Transplanckian masses in inflation

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ICHEP 14, Valencia, Spain

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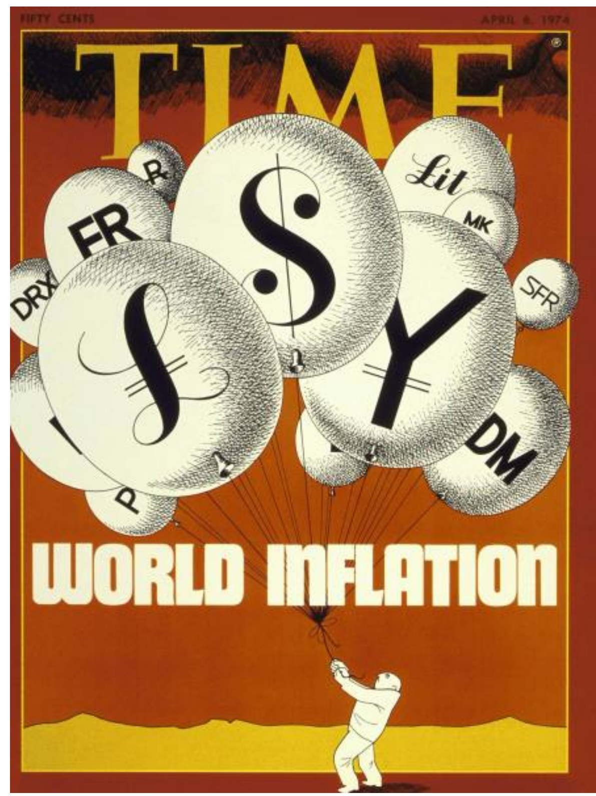


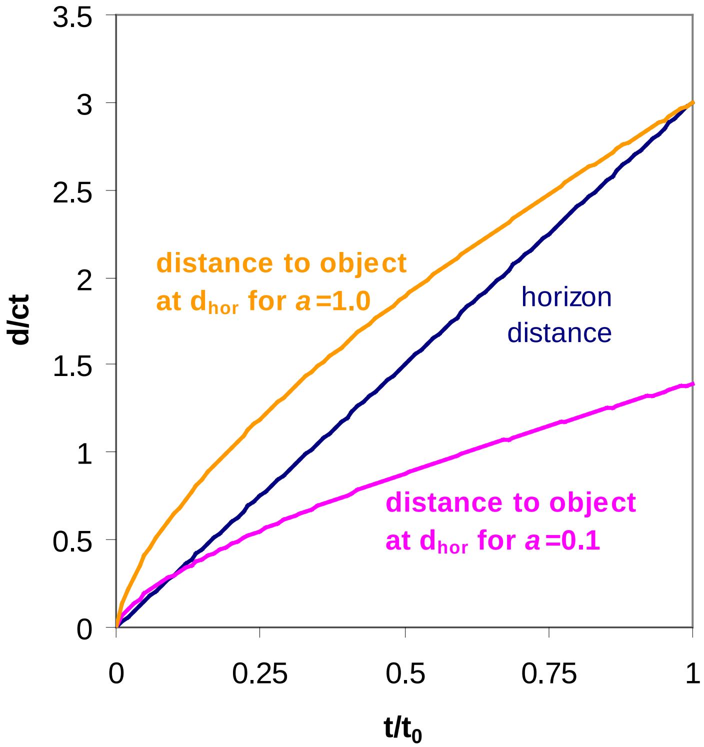
, Spain

Unsolved issues in the standard model

- Horizon problem
  Why is the CMB so smooth ?
- The flatness problem
  Why is the Universe flat ? Why is $\Omega \sim 1$?
- The structure problem
  Where do the fluctuations in the CMB come from ?
- The relic problem
  Why aren't there magnetic monopoles ?

Outstanding Problems

- Why is the CMB so isotropic?
  - consider matter-only universe:
    - horizon distance $d_H(t) = 3ct$
    - scale factor $a(t) = (t/t_0)^{2/3}$
    - therefore horizon expands faster than the universe
      - "new" objects constantly coming into view
  - CMB decouples at $1+z \sim 1000$
    - i.e. $t_{CMB} = t_0/10^{4.5}$
    - $d_H(t_{CMB}) = 3ct_0/10^{4.5}$
    - now this has expanded by a factor of 1000 to $3ct_0/10^{1.5}$
    - but horizon distance now is $3ct_0$
    - so angle subtended on sky by one CMB horizon distance is only $10^{-1.5}$ rad $\sim 2°$
  - patches of CMB sky >2° apart should not be causally connected



Outstanding Problems

- Why is universe so flat?
  - a multi-component universe satisfies

$$1-\Omega(t) = -\frac{kc^2}{H(t)^2 a(t)^2 R_0^2} = \frac{H_0^2(1-\Omega_0)}{H(t)^2 a(t)^2}$$

and, neglecting Λ,

$$\left(\frac{H(t)}{H_0}\right)^2 = \frac{\Omega_{\mathrm{r0}}}{a^4} + \frac{\Omega_{\mathrm{m0}}}{a^3}$$

  - therefore
    - during radiation dominated era $|1 - \Omega(t)| \propto a^2$
    - during matter dominated era $|1 - \Omega(t)| \propto a$
    - if $|1 - \Omega_0| < 0.06$ (WMAP) ... then at CMB emission $|1 - \Omega| < 0.00006$
  - we have a fine tuning problem!

