Running top Yukawa for the naturalness

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with Raffaele D'agnolo

Higgs as pNGB

works in **Nnaturalness**

works in **running Yukawa couplings**

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

Nnaturalness

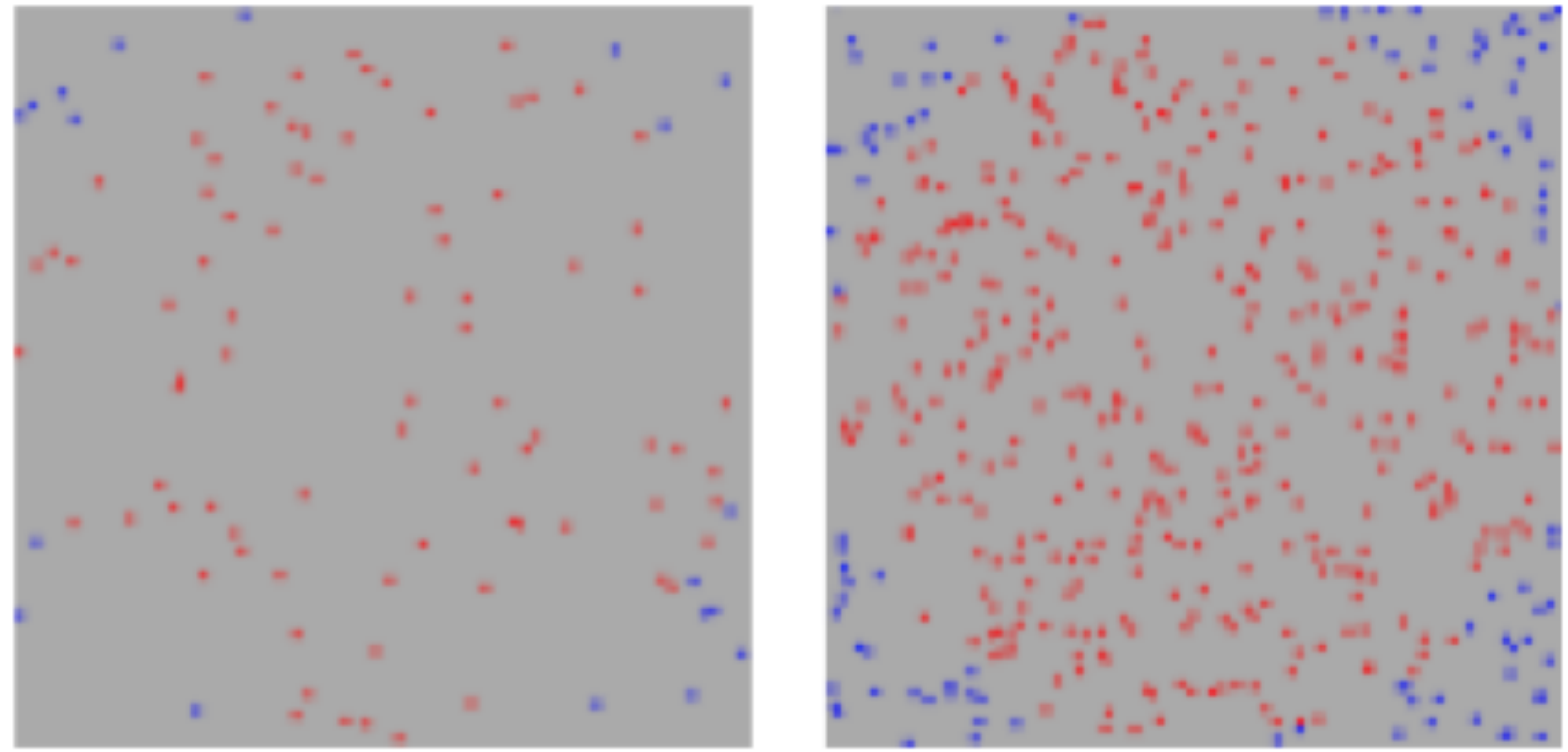
Running Yukawa

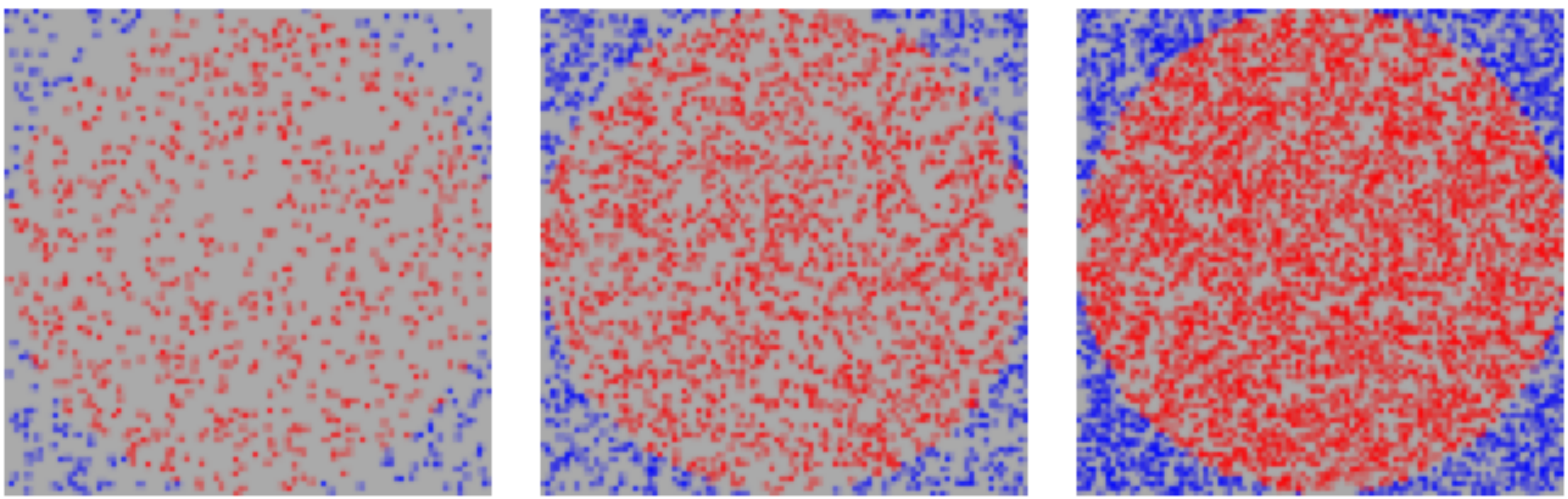
by S Dimopoulos

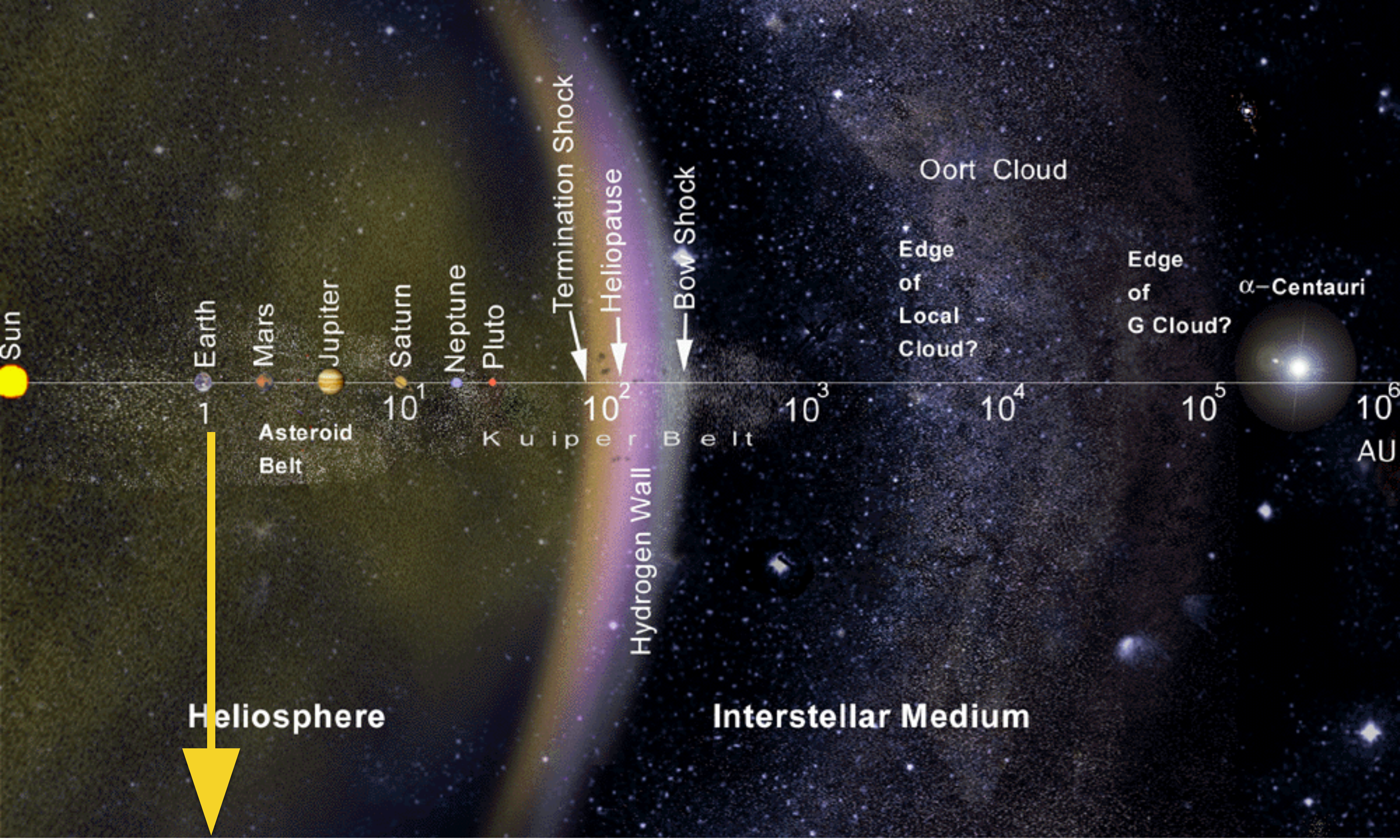
Nnaturalness

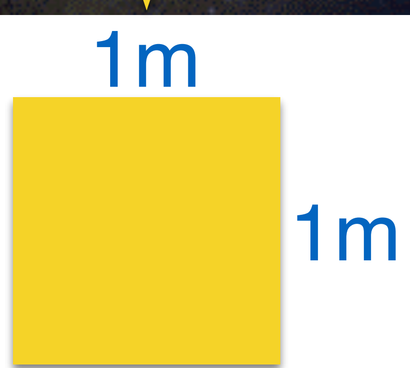
Nnaturalness

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)

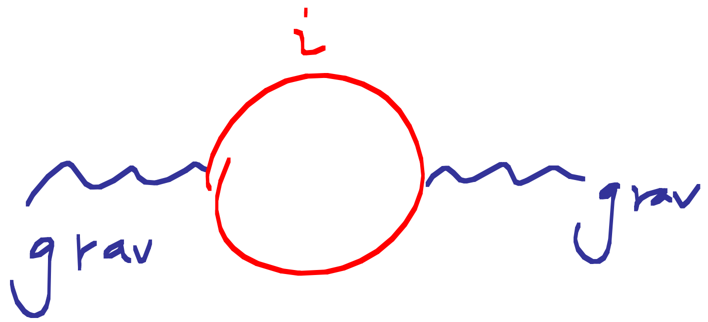
Arkani-Hamed Cohen D'agnolo Hook HDK Pinner, PRL (2016)

