string phenomenology today

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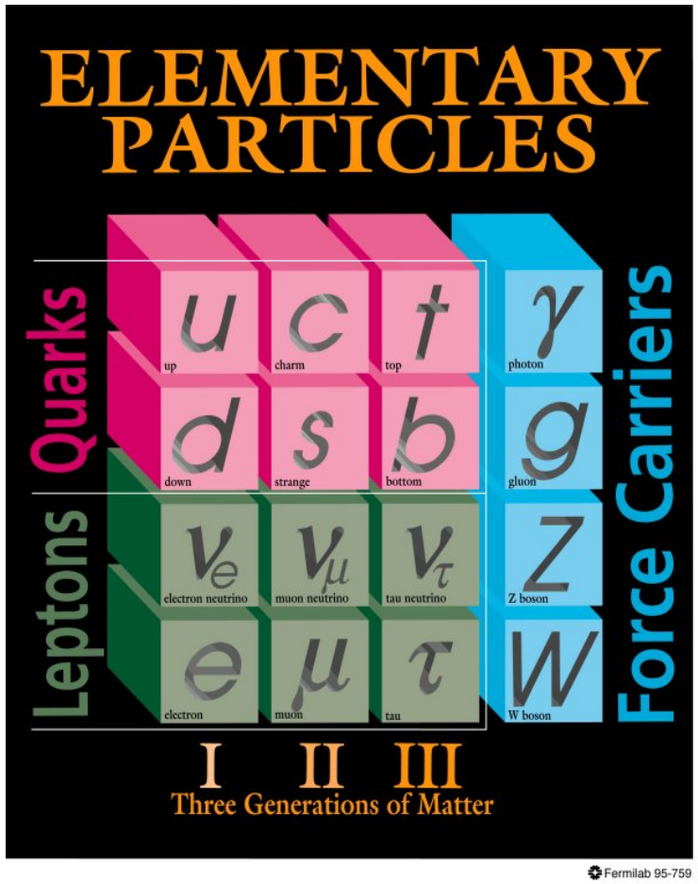
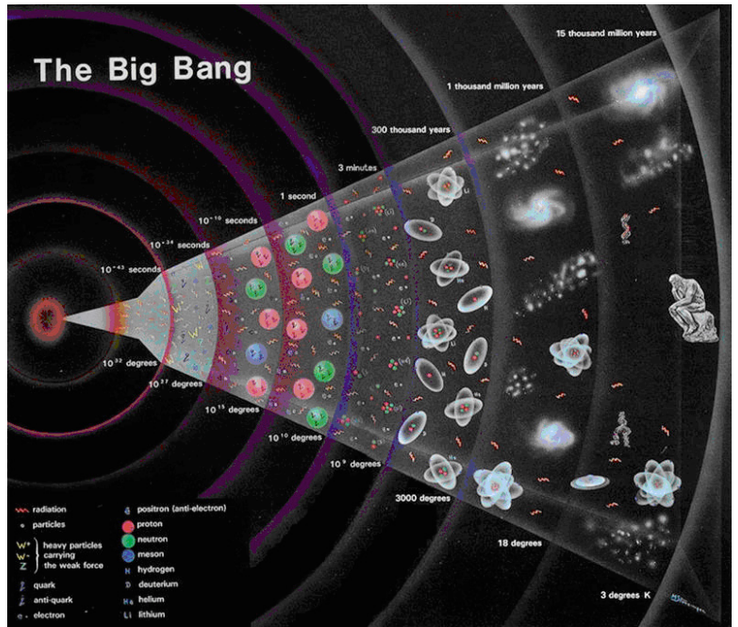
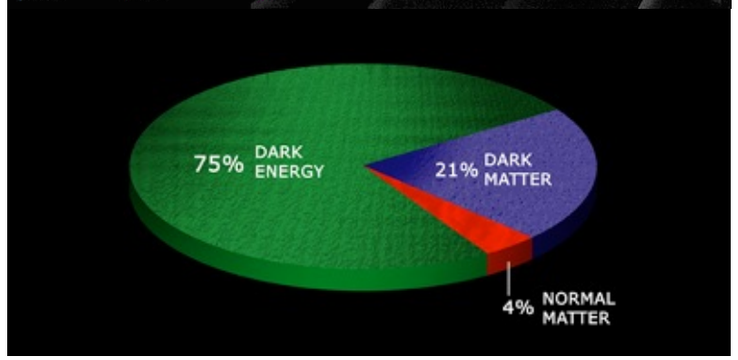
Why string phenomenology?

- String phenomenology aims to embed the SM of Particle Physics and Cosmology within string theory, providing a UV completion for both that also includes Quantum Gravity
- Because string theory is rather complex and rich we do not have a clear or unique prescription on how to achieve this goal







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So how do we proceed?

1. We need to fully understand the theory before trying to connect it with the real world
2. With our current understanding we try to get as close as possible to these SM and realise them as effective theories of string theory

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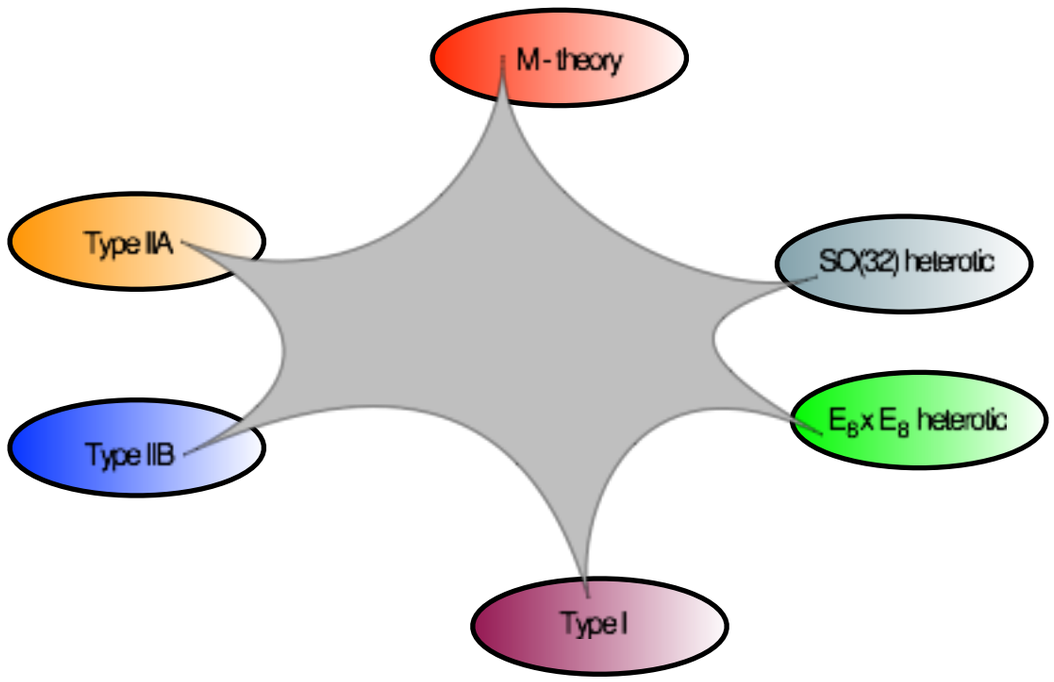
string phenomenologist go for option #2

The quest for the Standard Model

Question: Can we reproduce the SM from string theory?

- To answer this we need to focus on a region of the theory which is under control, and try to reproduce our universe as a string theory vacuum



The quest for the Standard Model

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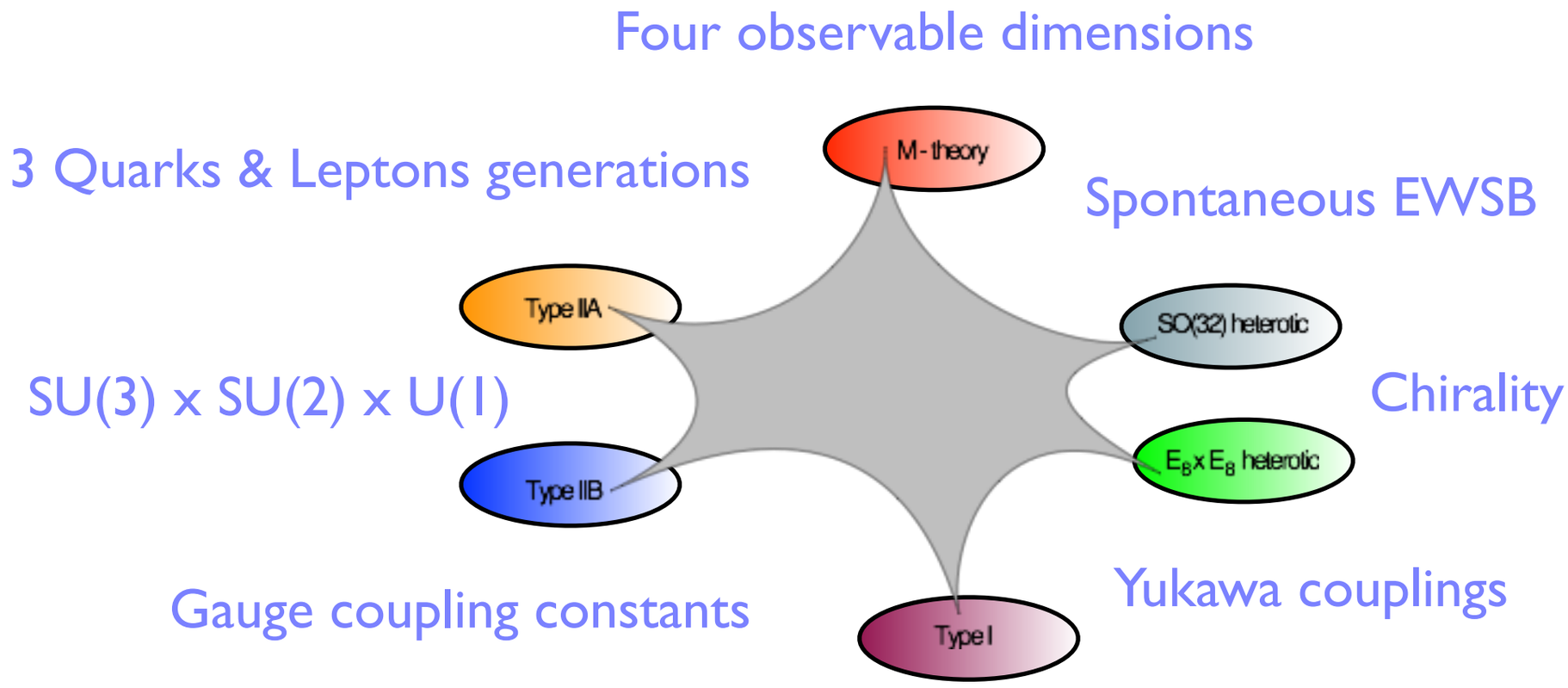
- For the SM of Particle Physics many "ingredients" are needed



The quest for predictions

- String theory does not provide a unique effective 10d theory, and the situation is much more dramatic when we construct effective 4d theories, for which there is a myriad of possibilities
- As a result, even if we know how to construct semi-realistic 4d vacua, there is not a definite consensus nowadays on how to obtain a prediction from string theory

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different approaches:

a) We focus on a vacuum that we particularly like and we try to obtain a whole bunch of BSM predictions from it

b) We try to get an overall picture of the BSM features of 4d vacua, as well as the kind of scenarios that they generate

c) We take and statistical approach on the ensemble of string vacua and try to extract predictions from statistical correlations and from the percentage of vacua with a certain property (e.g., small Λ)

Which superstring is the best?

