Strings and Phenomenology: Chalk and Cheese?

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Thanks to my collaborators:

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Chalk and Cheese?

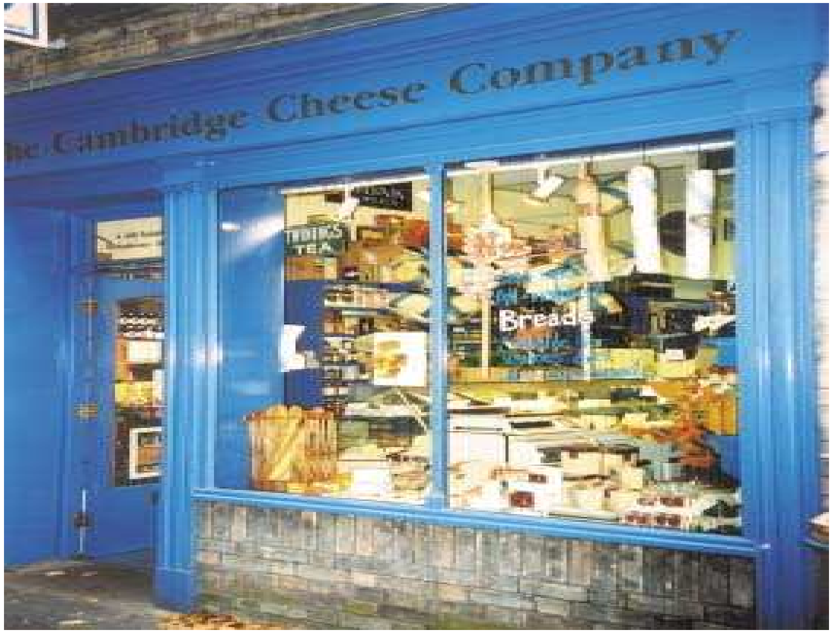

Figure 1: String theory and phenomenology?

Talk Structure

- Chalk and Cheese?
- Supersymmetry Breaking
- LARGE Volume Models
- Axions
- Global Flavour Symmetries
- Conclusions

String Theory

- String theory is where one is led by studying quantised relativistic strings.
- It encompasses lots of areas (black holes, quantum field theory, quantum gravity, mathematics, particle physics....) and is studied by lots of different people.
- This talk is on the relevance of strings to phenomenology - theory aiming at explaining and predicting experimental measurements.
- But why should strings have any relevance to phenomenology at all?

Chalk and Cheese?

Strings became famous due to their promise for quantum gravity:

The equations of motion for a quantum string are only consistent if spacetime satisfies Einstein's equations:

$$\begin{aligned} 16\pi M_P^2 \left(\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} \right) &= T_{\mu\nu}, \\ \text{curvature} &= \text{matter}. \end{aligned}$$

Quantum gravity will not be directly probed anytime soon.

Chalk and Cheese?

At energies $E \ll M_W$, electroweak theory is described by Fermi theory

$$\mathcal{L} = \sum_i \bar{\psi}_i \gamma^\mu \partial_\mu \psi_i + \frac{1}{M_W^2} (\bar{\psi}\gamma^\mu \psi)(\bar{\psi}\gamma_\mu \psi)$$

Fermi theory is non-renormalisable and is the *effective field theory* of electroweak $SU(2) \times U(1)$ theory.

At energies $E \ll M_W$, we only need know Fermi theory: electroweak theory reduces to Fermi theory up to terms suppressed by $\left(\frac{E}{M_W}\right)^2$.

Chalk and Cheese?

At energies $E \ll M_P$, dynamics of string theory is described by general relativity

$$\mathcal{L} = \int \frac{M_P^2}{2}\sqrt{g}\mathcal{R} + \sqrt{g}(\sum_i \bar{\psi}\gamma^\mu \partial_\mu \psi + \phi \bar{\psi}_i \psi_j + \ldots)$$

Metric perturbations δh interact non-renormalisably

$$\mathcal{L} = \int \partial_\mu (\delta h_{\mu\nu}) \partial^\mu (\delta h^{\mu\nu}) + \frac{\delta h_{\mu\nu}}{M_P} \phi \bar{\psi}_i \psi_j + \ldots$$

General relativity is non-renormalisable and is the *effective field theory* of string theory.

Chalk and Cheese?

At energies $E \ll M_P$, string theory reduces to (general relativity + matter).

Additional stringy corrections are suppressed by $\left(\frac{E}{M_P}\right)^2$.

At $E = 14$TeV,

$$\left(\frac{E}{M_P}\right)^2 \sim 10^{-28},$$

and any intrinsically stringy effects are so small as to be unobservable.

