De Sitter Universes

from

String Theory

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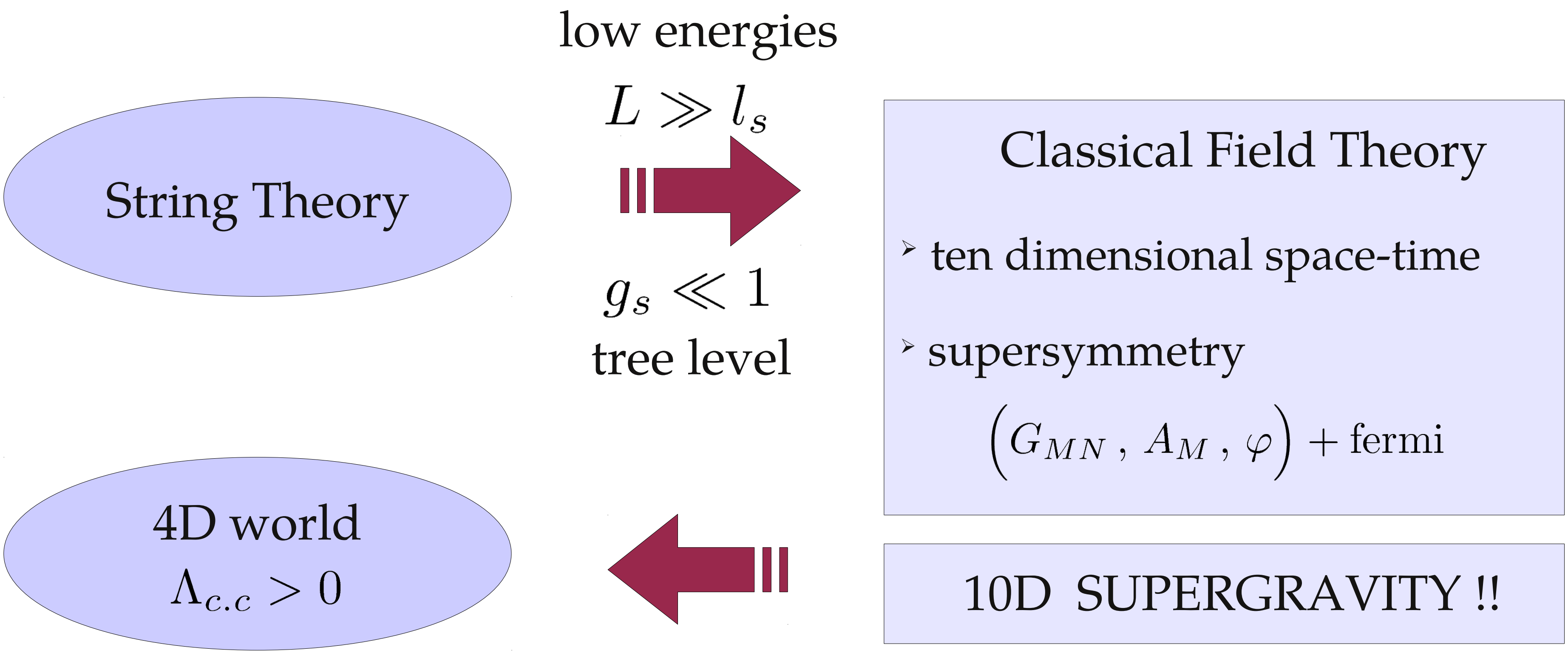
Linking strings to the world

- String Theory = best known framework where to describe GR + QFT
- The fundamental building blocks are tiny strings with $l_s \sim 10^{-33}$cm



Six extra dimensions !!

The footprint of the extra dimensions

- Fluctuations of the internal space around a fixed geometry translates into massless 4d scalar fields known as ``*moduli*"

$$\mathcal{L} = \frac{1}{2}\, R - \frac{1}{2}\, \partial_\mu \phi_i \, \partial^\mu \phi^i$$

Deviations from GR !!

massless scalars = long range interactions (precision tests of GR)

- String Phenomenology → Mechanisms for moduli stabilisation !!