$N = 10^{32}$

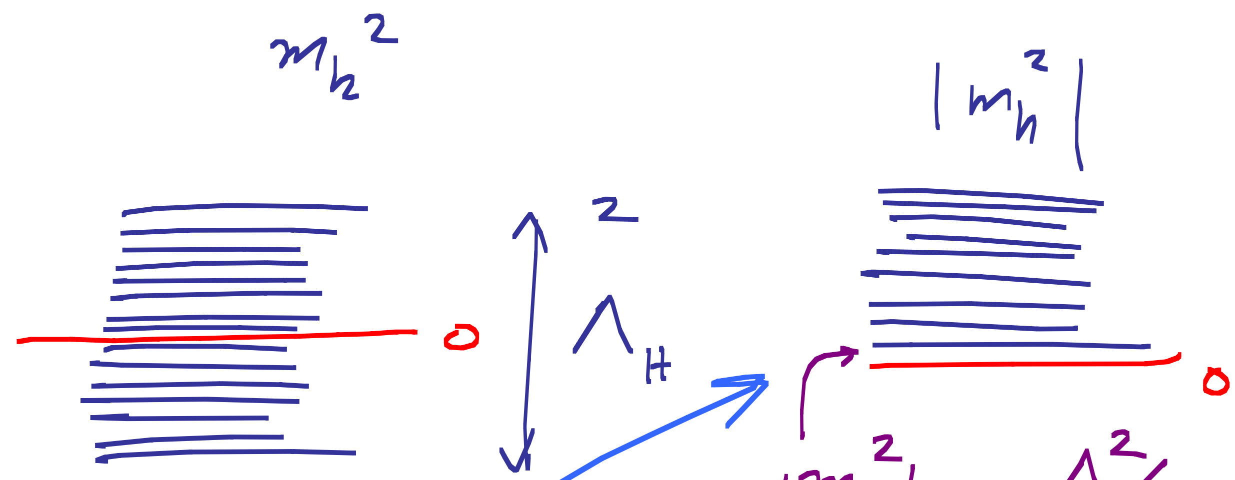
$\Lambda_* = 100$ GeV

N copies of (MS) SM

enormous reduction of dof



$M_{pl}^2 \sim N \Lambda_*^2$



$|m^2_{min}| \sim \Lambda^2 / N$

if reheaton is a pNGB

Cosmology Dominantly Reheats Bottom of Spectrum

scenario I

$N = 10^{16}$

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

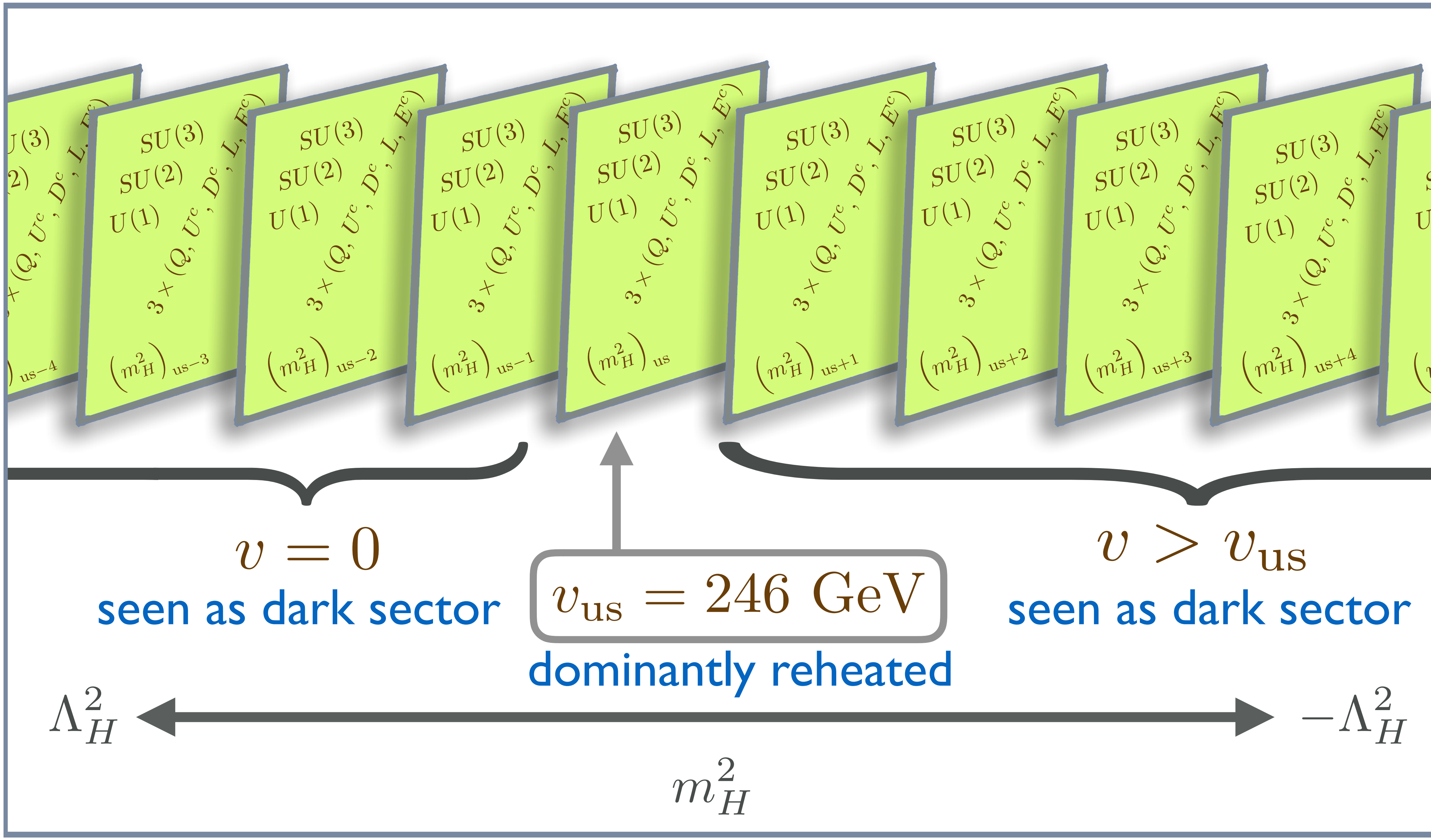
scenario II

$N = 10^4$

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

$\Lambda_H = 10$ TeV

by N Arkani-Hamed



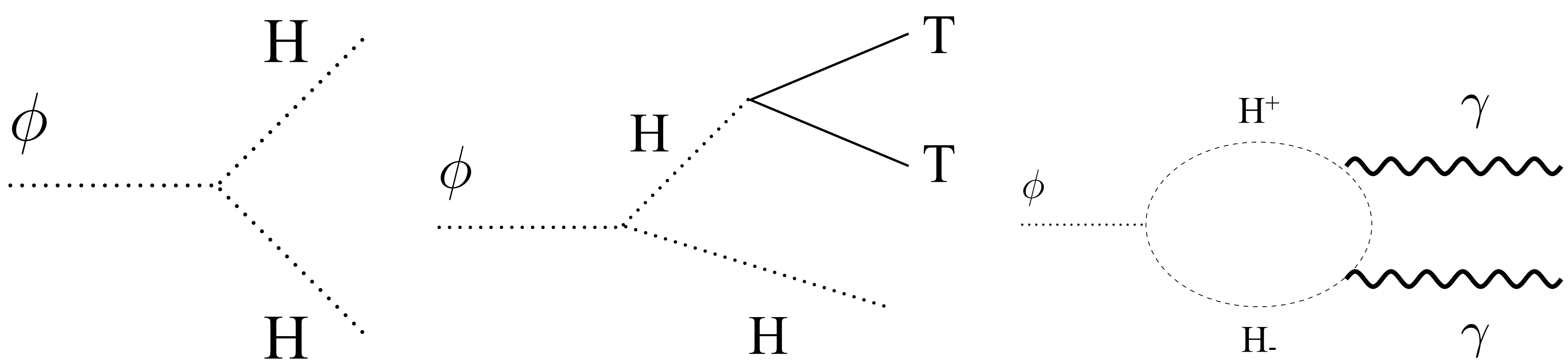
$$\left(m_H^2\right)_i = -\frac{\Lambda_H^2}{N}\left(2\,i + r\right), \qquad -\frac{N}{2} \leq i \leq \frac{N}{2}$$

