L'UNIVERS: de son origine à nos jours

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The History of the Universe

It is a history of EXPANSION and cooling down.

EXPANSION: the space itself expands with the time.
All lengths grow as time goes on: wavelengths, distances between objects. Atoms and elementary particle sizes remain unchanged.

Cooling: temperature decreases as lenghts increase.

The expansion of the Universe started explosively fast: the Big Bang !!

The Big Bang has no center.
The Universe expands similarly at all space points.
This is very different to supernova explosions, atomic bombs or firecrackers.

Universe homogeneous and isotropic during 80 Myr.
Since then, structures (galaxies) form via dynamical gravitational processes.

Inflation and subsequent eras of the Universe

Main Events	Time from beginning	Tempe-rature	Expansion factor since beginning
Inflation	10^{-36} sec	10^{29} K	10^{28}
Protons & neutrons form	10^{-5} sec	10^{12} K	10^{45}
D, He, Li form	20 sec	10^{9} K	10^{48}
Non-relativistic particles dominate	57000 yr	8000 K	3×10^{53}
Atoms form	370000 yr	3000 K	10^{54}
Galaxies and Stars start to form	80 Myr	90 K	10^{55}
Today	13.7 Gyr	3 K	10^{57}

Standard Cosmological Model:

Ordinary Matter + Dark Matter + Cosmological Constant

- Begins by the inflationary era.
- Gravity is described by Einstein's General Relativity. Matter determines the spacetime geometry.
- Ordinary Matter described by the Standard Model of Particle Physics: $SU(3) \otimes SU(2) \otimes U(1) =$ qcd+electroweak model. Strong, electromagnetic and weak interactions involving quarks, gluons, baryons, electrons, photons and neutrinos.
- Dark matter plays a crucial role in galaxy and structures formation. DM is outside the SM of particle physics.
- Dark energy uniformely distribute in space. Described by the cosmological constant Λ.

The effective theory of inflation

Follows the ideas of Ginsburg & Landau who developed effective theories in other domains of physics: phase transitions, superconductivity...

Combining the effective theory of inflation with observational data from CMB anisotropies and large scale structures (> 1 Mpc) yields:

- Excellent description of the primordial power spectrum $P(k) = |\Delta^{(S)}|^2 \ \ k^{n_s - 1} \ , \quad k = 2\,\pi/\lambda \ , \ \lambda =$ wavelength. $n_s = 0.963 \pm 0.014 \ , \quad |\Delta^{(S)}| = (0.493 \pm 0.01) \times 10^{-4}$.
- Predicts as energy scale of inflation 10^{16} GeV $\sim 10^{29}$ K $\Longrightarrow$ Grand unification scale in particle physics.
- Predicts 4 to 5% of primordial gravitons (see later)

[Effective theory: valid on the relevant range of scales, not till infinite energy].

The Fossil Cosmic Microwave Background

Protons and electrons bind together forming neutral hydrogen by time $= 370000$ yr.
Since then the Universe became electrically neutral photons were free to travel across the Universe.
Photons temperature was then ~ 3000 K. Temperature today is $\simeq 2.725$ K (cooling down due to universe expansion).

Cosmic Microwave background almost homogeneous and isotropic with a black-body spectrum, plus small inhomogeneities $\sim 10^{-4}$.

Inflation is the only explanation for the CMB including these small fluctuations of quantum origin $\sim 10^{-4}$.
CMB fluctuations have unique information about the inflationary era, the first 10^{-36} sec of the Universe.

CMB anisotropies first detected in 1992 by COBE satellite.
Later data by Boomerang et al. and especially WMAP.

Primordial Gravitons detected from the CMB

Einstein's General Relativity predicts the existence of gravitational waves. Oscillations of the space-time itself.

Gravitational waves were produced in the inflationary era via quantum fluctuations (gravitons).

Effective theory of inflation gives a precise prediction for the amount of primordial gravitons produced:
4 to 5 % compared with the CMB temperature fluctuations.

Primordial gravitons much harder to detect in the CMB anisotropies than the known temperature fluctuations.

The Planck satellite will hopefully be able to detect the primordial gravitons (borderline !).

How the Universe took its present aspect?

The Universe was homogeneous and isotropic after inflation thanks to the fast and gigantic expansion stretching lenghts by a factor $e^{64} \simeq 10^{28}$.

The universe by the end of inflation is a extraordinarily hot plasma at $T \sim 10^{14}$ GeV $\sim 10^{27}$ K.

However, small ($\sim 10^{-5}$) quantum fluctuations were of course present.

These inflationary quantum fluctuations are the seeds of

- the structure formation in the universe: galaxies, clusters, stars, planets (and all on them), ...
- the CMB anisotropies today.

That is, our present universe (including ourselves) was built out of inflationary quantum fluctuations.

Universe Inventory Today

The universe is spatially flat.
Curvature is present in the space-time geometry.

Today: Dark Energy (Λ): 73 % , Dark Matter: 22 %

Baryons $+$ electrons: 4.5 % , Radiation ($\gamma + \nu$): 0.0085%

83 % of the matter in the Universe is DARK.

Total average energy density today (very dilute!):

$$\rho(\text{today}) = 0.947\ 10^{-29}\ \frac{\text{g}}{\text{cm}^3} = 5.31\ \frac{\text{GeV}}{\text{m}^3} = (2.528\ 10^{-3}\ \text{eV})^4$$

DM dominates in the halos of galaxies (external part).
Baryons dominate around the center of galaxies.
Most galaxies exhibit a gigantic black hole in the center.
Central black hole mass ~ 0.001 galaxy mass.
Galaxies form out of matter collapse via nonlinear gravitational dynamics.

