string phenomenology today

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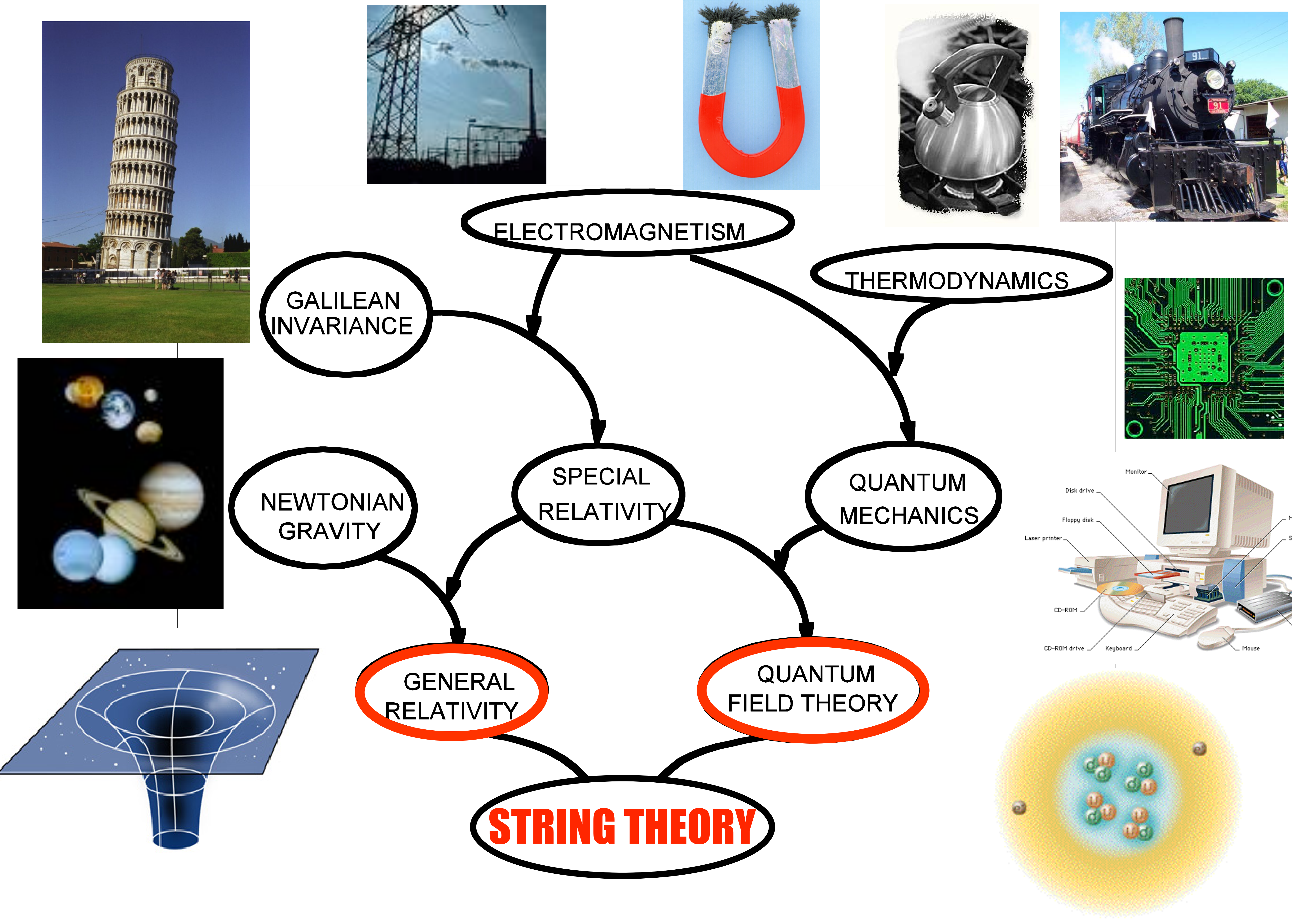
ELECTROMAGNETISM
GALILEAN INVARIANCE
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SPECIAL RELATIVITY
NEWTONIAN GRAVITY
QUANTUM MECHANICS
GENERAL RELATIVITY
QUANTUM FIELD THEORY
STRING THEORY
Monitor
Disk drive
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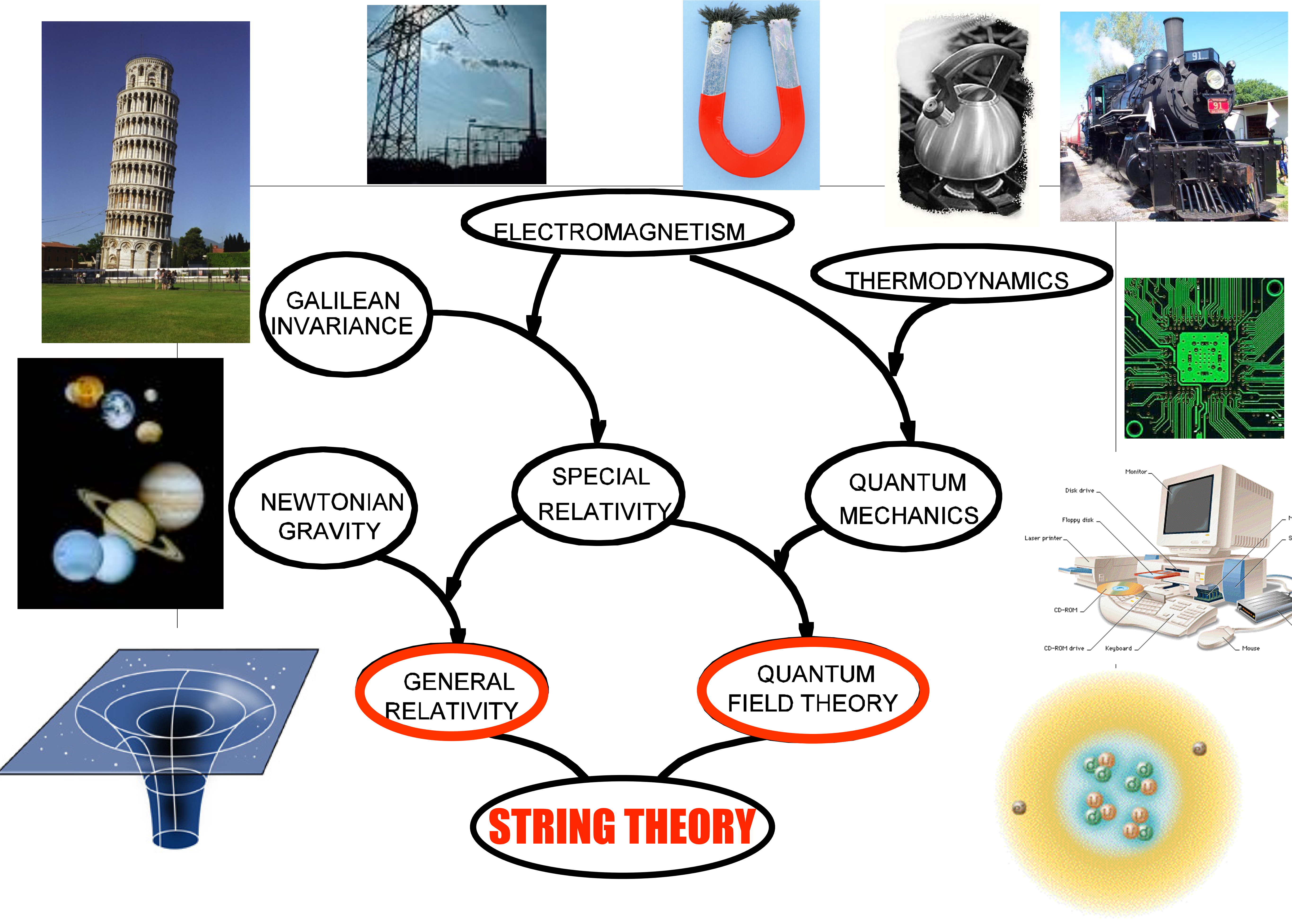
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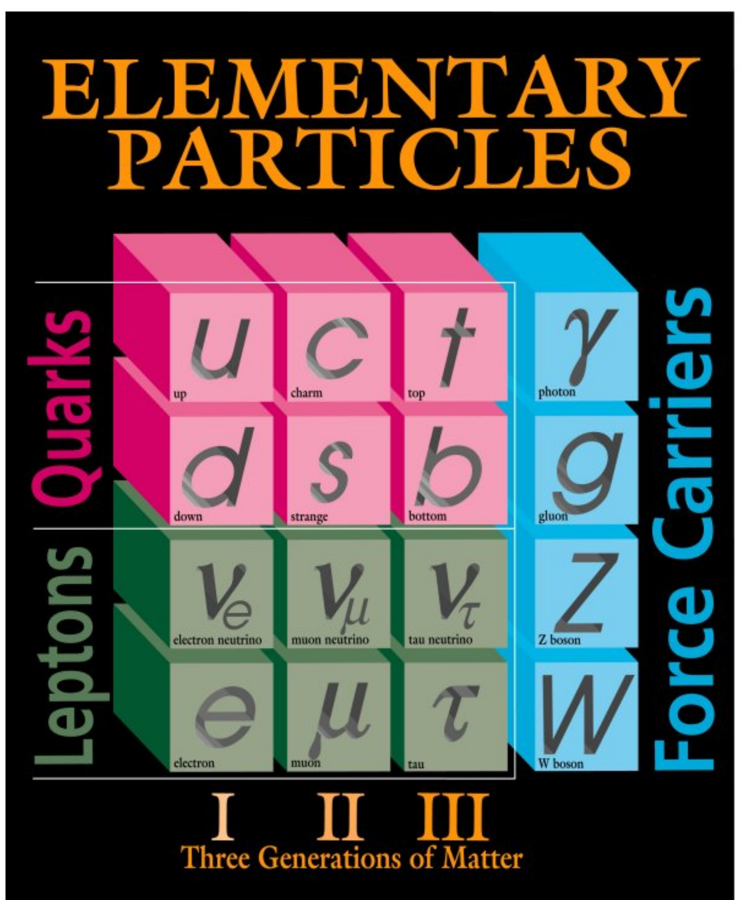
Why string phenomenology?

- 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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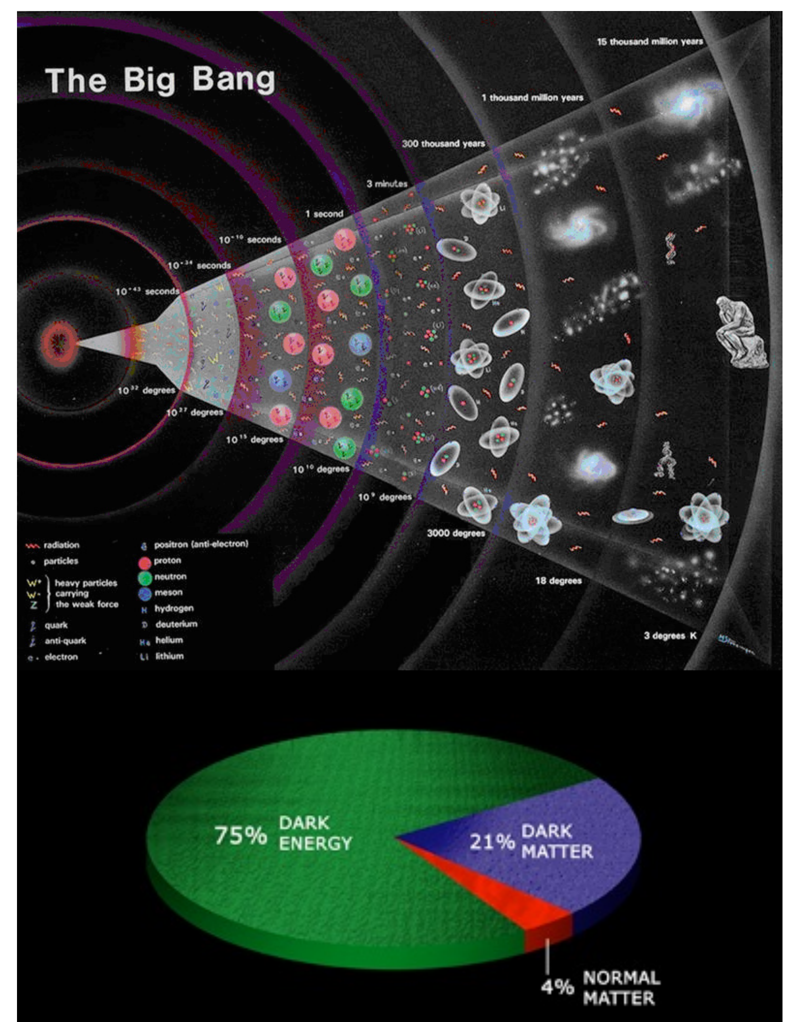

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So how do we proceed?

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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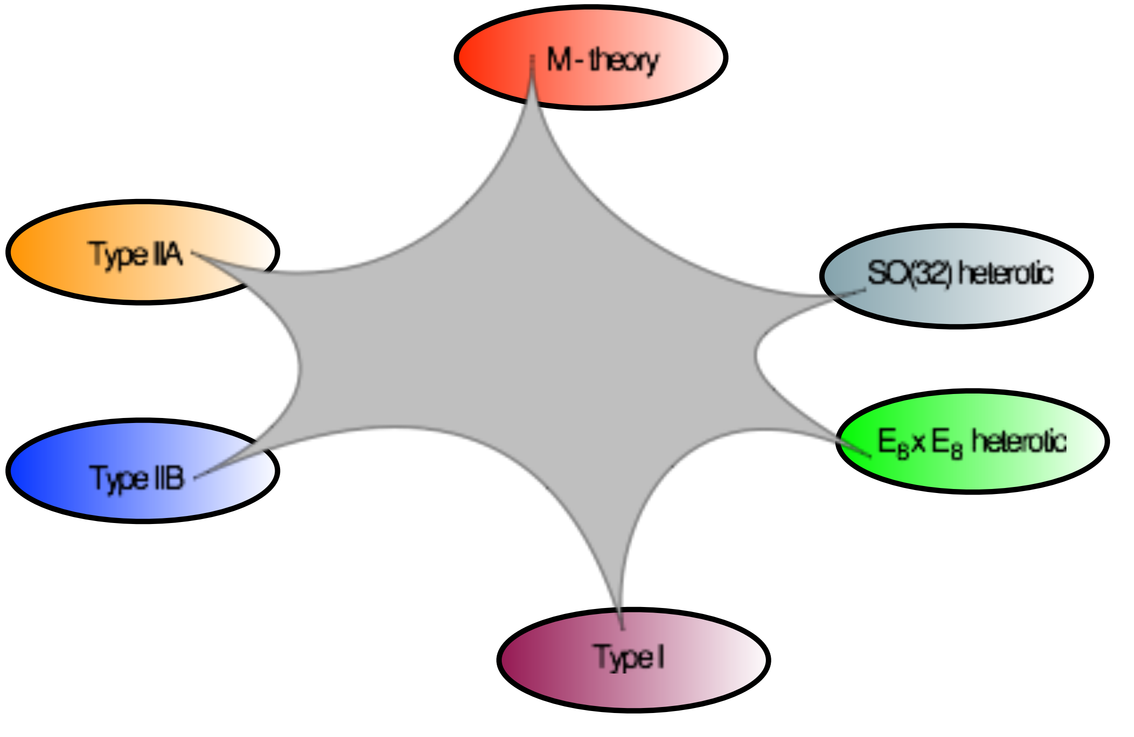
string phenomenologist go for option #2

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

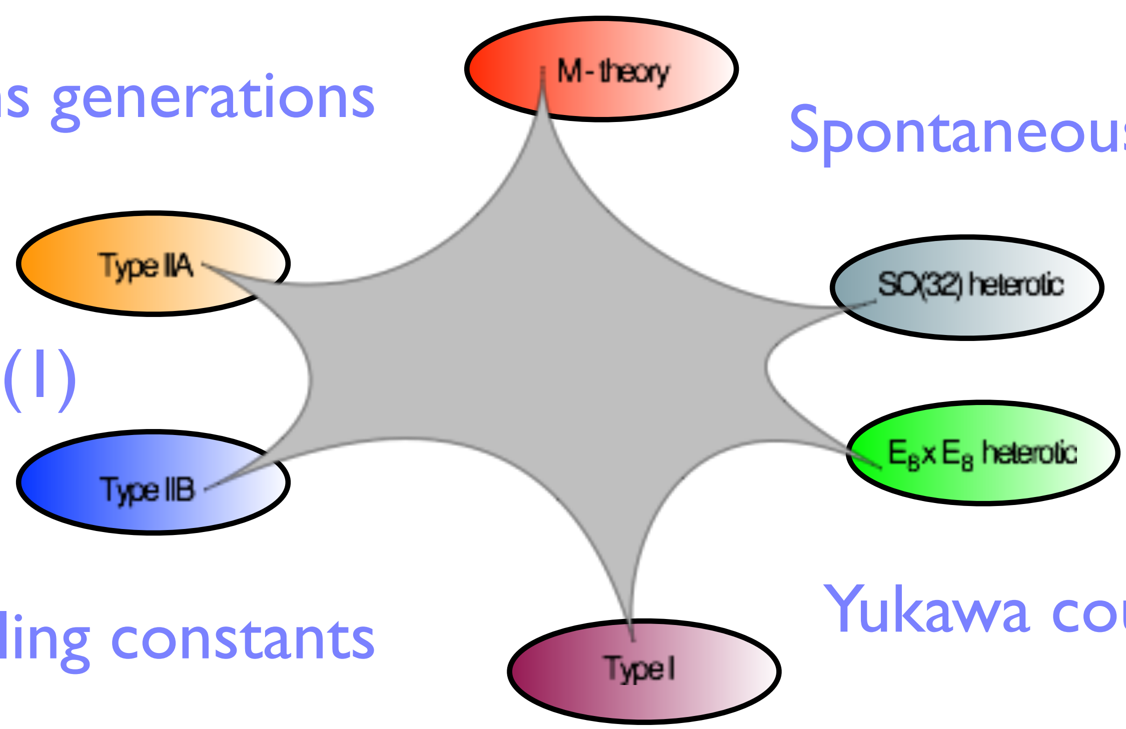
Spontaneous EWSB

SU(3) x SU(2) x U(1)

Chirality

Gauge coupling constants

Yukawa couplings

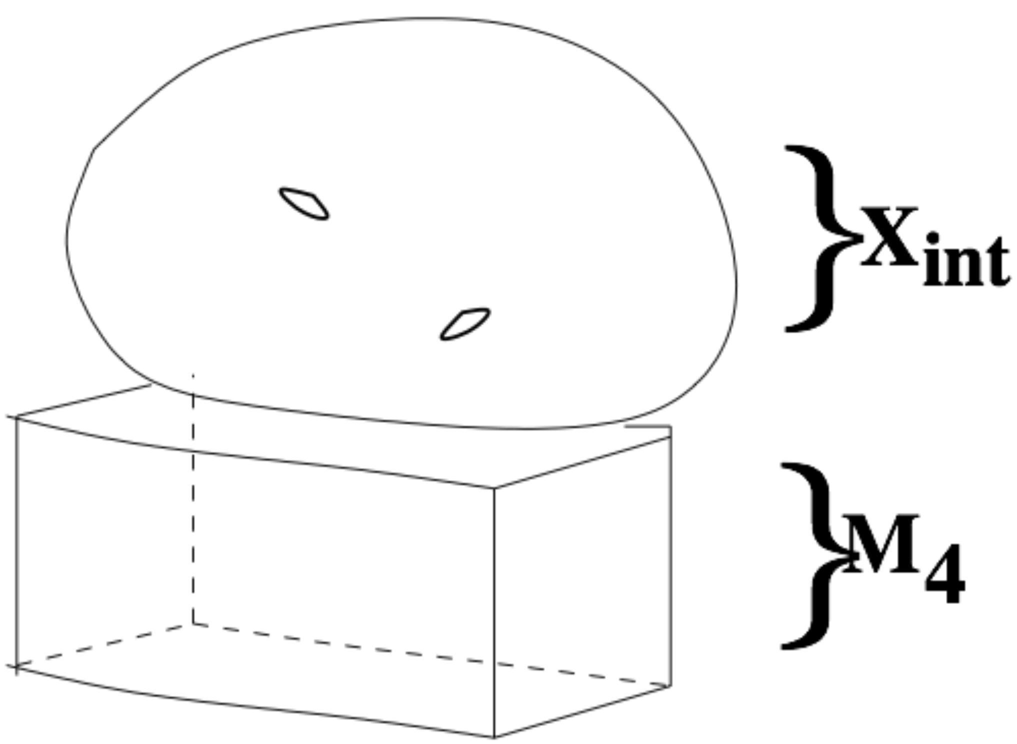


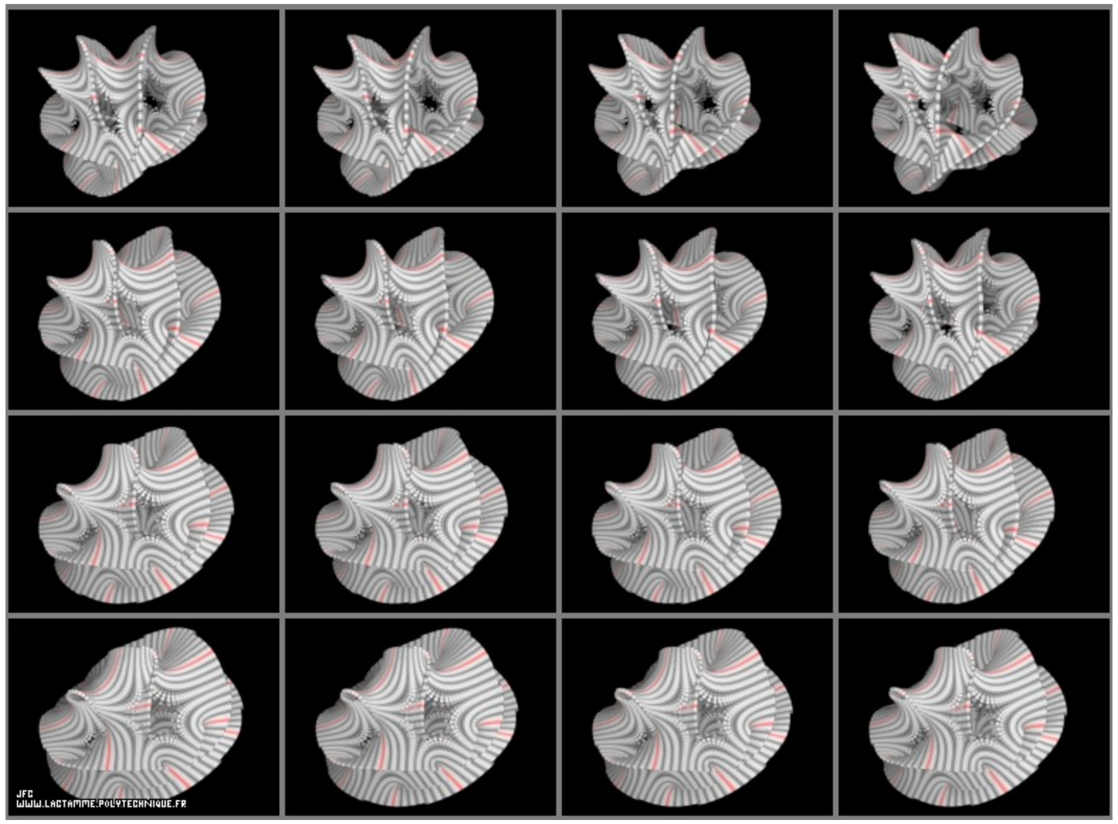
The quest for predictions

- From the 10d viewpoint string theory is rather unique, because its different versions are related by dualities. However, there is a myriad of possibilities to construct effective 4d theories by compactification

string Landscape

- 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 set of vacua that we particularly like and we try to obtain a whole bunch of BSM predictions from it

