F-theory phenomenology

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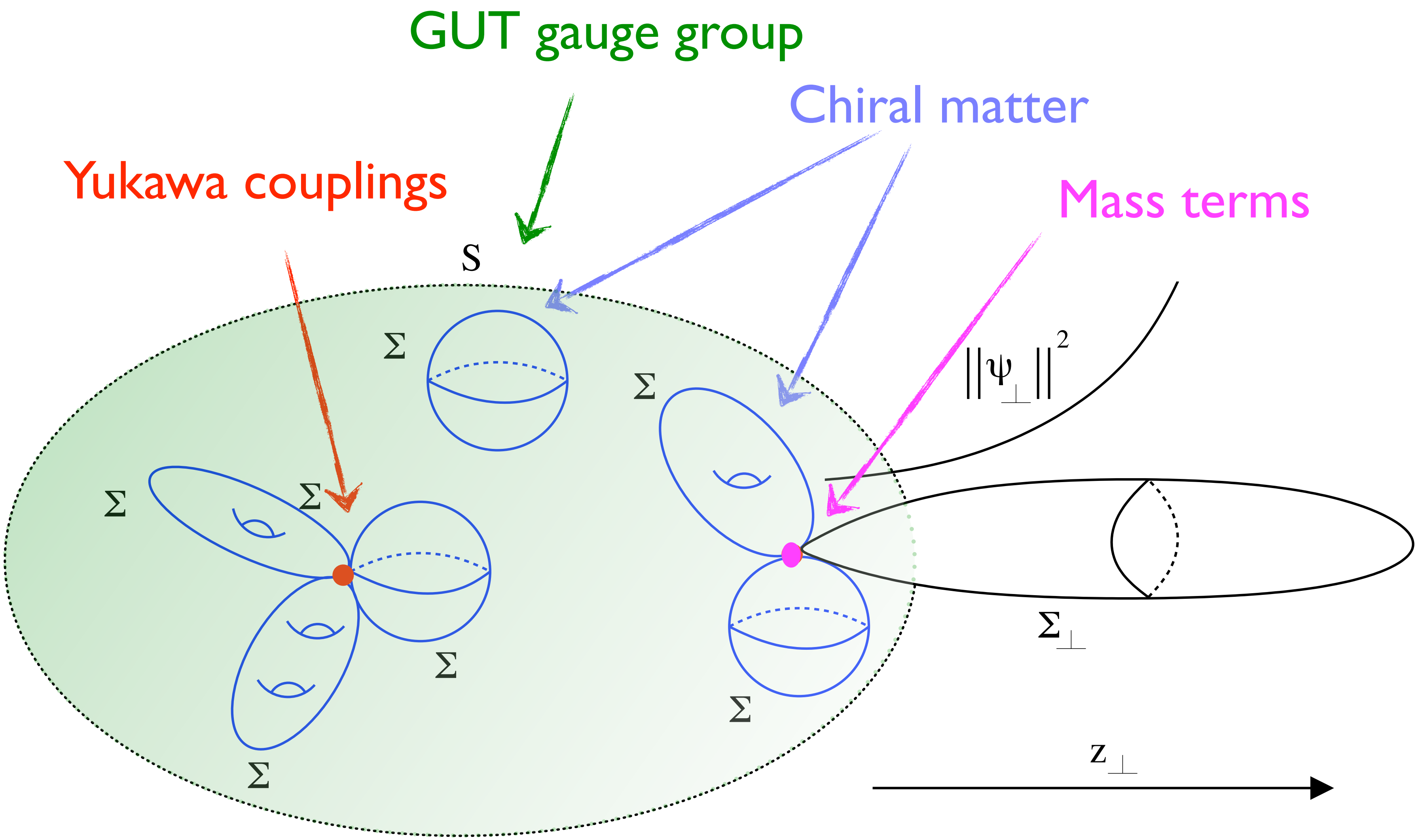
Block II:
From GUTs to the MSSM

GUT's from F-theory

- We have just seen how to engineer a 4D GUT local model via F-theory, and to achieve a number of essential model building ingredients



GUT's from F-theory

- We have just seen how to engineer a 4D GUT local model via F-theory, and to achieve a number of essential model building ingredients
- However, it remains to be seen if we can obtain acceptable physics below M_{GUT}
- In particular, in the range $M_{\not{SUSY}} << M << M_{GUT}$ we would like to have

SM gauge group

MSSM matter content

No exotic matter

Acceptable Yukawas and μ-term

Acceptable proton lifetime → R-parity
→ No 5D & 6D operators (No Higgs triplets)

MSSM from GUT's

- In the following we will see how F-theory GUT's can realize all these phenomenological features
- We will also see that each item in our "wish list" translates into a topological or geometrical condition to be satisfied by our model
- In fact, such geometrical picture will provide new mechanisms to deal with typical problems that arise in classical 4D field theory GUT models

Bibliography:

Beasley, Heckman, Vafa - 0806.0102

Donagi & Wijnholt - 0808.2223

Font & Ibáñez - 0811.2157

Basic Assumptions

- $M_{GUT} << M_{Planck}$, and in principle there is the limit $M_{GUT}/M_{Planck} \to 0$

  Hence, we can formally decouple gravity from our gauge theory, as usually assumed in 4D field theory GUT model building

- $M_{GUT} >> M_{SUSY}$ (~ TeV)

  At this level of the construction everything is supersymmetric (see next block for SUSY-breaking)

