Inflation and the BSM quest

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IFIC (UV-CSIC)

Invisibles 16, Padova

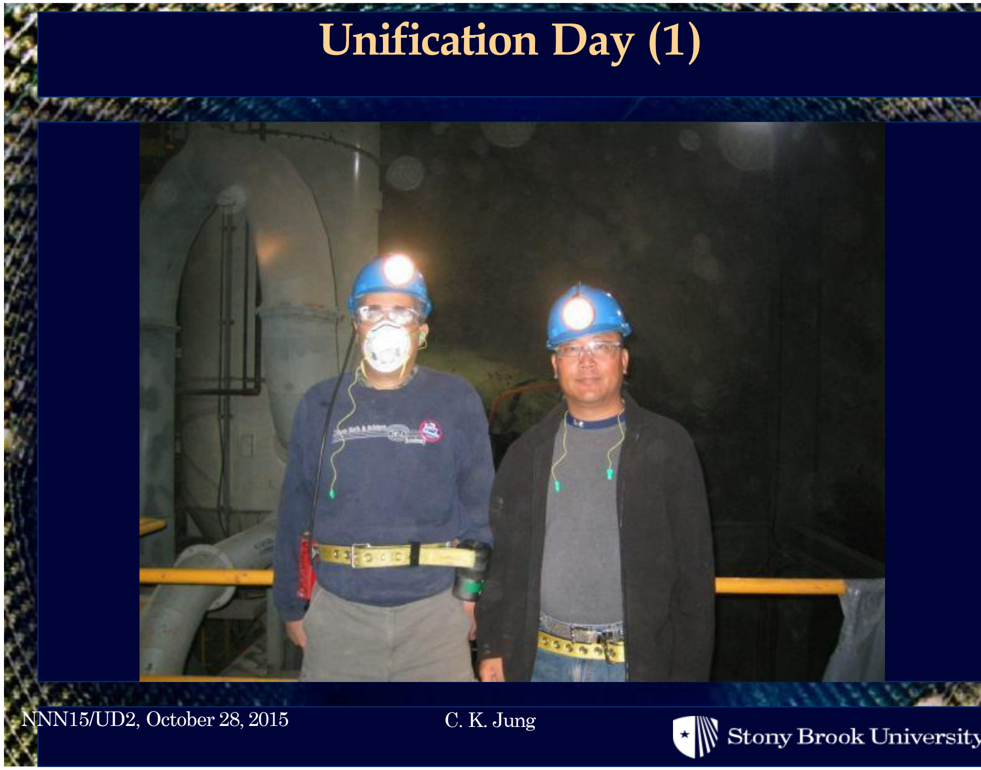
The inner space outer space connection

From the very beginning, a connection based on physics Beyond the Standard Model of particle physics:

- Who are the inflatons?
- Dark matter: axions, neutralinos, Wimpzillas, … all of the above?
- Dark energy!
- Baryo/leptogenesis

Unification

- The idea of unification is at the heart of particle physics
- Pulls together our seemingly very different communities studying Higgs, dark matter, large scale structure, neutrinos, string theory, etc



Unification Day (1)

NNN15/UD2, October 28, 2015

C. K. Jung

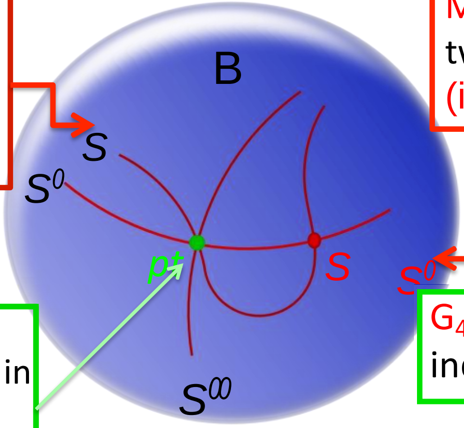
Stony Brook University

string theorist neutrino experimenter

The challenge of top-down unification

Full theory: basic ingredients

- Total space of torus-fibration: singular elliptic Calabi"Yau manifold X D=4, N=1 vacua: fourfold X_4
- Singularities encode complicated set"up of intersecting D-branes:



Non"Abelian gauge symmetry in codimension" one singul. in B (divisors wrapped by branes)

Matter in codimension" two singul. in B (intersecting branes)

Yukawa couplings in codimension"three singul. in B $pt = S \setminus S^0 \setminus S^{00}$

G_4<flux at intersec+on induces chiral 4D majer

- Don't know what is the right framework to start with
- Difficult to connect to observables
- We need more clues – many of these could come from cosmology

The standard model rules on Earth (if not in Heaven)

•The last seven particle colliders (three B factories plus
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let alone Elusive…

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

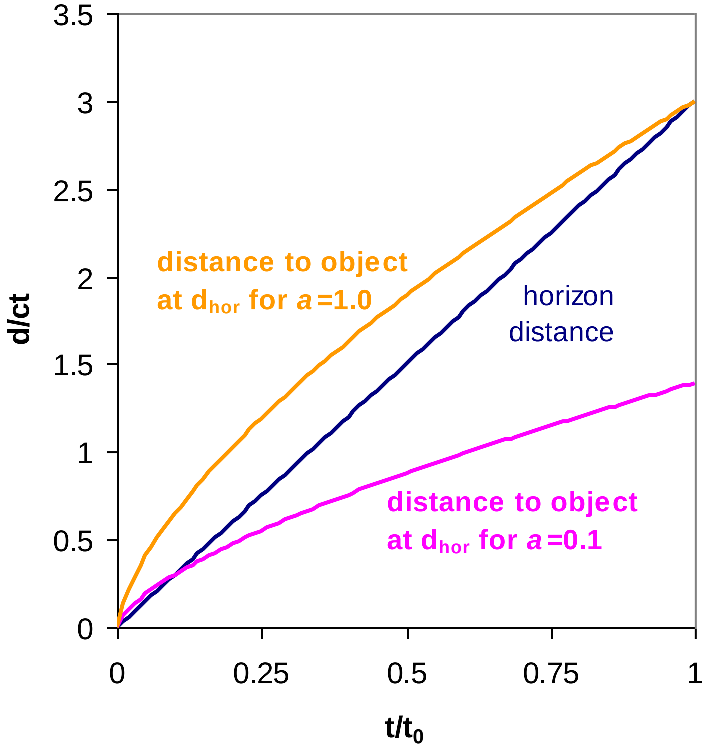
  Where do the fluctuations in the CMB come from ?

- 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 ~ 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,

$$\left(\frac{H(t)}{H_0}\right)^2 = \frac{\Omega_{\mathrm{r}0}}{a^4} + \frac{\Omega_{\mathrm{m}0}}{a^3}$$

  - 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 ?

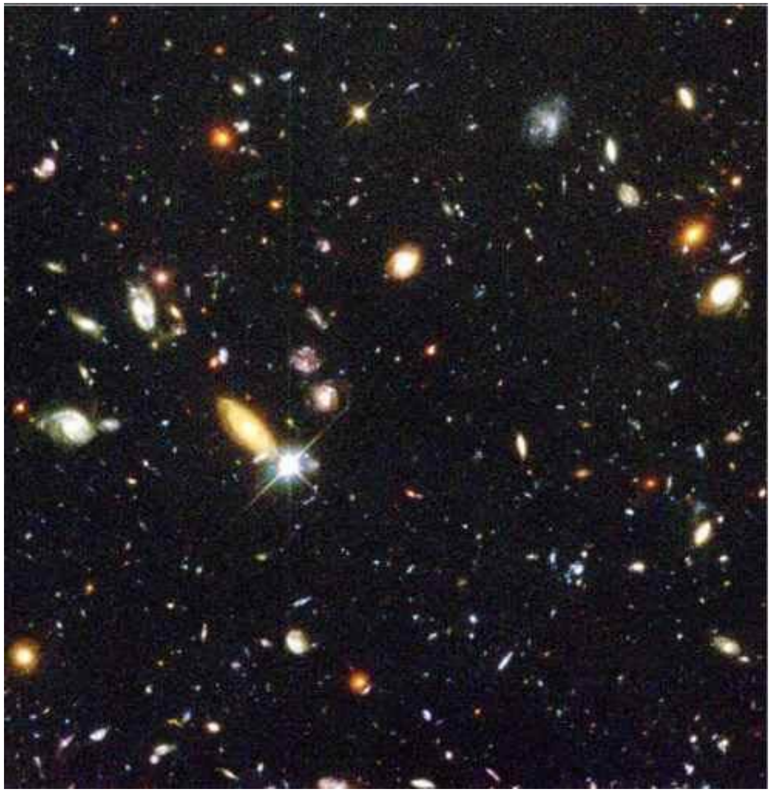
Models like CDM nicely explain how the fluctuations we can observe in the CMB grew to form galaxies.