scalar reheat
$A\phi H^\dagger H$

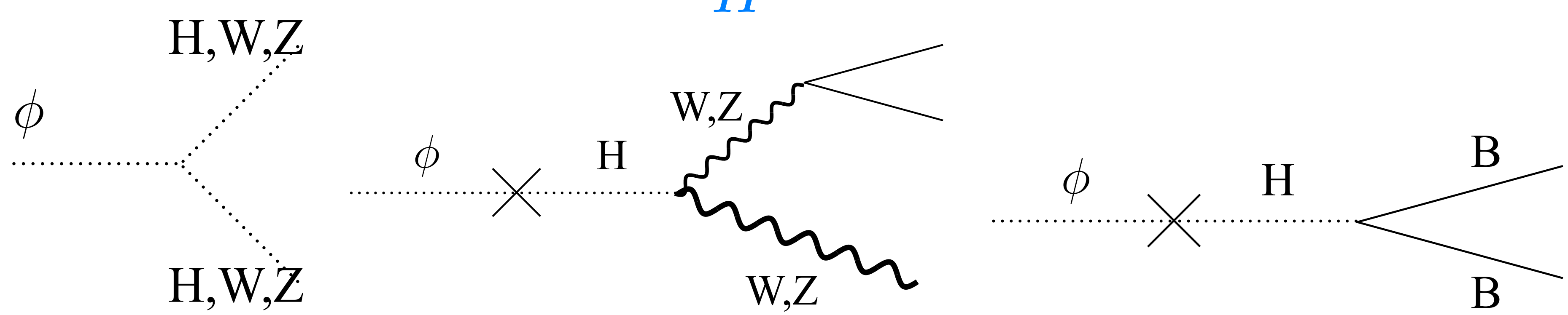
fermion reheat
$\lambda S L H$

population of the sectors

$$m_H^2 > 0$$



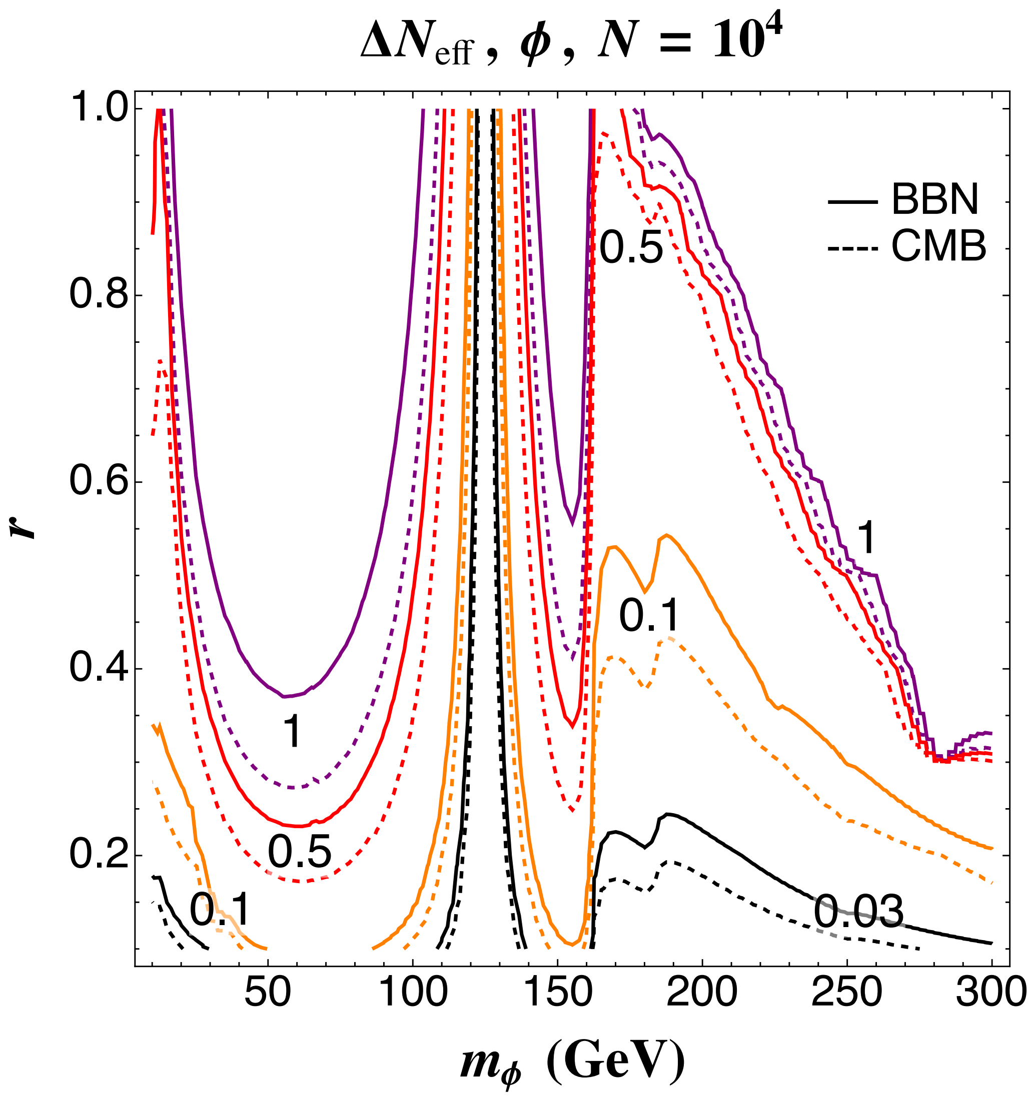
$$m_H^2 < 0$$

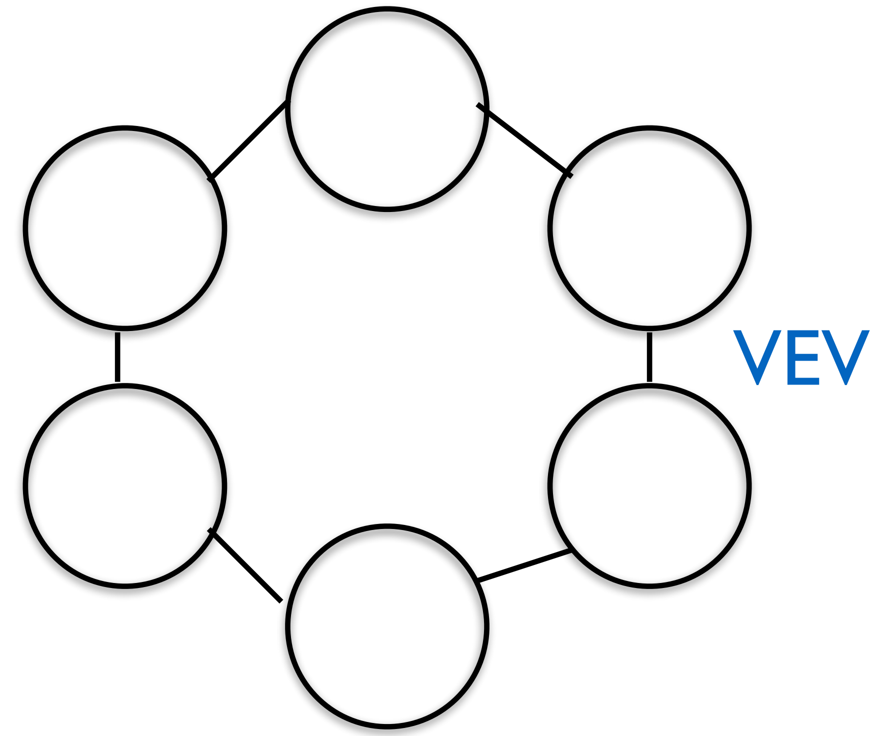


$$\mathcal{L}_\phi^{\langle H\rangle \neq 0} \supset \mathcal{C}_1^\phi\, a\, y_q \frac{v}{m_h^2} \phi\, q\, q^c\, ;$$

$$\mathcal{L}_\phi^{\langle H\rangle = 0} \supset \mathcal{C}_3^\phi\, a\, \frac{g^2}{16\,\pi^2} \frac{1}{m_H^2}\, \phi\, W_{\mu\nu} W^{\mu\nu}\, ,$$

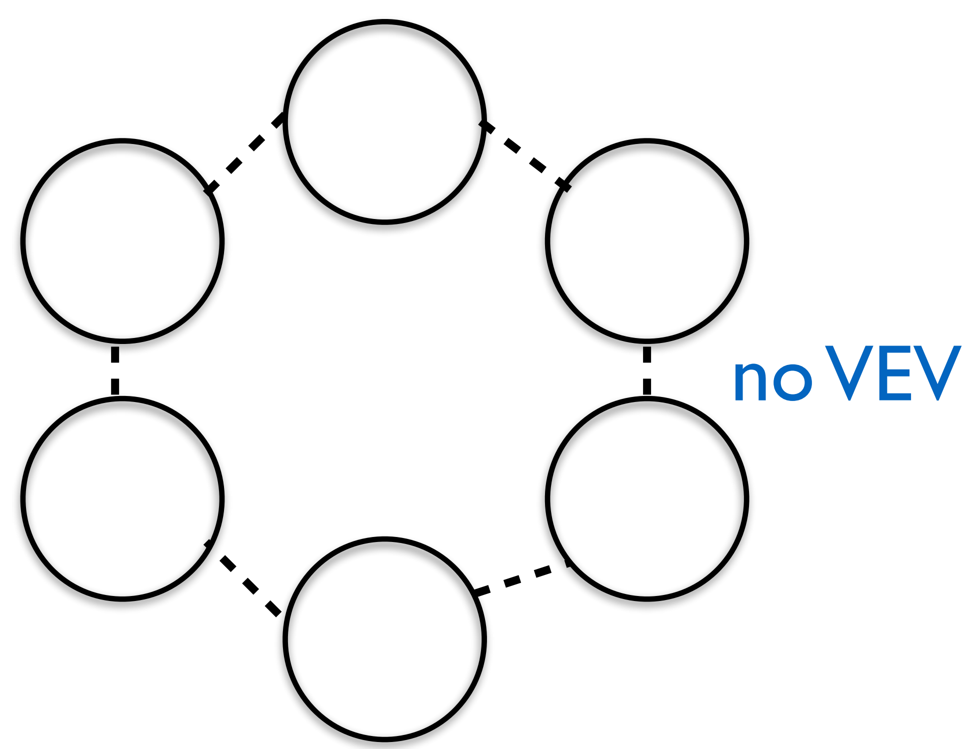
different phase of deconstruction





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)

Nnaturalness

Cosmological solution
to the naturalness

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

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

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

Running Yukawa Couplings

Talk at LHCP2017 , May 15-20

1709.00766

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

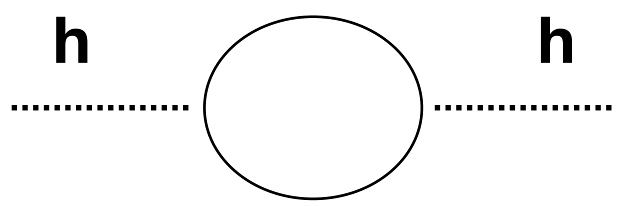
3

$$\Delta[Qt^c] = 2 \qquad \Delta[y_t] = 1$$

$$y_t(\Lambda) = (\frac{\mu}{\Lambda}) y_t(\mu) \ll y_t(\mu)$$

origin of fine tuning
:SUSY as an example

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



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

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

Let's accept μ and focus on the remaining parts

10% to 20% fine tuning would be acceptable

$$\Delta = \frac{\delta m_H^2}{\left(\frac{m_H^2}{2}\right)} \sim \frac{\delta m_H^2}{(100\ \mathrm{GeV})^2}$$

$$\delta m_H^2 \sim (200\ \mathrm{GeV})^2 \qquad 20\% \qquad \Delta \sim 5$$

$$\delta m_H^2 \sim (300\ \mathrm{GeV})^2 \qquad 10\% \qquad \Delta \sim 10$$

$$\delta m_H^2 \propto -\frac{3y_t^2}{16\pi^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + |A_t|^2\right)\log\left(\frac{\Lambda}{m_{\tilde{t}}}\right)$$

$\sim 10^{-2}$

$3 \sim 30$

$-(\frac{m_{\tilde{t}}}{3})^2$

$-m_{\tilde{t}}^2$

$-(200\ \mathrm{GeV})^2$

$m_{\tilde{t}} \sim 600\ \mathrm{GeV} : 20\%\ \mathrm{to}\ 2\%$

$(M_3, M_2 \sim 900\ \mathrm{GeV})$

Below the sparticle mass scales,
the correction is negligible

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

$< 10\%$ correction

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 $\longrightarrow -\frac{6y_t^2}{8\pi^2} m_{\rm SUSY}^2 \log(\frac{\Lambda}{m_{\rm SUSY}})$

Top Yukawa : constrained at the weak scale

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

bounds from direct search

$\mu = m_{\tilde{t}}$

$$m_H^2(m_{\tilde{t}}) = c\frac{y_t^2(m_{\tilde{t}})}{16\pi^2}m_{\tilde{t}}^2$$ computed at high scale

