Introduction to Cosmology

Mostly Dark Matter and a bit of everything

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Plan

Particle Physics – Standard Model!

Our Universe – Today and in the past

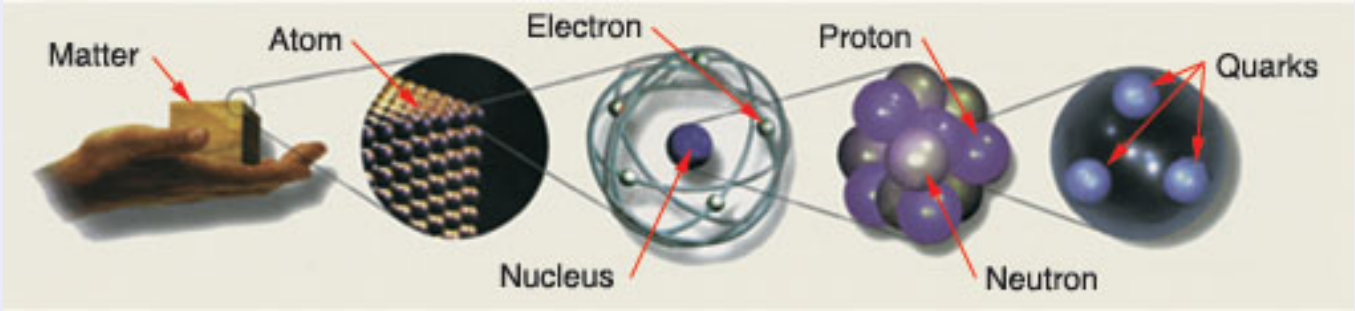
- Astrophysics: Dark Matter in the Galaxies
- Astrophysics: Dark Matter in Galaxy Clusters
- Dark Matter and Cosmology

Particle physics realization

- Particle Dark Matter properties
- “Most natural” (or usual) candidate – WIMP
  - Searches for WIMPS
  - Direct searches of Dark Matter
  - Indirect searches – decay or annihilation of DM
- Sterile neutrino Dark Matter

Standard Model

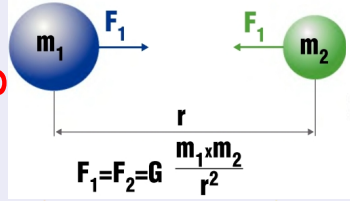
Matter constituents

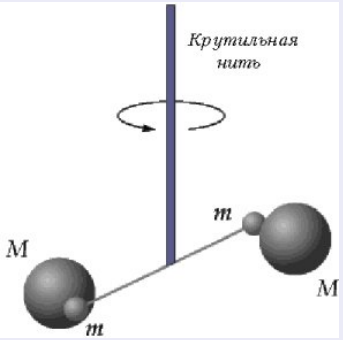


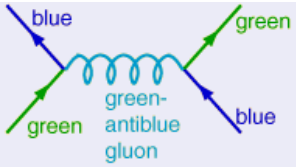
Interactions

Short range Long range

Gravity







Feynman diagram for an interaction between quarks generated by a gluon.

Strong

$L \lesssim 10^{-13}$ cm

Electromagnetism

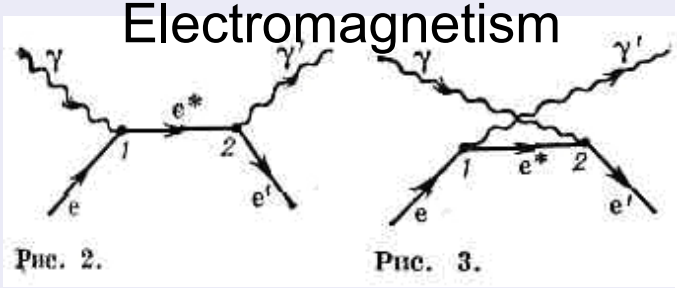
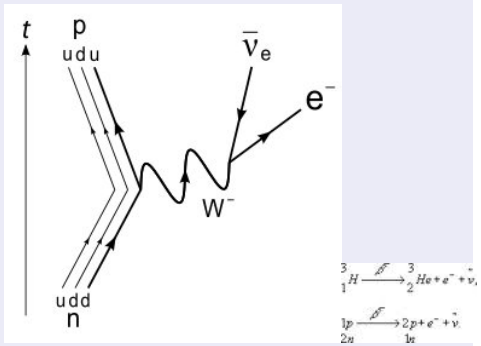


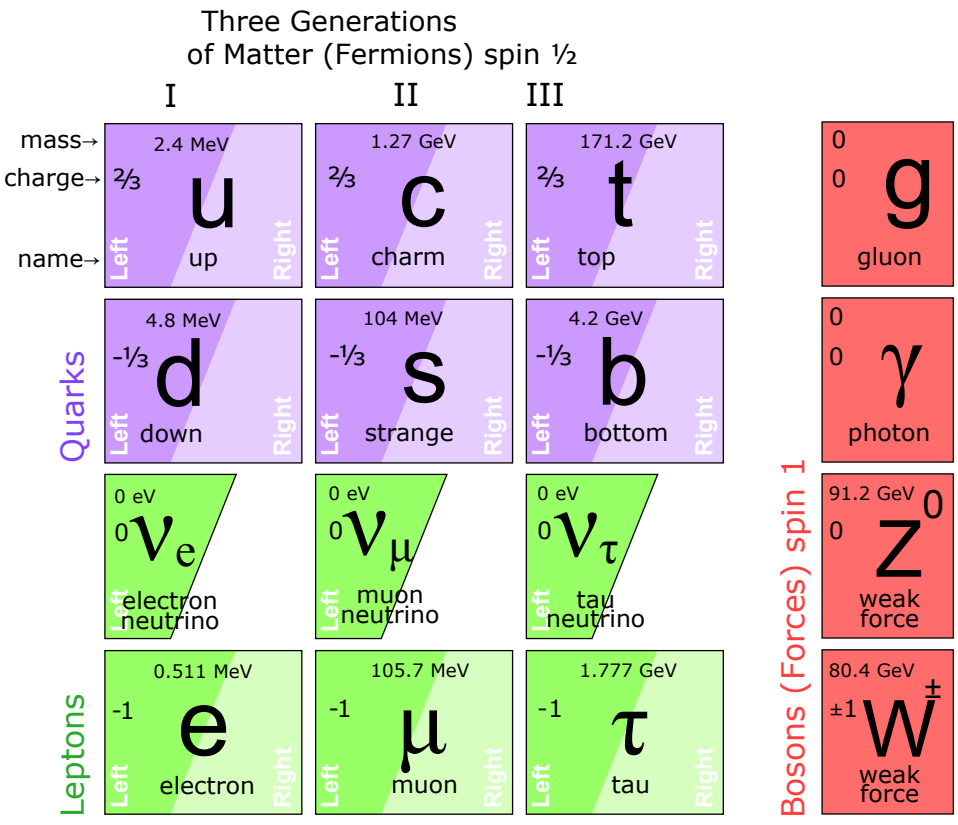
Рис. 2. Рис. 3.

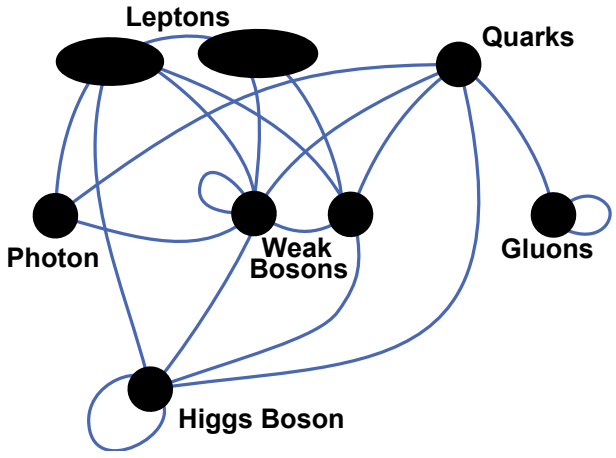
Weak

$L \lesssim 10^{-16}$ cm



All particles of the Standard Model





(+ Einstein gravity)

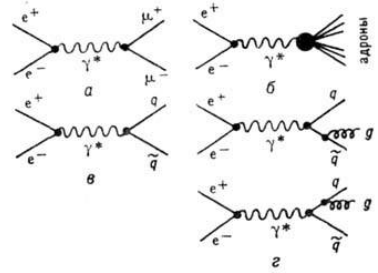
Tests of the Standard Model are numerous

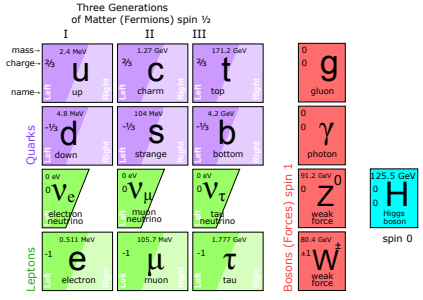
- Precise predictions of SM for particle properties
  - QED

    $\alpha^{-1} = 137.035999070(98)$ from anomalous magnetic moment

    $\alpha^{-1} = 137.03599878(91)$ from atom recoil measurements

- Particle decays: $\mu \to e\bar{\nu}_e\nu_\mu$, $Z \to \mu^+\mu^-$
- Particle scattering:





- Tests of predictions from some motivated generalizations

Regularly updated, public data at `http://pdg.lbl.gov`

Successes and problems of the Standard Model

SM is perfect for

Explaining all the everyday/lab physics phenomena

Full set of experimental problems of the SM

- Neutrino oscillations
- *Dark Matter*
- Baryon asymmetry of the Universe
- Inflation

Theoretical concerns about the SM

- (Small value of) CP violation in strong interactions
- (Small value of) Dark energy (compared to all other scales)
- (Small value of) the Higgs boson mass (compared to the Planck/Grand Unification scale)
- Fermion mass hierarchies
- Unification of the interactions

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Why Dark Matter?

Astrophysical data (“today”)

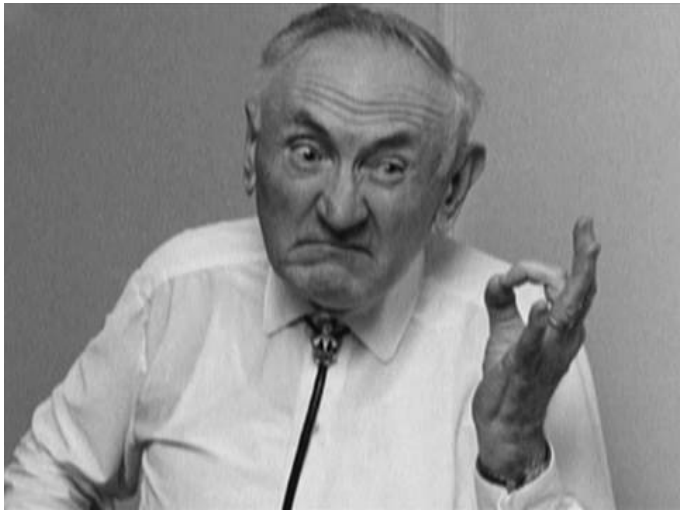
- Observations of objects in the galaxies
- Observations of gravitational lensing by galaxies
- Observations of the galaxy clusters

Cosmological data (“past”)

- Abundance of structure in the present Universe
- Analysis of the anisotropy of the Cosmic Microwave Background radiation
- Baryon acoustic oscillations (distribution of far away galaxies)

Astrophysics – movement of stars in the galaxies

- Look at movement of stars in a galaxy
- Their movement is governed by gravitational field of the galaxy
- Knowing the gravitational force estimate the mass required to create it
- Compare to the visible (stars/gas) mass
- Not enough by a lot!

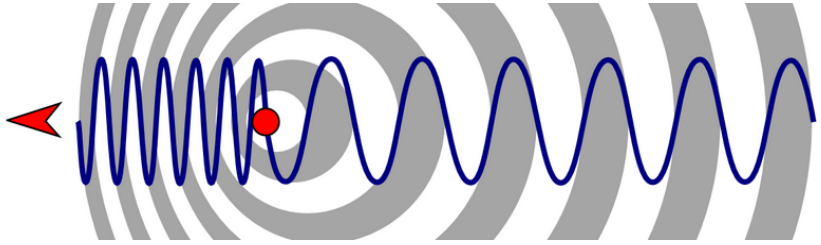


Fritz Zwicky, 1933

Measuring of the velocities of the objects in galaxies

Doppler effect

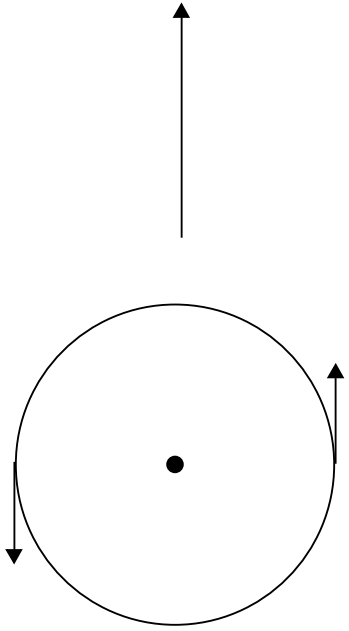
$$\omega = \omega_0 \frac{1 + \frac{u_{\text{detector}}}{c_{\text{waves in media}}}}{1 - \frac{u_{\text{source}}}{c_{\text{waves in media}}}}$$



