Ratchet baryogenesis during reheating

Kimiko Yamashita (Ochanomizu Univ.)

Collaborators:
Kazuharu Bamba (Fukushima Univ.)
Akio Sugamoto (Ochanomizu Univ.)
Tatsu Takeuchi (Virginia Tech.)

SUSY 2015
Aug. 23rd-29th, 2015
Lake Tahoe, California

Table of contents

Motivation (1/4)

The aim of our research is ･･･

Proposing a new mechanism for baryogenesis

Baryogenesis during reheating after inflation

Motivation (2/4)

- Baryon asymmetry (1/2)
  - Baryon number and anti-baryon number are NOT equal
    - Cosmic rays
    - Absence of strong γ-ray emission
    - Anisotropy of the Cosmic Microwave Background
    - Big-Bang Nucleosynthesis

Motivation (3/4)

- Baryon asymmetry (2/2)
  - Baryon-to-photon ratio:

K. A. Olive *et al*. [Particle Data Group Collaboration], Chin. Phys. C 38, 090001 (2014)

$$\eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \sim 6.05(7) \times 10^{-10} \text{ (CMB)}$$

Nonzero

Motivation (4/4)

A. D. Sakharov, JETP Lett. 5, 24(1967)

- Sakharov’s conditions :
  1. B violation
  2. C and CP violation
  3. Out of thermal equilibrium

Model (1/6)

Action

Complex scalar carrying the baryon number

$$S = \int dx^4 \sqrt{-g} \left[g^{\mu\nu}\partial_\mu \phi \partial_\nu \phi^* - V_0(\phi, \phi^*) \right.$$

$$\left. + \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi \partial_\nu \Phi - U(\Phi) - \frac{i}{\Lambda} g^{\mu\nu} \left(\phi \overleftrightarrow{\partial_\mu} \phi^* \right) \partial_\nu \Phi \right]$$

Inflaton or scalaron

Real scalar

Derivative coupling

Model (2/6)

If Lagrangian has global U(1) symmetry,

U(1) charge: baryon number

$$(\phi, \phi^*) \to (e^{i\alpha}\phi, e^{-i\alpha}\phi^*)$$

$$\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$$

$$\theta(t, \vec{x}) \to \theta(t, \vec{x}) + \alpha$$

there is baryon conservation law:

Noether current: $j^\mu = i\phi \overleftrightarrow{\partial^\mu} \phi^*$

Baryon density: $n_b = j^0 = \phi_r^2 \dot{\theta}$

Model (3/6)

Transformation

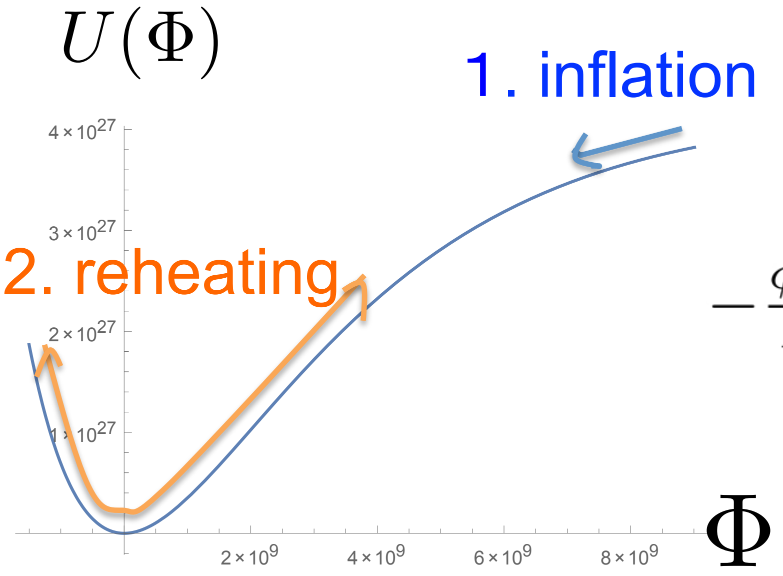
$$\phi = \frac{1}{\sqrt{2}}\phi_r e^{i\theta}$$

