Towards Realistic Stringy Models of Particle Physics & Cosmology

as viewed by

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espresso

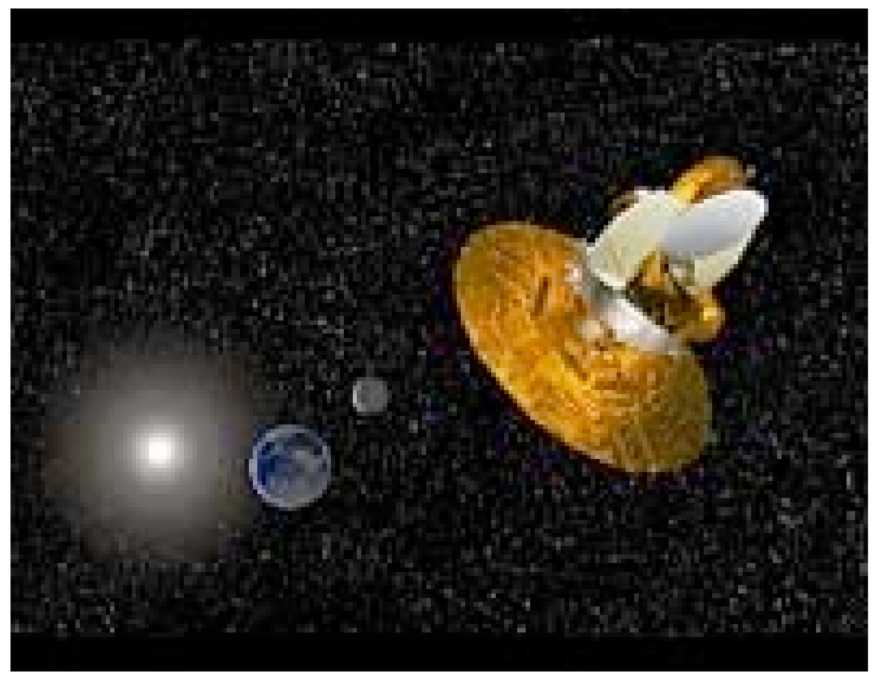

fluff


Sugar Free
Coca-Cola
light

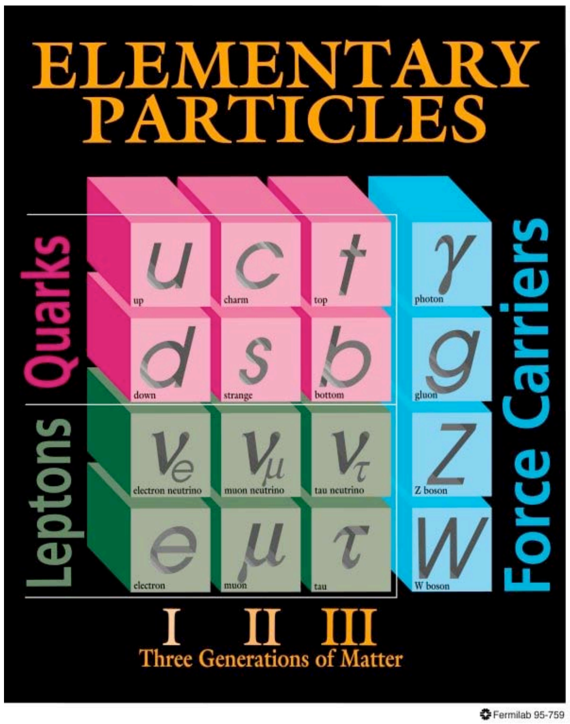
What is String Phenomenology?

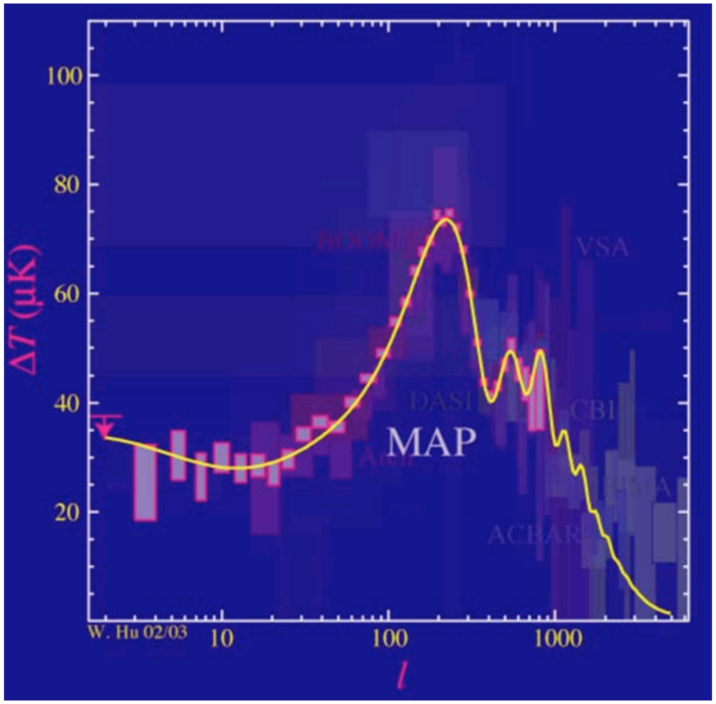
Particle Physics & Cosmology

- Deep connection, e.g., inflation, dark matter, neutrinos...
- Both study the universe in the extreme conditions.



The Standard Model(s)





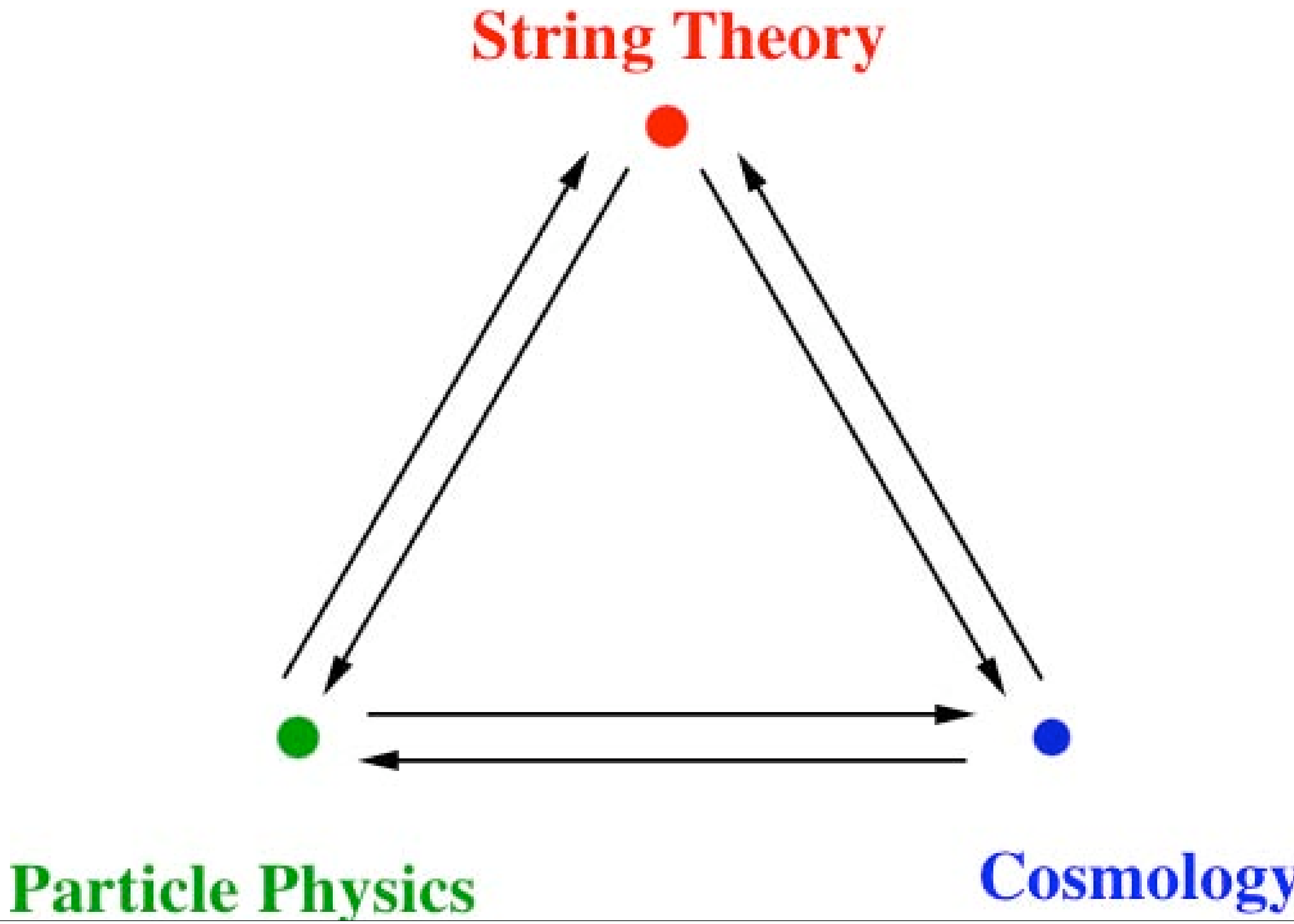
Hierarchy problem
SUSY?

.....

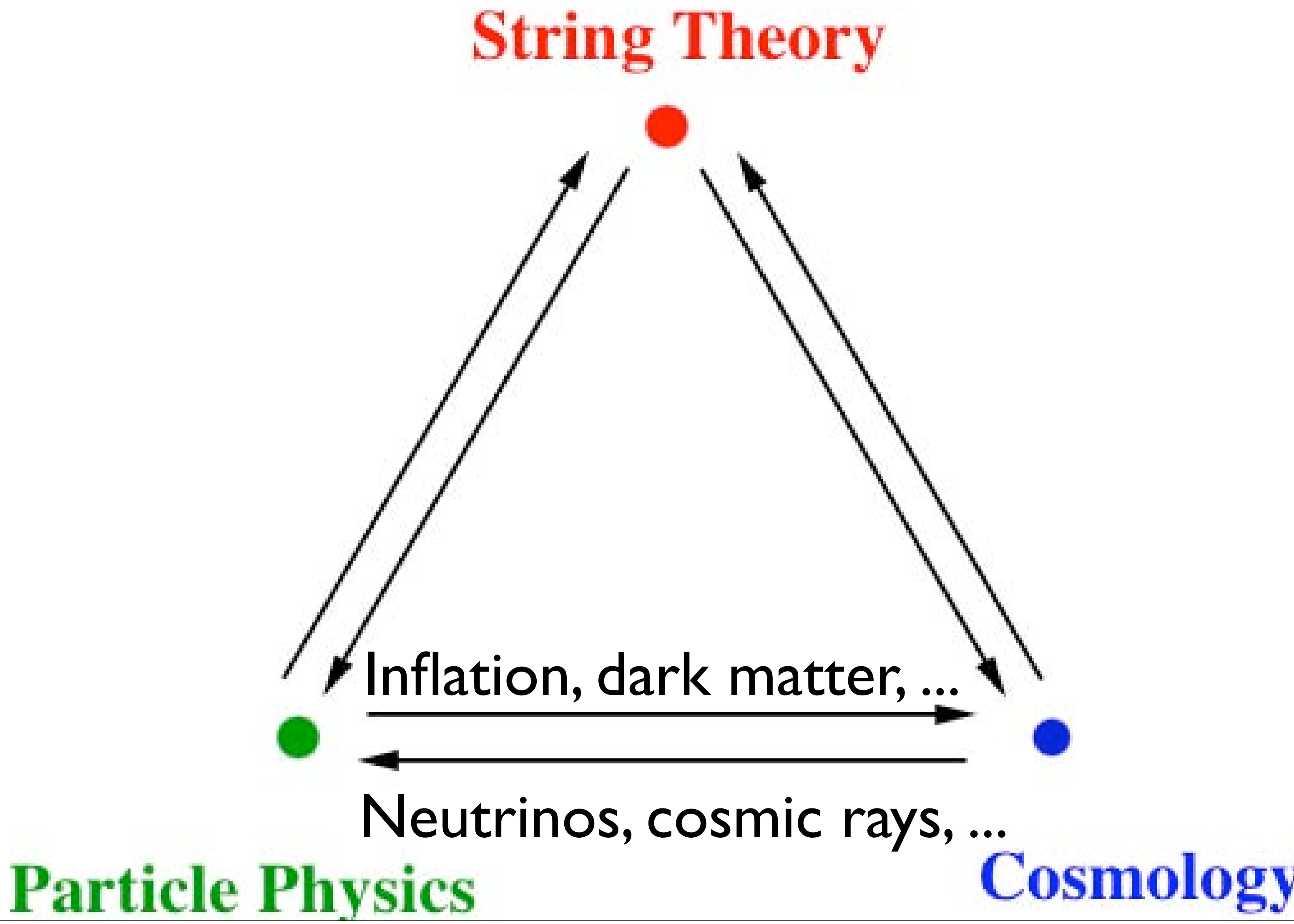
Flatness, horizon, anisotropy
Inflation? Dark Energy?

.....