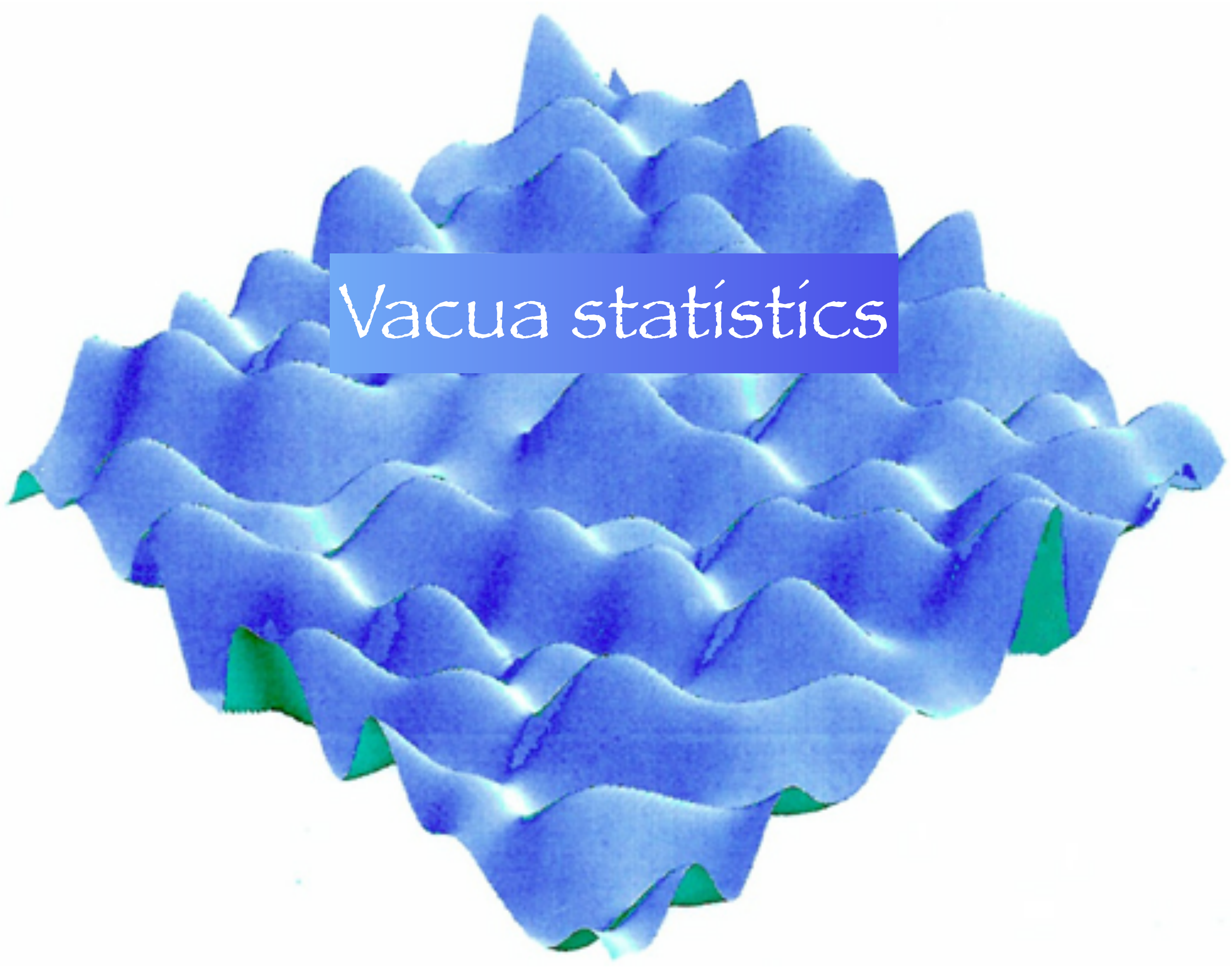
b) We try to get an overall picture of the BSM features of 4d vacua, as well as the kind of scenarios that they generate

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)

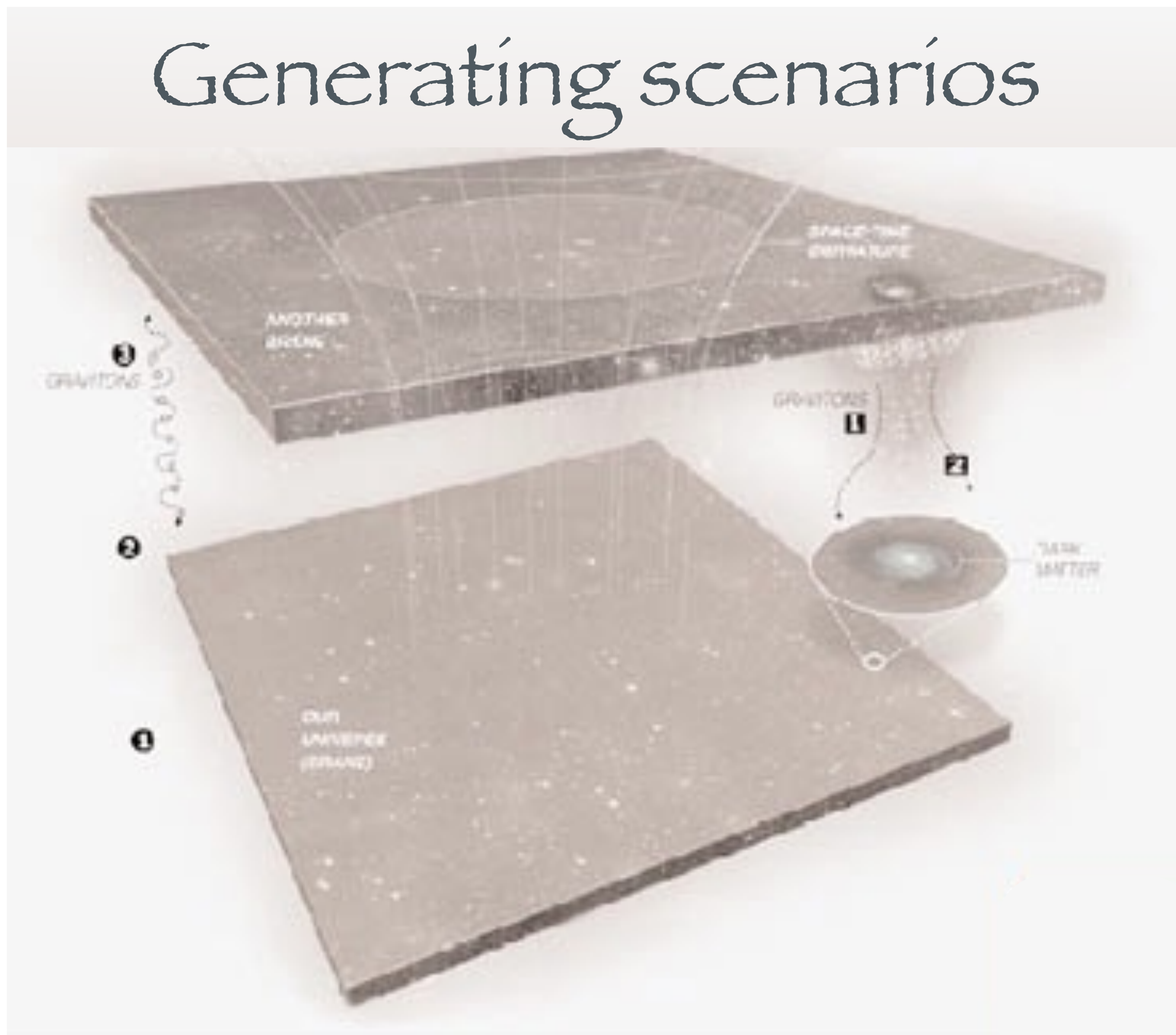
3+1 strategies for (3+1)d physics

Building vacua

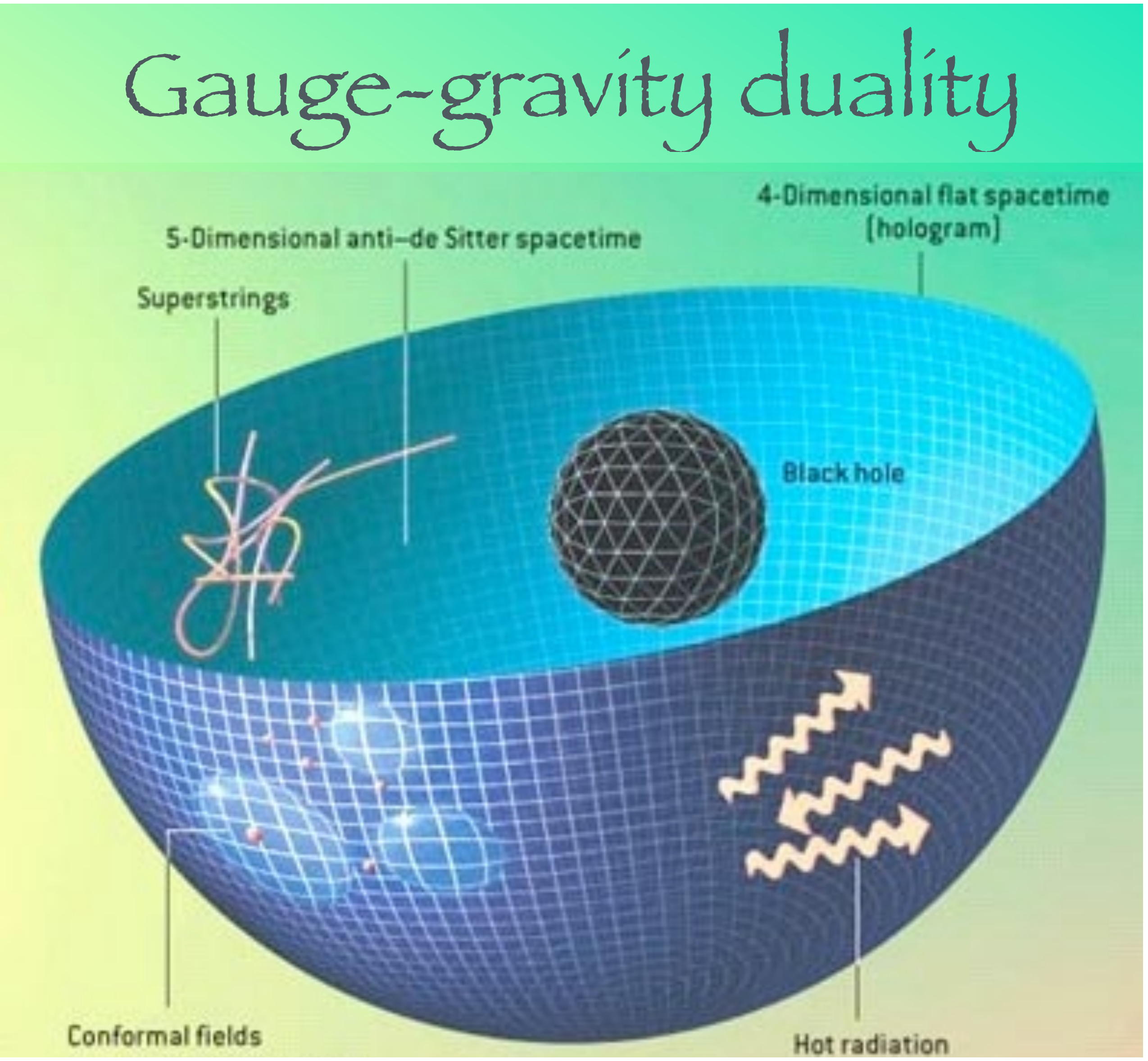
3+1 strategies for (3+1)d physics



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



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



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- From the 10d viewpoint string theory is rather unique, because its different versions are related by dualities. However, there is a myriad of possibilities to construct effective 4d theories by compactification
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different approaches:

a) Building vacua

b) Vacua statistics

c) BSM scenarios

+

d) holography

for each of these approaches, it is important to understand which vacua lead to realistic 4d theories and how close we can get to them

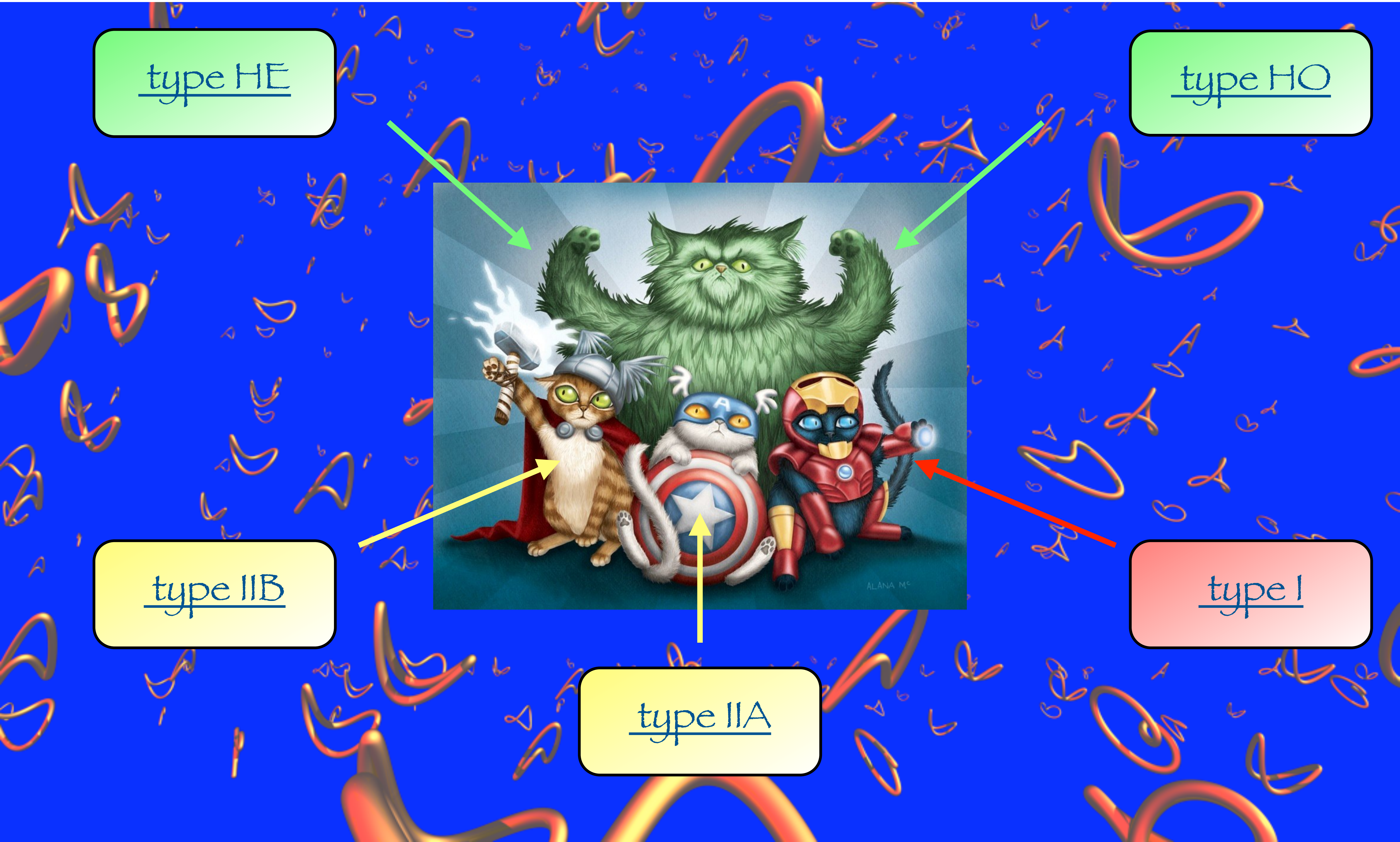
Building vacua

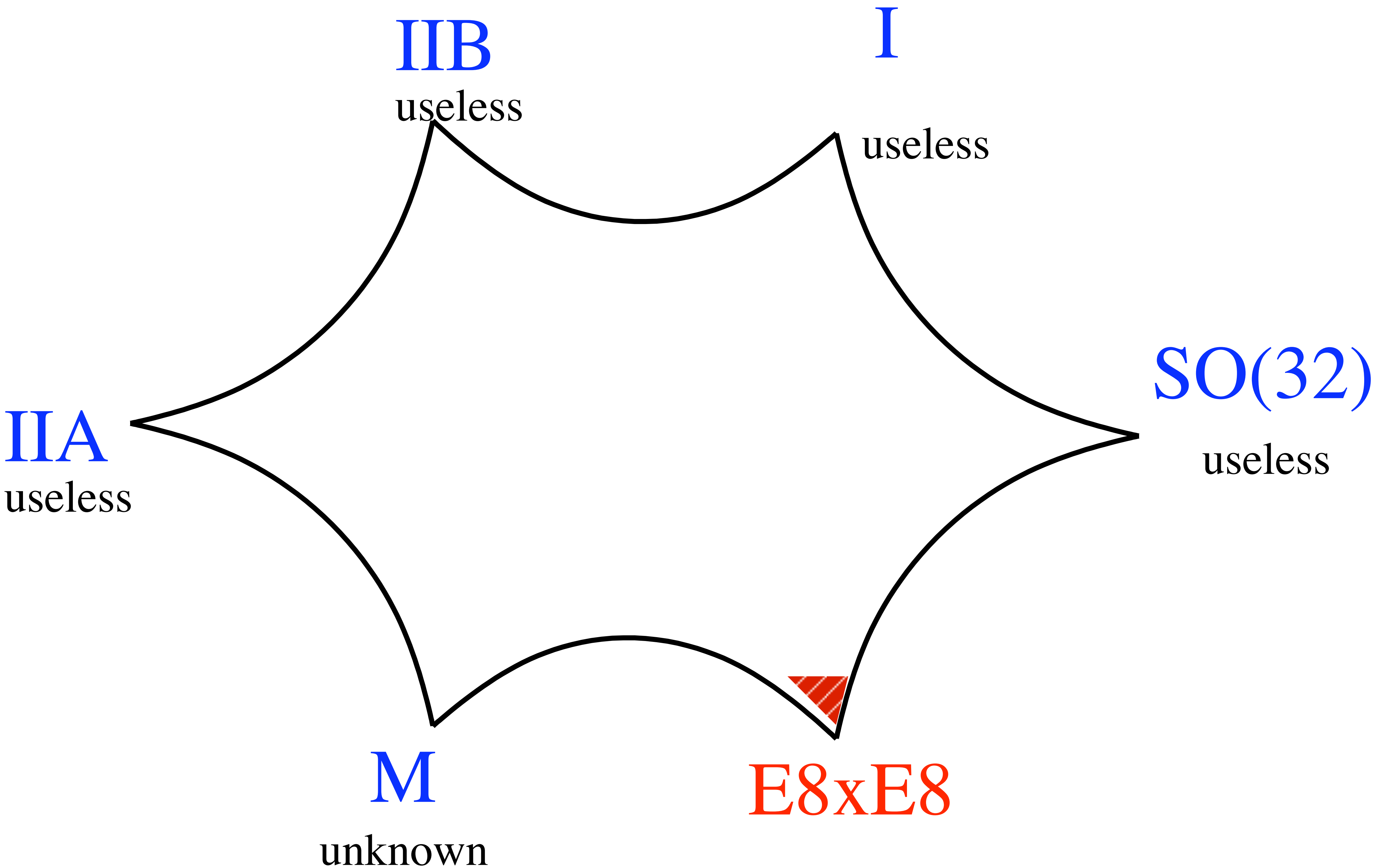
Building vacua

- 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?





