

# Dark Energy and $\Lambda$ in String Theory

## - Status Report for Planck 2022

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University of Liverpool

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*Thanks to collaborators and friends:*

Bruno Bento, Cliff Burgess, Dibya Chakraborty, Michele Cicoli, Fridrik Gautasson, Joaquim Gomes, Ed Hardy, Anshuman Maharana, Yessenia Olguín, Fernando Quevedo, Marco Serra, Gianmassimo Tasinato, Radu Tatar, Flavio Tonioni, Thomas van Riet, Ivonne Zavala...  
*biases and omissions all mine!*

# The Cosmological Constant Problem

- ▶ So far, observational constraints on Dark Energy are consistent with a tiny Cosmological Constant i.e. vacuum energy:

$$\langle V \rangle_0 = 7 \times 10^{-121} M_{pl}^4 \quad \text{and} \quad w_0 = -1.028 \pm 0.032$$

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- ▶ A low-energy problem posed at scales we think we understand well e.g. summing vacuum-loop diagrams from the electron up to  $M_{UV}$ :

$$\rho_e \sim \mathcal{O}(M_{UV}^4) + \mathcal{O}(M_{UV}^2 m_e^2) + \mathcal{O}\left(m_e^4 \ln \frac{M_{UV}}{m_e}\right).$$

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Using a Lorentz invariant dimensional regularisation gives

$$\rho_e \sim m_e^4 \ln \frac{m_e^2}{\mu^2} \quad \text{and} \quad \rho_{SM} \sim -3.2 \times 10^8 \text{GeV}^4.$$

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- ▶ Quantum loops have a gravitational effect – e.g. loop corrections to the electrostatic energy of a nucleus have been verified to satisfy the equivalence principle to at least  $1 : 10^9$ .

See Polchinski '06 for a nice discussion

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- ▶ Growing tension between direct measurements of  $H_0$  and CMB fit using  $\Lambda$ CDM:

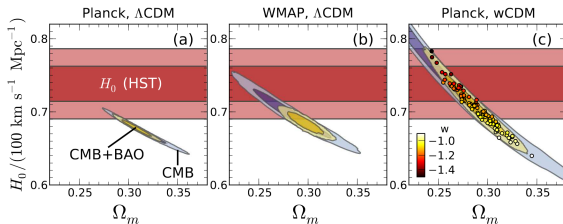


Figure from Mortonson et al '14

4.4  $\sigma$  discrepancy...

Reiss et al '19  
see DiValentino's talk on Thursday!

- ▶ Consider  $\Lambda$  and alternatives...

# Plan

- ▶ Naturalness vs Anthropics
- ▶ The String Landscape and de Sitter vacua
- ▶ Quintessence in string theory
- ▶ Some stringy alternatives - UV/IR mixing, thermal effects, axions, coupled DM/DE...
- ▶ Outlook

# Naturalness vs. Anthropics

see Craig '22 Naturalness Snowmass White Paper for a nice recent review

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- ▶ To use anthropic arguments we need a theory to produce a multitude of vacua, including ones with anthropically viable total vacuum energies, and a mechanism to populate them all.

# The String Landscape and Bousso-Polchinski

Bousso & Polchinski '00

- ▶ To solve cc problem we need landscape of 4D string solutions with densely packed vacuum energies  $\Delta\rho_\Lambda \lesssim 10^{-120} M_{pl}^4$ .

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$$\rho_{4-form} = \frac{1}{2} \sum_{i=1}^N n_i^2 q_i^2$$

depletes via spontaneous appearance of spherical membranes inside which  $n_j q_j \rightarrow (n_j - 1) q_j$  and  $\rho_{4-form j} \rightarrow (n_j - \frac{1}{2}) q_j^2$ .