Outstanding Problems

- Where is everything coming from ?

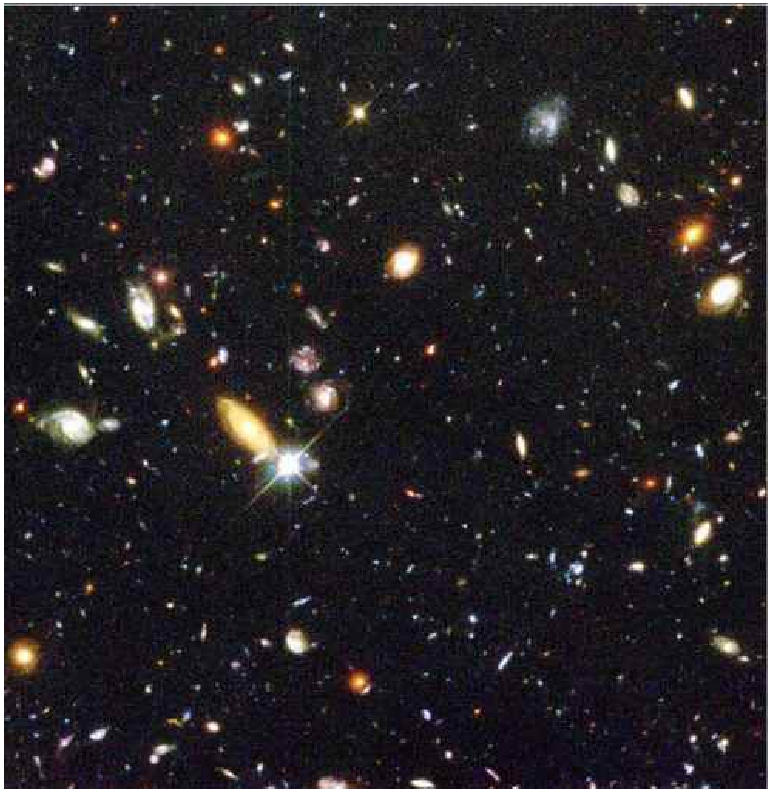
  Models like CDM nicely explain how the fluctuations we can observe in the CMB grew to form galaxies.

  They can also reproduce the observe large scale distribution of galaxies and clusters.

BUT .. why are there fluctuations in the first place ?

Outstanding Problems

- Where is everything coming from ?



