Preheating : Density Perturbations from the Shock-in-Time Connecting Inflation to the Hot Big Bang

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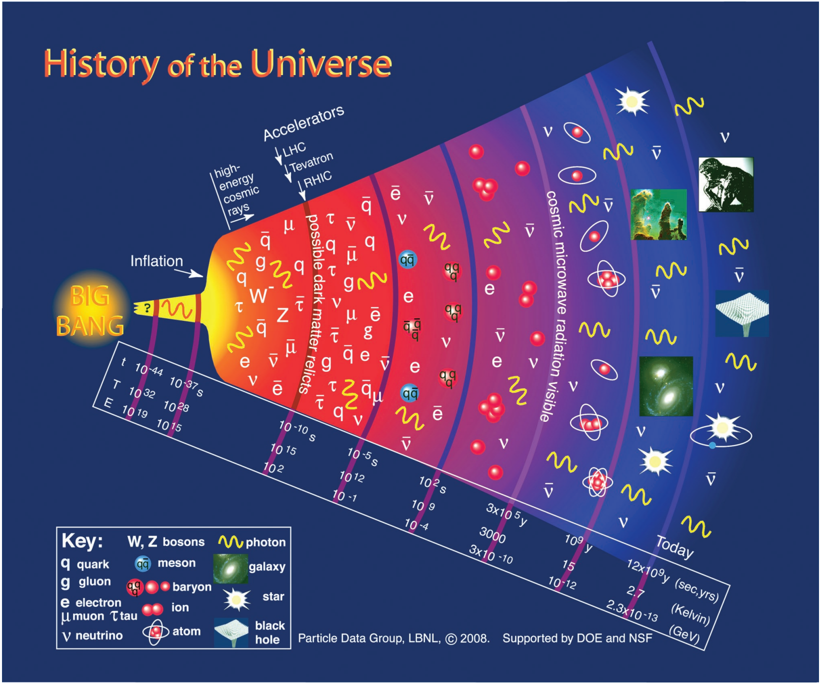
History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Today
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
μ muon τ tau
ion
ν neutrino
atom
black hole
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Why Is This Regime Interesting

Theoretical Consistency

- Inflationary cosmology is incomplete without this transition
- Understand nonequilibrium quantum field theory

More practical concerns

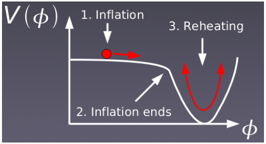
- $N \equiv \ln(a_0/a_{end})$ needed to match observations to inflationary models
- Production of
  - nonGaussian density perturbations [Bond,Frolov,Huang,Kofman],[Rajantie,Chambers]
  - tensors [Easter,Giblin,Lim],[Figueroa,Garcia-Bellido],[Dufaux,Felder,Kofman,Huang]
- Linear structure growth depends on background expansion
- Nonequilibrium - baryogenesis?, nonthermal DM production?

Outline

- Review of linear preheating
- Nonlinear stage of preheating
- Entropy Production
- Production of adiabatic perturbations from isocurvature modes

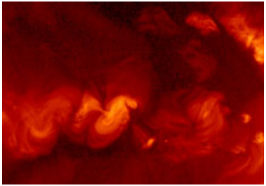
Starting the Big Bang

Inflation



- Cold ($T \sim 0$), $\frac{S}{V} \approx 0$
- Few active d.o.f.

Hot Big Bang



- Hot ($T > MeV$), $\frac{S}{V} \propto g_{eff}(T)T^3$
- Many active d.o.f.

Huge entropy production

But how does it happen?

