Ratchet Model of Baryogenesis

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Work in collaboration with

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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
     → B production process must proceed without the reverse process erasing B-number.

- #3 is tricky.

Dimopoulos-Susskind Model:

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

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

- Assume B, C, and CP violating potential:

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

$$\begin{aligned} B &: \phi \longrightarrow e^{i\gamma}\phi \\ C &: \phi \longrightarrow \phi^{*} \\ CP &: \phi(t,x) \longrightarrow \pm\phi^{*}(t,-x) \end{aligned}$$

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:

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

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

Simplifying Assumptions:

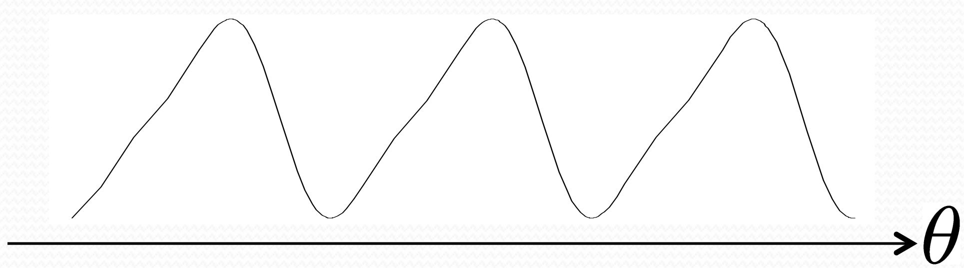
- Only consider the dynamics of the phase:

$$\hat{\phi} = \left|\hat{\phi}\right| e^{i\theta}, \qquad B = R^3(t)\, i\phi \overleftrightarrow{\partial}_t \phi^* = i\hat{\phi} \overleftrightarrow{\partial}_\tau \hat{\phi}^* = 2\frac{d\theta}{d\boldsymbol{\tau}}$$

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

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

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



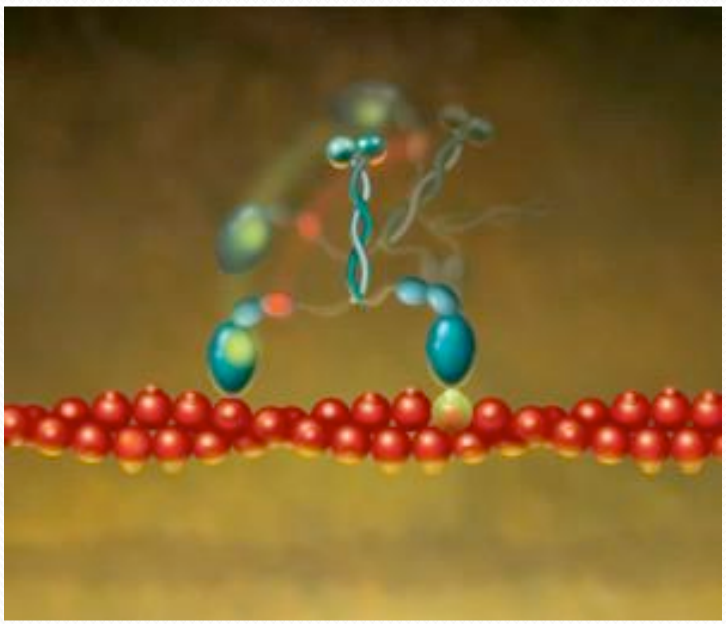
Equation of Motion:

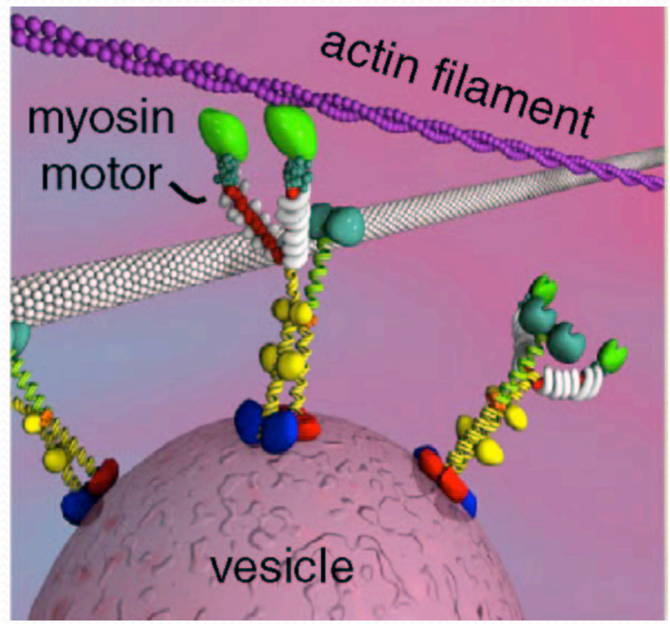
$$\frac{d^2\theta}{d\tau^2} + \frac{1}{\tau^{2n}}\frac{\partial V}{\partial\theta} + \frac{\lambda^2}{\tau^{4n}}\frac{d\theta}{d\tau} = 0$$

- 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 if one neglects all other sources of friction.
- θ must evolve very slowly during which $d\theta/dt$ must be converted to fermionic baryons.

Ratchet Model:

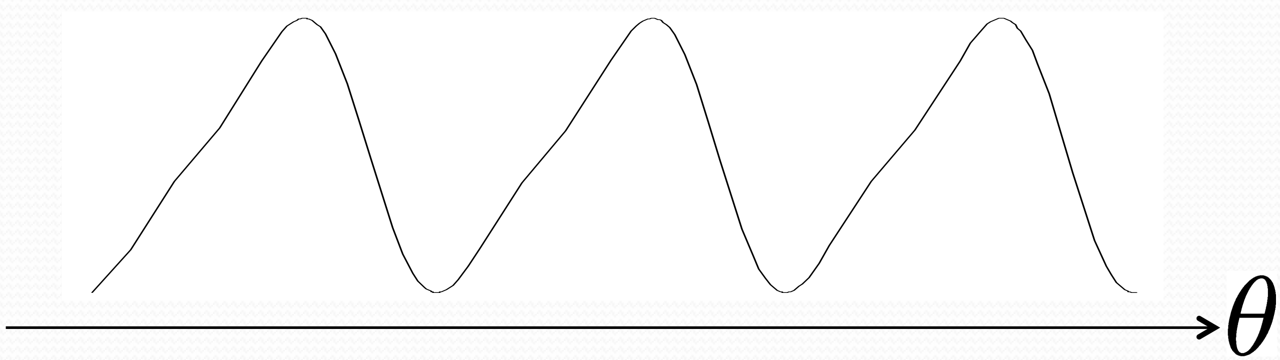
- Used in the theory of biological motors.