B: $\theta(t,\vec{x}) \to \theta(t,\vec{x}) + \alpha$

C: $\theta(t,\vec{x}) \to -\theta(t,\vec{x})$

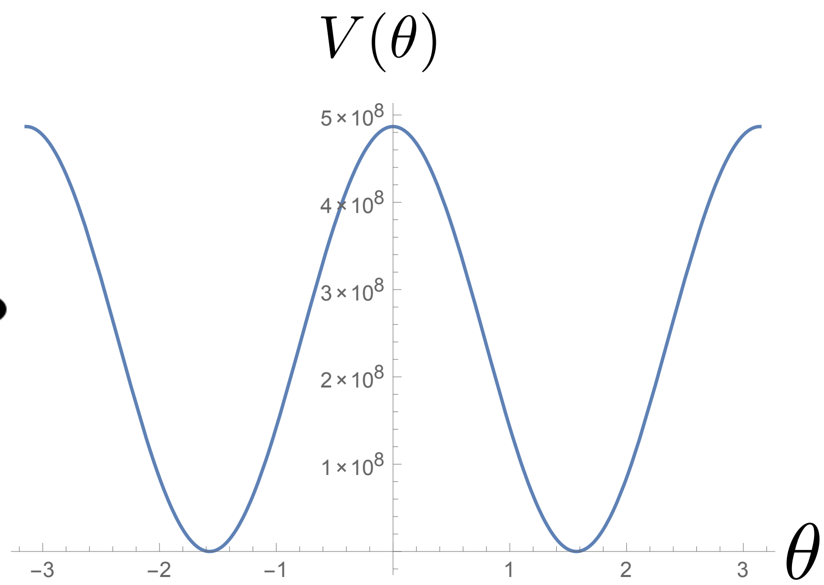
CP: $\theta(t,\vec{x}) \to -\theta(t,-\vec{x})$

Model (4/6)



$$-\frac{\phi_r^2}{\Lambda}\partial_\mu\theta\partial^\mu\Phi$$

~~C~~, C~~P~~



~~thermal equilibrium~~

~~B~~

$$U(\Phi) = \frac{3\mu^2\overline{M}_{Pl}^2}{4}\left(1 - e^{-\sqrt{2/3}\Phi/\overline{M}_{Pl}}\right)^2$$

Starobinsky (1980), Magnano, *et al.*(1987)

$$V(\theta) = \lambda\phi_r^4\cos^2\theta$$

Model (5/6)

	B Violation	C Violation	CP Violation	Out of Thermal Equilibrium
Inflaton Potential	✖	✖	✖	◯
Scalar Baryon Potential	◯	✖	✖	✖
Derivative Coupling	✖	◯	◯	MEDIATOR

Model (6/6)

- Baryon density

$$n_b = \phi_r^2 \dot{\theta}$$: From Noether current

$$\sim 4.4 \times 10^{-10} T_{reh}^3$$: From observation and calculation

$$T_{reh} = 10^9 \text{ GeV}$$
$$\phi_r = 10^3 \text{ GeV}$$

Phase velocity of scalar baryon

$$\dot{\theta} = 440 \times T_{reh} \times b$$

Associated mechanism (1/3)

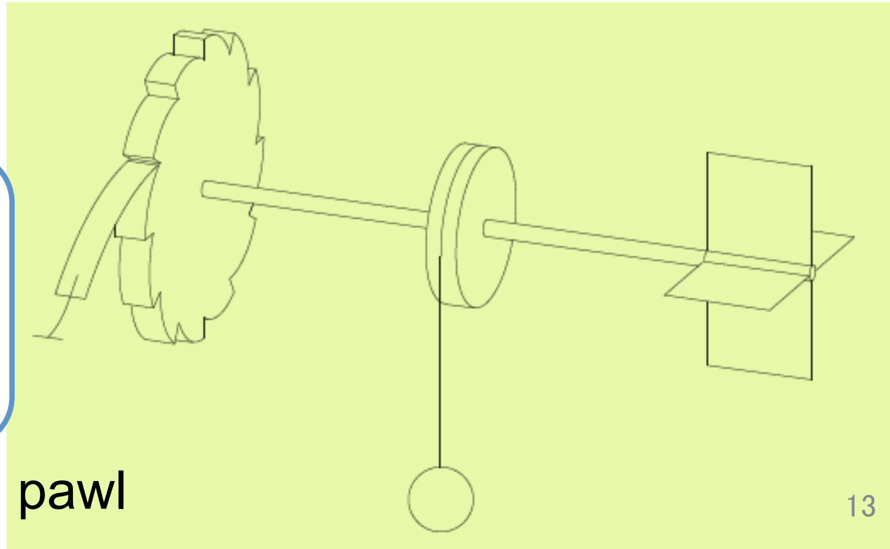
P. Reimann, Phys. Rep. 361, 57(2002)

- Ratchet mechanism :
  - Generate directed motion

    spatially periodic system is in focus

1. Thermal noise
2. Perturbation with breaking of the spatial inversion

1) Random force from molecular
2) With the pawl and “ratchet”, this gear moves the forward direction.