Preheating : Linear Regime [Kofman, Linde, Starobinski]

QFT $\implies$ inhomogeneity

$$[\delta\phi_i, \delta\dot{\phi}_i] \neq 0 \implies \langle|\delta\phi_k|^2\rangle, \langle|\delta\dot{\phi}_i|^2\rangle \neq 0$$

Generic Equations for $\mathcal{L}_{mat} = -\frac{1}{2}\partial_\mu\phi^I\partial^\mu\phi^I - V(\vec{\phi})$

$$\partial_{tt}(a^{3/2}\delta\phi)_i + \left(\frac{k^2}{a^2} + F_{ij}(\bar{\phi}(t), a)\right)(a^{3/2}\delta\phi_j) = 0$$

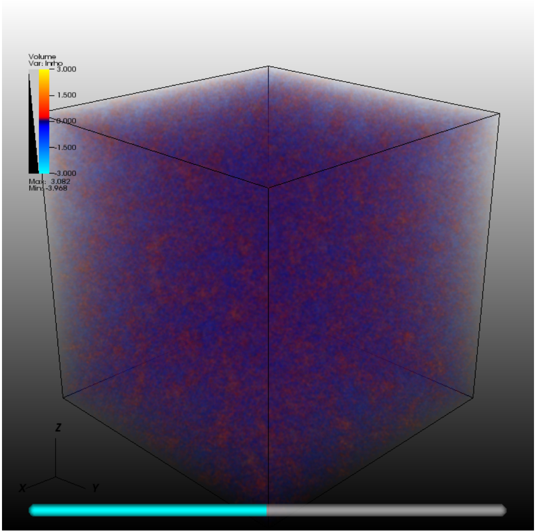
Harmonic oscillator with (∼periodic) time-dependent frequency

Exponential Growth of Inhomogeneities

- Narrow Parametric Resonance
- Broad Parametric Resonance
- Tachyonic Resonance
- Spinodal (Tachyonic) Instability

Preheating : Nonlinear Evolution of ln $\rho/\bar{\rho}$

$$\ddot{\phi}_i + 3H\dot{\phi}_i - a^{-2}\nabla\phi_i^2 + \partial_i V = 0 \qquad 3H^2 = \langle\rho\rangle$$



Entropy and Coarse Graining

Shannon Entropy

$$S = -\int \mathcal{D}\varphi f[\varphi] \ln f[\varphi]$$

$\varphi(x) = (\varphi_1(x), \ldots, \varphi_{N_s}(x)) \to$
$(\varphi_1(x_1), \varphi_1(x_2), \ldots, \varphi_1(x_N), \varphi_2(x_1), \ldots)$

Entropy and Coarse Graining

Shannon (or von Neumann) Entropy

$$S = -\int \mathcal{D}\varphi f[\varphi] \ln f[\varphi] = -\mathrm{Tr}\hat{\rho}(\hat{\varphi}) \ln \hat{\rho}(\hat{\varphi})$$

$\varphi(x) = (\varphi_1(x), \ldots, \varphi_{N_s}(x)) \rightarrow$
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Entropy and Coarse Graining

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Maximize S Subject to Measured $C(x,y) \equiv \langle \varphi(x)\varphi^\dagger(y) \rangle$

$$S_{ME} - \frac{N_{lat} \ln 2\pi}{2} - \frac{N_{lat}}{2} = \frac{1}{2} \ln \det C$$

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$$S_{ME} - \frac{N_{lat} \ln 2\pi}{2} - \frac{N_{lat}}{2} = \frac{1}{2} \sum_{k_i} \ln \Delta(k_i)$$

Statistically Homogeneous : $\Delta(k_i) = \det \langle \tilde{\varphi}(k_i) \tilde{\varphi}(k_i)^\dagger \rangle$

Entropy and Coarse Graining

Shannon (or von Neumann) Entropy

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Maximize S Subject to Measured $C(x, y) \equiv \langle \varphi(x) \varphi^\dagger(y) \rangle$

$$S_{ME} - \frac{N_{lat} \ln 2\pi}{2} - \frac{N_{lat}}{2} = \frac{1}{2} \ln \left(\frac{\Pi_{k_i} \Delta(k_i)}{\mathcal{J}^2} \right) + \ldots$$

Statistically Homogeneous : $\Delta(k_i) = \det \langle \tilde{\varphi}(k_i) \tilde{\varphi}(k_i)^\dagger \rangle$

