Cosmo17@paris

Asymmetric Preheating

``Asymmetric Preheating,“ 1707.05310

Tomohiro Matsuda / Saitama Institute of Technology
And
Seishi Enomoto / University of Florida

Why reheating ?

Inflation explains …
Origin of the large-scale structure of the cosmos

Inflation solves …
Horizon problem, Flatness problem, Monopole etc…

At the end of inflation
the Universe is

Cold and Empty
*Vacuum Energy

What we see in our Universe is

Stars and Galaxies
Big Bang (Hot) Universe

Reheating

Why “p”reheating ?

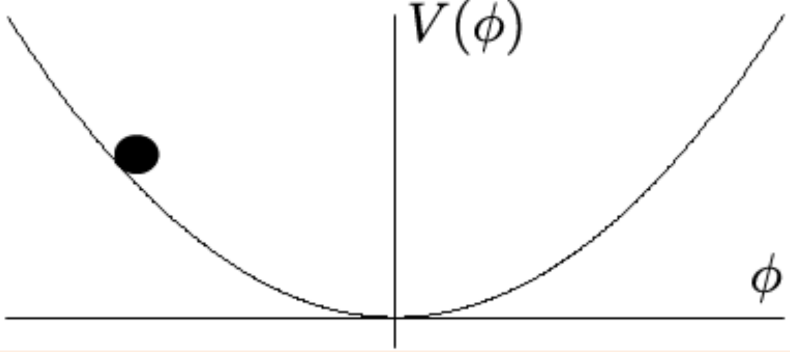
Classical picture

Reheating was explained using Perturbative decay

“Not enough to explain…”
Traschen and Brandenberger 1990
Dolgov and Kirilova 1990

Preheating*Kofman, Linde, Starobinsky 1994

Non-perturbative production of matter
on a classical time-dependent background



Describes the initial energy transfer
Highly non-thermal

“Thermalization after preheating”
is highly non-trivial
and model-dependent
*We avoid this argument

Why Asymmetric Preheating?

To solve the Baryon number Asymmetry of the Universe (BAU)

In the past,

Preheating has been used to explain BAU, but *mostly*…

Sources of the asymmetry are "indirect"

1. Decay of a heavy particle
2. Phase transition after preheating
3. …

Preheating itself does not generate asymmetry

What we want is a "direct" scenario.

Is it possible to BIAS the particle production?

If possible, what is essential for the mechanism?

We have tried two different ways…

Simple model, Bogoliubov eqs. are solved analytically

1. Chemical potential
2. Violation of CP in the Initial condition

Helps to understand the mechanism, but not enough to understand the whole story

"Phenomenological" CP violation usually has many fields.

"Phenomenological" model. Eqs. are solved numerically
Analytical discussions are for the eigenstates

1. "Kaon"-like Quantum correction
2. Berry Phase-like "Geometric" correction

Chemical potential

We start with the action for a complex scalar field

$$S_0 = \int d^4 x \sqrt{-g} [\, \partial_\mu \hat{\phi}^* \partial^\mu \phi - m(t)^2 \, |\hat{\phi}|^2 + \xi \, R |\hat{\phi}|^2 \,].$$

Using conformal time η and cosmological scale factor a, rewrite the action

$$S_0 = \int d^4 x \left[|\dot{\phi}|^2 - \omega(\eta)^2 |\phi|^2 \right]$$

Time-dependent background
(Inflaton oscillation)

$$\omega^2 \equiv \; a^2 m^2 \; + \left(-\Delta + \frac{\ddot{a}}{a} (6\xi - 1) \right)$$

(Effective) Chemical potential is introduced by

$$L_c = -\frac{\partial_\mu \varphi}{M_*} J^\mu .$$

$\dot{\varphi} \neq 0$ by hand, $\mu \equiv \frac{\dot{\varphi}}{M_*}$

using the current

$$J^\mu \equiv -i(\phi \, \partial^\mu \phi^* - \phi^* \partial^\mu \phi)$$

Chemical potential

Equation of motion $\ddot{\phi} - 2i\mu\,\dot{\phi} + (\omega^2 - i\,\dot{\mu})\phi = 0$

