The Big Bang Cosmology: Lecture #1 Overview of the History of the Universe

Dmitry Gorbunov

Institute for Nuclear Research of RAS, Moscow, Russia

Plan of the Course

1. Overview of the History of the Universe
2. Friedmann–Robertson–Walker Cosmology
3. The Universe: from Today back to BBN
4. Big Bang Nucleosynthesis
5. Dark Matter Production
6. Baryogenesis

Outline

“Natural” units in particle physics

$$\hbar = c = k_{\rm B} = 1$$

measured in GeV: energy E, mass M, temperature T

$m_p = 0.938$ GeV, $\quad 1\ {\rm K} = 8.6 \cdot 10^{-14}$ GeV

measured in GeV^{-1}: time t, length L

$1\ {\rm s} = 1.5 \cdot 10^{24}\ {\rm GeV}^{-1}, \quad 1\ {\rm cm} = 5.1 \cdot 10^{13}\ {\rm GeV}^{-1}$

Gravity (General Relativity): $V(r) = -G\frac{m_1 m_2}{r}$ $\qquad [G] = M^{-2}$

$$M_{\rm Pl} = 1.2 \cdot 10^{19}\ {\rm GeV} = 22\ \mu{\rm g} \qquad G \equiv \frac{1}{M_{\rm Pl}^2}$$

“Natural” units in cosmology

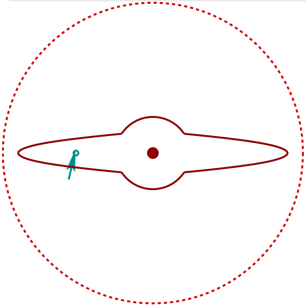
$$1\ \mathrm{Mpc} = 3.1 \cdot 10^{24}\ \mathrm{cm}$$

$1\ \mathrm{AU} = 1.5 \cdot 10^{13}$ cm — mean Earth-to-Sun distance

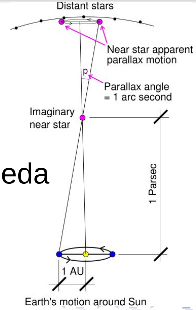
$1\ \mathrm{ly} = 0.95 \cdot 10^{18}$ cm — distance light travels in one year

$1\ \mathrm{yr} = 3.16 \cdot 10^{7}$ s

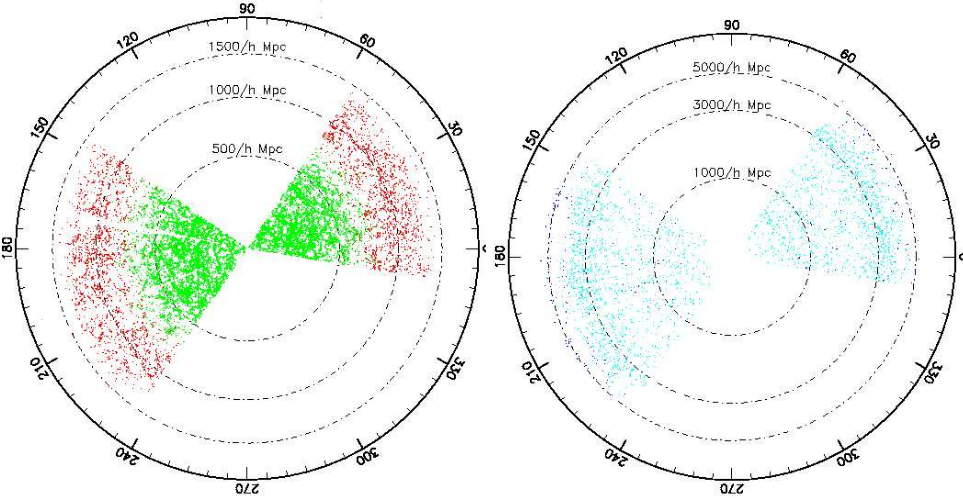
$1\ \mathrm{pc} = 3.3\ \mathrm{ly} = 3.1 \cdot 10^{18}$ cm — distance to object which has a parallax angle of one arcsec



