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lecture cource on

Astroparticle physics

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10 Cosmic microwave background

Content

10.0 Big Bang and CMB

General

- The cosmic microwave background and nucleosynthesis are the two most important supports for the Big Bang theory
- The third is expanding universe

- Cosmic microwave background is unique and rich source of information on several astrophysical and cosmological questions
  - in principle, it is possible to find out exact circumstances of the universe 380000 years after the Big Bang

10.0 Big Bang and CMB

The beginning of the Big Bang in short

- The universe started to expand 13.7×10^9 years ago from a hot and dense point
- At the age of approximately $10^{-37} - 10^{-35}$ seconds, a fast and short phase called inflation took plase
  - produced tiny inhomogenities (temperature variations) in the hot and homogenous (baby) universe
  - these inhomogenous regions later on developed into galaxies and other structures
- During the expansion the universe was cooled down

10.1 Cosmic microwave background

General

- The existence of cosmic microwave background was predicted by George Gamow, Ralph Alpher and Robert Herman (1948–1949)
  - $T_{\mathrm{CMB}} \sim 5$ K
  - did not rised much of interest, was forgotten

- After inflation, the young universe was hot and full of radiation and particles
- The inhomogenities tend to grow (by gravitation) to form larger "structures" (nuclei, atoms)
  - as soon as a larger structure was formed it was destroyed by the radiation
- After $\sim$3 mins, the expansion had cooled down the universe such that protons were able to fuse (to form helium nuclei)
  - $\sim 10^9$ K
  - era of Big Bang nucleosynthesis (H and He were created)

10.1 Cosmic microwave background

How was it formed?

- After 380000 years
  - the expanding universe was cooled down to approximately 3000 K
  - the radiation pressure was not able to destroy atoms any more (to break down electrons from protons)
  - first ("stable") hydrogen and helium atoms were formed
- Recombination
  - when electrons were attached on protons the matter and radiation (photons) were not interacted any longer
    $\Longrightarrow$ photons were able to travel freely
- CMB started as a radiation with $T \approx 3000$ K ($\sim$orange light)
- Now (13.7×10^9 years later) $T \approx 2.7$ K
  - $\sim$400 CMB-γ cm^{-3}

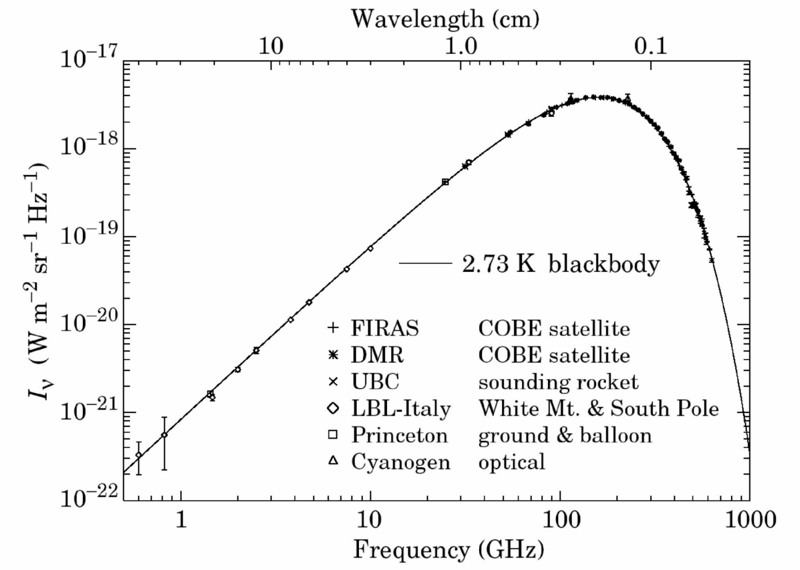
10.1 Cosmic microwave background

Experimental verification

- Found experimentally in 1965 by Arno Penzias and Robert Wilson
  - calibration of an antenna for radioastronomic measurements (at $\nu \approx 4.0$ GHz or $\lambda \approx 8$ cm)
  - consistent with a blackbody radiation at temperature $T \approx 3$ K, and peaking at $\lambda \approx 2$ mm
- One of the most important scientific discovery ever
  - complete accident
  - solid evidence favouring Big Bang theory
    $\longrightarrow$ predicted the existence of the background
- Wavelengths shorter than several cm are strongly absorbed by the water in the atmosphere
  - Frequency used by Penzias and Wilson was too low
  - COBE satellite at 1992 made more accurate measurements

