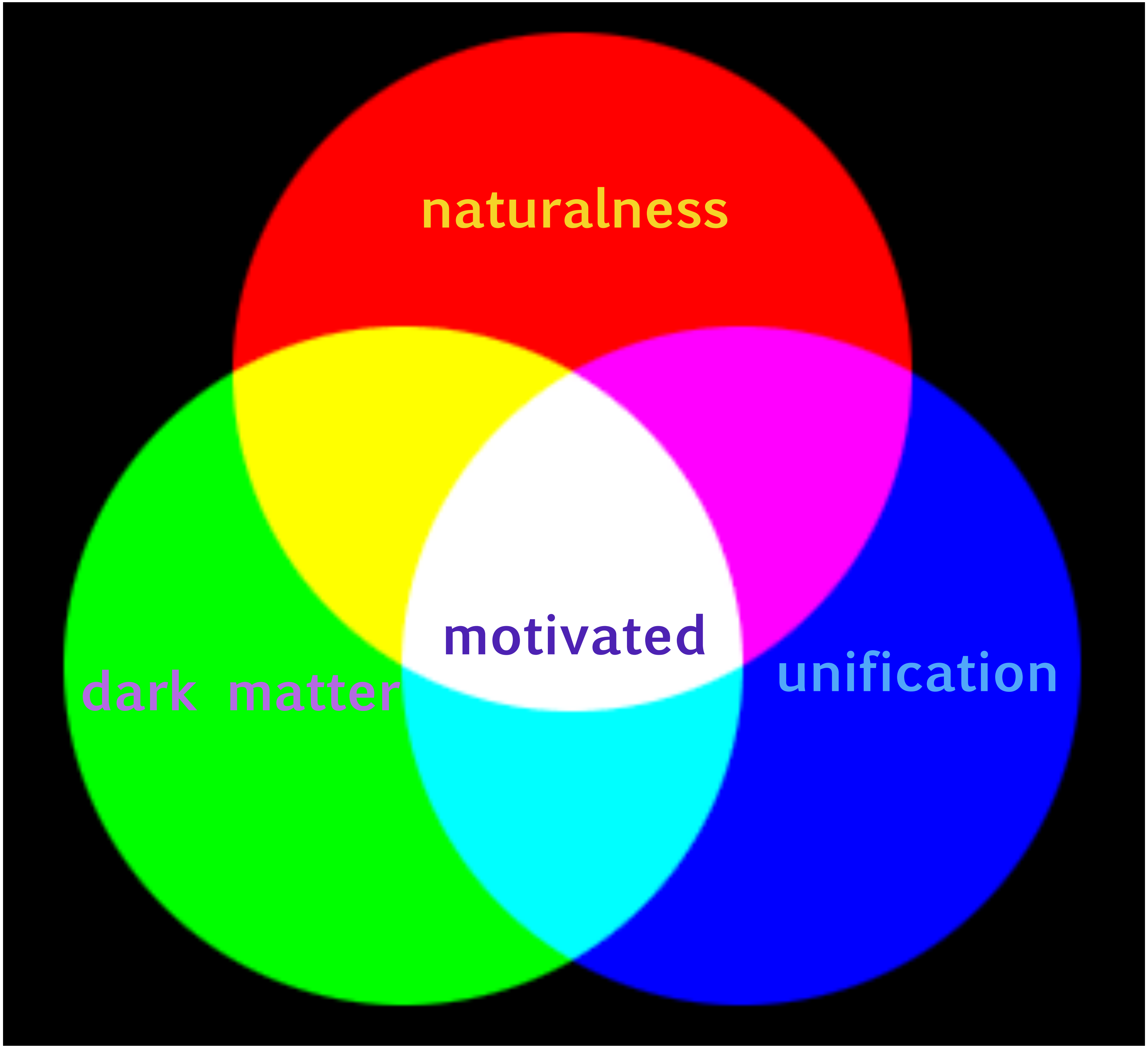
Confronting Naturalness
: From LHC to future colliders
2018. 4. 25-27
DESY, Germany

Beyond the Standard Model

Why? Why not?


naturalness
motivated
dark matter
unification

naturalness

light particle is natural if symmetry is enhanced when the particle becomes massless

Pion, photon, neutrino, top quark, electron, ...

dark matter

5 or 6 times of ordinary matter density is not made of SM fermions (protons, neutrons, electrons, neutrinos)

new particle or new paradigm?