Outstanding Problems

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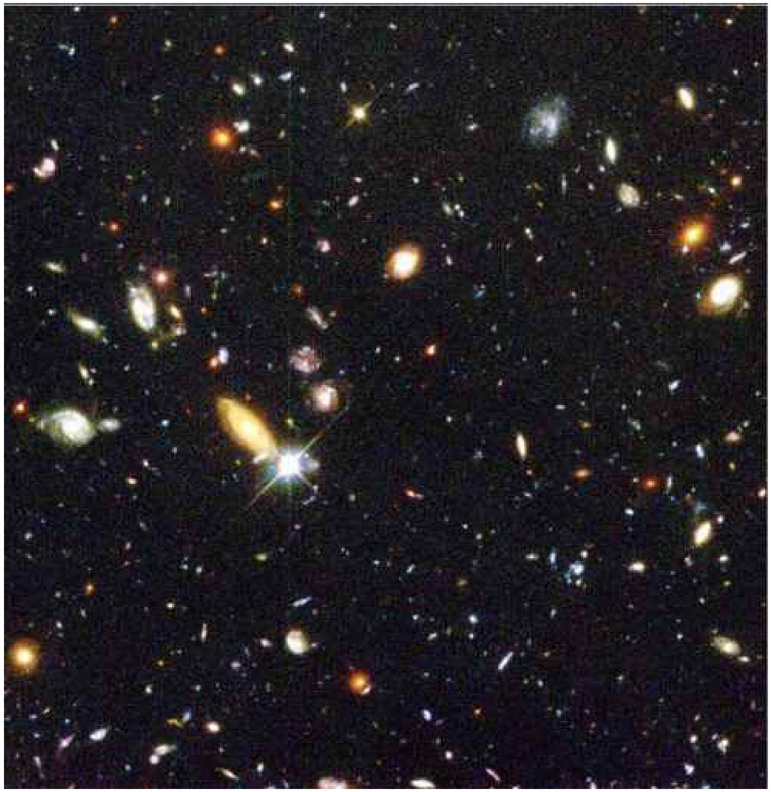
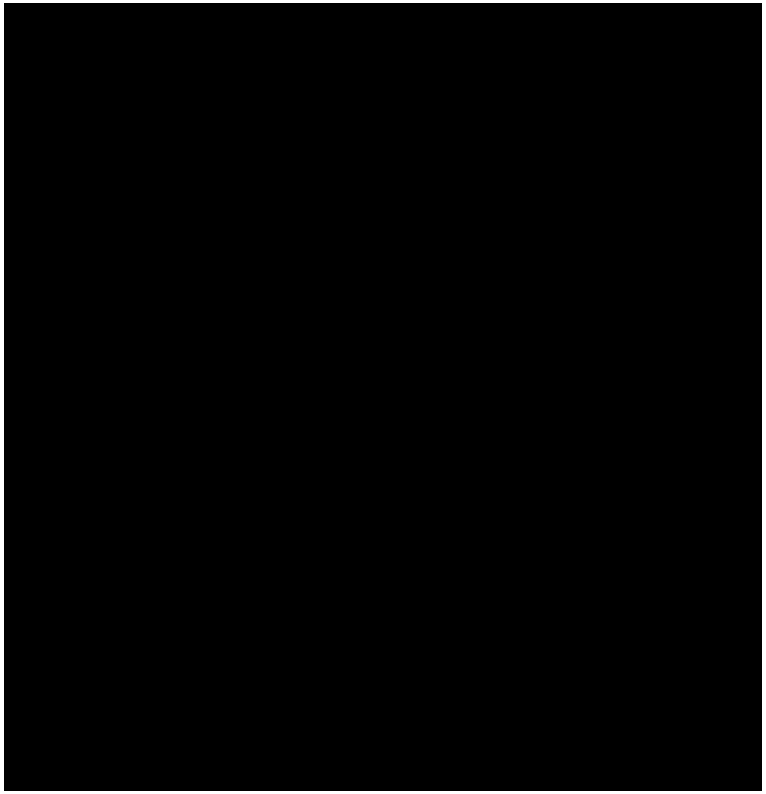




Outstanding Problems

- The monopole problem
  - big issue in early 1980s
    - Grand Unified Theories of particle physics → at high energies the strong, electromagnetic and weak forces are unified
    - the symmetry between strong and electroweak forces 'breaks' at an energy of ~10^{15} GeV ($T \sim 10^{28}$ K, $t \sim 10^{-36}$ s)
      - this is a phase transition similar to freezing
      - expect to form 'topological defects' (like defects in crystals)
      - point defects act as magnetic monopoles and have mass ~10^{15} GeV/c^2 (10^{-12} kg)
      - expect one per horizon volume at $t \sim 10^{-36}$ s, i.e. a number density of 10^{82} m^{-3} at 10^{-36} s
      - result: universe today completely dominated by monopoles (not!)

The concept of inflation

The idea (A. Guth and A. Linde, 1981): Shortly after the Big Bang, the Universe went through a phase of rapid (exponential) expansion. In this phase the energy and thus the dynamics of the Universe was determined by a term similar to the cosmological constant (vacuum energy).

Why would the Universe do that ?

Why does it help ?

What powers inflation?

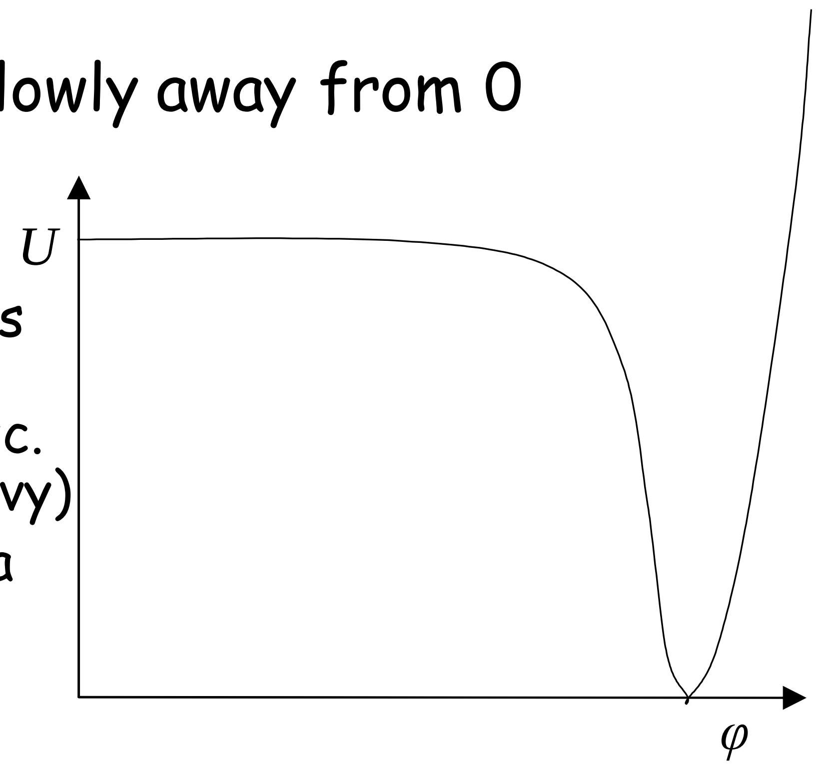
- We need $H_{inf}(t_{end} - t_{inf}) \geq 58$
  - if $t_{end} \sim 10^{-34}$ s and $t_{inf} \sim 10^{-36}$ s, $H_{inf} \sim 6 \times 10^{35}$ s^{-1}
  - energy density $\rho_\Lambda \sim 6 \times 10^{97}$ J m^{-3} ~ 4×10^{104} TeV m^{-3}
    - cf. current value of $\Lambda \sim 10^{-35}$ s^{-2}, $\rho_\Lambda \sim 10^{-9}$ J m^{-3} ~ 0.004 TeV m^{-3}
- We also need an equation of state with negative pressure

