INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Higgs inflation with a running kinetic term

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(IPMU, Univ. of Tokyo)

FT, PLB 693 (2010) 140-143 [arXiv:1006.2801]

Nakayama and FT, 1008.2956, 1008.4457, 1009.3399

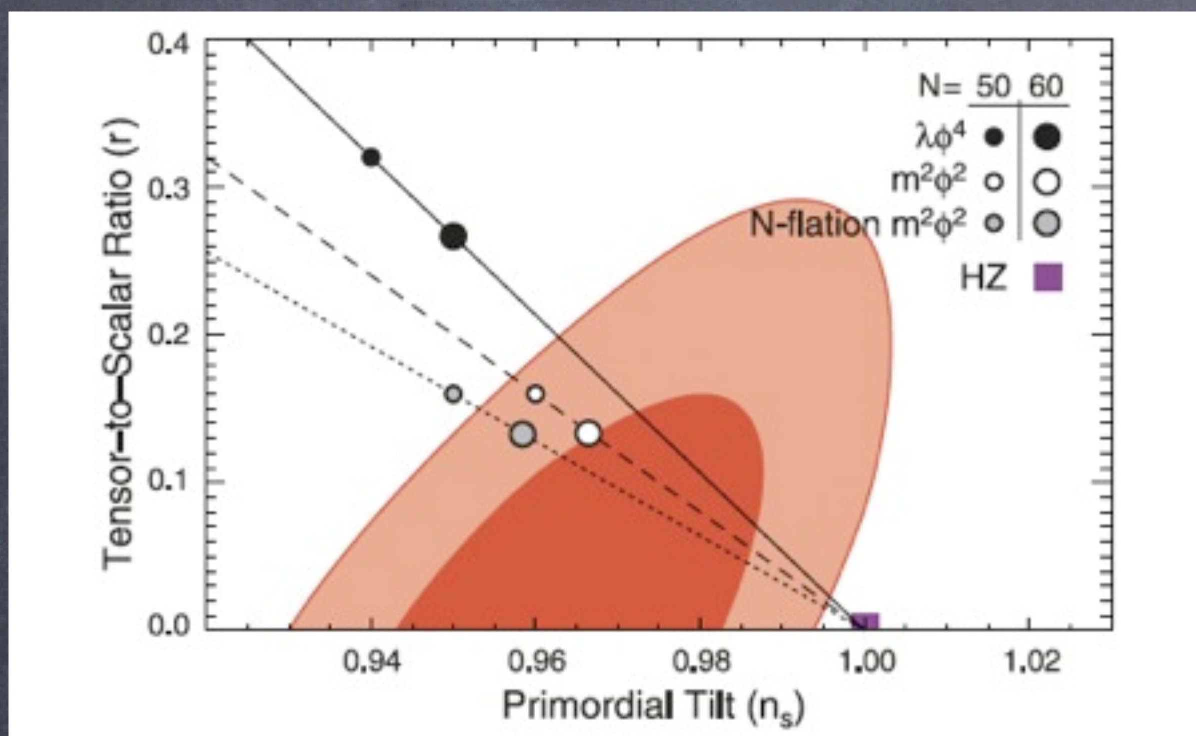
Talk plan

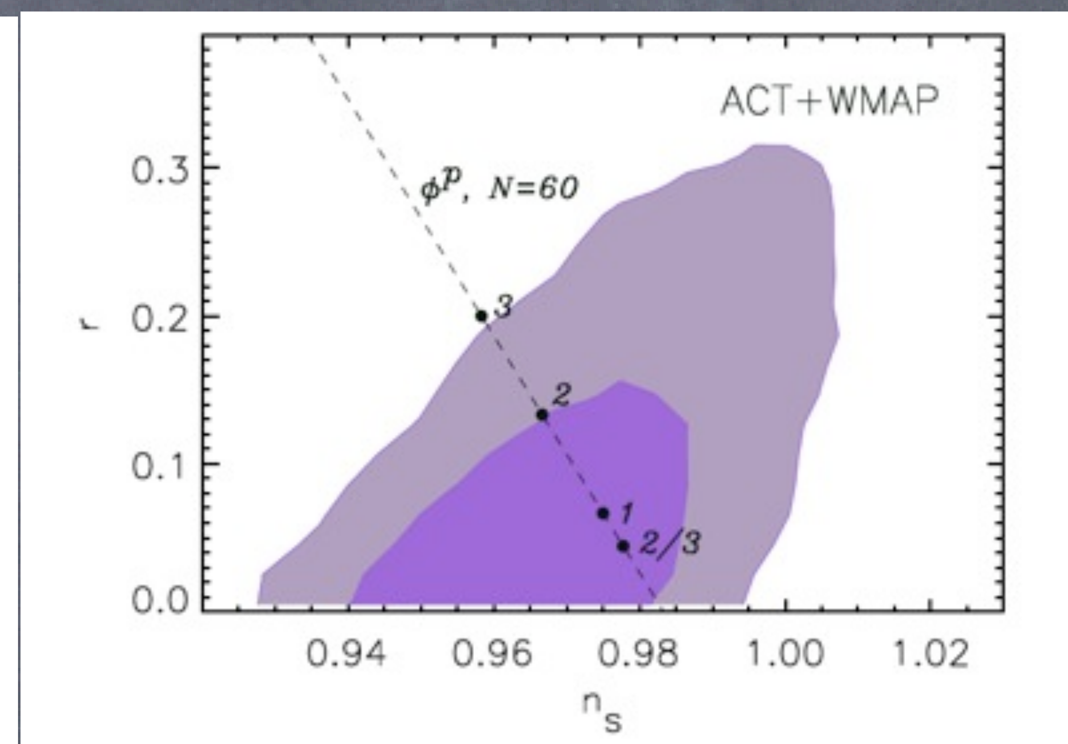
1. Introduction
2. Running kinetic inflation
3. Application to Higgs inflation
4. Conclusion

1. Introduction

Inflation solves theoretical problems of the std. cosmology, and it is strongly supported by observation.

Starobinsky `79, Guth `81, Sato `81
Linde `82, Albrecht and Steinhardt `82





Komatsu et al (2010)

Talk by Dunkley

The constraint on "r" will be improved by the Planck, QUIET, PolarBeaR, and LiteBIRD.

Talk by Hazumi

However, the inflation model is not yet determined.

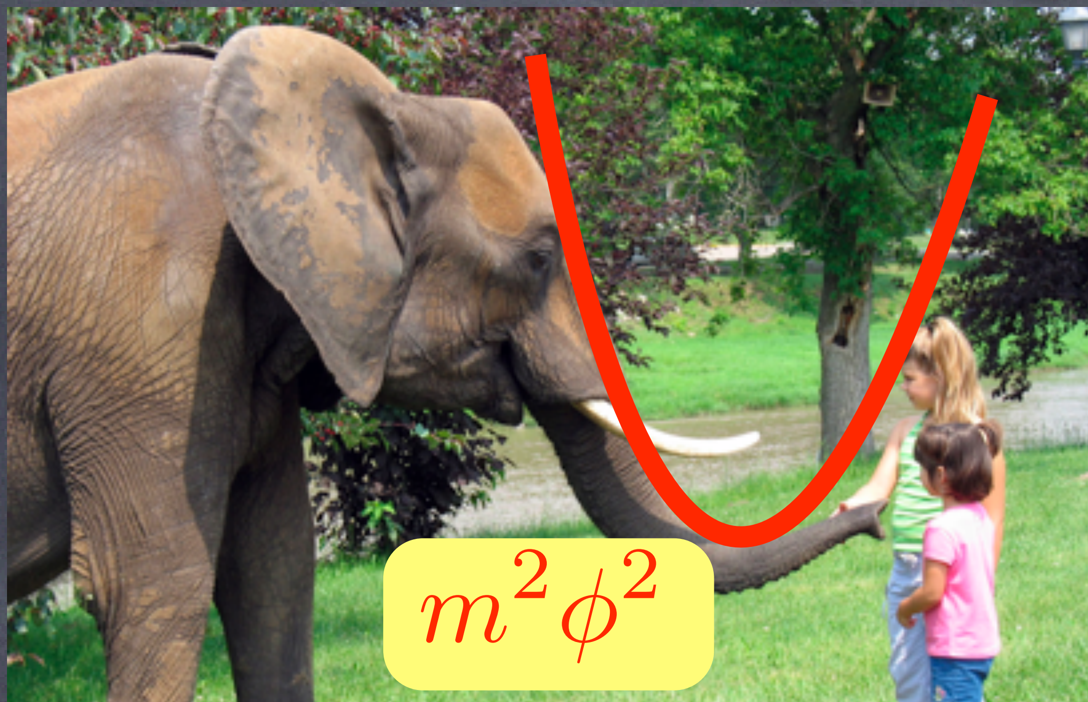
Inflationary Zoo

Inflationary Zoo

Large-field inflation

Talk by Kaloper, Silverstein

Inflationary Zoo



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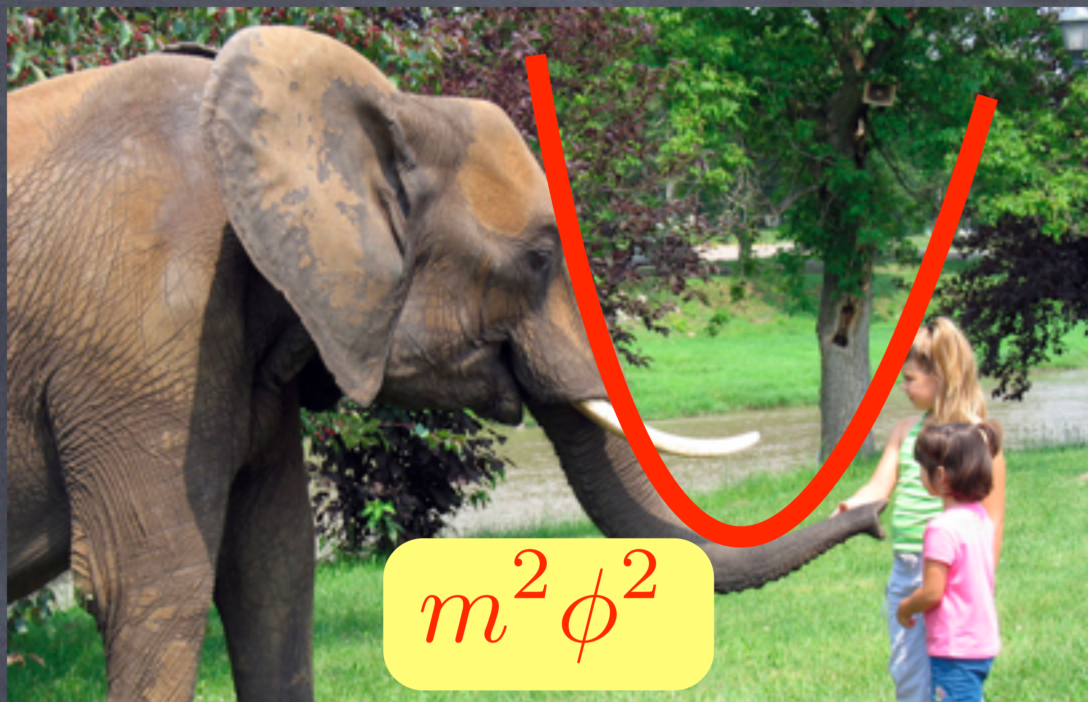
Inflationary Zoo



$m^2\phi^2$

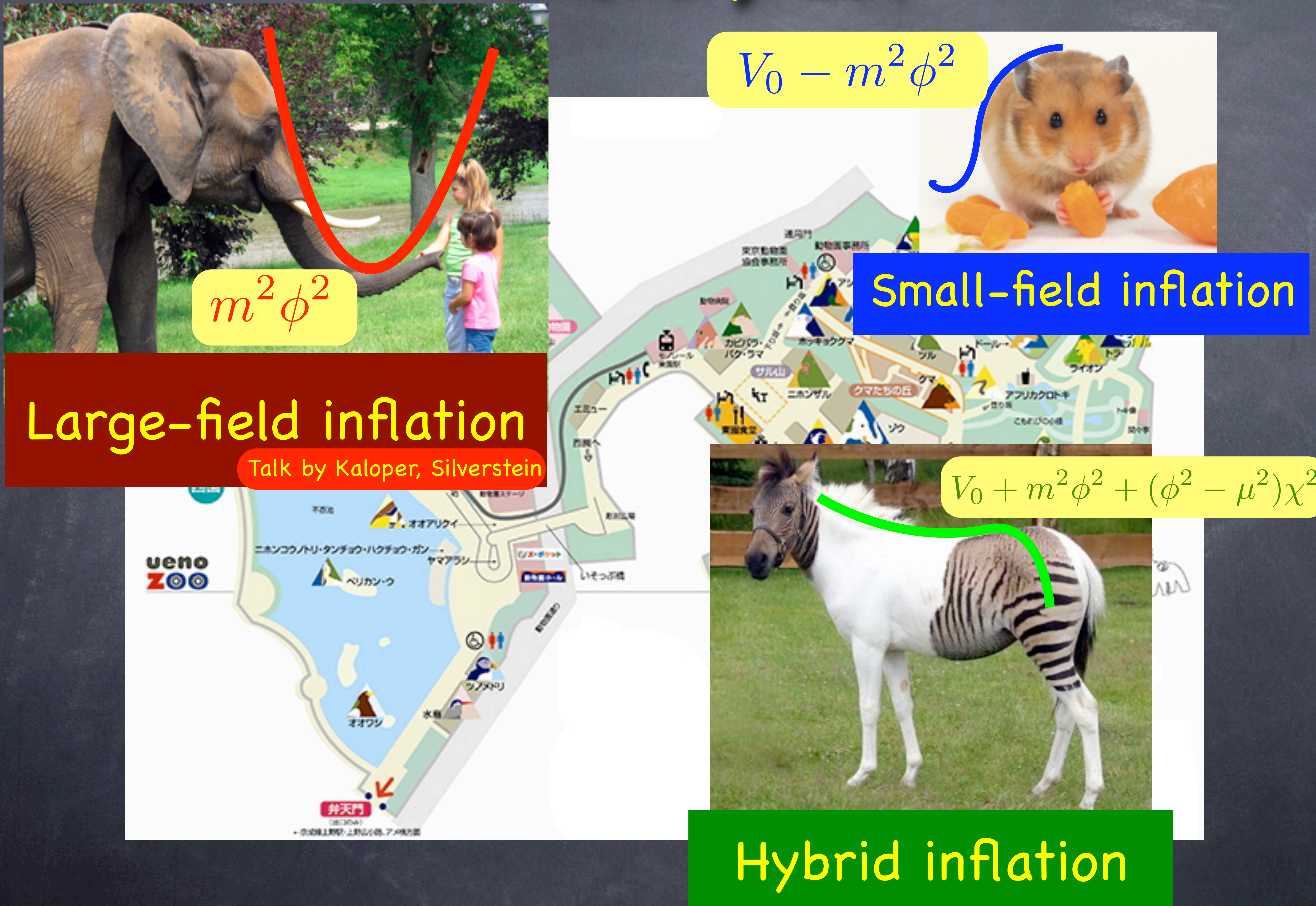
Large-field inflation

Talk by Kaloper, Silverstein

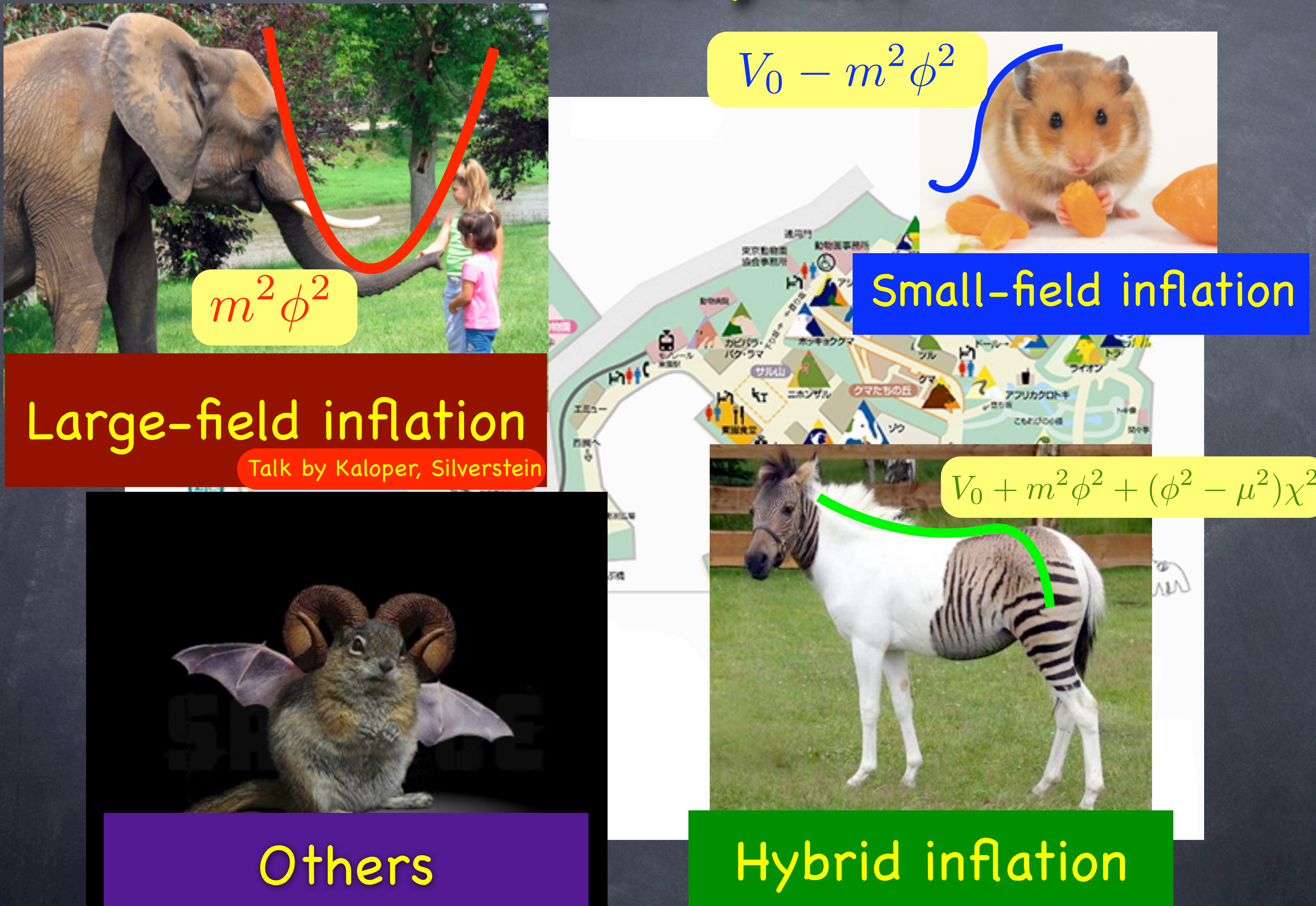
$V_0 - m^2\phi^2$

Small-field inflation

Inflationary Zoo



Inflationary Zoo



Goal

Build a new inflation model which predicts the tensor-to-scalar ratio within the reach of observations.

It would be nicer if

the model has implications for other probes such as the direct GW detection experiment and/or LHC.

