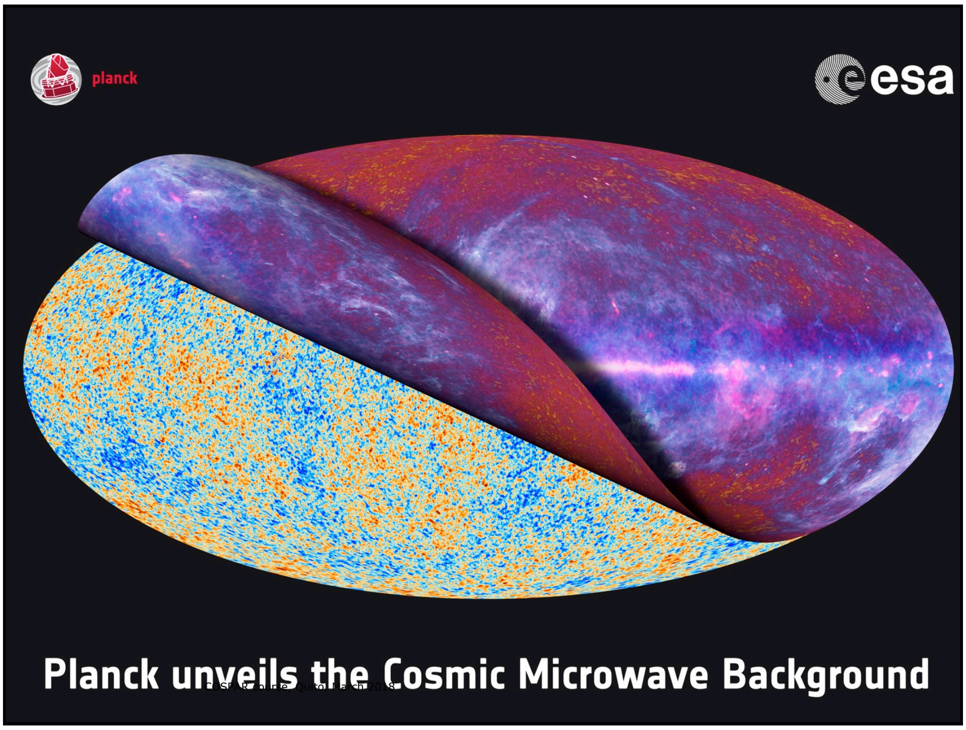
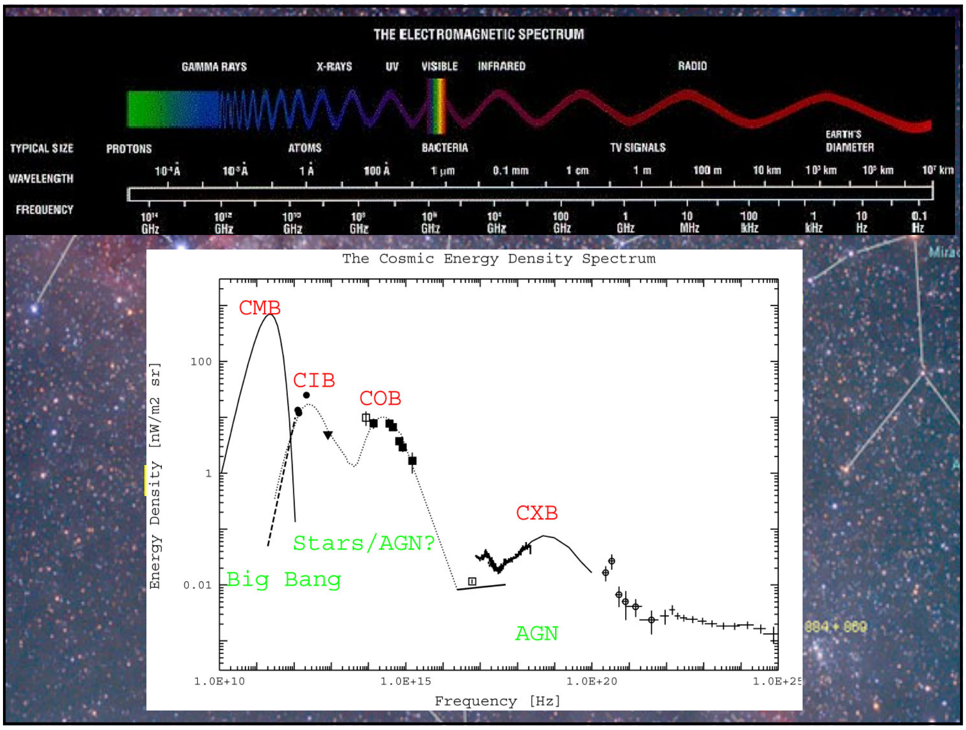
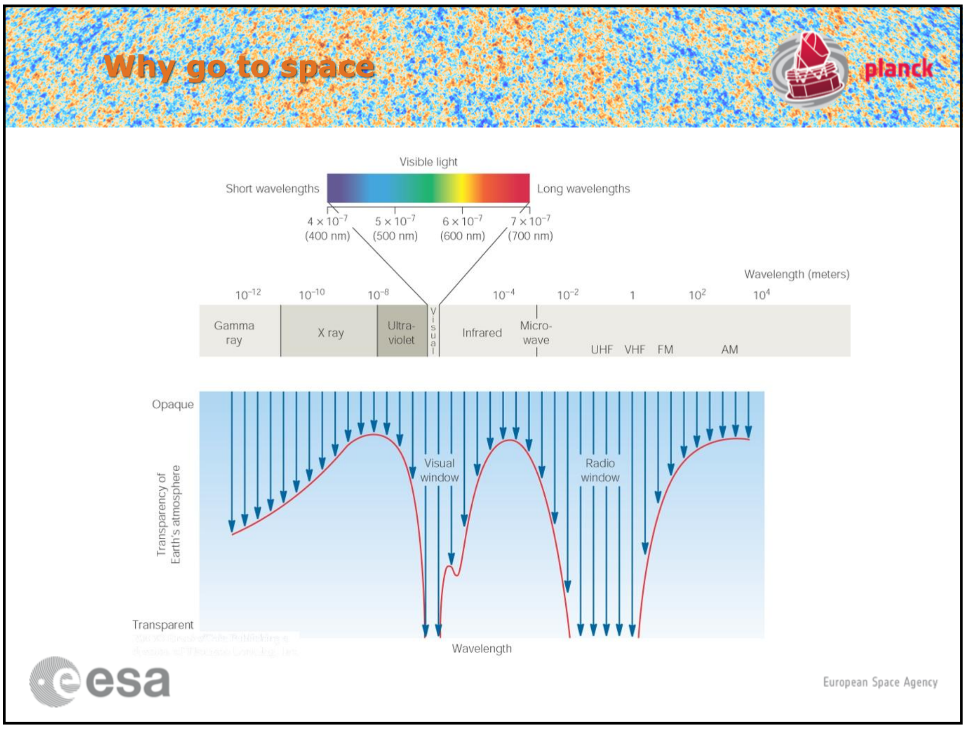


2nd lecture: Measuring the CMB from space

J. Tauber
Planck Project Scientist
European Space Agency


THE ELECTROMAGNETIC SPECTRUM
GAMMA RAYS
X-RAYS
UV
VISIBLE
INFRARED
RADIO
TYPICAL SIZE
PROTONS
ATOMS
BACTERIA
TV SIGNALS
EARTH'S DIAMETER
WAVELENGTH
FREQUENCY
The Cosmic Energy Density Spectrum
CMB
CIB
COB
CXB
Stars/AGN?
Big Bang
AGN
Energy Density [nW/m2 sr]
100
1
0.01
1.0E+10
1.0E+15
1.0E+20
1.0E+25
Frequency [Hz]


