Primordial gravitational waves in string inflation

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Towards String Cosmology with Fernando

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- The cosmological moduli problem (pre-D-branes)

[de Carlos, Casas, **Quevedo**, Roulet '93]
[Banks, Kaplan, Nelson '93]

(See also Maharana's talk)

Towards String Cosmology with Fernando

- The cosmological moduli problem (pre-D-branes)

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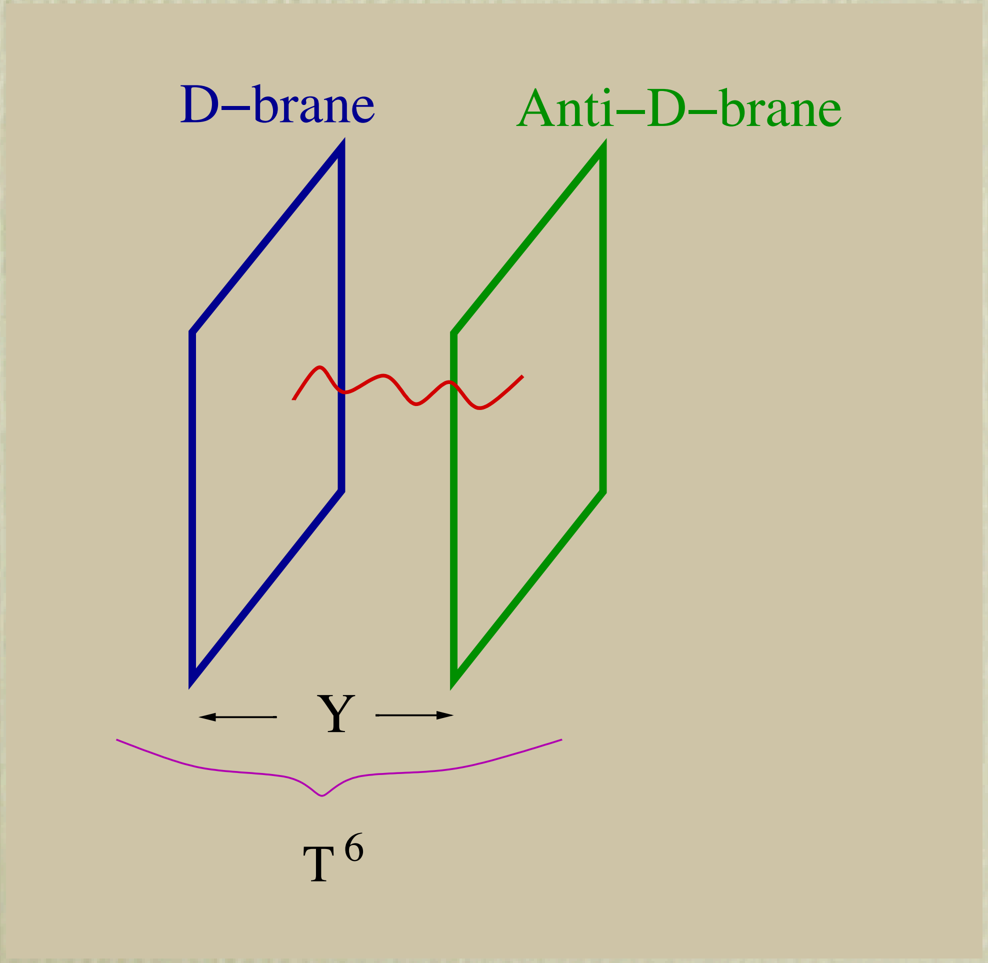
(See also Maharana's talk)

- Brane-anti-Brane Inflation (pre-moduli stabilisation)

