Particules Elémentaires, Gravitation et Cosmologie
Année 2008-'09

Gravitation et Cosmologie: le Modèle Standard

Cours 7: 6 fevrier 2009

Succès et énigmes de la cosmologie conventionnelle

- Early predictions about a CMBR
- Primordial nucleosynthesis & rel.^{ve} abundances
- The unexpected dark components
- Baryon asymmetry
- Singularities & limits of applicability of GR

Early predictions about a CMBR

The cosmic microwave background radiation (CMBR) was discovered accidentally in 1965 by Penzias and Wilson

However, since the 1940s, Gamow and coll. had realized that the Universe should now be filled with a black-body spectrum of electromagnetic radiation.

Their argument was that, because of its expansion, the Universe had been so hot in the past that photons and a plasma of electrons and nuclei (mainly protons) were in thermal equilibrium.

As the Universe cooled below T ~ 3000K, electrons and nuclei (re)combined into neutral atoms. Since then (recombination, decoupling, last scattering) photons kept their original Planck spectrum modulo a redshift of its temperature.

The first theoretical estimate (~1950) for the present temperature was 5K in quite good agreement with the first determination of 3.5±1.0 K. At that temperature the dominant wavelengths are in the so-called microwave range, hence the name of CMBR (more simply CMB).

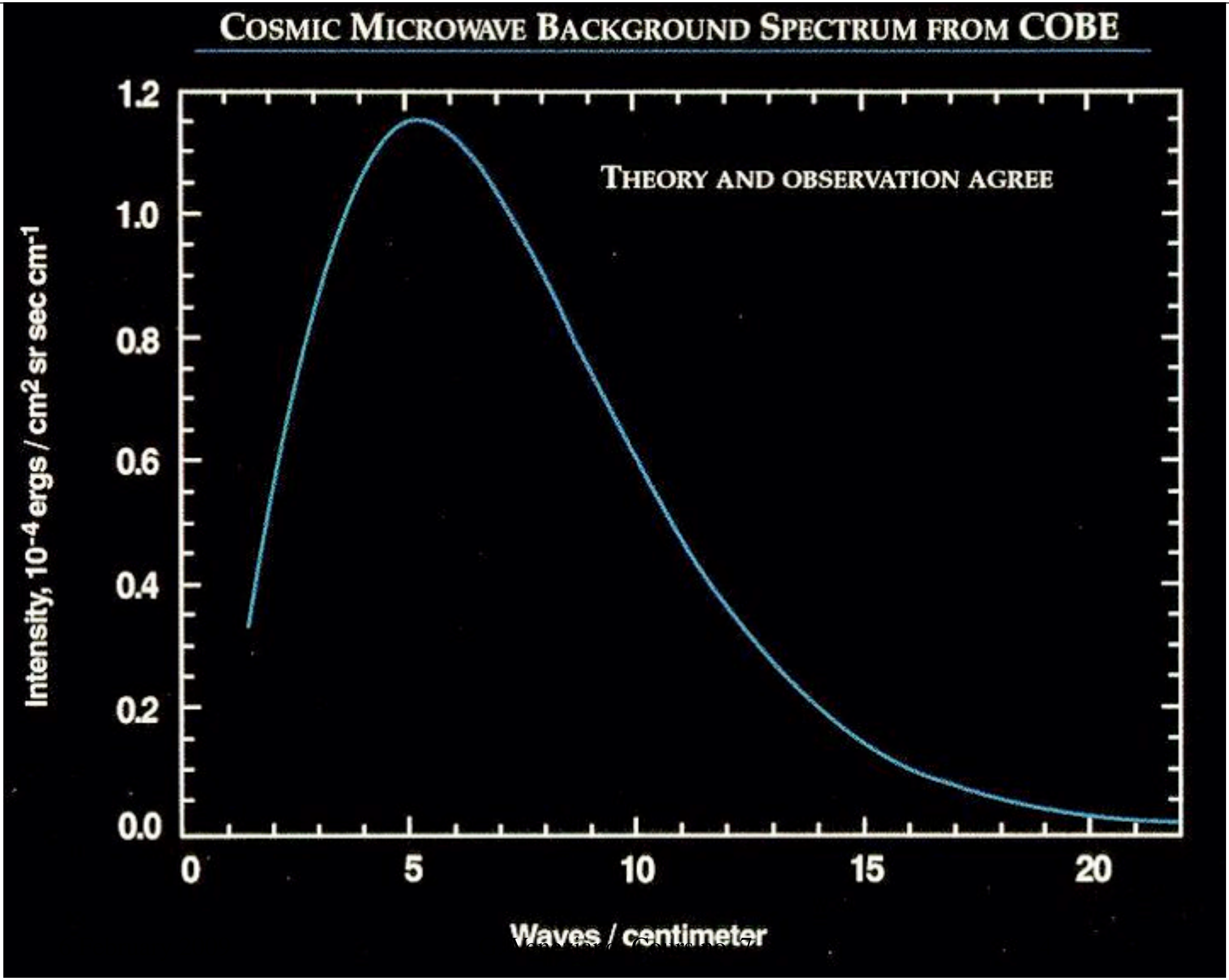
Today, the CMB spectrum is the best Planck spectrum known in Nature. Its average temperature (as we shall see there are fluctuations at the level of 10^{-5}) is 2.725±0.002K. The black-body photon's density is (c=1):

