Cosmology & Astroparticle Physics

CERN programme for teachers, 9 July 2009

Julien Lesgourgues
Theory Division, CERN
www.cern.ch/Julien.Lesgourgues

- What is cosmology ?

  ⇨ application of laws of physics to the whole universe in order to understand its global properties and evolution

- What is our current knowledge in this field ?

  ⇨ (brief) summary of 80 years of breakthroughs and discoveries…

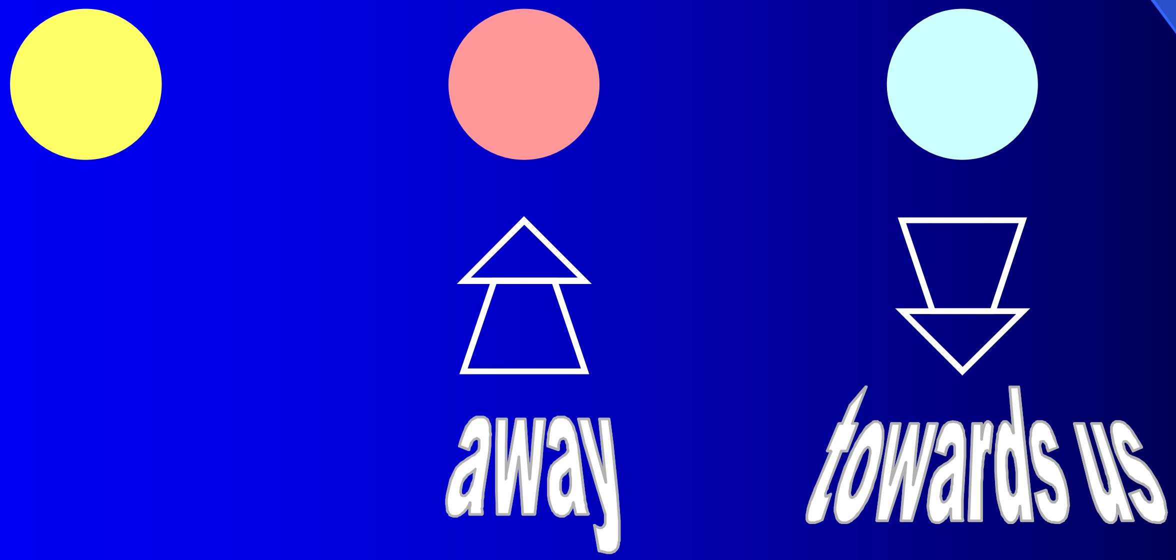
- Why studying cosmology at CERN ?

  ⇨ microcosm-macrocosm connection

modern cosmology summarized in eight points

1) Universe expansion

- Doppler effect for light:



1) Universe expansion

- Edwin Hubble (et al.), 1920's :

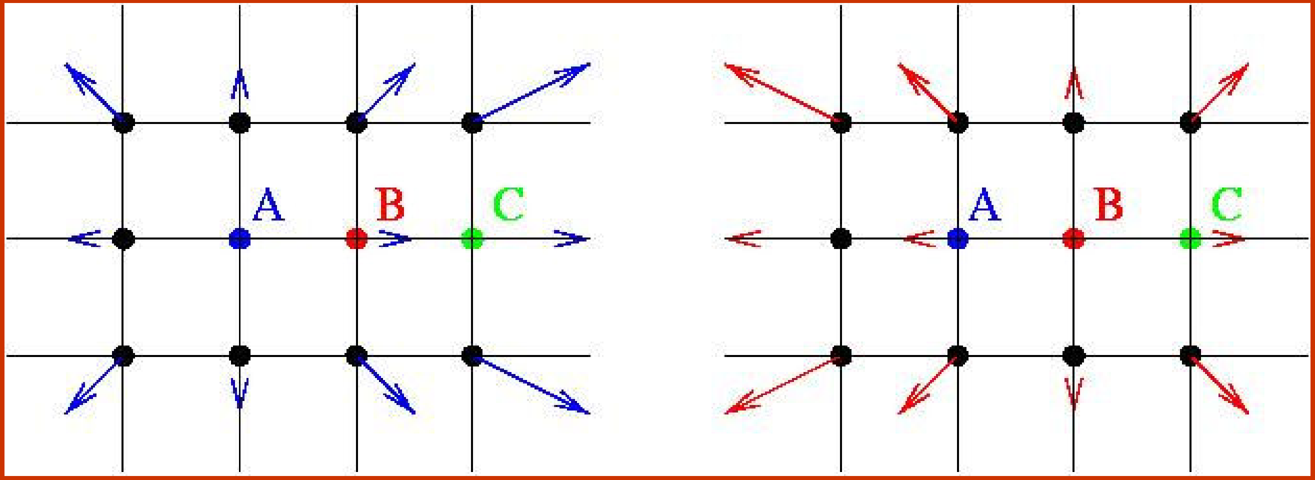
(observations at Mt Wilson, CA, 2.5m telescope)

- If we look far enough, most object are redshifted
- Redhsift roughly proportional to distance

1) Universe expansion

- Homogeneous expansion (without a center) :

like infinite rubber grid streched equally along all directions:



2) FLRW model

- 1916: General Relativity proposed by Einstein
- 1917: applied to whole Universe by Einstein himself with static Universe prior

- 1922-33: Applied to homogeneous, expanding Universe by Friedmann, Lemaitre, Robertson & Walker: FLRW model

