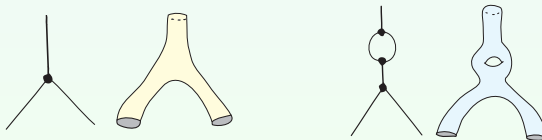# F-Theory GUTs

Benjamin Jurke

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- Grand Unification
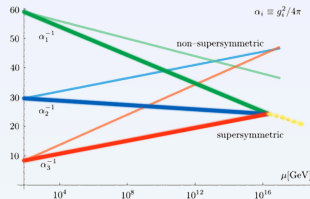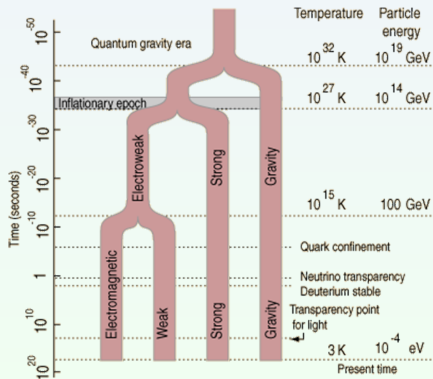- F-Theory basics
- GUTs in F-Theory

IMPRS Young Scientists Workshop (Ringberg) — July 29th, 2009

Field-theoretic Grand Unification

1970s issue: **Running gauge couplings suggest unification** of the electromagnetic, weak and strong force at high energies.

➤ Early Universe physics, ...

Idea: The Standard Model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ is to be embedded in a **larger GUT group**.
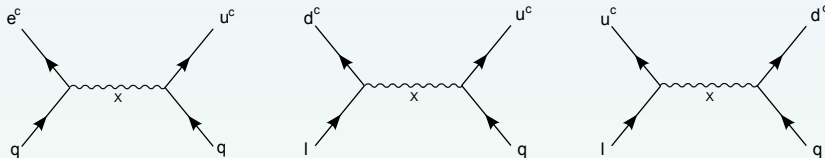
> ## GUT group candidates
> - **SU(5)** or **SO(10)**
> - E_6, E_7, E_8...

Field-theoretic Grand Unification

Several problems with traditional GUT theories:

- **doublet-triplet problem** (Higgs → weak doublet, but no color triplet)

- additional **exotic particles**

- rapid **proton decay** (no baryon/lepton number conservation)


Bottom line: Field-theoretic GUTs are a nice & elegant idea, but without further modification the <u>plain phenomenology</u> is rather off...

there are many modifications to deal with the problems

Besides: What about **gravity**? → "Super-Unification"

String Theory as a gravity framework

A "natural" framework which contains gravity is string theory, as each of the five duality-related 10d string theories contains gravitons / spin-2 bosons in the massless particle spectrum in the form of **closed strings**.
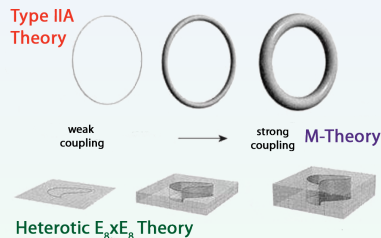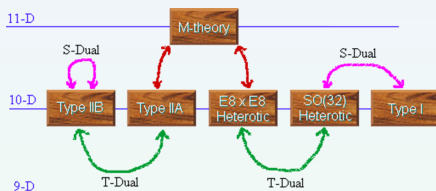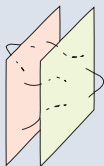

How about gauge theories / groups?

- **Heterotic:** Closed strings, either $E_8 \times E_8$ or $SO(32)$.
- **Type I:** Open & closed strings, gauge group $SO(32)$.
- **Type II:** Closed strings, no non-abelian gauge group.

GUTs in String Theory?

D-branes...

- ...are **higher-dimensional objects**
- ...have open strings ending on them
- ...carry a **worldvolume gauge theory**
- ...can **intersect**, giving additional states

terminology: 7-brane = 7 spatial dimensions, i.e. 8d worldvolume

In (perturbative) 10d type-IIA or IIB superstring theory a stack of n D-branes carries an **U(n) worldvolume gauge theory**. In orientifold settings one can also obtain **SO(n)** and **Sp(n)** gauge groups.

