Inflaton Fragmentation & The Matter-Antimatter Asymmetry

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History of the Universe

Accelerators: CERN-LHC

time

temperature

energy

10^{16} \text{ GeV}

10^{-4} \text{ GeV}

reheating

dark matter

Electroweak, Strong phase transitions

baryogenesis

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main idea

inflation \longrightarrow \text{end of Inflation} \longrightarrow \text{matter-antimatter asymmetry}

\eta \approx 6 \times 10^{-10}
main idea

inflaton/anti-inflaton asymmetry locked in solitons (oscillons!)

inflaton fragmentation and generation of $A_\phi$: inflaton/anti-inflaton asymmetry

inflation

$\eta \sim \mathcal{O}[10^2] \times A_\phi \left( \frac{T_{\text{reh}}}{m_\phi} \right)$

observed asymmetry (baryon-to-photon ratio)
synopsis

- the inflaton model & asymmetry
- dynamics:
  - homogeneous
  - linearized dynamics - instabilities
  - nonlinear dynamics - fragmentations & solitons
- asymmetry generation
  - dependence on params.
  - inflaton asymmetry — baryon asymmetry
- observational consequences
the model details

A variation of the Affleck-Dine Mechanism (1985)
Hertzberg & Karouby (2013)

\[ S = \int d^4 x \sqrt{-g} \left[ \frac{m_{Pl}^2}{2} R - g^{\mu \nu} \partial_\mu \phi \partial_\nu \phi^* - V(\phi, \phi^*) \right] \]

\[ V(\phi, \phi^*) = V_s(|\phi|) + V_{br}(\phi, \phi^*) \]

- \( V_s(|\phi|) = m^2 M^2 \left[ \sqrt{1 + 2\frac{|\phi|^2}{M^2}} - 1 \right] \)
  
- \( V_{br}(\phi, \phi^*) = \frac{c_3}{3} \frac{m^2}{M} \frac{\phi^3 + \phi^{*3}}{f(|\phi|)} \)
  
- respects U(1) symmetry responsible for inflation
- breaks U(1) symmetry responsible for generating inflation/antiinflaton asymmetry small, symmetry breaking ...
- observationally consistent choice
- our choice: subdominant during and after inflation
inflaton asymmetry — baryon asymmetry

\[ \Delta N_\phi = N_\phi - N_{\bar{\phi}} = i \int d^3x a^3 (\phi* \dot{\phi} - \dot{\phi}* \phi) \]

- generated at end of inflation

\[ \phi \to b \]

\[ N_b - N_{\bar{b}} = b_\phi (N_\phi - N_{\bar{\phi}}) \]

- decay

baryon number
inflaton dynamics

inflation $|\phi|$ | $V(|\phi|) < \mathbb{E}$

end: oscillatory regime
Linearized Perturbations: Initial Conditions

\[ \delta \dot{\varphi}^I_k + 3H \delta \dot{\varphi}^I_k + \left[ \delta^I J \frac{k^2}{a^2} + \partial^I \partial J \mathcal{V} \right] \delta \varphi^J_k = -2\Psi_k \partial^I \mathcal{V} + 4\dot{\Psi}_k \dot{\varphi}^I_k. \]

\[ \delta \varphi^J_k(t) = \sum_{n=1}^N a_{kn} u_n^J(t, k) + a_{-kn} u_n^J(t, k). \]

\[ [\hat{a}_{qn}, \hat{a}_{km}] = 0, \]

\[ [\hat{a}_{qn}, \hat{a}_{km}^\dagger] = \delta(q - k) \delta_{nm}. \]

\[ \langle 0 | \delta \dot{\varphi}^I_q(t) \delta \dot{\varphi}^J_k(t) | 0 \rangle = \delta(q - k) P^{IJ}(t, k) \]

\[ P^{IJ}(t, k) = \sum_{n=1}^N u_n^I(t, k) u_n^{J*}(t, k). \]

includes metric perturbations

\[ \dot{\Psi}_k + H \Psi_k = \frac{1}{2m_{Pl}^2} \delta_{IJ} \dot{\varphi}^I_k \dot{\varphi}^J_k, \]

\[ \left( \dot{H} + \frac{k^2}{a^2} \right) \Psi_k = \frac{1}{2m_{Pl}^2} \delta_{IJ} \left[ -\dot{\varphi}^I_k \dot{\varphi}^J_k + \delta \varphi^J_k \dot{\varphi}^I_k \right] \]

Full multifield evolution with metric fluctuations on super and subhorizon scales.
Linearized Perturbations: instabilities

\[ \delta \dot{\varphi}_k^I + 3H \delta \varphi_k^I + \left[ \delta^I_J \frac{k^2}{a^2} + \partial^I \partial_J \mathcal{V} \right] \delta \varphi_k^J = -2\Psi_k \partial^I \mathcal{V} + 4\dot{\varphi}_k \varphi_k^I. \]

\[ \delta \varphi_k(t) \sim e^{\mu_k t}. \]

unstable when
\[ \frac{\Re(\mu_k)}{H} \gg 1 \]

Also See: Hertzberg, Karouby, William G. Spitzer, Juana C. Becerra, Lanqing Li (2014)
“actual” dynamics

Fragmentation!