Decoupling Limit

- $M_{GUT} << M_{Planck}$, and in principle there is the limit $M_{GUT}/M_{Planck} \to 0$

  Hence, we can formally decouple gravity from our gauge theory, as usually assumed in 4D field theory GUT model building

  - This implies that the volume of the 4-cycle S and the volume of the compact manifold B_3 are not linked, so that we can take $M_{Planck} \to \infty$ while keeping M_{GUT} fixed

  - This imposes a strong constraint on S, namely that it should be a del Pezzo surface dP_N

$G_{GUT} \to G_{MSSM}$ breaking

- An important question is how the gauge group G_{GUT} is broken down to G_{MSSM} = SU(3) x SU(2) x $U(1)_Y$ below M_{GUT}
- In usual 4D GUT's this is essentially realized via adjoint Higgsing

$$SU(5) \xrightarrow{24} SU(3) \times SU(2) \times U(1) \xrightarrow{5} SU(3) \times U(1)_{em}$$

$$\langle \Phi \rangle = \mathrm{diag}(2V, 2V, 2V, -3V, -3V), \quad \langle H \rangle = (0,0,0,0,v)^t$$

SO(10) ⟶ SU(3) x SU(2) x U(1)

SO(10) ⟶ SU(5) x U(1) ⟶ SU(3) x SU(2) x U(1)

SO(10) ⟶ SU(3) x $SU(2)_L$ x $SU(2)_R$ x $U(1)_{B-L}$ ⟶ SU(3) x SU(2) x U(1)

$$\Downarrow$$

We need a field Φ in the adjoint of G_{GUT}
as well as a way to generate a potential for it

$G_{GUT} \rightarrow G_{MSSM}$ breaking

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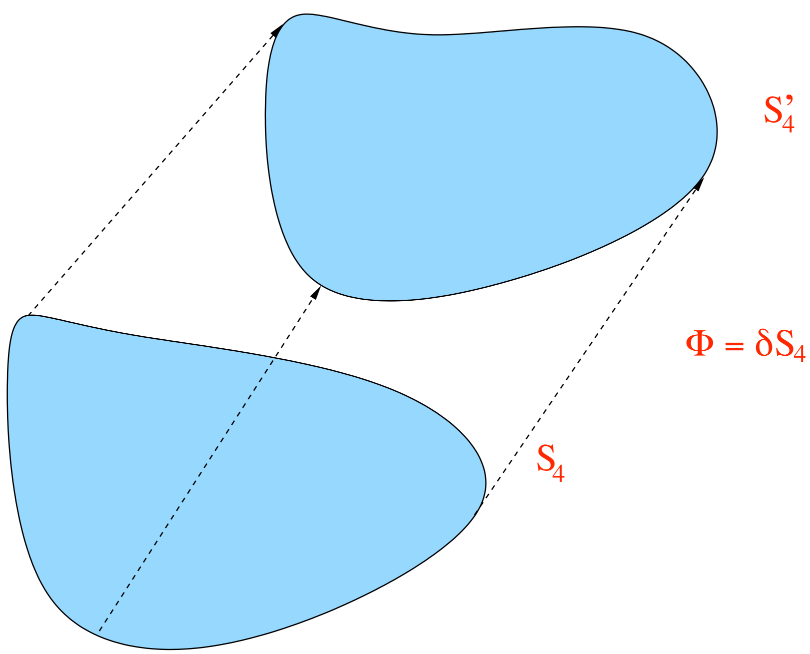
- In usual 4D GUT's this is essentially realized via adjoint Higgsing
- Just like for a D7-brane wrapping a 4-cycle S, adjoint fields appear if

$h^{(0,1)}(S) \neq 0 \Rightarrow$ Wilson lines

No potential

$h^{(0,2)}(S) \neq 0 \Rightarrow$ Geometric deformations of S



Potential generated by background fluxes

$G_{GUT} \rightarrow G_{MSSM}$ breaking

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- Just like for a D7-brane wrapping a 4-cycle S, adjoint fields appear if

  $h^{(0,1)}(S) \neq 0 \Rightarrow$ Wilson lines

  $h^{(0,2)}(S) \neq 0 \Rightarrow$ Geometric deformations of S

  - However, for a del Pezzo surface $h^{(0,1)} = h^{(0,2)} = 0 \Rightarrow$ No adjoints

$$\Downarrow$$

The usual 4D GUT model is incompatible with decoupling gravity

$G_{GUT} \rightarrow G_{MSSM}$ breaking

- An important question is how the gauge group G_{GUT} is broken down to $G_{MSSM} = SU(3) \times SU(2) \times U(1)_Y$ below M_{GUT}

- Adjoint Higgsing ✗

- An alternative mechanism relies on turning on discrete Wilson lines, available whenever $h^{(0,1)}(S) = 0$ but $\pi_1(S) \neq 0$

  - However for S = del Pezzo $\pi_1(S) = 0 \Rightarrow$ No discrete Wilson lines

$G_{GUT} \rightarrow G_{MSSM}$ breaking

- An important question is how the gauge group G_{GUT} is broken down to G_{MSSM} = SU(3) x SU(2) x $U(1)_Y$ below M_{GUT}

- Adjoint Higgsing ✗

- Discrete Wilson lines ✗

- Finally, one can turn on a $F_{U(1)}$ flux along S, so that G_{new} = [G_{GUT},U(1)]