Why go to space
planck
Visible light
Short wavelengths
Long wavelengths
4 × 10⁻⁷ (400 nm)
5 × 10⁻⁷ (500 nm)
6 × 10⁻⁷ (600 nm)
7 × 10⁻⁷ (700 nm)
Wavelength (meters)
10⁻¹²
10⁻¹⁰
10⁻⁸
10⁻⁴
10⁻²
1
10²
10⁴
Gamma ray
X ray
Ultra-violet
Visual
Infrared
Micro-wave
UHF
VHF
FM
AM
Opaque
Transparency of Earth's atmosphere
Visual window
Radio window
Transparent
Wavelength
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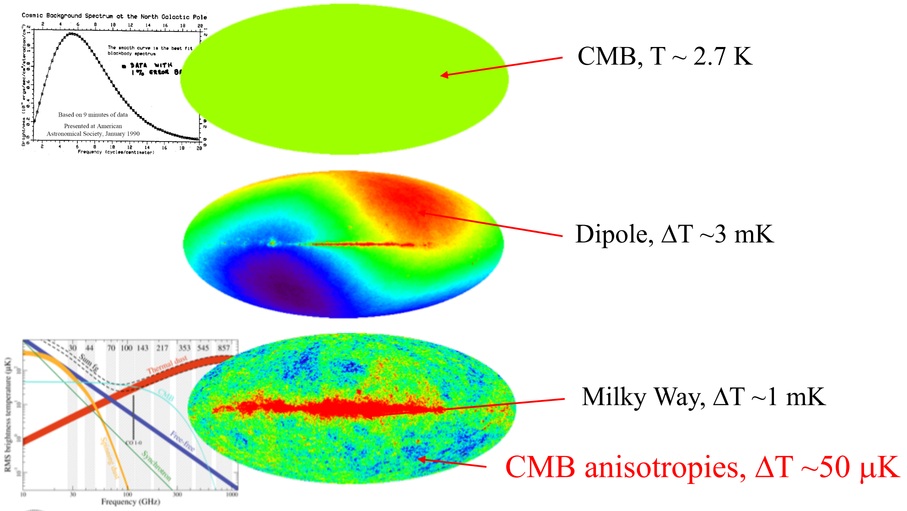
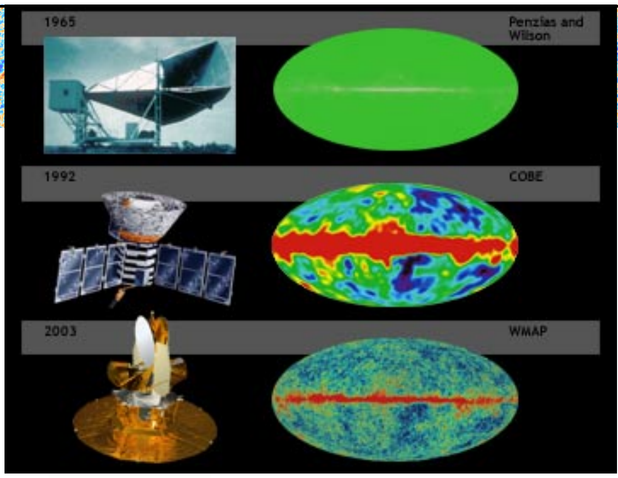
CMB measurement key factors

1. The signal has a black-body spectrum
2. The signal peaks in the microwave range λ ~3 mm; ν ~ 100 GHz
3. The signal has three main spatial components
   - A monopole at ~2.7 K
   - A "cosmological" dipole at 3 mK
   - Anisotropies at ~ 50 μK
4. The cosmological signal is very faint and is superimposed on a strong background, implying the need for
   - Broadband measurements with many receivers (sensitivity)
   - Extreme stability
   - Immunity from systematic effects
   - Large spatial coverage

The sky as seen by a CMB experiment, e.g. Planck



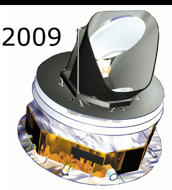
Penzias & Wilson

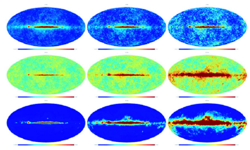


COBE

WMAP

2009





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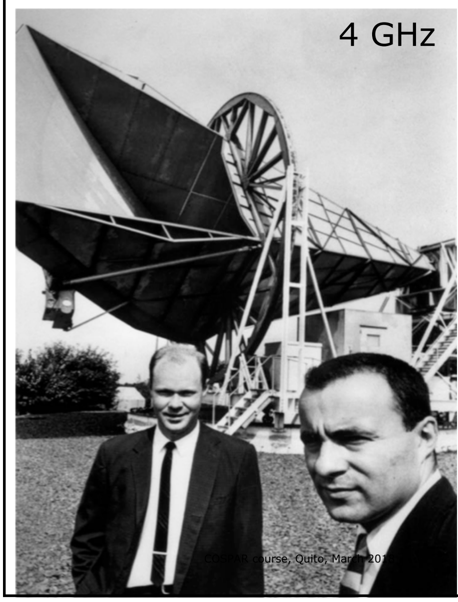
Penzias & Wilson 1964-1965



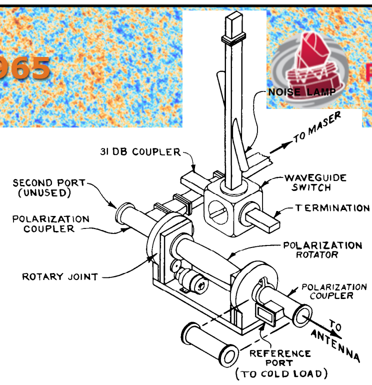


Fig. 3 The switching and calibration system of our 7.35 cm radiometer. The reference port was normally connected to the helium cooled reference source through a noise adding attenuator.

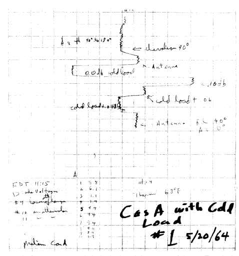


Fig. 9 The first measurement which clearly showed the presence of the microwave background. Noise temperature is plotted increasing to the right. At the top, the antenna pointed at 90° elevation is seen to have the samt noise temperature as the cold load with 0.04 db attenuation (about 7.5K). This is considerably above the expected value of 3.3K.

The Nobel Prize in Physics 1978

"for his basic inventions and discoveries in the area of low-temperature physics"

"for their discovery of cosmic microwave background radiation"

Pyotr Leonidovich Kapitsa
1/2 of the prize
USSR
Academy of Sciences
Moscow, USSR
b. 1894
d. 1984

Arno Allan Penzias
1/4 of the prize
USA
Bell Laboratories
Holmdel, NJ, USA
b. 1933
(in Munich, Germany)

Robert Woodrow Wilson
1/4 of the prize
USA
Bell Laboratories
Holmdel, NJ, USA
b. 1936

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A.A. Penzias, R.W. Wilson,
"A Measurement of Excess Antenna Temperature at 4080 Mc/s"
Ap. J. 142, 419 (1965)

"…Measurements of the … noise temperature have yielded a value about 3.5 K higher than expected. … isotropic, unpolarized, and free from seasonal observations…
A possible explanation is the one given by Dicke et al…"

Press release 1978

Mysterious background radiation

It has been known for a relatively long time that various astronomical objects emit radiation in the form of radio waves. Radioastronomy has grown in significance and is now a very important complement to classical optical astronomy. The radiation is emitted in various ways; for example, hydrogen clouds in the Galaxy radiate when excited, and cosmic ray electrons radiate when spiralling in the weak

planck

These two researchers made no suggestions about the origin of this mysterious radiation. When their discovery became known, however, it was found that speculations had already been made about the existence of a weak, microwave background radiation.
… , it was reasonable to suspect that it was fossil radiation from the 'big bang'. Support for this interpretation came from a number of investigations of the shape of the spectrum, which soon showed that it was indeed that which would be expected for a body with a temperature of 3 degrees. This provided solid support for the view that background radiation is the fossil remains of the 'big bang'; other interpretations are possible, however, even if they lack detailed theoretical backgrounds.

