UNIVERSITY OF LIVERPOOL

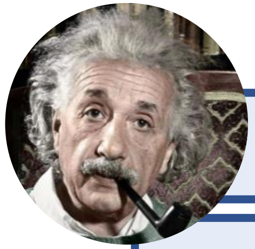
Young Theorists Forum 20
16th December 2020

NEVER HAVE I EVER
used a constant to fix my problem

Bruno Valeixo Bento

Partly based on work in collaboration with
Susha Parameswaran, Ivonne Zavala, Dibya Chakraborty

The Cosmological Constant [Chapter 1]



Albert

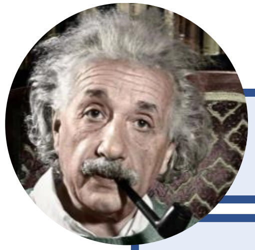
Hey guys! Here's gravity!

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Karl

As you see, the war treated me kindly enough, in spite of the heavy gunfire, to allow me to get away from it all and take this walk in the land of your ideas.

$$ds^2 = -\left(1 - \frac{2GM}{r}\right) dt^2 + \left(1 - \frac{2GM}{r}\right)^{-1} dr^2 + r^2 (d\theta^2 + \sin^2\theta\, d\phi^2)$$



Albert

Ups...There was a mistake!

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

That term is necessary only for the purpose of making possible a quasi-static distribution of matter, as required by the fact of the small velocities of the stars.

The Cosmological Constant [Chapter 1]

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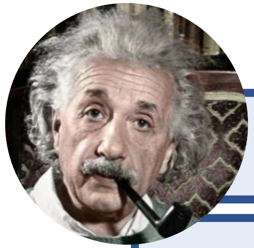
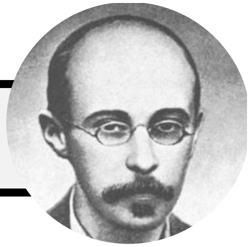


Albert

Ups…There was a mistake! No static Universe otherwise…

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

Alexander



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The Cosmological Constant [Chapter 1]

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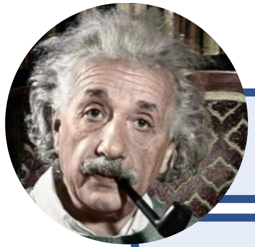

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Totally agree with this! ^

The Cosmological Constant [Chapter 1]

FLRW background

curvature

$$ds^2 = -dt^2 + a^2(t)\left(\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\varphi^2)\right)$$

Einstein Equations ⇒ Friedmann Equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho_{tot}}{3M_{Pl}^2} - \frac{k}{a^2} \qquad \frac{\ddot{a}}{a} = -\frac{1}{6\,M_{Pl}^2}(\rho_{tot} + 3P_{tot})$$

acceleration requires

$$\boxed{\omega_{eff} = \frac{P_{tot}}{\rho_{tot}} < -\frac{1}{3}}$$

$$ds^2 = -\left(1-\frac{2GM}{r}\right)dt^2 + \left(1-\frac{2GM}{r}\right)^{-1} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)$$

The Cosmological Constant [Chapter 1]

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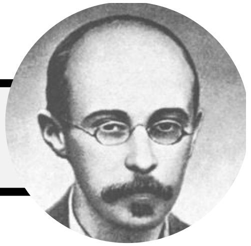

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Sorry bro... Those galaxies are definitely running away! Red as a tomato...

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The Cosmological Constant [Chapter 1]

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This message was removed

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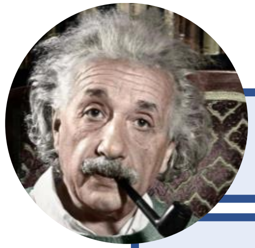