$$dn(\nu) = \frac{8\pi\nu^2 d\nu}{\exp(h\nu/k_B T) - 1}$$

This means 410 photons/cm^3 and an energy density

$$\rho_{\gamma,0} = 4.64 \times 10^{-34}\mathrm{gcm}^{-3} \Rightarrow \Omega_{\gamma,0} = 2.47 \times 10^{-5} h^{-2}$$

Predicting the CMB and its T was the first clear success of HBB cosmology!


COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter

Primordial (BB) nucleosynthesis

A second big success of HBB cosmology is that it provides a mechanism (BBN) for producing light nuclei*) (d, He, Li, ..) out of protons and neutrons. Temperatures of order 10^{10}K are needed for this to happen. The success of BBN is not just qualitative: we know the physics of the underlying processes, we can calculate the relative abundances of those light elements and compare them with the data.

Indeed, the successful predictions of BBN are often used to constrain different theoretical models. As an example, BBN requires that there can be (at most and barely) one extra standard neutrino (or its equivalent in relativistic species) besides the 3 already known ν_e, ν_μ, ν_τ.

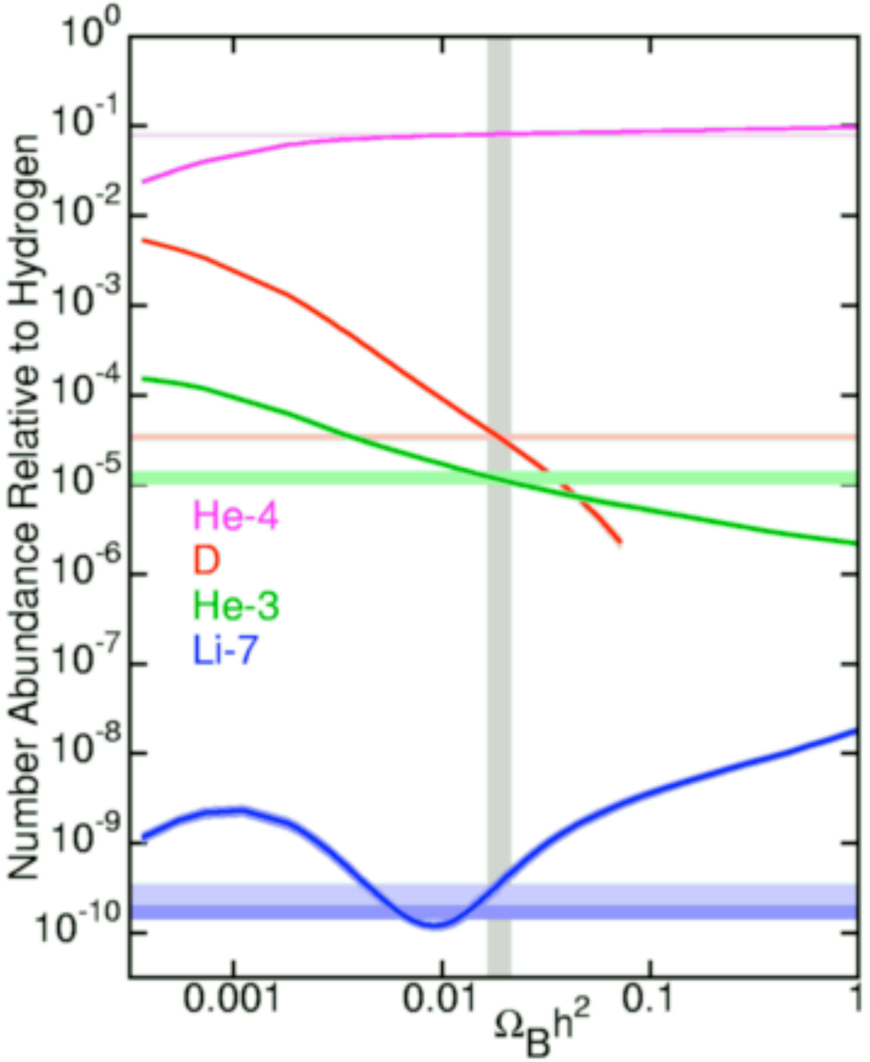
*) Heavier elements, like C, are believed to be produced much later in very hot and dense stars, like supernovae.

Different light nuclei are produced in steps through 2-body processes. First, protons and neutrons come in thermal equilibrium through weak-interaction processes involving electrons, positrons and neutrinos (e + p--> n + ν and the like)

Then the following chains of reactions:

$$p + n \to d + \gamma \quad ; \quad d + d \to H^3 + p \; ; \; d + d \to He^3 + n$$
$$d + H^3 \to He^4 + n \quad ; \quad d + He^3 \to He^4 + p \; ; H^3 + He^4 \to Li^7 + \gamma$$

