Field-space Effects in Preheating

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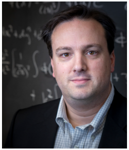
Cosmology from Home 2020

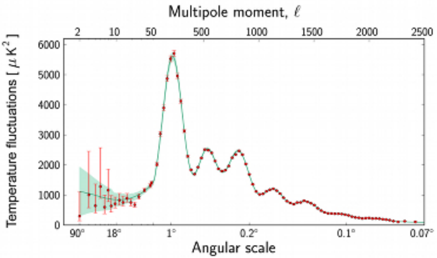
with R. Nguyen, J. van de Vis, J. T. Giblin, D. I. Kaiser

- PRL **123**, 171301 (2019) [arXiv:1905.12562 [hep-ph]]
- arXiv:2005.00433 [astro-ph.CO], accepted PRD

Inflation: Successes and Predictions

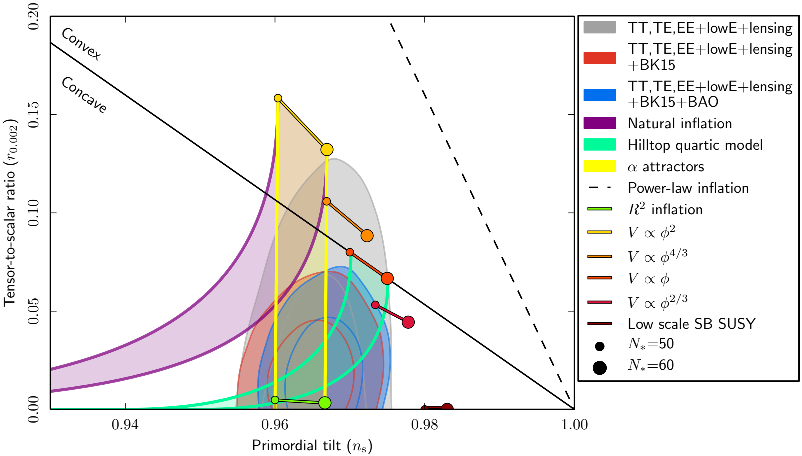
- Solve horizon & flatness problems
- Explain **fluctuations** as stretched quantum mechanical perturbations



- Predict a **nearly scale invariant** spectrum (of tunable amplitude)
- Predict almost **Gaussian** perturbations

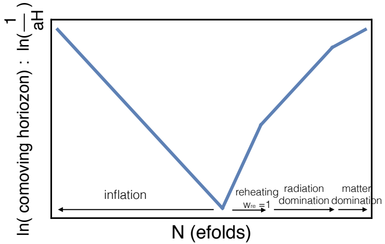
- Spectral index is 5σ **away from flat**
- Spectral index running is small
- $|f_{NL}| \lesssim \mathcal{O}(1)$

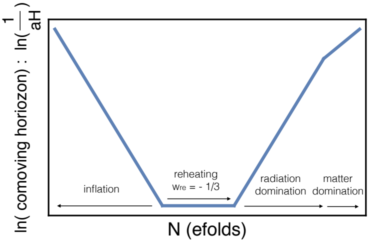
Hints from the sky



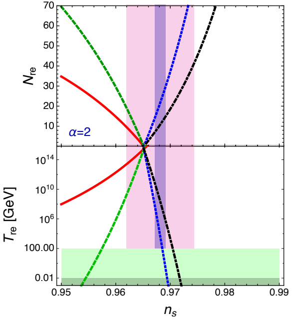
Plateau models of inflation are consistent with *Planck* data.

