Lecture 1.
Radio cosmology. Introduction

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What these lectures are about

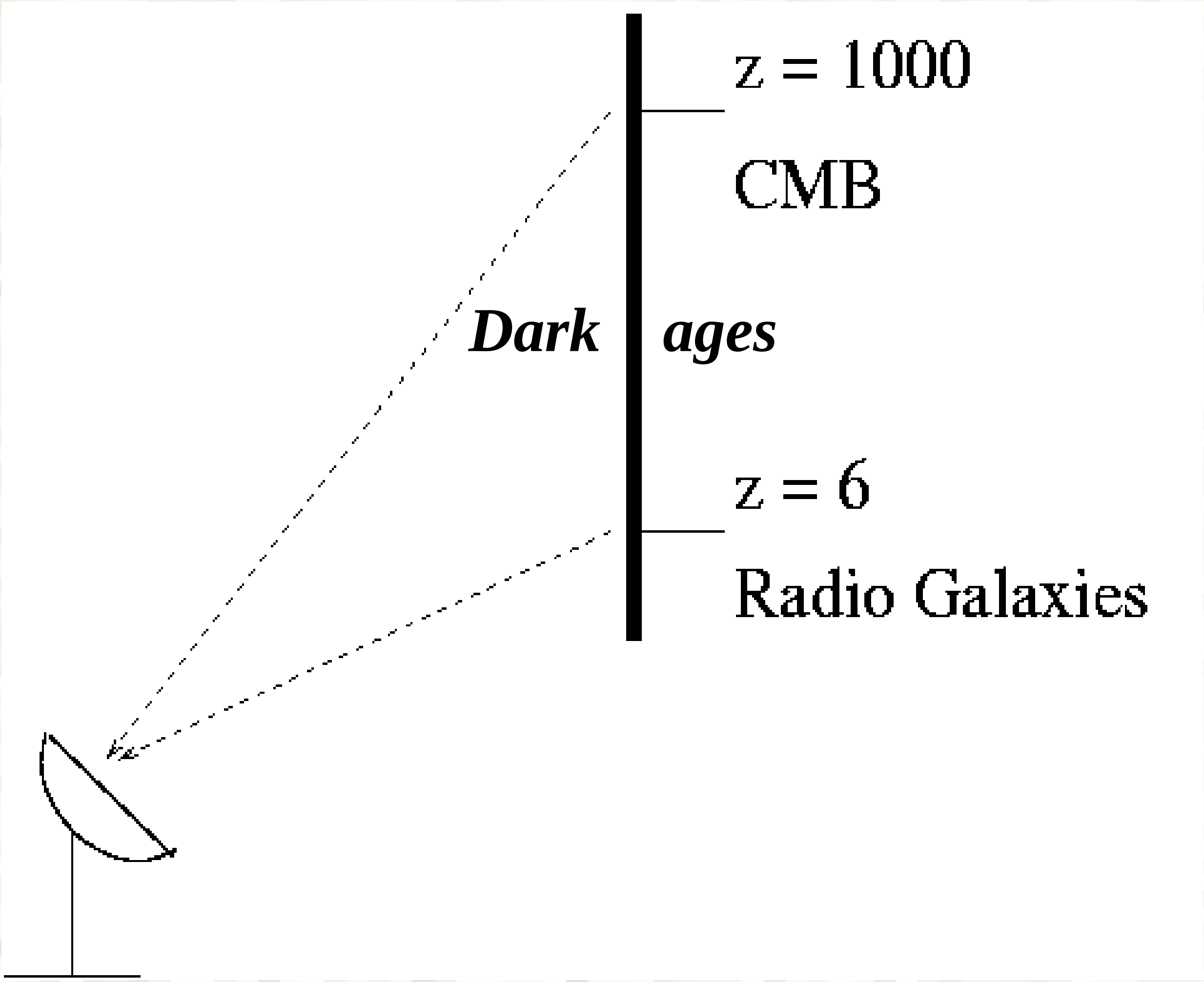
1) *basic concepts of radio astronomy:*
How it works and what we can see.
Radio astronomy and cosmology.

2) *CMB as the best cosmological test*
How we can get the CMB map and power specrum.
Technological chain of CMB data processing on a sphere.

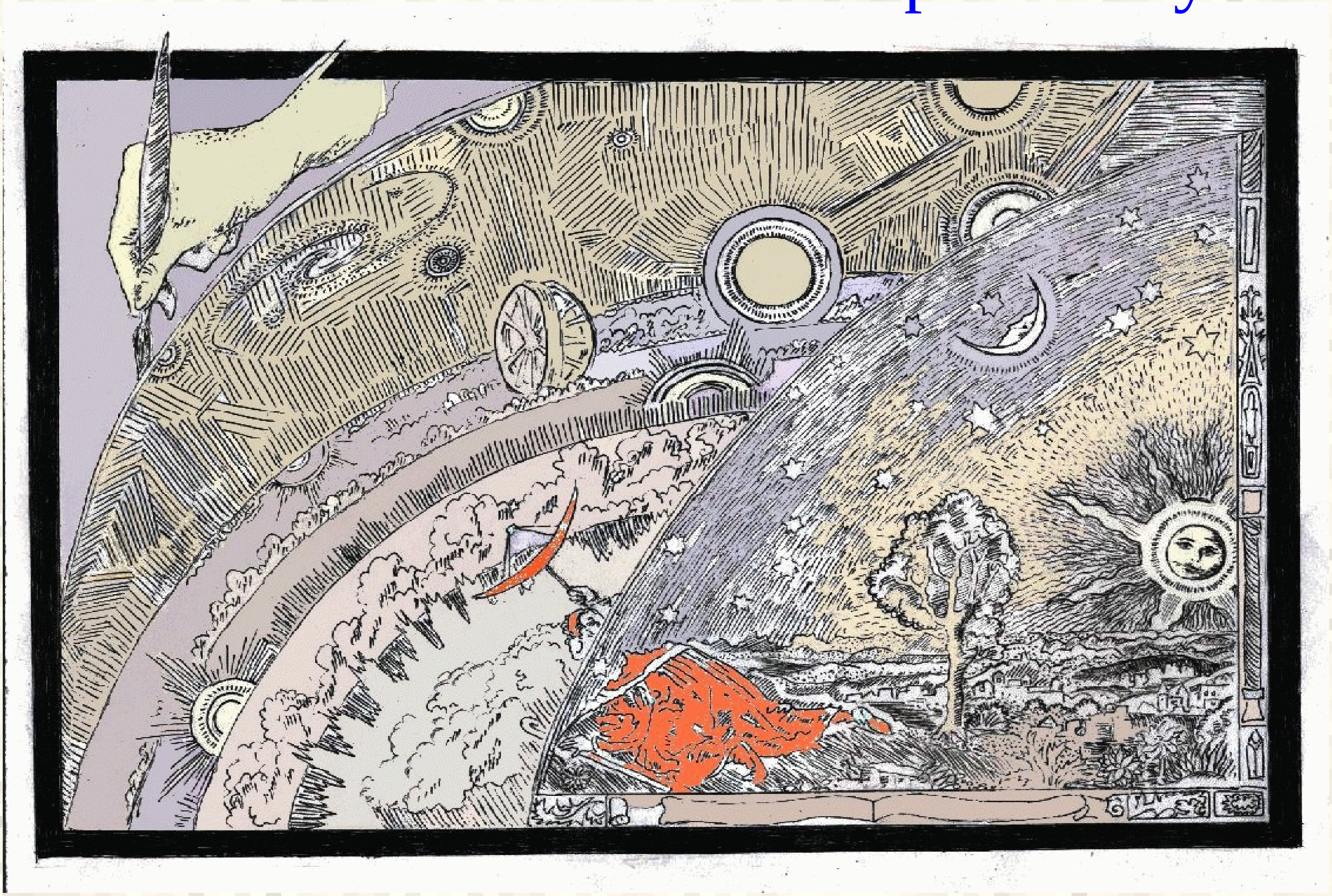
3) *What is wrong with CMB data*
Non-gaussianity via systematic effects of observations
and data reduction. Low harmonics magic (anomalies).
Comparison of the WMAP and Planck missions data.

4) Make some simulations of CMB with the GLESP package
(find GLESP package at http://sed.sao.ru/~vo/GLESP/
or using registration: http://www.glesp.nbi.dk)

What can we see in radio astronomy ?