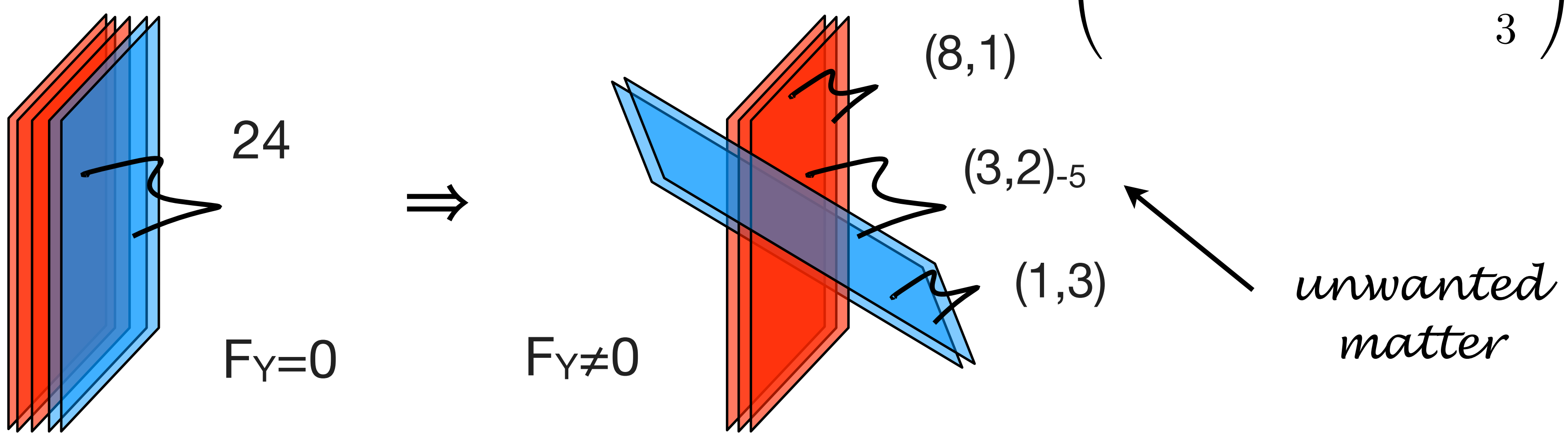
    - In particular SU(5) $\xrightarrow{F_Y}$ SU(3) x SU(2) x $U(1)_Y$

$$F_Y = \begin{pmatrix} -2 & & & & \\ & -2 & & & \\ & & -2 & & \\ & & & 3 & \\ & & & & 3 \end{pmatrix}$$

$G_{GUT} \to G_{MSSM}$ breaking

- An important question is how the gauge group G_{GUT} is broken down to G_{MSSM} = SU(3) x SU(2) x U(1)$_Y$ below M_{GUT}
- Adjoint Higgsing ✗
- Discrete Wilson lines ✗
- Finally, one can turn on a $F_{U(1)}$ flux along S, so that $G_{new} = [G_{GUT}, U(1)]$
  - In particular SU(5) $\xrightarrow{F_Y}$ SU(3) x SU(2) x U(1)$_Y$
  - Dual picture of intersecting D-branes

$$F_Y = \begin{pmatrix} -2 & & & & \\ & -2 & & & \\ & & -2 & & \\ & & & 3 & \\ & & & & 3 \end{pmatrix}$$



$G_{GUT} \to G_{MSSM}$ breaking

- An important question is how the gauge group G_{GUT} is broken down to $G_{MSSM} = SU(3) \times SU(2) \times U(1)_Y$ below M_{GUT}
- Adjoint Higgsing ✗
- Discrete Wilson lines ✗
- Hypercharge flux F_Y ✔

Caveats:

- If F_Y couples to RR bulk fields, $U(1)_Y$ will get a Stückelberg mass
- In general F_Y will generate reps. $(\bar{3},2)_5$, $(3,\bar{2})_{-5}$ that mediate proton decay
- Just as F_Y modifies the gauge group on S, it can modify the matter content on $\Sigma \Rightarrow$ we could induce MSSM exotics

Massless Hypercharge

- In type IIB, a D7-brane with gauge group U(1) contains the coupling

$$\int_{\mathbb{R}^{1,3}\times S} F^2 \wedge C_4 = \sum_i \int_{\mathbb{R}^{1,3}} F \wedge B_2^i \int_S F_{U(1)} \wedge \alpha_2^i$$

where α_2 are harmonic forms of the bulk. If $\int_S (^i) \neq 0$ for any i, the 4D coupling renders the U(1) massive via a Stückelberg mechanism

- One can achieve that $\int_S (^i) = 0 \ \forall$ i, by taking the P.D.($F_{U(1)}$) a non-trivial 2-cycle of S which is nevertheless trivial in the homology of B_3

Buican et al. - hep-th/0610007

- The same happens in F-theory, so a viable F-theory GUT model is based on a del Pezzo surface $S \subset B_3$, where some 2-cycles of S are trivial in B_3

