More compelling evidences of the presence of Dark Matter

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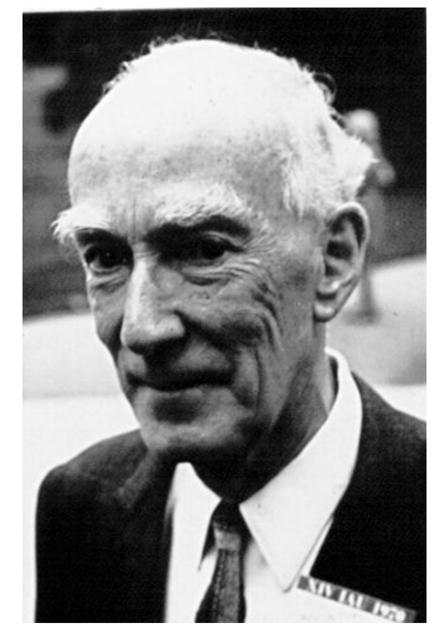
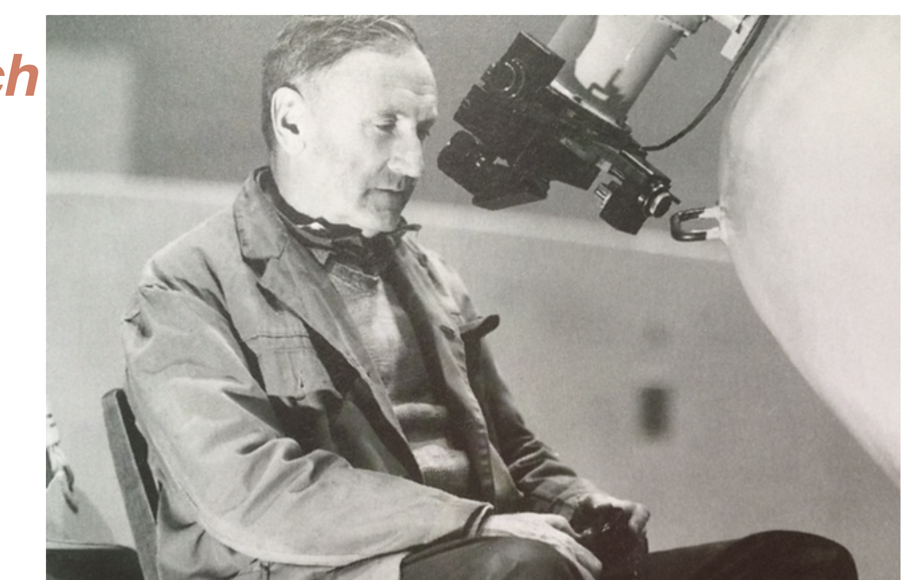
Dark matter: a brief history

- **1922: Jacobus Kapteyn** coined the name *'dark matter'.* In his studies of stellar motion he realized that MW rotates as contrary to the common believe where stars were thought to move randomly. (He thought there was dark matter around the Sun, later on happened to be not true)



- **1932: Jan Oort** determined the MW center of rotation and showed that was not the Sun. He claimed that there was more dark than visible matter in the vicinity of the Sun *(later the result turned out to be wrong)*

- **1933: F. Zwicky found *'dunkle Materie'* in the Coma cluster - *the redshift of galaxies were much larger than the escape velocity due to luminous matter alone***



Rotverschiebung extragalaktischer Nebel. 125

Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Historical arguments from Fritz Zwicky

only require to know F=ma applied to nebula (at the time the galaxy were named nebulae)
In particular he applied his consideration to the COMA cluster.

$$\vec{r}_i \cdot \left(M_i \frac{d^2 \vec{r}_i}{dt^2} = \vec{F}_i \right)$$

$$\Theta \equiv \sum_i M_i r_i^2$$

Polar moment of inertia.

$$Vir \equiv \sum_i \vec{r}_i \cdot \vec{F}_i$$

Virial of the cluster

$$\frac{1}{2} \frac{d^2 \Theta}{dt^2} = Vir + 2K_T$$

It fluctuate around a constant value and its time derivatives vanishes in stationary conditions

Assuming that the Newton law describe properly the gravitational interaction in the "nebulae"

$$\overline{Vir} = \overline{\mathcal{U}} = -\sum_{i<j} G_N \frac{M_i M_j}{r_{ij}}$$

$$-\overline{\mathcal{U}} = 2\overline{K_T}$$

Self energy

$$\mathcal{U} = -G_N \frac{3M^2}{5R_{tot}}$$

$$\sum_i M_i \overline{v_i^2} = M_{tot} \overline{\overline{v^2}}$$

U, is the potential energy of a uniformly dense sphere. Double bar stands for averaging on time and over "nebula velocity distribution. Thus the mean on time and on all elements of the sum of v^2 tells us how much matter is contained in the sphere inside the radius at which we are measuring.

$$M_{tot} = \frac{5R_{tot} \overline{\overline{v^2}}}{3G_N}$$

The comparison of M_{tot} and the mass of the cluster of galaxies in the COMA cluster showed a striking discrepancy.

Textbook: Particle Dark Matter, S. Profumo

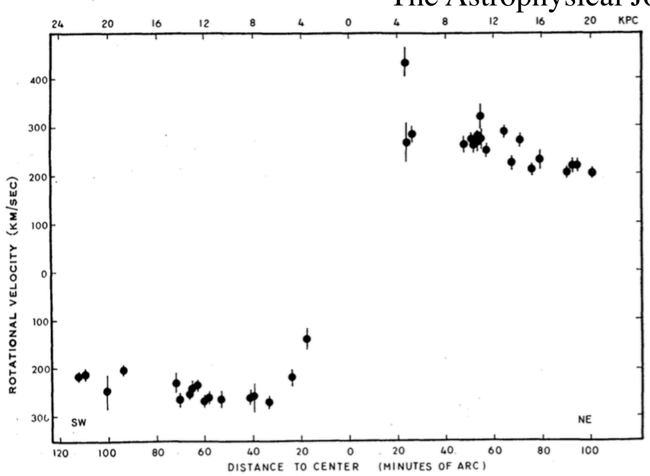
What Vera Rubin did?

She repeated Zwicky's "exercise" with more precise measurements for stars velocity at the galaxy scale thanks to the advent of radio telescope. The circular velocity of stars was measured by means of the line 21 cm observation of the hyperfine transition of neutral hydrogen. With the assumption of axisymmetric galaxy and by measuring the distance from the axis by means of red/blue-shift, and with some assumptions one obtains:

Vera Rubin measurement

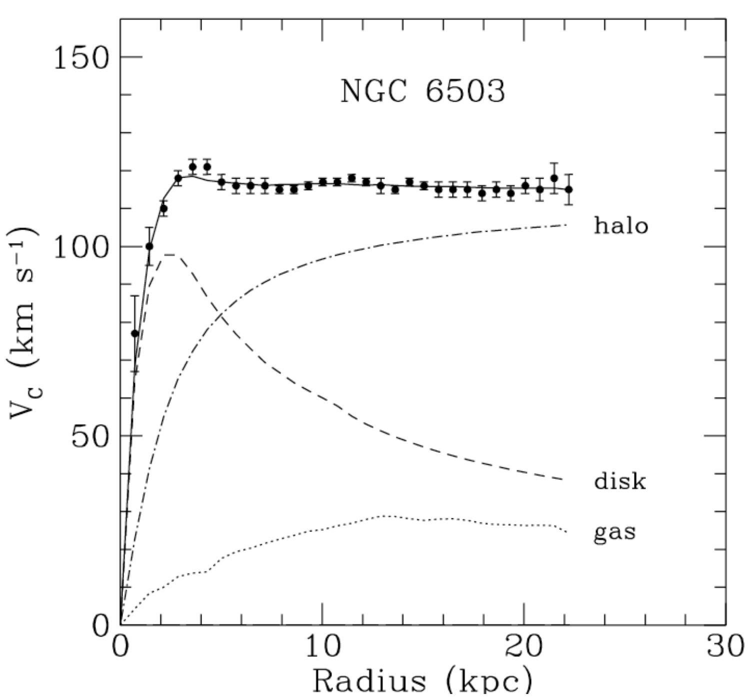
ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS

The Astrophysical Journal, Vol. 159, February 1970



$$v_c^2(r) = \frac{G_N M(r)}{r}$$

Keplerian fall-off. The absence of this phenomenon was believed to be due to lack of precision in the measurements. Only in 1970 it was definitively assessed and interpreted as due to missing matter, i.e. Dark Matter.



Picture of NGC 6503 spiral galaxy, from *Begeman at al, 1991*, curtesy from G. Plante thesis.

The observation can be accomodate by assuming an homogeneous sphere of constant density of radius R then:

$$v_c(r) = \sqrt{\frac{4\pi G_N \rho}{3} r} \qquad (r \leq R)$$

Most of the Spiral galaxies do not show the Keplerian fall-off

1970 Freeman, APJ 160 (1970) 811, made the hypothesis of missing mass to explain the absence of Keplerian fall-off. Something that is not stated enough is that the elliptical galaxies do not show Dark Matter or maybe we did not find yet a way to point out the presence of Dark Matter in them.

$$\rho(r) = \frac{1}{4\pi r^2}\frac{dM(r)}{dr} = \frac{v_c^2}{4\pi G_N r^2}$$

This makes a spherical dark halo which imply linear increase of total mass as function of distance form the rotation centre and a flat rotation curve

$$\rho(r) = \frac{\rho_0}{1+(r/a)^\gamma} \qquad \gamma = 2$$

Isothermal spherical profile, where a is the characteristic linear scale of the system and it is also the turning point of the density function.

One more mechanical argument to support the DM hypothesis

Gravitational instability of spiral galaxies

Numerical work, since 1970, had shown that self-gravitating disk tends to quickly form bars (“bar instability”) unless the rotational energy T w.r.t. to the potential energy is quite small or the random kinetic **Π** energy is very large w.r.s. to the potential . Thus indicating with t

$$t = T/|\mathcal{U}|$$

$$t < t_{crit} = 0.14 \pm 0.02 \quad or \quad \Pi/\mathcal{U} \geq 5$$

Stability conditions of Ostriker and Peebles which states that either the galaxy has very large potential energy compared to the rotational one or the energy dispersions is very large compared to the potential energy.