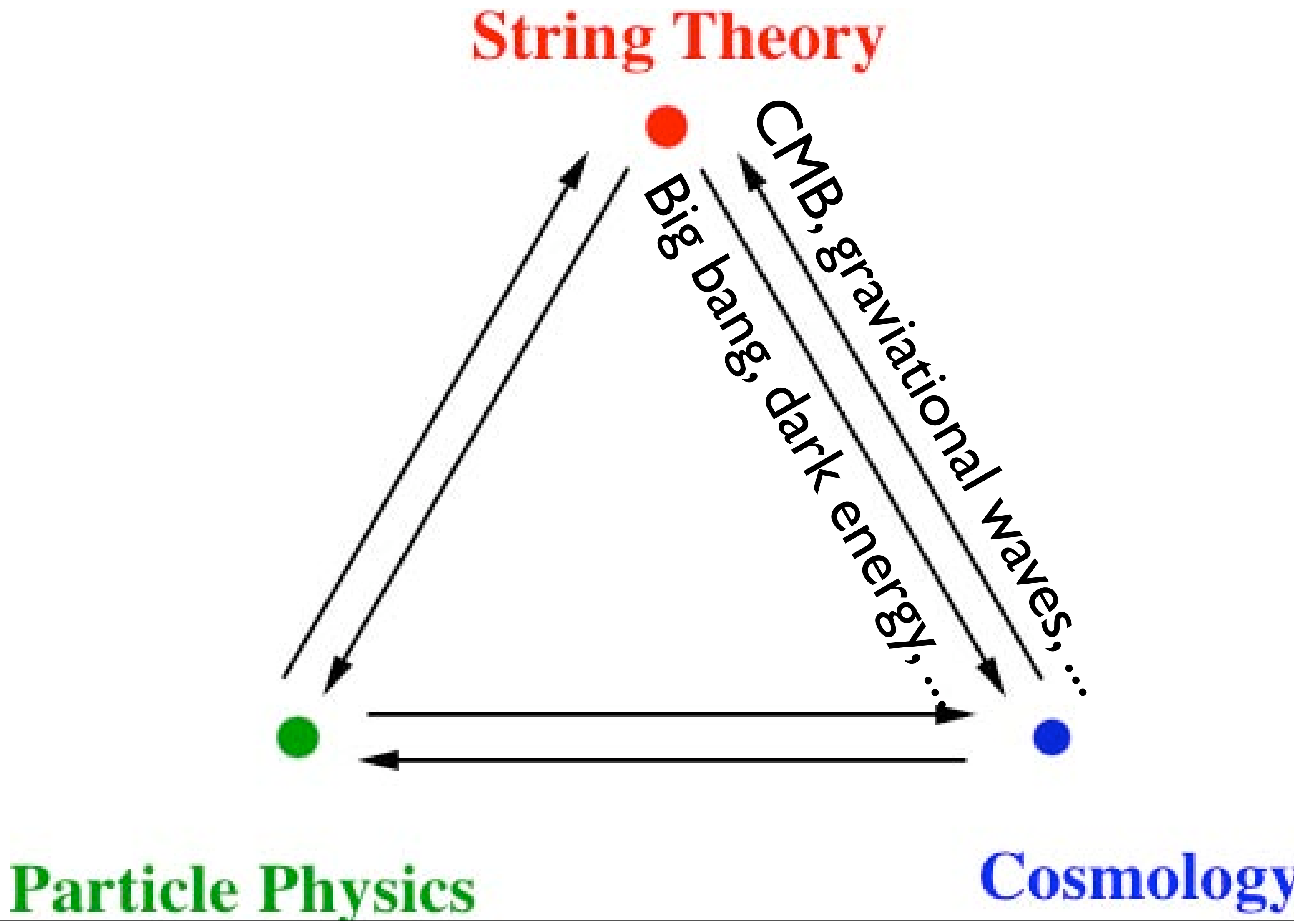
The Quiver Diagram



The Quiver Diagram



The Quiver Diagram



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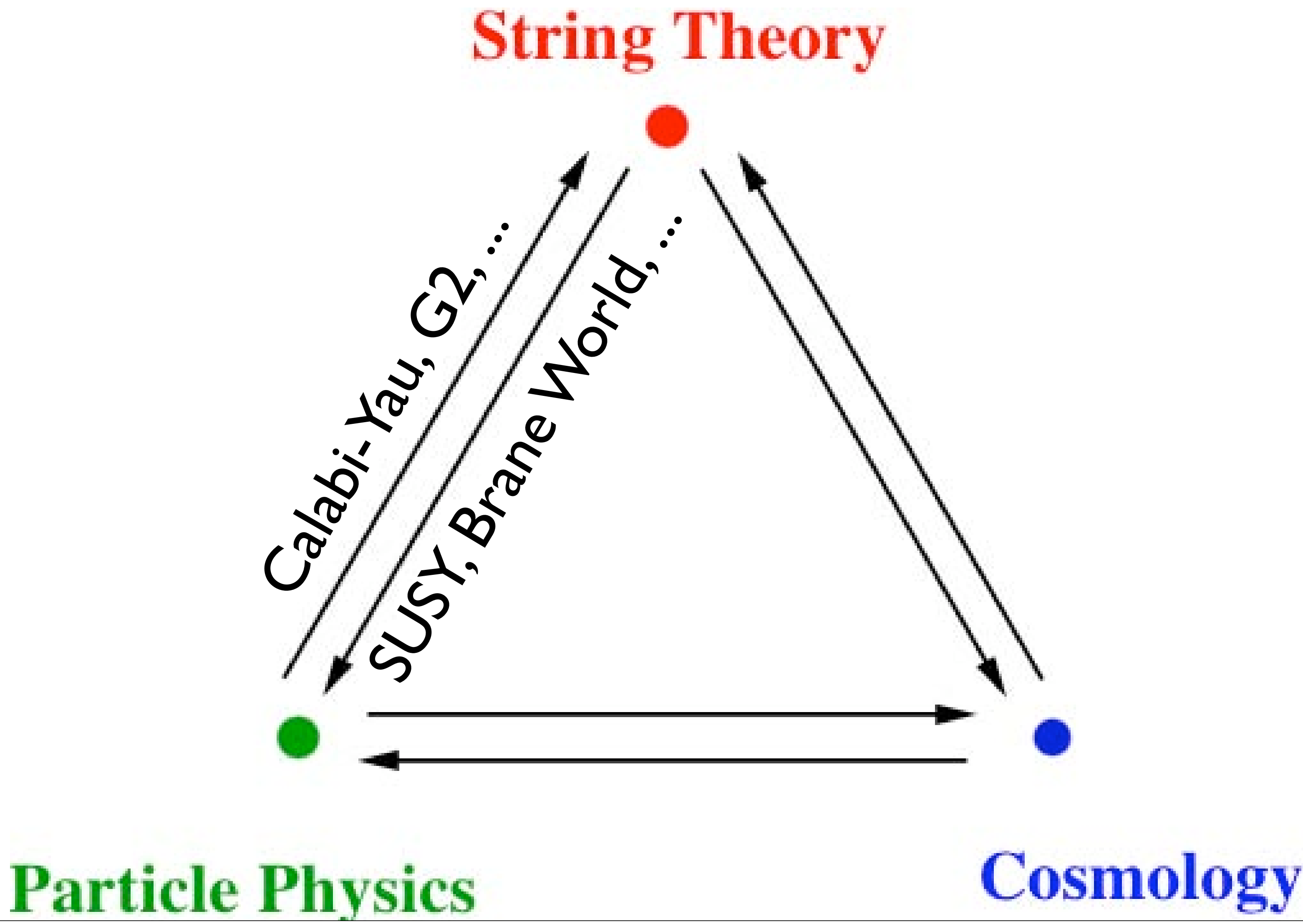
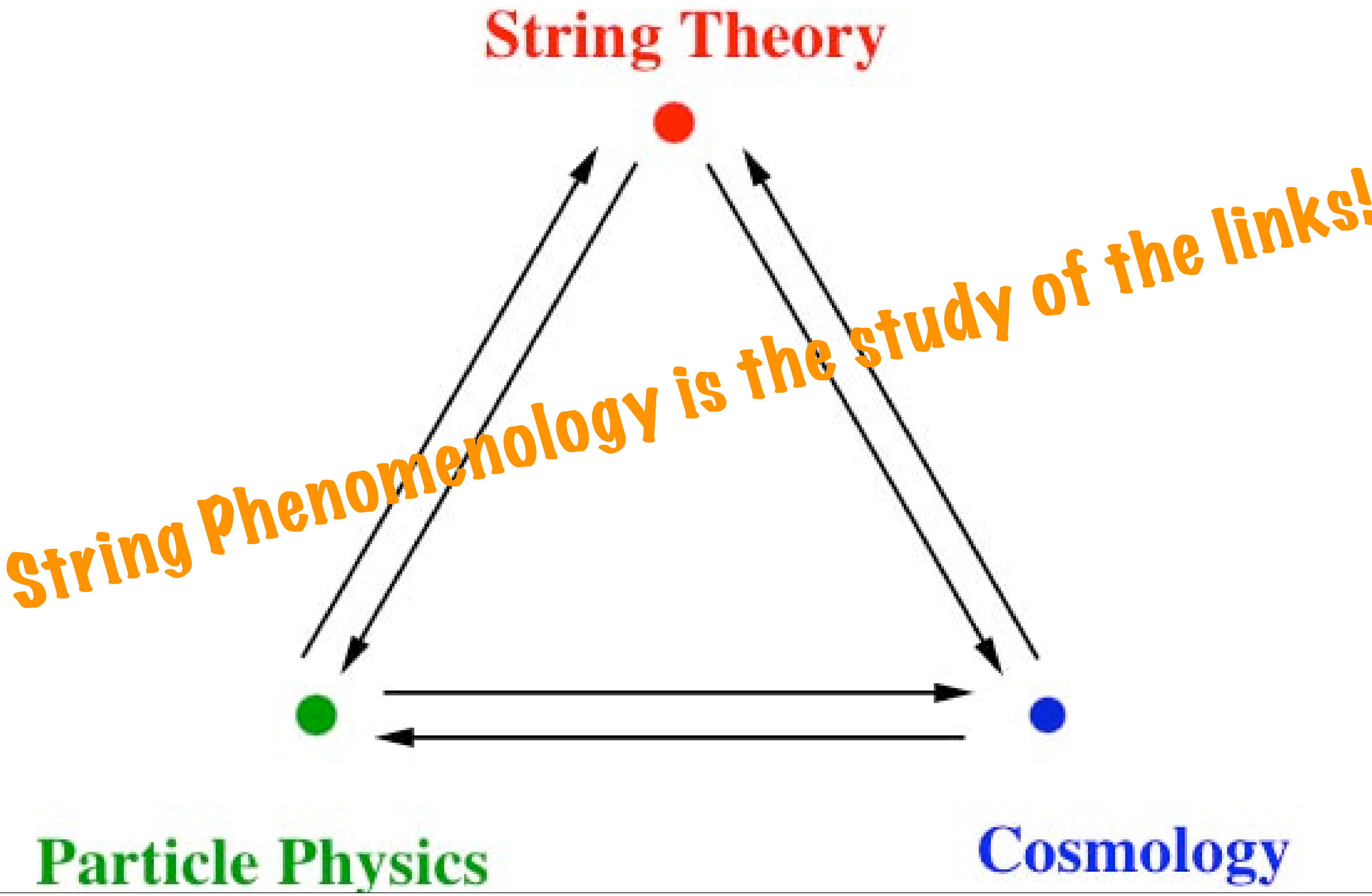
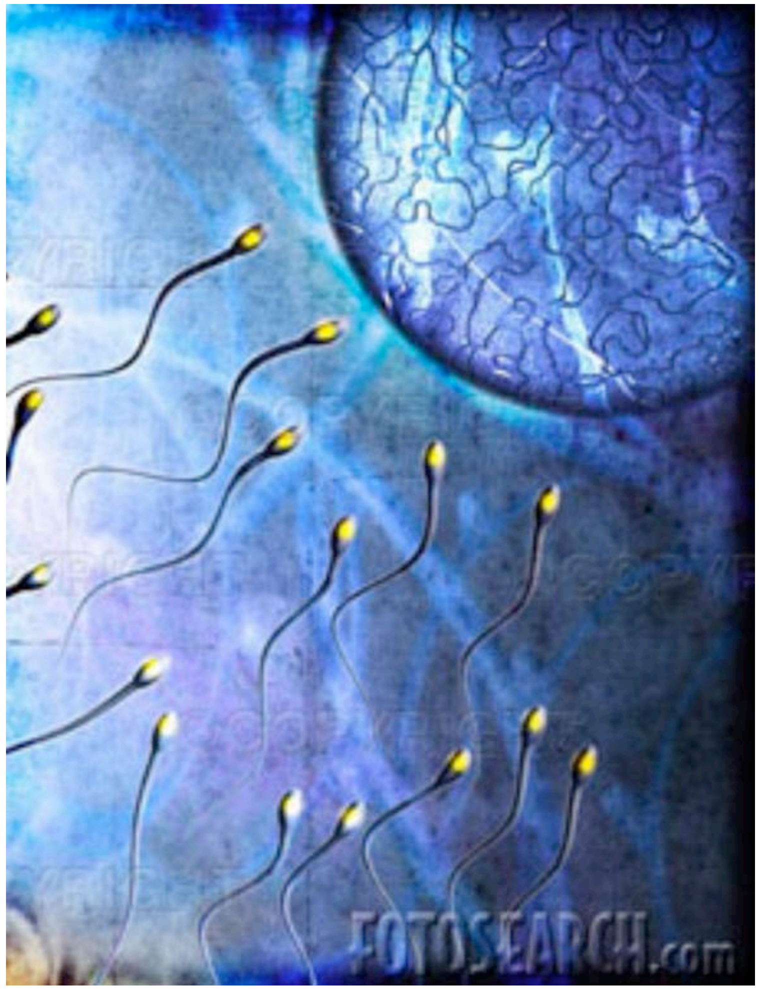


The Quiver Diagram

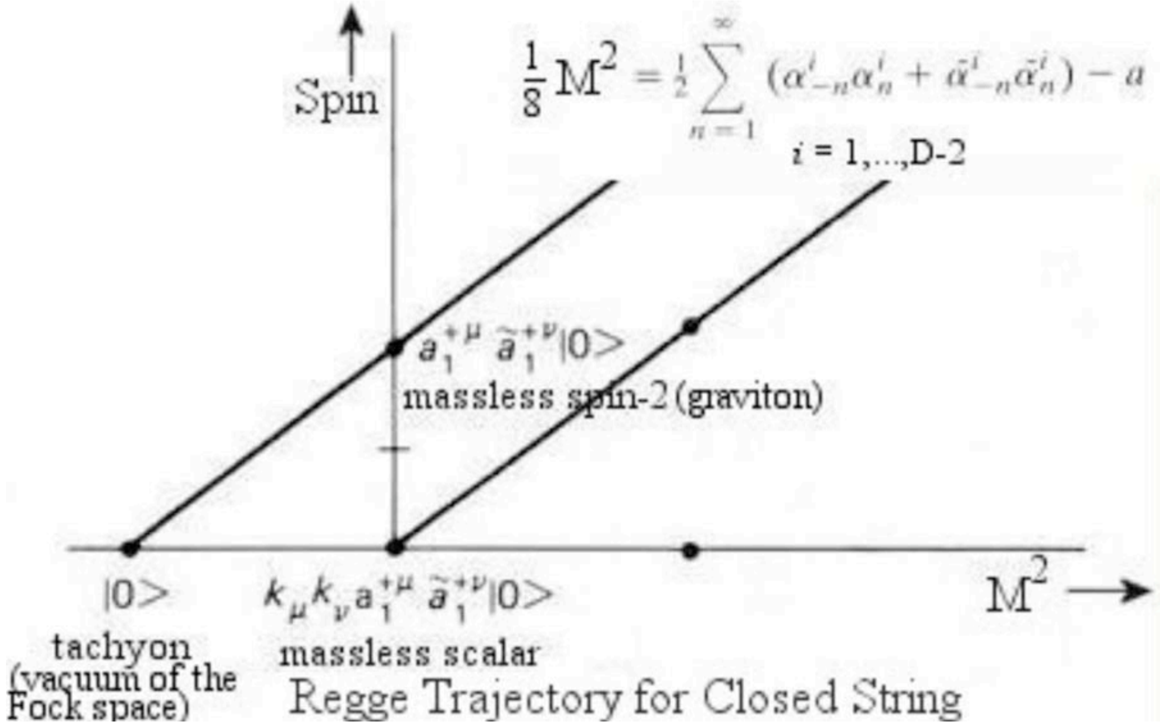


Are we ready for String Phenomenology?

