String Theory

Angel M. Uranga
IFT-UAM/CSIC Madrid

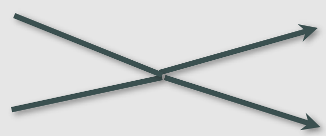
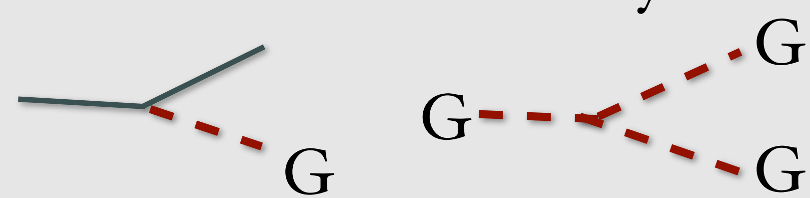
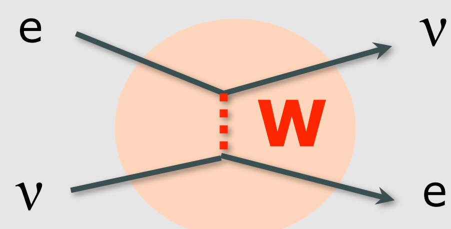
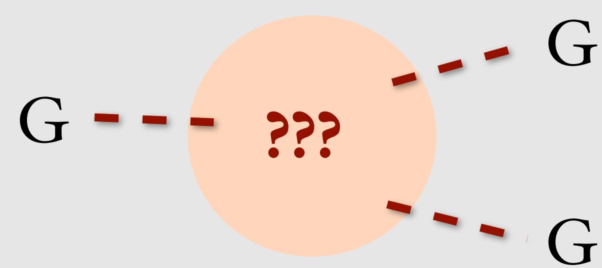
IMFP, Madrid, April 2016

Plan

- Introduction
- Applications
  - Particle Physics
  - Cosmology
- Conclusions

String theory

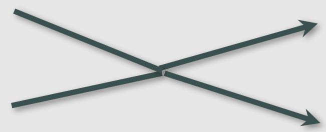
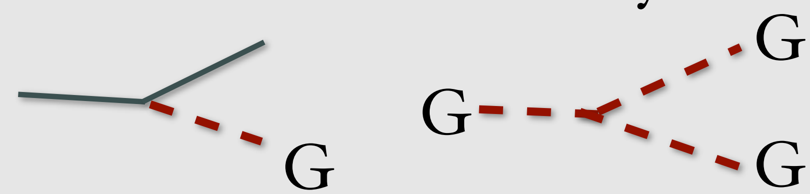
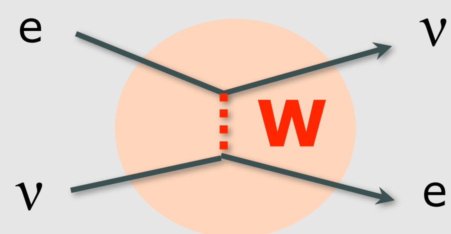
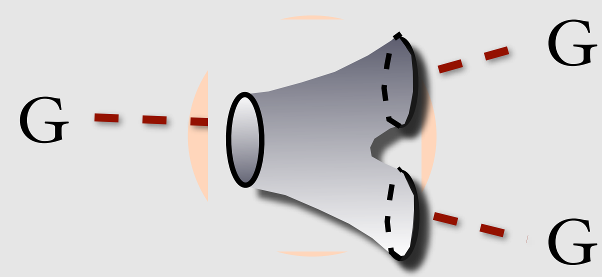
- Reconcile gravity with rules of Quantum Mechanics.
- General Relativity as effective field theory, UV completed by string theory

Analogy:	Fermi theory	General Relativity
- Vertex		
- Coupling	G_F	G_N
- Cutoff	$L_F \approx (100\ \mathrm{GeV})^{-1}$	$L_F \approx (10^{19}\ \mathrm{GeV})^{-1}$
- UV compl.		
	Electroweak theory	String theory

String theory

- Reconcile gravity with rules of Quantum Mechanics.
- General Relativity as effective field theory, UV completed by string theory

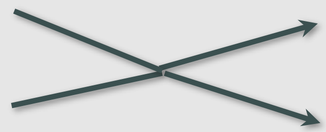
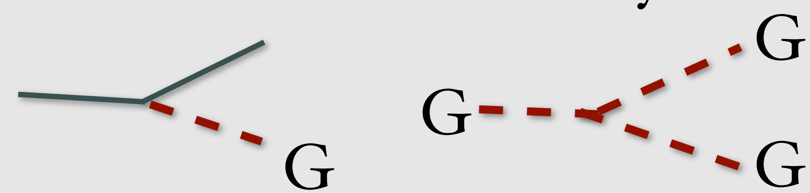
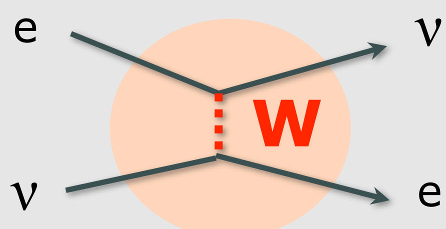
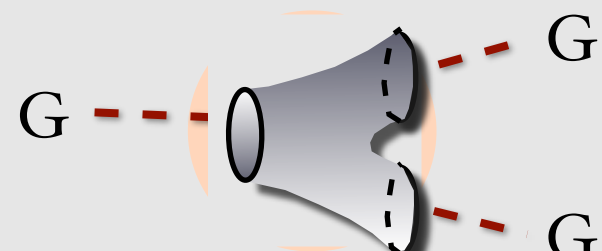
Analogy:

	Fermi theory	General Relativity
- Vertex		
- Coupling	G_F	G_N
- Cutoff	$L_F \approx (100\ \mathrm{GeV})^{-1}$	$L_F \approx (10^{19}\ \mathrm{GeV})^{-1}$
- UV compl.	 Electroweak theory	 String theory

Strings!

String theory

- Reconcile gravity with rules of Quantum Mechanics.
- General Relativity as effective field theory, UV completed by string theory

Analogy:	Fermi theory	General Relativity
- Vertex		
- Coupling	G_F	G_N
- Cutoff	$L_F \approx (100\ \text{GeV})^{-1}$	$L_F \approx (10^{19}\ \text{GeV})^{-1}$
- UV compl.		
	Electroweak theory	String theory

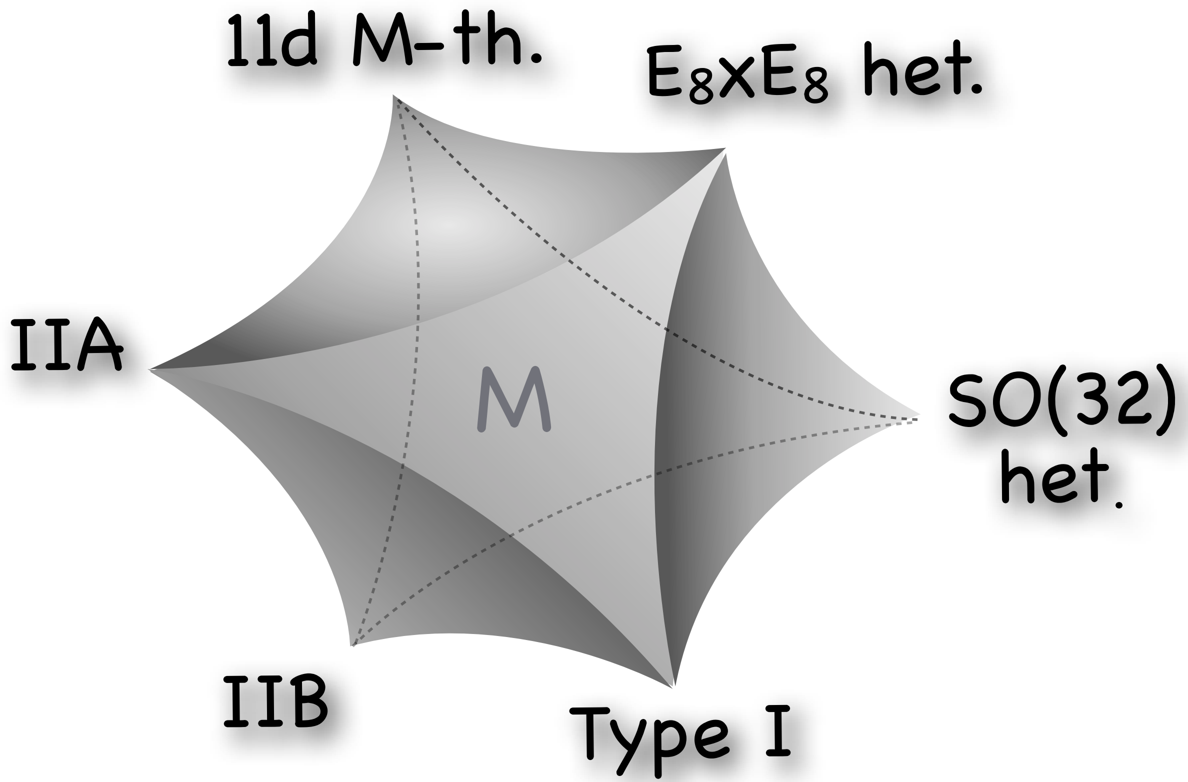
- Elementary particles are oscillation modes of strings

gravity

gauge, matter, Higgs

String theory

- Formulated in 10d, string theory is a remarkably unique theory



String theory

- Formulated in 10d, string theory is a remarkably unique theory

- But need to 'compactify' 6 dimensions in small finite size geometry

  Spacetime $M_4 \times X_6$

- Far from unique, and each choice of 'compactification' space leads to different 4d physics

"String landscape"

String theory

- Formulated in 10d, string theory is a remarkably unique theory

- But need to 'compactify' 6 dimensions in small finite size geometry

  Spacetime $M_4 \times X_6$

- Far from unique, and each choice of 'compactification' space leads to different 4d physics

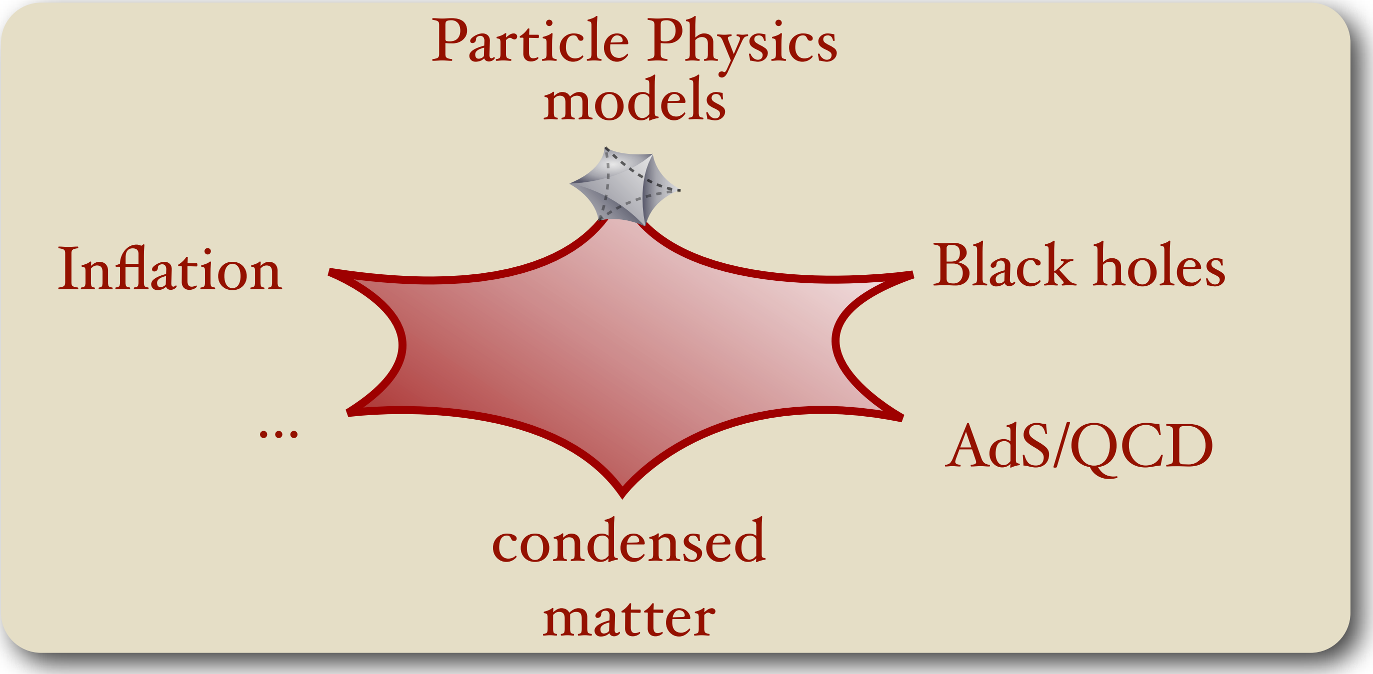
"String landscape"

Analogy with General Relativity:
Unique set of equations, but many solutions

‘Landscape’ of string theory applications

‘70s Early string theory
’80s The superstring revolution
’90s Non-perturbative string theory