To cure bar instability the disk must be embedded in a dark halo whose mass is equal or larger than that of the disk. Actually there are other way to supper the bar instability assuming the most part of the mass of the galaxy is in the center of the galaxy. In this case the rotational curve near the galactic center is steeper.

Key definitions for understanding expanding Universe

Friedmann equation

and the energy density of the Universe

The evolution of the Universe is described by the solution of Einstein's equations of General Relativity. What nowadays goes under the name of Standard Cosmological model is the solution proposed by Friedmann-Lamaitre-Roberston-Walker (FLRW) in which the Universes is assumed to contain a completely homogeneous and isotropic distribution of matter and radiation which is behaving like a perfect frictionless fluid (Cosmological principle). These assumptions plus the energy conservation are sufficient to fix the evolution equations of the Universe. Robertson-Walter had shown on 1930 that the most general metric describing an expanding homogeneous and isotropic Universe is defined by the four distance:

$$dl^2 = (cdt)^2 - \left(\frac{dr^2}{\sqrt{1-K(t)r^2}}\right) - (rd\theta)^2 - (r\sin\theta d\phi)^2$$

At this point makes sense to use the coordinates well defined in the reference frame where Universe is expanding, thus in the comoving reference frame r(t)=R(t)x and K(t)=k/R²(t) with k=-1,0,1. The sign of K depends on the total energy content and also the sign or the curvature of the spatial part of the space-time.

$$dl^2 = (cdt)^2 - R^2(t)\left[\frac{dx^2}{\sqrt{1-kx^2}} - (xd\theta)^2 - (x\sin\theta d\phi)^2\right]$$

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho_{tot}}{3} - \frac{kc^2}{R^2}$$

Friedmann equation describes the evolution of the expansion parameter R=R(t). **ρ** , i.e. energy density of the Universe, contains contributions from matter, radiation and vacuum. k is a pure curvature term which makes the difference between flat Euclidean space and and the curved space of GR.

Few words on the uniformity of the Universe. It is uniform in the same sense in which the gas in a large volume is uniform with respect the molecules size. Whatever was the Universe in the early time nowadays it shows large fluctuations in density in form of galaxies and large structures. The mean separation among galaxies is of the order of 100 times their diameter and the evolution of billions of galaxies over large scale is still described by the FLRW model. The best evidence of the homogeneity and uniformity of the Universe is the observation of the Cosmic Microwave Background which reflects the distribution of matter and radiation as it was produced when the Universe was only 350000 y old (present age of the Universe is 14 Gyr).

Critical energy density

For the case k=0 the Friedmann equations gives the critical density which corresponds to the limit above which the Universe will be closed

$$\rho_c = \frac{3}{8\pi G_N} H_0^2 = 9.2 \times 10^{-27}\ kg\ m^{-3} = 5.1\ GeV\ m^{-3}$$

The ratio between the actual density and the critical one define the closure parameters Ω

$$\Omega = \frac{\rho}{\rho_c} = 1 + \frac{kc^2}{[H_0 R(0)]^2}$$

The different contributions to the total value of $\Omega = \Omega_m + \Omega_r + \Omega_V$ come from matter, radiation and vacuum, respectively.
For k not zero the curvature term can be defined as $\Omega_K = \rho/\rho_k = -kc^2/[H_0\ R(0)]^2$ and from the previous equation $\Omega + \Omega_K = \Omega_m + \Omega_r + \Omega_V + \Omega_K = 1$

At present time $\Omega_r = 5 \times 10^{-5}$ and it is completely negligible with respect to matter contribution. To anticipate some results:

Hubble expansion

In 1929 Hubble while observing the spectral lines of distant galaxies realised that the lines of the spectrum were shifted towards red end of the spectrum and the amplitude of the shift were depending on the apparent luminosity, i.e. distance. This red-shift was interpreted as due to a Doppler shift so by measuring the recession velocity of galaxies

$$\lambda^{'} = \lambda\sqrt{\frac{1\beta}{1-\beta}} = \lambda(1+z)$$

$$z = \frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

$$H_0 = 72\ Km\ s^{-1}Mpc^{-1}$$

Hubble law

$$1\ Mpc = 3.09 \times 10^{19}\ km$$

$$v = H_0 r$$

Friedmann theoretical prediction confirmed by empirical Hubble law

The distance is measure by means of apparent luminosity: $F = \frac{L}{4\pi D_L^2}$

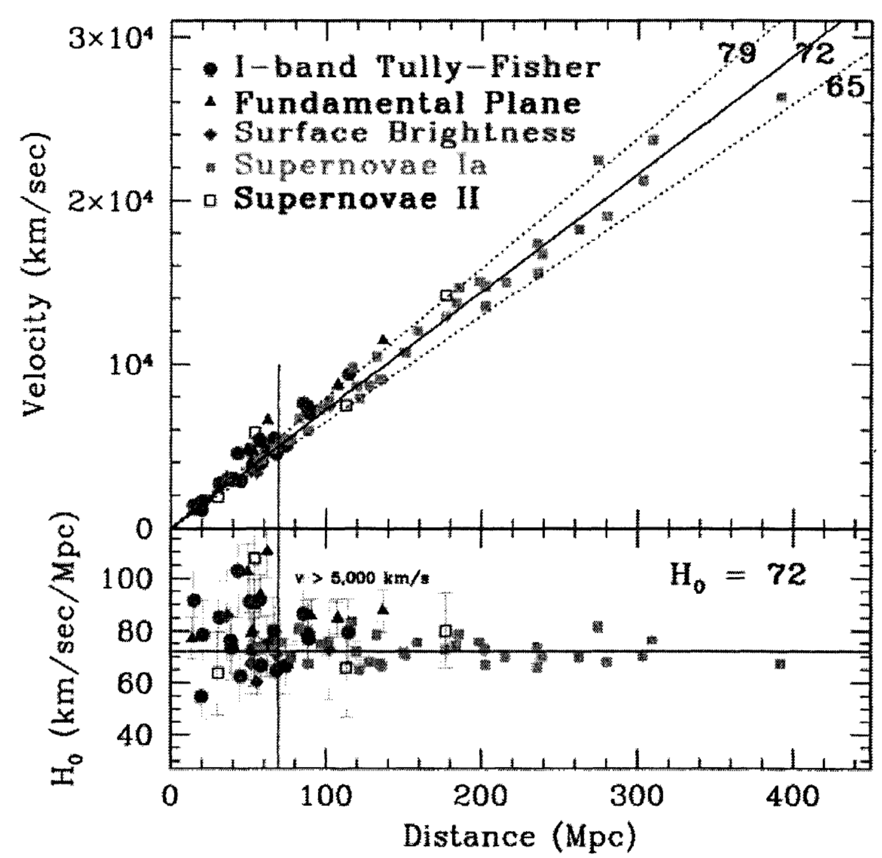
Thus it appears clearly that if the expansion rate of the universe is changing and the rate over the value of the scale fact R is given by the H_0 where 0 stands for value as measure today, we will see that also H changes too and this has strong consequences.

The actual Hubble low holds for the expansion rate of the Universe:

$$r(t) = R(t)r_0$$

$$R(t) = \frac{R(0)}{1+z}$$

$$\dot{R}(t) = HR(t)$$



S. Dodleson, Modern Cosmology

Dark Energy from Hubble plot at high red shifts

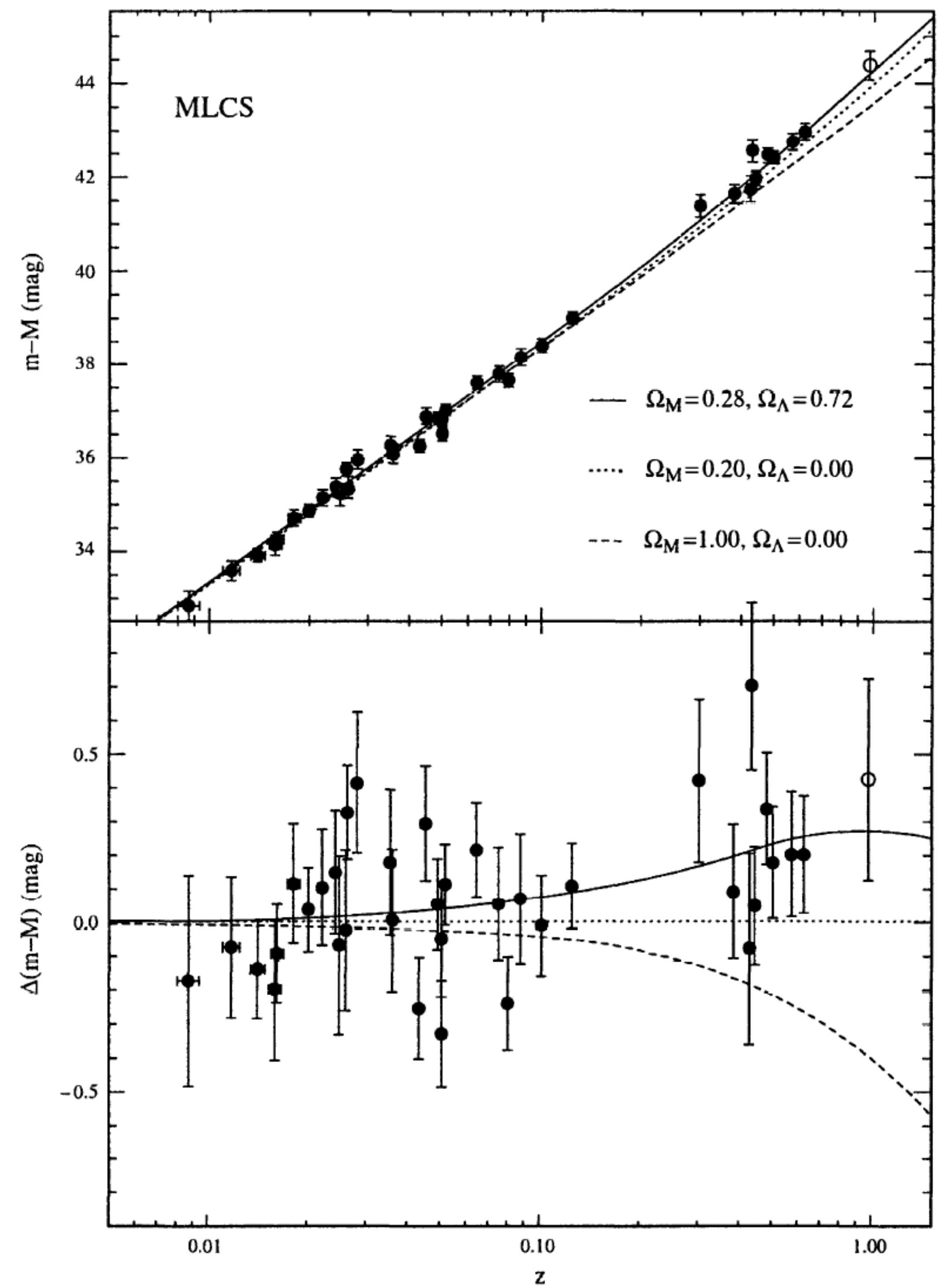
$$F = \frac{L}{4\pi D_L^2}$$

$$m = -5/2 log(F) + C$$

$$m = -5 log(D_L) + C$$

$$m - M = -5 log(D_L) + C \Rightarrow$$

Where m-M is an indicator of distance and M is the absolute magnitude at 10 pc distance. The bottom panel is showing the residual with respect the case of non accelerating flat Universe with $\Omega_m=\Omega_V=0$ and $\Omega_K=1$



