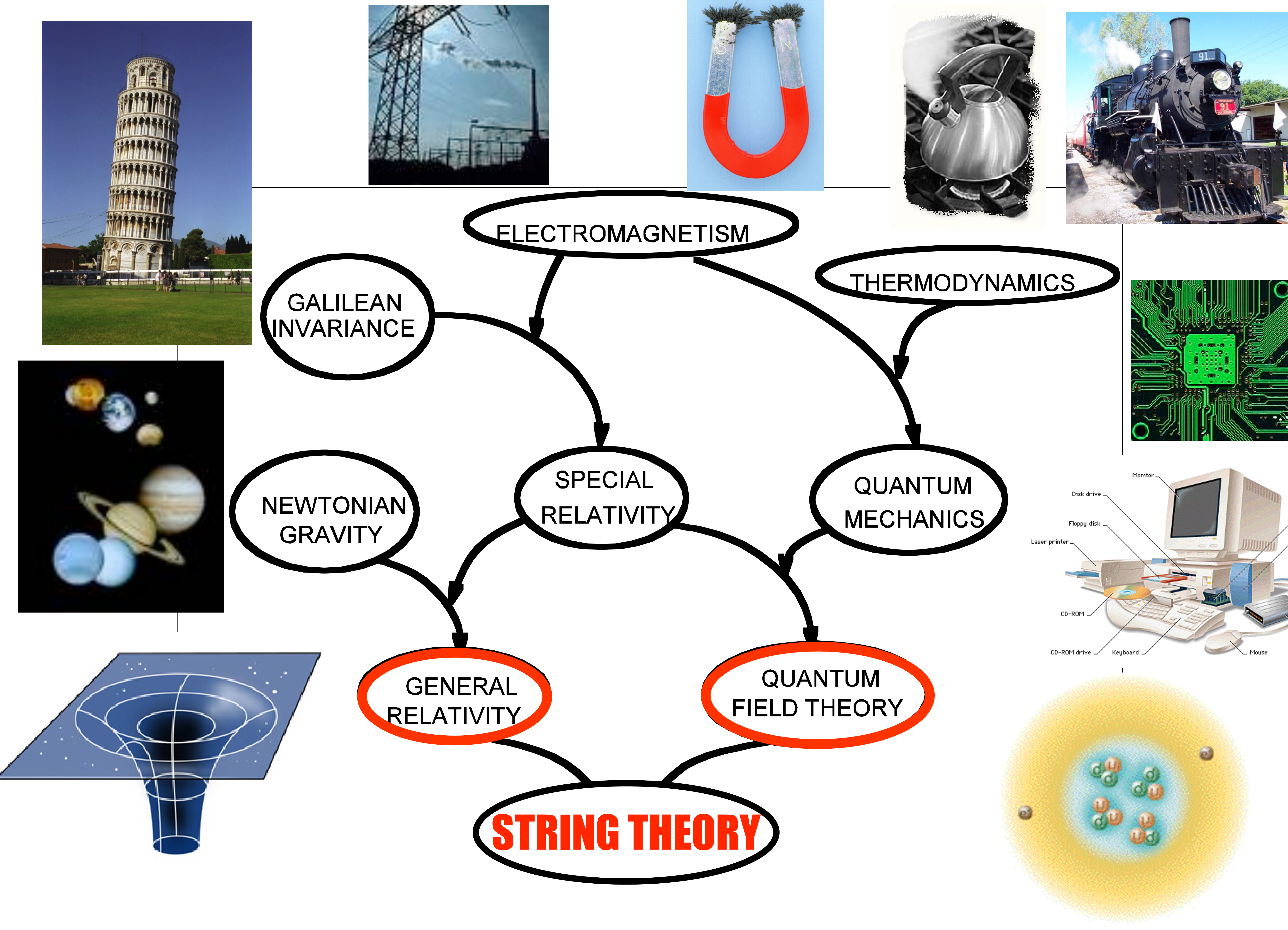
string phenomenology today

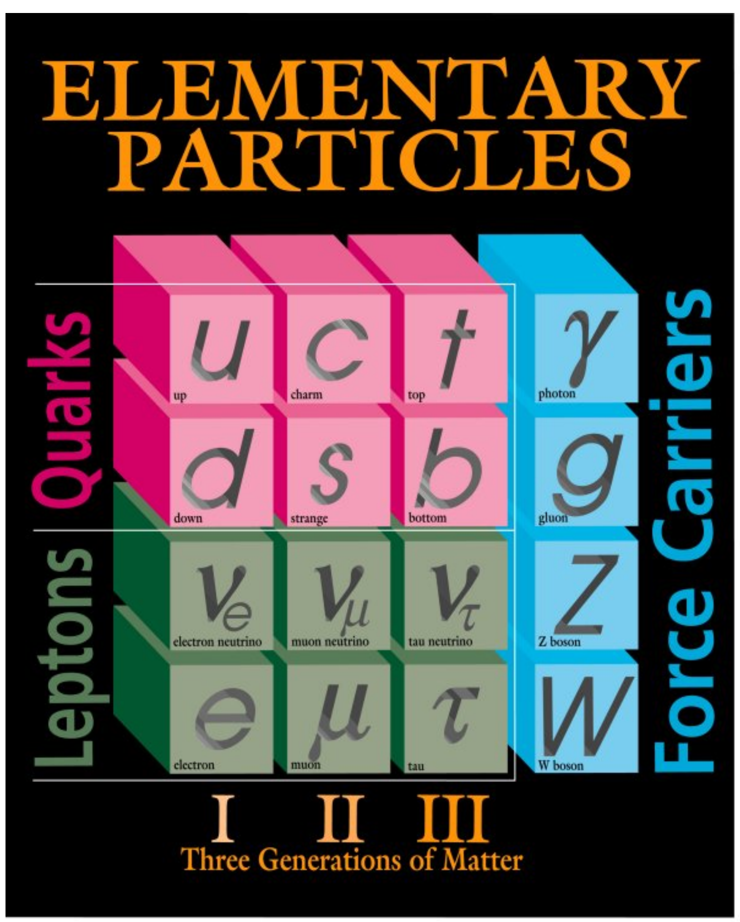
fernando marchesano

Instituto de Física Teórica
UAM-CSIC


ELECTROMAGNETISM
GALILEAN INVARIANCE
THERMODYNAMICS
NEWTONIAN GRAVITY
SPECIAL RELATIVITY
QUANTUM MECHANICS
GENERAL RELATIVITY
QUANTUM FIELD THEORY
STRING THEORY
Monitor
Disk drive
Floppy disk
Laser printer
CD-ROM
CD-ROM drive
Keyboard
Mouse

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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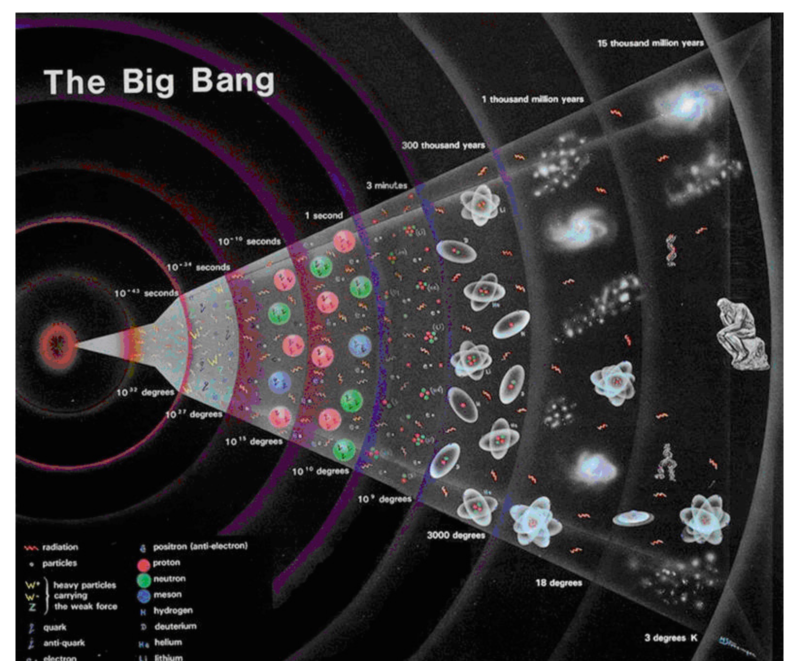

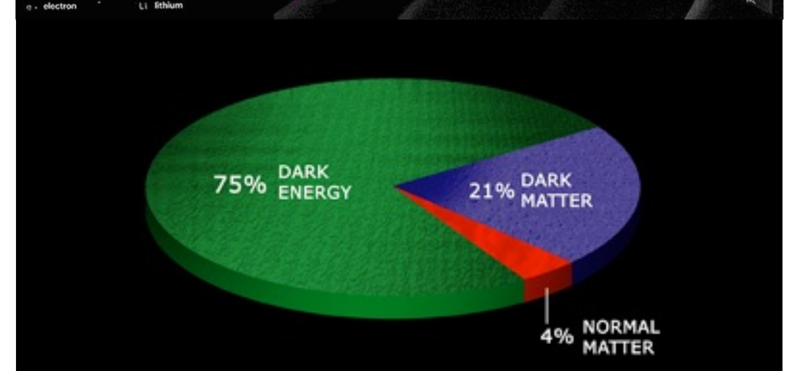

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So how do we proceed?

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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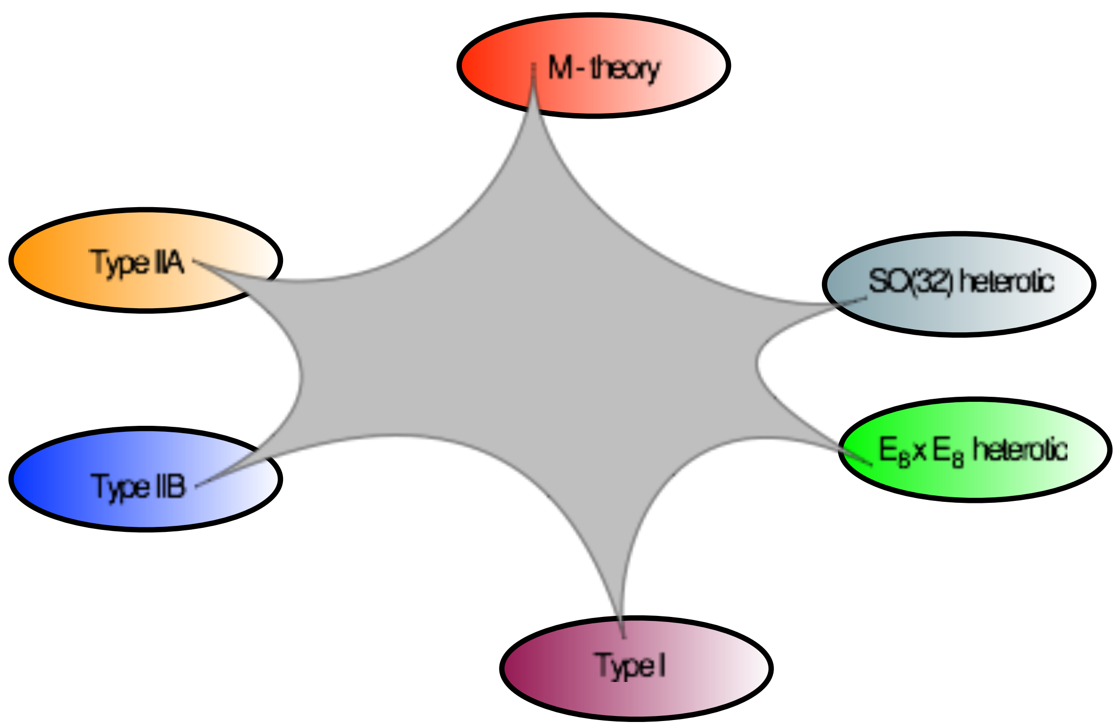
string phenomenologist go for option #2

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

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
- For the SM of Particle Physics many “ingredients” are needed

Four observable dimensions

3 Quarks & Leptons generations

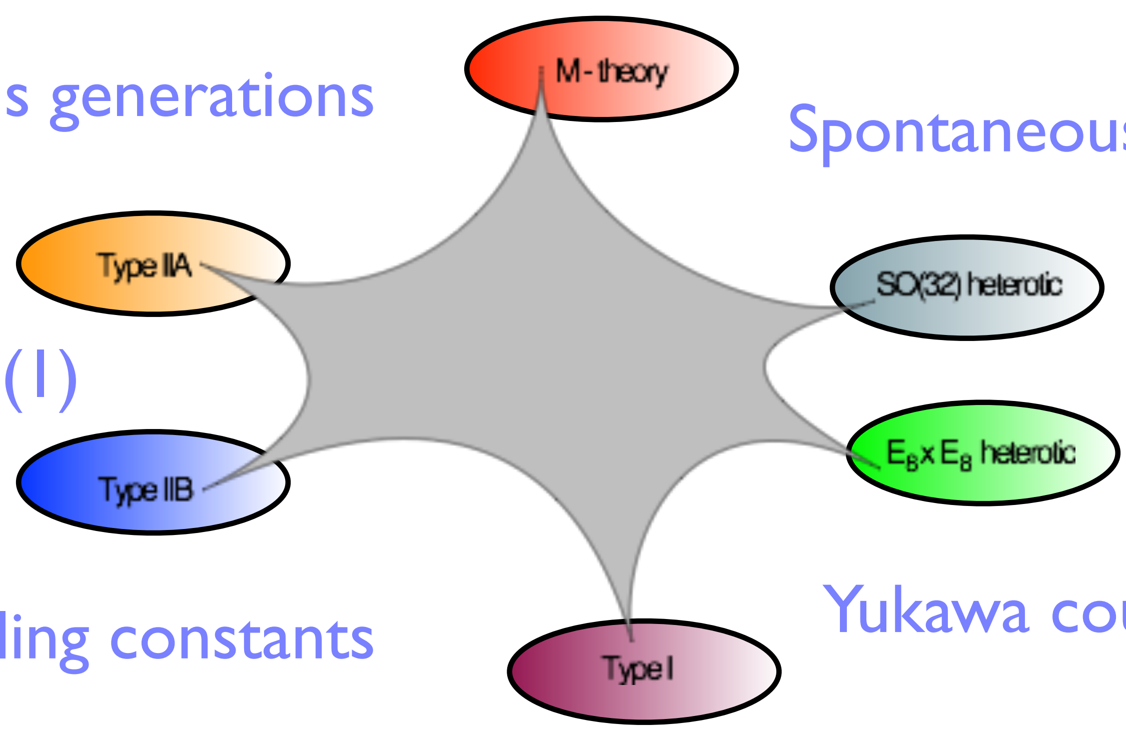
Spontaneous EWSB

$SU(3) \times SU(2) \times U(1)$

Chirality

Gauge coupling constants

Yukawa couplings



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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- 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

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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

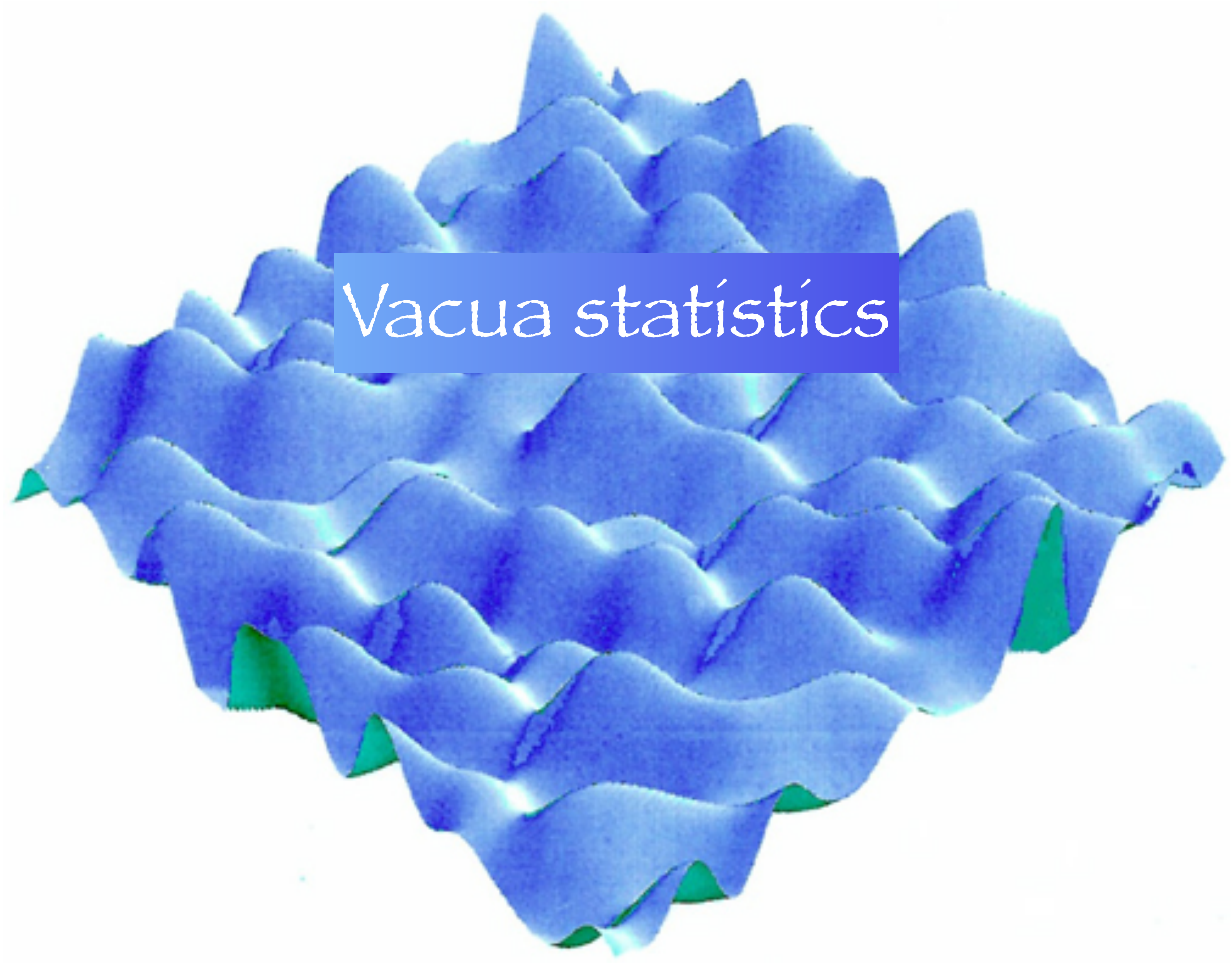
b) We try to get an overall picture of the BSM features of 4d vacua, as well as the kind of scenarios that they generate

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)