Albert

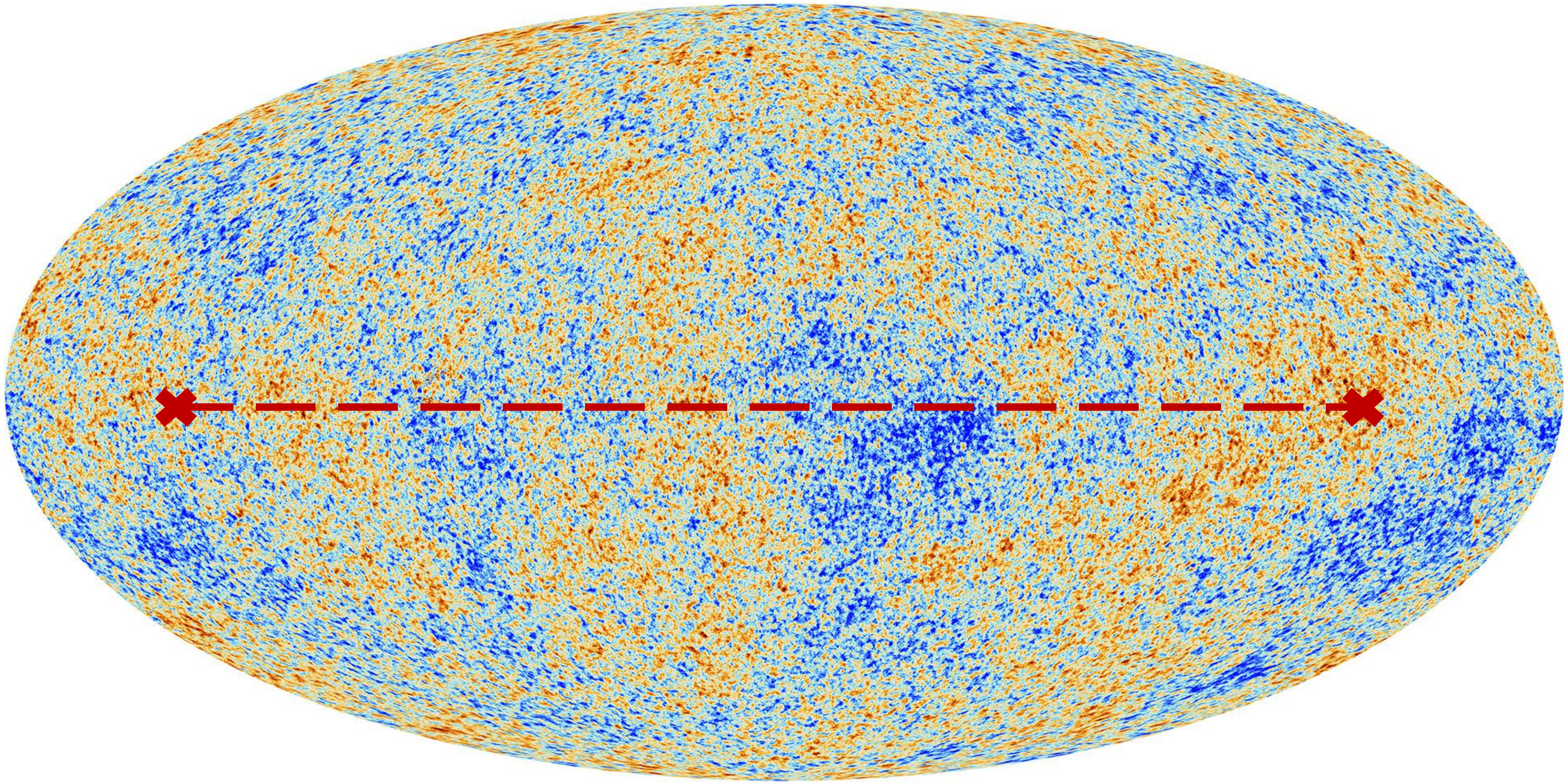
Oh... What a *blunder*!

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

$$\boxed{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = T_{\mu\nu}}$$

The Cosmological Constant [Chapter 2]

The Fake Return or the subtleties of Inflation



The Cosmological Constant [Chapter 2]

The Fake Return or the subtleties of Inflation

A temporary cosmological constant in the early universe would help with…

1. Horizon problem
2. Flatness problem
3. Magnetic monopoles problem

$\Rightarrow$ INFLATION

Period of exponential expansion in the early universe

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = T_{\mu\nu}$$

$$= T_{\mu\nu}^{vac} + \tilde{T}_{\mu\nu}$$

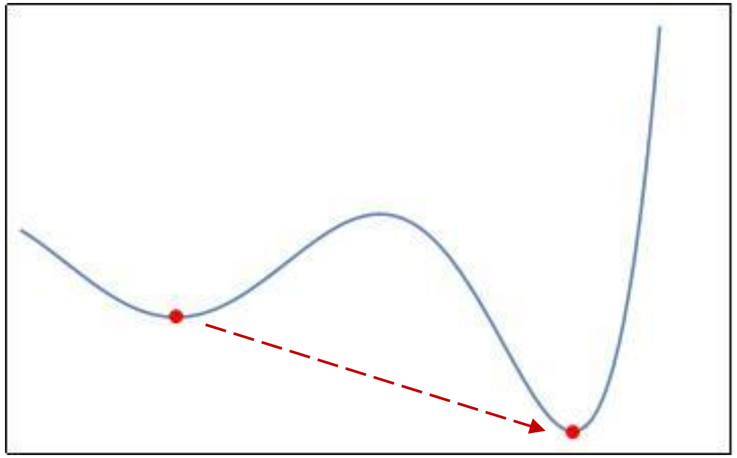
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda^{\text{vac}} g_{\mu\nu} = \tilde{T}_{\mu\nu}$$

Any vacuum energy will look like a cosmological constant!