Relativistic generalization

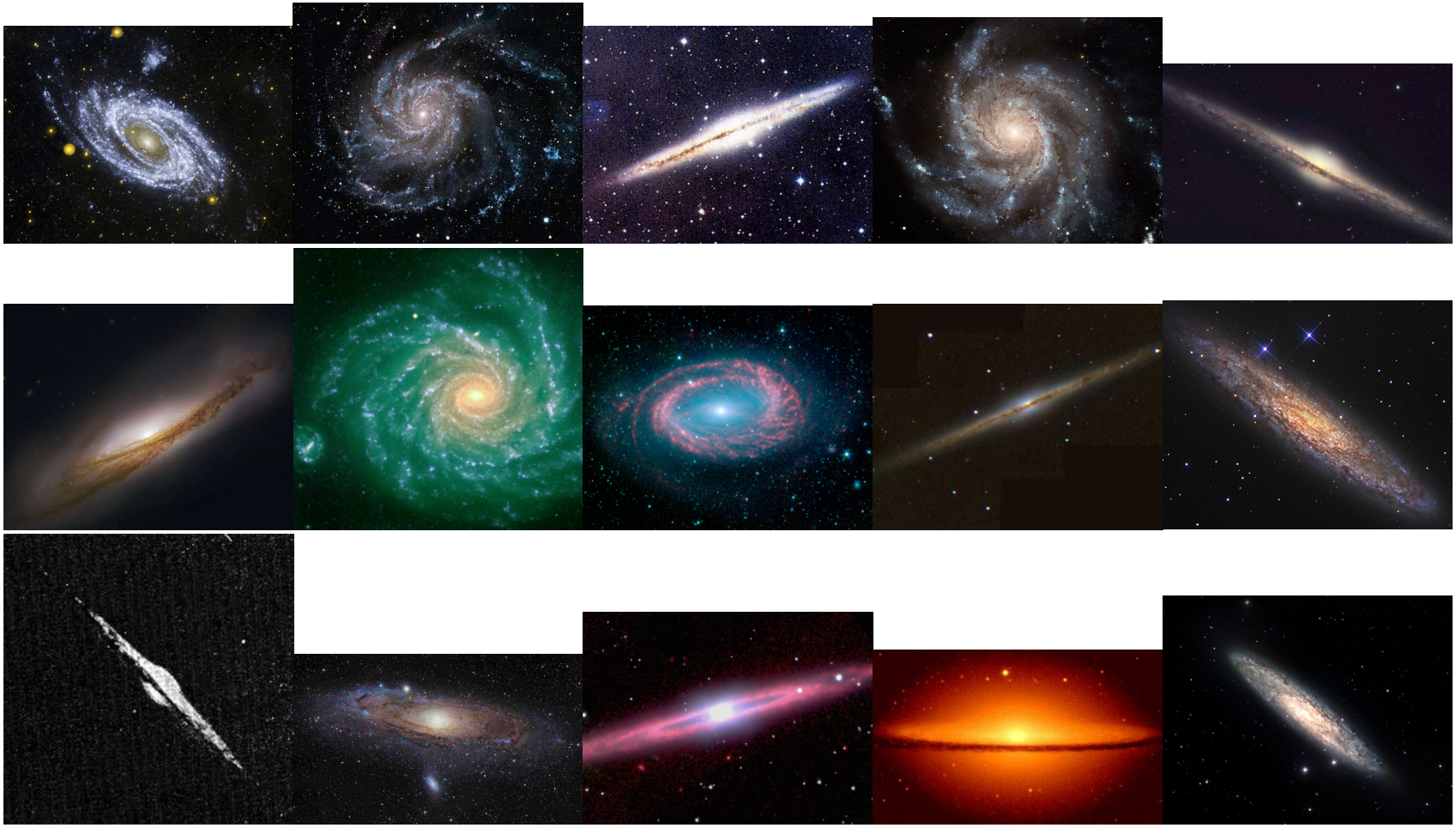
$$\omega = \omega_0 \frac{\sqrt{1 - \frac{u^2}{c^2}}}{1 + \frac{u}{c}\cos\theta}$$

θ–angle between object velocity and line of sight $\vec{u}$



You can find the rotation velocity independent of the velocity of the center of rotation

Stars and cold gas clouds in spiral galaxies

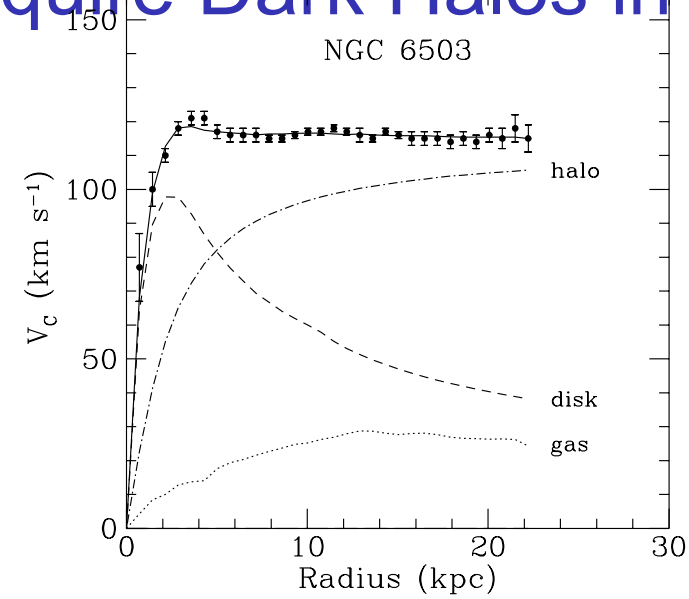


Flat “rotation curves” require Dark Halos in galaxies

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

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

1 kpc $= 10^3$ parsec $=$
3.3 thousand light years

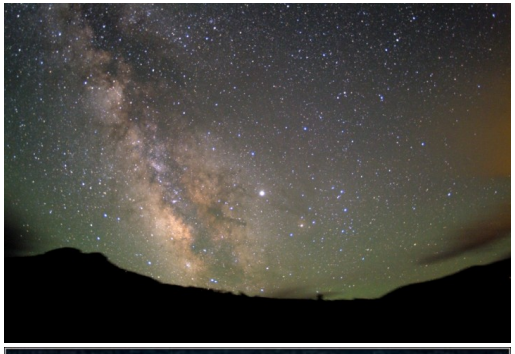


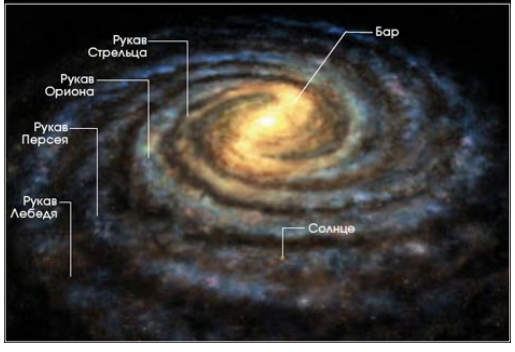
Observations: $v(R) \simeq$ const

Visible matter would account for:

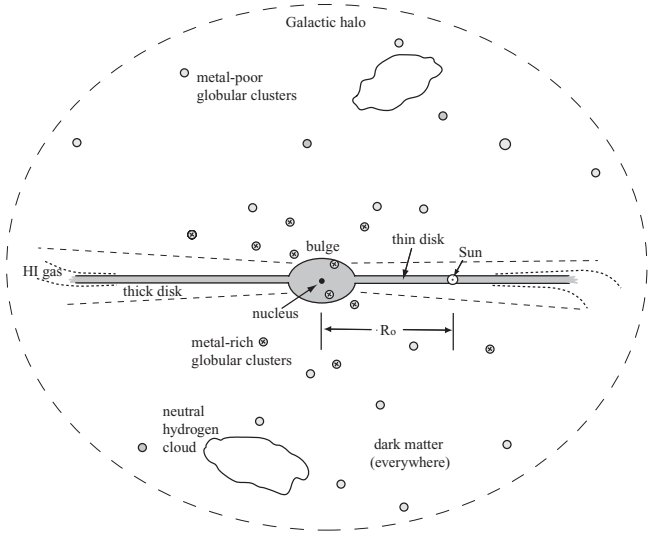
internal region $v(R) \propto \sqrt{R}$
external (“empty”) region $v(R) \propto 1/\sqrt{R}$

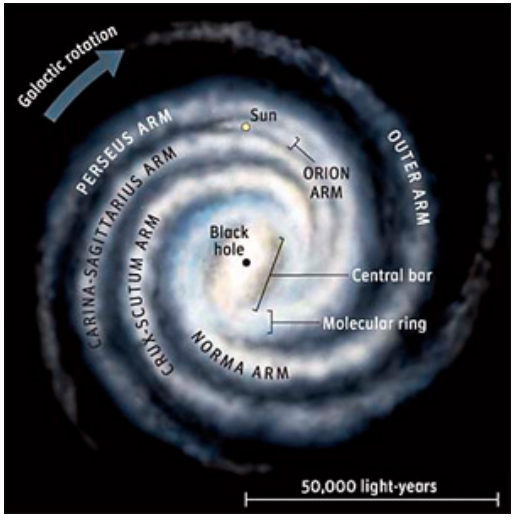
Milky Way details





Halo also helps to stabilise the disk…





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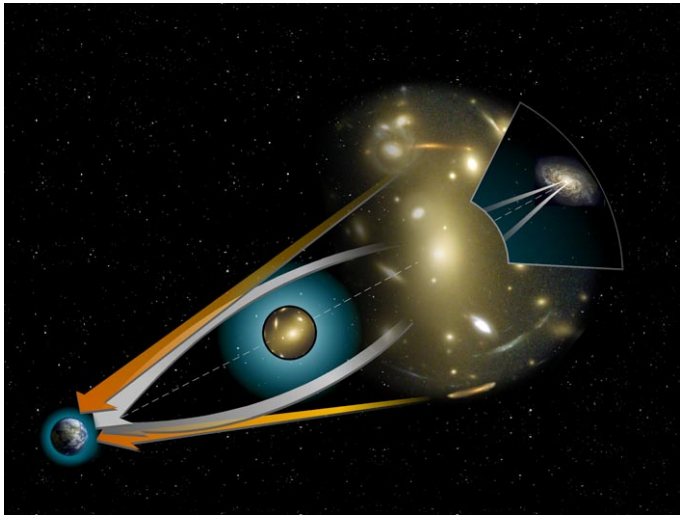
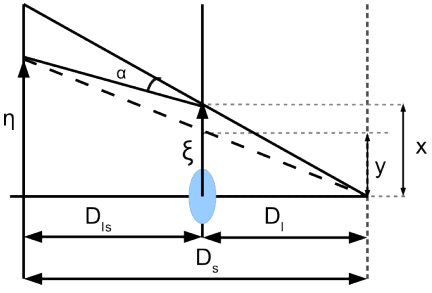
Gravitational lensing: GR $\alpha = 4GM/(c^2 b)$



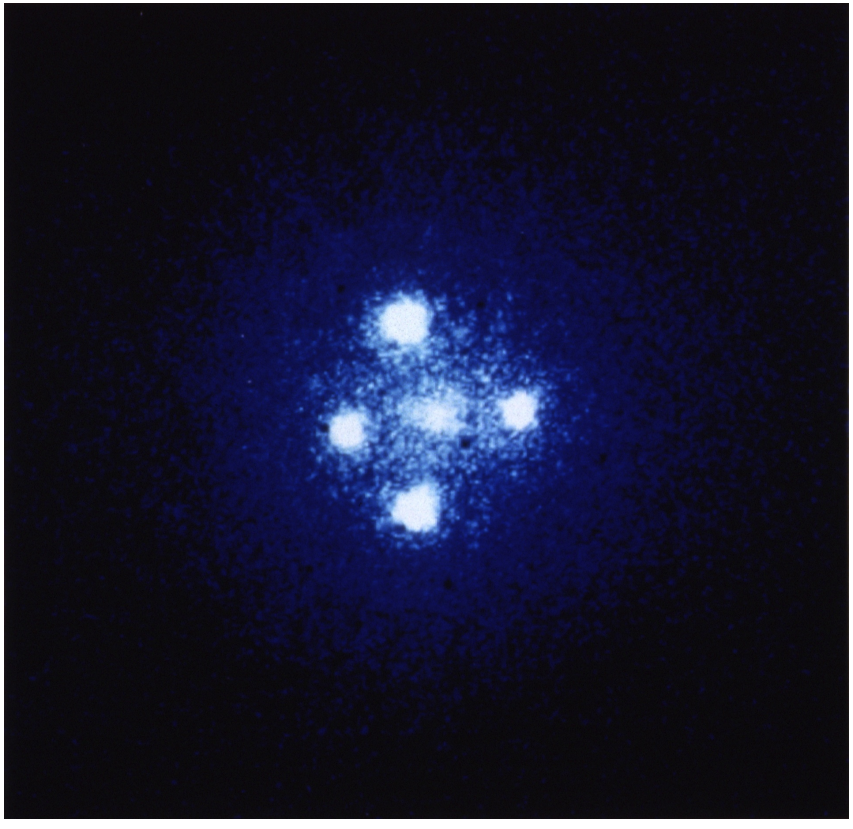


$$\vec{\eta} = \frac{D_s}{D_l}\vec{\xi} - D_{ls}\vec{\alpha}\left(\vec{\xi}\right)$$

Ordinary lens with a specific refraction coefficient

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

Einsteins cross

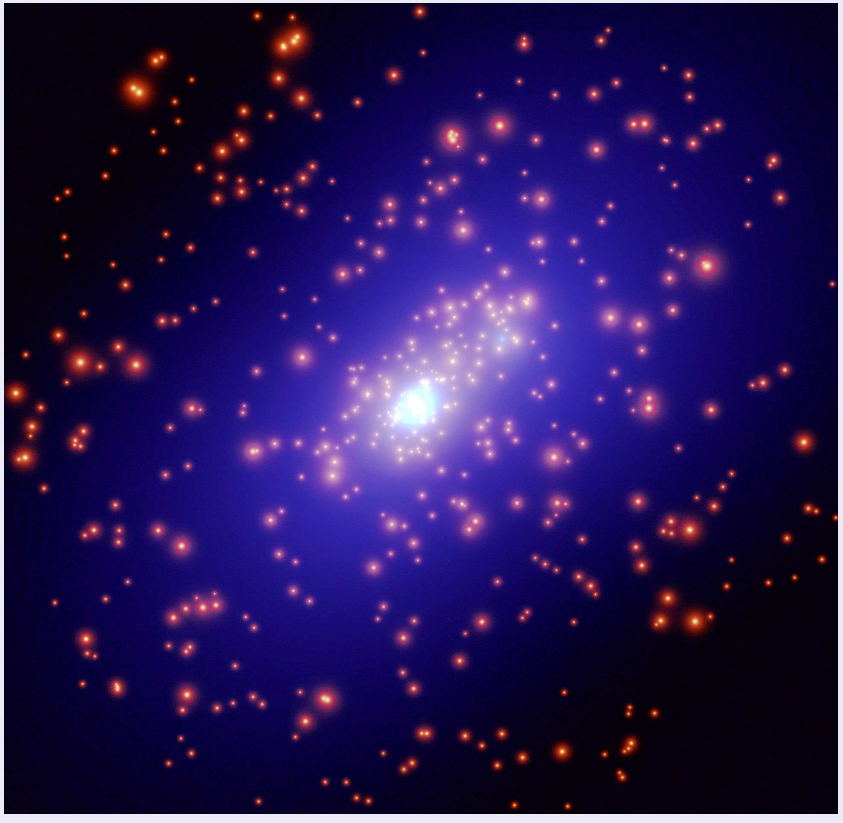


source: quasar $D_s = 8$ billion ly
lens: galaxy $D_l = 0.4$ billion ly

Dark matter in the center of galaxy clusters

Gravitational lensing

Reconstruction of the lens from the image



Dark matter in galaxy clusters

X-rays from hot gas in the cluster centers

$$\frac{\Delta P}{\Delta R} = -\mu n_e(R) m_p \frac{GM(R)}{R^2},$$

$$M(R) = 4\pi \int_0^R \rho(r) r^2 dr, \quad P(R) = n_e(R) T_e(R)$$

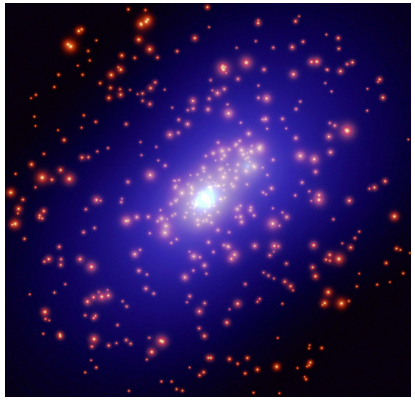
Galaxies in the clusters

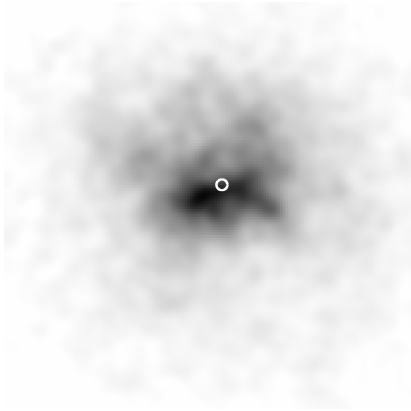
Galaxies are virialized,

$U + 2E_k = 0$

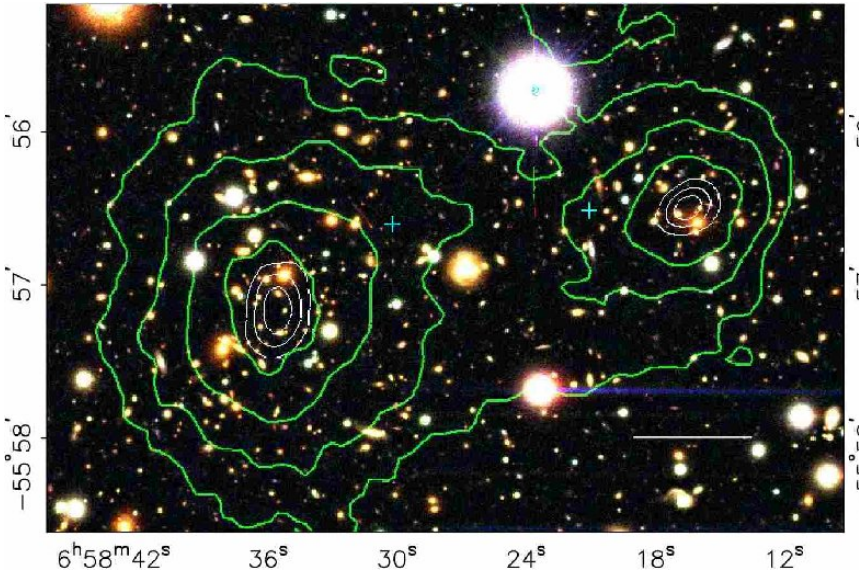
$$3M\langle u_r^2 \rangle = G\frac{M^2}{R}$$

