

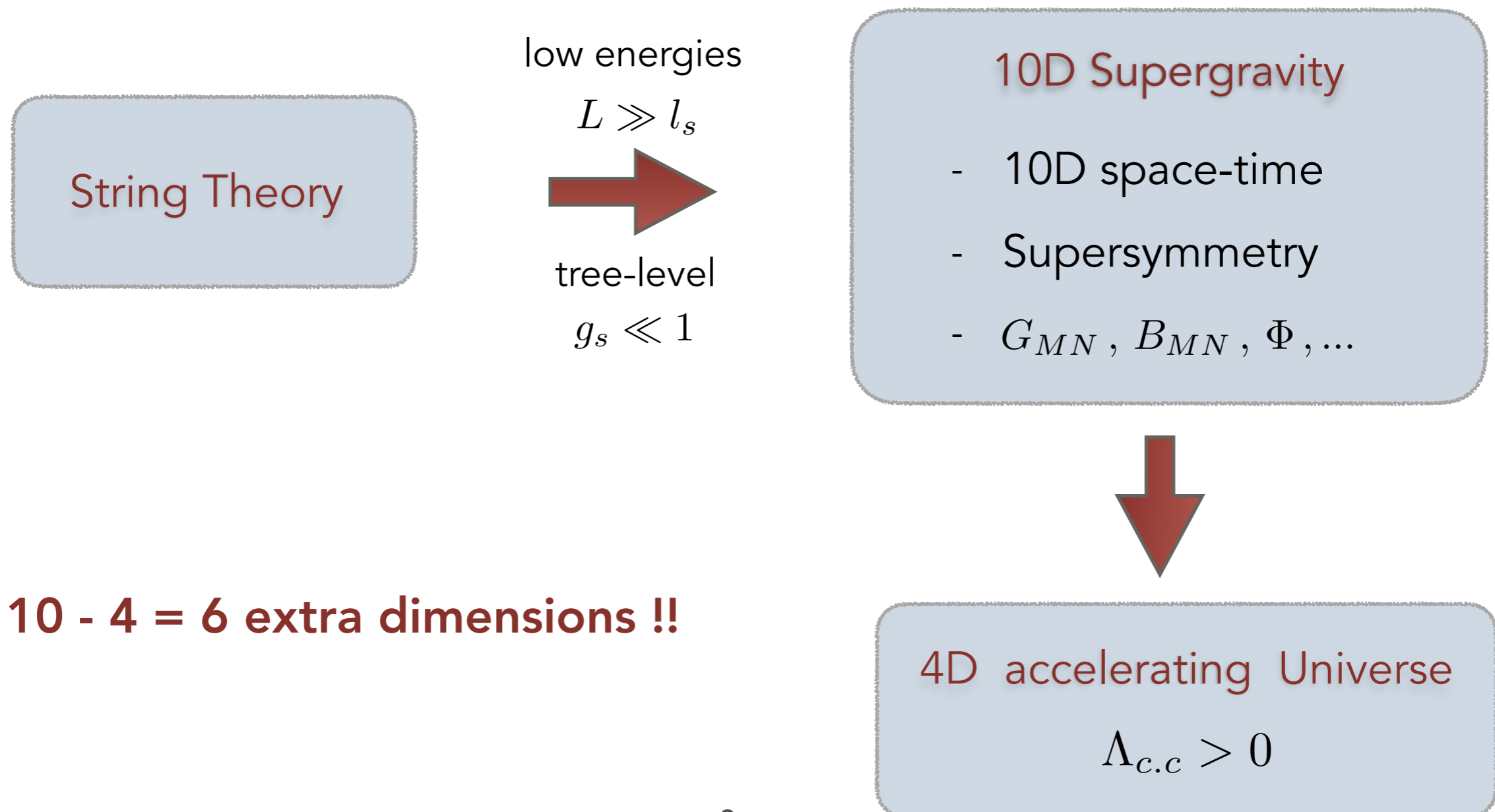
Accelerating Universes from String Theory



Be.Hep Summer Solstice 2018

Linking strings to the real world

- ❖ String theory provides a framework where to describe General Relativity and Quantum Field Theory in a unified manner
- ❖ The fundamental building blocks are tiny vibrating strings with $l_s \sim 10^{-33}$ cm



String Theory & Extra Dimensions

Best candidate to **quantum gravity**...