Reheating





Cook et al. 2015

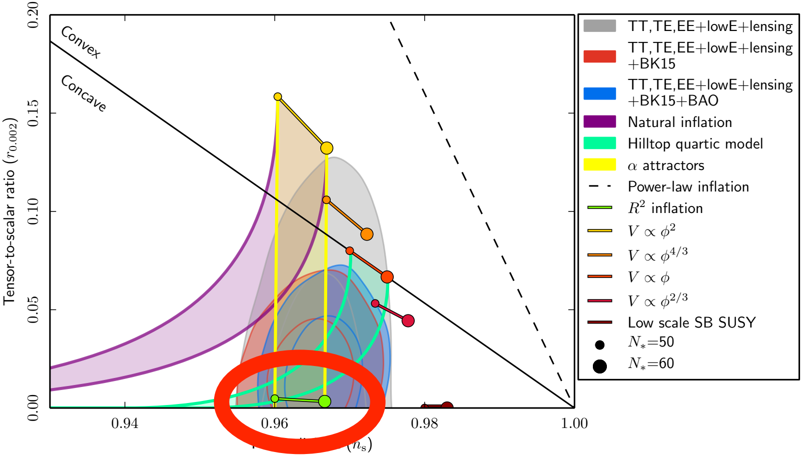


The **reheating history** connects the times of horizon exit & re-entry of perturbations $\Rightarrow$ **shifts CMB observables**

"The value of $\mathcal{N}_*$ is not well constrained and depends on unknown details of reheating"

CMB-S4 Science Book, 2016

Hints from the sky



Plateau models of inflation are consistent with *Planck* data,

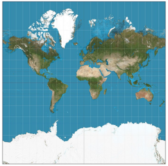
$\Rightarrow$ the time of horizon exit is being constrained.

Mon-minimal coupling & Conformal Transformations

Non-minimal coupling to gravity: $\mathcal{L} \subset \xi\phi^2 R$

$$S_{\mathrm{Jordan}} = \int d^4x \sqrt{-\tilde{g}} \left[f(\phi^I)\tilde{R} - \frac{1}{2}\tilde{\mathcal{G}}_{IJ}\tilde{g}^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - \tilde{V}(\phi^I) \right]$$

$$g_{\mu\nu}(x) = \frac{2}{M_{\mathrm{Pl}}^2} f(\phi^I(x))\, \tilde{g}_{\mu\nu}(x)$$

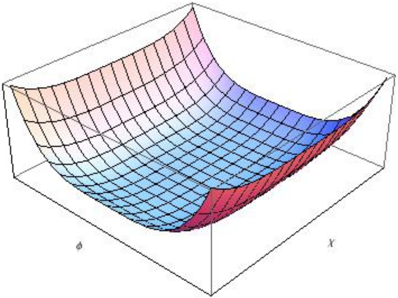


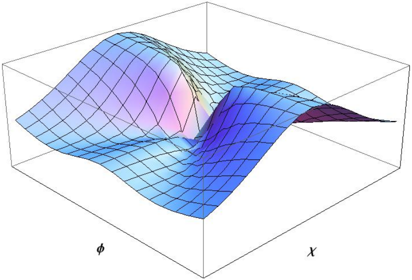
$$S_{\mathrm{Einstein}} = \int d^4x \sqrt{-g} \left[\frac{M_{\mathrm{Pl}}^2}{2} R - \frac{1}{2}\mathcal{G}_{IJ} g^{\mu\nu}\partial_\mu\phi^I\partial_\nu\phi^J - V(\phi^I) \right]$$

$$V(\phi^I) = \frac{M_{\mathrm{Pl}}^4}{4f^2(\phi^I)} \tilde{V}(\phi^I)$$

Jordan vs Einstein

$$f(\phi,\chi)=\frac{1}{2}\left[M_{Pl}^2+\xi_\phi\phi^2+\xi_\chi\chi^2\right]\ ,\quad V(\phi,\chi)=\frac{\lambda_\phi}{4}\phi^4+\frac{\lambda_\chi}{4}\chi^4+\frac{g}{2}\phi^2\chi^2$$





$$V(\phi^I)\to\frac{M_{Pl}^2}{4}\frac{\lambda_I}{\xi_I}\Rightarrow H=\frac{M_{Pl}}{\sqrt{12}}\sqrt{\frac{\lambda}{\xi^2}}$$

Einstein-frame Field-space

In the Einstein frame, the field-space manifold is curved:

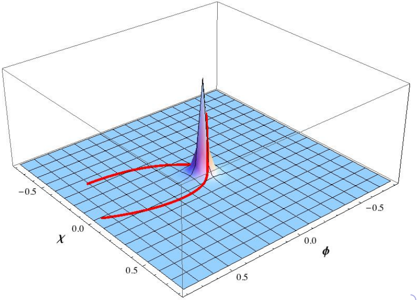
$$\mathcal{G}_{IJ}(\phi^K) = \left(\frac{M_{Pl}^2}{2f(\phi^K)}\right)\left[\delta_{IJ} + \frac{3}{f(\phi^K)} f_{,I} f_{,J}\right] \neq F(\phi^K)\delta_{IJ}$$