Noncanonical : $\Pi P(k) \sim V_{fluc}^2, \; \mathcal{J}^2 = \left| \frac{\partial \varphi}{\partial \varphi_{can}} \right|^2 \sim V_{quantum}^2$

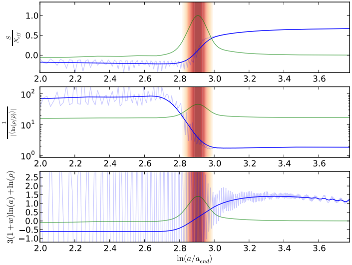
Linear Evolution of Field Variables

$$\frac{dS_{ME}}{dt} = 0 \qquad \text{and} \qquad \text{Gaussianity preserved}$$

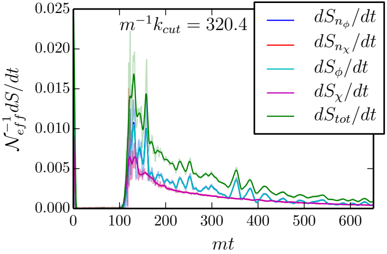
Preheating : The Shock-in-Time

$$\mathcal{L} = -\frac{\partial_\mu \phi \partial^\mu \phi}{2} - \frac{\partial_\mu \chi \partial^\mu \chi}{2} - \frac{m^2 \phi^2}{2} - \frac{g^2 \phi^2 \chi^2}{2}$$

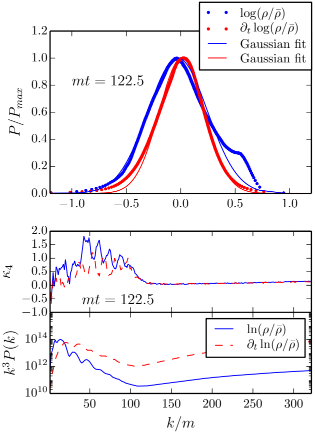
Phonons $(\ln \rho, \partial_t \ln \rho)$



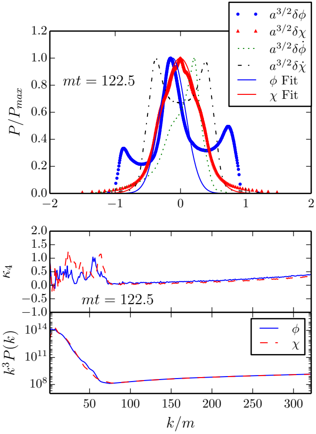
Fields (ϕ_i, Π_{ϕ_i})