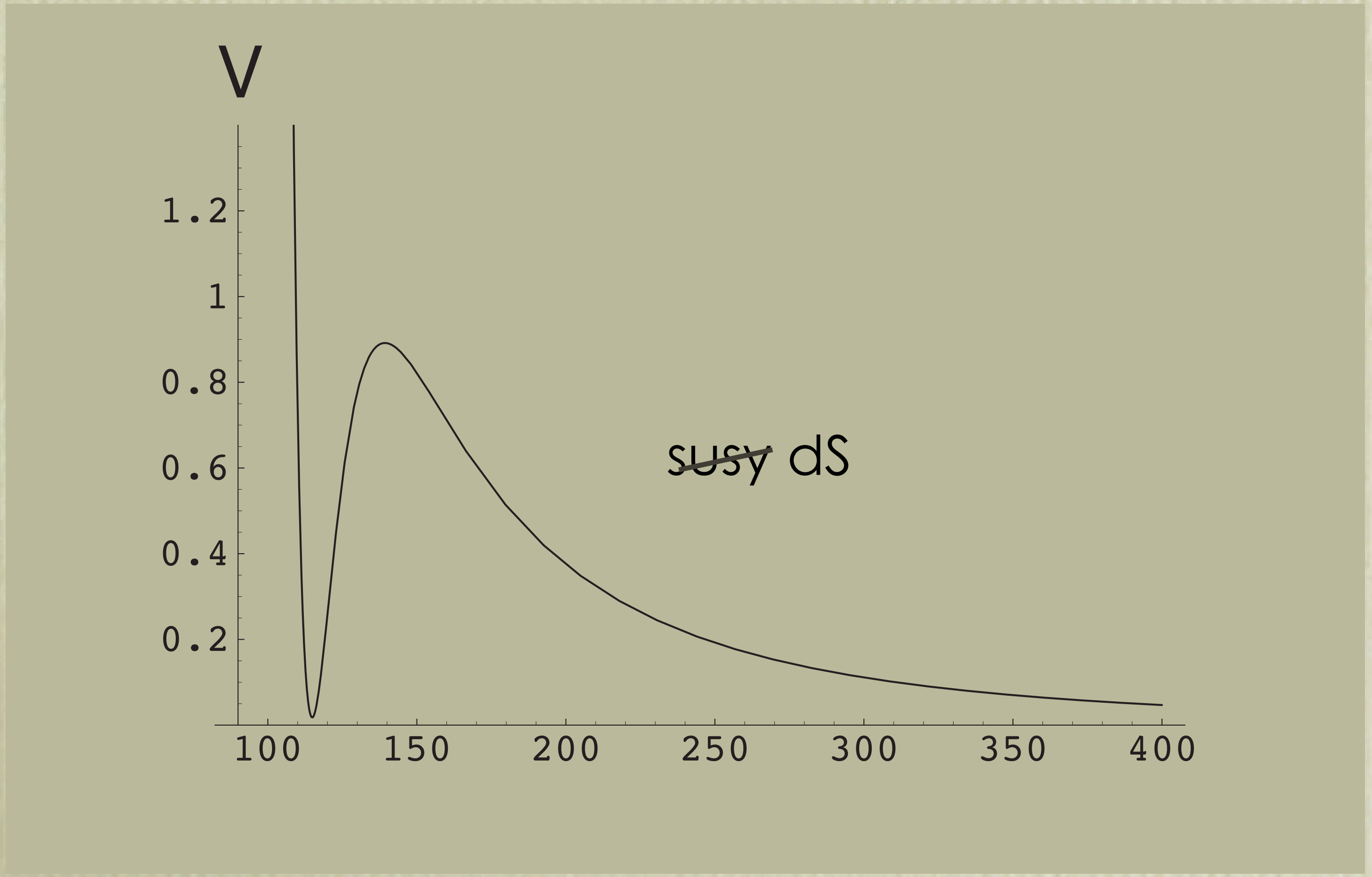
[Dvali, Tye '99]
[Burgess, Majumdar, Nolte, **Quevedo**, Rajesh, Zhang '01]
[Gómez-Reino, IZ, '02]



- De Sitter in String Theory

(See also Kallosh's talk)

[Aghababaie, Burgess, Parameswaran, **Quevedo**, '02-'03]
[Escoda, Gómez-Reino, **Quevedo**, '03]
[Burgess, Kallosh, **Quevedo**, '04]
[Cremades, García del Moral, **Quevedo**, Suruliz, '07]
[Krippendorf, **Quevedo**, '09]
[Burgess, Maharana, van Nierop, Nizami, **Quevedo**, '11]
[Cicoli, Maharana, **Quevedo**, Burgess, '12]
[Cicoli, Klevers, Krippendorf, Mayhofer, **Quevedo**, Valandro, '13]
[Alwis, Gupta, Hatefi, **Quevedo**, '13]
[Blåbäck, Roest, IZ, '13]
[Aparicio, Cicoli, Krippendorf, Maharana, Muia, **Quevedo**, 14]
[Cicoli, **Quevedo**, Valandro, '15]



