String Cosmology
– From the Early Universe to Today

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Some highlights from recent Physics Reports Invited Review – 2303.04819
with Michele Cicoli, Joe Conlon, Anshuman Maharana, Fernando Quevedo, Ivonne Zavala
1100+ references therein

String Cosmology

Golden Age for Cosmology - precision science dominated by Big Data at all scales:

- ΛCDM provides accurate match to most observations with only 6 parameters!
- Inflation provides solutions to flatness, horizon and monopole problems – and seeds for structure formation – consistent with observation.

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- UV problems – at early times we need such a theory at high energies and high temperatures – quantum gravity?
- IR problems – how to formulate quantum mechanics in an accelerating spacetime, what is Dark Matter and Dark Energy?

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Can string theory provide the necessary framework for cosmology and can cosmology provide opportunities to test string theory observationally? Might we learn more about string theory on the way?

Plan

String theory has a number of phenomena with potential cosmological implications – moduli, extra dimensions, towers of states (susy or misaligned), modular invariance and UV/IR mixing, hidden sectors,...

- String moduli and their stabilisation
- Update on string inflation
- Post-inflation – exotic cosmological epochs
- Novel scenarios for Dark Energy in string theory
- Outlook

Some physics I won't mention - (p)re-heating, baryogenesis, candidates for Dark Matter...

String compactifications and moduli

The Calabi-Yau Moon, Mariam Hashemi (acrylic on canvas)

Extra dims/moduli v important physical implication of string theory!

- Quantum consistency $\Rightarrow$ string theory is 10D, well-understood perturbatively in weak coupling g_s and weak curvature/large volume $1/\mathcal{V}$ expansions.
- Six extra dimensions must be compact and small – at energies < $1/\mathcal{V}^{1/6} \Rightarrow$ a 4D LEEFT – Einstein + (S)SM + Dark Sectors.
- Size $\mathcal{V}$ and shape of the extra dimensions and g_s correspond to scalar fields – moduli – in the 4D LEEFT.
- moduli vevs determine the masses and couplings of SM and Dark Sectors – and must be consistent with perturbative expansions!

String Moduli

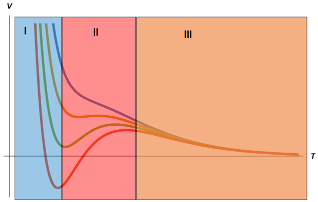
- May be hundreds or thousands of moduli! Their number determined by topological data of Calabi-Yau manifold - we now have databases of millions of CYs.
- Gauge-singlets typically interacting with gravitational strength.
- To leading order, massless with flat potential energy functional $\Rightarrow$ unobserved long-range fifth-forces.
- Various string theory ingredients – *higher dimensional fluxes, D-branes, gaugino condensates, instantons* – induce a potential energy functional for the moduli – schematically

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

  with $\phi(x)$ related to e.g. string coupling or $1/\mathcal{V}$.
- Weak coupling/large $\mathcal{V}$ typically implies only leading order term relevant $\Rightarrow$ runaway potentials in regime of control. Dine & Seiberg '85

Moduli stabilisation and Cosmological Constant

- For some topological choices, a_i are such that $\phi(x)$ can be fixed dynamically at weak coupling and large volume at dS vacuum.



e.g. for $V(\phi) = M^4\left(a_0 + a_1\left(\frac{\phi}{M}\right) + a_2\left(\frac{\phi}{M}\right)^2 + a_3\left(\frac{\phi}{M}\right)^3 + \ldots\right)$,

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

- Potential energy at minimum corresponds to full vacuum energy – corrections from g_s and α' suppressed!
- We will only ever have numerical control, not parametric control...
- ...but compelling evidence that our unique theory has $\gtrsim \mathcal{O}(10^{272,000})$ possible solutions including anthropically viable ones – is Λ just an environmental parameter?

Bousso & Polchinski '00; Taylor & Wang '15

Motivations for String Inflation

Inflation can be driven by scalar field slowly-rolling down shallow potential, with $\epsilon_V \equiv M_{pl}^2 (V'/V)^2 \ll 1$ and $\eta_V \equiv M_{pl}^2 \frac{V''}{V} \ll 1$.