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

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

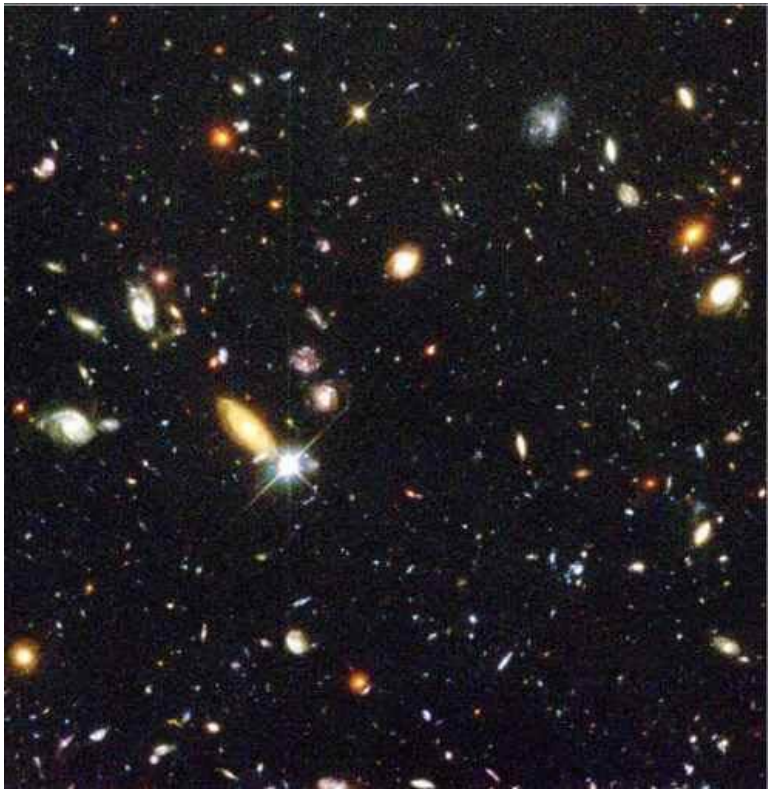
Outstanding Problems

- Where is everything coming from ?



Outstanding Problems

- Where is everything coming from ?



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

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

accelerating expansion needs $P < 0$

Basic gravity physics: matter and gravity

- No ‘force field’ for gravity: matter falls freely through (curved) spacetime

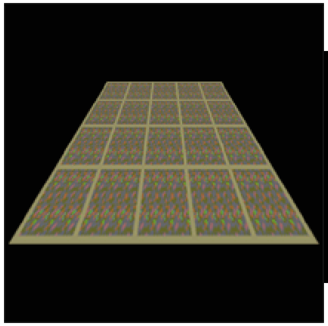
- BUT: matter generates the curvature

- ‘Normal’ matter always makes curvature that causes two objects to move towards each other

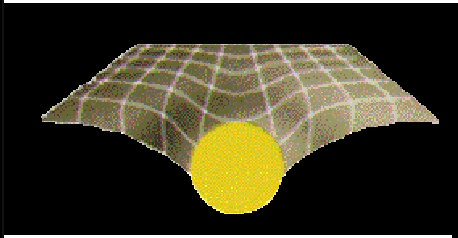
⇒ **gravity is always attractive**

More mass (density) = more spacetime curvature:

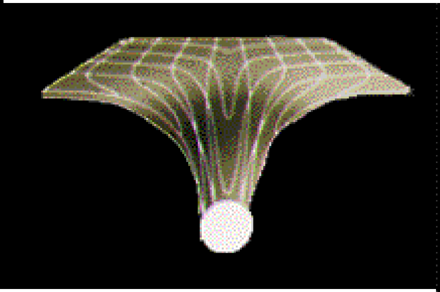
Flat space



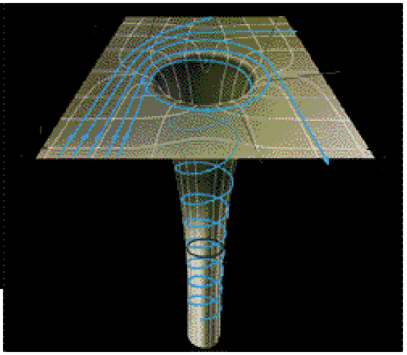
The sun



Neutron star



Black hole



Inflating the universe

- What if we could make matter ('gas') with negative pressure?
- Would generate gravity that's repulsive
- Universe would expand even faster

⇒ **INFLATION**

Inflating the universe

- Not possible with 'normal' matter
- Need something a bit exotic

A SCALAR FIELD

(Physically scalar field isn't really like a gas, it only makes curvature in the same way as a gas, but like a gas with negative pressure would)

The physics of inflation

How does a scalar field generate curvature (gravity)?

- All matter generates gravity through its **stress-energy tensor** T_{ab}
- Einstein's equations are

$$G_{ab} = 8\pi T_{ab}$$

(CURVATURE = MATTER DENSITY)

- T_{ab} has the same form for gases and scalar fields
- Scalar fields are only like gases in terms of their gravity

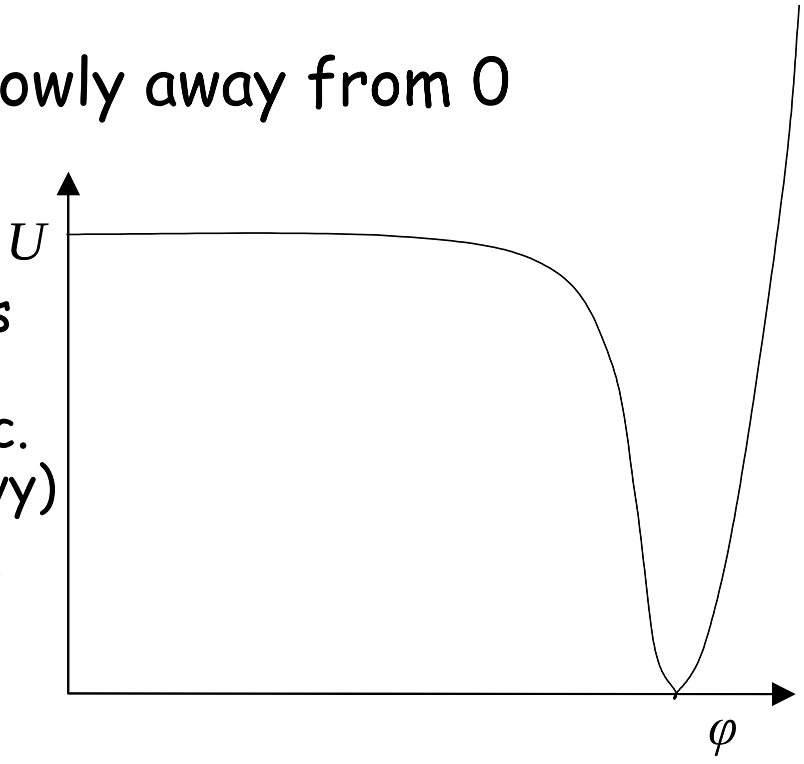
Normal gas: $T_{ab} = (\rho+p)u_a u_b + p g_{ab}$

Scalar field: $T_{ab} = \underbrace{\partial_a\phi\,\partial_b\phi}_{\text{Energy part}} - \underbrace{[\partial_a\phi\,\partial^a\phi/2 + V(\phi)]g_{ab}}_{\text{Pressure part}}$

- The important bit is $V(\phi)$, the scalar potential. Its value at any point just depends on ϕ
- It does exactly what pressure p does for gases
- For gases p must be positive, BUT: $V(\phi)$ can have any value at all
- We get negative pressures with the right $V(\phi)$

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

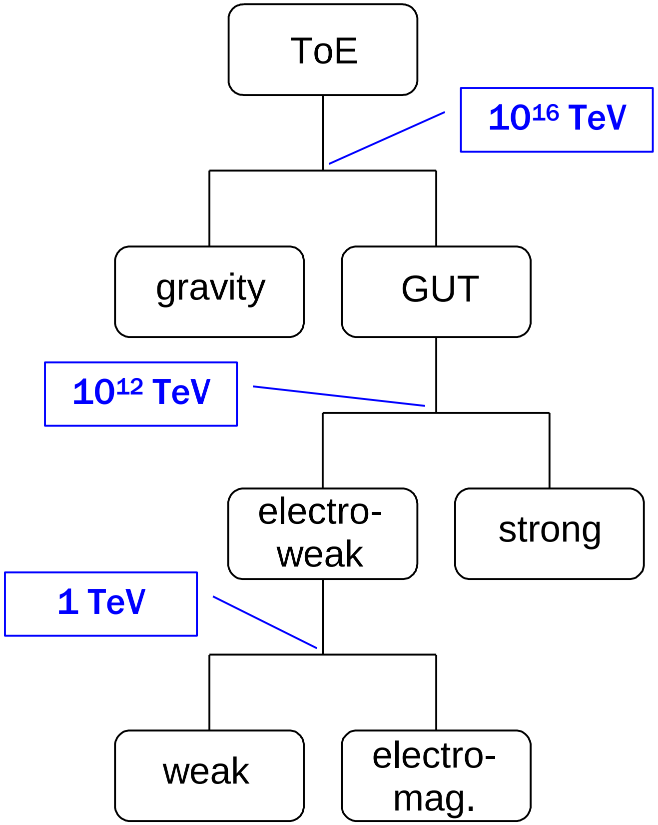


Inflation and particle physics

- 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

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

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



ToE

10^{16} TeV

gravity

GUT

10^{12} TeV

electro-weak

strong

1 TeV

weak

electro-mag.

