Mirror Mediation

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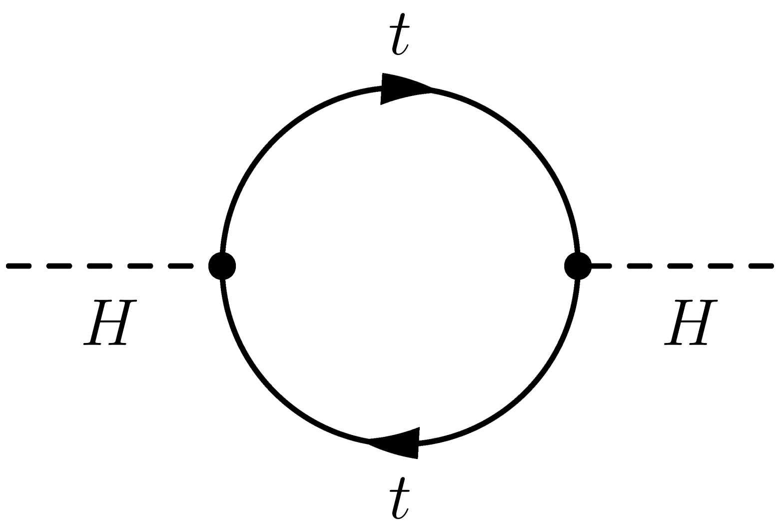
Talk Structure

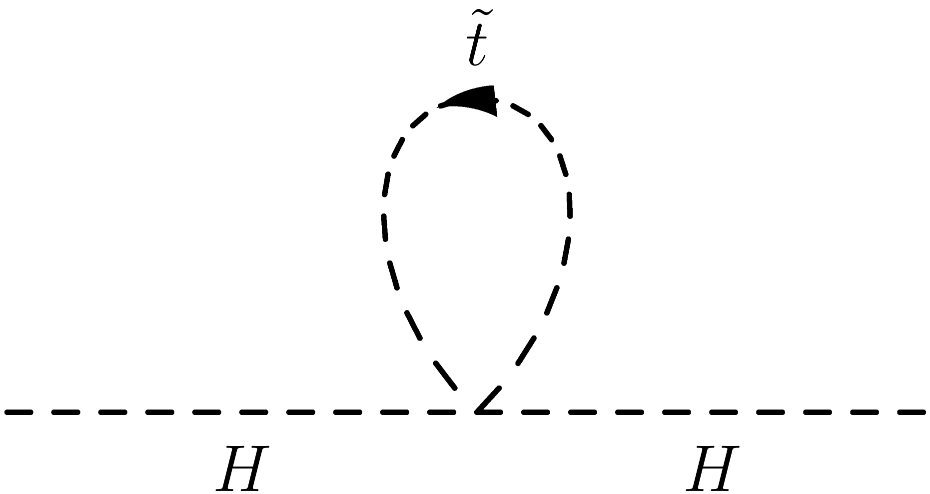
- Supersymmetry and the MSSM Flavour Problem
- Flavour Universality in Effective Field Theory
- Flavour Universality in String Theory
- Moduli Stabilisation
- Conclusions

Supersymmetry

Supersymmetry is a great solution to the gauge hierarchy problem:



$$\sim \quad \Lambda^2$$



$$\sim \quad -\Lambda^2$$

Supersymmetry

TeV supersymmetry

- stabilises the Higgs mass against radiative corrections
- gives a good dark matter candidate
- explains gauge symmetry breaking through radiative electroweak symmetry breaking
- is compatible with LEP I precision electroweak data
- is a principal candidate for new physics discovered at the LHC

Supersymmetry

The MSSM soft Lagrangian is $\mathcal{L}_{soft} = \mathcal{L}_{susy} +$

$$\frac{1}{2}[M_3 \lambda_{\tilde{g}} \lambda_{\tilde{g}} + M_2 \tilde{W}^a \tilde{W}^a + M_1 \tilde{B} \tilde{B} + h.c.] + \epsilon_{\alpha\beta}[-b H_d^\alpha H_u^\beta$$
$$-H_u^\alpha \tilde{Q}_i^\beta \tilde{A}_{uij} \tilde{U}_j^c + H_d^\alpha \tilde{Q}_i^\beta \tilde{A}_{dij} \tilde{D}_j^c + H_d^\alpha \tilde{L}_i^\beta \tilde{A}_{eij} \tilde{E}_j^c + h.c.]$$
$$+m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \tilde{Q}_i^\alpha m_{Qij}^2 \tilde{Q}_j^{\alpha *}$$
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Susy is explicitly broken by:

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trilinear scalar A-terms $A_{ijk} \phi^i \phi^j \phi^k$, B-term $b \epsilon_{\alpha\beta} H_u^\alpha H_d^\beta$.