2.Running Kinetic Inflation

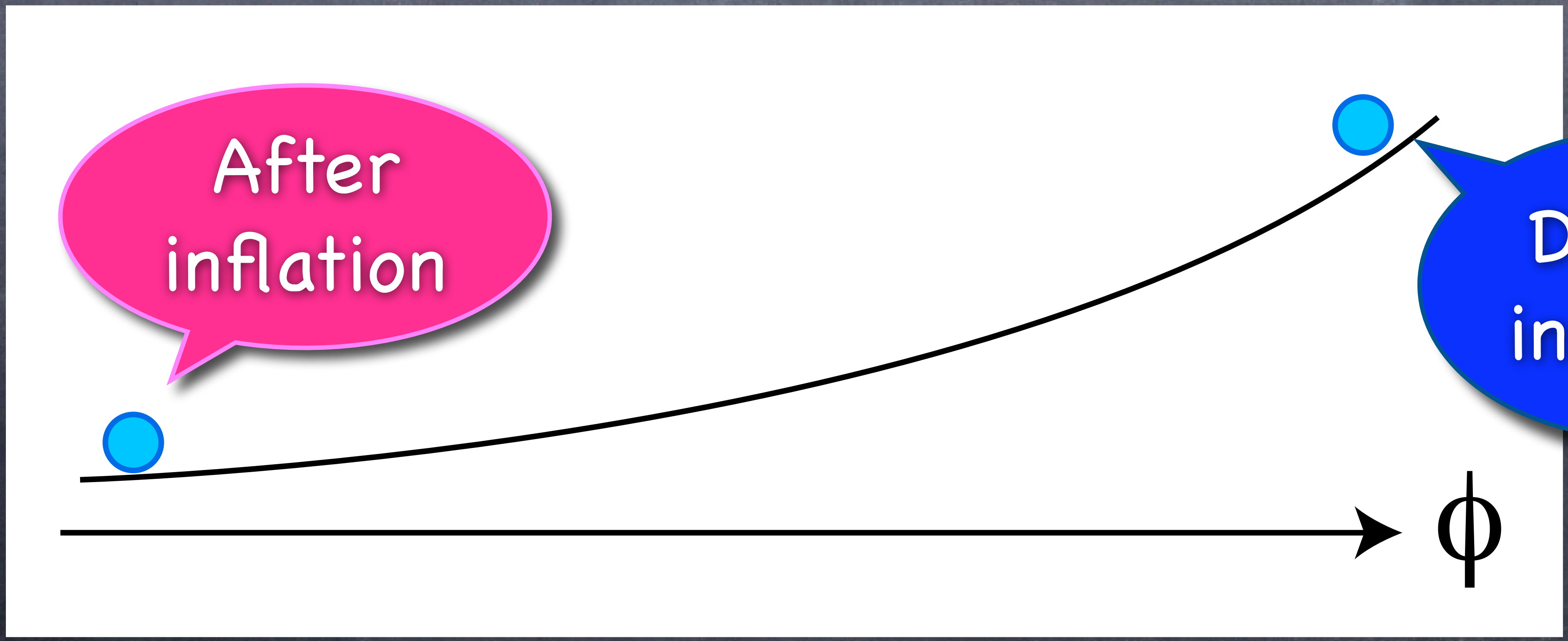
FT, PLB 693 (2010) 140-143 [arXiv:1006.2801]
Nakayama and FT, 1008.2956

2.1 Basic Idea

The inflaton moves over a long distance during inflation, especially if r > 0.01.

$$\frac{\Delta\phi}{M_p} \gtrsim \sqrt{\frac{r}{0.01}}$$

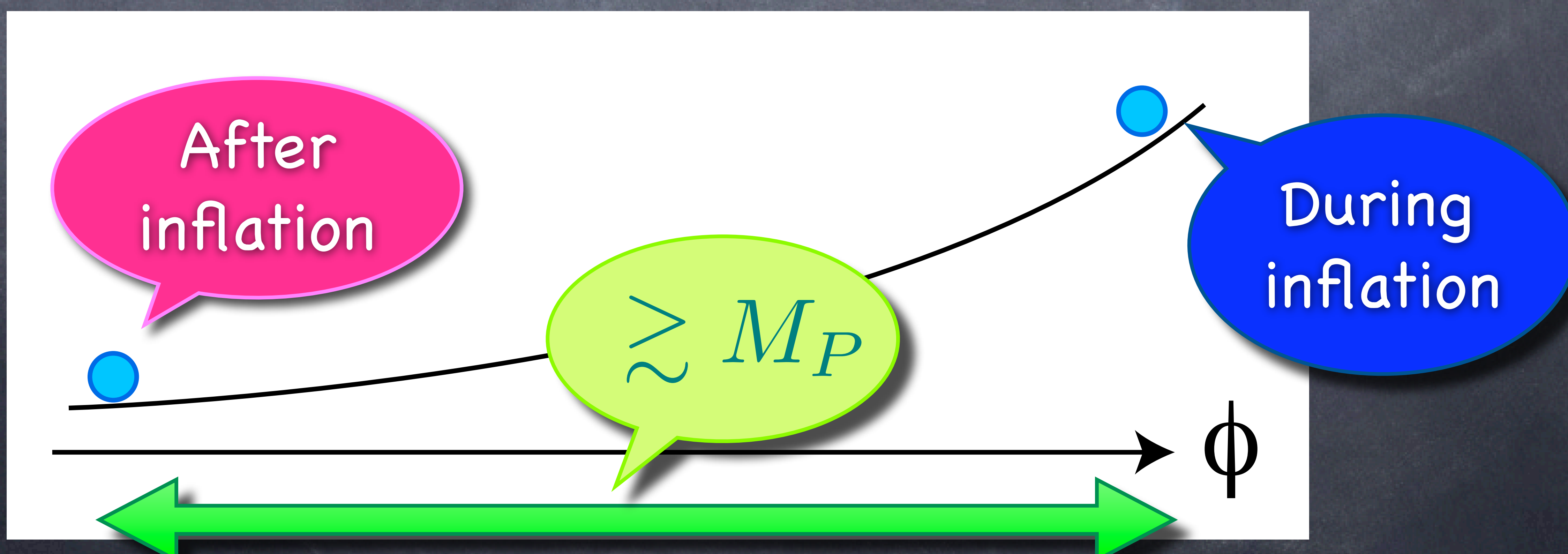
Lyth `96



2.1 Basic Idea

The inflaton moves over a long distance during inflation, especially if r > 0.01.

The physics during inflation may be different from after inflation.



- For instance let us consider

$$\mathcal{L} = \frac{1}{2}(1+\phi^2)(\partial\phi)^2 - V(\phi)$$

Planck unit

$M_p = 1$

At $\phi = 0$, canonically normalized.

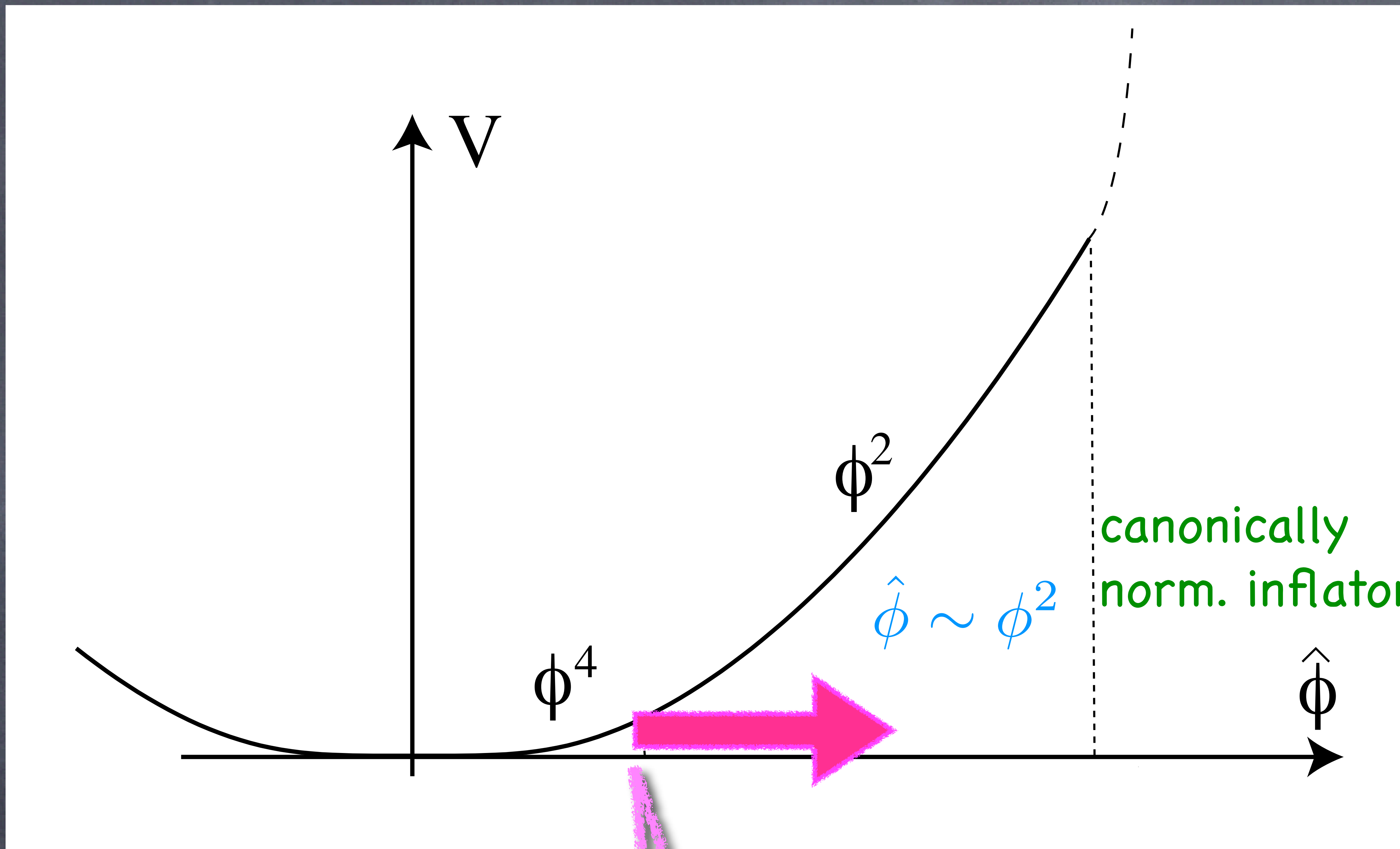
At $\phi \gg 1$, $\hat{\phi} \sim \phi^2$ is the canonically norm field.

So, the effective potential changes!

$\lambda\phi^4 \Rightarrow \lambda\hat{\phi}^2$

$m^2\phi^2 \Rightarrow m^2\hat{\phi}$

for $\phi \gg 1$



The power of the potential changes due to the running kinetic term.

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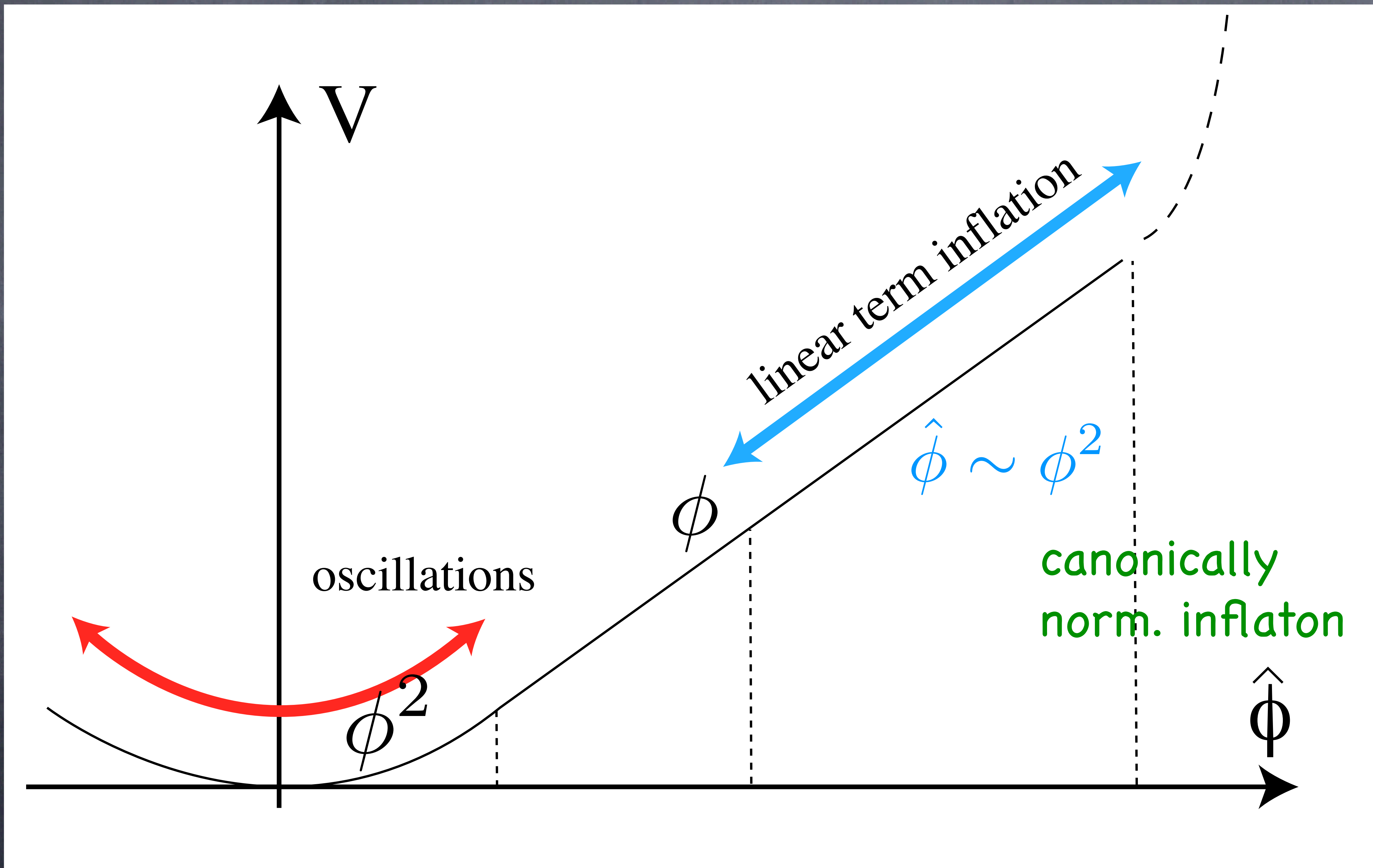
Similarly a linear term can be realized:



✓ It seems generic that the form of the kinetic term changes, especially if the inflaton moves over a large scale as in the chaotic inflation.

✓ A large kinetic term is advantageous for the inflation to occur, because the potential becomes flatter!

$$\mathcal{L}_K = \frac{A}{2}(\partial\phi)^2$$

In the limit of A >> 1, the potential becomes flat.

Dimopoulos, Thomas, hep-th/0307004

2.2 RK inflation in sugra

Some sort of shift symmetry is needed to prevent the inflaton from appearing in the exponential pre-factor.

$$V = e^{K}\left(D_i W g^{i\bar{j}}(D_j W)^* - 3|W|^2)\right)$$

For instance, $\phi \longrightarrow \phi + \alpha \qquad \alpha \in \mathbf{R}$

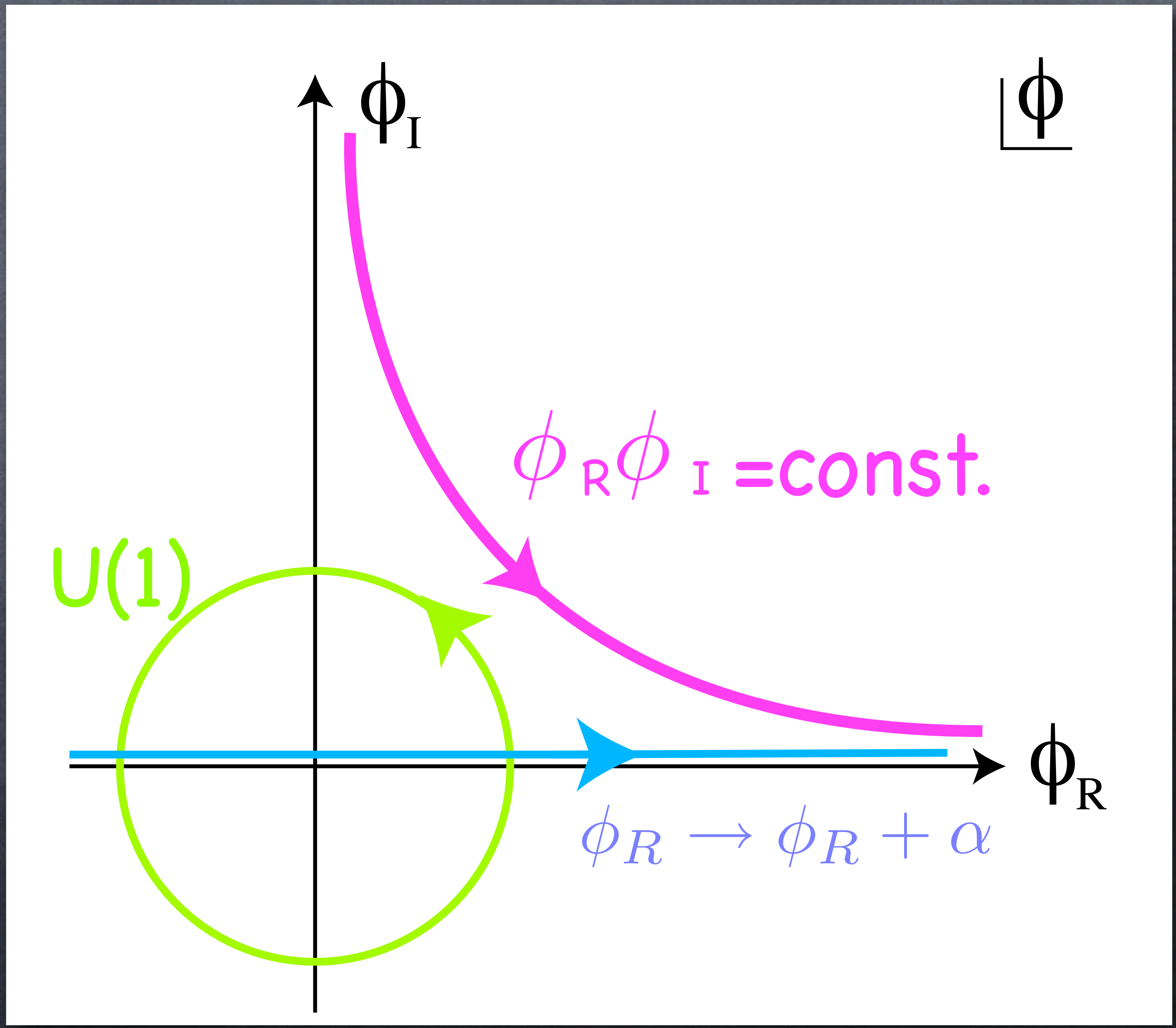
$$K = ic_1(\phi - \phi^\dagger) - \frac{1}{2}(\phi - \phi^\dagger)^2 + \cdots$$

The inflaton is ϕ_R in this case.