Design: L. E. Ibañez

Circa 1995

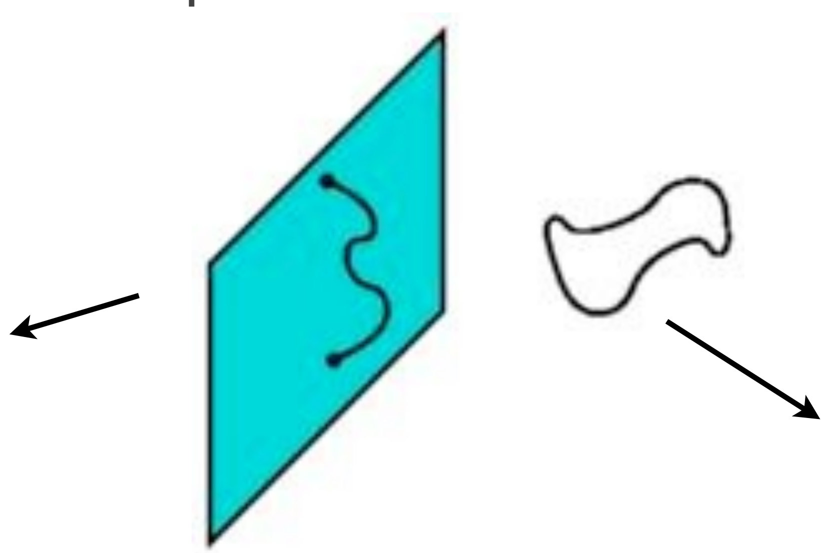
D-branes and dualities

- Dp-branes: solitonic objects that appear in 10d superstring and supergravity theories
- In string theory, described as p+1 dimensional hypersurfaces where open string endpoints are confined

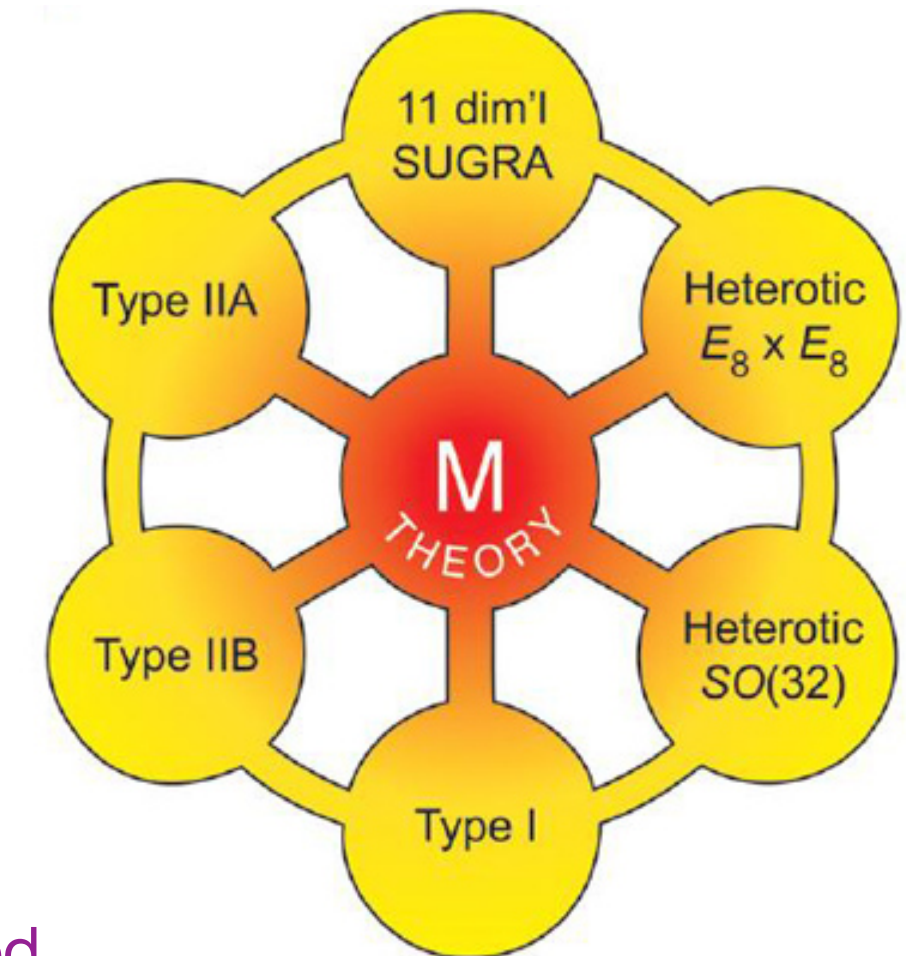
Polchinski '95

- Leads to the general picture:

confined
(p+1) dim.
gauge theory



unconfined
10 dim.
gravity

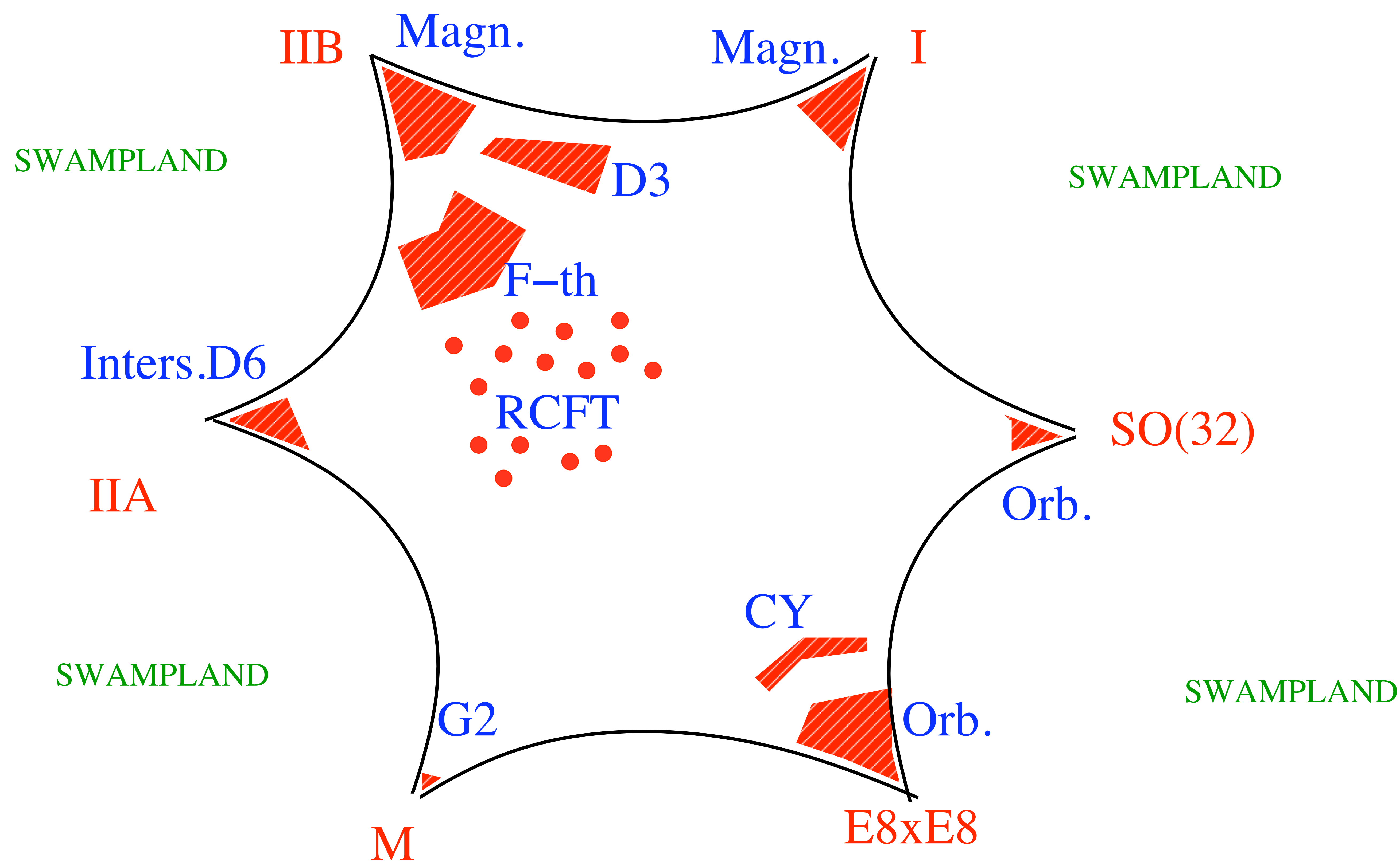


web of dualities
connecting different
string theories

Witten '95

...

2nd string revolution



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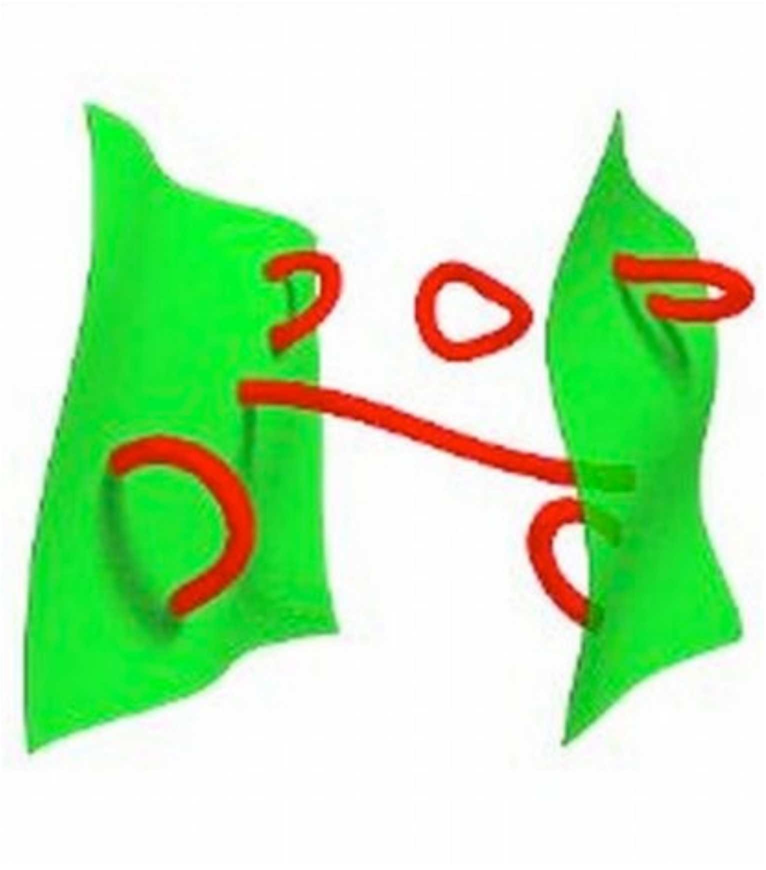
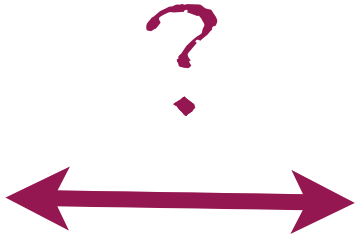
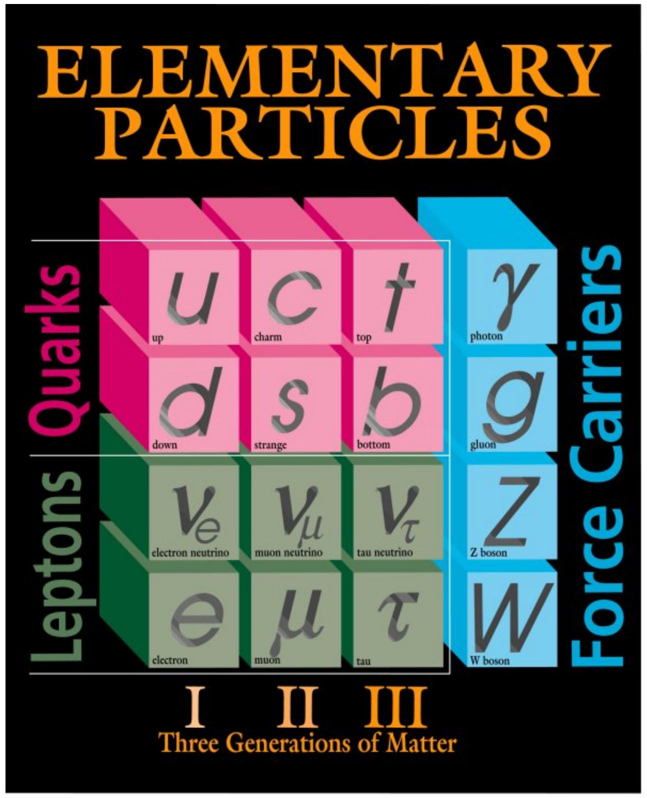
Circa 2017

From strings to Particle Physics







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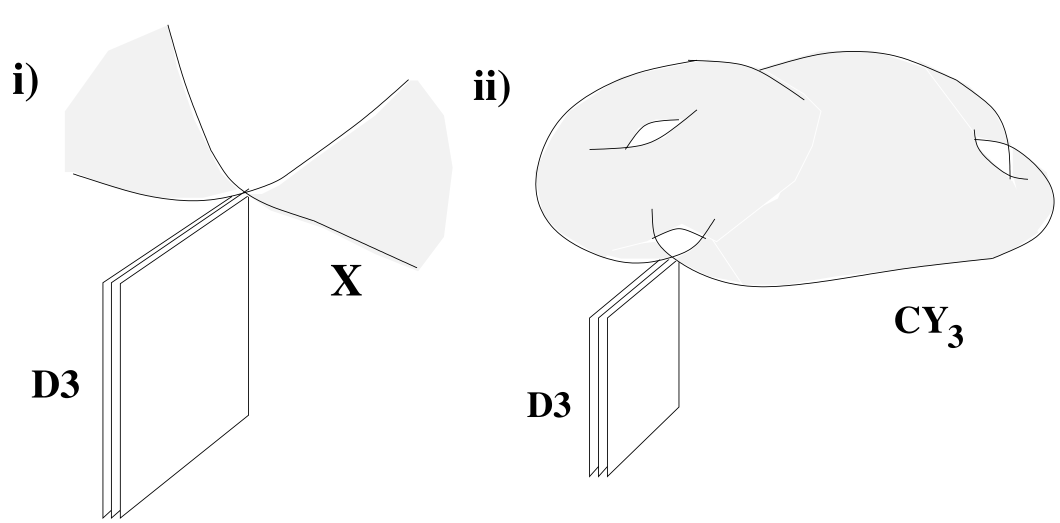
Two main approaches

- 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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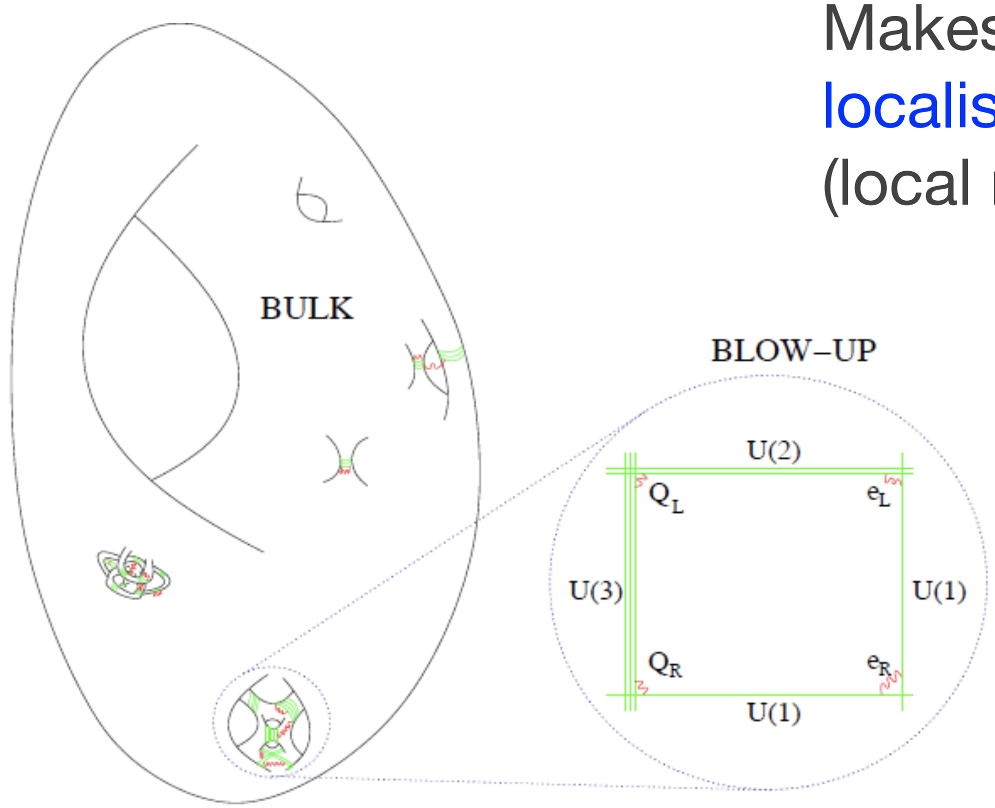
Candelas et al. '86

- 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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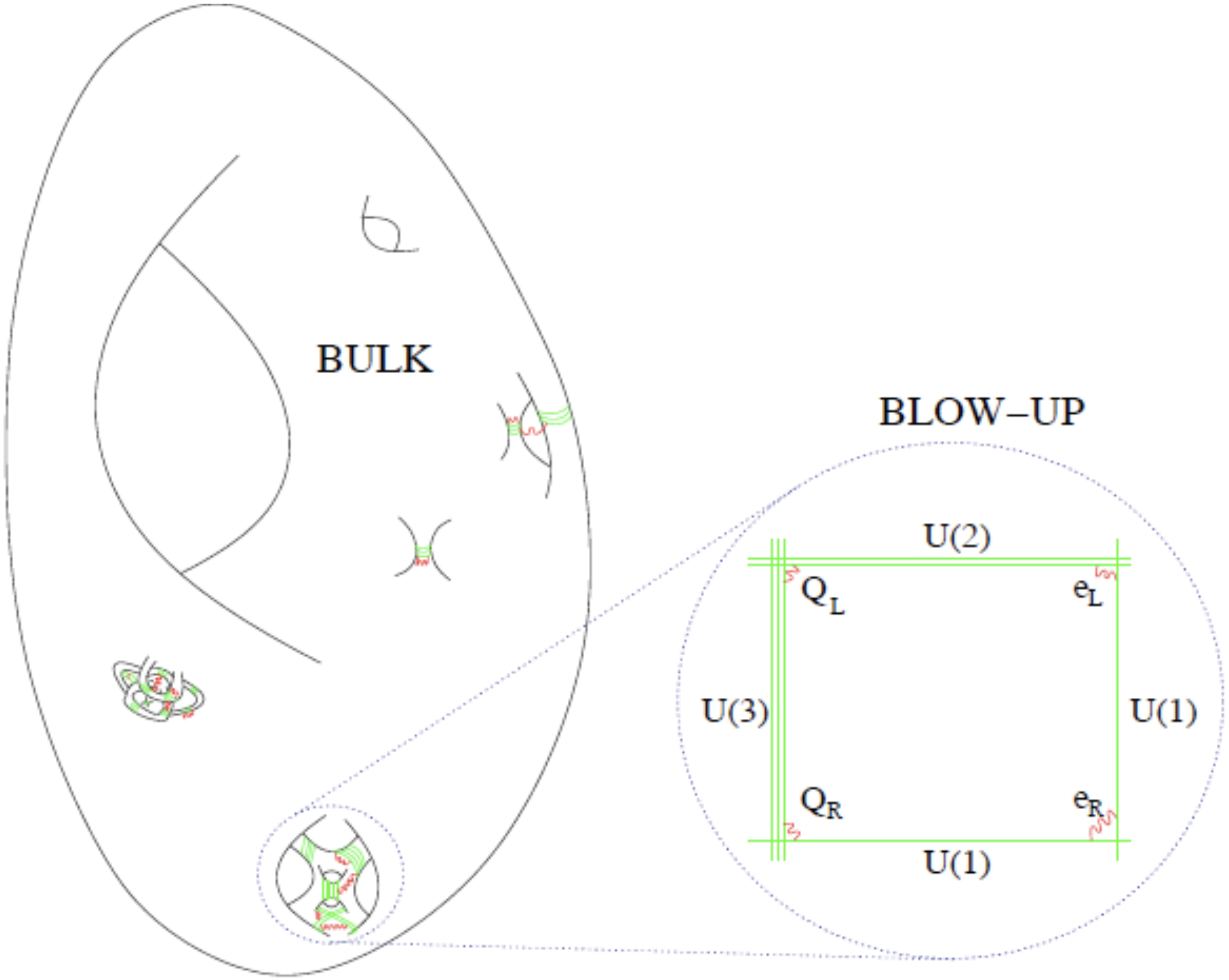
F-theory

