F-theory Approach to Particle Phenomenology

June 24, 2009

Strings '09
Rome

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This talk is based on joint work with a number of students and colleagues in the past couple of years. They are all in collaboration with Jonathan Heckman. The other collaborators are Chris Beasley, Vincent Bouchard, Sergio Cecotti, Miranda Cheng, Gordon Kane, Joe Marsano, Natalia Saulina, Sakura Schafer-Nameki, Jihye Seo, Jing Shao and Alireza Tavanfar.

Related works:

Donagi+Wijnholt

Hayashi,Kawano,Tatar,Watari
+………

Plan for this talk

1-Elements of F-theory Approach to Particle Phenomenology

2-Constraints and Emergence of an E_8 Point

3-Deformed Gauge Mediatied Supersymmetry Breaking

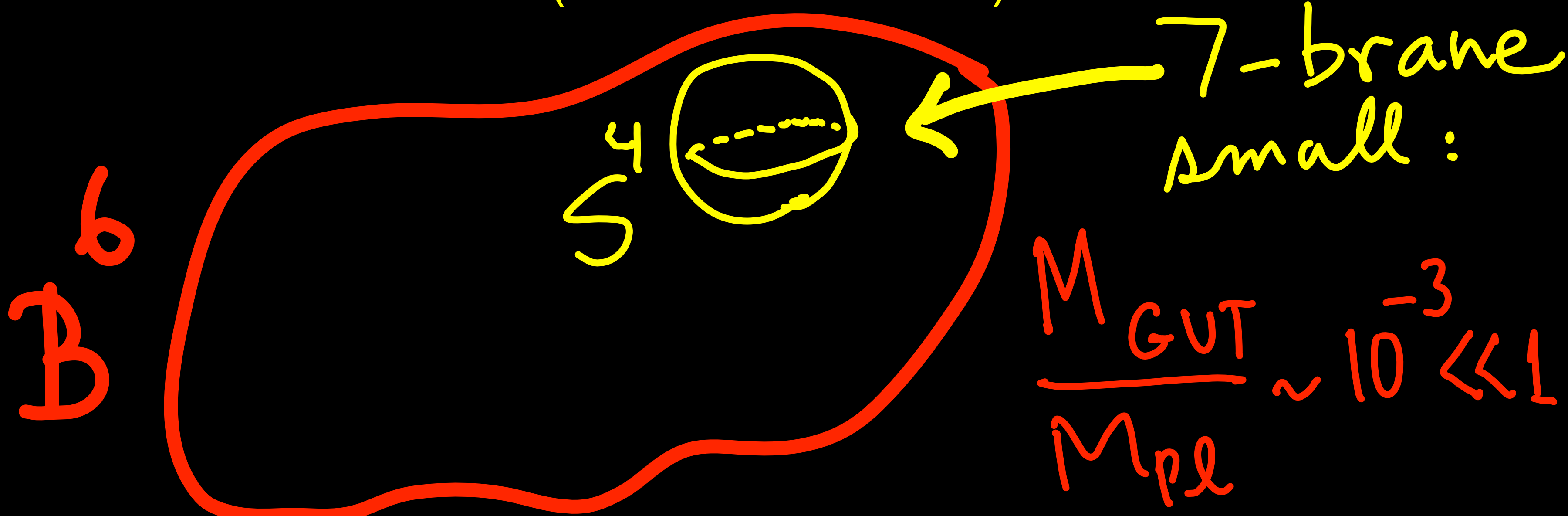
4-Consequences:

i) Cosmological / Astrophysical
ii) Accelerator Physics

Elements of F-theory Approach to Phenomenology

Basic assumptions:

1)Standard model gauge interactions are localized on small 7-branes of type IIB, or more precisely its strong coupling limit, F-theory. The GUT 7-brane being small can appear in one of two ways: Contractible at finite distance (leading only to del Pezzo or Hirzebruch surfaces), studied in detail by Donagi+Wijnholt or at infinite distance (see Sakura's talk).



$$\frac{M_{GUT}}{M_{pl}} \sim 10^{-3} \ll 1$$

2-Near the GUT scale the gauge forces unify to a simple group, such as SU(5).

3-Supersymmetry is preserved all the way down to near the weak scale.

4-All the known phenomenological facts should be imposed as constraints but without any additional fine tuning. These include,

-- the standard model gauge group SU(3)xSU(2)xU(1)
-- the number of generations in suitable reps is 3
-- Higgs fields do not come from full GUT multiplets (2+3 split)
-- suitable flavor hierarchy in both the quark and lepton sectors (this includes hierarchies in both mass and mixing matrices)
-- absence of FCNC

Breaking the GUT group: contractible flux in U(1) hypercharge

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

$$F_{U(1)} \neq 0$$

In F-theory various structures separate evenly in dimensions:

	Total d	internal d
Gravity:	10 →	6
Gauge Fields:	8 (on 7-branes) →	4
Matter Fields:	6 (intersection of two 7-branes) →	2
Interactions:	4 (triple intersection of 7-branes) →	0

Moreover gauge, matter and the interactions are determined by A-D-E singularity type of elliptic fibration over the 7-branes.

e.g.

$$y^2 = x^2 + z^N \qquad SU(N)$$

N 7-branes at $z=0$: 8d

Brane Monodromies

The unfolding of singularities depends on coordinates of the base and generically undergo monodromy:

$$y^2 = x^2 + z^N + \sum \alpha_i(z_1, z_2)\, z^{N-i}$$

$$y^2 = x^2 + \prod_{i=1}^{N} \left(z - a_i(z_1, z_2)\right)$$

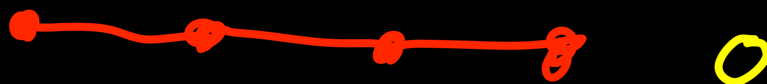
7-branes are localized at $z = a_i$

but are not single valued: $a_i \rightarrow \text{mix } S_N$

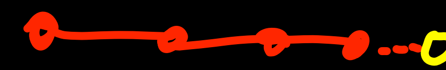
Matter from colliding singularities (7-branes):

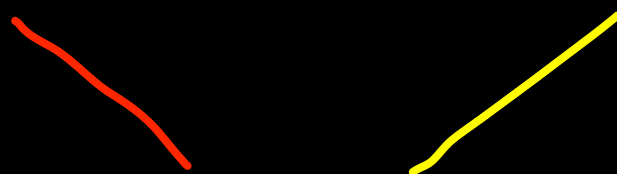
$$G_1 + G_2 \to G$$

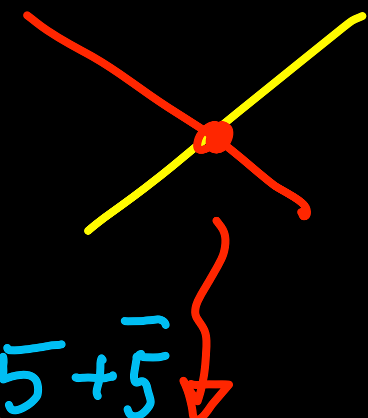
$$SU(5) + U(1) \to SU(6)$$



$\Rightarrow$



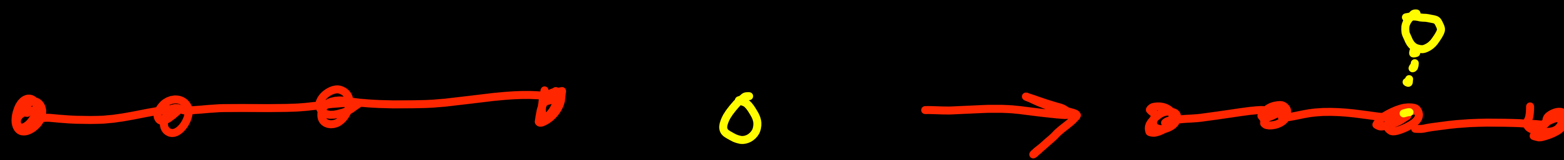




$5+\bar{5}$

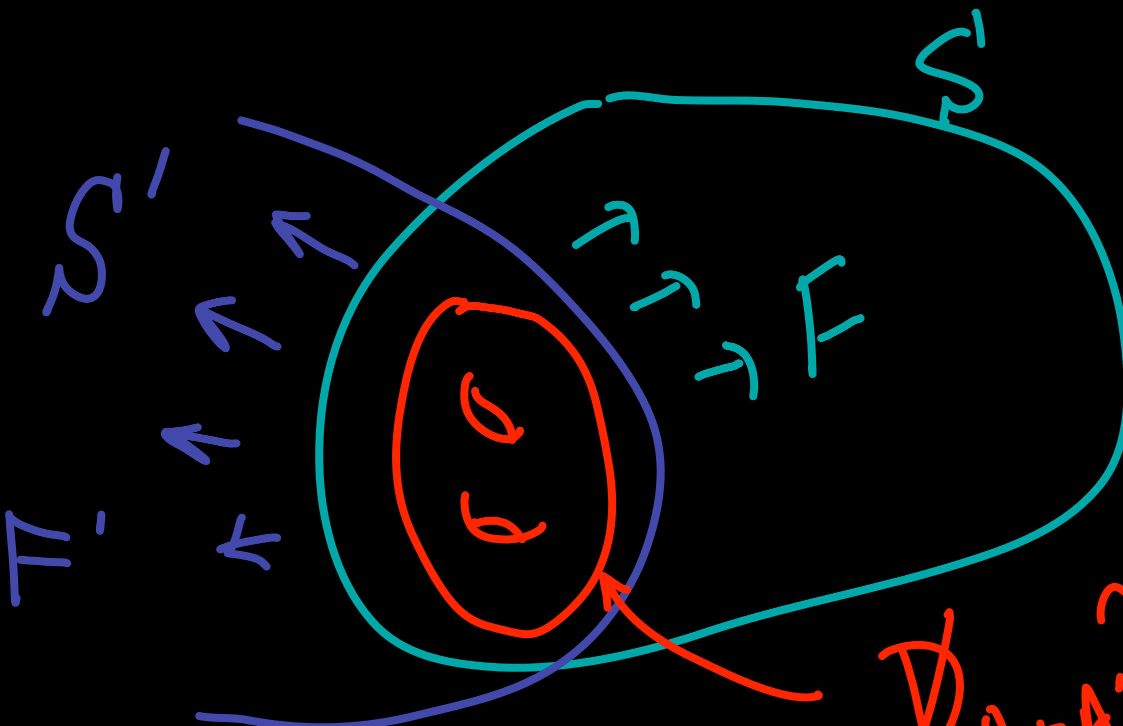
$$\mathrm{Adj}\,G = \mathrm{Adj}\,G_1 + \mathrm{Adj}\,G_2 + R(G_1, G_2)$$

$10 + \overline{10}$

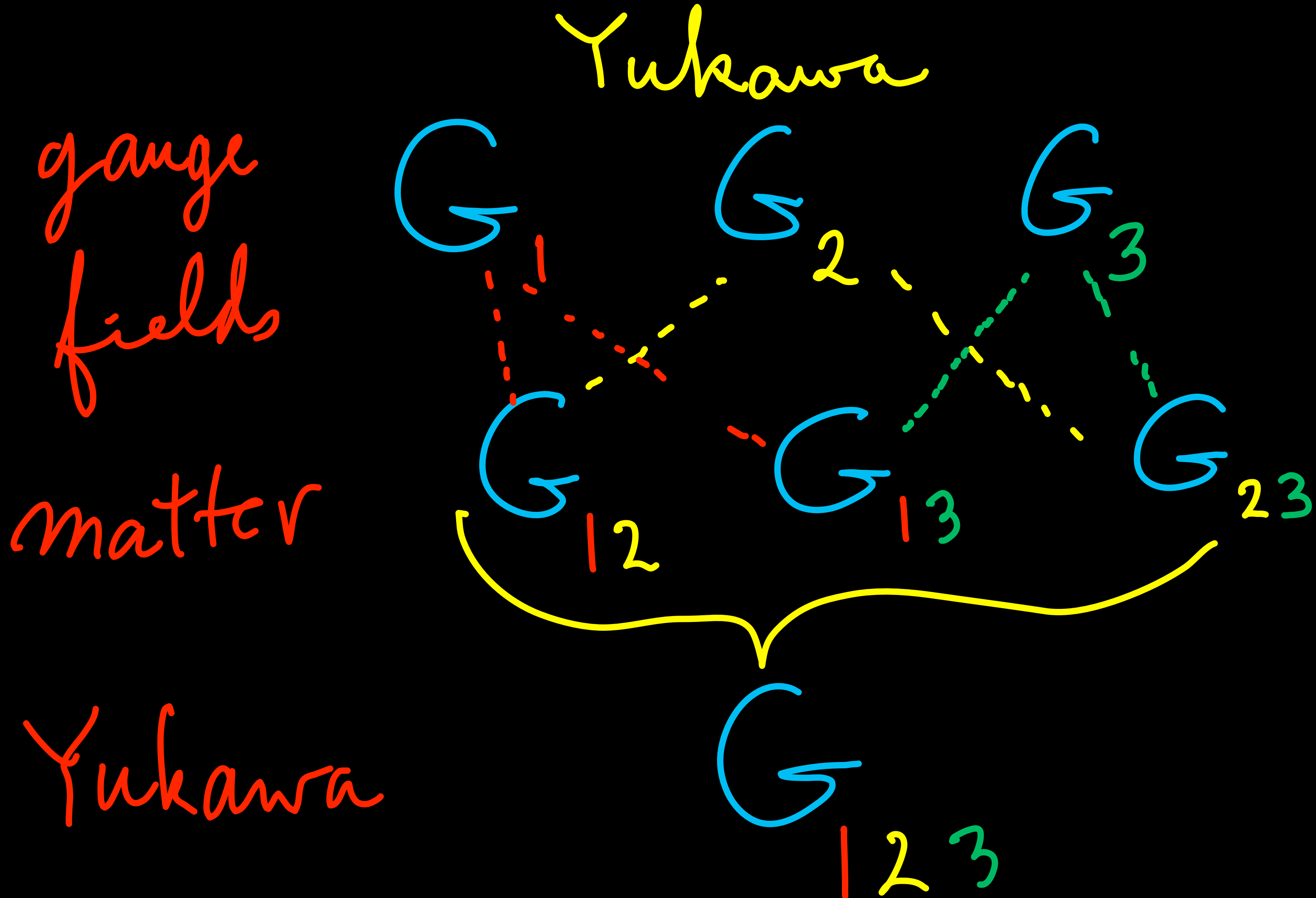


$SU(5) + U(1) \to SO(10)$

For the matter spectrum all we have to do is simply make sure that we get the right types of intersecting 7-branes, to give us 10's and 5's and turn on appropriate flux on the 7-branes, so that the spectrum of the Dirac field on the intersection gives rise to the appropriate number of matter fields.