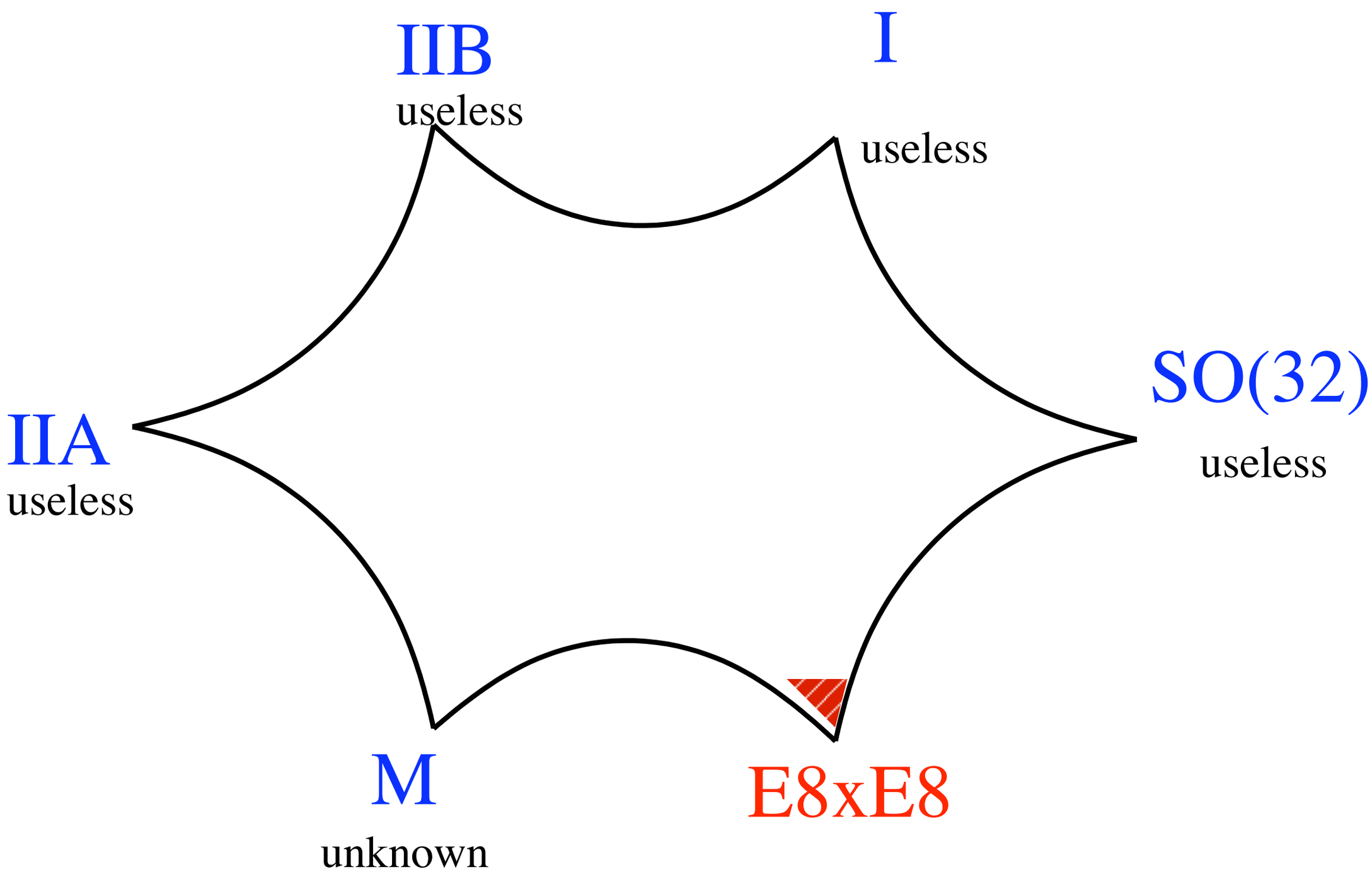
type HE

type HO

type IIB

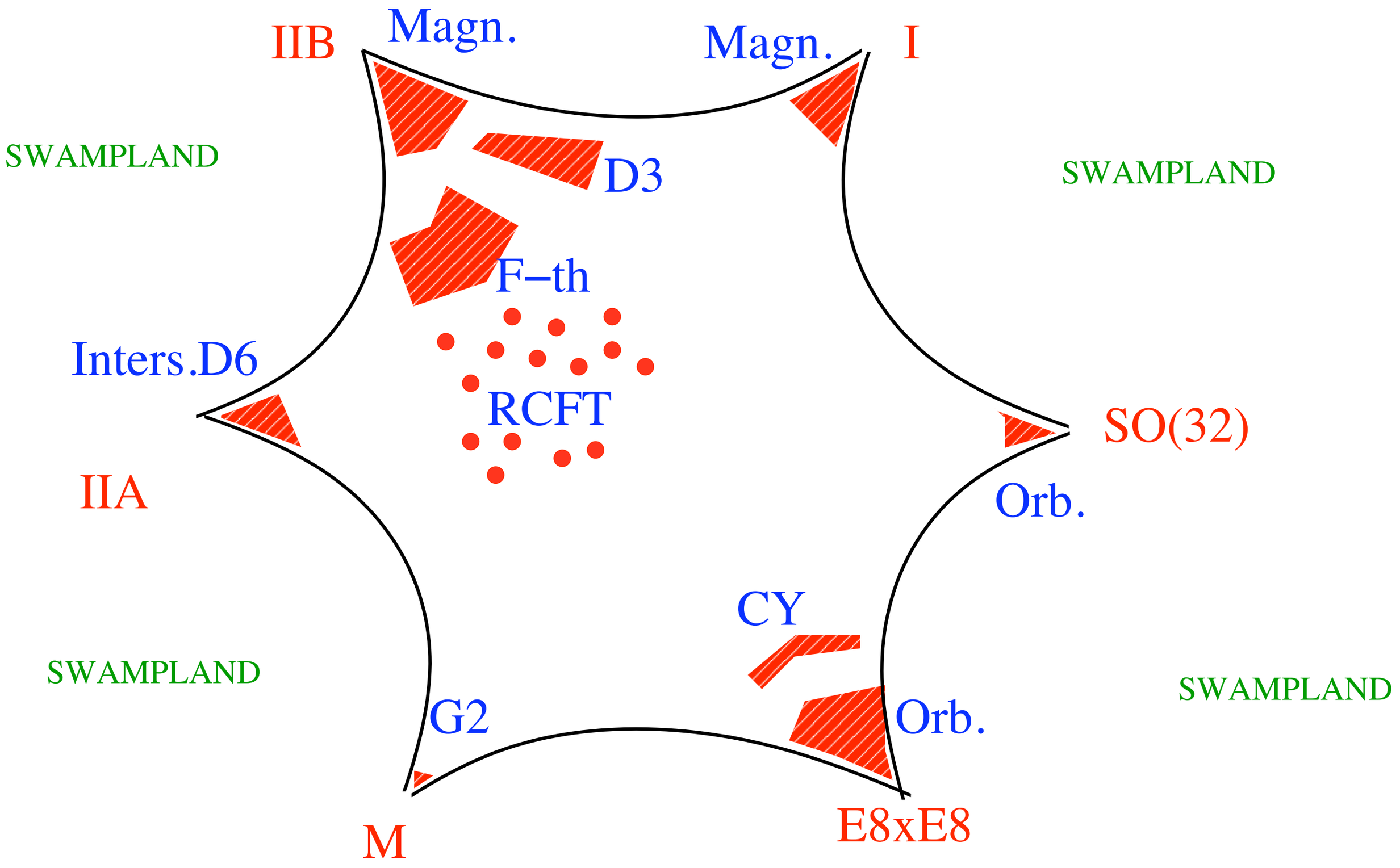
type I

type IIA



Design: L. E. Ibañez

Circa 1995



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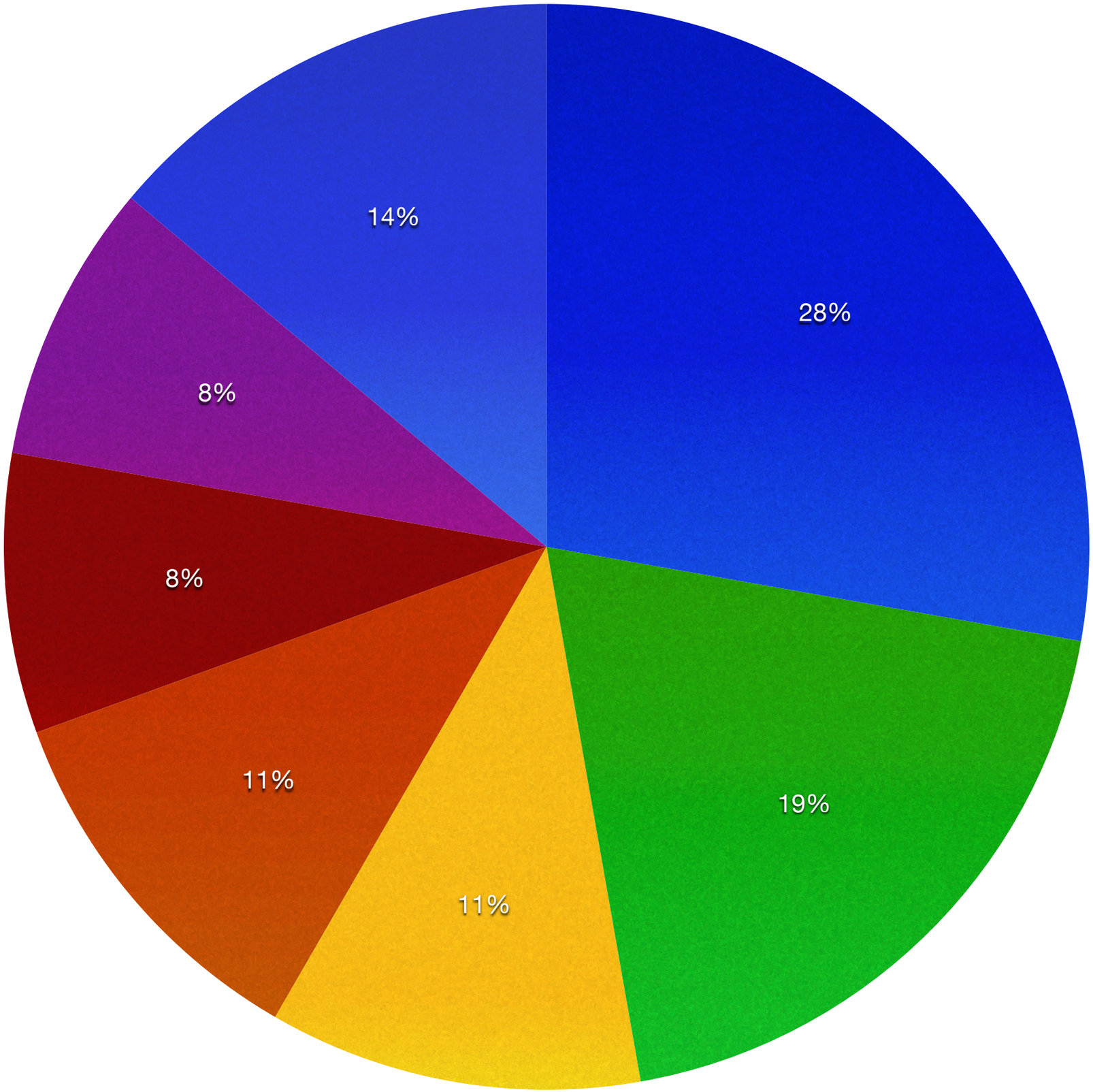
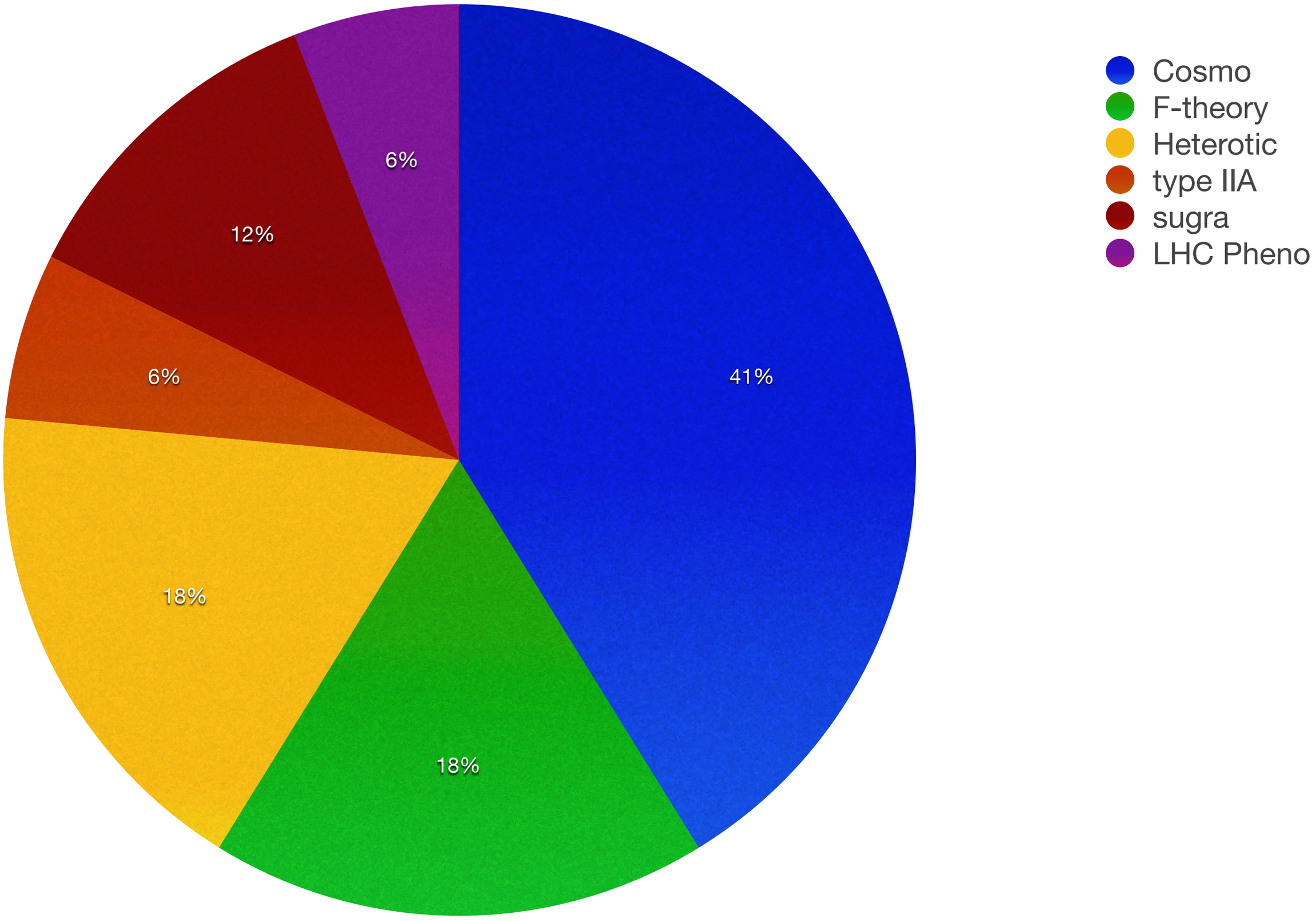
Circa 2014