ϕ^I: coordinates in field space $\longleftrightarrow x^\mu$

$\mathcal{G}_{IJ}\left(\sim \frac{1}{\phi^2}\right)$: metric on field space $\longleftrightarrow g_{\mu\nu}$ (Note: $\mathcal{G}_{IJ} \propto \phi^{-2}$)

$\mathcal{D}_J A^I = \partial_J A^I + \Gamma^I_{JK} A^K$

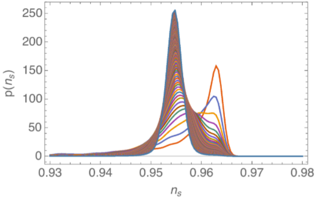
We can "turn off" the potential and **visualize the effects of the field-space metric** alone.



Inflation and multiple fields

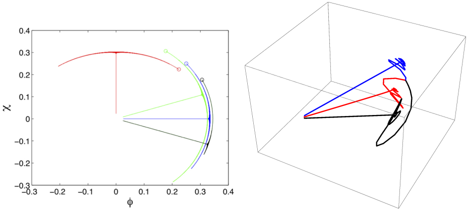
Only one scalar field at **high energies** is rather unlikely.

How do these models, $\mathcal{L} \subset \xi\phi^2 R$, cope with **many scalar fields**?



Easther, Frazer, Peiris, Price

- Multi-field quadratic model $V = \sum m_I^2 \phi_I^2$
- Simple models shift predictions for n_s.



Kaiser & EIS 2014

- Non-minimal couplings lead to strong single-field attractors
- **Robust** Starobinsky-like **predictions**

$$n_s \simeq 1 - \frac{2}{N} \simeq 0.96\ldots\,, \qquad r \simeq \frac{12}{N^2} = \mathcal{O}(10^{-3})$$

Equations of motion

Background fields:

$$\mathcal{D}_t\dot{\phi}^I + 3H\dot{\phi}^I + \mathcal{G}^{IK} V_{,K} = 0$$

where $\mathcal{D}_t A^I \equiv \dot{A}^I$ for our choice of variables

Fluctuations:

$$\ddot{Q}^I_k + 3H\dot{Q}^I_k + \left[\frac{k^2}{a^2}\delta^I_J + \mathcal{M}^I_J\right] Q^I_k = 0$$

where

$$\mathcal{M}^I_J = \mathcal{G}^{IK}\mathcal{D}_J\mathcal{D}_K V - \mathcal{R}^I_{LMJ}\dot{\phi}^L\dot{\phi}^M - \frac{1}{M_{Pl}^2 a^3}\mathcal{D}_t\left(\frac{a^3}{H}\dot{\phi}^I\dot{\phi}_J\right)$$

Quantizing the fluctuations

For motion **along the** single-field **attractor**,
quantization is simple

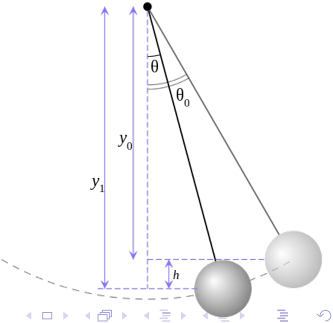
$$\hat{Q}^{\phi}(x^\mu) = \sqrt{\mathcal{G}^{\phi\phi}}\, a(t) \int \frac{d^3k}{(2\pi)^{3/2}} \left[\left(v_k \hat{b}_{\mathbf{k}}\right) e^{i\mathbf{k}\cdot\mathbf{x}} + c.c.\right]$$

$$\hat{Q}^{\chi}(x^\mu) = \sqrt{\mathcal{G}^{\chi\chi}}\, a(t) \int \frac{d^3k}{(2\pi)^{3/2}} \left[\left(z_k \hat{c}_{\mathbf{k}}\right) e^{i\mathbf{k}\cdot\mathbf{x}} + c.c.\right]$$