The beginning of the unexpected ...



String Theory as a model of hadrons



String theory began as a phenomenological model.

Massless spin 2 particle: graviton!

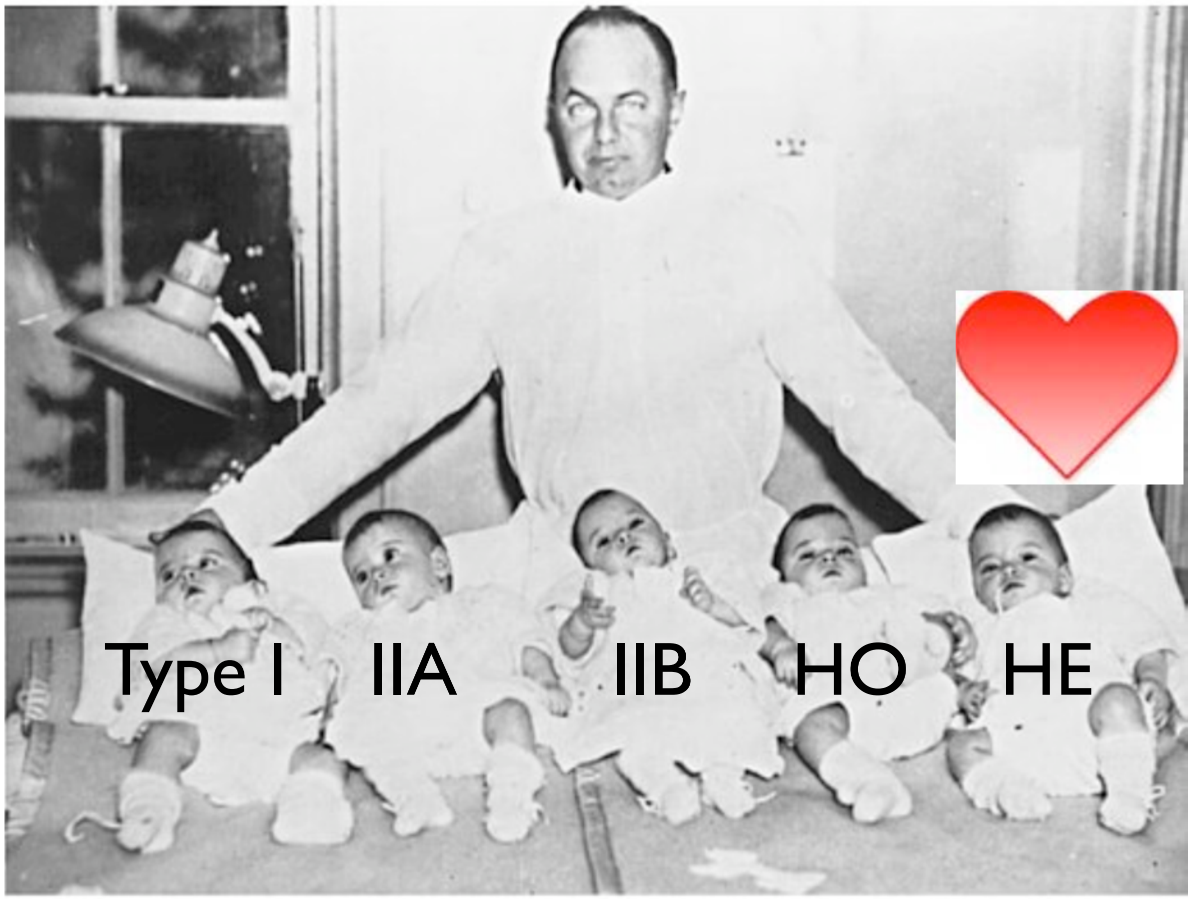
Lessons

- Ideas driven by phenomenological questions.
- Need explicit models (c.f. QFT versus the Standard Model).
- Fixing problems that plague the theory often leads to new and far-reaching ideas:

  Extra spin-2 particle ⇨ graviton

  Tachyon ⇨ SUSY
- Works better than expected.

Meet the Quintuplets



The Heterotic Supremacy

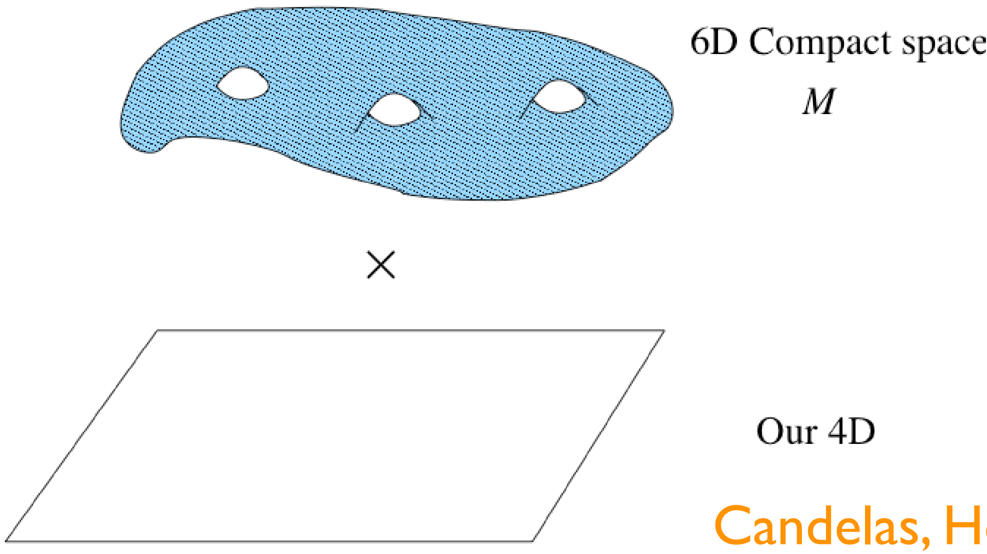
- Type IIA/IIB: Difficult to implement non-Abelian gauge groups and chiral fermions. In fact, a no-go theorem for constructing the Standard Model. [Dixon, Kaplunovsky, Vafa]

- Heterotic E8xE8: naturally contains GUTs (E6, SO(10), SU(5),...) and hidden sectors.
- Type I and Heterotic SO(32): two other siblings that are largely ignored ...

String Phenomenology Begins

1985

Calabi-Yau Compactification



N=1 SUSY

⇒ Calabi-Yau

Candelas, Horowitz, Strominger, Witten

- Low energy physics (spectrum, couplings,...) determined by topology & geometry of M.
- Building realistic heterotic string models: a huge industry beginning in the mid 80s.

The Score Card

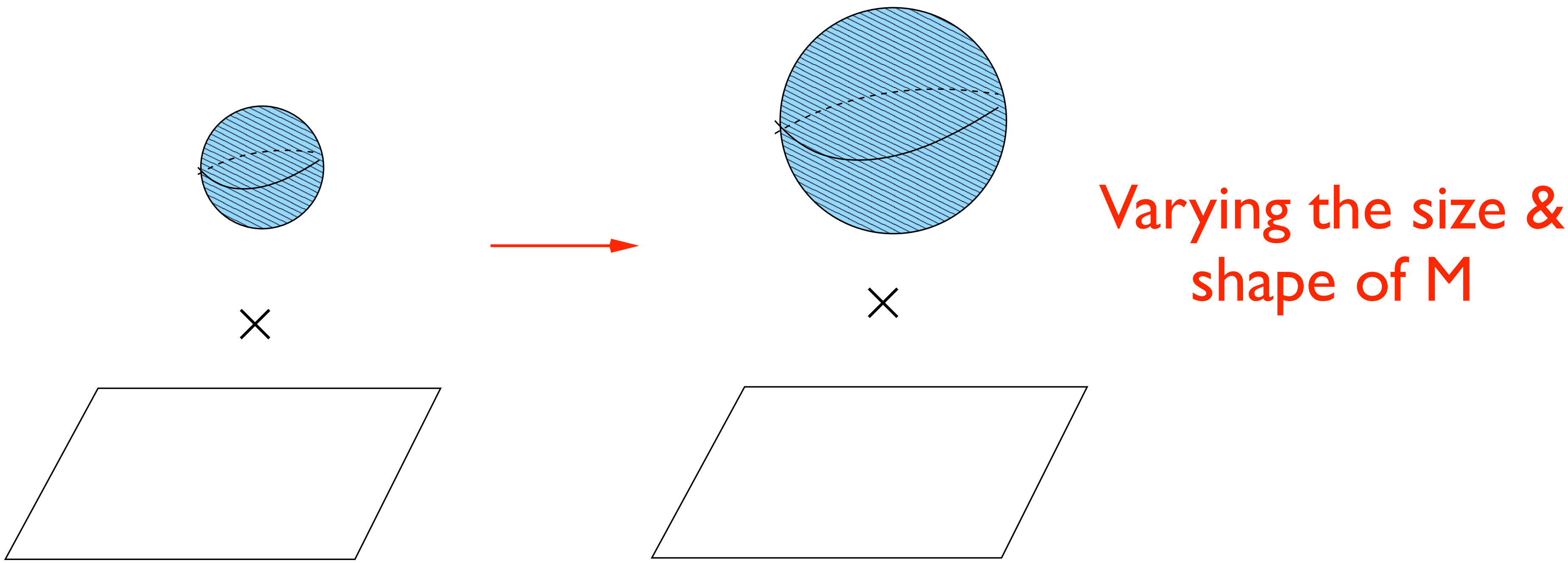
- E6, SO(10), SU(5) GUTs & MSSM-like vacua.
- Rank ≤ 22.
- Constraints on gauge groups & matter reps.
- Gauge unification.
- Exotic matter: Schellekens' theorem.

Internal consistencies + phenomenological constraints

$\Longrightarrow$ a very tight system!

However, two nagging problems ...

Moduli Problem



In 4D, this freedom implies moduli: scalar fields ϕ_i

$$V(\phi_i) = 0 \qquad \forall \phi_i$$

Moduli Problem

Loss of predictivity

- Different $< \phi_i >$ give inequivalent physics (e.g., couplings, particle masses, ...)

Phenomenological problems

- Existence of light scalars:
  - Equivalence principle violations.
  - Time varying α .
  - Energy in ϕ_i can ruin cosmology.

SUSY Breaking

- Assumptions:

  - Non-perturbative effects (e.g., gaugino and/or matter condensate) break SUSY.

  - The *same* NP effects also lift all moduli.

  - ~~SUSY~~ scale ~ TeV (hierarchy problem).

- But ...

SUSY breaking effects on SM and moduli lifting potential not computed in a *controlled* stringy way.

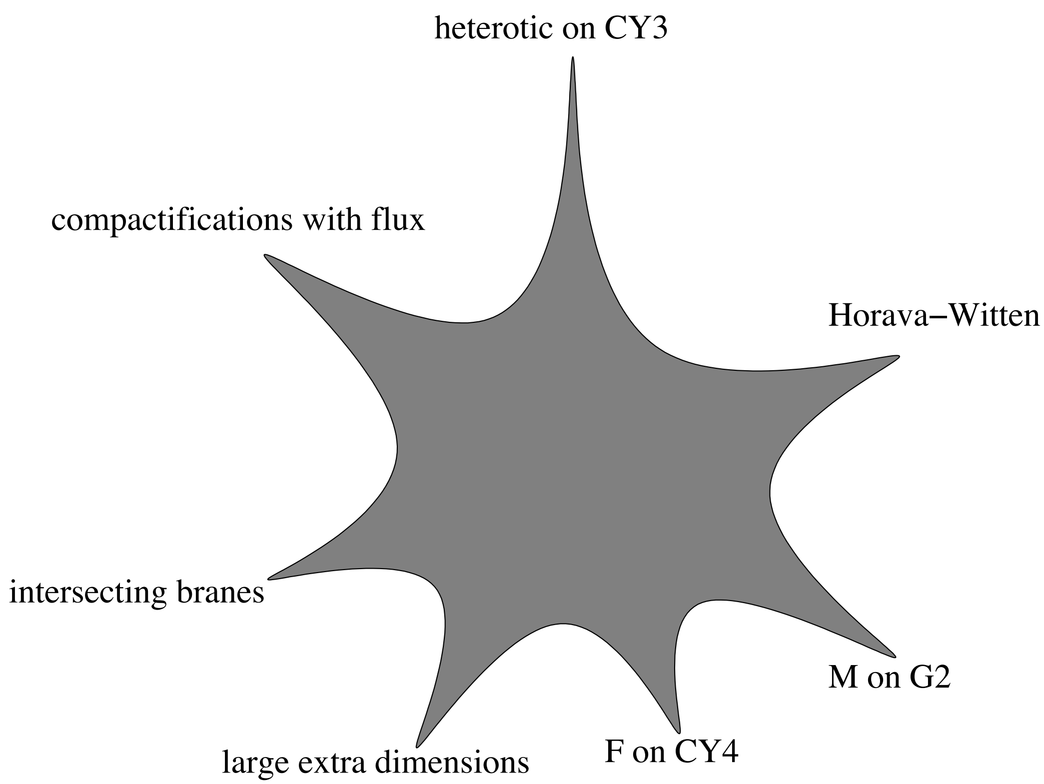
1995

"When you come to a fork in the road, take it."