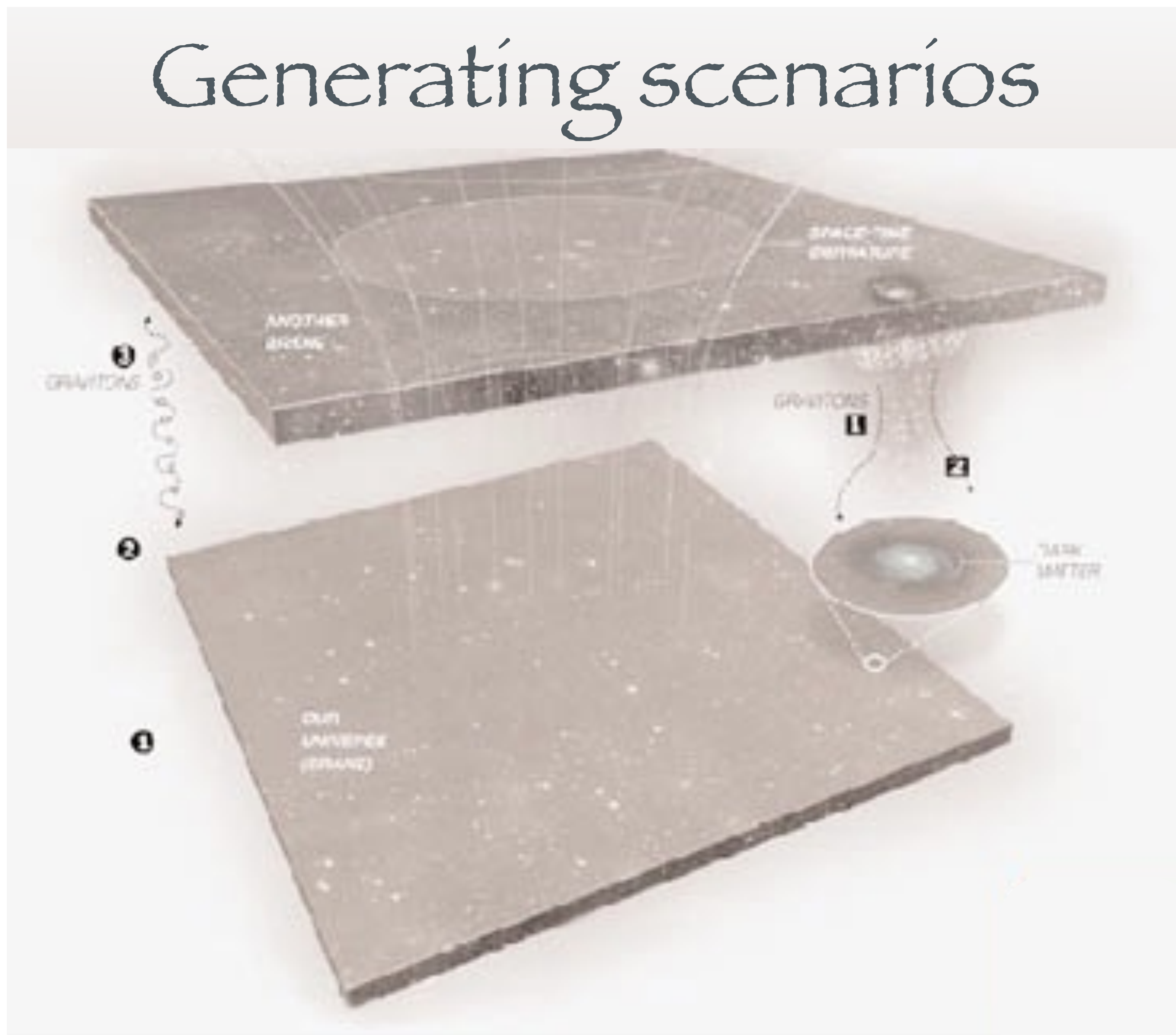
3+1 strategies for (3+1)d physics

Building vacua

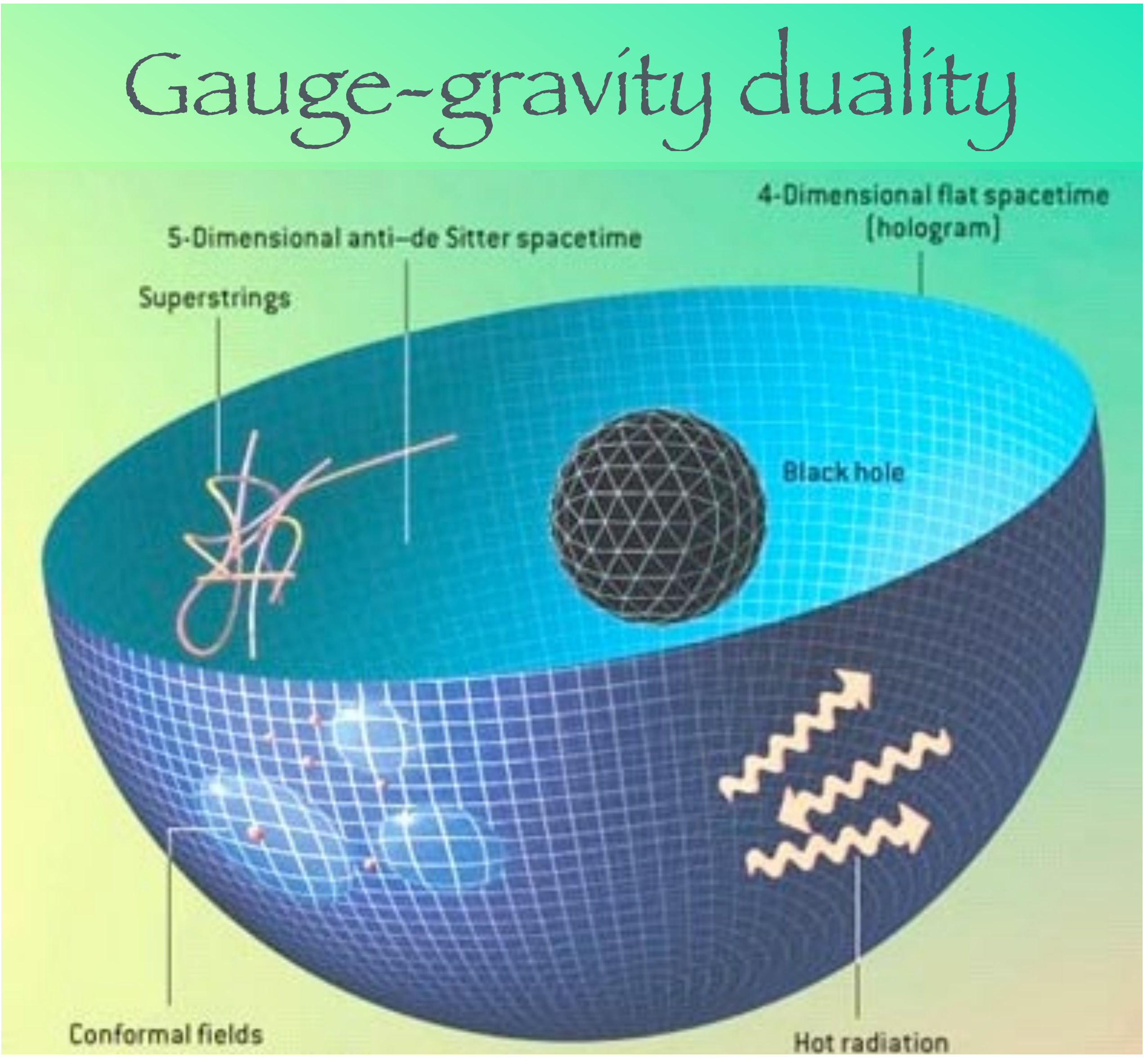
3+1 strategies for (3+1)d physics



3+1 strategies for (3+1)d physics



3+1 strategies for (3+1)d physics



Building vacua

Building vacua

- Classical strategy:
  - Search for more and more realistic models, until finding a vacuum reproducing empiric data and able to provide testable predictions
  - Once found, see which insight it may give over the SM and ΛCDM, as well as over their problems and puzzles
  - Wonder if there is a dynamical vacuum selection mechanism in favour of this vacuum with respect to others

Most of the effort in string phenomenology up to today has been devoted to the first point. A recurrent question is…

Which superstring is the best?