All the fine tuning issues are at this scale

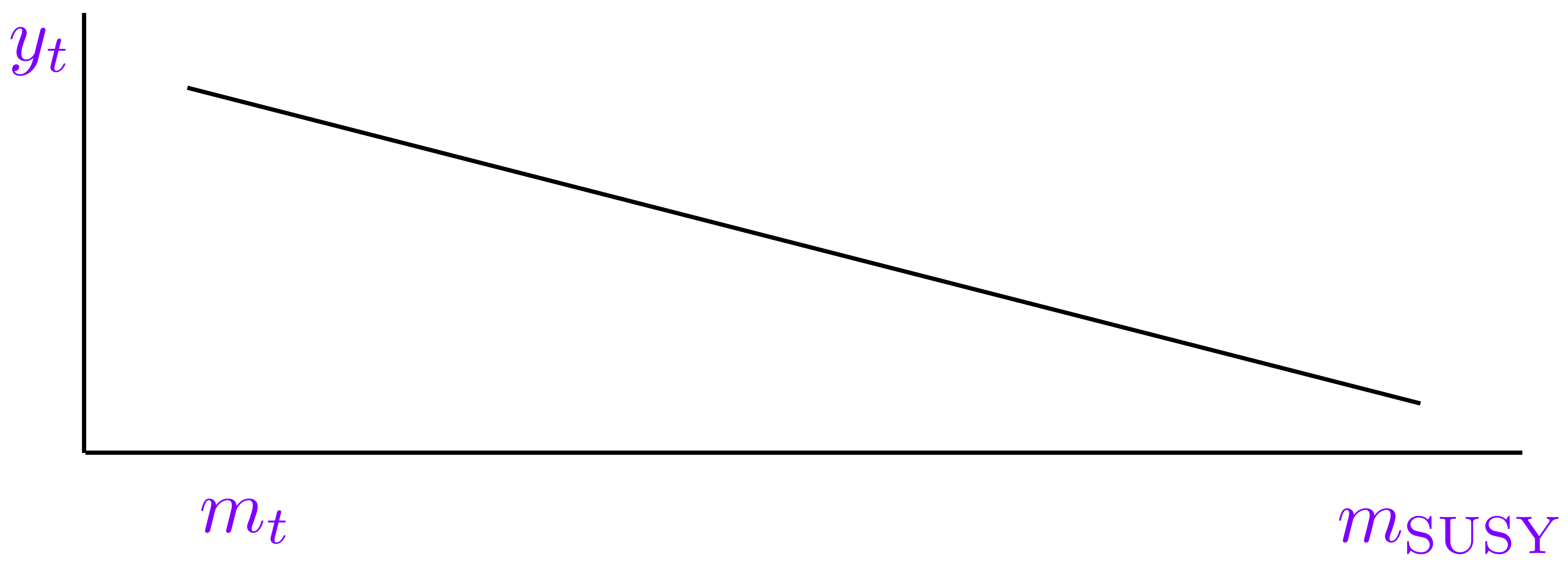
$\mu = M$ exit from conformal window

$\mu = M_Z, M_h$ electroweak symmetry breaking

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

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

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



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

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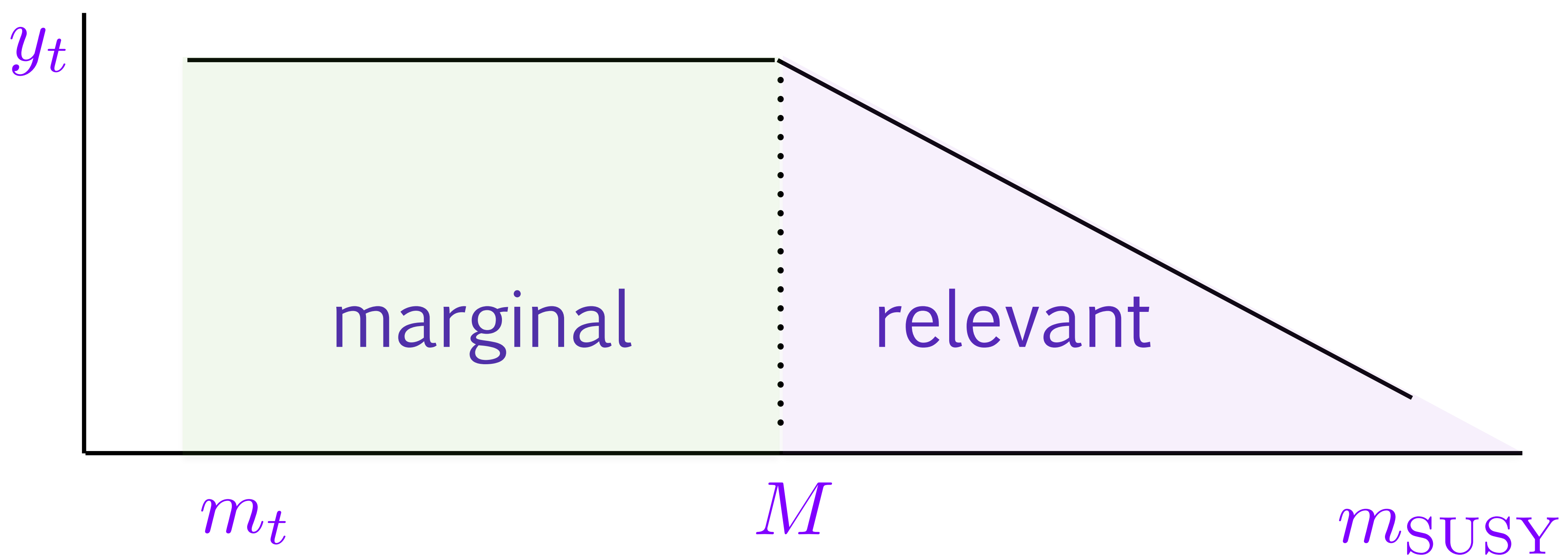
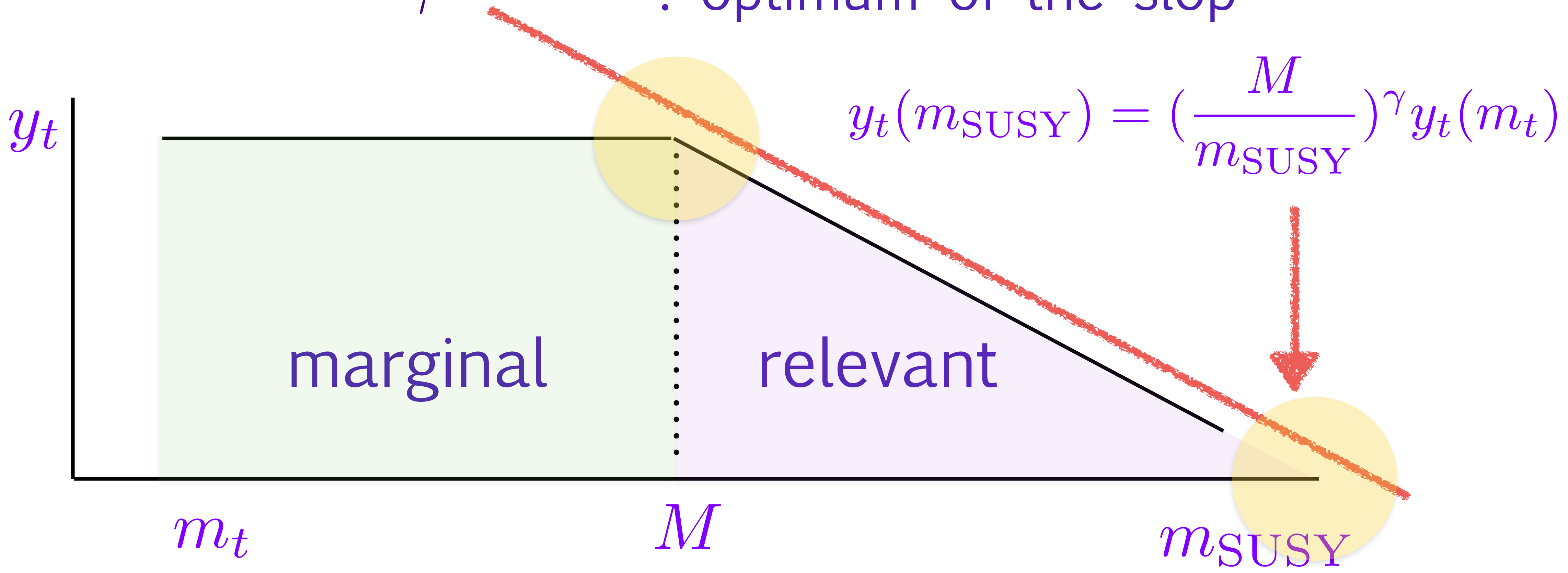


$$\Delta[Qt^c] = 3 - \gamma$$

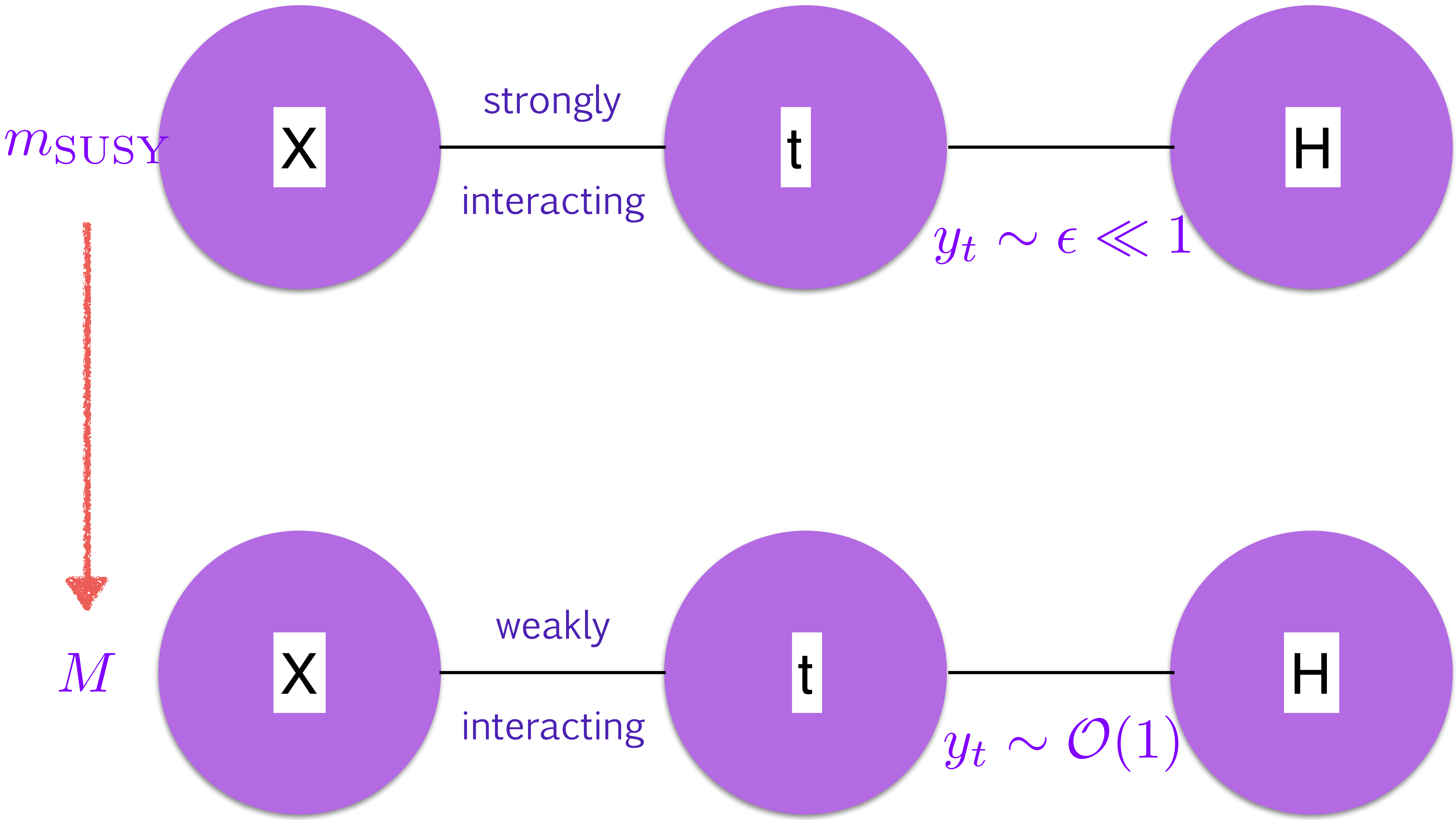
$\gamma < 1$: UV dominates

$\gamma > 1$: IR dominates

$\gamma = 1$: optimum of the slop



The idea works for $\gamma \geq 1$


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

Conformal Window

Conformal window of QCD

$$a_s = \frac{g^2 N_c}{(4\pi)^2} \qquad x = \frac{N_f}{N_c}$$

$$\beta(a_s) = -\frac{2}{3}\left[(11 - 2x)a_s^2 + (34 - 13x)a_s^3 + \cdots\right]$$

> 0 < 0

$$5.5 > x > 2.6$$

$$a_{s*} = \frac{2}{75}(11 - 2x)$$:fixed point for x close to 11/2

$$a_{s*} \sim \frac{11 - 2x}{13x - 34} \sim 0.5$$

$$x_c = 3.25$$

Conformal window

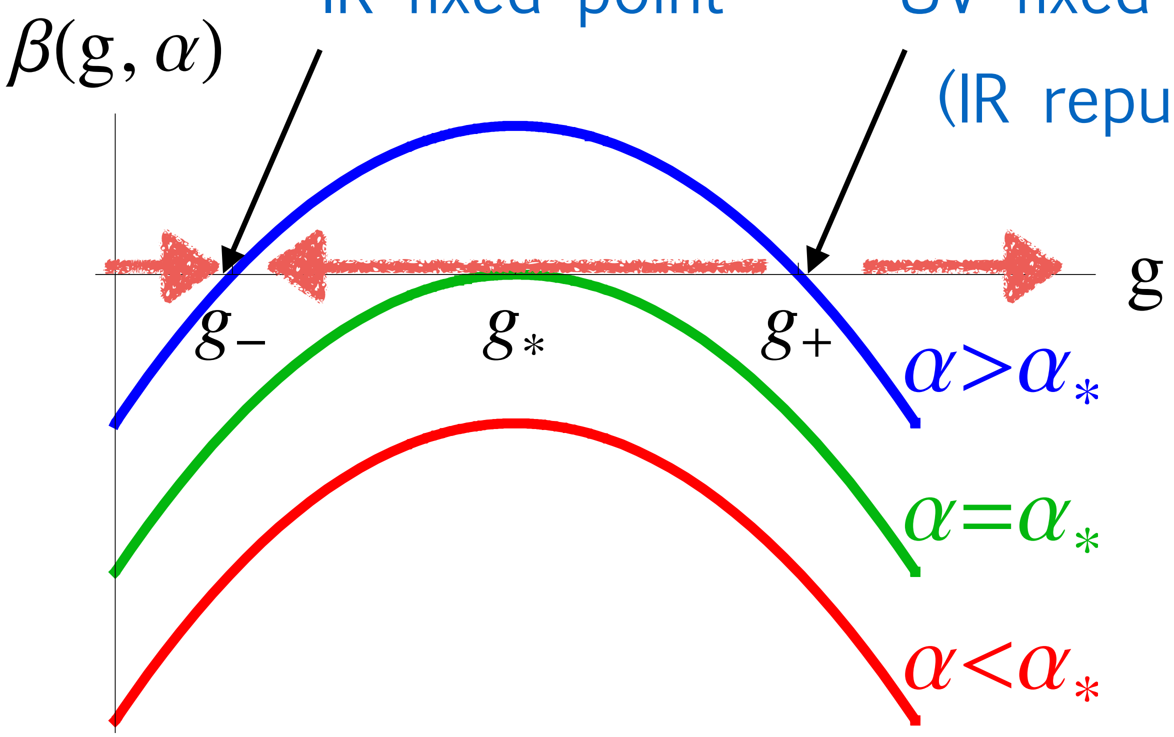
$$g_\pm = g_* \pm \sqrt{\alpha - \alpha_*}$$

(IR attractive)

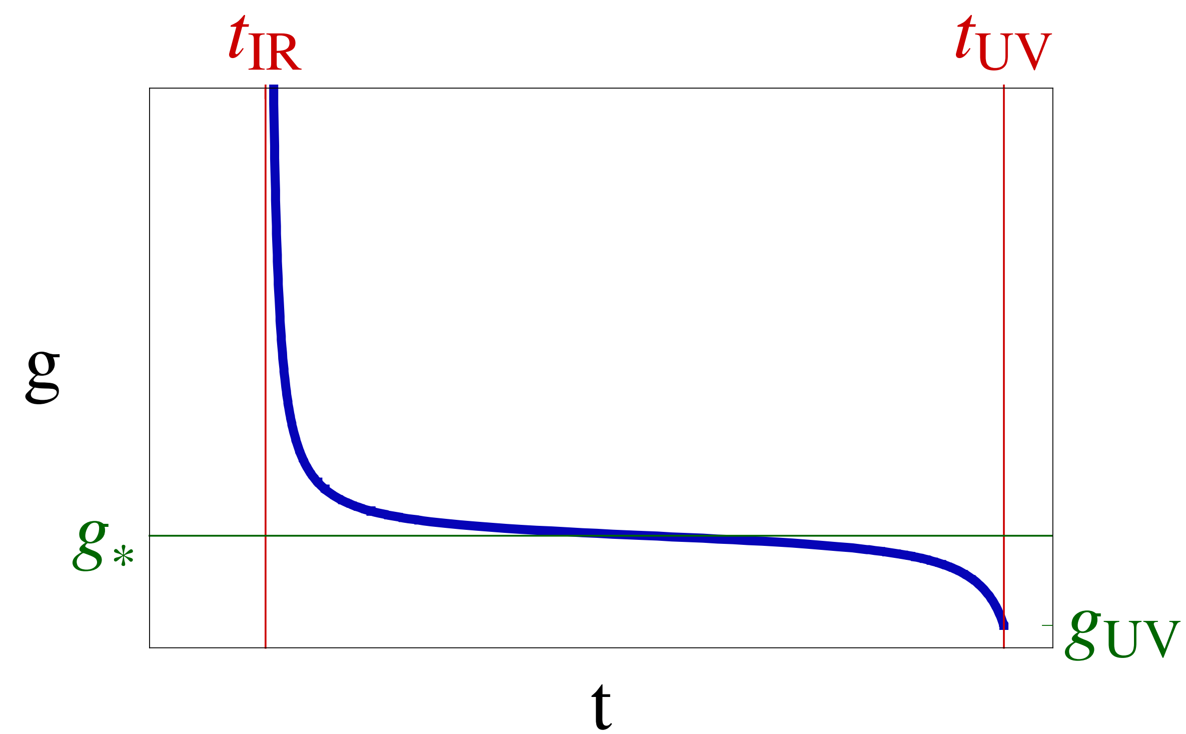
IR fixed point

UV fixed point

(IR repulsive)