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\rho + 3P\right)$$

accelerating expansion needs $P < 0$

Inflation with scalar field

- Need potential *U* with broad nearly flat plateau near $\varphi = 0$
  - metastable false vacuum
  - inflation as φ moves very slowly away from 0
  - stops at drop to minimum (true vacuum)
    - decay of inflaton field at this point reheats universe, producing photons, quarks etc. (but not monopoles – too heavy)
    - equivalent to latent heat of a phase transition

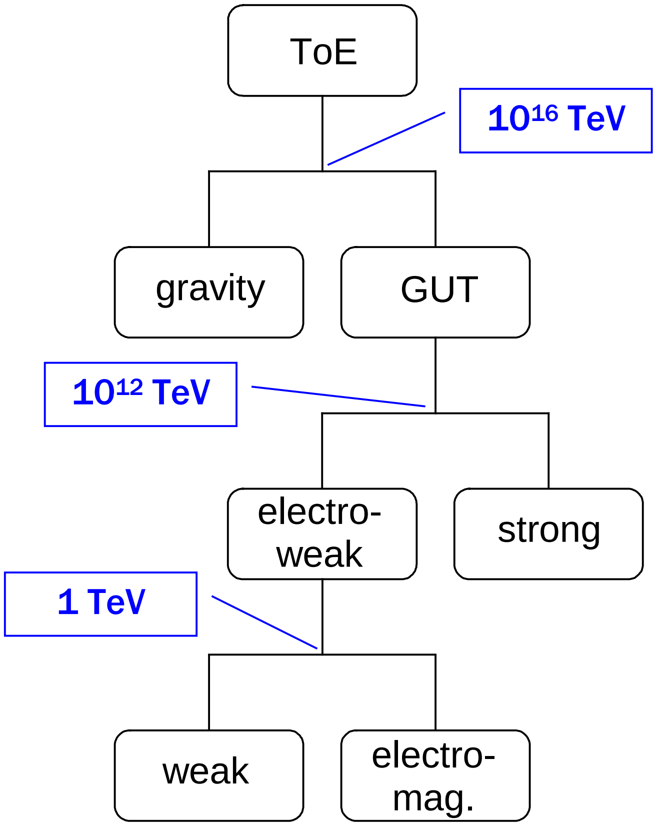


Inflation and particle physics

- At very high energies particle physicists expect that all forces will become unified
  - this introduces new particles
  - some take the form of scalar fields φ with equation of state

$$\rho_\varphi = \frac{1}{2\hbar c^3}\dot{\varphi}^2 + U(\varphi)$$

$$P_\varphi = \frac{1}{2\hbar c^3}\dot{\varphi}^2 - U(\varphi)$$



if $\dot{\varphi}^2 << 2\hbar c^3 U(\varphi)$ this looks like Λ

… the scalar field turns out to be transplanckian

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$$\frac{\Delta\phi}{M_{Pl}} \gtrsim 5.8 \left(\frac{N_e}{50}\right) \left(\frac{r}{0.2}\right)^{1/2}$$

… the scalar field turns out to be transplanckian

$$\frac{\Delta\emptyset}{M_{Pl}} \geq 5.8 \left(\frac{N_e}{50}\right)\left(\frac{r}{0.2}\right)^{1/2}$$

but the field is a "dummy" variable… it is just a field redefinition away from being subplanckian.