Kawasaki, Yamaguchi, Yanagida, \`00

There are in general other possibilities.

$$K = f(\phi_R \phi_I) \quad \Rightarrow \quad \phi^2 \to \phi^2 + \alpha$$



We assume that the Kahler potential respects the shift symmetry.

$$K = ic(\phi^2 - \phi^{\dagger 2}) - \frac{1}{4}(\phi^2 - \phi^{\dagger 2})^2 + \cdots ,$$

$$\Delta K = \kappa |\phi|^2$$

$$\Rightarrow \boxed{\mathcal{L}_K = \left(\kappa + (2 + \cdots)|\phi|^2\right) \partial^\mu \phi^\dagger \partial_\mu \phi,}$$

The kinetic term grows at large field values, in a controlled way thanks to the shift symmetry.

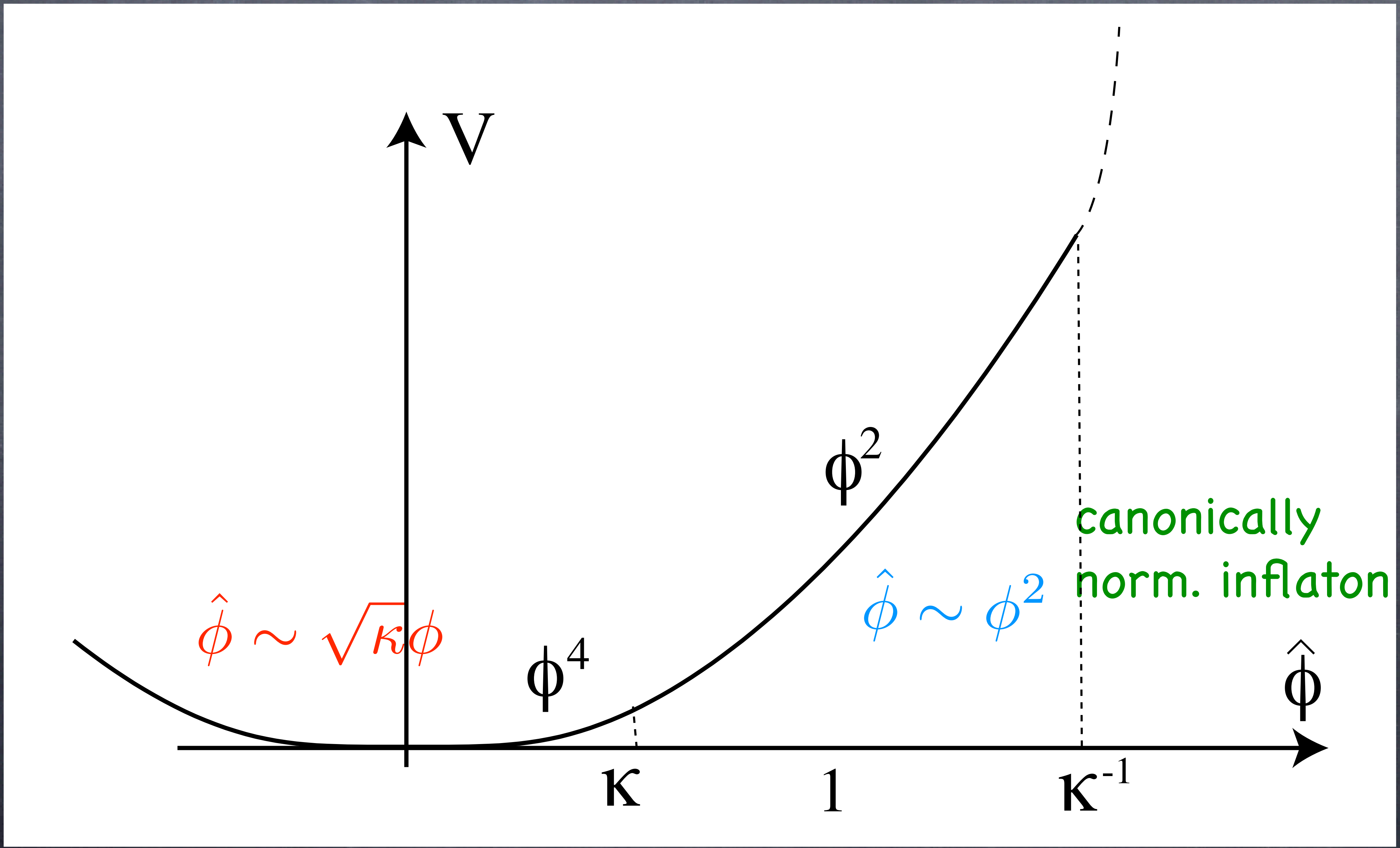
Note: $\phi^2 - \phi^{2\dagger} = \mathrm{const.}$ along the inflation trajectory.

Quadratic chaotic inflation with RK term

$$K = \kappa|\phi|^2 + ic(\phi^2 - \phi^{\dagger 2}) - \frac{1}{4}(\phi^2 - \phi^{\dagger 2})^2 + |X|^2$$

$$W = \lambda X \phi^2,$$

We impose Z_4 and $U(1)_R$ symmetries.



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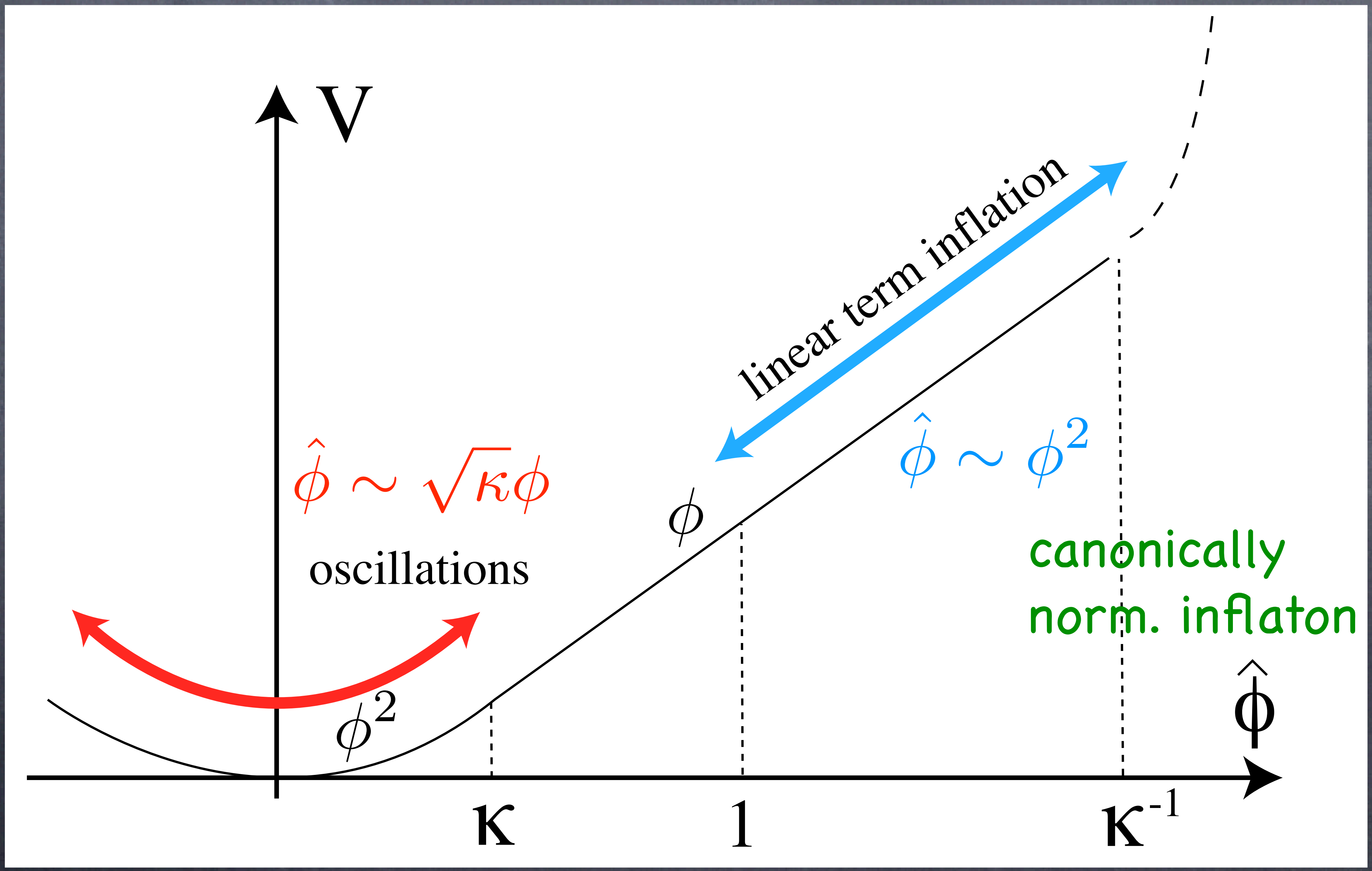
Linear chaotic inflation

FT, arXiv:1006.2801

$$K = \kappa|\phi|^2 + ic(\phi^2 - \phi^{\dagger 2}) - \frac{1}{4}(\phi^2 - \phi^{\dagger 2})^2 + |X|^2$$

$$W = mX\phi,$$

We impose Z_2 and $U(1)_R$ symmetries.



Cf. McAllister, Silverstein and Westphal 0808.706 for the stringy construction.

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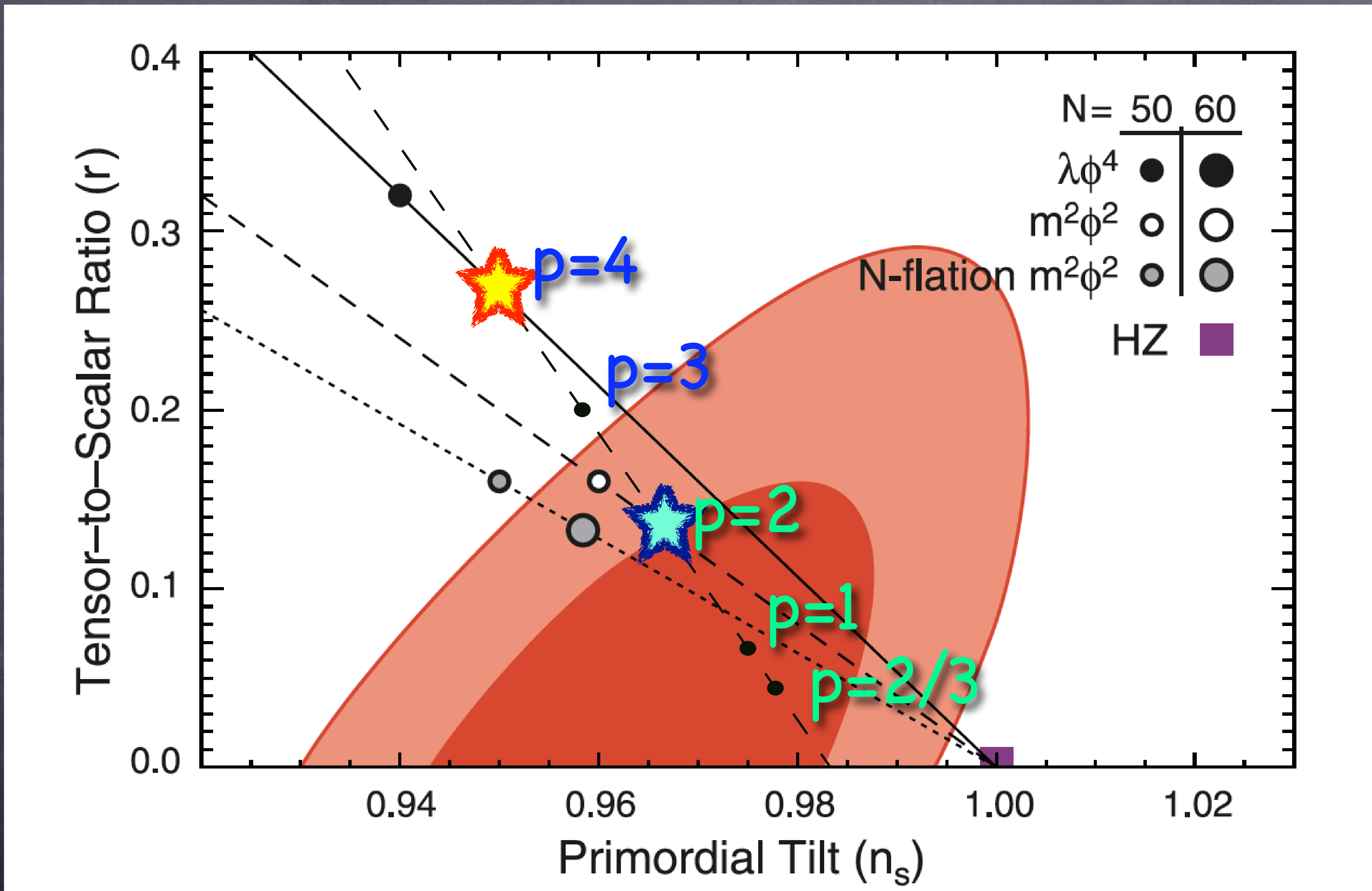
(n_s, r)

$$V = \phi^p$$



Komatsu et al (2010)

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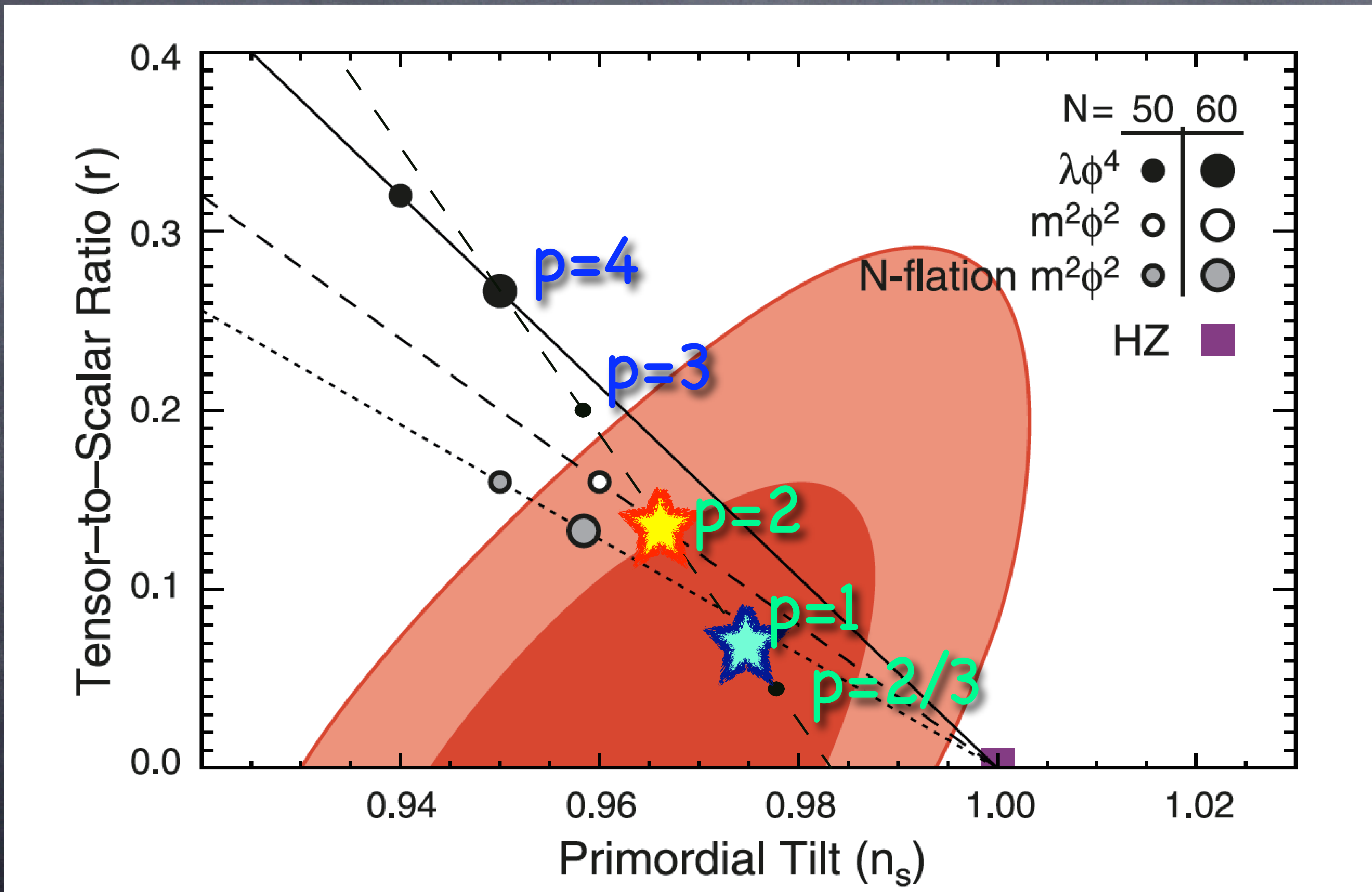
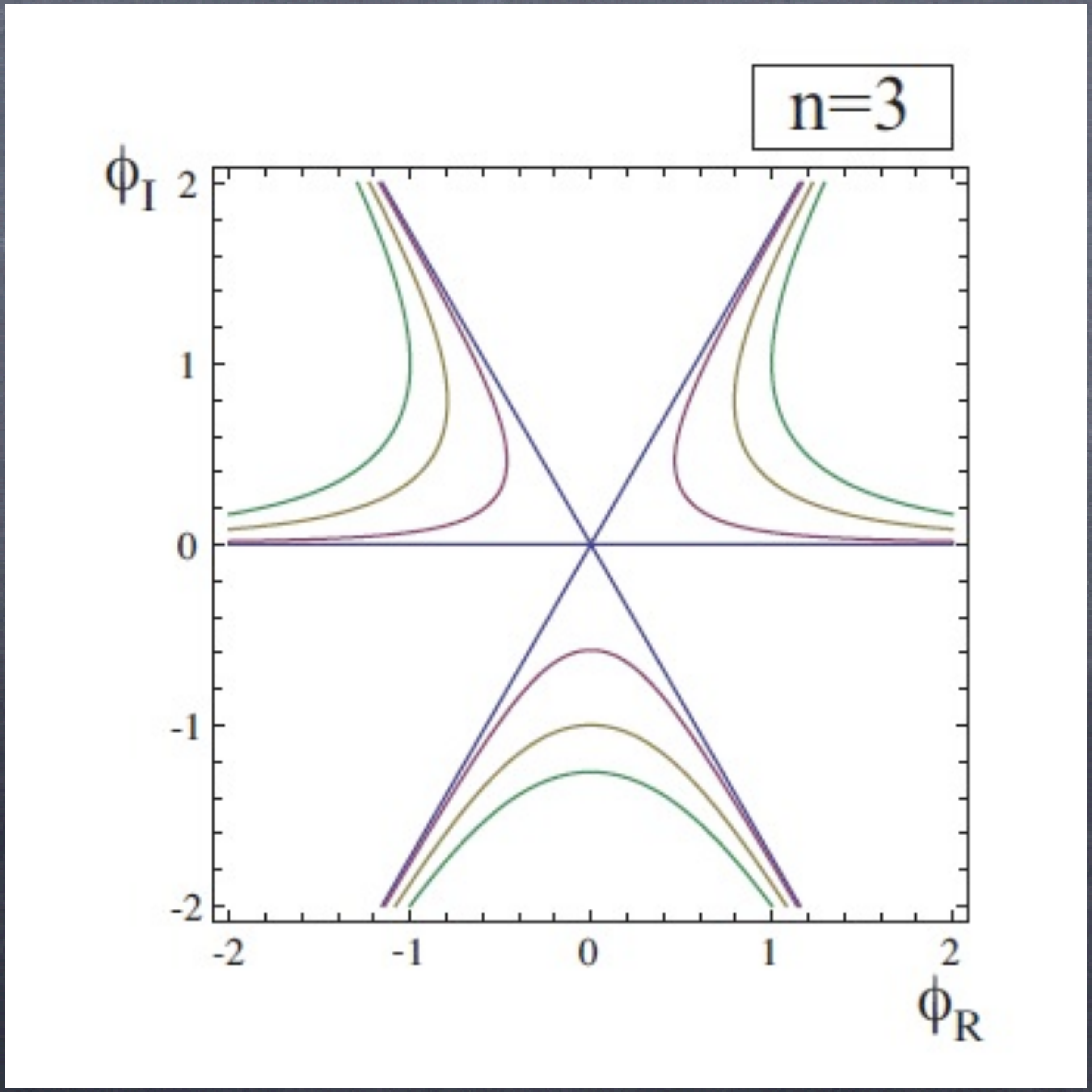


Komatsu et al (2010)

Generalization is straightforward.