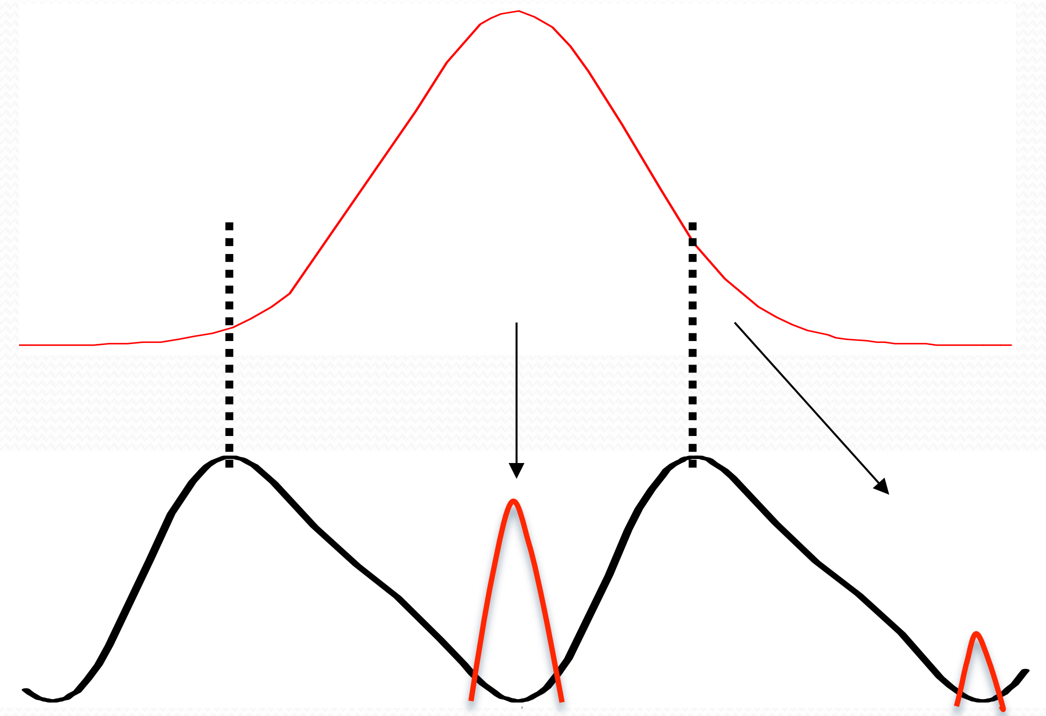


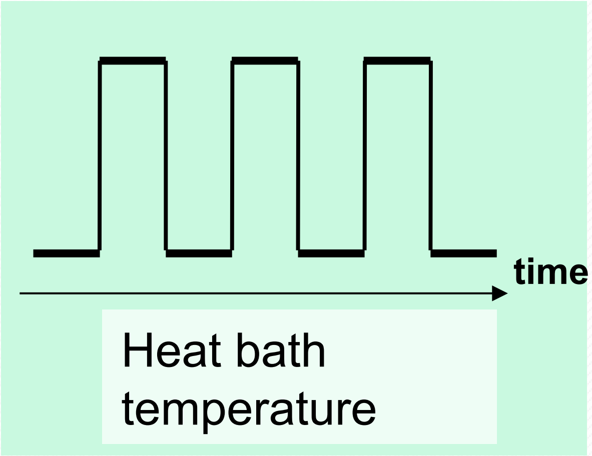
Ratchet Model:

- 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.



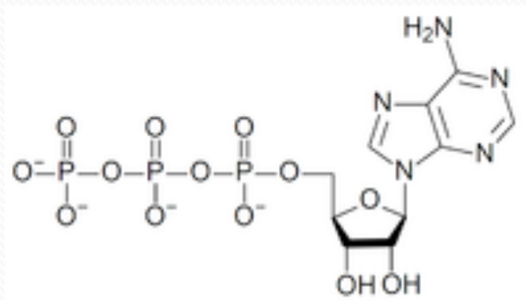
Ratchet Model:

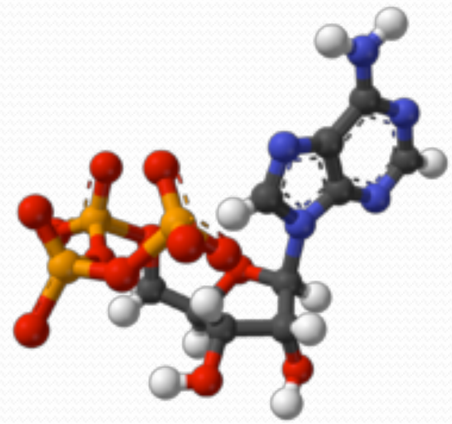




Thermal Equilibrium is broken by ATP:

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





- Introduce interaction with ATP-like particle:

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

Assume Q ≈ potential barrier height.

Equation of Motion:

- Dimopoulos-Susskind with $n = 0$

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

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

- 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:

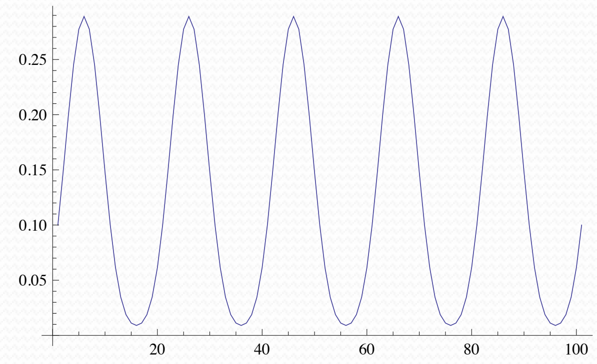
- The equation of motion is equivalent to:

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

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

- Assume:

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

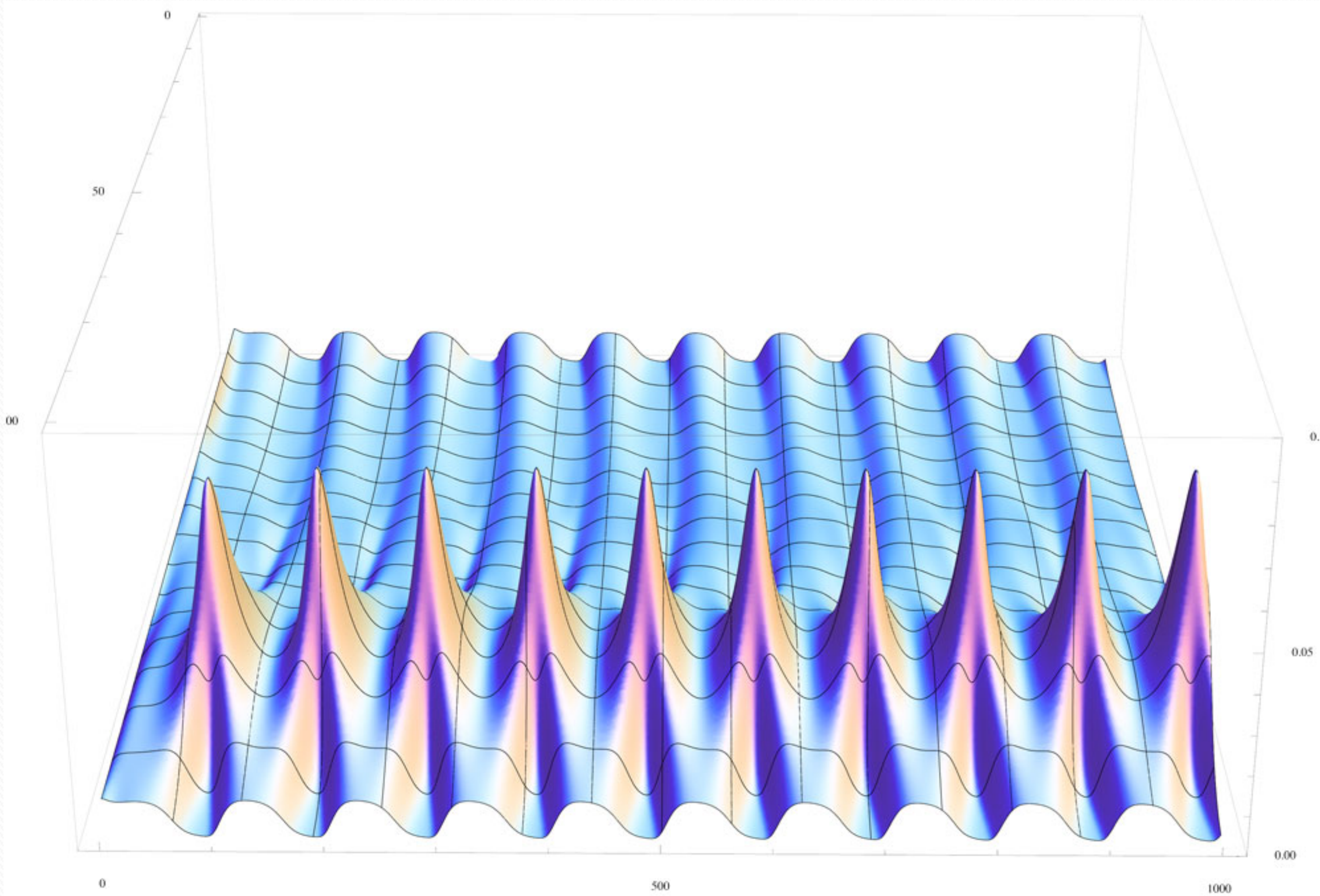


- Generate:

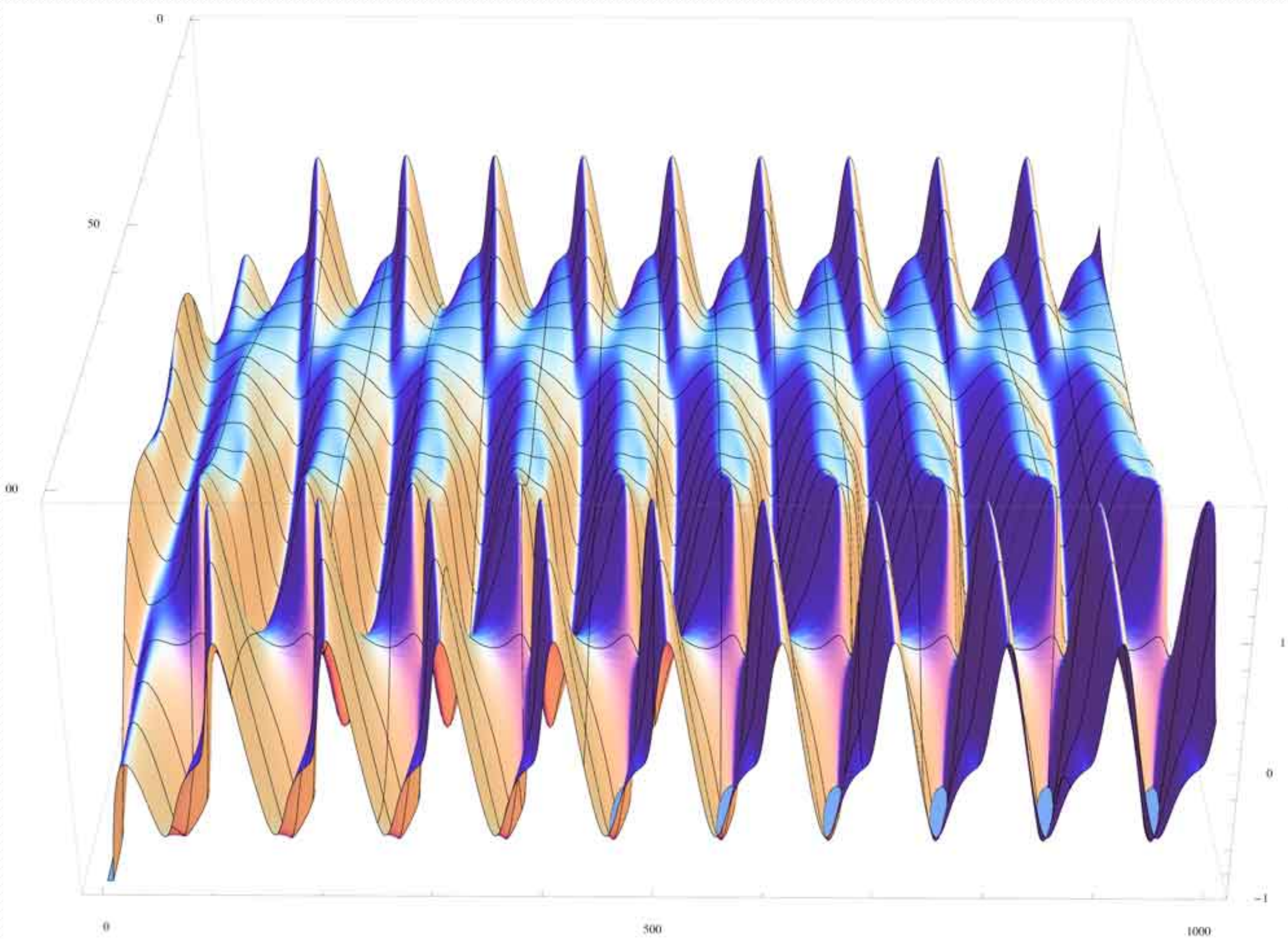
$$B \propto \frac{1}{T}\int_0^T j(\theta,\tau)\, d\tau$$