Ratchet and pawl

Associated mechanism (2/3)

P. Reimann, Phys. Rep. 361, 57(2002)

2. Perturbation with breaking of the spatial inversion

   a. Periodic and asymmetric potential

$$V(x) \neq V(-x+C)$$

For baryogenesysis:

Takeuchi, Minamizaki and Sugamoto, arXiv: 1008.4515 (2010)
Bamba, Takeuchi, Minamizaki, Sugamoto and KY, in preparation

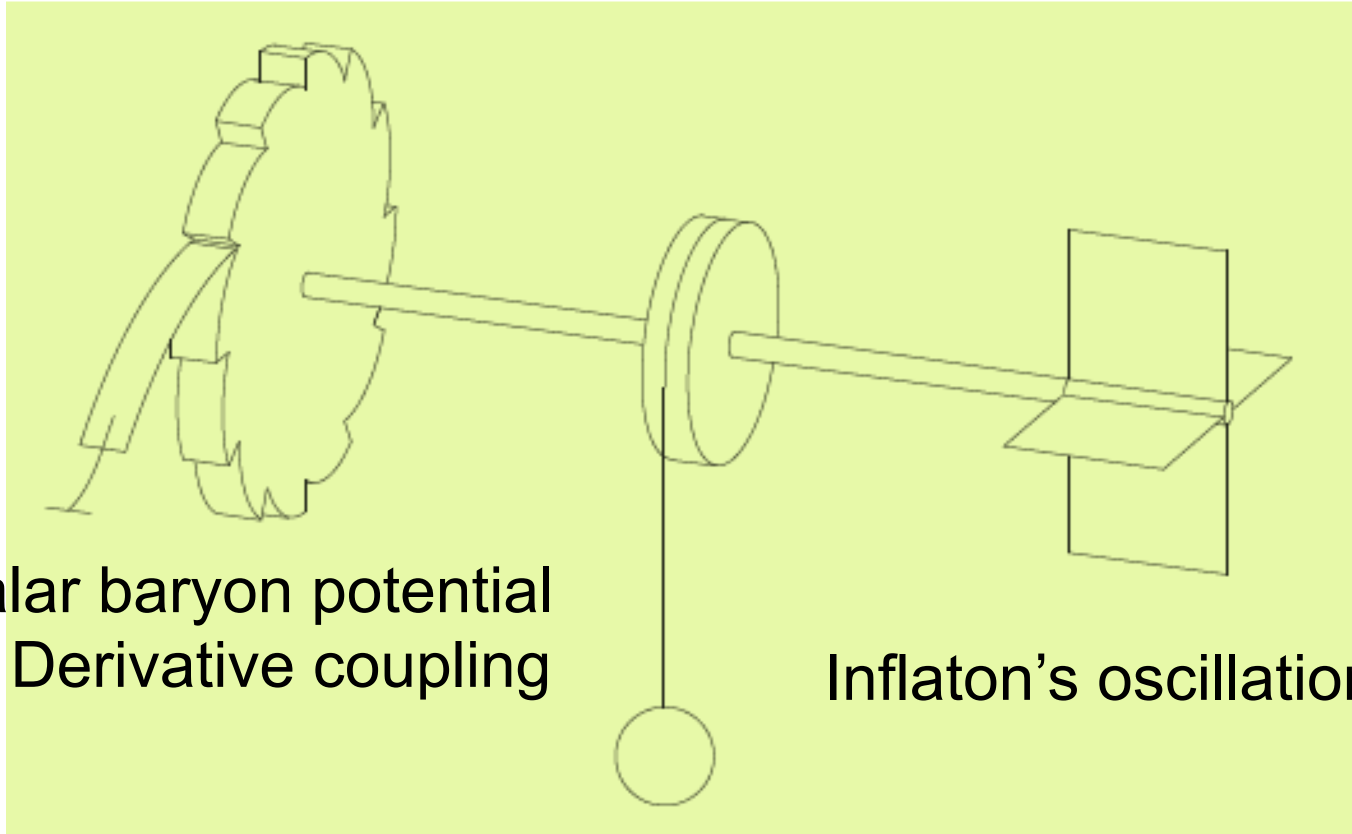
OR

   b. Spatial asymmetry of the dynamics

For baryogenesys: This talk

$$-\frac{\phi_r^2}{\Lambda}\partial_\mu \theta \partial^\mu \Phi$$

Associated mechanism (3/3)



Calculation (1/2)

Euler-Lagrange equations:

$$\ddot{\Phi} + 3H\dot{\Phi} + \eta\dot{\Phi} + U'(\Phi) - \frac{\phi_r^2}{\Lambda}(\ddot{\theta} + 3H\dot{\theta}) = 0$$

$$\ddot{\theta} + 3H\dot{\theta} - \lambda\phi_r^4 \cos\theta \sin\theta - \frac{\phi_r^2}{\Lambda}(\ddot{\Phi} + 3H\dot{\Phi}) = 0$$

$$U(\Phi) = \frac{3\mu^2 \overline{M}_{Pl}^2}{4}\left(1 - e^{-\sqrt{2/3}\Phi/\overline{M}_{Pl}}\right)^2$$

Calculation (2/2)

