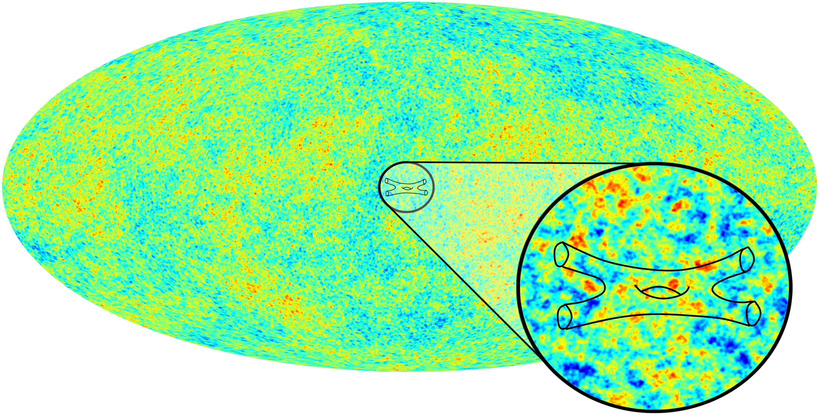
The String Theory Landscape and Cosmological Inflation



Background Image: Planck Collaboration and ESA

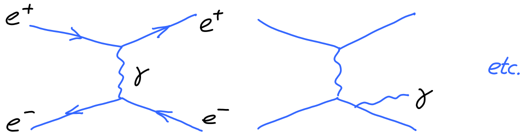
The String Theory Landscape and Cosmological Inflation

Outline

- Preliminaries: From Field Theory to Quantum Gravity
- String theory in 10 dimensions – a "reminder"
- Compactifications to 4 dimensions
- The (flux-) landscape
- Eternal inflation and the multiverse
- Slow-roll inflation in our universe
- Recent progress in inflation in string theory

From Particles/Fields to Quantum Gravity

- Naive picture of particle physics:



- Theoretical description: Quantum Field Theory
- Usually defined by an action:

$$S_{(Q)ED} = \int d^4x \, F_{\mu\nu} \, F_{\rho\sigma} \, g^{\mu\rho} \, g^{\nu\sigma}$$

with

$$F_{\mu\nu} = \frac{\partial A_\mu}{\partial x^\nu} - \frac{\partial A_\nu}{\partial x^\mu} = \begin{pmatrix} 0 & \overline{E}^T \\ -\overline{E} & \varepsilon B \end{pmatrix}$$

Gravity is in principle very similar:

- The metric $g_{\mu\nu}$ becomes a field, more precisely

$$S_G = \int d^4x \sqrt{-g}\ R[g_{\mu\nu}] \ ,$$

where R measures the curvature of space-time

- In more detail: $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Now, with $h_{\mu\nu}$ playing the role of A_μ, we find

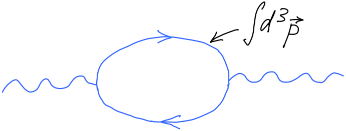
$$S_G = \int d^4x \ (\partial_\rho h_{\mu\nu})\,(\partial^\rho h^{\mu\nu}) + \cdots$$

- Waves of $h_{\mu\nu}$ correspond to gravitons,
just like waves of A_μ correspond to photons

- Now, replace S_{QED} with $S_{Standard\ Model}$ (that's just a minor complication....) and write

$$S = S_G + S_{SM} \ .$$

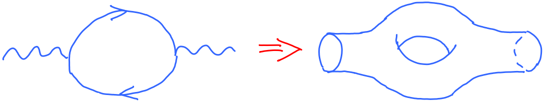
This could be our 'Theory of Everything', but there are divergences ....



