



Affleck-Dine baryogenesis with modulated reheating

Kazunori Kohri (郡 和範)

KEK, IPNS

Based on

Kohri, Lyth, Valenzuela-Toledo, arXiv:0904.0793 [hep-ph]

Kamada, Kohri and Shuichiro Yokoyama, arXiv:1008.1450 [astro-ph]

Abstract

In “Modulated” Reheating or Preheating” scenario, fluctuation of a light field σ contributes to curvature perturbation and produces sizable amount of f_{NL}

Modulated reheating scenario can be still consistent with Affleck-Dine baryogenesis. We can check the scenario in future experiments such as Planck, PolarBeaR and LiteBIRD

Hubble expansion rate (Hubble parameter)

$$H \equiv \frac{1}{a(t)} \frac{da(t)}{dt}$$

$$\sim \begin{cases} \text{const during Inflation} \\ 1/t \text{ for usual expansion} \end{cases}$$

$a(t)$: scale factor, $r = a(t) \times$ in
expanding universe

Introduction

■ Inflation paradigm is attractive ($N \sim H \times t$)

- Solving horizon problem ($N > 50 - 60$ where $a(t_f) / a(t_i) \sim e^N$)
- Solving flatness problem ($N > 50 - 60$)
- Solving GUT monopole problem ($T_R < 10^{15}$ GeV)
- Producing density (curvature) fluctuation

■ Observation (WMAP)

- Power spectrum of density fluctuation

$$\sqrt{P_\zeta} \sim \frac{v}{M_p^4} \frac{1}{\epsilon} = (4.9 \pm 0.2) \times 10^{-5}$$

- Spectral index

$$n = \frac{d \ln P_\zeta}{d \ln k} + 1 = 0.96 \pm 0.03 \text{ (2}\sigma\text{)}$$

- Running of $n(k)$

$$-0.07 < \frac{dn}{d \ln k} < 0.02 \text{ (2}\sigma\text{)}$$

Tensor to scalar ratio vs spectral index

In chaotic inflation

$$V = \frac{1}{2} m_\phi^2 \phi^2$$

- Slow-roll parameters

$$\varepsilon = \frac{1}{2} \left(M_G \frac{V'}{V} \right)^2 = 2(M_G/\phi)^2 \ll 1$$

$$\eta = M_G^2 \frac{V''}{V} = 2(M_G/\phi)^2 \ll 1$$

- Spectral index

$$n_s - 1 = 2\eta - 6\varepsilon < 0$$

- Tensor to scalar ratio

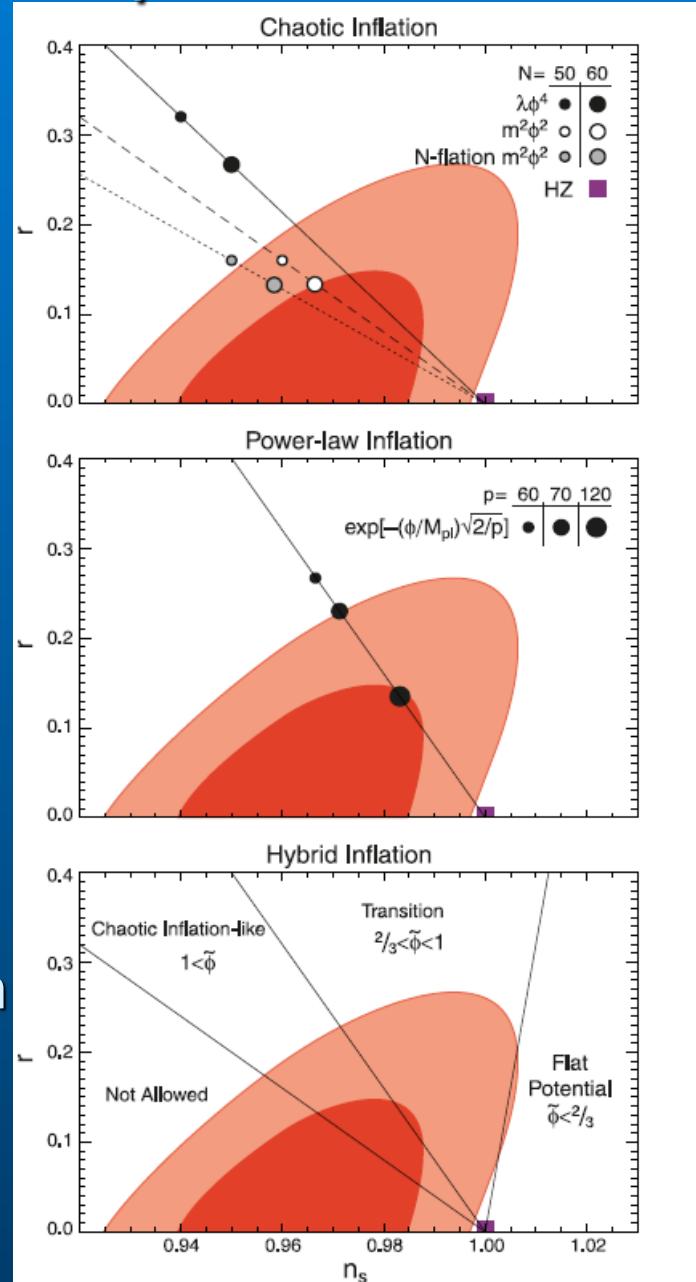
$$r \sim 16\varepsilon \sim 0.1$$

- E-folding number during inflation

$$N \sim \frac{\phi_*^2 - \phi_{end}^2}{M_G^2} \sim 50 - 60$$

- Field value at horizon exit

$$\phi_* \sim 7M_G \sim 2M_P$$



WMAP 7-year, Komatsu et al (10)

Constraints on non-gaussianity

- WMAP 7-year reported

$$f_{NL}^{local} = 32 \pm 21 \quad (68\% C.L.)$$

Komatsu et al, (2010)

Gaussian perturbation

■ Correlators

1. 2-point correlation function

$$\langle \zeta_{\vec{k}} \zeta_{\vec{k}'} \rangle = (2\pi)^3 \delta^3(\vec{k} + \vec{k}') P_\zeta(k)$$

$$\zeta_{\vec{k}} = \int \zeta(\vec{x}) e^{-i\vec{k} \cdot \vec{x}} d^3x$$

2. Odd-number point correlation funcs.

$$\langle \zeta_{\vec{k}} \rangle = 0$$

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = 0$$

$$P_\zeta = \frac{k^3}{2\pi^2} P_\zeta \left(\sim \text{scale invariant} \propto k^0 ? \right)$$

Power spectrum

Red galaxies, $b = 1$

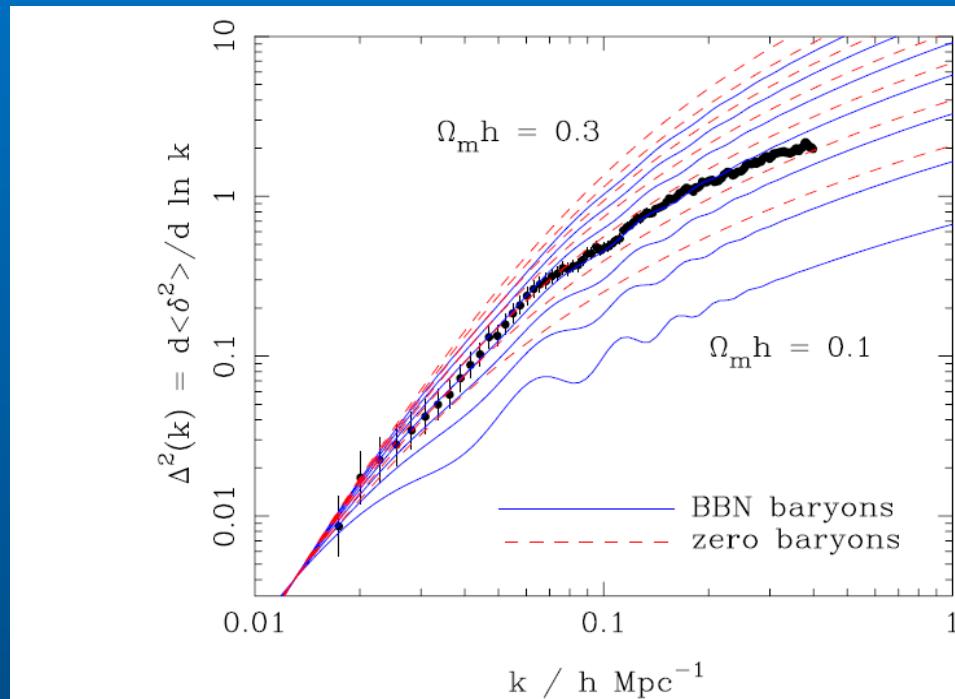
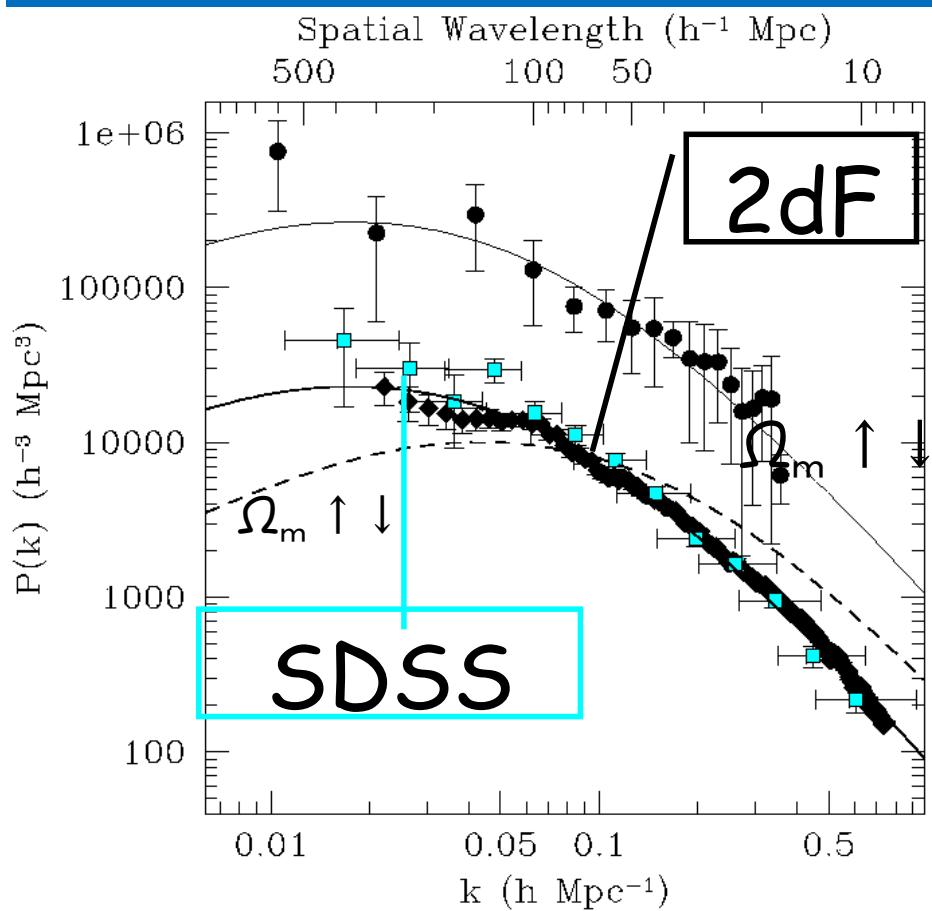


