STRING THEORY AND THE EARLY UNIVERSE: CONSTRAINTS AND OPPORTUNITIES

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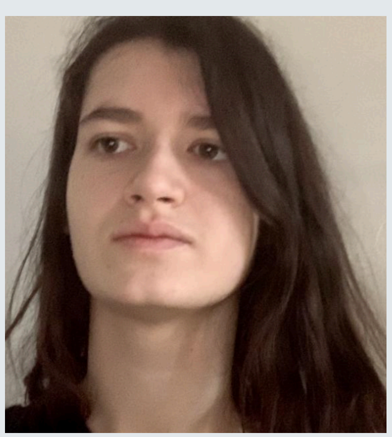
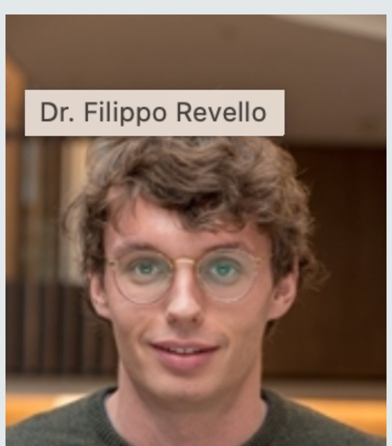
(Relevant work
Apers, JC, Copeland, Mosny, Revello 2401.04064,
Apers, JC, Mosny, Revello 2212.10293
JC, Revello 2207.00567)



STRING THEORY: THE CASE FOR THE PROSECUTION

String theory claims to be a theory of *quantum gravity*, relevant for physics near the Planck scale $M_P \simeq 2.4 \times 10^{18}\,\mathbf{GeV}$.

Inflation occurs at $\Lambda_{inf} \lesssim 10^{16}\,\mathbf{GeV}$ and all other subsequent physics scales are even smaller.

For physicists interested in `ordinary' sub-Planckian physics, why care about string theory?

STRING THEORY: THE CASE FOR THE PROSECUTION

If $\Lambda_{\text{everything else}} < M_P$, what can string theory offer that is not already provided by

- Low-energy effective quantum field theory
- The Standard Model and Beyond-the-Standard-Model particle physics (susy, axions, WISPs, etc etc)
- The Standard Cosmology and extensions (dark radiation, quintessence etc)

WHAT DOES STRING THEORY OFFER

Theories of quantum gravity allow Planck-scale computation and so give control over Planck-suppressed operators (cf Fermi theory and electroweak theory)

- Control of Planck-suppressed operators implies that in an expansion

$$\mathscr{L}(\phi) \rightarrow \mathscr{L}(\phi)\left(1 + \frac{\alpha\phi}{M_P} + \frac{\beta\phi^2}{M_P^2} + \frac{\gamma\phi^3}{M_P^3} + \ldots\right)$$

  we are able to determine the coefficients α, β and γ.

- Such operators require an understanding of Planck-scale physics to determine their nature and coefficients; they cannot be understood just in low-energy EFT.

- When do they matter?

WHEN DOES STRING THEORY MATTER?

When does control over Planck-suppressed operators matter?

- Long-lived particles (e.g. moduli) with only gravitational-strength interactions

  Their decay rate is $\Gamma_\Phi \sim \frac{1}{8\pi}\frac{m_\Phi^3}{M_P^2}$ and they can dominate the energy density of the early universe (moduli problem).

- η problem of inflation: how to control contributions to potential of form.
  $\delta V(\phi) = \frac{\phi^2}{M_P^2}V(\phi)$ which can destroy flatness of inflationary potential

- Transplanckian field excursions $\Delta\phi \geq M_P$ in field space.

TRANSPLANCKIAN FIELD EXCURSIONS AND COSMOLOGY

Much of cosmology involves scalar fields Φ_i coupled to general relativity (inflation / quintessence / dynamical dark energy). Which epochs of the universe involve transPlanckian field excursions?

- Large-field inflation models (e.g. chaotic inflation) resulting in large CMB tensor B modes)

- Extended epochs where scalar field kinetic energy $\dot{\Phi}^2$ is a large contribution to universe energy density: occurs through either kination or tracker epochs

KINATION

- During roll, with universe in kination epoch, field evolves as

$$\Phi(t) = \Phi_0 + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

- Field moves through $\sim M_P$ in field space each Hubble time

  Extended kination epoch implies large transPlanckian field excursions

- String theorists should **care!** - any extended kination epoch requires trans-Planckian field excursions $\Delta\Phi \gg M_P$.