end up producing mostly He^4 but also some leftover H^2, He^3 and Li^7 and of course protons (neutrons decay within τ ~ 886 sec.). Helium abundance in mass, $Y_p = 2 X_n$ = fraction of neutrons among all nucleons, is quite sensitive to the expansion rate at BBN time and this is why, through Friedmann's equation, it is sensitive to the number of light species in the primordial hot soup. It is also a test that certain "constants" were the same at BBN as they are today



Comparison with data

Horizontal bands correspond to experimental bounds;

Vertical band to allowed range for $\Omega_B \sim 0.021\ h^{-2}$

The unexpected dark components: I: dark energy

We have already mentioned the apparent necessity of a large fraction (70%) of the energy density in something having negative pressure ($w = p/\rho < -1/3$, $w \sim -1$?). This "dark energy" is supposedly distributed quite uniformly throughout space.

A possible candidate for DE is just the cosmological constant introduced by Einstein in 1917. However, the potential energy of a scalar field (called in this context quintessence) can do a similar job, while giving the possibility of a dynamical equation of state ($w = w(t)$). Future data on cosmic acceleration should be able to distinguish between these two alternatives.

The existence of dark energy, and even more its present magnitude, represents one of the biggest challenges ever met by (theoretical) physics. The reasons:

1. Quantum effects naturally induce a vacuum energy which is many many orders of magnitude larger than the observed value ($\rho_{vac} \sim \Lambda_{UV}^4$ vs. $(10^{-3}eV)^4$)... unless huge cancellations take place (e.g. if supersymmetry were exact bosonic and fermionic contributions to ρ_{vac} would cancel out, but SUSY breaking is way too large...)
2. Coincidence problem: Given that ρ_{vac} and ρ_m redshift so differently, how come they are of the same order today?