Friedmann

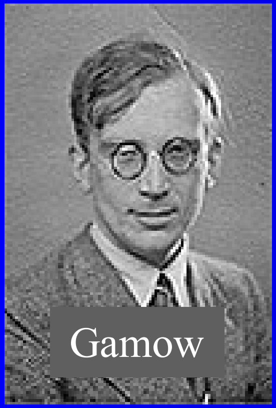
Lemaître

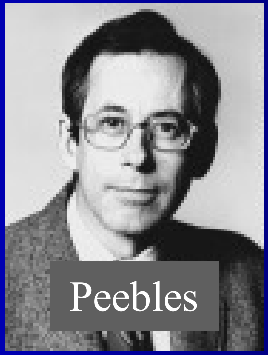
2) FLRW model

- General Relativity: Matter ⇔ Curvature of space-time
- FLRW model: given that Universe is homogeneous "on average", its own matter content can only induce two types of space-time curvature:
  1) <u>Homogeneous spatial curvature</u>:
     - R=0: flat, Euclidian — sum of triangle angles = 180°
     - R>0: closed (3-sphere) — " > 180°
     - R<0: open (3-hyperboloid) — " < 180°
  2) <u>Global expansion</u>: scale factor a(t) describes increase of all distances
- Redshift = streching of wavelength of light rays
- Matter ⇒ expansion ⇒ dilution ⇒ slow-down of expansion

3) Nucleosynthesis

- 1940's to 60's: progresses in nuclear physics
- Some pioneers try to combine FLRW model with nuclear physics:





- Provide a precise description of the formation of atoms

3) Nucleosynthesis

- Hot Big Bang scenario:
  - density decreases with time
  - backward in time, initial singularity: infinite density
  - <u>Two stages of expansion:</u>
    - After singularity, energy of relativistic particles (photons, neutrinos) dominates: RADIATION DOMINATION. This energy dilutes very quickly with expansion.
    - At some point, energy of non-relativistic particles ($E=mc^2$) dominates: MATTER DOMINATION.
  - <u>Three phases for the "state of matter":</u>
    1) Density too high for nuclei.
       Mixture of protons, neutrons, electrons, photons, neutrinos.

    ⇒ NUCLEOSYNTHESIS

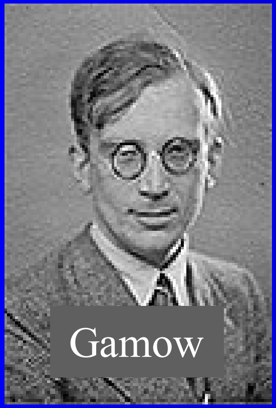
    2) Density still too high for atoms.
       Mixture of nuclei (H, He, Li, etc.), electrons, photons, neutrinos.

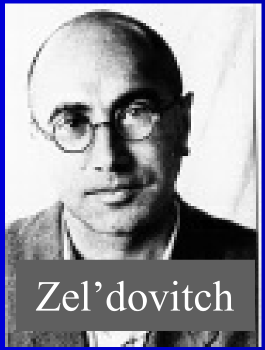
    ⇒ RECOMBINATION

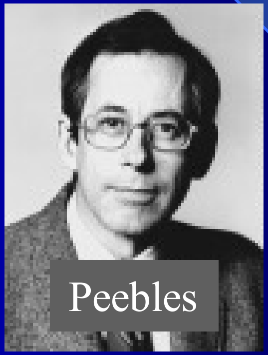
    3) Small density. Mixture of atoms, photons, neutrinos.

3) Nucleosynthesis

- 1940's to 60's: first models of nucleosynthesis:







- Main result: relation between:
  - Photons density / non-relativistic matter density
  - Amplitude of helium / hydrogen in the Universe

- Prediction of a "Cosmic Microwave background" emitted at recombination (homogeneous EM background with wavelength~mm, T~a few Kelvin)