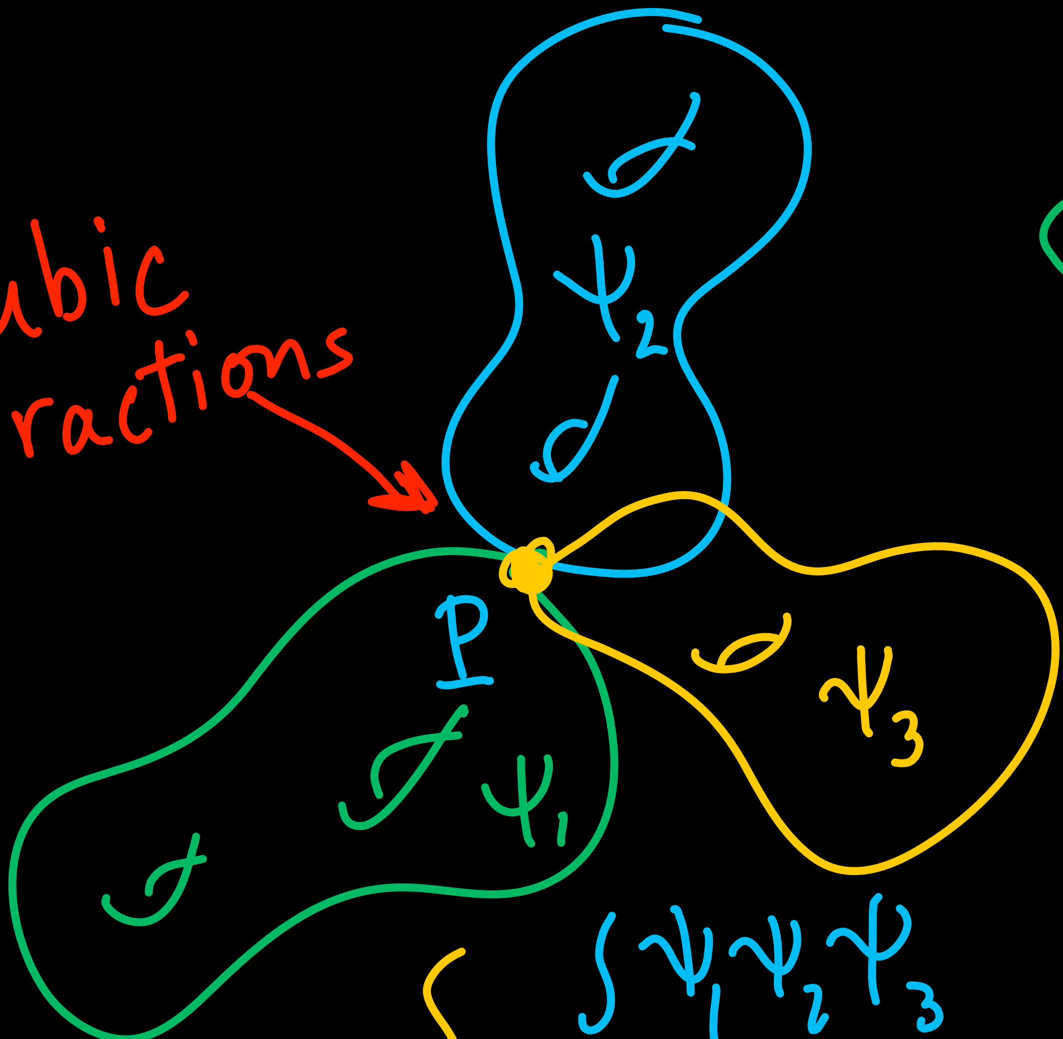


$$\not{D}_{A+A'}\psi = 0$$



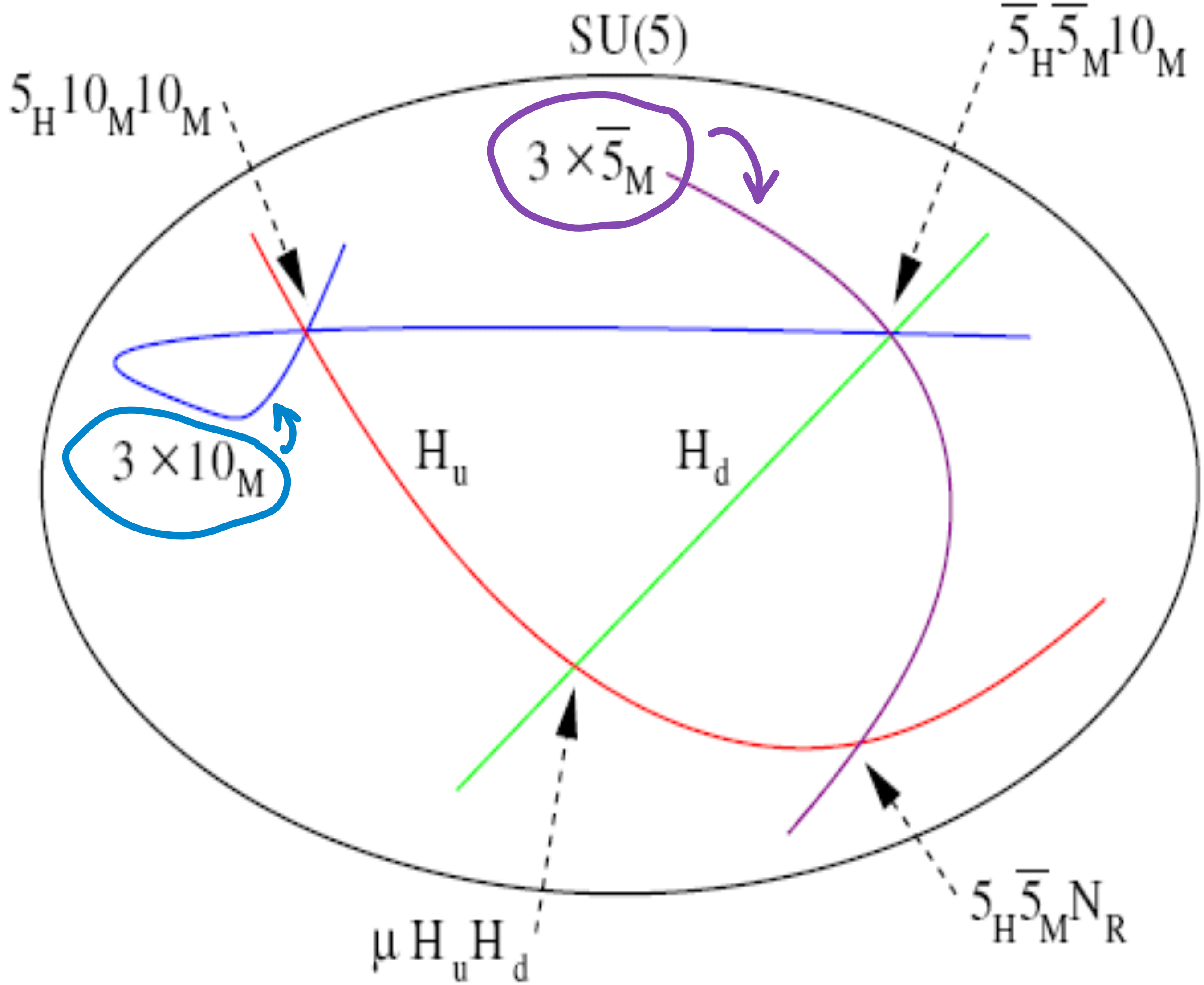
Lie bracket on G_{123} induces Yukawa on G_{ij}

Cubic interactions



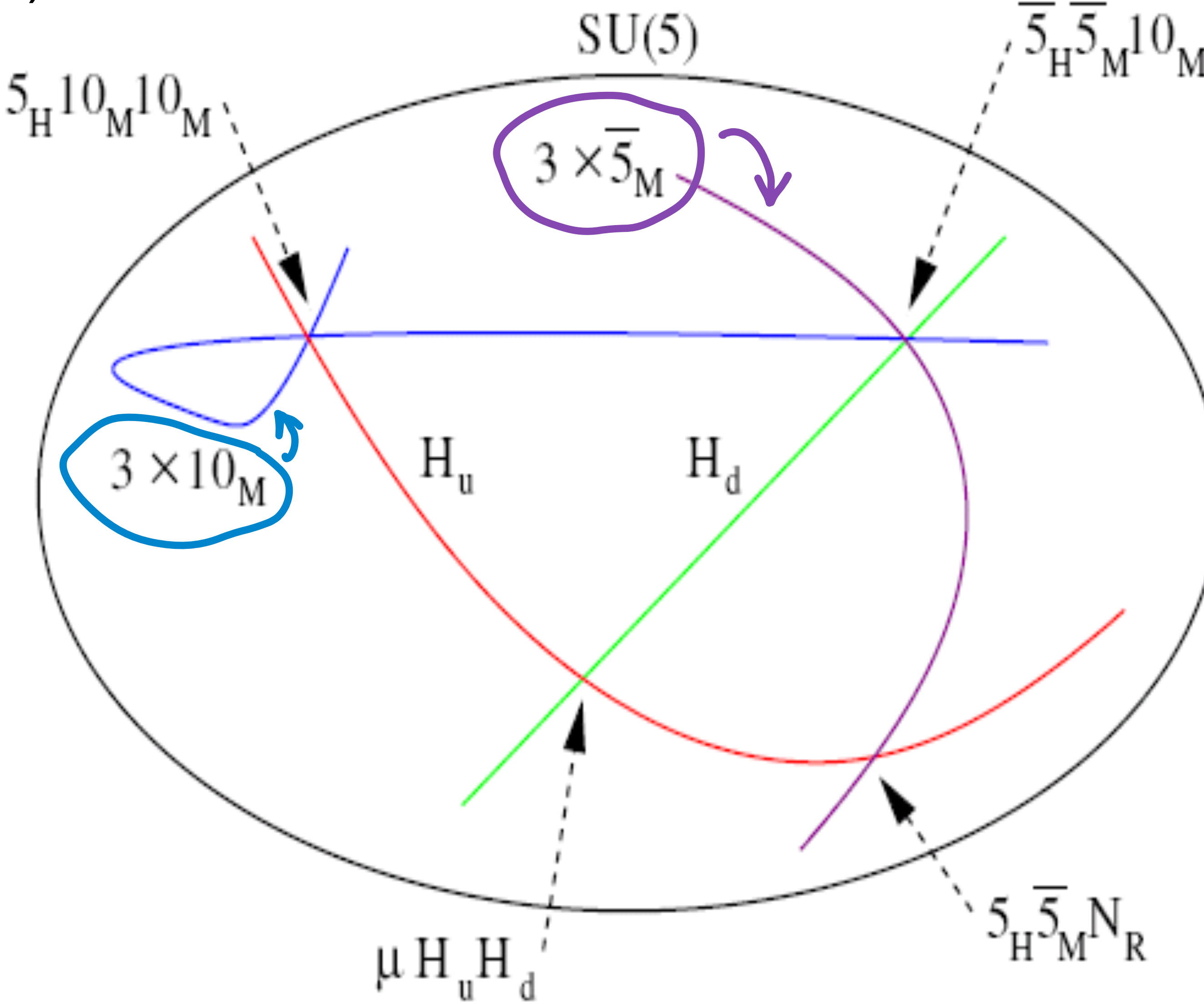
Two possibilities:

$$\begin{cases} \int \Psi_1 \Psi_2 \Psi_3 \; d^2\theta \\ \frac{1}{M} \int \Psi_1^{\dagger} \Psi_2 \Psi_3 \; d^4\theta \end{cases}$$



SU(5)
$5_H 10_M 10_M$
$\overline{5}_H \overline{5}_M 10_M$
$3 \times \overline{5}_M$
$3 \times 10_M$
H_u
H_d
$\mu H_u H_d$
$5_H \overline{5}_M N_R$

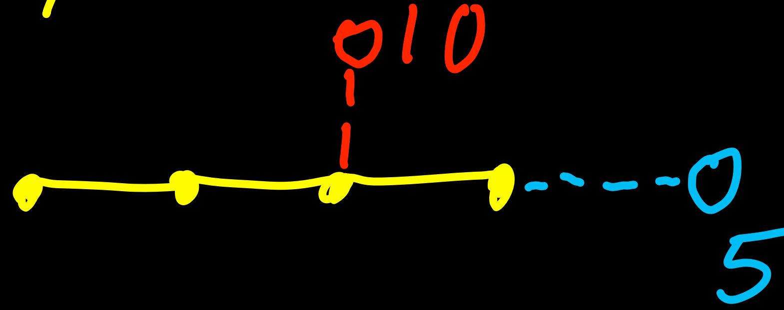
That all 3 flavors live on the same curve follows from a simple solution to mass hierarchy among flavors (Jonathan's talk)