(1) highly nonlinear
(2) homogeneous analysis fails
(3) linear analysis helps to see the instability, but fails soon after …

Also see: Khlopov, Molamed and Zeldovich (1985)
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surfaces drawn at 5 x the avg. density

time after inflation = 120 m\(^{-1}\) — 300 m\(^{-1}\)
“actual” dynamics

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“actual” dynamics

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time after inflation = 120 m$^{-1}$ — 300 m$^{-1}$
“actual” dynamics

surfaces drawn at 5 x the avg. density

time after inflation = 120 m$^{-1} \rightarrow 300$ m$^{-1}$
what are these lumps?

(1) oscillatory (2) spatially localized (3) very long lived


Long wavelength stability: MA & Shirokoff 2010
Existence conditions (including non-canonical cases): MA 2013
Oscillons after Inflation: MA, Easther, Finkel, Hertzberg 2011
“actual” dynamics

surfaces drawn at 5 x the avg. density

FIG. 4. The homogeneous inflaton condensate starts fragmenting within $$t \approx 20$$ oscillations after the end of inflation. The fragmentation is driven by parametric resonance in the fluctuations along the direction of motion of the field. After the perturbations become nonlinear, localized, long-lived field configurations called oscillons form and dominate the energy density of the inflaton field. The oscillons once formed maintain a fixed size and density, and can be very long lived with lifetimes $$t \approx 10^6/H$$. They are highly over dense regions, the contours in the above plots are drawn at 5 x the average density. Most of the inflaton asymmetry is locked in these oscillons although they occupy a small fraction of the volume. The co-moving size of the box is comparable to the Hubble horizon at the end of inflation.

Furthermore, the ratio of the real and imaginary parts of the field inside the two types of pseudo-solitons is given by

$$\left( \alpha \right) = \left( \beta \right) \tan(\pi t)$$

const., oscillons, Q-balls.

Again, for our sampled objects we found that this ratio was constant, consistent with oscillons. We also note that the oscillons we find here have a breathing mode (as seen in [5]) making the higher order terms ignored above also relevant.

For the length of the simulation, we found that our sample objects were oscillons. However, [30] have argued that similar fragmentation, albeit in a different potential and without a symmetry breaking term, generates Q-balls. We cannot rule out the possibility that if one waits for a longer time ($$t \approx 300 m^{-1}$$) some of the oscillons will become Q-balls.

We note that the motion of the field inside the scalar field lumps cannot be purely radial. Since in this case the asymmetry is obviously zero. Some deviation from collinear motion in the complex plane, sourced by the symmetry breaking term and/or nonlinear couplings between the radial and tangential directions, is necessary for there to be non-zero asymmetry. The exact nature of “oscillon like” solutions and their corresponding asymmetry is left for

$$t = 140 m^{-1}$$

$$t = 150 m^{-1}$$

$$t = 200 m^{-1}$$

$$t = 300 m^{-1}$$
inflaton dynamics — asymmetry generation
Asymmetry generated at the end of inflation, and freezes after fragmentation.

The right hand side of the discretized form (although we include them in the initial conditions).

We ignore metric perturbations in the lattice code of the fields in an expanding universe using a model etc. will be studied elsewhere.

Interactions [48, 49], their size distribution [36, 50] profiles of oscillons and their lifetimes [19, 45–47], late in phase with a frequency amplitudes that the oscillons are one complex field), the dynamics is very similar to oscillons in what follows.

Future work. We will continue to call our overdensities (fractions of the universe) as oscillons for simplicity. We have not checked the asymmetry for the homogeneous case continues to significantly longer timescales due to numerical considerations.

After the inflaton fragments into localized solitons (or pseudo-solitons (oscillons)), the asymmetry settles down to a constant value. We have not checked the asymmetry for the asymmetry for the homogeneous case continues to significantly longer timescales due to numerical considerations.

Asymmetry generated at the end of inflation, and freezes after fragmentation.

