united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-17

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Dark Matter and Energy - 1

P. Ullio

SISSA, Trieste

Dark Matter

and Dark Energy

Piero Ullio

SISSA, Trieste

VII School on Non-Accelerator Astroparticle Physics

Trieste, July 28-29, 2004

Outline

The dark side of the Universe from astrophysical and cosmological observations:

- the long-standing issue of dark matter

- the recent big surprise of dark energy

Fitting the dark terms in a particle physics framework:

- candidates for dark matter and dark energy

- searching methods

The Universe is weird:

most matter in the Universe does not shine.

Back in 1933, Zwicky found evidence for the presence of *"dark matter"* in the Coma cluster.

A galaxy cluster is a large, gravitationally bound group of galaxies. Assuming the system has relaxed to dynamical equilibrium, the virial theorem holds:

$$K + \frac{U}{2} = 0$$

Zwicky found that the kinetic term K, estimated by measuring proper velocities of individual galaxies in Coma, was much larger than the potential term U computed assuming that the mass in the cluster is the sum of the mass of the galaxies: $M/L \simeq 300M \odot /L_{\odot}$.

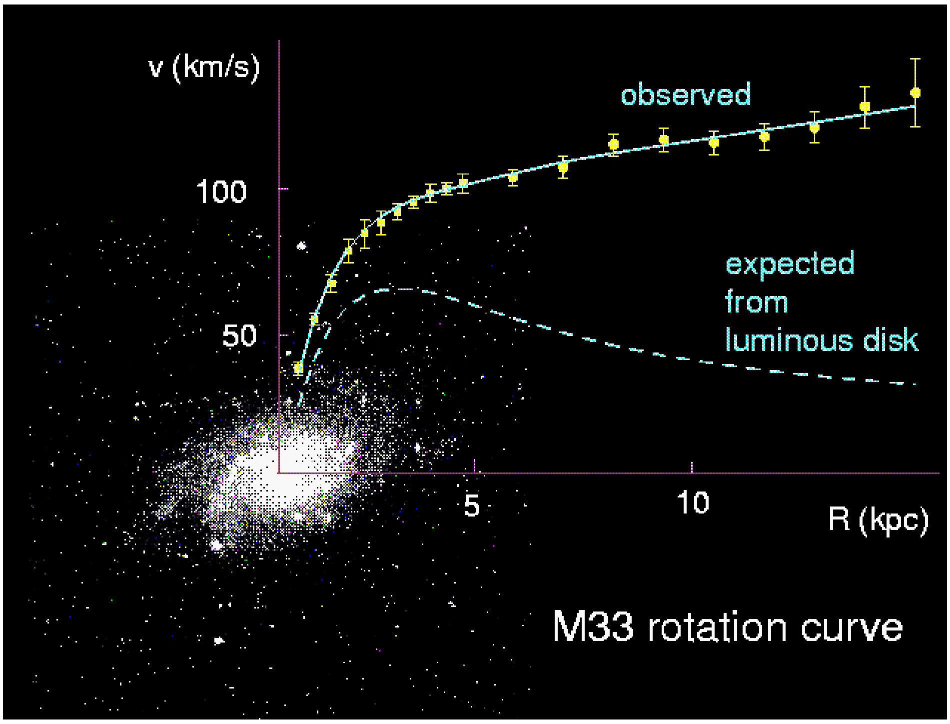
More precisely, clusters contain hot, X-ray emitting gas: $M/M_{\mathrm{vis}} \simeq 20$.

1970s: dark matter shows up in galaxies.

The presence of dark matter was inferred through Kepler's third law:

$$v_{\mathrm{circ}}(r) = \sqrt{\frac{GM(r)}{r}} \, .$$

For $M(r)$ dominated by stars, at r much larger than the scale of luminous terms, you predict $v_{\mathrm{circ}}(r) \propto r^{-1/2}$, while find it flat. E.g.:



Corbelli & Salucci (2000), Bergström (2000)

- in spirals and ellipticals $M/L \sim 10 - 20 M_{\odot}/L_{\odot}$
- in LSBs or dwarfs $M/L \sim 200 - 600 M_{\odot}/L_{\odot}$

The Universe is weird:

most of the dark matter is non-baryonic.

The primordial abundance of light elements as a very accurate probe of the total baryon density in the Universe.

Extrapolate back to the early Universe when $T \sim 1$ MeV (or age about 1 s). It the time when neutrons (1.29 MeV heavier than p) go out of equilibrium. Before decaying, the leftover neutrons end up in Helium nuclei. Two steps and two possibilities:

step 1: $p + n \rightarrow d + \gamma$

step 2a: $d + d \rightarrow {}^3He + n \quad {}^3He + d \rightarrow {}^4He + p$

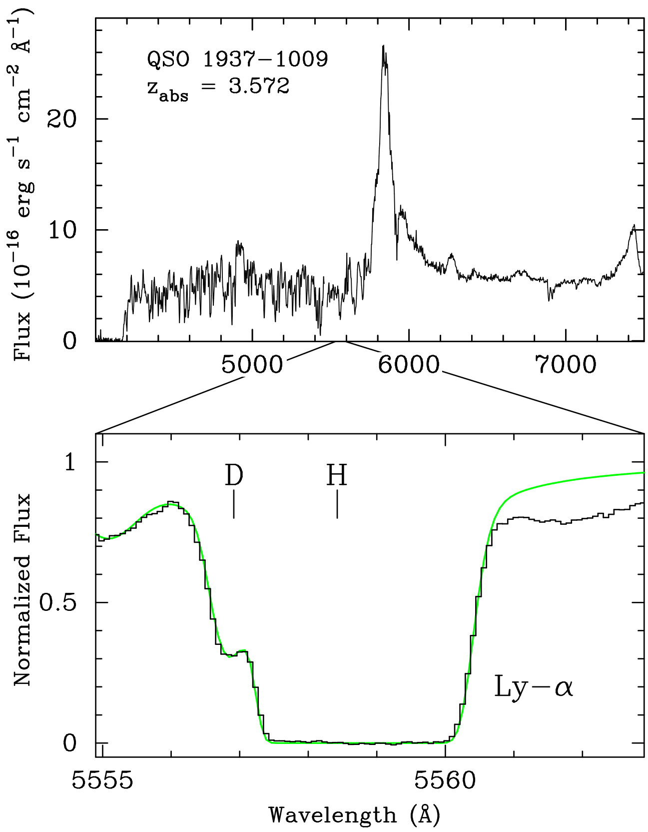
step 2b: $d + d \rightarrow {}^3H + p \quad {}^3H + d \rightarrow {}^4He + n$

Compute conversion probabilities in the expanding and cooling Universe and find the primordial abundance of ${}^4He$, D and ${}^3He$ (plus ${}^7Li$)

Theory of Big Bang Nucleosynthesis was understood and developped in the late 1960s.

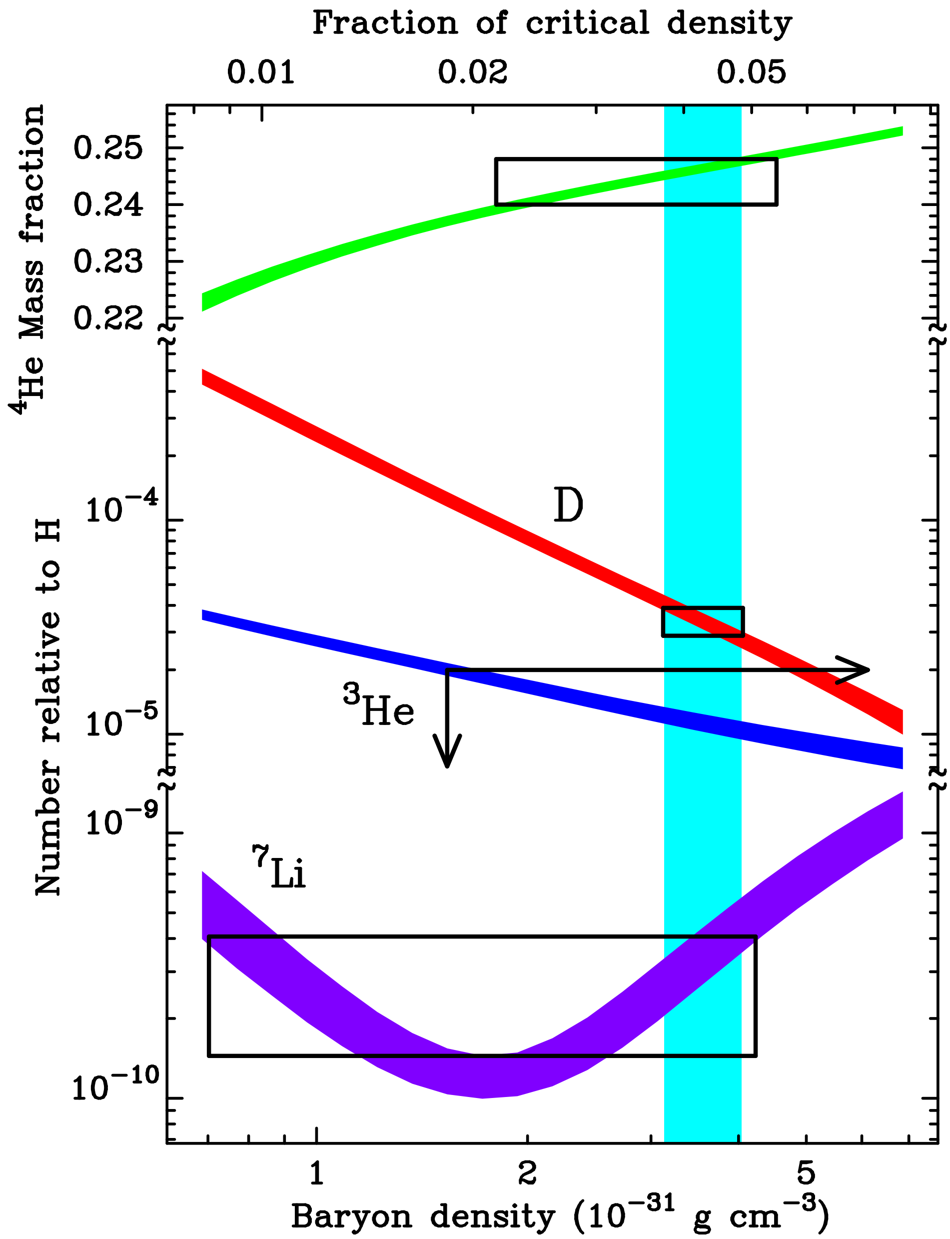
Experimentally challenging, as the abundance of primordial elements can be measured only in environment where no significant star formation occurred.