2 horizont observational possibility



Cosmological tests with radio astronomy

Radio galaxies

a) "size – redshift" (standard rod)
b) "flux density – redshift" (standard candle)
c) "log N - log S" ("number of sources – flux density")
d) Gravitational lensing
e) Large scale structure formation
f) "Galaxy age – redshift"
g) Dark matter with HI observations

Pulsars

a) Double pulsars – gravitational wave emission
b) Net of pulsars – gravitational wave propagation

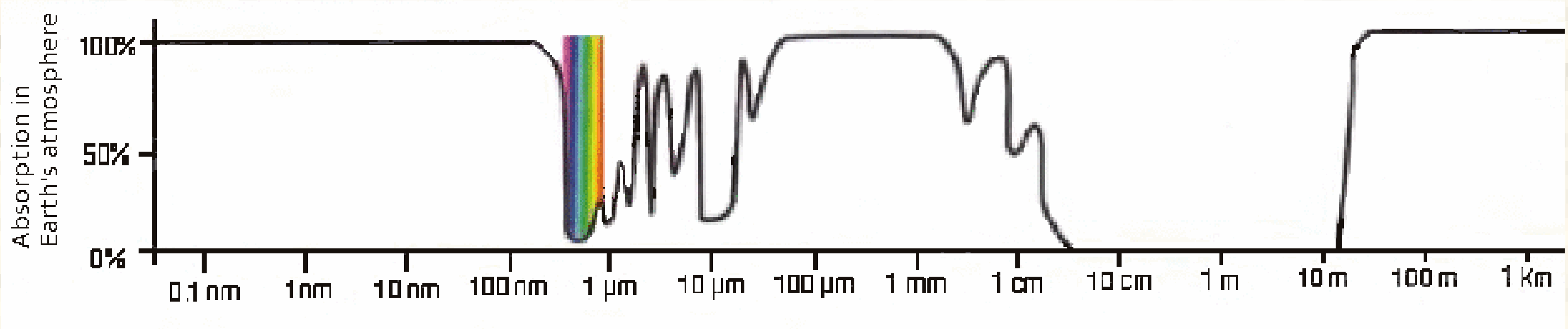
Cosmic microwave background

a) Angular power spectrum
b) Statistical properties of the CMB signal (gaussianity)

Radio astronomy contribution to cosmology

1) Identification of radio galaxies (1947-1951)
2) Identification of quasars (1961)
3) Radio source counts *log N* - *log S* (1964-1997)
4) Discovery of CMB (1965, 1978)
5) Theory of fluctuation formation, SZ-effect (1969-1980,2003)
6) Correction of LSS formation (1970-1980)
7) Aperture synthesis (1967-1974)
8) Discovery of pulsars (1967-1974)
9) Galaxy kinematics in HI (21cm): DM (since 1980th)
10) Exploration of the double pulsar (1974, 1993)
11) Discovery of CMB fluctuations (1992, 2006)
12) Determination of cosmological parameters (2003,2012)

Astronomical window for observations from Earth



Radio waves visible from Earth

What is a radio telescope ?

What is a radio telescope ?

Astronomical apparatus which receives the self-radioemission of celestial objects

It contains two main components:

the antenna and *the radiometer*.

Main parameters of a radio telescope

Resolution

$$\theta_{\min} \simeq \frac{\lambda}{D}$$

Sensitivity

$$\Delta S = \frac{S_{\text{noise}}}{A_{\text{eff}}\sqrt{\Delta f t}}$$

Antenna smoothing

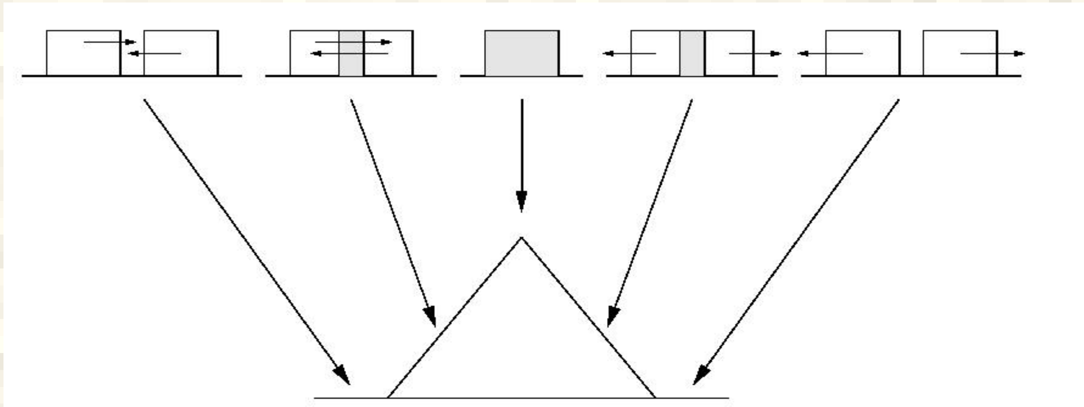
$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} T(x-x', y-y')B(x',y')dx'dy'$$

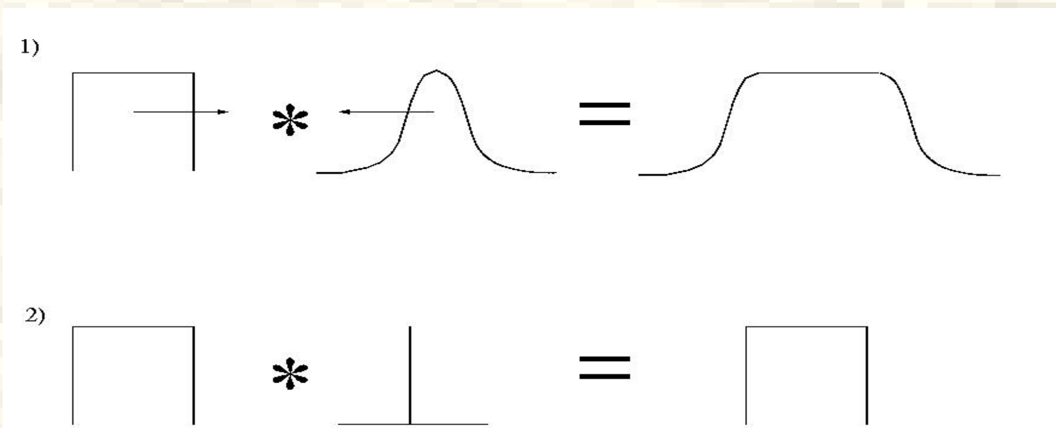
Fourier transform of a registrated signal

$$I = T * B + N$$

Note 1. Convolution

$$I(x,y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} B(x-x', y-y')A(x',y')dx'dy'$$





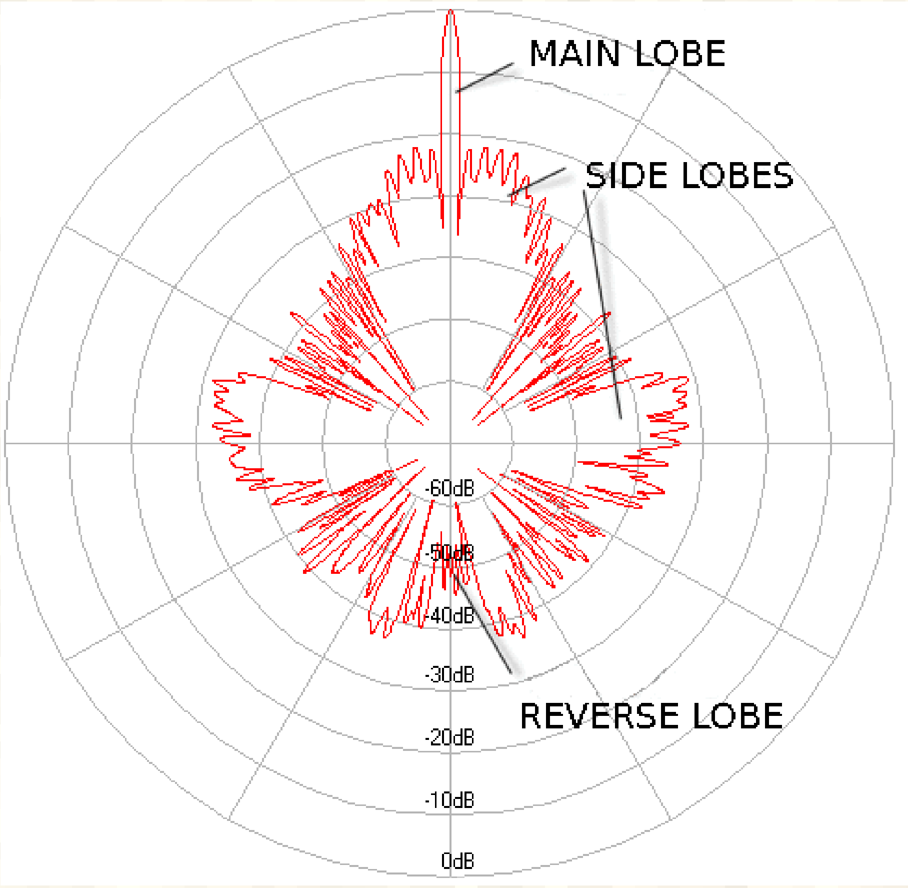
Smoothing and smearing detailed less than beam size

Antenna beam pattern

Antenna gain versus direction

Beam shape = Fourier Transform of field in aperture

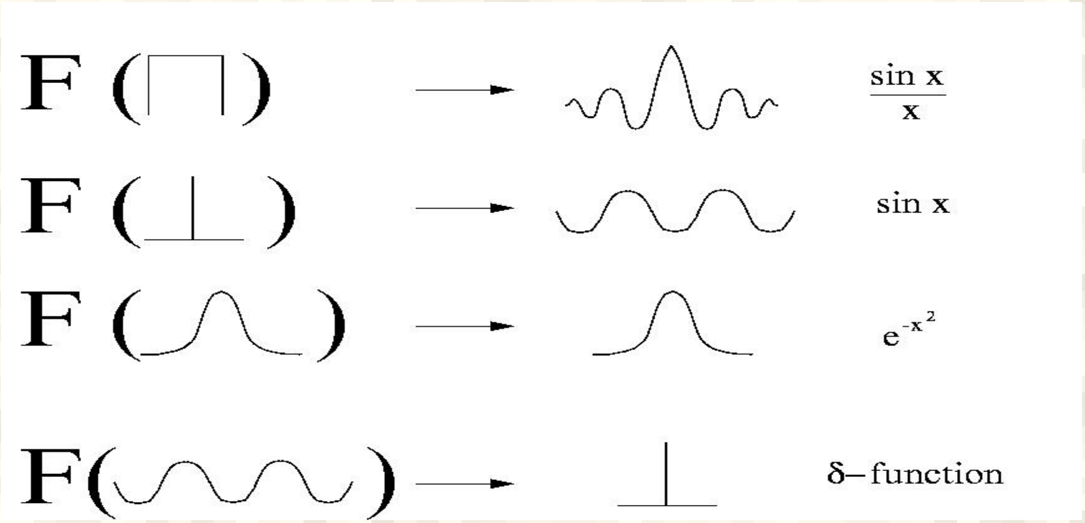
Resolution of RT = width of main lobe of a beam



