Cosmology and particle physics
Lecture #1
Overview of basic facts and problems

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Standard Model: Major Problems

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

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

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe (PHENO) (THEORY)
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry (Ω_B)
  - Inflationary stage
  - Reheating
  - Dark energy (Ω_Λ)
  - Strong CP-problem
  - Gauge hierarchy
  - Quantum gravity

Must explain all above ???

Problems in astrophysics. . . (?)

- Origin of extragalactic magnetic fields
- First stars and reionization of the Universe
- Mechanism of SuperNovae explosion
- Sources of Ultra-high energy cosmic rays (EeV-scale)
- Extremely low IR extragalactic background
- Too old White Dwarfs
- Origin of Fast Radio Bursts
- Origin of ICECUBE neutrinos (PeV-scale)
- Black hole physics
- . . .
- Helioseismology vs helioemissivity
- Origin of the heat at the Earth

New Physics and New Cosmology may be

either responsible for

or testable there

Experimenal data in Cosmology and Astrophysics

- Each experiment may be unique (unrepeatable):

  – observe only one Universe

  – (so far) registered only one SN explosion

  – might observe only one magnetic monopole (?)

  – can study only one star

  – (so far) can study only one planet

  . . .
- we register photons, neutrinos, gravitational waves, electrons, positrons, protons, nuclei,

  but only photons, neutrinos and gravitational waves can point at the source

  only gravitational waves trace the early Universe evolution
- Can not directly check the model of sources
- Can not directly check the media in between

Outline

“Natural” units in particle physics

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

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

$m_p = 0.938$ GeV, $1\ \mathrm{K} = 8.6 \times 10^{-14}$ GeV

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

$1\ \mathrm{s} = 1.5 \times 10^{24}\ \mathrm{GeV}^{-1}$, $1\ \mathrm{cm} = 5.1 \times 10^{13}\ \mathrm{GeV}^{-1}$

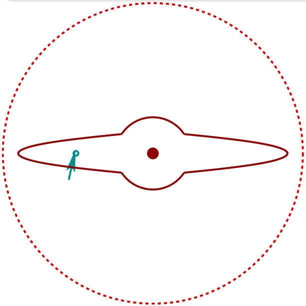
Gravity (General Relativity): $V(r) = -G\frac{m_1 m_2}{r}$ $[G] = M^{-2}$

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

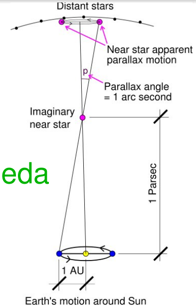
“Natural” units in cosmology

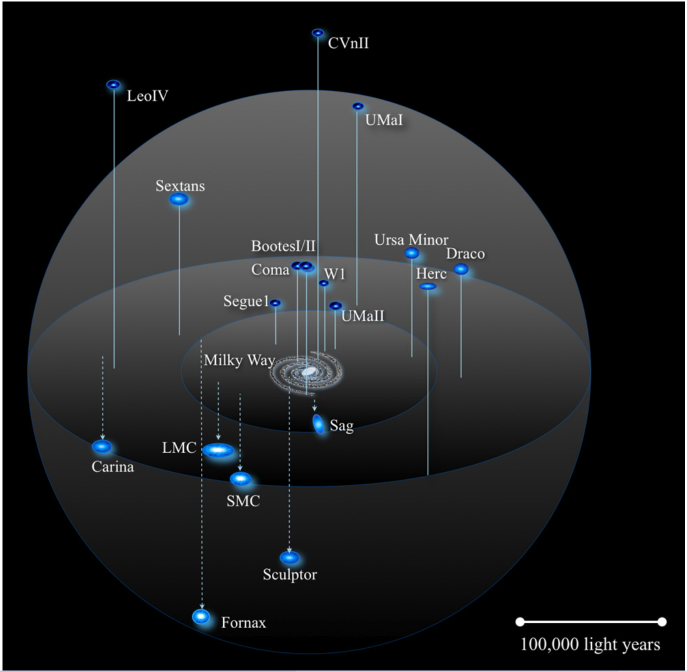
$$1\ \text{Mpc} = 3.1 \times 10^{24}\ \text{cm}$$