The Cosmological Constant [Chapter 2]

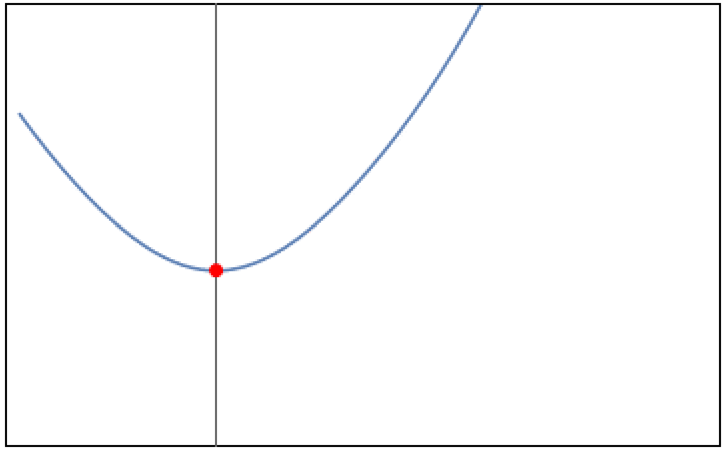
The Fake Return or the subtleties of Inflation

OLD INFLATION



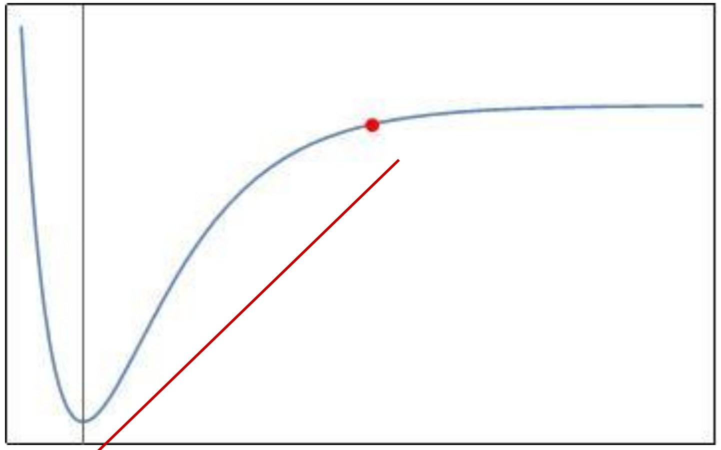
Only phase transitions

NEW INFLATION



Phase transition + slow-roll

CHAOTIC INFLATION



Only slow-roll
"Chaotic" initial conditions

Find flat enough potentials

The Cosmological Constant [Chapter 2]

The Fake Return or the subtleties of Inflation

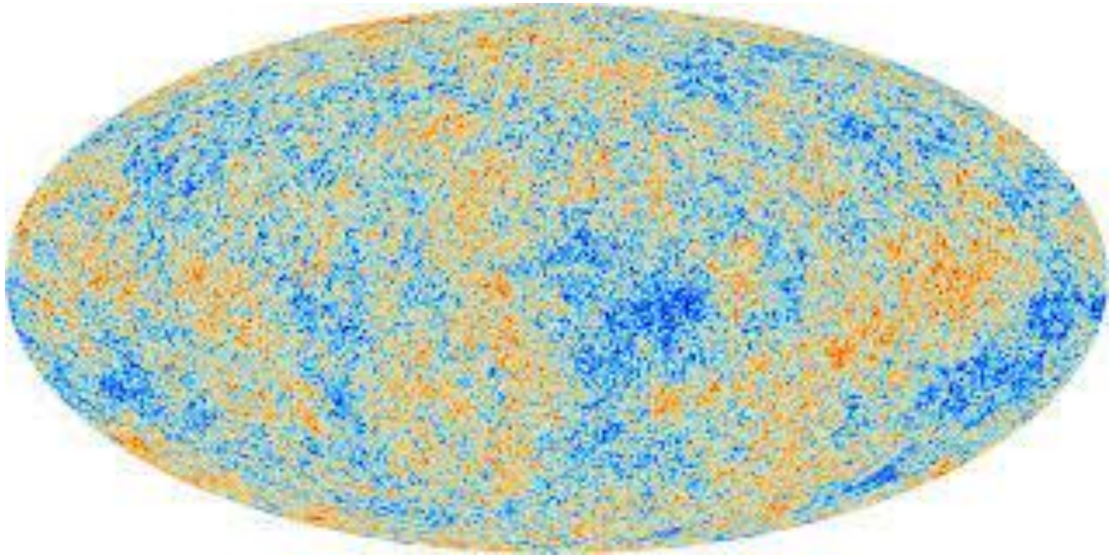
Inflation has its own specific needs:

- Enough expansion ($N \sim 60$)
- To reproduce power spectrum, e.g.

$$n_s = 0.9626 \pm 0.0057$$

$$r < 0.056$$

- To end → Not *the* Λ
- with reheating



The anisotropies of the CMB as observed by Planck.
Image by ESA and Planck collaboration

Planck collaboration
[arxiv:1807.06211]

The Cosmological Constant [Chapter 3]

The True Return or the birth of Dark Energy

[1998] Houston, we have a problem… The Universe is accelerating!