... but **requires extra dimensions !**

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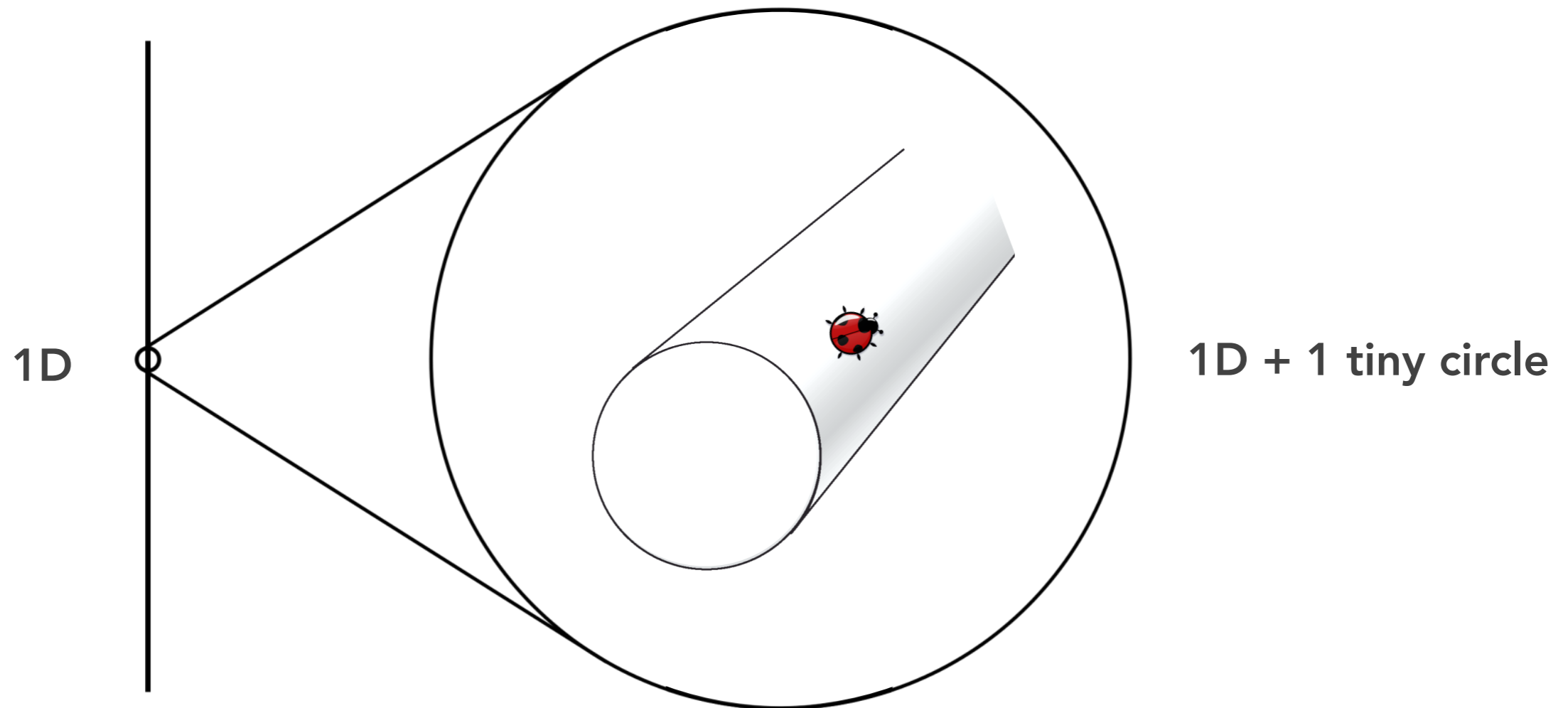
1D

A vertical black line is positioned on the left side of the slide, extending from the middle to the bottom. To its left, the text '1D' is written in a bold, black, sans-serif font.

String Theory & Extra Dimensions

Best candidate to **quantum gravity**...

