Axions, WIMPs and WISPS: Top-Down Motivation

Joseph Conlon (Oxford University)

Patras Axions/WIMPs/WISPS Meeting, Durham

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Plan

1. Axions
2. WIMPs (not much)
3. WISPs

'Top-down' here will mostly mean string theory and string compactifications.

Aim to motivate why such particles should (must?) exist and what their properties are.

Axions

A dynamical θ angle solves the strong CP problem

- The canonical Lagrangian for θ is

$$\mathcal{L} = \frac{1}{2}\partial_\mu \theta \partial^\mu \theta + \int \frac{\theta}{f_a} \epsilon^{\mu\nu\rho\sigma} F_{a,\mu\nu} F_{a,\rho\sigma}.$$

  f_a is the axionic decay constant.
- Constraints on supernova cooling and direct searches imply $f_a \gtrsim 10^9\text{GeV}$.
- Avoiding the overproduction of axion dark matter prefers $f_a \lesssim 10^{12}\text{GeV}$.
- There exists an axion 'allowed window',

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

Why Should Axions Exist?

Why should axions exist?

In field theory a gauge field has two self-couplings:

$$\frac{1}{g^2}\int \sqrt{g} F_{\mu\nu}F^{\mu\nu} + i\theta \int \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}F_{\rho\sigma}$$

A priori, such couplings are unrelated.

In supersymmetry/supergravity, the action is

$$\mathrm{Re}(f(\Phi)) \int \sqrt{g} F_{\mu\nu}F^{\mu\nu} + \frac{i}{2}\mathrm{Im}(f(\Phi)) \int \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}F_{\rho\sigma}$$

This connects gauge and axionic couplings through a single holomorphic function.

Why Should Axions Exist?

$$\mathrm{Re}(f(\Phi)) \int \sqrt{g} F_{\mu\nu} F^{\mu\nu} + \frac{i}{2} \mathrm{Im}(f(\Phi)) \int \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

$f(\Phi)$ be either constant or field-dependent.

Suppose $f(\Phi) = \frac{\Phi}{M_P}$.

A single complex field Φ controls both the gauge coupling and the axionic coupling.

$\mathrm{Re}(\Phi)$ determines the gauge coupling and $\mathrm{Im}(\Phi)$ is an axion for the gauge group.

Why Should Axions Exist?

What does this imply?

- Any theory with both supersymmetry and field-dependent gauge couplings has axions.
- This is always true of string compactifications: 'string theory has no free parameters: all is dynamical'.
- Conclusion: every gauge field in every string compactification has an associated axion.

How does this come about?

Axions in (Type IIA/B) String Theory

- Gauge groups are realised on D-branes, extended objects with tension wrapping $p = 4 + n$-dimensional surfaces.
- The D-brane action is

$$S = \underbrace{\int_{\mathbb{M}^4 \times \Sigma_n} \sqrt{g + F}}_{\text{DBI}} + i \underbrace{\int_{\mathbb{M}^4 \times \Sigma_n} \sum C_q \wedge e^F}_{\text{Chern-Simons}}$$

- DBI action gives

$$S_{DBI} = \ldots + \int_{\mathbb{M}_4} \sqrt{g} F_{\mu\nu} F^{\mu\nu} \underbrace{\int_{\Sigma_n} \sqrt{g}}_{(g^2)^{-1}}$$

The gauge coupling is determined by the extra-dimensional volume of the brane.

Axions in (Type IIA/B) String Theory

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- Chern-Simons action gives

$$S_{CS} = \ldots + \int_{\mathbb{M}_4} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F^{\mu\nu} \underbrace{\int_{\Sigma_n} C_n}_{Axion}$$

Axion comes from the Ramond-Ramond antisymmetrical field C_n reduced on the cycle.

Axions in String Theory

- Axions also arise for other string theories (heterotic string/M-theory).
- Axions have an underlying exact non-perturbative $a \to a + 2\pi$ shift symmetry.
- This symmetry has geometric/topological origins: (as for the $\theta \to \theta + 2\pi$ symmetry of the circle).
- Candidate axions therefore always arise in string compactifications.