u_r — Projection on the line of sight

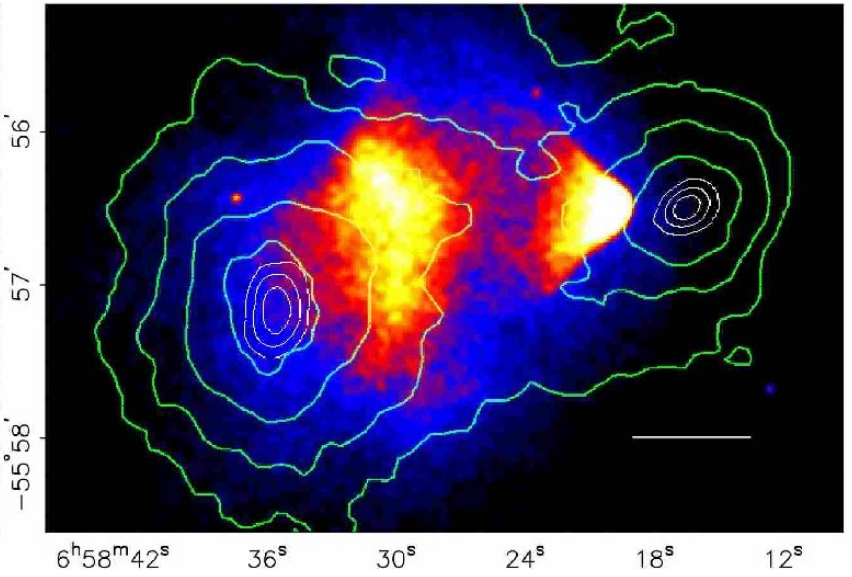




Clusters who collided (Bullet cluster) 1E0657-558



Gravitational lensing



Roentgen image

$M \simeq 10 \times m$

Scale is in 700 thousand ly

clusters are separated by 5 billion ly

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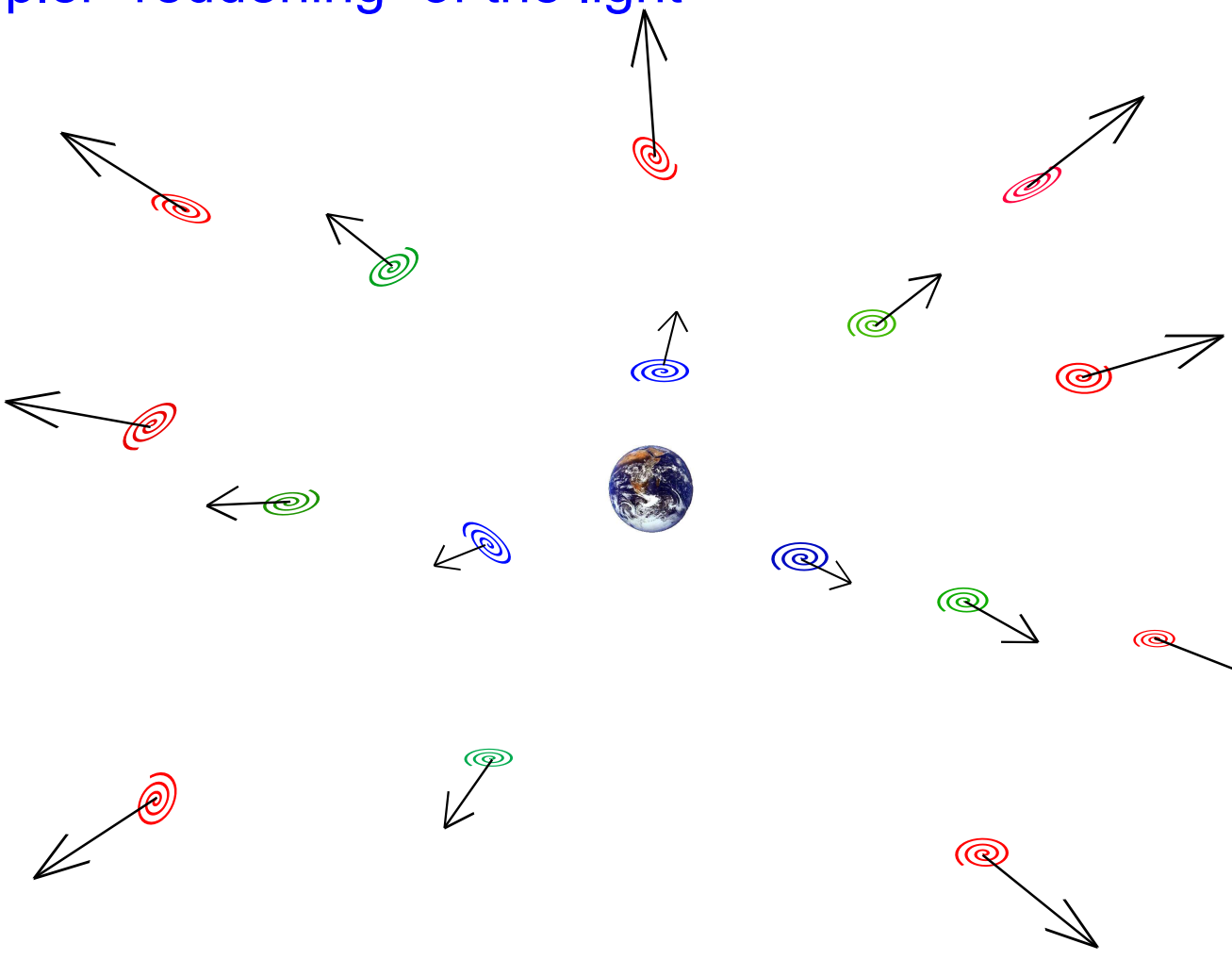
Basic (experimental) facts about the Universe: Expansion

Doppler “reddening” of the light

$L \propto a(t)$



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

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

Hubble parameter

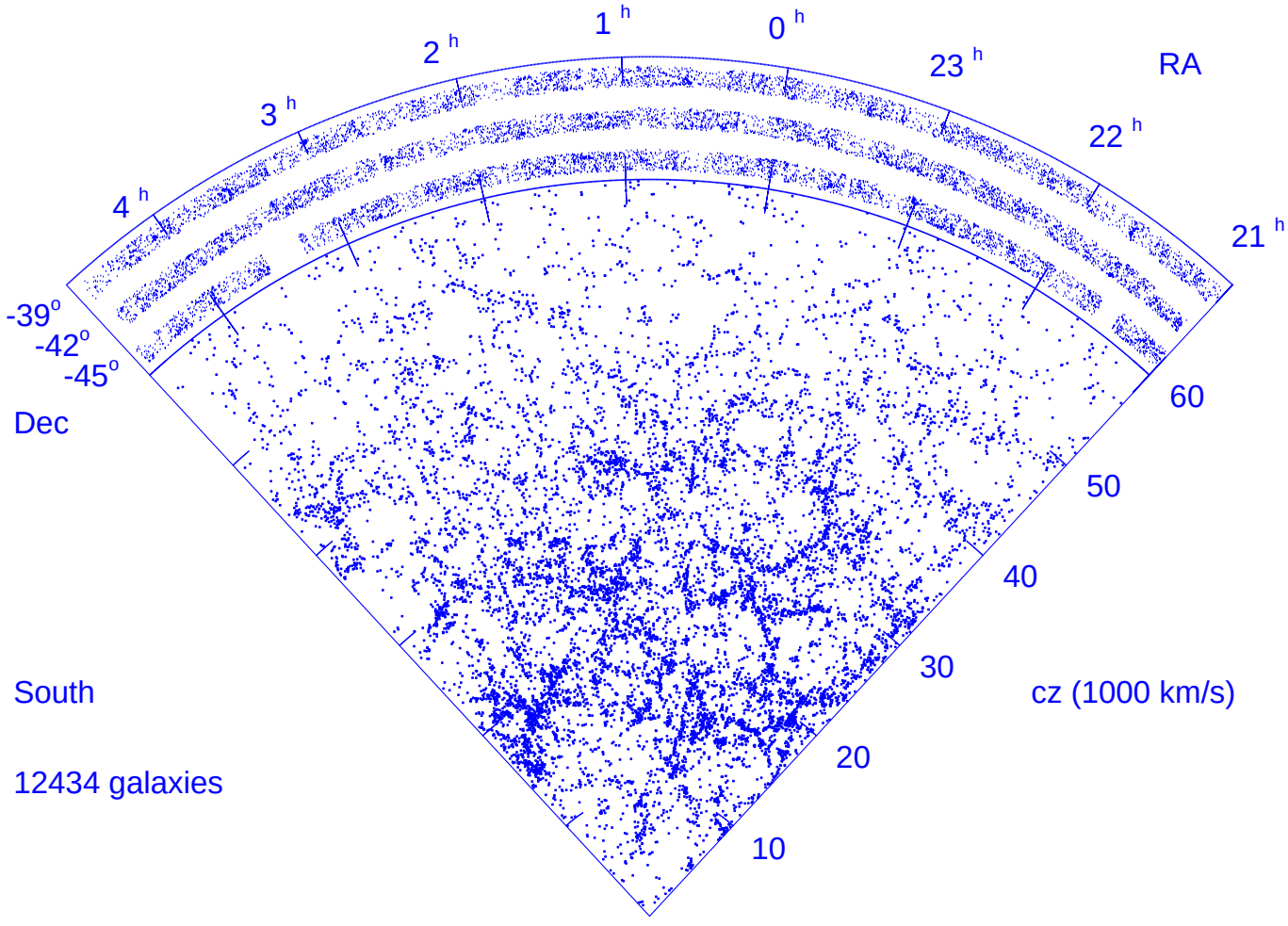
Hubble law

$H(0)\, r = v_r$

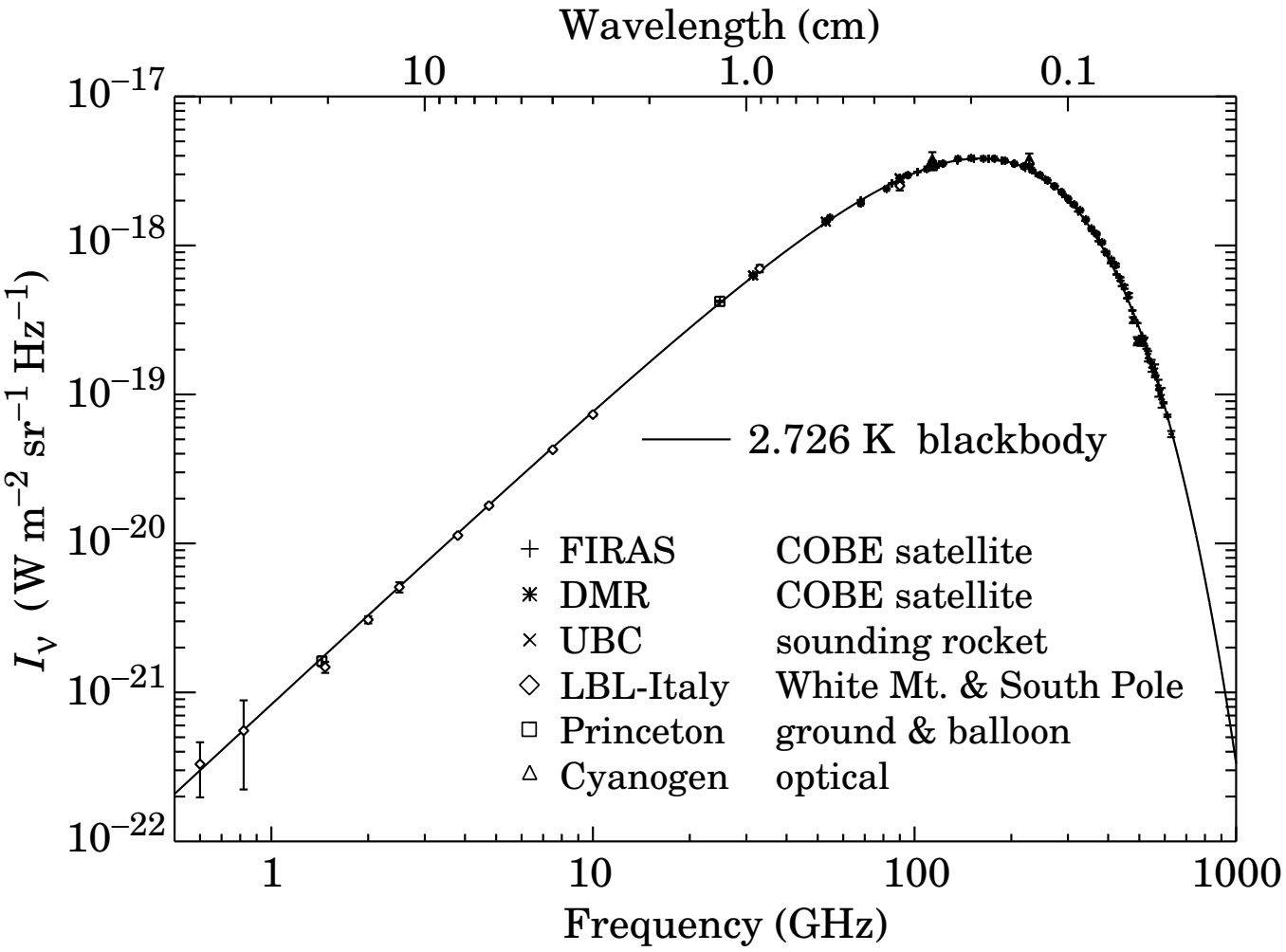
Our Universe: Uniform and isotropic

redshift

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



The Universe is filled with “hot” photons



$T_0 = 2.726\ ^\circ\mathrm{K}$

Both spectrum and density correspond to thermody-namic equilibrium

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

Conclusions from the observations

So – the Universe is uniform, isotropic, is expanding, and “hot”…

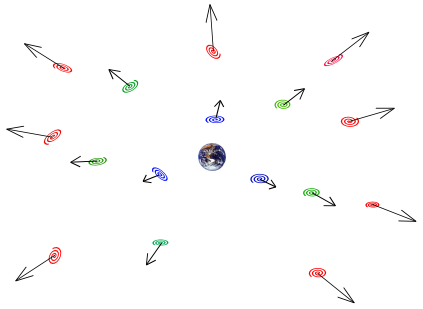
- interval between events is modified

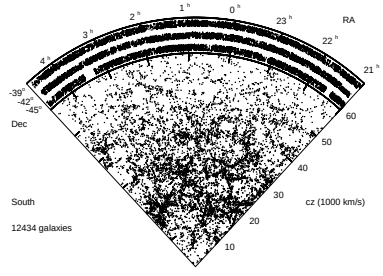
$$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta \vec{x}^2$$

