Dark Matter Models (I)

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow

The Helmholtz International School
“Cosmology, strings, and New Physics”

DIAS-TH Program at BLTP, JINR
Dubna, Russia

Outline

Interplay: Standard Model and Cosmology

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

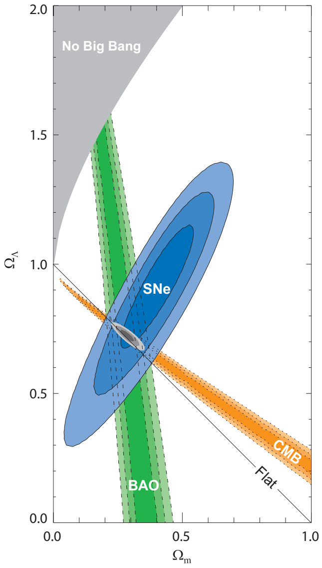
Three generations of matter: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- 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 and limits neutrino mass

severely constrains many BSM relaxation..?

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

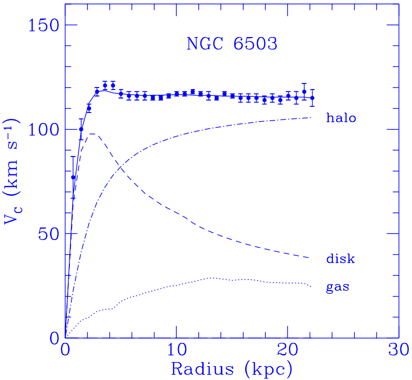
Observations we use in the analysis

- Astrophysical data (favor Dark Matter)
  - Observations in galaxies: rotation curves, number of dwarfs
  - Observations in galaxy clusters: X-rays, strong lensing
- Cosmological data (favor Dark Matter and Dark Energy)
  - Observation of objects at cosmological distances (cosmic ladder): cefeids, SN Ia, LRG, RGB?
  - Baryonic Acoustic (Sakharov) Oscillations (BAO): two-point galaxy correlation function
  - Galaxy formation process: time-dependent galaxy spectrum
  - Evolution of galaxy clusters: X-rays, Sunyaev–Zeldovich effect
  - Anisotropy and Polarization of Cosmic Microwave Background (CMB): gaussianity, angular size of the sound horizon at recombination, ISW-effect, reionization, weak lensing, GW?, . . .

Galactic dark halos: flat rotation curves

$$v(R) = \sqrt{G\frac{M(R)}{R}}$$

$$M(R) = 4\pi \int_0^R \rho(r) r^2 dr$$



observations: $v(R) \simeq \text{const}$

visible matter:

internal regions $v(R) \propto \sqrt{R}$

external (“empty”) regions $v(R) \propto 1/\sqrt{R}$

Dark Matter in clusters

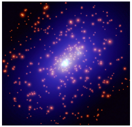
X-rays from hot gas in clusters

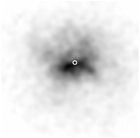
$$\frac{dP}{dR} = -\mu n_e(R) m_p \frac{GM(R)}{R^2}\,, \quad M(R) = 4\pi \int_0^R \rho(r) r^2 dr\,, \quad P(R) = n_e(R) T_e(R)$$

galaxies in clusters — virial theorem

$$U + 2E_k = 0$$

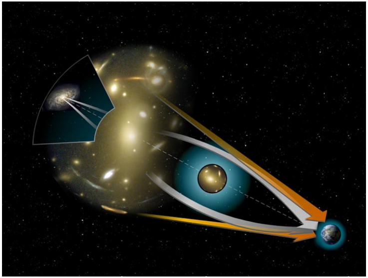
$$3M\langle v_r^2 \rangle = G\frac{M^2}{R}$$



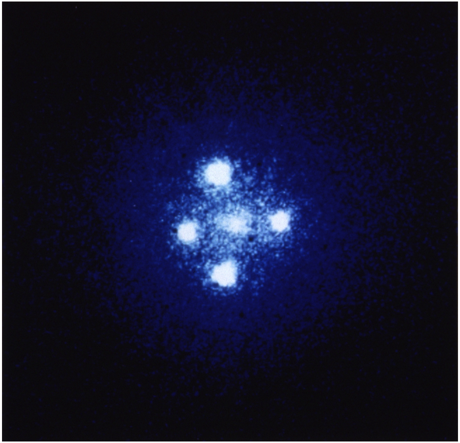


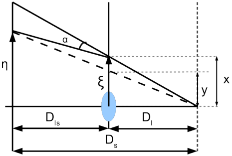
Milky Way: Virgo infall

Gravitational lensing in GR: $\alpha = 4GM/(c^2 b)$



Einstein Cross





$$\vec{\eta} = \frac{D_s}{D_l}\,\vec{\xi} - D_{ls}\,\vec{\alpha}\left(\vec{\xi}\right)$$