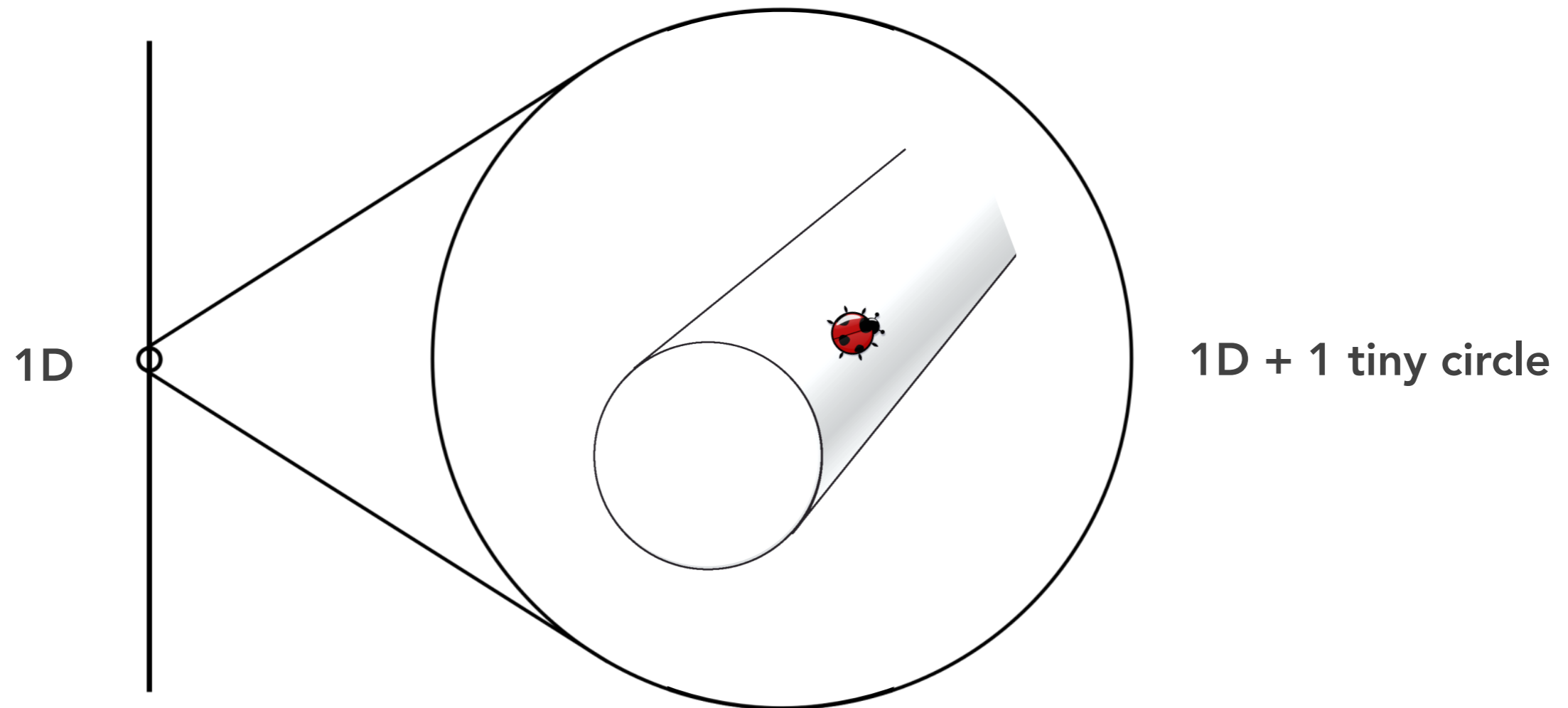
... but **requires extra dimensions !**



String Theory & Extra Dimensions

Best candidate to **quantum gravity**...

... but **requires extra dimensions !**



Striking consequence: physical laws in our **4D reality** encoded in the geometry (shape and size) of **6 extra dimensions**.

The footprint of the extra dimensions

- ❖ Fluctuations of the extra dimensions (size and shape) translate into a set of **massless** 4D scalar fields known as “**moduli fields**”

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



Deviations
from GR !!

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

- ❖ String phenomenology \rightarrow Mechanisms for “**moduli stabilisation**”

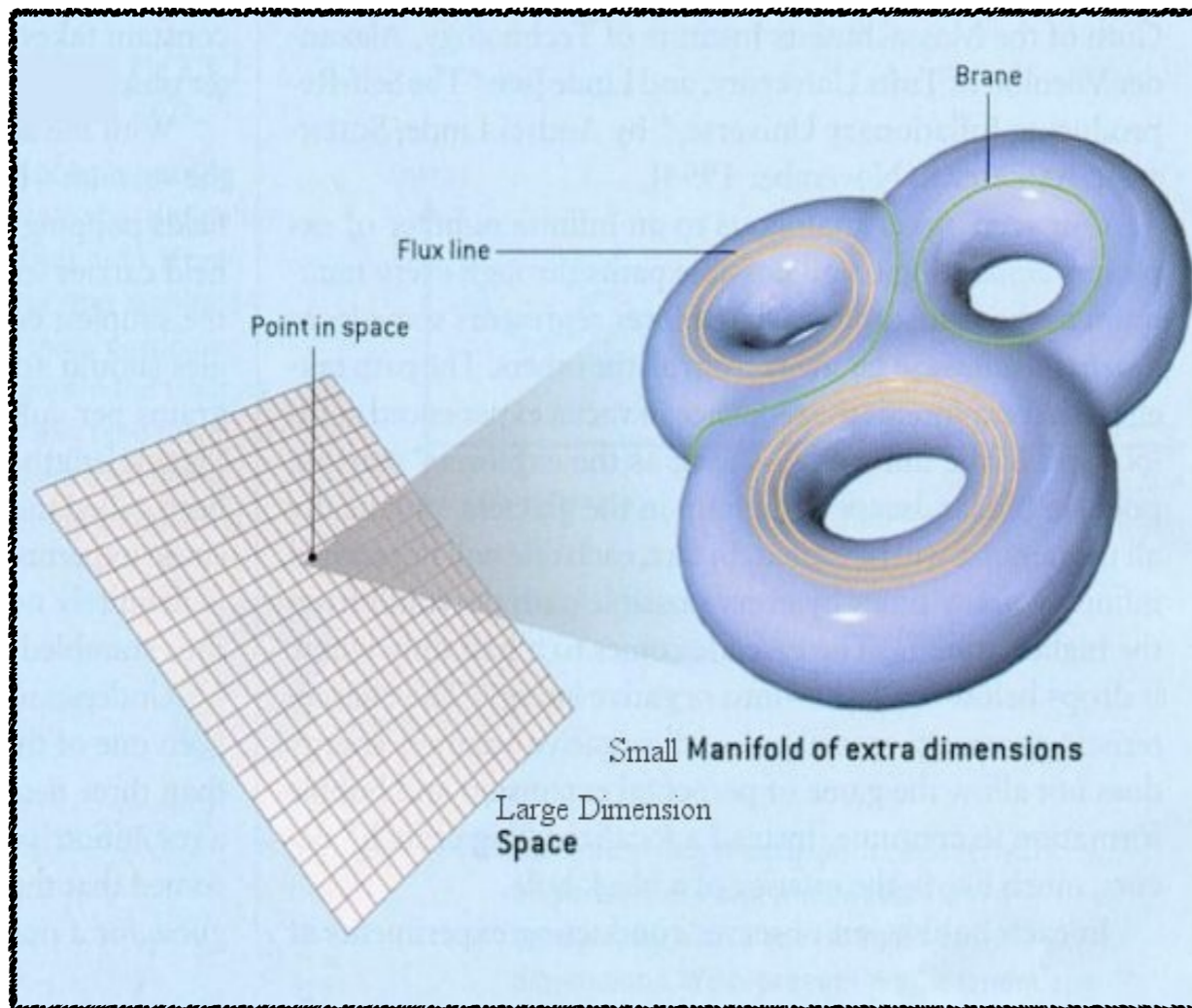
$$V(\phi) = m_{ij}^2 \phi^i \phi^j + \dots$$