in GR the expansion is describe by the Friedman equation

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

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

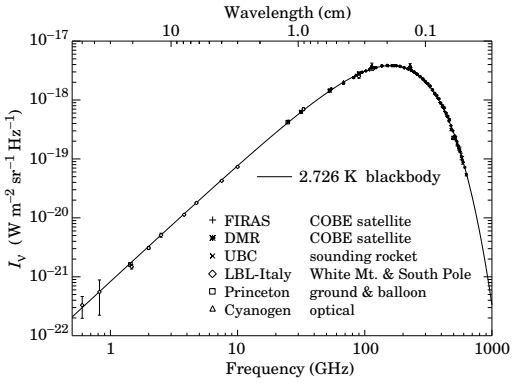




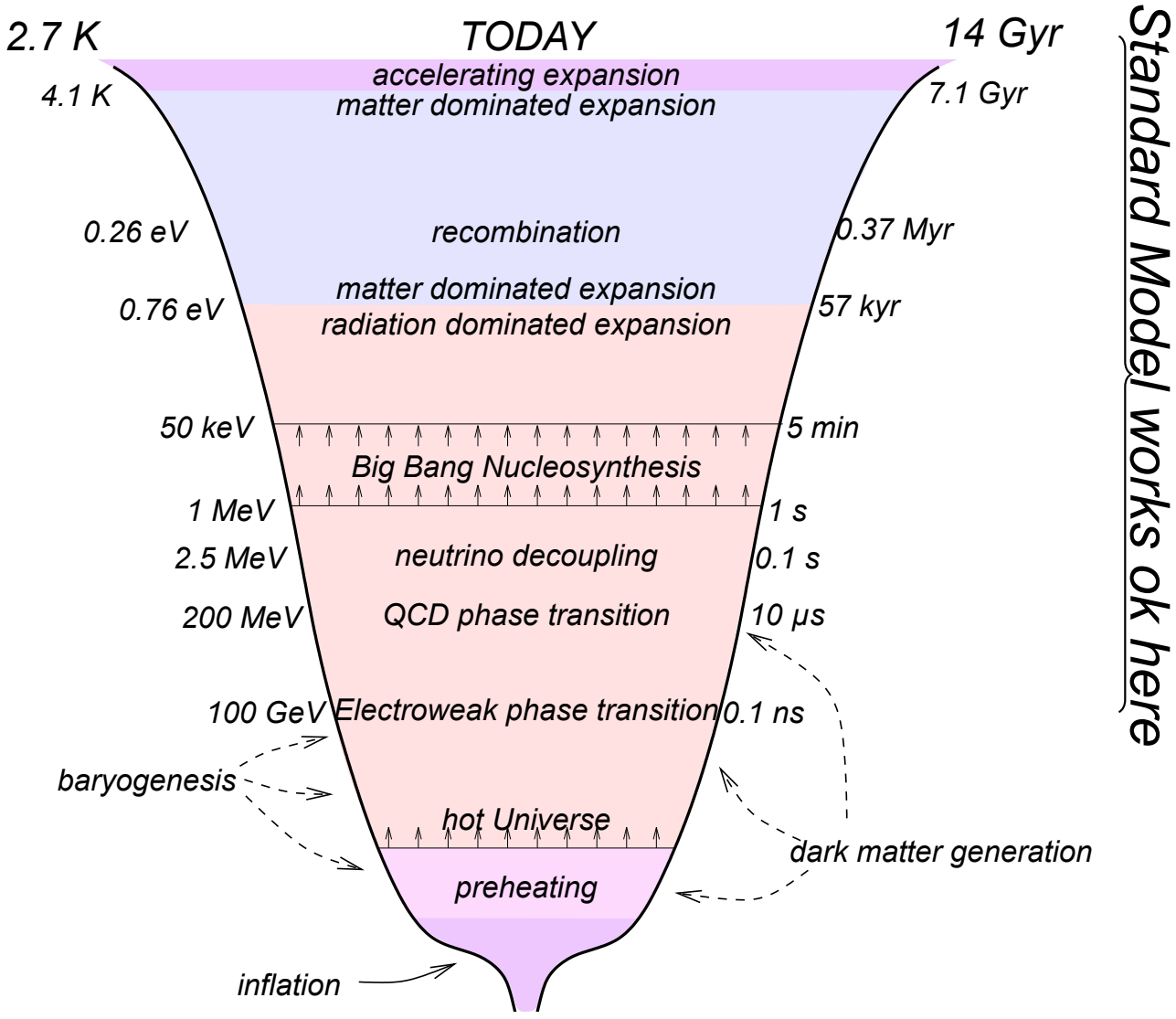
- in the past the Universe was “denser” and “hotter”, at some moment it was constructed out of electromagnetic plasma

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

We are very confident up to
$T \sim 1\,\text{MeV}\,c^2/k \sim 10\,\text{billion}\,^\circ\text{K}$



Universe history



Measurement of the scale factor $a(t)$ recovers the composition of the present Universe

$\Delta s^2 = c^2\,\Delta t^2 - a^2\,(t)\,\Delta \vec{x}^2$ The light propagation changes

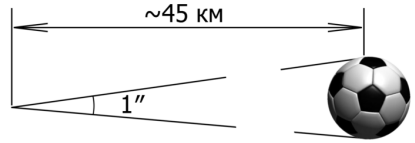
How to check it?

Measure distance L of an object!

- Measure angular distance θ of a known sized object d

galaxies of a fixed type

$$\theta = \frac{d}{L}$$



- Measuring angular size $\theta(t)$ corresponding to an object with known evolving size $d(t)$

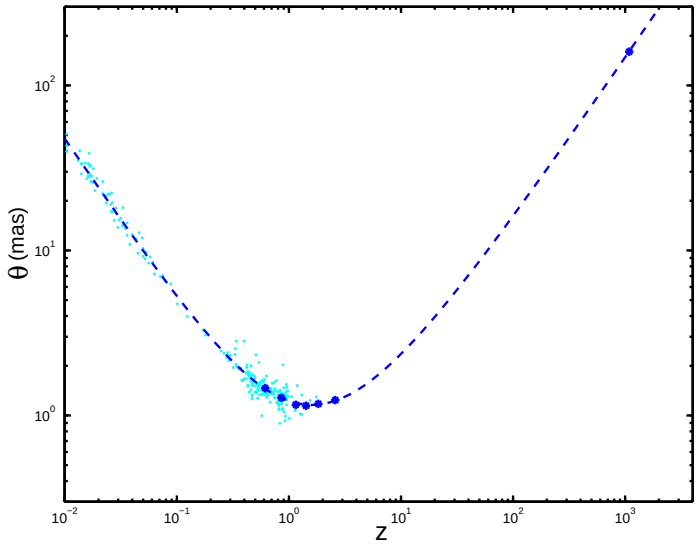
$$\theta(t) = \frac{d(t)}{L}$$

- Measuring brightness J for an object with known luminosity F “standard candle”

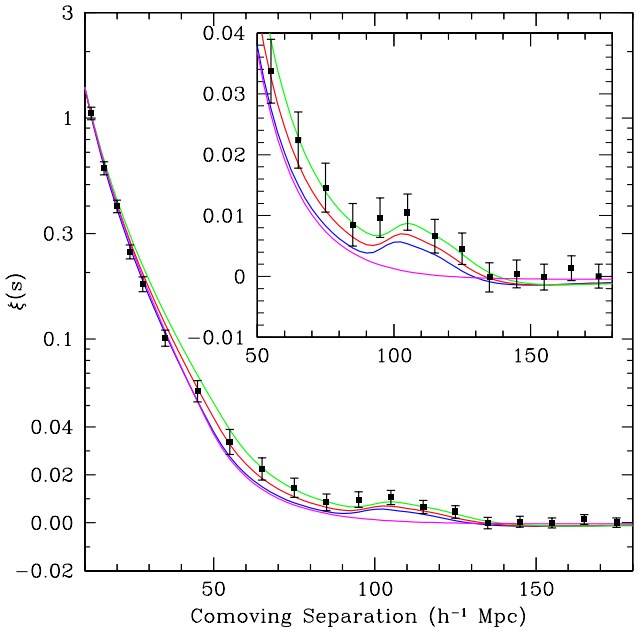
$$J = \frac{F}{4\pi\,L^2}$$

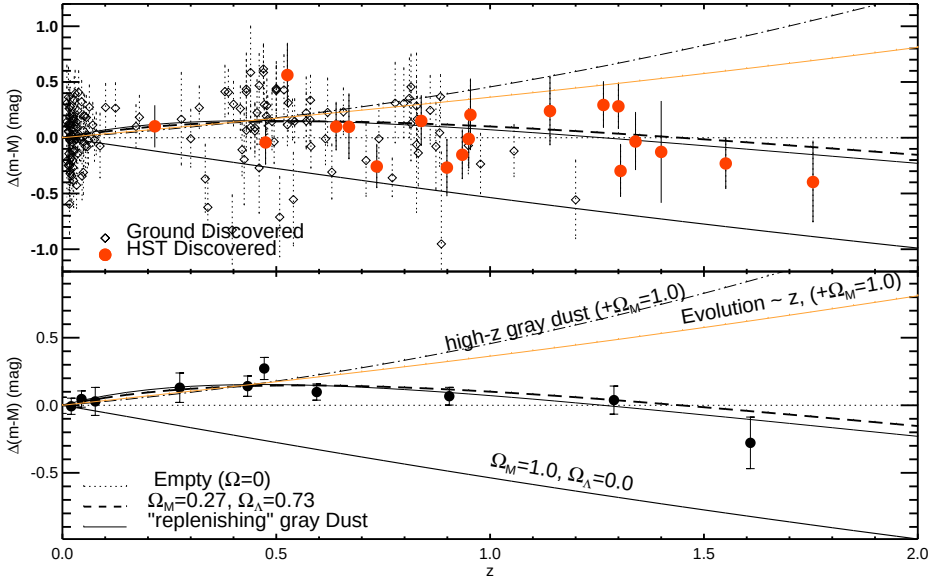
All the relations are modified in an expanding Universe

Results of the “length measurements”



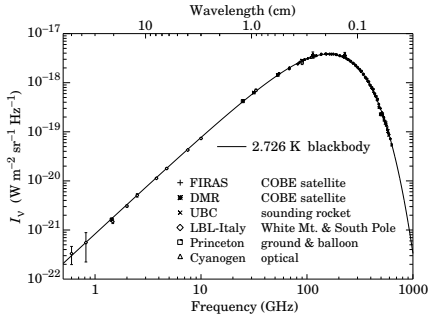
$$\Delta(m-M) = 5\log\frac{r_{ph}}{r_{ph}(\Omega_c = 0.8, \Omega_M = 0.2)}$$

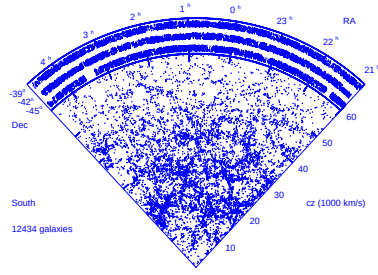


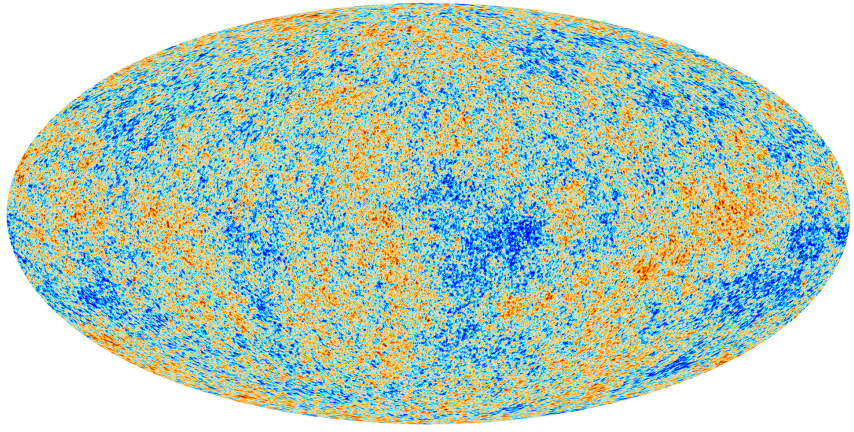


Dark matter and generation of structures

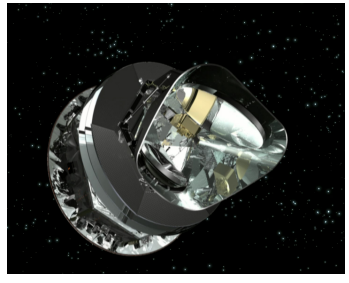
- Relic radiation is not completely isotropic.
  - Earth movement relative to CMB
$$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  - More complex anisotropies are there!
$$\frac{\Delta T}{T} \sim 10^{-4} - 10^{-5}$$
- Density of matter was inhomogeneous $\Delta\rho/\rho \sim \Delta T/T$ at recombination (formation of Hydrogen from plasma)
- Gravitational (Jeans) instability of a system of particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow \Longrightarrow$ galaxies
- Only baryons would not have done that on time! After recombination they “fall” into gravitational wells formed by Dark Matter.