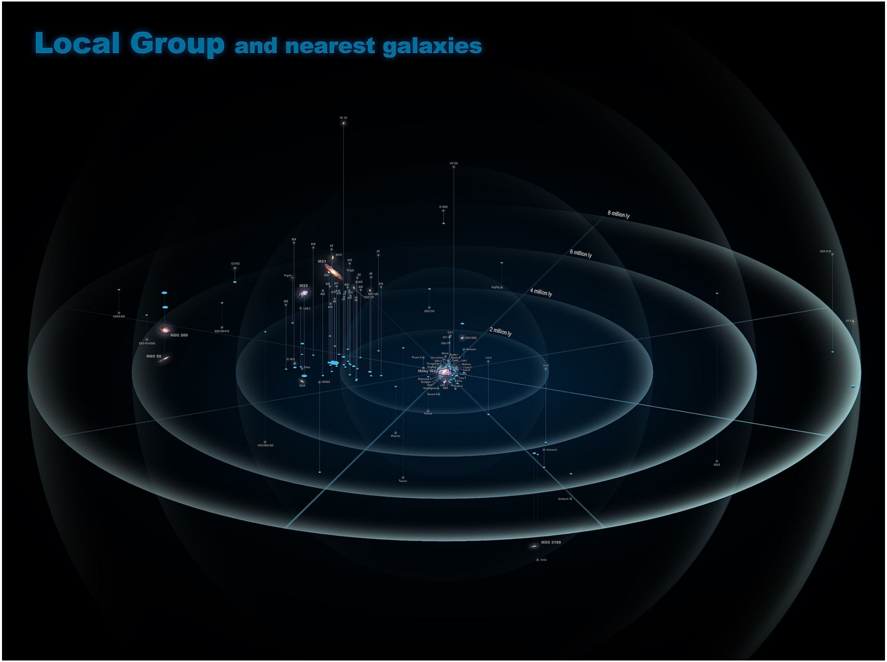
$1\ \text{AU} = 1.5 \times 10^{13}$ cm	mean Earth-to-Sun distance
$1\ \text{ly} = 0.95 \times 10^{18}$ cm	distance light travels in one year
	$1\ \text{yr} = 3.16 \times 10^{7}$ s
$1\ \text{pc} = 3.3\ \text{ly} = 3.1 \times 10^{18}$ cm	distance to object which has a parallax angle of one arcsec



