

Ratchet Model of Baryogenesis

Tatsu Takeuchi (Virginia Tech)

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Work in collaboration with
Azusa Minamizaki and Akio Sugamoto (Ochanomizu)

Paper in preparation

What does baryogenesis need to explain?

- Baryon number to photon number ratio:

$$\eta = \frac{n_B}{n_\gamma} = 6 \times 10^{-10}$$

See:

- B. D. Fields and S. Sarkar in the Review of Particle Properties
- S. Weinberg “The First Three Minutes”, “Cosmology”
- If equal numbers of particles and anti-particles were created at the Big Bang, why are there any baryons left-over?

Sakharov Conditions:

- A. D. Sakharov, JETP Letters, 5 (1967) 24
 1. B violation
 2. C and CP violation
 3. Out of thermal equilibrium



Examples:

- Electroweak Baryogenesis
- Leptoquark decay in GUT
- Leptogenesis
- Affleck-Dine
- etc.



Weinberg

Cosmology, page 185:

“The crucial confirmation of any theory of baryon synthesis would be a successful prediction of the present baryon/photon ratio. So far, none of the proposals discussed here are anywhere near this goal.”

Dimopoulos-Susskind Model:

- Phys. Rev. D18, 4500 (1978)
- Consider a scalar field which carries Baryon number:

$$J^\mu = i\phi^* \vec{\partial}^\mu \phi, \quad B(t) = \int d\vec{x} J^0(\vec{x}, t)$$

- Assume B, C, and CP violating potential:

$$V(\phi) = \lambda(\phi\phi^*)^n (\phi + \phi^*)(\alpha\phi^3 + \alpha^*\phi^{*3})$$

$$B : \phi \longrightarrow e^{i\gamma} \phi$$

$$C : \phi \longrightarrow \phi^*$$

$$CP : \phi(t, x) \longrightarrow \pm\phi^*(t, -x)$$

Dimopoulos-Susskind Model:

- Place in FRW metric for radiation dominated universe:

$$ds^2 = dt^2 - R(t)^2 d\vec{x}^2 = dt^2 - 2t d\vec{x}^2$$

$$S = \int d^4x \sqrt{-g} \left[g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi^* - V(\phi) \right]$$

- Introduce conformal variables and fields:

$$\tau = \sqrt{2t}, \quad ds^2 = \tau^2 \left[d\tau^2 - d\vec{x}^2 \right], \quad \hat{\phi} = \tau \phi$$

$$S = \int d\tau d\vec{x} \left[\left(\frac{d\hat{\phi}}{d\tau} \right)^2 - (\nabla \hat{\phi})^2 - \frac{V(\hat{\phi})}{\tau^{2n}} \right]$$

Simplifying Assumptions:

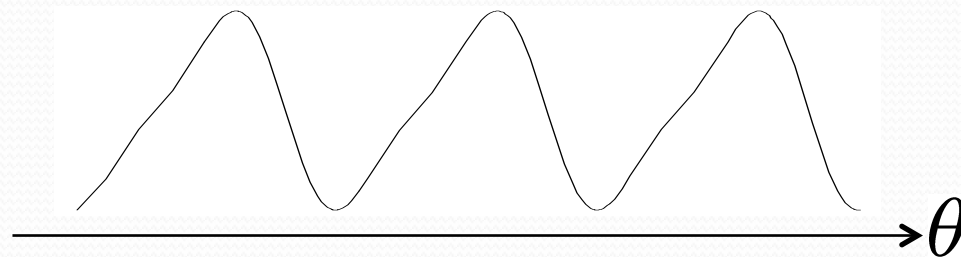
- Only consider the dynamics of the phase:

$$\hat{\phi} = |\hat{\phi}| e^{i\theta}, \quad B = R^3(t) i \hat{\phi} \vec{\partial}_t \hat{\phi}^* = i \hat{\phi} \vec{\partial}_\tau \hat{\phi}^* = 2 \frac{d\theta}{d\tau}$$

- Consider small spatial cell within which the phase is constant:

$$L = \left[\left(\frac{d\hat{\phi}}{d\tau} \right)^2 - (\nabla \hat{\phi})^2 - \frac{V(\hat{\phi})}{\tau^{2n}} \right] \rightarrow \left(\frac{d\theta}{d\tau} \right)^2 - \frac{V(\theta)}{\tau^{2n}}$$

$$V(\theta) = 4\lambda |\hat{\phi}|^{4+2n} \cos\theta \cdot \cos(3\theta + \beta), \quad \alpha = e^{i\beta}$$