- Divergences are a hard but solvable problem for QFT
- However, these very same divergences make it very difficult to even define quantum gravity at $E \sim M_{Planck}$

String theory: 'to know is to love'

- String theory solves this problem in 10 dimensions:



- The divergences at $\vec{k} \to \infty$ are now removed (cf. Timo Weigand's recent colloquium talk)

- Thus, in 10 dimensions but at low energy ($E \ll 1/l_{string}$), we get an (essentially) unique 10d QFT:

$$\mathcal{L} = R[g_{\mu\nu}] + F_{\mu\nu\rho}F^{\mu\nu\rho} + H_{\mu\nu\rho}H^{\mu\nu\rho} + \cdots$$

'Kaluza-Klein Compactification' to 4 dimensions

- To get the idea, let us first imagine we had a 2d theory, but need a 1d theory
- We can simply consider space to have the form of a cylinder or 'the surface of a rope':

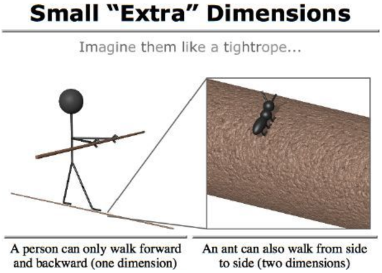
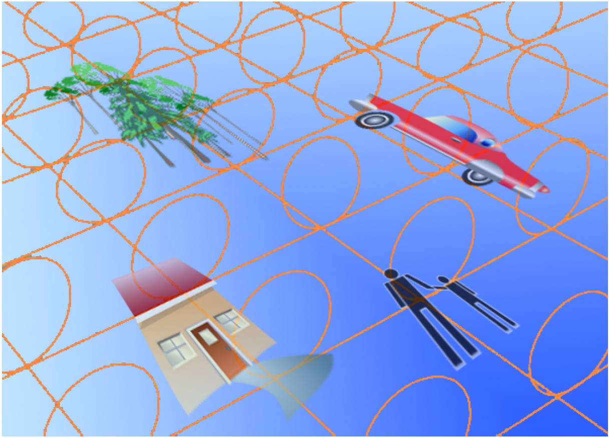


Image by S. Edwards on wikispaces

- Here we have compactified on a circle or an S^1

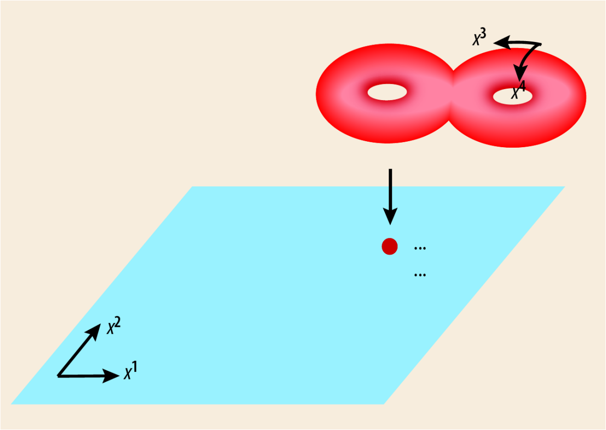
‘Compactification’ continued

- Quite analogously, we can compactify on S^1 from 3d to 2d, i.e. using $\mathbb{R}^2 \times S^1$ as our space:



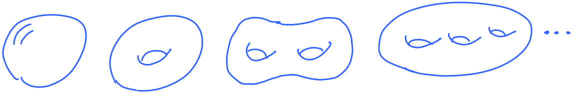
'Compactification' continued

- We can compactify on Riemann surfaces from 4d to 2d:



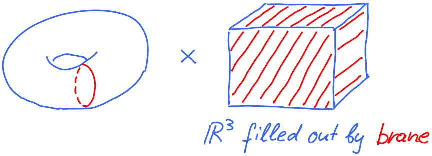
'Compactification' continued

- Fairly obviously, there is an infinite series of such 2d compact spaces (Riemann surfaces):



- Crucially, string compactifications involve D-branes (non-perturbative extended objects, on which gauge theories are localized)

- Here is a picture of going from 5d to 3d on a torus, with a 4-dim. brane also present:



Closer to reality:

- To go from 10d to 4d, i.e. we need 6d compact spaces
- We also want these spaces to solve Einstein's equations ($R_{\mu\nu} = 0$)
- Such geometries are called 'Calabi-Yau spaces' and $\sim 10^4$ of them are known (finiteness is conjectured but not established)

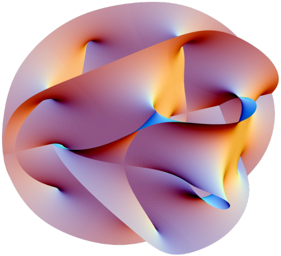
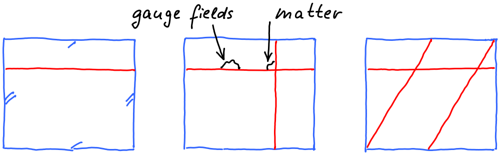