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

Inflation-issues

- Flatness of inflaton potential

Observations require slow-roll parameters to satisfy

$$\epsilon \equiv \frac{1}{2}\left|\frac{M_{\rm P}V'}{V}\right|^2 \lesssim 10^{-2}, \quad \eta \equiv \frac{M_{\rm P}^2 V''}{V} \lesssim 10^{-2}$$

(slope) (curvature)

However, in many simple UV-realization of inflation, the slow-roll parameter associated with inflaton curvature is of order unity due to gravitational effects.

$$\Delta V \sim cV\frac{\phi^2}{M_{\rm P}^2} \sim cH^2\phi^2 \quad \Rightarrow \quad \eta \sim \pm\mathcal{O}(c) \sim \pm\mathcal{O}(1)$$

($\langle\phi\rangle \lesssim M_{\rm P}$ is assumed)

This is called "η-problem".

- # Trans-Planckian excursion

Even if η-problem is assumed to be cured somehow, generically the observed power spectrum requires a trans-Planckian excursion of inflaton field.

E.g., $V = \begin{cases} V_0 - \frac{1}{2}m^2\phi^2 + \dots & \text{for } \phi \ll \phi_0 \\ \frac{1}{2}m^2\phi^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$

⇒ $$\epsilon \equiv \frac{1}{2}\left|\frac{M_{\rm P}V'}{V}\right|^2 \sim \begin{cases} \left(M_{\rm P}\phi/\phi_0^2\right)^2 & \text{for } \phi \ll \phi_0 \\ \left(M_{\rm P}/\phi\right)^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$$

$$\eta \equiv \frac{M_{\rm P}^2 V''}{V} \sim \begin{cases} M_{\rm P}^2/\phi_0^2 & \text{for } \phi \ll \phi_0 \\ M_{\rm P}^2/\phi^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$$

⇒ $\phi_* \text{ or } \phi_0 \sim \mathcal{O}(10)M_{\rm P}$

This raises a question on the validity of inflaton potential in view of EFT.

Solutions(?)

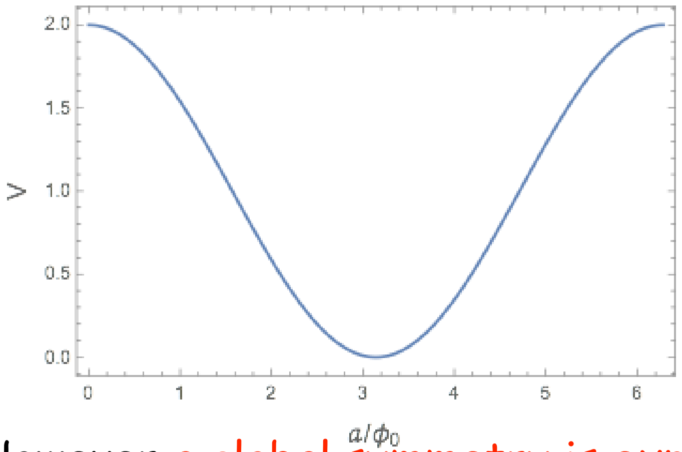
- To eta-problem

* Forbidding mass correction

⇒ Shift symmetry, pNGB, Heisenberg symmetry, ...?

$K = f(\phi - \phi^\dagger) + \dots$ $\quad K = f(\rho);\ \rho = T + T^\dagger - |\Phi|^2 + \dots$

e.g.) Natural inflation (using a pNGB)



$$\text{For } \Phi = \frac{1}{\sqrt{2}}\phi e^{ia/\phi_0},$$

$$V = \Lambda^4 \left[1 + \cos\left(\frac{a}{\phi_0}\right)\right]$$

☞ However a global symmetry is expected to be broken by gravity.
☞ Hence there would be dangerous Planck-suppressed symmetry breaking operators.

- To trans-Planckian excursion

* Conformal symmetry(?): Dangerous higher order operators are not allowed.

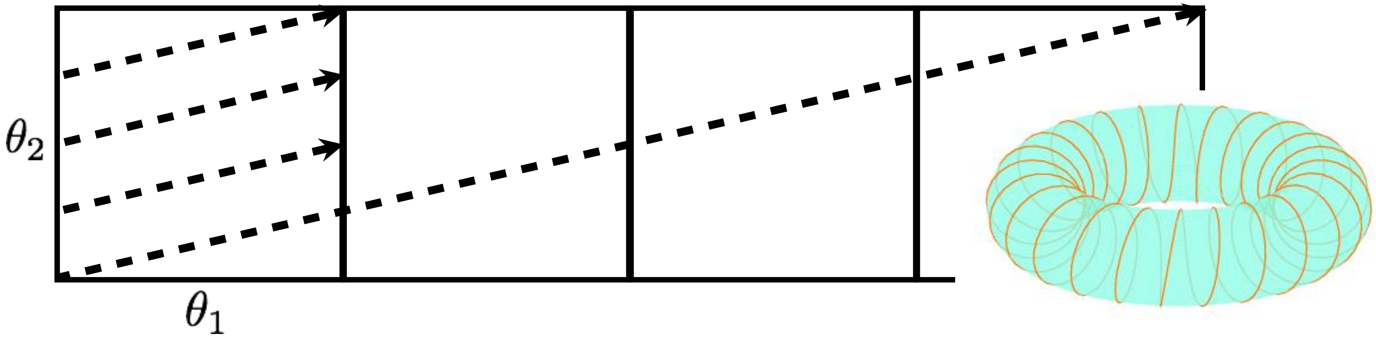
$$V = \frac{1}{4}\lambda\phi^4 \text{ where } \lambda \begin{cases} \sim \mathcal{O}(10^{-12}) & \text{in GR} \\ \lesssim \mathcal{O}(1) & \text{in modified graivty} \end{cases}$$

but (i) Conformal sym. is broken at loop-level.
(ii) Inconsistent with data or unitarity issue

* Compactification of trajectory(?): Trans-Planckian excursion can be compactified in a sub-Planckian regime of multi-dimensional field space.

(e.g.) Aligned natural inflation, axion monodromy, etc.

$$V = \Lambda^4 \left[2 + \cos\left(f(\theta_1, \theta_2)\right) + \cos\left(g(\theta_1, \theta_2)\right)\right]$$



Spiral inflation

[GB and Wan Il Park, Phys.Lett. B741, 252 (2015)

- Potential

$$V = V_\phi + V_{\rm M} \; ; \quad \Phi = \frac{1}{\sqrt{2}} \phi e^{i\theta}$$

$$V_\phi = \begin{cases} \frac{1}{4}\lambda\left(\phi^2 - \phi_0^2\right)^2 \\ \frac{1}{4}\lambda\phi_0^4 + \lambda\left[\ln\left(\frac{\phi}{\phi_0}\right) - \frac{1}{4}\right] \\ \ldots \end{cases}$$

Symmetry-breaking potential

$$V_{\rm M} = \Lambda^4\left[1 + \sin\left(\phi/M + \theta\right)\right]$$

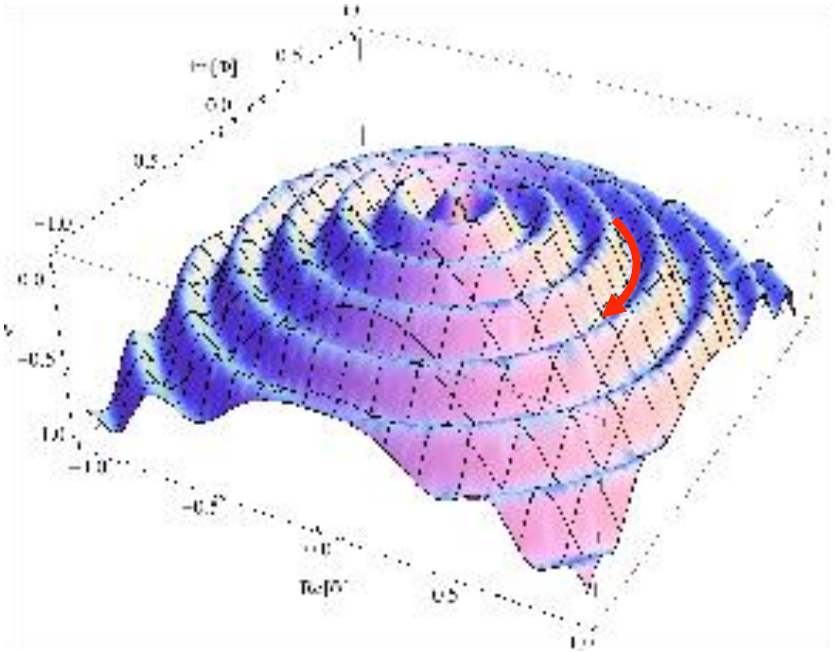
Modulating potential

$$\boxed{\mathcal{L} \supset \frac{g^2}{32\pi^2}\left(\frac{\phi}{M} + \theta\right) G\tilde{G}}$$

Planck scale physics?