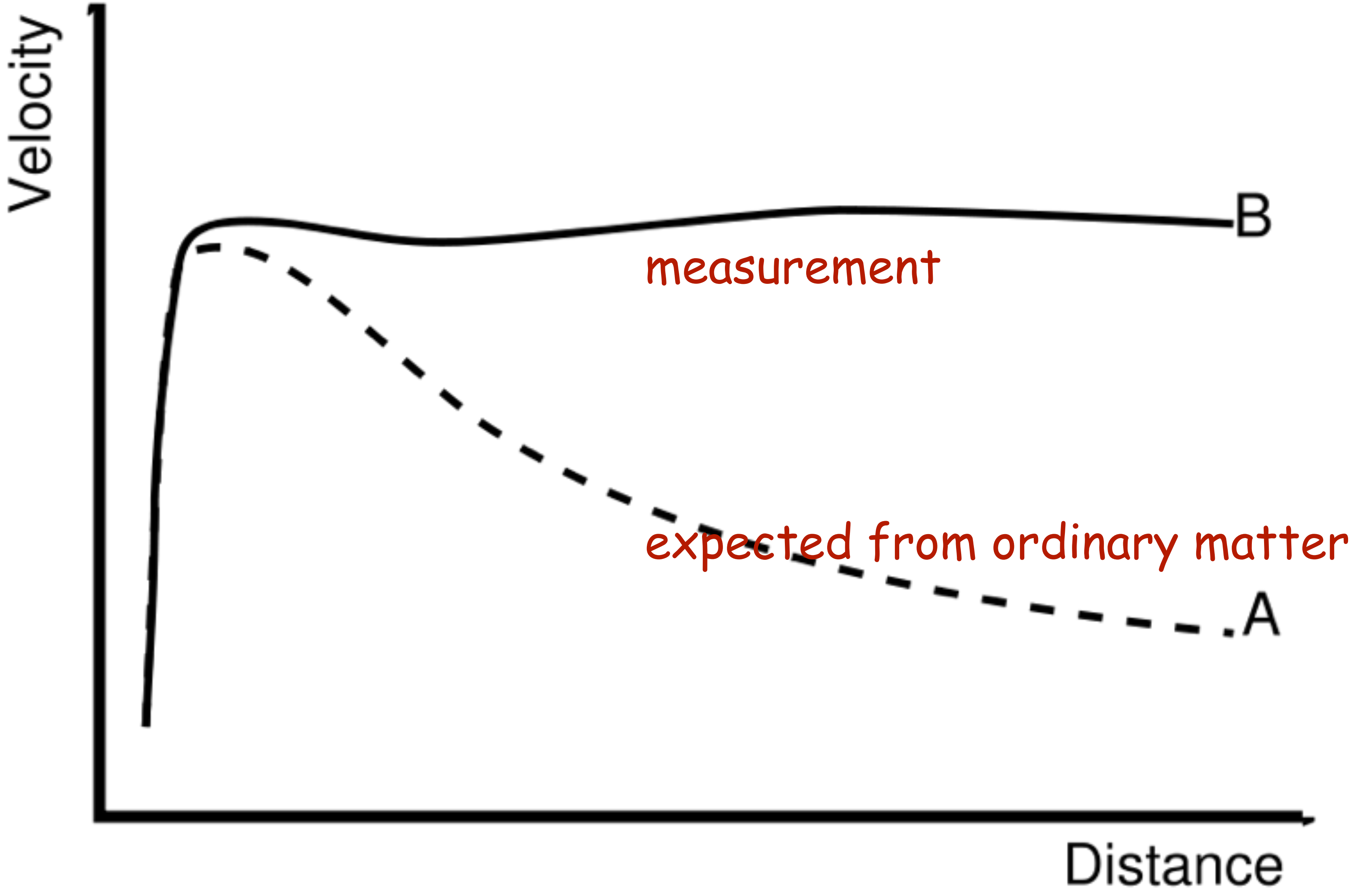
Does the solution lie in formulating a consistent theory of quantum gravity? So far string theory has not really provided new clues... a big disappointment!