Image by J.F. Colonna

Closer to reality:

- In fact, there are many more possibilities, due to the presence of branes

- For example, a torus has two '1-cycles' on which branes can be 'wrapped':

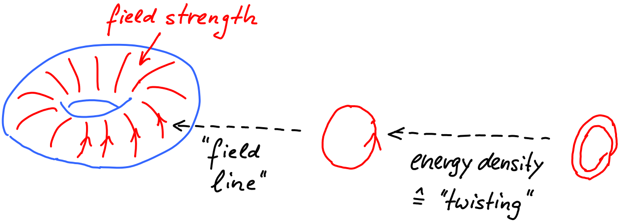


- In this context (with CYs instead of tori), building the Standard Model leads to highly non-trivial geometrical questions (cf. work in the groups of T. Weigand and E. Palti)

- But this is not yet 'the landscape' ....

Next crucial ingredient: Fluxes

- Fluxes are field strengths of (higher-dimensional analogues) of gauge fields, such as $F_{\mu\nu\rho}$, $G_{\mu\nu\rho}$
- They are crucial for the landscape since they stabilize the geometry and lead to $\sim 10^{500}$ possibilites
- Simplest version of an explanation:



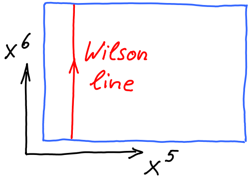
- This illustrates a flux wrapped on a 1-cycle of the torus

Next-simplest version:

(For those who know about quantization
of magnetic monopole charges.)

- Consider magnetic monopole in $\mathbb{R}^3$
- For reasons of quantum mechanical consistency, the charge is quantized in units of the electron charge
- In fact, this can be seen focussing only on the field strength on an S^2 surrounding this monople
- The field strength on this S^2 is 'twisted' in analogy to the Moebius strip on the previous slide
- Here, we are dealing with an $F_{\mu\nu}$-flux on a 2-cycle (the S^2)

Next-simplest version, but for $S^2 \rightarrow T^2$

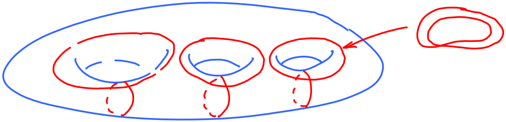


- With $A_6 = \alpha x^5$ we have $F_{56} = \alpha$
- The 'Wilson line' $w = \int dx^6 \, A_6$ induces a phase $\exp(iw)$ of the electron wave function
- In our case $w = w(x^5)$, which is only OK if

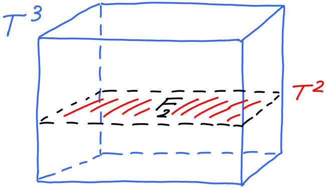
$$w(0) = w(1) + 2\pi N$$

$\Rightarrow$ Flux quantization

- Quite generally, fluxes ‘live’ on cycles of the compact space
- Example: several 1-cycles in 2d space



- Crucial: Higher-dimensional cycles (with fluxes) exist in higher-dimensional spaces
- Example: a 2-cycle in T^3



The string theory landscape

- Typcial CYs have $\mathcal{O}(300)$ 3-cycles
- Each can carry some integer number of flux of $F_{\mu\nu\rho}$, $H_{\mu\nu\rho}$
- With, for example, $N_{flux} \in \{-10, \ldots, 10\}$ on gets

$$(2 \times 20)^{300} \ \sim \ 10^{500} \text{ possibilities}$$

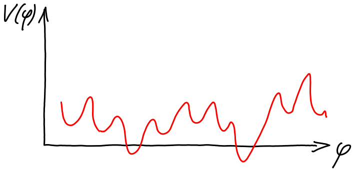
- This is the string theory landscape!
- To appreciate the complexity, recall that there are only $\sim 10^{80}$ atoms in our universe

...our mistake is not that we take our theories too seriously, but that we do not take them seriously enough.