- Such setup is impossible if $B_3 \xrightarrow{\mathbb{P}^1} S$ $\Rightarrow$

No obvious heterotic dual

Avoiding Exotics

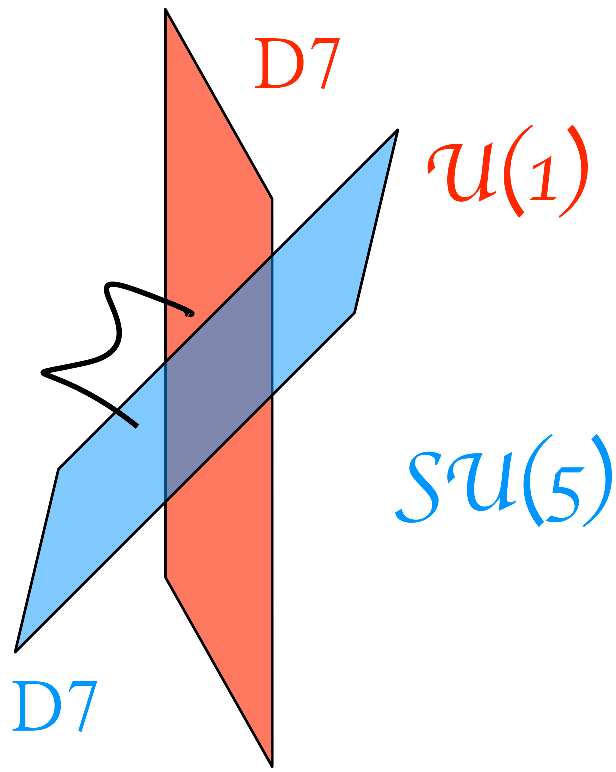
- An extra condition is that no $(3,2)_{-5} + (\bar{3},2)_{5}$ should appear upon introducing F_Y, not even in vector-like pairs, since that could mediate proton decay

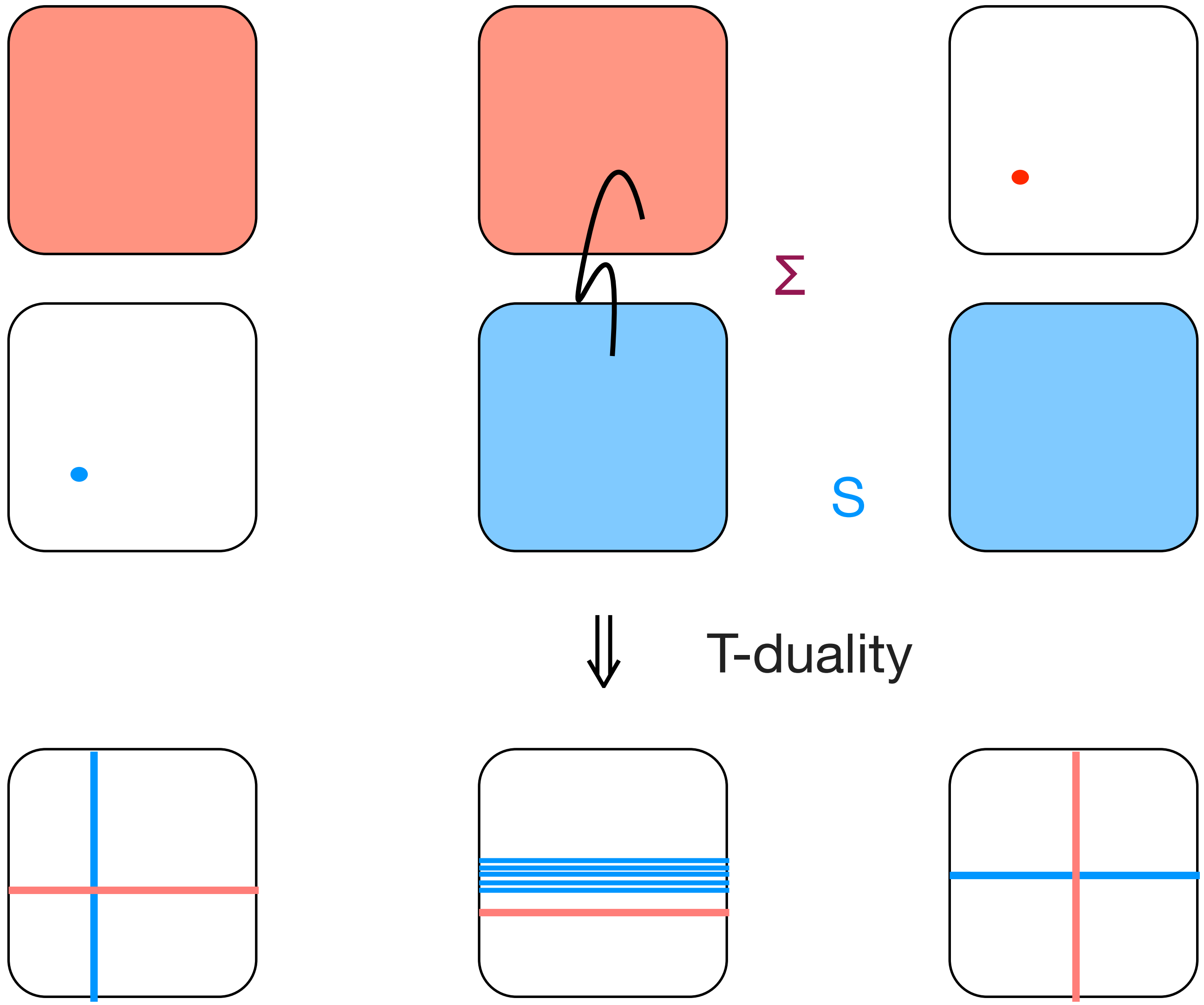
- In terms of the topology of dP_N, this means that $5F_Y$ must live in a specific set of $H_2(dP_N,Z)$, that correspond to the simple roots of the Lie algebra E_N ⇒ N choices

- It turns that $F_Y \notin H_2(dP_N,Z)$ but only $5F_Y$ does. This is not incompatible with Dirac quantization, since all the fields are also charged under some extra U(1)'s that should be turned on for consistency