Conclusion: string theory may be useful for quantum gravity, but is permanently irrelevant for phenomenology.

Chalk and Cheese?

The purpose of this talk is to explain why this is not so.

UV theories (such as string theories) play two important roles at low energy.

1. They constrain the low-energy couplings in ways not evident from effective field theory alone.
2. They relate areas of physics that are unconnected from a low-energy viewpoint.

I will justify these points in the rest of the talk.

Both points have significant effects on low-energy phenomenology.

String Theory

- For technical reasons string theory is consistent in ten dimensions.
- Six dimensions must be compactified.
- $$\text{Ten} \quad = \quad (\text{Four}) \quad + \quad (\text{Six})$$
- All scales, matter, particle spectra and couplings come from the geometry of the extra dimensions.

String Theory

- For technical reasons string theory is consistent in ten dimensions.
- Six dimensions must be compactified.
- $$\text{Ten} \quad = \quad (\text{Four}) \quad + \quad (\text{Six})$$

$$\text{Spacetime} = (\text{Normal}) + (\mathcal{HERE\ BE\ DRAGONS})$$

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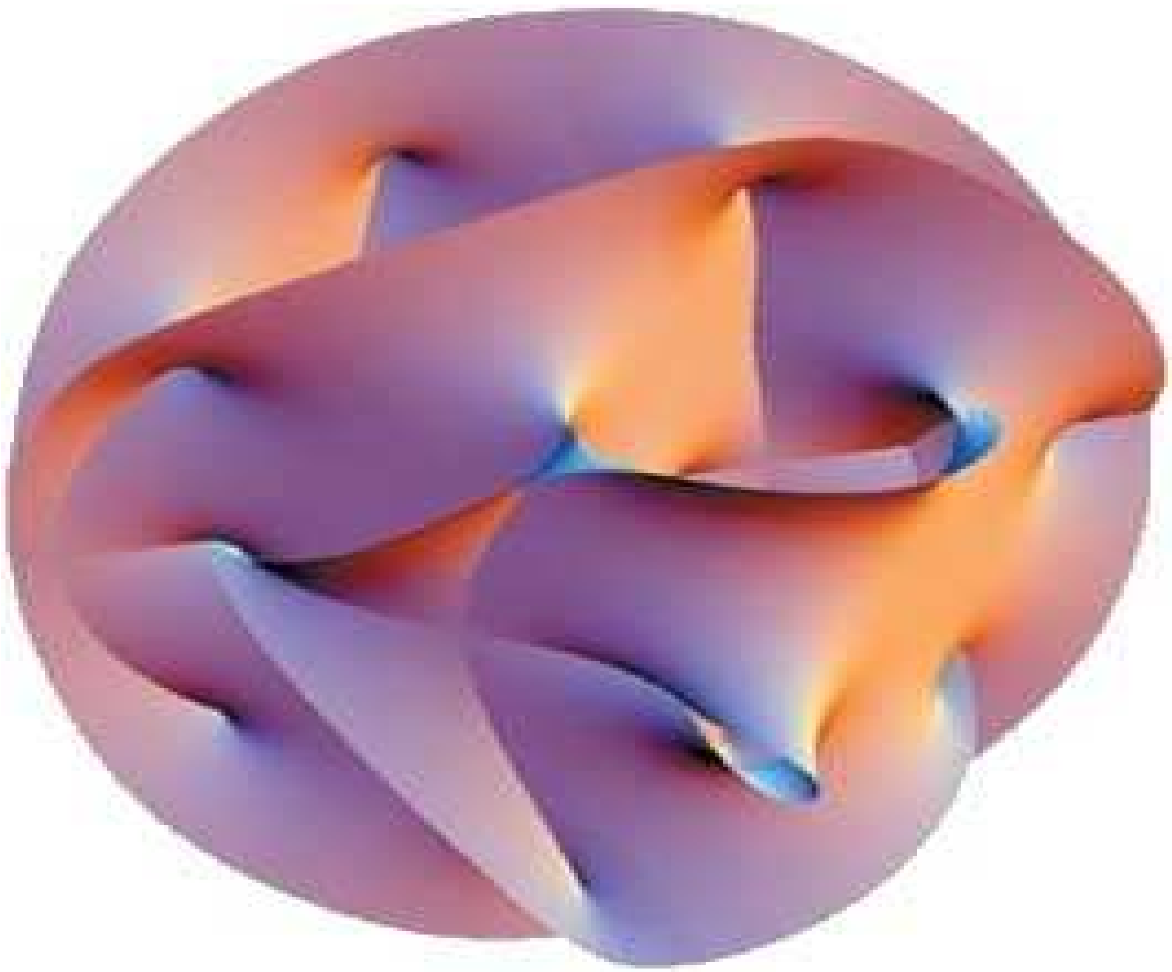
String Theory

The extra dimensions form a *Calabi-Yau manifold*.