Plenary talk distribution at String Pheno 2014

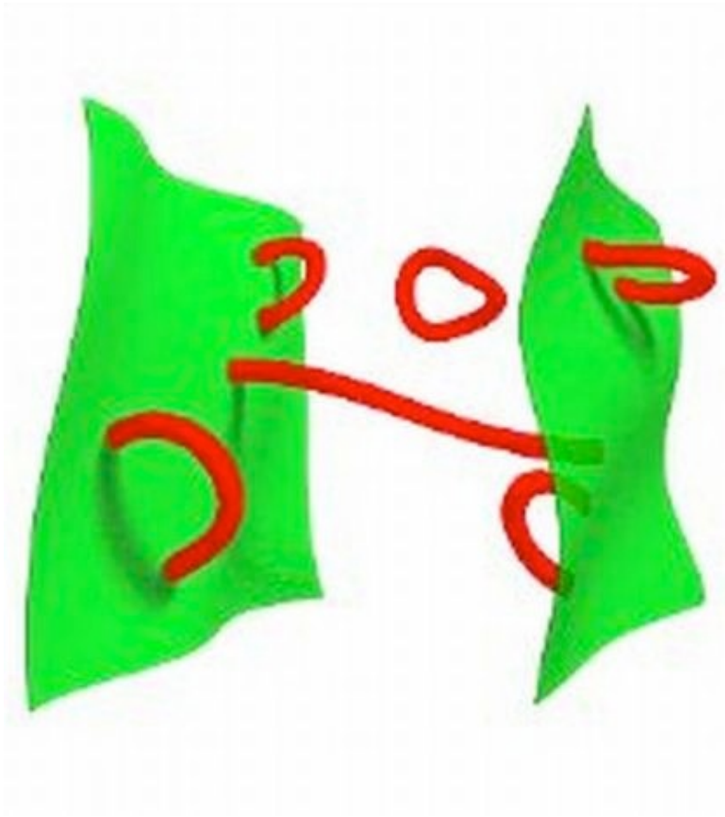


- Cosmo
- F-theory
- Heterotic
- LHC Pheno
- Axions
- Formal
- Other

String pheno talk distribution at STU Conference



From strings to Particle Physics



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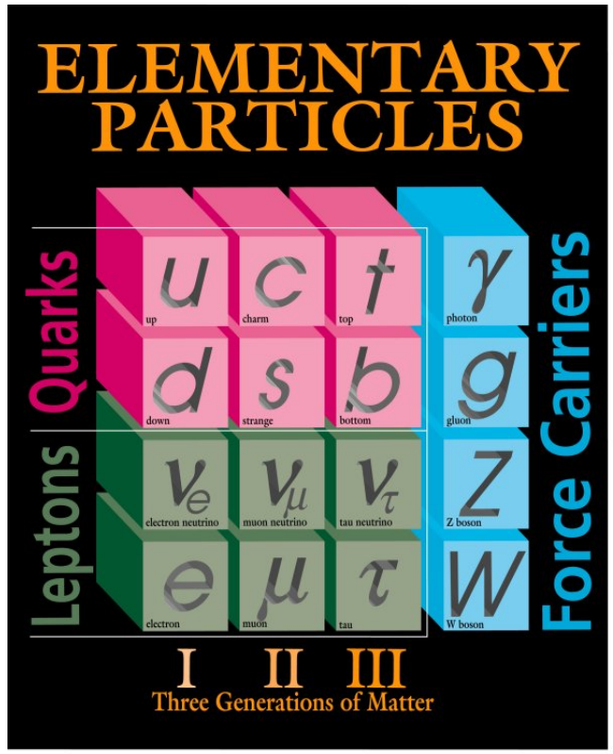
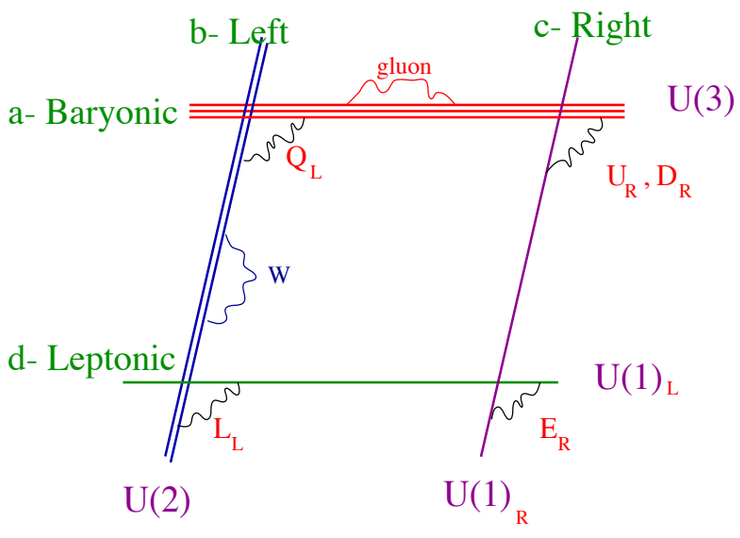
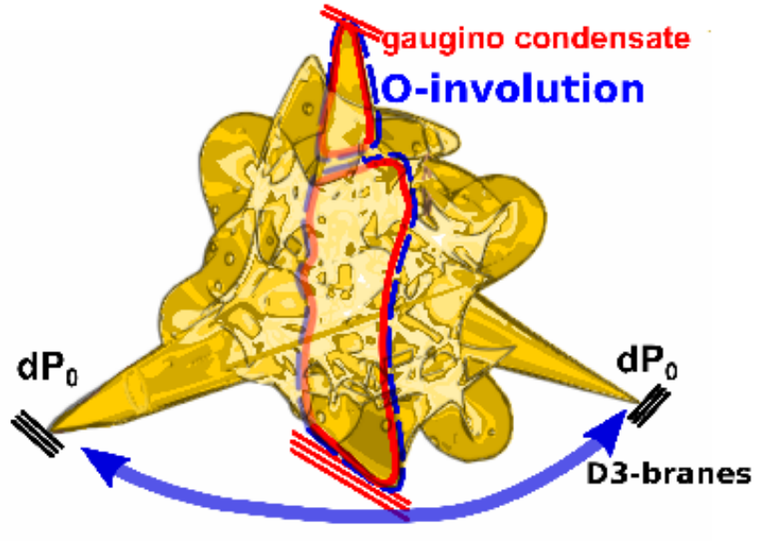


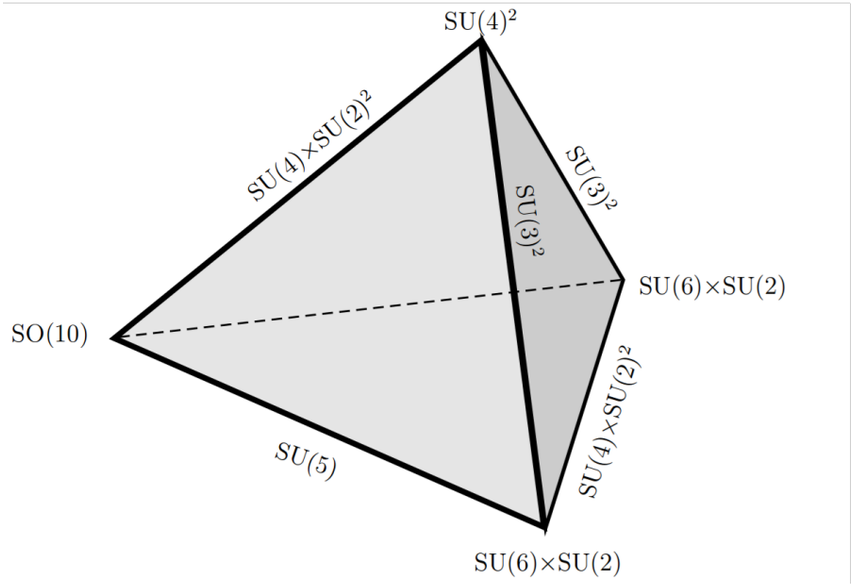
Different approaches to model building

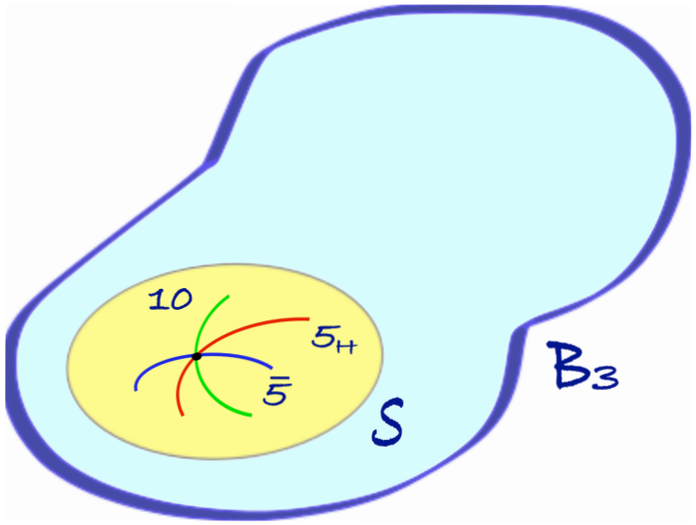




type IIA

type IIB





Heterotic

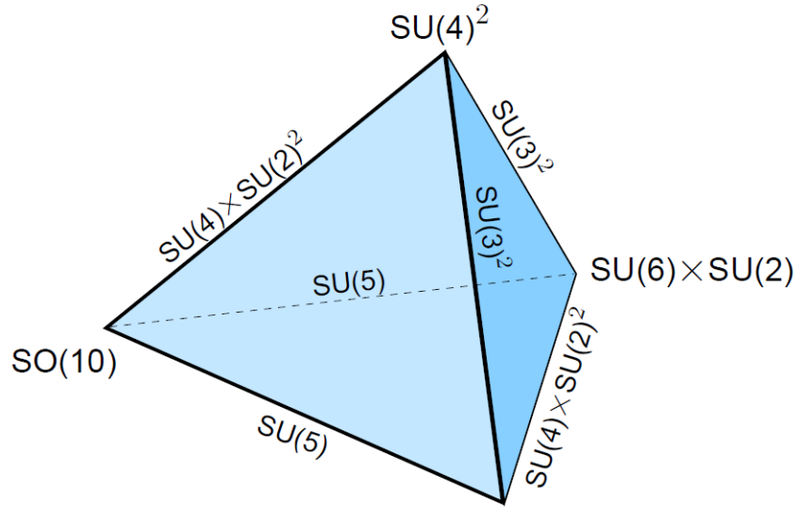
F-theory

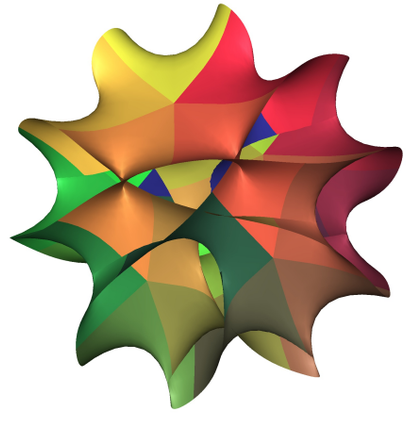
The asset of heterotic: GUTs and history