- ❖ The moduli VEVs $\langle \phi^i \rangle = \phi_0^i$ determine the **4D cosmological constant** !!

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

[positive sign = accelerated expansion (dS)]

Extra dimensions...



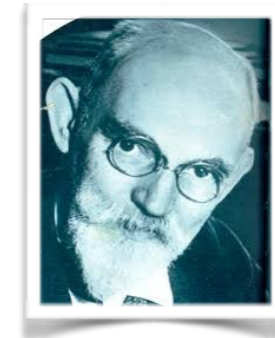
... will be non empty !!

- D-branes
- magnetic fluxes
- funny geometries

...

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

The problem = finding

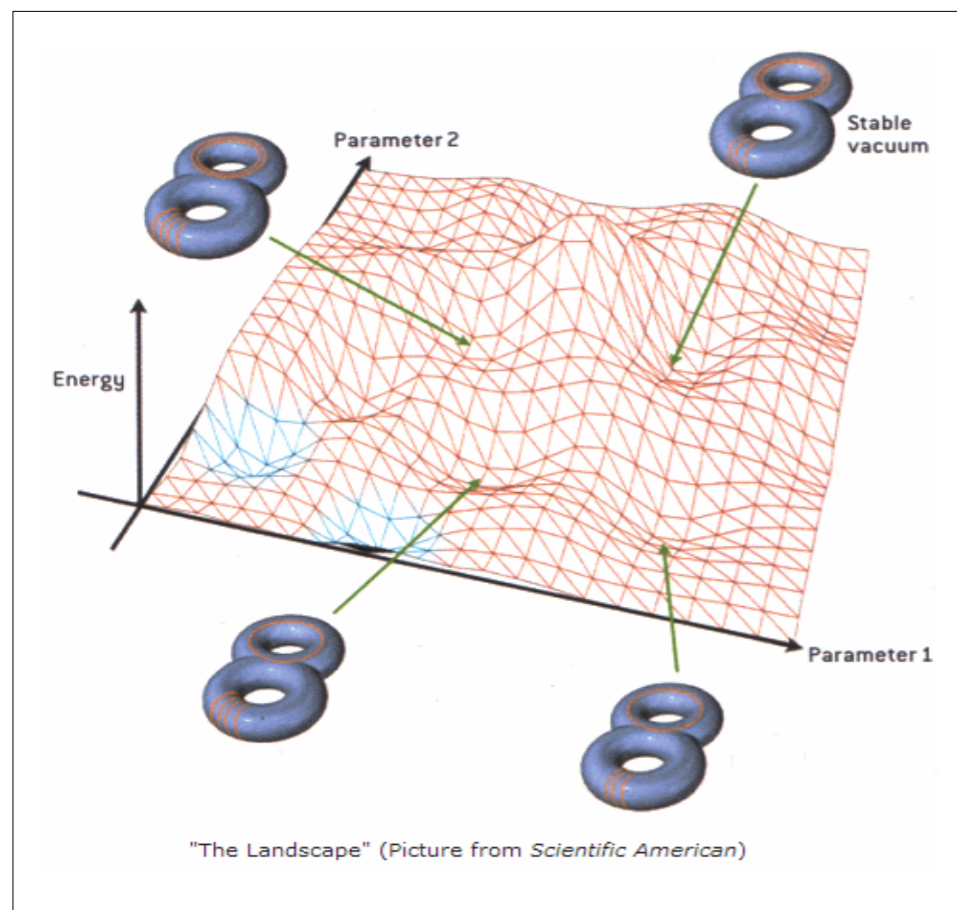


Willem de Sitter
(1872 – 1934)