Parameter order

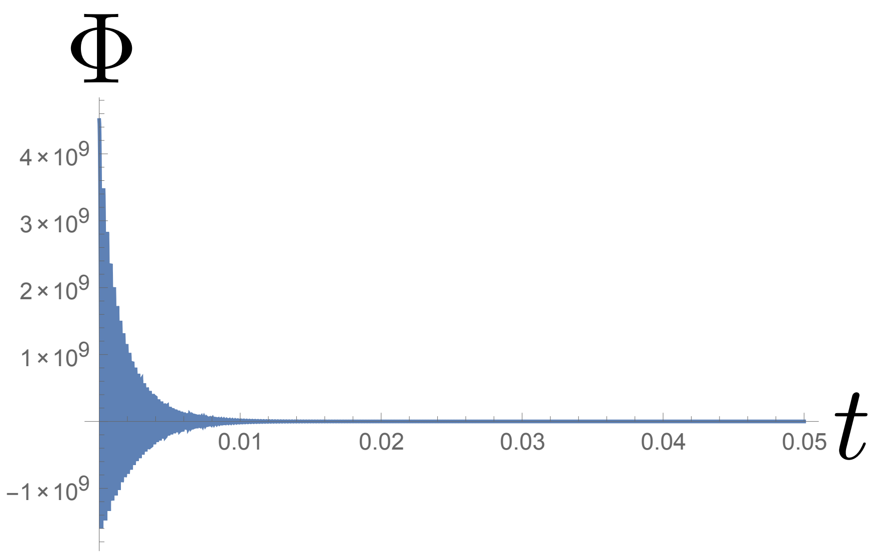
T_{reh}	10^9 GeV	Reheating temperature
H_R	$23 \cdot T^2_{reh} / \overline{M}_{Pl}$	Hubble parameter
μ	$1.3 \cdot 10^{-5} \cdot \overline{M}_{Pl}$	Potential for inflaton*
$\Phi(0)$	$1.9 \cdot \overline{M}_{Pl}$	Initial value of inflaton**
ϕ_r	10^3 GeV	Radius of baryon scalar
λ	$U(T_{reh})/\phi_r^{\,4}$	Potential for scalar baryon
$1/\Lambda$	$1/\overline{M}_{Pl}$	Derivative coupling
η	$1000 \cdot T_{reh}$	Friction for inflaton
Δt_B	$1/(20 \cdot T_{reh})$	Reheating time

$$^{*}U(\Phi) = \frac{3\mu^2 \overline{M}_{Pl}^2}{4}\left(1 - e^{-\sqrt{2/3}\Phi/\overline{M}_{Pl}}\right)^2$$

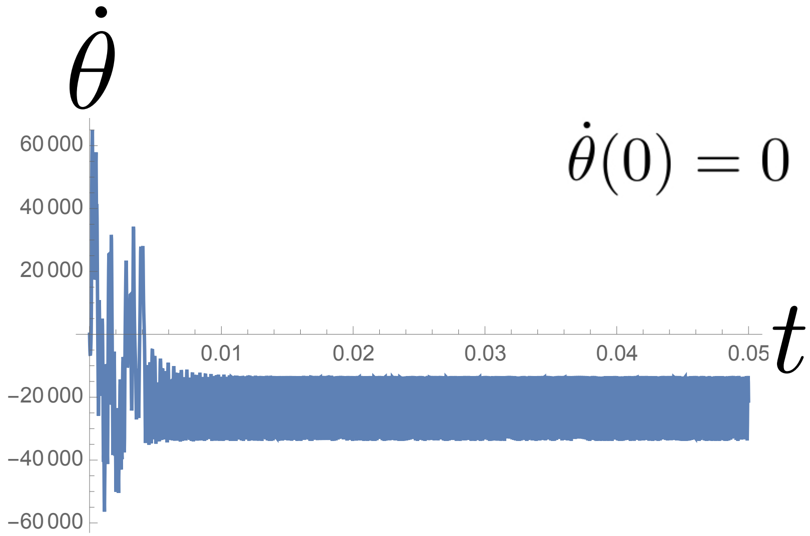
**end of inflation Gorbunov, Tokareva(2013)

Result (1/4)

