Dark energy, the string landscape and the swampland

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VCES

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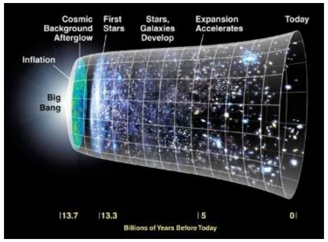
FWF
Der Wissenschaftsfonds.

Outline

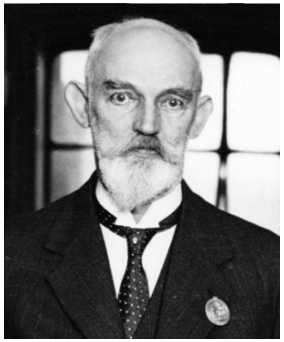
- Introduction to dark energy



- The landscape of dS vacua

- The dS swampland conjecture

- Status of dS vacua in string theory



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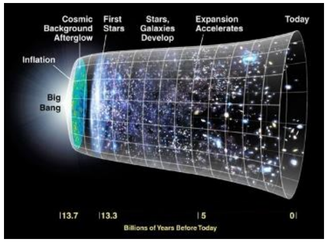

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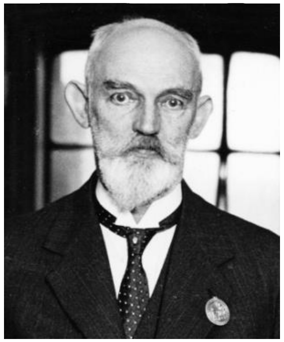

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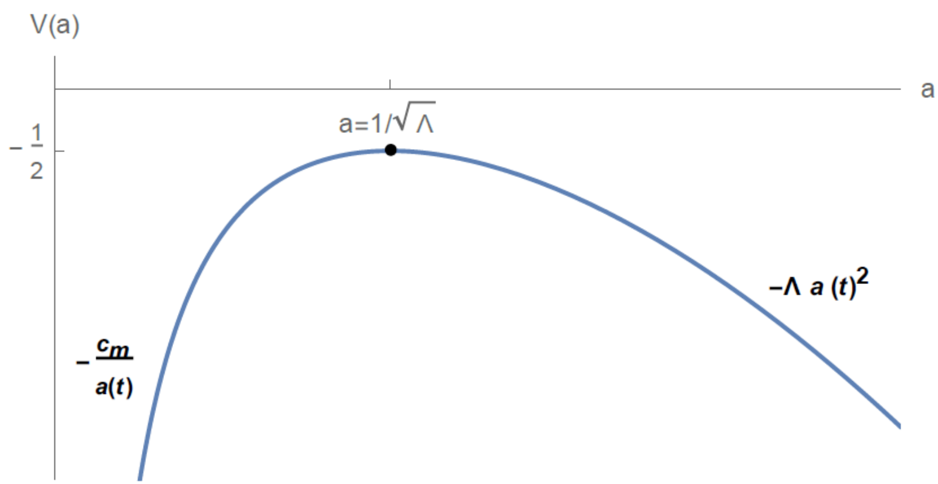
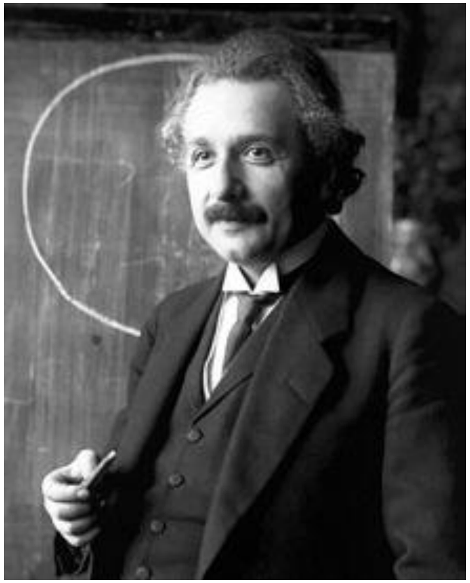
Einstein's static universe

- In 1917 Einstein tried to apply his theory of general relativity to our universe, which he believed to be static
- A universe filled only with matter does not allow static solutions, so he added a cosmological constant Λ





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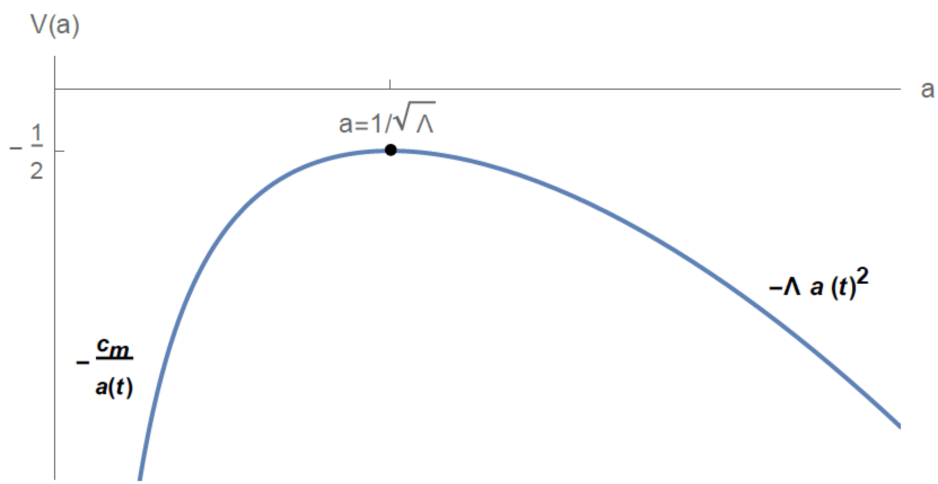
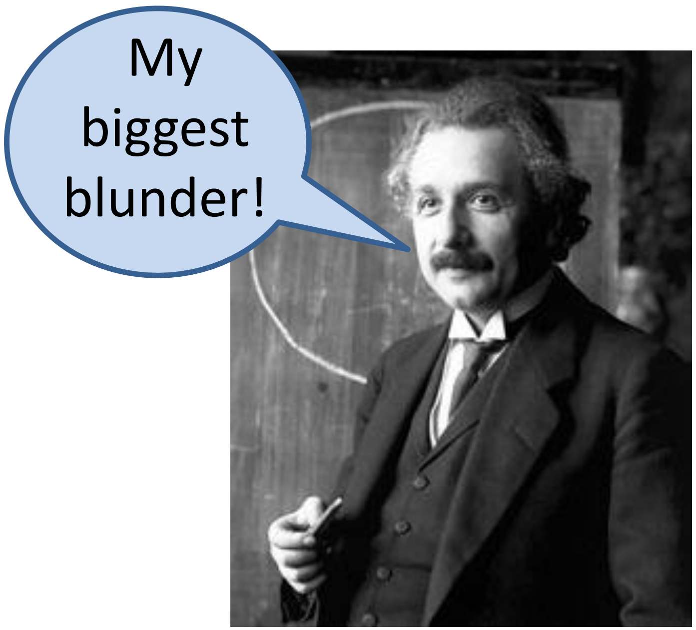
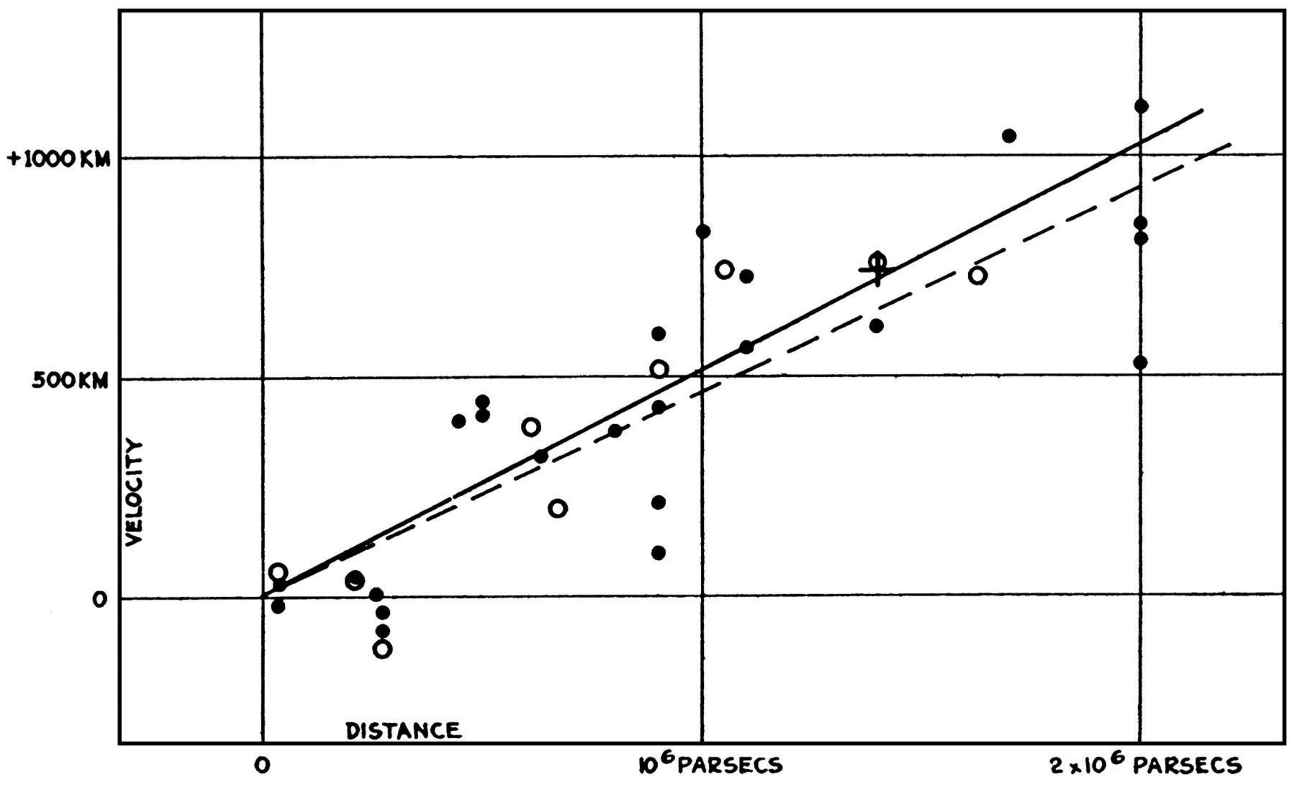