R.H. Dicke, P.J.E. Peebles, et al.
"Cosmic Black-Body Radiation"
Ap. J. 142, 414 (1965)

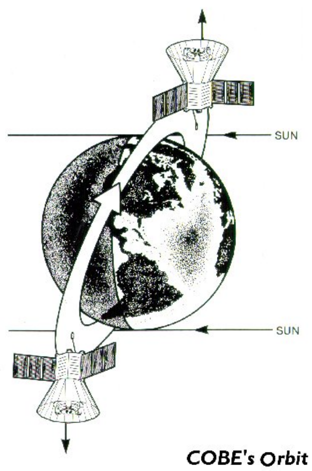
esa

COBE - Cosmic Background Explorer

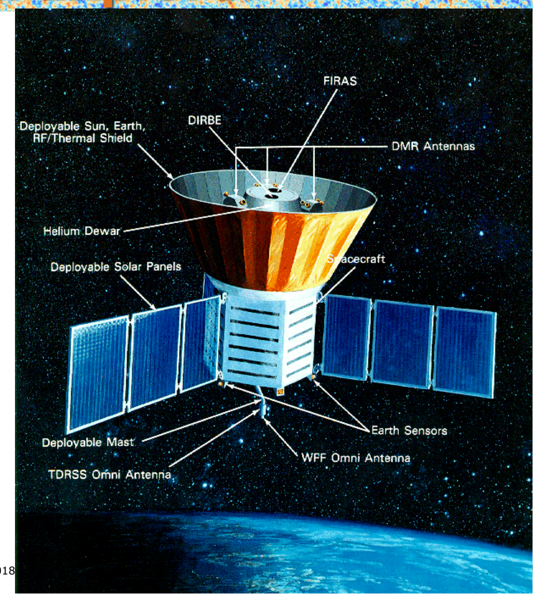
- The COBE satellite was developed by NASA's Goddard Space Flight Center to measure the diffuse infrared and microwave radiation from the early universe to the limits set by our astrophysical environment.
- launched November 18, 1989
- 3 instruments:
  - Far Infrared Absolute Spectrophotometer (FIRAS) to compare the spectrum of the cosmic microwave background radiation with a precise blackbody,
  - Differential Microwave Radiometer (DMR) to map the cosmic radiation sensitively, and
  - Diffuse Infrared Background Experiment (DIRBE) to search for the cosmic infrared background radiation.

Source: The COBE Home Page, http://space.gsfc.nasa.gov/astro/cobe/

COBE - Cosmic Background Explorer



COBE's Orbit



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FIRAS: Far-Inftared Absolute Spectrometer

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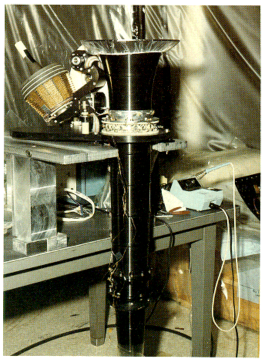
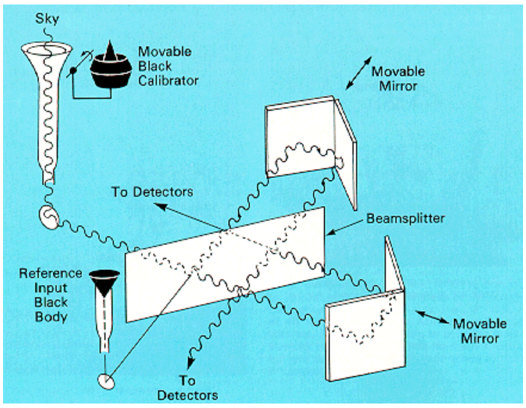


Horn antenna with movable calibrator. Protective plastic covers will be removed.



- Should measure precisely the spectrum of the cosmic microwave background radiation over the wavelength range from 0.1 to 10 mm
- 7 degree field of view
- polarizing Michelson interferometer with bolometer detectors to determine the intensity of the incoming light at a large number of wavelengths (i.e., a spectrum) simultaneously.

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Far Infrared Absolute Spectrophotometer (FIRAS)

FIRAS products

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FIRAS maps cover the whole sky and provide spectrophotometric data at frequencies ranging from 1 to 97 cm^{-1} (30 to 2910 GHz). The main celestial emission components in this interval are the cosmic microwave background, the spectrum of which FIRAS was designed to measure precisely, thermal emission from interstellar dust, and line emission from various molecules, atoms, and ions, including the CO rotational ladder (from J=1-0 to J=6-5), the C^+ 158 micron line, and other important interstellar cooling lines.

1. **CMB Temperature Map**
2. **Galactic Dust Continuum Spectra and Interstellar Dust Parameters:** maps of the residual sky spectrum after modelled emission from the CMBR, interplanetary dust (zodiacal emission), and interstellar lines have been subtracted.
3. **Spectral Sky Maps:** two low-spectral resolution products which cover the full FIRAS frequency range at ~25 GHz resolution; and a high-spectral resolution product which covers the frequency range 30 - 660 GHz at 6.9 GHz resolution. These files contain a spectrum at each pixel.
4. **Line Emission Maps** give the intensity and the associated uncertainty in each of 18 emission lines, of which the following 9 were detected: the 158 micron ground state transition of C^+, an important neutral interstellar gas coolant; the N^+ 122 micron and 205 micron transitions, which trace extended low-density ionized gas; the 370 micron and 609 micron lines of neutral carbon, which arise in photodissociation regions; and the CO J=2-1, 3-2, 4-3, and 5-4 lines, which trace the molecular gas.

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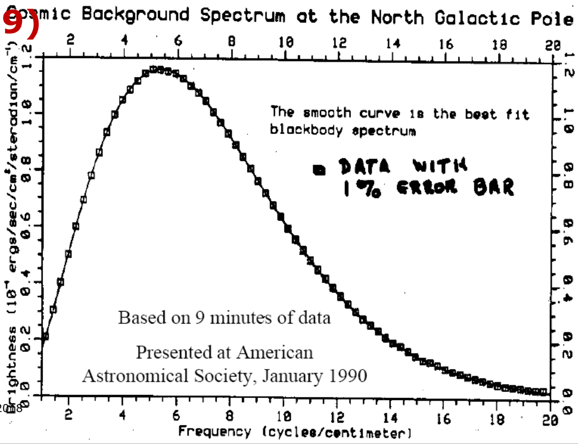
Cosmological discovery: FIRAS

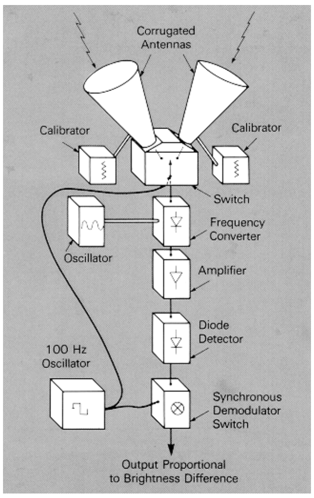
- **The cosmic microwave background (CMB) spectrum is that of a nearly perfect blackbody with a temperature of 2.726 +/- 0.0013 K (Fixsen et al 2009)**

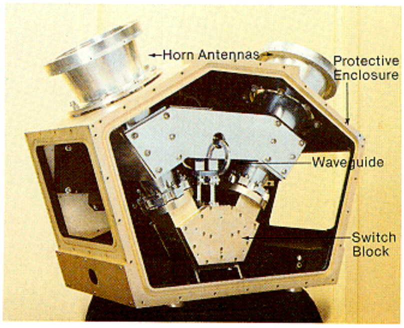
- **This observation matches the predictions of the hot Big Bang theory extraordinarily well**



Far Infrared Absolute Spectrophotometer (FIRAS)

DMR: Differential Microwave Radiometer



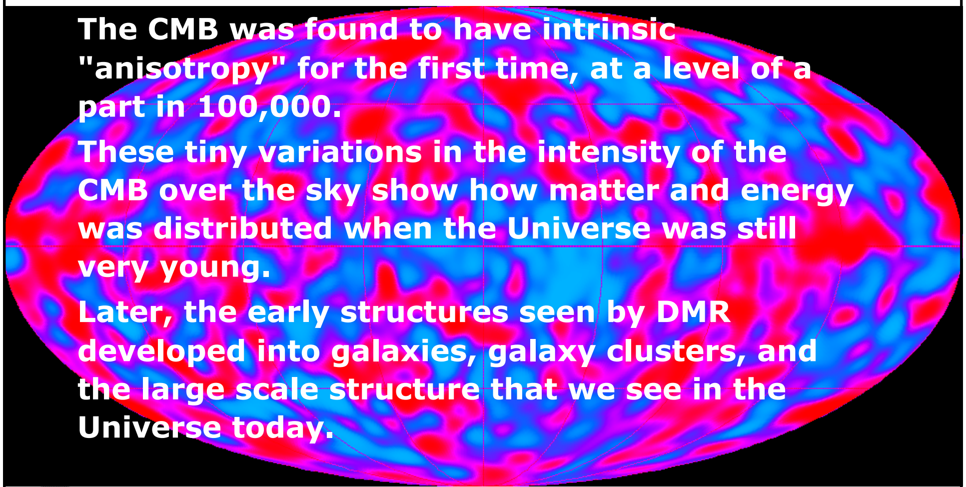


The 9.6 mm DMR receiver partially assembled. Corrugated cones are antennas.