common lens with specific refraction coefficient

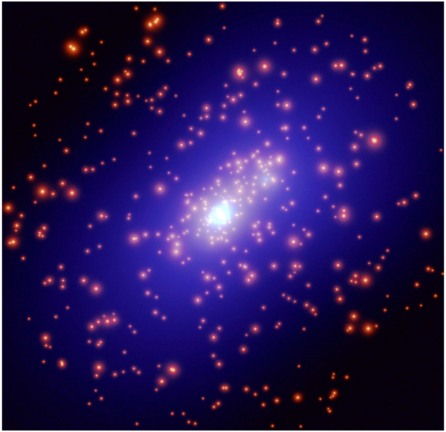
$$\vec{\alpha}\left(\vec{\xi}\right) = \frac{4G}{c}\int \frac{\vec{\xi}-\vec{\xi}'}{\left|\xi-\vec{\xi}'\right|^2}\, d^2\xi' \int \rho\left(\vec{\xi}',z\right) dz$$

source: quasar $D_s = 2.4$ Gpc

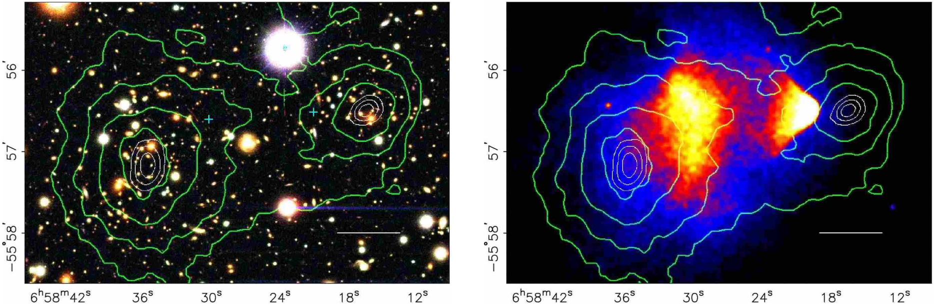
lens: galaxy $D_l = 120$ Mpc

Dark Matter in clusters

gravitational lensing $\rho_{\rm B} \approx 0.25\rho_{DM}$



Colliding clusters (Bullet clusters 1E0657-558)



gravitational lensing

Observations in X-rays

$M \simeq 10 \times m$

scale is 200 kpc

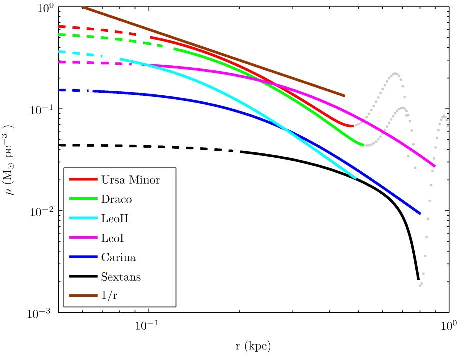
clusters are at 1.5 Gpc

implies collisionless DM

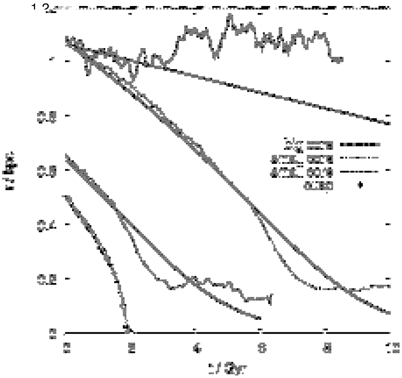
CDM Problems at small-scales . . . ?

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r+r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
  most DM-dominated objects

Cores observed (?)