Yogi Berra

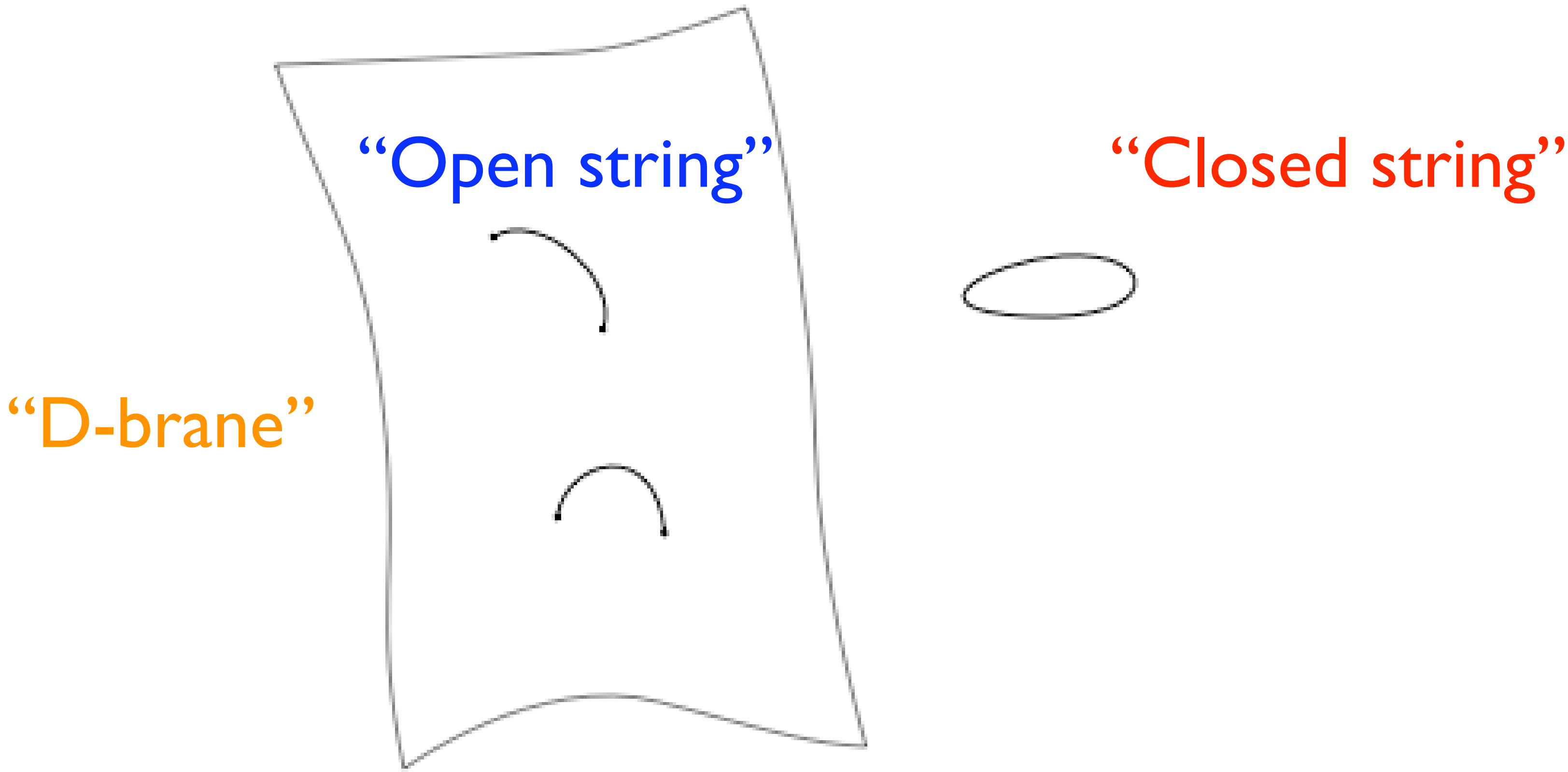
Return of the Lost Family

The Post-1995 Picture



Worth taking a fresh look at these long-standing problems.

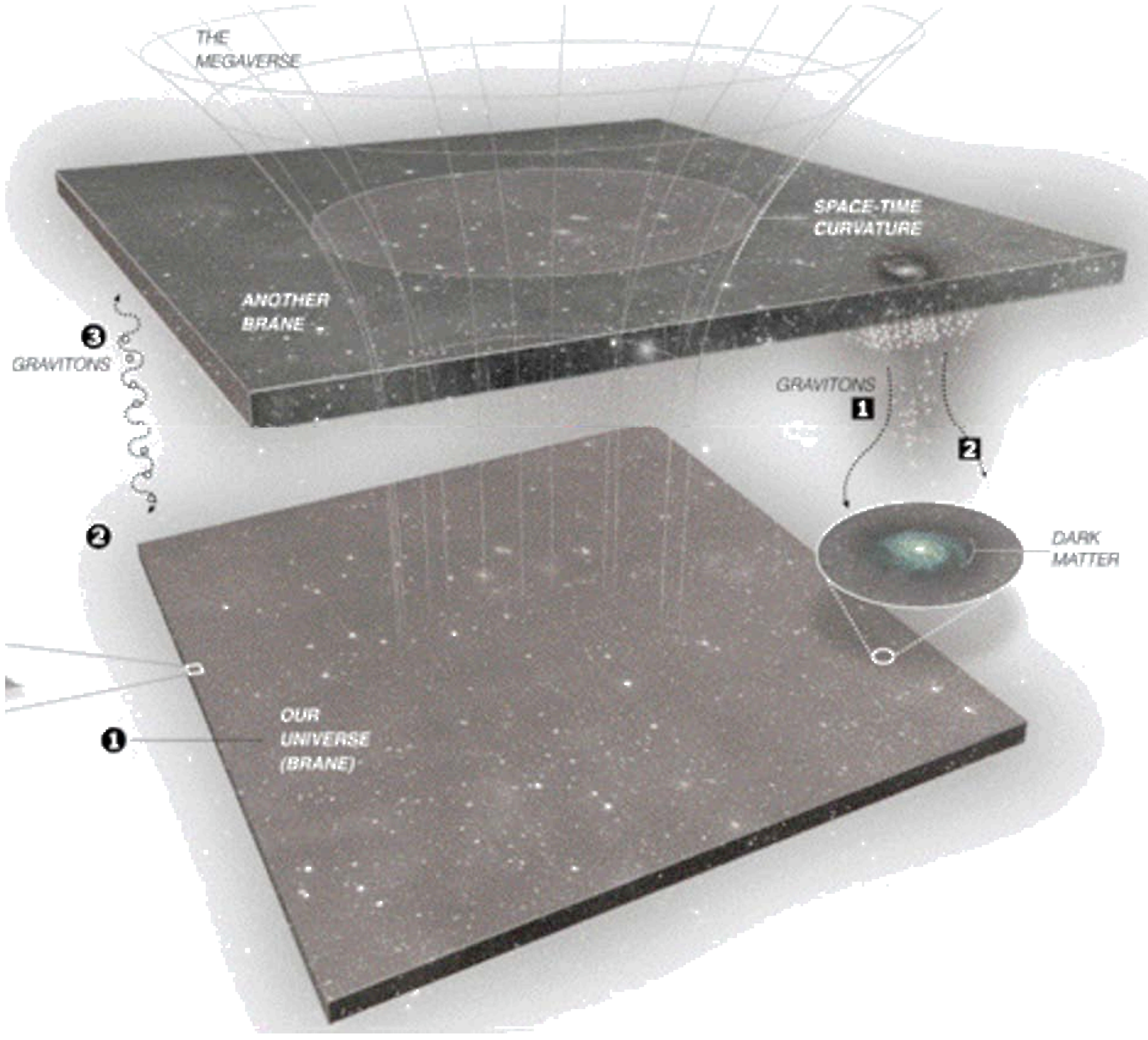
All (new) roads lead to branes



Duality between geometry and branes:

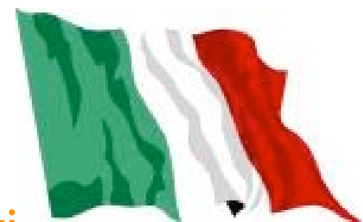
M-theory on G2, F-theory on CY4, Horava-Witten, ...

Brane World


THE
MEGAVERSE
SPACE-TIME
CURVATURE
ANOTHER
BRANE
GRAVITONS
GRAVITONS
DARK
MATTER
OUR
UNIVERSE
(BRANE)

Open Strings

- Pioneering work (before 1995)



Bianchi, Pradisi, Sagnotti, ...
Polchinski
....

- Recent review articles

Formalism: Angelantonj, Sagnotti

Model Building: Blumenhagen, Cvetic, Langacker, Shiu

Flux Compactification

- Just like particle couples to gauge field via

$$\int_{\text{worldline}} A$$

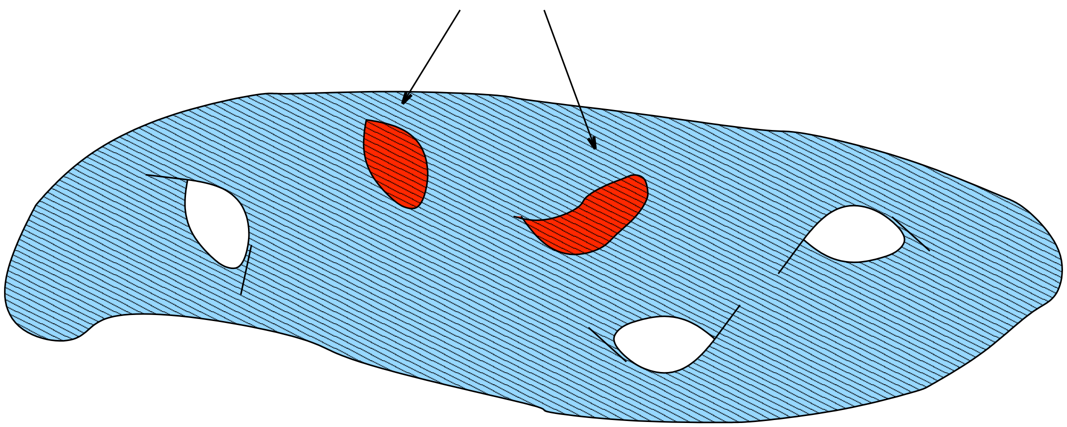
- Dp-brane couples to p+1 index gauge fields:

$$\int_{\text{worldvolume}} A_{p+1}$$

- Thus p+2-form field strengths:

$$F_{p+2} = dA_{p+1}$$

Flux Compactification



- For each p-cycle in M, we can turn on

$$\int_{\Sigma_p} F_p \in Z$$

Dirac Quantization

- Analogous to turning on a B-field

$$\text{Energy} \sim \frac{1}{8\pi} \int (E^2 + B^2)$$

Moduli Stabilization

- The energy cost of a given flux depends on detailed geometry of M:

$$V_{n_1,n_2,\ldots,n_k}(\phi_i)$$

where $$n_j = \int_{\Sigma_j} F \,, \qquad j = 1, \ldots, k.$$

- Lift moduli ϕ_i !

Type IIB Flux Vacua

- Superpotential induced by $G_3 = F_3 - \tau H_3$

$$W = \int_{\mathcal{M}} G \wedge \Omega$$

Gukov, Vafa, Witten

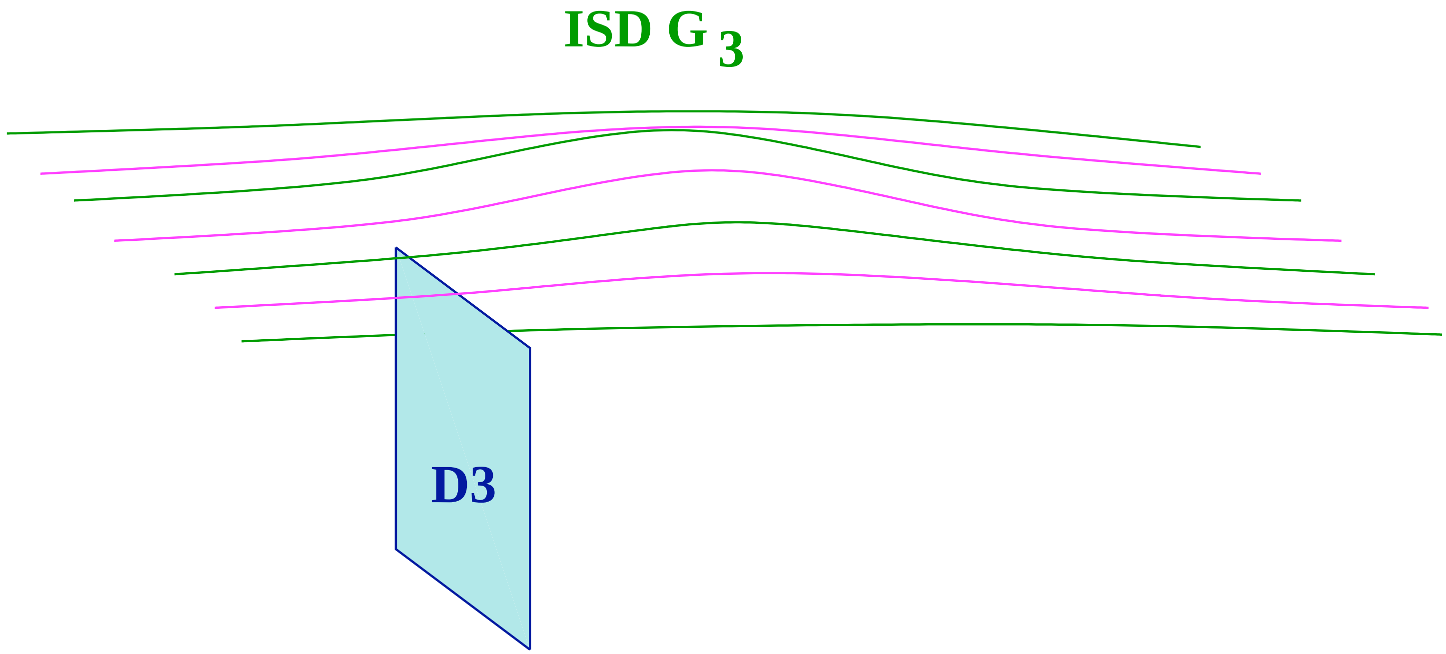
- Stabilizes the dilaton and complex structure moduli (shape) of M.