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

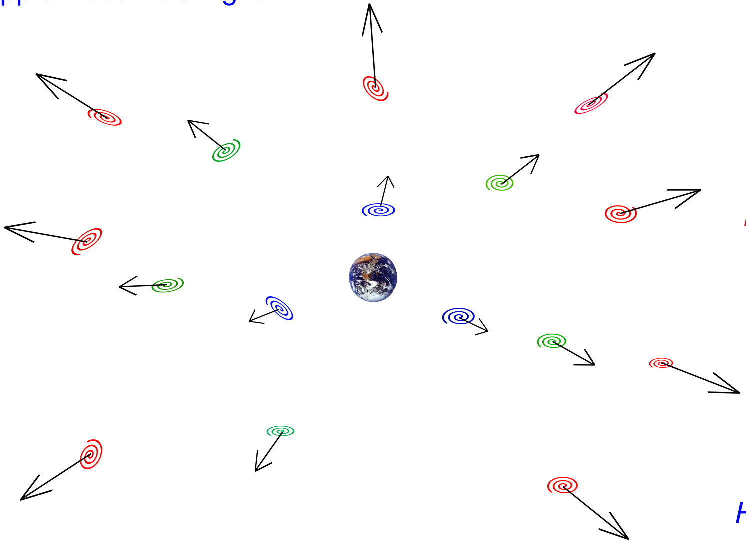



CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years


Local Group and nearest galaxies
IC 10
VV 124
IC 4662
8 million ly
6 million ly
4 million ly
2 million ly
UGC 9128
GR 8
A24
A18
A5
M110
M31
M32
A10
A21
A7
C2
A9
A15
A16
A20
A26
A28
A11
A13
A19
A1
A25
A3
A17
A2
A6
A14
A23
A22
NGC 185
NGC 147
Peg Irr
M33
LGS 3
IC 1613
Cetus
WLM
KKR25
IC 5152
UGCA 438
ESO 294-010
NGC 300
ESO 410-G005
NGC 55
UKS 2323-326
DDO 210
SagDig
CV II
CV I
NGC 6822
UMa I
Hercules
Draco
Boote I
Boote III
Ursa minor
UMa II
Coma
Leo I
Pisces II
Triangulum 2
Sextans
SagDeg
Leo V
Leo IV
Milky Way
Leo II
Reticulum II
Leo T
Sculptor
Carina
Grus
LMC
Crater 2
Horologium
SMC
Tucana II
Leo A
Leo P
Fornax
Phoenix
Tucana
Sextans B
Sextans A
KKs3
NGC 3109
Antlia

Universe is expanding

Doppler redshift of light



$L \propto a(t)$

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

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

Hubble parameter

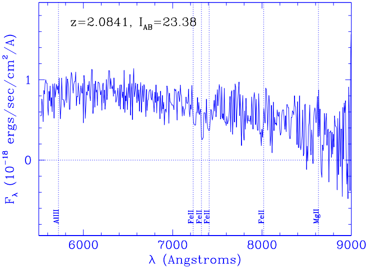
Hubble Law

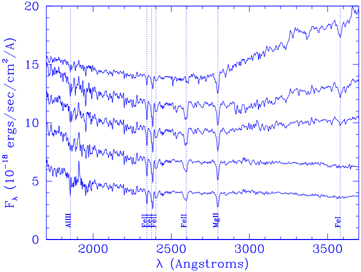
$H(t_0)\, r = v_r$

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

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

$$H_0 = h \cdot 100\,\frac{\text{km}}{\text{s}\cdot\text{Mpc}}\,, \qquad h \approx 0.68$$





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

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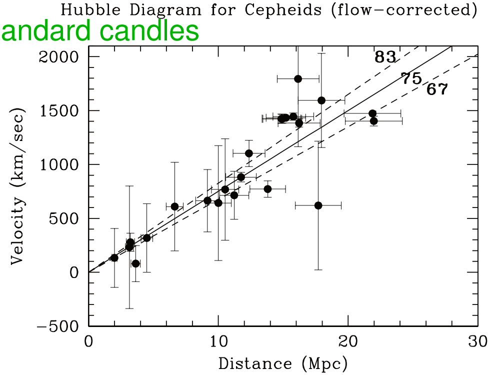
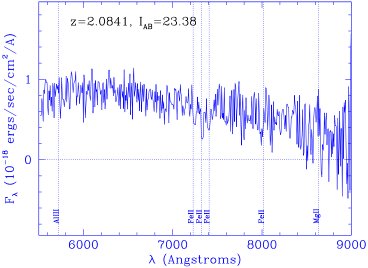
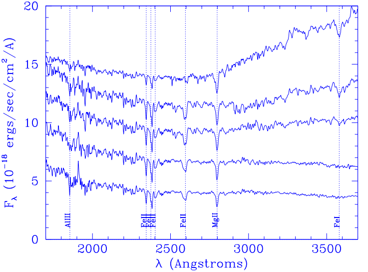
standard candles