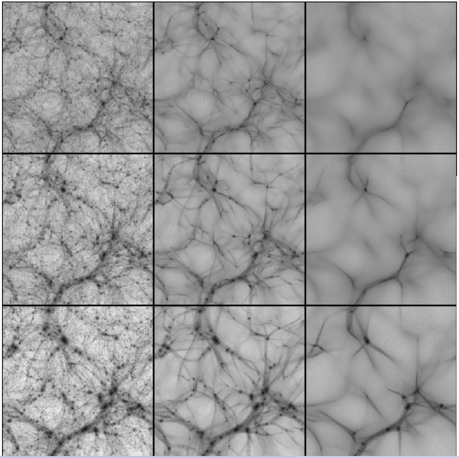


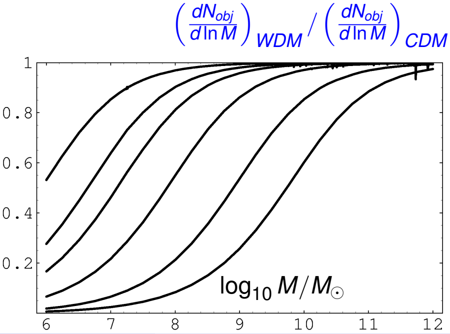
5 Clusters in the Fornax dSph



CDM Problems . . . ?

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 100 instead of 1000
- "Too big to fail" problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming

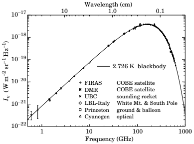


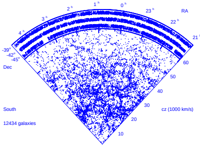


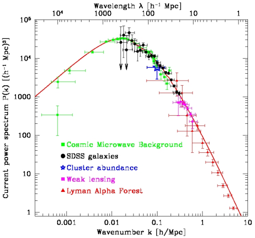
Matter perturbations

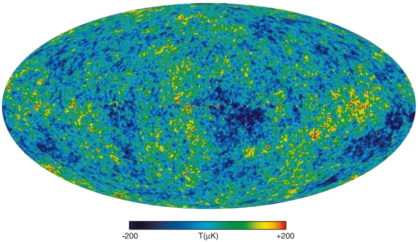
- CMB is isotropic, but "up to corrections, of course..."
  1. Earth movement with respect to CMB
  $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of 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!

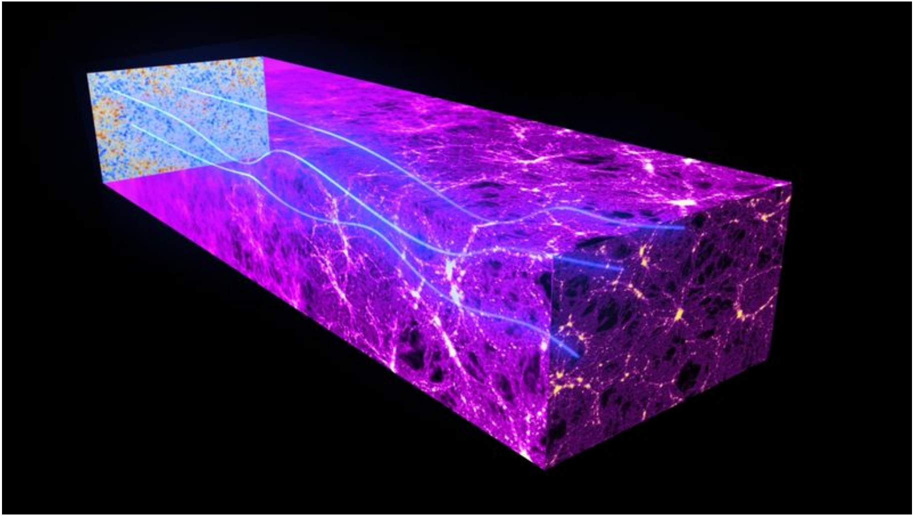








On top of that: propagation in expanding Universe



So far only gravitational evidence for DM

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

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

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

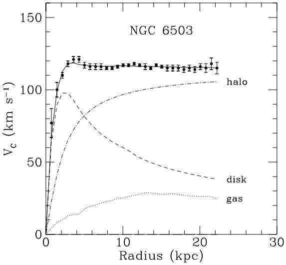
$$\rho_{\Lambda} = \text{const}$$

Why do we think it is most probably new particle physics
(new gravity if any is not enough) ?

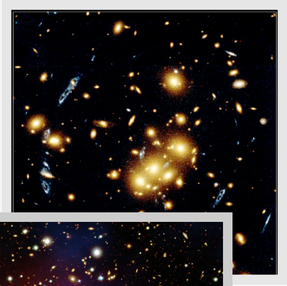
DM phenomena happen at various spatial and time scales