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Why haven't its effects shown up already?

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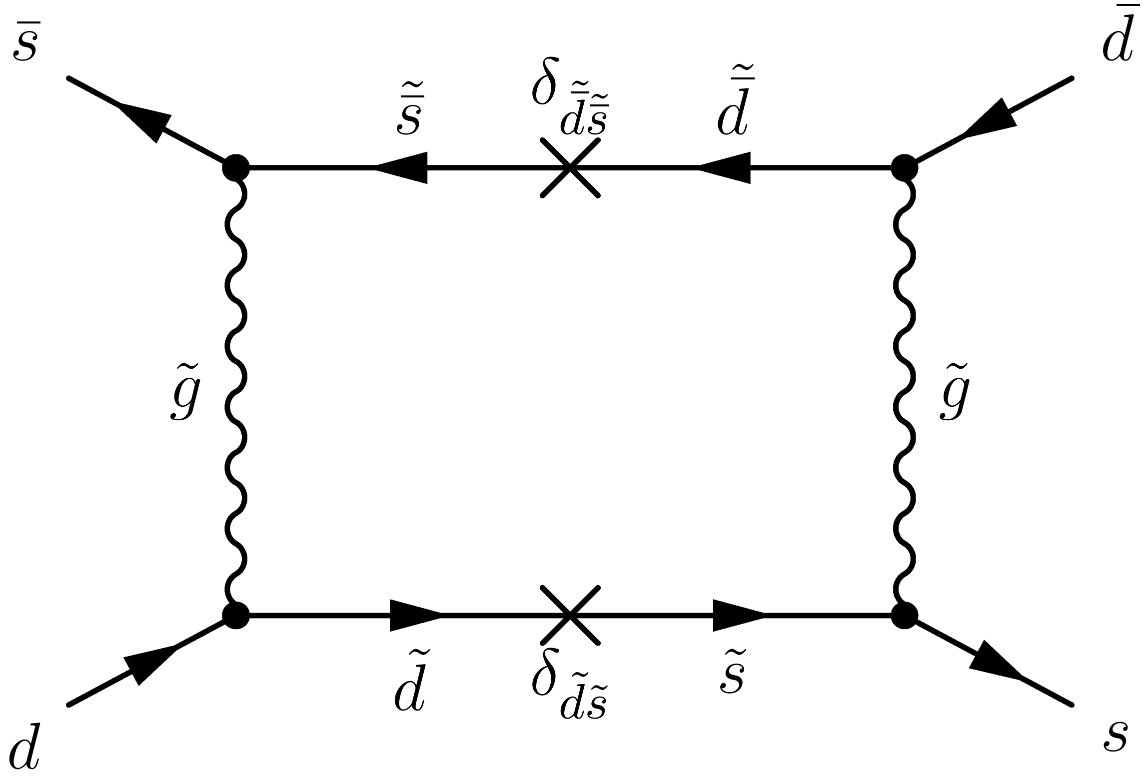
- The c quark - predicted before discovery through its contribution to FCNCs (the GIM mechanism)
- The t quark - mass predicted accurately through loop contributions at LEP I.

Why haven't we seen SUSY effects?

The MSSM Flavour Problem



The MSSM gives new contributions to $K_0 - \bar{K}_0$ mixing.