A field redefinition to turn the field subplanckian may end up shedding light on the shape of gravity close to the Planck scale

$$S = -\int d^4x \, \sqrt{-g} \left[\frac{k^2}{4} D(\theta) \, R - \frac{1}{2} \, g^{\mu\nu} \, \partial_\mu \theta \partial_\nu \theta + V(\theta) \right]$$

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$$D(\theta) \, H^2 = \frac{\dot{\theta}^2}{3k^2} + \frac{2V(\theta)}{3k^2} - \dot{D}(\theta) \, H$$

$$\ddot{\theta} + 3H\dot{\theta} + \frac{k^2}{4} \, D'(\theta) \, R + V'(\theta) = 0$$

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$$\phi(\theta) = \pm\int\sqrt{\frac{3}{2}\left(\frac{D'(\theta)}{D(\theta)}\right)^2 + \frac{2}{k^2 D(\theta)}}\ d\theta$$

Non-minimal coupling to gravity

$$D(\theta) = (1 - \theta^2/(3k^2))$$

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$$D(\theta) = (1 - \theta^2/(3k^2))$$

$$\phi(\theta) = 2\sqrt{6\pi}\, k \,\mathrm{arctanh}\left[\frac{\theta}{\sqrt{3}\, k}\right]$$

$$\theta(\phi) = \sqrt{3}\, k \tanh\left[\frac{\phi}{2\sqrt{6\pi}\, k}\right]$$

Generic scalar-tensor theories

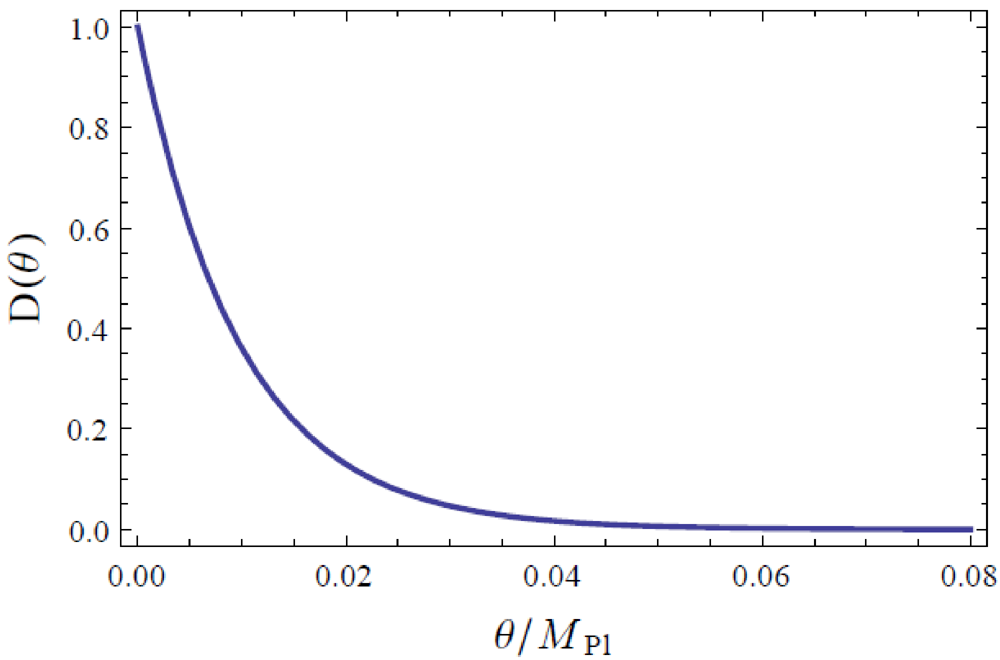
$$a = \exp\left(-\theta/b\right)$$

Generic scalar-tensor theories

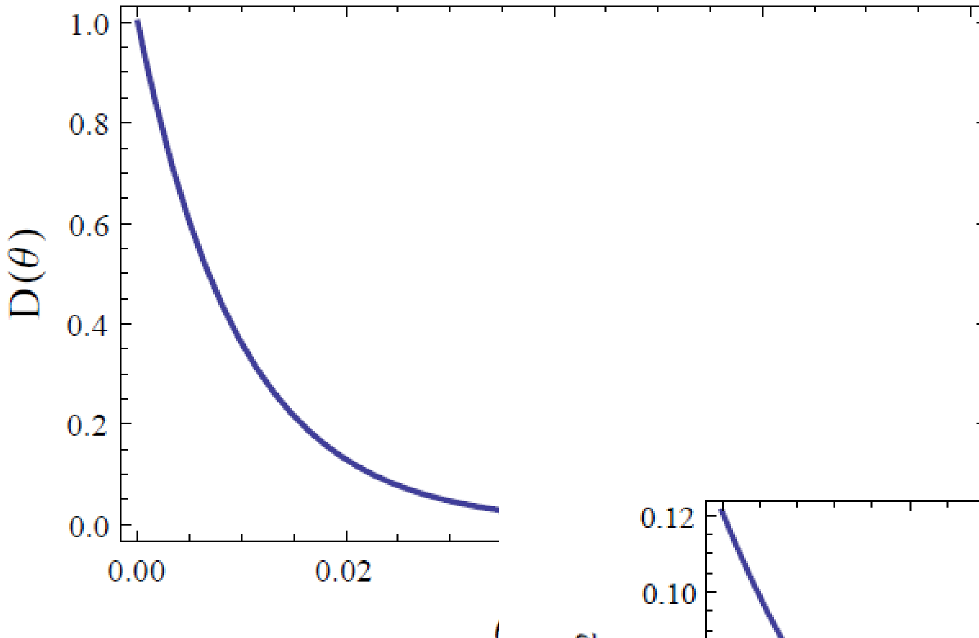
$$a = \exp(-\theta/b) \qquad H = \dot{a}/a = -\dot{\theta}/b$$

$$N_e = \int H dt = -\int \frac{\dot{\theta}}{b} dt = \frac{-1}{b} \int d\theta = \frac{1}{b}(\theta_i - \theta_f) \simeq \frac{\theta_i}{b}$$

