Dark Matter Models (II)

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Outline

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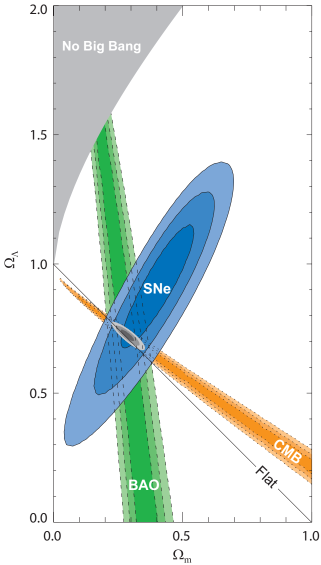
Astrophysical and cosmological data are in agreement



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

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

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

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

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

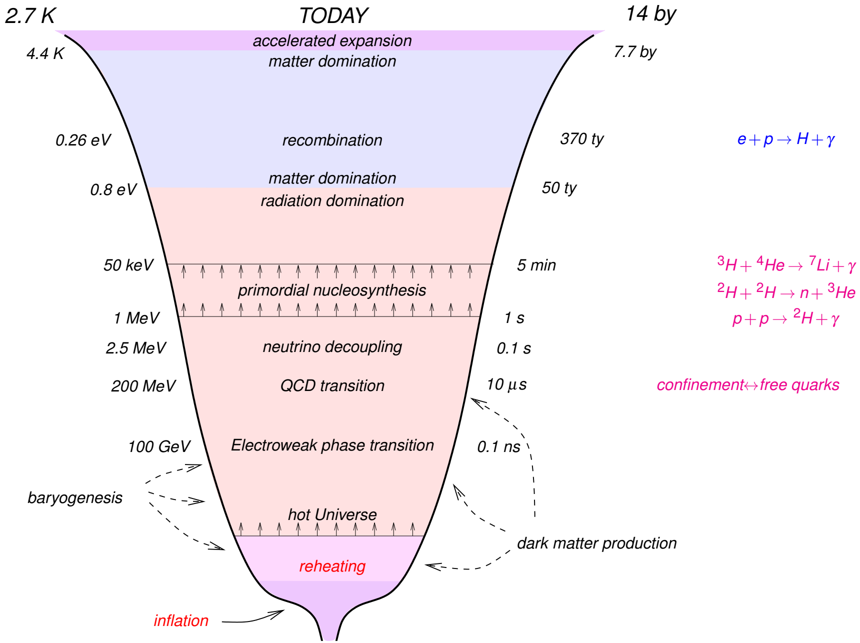
Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

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: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$


2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
radiation domination
50 ty
50 keV
5 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 µs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations):
   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 $H \sim M_X$

Gravitino production

$$\mathscr{L} = \frac{1}{F}\partial^\mu \psi \cdot J_\mu^{SUSY} \;, \quad \tilde{G}_\mu \to \tilde{G}_\mu + i\sqrt{4\pi}\frac{M_{Pl}}{F}\partial_\mu \psi$$

$$m_{3/2} = \sqrt{\frac{8\pi}{3}}\frac{F}{M_{Pl}} \quad \longleftrightarrow \quad \Lambda = 0$$

$$1\text{ TeV} \lesssim \sqrt{F} \lesssim M_{Pl} \;, \quad 2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim M_{Pl}$$

LSP in low scale SUSY breaking models

$$2\cdot 10^{-4}\text{ eV} \lesssim m_{3/2} \lesssim 100\text{ GeV} \longrightarrow \sqrt{F} \lesssim 10^{10}\text{ GeV}$$

Thermal equilibrium is forbidden (fermion; would be hot DM):

$$\Omega_{3/2} = \frac{m_{3/2}\cdot n_{3/2}}{\rho_c} = 0.2\left(\frac{m_{3/2}}{200\,\text{eV}}\right)\left(\frac{g_{3/2}}{2}\right)\left(\frac{210}{g_*(T_d)}\right)\frac{1}{2h^2}$$

Gravitino production in scatterings and decays

$$\tilde{X}_i \to \tilde{G} + X_i\,, \quad X_i + X_j \to \tilde{X}_k + \tilde{G}$$