- Cosmologist should **care!** - any extended kination epoch requires theory of the Planck scale to control it.

- Relatively little work on understanding kination epochs in string theory

TRACKER EPOCHS

- A rolling scalar field on an exponential potential $V = V_0 e^{-\lambda\Phi}$ in a radiation background reaches a tracker solution in which field evolves as

$$\Phi(t) = \Phi_0 + \frac{2M_P}{\lambda} \ln\left(\frac{t}{t_0}\right)$$

- Field motion is *slightly* slower than for kination but field still moves through $\sim M_P$ in field space each Hubble time

  Extended tracker epoch implies large transPlanckian field excursions

- String theorists should **care!** - any extended tracker epoch requires trans-Planckian field excursions $\Delta\Phi \gg M_P$

- Cosmologists should **care!** - any extended tracker epoch requires theory of the Planck scale to control it

TRANSPLANCKIAN FIELD EXCURSIONS: STRING THEORY CONSTRAINTS

- What is the problem with transPlanckian field excursions?
- (Swampland) distance conjecture: when fields move through transPlanckian distances $\Delta\Phi \gtrsim M_P$ in field space a tower of states comes down

$$m_{tower,i}^2(\Phi) \sim m_0^2 e^{-\mu(\Delta\Phi)/M_P}$$

- This conjecture is supported by many examples in string theory and appears to be valid.
- Parametrically transPlanckian field excursions involve large changes to the effective field theory

TRANSPLANCKIAN FIELD EXCURSIONS: STRING THEORY CONSTRAINTS

- The distance conjecture makes large-field inflation models very hard (impossible?) to construct in string theory

- On normal effective field theory grounds, it is hard to keep a potential flat across transPlanckian distances $\Delta\Phi \gtrsim M_P$ in field space when a tower of states comes down

$$m^2_{tower,i}(\Phi) \sim m_0^2 e^{-\mu(\Delta\Phi)/M_P}$$

- Issues of backreaction become significant; this is supported by careful studies of attempts to realise large-field inflation within string theory.

STRING THEORY: OPPORTUNITIES?