Decompose ϕ using ($a^\dagger$ /matter, $b^\dagger$ /antimatter creation)

$$\phi = \int \frac{d^3k}{(2\pi)^{3/2}}[h(\eta)a(k)e^{ikx} + g^*(\eta)b^\dagger\,(k)e^{-ikx}]$$

(Standard calculation)

$$h = \frac{e^{-i\int^\eta \omega\, d\,\eta'}}{\sqrt{2\omega}}A_h + \frac{e^{i\int^\eta \omega\, d\,\eta'}}{\sqrt{2\omega}}B_h,$$

$$\alpha_h \equiv e^{-i\int^\eta \omega\, d\eta'}A_h$$

*also for $\Pi \equiv \dot{\chi}$ and antimatter (g)

We find

matter

$$\dot{\alpha}_h = -i(\omega - \mu)\alpha_h + \frac{\dot{\omega}}{2\omega}\beta_h$$

$$\dot{\beta}_h = \frac{\dot{\omega}}{2\omega}\alpha_h + i(\omega + \mu)\beta_h$$

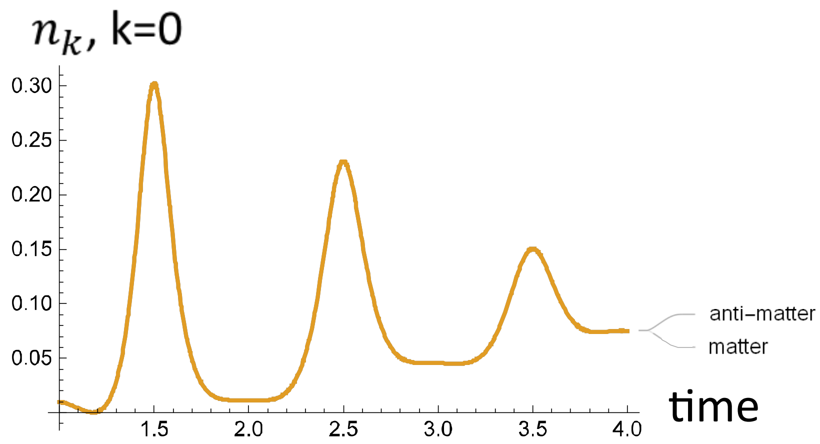
antimatter

$$\dot{\alpha}_g = -i(\omega + \mu)\alpha_g + \frac{\dot{\omega}}{2\omega}\beta_g$$

$$\dot{\beta}_g = \frac{\dot{\omega}}{2\omega}\alpha_g + i(\omega - \mu)\beta_g$$

Sign flips

However, in spite of the difference in the evolution equations, our numerical calculation shows the number densities are identical



Looking more closely, we find

$$\dot{n} \sim \frac{d}{dt}|\beta^2| = \frac{\dot{\omega}}{\omega}|\alpha||\beta|\cos(\theta_\alpha - \theta_\beta)$$

$$\alpha \equiv |\alpha| e^{i\theta_\alpha}$$

To make difference between matter and antimatter, this factor must be different… but we soon realized μ can be rotated away. Therefore, phase factors must coincide.

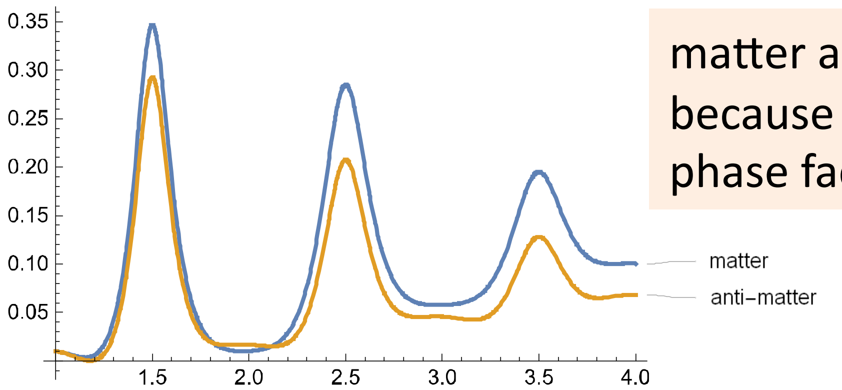
This is a textbook issue.