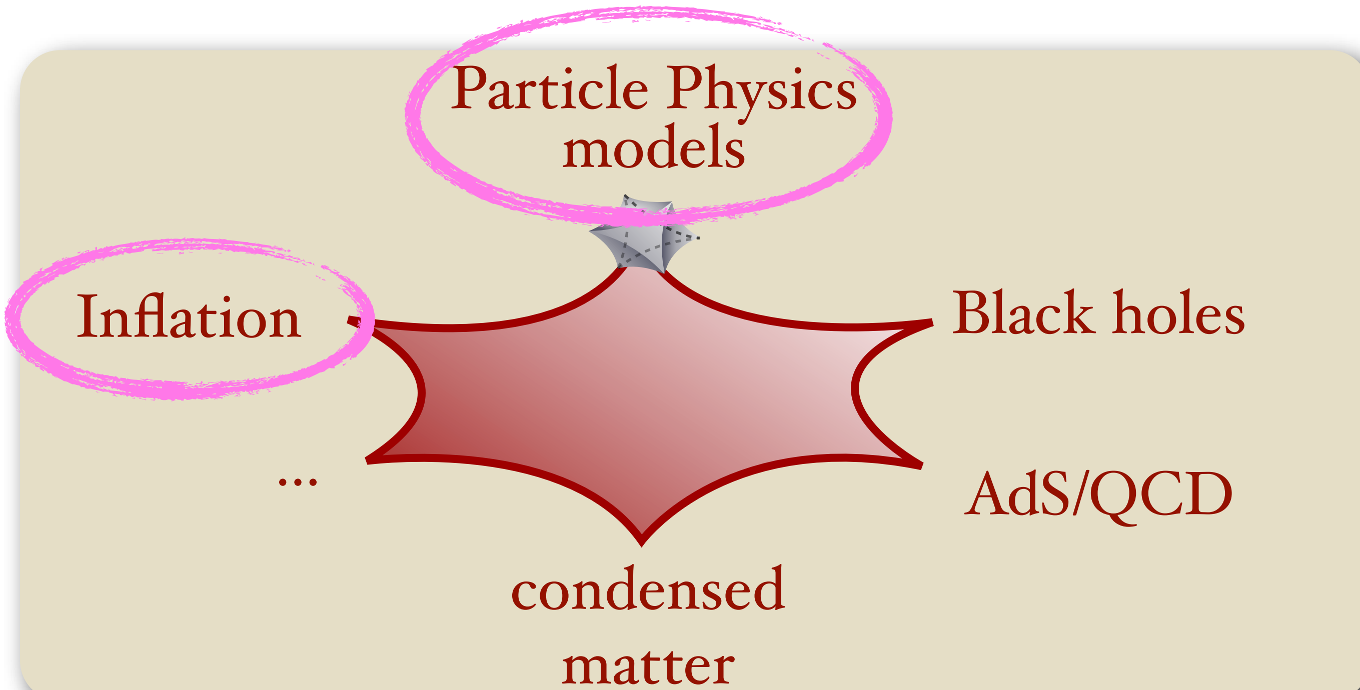
- Since 2000 we are having a great ‘decade’ of ‘applied string theory’



‘Landscape’ of string theory applications

‘70s Early string theory
’80s The superstring revolution
’90s Non-perturbative string theory

- Since 2000 we are having a great ‘decade’ of ‘applied string theory’

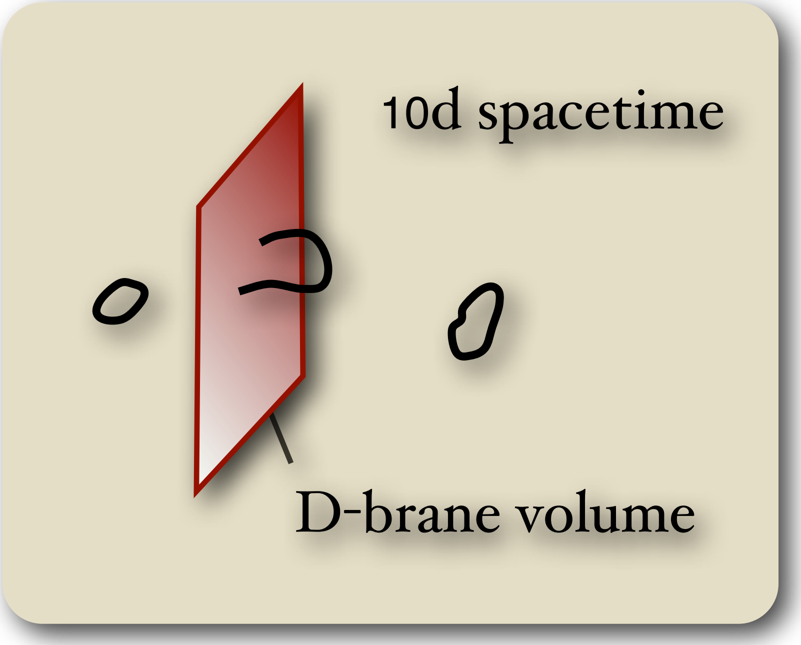


- Brief overview of “traditional” String Phenomenology

D-branes [Polchinski '95]

Some of most successful applications are based on D-branes

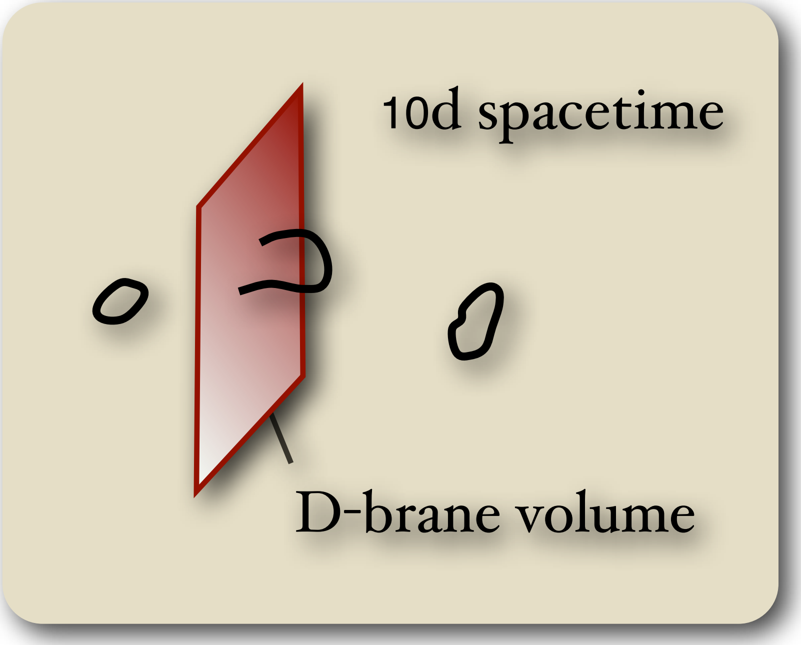
High-dim. planes on which open strings end



D-branes [Polchinski '95]

Some of most successful applications are based on D-branes

High-dim. planes on which open strings end

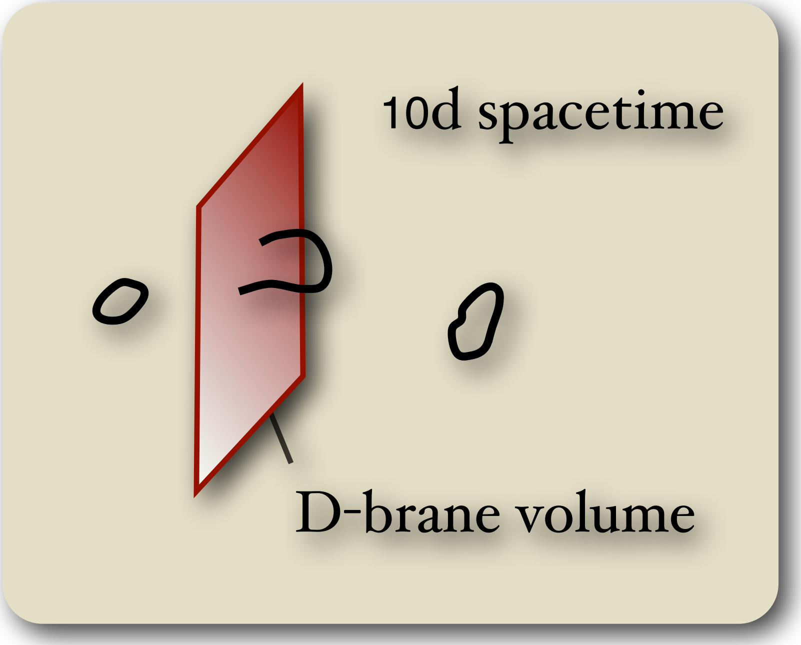


- Brane world:
  - Closed strings: gravity in 10d
  - Open strings: gauge+matter on brane

D-branes [Polchinski '95]

Some of most successful applications are based on D-branes

High-dim. planes on which open strings end

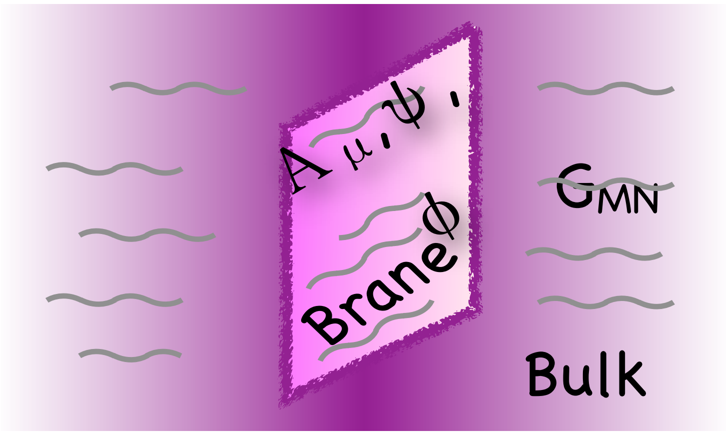


- Brane world:
  - Closed strings: gravity in 10d
  - Open strings: gauge+matter on brane

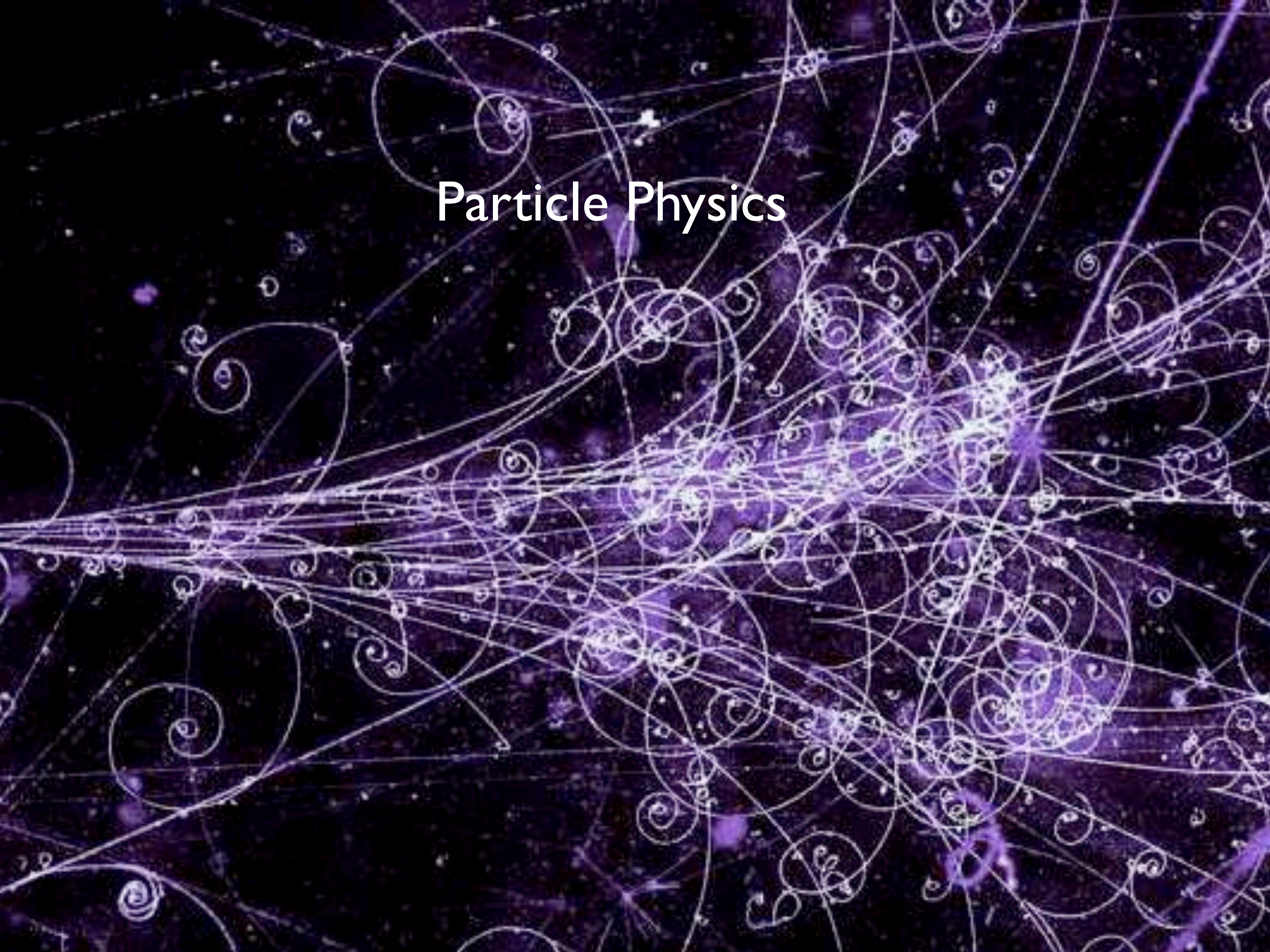
- Allows large extra dimensions

$$\boxed{M_P^2\, g_{SM}^2 = \frac{M_s^{11-p}\, V_\perp}{g_s}}$$

[Antoniadis, Arkani-Hamed, Dimopoulos, Dvali '98]



Particle Physics



String Phenomenology

- String theory describes gravitational and gauge interactions in a unified framework, consistent at the quantum level

- If string theory is realized in Nature, it should be able to describe a very specific gauge sector: Standard Model

- Aim of String Phenomenology:

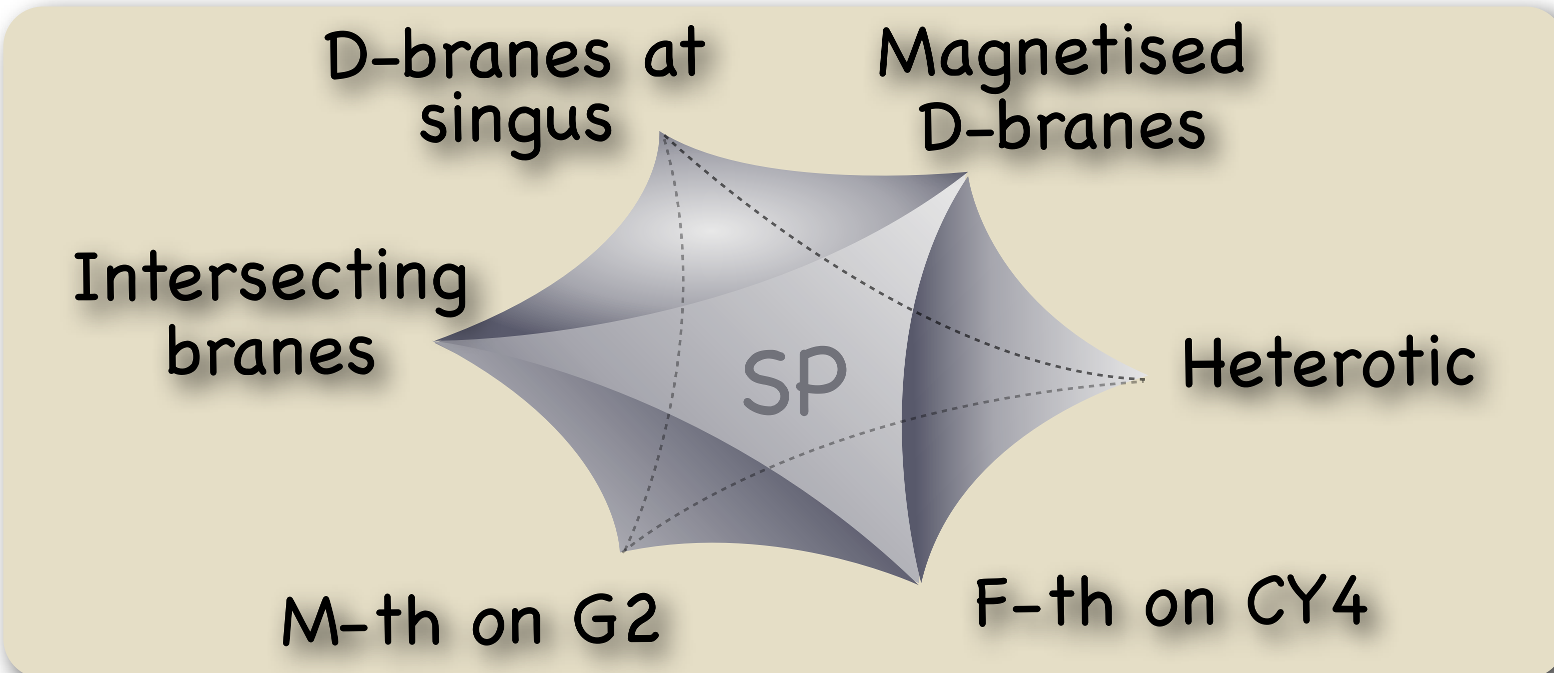
- Determine classes of constructions with a chance to lead to SM
  Non abelian gauge interactions, replicated charged fermions, Higgs scalars with appropriate Yukawa couplings, ...

- Within each class, obtain explicit models as close to SM as possible with the hope of learning more about the high energy regime of SM in string theory

- Old program, yet continuous progress

‘Landscape’ of String Phenomenology tools

- Plenty of (related) constructions to ‘engineer’ SM in string theory



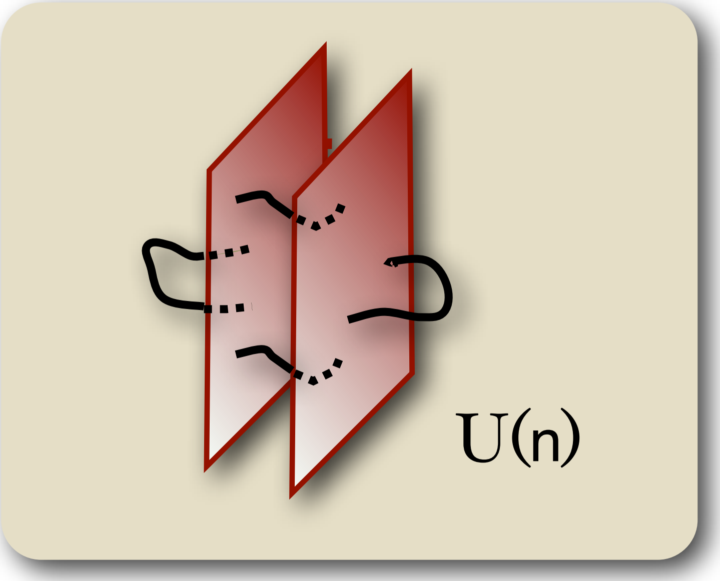
- Sketch ideas of models based on D-branes / F-theory

The geometry of gauge theories

- Non-abelian U(n) gauge interactions from "n" coincident D-branes

Matrix of open string sectors

$$\begin{pmatrix} 11 & 12 & \dots & 1n \\ 21 & 22 & \dots & 2n \\ \dots & \dots & \dots & \dots \\ n1 & n2 & \dots & nn \end{pmatrix}$$

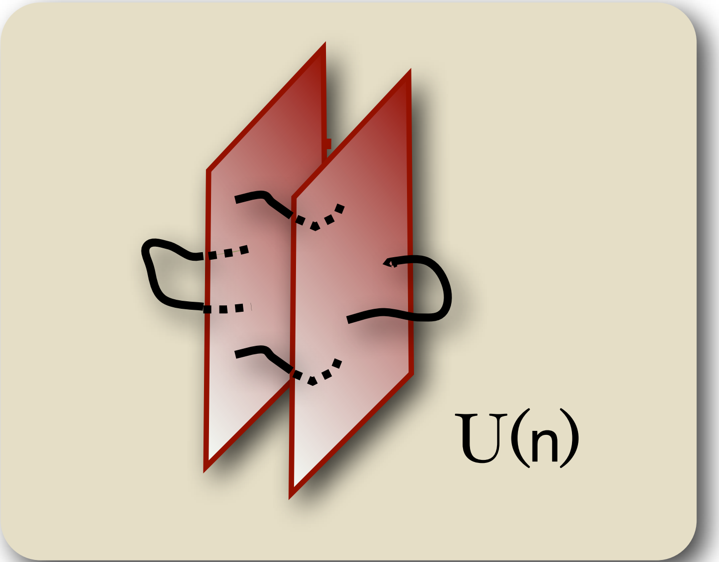


The geometry of gauge theories

- Non-abelian U(n) gauge interactions from "n" coincident D-branes

Matrix of open string sectors

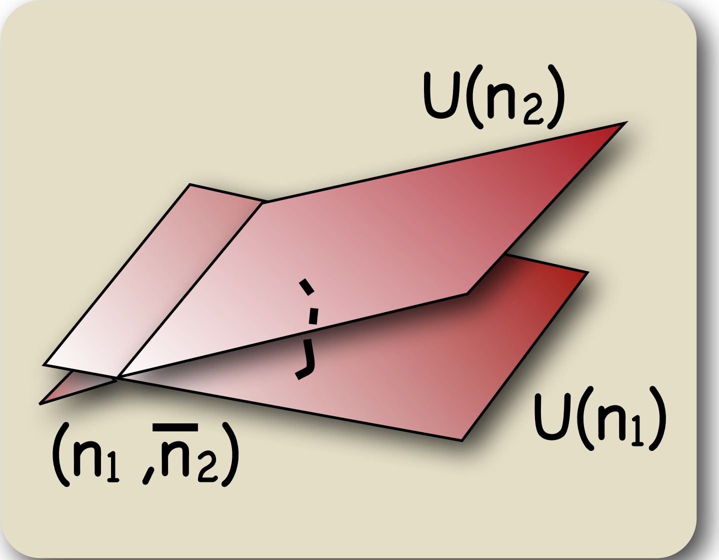
$$\begin{pmatrix} 11 & 12 & \ldots & 1n \\ 21 & 22 & \ldots & 2n \\ \ldots & \ldots & \ldots & \ldots \\ n1 & n2 & \ldots & nn \end{pmatrix}$$



- 4d Charged matter from intersection of stacks of D6-branes

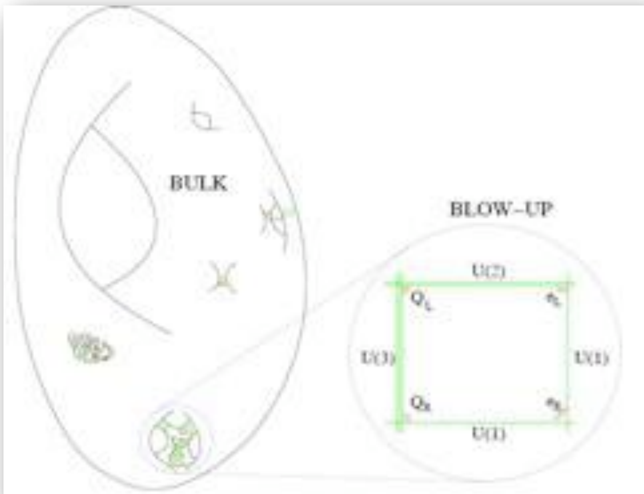
Matrix of open string sectors

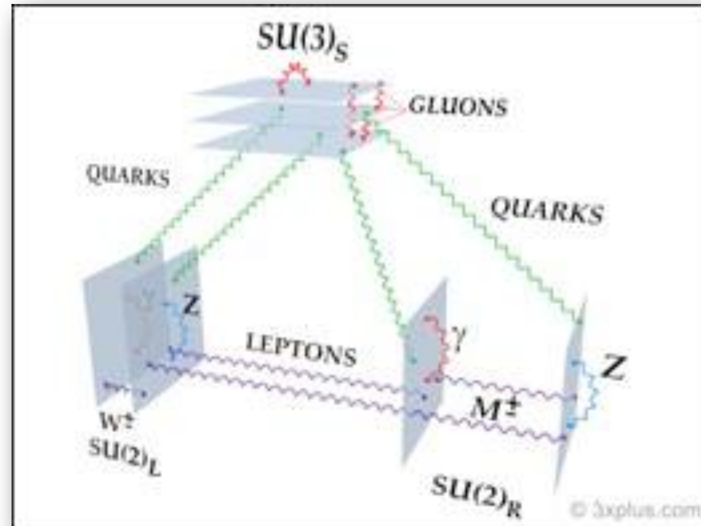
$$\begin{pmatrix} 11 & 12 & \ldots & 1n_1 \\ 21 & 22 & \ldots & 2n_1 \\ \ldots & \ldots & \ldots & \ldots \\ n_2 1 & n_2 2 & \ldots & n_2 n_1 \end{pmatrix}$$



Particle Physics from Intersecting D-branes

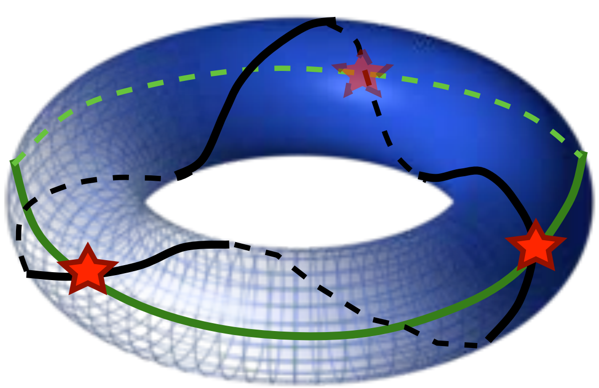
- Charged matter arises from open strings among stack of D-branes intersecting in the extra dimensions





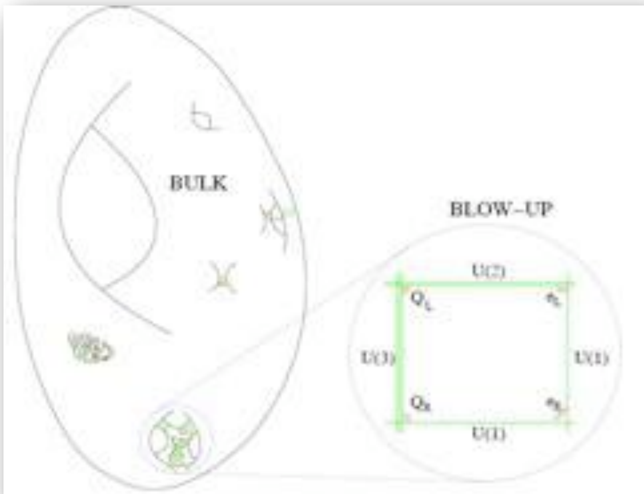
- Multiple intersections ⇒ multiple copies of each fermion

