Dark Matter and Baryon Asymmetry Production during Inflation

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Interplay: Standard Model and Cosmology

Gauge fields (interactions): $\gamma$, $W^\pm$, $Z$, $g$

Three generations of matter: $L = \left( \begin{array}{c} \nu_L \\ e_L \end{array} \right)$, $e_R$; $Q = \left( \begin{array}{c} u_L \\ d_L \end{array} \right)$, $d_R$, $u_R$

- SM Describes
  - all experiments dealing with electroweak and strong interactions

- SM fails to describe (PHENO)
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$)
  - Baryon asymmetry ($\Omega_B$)
  - Inflationary stage

Cosmology asks for new physics
Can all the three have the same origin...?
Astrophysical and cosmological data are in agreement

\[
\left( \frac{\dot{a}}{a} \right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{energy}}
\]

\[
\rho_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \rho_{\text{dark matter}} + \rho_{\Lambda}
\]

\[
\rho_{\text{radiation}} \propto \frac{1}{a^4(t)}, \quad \rho_{\text{matter}} \propto \frac{1}{a^3(t)}, \quad \rho_{\Lambda} = \text{const}
\]

\[
\frac{3H_0^2}{8\pi G} = \rho_{\text{energy}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5} \text{ GeV cm}^3
\]

Radiation:
\[
\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}
\]

Baryons (H, He):
\[
\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05
\]

Neutrino:
\[
\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01
\]
\[
N_\nu \approx 3, \sum m_\nu \lesssim 0.2 \text{ eV}
\]

Dark matter:
\[
\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27
\]

Dark energy:
\[
\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68
\]
Dark Matter Properties

- dust-like **pressureless** component, $p = 0$
- clumping substance, gets confined in structures

If particles (or compact macroscopic objects):
1. **stable** on cosmological time-scale
2. electrically **neutral**
3. decoupled from visible matter
Dark Matter properties from astrophysics

1. **stable** on cosmological time-scale
   - to form ellipsoidal halos

2. (almost) **collisionless**
   - (almost) electrically neutral
   - (almost) electrically neutral to be Dark
   - stability of globular stellar clusters

3. $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   - otherwise too strong tidal forces

4. confinement in a galaxy:
   - de Broglie wavelength: $\lambda = \frac{2\pi}{(M_X v_X)} < l_{\text{galaxy}}$, for bosons
   - in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$
   - $M_X \gtrsim 3 \cdot 10^{-22}$ eV
   - for fermions $M_X \gtrsim 750$ eV

5. Pauli blocking:

$$f(p, x) = \frac{\rho_x(x)}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{p^2}{2M_X^2 v_X^2}} \bigg|_{p=0} \leq \frac{g_x}{(2\pi)^3}$$

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DM and BAU production at inflation

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Key observable: matter perturbations

- CMB is isotropic, but “up to corrections, of course...”
  - Earth movement with respect to CMB
    \[ \Delta T_{\text{dipole}} \sim 10^{-3} \]
  - More complex anisotropy: \[ \frac{\Delta T}{T} \sim 10^{-4} \]
- There were matter inhomogeneties \( \Delta \rho / \rho \sim \Delta T / T \) at the stage of recombination \((e + p \rightarrow \gamma + H^*)\)
  - Jeans instability in the system of gravitating particles at rest \( \Rightarrow \Delta \rho / \rho \uparrow \) galaxies (CDM halos)
  - \( \Delta \rho_{\text{DM}} / \rho_{\text{DM}} \propto a \propto 1 / T \) from \( T = 0.8 \text{ eV} \),
    while \( \Delta \rho_{\text{B}} / \rho_{\text{B}} \propto a \propto 1 / T \) only after recombination \( T = 0.25 \text{ eV} \)
  - without DM total growth factor would be 1100
    not enough to explain structures!
Dark Matter properties from cosmology: $\rho = 0$

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number

2. produced in the early Universe
   some time before RD/MD-transition ($T = 0.8$ eV)

3. nonrelativistic particles long before RD/MD-transition ($T = 0.8$ eV)
   (either Cold or Warm, $\nu_{RD/MD} \lesssim 10^{-3}$)

Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming

If were in thermal equilibrium:

4. (almost) collisionless
   $M_X \gtrsim 1$ keV
   $\rho = 0$, $\nu_{\text{sound}} = 0$

5. (almost) electrically neutral
   CMB distortion

6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta \left( \frac{n_B}{n_{DM}} \right) = \delta \left( \frac{n_B}{n_\gamma} \right) = \delta \left( \frac{n_\nu}{n_\gamma} \right) = 0$$
2.7 K

TODAY

4.4 K

accelerated expansion

matter domination

recombination

matter domination

radiation domination

primordial nucleosynthesis

neutrino decoupling

QCD transition

Electroweak phase transition

baryogenesis

hot Universe

reheating

e + p → H + γ

3H + 4He → 7Li + γ

2H + 2H → n + 3He

p + p → 2H + γ

confinement ↔ free quarks

dark matter production

inflation

14 by 7.7 by

7.7 by

4.4 K

2.7 K

0.26 eV

0.8 eV

50 keV

1 MeV

2.5 MeV

200 MeV

100 GeV

baryogenesis

hot Universe

reheating

inflation

DM and BAU production at inflation

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Nonthermal production mechanisms

Dark Matter production mechanisms

1. in the primordial plasma of SM particles (via scatterings, oscillations):
   - WIMPs
   - gravitino
   - sterile neutrino of 1-50 keV

2. at phase transitions:
   - axion of $10^{-4} – 10^{-7}$ eV
   - Q-balls
   - strangelets (?)