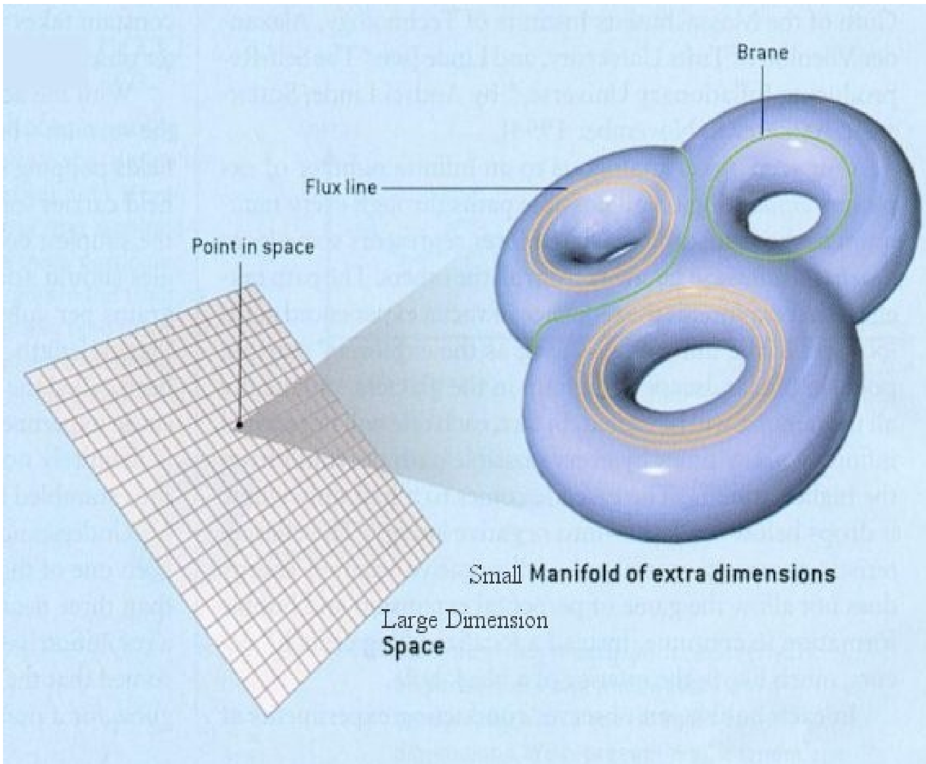
$$V(\phi) = m_{ij}^2 \, \phi^i \phi^j + \ldots$$

$$m_{ij}^2 > 0$$

- Moduli VEVs $\langle \phi \rangle = \phi_0$ determine 4d physics !!

$\Lambda_{c.c} \equiv V(\phi_0)$ $\left(g_s \, , \, \mathrm{Vol}_{int}\right)$ fermi masses

Extra dimensions . . .



… will be non empty !!

- D-branes $\left(M \propto 1/g_s\right)$
- magnetic fluxes
- funny geometries

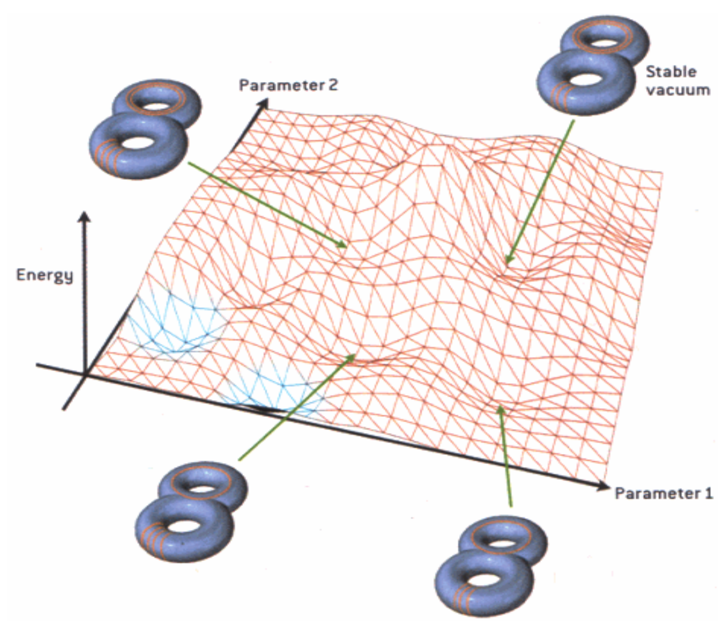
. . .

$$V(\phi) = V_{brane} + V_{flux} + V_{geom} + \ldots$$

The problem

- Model building :

branes + fluxes + geometries + … = parameters



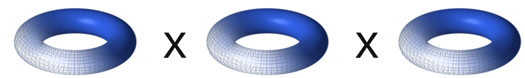
"The Landscape" (Picture from *Scientific American*)

$$\Lambda_{c.c} \equiv V(\phi_0) > 0$$

… but where is de Sitter within the string landscape ??