Breakthough in 1998 with the high precision measurement of the D abundance, looking at absorption lines in very distant quasars:



Burles & Tyler (1998)

Predictions of Big Bang Nuclesynthesis versus observational data:



Burles & Tyler (1998)

Assuming the standard model as particle physics framework, the baryon to photon ratio is the only free paramter.

one step back:

Cosmology in a nutshell

The standard cosmological model, the Big Bang model, is based on the cosmological principle, i.e. the assumption that, on large scales, the Universe is homogeneous and isotropic, i.e with metric equation:

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

where $k = -1, 0, +1$ labels a open, flat or closed geometry. The dynamics of the model, i.e. the time dependence of the scale factor $a(t)$, follows from Einstein's equations of general relativity:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}\ ,$$

with source terms of the form:

$$T_\mu^\nu = \mathrm{diag}\left(\rho(t), -p(t), -p(t), -p(t)\right)\ ,$$

where ρ and p are the energy density and pressure for each component of the Universe.

Friedmann's equations (from Einstein's eq.):

$$[H(t)]^2 \equiv \left[\frac{\dot{a}}{a}\right]^2 = \frac{8\pi G_N}{3}\rho - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho + 3p)$$

From the first, if $\rho(t) = \rho_c(t) \equiv \frac{3[H(t)]^2}{8\pi G_N}$, the *critical density*, the Universe is flat (i.e. $k = 0$).

Focus on quantities at current time, say $t = t_0$.

The Hubble constant:

• it is the expansion rate of Universe today, usually written as $H_0 = h \cdot 100$km/sec/Mpc; observationally, $h \simeq 0.7$;
• acts as overall normalization, e.g., in the critical density today $\rho_c(t_0)$.

Contributions to the energy density today, measured as:

$$\Omega_i \equiv \frac{\rho_i(t_0)}{\rho_c(t_0)}.$$

From BBN, the baryon contribution is found to be:

$\Omega_{\text{baryons}} h^2 \simeq 0.02 \pm 0.002$ or $\Omega_{\text{baryons}} \simeq 0.04$

much larger than the contribution of stars only, which from photometric maps is found to be:

$\Omega_{\text{stars}} \simeq 0.005$.

In its turn, Ω_{baryons} is much smaller than the *l*ower limit on the total mass contribution estimated from galaxy clusters (from X-ray maps + hydrodynamics)

$\Omega_{\text{M}} \sim 5 - 10\ \Omega_{\text{baryons}} \sim 0.2 - 0.4$

$\rightarrow$ most dark matter is non-baryonic!

$\rightarrow$ the matter energy density today is close to critical, with $\Omega_{\text{tot}} = 1$ being one of the predictions of the cosmological inflation mechanism, formulated in the beginning of the 1980s, the standard approach to understand initial conditions in the early Universe.

The Universe is even more weird:

We are in a period of accelerated expansion!

In 1998, the breakthrough which wiped out the framework theoretically favoured at that time, i.e. the $\Omega_\mathrm{M} = 1$ Einstein – de Sitter model:

The Hubble's diagram from SNe Ia standard candles, derived by measuring apparent magnitudes (i.e. luminosity distances) and redshifts, turned out to be consistent with a late phase of the Universe with $\ddot{a} > 0$, rather than $\ddot{a} < 0$ (by two different teams independently, Perlmutter et al., Riess et al.).

From the second Friedmann equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\rho + 3p)$$