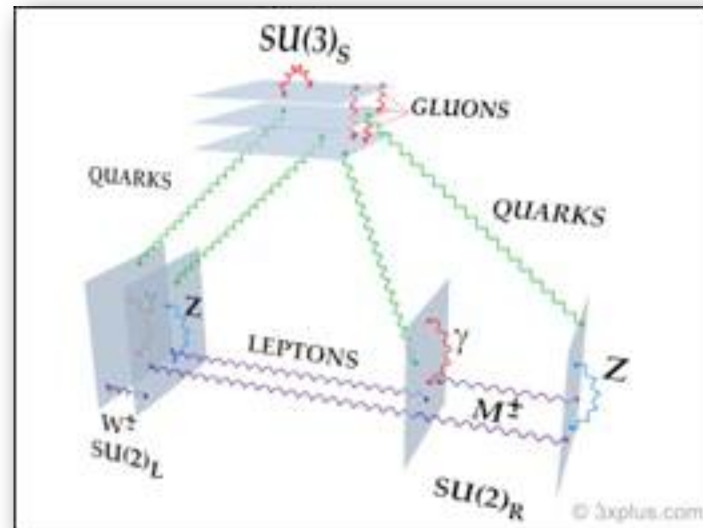
Number of SM families given by number of geometric intersections



Particle Physics from Intersecting D-branes

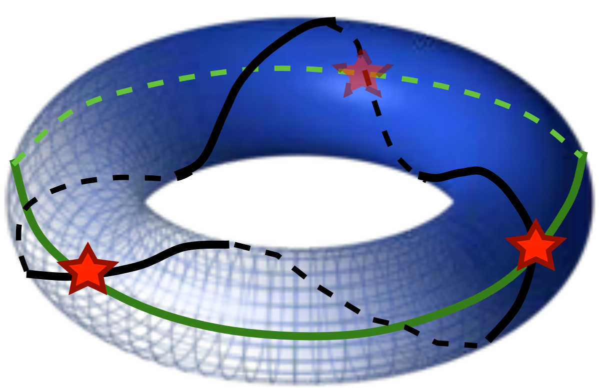
- Charged matter arises from open strings among stack of D-branes intersecting in the extra dimensions





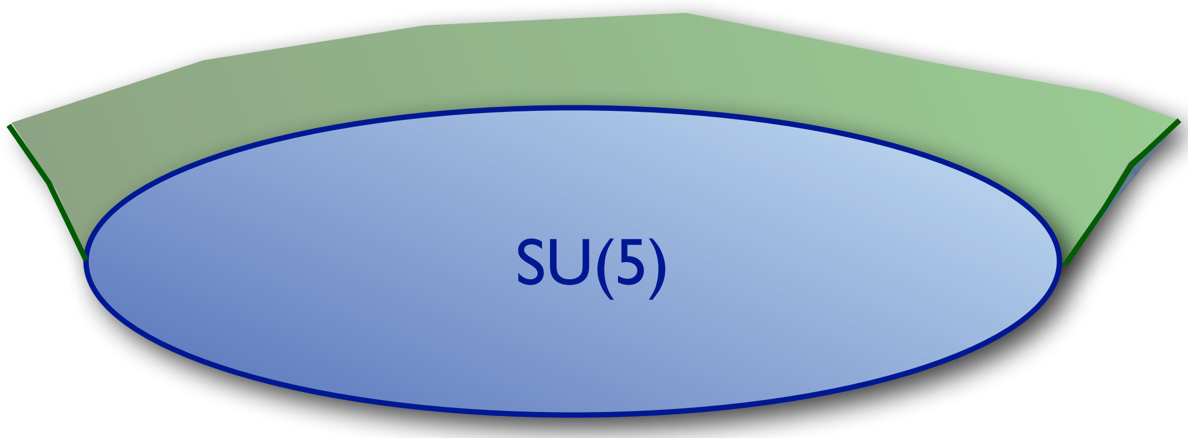
- Multiple intersections ⇒ multiple copies of each fermion

Number of SM families given by number of geometric intersections



F-theory GUTs

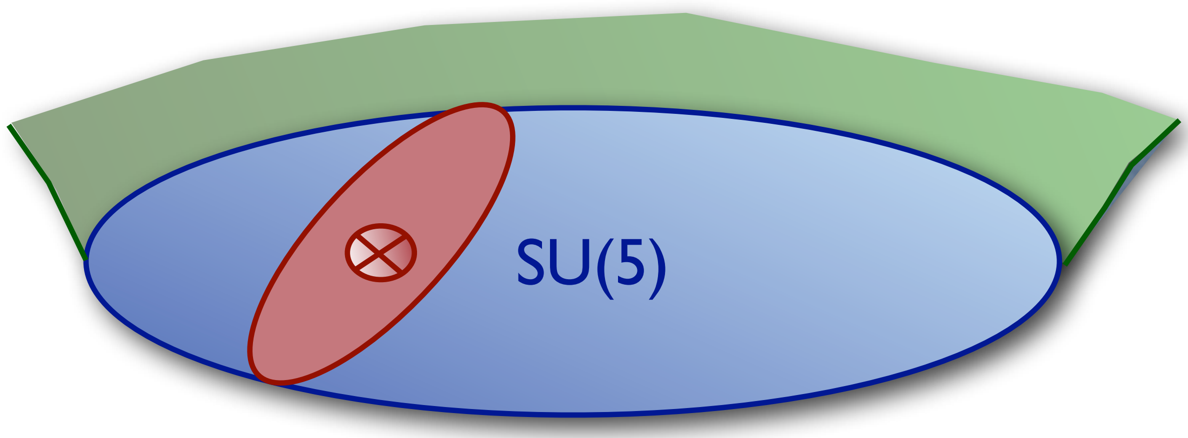
- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)



F-theory GUTs

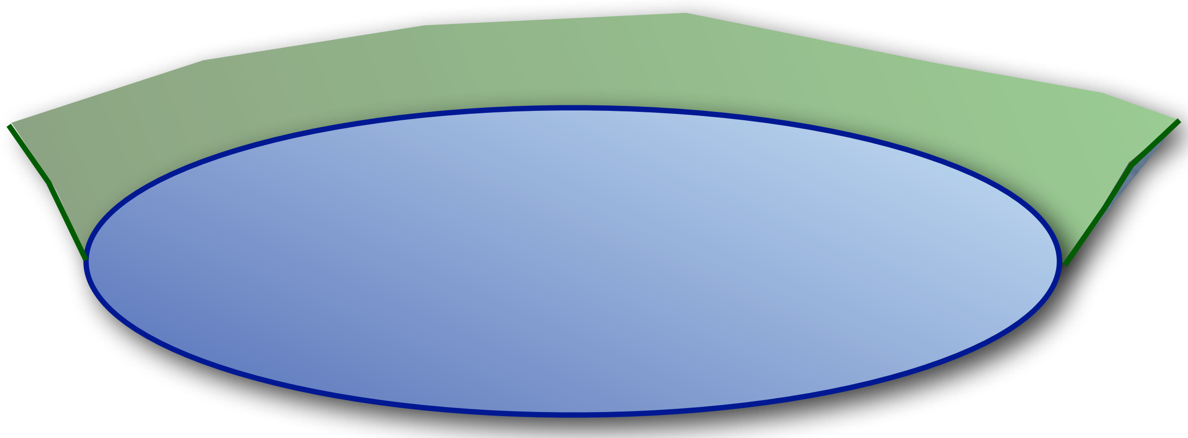
- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)

subsequently broken by hypercharge flux
SU(5) → SU(3) x SU(2) x U(1)$_Y$



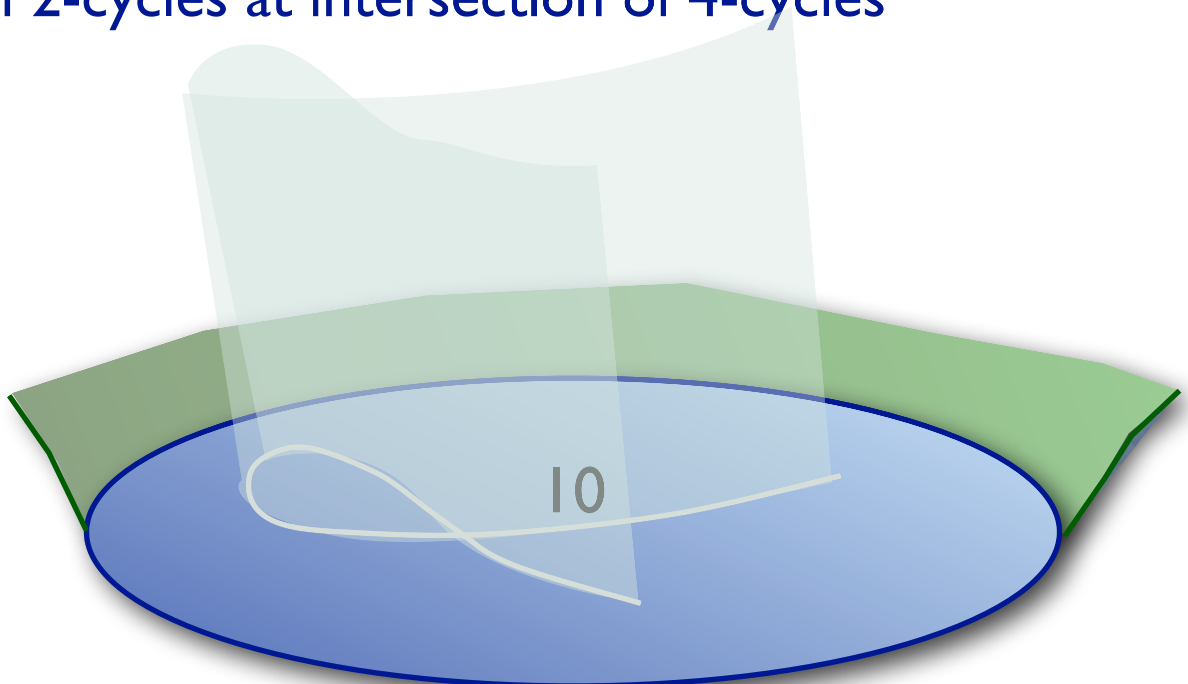
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles at intersection of 4-cycles



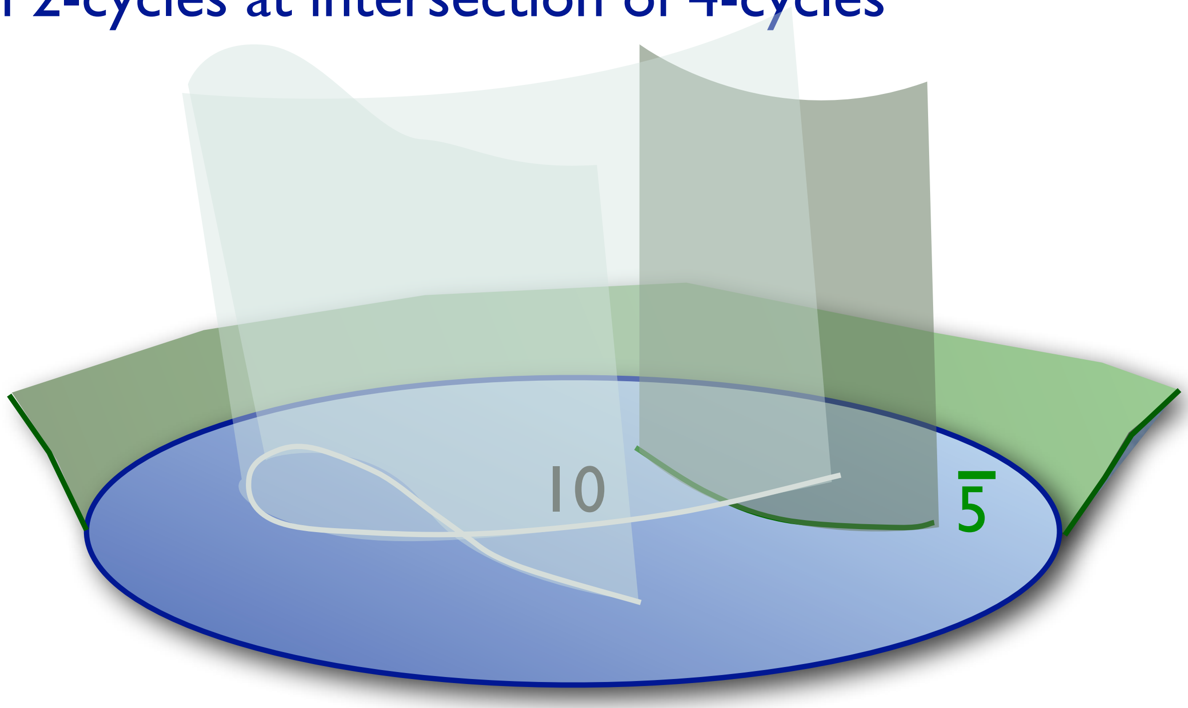
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles at intersection of 4-cycles