4) Cosmic Microwave Background

- 1964: A. Penzias & R. Wilson, Bell laboratories

- T ~ 3 Kelvin

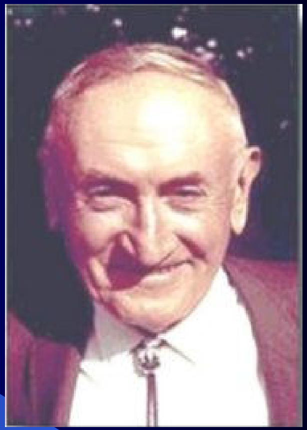
4) Cosmic Microwave Background

- 1964: A. Penzias & R. Wilson, Bell laboratories

A. Penzias (Bell) ⇔ B. Burke (MIT) ⇔ Ken Turner (MIT) ⇔ R. Dicke, J. Peebles (Princeton)

- Nobel prize for Penzias & Wilson in 1978

5) Dark Matter



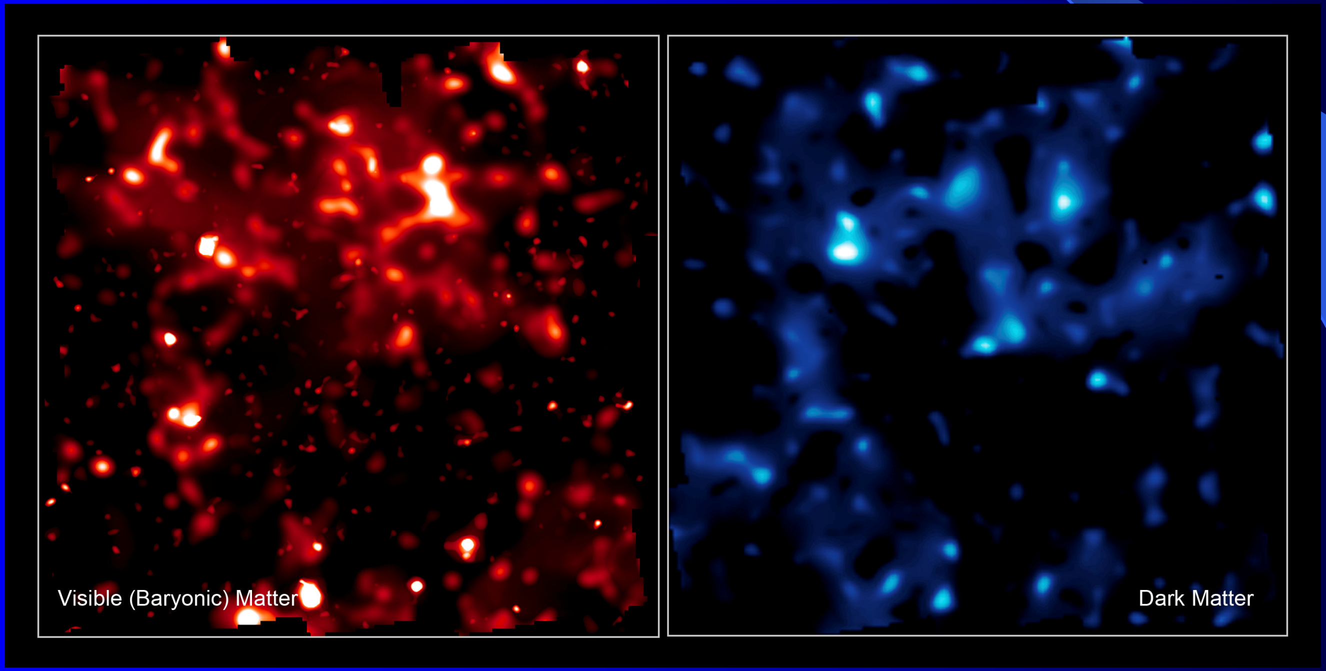
- 1933: F. Zwicky notices unconsistency in galaxy rotation curves and proposes the existence of:

DARK MATTER = unknown type of matter manifesting itself through gravitational forces, but uncoupled to the rest of matter (hence invisible: cannot emit/reflect photons)

- 90's - today:
  - Various astrophysical observations confirmed the existence of dark matter
  - Nature still unknown (cannot be atoms neither massive neutrinos)

5) Dark Matter

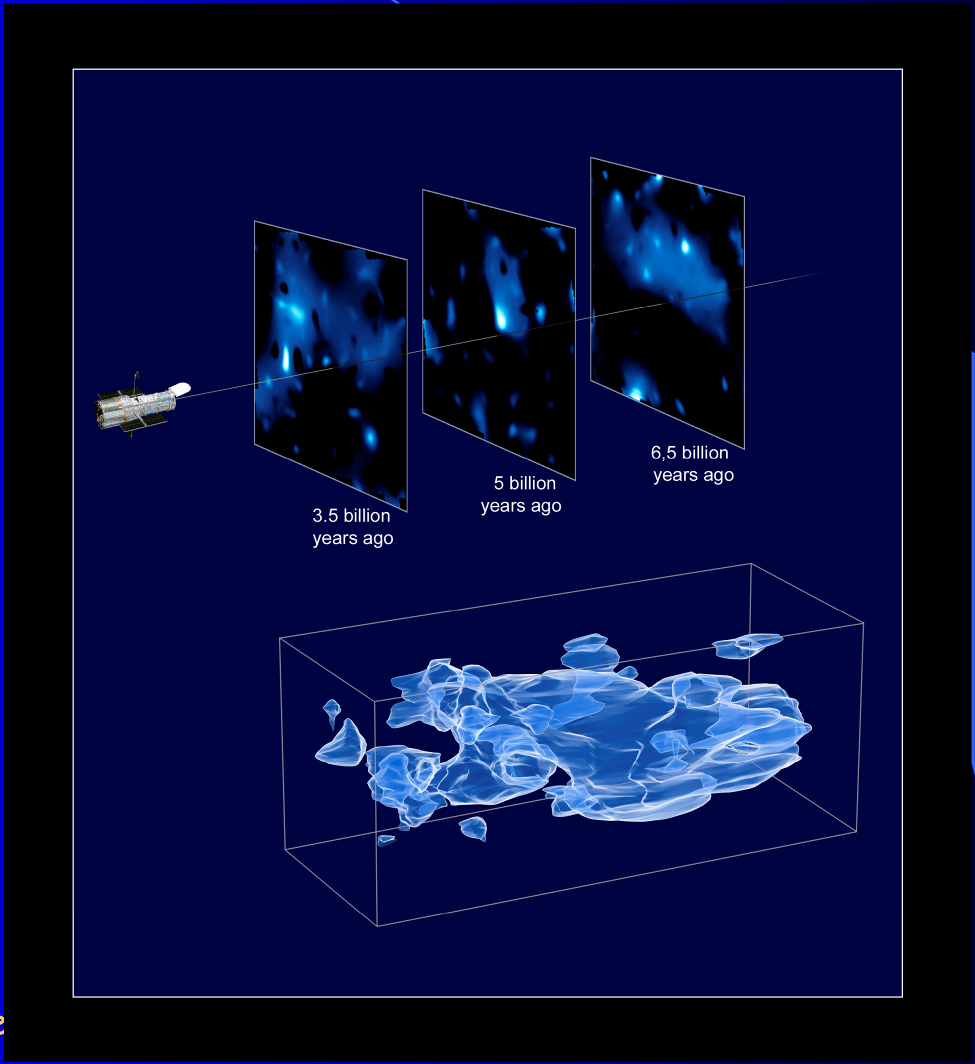
- Indirect map of dark matter through gravitational lensing:



January 2007 results by COSMOS, based on HST

5) Dark Matter

- Indirect 3D map of dark matter through gravitational lensing:



January 2007 results by COSMOS, based on HST

6) Dark Energy

- FLRW model: since matter dilutes, expansion is decelerated…
- … unless expansion is driven by some strange form of energy which cannot dilute (like a vacuum energy)

- How to measure a(t) and check the deceleration? With luminosity-redshift diagrams…
  - In everyday life: luminosity decreases with square of distance
  - In accelerating Universe: depends on a(t)
  - Can be checked with “standard candles”: Type Ia supernovae