Figure 19.5: The galaxy power spectrum from the 2dFGRS, shown in dimensionless form, $\Delta^2(k) \propto k^3 P(k)$. The solid points with error bars show the power estimate. The window function correlates the results at different k values, and also distorts the large-scale shape of the power spectrum. An approximate correction for the latter effect has been applied. The solid and dashed lines show various CDM models, all assuming $n = 1$. For the case with non-negligible baryon content, a big-bang nucleosynthesis value of $\Omega_b h^2 = 0.02$ is assumed, together with $h = 0.7$. A good fit is clearly obtained for $\Omega_m h \simeq 0.2$.

Angular spectrum of CMB anisotropy

- Temperature fluctuation

$$\frac{\delta T}{T}(\vec{n}) = \sum_{\ell,m} (-1)^\ell a_{\ell m} Y_{\ell m}(\vec{n})$$

- Angular spectrum

$$\langle a_{\ell m} a_{\ell' m'}^* \rangle = \delta_{\ell m} \delta_{\ell' m'} C_\ell$$

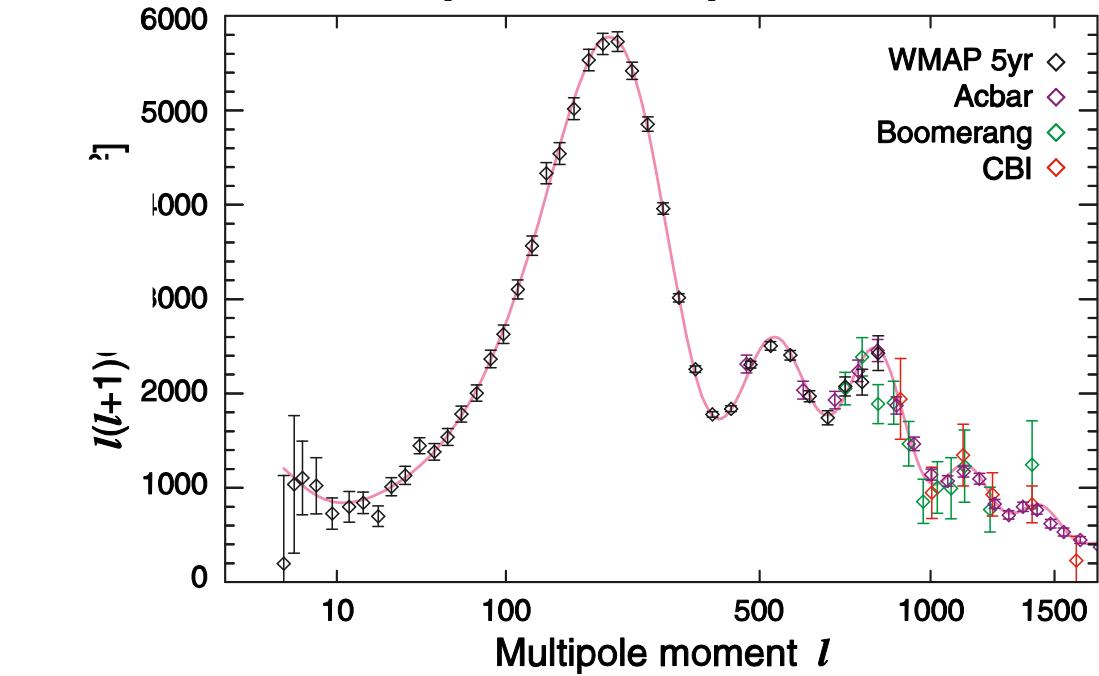
- Correlation function of temperature fluc.

$$\left\langle \frac{\delta T}{T}(\vec{e}_1) \frac{\delta T}{T}(\vec{e}_2) \right\rangle = \sum_{\ell} \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos \theta)$$

- Curvature fluctuation

$$a_{\ell m} = \frac{4\pi}{(2\pi)^3} i^\ell \int \Theta_\ell(\vec{k}) Y_{\ell m}^* d^3 k \quad \Theta_\ell(\vec{k}) = T_\ell(k) \xi_{\vec{k}}$$

Cosmic Microwave Background (CMB) Anisotropy



Non-gaussian perturbation

- 3-point correlator and bispectrum B

$$\left\langle \zeta_{\vec{\mathbf{k}}_1} \zeta_{\vec{\mathbf{k}}_2} \zeta_{\vec{\mathbf{k}}_3} \right\rangle = (2\pi)^3 \delta^3(\vec{\mathbf{k}}_1 + \vec{\mathbf{k}}_2 + \vec{\mathbf{k}}_3) B_\zeta(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

- Nonlinearity parameter f_{NL}

$$B_\zeta(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) = \frac{6}{5} f_{NL}(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3) [P_\zeta(\mathbf{k}_1)P_\zeta(\mathbf{k}_2) + P_\zeta(\mathbf{k}_2)P_\zeta(\mathbf{k}_3) + P_\zeta(\mathbf{k}_3)P_\zeta(\mathbf{k}_1)]$$

$$\begin{aligned} \zeta(\vec{x}) &= \zeta_{gaussian} + \zeta_{nongaussian} \\ &= \zeta_{gaussian} + b(\zeta_{gaussian})^2 \end{aligned}$$

$$b = \frac{3}{5} f_{NL}$$

δN formalism and curvature perturbation

Sasaki-Stewart ('96), Sasaki-Tanaka('98), Lyth-Rodriguez ('04)

- Curvature perturbation ζ with choosing a gauge in which threads are comoving and the slice of uniform-energy density

$$a(\vec{x}, t) = a(t) e^{\zeta(\vec{x}, t)}$$

$$g_{ij} = a^2(\vec{x}, t) \gamma_{ij}(\vec{x})$$

$$\begin{aligned}\delta N(x, t) &= \ln a(x, t) / a(x, 0) - \ln a(t) / a(0) \\ &= \ln a(x, t) / a(t) - \ln a(x, 0) / a(0) \\ &= \zeta(\vec{x}, t) - 0\end{aligned}$$

$$\zeta(\vec{x}, t) = \delta N(x, t)$$

[Generally $a(x, t) = a(t) e^{\psi(x, t)}$ with $\psi(x, t) = \zeta(x, t)$ for uniform-density slice,
 $\psi(x, 0) = 0$ for flat slicing]

δN formalism

- Curvature perturbation

$$\zeta = \delta N = \underbrace{\frac{\partial N}{\partial \phi} \delta \phi}_{\text{g part}} + \underbrace{\frac{1}{2} \frac{\partial^2 N}{\partial \phi^2} (\delta \phi)^2}_{\text{non-g part}} + \dots$$

- Power spectrum

$$P_{\zeta_\phi} = (N_\phi)^2 P_{\delta\phi} \text{ where } N_\phi = dN / d\phi$$

- Nonlinear parameter

$$\frac{5}{6} f_{NL} = \left(\frac{P_{\zeta_\phi}}{P_{\zeta, obs}} \right)^2 \frac{N_{\phi\phi}}{(N_\phi)^2}$$

Practice in chaotic inflation

- Potential

$$V = \frac{1}{2} m_\phi^2 \phi^2$$

- Slow roll parameters

$$\varepsilon = \frac{1}{2} \left(M_G \frac{V'}{V} \right)^2 = 2(M_G/\phi)^2 \ll 1$$

$$\eta = M_G^2 \frac{V''}{V} = 2(M_G/\phi)^2 \ll 1$$

- Horizon exit

$$\phi_* \sim 7M_G \sim 2M_P$$

Practice in chaotic inflation model

part II

■ e-folding number N

$$N = \ln \frac{a(t_{end})}{a(t_*)} = \int_{t_*}^{t_{end}} \frac{da}{a} = \int_{t_*}^{t_{end}} H dt$$

■ Friedman equation

$$H^2 = \frac{V}{3M_G^2}$$

■ Slow-roll

$$\ddot{\phi} + 3H\dot{\phi} = -\frac{dV}{d\phi}$$

$$H dt = \frac{H}{\dot{\phi}} d\phi = -\frac{3H^2}{V'} d\phi = -\frac{1}{M_G^2} \frac{V}{V'} d\phi$$