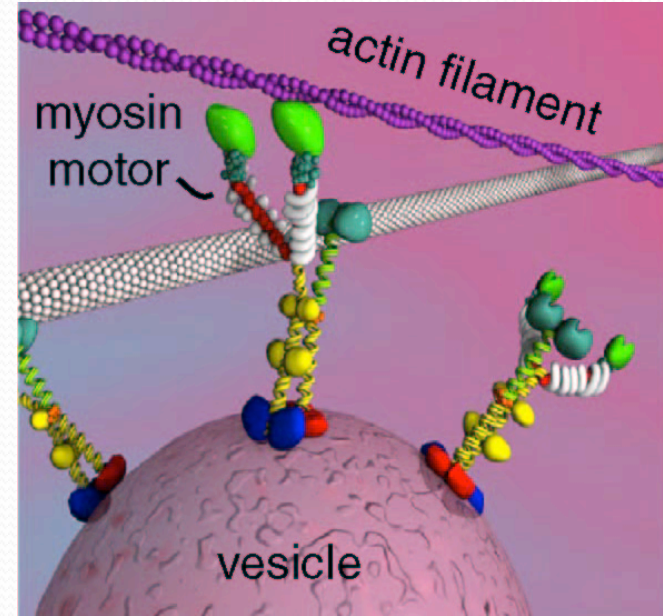
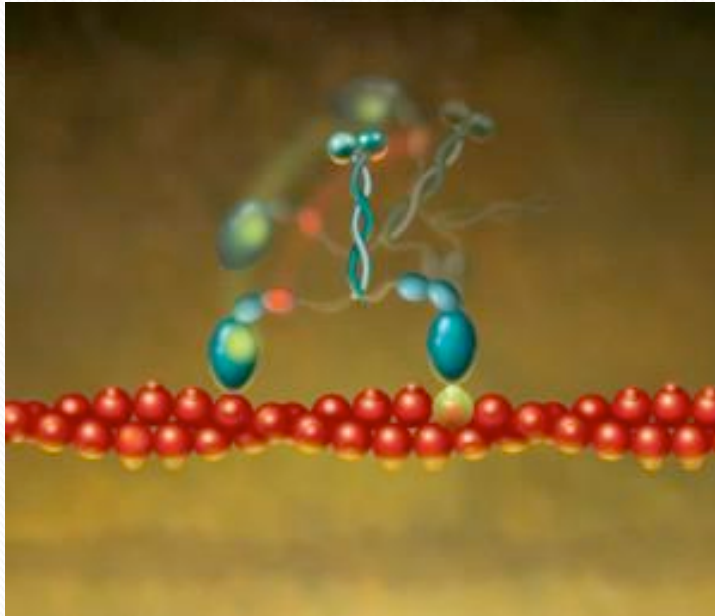
Equation of Motion:

$$\frac{d^2\theta}{d\tau^2} + \frac{1}{\tau^{2n}} \frac{\partial V}{\partial \theta} + \frac{\lambda^2}{\tau^{4n}} \frac{d\theta}{d\tau} = 0$$

- Friction term comes from the self-interaction of ϕ , the coefficient determined by dimensional analysis.
- Without the friction term, the phase cannot flow preferentially in one direction. On the other hand, the friction will grind the flow to a halt eventually.
- If $n \geq 1$, the friction term will be important for small τ , but damp out for large τ , allowing for a non-zero flow to develop asymptotically.
- θ must evolve very slowly during which $d\theta/dt$ must be converted to fermionic baryons.

Ratchet Model:

- Used in the theory of biological motors.