Our expanding universe

In 1929 Hubble discovered that the space in our universe is expanding (instead of being static):



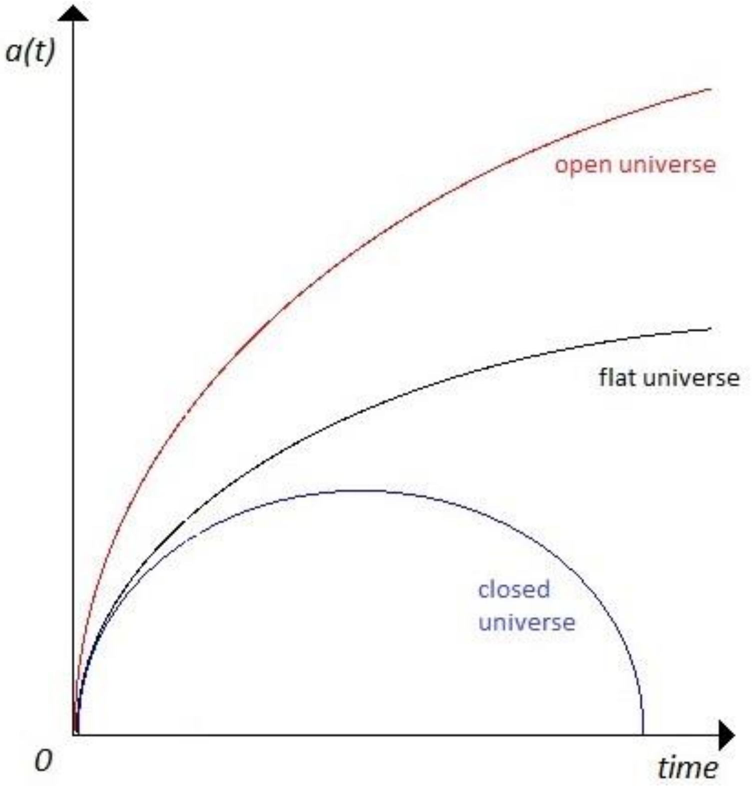
Our expanding universe

In 1929 Hubble discovered that the space in our universe is expanding (instead of being static):

Our universe is filled with matter that slows down the expansion

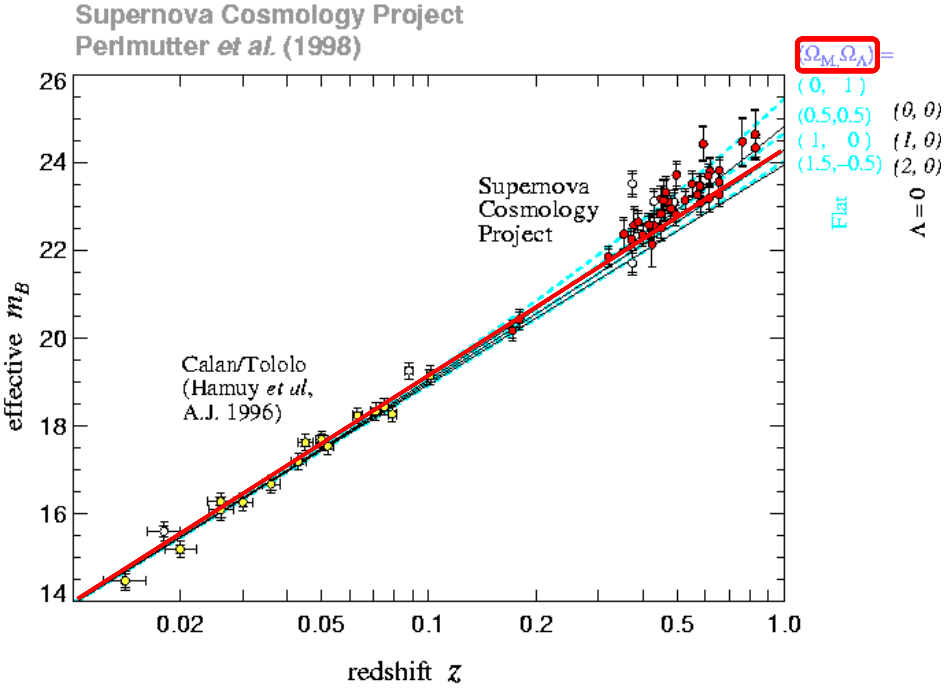
⇒ decellaration

$$\ddot{a}(t) < 0$$



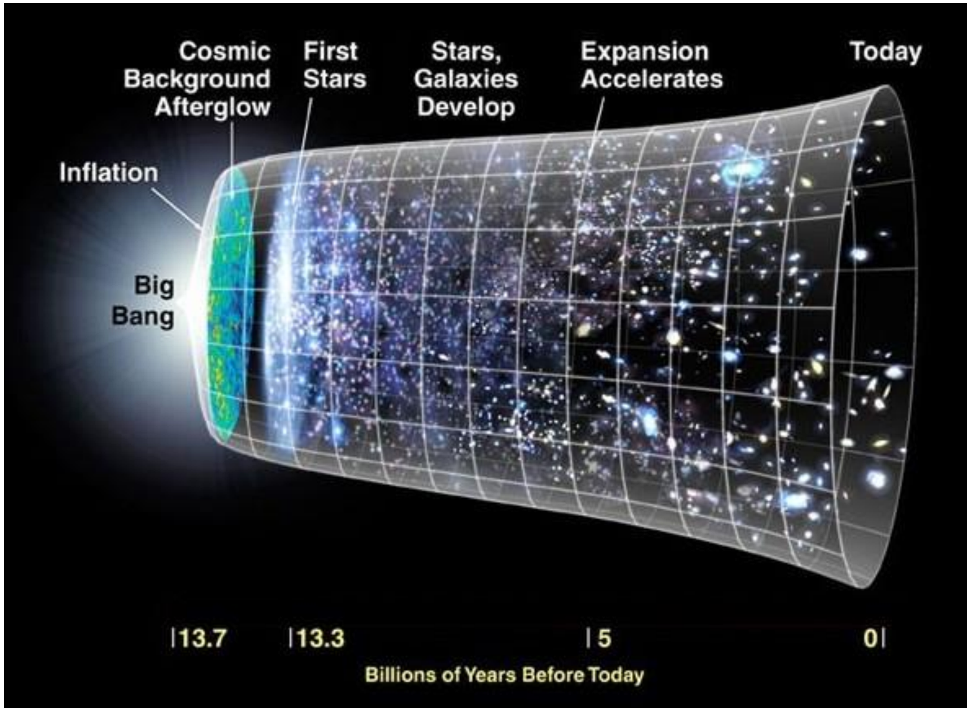
Accelerated expansion of our universe

In 1998 the Supernova Cosmology Project and the High-Z Supernova Search Team observed type Ia supernovae and found evidence for an accelerated expansion of our universe