- Inflation

$$V = V_\phi + \Lambda^4 \left[1 - \sin(\phi/M + \theta)\right]$$



* Inflation along spiraling-out valley
* M≪$\boldsymbol{\Phi}_0$ ⇒ Many turns ⇒ Elongated trajectory
* ϵ and ηcan be adjusted by “M/$\boldsymbol{\Phi}_0$”

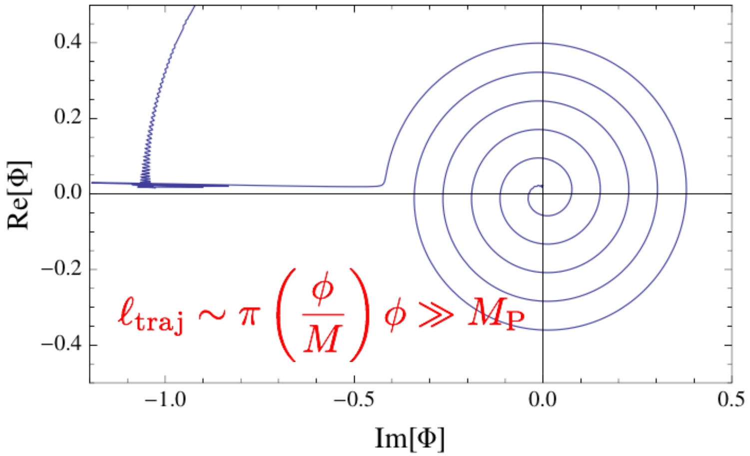
* $\boldsymbol{\Phi}_0$≪M_P is possible
* η-problem is absent.

$$\epsilon \approx \epsilon_\phi/a^2, \quad \eta \approx \eta_\phi/a^2 \quad \text{with } a \equiv \phi/M \gg 1$$

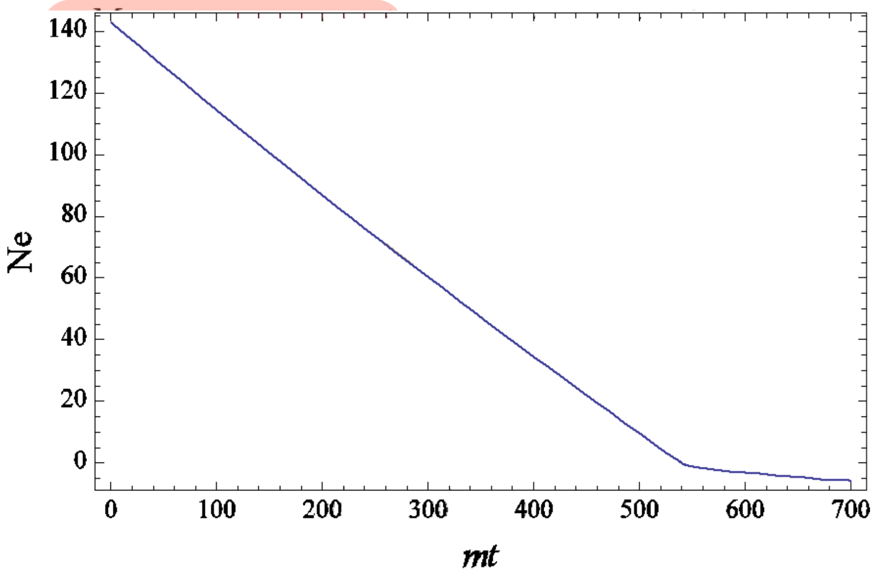
- A numerical simulation

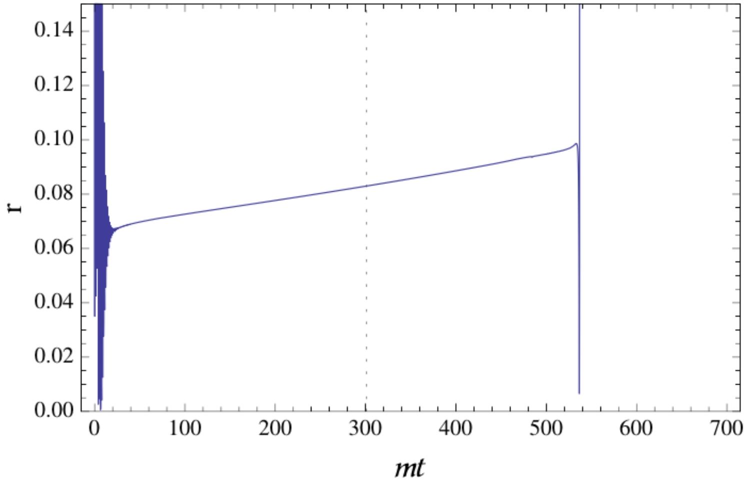
$$V_\phi = V_0 - \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \ ,$$

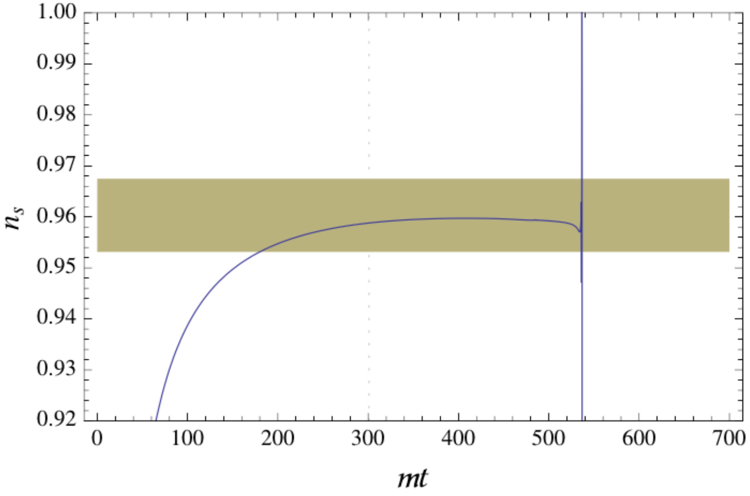
$$\frac{m}{10^{14}\mathrm{GeV}} = 0.796 \times 2\sqrt{3}, \quad \frac{\Lambda^4}{m^2 M_\mathrm{P}^2} = 4 \times 10^{-3}$$



$$\ell_\mathrm{traj} \sim \pi \left(\frac{\phi}{M}\right)\phi \gg M_\mathrm{P}$$







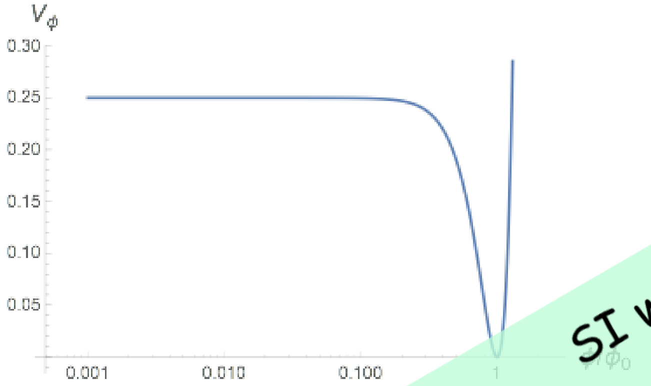
- Difficulty of Coleman-Weinberg inflation

[GB, Eung Jin Chun and Hyun Min Lee, PLB730, 81 (2014)]

SI with CW potential

[GB and Wan Il Park, PRD91, 063511 (2015)]

$$V_\phi \;=\; \lambda\phi^4\left[\ln\left(\phi/\phi_0\right) - 1/4\right] + \lambda\phi_0^4/4$$



$$\epsilon = 8\left(\frac{4M_P}{v_\phi}\right)^2\left(\frac{\phi}{v_\phi}\right)^6\ln^2\left(\frac{\phi}{v_\phi}\right),$$

$$\eta = \left(\frac{4M_P}{v_\phi}\right)^2\left(\frac{\phi}{v_\phi}\right)^2\left(3\ln\left(\frac{\phi}{v_\phi}\right)+1\right)$$