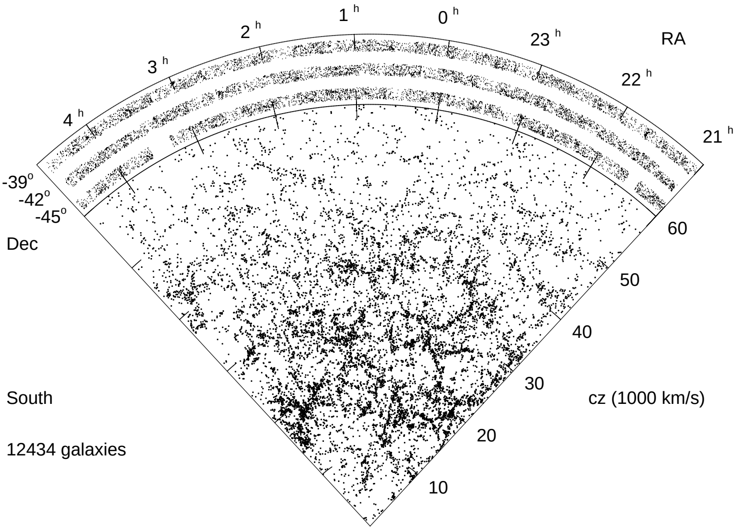
100 AU — Solar system size
1.3 pc — nearest-to-Sun stars
1 kpc — size of dwarf galaxies
50 kpc — distance to dwarves
0.8 Mpc — distance to Andromeda
1-3 Mpc — size of clusters
15 Mpc — distance to Virgo



Very large scales: homogeneity and isotropy

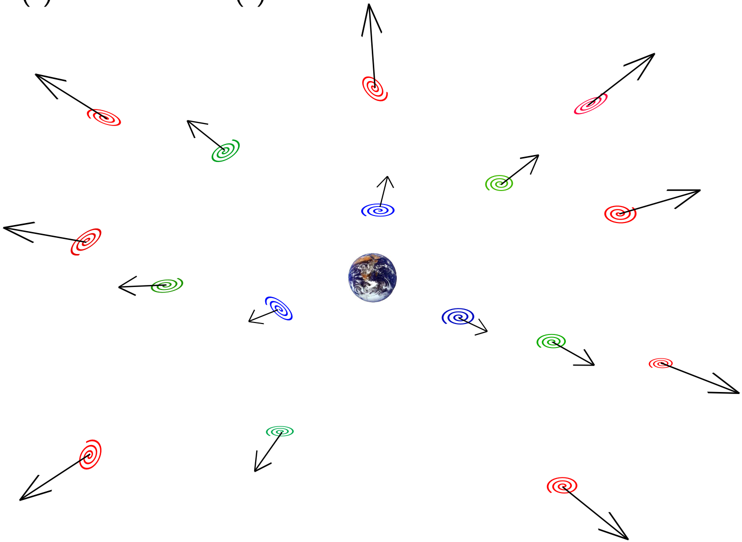


Large scales: structures



Expansion: $H(t) = \frac{\dot{a}(t)}{a(t)}$

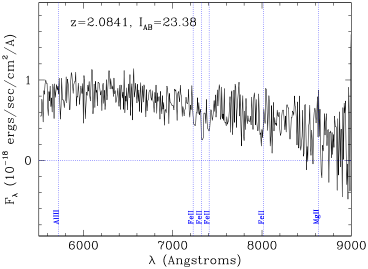
$L \propto a(t)$ $\qquad$ $n \propto a^{-3}(t)$

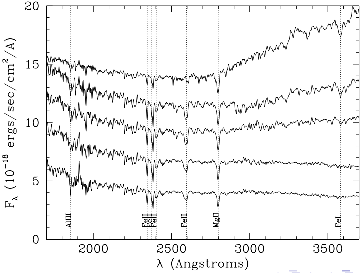


Expansion: redshift z $\qquad \lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1+z$

