Gravitational Growth of Perturbations During Reheating

arXiv:1909.11678

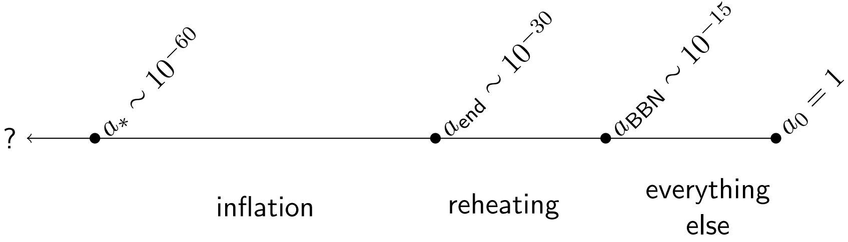
PPC 2021

Nathan Musoke

University of New Hampshire

2021 05 19

Inflation & Reheating



- Inflation solves cosmology's initial conditions problems
  - Explains homogeneity and flatness
  - Predicts the observed spectrum of perturbations in the CMB
- How does inflation transition into big bang nucleosynthesis? **Reheating**

Reheating

The way reheating happens affects the predictions of an inflationary model

- Viability
- Amount of inflation
- Coupling to dark matter

Scenarios:

- Self-interactions or couplings to other fields
  - Resonance
  - Rapid reheating
  - Formation of solitons or oscillons
- Weak couplings
  - Slow reheating
  - Less understood

Slow Reheating

What happens when couplings are weak?

- The universe can expand for a long time without significant reheating
- Perturbations in the inflaton field grow gravitationally

$$\delta \equiv \frac{\rho}{\langle \rho \rangle} \sim a$$

- Perturbation theory breaks down

$$\delta \sim 1 \quad \text{when} \quad \frac{a}{a_{\text{end}}} \sim 10^6$$

K. Jedamzik, M. Lemoine and J. Martin, arXiv:1002.3039
R. Easther, R. Flauger and J. B. Gilmore, arXiv:1003.3011

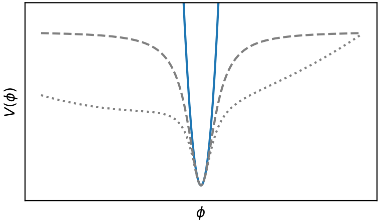
Slow Reheating

Possible consequences

- Nonlinear phenomena in even the simplest models of inflation
- Decay of the inflaton enhanced in overdensities
- Collapse to primordial black holes
  - Hawking radiation as reheating mechanism
- Gravitational radiation sourced by overdensities and/or primordial black holes
- Remnants could be dark matter

Scenario

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \mathcal{O}(\phi^3)$$



- The inflaton has coherent oscillations

$$\phi \sim \frac{1}{t}\sin(mt)$$

- The density grows with the scale factor

$$\delta \sim a$$

- These are on different timescales

$$\frac{t_H}{t_\phi} = \sqrt{3}\left(\frac{a}{a_{\text{end}}}\right)^{3/2}$$

NM, S. Hotchkiss and R. Easther, arXiv:1909.11678, Phys. Rev. Lett. **124**, no.6, 061301 (2020)

Klein-Gordon Equations → Schrödinger-Poisson Equations

- The inflaton ϕ obeys the Klein-Gordon and Einstein equations
- Make a transformation

$$\phi = \frac{1}{ma^{3/2}} \left(\psi e^{-imt} + \psi^* e^{imt}\right)$$

- The Klein-Gordon equations become the Schrödinger-Poisson equations

$$i\frac{\partial \psi}{\partial t} = -\frac{1}{2ma^2}\nabla^2\psi + m\psi\Phi$$
$$\frac{1}{a^2}\nabla^2\Phi = \frac{4\pi G}{a^3}\left(\psi\psi^* - \langle|\psi|^2\rangle\right)$$

Klein-Gordon Equations $\rightarrow$ Schrödinger-Poisson Equations

- The inflaton ϕ obeys the Klein-Gordon and Einstein equations
- Make a transformation