 [Saul Perlmutter, Brian P. Schmidt, Adam G. Riess]

1. Bring back Λ (ΛCDM)
2. Have a positive energy vacuum (de Sitter)
3. Have a slowly rolling scalar field (Quintessence)
4. ???

The Cosmological Constant [Chapter 3]

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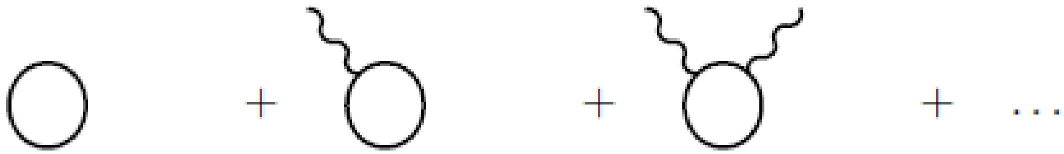


Too large in SM

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda^{\mathrm{vac}} g_{\mu\nu} = \tilde{T}_{\mu\nu}$$

Antonio Padilla
[arxiv:1502.05296]

The Cosmological Constant [Chapter 3]

The True Return or the birth of Dark Energy

[1998] Houston, we have a problem… The Universe is accelerating!

[Saul Perlmutter, Brian P. Schmidt, Adam G. Riess]

Use Λ to cancel

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + (\Lambda^{\text{vac}} - \Lambda) g_{\mu\nu} = \tilde{T}_{\mu\nu}$$

The Cosmological Constant Problem

The problem is not that the constant needs to be extremely small,
it's that it needs to *stay extremely small at all orders* *(radiative instability)*

Antonio Padilla
[arxiv:1502.05296]

The Cosmological Constant [Chapter 3]

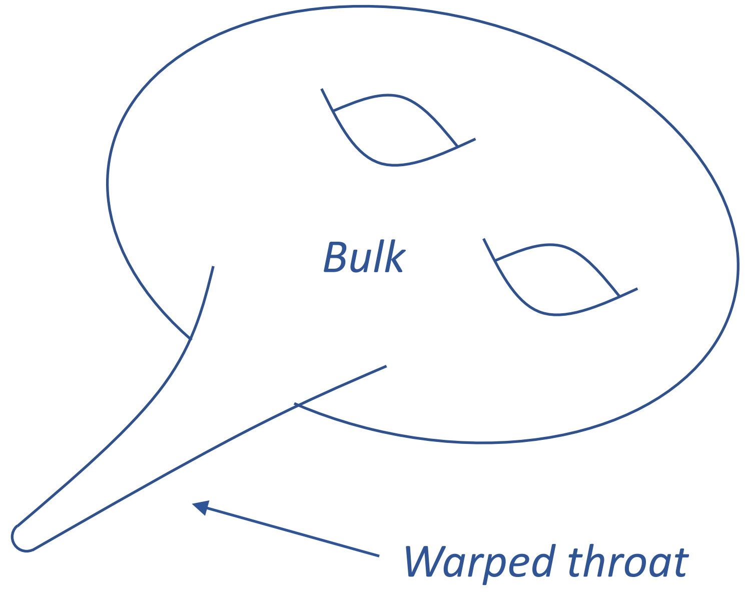
The True Return or the birth of Dark Energy

A tempting guess is to use (un)broken symmetries…

What about UV complete theories?

Really hard to get de Sitter in supergravity and String Theory

- SUSY breaking scale is at least 1 TeV;
- Not compatible with SUSY;
- KKLT and LVS



$$V = e^K\left[G^{I\bar{J}}(D_I W)(D_{\bar{J}}\bar{W}) - 3|W|^2\right]$$

with S. Parameswaran, I. Zavala, D. Chakraborty

The Cosmological Constant [Chapter 3]

The True Return or the birth of Dark Energy

De Sitter Space and the Swampland

Georges Obied, Hirosi Ooguri, Lev Spodyneiko, Cumrun Vafa

[arxiv:1806.08362]

Distance and de Sitter Conjectures on the Swampland

Hirosi Ooguri, Eran Palti, Gary Shiu, Cumrun Vafa

[arxiv:1810.05506]

Refined de Sitter Conjecture: *The scalar potential $V(\phi)$ for scalar fields in a low energy EFT of any consistent Quantum Gravity must satisfy either:*

$$\frac{|\nabla V|}{V} \geq \frac{c}{M_p^2} \qquad \text{or} \qquad \frac{\min(\nabla_i \nabla_j V)}{V} \leq -\frac{c'}{M_p^2} \tag{1}$$

for some universal constants $c, c' \sim \mathcal{O}(1)$, where $\min(\nabla_i \nabla_j V)$ stands for the minimum eigenvalue of the Hessian matrix in an orthonormal frame.

This forbids de Sitter vacua.