$z \ll 1$ Hubble law : $z = H_0 r$

$$H_0 = h \cdot 100\,\frac{\text{km}}{\text{s}\cdot\text{Mpc}} \qquad h = 0.73^{+0.04}_{-0.03}$$



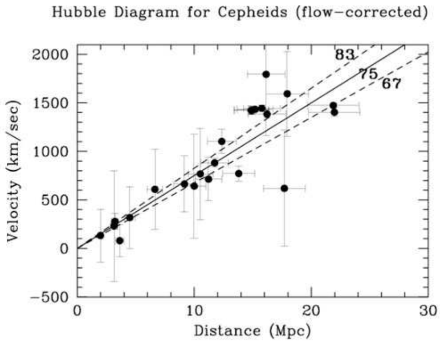


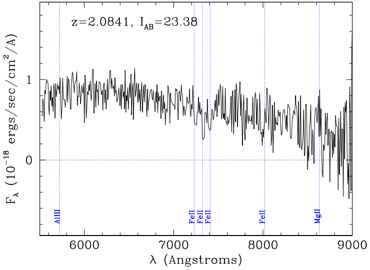
Expansion: redshift z $\lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1 + z$

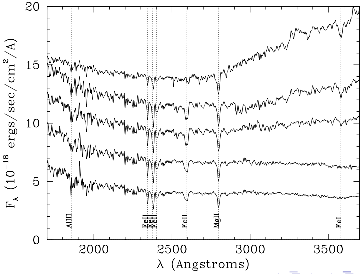
$z \ll 1$ Hubble law : $z = H_0 r$

$$H_0 = h \cdot 100 \; \frac{\text{km}}{\text{s} \cdot \text{Mpc}} \qquad h = 0.73^{+0.04}_{-0.03}$$

standard candles







The Universe: age & spatial geometry

$$[H_0] = L^{-1} = t^{-1}$$

time scale: $t_{H_0} = H_0^{-1} \approx 14 \cdot 10^9$ yr

spatial scale: $l_{H_0} = H_0^{-1} \approx 4.3 \cdot 10^3$ Mpc

age and size of the visible Universe

t_{H_0} is in agreement with various observations

homogeneity and isotropy in 3d:

flat, spherical or hyperbolic

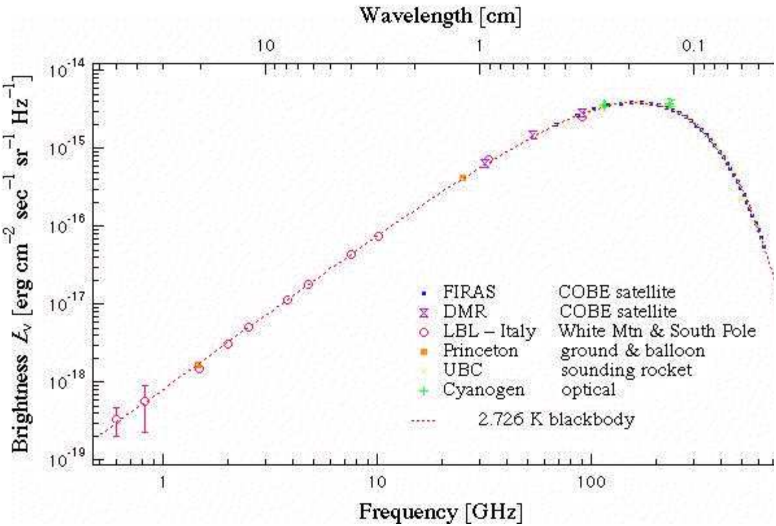
Observations:

"very" flat

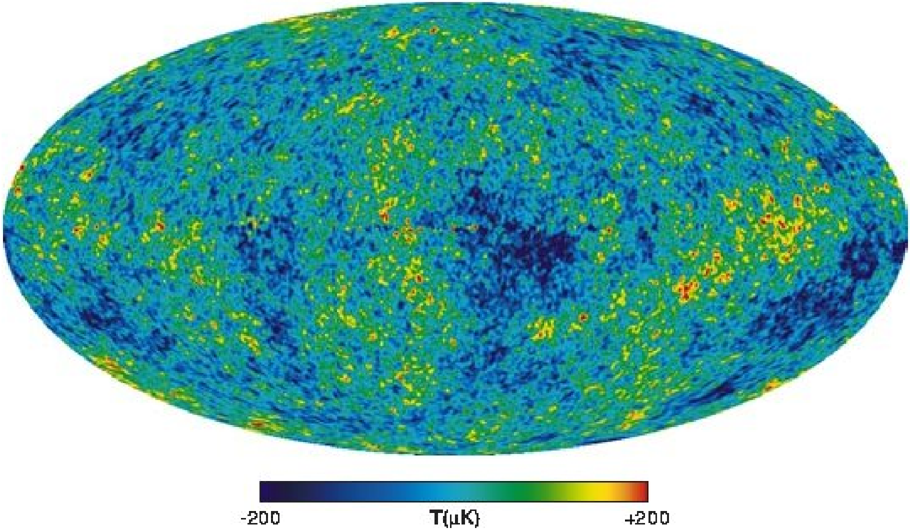
$l_{H_0}/R_{curv} \lesssim 0.1$

The Universe is hot: $T_0 = 2.725 \pm 0.001$ K

$$n_\gamma = 410 \text{ cm}^{-3}$$



CMB anisotropy: $\delta T / T_0 \sim 10^{-5}$



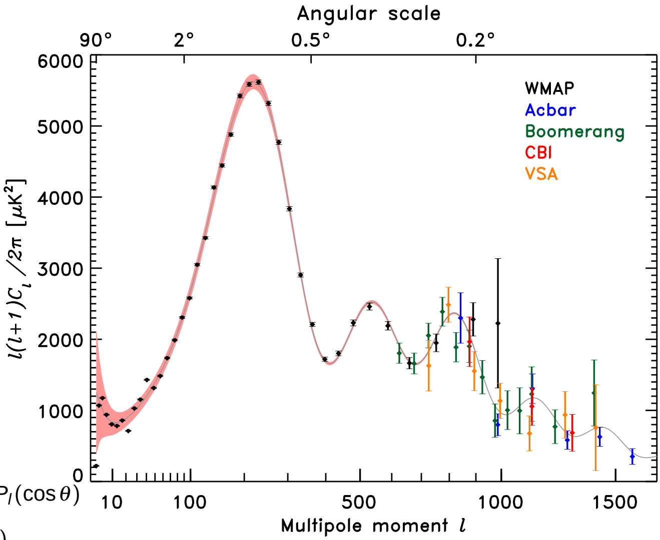
CMB anisotropy: $\delta T(\mathbf{n}) \equiv T(\mathbf{n}) - T_0 - \delta T_{\rm dipole}$

$\delta T_{\rm dipole} = 3.346 \pm 0.017\ \mathrm{mK}$

$\delta T(\mathbf{n}) = \sum_{l,m} a_{l,m} Y_{lm}(\mathbf{n})$

$a^*_{l,m} = (-1)^m a_{l,-m}$

observations



$\delta T(\mathbf{n})$ is Gaussian
$\langle a_{l,m} a^*_{l',m'} \rangle = C_{lm} \delta_{ll'} \delta_{mm'}$