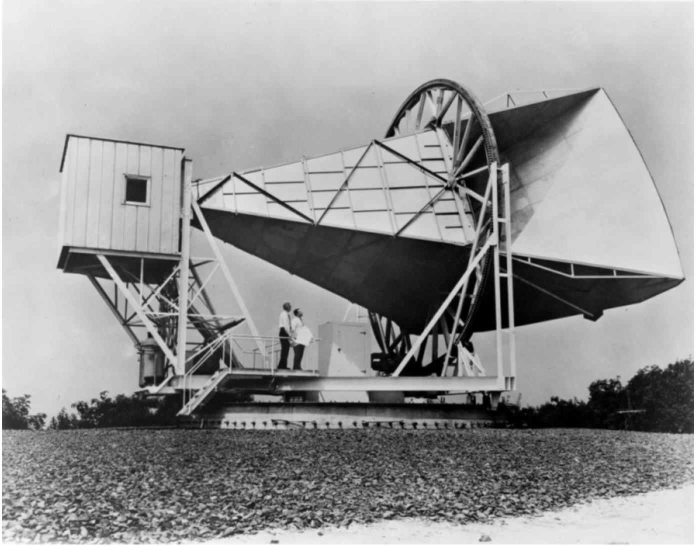
10.1 Cosmic microwave background

Blackbody spectrum at 2.7 K



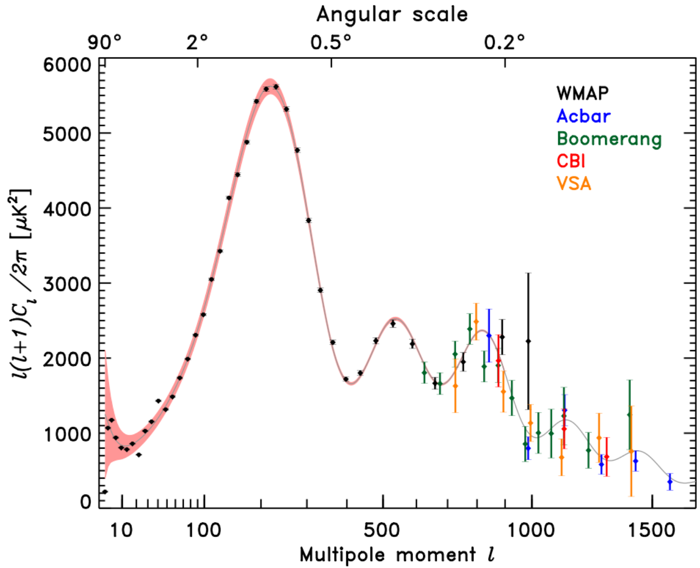
10.1 Cosmic microwave background

Antenna of Penzias and Wilson



10.1 Cosmic microwave background

Power spectrum – 1



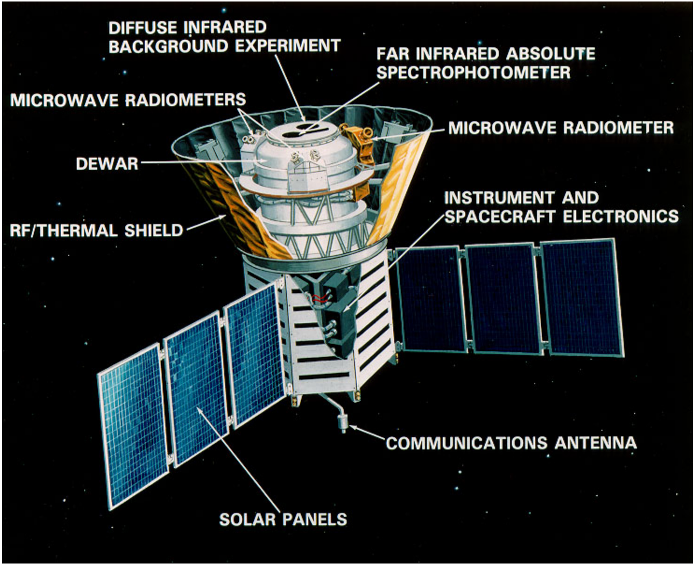
- The results of the power spectrum are model dependent
  - for example, models with varying dark matter amount and nature can be fitted on the data
- More accurate measurements are still needed
  - especially to resolve more peaks