Accelerated expansion of our universe

This discovery led to the 2011 Nobel Prize for
Saul Perlmutter, Adam Riess and Brian Schmidt
and the following picture of our universe



Accelerated expansion of our universe

The equations follow from GR coupled to matter

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N \, T_{\mu\nu}$$

For the homogeneous and isotropic FRW metric

$$ds^2 = -dt^2 + a(t)^2 (dx^2 + dy^2 + dz^2)$$

$$T_{\mu\nu} = \sum_k \begin{pmatrix} \rho_k & \vec{0} \\ \vec{0} & P_k g_{ij} \end{pmatrix}, \quad k = \text{matter, dark energy,...}$$

Accelerated expansion of our universe

An accelerated expansion of an FRW-universe requires

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) = -\frac{4\pi G}{3}\rho(1 + 3w) > 0$$

$P = w\rho$ $\qquad$ $w < -\frac{1}{3}$ $\qquad$ equation of state parameter

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Simplest GR explanation is a cosmological constant

$$S_{EH} = \int d^4x \sqrt{-g}\left(-\mathrm{M}_\mathrm{p}^4\,\lambda - M_P^2 R + \cdots\right)$$

$$T_{\mu\nu} = \begin{pmatrix} \rho & \vec{0} \\ \vec{0} & P\,g_{ij} \end{pmatrix} \propto \lambda\, g_{\mu\nu} \quad \Rightarrow \quad w = -1$$

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Simplest GR explanation is a cosmological constant

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Cannot do that in string theory. No free parameters!

Accelerated expansion of our universe

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Simplest GR explanation is a cosmological constant

$$S_{EH} = \int d^4x \sqrt{-g}\left(-\mathrm{M_p^4}\,\lambda - M_P^2 R + \cdots\right)$$

$$S_{string} = \int d^4x \sqrt{-g}\left(-V(\phi) - M_P^2 R + \cdots\right)$$

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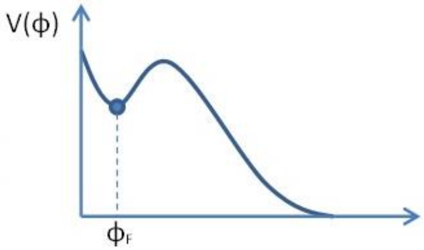
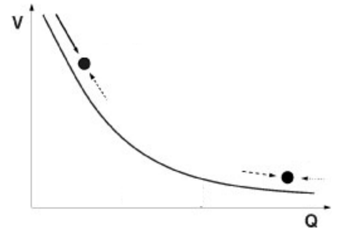
dS vacua /Λ: $w = -1$



Quintessence: $w = \frac{\frac{1}{2}m\dot{\phi}^2 - V(\phi)}{\frac{1}{2}m\dot{\phi}^2 + V(\phi)} > -1$



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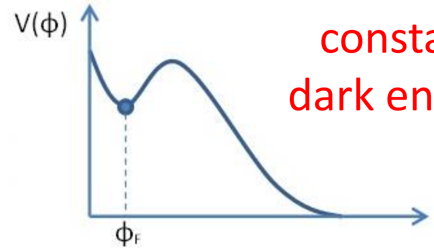


constant dark energy

Quintessence: $w = \frac{\frac{1}{2}m\dot{\phi}^2 - V(\phi)}{\frac{1}{2}m\dot{\phi}^2 + V(\phi)} > -1$

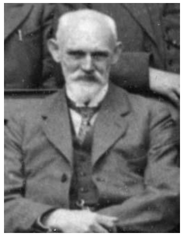
dark energy changes in time

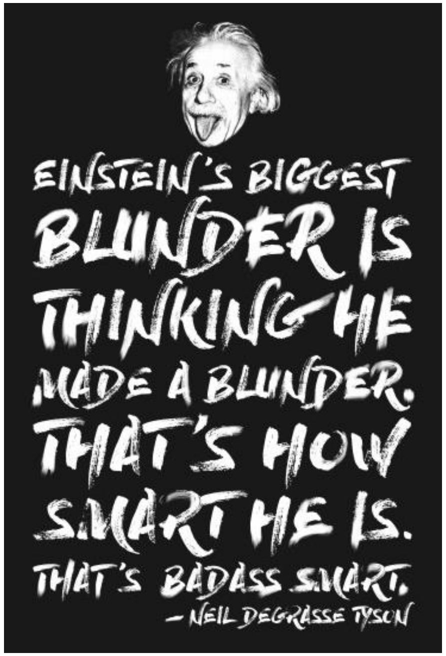
Accelerated expansion of our universe

The tremendous amount observational progress in the last decade has led to very stringent bounds on w. Combining results from the Planck Satellite with other astrophysical data leads to

Planck Collaboration 1807.06209

$$w = -1.03 \pm .03$$





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Accelerated expansion of our universe

Assuming that the acceleration is due a cosmological constant (or a de Sitter vacuum in string theory), we are faced with the cosmological constant problem:

$$S_{EH} = \int d^4x \sqrt{-g} \left(\mathrm{M}_\mathrm{p}^4 \, \lambda + M_P^2 R \cdot 1 + \cdots \right)$$

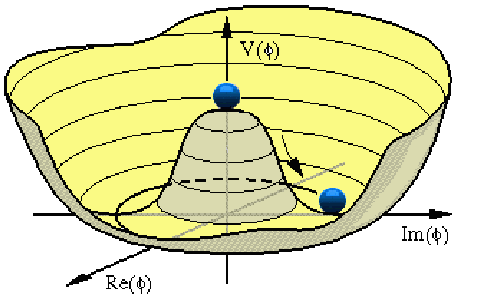
$$\Lambda = M_P^4 \, \lambda \sim 10^{-120} M_P^4$$

Why is Λ so incredibly small???

Accelerated expansion of our universe

Λ consist of a bare value Λ_{bare} plus corrections:

- Electroweak phase transition



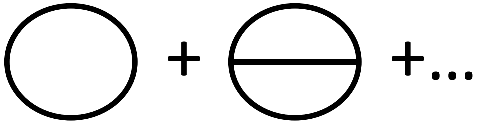
$$\Lambda_{EW} \approx -1.2 \times 10^8 GeV^4$$

- QCD transitions

$$\Lambda_{QCD} \approx 10^{-2} GeV^4$$

- Quantum corrections (for standard model particles)

$$\Lambda_{vac} \approx -2 \times 10^8 GeV^4$$



Accelerated expansion of our universe

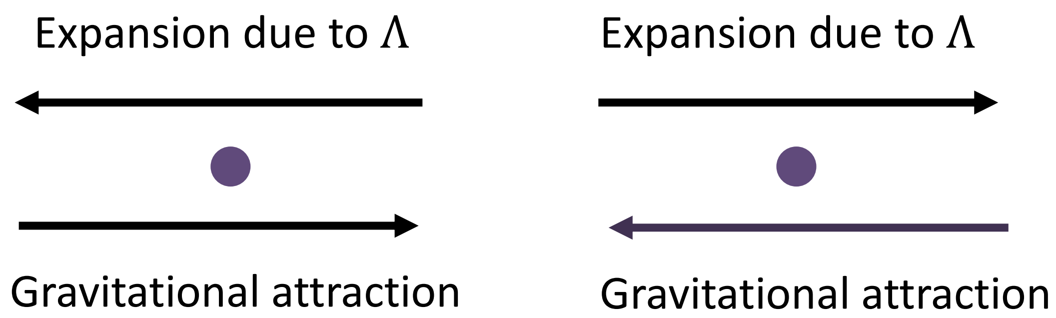
All these contributions to Λ need to cancel very precisely:

$$\Lambda = \Lambda_{bare} + \Lambda_{EW} + \Lambda_{QCD} + \Lambda_{vac} + \cdots \approx 10^{-47} GeV^4$$

Since $|\Lambda_{\mathrm{EW}}| \approx 10^8 GeV^4$ we need to cancel numbers at least to 55 digits!

