# Sub-Planckain G-axion inflation

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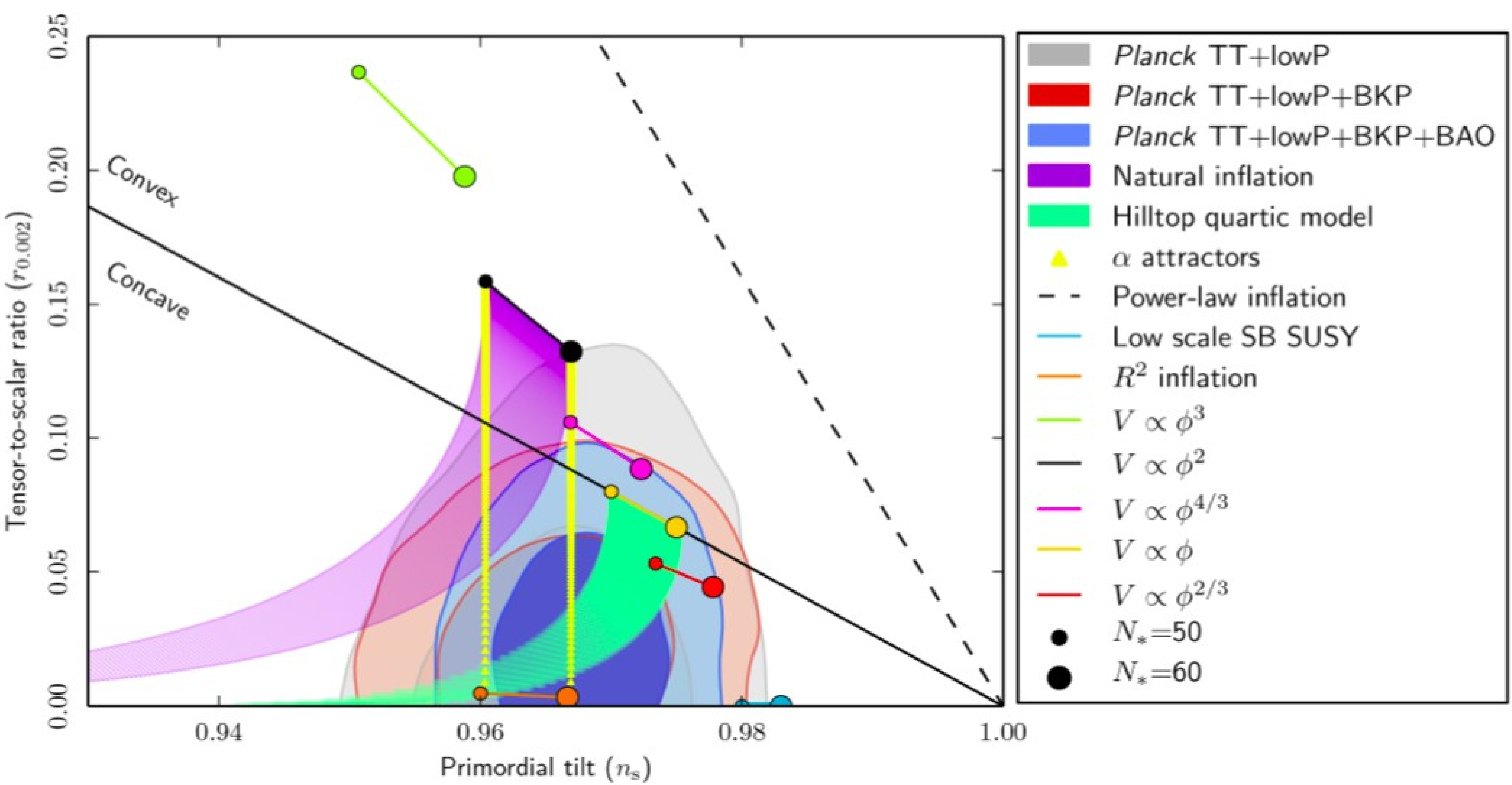
III Saha Theory Workshop

16th January, 2017

# Plan

- Introduction and Motivation
- Model and Results
- Future directios and conclusion