The Cosmological Constant [Chapter 4]

Endgame or the Rise of Quintessence

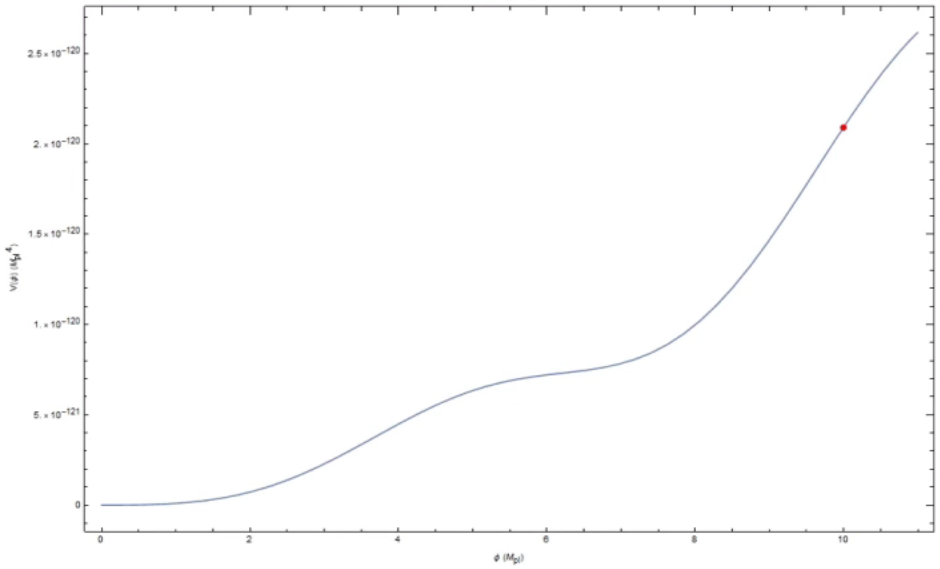
What if we give up [illegible] imum?

QUINTESSENCE

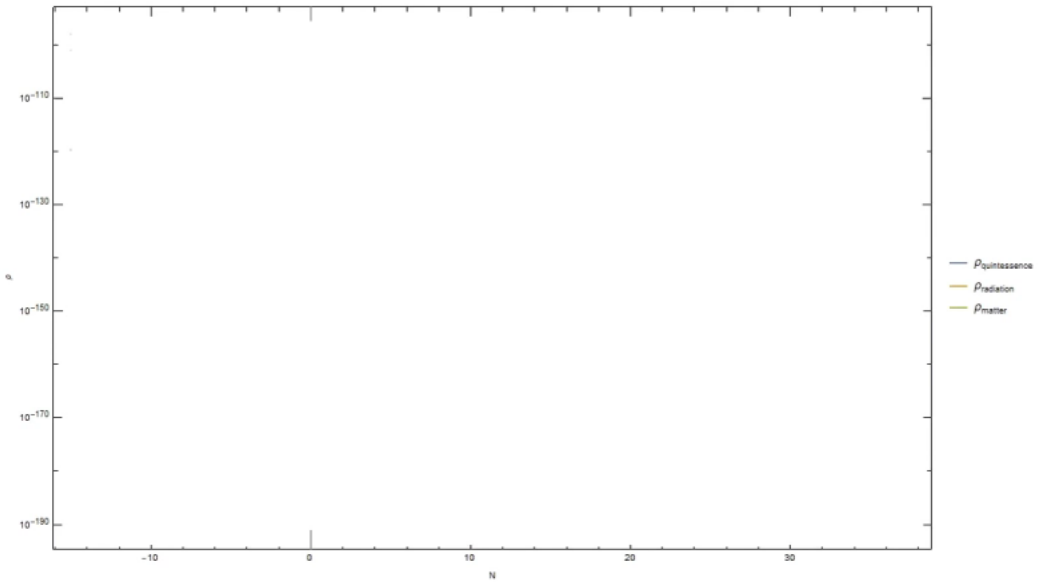
We can try [illegible] ld (or more) slowly rolling

- Plenty of scalar fields in string compactifications;
- Vast landscape might help find flat enough potentials;
- Could be a maximum (hilltop quintessence).

