The Big Bang Cosmology: Lecture #5 Unsolved problems

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow, Russia

Outline

1. The list of problems

2. Dark Matter
   - General properties and candidates
   - WIMPs
   - Sterile neutrinos
   - Gravitino
   - Axion

Big Bang within GR and SM: problems

- Dark Matter
- Baryogenesis
- Horizon, Enthropy, Flatness, ...problems
- Heavy relics
- Initial fluctuations
- Dark Energy
- Coincidence problem: $\Omega_B \sim \Omega_{DM} \sim \Omega_\Lambda$

Dark Matter Properties $p = 0$

If particles:

1. stable on cosmological time-scale
2. nonrelativistic before RD/MD-transition (either Cold or Warm)
3. (almost) collisionless
4. (almost) electrically neutral
5. unsuppressed fluctuations @ scales $l_0 \gtrsim 100$ kpc

If were in thermal equilibrium: $M_X \gtrsim 1$ keV

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, 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

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

Dark Matter Candidates

- WIMPs (neutralino, . . .)
- sterile neutrinos
- axion
- gravitino
- Heavy relics
- (Topological) defects
- Mfssive Astrophysical Compact Heavy Objects
- Primordial black hole remnants

Weakly Interacting Massive Particles

Assumptions:

1. no $X - \bar{X}$ asymmetry $\qquad n_{\rm X} = n_{\bar{\rm X}}$
2. @ $T < M_X$ in thermal equilibrium with plasma

$$n_{\rm X} = n_{\bar{\rm X}} = g_{\rm X} \left(\frac{M_{\rm X} T}{2\pi} \right)^{3/2} \mathrm{e}^{-M_{\rm X}/T}$$

$$X\bar{X} \longrightarrow \text{light particles}$$

freeze-out temperature T_f

$$\frac{1}{n_{\rm X}} \frac{1}{\langle \sigma_{\rm ann} v \rangle} = H^{-1}(T_f) \longrightarrow T_f = \frac{M_{\rm X}}{\ln \left(\frac{g_{\rm X} M_{\rm X} M_{\rm Pl}^* \sigma_0}{(2\pi)^{3/2}} \right)} \; .$$

Bethe formulae: $\qquad$ s-wave: $\sigma_{\rm ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles

density after freeze-out: $n_X(T_f) = \frac{T_f^2}{M_{Pl}^* \sigma_0}$

today's density: $n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f)$

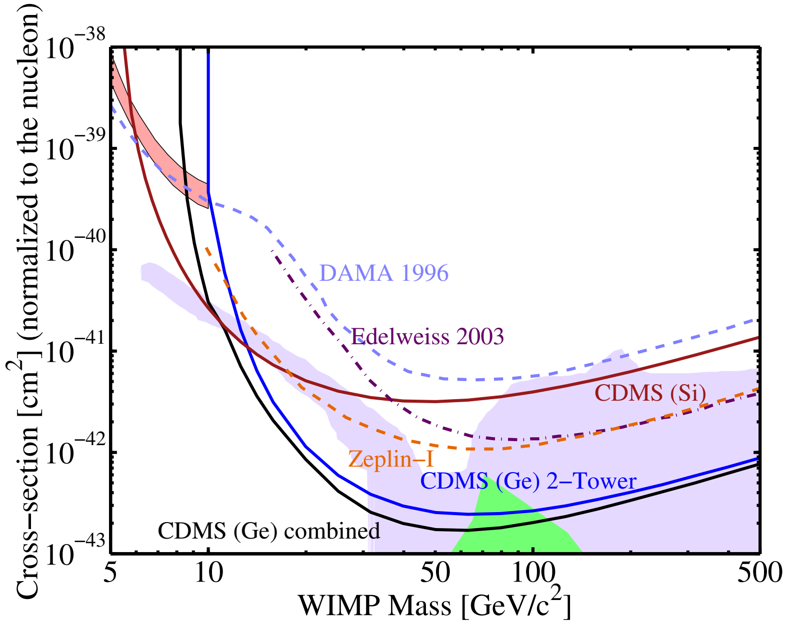
$X + \bar{X}$ contribution to critical density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} = 7.6\frac{s_0 \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right)}{\rho_c \sigma_0 M_{Pl}\sqrt{g_*(T_f)}}$$