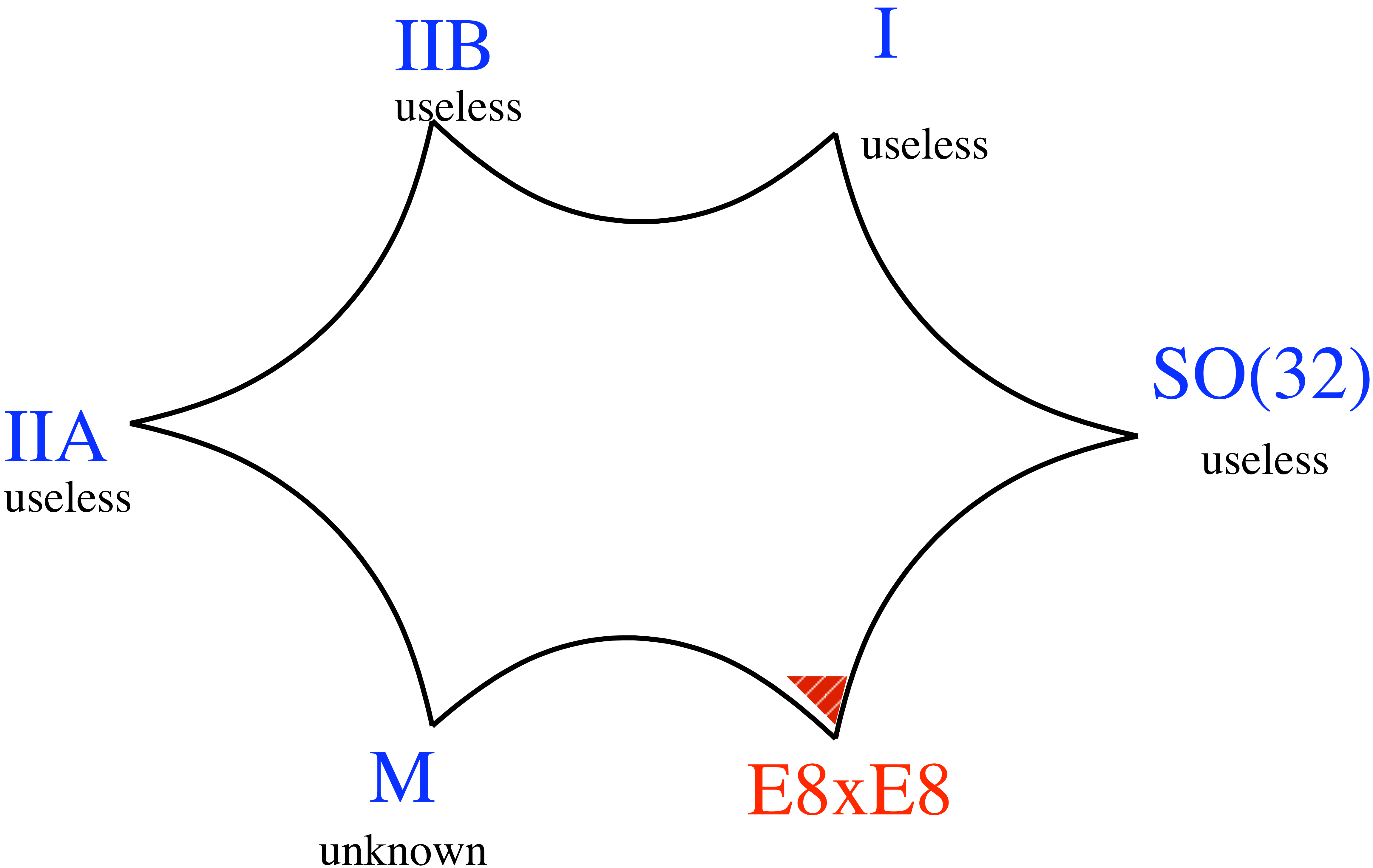
type HE

type HO

type IIB

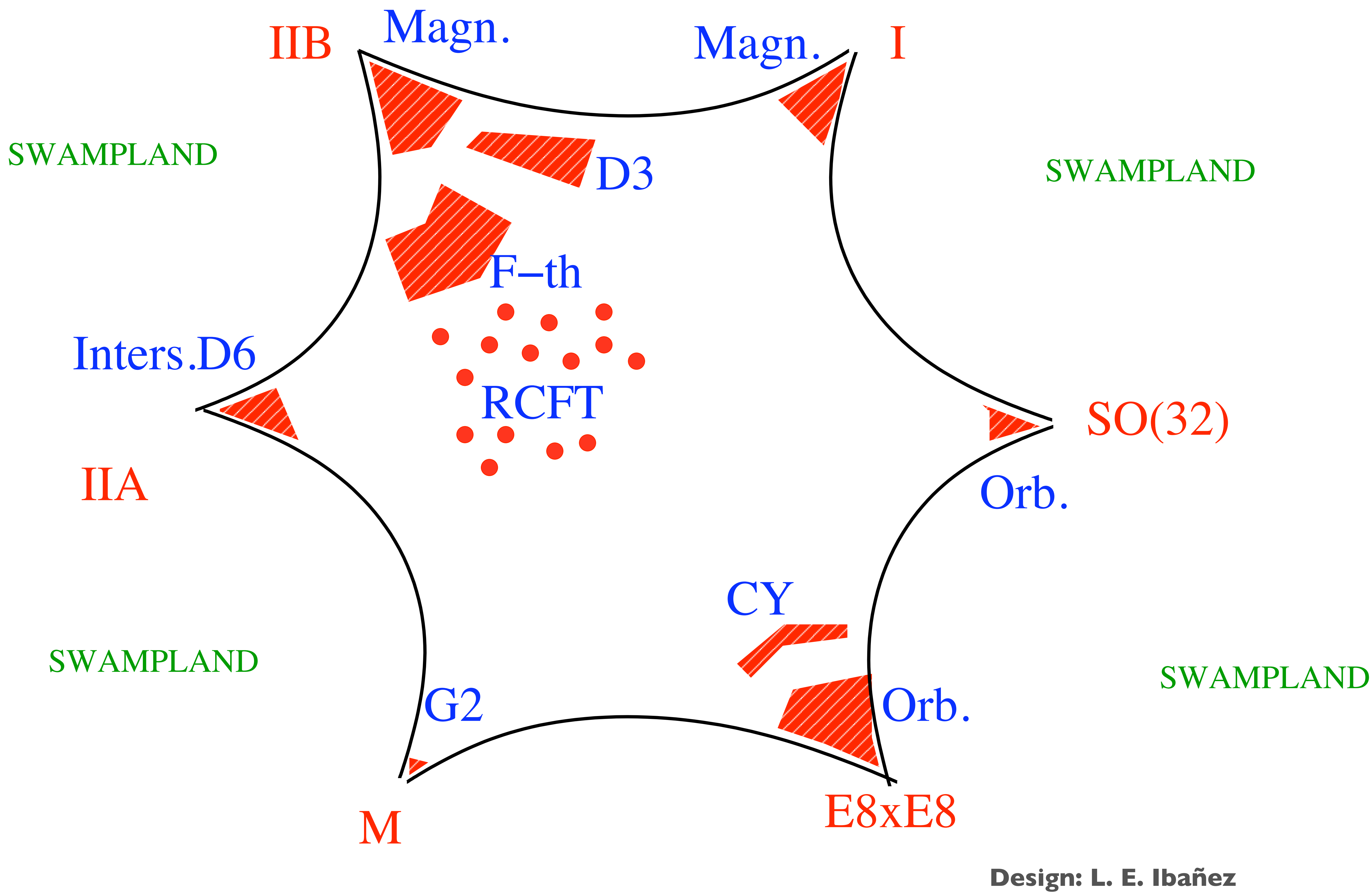
type I

type IIA



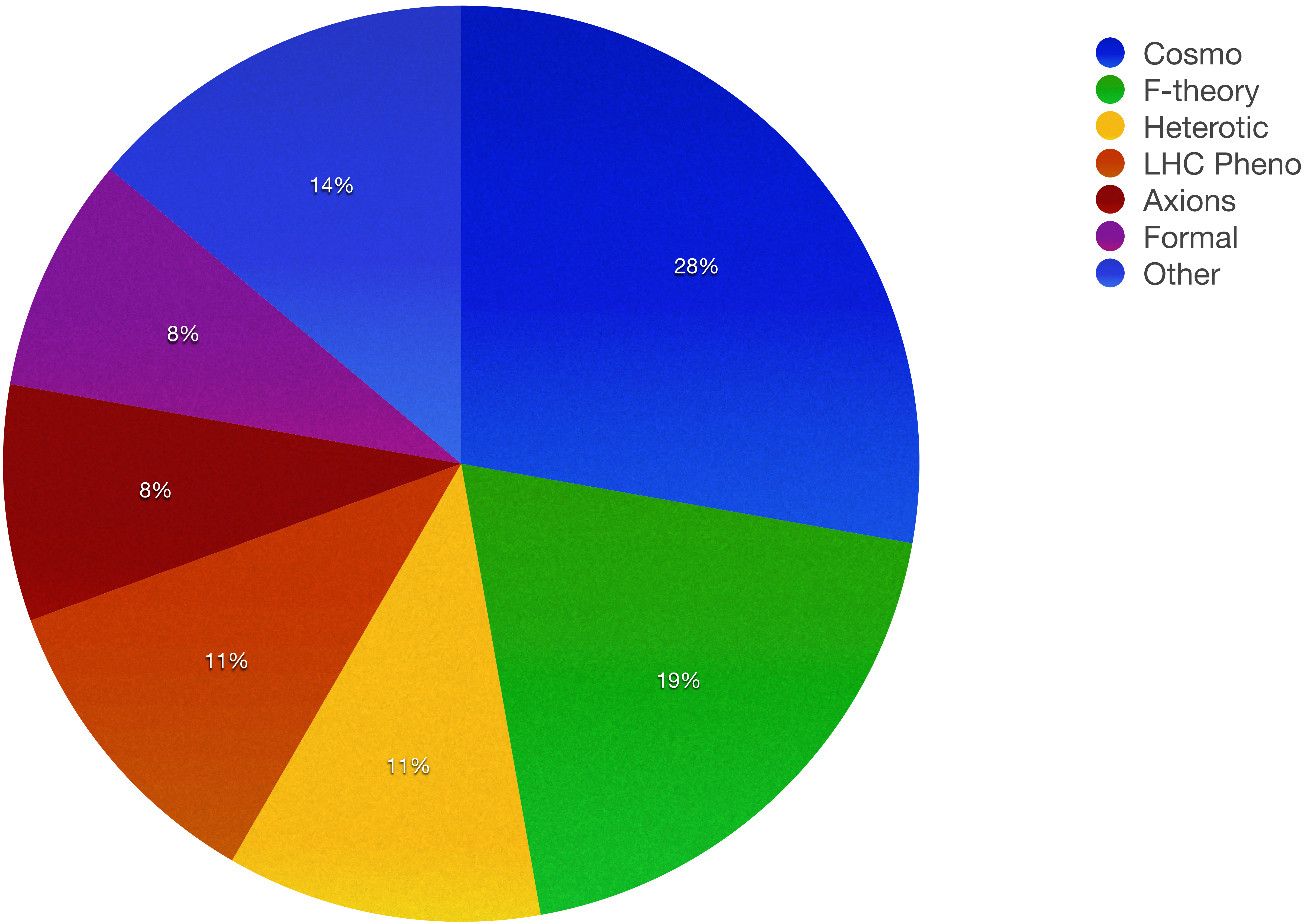
Design: L. E. Ibañez

Circa 1995

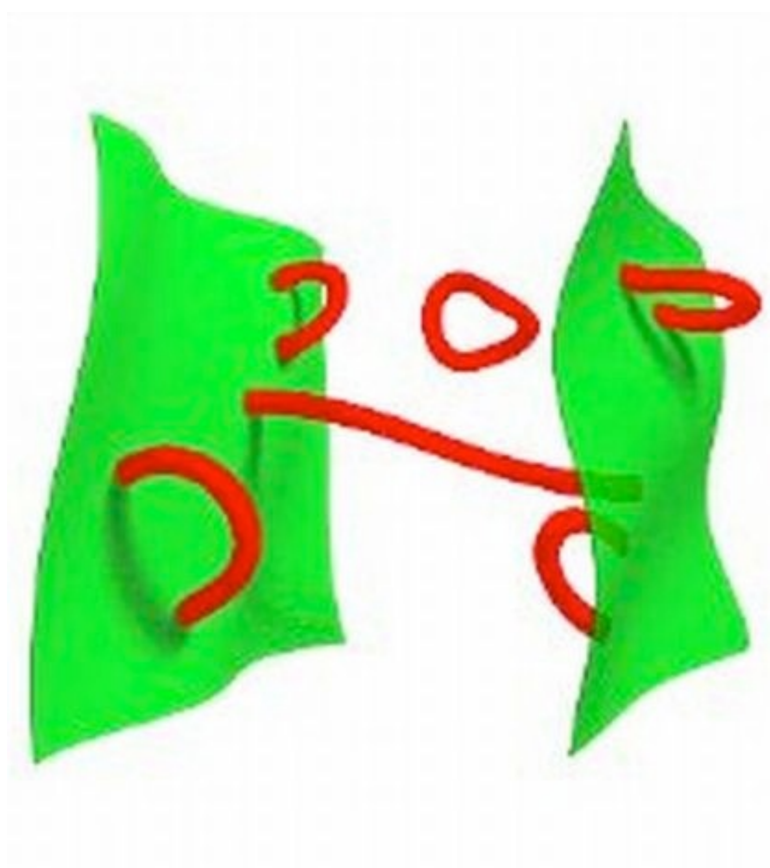

IIB
Magn.
Magn.
I
SWAMPLAND
D3
SWAMPLAND
F–th
Inters.D6
RCFT
SO(32)
IIA
Orb.
CY
SWAMPLAND
SWAMPLAND
G2
Orb.
M
E8xE8
Design: L. E. Ibañez

Circa 2015

Plenary talk distribution at String Pheno 2014



From strings to Particle Physics



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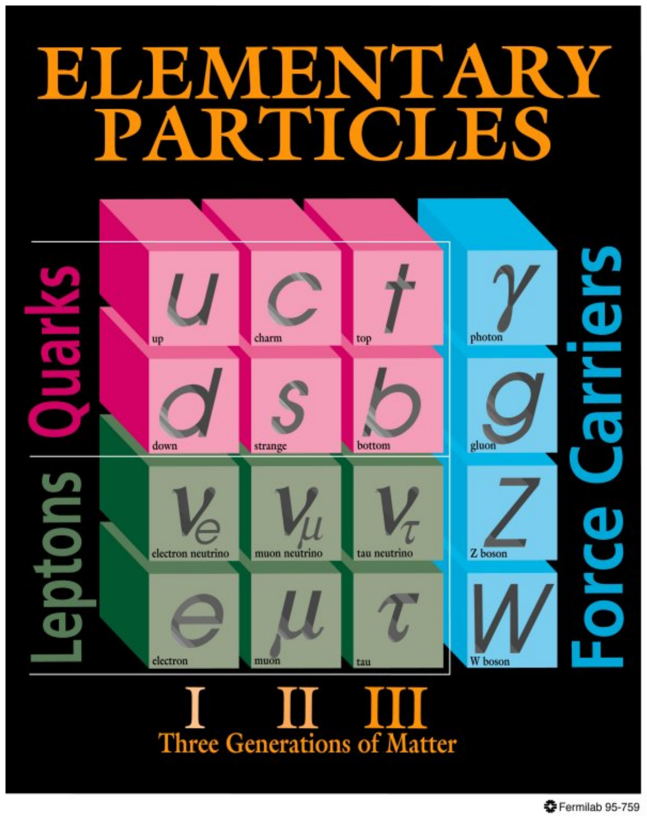


Two main approaches

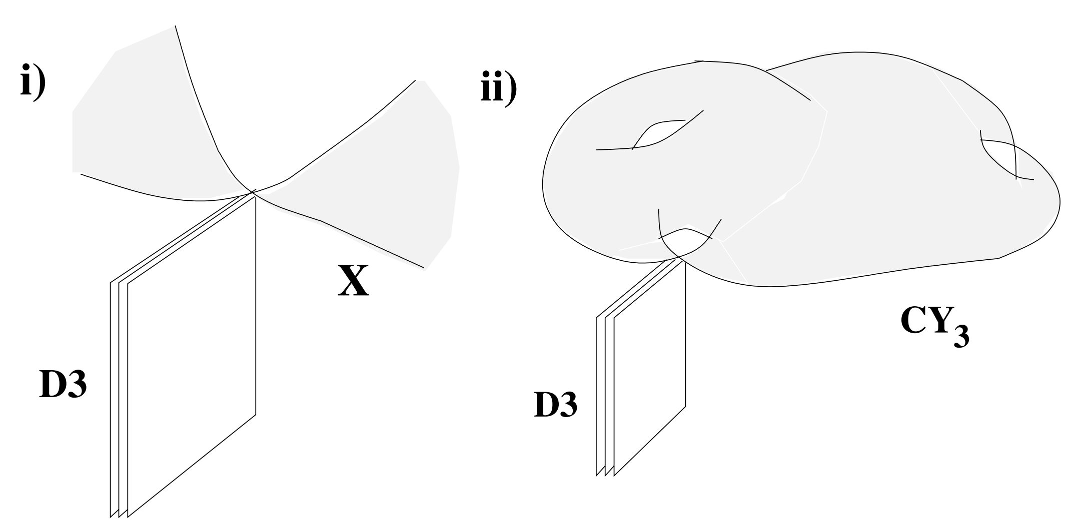
- The “top-down” approach
  - One considers a large class of vacua, and then restricts them to those vacua with realistic 4d effective field theories
  - Classical Example: early SM search in the heterotic

Candelas et al. '86

- The “bottom-up” approach
  - Made of two steps:

    i) We build a gauge sector containing the SM

    ii) We embed this sector in a fully-fledged compactification including gravity



Aldazábal et al. '00

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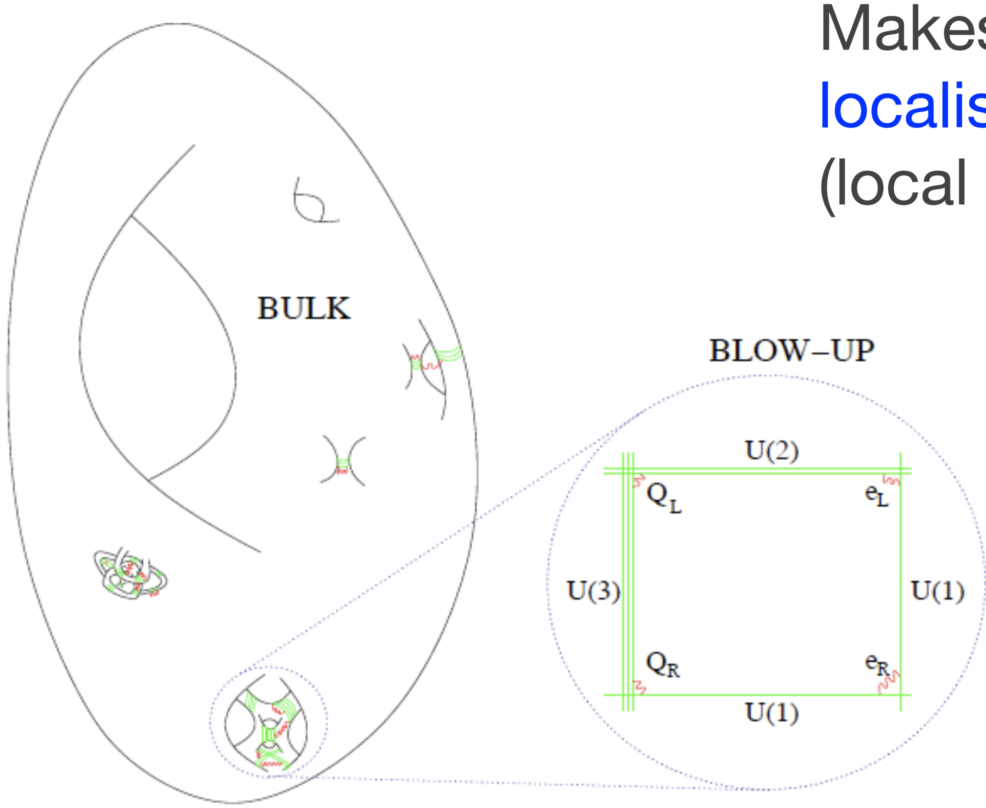
Candelas et al. '86

- The "bottom-up" approach

Makes sense in D-brane models, since these localise gauge theories and much of their data (local models)



Aldazábal et al. '00

Models and Geometry

- For any of these approaches there is a geometric 10d description of the 4d effective field theory quantities, specially in D-brane models

- The more robust the 4d quantity is, the more it is its geometric description

Four observable dimensions

Gauge group SU(3) x SU(2) x U(1)$_Y$

Chiral Fermions

3 families of Quarks & Leptons

Gauge coupling constants

Yukawa couplings

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- The hardest quantity to reproduce are the Yukawas

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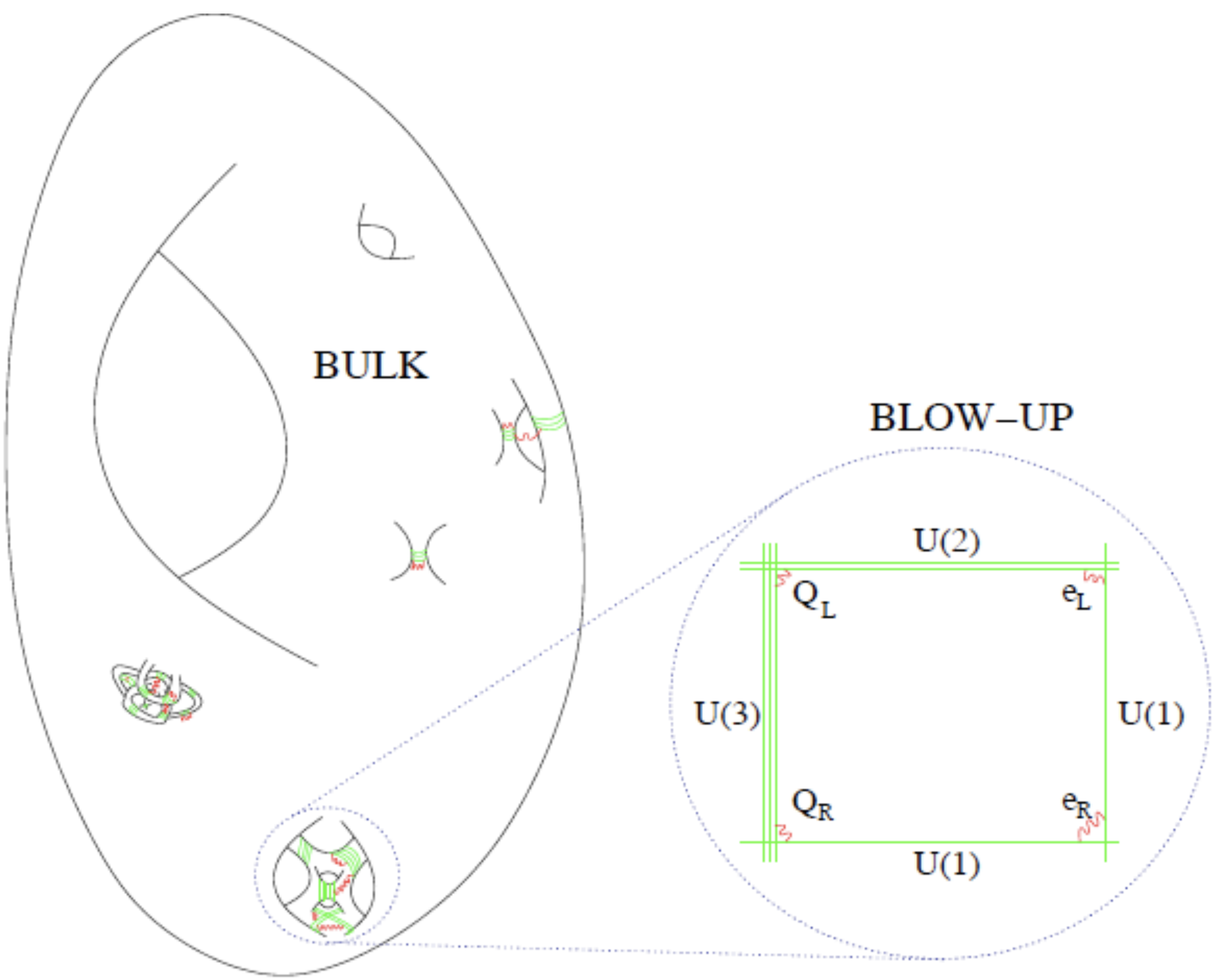
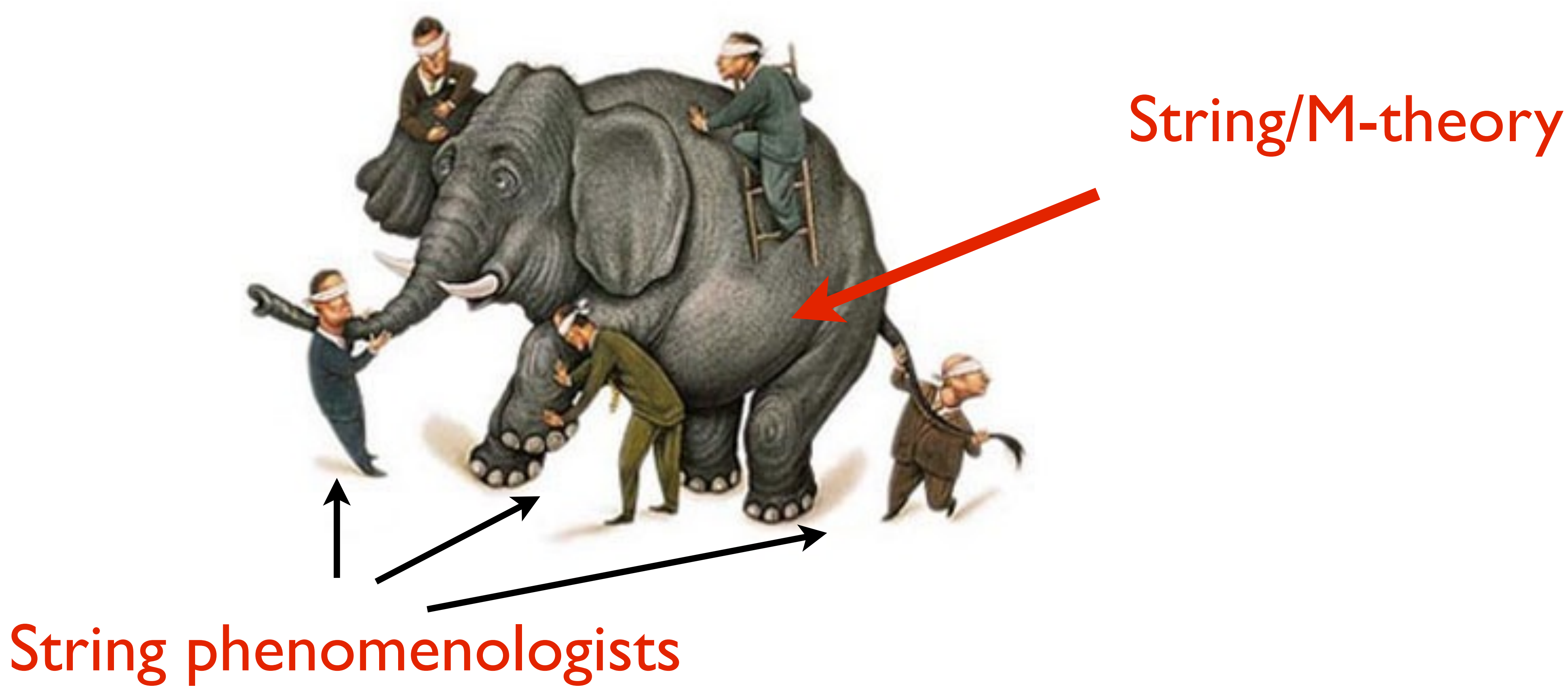
F-theory

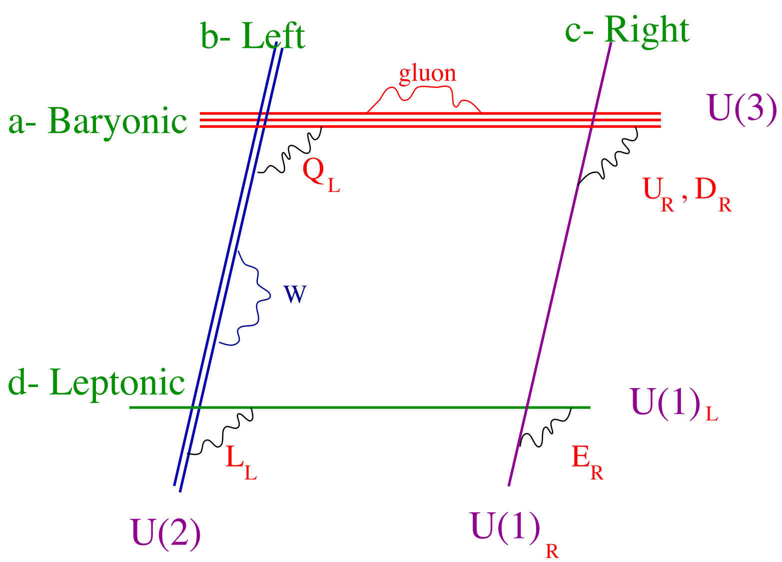
- A quite promising novel class of vacua are those based on F-theory local models
- Cousins of D-brane models
- Bottom-up approach
- Realise gauge coupling unification via GUTs



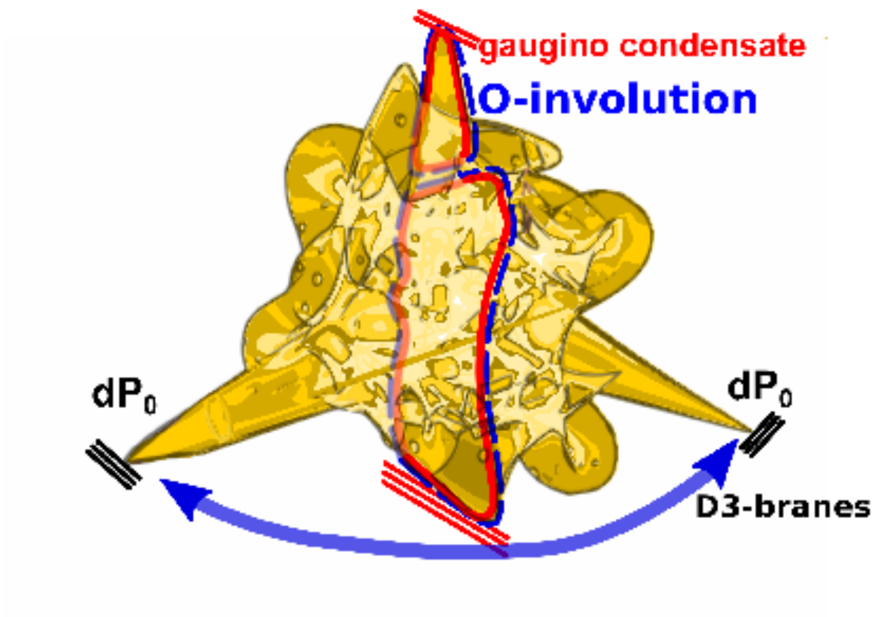
What have we learnt lately?