For $v_\phi \lesssim M_P$,

$$\epsilon^{\rm obs},\ \eta^{\rm obs} \lesssim 10^{-2} \Rightarrow \frac{\phi}{\phi_0} \lesssim \mathcal{O}(10^{-2} - 0.1)$$

$$\Rightarrow \epsilon \lll \eta$$

$$P_{\mathcal{R}} = 2.2\times 10^{-9} \Rightarrow \lambda \sim 10^{-14}$$

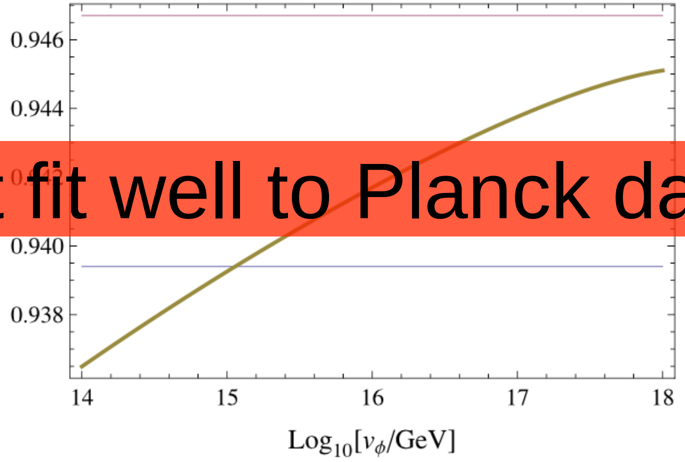
Also,

$$N \approx \frac{3}{1-n_s}\ ;\ n_s \approx 0.96 \pm 0.007 \Rightarrow N \approx 75$$

but

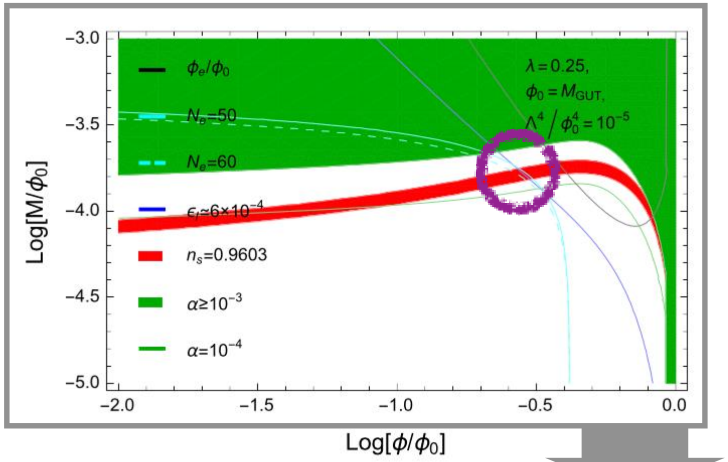
$$N_* = \frac{1}{3}\ln\left(\frac{\rho_{\rm reh}}{\rho_{\rm end}}\right) + \frac{1}{4}\ln\left(\frac{\rho_{0r}}{\rho_{\rm reh}}\right) + \frac{1}{2}\ln\left(\frac{\rho_*}{\rho_0}\right)$$

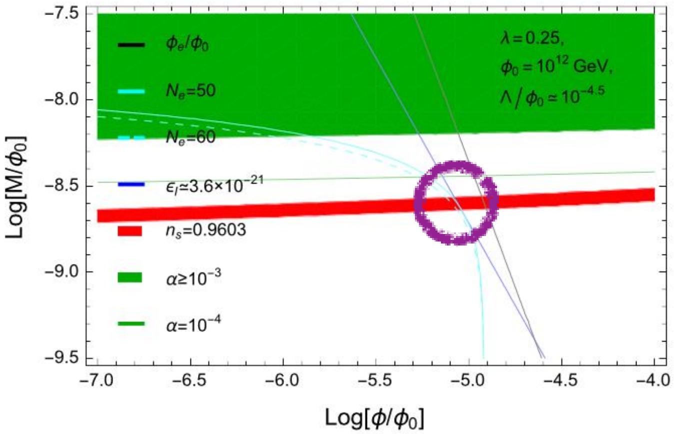
$$\simeq 61 - \ln\left(\frac{10^{16}\ {\rm GeV}}{V_*^{1/4}}\right) + \ln\left(\frac{V_*^{1/4}}{V_{\rm end}^{1/4}}\right) - \frac{1}{3}\ln\left(\frac{V_{\rm end}^{1/4}}{\rho_{\rm reh}^{1/4}}\right)$$

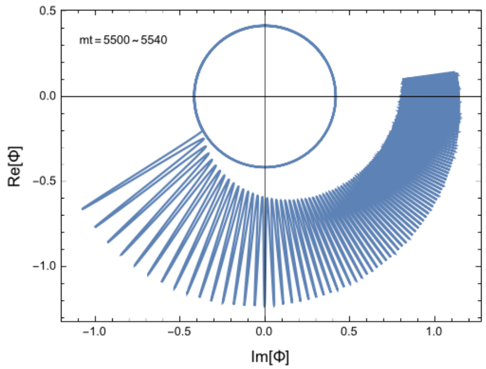


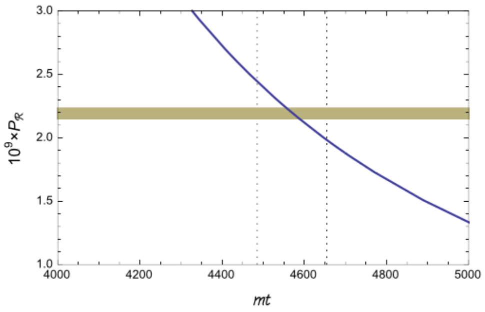
not fit well to Planck data!