Low-Point Statistics

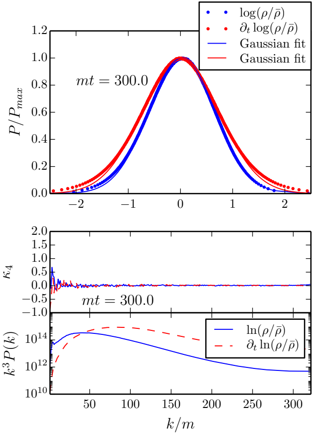


During Shock

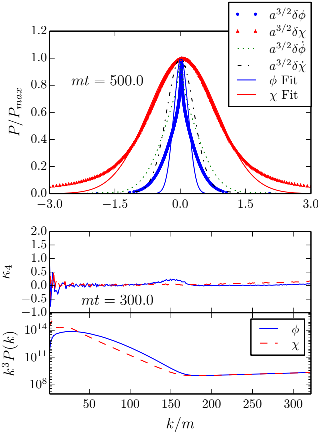


During Shock

Low-Point Statistics : Gaussian ln ρ Post-Shock



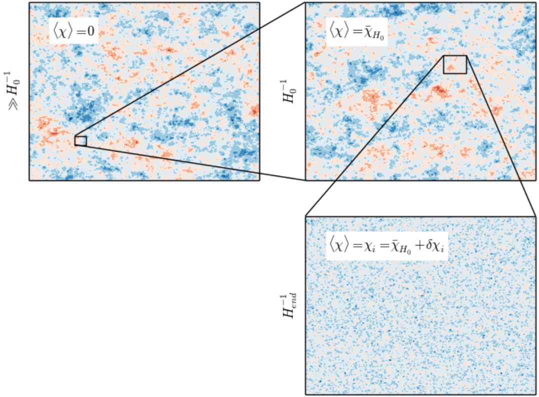
Post-Shock



Post-Shock

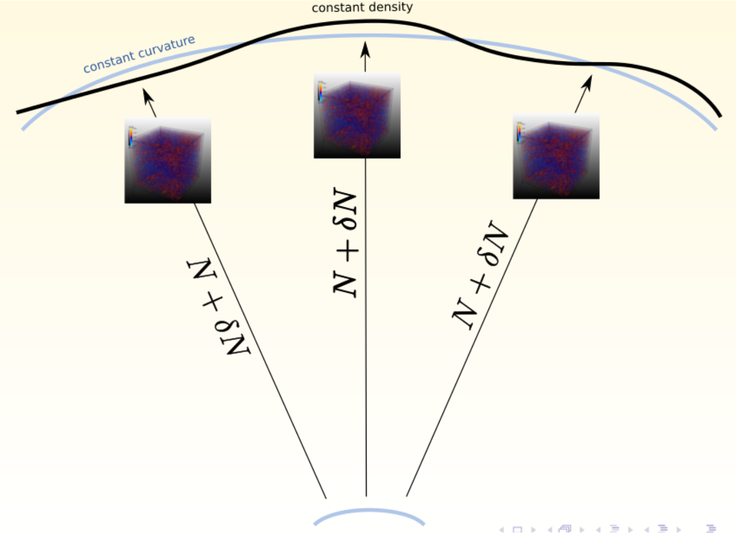
Multiscale View of Isocurvature Fluctuations χ

To decay, inflaton must couple to other fields (e.g. $g^2\phi^2\chi^2$)



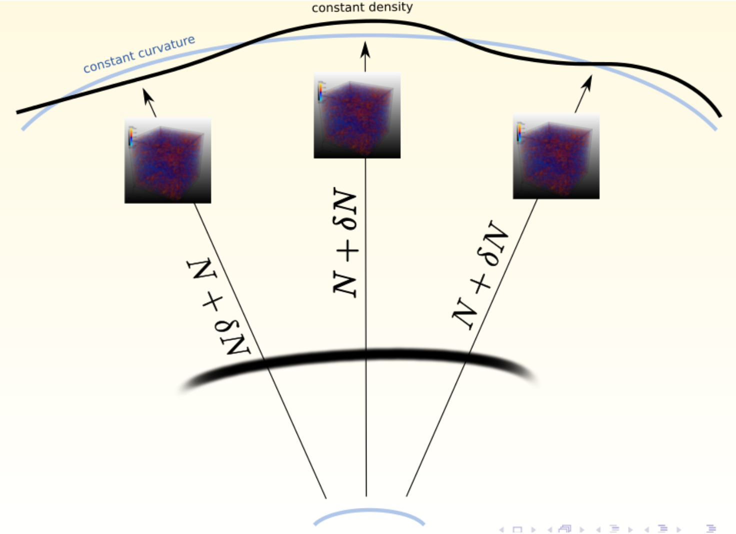
Can χ_i influence preheating?

Preheating Density Perturbations [Chambers, Rajantie],[Bond,Frolov,Huang,Kofman]



$$\zeta_{tot} = \zeta_{inflaton} + F_{NL}(\chi)$$

Preheating Density Perturbations [Chambers, Rajantie],[Bond,Frolov,Huang,Kofman]



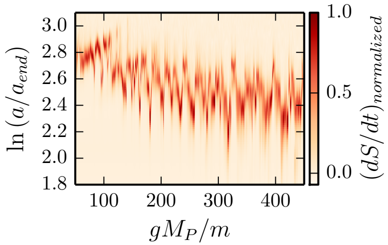
$$\zeta_{tot} = \zeta_{inflaton} + F_{NL}(\chi)$$