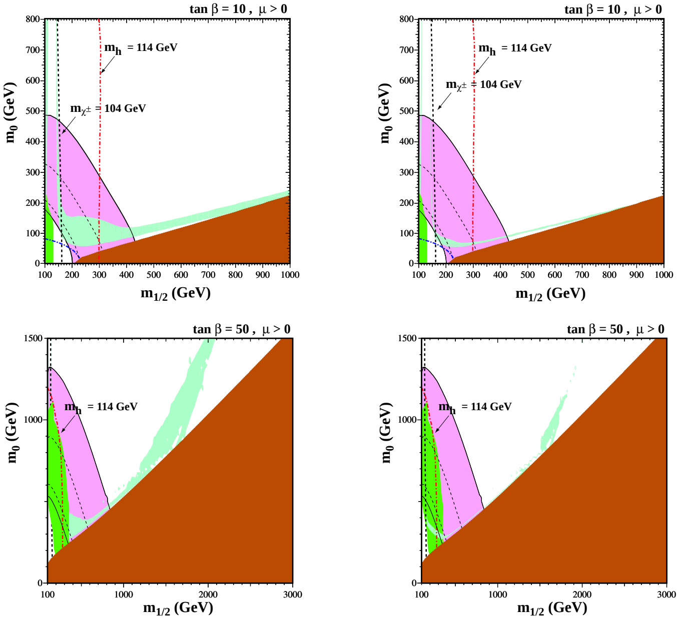
$$= 0.1 \cdot \left(\frac{(10\ \text{TeV})^{-2}}{\sigma_0}\right) \frac{0.3}{\sqrt{g_*(T_f)}} \ln\left(\frac{g_X M_{Pl}^* M_X \sigma_0}{(2\pi)^{3/2}}\right) \cdot \frac{1}{2h^2}$$

naturaly dark matter

naturaly "light" $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100$ TeV



Cross–section [cm^2] (normalized to the nucleon)
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
5
10
50
100
500
WIMP Mass [GeV/c^2]
DAMA 1996
Edelweiss 2003
CDMS (Si)
Zeplin–I
CDMS (Ge) 2–Tower
CDMS (Ge) combined


tan β = 10 , μ > 0
m_h = 114 GeV
$m_{\chi^\pm}$ = 104 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
tan β = 10 , μ > 0
m_h = 114 GeV
$m_{\chi^\pm}$ = 104 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)
tan β = 50 , μ > 0
m_h = 114 GeV
m_0 (GeV)
$m_{1/2}$ (GeV)

DM keV neutrino constraints

Sterile neutrino of keV scale mass provides the Warm Dark Matter

Bounds on mass

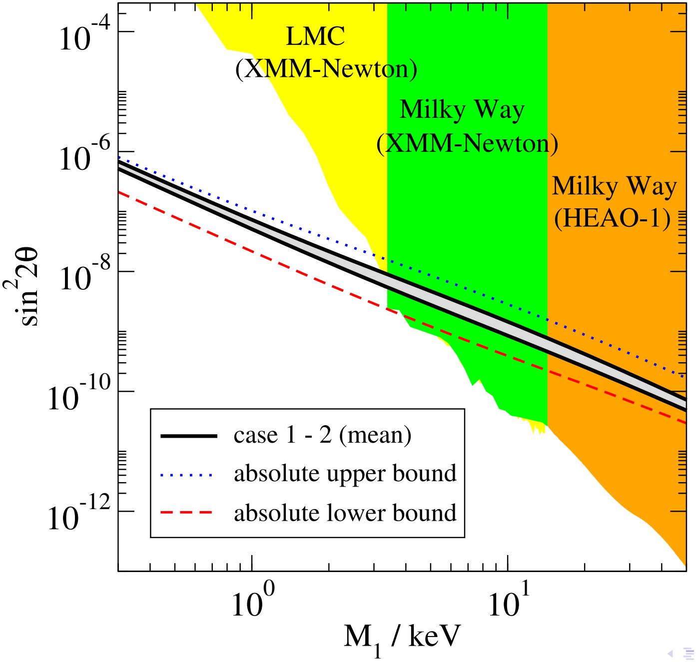
- Tremaine-Gunn bound $M_1 \gtrsim 0.3$ keV
- Lyman-α bound $M_1 \gtrsim 11.6$ keV or 8 keV

