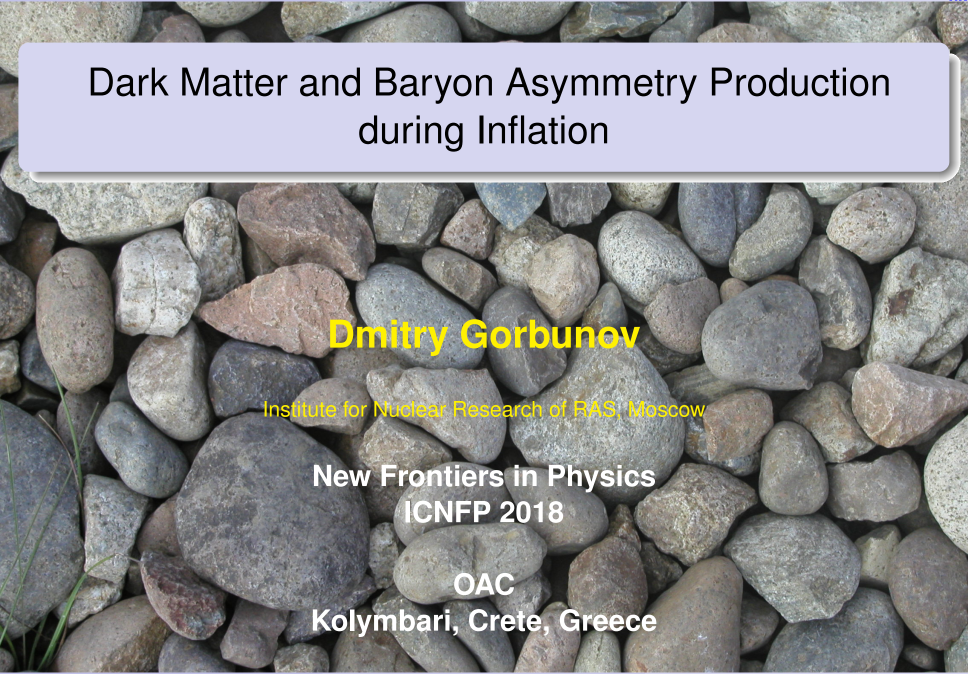

Dark Matter and Baryon Asymmetry Production during Inflation

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

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Interplay: Standard Model and Cosmology

Gauge fields (interactions): γ, $W^{\pm}$, Z, g

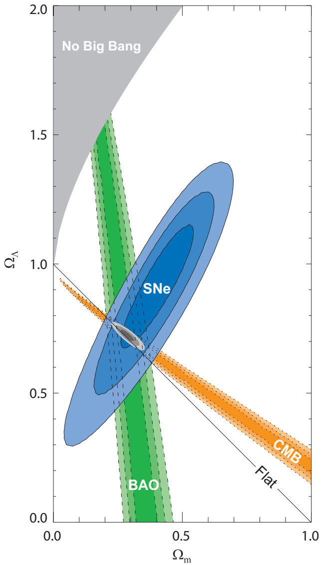
Three generations of matter: $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, e_R; $Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, d_R, u_R

- SM Describes
  - all experiments dealing with electroweak and strong interactions
- SM fails to describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Cosmology asks for new physics $\Omega_{DM} \sim \Omega_B$

Can all the three
have the same origin…?

Astrophysical and cosmological data are in agreement



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

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_\Lambda$$

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

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

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: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

$N_\nu \simeq 3\,, \sum m_\nu \lesssim 0.2\,\text{eV}$

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
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV

   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, — for bosons

   in a galaxy $v_X \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_X \gtrsim 3 \cdot 10^{-22}$ eV

   for fermions

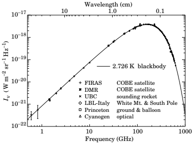
   Pauli blocking: — $M_X \gtrsim 750$ eV

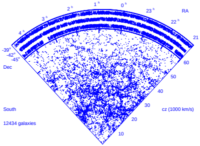
$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}} \bigg|_{\mathbf{p}=0} \le \frac{g_X}{(2\pi)^3}$$