Note 2. Fourier transform

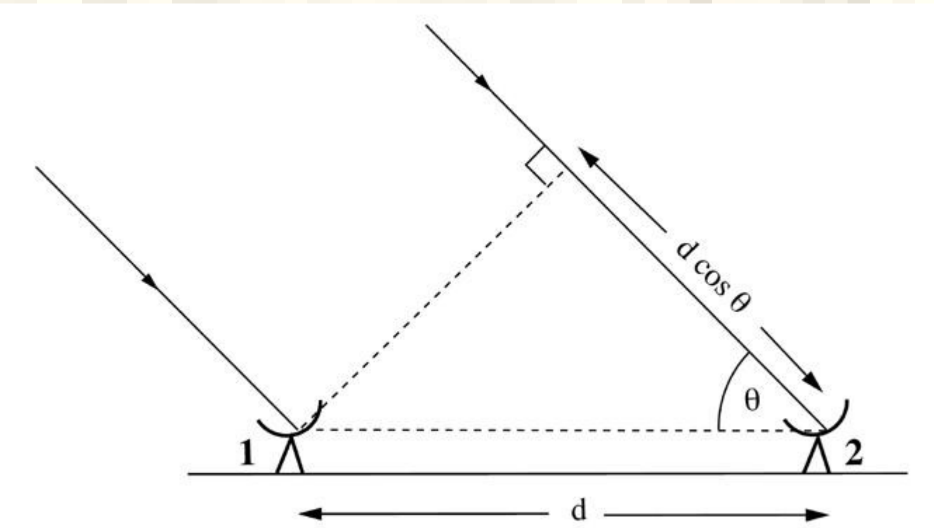
$$V(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)e^{2\pi i(ux+vy)}dx\,dy$$

UV-plane



Theorem of convolution $I = B * A \Longleftrightarrow F(I) = F(B) \times F(A)$

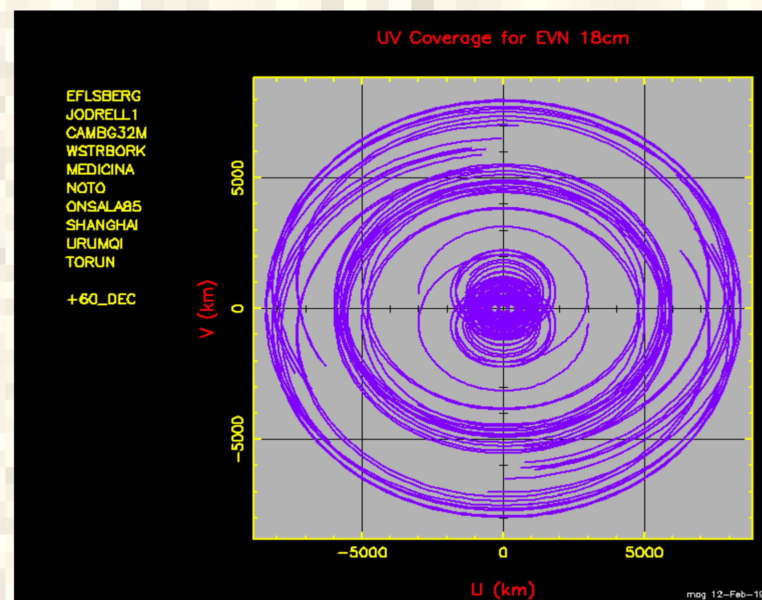
Radio interferometer



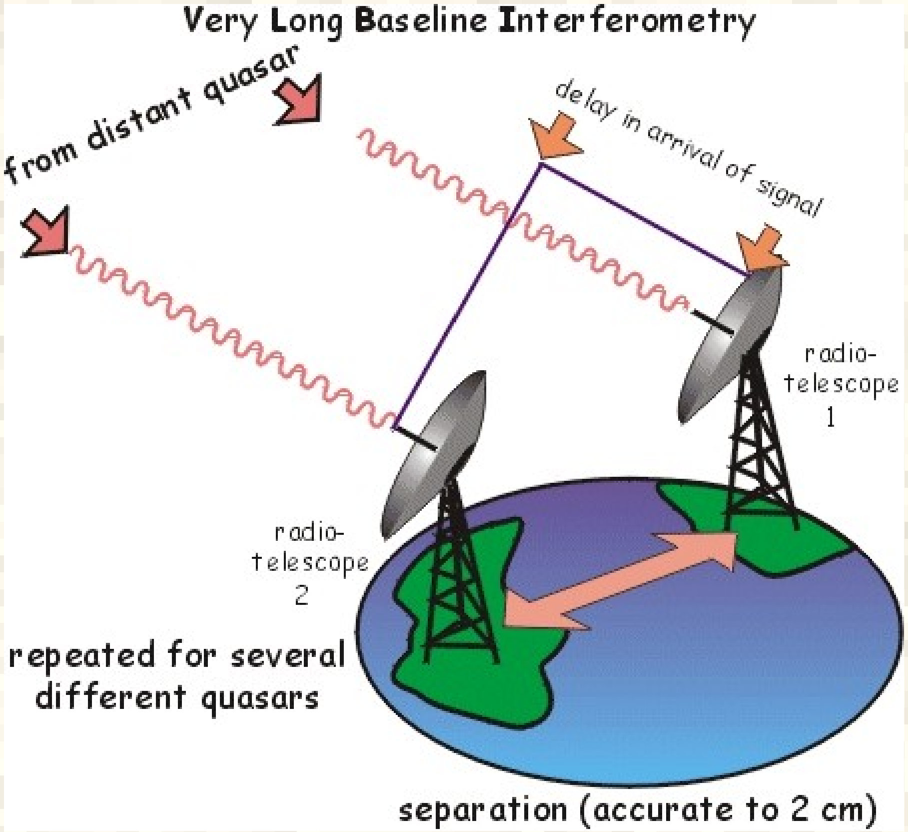
One observation - 1 point on the UV-plane

Aperture synthesis. UV-plane.

$$V(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x,y)e^{2\pi i(ux+vy)}dx\,dy$$



Very Long Baseline Interferometer



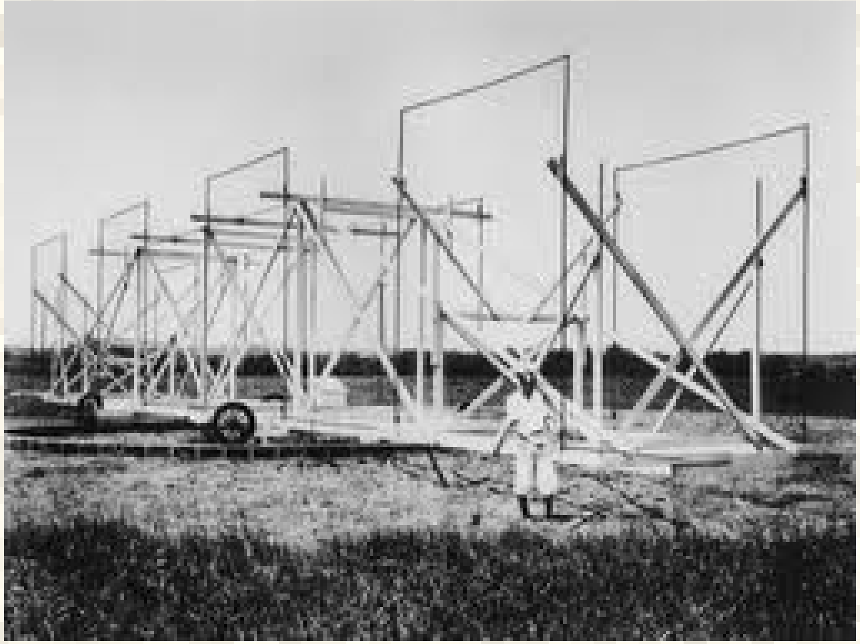
Which radio telescopes are useful for cosmology ?

Which radio telescopes are useful for cosmology ?

All !

More than 1000...