An anthropic argument

- In 1987, 11 years before the discovery of a non-zero cosmological constant, Weinberg asked how large can a positive Λ be, while still allowing for the formation of structure (= life)



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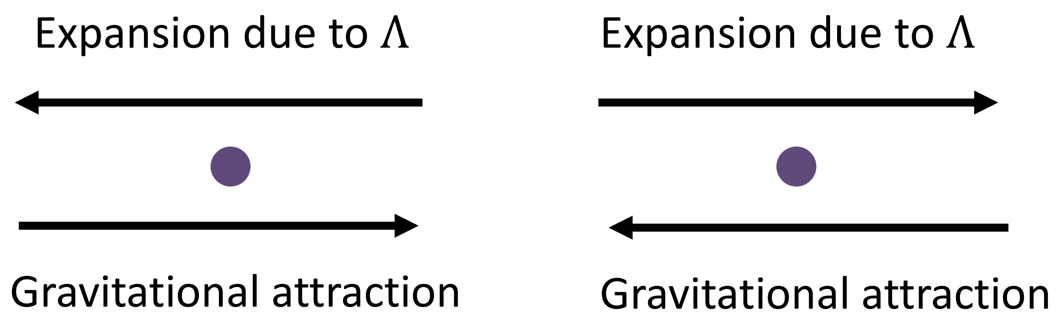

Structure formation requires $\Lambda < 200 \cdot 10^{-120} M_P^4$

An anthropic argument

Steven Weinberg:

"It would be a disappointment if this were the solution of the cosmological constant problems, because we would like to be able to calculate all the constants of nature from first principles, but it may be a disappointment that we will have to live with."

An anthropic argument

- Kepler tried to derive the distances between the planets and the sun from an underlying theory
- We now know that the radii are `accidents’

An anthropic argument

- Kepler tried to derive the distances between the planets and the sun from an underlying theory
- We now know that the radii are `accidents’
- There are many planets inside and outside our solar system and we are of course living on a planet inside the Goldilock zone
- This *anthropic argument* crucially relies on the existence of many planets

An anthropic argument

- This *anthropic argument* crucially relies on the existence of many "universes"

- Assuming that we have an ensemble of universes with equally spaced values of the cosmological constant between 0 and M_P^4, we would need to have:

number of universes > 10^{120}

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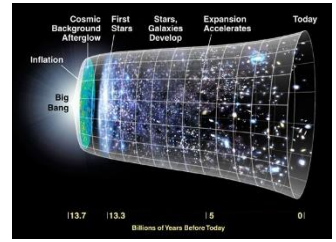

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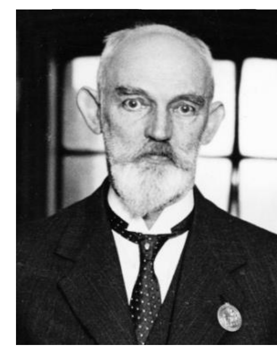

- Conclusion

What is string theory?

- String theory is a theory of *quantum gravity*
- It can unify the two pillars of fundamental physics:
  - General Relativity: Standard Model of Cosmology
  - Quantum Field Theory: Standard Model of Particle Physics

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  } String Theory
- No evidence that string theory is the correct theory to describe our universe
- `Stringy' effects could in principle appear at any energy scale, but don't have to unless $E \geq M_P$

Why string theory?

- String theory is UV complete so it does not break down at high energies, but the cosmological constant problem deals with the lowest energy scales ($\sim meV$). So do we *need* string theory?

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Yes! Let‘s assume there is a new massive particle we have not yet discovered. It contributes to Λ as

Martin 1205.3365

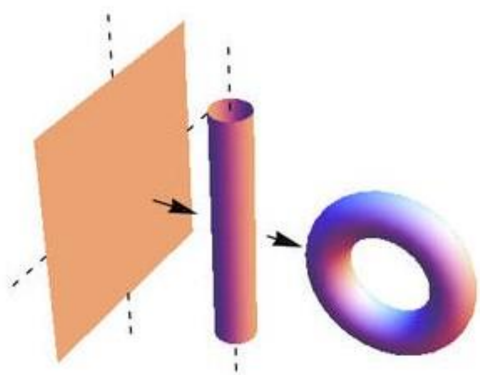
$$\Lambda_{new} \propto m^4 \ln\left(\frac{m^2}{\mu^2}\right)$$

$\Rightarrow$ So need to know all massive particles to calculate Λ

This can be done in string theory

String compactifications

- String theory has many extra dimensions that we need to compactify (usually 6 extra dimensions)

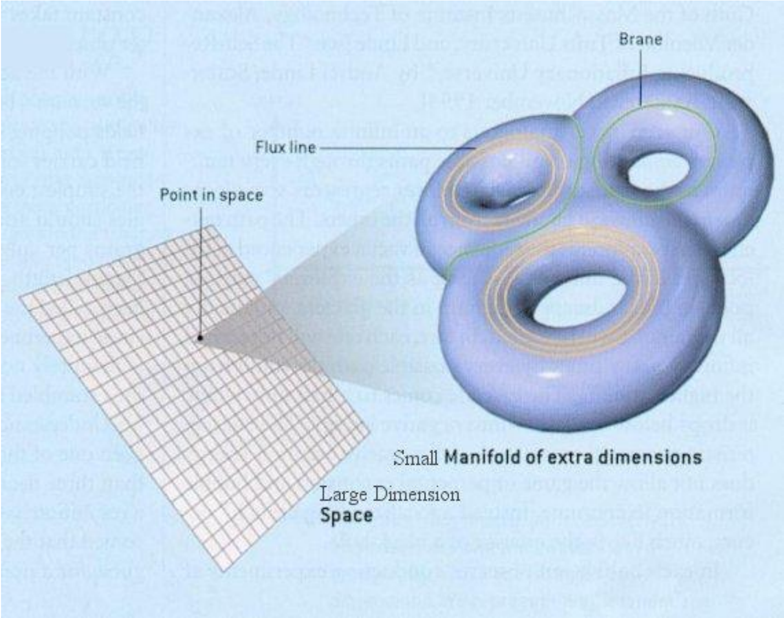


- The simplest compactifications give rise to 4D theories with many massless scalar field ϕ^I

$\Rightarrow$ Moduli Problem

String compactifications

- We can generate a potential for these scalar fields by including fluxes, D-branes, O-planes, …

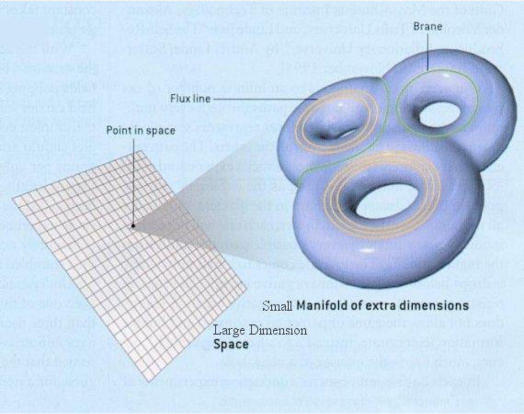


- This leads to a potential for the scalars $V(\phi^I)$

The landscape

String theory additionally provides insight into what is and isn't possible in a theory of quantum gravity:

1. No free parameters like $\Lambda \;\Rightarrow V(\phi)$
2. The scalar potentials in string theory depend on many different parameters and moduli ϕ^I, the number of choices are estimated to be



$$10^{500} \;-\; 10^{272\,000}$$

$\Rightarrow$ The string landscape + Weinberg "explain" small Λ

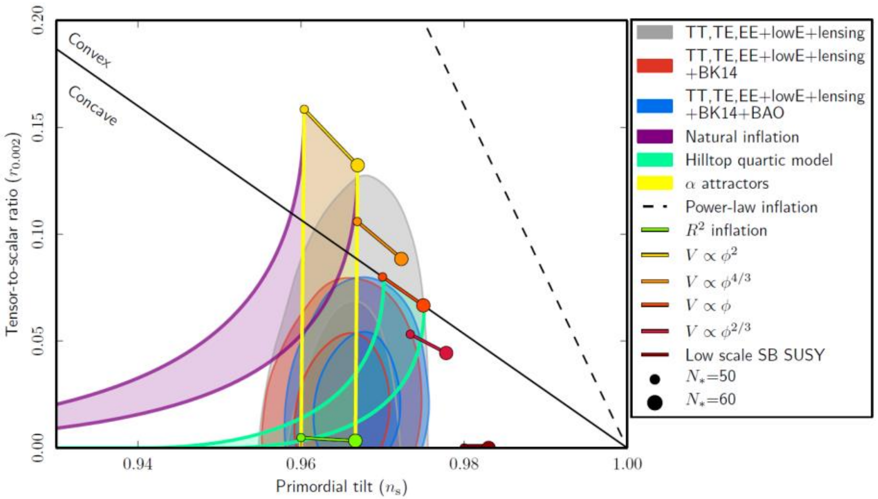
String cosmology

- The *first dS vacua* in string theory without massless fields and tunable $\Lambda = V_{\min}$ where constructed in 2003