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

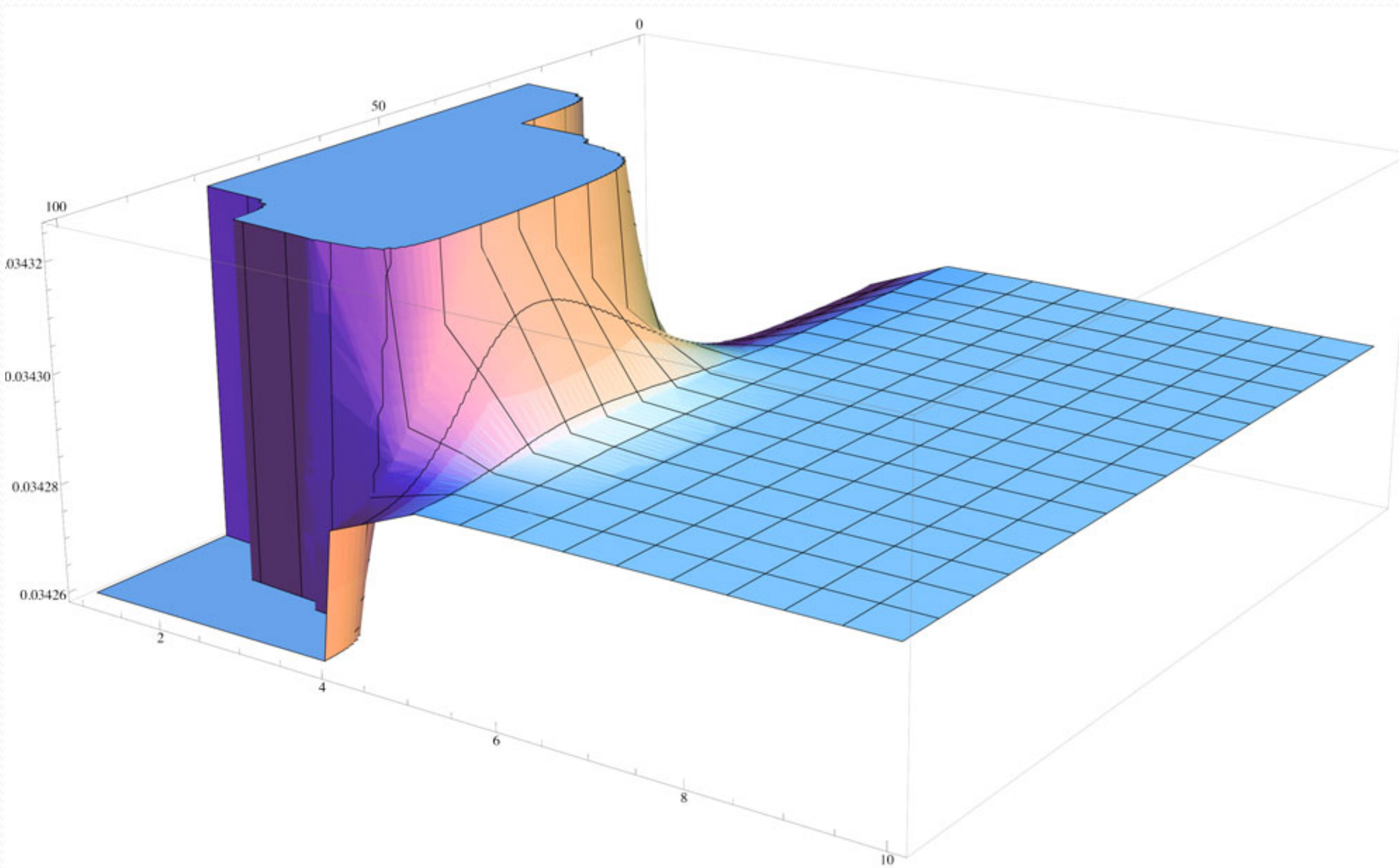
Sample Solution: Probability Density



Sample Solution: Current Density



Sample Solution: Average Current per Period



What could the ATP/ADP particles be?

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

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

- The ATP particles must decouple from thermal equilibrium and not decay away → dark matter?

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.)