Dasgupta, Rajesh, Sethi
Greene, Schalm, Shiu
Taylor, Vafa
Giddings, Kachru, Polchinski
...

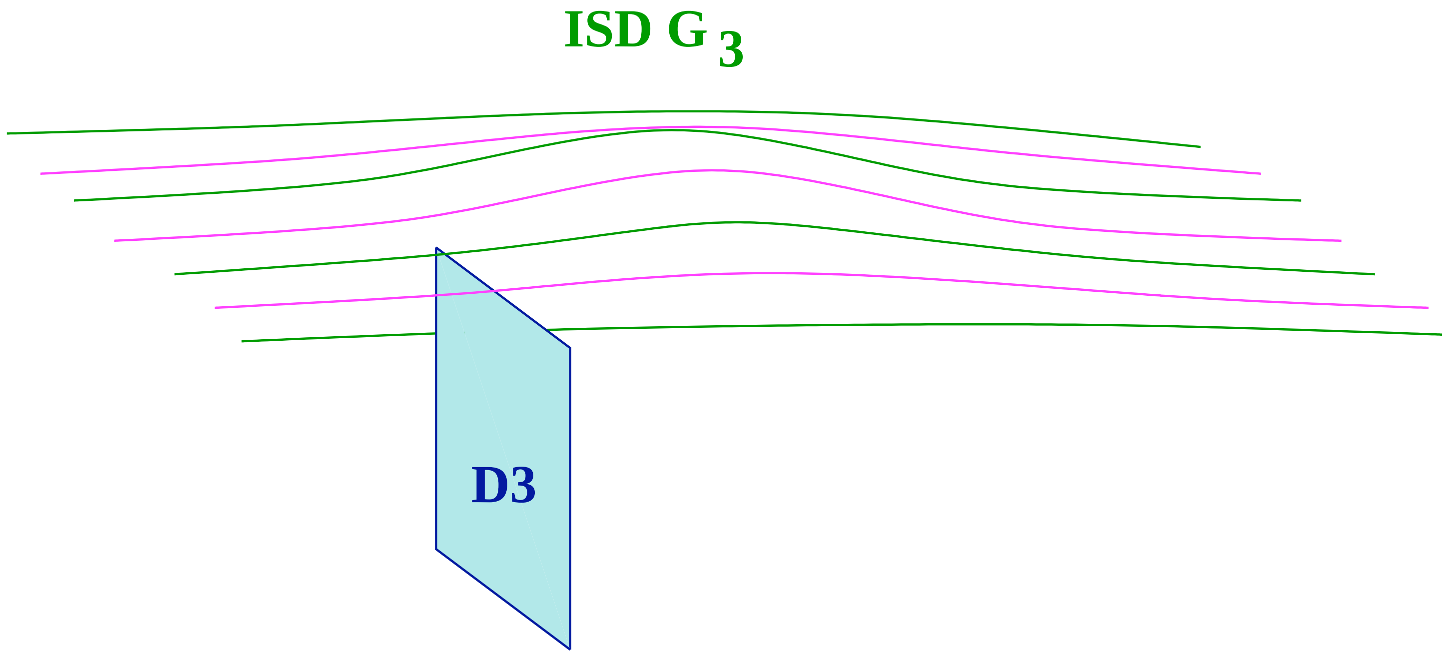
- Additional mechanism stabilizes the Kahler moduli (size).

Kachru, Kallosh, Linde, Trivedi
...

Flux Induced ~~SUSY~~

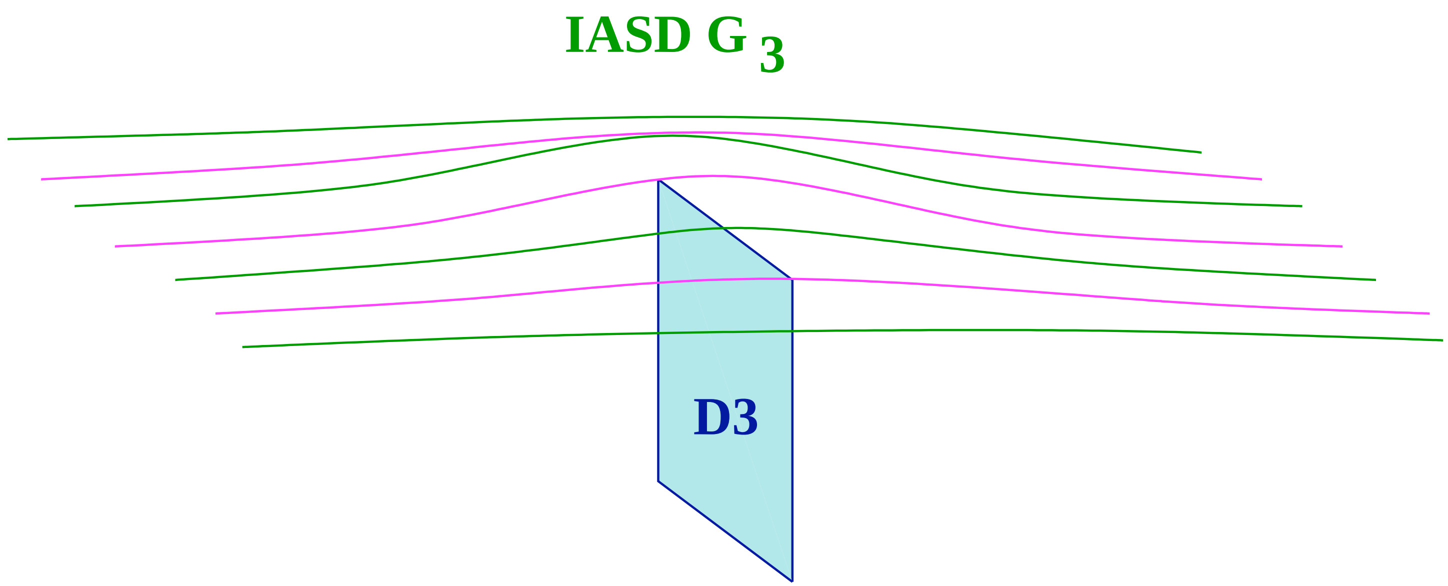


Flux Induced ~~SUSY~~

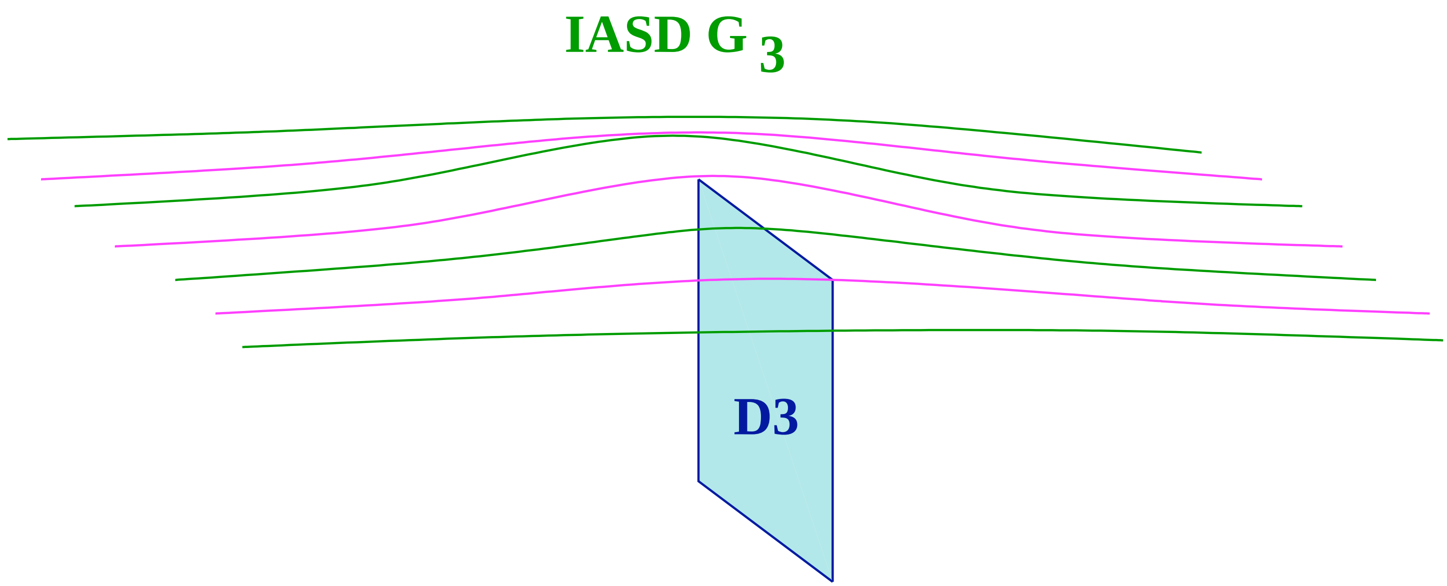


No soft terms

Flux Induced ~~SUSY~~



Flux Induced ~~SUSY~~



Non-trivial soft terms

Explicit calculations.

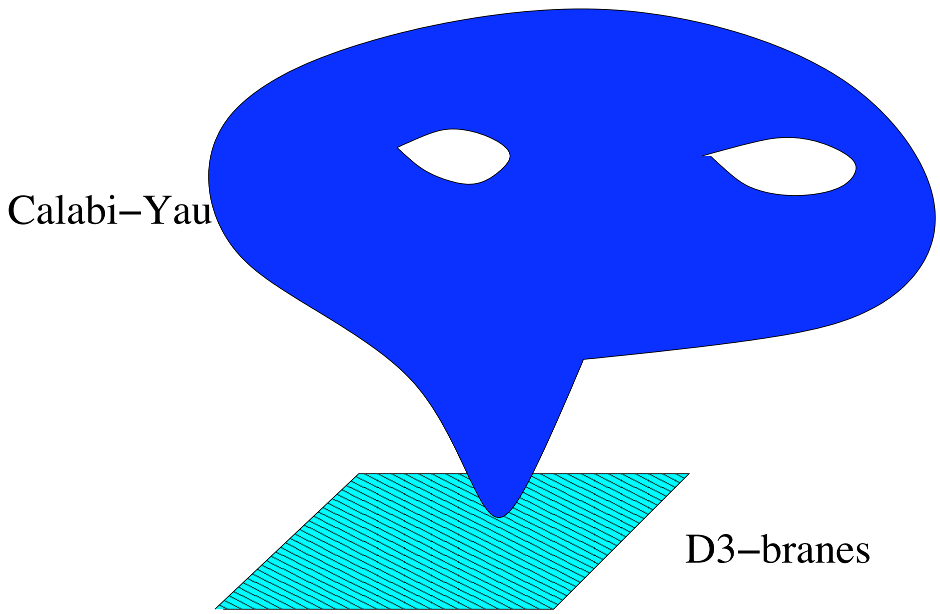
Lust, Reffert, Stieberger
Camara, Ibanez, Uranga
Grana, Grimm, Jockers, Louis

Can the Standard Model fit into this picture?

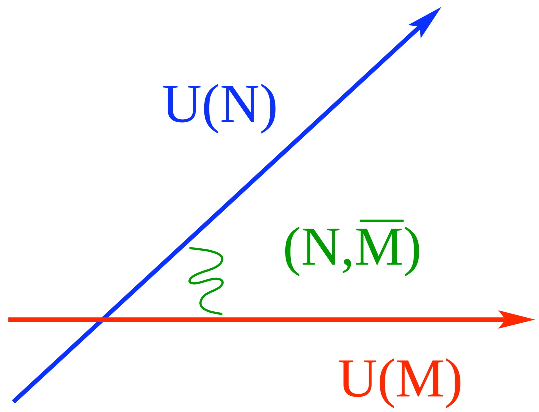
Chiral D-brane Models

Two known ways to obtain chiral fermions:

- Branes at singularities



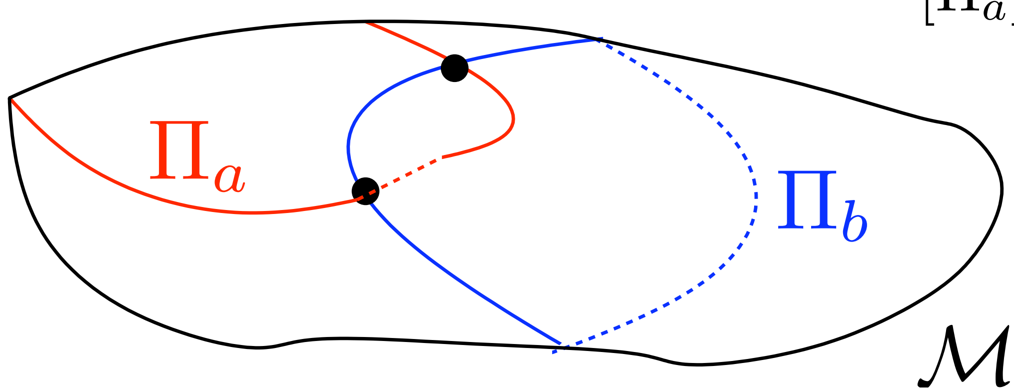
- Intersecting branes



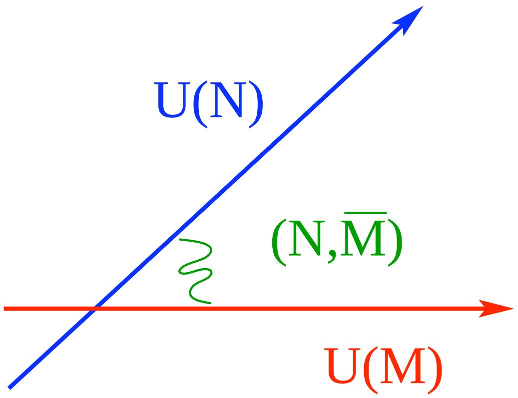
Type IIA

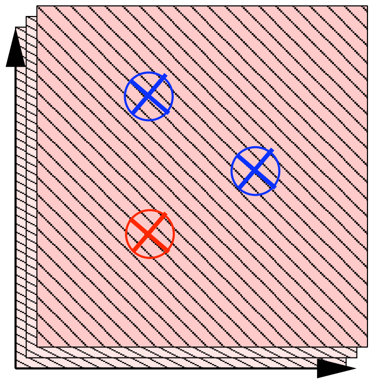
Number of generations given by:

$$[\Pi_a] \circ [\Pi_b] = \text{topological}$$



- Intersecting branes/magnetized D-branes





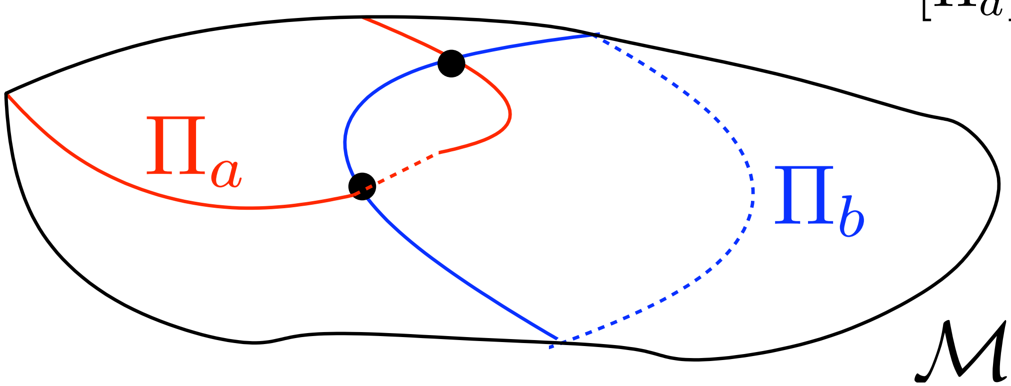
“Toron”

Type IIA

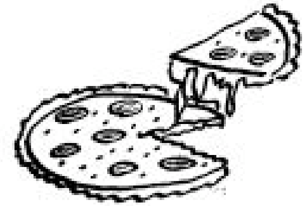
Type IIB

Number of generations given by:

$$[\Pi_a] \circ [\Pi_b] = \text{topological}$$



The Recipe



- Pick your $\mathcal{M}$, and the associated sLAG Π_a
- Chiral spectrum:

Representation	Multiplicity
$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}_a$	$\frac{1}{2}\left(\pi'_a \circ \pi_a + \pi_{O6} \circ \pi_a\right)$
$\Box\Box_a$	$\frac{1}{2}\left(\pi'_a \circ \pi_a - \pi_{O6} \circ \pi_a\right)$
$(\overline{\Box}_a, \Box_b)$	$\pi_a \circ \pi_b$
$(\Box_a, \Box_b)$	$\pi'_a \circ \pi_b$

- Tadpole cancellation (Gauss's law):

$$\sum_a N_a \left(\Pi_a + \Pi'_a\right) - 4\Pi_O = 0$$

- K-theory constraints

K-theory Constraints

- D-brane charges are classified by K-theory.
  Minasian & Moore
  Witten
- Discrete charges invisible in SUGRA, forbid certain non-BPS branes to decay. Sen
- Uncanceled K-theory charges can manifest as Witten anomalies on D-brane probes.
  Uranga
- Implications to the statistics of string vacua.
  Blumenhagen et al
  Schellekens et al
- Direct construction of such discrete charged branes. Maiden, Shiu, Stefanski

Toward Realistic D-brane Models

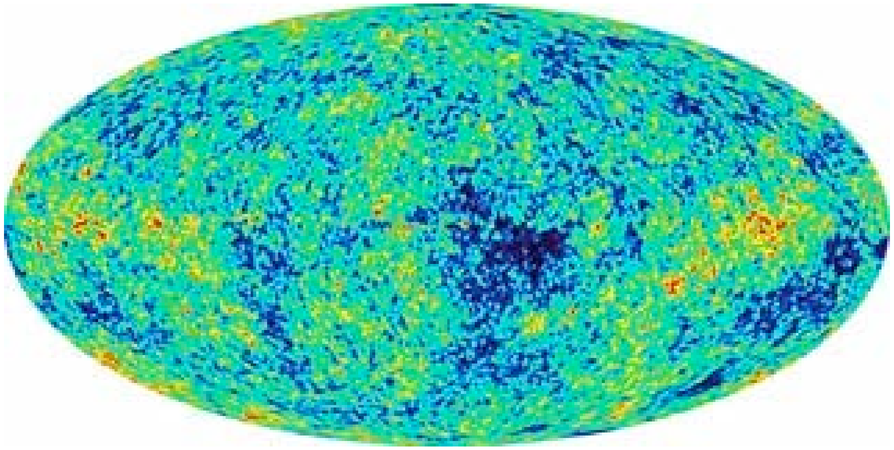
For a review, see, e.g., Blumenhagen, Cvetic, Langacker, Shiu, hep-th/0502005.

- Many toroidal orbifold/orientifold models.
- MSSM flux vacua. Marchesano, Shiu
- D-branes in general Calabi-Yau (less is known about supersymmetric Π_a).
- Gepner orientifolds

Angelantonj, Bianchi, Pradisi, Sagnotti, Stanev
Dijkstra, Huiszoon, Schellekens
Blumenhagen, Weigard

How about Cosmology?

Inflation as a probe of stringy physics



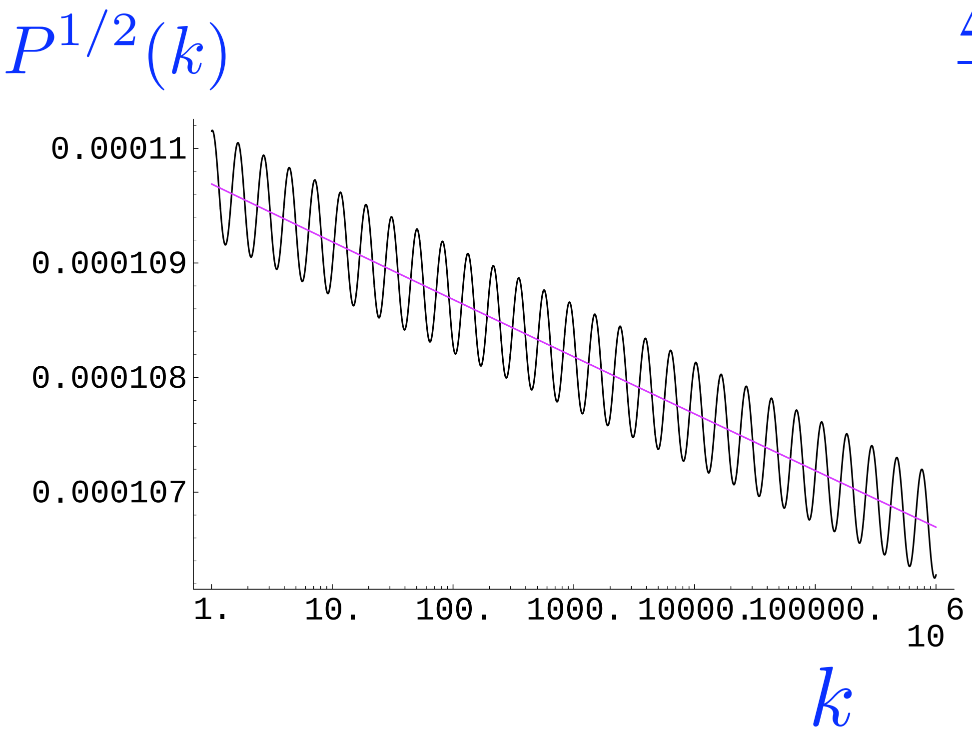
WMAP

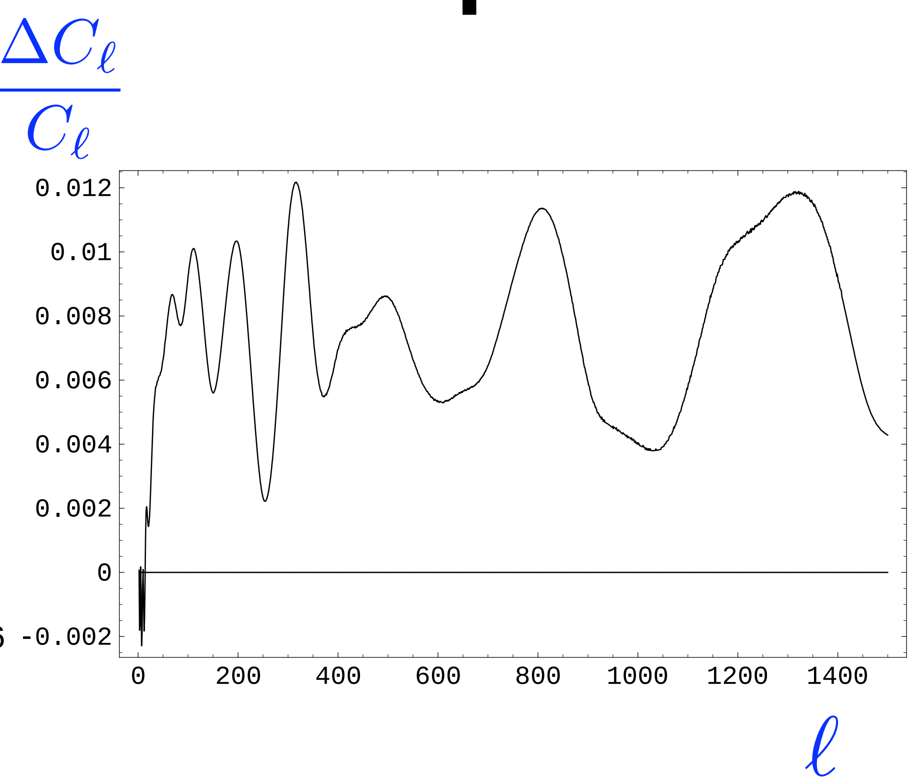
- Almost scale invariant, Gaussian primordial spectrum predicted by inflation is in good agreement with data.

- A tantalizing upper bound on the energy density during inflation:

$$V \sim M_{GUT}^4 \sim (10^{16}\text{GeV})^4 \quad \text{i.e.,} \quad H \sim 10^{14}\text{GeV}$$

Planckian Microscope?