String Theory

The geometry of the Calabi-Yau manifold determines the structure of low-energy interactions.

Special geometric properties of Calabi-Yaus generate special properties of the low-energy particle spectrum and interactions.

One special geometric property of Calabi-Yaus - the deformations of their sizes and shapes - has important effects on supersymmetry breaking.

The MSSM Flavour Problem

ATLAS hopes to discover supersymmetry.

But why should any new susy signatures occur at all?

One major problem:

The MSSM Flavour Problem

ATLAS hopes to discover supersymmetry.

But why should any new susy signatures occur at all?

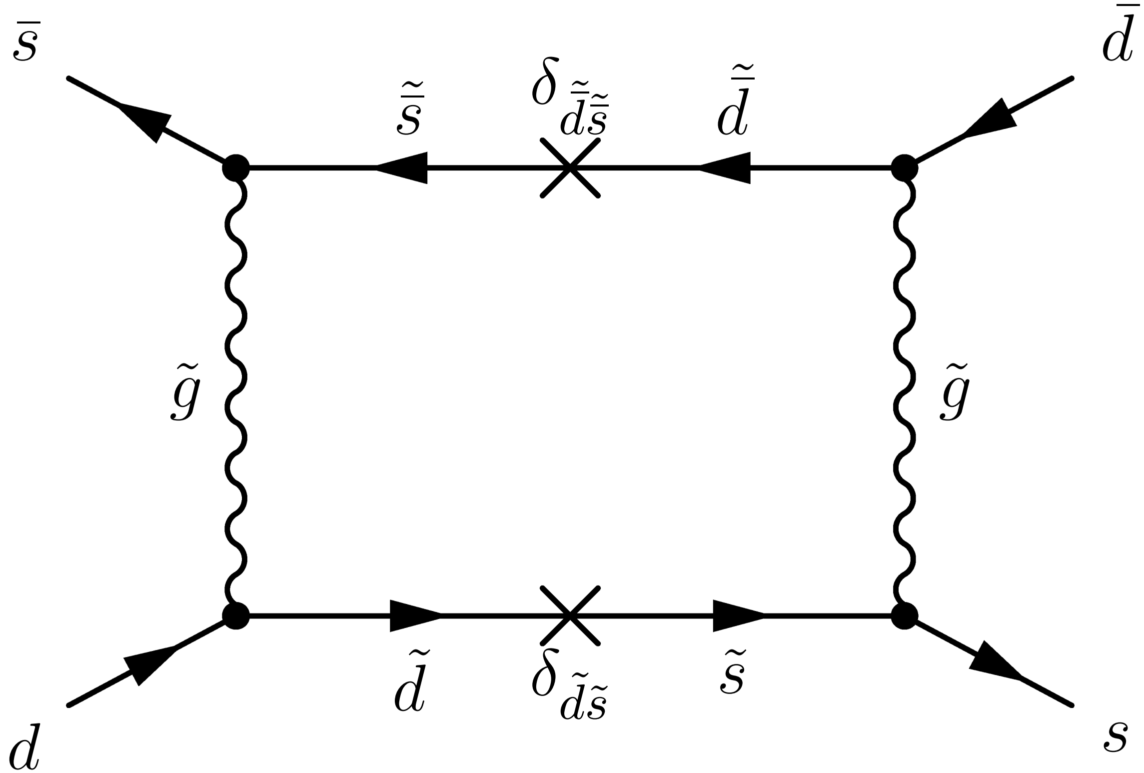
One major problem:

Why hasn't supersymmetry been discovered already?