Re-write as a harmonic oscillator

$$v_k'' + \Omega^2_{(\phi)}(k,\tau)\, v_k \simeq 0\,, \qquad v_k \longleftrightarrow \delta\phi_k$$

$$z_k'' + \Omega^2_{(\chi)}(k,\tau)\, z_k \simeq 0\,, \qquad z_k \longleftrightarrow \delta\chi_k$$



Effective Mass-squared: Ingredients

$$\partial_\tau^2 v_k + (k^2 + a^2 m_{\mathrm{eff},\phi}^2) v_k = 0 \quad , \quad \partial_\tau^2 z_k + (k^2 + a^2 m_{\mathrm{eff},\chi}^2) z_k = 0$$

$$\boxed{m_{\mathrm{eff,I}}^2 = m_{1,I}^2 + m_{2,I}^2 + m_{3,I}^3 + m_{4,I}^2}$$

$$m_{1,\phi}^2 \equiv \mathcal{G}^{\phi K} \left(\mathcal{D}_\phi \mathcal{D}_K V\right) \longleftrightarrow \text{potential gradient}$$

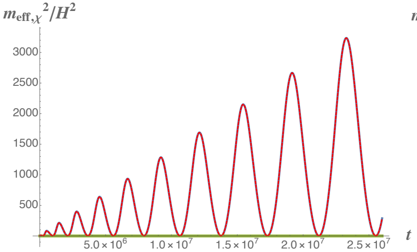
$$m_{2,\phi}^2 \equiv -\mathcal{R}^{\phi}{}_{LM\phi} \dot{\varphi}^L \dot{\varphi}^M \longleftrightarrow \text{non-trivial field-space manifold}$$

$$m_{3,\phi}^3 \equiv -\frac{\delta^\phi_I \delta^J_\phi}{M_{\mathrm{Pl}}^2 a^3} \mathcal{D}_t \left(\frac{a^3}{H} \dot{\varphi}^I \dot{\varphi}_J\right) \longleftrightarrow \text{coupled metric perturbations}$$

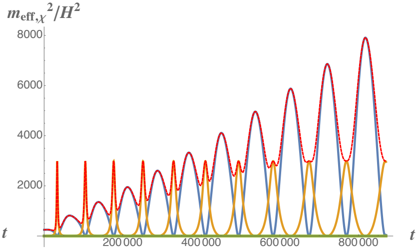
$$m_{4,\phi}^2 \equiv -\frac{1}{6} R \longleftrightarrow \text{changes in the background spacetime}$$

Effective Mass-squared for χ fluctuations

$\xi = 0.1 \ll 1$



$\xi = 10$

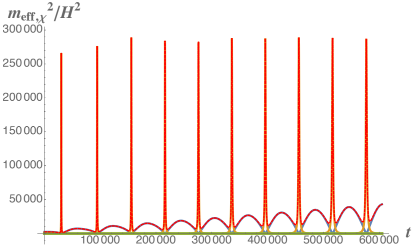


$$m_{\mathrm{eff}}^2 \approx m_1^2 + m_2^2 + m_3^3$$

$$m_{\mathrm{eff}}^2 \approx \textit{potential} + \textit{fieldspace} + \textit{metric}$$

Effective Mass-squared for $\xi = 100 \gg 1$

An "unusual" way for **adiabaticity violation** when $\mathcal{R}$ spikes.



We define

$$\mathcal{A}(k,\tau) \equiv \frac{\Omega'(k,\tau)}{\Omega^2(k,\tau)}$$

where

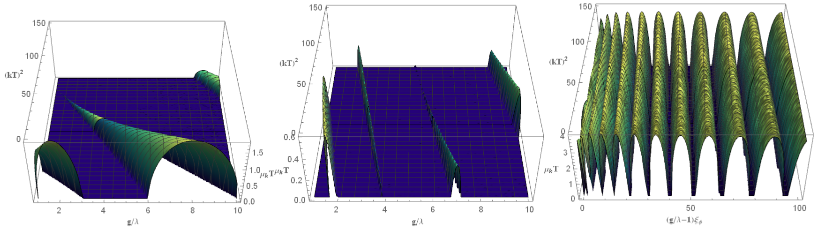
$$\Omega^2(k,\tau) = k^2 + a^2 m^2_{\text{eff},\phi}(\tau)$$

Adiabaticity is violated for $\Omega' \gg \Omega^2$, rather than $\Omega \approx 0$.