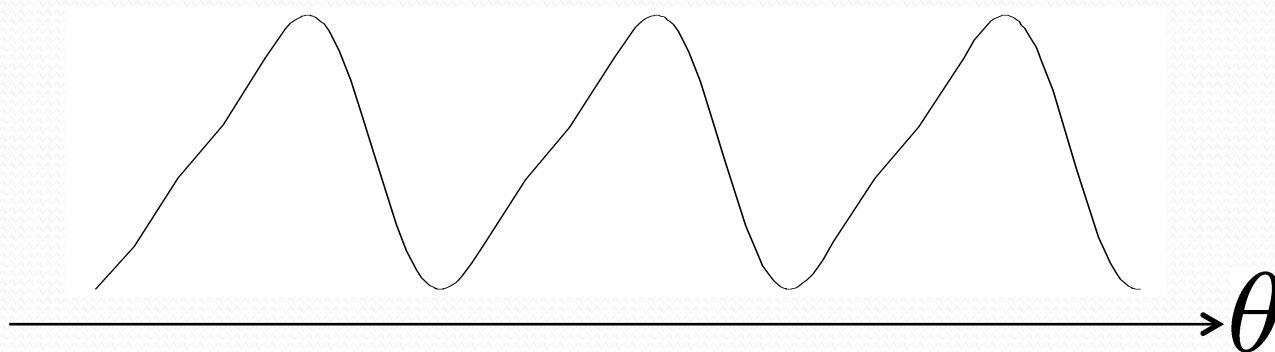


Ratchet Model:

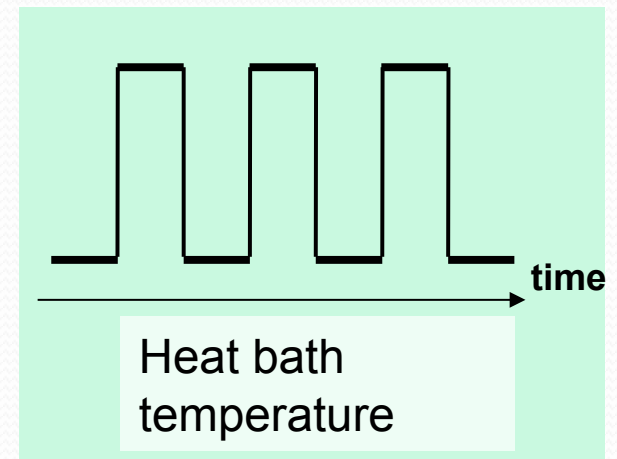
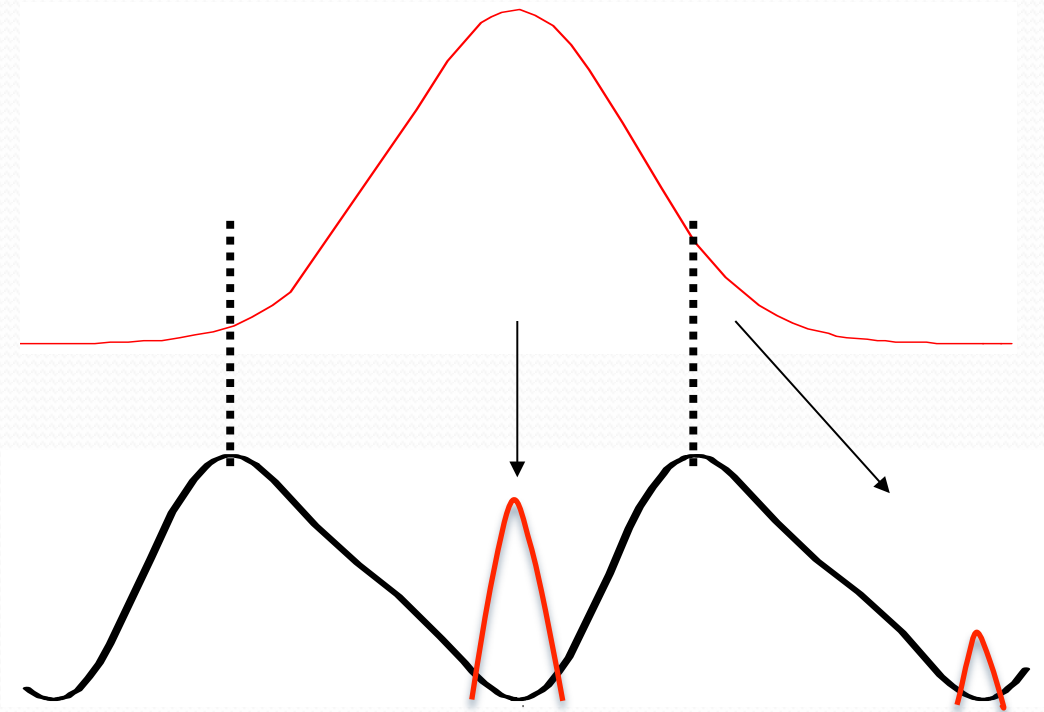
- Generates directed motion from random thermal fluctuations without a biased external force.

