Dark matter and dark energy

Lecture from the course
« Introduction to
cosmoparticle physics »

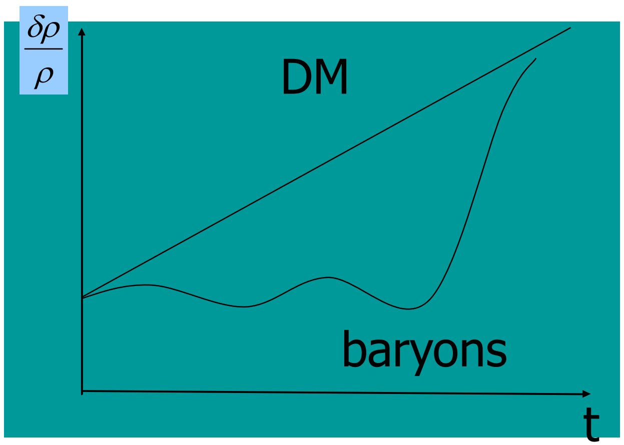
The bedrocks of modern cosmology

Our current understanding of structure and evolution of the Universe implies three necessary elements of Big Bang cosmology that can not find physical grounds in the standard model of electroweak and strong interactions. They are:

- Inflation
- Baryosynthesis
- Dark matter/energy

The latter (Dark matter and dark energy) is the topic of our discussion today

Cosmological Dark Matter



$$\frac{\delta\rho}{\rho} \Rightarrow \frac{\delta T}{T}$$

Cosmological Dark Matter explains:
- **virial paradox in galaxy clusters,**
- **rotation curves of galaxies**
- **dark halos of galaxies**
- **effects of macro-lensing**

But first of all it provides formation of galaxies from small density fluctuations, corresponding to the observed fluctuations of CMB

To fulfil these duties Dark Matter should interact sufficiently weakly with baryonic matter and radiation and it should be sufficiently stable on cosmological timescale.

Baryon density estimated from the results of BBN (mainly from Primordial deuterium) is not sufficient to explain the matter content of the modern Universe

Dark Matter – Cosmological Reflection of Microworld Structure

Dark Matter should be present in the modern Universe, and thus is stable on cosmological scale.

This stabilty reflects some Conservation Law, which prohibits DM decay.

Following Noether's theorem this cosnservation law should correspond to a (nearly) strict symmetry of microworld.

Dark Matter from Elementary Particles

By definition Dark Matter is non-luminous, while charged particles are the source of electromagnetic radiation. Therefore, neutral weakly interacting elementary particles are usually considered as Dark Matter candidates. If such neutral particles with mass m are stable, they freeze out in early Universe and form structure of inhomogeneities with the minimal characterstic scale

$$M = m_{Pl} \left(\frac{m_{Pl}}{m} \right)^2$$

- However, if charged particles are heavy, stable and bound within neutral « atomic » states they can also play the role of specific composite Dark matter (Dark atoms).
- Physical models, underlying dark matter scenarios, their problems and nontrivial solutions as well as the possibilities for their test will be the subject of the successive talks.

Stable DM models

For weakly interacting particles that were in equilibrium, the scale of structure is in the inverse dependence on mass of particles:

- Hot Dark Matter (HDM) – particles with mass of tens eV (scale of superclusters)
- Cold Dark Matter (CDM) – particles with mass, exceeding GeVs (planet scale – biasing)
- Warm Dark Matter (WDM) – particles with mass few keV (scale of galaxies)

Unstable DM models

For metastable particles the necessary condition to form the structure is to have lifetime, exceeding the time of structure formation :

- Unstable Dark Matter (UDM) – particles with lifetime, less than the age of the Universe. Modern dark matter is explained by primordial particles and/or their decay products.
- Decaying Dark Matter (DDM) – particles with lifetime, exceeding the age of the Universe. Their decays can be a source of CR anomalies.