Internal geometries and massless theories . . .

``maximal''

$\mathbb{T}^6 =$ 

$\mathcal{N} = 8$ (70 scalars)

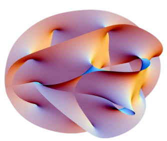
Type II 10d supergravity

``half-maximal''

Orientifolds of $\mathbb{T}^6$

$\mathcal{N} = 4$ (38 scalars)

``minimally extended''

$CY_3 =$ 

$\mathcal{N} = 2$

scalars $\leftrightarrow \left(h^{(1,1)}, h^{(1,2)} \right)$

``minimal''

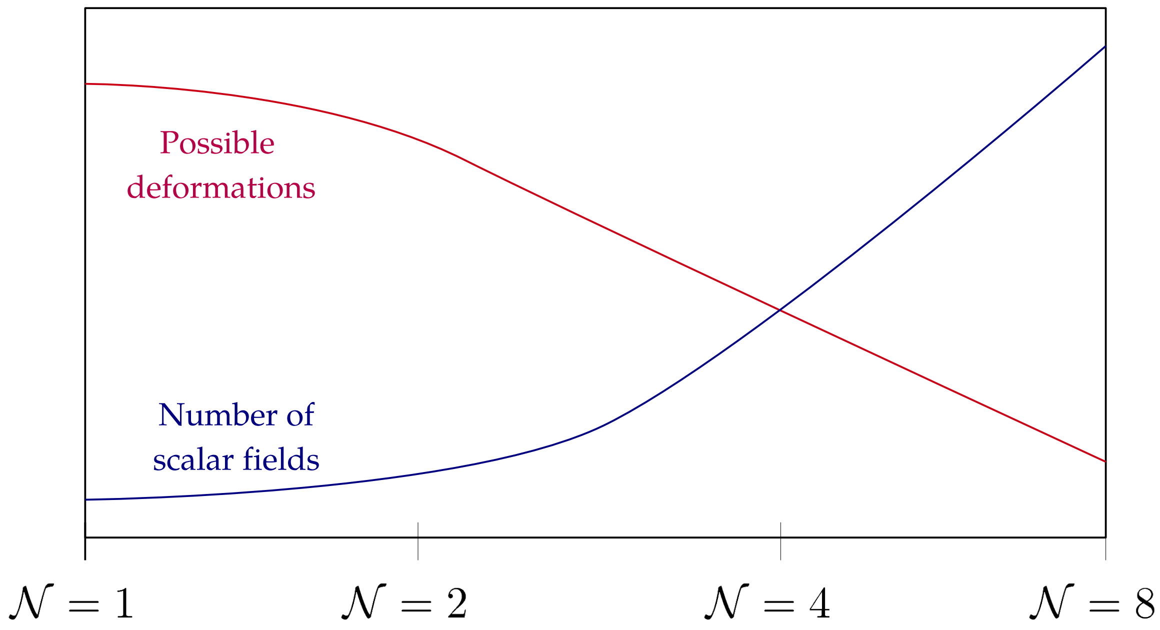
Orientifolds of CY_3

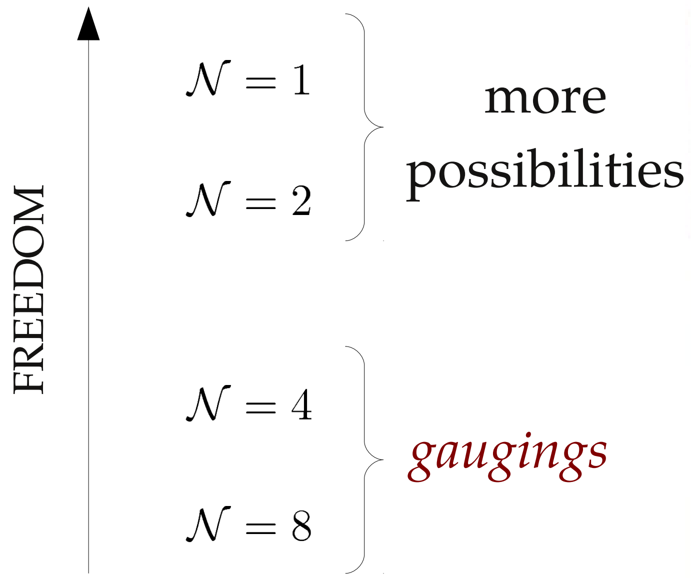
$\mathcal{N} = 1$ scalars $\leftrightarrow \left(h^{(1,1)}, h^{(1,2)} \right)$

Lower bound on topologically distinct CY_3
30108

. . . how to deform massless theories to have $V(\phi) \neq 0$?

- Supersymmetry dictates what deformations are allowed





gaugings = part of the global symmetry is promoted to local (*gauge*)

Questions :

- Which deformations induce potentials with stable De Sitter extrema ?

- Where do these deformations come from in string theory ?

De Sitter in extended supergravity

- $\mathcal{N} = 8$: unstable dS solutions with $SO(4,4)$ and $SO(5,3)$ gaugings

[Hull, Warner '85]

- $\mathcal{N} = 4$: unstable dS solutions with gaugings at *angles*

[De Roo, Wagemans '85]

i) $G_1 \times G_2$ gaugings with $\begin{cases} G_i = SO(p_i, q_i) \quad , \quad p_i + q_i = 4 \\ G_i = CSO(p_i, q_i, r_i) \quad , \quad p_i + q_i + r_i = 4 \end{cases}$