- A quite promising novel class of vacua are those based on F-theory local models

- Cousins of D-brane models

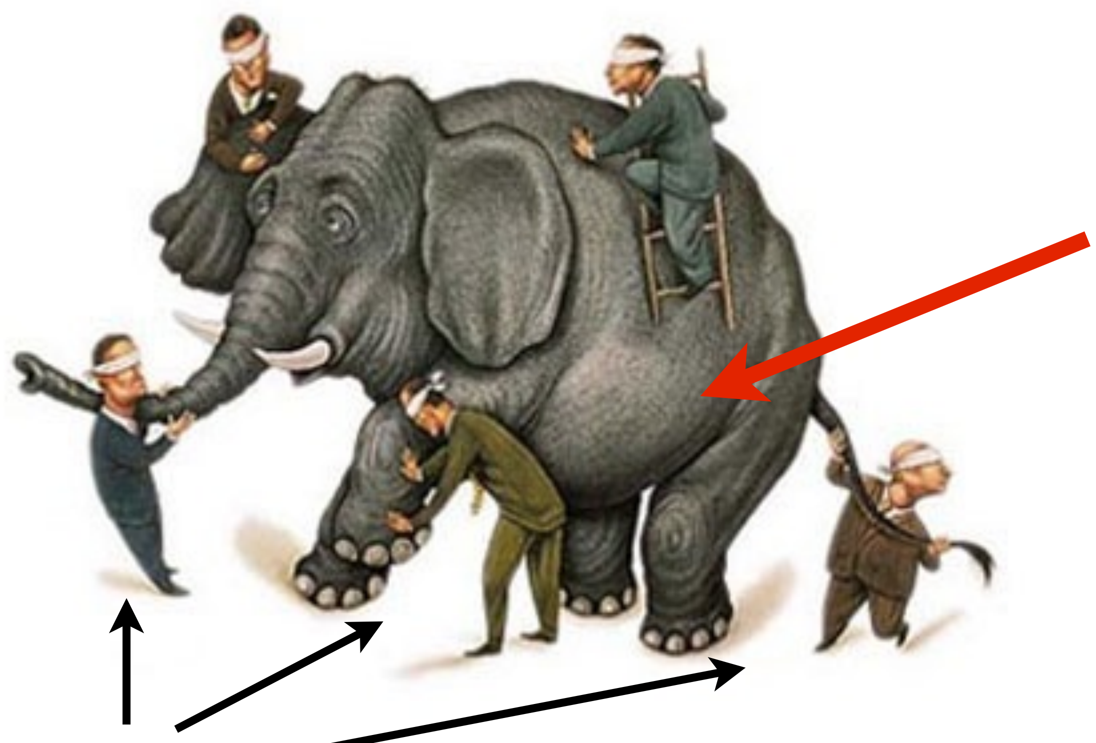
- Bottom-up approach

- Realise gauge coupling unification via GUTs



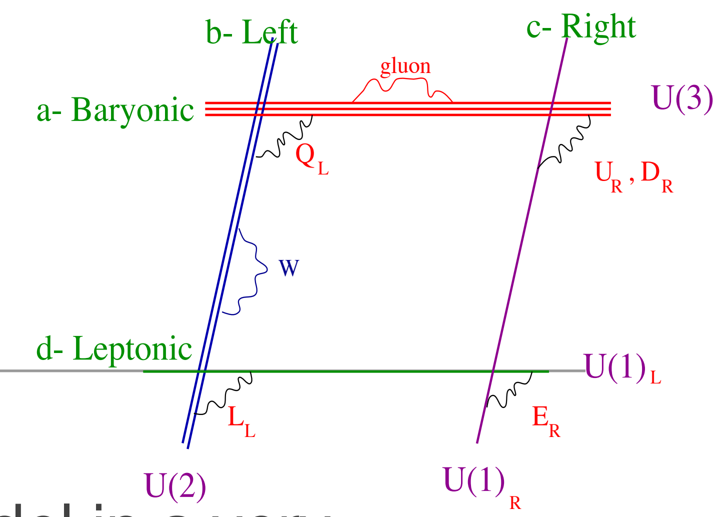
What have we learnt lately?

String/M-theory

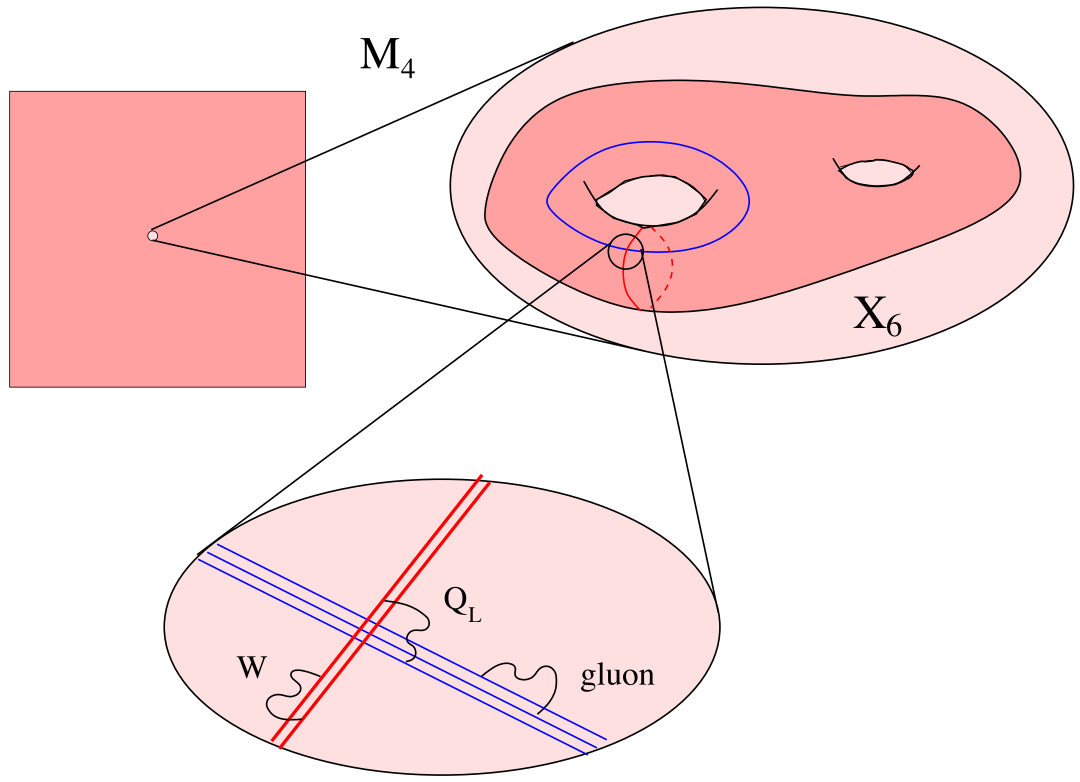


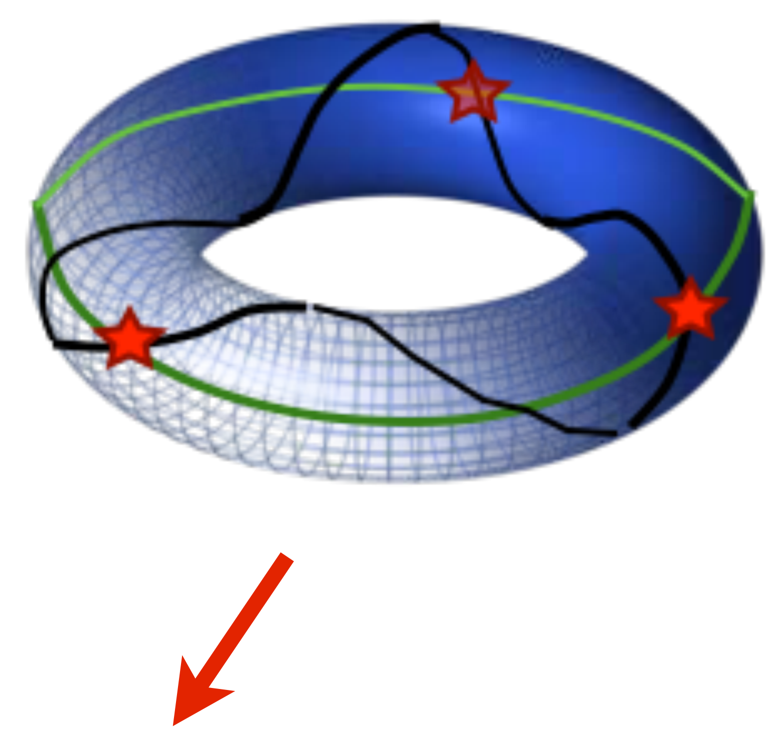
String phenomenologists

The type IIA insight



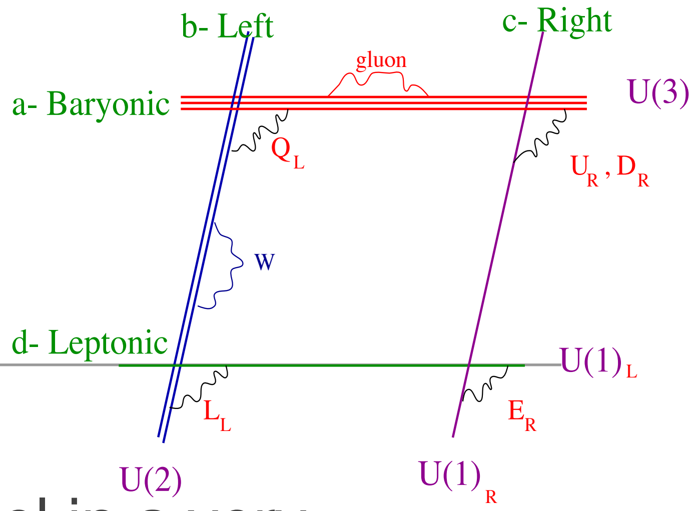
- Type IIA vacua describe the most relevant features of a model in a very intuitive and pictorial way.
  - Example: chiral fermions from internal intersections → family replication





3 families

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, and to better understand their 4d effective theories.
- Recently:
  - D-brane instantons
  - Discrete gauge symm.

  } hierarchy of couplings

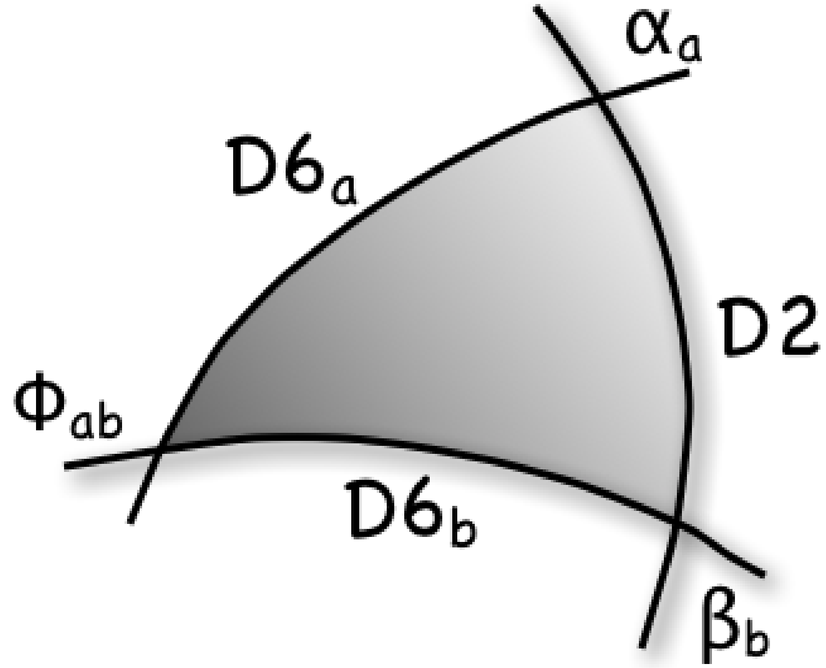
Instantons and discrete gauge symmetries

- 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

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

Blumenhagen, Cvetic, Weigand '06

Ibañez & Uranga '06



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Blumenhagen, Cvetic, Weigand '06

Ibañez & Uranga '06

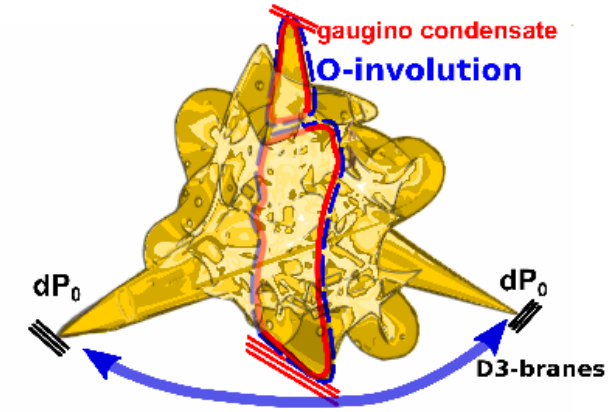
- In general they can break the U(1) completely or to a $\mathbb{Z}_k$ subgroup

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

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

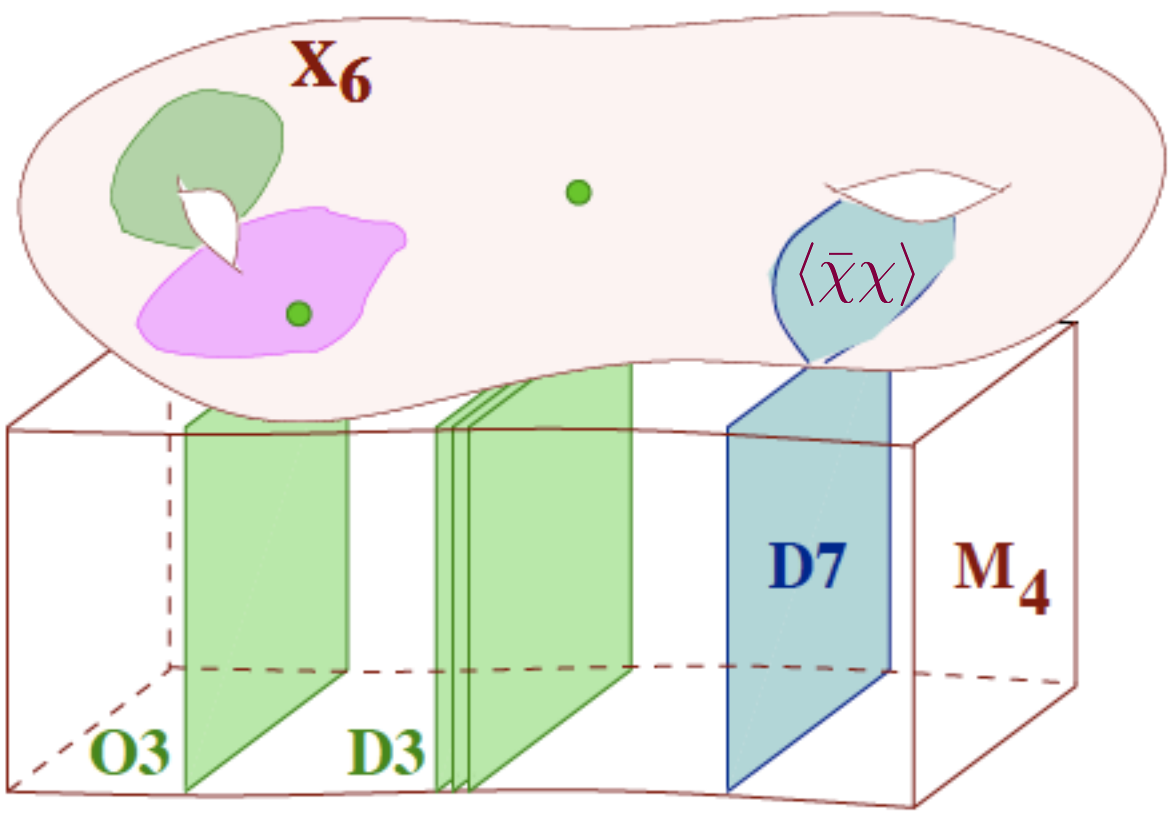


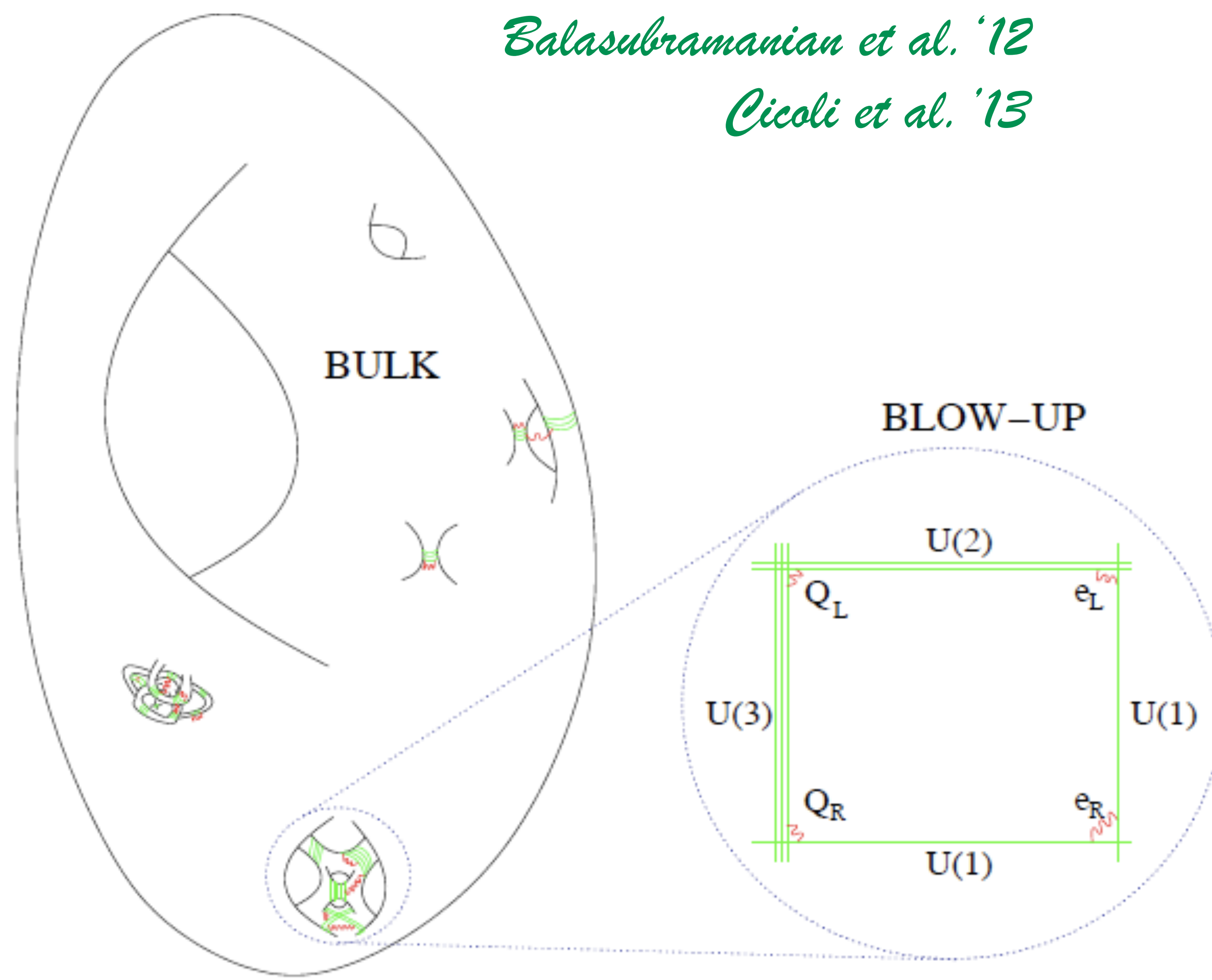
The type IIB strength

- 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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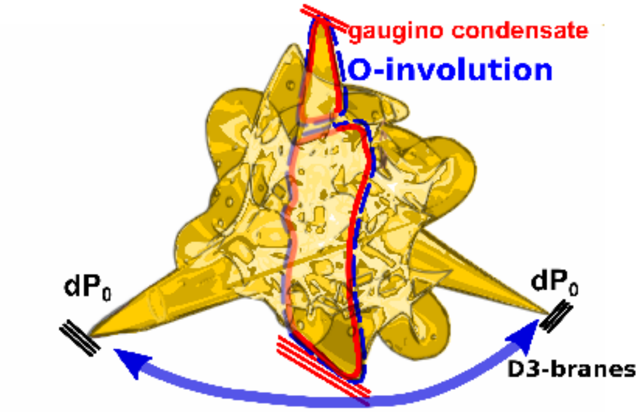