- N=0 supersymmetry
  Hierarchies
  Weak couplings

Strong coupling

$$AdS_5 \times S^5$$

M-theory

$$g_s \sim 1, \text{Volume} \sim \mathrm{l}_\mathrm{s}^6$$

Black hole entropy

Dualities

$$\mathcal{N} \geq 2 \text{ Supersymmetry}$$

Landau-Ginzburg models

The Map of
String Theory

OUR HOME, THE UNIVERSE

- Our universe is *filled* with hierarchies and small numbers

$$\frac{\Lambda_{EW}}{M_P} \sim 10^{-16}$$

$$\frac{\delta\rho_{CMB}}{\rho} \sim 10^{-5}$$

$$\Lambda_{cc} \sim 10^{-120} M_P^4$$

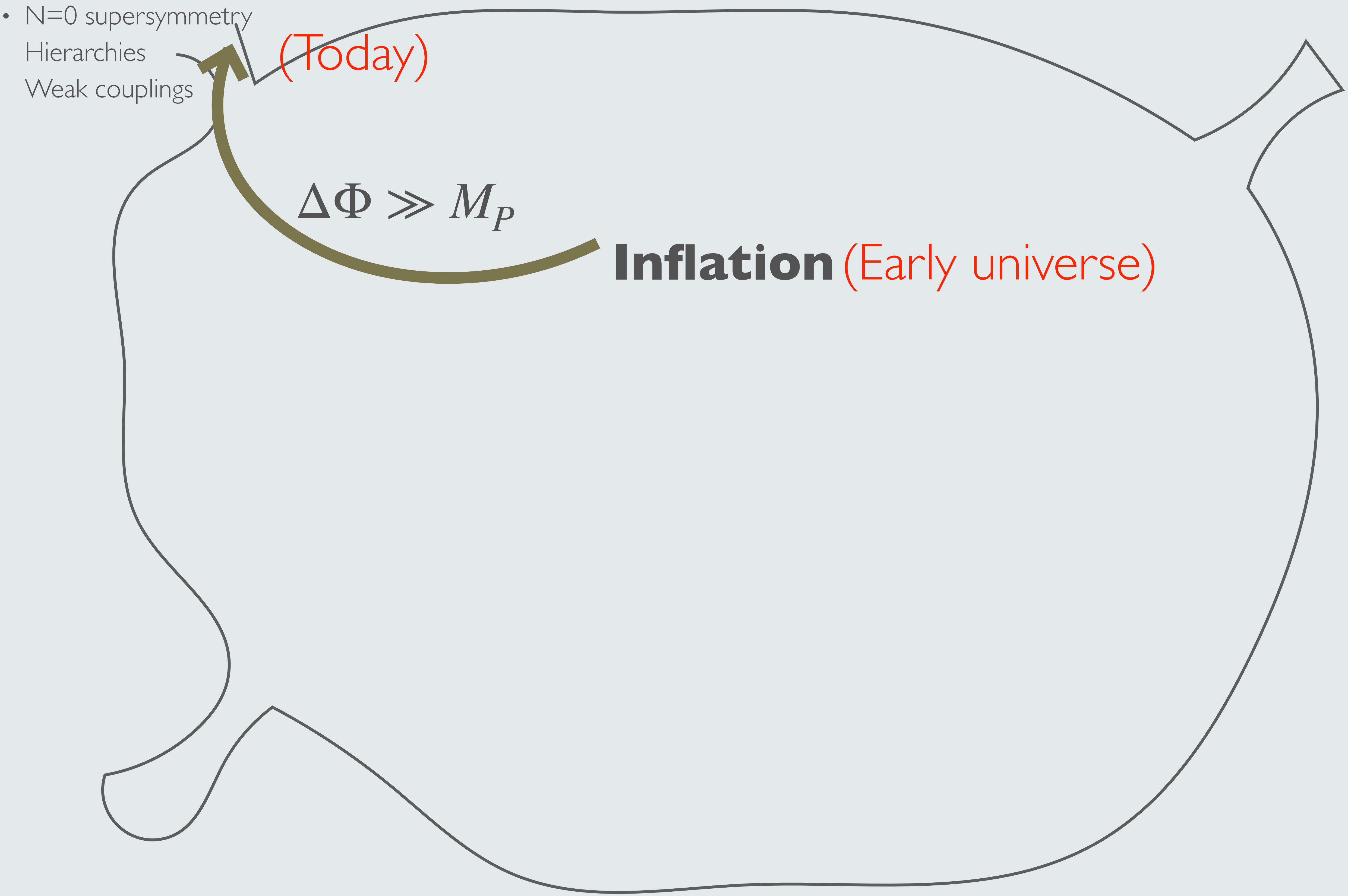
$$\alpha_{SU(3)} \sim \frac{1}{11}, \alpha_{SU(2)} \sim \frac{1}{30}, \alpha_{U(1)_Y} \sim \frac{1}{60}$$