- The position of the peaks depend on, among others, the geometry of the universe, the amount of radiation and normal and dark matter
- The highest peak tells the geometry and the mass of the universe
- The position and height of the second peak depends mostly on the amount of the normal matter
- The position and height of the thirs peak depends mostly on the amount of the dark matter

- All peaks, however, are needed, as every component effects slightly on the character of others

10.2 CMB experiments

COBE – Cosmic Background Explorer



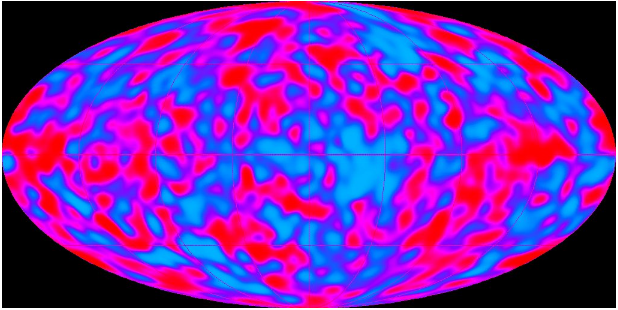
10.2 CMB experiments

COBE – general

- The first satellite for the research in cosmology
- Was launched in November 1989, measured $\sim$4 years
- Carried three instruments (DIRBE, DMR, FIRAS)
  - DIRBE – to measure cosmic infrared background
  - DMR – to map the CMB radiation precisely
  - FIRAS – to compare the CMB radiation with that of a precise blackbody
- Covered all the sky, but could not resolve inhomogenities of seven degrees or smaller
  - the seeds of the galaxies are much smaller $\Longrightarrow$ only hints from the existence of inhomogenities were observed
- Measured accurately the temperature of CMB: $T = 2.74$ K
  - ideal blackbody radiation
- Observed fluctuations in temperature of $\Delta T/T = 6 \times 10^{-6}$

10.2 CMB experiments

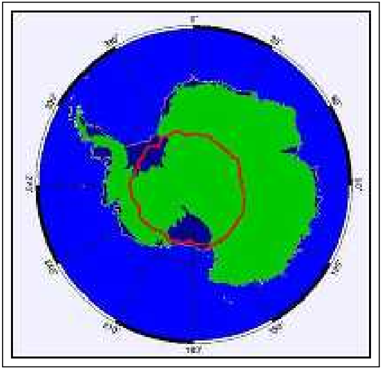
COBE – sky map



10.2 CMB experiments

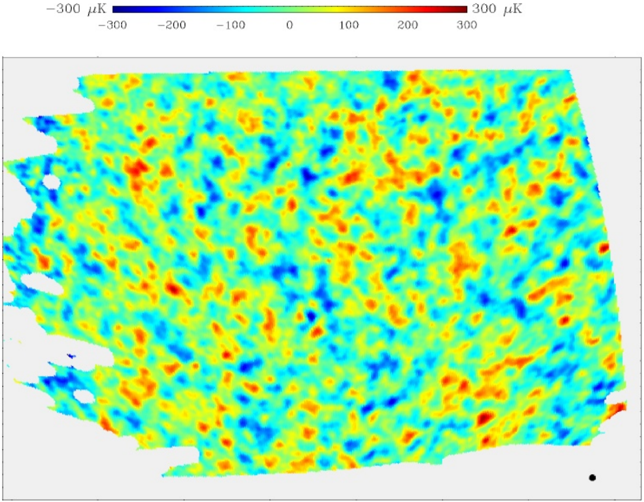
BOOMERANG – Balloon Observations Of Millimetric Extragalactic Radiation and Geophysics