S. Dodleson, Modern Cosmology

This was one the first evidence of Dark Energy in di Universe, i,e. Ω_V=0.7. This energy is responsible of the fact that the Universe expansion is accelerating as shown by the the acceleration parameter $q=\Omega_m/2+\Omega_r-\Omega_V$ $q=\Omega_m/2+\Omega_r-\Omega_V<0$

Let’s move back to the measurements pointing towards presence of non visible matter

X-ray halos

Large astrophysical objects contain hot gas, falling in gravitational well while emitting thermal bremsstrahlung at X-ray frequency. In this process significant not shining baryonic matter, such as interstellar gas, can remain undetected

Good reasons to look at X-ray halos

- Allow to distinguish between gas and non-baryonic dark matter
- Potential source of background for dark matter detection
- Hope we can work out a model where dark matter interacts with thermal gas producing a signal

What we can deduce from the hot gas observations? Let’s start form Euler equations of guild dynamics

$$\rho \frac{d\vec{v}}{dt} = -\nabla p - \rho \nabla \Phi$$

$$\frac{dp}{dr} = -\frac{G_N M(r) \rho}{r^2}$$

For spherical system in equilibrium v=0

$$p = \frac{\rho k_B T}{m_p} \Rightarrow \frac{dp}{dr} = \frac{k_B}{m_p}\left(\frac{d\rho}{dr} + \frac{dT}{dr}\right)$$

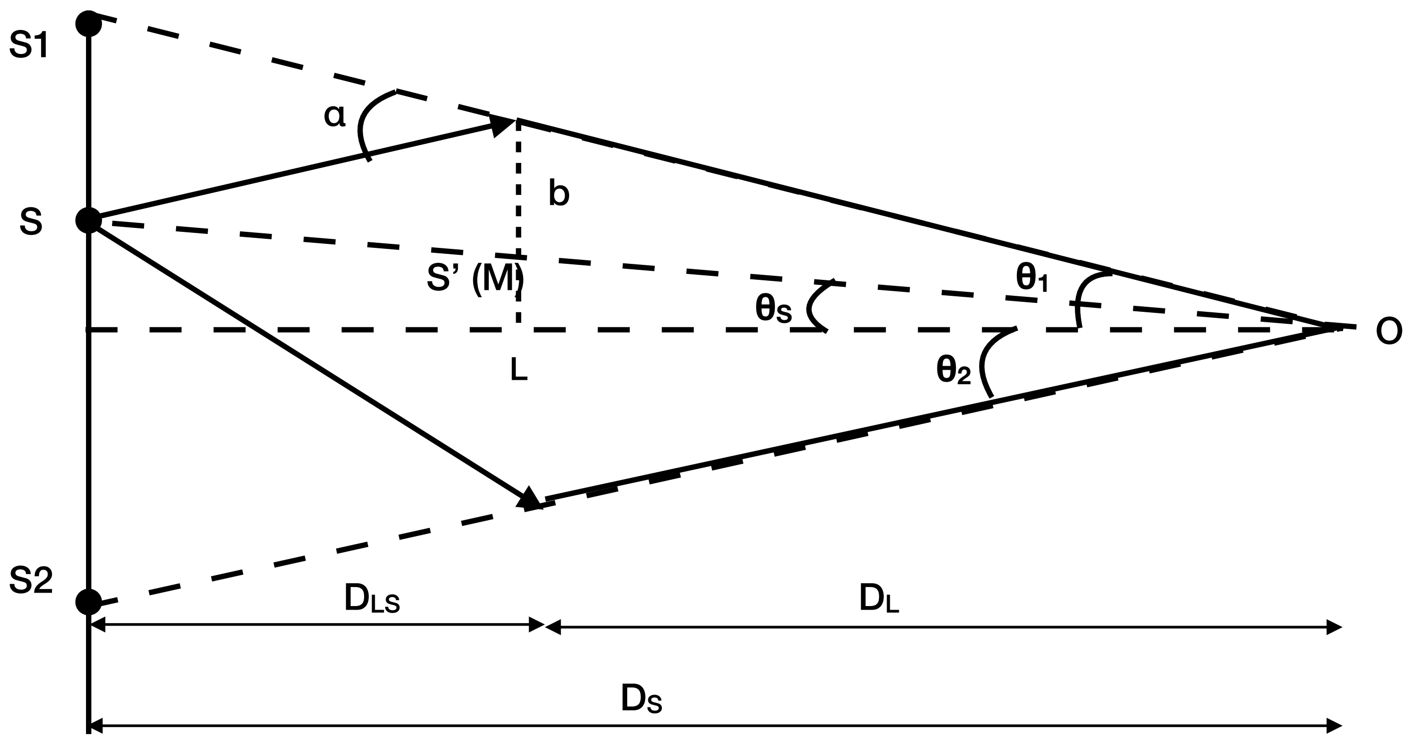
$$M(r) = -\frac{k_B T r}{G_N m_p}\frac{r}{\rho T}\left(T\frac{d\rho}{dr} + \rho\frac{dT}{dr}\right) = -\frac{k_B T r}{G_N m_p}\left(\frac{d\ ln(\rho)}{d\ ln(r)} + \frac{d\ ln(T)}{d\ ln(r)}\right)$$

Thus by measuring gas T and **ρ** profile one infers M(r), i.e. any mass that shows gravitational interaction. It is worth saying that given the isotropy of gas pressure this measurement does not requires to know stellar dynamics. This measurement in also crucial to get to the results Ω_m=0.3 as we will in the the cluster of galaxies.

Gravitational lensing

$$\alpha = \frac{4GM}{c^2 b}$$

Angular deflection of a photon passing by a point of mass M at the closest distance b as predicted by General Relativity and a factor 2 larger than in a Newtonian mechanism.



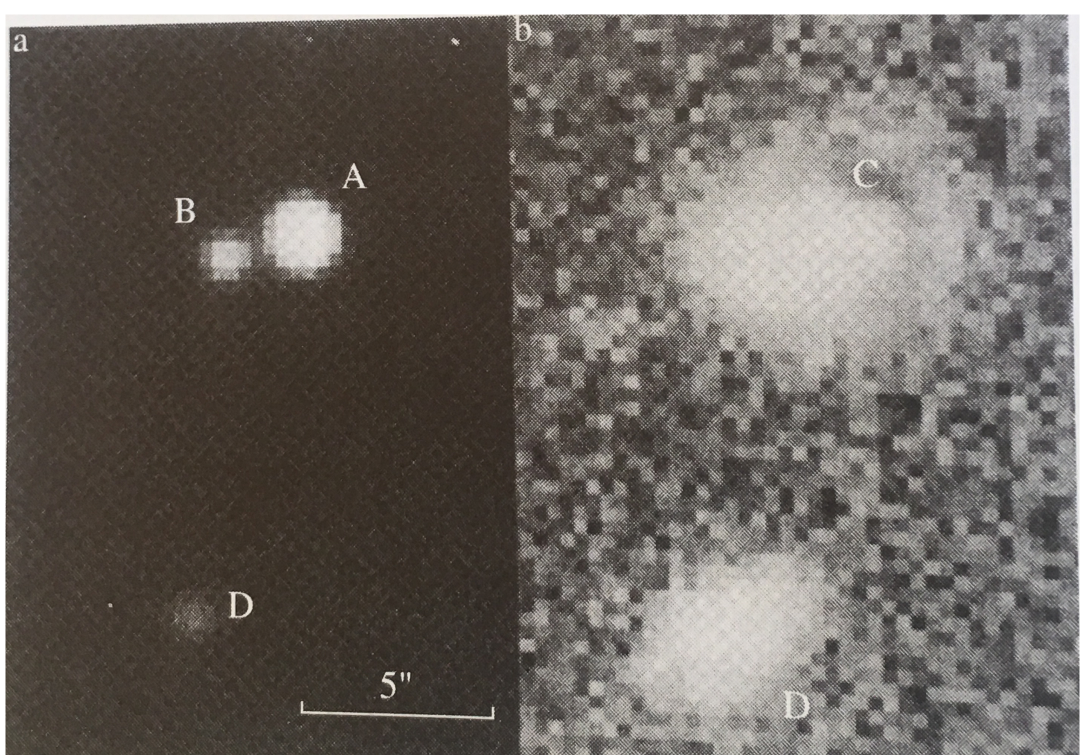
$$\alpha D_L S \simeq D_S(\theta_1 - \theta_2)$$

$$\theta_S = \theta_1 - \frac{4GM}{c^2}\frac{D_{LS}}{bD_S} = \theta_1 - \frac{4GM}{c^2}\frac{D_{LS}}{D_S D_L}\frac{1}{\theta_1}$$

$$\theta_S = 0 \qquad \theta_1 = \theta_E = \left(\frac{4GM}{c^2}\frac{D_{LS}}{D_S D_L}\right)^{1/2}$$