➙ Try a D-brane GUT theory...

Unfortunately: Important Yukawa couplings and states/representations are missing, doublet-triplet splitting remains an issue. **Nothing gained...**

Non-perturbative ingredients

However, we are missing a great number of **non-perturbative ingredients** if we restrict to perturbative string theory:

- D-brane instantons → additional states & couplings
- String junctions → further gauge groups
- Geometry backreactions → consistency conditions
- ...

Bottom line: There are many non-perturbative ingredients that might help with the shortcomings of GUTs in both field theory and string theory.

Big issue: **Find a suitable description** for all of this...

→ **F-theory** = non-perturbative type-IIB superstring theory

F-theory basics

Type-IIB string theory comes with 2 scalar fields: the axion & the dilaton, which can be used to **parameterize the geometry of a torus**.

➤ "Shape of torus = value of 2 background scalars"

As we move around in 10d space-time, the value of the fields / shape of the torus varies.
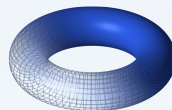
➤ Put together, this gives an **elliptically-fibered 12d space**.

roughly: *locally* the space looks like (10d base)×(torus fibre)

In short: "Geometrization" of the 10d space-time and 2 background fields.

What is F-theory?

F-theory is the "uplifted theory" defined on an ell.-fib. 12d space, which is understood as a **non-perturbative completion of type-IIB string theory**. It can be directly derived from M-theory, but the details are rather technical...

F-theory basics

Consider a 7-brane (recall: 8d worldvolume!) in 10d space-time, leaves 2 transverse dimensions. Now consider walking around the 7-brane in this "transverse plane": **The value of the axion field changes!**

➜ There must be a **singularity** in the axion where the D-brane sits!!!

The associated torus must then become singular as well, i.e. collapses to a circle or some other deformity.
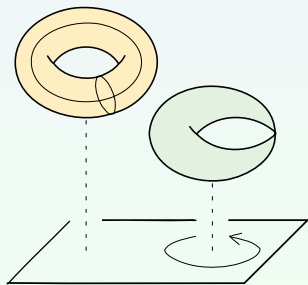
The elliptic fibration encodes...

- ...2 scalar fields: axion & dilaton
- ...the coupling constant
- ...the location of 7-branes

F-theory basics

Question: Given an elliptically-fibered 12d space, what can happen?

In fact, besides the location of the 7-branes, **the elliptic fibration also encodes the world-volume gauge group**.

� "Kodaira classification of singular fibres"

Worldvolume gauge groups

plain theory:	$U(n)$
orientifolds:	$+ SO(n)$, $Sp(n)$
F-theory:	$+ E_6$, E_7, E_8, F_4, G_2

Obviously, using F-theory we now have **access to all classical & exceptional groups** in a "geometrically unified" description.

F-theory basics

As mentioned, intersecting D-branes provide bifundamental matter states. Those come from the **decomposition of the adjoint representation of the "intersection group"**.

F-theory: Due to the exceptional groups, there are many more possibilities!

➜ clashing singularities lead to a singularity enhancement

Dimension counting

Usually four dimensions of the 10d space-time are assumed to be flat. All 7-branes are assumed to be space-time filling, such that the actual intersections are between the remaining 4d surfaces inside the 6 non-flat coordinates. Furthermore, everything is complex / holomorphic, such that **the intersection is a complex curve - a 2d surface**.

Terminology: The intersection curve is there called the matter curve.

Local F-theory GUTs

Coming back to GUT theories, now take a 7-brane carrying a suitable GUT group. Intersections with further 7-branes provide the matter curves.
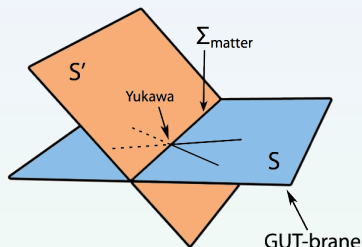
Local F-theory

In order to simplify things **select a 7-brane to be the "stage"** and just consider the effective 8d worldvolume theory.

➜ only the local intersections (matter curves) are perceived.

