Perturbative Reheating After Multiple Field Inflation

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Benasque Modern Cosmology

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with Joel Meyers (CITA)

- The region of the inflationary potential to which observations are sensitive depends on the reheating phase:

$$N_{\rm total} \sim 63 + \frac{1}{4}\ln\epsilon + \frac{1}{4}\ln\frac{V_*}{\rho_{\rm end}} + \frac{1}{12}\ln\frac{\rho_{\rm reh}}{\rho_{\rm end}}$$

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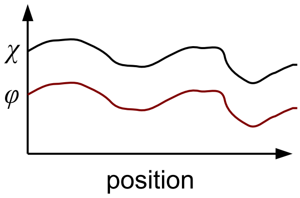
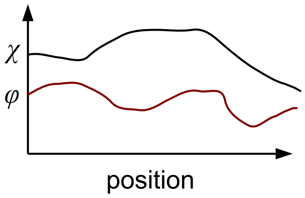
- Multiple field inflation supports isocurvature fluctuations:

Adiabatic fluctuations

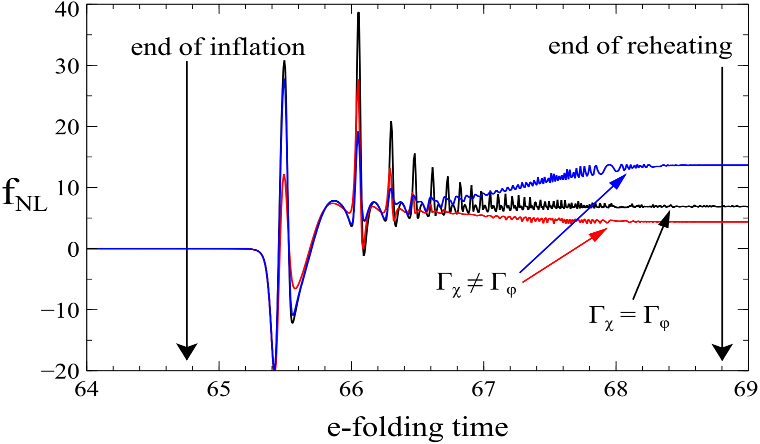


Isocurvature fluctuations



- ζ can evolve outside the Hubble radius in the presence of isocurvature (non–adiabatic) fluctuations
- If isocurvature fluctuations are still important at the end of inflation, ζ will be sensitive to reheating.

Reheating can change the observable predictions of the underlying inflationary model:



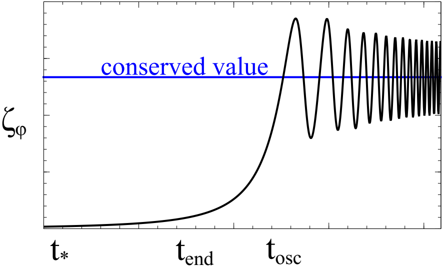
[Leung,Tarrant,Byrnes,Copeland JCAP 1209, 008 (2012)]

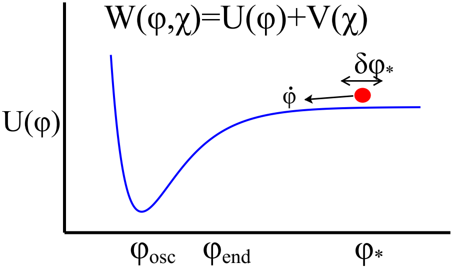
See also: Elliston,Mulryne,Seery,Tavakol, JCAP 1111, 005 (2011)

Fluids with a barotropic equation of state have an individually conserved curvature perturbation:

$$\zeta_\varphi = \zeta + \frac{1}{3}\int_{\bar{\rho}_\varphi(t)}^{\rho_\varphi(t,\mathbf{x})} \frac{\mathrm{d}\tilde{\rho}_\varphi}{\tilde{\rho}_\varphi + P_\varphi(\tilde{\rho}_\varphi)}$$

[Lyth, Malik, Sasaki (2005), Sasaki,Valiviita,Wands (2006)]





Solve order by order:

$$\zeta_\varphi = \zeta_\varphi^{(1)} + \frac{1}{2}\zeta_\varphi^{(2)} + \dots$$

$$\begin{aligned}\zeta_\varphi^{(1)} &= \frac{1}{M_{\mathrm{p}}^2}\left[\frac{U_*}{U'_*} + \frac{G}{U'_*}\right]\delta\varphi_* \\ &+ \frac{1}{M_{\mathrm{p}}^2}\left[\frac{V_*}{V'_*} - \frac{G}{V'_*}\right]\delta\chi_*\end{aligned}$$

