Spiral inflation
&
Baryogenesis

[arXiv: 1901.05799 collaborated with **Gabriela Barenboim**]

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Spiral inflation

Inflation - basics

- Definition

$$\frac{\ddot{a}}{a} = -\frac{2}{3}\frac{\rho + 3p}{M_{\rm P}^2} > 0 \Rightarrow w \equiv \frac{p}{\rho} < -\frac{1}{3}$$

(← energy density; ← pressure; scale factor →)

- Purpose

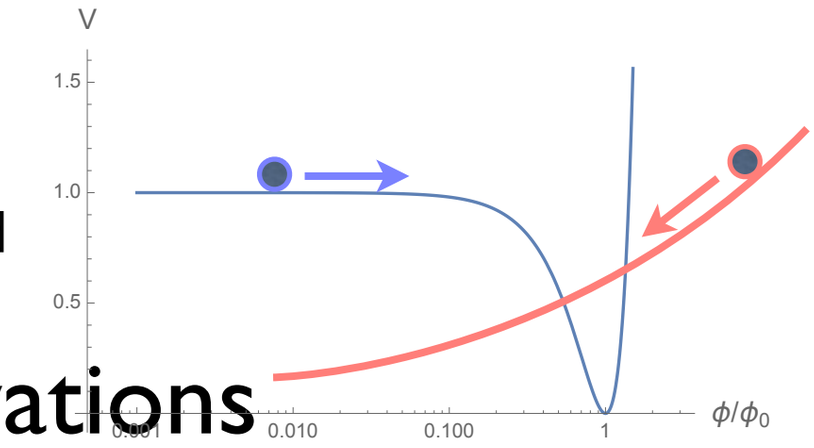
1. Solution to monopole-problem
2. Solution to horizon- and flatness-problem