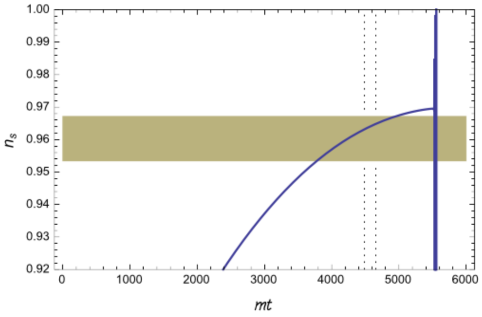
- Spiral inflation with CW potential









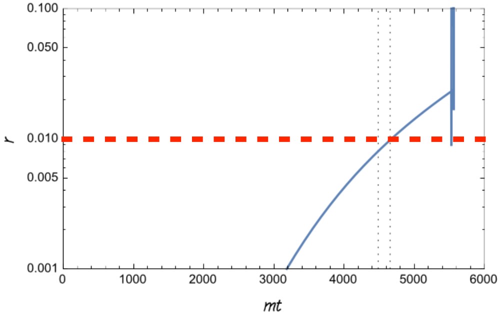


☞ Inflation works well for λ~ 0.1

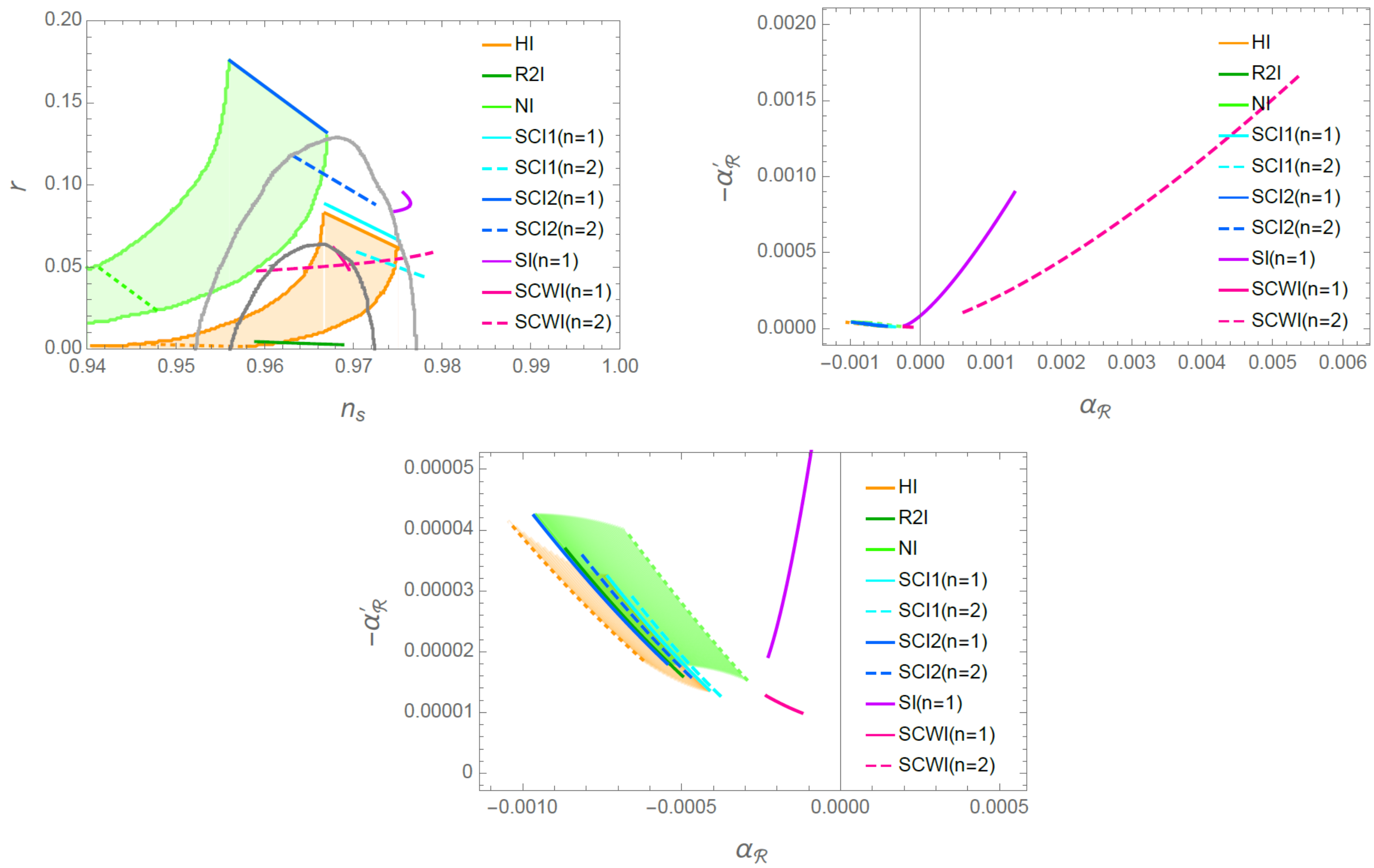
and

$$10^{12}{\rm GeV} \lesssim \phi_0 \lesssim M_{\rm GUT}$$

$$10^{-9} \lesssim M/\phi_0 \lesssim 10^{-4}$$



☞ However UV-realization is not clear yet.



G.B. and W.Park, JCAP 1602, 061 (2016)

- Generically, inflation models suffer from eta-problem and/or trans-Planckian excursion of inflaton
- Both problems can be solved if inflaton is a elongated compactified trajectory in a sub-Planckian multi-dimensional field space (e.g., aligned natural inflation, axion monodromy, spiral inflation)
- In particular, spiral inflation is a interesting possibility although its a full UV-realization is not clear yet.

… the scalar field turns out to be transplanckian

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

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

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

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

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

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

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

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

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

$$\tilde{H} = \frac{H + \dot{D}(\theta)/(2D(\theta))}{\sqrt{D(\theta)}}$$

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

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

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

$$\tilde{H} = \frac{H + \dot{D}(\theta)/(2D(\theta))}{\sqrt{D(\theta)}}$$

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

Non-minimal coupling to gravity

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

Non-minimal coupling to gravity

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

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

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

Generic scalar-tensor theories

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

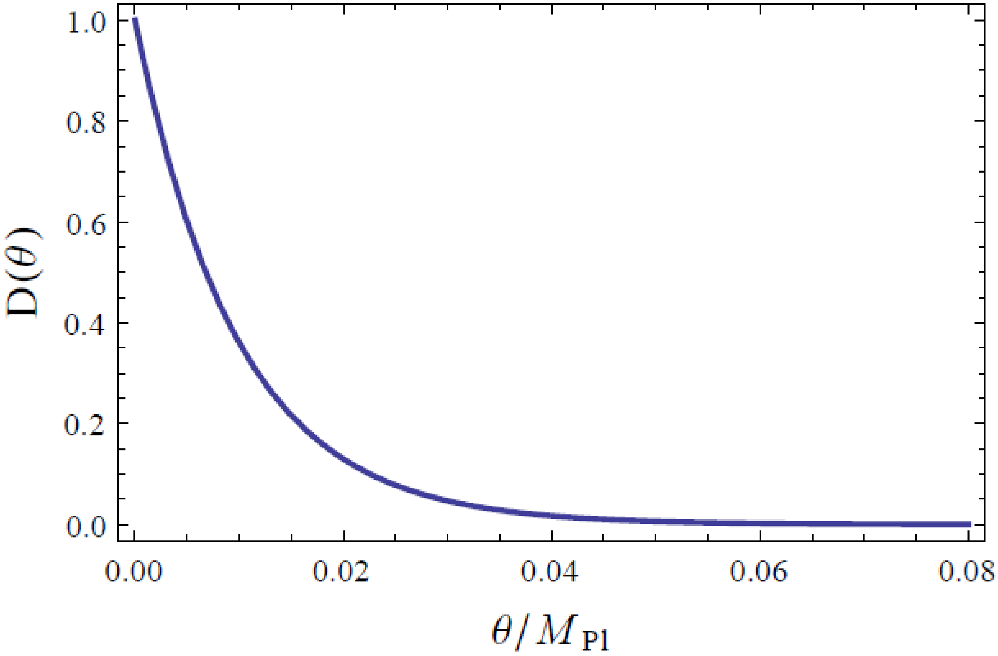
G. B and O. Vives, Phys.Lett. B748 (2015)

