A String Landscape Perspective on Naturalness

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Outline

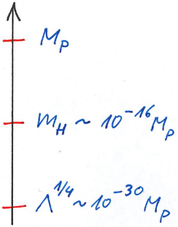
- Preliminaries (I): The problem(s) and the multiverse 'solution'
- Preliminaries (II): From field theory to quantum gravity
  (String theory in 10 dimensions)
- Compactifications to 4 dimensions
- The (flux-) landscape
- Eternal inflation, multiverse, measure problem

The two hierarchy/naturalness problems

- A much simplified basic lagrangian is

$$\mathcal{L} \sim M_P^2 R - \Lambda - |DH|^2 + m_h^2 |H|^2 - \lambda |H|^4 \ .$$

- Assuming some simple theory with $\mathcal{O}(1)$ fundamental parameters at the scale $E \sim M_P$, we generically expect Λ and m_H of that order.

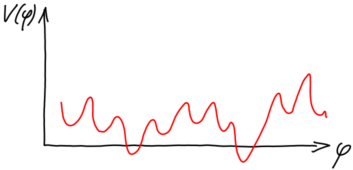


- For simplicity and because it is experimentally better established, I will focus in on the Λ-problem.
(But almost all that follows applies to both problems!)

The multiverse 'solution'

- It is quite possible that in the true quantum gravity theory, Λ comes out tiny as a result of an accidental cancellation.
- But, we perceive that us unlikely.
- By contrast, if we knew there were 10^{120} valid quantum gravity theories, we would be quite happy assuming that one of them has small Λ.
  (As long as the calculations giving Λ are sufficiently involved to argue for Gaussian statisics of the results.)
- Even better (since in principle testable): We could have one theory with 10^{120} solutions with different Λ.

Λ-values $\rightarrow$



The multiverse 'solution' (continued)

- This 'generic multiverse logic' has been advertised long before any supporting evidence from string theory existed.

  This goes back at least to the 80's and involves many famous names: Barrow/Tipler , Tegmark , Hawking , Hartle , Coleman , Weinberg ....

- Envoking the 'Anthropic Principle',

  [the selection of universes by demanding features which we think are necessary for intelligent life and hence for observers]

  it is then even possible to predict certain observables.

- Personally, I am not particularly attracted by this approach (e.g. because we do not know the conditions for life etc.)

- In my opinion, the situations changes fundamentally with the string theory landscape.

String Theory – a brief introduction/reminder

- I assume familiarity with Quantum Field Theory and want to view gravity as (very special) QFT

- 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.

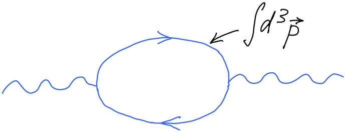
- In more detail: $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

- Expanding in the fluctuations $h_{\mu\nu}$, we find a standard QFT action (the ellipsis stands for interaction terms)
$$S_G = \int d^4x \, (\partial_\rho h_{\mu\nu}) \, (\partial^\rho h^{\mu\nu}) + \cdots$$

- Now, adding the Standard Model action (recall first slide), we have

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

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



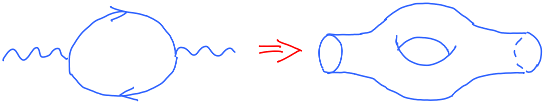
- Divergences are a hard but solvable problem for QFT.

(Crucially, in renormalizable QFTs
the number of free parameters stays finite.)

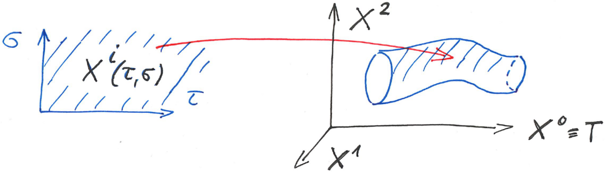
- However, these very same divergences make it very difficult to even define quantum gravity at $E \sim M_{Planck}$

String theory: ‘to know is to love’

- String theory replaces particles (photons, gravitons etc.) by small loops of a ‘unique, fundmanetal string’.