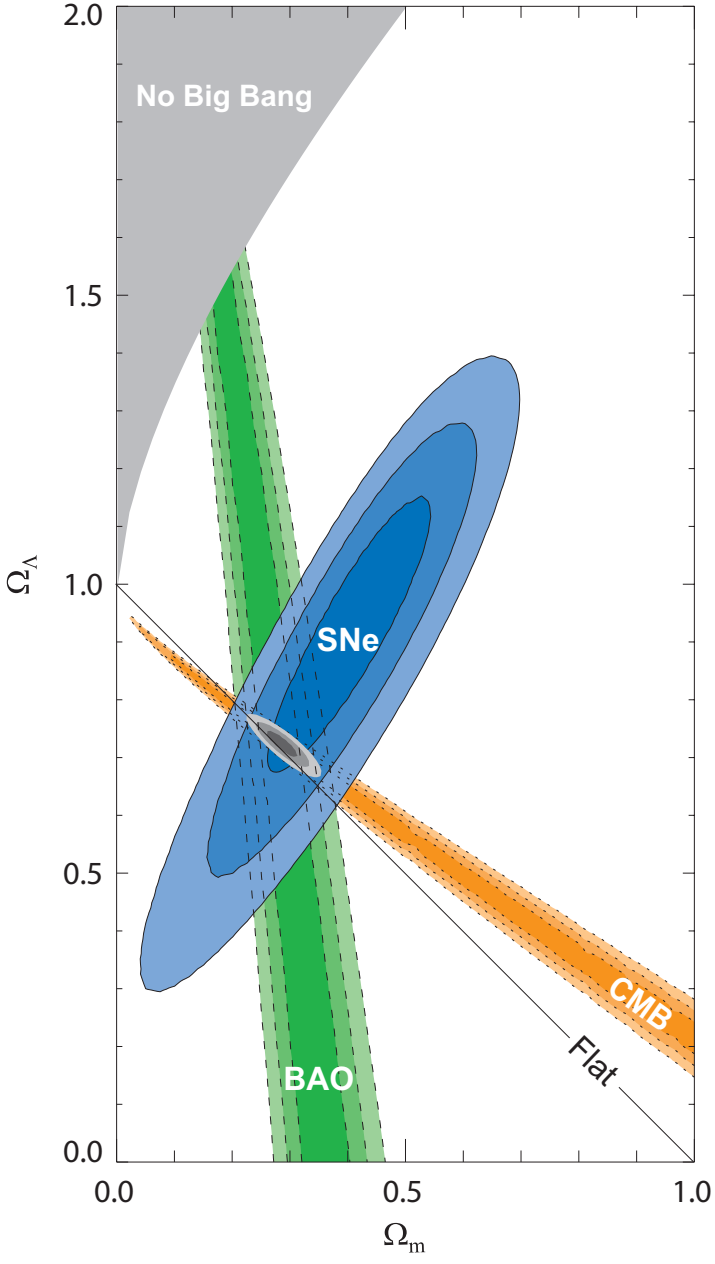




PLANCK satellite:



Cosmology data



- Estimate of the mass in galaxies, clusters and other structures
- Corrections to the Hubble law: relation between the redshift and light curves of the "standard candles" (SNe Ia)
- CMB anisotropies, structure distributions (BAO, etc.)

$$\rho^{\text{energy}}_{\text{density}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5} \, \frac{\text{GeV}\, c^2}{\text{cm}^3}$$

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

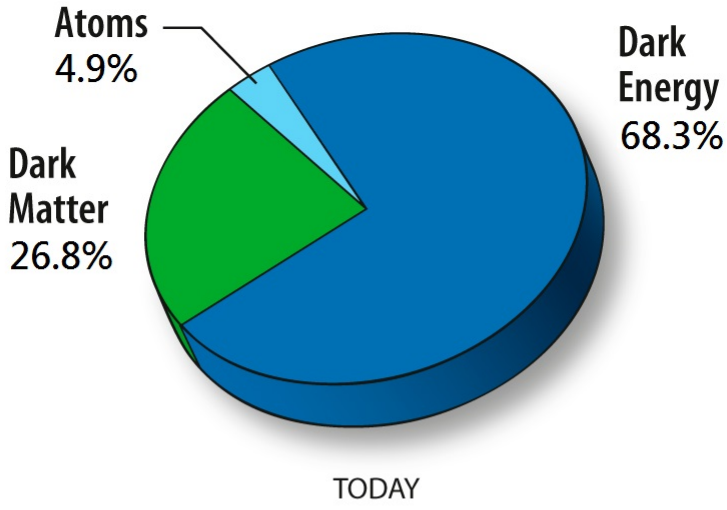
Baryon contribution (Hydrogen, Helium):
$\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.049$

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

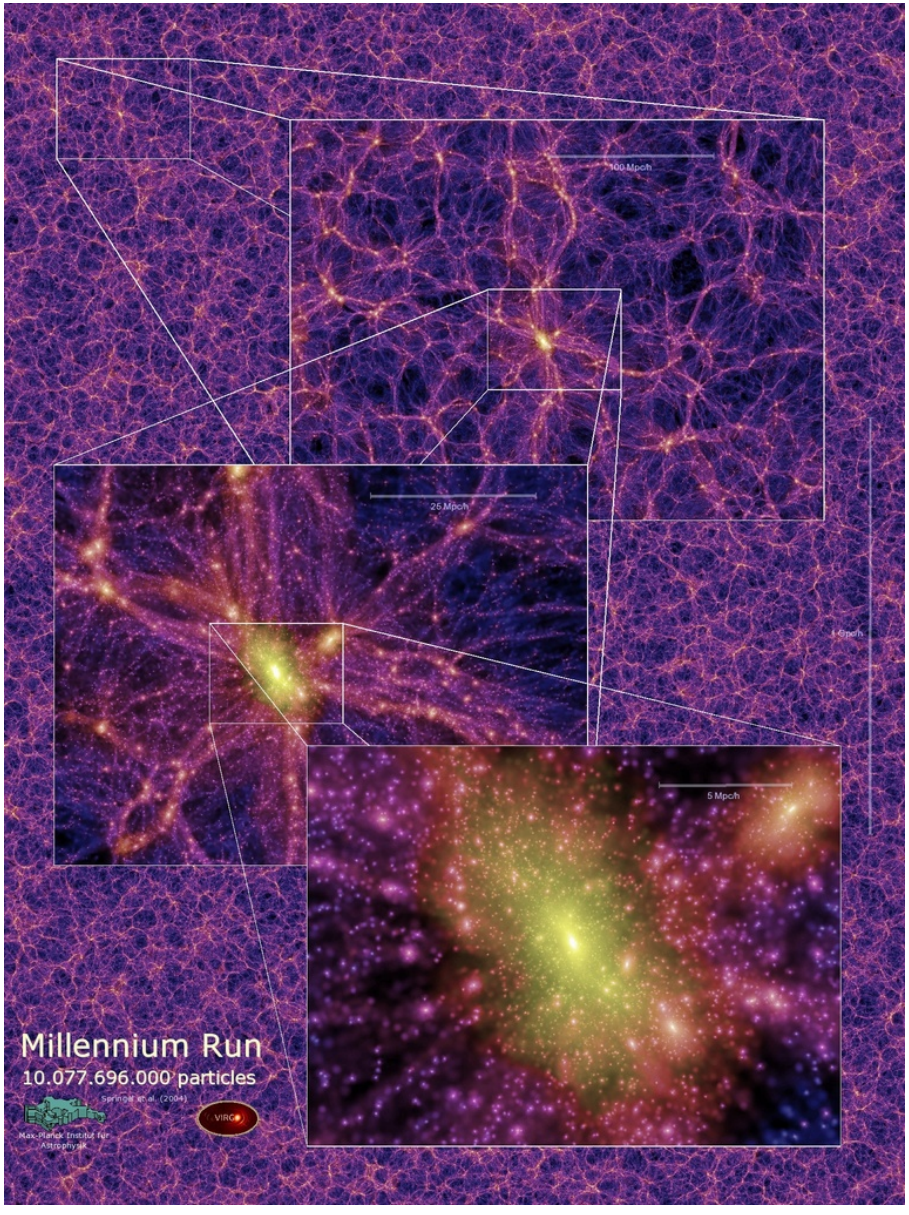
Dark Matter contribution: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

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

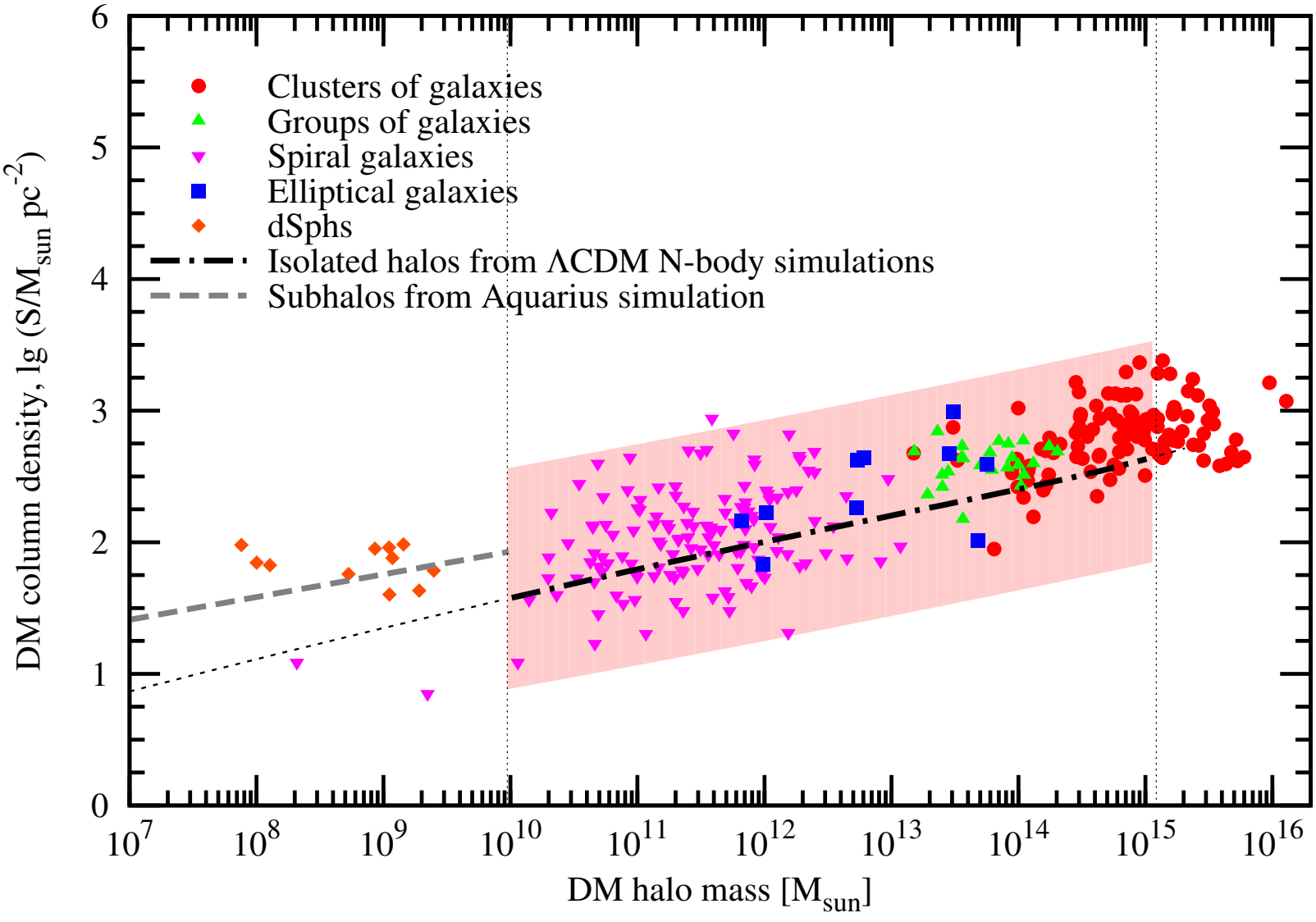
Universe energy balance changes with time



Simulations of the structure formation



DM simulations gives the observed structure distribution over 5 orders of magnitude



Plan

Particle Physics – Standard Model!

Our Universe – Today and in the past

- Astrophysics: Dark Matter in the Galaxies
- Astrophysics: Dark Matter in Galaxy Clusters
- Dark Matter and Cosmology

Particle physics realization

- Particle Dark Matter properties
- “Most natural” (or usual) candidate – WIMP
  - Searches for WIMPS
  - Direct searches of Dark Matter
  - Indirect searches – decay or annihilation of DM
- Sterile neutrino Dark Matter

Possible explanations

- Modification of Gravity/Modification of Newtonian Dynamics (MOND)
- Additional matter – Dark Matter
  - Elementary particles
    - Weakly interacting massive particles “WIMPs” } “found”!
    - sterile neutrino
    - axion
    - heavy relics
    - (Topological) defects
  - Large objects
    - Massive Astrophysical Compact Halo Objects (MACHOs)
    - Primordial black holes (remnants)

Properties of Dark Matter particles

Some new (non-baryonic) particle X

1. Stable on cosmological time scale ($t \gg 14$ billion years)
2. Non-relativistic (otherwise they escape from galaxies!
   Milky Way: $v_X \sim v_{\text{stars}} \sim 10^{-3}\, c \simeq 300$ km/s)
3. (nearly) collisionless
4. (nearly) neutral (electrically)

Quantum condition of localization in galaxies

For bosons – de Broglie wavelength

$$\lambda = h/(M_X v_X), \lambda \lesssim L_{\text{galaxy}} \quad \longrightarrow \quad M_X \gtrsim 3 \times 10^{-22}\,\text{eV}/c^2$$

For fermions –

Pauli principle: 1 state $\leq$ 1 particle $M_X \gtrsim 750$ eV/c^2

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

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Weakly Interacting Massive Particles (WIMPs)

Assumptions:

1. no $X - \bar{X}$ asymmetry $\qquad n_X = n_{\bar{X}}$
2. at $T < M_X$ the DM is in thermal equilibrium in the plasma Boltzmann distribution!

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

Then:

- The Universe is expanding $\Longrightarrow T \searrow, n_X \searrow$
- $T k \ll M_x c^2$: Stop being created, just annihilate

$$X + \bar{X} \longrightarrow \text{light Standard Model particles}$$

$$\tau^{-1}_{\text{annihilation}} \propto n_X$$

- annihilation stops at the temperature T_f, when

$$\tau^{-1}_{\text{annihilation}} \lesssim H$$

WIMPS $\rightarrow$ LHC

After freeze-out: $n_X(t) \propto a^{-3}(t)$

$X + \bar{X}$ contribution to the modern energy density:

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} \simeq 0.1 \times \left(\frac{0.01 \times \sigma_{\text{weak}}}{\sigma_{\text{annihilation}}}\right)$$

σ_{weak} — weak interactions — energy $E \sim 100$ GeV

$\sigma_{\text{annihilation}}$ — "super"weak interactions — energies $E \gtrsim$ 1-10 TeV

close scales — "natural" Dark Matter

naturally "light" for LHC

cross-section is not above the geometric one —

$\sigma_0 \lesssim \frac{h^2}{M_X^2 c^2} \longrightarrow M_X \lesssim 100$ TeV c^2

Find "natural" Dark Matter in LHC may be quite possible

WIMPs X interact with the matter!