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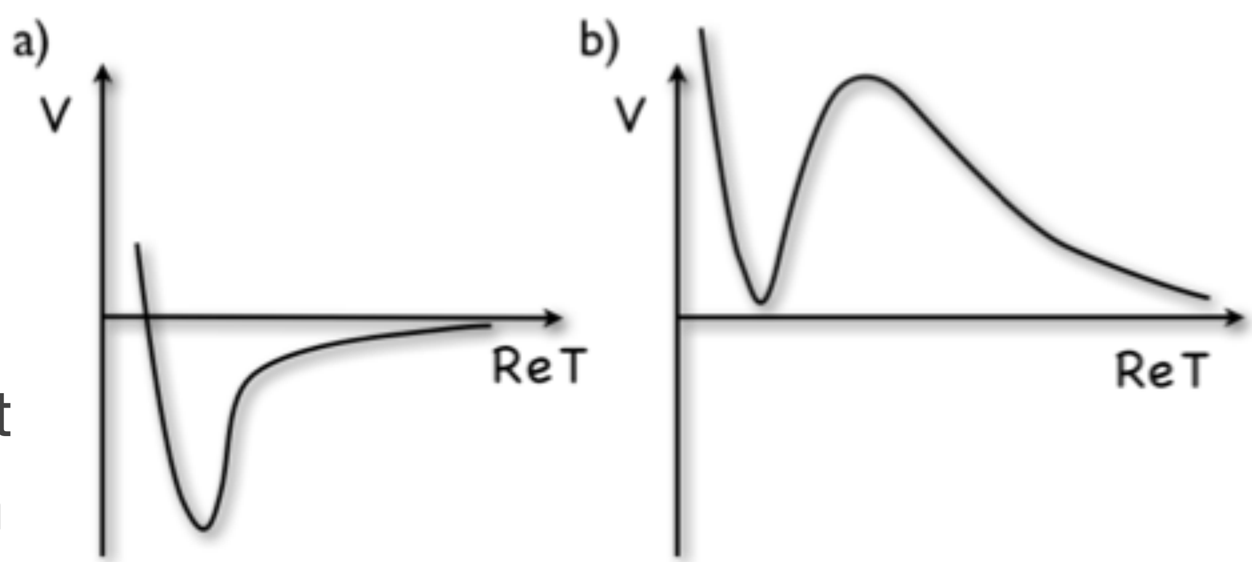
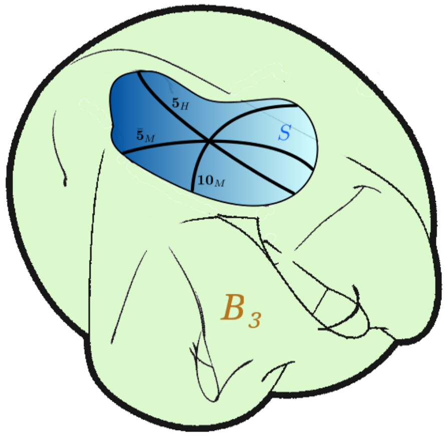
Balasubramanian et al. '12
Cicoli et al. '13

- 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

Type IIB and SUSY breaking



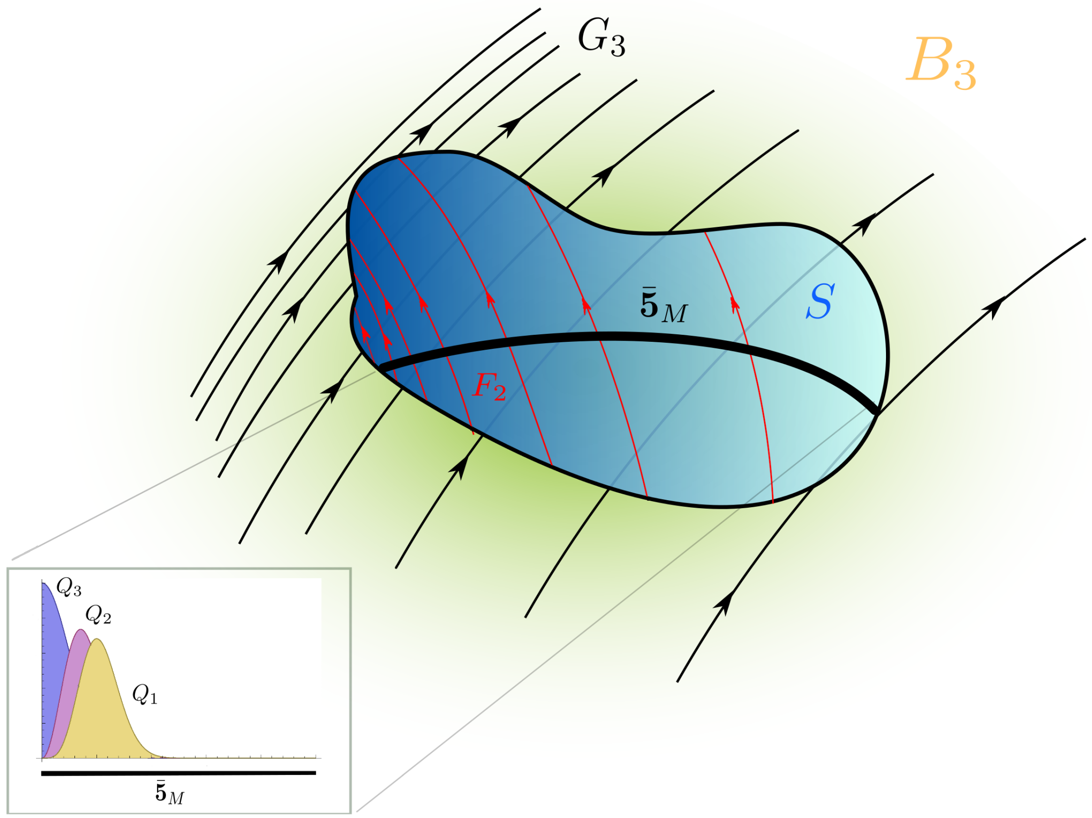
- Type IIB models are also particularly suitable to analyse SUSY breaking effects on particle physics models

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

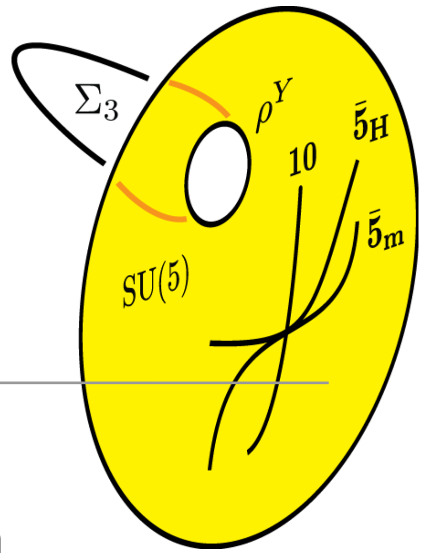
    Camara et al. '04-13

  - 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



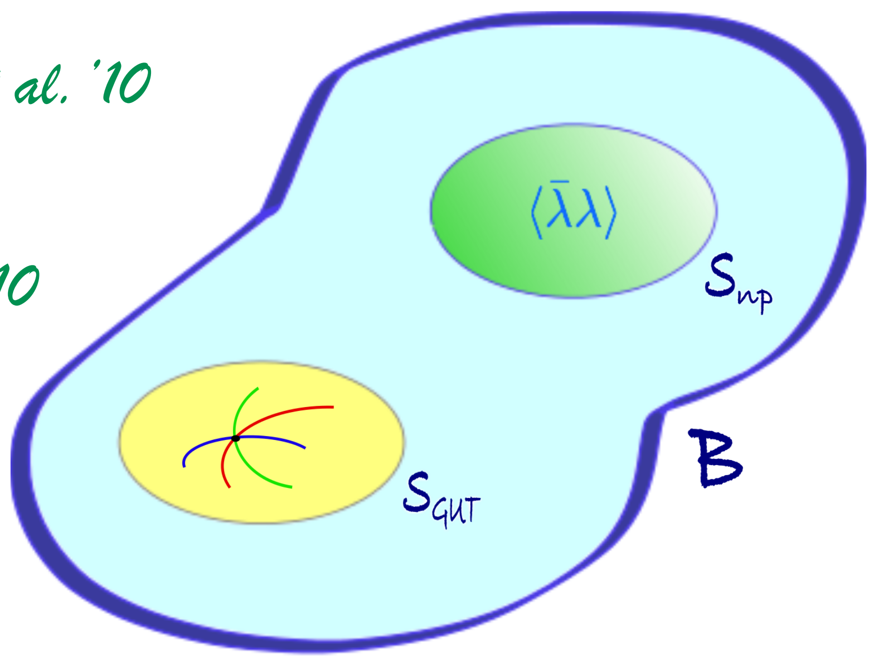
The power of F-theory



- 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*
  - Deviation from 4d GUT relations thanks to hypercharge flux dependence of masses: $Y_\tau \neq Y_b$
  - Good fits in MSSM-like scenarios with large tan β

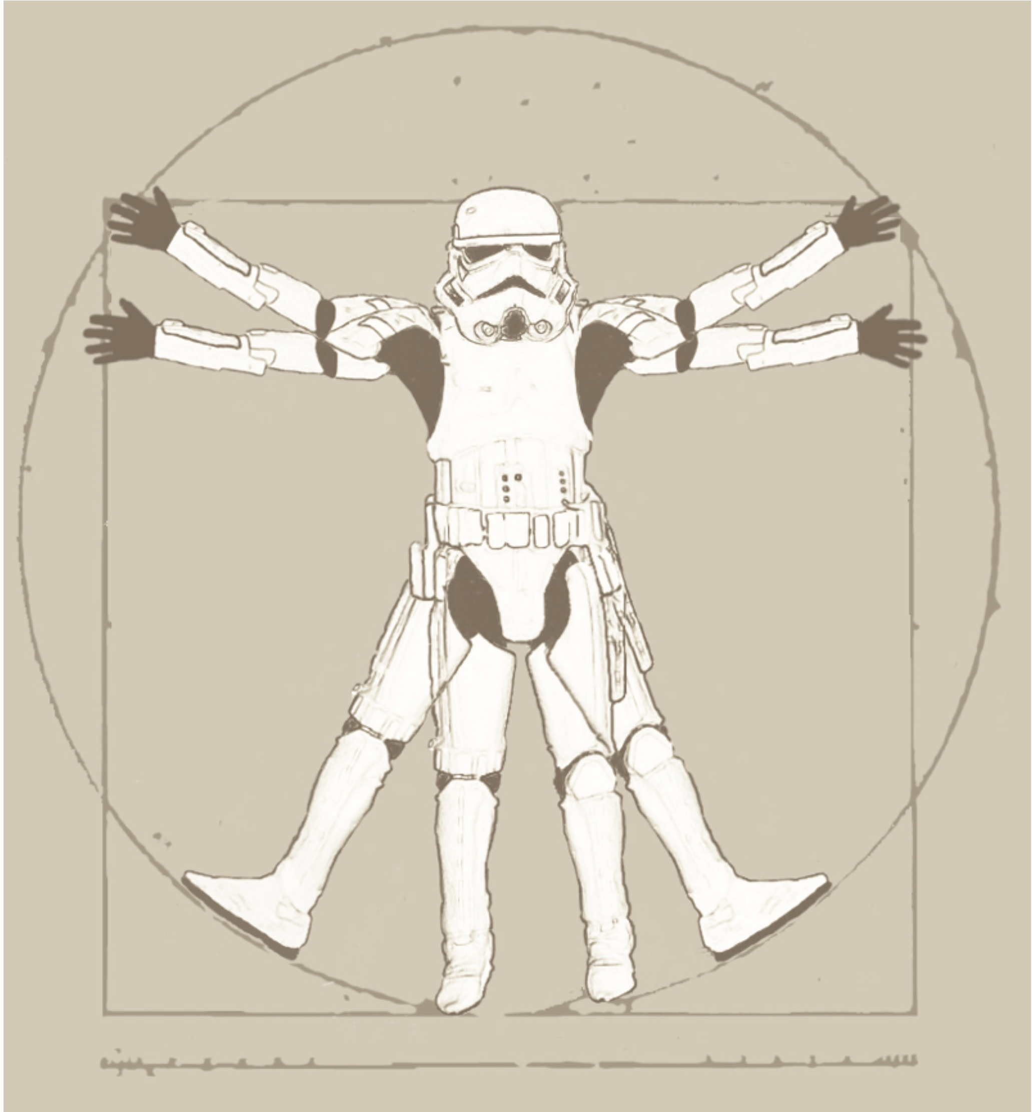


Regalado et al. '15 *Carta et al. '15*

What are the open questions?

The String Landscape

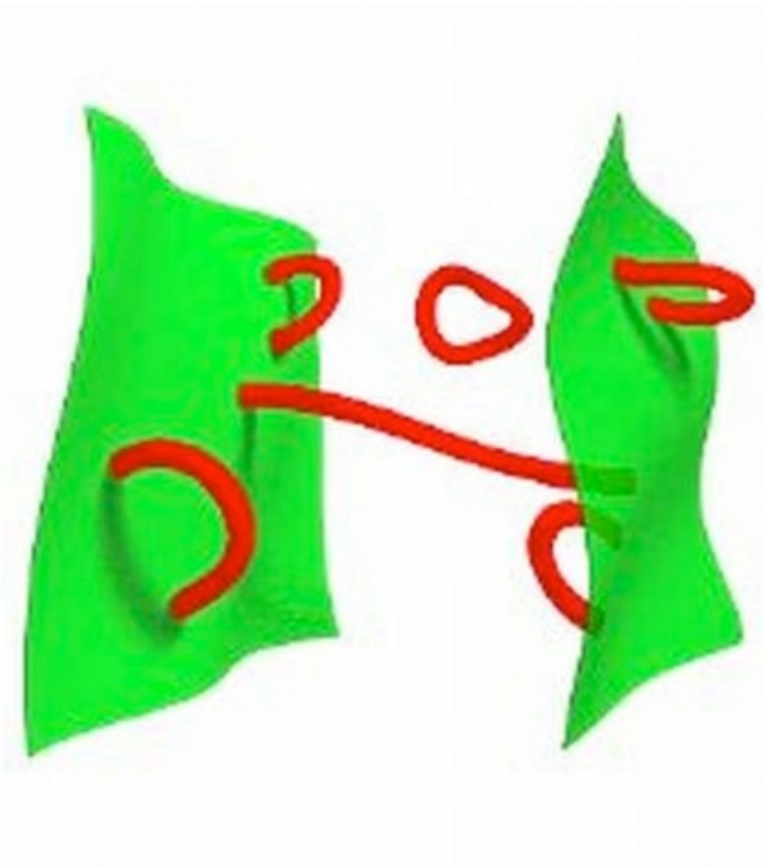
- Is there a landscape with… ?
  - Reasonable cosmological constant
  - Standard Model spectrum
- If no, which dynamical vacuum selection principle are we missing?
- If yes, do environmental/anthropic selection principles play a role in explaining observable physics?
  To which quantities do they affect?



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



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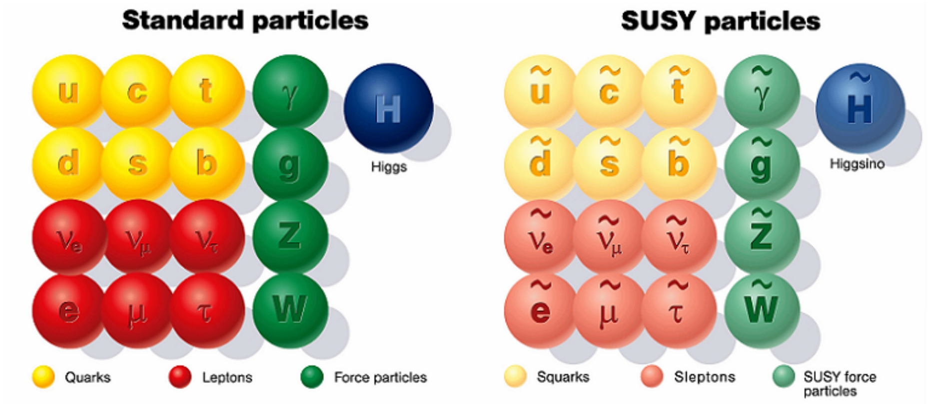


What is the string scale?

- 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

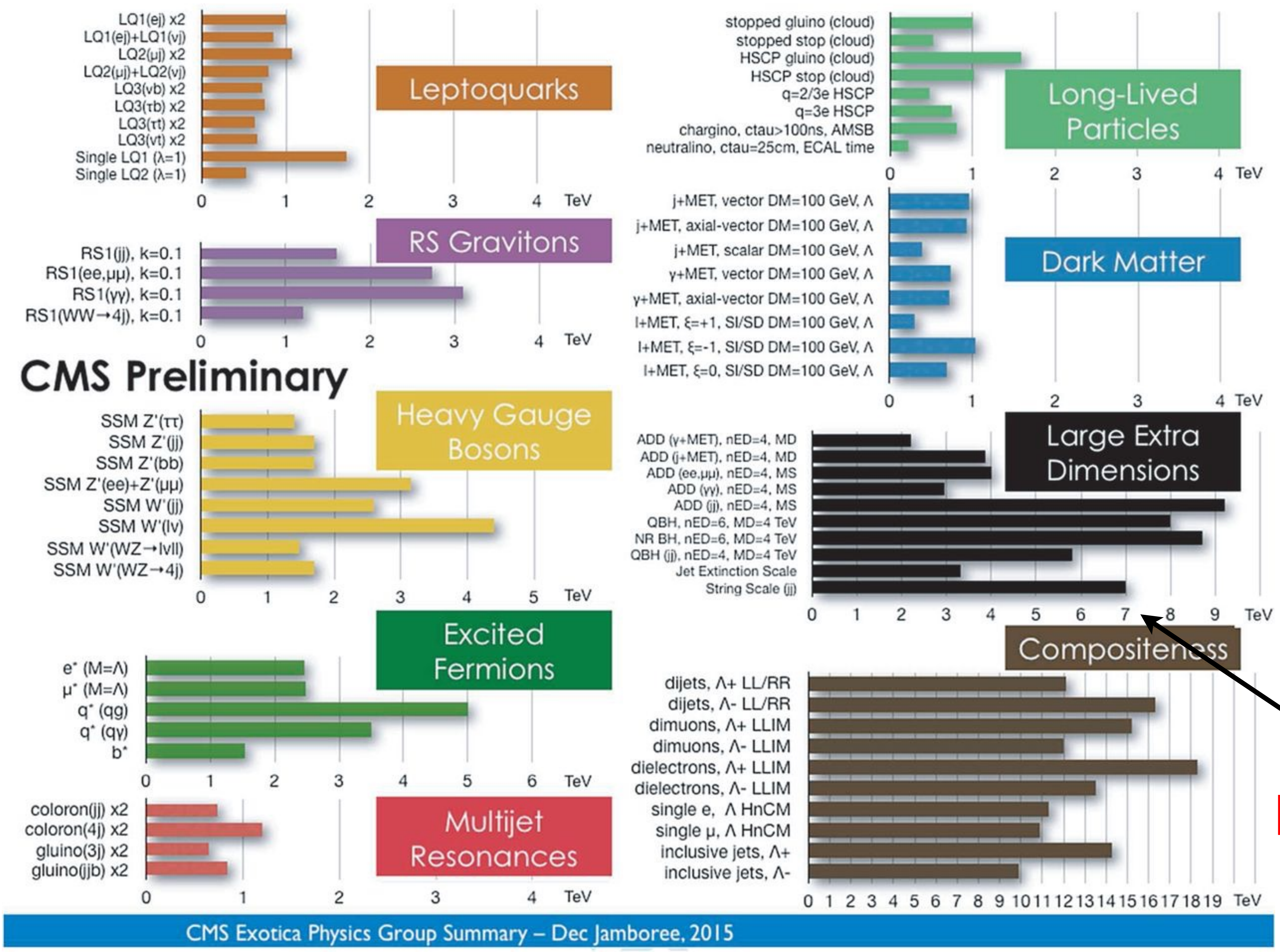
- D-brane scenario: allows to dilute gravity $M_s \sim g_{YM} M_P [V_\perp/g_s]^{1/2}$
  → we can lower the M_s down to the TeV
  → no need for SUSY, even at M_s

  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

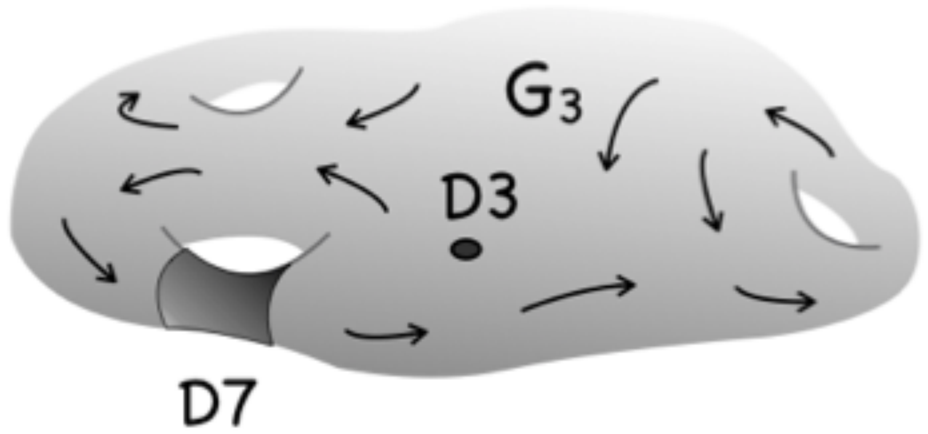
TeV string scale?