UV complete description of inflation necessary, e.g. for single-field:

- Quantum corrections $\Delta V \sim cV(\phi) \left(\frac{\phi}{\Lambda}\right)^2$ tend to drive

$$\eta_V \equiv M_{pl}^2 \frac{V''}{V} \sim \mathcal{O}(1)$$

$\Rightarrow$ need a fine-tuning or a symmetry to explain why $c \ll 1$.

- Tensor-to-scalar ratio and transplanckian field displacements:

$$\frac{\Delta \phi}{M_{pl}} = \int_{N_{end}}^{N_{hc}} \sqrt{\frac{r}{8}}\,.$$

But $\Delta V \sim \sum c_n V(\phi) \frac{\phi^n}{M_{pl}^n} \Rightarrow$ observable tensors would require control of all QG corrections! Superplanckian field distances also tend to imply towers of states becoming light.

String Inflation - symmetries

see also e.g. M-flation, Ashoorioon, Sheikh-Jabbari et al

Moduli stabilisation may lead to sufficiently flat potentials to source cosmic inflation – protected by shift symmetries, e.g:

- closed string saxions - Kähler moduli in IIB flux compactifications

$$V(\phi) = V_0 \left(1 - C_0 e^{-(\phi/f)^p}\right)$$

- open string saxions - D7-brane moduli or Wilson line moduli, e.g.

$$V(\phi) = V_0 \left(1 + \alpha \left(\frac{\phi}{\phi_0}\right)\right)$$

- axions - perturbatively exact but broken non-perturbatively:

$$V(\phi) = V_0 \left(1 - \cos\left(\frac{\theta}{f}\right)\right)$$

  where we need $f \gtrsim M_{pl}$ via alignment mechanism or N-flation.
- axions - broken at tree-level giving 'axion-monodromy':

$$V(\phi) = \mu^{4-p} \left(\frac{\phi}{f}\right)^p$$

in addition to many models with fine-tuning.

String Inflation - status

Comparison among the predictions for the main models of string inflation, using benchmark $N_e \simeq 52$.

String model	n_s	r
Fibre Inflation	0.967	0.007
Blow-up Inflation	0.961	10^{-10}
Poly-instanton Inflation	0.958	10^{-5}
Aligned Natural Inflation	0.960	0.098
N-Flation	0.960	0.13
Axion Monodromy	0.971	0.083
D7 Fluxbrane Inflation	0.981	5×10^{-6}
Wilson line Inflation	0.971	10^{-8}
D3-$\overline{\text{D3}}$ Inflation	0.968	10^{-7}
Inflection Point Inflation	0.923	10^{-6}
D3-D7 Inflation	0.981	10^{-6}
Racetrack Inflation	0.942	10^{-8}
Volume Inflation	0.965	10^{-9}
DBI Inflation	0.923	10^{-7}

c.f. Planck '18: $n_s = 0.9649 \pm 0.0042$ (68%CL), $r < 0.036$ (95%CL).

String Inflation - status

Many favourite string models from a decade ago, with very low r, are now ruled out by precision data on n_s:

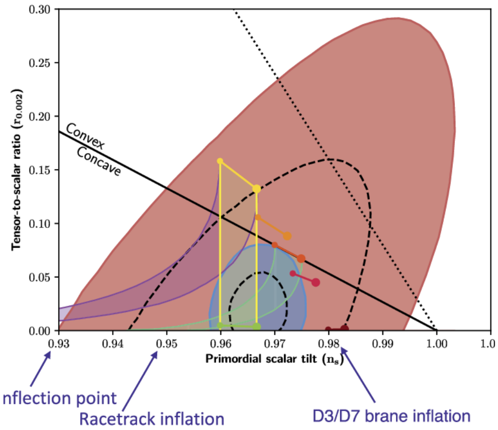
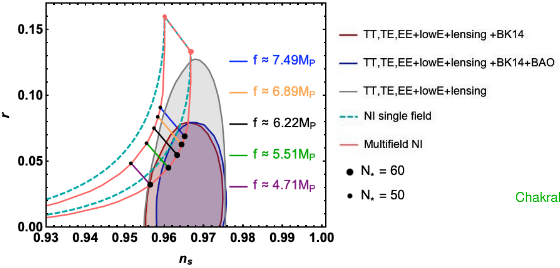