  Kachru, Kallosh, Linde, Trivedi hep-th/0301240

- There were many more dS vacua constructions in the last 15 years (but also criticism, as reviewed below)

- Very fruitful collaboration with cosmologists



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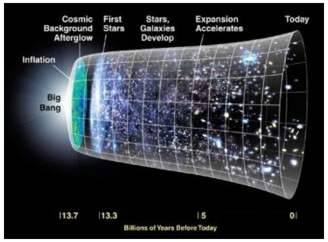

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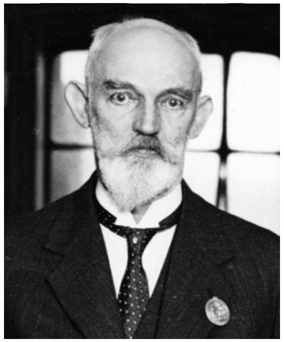

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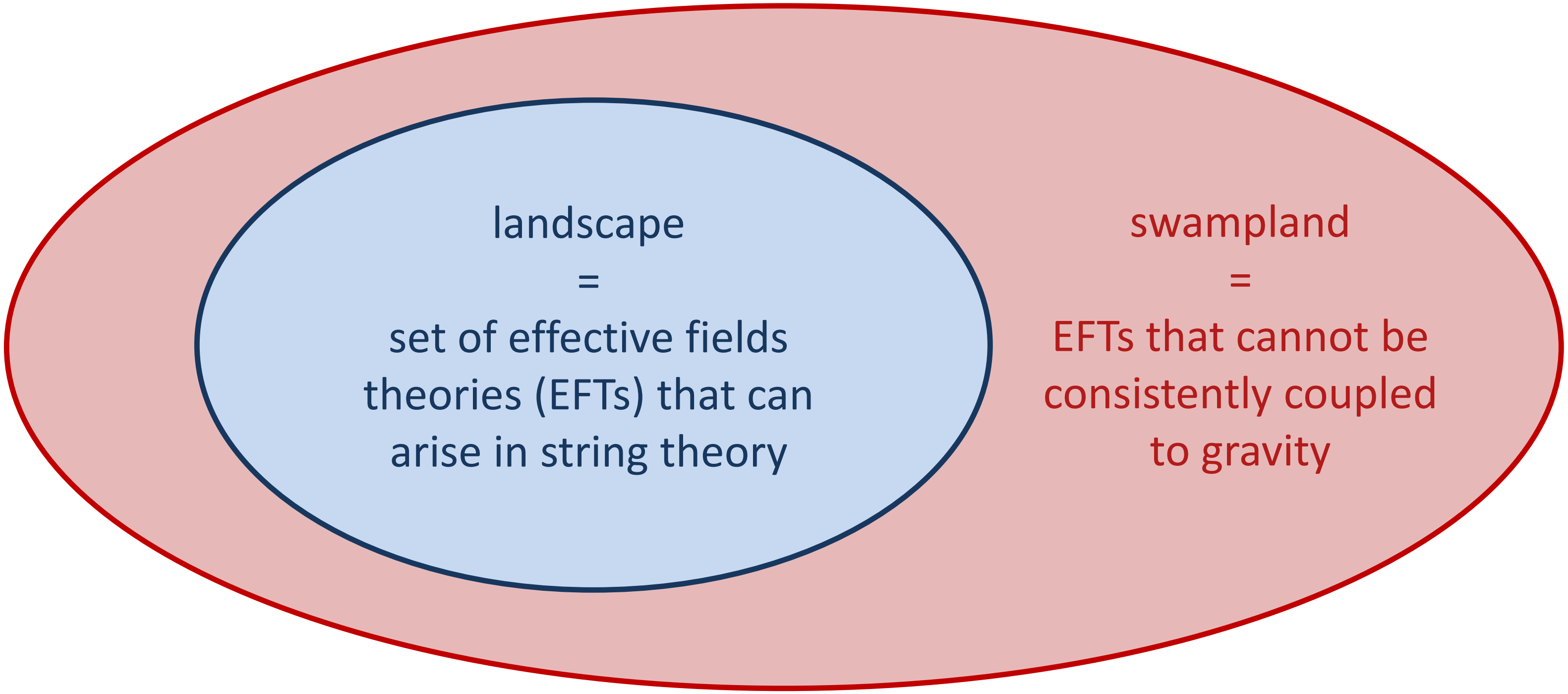
The swampland

- The landscape has led to unjustified criticism of string theory (everything goes ⇔ no predictive power)
- It has been always conjectured that not everything goes

Brennan, Carta, Vafa 1711.00864



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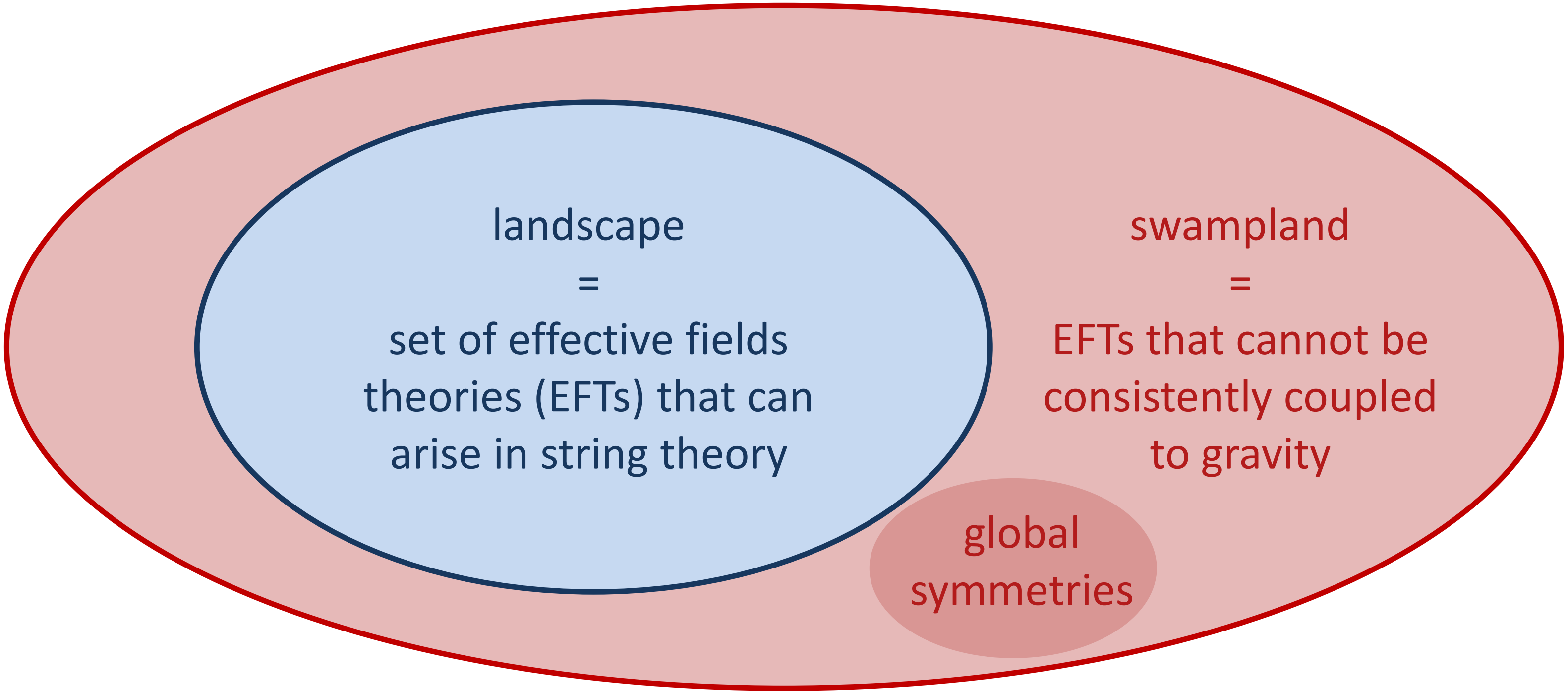