Walking for $\alpha < \alpha_*$



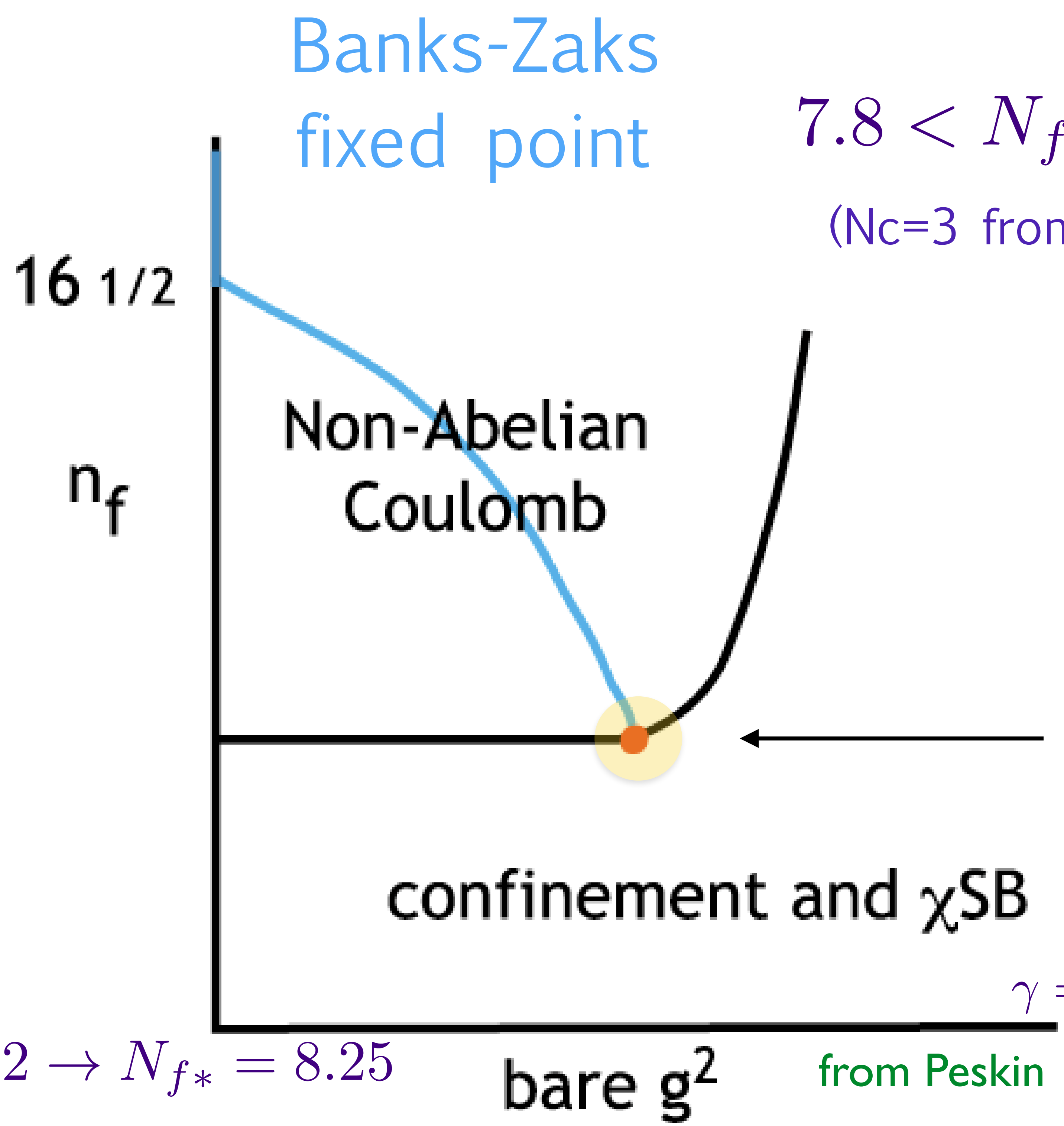
$$\beta(g;\alpha) = \frac{\partial g}{\partial t} = (\alpha - \alpha_*) - (g - g_*)^2$$

$t = \log \mu$

external parameter

coupling

Conformal window of QCD



$$7.8 < N_f < 16.5$$

(Nc=3 from large Nc)

no chiral symmetry breaking above 12

$$8 < N_{f*} < 12$$

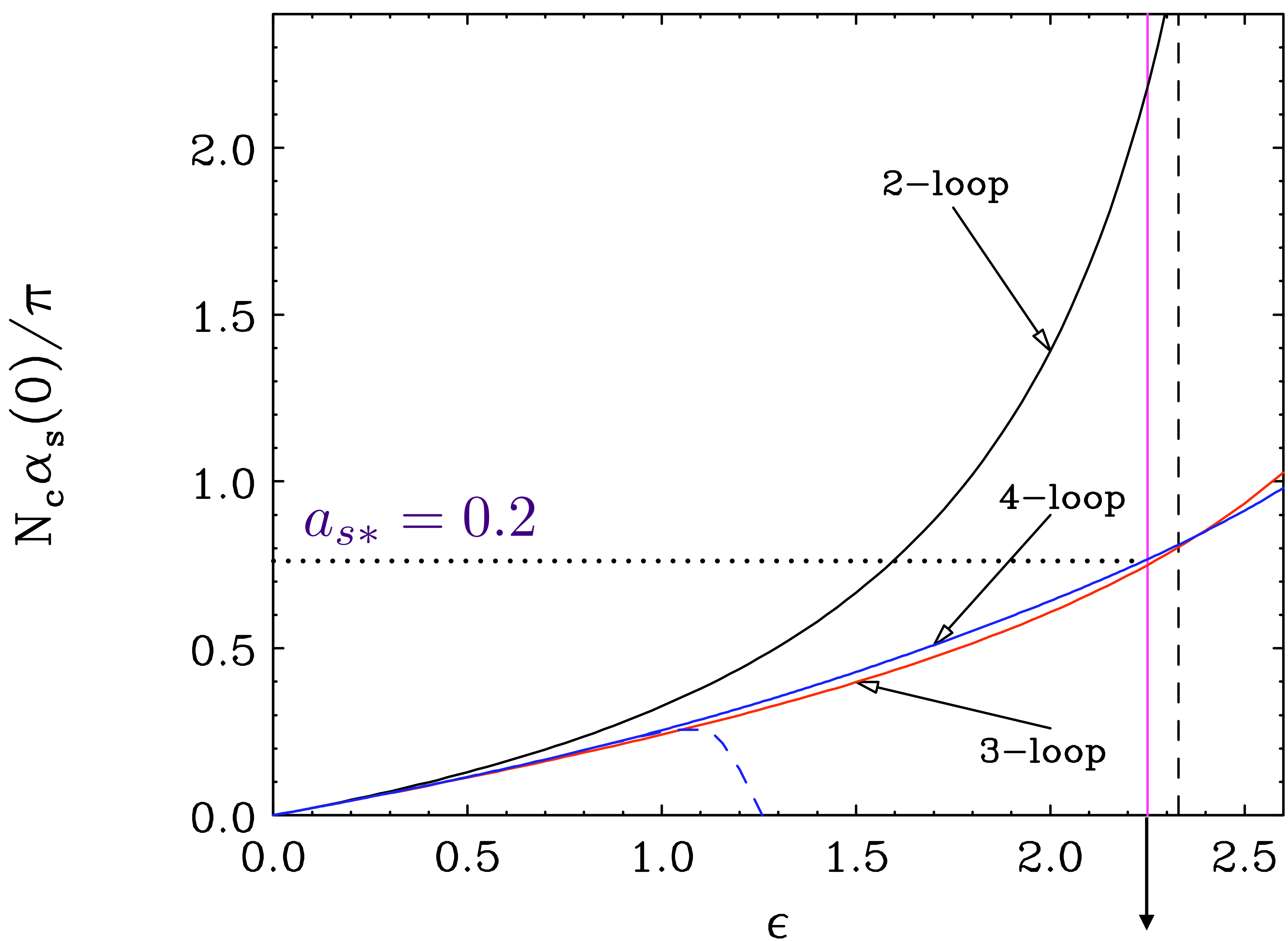
$$N_{f*} = 3x_c = 9.75$$

$$\gamma = \frac{33 - 2N_f}{N_f} = 1 \longrightarrow N_{f*} = 11$$

anomalous dimension conjecture from SUSY

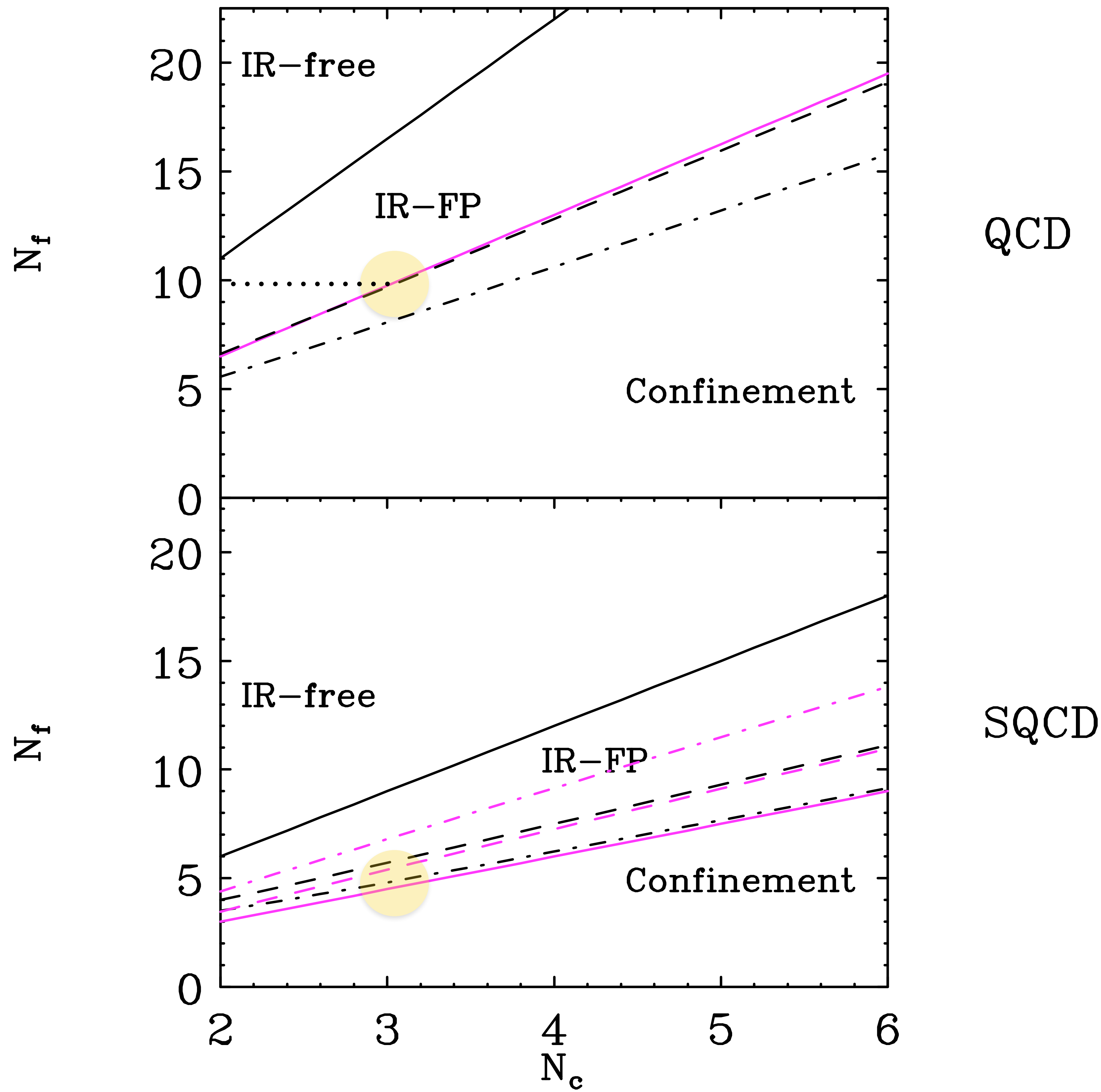
$$\gamma = 2 \rightarrow N_{f*} = 8.25$$