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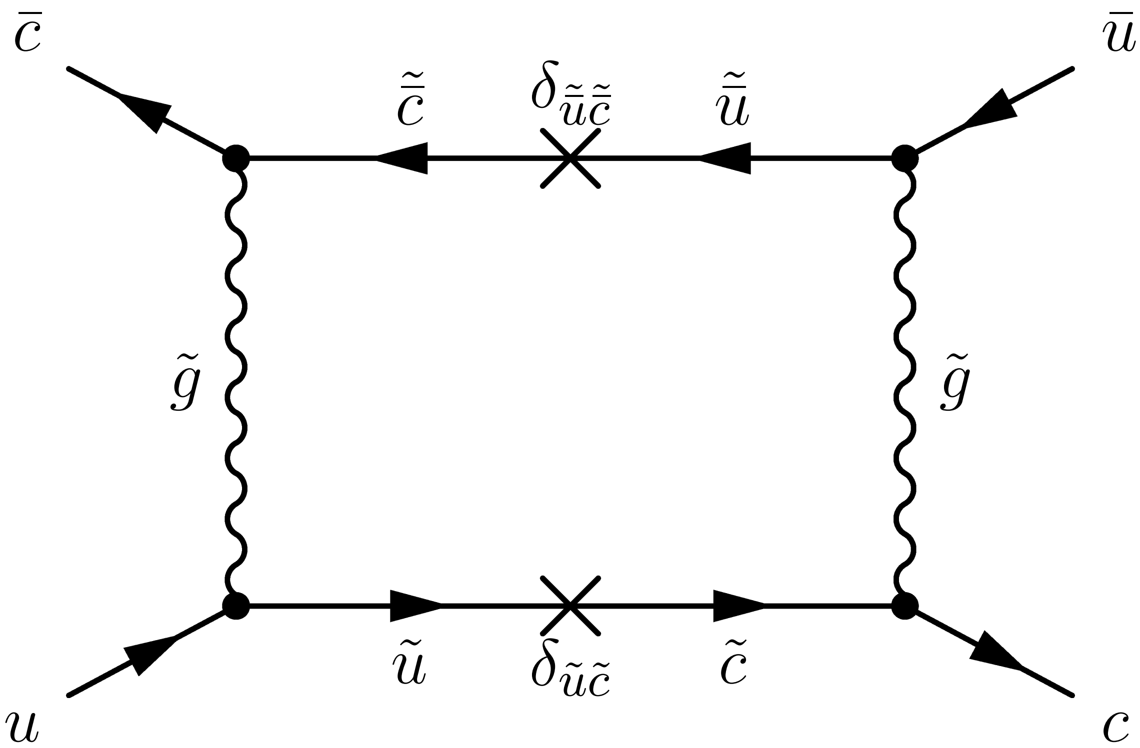

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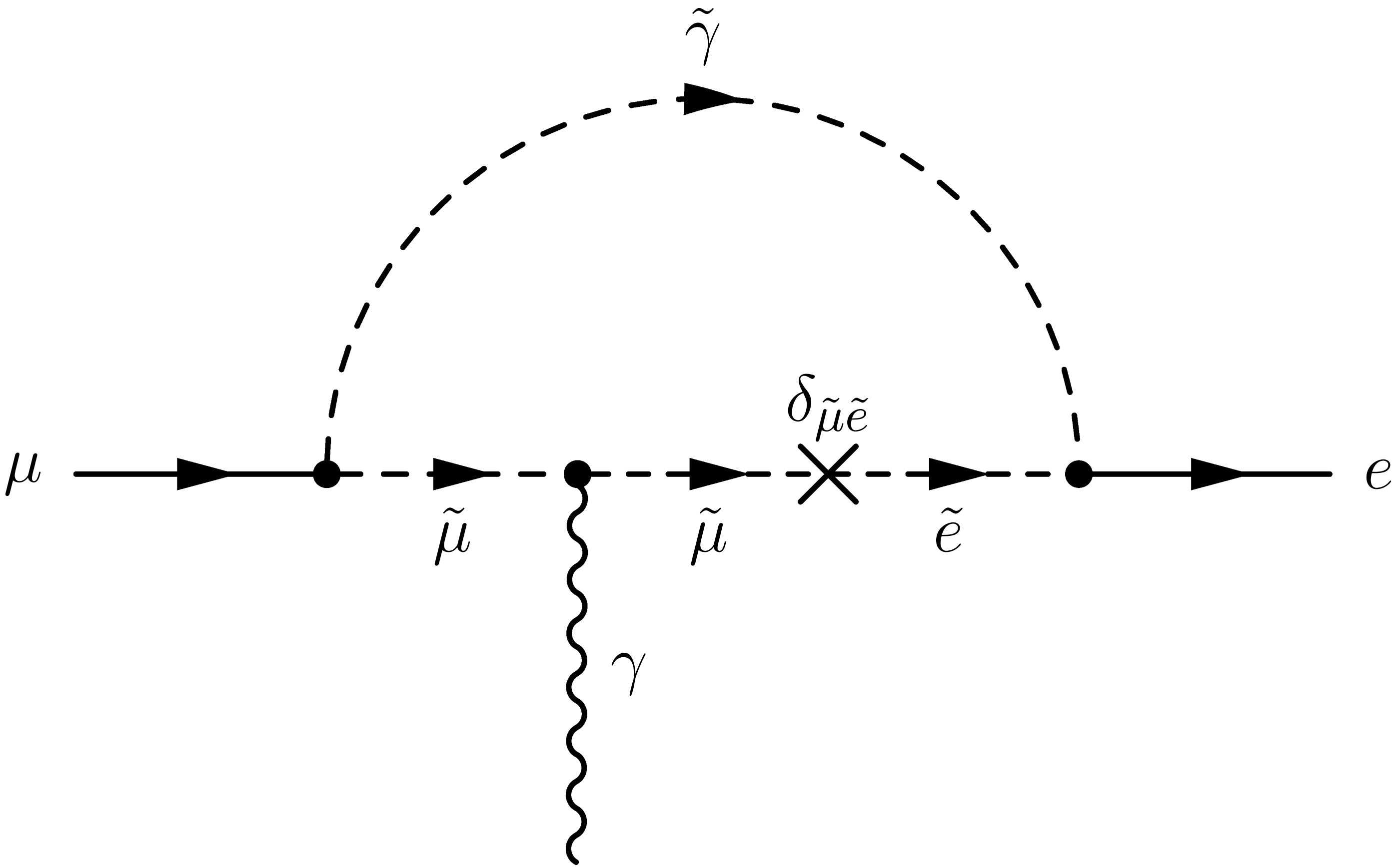