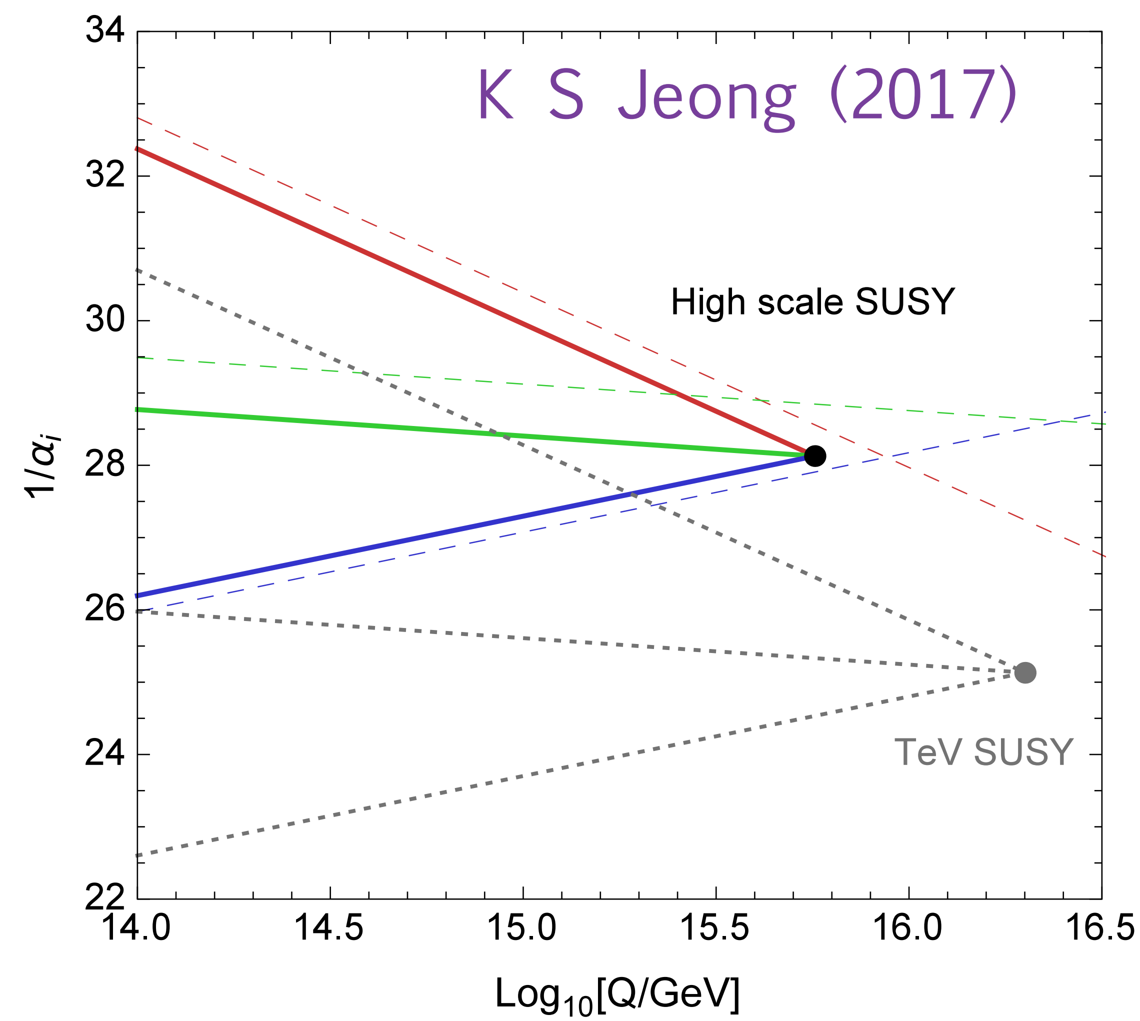
unification of gauge couplings

charge quantization is one of the puzzle in the SM

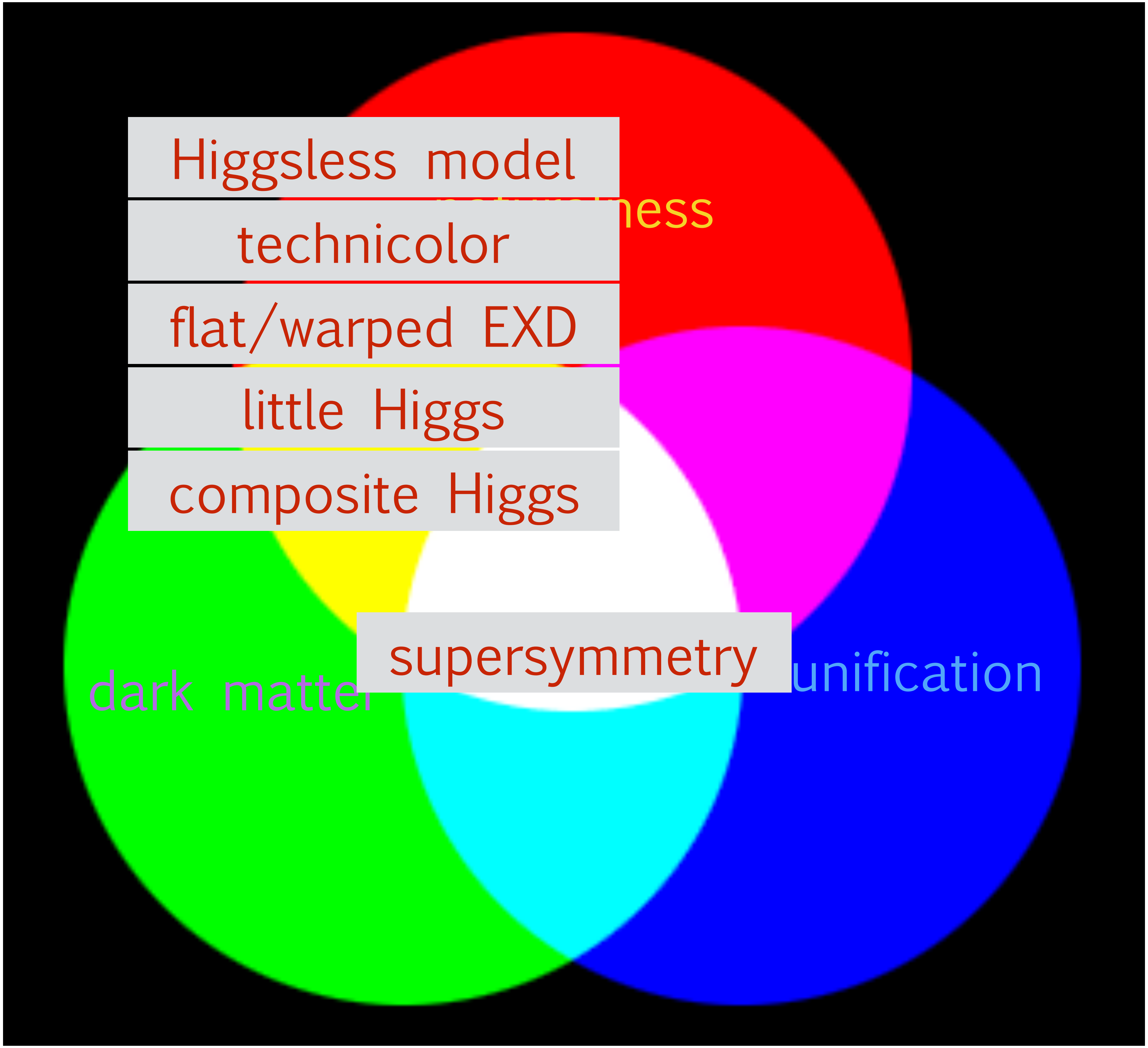
$$Q_d = \frac{1}{3} Q_e \qquad\qquad 2Q_u + Q_d + Q_e = 0$$

anomaly cancellation could have worked differently

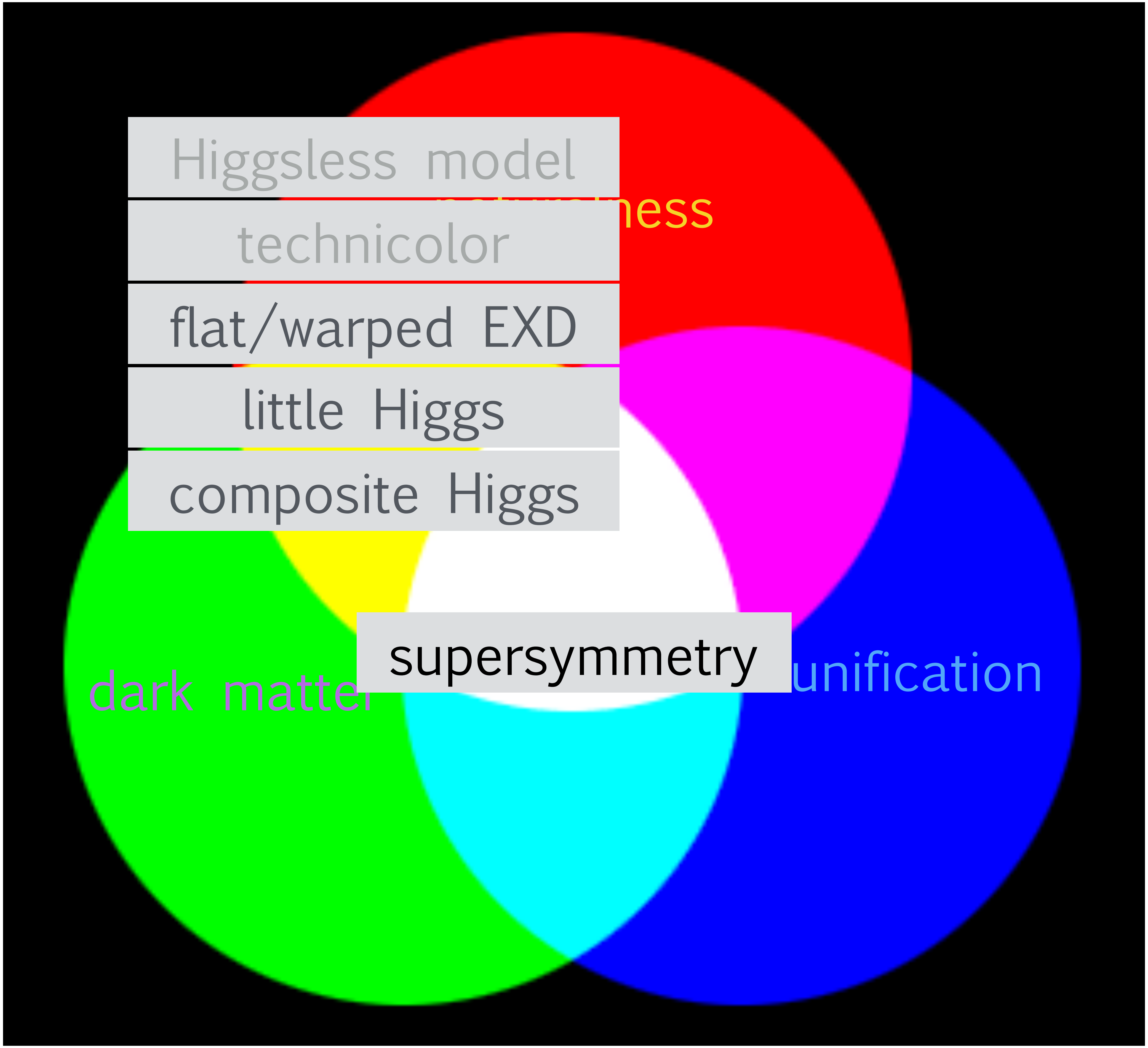
furthermore,
accidental observations



0. two lines meet at one point (or ||)
1. three lines meet at one point
2. below Planck scale & avoid proton decay


Higgsless model
technicolor
flat/warped EXD
little Higgs
composite Higgs
supersymmetry
dark matter
unification