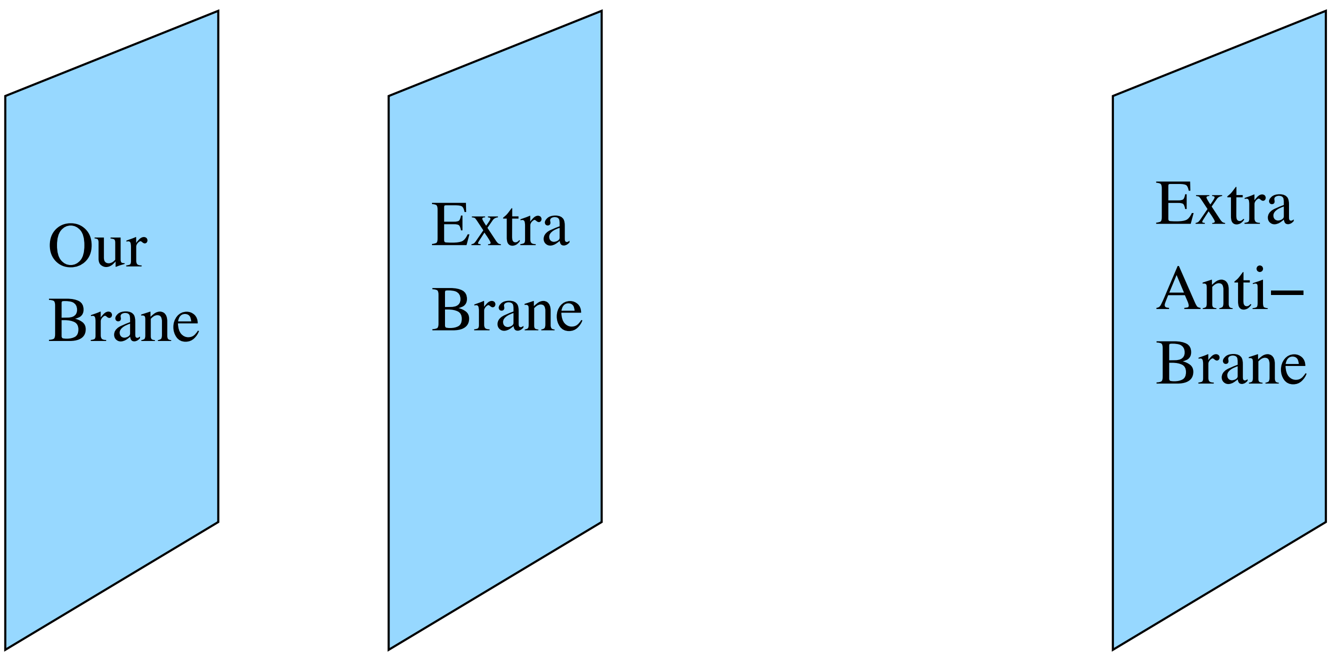




Easther, Greene, Kinney, Shiu
Schalm, Shiu, van der Schaar

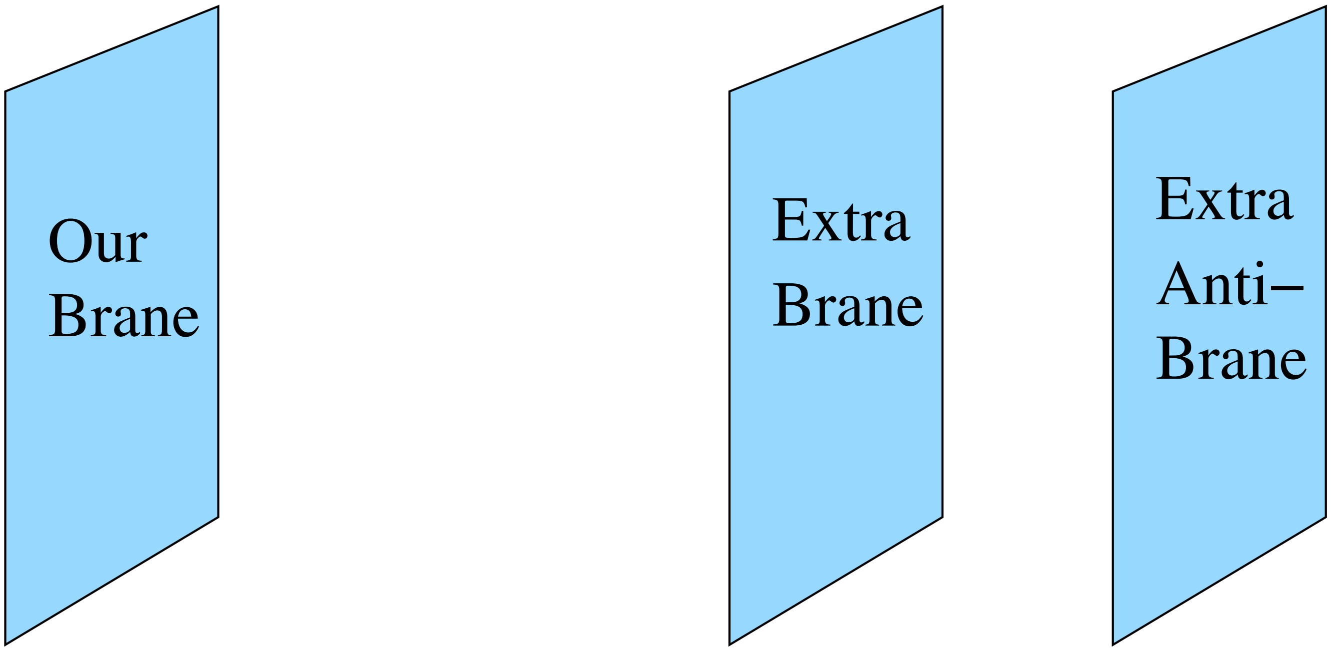
Brane Inflation

Dvali and Tye



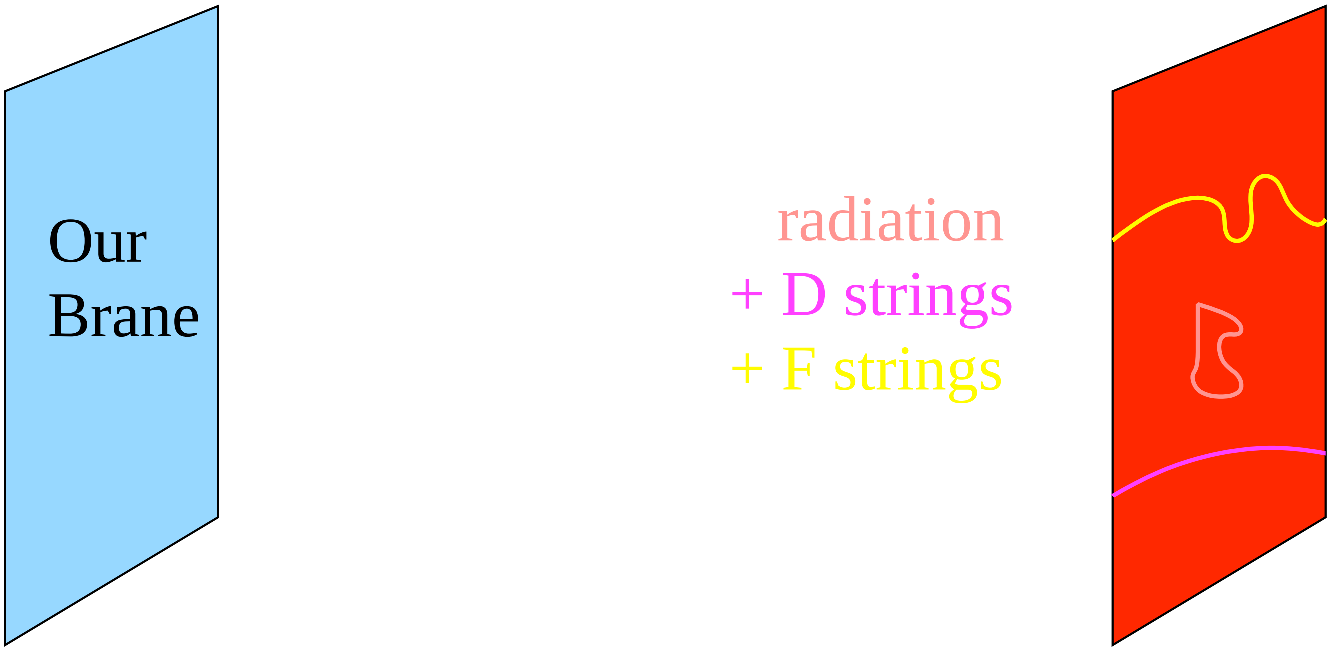
Brane Inflation

Dvali and Tye



Brane Inflation

Stringy signatures, e.g., gravitational waves ...

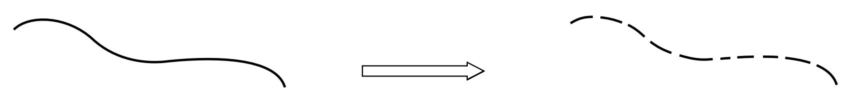


Tye et al
Copeland, Myers, Polchinski
...

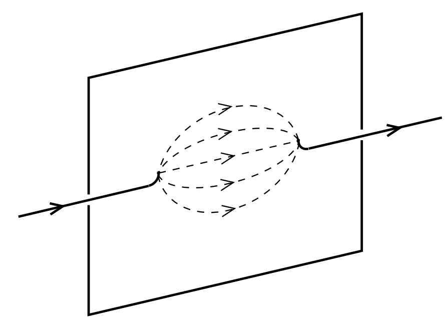
Brane Inflation

- Are the branes moving slowly enough?

- Is reheating efficient?



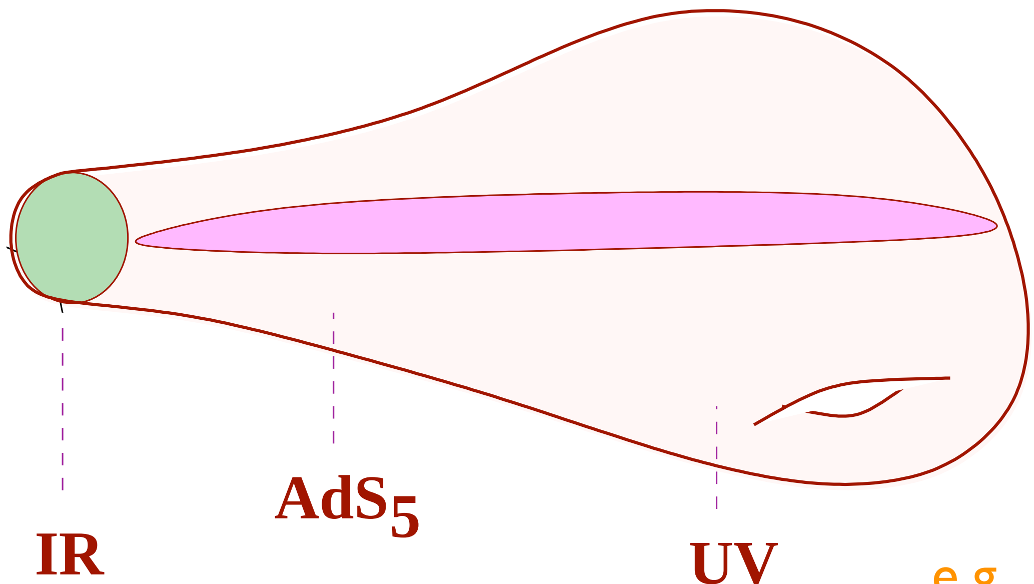
- Can the cosmic strings be stable?



Warping by Fluxes

Warped Throats

- Fluxes back-react on the metric:

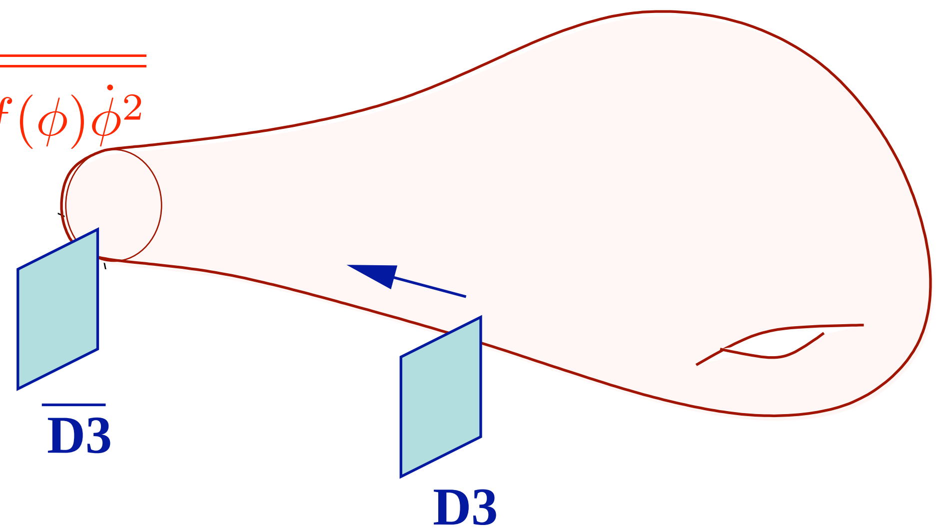


e.g., Klebanov, Strassler

"warped deformed conifold"

Warped Throats

$$\gamma = \frac{1}{\sqrt{1 - f(\phi)\dot{\phi}^2}}$$

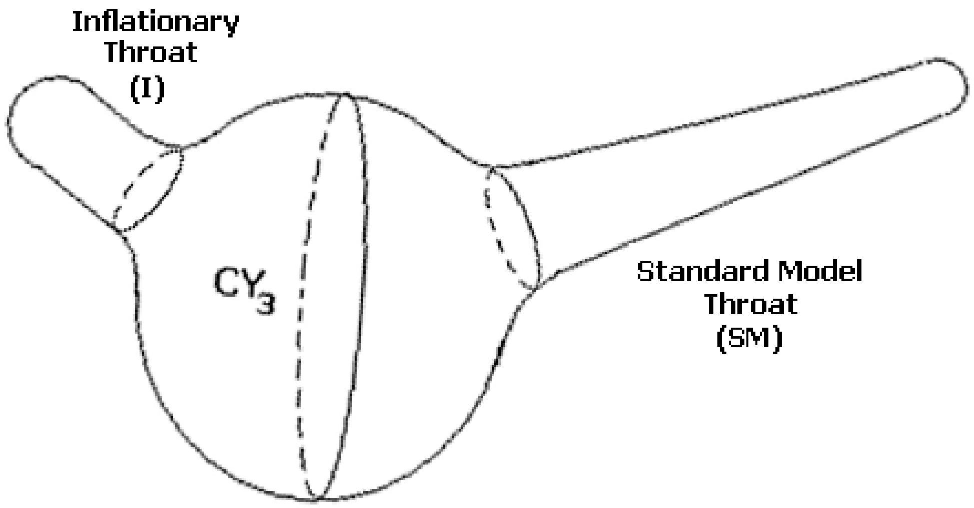


DBI inflation — Silverstein and Tong

$$S = -\int d^4x \sqrt{-g} \left(f(\phi)^{-1} \sqrt{1 - f(\phi)\dot{\phi}^2} - V(\phi) - f(\phi)^{-1} \right)$$

Casual speed limit: $\dot{\phi}^2 \leq f(\phi)^{-1}$ warp factor

Warped Throats



- Cosmic strings spatially separated from SM branes: not susceptible to breakage.
- Reheating via tunneling is efficient due to KK versus graviton wavefunctions.

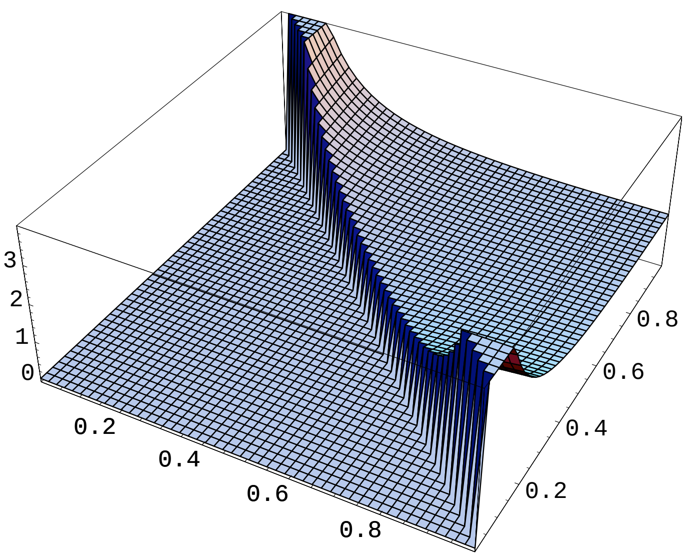
Barneby, Burgess, Cline
Kofman and Yi
Chialva, Shiu, Underwood
Frey, Mazumdar, Myers

Non-Gaussianities

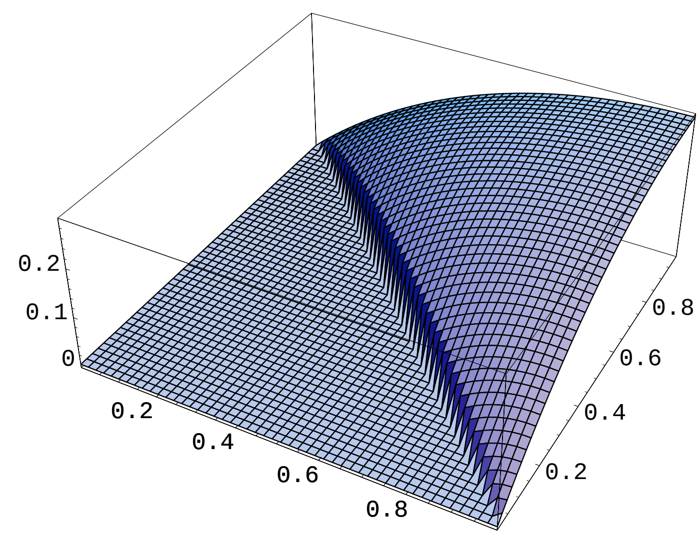
Large 3-point correlations that are potentially observable.