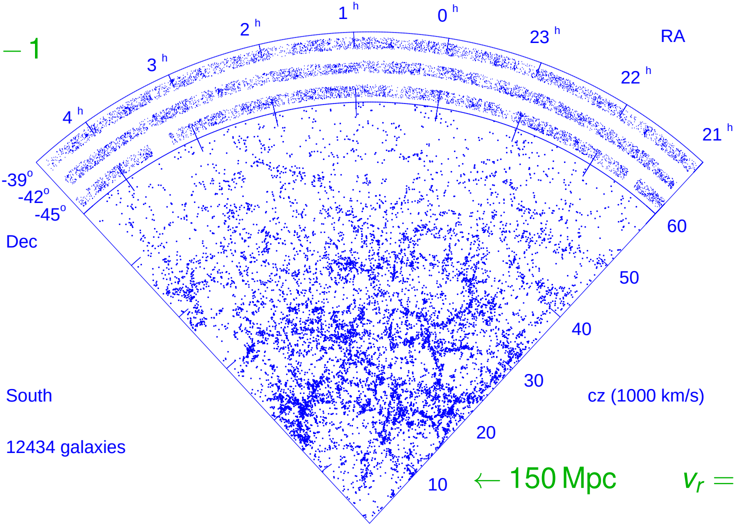




Universe is homogeneous and isotropic

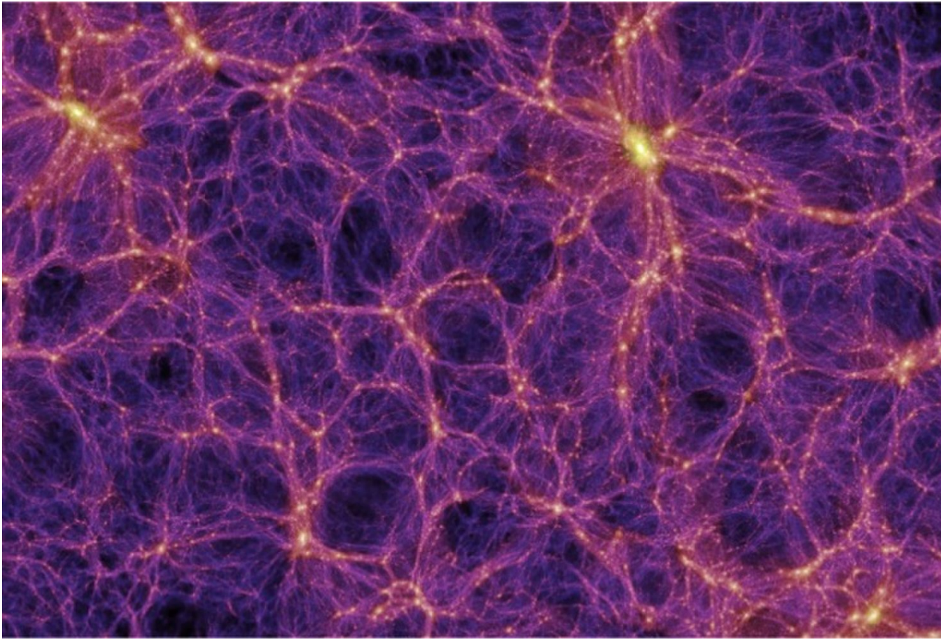
redshift

$$z \equiv \frac{\lambda_{\text{detector}}}{\lambda_{\text{source}}} - 1$$



$\leftarrow$ 150 Mpc

$$v_r = c\,z$$



The Universe: age & geometry & energy density

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

time scale: $t_{H_0} = H_0^{-1} \approx 14 \times 10^9$ yr age of our Universe

spatial scale: $l_{H_0} = H_0^{-1} \approx 4.3 \times 10^3$ Mpc 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 $R_{curv} > 30 \times l_{H_0}$

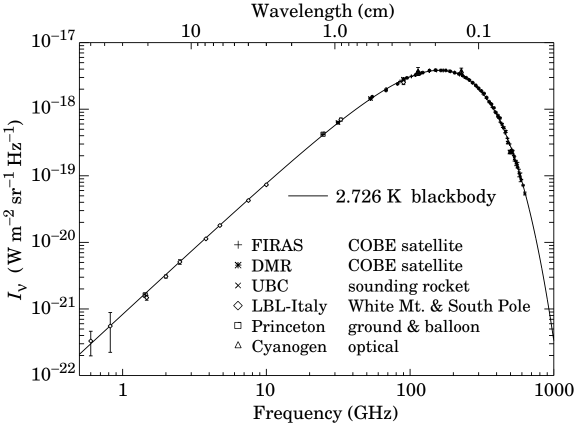
order-of-magnitude estimate: $v^2/r \sim (Hr)^2/r \sim GM_r/r^2 \sim G\rho r^3/r^2$

flat Universe

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

$\longrightarrow$ 5 protons in each 1 m^3

Universe is occupied by “thermal” photons



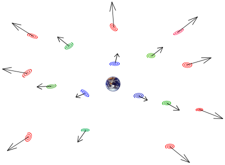
$T_0 = 2.726\,\text{K}$

the spectrum (shape and normalization!) is thermal

$n_\gamma = 411\ \text{cm}^{-3}$

Conclusions from observations

The Universe is homogeneous, isotropic, hot and expanding...