Mechanism I : Modulation of the Shock-in-Time [Bond,JB]

$$F_{NL} = F_{NL}(g^2(\bar{\chi}))$$

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{g^2}{2}\phi^2\sigma^2$$

Fixed g^2

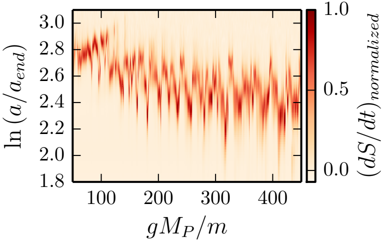


Mechanism I : Modulation of the Shock-in-Time [Bond,JB]

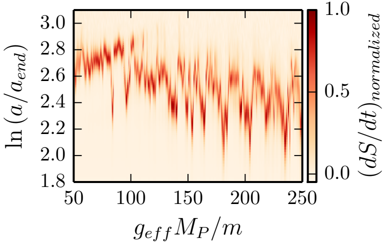
$$F_{NL} = F_{NL}(g^2(\bar{\chi}))$$

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \frac{\alpha}{2}\chi^2\phi^2\sigma^2$$

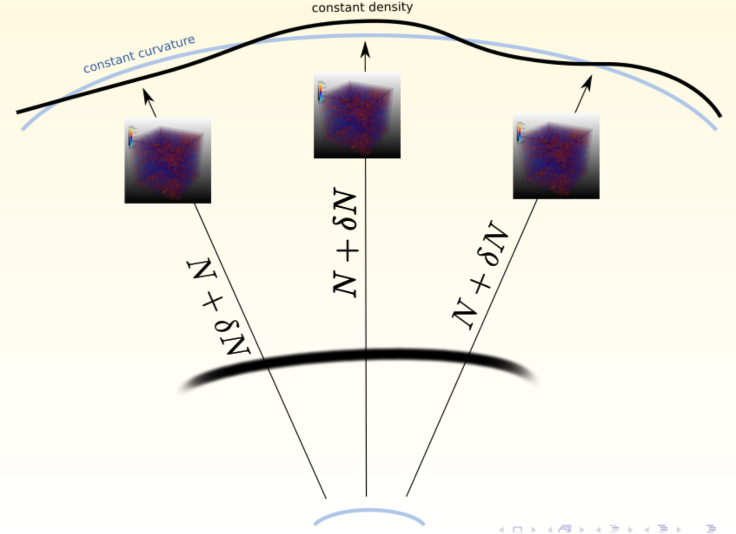
Fixed g^2



Dynamical $g_{eff}^2 = \alpha\bar{\chi}^2$



Preheating Density Perturbations [Chambers, Rajantie],[Bond,Frolov,Huang,Kofman]



$$\zeta_{tot} = \zeta_{inflaton} + F_{NL}(\chi)$$

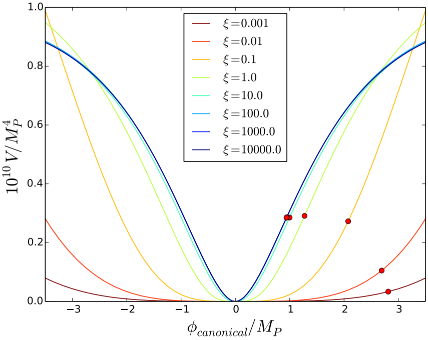
Mechanism II : Density Perturbations from Ballistic Motion

Caustics [Bond,JB,Frolov,Huang]

Jordan Frame

$$\frac{\mathcal{L}}{\sqrt{|g|}} = \frac{M_P^2}{2}(1+\xi\phi^2)\mathcal{R} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\partial_\mu\chi\partial^\mu\chi$$

$$- \frac{\lambda}{4}\phi^4 - \frac{g^2}{2}\phi^2\chi^2$$

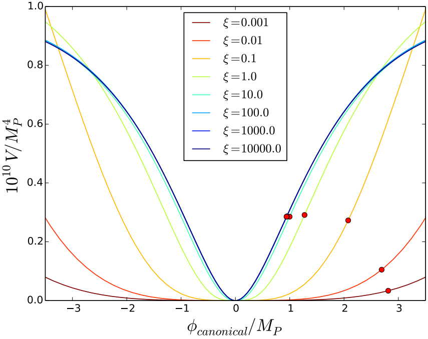


Mechanism II : Density Perturbations from Ballistic Motion

Caustics [Bond,JB,Frolov,Huang]