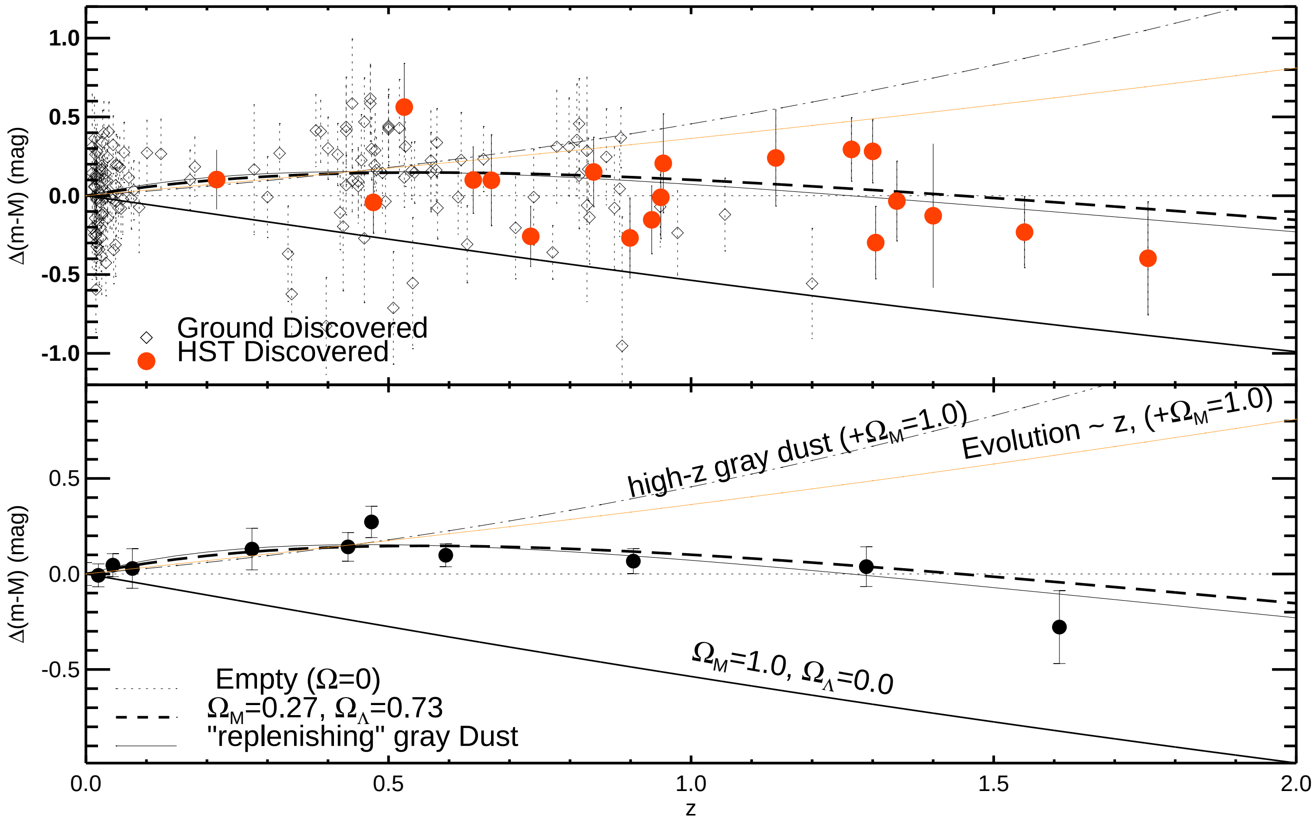
For matter, i.e. a fluid with $p = 0$, you find $\ddot{a} < 0$.

You need instead to introduce a fluid with equation of state:

$$p = w\rho \text{ and } w < -1/3$$

which acts like a repulsive term at large distances!

Latest data set:



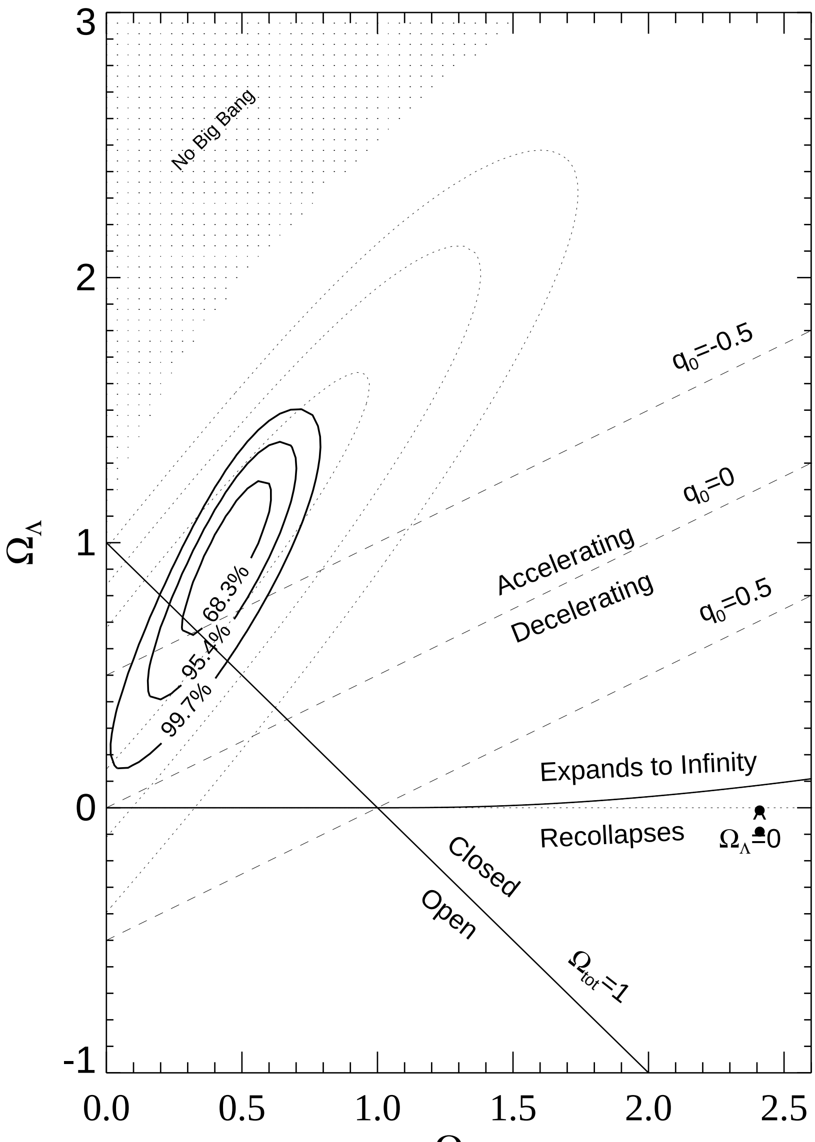
Riess et al. (2004)