Conclusions

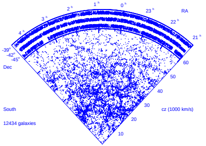
- interval between events gets modified

$$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta \mathbf{x}^2$$

in GR expansion is described by the Friedmann equation

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

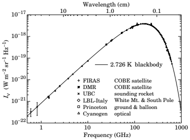
$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$

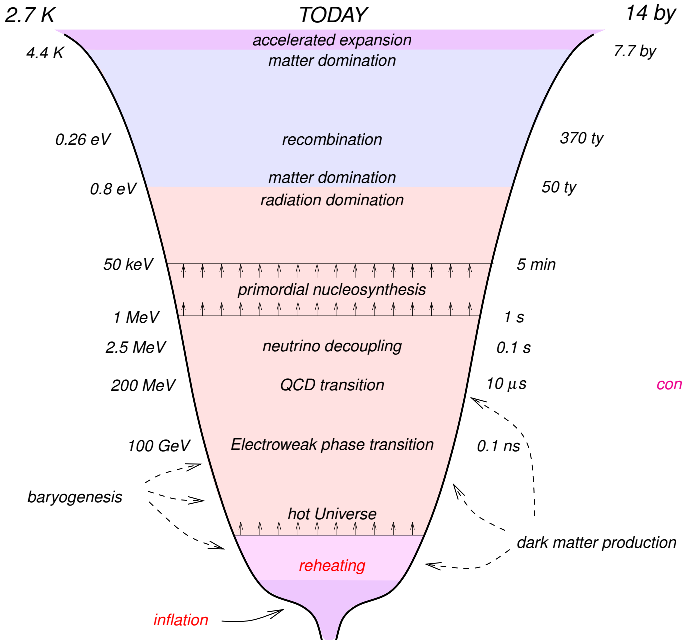


- in the past the matter density was higher, our Universe was "hotter" filled with electromagnetic plasma

$$\rho_{\text{matter}} \propto 1/a^3(t)\,,\;\; \rho_{\text{radiation}} \propto 1/a^4(t)\,,\;\; \rho_{\text{curvature}} \propto 1/a^2(t)$$

certainly known up to $T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$





2.7 K TODAY 14 by

accelerated expansion

4.4 K matter domination 7.7 by

0.26 eV recombination 370 ty $e+p\to H+\gamma$

0.8 eV matter domination 50 ty

radiation domination

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

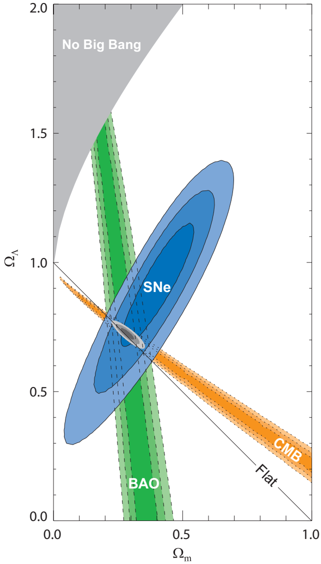
hot Universe

dark matter production

reheating

inflation

Astrophysical and cosmological data are in agreement



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

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

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

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

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: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