The Axion Decay Constant

The axion decay constant is phenomenologically crucial.

$$\mathcal{L} = \frac{1}{g^2} F_{\mu\nu} F^{\mu\nu} + \partial_\mu a \partial^\mu a + \frac{a}{f_a} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu} F_{\rho\sigma}$$

What does string theory give?

Physically, the coupling f_a is a measure of the strength of the coupling of the axion to the gauge fields.

f_a should be M_P for gravitational strength couplings: $f_a \ll M_P$ implies the axionic coupling is much stronger than gravitational.

The Axion Decay Constant

Fundamental scale in string theory is M_s not M_P. If $M_s \neq M_P$ then we expect to get $f_a \ll M_P$.

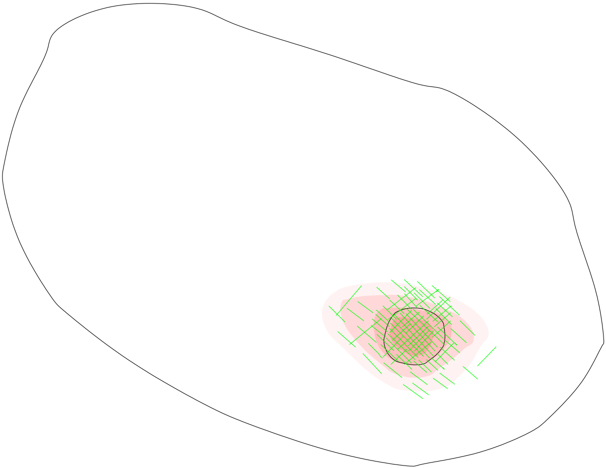
In heterotic string phenomenology requires $M_s \sim M_P$ and consequently $f_a \sim M_P$.

For brane theories: M_P is associated to the full bulk of extra dimensions.

If $M_s \ll M_P$ then $f_a \ll M_P$. Two ways to realise this:

1. A large volume, $M_s = M_P/\sqrt{\mathcal{V}} \ll M_P$ if $\mathcal{V} \gg 1$
2. Large warping such that M_s is warped down in a throat region.

The Axion Decay Constant



The Axion Decay Constant

So in brane models with $M_s \ll M_P$ we can get $f_a \ll M_P$.

Note

- M_s is a single scale holding across the compactification.
- If we have many axions, expect them to have similar values of f_a.
- (Possible exception: many warped throats with different local string scales)

Axion Masses

Axions get their masses from non-perturbative effects (QCD instantons for Peccei-Quinn axion).

Mass of QCD axion is given by

$$m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$$

Expect non-perturbative effects to be distributed equally in log space.

If other axions exist for other (hidden) sectors expect similar decay constant but different masses.

Axion Summary

Summary:

- In string theory every gauge group always has an associated axion.
- These axions have exact $a \rightarrow a + 2\pi$ symmetries and so cannot get masses in perturbation theory.
- Axion decay constants are normally set by the string scale and so can be much less than M_P in brane models.
- Axion masses depend sensitively on non-perturbative effects and may take a wide range of values.

WIMPs

Weakly Interacting Massive ParticleS are naturally associated with new physics at the TeV scale.

Arise if supersymmetry is present at the TeV scale:

$$\delta_{susy} : W \to \tilde{W}, \quad \gamma \to \tilde{\gamma}, \quad H_u, H_d \to \tilde{H}_u, \tilde{H}_d.$$

Neutralinos are given by

$$\chi_i = \alpha_{i,0}\tilde{W} + \alpha_{i,1}\tilde{\gamma} + \alpha_{i,2}\tilde{H}_u + \alpha_{i,3}\tilde{H}_d$$

In R-parity MSSM lightest neutralino χ_0 is a good candidate for dark matter.