- Additional crucial role

The most compelling source of the present density perturbation

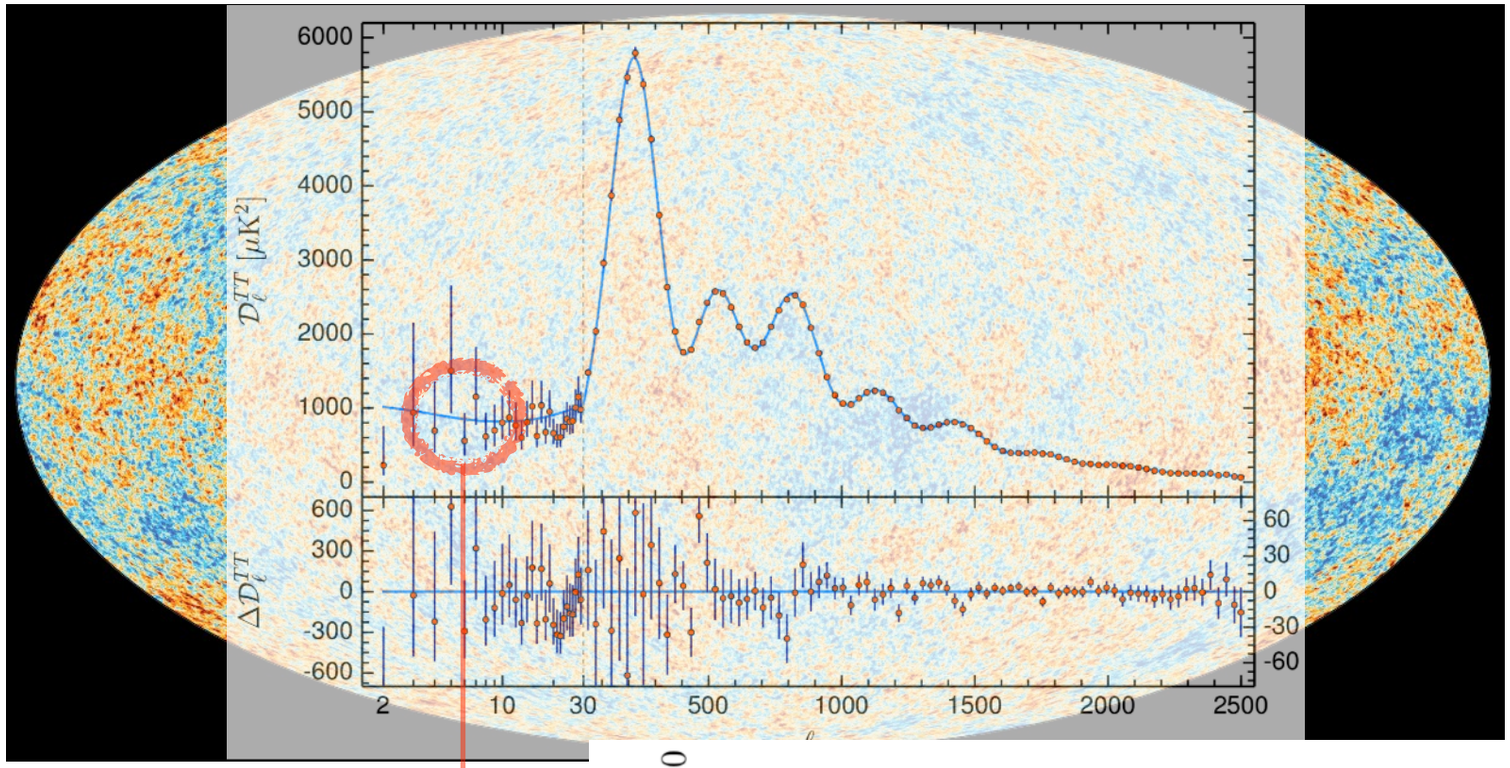
- Simple realization

A slow-rolling scalar field



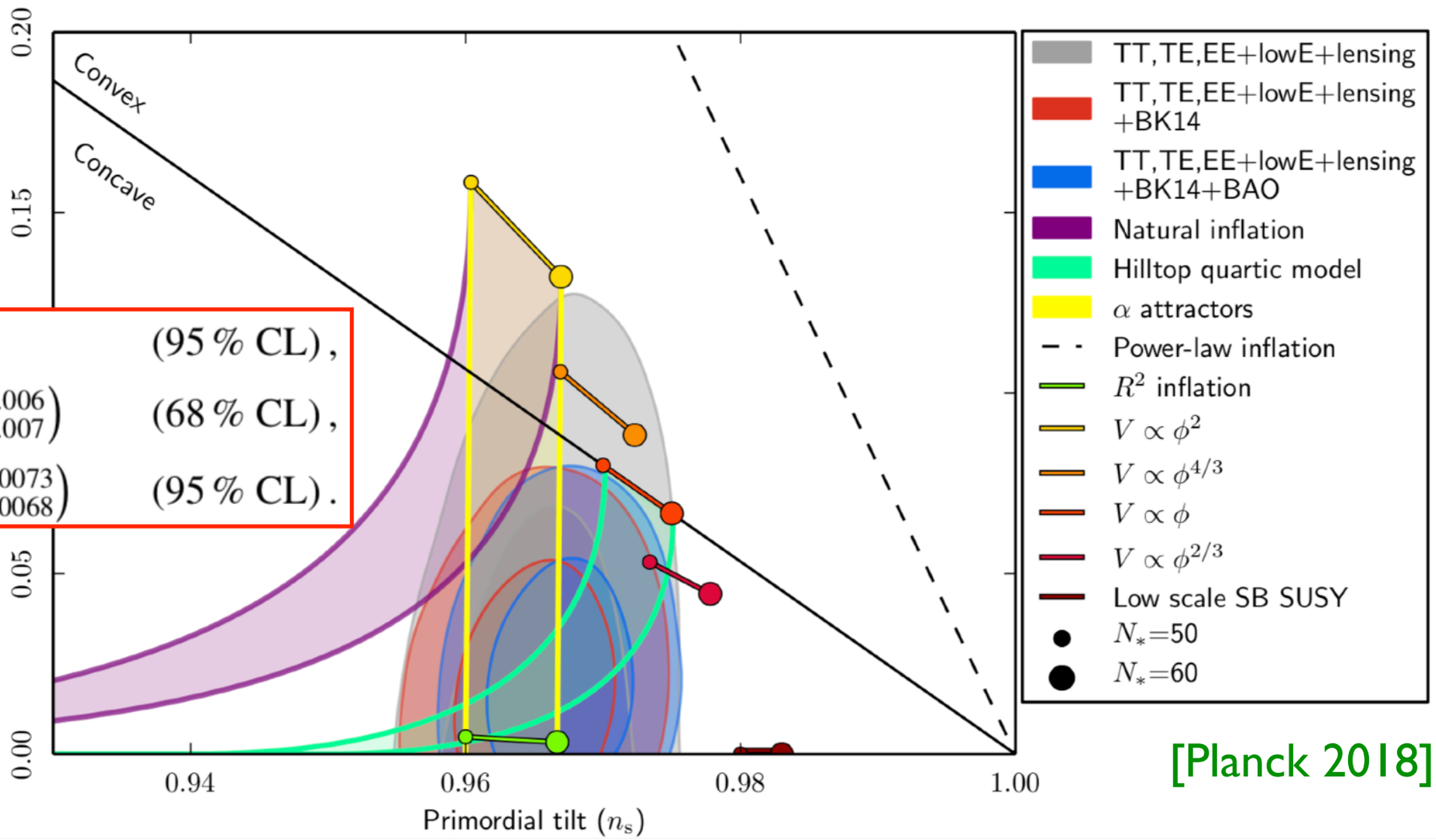
- Requirements from observations

1. At least about 60 e-foldings
2. Nearly flat red-tilted density power spectrum



$$n_s - 1 \equiv \frac{d\ln P_R}{d\ln k} \sim -4\times 10^{-2}$$

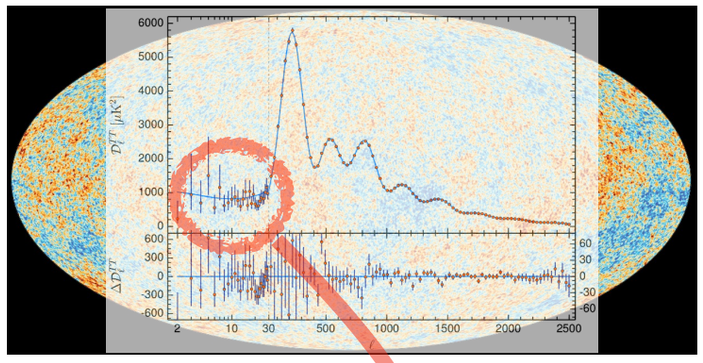
$$\begin{aligned}
&\epsilon_V < 0.0097 && (0.0053) && (95\,\%\ \mathrm{CL})\,,\\
&\eta_V = -0.010^{+0.007}_{-0.011} && \left(-0.014^{+0.006}_{-0.007}\right) && (68\,\%\ \mathrm{CL})\,,\\
&\xi_V^2 = 0.0035^{+0.0078}_{-0.0072} && \left(0.0023^{+0.0073}_{-0.0068}\right) && (95\,\%\ \mathrm{CL})\,.
\end{aligned}$$



[Planck 2018]

Inflation - Issues in modeling

- Flatness of inflaton potential



Observations require slow-roll parameters to satisfy

$$\epsilon \equiv \frac{1}{2}\left|\frac{M_{\rm P}V'}{V}\right|^2 \lesssim 10^{-2}, \quad \eta \equiv \frac{M_{\rm P}^2 V''}{V} \lesssim 10^{-2}$$

(slope) (curvature)

However, in many simple UV-realization of inflation, gravitational effects causes

$$\Delta V \sim cV\frac{\phi^2}{M_{\rm P}^2} \sim cH^2\phi^2 \Rightarrow \eta \sim \pm\mathcal{O}(c) \sim \pm\mathcal{O}(1)$$

($\langle\phi\rangle \lesssim M_{\rm P}$ is assumed)

This is called "η-problem".

- Trans-Planckian excursion

Even if η-problem is assumed to be cured somehow, generically the observed power spectrum requires a trans-Planckian excursion of inflaton field.

E.g., $$V = \begin{cases} V_0 - \frac{1}{2}m^2\phi^2 + \dots & \text{for } \phi \ll \phi_0 \\ \frac{1}{2}m^2\phi^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$$

$$\epsilon \equiv \frac{1}{2}\left|\frac{M_{\rm P}V'}{V}\right|^2 \sim \begin{cases} \left(M_{\rm P}\phi/\phi_0^2\right)^2 & \text{for } \phi \ll \phi_0 \\ \left(M_{\rm P}/\phi\right)^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$$

$$\eta \equiv \frac{M_{\rm P}^2 V''}{V} \sim \begin{cases} M_{\rm P}^2/\phi_0^2 & \text{for } \phi \ll \phi_0 \\ M_{\rm P}^2/\phi^2 & \text{for } \phi \gg M_{\rm P} \end{cases}$$

$$\phi_* \text{ or } \phi_0 \sim \mathcal{O}(10) M_{\rm P}$$

This raises a question on the validity of inflaton potential in view of EFT.

Inflation - solutions(?)