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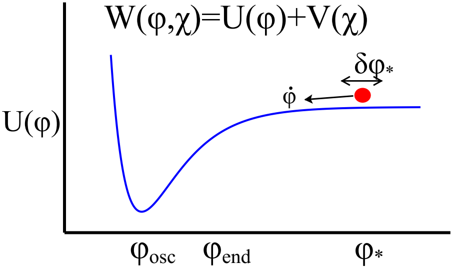

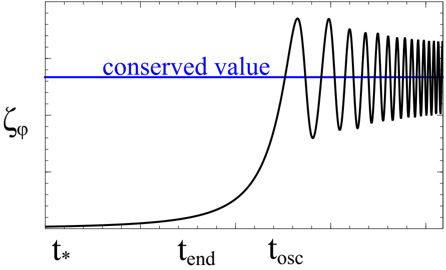

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At 2^{nd} order, four functions F, G, J, K determine conserved values of ζ_φ and ζ_χ.

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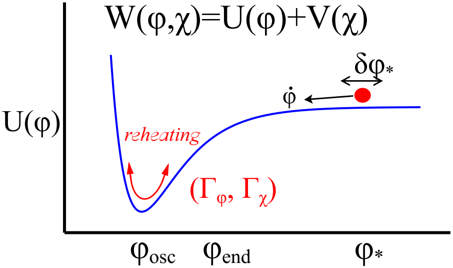

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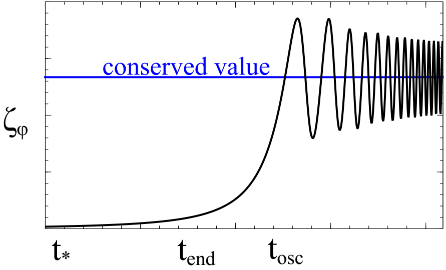

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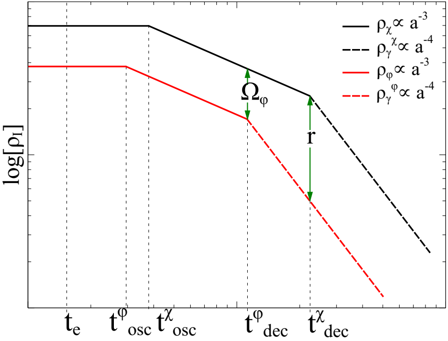


To first order:

$$\zeta^{(1)}_{\rm final} = (1-\mathcal{A})\zeta^{(1)}_{\varphi} + \mathcal{A}\zeta^{(1)}_{\chi}$$

where

$$\mathcal{A} \equiv \frac{1}{4}(1+3r-\Omega_\varphi + r\Omega_\varphi) \in [0,1]$$

(similar result at second order)

[see also: Assadullahi,Valiviita,Wands (2007)]

$$\left(\frac{\Gamma_\chi}{\Gamma_\varphi}\right)^2 = \frac{27(1-\Omega_\varphi)^4(1-r)^3(3+r)}{256r^4\Omega_\varphi^3}$$

- $\zeta_{\rm final}$ is only sensitive to *ratio* of decay rates
- Reheating *interpolates* between ζ_φ and ζ_χ
- Sensitive to reheating whenever $\zeta_\chi \neq \zeta_\varphi$

Observables:

$$\mathcal{P}_\zeta = \frac{\mathcal{P}_*}{M_\mathrm{p}^4}\left[\left(\frac{U_* + \alpha}{U'_*}\right)^2 + \mathrm{sym}\right], \quad r_T = 8M_\mathrm{p}^2\left[\left(\frac{U_* + \alpha}{U'_*}\right)^2 + \mathrm{sym}\right]^{-1}$$