Dark Matter in astrophysics

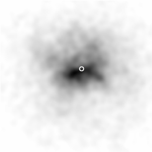
Rotational curves



Gravitational lensing



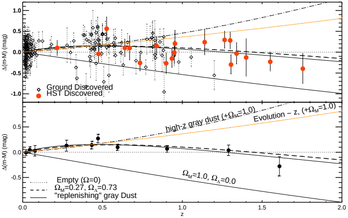
X-rays from centers of galaxy clusters



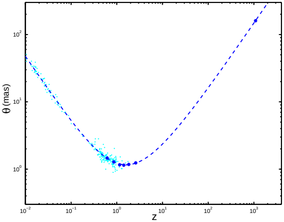
“Bullet” cluster

Dark matter in cosmology

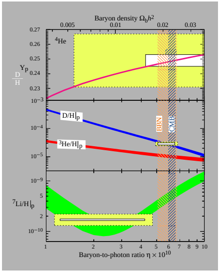
Standard candles

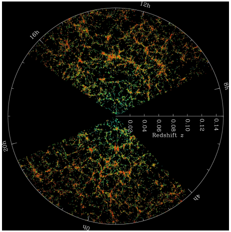


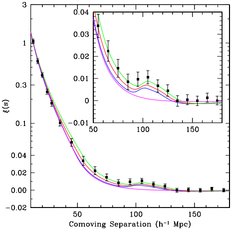
Angular distance

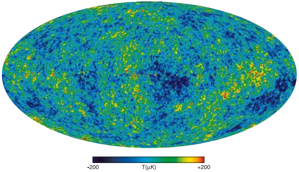


Nucleosynthesis









Large Scale Structures

Baryon acoustic oscillations

CMB anisotropy

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:

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

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!

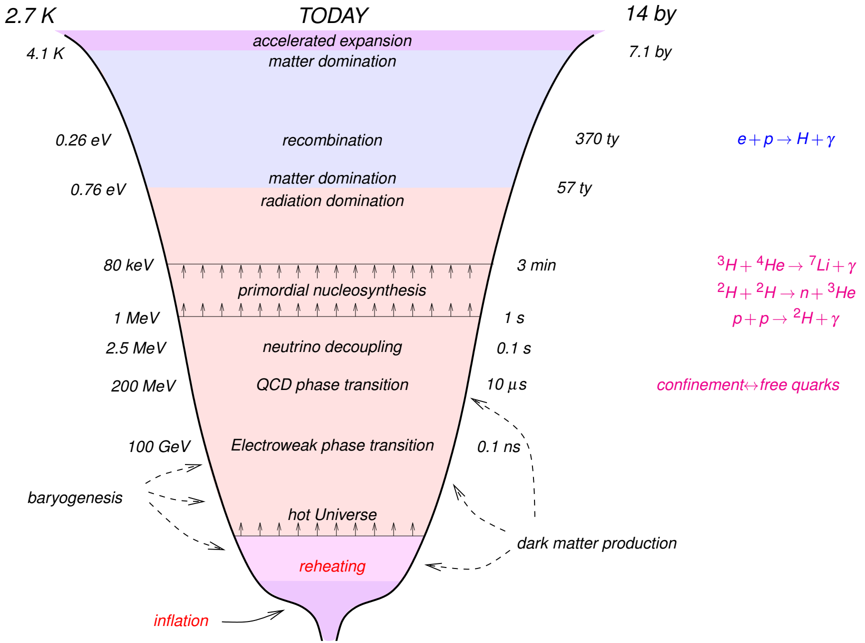
   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, — for bosons

   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

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


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e+p \to H+\gamma$
matter domination
0.76 eV
radiation domination
57 ty
80 keV
3 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 phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Decoupling of relativistic Dark Matter

Assumptions

1. DM particles are in equlibrium in plasma
2. DM decouple from plasma at temperature $T_d \gtrsim M_X$, so they are relativistic (e.g. neutrino)

$$n_X(T_d) = g_X \cdot \begin{pmatrix} 1 \\ \frac{3}{4} \end{pmatrix} \cdot \frac{\zeta(3)}{\pi^2} T_d^3$$

Later on useful

$$n_X a^3 = \text{const}, \quad s a^3 = \text{const} \quad \Longrightarrow \quad \frac{n_X}{s} = \text{const} = \# \frac{g_X}{g_*(T_d)}$$

DM particle mass M_X fixes Ω_X:

$$\Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c} \frac{n}{s} \approx 0.2 \times \frac{M_X}{100\text{ eV}} \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_d)}\right)$$

– NO heavy stable feebly coupled to SM particles !