- Heterotic compactifications have built-in large gauge groups in 10d that are broken to smaller groups when compactifying to 4d chiral vacua.
- This can be used for GUT model-building via a well-defined top-down approach, that has been explored since the early days. This has resulted in a fairly large set of models that come in two main categories
  - Heterotic orbifolds

    CFT exactness
  - Smooth Calabi-Yaus with bundles

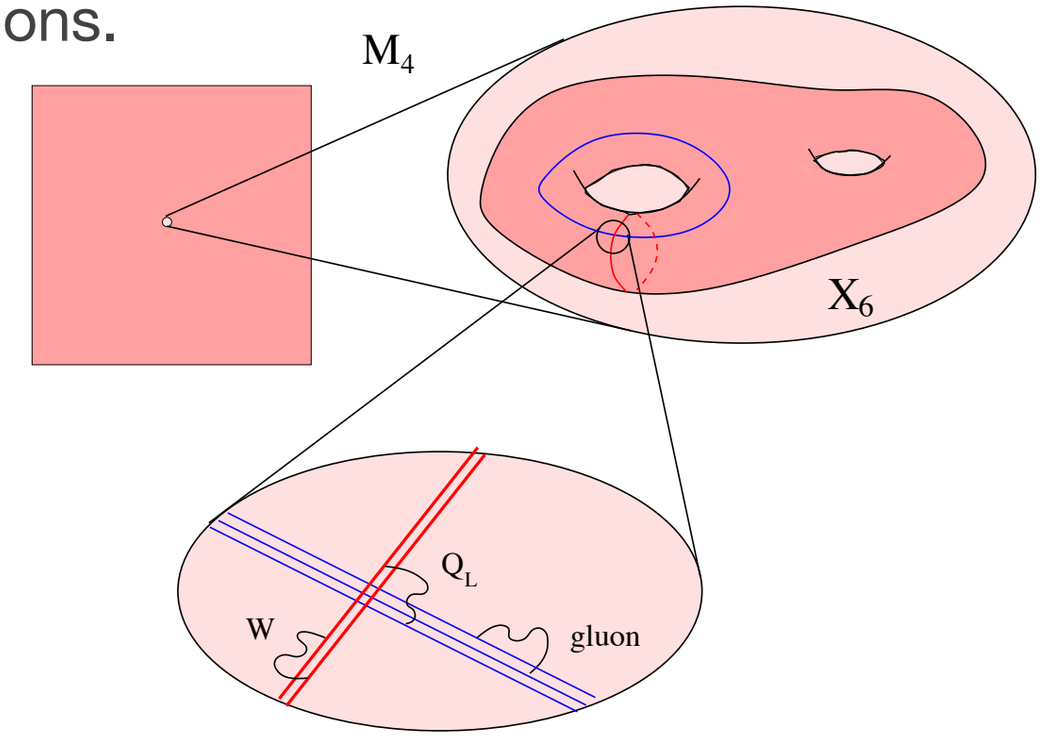
    Algebraic geometry & genericity





The type IIA insight: thinking outside the box

- Type IIA intersecting D6-brane models describe the most relevant features of a model in a very intuitive and pictorial way.
- For instance, they associate chirality to the intersection number of two three-cycles, making manifest that a chiral fermion must be localised in the internal dimensions.



- This property has allowed to conceive new kinds of models, even in other model building approaches, and to understand 4d effective theories in the first place.

The type IIB strength: moduli fixing & locality

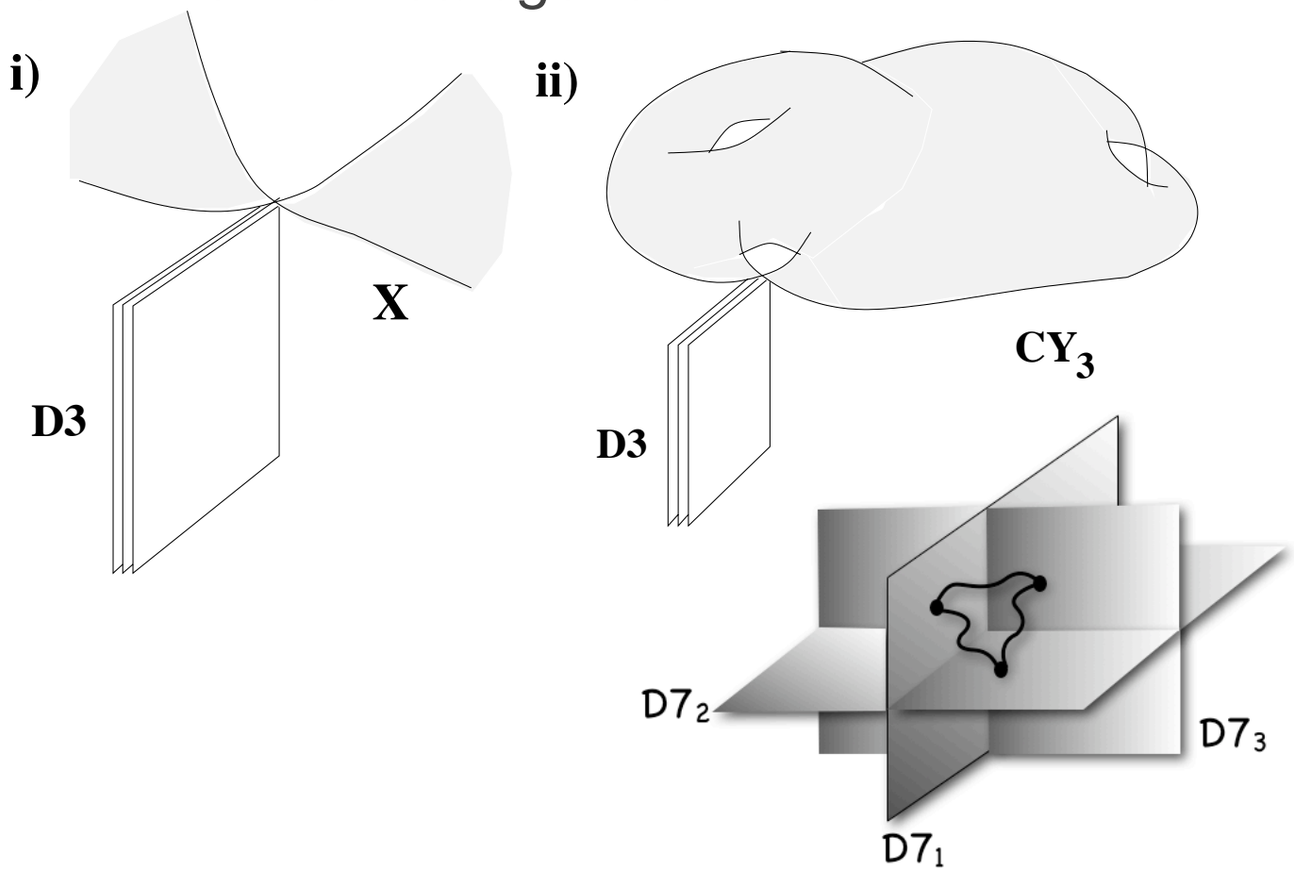
- Type IIB compactifications provide a controlled framework for moduli stabilisation and SUSY breaking. This has opened the gate to more elaborate and complete cosmological models in string theory.
- In addition warped geometries are reasonably well-understood, and one may implement AdS/CFT techniques to describe and understand vacua
- These models are particularly suitable for implementing a bottom-up model building approach, and come in two main categories

- D3-branes at singularities

  large extra dimensions

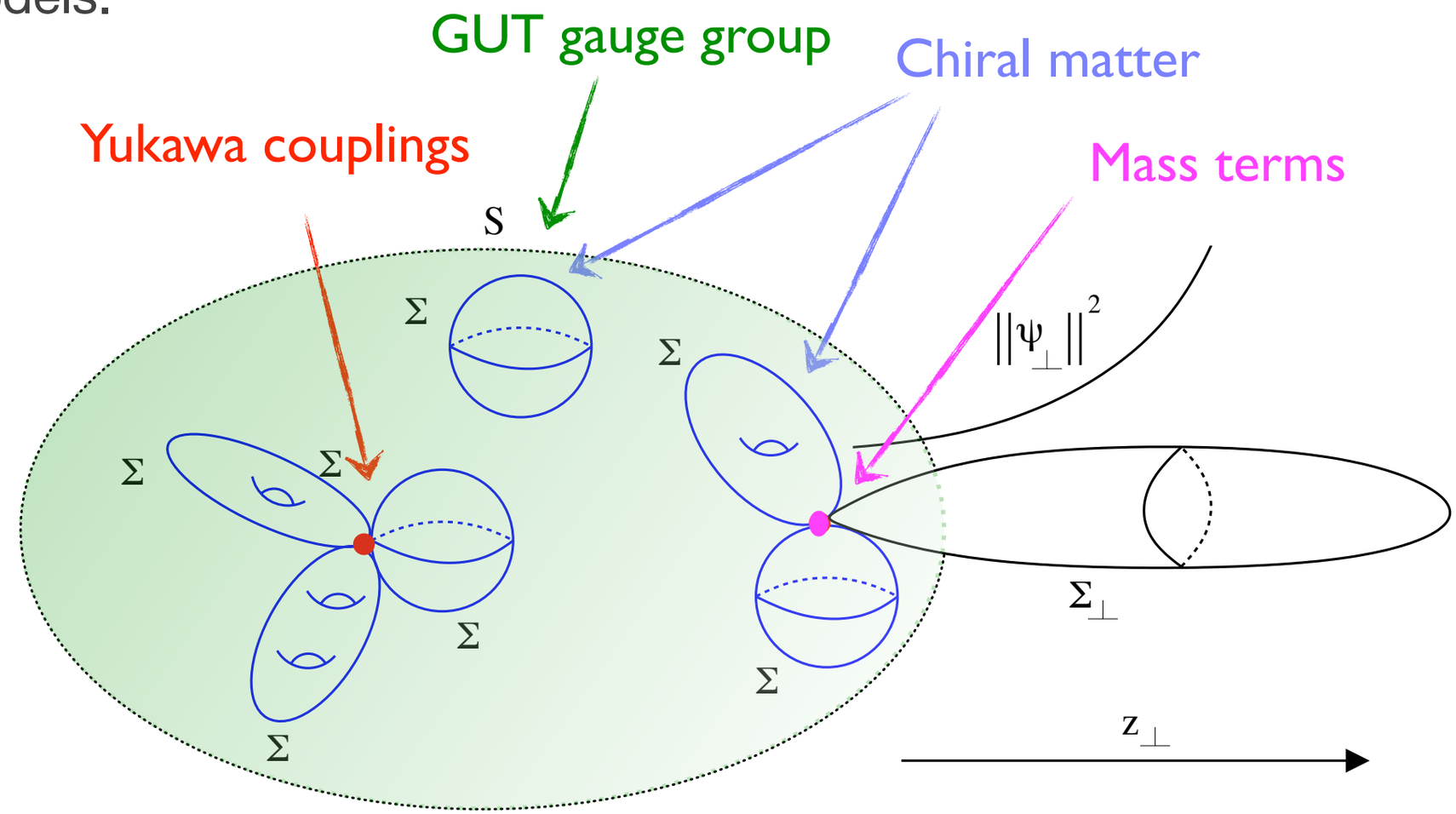
- Intersecting D7-branes

  soft terms via fluxes



The power of F-theory: universality

- F-theory allows to implement a bottom-up approach for GUT models. They accommodate important features like a large top quark Yukawa while in principle keeping many nice features of type IIB models.
- They encode the model building possibilities in the geometry of singular Calabi-Yau four-folds. This allows the techniques of algebraic geometry to construct and classify the landscape of global completions for these local GUT models.