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II. All charges appear
III. Finite number of massless fields
IV. No free parameters
V. Non-compact moduli space

VI. Distance conjecture
VII. Simply connected moduli space
VIII. Weak gravity conjecture
IX. No AdS/CFT without SUSY
X. No de Sitter vacua

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The swampland

- The weak gravity conjecture states that gravity is always the weakest force

Arkani-Hamed, Motl, Nicolis, Vafa hep-th/0601001

- In any theory with gravity and a $U(1)$ gauge field there exist a particle with mass m and charge q such that

$$\frac{m}{M_P} < q \qquad \text{(trivial for } M_P \to \infty\text{)}$$

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- Clearly satisfied in our universe for example for the electron
- Always satisfied in string theory

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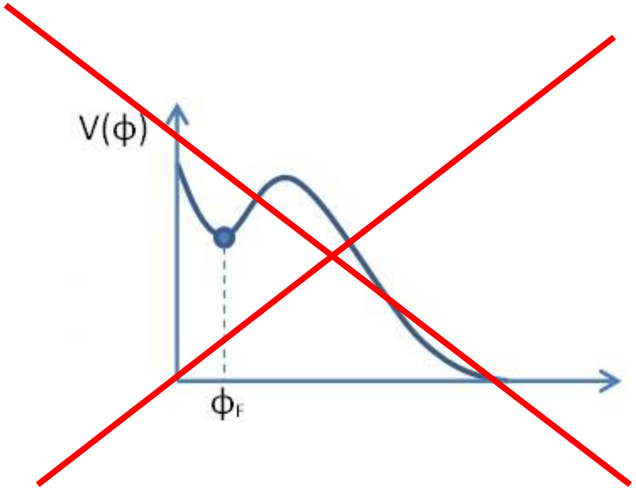
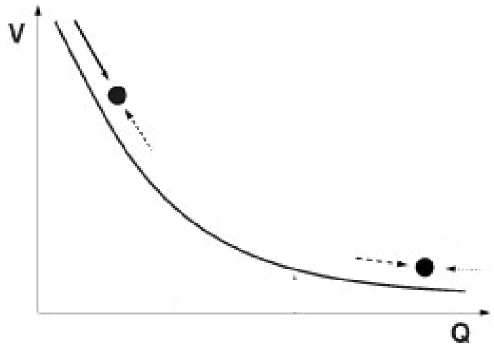
dS extrema and the swampland

Recent papers call for a paradigm change

Brennan, Carta, Vafa 1711.00864
Danielsson, Van Riet 1804.01120
Obied, Ooguri, Spodyneiko, Vafa 1806.08362
Agrawal, Obied, Steinhardt, Vafa 1806.09718

Conjecture: $|\nabla V| \geq c\,V$ for $c \sim O(1)$





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Inflation $\overset{?}{\Rightarrow}$ string gas cosmology, bouncing cosmology, …

dS vacua $\Rightarrow$ quintessence

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Conjecture: $|\nabla V| \geq c\, V$ for $c \sim O(1)$

Inflation $\overset{?}{\Leftrightarrow}$ current experimental bound $c \leq .09$, $\nabla V \leq .09V$

dS vacua $\Rightarrow$ quintessence $V(\phi) \sim e^{c\phi}$ bound $c < .54$, $\nabla V \leq .54V$

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Ein hochgeachteter Physiker der Harvard-Universität äußert eine verwegene Hypothese - und erschüttert damit die Fachwelt. *Von Johann Grolle*

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KOSMOLOGIE

Führt die Stringtheorie ins Sumpfland?


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The dS swampland conjecture

- What is the conjecture based on?

1. Ongoing debate about the correctness of existing constructions of dS vacua in string theory
2. Absence of simple dS vacua in string theory (for example with large cc in D-dimension)
3. Many explicit and simple setups do not give rise to dS vacua but satisfy the conjecture with $c > 1$

The dS swampland conjecture

- What is the conjecture not based on?

1. Explicit calculations that show how all the existing counter-examples to the conjecture are wrong*

   *) admittedly very difficult because there are many

2. Discussion of one or more explicit problems in the existing constructions that the authors believe to be fatal

The dS swampland conjecture

- The original conjecture is in tension with the Higgs potential (and pion potential)

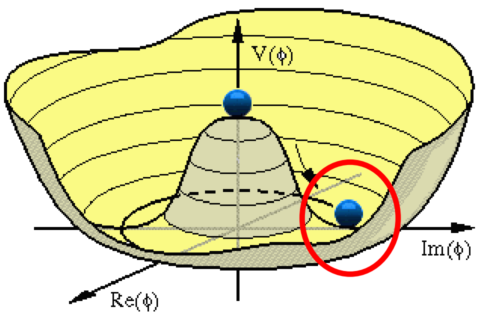
Denef, Hebecker, Wrase 1807.06581
Cicoli, De Alwis, Maharana, Muia, Quevedo 1808.08967
Murayama, Yamazaki, Yanagida 1809.00478
Choi, Chway, Shin 1809.01475
Hamaguchi, Ibe, Moroi 1810.02095

$|\nabla V| \geq c\, V$ for $c \sim O(1)$

If $V(\phi, H) = V_\phi(\phi) + V_H(H)$, then for

$H = H_{min}$ we have

$\nabla V = \partial_\phi V = \partial_\phi V_\phi \approx .54\, V \approx 10^{-120} M_P^4$



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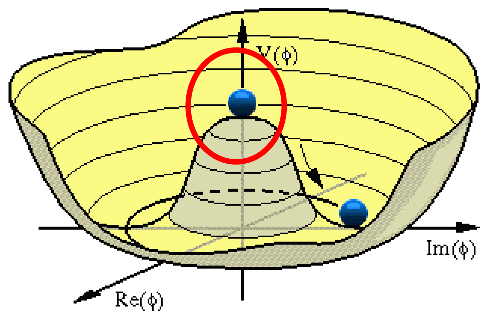
and for $H = 0$ we have

$\nabla V = \partial_\phi V = \partial_\phi V_\phi \approx 10^{-120} M_P^4 \ll \Lambda_{EW}$



The dS swampland conjecture

- One would have to couple the very light quintessence scalar ϕ to the Standard Model, e.g.

$$V(H,\phi) = e^{-c\phi}V_H(H)$$

- This leads to a fifth forth/equivalence principle violation and needs to be compatible with all current observations

- This seems very difficult for $c{\sim}O(1)$ (similar problem for π_0)

Choi, Chway, Shin 1809.01475

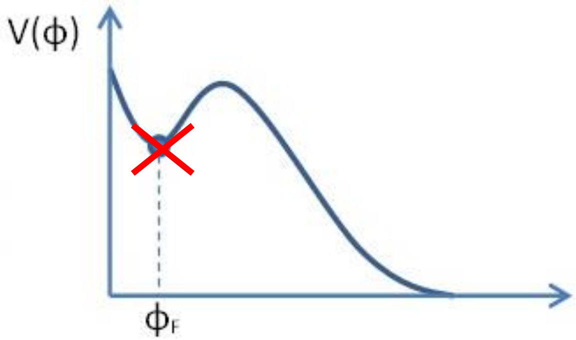
The dS swampland conjecture

- The refined dS swampland conjecture states

Dvali, Gomez 1806.10877
Andriot 1806.10999
Garg, Krishnan 1807.05193
Ooguri, Palti, Shiu, Vafa 1810.05506

$|\nabla V| \geq c\, V$ or $\min(\nabla_i \nabla_j V) \leq -c' V$ $\quad c, c' \sim O(1)$

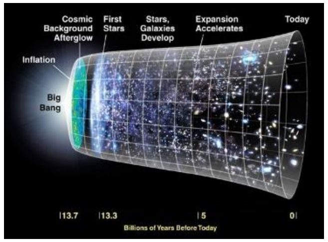
This forbids minima but allows dS maxima (that are not overly flat)



Similar to *no* slow-roll, $\epsilon_V \geq O(1)$ or $\eta_V \leq -O(1)$

Outline

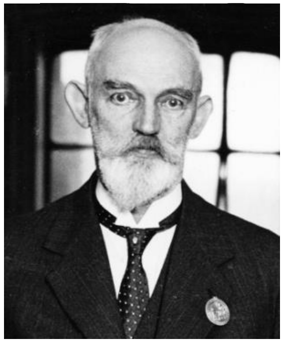
- Introduction to dark energy



- The landscape of dS vacua

- The dS swampland conjecture

- Status of dS vacua in string theory



- Conclusion

Status of dS vacua in string theory

Why are dS vacua harder to find?