# Planck-2015

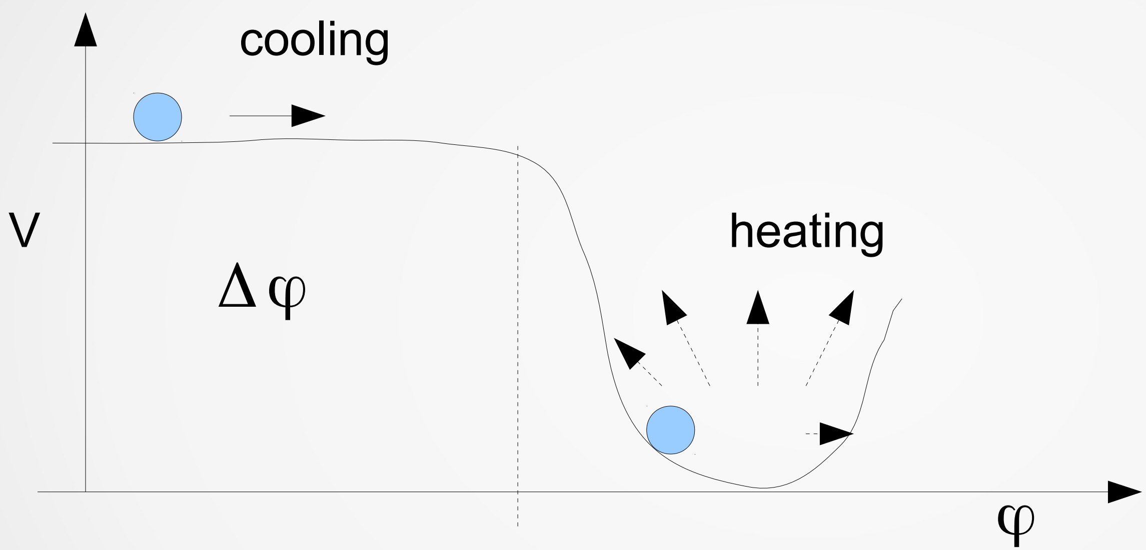


Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt ($n_s$)
0.00
0.05
0.10
0.15
0.20
0.25
0.94
0.96
0.98
1.00
Convex
Concave
*Planck* TT+lowP
*Planck* TT+lowP+BKP
*Planck* TT+lowP+BKP+BAO
Natural inflation
Hilltop quartic model
$\alpha$ attractors
Power-law inflation
Low scale SB SUSY
$R^2$ inflation
$V \propto \phi^3$
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
$N_*$=50
$N_*$=60

# Inflationary mechanism

Extremely successful in solving outstanding problems of cosmology

Simple realization: maintain flat potential for long enough time



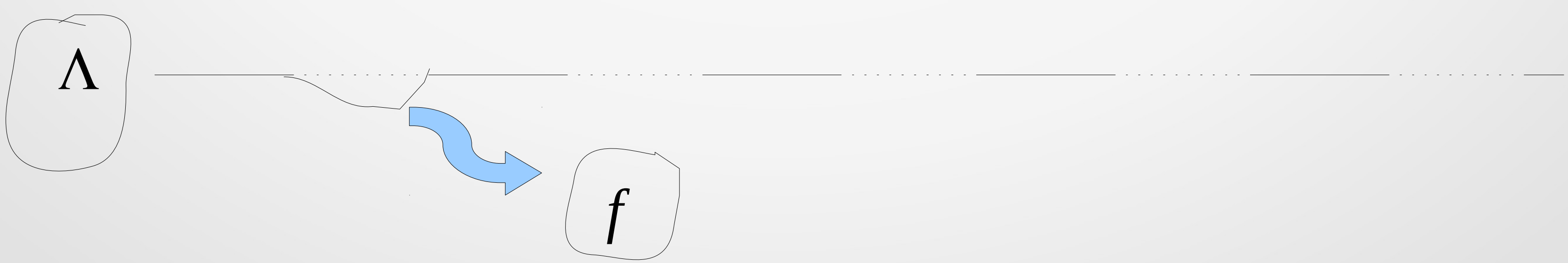

Scale factor

$$a(t) \sim e^{Ht}$$

$$\eta - problem$$

$$\eta \sim M_p^2 \frac{V''(\varphi)}{V(\varphi)}$$

Natural guess: Shift symmetry (Natural inflation)



# Axion/Natural inflation

- who could be a good candiate?

  Best and simplest possible candiate would the Goldstone boson mode of a global U(1) scalar field theory.