Asymmetry generated at the end of inflation, and freezes after fragmentation.

\[ A_\phi = \frac{m_\phi \Delta n_\phi}{\rho_\phi} \]
where is the asymmetry?

small volume occupied by solitons — most of asymmetry!
Our main aim here is to connect the inflaton asymmetry to the observable, more specifically the baryon-to-photon ratio in great detail. However, the observable we get below as a function of the fragmentation efficiency parameter (see Eq.(42)). How does the efficiency of fragmentation and the asymmetry of the inflaton particles change with the inflaton field amplitude? For the right hand side, where the potential changes shape, we can interpret the efficiency as the number of photons for the volume of interest. The expression evaluated at late times (after thermalization, and after any relevant processes have become negligible) can be written as

$$A_{\phi} \propto \frac{N_b}{N_{\gamma}}$$

where the potential changes shape. However, the high density, coherent "inflaton oscillon/Q-balls configurations might affect the decrease in asymmetry as a function of the fragmentation efficiency parameter (see Eq.(42)). How does the efficiency of fragmentation and the asymmetry of the inflaton particles change with the inflaton field amplitude? For the right hand side, where the potential changes shape, we can interpret the efficiency as the number of photons for the volume of interest. The expression evaluated at late times (after thermalization, and after any relevant processes have become negligible) can be written as

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$$A_{\phi} \propto \frac{N_b}{N_{\gamma}}$$
dependence on params.
dependence on magnitude of symmetry breaking term

\[ A_\phi \propto c_3^2 \text{ important!} \]

\[ V_{\text{br}}(\phi, \phi^*) = \frac{c_3}{3} \frac{m^2}{M} \frac{\phi^3 + \phi^*}{f(|\phi|)} \]

\[ c_3 \ll 1 \]
dependence on initial angle

\[ A_\phi \propto \sin 3\theta_i \]

\[ V_{br}(\phi, \phi^*) = \frac{c_3}{3} \frac{m^2}{M} \frac{(\phi^3 + \phi^*^3)}{f(|\phi|)} \quad \text{with} \quad c_3 \ll 1 \]
asymmetry- parameters

initial angle

increasing $c_3$

- $c_3 = 10^{-2}$
  - homogeneous
  - fragmented
- $c_3 = 10^{-1}$
- $c_3 = 1$
inflaton asymmetry—dependence on parameters

\[ A_\phi \sim \mathcal{O}[10^2] \times \frac{M}{m_{\text{Pl}}} c_3^2 \sin 3\theta_i \]

(inverse) strength of instability \hspace{1cm} symmetry breaking \hspace{1cm} initial conditions—infation

\[ V_{\text{br}}(\phi, \phi^*) = \frac{c_3}{3} \frac{m^2 (\phi^3 + \phi^{*3})}{M} \frac{f(|\phi|)}{f(|\phi|)} \]

\[ c_3 \ll 1, M \ll m_{\text{Pl}} \]
inflaton to baryons (incomplete!)

\[ \eta \sim O[10^2] \times A_{\phi} \left( \frac{T_{\text{reh}}}{m_{\phi}} \right) \sim 10^{-9} \]

from end of inflation

decay rate to baryons

sample numbers:

\[ A_{\phi} \sim 10^{-4}, \ T \sim 10^7 \text{ GeV}, \ m_{\phi} \sim 10^{14} \text{ GeV} \]

\textbf{caveats:} uncertainty here!! particle physics details, inhomogeneous decay …
other connections ...

- isocurvature fluctuations $\alpha_{II} \sim 2.6 \times 10^{-4}$

- (usual Affleck-Dine runs into problems with isocurvature for high scale inflation)

- dark matter

- change in expansion history — number of e-folds
to do

- careful analysis needed:
  - inhomogeneous decay and annihilation to baryons
  - connection to isocurvature perturbations
  - dark matter connection?
  - detailed properties of the solitons (we have checked that they are oscillons *NOT* Q-balls)
- particle physics model building
different model: “long” wavelength asymmetry

\[ V(|\phi|) = m^2 |\phi|^2 + \lambda |\phi|^4 \]

Lozanov & MA (in progress)
The End of Inflation, Oscillons & The Matter-Antimatter Asymmetry

inflaton/anti-inflaton asymmetry locked in solitons (oscillons!)

inflaton fragmentation and generation of $A_\phi$:
inflaton/anti-inflaton asymmetry

inflation ends: oscillatory phase

complex inflaton $\mathbb{U}(1)$

observed asymmetry (baryon-to-photon ratio)

$\eta \sim \mathcal{O}[10^2] \times A_\phi \left( \frac{T_{\text{reh}}}{m_\phi} \right)$

decay into baryons/anti-baryons

connects reheating and baryon asymmetry, with additional observational implications
Our understanding: \( ? \)-Inflation — \( ? \) — Nucleosynthesis

Reheating — populating our universe

- non-perturbative, complex dynamics with obs. implications …
- analytic and numerical techniques available (but long way to go)

- connect inflationary physics to known physics and obs. beyond fluctuations

- Help! — include end of inflation physics with inflation models