Nonlinear evolution during the primordial dark age

Cosmology from Home

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Outline

Inflation

Reheating

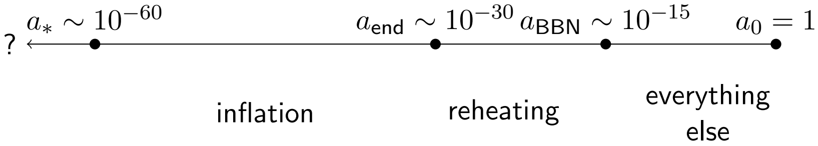
PyUltraDark

Results

Conclusion

Inflation

Exponential growth in the early universe solves cosmology's initial conditions problems



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inflation

reheating

everything else

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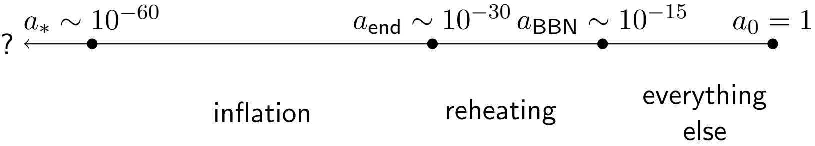

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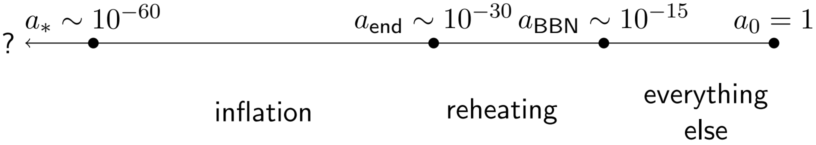

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How does inflation transition into big bang nucleosynthesis?

Reheating

- At the end of inflation the universe is full of an almost homogeneous condensate
- Need to transition to big bang nucleosynthesis
- The way and speed with which reheating happens affects the predictions of a model
    - General viability
    - Required amount of inflation
    - Coupling to dark matter
- Scenarios:
    - Self-interactions or couplings to other fields $\rightarrow$ resonance and preheating
    - **Weak coupling** $\rightarrow$ slow reheating

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

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

- The scales with the most growth are those on the horizon at the end of inflation

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

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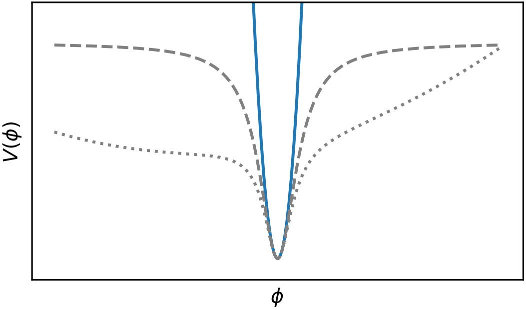
NM, S. Hotchkiss and R. Easther, arXiv:1909.11678

Scenario

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



Scenario

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:

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

The Klein-Gordon Equations

ϕ obeys the Klein-Gordon and Einstein equations

$$\nabla_\mu \nabla^\mu \phi - \frac{\mathrm{d}V}{\mathrm{d}\phi} = 0$$

$$G_{\mu\nu} = 8\pi T_{\mu\nu} = 8\pi \left(\partial_\mu \phi \partial_\nu \phi - \frac{1}{4} g_{\mu\nu} \left(\partial_\kappa \partial^\kappa \phi - V(\phi) \right) \right)$$

The Schrödinger-Poisson Equations

After making 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

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

The Schrödinger-Poisson Equations

- The largest scales must be sub-horizon
- 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

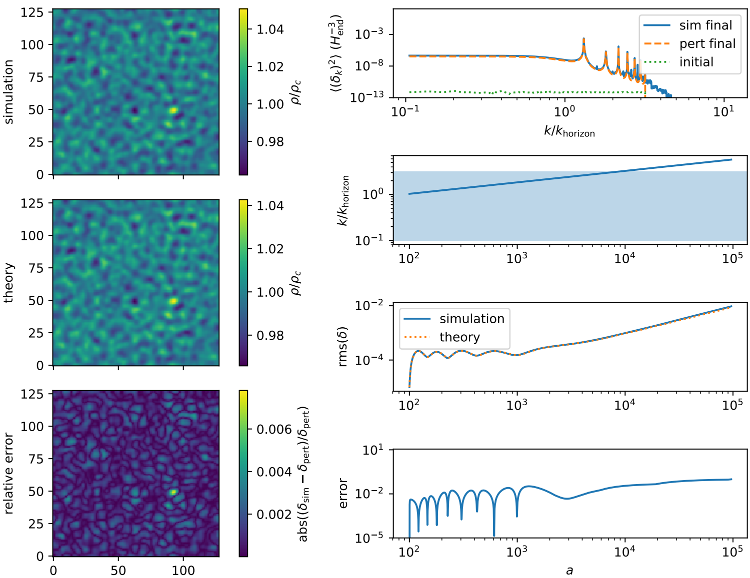
$$H \ll m$$

$$\dot{H} \ll mH$$

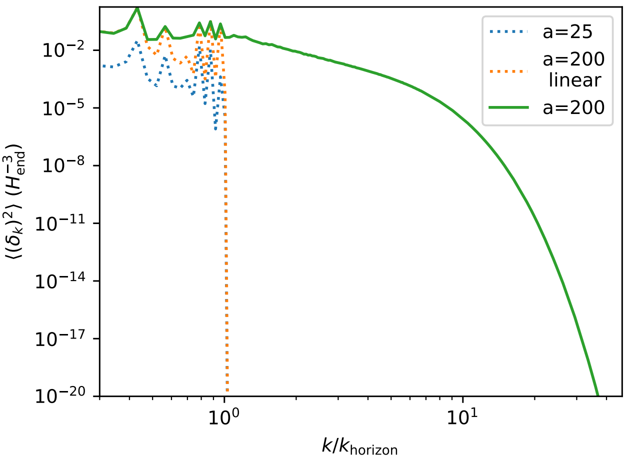
PyUltraDark

- Based on `PyUltraLight`, an ultralight dark matter code
- Added
  - expansion with $a \propto t^{2/3}$
  - adaptive time steps
  - cosmological initial conditions
  - consistency checks on phase
- Can't handle:
  - large velocities
  - formation of black holes, etc.