The shift symmetry can be generalized to ϕ^n.

$$\phi^n \to \phi^n + \alpha$$



The Kahler and super-potentials are given by

$$K = \kappa|\phi|^2 + c_1(\phi^n - \phi^{\dagger n}) - \frac{1}{2}(\phi^n - \phi^{\dagger n})^2 + \cdots$$

$$W = \lambda X \phi^m$$

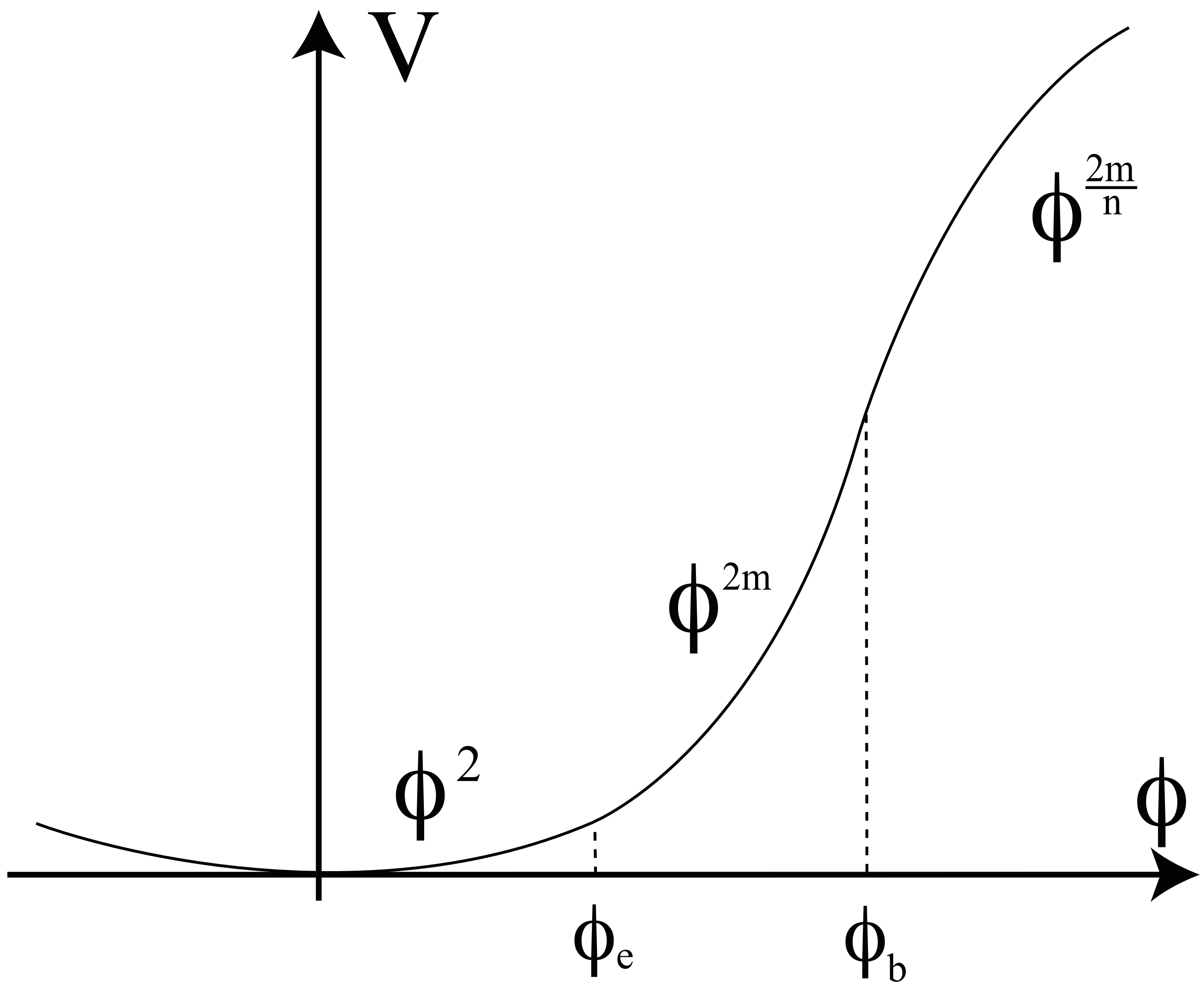
	ϕ	X
$U(1)_R$	0	2
Z_k	1	$-m$

$$V \propto \begin{cases} \phi^{\frac{2m}{n}} & \text{during inflation} \\ \phi^{2m} & \text{after inflation} \end{cases}$$

$$n_s = 1 - \frac{n+m}{n}\frac{1}{N_e}$$

$$r = \frac{8m}{n}\frac{1}{N_e}$$

The potential looks like



Thus, we can have a variety of chaotic inflation models.

Implications of RK inflation

- The gravity waves can be enhanced if m > 2.
- Naturally avoids the non-thermal gravitino problem.

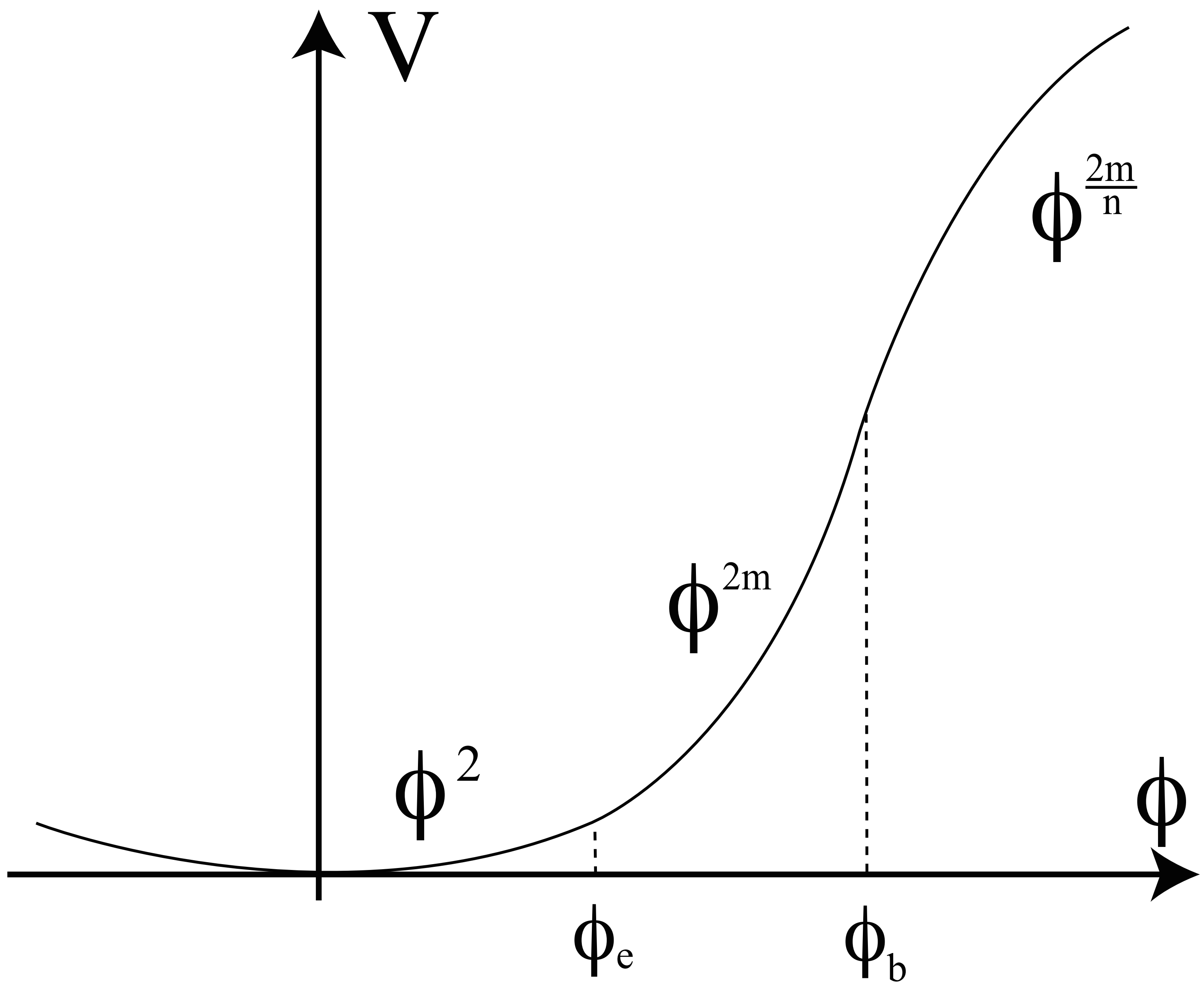
Kawasaki, F.T. and Yanagida, hep-ph/0603265, 0605297
Asaka, Nakamura and Yamaguchi, hep-ph/0604132

- Likely coupled to the Higgs sector for successful reheating. In this case the inflation sector can be studied thru experiments!! Inflatino can be dark matter.

See Nakayama and FT 1008.2956 for details.

Enhancement of gravity waves

There are a kination epoch after inflation, during which the inflaton energy decreases faster than radiation.



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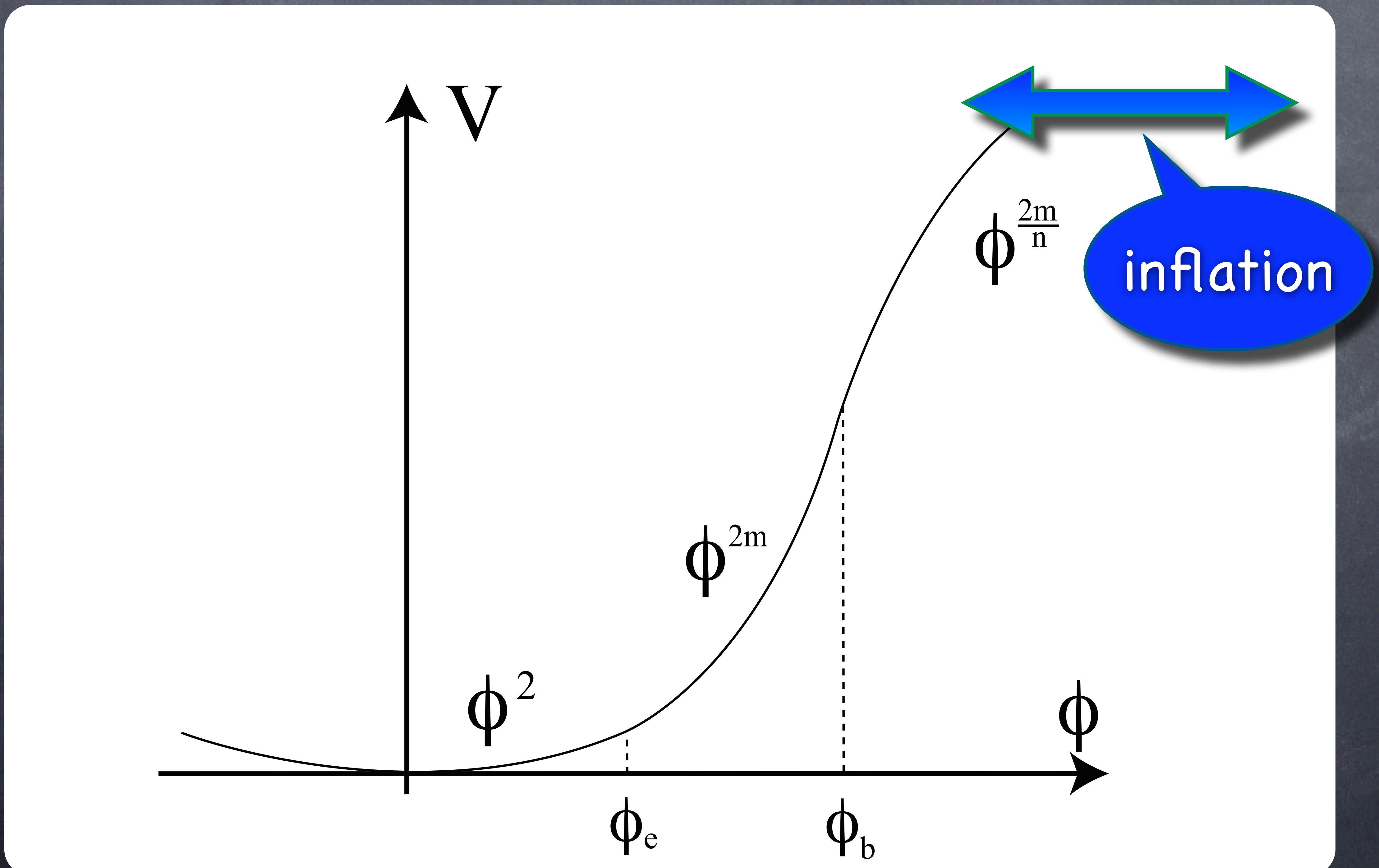
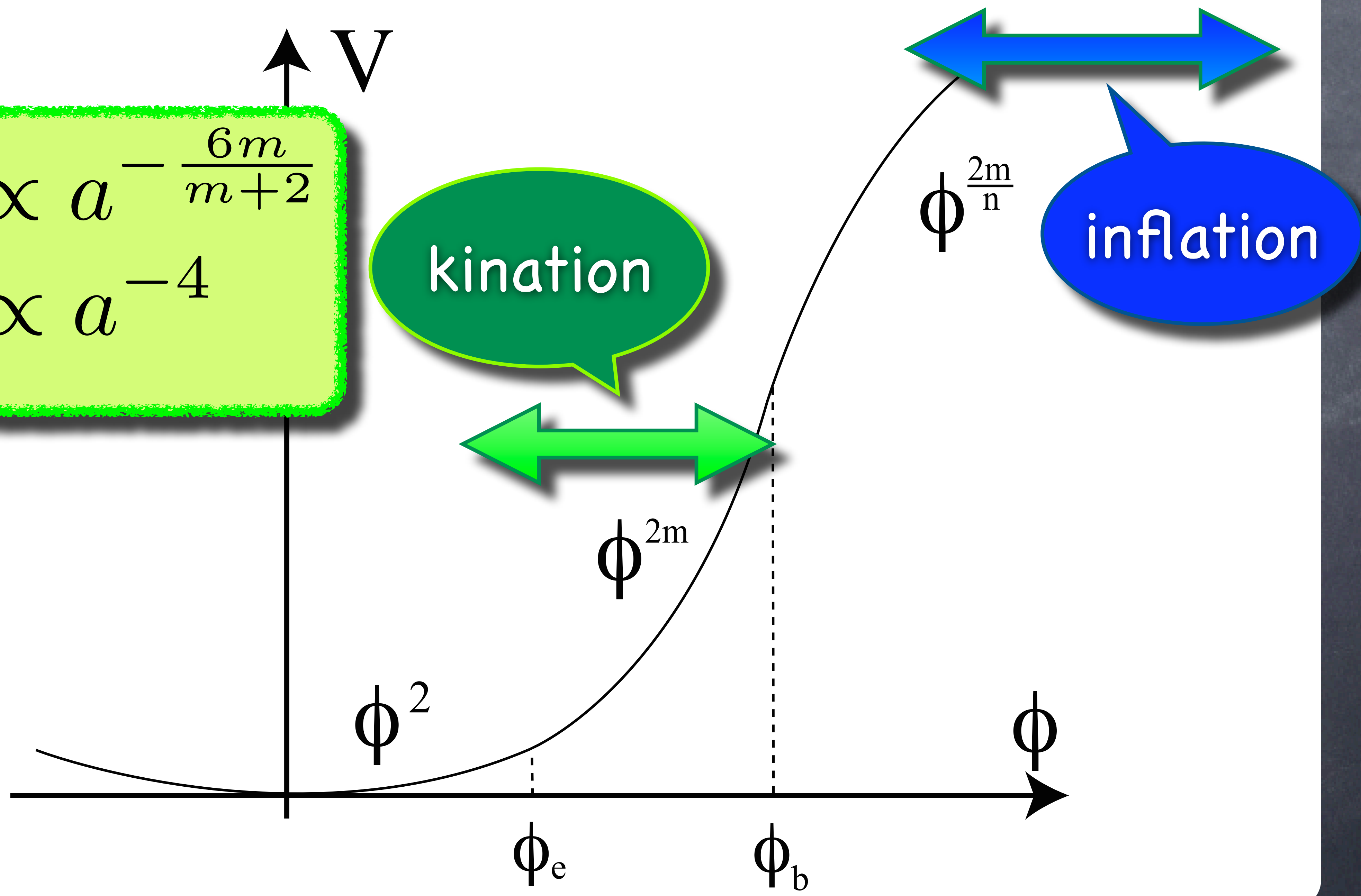


Enhancement of gravity waves

There are a kination epoch after inflation, during which the inflaton energy decreases faster than radiation.