WIMPs

Supersymmetry as a symmetry of nature at some energy scale is strongly motivated by string theory.

However

- Motivation for TeV scale susy relies on the detailed properties of the Standard Model.
- Weak scale is not a top-down scale.
- Viability of any *particular* proposed WIMP depends on particle physics model.

WISPs

What about Weakly Interacting Sub-eV ParticleS?

At first sight WISPs seem unnatural - very light particles interacting weakly with matter.

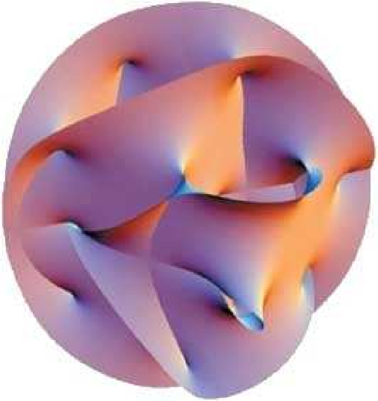
WISPs require new sectors beyond the Standard Model.

There are two possibilities:

- New sector can interact directly with Standard Model but is intrinsically weakly coupled.
- New sector has very small mixing with the Standard Model.

Origin of Hidden Sectors

Strings are compactified on Calabi-Yau manifolds.



Origin of Hidden Sectors (Type IIA/B)

The low energy gauge group is connected to the geometry of the Calabi-Yau.

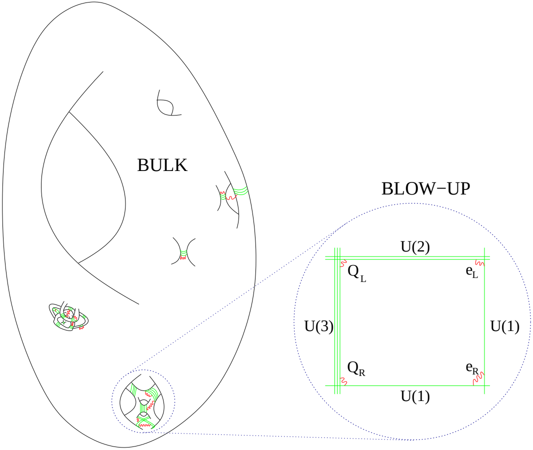
Typical Calabi-Yaus have hundreds of cycles: all of these can be wrapped by branes.

Each brane gives a new gauge factor at low energy; intersections of branes give matter.

Expect many hidden sectors, with many additional gauge groups with no direct couplings to the Standard Model.

Sectors can be geometrically separated from Standard Model.

Origin of Hidden Sectors (Type IIA/B)



Origin of Hidden Sectors (Heterotic)

In heterotic string theory hidden sectors arise in a different way.

- Fundamental gauge group is $\underbrace{E_8}_{visible} \times \underbrace{E_8}_{hidden}$
- Standard Model aries by breaking the visible E_8 down to $SU(3) \times SU(2) \times U(1)$.
- Hidden E_8 remains and gives a new gauge sector separated from the visible sector.
- Note that this is not a geometric separation: both gauge groups come from the whole Calabi-Yau.

Origin of Hidden Sectors

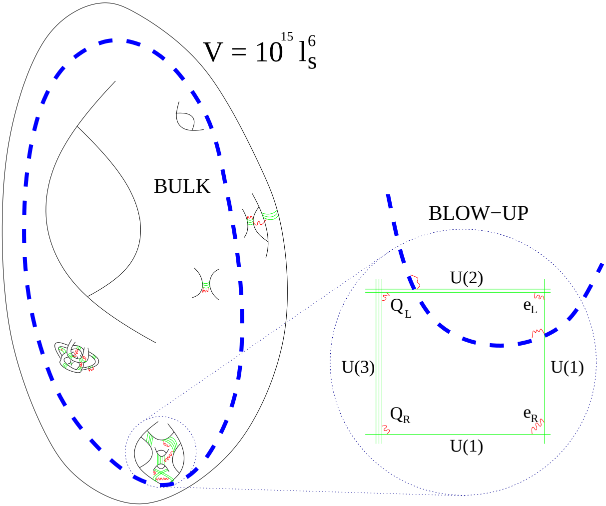
Summary:

- String compactifications generically give additional gauge sectors beyond that of the Standard Model.
- No compelling reason why these should be massive.
- Suggests there could exist new light/massless gauge sectors, either Abelian or non-Abelian.
- Such sectors are Wispy if they interact weakly with the Standard Model.