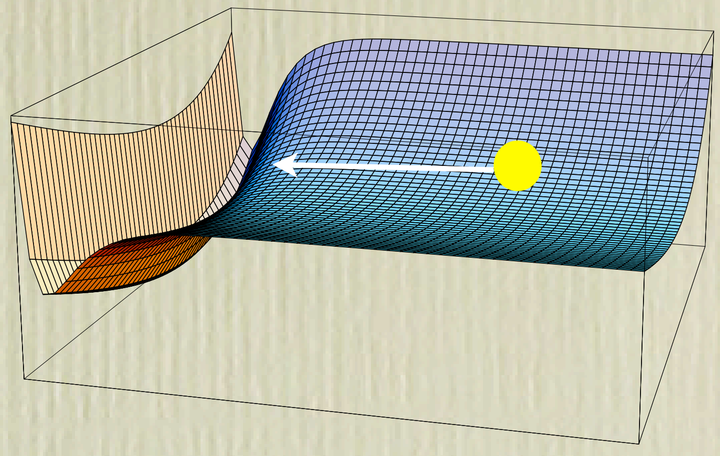
- Racetrack Inflation

[Blanco-Pillado, Burgess, Cline, Escoda, Gómez-Reino, Kallosh, Linde, **Quevedo**, '04, '06]

- Kähler moduli/Fiber Inflation (LVS)

(See also Conlon's talk)

[Conlon, **Quevedo**, '05]
[Cicoli, Burgess, **Quevedo**, '08]



- Non-Gaussianity in String Inflation (LVS)

$$f_{NL} \sim \mathcal{O}(10) - \mathcal{O}(20)$$

[Burgess, Cicoli, Gómez-Reino, **Quevedo**, Tasinato, IZ, '10]
[Cicoli, Tasinato, IZ, Burgess, **Quevedo**, '12]

- Primordial Gravitational Waves in String Inflation

(This talk)

[Silvestein, Westphal, '08]
[Cicoli, Burgess, **Quevedo**, '08]
[Avgoustidis, IZ,'08]
[Kooner, Parameswaran, IZ, '15]
[Parameswaran, Tasinato, IZ, '16]
[Burgess, Cicoli, Alwis, **Quevedo**,'16]
[Parameswaran, IZ, '16]

PLAN

- PGW's in Inflation
- PGW's in String Inflation
- An upper bound on r

PGW'S IN INFLATION

- The recent direct detection of gravitational waves opens a new powerful way to study our universe

- A very exciting but challenging prospect is the measurement of primordial gravitational waves (PGW's) produced in the very early universe via cosmological inflation

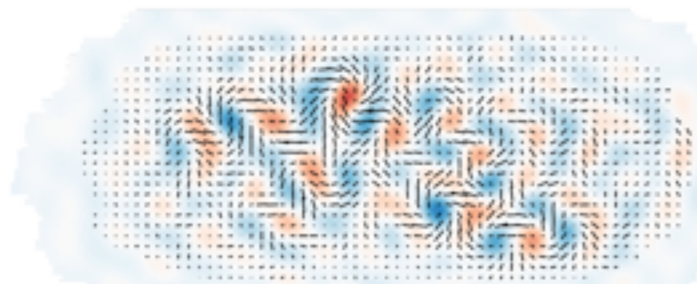
[Guth, '81; Linde, '82]

- During an inflationary epoch, quantum fluctuations in the inflaton and metric stretched to observables scales, setting up the initial conditions for structure growth.

[Mukhanov, Chibisov, '81]

- Density perturbations and gravitational waves are measured in the cosmic microwave background (CMB) emitted during the epoch of recombination.

- The dominant contribution to the CMB temperature anisotropies is from density perturbations, while gravitational waves lead to B-modes in the CMB polarisation



[Zaldarriaga, Seljak, '96]
[Kamionokowski, et al. '96]

- These are being searched for by a wide range of ground-based, balloon and satellite experiments

Current bounds $r < 0.07$ [BICEP/Keck, '15]

Future prospects $r \sim 10^{-4}$ [PRISM]