$M_S > 7$ 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

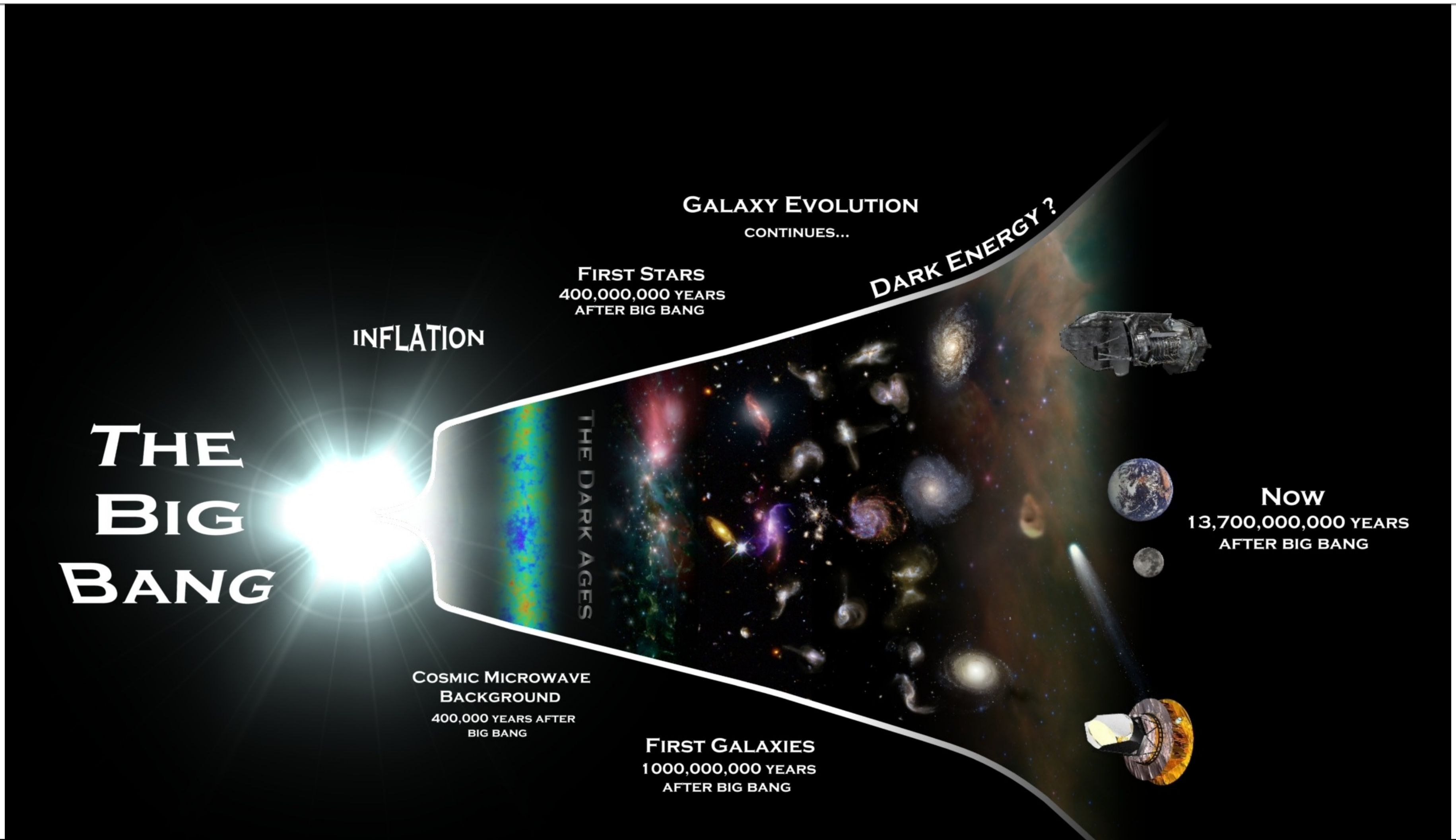


Strings and supersymmetry

- 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
    - KKLT scenario: $M_s \sim 10^{16}$ GeV and $W_0 / M_p^3 \sim 10^{-15}$
    - LVS: $M_s \sim 10^{11}$ GeV, $V \sim 10^{16} \rightarrow W_0 / M_p^3 \sim 1$

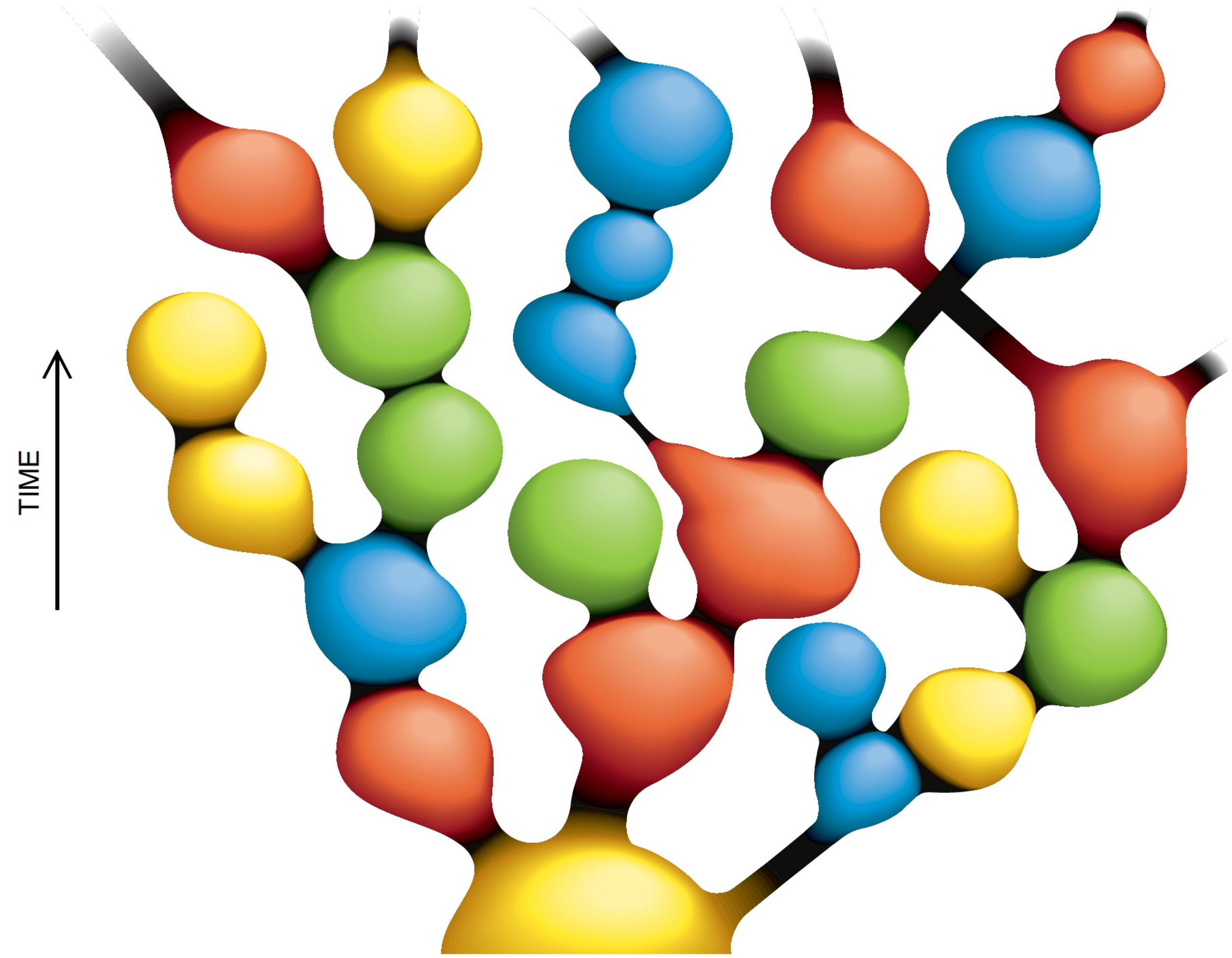
for $m_{3/2} \sim 1$ TeV

From strings to Cosmology



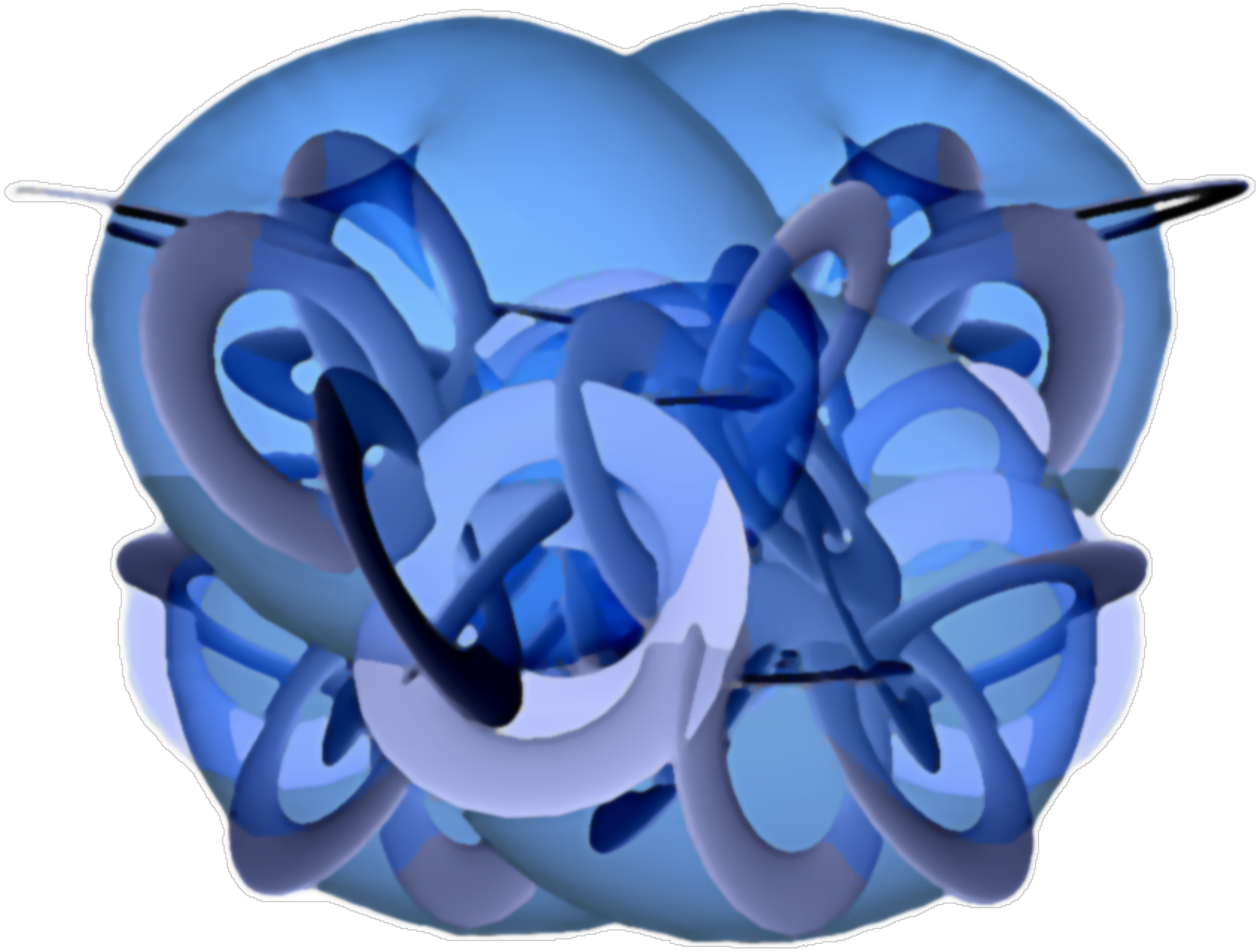
Inflation

- 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 → extremely sensitive to UV completion



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

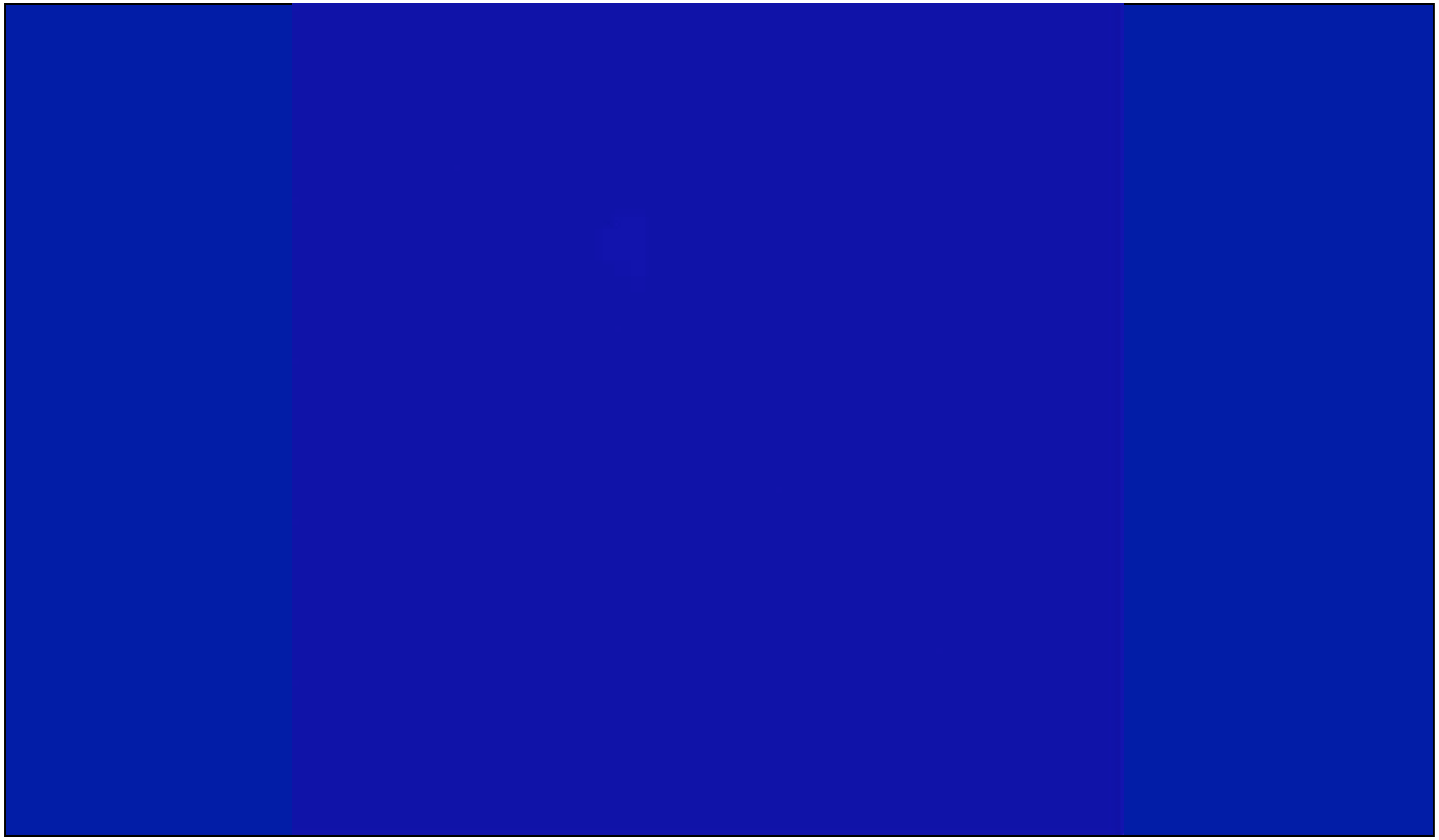
Best framework: Type IIB flux compactifications

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:



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Dvali & Tye'98

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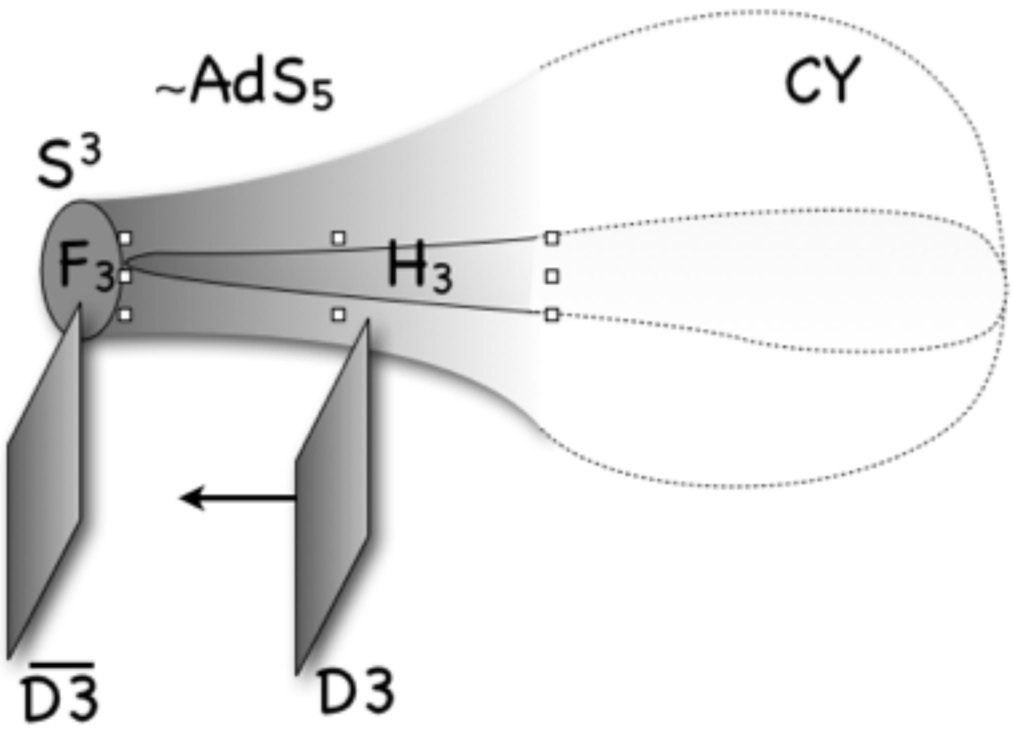


Kachru, Kallosh, Linde, Maldacena, McAllister, Trivedi'03

Large field inflation

- In the BICEP2 aftermath, we have no clear hint if early-universe cosmology is described by large field inflation. However the whole turmoil has awaken the interest on whether such models can actually be embedded in string theory.

- For a model of large tensor-to-scalar ratio r one would have that

  - The energy scale of inflation is the GUT scale

$$E_{\rm inf} \simeq 0.75 \times \left(\frac{r}{0.1}\right)^{1/4} \times 10^{-2} M_{\rm Pl}$$

  - The inflaton field excursion is super-Planckian

$$\Delta\phi \gtrsim \left(\frac{r}{0.01}\right)^{1/2} M_{\rm Pl}$$

Lyth '96

  - Inflation is extremely sensitive to UV dynamics

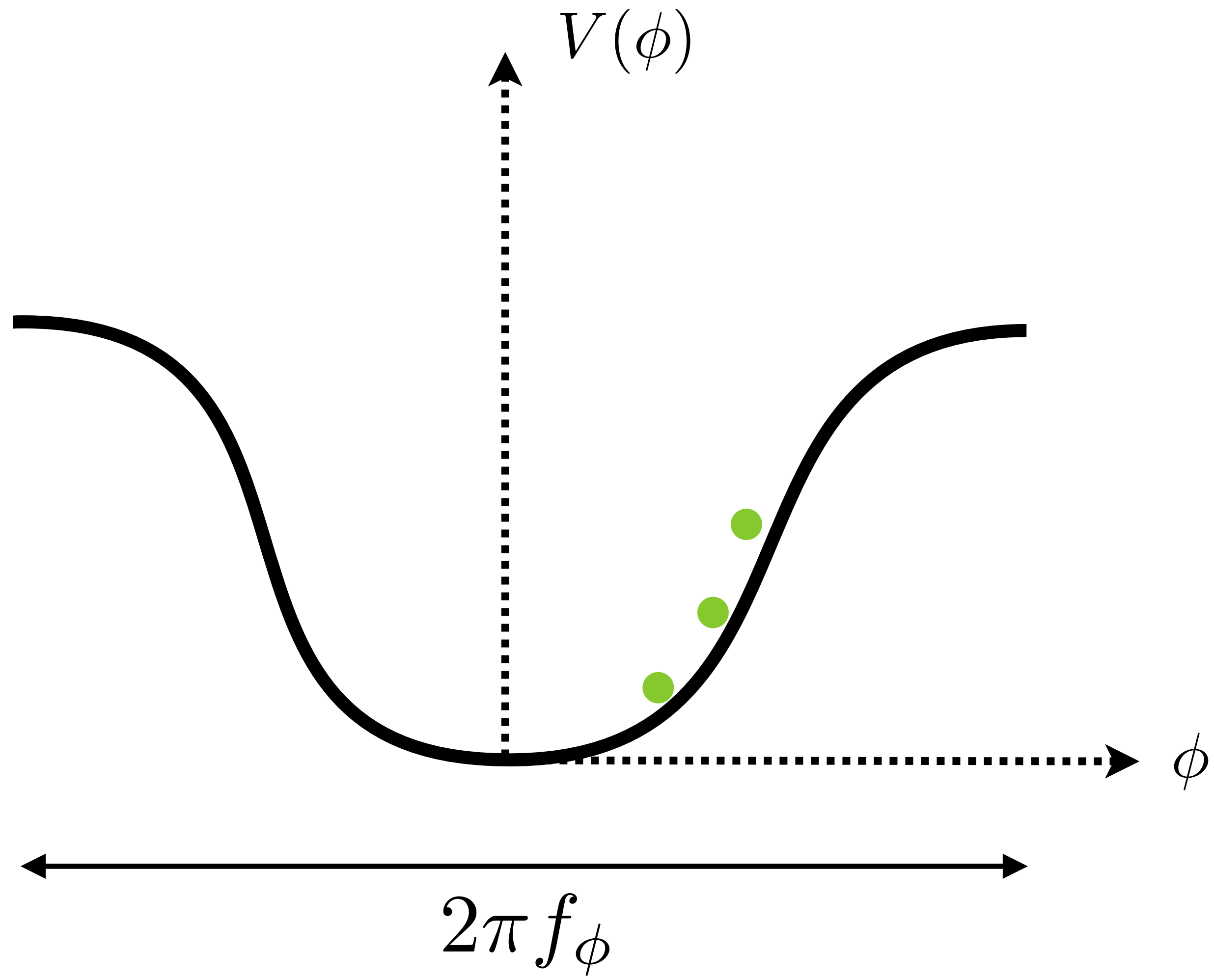
Natural inflation

Freese, Frieman, Olinto '90

- An interesting field theory idea is to propose an axion as an inflaton candidate