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As fluxes deplete, they can eventually cancel an order one  $\Lambda_{bare} < 0$

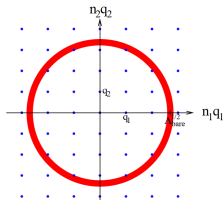


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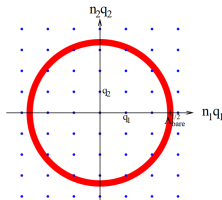


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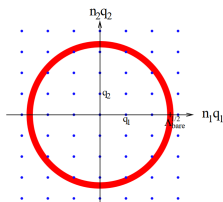


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- ▶ Nested bubble nucleations drive eternal inflation and Universes with all possible vacuum energies  $< \rho_{4-form}^{initial}$  are produced.
- ▶ Open questions include: variation of other physical parameters, measure problem, landscape searches, ...??

see He's talk on Thursday!

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- ▶ Many scenarios and highly developed constructions, with spirit:

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see talk by Leontaris on Friday!

$$V(\phi) = M^4 \left( a_0 + a_1 \left( \frac{\phi}{M} \right) + a_2 \left( \frac{\phi}{M} \right)^2 + \mathcal{O} \left( \left( \frac{\phi}{M} \right)^3 \right) \right)$$

for  $a_2 \gg a_i \Rightarrow \phi \approx -\frac{a_1 M}{2a_2} \ll M$  and  $\Lambda = \left( a_0 + \frac{4a_2^3}{27a_3^2} \right) M^4$ .

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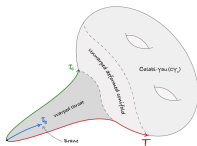
- ▶ String theory allows us to compute the vacuum energy and understand its backreaction on the geometry (even if we can't fine-tune to the observed Dark Energy yet...)!
- ▶ Consistency of long-lived metastable dS vacua (and scale separated adS) still being tested, and challenged by Swampland Conjectures, stimulating new ideas..

# Interlude: Testing Warped Flux Compactifications

Bento, Chakraborty, SLP & Zavala '22; see Bento's parallel talk on Thursday

Fluxes can source a 'warped throat' geometry with explicit metric – useful for creating hierarchies á la Randall-Sundrum.

Klebanov & Strassler '00

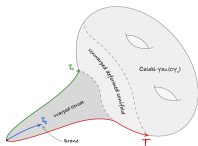


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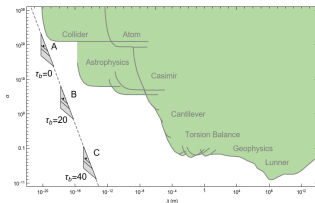
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KK spectrum  $\Rightarrow$  modifications to Newton's inverse square law  $\Rightarrow$  directly constrain the parameters of the string compactifications.



Right bound  $g_s < 1$ , left bound  $g_s M > 1$ , lower bounds  $M < 32, 100, 1000$ .

see Alvaro Herrera's parallel talk on Thursday!

# Quintessence No-Go Theorems in SUGRA

Olguin-Trejo, Parameswaran, Tasinato & Zavala '18; Bento, Chakraborty, Parameswaran & Zavala '20; Cicoli, Cunillera, Padilla, Pedro '21;  
see also Hebecker, Skrzypek & Wittner '19

- ▶ Runaway potentials ubiquitous in string compactifications; if modulus were  $\phi$  frozen at the tail of  $V(\phi)$  by Hubble friction  $\Rightarrow$  effectively an exponentially suppressed  $\Lambda$ .

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- ▶ If modulus hidden and sequestered from visible sector, we may avoid fifth-forces and time-variation of fundamental constants...  
e.g. Berg, Marsh, McAllister, Pajer '10; Aparicio, Cicoli, Krippendorf, Maharana, Muia, Quevedo '14; Acharya, Maharana, Muia '18



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- ▶ But  $V(\phi)$  arising in N=1 LEEFT sugras from string compactifications are always either too steep or negative:

Model	$V(\phi) > 0$ and $\epsilon_V < 1$ at tail
bulk/fibre modulus	
$K = -n \log(\Phi + \bar{\Phi}), \quad W = W_0 + Ae^{-a\Phi}$	no-go
$K = -n \log(\Phi + \bar{\Phi}), \quad W = W_0 + A\Phi^p$	no-go
deformation modulus	
$K = k_0 + \frac{ \Phi ^{2n}}{k_1}, \quad W = W_0 + Ae^{-a\Phi}$	no-go
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blow-up modulus	
$K = k_0 + \frac{(\Phi + \bar{\Phi})^{2n}}{k_1}, \quad W = W_0 + Ae^{-a\Phi}$	no-go
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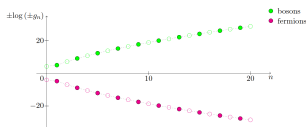
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- ▶ Set of 10D tachyon-free string theories includes non-susy string theories, including brane-susy-breaking models, e.g.  $\overline{Dp}/Op$ .

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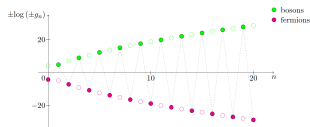
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- ▶ Brane-susy-breaking realises misaligned susy: Cribiori, SLP, Tonioni, Wrase '21  
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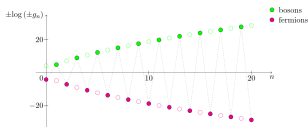
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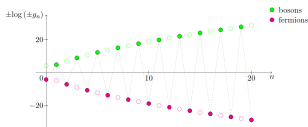
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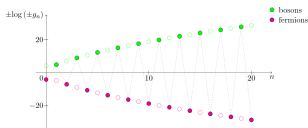
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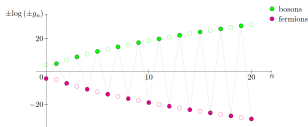
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- ▶ Modular invariance does not introduce new light states so does not need to be broken, and is a kind of UV/IR mixing...
- ▶ Can we solve the Cosmological Constant Problem (and Hierarchy Problem) through a conspiracy involving physics at all scales simultaneously?  
Dienes '01; Abel, Dienes, Mavroudi '16; Abel & Dienes '21



# Thermal Dark Energy

Hardy & Parameswaran '20; Gomes, Hardy & Parameswaran *w.i.p.*



Elephant in the Room by Banksy

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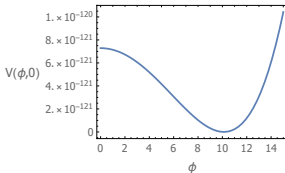
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# Finite Temperature in String Cosmology

Hardy & Parameswaran '20, Gomes, Hardy & Parameswaran *w.i.p.*

- ▶ A light hidden scalar field (matter or modulus) with non-zero vev and Higgs-like interactions with other hidden states, e.g.:

$$V_{tot}(\phi, 0) = \lambda\phi^4 - \frac{m_\phi^2}{2}\phi^2 + \frac{m_\phi^4}{16\lambda}$$

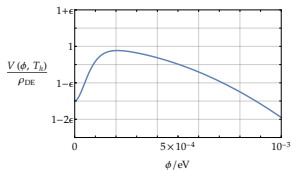


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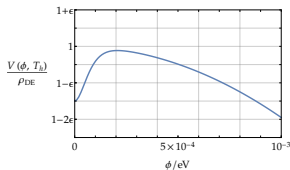


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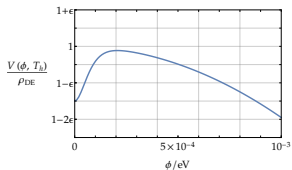


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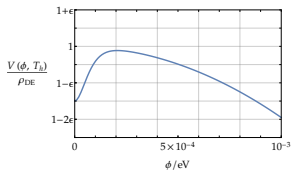
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- ▶ Hot Early DE - relieves  $H_0$  tension (to  $2.5\sigma$ ), explains neutrino masses, predictive for CMB and LSS.

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- ▶ Solving the CC problem and DE will hopefully provide some deep insights into string theory and help us connect to observations.