before/after Higgs discovery


Higgsless model
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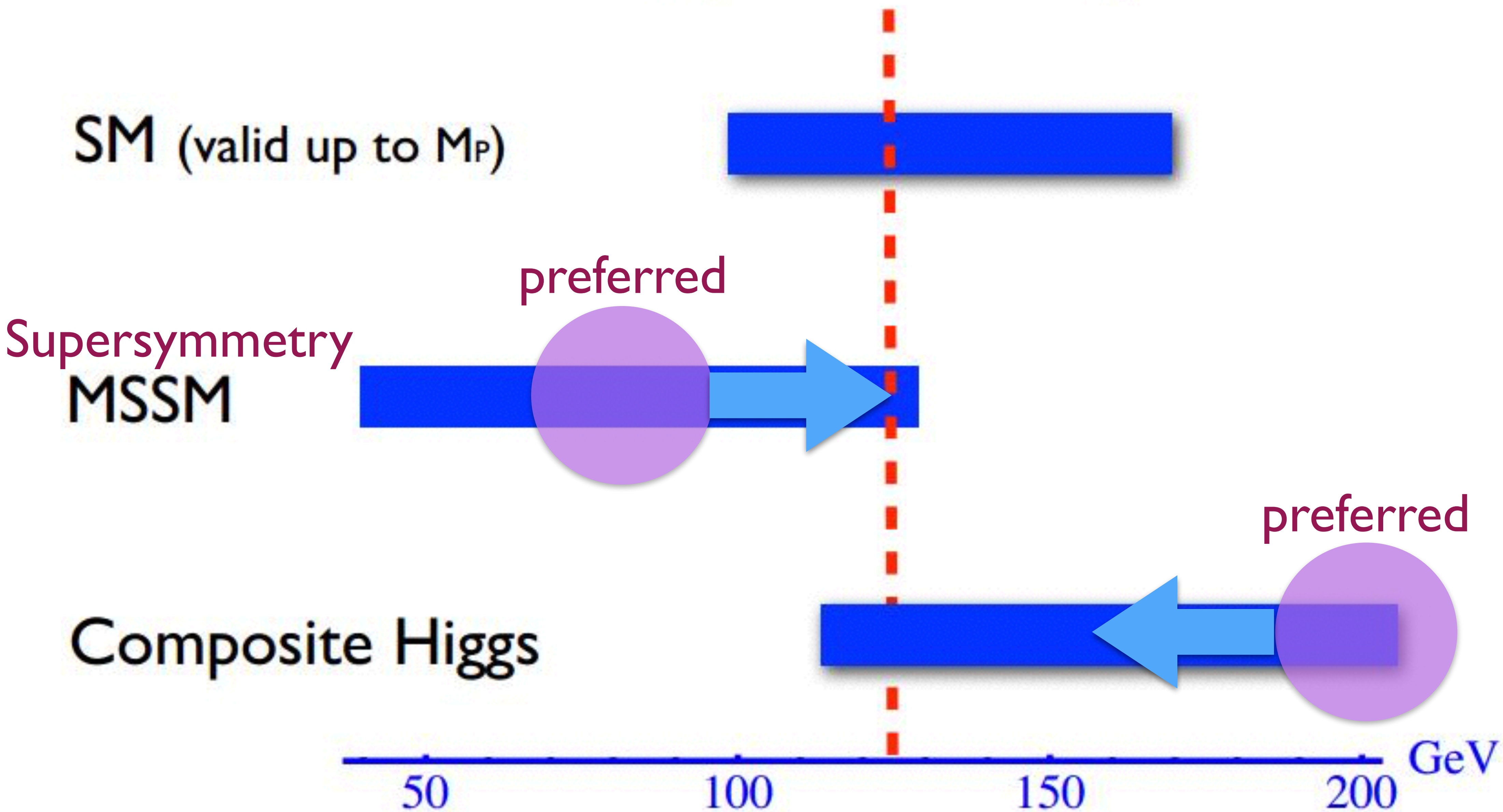
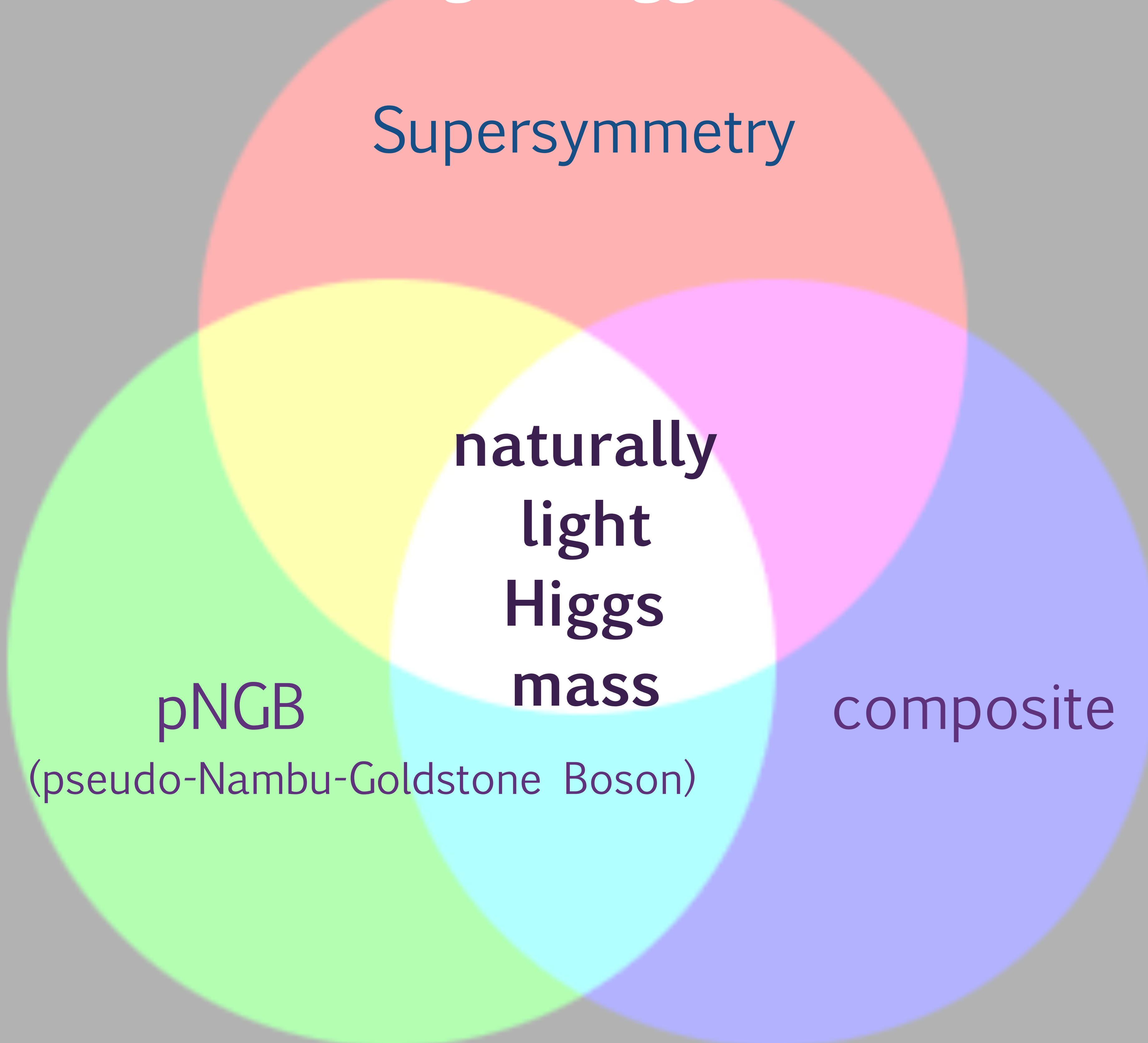
Higgs mass range



By A Pomarol

How to make light Higgs to be natural?



$$V(H) = -\frac{m_h^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4$$

Two mass terms used in the literature

$$V(H) = -\frac{m_h^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4$$

$$m_h^2 = \lambda v^2$$

Higgs mass prediction is obtained from it as v=174 GeV is fixed from W,Z mass

This is the source of fine tuning to keep the weak scale

Supersymmetry

stop mass

$$-\frac{m_h^2}{2} = m_{H_u}^2 + \mu^2 \longrightarrow m_{H_u}^2|_\Lambda - c\frac{m_{\rm SUSY}^2}{16\pi^2}\log\left(\frac{\Lambda}{m_{\rm SUSY}}\right)$$

$$\lambda v^2 = M_Z^2 \qquad\qquad \lambda v^2 = M_Z^2 + c y_t^2 \frac{m_t^2}{16\pi^2}\log\left(\frac{m_{\rm SUSY}}{m_t}\right)$$

Composite Higgs

top partner

$$-\frac{m_h^2}{2} = -a\frac{M^2}{16\pi^2}\log\left(\frac{\Lambda}{M}\right)$$

spontaneous symmetry breaking scale

$$\lambda v^2 = b\left(\frac{v}{f}\right)^2\frac{M^2}{16\pi^2}\log\left(\frac{\Lambda}{M}\right) \qquad\qquad M = g_* f$$

$$\lambda v^2 = b\frac{g_*^2}{16\pi^2}v^2\log\left(\frac{\Lambda}{M}\right)$$

Supersymmetry with no fine tuning predicts

$$v \sim \frac{m_{\mathrm{SUSY}}}{4\pi\lambda^{\frac{1}{2}}}$$

$$\text{fine tuning} \quad \sim \frac{m_h^2}{m_{\mathrm{SUSY}}^2}\frac{5}{L}$$

$$m_{\mathrm{SUSY}} = 1\ \mathrm{TeV} \;\downarrow\;\; 10^{-2} \sim 10^{-4} \;\uparrow\;\; m_{\mathrm{SUSY}} = 10\ \mathrm{TeV}$$