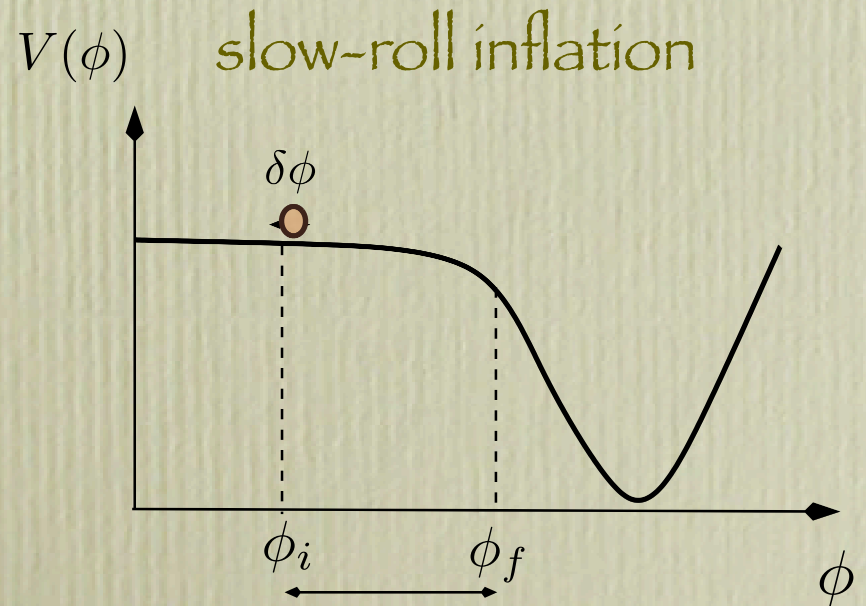
(B-modes in the lensing distortions of the 21 cm radiation emitted by hydrogen atoms during the reionisation epoch could reach $r \sim 10^{-9}$)

INFLATION IN EFT

- Observations are consistent with the simplest EFT inflation model with single canonically normalised scalar field, coupled minimally to gravity, whose potential

$$V(\phi) = V_{ren}(\phi) + \sum_{n=5}^{\infty} c_n \frac{\phi^n}{M_{Pl}^{n-4}}$$

drives a prolonged epoch of slow-roll inflation encoded in the potential slow-roll parameters



$$\epsilon \equiv \frac{M_{Pl}^2}{2} \left(\frac{V'}{V}\right)^2 \ll 1\,,$$

$$\eta \equiv M_{Pl}^2 \left|\frac{V''}{V}\right| \ll 1\,.$$

INFLATION IS SENSITIVE TO UV PHYSICS

- Higher order corrections to $V(\phi)$ generically spoil slow roll

- Unknown physics above UV cutoff parameterised by higher dimensional operators:

$$\mathcal{O}_{p\geq 6} \quad \rightarrow \quad V(\phi)\left(\frac{\phi}{M_P}\right)^{p-4}$$

- All inflation models are sensitive Planck suppressed corrections to the potential: η-problem

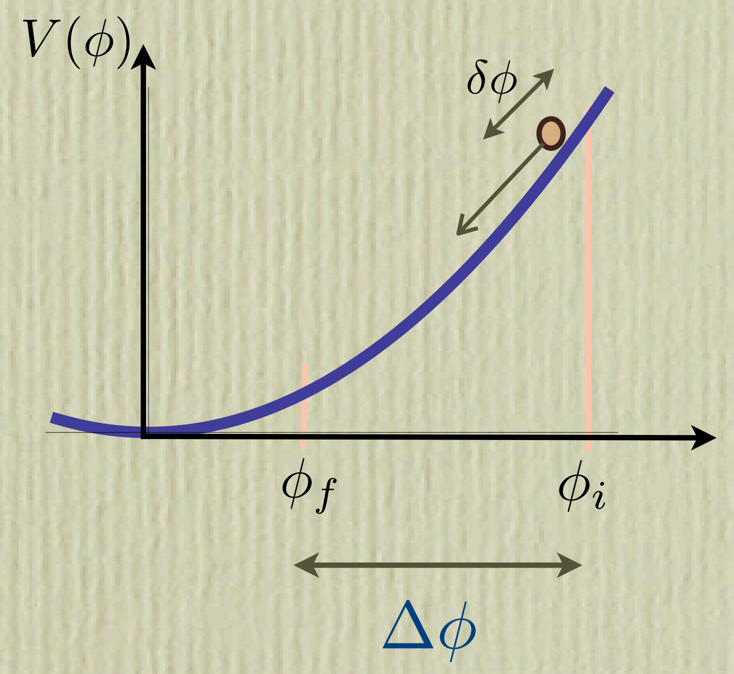
$$\Delta\eta \quad \rightarrow \quad \left(\frac{\phi}{M_P}\right)^{p-6} \gtrsim 1 \qquad\qquad \left(\eta \equiv M_{Pl}^2\left|\frac{V''}{V}\right| \ll 1\right)$$

- *Large field inflationary models are* sensitive to *all* Planck suppressed interactions.