$$\rho_\phi \propto a^{-\frac{6m}{m+2}}$$
$$\rho_{\rm rad} \propto a^{-4}$$



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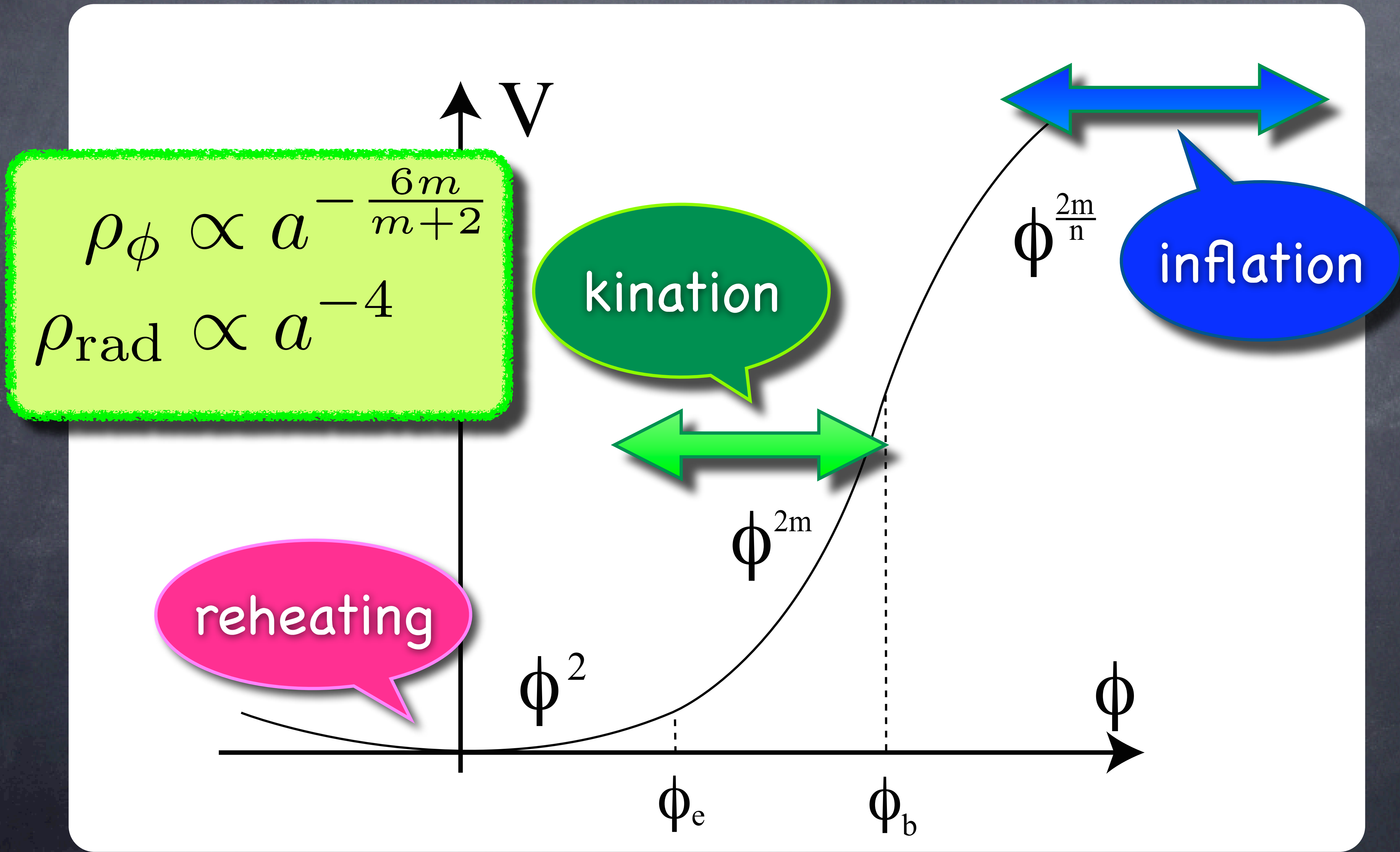

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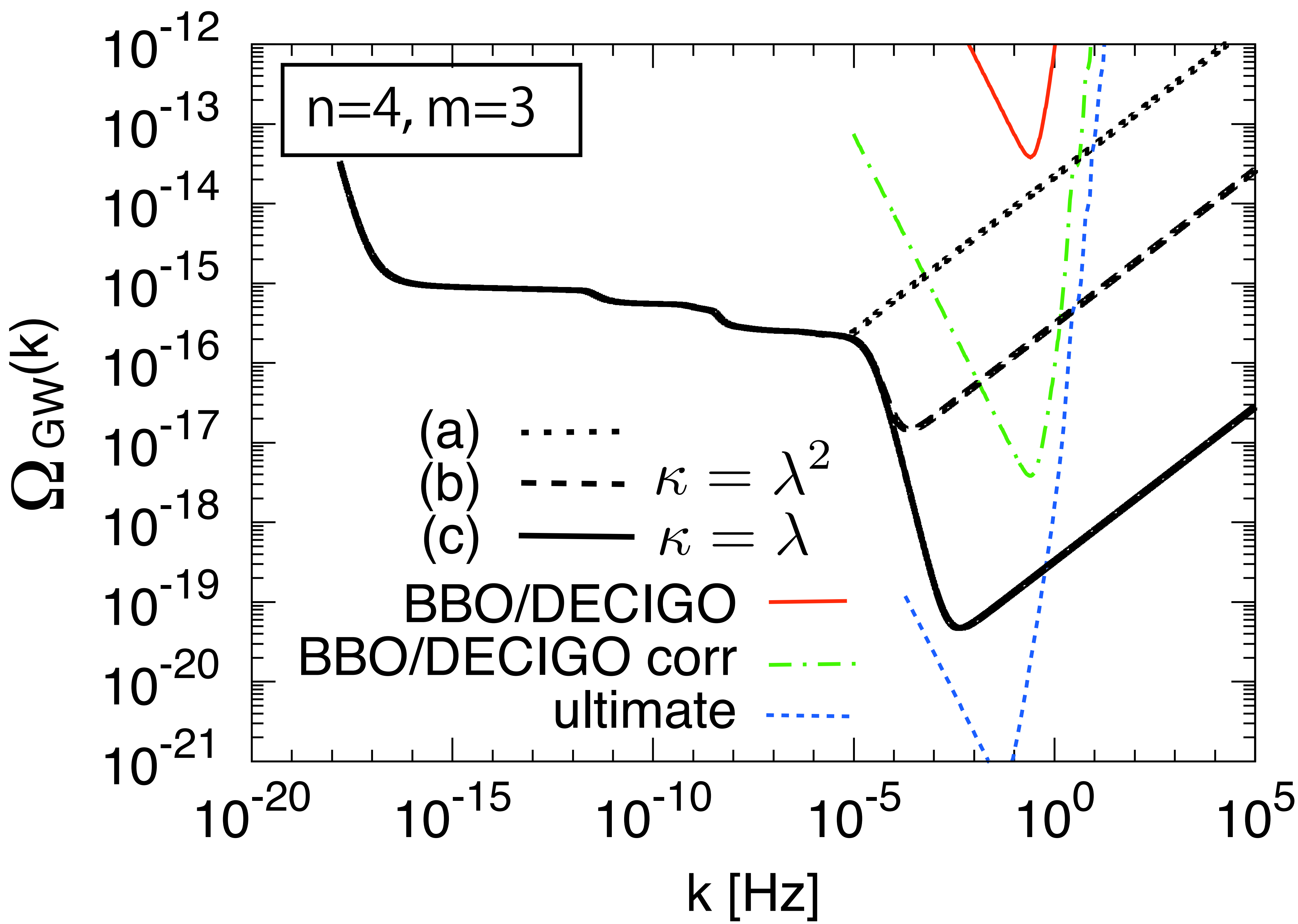
Example: n=4 and m=3



Nakayama and FT, 1008.2956

Summary of RK inflation

- The form of the potential changes due to the running of the kinetic term.
  - ✓ Linear or fractional power potential is possible.
  - ✓ Inflaton can be massless at the origin (in the SUSY limit), while r is large but consistent with observation.

➡ Many interesting phenomena:
Enhancement of GW, Inflaton may be produced at LHC, Inflatino DM, etc.

3. Higgs Inflation

Let us consider a possibility that the Higgs field plays a role of the inflaton.

$$V = \frac{\lambda}{4}(h^2 - v^2)^2$$

✓The SM particles are naturally produced by the reheating.

✓The inflaton can be studied thru experiments.

✓Favored from a minimalistic point of view.

However,

✓Quartic chaotic inflation is strongly disfavored.

✓ A very small coupling is needed for the WMAP normalization of density perturbation.

⬇

We need to somehow **make the potential flatter at large field value.**

⬇

Bezrukov and Shaposhnikov, 0710.3755 and many other references.

(1) Non-minimal coupling to gravity
(2) Running kinetic term

3.1 Higgs inflation with a non-minimal coupling to gravity

Bezrukov and Shaposhnikov, 0710.3755
and many other references such as
Lerner and McDonald 0912.5463,1005.2978
Germani and Kehagias 1003.2635
Barvinsky et al 0910.1041,0911.1408

- Non-minimal coupling to gravity:

$$S_J = \int d^4x\sqrt{-g}\left\{-\frac{M_P^2}{2}R - \xi\frac{h^2}{2}R + \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4}(h^2-v^2)^2\right\}$$

After the Weyl transformation, the potential becomes very flat in the Einstein frame,

$$U(\chi) \approx \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)^{-2} \quad \text{for} \quad \chi > \sqrt{6}M_P$$

with $h \simeq \frac{M_P}{\sqrt{\xi}}\exp\left(\frac{\chi}{\sqrt{6}M_P}\right)$

Salopek, Bond, and Bardeen `89
Futamase and Maeda `89
Spokoiny,`84, Fakir and Unruh `90
Komatsu and Futamase `97

$\xi = O(10^4)$ from COBE norm.

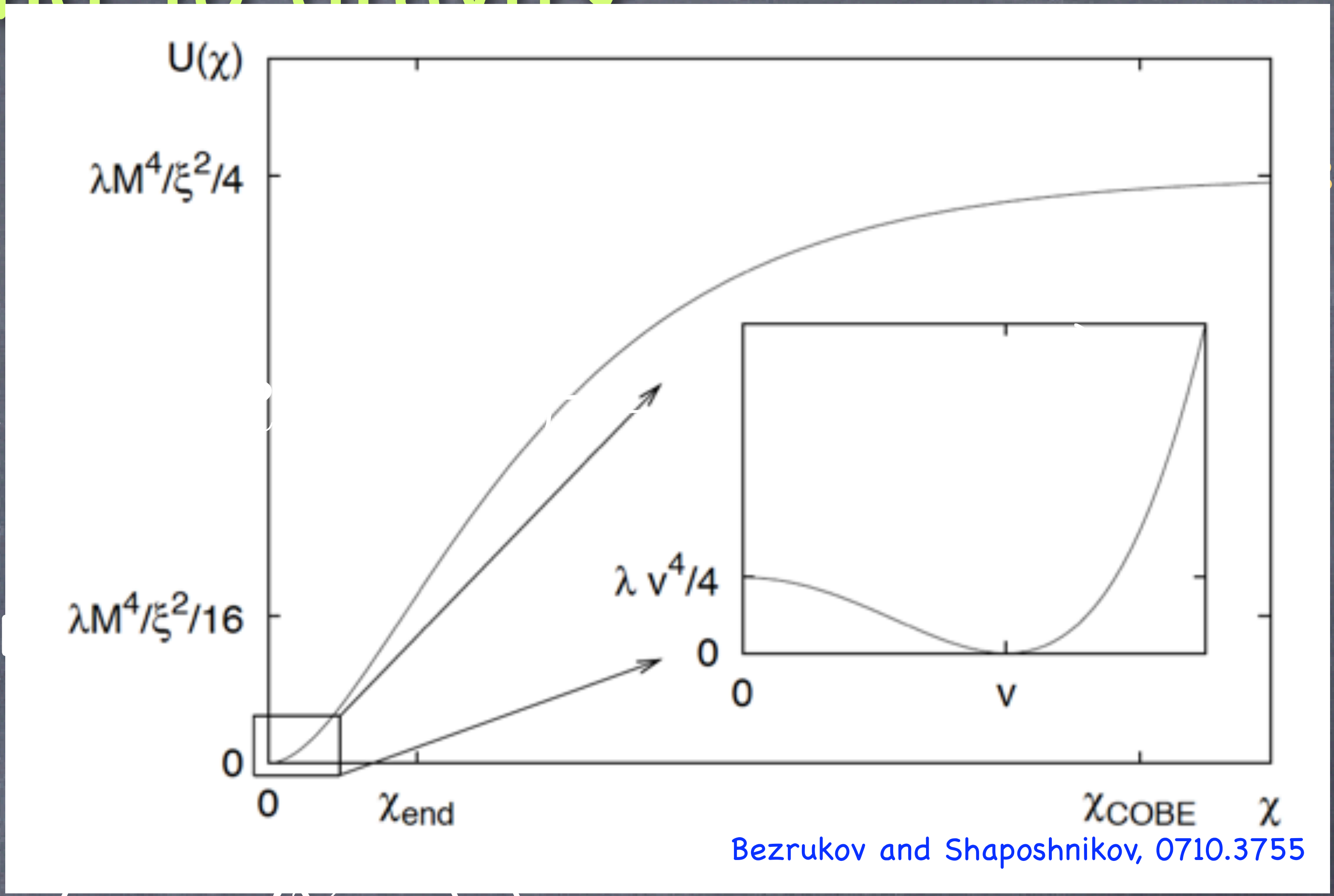
See talk by Lerner, Steinwachs, and Germani.

3.1 Higgs inflation with a non-minimal coupling to gravity

- Non-minimal coupling to

$$S_J = \int d^4x \sqrt{-g} \left\{ -\frac{M_P^2}{2} R \right.$$

After the Weyl transfor
very flat in the Einstein



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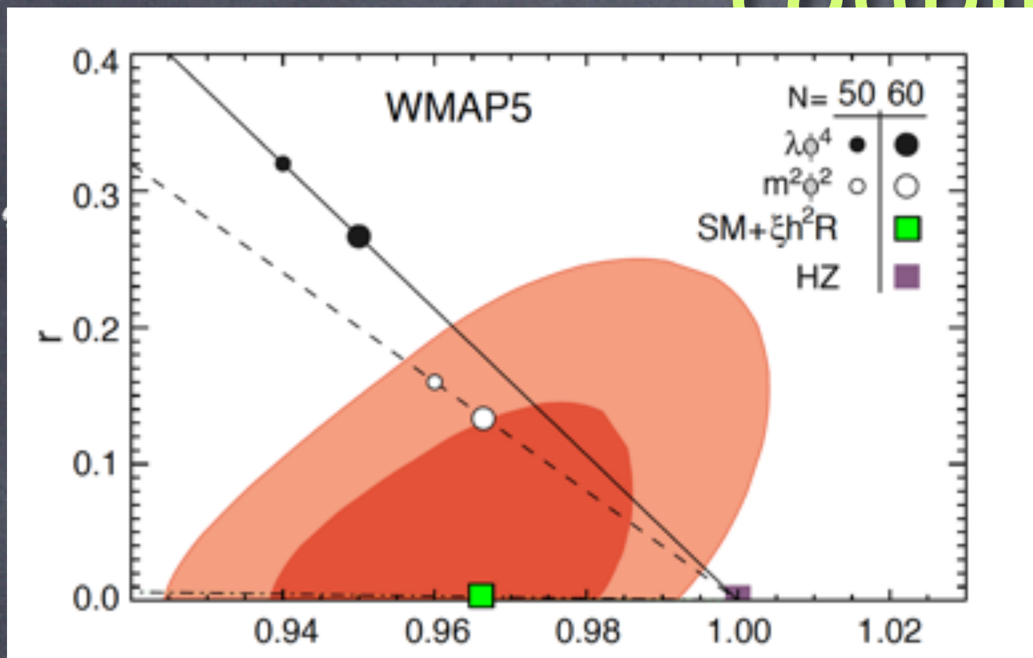
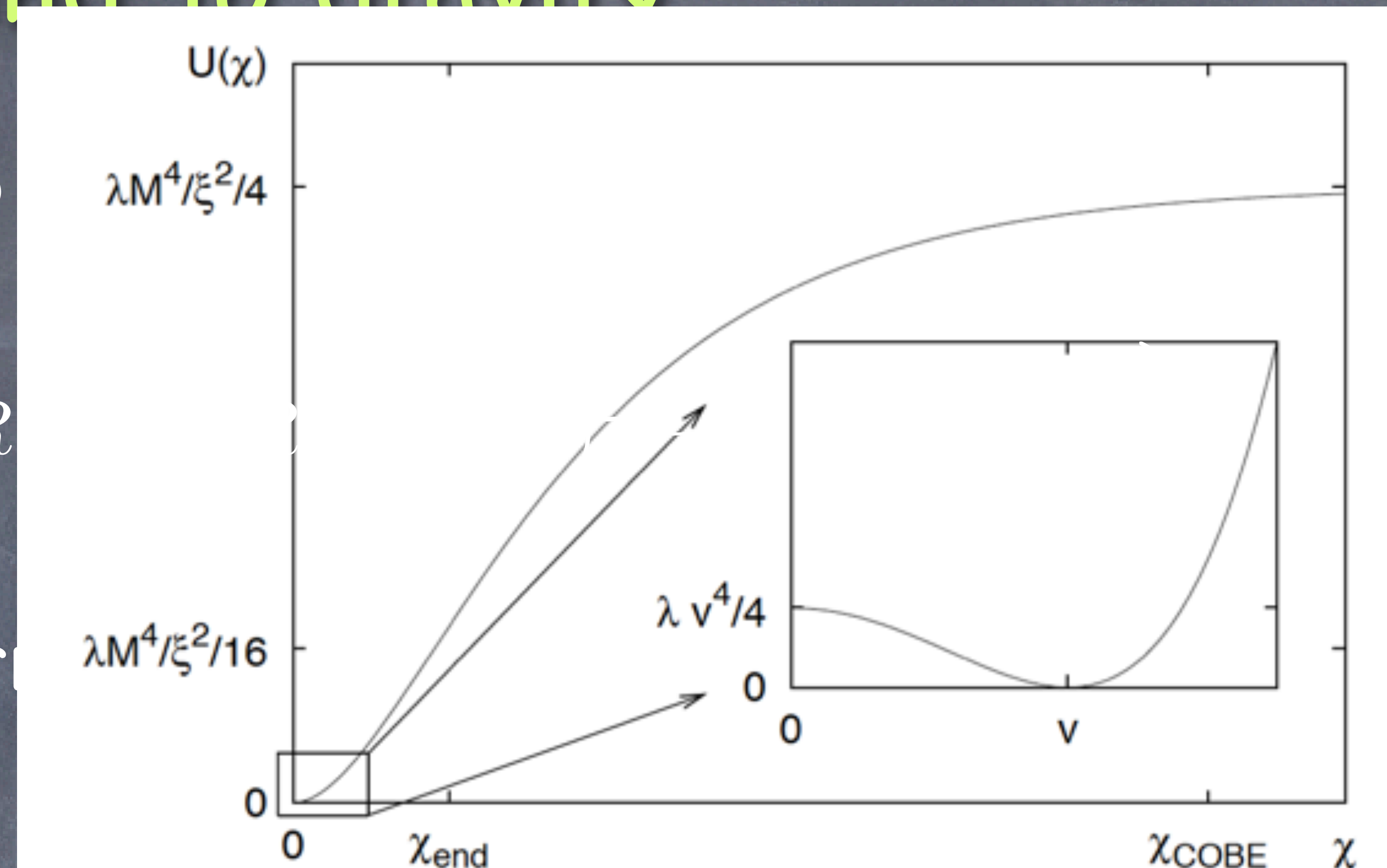
3.1 Higgs inflation with a non-minimal coupling to gravity



Bezrukov et al 0812.3622



Bezrukov and Shaposhnikov, 0710.3755

After the Weyl transfor...
very flat in the Einstein ...

$$U(\chi) \approx \frac{\lambda M_P^4}{4\xi^2}\left(1+\exp\left(-\frac{2\chi}{\sqrt{6}M_P}\right)\right)$$ for $\chi > \sqrt{6}M_P$

with $h \simeq \frac{M_P}{\sqrt{\xi}} \exp\left(\frac{\chi}{\sqrt{6}M_P}\right)$

Salopek, Bond, and Bardeen `89
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Komatsu and Futamase `97

$\xi = O(10^4)$ from COBE norm.