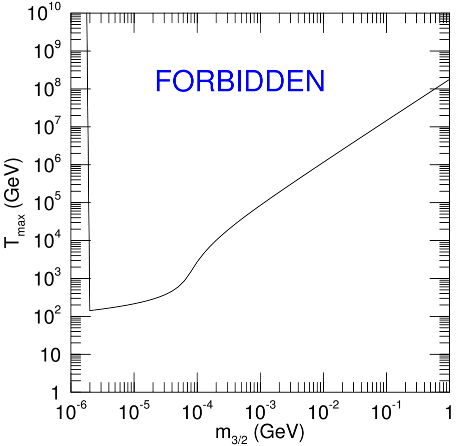
$$\Gamma \propto \frac{1}{F^2} \propto \frac{1}{m_{3/2}^2}\,, \quad \sigma \propto \frac{1}{F^2} \propto \frac{1}{m_{3/2}^2}$$

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \sum_i \Gamma_{\tilde{X}_i} \cdot \gamma_i^{-1} \cdot n_{\tilde{X}_i} + \sum_{i,j} \langle \sigma_{ij} \rangle \cdot n_{X_i} n_{X_j}\,,$$

$$\frac{d}{dT}\left(\frac{n_{3/2}}{s}\right) = -\sum_i \Gamma_{\tilde{X}_i} \cdot \frac{n_{\tilde{X}_i}}{\gamma_i \cdot sHT} - \sum_{i,j} \frac{\langle \sigma_{ij} \rangle \cdot n_{X_i} n_{X_j}}{sHT}\,,$$

$$\propto \frac{1}{T^3} \qquad \propto \text{const}$$

$$\Omega_{3/2} \sim \left(\frac{200\ \text{keV}}{m_{3/2}}\right) \cdot \left(\frac{T_{max}}{10\ \text{TeV}}\right) \times \left(\frac{M_S}{1\ \text{TeV}}\right)^2 \cdot \left(\frac{15}{\sqrt{g_*(T_{max})}}\right) \cdot \frac{1}{2h^2}$$



…issues of QFT description

of a gauge theory at finite temperature

Outcome depends on initial conditions !!!

Free massive scalar field

$$\mathscr{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2$$

For the homogeneous scalar field in FLRW expanding Universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

we find two-stage evolution:

$$m_\phi < H(t) \quad \Longrightarrow \quad \phi = \phi_i = \text{const}$$

$$m_\phi > H(t) \quad \Longrightarrow \quad p = \langle E_k \rangle - \langle E_p \rangle = 0\,, \quad \rho \sim m_\phi^2 \phi^2 \propto 1/a^3$$

- dust-like substance in the late Universe, $\Omega \propto m_\phi^{1/2} \phi_i^2$
  depends on initial conditions
- presureless at spatial scales $l > 1/m_\phi$ — fuzzy DM
- may help (?) with CDM-problems (core-cusp, lack of dwarfs, etc)

Axion: well-motivated but fine-tuned

$$L_\theta = \frac{\alpha_s}{8\pi}\left(\theta_0 + \mathrm{Arg}\left(\mathrm{Det}\hat{M}_q\right)\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a} \equiv \frac{\alpha_s}{8\pi}\theta G^a_{\mu\nu}\tilde{G}^{\mu\nu\,a} \equiv \partial_\mu K^\mu$$ *P*- *CP*-violation

tree-level and $U(1)_A$-anomaly contributions, $\bar{q}_L \hat{M}_q q_R + h.c$ strong *CP*-problem

Theory and Nature: neutron EDM $\theta < 10^{-9}$ nonantropic parameter!

Transformation (PQ-symmetry)