1st radio telescope: Carl Jansky antenna



Carl Jansky

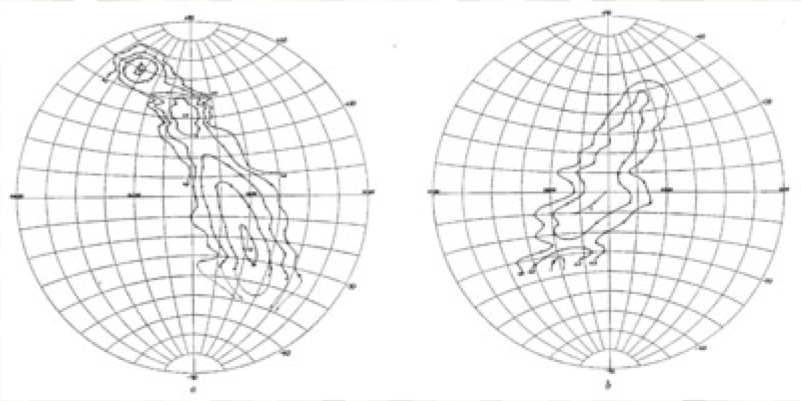
1933, New York Times,
radio emissiom of Galactic center, lambda=14m

Jansky -unity of flux density now:
1 Jy = 10^-26 Wt / (m^2 Hz)

Grote Reber antenna

D=9.5m,
lambda=1.9m

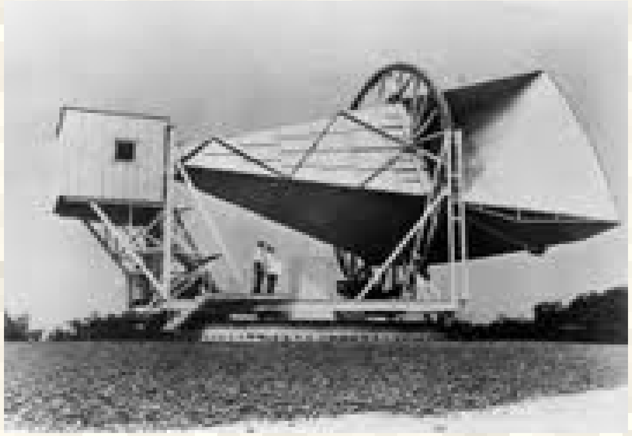
Grote Reber



1^{st} map, ApJ, 1944
Miljy Way, Cygnus, Casseopea

A.Penzias and R.Wilson antenna

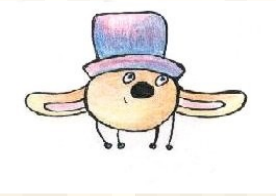
Epoch of the CMB study



Holmdell horn antenna,
15m length
4.08 GHz

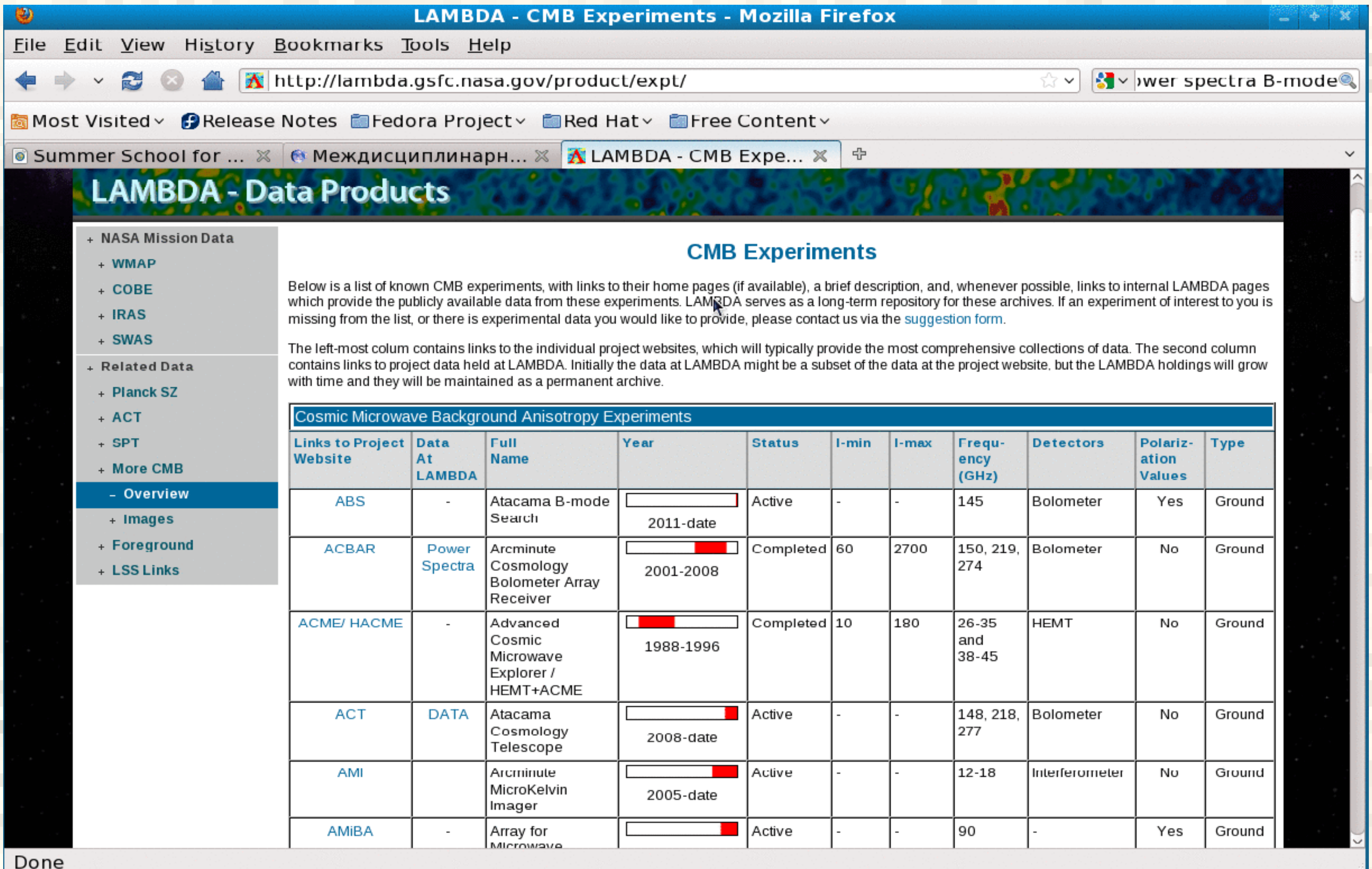
1965 – CMB discovery
1978 – Nobel Prize
(*Wilson*, *Penzias*, Science, 1967)

How many experiments are done in exploration of CMB ?



How many experiments are done in exploration of CMB ?

> 60 ! **http://lambda.gsfc.nasa.gov/product/expt**



LAMBDA - CMB Experiments - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://lambda.gsfc.nasa.gov/product/expt/

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LAMBDA - Data Products

- NASA Mission Data
  - WMAP
  - COBE
  - IRAS
  - SWAS
- Related Data
  - Planck SZ
  - ACT
  - SPT
  - More CMB
    - Overview
    - Images
  - Foreground
  - LSS Links

CMB Experiments

Below is a list of known CMB experiments, with links to their home pages (if available), a brief description, and, whenever possible, links to internal LAMBDA pages which provide the publicly available data from these experiments. LAMBDA serves as a long-term repository for these archives. If an experiment of interest to you is missing from the list, or there is experimental data you would like to provide, please contact us via the suggestion form.

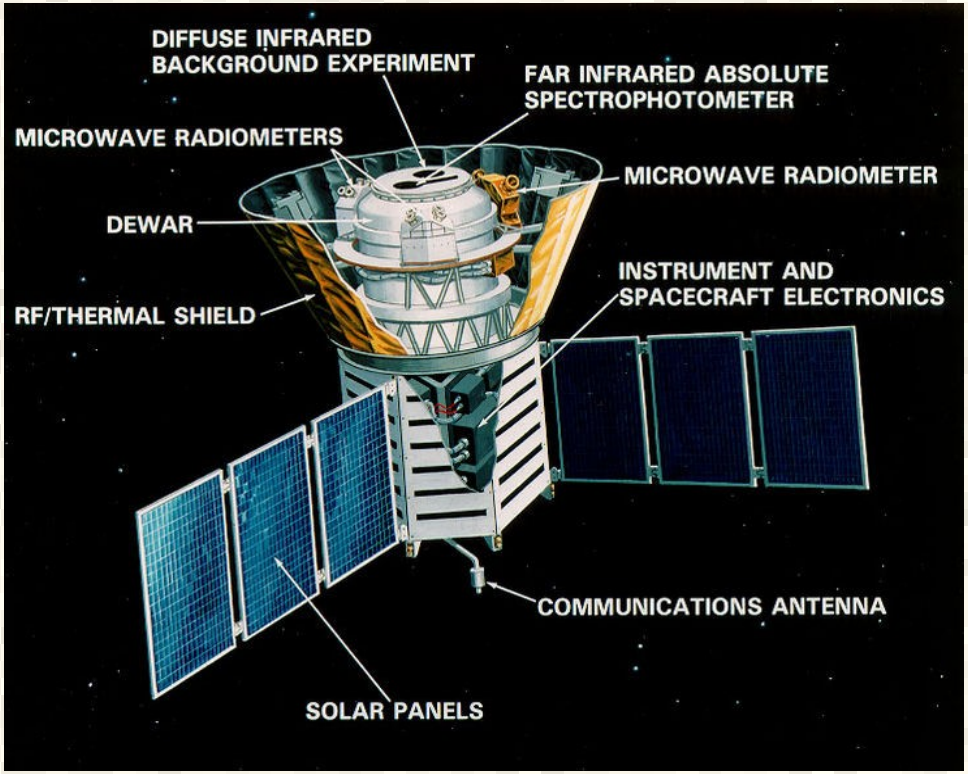
The left-most colum contains links to the individual project websites, which will typically provide the most comprehensive collections of data. The second column contains links to project data held at LAMBDA. Initially the data at LAMBDA might be a subset of the data at the project website, but the LAMBDA holdings will grow with time and they will be maintained as a permanent archive.