See talk by Lerner, Steinwachs, and Germani.

In supergravity, the Higgs inflation with non-minimal coupling to gravity occurs in a similar way.

Einhorn and Jones 0912.2718
Ferrara, Kalosh, Linde, et al 1004.0712, 1008.2942,
Kallosh and Linde 1008.3375, H.M.Lee 1005.2735

$$\frac{1}{\sqrt{-g}}\mathcal{L}_{grav} = \frac{1}{6}\Omega\,\mathcal{R} + \cdots$$

where the frame function Ω is related to the Kahler potential,

$$K = -3\log\left(-\frac{\Omega}{3}\right)$$

For the frame function and the superpotential,

$$-\frac{1}{3}\Omega = 1 - \frac{1}{3}\left(|H_u|^2 + |H_d|^2 + |X|^2\right) + \xi H_u H_d + \mathrm{h.c.}$$

$$W = \lambda X H_u H_d + y\frac{X^3}{3},$$

the inflation occurs with the same potential.

3.2.1 Higgs RK inflation [SM]

Nakayama and FT, 1008.4457

We consider a RK term:

Cf. Germani and Kehagias 1003.2635
Lerner and McDonald 1005.2978

$$\mathcal{L} = \frac{1}{2}\left(1+\xi\frac{h^2}{2}\right)(\partial h)^2 - \frac{\lambda_h}{4}(h^2-v^2)^2.$$

For large $h \gtrsim \frac{1}{\sqrt{\xi}}$,the canonically norm. field is

$$\hat{h} \approx \frac{\sqrt{\xi}h^2}{2\sqrt{2}},$$

and the potential is

$$V(\hat{h}) \simeq \frac{1}{2}\left(\frac{4\lambda_h}{\xi}\right)\hat{h}^2.$$

$$\frac{\lambda_h}{\xi} \sim 10^{-11}$$

for COBE norm.

3.2.2 Higgs RK inflation [NMSSM]

Nakayama and FT, 1008.4457

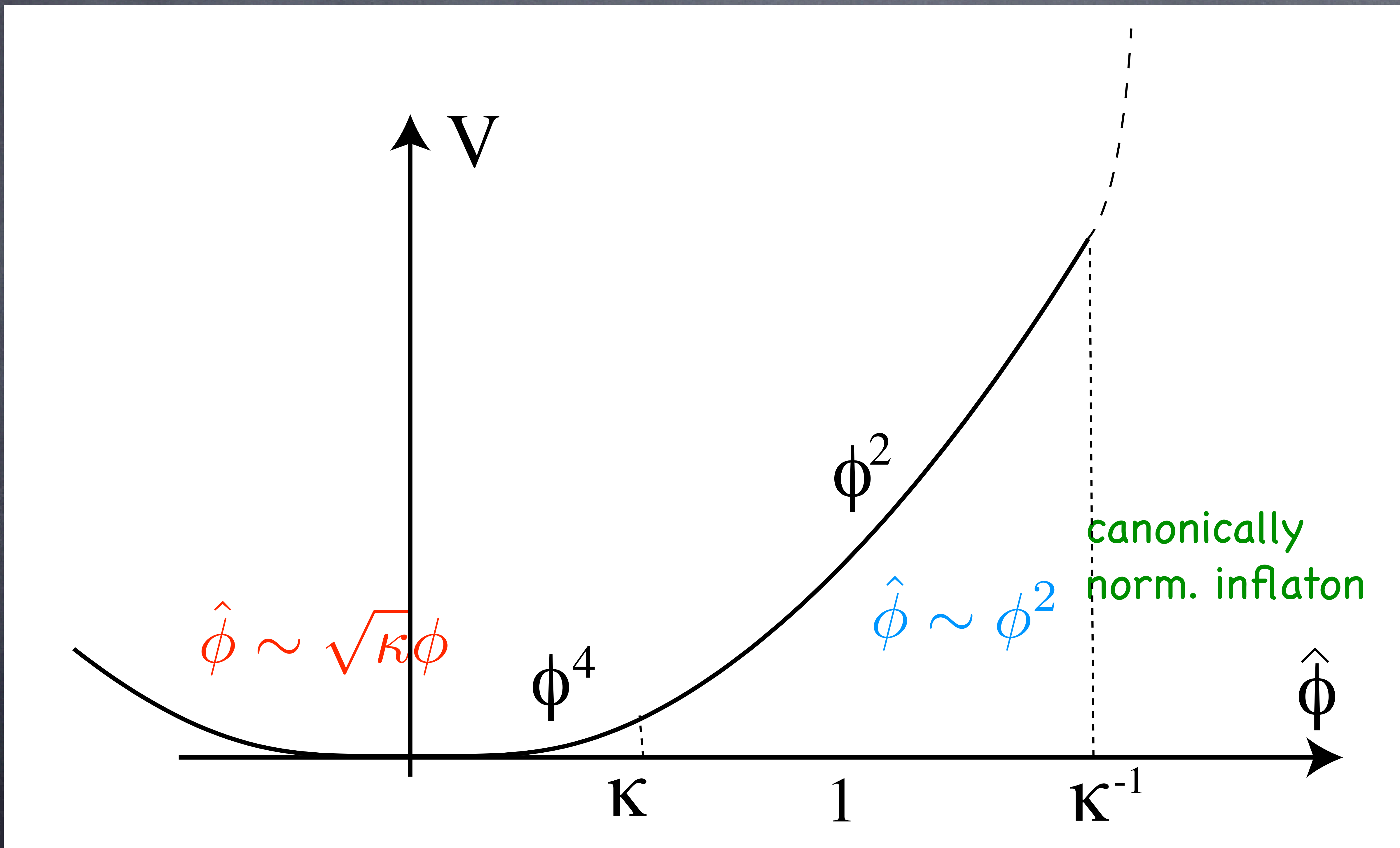
We consider a D-flat direction, $\phi^2 \equiv H_u H_d$

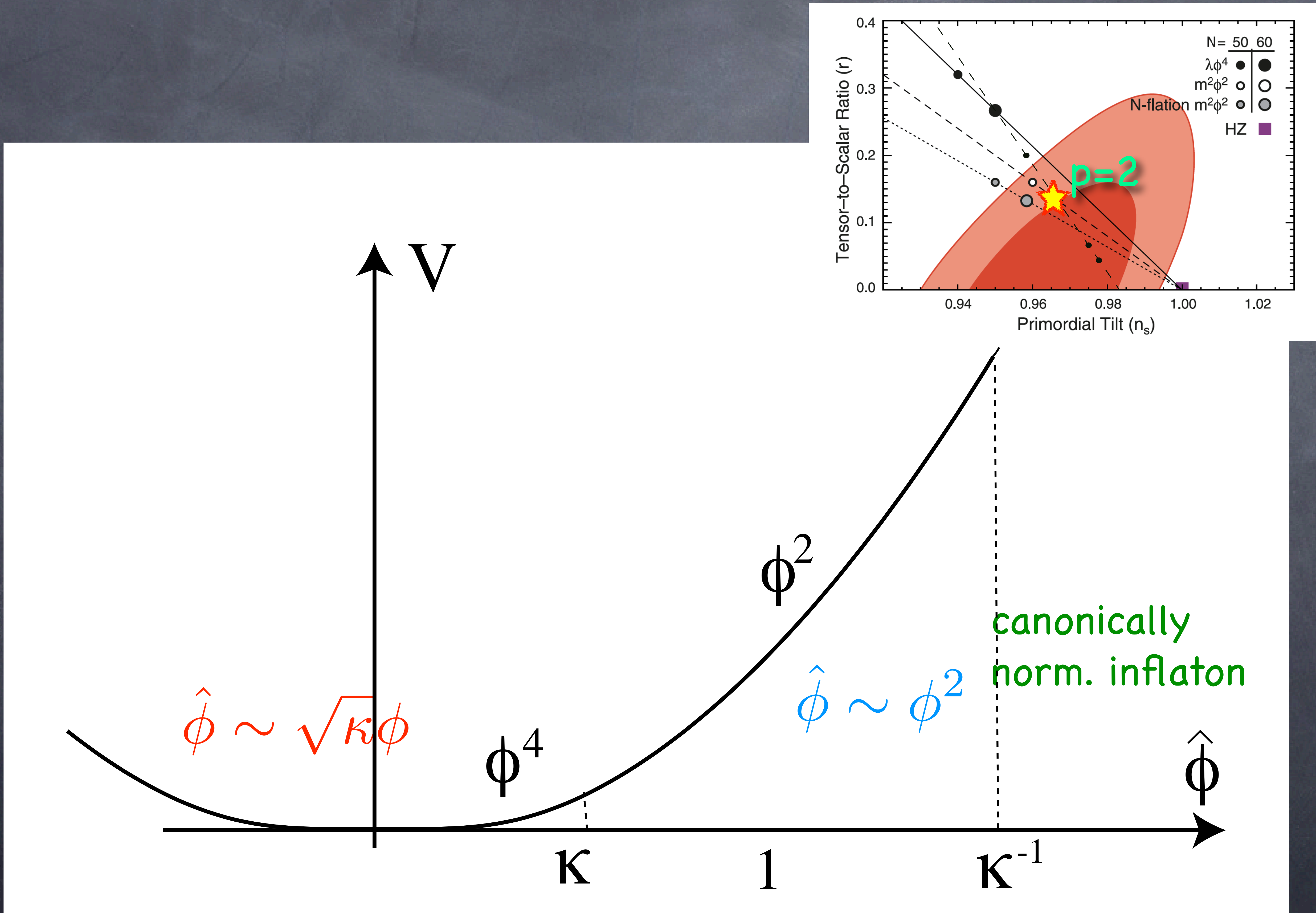
$$
\begin{aligned}
K &= \kappa_u |H_u|^2 + \kappa_d |H_d|^2 - \frac{1}{2}\left(H_u H_d - (H_u H_d)^\dagger\right)^2 + |X|^2, \\
W &= \lambda X H_u H_d,
\end{aligned}
$$

Singlet X is needed

$$
\begin{aligned}
\mathcal{L} &= \left(\kappa + 2^2 |\phi|^2\right) \partial^\mu \phi^\dagger \partial_\mu \phi - V(\phi), \\
V(\phi) &\approx e^{\kappa|\phi|^2} \lambda^2 |\phi|^4.
\end{aligned}
$$

$\lambda \sim 10^{-5}$ from COBE normalization


V
$\hat{\phi} \sim \sqrt{\kappa}\phi$
ϕ^4
ϕ^2
$\hat{\phi} \sim \phi^2$
canonically
norm. inflaton
$\hat{\phi}$
κ
1
κ^{-1}



Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
N= 50 60
λφ4
m2φ2
N-flation m2φ2
HZ
p=2
V
φ2
φ4
κ
1
κ-1
φ̂
φ̂ ~ √κ φ
φ̂ ~ φ2
canonically
norm. inflaton

- The form of the kinetic term depends on the discrete symmetry of the Higgs.

In NMSSM,

$$W = \lambda X H_u H_d + y\frac{X^3}{3},$$

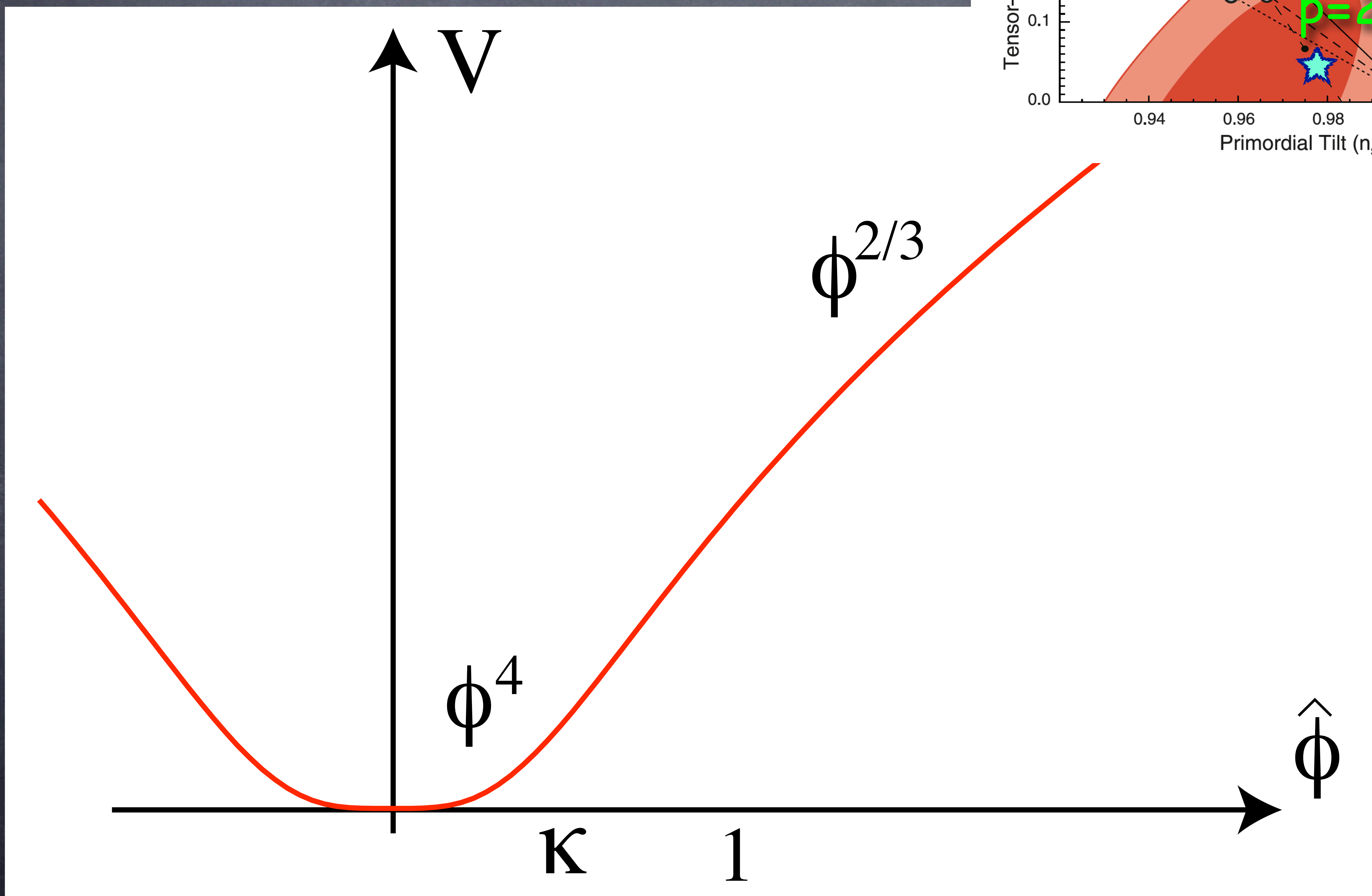
there is Z_3 symmetry. Then

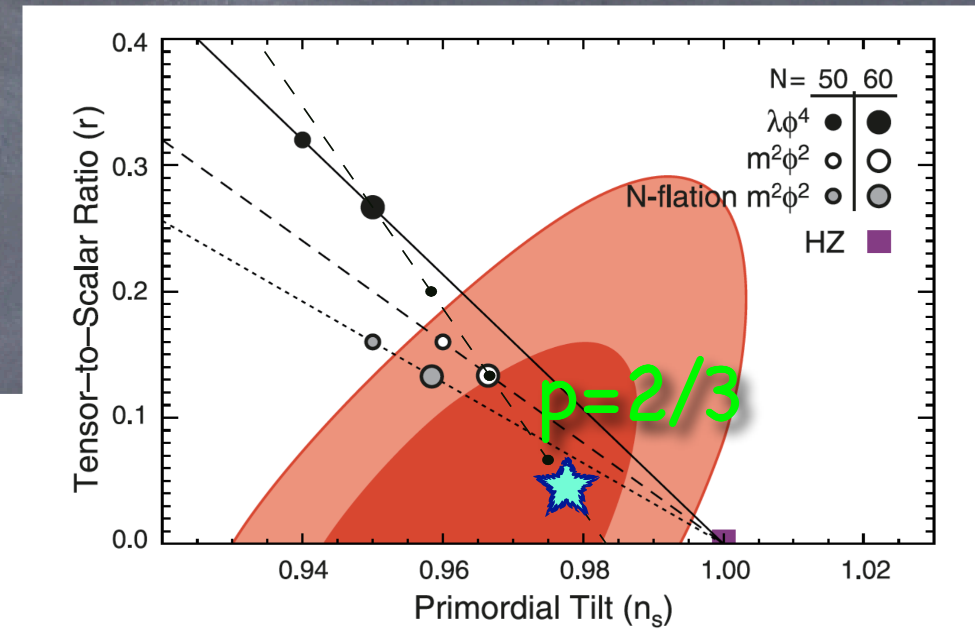
$$K = \kappa|\phi|^2 + c_1\left(\phi^6 - \phi^{\dagger 6}\right) - \frac{1}{2}(\phi^6 - \phi^{\dagger 6})^2 + \cdots,$$

$$\mathcal{L} = \left(\kappa + 6^2|\phi|^{10}\right)\partial^\mu\phi^\dagger\partial_\mu\phi - V(\phi),$$

$$V(\phi) \approx e^{\kappa|\phi|^2}\lambda^2|\phi|^4.$$

$\hat{\phi} \approx \phi^6$ is the canonically norm. field.


V
$\phi^{2/3}$
ϕ^4
κ
1
$\hat{\phi}$


Tensor-to-Scalar Ratio (r)
Primordial Tilt (n_s)
0.4
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1.00
1.02
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
HZ
p=2/3

General Analysis

Nakayama and FT, 1009.3399

$$-\frac{1}{3}\Omega = 1 - \frac{1}{3}\left(g(\phi,\bar{\phi}) + |X|^2 + \zeta|X|^4 + J(\phi) + \bar{J}(\bar{\phi})\right),$$
$$W = \lambda X \phi^m,$$

1. $g(\phi,\bar{\phi}) \gg |J(\phi)|,$
2. $g(\phi,\bar{\phi}) \ll |J(\phi)|,$
3. $g(\phi,\bar{\phi}) \sim |J(\phi)|,$

For simplicity we have taken

$$g(\phi,\bar{\phi}) \approx |\phi|^2 + a|\phi|^{2\ell},$$
$$J(\phi) \approx b\,\phi^n,$$

In the NM Higgs inflation,

$$J(\phi) = \xi\phi^2$$

General Analysis

Nakayama and FT, 1009.3399

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$$W = \lambda X \phi^m,$$

No inflation

1. $g(\phi,\bar\phi) \gg |J(\phi)|,$
2. $g(\phi,\bar\phi) \ll |J(\phi)|,$
3. $g(\phi,\bar\phi) \sim |J(\phi)|,$

For simplicity we have taken

$$g(\phi,\bar\phi) \approx |\phi|^2 + a|\phi|^{2\ell},$$
$$J(\phi) \approx b\,\phi^n,$$

In the NM Higgs inflation,

$$J(\phi) = \xi\phi^2$$

General Analysis

Nakayama and FT, 1009.3399

$$-\frac{1}{3}\Omega = 1 - \frac{1}{3}\left(g(\phi,\bar{\phi}) + |X|^2 + \zeta|X|^4 + J(\phi) + \bar{J}(\bar{\phi})\right),$$
$$W = \lambda X \phi^m,$$

1. $g(\phi,\bar{\phi}) \gg |J(\phi)|,$
2. $g(\phi,\bar{\phi}) \ll |J(\phi)|,$
3. $g(\phi,\bar{\phi}) \sim |J(\phi)|,$

No inflation

Higgs inflation w/ non-min. coupling or power-law inf.