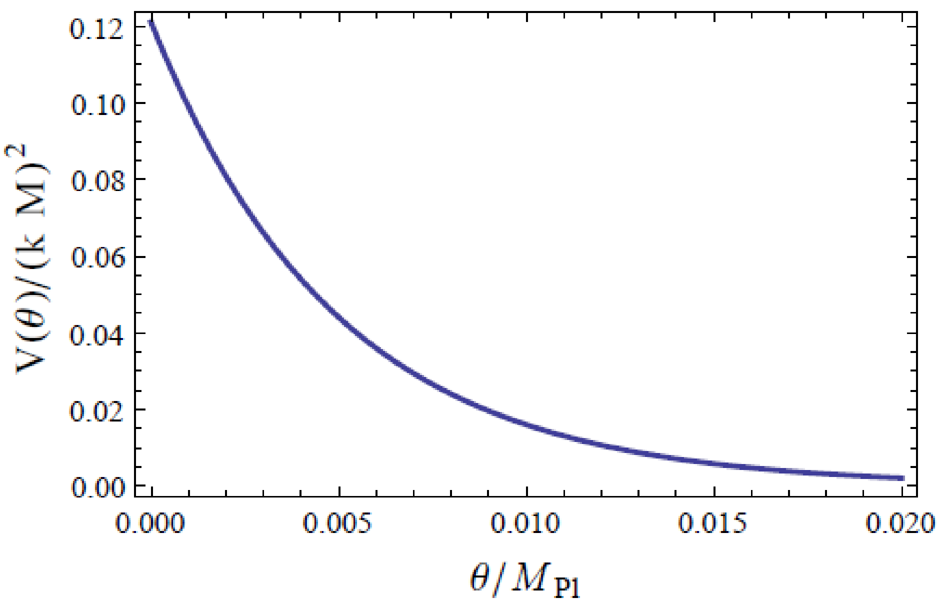
$$\frac{H'}{H} = \frac{2b/k^2 + bD'' + D'}{2D - bD'}$$



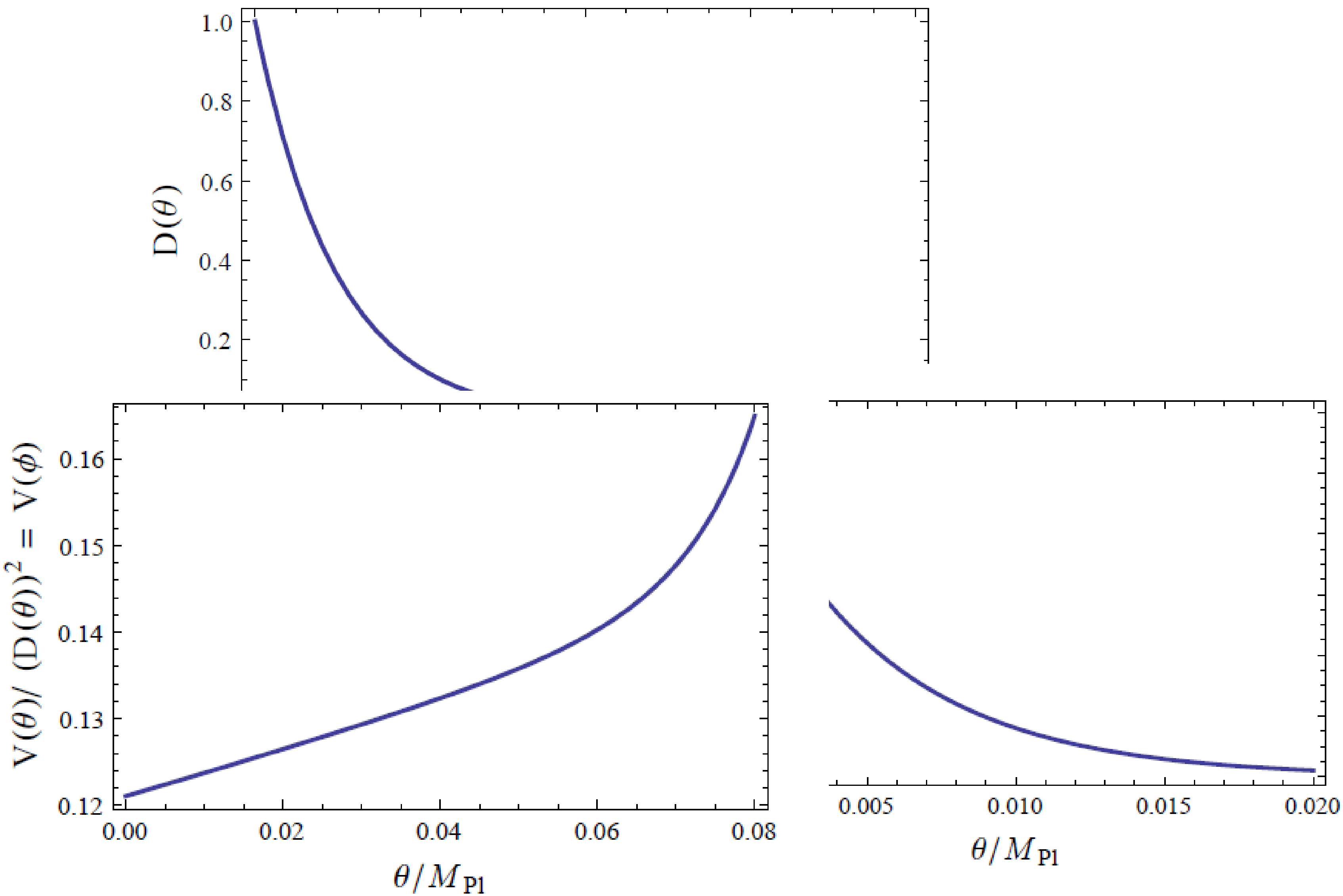
1.0
0.8
0.6
0.4
0.2
0.0
D(θ)
0.00
0.02
0.04
0.06
0.08
θ/M_Pl