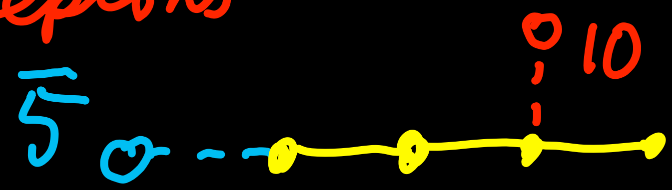
Emergence of the E8 Point

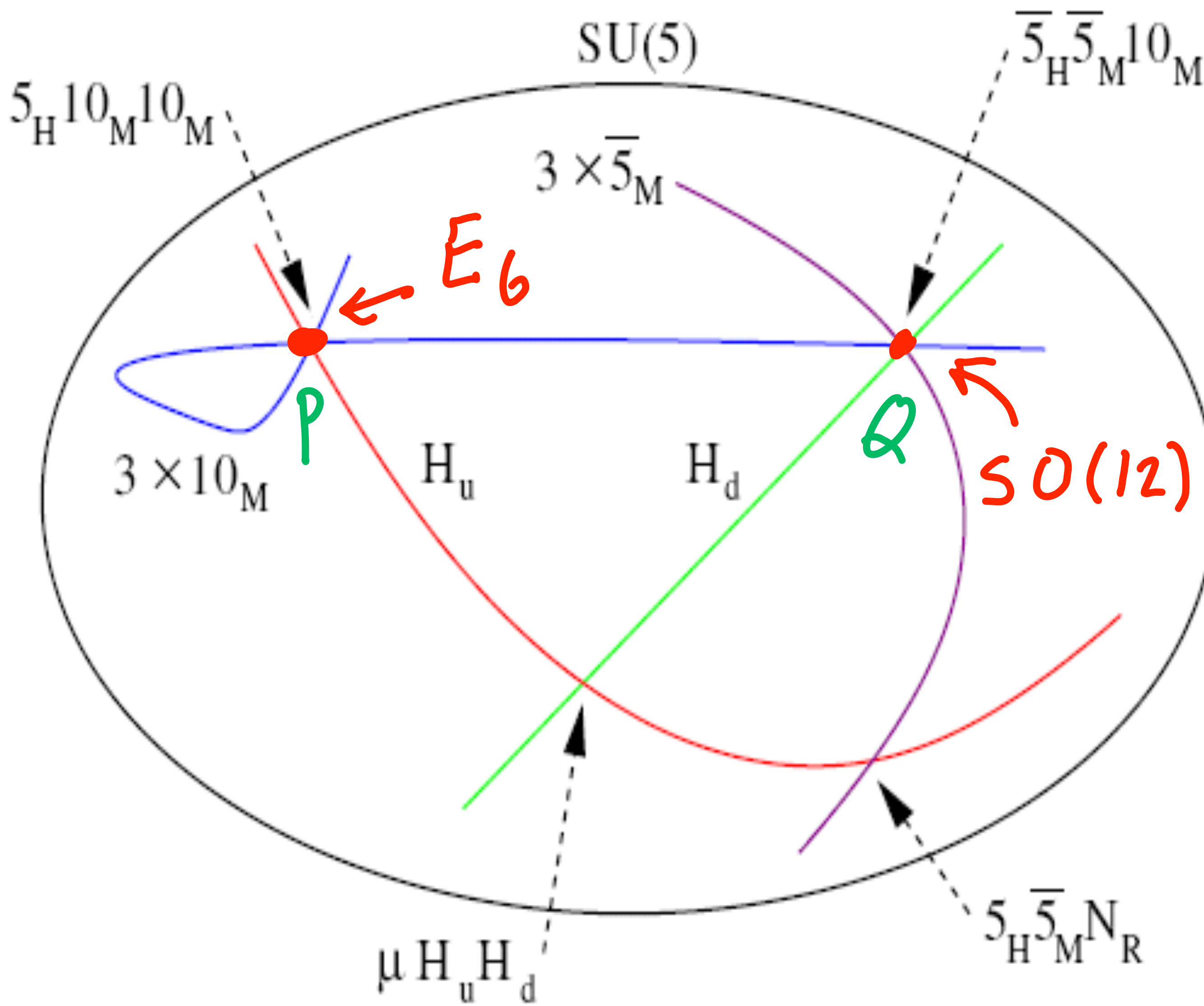
To give mass to up and down quarks and charged leptons:

$$\left(5_{H_u}\, 10_M\, 10_M\right) \xrightarrow{\text{up}} E_6:$$

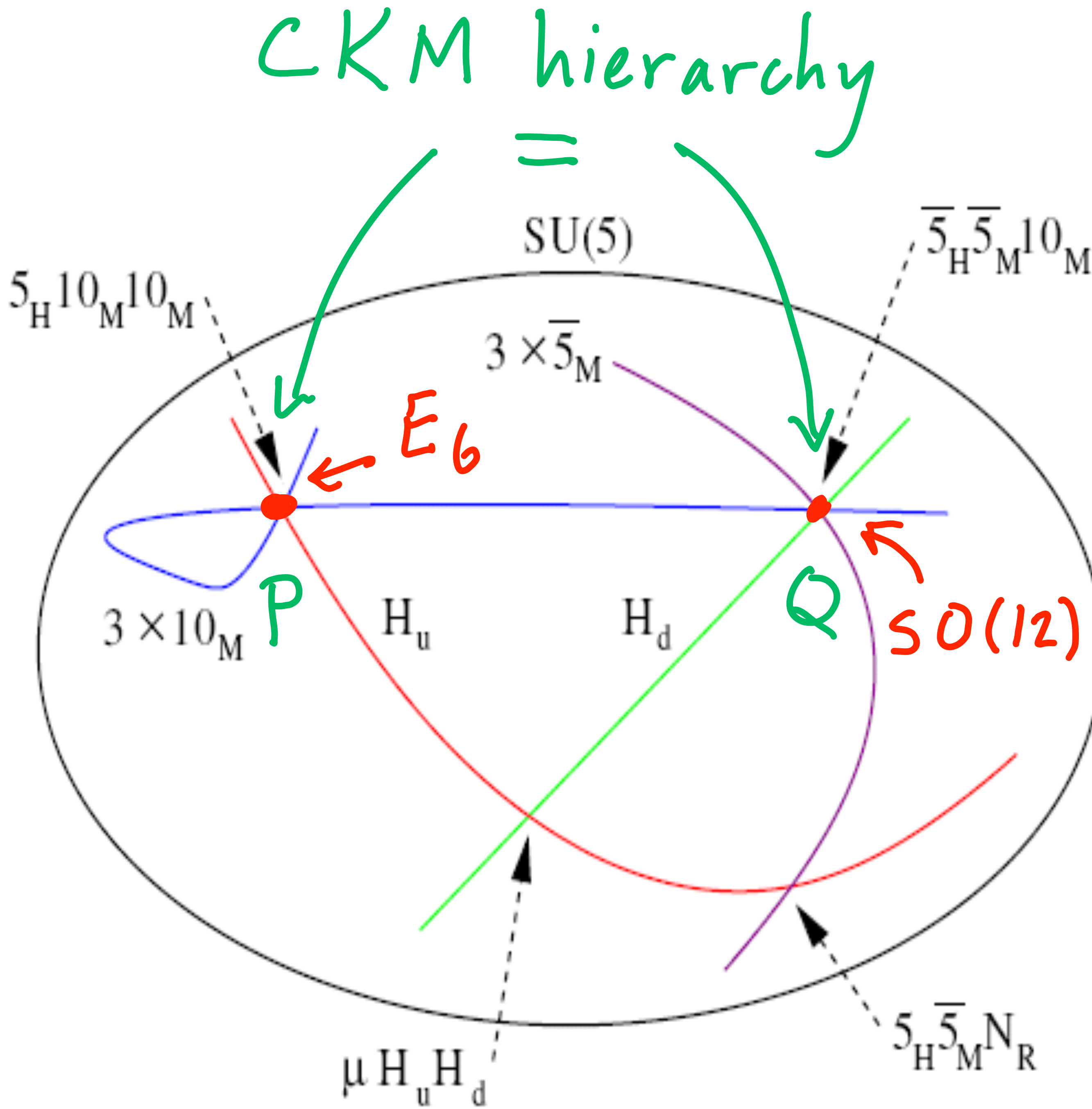


$$\left(\bar{5}_{H_d}\, \bar{5}_M\, 10_M\right) \xrightarrow[\text{leptons}]{\text{down}} SO(12)$$



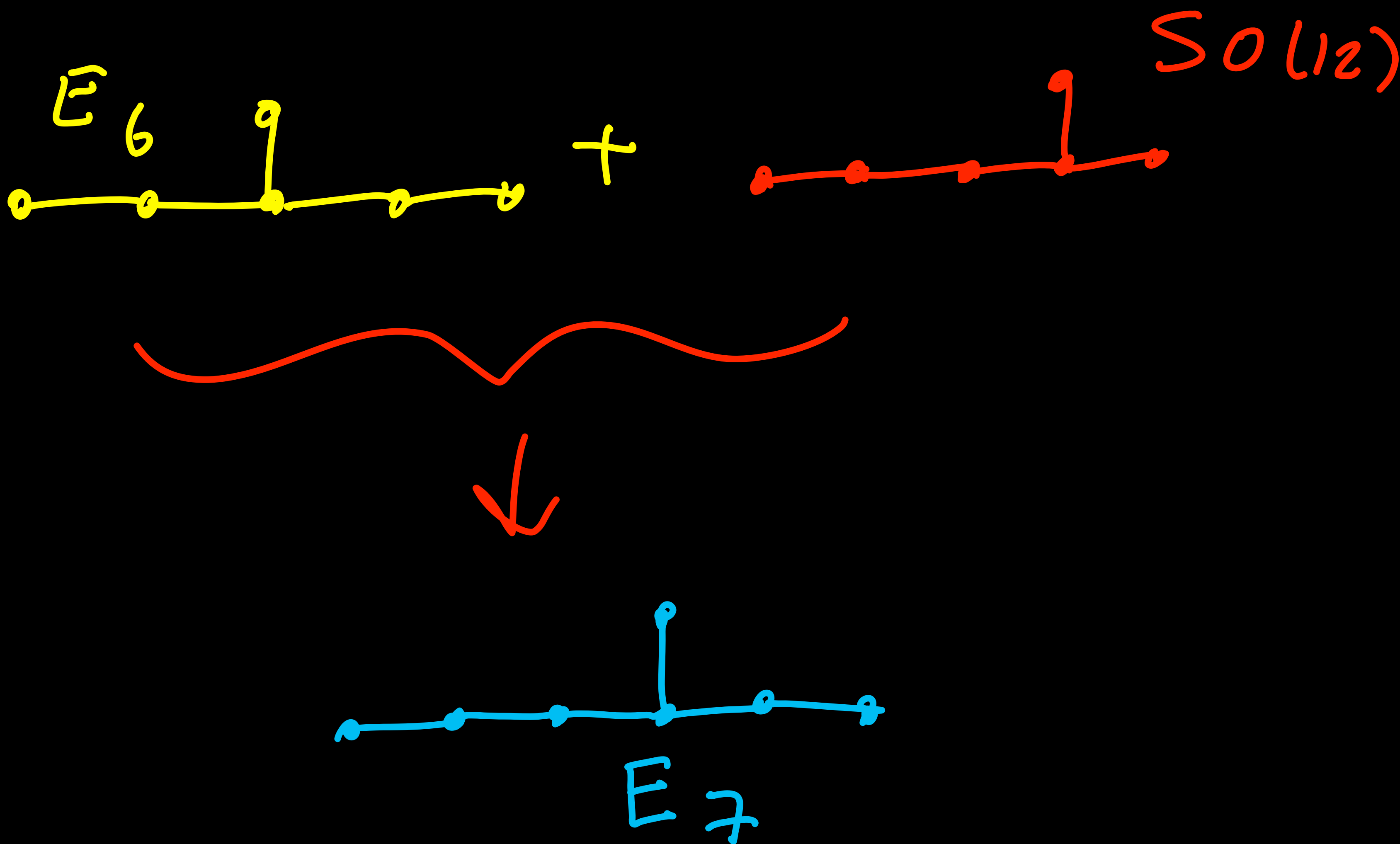


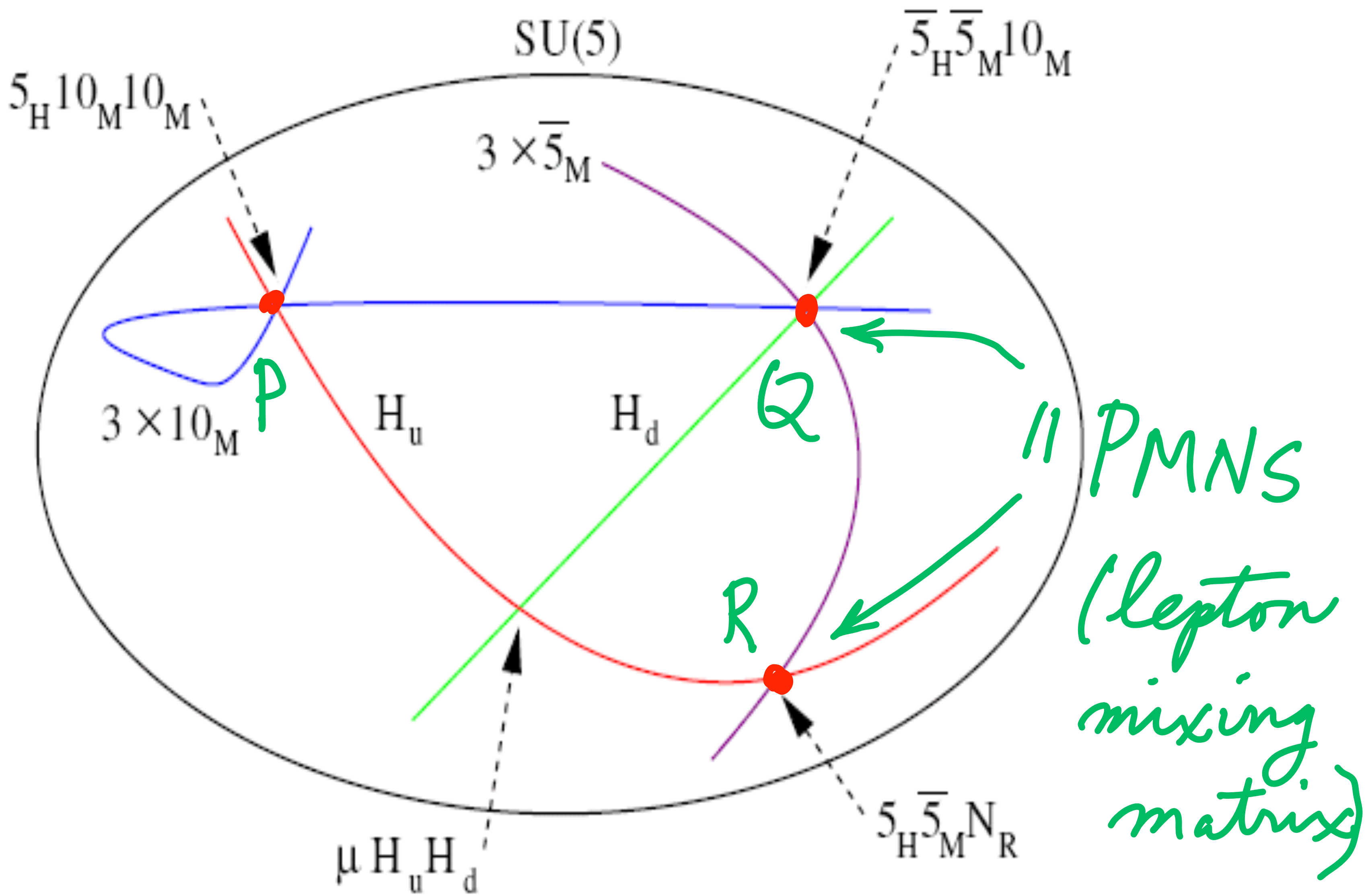
SU(5)
$5_H 10_M 10_M$
$\bar{5}_H \bar{5}_M 10_M$
$3 \times \bar{5}_M$
E_6
P
Q
SO(12)
$3 \times 10_M$
H_u
H_d
$\mu H_u H_d$
$5_H \bar{5}_M N_R$