For simplicity we have taken

$$g(\phi,\bar{\phi}) \approx |\phi|^2 + a|\phi|^{2\ell},$$
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In the NM Higgs inflation,

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2010年9月29日水曜日

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2. $g(\phi,\bar{\phi}) \ll |J(\phi)|,$ — Higgs inflation w/ non-min. coupling or power-law inf.
3. $g(\phi,\bar{\phi}) \sim |J(\phi)|,$ — RK inflation!

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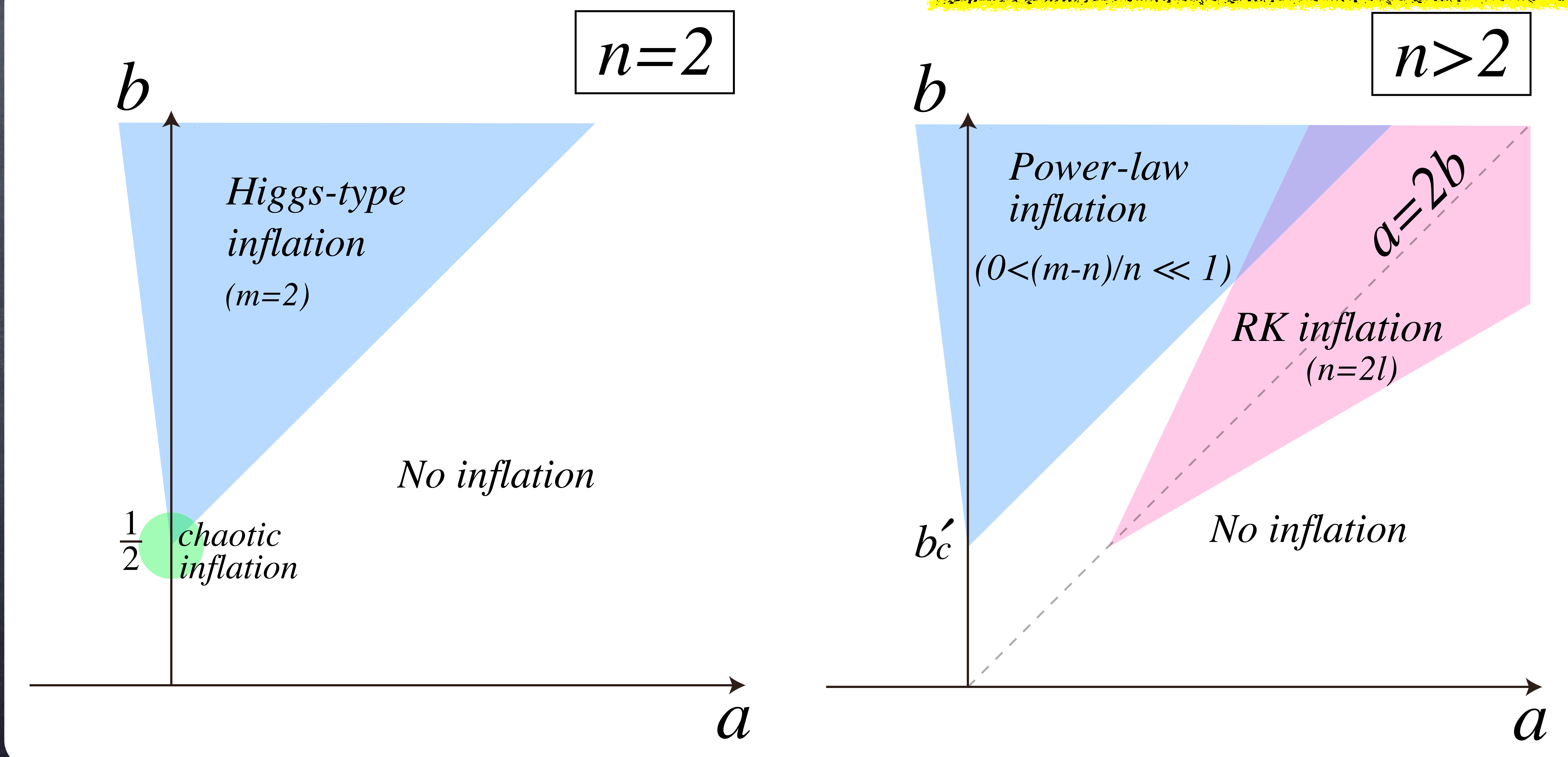

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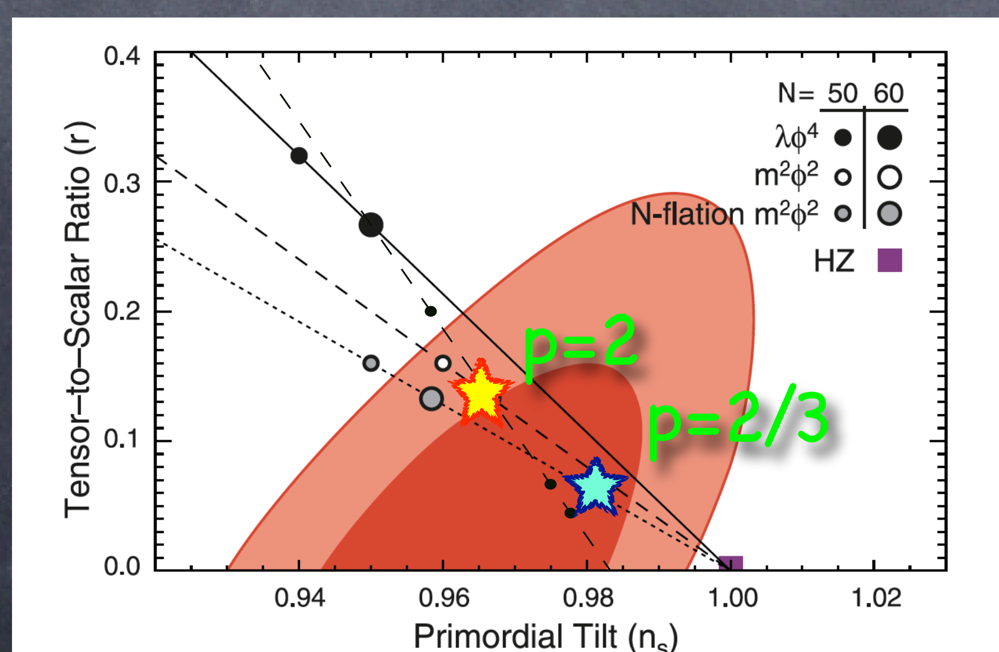


Back-up slides

The inflaton potential

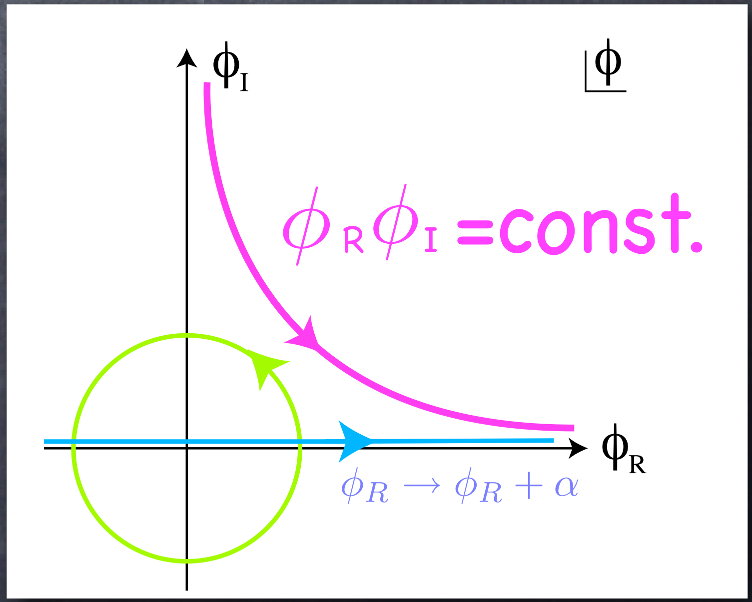
- X is stabilized at the origin during and after inflation.

$$V \approx \frac{1}{2} e^{\frac{\kappa}{2}(\phi_R^2+\phi_I^2)-4c\phi_R\phi_I+2\phi_R^2\phi_I^2} m^2 \left(\phi_R^2+\phi_I^2\right).$$

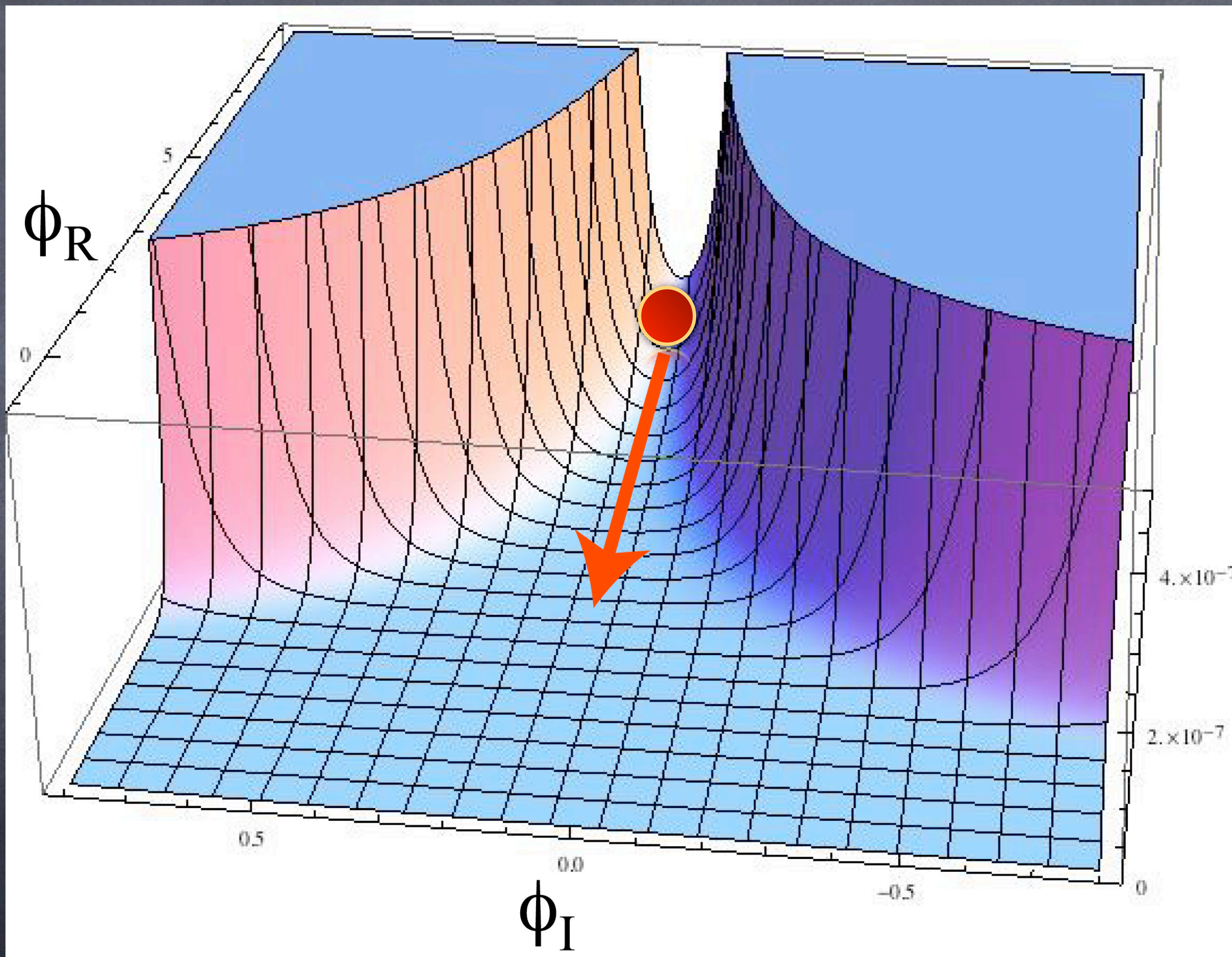
- ϕ_I is stabilized at $\phi_I \approx \frac{c}{\phi_R}.$ during inflation.

$$\mathcal{L} \approx \frac{1}{2}\phi_R^2(\partial\phi_R)^2 - \frac{1}{2}m^2\phi_R^2,$$

for ϕ_R >> 1.



The bird's-eye view of the inflaton potential



4.1 Solution to the non-thermal gravitino problem

Gravitino Pair-Production

Kawasaki, F.T. and Yanagida, hep-ph/0603265, 0605297
Asaka, Nakamura and Yamaguchi, hep-ph/0604132
Endo, Hamaguchi and F.T., hep-ph/0602061
Nakamura and Yamaguchi, hep-ph/0602081

- Relevant interactions:

$$e^{-1}\mathcal{L} = -\frac{1}{8}\epsilon^{\mu\nu\rho\sigma}\left(G_\phi \partial_\rho \hat{\phi} + G_z \partial_\rho z - \text{h.c.}\right)\bar{\psi}_\mu \gamma_\nu \psi_\sigma$$

$$-\frac{1}{8} e^{G/2}\left(G_\phi \hat{\phi} + G_z z + \text{h.c.}\right)\bar{\psi}_\mu \left[\gamma^\mu, \gamma^\nu\right]\psi_\nu,$$

ϕ : inflaton field

$$G \equiv K + \ln|W|^2$$

z : SUSY breaking field, w/ $G^z G_z \simeq 3$

Taking account of the mixings,

$$G_\phi \sim \langle\phi\rangle \frac{m_{3/2}}{m_\phi} \quad \text{for} \quad m_\phi < m_z$$

Gravitino Pair Production Rate:

$$\Gamma_{3/2} \simeq \frac{|G_\phi|^2}{288\pi} \frac{m_\phi^5}{m_{3/2}^2 M_P^2} \simeq \frac{1}{32\pi} \left(\frac{\langle \phi \rangle}{M_P} \right)^2 \frac{m_\phi^3}{M_P^2}$$

Endo, Hamaguchi and F.T., hep-ph/0602061
Nakamura and Yamaguchi, hep-ph/0602081

for $m_\phi < m_z$

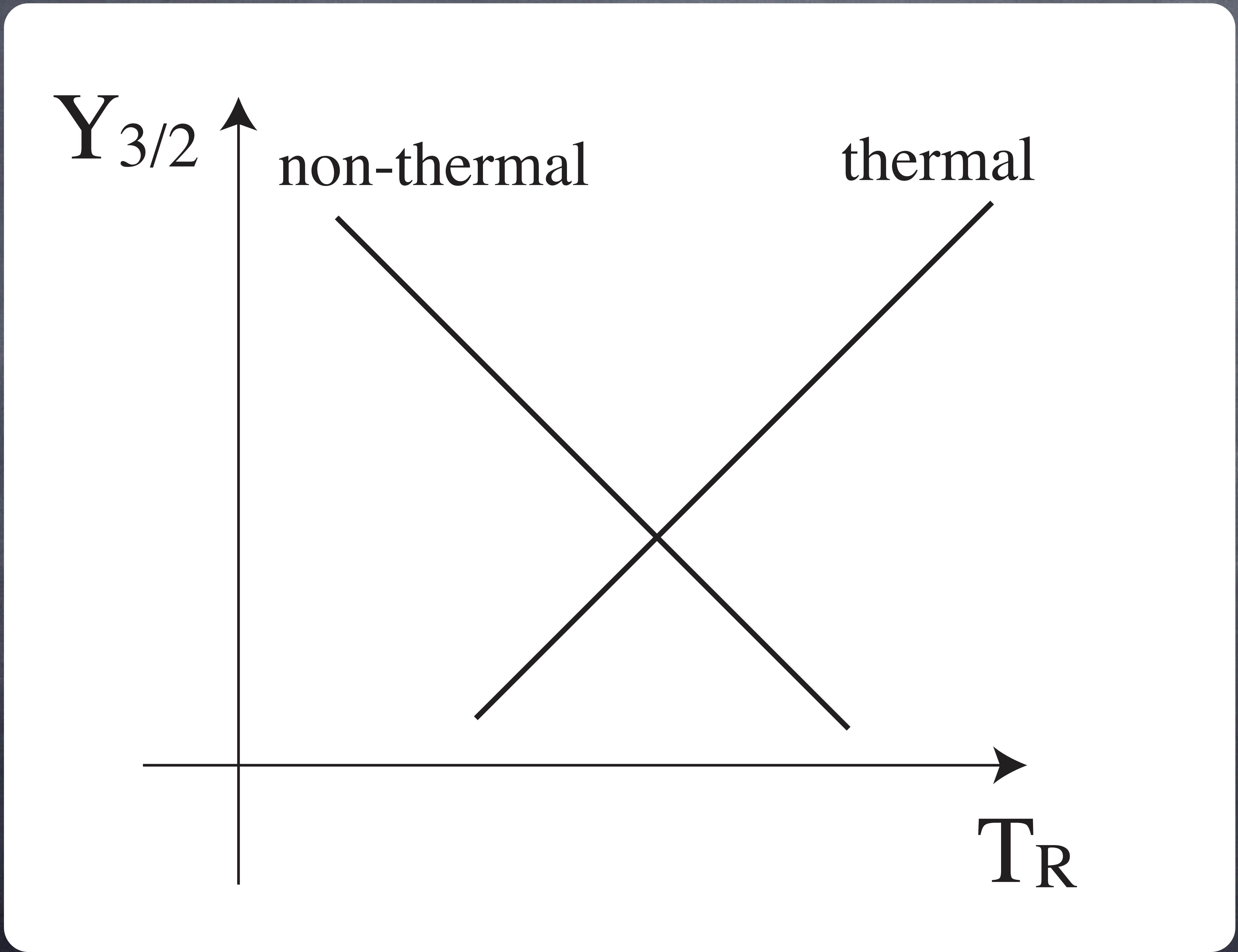
- Gravitino pair production is effective especially for low-scale inflation models.
- Gravitino abundance is inversely proportional to the reheating temperature!