Sectors with Small Couplings

- Gauge couplings on branes are inversely proportional to the size of the cycle wrapped.
- If the Calabi-Yau is large, then gauge couplings can be much smaller than 1.
- For bulk D7 branes, gauge couplings are
  $$g^2 \sim \mathcal{V}^{-2/3} \sim \left(\frac{M_s}{M_P}\right)^{4/3}.$$
  For $M_s \ll M_P$ then extremely weakly coupled gauge sectors can exist.
- Best illustrated by picture....

Sectors with Small Couplings



Sectors with Small Couplings

This geometry is realised in many Standard Model-like constructions in type IIB.

- Standard Model gauge group comes from D3 branes at a singularity/D7 branes wrapping a collapsing 4-cycle.
- A bulk D7 brane intersects the Standard Model branes and matter comes from the intersection of the two.
- Standard Model could be directly charged under a new, light, very weakly coupled gauge group ($B-L$?)
- For low string scales hidden sector gauge coupling becomes very weak.

Moduli

Moduli ϕ are gravitational modes that parametrise the geometry of the compactification manifold.

They are naively massless and need to obtain a mass to avoid fifth force experiments.

- Fifth force experiments require $m_\phi \gtrsim 10^{-3}\mathrm{eV}$

  Generally moduli acquire masses $m_\phi \sim m_{3/2} \gtrsim 10^{-3}\mathrm{eV}$.
- However if moduli are anomalously light(for example no-scale models) then can have $m_\phi \ll m_{3/2}$.

  In this case fifth forces arise at a distance $l \sim \frac{1}{m_\phi}$.
- Moduli are always present, but unlikely to be $< 1\mathrm{eV}$.

Sectors with Small Mixing

Additional $U(1)$s are generic.

$U(1)$s can mix through the kinetic mixing parameter

$$\frac{1}{g_A^2} F_{A,\mu\nu} F_A^{\mu\nu} + \frac{1}{g_B^2} F_{B,\mu\nu} F_B^{\mu\nu} + \epsilon F_{A,\mu\nu} F_B^{\mu\nu}$$

If $\epsilon \ll 1$ then small mixing can generate milli-charged fermions as hidden sector particles acquire small charges through kinetic mixing.

Mixing can occur at 1-loop through heavy particles charged under both gauge groups.

Sectors with Small Mixing

Kinetic mixing arise in string theory and can be computed in CFT:

(Abel, Goodsell, Jaeckel, Khose, Ringwald)

For D6 branes,

$$\epsilon_{ij} = \frac{g_a g_b}{4\pi^2} I_{AB} \left[\log \left| \frac{\theta_1\left(\frac{i\delta_{ij} L_1}{2\pi^2 \alpha'}, \frac{iT_1^2}{\alpha'}\right)}{\eta\left(\frac{iT_1^2}{\alpha'}\right)} \right|^2 - \frac{\delta_{ij}^2}{2\pi^3 \alpha'} \frac{(L_1)^2}{T_1^2} \right]$$

Magnitude of the mixing depends on the geometry.

Mixing can be large and excluded - but also very small values of ϵ can arise. More in Mark Goodsell's talk

Conclusions

- From top-down perspective we expect the existence of new, light weakly coupled particles.
- Axions and moduli are the most generic and most unavoidable.
- Hidden gauge sectors occur generically in string compactifications and may be massless.
- Both very weakly coupled and very weakly mixed sectors can arise.