The angle of Einstein ring

$$\theta_{1,2} = \frac{\left[\theta_S \pm \sqrt{\theta_S^2 + 4\theta_E^2}\right]}{2}$$



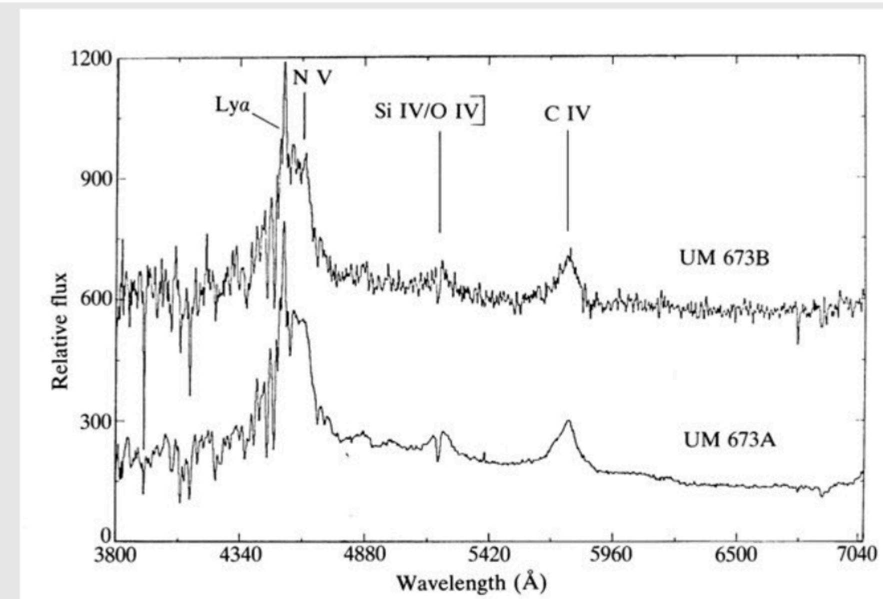
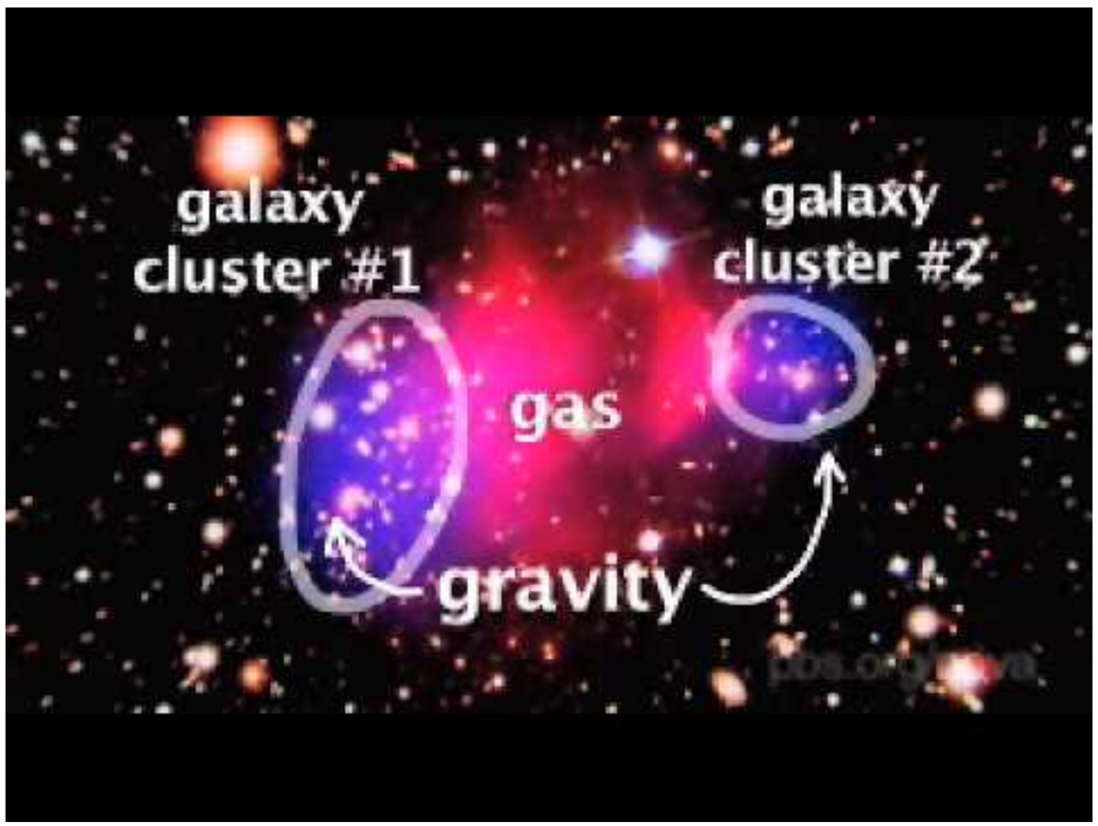


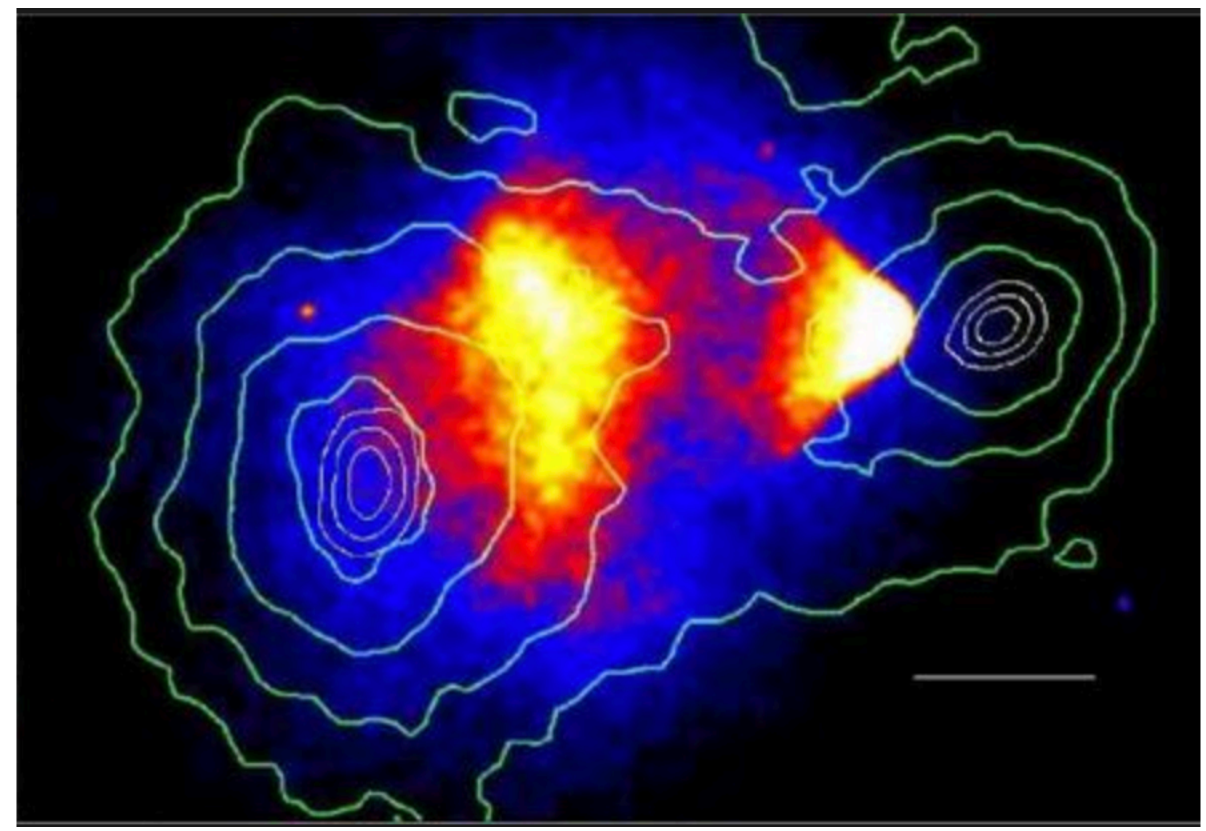
Fig. 8.6 The low dispersion spectra of UM 673A and UM673B recorded in December 1986. The resolution is about 1.3 nm. (With kind permission of Nature; courtesy J. Surdej.)

J. Surdej et al., Nature, London 329 (1987) 695.

Weak lensing in bullet clusters

Often the gravitation lensing is not given by point-like large mass but by diffused masses and often the images are not doubled but deformed. This is called weak lending





The red spot are generated by hot gas which suffers hard scattering (interacting matter) and the two visible mass canters participate to a scattering process. At the same time the weak lensing measurements allow to measure gravitational potential profile which shows large mass which do not scatter (contactless) and cross each other without any deformation of the trajectory. The largest amount of mass in those clusters are in form of non visible mass. The total mass of the Universe found by means of lensing contributes to the critical density as Ω_m=0.3. This is the contribution of all matter visible and not.