Avoiding Triplets

- In flat space:





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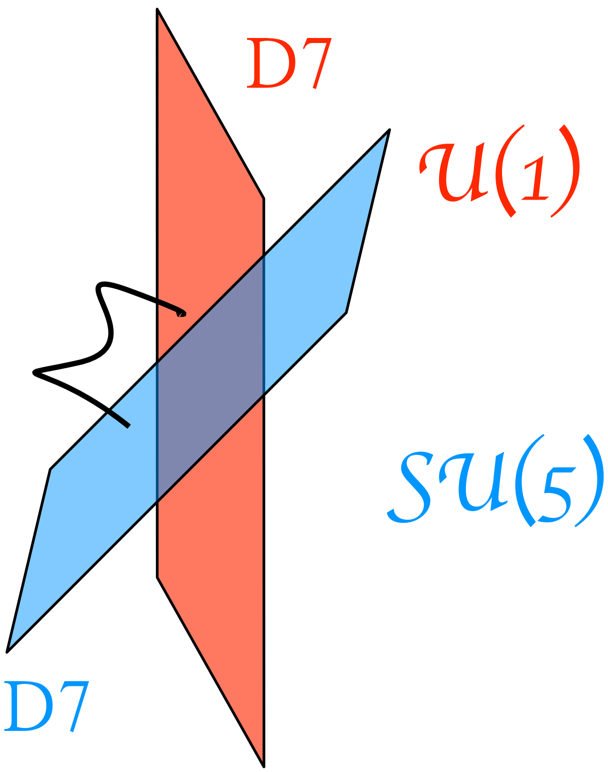