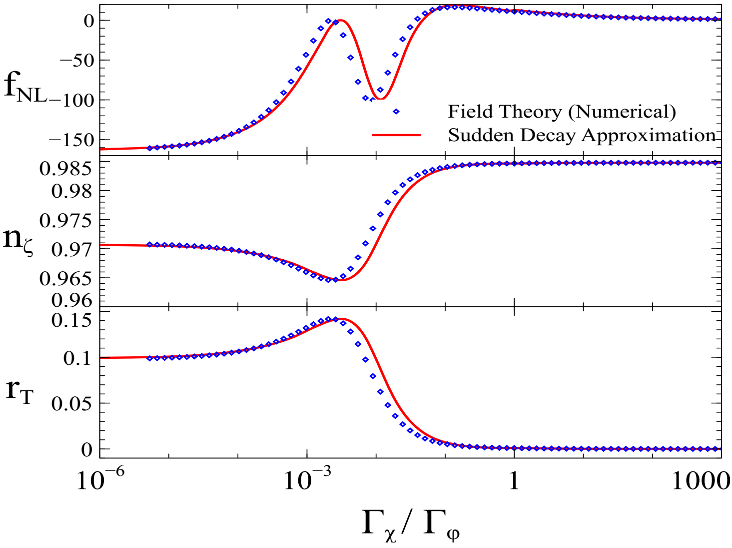
$$n_\zeta - 1 = -2\epsilon_* - \frac{2M_\mathrm{p}^2}{W_*}\left[\left(\frac{U_* + \alpha}{U'_*}\right)^2 + \mathrm{sym}\right]^{-1} \times \left[\left((U_* + \alpha) - \frac{U''_*\,(U_* + \alpha)^2}{{U'_*}^2}\right) + \mathrm{sym}\right]$$

$$\frac{6}{5}f_\mathrm{NL} = M_\mathrm{p}^2\left[\left(\frac{U_* + \alpha}{U'_*}\right)^2 + \mathrm{sym}\right]^{-2} \times \left[\left(1 + \frac{-U''_*(U_* + \alpha) + \beta}{{U'_*}^2}\right)\left(\frac{U_* + \alpha}{U'_*}\right)^2 + \mathrm{sym}\right]$$

$$\alpha \equiv \mathcal{A}F + (1 - \mathcal{A})G\,, \qquad \beta \equiv \mathcal{A}J + (1 - \mathcal{A})K + \frac{\mathcal{B}}{M_\mathrm{p}^2}(F - G)^2$$

- α and β encode super–Hubble evolution of ζ (through F, G, J, K), and also account for reheating (through $\mathcal{A}, \mathcal{B}$).
- See Joe Elliston's talk where the same algebraic form is preserved in more complicated scenarios.

$$W(\varphi,\chi) = \frac{1}{2}m^2\chi^2 + \Lambda^4\left[1 - \cos\left(\frac{2\pi}{f}\varphi\right)\right]$$



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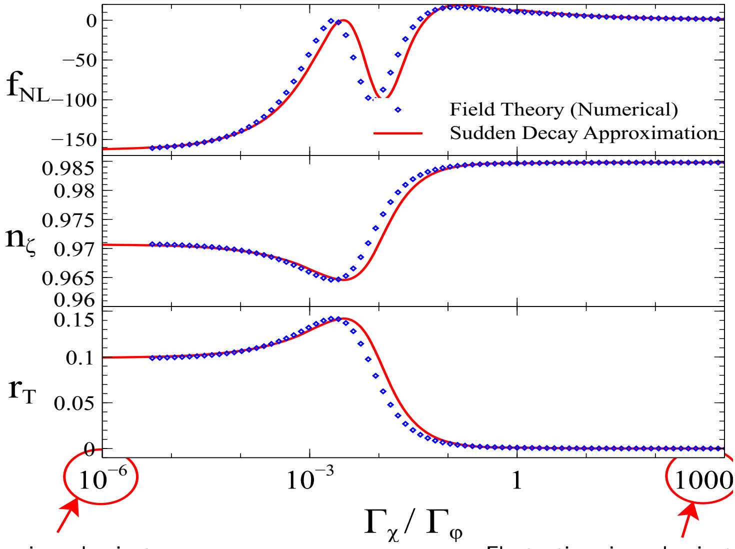
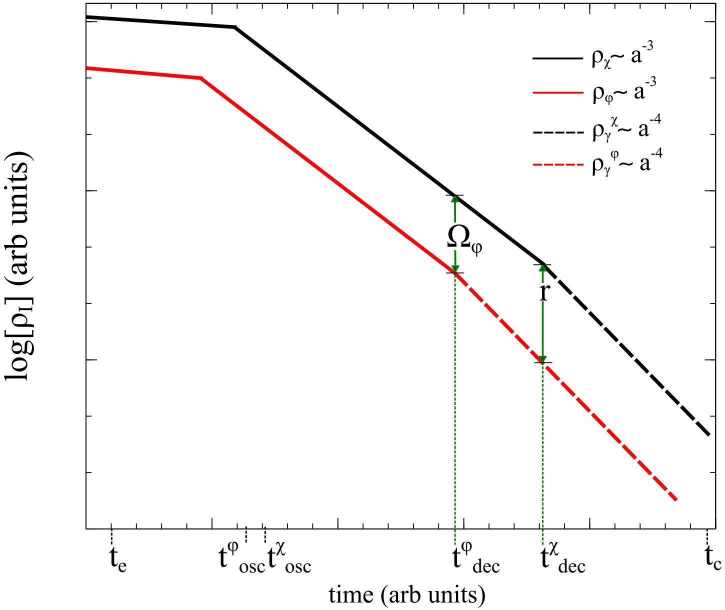