▪ Inflaton



▪ Phase velocity of scalar baryon

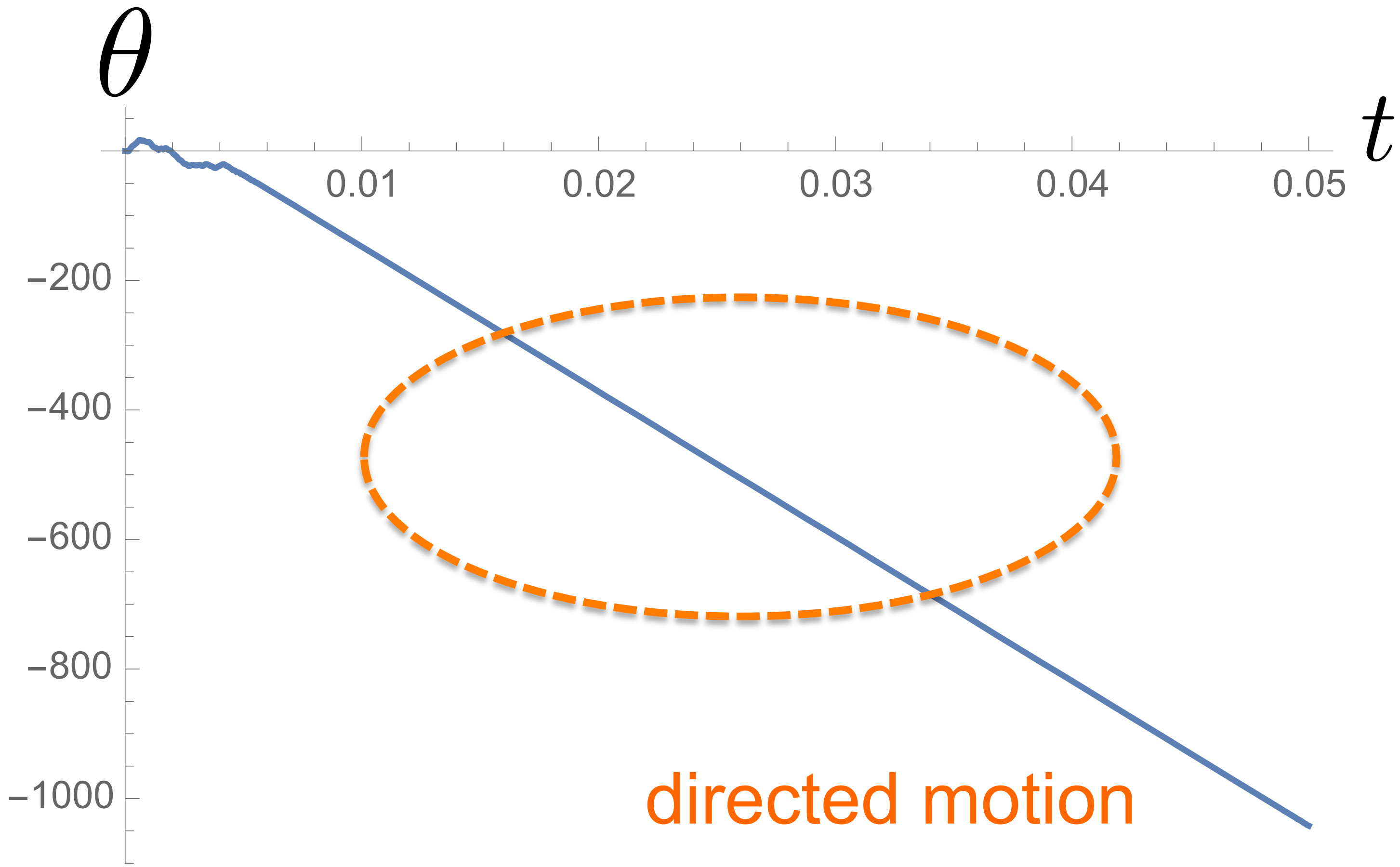


Non zero value

$$n_b = \phi_r^2 \dot{\theta}$$

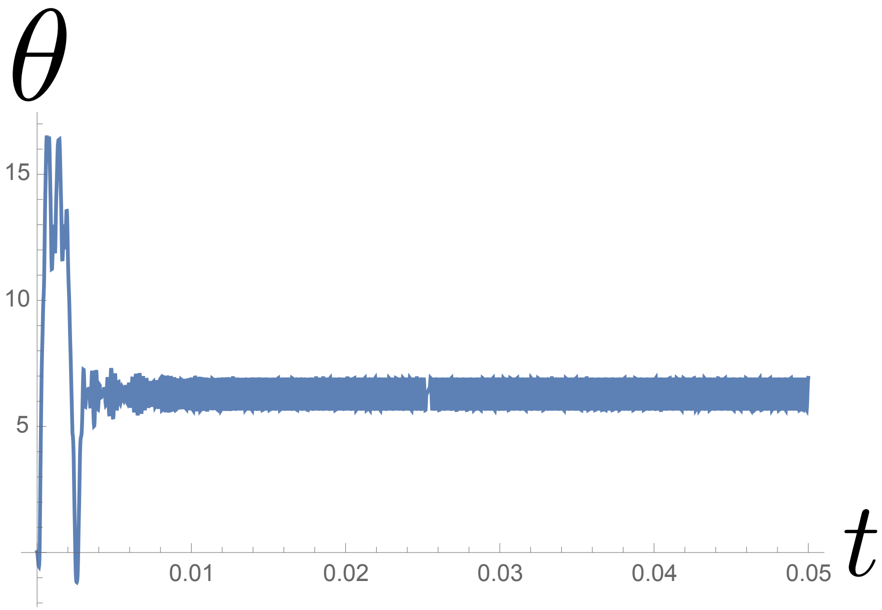
Result (2/4)