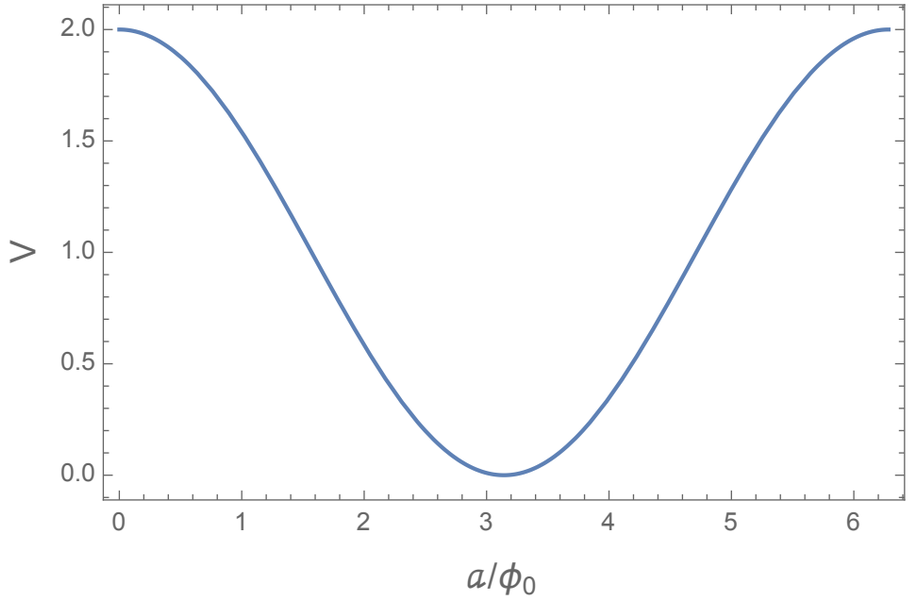
- to eta-problem

*** Forbidding mass correction**

⇒ Shift symmetry, pNGB, Heisenberg symmetry, ...?

$K = f(\phi - \phi^\dagger) + \ldots$ $\quad K = f(\rho);\ \rho = T + T^\dagger - |\Phi|^2 + \ldots$

e.g.) Natural inflation (using a pNGB)



$$\text{For } \Phi = \frac{1}{\sqrt{2}}\phi e^{ia/\phi_0},$$

$$V = \Lambda^4\left[1 + \cos\left(\frac{a}{\phi_0}\right)\right]$$

☞ However a global symmetry is expected to be broken by gravity.

☞ Hence there would be dangerous Planck-suppressed symmetry breaking operators.

- to trans-Planckian excursion

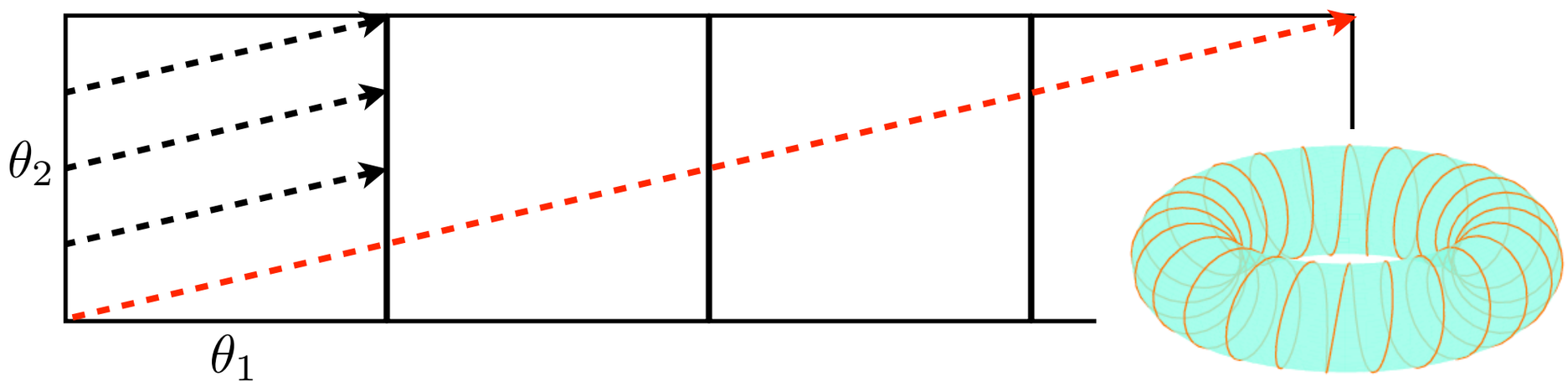
*** Conformal symmetry(?)**: Dangerous higher order operators are not allowed.

$$V = \frac{1}{4}\lambda\phi^4 \text{ where } \lambda \begin{cases} \sim \mathcal{O}(10^{-12}) & \text{in GR} \\ \lesssim \mathcal{O}(1) & \text{in modified graivty} \end{cases}$$

*** Compactification of trajectory(?)**: Trans-Planckian excursion can be compactified in a sub-Planckian regime of multi-dimensional field space.

(e.g.) Aligned natural inflation, axion monodromy, etc.

$$V = \Lambda^4 \left[2 + \cos\left(f(\theta_1, \theta_2)\right) + \cos\left(g(\theta_1, \theta_2)\right)\right]$$



Spiral Inflation

[Gabriela Barenboim and WIP, Phys.Lett. B741, 252 [arXiv:1412.2724]]

- Potential

$$V = V_\phi + V_{\rm M} \; ; \quad \Phi = \frac{1}{\sqrt{2}}\phi e^{i\theta}$$

$$V_\phi = \begin{cases} \frac{1}{4}\lambda\left(\phi^2 - \phi_0^2\right)^2 \\ \frac{1}{4}\lambda\phi_0^4 + \lambda\left[\ln\left(\frac{\phi}{\phi_0}\right) - \frac{1}{4}\right] \\ \dots \end{cases}$$