"Any interaction that can be rotated away does not violate CP"

But, from this failure we learned something more

CP violation in the Initial Condition

If something in high energy violates CP and shifted initial $\cos(\theta_\alpha - \theta_\beta)$, it may cause asymmetry production in low energy. In this case nothing is needed except for the initial condition.



matter and antimatter evolve differently because of the CP violation in the initial phase factor

Growth of Asymmetry is not monotonic but rather chaotic.

Matter and antimatter densities are identical at t=0

Merit	: CP violation is not needed in the effective action.
Demerit	: CP violation in the initial condition is speculative.

*AD baryogenesis does not consider preheating, and it uses the phase of a field staying at far distance. Our model uses the phase of a field sitting at the minimum.

Now we try to generate asymmetry with some “realistic” CP violation

CP violating interaction (Why Kaon?)

Thinking about SM, matter-antimatter asymmetry is far from simple.
Even in the (introductory) Kaon model, the story is complicated.

CP violating interaction
Quantum corrections

Both are needed for the asymmetry

Require many fields

Soon we realized that the model of
asymmetric preheating has to be as complicated as the SM.

CP violation in the initial condition is an exception

The best way to realize the asymmetric preheating is to borrow the setup of a well-known (Kaon) model, since model-building is not essential for our purpose

So we start the 2nd part with "Preheating with Kaon"

Introduction to Kaon model

Neutrally charged matter and antimatter are defined by

$$\mathrm{K}^0 = d\bar{s}, \quad \overline{\mathrm{K}}^0 = \bar{\mathrm{d}}s$$

CP eigenstates are

$$\mathrm{K}_1 = \frac{\mathrm{K}^0 + \overline{\mathrm{K}}^0}{\sqrt{2}} \text{(CP even,+1)} \quad \text{and} \quad \mathrm{K}_2 = \frac{\mathrm{K}^0 - \overline{\mathrm{K}}^0}{\sqrt{2}} \text{(CP odd, -1)}$$

If these were the eigenstates of weak interaction, CP is conserved.

Simple check

Consider the Schrödinger equation given by

$$i\frac{d}{dt}\psi_0 = H\psi_0, \quad \begin{pmatrix} H_{22} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & \Delta \\ \Delta^* & M \end{pmatrix} \quad \psi_0^t \equiv (\mathrm{K}^0, \overline{\mathrm{K}}^0)$$

If one chooses real Δ, this gives the eigenstates K_1 and K_2.
Complex Δ gives a phase factor (complex eigenvalue),
yet the eigenstates remain CP conserving.

CP violation in Kaon

For Kaon, CP violation is realized by higher corrections.
Essentially the source of CP violation is anti-Hermitian Matrix $i\Gamma$;

$$H \to H - i\Gamma$$

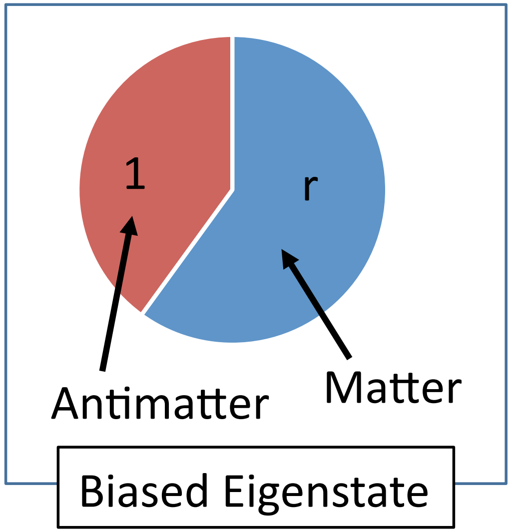
Because of $i\Gamma$, the eigenstates "violate CP"