$$y_e \sim 10^{-5}, y_\mu \sim 10^{-3}, y_\tau \sim 10^{-2}$$

$$m_\nu \sim 10^{-3}\mathrm{eV}$$

$$\theta_{QCD} \lesssim 10^{-10}$$

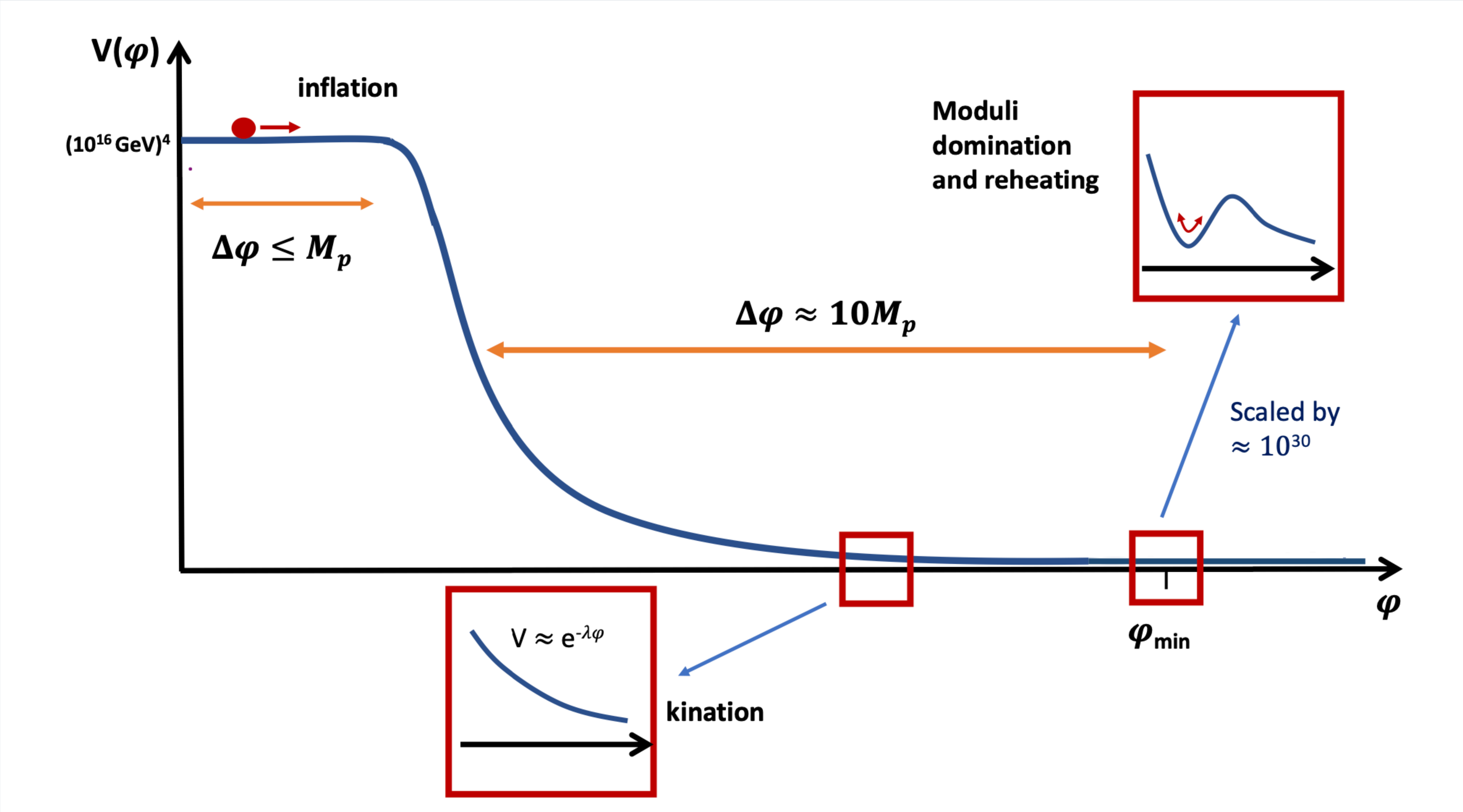
FROM CENTRE TO END OF THE WORLD



WHERE IS THE CENTRE OF THE WORLD?