❖ Model building :

branes + fluxes + geometries + ... = parameters

[Giddings, Kachru, Polchinski '01]



[Blumenhagen, Cámara, de Carlos, Dall'Agata, Danielsson, Derendinger, DeWolfe, Giravets, Graña, Ibáñez, Kachru, Kounnas, Kors, Lüst, Minasian, Petrini, Petropoulos, Reffert, Schulz, Schulgin, Shiu, Stieberger, Taylor, Tomasiello, Trigiante, Tripathy, Trivedi, van Riet, Villadoro, Zwirner, ... 2002 - 2007]

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

... but where is de Sitter

within the string landscape?

No-go theorems forbid perturbative dS vacua !!

[under reasonable assumptions]



[Maldacena, Nuñez '00]

[Hertzberg, Kachru, Taylor, Tegmark '07]

[van Riet et al '08, '09, '10]

[de Carlos, AG, Moreno '09]

1. Non-geometric fluxes

Mysterious 4D objects conjectured to exist based on string dualities

[strong-weak coupling, winding-momentum states, ...]

[Hull, Townsend '94]

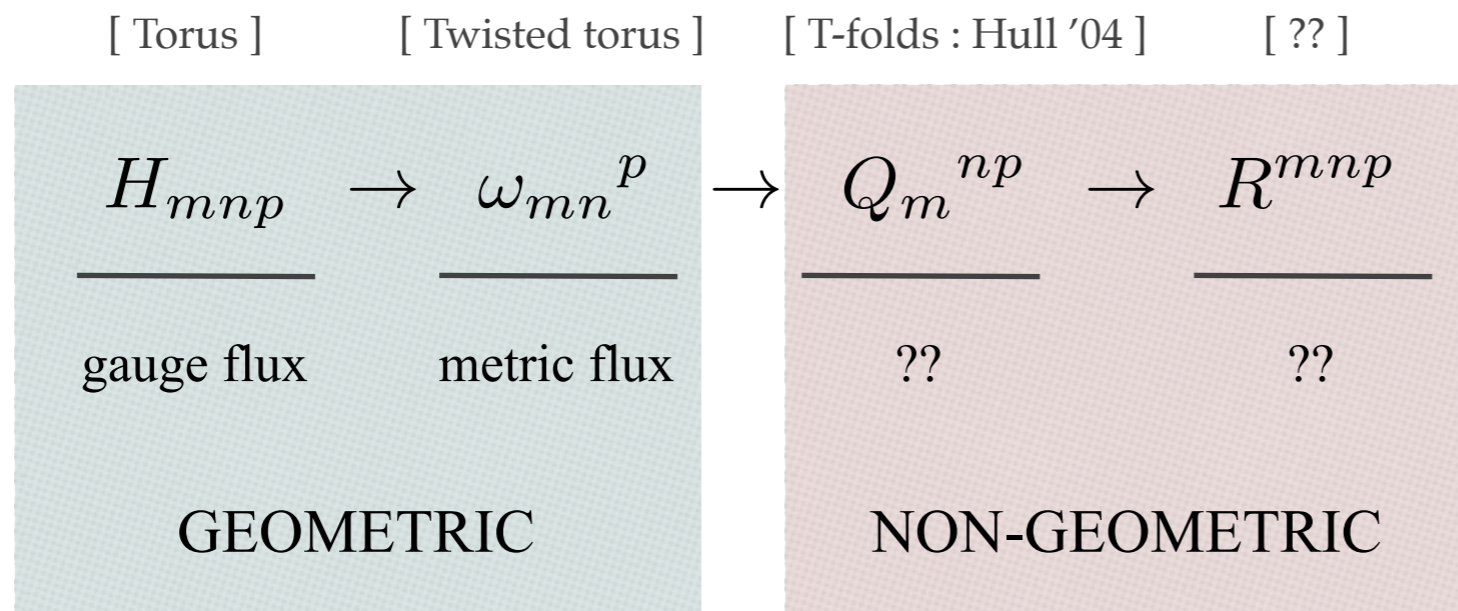
2. Non-perturbative effects

1. Non-geometric fluxes

- ❖ Introduced in the context of N=1 effective supergravity to restore the **stringy T-duality** at the 4D level

T-duality (torus) : $R \rightarrow \frac{1}{R}$ [review by Giveon, Porrati, Rabinovici '94]