Cosmic Microwave Background Anisotropy Experiments

Links to Project Website	Data At LAMBDA	Full Name	Year	Status	l-min	l-max	Frequency (GHz)	Detectors	Polarization Values	Type
ABS	-	Atacama B-mode Search	2011-date	Active	-	-	145	Bolometer	Yes	Ground
ACBAR	Power Spectra	Arcminute Cosmology Bolometer Array Receiver	2001-2008	Completed	60	2700	150, 219, 274	Bolometer	No	Ground
ACME/ HACME	-	Advanced Cosmic Microwave Explorer / HEMT+ACME	1988-1996	Completed	10	180	26-35 and 38-45	HEMT	No	Ground
ACT	DATA	Atacama Cosmology Telescope	2008-date	Active	-	-	148, 218, 277	Bolometer	No	Ground
AMI		Arcminute MicroKelvin Imager	2005-date	Active	-	-	12-18	Interferometer	No	Ground
AMiBA	-	Array for Microwave		Active	-	-	90	-	Yes	Ground

Done

Cosmic Backgound Explorer (COBE, NASA)

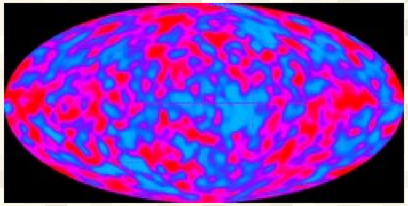


Differential Microwave Radiometer (DMR)
(*George Smoot*) - CMB fluctuations

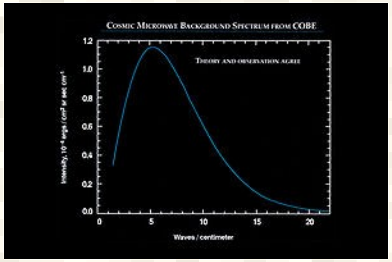
Far-IR Absolute Spectrophometer (FIRAS) - CMB Planck spectrum 0.1-10mm, (*John Mather*)

Diffuse IR Background Experiment (DIRBE) - dust emission, 1.25-240mc (*Mike Hauser*)

31.5, 53, 90 GHz
Orbit: 900 km



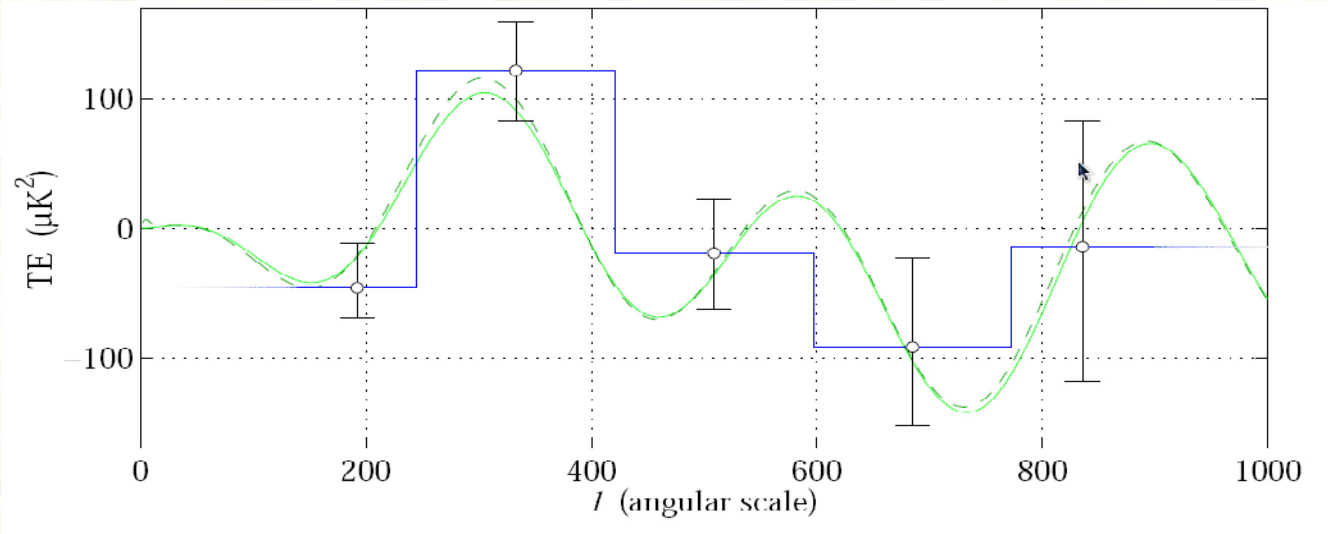
map



BB spectrum

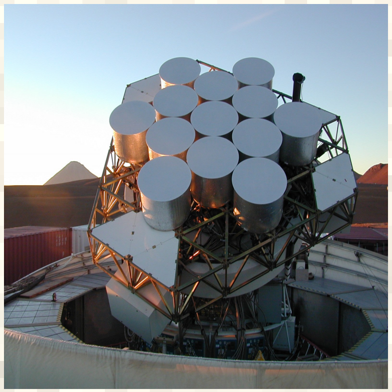
Degree Angular Scale Interferometer (DASI)

13 element interferometer
26-36 GHz
NSF Amundsen-Scott S.Pole station



E-polarization discovery (2003)

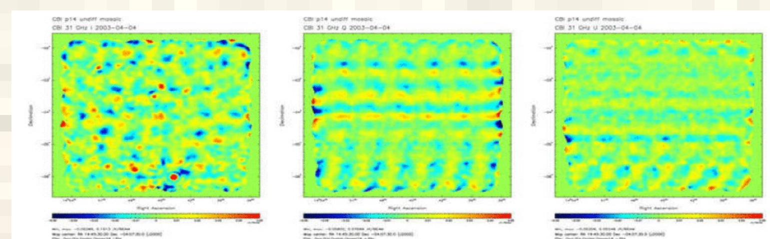
Cosmic Background Imager (CBI)



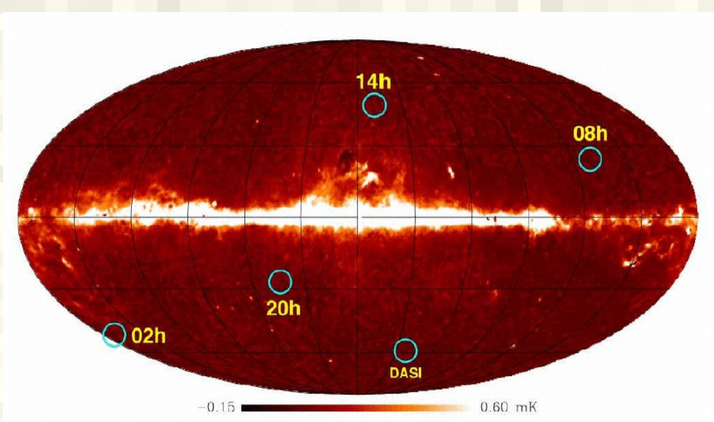
Chajnantor Observatory
Chealiean Andes, 5080m
26-36 GHz,
5arcm<th<1deg, 300<l<3000

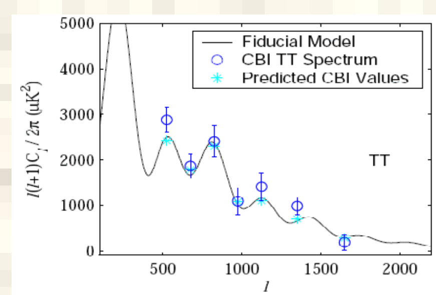
CBI (1999-2006yr)
13 antennas of 0.9m

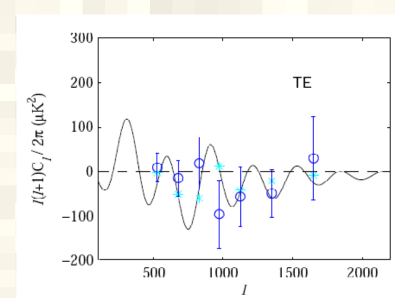
CBI 2 (2006-208yr)
13 antennas of 1.4m



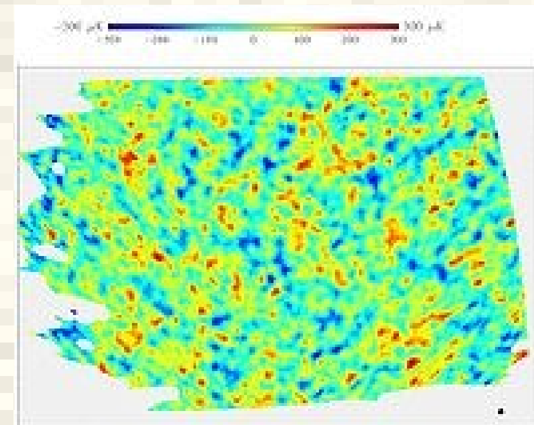
14h
I,Q,U



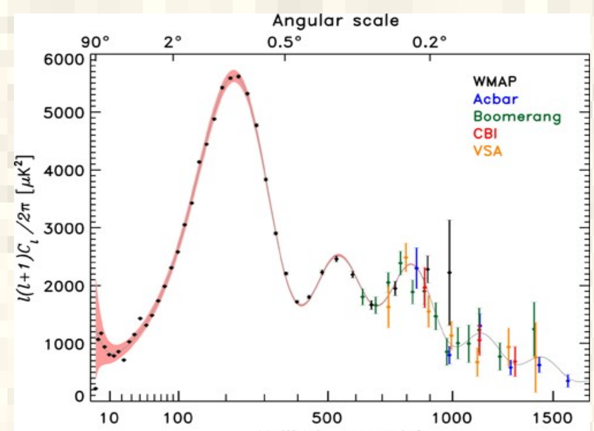




Baloon Observations Of Millimetric Extragalactic Radiation and Geophysics (BOOMERanG)