https://www.youtube.com/watch?v=rLx_TXhTXbs&t=0s

Simulation of bullet clusters allow to set a limit on the self-interaction cross section $\sigma_{\chi\chi}$ for mass unit m_χ

$$\frac{\sigma_{\chi\chi}}{m_\chi} \simeq 1\ cm^2/g$$

Big Bang Nucleosynthesis

In 1950-60 the predominant theory on the chemical elements formation in the Universe was due to G.Burbidge, M.Burbidge, Fowler, and Hoyle. According to the BBFH theory all elements were produced in the stellar interior or emitted in supernova explosion. While this theory became quit accepted the measurement soon showed striking disagreement with the theory. The Deuterium appearing to be much larger than expected if those elements were only produced in the stars where they are mainly burned in fusion processes. No Deuterium nucleus could survive given the low binding energy.
Thus George Gamow and his collaborator elaborated a new theory of light elements production in the early Universe. The story begins when kT< 100 MeV at almost t > 10^{-4} s when all hadrons decayed but nucleons and anti-nucleons (p,n) which annihilated, not completely, but almost one billionth of the initial nucleons survived to form the constituent of the matter we know todays. At this point the relative number of p and n are fixed by the weak interactions:

$$\nu_e + n \leftrightarrow e^- + p \qquad \text{a)}$$

$$\bar{\nu}_e + p \leftrightarrow e^+ + n$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Given the very similar cross-sections and the fact that nucleons are not relativistic at the T considered, the ratio p to n is just given by the Boltzmann factor $\frac{N_n}{N_p} = \exp(-\frac{Q}{kT}) \qquad Q = (M_n - M_p)c^2 = 1.293\ MeV$

while the Universe cools down the rate of reactions a) slow down, actually first neutrinos produced by means of reaction $e^+ + e^- \rightarrow \nu_e + \text{anti-}\nu_e$ get frozen out at kT< 3 MeV ($\Gamma = n\sigma v < H$) before the reactions a) which will be out of equilibrium when kT< 0.8 MeV, thus the initial value of neutron-proton ratio is:

$$\frac{N_n(0)}{N_p(0)} = \exp(-\frac{1.293}{0.8}) = 0.2$$

and considering the neutron decay $N_n(t)=N_n(0)\exp(-t/\tau)$ and protons $N_p(0)+N_n(0)\{1-\exp(-t/\tau)\}$

$$\frac{N_n(t)}{N_p(t)} = \frac{0.20 \cdot \exp(-\frac{t}{\tau})}{1.20 + 0.2 \cdot exp(-\frac{t}{\tau})} \qquad \tau = 887 \pm 2\ s$$

If no other process were to be considered the Universe would have ended up crowded only of protons, electrons and neutrinos. Conversely, since protons and neutrons co-exists, the electromagnetic process of deuteron formation have been active with a cross-section 0.1 mb, much larger than the one of the weak reactions a). The deuteron formation has a Q value of 2,2 MeV and it has been in equilibrium with photo disintegration and has been active till the decoupling happened at kT~Q/40=0.05 MeV,

Big Bang Nucleosynthesis (II)

As soon as photo-disintegration ceases at kT~0.05 MeV the following reactions leading to helium production take over:

$$^{2}H + n \rightarrow {}^{3}H + \gamma$$
$$^{3}H + p \rightarrow {}^{4}He + \gamma$$
$$^{2}H + p \rightarrow {}^{3}He + \gamma$$
$$^{3}H + n \rightarrow {}^{4}He + \gamma$$

Thus at expansion time t=300 s, for 3 neutrinos flavour, the neutron-proton ration is r=0.135 . This value brings to a mass fraction of ^{4}He much larger than what expected in the case of He generation in stellar interior.
At this point putting together nuclear physics and some statistics and few other ingredient we ends up with the following correlation between the mass fraction of He and D as function of the proton to photon ration in the Universe.

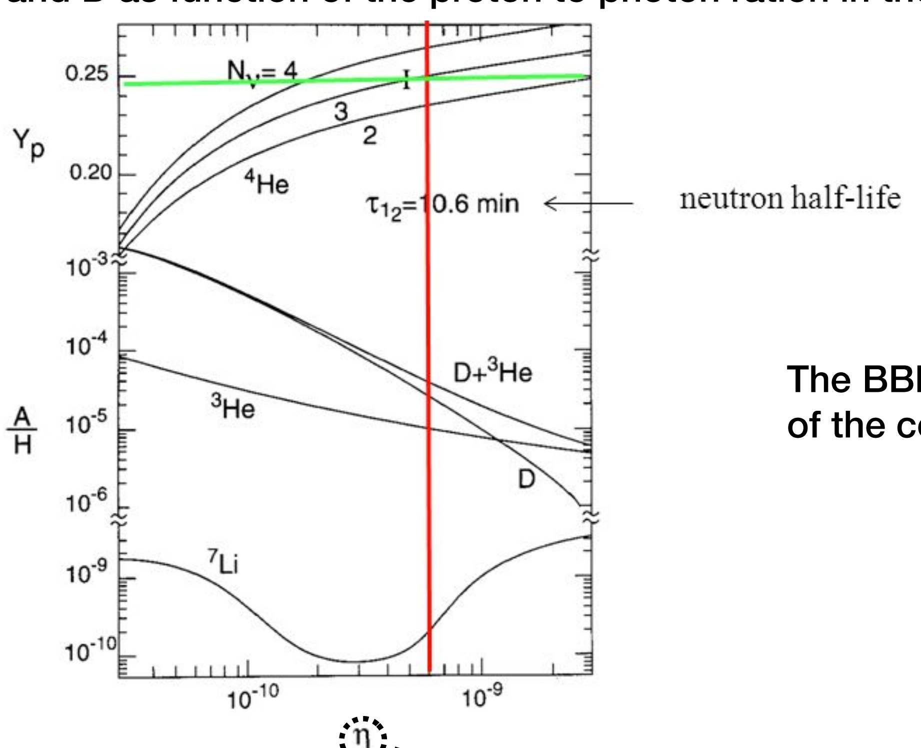


Figure 4.5. The primordial abundances of the light elements, as predicted by the standard model of cosmology, as a function of today's baryon density n_B or of $\eta = n_B/n_\gamma$. The ^{4}He fraction is shown under the assumptions N_ν = 2, 3 and 4 where N_ν is the number of light neutrino flavours. A consistent prediction is possible over 10 orders of magnitude (from [Tur92a]).

This BBN prediction gave indirect evidence of 3 neutrinos before of the Z^0 line shape analysis at the LEP accelerators.

The BBN is a very reliable theory well constrained by data that allows to give an evaluation of the contribution of the baryons to the Universe energy density of $\Omega_b=\rho_b/\rho_{crit}$ =0.01-0.02

Critical energy density

For the case k=0 the Friedmann equations gives the critical density which corresponds to the limit above which the Universe will be closed

$$\rho_c = \frac{3}{8\pi G_N} H_0^2 = 9.2 \times 10^{-27}\ kg\ m^{-3} = 5.1\ GeV\ m^{-3}$$

The ratio between the actual density and the critical one define the closure parameters Ω

$$\Omega = \frac{\rho}{\rho_c} = 1 + \frac{kc^2}{[H_0 R(0)]^2}$$

The different contributions to the total value of $\Omega=\Omega_m+\Omega_r+\Omega_V$ come from matter, radiation and vacuum, respectively. For k not zero the curvature term can be defined as $\Omega_K = \rho/\rho_k = -kc^2/[H_0\ R(0)]^2$ and from the previous equation $\Omega+\Omega_K=\Omega_m+\Omega_r+\Omega_V+\Omega_K=1$

At present time $\Omega_r = 5 \times 10^{-5}$ and it is completely negligible with respect to matter contribution. To anticipate some results:

Luminous baryonic matter, i.e. protons, neutrons, nuclei in the form of stars, gas and dust from direct observations is

$$\rho_{lum} \approx 9 \times 10^{-29}\ kg\ m^{-3}$$

$$\Omega_{lum} \approx 0.01$$

Total density of baryons, visible or invisible inferred form the model of nucleosynthesis ~0.25 baryons/m^3

$$\rho_b \approx 4.5 \times 10^{-28}\ kg\ m^{-3}$$

$$\Omega_b \approx 0.05$$

Total matter density, as inferred from gravitational potential energy deduced from galactic rotational curves.

$$\rho_m \approx 3 \times 10^{-27}\ kg\ m^{-3}$$

$$\Omega_m \approx 0.30$$

Vacuum energy density, is estimated from upward curvature of the Hubble plot of the type I supernovae at large redshift. The most relevant measurement is obtained form the anisotropy of the CMB in particular from the intensity of the caustic peak.

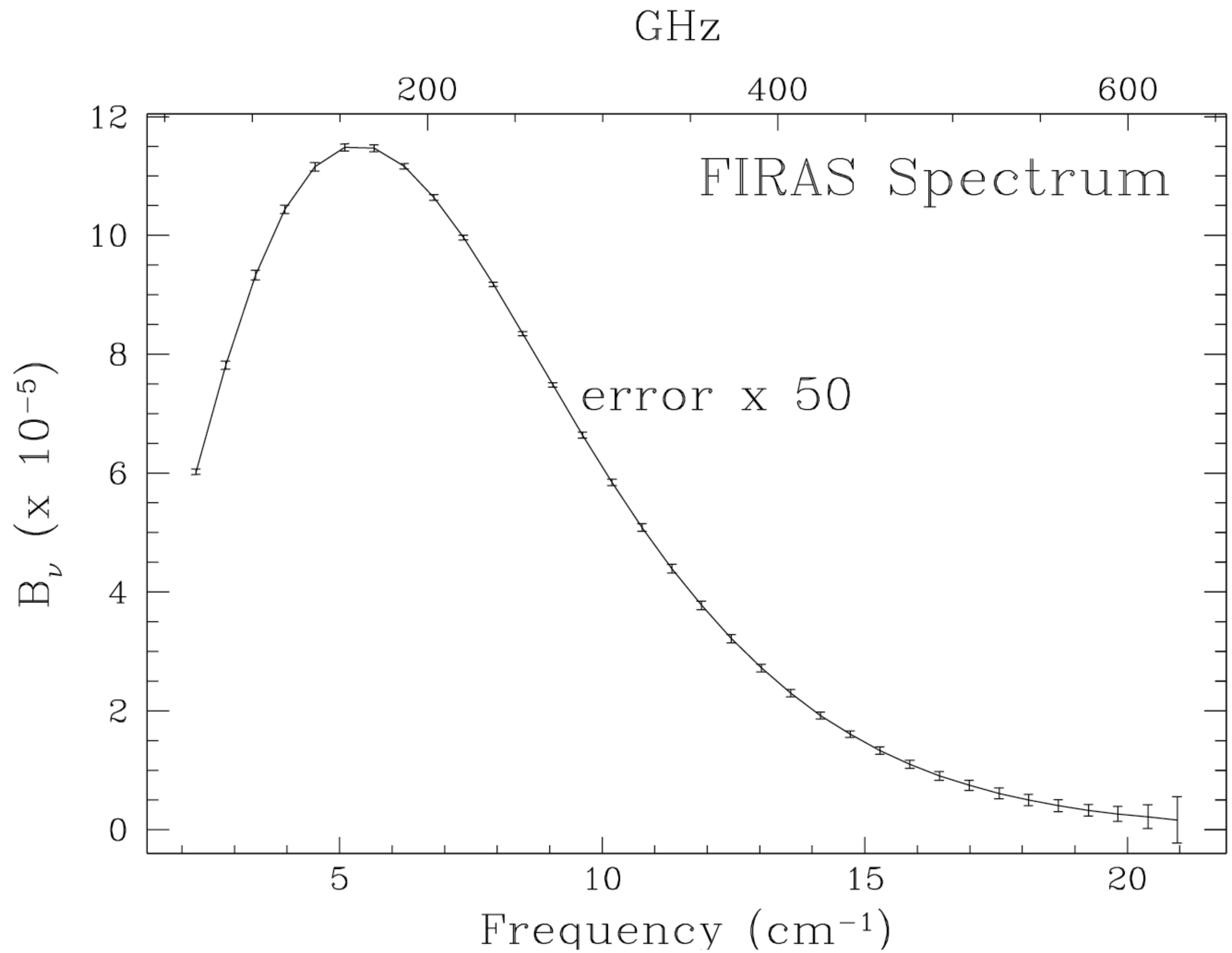
$$\Omega_V \approx 0.70$$

A close look at the CMB spectrum.