Gardi Grunberg 1998

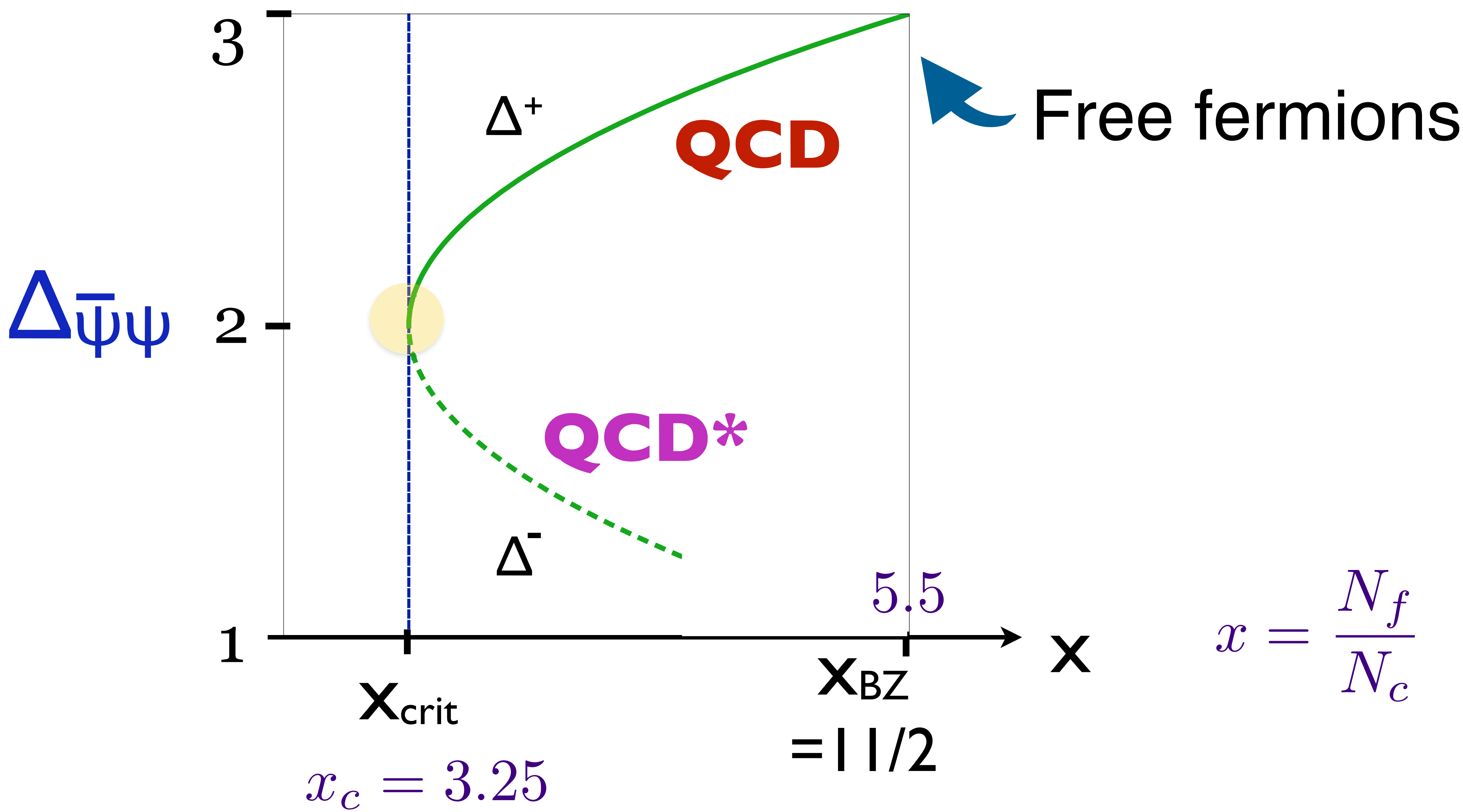


$$\epsilon = \frac{11}{2} - \frac{N_f}{N_c}$$

$$x_c = \frac{N_f}{N_c} = 3.25$$



Gardi Grunberg 1998



from D Kaplan et al : conformality lost

Conformal window of QCD at the critical point

$$[\bar{\psi}\psi] = 2$$

$$N_{f*} \simeq 10$$

$$g^2_{s*} \simeq 10$$

$$\alpha_{s*} \simeq 0.8$$

$$a_{s_*} = \frac{N_c \alpha_{s*}}{4\pi} \simeq 0.2$$

Conformal window of SQCD

Seiberg

gauge group $SU(N_c)$ $\quad N_f \quad Q, \tilde{Q}$

$$\Delta[Q\tilde{Q}] = \frac{3}{2} R[Q\tilde{Q}] = \frac{3(N_f - N_c)}{N_f}$$

$$2N_c < N_f < 3N_C$$

$$\gamma = \frac{1}{2} \qquad g_- \to 0$$

electric description

$$\frac{3N_c}{2} < N_f < 2N_C$$

$$\gamma = 1 \qquad \gamma = \frac{1}{2}$$

$$g_- \to \infty$$

$$g_-(\text{magnetic}) \to 0$$

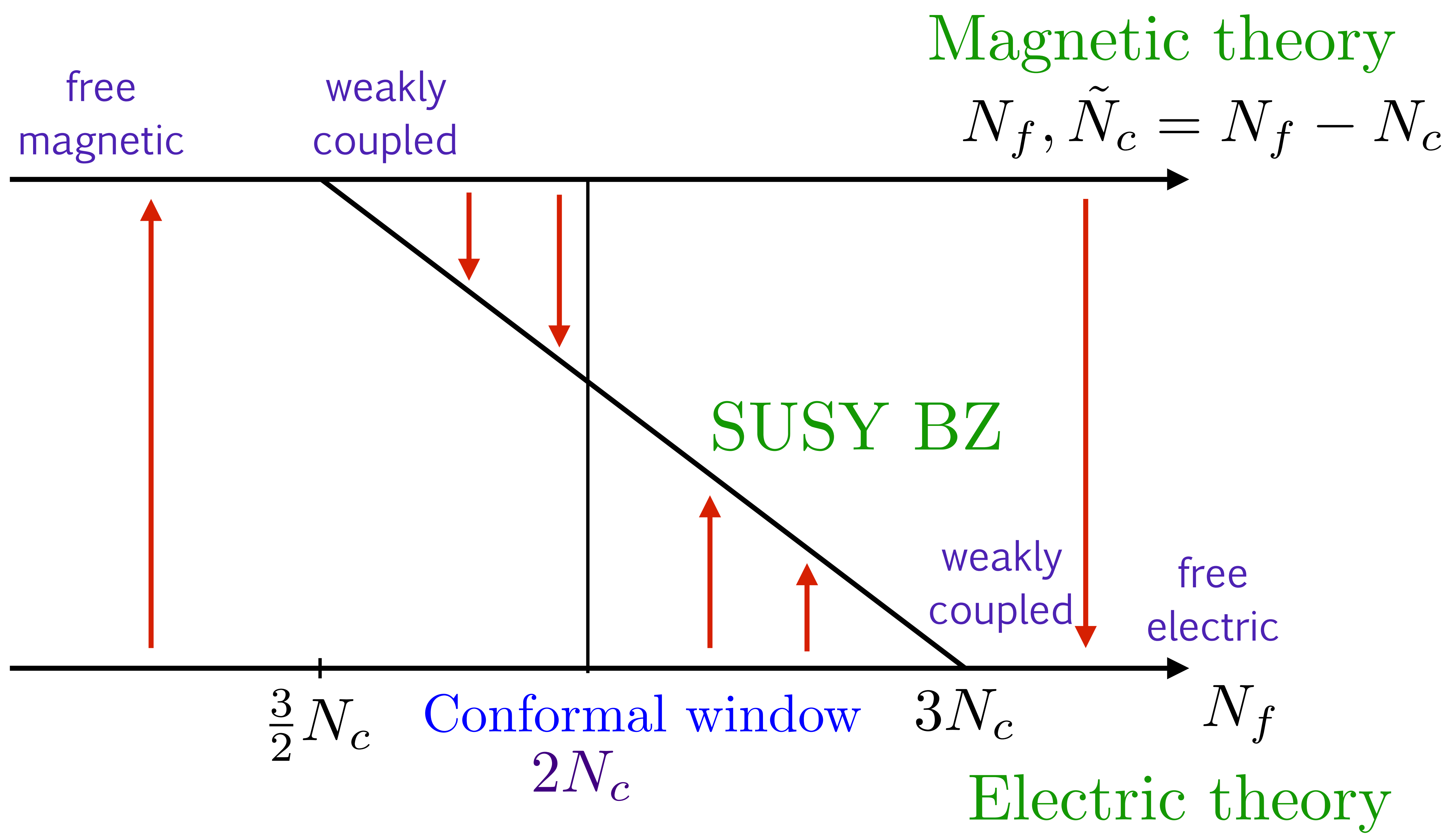
magnetic description

$SU(N_f - N_c)$ $\quad N_f \quad q, \tilde{q}$

gauge group

$$M = Q\tilde{Q}$$

Conformal window of SQCD



Running Yukawa Couplings

One concrete realization :

how to make $\Delta[Qt^c] = 2$?