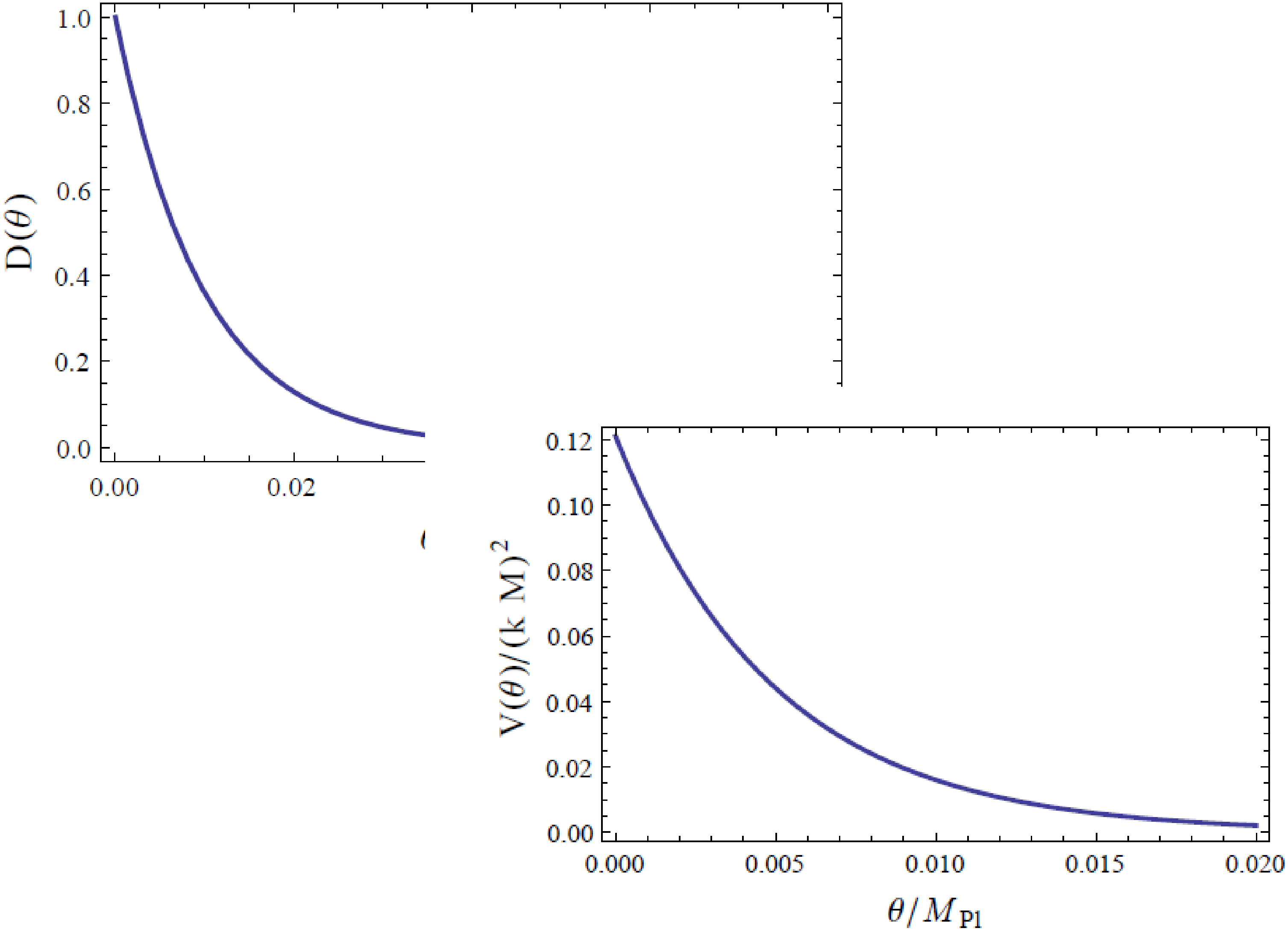
Generic scalar-tensor theories

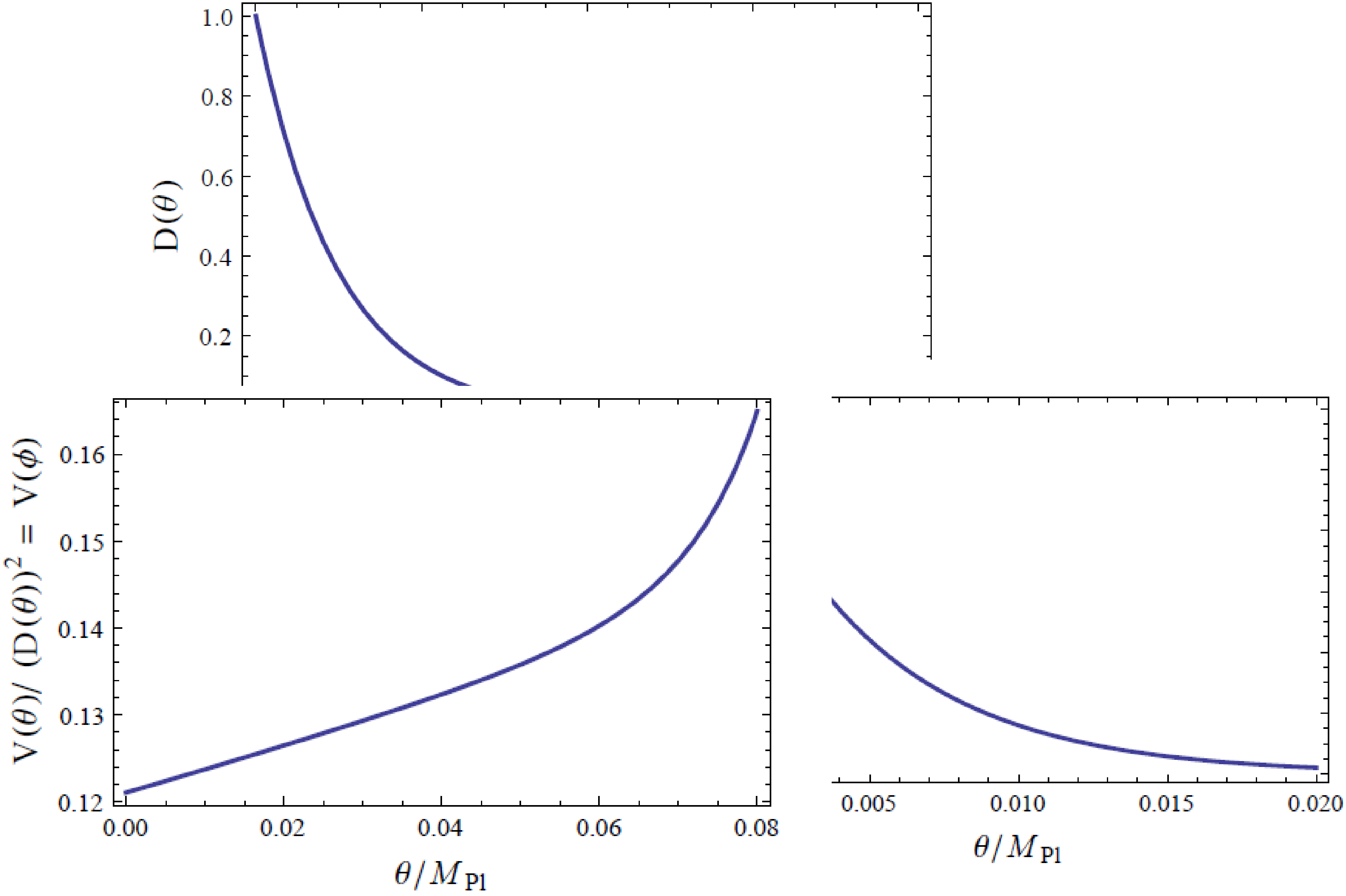
$$a = \exp\left(-\theta/b\right) \qquad H = \dot{a}/a = -\dot{\theta}/b$$

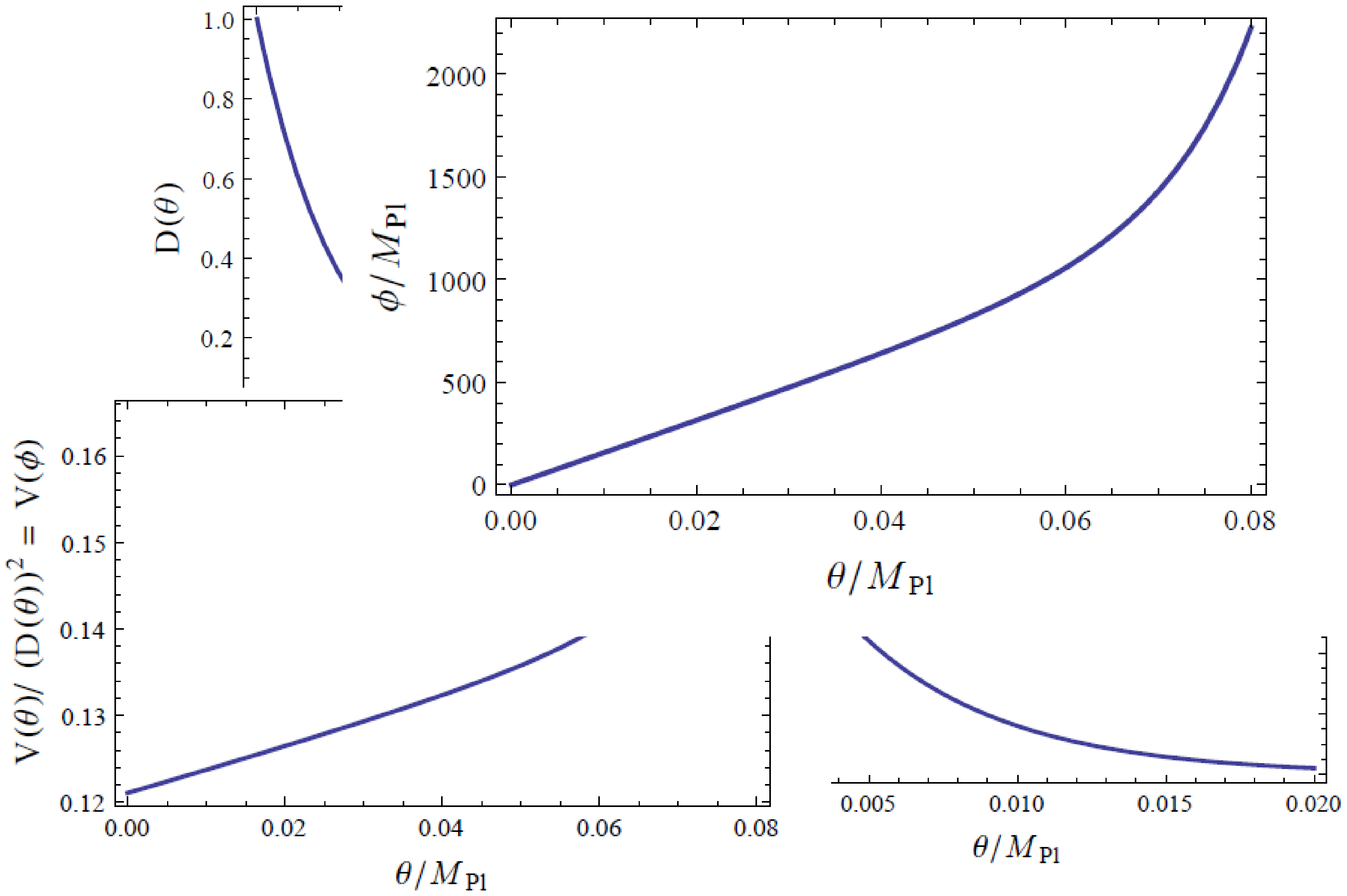
$$N_e = \int H\,dt = -\int \frac{\dot{\theta}}{b} dt = \frac{-1}{b} \int d\theta = \frac{1}{b}\left(\theta_i - \theta_f\right) \simeq \frac{\theta_i}{b}$$

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


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


D(θ)
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.02
V(θ)/(k M)^2
0.12
0.10
0.08
0.06
0.04
0.02
0.00
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