A broad range of wavenumbers is excited $k \lesssim \xi_\phi H_{\text{end}}$

Floquet charts

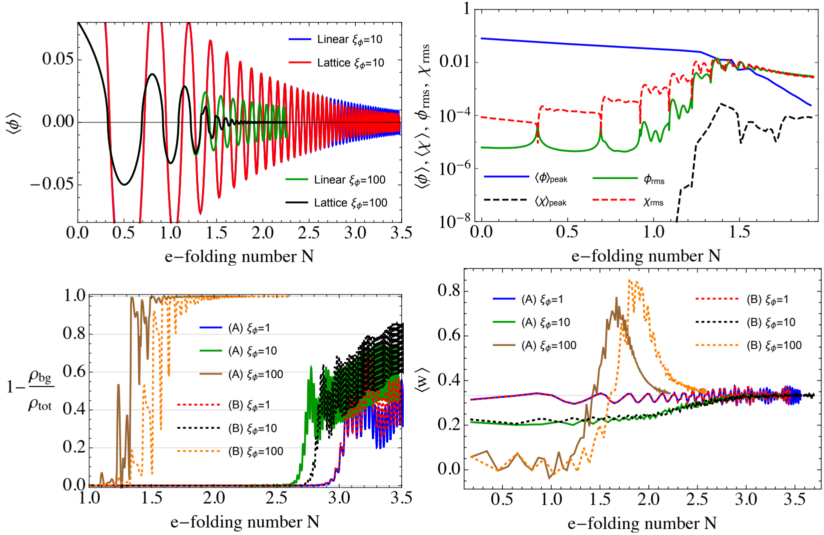
$\xi = 0$ $\xi = 10$ $\xi = 100$



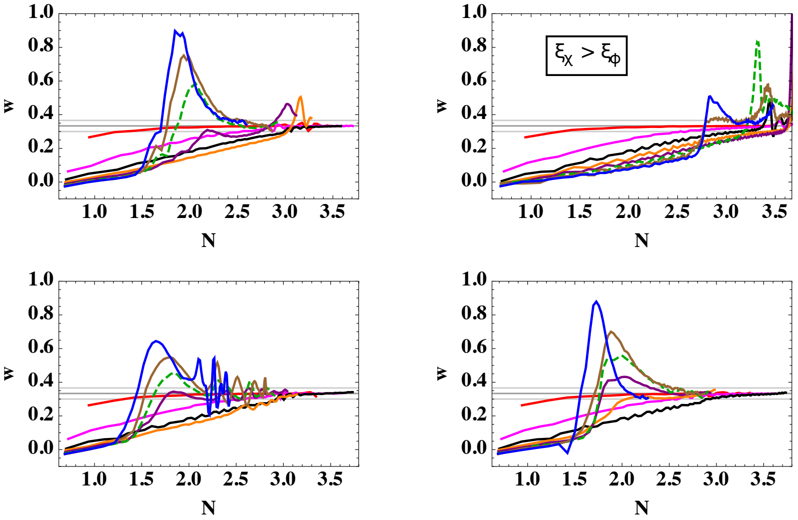
Efficient particle production
can lead to **nonlinear effects** $\Rightarrow$

Need for
lattice simulations

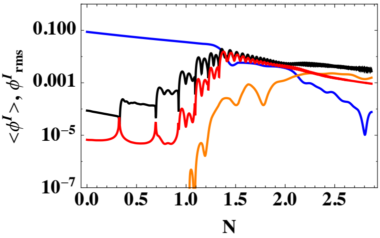
Lattice results: Benchmark Case

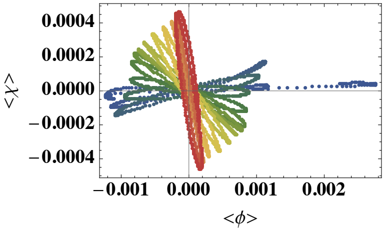


Lattice results: Parameter Scan

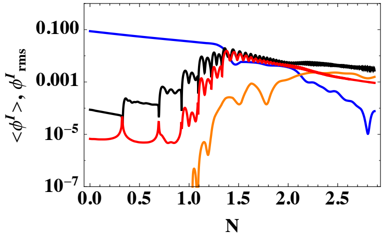


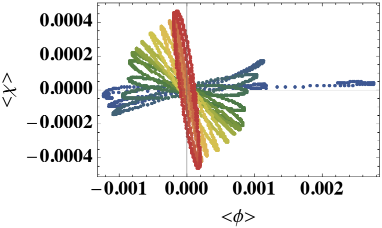
Strong resonance and single-field motion