Opportunity to connect quantum gravity to observations

PRIMORDIAL GRAVITY WAVES AND r

Tensor to scalar ratio ***r***, is related to



- *The scale of inflation*

$$V_{inf}^{1/4} \approx 1.8 \times 10^{16}\mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

inflationary scale is close to the GUT scale for values of r as small as $r \sim 10^{-5}$!

- *The inflaton field range*

$$\frac{\Delta\phi}{M_{Pl}} \gtrsim \mathcal{O}(1) \left(\frac{r}{0.01}\right)^{1/2}$$

[Lyth, '96; Boubekeur-Lyth, '05]
[García-Bellido, Roest, Scalisi, IZ '14]

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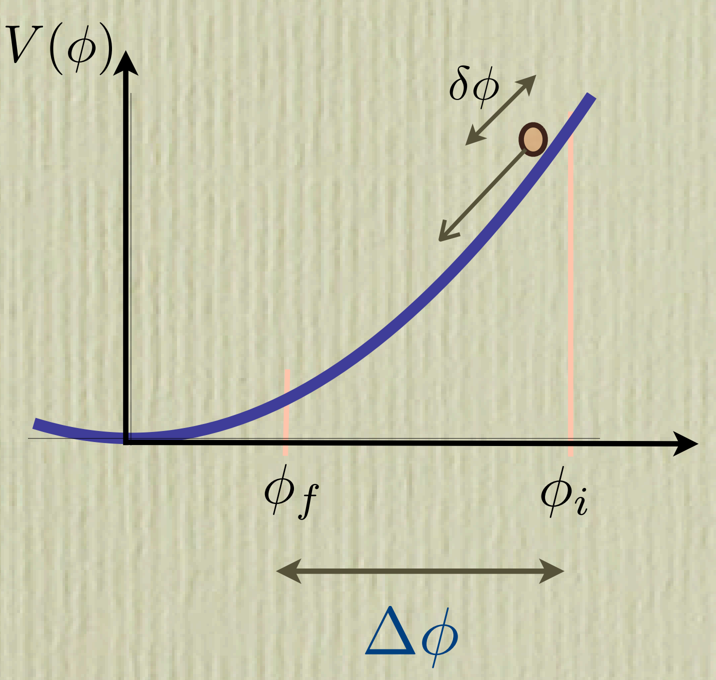

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Monomial chaotic: $\Delta\phi \sim 15 M_{Pl}\,,\quad r \sim 10^{-1}\,,\quad V_{inf}^{1/4} \sim 1.8 \times 10^{16}\mathrm{GeV}$

Starobinsky: $\Delta\phi \sim 5 M_{Pl}\,,\quad r \sim 10^{-3}\,,\quad V_{inf}^{1/4} \sim 5.7 \times 10^{15}\mathrm{GeV}$

PRIMORDIAL GRAVITY WAVES AND r

- Therefore, an observation of primordial gravitational waves with $r \sim 10^{-1} - 10^{-2}$ would indicate a scale of inflation of order the GUT scale and the inflaton field range to be super-Planckian.

➠ inflation is highly sensitive to quantum gravity effects.

Inflation and PGW represent a unique opportunity to connect observations to theories of quantum gravity.

String Theory

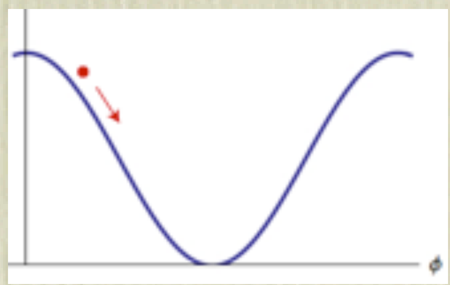
PGW'S IN STRING INFLATION

In string theory, large field inflation with large PGW's models proposed in regimes where *backreaction and moduli stabilisation* are under control are:

- Axion Inflation. Shift symmetry broken NP/spontaneously

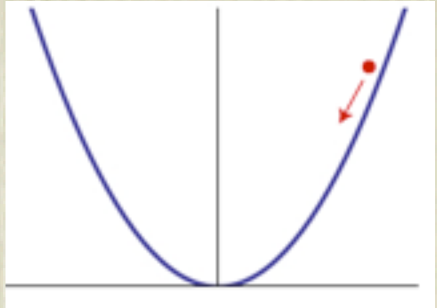
  [Freese-Frieman-Linto, '90; Kaloper-Sorbo '08]