Practice in chaotic inflation model part III

■ e-folding number N

$$N \sim \frac{\phi_*^2 - \phi_{end}^2}{M_G^2} \sim 60$$

$$N_\phi \sim \frac{2\phi_*}{M_G^2}$$

$$N_{\phi\phi} \sim \frac{2}{M_G^2}$$

■ Spectrum $P_\zeta = (N_\phi)^2 P_{\delta\phi} \sim \left(\frac{2\phi_*}{M_G^2}\right)^2 \left(\frac{H}{2\pi}\right)^2 \sim \left(\frac{\phi_*}{\pi M_G}\right)^2 \left(\frac{m_\phi \phi_*}{2M_G^2}\right)^2$
 $\sim 3 \times 10^{-9}$

$$(\rightarrow m_\phi \sim 10^{-5} M_G \sim 10^{13} GeV)$$

■ Non-gaussianity

$$\frac{5}{6} f_{NL} = \left(\frac{P_\zeta}{P_{\zeta,obs}} \right)^2 \frac{N_{\phi\phi}}{(N_\phi)^2} \sim \frac{1}{2(\phi_*/M_G)^2}$$

$$\sim \eta - 2\varepsilon \sim O(0.01)$$

Large non-gaussianity?

$$f_{NL} \sim O(10)$$

Modulated Reheating

Dvali, Gruzinov, Zaldarriaga(04)
Kofman {04}
Zaldarriaga (04)

- If decay rate $\Gamma = 1/t_{\text{dec}} \sim T_R^2/M_{\text{pl}}$ depends on another field σ $\Gamma = \Gamma(\sigma)$

$$\frac{a_{\text{dec}}}{a_i} \propto t_{\text{dec}}^{2/3} \propto \Gamma^{-2/3}$$

$$\frac{a_f}{a_{\text{dec}}} \propto t_{\text{dec}}^{-1/2} \propto \Gamma^{1/2}$$

$$N = \ln\left(\frac{a_{\text{dec}}}{a_i}\right) + \ln\left(\frac{a_f}{a_{\text{dec}}}\right) = \left(-\frac{2}{3} + \frac{1}{2}\right) \ln(\Gamma) + \dots$$

$$= -\frac{1}{6} \ln(\Gamma) + \dots$$

See also, Alabidi, Malik, Byrnes, Choi, JCAP 1011:037,2010, arXiv:1002.1700

Decay rate with σ

- An example of interaction Lagrangian

$$\mathcal{L}_{\text{int}} = g \varphi \bar{\psi} \psi$$

- Decay rate

$$\Gamma_\varphi \sim g^2 m_\varphi$$

- Coupling with σ

$$g(\sigma) \sim g \left[1 + \lambda \left(\frac{\sigma}{M_{\text{cut}}} \right)^2 \right]$$

Calculation in modulated reheating

$$N_\sigma = \frac{\partial N}{\partial \Gamma} \frac{\partial \Gamma}{\partial \sigma} \quad N_{\sigma\sigma} = \frac{\partial N}{\partial \Gamma} \frac{\partial^2 \Gamma}{\partial \sigma^2} + \frac{\partial^2 N}{\partial \Gamma^2} \left(\frac{\partial \Gamma}{\partial \sigma} \right)^2$$

$$P_{\zeta_\sigma} = (N_\sigma)^2 (H_* / 2\pi)^2$$

$$\frac{6}{5} f_{NL} = \left(\frac{P_{\zeta_\sigma}}{P_{\zeta, \text{obs}}} \right)^2 \frac{N_{\sigma\sigma}}{(N_\sigma)^2}$$

Detectable non-gaussianity and tensor to scalar ratio

$$\mathcal{L}_{\text{int}} = g\varphi\bar{\psi}\psi$$

$$\Gamma_\varphi \sim g^2 m_\varphi \quad g(\sigma) \sim g \left[1 + \lambda \left(\frac{\sigma}{M_{cut}} \right)^2 \right]$$

- Non-gaussianity

$$f_{\text{NL}} \sim -10^2 \lambda^{-1} \left(\frac{\sigma}{0.1 M_{cut}} \right)^{-2} \left(\frac{P_{\zeta_\sigma}}{P_{\zeta_\sigma} + P_{\zeta_I}} \right)^2$$

- Tensor to scalar ratio

$$r = 16\varepsilon \left(\frac{P_{\zeta_I}}{P_{\zeta_\sigma} + P_{\zeta_I}} \right) \sim 0.1 \left(H_{\text{inf}} / 10^{13} \text{GeV} \right)^2 \left(\frac{P_{\zeta_I}}{P_{\zeta_\sigma} + P_{\zeta_I}} \right)$$

Affleck-Dine baryogenesis with modulated reheating

Kamada, Kohri, Yokoyama, arXiv:1008.1450 [astro-ph]

How does it depend on T_R ?

- The baryon number often depends on the reheating temperature in cosmologies with SUSY or SUGRA

$$\frac{n_B}{s} \propto (T_R)^p, \quad p = 0, 1, \dots$$

Is baryonic-Isocurvature perturbation induced?

- Baryonic-Isocurvature perturbation

$$S_B \equiv \frac{\delta(n_B/s)}{n_B/s} = p \frac{\delta T_R}{T_R}$$

- Adiabatic curvature perturbation

$$\sqrt{P_\zeta} = \delta N = -\frac{1}{6} \frac{\delta \Gamma}{\Gamma} = \frac{1}{3} \frac{\delta T_R}{T_R}$$
$$\Gamma \sim T_R^2 / M_{pl}$$

Is it observationally allowed?

- Theoretically

$$\frac{S_B}{\sqrt{P_\zeta}} = -3p$$

- Observationally

$$\left| \frac{S_B}{\sqrt{P_\zeta}} \right| \leq O(1)$$
$$\Rightarrow |p| < 1/3$$

Affleck-Dine baryogenesis

- Powerful mechanism in SUSY or SUGRA cosmology

Φ : AD field which carries baryon #

$$W = \lambda_0 \frac{\Phi^{n+3}}{M_*^n} \quad K = |\Phi|^2 + |I|^2 + \lambda |\Phi|^2 |I|^2 / M_{pl}^2$$

$$\begin{aligned} V &= e^{K/M_{pl}} \left[\left(W_i + \frac{W K_i}{M_{pl}^2} \right) K^{i,\bar{j}} \left(W_{\bar{j}}^* + \frac{W^* K_{\bar{j}}}{M_{pl}^2} \right) - 3 \frac{|W|^2}{M_{pl}^2} \right] \\ &= V_{mass} - \underbrace{c_H H^2 |\Phi|^2}_{|\Phi| \sim (H M_*)^{\frac{1}{n+1}}} + |\lambda_0|^2 \frac{|\Phi|^{2n+4}}{M_*^{2n}} + \left(a_B \lambda_0 m_{3/2} \frac{\Phi^{n+3}}{M_*^n} + h.c. \right) \end{aligned}$$

“Mass term” before reheating

- i. Soft-mass term

$$T = \left(H M_G T_R^2 \right)^{1/4}$$

$$m_{\text{soft}}^2 |\Phi|^2$$

- ii. Thermal mass term from plasma

$$h^2 T^2 |\Phi|^2$$

- iii. Thermal log from 2nd order and running of gauge coupling

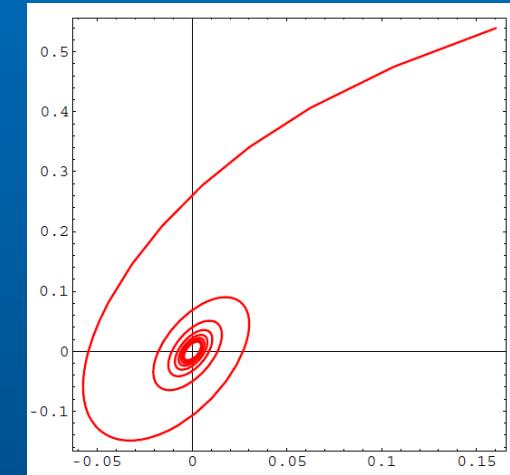
$$\alpha_g^2 T^4 \log \left(h^2 |\Phi|^2 / T^2 \right)$$