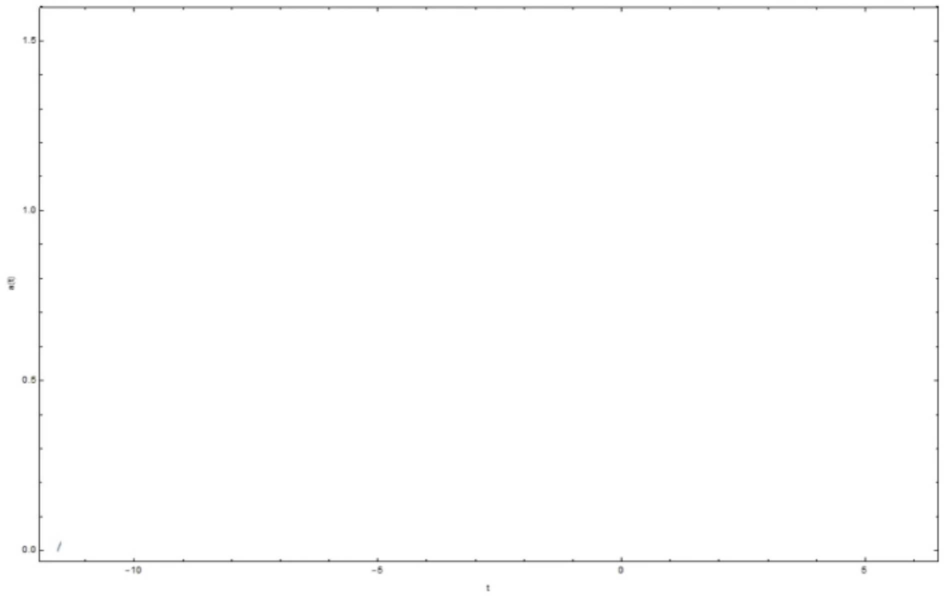
Potential



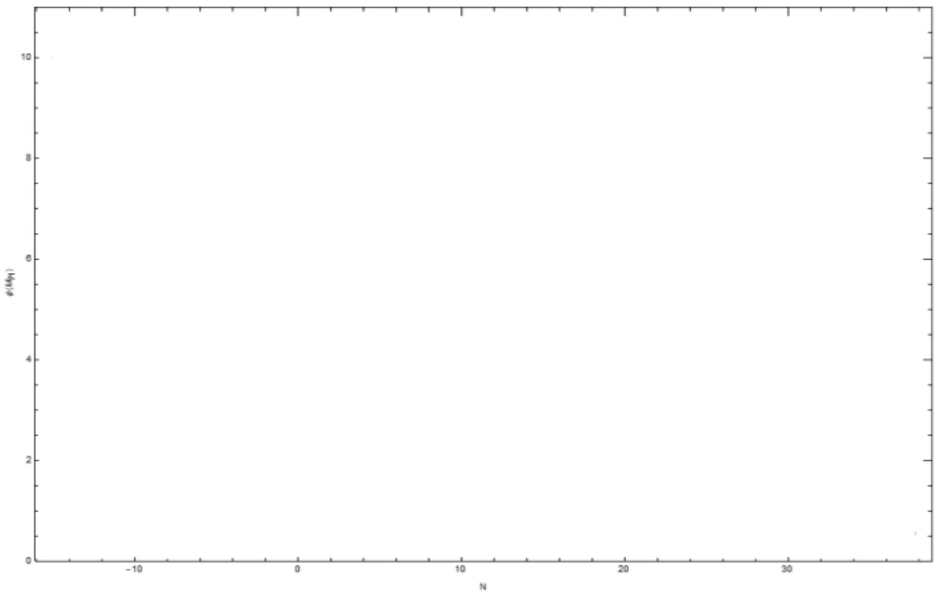
Energy densities



Scale factor



Field Evolution



The Cosmological Constant [Chapter 4]

Endgame or the Rise of Quintessence

Dark Energy in String Theory

Bruno Valeixo Bento, Dibya Chakraborty, Susha L. Parameswaran, Ivonne Zavala

[arxiv:2005.10168]

$K = -n \log\left(\Phi + \bar{\Phi}\right)$	Bulk/fibre moduli	$W = W_0 + Ae^{-a\Phi}$
$K = k_0 + \dfrac{(\Phi + \bar{\Phi})^{2n}}{k_1}$	Blow-up moduli	$W = W_0 + A\Phi^p$
$K = k_0 + \dfrac{\lvert\Phi\rvert^{2n}}{k_1}$	Deformation moduli	

Generalizing the analysis with all the possible combinations, what do we get?

The Cosmological Constant [Chapter 4]

Endgame or the Rise of Quintessence

de Sitter $V > 0$

Slow-roll $\epsilon_V = \frac{M_{Pl}^2}{2} g^{\phi\phi} \left(\frac{V'}{V}\right)^2 < 1$

Only for a local modulus, with a perturbative leading W

$$K = k_0 + \frac{|\Phi|^{2n}}{k_1} \qquad K = k_0 + \frac{(\Phi + \bar{\Phi})^{2n}}{k_1}$$

$$W = W_0 + A\Phi^p \qquad \boxed{p = n}$$

$$K = k_0 + \frac{|\Phi|^{2n}}{k_1}, \qquad W = W_0 + A\Phi^p$$

$$V = \frac{W_0^2}{M_{pl}^2}\frac{e^{k_0+y}}{n^2 y}\left((px + n(1+x)y)^2 - 3n^2(1+x)^2 y\right)$$

$$\varepsilon_V = \frac{(p^3x^2 + 3n^2px(1+x)(y-1)y + n^3(1+x)^2(y-2)y^2 + np^2x(y+x(3y-1)))^2}{n^2y(p^2x^2 + 2npx(1+x)y + n^2(1+x)^2(y-3)y)^2}$$