Here we start to have a look at the angular power spectrum of the CMB. The idea behind is to catch the physical connection between the angular power spectrum and the key parameters of our Universe. In no way I aim at a rigorous explanation of the analysis on which the measurement of the components of the energy content of the Universe is based. This would enquire more than lecture and and a real scholar on this topic.

High Precision CMB measurement

COBE FIRAS satellite launched 1989 started the era of precision cosmology. It revealed that the CMB frequency spectrum is in perfect agreement with a blackbody emission with a T=2.726±0.010 K. The anisotropy visible only at part per 10^5. This spectrum is almost perfect but its tiny imperfections tells us all we know about the Universe.

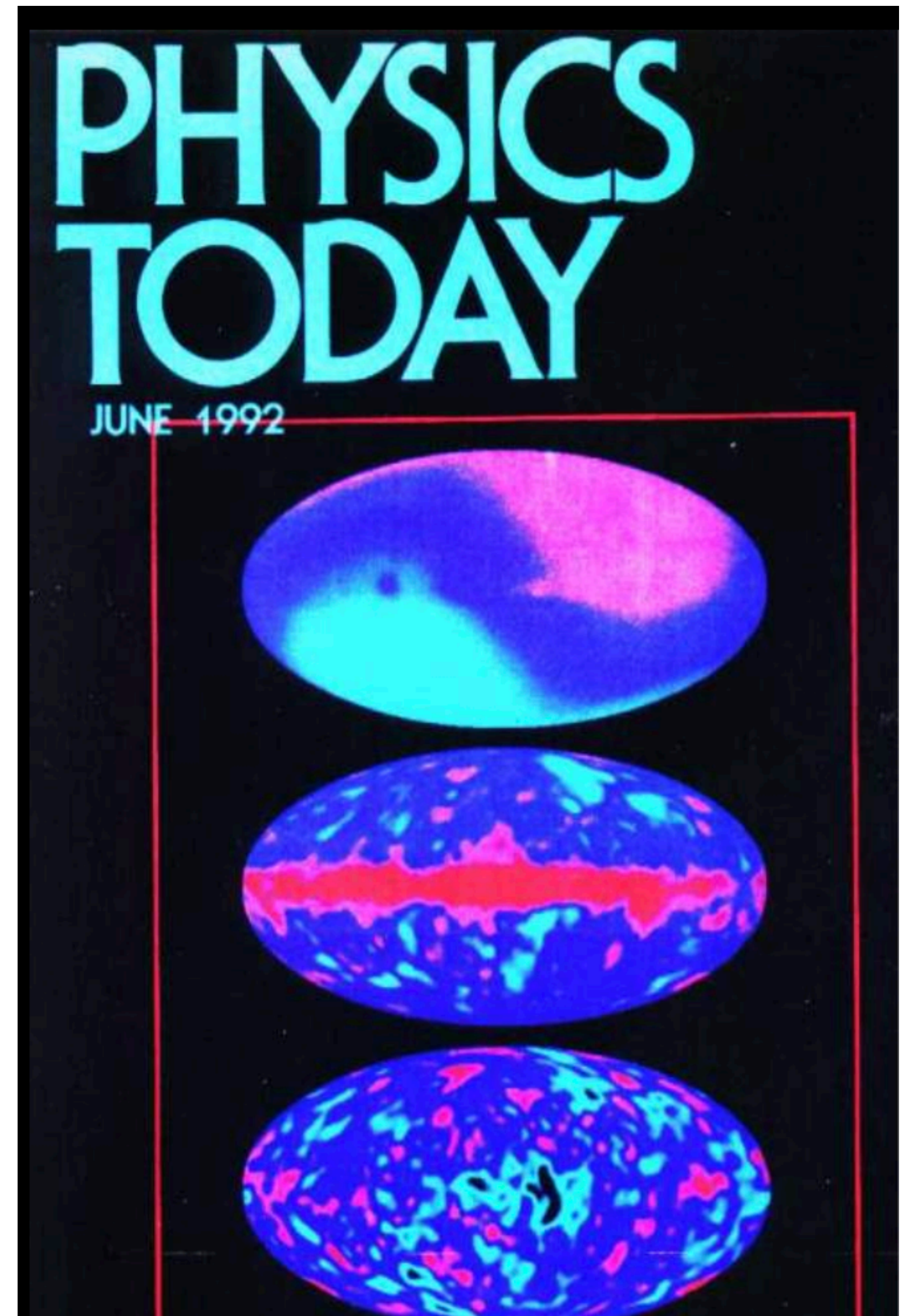


Mather, J.C., et al, ApJL 420, 439, (1994)

Importance of anisotropy

The T of the Universe is 2.7 K, was it much more before?

Light form galaxies is redshifted in proportion to their distance because during its flight the Universes expands as predicted by Big Bang model. Wavelength of light from very far sources is stretched in proportion of the distance and so of the time interval between the emission and detection. Thus looking very far means also looking very early in time. During the expansion the particle density also drops. So it is easy to extrapolate that going backward in time the Universe was very hot and dense. At very high temperature the radiation and particles were in equilibrium. This together with the fact that an adiabatic expansion preserve the blackbody spectrum it explains what we see nowadays.



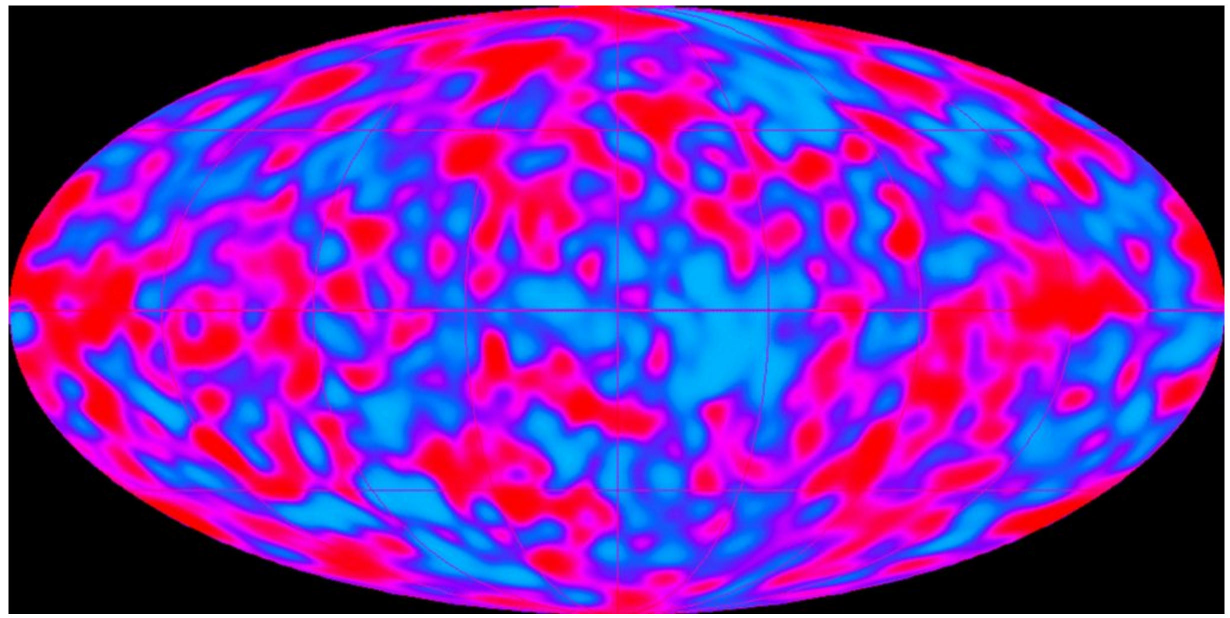
Sky map from COBE DMR:
2.700 ± 0.003 K

Doppler Effect od Sun's
motion v/c = 0.001

Cosmic temperature variation at 389000 y
at 3 parts per 100000

What we learn from the temperature map of the Universe

This map is a screenshot of what was the T field on the surface of last scattering, where the light made the “last” scattering with protons. After this moment, ~ 350000 y after the Big Bang and at a redshift z=1100 the H was formed (Freeze out of H ionisation process: nσv<H). Thus the radiation freely streamed out and the un-uniformity on the surface of last scattering propagated up to us by mean of acoustic waves of Different wavelengths generated and propagate throughout the cosmic medium. The power spectrum of the matter and radiation un-uniformity evolved since then and it is responsible of how we see the Universe.