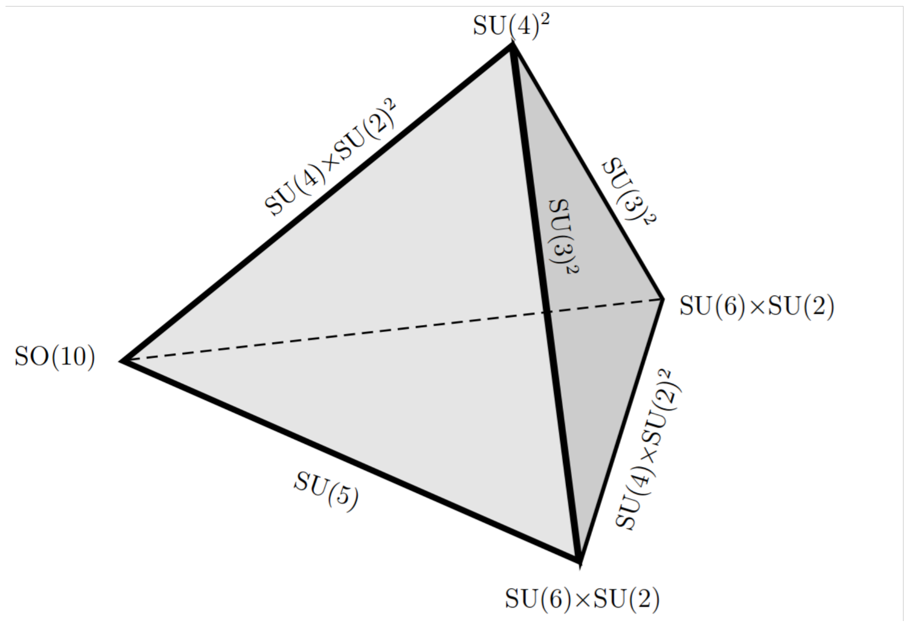
Different approaches to model building



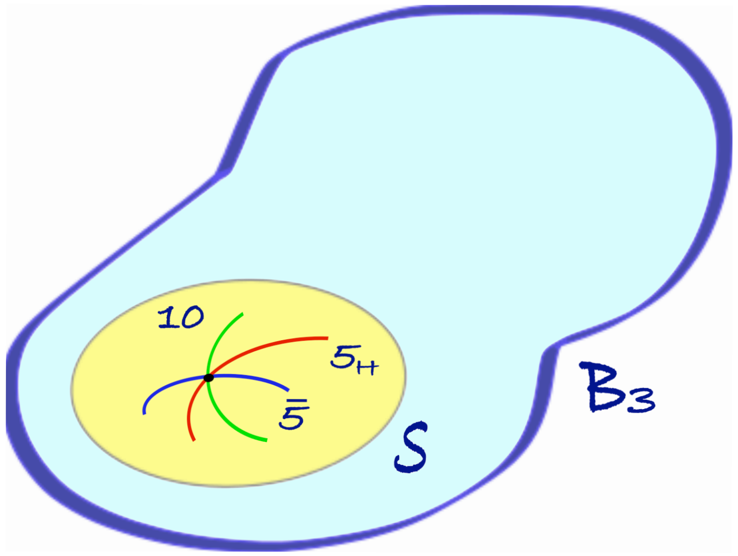
type IIA



type IIB

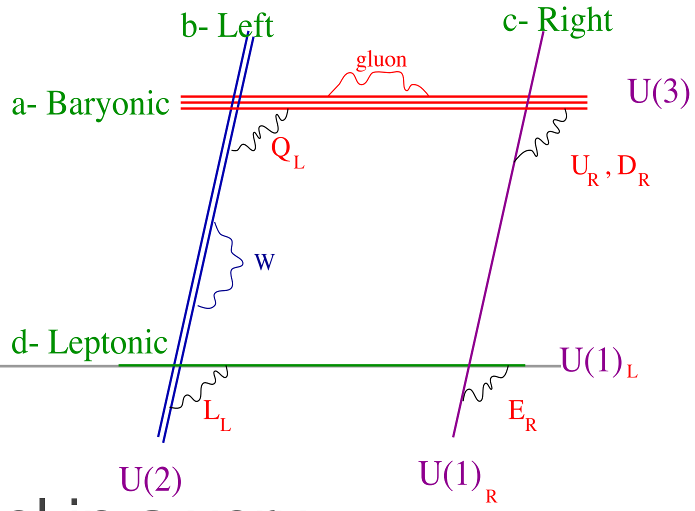


Heterotic



F-theory

The type IIA insight



- Type IIA vacua describe the most relevant features of a model in a very intuitive and pictorial way.
- This has allowed to conceive new kinds of models, even in other model building approaches, and to better understand their 4d effective theories.
- Recently:
  - D-brane instantons
  - Discrete gauge symm.

  } hierarchy of couplings

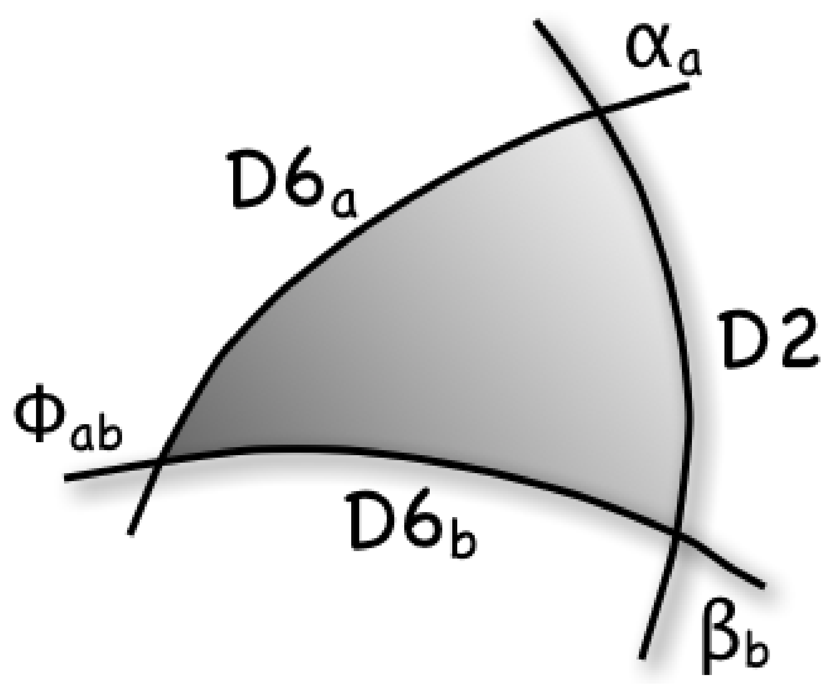
Instantons and discrete gauge symmetries

- 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

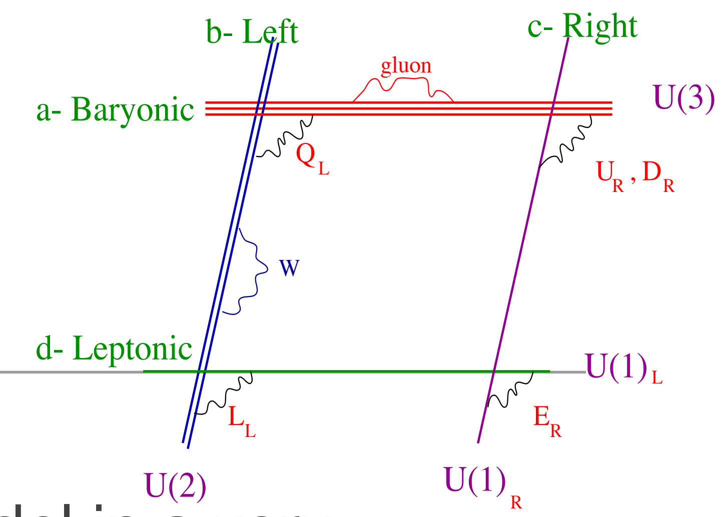
$$\mathcal{L}_{\rm Stk} = \frac{1}{2}(d\phi + kA)$$

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

The type IIA insight



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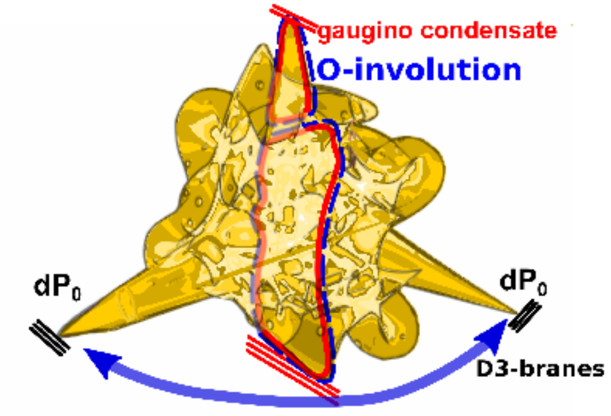
- Recently:
  - D-brane instantons
  - Discrete gauge symm.

  } hierarchy of couplings
  - Non-Abelian discrete flavour symmetries
- Also:
  - Systematic scan on MSSM-like models in toroidal and RCFT orientifolds

    Honecker. et al. '08-14 *Schellekens et al. '10*
  - Systematics of classical de Sitter solutions

    Danielsson et al. '09-12

The type IIB strength

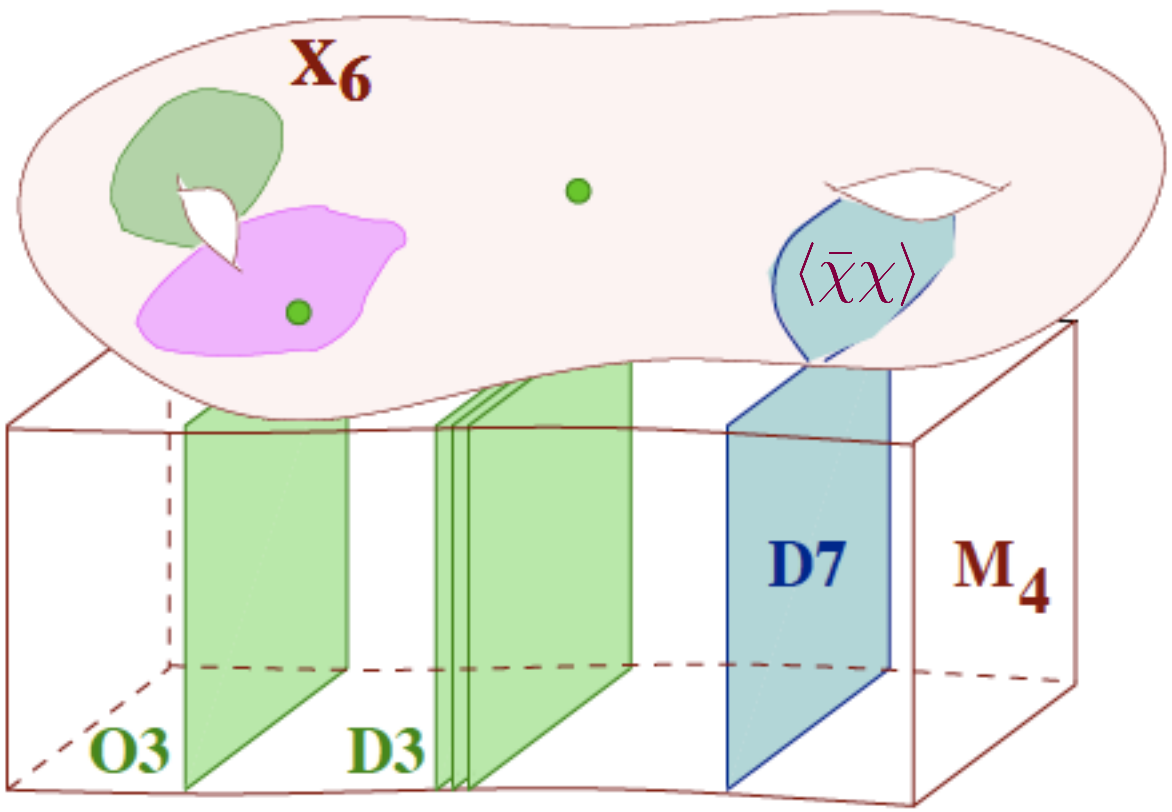


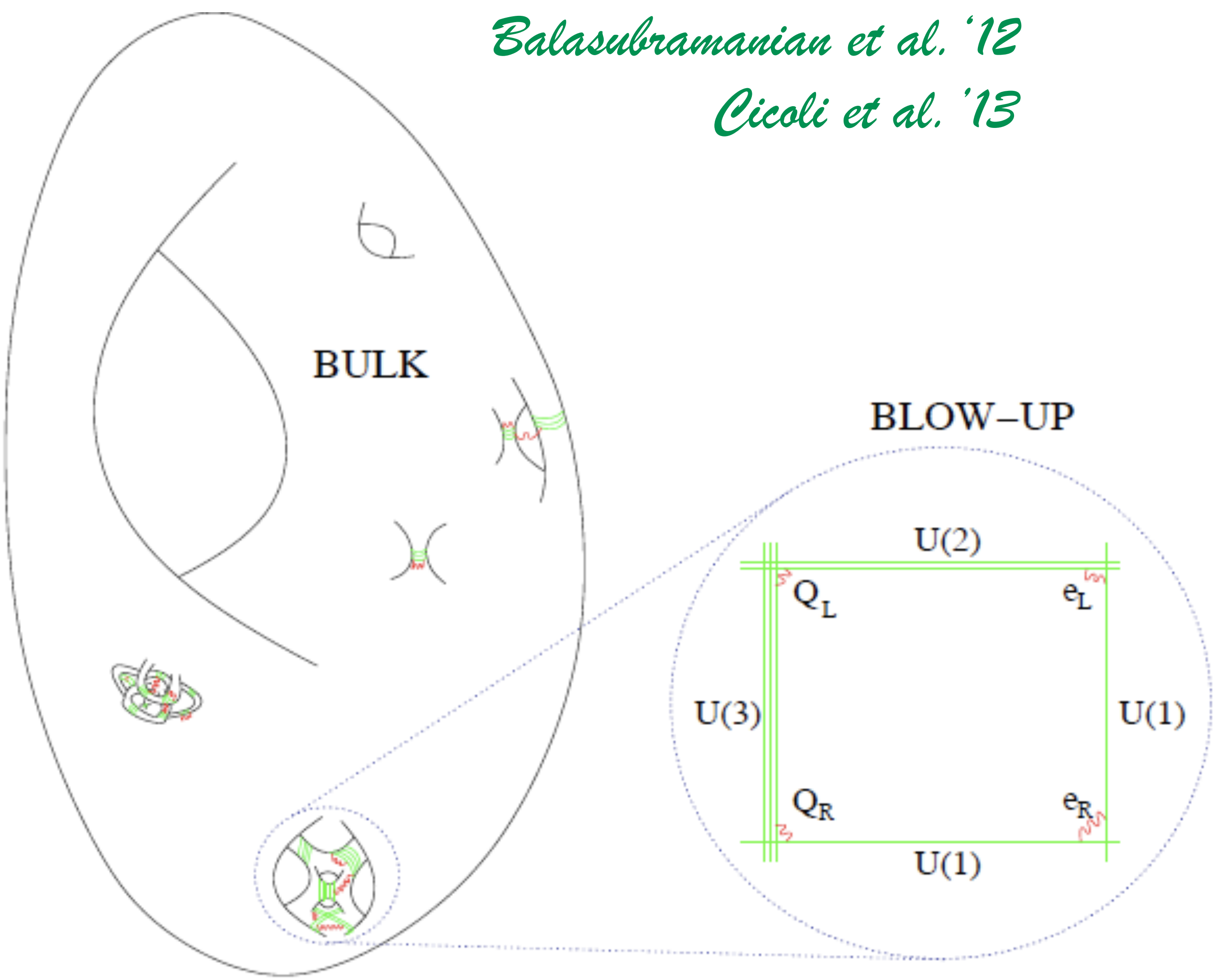
- Type IIB models provide a unique framework to combine particle physics model building with the program on moduli stabilisation & string cosmology

- 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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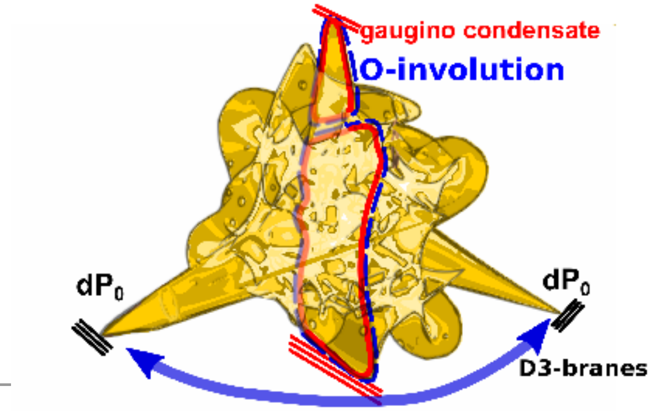