- Experiment at South Pole
  - McMurdo Station, unique high-altitude wind patterns
- Two ∼two-weeks balloon flights, at 1998 and 2003, at the height of 42 km
  - very little emission or absorption from the atmosphere
- More accurate than COBE but small sky coverage, unexpensive
  - detector bolometer
  - operated at 145, 245, and 345 GHz



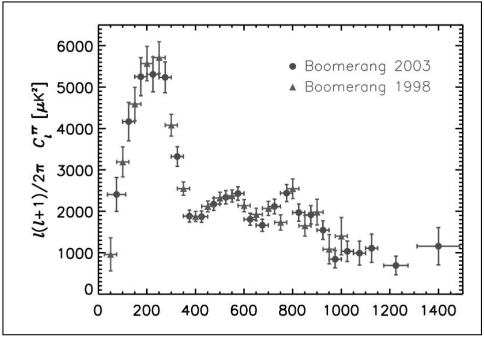
10.2 CMB experiments

BOOMERANG – sky map



10.2 CMB experiments

BOOMERANG – results



- The position of the highest peak gave hint on the flat universe
- For the flat universe the highest peak should be followed by two smaller and about equal peaks, but the resolution of Boomerang was not good enough for resolving those
  $\Longrightarrow$ WMAP

10.2 CMB experiments

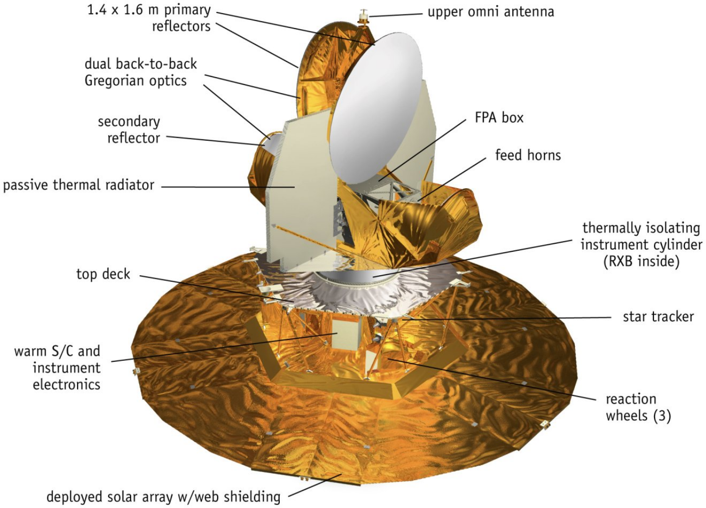
WMAP – Wilkinson Microwave anisitropy Probe

- WMAP was launched in summer 2001
  - originally 2-year program, extended by two years, ...
- Measures at five different frequencies (23, 33, 41, 61, 94 GHz)
- Operates at Lagrange poit L2 (1.5×10^6 km away)

- Main results
  - the age of the universe: $(13.73 \pm 0.12) \times 10^9$ years
  - prefers the flat universe
  - cosmic (Big Bang) neutrinos