Parameters			$V \to$	$\varepsilon_V \to$	$V>0 \quad \varepsilon_V<1$
$p \neq n$	$x \gg 1$		$\frac{W_0^2}{M_{pl}^2} e^{k_0} \frac{p^2}{n^2} \frac{x^2}{y} > 0$	$\frac{(p-n)^2}{n^2}\frac{1}{y} > 1$	No-go
	$x \ll 1$	$x \gg y$	$\frac{W_0^2}{M_{pl}^2} \frac{p^2 e^{k_0}}{n^2} \left(\frac{x^2}{y} - 3\frac{n^2}{p^2}\right)$	$\frac{(n-p)^2}{n^2\left(\frac{x^2}{y} - 3\frac{n^2}{p^2}\right)^2}\frac{x^2}{y}\left(\frac{x}{y}\right)^2 > 1$	No-go
		$x \ll y$	$-\frac{3W_0^2 e^{k_0}}{M_{pl}^2} < 0$	$\frac{4y}{9} < 1$	No-go
Parameters			$V \to$	$\varepsilon_V \to$	$V>0 \quad \varepsilon_V<1$
$p = n$	$x \gg 1$		$\frac{W_0^2}{M_{pl}^2} e^{k_0} \frac{x^2}{y} > 0$	$(1+xy)^2\frac{y}{x^2} < 1$	Yes
	$x \ll 1$	$x^2 \gg y$	$\frac{W_0^2}{M_{pl}^2} e^{k_0} \frac{x^2}{y} > 0$	$\frac{4y}{x^2} < 1$	Yes
		$x^2 \ll y$	$-\frac{3W_0^2 e^{k_0}}{M_{pl}^2} < 0$	$\frac{4y}{9}\left(1+\frac{x}{y}\right)^2 < 1$	No-go

$$K = k_0 + \frac{(\Phi+\bar{\Phi})^{2n}}{k_1}, \qquad W = W_0 + A\Phi^p$$

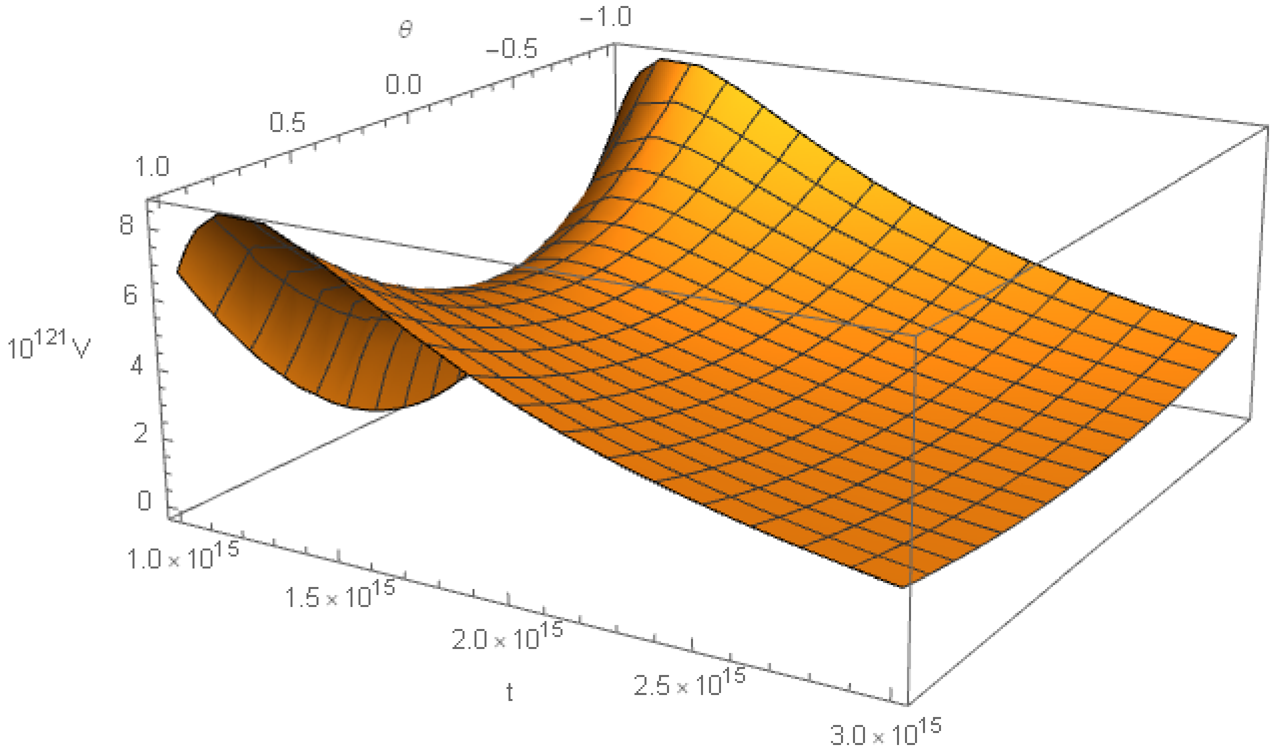
$$V = \frac{W_0^2}{M_{pl}^2}\frac{e^{k_0+y}}{n(2n-1)y}\left(2p^2x^2 + 4npx(1+x)y + n(1+x)^2(3+2n(y-3))y\right)$$