6) Dark Energy

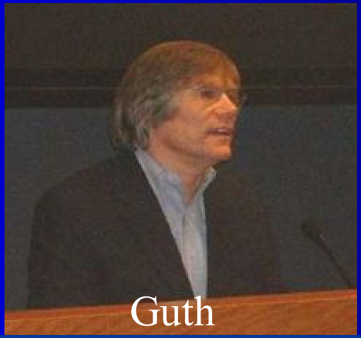
- 1998: Supernovae Cosmology Projecy (S. Perlmutter et al.)
  - Evidence for accelerated expansion! First convincing evidence in favor of:

DARK ENERGY = unknown type of matter which energy does not dilute with the Universe expansion, causing its acceleration

  - Most probably, dark energy has been driving the expansion only in the “recent” universe, after radiation domination and matter domination

7) Inflation

- 1979: A. Starobinsky and A. Guth find a solution to various problems present in the Hot Big Bang scenario:
  - Large-scale homogeneity violates causality principle
  - It is a coincidence that space is not very strongly curved
  - We should see a high density of strange objects ("monopoles")
  - We don't know how the first inhomogeneities (= seeds of stars, galaxies, clusters…) formed



7) Inflation

- Solution: a stage of accelerated expansion in the very early universe, before radiation domination
- First inhomogeneities form through quantum mechanics effects, and are streched to macroscopic scales during inflation
- Their evolution can be :
  - exactly predicted till recombination (need a computer)
  - approximately predicted till today (need supercomputers)

… "universe simulators"

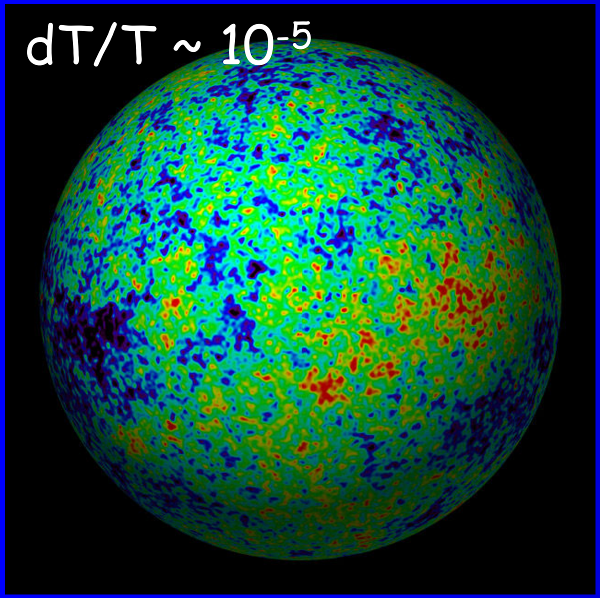
8) CMB anisotropies

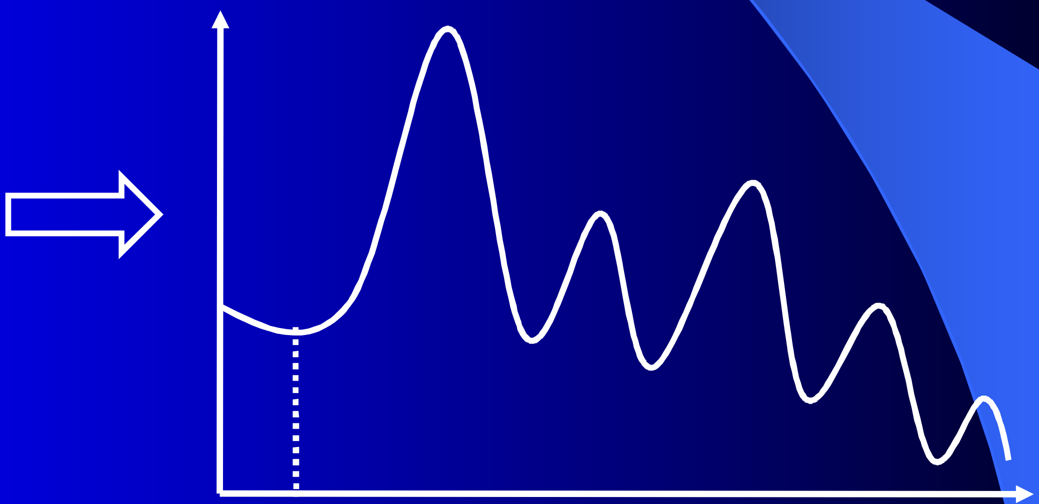
- Inhomogeneities should be present at recombination, when CMB is emitted : T~3K not exactly uniform ?
- Statistical properties are very special and entirely predictible
- What do we mean by statistical properties?
  - Sound of an instrument
  - Light source
  - CMB temperature fluctuations in the sky

  $\Rightarrow$ frequency spectrum, harmonics

8) CMB anisotropies

- Predictions of cosmologists in the 70's, 80's, 90's:

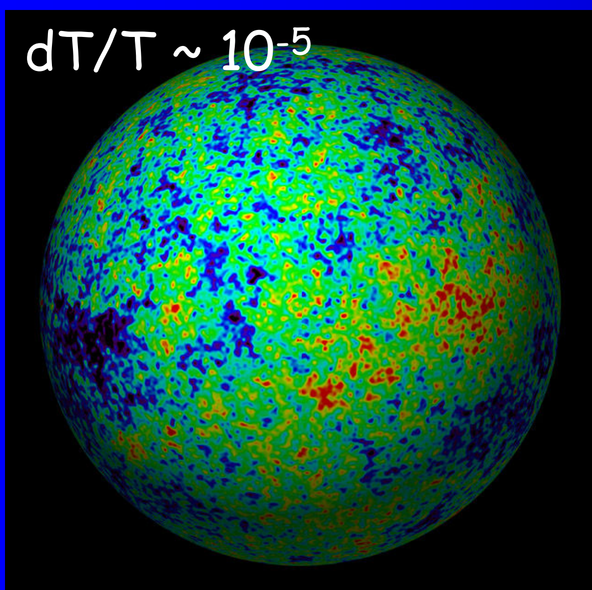


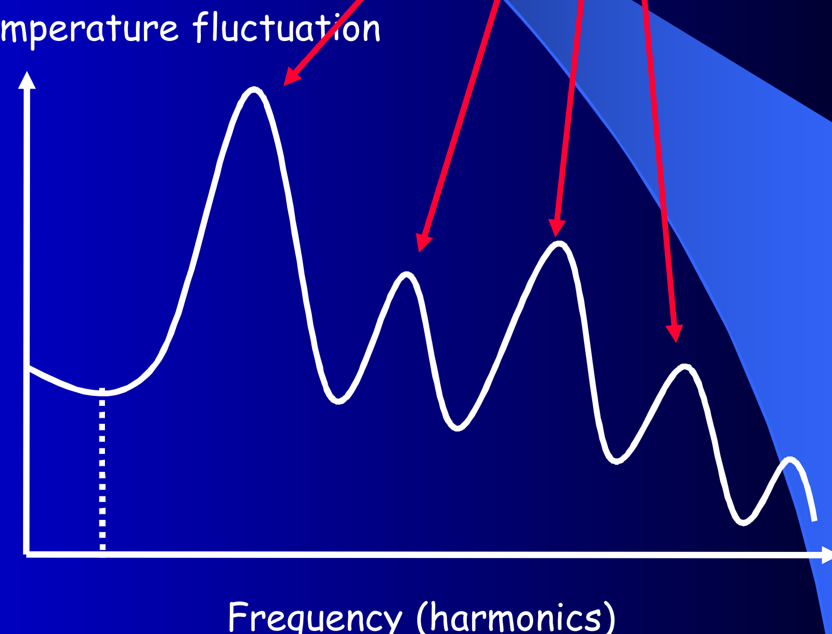


8) CMB anisot

- Predictions of cosmologists in the 7

Peaks
(acoustic waves in
early universe with
smallest possible frequency:
age of Universe
at recombination time,
380.000 yr)

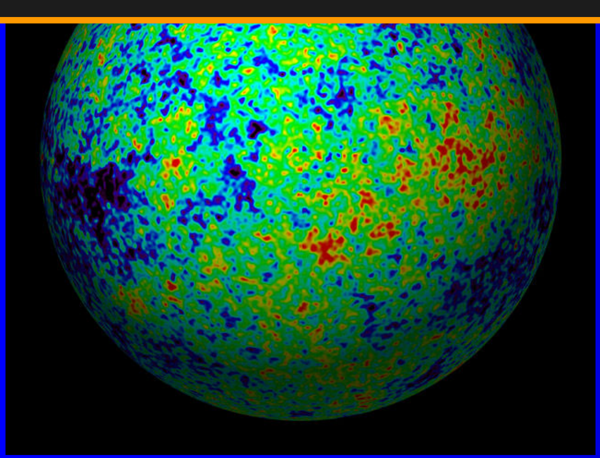


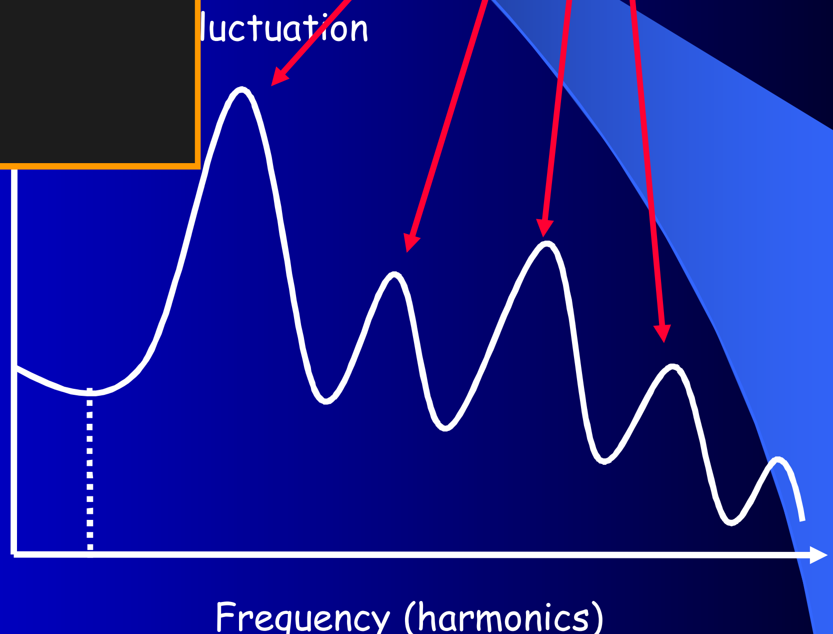


8) CMB anisot

Details of this spectrum
depend on precise cosmological evolution:
density of ordinary matter, dark matter,
dark energy, spatial curvature, neutrinos,
+ age of universe
+ dynamics of inflation
… A GOLD MINE !!!