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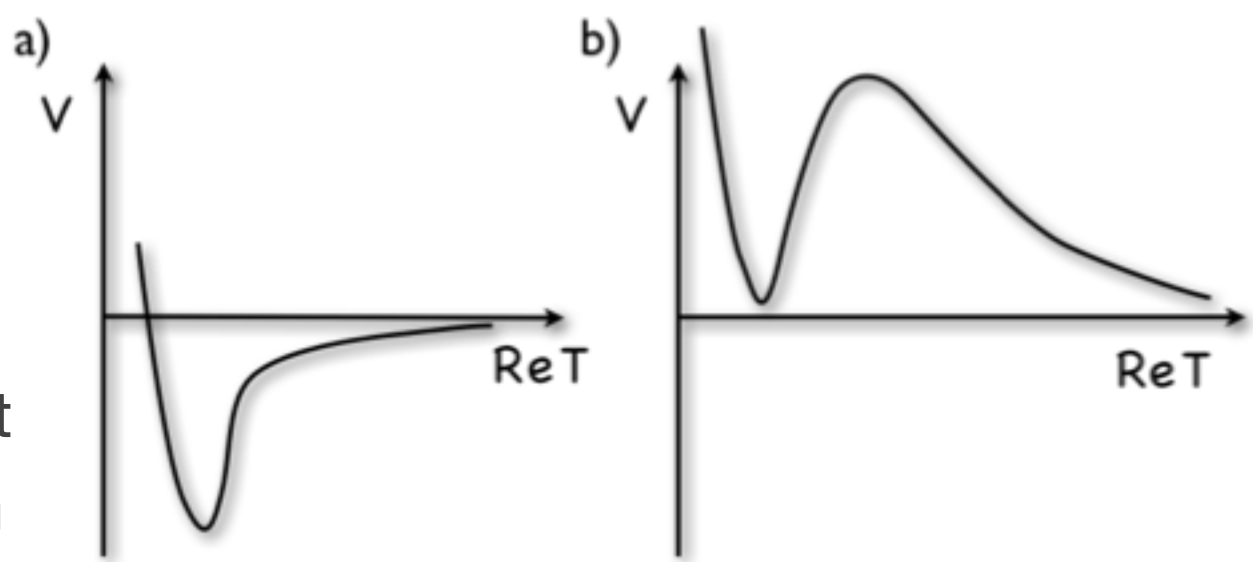
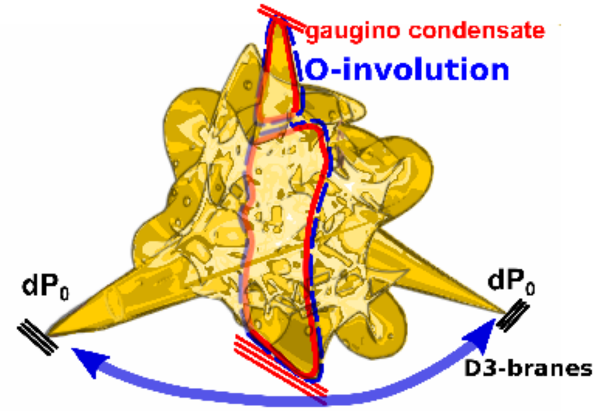
- Most popular settings for dS vacua
  - KKLT
  - Large Volume Scenario
- Both need of anti-D3-branes to uplift from AdS to metastable dS_4 vacuum



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

The type IIB strength



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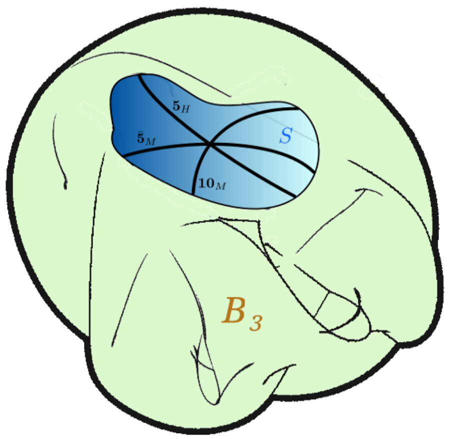
- Most popular settings for dS vacua
  - KKLT
  - Large Volume Scenario
- These settings could in principle be realised in other string corners by using generalised geometry techniques. So far not much progress due to lack of existence theorems for manifolds beyond Calabi-Yau
  - Current attempt: non-geometric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

see Deredinger's talk

Blumenhagen, Lüst et al. '11-14

Type IIB and SUSY breaking

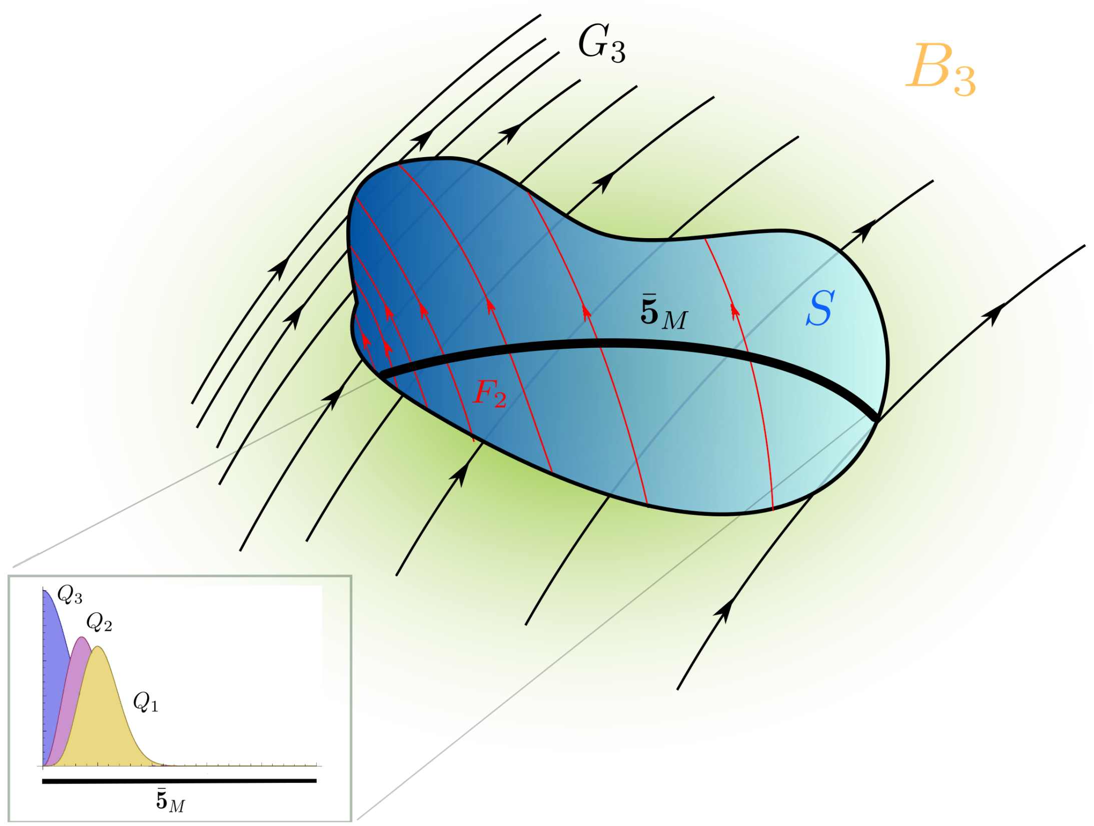


- Type IIB models are also particularly suitable to analyse SUSY breaking effects on particle physics models
  - Flux-induced SUSY breaking soft terms can be computed microscopically on D7-brane models → flavour dependence

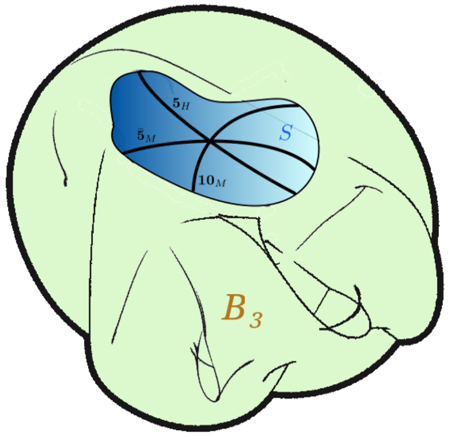
    Camara et al. '04-13

  - 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



Type IIB and SUSY breaking



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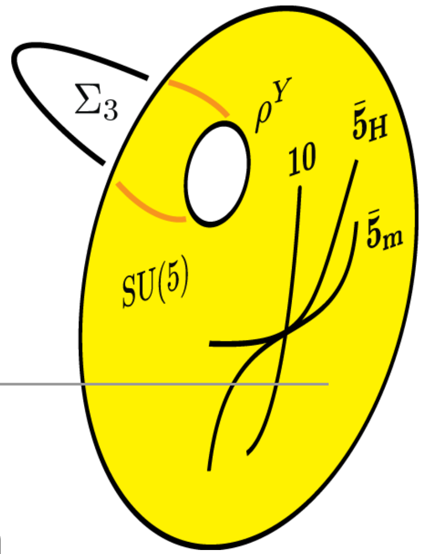
  - Flux-induced SUSY breaking soft terms can be computed microscopically on D7-brane models → flavour dependence *Camara et al. '04-13*
  - D3-brane at singularity models may present the feature of sequestering → microscopic understanding still to be developed *Blumenhagen et al. '09* *Aparicio et al. '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*
  - Holographic gauge mediation *Benini et al. '09*

The power of 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 & Winjholt'08
Beasley, Heckman, Vafa'08

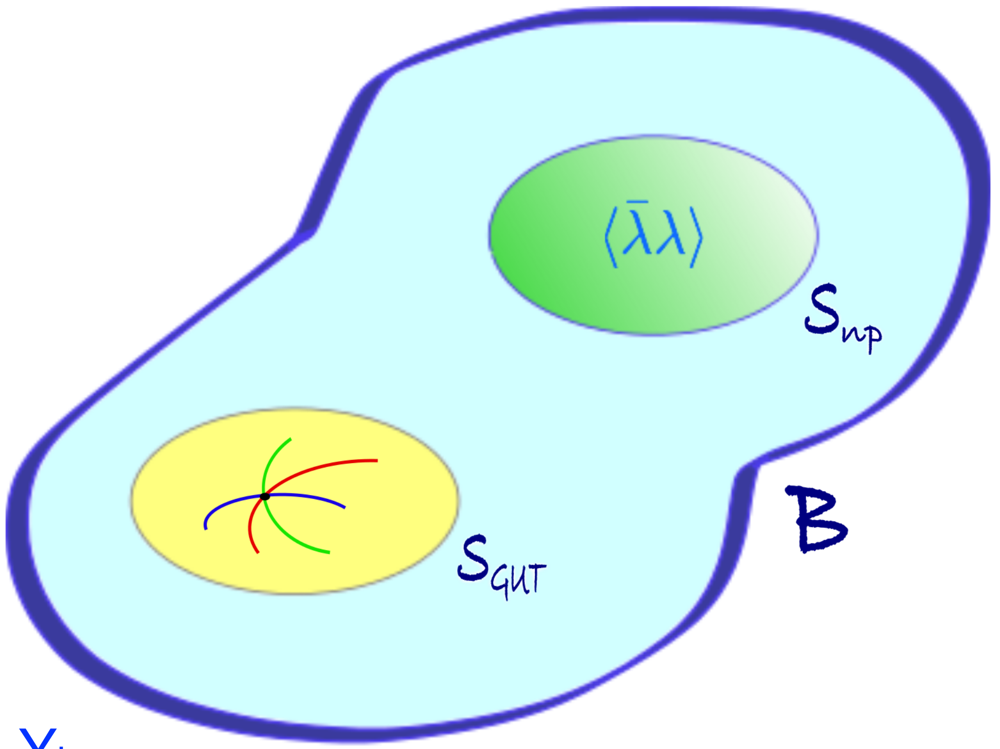
- Large top Yukawa and hierarchical mass spectrum $\mathcal{O}(1), \mathcal{O}(\epsilon), \mathcal{O}(\epsilon^2)$

  - Rank 1 Yukawas via topological conditions

Cecotti et al. '10

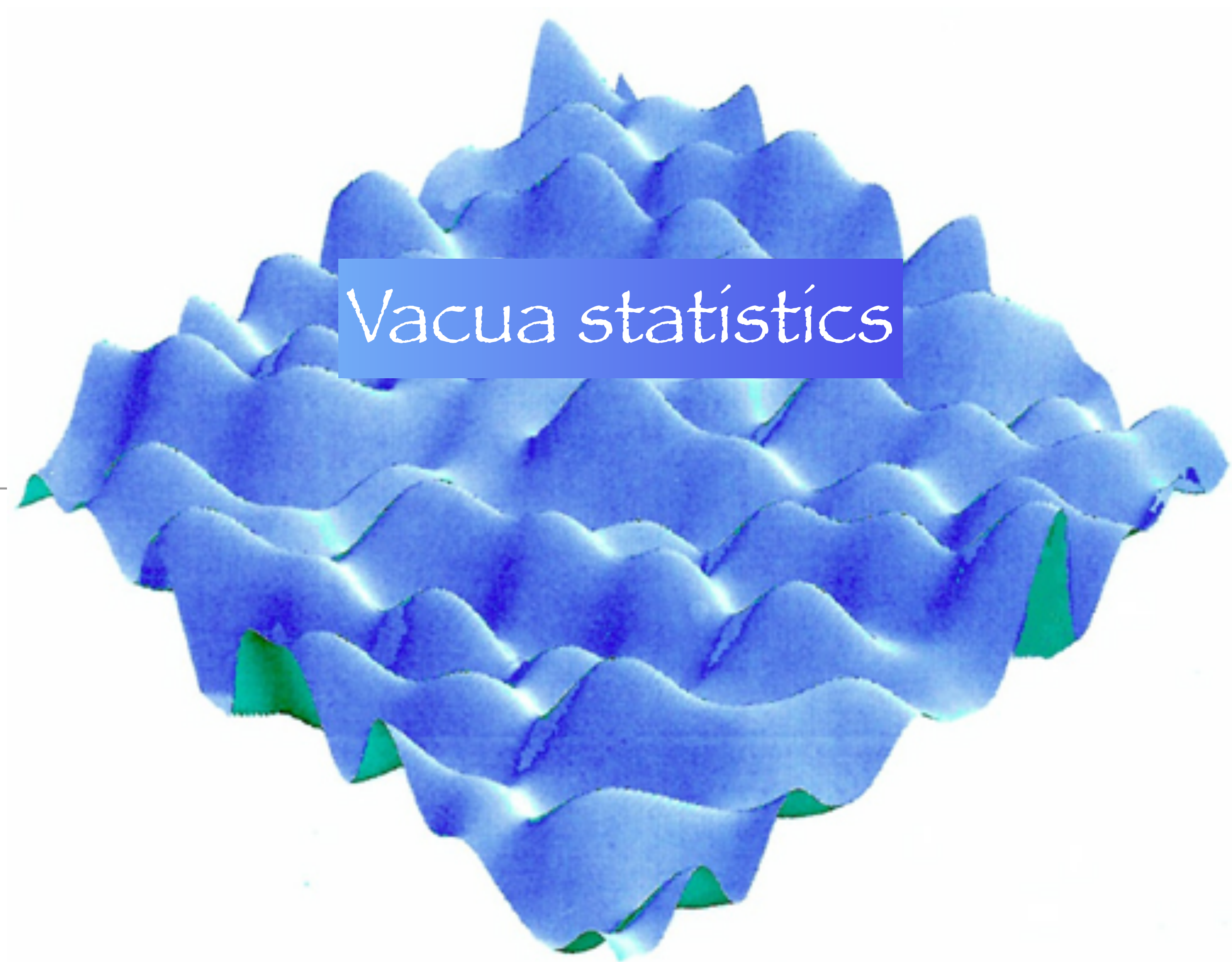
  - Non-perturbative effects increasing the rank

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



  - Deviation from 4d GUT relations thanks to hypercharge flux dependence of masses: $Y_\tau \neq Y_b$

Vacua statistics



How many vacua?

- It has been estimated that the number of semi-realistic string vacua could be of order 10^{500}

  Bousso & Polchinski '00

  Douglas '03

- If this is the case it may not make much sense to search for elegant schemes to, e.g., reproduce quark masses.

- Instead, a more elegant manner to extract predictions from the theory could be a statistical strategy, posing questions like “Which fraction of vacua have a small positive cosmological constant?”