➡ Symmetry-breaking potential

$$V_{\rm M} = \Lambda^4\left[1 + \sin\left(\phi/M + \theta\right)\right]$$

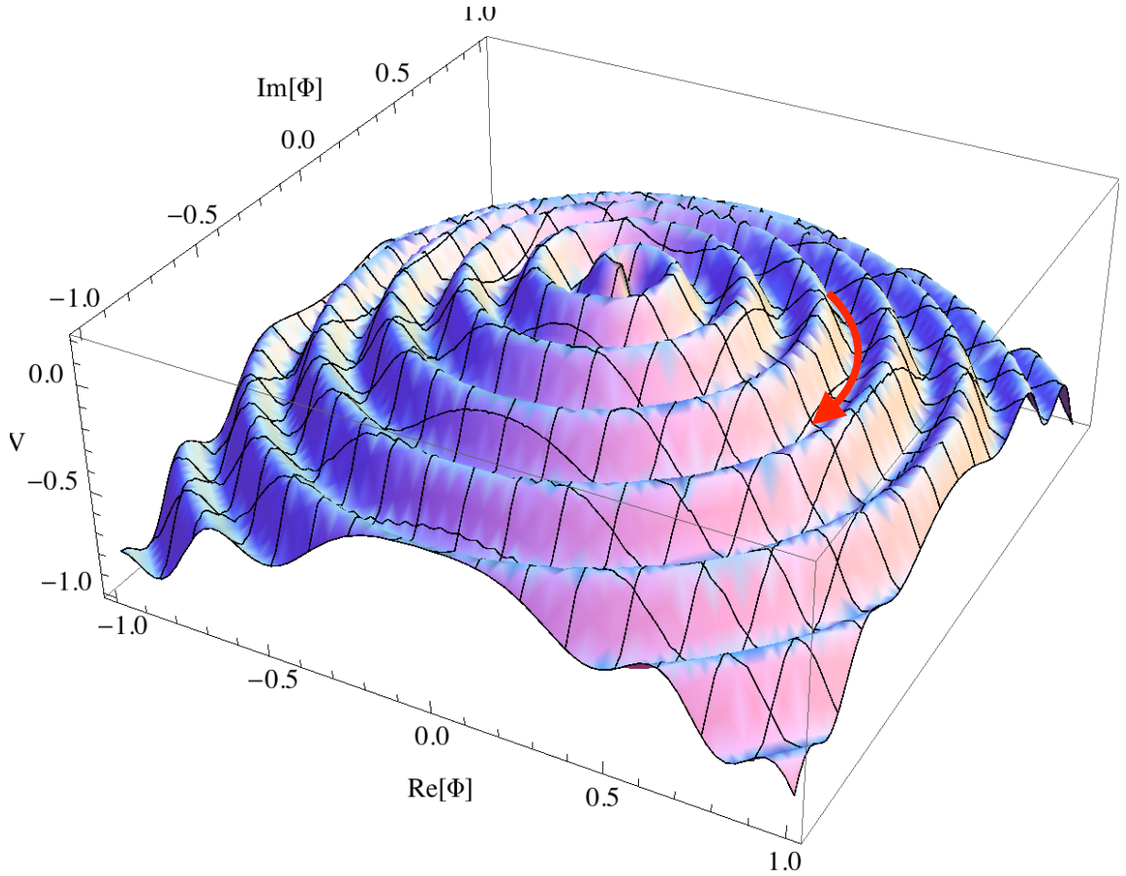
➡ Modulating potential

↑

For an UV origin, see "Berg, Pajer & Sjors, PRD81 (2010)" for example

- Inflation

$$V = V_\phi + \Lambda^4 \left[1 - \sin(\phi/M + \theta)\right]$$



* Inflation along spiraling-out valley
* $M \ll \Phi_0 \Rightarrow$ Many turns $\Rightarrow$ Elongated trajectory
* ϵ and η can be adjusted by "M/Φ_0"

* $\Phi_0 \ll M_P$ is possible
* η -problem is absent.

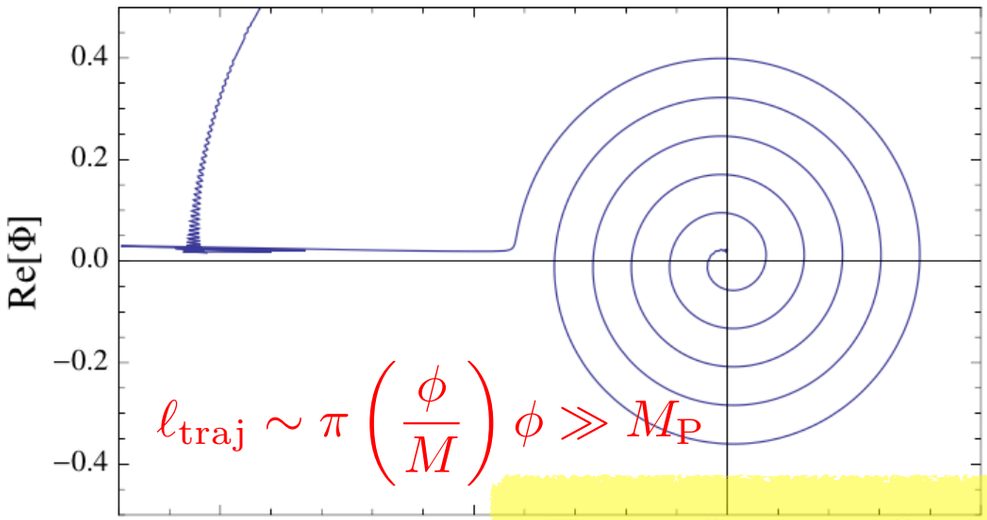
$$\epsilon \approx \epsilon_\phi / a^2, \quad \eta \approx \eta_\phi / a^2 \quad \text{with } a \equiv \phi/M \gg 1$$

- A numerical simulation

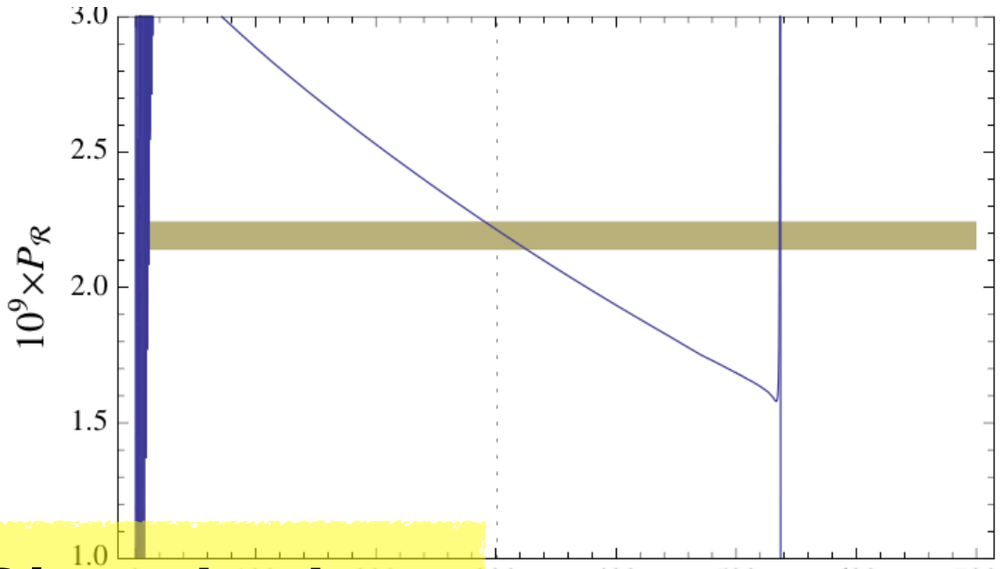
$$V_\phi = V_0 - \frac{1}{2}m^2\phi^2 + \frac{1}{4}\lambda\phi^4 \ ,$$

$$\frac{m}{10^{14}\mathrm{GeV}} = 0.796 \times 2\sqrt{3}, \ \frac{\Lambda^4}{m^2 M_\mathrm{P}^2} = 4 \times 10^{-3}$$