  - Shift symmetry broken by non-perturbative effects + UV completion, periodicity is exact

  - In string theory, axions come generically from integrals of p-forms over p-cycles, so above the KK scale the shift symmetry becomes a gauge symmetry



Dimopoulos et al. ' 05

$$\phi = \int_{\pi_p} C_p$$

$$F_{p+1} = dC_p$$
$$C_p \rightarrow C_p + d\Lambda_{p-1}$$

Natural inflation vs. the WGC

Arkani-Hamed et al. '06

- However, either by direct inspection or by using a generalisation of the Weak Gravity Conjecture one arrives to the conclusion that in string theory axions cannot have a trans-Planckian decay constant.
  - The WGC states that in 4d theories with U(1) gauge fields of coupling g and quantum gravity there exist particles satisfying a mass-to-charge relation

    $$m \leq q\, g\, M_P$$

  - When generalised to axions this implies either a sub-Planckian decay constant or loss of control.

    $$f\, S_{\mathrm{inst}} \leq 1$$

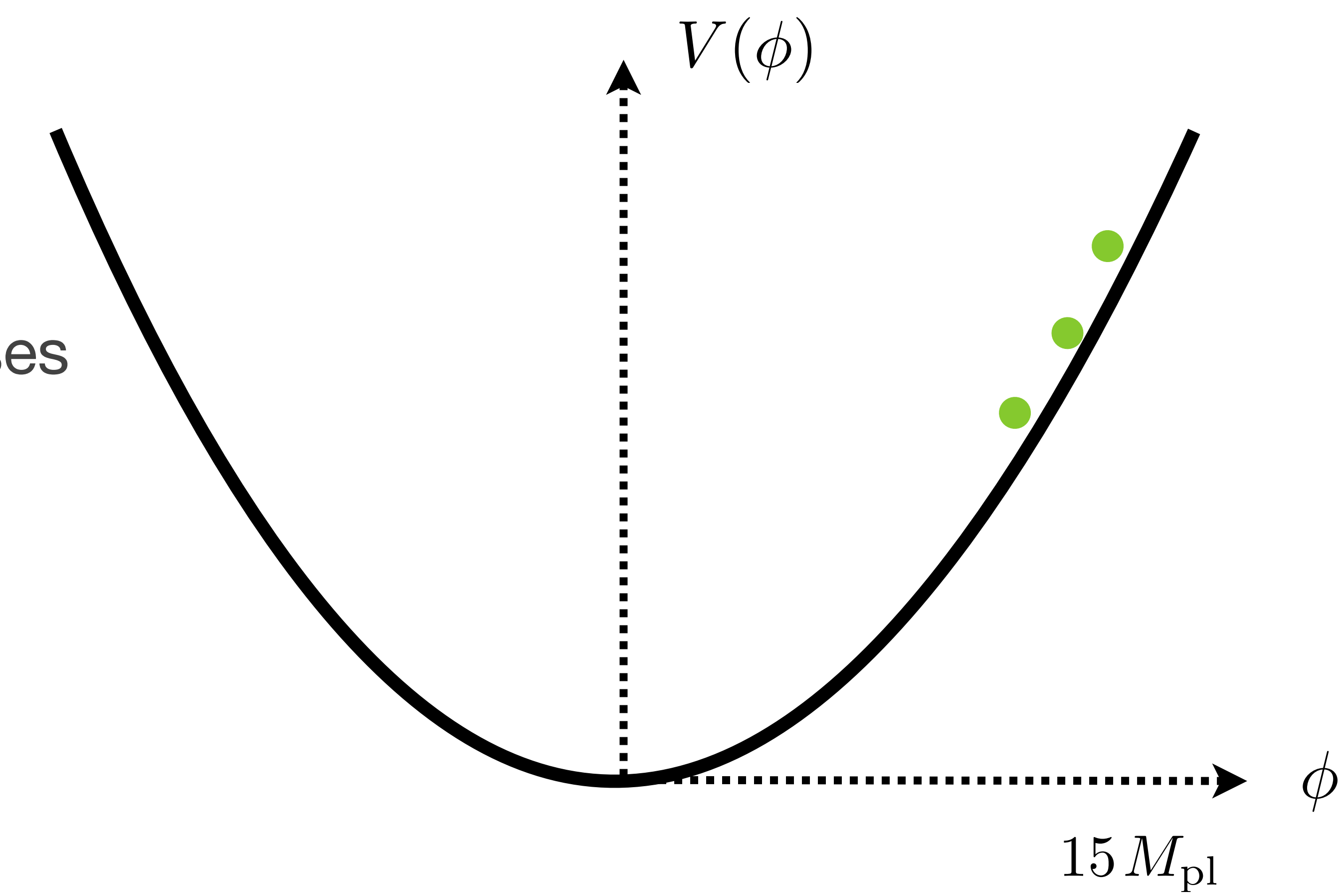
  - In string theory, this can be checked directly by direct inspection of axion decay constants.
  - The same reasoning can be applied to more involved field theory configurations, like several axions in which one particular direction is chosen dynamically. The general conclusion is that large field inflation models of axions are in tension with string theory.

Rudelius '15
Montero et al. '15
Brown et al. '15

Chaotic inflation

Linde '86

- Another key proposal would be a polynomial potential like $V = m^2\phi^2$



- Loop corrections involving inflatons and gravitons are small if one imposes an approximate shift symmetry

$$\phi \mapsto \phi + \text{const.}$$

- But coupling to UV degrees of freedom in quantum gravity a priori breaks this shift symmetry and leads to corrections that spoil inflation, because of the large field excursions

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

Chaotic inflation

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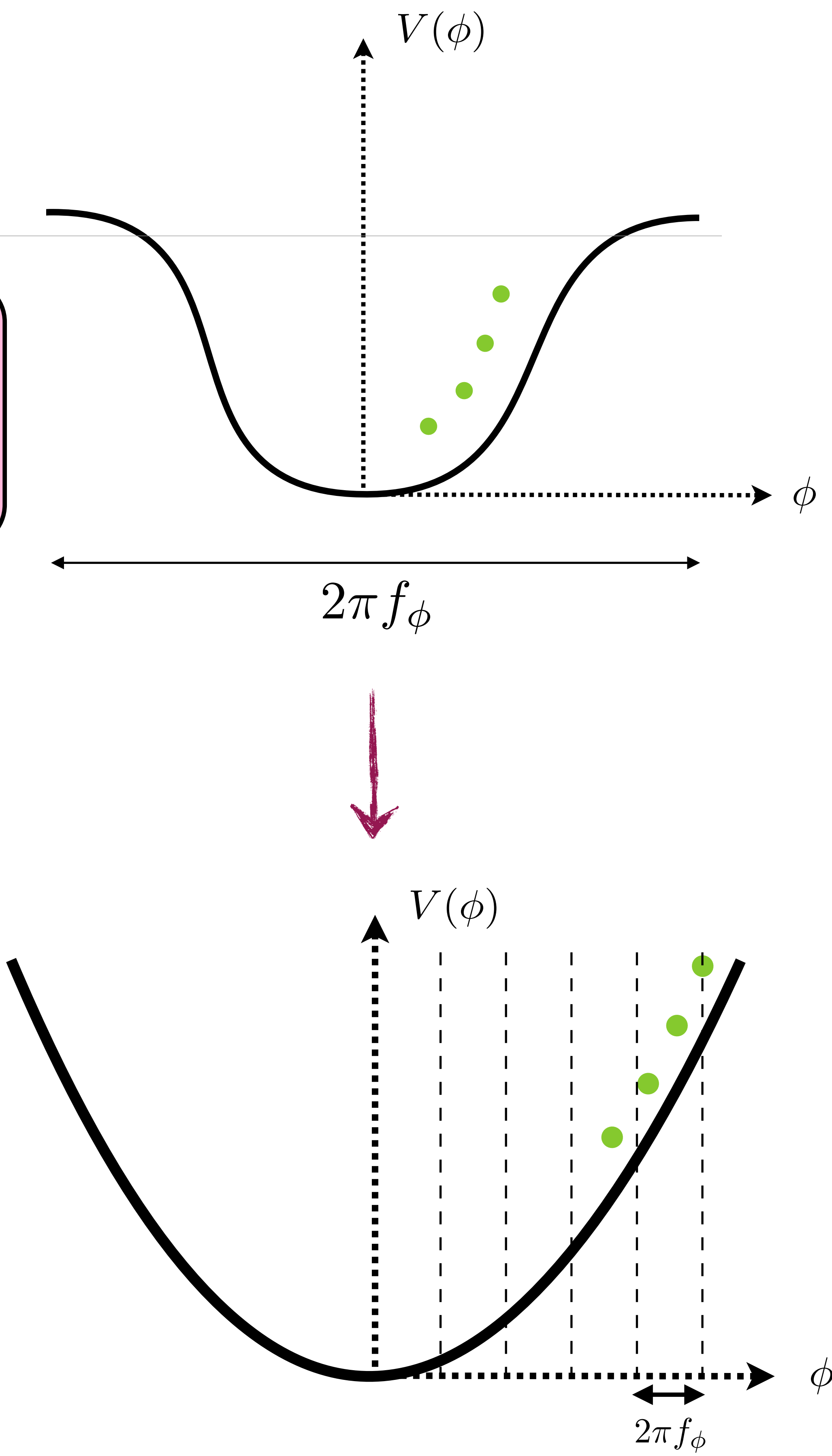
taken from Baumann & McAllister '14

Axion monodromy

Idea: Combine chaotic inflation and natural inflation

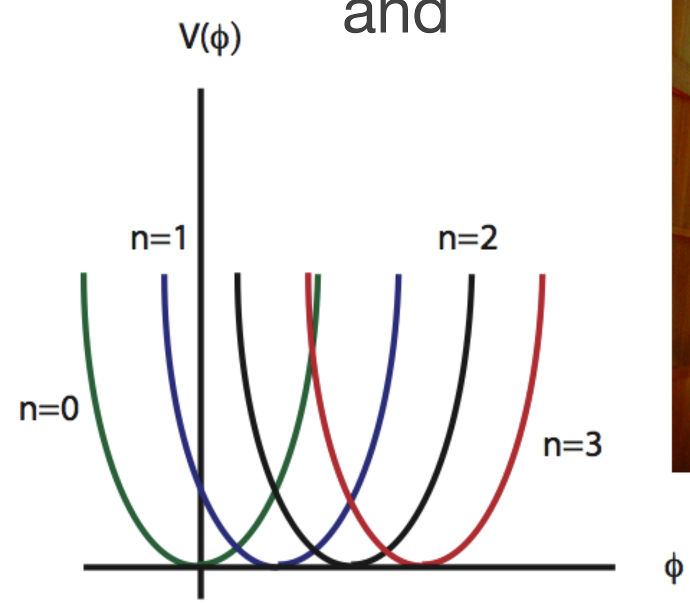


- We identify the inflaton with an axion and we give it a non-periodic potential
- Axion periodicity lifted, allowing for super-Planckian displacements. UV corrections to the potential should still be constrained by the underlying symmetry

Silverstein & Westphal '08

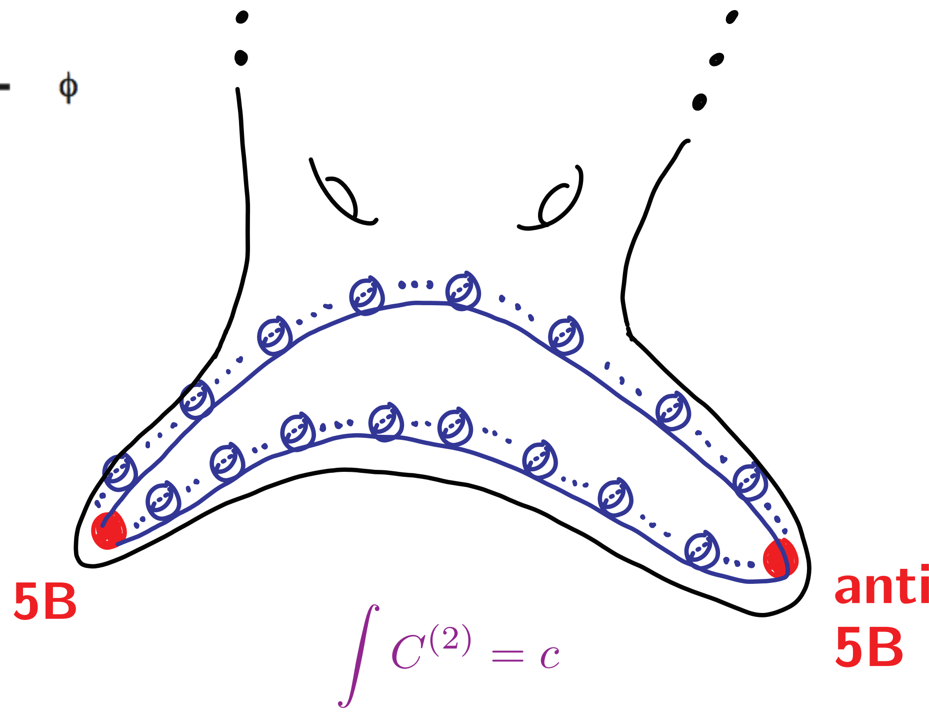
Axion monodromy inflation

- Main ingredients:
  - Axion ϕ (shift symmetry periodicity) and
  - Source of a non-periodic, multi-branched potential



- Early string theory constructions use boundaries:

McAllister, Silverstein, Westphal '08
Berg, Pajer, Sjörs '09
Palti & Weigand '14



taken from McAllister, Silverstein, Westphal '08

The 4d viewpoint

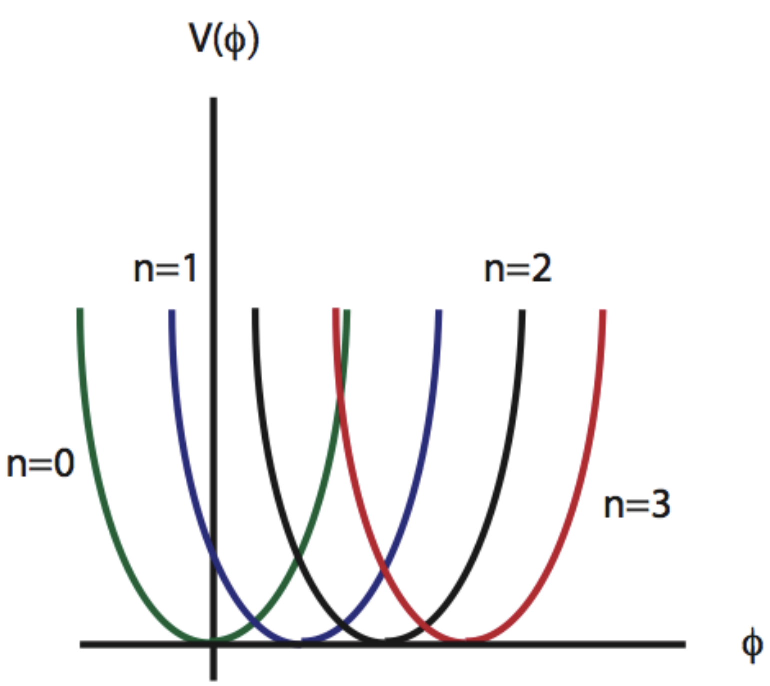
- In 4d one may obtain these ingredients by allowing the axion to couple (only) to a 4d four-form field strength

$$\int d^4x\, |F_4|^2 + |d\phi|^2 + \phi F_4$$

- When we integrate out the 4d four-form we are left with a potential for the axion

$$V = \frac{1}{2}\mu^2 f_\Phi^2 (n+\phi)^2$$

jump by DW charged under F_4



Proposal for large field chaotic inflation

Kaloper & Sorbo '08
Kaloper, Lawrence, Sorbo '11

The 4d viewpoint

- Dual formulation in terms of two and three-forms

$$\int d^4x\, |dC_3|^2 + \frac{\mu^2}{k^2}|db_2 - kC_3|^2$$

$$F_4 = dC_3$$
$$d\phi = *_4 db_2$$

Kallosh et al. '95
Dvali, Jackiw, Pi '05
Dvali, Folkerts, Franca '13

also describes a massive axion. Applied to QCD axion

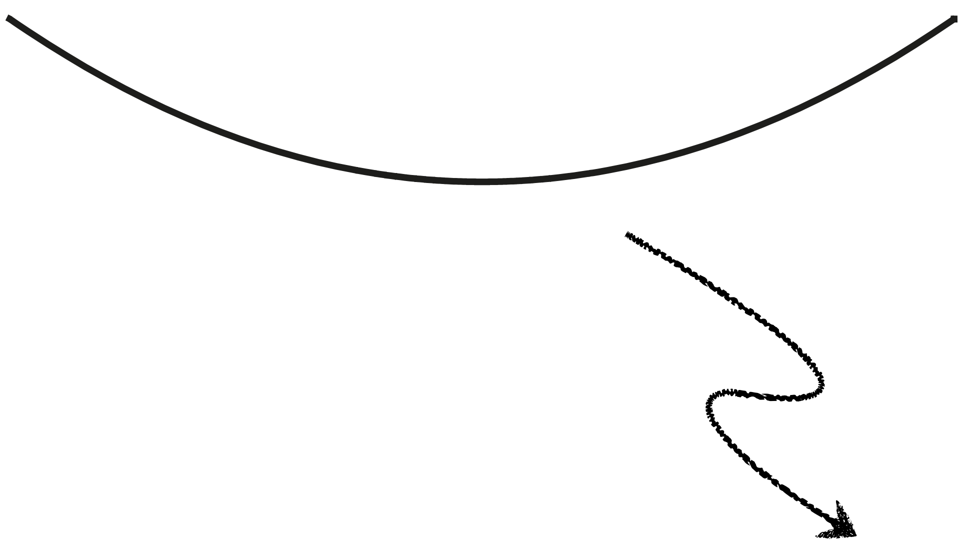
- Makes manifest the gauge symmetry of the Lagrangian ⇒ UV corrections only depend on F_4

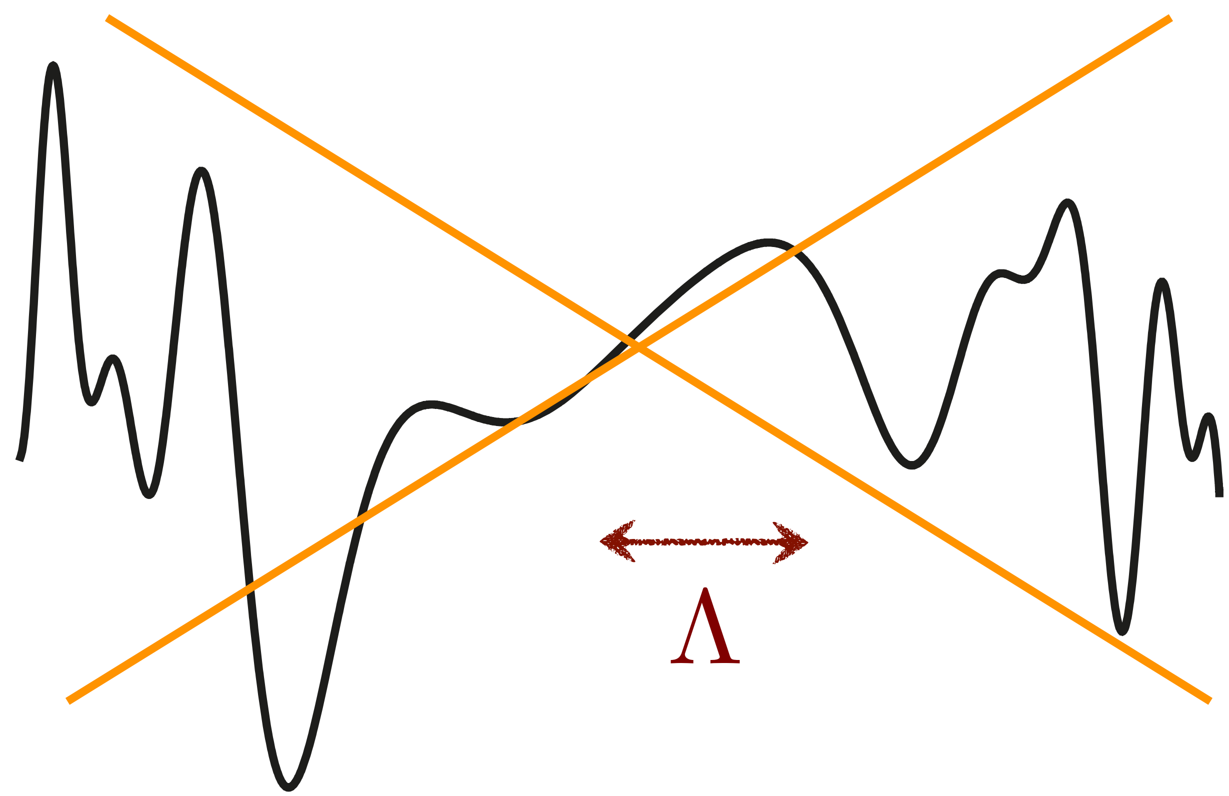
$$\mathcal{L}_{\text{eff}}[\phi] = \frac{1}{2}(\partial\phi)^2 - \frac{1}{2}\mu^2\phi^2 + \Lambda^4 \sum_{i=1}^{\infty} c_i \frac{\phi^{2i}}{\Lambda^{2i}}$$

$$\sum_j c_j \frac{F^{2j}}{\Lambda^{4j}} \longrightarrow \mu^2 f_\Phi^2 (n+\phi)^2 \sum_j c_j \left(\frac{\mu^2 f_\Phi^2 (n+\phi)^2}{\Lambda^4}\right)^j$$