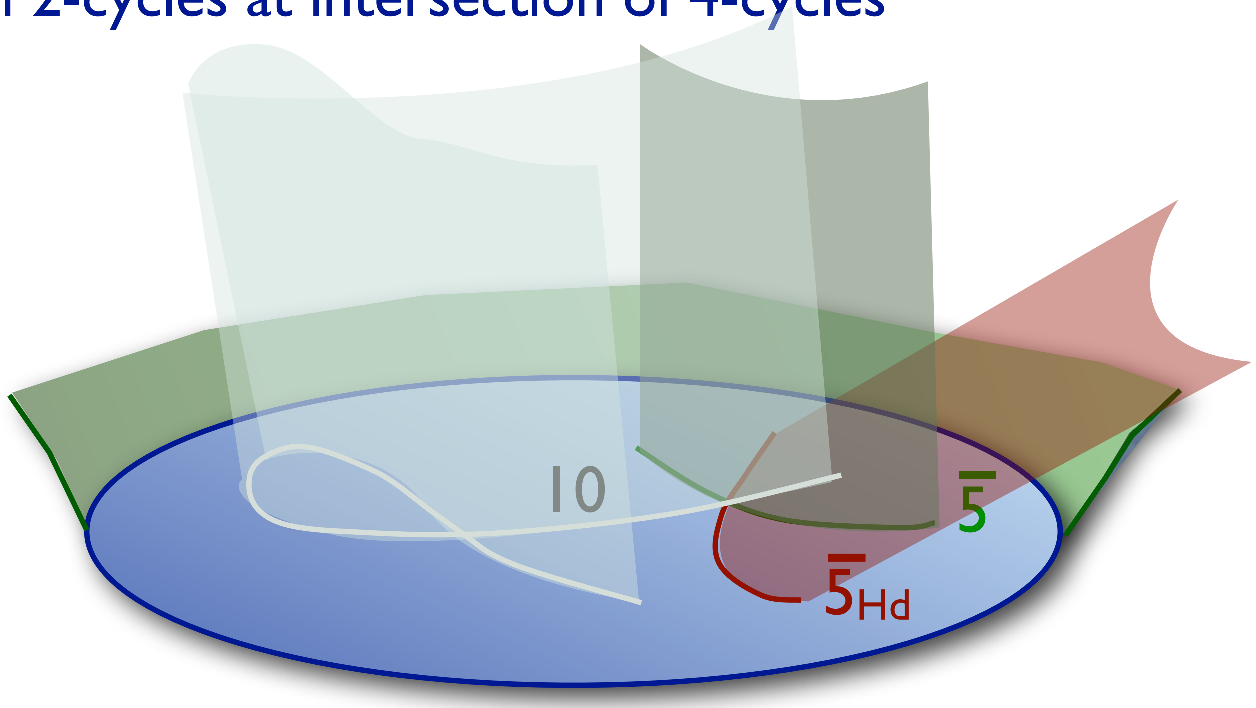
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles at intersection of 4-cycles



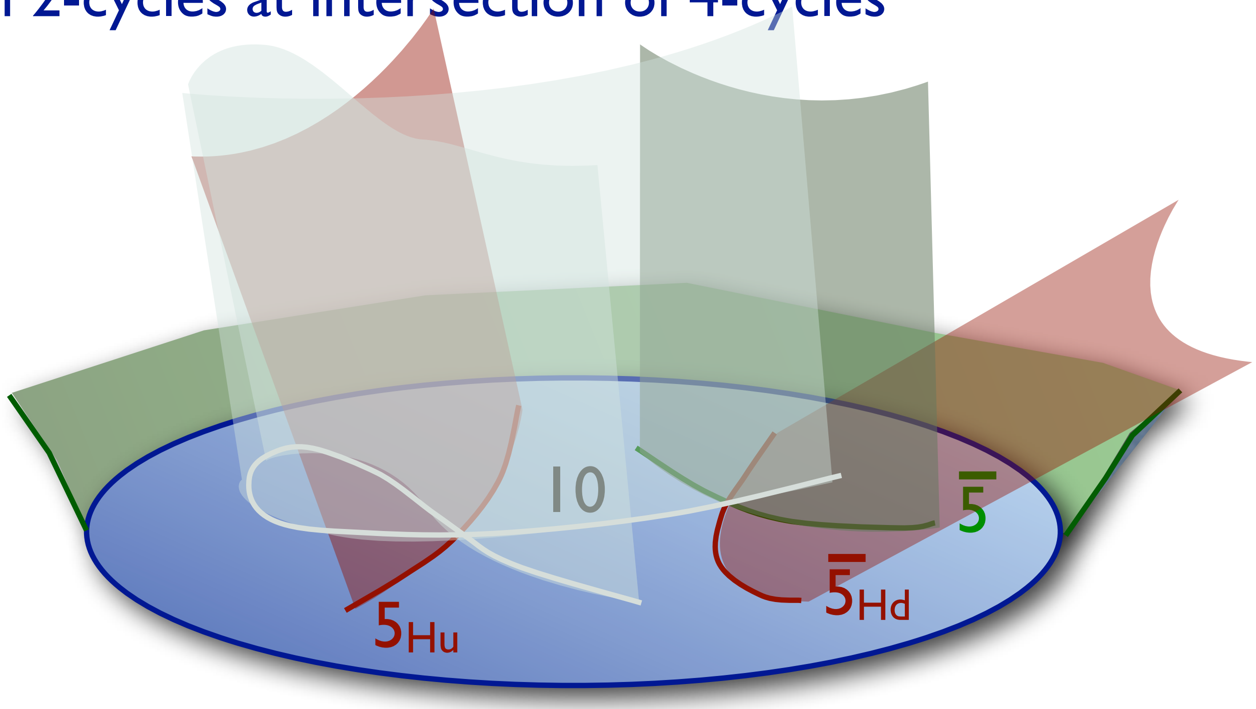
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles at intersection of 4-cycles



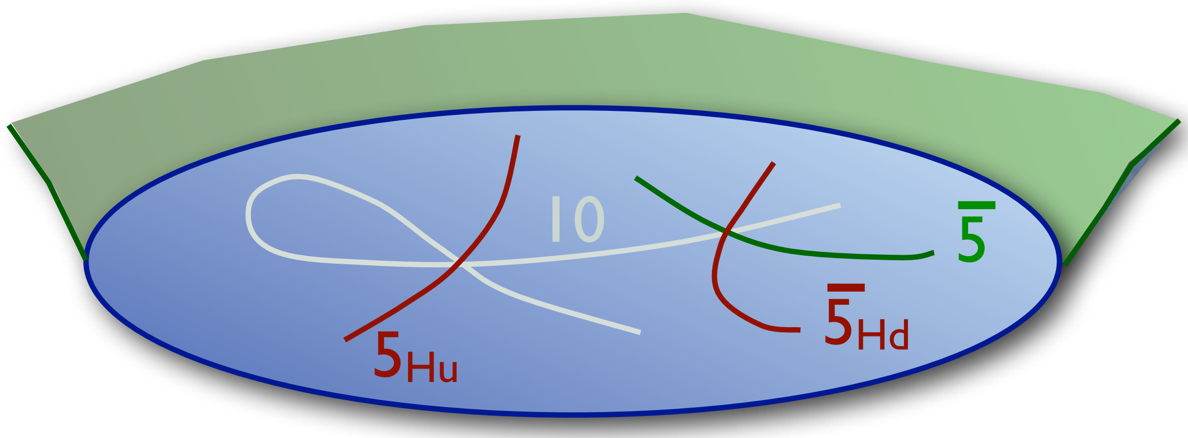
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles at intersection of 4-cycles



F-theory GUTs

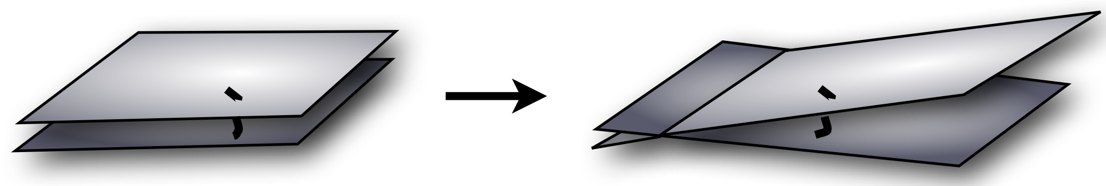
- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles

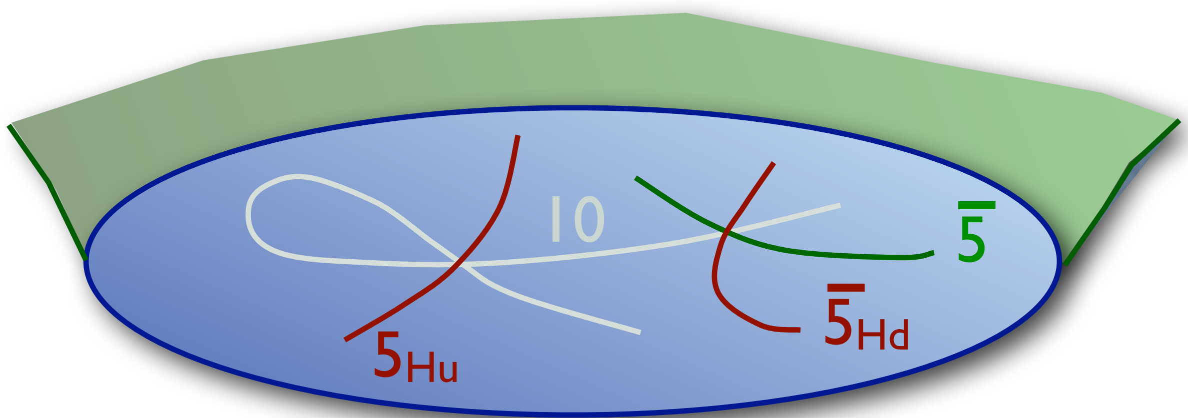


F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles

- Representations from unfolding G→H1 x H2



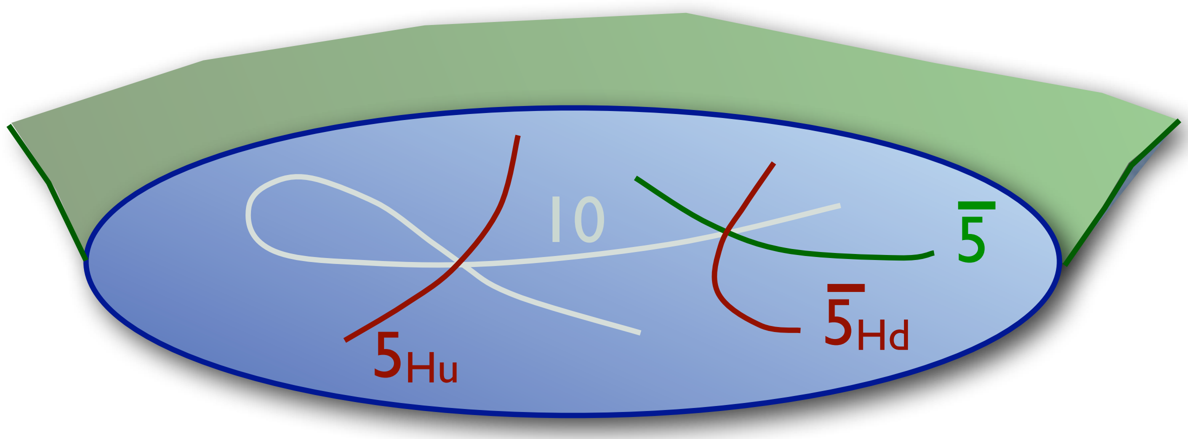


SO(10) → SU(5) x U(1)
45 → 24 + 1 + 10 + 10b

SU(6) → SU(5) x U(1)
35 → 24 + 1 + 5 + 5b

F-theory GUTs

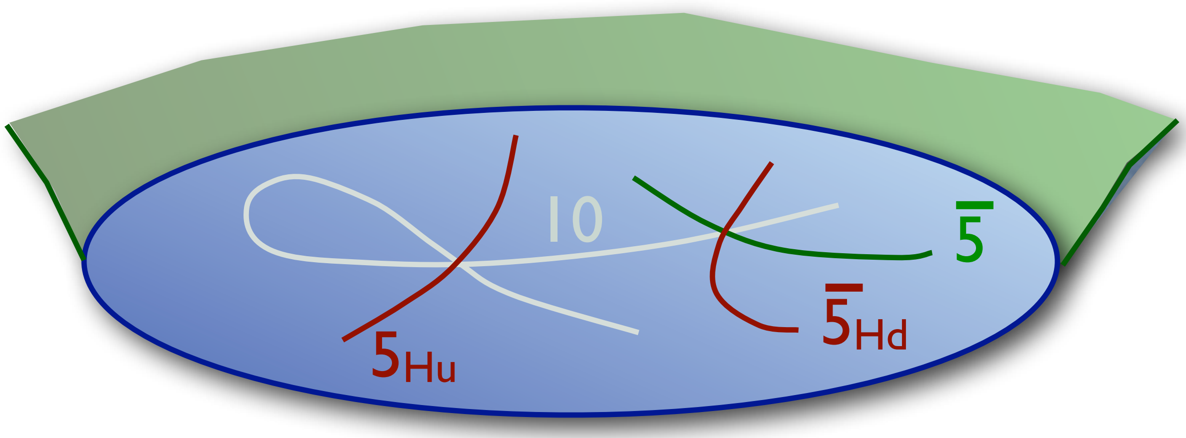
- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles
  - Yukawas at points



F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles
  - Yukawas at points

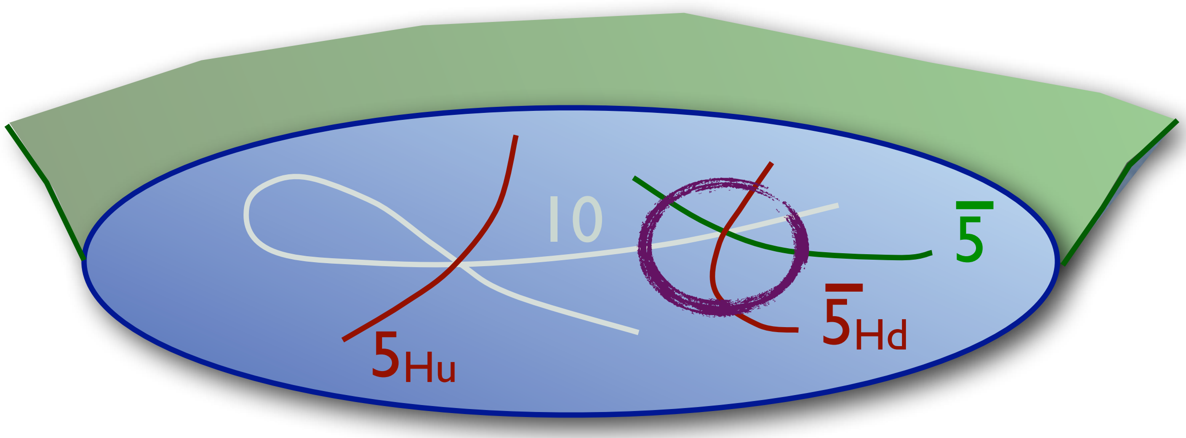
Also from unfolding G→H1 x H2



F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles
  - Yukawas at points

Also from unfolding G→H1 x H2



SO(12) → SU(5) x U(1) xU(1)