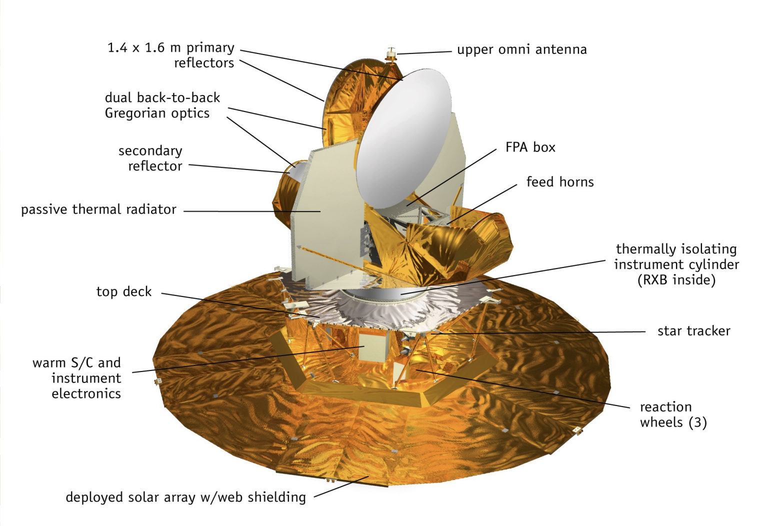


Baloon, 1.2m - mirror,
16 horns, 145, 245, 345 GHz

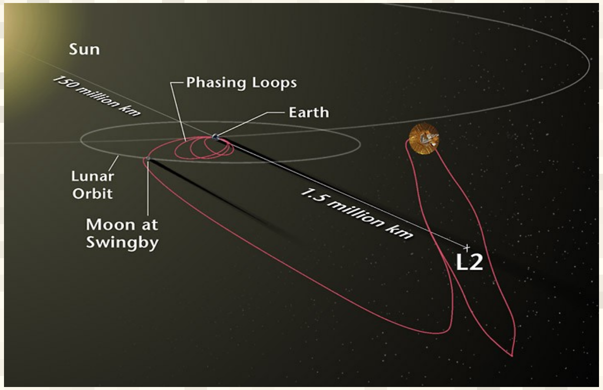


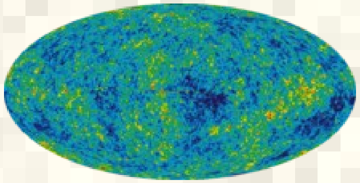
- Universe geometry (1998)
- CMB T-anisotropy (2003)

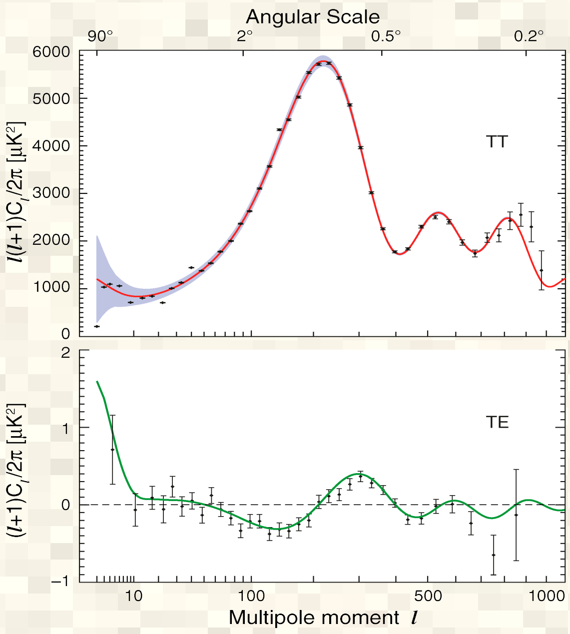
Wilkinson Microwave Anisotropy Probe (WMAP, NASA)



2001-2011



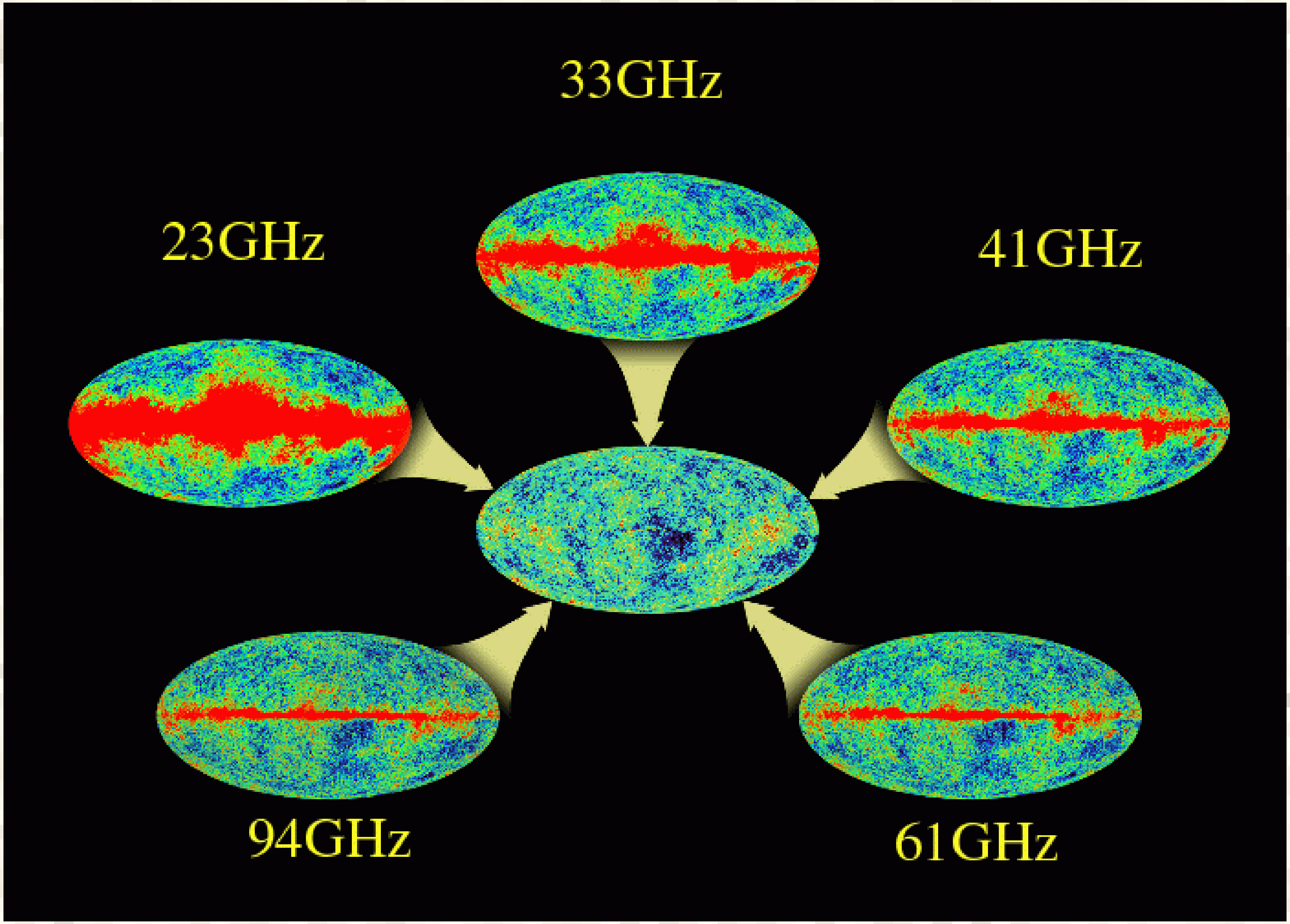




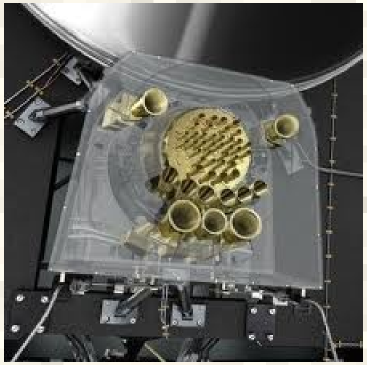
5 frequencies:
23, 33, 41, 61, 94 GHz

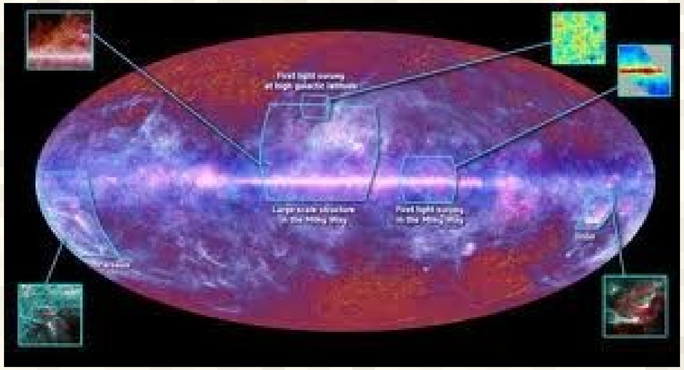
Best definition
of cosmological parameters !