Figure from Akrami et al '18

WMAP '10 in red, Planck '18 in blue

String Inflation - multifield

- Multifield models well-motivated theoretically.
- Trajectories can be non-geodesic, with strong turns, $\eta_V^m = M_{pl}^2 |\min \nabla_a \nabla_b V/V|$ can be large.
- Predictions altered, e.g. for strongly non-geodesic D5-brane multifield inflation:



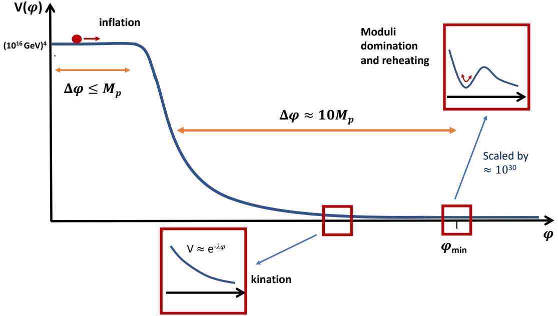
Chakraborty & Zavala '19

Single-field natural inflation predictions in cyan dashed, multifield predictions in red continuous.

providing targets also for future observations on non-gaussianities, anisotropies, inhomogeneities and tensors.

Post String Inflation

- In ‘standard cosmology’ inflation ends with reheating to SM dofs.
- String inflation ends with rolling moduli with energies $\gg$ particle physics scales:



Overshoot problem...

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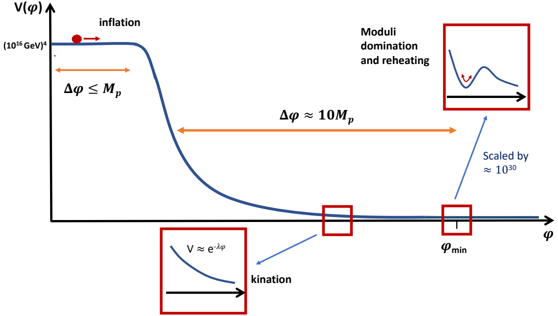

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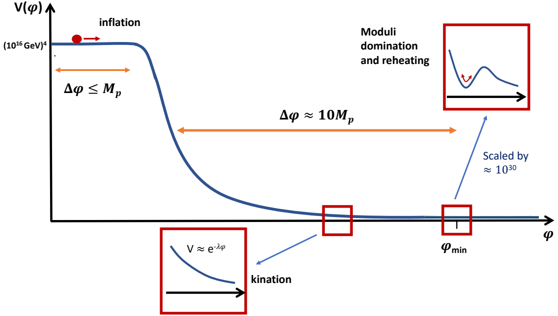

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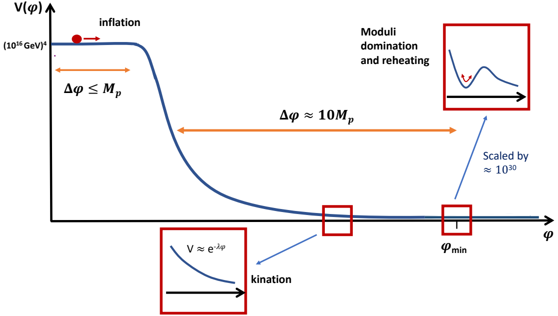
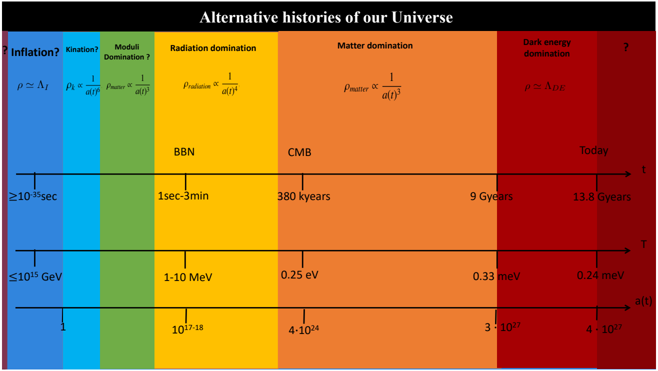


Overshoot problem... evaded by kination followed by moduli domination $\Rightarrow$ reheating temperature lowered.