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

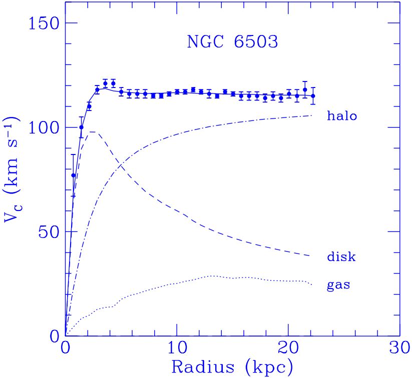
Observables in cosmology

- Astrophysical data
  - Observations in galaxies: stars and clouds
  - Observations in galaxy clusters: galaxies, gas, distortions
- Cosmological data
  - Observation of sources at cosmological distances (far=early)
  - Baryonic Aciustic (Sakharov) Oscillations (BAO) in two-point galaxy correlation function
  - Evolution of galaxy clusters in the Universe
  - Anisotropy and polarization of Cosmic Microwave Background (CMB)
  - Weak lensing on late-time cosmic structures
  - Sunyaev–Zeldovich clusters
  - Ly-α forest
  - ...
  -
  - 3d-map of galaxies
  - 21cm cosmic field

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

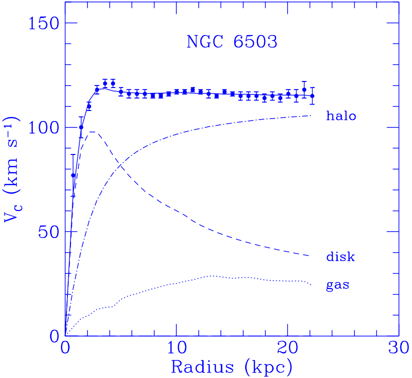
Alternatives to the galactic dark matter

MOdified Newtonian Dynamics (M. Milgrom, 1983)

$$m\frac{a^2}{a+a_0} = F = G\frac{mM(R)}{R^2}$$

Weyl Gravity (Mannheim–Kazanas metric)

$$\Delta^2\Phi(r) \propto \rho$$



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Matter distribution in the Milky Way

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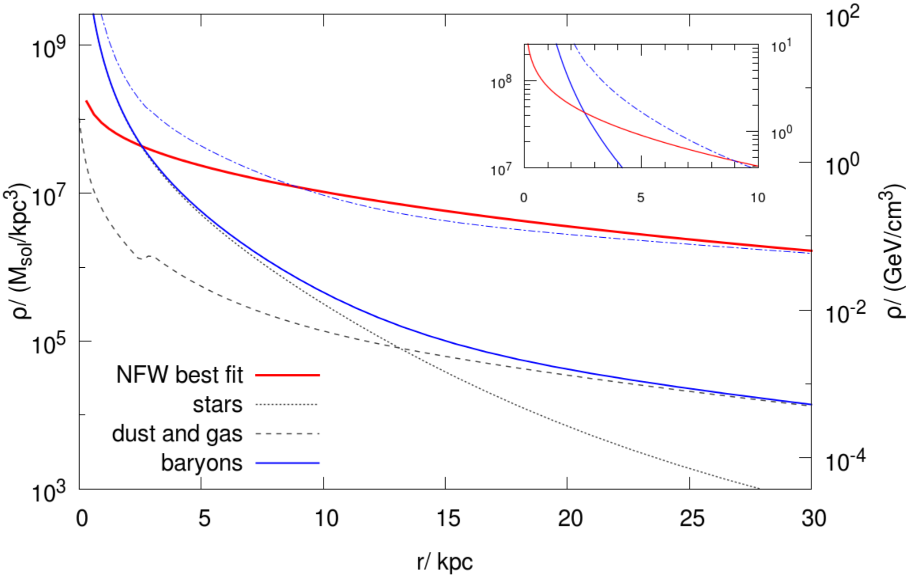


Dark Matter in clusters

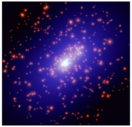
X-rays from hot gas in clusters

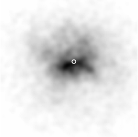
$$\frac{dP}{dR} = -\mu n_e(R) m_p \frac{GM(R)}{R^2}\,, \quad M(R) = 4\pi \int_0^R \rho(r) r^2 dr\,, \quad P(R) = n_e(R) T_e(R)$$

galaxies in clusters virial theorem

$$U + 2E_k = 0$$

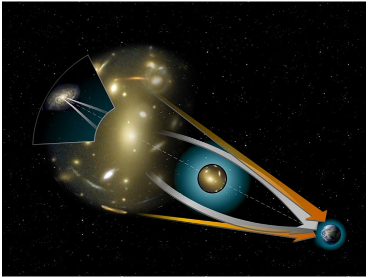
$$3M\langle v_r^2\rangle = G\frac{M^2}{R}$$