Compare with

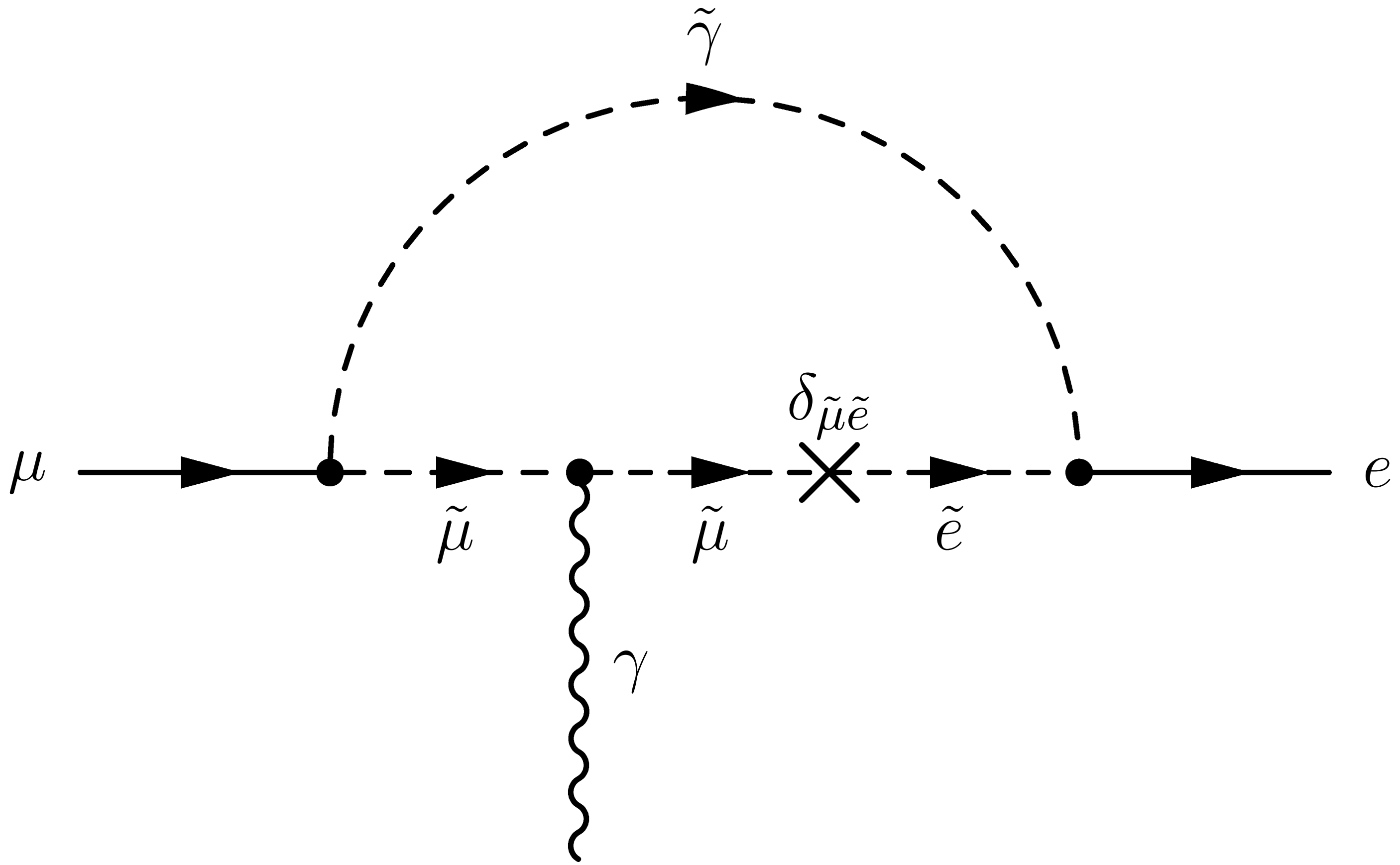
- The c quark - predicted before discovery through its contribution to FCNCs (the GIM mechanism)
- The t quark - mass predicted accurately through loop contributions at LEP I.

The MSSM Flavour Problem



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

The MSSM Flavour Problem



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

The MSSM Flavour Problem

SUSY is a happy bunny if soft terms are flavour universal.

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

Why should this be?

- Answer to flavour problem significantly affects all of susy phenomenology.
- This problem cannot be addressed purely within effective field theory - needs UV completion.

The MSSM Flavour Problem

- The flavour problem says that supersymmetry breaking cannot know about flavour physics.
- *A priori*, this is unnatural - why should the susy breaking sector be entirely ignorant of flavour?
- String theory can give a natural answer.

  The size and shape fields of the Calabi-Yau are factorised

$$\Phi_{all} = \Psi_{size} \oplus \chi_{shape}$$

  Ψ and χ represent two distinct and decoupled sectors.

  This is a *mathematical* statement about Calabi-Yaus.

The MSSM Flavour Problem

We have

$$\Phi_{all} = \Psi_{size} \bigoplus \chi_{shape}$$

with Ψ and χ representing two distinct and decoupled sectors.

It turns out that

1. Ψ_{size} gives rise to supersymmetry breaking.
2. χ_{shape} generates the flavour structure: $Y_{\alpha\beta\gamma} = Y_{\alpha\beta\gamma}(\chi)$.

Supersymmetry breaking and flavour physics decouple and soft terms are flavour universal!

The origin of this decoupling is the geometric properties of Calabi-Yaus.