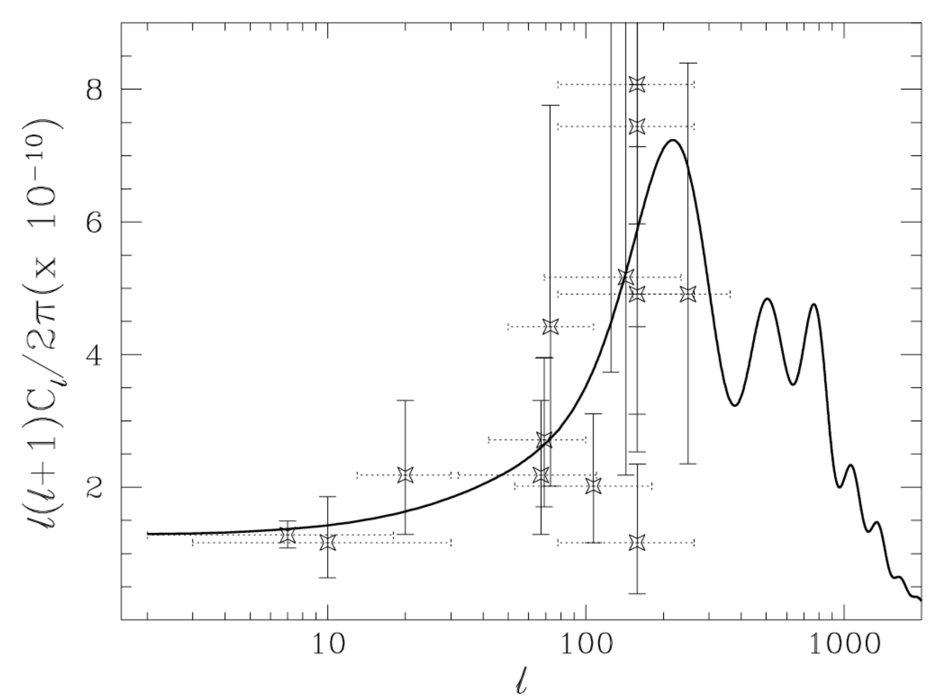
If we want to analyse the temperature fluctuations as function of the position in the sky and the correlation of the T variation between two points (identified by unit-vector **m** and **n**) we first represent the T fluctuations in spherical harmonics:

$$\Theta(\mathbf{n}) = \frac{T(\mathbf{n}) - \langle T \rangle}{T} = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\mathbf{n})$$

$$\xi_{\Theta\Theta}(\theta) = \langle \Theta(\mathbf{n}) \Theta(\mathbf{m}) \rangle \qquad with \qquad m \cdot n = cos\theta$$

$$= (1/4\pi) \sum (2l+1) C_l P_l(cos\theta)$$

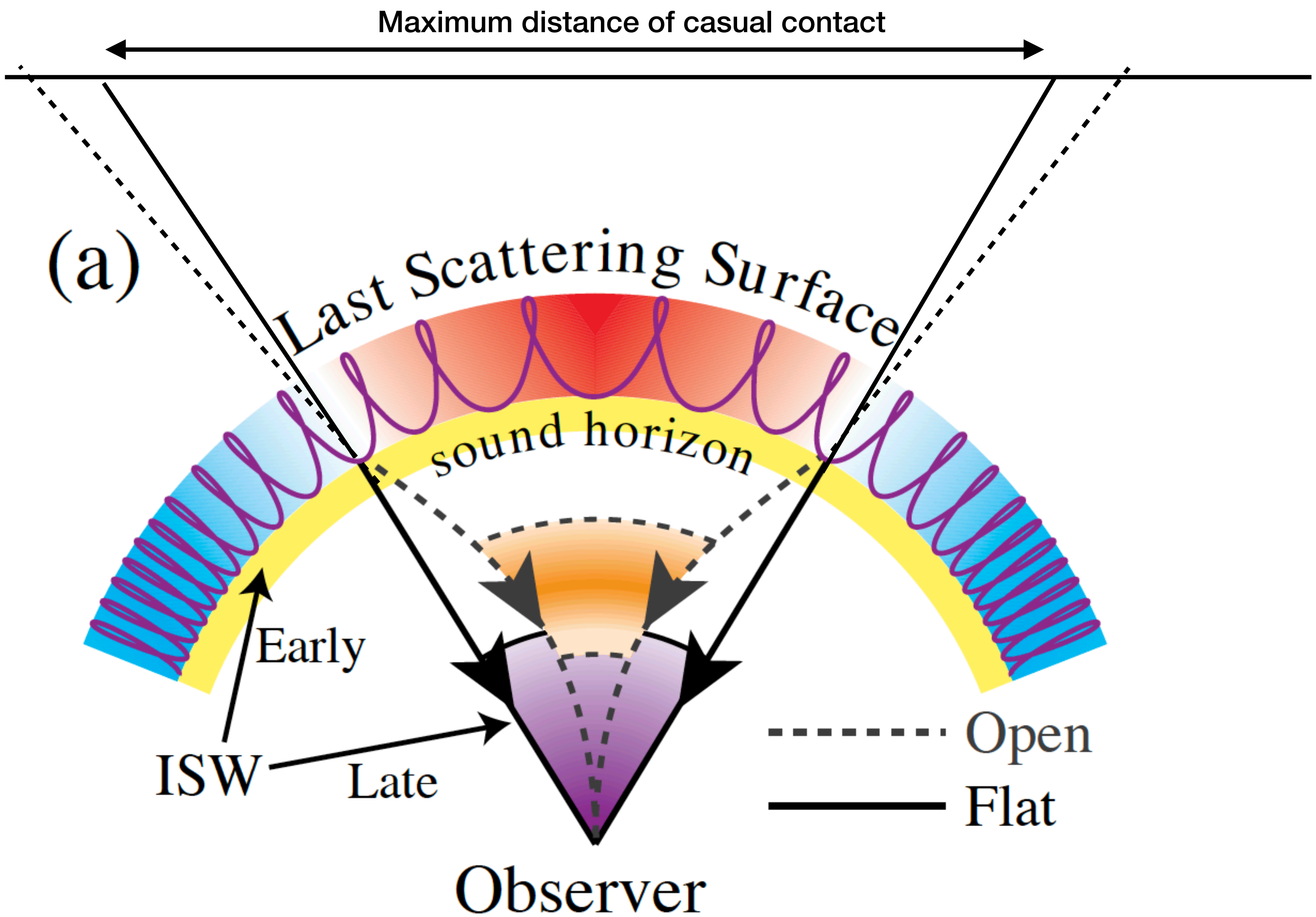
$$C_l = \frac{1}{2l+1} \sum_{-m}^{m} \langle |a_{lm}|^2 \rangle$$



The ξ function is the correlation between the two points identified by the unit-vectors **n** and **m**
The present CSM assume that a_{lm} have gaussian fluctuations with mean zero and variance C_l. So all informations are hidden in the power spectrum
All we deduce about the Universe is encoded in the peak positions, relative amplitudes and dumping of the peaks.