The MSSM generates new contributions to $BR(\mu \to e\gamma)$.

The MSSM Flavour Problem

- Low energy flavour experiments already highly constrain the MSSM parameter space.
- This arises through the requirement of no large new contributions to $K_0 - \bar{K}_0$ mixing, $D_0 - \bar{D}_0$ mixing, $BR(\mu \rightarrow e\gamma)$....
- New TeV particles with generic couplings would have showed up already in violations from SM measurements

Universality in Effective Field Theory

SUSY does not generate large new FCNCs provided the soft terms are flavour universal.

Soft terms must be family-independent and insensitive to flavour.

For flavour universality, we require

$$\begin{aligned} m^2_{Q,\alpha\bar{\beta}} &= m^2_Q \tilde{K}_{\alpha\bar{\beta}}, \\ A_{\alpha\beta\gamma} &= A Y_{\alpha\beta\gamma}, \\ \phi_{M_1} &= \phi_{M_2} = \phi_{M_3} = \phi_A. \end{aligned}$$

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Universal scalar masses, A-terms proportional to the Yukawa couplings, gaugino mass phases are aligned.

Universality in Effective Field Theory

Why should this happen?

- One proposal - gauge mediated supersymmetry breaking.

  Unfortunately this generates many other phenomenological problems ($\mu/B\mu$ problem, additional hierarchies required...).

- In this talk we look at the structure of soft terms arising within supergravity and string compactifications.

Universality in Effective Field Theory

- To compute soft terms, we expand K and W in powers of matter fields C^α and moduli fields Φ,

$$\begin{aligned} W &= \hat{W}(\Phi) + \mu(\Phi) H_1 H_2 + \frac{1}{6} Y_{\alpha\beta\gamma}(\Phi) C^\alpha C^\beta C^\gamma + \ldots, \\ K &= \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi}) C^\alpha C^{\bar{\beta}} + [Z H_1 H_2 + h.c.] + \ldots, \\ f_a &= f_a(\Phi). \end{aligned}$$

- To compute soft terms, need to know $\tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi})$, $Y_{\alpha\beta\gamma}(\Phi)$ and $f_a(\Phi)$.

Universality in Effective Field Theory

Soft scalar masses $m^2_{i\bar{j}}$ and trilinears $A_{\alpha\beta\gamma}$ are given by

$$
\begin{aligned}
\tilde{m}^2_{\alpha\bar{\beta}} &= (m^2_{3/2}+V_0)\tilde{K}_{\alpha\bar{\beta}} \\
&\quad -\bar{F}^{\bar{m}}F^n\left(\partial_{\bar{m}}\partial_n\tilde{K}_{\alpha\bar{\beta}}-(\partial_{\bar{m}}\tilde{K}_{\alpha\bar{\gamma}})\tilde{K}^{\bar{\gamma}\delta}(\partial_n\tilde{K}_{\delta\bar{\beta}})\right) \\
A'_{\alpha\beta\gamma} &= e^{\hat{K}/2}F^m\Big[\hat{K}_m Y_{\alpha\beta\gamma}+\partial_m Y_{\alpha\beta\gamma} \\
&\quad -\Big((\partial_m\tilde{K}_{\alpha\bar{\rho}})\tilde{K}^{\bar{\rho}\delta}Y_{\delta\beta\gamma}+(\alpha\leftrightarrow\beta)+(\alpha\leftrightarrow\gamma)\Big)\Big]. \\
M_a &= \frac{F^m\partial_m f_a}{\mathrm{Re}(f_a)}
\end{aligned}
$$

Similar expressions hold for μ and $B\mu$.