  - Natural Inflation. Hard to achieve large decay constants $f \gg M_{Pl}$ [Banks, Dine, Fox & Gorbatov, '03]

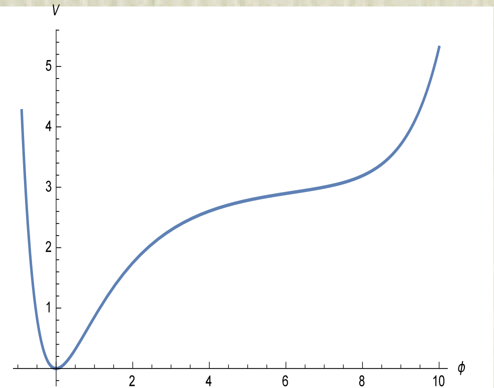
  - Axion monodormy. But not explicit realisation

    [Westphal-Silverstein, '08, '14]

- Fibre Inflation. Exponential potential with a positive plateau at large field values.

  [Cicoli, Burgess, **Quevedo**, '08]

LARGE FIELD INFLATION IN STRING THEORY

However, to ensure a valid 4D EFT description throughout the inflationary epoch, any string model of inflation has to feature the hierarchy of scales

[Baumann, McAllister, '14]
[Mazumdar, Shukla, '14]
[Kooner, Parameswaran, IZ, '15]
[Burgess, Cicoli, de Alwis, **Quevedo**, '16]
[Parameswaran, IZ, '16]

$$M_{inf} < M_{mod} \lesssim M_{kk} \lesssim M_s \lesssim M_{Pl}$$

$(M_s = 1/\ell_s\,, \quad \alpha' = \ell_s^2/(2\pi)^2)$

- If $M_{inf} \gtrsim M_{kk}$ then physics is extra-dimensional
- If $M_{inf} \sim M_s$ one cannot use an EFT description of inflation
- If $M_{inf} \lesssim M_{mod}$ light moduli must be taken into account

But models with large *r* have high inflationary scale

$$M_{inf} \approx 1.8 \times 10^{16}\mathrm{GeV}\,\left(\frac{r}{0.1}\right)^{1/4}$$

little room for required hierarchy to be achieved...

UPPER BOUND ON r IN STRING INFLATION

[Parameswaran, IZ, '16]

The relation between the string and Planck scales in regimes of perturbative control is

$$M_s = M_{Pl} \frac{g_s}{\sqrt{4\pi \mathcal{V}_6}}$$

g_s string coupling

$\mathcal{V}_6$ 6D volume in string units

Using the general relation between r and M_{inf}

$$V_{inf}^{1/4} \approx 1.8 \times 10^{16} \mathrm{GeV} \left(\frac{r}{0.1}\right)^{1/4}$$

We can derive an upper bound on r for different sensible values of the string coupling and α'

UPPER BOUND ON r IN STRING INFLATION

[Parameswaran, IZ, '16]

- A very conservative upper bound.

$g_s \lesssim 0.3$ for a valid weak coupling expansion

$(\ell_s/L)^2 \lesssim 1$ at the limits of weak curvature α' expansion.

L = typical length/curvature scale of XD

$(M_s = 1/\ell_s\,, \quad \alpha' = \ell_s^2/(2\pi)^2)$

KK masses scale generically as $M_{kk} \sim 1/L$.

➠ $M_s \lesssim 0.08 M_{Pl}$ and $M_{kk} \lesssim 0.08 M_{Pl}$

Asking further: $M_{inf} < 0.1 M_{kk}$, $V_{inf}^{1/4} \approx 1.8 \times 10^{16}\text{GeV} \left(\frac{r}{0.1}\right)^{1/4}$

➠ $r < 0.2$

Note: bound very sensitive to changes in parameters

$(\ell_s/L)^2 \lesssim 0.7$ $r < 0.01!$

Explicit examples

- E.g. axion monodromy long warped throats within throats are used to prevent brane-anti-brane annihilation and suppress brane backreaction.

  The large internal volume drives the string scale down and so also M_{inf} and thus r.