Simple check

Example $$\begin{pmatrix} H_{22} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & \Delta + i\Gamma \\ \Delta^* + i\Gamma^* & M \end{pmatrix}$$

gives "Biased ($r \neq 1$)" eigenvectors

$$\left(\pm \frac{r}{\sqrt{1+r^2}}, \frac{1}{\sqrt{1+r^2}} \right), \qquad r \equiv \sqrt{\frac{\Delta + i\Gamma}{\Delta^* + i\Gamma^*}}$$



We have seen that in Kaon model

CP	Eigenstates
○	1-1 mixed state of K^0 and $\overline{K}^0$ $(\pm 1, 1)$ or $(\pm e^{i\theta}, 1)$
×	Biased product of K^0 and $\overline{K}^0$ $\left(\pm \frac{r}{\sqrt{1+r^2}}, \frac{1}{\sqrt{1+r^2}}\right)$

Since the equations of motion are diagonalized (separated) for the eigenstates, what is generated during preheating is the eigenstates. Asymmetry in the eigenstate is the direct source of the matter-antimatter asymmetry.

If so, $R \equiv \frac{n-\bar{n}}{n+\bar{n}}$ has to be constant during preheating

This fact is Distinguishable in numerical calculations!

From the Kaon model we learned…

1. CP violation appears as the bias in the eigenstate.
2. $\mathrm{R} \equiv \frac{n-\bar{n}}{n+\bar{n}}$ does not depend on the details of preheating.

Surprising

Otherwise R depends on the preheating process and it has to grow (like ~~CP~~ in the initial condition)

One thing that is not clear is that the bias may be a time-dependent parameter. If CP violation depends on the background, R may also depend on time.

New Question

What happens if the eigenstates "depend" on time?

“Geometric” property of the quantum mechanics is the key

The Nobel Prize in Physics 2016

Nobelprize.org

Prize motivation:
"for theoretical discoveries of topological phase transitions and topological phases of matter"

The geometric phase (Pancharatnam–Berry phase) results from the geometrical properties of the parameter space of the Hamiltonian.

If you are familiar with string theory,
“Parameter space of the Hamiltonian” -> Landscape

If the background (a parameter) is time dependent, or you are moving on the landscape of the parameter space, you will feel “geometrical changes”.

OK, geometric corrections could be important.
Geometric phase shift (Berry) may appear.
But how CP is violated by such correction?

Nobel prize in Physics in 2008

Prize motivation for KM:
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"

Nobelprize.org

"CP violation in the geometric correction"
may appear when the matrix goes to 3×3
If so, the geometric phase may distinguish matter/antimatter

Let us check this statement using a simple model

3×3 model (simplest)

$$L = \left|\partial_\mu \phi\right|^2 - m_{\phi^2}(t)\,|\phi|^2 + \frac{1}{2}\left(\partial_\mu \chi\right)^2 - \frac{1}{2} m_\chi^2 \chi^2$$
$$- \frac{1}{2}\left(\epsilon \phi^2 + h.c.\right) - \left(g\phi + h.c\right)\chi,$$

(χ is real)

Oscillating background
*m_χ^2 is constant

"Δ" in Kaon (real)

Complex parameter(new)

Equation of motion

$$\ddot{\Psi} + \Omega^2 \Psi = 0$$

$$\Psi \equiv \begin{pmatrix} \phi \\ \phi^* \\ \chi \end{pmatrix} \text{ and } \Omega^2 \equiv \begin{pmatrix} \omega_\phi^2 & \epsilon & g \\ \epsilon & \omega_\phi^2 & g^* \\ g^* & g & \omega_\chi^2 \end{pmatrix}$$

If one (naively) diagonalizes $\Omega^2 (\rightarrow \omega^2 \equiv U^\dagger\, \Omega\, U)$, one will find…

1. "Eigenfunctions" are symmetric (1-1) for ϕ and ϕ^*
2. No CP violation??
3. Something is wrong with the kinetic terms

Kinetic terms are not diagonal when the time-dependent background causes geometric correction

$$\hat{\Psi} \equiv U^{\dagger}\Psi$$

Original $\Psi = (\phi^{*} \quad \phi \quad \chi)^{t}$

Rotation Matrix (Unitary)