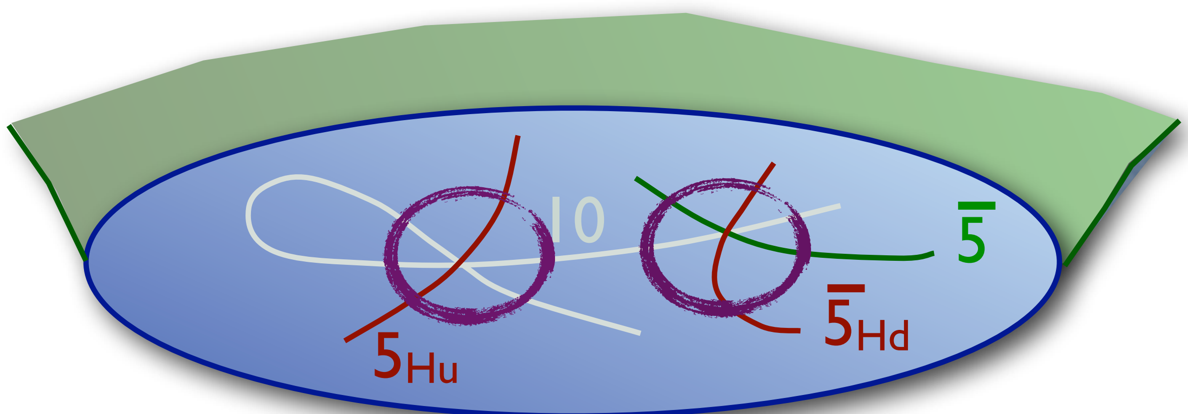
66 → 24 + 1 +1+ 10b + 5 + 5

+ **10 + 5b +5b**

F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles: Pick SU(5)
  - Matter on 2-cycles
  - Yukawas at points

Also from unfolding G→H1 x H2



SO(12) → SU(5) x U(1) xU(1)
66 → 24 + 1 +1+ 10b + 5 + 5
+ **10 + 5b +5b**

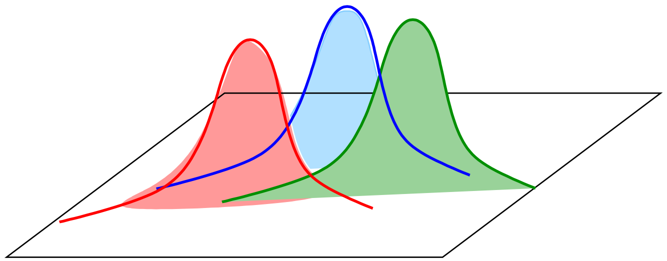
E6 → SU(5) x U(1) x U(1)
78 → 24+1+1+1+1+ 10b + 10b + 5b
+ **10 + 10 + 5**

F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles
  - Matter on 2-cycles
  - Yukawas at points

Overlap of chiral matter wavefunctions

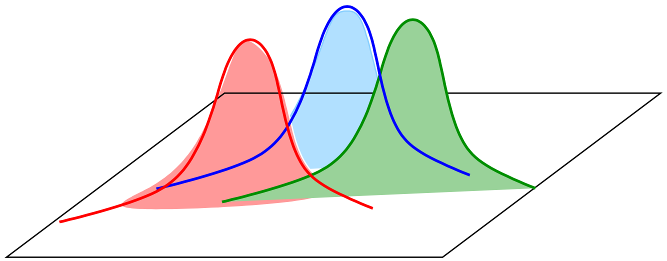
$$\int \phi_1 \phi_2 \phi_3$$



F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles
  - Matter on 2-cycles
  - Yukawas at points

Heuristics



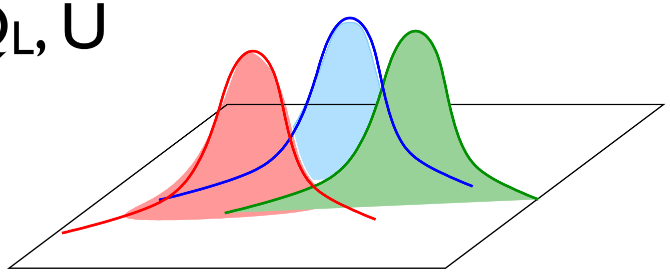
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles
  - Matter on 2-cycles
  - Yukawas at points

Heuristics

Choose local coords z, u, v for e.g. H_U, Q_L, U

Three families: 1,u, u^2 ; 1,v, v^2 for Q_L, U



$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Order 1 top Yukawa. Everyone else massless

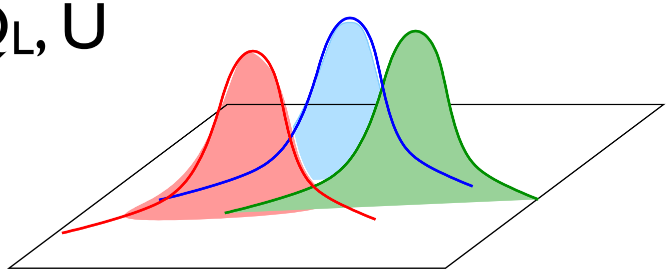
F-theory GUTs

- Non-perturbative generalization of D-brane models,
  - Gauge group on 4-cycles
  - Matter on 2-cycles
  - Yukawas at points

Heuristics

Choose local coords z, u, v for e.g. H_U, Q_L, U

Three families: 1, u, u^2 ; 1, v, v^2 for Q_L, U



$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Order 1 top Yukawa. Everyone else massless

A whole industry of refinement

Some properties

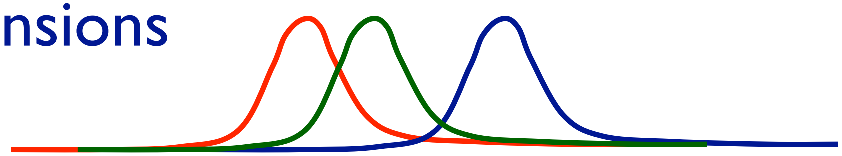
[Aldazabal, Franco, Ibanez, Rabadan, AU '01]

- Gauge coupling unification

  Reasonable, but not perfect, in F-theory GUT models

- Yukawa couplings

  Overlap of wavefunctions in extra dimensions



$$Y_{jk} \simeq e^{-A_{Hjk}+i\phi_{jk}}$$

  Realistic textures for masses and mixings in particular models

  [Vafa, Heckman; Font, Ibanez; ...'08]

- String scale

  - Susy models, can have large string scale [later for susy breaking]
  - Non-susy models: large extra dimensions [ADD'98] or warping [later]

- Proton decay

  In SM models, forbidden by $U(1)_a$ baryon number (Z' boson)

  In GUT models, possible but suppressed just above experimental bound

- Interesting pattern of Z' bosons beyond SM

What at the LHC?

What at the LHC?

Before, must address some "details"...

What at the LHC?

Before, must address some “details”...

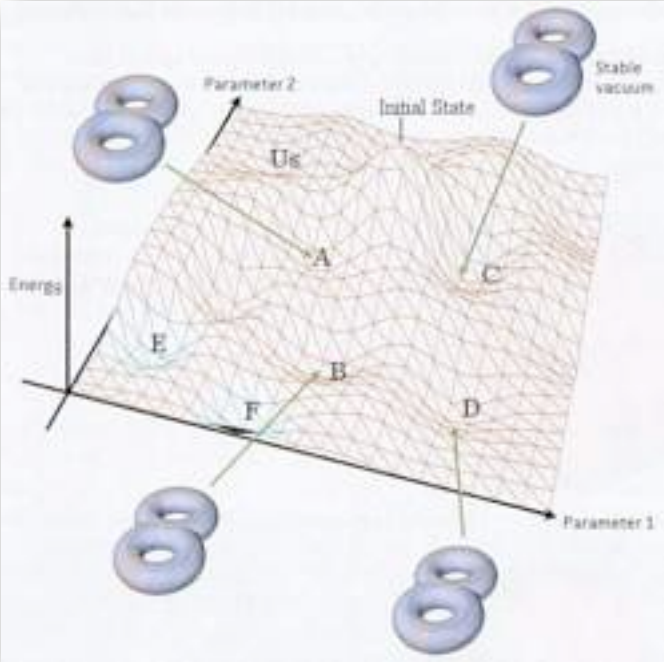
Moduli problems

What fixes geometry of compactification space?

- Free parameters in the compact geometry are massless fields in 4d (moduli')

  Phenomenological disaster!

  5th forces, cosmological problems,...



- Tied up to the question of SUSY breaking

  Flat potentials, protected with susy
  Are lifted by corrections in non-susy, or upon susy breaking

How to break susy and lift moduli in a controlled way?

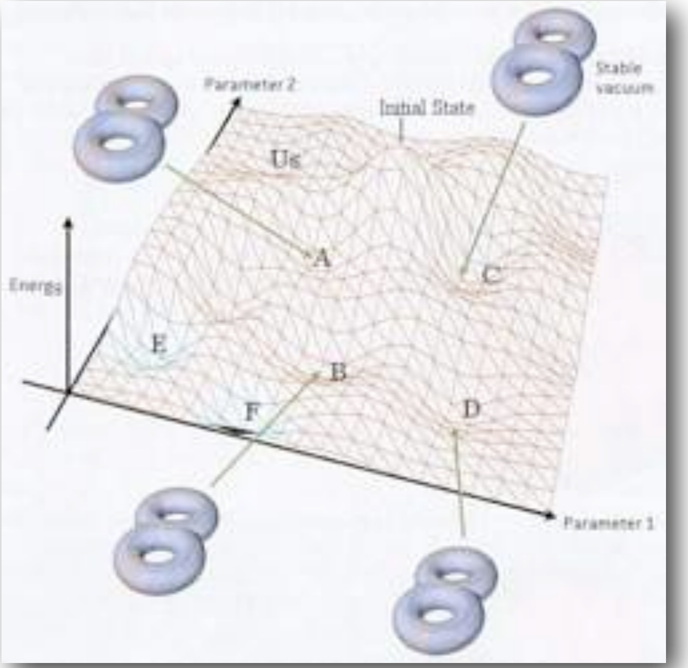
Moduli problems

What fixes geometry of compactification space?

- Free parameters in the compact geometry are massless fields in 4d (moduli')

  Phenomenological disaster!

  5th forces, cosmological problems,...



- Tied up to the question of SUSY breaking

  Flat potentials, protected with susy
  Are lifted by corrections in non-susy, or upon susy breaking

How to break susy and lift moduli in a controlled way?

Fluxes
Antibranes
...

“True” phenomenology

<u>3-line lesson to take home</u>

Questions on the Higgs, SUSY spectrum, etc CAN be addressed in string theory

General plausible scenarios (with assumption, of course)

They differ slightly in new physics at LHC (testable)

“True” phenomenology

3-line lesson to take home

Questions on the Higgs, SUSY spectrum, etc CAN be addressed in string theory

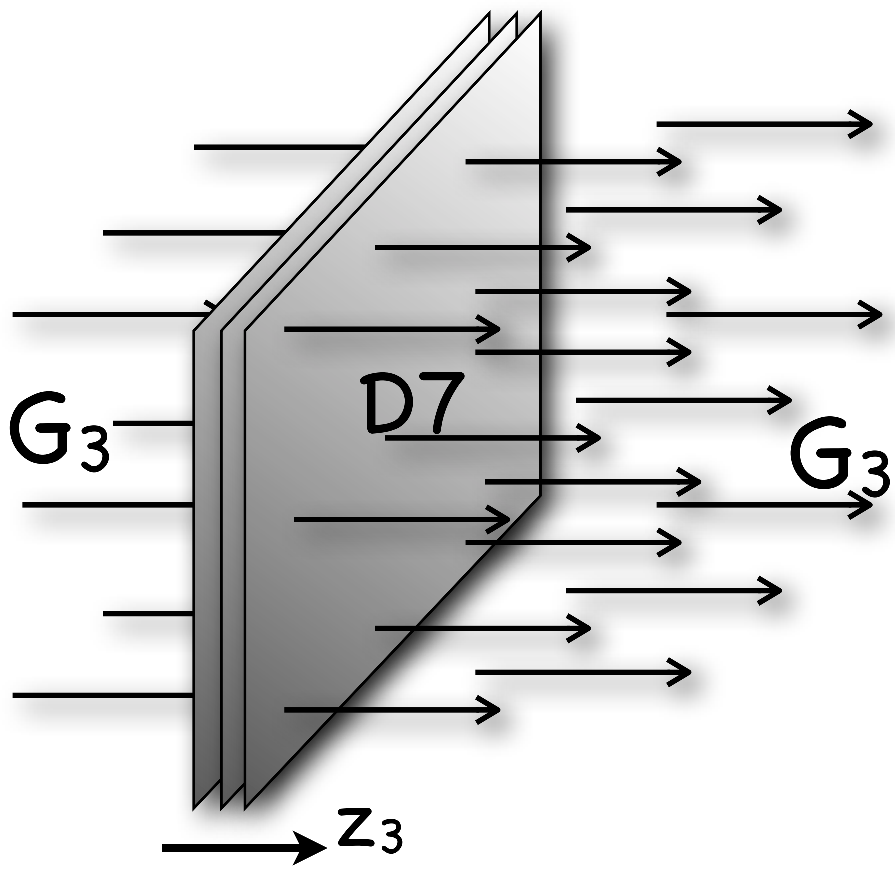
General plausible scenarios (with assumption, of course)

They differ slightly in new physics at LHC (testable)

And life apart from Higgs and susy:
low string scale, Z’ resonances, dark sectors, ...)