- LHC searches for process with the "loss" of energy and momentum

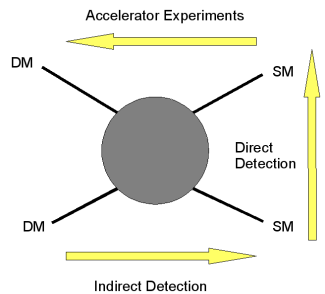
$$p + p \to X + \bar{X} + \text{usual particles}$$

- Laboratory searches of the processes "getting" energy and momentum

$$\text{Nucleus} + X \to \text{Nucleus} + X$$

- Search with "telescopes" of ordinary particles from annihilation or decay of the Dark Matter particles

$X + \bar{X} \to$ ordinary particles $\quad X \to$ ordinary particles



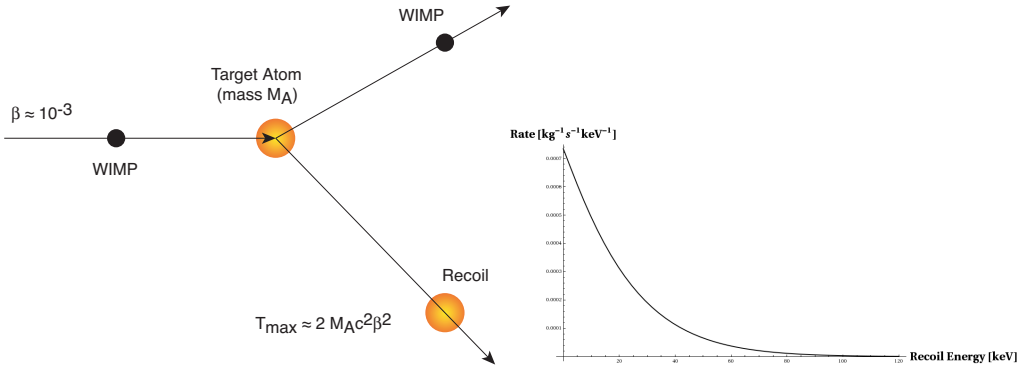
Direct WIMPs searches

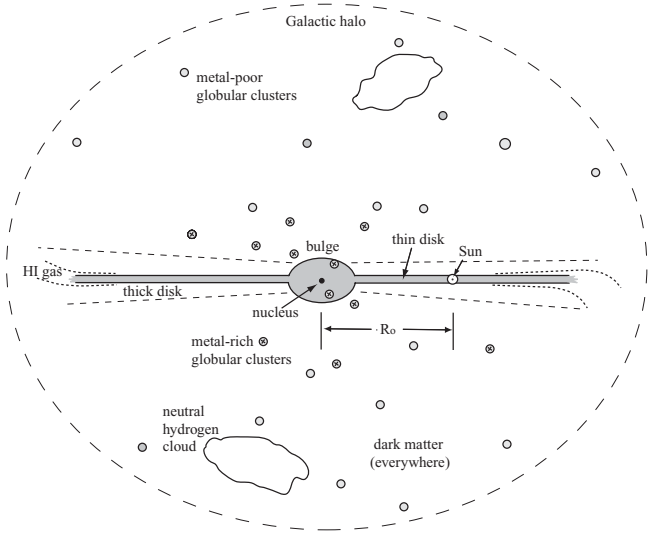
Laboratory searches "getting" energy and momentum

$$\text{Nucleus} + X \rightarrow \text{Nucleus} + X$$

Just non-relativistic kinematics of particles (nucleus at rest $v_X \sim 10^{-3}c$)

$$\Delta E = 2 M_X v_X^2 \frac{M_{\text{Nucleus}}/M_X}{(1 + M_{\text{Nucleus}}/M_X)^2}$$

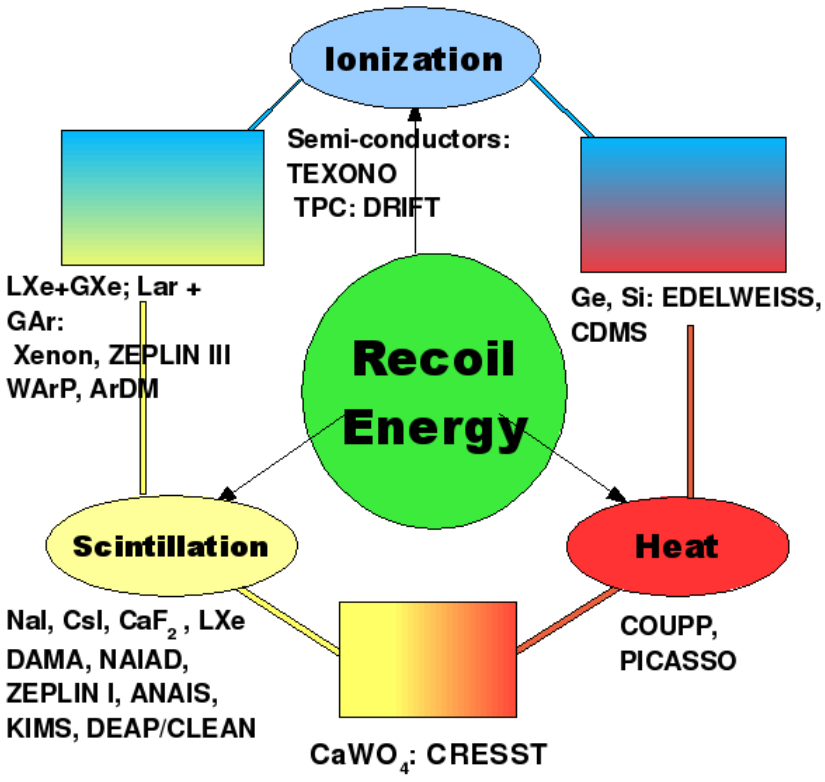




Methods of registration of the released energy

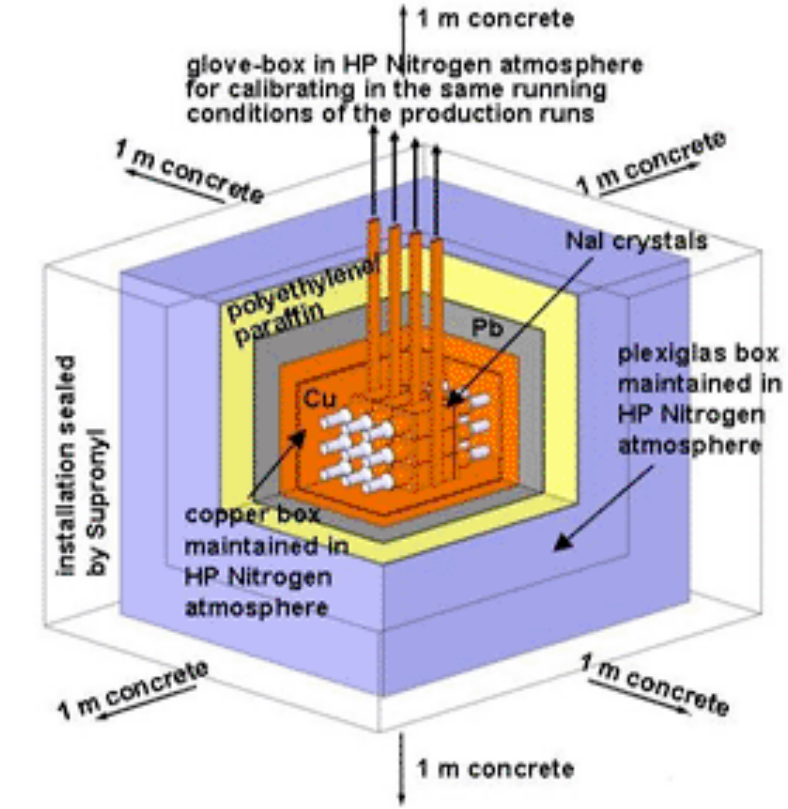
Different forms of “friction”!

- Heating of the detector material: conversion into heat
- Ionization of the detector material: registration of “detached” electrons
- Scintillation of the detector material: conversion into light

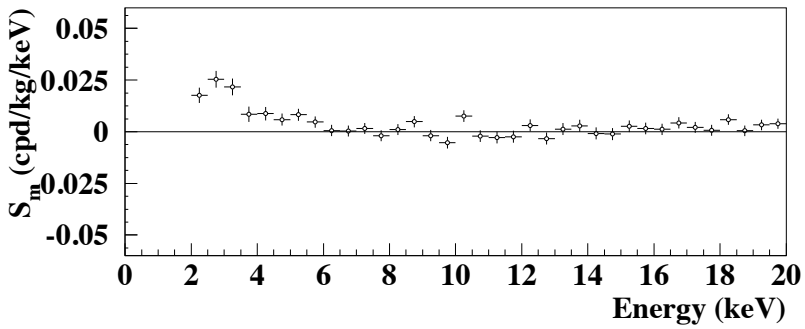


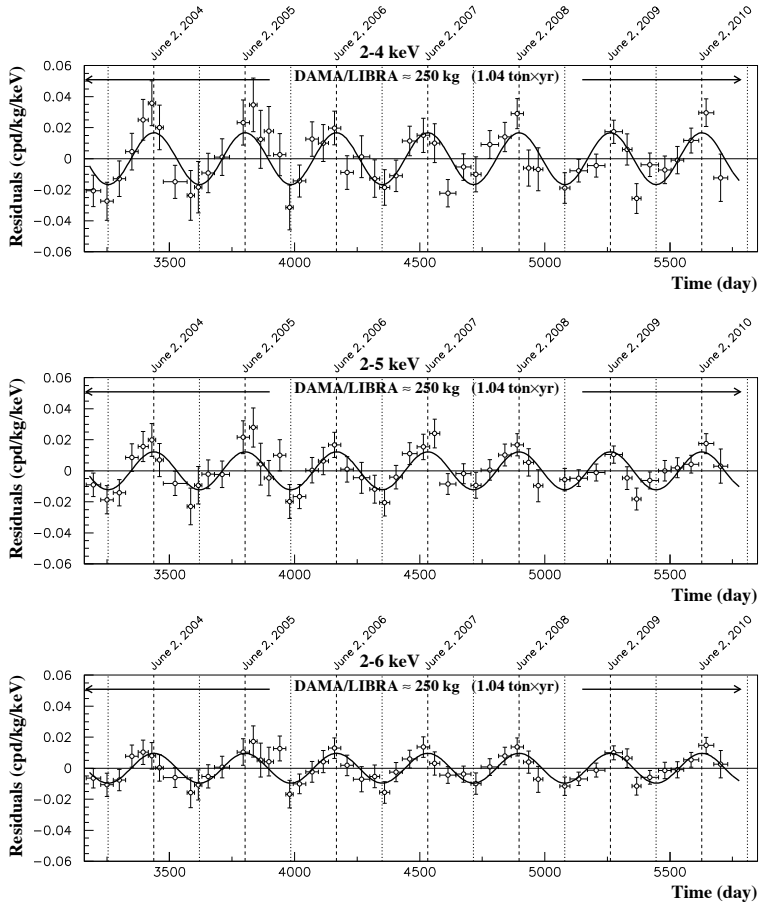
Dark Matter found (1) ! – DAMA/Libra

~ 10 GeV Dark Matter



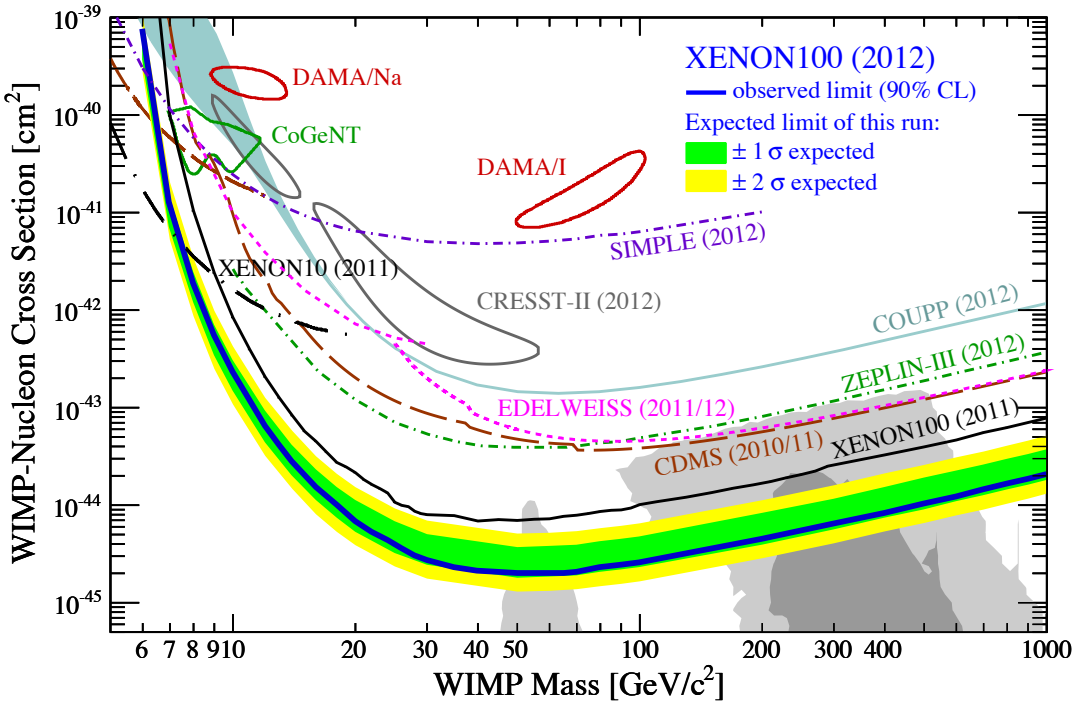
Simplified schema of ~ 100 kg NaI(Tl) set-up





Other did not: modern bounds

XENON-100, LUX



- $1\,\mathrm{pb} = 10^{-12}\,\mathrm{b}$, $1\,\mathrm{b} = 1\,\mathrm{barn} = 10^{-24}\,\mathrm{cm}^2$
- $\sigma_{WIMP-\mathrm{nucleon}} \lesssim 10^{-43}\,\mathrm{cm}^2$
- relation to LHC: predictions of concrete physical models
- Annual signal modulations…

To make things worse – CDMS ans CoGeNT saw DM, but for other parameters.