Einstein Frame

$$\frac{\mathcal{L}}{\sqrt{|g|}} = \frac{M_P^2}{2}\mathcal{R} - \frac{1}{2}\frac{1+\xi(1+6\xi)\phi^2}{(1+\xi\phi^2)^2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\frac{\partial_\mu\chi\partial^\mu\chi}{1+\xi\phi^2}$$
$$- \frac{\lambda}{4}\frac{\phi^4}{(1+\xi\phi^2)^2} - \frac{g^2}{2}\frac{\phi^2\chi^2}{(1+\xi\phi^2)^2}$$



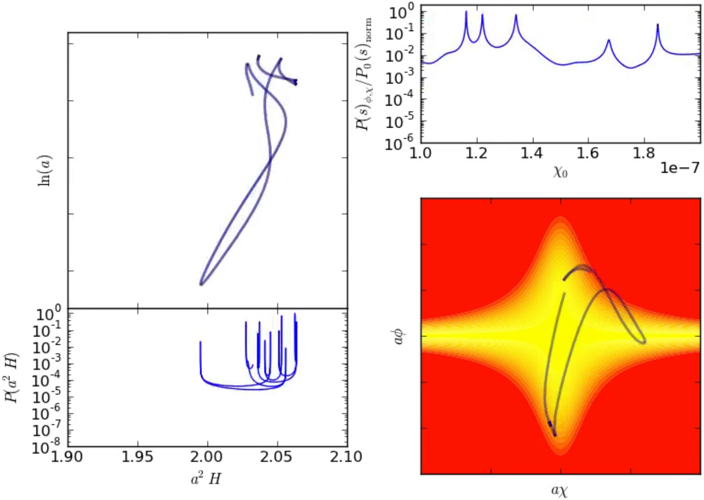
Mechanism II : Density Perturbations from Ballistic Motion Caustics [Bond,JB,Frolov,Huang]

Einstein Frame

$$\frac{\mathcal{L}}{\sqrt{|g|}} = \frac{M_P^2}{2}\mathcal{R} - \frac{1}{2}\frac{1+\xi(1+6\xi)\phi^2}{(1+\xi\phi^2)^2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}\frac{\partial_\mu\chi\partial^\mu\chi}{1+\xi\phi^2} - \frac{\lambda}{4}\frac{\phi^4}{(1+\xi\phi^2)^2} - \frac{g^2}{2}\frac{\phi^2\chi^2}{(1+\xi\phi^2)^2}$$

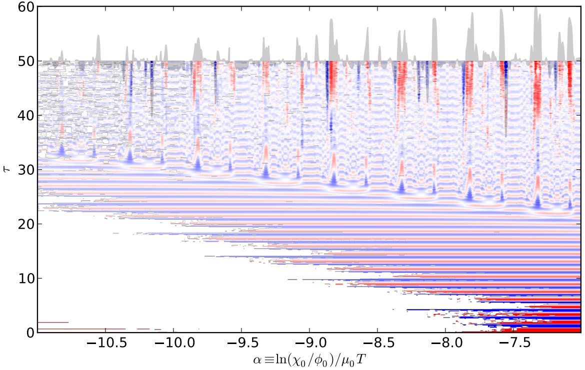
- For certain choices of $\frac{g^2}{\lambda}$, $\chi_{k=0}$ mode is unstable
- $\langle\chi\rangle \equiv \chi_i$ has superhorizon fluctuations from inflation
- Chaotic billiards in a potential $\rightarrow$ caustics