- Should detect anisotropy
- 2 antennas for each wavelength: 3.3, 5.7 and 9.6mm
- Antennas are 60 degrees apart
- Antennas are switched to ensure difference comes from the sky and not from differences in the antennas
- 7 degree field of view

Differential Microwave Radiometer (DMR)

Cosmological discovery: DMR



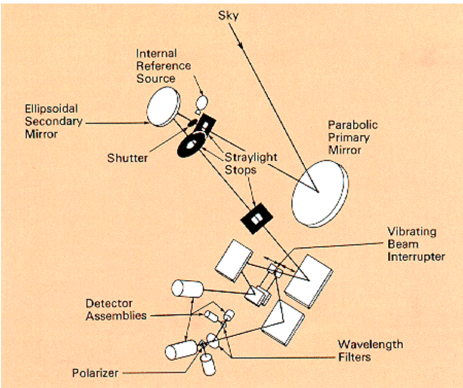
The CMB was found to have intrinsic "anisotropy" for the first time, at a level of a part in 100,000.

These tiny variations in the intensity of the CMB over the sky show how matter and energy was distributed when the Universe was still very young.

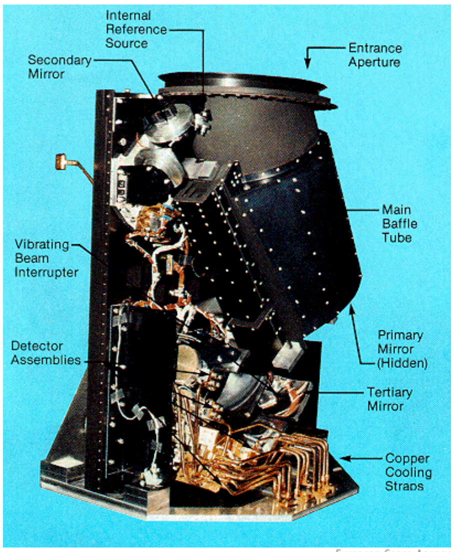
Later, the early structures seen by DMR developed into galaxies, galaxy clusters, and the large scale structure that we see in the Universe today.

Differential Microwave Radiometer (DMR)

DIRBE: Diffuse Infrared Background Experiment



- Measures absolute brightness at ten wavelengths (1.25 to 240μm)
  - Internal temperature comparison
- Polarisation at three shortest wavelengths



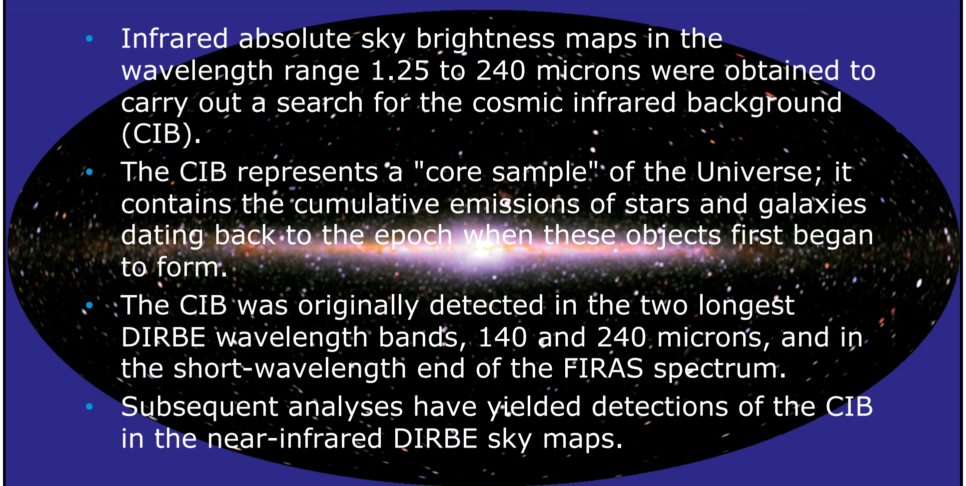
Diffuse Infrared Background Experiment (DIRBE)

DIRBE data products

- **A model of zodiacal emission**
- **Zodi-Subtracted Mission Average (ZSMA) Maps** at 1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140 and 240 microns.
- **Galactic Plane Maps** cover Galactic latitudes |b| < 10 deg at longitudes 30 deg < l < 330 deg and cover |b| < 15 deg elsewhere.
- **Solar System Objects Data:** flux densities and other data pertaining to individual passages of solar system objects through the DIRBE field of view during the period of cryogenic operation, from 11 December 1989 to 21 September 1990. The data include the following objects: Mars, Jupiter, Saturn, Uranus, Ceres, Pallas, and Vesta.
- …

Cosmological discovery: DIRBE

DIRBE 1.25, 2.2, 3.5 μm Composite



- Infrared absolute sky brightness maps in the wavelength range 1.25 to 240 microns were obtained to carry out a search for the cosmic infrared background (CIB).
- The CIB represents a "core sample" of the Universe; it contains the cumulative emissions of stars and galaxies dating back to the epoch when these objects first began to form.
- The CIB was originally detected in the two longest DIRBE wavelength bands, 140 and 240 microns, and in the short-wavelength end of the FIRAS spectrum.
- Subsequent analyses have yielded detections of the CIB in the near-infrared DIRBE sky maps.

Diffuse Infrared Background Experiment (DIRBE)

The Nobel Prize in Physics 2006

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"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"


Photo: P. Izzo

John C. Mather

1/2 of the prize

USA

NASA Goddard Space Flight Center
Greenbelt, MD, USA

b. 1946


Photo: J. Bauer

George F. Smoot

1/2 of the prize

USA

University of California
Berkeley, CA, USA

b. 1945

J. Mather, et al.,
"A preliminary measurement of the cosmic microwave background spectrum by the Cosmic Background Explorer (COBE) satellite,"
Ap. J. Lett. 354, L37 (1990)

G. F. Smoot, C. L Bennett, A. Kogut, et al.,
"Structure in the COBE DMR first year maps,"
Ap. J. Lett. 396, L1 (1992)

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Press release 2006

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Pictures of a newborn Universe

This year the Physics Prize is awarded for work that looks back into the infancy of the Universe and attempts to gain some understanding of the origin of galaxies and stars. It is based on measurements made with the help of the COBE satellite launched by NASA in 1989.

The COBE results provided increased support for the Big Bang scenario for the origin of the Universe, as this is the only scenario that predicts the kind of cosmic microwave

The COBE results provided increased support for the Big Bang scenario for the origin of the Universe, as this is the only scenario that predicts the kind of cosmic microwave background radiation measured by COBE. These measurements also marked the inception of *cosmology as a precise science.*

temperature show us how the matter in the Universe began to "aggregate". This was necessary if the galaxies, stars and ultimately life like us were to be able to develop. Without this mechanism matter would have taken a completely different form, spread evenly throughout the Universe.

COBE was launched using its own rocket on 18 November 1989. The first results were received after nine minutes of observations: COBE had registered a perfect blackbody spectrum. When the curve was later shown at an astronomy conference the results received a standing ovation.