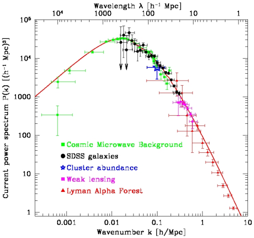
Key observable: matter perturbations

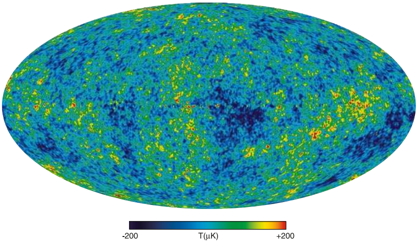
- CMB is isotropic, but “up to corrections, of course...”
    1. Earth movement with respect to CMB
    $$\frac{\Delta T_{\text{dipole}}}{T}\sim 10^{-3}$$
    2. More complex anisotropy: $\frac{\Delta T}{T}\sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho\sim\Delta T/T$ at the stage of recombination ($e+p\to\gamma+H^*$) $\Longrightarrow$

  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho\nearrow$ galaxies (CDM halos)
- $\Delta\rho_{DM}/\rho_{DM}\propto a\propto 1/T$ from $T=0.8\,\text{eV}$,
  while $\Delta\rho_B/\rho_B\propto a\propto 1/T$ only after recombination
  $T=0.25\,\text{eV}$
  without DM total growth factor would be 1100
  not enough to explain structures!







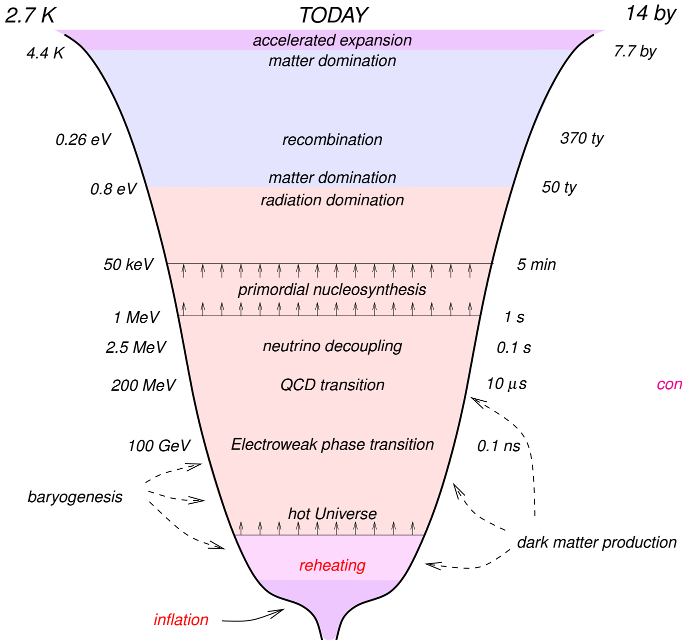


Dark Matter properties from cosmology: $p = 0$

(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 ($T = 0.8\,\text{eV}$)
3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming
   If were in thermal equilibrium: $M_X \gtrsim 1$ keV
4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
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* *14 by*

accelerated expansion

4.4 K *matter domination* *7.7 by*

0.26 eV *recombination* *370 ty*

matter domination

0.8 eV *radiation domination* *50 ty*

50 keV *5 min*

primordial nucleosynthesis

1 MeV *1 s*

2.5 MeV *neutrino decoupling* *0.1 s*

200 MeV *QCD transition* *10 μs*

100 GeV *Electroweak phase transition* *0.1 ns*

baryogenesis

hot Universe

dark matter production

reheating

inflation

$e+p \to H+\gamma$

$^3H+{}^4He \to {}^7Li+\gamma$

$^2H+{}^2H \to n+{}^3He$

$p+p \to {}^2H+\gamma$

confinement↔free quarks

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:

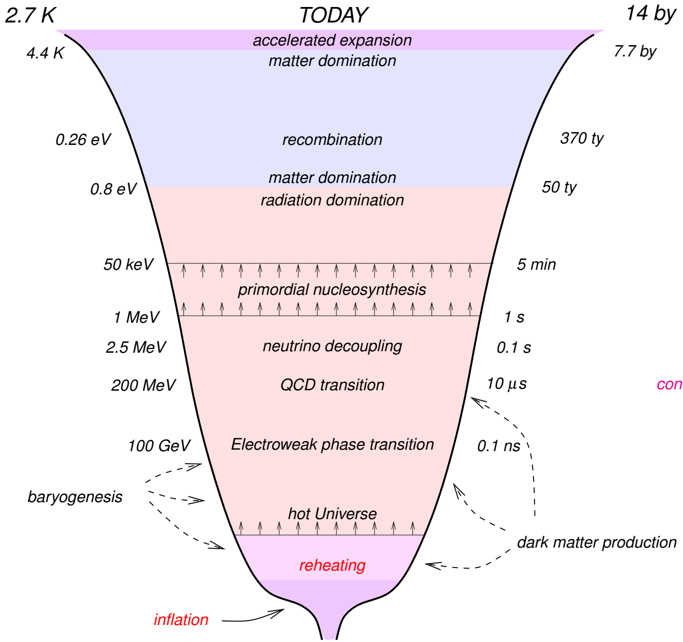
     inflaton decays
     production by external (inflaton) field