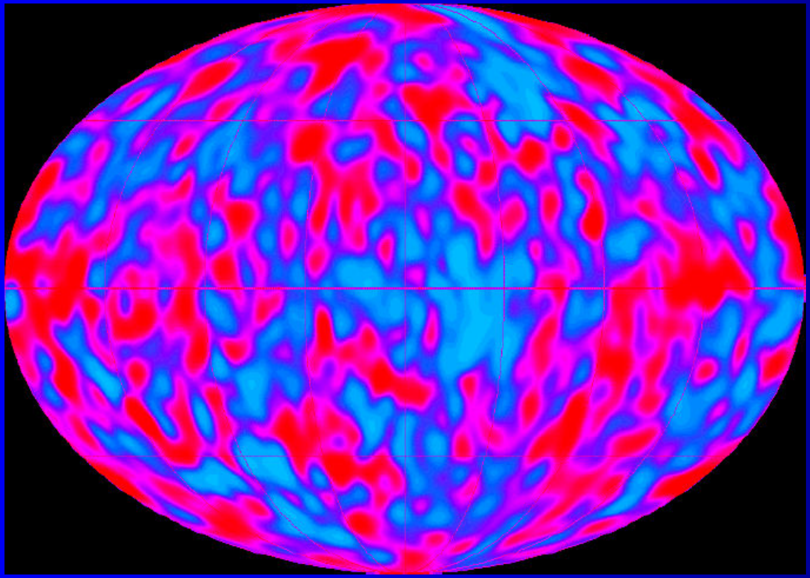
Peaks
(acoustic waves in
early universe with
smallest possible frequency:
age of Universe
at recombination time,
380.000 yr)

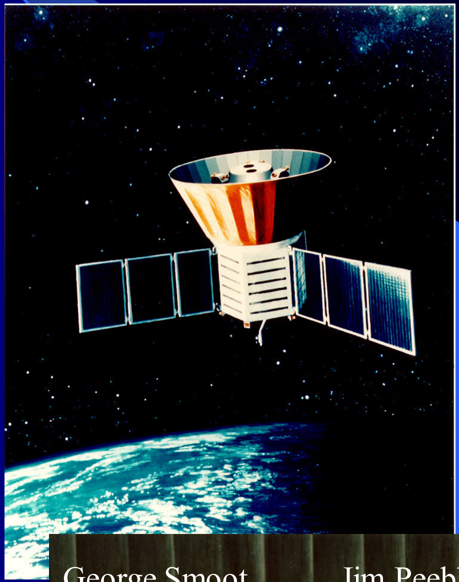




8) CMB anisotropies

- 1992: COBE sees fluctuations for first time ($dT/T \sim 10^{-5}$)

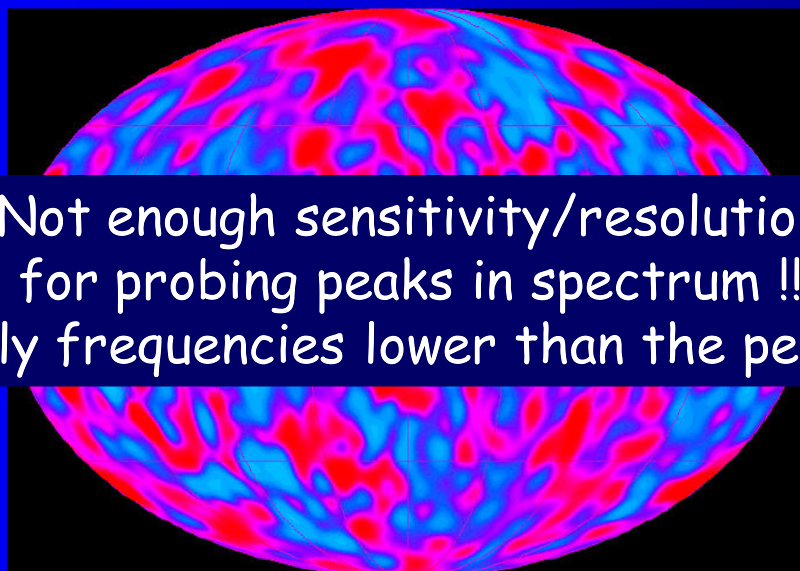




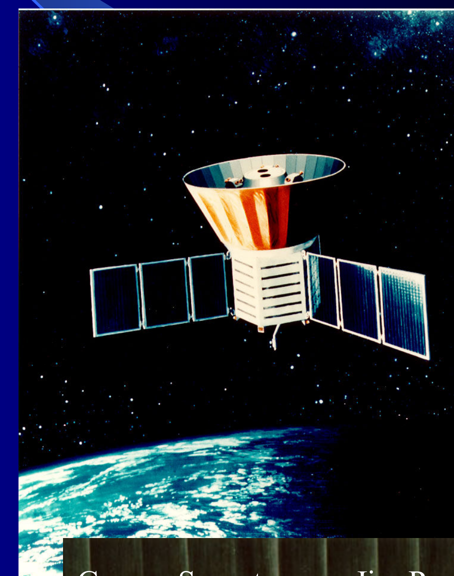
- first "picture of the baby Universe"
- Nobel prize to G. Smoot in 2006

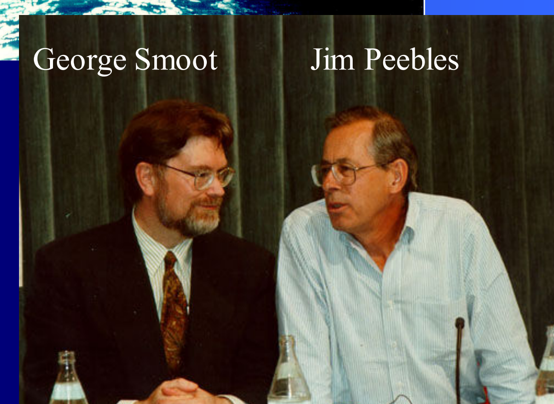
8) CMB anisotropies

- 1994: COBE sees fluctuations for first time ($dT/T \sim 10^{-5}$)



Not enough sensitivity/resolution
for probing peaks in spectrum !!
(only frequencies lower than the peaks)