Baryon number generation

- Oscillation of Affleck-Dine Field Φ starts when

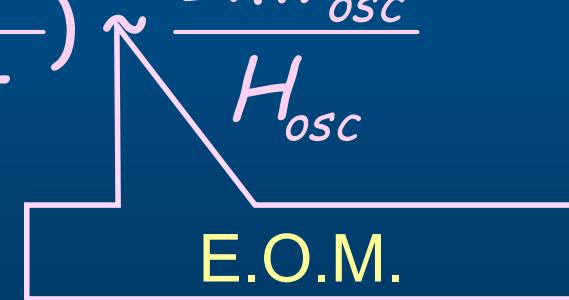
$$\sqrt{|V''|} = H_{osc}$$

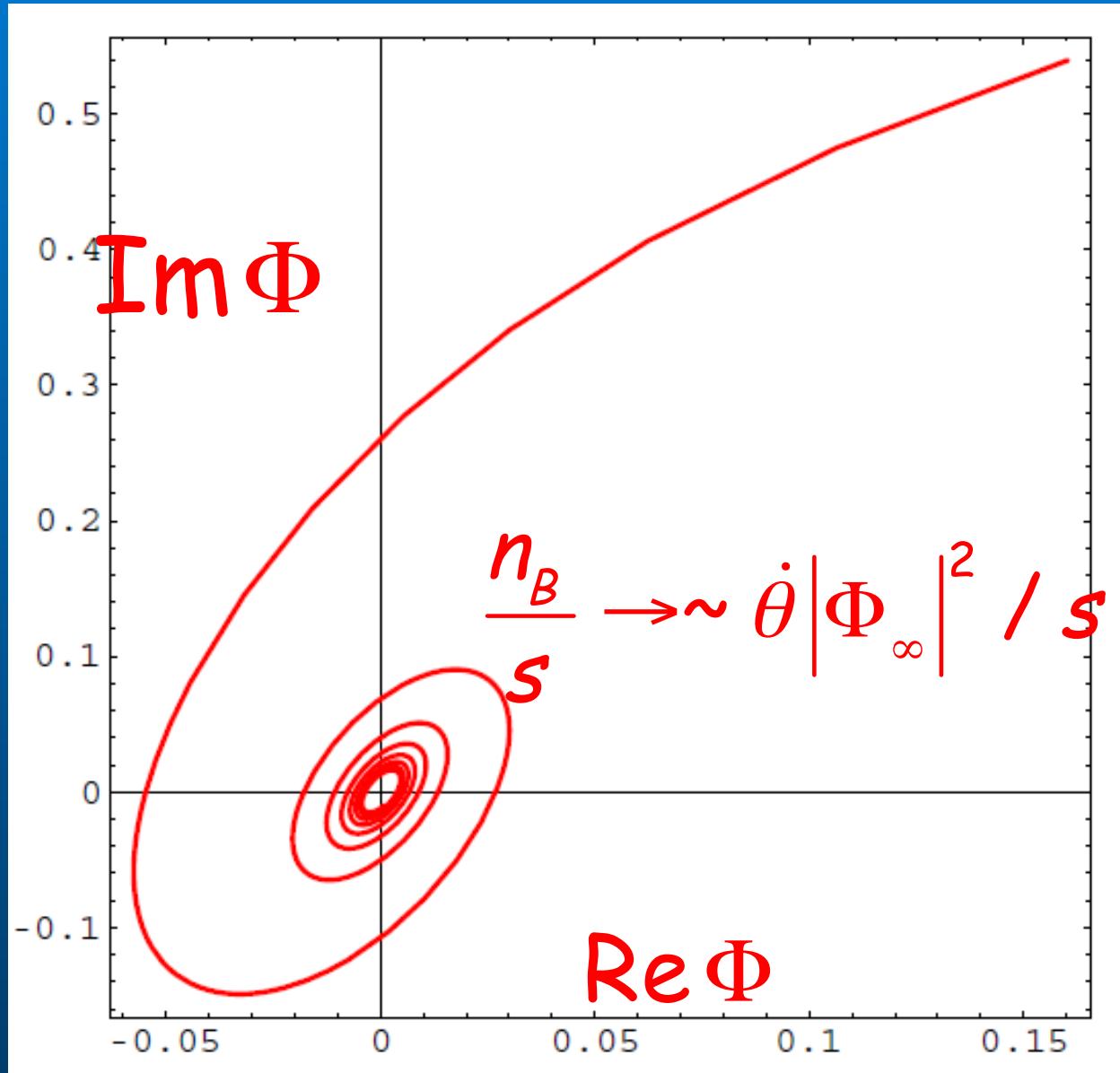
- Baryon number



$$n_B = iq\left(\frac{d\Phi^*}{dt}\Phi - \Phi^*\frac{d\Phi}{dt}\right) \xrightarrow{\frac{\text{Im}V_{osc}}{H_{osc}}}$$

$$\sim m_{3/2} |\Phi_{osc}|^2$$





Baryon to entropy ratio

- Dilution before reheating

$$\frac{n_B}{s} \sim \frac{n_B(t_R)}{T_R^3} \sim \frac{n_B(t_{osc}) (H_R / H_{osc})^2}{T_R^3}$$
$$\sim \frac{m_{3/2} M_*^{2/(n+1)}}{M_G^2} T_R H_{osc}^{-2n/(n+1)}$$

Generally $H_{osc} = H_{osc}(T_R)$

T_R dependence on baryon#

i. Soft-mass term

$$\frac{n_B}{s} \propto T_R^{-1} \quad \text{with } H_{osc} \sim m_{soft}$$

ii. Thermal mass term

$$\frac{n_B}{s} \propto T_R^0 \quad \text{with } n=3, \quad H_{osc} \propto T_R^{2/3}, \\ M_* \sim 10^{16} \text{GeV}, \quad T_R \sim 10^6 \text{GeV}$$

iii. Thermal log term

$$\frac{n_B}{s} \propto T_R^0 \quad \text{with } n=1, \quad H_{osc} \propto T_R^{-1} \\ M_* \sim 10^{23} \text{GeV}, \quad T_R \geq 10^7 \text{GeV}$$

Isocurvature mode originated from the phase component

Kawasaki, Nakayama, F.Takahashi (09)

$$S_{B,\text{phase}} \sim \cot(n\theta_{\text{inf}} + \alpha) \left(\frac{H_{\text{inf}}}{M_*} \right)^{n/(n+1)}$$

- In case of thermal mass term

$$H_{\text{inf}} \leq 10^9 \text{ GeV} \quad \text{with } n=3, M_* \sim 10^{16} \text{ GeV}, \\ T_R \sim 10^6 \text{ GeV}$$

- In case of thermal log

$$H_{\text{inf}} \leq 10^{13} \text{ GeV} \quad \text{with } n=1, M_* \sim 10^{23} \text{ GeV}, \\ T_R \geq 10^7 \text{ GeV}$$

Detectable non-gaussianity and tensor to scalar ratio

$$\mathcal{L}_{\text{int}} = g\varphi\bar{\psi}\psi$$

$$\Gamma_\varphi \sim g^2 m_\varphi \quad g(\sigma) \sim g \left[1 + \lambda \left(\frac{\sigma}{M_{cut}} \right)^2 \right]$$

- Non-gaussianity

$$f_{\text{NL}} \sim -10^2 \lambda^{-1} \left(\frac{\sigma}{0.1 M_{cut}} \right)^{-2} \left(\frac{P_{\xi_\sigma}}{P_{\xi_\sigma} + P_{\xi_I}} \right)^2$$

- Tensor to scalar ratio

$$r = 16\varepsilon \left(\frac{P_{\xi_I}}{P_{\xi_\sigma} + P_{\xi_I}} \right) \sim 0.1 \left(H_{\text{inf}} / 10^{13} \text{GeV} \right)^2 \left(\frac{P_{\xi_I}}{P_{\xi_\sigma} + P_{\xi_I}} \right)$$

Conclusion

- Modulated reheating scenarios are quite attractive because coupled massless σ quanta can contribute to curvature perturbation and f_{NL}
- This scenario will be able to be checked by Planck, PolarBeaR and LiteBIRD.

Model of preheating

Kofman, Linde, Starobinsky ('94), ('97)

See also Fujisaki, Kumekawa, Yamaguchi, Yoshimura (95)

- Motivated by particle physics (Chaotic Inflation, A-term Inflation, Inflection point Inflation.), we may adopt $\frac{1}{2} m^2 \phi^2$ for inflaton potential

$$L = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} g^2 \chi^2 \phi^2$$

Reduction of ρ_ϕ and resonant production of ρ_χ

- See massless preheating models.

$$L = \frac{1}{4} \lambda \phi^4 + g^2 \chi^2 \phi^2$$

See Bond, Frolov, Huang, Kofman, arXiv:0903.3407

How large/small is g^2 ?

- For no radiative corrections to the potential

$$g^2 \ll 10^{-6} \quad (V_{\text{l-loop}} \sim g^4 \phi^4 \log(\phi/Q))$$

But see Barnaby, Huang, Kofman, Pogosyan, [arXiv:0902.0615](https://arxiv.org/abs/0902.0615)

- Massless fluctuation of χ during inflation $g^2 < 10^{-10}$ ($gM_p < H_* \sim m_\phi$)

Mathew Equation

Mode expansion

$$\hat{\chi}(t, \mathbf{x}) = \frac{1}{(2\pi)^{3/2}} \int d^3 k \left(\hat{a}_k \chi_k(t) e^{-i\mathbf{k}\mathbf{x}} + \hat{a}_k^+ \chi_k^*(t) e^{i\mathbf{k}\mathbf{x}} \right)$$