- ❖ Starting from the field strength $H_{mnp} = \partial_{[m} B_{np]}$ of a gauge potential B_{np} of string theory and applying a chain of T-dualities

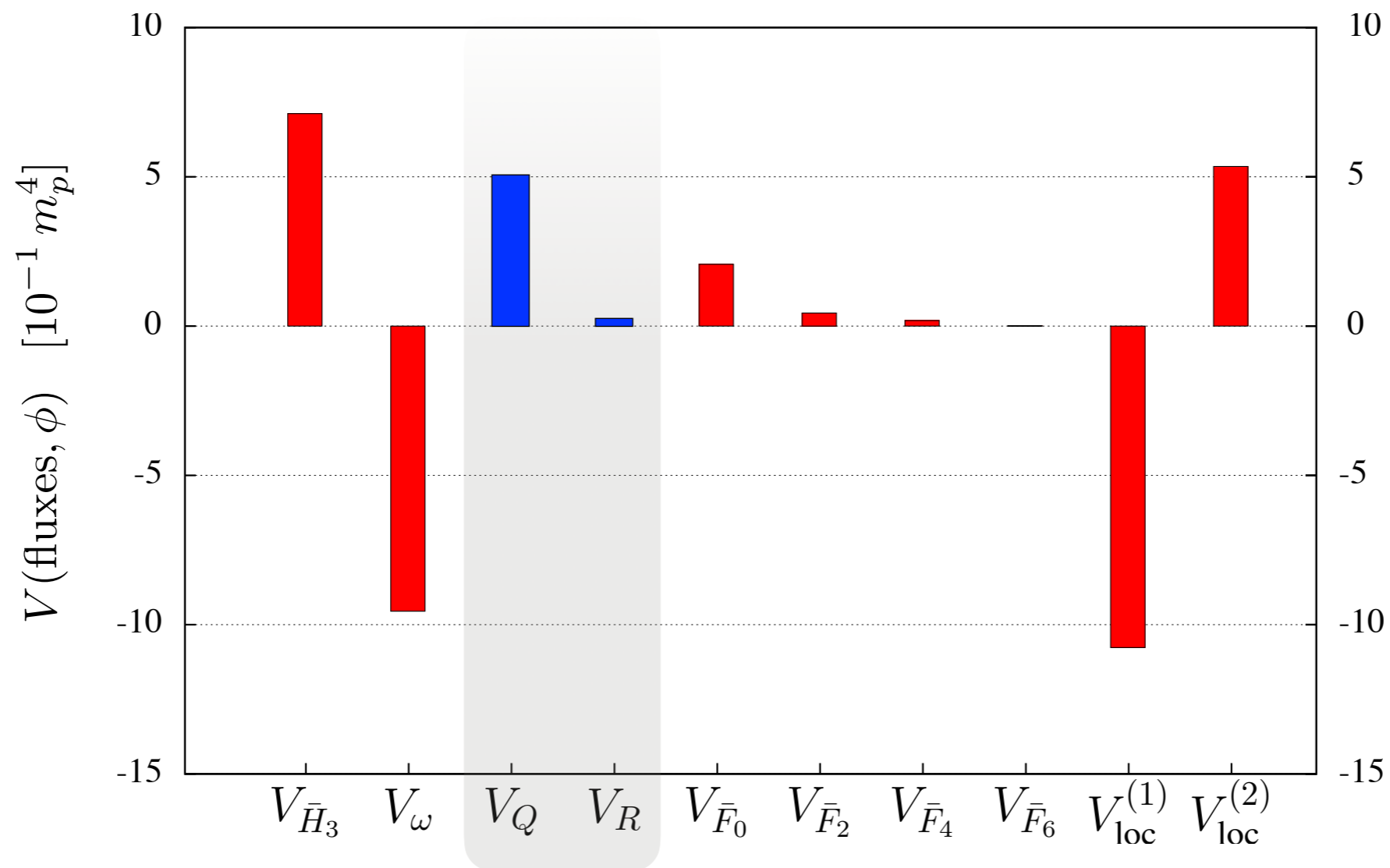


- [Kaloper, Myers '99]
- [Hellerman, McGreevy, Williams '02]
- [Dabholkar, Hull '02]
- [Kachru, Schulz, Tripathy, Trivedi '02]
- [Shelton, Taylor, Wetch '05]

- ❖ Generalisation to other stringy dualities: S-duality & U-duality

de Sitter vacua from non-geometric fluxes

$$W(\phi) = W_{\text{geom}}(\phi^{\text{low powers}}) + W_{\text{non-geom}}(\phi^{\text{high powers}})$$

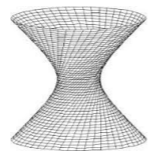
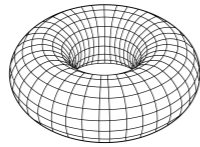
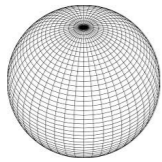


[de Carlos, AG, Moreno '10]

... although their higher-dimensional origin remains unclear !!