Universality in Effective Field Theory

Sufficient conditions for flavour universality:

1. Hidden sector factorises

$$\Phi_{hidden} = \Psi_{susy} \oplus \chi_{flavour}.$$

2. The kinetic terms are decoupled

$$\mathcal{K}(\Phi, \bar{\Phi}) = \mathcal{K}_1(\Psi + \bar{\Psi}) + \mathcal{K}_2(\chi, \bar{\chi}),$$

3. The superpotential Yukawas depend only on $\chi_{flavour}$:

$$Y_{\alpha\beta\gamma}(\Psi, \chi) = Y_{\alpha\beta\gamma}(\chi).$$

4. The gauge kinetic functions depend only on Ψ fields:

$$f_a(\Psi, \chi) = \sum_i \lambda_i \Psi_i.$$

Universality in Effective Field Theory

5. The visible metric factorises.

$$\mathcal{K}_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = h(\Psi + \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})$$

6. Ψ breaks susy, χ does not:

$$D_{\Psi_i} W \neq 0, D_{\chi_j} W = 0.$$

If all these assumptions hold, susy breaking generates flavour universal soft terms.

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Totally *ad hoc* in effective field theory!

Universality in Effective Field Theory

$$
\begin{aligned}
\tilde{m}^2_{\alpha\bar{\beta}} &= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} \\
&\quad - \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \left(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} \tilde{K}_{\alpha\bar{\beta}} - (\partial_{\bar{\Psi}_j} \tilde{K}_{\alpha\bar{\gamma}}) \tilde{K}^{\bar{\gamma}\delta} (\partial_{\Psi_i} \tilde{K}_{\delta\bar{\beta}}) \right) \\
&= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} - \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \Bigg(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} h(\Psi, \bar{\Psi}) \\
&\quad - \frac{\partial_{\bar{\Psi}_j} h(\Psi, \bar{\Psi}) \partial_{\Psi_i} h(\Psi, \bar{\Psi})}{h(\Psi, \bar{\Psi})} \Bigg) k_{\alpha\bar{\beta}}(\chi, \bar{\chi}) \\
&= \Bigg((m^2_{3/2} + V_0) h \\
&\quad \bar{F}^{\bar{\Psi}_j} F^{\Psi_i} \left(\partial_{\bar{\Psi}_j} \partial_{\Psi_i} - \frac{\partial_{\bar{\Psi}_j} h \partial_{\Psi_i} h}{h} \right) \Bigg) (\Psi, \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})
\end{aligned}
$$

Universality in Effective Field Theory

$$
\begin{aligned}
A'_{\alpha\beta\gamma} &= e^{\hat{K}/2} F^m \Big[\hat{K}_m Y_{\alpha\beta\gamma} + \partial_m Y_{\alpha\beta\gamma} \\
&\quad - \Big((\partial_m \tilde{K}_{\alpha\bar{\rho}}) \tilde{K}^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \Big) \Big]. \\
&= e^{\hat{K}/2} F^{\Psi_i} \Big[\hat{K}_{\Psi_i} Y_{\alpha\beta\gamma} + \partial_{\Psi_i} Y_{\alpha\beta\gamma} \\
&\quad - \Big(((\partial_{\Psi_i} h) k_{\alpha\bar{\rho}}) h^{-1} k^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \Big) \Big] \\
&= e^{\hat{K}/2} F^{\Psi_i} \Big[\hat{K}_{\Psi_i} + \frac{3\partial_{\Psi_i} h}{h} \Big] (\Psi, \bar{\Psi}) Y_{\alpha\beta\gamma}(\chi),
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\end{aligned}
$$

A-terms proportional to Yukawa couplings!

Universality in Effective Field Theory

$$M_a = \frac{F^m \partial_m (\sum_i \lambda_i \Psi_i)}{\text{Re}(f_a)} = \frac{\sum_i \lambda_i F^{\Psi_i}}{\text{Re}(f_a)}.$$

This has a universal phase so long as the phase of F^{Ψ_i} is universal.

This will occur in flux compactifications.

Universality in String Theory

String theory knows this structure!

- Calabi-Yau moduli space factorises in precisely this fashion.
- Kähler (T) and complex structure (U) moduli have factorised moduli spaces
- $$IIB : \Psi_{susy} \to T, \chi_{flavour} \to U,$$
  $$IIA : \Psi_{susy} \to U, \chi_{flavour} \to T.$$
- In flux compactifications susy breaking factorises:

$$F^T \neq 0, \qquad F^U = 0.$$

Universality in String Theory

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$$\Phi_{hidden} = \Psi_{susy} \bigoplus \chi_{flavour}.$$

$$\Phi_{moduli} = \Psi_{\text{Kähler(T)}} \bigoplus \chi_{\text{complex structure(U)}}.$$

The moduli space of Calabi-Yau manifolds has two distinct, factorised parts: Kähler and complex structure moduli.