- The divergences at $\vec{p} \to \infty$ disappear.
- To describe gravity in D dimensions, one now works with a 2d QFT with D scalar fields.



String theory: 'to know is to love' (continued)

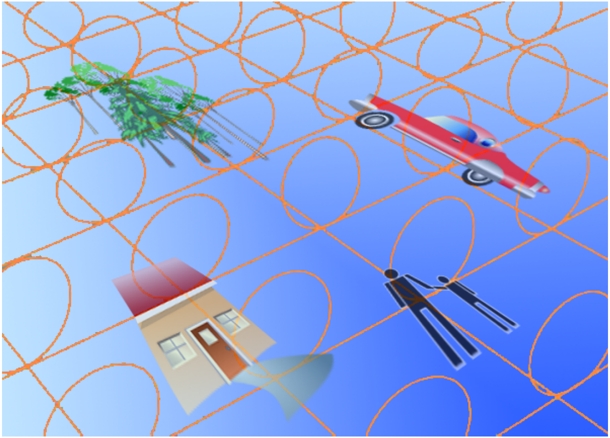
- Crucially, the 2d theory is actually conformal (a CFT).
- Consistency/calculability single out (2d) SUSY and $D = 10$.
- 10d scattering amplitudes map to CFT correlation functions.

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

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

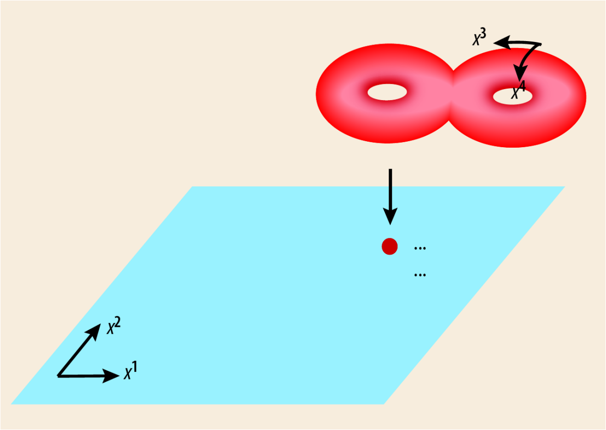
We need to 'compactify' 6 dimensions, going from 10d to 4d

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



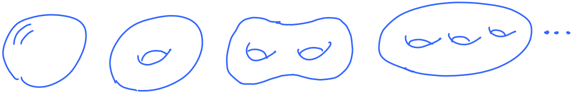
Compactification continued

- 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):



- To go from 10d to 4d, i.e. we need 6d compact spaces.
- These spaces must 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 expected but not established).

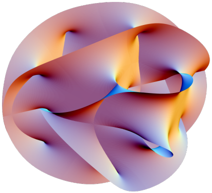


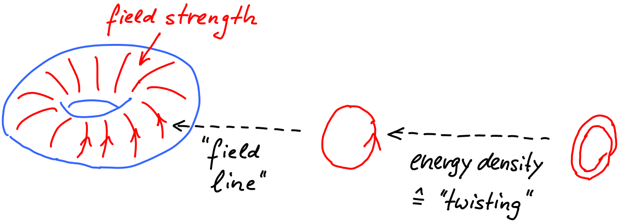
Image by J.F. Colonna

A crucial ingredient: Fluxes

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

Bousso/Polchinski '00
Susskind '03
Denef/Douglas '04

- Simplest version of an explanation:



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

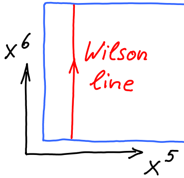
Next-simplest version:

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

- Consider magnetic monopole in $\mathbb{R}^3$
- For reasons of quantum mechanical consistency, its 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)

Proper math. language: The gauge theory over the S^2 is described by a non-trivial principal bundle