$$q^k_L \to e^{ie^{(PQ)}_k \beta/2} q^k_L$$

$$q^k_R \to e^{-ie^{(PQ)}_k \beta/2} q^k_R,$$

with $\sum_k e^{(PQ)}_k \neq 0$

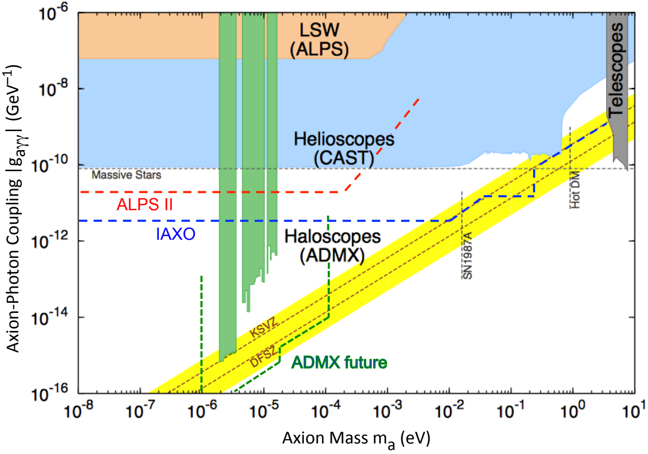
cancels θ with β

$$\theta \to \theta + a(x)/f_a$$

$$m_{\mathrm{axion}} \simeq f_\pi m_\pi / f_a$$

Dark Matter region

$$\mathscr{L} \sim g_{a\gamma\gamma} \times a(x) F_{\mu\nu} F^{\mu\nu}$$



Axion as Cold Dark Matter

$$\theta \to \bar{\theta}(x) = \theta + C_g \frac{a(x)}{f_{PQ}} \,.$$

Free scalar field starts to evolve at $m \simeq H$

$$\mathscr{L} = \frac{f_{PQ}^2}{2} \cdot \left(\frac{d\bar{\theta}}{dt}\right)^2 - \frac{m_a^2(T)}{2} f_{PQ}^2 \bar{\theta}^2 \,,$$

Temperature-dependent mass-term

$$m_a(T) \simeq 0.1 \cdot m_a(0) \cdot \left(\frac{\Lambda_{QCD}}{T}\right)^{3.7} \,, \quad T > \Lambda_{QCD}$$

$$\Omega_a \simeq 0.2 \cdot \bar{\theta}_i^2 \cdot \left(\frac{4 \cdot 10^{-6}\ \text{eV}}{m_a}\right)^{1.2} \cdot \frac{1}{2h^2}$$

- initial conditions
- instantons vs lattice
- domain walls, axion clumps, etc

Sterile neutrino: well-motivated Dark Matter

$$\mathscr{L}_N = \overline{N}_I i\partial\!\!\!/ N_I - f_{\alpha I}\overline{L}_\alpha \tilde{H} N_I - \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.}$$

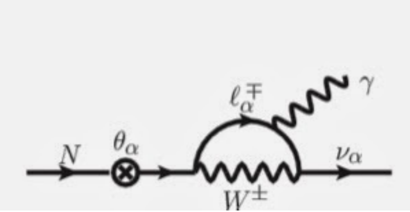
- massive fermions giving mass to active neutrino through mixing

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

- unstable, but exceeding the age of the Universe at condition

$$\theta^2 < 1.5\times 10^{-7}\left(\frac{50\,\text{keV}}{M_N}\right)^5$$

- can be searched for because of two-body radiative decay



Production in oscillations

$$\frac{\partial}{\partial t} f_s - H\mathbf{p}\,\frac{\partial}{\partial \mathbf{p}} f_s = \Gamma_\alpha\, P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p}).$$

where $\Gamma_\alpha \sim G_F^2 T^4 E$ is the weak interaction rate in plasma

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\text{mat}} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\text{mat}}}\right),$$

$$t_\alpha^{\text{mat}} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}},$$

$$\sin 2\theta_\alpha^{\text{mat}} = \frac{t_\alpha^{\text{mat}}}{t_\alpha^{vac}}\cdot \sin 2\theta_\alpha, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

and effective plasma potential for active neutrinos

$$V_{\alpha\alpha} \sim -\#G_F^2 T^4 E + \#G_F T^2 \mu_{L_\alpha}$$

resonant production in the lepton asymmetric plasma

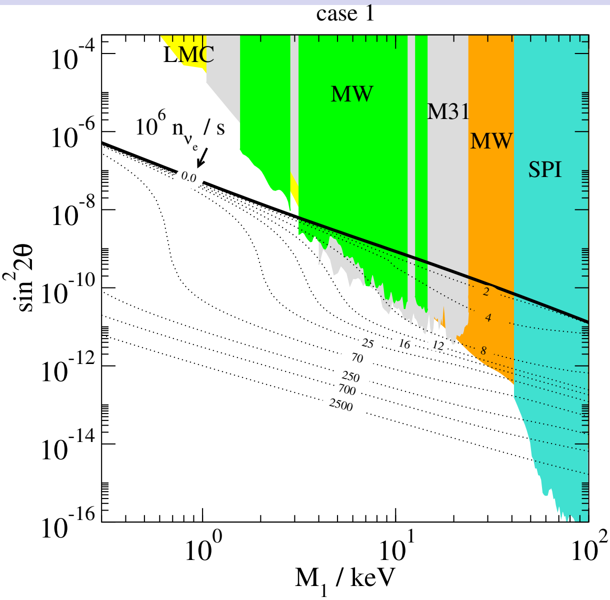
BAU-DM connection?