Bound on mass and mixing angle

- X-ray observation: $N_1 \to \nu + \gamma$

Production mechanism

- Dodelson-Widrow (thermal) scenario
- Primordial abundance: physics at higher energies
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.


LMC
(XMM-Newton)
Milky Way
(XMM-Newton)
Milky Way
(HEAO-1)
case 1 - 2 (mean)
absolute upper bound
absolute lower bound
$\sin^2 2\theta$
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^0
10^1
M_1 / keV

DM keV neutrino constraints

Sterile neutrino of keV scale mass provides the Warm Dark Matter

Bounds on mass

- Tremaine-Gunn bound $M_1 \gtrsim 0.3$ keV
- Lyman-α bound $M_1 \gtrsim 11.6$ keV or 8 keV

Bound on mass and mixing angle

- X-ray observation: $N_1 \to \nu + \gamma$

Production mechanism

- Dodelson-Widrow (thermal) scenario is ruled out
- Primordial abundance: physics at higher energies
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.

Gravitino production

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

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

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

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:

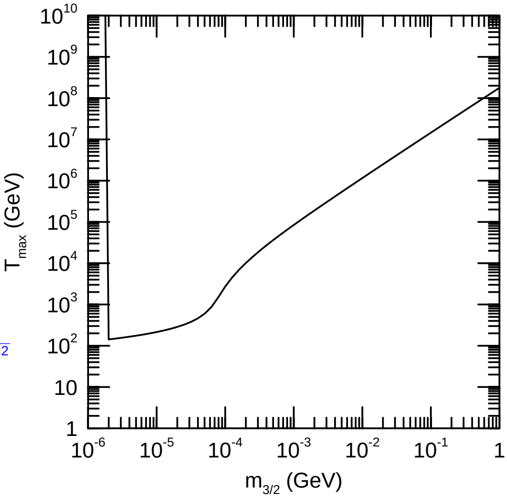
$$\Omega_{3/2} = \frac{m_{3/2} \cdot n_{3/2}}{\rho_c} = 0.2\frac{m_{3/2}}{200 \text{ eV}}\left(\frac{g_{3/2}}{2}\right) \cdot \left(\frac{210}{g_*(T_f)}\right) \cdot \frac{1}{2h^2}$$

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

Gravitino non-thermal production

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = \sum_i \Gamma_{\tilde{X}_i} \cdot \gamma_i^{-1} \cdot n_{\tilde{X}_i} + \langle \sigma_{tot} \rangle \cdot n_\gamma^2 ,$$

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



Axion as Cold Dark Matter

nonperturbative CP-violation in QCD

$$L_\theta = \frac{\alpha_s}{8\pi}\left(\theta_0 + \mathrm{Arg}\left(\mathrm{Det}\hat{M}_q\right)\right) G^a_{\mu\nu}\tilde{G}^{\mu\nu\, a} \equiv \frac{\alpha_s}{8\pi}\cdot\theta\cdot G^a_{\mu\nu}\tilde{G}^{\mu\nu\, a}\,.$$

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

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

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

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

Big Bang within GR and SM: problems

- Dark Matter
- Baryogenesis
- Horizon, Enthropy, Flatness, ... problems
- Heavy relics
- Initial fluctuations
- Dark Energy
- Coincidence problem: $\Omega_B \sim \Omega_{DM} \sim \Omega_\Lambda$