The unexpected dark components: II: dark matter

The first indications for the existence of another strange form of energy, dark matter, came from the study of the rotation curves of galaxies.

Obviously, the higher the angular velocity the higher the acceleration and thus the (gravitational) force responsible for that acceleration.

If one looks just at the distribution of visible matter in galaxies, one finds that there is simply not enough of it to give such flat rotation curves: the angular velocity should decrease (as a function of the distance from the galactic center) much faster than observed.

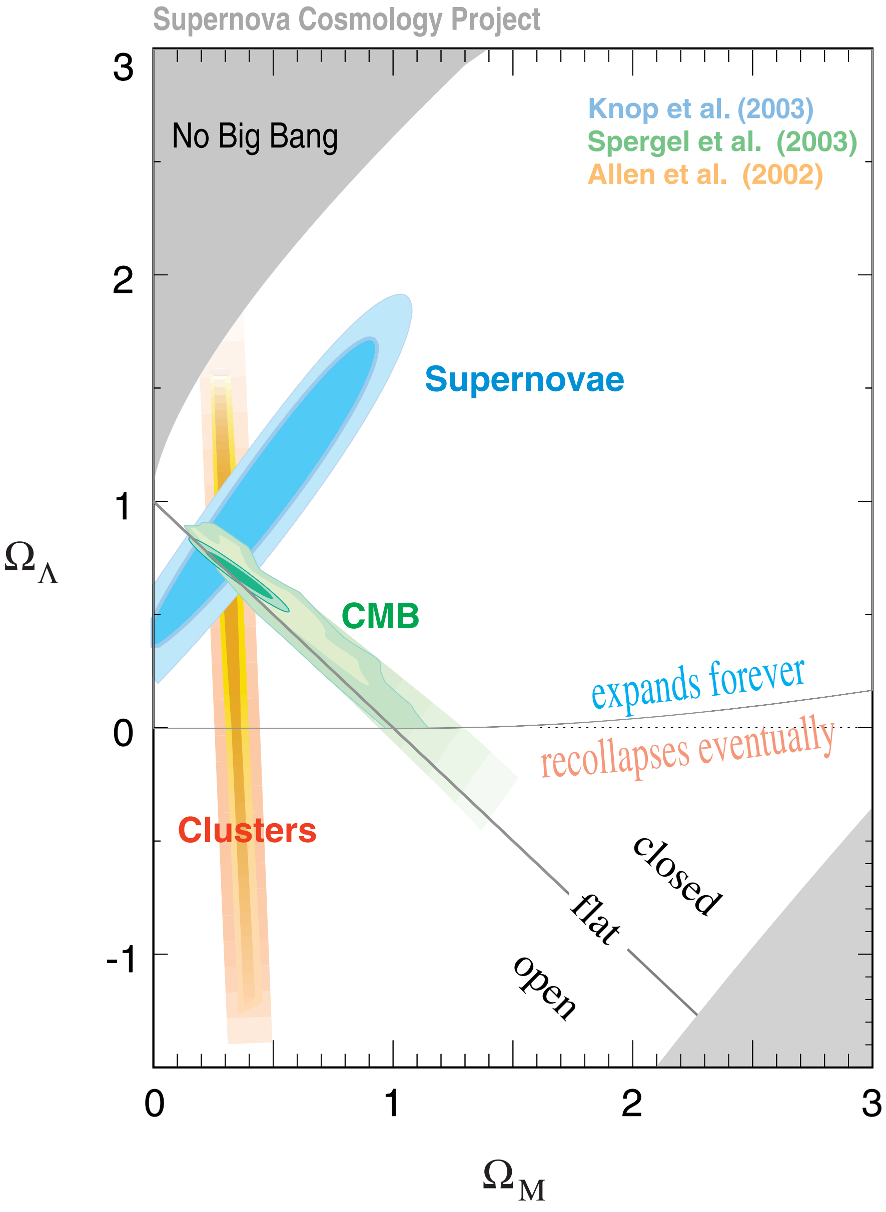

Velocity
B
measurement
expected from ordinary matter
A
Distance

This non-luminous (dark) matter, unlike dark energy, is supposed to have small pressure ($w \sim 0$, CDM) and to cluster roughly like ordinary matter.