Alternative Cosmological Histories



UV complete models may connect otherwise uncorrelated aspects of early universe and particle physics.

Dark Energy in string theory

- Consistency of long-lived metastable dS vacua being tested and challenged by Swampland Conjectures, stimulating new ideas...

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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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- $V(\phi)$ 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
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- Generalises to multifield - no asymptotic accelerated expansion (for $k = 0$) – conceptual issues around cosmological horizons.
  Tonioni & Shiu '23; see however Andriot, Tsimpis, Wrase '23 for k=-1

Interacting Dark Sectors

Elephant in the Room by Banksy

Claim: interacting Dark Sectors can source a transient dS epoch for the steep runaway potentials typical from string compactifications.

Interacting Dark Sectors

Gomes, Hardy & SLP '23

Toy model - two interacting dark scalar fields:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + \frac{1}{2} g^{\mu\nu} \partial_\mu \psi \partial_\nu \psi + V(\phi, \psi) \ ,$$

with canonical kinetic terms and a scalar potential of the form:

$$V(\phi, \psi) = V(\phi) + \frac{1}{2} m_\psi^2 \psi^2 + \frac{1}{2} \frac{m_{\rm int}^2}{\Lambda^2} \phi^2 \psi^2 \ .$$

and Higgs-like hilltop or runaway potential for ϕ:

$$V(\phi) = \rho_{\rm de} \left(\left(\frac{\phi}{\Lambda} \right)^2 - 1 \right)^2 \quad \text{or} \quad V(\phi) = \rho_{\rm de} \, e^{-\frac{\phi}{\Lambda}}$$

With $m_{\rm int} = 0$ either ϕ or ψ could source slowly-rolling quintessence... but only with fine-tuning i.c's or dangerous large field distances.

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With $m_{\rm int} \neq 0$ and ψ behaving as DM, DR or subdominant DE - can stabilise ϕ near $\phi = 0$ to source observed DE as transient dS!

DM Assisted DE - Runaway Example

Dvali & Kachur '03; Axenides & Dimopoulos '04; Copeland & Rajantie '05; Gomes, Hardy & SLP to appear

- For $\psi_{init} \neq \psi_{min} = 0$ and $m_\psi > H_0 \Rightarrow \psi$ classically oscillates:

$$\psi(t) = \psi_0 e^{-3H(t-t_0)/2} \cos(m_\psi t)$$

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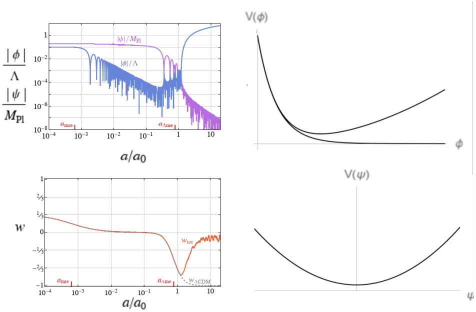
- Quartic interaction $\frac{m_{\rm int}^2}{\Lambda^2}\langle\psi^2\rangle\phi^2 \Rightarrow \frac{\phi_{min}}{\Lambda} = W_0\left(\frac{\rho_{\rm de}}{m_{\rm int}\langle\psi^2\rangle}\right)$



- No tuning of initial conditions, no super-Planckian distances, a transient dS with no fine-tuning in Lagrangian parameters!

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- Nature likely to go beyond simplest, single-field models – multifield inflation, coupled Dark Sectors.
- Solving the CC problem and DE will hopefully provide some deep insights into string theory and help us connect to observations.