Moreover, distinctive shape. [Figures from Chen, Huang, Kachru, Shiu]

$$-54 < f_{NL} < 114 \text{ (WMAP3)} \quad f_{NL} \sim 5 \text{ (PLANCK)}$$



Slow-roll $(f_{NL} \sim \epsilon)$

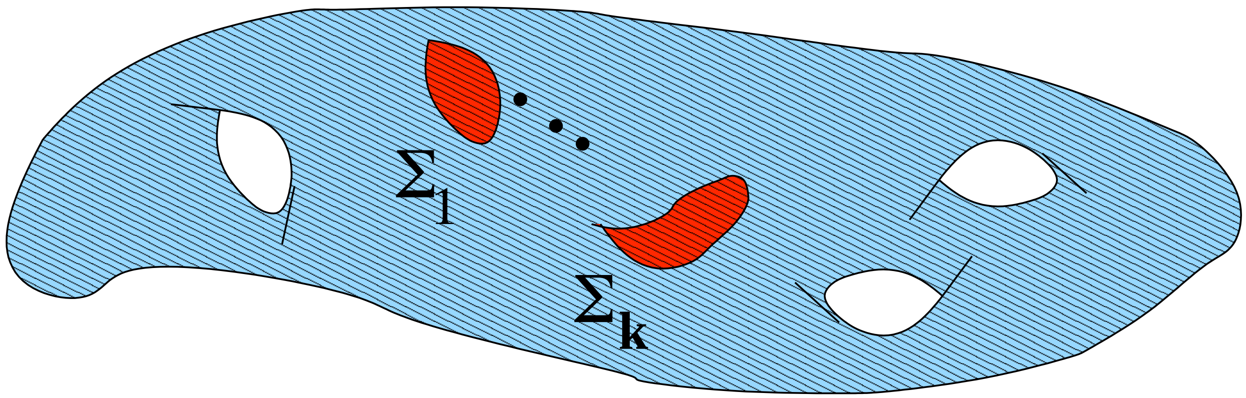


DBI $(f_{NL} \sim \gamma^2)$

Have we gone too far?

The Landscape

Number of vacua



$$\int_{\Sigma_j} F_p = n_j$$

Gauss's law: $$\sum_{j=1}^{k} n_j^2 \leq N^2$$

N^2 and k depend on the topology of $\mathcal{M}$, roughly $\mathcal{O}(100)$.

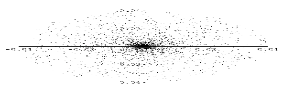
$$\boxed{\#\ \text{vacua}\ \sim N^k}$$

naively can exceed 10^{100}

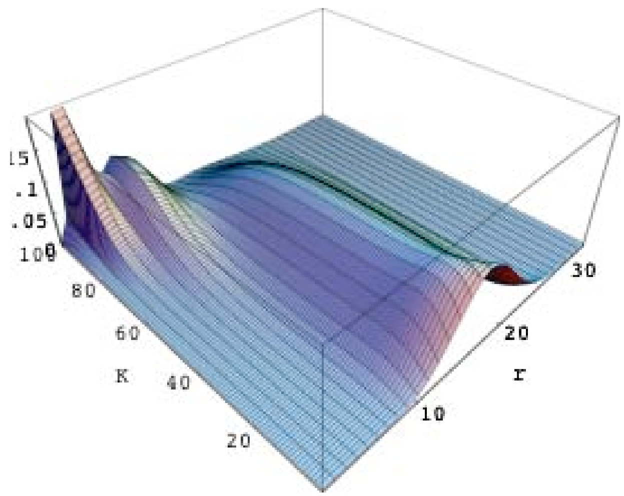
Sightseeing in the Landscape

- These are *candidate* vacua (very few known examples where *all* moduli are stabilized.)
- The open string landscape (relevant to phenomenology!) is less understood.
- Realistic models are rare (QFT vs the Standard Model).

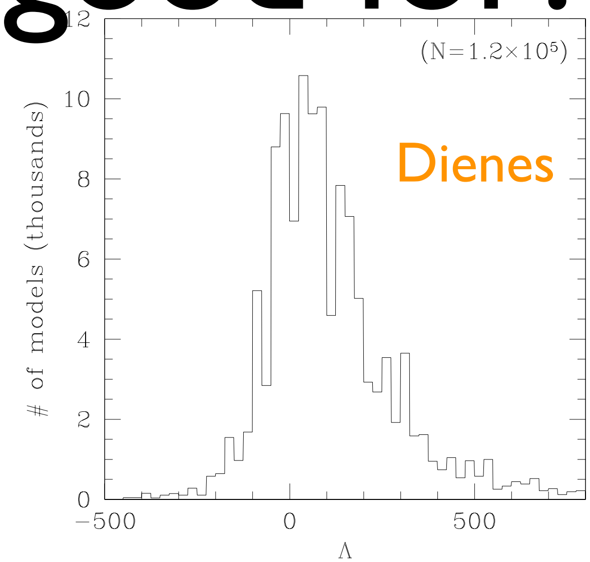
Landscape: what is it good for?



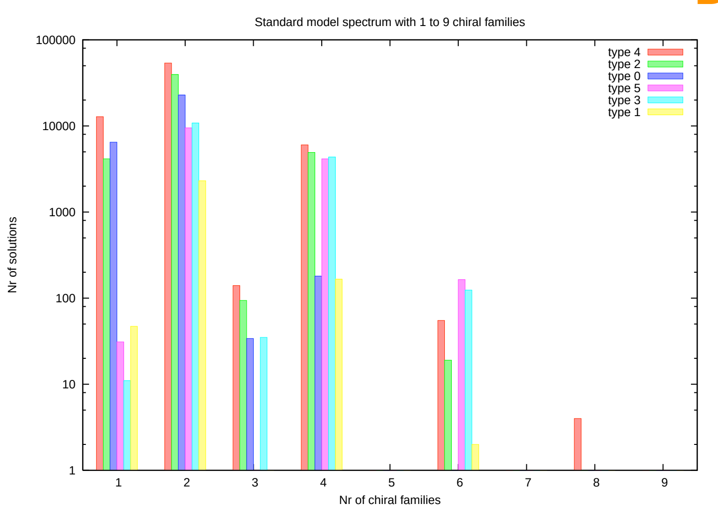
Douglas et al
Kachru et al
Conlon & Quevedo



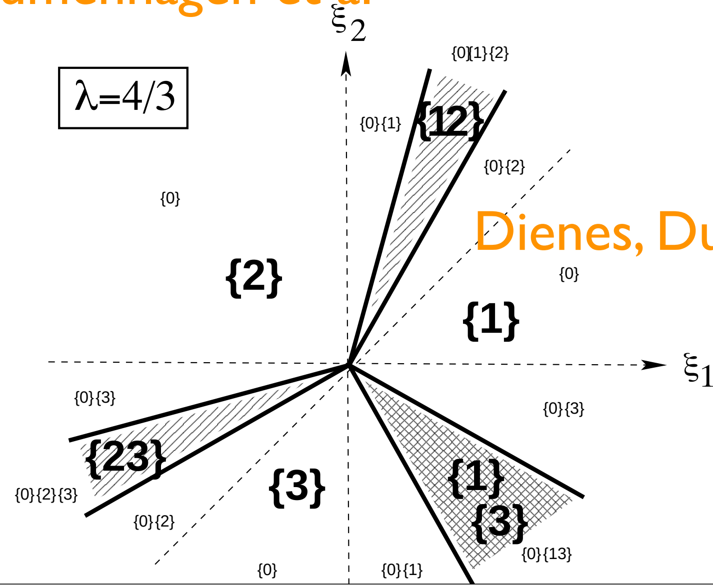
Blumenhagen et al



Dienes



Schellekens et al



Dienes, Dudas, Gherghetta

The Wave Function?

Ψ ()

Hartle, Hawking, Vilenkin, Linde, ...

In the context of string landscape

Sarangi, Tye
Kane, Perry, Zytkow
Ooguri, Vafa, Verlinde
...

Summary

- String phenomenology ~ 20+ year old baby --not fully accomplished but no longer naive.
- Too early for string phenomenology? Part of the SM was developed before gauge theories were shown to be renormalizable.
- Spin-off results (e.g., Calabi-Yau, G2, mirror symmetry, duality, topology change, ...).

Summary

- Fountain of new ideas/scenarios for particle physics and cosmology:

  SUSY: high/low, split, ...

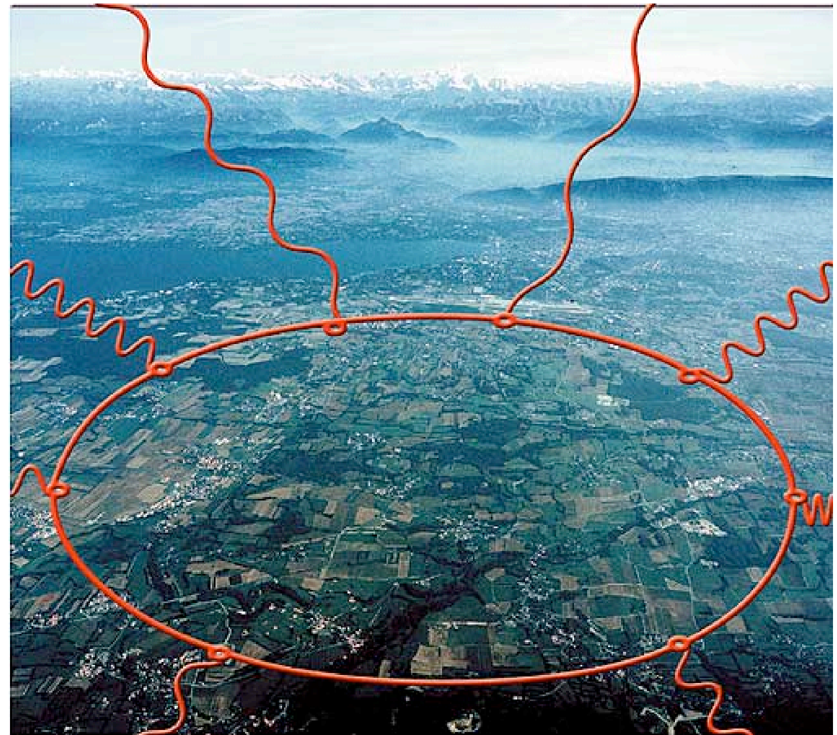
  Extra dimensions: large/small, warped/unwarped, universal/brane world.

  Technicolor: AdS/CFT

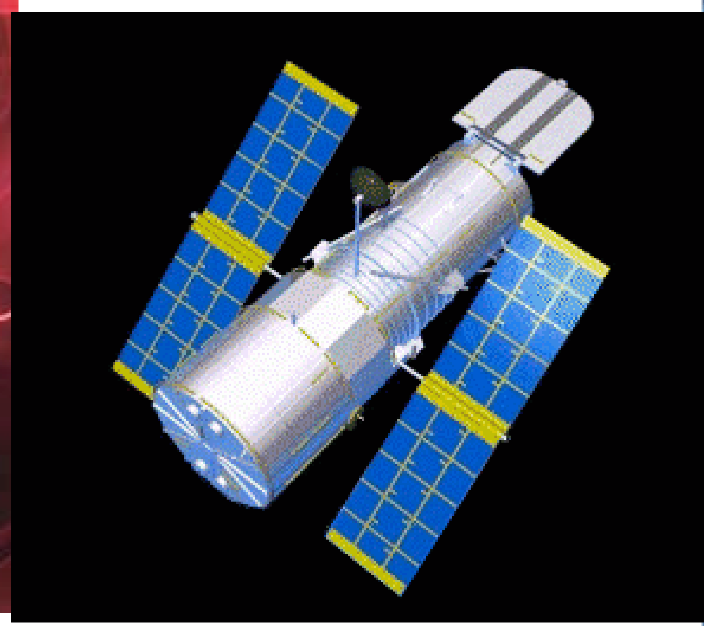
  Brane universe: brane inflation, DBI inflation, ...

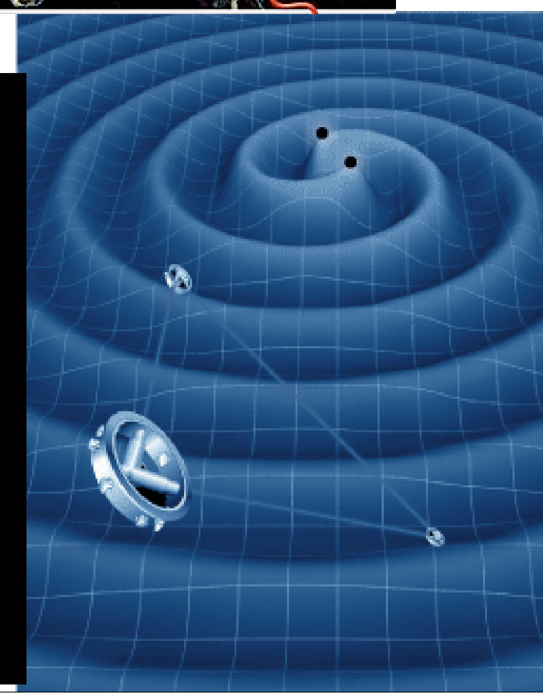
  ......

2005 +




esa
PLANCK
Looking back to the dawn of time
Un regard vers l'aube du temps





Thank you