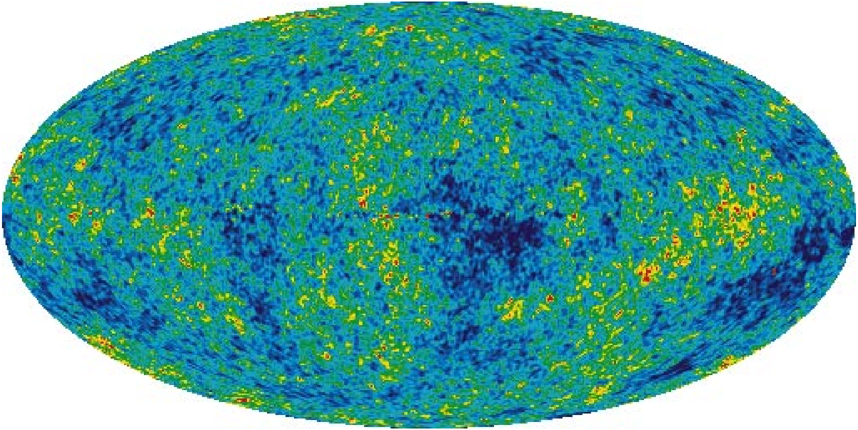
10.2 CMB experiments

WMAP – the device



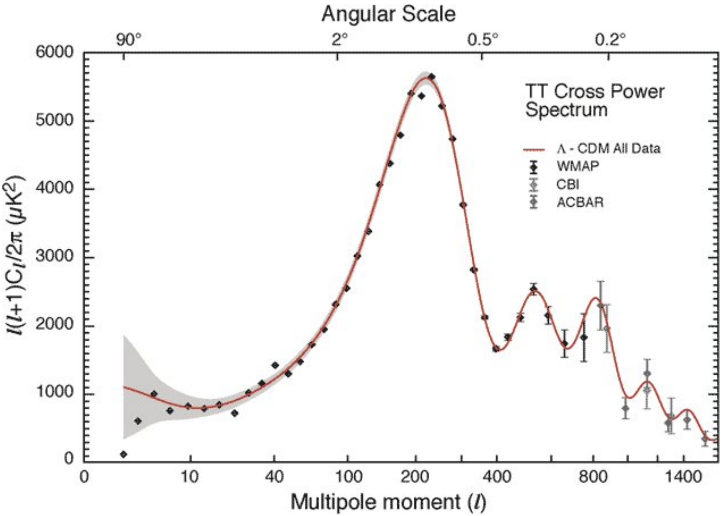
10.2 CMB experiments

WMAP – results – sky map



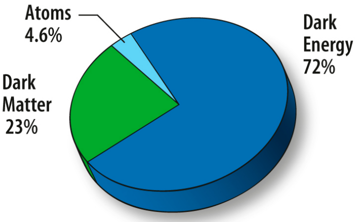
10.2 CMB experiments

WMAP – results – power spectrum

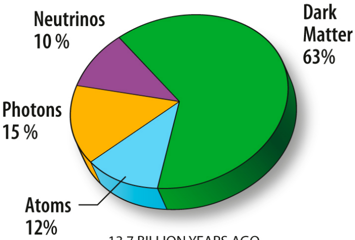


10.2 CMB experiments

WMAP – results – dark matter & dark energy



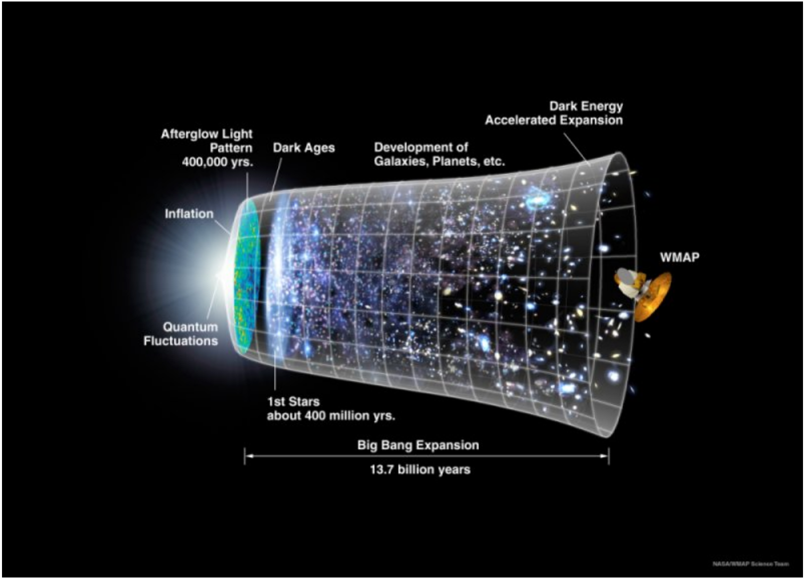
TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

10.2 CMB experiments

WMAP – results – the time line



10.2 CMB experiments

Planck

- More accurate information still needed
  - inflation, polarisation, neutrinos, ...
- Planck satellite of ESA
  - was launched in May, 2009 and is just started measurements
- Some instruments also built in Finland (8 Meuros)