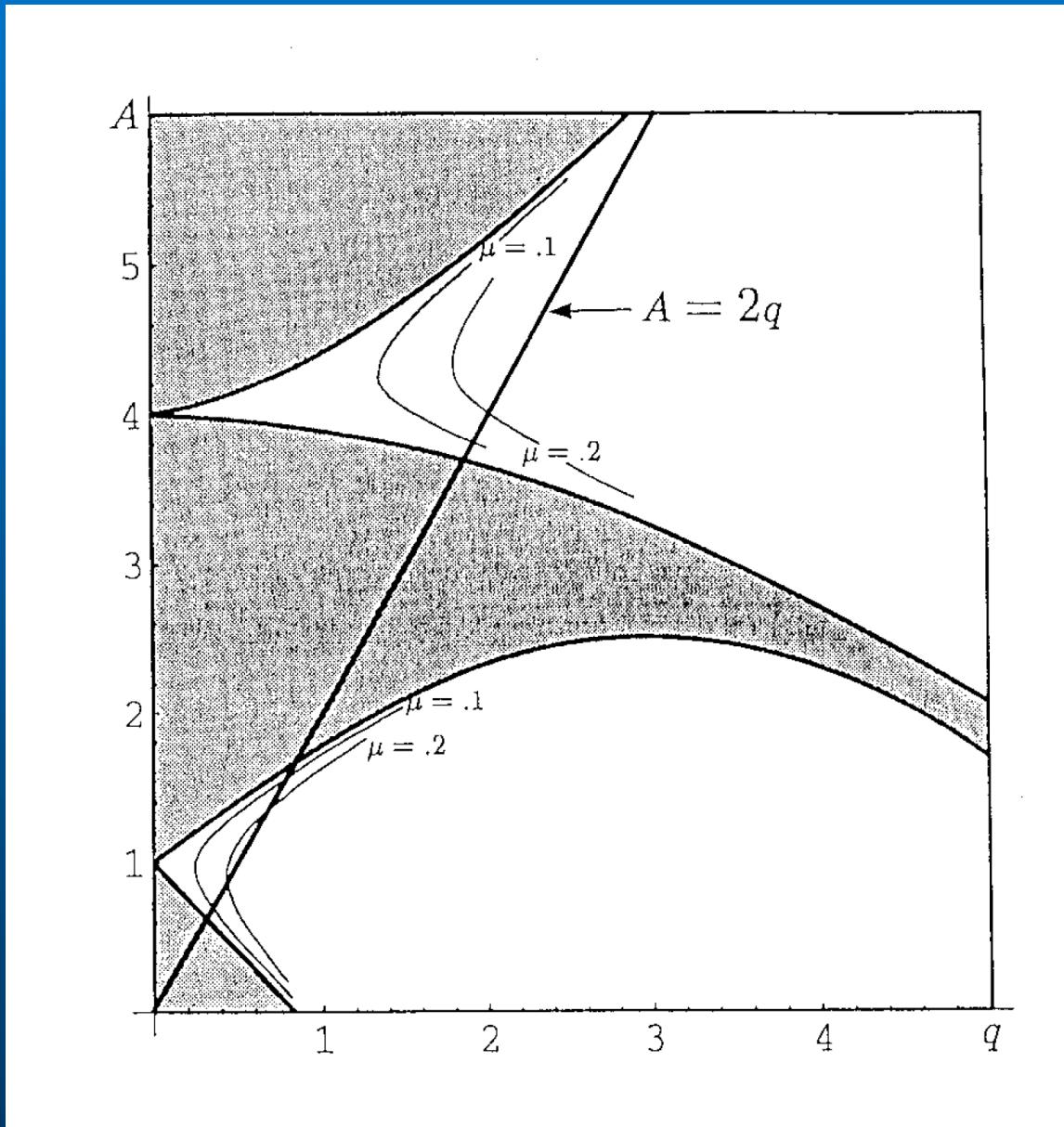
Equation of Motion

$$\ddot{\chi}_k + 3 \frac{\dot{a}}{a} \dot{\chi}_k + \left(\frac{\mathbf{k}^2}{a^2} + g^2 \phi^2 \right) \chi_k = 0$$

Instability band

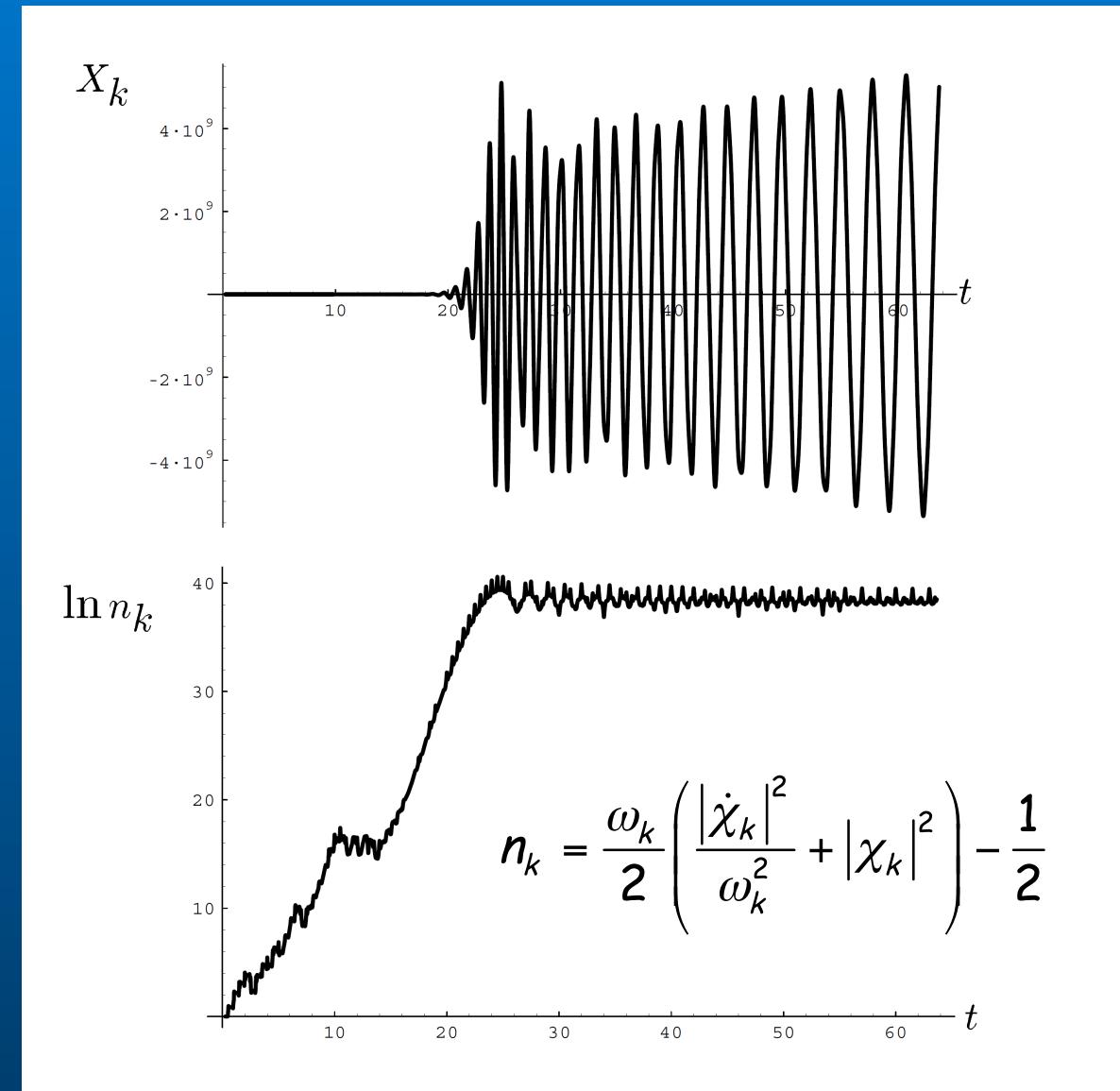
$$q \equiv g^2 \Phi^2 / m_\phi^2$$

$$A = k^2 / m_\phi^2 + 2q$$



Kofman,Linde,Starobinsky(97)

Evolution



End of preheating

Kofman,Linde,Starobinsky(97)

$$q \equiv g^2 \Phi^2 / m_\phi^2$$

$$\Phi(t) \approx \frac{M_p}{m_\phi t}$$

$$A = 2q$$

$$q(t_f) = O(1)$$

$$t_f = g M_p / m_\phi^2 \quad (g\Phi(t_f) = m_\phi)$$

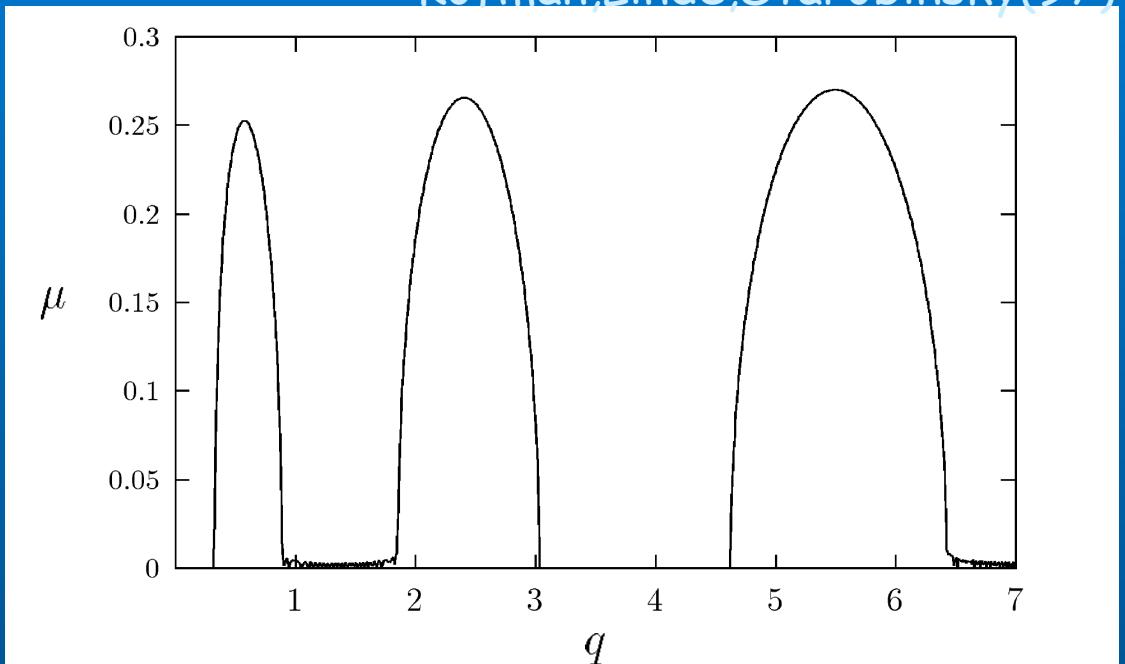


FIG. 7. The structure of the resonance bands for the Mathieu equation along the line $A = 2q$, which correspond to excitations with $k = 0$ in our model. The modes with small k are especially interesting because the momenta of the excitations are redshifted during the expansion of the universe. A small plateau at $10 \lesssim t \lesssim 15$ on Fig. 5 corresponds to the time where stochastic resonance ceases to exist, all modes are redshifted to small k , and the system spends some time in the interval with $1 \lesssim q \lesssim 2$, which is outside the instability zone. The last stage of the resonance shown in Fig. 6 corresponds to the resonance in the first instability band with $q < 1$.

Does narrow parametric resonance occur in expandin universe?