Composite Higgs with no fine tuning predicts

$$v \sim \frac{M}{4\pi\lambda^{\frac{1}{2}}}$$

$$\text{fine tuning} \quad \sim \frac{m_h^2}{M^2}\frac{5}{L}$$

$M \geq 1$ TeV

fine tuning : a few %

50% 50%

Supersymmetry : tree+1loop tree+1loop

$$V(H) = -\frac{m_h^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4$$

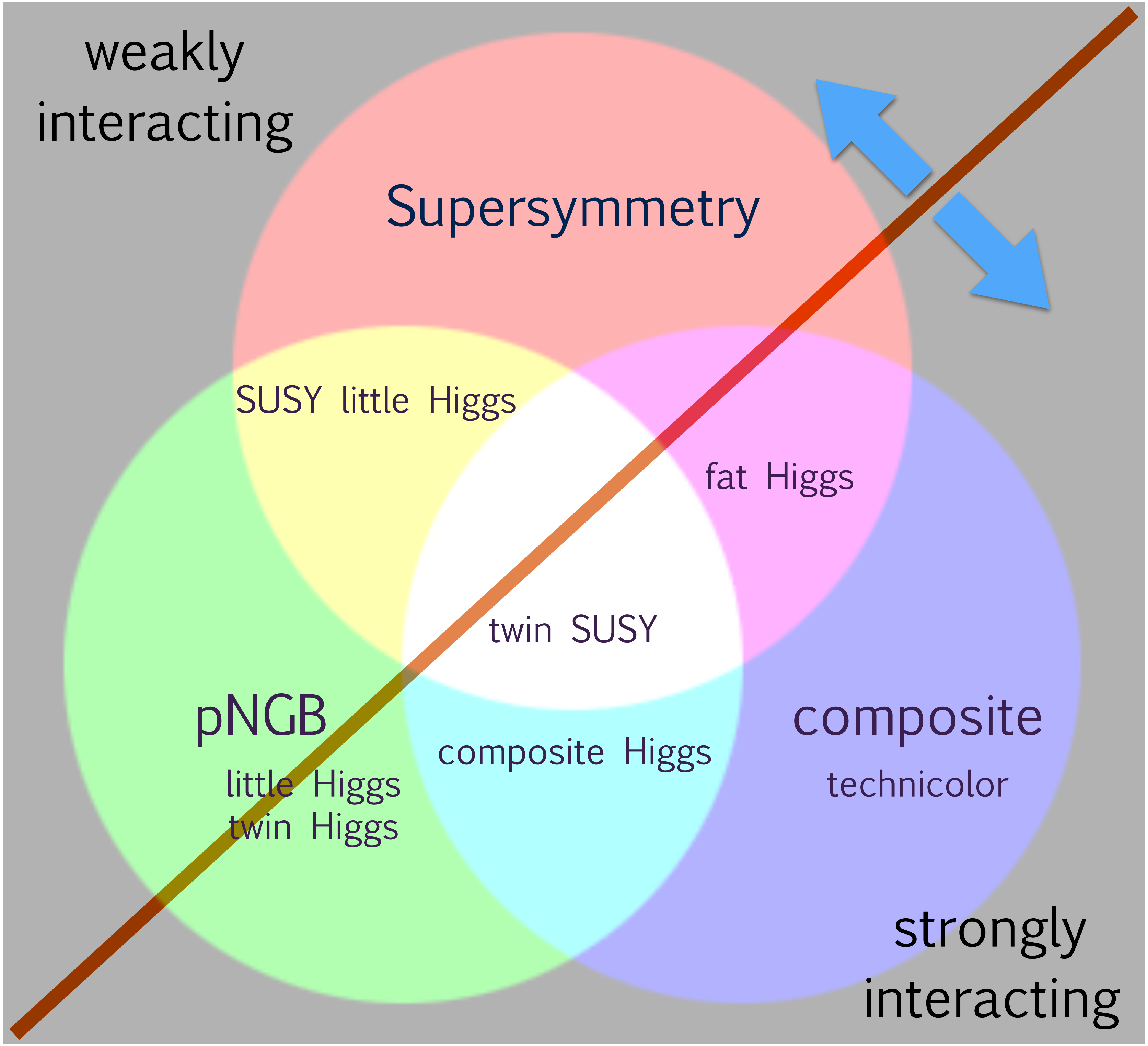
Composite Higgs : 1loop 1loop

MSSM : stop at 5~10 TeV for H(125)

$m_h \sim m_{\rm SUSY}$ is violated

Composite Higgs : v ~ f relation is violated

No motivated models are in good shape now.



Supersymmetric little twin composite Higgs?

Twin Higgs : Neutral Naturalness
(assuming two copies of the SM)
$$SU(4) \to SU(2) \times SU(2) \times Z_2$$

top loop cancelled by (our) colorless one

similar to tan beta=1 of THDM
large invisible decay
problem in cosmology, ...

$$V = yH_A q_A t_A + yH_B q_B t_B - m^2(|H_A|^2 + |H_B|^2) + \lambda(|H_A|^2 + |H_B|^2)^2$$

$$V_{1\mathrm{L}} = \frac{3y^2}{8\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2)$$

$$H_A = \frac{1}{\sqrt{2}}(h + H) \qquad H_B = \frac{1}{\sqrt{2}}(-h + H)$$

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$$V = yH_A q_A t_A + yH_B q_B t_B - m^2(|H_A|^2 + |H_B|^2) + \lambda(|H_A|^2 + |H_B|^2)^2$$

$$+m_A^2 |H_A|^2$$

$$V_{1\mathrm{L}} = \frac{3y^2}{8\pi^2}\Lambda^2(|H_A|^2 + |H_B|^2)$$

explicit SU(4) breaking term
should be as large as the cutoff

$$\frac{|m_A^2 - m^2|}{|m^2|} \ll 1$$ for h to be SM like

Higgs as pNGB

works in **Nnaturalness**

works in **relevant Standard Model**

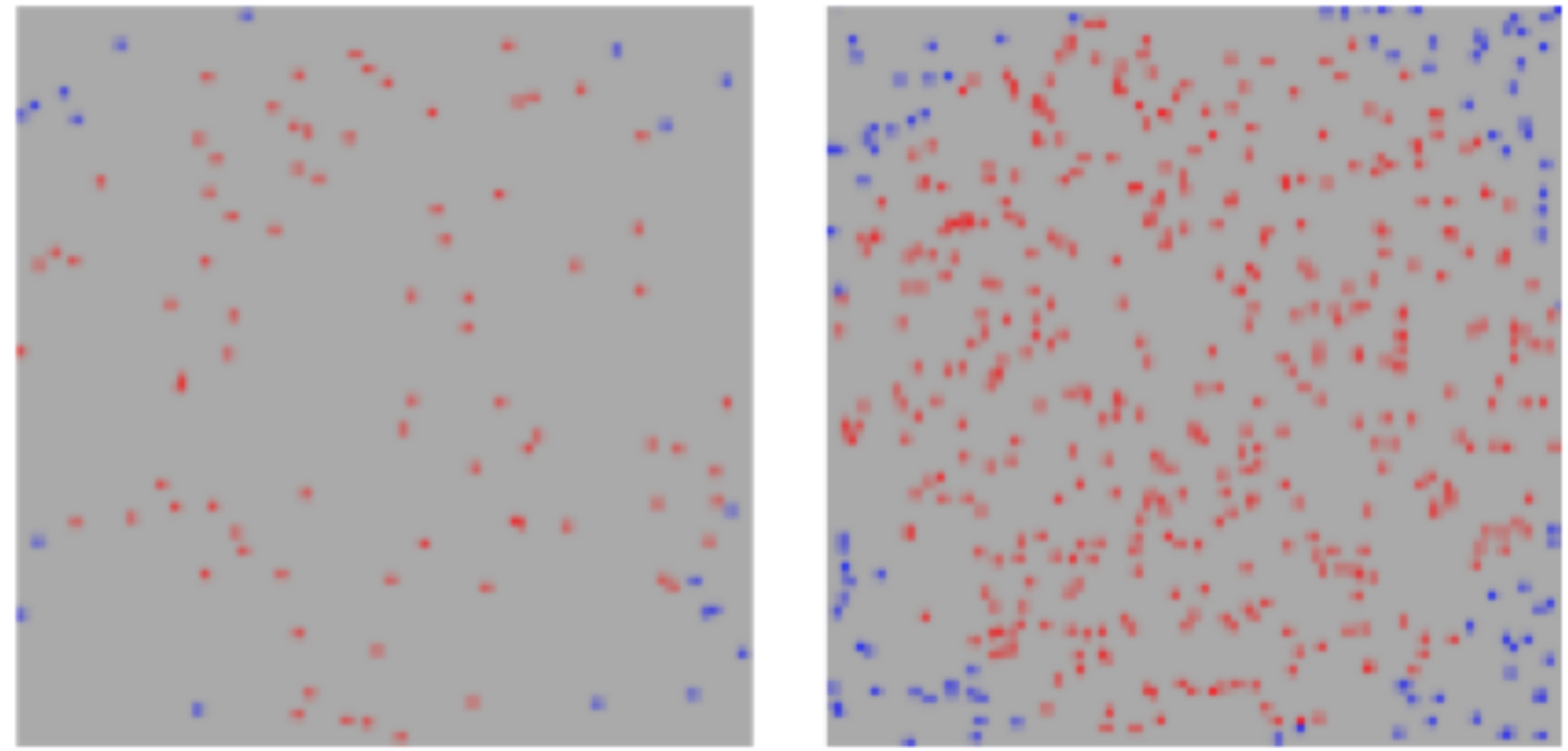
It is important
to fill up
the loophole
in all possible
explanation
of the hierarchy