The simplest framework to fit the data is the one with a "cosmological constant", i.e. a constant term added in Einstein's equations:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu} + \Lambda g_{\mu\nu}$$

behaving like a contribution to $T_{\mu\nu}$ with $p = -\rho$.

Fit in case of a Universe with matter plus a cosmological constant:



Riess et al. (2004)

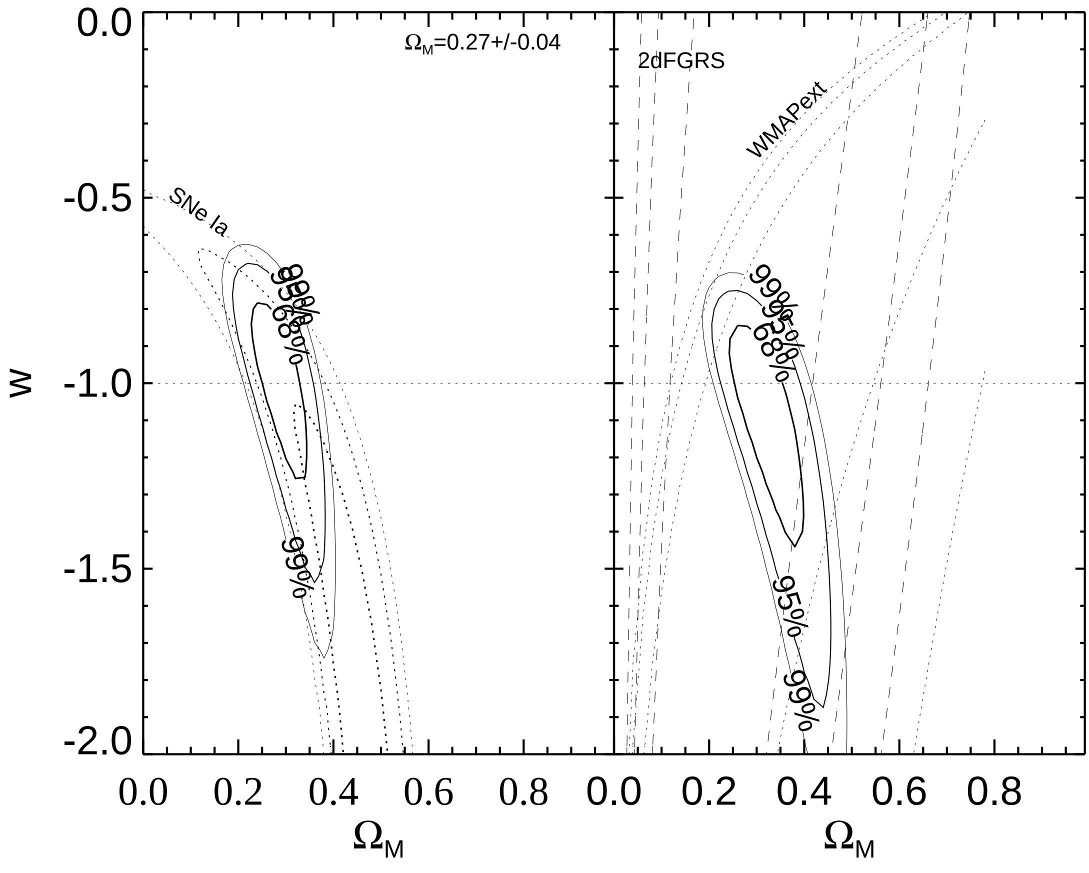
$$\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_c(t_0)} \equiv \frac{\Lambda}{8\pi G \rho_c(t_0)}$$

For a flat universe:

$$\Omega_M \sim 0.3 \quad \Omega_\Lambda \sim 0.7$$

Fit in the more general case of a Universe with matter plus a dark energy term, fluid component defined by the equation of state:

$$p = w\rho \quad \text{with } w < -1/3$$



Riess et al. (2004)

A constant w is assumed. A flat geometry is taken as a prior as well.

Another milestone:

the measurements of temperature anisotropies in the Cosmic Microwave Background radiation.

1992: the COBE satellite verified that the 2.728 K CMBR, the snapshot of the Universe at the redshift of recombination $z_{\rm rec} \simeq 1100$, showed anisotropies at the level of $\Delta T/T \sim 10^{-5}$.