[De Roo, Westra, Panda, (Trigiante) '02, '03, '06]

ii) $SO(3,1) \ltimes U(1)^6$ gauging

[Dibitetto, A.G, Roest '11]

non-geometric fluxes in string theory !!

[Dibitetto, Linares, Roest '10]

- $\mathcal{N} = 2$: stable dS solutions with $SO(2,1) \times SO(3)$ gauging plus Fayet-Iliopoulos terms

[Fré, Trigiante, Van Proeyen '03]

unclear origin in string theory !!

De Sitter in minimal supergravity

- No-go theorems forbidding dS solutions in $\mathcal{N}=1$ compactifications with magnetic fluxes

$$V_o = -\frac{1}{9}\sum \bar{F}^2 \leq 0 \quad \Rightarrow \quad \text{AdS !!}$$

[Hertzberg, Kachru, Taylor, Tegmark '07]

- Including **more general fluxes** : (metric + non-geometric)

$$V_o = -\frac{1}{9}\sum \bar{F}^2 + \Delta V_{\text{metric}} + \Delta V_{\text{non-geom}}$$

a) metric fluxes ⟷ unstable dS in type IIA models

[Caviezel, Koerber, Kors, Lust, Wrase, Zagerman '08]

b) non-geometric fluxes ⟷ stable dS in type IIA models

[de Carlos, A.G, Moreno '09, '10]

- Including D-branes to **uplift an AdS** solution

[Kachru, Kallosh, Linde, Trivedi '03]

a) D-terms from D-branes ⟷ stable dS in type IIB models

[Burgess, Kallosh, Quevedo '03]

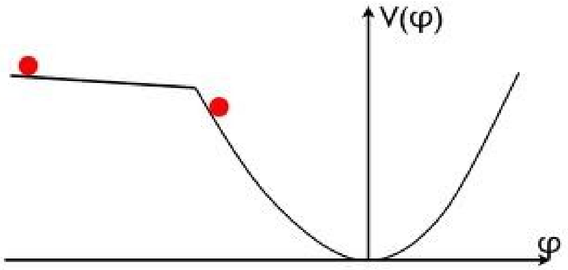
b) non-perturbative effects from D-branes ⟷ stable dS in type IIB

[Achúcarro, de Carlos, Casas, Doplicher '06]

Cosmology from moduli ?