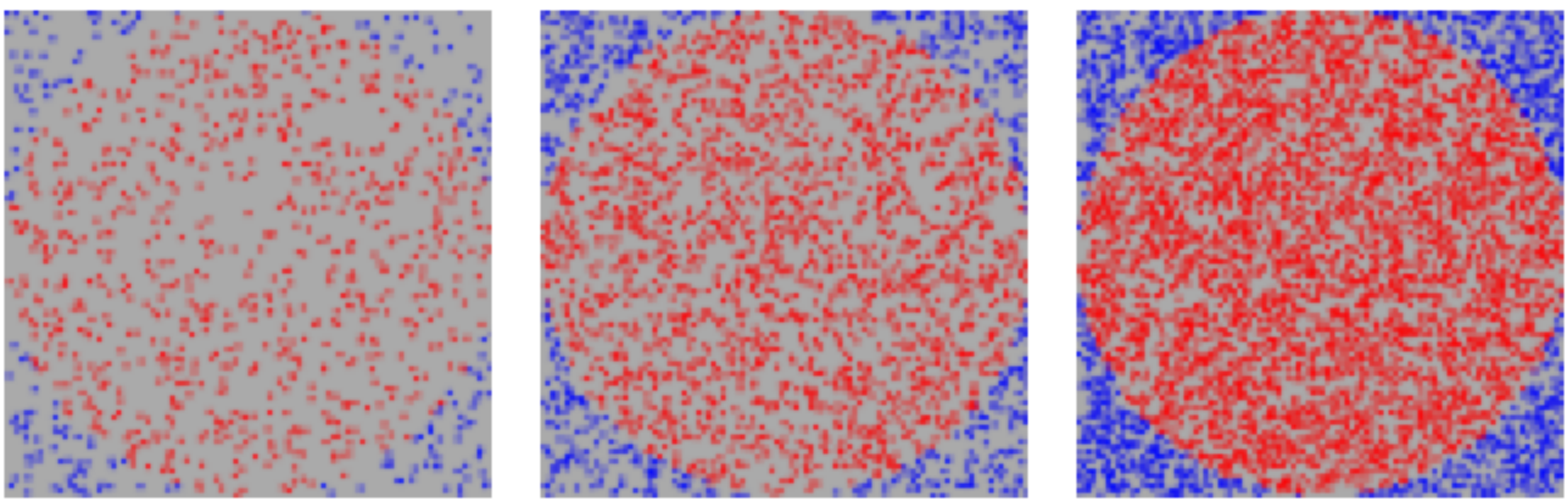
Nnaturalness

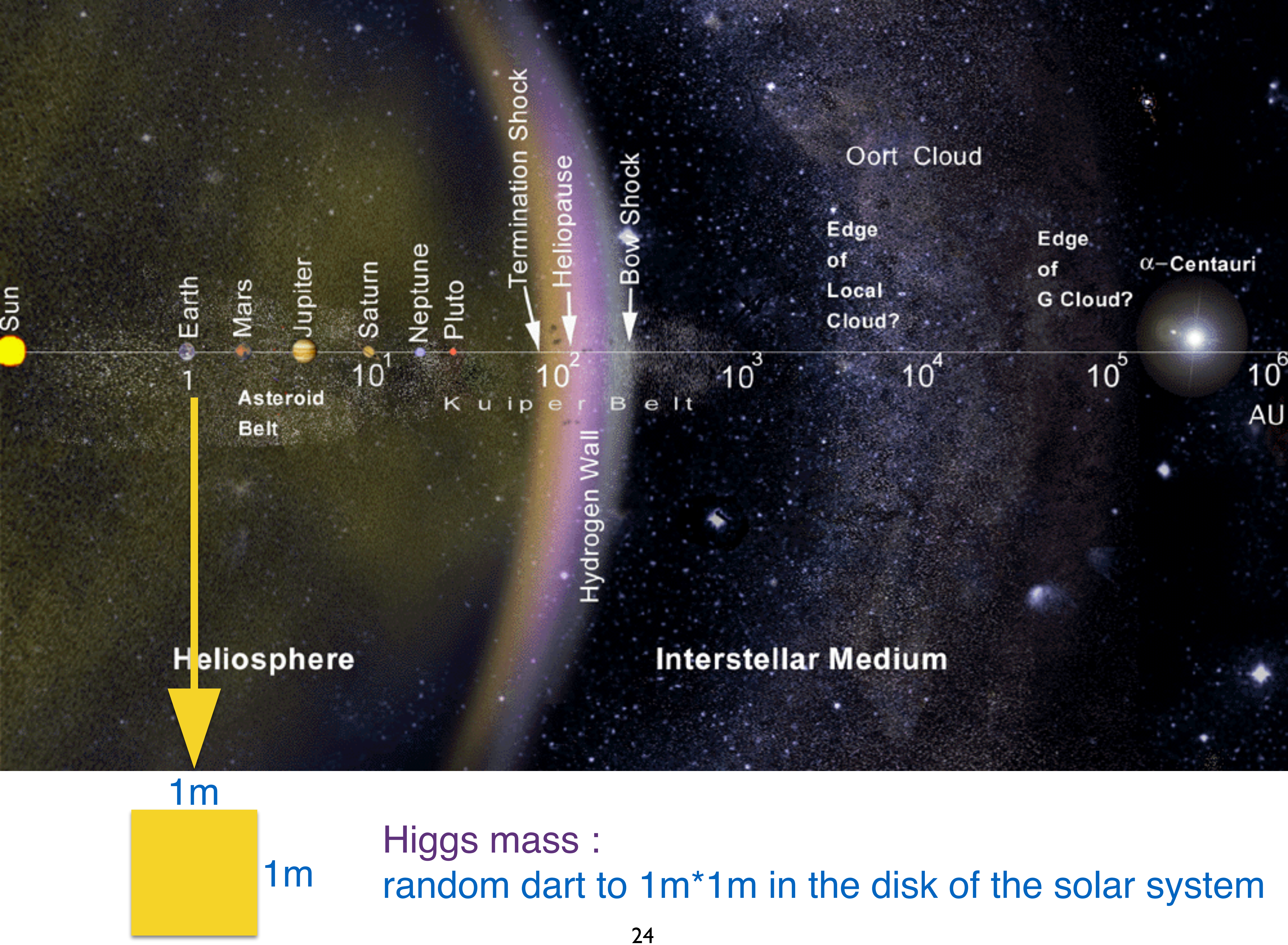
by S Dimopoulos

Nnaturalness

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)







Higgs mass :

random dart to 1m*1m in the disk of the solar system

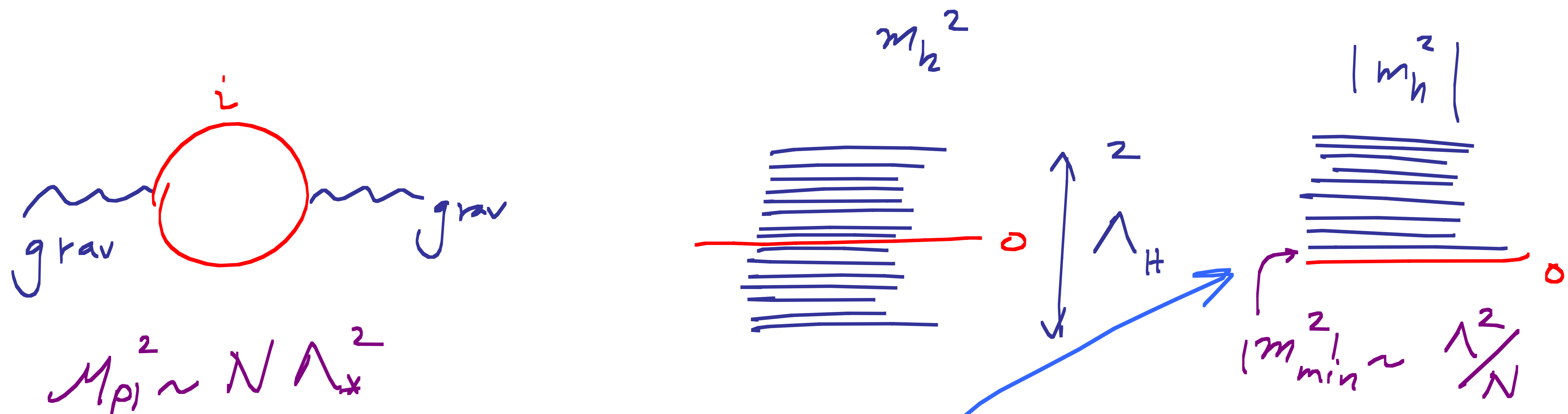
Dvali Redi PRD (2009)

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

$N = 10^{32}$

$\Lambda_* = 100$ GeV

N copies of (MS) SM



if reheaton is a pNGB

Cosmology Dominantly Reheats Bottom of Spectrum

enormous reduction of dof

scenario I

$N = 10^{16}$

$\Lambda_* = \Lambda_H = 10^{10}$ GeV

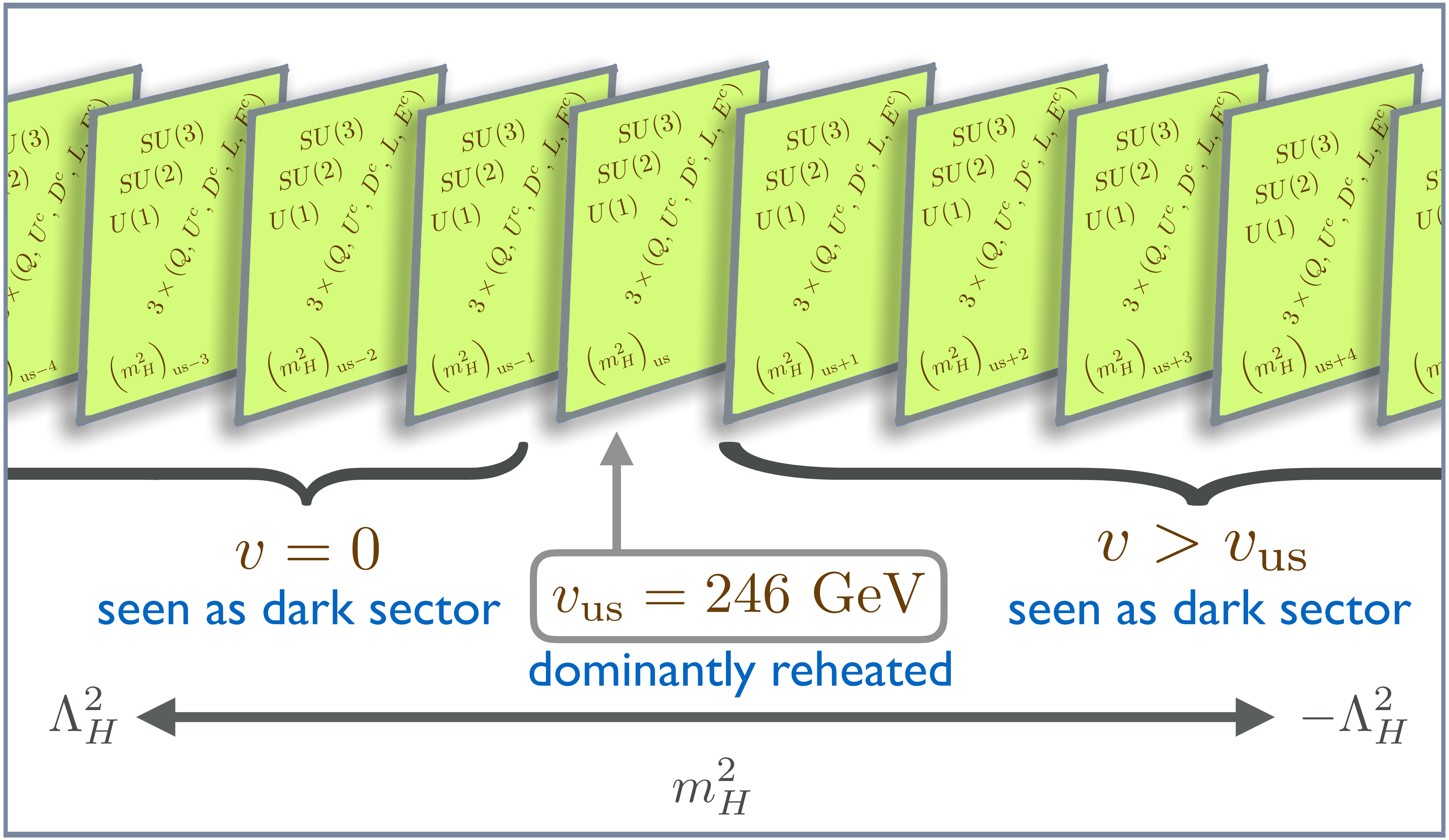
scenario II

$N = 10^4$

$\Lambda_* = 10^{16}$ GeV

$\Lambda_H = 10$ TeV

by N Arkani-Hamed



$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right), \qquad -\frac{N}{2} \le i \le \frac{N}{2}$$

