Curvature Perturbations from Entropy Generation on Cosmic Trajectories

Jonathan Braden
CITA / UCL
www.cita.utoronto.ca/~jbraden

Work with
Dick Bond, Andrei Frolov, Zhiqi Huang, Thomas Morrison

Origins of the Universe, Simons Foundation, NYC, September 20, 2018
Standard Inflation: Explain a few parameters

\[ P_s(k) = A_s k^{n_s - 1} \]

\[ r = 16 \epsilon \]

\[ f_{NL} \]

Are there nonconventional signatures?
How do we parametrize them?
What is the Inflaton?

Observations

1. Inflation
2. Inflation ends
3. Reheating

Isocurvature fluctuations modulate adiabatic modes

\[ \zeta = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi) \]
Possible Effects

- Potential features during inflation
- Nonlinear superhorizon evolution
- Particle production during inflation (Green, Linde, McAllister, Senatore, Silverstein, Zaldarriaga)
- End-of-inflation dynamics
- Initial Conditions (JB, Flauger, Linde, Senatore, …)
Lattice Simulations

[Braden]

- Solve field equation
  \[
  \ddot{\phi} + 3H \dot{\phi} + a^{-2} \nabla^2 \phi + V'(\phi) = 0
  \]
  \[
  H^2 = \frac{\rho}{3M_P^2}
  \]
- Finite-difference or pseudospectral
- 10th order Gauss-Legendre (general) or 8th order Yoshida (nonlinear sigma model)
- Quantum fluctuations random field realization

constant density
\[ \zeta = \delta \ln a \big|_{H^*} \]

\[ \zeta = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi) \]
\[ \frac{d\zeta}{dt} = \frac{1}{3(1 + w)} \frac{d\ln \rho}{dt} + \frac{d\ln a}{dt} \]

\[ = \frac{T}{3V(\rho + P)} \frac{dS}{dt} \]

Entropy Production $\rightarrow$ $\zeta$ Production

- Stochastic noise from smoothing + subhorizon modes
- Nonlinear dynamics of superhorizon modes
- Nonlinear dynamics of subhorizon modes
End-of-Inflation

[JB, Bond, Frolov, Huang]
End-of-Inflation

[JB, Bond, Frolov, Huang]

Many degrees of freedom
Hot (T = O MeV)
High entropy
Simple Model

\[ V(\phi, \chi) = \frac{\lambda}{4} \phi^4 + \frac{g^2}{2} \phi^2 \chi^2 \]

Precise Form Not Crucial
Lattice Evolution
Sources of $\zeta$

\[
\frac{d\zeta}{dt} = \frac{\partial_i T^{i0}}{3(\rho + P)} = \sum_I \frac{\nabla \cdot (\phi_I \nabla \phi_I)}{a^2(\rho + P)}
\]

$mt = 300.0$
Connection to Part. Prod.

Bursts of $\zeta$ production

Nonadiabatic fluctuation growth (c.f. particle creation)
Production Over Smooth Lattice

\[ \frac{S_{n,\rho} - S_{n,\rho}(t=0)}{N_{\text{eff}}} \]

\[ \frac{1}{|\ln(\rho/\bar{\rho})|} \]

\[ \ln a + \frac{\ln \rho}{g(1+\omega)} \]

\[ \ln(a/a_{\text{end}}) \]
\[ \zeta = \delta \ln a \big|_{H^*} \]
Isocon Dependent Zeta

Gigafigure: 1 point = 1 lattice simulation
Ballistics

Drop derivative couplings (reduced phase space)
Reproduce the Lattice

Billiard caustics ubiquitous $\rightarrow$ generic mechanism
Transverse Instability During Inflation

[JB, Bond, Morrisson] [c.f. Bond talk at Princeton meeting]
Transverse Instability

[JB, Bond, Morrisson]

\[ V(\phi, \chi) = \frac{\lambda_\phi}{4} \phi^4 + \frac{\lambda_\chi}{4} \chi^4 \]

\[ - \frac{A^2 \sqrt{e}}{b} (\phi - \phi_p) \exp \left[ - \frac{(\phi - \phi_p)^2}{2b^2} \right] \chi^2 \]
Local Values of $\zeta$
Bubble Nucleation
[c.f. JB talk at Princeton Meeting]
Motion

[JB, Johnson, Peiris, Pontzen, Weinfurtner]

Agrees with instanton approach!

Classical evolution from quantum vacuum samples

Conclusions / Future Work
Conclusions / Future Work

- Isocurvature fluctuations can modulate $\zeta$ production via nonlinear evolution
- Generalized form of local nonGaussianity $\zeta = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi)$
- Production of $\zeta$ tied to entropy production and relation to conventional particle creation
- General framework based on (smoothed) trajectory dynamics
- Detailed connection with CMB and LSS observations
  [Alvarez, Bond, JB, Frolov, Huang, Stein]
Relation to Observations

Perturbative NG

Intermittent $\tilde{\zeta} = \zeta_{\text{inf}} + \zeta_{\text{NL}}(\chi)$

tSZ

B2FH, b+braden+frolov+huang

ABSB+FH, alvarez+b+stein+frolov+huang