Surface of last scattering

Projection on flat Universe as of today

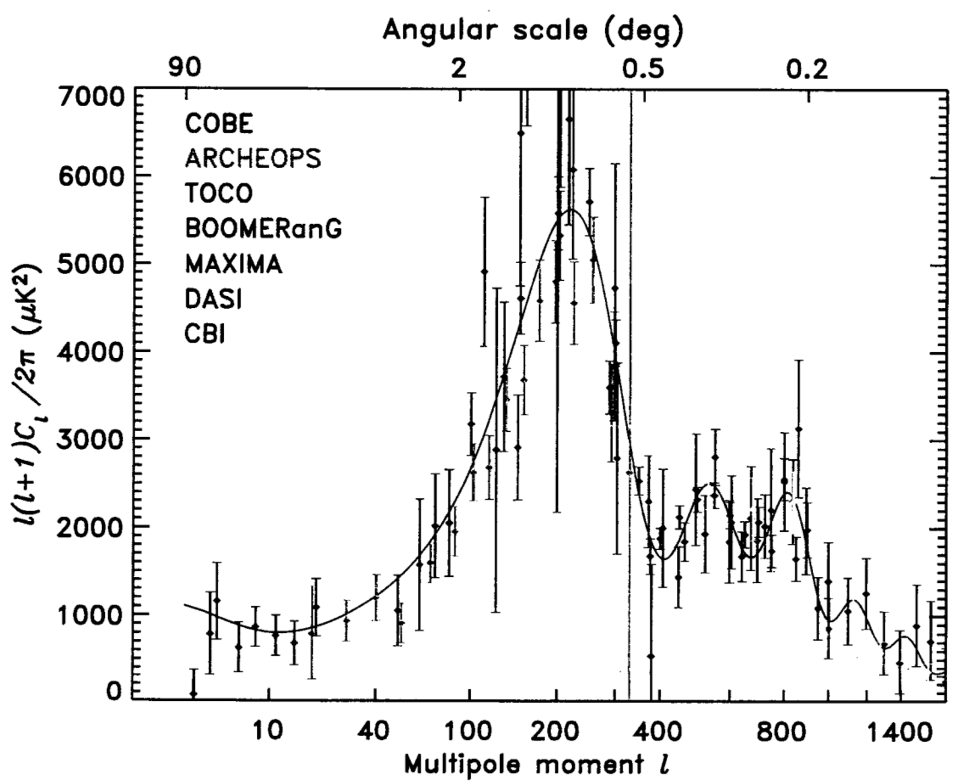


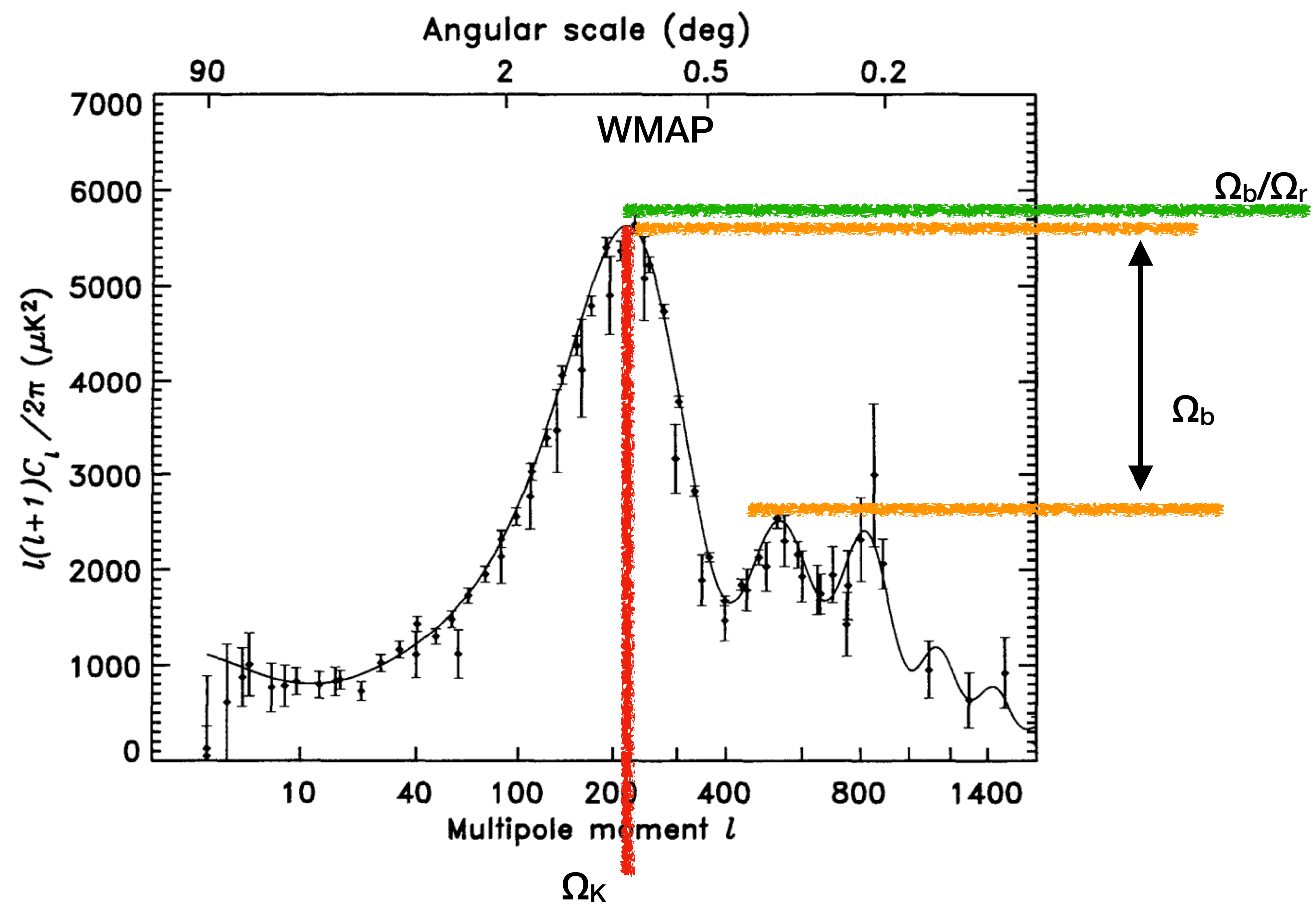
Wayne Hu Ph.D. thesis

Another important effect to understand is is the capability of the Universe to behave like a cosmic lens converging or diverging depending on Ω_K, i.e. the total energy content, or also space curvature. This is embedded in the angular power spectrum of the CMB. In fact, the maximum distance of causal contact will be magnified if $\Omega_K<0$ (open Universe), or demagnified, $\Omega_K>0$ (close Universe). The distance of maximum casual contact on the surface of last scattering is encoded in the position of the acoustic peaks l in the angular power spectrum. The recent measurement of angular power spectrum are perfectly compatible with a Universe where $\Omega_K=0$, indeed the position of the peaks are exactly were expected as there is not magnification or demagnification.

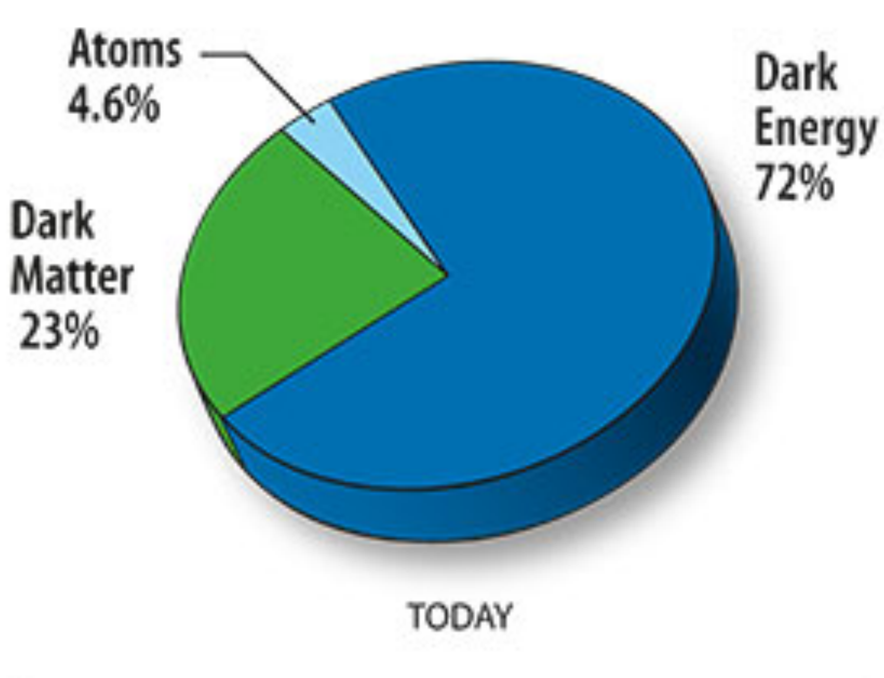
$$l \simeq 200 \Rightarrow \pi/200 \sim 1.8^o$$

Final results form angular power spectrum





The first peak height depends on the Ω_b/Ω_r while the next peak dumping depends on the Ω_V and Ω_m. The dept of the potential well is affected by Ω_m as well.



The pie chart reported on the side is in agreement with the results of the independent measurements listed at the beginning and confirmed by the higher precision experimental cosmology that starts with the measurement of the angular power spectrum of the CMB.

Power spectrum of Galaxies density function

Modern Cosmology, Scott Dodelson

both the CMB and large-scale structure is the *two-point function*, called the *power spectrum* in Fourier space. If the mean density of the galaxies is $\bar{n}$, then we can characterize the inhomogeneities with $\delta(\vec{x}) = (n(\vec{x}) - \bar{n})/\bar{n}$, or its Fourier transform $\tilde{\delta}(\vec{k})$. The power spectrum $P(k)$ is defined via

$$\langle \tilde{\delta}(\vec{k})\tilde{\delta}(\vec{k}')\rangle = (2\pi)^3 P(k)\delta^3(\vec{k} - \vec{k}'). \tag{1.9}$$

Here the angular brackets denote an average over the whole distribution, and $\delta^3()$ is the Dirac delta function which constrains $\vec{k} = \vec{k}'$. The details aside, Eq. (1.9) indicates that the power spectrum is the spread, or the variance, in the distribution. If there are lots of very under- and overdense regions, the power spectrum will be large, whereas it is small if the distribution is smooth. Figure 1.13 shows the power spectrum of the galaxy distribution. Since the power spectrum has dimensions of k^{-3} or (length)^3, Figure 1.13 shows the combination $k^3P(k)/2\pi^2$, a dimensionless number which is a good indication of the clumpiness on scale k.

The best measure of anisotropies in the CMB is also the two-point function of the temperature distribution. There is a subtle technical difference between the two power spectra which are used to measure the galaxy distribution and the CMB, though. The difference arises because the CMB temperature is a two-dimensional field, measured everywhere on the sky (i.e., with two angular coordinates). Instead of Fourier transforming the CMB temperature, then, one typically expands it in

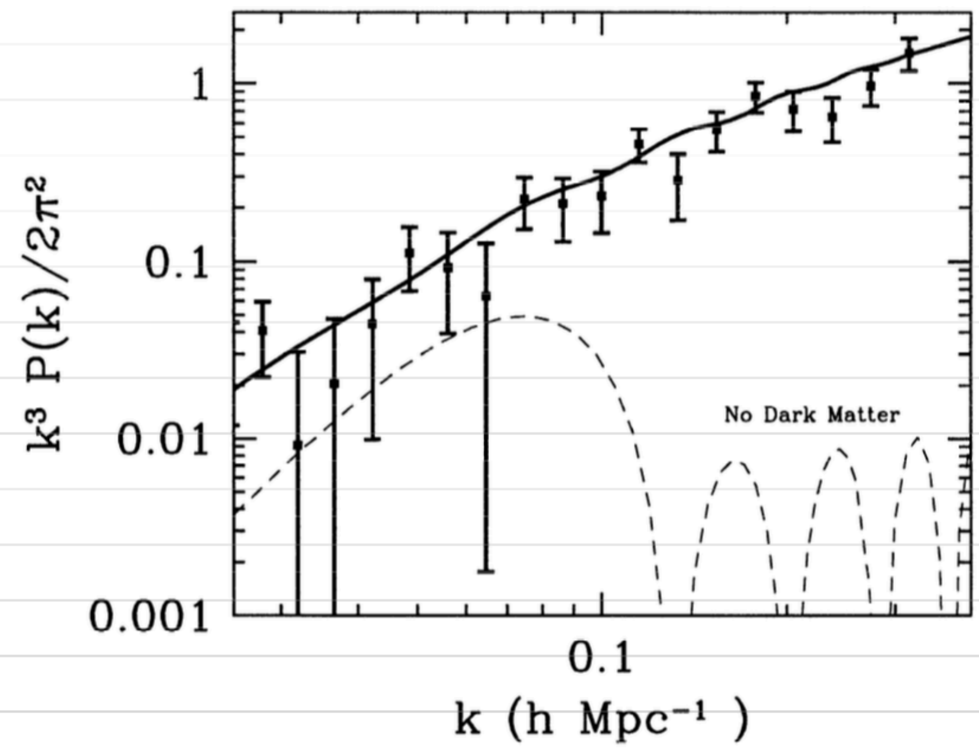


Figure 1.13. The variance $\Delta^2 \equiv k^3P(k)/2\pi^2$ of the Fourier transform of the galaxy distribution as a function of scale. On large scales, the variance is smaller than unity, so the distribution is smooth. The solid line is the theoretical prediction from a model in which the universe contains dark matter, a cosmological constant, with perturbations generated by inflation. The dashed line is a theory with only baryons and no dark matter. Data come from the PSCz survey (Saunders *et al.*, 2000) as analyzed by Hamilton and Tegmark (2001).

To conclude

With what I said in the last hour I did not pretend to demonstrate the existence of Dark Matter but only to make a list of the most compelling indirect evidences that justify our motivation to search for Dark Matter. The demonstration of the existence of Dark Matter is expected to come from measurements