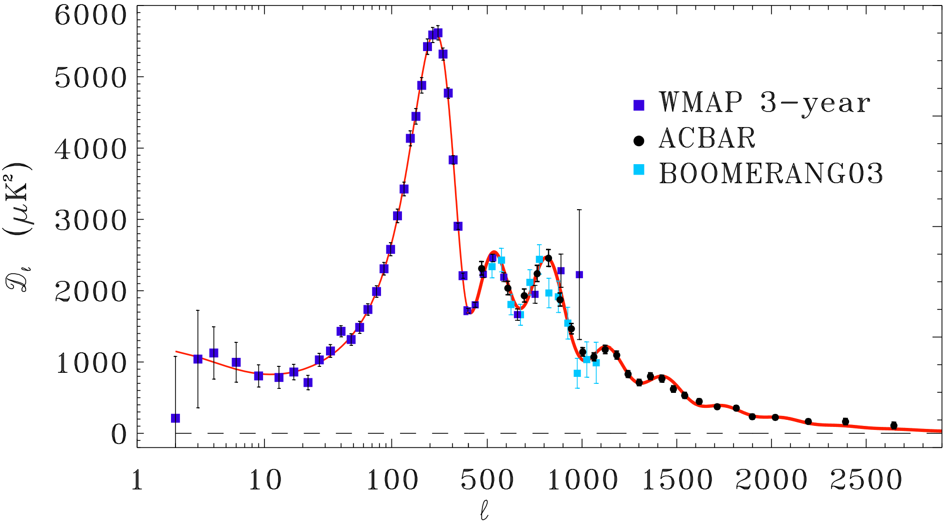
in isotropic Universe

$C_{lm} = C_l$

$$\langle \delta T(\mathbf{n_1}) \delta T(\mathbf{n_2}) \rangle = \sum_l \frac{2l+1}{4\pi} C_l P_l(\cos\theta)$$

$$\langle \delta T^2 \rangle = \sum_l \frac{2l+1}{4\pi} C_l \approx \int \frac{l(l+1)}{2\pi} C_l \, d\ln l$$

CMB anisotropy: the very recent results



Energy density

order-of-magnitude estimate: $G\rho_0 \sim H_0^2$

Spatially flat Universe

$$\rho_c = \frac{3}{8\pi} H_0^2 M_{\rm Pl}^2 \approx 0.53 \cdot 10^{-5} \frac{\rm GeV}{\rm cm^3}$$

CMB contribution: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \cdot 10^{-4}$

Baryon contribution: $\Omega_{\rm B} \equiv \frac{\rho_{\rm B}}{\rho_c} = 0.042$

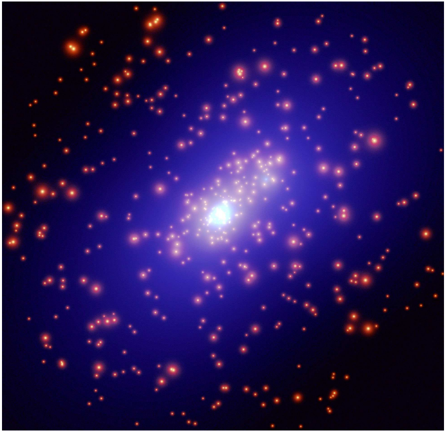
Neutrino contribution: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.016$

Dark Matter contribution: $\Omega_{\rm DM} \equiv \frac{\rho_{\rm DM}}{\rho_c} = 0.2$

Dark Energy contribution: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.75$