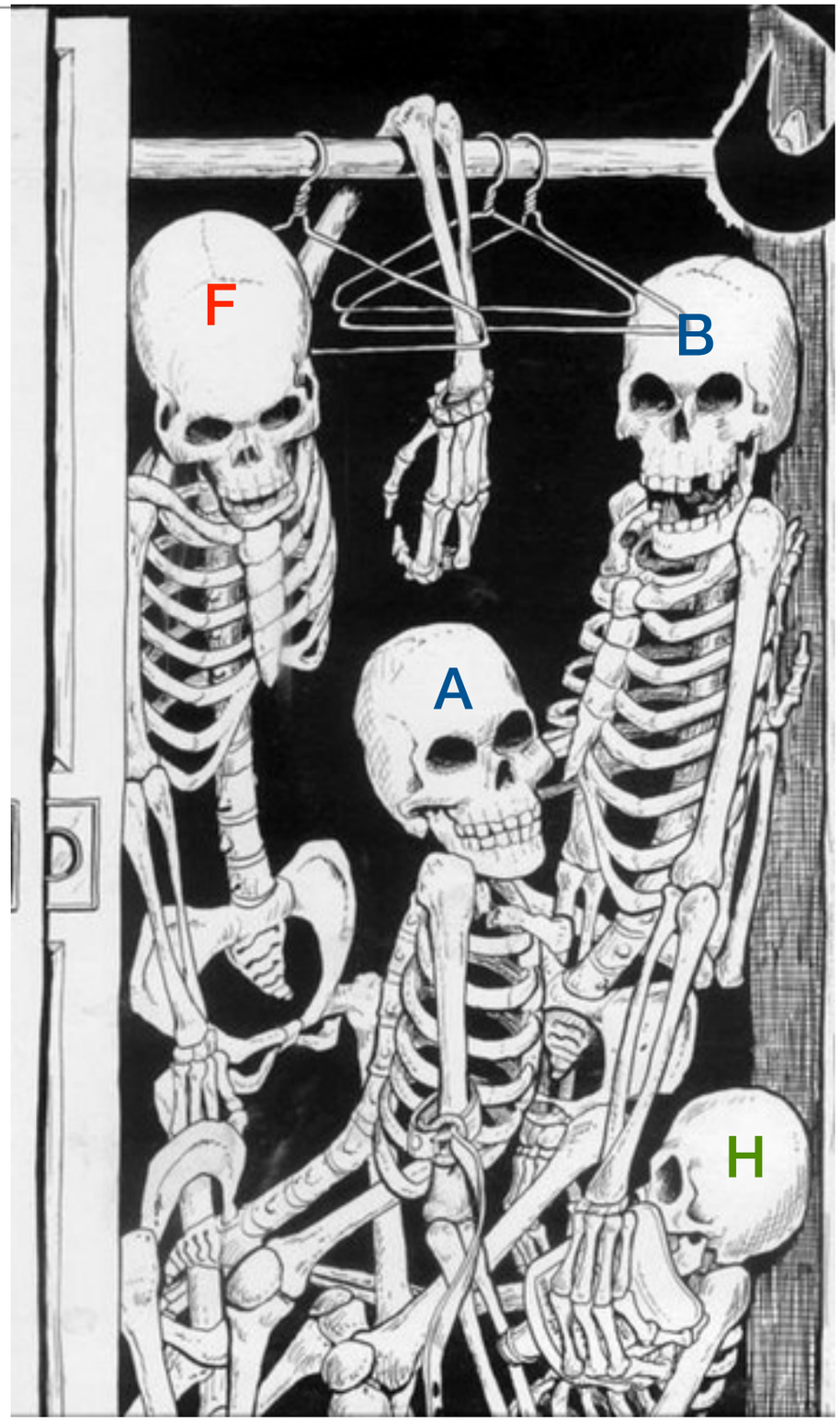


Limitations of each approach

- Each model building approach has different strengths and limitations. Some of the latter are:

Heterotic

- Difficult to implement full moduli stabilisation
- Top-down approach makes difficult to obtain universal results
- Non-orbifold singularities not well understood

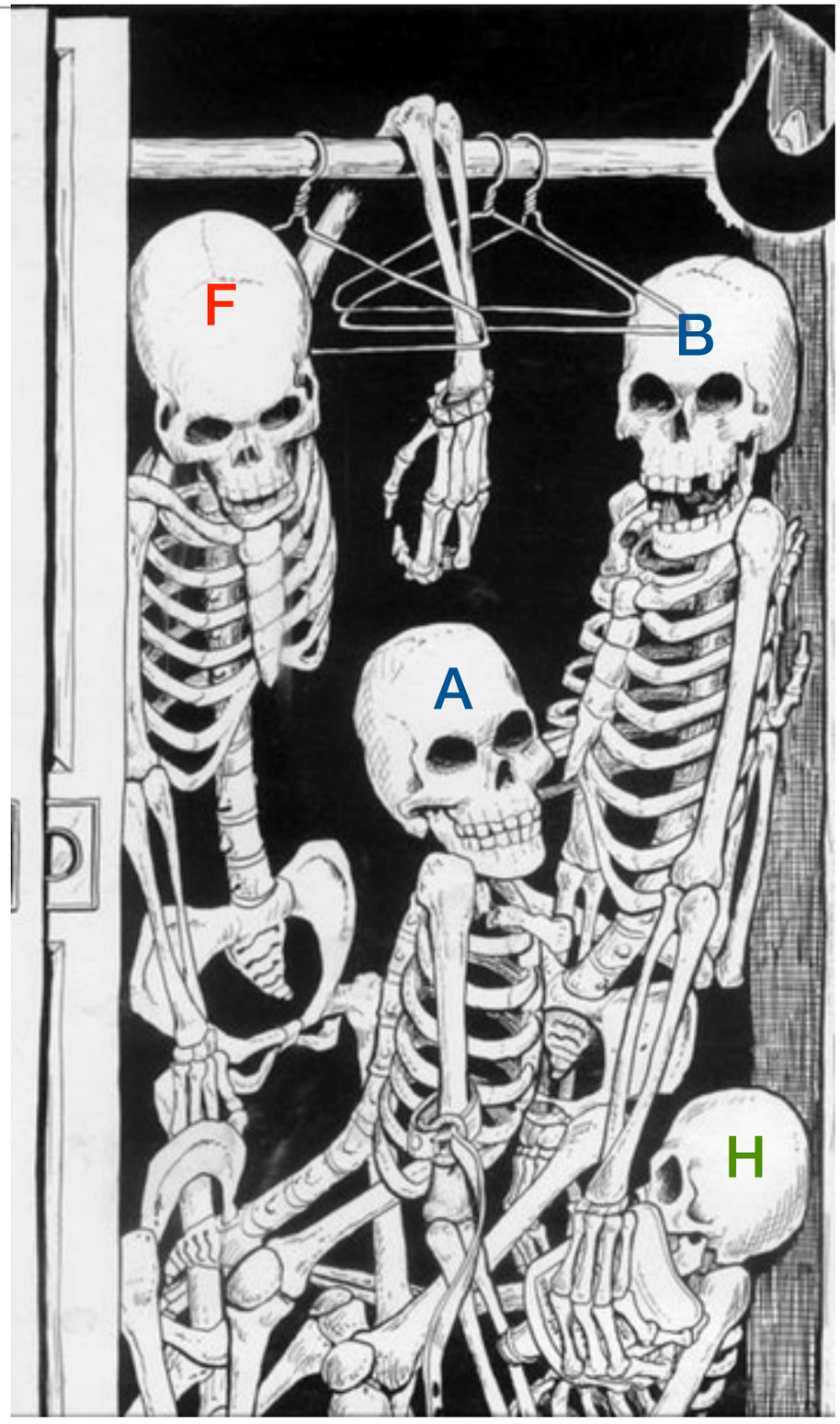


Limitations of each approach

- Each model building approach has different strengths and limitations. Some of the latter are:

type IIB

- GUT models difficult to obtain
  (e.g. top Yukawa forbidden perturbatively)
- Non-perturbative sector not understood systematically

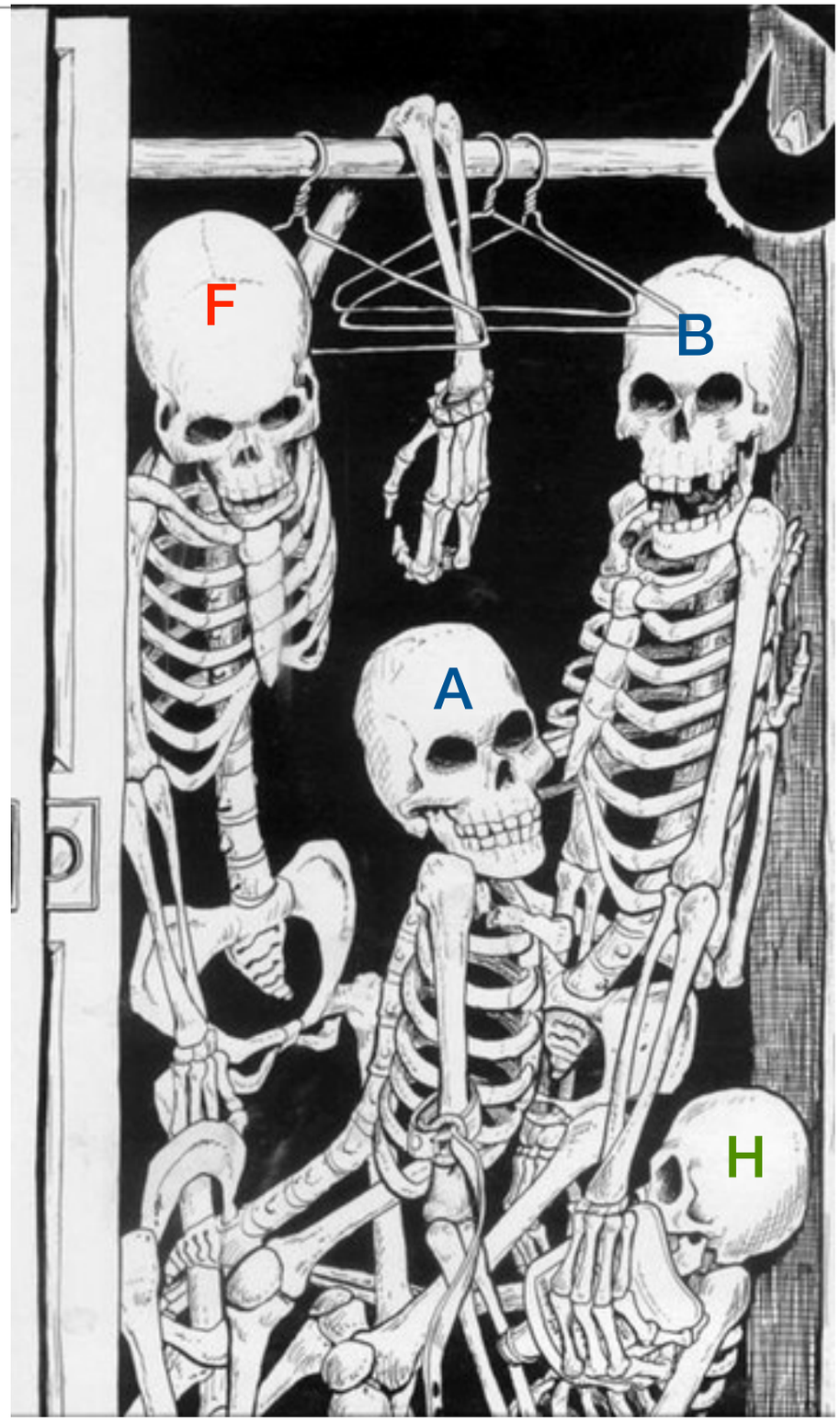


Limitations of each approach

- Each model building approach has different strengths and limitations. Some of the latter are:

type IIA

- Difficult to implement full moduli stabilisation (maybe via non-geometric fluxes)
- Symplectic geometry and hence no algebraic geometry techniques. Difficult to build examples in Calabi-Yau geometries
- Superpotential corrected by world sheet instantons. Difficult to describe an A-brane mathematically