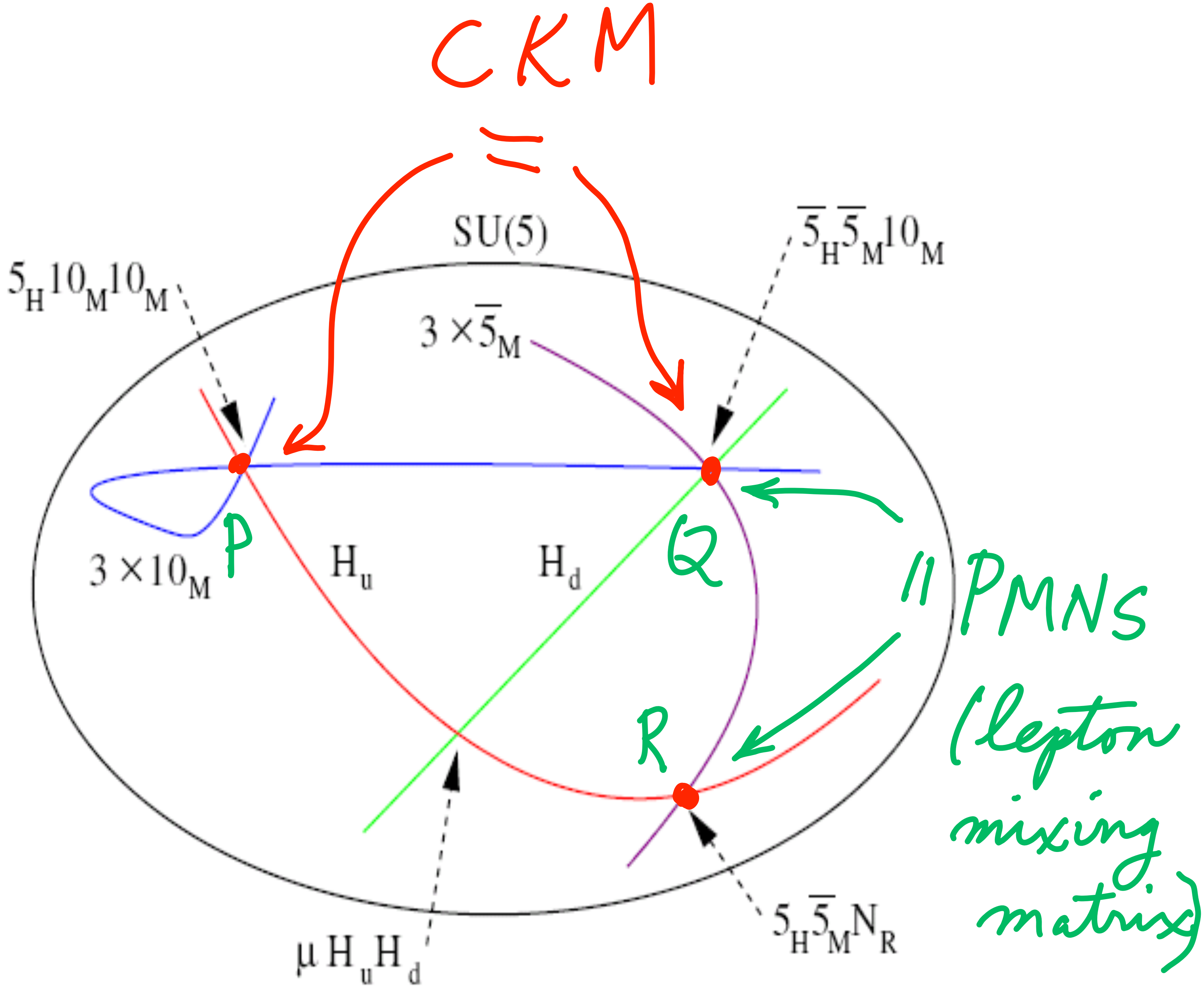
CKM hierarchy
=
SU(5)
$5_H 10_M 10_M$
$\overline{5}_H \overline{5}_M 10_M$
$3 \times \overline{5}_M$
E_6
$3 \times 10_M$
P
H_u
H_d
Q
SO(12)
$\mu H_u H_d$
$5_H \overline{5}_M N_R$

$P = Q \Rightarrow$





SU(5)
$5_H 10_M 10_M$
$\overline{5}_H \overline{5}_M 10_M$
$3 \times \overline{5}_M$
$3 \times 10_M$
P
Q
R
H_u
H_d
$\mu H_u H_d$
$5_H \overline{5}_M N_R$
= PMNS (lepton mixing matrix)



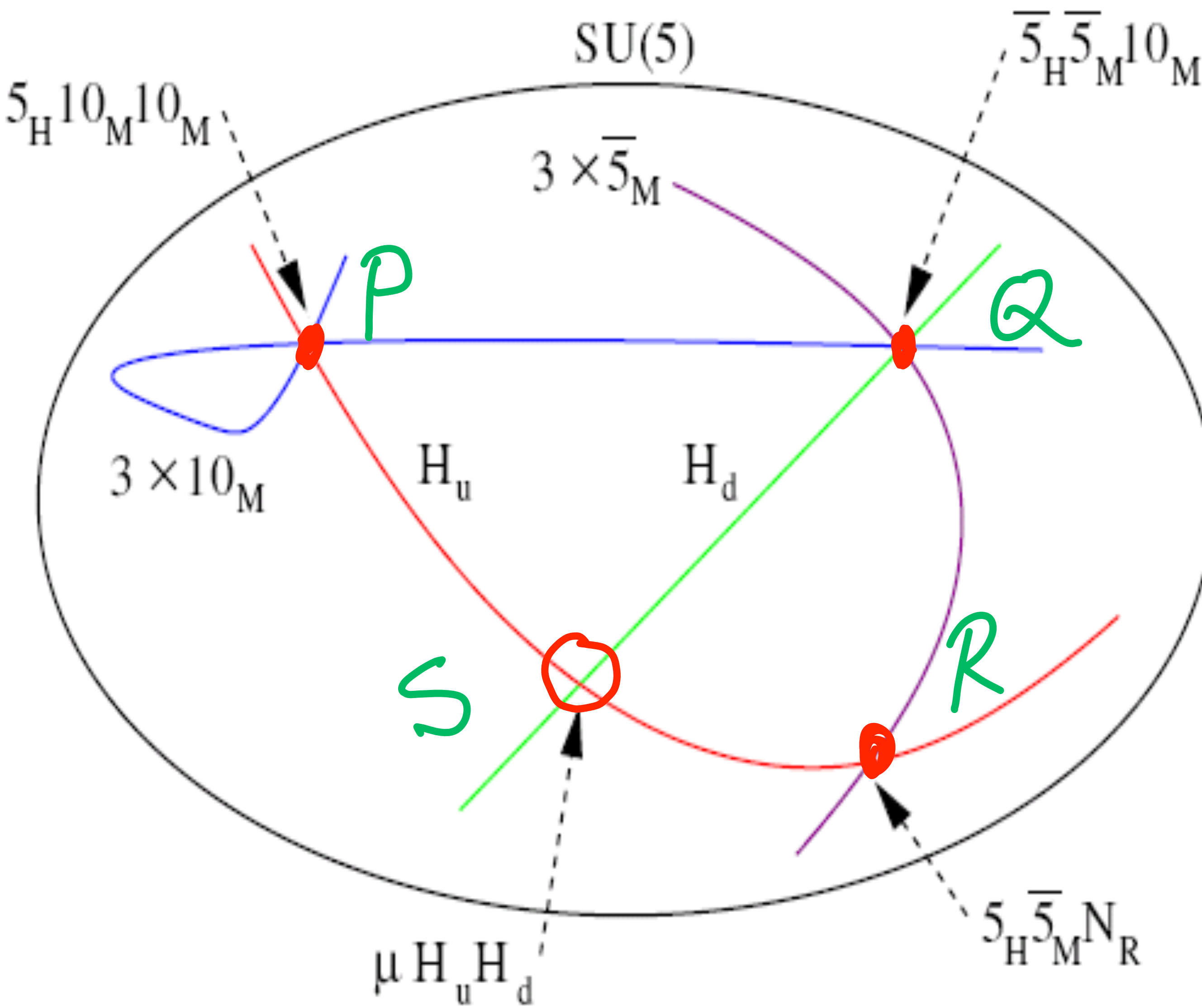
CKM
=
SU(5)
$5_H 10_M 10_M$
$\overline{5}_H \overline{5}_M 10_M$
$3 \times \overline{5}_M$
$3 \times 10_M$
P
H_u
H_d
Q
= PMNS (lepton mixing matrix)
R
$\mu H_u H_d$
$5_H \overline{5}_M N_R$

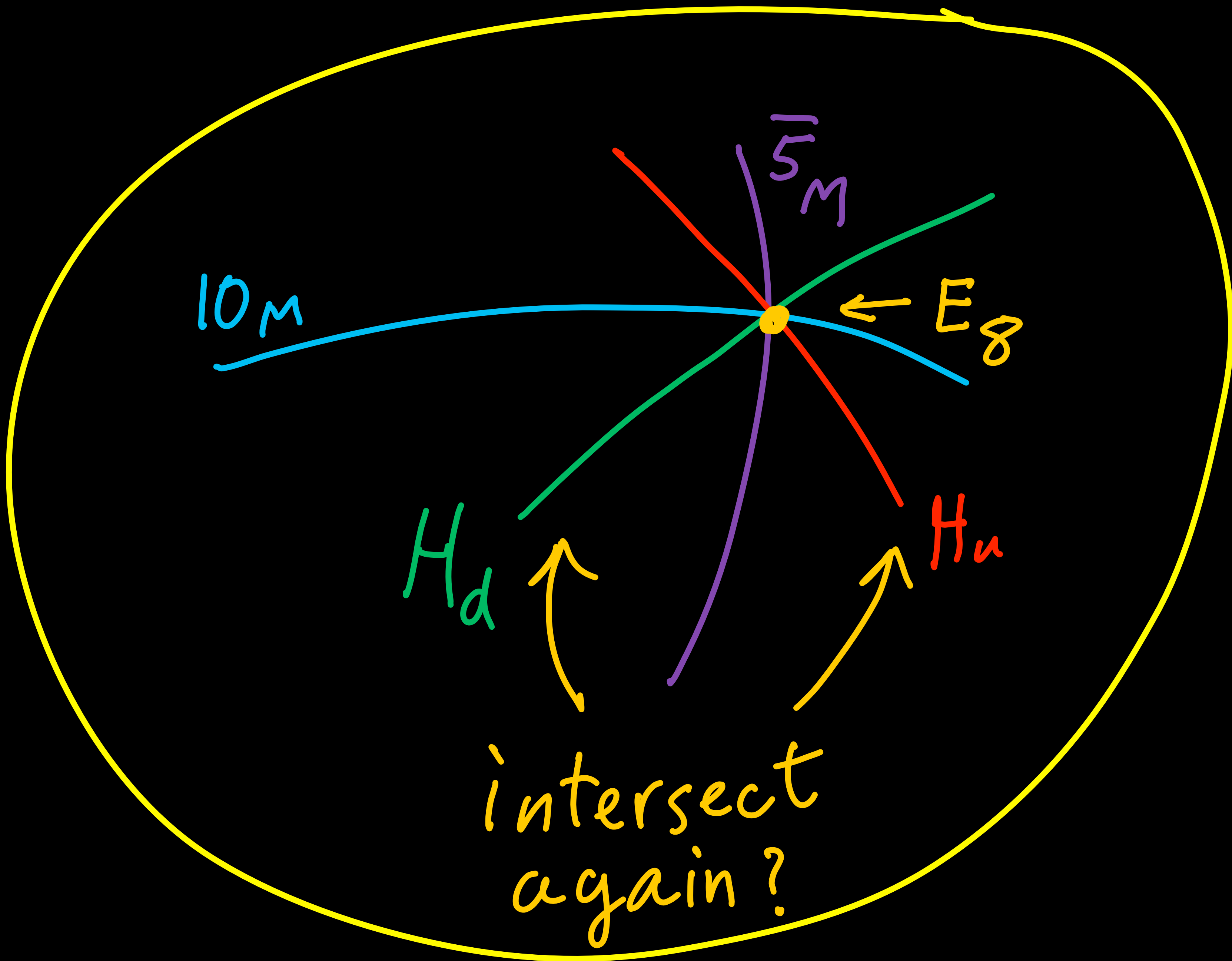
$$P = Q = R$$

Moreover as noted by Hayashi, Kawano, Tatar, Watari it is important to assume monodromies are acting on the 7-branes to get a consistent interactions for neutrinos as well as to avoid fine tuning for the up quark mass hierarchy. Using these facts one can deduce that at

$$P = Q = R \rightarrow E_8 \, !$$

$S \stackrel{?}{=} (P, Q, R)$




10_M
$\bar{5}_M$
E_8
H_d
H_u
intersect again?