Indirect searches of DM

Annihilation in the galaxy halo $n_X(\vec{r}) = n_{\bar{X}}(\vec{r})$

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

photons ($\gamma\gamma$), neutrino ($\nu\bar{\nu}$), electrons (e^+e^-), …

Light particle flux $I_{e^+e^-}(\vec{r}) \propto \sigma^{X+\bar{X}\to e^+e^-}_{\text{annihilation}}\ n_X^2(\vec{r})$

Spectrum of relativistic particles in the decay point

$E_{e^+} = E_{e^-} = M_X c^2$

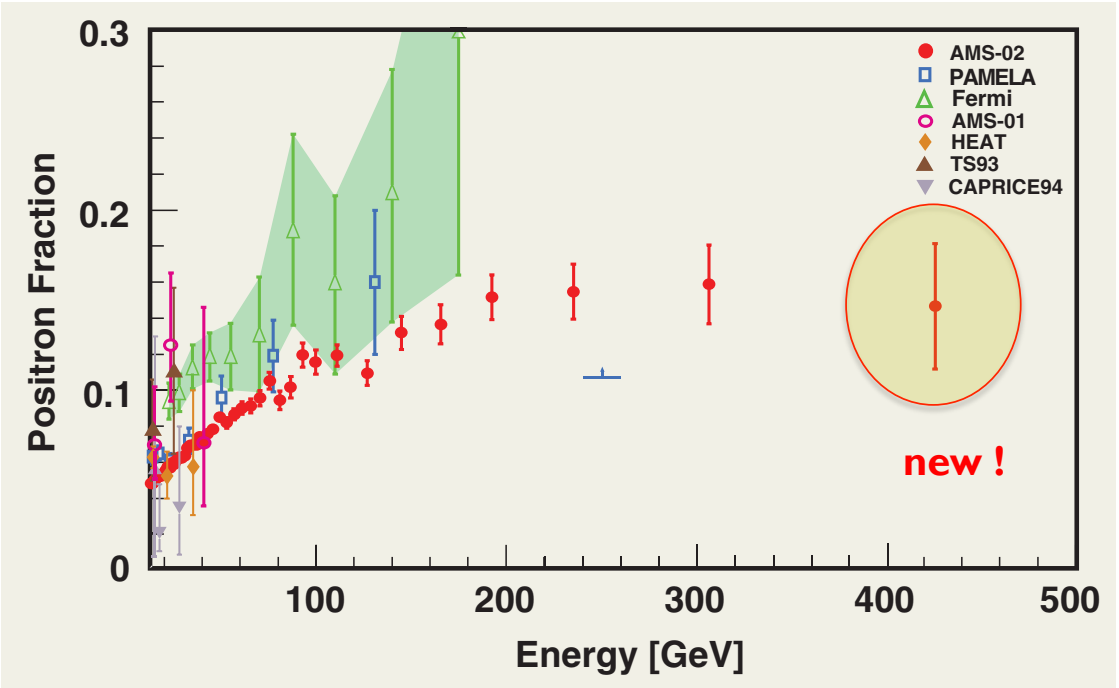
$X + \bar{X}$ contribution to the present energy density

$$\Omega_X = 2\frac{M_X n_X(T_0)}{\rho_c} \simeq 0.1 \times \left(\frac{0.01 \times \sigma_{\text{weak}}}{\sigma^{\text{full cross section}}_{\text{annihilation}}}\right)$$

- For any channel $\sigma^{X+\bar{X}\to e^+e^-}_{\text{annihilation}} \leq \sigma^{\text{full cross-section}}_{\text{annihilation}}$
- Look for regions with high density: Galaxy center, Dwarf galaxies, Sun, …
- Interactions in the galaxy: the spectrum is not monochromatic!

Dark Matter found (2) ! AMS and others …

∼ 200 GeV Dark Matter



Not monochromatic!

- Interactions in the galaxy
- fragmentation and decay

$$X + \bar{X} \rightarrow quark + antiquark \rightarrow \ldots$$

$$\rightarrow p\ ,\bar{p}\ ,\ \pi^0\ ,\ \pi^+\ \pi^-\ ,\cdots\rightarrow$$

$$\rightarrow p\ ,\bar{p}\ ,\ \gamma\ ,\ e^+\ e^-\ ,\nu\ \bar{\nu}$$

- Antiparticles should also be present!
- Usually also leptons, hadrons, and photons
- “Accompanying radiation” is expected (gamma, Roentgen, radio, etc.)
- Asymmetry should be present in arrival directions for neutrino, photons and secondary radiation
- Astrophysical contributions?

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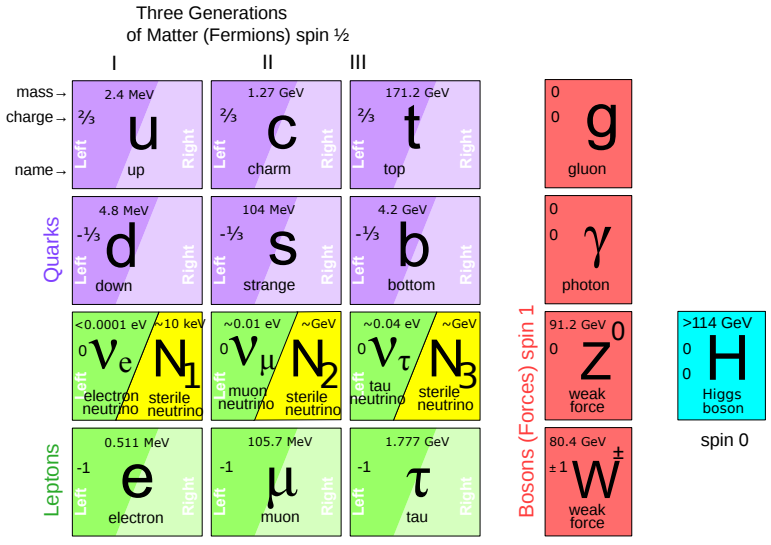
Best candidate – sterile neutrino Dark matter

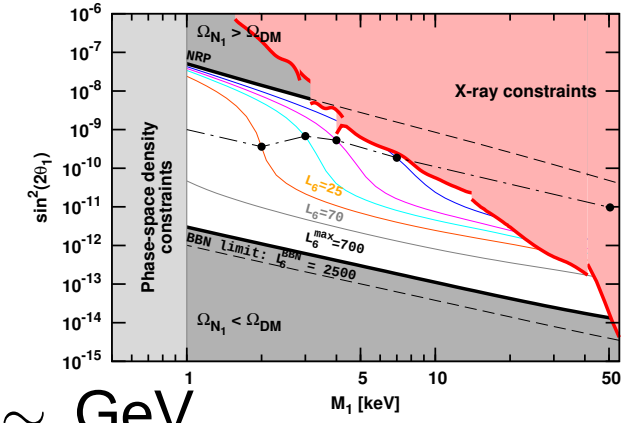
SM +



- DM sterile neutrinos are produced by oscillations from active neutrinos
- Two heavier sterile neutrino provide for the baryon asymmetry (via low scale leptogenesis)

Possible search for *ν*MSM neutrino in the lab and in the Universe

- DM sterile neutrino N_1, $M_1 \sim 1 - 80\,\mathrm{keV}$
  - X-ray line from the DM radiative decay $N_1 \to \nu\gamma$
  - Neutrinoless double beta decay $m_{ee} < 50 \times 10^{-3}\,\mathrm{eV}$



- Lepton asymmetry generating $N_{2,3}$, $M_{2,3} \sim$ GeV
  - Neutrino production hadron decays: kinematics
    - Missing energy in K decays
    - Peaks in momentum of charged leptons for two body decays
  - Neutrino decays into SM particles: “nothing” to leptons and hadrons
    - Beam target experiments with high intensity proton beam, detector (preferably not dense) after the shielding.

Search for the line in X-rays

Two groups studying the results of X-ray satellites found an unidentified line at 3.5 keV

- seen by two different satellites (XMM-Newton and Chandra)
- seen in several objects with different astrophysical composition
  - Andromeda galaxy (M31)
  - clusters: Perseus, Centaurus+Ophiuchus+Coma, and more
- the line has proper redshift for different sources
- the intensity is (more or less) consistent the Dark Matter profiles and abundances in the objects
- the line is absent in the blanc sky observations
- two groups use complementary datasets (even for the Perseus cluster)

Bulbul, Markevitch, Foster, Smith et.al.'14, Boyarsky, Ruchayskiy, Iakubovskyi, Franse'14

Dark Matter found (3) !

7 keV Dark Matter

Line in Andromeda galaxy observations

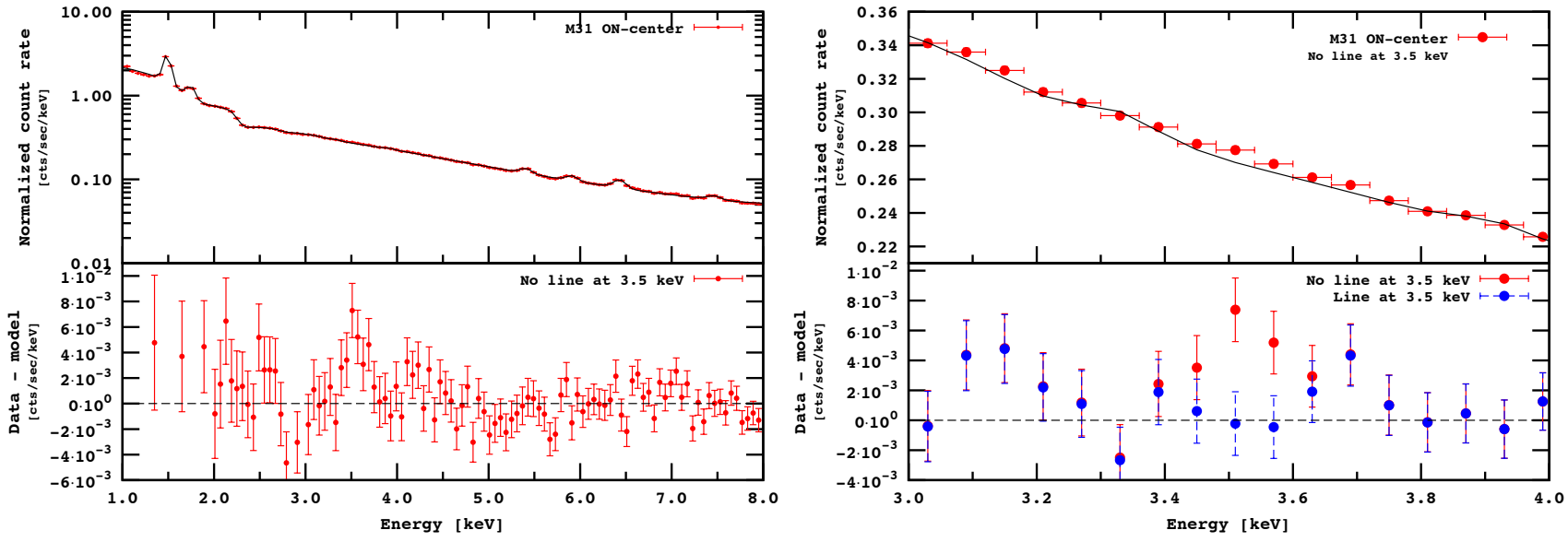
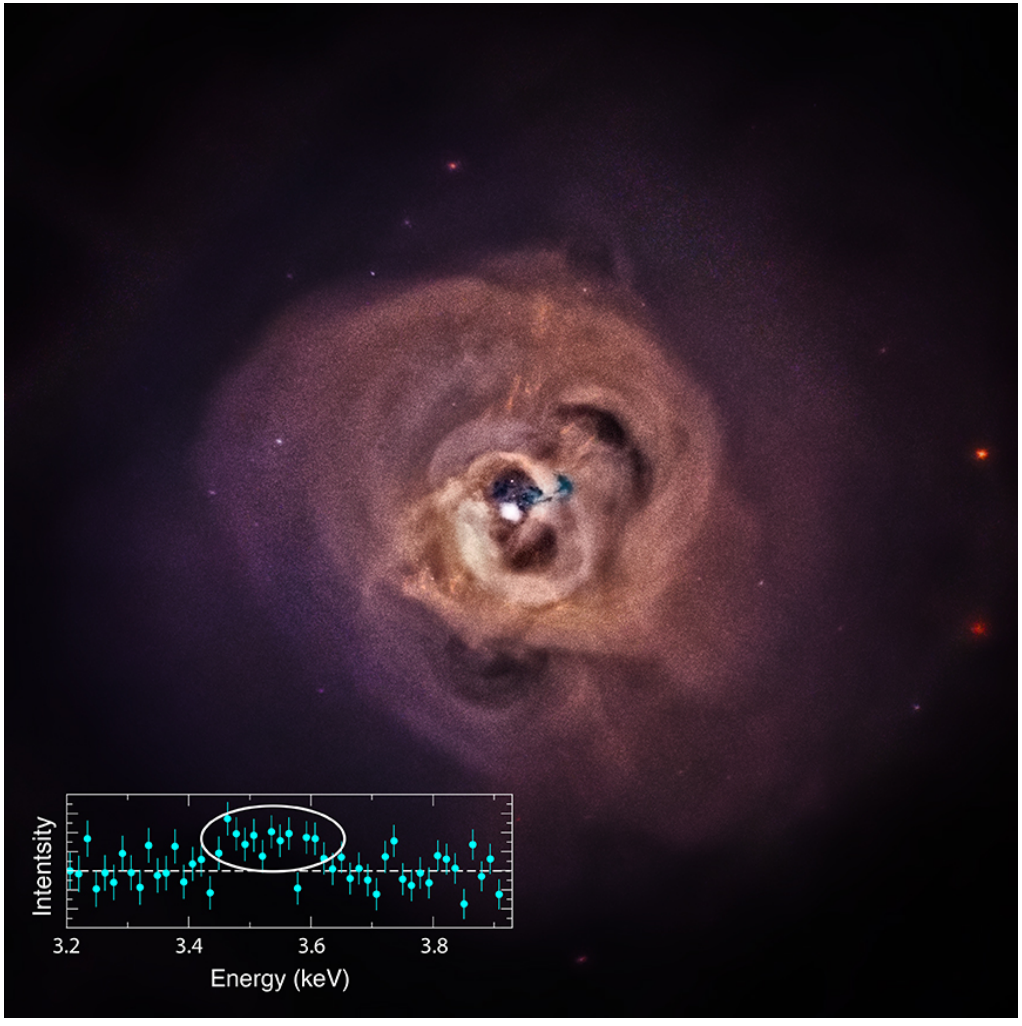
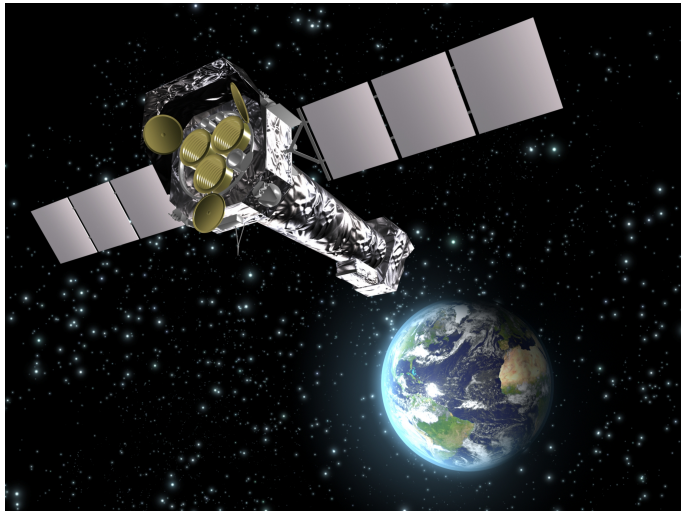


FIG. 1: *Left:* Folded count rate (top) and residuals (bottom) for the MOS spectrum of the central region of M31. Statistical Y-errorbars on the top plot are smaller than the point size. The line around 3.5 keV is *not added*, hence the group of positive residuals. *Right*: zoom onto the line region.