"Eigenstate"

Rewrite the kinetic term using $\hat{\Psi}$ $\sim (\partial_{\mu}\Psi)^{2} = \left(\partial_{\mu}(U\hat{\Psi})\right)^{2}$

The geometric correction appears in the kinetic term

$$\ddot{\hat{\Psi}} + 2\gamma\dot{\hat{\Psi}} + (\omega^{2} + \gamma^{2} + \dot{\gamma})\hat{\Psi} = 0, \qquad \omega^{2} \equiv U^{\dagger}\Omega\, U$$

In the adiabatic limit, $i\gamma \equiv iU^{\dagger}\dot{U}$ is the Berry connection
(Easy to verify using the Schrödinger equation)

Although Ω^{2} is diagonal for the "eigenstate" $\hat{\Psi}$, the kinetic terms are not diagonal. $\hat{\Psi}$ is not the true eigenstate(*unable to diagonalize)

$i\gamma \neq 0$ gives "geometric (berry) phase".
This phase appears because m_ϕ(t) (geometry) is changing.
U have the CP phase (KM-phase), and so does γ.
Therefore the Berry phase distinguishes matter/antimatter.
*Phase determines the evolution and the phase is shifted.
The shift is different between matter and antimatter

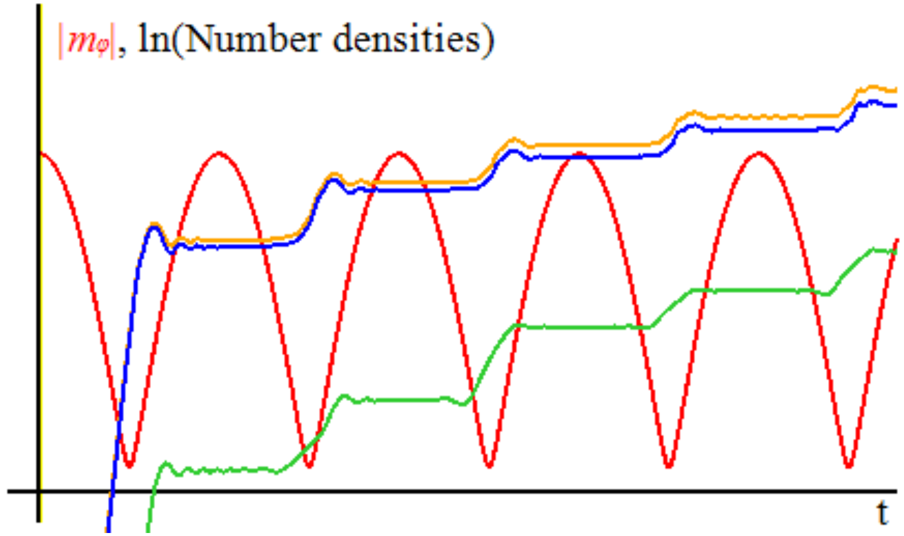
One of us (S.E) numerically solved particle production with $\gamma \neq 0$
The result precisely matches our expectation