Fluxes, susy breaking and soft terms

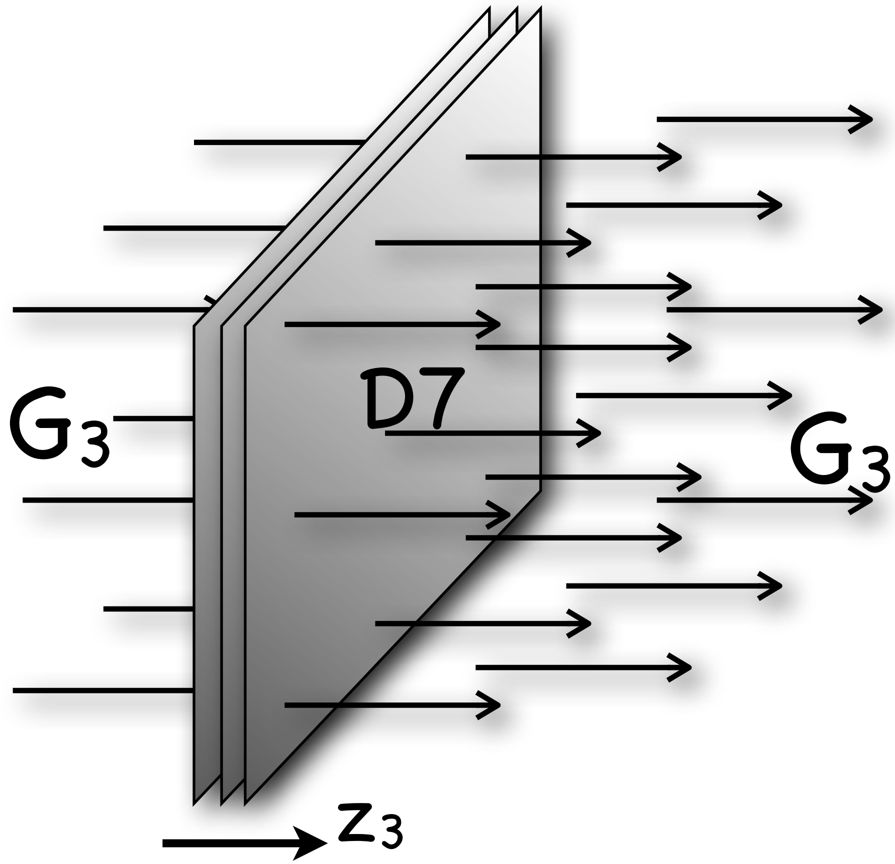
- An appealing scenario: Susy MSSM D-brane sector and non-susy flux
- Soft terms arise from effect of non-susy flux on susy D-branes



Fluxes, susy breaking and soft terms

- An appealing scenario: Susy MSSM D-brane sector and non-susy flux
- Soft terms arise from effect of non-susy flux on susy D-branes

Explicitly computable in terms of the local flux density



Fluxes, susy breaking and soft terms

- Gravity mediation (in general, not universal, no mSUGRA)

Fluxes, susy breaking and soft terms

- Gravity mediation (in general, not universal, no mSUGRA)
- Scales $M_{SUSY} \sim f \dfrac{\alpha'}{R^3} \sim f \dfrac{M_c^2}{M_p}$ f: possible local suppression

LowE Susy: TeV soft terms from $M_c \sim 10^{11}\mathrm{GeV}$

~~LowE Susy~~: Choose $M_c \sim 10^{14}\mathrm{GeV}$ then $M_{SUSY} \sim 10^{10}\mathrm{GeV}$

Fluxes, susy breaking and soft terms

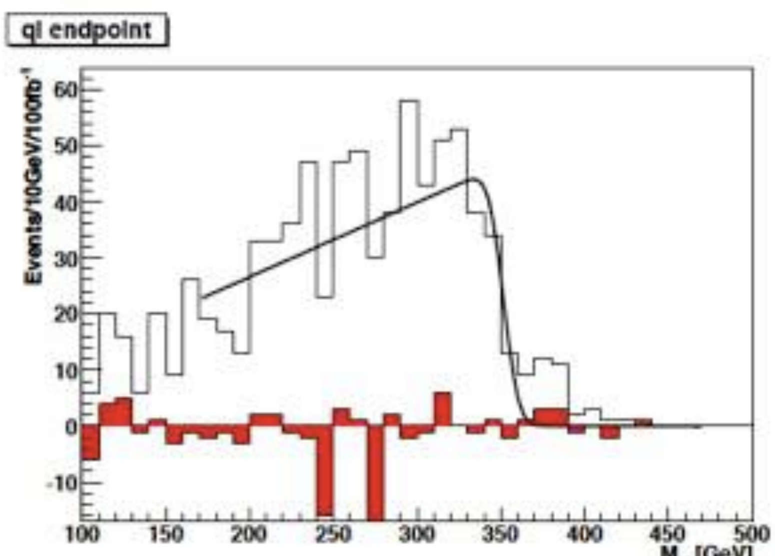
- Gravity mediation (in general, not universal, no mSUGRA)

- Scales $$M_{SUSY} \sim f \frac{\alpha'}{R^3} \sim f \frac{M_c^2}{M_p}$$ f: possible local suppression

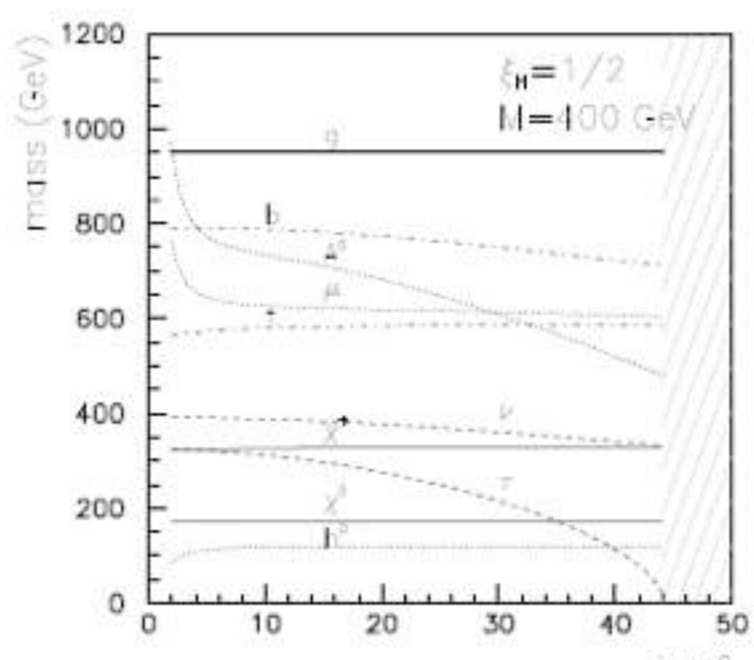
LowE Susy: TeV soft terms from $M_c \sim 10^{11}\mathrm{GeV}$

~~LowE Susy:~~ Choose $M_c \sim 10^{14}\mathrm{GeV}$ then $M_{SUSY} \sim 10^{10}\mathrm{GeV}$

- Can get to make plots



Ex: spectrum reconstruction from edges
Conlon, Kom, Suruliz, Allanach, Quevedo '07



Ex: MSSM parameters Aparicio, Cerdeno, Ibañez '08

What is it good for?

- Many realistic vacua: No unique testable prediction

Each particular consistent realistic model is probably wrong
But some general lessons may be right and key to the UV of SM

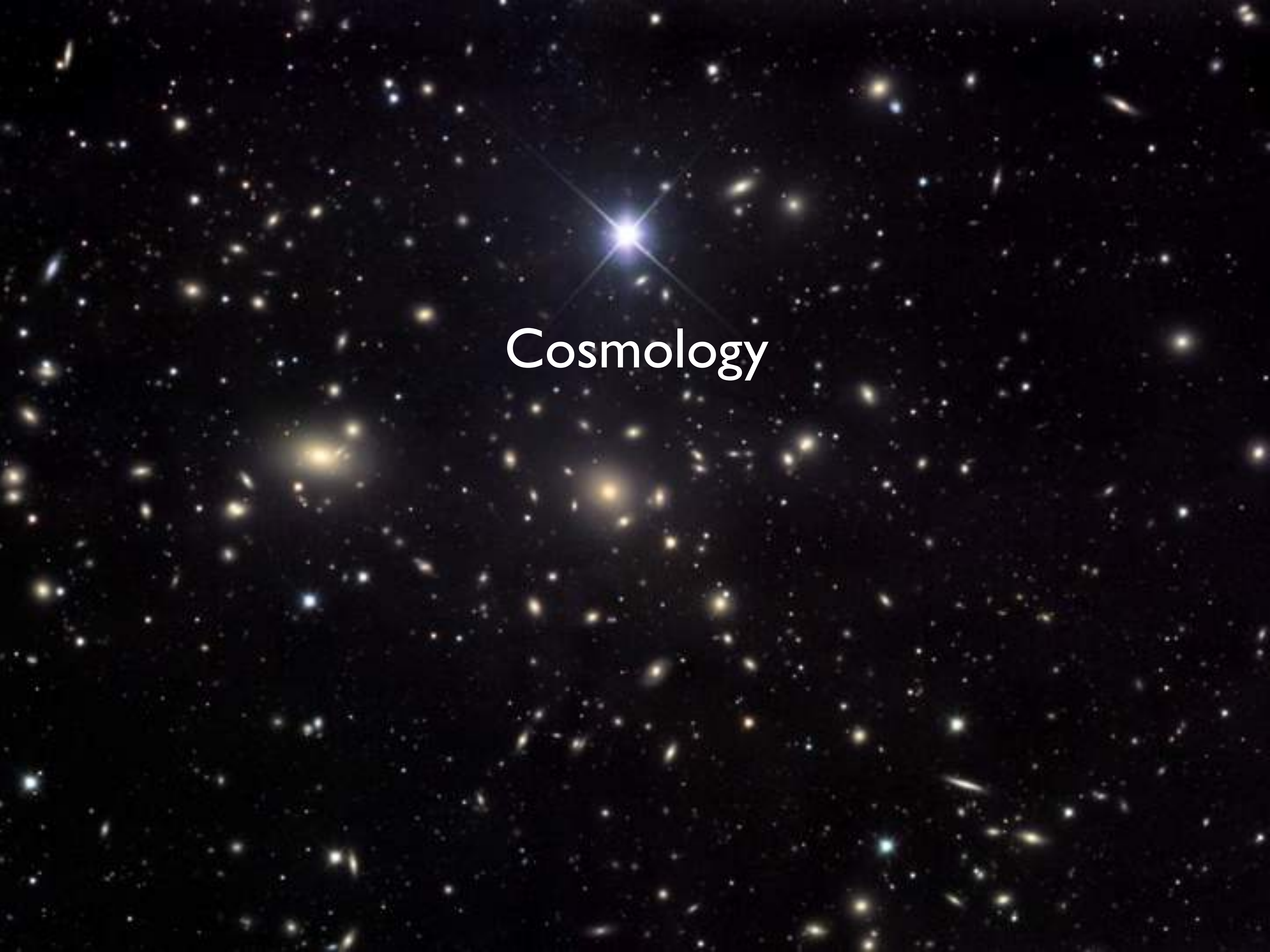
- New scenarios (in UV complete theory):
Extra dimensions, brane world, warping, ...

- Plausible patterns within each
e.g. Low energy susy and susy breaking soft terms

- Smoking guns for some scenarios (±contrived)
e.g. string resonances in TeV scale models

- Expect interesting impact of LHC results

Cosmology



The questions

Late Dark Energy

Early Dark Energy

The questions

Late Dark Energy

- Full moduli stabilization in a deSitter vacua

with tunably small cosmological constant

Susy breaking is ingrained in deSitter

Early Dark Energy

The questions

Late Dark Energy

- Full moduli stabilization in a deSitter vacua

with tunably small cosmological constant

Susy breaking is ingrained in deSitter

Early Dark Energy

- Inflationary scenarios

Controlable corrections to guarantee slow roll

Computation of spectral index, tensor modes, non-Gaussianities,...

deSitter

(1**)** Type IIB with 3-form flux stabilizing dilaton and complex structure

Kähler moduli not stabilized

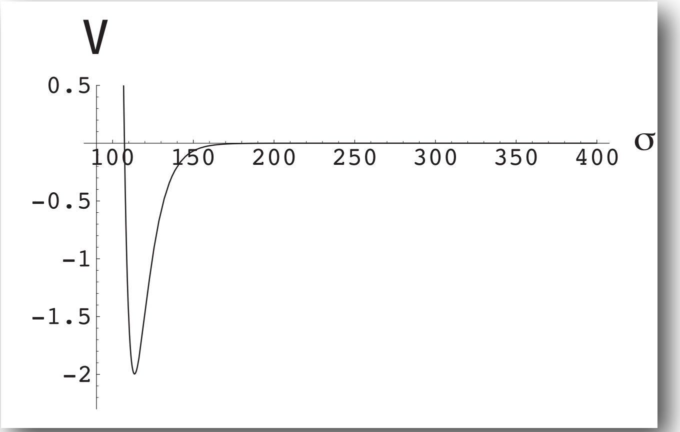
deSitter

(1) Type IIB with 3-form flux stabilizing dilaton and complex structure

Kähler moduli not stabilized

(2) Non-pertubative effects from D-brane instantons

(full stab. in AdS)



deSitter

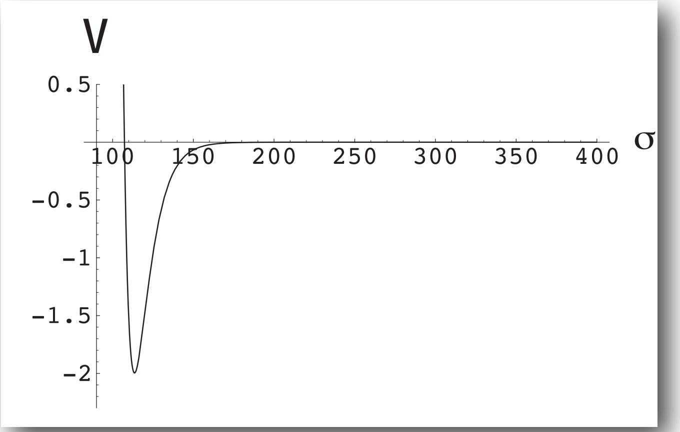
(1**)** Type IIB with 3-form flux stabilizing dilaton and complex structure