10D

String Theory



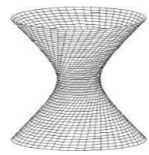
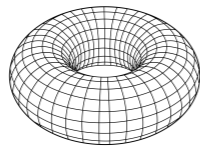
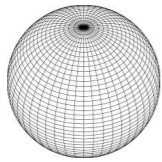
6 extra dimensions

4D

Geometric models

10D

String Theory



6 extra dimensions

4D

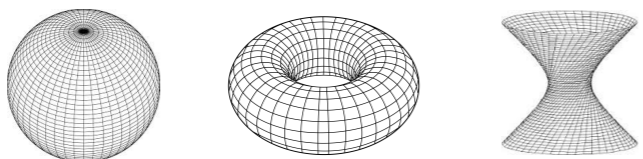
Geometric models

Non-Geometric models

"terra incognita"

10D

String Theory

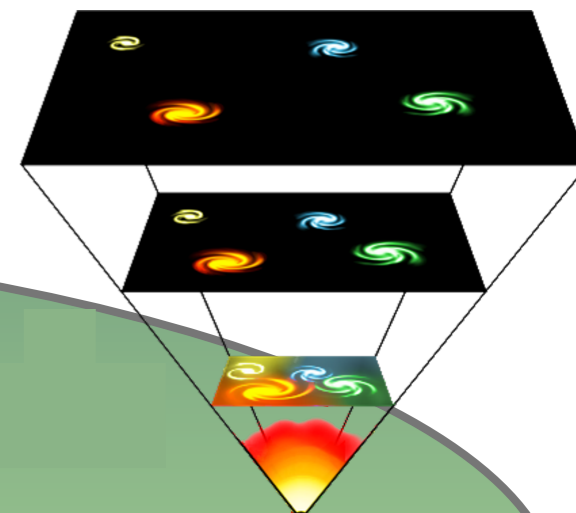
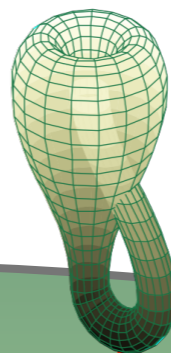


6 extra dimensions

[Hitchin & Gualtieri '03, '07]
 [Pacheco, Waldram '08]
 [Hull, Zwiebach & Hohm '09 '10]
 [Coimbra, Strick-Const, Waldram '11] [de Carlos, AG, Moreno '10]
 [Dibitetto, AG, Roest '11 '12 '14]
 [Berman, Blair, Malek, Perry '13] [Danielsson, Dibitetto '12]
 [Hohm, Samtleben '13] [Hassler, Lüst, Massi '14]
 [Ciceri, AG, Inverso '16] [Kodama, Nozawa '15]
 [Ciceri, Dibitetto, Melgarejo, AG, Inverso '16] [Blumenhagen et al '15]
 ...

generalised geometries

Accelerating Universes & inflation



4D

Geometric models

Non-Geometric models
"terra incognita"

2. Non-perturbative effects

The KKLT mechanism

❖ Ingredients :

- Calabi-Yau manifold (geometry)
- Background fluxes and D-branes
- Non-perturbative effects
- Anti D3-branes

❖ Two-step process

- **Step 1 = stabilisation** (*wrong sign !!*)

The moduli fields get stabilised in a minimum with $V < 0$

- **Step 2 = uplift to a positive c.c**

Anti D3-branes uplift the minimum to a de Sitter one with $V > 0$

[Alwis, Bena, Blåbæk, Danielsson, Gautason, Graña, Halmagyi, Kuperstein, Massai, Truijen, van Riet, Vercoocke, ... '09-'16]

de Sitter Vacua in String Theory

Shamit Kachru,^{1,2} Renata Kallosh,¹ Andrei Linde¹ and Sandip P. Trivedi³

¹Department of Physics, Stanford University, Stanford, CA 94305-4060, USA

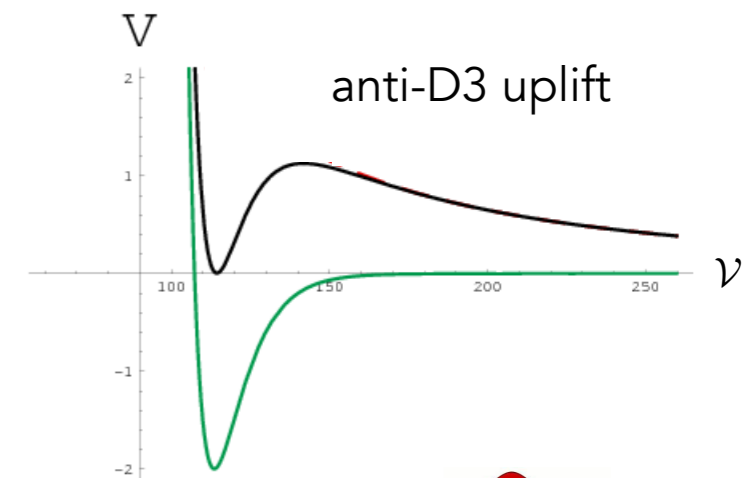
²SLAC, Stanford University, Stanford, CA 94309, USA and