Ballistic Motion of Trajectories



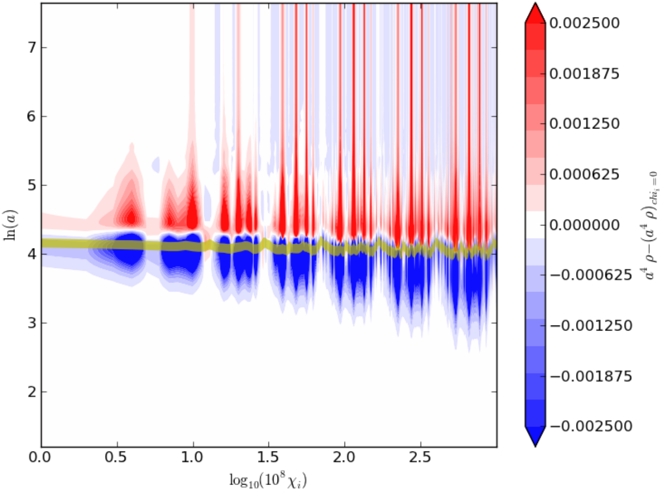
Caustics Lead to Curvature Spikes

Density Perturbations from Caustics

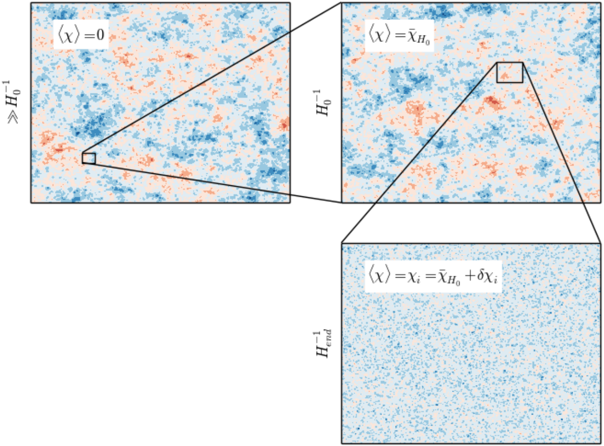


Decoupled Trajectories

Density Perturbations from Caustics

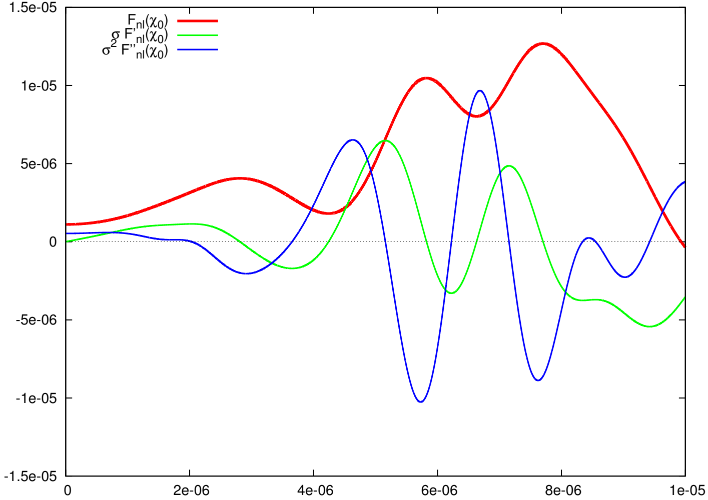


Lattice Simulations



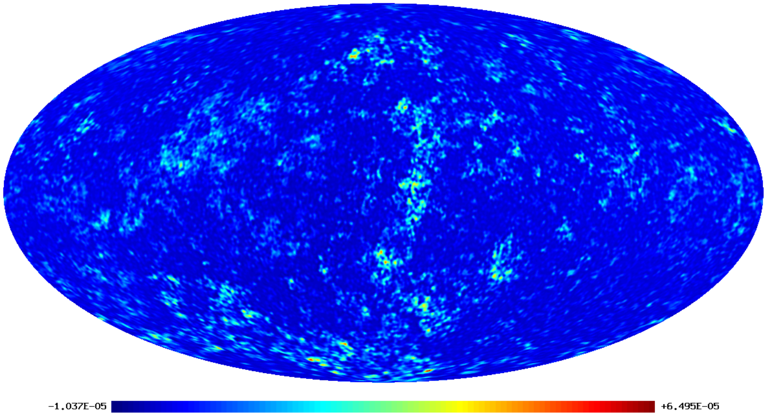
$$\zeta = \zeta_{inf} + F(\chi_i)$$

Back up the Hierarchy - A CMB Pixel



$$\zeta = \zeta_{inf} + F(\chi_i)$$

Sample CMB Maps - Vary χ_{H_0}



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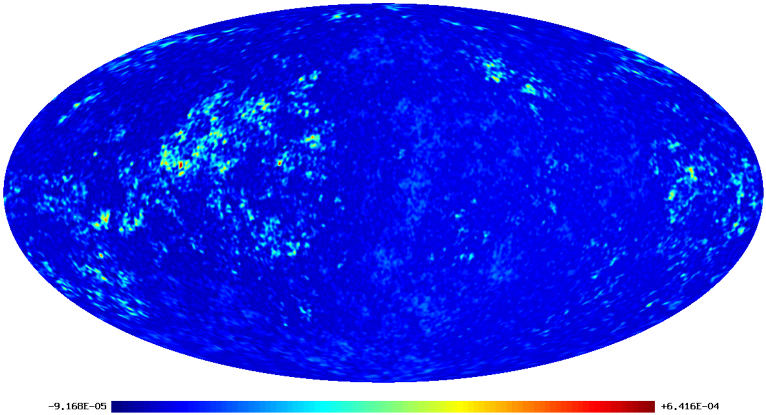