Signal from the Perseus cluster

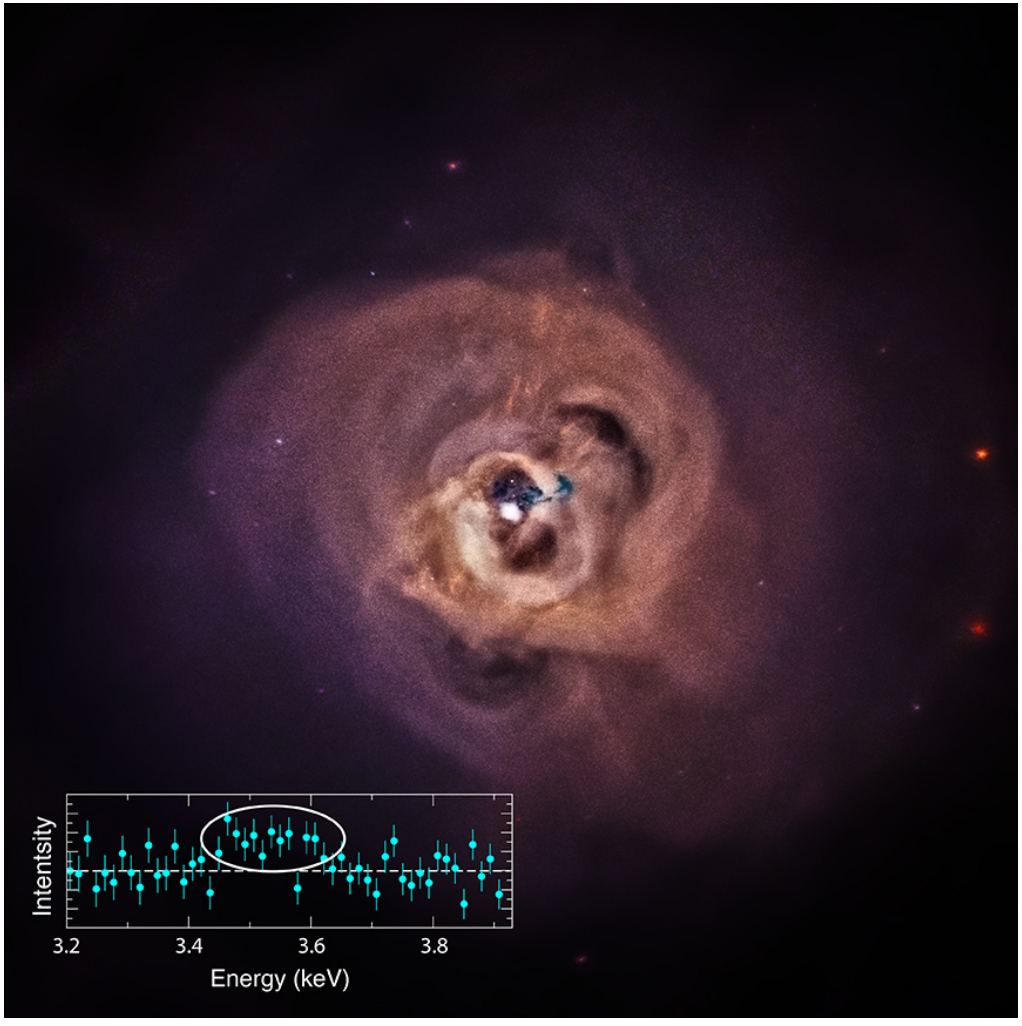


XMM-Newton satellite:

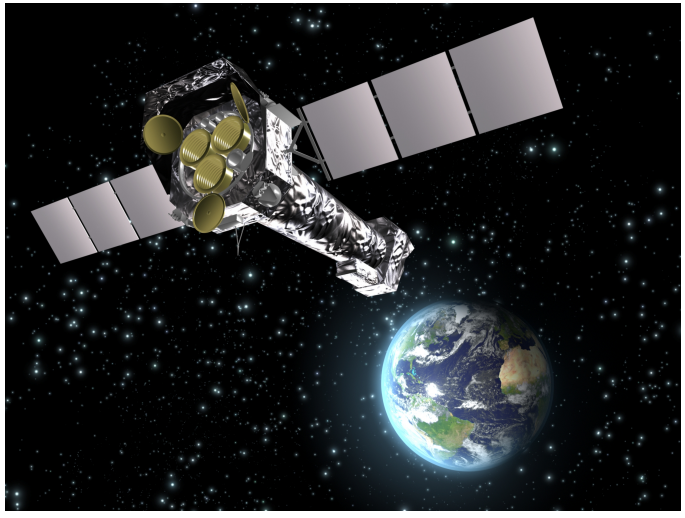


Chandra:

Signal from the Perseus cluster



XMM-Newton satellite:



Chandra:

Spectrum: Perseus and stacked cluster spectrum

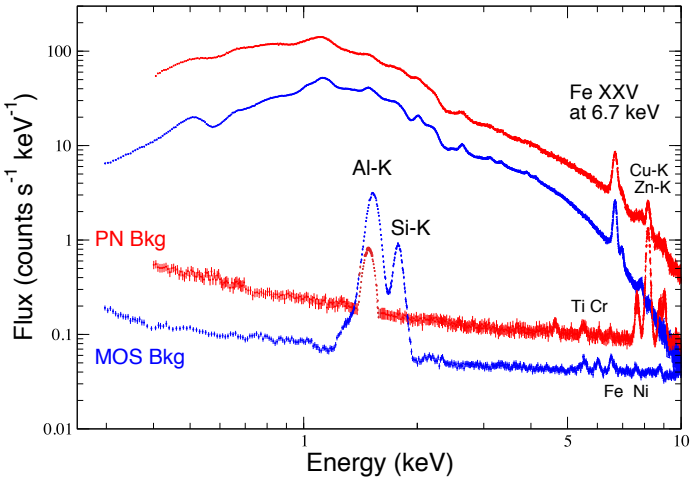


Figure 2. *XMM-Newton* MOS and PN background subtracted source spectra and particle background spectra for the Perseus cluster. The spectra were obtained by co-adding the observations of the cluster in the cluster's rest frame. In the co-added scaled spectra, the Fe XXV line is located at its rest energy, ~ 6.7 keV. Energy of background and instrumental lines are blue-shifted according to the cluster's redshift.

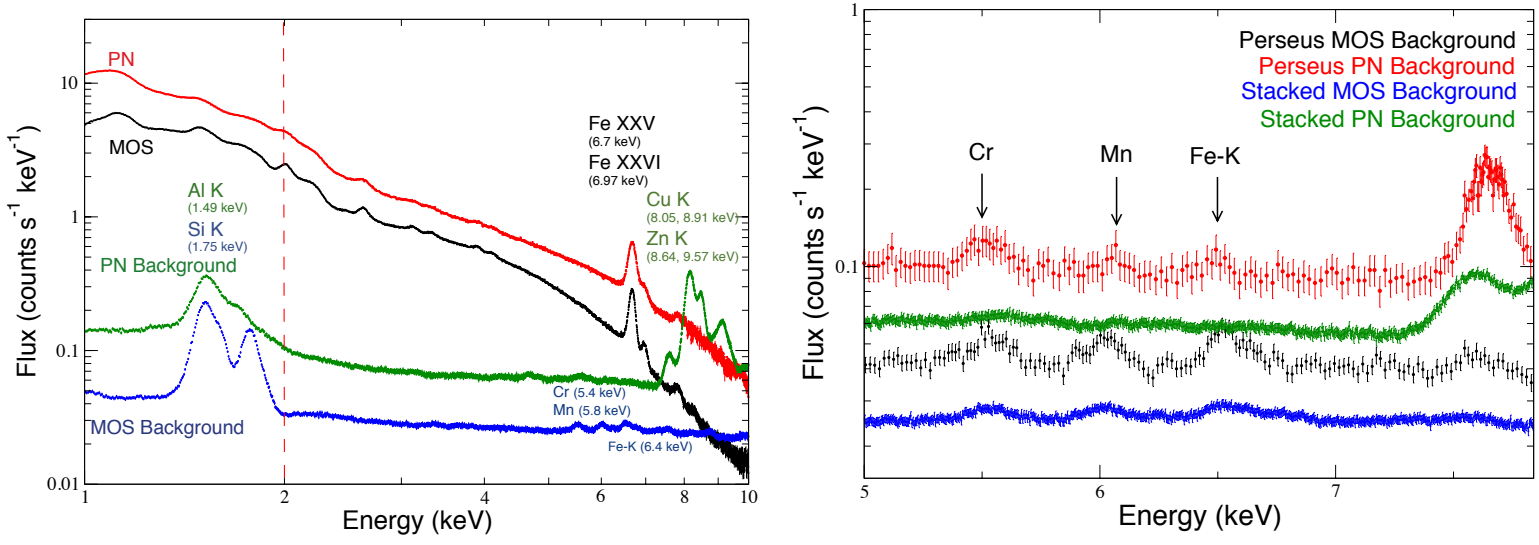
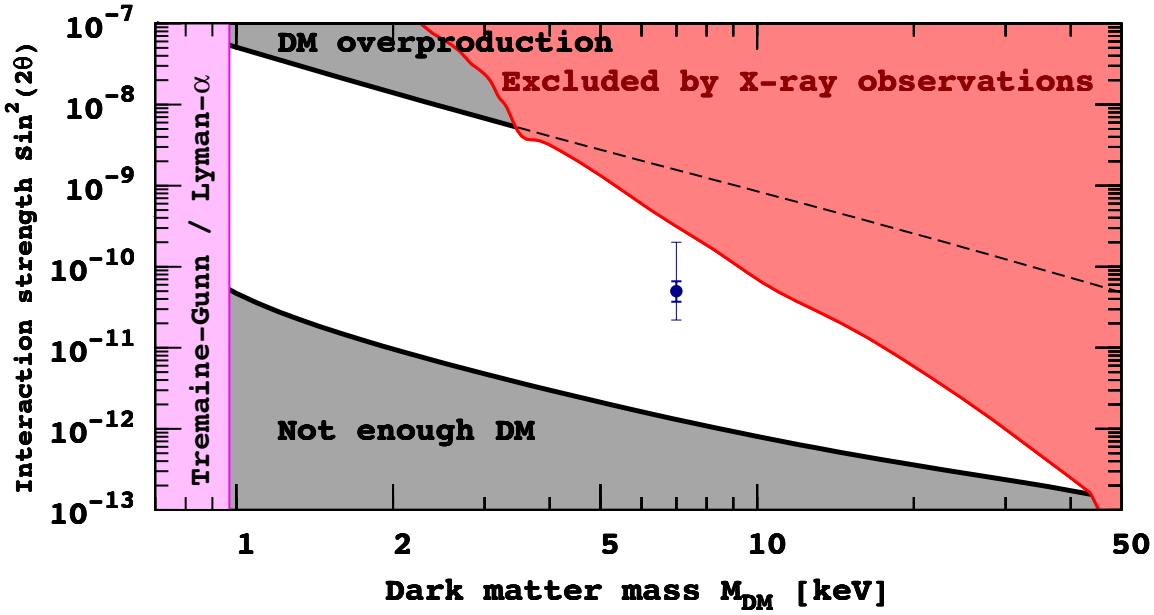
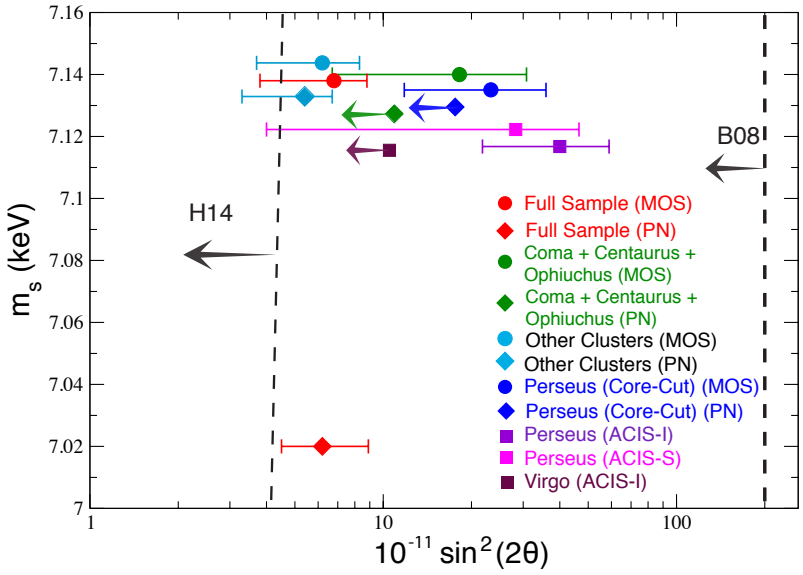


Figure 3. Left Panel: Stacked *XMM-Newton* MOS and PN background-subtracted source spectra and particle background spectra of the full sample. The spectrum of each observation was scaled to the rest frame prior to stacking. The total filtered exposure time was 6 Ms for MOS and 2 Ms for PN. The background MOS (in blue) and PN (in green) spectra show the effect of smearing of instrumental lines, such as Cr, Mn, Fe and Ni, as well as Al-K and Si-K fluorescent lines. The effect is due to the stacking of background spectra which are scaled by different cluster redshifts. **Right Panel:** Close-up view of $5.0 - 8.0$ keV band of the background *XMM-Newton* MOS and PN spectra of the Perseus cluster compared to the stacked *XMM-Newton* MOS and PN background spectra. The background lines are less prominent in the stacked background spectra than in the single source background spectra.

Sterile neutrino N_1 parameters would be



Controversy and future



- Current status: A lot of discussion, mainly excluding the DM interpretation by not seeing the line from some objects

Next?

Take a better satellite (better energy resolution and sensitivity) and check that the signal follows the DM distribution

- All galaxies, clasters, etc., Milky Way halo

ASTRO-H! 2015?

Dark Matter: Other candidate searches

- WIMPs (neutralino, …) — recoil energy, missing energy
- sterile neutrinos — sharp line: $\nu_s \to \nu_a + \gamma$, (XMM, INTEGRAL, …)
- light scalar field
- axion — oscillations $a + \mathbf{B} \to \gamma$
- gravitino — missing energy at LHC, …
- Heavy relics — if unstable — Cosmic rays
- (Topological) defects — lensing of CMB
- Massive Astrophysical Compact Heavy Objects — microlensing
- Primordial black hole remnants — Cosmic rays

Вместо заключения

Темная материя	WIMPs	Прямой поиск, поиск на ускорителях
Темная материя	стерильные нейтрино (*v*MSM)	наблюдение в X-лучах
Барионная асимметрия	Лептогенезис (*v*MSM)	редкие распады
Инфляция	Хиггс инфляция	Ограничение на массу бозона Хиггса
Инфляция	лекгий инфлатон	Поиски на LHCb, SHiP

И множество других примеров!