The success of COBE was the outcome of prodigious team work involving more than 1,000 researchers, engineers and other participants. John Mather coordinated the entire process and also had primary responsibility for the experiment that revealed the blackbody form of the microwave background radiation measured by COBE. George Smoot had main responsibility for measuring the small variations in the temperature of the radiation.

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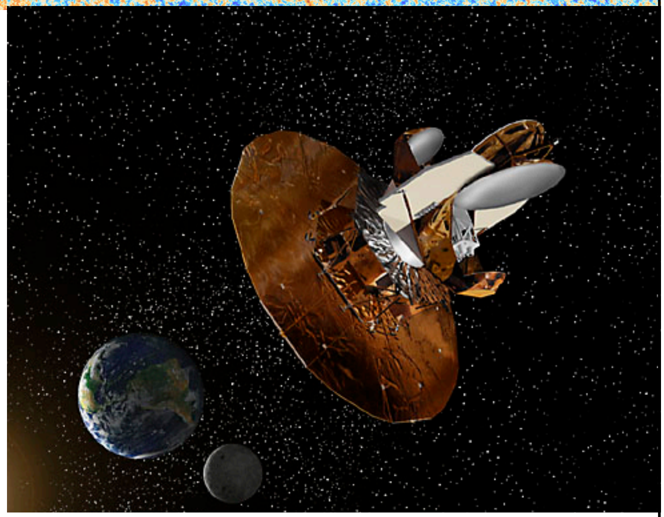
WMAP

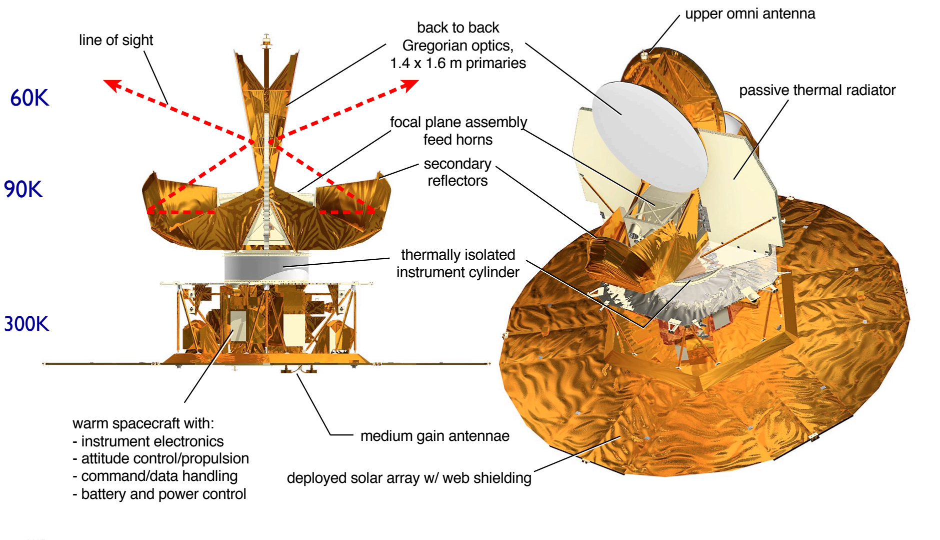
A partnership between NASA/GSFC and Princeton

Launched 2001

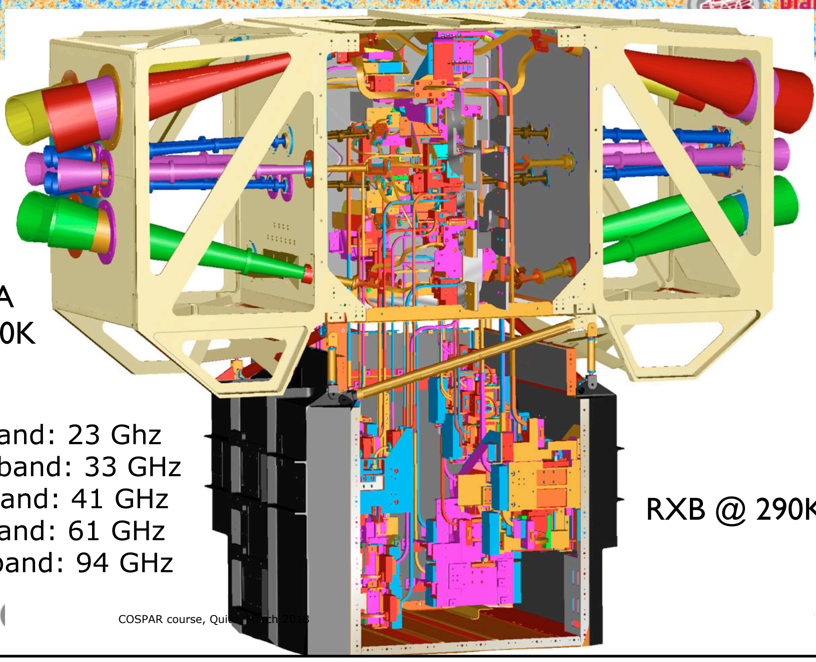
Operated ~10 years



WMAP Spacecraft



WMAP Instrument

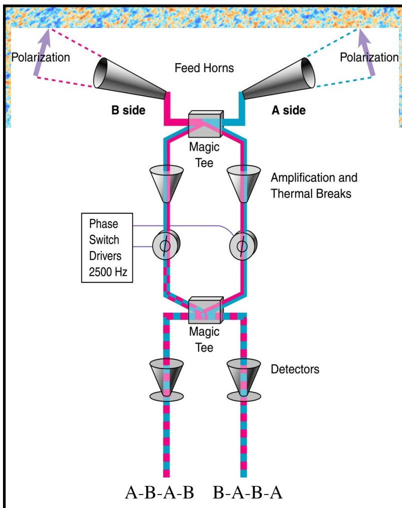


FPA
@ 90K

K-band: 23 Ghz
Ka-band: 33 GHz
Q-band: 41 GHz
V-band: 61 GHz
W-band: 94 GHz

RXB @ 290K

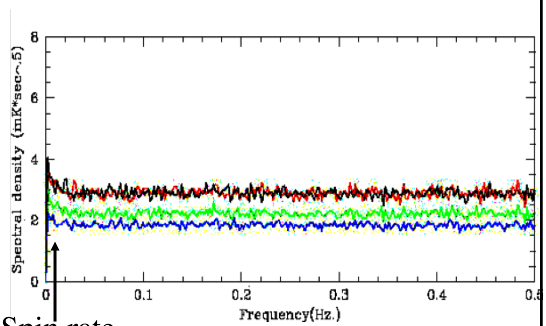
Why low 1/f ?



One of 20

Differential design...

....mK thermal stability

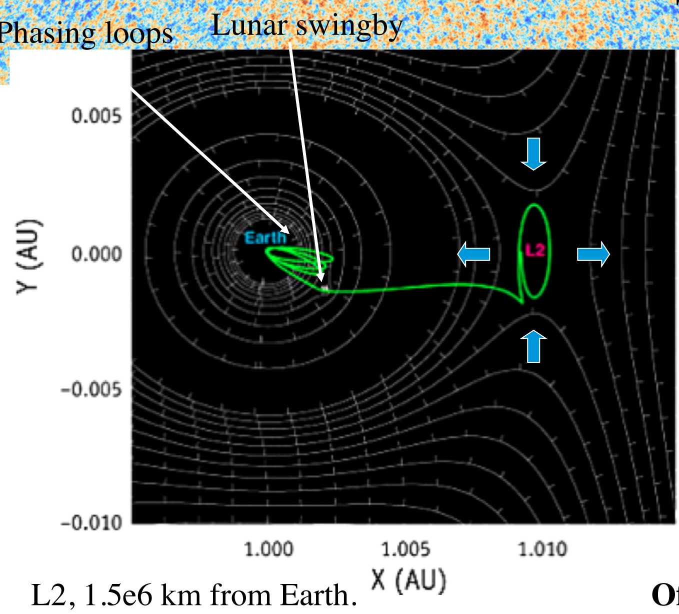


Amplifiers from NRAO,
M. Pospieszalski design

Noise in maps Gaussian
over five decades.