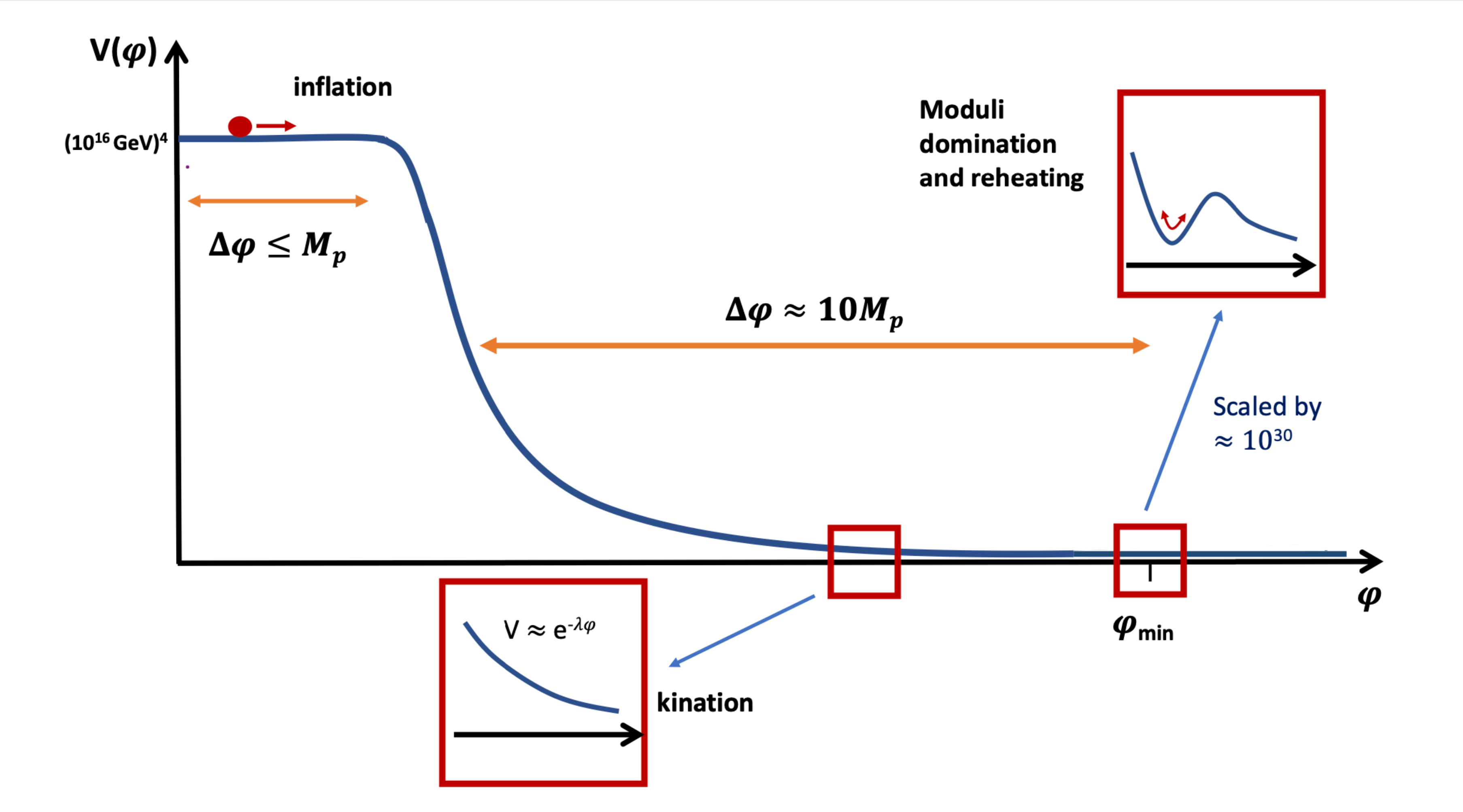
WHERE IS THE CENTRE OF THE WORLD?