scalar reheat

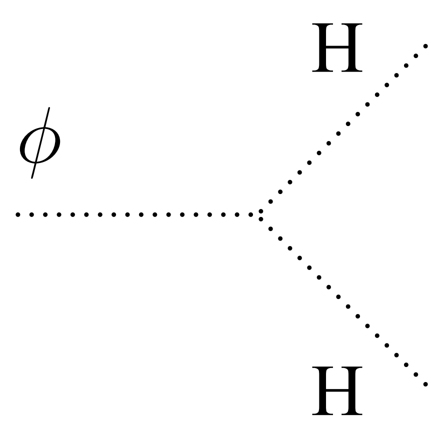
$A\phi H^\dagger H$

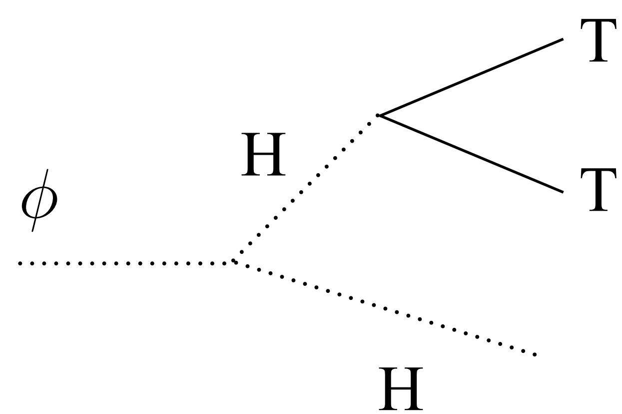
fermion reheat

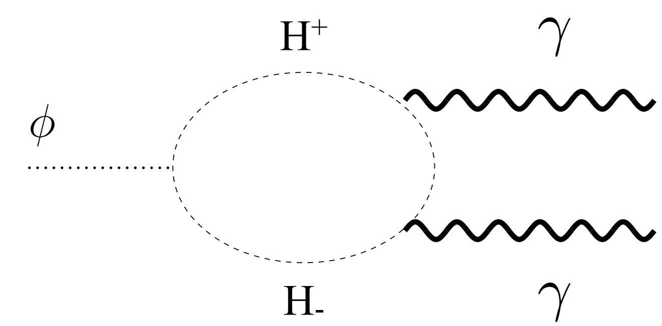
$\lambda S L H$

population of the sectors

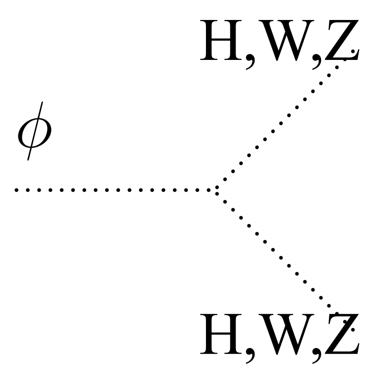
$m_H^2 > 0$

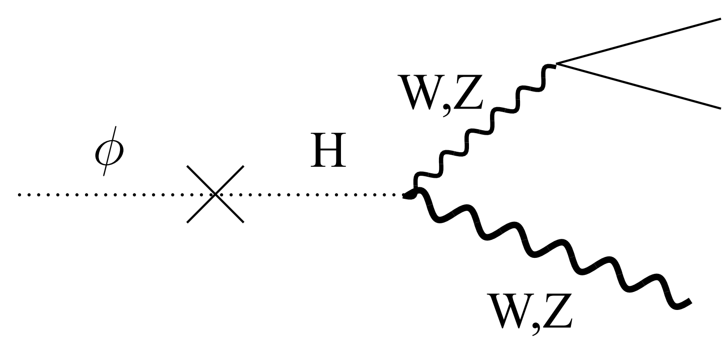


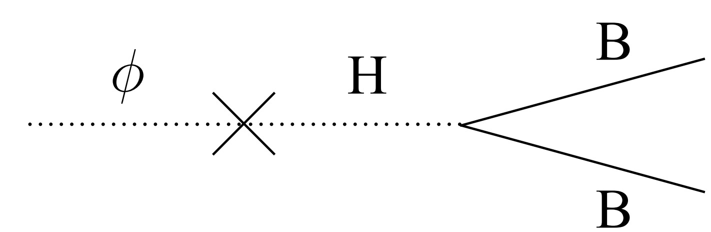




$m_H^2 < 0$



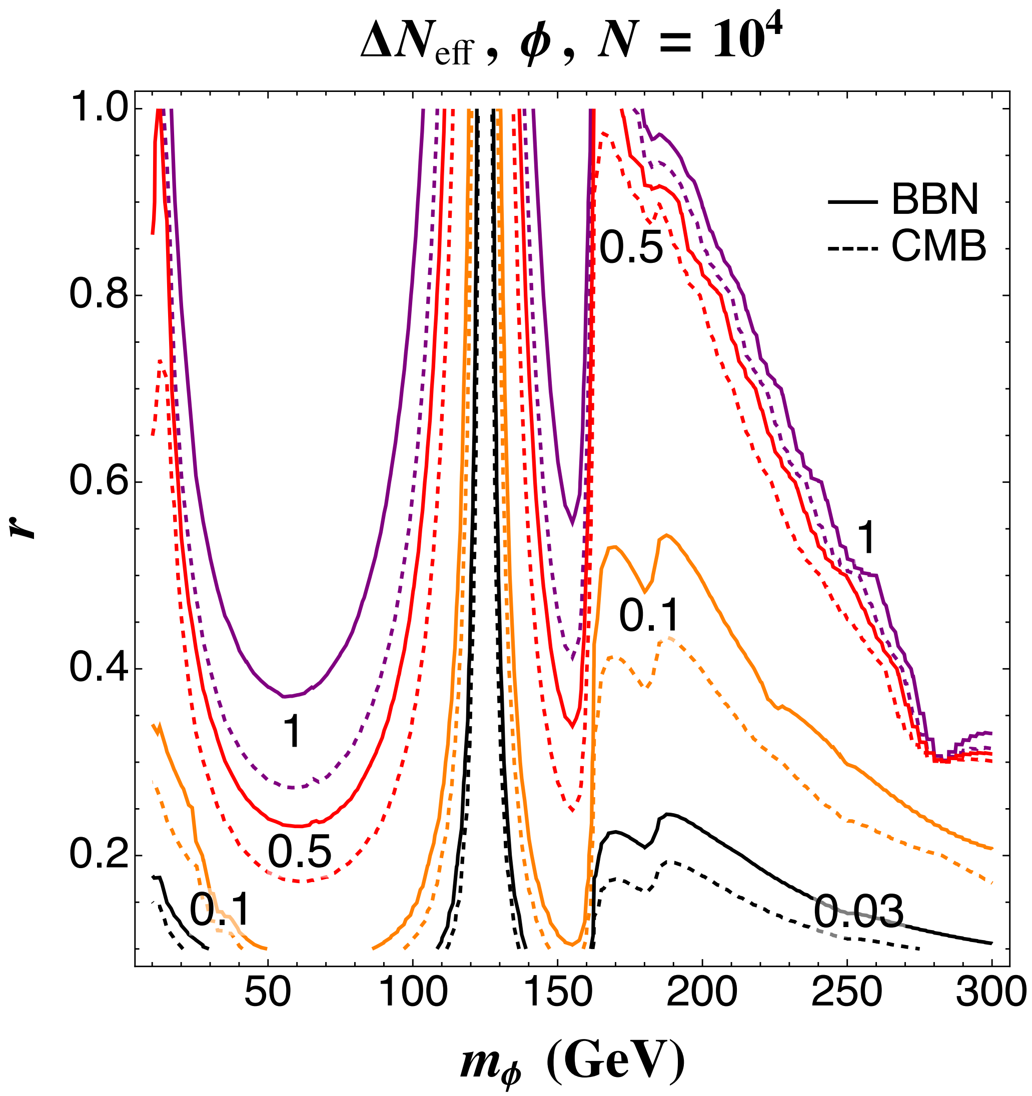


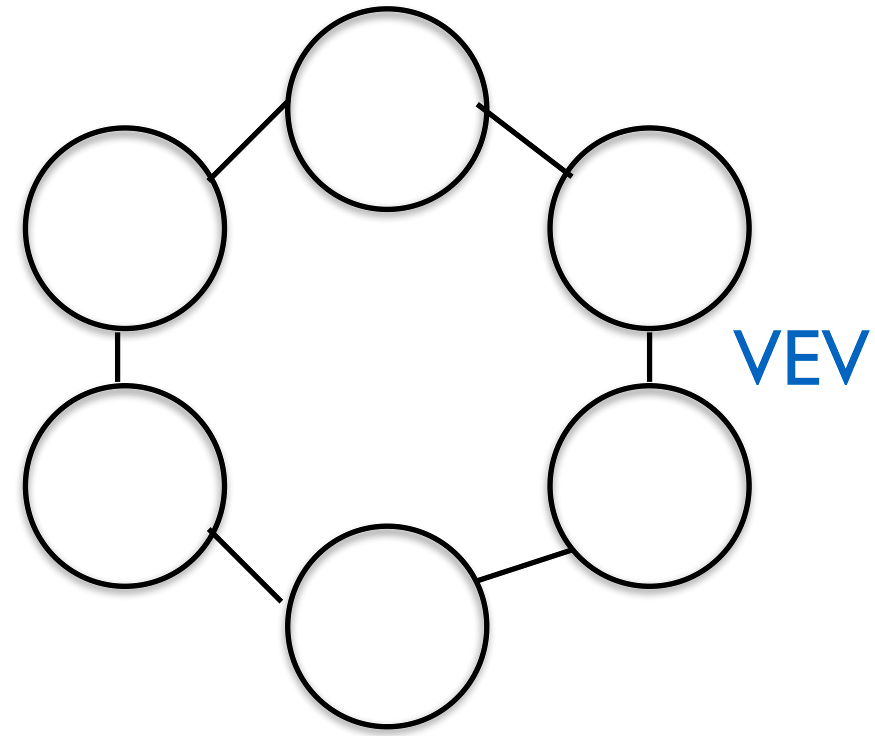


$$\mathcal{L}_\phi^{\langle H\rangle\neq 0} \supset C_1^\phi\, a\, y_q \frac{v}{m_h^2} \phi\, q\, q^c\,;$$