Jarosik et al.

Trajectory



Co-rotating potential.

L2, 1.5e6 km from Earth.

Official arrival date: Oct 1, 2001

Scan pattern

Need to scan in a criss-cross pattern to avoid striping and to minimize pixel-pixel correlations.
(Wright and Tegmark)

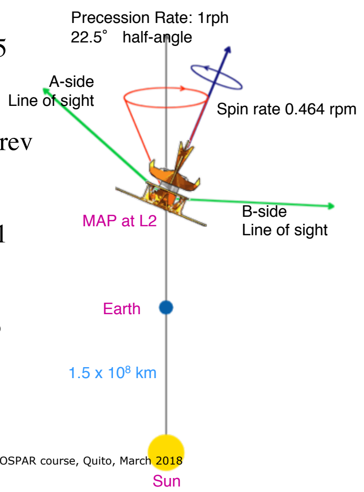
Four fold switching:

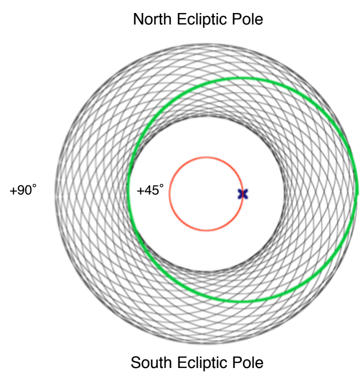
1) Phase switch 2.5 KHz

2) Spin at 2.2 min/rev

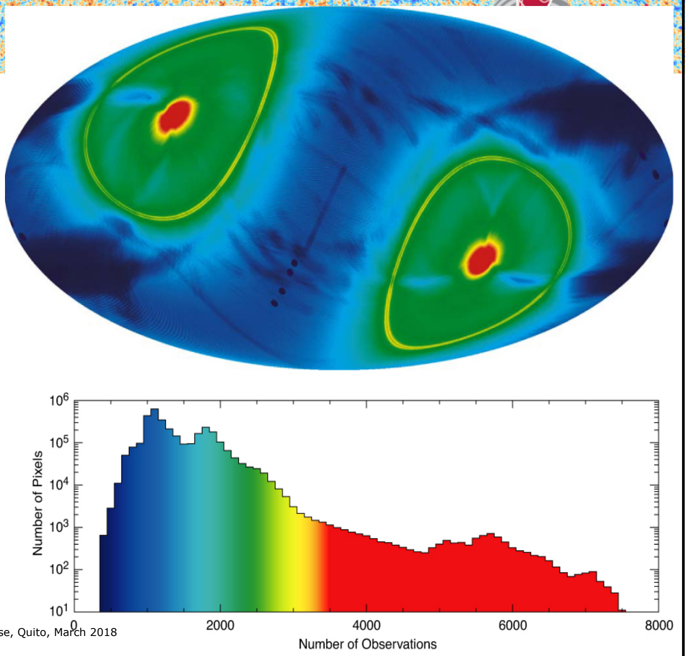
3)Precess through 30% of the sky in 1 hour.

4) Full sky every 6 months.





First Year Coverage Map



COBE-WMAP Comparison

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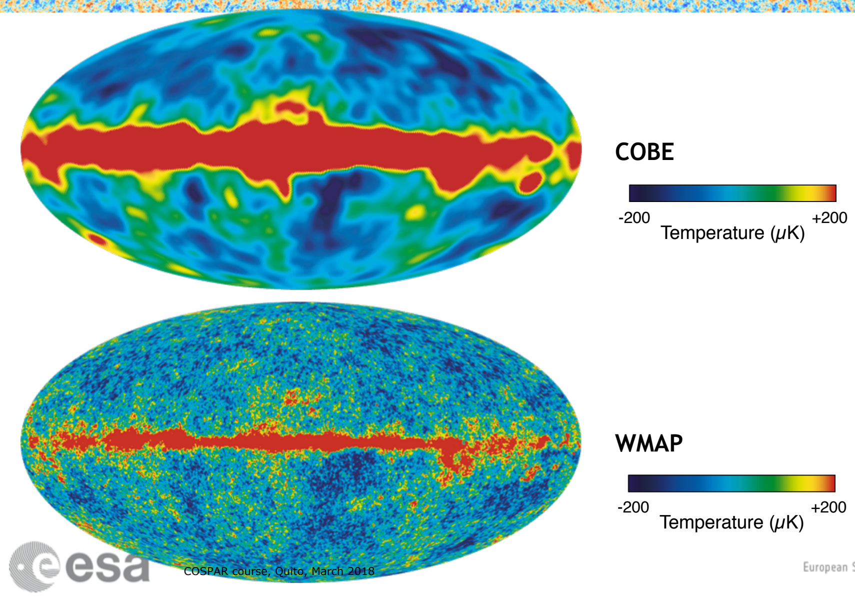
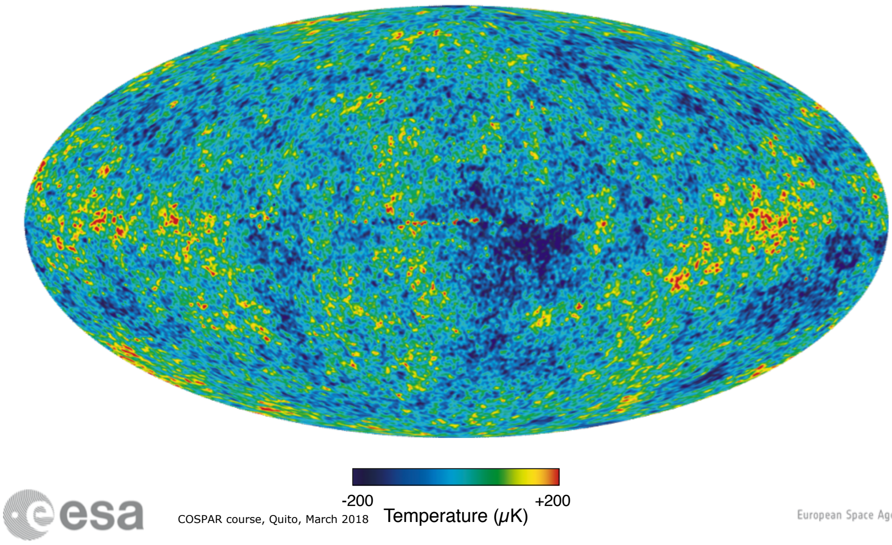
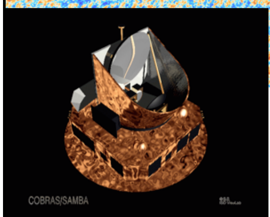


European Space Agency

WMAP Internal Linear Combination CMB



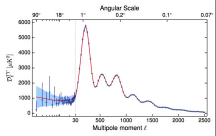
Planck – overview

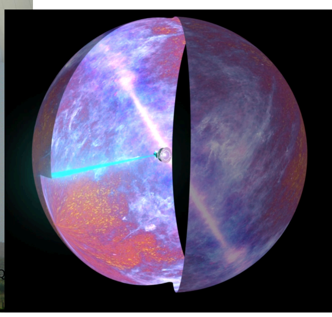


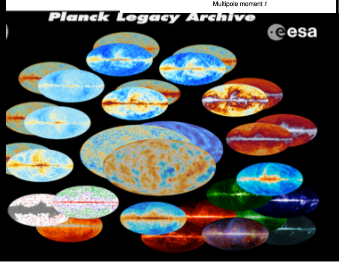
- First proposals – COBRAS & SAMBA – in 1993
- Start of Planck in 1996
- Launch in May 2009
- Operations Aug 2009- Oct 2013
- First data release March 2013
- Second data release Feb – July 2015
- *"Legacy" data release: 2017*