$\gamma = 1$

The setup

conformal window

$$SU(3)_1 \times SU(3)_2 \to SU(3)_C$$

$$\langle \Sigma \rangle = \mathrm{diag}(f, f, f)$$

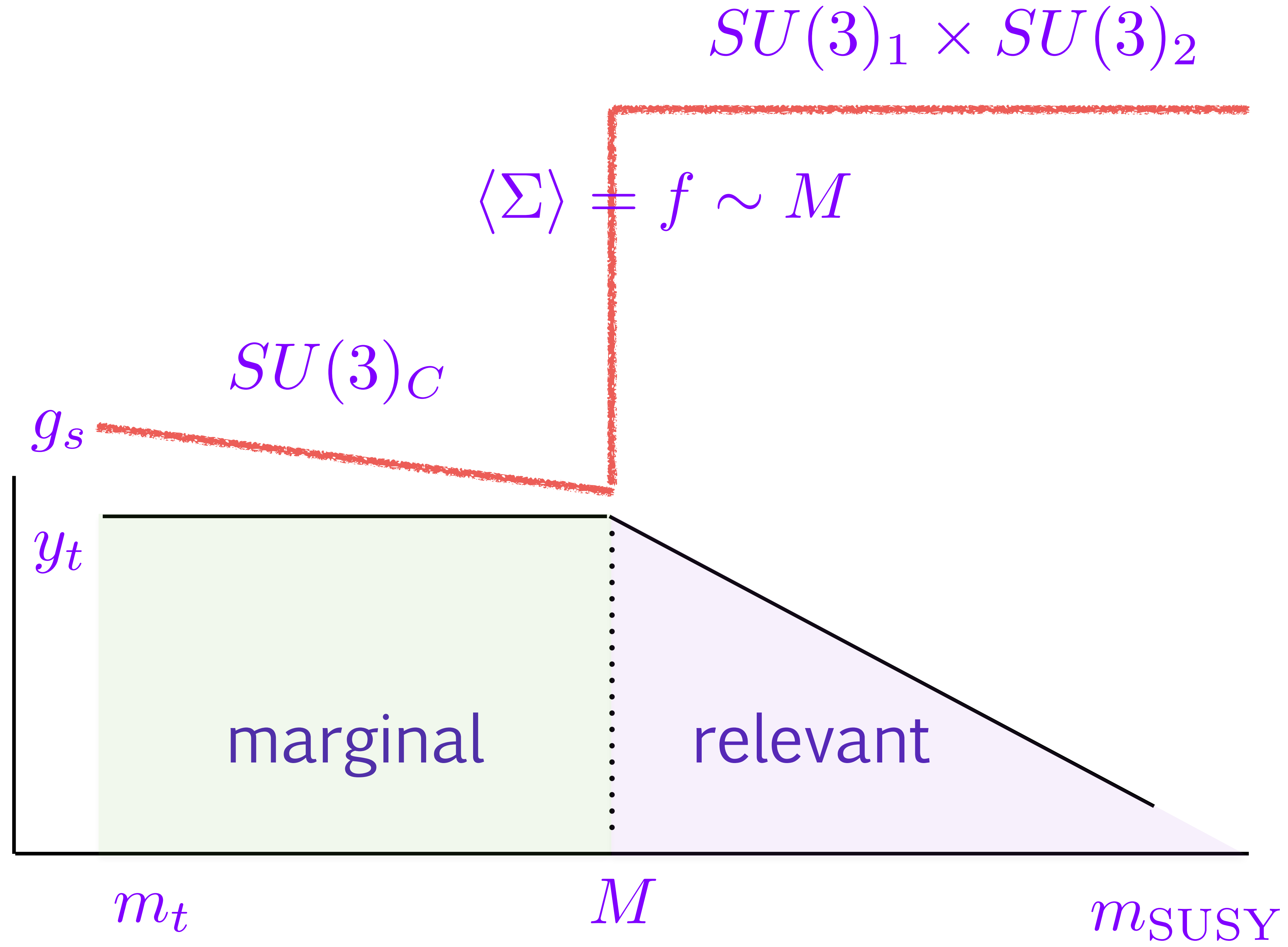
$$(3, \bar{3})$$

All the SM quarks are charged under $SU(3)_1$

$$\frac{1}{g_s^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2}$$

$$g_1^2 \simeq 10$$

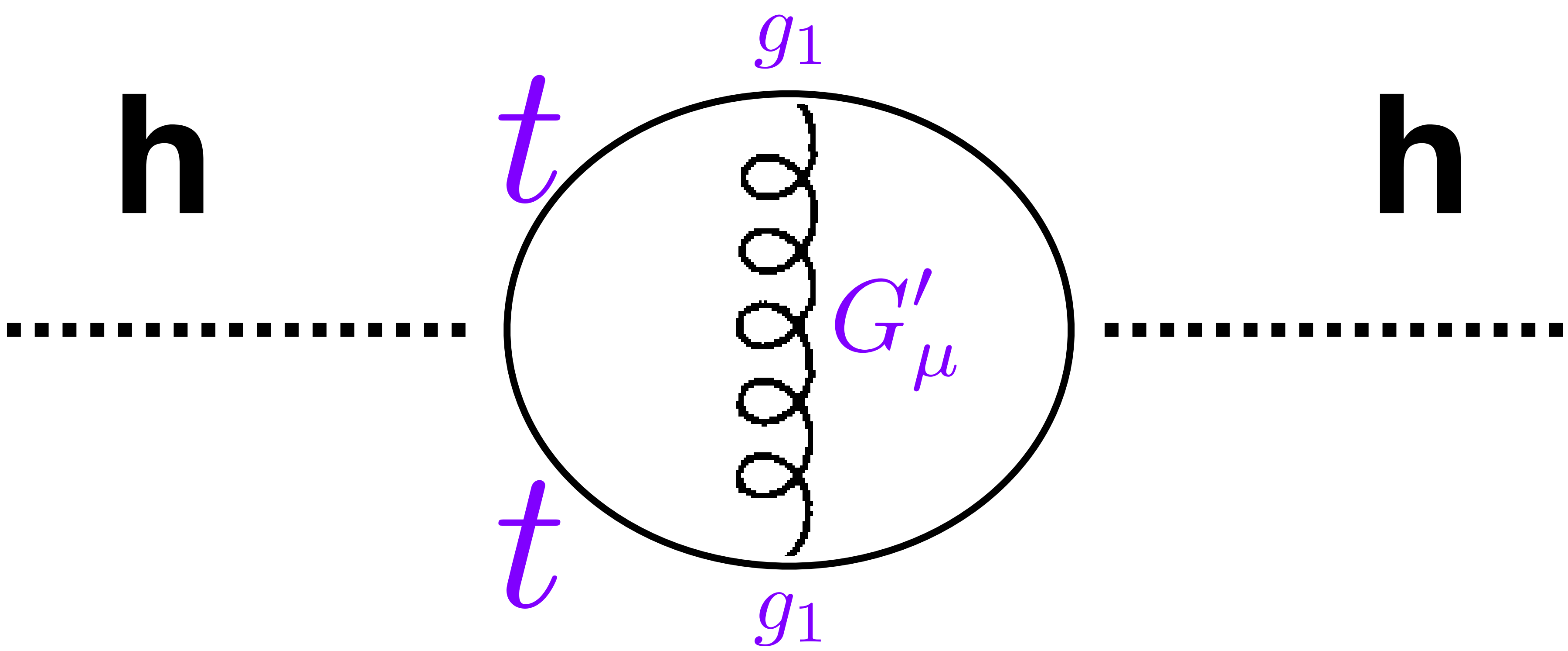
$$g_2^2 \simeq 1$$



$SU(3)_1 \times SU(3)_2$
$\langle \Sigma \rangle = f \sim M$
$SU(3)_C$
g_s
y_t
marginal
relevant
m_t
M
m_{SUSY}

Higgs modified by hidden sector

Two loop corrections : Higgs, top, hidden color



$$a_{s_*} = \frac{N_c \alpha_{s*}}{4\pi} \simeq 0.2$$

M can be 1 TeV or higher

Flavor Universal Coloron

(massive color octet vector boson)

$$f \sim 1 - 2 \text{ TeV}$$

$$M_{G'} = g_1 f \sim 3f \qquad : \qquad 3 - 6 \text{ TeV}$$

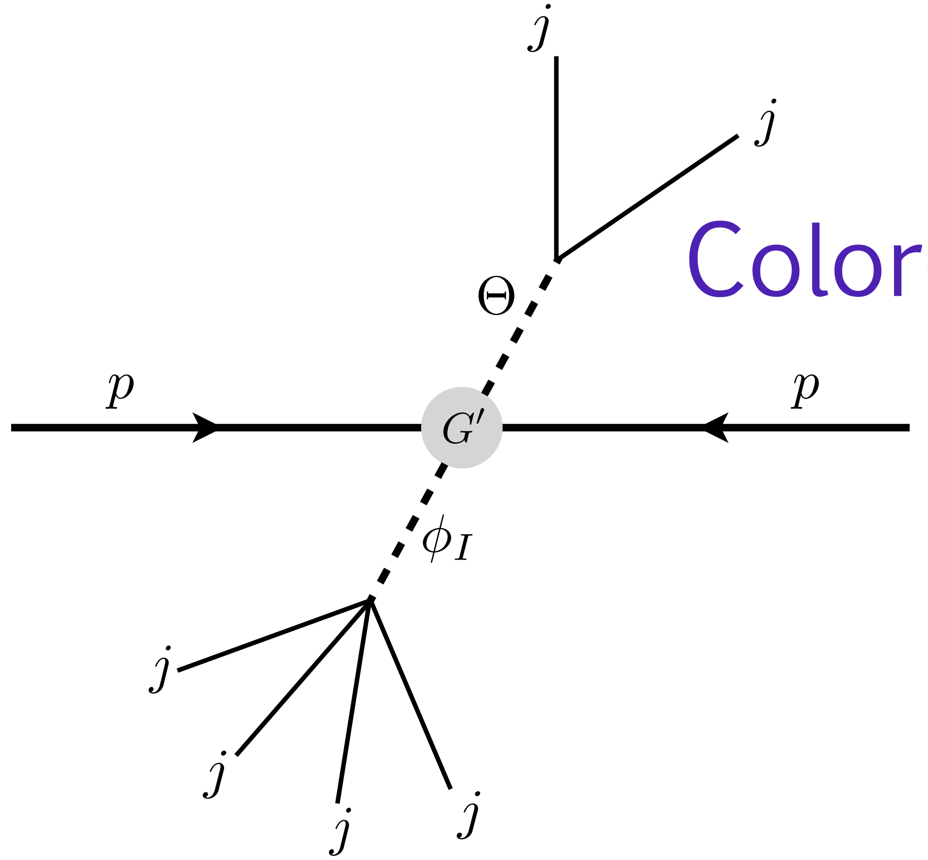
$$g_1 \bar{q} \gamma^\mu T^a G'^a_\mu q$$

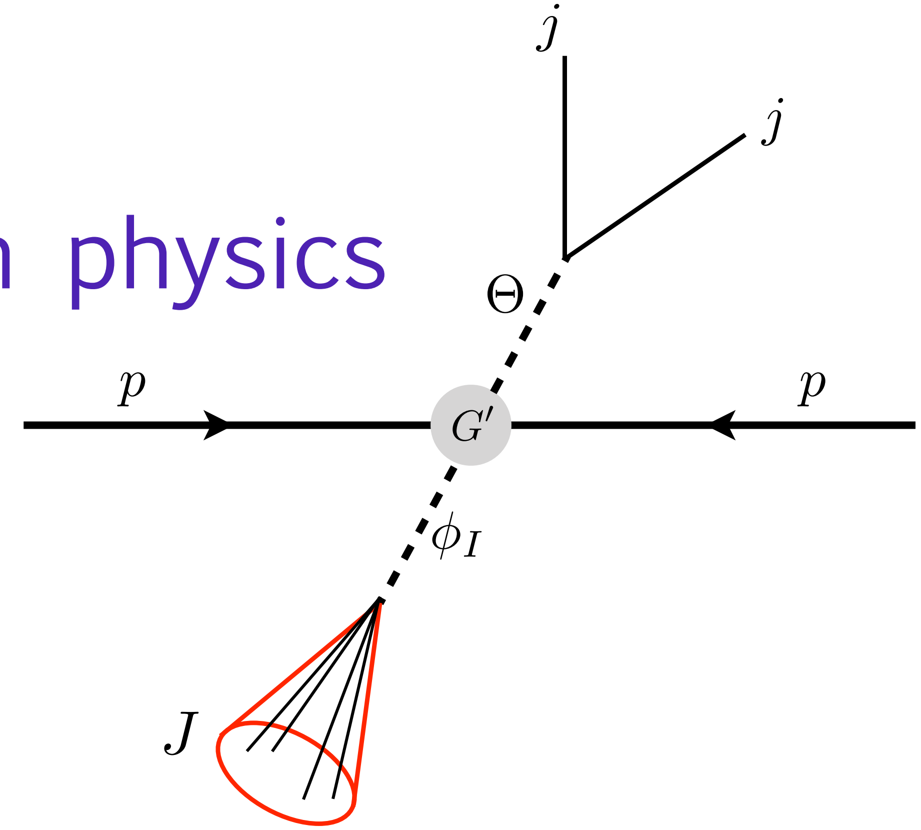
$$\Sigma = \phi_R + \phi_I + \Theta + \text{Goldstone}$$