- In LARGE volume scenario, to keep control of moduli stabilisaiton $\mathcal{V}_6 \gtrsim 10^3$. Assuming such volumes the bound becomes much stronger

$$r < 2 \times 10^{-9}$$

Can we evade this bound going to strong coupling and/or strong curvatures

$$g_s > 1\,, \quad L/\ell_s < 1$$

to drive $M_s\,,\;\; M_{kk}$ up?

In this case, $M_s = M_{Pl}\frac{g_s}{\sqrt{4\pi\mathcal{V}_6}}$ no longer valid.

But one could perform a *duality* transformation to an equivalent weak coupling weak curvature description and back to the same bound and conclusions

$$r < 0.2$$

Comments

- The relation $V_{inf}^{1/4} \approx 1.8 \times 10^{16}\mathrm{GeV}\left(\frac{r}{0.1}\right)^{1/4}$ remains unchanged for multifield and non-standard kinetic field inflation

[Sasaki, Stewart, '95; Wands, '07]
[Garriga, Mukhanov, '99]

- The bound assumes
  i) inflation in a 4D EFT
  ii) perturbative string theory and its supergravity limit as a good description of the early Universe.

- A positive observation of PGW with $r \sim 10^{-1} - 10^{-2}$ would make convincing string realisations of inflation challenging, but very exciting!

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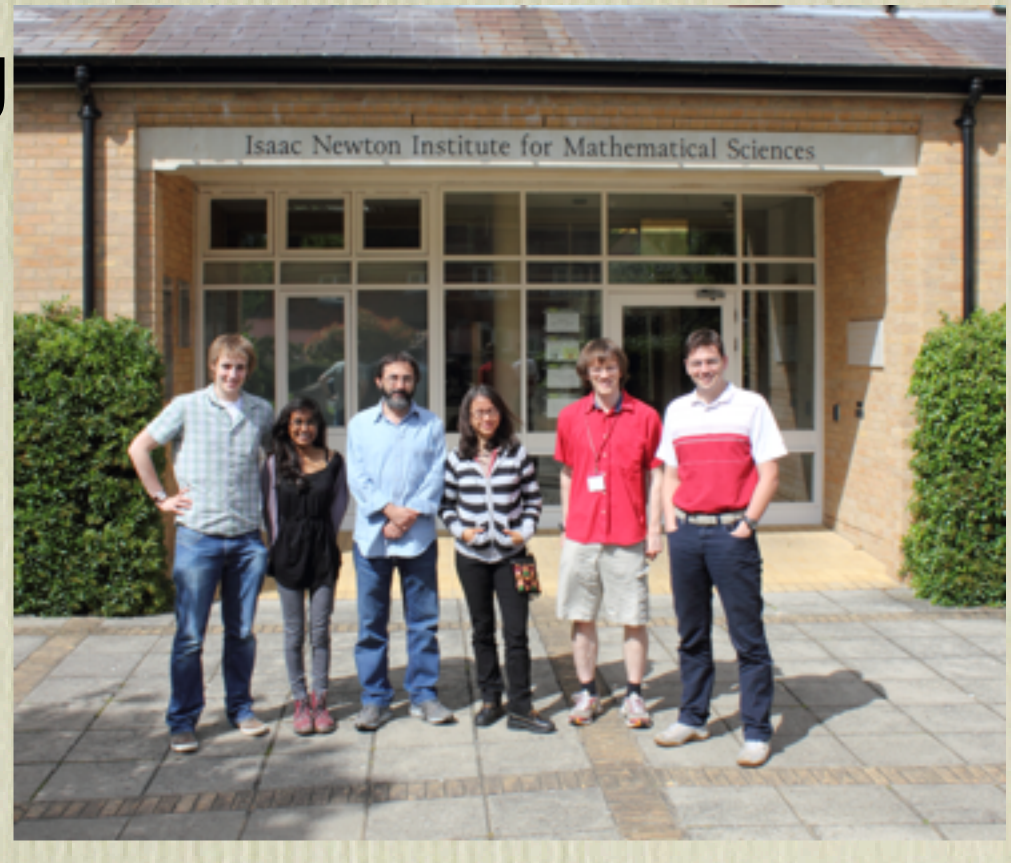
"Universe was at the limits of string perturbation theory and sugra limit and at the limits of validity of the 4D EFT"

Fernando

LESSONS FROM FERNANDO

- Important contributions to string *cosmology* and phenomenology



- Honesty & Integrity
- Enthusiasm
- Kindness, respect, drive for knowledge

¡Feliz cumpleaños fernando!