LARGE Volume Models

- In string theory all scales, matter, particle spectra and couplings come from the geometry of the extra dimensions.
- To be predictive in any way, we need to fix the geometry of the extra dimensions.
- This is a hard problem and is called moduli stabilisation.
- One attractive method of moduli stabilisation are the LARGE volume models.

LARGE Volume Models

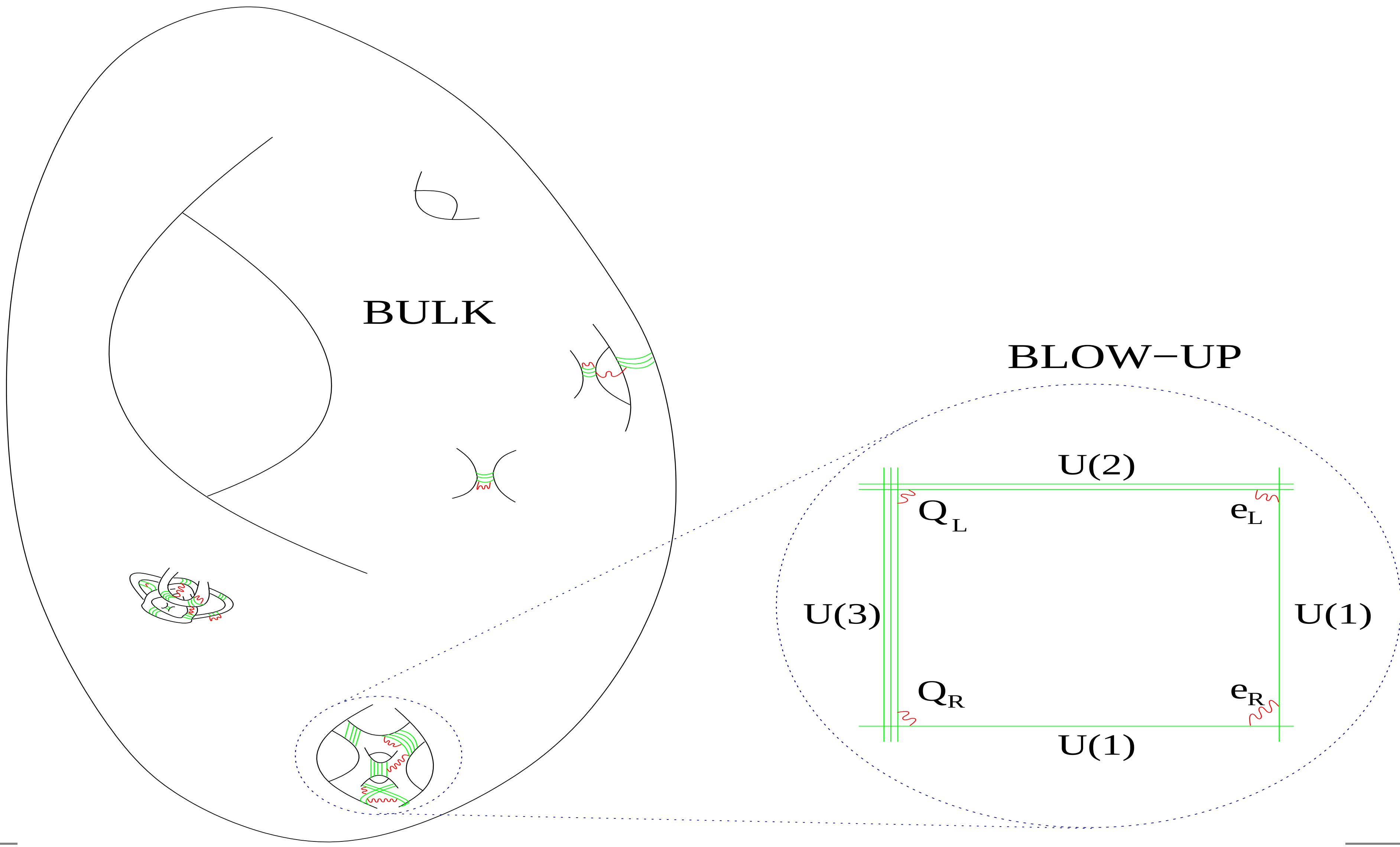
- LARGE volume models stabilise the volume at exponentially large values.
- The string scale and supersymmetry breaking scales are hierarchically low,

$$M_{string} = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad M_{susy} = \frac{M_{string}^2}{M_P}.$$

- A volume $\mathcal{V} \sim 10^{15} l_s^6$ gives

1. an intermediate string scale $M_{string} \sim 10^{11}$GeV
2. TeV supersymmetry $m_{susy} \sim 1$TeV.