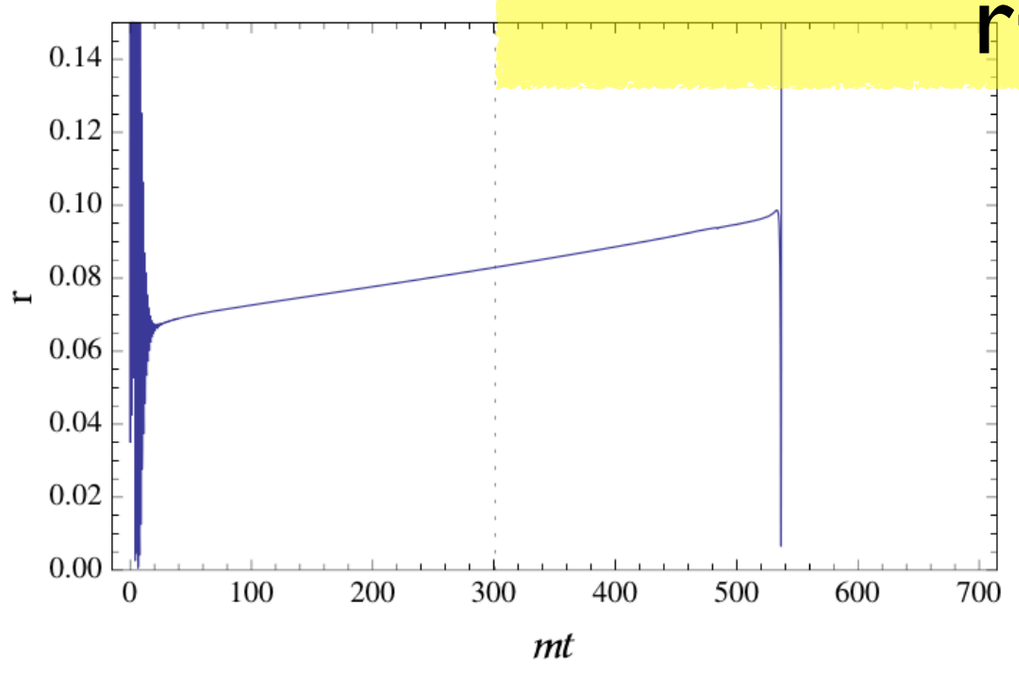
$$\frac{M}{M_\mathrm{P}} = 7.3 \times 10^{-2}, \ \lambda = (m/M_\mathrm{P})^2$$

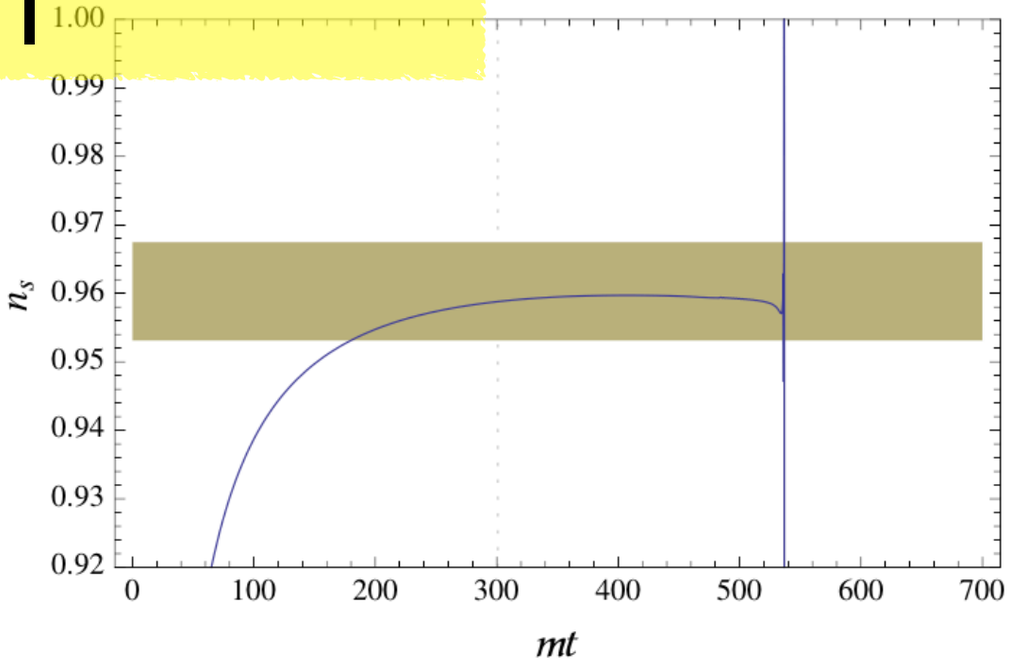


$$\ell_\mathrm{traj} \sim \pi \left(\frac{\phi}{M}\right) \phi \gg M_\mathrm{P}$$