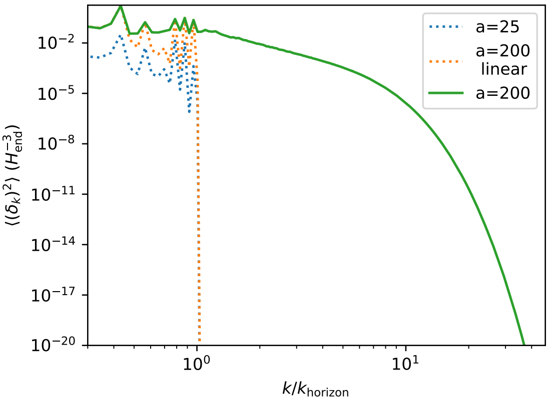
$$\phi = \frac{1}{ma^{3/2}} \left(\psi e^{-imt} + \psi^* e^{imt} \right)$$

- The Klein-Gordon equations become the Schrödinger-Poisson equations

$$i\frac{\partial \psi}{\partial t} = -\frac{1}{2ma^2}\nabla^2 \psi + m\psi\Phi$$
$$\frac{1}{a^2}\nabla^2 \Phi = \frac{4\pi G}{a^3}\left(\psi\psi^* - \left\langle |\psi|^2 \right\rangle \right)$$

- The Schrödinger-Poisson equations are already of interest
  - Ultralight dark matter

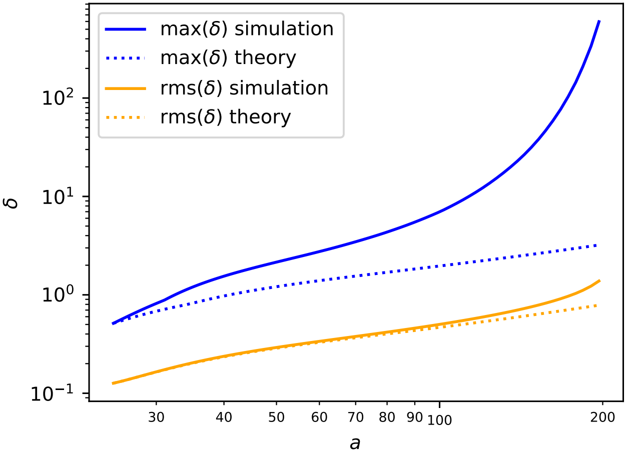
Results



$$\delta_{\text{end},k} = \begin{cases} 0 & \text{for } k = 0 \\ \frac{1}{\sqrt{3}} M_{\text{Pl}} m k^{1/2} & \text{for } k < k_{\text{Horizon}} \\ 0 & \text{for } k > k_{\text{Horizon}} \end{cases} .$$

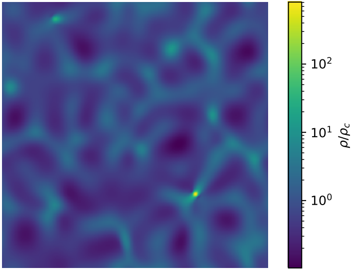
NM, S. Hotchkiss and R. Easther, arXiv:1909.11678, Phys. Rev. Lett. **124**, no.6, 061301 (2020)