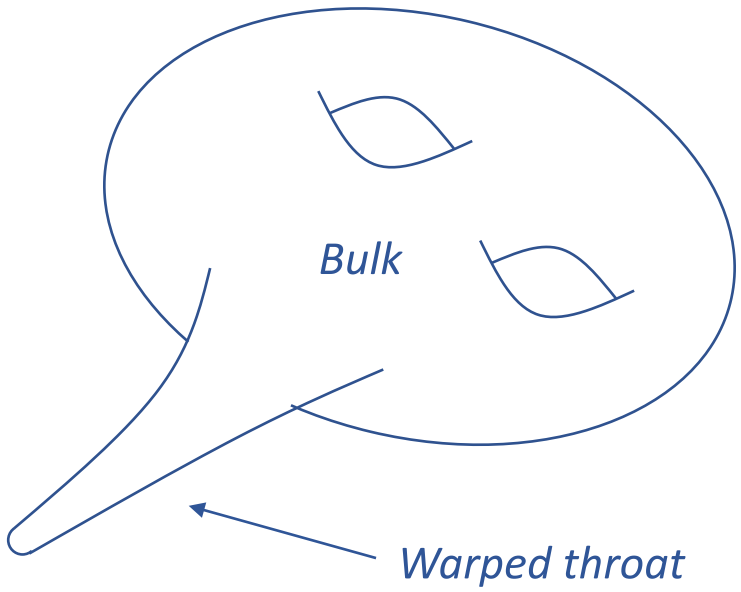
$$\varepsilon_V = \frac{2(2p^3x^2 + 2n^3(1+x)^2(y-2)y^2 + 3n^2(1+x)y(2px(y-1)+(1+x)y) + npx(3(1+x)y + 2p(y+x(3y-1))))^2}{n(2n-1)y(2p^2x^2 + 4npx(1+x)y + n(1+x)^2(3+2n(y-3))y)^2}$$

Parameters			$V \to$	$\varepsilon_V \to$	$V>0 \quad \varepsilon_V<1$
$p \neq n$	$x \gg 1$		$\frac{W_0^2}{M_{pl}^2} \frac{2p^2 e^{k_0}}{n(2n-1)} \frac{x^2}{y} > 0$	$\frac{2(n-p)^2}{n(2n-1)}\frac{1}{y} > 1$	No-go
	$x \ll 1$	$x \gg y$	$\frac{W_0^2}{M_{pl}^2} \frac{2p^2 e^{k_0}}{n(2n-1)} \left(\frac{x^2}{y} - \frac{3n(2n-1)}{2p^2}\right)$	$\frac{2(n-p)^2}{n(2n-1)\left(\frac{x^2}{y} - \frac{3n(2n-1)}{2p^2}\right)^2}\frac{x^2}{y}\left(\frac{x}{y}\right)^2 > 1$	No-go
		$x \ll y$	$-\frac{3W_0^2 e^{k_0}}{M_{pl}^2} < 0$	$\frac{2n(4n-3)^2}{9(2n-1)^3} y < 1$	No-go
Parameters			$V \to$	$\varepsilon_V \to$	$V>0 \quad \varepsilon_V<1$
$p = n$	$x \gg 1$		$\frac{W_0^2}{M_{pl}^2} e^{k_0} \frac{2n}{2n-1} \frac{x^2}{y} > 0$	$\frac{9y}{2n(2n-1)} < 1$	Yes
	$x \ll 1$	$x^2 \gg y$	$\frac{W_0^2}{M_{pl}^2} e^{k_0} \frac{2n}{2n-1} \frac{x^2}{y} > 0$	$\frac{(4n-3)^2}{2n(2n-1)}\frac{y}{x^2} < 1$	Yes
		$x^2 \ll y$	$-\frac{3W_0^2 e^{k_0}}{M_{pl}^2} < 0$	$\frac{2n}{9}\frac{(4n-3)^2}{(2n-1)^3}\left(1+\frac{x}{y}\right)^2 y$	No-go

The Cosmological Constant [Chapter 4]

Endgame or the Rise of Quintessence





with S. Parameswaran, I. Zavala, D. Chakraborty

To be continued…

What's the take away?

- The cosmological constant problem is not its size
- [Inflation] Scalar fields are natural solutions for accelerated expansion
- It's hard to get de Sitter in String Theory
- Quintessence is a very natural alternative

THANK YOU