- Narrow resonance $\chi_k \propto e^{\mu m_\phi t}$ $\mu = \sqrt{(q/2)^2 - (2k/a/m_\phi - 1)^2}$
 $k/a \sim m_\phi$ $\Delta(k/a) \sim qm_\phi$ ($q \equiv g^2 M_P^2 / m_\phi^2 < 1$)

$$g^2 < 10^{-10}$$

- Conditions for efficient resonance

$$\Delta t = \frac{qm_\phi}{d(k/a)/dt} \sim q/H \gg m_\phi^{-1} \quad (q \equiv g^2 M_P^2 / m_\phi^2 > 1)$$

$$g^2 > 10^{-10}$$

Big difference from Enqvist, Jokinen, Mazumdar, Vaihkonen (05)

We may need another mechanism

- Broad resonance

$$10^{-10} < g^2 < 10^{-6}$$

- Large fluctuation?
- Large non-gaussianity?

Modulated preheating

Kohri, Lyth, Valenzuela-Toledo (09)

Model of preheating

Kofman, Linde, Starobinsky ('94), ('97)

See also Fujisaki, Kumekawa, Yamaguchi, Yoshimura (95)

- Motivated by particle physics (Chaotic Inflation, A-term Inflation, Inflection point Inflation.), we may adopt $\frac{1}{2} m^2 \phi^2$ for inflaton potential

$$L = \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} g^2 \chi^2 \phi^2$$

Reduction of ρ_ϕ and resonant production of ρ_χ

- See massless preheating models.

$$L = \frac{1}{4} \lambda \phi^4 + g^2 \chi^2 \phi^2$$

See Bond, Frolov, Huang, Kofman, arXiv:0903.3407

Modulated Preheating

See Podolsky, Felder, Kofman, Peloso (05)

- Coupling constant g can depend on another field

Ackerman et al (05)

$$g^2 = g_0^2 \left(1 + \frac{\sigma^2}{M^2} \right)^2$$

$$(10^{-10} < g^2 < 10^{-6}) \quad \text{Broad resonance}$$

- Then perturbation produced by σ is important

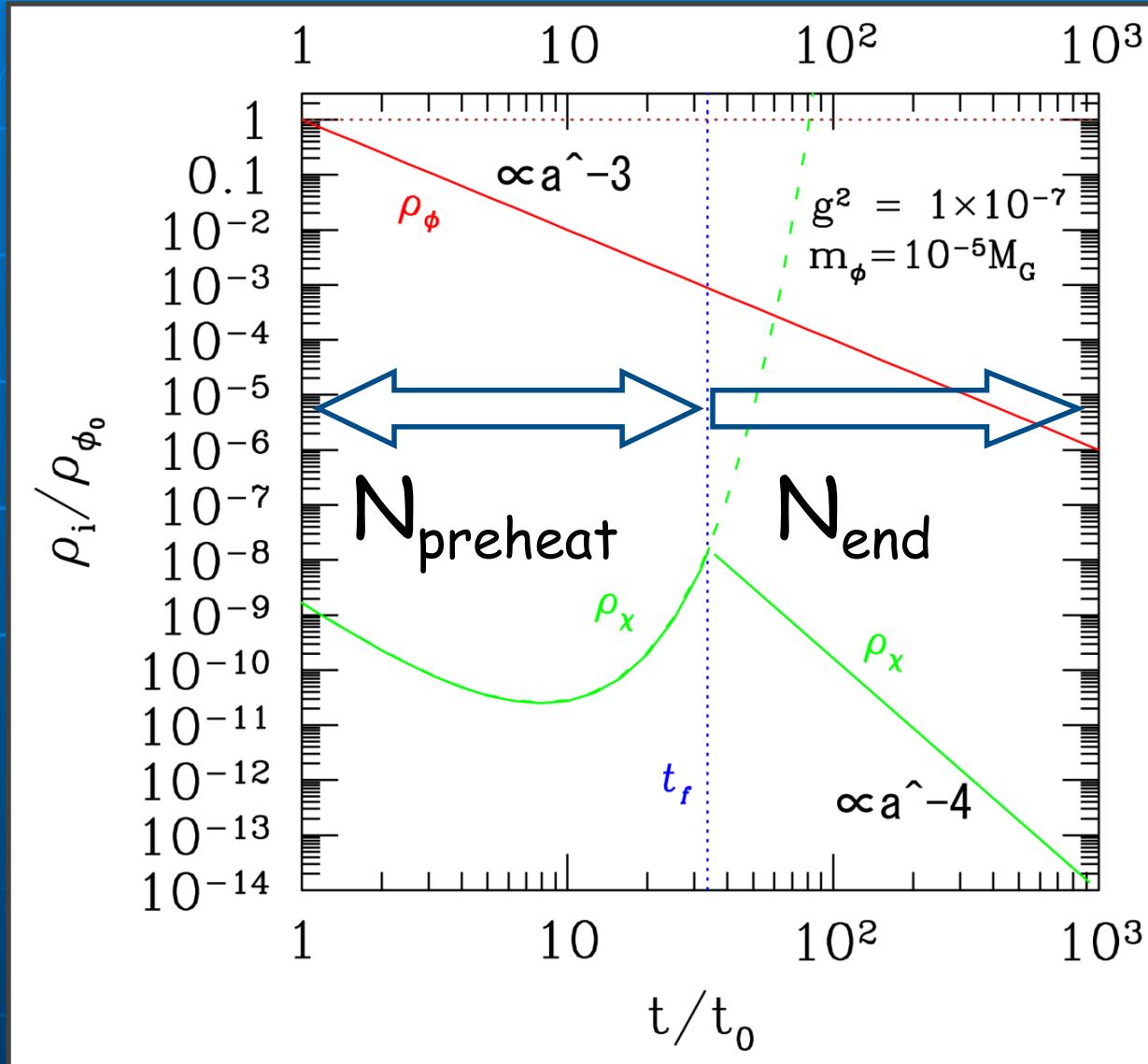
$$N_\sigma = g_\sigma \frac{\partial N}{\partial g}$$

$$N_{\sigma\sigma} = g_{\sigma\sigma} \frac{\partial N}{\partial g} + (g_\sigma)^2 \frac{\partial^2 N}{\partial g^2}$$

Preheating

$$\rho_\chi \propto e^{2\mu m_\phi t}$$

Kofman,Linde,Starobinsky(97)

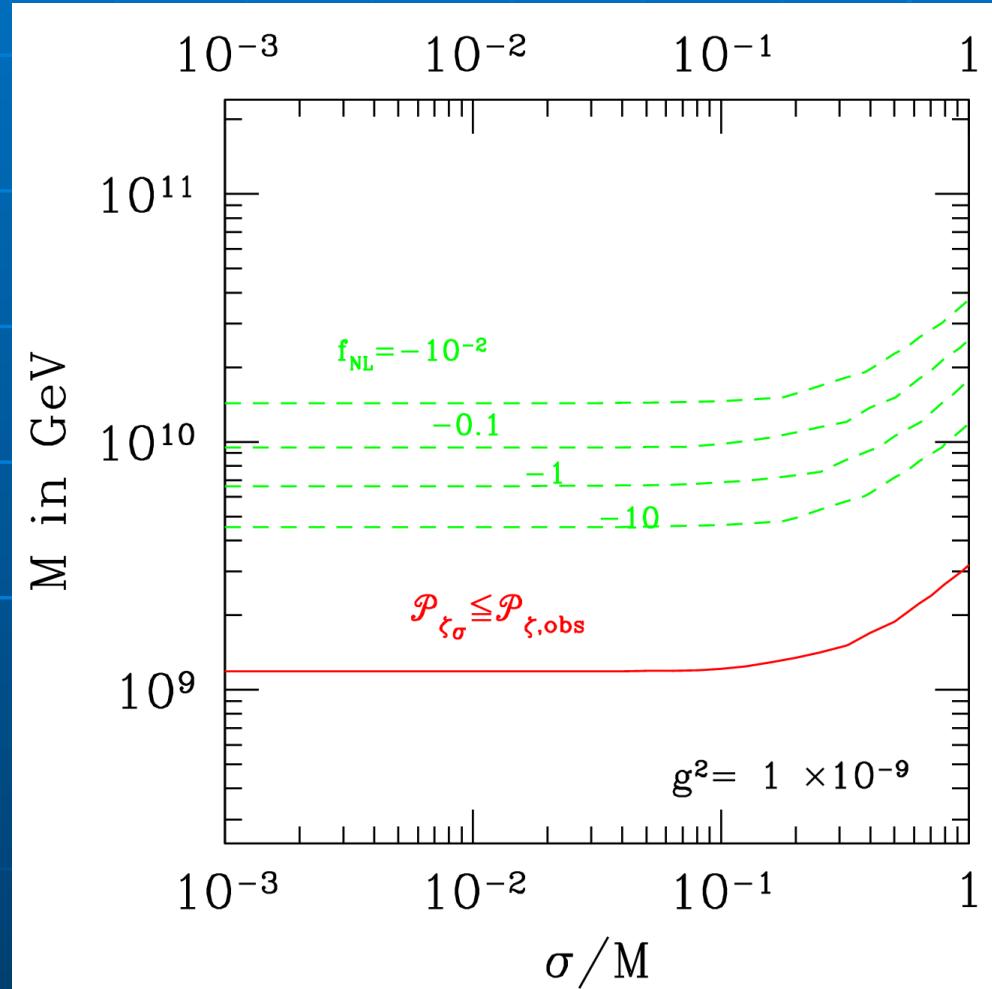
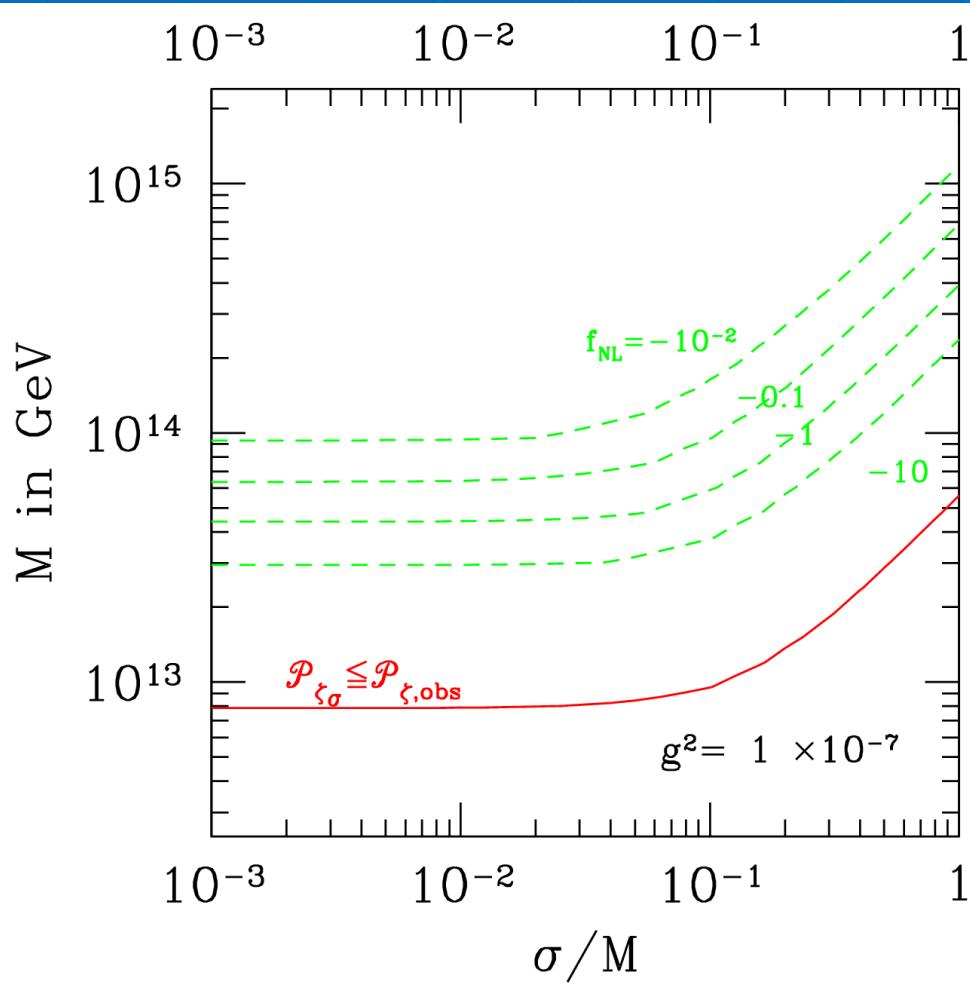