Dark Matter in clusters

gravitational lensing $\rho_{\mathrm{M}} \approx 0.25\rho_c$



Dark Matter in clusters

X-rays from hot gas in clusters

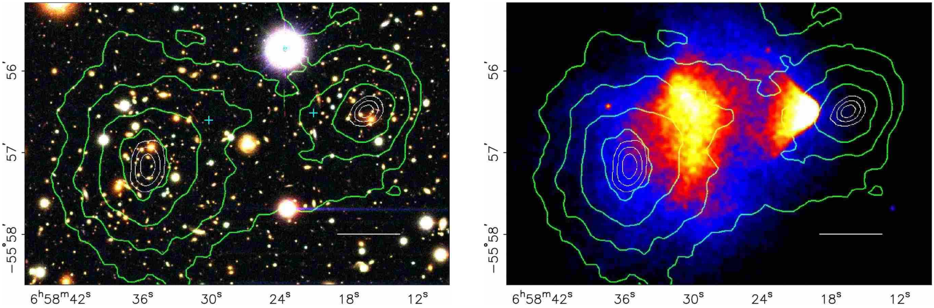
$$\frac{dP}{dR} = -\mu n_e(R) m_p \frac{GM(R)}{R^2}\,, \quad M(R) = 4\pi \int_0^R \rho(r) r^2 dr\,, \quad P(R) = n_e(R) T_e(R)$$

galaxies in clusters

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

Milky Way: Virgo infall

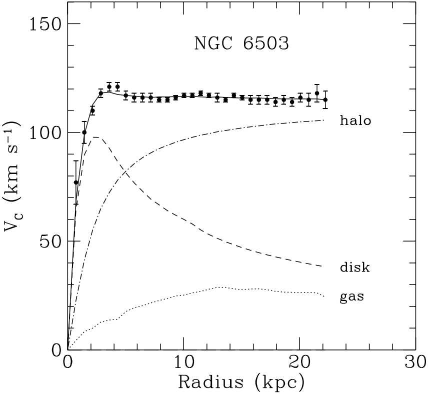
Bullet clusters



Dark Matter in galaxies: flat rotation curves

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

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



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

visible matter:

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

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

Dark Energy: nonclumping matter?

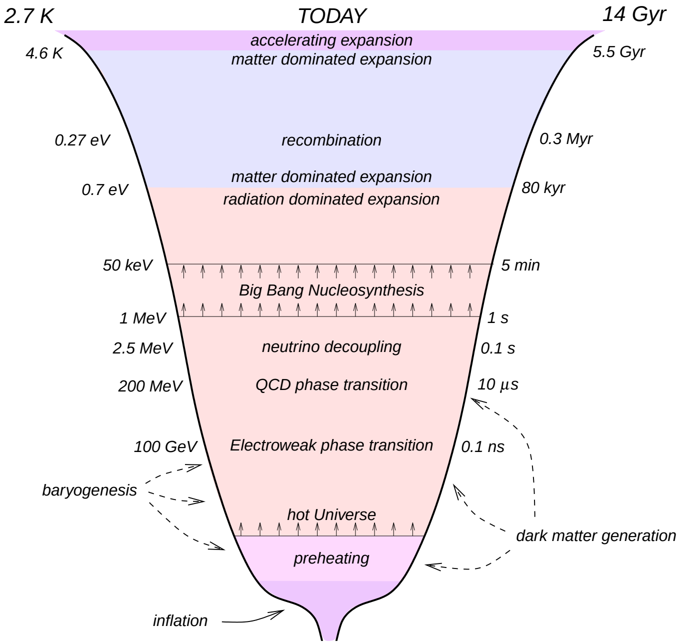
- estimates of Matter contribution confined in galaxies and clusters $\rho_c - \rho_{\rm M} \neq 0$ but the Universe is flat, so $\rho_{curv} \simeq 0$
- corrections to the Hubble law : red shift — brightness curves for standard candles — SN Ia
- The age of the Universe
- CMB anisotropy, large scale structures, etc

$$\rho_\Lambda = 0.75\rho_c$$

$$\rho_\Lambda \sim 10^{-5}\ \text{GeV/cm}^3 \sim \left(10^{-11.5}\ \text{GeV}\right)^4$$

The future Universe

the same period with the same expansion rate


2.7 K
TODAY
14 Gyr
accelerating expansion
4.6 K
matter dominated expansion
5.5 Gyr
0.27 eV
recombination
0.3 Myr
matter dominated expansion
0.7 eV
radiation dominated expansion
80 kyr
50 keV
5 min
Big Bang Nucleosynthesis
1 MeV
1 s
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD phase transition
10 μs
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter generation
preheating
inflation