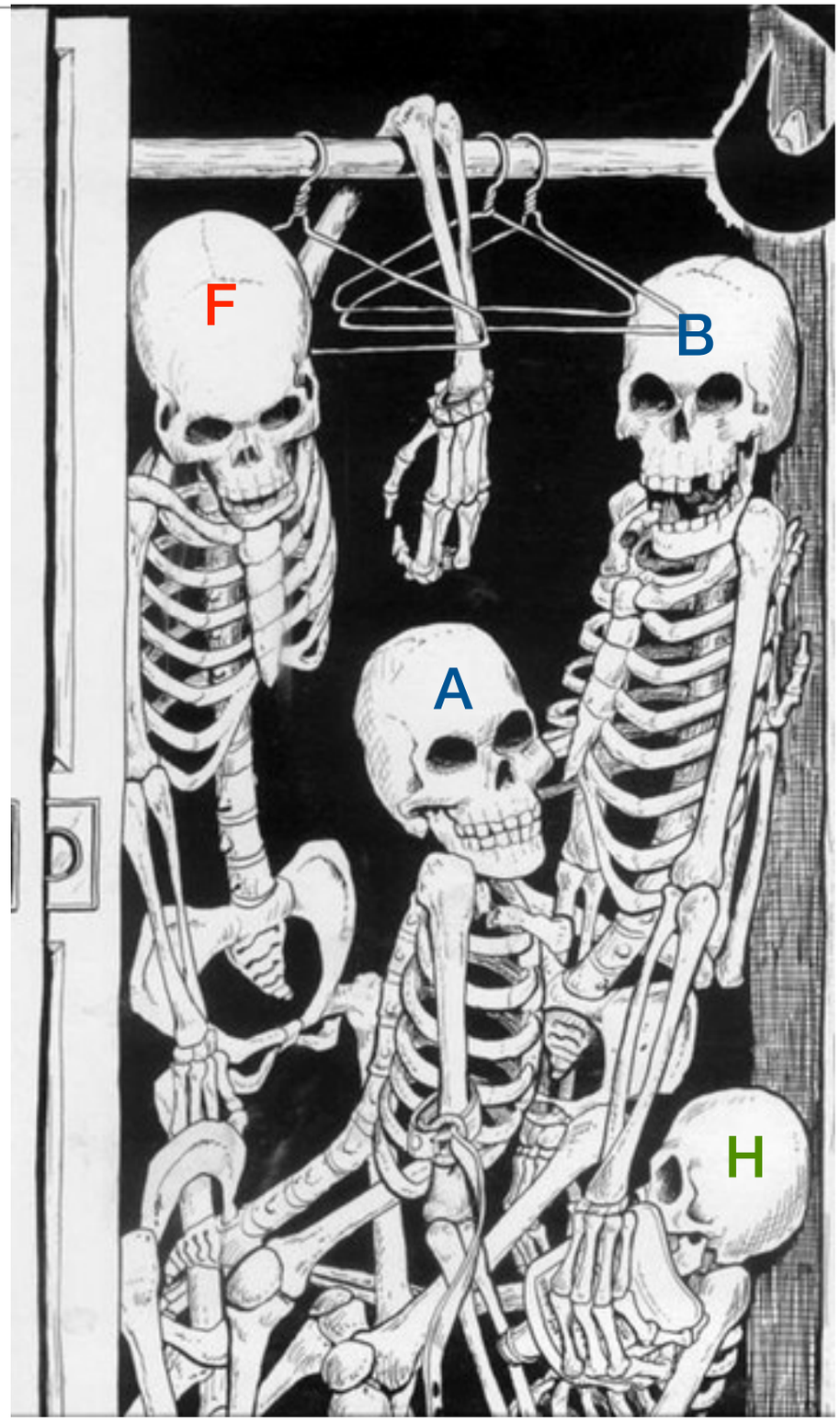


Limitations of each approach

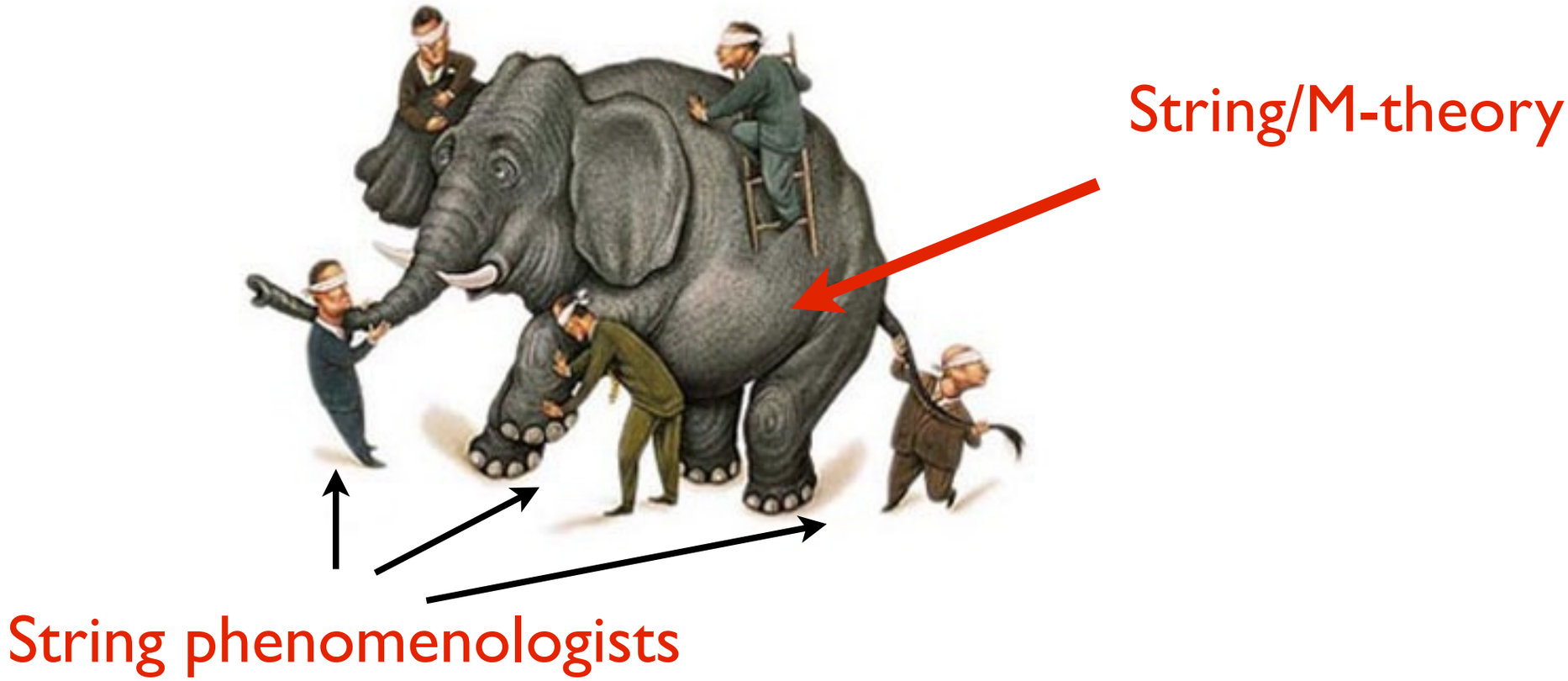
- Each model building approach has different strengths and limitations. Some of the latter are:

F-theory

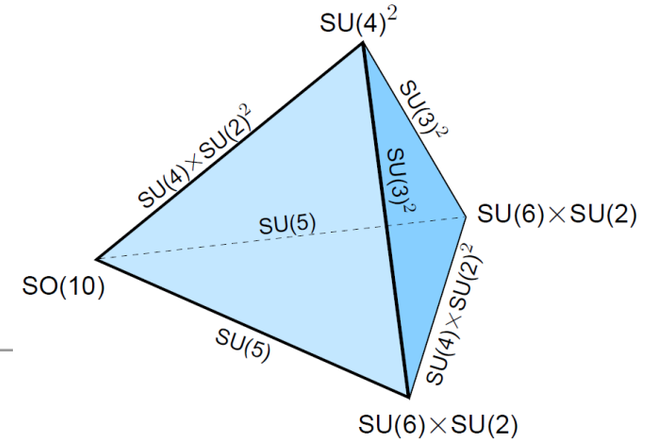
- Difficult to compute bulk non-holomorphic quantities at strong coupling
- Because of that, difficult to study SUSY breaking vacua and models of cosmology



What have we learnt lately?



Progress in heterotic orbifolds



- Large amount of models with MSSM chiral spectrum [Mini-landscape]

Lebedev et al. '08 *Groot-Nibbelink & Loukas '13*

- Systematic analysis via computer technology [Orbifolder]

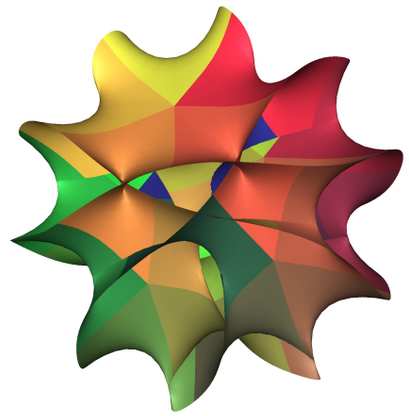
Nilles et al. '13

- Discrete symmetries (non-Abelian flavour and R symmetries) and their geometric origin. Implications for flavour structure

Kobayashi et al. '06 *Mayorga-Peña et al. '12*

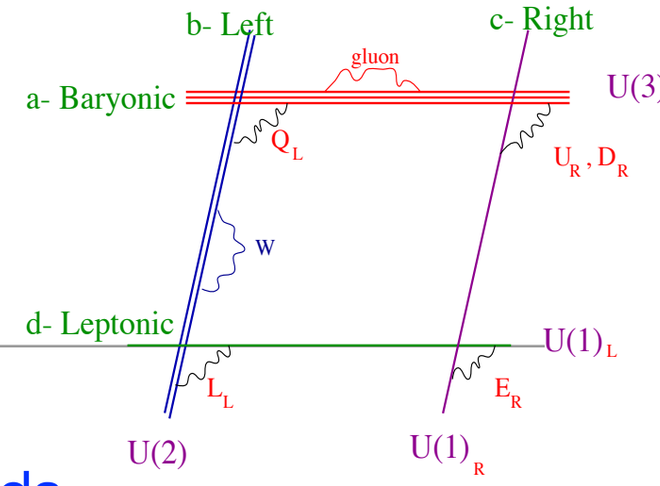
- Relation between orbifold blow-up modes and effective field theory

Progress in heterotic Calabi-Yau's



- Large amount of MSSM-like models beyond the standard embedding with
  - Non-Abelian bundles — *Braun et al. '05-13*
  - Abelian bundles [type IIA input] ~ 35,000 models — *Anderson et al. '11-14*
- Bundle moduli space, and interplay between moduli in the gauge and gravity sector — *Anderson et al. '09-11*
- Related LHC phenomenology — *see Ovrut's talk*
- Construction of stable non-supersymmetric compactifications — *see Groot-Nibbelink's and Blaszczyk's talks*

Progress in type IIA



- Systematic study of MSSM-like models in toroidal orientifolds

  Honecker. et al. '08-14 *see Staessens' talk*

- Systematic scan on MSSM-like models in RCFT orientifolds

  Schellekens et al. '10

- Intuitive framework for crucial developments in the field

  - D-brane instantons
  - Discrete gauge symm.

  } hierarchy of couplings

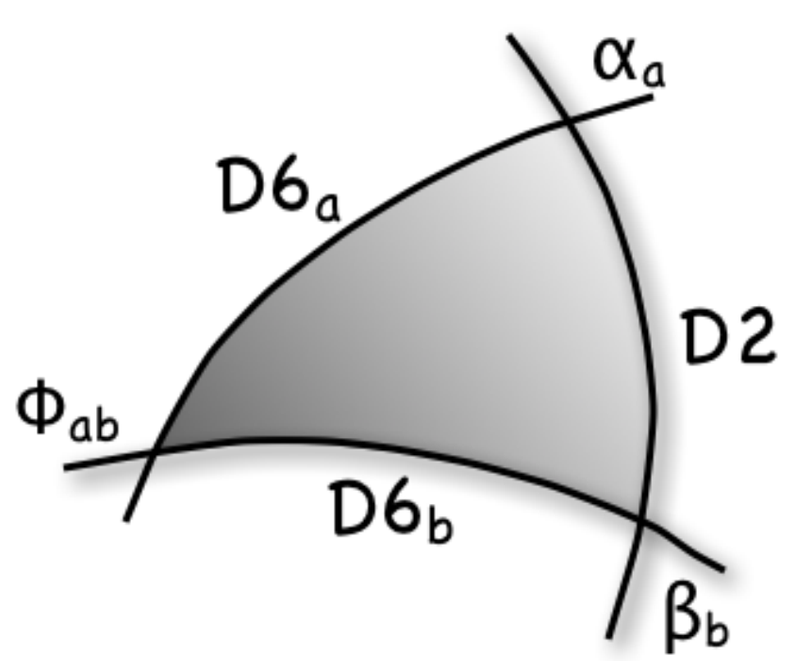
Instantons and discrete gauge symmetries

- D-brane instantons are the only effects that break the global U(1) symmetries of D-brane models, and can generate neutrino Majorana masses, forbidden at the perturbative level by lepton number conservation

$$\nu_R \nu_R \, M_s e^{-2\pi T} \qquad T = \rho + i\phi$$

Blumenhagen, Cvetic, Weigand '06

Ibañez & Uranga '06



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- In general they can break the U(1) completely or to a $\mathbb{Z}_k$ subgroup

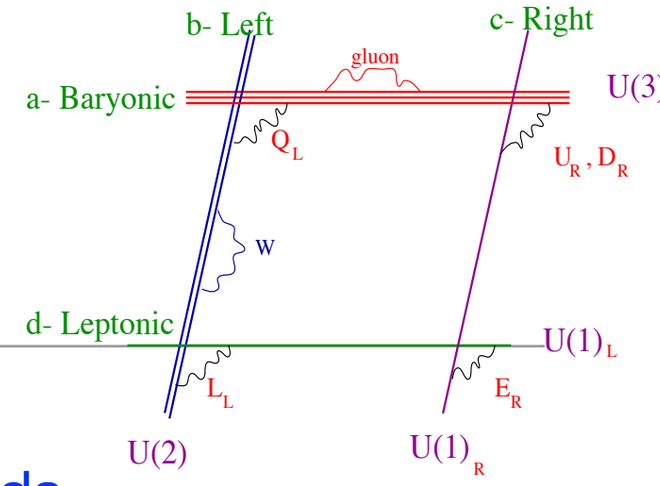
$$\mathcal{L}_{\rm Stk} = \frac{1}{2}(d\phi + kA)$$