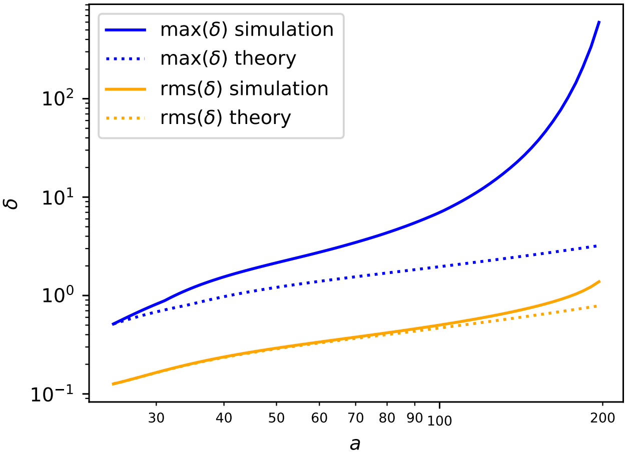
PyUltraDark



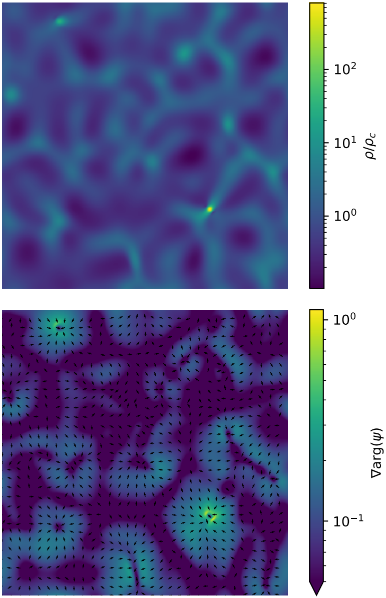
Results

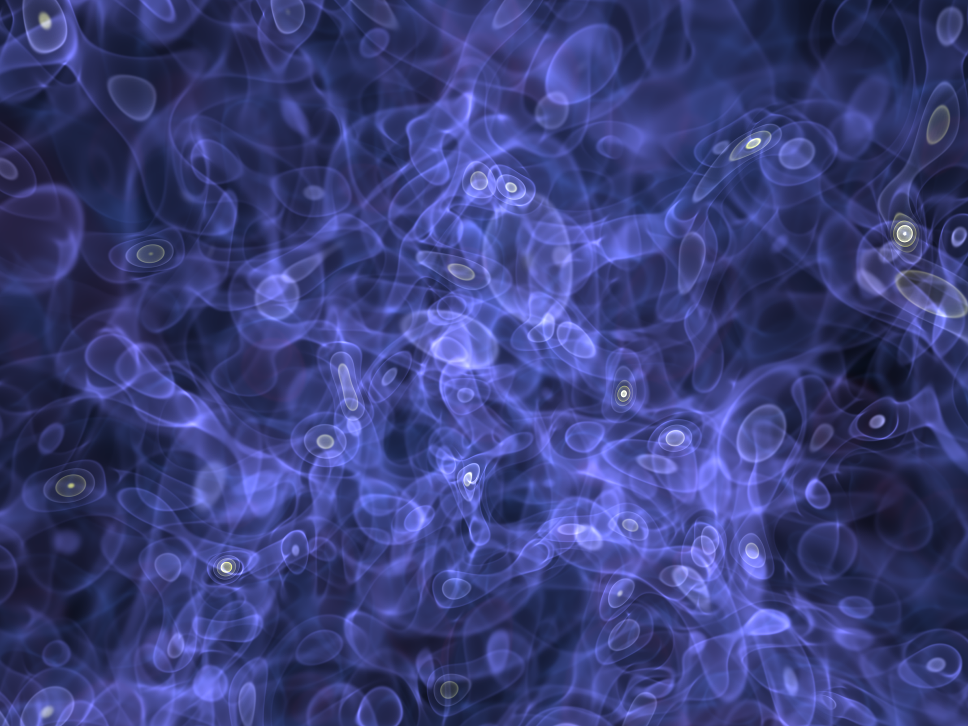

a=25
a=200 linear
a=200
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{-20}
$\langle(\delta_k)^2\rangle\ (H_{\mathrm{end}}^{-3})$
10^{0}
10^{1}
k/k_{horizon}

Results


max(δ) simulation
max(δ) theory
rms(δ) simulation
rms(δ) theory
δ
10^2
10^1
10^0
10^{-1}
30
40
50
60
70
80
90
100
200
a

Results





Conclusion

- Showed that the post-inflation dynamics of the inflaton are described by the Schrödinger-Poisson equations
- Can simulate the gravitational growth of perturbations in the inflaton field during reheating
- Confirmed structure formation and showed that it is analogous to the late universe
- More advanced codes will go further and make observational predictions

References I

N. Musoke, S. Hotchkiss and R. Easther, *Lighting the Dark: Evolution of the Postinflationary Universe*, *Phys. Rev. Lett.* **124** (2020) 061301, [`1909.11678`].