1. Usually we use SUSY to simplify our lives. This allows us to solve 1st order equations. Not possible for dS, which requires 2nd order equations.

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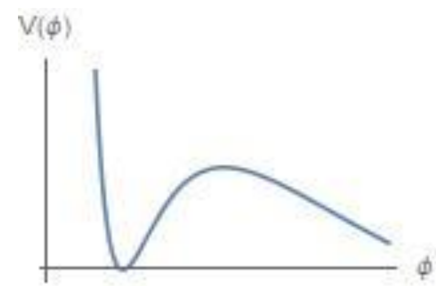
3. Scalar potentials vanish for $\phi \to \infty$, so usually we need at least three different terms to stabilize ϕ

$$V(\phi) \propto \frac{a}{\phi^2} - \frac{b}{\phi^3} + \frac{c}{\phi^4}$$



Status of dS vacua in string theory

What can we do about the (refined) dS swampland conjecture?

1. We can find a deep reason why dS minima should be forbidden in quantum gravity

2. We can scrutinize existing constructions to spell out explicitly potential shortcomings

3. We can try to construct simple dS vacua in string theory to gain insight into what is and what isn't possible

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KKLT dS vacua in string theory

- The KKLT scenario of dS vacua gives realistic dS vacua

  Kachru, Kallosh, Linde, Trivedi hep-th/0301240

- It first gives a large mass to all but one complex scalar by threading the internal space with fluxes

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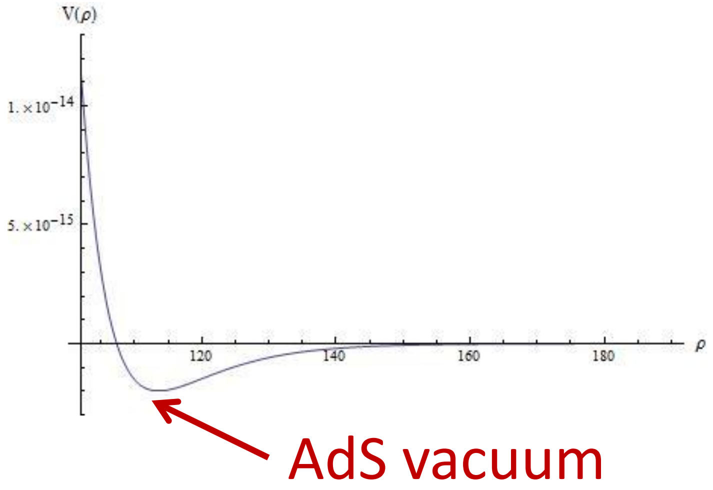
- Then it includes non-perturbative corrections for the single remaining scalar field to generate an AdS vacuum



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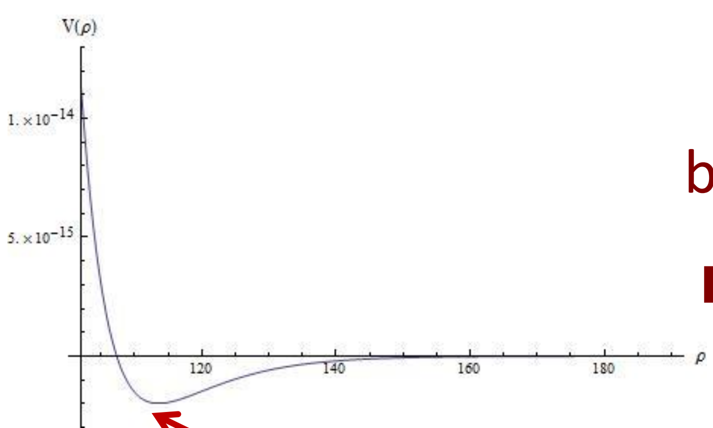
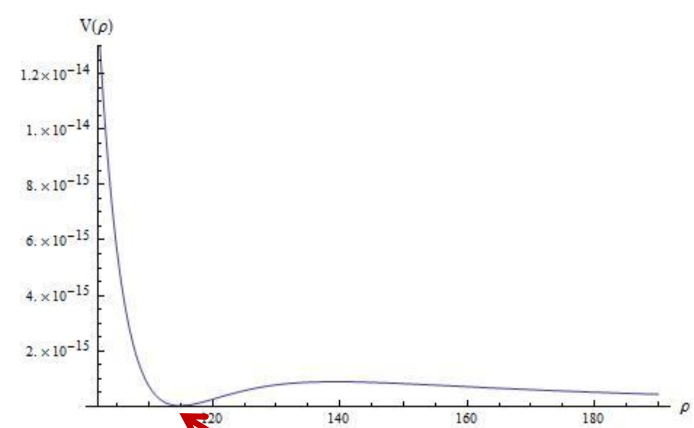


AdS vacuum

Adding an anti-D3-brane "uplift"



dS vacuum

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- It first gives a large mass to all but one complex scalar by threading the internal space with fluxes
- Then it includes non-perturbative corrections for the single remaining scalar field to generate an AdS vacuum
- The SUSY breaking scale is arbitrary and much larger than the cosmological constant
- The “uplift” is dialable in such a way that extra corrections do not spoil the setup (addition of SM)

Partly full Partly empty

Taken from talk by F. Quevedo @ Vistas over the swampland, Madrid, September 2018

Status of dS vacua in string theory

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- So called type IIA and IIB look easiest

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DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

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DeWolfe, Giryavets, Kachru, Taylor hep-th/0505160

- Stable dS vacua have been searched for but only critical points have been found (until recently)

Flauger, Robbins, Paban, TW 0812.3886

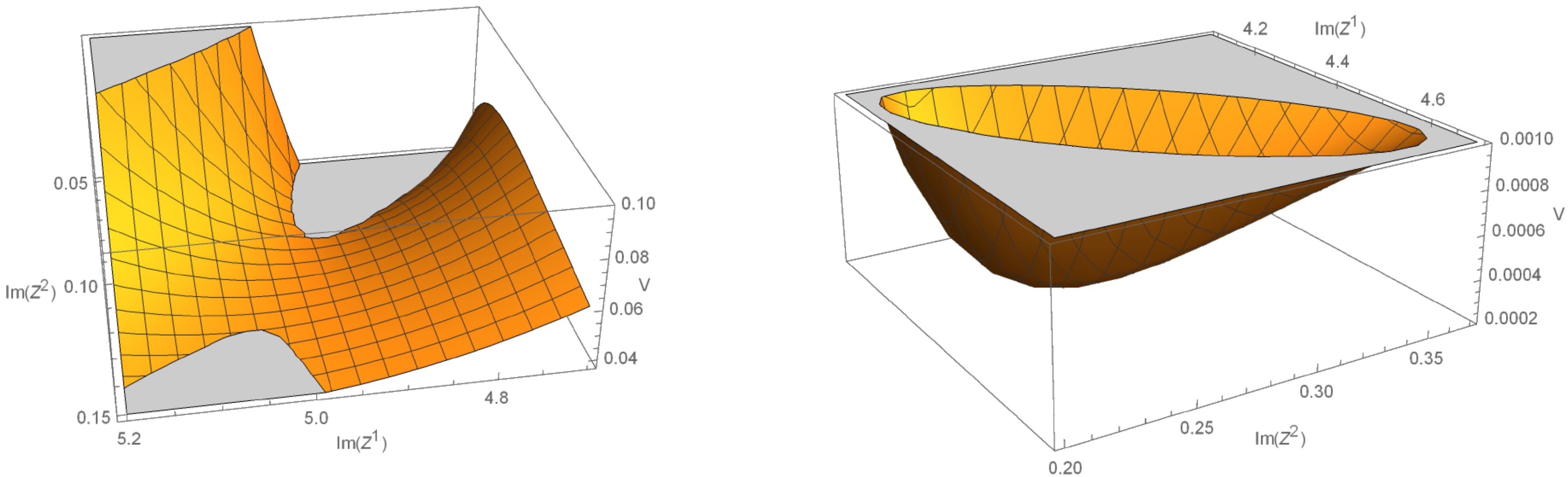
Caviezel, Koerber, Körs, Lüst, TW, Zagermann 0812.3551