Fluctuation in χ dominate
– observables determined by ζ_χ

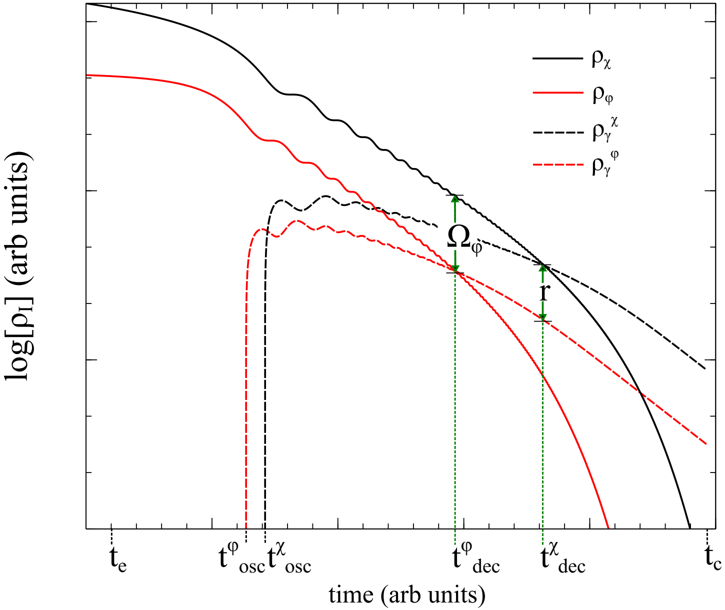
Fluctuations in φ dominate
– observables determined by ζ_φ

Conclusions (arXiv:1311.3972)

- If the adiabatic limit has not been reached during inflation, reheating will alter the predictions of the underlying inflationary model.
- Perturbative reheating rescales the inflationary correlation functions.
- At the end of reheating, observables take values within finite ranges, the limits of which are determined completely by the conditions during inflation.
- More work is needed to calculate F, G, J, K for arbitrary models.



$\rho_\chi \sim a^{-3}$
$\rho_\varphi \sim a^{-3}$
$\rho_\gamma^\chi \sim a^{-4}$
$\rho_\gamma^\varphi \sim a^{-4}$
Ω_φ
r
$\log[\rho_I]$ (arb units)
t_e
t^φ_{osc}
t^χ_{osc}
t^φ_{dec}
t^χ_{dec}
t_c
time (arb units)



ρ_χ
ρ_φ
ρ_γ^χ
ρ_γ^φ
Ω_φ
r
$\log[\rho_I]$ (arb units)
t_e
t^φ_{osc}
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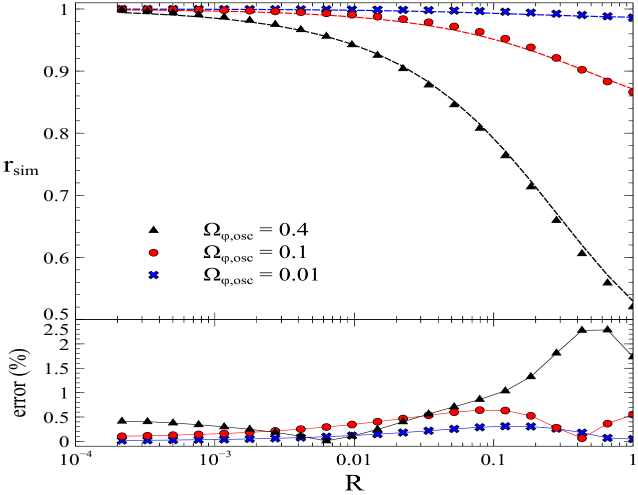

$$r_{\rm sim}(R,\Omega_\varphi) = 1 - \left[p + \frac{q}{R}\right]^{-v}, \qquad v = 0.60\,, \qquad q = 0.63\,\frac{\ln\Omega_\varphi}{\ln(1-\Omega_\varphi)}\bigg|_{\rm osc}$$

$$p = \left[\frac{4\Omega_\varphi}{3+\Omega_\varphi}\right]_{\rm osc}^{-1/v} - q$$