The list of some physical candidates for DM

- Sterile neutrinos – physics of neutrino mass
- Axions – problem of CP violation in QCD
- Axinos - SUSY
- Gravitinos - SUGRA
- Neutralinos - SUSY
- KK-particles: B_{KK1}
- Anomalous hadrons, O-helium
- Supermassive particles…
- Mirror and shadow particles, PBHs…

WIMP

(weakly interacting massive particles)

SIMP

(strongly interacting massive particles)

Physical candidates for DM

Axions and axinos

Peccei-Quinn model resolves the problem of strong CP-violation:

$$\Delta L_{\text{QCD}} = \frac{\alpha_s^2}{16\pi}\theta \cdot \varepsilon_{\alpha\beta\mu\nu} G^{a\alpha\beta} G^{a\mu\nu}$$

$d_n \approx e\theta m_u / m_n^2 \sim \theta \cdot 10^{-16}\, e \cdot \text{cm}$ From experiment one has $|\theta| < 10^{-9}$

Solution comes from adding extra $U(1)_{PQ}$ symmetry. Scalar field, associated with spontaneous $U(1)_{PQ}$ violation at energy scale f_a, provides mechanism of dynamical suppression of θ (due to its Nambu-Goldstone boson – axion).

Axion interacts with quarks as

$$L_{aff} = ic_{aff} \frac{m_f}{f_a} a\bar{f}\gamma_5 f$$

and have potential $V_{\text{eff}} \sim m_u \Lambda_{\text{QCD}}^3 \left(1 - \cos(\theta + a / f_a)\right)$

minimizing at $a = \langle a \rangle = -\theta f_a$

Physical candidates for DM

Axions and axinos

The axion has the mass

$$m_a \approx 0,6\,\text{мэВ}\,\frac{10^{10}\ \text{ГэВ}}{f_a}$$

According existing constraints its mass and energy scale must be

$$f_a > 2 \cdot 10^9\,\text{GeV},\ m_a < 0,5 \cdot 10^{-2}\,\text{eV}$$

At early Universe axions might be born as Bose-condensate after succession of PQ- and QCD-phase transitions. So, its density could be

$$\Omega_a \approx 0,2 \cdot \left(\frac{f_a}{10^{12}\,\text{ГэВ}}\right)^{7/6} \approx 0,1\left(\frac{10^{-5}\,\text{эВ}}{m_a}\right)^{7/6}$$

It restricts axion parameter as

$$2 \cdot 10^9\,\text{ГэВ} < f_a < 10^{12}\,\text{ГэВ}$$

Physics of dark Energy

Others

Antropic principle

Λ-term

(True cosmological constant)

Quintessence

(a field out of minimum)

Modified law of gravity

K-essence

$$\Lambda \sim 10^{-120}\, G^{-1} \;!!!$$

Evidences for Standard LCDM

- H>50, age of Universe needs Lamda term
- LSS evolution slows down **relative** to accelerated expansion
- SN data are interpreted in terms of accelerated expansion

Homogeneous dark energy is provided by Lambda-term, quintessence…

UDM versus LCDM

- **UDM:**
- H<50, age of Universe does not need Lamda
- LSS evolution slows down **absolutely** due to decrease of density in it
- Homogeneously distributed dark matter – products of decay of unstable dark matter
- SN data are interpreted in terms of non-accelerated expansion

- **LCDM:**
- H>50, age of Universe needs Lamda
- LSS evolution slows down **relative** to accelerated expansion
- Homogeneous dark energy is provided by Lambda-term, quintessence…
- SN data are interpreted in terms of accelerated expansion

Conclusions

- Inflation, Baryosynthesis and Dark matter/energy are the cornerstones of modern cosmology.
- They relate the observed structure of the Universe to physical processes in the early Universe.
- Methods of cosmoparticle physics can provide probes for various mechanisms of inflation, baryosynthesis and various candidates for dark matter.
- These methods are the subject of our further discussions