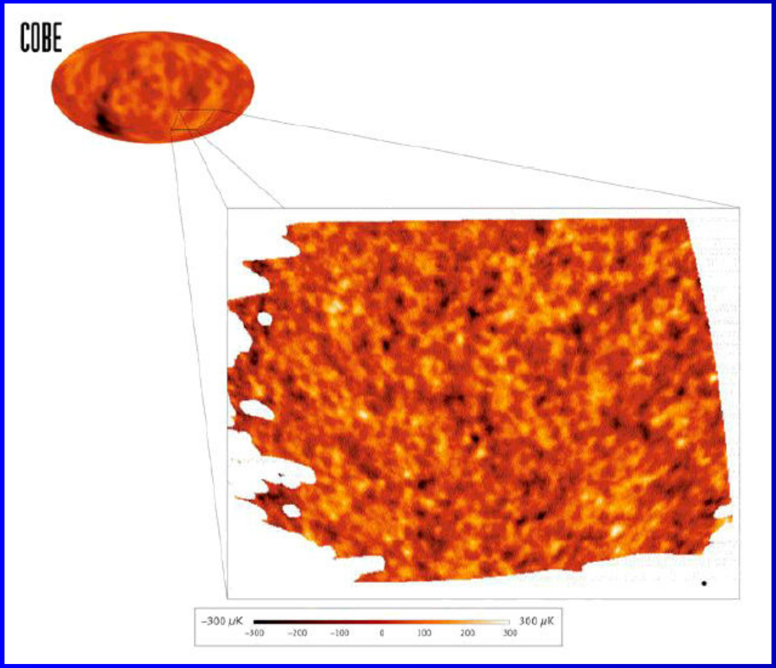


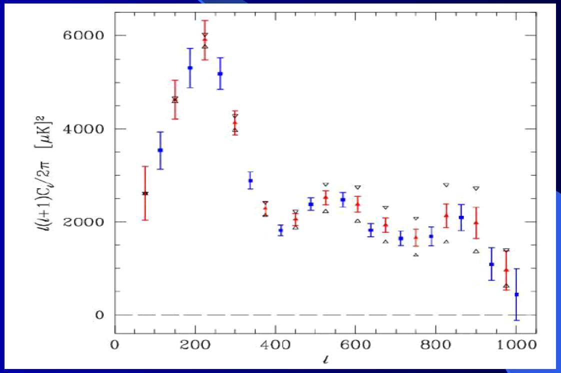


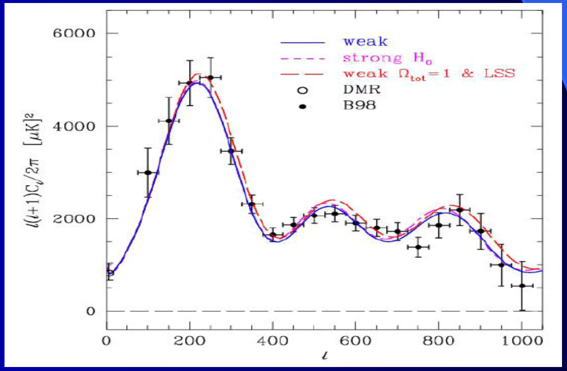
- first "picture of the baby Universe"
- Nobel prize to G. Smoot in 2006