- Gravitino Abundance:

$$
\begin{aligned}
Y_{3/2} &\simeq 2\,\frac{\Gamma_{3/2}}{\Gamma_{\rm total}}\frac{3}{4}\frac{T_R}{m_\phi}, \\
&\sim 10^{-14}\left(\frac{g_*}{200}\right)^{-\frac{1}{2}}\left(\frac{T_R}{10^6\,{\rm GeV}}\right)^{-1} \\
&\quad\times\left(\frac{\langle\phi\rangle}{10^{15}\,{\rm GeV}}\right)^2\left(\frac{m_\phi}{10^{10}\,{\rm GeV}}\right)^2
\end{aligned}
$$

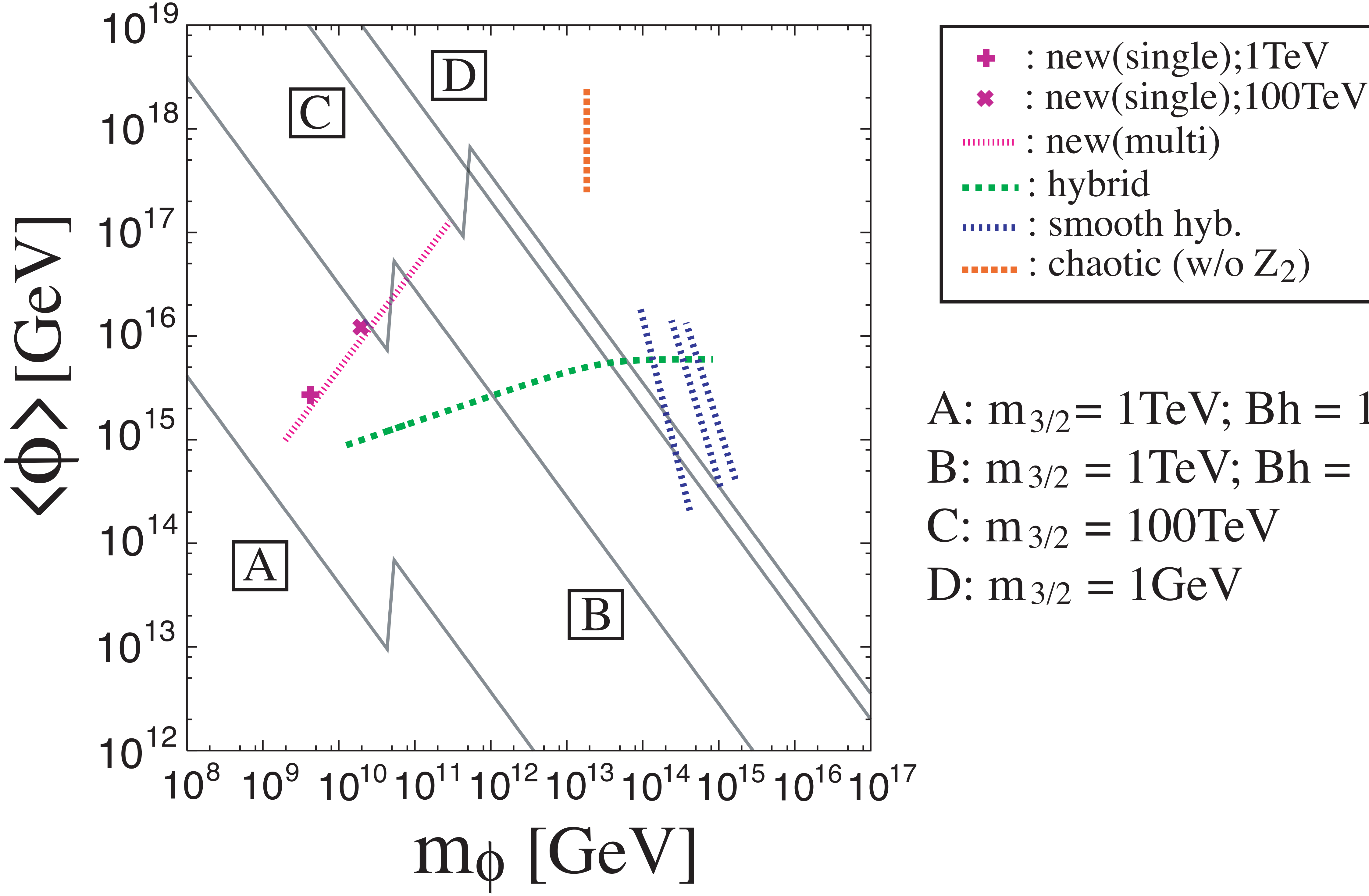
Note: $\Gamma_{\rm total} \sim \frac{T_R^2}{M_P}$

Gravitino Abundance



Conservative

Constraints on the inflation models;



A: $m_{3/2}$ = 1TeV; Bh = 1

B: $m_{3/2}$ = 1TeV; Bh = 10^{-3}

C: $m_{3/2}$ = 100TeV

D: $m_{3/2}$ = 1GeV

Inflatino dark matter

Nakayama and FT,1008.2956

The inflaton is massless in the SUSY limit, if $m \geq 2$.

$$m_\phi = O(m_{3/2})$$

For successful reheating, the inflaton should have unsuppressed couplings with the SM sector.

$$\int d^2\theta \, \lambda_\phi \phi H_u H_d$$

The set-up resembles nMSSM, where the singlino becomes DM. The discrete Z_{nR} symmetry in nMSSM can be consistent with the shift symmetry;

$$\phi^n \to \phi^n + \alpha$$

Reheating of RK inflation

- Preheating depends on the global shape of the potential and the interactions.
- Generically, for the preheating to proceed efficiently,

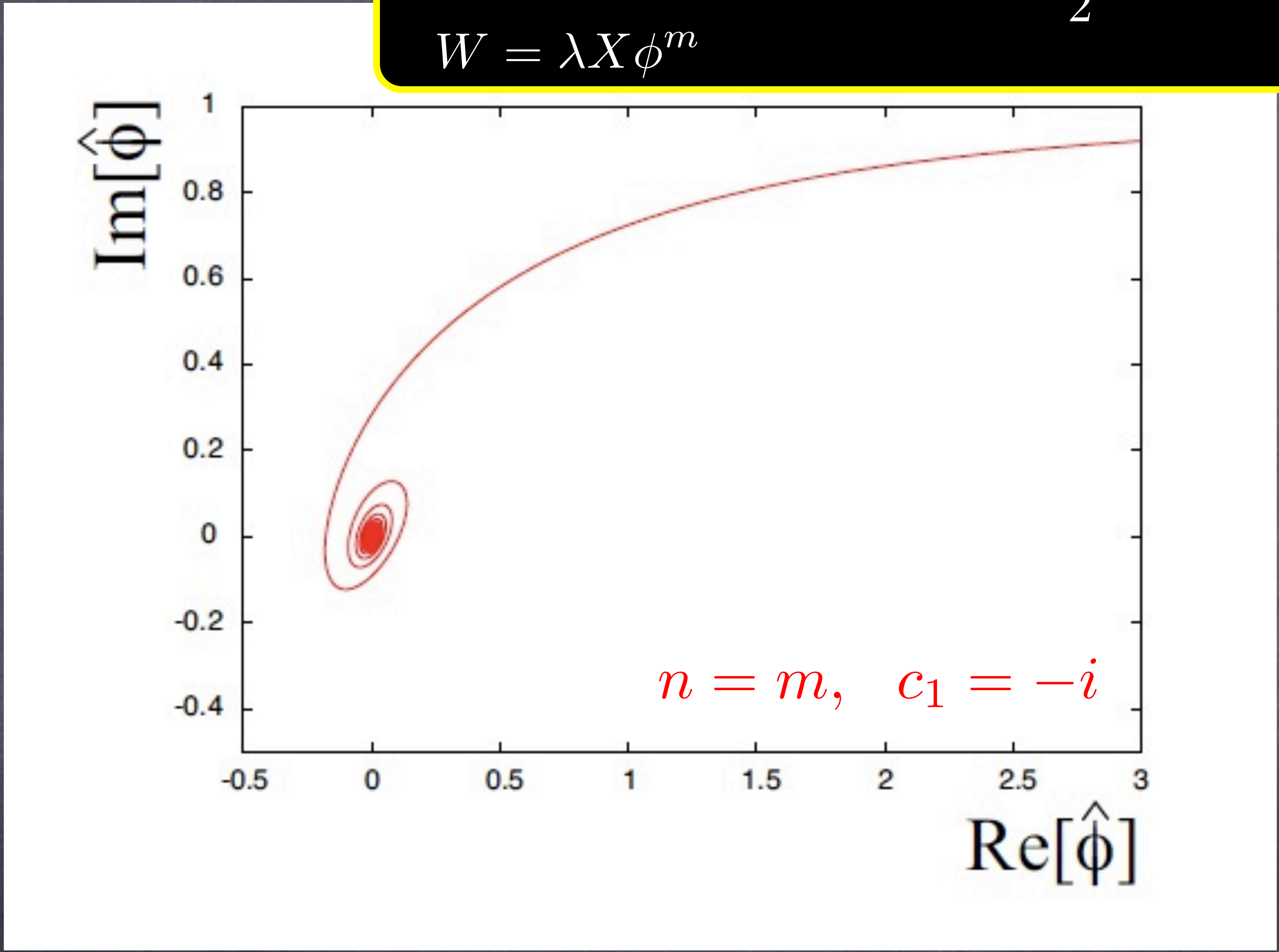
(1) the inflaton should pass near the origin

(2) the back reaction should not be important.

The second requirement is likely satisfied if the produced particles decay soon, as in the instant preheating. Otherwise, the preheating will stop to proceed, and in general it is difficult to follow the evolution until thermalization.

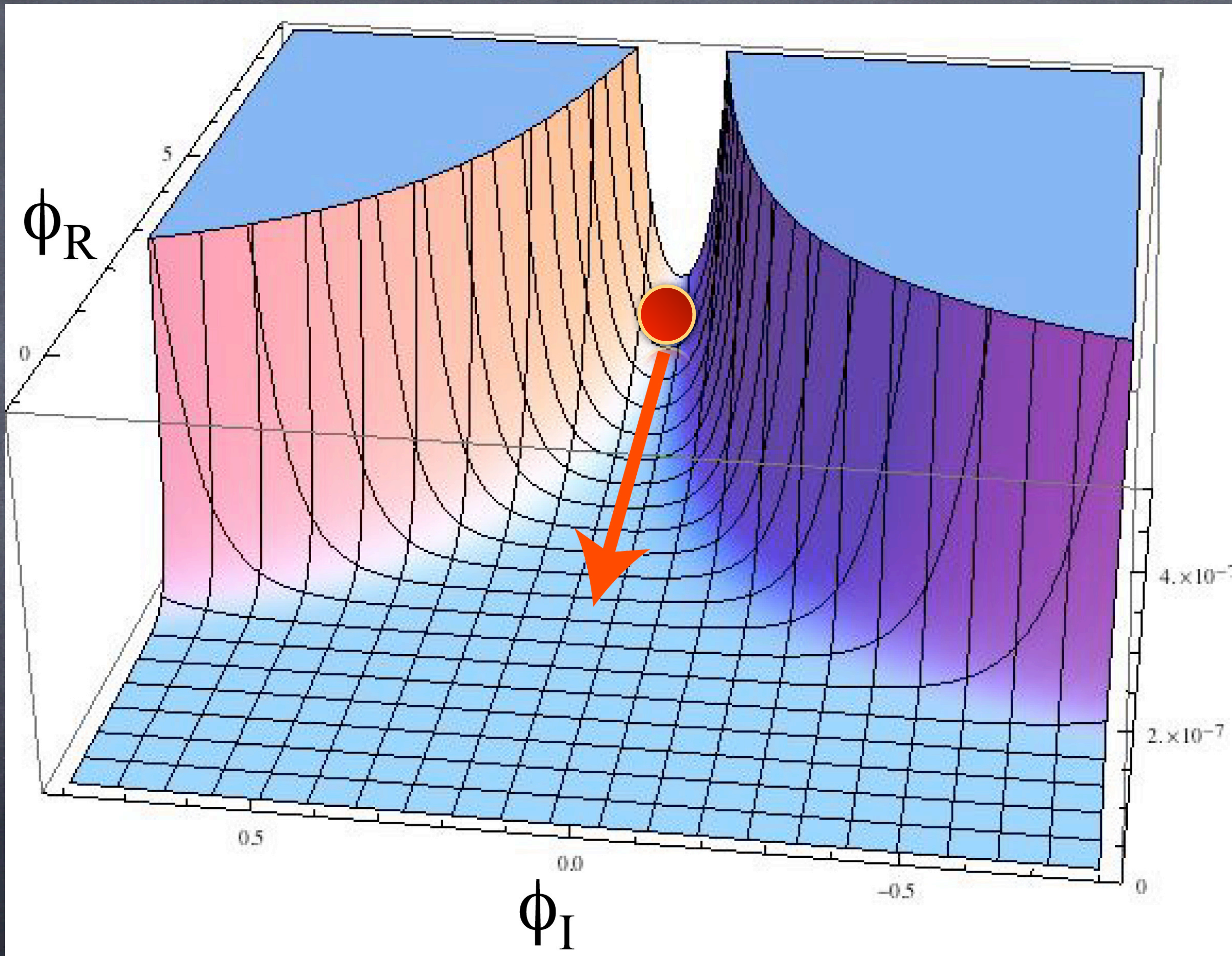
See Garcia-Bellido et al 0812.4624 and Bezrukov et al 0812.3622 for the preheating of the SM Higgs inflation.

$$K = \kappa|\phi|^2 + c_1(\phi^n - \phi^{\dagger n}) - \frac{1}{2}(\phi^n - \phi^{\dagger n})^2 + \cdots$$
$$W = \lambda X \phi^m$$



Preheating can be suppressed if the inflaton does not pass near the origin. This depends on the symmetry.

The bird's-eye view of the inflaton potential



Symmetry or tuning?

- A large coefficient of the kinetic term is advantageous for the inflation to occur.

$$\mathcal{L}_K = \frac{A}{2}(\partial\phi)^2$$

- In the limit of large coefficient, an approximate shift symmetry appears. Dimopoulos, Thomas, hep-th/0307004

In supergravity,

$$K(x,y) = Ax^2 + y^2 \quad \text{with} \quad A \gg 1 \qquad \phi = x + iy$$

results in an approximate shift sym. along y direction

Izawa and Shinbara 0710.1141

- The RK inflation appears if

$$K = x^2 + y^2 + Ax^2y^2 + \cdots \qquad A \gg 1$$

The coefficient of the kinetic term is

$$K_{\phi\bar{\phi}} = \frac{1}{4}(K_{xx} + K_{yy}) = 1 + \frac{A}{2}(x^2 + y^2) \simeq \frac{A}{2}|\phi|^2$$

Note that the inflation takes place with sub-Planckian value of ϕ in the original frame.

Higgs inflation with non-minimal coupling

After the Weyl transformation,

$$g^{(E)}_{\mu\mu} = \Omega^2 g_{\mu\nu} \qquad\qquad \Omega^2 = 1 + \xi \frac{h^2}{M_P^2}$$

the potential becomes very flat in the Einstein frame,

$$U(\chi) \approx \frac{\lambda M_P^4}{4\xi^2}\left(1 + \{\exp\left(-\frac{2\chi}{\sqrt{6}\mathrm{M_P}}\right)\right)^{-2}$$

for $\chi > \sqrt{6}M_P$

with $h \simeq \frac{M_P}{\sqrt{\xi}} \exp\left(\frac{\chi}{\sqrt{6}M_P}\right)$.

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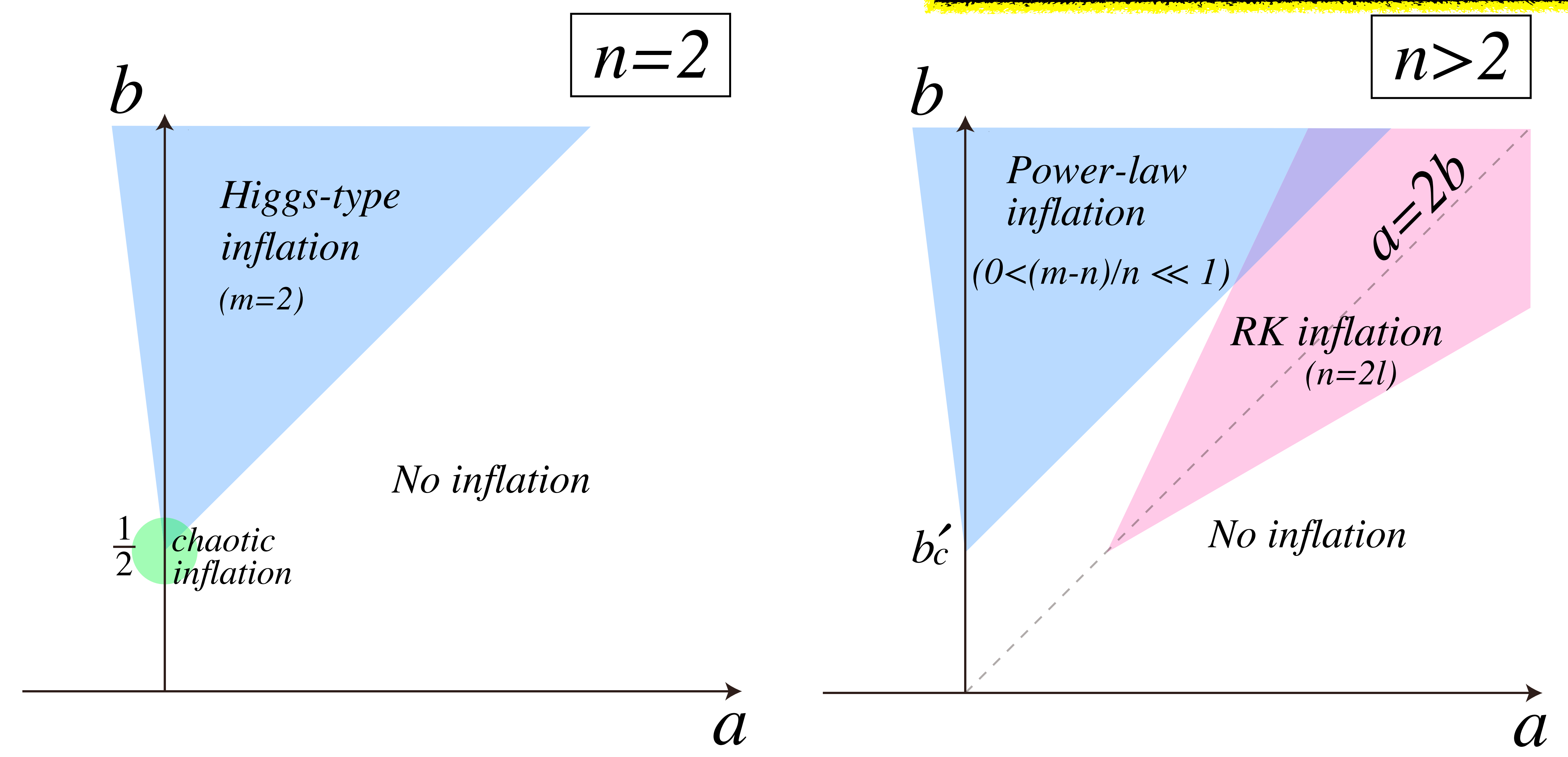

$$\Omega^2 = 1 - \frac{1}{3}\left(|\phi|^2 + b\phi^n + b\phi^{\dagger n}\right).$$

$$V(\phi,\phi^\dagger) = \frac{\lambda^2|\phi|^{2m}}{\Omega^4},$$

$$W = \lambda X \phi^m,$$

For $\varphi \gg b^{-1/(n-2)}$

$$\mathcal{L} \approx \frac{3n^2}{4}\varphi^{-2}\partial\varphi^2 - \frac{9\lambda^2}{4b^2}\varphi^{2(m-n)}\left(1 - \frac{1}{2b}\varphi^{2-n} + \frac{3}{2b}\varphi^{-n}\right)^{-2}.$$

where we defined $\alpha \equiv \sqrt{2/3}$. As we have mentioned, the potential V exhibits runaway behavior for $m < n$ as well as $m = n \geq 3$, while the potential is an exponentially growing function for $m > n$. If $m = n = 2$, the scalar potential asymptotically approaches a constant value and the tilt of the potential is exponentially suppressed. The last case corresponds to