Perfect fit to Planck data, r~0.1

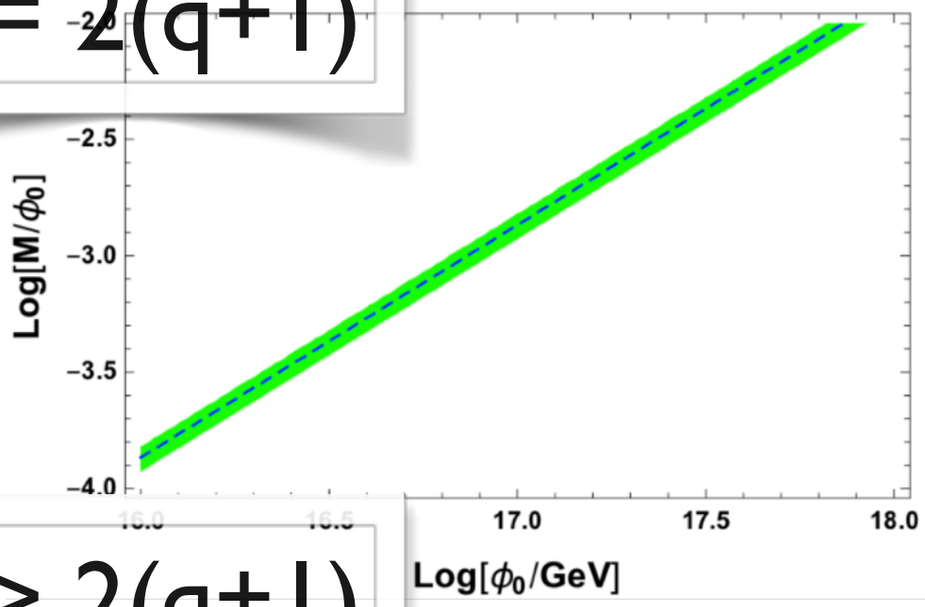




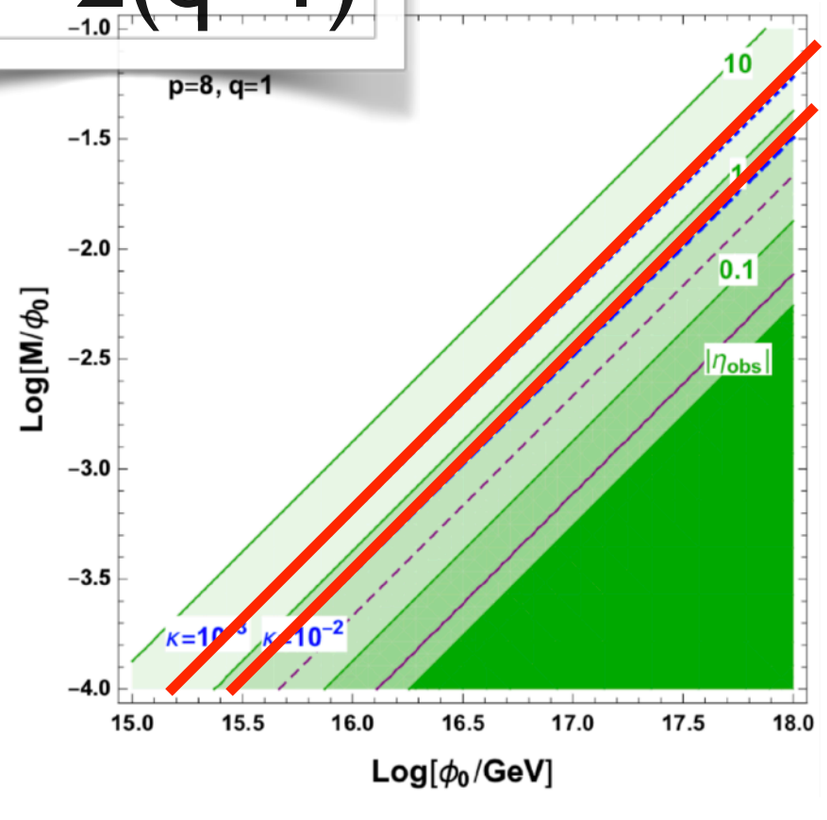
- For a more generic potential

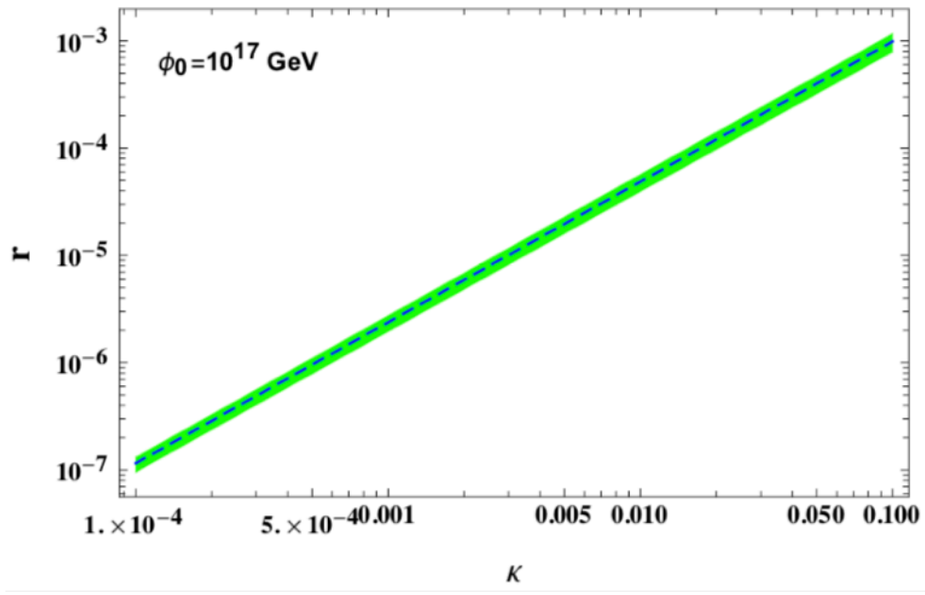
$$V = V_0 \left[1 - f(\phi)\right]^2 + \Lambda^4 \left[1 - \cos\left(h(\phi) - \theta\right)\right] \quad \begin{cases} f(\phi) = (\phi/\phi_0)^p \\ h(\phi) = (\phi/M)^q \end{cases}$$

p = 2(q+1)



p > 2(q+1)





$$\eta \simeq -\frac{2p\left[p-(q+1)\right]}{(qh_0)^2}\left(\frac{M_{\rm P}}{\phi_0}\right)^2\left(\frac{\phi}{\phi_0}\right)^{p-2(q+1)} \equiv -g(M,\phi_0)\left(\frac{\phi}{\phi_0}\right)^{p-2(q+1)}$$

$$\epsilon \simeq -\frac{pf}{p-(q+1)}\eta$$

$\kappa \sim 1 - \phi_{\rm r}/\phi_0 \sim \mathcal{O}(10^{-3\pm1})$

$$r \sim \mathcal{O}(10^{-4} - 10^{-5})$$

Baryogengesis in spiral infaltion

(conventional) Ingredients

- B or L violation

$$\left[\hat{B}, \hat{H}\right] \neq 0$$

- C & CP violation

$$\left|\mathcal{M}\left(X \to AB\right)\right|^2 - \left|\mathcal{M}\left(\bar{X} \to \bar{A}\bar{B}\right)\right|^2 \neq 0$$

$\Leftrightarrow$ interference term with non-zero CP-phases

- Out-of-equilibrium decay

In thermal equilibrium, CPT-invariant theory gives

$$\begin{aligned}\langle \hat{B} \rangle &= \mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{B}\right] \\ &= \mathrm{Tr}\left[\hat{\mathcal{O}}_{\mathrm{CPT}} \hat{\mathcal{O}}_{\mathrm{CPT}}^{-1} e^{-\beta \hat{H}} \hat{B}\right] = \mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{\mathcal{O}}_{\mathrm{CPT}}^{-1} \hat{B} \hat{\mathcal{O}}_{\mathrm{CPT}}\right] = -\langle \hat{B} \rangle\end{aligned}$$

Spontaneous baryogengesis

(1/3)

- B or L violation

$$\left[\hat{B}, \hat{H}\right] \neq 0$$

- C & CP violation

$$|\mathcal{M}(X \to AB)|^2 - |\mathcal{M}(X \to \overline{AB})|^2 \neq 0$$

$\Leftrightarrow$ interference term with non-zero CP-phases

Dynamical CPT-violation!

with

- processes in equilibrium

Out-of-equilibrium decay

In thermal equilibrium, CPT-invariant theory gives

$$\begin{aligned}\langle \hat{B} \rangle &= \mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{B}\right] \\ &= \mathrm{Tr}\left[\hat{\mathcal{O}}_{\mathrm{CPT}} \hat{\mathcal{O}}_{\mathrm{CPT}}^{-1} e^{-\beta \hat{H}} \hat{B}\right] = \mathrm{Tr}\left[e^{-\beta \hat{H}} \hat{\mathcal{O}}_{\mathrm{CPT}}^{-1} \hat{B} \hat{\mathcal{O}}_{\mathrm{CPT}}\right] = -\langle \hat{B} \rangle\end{aligned}$$

Spontaneous baryogenesis (2/3)

- Temporary dynamical CPT-violating operator

$$\mathcal{L} \supset \frac{1}{f}\left(\partial_\mu \phi\right) j_B^\mu \to \frac{\dot{\phi}}{f} j_B^0 \equiv \mu_{\rm eff} n_B$$

- $\not{B}$(or $\not{L}$) processes in equilibrium traces $\mu_{\rm eff.}$

$$\left.\frac{n_B}{s}\right|_0 \sim \left.\frac{\mu_{\rm eff}}{T}\right|_{\rm decoupling}$$

(if $\mu_{\rm eff}$ has a definite sign - i.e., during the rolling phase of ϕ)

Spontaneous baryogenesis

(3/3)