$$\mathcal{L}_\phi^{\langle H\rangle = 0} \supset C_3^\phi\, a\, \frac{g^2}{16\,\pi^2} \frac{1}{m_H^2}\, \phi\, W_{\mu\nu} W^{\mu\nu}\,,$$

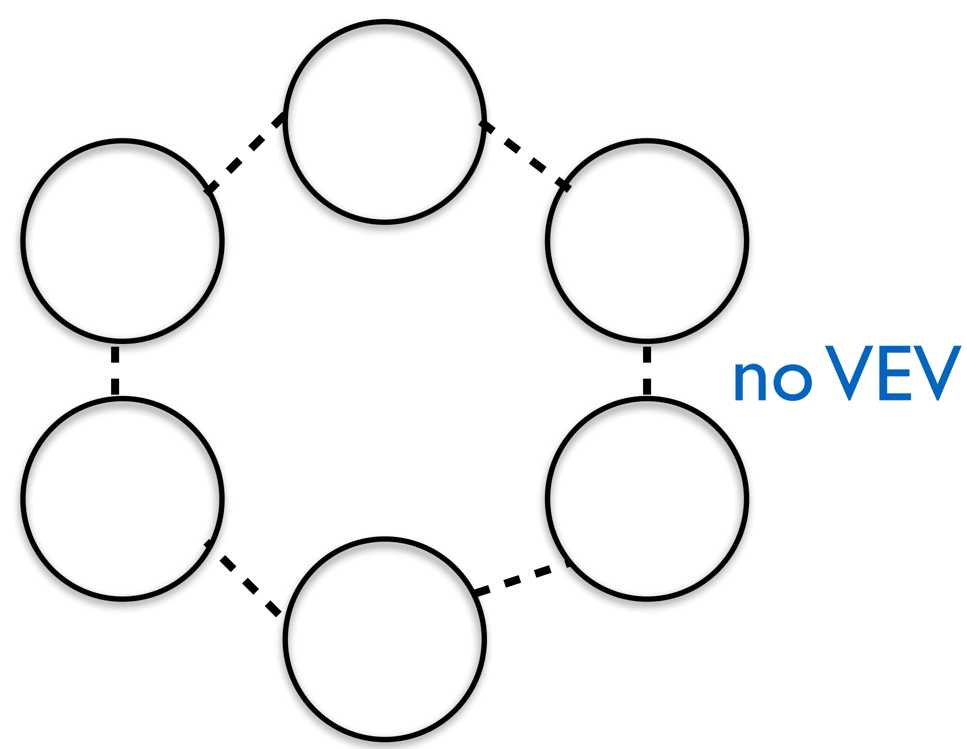
different phase of deconstruction





phase A : extra dimension

phase B : Nnaturalness



dark radiation $4.4 + 3 = 7.4$

photon neutrino

Br(i=2)~ 0.1

generic prediction $\Delta N_{\rm eff} \sim \mathcal{O}(1)$

Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

Cosmological solution to the naturalness

Relaxion

Nnaturalness

It might explain no new physics at the LHC
Cosmological observables might be interesting

Why is it working?

Reheaton is pNGB (not Higgs itself)

The presence of light scalar can be explained by pNGB idea

and

extra assumption of decay via Higgs can explain why it decays predominantly to the lightest Higgs sector

Talk at LHCP2017 , May 15-20

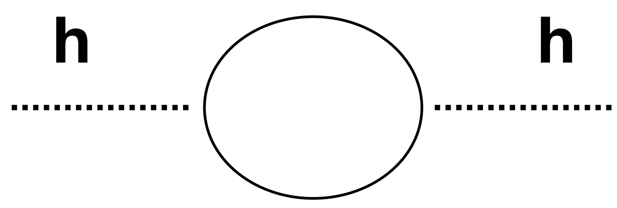
1709.00766

[‡]One possible way out is to make the SM Yukawa and gauge couplings to be relevant.

3

origin of fine tuning
:SUSY as an example

$$-\frac{m_h^2}{2} = \mu^2 + m_H^2 + \delta m_H^2$$



$$\delta m_H^2 \propto -y_t^2 m_{\rm soft}^2$$

$\mu > 100$ GeV (bound from Higgsino mass)

Let's accept μ and focus on the remaining parts

Below the sparticle mass scales,
the correction is negligible

$$\beta_{m_h^2} = \frac{dm_h^2}{d\log\bar{\mu}} = \frac{3m_h^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g^2}{4} - \frac{g'^2}{4}\right)$$

Fine tuning is determined at the sparticle mass scales,

$$m_h^2(m_{\rm SUSY}) = m_h^2(\Lambda) + \delta m_h^2(\Lambda \to m_{\rm SUSY})$$

Focus on the couplings $\longrightarrow$ $-\frac{6y_t^2}{8\pi^2} m_{\rm SUSY}^2 \log\left(\frac{\Lambda}{m_{\rm SUSY}}\right)$

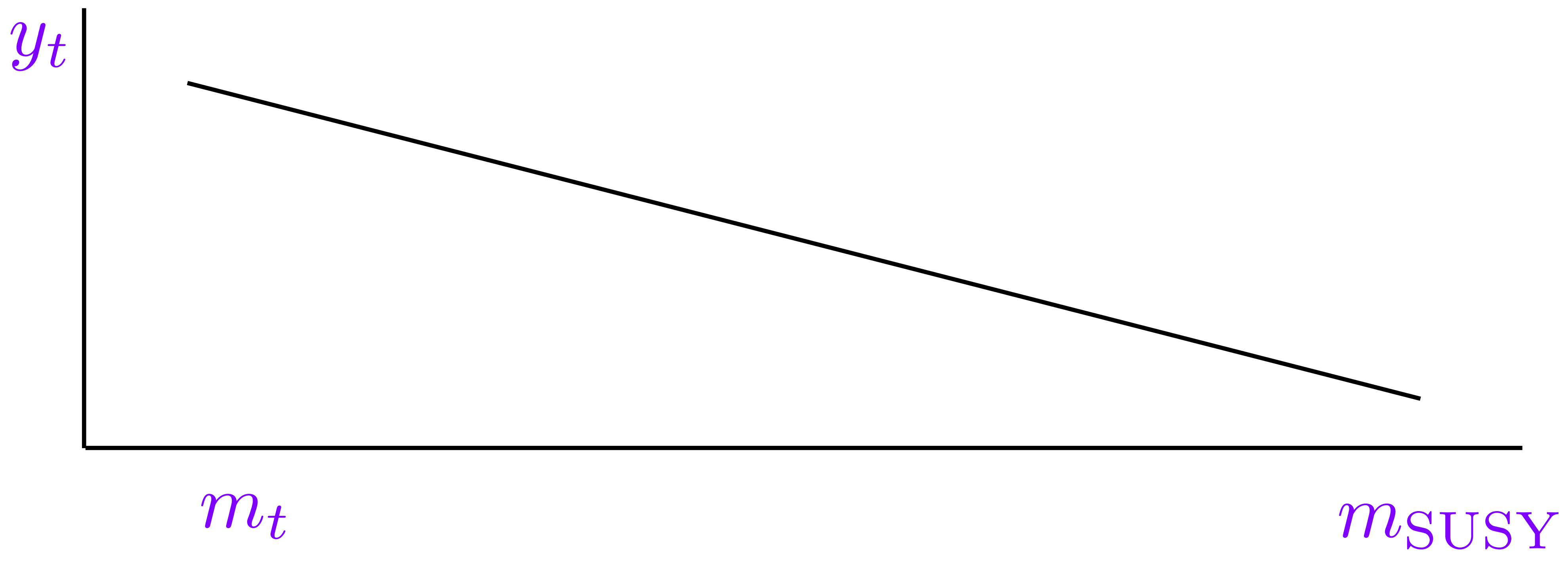
$$= \mathcal{O}(m_{\rm SUSY}^2)$$

bounds from direct search

$$\delta m_h^2(m_{\rm SUSY}) = c y_{t*}^2 m_{\rm SUSY}^2$$

$$y_{t*} = y_t(\mu = m_{\rm SUSY})$$

If y_t is drastically different at $m_{\rm SUSY}, m_t$, EWSB can be natural with heavy stops.