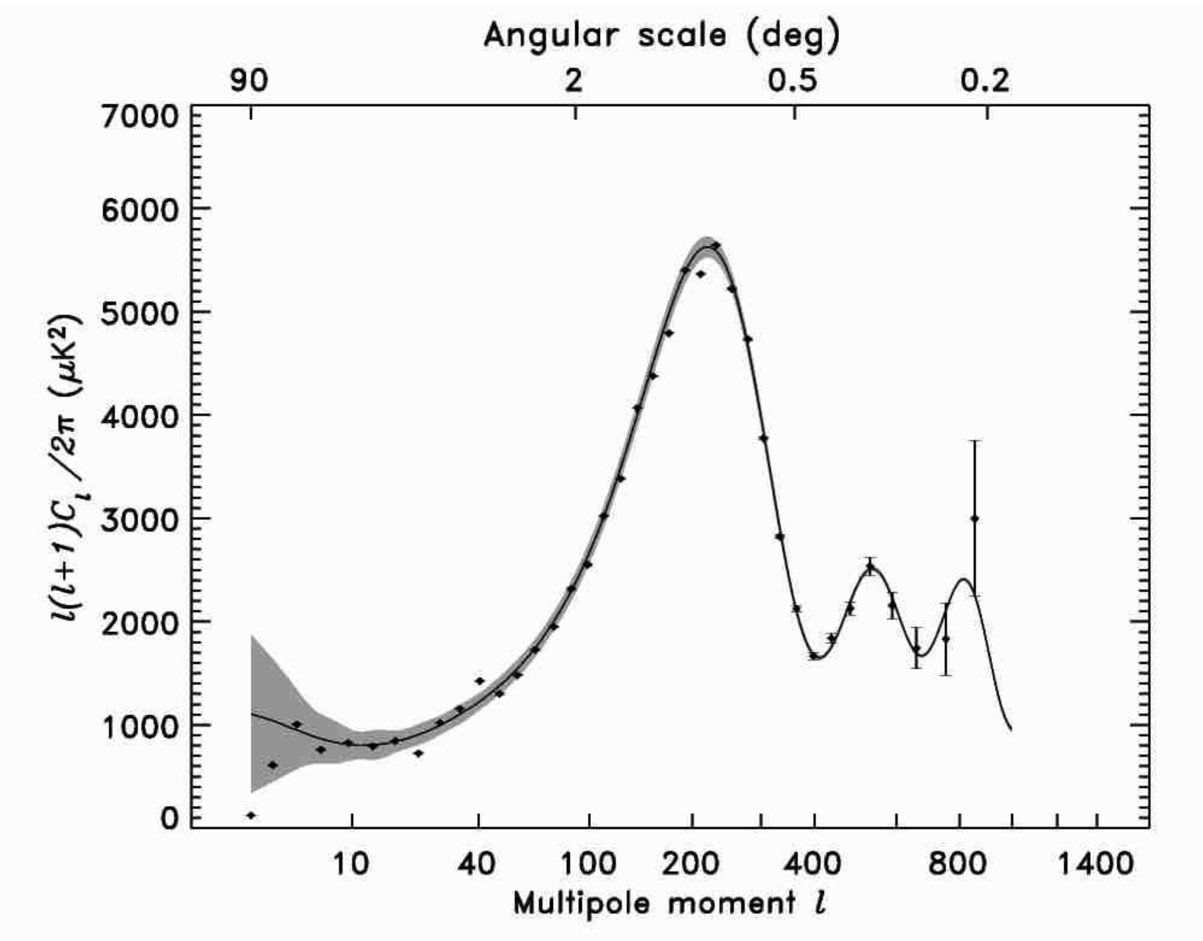
This marked the final death of baryonic dark matter: baryonic density perturbations, $\delta\rho_{\rm B}/\rho_{\rm B} \sim \Delta T/T$, would at most have grown up to $10^{-5} \cdot z_{\rm rec} \sim 10^{-2}$, i.e. they would still be in the linear regime today instead of having gone through gravitational collapse and formed the structures we see in the Universe.

Picture consistent with non-baryonic dark matter, not coupled to photons, whose density perturbations started to grow much earlier than $z_{\rm rec}$, and with baryonic matter falling into the potential wells of dark matter at a later time.

CMBR as the frontier of high precision cosmology:

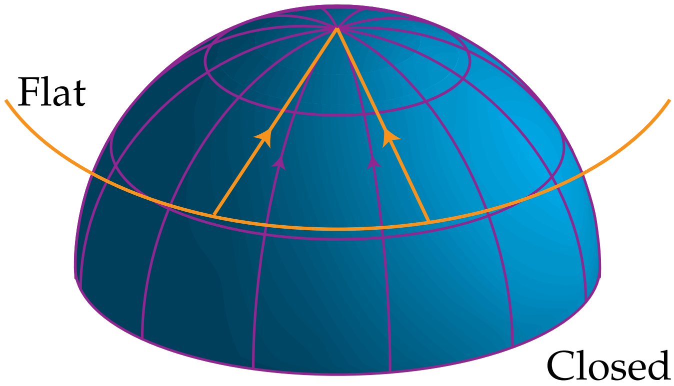
Boomerang and Maxima balloons (first precision measurements on a small patch of the sky, 2000), the WMAP satellite (first high precision full map of the sky, 2003) + several other recent experiments on different angular scales