S. Weinberg

The string theory landscape (continued)

- Each of these geometries corresponds to a solution ('vacuum') of the same, unique fundamental theory
- As an analogy: Think of all the different macromolecules that can be built in quantum mechanics from, e.g., nuclei of carbon, hydrogen and sulfur together with electrons
- Each solution has a different vacuum energy

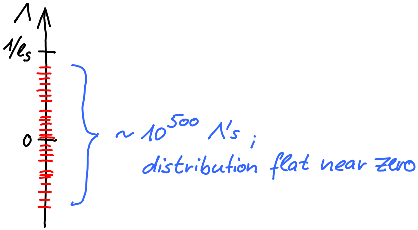


Here φ corresponds to $\{\varphi_1, \ldots, \varphi_n\}$, parametrizing the shape of the CY

The cosmological constant in the landscape

- Crucially, at least for part of the landscape, the statistical distriution of $\Lambda = V(\varphi_{\text{min}})$ can be calculated.

  It is 'flat' in the region near $\Lambda = 0$



- Thus, while having $\Lambda \sim 10^{-120}$ (as is measured) is extremely unlikely, it is known that such vacua do exist

- One can appeal to anthropic arguments to explain why we find ourselves in such an 'rare' vacuum

- If accepted, the above corresponds to a paradigm change in fundamental physics similar to the Copernican Revolution

- In brief: Our fundamental (4d) theory is not special - it is just one of many possibilities

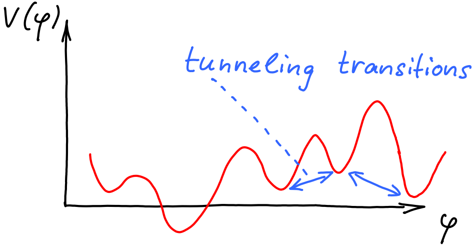
Weinberg '87
Bousso/Polchinski '00
Giddings/Kachru/Polchinski '01 (GKP)
Kachru/Kallosh/Linde/Trivedi '03 (KKLT)
Denef/Douglas '04

Populating the landscape

- Any vacuum with $\Lambda > 0$ gives classically an eternally expanding (de Sitter) universe

- However, by a quantum fluctuation, a bubble of a different vacuum can form, which then also expands

- .... just like bubble nucleation in first order phase transitions



Bubbles within bubbles within bubbles ....

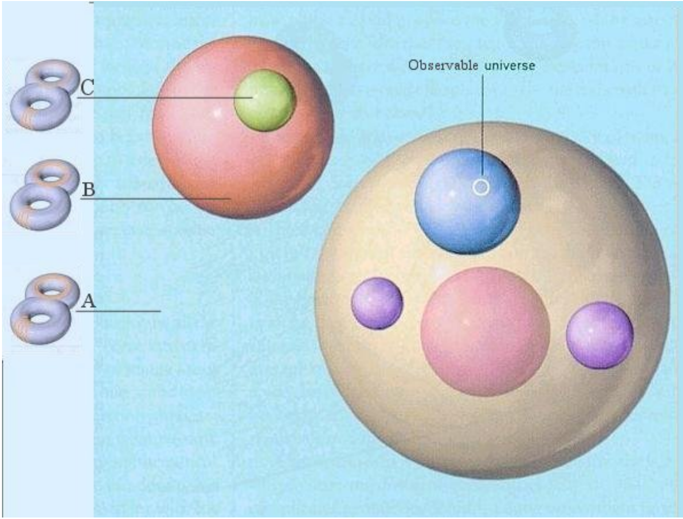
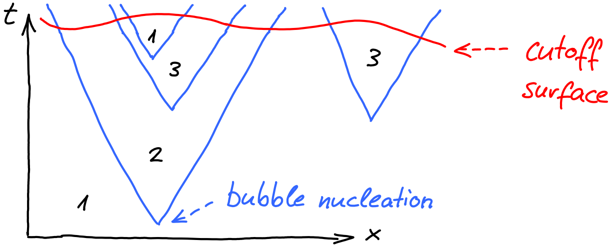


image from "universe-review.ca"

Bubbles within bubbles within bubbles ....