$$\Phi(t) \approx \frac{M_p}{m_\phi t}$$

$$t_f = g M_p / m_\phi^2 \quad (g\Phi(t_f) = m_\phi)$$

$$g\Phi(t_1)n_\chi(t_1) \equiv \frac{1}{2} m_\phi^2 \Phi^2(t_1)$$

Non-gaussianity



Modulated Preheating

See Podolsky, Felder, Kofman, Peloso (05)

- Coupling constant g can depend on another field

Ackerman et al (05)

$$g^2 = g_0^2 \left(1 + \frac{\sigma^2}{M^2} \right)^2$$

$$(10^{-10} < g^2 < 10^{-6}) \quad \text{Broad resonance}$$

- Then perturbation produced by σ is important

$$N_\sigma = g_\sigma \frac{\partial N}{\partial g}$$

$$N_{\sigma\sigma} = g_{\sigma\sigma} \frac{\partial N}{\partial g} + (g_\sigma)^2 \frac{\partial^2 N}{\partial g^2}$$

Is X nonrelativistic or relativistic?

- X's momentum at the resonance

$$k \sim \sqrt{gm_\phi M_p}$$

$$(k/a) = \sqrt{gm_\phi M_p} \left(\frac{a_*}{a} \right) = \sqrt{gm_\phi M_p} (tm_\phi)^{-2/3}$$

- Mass of X

$$m_\chi(t) = g \Phi(t) = g M_p (a_*/a)^{3/2} = g M_p (m_\phi t)^{-1}$$

- After $t \gtrsim t_f$ $t_f = gM_p / m_\phi^2$ ($g\Phi(t_f) = m_\phi$)

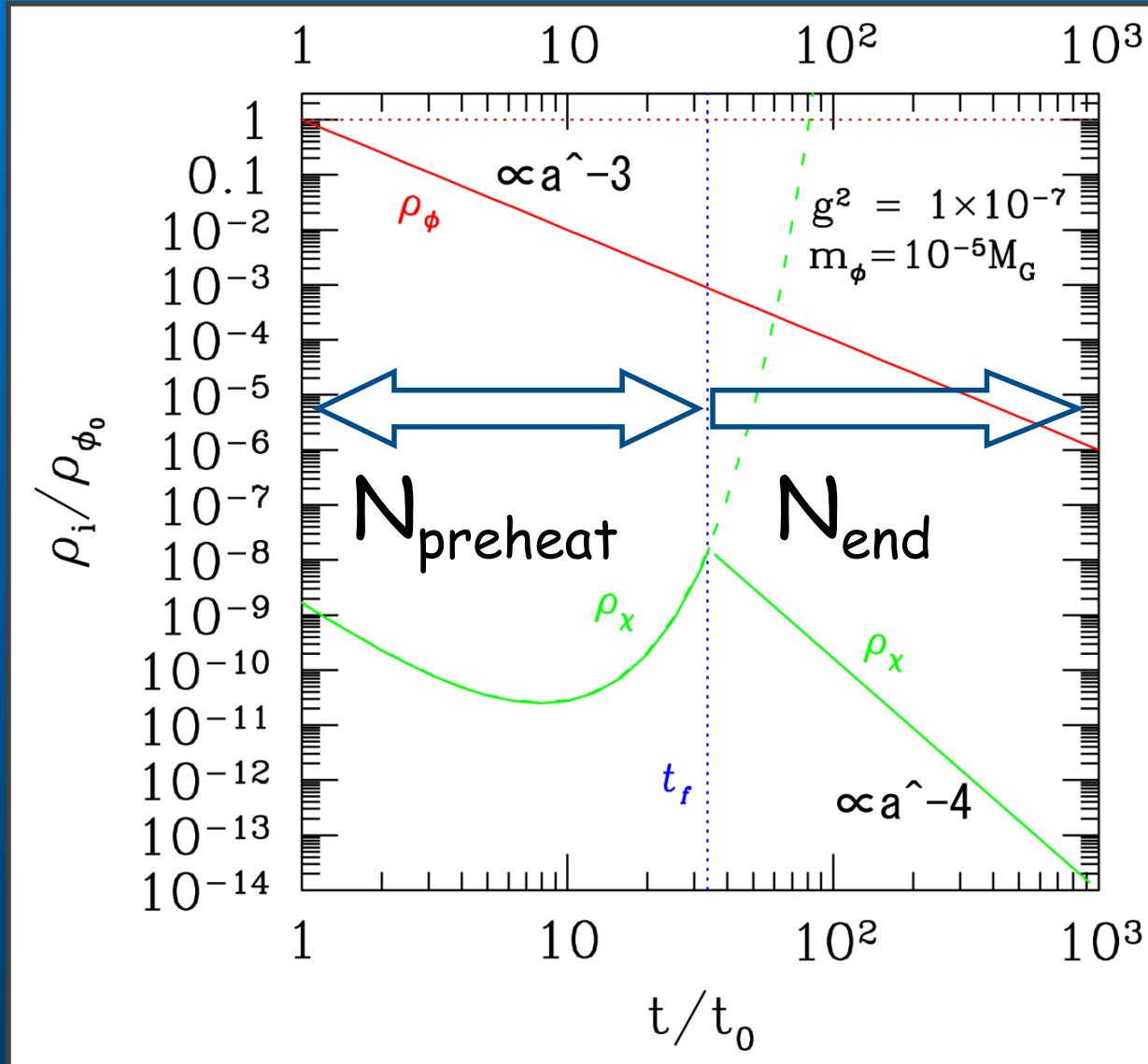
$$\frac{k/a(t_f)}{m_\chi(t_f)} \gtrsim (g/10^{-5})^{-1/6}$$

Relativistic particle $\rho \propto a^{-4}$ for $t \gtrsim t_f$

Preheating

$$\rho_\chi \propto e^{2\mu m_\phi t}$$

Kofman,Linde,Starobinsky(97)