One can also consider multiple D-branes intersecting:

- Matter curves: 1 brane intersecting the GUT brane ➜ curve
- Interactions: 2 branes intersecting the GUT brane ➜ point
- Yukawa couplings: 3 branes intersecting the GUT brane ➜ point

Local F-theory GUTs

Dimensional "hierarchy" in local GUTs

|		
gravity:	10d	bulk
gauge group:	8d	GUT 7-brane
matter fields:	6d	matter curves on GUT brane
interactions:	4d	intersecting matter curves

What is the actual benefit of all those contructions?

- all the necessary **Yukawa couplings** can be obtained ✓
- all the necessary **states / representations** can be obtained ✓
- **fine-tuning of couplings** etc. via geometry (intersection moduli) ✓
- the **doublet-triplet splitting** can be solved by localizing H_u and H_d on different matter curves ✓
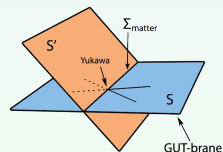
Local F-theory GUTs

The intersections in a **SU(5)-GUT toy model** can be like the following:
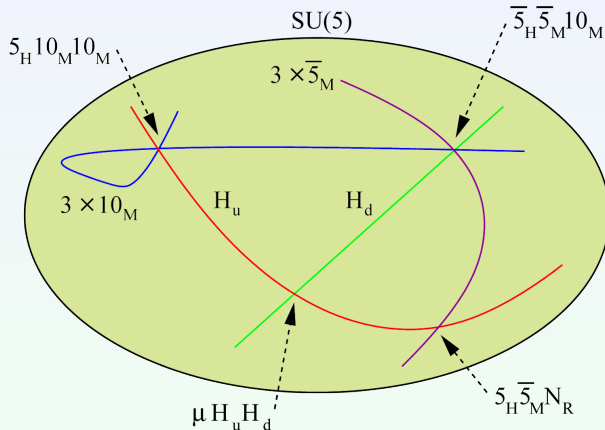
This shows the "birds perspective" with the GUT brane in the background.

Recall:

Why **"toy"** model?
Still unrealistic in details like flavor structure, SUSY breaking, etc...

Global issues

Ultimately, **for consistency one has to consider a global model** (e.g. tadpole & charge cancellation...)

Assuming four flat coordinates, what are we actually looking for?

- A compact Calabi-Yau 4-fold (8d space),
  elliptically-fibered over a Kähler 3-fold base,
  such that the elliptic fibration...
  - ...provides a suitable GUT 7-brane
  - ...provides further 7-branes intersecting the
    GUT 7-brane just right in order to satisfy
    the phenomenological constraints
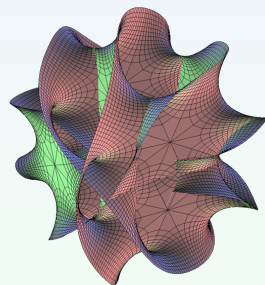
Those mathematical conditions are *extremely hard* to satisfy all at the same time.

➜ **Global F-theory GUT model building** is a rather active niche of string theory since mid-2008...

Summary and Conclusion

Old concepts & their problems:

- Plain GUT theories suffer from proton decay, doublet-triplet splitting, come with exotics, do not incorporate gravity.
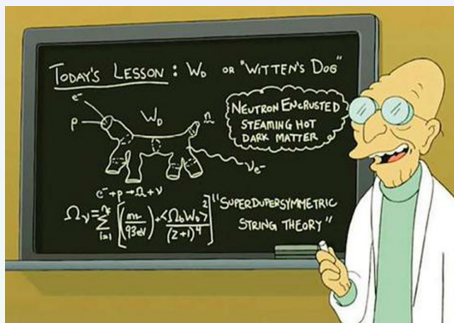- "D-brane GUTs" have gravity but lack necessary couplings and states.

Old concepts & new frameworks:

- F-theory is a geometrization of type-IIB superstring theory which includes non-perturbative elements.
- The unified framework allows for "Super-Unification" based on plain GUT ideas using "geometrical fine-tuning"!

New problems:

- Actually construction fully consistent global models with the right phenomenology becomes a technically challenging issue...

    ➡ Toric / algebraic geometry

Thanks for your attention...