WMAP maps



Planck mission, ESA

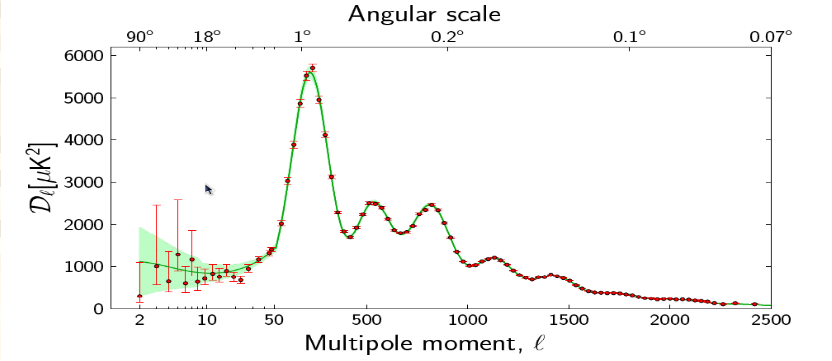




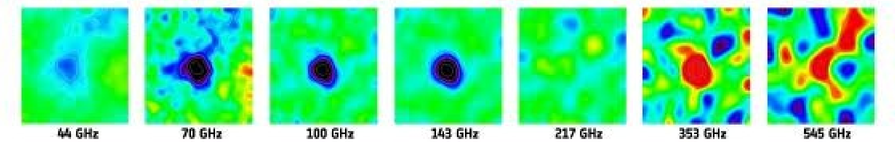
Low Frequency Instrument: 30,44,70
HFI: 100, 143, 217, 353, 545, 857 GHz

2010-2013

1)

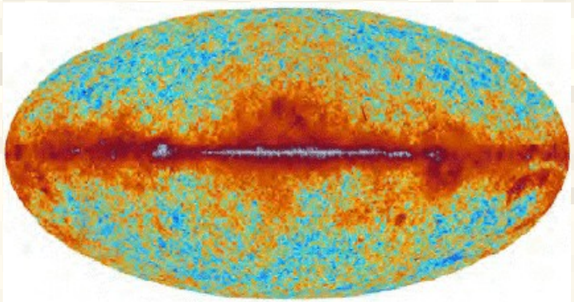


2) Zeldovich-Sunyaev effect

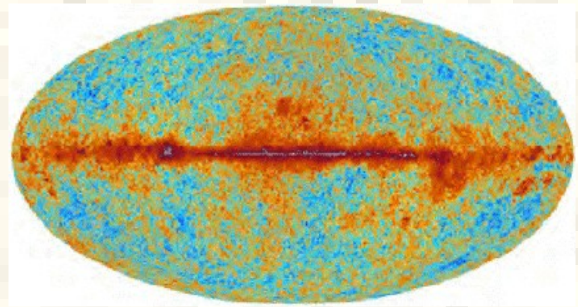


3) Gravitational waves in the B-mode of polarization ?