8) CMB anisotropies

- 2000: Boomerang

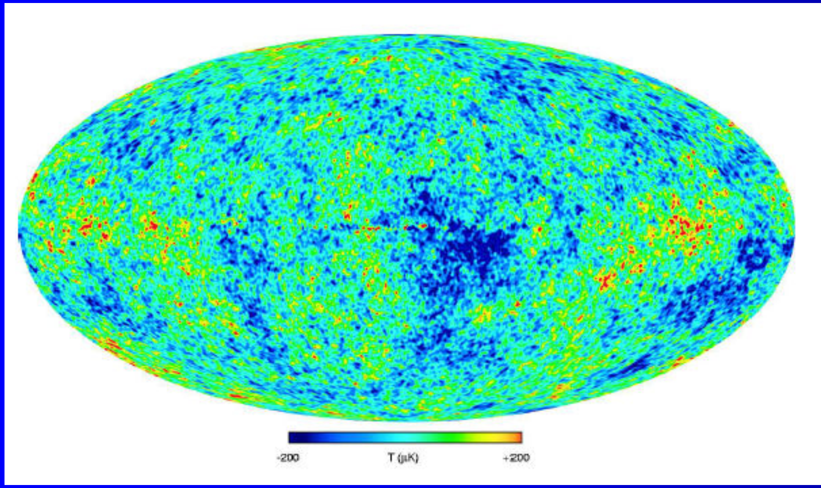


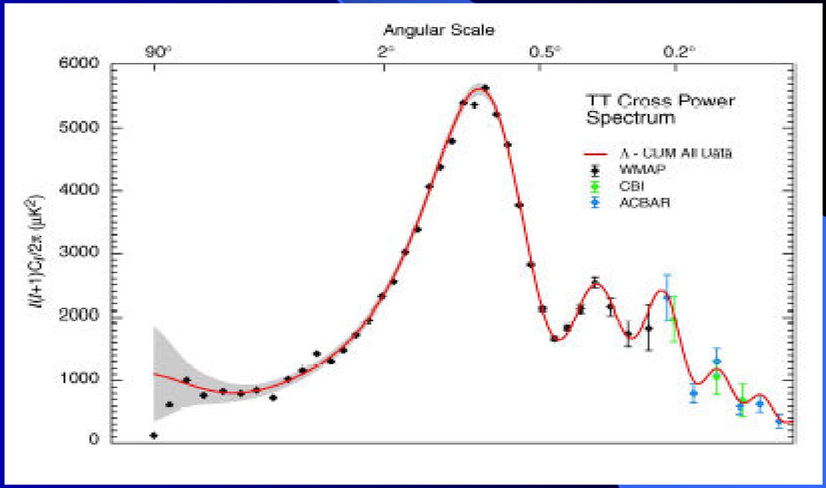




8) CMB anisotropies

- 2003 - now: WMAP

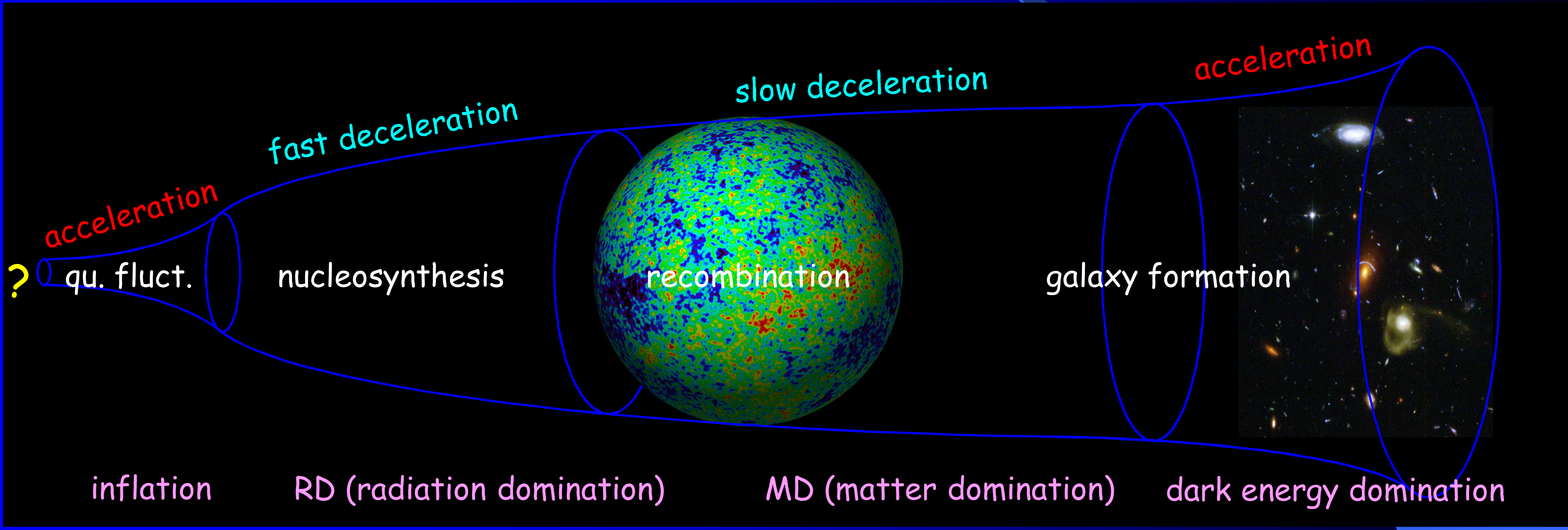




8) CMB anisotropies

- conclusions from CMB spectrum:
  - cosmological model works (inflation + hot big bang + DM + DE)
  - Universe aged 13.7 billion year (recombination: 380 000 yr, nucleosynthesis: few seconds)
  - Nearly or exactly flat
  - Today:
    - 5% ordinary matter,
    - 25% dark matter,
    - 70% dark energy,
    - small neutrino background

Summary


acceleration
fast deceleration
slow deceleration
acceleration
?
qu. fluct.
nucleosynthesis
recombination
galaxy formation
inflation
RD (radiation domination)
MD (matter domination)
dark energy domination

Paradox of modern cosmology

- Composition and evolution now known with exquisite precision
- We learnt that 70 + 25 = 95% of the universe is of mysterious, unexplained nature !!!
  - New particles? New laws of physics?
  - Raises very same questions as particle physics…

Microcosm-macrocosm connection
(and why cosmology is also present at CERN)

- First connection: dark matter
  - Cosmology & astrophysics found evidence for dark matter, opening a challenge for particle physicists: find a new stable, non-interacting particle
  - Viability of each new candidate tested both by particle physicists and cosmologists:
    - PP: Is it stable? Natural? Compatible with previous experiments?
    - C: Is the particle produced at the right time? Is its relic density in agreement with CMB? Does the particle leave an imprint on inhomogeneities? Is it compatible with galaxy formation? With cosmic rays? With supernovae explosions? Etc.
  - Case of neutralino, axions, ...; many other candidates excluded through cosmological arguments (e.g. massive neutrinos, ...)

Microcosm-macrocosm connection
(and why cosmology is also present at CERN)

Astroparticle physics = study of known/hypothetical particles in cosmological context

If evidence for new particle(s) discovered at LHC, careful interpretation requires dialog between particle physicists and cosmologists

Microcosm-macrocosm connection
(and why cosmology is also present at CERN)

- Second connection : dark energy
  - two challenges for particle physicists:
    - Why vacuum energy so small
    - Why still non-zero
  - New particle (ultra-light boson: $m \sim 10^{-33}$ eV)?
  - Non-standard interactions of known particles?
  - Need better understanding of quantum field theory/ vacuum energy?
  - Departure from Einstein's gravity (general relativity)?
  - Extra dimensions?
  - Artifact; need better understanding of cosmological scenario?

Microcosm-macrocosm connection
(and why cosmology is also present at CERN)

- Second connection : dark energy
  - two challenges for p
    - Why vacuum energ
    - Why still non-zero
  - New particle (ultra-l
  - Non-standard intera
  - Need better underst
    energy?
  - Departure from Eins
  - Extra dimensions?
  - Artifact; need bette

Many of these assumptions
might be testable in accelerators

Dark energy is a field
in which frontier between
particle physics and cosmology
is almost absent

Microcosm-macrocosm connection
(and why cosmology is also present at CERN)

- Third connection : inflation
  - Took place at very high energy: between electroweak phase transition and grand unification
  - Possibly, scale of supersymmetry breaking
  - Possibly, just below string scale

  - Cosmology offers opportunity to understand the dynamics of one of the above symmetry breaking: complementary to accelerators in the quest for a high-energy "grand unfied theory" or "theory of everyhting"