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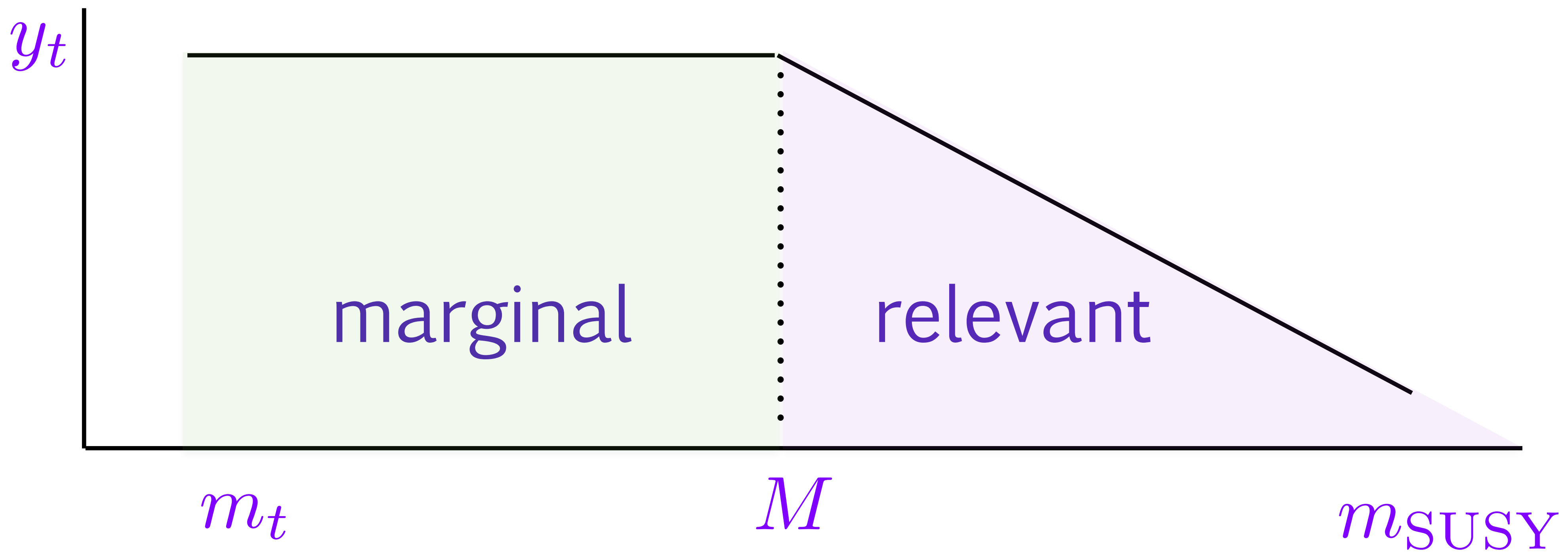


Higgs as pNGB

does not work well since

$$y_t \sim \mathcal{O}(1)$$

For the relevant operators, it is more important (relevant) at IR

$$g_{\rm eff}(\mu) = c\frac{\Lambda}{\mu} \qquad\qquad c = \epsilon \ll 1$$

Suppose the dimension of spacetime changes from D to 4 at the scale M and below.

$y_t = \epsilon \frac{m_{\rm SUSY}}{M}$ can be order one if $\epsilon \sim \frac{M}{m_{\rm SUSY}} \ll 1$

This is very compatible with pNGB idea of having suppressed coupling at Λ

$y_{t({\rm eff})} = \epsilon \ll 1$

In 4 spacetime dimensions

$$[HQt^c] = 3 \qquad [y_t] = 1$$

$$[H^* H A_\mu A^\mu] = 2 \qquad [g] = 1$$

$$[(H^* H)]^2] = 2 \qquad [\lambda] = 2$$

Possible strongly interacting theory above M

$$[H] = 1 \qquad [y_t] = 1, [g] = 1, [\lambda] = 0$$

$$[Qt^c] = 2 \qquad \frac{d\lambda}{d\log\mu} = c\lambda^2$$

$$[A_\mu] = 0$$

multiplicative running
make it even smaller

In 4 spacetime dimensions

$$[HQt^c] = 3 \qquad [y_t] = 1$$

$$[H^*HA_\mu A^\mu] = 2 \qquad [g] = 1$$

$$[(H^*H)^2] = 2 \qquad [\lambda] = 2$$

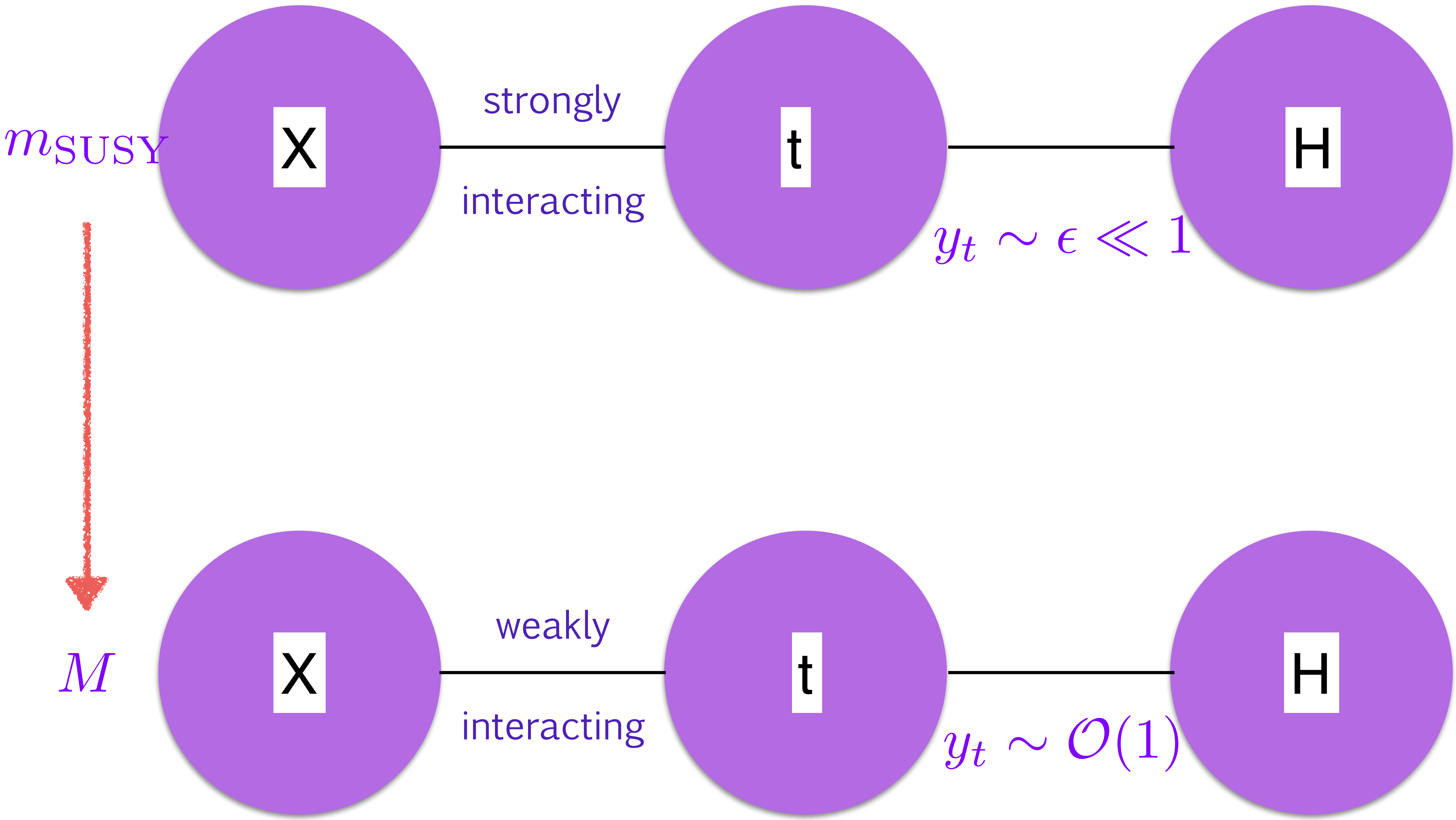
Possible strongly interacting theory above M

$$[H] = 1 \qquad [y_t] = 1 - r_t$$

$$[Qt^c] = 2 + r_t \qquad [g] = 1 - r_A$$

$$[A_\mu] = r_A \qquad \frac{d\lambda}{d\log\mu} = c\lambda^2$$

multiplicative running


$m_{\rm SUSY}$
X
strongly
interacting
t
$y_t \sim \epsilon \ll 1$
H
M
X
weakly
interacting
t
$y_t \sim \mathcal{O}(1)$
H

In 4 spacetime dimensions

$$[HQt^c] = 3$$

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$$[g] = 1$$

$$[(H^* H)]^2] = 2$$

$$[\lambda] = 2$$

Classical scaling dimension in d spacetime dimensions

$$[H] = [A_\mu] = \frac{D-2}{2}$$

$$[y_t] = 2 - \frac{D}{2}$$

$$[g] = 2 - \frac{D}{2}$$

$$[Qt^c] = D - 1$$

$$[\lambda] = 4 - D$$

vanishing dimension : Lorentz violation(?)

Phenomenology

Couplings are suppressed at and above M

Cross sections are suppressed accordningly

$$\sigma(t\bar{t}) \propto \frac{M^2}{E^4} \quad \text{for} \quad E \geq M$$

$M \gg 1\ \mathrm{TeV}$ from the LHC

Summary

Light Higgs might be due to smaller couplings at high energy

It is consistent with Higgs being a pseudo-Nambu-Goldstone boson at high energy

To realize the idea in the SM, we can take several possibilities (strongly interacting QFT above M, spacetime dimension 4 to 2 above M)