D(θ)
1.0
0.8
0.6
0.4
0.2
$\phi/M_{\rm Pl}$
2000
1500
1000
500
0
0.00
0.02
0.04
0.06
0.08
$\theta/M_{\rm Pl}$
$V(\theta)/(D(\theta))^2 = V(\phi)$
0.16
0.15
0.14
0.13
0.12
0.00
0.02
0.04
0.06
0.08
$\theta/M_{\rm Pl}$
0.005
0.010
0.015
0.020
$\theta/M_{\rm Pl}$

f(R) gravity

f(R) gravity

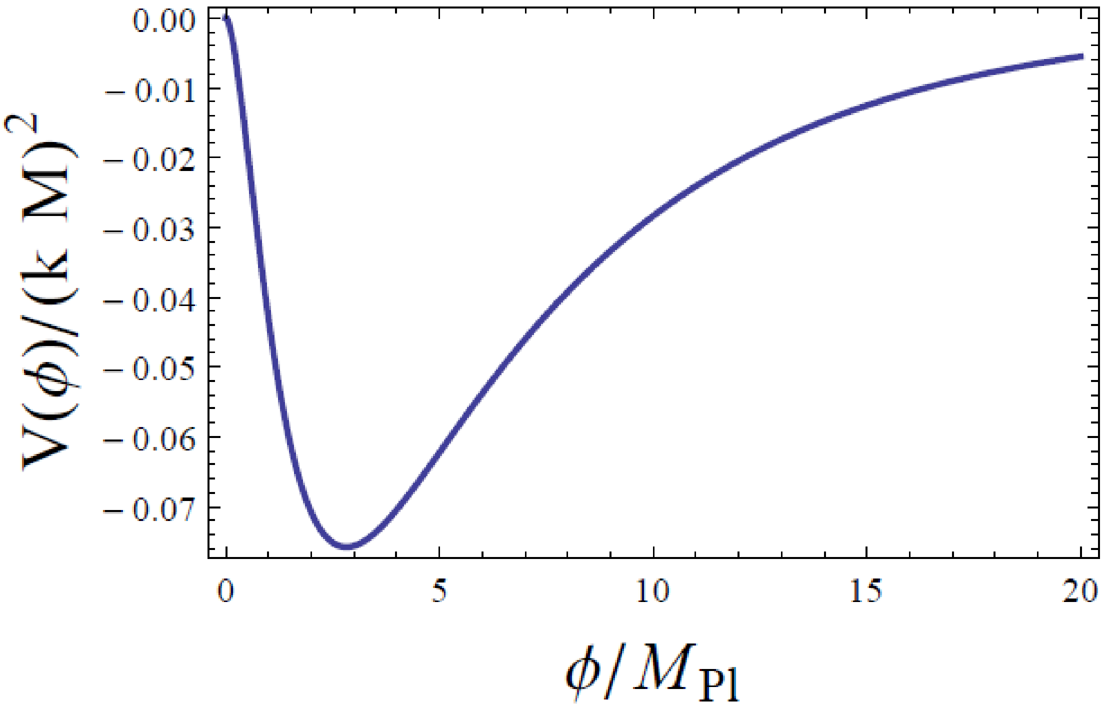
$$f(R) = R\left(1 + (R/M^2)^{5/4}\right)$$

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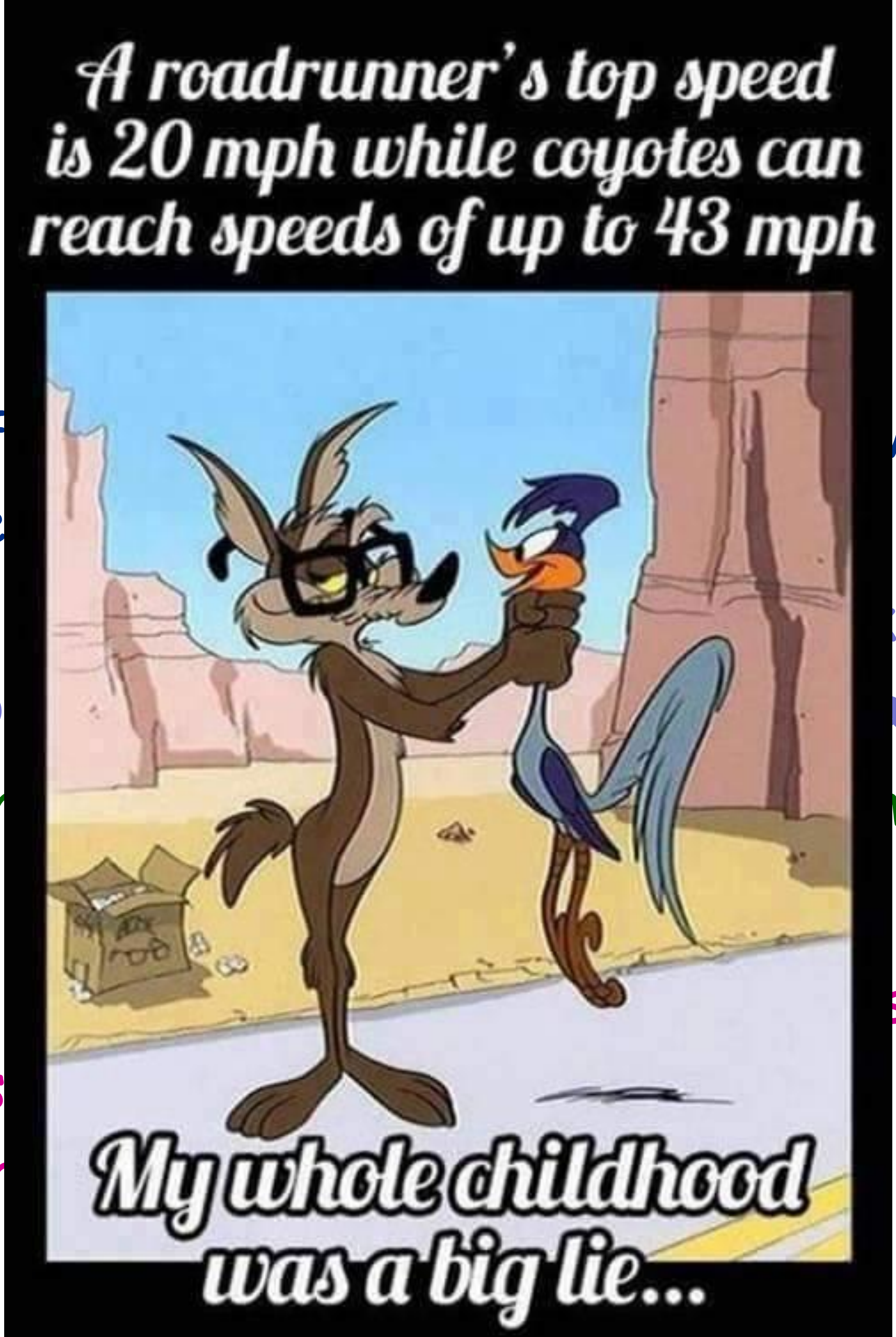
Transplanckian fied values needed to accomodate inflation phenomenology may be due to our insistence of imposing a minimal coupling of the inflaton field to gravity.

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



- To cast of … Model, it will not be … physics –

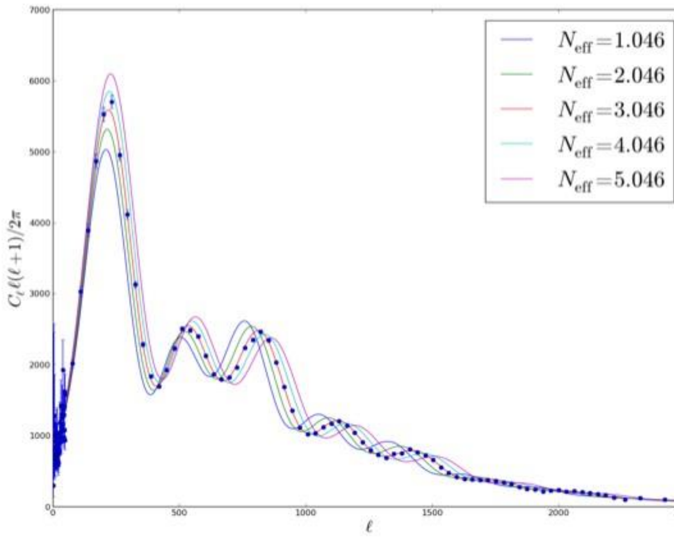
  this we … energy, inflatio … asses)

- It is also r … eworks –

- We seem … s that will propel us … and new connection

Cosmology is a probe of neutrino properties

The standard model $N_{\mathrm{eff}} = 3.046$



Latest Planck measurement $N_{\mathrm{eff}} = 3.15 + / - 0.23$

This would seem to rule out any "sterile" neutrinos that have significant mixing with the 3 species of active neutrinos… and might imply large neutrino asymmetries.