It should mainly interact gravitationally (with, possibly, some other weak interaction) with ordinary matter

Its necessity also comes from other considerations:

1. One needs extra gravitating stuff in order to have successful many-body simulations for the formation of large-scale structures ($\Omega_m \sim 0.2$ while from BBN $\Omega_B \sim 0.021\ h^{-2}$)
2. The same comes out of CMB data (see next week, picture)
3. It cannot be baryonic, otherwise BBN is spoiled
4. Theoretical candidates: WIMPS, axions (LHC may help pinning it down!). The LSP is an excellent bet!


Supernova Cosmology Project
No Big Bang
Knop et al. (2003)
Spergel et al. (2003)
Allen et al. (2002)
Supernovae
CMB
Clusters
expands forever
recollapses eventually
closed
flat
open
3
2
1
0
-1
0
1
2
3
Ω_Λ
Ω_M

Baryon asymmetry

As far as we know, the $\Omega_B \sim 0.021\ h^{-2}$ worth of ordinary matter has no antimatter counterpart in our visible Universe.

Although antibaryons are known to exist (one famous CERN accelerator, leading to the discovery of the W and Z bosons, used collisions of protons with antiprotons, LEP used positrons) and to have almost identical interactions as baryons, our Universe appears to have done without them.

At present, there is no detailed model explaining quantitatively this baryon asymmetry, although we know, since the work of A. Sakharov in 1967, that three conditions are necessary: 1. Baryon-number violation; 2. C and CP violation; 3. Out-of-equilibrium processes

At least all three are qualitatively present!

Singularities and the limits of GR

One theoretically unsatisfactory aspect of GR is that it "likes" to produce singularities.

Theorems, due mainly to Hawking and Penrose in the seventies, tell us that, under quite general conditions, very innocent-looking initial (present) data develop later (or imply earlier) spacetime singularities.

Typical examples are the singularities that develop inside the horizon of a black hole (a singularity in time rather in space!) and, as we have seen, that of the big bang at t=0.

From a practical point of view these singularities are less harmful that one would have guessed: Nature appears to have provided “screens” for them (cosmic censorship).

In the case of Black Holes the singularities lie beyond the horizon and do not affect physics for observers living outside

For the cosmological (BB) singularity the situation is different but the theory of inflation has the “virtue” of washing out whatever preceeded the inflationary epoch. Hence, inflation can afford being agnostic as to whether there was -or there wasn’t- a BB singularity before the onset of inflation.

If any, our ignorance about the BB singularity limits our ability to determine the (rather peculiar) initial conditions for inflation.

From a more conceptual point of view, however, the ubiquitous presence of singularities in GR, does look like a serious theoretical limitation and one can ask whether one should trust this almost inevitable prediction of GR.

The answer is most likely negative.

Even without appeal to quantum effects (completely ignored in GR) we have already stressed that the Einstein-Hilbert action was based on a low-energy, low-curvature approximation allowing us to stop at the two-derivative level. General covariance per se certainly does not forbid terms like:

$$\Delta S_{\rm gr} = \int d^4x \sqrt{-g(x)} \left(\alpha R(x)^2 + \beta R_{\mu\nu} R^{\mu\nu} + \gamma R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} + \dots\right)$$

where α, β, γ are numbers O(1) (actually with the dimensions of h = Planck's constant). A trivial analysis shows that these terms become dominant when $R > (G\,\alpha)^{-1} \to l_P^{-2}$ if $\alpha \sim h$ ($l_P \sim 10^{-33}$ cm)

Estimates of quantum effects do lead to $\alpha, \beta, \gamma \sim h \log\Lambda_{UV}$ ...