   - non-perturbatively:

     Bose-enhancement of
     coherent production by external field

4. while the Universe expands:

   gravity produces any particles at $H \sim M_X$



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Baryogenesis

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

Sakharov conditions of successful baryogenesis

- B-violation $(\Delta B \neq 0)\ XY \dots \to X'Y' \dots B$
- C- & CP-violation $(\Delta C \neq 0,\ \Delta CP \neq 0)\ \bar{X}\bar{Y} \dots \to \bar{X}'\bar{Y}' \dots \bar{B}$
- processes above are out of equilibrium $X'Y' \dots B \to XY \dots$

At $100\,\mathrm{GeV} \lesssim T \lesssim 10^{12}\,\mathrm{GeV}$ nonperturbative processes (EW-sphalerons) violate B, L_α, 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

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

It yields CONSTANT force settling Φ to CONSTANT nonzero value

$$\Phi'' + 3H\Phi' + V'(\Phi) = F(inflaton)$$

Illustration with scalar complex field $\Psi = \lambda\, e^{i\varphi}$

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

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

so inflaton couples to φ, but not to λ

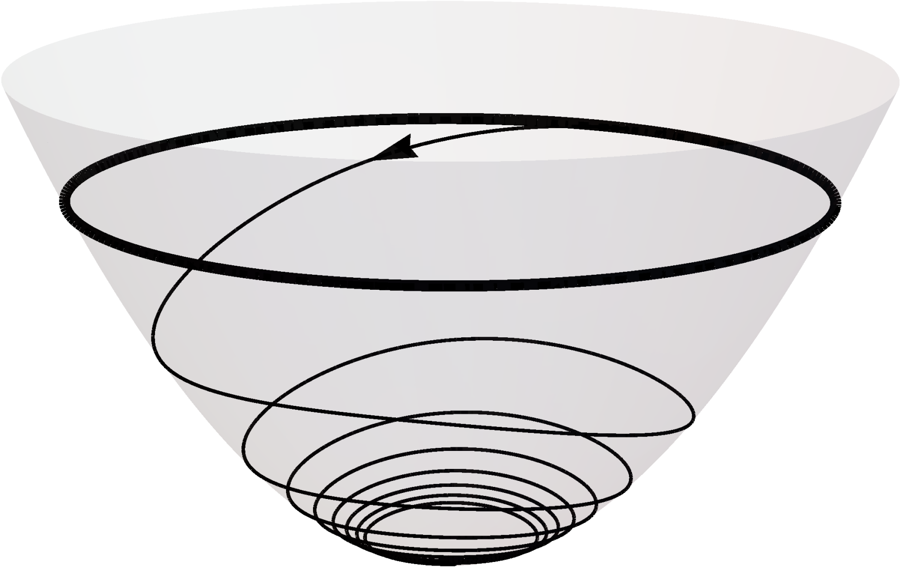
$U(1)$ charge $Q \equiv J_0 = \lambda^2\dot\varphi$ evolves as

$$\frac{1}{a^3}\frac{d}{dt}\left(Qa^3\right) = \beta\, T^\mu_\mu\,(inflaton)$$

and induce a potential for the field amplitude λ

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

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



probably the simlpest realization

- take inflation as (keeping coupling to T^μ_μ, and $M \gtrsim H$ to avoid isocurvature):

$$\varkappa X^4 + \xi R X^2$$

- Dark Matter from Q (responsible for stability)

$$\beta \simeq \frac{T_{end}}{M_{Pl}} \cdot \frac{T_{eq}}{M} \to \left(T_{end} = 10^{16}\,\text{GeV},\; M = 10^{-5}\,M_{Pl} \right) \to 10^{-26}\,.$$

- Baryon Asymmetry of the Universe, e.g. $Q = B$

$$\beta \simeq 10^{-10} \sqrt{\frac{H(t_{end})}{M_{Pl}}}$$

Summary

- The both DM and BAU may be orignated 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, $\varphi F(inflaton)$
- The Ψ-sector can be more complicated (e.g. transfer of Q to BAU, or Q to another DM candidate)
- Light Ψ are allowed with, e.g. $\xi R\bar{\Psi}\Psi$-term

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