Sterile neutrino Dark Matter

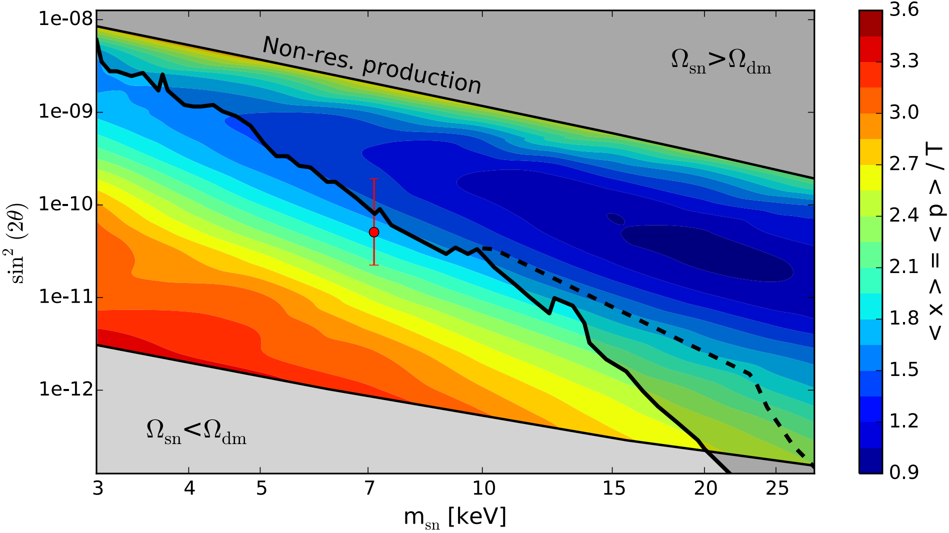
$\sin^2 2\theta$, n_{ν_e} and M_N to saturate Ω_{DM}

- larger asymmetry $10^6\, n_{\nu_e}/s > 2500$ is forbidden by BBN
- above the solid line "0.0" $\Omega_N > \Omega_{DM}$
- selected upper limits from X-ray telescopes
- recall $m > 0.75$ keV for fermionic DM

  It can be refined with estimates of neutrino velocities



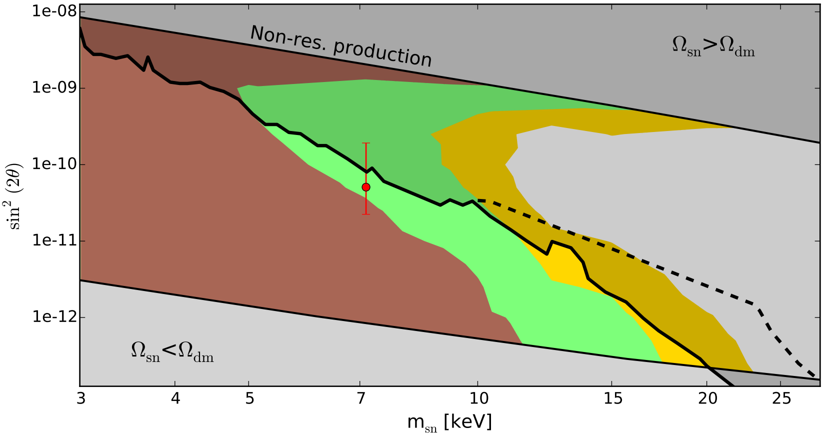
Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)



brown: MW satellite counts

green and yellow: Lyman-α

production by inflaton

Outline

Dark Matter: possible guiding principles

Naturality:

- exploit known interactions
  examples: WIMPs, free particles
- part of a well-motivated model
  examples: LSP, axion, sterile neutrinos
- Why $\Omega_B \sim \Omega_{DM}$?
  examples: Mirror World antibaryonic DM
- Why $\Omega_\Lambda \sim \Omega_{DM}$?
  examples: DM-DE coupling

Minimality:

Use as little new physics as possible

Motivation: No any hints of new physics in experiment

Many models are untestable

example: gravitationally produced free massive fermion

Reality:

Deep insight into the gravitational properties of dark matter

what happen at small scales?

status of:
cusp/core in galactic centers
lack of dwarf galaxies
lack of small galaxies

examples:
cold dark matter
warm dark matter
selfinteracting dark matter

Examples: both Natural and Minimal

Natural source of dark matter production: gravity

Gravity produces any free massive particle when metric changes in the expanding Universe

most efficiently when $H \sim M$

say, at radiation domination stage

$$\Omega_X \sim \left(\frac{M_X}{10^9\,\mathrm{GeV}}\right)^{5/2}$$

S.Mamaev, V.Mostepanenko, A.Starobinsky (1976)