Next-simplest version, but for T^2 rather than S^2

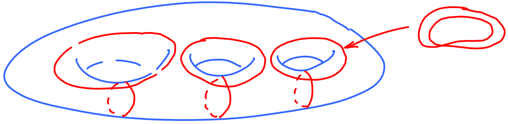


- With $A_6 = \alpha x^5$ we have $F_{56} = \alpha$
- The 'Wilson line' $w = \int dx^6 \, A_6$ induces a phase $\exp(iw)$ of the electron wave function
- In our case $w = w(x^5) = \alpha x^5$, which is only OK if

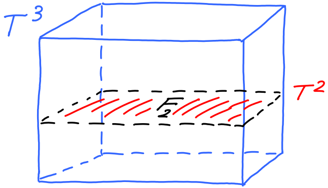
$$w(0) = w(1) + 2\pi N$$

$\Rightarrow$ α-quantization $\Rightarrow$ 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

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

Proper math. language: Number of points in some compact region of the (3-cycle lattice)^2

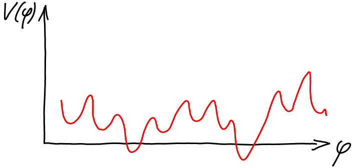
- This is the string theory landscape!
- To appreciate the complexity, recall that there are only $\sim 10^{80}$ atoms in our universe

...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

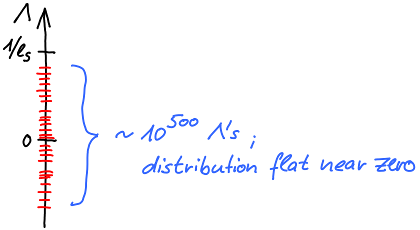


Here φ corresponds to $\{\varphi_1, \ldots, \varphi_n\}$, parametrizing the shape of the CY – they could e.g. be complex structure moduli

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

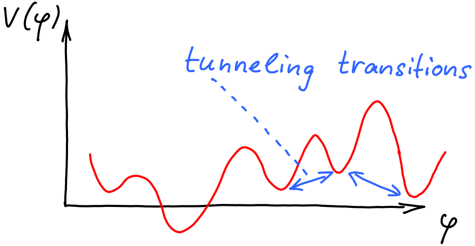
- If accepted, the above corresponds to a paradigm change in fundamental physics similar to the Copernican Revolution

- 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 ....

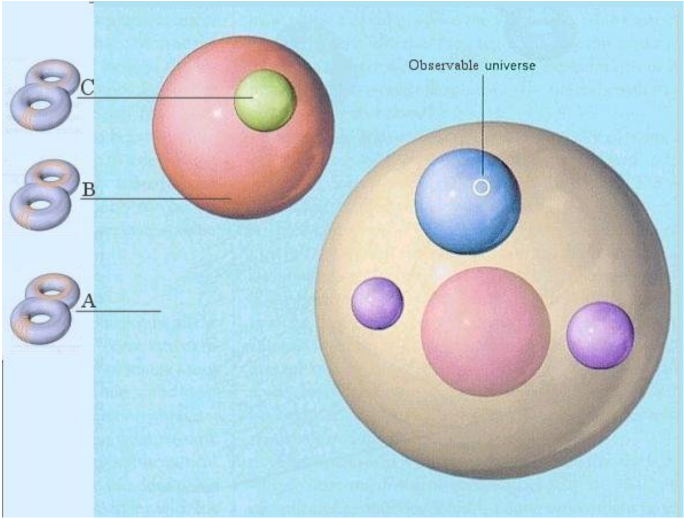
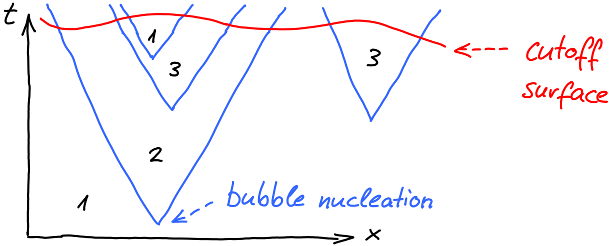


image from "universe-review.ca"

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

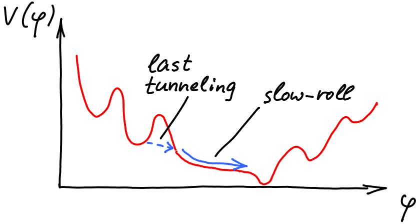
- While we could be in one of the suitable bubbles with $\Lambda \sim 10^{-120}$, all bubbles are strongly curved

  (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 – yet another fine tuning?