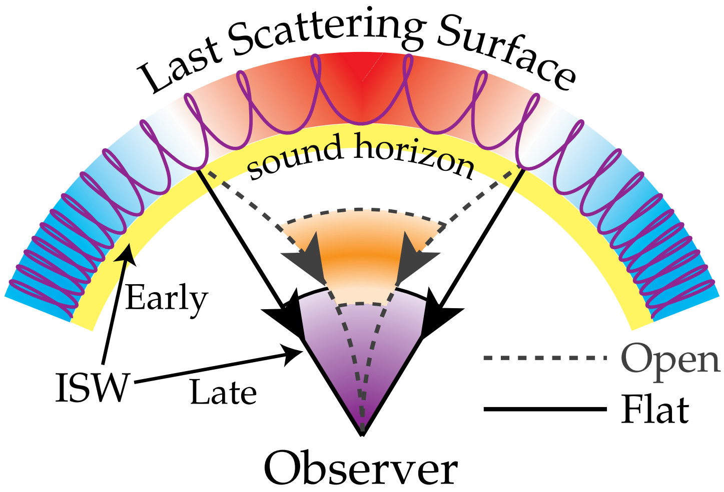
measured the acoustic peaks of the baryon-photon fluid at the surface of last scattering:



Hinshaw et al. (2003)

The position of the first acoustic peak measures the angular size of the sound horizon on the surface of last scattering; it's the meter stick we need to measure the geometry of the Universe:





The data give:

$$\Omega_{\text{tot}} = 1.056 \pm 0.045 \ ,$$

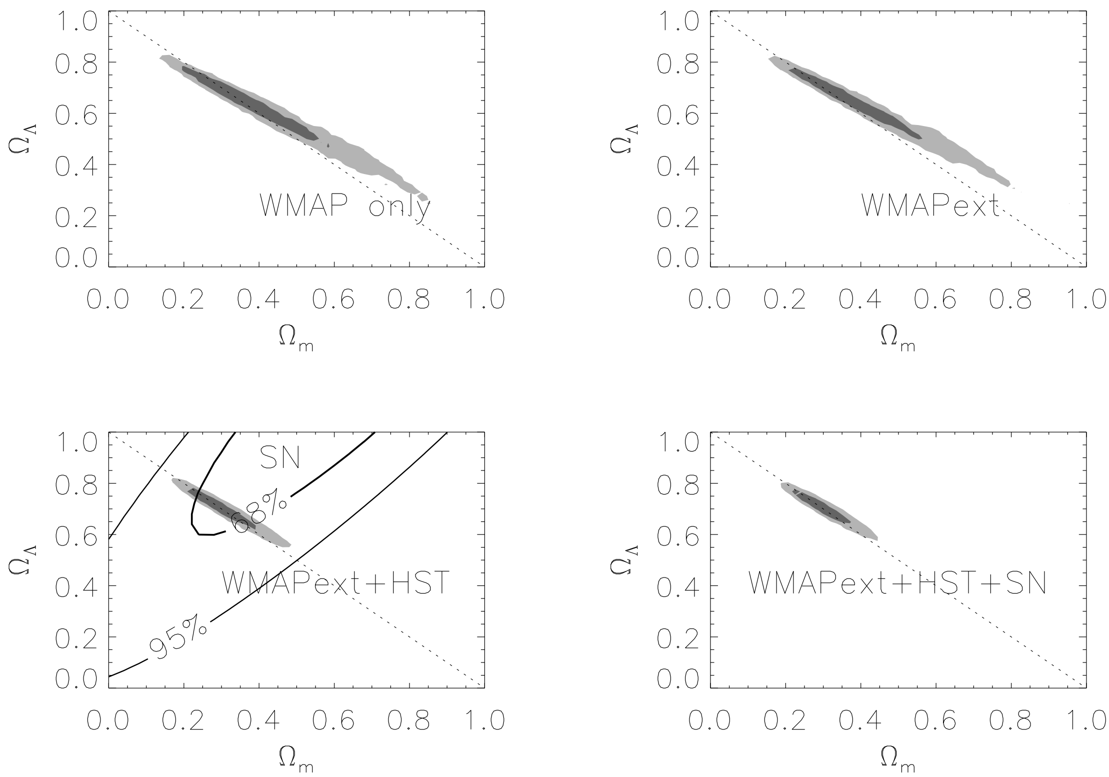
i.e., the Universe is flat, as predicted by inflation.

From the full shape of the angular power spectrum, more information about cosmological parameters, and in particular about:

Ω_B in very good agreement with BBN;

Ω_M, favored ~ 0.3 and inconsistent with ~ 1;

Ω_Λ, as the term matching Ω_M with Ω_{tot}.