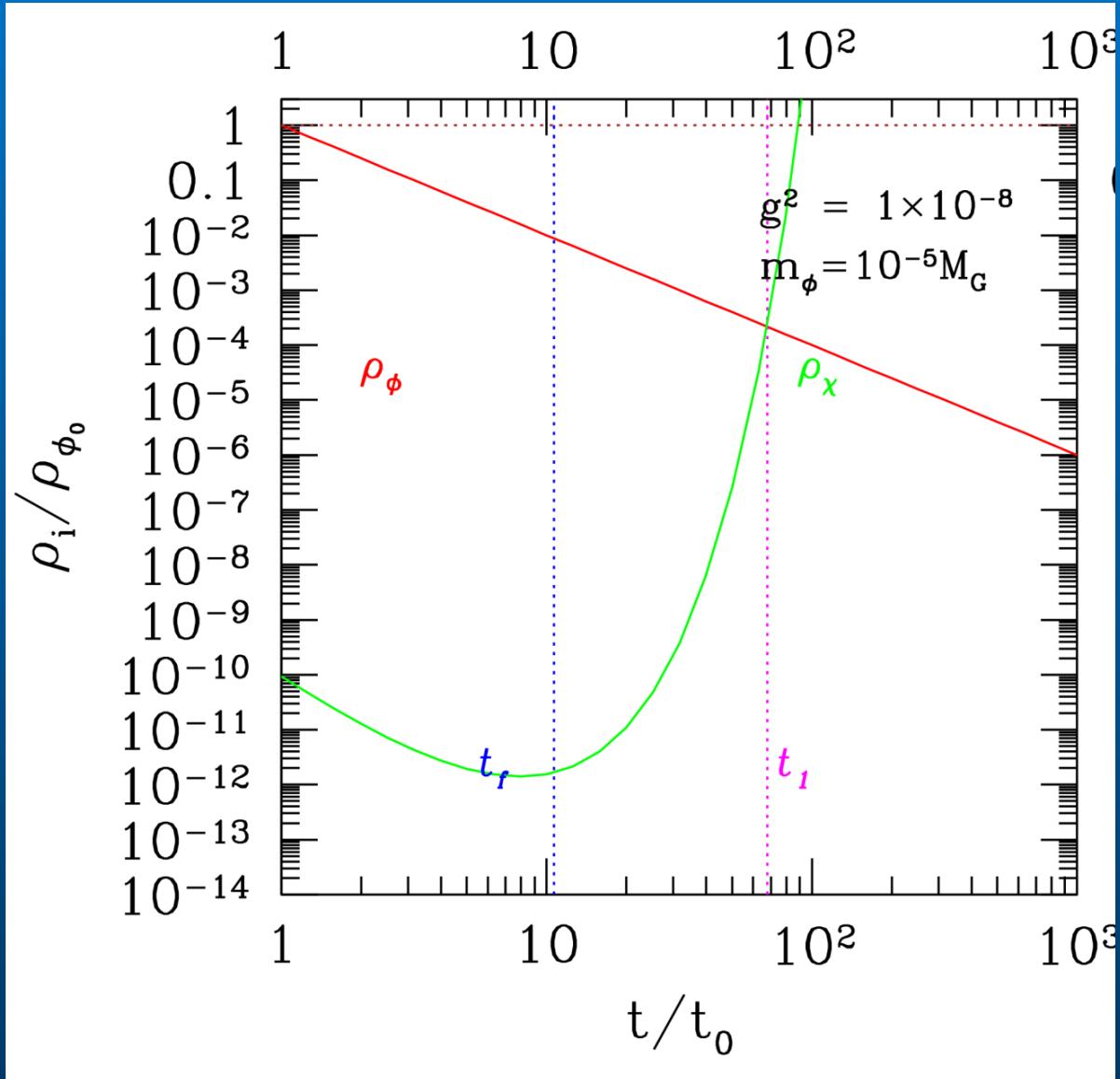


$$\Phi(t) \approx \frac{M_p}{m_\phi t}$$

$$t_f = g M_p / m_\phi^2 \quad (g\Phi(t_f) = m_\phi)$$

$$g\Phi(t_1)n_\chi(t_1) \equiv \frac{1}{2} m_\phi^2 \Phi^2(t_1)$$

$g^2=10^{-8}$

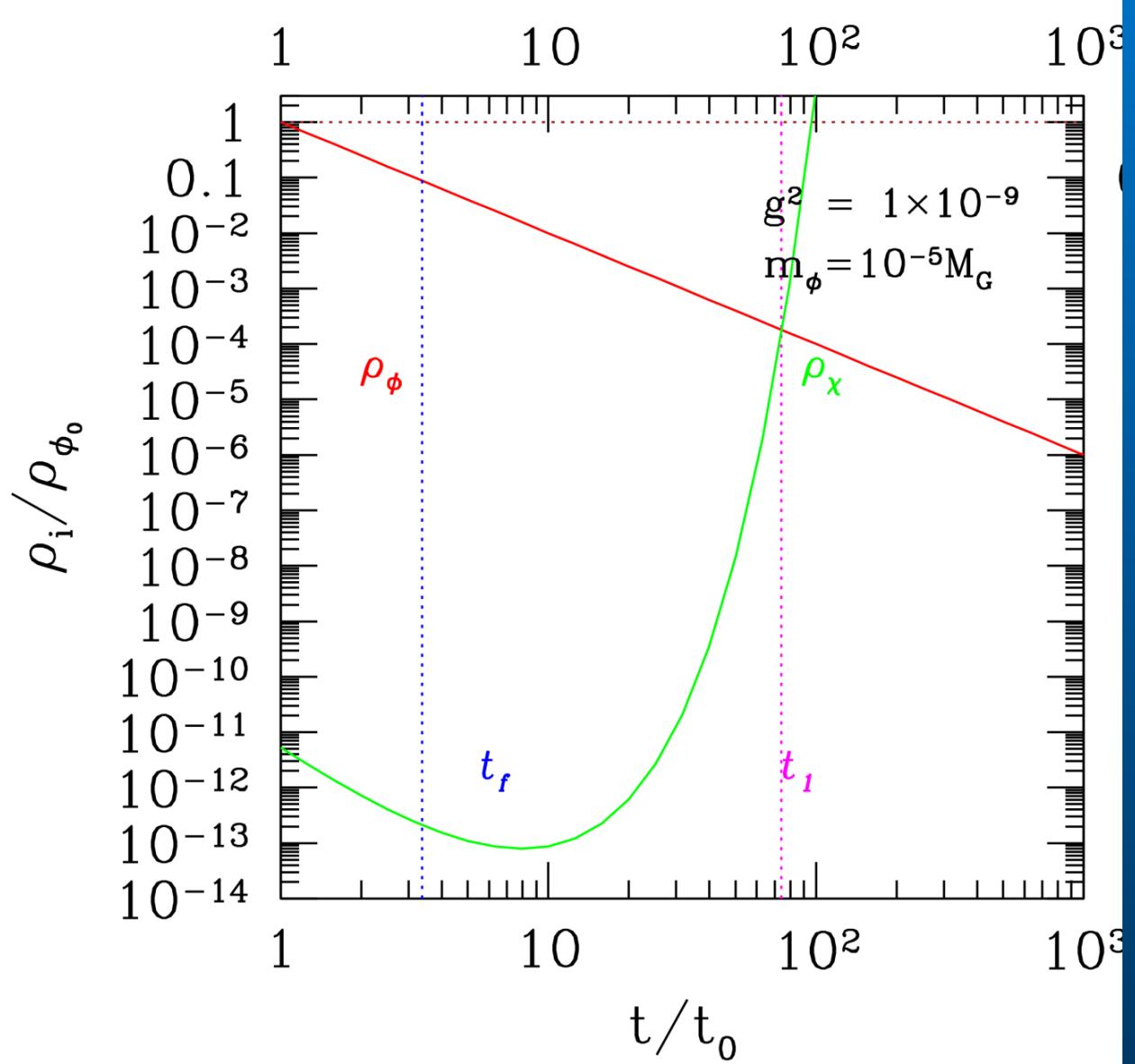


$$\Phi(t) \approx \frac{M_p}{m_\phi t}$$

$$t_f = g M_p / m_\phi^2 \quad (g \Phi(t_f) = m_\phi)$$

$$g \Phi(t_1) n_\chi(t_1) \equiv \frac{1}{2} m_\phi^2 \Phi^2(t_1)$$

$g^2=10^{-9}$



$$\Phi(t) \approx \frac{M_p}{m_\phi t}$$

$$t_f = g M_p / m_\phi^2 \quad (g\Phi(t_f) = m_\phi)$$

$$g\Phi(t_1)n_\chi(t_1) \equiv \frac{1}{2} m_\phi^2 \Phi^2(t_1)$$

Analytical estimate of 1st stage

- During preheating
 φ and χ are massive

$$\frac{a_f}{a_i} = (t_f / m_\varphi^{-1})^{2/3} = (gM_p / m_\varphi)^{2/3}$$

$$t_f = gM_p / m_\varphi^2 \quad (g\Phi(t_f) = m_\varphi)$$

$$N_{\text{preheat}} = \ln\left(\frac{a_f}{a_i}\right)$$

$$\frac{\partial N_{\text{preheat}}}{\partial g} = \frac{2}{3g}$$

$$\frac{\partial^2 N_{\text{preheat}}}{\partial g^2} = -\frac{2}{3g^2}$$

Analytical estimation of 2nd stage

- After preheating
 φ is massive, χ is almost massless

$$N_{\text{after}} = \ln\left(\frac{a(t)}{a(t_f)}\right) = \frac{1}{3} \ln\left(\frac{\rho_\phi^{\text{end}}}{\rho(t)}\right) = \frac{1}{3} \ln\left(\frac{\rho_{\text{tot}}^{\text{end}} - \rho_\chi^{\text{end}}}{\rho(t)}\right)$$

$$\rho_\chi^{\text{end}} = Ag^{-1} \text{Exp}[Bg]$$

$$\frac{\partial N_{\text{after}}}{\partial g} \sim -10^5 \frac{\rho_\chi^{\text{end}}}{\rho_{\text{tot}}^{\text{end}}} \quad \frac{\partial^2 N_{\text{after}}}{\partial g^2} \sim -10^{10} \frac{\rho_\chi^{\text{end}}}{\rho_{\text{tot}}^{\text{end}}}$$

Spectrum and non-linear parameter

$$N_\sigma = g_\sigma \frac{\partial N}{\partial g} \quad N_{\sigma\sigma} = g_{\sigma\sigma} \frac{\partial N}{\partial g} + (g_\sigma)^2 \frac{\partial^2 N}{\partial g^2}$$

$$P_{\xi_\sigma} = (N_\sigma)^2 (H_* / 2\pi)^2 \times (1 + R_{\text{1-loop}})$$

$$\frac{6}{5} f_{\text{NL}} = \left(\frac{P_{\xi_\sigma}}{P_{\xi, \text{obs}}} \right)^2 \frac{N_{\sigma\sigma}}{(N_\sigma)^2} \times (1 + R_{\text{1-loop}})$$

$$R_{\text{1-loop}} = \left[\frac{N_{\sigma\sigma}}{N_\sigma} \left(\frac{H_*}{2\pi} \right) \right]^2 \ln(kL)$$

Non-gaussianity