Universality in String Theory

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$$\mathcal{K}(\Phi, \bar{\Phi}) = \mathcal{K}_1(\Psi + \bar{\Psi}) + \mathcal{K}_2(\chi, \bar{\chi}),$$

The IIB moduli space Kähler potential is

$$K = -2\ln(\mathcal{V}(T + \bar{T})) - \ln\left(\int \Omega \wedge \bar{\Omega}(U, \bar{U})\right) - \ln(S + \bar{S})$$

The moduli space of Calabi-Yau manifolds has two distinct parts, Kähler and complex structure moduli.

Universality in String Theory

The T fields are defined as

$$T = \int_{\Sigma_4} e^{-\phi}\sqrt{g} + i\int_{\Sigma_4} C_4$$

The imaginary part of T is axionic and T has a perturbative shift symmetry,

$$T \to T + i\epsilon.$$

The shift symmetry is unbroken in both world-sheet (α') and space-time (g_s) perturbation theory.

Perturbative quantities depend only on $(T + \bar{T})$.

Universality in String Theory

Example: T^6

$$
\begin{aligned}
\hat{K} &= -\ln\big((T_1+\bar{T}_1)(T_2+\bar{T}_2)(T_3+\bar{T}_3)\big) \\
&\quad -\ln\big((U_1+\bar{U}_1)(U_2+\bar{U}_2)(U_3+\bar{U}_3)\big) - \ln(S+\bar{S}).
\end{aligned}
$$

In the large-radius limit, Calabi-Yau moduli space factorises exactly into two distinct sectors - Kähler and complex structure moduli.

Universality in String Theory

3. The superpotential Yukawas depend only on $\chi_{flavour}$:

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Perturbativity would require $Y_{\alpha\beta\gamma}(T) \sim T^{\lambda}$.

The shift symmetry $T \rightarrow T + i\epsilon$ forbids this.

In perturbation theory, $Y_{\alpha\beta\gamma}(T, U) = Y_{\alpha\beta\gamma}(U)$.

Universality in String Theory

Example:

For toroidal compactifications, the superpotential Yukawas take the following form,

$$Y_{ijk}(U) = \vartheta \begin{bmatrix} \delta^r_{ijk} \\ 0 \end{bmatrix} (0; U^r I^r_{ab} I^r_{bc} I^r_{ca})$$

- No dependence on T
- A very complicated dependence on U.

Universality in String Theory

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D7 brane gauge kinetic function:

$$f_a = T + h_a(F) S.$$

- No U-dependence
- Linear dependence on T.

Universality in String Theory

5. The visible metric factorises.

$$\mathcal{K}_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = h(\Psi + \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})$$

Universality in String Theory

5. The visible metric factorises.

$$\mathcal{K}_{\alpha\bar{\beta}}(\Psi, \bar{\Psi}, \chi, \bar{\chi}) = h(\Psi + \bar{\Psi}) k_{\alpha\bar{\beta}}(\chi, \bar{\chi})$$

This comes from the universal scaling property of physical Yukawa couplings

$$\hat{Y}_{\alpha\beta\gamma} = e^{\hat{K}/2} \frac{Y_{\alpha'\beta'\gamma'}}{(\tilde{K}_{\alpha\alpha'}\tilde{K}_{\beta\beta'}\tilde{K}_{\gamma\gamma'})^{\frac{1}{2}}}.$$

This arises from the origin of physical Yukawa couplings as due to wavefunction overlap.

Universality in String Theory

Example: For toroidal compactifications, the Kähler metric is

$$K_{ij}^{ab} = \delta_{ij} S^{-1/4} (T^1 T^2 T^3)^{-1/4} \times$$
$$\prod_{I=1}^{3} U_I^{-\left(\frac{1}{2} \pm \frac{1}{2} \mathrm{sign}(\mathrm{I_{ab}}) \theta^{\mathrm{I}}_{\mathrm{ab}}\right)} \left(\frac{\Gamma(\theta^1_{ab}) \Gamma(\theta^2_{ab}) \Gamma(1 - \theta^1_{ab} - \theta^2_{ab})}{\Gamma(1 - \theta^1_{ab}) \Gamma(1 - \theta^2_{ab}) \Gamma(\theta^1_{ab} + \theta^2_{ab})} \right)$$

This has

- At leading order a universal scaling dependence on $(T + \bar{T})$
- Subleading (universal) corrections at $\mathcal{O}(\alpha'^2)$

Universality in String Theory

6. Ψ breaks susy, χ does not:

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$$D_{\Psi_i} W \neq 0, D_{\chi_j} W = 0.$$

- This is a statement about the vacuum structure and is equivalent to $F^T \neq 0, F^U = 0$.
- The T fields break supersymmetry and the U fields do not.
- In IIB flux compactifications it turns out that these conditions are satisfied.