3. during reheating (after inflation?):
   - black holes
   - any guy coupled (only) to inflaton
     - perturbatively: inflaton decays
     - non-perturbatively: Bose-enhancement of coherent production by external field

4. while the Universe expands:
   - gravity produces any particles at $H \sim M_X$
Nonthermal production mechanisms

2.7 K

TODAY

accelerated expansion
matter domination

370 ty

14 by

7.7 by

4.4 K

0.26 eV

recombination
matter domination

50 ty

0.8 eV

radiation domination

5 min

3 H + 4 He → 7 Li + γ

0.8 eV

e + p → H + γ

50 keV

primordial nucleosynthesis

2.5 MeV

neutrino decoupling

1 s

3 H + 4 He → 7 Li + γ

2 H + 2 H → n + 3 He

0.1 s

p + p → 2 H + γ

200 MeV

QCD transition

10 µs

confinement ↔ free quarks

1 MeV

Electroweak phase transition

0.1 ns

100 GeV

hot Universe

0.1 ns

baryogenesis

reheating

dark matter production

1 MeV

baryogenesis

inflation

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Baryogenesis

– Need BAU $\eta_B \equiv n_B/n_\gamma \approx 6 \times 10^{-10}$ starting from BBN epoch, $T \lesssim 1\text{ MeV}$
– The same number at recombination and later

Sakharov conditions of successful baryogenesis

- $B$-violation
  
  \[ (\Delta B \neq 0) \quad \text{out of equilibrium:} \quad X Y \rightarrow X' Y' \rightarrow B \]

- $C$- & $CP$-violation
  
  \[ (\Delta C \neq 0, \Delta CP \neq 0) \quad \bar{X} \bar{Y} \rightarrow \bar{X}' \bar{Y}' \rightarrow \bar{B} \]

- processes above are out of equilibrium
  
  \[ X' Y' \rightarrow B \rightarrow XY \]

At 100 GeV $\lesssim T \lesssim 10^{12}$ GeV nonperturbative processes (EW-sphalerons) violate $B, L_\alpha$, so that only three charges are conserved out of four, e.g.

\[ B - L, \quad L_e - L_\mu, \quad L_e - L_\tau \]

Leptogenesis: Baryogenesis from lepton asymmetry of the Universe . . . due to sterile neutrinos

Why $\Omega_B \sim \Omega_{DM}$? antropic principle?
Production at inflation

- All particles get separated by exponentially large distance
- All homogeneous scalar fields uncoupled to inflaton
  - either fall to origin (if $M > H$)
  - or remain frozen (if $M < H$) at any pre-inflationary value
- It can be dark matter, but check for isocurvature (non-adiabatic) perturbations
- All homogeneous scalar fields coupled to inflaton
  - either fall to origin (if $M > H$)
  - or participate in inflation (multi-field inflation)
- Only one exception is linear coupling to inflaton

$$\mathcal{L}_{\text{int}} = -\Phi \times F(\text{inflaton})$$

It yields CONSTANT force settling $\Phi$ to CONSTANT nonzero value

$$\Phi'' + 3H\Phi' + V'(\Phi) = F(\text{inflaton})$$
Illustration with scalar complex field $\Psi = \lambda e^{i\varphi}$

In this way any relics (including Dark matter and baryons) can be produced

$$S_\Psi = \int d^4x\sqrt{-g} \left[ \frac{1}{2} |\partial_\mu \Psi|^2 - \frac{1}{2} |M \Psi|^2 - \beta \varphi T_\mu^\mu (\text{inflaton}) \right]$$

so inflaton couples to $\varphi$, but not to $\lambda$

$U(1)$ charge $Q \equiv J_0 = \lambda^2 \dot{\varphi}$ evolves as

$$\frac{1}{a^3} \frac{d}{dt} (Q a^3) = \beta T_\mu^\mu (\text{inflaton})$$

and induce a potential for the field amplitude $\lambda$

$$\ddot{\lambda} + 3H \dot{\lambda} - \frac{Q^2}{\lambda^3} + M^2 \lambda = 0 .$$

- at inflation $Q \to \beta T_\mu^\mu (\text{inflaton})$ and $\lambda \to \lambda_{\text{min}} = \sqrt{Q/M}$ (attractor)
- after inflation, $T_\mu^\mu \text{inflaton} \to 0$ (reheating, or RD-like stage as for $X^4$)
  $Q \propto 1/a^3$ like DM or BAU
Production at inflation

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probably the simplest realization

- take inflation as (keeping coupling to $T^\mu_\mu$, and $M \gtrsim H$ to avoid isocurvature):
  \[ \varphi X^4 + \xi RX^2 \]

- Dark Matter from Q (responsible for stability)
  \[ \beta \approx \frac{T_{end}}{M_{Pl}} \cdot \frac{T_{eq}}{M} \rightarrow \left( T_{end} = 10^{16} \text{GeV}, M = 10^{-5} M_{Pl} \right) \rightarrow 10^{-26}. \]

- Baryon Asymmetry of the Universe, e.g. $Q = B$
  \[ \beta \approx 10^{-10} \sqrt{\frac{H(t_{end})}{M_{Pl}}} \]
The both DM and BAU may be originated from inflation.

The mechanism is very simple and can be easily implemented into particular inflationary models.

Feature: Predictions for DM and BAU are fixed by model parameters, rather than inflationary initial conditions.

Feature: DM and baryons are unstable, $\varphi F(\text{inflaton})$.

The $\Psi$-sector can be more complicated (e.g. transfer of $Q$ to BAU, or $Q$ to another DM candidate).

Light $\Psi$ are allowed with, e.g. $\xi R\bar{\Psi}\Psi$-term.

For more details see arXiv:1805.05904 (with Eugeny Babichev & Sabir Ramazanov).