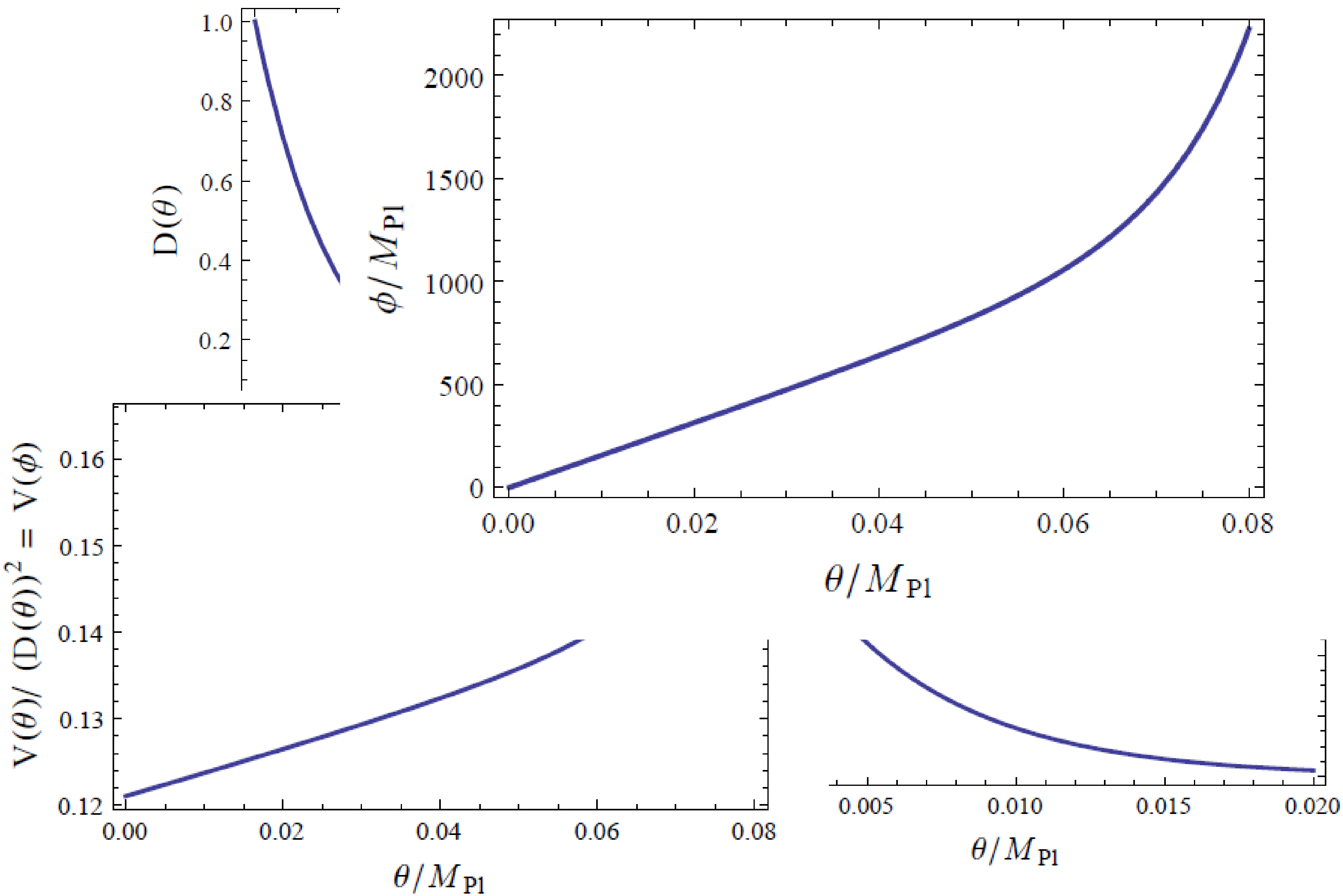
1.0
0.8
0.6
0.4
0.2
0.0
D(θ)
0.00
0.02



0.12
0.10
0.08
0.06
0.04
0.02
0.00
V(θ)/(k M)^2
0.000
0.005
0.010
0.015
0.020
θ/M_{P1}



D(θ)
1.0
0.8
0.6
0.4
0.2
V(θ)/ (D(θ))² = V(ϕ)
0.16
0.15
0.14
0.13
0.12
0.00
0.02
0.04
0.06
0.08
θ/M_Pl
0.005
0.010
0.015
0.020
θ/M_Pl



1.0
0.8
0.6
0.4
0.2
D(θ)
2000
1500
1000
500
0
φ / M_Pl
0.00
0.02
0.04
0.06
0.08
θ / M_Pl
0.16
0.15
0.14
0.13
0.12
V(θ)/ (D(θ))^2 = V(φ)
0.00
0.02
0.04
0.06
0.08
θ / M_Pl
0.005
0.010
0.015
0.020
θ / M_Pl

f(R) gravity

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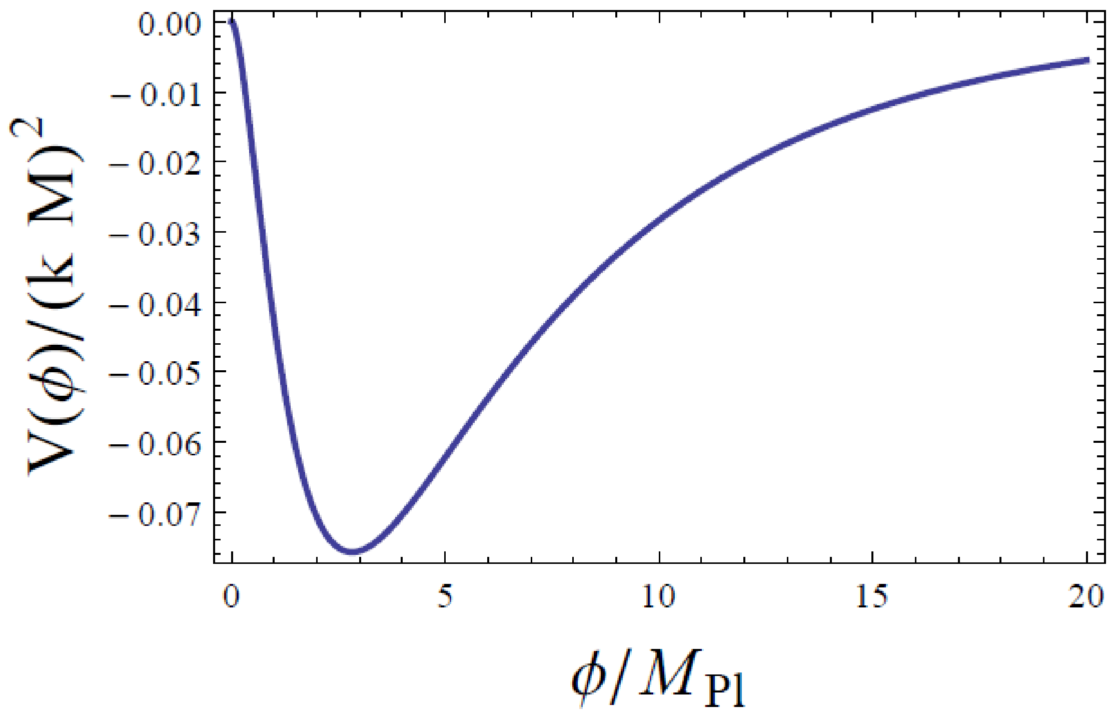
$$f(R) = R\left(1 + (R/M^2)^{5/4}\right)$$

f(R) gravity

$$f(R) = R\left(1 + (R/M^2)^{5/4}\right)$$

$$F(R) = \exp\left(\sqrt{\frac{2}{3}}\phi\right)$$

f(R) gravity



Conclusions

Transplanckian fied values needed to accomodate inflation phenomenology may be due to our insistence of imposing a minimal coupling of the inflaton field to gravity.

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Maybe transplanckian values are telling us that it is gravity and not the inflation self-couplings the true driver of inflation.