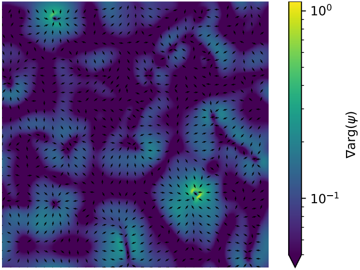
Results



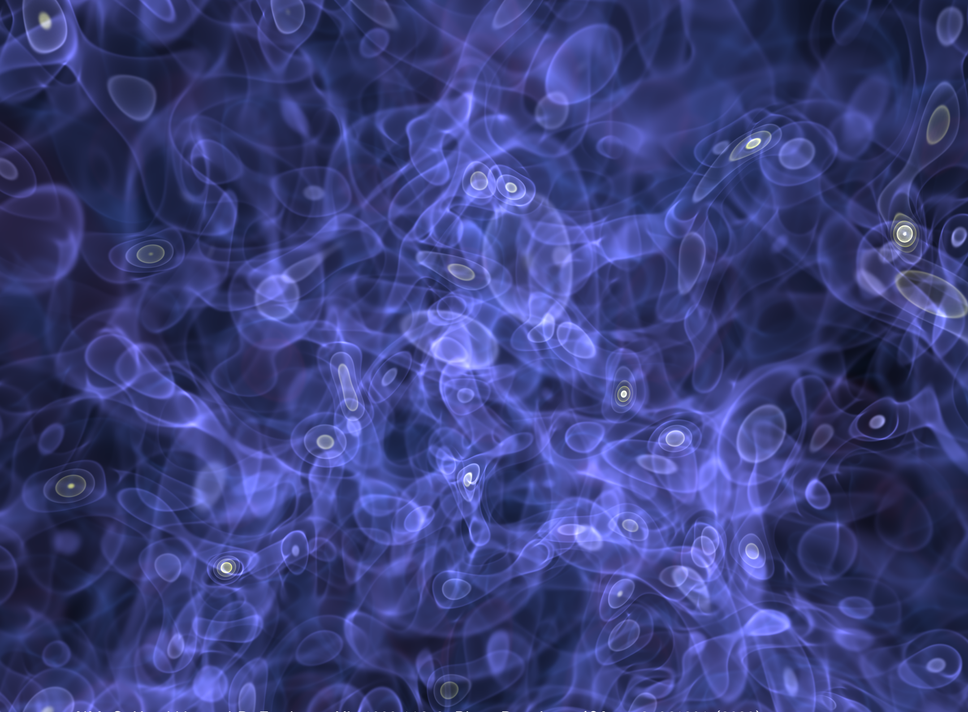
NM, S. Hotchkiss and R. Easther, arXiv:1909.11678, Phys. Rev. Lett. **124**, no.6, 061301 (2020)

Results





NM, S. Hotchkiss and R. Easther, arXiv:1909.11678, Phys. Rev. Lett. **124**, no.6, 061301 (2020)



NM, S. Hotchkiss and R. Easther, arXiv:1909.11678, Phys. Rev. Lett. **124**, no.6, 061301 (2020)

Future

- More detailed simulations
  - More realistic initial conditions
  - Compare models
  - What is the end state of the collapse?
- Further application of techniques from dark matter and structure formation
- Add couplings to standard model
- Similar use of Schrödinger-Poisson equations to simulate gravitational interactions of structures formed during preheating

Summary

- The post-inflation dynamics of the inflaton are described by the Schrödinger-Poisson equations
- Gravitational collapse in the early universe can be analogous to structure formation in the late universe
- First simulations of the gravitational growth of perturbations in the inflaton field during reheating
- Confirmed formation of large overdensities
- More advanced codes will go further and make observational predictions

The Schrödinger-Poisson Equations

Constraints

- The largest scales must be sub-horizon

$$L_{\mathsf{box}} \ll \frac{1}{H}$$

- The field should have small derivatives

$$|\ddot{\psi}| \ll m|\dot{\psi}| \ll m^2|\psi|$$
$$\left|\frac{1}{a^2}\nabla^2\psi\right| \ll m|\psi|$$

- Expansion should not be too fast

$$H \equiv \frac{\dot{a}}{a} \ll m$$
$$\dot{H} \ll mH$$

Matching Equation

- The reheating temperature is useful for constraining models of inflation
- The *matching equation* determines how much inflation is needed

$$\log \frac{a_{\text{end}}}{a_*} = N = 56.12 - \log \frac{k}{k_*} + \frac{1}{3(1+w)} \log \frac{2}{3} + \log \frac{V_k^{1/4}}{V_{\text{end}}^{1/4}} + \frac{1-3w}{3(1+w)} \log \frac{\rho_{\text{reheat}}^{1/4}}{V_{\text{end}}^{1/4}} + \log \frac{V_k^{1/4}}{10^{16}\ \text{GeV}}$$

  - w = equation of state during reheating
  - ρ_{reheat} = density at end of reheating

Perturbation Theory

$$\psi = \sqrt{\rho_0}\sqrt{1+\delta}\,\exp(iS)$$

$$\delta_{d,k} = +\left(\frac{3}{x^2} - 1\right)\sin x - \frac{3}{x}\cos x \qquad \text{decaying for } x^2 < 6$$

$$\delta_{g,k} = -\left(\frac{3}{x^2} - 1\right)\cos x - \frac{3}{x}\sin x \qquad \text{growing for } x^2 < 6$$

$$S_{d,k} = \left(-\frac{6}{x^3} + \frac{3}{x}\right)\sin x + \left(\frac{6}{x^2} - 1\right)\cos x$$

$$S_{g,k} = \left(+\frac{6}{x^3} + \frac{3}{x}\right)\cos x + \left(\frac{6}{x^2} - 1\right)\sin x$$

$$x = \frac{k^2}{mH_0\sqrt{a}}$$