LARGE Volume Models



LARGE Volume Models

- With a UV theory, supersymmetry breaking can be computed from first principles.
- The high scale squark and slepton masses can be computed and evolved to the TeV scale.
- The resulting spectrum can be Monte-Carloed and compared to data.

LARGE Volume Models

- With a UV theory, supersymmetry breaking can be computed from first principles.
- The high scale squark and slepton masses can be computed and evolved to the TeV scale.
- The resulting spectrum can be Monte-Carloed and compared to data.
- May be useful in unlikely event real world is not described by SPS1A....

LARGE Volume Models

The mass scales present are:

Planck scale:	$M_P = 2.4 \times 10^{18}$GeV.
String scale:	$M_S \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
KK scale	$M_{KK} \sim \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^{9}$GeV.
Gravitino mass	$m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 30$TeV.
Supersymmetry breaking	$m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.
Volume modulus	$m_{\tau_b} \sim \frac{M_P}{\mathcal{V}^{3/2}} \sim 1$MeV.

Axions

Axions are a well-motivated solution to the strong CP problem of the Standard Model.

The Lagrangian for QCD contains a term

$$\mathcal{L}_{QCD} = \frac{1}{4\pi g^2} \int d^4 x F^a_{\mu\nu} F^{a,\mu\nu} + \frac{8\pi\theta}{g^2} \int \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}.$$

The θ term

$$\mathcal{L}_\theta = \frac{\theta}{8\pi^2} \int \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}.$$

gives rise to the strong CP problem.

This term vanishes in perturbation theory and is only non-vanishing for non-perturbative instanton computations.

Axions

θ is an angle and in principle takes any value $\theta \in (-\pi, \pi)$.

It can be shown that non-vanishing θ generates an electric dipole moment for the neutron.

The measured absence of a neutron electric dipole moment implies that

$$|\theta_{QCD}| \lesssim 10^{-10}.$$

No symmetry of the Standard Model requires $|\theta|$ to be so small.

The problem of why $|\theta_{QCD}| \ll \pi$ is the *strong CP* problem of the Standard Model.

Axions

The best solution to the strong CP problem is due to Peccei and Quinn.

The angle θ is promoted to a dynamical field with Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial_\mu \theta \partial^\mu \theta + \int \frac{\theta}{8\pi f_a} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma}.$$

f_a is called the *axion decay constant* and measures the strength of the non-renormalisable axion-matter coupling.

Axions

Non-perturbative QCD effects generate a potential for θ,

$$V_\theta \sim \Lambda^4_{QCD}\left(1-\cos\left(\frac{\theta}{f_a}\right)\right) \quad = \quad \frac{\Lambda^4_{QCD}}{f_a^2}(\theta^2+\ldots)$$

The axion field θ gets a mass

$$m_\theta = \frac{\Lambda^2_{QCD}}{f_a} \sim 0.01\text{eV}\left(\frac{10^9\text{GeV}}{f_a}\right)$$

Axion phenomenology depends entirely on the value of f_a.

Axions

Constraints from supernova cooling and direct searches imply $f_a \gtrsim 10^9$GeV (axions cannot couple too strongly to matter).

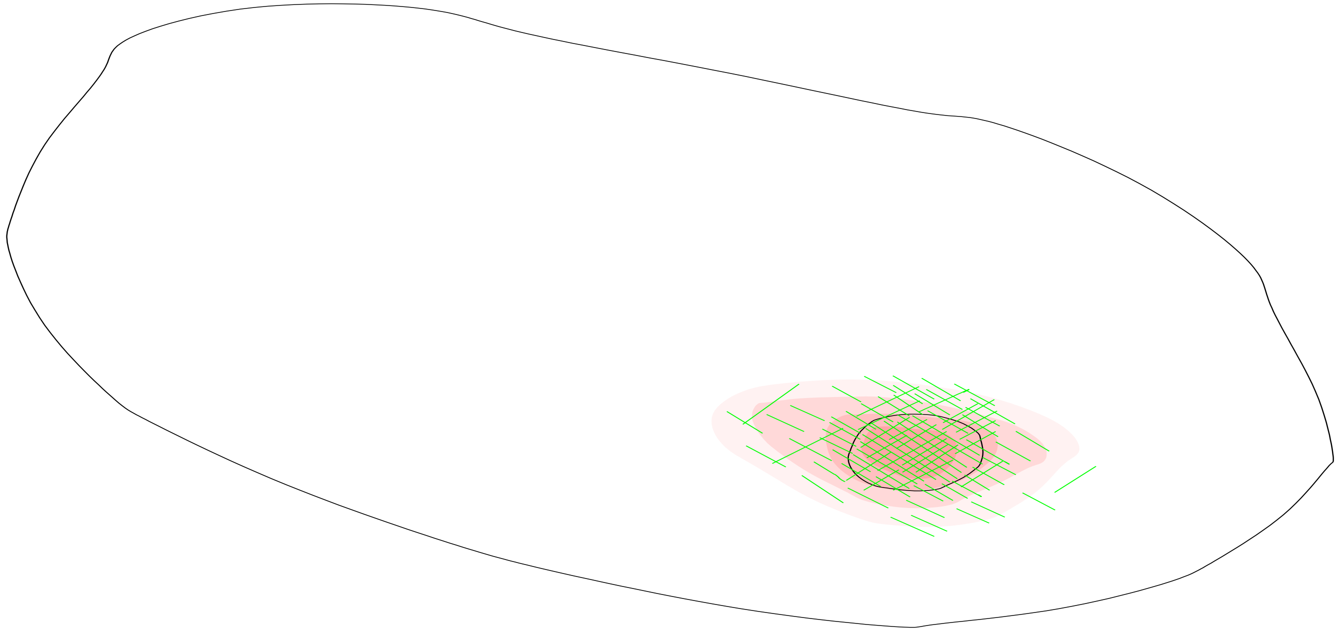
Avoiding the overproduction of axion dark matter during a hot big bang prefers $f_a \lesssim 10^{12}$GeV (axions cannot couple too weakly to matter).