The 4d viewpoint

$$\phi' = f_\Phi \phi \qquad n = 0 \quad \longrightarrow \quad \mu^2 \phi'^2 \sum_j c_j \left(\frac{\mu^2 \phi'^2}{\Lambda^4} \right)^j$$





$$\Lambda \to \Lambda_{\text{eff}} = \Lambda \left(\frac{\Lambda}{\mu} \right)$$

⇒ suppressed corrections up to the scale where V(ϕ) ~ Λ^4

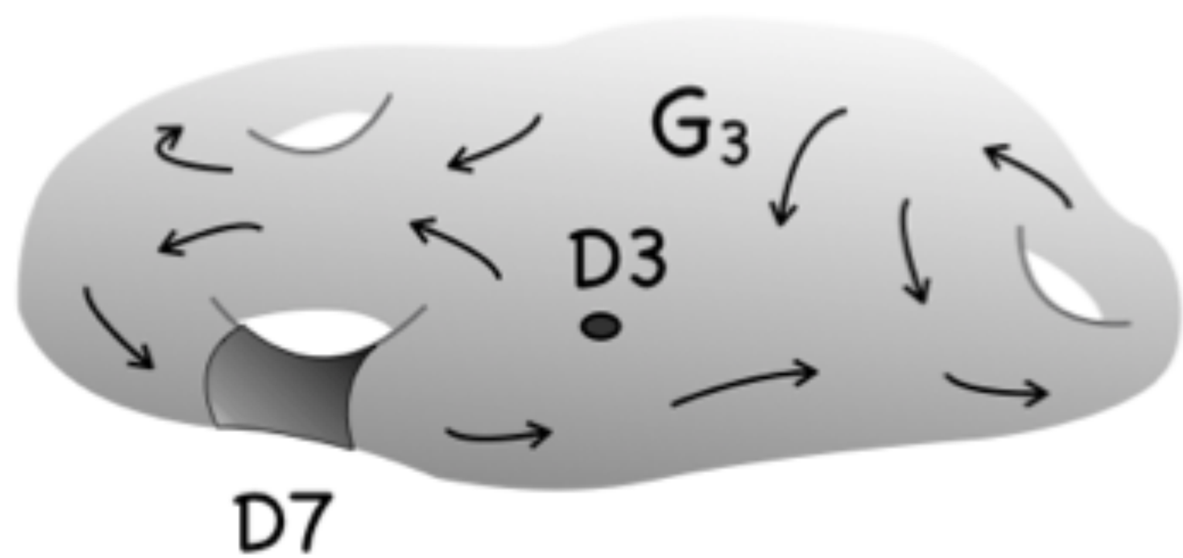
F-term axion monodromy

F.M., Shiu, Uranga '14

- In string compactifications this 4d effective action is recovered whenever the source for the axion potential is a superpotential

- Reminiscent of the moduli stabilisation program, where one adds ingredients like background fluxes to generate superpotentials

Idea: **Use same techniques to generate an inflaton potential**



taken from Ibañez & Uranga '12

F-term axion monodromy

F.M., Shiu, Uranga '14

Advantages:

- Spontaneous SUSY breaking, no need for brane-anti-brane
- Supergravity description at small field, allows to connect with large field inflation models in SUGRA

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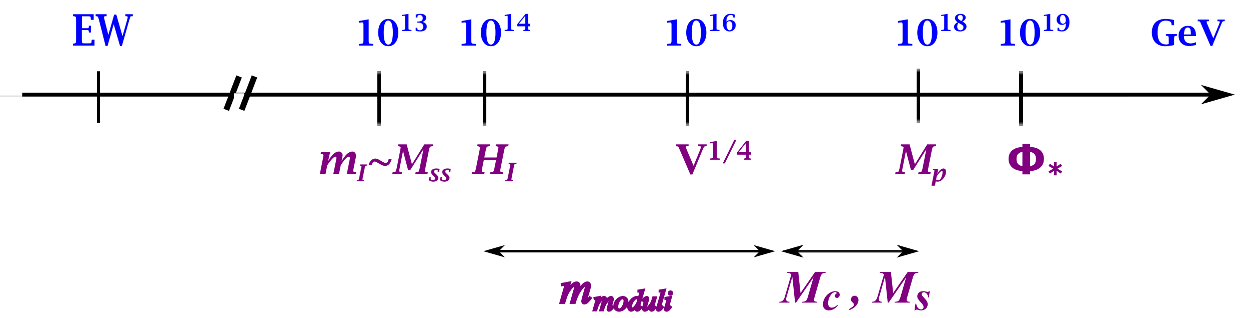
- Supergravity description at small field, allows to connect with large field inflation models in SUGRA

Difficulties:

- String compactifications contain many scalars. If we stabilise all of them with the same mechanism it seems difficult to single out an inflaton candidate (hierarchically lighter than the rest)
- Supergravity description shows the interplay of all these scalars in the same scalar potential → a large vev to one of them you can destabilise the others

Current status



Philosophy:

- Large field inflation in string theory → realise (F-term) axion monodromy
- Multi-branched potential/KS structure allows for trans-Planckian excursions and demands milder UV corrections.

Challenges:

- Generically we need to package many different scales in a small window between H and M_{Pl}, like M_{moduli}, M_{KK}, M_s
- We need the inflaton to be much lighter than all other scalars
- Large inflaton values may shift the value of the other scalar vevs and this, in turn, destabilise the inflationary trajectory (4d backreaction)

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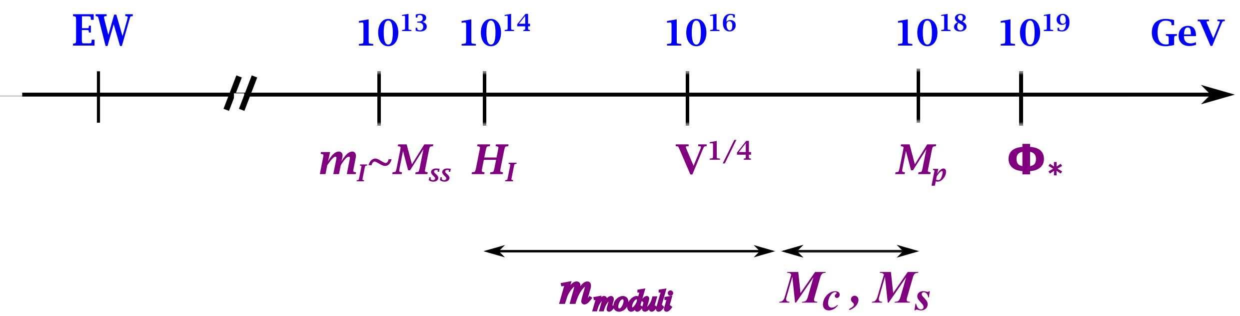

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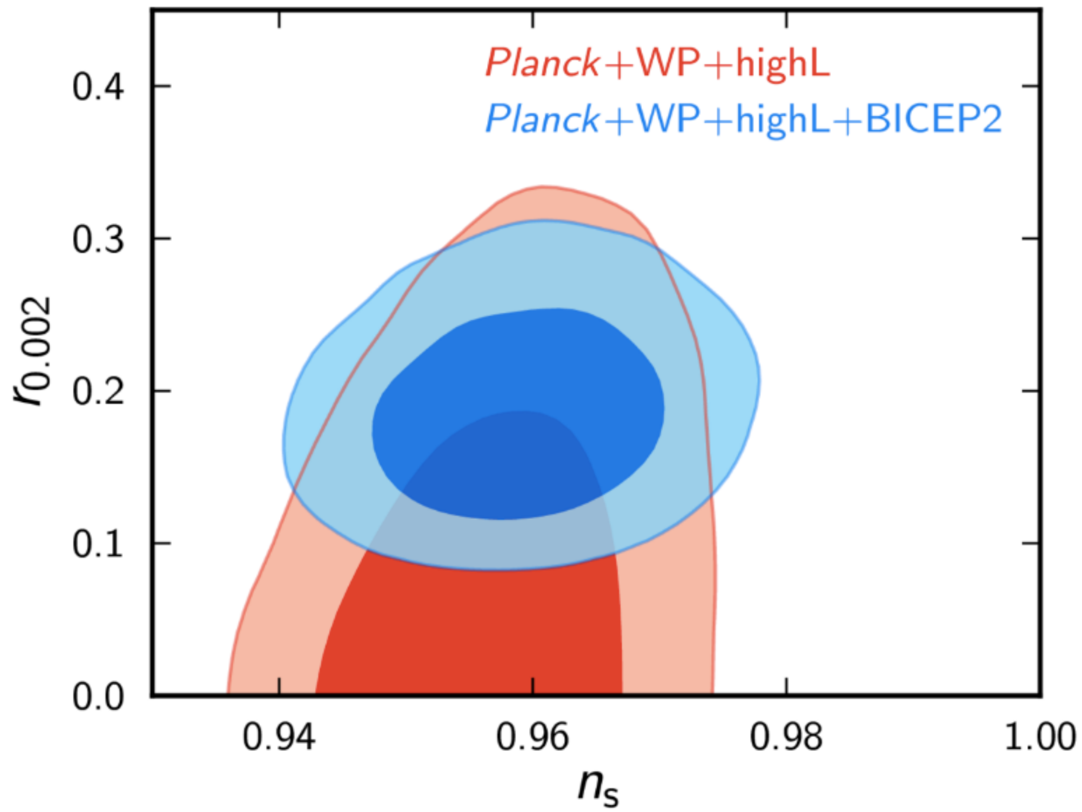
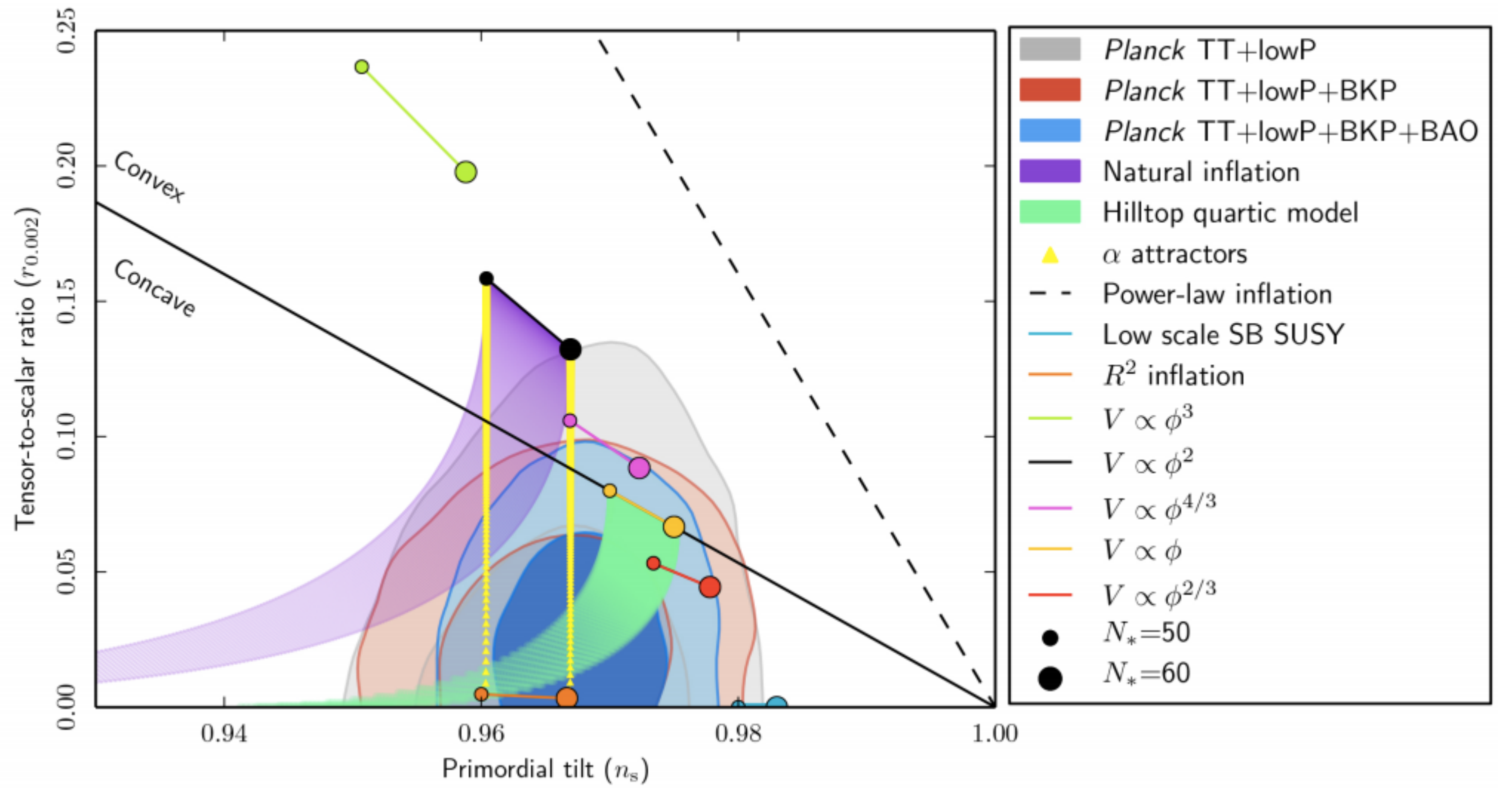
One nice surprise is that stringy potentials are flatter than in field theory

A brief history of BICEP2/Planck





2014 → 2015 → soon

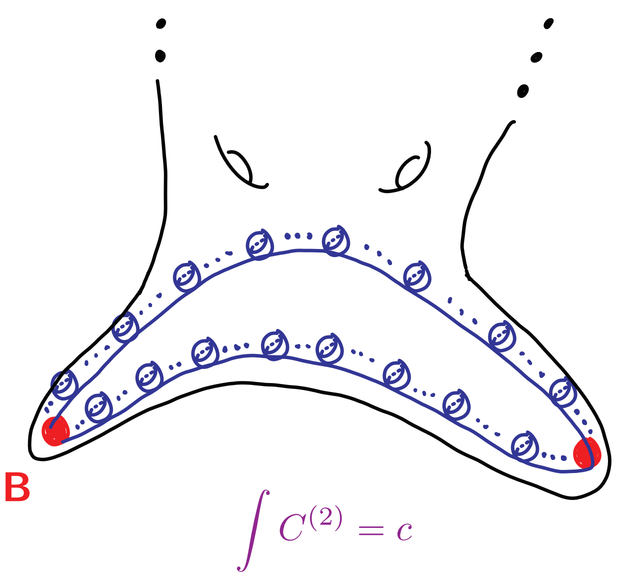
ϕ^2 ϕ^2 ϕ ϕ




DBI flattening

b-field over D5-brane

McAllister, Silverstein, Westphal '08

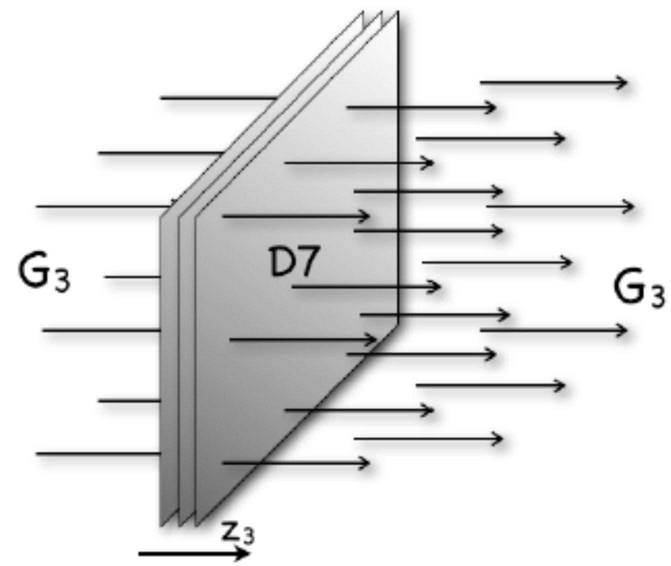


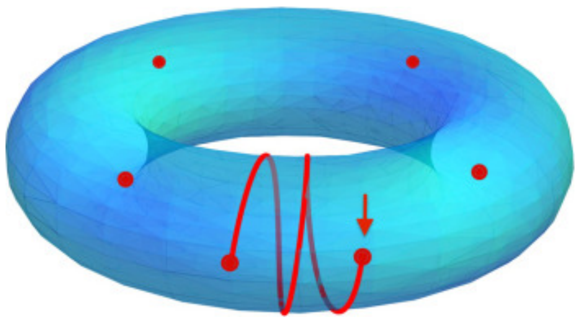
$$V \sim \sqrt{a + c\,\phi^2}$$

linear behaviour
at large field

mobile D7-brane
in flux compactifications

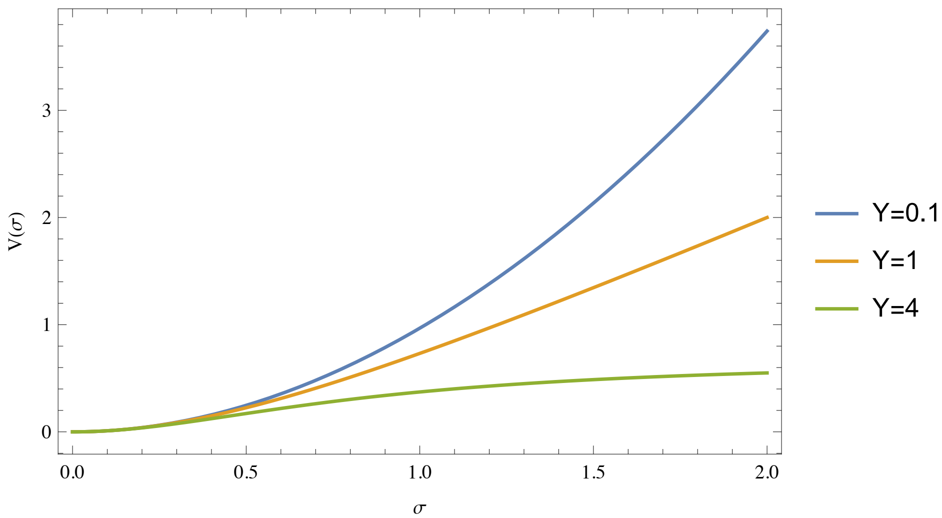
Hebecker, Kraus, Witkowski '14
Ibañez, F.M. Valenzuela '14





$$\mathcal{L} = g(\Phi)(\partial_\mu \Phi)^2 - V(\Phi)$$

field-dependent kinetic terms:
- quadratic at small field
- at most linear at large field



Landete et al. '17

So can we make it work?

- Ongoing debate on whether one can build a string theory model of large field inflation under theoretical control from the 4d viewpoint

  ✦ Package of scales between H and M_P is difficult but feasible in compactifications where moduli stabilisation is well understood

  ✦ Backreaction effects modify the inflaton kinetic term such that the proper field distance has a logarithmic behaviour compared to the naive variable

$$\varphi \sim \lambda^{-1} \log \phi$$

Baume & Palti '16

  ✦ The Swampland Conjecture states that for sufficiently large field excursions in a quantum gravity theory we lose control of the initial effective field theory, as a tower of modes becomes very light

$$M_n \sim e^{-n\lambda\varphi}$$

Ooguri & Vafa '16
Klaewer & Palti '16

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    Ooguri & Vafa '16
    Klaewer & Palti '16

The question remains if we can make λ very small to embed large field excursions

In explicit simple cases λ ~ O(1). We also have that $\lambda \sim \dfrac{M_{\rm inf}}{M_{\rm heavy}}$

Still unclear the value of λ in string theory/quantum gravity can be made small

Conclusions

- Since the year 2000, we have had a very fruitful period in string phenomenology, as the technology to build models of particle physics and cosmology developed. → possibility to address fundamental questions in High Energy Physics in the string theory context, by mainly using theoretical tools (i.e., consistency).

- Most recent progress in string models particle physics within F-theory GUTs. There, the debate has been focused on the details of gauge coupling unification, proton decay, existence of exotics, the μ-problem and the doublet-triplet splitting.

- Thanks to the advances in moduli stabilisation, there has also been a debate on the existence of de Sitter vacua in string theory (still going on).

- But the most intense current open question is about realising large field inflation, because there the debate is phrased in terms of general features of string theory. More generally, it is phrased in terms of the restrictions that a theory of quantum gravity may impose on effective quantum field theories.

- As of today, the main challenge is to decouple the inflaton sector from the other scalars of the compactification, making it hierarchically lighter than everyone else.

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