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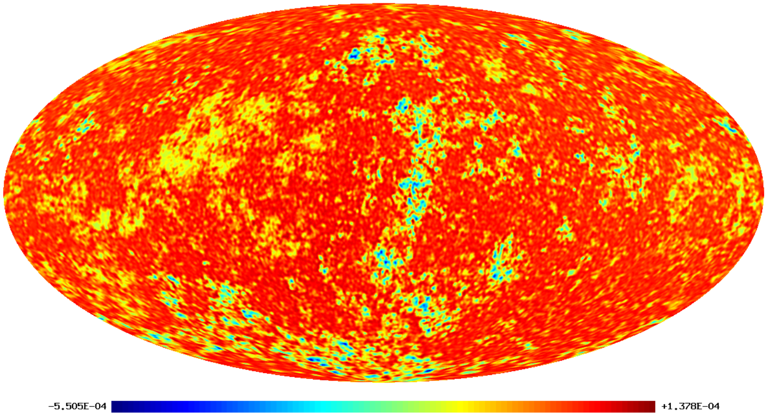

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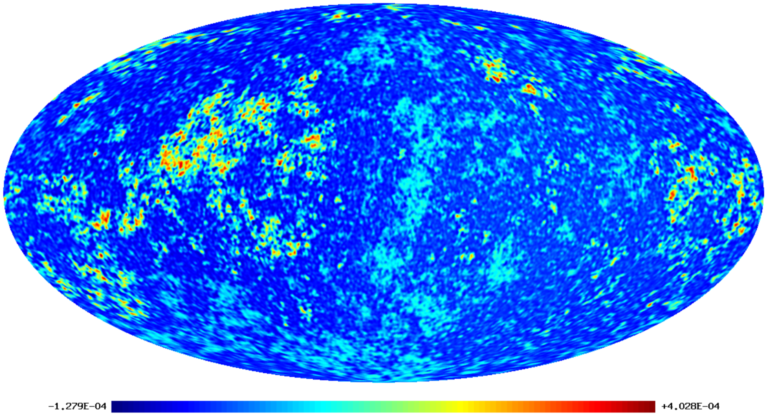

Conclusions

- Post-inflation instabilities are common
- Sharp transition from ballistic to strongly coupled evolution — shock-in-time
- Can generate density perturbations from preheating
  1. Caustic formation from pre-shock billiards
  2. Modulation of shock surface
- Generic given isocurvature mode coupled to inflaton