Back to the issue of fine-tuning (Λ and/or m_H) etc.

Now that we have the overall picture, let us return to the 'observed' fine tuning(s) in our universe.

- First, it is progress that now these tunings are not in conflict with a simple and unique fundamental (10d) lagrangian.
- Second, contrary to what is sometimes claimed, this success does not come at the price of losing predictibility.

  [Indeed, given a large enough collider, we could resolve the strings or trigger the nucleation of a new bubble inside our horizon.]

  We should not blame the theory for our inability to test it!
- Third, it is legitimiate to ask whether we can test theory at low energies by predicting (or even just understanding/postdicting) its 'accidental' parameters.

This predictivity aspect has two facets:

(1) Understanding the landscape

- We can ask how often which paramaters appear in the landscape.
- One can also ask about correlations between different parameters.
- This is an extremely challenging program (much of it in geometry at the mathematical research level).

A large part of the string community... '04 ... '17

Nevertheless, even the question whether TeV SUSY is more frequent than just a fine-tuned light Higgs is not unambiguously settled.

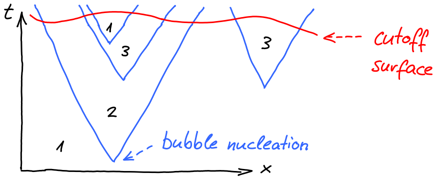
Susskind, Douglas, Banks ('04 ... '14) and refs. therein

But things get even worse:

(2) The measure problem

- Even knowing the landscape perfectly (including bubble nucleation rates), making predictions remains hard, even in principle.
- Ideally, we would simply count all observers who have measured certain values for $\mathcal{O}_1, \cdots, \mathcal{O}_n$.
- Then we want to ask which fraction of them measured e.g. $\mathcal{O}_{n+1} < 0.01$ and thus make a statistical prediction.
- But how do you count in an (unordered) infinity?

- Technically, the problem is the arbitrariness of the cutoff (which is needed for counting).



- The ambiguity comes from the absence of a universal clock
- Using e.g. the scale factor or the time (in Planck units) of a comoving observer are different options.
- Is there a fundamentally justifed measure?

  ... or is the measure a new theory input?

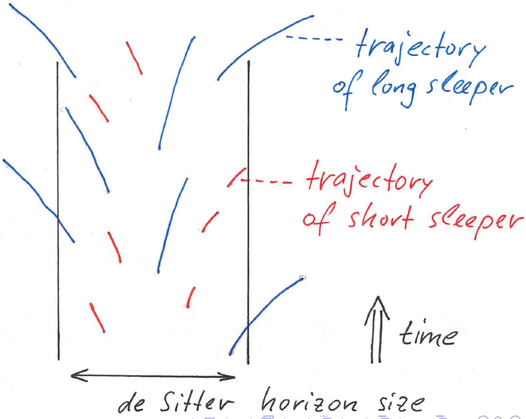
  ... or are such statistical predictions simply impossible?

See work by Linde, Vilenkin, Bousso, Nomura, Freivogel, Garriga, ...

The Guth-Vanchurin paradox as an illustration of how confusing the measure problem can be...

(see also Bousso et al. '10)

- Observers in de Sitter space randomly (50/50) go to bed for a long or short sleep.
- What is the probability for an awakening observer that he slept for a long or short time?
- Of course 50/50 !
- But: the awakening observers see themselves surrounded mostly by short sleepers.



Summary / Conlcusions

- The eternally inflating multiverse based on the string landscape offers a ‘solution’ to (perceived?) fine tuning problems.
- It is a solution only in the sense of explaining why, in a simple and unique theory, there can be observers who see a fine-tuned world.
- The landscape also offers hope for an actual understanding or prediction of apparently fine-tuned constants of nature.
- But two obstacles have to be overcome:
  the compexity of the landscape and the measure problem.