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We outline the construction of metastable de Sitter vacua of type IIB string theory. Our starting point is highly warped IIB compactifications with nontrivial NS and RR three-form fluxes. By incorporating known corrections to the superpotential from Euclidean D-brane instantons or gaugino condensation, one can make models with all moduli fixed, yielding a supersymmetric AdS vacuum. Inclusion of a small number of $\overline{D3}$ branes in the resulting warped geometry allows one to uplift the AdS minimum and make it a metastable de Sitter ground state. The lifetime of our metastable de Sitter vacua is much greater than the cosmological timescale of 10^{10} years. We also prove, under certain conditions, that the lifetime of dS space in string theory will always be shorter than the recurrence time.

PACS numbers: 11.25.-w, 98.80.-k; SU-ITP-03/01, SLAC-PUB-9630, TIFR/TH/03-03, hep-th/0301240

2.527 citations (2003) !!



Anti D3-branes
are controversial !!

Matter fields as an alternative to uplift mechanisms

❖ Ingredients :

- Calabi-Yau manifold (geometry)
- Background fluxes and D-branes
- Non-perturbative effects usually require matter fields M

[Affleck, Dine, Seiberg '84]

[Haack, Krefl, Lüst, van Proeyen, Zagermann '07]

$$[\text{KKLT}] \quad W_{n.p} \sim A e^{-\mathcal{V}^{2/3}} \quad \longrightarrow \quad W_{n.p} \sim A(M) e^{-\mathcal{V}^{2/3}} \quad [\text{AG, Inverso '16}]$$

- ❖ Single-step process = *No need for uplift mechanisms or ~~Anti-D3-branes~~ !!*

Single-step moduli stabilisation in a de Sitter minimum ($V > 0$)

[Blåbæk, Roest, Zavala & Danielsson, Dibitetto '13]

[Kallosh, Linde, Vercnocke, Wrase '14]

Single-step de Sitter vacua from non-perturbative effects with matter

Adolfo Guarino and Gianluca Inverso

Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands

A scenario of moduli stabilisation based on the interplay between closed and open string sectors is explored in a bottom-up approach. We study $\mathcal{N} = 1$ effective supergravities inspired by type IIB orientifold constructions that include background fluxes and non-perturbative effects. The former generate the standard flux superpotential for the axiodilaton and complex structure moduli. The latter can be induced by gaugino condensation in a non-Abelian sector of D7-branes and involve the overall Kähler modulus of the compactification as well as matter fields. We analyse the dynamics of this coupled system and show that it is compatible with single-step moduli stabilisation in a metastable de Sitter vacuum. A novelty of the scenario is that the F-term potential suffices to generate a positive cosmological constant and to stabilise all moduli, except for a flat direction that can be either lifted by a mass term or eaten up by an anomalous U(1).

NIKHEF 2015-044

e-mails: aguarino@nikhef.nl, ginverso@nikhef.nl

Summary

- ❖ The fact that our Universe is currently undergoing a phase of accelerated expansion makes the **search for de Sitter vacua** a key step towards linking strings to cosmological data
- ❖ Finding de Sitter vacua in string theory is a complicated endeavour. At the **4D effective supergravity level**, some examples based on exotic **non-geometric fluxes** or **non-perturbative effects** have been put forward
- ❖ The search for a **higher-dimensional understanding of non-geometric fluxes** in string theory has led to the discovery of new (stringy) **generalised geometries** challenging classical concepts in Riemannian geometry
- ❖ Non-perturbative scenarios often require uplift mechanisms based on anti-branes which are controversial. **Single-step mechanisms of moduli stabilisation** taking into account **matter fields** offer an alternative to anti-branes. **Solid string embedding?**

After 20 years no fully satisfactory de Sitter vacuum has been found ... so ...

(2018)

What if string theory has no de Sitter vacua?

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Abstract

We present a brief overview of attempts to construct de Sitter vacua in string theory and explain how the results of this 20-year endeavor could point to the fact that string theory harbours no de Sitter vacua at all. Making such a statement is often considered controversial and “bad news for string theory”. We discuss how perhaps the opposite can be true.

To be continued...

Dank u wel!!

Extra material

Non-perturbative vs non-geometric

$$e^\phi = 1 + \phi + \frac{1}{2!} \phi^2 + \frac{1}{3!} \phi^3 + \frac{1}{4!} \phi^4 + \dots$$

high powers
(non-geometric)