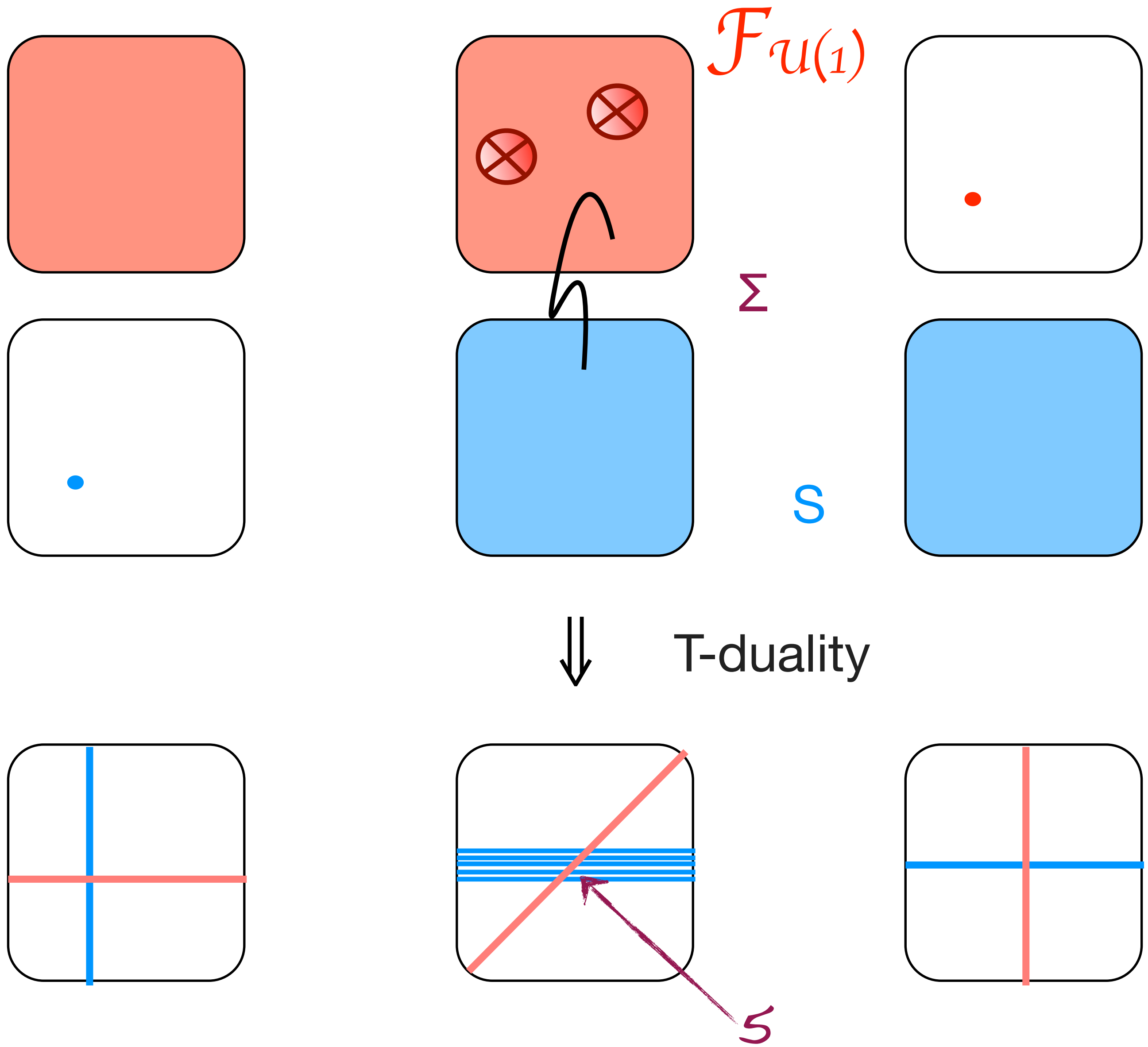

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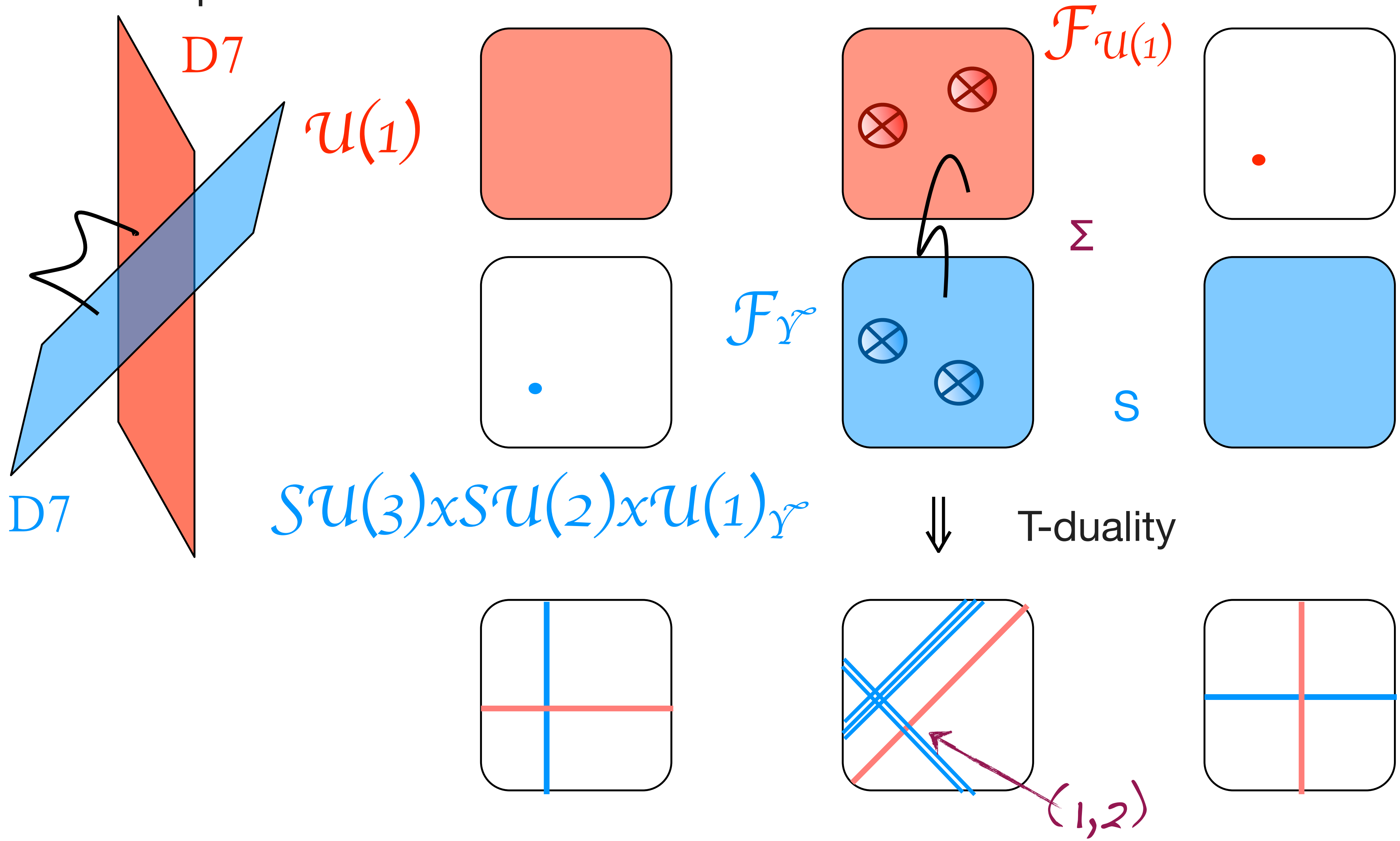


Avoiding Exotics

- In general, whenever $\int_\Sigma F_Y \neq 0$, Σ will no longer contain full GUT multiplets

- This can be positive for the Higgs curve Σ_H, since we may get rid of the triplet Higgsses, but potentially dangerous for the rest of the matter curves, since no exotics are contained there

- Indeed, for SU(5) each family = 10 + $\bar{5}$ ⇒ anomaly free combination

$$\bar{5} = \begin{pmatrix} d_R^1 \\ d_R^2 \\ d_R^3 \\ e \\ \nu_e \end{pmatrix}, \qquad 10 = \begin{pmatrix} 0 & u_R^3 & -u_R^2 & u_L^1 & d_L^1 \\ & 0 & u_R^1 & u_L^2 & d_R^2 \\ & & 0 & u_L^3 & d_L^3 \\ & & & 0 & e_R \\ & & & & 0 \end{pmatrix}$$

- For SO(10):

$$16 = (\nu_L, u_L^1, u_L^2, u_L^3; e_L, d_L^1, d_L^2, d_L^3; d_R^3, d_R^2, d_R^1, e_R; u_R^3, u_R^2, u_R^1, \nu_R)$$

Avoiding Exotics

- In general, whenever $\int_{\Sigma} F_Y \neq 0$, Σ will no longer contain full GUT multiplets

- This can be positive for the Higgs curve Σ_H, since we may get rid of the triplet Higgsses, but potentially dangerous for the rest of the matter curves, since no exotics are contained there