For the mechanism to work, it is known that:

1. The potential must be spatially asymmetric.
2. The heat bath must transition either periodically or randomly between two or more states.

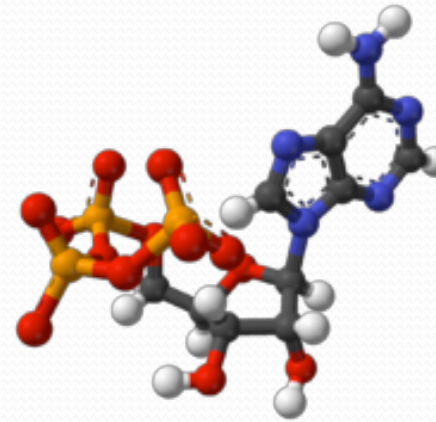
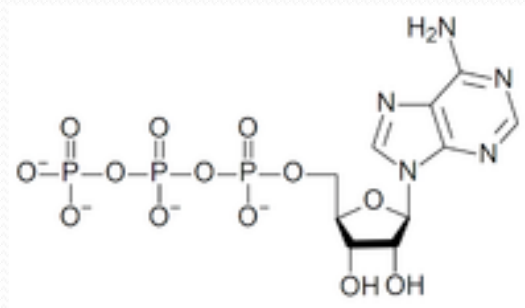


Ratchet Model:



ATP:

- Biological motors are fueled by ATP (Adenosine Tri-Phosphate)



- Introduce interaction with ATP-like particle:



Assume $Q \approx$ potential barrier height.

Equation of Motion:

- Dimopoulos-Susskind with $n = 0$

$$\frac{d^2\theta}{d\tau^2} + \frac{\partial V}{\partial\theta} + \lambda^2 \frac{d\theta}{d\tau} = 0$$

$$\begin{aligned} V &= \lambda(\phi + \phi^*)(\alpha\phi^3 + \alpha^*\phi^{*3}) \\ &= 4\lambda \left| \hat{\phi} \right|^4 \cos\theta \cdot \cos(3\theta + \beta) \end{aligned}$$

- With fluctuating thermal bath

$$\frac{d^2\theta}{d\tau^2} + \frac{\partial V}{\partial\theta} + \lambda^2 \frac{d\theta}{d\tau} - \sqrt{2D(\tau)} \xi(\tau) = 0$$

$$\langle \xi(\tau) \rangle = 0, \quad \langle \xi(\tau) \xi(\sigma) \rangle = \delta(\tau - \sigma)$$

Fokker-Planck Equation:

- The equation of motion is equivalent to:

$$\frac{\partial}{\partial \tau} p(\theta, \tau) + \frac{\partial}{\partial \theta} j(\theta, \tau) = 0$$

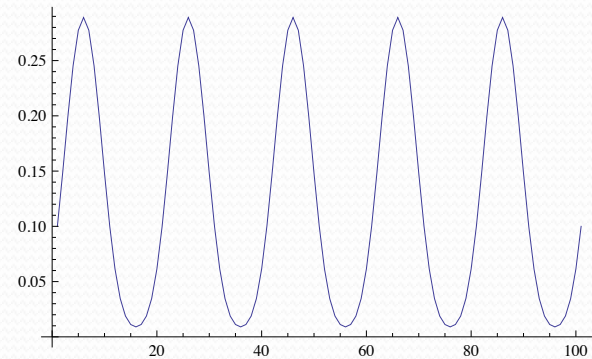
$$j(\theta, \tau) = - \left[V'(\theta) + D(t) \frac{\partial}{\partial \theta} \right] p(\theta, \tau)$$

- Assume:

$$D(\tau) = D_0 [1 + A \sin(\omega \tau)]^2$$

- Generate:

$$B \propto \frac{1}{T} \int_0^T j(\theta, \tau) d\tau$$



- P. Reimann, et al., Phys. Lett. A215 (1996) 26



Sample Solutions:

- Graphs take too long to render within Powerpoint.
Please see separate pdf files.

What could the ATP/ADP particles be?

$$\phi + \Phi_{ATP} \leftrightarrow \phi + \Phi_{ADP} + Q$$

- Inflaton at reheating?
- KK modes?
- Technimesons?



Conclusions:

- The ratchet model may provide a new method of baryogenesis.
- By choosing the parameters carefully, it may be possible to generate a fairly large range of baryon number.
- Whether it can be embedded into a realistic scenario remains to be seen. (Working on it.)