So we see that at one point all the main interactions take place. Can E_8 structure accommodate other aspects of standard model such as right-handed neutrinos and PQ symmetry? Is it overconstraining? What other matter will be forced on us by this assumption?

$$\underbrace{SU(5)_{GUT}}_{\text{preserved}} \times SU(5)_{\perp} \subset E_8$$

Can be broken by monodromy S_5

$$G_{mono} \subset S_5$$

In fact just to get the required structure of interactions are very restrictive, and just by the assumption of having the required symmetries and a PQ symmetry, it can be classified:

$G_{\text{Dirac Neutrino}}$: $\left\{ \begin{array}{l} Z_2,\ Z_2 \times Z_2 \\ Z_3,\ S_3 \end{array} \right.$

$G_{\text{Majorana Neutrino}}$: $\left\{ \begin{array}{l} Z_2 \times Z_2 \\ D_4^{(a,b)} \end{array} \right.$

This also leads to specific extra matter and gauge bosons:

Extra Gauge Symmetries:

Dirac Scenario: $U(1)_{B-L} \times U(1)_{PQ}$

Majorana Scenario:

$U(1)_{PQ}$

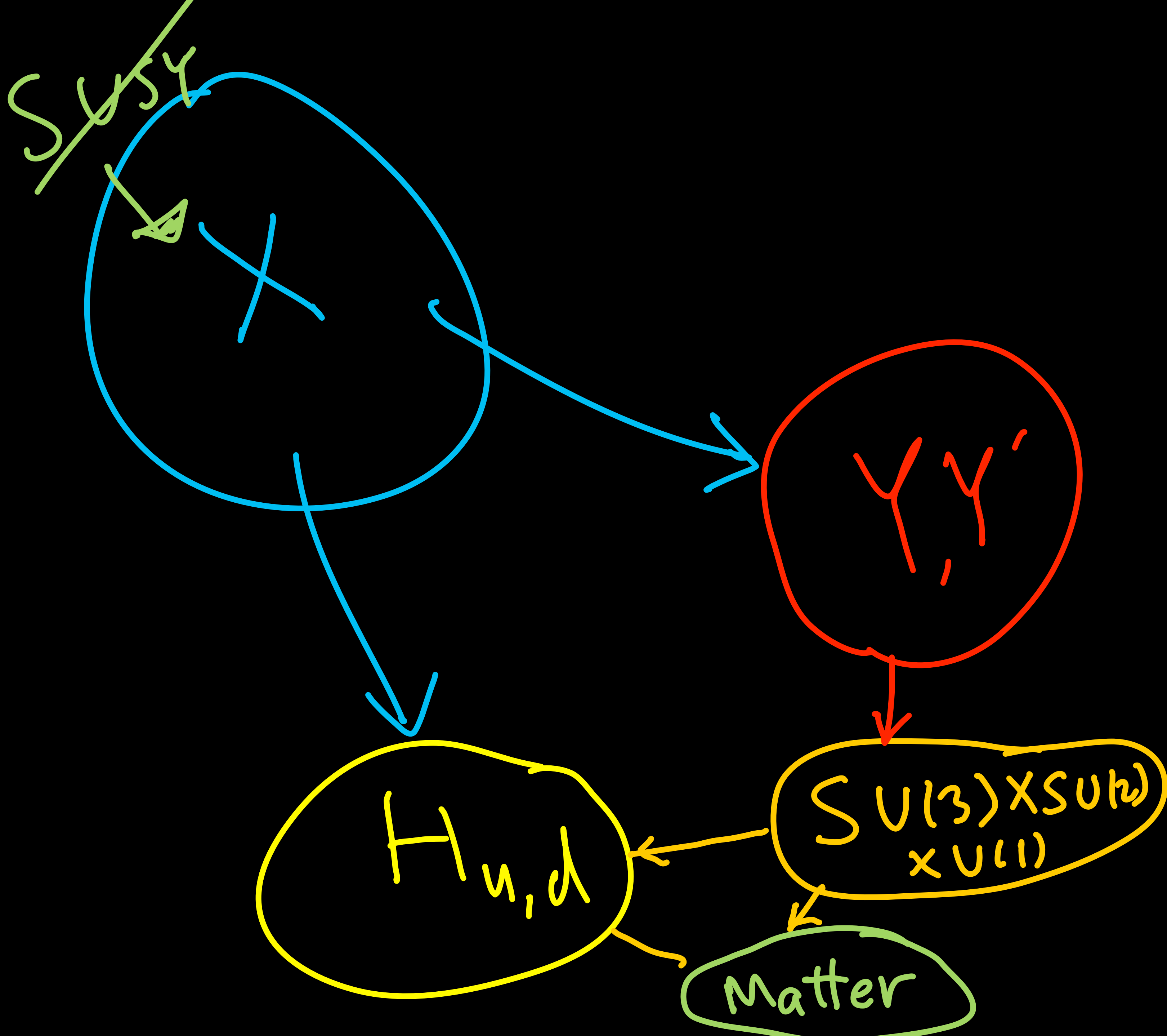
Deformed Gauge Mediated ~~SUSY~~

Lack of FCNC motivates GMSB. Natural for F-theory (though some other approaches can be taken, e.g. Ibanez et. al.). For GMSB messenger fields Y,Y' (charged under MSSM) feel SUSY breaking via their coupling to the Goldstino field X which is neutral under MSSM.

$$\langle X \rangle = x + \theta^2 F$$

$$\int X \cdot Y Y' \, d^2\theta \rightarrow \Lambda^{gaugino} = \frac{F}{x} \sim 10^5 \, \mathrm{GeV}$$

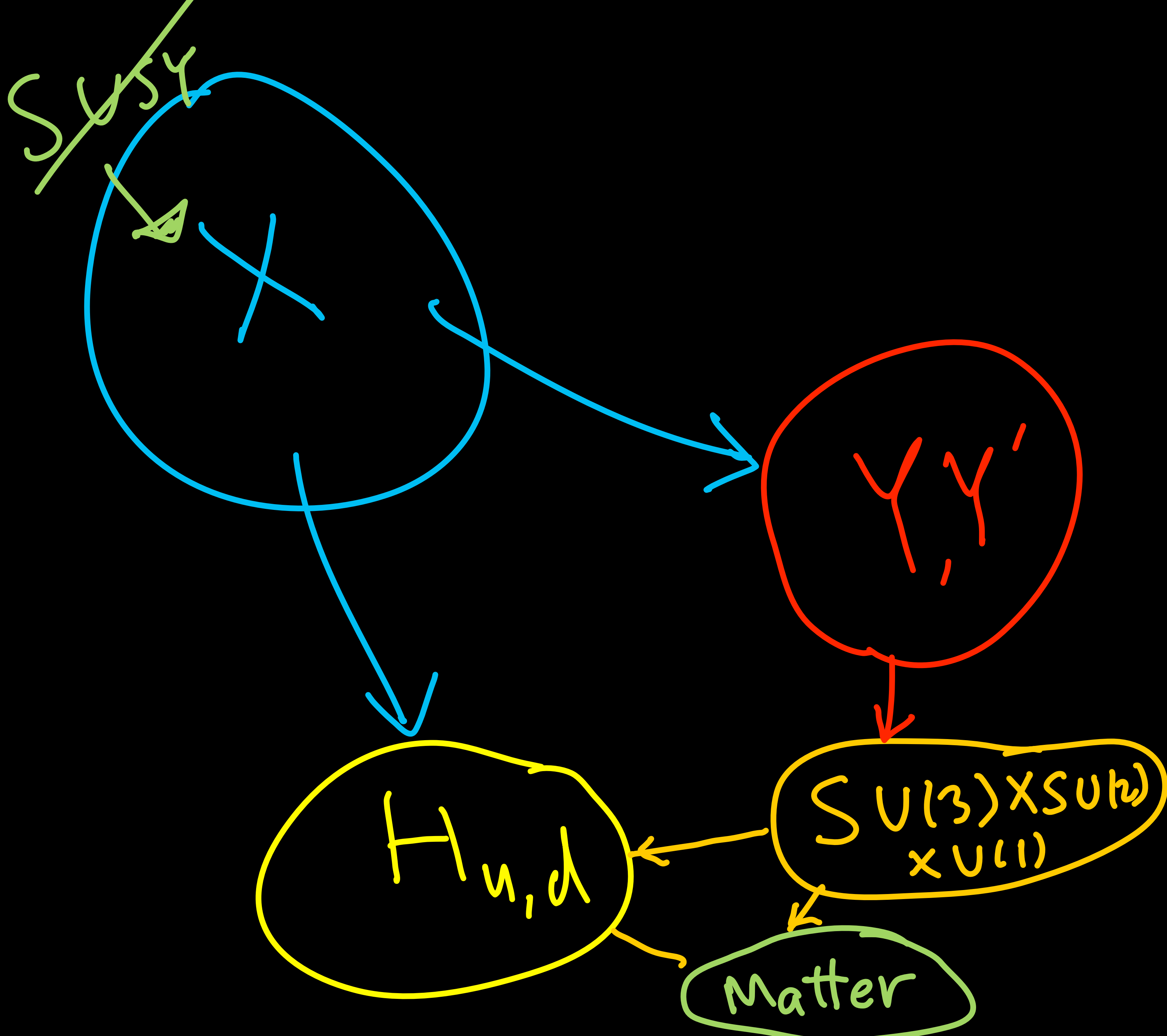
$$\frac{1}{M_G}\int X^\dagger H_u H_d \, d^4\theta \rightarrow \mu = \frac{F}{M_G} \sim 10^2 \, \mathrm{GeV}$$


Susy
X
Y, Y'
SU(3)×SU(2)
×U(1)
$H_{u,d}$
Matter

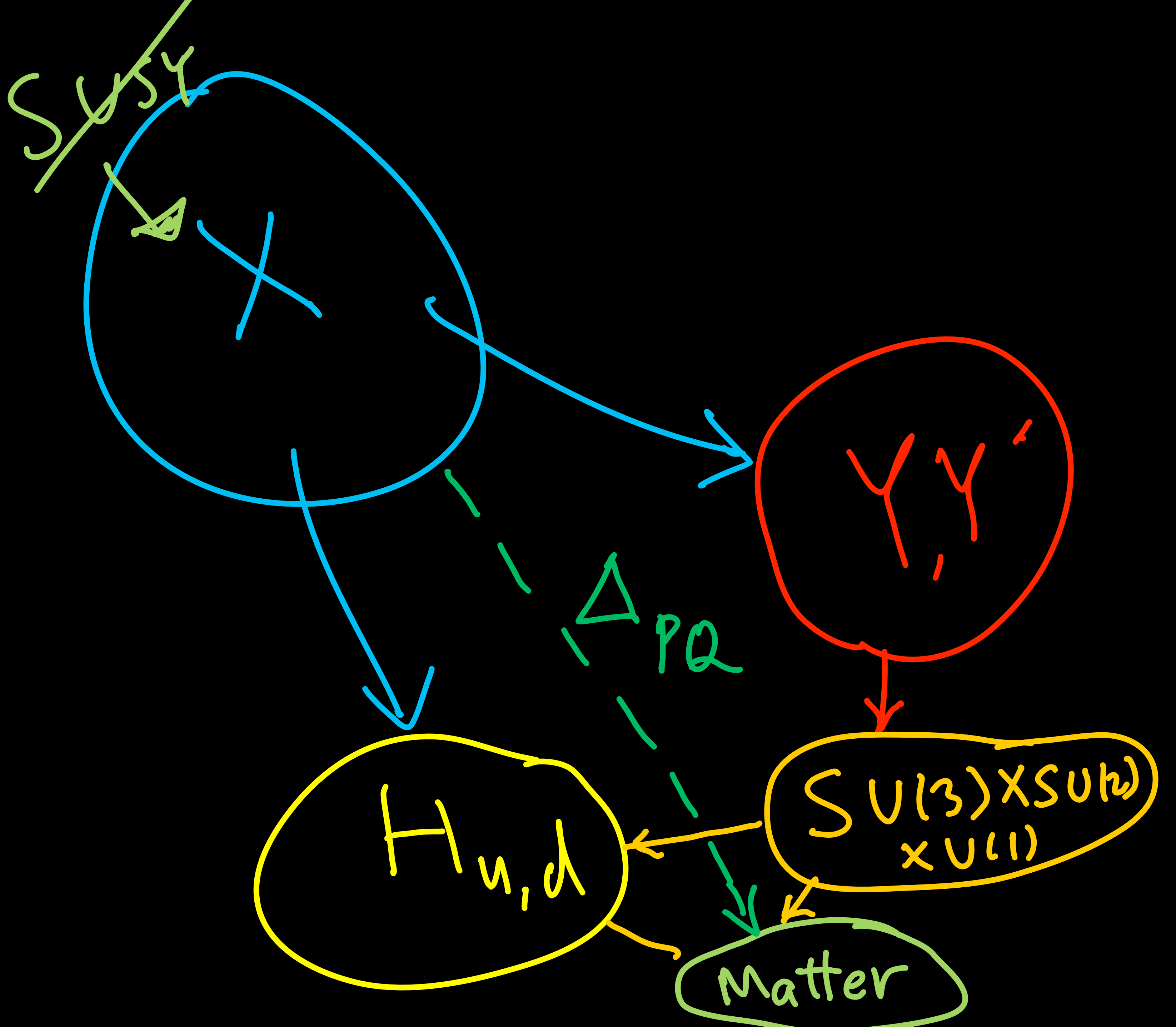
In F-theory models it is natural to assume that the anomalous U(1) PQ is responsible for SUSY breaking. The U(1) PQ also feeds to matter which is charged under it, and also induces additional supersymmetry breaking terms i.e. we have a deformed version of GMSB. This deformation is parameterized by a D-term in the U(1) PQ sector