GETTING TO THE END OF THE WORLD

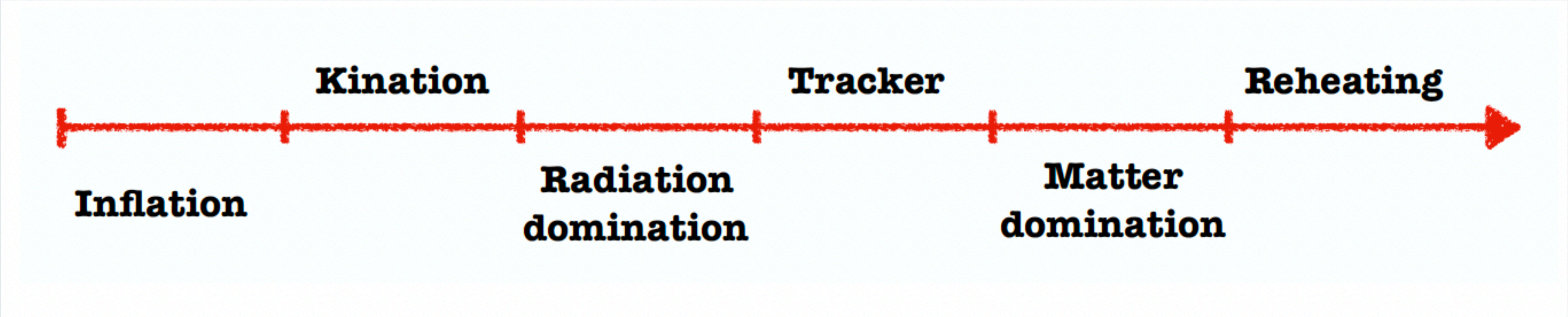


From review 2303.04819 Cicoli, JC, Maharana, Parameswaran, Quevedo, Zavala

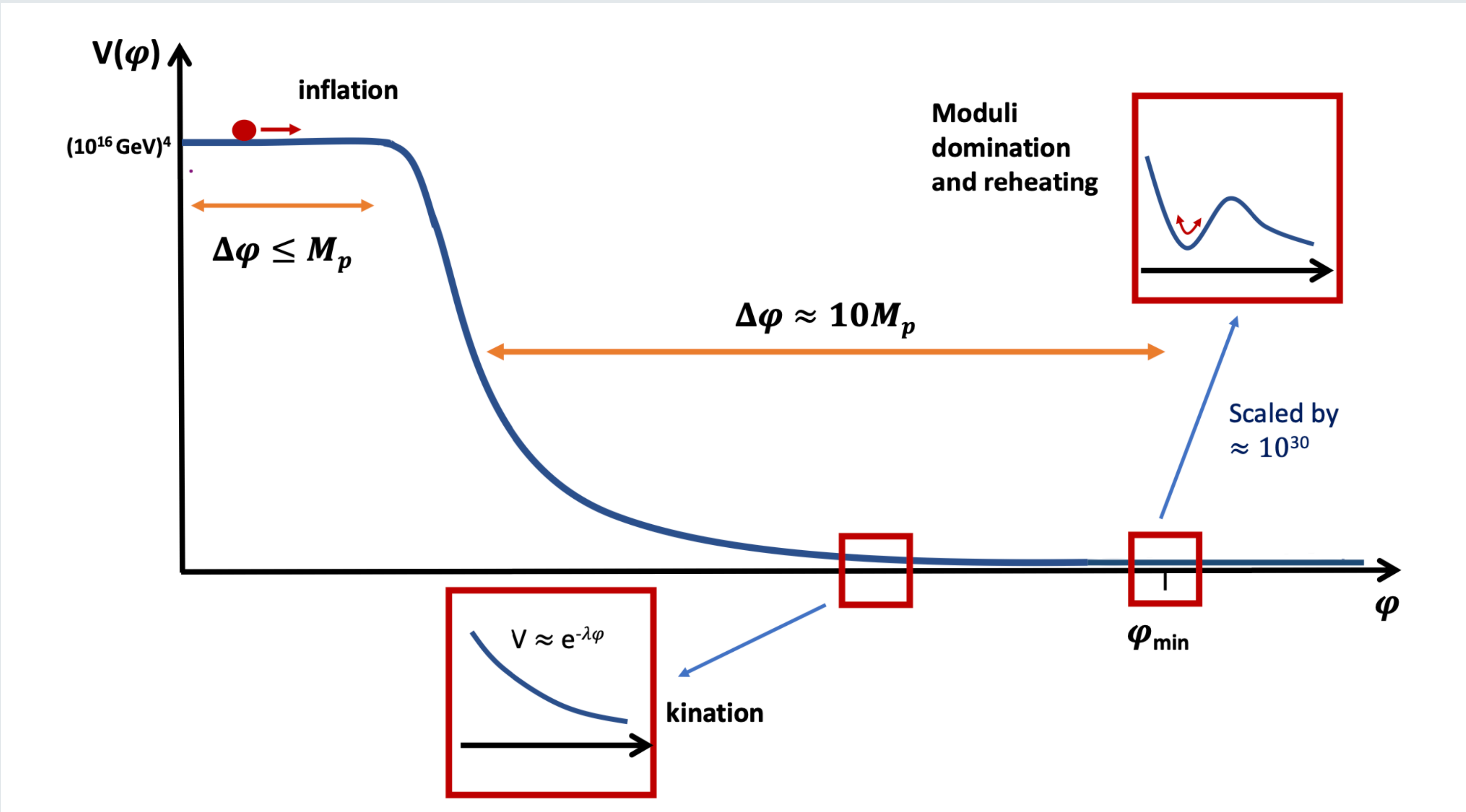
NOVEL COSMOLOGICAL HISTORY



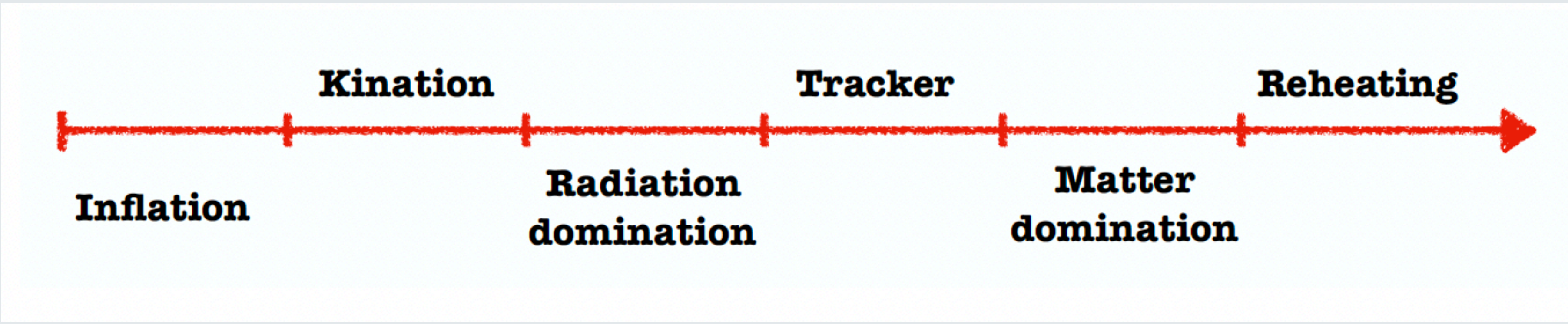
This motivates a distinctive 'stringy' cosmological history quite distinct from the normal assumption of radiation domination after inflation



NOVEL COSMOLOGICAL HISTORY



We know almost NOTHING observationally about the ~ 30 orders in magnitude in time between end of inflation and the beginning of nucleosynthesis!



NOVEL COSMOLOGICAL HISTORY

- During kination, tracker and moduli epoch, universe would be dominated by stringy degrees of freedom (evolving moduli fields)
- All parameters of Standard Model are also varying during this time as in string theory moduli control all couplings of Standard Model and all physical scales
- This is an epoch where gauge couplings, Yukawa couplings, cosmic string tensions, axion decay constants may all be very different from values in today's universe
- This gives considerable opportunity for interesting physics

PERTURBATION IN KINATION EPOCHS

- Long kination epoch associated to roll of moduli towards boundaries of moduli space

- Perturbations in a kination epoch illustrate a nice aspect of quantum field theory

- During kination epoch, perturbations grow as