- There have been some attempts to implement this approach in simple vacua

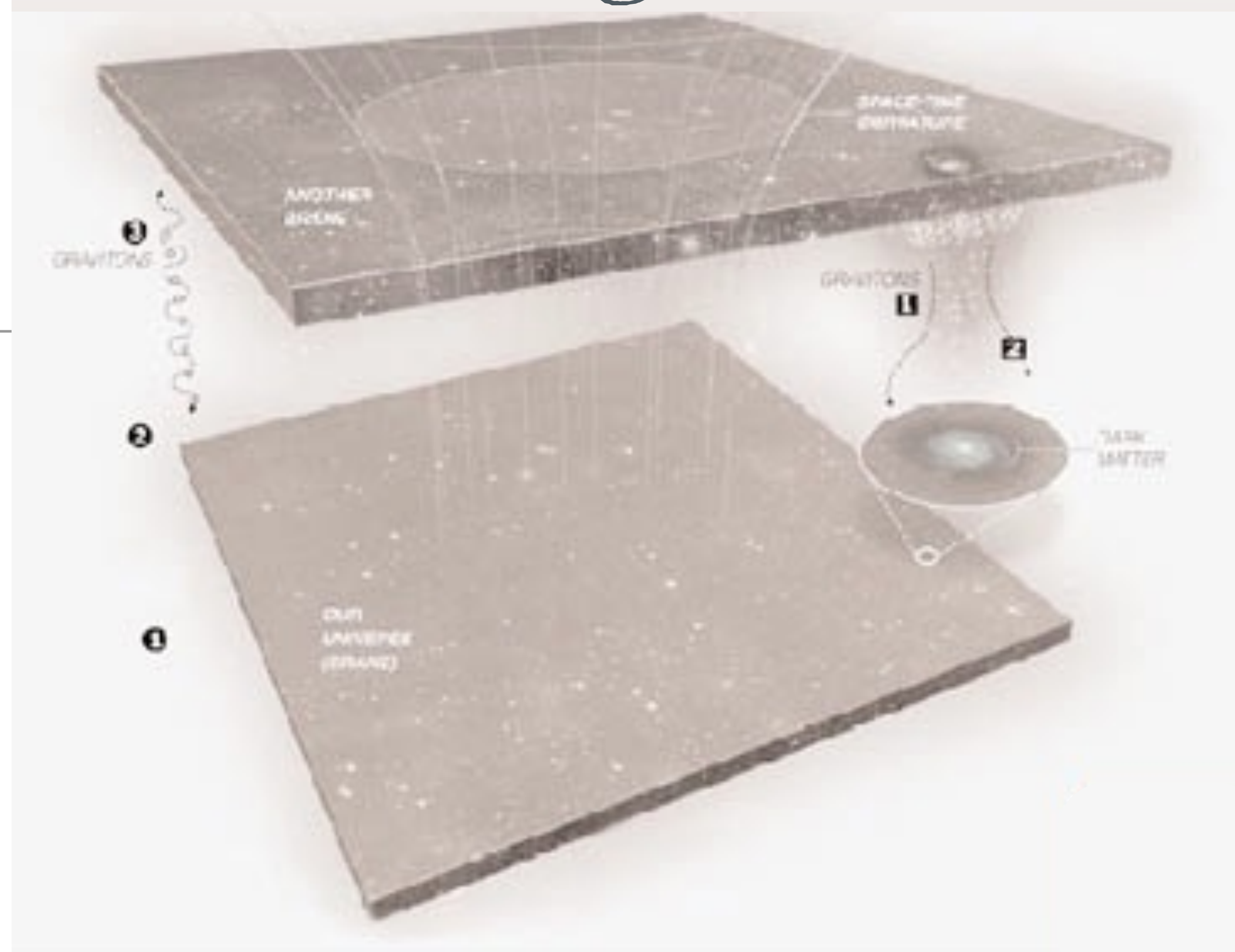
  Gmeiner et al. '05

In the 'Landscape'

- Determining whether there is a 'Landscape' of realistic vacua is an important and valid question
- However, it is also important to recall that we have not found a single fully realistic model yet
- In particular, none of the infinite families of isolated string vacua have a chiral spectrum, one of the key properties of the SM
- In addition, the 10^{500} vacua estimate neglects the interaction between
  - ✦ Fluxes (source of moduli stabilisation)
  - ✦ D-branes (source of chirality)

$\Rightarrow$ Tension between both

Generating scenarios



Inspiring scenarios

- A more indirect way to connect string theory with observable physics is via generating scenarios Beyond the Standard Model

- Examples up to now:

  SUSY

  Large Extra Dimensions

  Warped Extra Dimensions

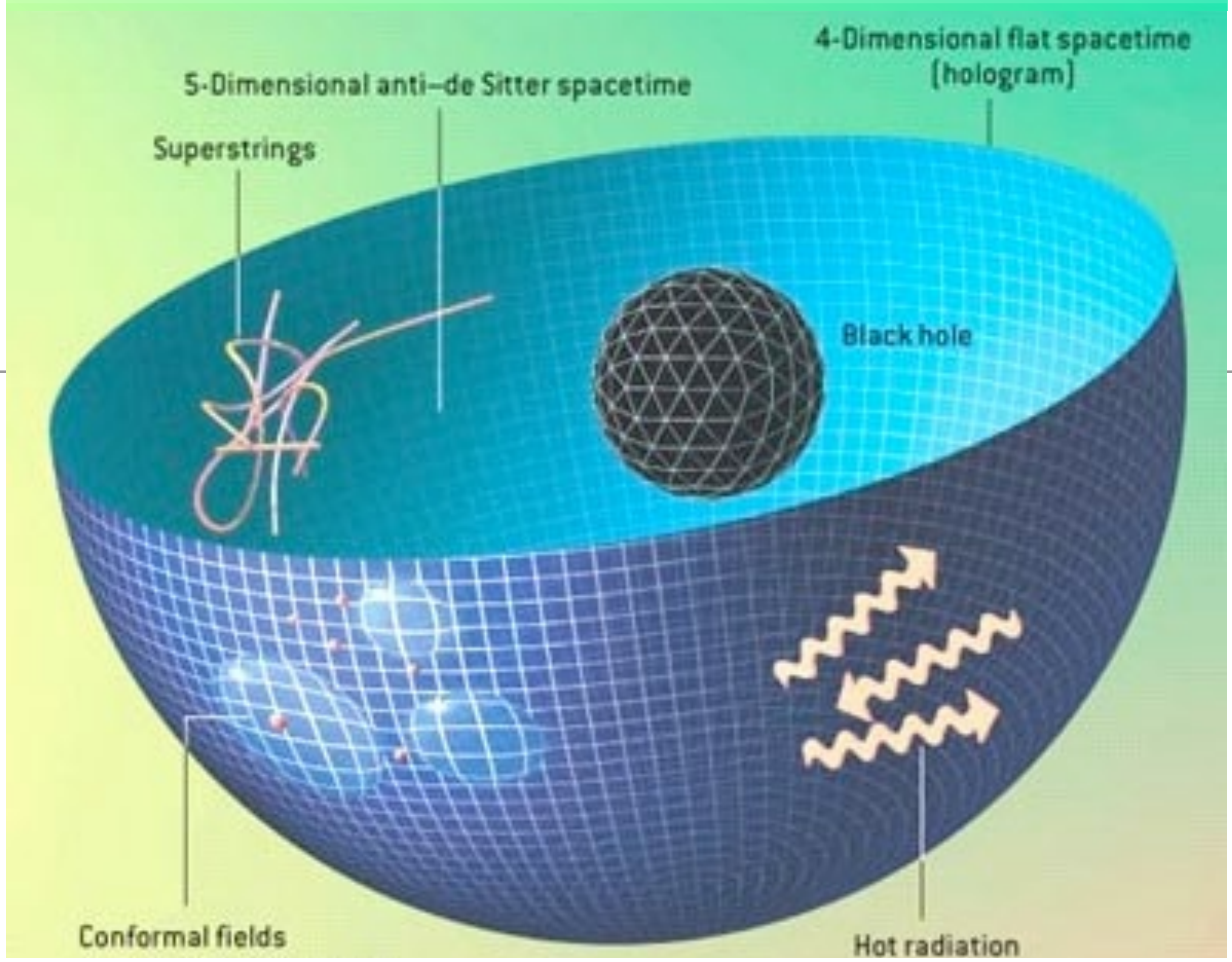
  D-brane Inflation

  Axion monodromy Inflation

  ...

- New string theory constructions give rise to new scenarios (example: GUT gauge group breaking via hypercharge flux)

Gauge-gravity duality



AdS/CFT and holography

see Petropoulos' talk

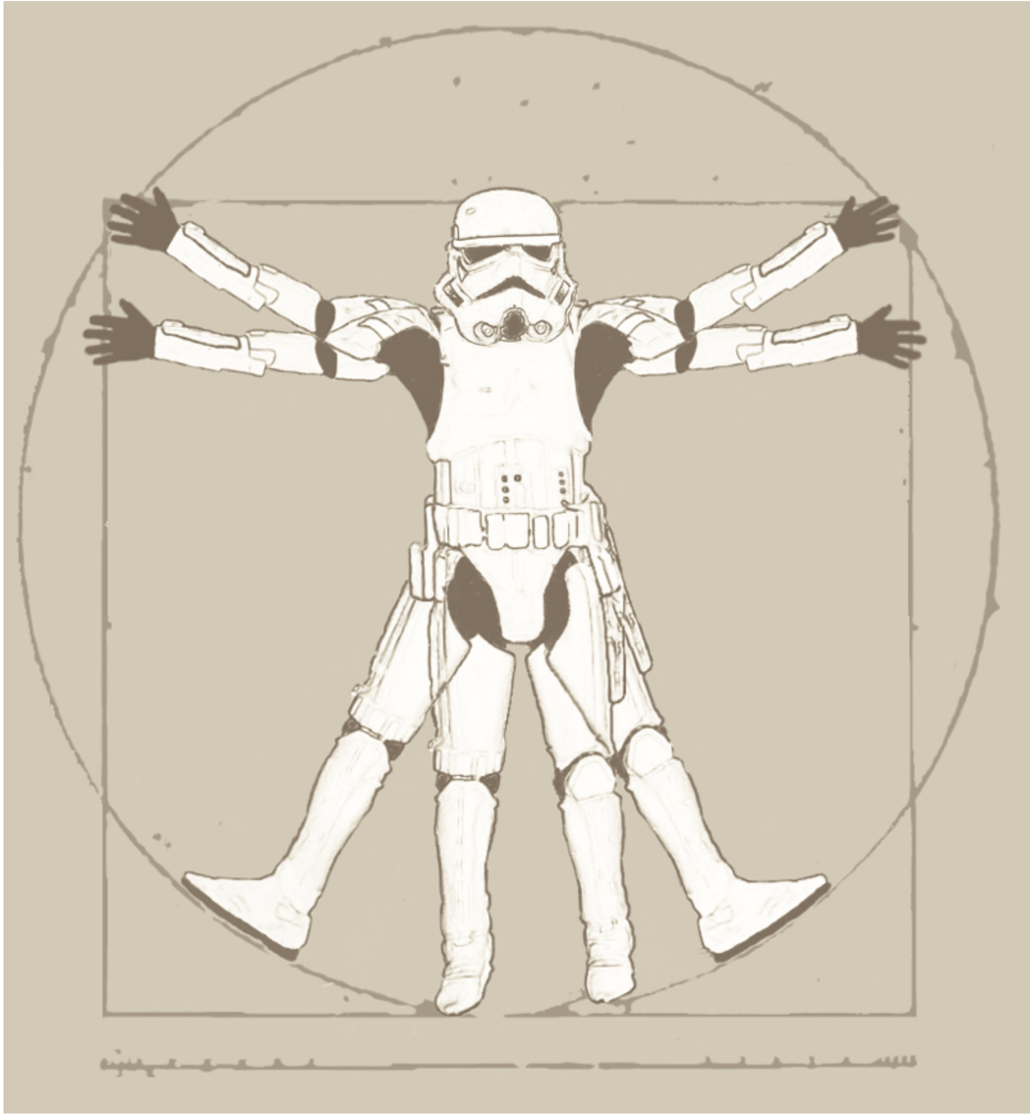
- String theory is used as a tool to extract the physics of field theories at strong coupling
- Gravity dual physics is similar to that of string vacua with strong warping
- In general, lessons learnt about such vacua contain valuable information on the physics of the gauge dual. Lessons on model building also useful here!!
- On the other hand, holographic duals allow to systematically explore the generation of scales due to strong gauge dynamics, which is one of the most robust mechanism to generate hierarchies.

➡ Holographic techniques are useful to implement hierarchies in string models of Particle Physics and Cosmology

What are the open questions?

The String Landscape

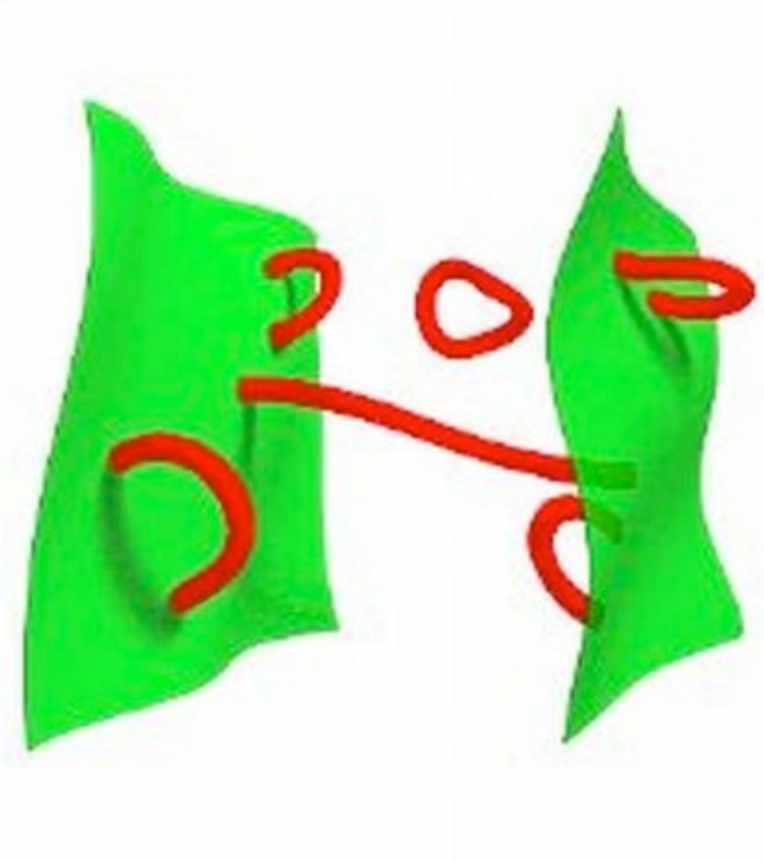
- Is there a landscape with… ?
  - Reasonable cosmological constant
  - Standard Model spectrum
- If no, which dynamical vacuum selection principle are we missing?
- If yes, do environmental/anthropic selection principles play a role in explaining observable physics?
  To which quantities do they affect?



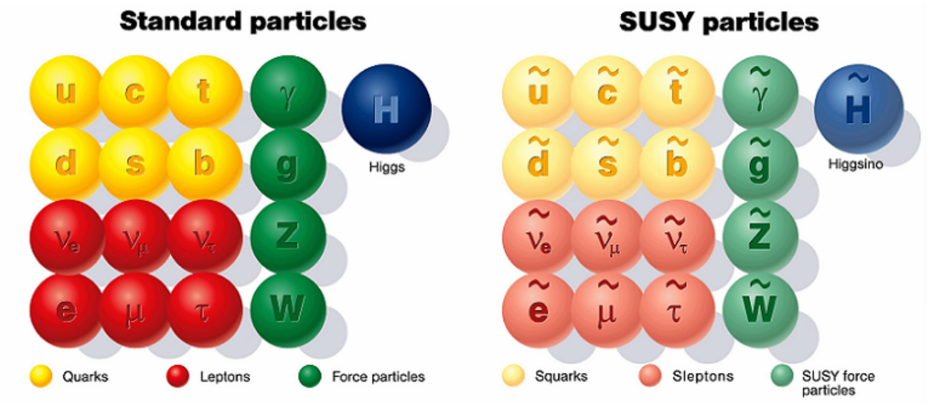
Other open questions

- 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
- …

Strings and SUSY



?



What is the string scale?

see Antoniadis' talk

- The string scale M_s is in principle the only free parameter of the theory.
  It is chosen depending on the string scenario

- Pre D-brane scenario: gravity and gauge interactions both propagate over X_6
  → realistic 4d couplings fix $M_s \sim g_{YM} M_P$ and M_{KK} slightly smaller
  → we need SUSY in the TeV - M_s range to address the hierarchy problem

- D-brane scenario: allows to dilute gravity $M_s \sim g_{YM} M_P [V_\perp/g_s]^{1/2}$
  → we can lower the M_s down to the TeV
  → no need for SUSY, even at M_s

  Antoniadis et al. '98

  - Light Z' bosons
  - Effects on SM amplitudes from exchange of Regge resonances or KK modes
  - Black hole production
  - …

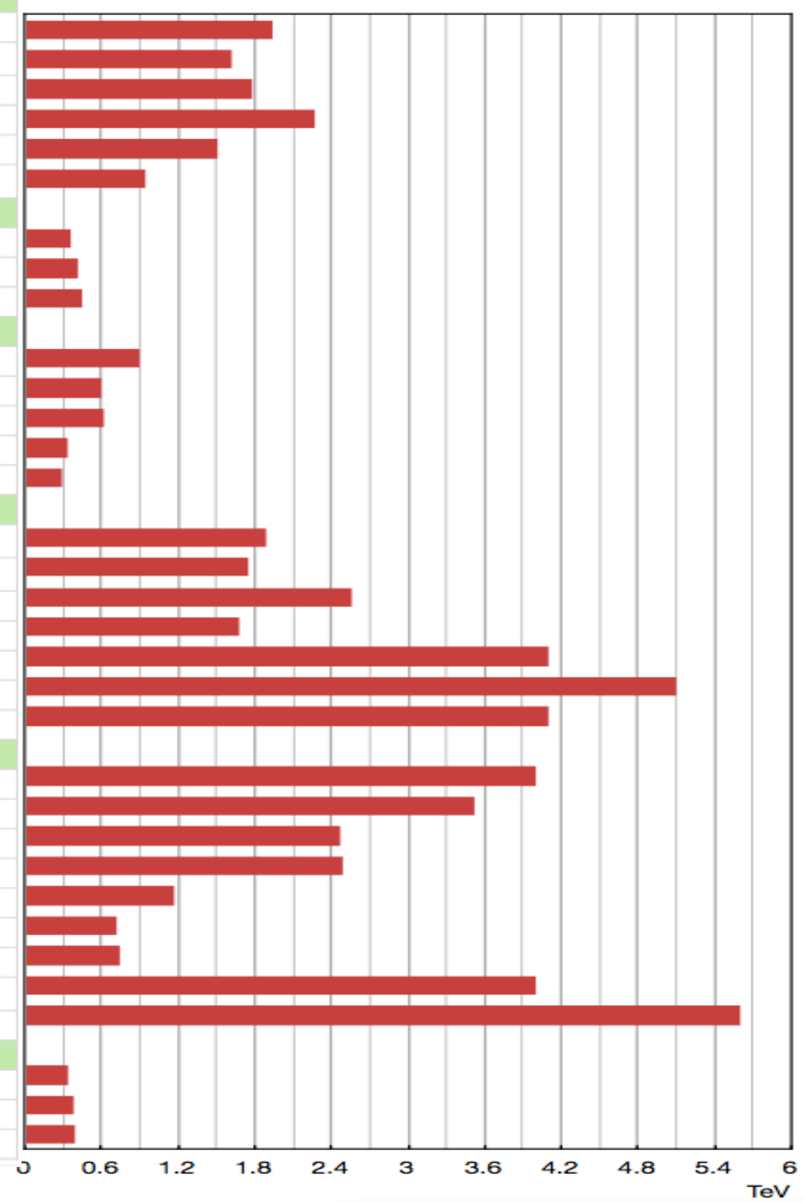
  Anchordoqui et al. '09-14

TeV string scale?