Moduli Stabilisation: Fluxes

- Flux compactifications can generate potentials for the moduli
- Fluxes source an energy density that depends on the size of cycles.
- In IIB, fluxes generate a superpotential

$$W = \int G_3 \wedge \Omega(U)$$

Moduli Stabilisation: Fluxes

$$\hat{K} = -2\ln\left(\mathcal{V}(T+\bar{T})\right) - \ln\left(i\int \Omega\wedge\bar{\Omega}(U)\right) - \ln\left(S+\bar{S}\right),$$

$$W = \int G_3 \wedge \Omega\,(U).$$

$$V = e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W} + \sum_{T}\hat{K}^{i\bar{j}}D_i W D_{\bar{j}}\bar{W} - 3|W|^2\right)$$

$$= e^{\hat{K}}\left(\sum_{U,S}\hat{K}^{\alpha\bar{\beta}}D_\alpha W D_{\bar{\beta}}\bar{W}\right)$$

Stabilise S and U by solving $D_S W = D_U W = 0$.

Moduli Stabilisation: Fluxes

$$\begin{aligned}\hat{K} &= -2\ln\left(\mathcal{V}(T_i+\bar{T}_i)\right)\,,\\ W &= W_0\,.\\ V &= e^{\hat{K}}\left(\sum_T \hat{K}^{i\bar{j}}D_iW D_{\bar{j}}\bar{W} - 3|W|^2\right)\\ &= 0\end{aligned}$$

No-scale model :

- vanishing vacuum energy
- broken susy ($F^T \neq 0, F^U = 0$)
- T unstabilised
- Goldstino is breathing mode $g_{\mu\nu} \to \lambda^2 g_{\mu\nu}$

Moduli Stabilisation: Fluxes

- Susy breaking factorises: $F^T \neq 0, F^U = 0$.

- Goldstino is breathing mode and is manifestly flavour universal.

  The breathing mode modifies the scale, but not the form, of Yukawa couplings.

- A great scenario for susy breaking - but not all moduli are stabilised yet.

Moduli Stabilisation: KKLT

$$\hat{K} = -2\ln(\mathcal{V}),$$
$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Non-perturbative ADS superpotential.
- T-moduli are stabilised by solving $D_T W = 0$.
- Minimum is supersymmetric - extra energy is now needed in order to uplift and break susy.
- No hierarchy in $m_{3/2}$.

Moduli Stabilisation: Large-Volume

$$\hat{K} = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right),$$
$$W = W_0 + \sum_i A_i e^{-a_i T_i}.$$

- Add the leading α' corrections to the Kähler potential.
- This leads to dramatic changes in the scalar potential at large volumes.
- A new minimum of the scalar potential appears at exponentially large volume.

Moduli Stabilisation: Large-Volume

The simplest model $\mathbb{P}^4_{[1,1,1,6,9]}$ has two Kähler moduli.

$$\mathcal{V} = \left(\frac{T_b + \bar{T}_b}{2}\right)^{3/2} - \left(\frac{T_s + \bar{T}_s}{2}\right)^{3/2} \equiv \left(\tau_b^{3/2} - \tau_s^{3/2}\right).$$