Berasaluce-Gonzalez et al. '11

- If k is non-trivial, they still have to preserve a residual $\mathbb{Z}_k$ gauge symmetry
  ⇒ some couplings are forbidden at all levels

Tree level	Y_{ijk}
Non-perturbative	$Y_{ijk}\, e^{-2\pi T}$
Forbidden	0

Progress in type IIA



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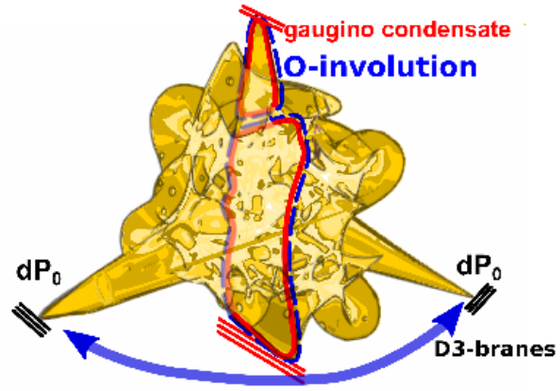
- U(1) mixing and axion physics

  see discussion at Working Group 2

- Systematics of classical de Sitter solutions

  Danielsson et al. '09-12

Progress in type IIB



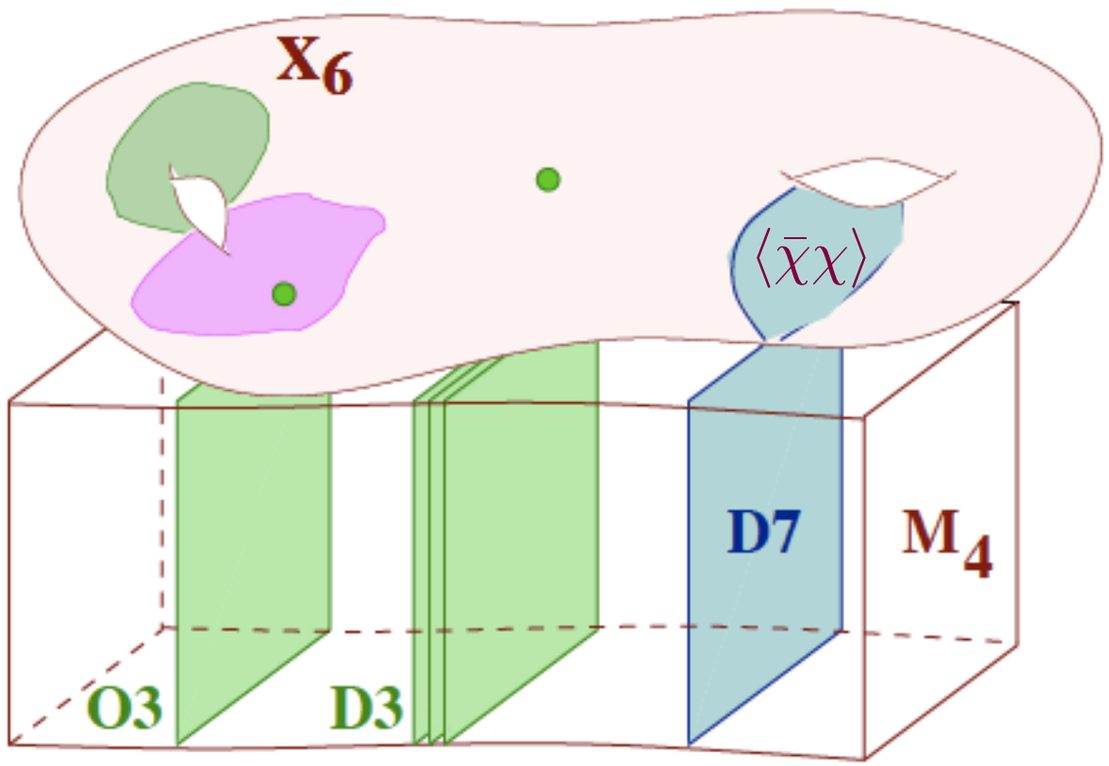
- Type IIB models provide a unique framework to combine particle physics model building with the program on moduli stabilisation & string cosmology

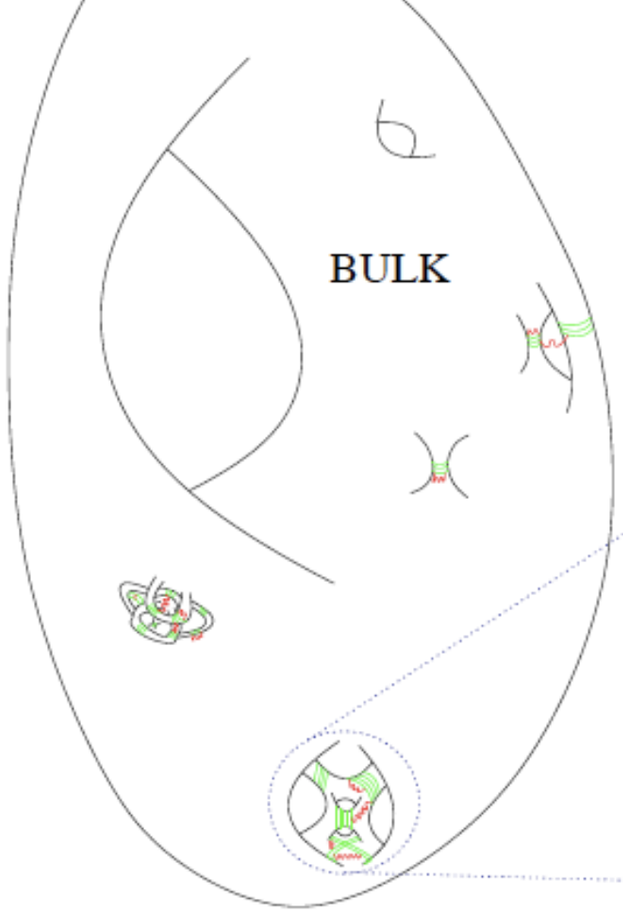
see Zavala's talk

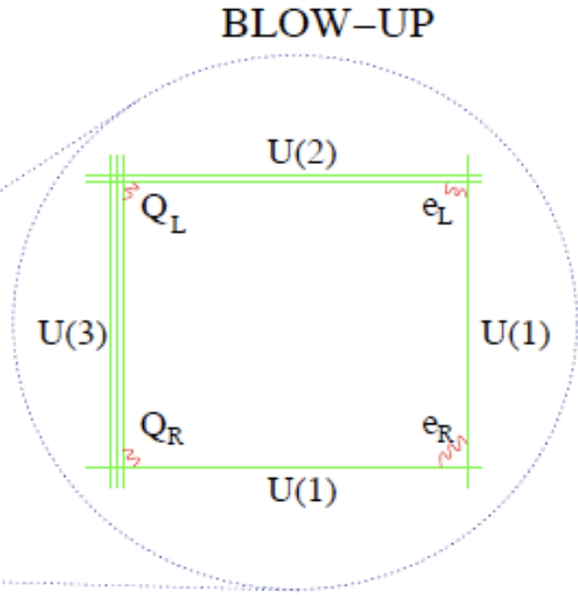
- Singularity model building well developed. Important to understand the global completion of local models

Balasubramanian et al. '12

Cicoli et al. '13







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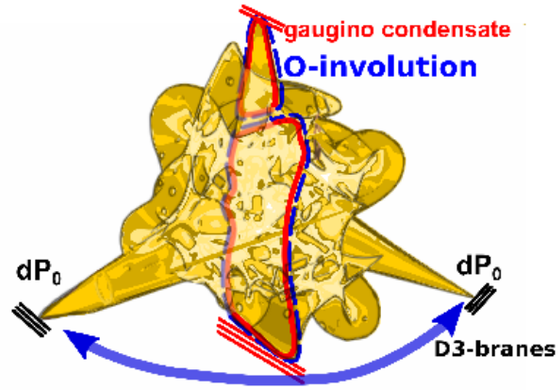

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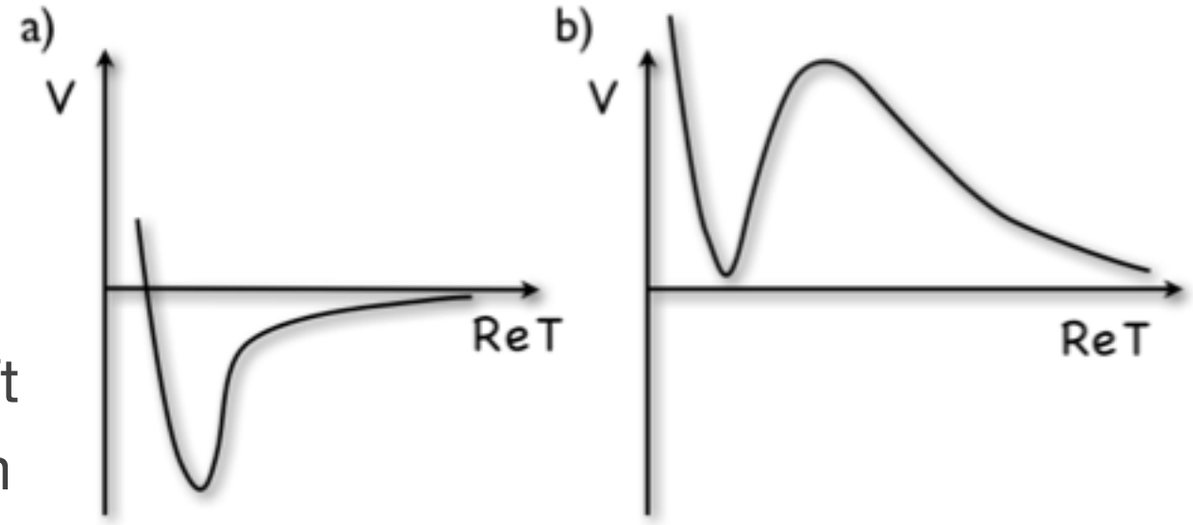
Balasubramanian et al. '12

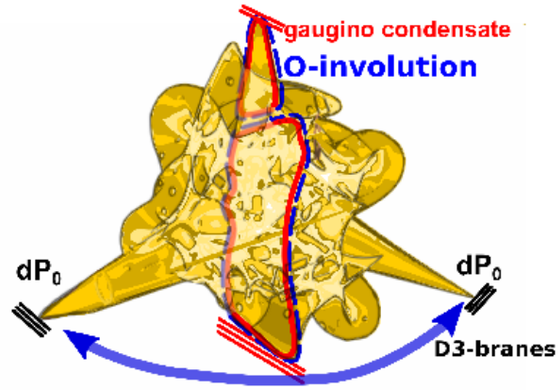
Cicoli et al. '13

- Most popular settings for dS vacua
  - KKLT
  - Large Volume Scenario
- Both need of anti-D3-branes to uplift from AdS to metastable dS_4 vacuum



Ongoing debate on whether anti-D3-brane vacua are metastable

Progress in type IIB



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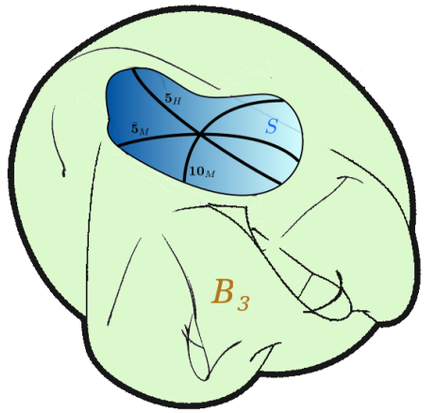
  Balasubramanian et al. '12

  Cicoli et al. '13

- Most popular settings for dS vacua
  - KKLT
  - Large Volume Scenario
- These settings could in principle be realised in other string corners by using generalised geometry techniques. So far not much progress due to lack of existence theorems for manifolds beyond Calabi-Yau
  - Current attempt: non-geometric backgrounds *Blumenhagen, Lüst et al. '11-14*

Progress in type IIB



- Type IIB models are also particularly suitable to analyse SUSY breaking effects on particle physics models