see Antoniadis' talk

Summary of the searches in EXO

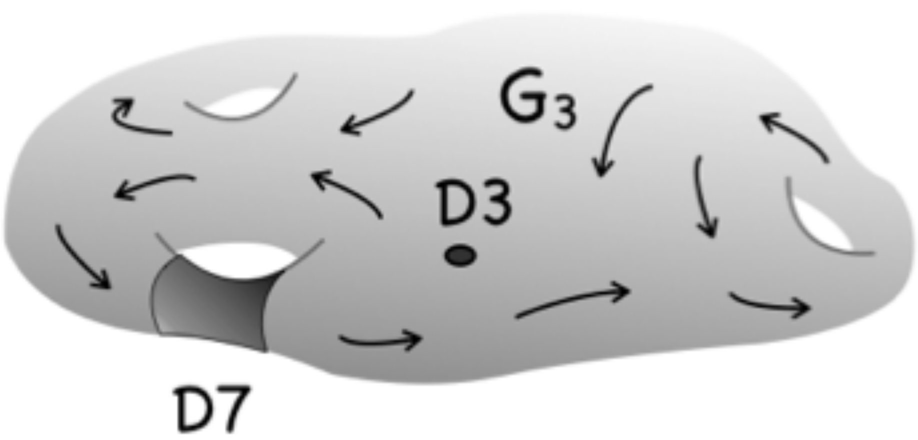
	Limits in TeV	
	Heavy Bosons	
Z'_{SSM} ll	1.94	2011
Z'_{ψ} ll	1.62	2011
G_{KK} ll k/M = 0.1	1.78	2011
W' lν	2.27	2011
W' dijet	1.51	2011
G_{KK} γγ k/M = 0.1 (2010)	0.945	2010
	4th Generation	
$M_{b'}$, b' ⇒ tW (2010)	0.361	2010
$M_{t'}$, t' ⇒ tZ (100%)	0.417	2011
$M_{t'}$, t' ⇒ bW (100%), l+jets	0.45	2011
	Heavy Stable Particles	
M_{gluino}, HSCP	0.899	2011
M_{gluino}, Stopped Gluino	0.601	2011
M_{stop}, HSCP	0.620	2011
M_{stop}, Stopped Gluino	0.337	2011
M_{stau}, HSCP	0.293	2011
	Large Extra Dimensions	
M_S, γγ, GRW (2010)	1.89	2010
M_S, μμ, GRW (2010)	1.75	2010
M_D, monojet, n_{ED} = 2 (2010)	2.56	2010
M_D, monojet, n_{ED} = 6 (2010)	1.68	2010
M_{BH}, rotating, M_D=3.5 TeV, n_{ED} = 2	4.1	2011
M_{BH}, non-rot, M_D=1.5 TeV, n_{ED} = 6	5.1	2011
String Ball M, M_D=2.1, M_s=1.7, g_s=0.4	4.1	2011
	Compositeness and Contact Interactions	
String Resonances	4.0	2011
E_6 diquarks	3.52	2011
Axigluon/Coloron	2.47	2011
q* , dijet	2.49	2011
q* , boosted Z	1.17	2010
e*, Λ = 2 TeV	0.720	2010
μ*, Λ = 2 TeV	0.745	2010
C.I. Λ , dijet mass (3 pb^{-1})	4.0	2010
C.I. Λ , X analysis	5.6	2010
	LeptoQuark	
LQ1, β=0.5 (2010)	0.340	2010
LQ1, β=1.0 (2010)	0.384	2010
LQ2, β=1.0 (2010)	0.394	2010



$M_S > 4\text{-}5$ TeV

Strings and supersymmetry

- In the most elaborated models, however, SUSY is lurking at some scale
- This is not so surprising because after all SUSY is a fundamental symmetry of string theory, and as such it should be present at some scale, even if very high
- In fact in many moduli stabilisation scenarios that include gravity, supersymmetry is necessary to guarantee vacuum stability, and to avoid tachyonic modes.
- Typical scenario: supersymmetry is broken spontaneously in the gravity sector via background fluxes and other ingredients (np effects), and this generates soft terms on the MSSM brane sector of the theory



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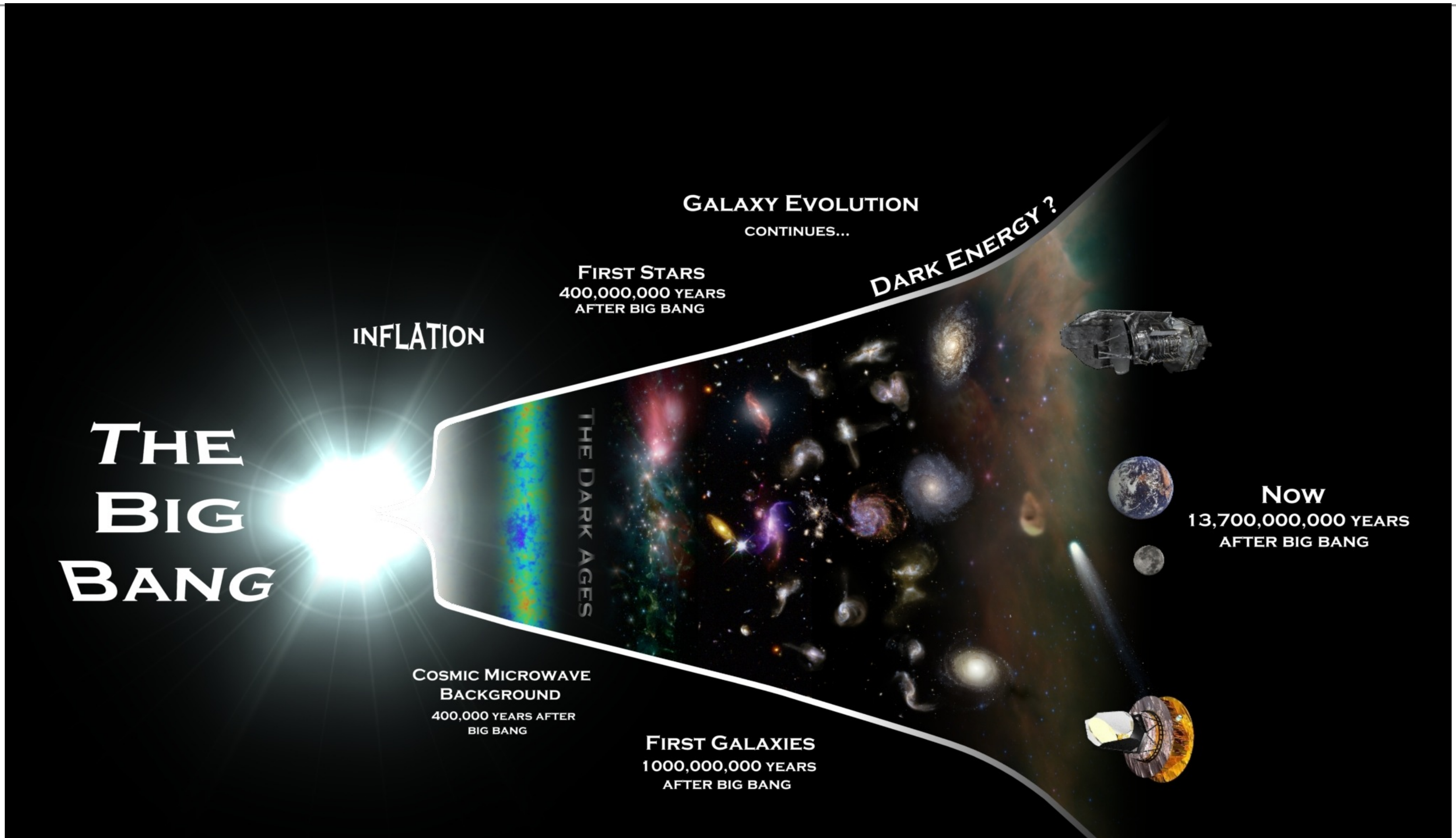
- Typical scenario: supersymmetry is broken spontaneously in the gravity sector via background fluxes and other ingredients (np effects), and this generates soft terms on the MSSM brane sector of the theory
    - KKLT scenario: $M_s \sim 10^{16}$ GeV and $W_0 / M_p^3 \sim 10^{-15}$
    - LVS: $M_s \sim 10^{11}$ GeV, $V \sim 10^{16} \rightarrow W_0 / M_p^3 \sim 1$

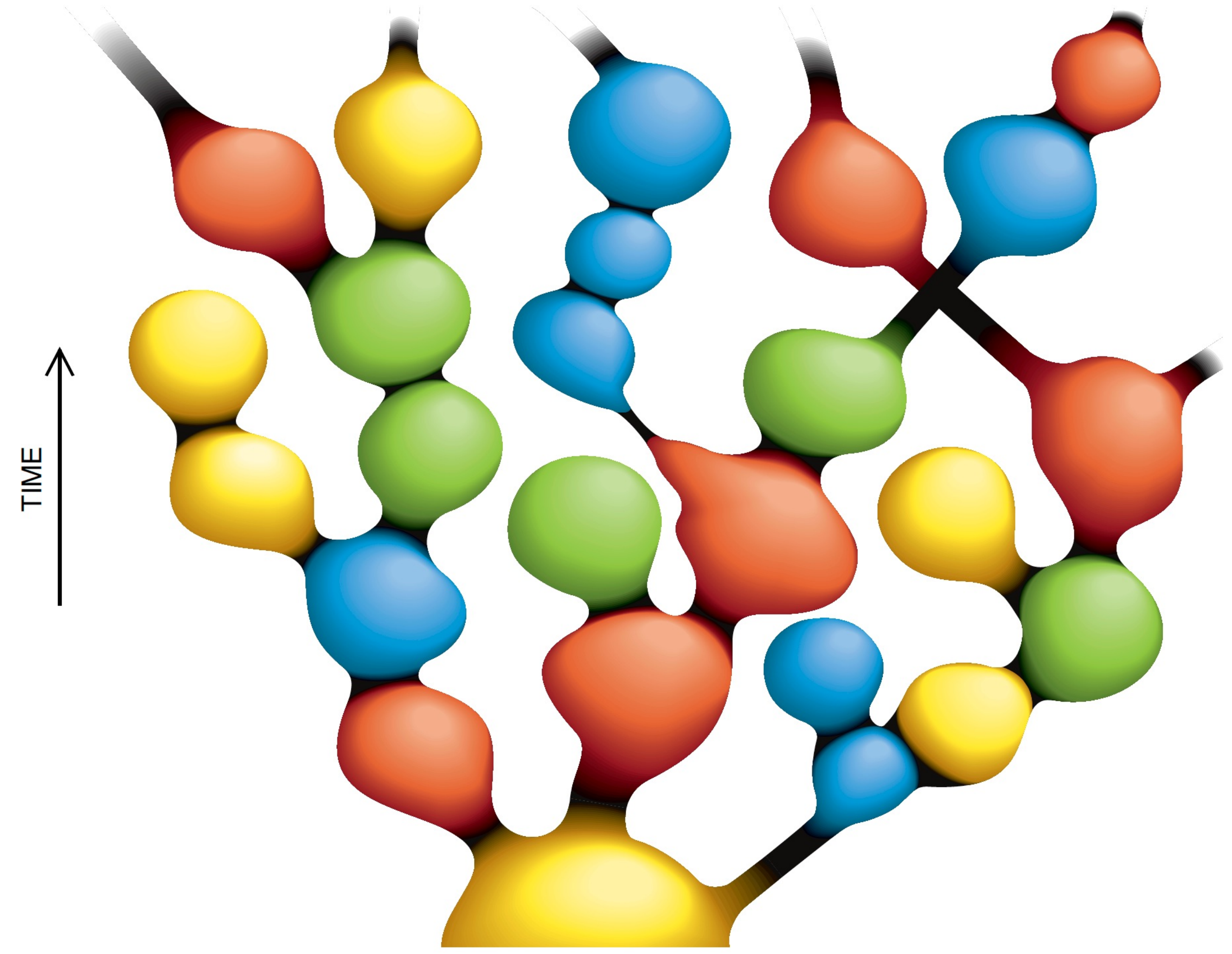
for $m_{3/2} \sim 1$ TeV

From strings to Cosmology



Inflation

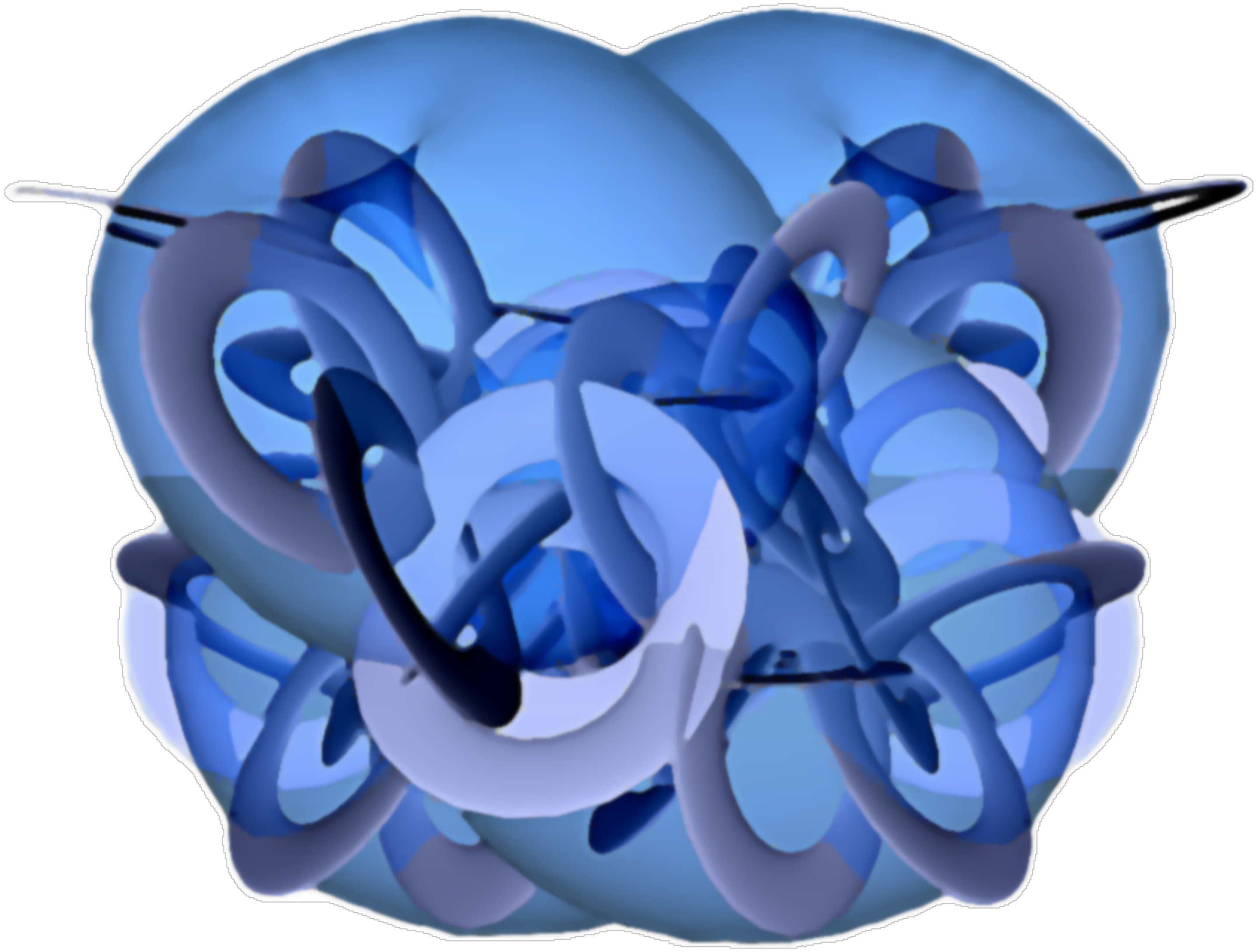
- A crucial mechanism for the string Landscape is the population of vacua via eternal inflation
  - Typical example: chaotic inflation
- It is therefore important to construct inflationary string models that also include the SM
- Very interesting case: large field inflation



Cosmology and moduli fixing

- When we couple the full gravity sector we encounter a lot of massless fundamental scalars in our theory: the closed string moduli

- Some of them are axions but some of them are not, and describe the shape of the compactification manifold X_6 (volume of some n-cycle $\Pi_n \subset X_6$)



Cosmology and moduli fixing

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- Some of them are axions but some of them are not, and describe the shape of the compactification manifold X_6 (volume of some n-cycle $\Pi_n \subset X_6$)
- We need to fix the value of such moduli because otherwise:
  - A de Sitter vacuum will quickly decay to a lower energy vacuum
  - An inflation potential is not reliable

Best framework: $\boxed{\text{Type IIB flux compactifications}}$

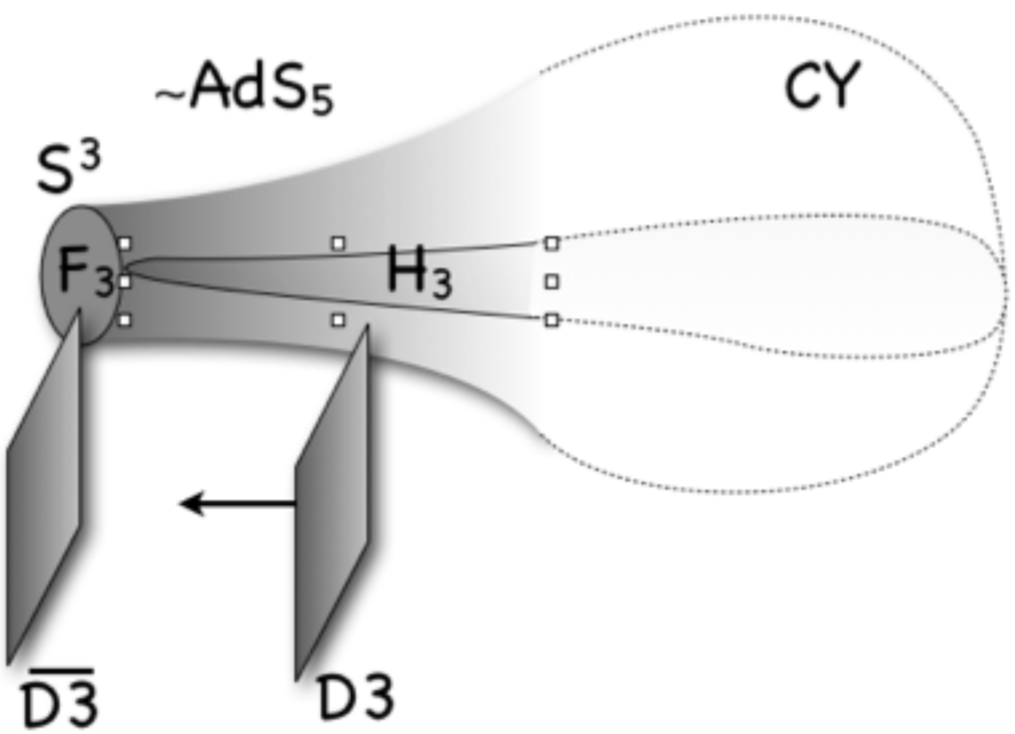
Most popular settings:

- KKLT
- Large Volume Scenario

D-brane inflation

- Given such moduli stabilisation scenarios one may consider models of inflation.
- Classes of models depend on the nature of the inflaton.
  Quite popular nowadays is D-brane inflation:

Dvali & Tye'98

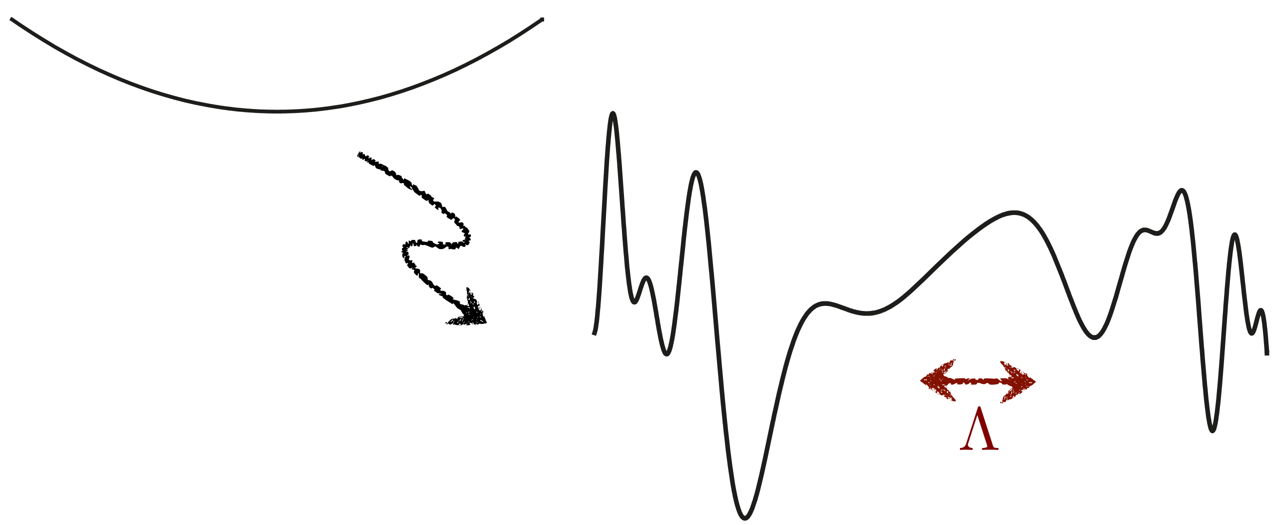


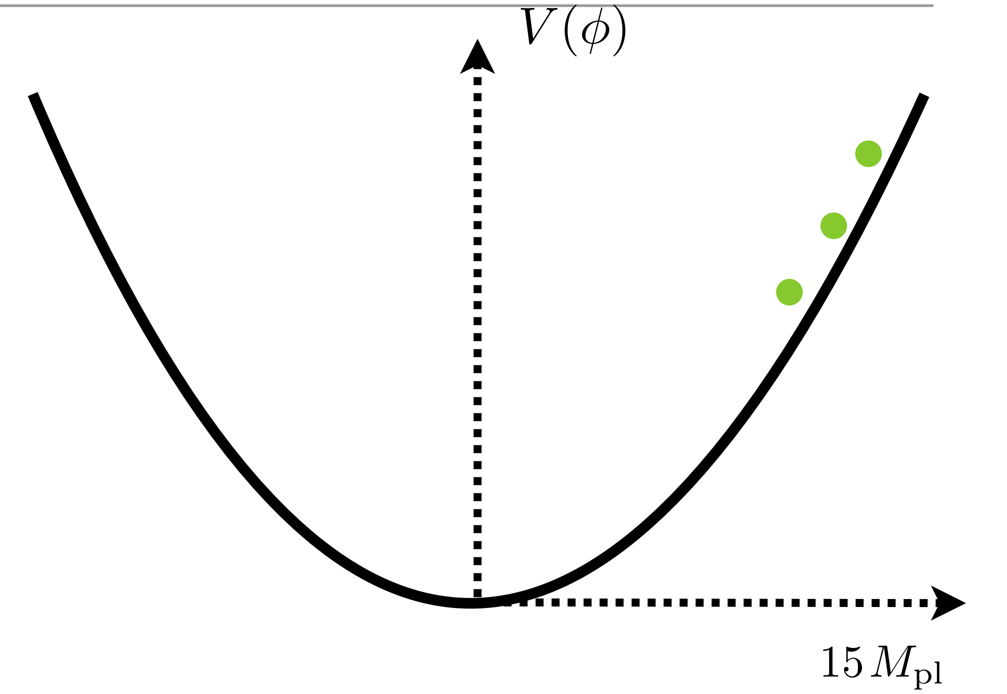
Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi'03

Large field inflation

- Large field inflation models are particularly sensitive to UV physics. We need a theory of quantum gravity to properly deal with them

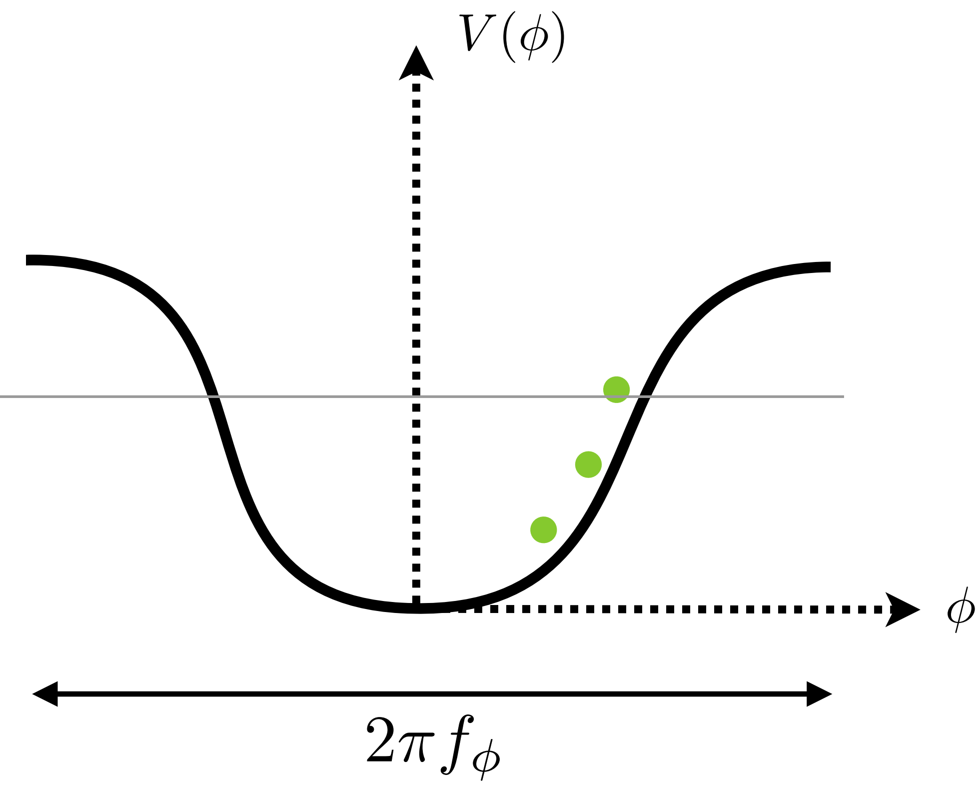
$$\mathcal{L}_{\rm eff}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}m^2\phi^2 + \sum_{i=1}^{\infty} c_i\, \phi^{2i}\Lambda^{4-2i}$$





- Moreover in them the typical inflationary scale is $M_{GUT} \sim 10^{16}$ GeV, which is very suggestive for models of unification.

Axions and strings

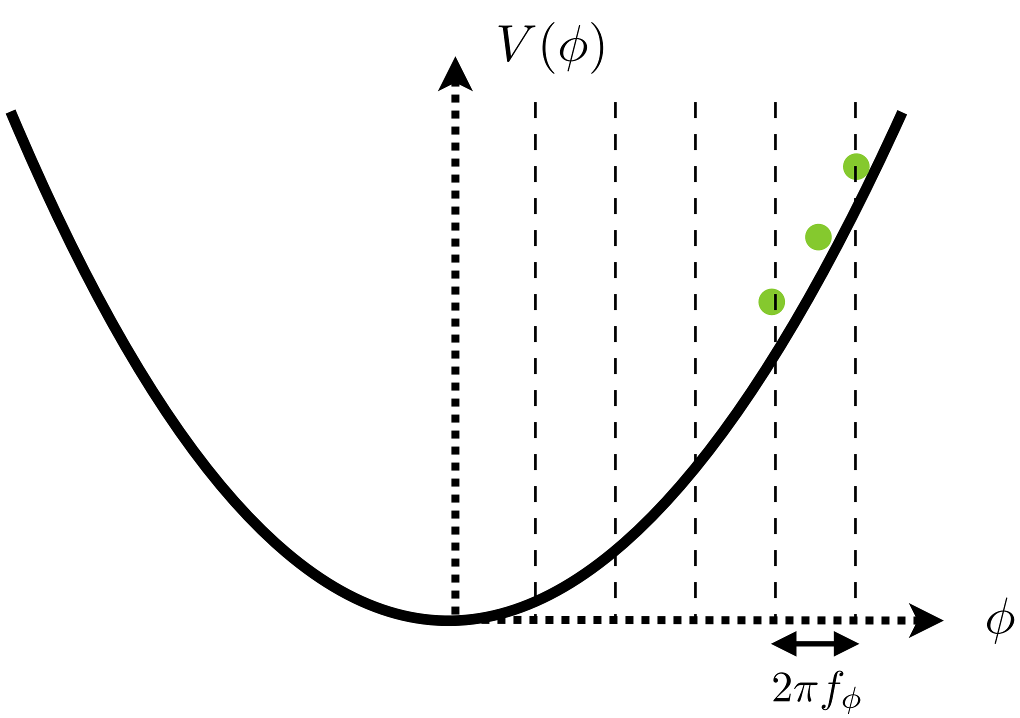


- In string theory one may elegantly implement large field inflation by identifying the inflaton with an axion and applying the axion-monodromy proposal

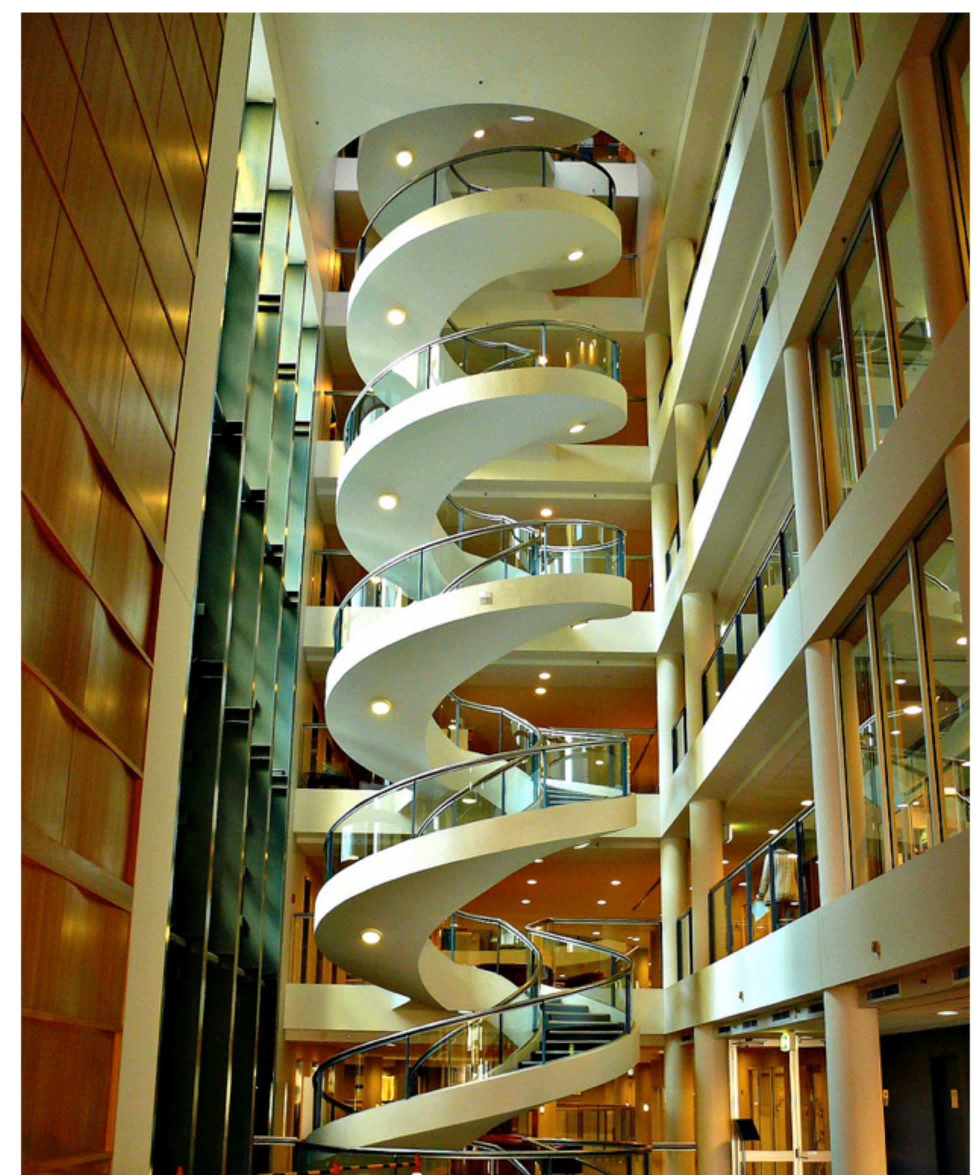
Silverstein & Westphal '08

- These ideas can be formulated in 4d effective field theory

Kaloper & Sorbo '08



What about string theory?



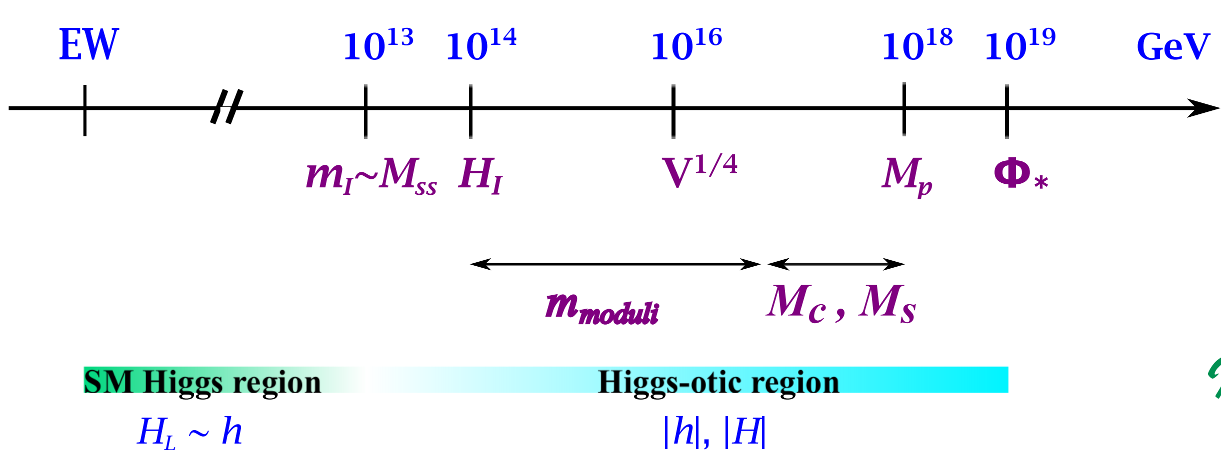
Strings and monodromies

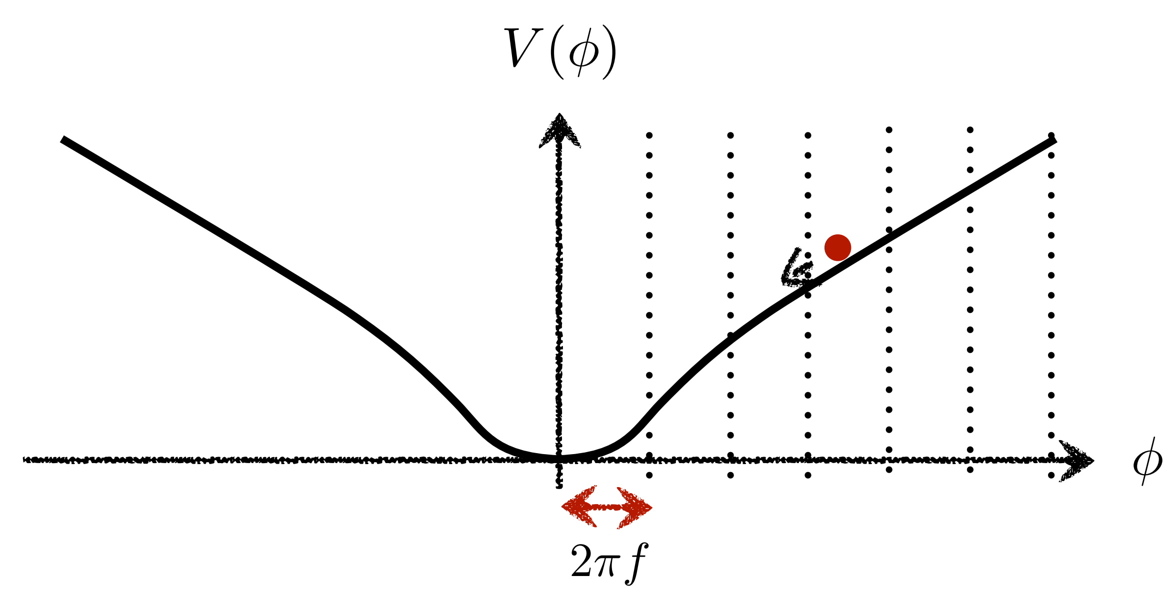
- One can obtain Kaloper-Sorbo by string compactifications where axions develop a superpotential

“F-term axion monodromy”

F.M., Shiu, Uranga ‘14

- Interesting results
  - Starting with a quadratic potential there is a flattening effect that reduces the tensor to scalar ratio *r* ➡ compatibility with current experimental bounds
  - Several kinds of models, some in direct connection with particle physics





Ibáñez, F.M., Valenzuela ‘14

Conclusions

- To build a string model, we need to reproduce a "wish list" of SM features
- The first items of the list are more universal, as well as more robust with respect to corrections. Further items are usually more model-dependent
- A key feature is chirality. One can classify models by how chiral fermions arise.
- A quantity difficult to reproduce are Yukawa couplings, but vacua based on F-theory models can realise a hierarchical structure in a natural way.
- Other recent developments involve moduli stabilisation, SUSY breaking and discrete gauge symmetries in string models.
- Open questions mostly involve the string Landscape, the SUSY and string scales and how to implement early cosmology in string theory
- Most of the recent activity in string cosmology has been devoted to construct models of small and large field inflation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ORGANIZERS:
L.E. IBAÑEZ
F. MARCHESANO
A.M. URANGA
sPheno
GRASSY