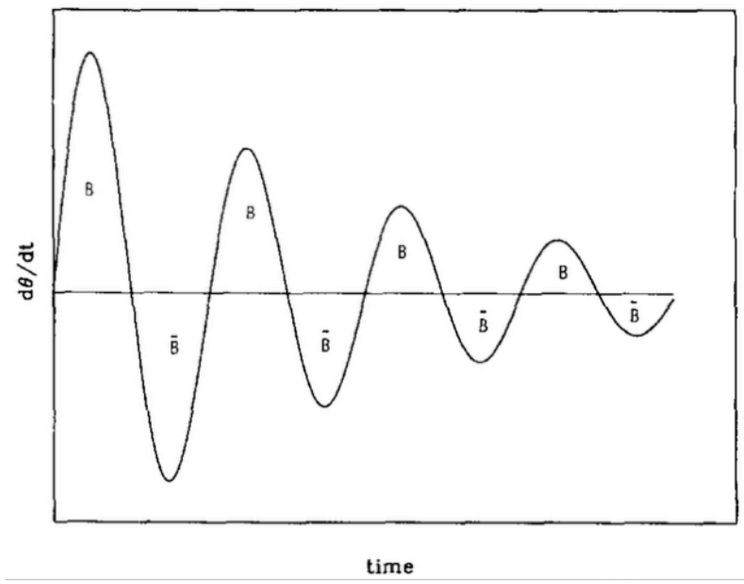
- Contribution after decoupling in osc.-phase:

$$\frac{1}{f}\left(\partial_\mu \phi\right) j_B^\mu \to \frac{1}{f}\phi \partial_\mu j_B^\mu \Rightarrow \not{B}(\not{L}) - \text{decay of } \phi$$

$$\left(\partial_\mu j_B^\mu \neq 0\right)$$

In case of pseudo-scalar example,

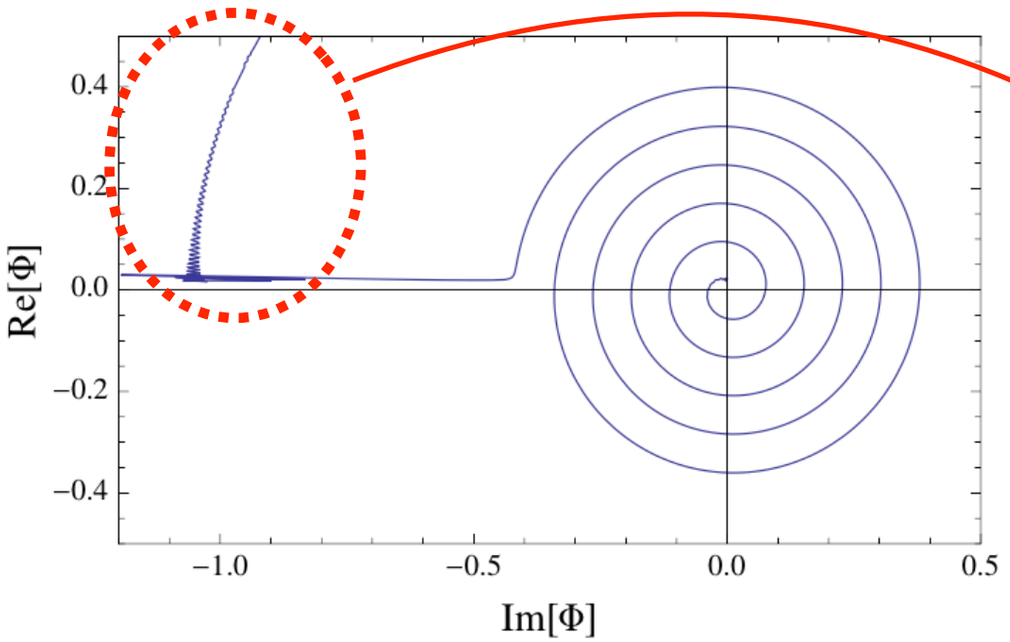
$$\dot{n}_B + 3Hn_B = \Gamma_\theta n_\theta \quad \left(n_\theta = qf^2\dot{\theta}\right)$$



$but\ \langle n_B \rangle \neq 0$

Barygenesis in Spiral inf. (1/3)

- Generation from inflation decay at t > t_dec



$$\dot{\theta} \neq 0 \; at \; t \gg t_{\rm end}$$

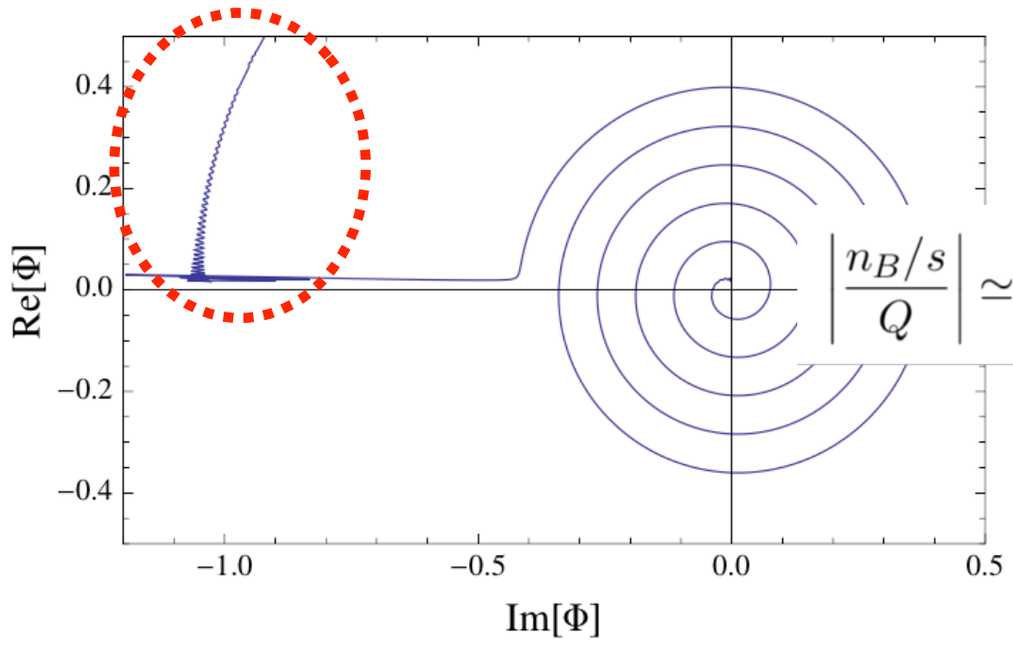
(but falls quickly into an oscillating phase)

$$n_B \sim \frac{\Gamma_\theta}{H_{\rm soc}} n_\theta(t_{\rm osc}) \left(\frac{a_{\rm osc}}{a}\right)^3 \quad ; \; \Gamma_\theta \equiv \frac{\gamma_\theta}{8\pi} \frac{m_\theta^3}{\phi_0^2}$$

$$\hookrightarrow n_B(t_{\rm osc})$$

Barygenesis in Spiral inf. (2/3)