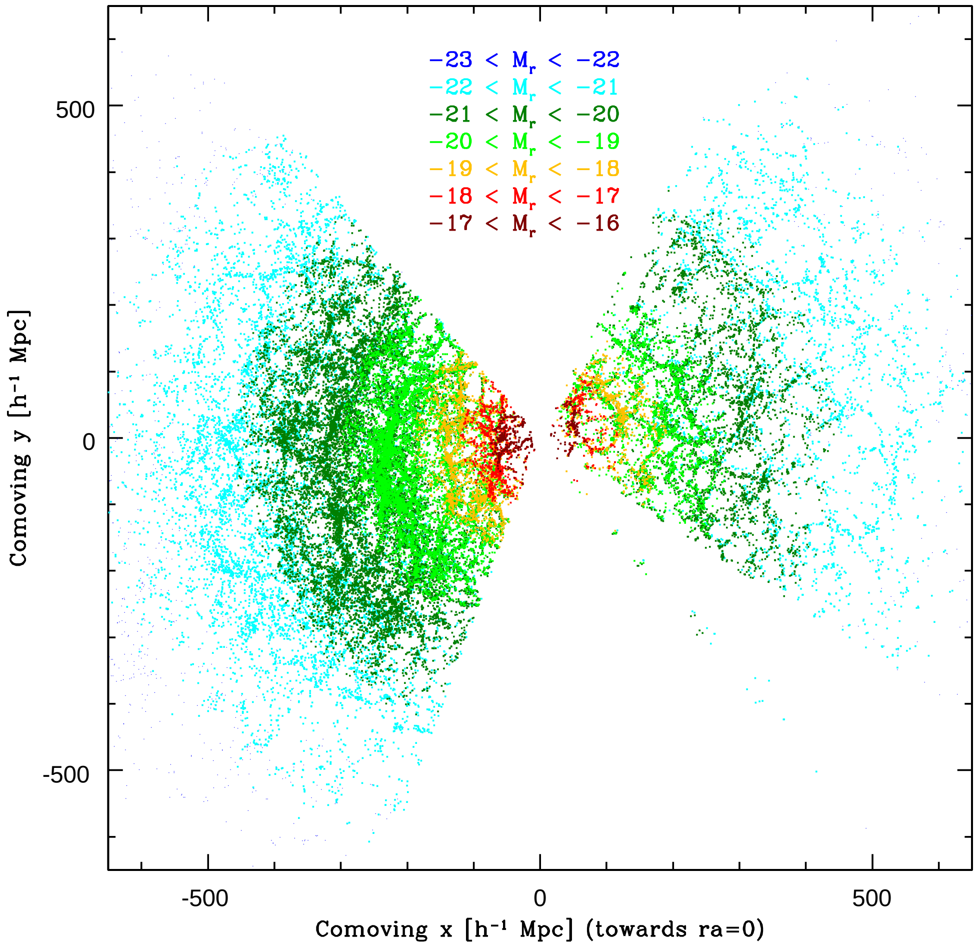


Spergel et al. (2003)

The latest goal:

mapping the large scale structure of the Universe

2dF (2002) and SDDS (2003) produced the first extended 3-D maps of the distribution of galaxies in the Universe, to be compared with predictions of the theory of structure formation.



Tegmark et al. (2003)

Structure formation discriminates between:

- the case of **hot dark matter** candidates, e.g., a massive but light neutrino, relativistic at the collapse epoch and free-streaming out of galaxy-sized overdense regions. This is a top-down scenario with very large structures forming early and then fragmenting into smaller ones;

- the case of **cold dark matter** candidates, with massive particles (GeV or heavier) moving with non-relativistic velocities at decoupling, forming structures in a hierarchical, bottom-up scenario.

Current data are consistent with the CDM picture (again with a $\Omega_\Lambda \sim 0.7$ term) and put rather tight upper bounds on a HDM term.

$\Longrightarrow$ neutrinos cannot the main dark matter component, and there is no viable dark matter candidate in the Standard Model of elementary particles.

Other routes to dark matter and dark energy as well, e.g.:

gravitational (weak or strong) lensing, observations of the Lyman-α forest, Sunyayev-Zel'dovich effect, ect.

Global best fit values of energy density terms Tegmark et al. (2004):

$$\Omega_{\rm tot} = 1.056 \pm 0.045$$

$$\Omega_\Lambda \simeq 0.73$$

$$\Omega_{\rm M} \simeq 0.27 \text{ made of:}$$

$$\Omega_{\rm B} \simeq 0.049 \text{ and } \Omega_{\rm CDM} \simeq 0.22$$

(again, for reference, $\Omega_{\rm stars} \simeq 0.005$)

The Universe is weird:

it has a simple (flat) geometry, but it is mostly made of dark energy that acts like a repulsive force, plus some CDM we did not find in labs so far, plus a baryonic term most of which does not shine and hence we cannot see.

Searching for the appropriate particle physics framework

Feedback from the astrophysical and cosmological observations on the particle physics model:

this is a typical exercise in astroparticle physics!

In the same way, e.g., BBN provided informations about the Standard Model of particles physics, before this was tested in detail at accelerators, dark energy and dark matter are most probably indicating the route to physics beyond the Standard Model.

At present:

• Plenty of candidates and detection strategies for dark matter.

• No detailed model fully working for dark energy, with several puzzling elements.