– NO realistic DM models:

Pauli blocking prevents fermionic DM

$$\frac{p_X}{M_X} \propto \frac{a_d}{a} \sim \frac{3T}{M_X} \left(\frac{g_*(T)}{g_*(T_d)}\right)^{1/3}$$

too energetic for the proper structure formation

Decoupling of relativistic Dark Matter

Can we save the relativistic Dark Matter ??

one can try, say, nonstandard cosmological evolution

with entropy production

1. hot stage (radiation domination) $\rho \propto 1/a^4$
2. add new nonrelativistic particles decoupled from plasma $\rho \propto 1/a^3$
3. later they start to dominate
   intermediate stage of matter domination terminates before BBN !!
4. both relativistic DM density and entropy density drop
5. new nonrelativistic particles decay reheating the Universe $T > 3\,\text{MeV}$
   entropy production

Decoupling of nonrelativistic Dark Matter

Assumptions:

1. no $X - \bar{X}$ asymmetry — either $X = \bar{X}$ or $n_X = n_{\bar{X}}$
2. @ $T \lesssim M_X$ in thermal equilibrium with plasma — (e.g. neutrons)

$$n_X = n_{\bar{X}} = g_X \left(\frac{M_X T}{2\pi} \right)^{3/2} e^{-M_X/T}$$

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

freeze-out temperature T_f — $H \equiv T^2/M_{Pl}^*$

$$n_X \langle \sigma_{ann} v \rangle = H(T_f) \longrightarrow T_f = \frac{M_X}{\ln \left(\frac{g_X M_X M_{Pl}^* \sigma_0}{(2\pi)^{3/2}} \right)} \, .$$

Bethe formula: — s-wave: $\sigma_{ann} = \frac{\sigma_0}{v}$

Weakly Interacting Massive Particles

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

present density: $$n_X(T_0) = \left(\frac{a(T_f)}{a(T_0)}\right)^3 n_X(T_f) = \left(\frac{s_0}{s(T_f)}\right) n_X(T_f) \propto \frac{1}{T_f}$$

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

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

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

WIMPs: discussion

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

- natural DM: subweak-scale cross section $\sigma_0 \sim 0.01 \times \sigma_W$
  say, $M_X \sim 1$ TeV or X is not a weak gauge eigenstate
- naturaly "light" unitarity $\sigma_0 \lesssim \frac{4\pi}{M_X^2} \longrightarrow M_X \lesssim 100$ TeV
- all stable particles with smaller σ_0 are forbidden !!
- WIMPs remain in kinetic equilibrium with plasma till $T \sim 10$ MeV

  this is Cold Dark Matter, $v_{RD/MD} \ll 10^{-3}$

  WIMPs may form dark halos (clumps) much lighter than

  dwarf galaxies

Weakly IMPs are mostly welcome (e.g. LSP in SUSY)

We can fully explore the model !! lectures by S.Demidov

- Direct searches for Galactic Dark Matter ($v \sim 10^{-3}$)

$$X + \text{nuclei} \to X + \text{nuclei} + \Delta E$$

- Can search for WIMPs in cosmic rays: products of WIMPs annihilation (in Galactic center, dwarf galaxies, Sun)

$$X + \bar{X} \to p\bar{p}\,,\;\; e^+e^-\,,\;\; \nu, \gamma, \ldots$$

- Can search for WIMPs in collision experiments (LHC):

$$X + \bar{X} \leftrightarrow \text{SM} + \text{SM'} + \ldots$$

If thermal CDM but not Weakly IMPs?

We still can study the model if DM annihilates (partly) into SM particles

- But DM particle X can be light and feebly coupled (t-channel)

$$\sigma_0 \sim \frac{\xi^4}{M_X^2}$$

  ξ is not a gauge coupling within GUT !

- With small σ_0 one needs entropy production
- σ_0 may be increased by s-channel resonance, $M_Y \approx 2M_X$
- annihilation can be amplified by co-annihilation channels, $X + A \to SM$
- With light messangers between Dark and Visible sectors many estimates change, say $\sigma_0 = \sigma_0(v)$
- DM interaction at freeze-out and now are not the same
  say, Sommerfield enhancement of the annihilation of slow particles $v \sim 10^{-3}$

Summary (I)

1. We need DM both in past (cosmology)
   and at present (astrophysics)
2. For stability a symmetry is needed
3. There are claimed discrepancies between CDM simulations and observations of small scale structures, observations of central regions of dwarf galaxies
4. WDM? selfinteracting DM? no proof
5. Structures: DM cannot be hot (e.g. SM neutrinos can not help)
6. WIMPs (neutralino) are natural candidates for Cold Dark Matter
7. Much more options for WIMP-like candidates. . .
8. Generally, heavy and/or feebly coupled thermal relics
   are forbidden !!