There exists an axion ‘allowed window’,

$$10^9\text{GeV} \lesssim f_a \lesssim 10^{12}\text{GeV}.$$

Axions

- In string theory, the axionic coupling comes from bulk-brane interactions.
- The axion decay constant f_a measures the coupling of the axion to matter.



Axions

- The axion coupling is a local coupling and does not see the overall volume.
- The coupling is set by the string scale:

$$f_a \sim m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}.$$

- This generates the axion scale,

$$f_a \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}\text{GeV}.$$

Axions

TeV-scale supersymmetry required

$$M_{susy} \sim m_{3/2} = \frac{M_P}{\mathcal{V}} = 1\text{TeV}.$$

This gives $\mathcal{V} \sim 10^{15} l_s^6$.

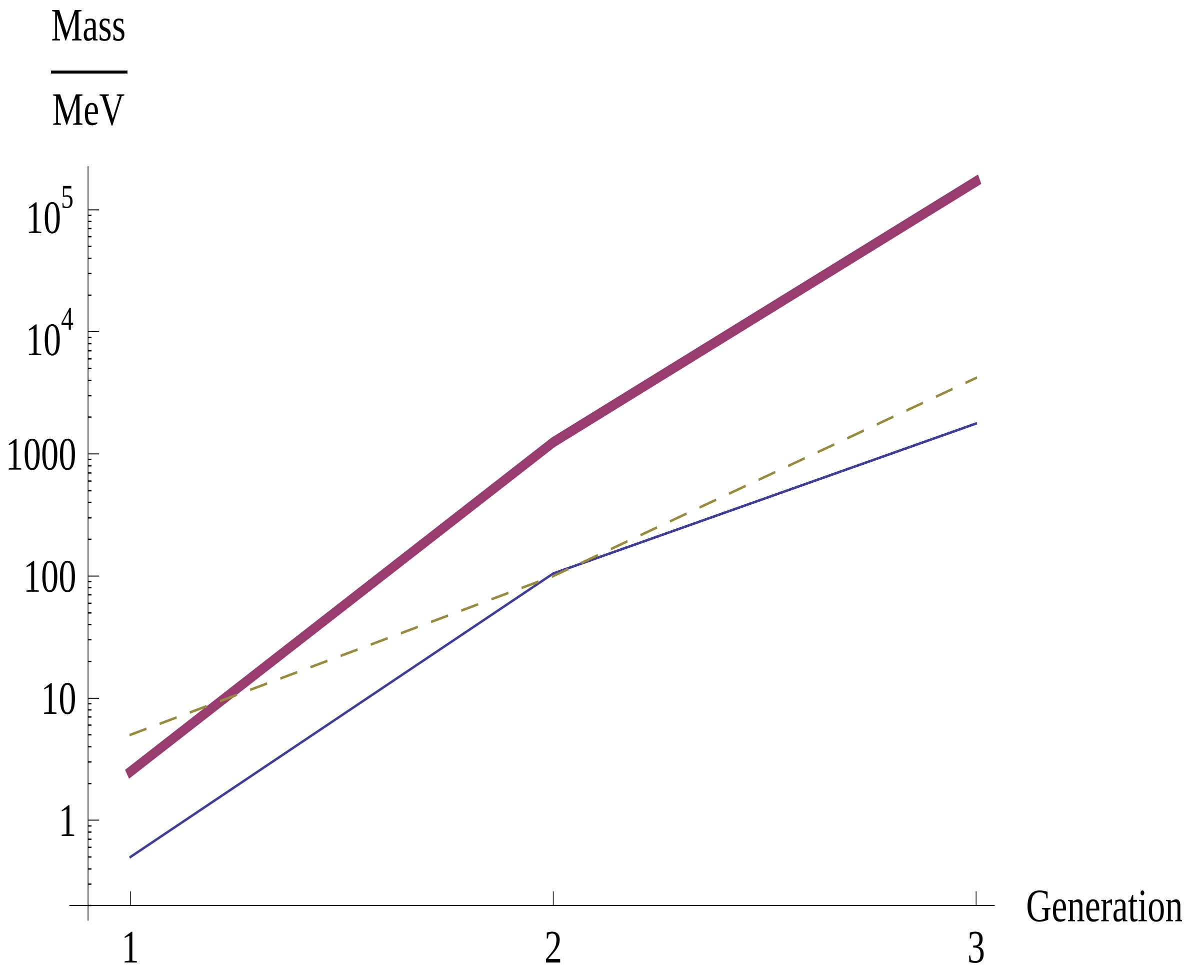
The axion scale is therefore

$$f_a \sim \sqrt{M_{susy} M_P} \sim 10^{11}\text{GeV}$$

The existence of an axion in the allowed window correlates to the existence of supersymmetry at the TeV scale.

Continuous Flavour Symmetries

The fermion mass spectrum is one of the most puzzling aspects of the Standard Model



Continuous Flavour Symmetries

Flavour symmetries are an attractive path to understanding the fermion masses

$$G_{total} = G_{SM} \times G_F = G_{SU(3)\times SU(2)\times U(1)} \times G_F.$$

Flavons Φ are charged under G_F and not under G_{SM}.

SM matter C_i is charged under both G_F and G_{SM}.

$$\mathcal{L}_{schematic} = C_{\alpha\beta\gamma\ldots ijk}(\Phi_\alpha \Phi_\beta \Phi_\gamma \ldots) C_i C_j C_k.$$

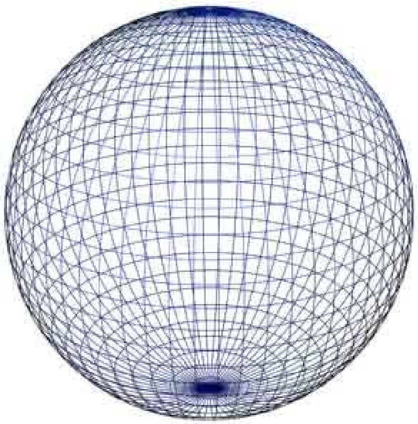
Flavon vevs break G_F and generate Yukawa textures.

The order parameter for G_F breaking is $< \Phi >$.

Continuous Flavour Symmetries