- A simple way to avoid exotics is then to impose

$$\int_{\Sigma_H} F_Y \neq 0 \qquad \text{For the Higgs curve}$$

$$\int_{\Sigma_i} F_Y = 0 \qquad \text{For the matter curves}$$

  ➡ allows to define R-parity in terms of the flux G_4

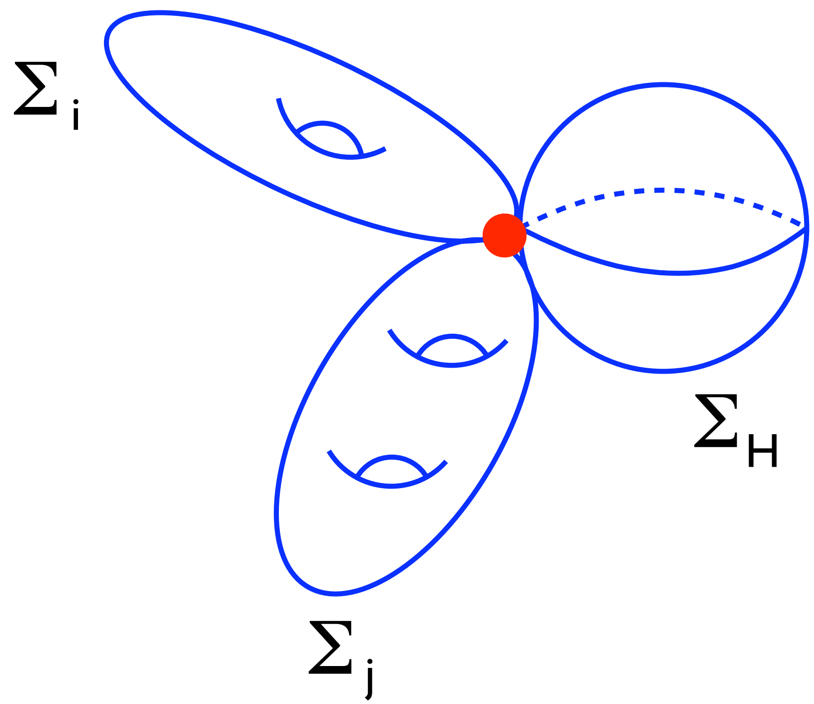
  ➡ favors that H_u and H_d arise from different curves Σ_H, which in turn suppresses 5D operators violating Baryon number

Yukawas and textures

- In the simplest GUT models, all MSSM matter localizes on curves
- Hence all Yukawas arise from triple intersections
- As each curve typically contains a different family of (up-like) quarks, we find a texture of the form

$$\lambda^u_{ij} = \begin{pmatrix} 0 & A & B \\ A & 0 & C \\ B & C & 0 \end{pmatrix}$$

that rather suggests one light family and two heavy ones



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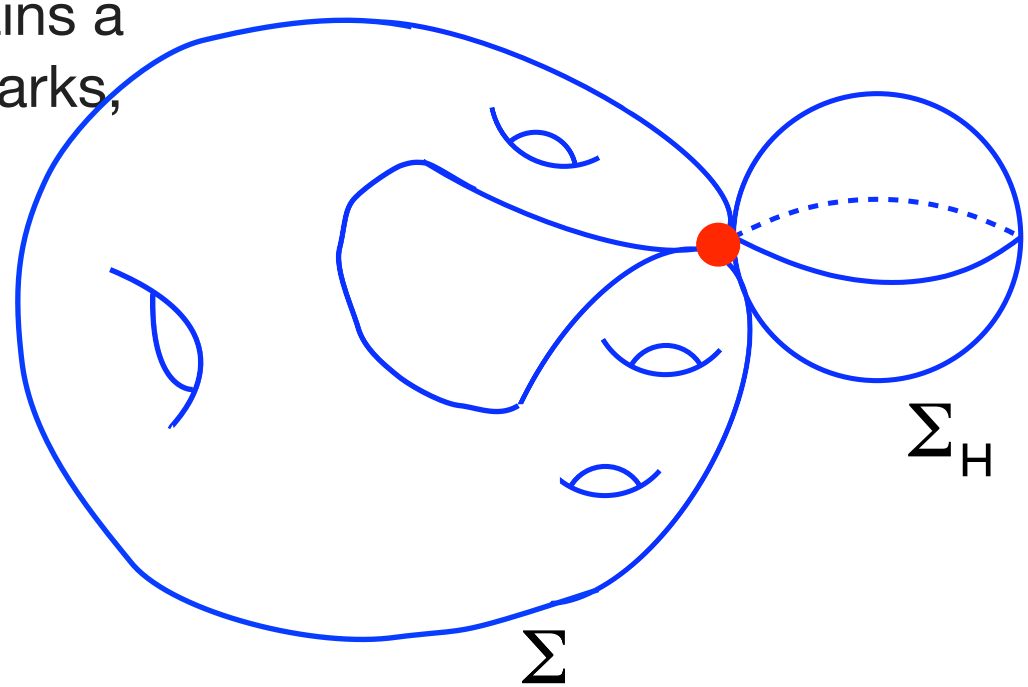


- A possibility to allow diagonal entries is to consider self-intersecting curves

Yukawas and textures

- In the simplest GUT models, all MSSM matter localizes on curves
- Hence all Yukawas arise from triple intersections
- Another possibility is to weaken the condition

$$\int_{\Sigma_i} F_Y = 0 \quad \forall i \qquad \text{to} \qquad \sum_i \int_{\Sigma_i} F_Y = 0$$