- Phase of scalar baryon

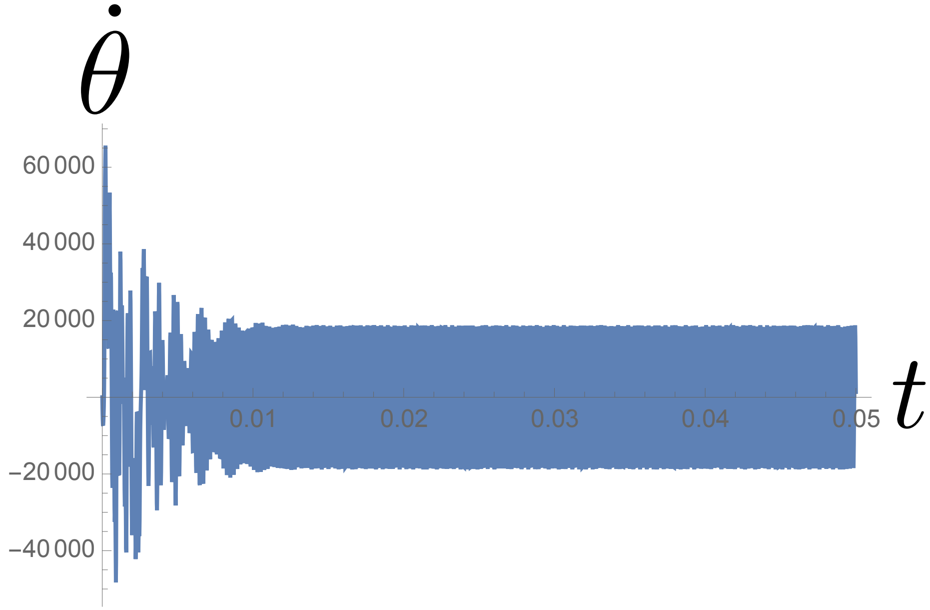


Result (3/4)

▪Phase of scalar baryon



▪Phase velocity of scalar baryon



Result (4/4)

1. Put initial value θ(0) at equal intervals
2. Take an average over initial value θ(0)

Number of division	10	20	50	100
$\bar{b}$	-16	-15	2.8	-0.39
Number of division	150	200	250	300
$\bar{b}$	5.8	5.6	6.5	5.5

$6 \cdot 10^{-10} \cdot 5.5$

$$\dot{\theta} = 440 \times T_{reh} \times b$$

Summary

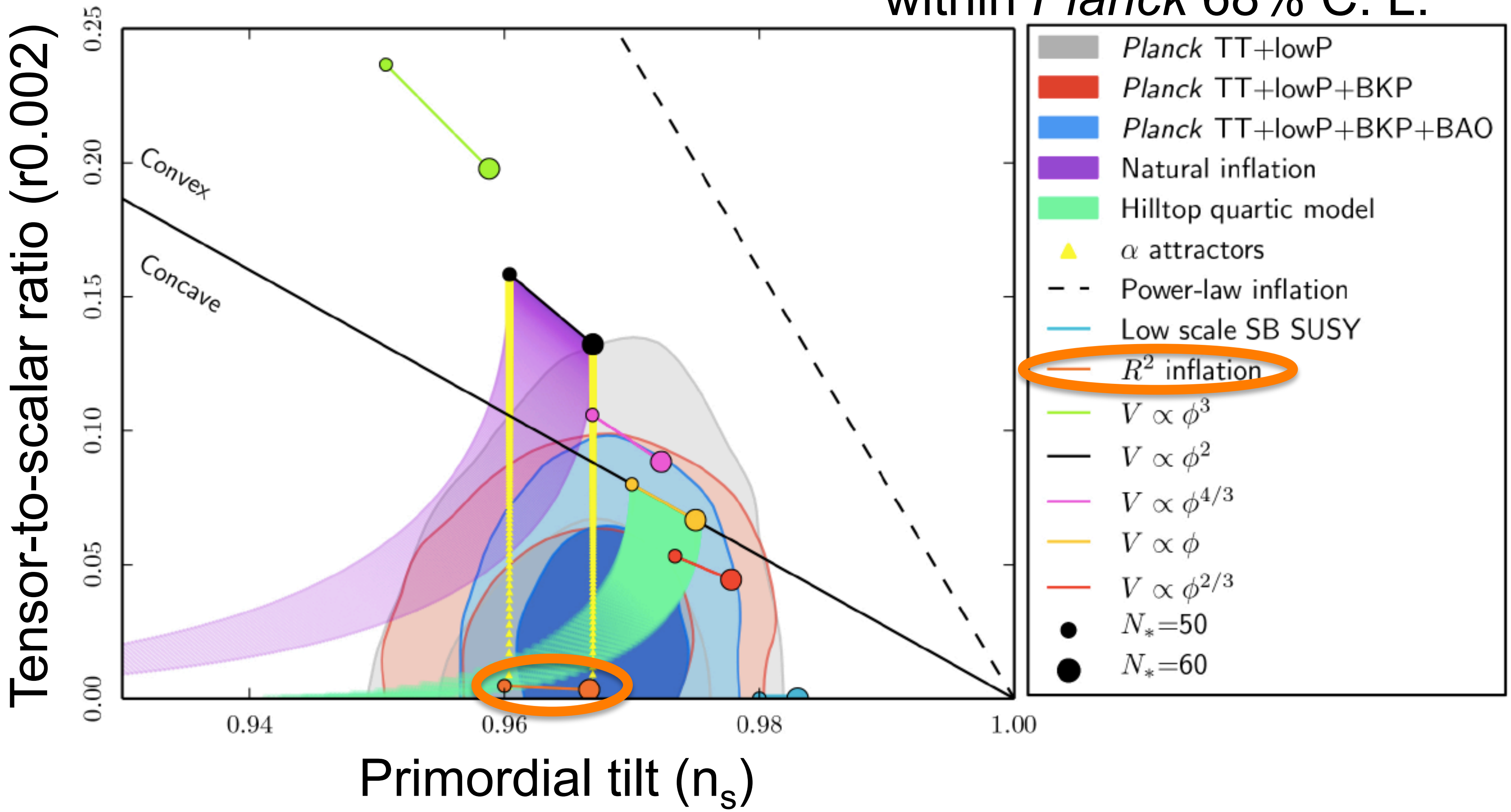
1. Baryogenesis model
   during reheating is proposed