- In LARGE volume models, the Standard Model is necessarily a local construction.
- The couplings of the Standard Model will all be determined only by the local geometry.
- Local geometries have isometries (cf the sphere).

  Isometries generate flavour symmetries on the brane.



Continuous Flavour Symmetries

- Brane flavour symmetries constrains the couplings of Standard Model matter.
- The hope is that with the right model the Yukawa couplings of the Standard Model come from an approximate flavour symmetry.
- Caveat: there is currently no brane construction giving the precise matter of the Standard Model.

Continuous Flavour Symmetries

- In the infinite bulk limit $\mathcal{V} \to \infty$ the metric isometry is perfect and the flavour symmetry exact.
- In the limit of a huge bulk $\mathcal{V} \gg 1$, the metric isometry is very good and the flavour symmetry approximate.
- The scale of the symmetry breaking is determined by the size of the bulk:

$$\frac{l_s}{R_{bulk}} \sim \left(\frac{M_{susy}}{M_P} \right)^{1/6} \sim \frac{1}{100}.$$

-

Low-scale supersymmetry $\Longrightarrow$ LARGE bulk

LARGE bulk $\Longrightarrow$ Approximate flavour symmetry

Conclusions

Strings will not be produced at the LHC.

However UV concepts are essential to understanding low-energy effective Lagrangians.

String theory feeds into effective field theories and relates very different physics.

In the context of the LARGE volume string models I have described the connections between

- TeV scale supersymmetry breaking
- axions in the allowed window $10^9\text{GeV} \lesssim f_a \lesssim 10^{12}\text{GeV}$
- the presence of approximate flavour symmetries acting on the Standard Model matter content.