Ibáñez & Font - 0811.2157

- If this is done, each matter curve Σ_i will not contain the usual GUT multiplets, but those will be unequally distributed among all the curves
- The total spectrum is however the same and the Yukawas present more interesting textures. Neat example: SO(10) model

quarks

$$\lambda^Q_{ij} \sim \begin{pmatrix} x & x & 0 \\ x & x & 0 \\ 0 & 0 & x \end{pmatrix}$$

leptons

$$\lambda^l_{ij} \sim \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

Yukawas and textures

- In conventional 4D GUT's there are very few independent Yukawas

$$L_{YUK}^{SU(5)} = Y_U^{ij}\bar{\psi}_{10}^{i}\psi_{10}^{j}H_{\bar{5}}^{*} + Y_{D,L}^{ij}\bar{\psi}_{\bar{5}}^{i}\psi_{10}^{j}H_{\bar{5}} + h.c.$$

  - $Y_D(M_{GUT}) = Y_L(M_{GUT})$
  - At M_{EW} : $m_b/m_\tau \sim 3$ (good for the 3rd family, bad for 1st and 2nd)
  - For SO(10) there is only one Yukawa coupling

- In models with extra dimensions we have more freedom.
  In the case at hand:

$$m_Q = m_l \left| \frac{\psi_Q(0)}{\psi_l(0)} \right| \longleftarrow$$

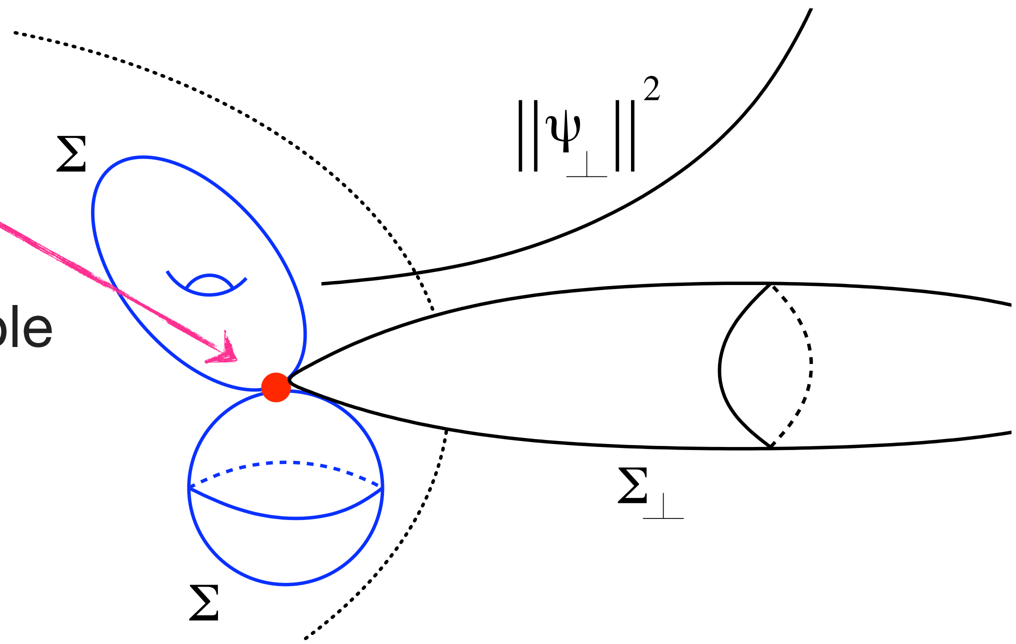
different ψ's expected from different hyperch.

- Such discrepancy will in average be bigger for larger Vol(Σ), which usually contain the lightest generations!!

Further couplings

- Another important class of cubic couplings are those that involve a singlet Φ under G_{GUT}

$$W_\perp = \lambda \Phi X Y$$



- Such singlet lives in a curve transverse to S and in principle will be a non-dynamical field

Example: μ-term

$$W_\mu = \lambda\,\Phi H_u H_d$$

- This coupling will be enhanced or suppressed depending on the behavior of the singlet wavefunction near S

Singlet wavefunctions

- Singlet wavefunctions satisfy the following Laplace equation in the coordinate *z* transverse to S

$$4\,\frac{\partial^2\psi}{\partial z\partial\bar{z}} = \left(\frac{1}{2}\mathcal{R} - \mathcal{F}\right)\psi \qquad \Rightarrow \qquad \psi = e^{\frac{1}{4}\left(\frac{1}{2}\mathcal{R}-\mathcal{F}\right)|z|^2} + \ldots$$

- In this frame the norm of ψ is given by

$$||\psi||^2 = M_*^2 \int_{\Sigma_\perp} e^{2\phi(z,\bar{z})}|\psi|^2 \qquad e^{2\phi(z,\bar{z})}|\psi|^2 \sim e^{-\frac{1}{2}\left(\frac{1}{2}\mathcal{R}+\mathcal{F}\right)|z|^2}$$

$$\mathcal{R} \sim -M_{GUT}^2$$

$$\mathcal{F} \sim \pm\mathrm{Vol}^{-1}(\Sigma_X) \pm \mathrm{Vol}^{-1}(\Sigma_Y) \sim \pm M_{GUT}^2$$

➡ Everything depends on the sign of $\mathcal{F} + \mathcal{R}/2$

- positive ⇒ coupling enhancement ⇒ $||\psi||^2 \sim M_*^2/M_{GUT}^2$
- negative ⇒ coupling suppression (μ-term)