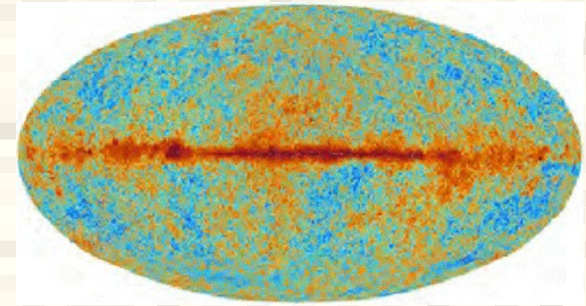
Planck maps



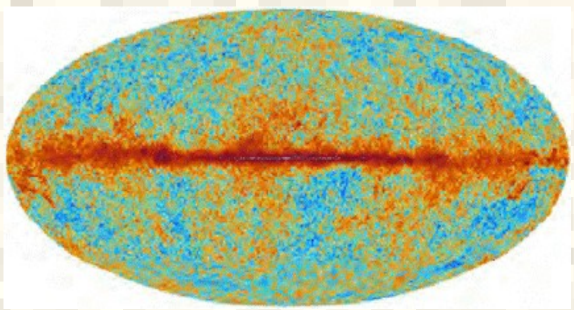
30GHz



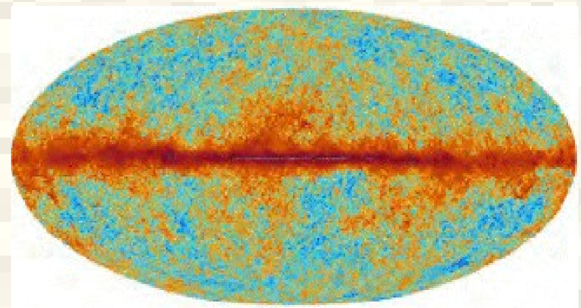
44GHz



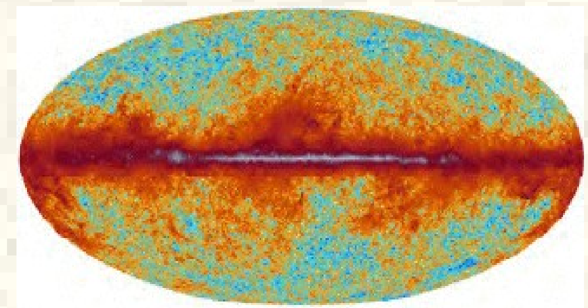
70GHz



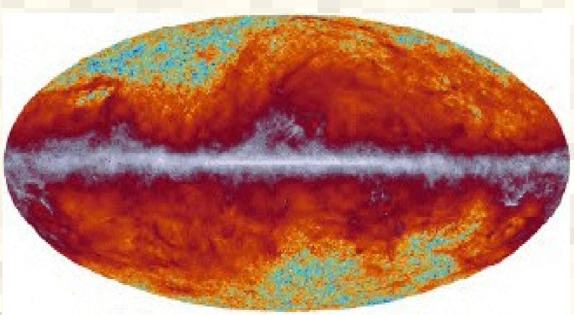
100GHz



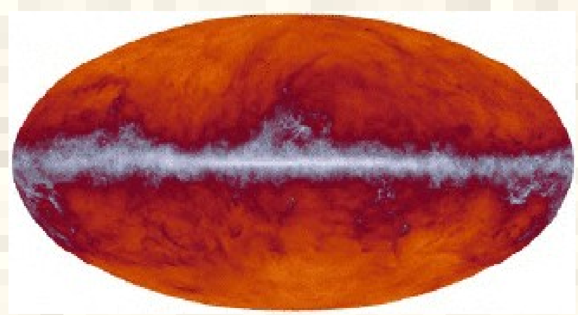
143GHz



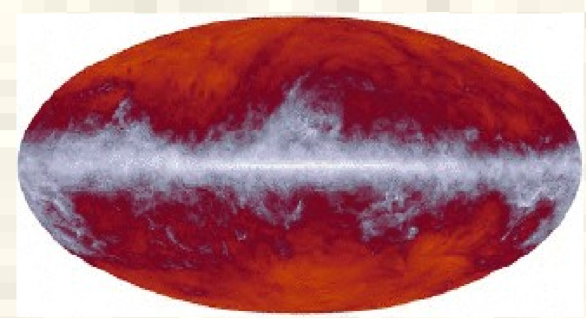
217GHz



353GHz



545GHz

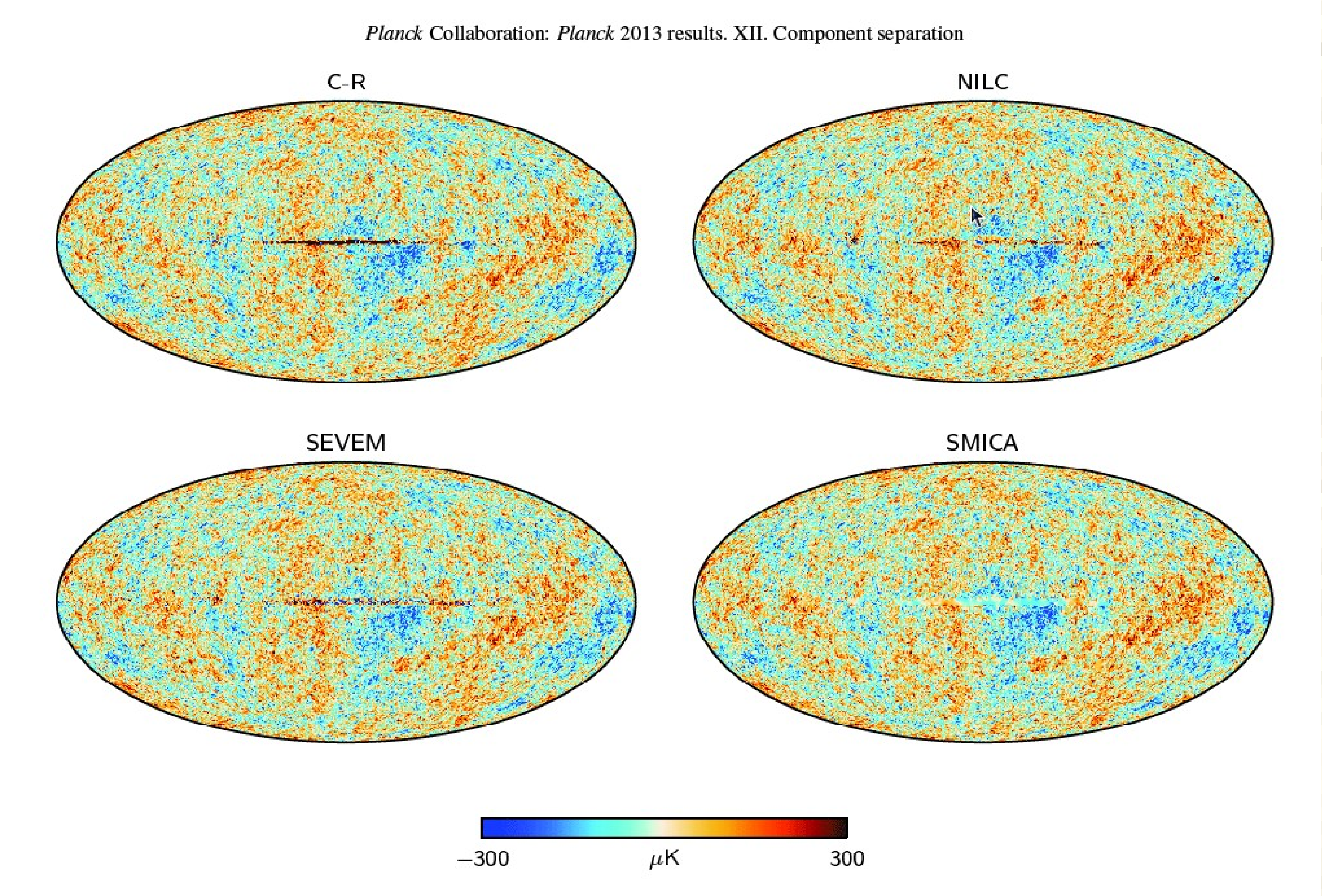


857GHz

Observational frequency maps

Legacy Planck Archive (LPA)

http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck



Legacy Planck Archive (LPA)

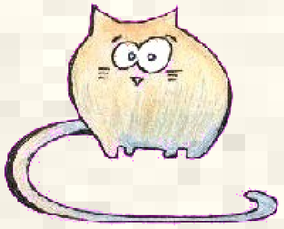
http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck

1) 4 CMB maps
2) maps at observational bands
   (30, 44, 70, 100, 143, 217, 353,545, 857 GHz)
3) CO emission maps
4) Maps of dust
5) Maps of galactic low frequency emission
   (synchrotron + free-free)
6) Zodiac light maps
7) Maps of gravitational lensing
8) y-comptonization maps
9) Masks

And at the end to the beginning...

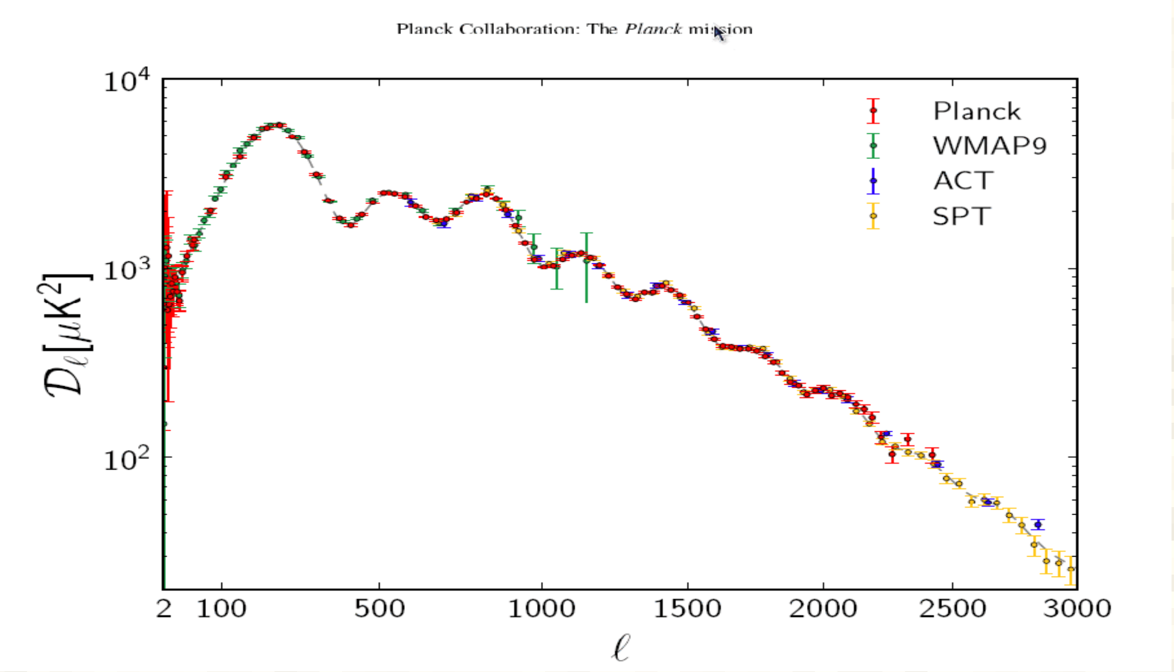
A few moments of history

1) A. McKellar et al.: additional emission of CN, 1941
2) Prediction of G.Gamow's group, 1946
3) T.Shmaonov (Pulkovo observatory): undeletable noise, 1957
4) A. Doroshkevich, I.Novikov, prediction of visibility at mm, 1964
5) A.Penzias, R.Wilson: discovery of CMB, 1965
6) Search for fluctuations and correction of the theory.
7) J.Mather, G.Smoot, discovery of CMB fluctuations, 1992
8) Measuring of cosmological parameters and investigation of statistical properties, now.

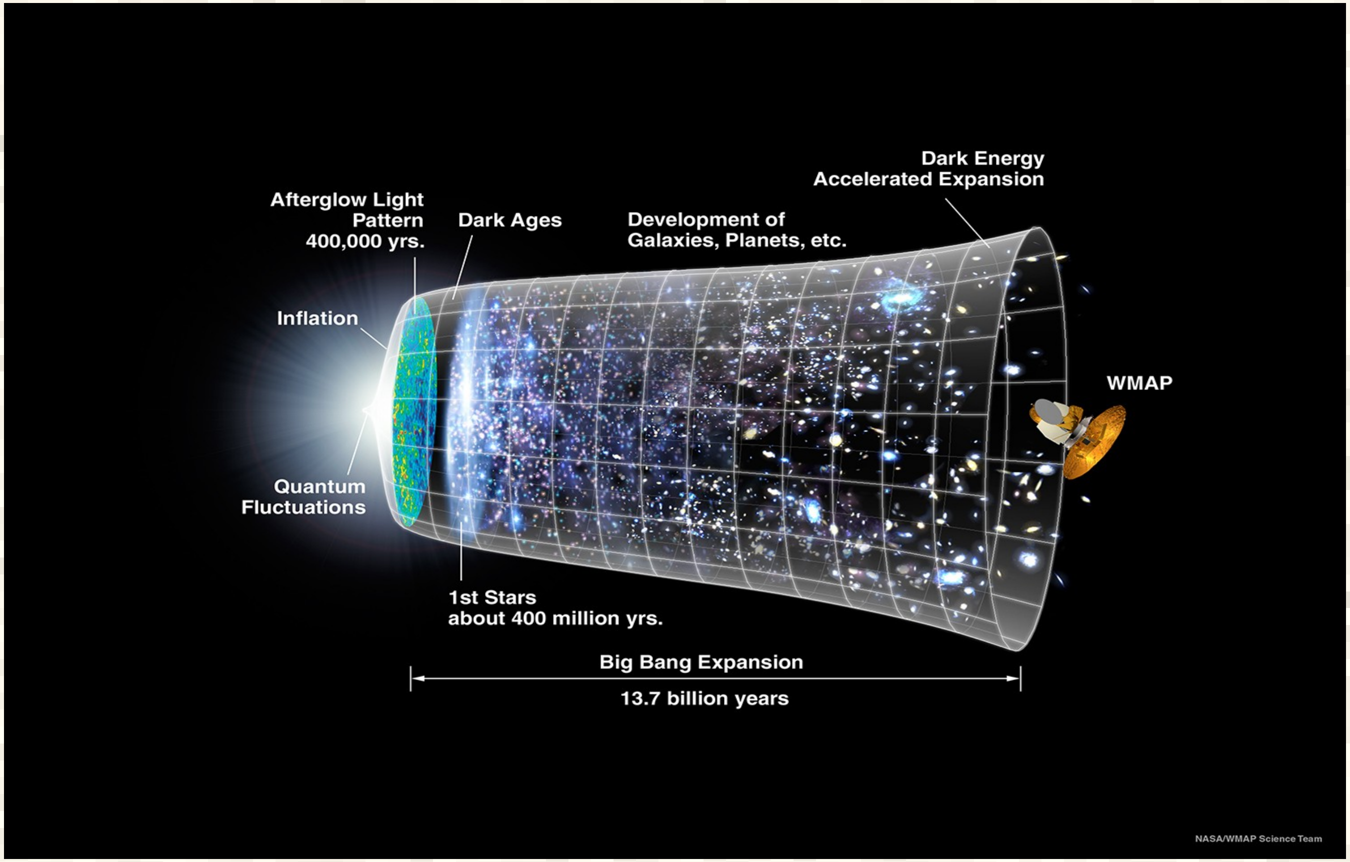


Few remarks

1) Measuring temperature of CMB with CN at different *z*
2) Estimating Tcmb by SZ-effect at different *z*
3) Prediction of the behavior of power spectrum *C(l)*
by 3 first peaks



We know cosmological parameters...
In general, we know Universe evolution laws...



No new revolutionary discoveries ?

Everything is just beginning !