Since the model is already complex,
further study requires numerical calculation

CP violation from the geometry

Numerical calculation 1

Confirmed asymmetry



Matter

Antimatter

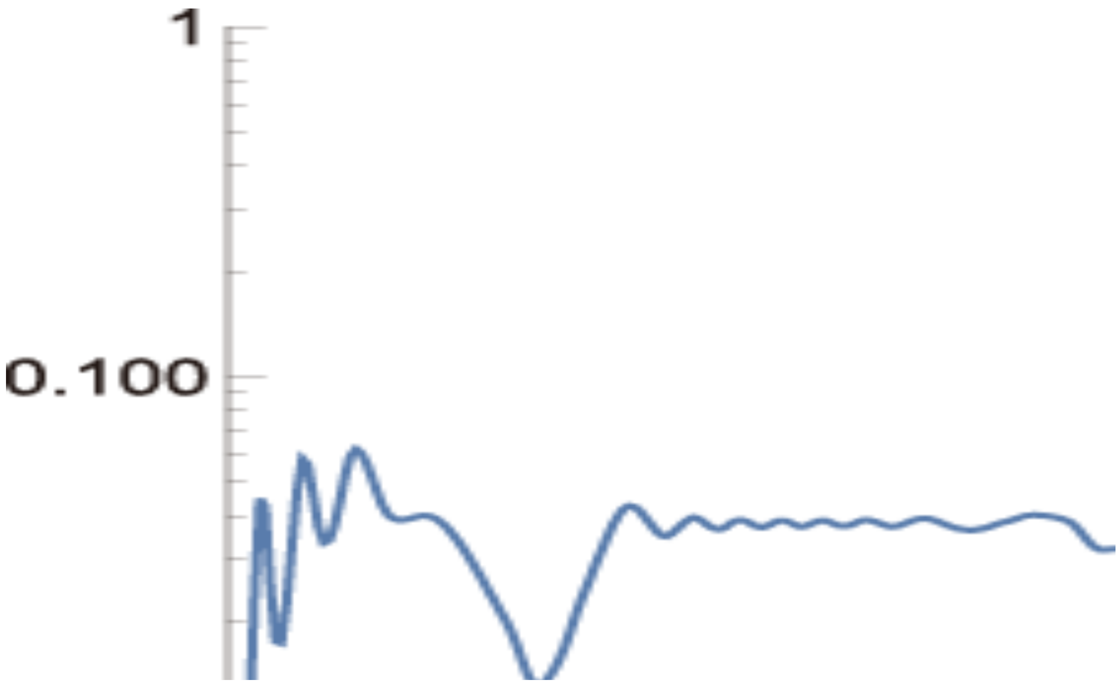
Asymmetry (not the ratio)

Background

CP violation from the geometry

Numerical calculation 2
Confirmed the origin

Asymmetry (by the "ratio" R)



The ratio is nearly constant during preheating. Since γ is not constant in this model, it is not easy to determine the origin of the asymmetry. Nevertheless, the numerical result seems to be suggesting that the asymmetry is mostly coming from the biased eigenstate, not from the biased multiplication factor of the resonance.

Summary (2^{nd} Half)

Standard approach

$\not{CP}$ + Quantum correction ($i\Gamma$) = asymmetry

GUT Baryogenesis
Leptogenesis
Kaon etc.

In the presence of $\not{CP}$
quantum correction (*phase)
distinguishes matter/antimatter

New paradigm?

$\not{CP}$ + Geometric correction ($i\gamma$) = asymmetry

Multi-field preheating (more than 3)
Geometric Baryogenesis?

In the presence of $\not{CP}$
geometric phase distinguishes
matter/antimatter
This biases the eigenstates

In the schrodinger eq.
$i\Gamma$ and $i\gamma$ appears in the same way

Conclusions

Preheating is already an old idea, but there has been no work explaining how CP violation affects the matter-antimatter asymmetry in preheating.

Considering preheating in Kaon, we found that anti-Hermitian correction $i\Gamma$ can generate asymmetry during preheating. Since the equation of motion is diagonalized for the eigenstates, particle production occurs for the eigenstates. (indivisually) Then the calculation is straight. The bias in the eigenstates is the source of the asymmetry. It is constant during preheating and does not depend on the details of the preheating process.

<u>This result is rather surprising</u>.

Then we extend the idea. Since the background is changing there may be some geometric correction, which appears as the shift of the phase(Berry phase). This “geometric” correction can distinguish matter and antimatter in the presence of $\not{CP}$ (KM phase). This is of course a very new result.

⬆

For completeness we note:
In 2001, similar calculation was given by Funakubo et.al. However, they claimed “at least two complex scalars interacting with the oscillating background” are needed for the asymmetry. Our model has only 1 complex and 1 real scalar fields. Also, the real scalar field is not interacting with the oscillating background.
K. Funakubo, A. Kakuto, S. Otsuki and F. Toyoda, ``Charge generation in the oscillating background,'' Prog. Theor. Phys. **105**, 773 (2001)[hep-ph/0010266].

Fermions at work

to be continued