$$\Delta_{PQ}$$

$$\Delta_{PQ} = 0 \longleftrightarrow \text{GMSB}$$



Susy
X
Y, Y'
$H_{u,d}$
SU(3)×SU(2) ×U(1)
Matter

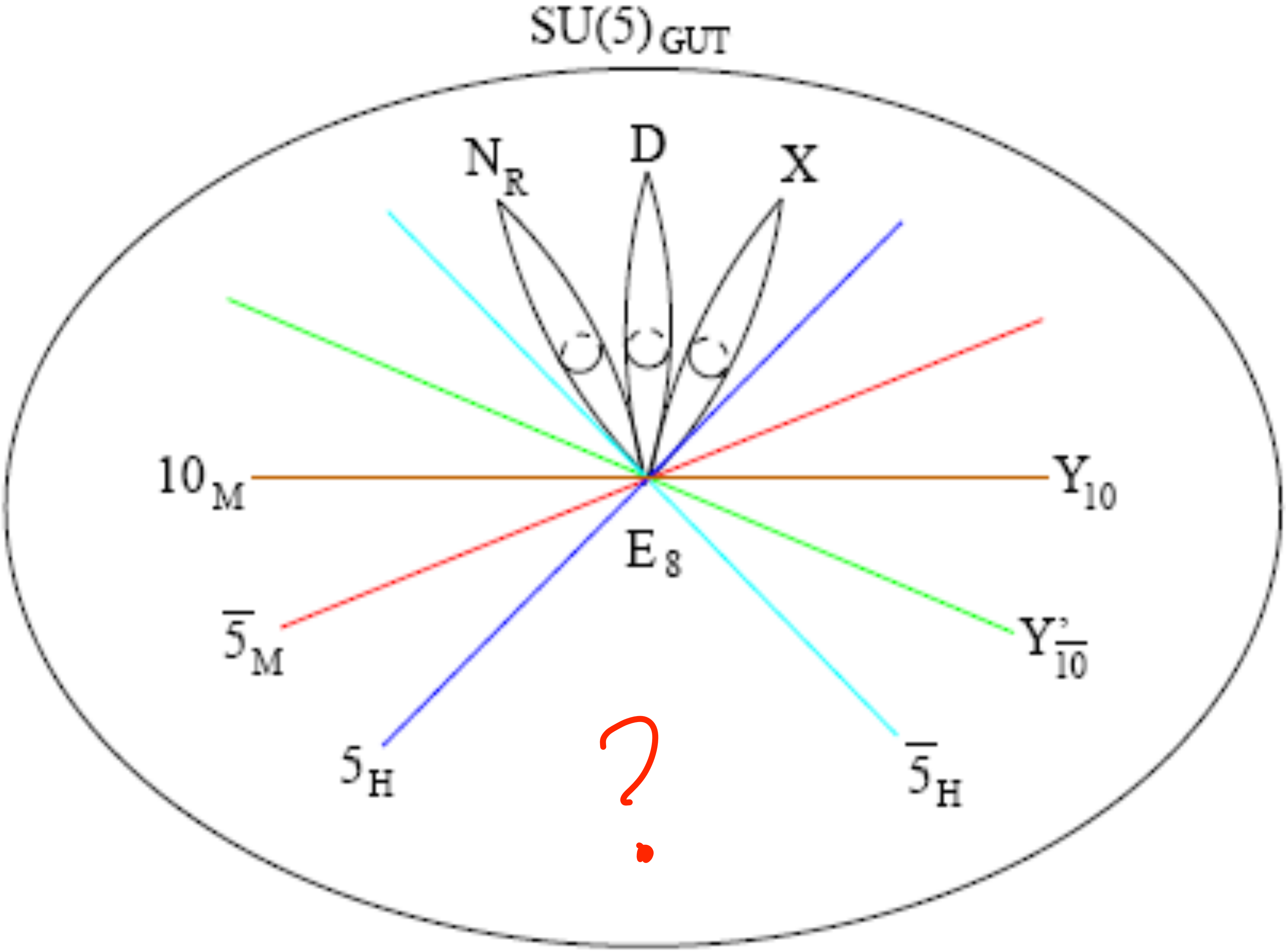


Susy
X
Y, Y'
Δ_{PQ}
$H_{u,d}$
SU(3)xSU(2)
xU(1)
Matter

The idea sounds good, but we seem to have departed from minimality:

Where do messenger fields come from? Which rep. of MSSM?
Where does X come from?
Why does it only couple to Higgses and the messengers?

We mentioned there are extra matter coming from the E_8 singularity. What are they? Could they be used for the GMSB?



SU(5)GUT
NR
D
X
10M
Y10
E8
5̄M
Y'10̄
5H
5̄H
?

The answer turns out to be very surprisingly YES!

Moreover there are only a handful of possible monodromies for the `invisible’ SU(5) which can work as we already noted with very specific predictions for potentially extra matter:

The Z_2, $Z_2 \times Z_2$ Monodromy for Dirac Neutrinos

Minimal	$10_M, Y_{10}$	$\overline{5}_M$	$Y'_{\overline{10}}$	5_H	$\overline{5}_H$	$X^\dagger$	N_R
$U(1)_{PQ}$	$+1$	$+1$	$+3$	-2	-2	$+4$	-3
$U(1)_\chi$	-1	$+3$	$+1$	$+2$	-2	0	-5

Extra Charged	$10_{(1)}$	$\overline{5}_{(1)}$	$\overline{5}_{(2)}$	$\overline{5}_{(3)}$
$U(1)_{PQ}$	$+4$	-2	$+5$	-6
$U(1)_\chi$	$+4$	-2	$+3$	-2

Extra Neutral	$D_{(1)}$	$D_{(2)}$	$D_{(3)}$	$D_{(4)}$	Z_{PQ}	Z_χ
$U(1)_{PQ}$	0	$+4$	0	-7	0	0
$U(1)_\chi$	0	0	0	-5	0	0

$$U_\chi(1) = \alpha\, U(1)_Y + \beta\, U(1)_{B-L}$$

The Dirac Neutrino Scenario with Z_3, S_3 monodromy

Minimal	$10_M, Y_{10}$	$\overline{5}_M, Y'_{\overline{5}}$	Y_5	$Y'_{\overline{10}}$	5_H	$\overline{5}_H$	$X^\dagger$	N_R
$U(1)_{PQ}$	$+1$	$+1$	$+3$	$+3$	-2	-2	$+4$	-3
$U(1)_\chi$	-1	$+3$	-3	$+1$	$+2$	-2	0	-5

Extra Charged	$10_{(1)}$
$U(1)_{PQ}$	0
$U(1)_\chi$	$+4$

Extra Neutral	$D_{(1)}$	$D_{(2)}$	Z_{PQ}	Z_χ
$U(1)_{PQ}$	$+1$	0	0	0
$U(1)_\chi$	-5	0	0	0

Majorana Neutrinos $\mathbb{Z}_2 \times \mathbb{Z}_2$ Monodromy

Visible Matter	$10_M, Y_{10}$	$Y'_{\overline{10}}$	$\overline{5}_M$	5_H	$\overline{5}_H$	$X^\dagger$	N_R
$U(1)_{PQ}$	$+1$	$+4$	$+2$	-2	-3	$+5$	0

Extra Charged	$\overline{5}_{(1)}$
$U(1)_{PQ}$	$+2$

Majorana Neutrinos D_4 Monodromy

Visible Matter	$10_M, Y_{10}$	$Y'_{\overline{10}}$	$\overline{5}_M$	5_H	$\overline{5}_H$	$X^\dagger$	N_R
$U(1)_{PQ}$	$+1$	$+4$	$+2$	-2	-3	$+5$	0

No extra charged matter!

$$\text{F-terms}\left\{\begin{array}{l} 10_M\, 10_M\, 5_H \\ 10_M\, \overline{5}_M\, \overline{5}_H \\ N_R\, \overline{5}_M\, 5_H \\ X\, Y\, Y' \end{array}\right. \qquad \text{D-term}\left\{ X^\dagger 5_H \overline{5}_H \right.$$

Cosmological Considerations

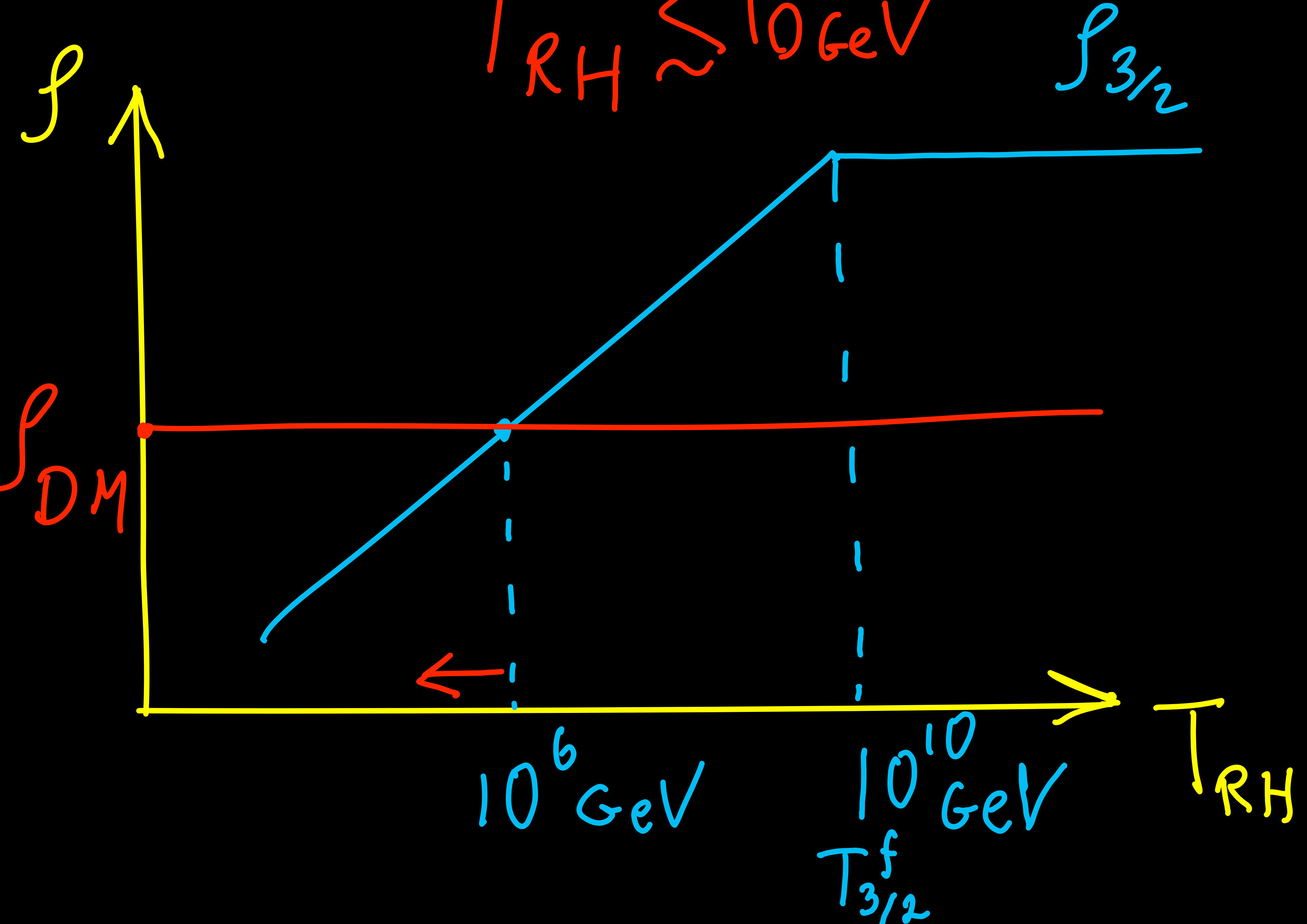
Dark Matter: primary candidate gravitino,

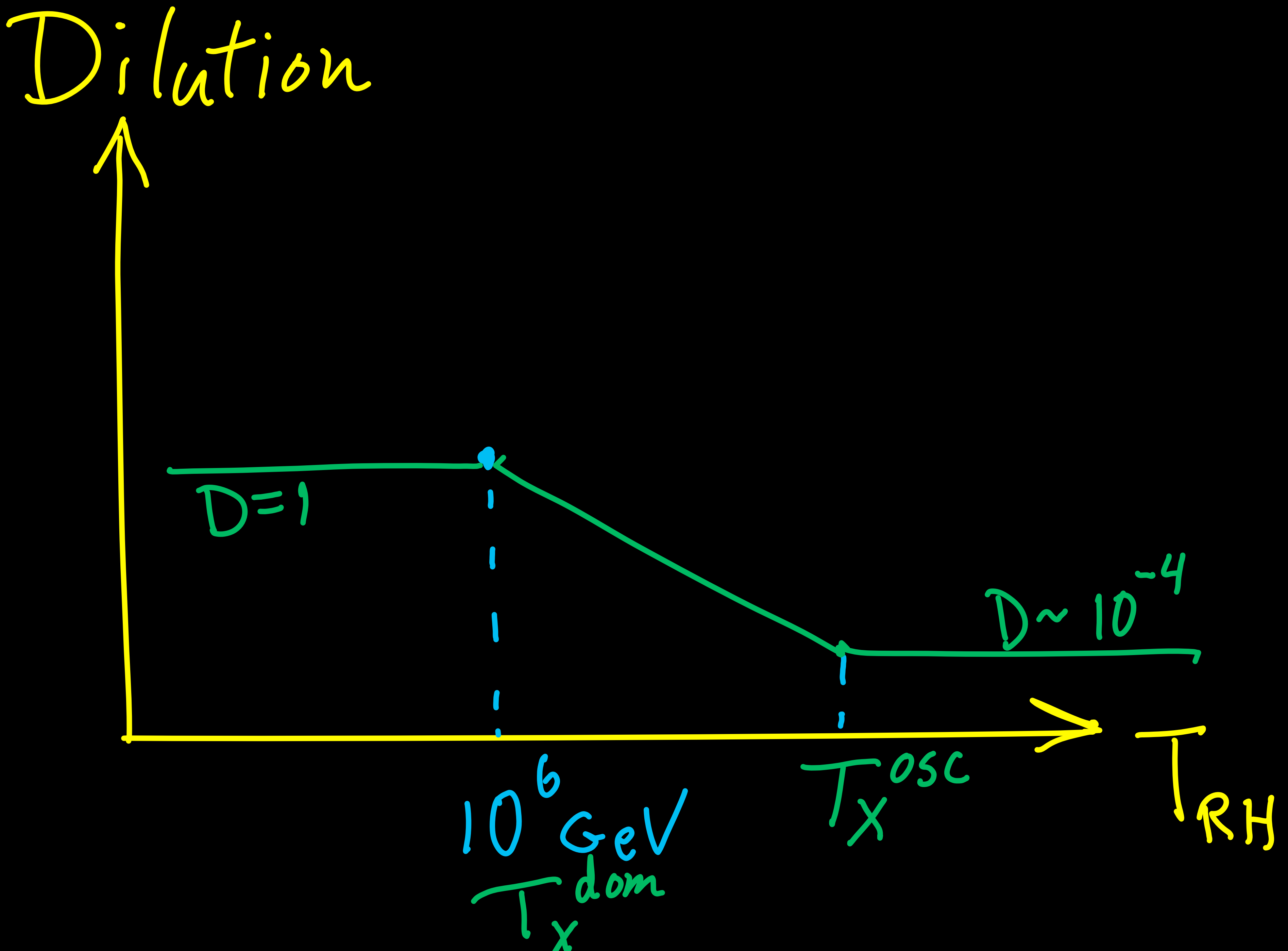
$$m_{3/2} \sim \frac{F}{M_{pl}} \sim 10-100 \text{ MeV}$$