2. Feasibility of baryongenesis has been
   discussed with our model
   Using inflaton potential of
   Starobinsky model :within Planck 68% C. L.
   → baryon-to-photon ratio
   compatible with observations

Backup

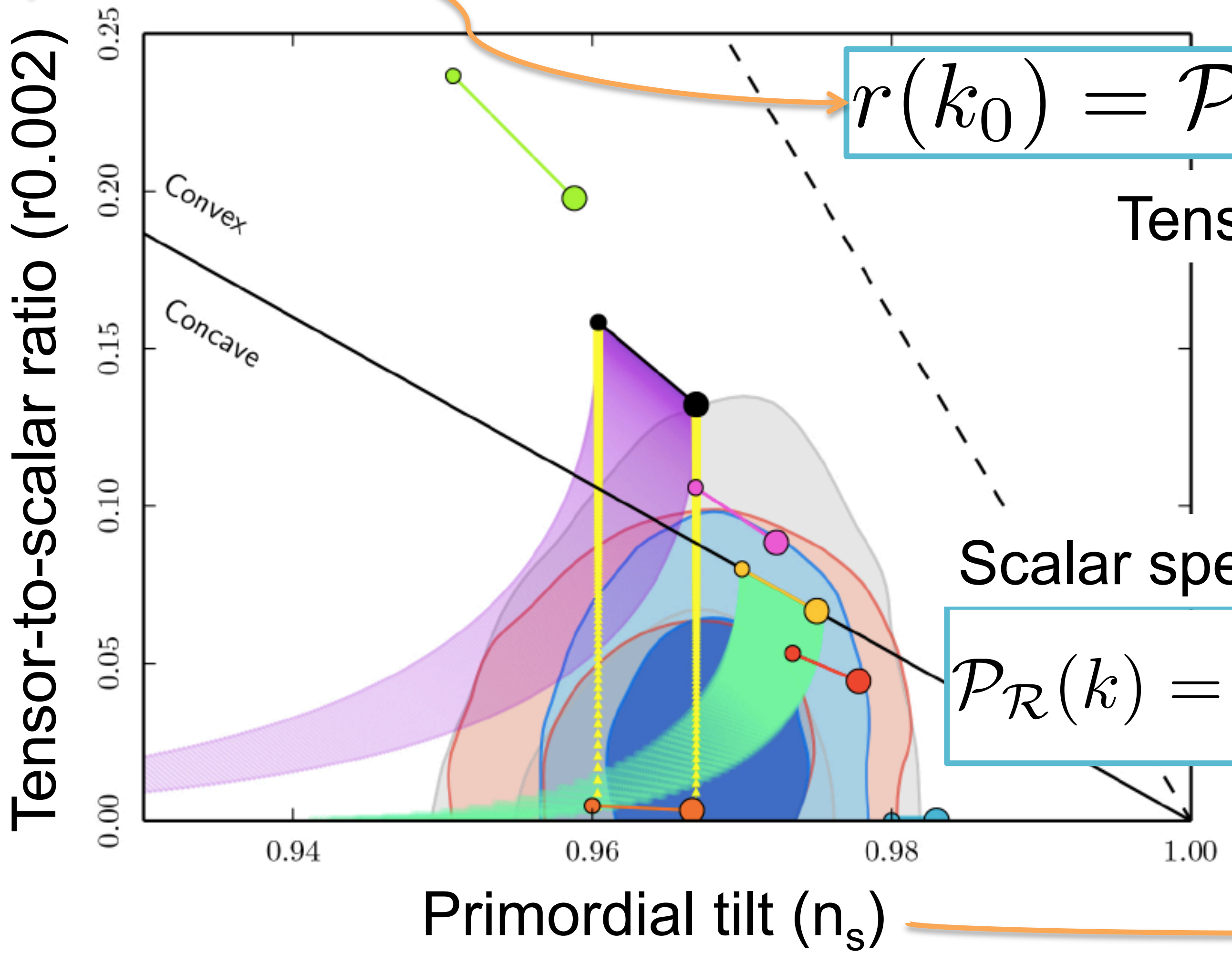
Starobinsky model (1/3)