- Interestingly this kind of theory was introduced to sovle the strong CP problem in QCD, and Goldstone boson mode is called axion

- Axion/Natural Inflation, K. Freese, J. A. Frieman and A. V. Olinto, PRL. 65, 3233 (1990).

$$\mathscr{L} \sim \frac{1}{2}\partial_\mu \psi \partial^\mu \psi * - \lambda \left(\psi * \psi - f^2\right)^2 + \mathscr{L}_b$$

$$\psi = <\psi> e^{i\varphi}$$

# Axion inflation (Natural) Freese et al 1990

One such model based on effective theory framework:

Natural/axion model

$$\mathscr{L}_g = \frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - \Lambda^4\left(1 - \cos\frac{\varphi}{f}\right)$$

$$\frac{\Lambda}{f} < 1$$

U(1) breaking term

Important symmetry: $\varphi = \varphi + 2\pi f$

Good!

$(f, \Lambda)$

- New problems:

Planck observation demands:

$$f > M_p$$

$$\delta\varphi > M_p$$

Super-Planckain!!

# Problems and model buliding

- Potential Problem: $\Lambda^4\left(1-\cos\left(\frac{\phi}{f}\right)\right)$ ???

- Qantum gravity effect many not be neglisible
- Effective field theory of inflation is in question.
- Alternatives: Aligned-axion : E. Kim, H. P. Nilles, M. Peloso JCAP 0501, 005 (2005)
- Chromonatural Inflation P. Adshead, M. Wyman, PRL, 108, 261302 (2012)
- Stringy axionic N-flation S. Dimopoulos et al. JCAP 0808 , 003 (2008)
- Axion monodromy E. Silverstein and A. Westphal, Phys. Rev. D 78, 106003 (2008),
- Warm Inflation, A. Berera, Phys.Rev.Lett. 75 (1995) 3218
- Electromagnetic dissipation N. Barnaby, M. Peloso, PRL. 106, 181301 (2011)

# G-axion: Towards sub-Planckian model

DM, Phys.Lett. B720 (2013) 389,

DM, P.Saha, Phys.Rev. D91 (2015) 023504

Tsutomu Kobayashi , et al. Phys.Rev.Lett. 105 (2010) 231302

- We start with the following Lagrangian (G: Generalized)

$$\mathscr{L} = \frac{M_p^2}{2} R - X - \frac{1}{s^3} M(\varphi) X \Box \varphi - \Lambda^4 \left(1 - \cos\frac{\varphi}{f}\right)$$

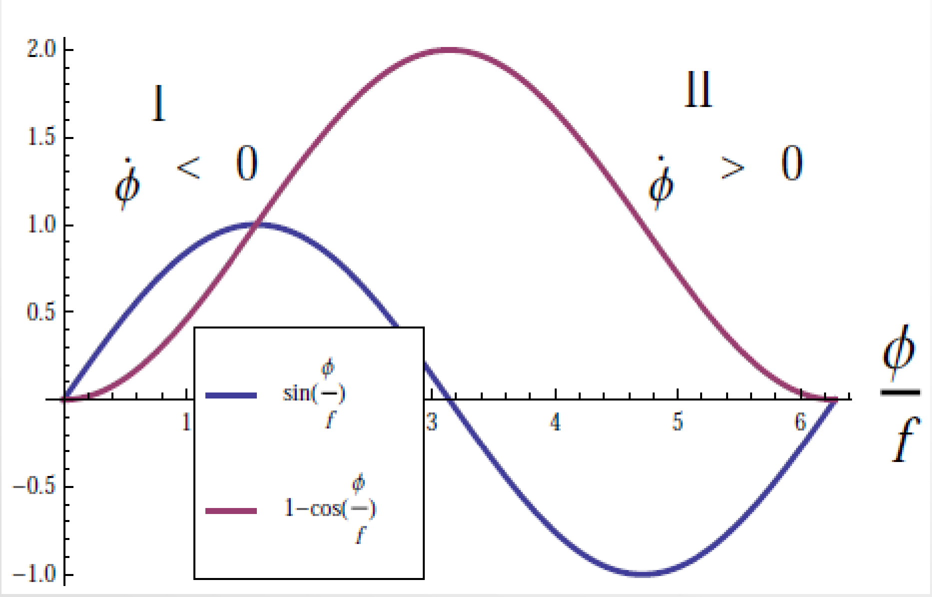
analogous to Gauss-Bonnet

Introduce no ghost degree of freedom!