- Generation from inflation decay at t > t_dec

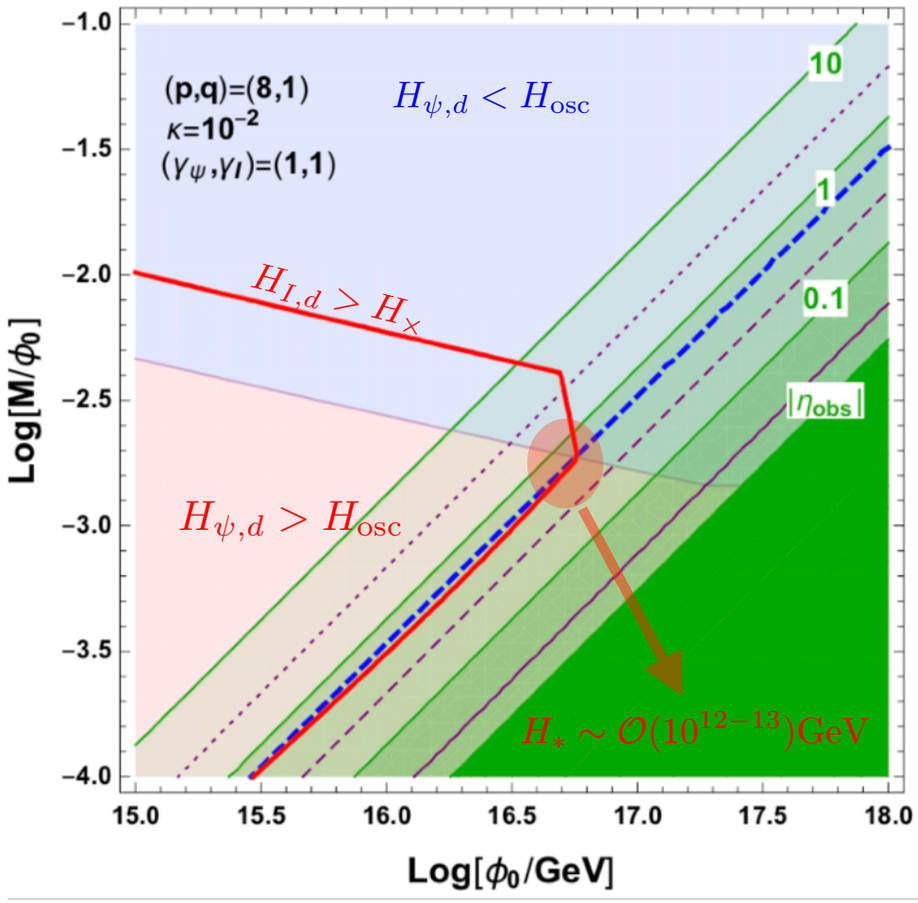


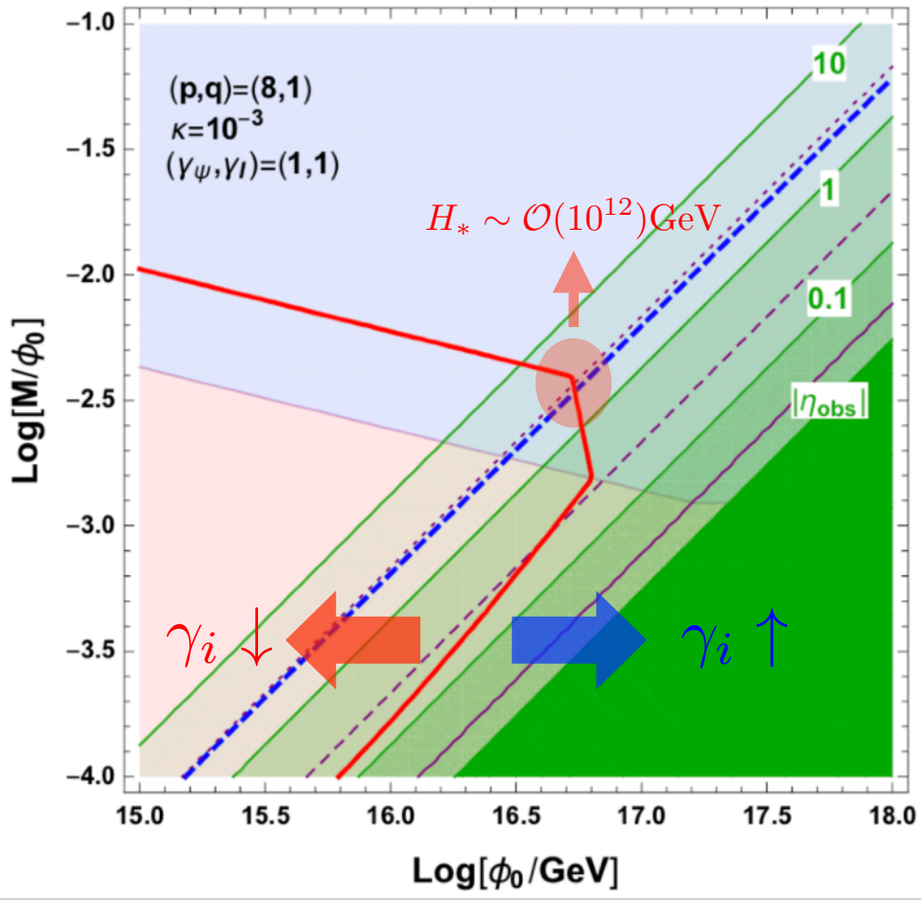
$$\left|\frac{n_B/s}{Q}\right| \simeq \mathcal{F}(x_{\rm osc},\infty)\frac{\gamma_I\alpha}{8\pi\beta}\left(\frac{m_{I,0}}{M_{\rm P}}\right)^{3/2}\left(\frac{m_{I,0}}{H_{\rm osc}}\right)^{3/2}\left(\frac{H_\psi}{H_{\rm osc}}\right)^{1/2}$$

$$\left|\frac{n_B/s}{Q}\right| \simeq \begin{cases} 1.0\times10^{-10}\mathcal{F}(x_{\rm osc},\infty)\gamma_I\alpha\left(\frac{g_*}{200}\right)^{-1/4}\left(\frac{H_*}{10^{14}\,{\rm GeV}}\right)^{3/2}\left(\frac{H_\psi}{H_{\rm osc}}\right)^{1/2} & : p = 2(q+1) \\ 2.7\times10^{-9}\mathcal{F}(x_{\rm osc},\infty)\gamma_I\alpha\left(\frac{g_*}{200}\right)^{-1/4}\left[\frac{pg(M,\phi_0)}{p-(q+1)}\right]^{3/2}\left(\frac{H_*}{10^{13}\,{\rm GeV}}\right)^{3/2}\left(\frac{H_\psi}{H_{\rm osc}}\right)^{1/2} & : p > 2(q+1) \end{cases}$$

Barygenesis in Spiral inf. (3/3)

- Generation from inflation decay at t > t_dec





Conclusions

1. Spiral inflation is a scenario of inflation, which is free from eta-problem and match well observations.

2. The parameter space for a right amount of baryon number asymmetry in spiral inflation was analyzed.

3. To be applied to model-dependent scenarios, B(L)-violating operator should be specified.