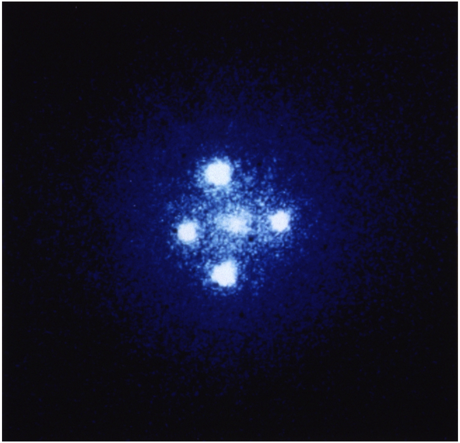


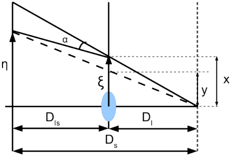
Milky Way: Virgo infall

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

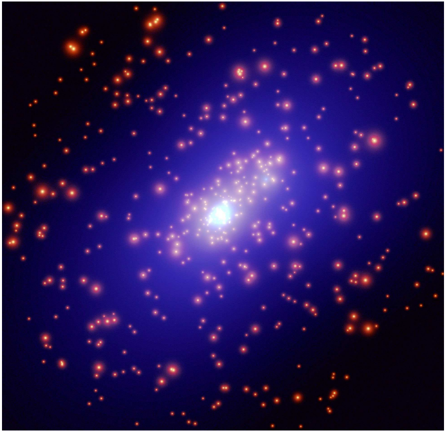
$$\vec{\alpha}\left(\vec{\xi}\right) = \frac{4G}{c}\int \frac{\vec{\xi}-\vec{\xi}'}{\left|\xi-\vec{\xi}'\right|^2}\, d^2\xi' \int \rho\left(\vec{\xi}',z\right) dz$$

source: quasar $D_s = 2.4$ Gpc

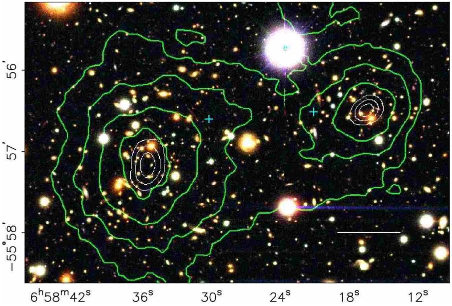
lens: galaxy $D_l = 120$ Mpc

Dark Matter in clusters

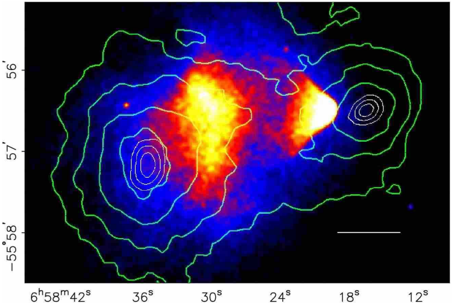
gravitational lensing $\rho_B \approx 0.25\rho_{DM}$



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

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

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

If not: for bosons

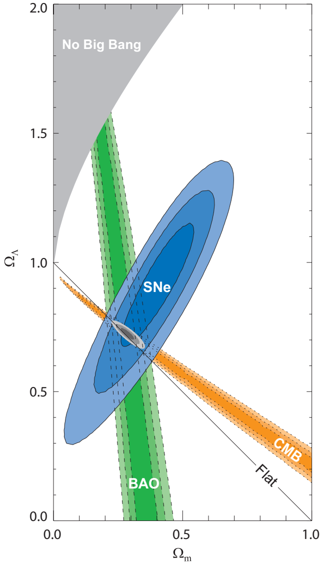
$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

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

Astrophysical and cosmological data are in agreement



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