$$X = \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi$$

Stable region: Inflation driven by G-term

$$\tau = \frac{M(\phi)\Lambda^4}{f} \sin\left(\frac{\phi}{f}\right) \gg 1.$$




Three parameters

$$(f, s, \Lambda)$$

GOAL: all parameteres should be < Mp

# Observables: $(n_s, r, dn_s^k)$

spectral index

$$n_s - 1 \equiv \frac{d\, lnP_{\mathcal{R}}}{d\, lnk} = -6\epsilon + 3\eta - \alpha,$$

Spectral running:

$$\frac{dn_s}{d\, lnk} \equiv dn_s^k = -3\xi + 24\epsilon\eta - 24\epsilon^2 - 3\alpha^2 - 8\alpha\epsilon + 4\alpha\eta + 3\eta^2 + 18\beta.$$

Tensor to Scalar ratio:

$$r = -\frac{64\sqrt{6}}{9}\epsilon$$

$$n_s = 0.968 \pm 0.006$$
$$dn_s^k = -0.003 \pm 0.007$$
$$r_{0.05} < 0.07$$

Keck Array, BICEP2 Collaborations: Phys. Rev. Lett. 116, 031302 (2016), Planck Collaborations. Phy. Rev. Lett. 114, 101301 (2015)

Modified Lyth bound

$$\Delta\phi = \delta\mathcal{N}\left|\frac{\sqrt{2\epsilon}}{\tau(\phi)^{\frac{1}{4}}}\right|\left[1 + \delta\mathcal{N}\left(2\epsilon - \eta + \frac{\alpha}{2}\right)\right]$$

$$\tau = \frac{M(\phi)\Lambda^4}{f}\sin\left(\frac{\phi}{f}\right) \gg 1.$$

# Inflation: Simple example

- Simple Example

$$M(\phi) = \frac{1}{s^3}$$

- Spectral index

$$n_s^I \simeq 1 - \frac{3}{\mathcal{A}} \frac{\sin\left(\frac{\phi}{f}\right)^{\frac{3}{2}}}{\left(1-\cos\left(\frac{\phi}{f}\right)\right)^2} + \frac{3}{2\mathcal{A}} \frac{\sqrt{\cos\left(\frac{\phi}{f}\right)\cot\left(\frac{\phi}{f}\right)}}{\left(1-\cos\left(\frac{\phi}{f}\right)\right)}$$