$$\Delta_k \sim \frac{\delta\rho_k}{\rho} \sim \sqrt{k\eta}\,\sin\left(k\eta\right) \sim a\sin\left(ka^{1/2}\right)$$

- However, kination is a pure scalar field: so why do the Fourier modes not behave as radiation $\rho_\gamma \sim a^{-4}$ against the kinating background $\rho \sim a^{-6}$?

PERTURBATION IN KINATION EPOCHS

Scalar field expansion for kination:

$$\phi_k(\eta) = \phi_0 + M_P \left(\frac{2}{3}\right)^{3/2} \ln \eta + \sum_k \left(A_k \frac{e^{ik\eta}}{\sqrt{k\eta}} + A_k^* \frac{e^{-ik\eta}}{\sqrt{k\eta}} \right).$$

This implies derivative is

$$\phi'(\eta) = \frac{M_P}{\eta} \left(\frac{2}{3}\right)^{3/2} + \sum_k \left(ikA_k \frac{e^{ik\eta}}{\sqrt{k\eta}} - ikA_k^* \frac{e^{-ik\eta}}{\sqrt{k\eta}} \right),$$

In calculating the kinetic energy, the Fourier modes cross-couple to the velocity term and so contribute as $\rho \sim a^{-5}$

$$\rho_{\text{cross term}} \propto \frac{\sin(k\eta + \theta)}{\eta^{5/2}},$$

CONCLUSIONS

- String theory matters for cosmology when Planck suppressed operators matter for cosmology.

- It is always relevant when fields evolve through transPlanckian field excursions

- Distance conjecture quantifies some of the behaviour of EFTs over transPlanckian field excursions

- String theory motivates a distinctive non-standard cosmology (with kination, tracker and moduli epochs) in the unexplored region between inflation and BBN.