- slow-roll inflation requires an almost flat dS saddle point of $V(\phi)$ from which to start rolling down

$$\eta \equiv M_p^2 \left(\frac{V''}{V} \right) \ll 1$$



- dS saddle points suffering from eta-problem, *i.e.* $\eta \sim \mathcal{O}(1)$

i) gaugings in extended supergravity

[Kallosh, Linde, Prokushkin, Shmakova '01]

ii) general fluxes in minimal supergravity

[Flauger, Paban, Robbings, Wrase '08]

[de Carlos, A.G, Moreno '10]

- dS saddle points with $\eta \ll 1$ in minimal supergravity including non-perturbative effects $\Longrightarrow$ axion inflation !!

[Dimopoulos, Kachru, McGreevy, Wacker '05]

Overview

- Finding dS solutions from string compactifications represents a crucial step in connecting strings with real world physics

- All known dS solutions coming from *gaugings* in $\mathcal{N} \geq 4$ turn out to be unstable. They correspond to string compactifications in the presence of non-geometric fluxes for which a higher-dimensional origin is still unclear

- Some stable dS solutions are found in $\mathcal{N} \leq 2$ considering *gaugings* together with additional ingredients. Their higher-dimensional origin is not well understood either

- D-branes seem to be crucial in order to find/understand stable dS solutions

- Cosmology certainly represents an interesing playground to test string theory

Thanks for your attention !!

Extra dimensions : compact vs non-compact

compactification

$$ds^2_{(5)} = ds^2_{(4)} + dy^2$$

$$M^2_{(4)} = M^3_{(5)} \, L_y$$

[Kaluza '21, Klein 26']

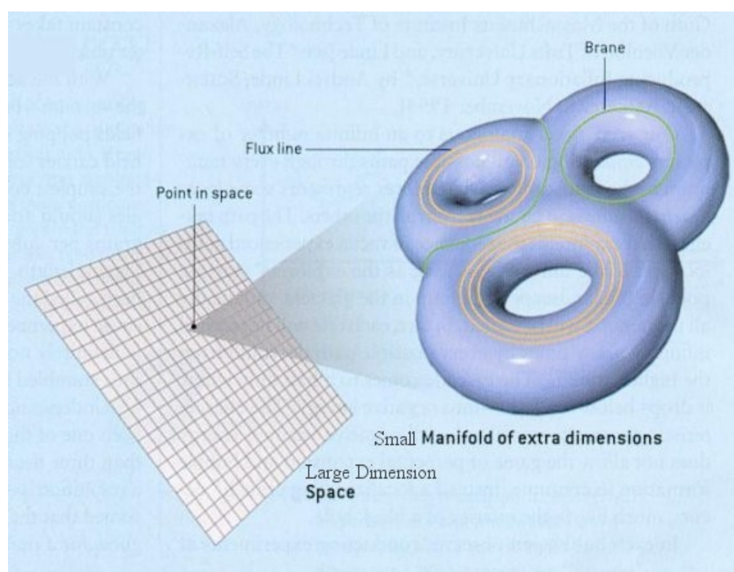
warped non-compact

$$ds^2_{(5)} = e^{-2k|y|} \, ds^2_{(4)} + dy^2$$

$$M^2_{(4)} = \frac{M^3_{(5)}}{k} \left(1 - e^{-2kL_y}\right)$$

[Randall, Sundrum '99]

10d space-time



… will be non empty !!

- funny geometries
- D-branes $\left(M \propto 1/g_s\right)$
- Magnetic fields

Gaugings and their higher-dimensional origin

- Scalars potentials are induced by *``gaugings''* : Part of the global symmetry is promoted to local (*gauge*)

[de Wit, Samtleben, Trigiante '07]
[Schon, Weidner '06]

- $\mathcal{N} = 8$: Gauging a subgroup of the global symmetry $G = E_7$

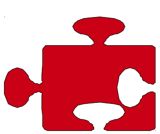
Internal space extension ⟷ Exceptional Generalised Geometry ?

[Pacheco, Waldram '08 , Grana, Louis, Sim, Waldram '09]
[Aldazabal, Andrés, Cámara, Grana '10]

- $\mathcal{N} = 4$: Gauging a subgroup of the global symmetry $G = SL(2) \times SO(6,6)$

Internal space extension ⟷ Doubled / Generalised Geometry ?

[Hitchin '02, Gualtieri '04]
[Hull '04, '06]



pathological
internal spaces

String compactifications including generalised flux backgrounds !!