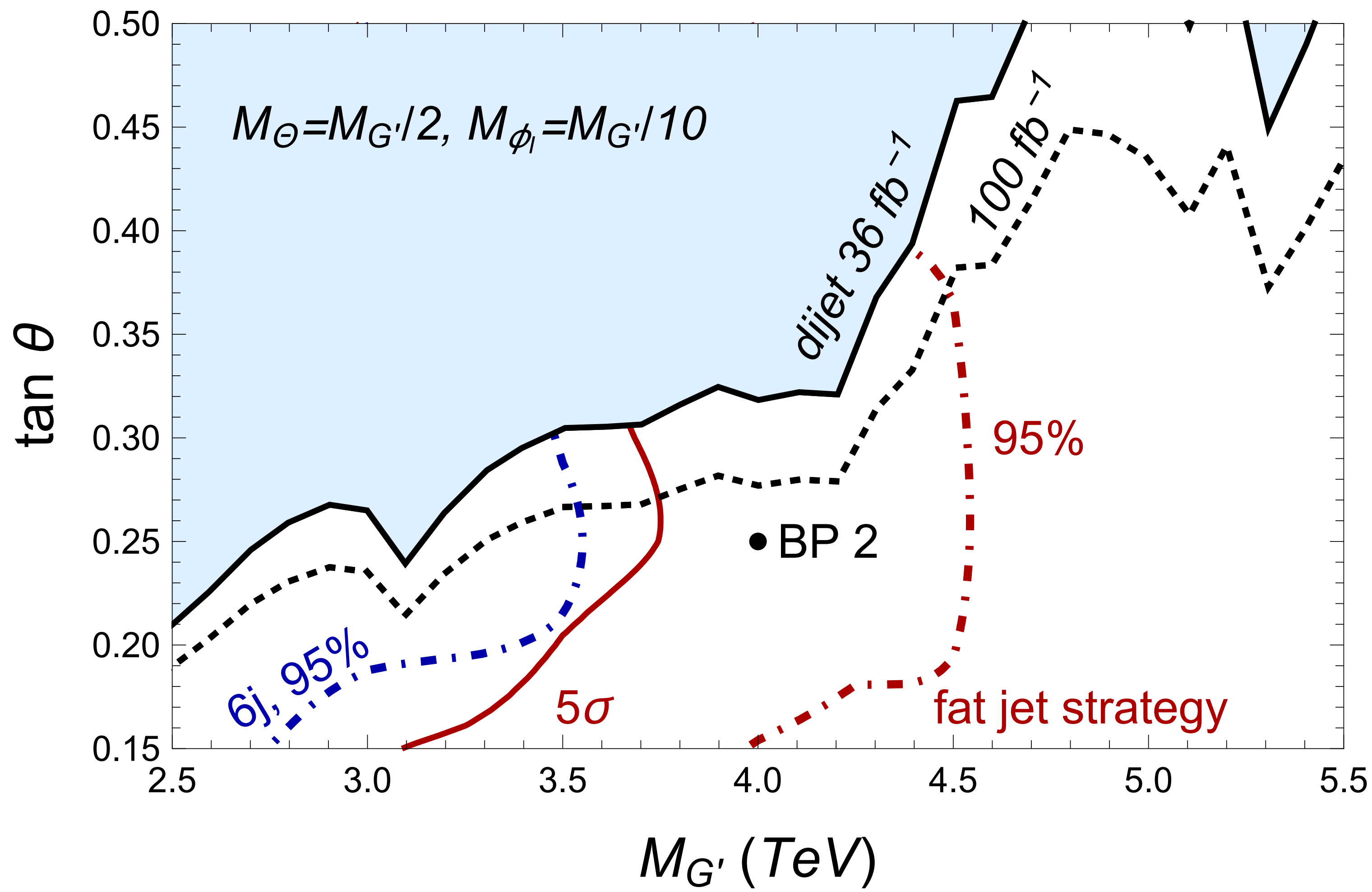
$$18 = 1 + 1 + 8 + 8$$

$\Sigma = (3, \bar{3})$ under $SU(3)_1 \times SU(3)_2$

Coloron physics



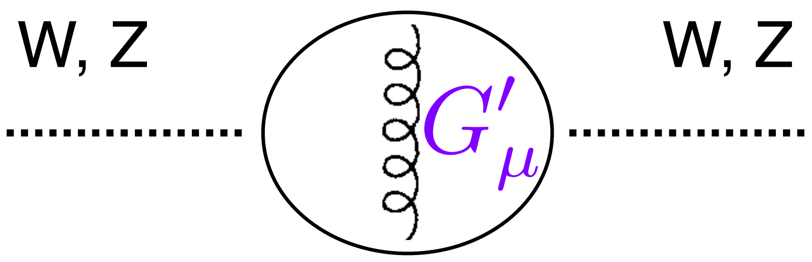


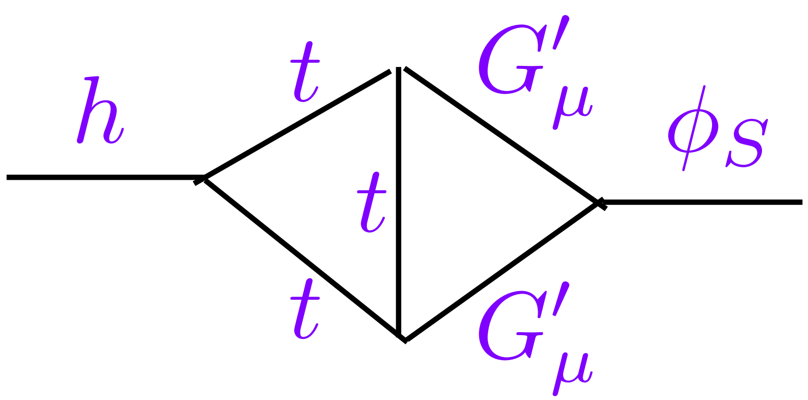


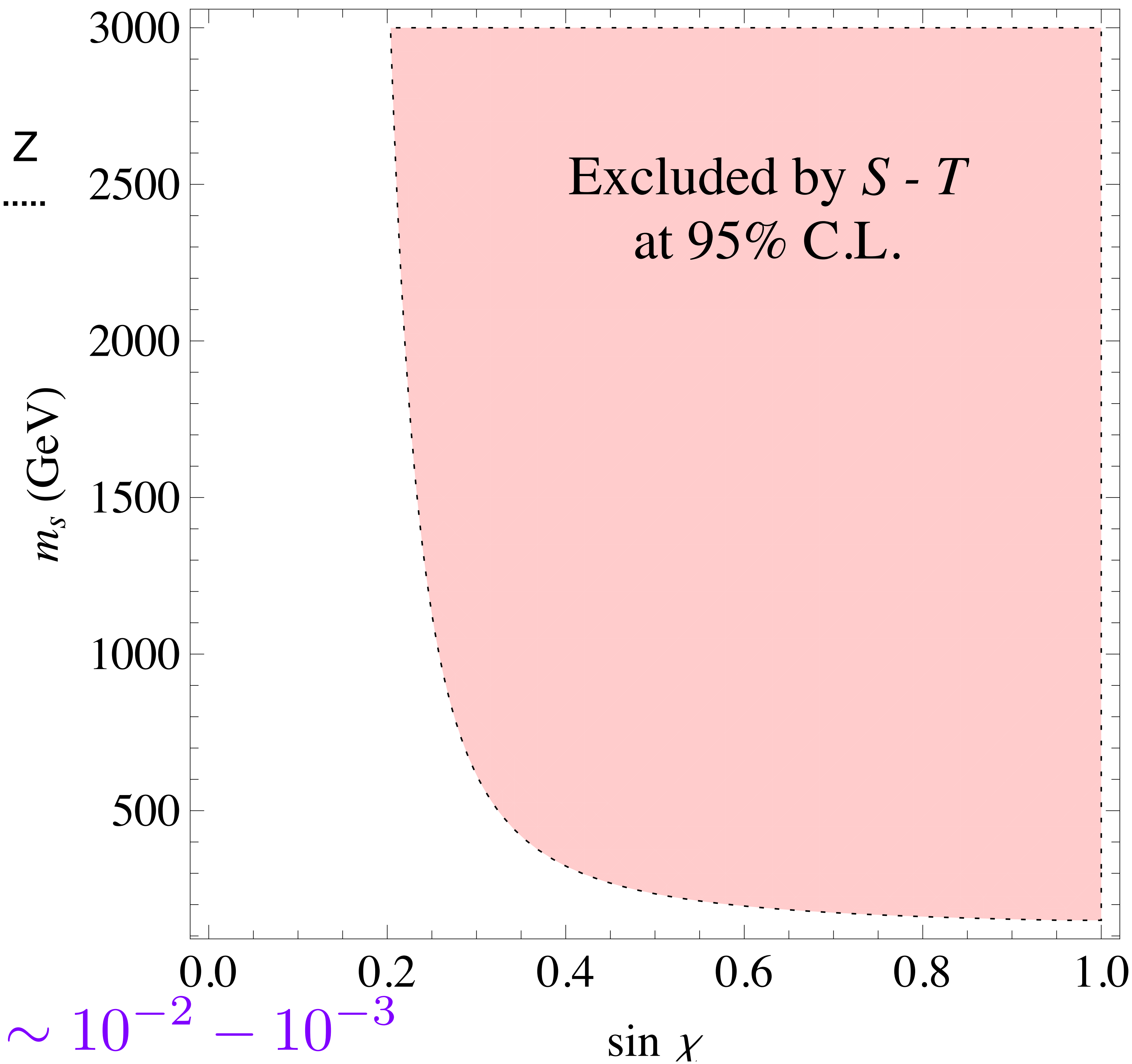
Bai Lu Xiang (2018)

Electroweak precision

Chivukula et al (2013)







$$\sin\chi \propto \frac{3y_t}{16\pi^2} a_{s*} \frac{v}{f} \sim 10^{-2} - 10^{-3}$$

conformal technicolor

$$\Delta[H^2] = 2 \to 4$$

relevant to marginal

relevant SM

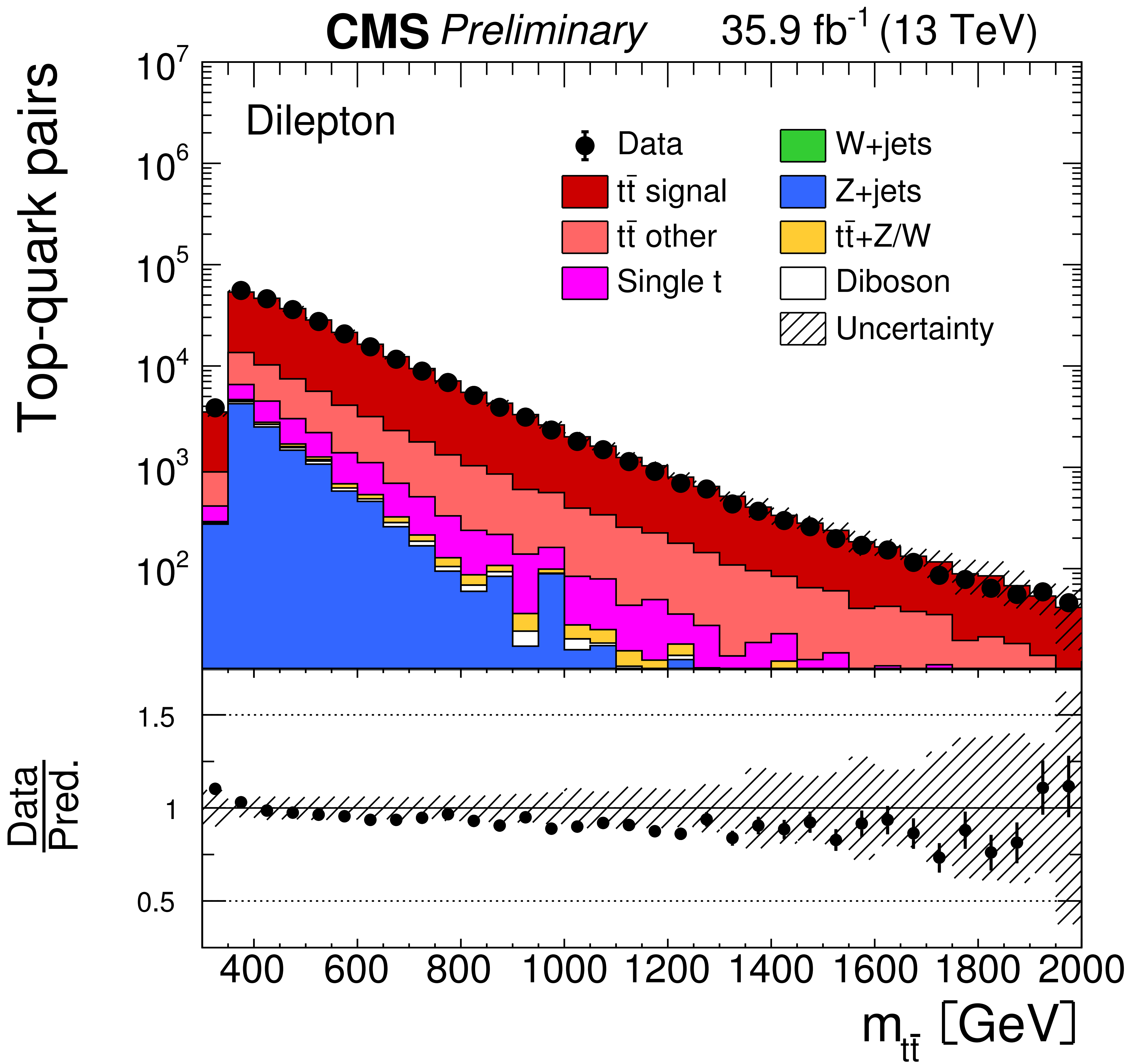
$$\Delta[Qt^c] = 3 \to 2$$

marginal to relevant

One concrete realization :
how to make $\gamma = 1$?

It was only half-way successful

Task : keep the anomalous dimension to be 1
while avoid large couplings
: SU(2) and U(1) extension?


CMS Preliminary
35.9 fb-1 (13 TeV)
Dilepton
Data
tt̄ signal
tt̄ other
Single t
W+jets
Z+jets
tt̄+Z/W
Diboson
Uncertainty
Top-quark pairs
Data/Pred.
m_tt̄ [GeV]

Summary

Light Higgs might be due to smaller couplings at high energy (off-shell)

Measuring off-shell top Yukawa coupling would be important to check this idea

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)