- More scientific but less pretty: A cartoon of eternal inflation in 2 dimensions



- The arbitrariness of the 'cutoff surface' is one of the faces of the measure problem – we don't know how to count and thus how to make even just statistical predictions

- Concerning ‘our’ universe, not all is well yet

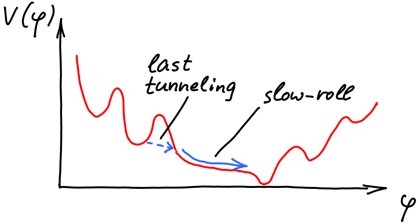
- While we could be in one of the suitable bubbles with $\Lambda \sim 10^{-120}$, all bubbles are strongly curved

  (i.e. the term k/a^2 dominates the Friedmann-Robertson-Walker equation from the start)

- To make our universe flat, we need a period of slow-roll inflation after the last tunneling event

Starobinsky ’80
Guth ’81
Linde ’82

Slow-roll inflation in the landscape



- This last period of slow-roll inflation is what we observe on the CMB-sky (Cosmic Microwave Background)

  (quantum fluctuations of φ transform into density perturbations transform into temperature fluctuations)

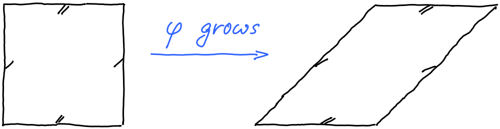
- The required flat part of the potential is surprisingly hard to get

Slow-roll inflation in the string theory landscape

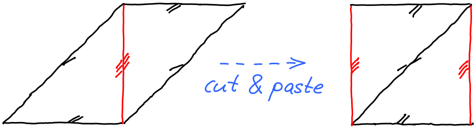
- Tho get slow roll inflation, the flat piece could be short and very flat or generic, but long ($\Delta\varphi \gg 1$))
- Only this last option describes 'primordial gravity waves' as recently 'suggested' (???) by BICEP
- As we will now see, this feature of '$\Delta\varphi \gg 1$' is extremely hard to get in string theory (chance of ruling our the landscape?)

Why is $\Delta\varphi \gg 1$ problematic?

- The field φ generically corresponds to some geometric feature of the CY, e.g. the shape of a torus

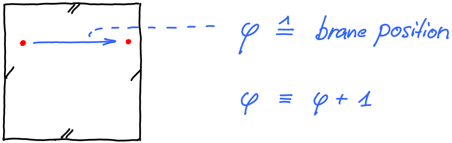


- However, after the angle of a torus has grown to 45°, it is secretly the same torus



- The problem is that this applies (more or less) to all 4d fields of a string compactification

- Another, even more obvious example arises if φ is a brane position. Clearly, this field is also periodic and the field space is hence limited:



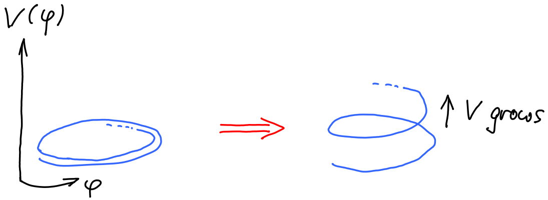
- One needs a new idea!

Monodromy inflation

- One relatively recent such idea is to introduce a monodromy

  Silverstein/Westphal '08

- A monodromy is a change in the potential,
  weakly breaking the periodicity in φ



- Various concrete stringy realizations have been discussed,
  especially since BICEP

  see e.g. Weigand/Palti '14

F-term axion inflation

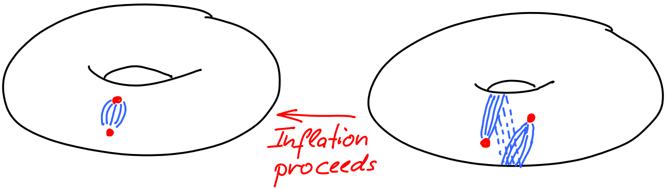
- Very recently, the first suggestions have emerged how this could be realized in a quantitatively controlled way

  (i.e. in a 4d supergravity description, with a stabilized compact space)

  Marchesano/Shiu/Uranga '14
  Blumenhagen/Plauschinn '14
  AH/Kraus/Witkowski '14

- In particular, in our suggestion inflation corresponds to brane-motion

- The monodromy arises from a flux sourced by the brane



Reminder of Outline

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- Compactifications to 4 dimensions
- The (flux-) landscape
- Eternal inflation and the multiverse
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'Conclusion'

- Inflation is developing into an interesting, quantitative playground for string theory and fundamental physics more generally....