If we compute the scalar potential, we get for $\mathcal{V} \gg 1$,

$$V = \frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

Moduli Stabilisation: Large-Volume

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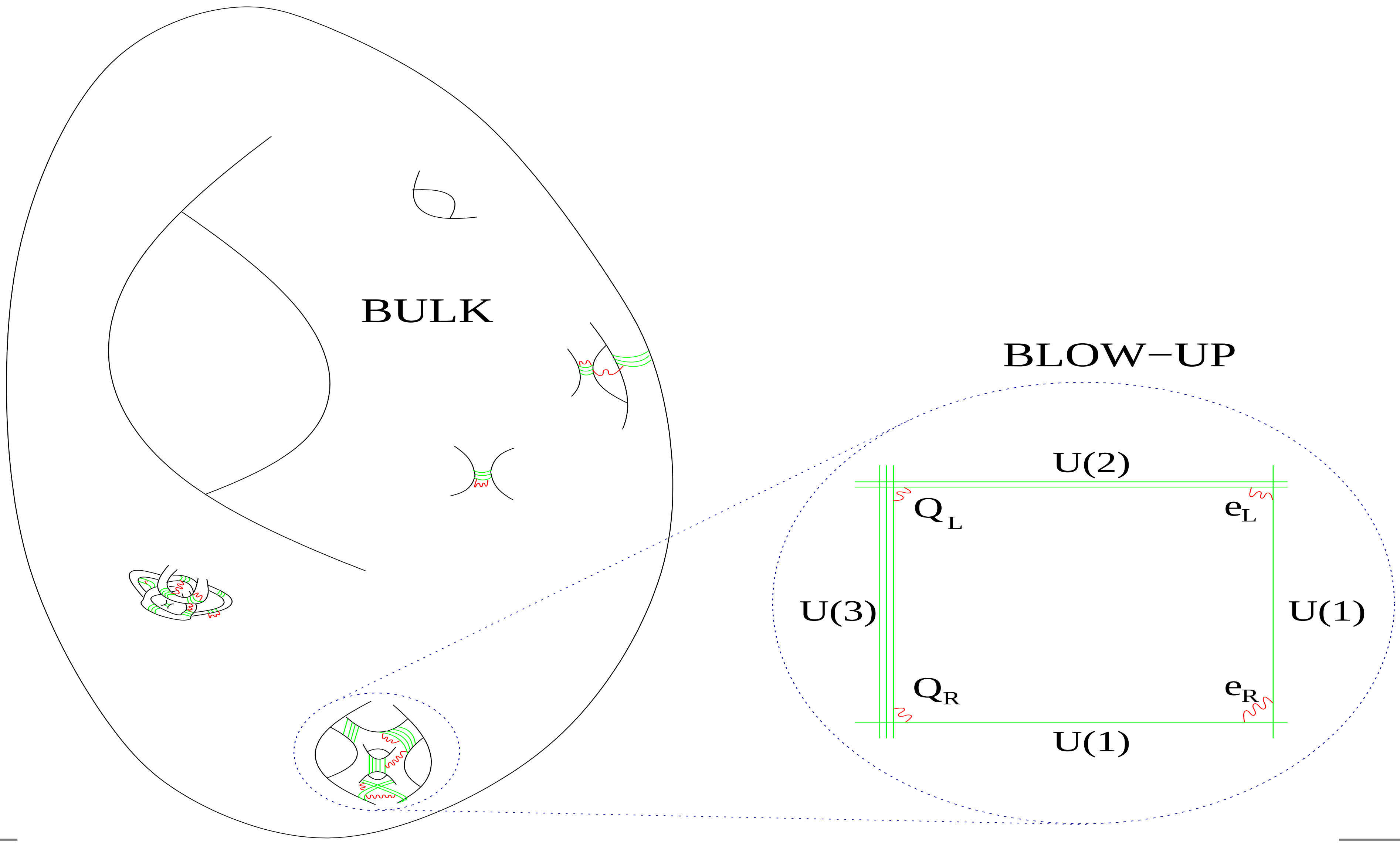
$$V = -\frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi|W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0|e^{a_s\tau_s}, \qquad \tau_s \sim \frac{\xi^{2/3}}{g_s}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

Moduli Stabilisation: Large-Volume



Moduli Stabilisation: Large-Volume

- The stabilised volume is exponentially large.
- The large volume lowers the string scale and gravitino mass through

$$m_s = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} = \frac{M_P}{\mathcal{V}}.$$

- To solve the gauge hierarchy problem, need $\mathcal{V} \sim 10^{15}$.
- This also automatically generates the axionic scale ($f_a \sim 10^{11}$GeV) and the neutrino scale ($\Lambda \sim 10^{14}$GeV).
- The vacuum generates the hierarchy, breaks susy and inherits the no-scale susy breaking structure:

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Corrections

- Factorisation holds at leading order.
- Factorisation is inherited from the underlying $\mathcal{N} = 2$ structure and holds in the large-radius limit.
- It is broken by e.g. loop corrections that are present in $\mathcal{N} = 1$ compactifications.
- Phenomenologically, this suggests soft terms that are

universal at leading order

with small subleading corrections

Conclusions

- The structure of string compactifications provides a natural solution to the flavour problems of the MSSM.
- Calabi-Yau moduli space factorises into Kähler and complex structure moduli.
- One sector is responsible for flavour, the other for susy breaking.
- This factorisation is explicitly realised in IIB flux compactifications.