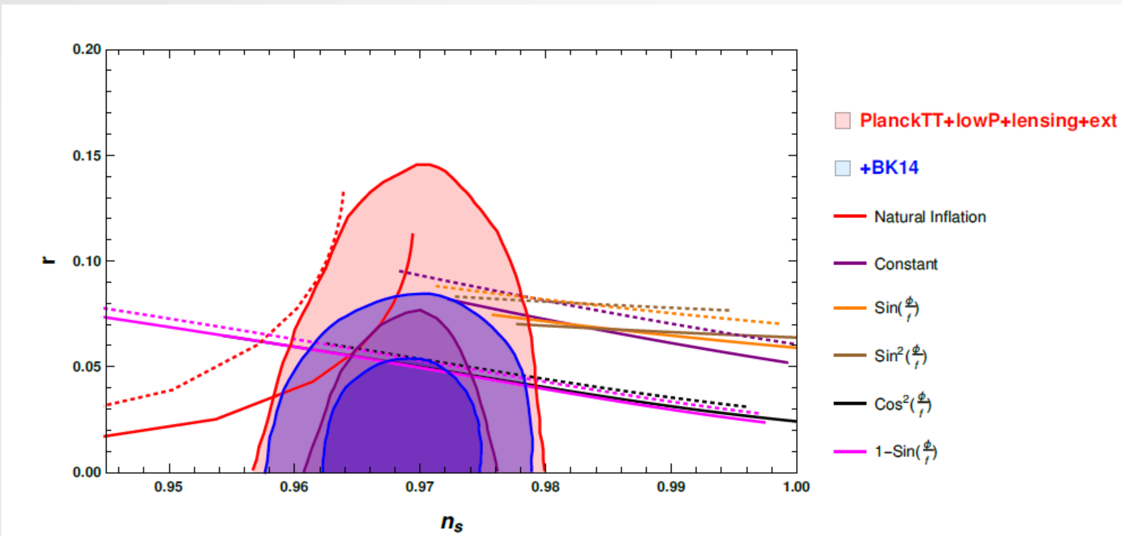
- E-folding Number

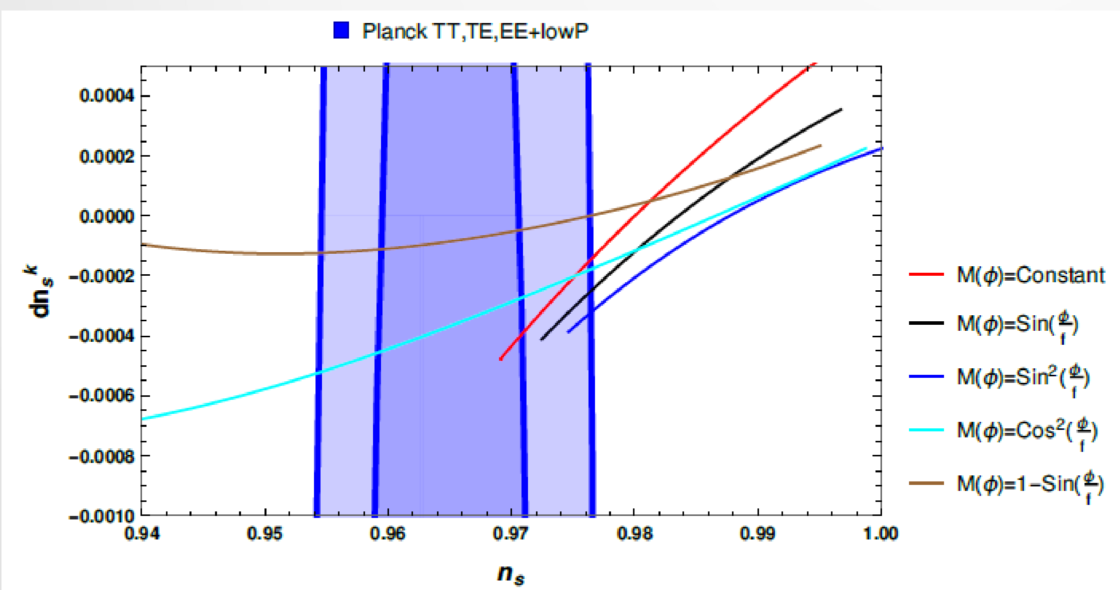
$$\mathcal{N}_I = -\mathcal{A}\left(2\sqrt{\sin x} + \frac{\sqrt{2}\sqrt{1+\sin x}}{\cos\frac{x}{2} + \sin\frac{x}{2}} \times \text{EllipticF}\left[\sin^{-1}\left(\cos\frac{x}{2} - \sin\frac{x}{2}\right), \frac{1}{2}\right]\right)\Big|_{x_1}^{x_2}$$

Where x = φ/f and

$$\mathcal{A} = \sqrt{\tau_0}(f/M_p)^2$$

# Planck and G-axion: ( $n_s$ vs $r$ ) and ( $dn_s^k$ vs $n_s$ )




$$P_{\mathcal{R}} = \frac{A\sqrt{6}}{32\pi^2}\left(\frac{\Lambda}{M_p}\right)^4 \frac{(1-\cos\tilde{\phi}_1)^3\sqrt{s^3 M(\tilde{\phi}_1)}}{\sin^{\frac{3}{2}}\tilde{\phi}_1} \simeq 2.4\times 10^{-9},$$

$$\frac{s^3}{f^3} = \frac{1}{A^2}\frac{\Lambda^4}{M_p^4}.$$

Sample values:

$$A = 40 \sim 300$$

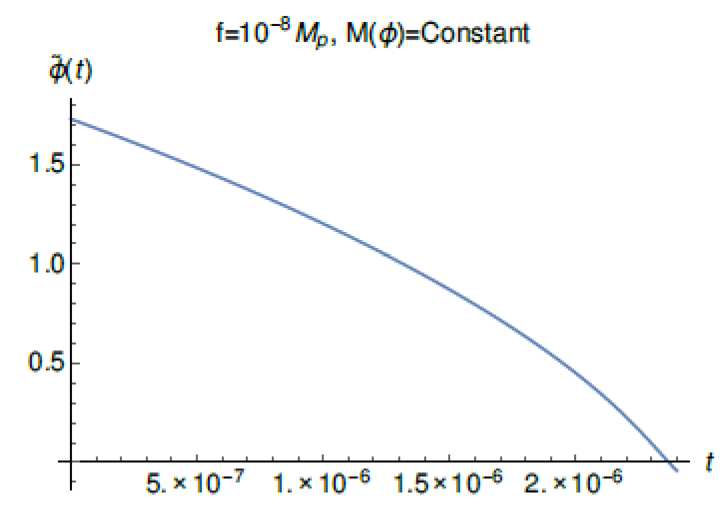
$$\Lambda \simeq 10^{-3} M_p \;;\; \delta\varphi < 10^{-1} M_p$$

$$f \simeq 10^{-2} M_p \;;\; s \simeq 10^{-5} M_p$$

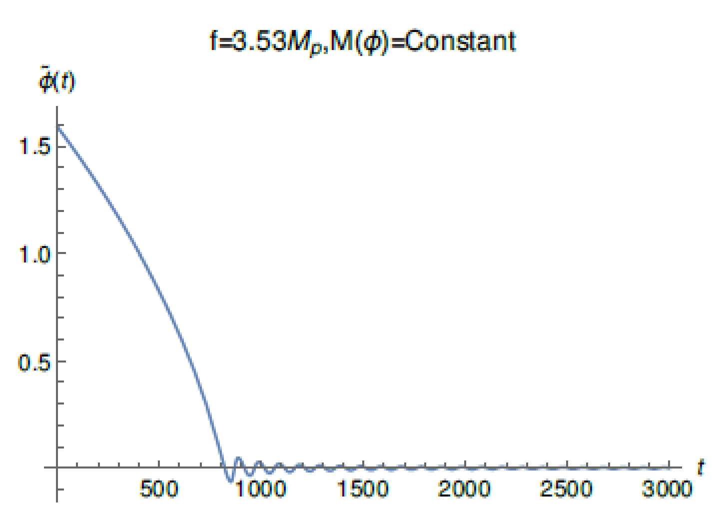
Not the end of the story!!

# Time evolution: End of inflation

No-oscillating




Oscillating




For each model,there exits a critical value of "f"

| Summary of the scalar-field dynamics | | | |
|---|---|---|---|
| $M(\phi)$ | $\mathcal{A}$ | $f_c/M_p$ | $\Delta\phi_c(=f_c(\tilde{\phi}_1-\tilde{\phi}_2))$ |
| Constant | 76 | 3.24 | 4.85158 |
| | 94 | 3.53 | 4.86092 |
| $Sin(\phi/f)$ | 92 | 0.94 | 1.29096 |
| | 110 | 0.99 | 1.27242 |

# Pre-heating

- Oscillating G-axion: Usual rehating scenario, parametric resonance
- Non-oscillating G-axion: We need to find out more efficient mechanism to transfer energy (Instant preheating?) G. Felder, L. Kofman, A. Linde, Phys. Rev. D 59 (1999) 123523,

No shift symmetric coupling

$$\mathcal{L}_{int} = -\frac{1}{2}g^2\phi^2\chi^2 - h\bar{\psi}\psi\chi$$

$$\rho_r \sim 4 \times 10^{-15} g^2 M_p^4$$

Shift symmetric coupling

$$\mathcal{L}_{int} = -\frac{1}{2}M^2\ sin^2\left(\frac{\phi}{f}\right)\chi^2 - h\bar{\psi}\psi\chi$$

$$\rho_\chi = 4 \times 10^{-21}\ \frac{M_b}{f_b} M_p^4$$

adiabaticity violation

$$|\dot{m}_\chi| \gtrsim m_\chi^2$$

Not too efficient

# Conclusions

- Usual axion inflation (super-Planckian!) $f > M_p$
- We propose higher derivative extension (G-axion)
- Predictions are at the right ball part
- No-oscillation is prefered for $f < M_p$
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# Future Directions

- Constructing UV theory ( Brane model )
- Effect of more higher derivative terms (shift symmetric)
- New mechanism of reheating
- Full non-linear evolution of coupled system after inflation
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