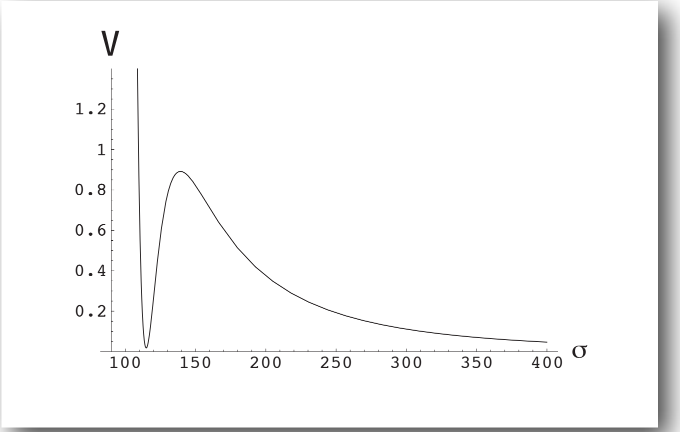
Kähler moduli not stabilized

(2**)** Non-pertubative effects from D-brane instantons

(full stab. in AdS)

(3**)** Add susy breaking sector of anti-D3-branes





deSitter

(1) Type IIB with 3-form flux stabilizing dilaton and complex structure

Kähler moduli not stabilized

Alternative constructions, but in general:

(2) Non-perturbative effects from D-brane instantons

Constructions of De Sitter are complicated and somewhat controversial

(full stab. in AdS)

(3) Add susy breaking sector of anti-D3-branes

Inflation

Being a gravitational theory, expect string theory to help understand origin and cosmological evolution of the Universe

Useful to address questions sensitive to the UV, e.g. Inflation

Slow roll condition requires detailed knowledge of inflaton potential, including certain Planck-scales suppressed terms

Very many models fitting Planck data

What critical feature to focus on a particular class?

For today, use tensor to scalar ratio r

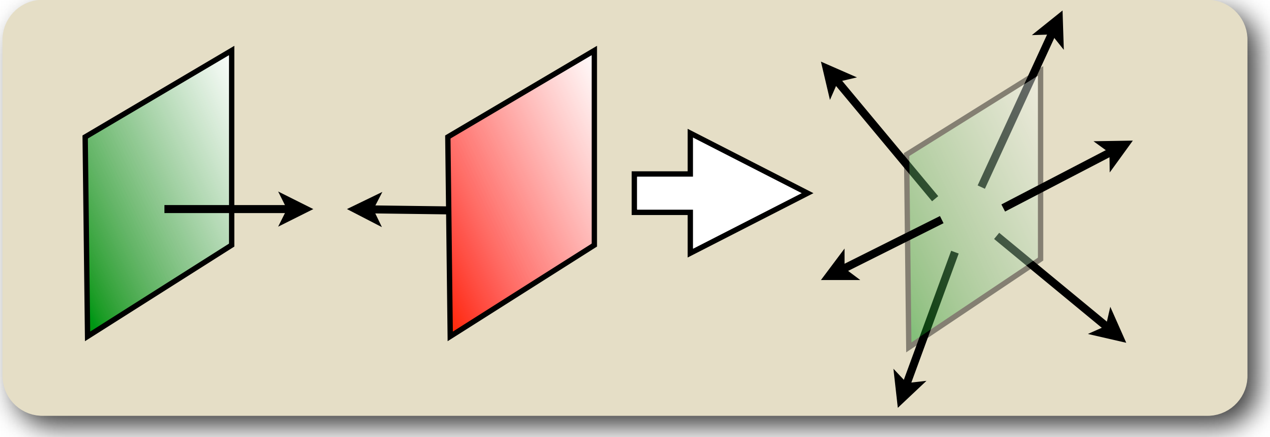
Discuss one small field model and one large field model

Brane inflation

Prototype of small field model

D3-brane at a point in CY moves slowly, attracted by anti D3-brane

At short distance, an instability develops, triggering annihilation



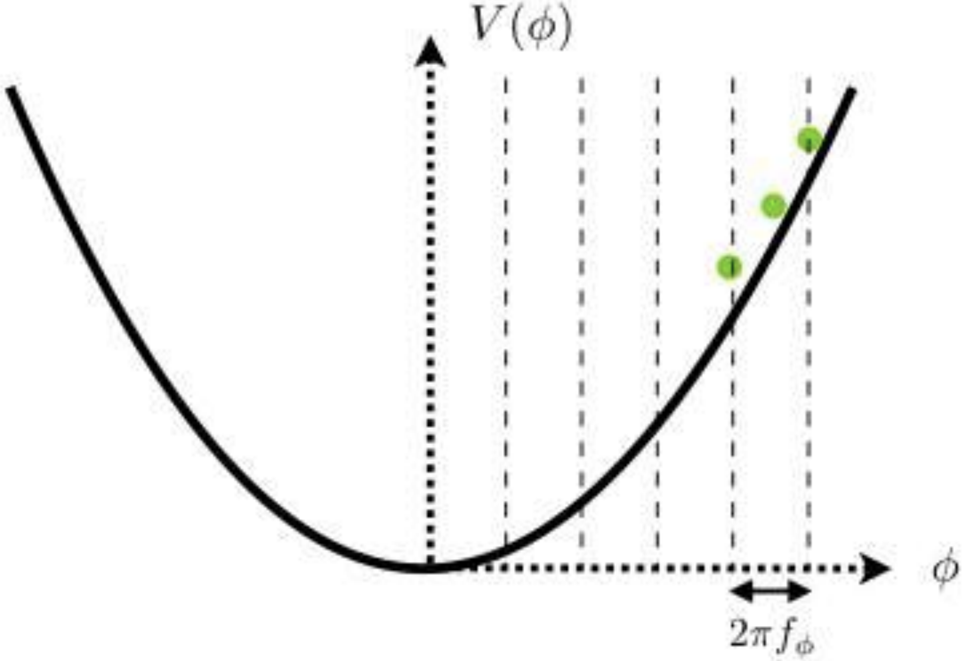
Large field models

Chaotic inflation model [Linde]

Simplest large field model is Linde's chaotic inflation $V = m\,\Phi^2$

Typically unprotected from higher order corrections

A symmetry protected version: Axion monodromy inflation



Axion periodicity is "lifted", allowing for super-Planckian range

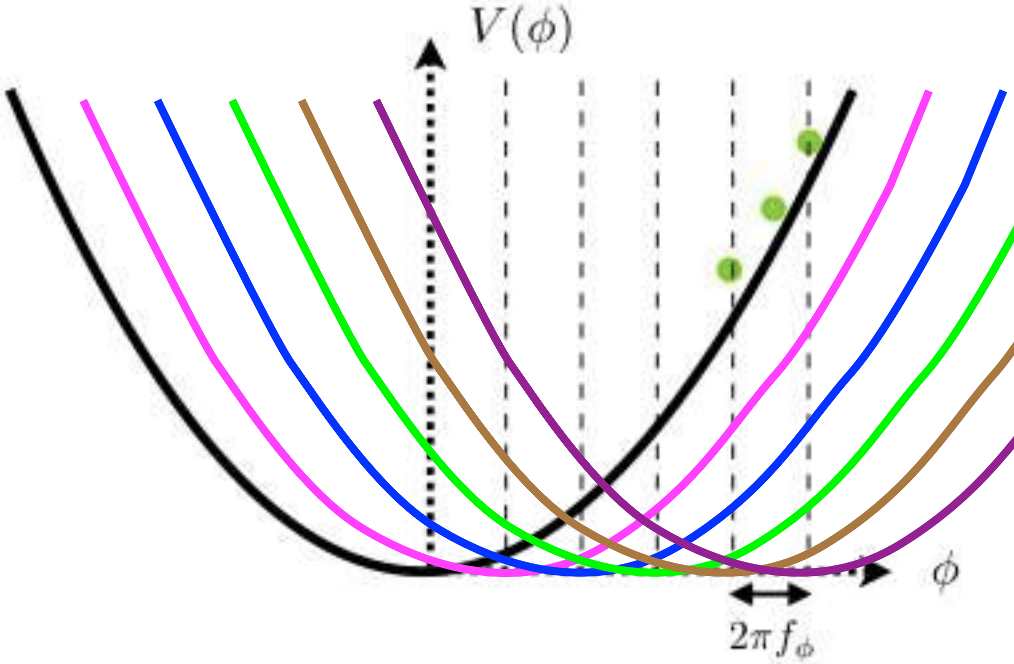
Large field models

Chaotic inflation model [Linde]

Simplest large field model is Linde's chaotic inflation $V = m\,\Phi^2$

Typically unprotected from higher order corrections

A symmetry protected version: Axion monodromy inflation



Axion periodicity is "lifted", allowing for super-Planckian range

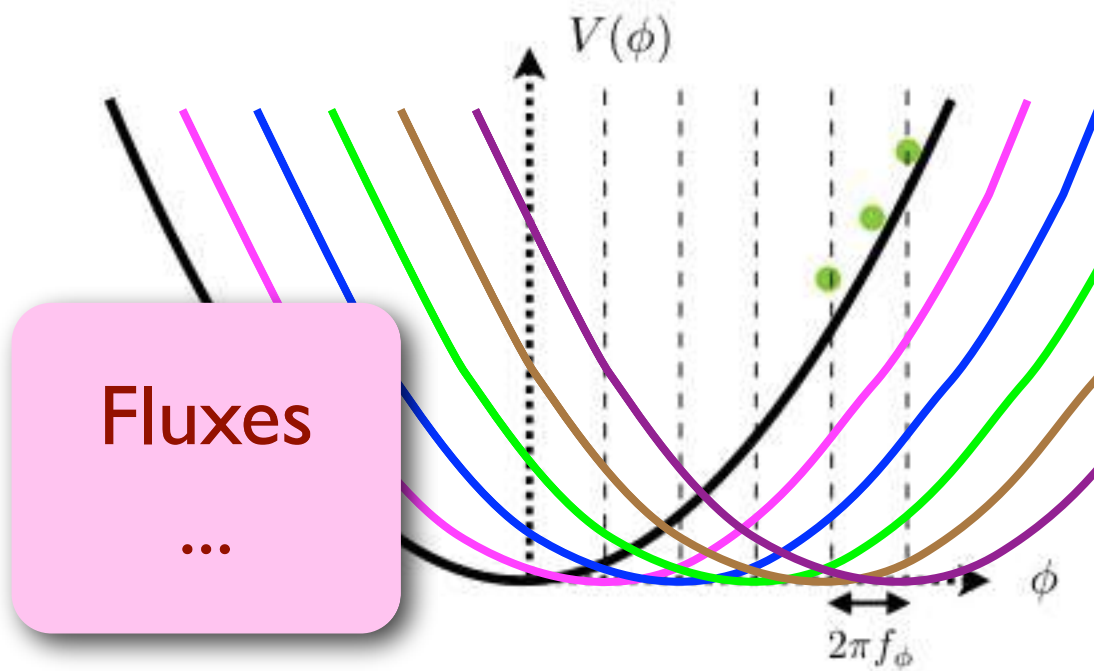
Large field models

Chaotic inflation model [Linde]

Simplest large field model is Linde's chaotic inflation $V = m\,\Phi^2$

Typically unprotected from higher order corrections

A symmetry protected version: Axion monodromy inflation



Axion periodicity is "lifted", allowing for super-Planckian range

Status of string theory

- An important piece of theoretical and mathematical physics

Status of string theory

- An important piece of theoretical and mathematical physics
- Richly connected with questions in Particle Physics & Cosmology

Status of string theory

- An important piece of theoretical and mathematical physics

- Richly connected with questions in Particle Physics & Cosmology

  BSM:

  Cosmology:

Status of string theory

- An important piece of theoretical and mathematical physics
- Richly connected with questions in Particle Physics & Cosmology

BSM: Many realistic vacua, no unique testable prediction

Each particular consistent realistic model is certainly wrong
But some general lessons may be right and key to the UV of Nature

Source of inspiration (extra dimensions, branes, warping,...)
and even of explicit models (e.g. susy breaking soft terms, Higgs, axion monodromy)

Cosmology:

Status of string theory

- An important piece of theoretical and mathematical physics

- Richly connected with questions in Particle Physics & Cosmology

BSM: Many realistic vacua, no unique testable prediction

Each particular consistent realistic model is certainly wrong
But some general lessons may be right and key to the UV of Nature

Source of inspiration (extra dimensions, branes, warping,...)
and even of explicit models (e.g. susy breaking soft terms, Higgs, axion monodromy)

Cosmology: Models and signatures of inflation

Status of string theory

- An important piece of theoretical and mathematical physics

- Richly connected with questions in Particle Physics & Cosmology

  BSM: Many realistic vacua, no unique testable prediction

  Each particular consistent realistic model is certainly wrong
  But some general lessons may be right and key to the UV of Nature

  Source of inspiration (extra dimensions, branes, warping,...)
  and even of explicit models (e.g. susy breaking soft terms, Higgs, axion monodromy)

  Cosmology: Models and signatures of inflation

- Expect to continue contributing in the LHC & post-Planck era

U,D
γ
E, ν
R
Z
g
Thank you!
W
Q
L