What is the nature of the Dark Matter?

83% of the matter in the universe is Dark.
Only the DM gravitational effects are noticed and they are necessary to explain the present structure of the Universe.

DM (dark matter) particles are neutral and so weakly interacting that no effects are so far detectable.

Theoretical analysis combined with astrophysical data from galaxy observations as:

- observed galaxy densities and velocity dispersions.
- observed galaxy density profiles.
- surface acceleration of gravity in DM dominated galaxies.

points towards a DM particle mass in the keV scale called warm dark matter (WDM). keV = 1/511 electron mass.

NGC1073 Galaxy

Number of galaxies in the Universe $\sim 10^{11}$

Spitzer Galaxy

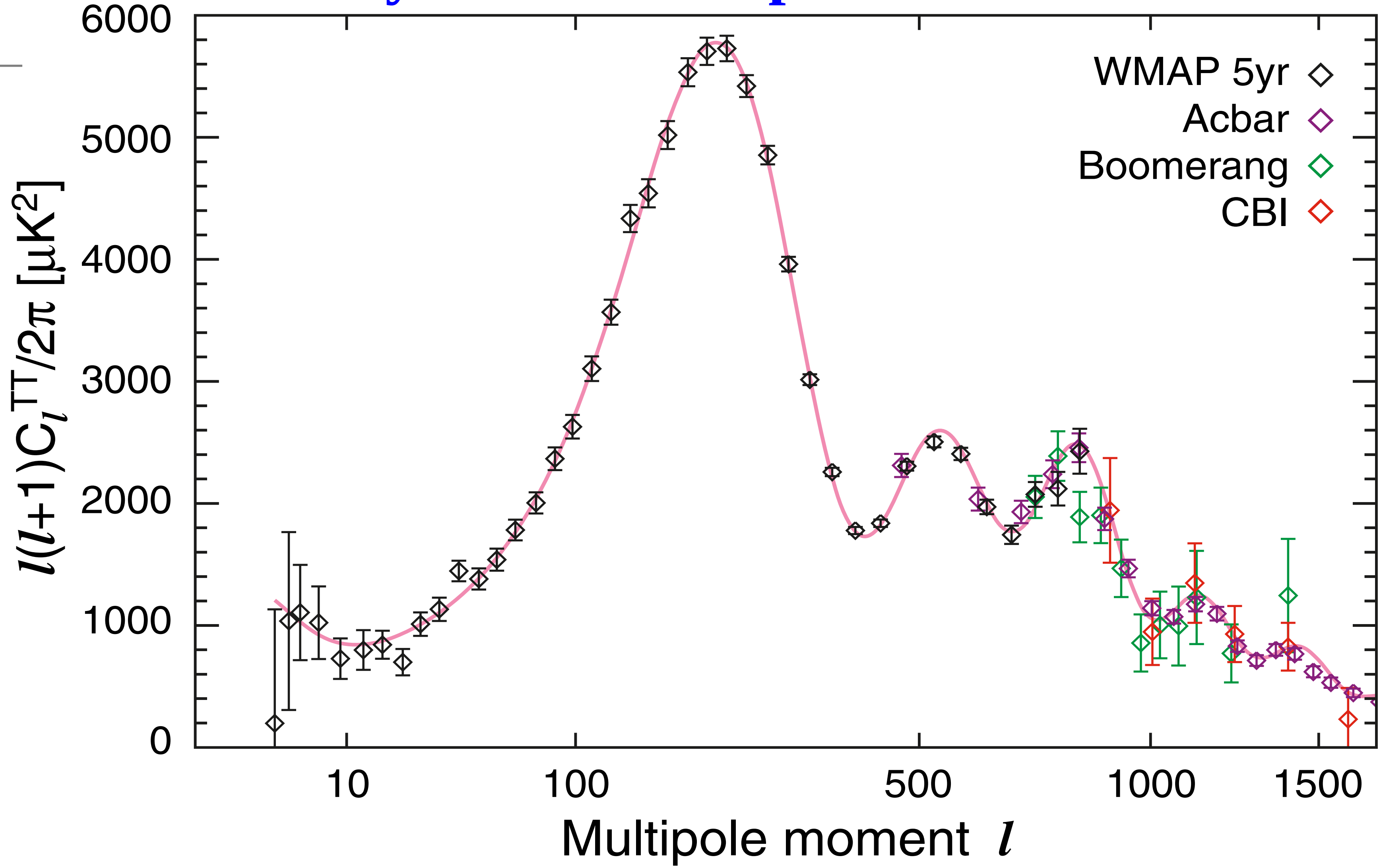
Abell 1689 cluster

The Universe is our ultimate physics laboratory !!

THANK YOU VERY MUCH

FOR YOUR ATTENTION!!

WMAP 5 years data set plus other CMB data



Theory and observations nicely agree except for the lowest multipoles: the quadrupole suppression.

Standard Cosmological Model: ΛWDM

ΛCDM = Warm Dark Matter + Cosmological Constant begins by the Inflationary Era. Explains the Observations:

- Seven years WMAP data and further CMB data
- Light Elements Abundances
- Large Scale Structures (LSS) Observations. BAO.
- Acceleration of the Universe expansion measured from Supernovas
- Gravitational Lensing Observations
- Lyman α Forest Observations
- Hubble Constant (H_0) Measurements
- Properties of Clusters of Galaxies
- Measurements of the Age of the Universe
- Galaxy structure only explained by WDM