within *Planck* 68% C. L.



Planck Collaboration, arXiv:1502.02114 (2015)

Starobinsky model (2/3)



$$r(k_0) = \mathcal{P}_h(k_0)/\mathcal{P}_{\mathcal{R}}(k_0)$$

Tensor spectrum: $\mathcal{P}_h(k)$

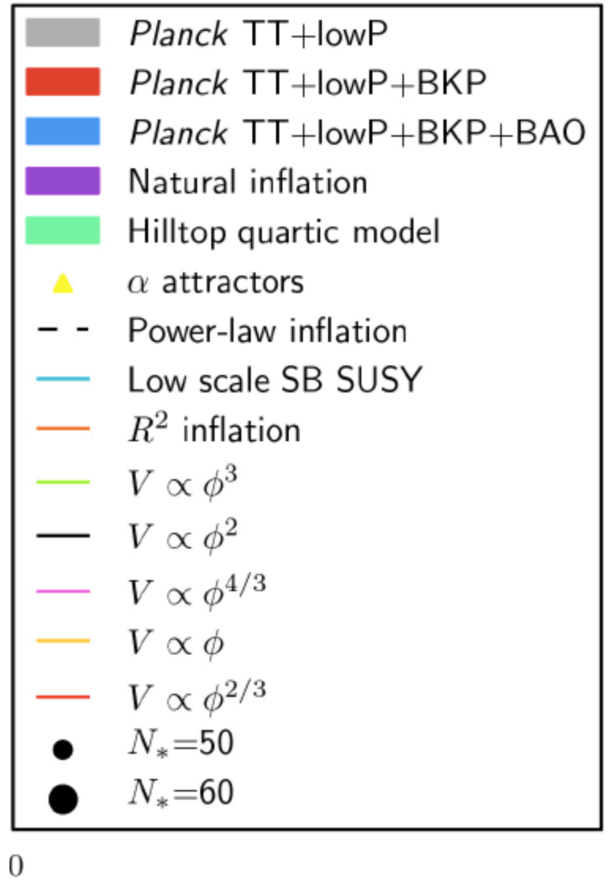
Scalar spectrum:

$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_{\mathcal{R}}(k_0)\left(\frac{k}{k_0}\right)^{n_s - 1}$$

Planck Collaboration, arXiv:1502.02114 (2015)

Starobinsky model (3/3)

BKP: BICEP2/Keck array and Planck
BAO: Baryon Acoustic Oscillation



Planck Collaboration, arXiv:1502.02114 (2015)

Model - backup

$$\mathcal{L}_I = \frac{1}{\Lambda}\partial_\mu \phi j^\mu_B .$$

Cohen and Kaplan,
Phys. Lett. B199, 251(1987)

Abstract

Ratchet Baryogenesis during reheating

Content

We propose a new baryogenesis scenario, which occurs during reheating after inflation. During reheating, the oscillation of the inflaton field breaks thermal equilibrium, providing one of the necessary conditions for baryogenesis. The inflaton field is assumed to couple to a complex scalar field which carries baryon number, whose self coupling breaks B, C and CP, providing the remaining two conditions for baryogenesis. The dynamics of our scenario utilizes the so-called "ratchet mechanism" found in models of biological molecular motors. There, the driving force of the ratchet movement (of molecular motors) usually comes from the oscillatory change of temperature in the non-equilibrium state. In the present scenario this driving force is provided by the oscillation of the inflaton field. Baryon number is generated by the phase of the complex scalar field being driven in a preferred direction due to the oscillatory energy provided by the inflaton and the "ratchet" of the self-coupling potential. We argue that for the inflaton potential supported by recent Planck results, this scenario allows for the generation of a baryon-to-photon ratio compatible with observations.