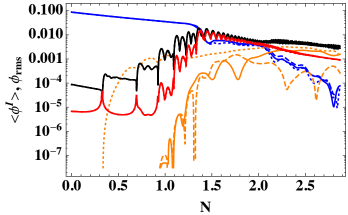




$\langle\chi\rangle > \langle\phi\rangle \Rightarrow$ Multi-field background motion (???)





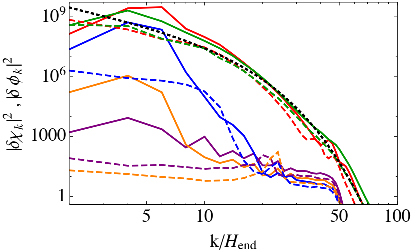


- $\langle\chi^2\rangle \gg \langle\chi\rangle^2$
- initial-condition-dependent $\langle\chi\rangle$
- No coherent background motion on super-horizon scales

$\Rightarrow$ **CMB modes are safe**

Summary

- **Fast preheating** for $\xi \gtrsim 100$
- Efficient re-scattering
  $\Rightarrow$ onset of **thermalization**
- **Robust single-field attractor**
- Fast approach to $w \to 1/3$
- Detailed understanding of the **whole parameter space**



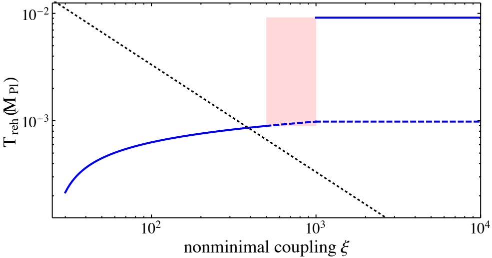
Non-minimal couplings quickly lead to a thermal radiation bath while preserving CMB predictions

One last thing!

Higgs inflation is a multi-field non-minimally coupled model with known SM couplings $\Rightarrow$ the inflaton decays into W, Z bosons.

$$m_{\text{spike}} \sim \xi H_{\text{end}}$$

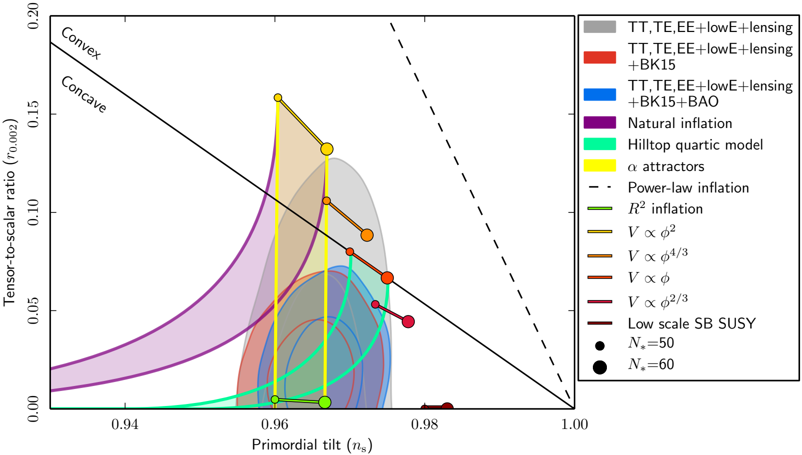
$$m_B \sim \frac{10^5}{\sqrt{\xi}} H_{\text{end}}$$



For $\xi \gtrsim 10^3$ preheating completes within **ONE** oscillation

van de Vis & E.I.S, Phys. Rev. D **99**, no.8, 083519 (2019)

Observations



Understanding **preheating** in major plateau models **reduces** theoretical **error-bars** of the $n_s - r$ plot