Danielsson, Haque, Shiu, Van Riet 0907.2041

Caviezel, TW, Zagermann 0912.3287

Danielsson, Koerber, Van Riet 1003.3590

Anti-D6-branes in massive IIA



- Checked explicitly in the simplest example $S^3 \times S^3/Z_2 \times Z_2$
- The one obstinate tachyonic direction is now stable
- dS solutions at slightly shifted values, *do not seem to be trustworthy* in this example (small volume, large coupling)

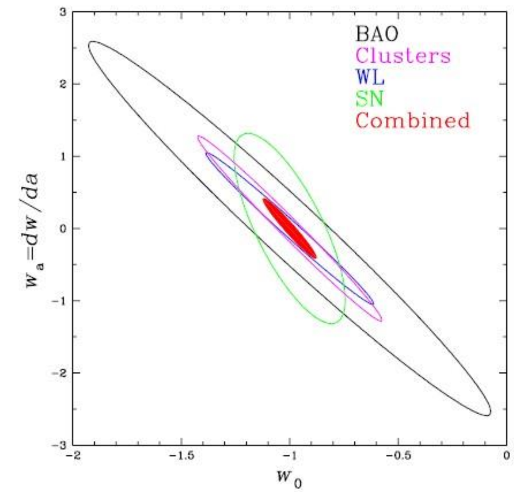
Kallosh, Wrase 1808.09427

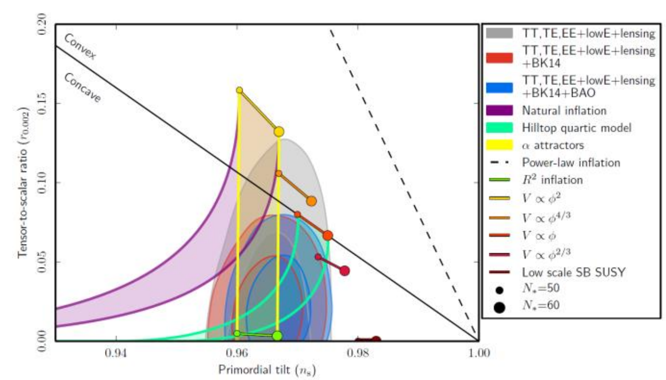
Banlaki, Chowdhury, Roupec, Wrase 1811.07880

Summary

Current experiments search for signatures of inflation and quintessence:

$$c_{inflation} < .09, \quad c_{dark\ energy} < .54$$





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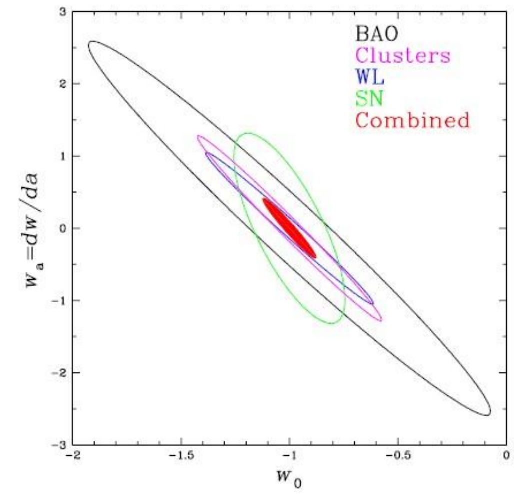
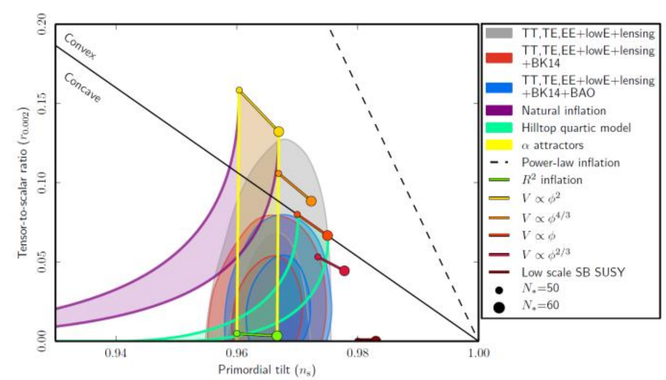
If the conjecture is right, then experiments should see something very soon $\Rightarrow$ super exciting!





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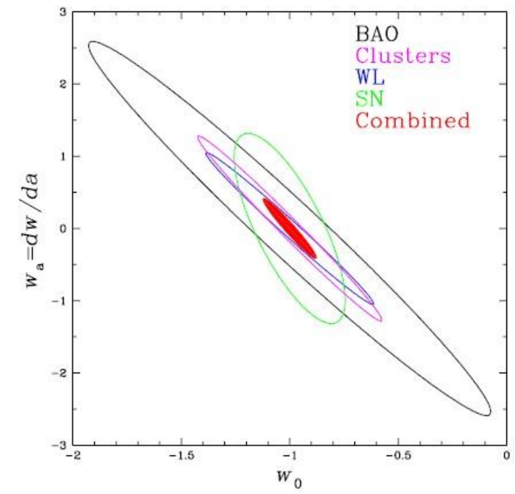

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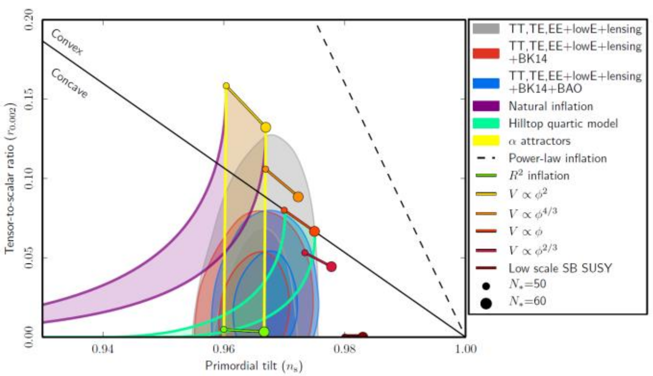
We as string theorist are trying to explore all possible ways of explaining existing and potential future observations, i.e. quintessence etc. should be studied more (independent of conjecture)



Cicoli, De Alwis, Maharana, Muia, Quevedo 1808.08967

Conclusion

- Recent conjecture states that dark energy cannot be constant. Do we need a paradigm change in string cosmology?
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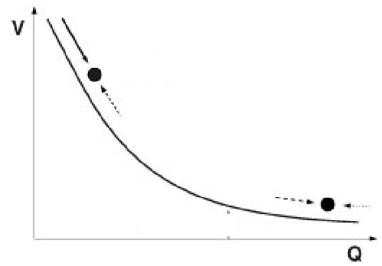
THANK YOU!

The dS swampland conjecture

- The dS swampland conjecture is *currently* compatible with our universe, $c_{dark\ energy} < .54 \approx O(1)$



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  - $M_P \to \infty$ makes it trivial: $\mathrm{M}_P |\nabla V| \geq c\ V$

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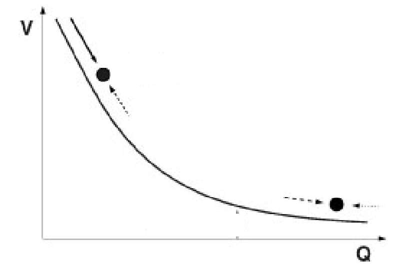

- It passes consistency checks:
  - $M_P \to \infty$ makes it trivial: $\mathrm{M}_P|\nabla V| \geq c\ V$
  - Condition is trivial for Minkowsi and AdS vacua $\mathrm{V} \leq 0$
  - Quadratic potentials are ok, $V = \frac{1}{2}m^2\phi^2$:

$$\frac{\mathrm{M}_P|\nabla V|}{V} = \frac{2\ \mathrm{M}_P}{\phi} \geq c,\ \text{for } \phi < M_P \text{ (SDC)}$$