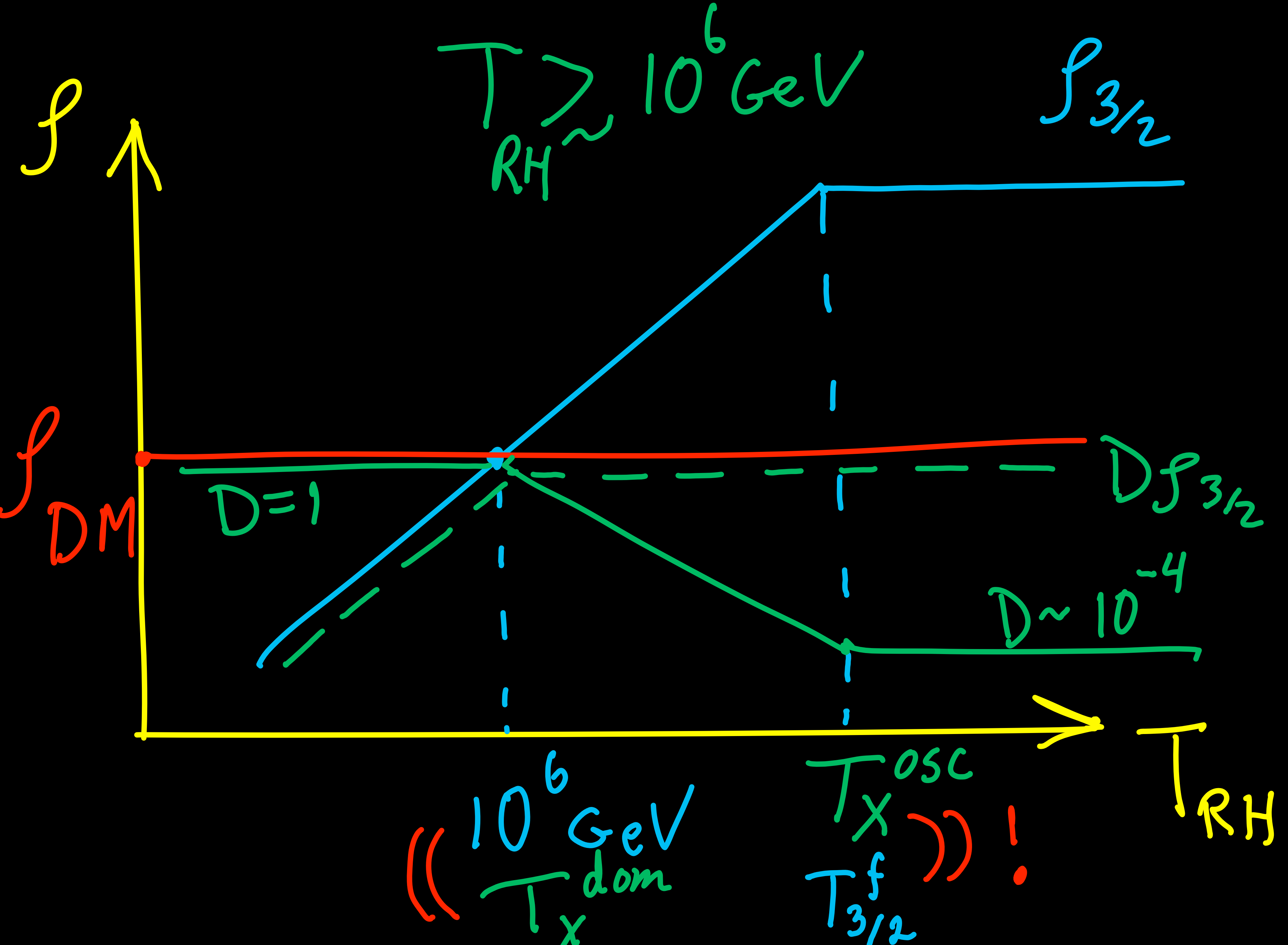
X field, plays a key role: Its phase plays the role of QCD axion, and its radial component, saxion, dominates the energy density of the universe for a while, and its later decay leads to dilution of gravitino density, thus solving in a natural way the gravitino overproduction problem. This also requires

$$\Delta_{PQ} \gtrsim 50 \text{ GeV}$$

$T_{RH} \lesssim 10^6\,\mathrm{GeV}$

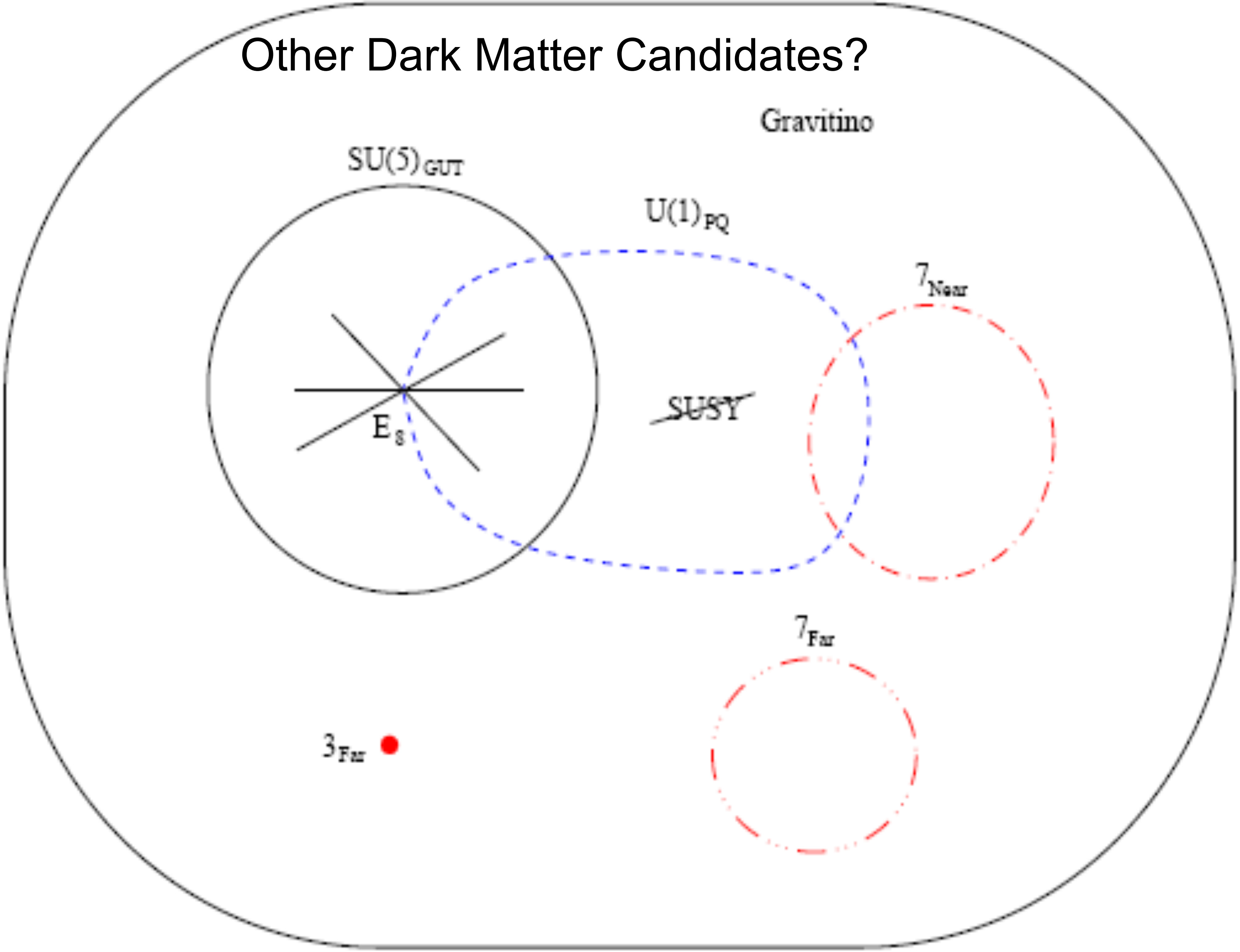



Dilution
D=1
D~10^-4
10^6 GeV
T_X^dom
T_X^osc
T_RH



$T_{RH} > 10^6$ GeV
ρ
$\rho_{3/2}$
ρ_{DM}
$D=1$
$D\rho_{3/2}$
$D \sim 10^{-4}$
T_{RH}
10^6 GeV
T_X^{osc}
$((T_X^{dom}$
$T_{3/2}^f))$!

Other Dark Matter Candidates?



Depending on which neutrino scenario, and which monodromy choice we make, we obtain a whole host of other possible candidates for TeV scale dark matter. In fact we have a list of all of them. One can show that NONE of them can be stable: There are dimension 5 decay channels available to all of them which are too rapid.

No other natural dark matter candidate: Predict that signals of PAMELA, ATIC and FERMI have astrophysical origins.

Consequences for Accelerator Physics

The most important aspect of this scenario for accelerator physics is the spectrum of supersymmetric partners. One has very little room to vary parameters: The messengers as we have seen are typically in 10+10* and the PQ deformation is constrained by astrophysical constraints as well as the requirement of avoiding tachyons.

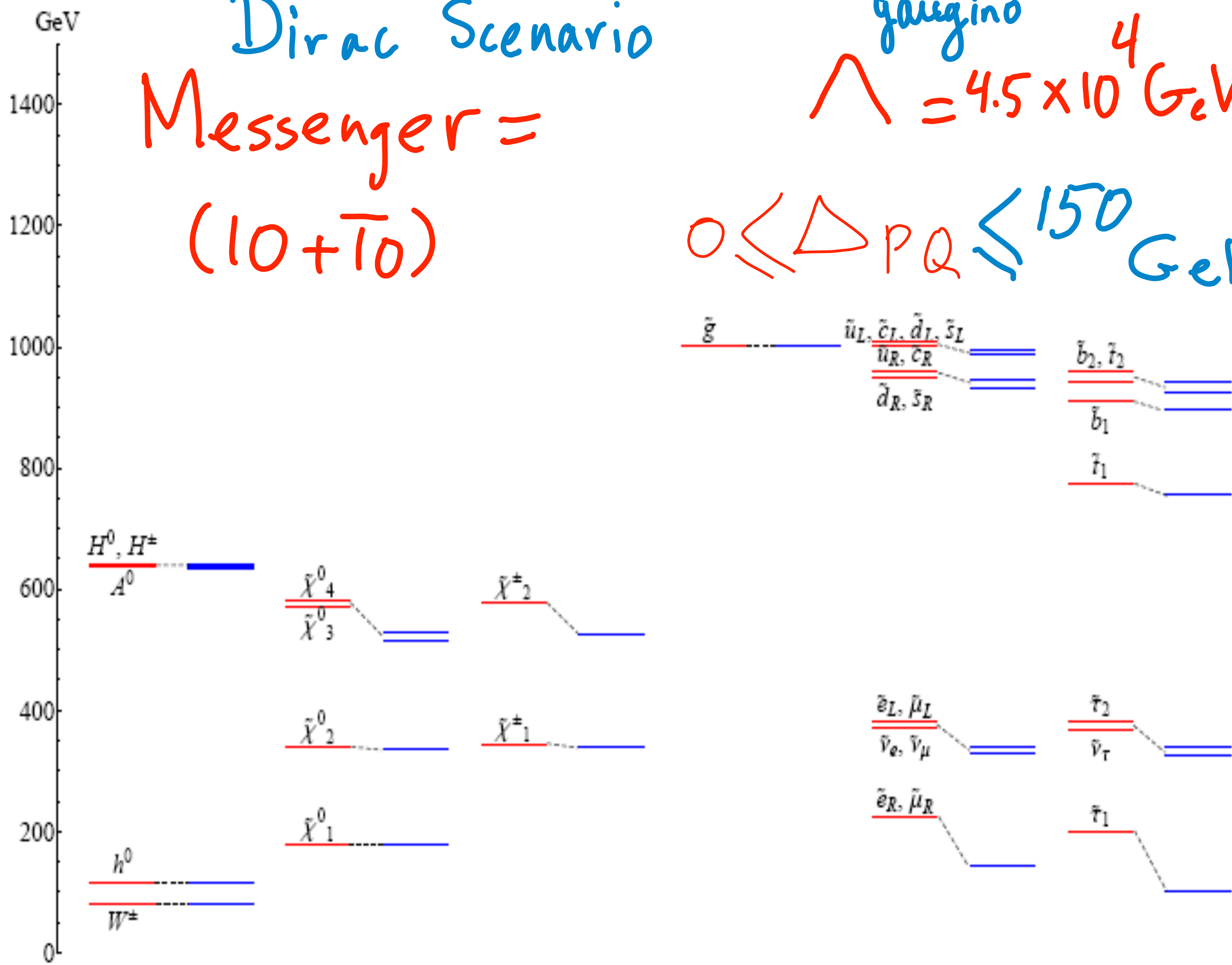
We can vary the gaugino mass scale, the number of the messengers and the PQ deformation scale in a narrow window:

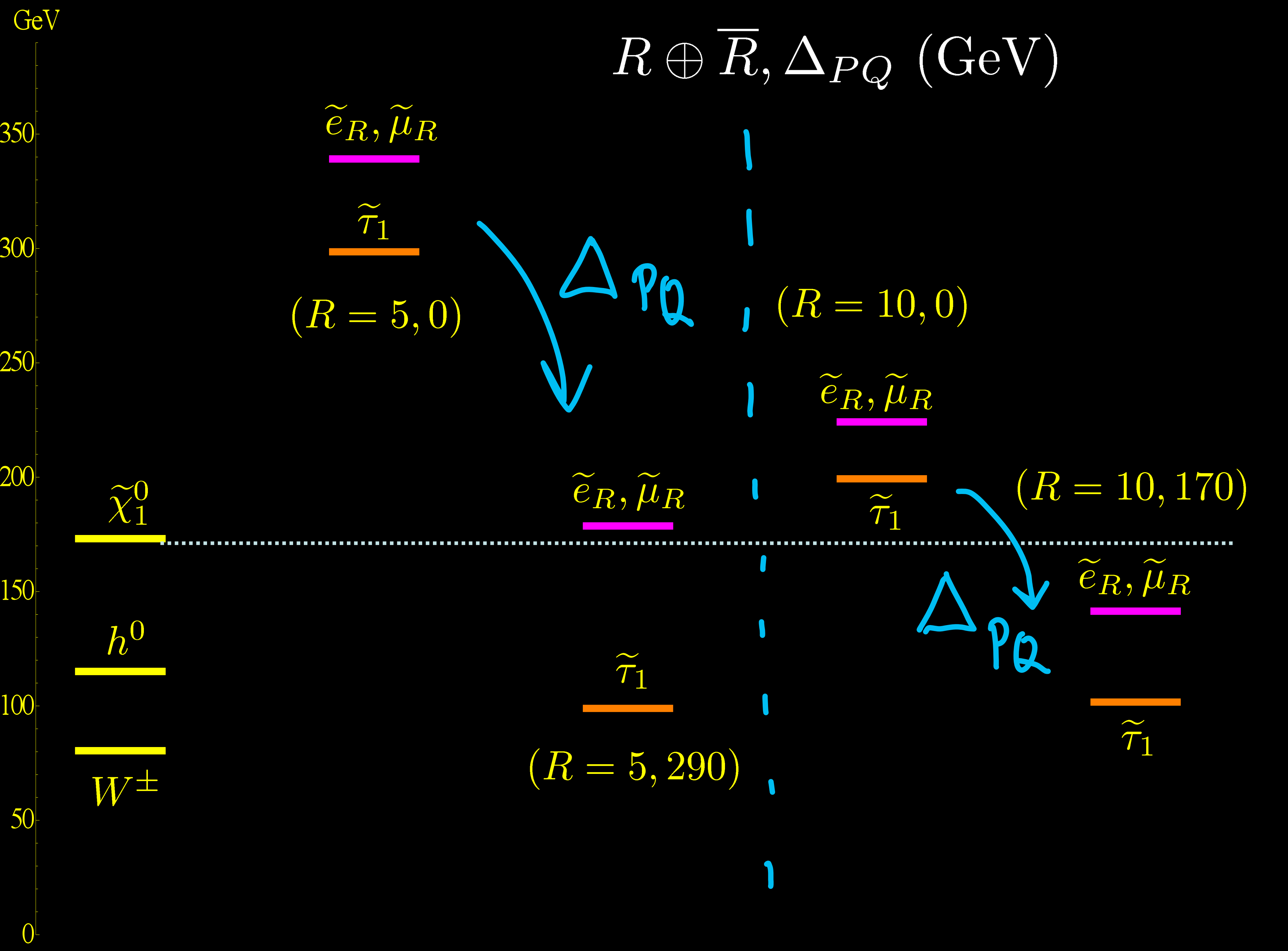
Dirac Scenario

Messenger = $(10+\overline{10})$

$\Lambda_{\text{gaugino}} = 4.5 \times 10^4$ GeV

$0 \leq \Delta_{PQ} \leq 150$ GeV





GeV
350
300
250
200
150
100
50
0
$R \oplus \overline{R}, \Delta_{PQ}$ (GeV)
$\widetilde{e}_R, \widetilde{\mu}_R$
$\widetilde{\tau}_1$
$(R = 5, 0)$
Δ_{PQ}
$(R = 10, 0)$
$\widetilde{e}_R, \widetilde{\mu}_R$
$\widetilde{\tau}_1$
$(R = 10, 170)$
$\widetilde{\chi}_1^0$
$\widetilde{e}_R, \widetilde{\mu}_R$
Δ_{PQ}
$\widetilde{e}_R, \widetilde{\mu}_R$
h^0
$\widetilde{\tau}_1$
$\widetilde{\tau}_1$
$W^\pm$
$(R = 5, 290)$

Experimental Predictions for the LHC

Narrow range of parameters: relatively specific predictions for the LHC.

Since $\Delta_{PQ} > 50$ GeV distinguishable for GMSB

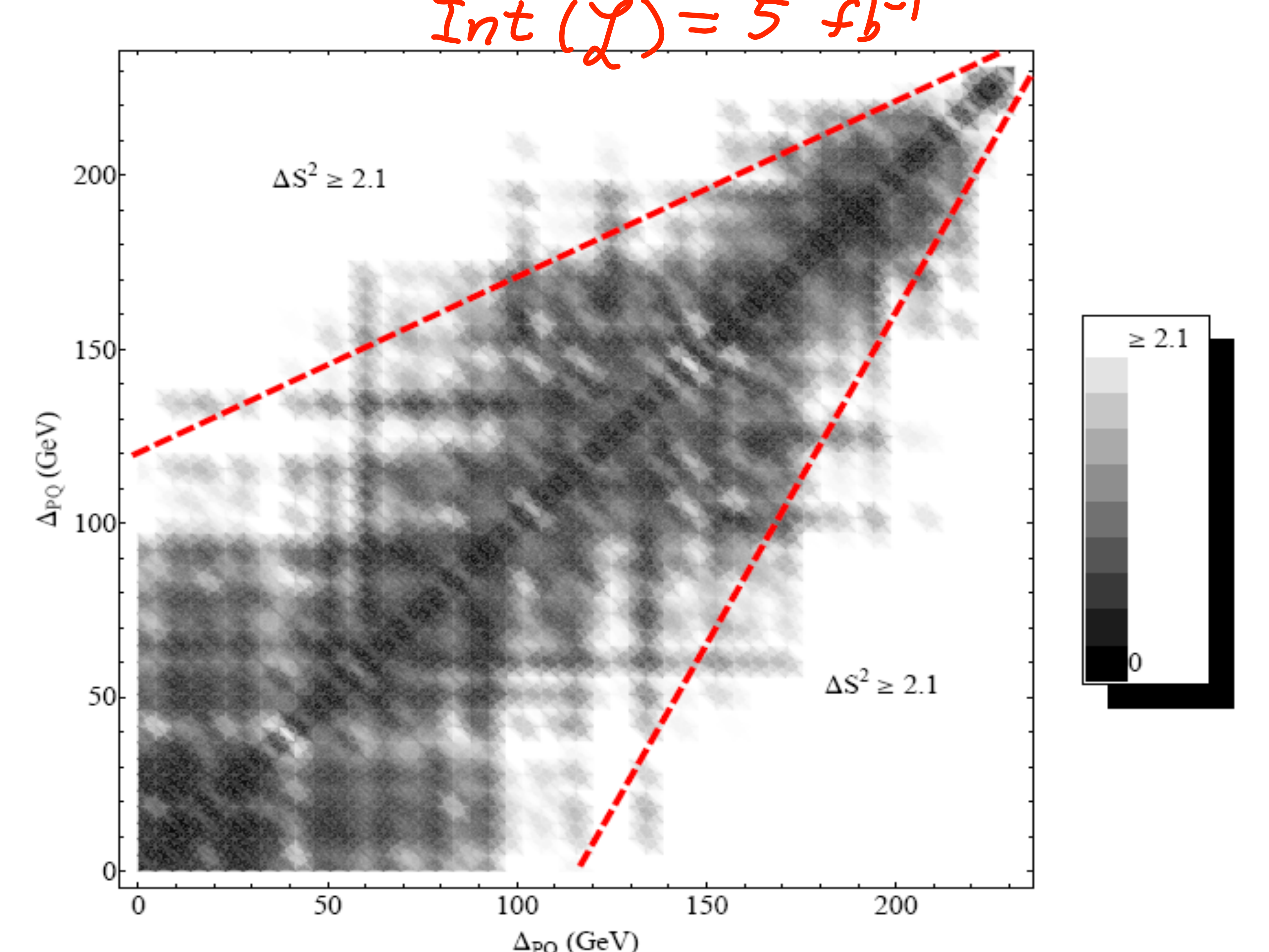
NLSP is typically $\tilde{\tau}$ (due to messenger in $10 + \overline{10}$)

$\tilde{\tau}$ lifetime $\sim 10^{1-4}$ sec

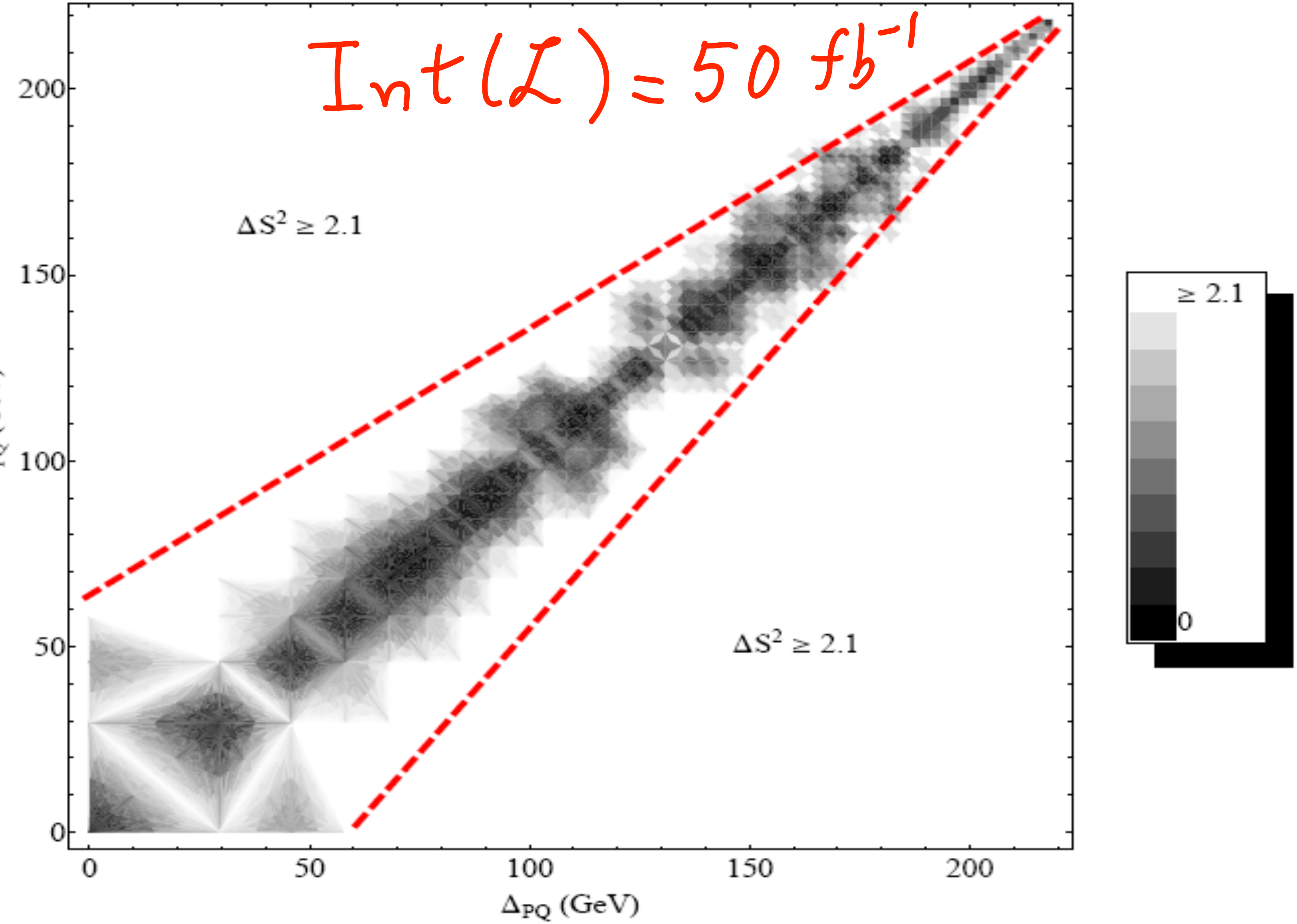
Striking experimental signature: Charged track leaving the detector!

How to distinguish from ordinary GMSB?

	Signature List D
1	$\geq 4\text{jets}(P_T > 100, 50, 50, 50)$
2	$\geq 4\text{jets}(P_T > 250, 250, 100, 100)$
3	$\geq 2\text{jets}(P_T > 350, 350)$
4	$\geq 6\text{jets}(P_T > 150, 150, 100, 100, 50, 50)$
5	$0\tau(P_T > 20), \geq 4\text{jets}(P_T > 100, 50, 50, 50)$
6	$1\tau(P_T > 40), \geq 4\text{jets}(P_T > 100, 50, 50, 50)$
7	$1b(P_T > 50), \geq 4\text{jets}(P_T > 100, 50, 50, 50)$
8	$0l(P_T > 10), \leq 4\text{jets}(P_T > 50)$, $M_{eff} > 1400$
9	$0l(P_T > 10)$, $\leq 4\text{jets}(P_T > 50)$, $M_{eff} > 1400$, $M_{inv}(\text{jets}) > 800$
10	$0l(P_T > 10)$, $\geq 5\text{jets}(P_T > 50)$, $M_{eff} > 1400$
11	$0l(P_T > 10)$, $\geq 5\text{jets}(P_T > 50)$, $M_{eff} > 800$, $P_T(\text{4th hardest jet}) > 140$
12	$\geq 1l(P_T > 10)$, $\geq 5\text{jets}(P_T > 50)$, $M_{eff} > 1400$
13	$\geq 1l(P_T > 10)$, $\geq 5\text{jets}(P_T > 50)$, $0.1 < \not{E}_T/M_{eff} < 0.3$



Int ($\mathcal{L}$) = 5 fb^{-1}
$\Delta S^2 \geq 2.1$
$\Delta S^2 \geq 2.1$
Δ_{PQ} (GeV)
Δ_{PQ} (GeV)
0
50
100
150
200
≥ 2.1
0



Int(ℒ) = 50 fb⁻¹
ΔS² ≥ 2.1
ΔS² ≥ 2.1
≥ 2.1
0
200
150
100
50
0
0
50
100
150
200
Δ_PQ (GeV)

Of course, it is a risky business making experimental predictions that are about to be tested!

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But it is also a lot of fun!