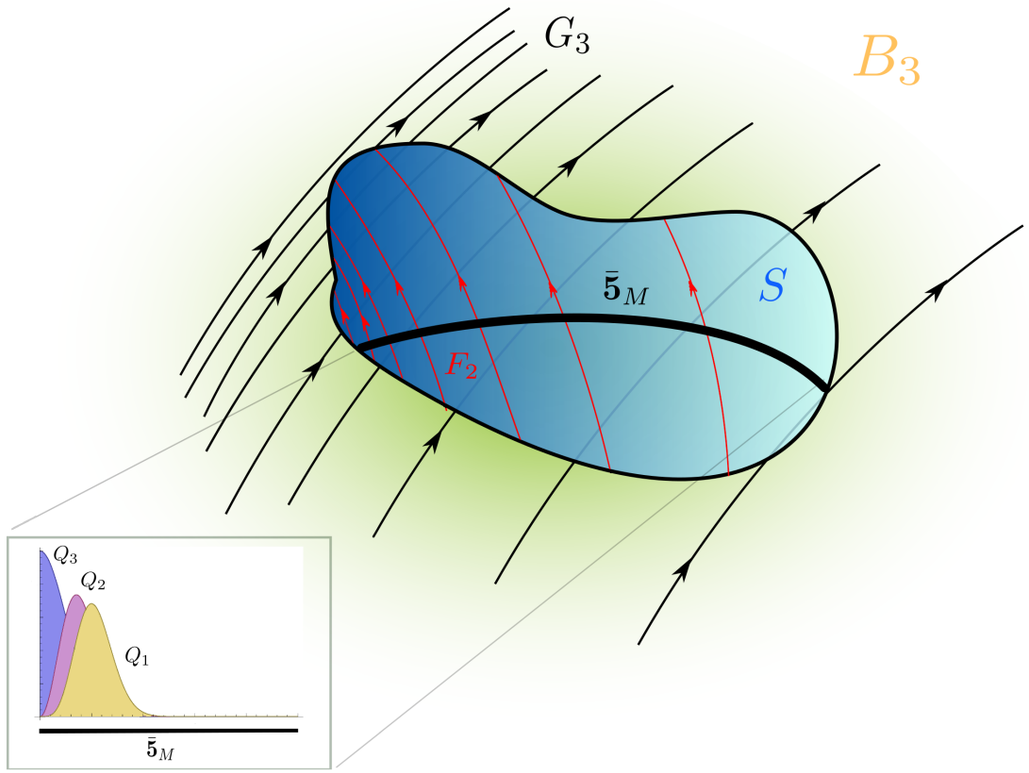
  - Flux-induced SUSY breaking soft terms can be computed microscopically on D7-brane models → flavour dependence

    Camara et al. '04-13

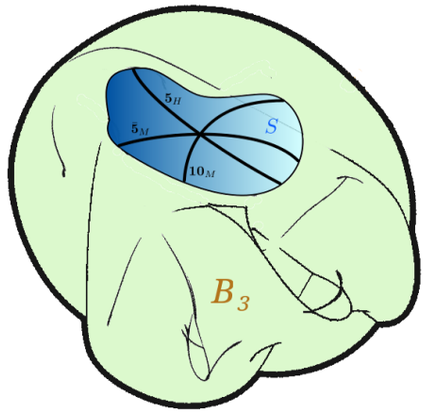
  - D3-brane at singularity models may present the feature of sequestering → microscopic understanding still to be developed

    Blumenhagen et al. '09

    Aparicio et al. '14



Progress in type IIB



- Type IIB models are also particularly suitable to analyse SUSY breaking effects on particle physics models

  - Flux-induced SUSY breaking soft terms can be computed microscopically on D7-brane models → flavour dependence

    Camara et al. '04-13

  - D3-brane at singularity models may present the feature of sequestering → microscopic understanding still to be developed

    Blumenhagen et al. '09
    Aparicio et al. '14

- Control over warping allows to endeavour the computation of warped effective actions, as well as to apply holographic techniques

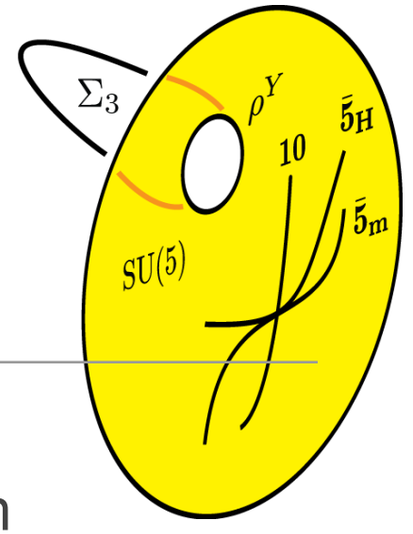
  - Holographic duals of the SM

    Cascales, Saad, Uranga '05
    Garcia-Etxebarria, Saad, Uranga '06

  - Holographic gauge mediation

    Benini et al. '09

Progress in F-theory



- F-theory provides the most direct strategy to build GUT models with universal features, thanks to the bottom-up approach

- New mechanism for GUT-breaking: hypercharge flux
  → new possibilities for doublet-triplet splitting

Donagi & Wijnholt '08
Beasley, Heckman, Vafa '08

- Large top Yukawa and hierarchical mass spectrum $\mathcal{O}(1), \mathcal{O}(\epsilon), \mathcal{O}(\epsilon^2)$

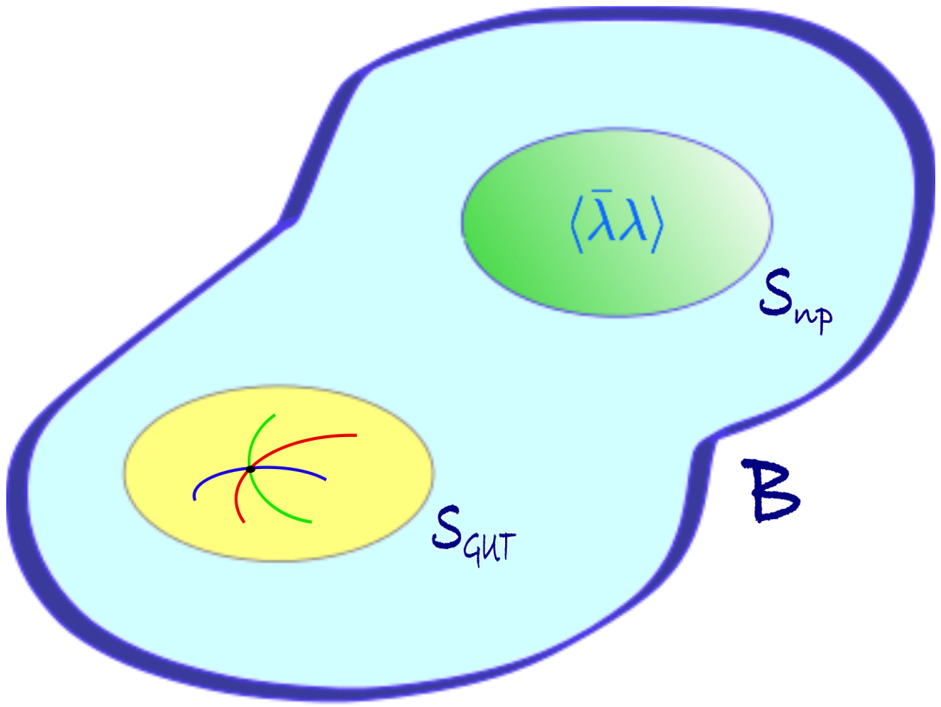
  - Rank 1 Yukawas via topological conditions

Cecotti et al. '10

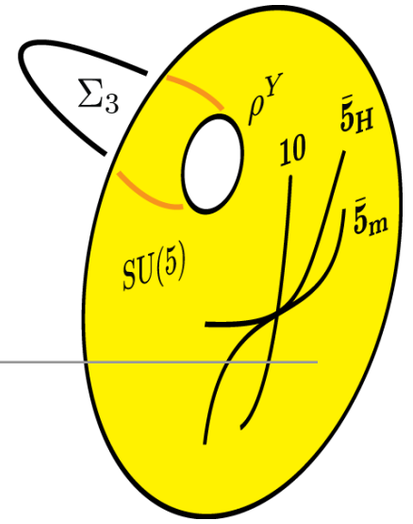
  - Non-perturbative effects increasing the rank

F.M. & Martucci '10
Font et al. '12-13

  - Deviation from 4d GUT relations thanks to hypercharge flux dependence of masses



Progress in F-theory



- In principle, F-theory contain all the nice features of type IIB models

- Most of the recent effort has been devoted to develop the basic model building rules and to translate effective 4d field theory quantities (couplings, spectra, etc.) into the geometry of singular, elliptically fibered CY 4-folds

too many references *see Klevers' & Mayrhofer's talks*

- Interesting output: Abelian and non-Abelian gauge symmetries are quite different from the microscopic viewpoint

  - Non-Abelian → localised in internal dimensions

  - Abelian → not localised *see Cvetic's talk*

this is in fact also true in type II models, despite naive intuition…

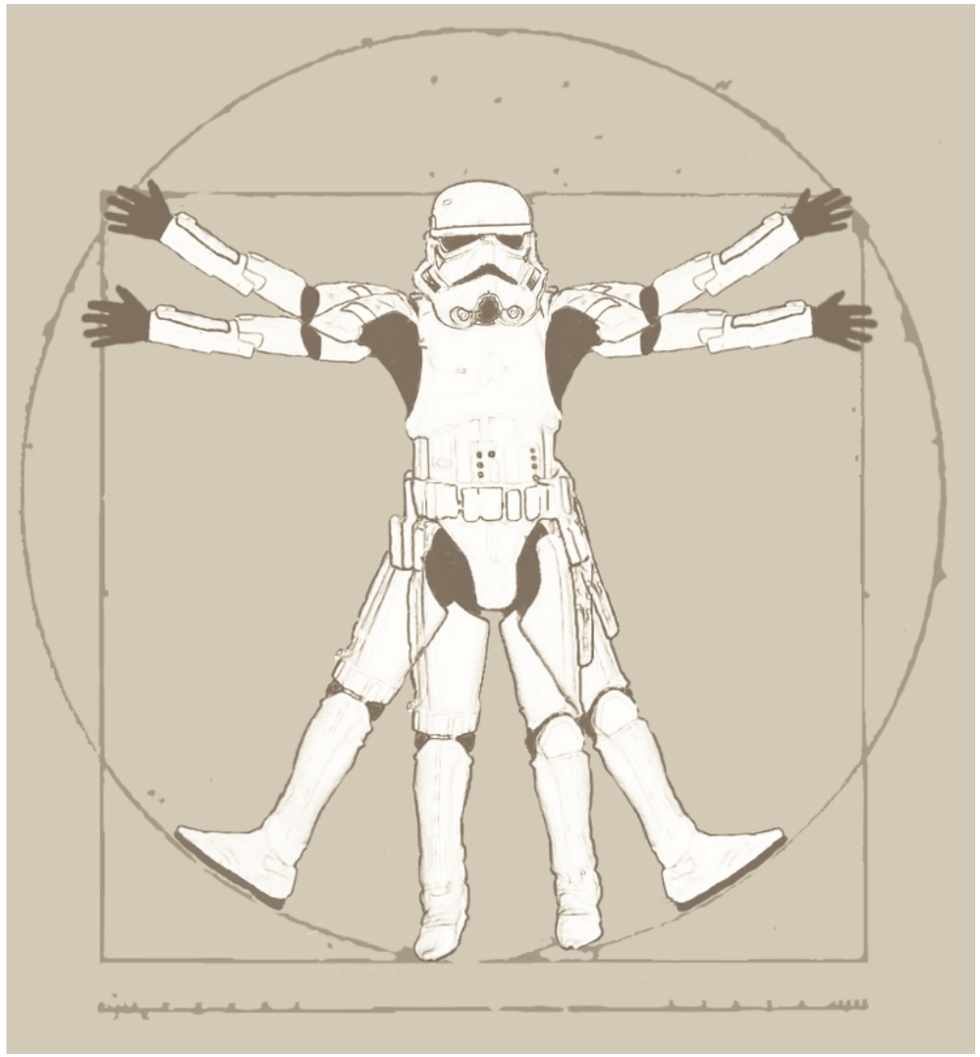
What are the open questions?

The String Landscape

- Is there a landscape with… ?
  - Reasonable cosmological constant
  - Standard Model spectrum

- If no, which dynamical vacuum selection principle are we missing?

- If yes, do environmental/anthropic selection principles play a role in explaining observable physics?
  To which quantities do they affect?



Other open questions

- Why is de Sitter so hard to get?
- What is the SUSY breaking scale?
  - Low
  - Intermediate
  - High
- What is the most natural string scale?
- Is gauge coupling unification favoured?
- Which input does the Higgs mass give?
- Small vs. large field inflation
- …

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STRING PHENO 2015

8-12 JUNE, MADRID