Modified gravity $(R \to R - R^2/6\mu^2)$

may be responsible for inflation and subsequent reheating

A.Starobinsky (1980)

that is (universal) production of all particles, including those of dark matter

$$\Omega_X \simeq 0.15 \times \left(\frac{M_X}{10^7\,\mathrm{GeV}}\right)^3$$

D.Gorbunov, A.Panin (2010)

Untestable

Minimal, but still testable: scalar Dark Matter

$$V_S = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 H^\dagger H$$

$$m_S = \sqrt{\mu_S^2 + \frac{1}{2}\lambda_{hS} v^2}$$

$$\Omega_S \propto m_S n_S \propto \frac{1}{\sigma_{ann}} \propto \frac{m_S^2}{\lambda_{hS}^2}$$

indirect:

$$\text{flux}(SS \to SM) \propto n_S^2 \sigma_{ann} \propto \frac{1}{\lambda_{hS}^2}$$

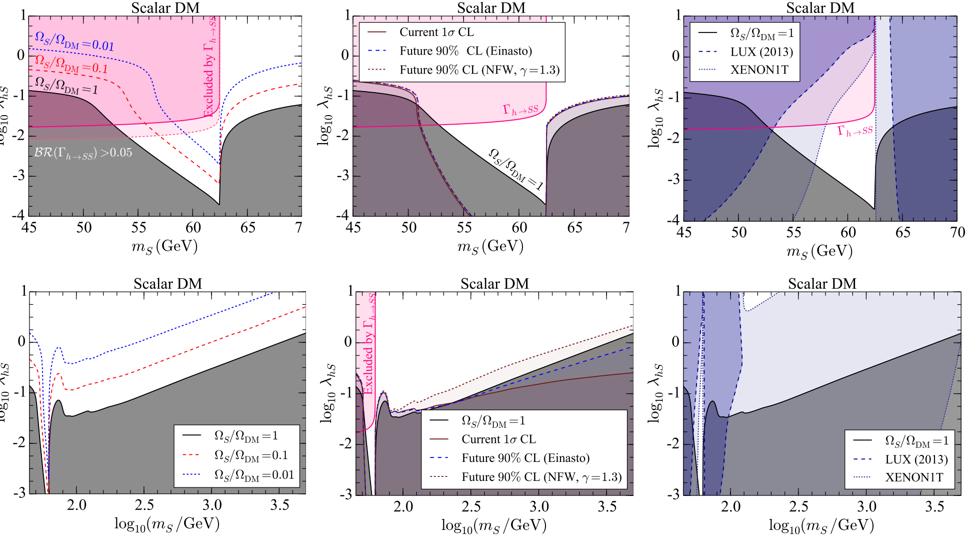
direct:

$$\Gamma(SA \to SA) \propto n_S \sigma_{ann} \propto \frac{1}{m_S}$$

- EW phase transition of I order ?
- EW vacuum stability ?

Constraints on scalar Dark Matter

A.Beniwal et al (2015)



Discussion on WIMPs

Most natural properties:

- to be in equilibrium in primordial plasma up to very freezout (and in kinetic equilibrium even later)
- to form a symmetric component:

$$X = \bar{X} \quad \text{or} \quad n_X = n_{\bar{X}}$$

But what we have in reality?

- We are sure there were
  - Big Bang Nucleosynthesis (starting from 1 MeV)
  - Recombination (at about 0.3 eV)

  and both are significantly "out-of-equilibrium" processes
- The visible matter is asymmetric, so that

$$f \neq \bar{f} \quad \text{and} \quad n_f = n_{\bar{f}}$$

Asymmetric Dark Matter

Sakahrov's conditions are involved !!!

- Two different quantum numbers work in two different (dark and visible) sectors
  Then a mechanism similar to baryogenesis is responsible for DM production
- A single quantum number is responsible for both asymmetries
  - Non-zero total asymmetry
    1. Generation of the asymmetry
    2. Redistribution of the asymmetry between two Worlds
  - The Universe is neutral
    1. Simutanaous production of particles in one sector and antiparticles in another
    2. Annihilation of the symmetric parts of charged particles in the both sectors

Baryon or lepton numbers can be naturally exploited !

Different (as compared to WIMPs) phenomenological signatures

Outline

Summary (II)

- A lot of models with nonthermal DM production
- Outcome generally depends on initial conditions
- Before BBN epoch everything is allowed
- DM may be multicomponent
- DM perturbations are adiabatic