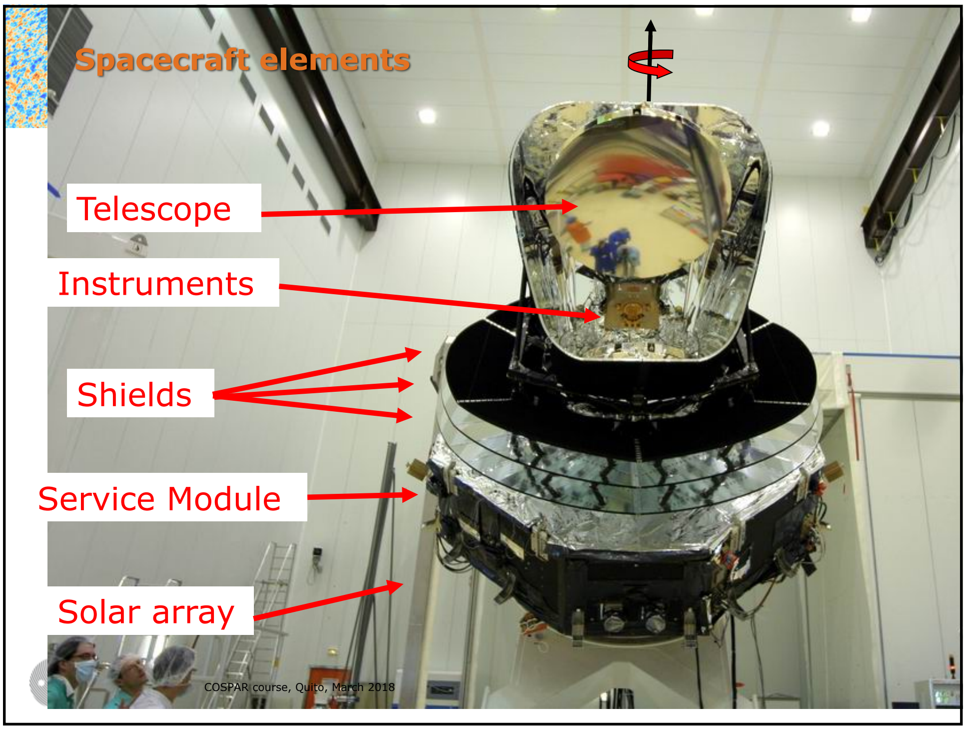
BASE ΛCDM MODEL

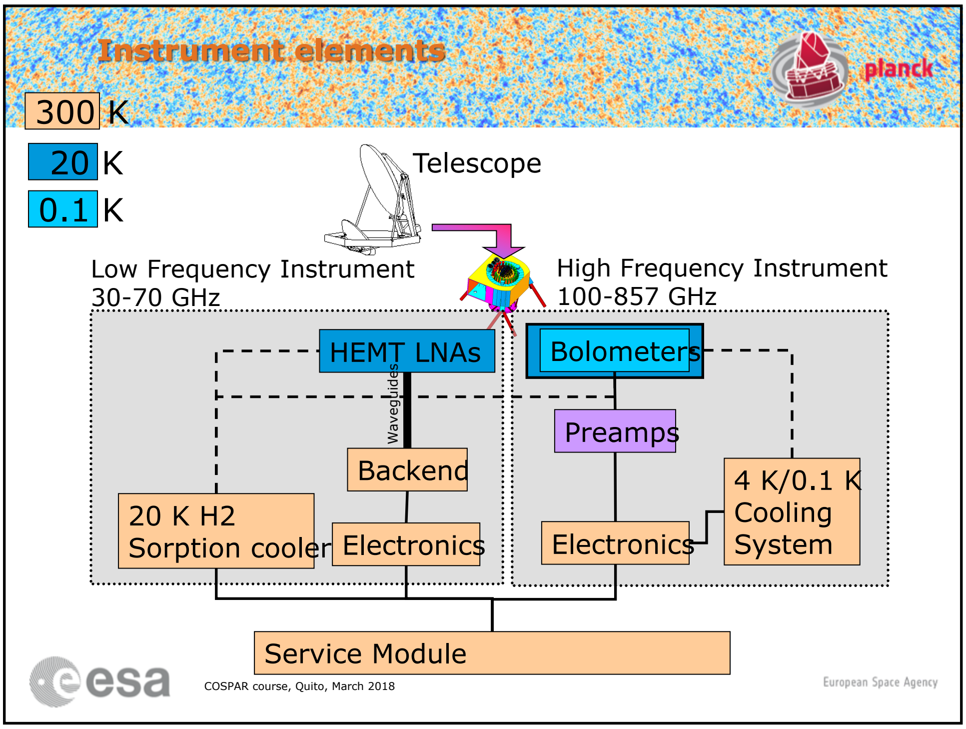
Parameter	TT	TT,TE,EE
$\Omega_b h^2$	0.02222±0.00023	0.02224±0.00015
$\Omega_c h^2$	0.1199±0.0022	0.1199±0.0014
$100\theta_*$	1.04086±0.00048	1.04073±0.00032
τ	0.078±0.019	0.079±0.017
n_s	0.9652±0.0062	0.9639±0.0047
H_0	67.3±1.0	67.23±0.64
Ω_m	0.316±0.014	0.316±0.009
σ_8	0.830±0.015	0.831±0.013
z_{re}	9.9±1.9	10.7±1.7








Spacecraft elements
Telescope
Instruments
Shields
Service Module
Solar array
COSPAR course, Quito, March 2018


Instrument elements
planck
300 K
20 K
0.1 K
Telescope
Low Frequency Instrument
30-70 GHz
High Frequency Instrument
100-857 GHz
HEMT LNAs
Bolometers
Waveguides
Preamps
Backend
4 K/0.1 K
Cooling
System
20 K H2
Sorption cooler
Electronics
Electronics
Service Module
esa
COSPAR course, Quito, March 2018
European Space Agency

Planck Telescope

planck

1. Primary: 1.50 x 1.89 m ellipsoid (CFRP)
2. Sec
   (CF
3. Syst
4. Refl
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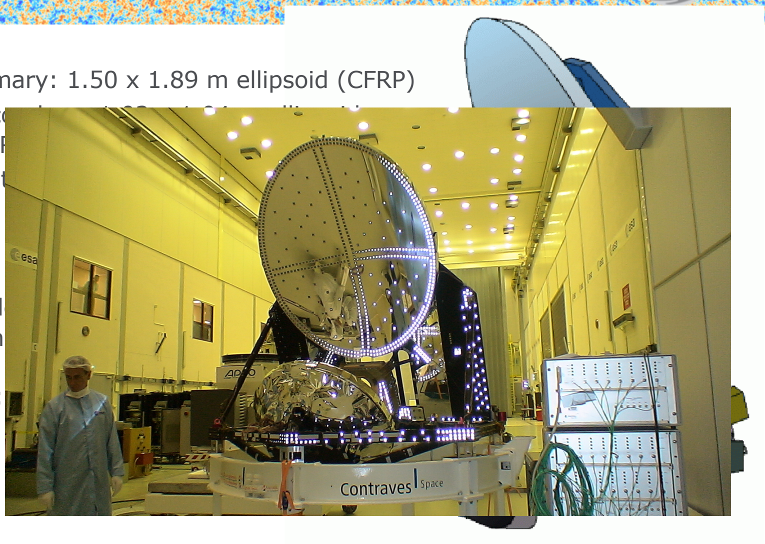
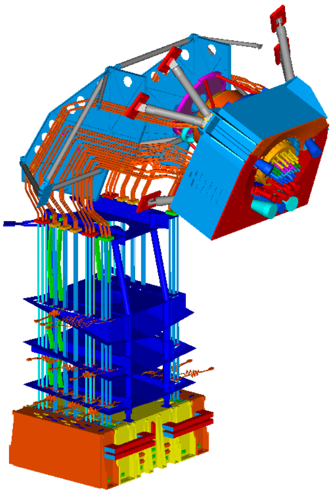
   (PI:



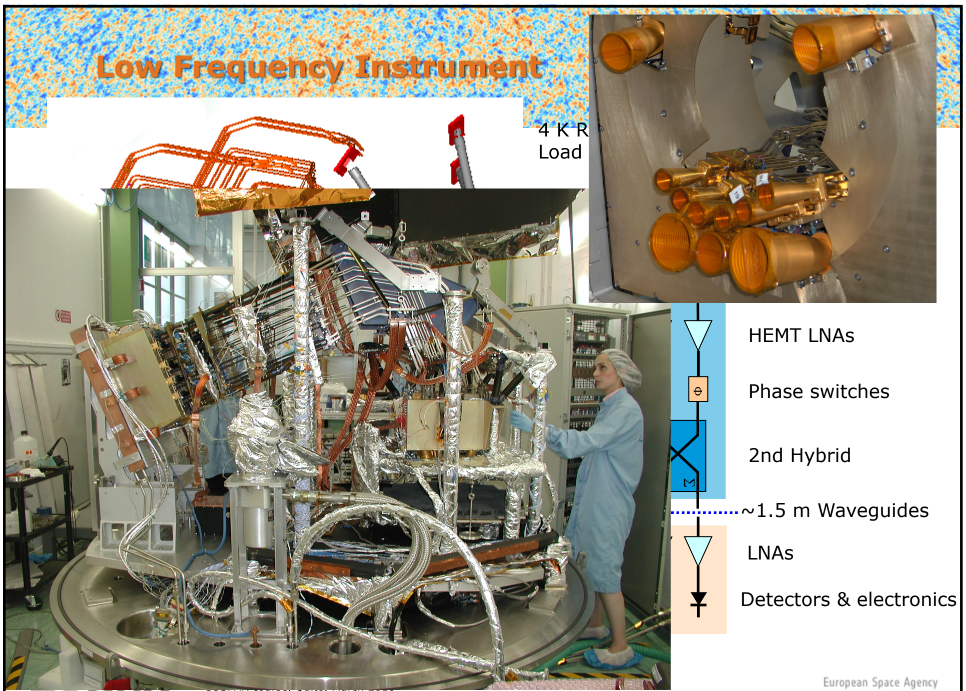
Low Frequency Instrument

planck



1. Freq.: 30 -70 GHz
2. Techn.: HEMT correlation receivers (22)
3. Temp.: 20 K (Front-end), 300 K (Back-end)
4. Ang. res.: 12' (70 GHz) to 33' (30 GHz)
5. Temp. sens. @30 GHz: ~5.4 μK; @70 GHz: 12.7 μK
6. PI: N. Mandolesi (CNR - Bologna)

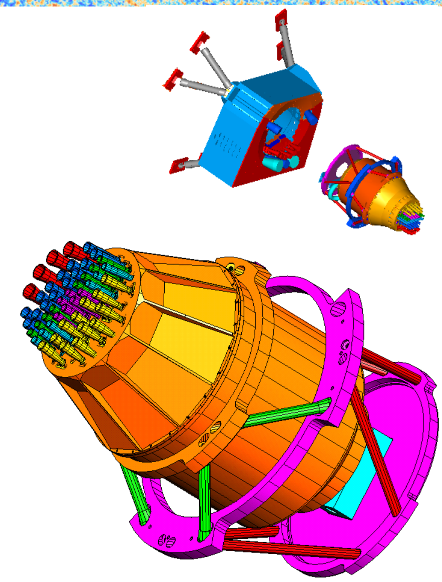
Low Frequency Instrument



High Frequency Instrument

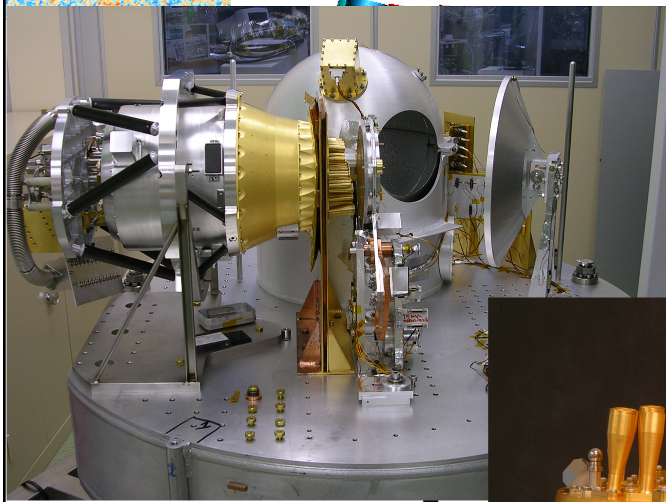
planck

1. Freq.: 100 -850 GHz
2. Techn.: spider-web bolometers (50)
3. Temp.: 0.1 K
4. Ang. res.: 9.2' (100 GHz) to 5' (850 GHz)
5. Temp. sens. (@100 GHz): ~5 μK
6. PI: J.L. Puget (IAS - Orsay)



High Frequency Instrument

planck



-to-back horns at 4 K

Filters at 1.6 K

Bolometers, horns and filters at 0.1 K

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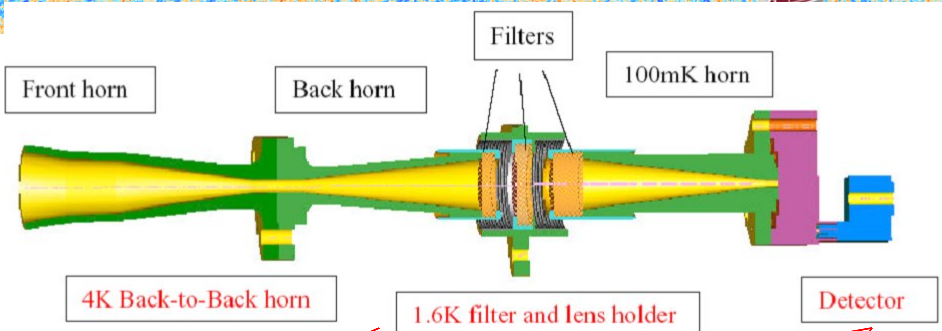
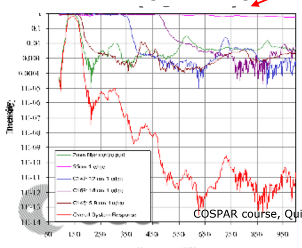
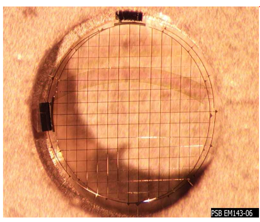
High Frequency Instrument

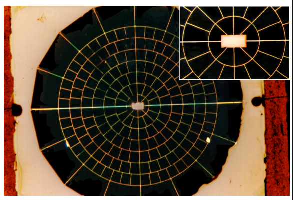
planck



Filters (QMW)







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Spider-web or polarisation-sensitiv

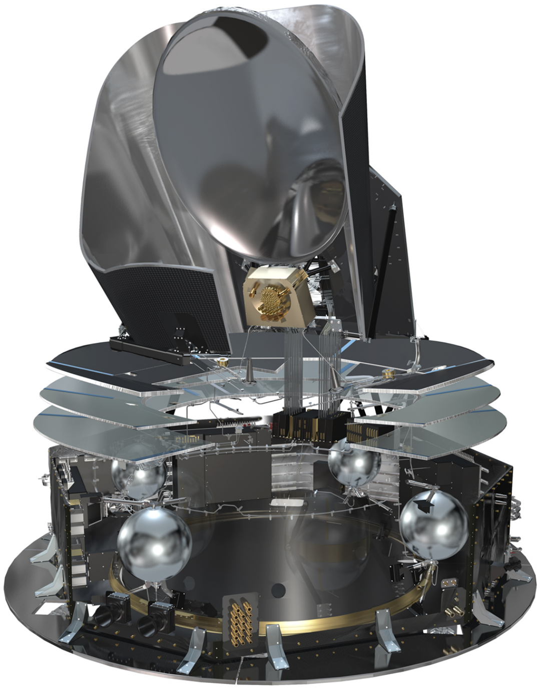
Cooling system

V-groove radiators

20 K H_2 sorption coole
(serves both LFI and H

4 K Stirling cooler (RA

0.1 K $^3He/^4He$ dilution



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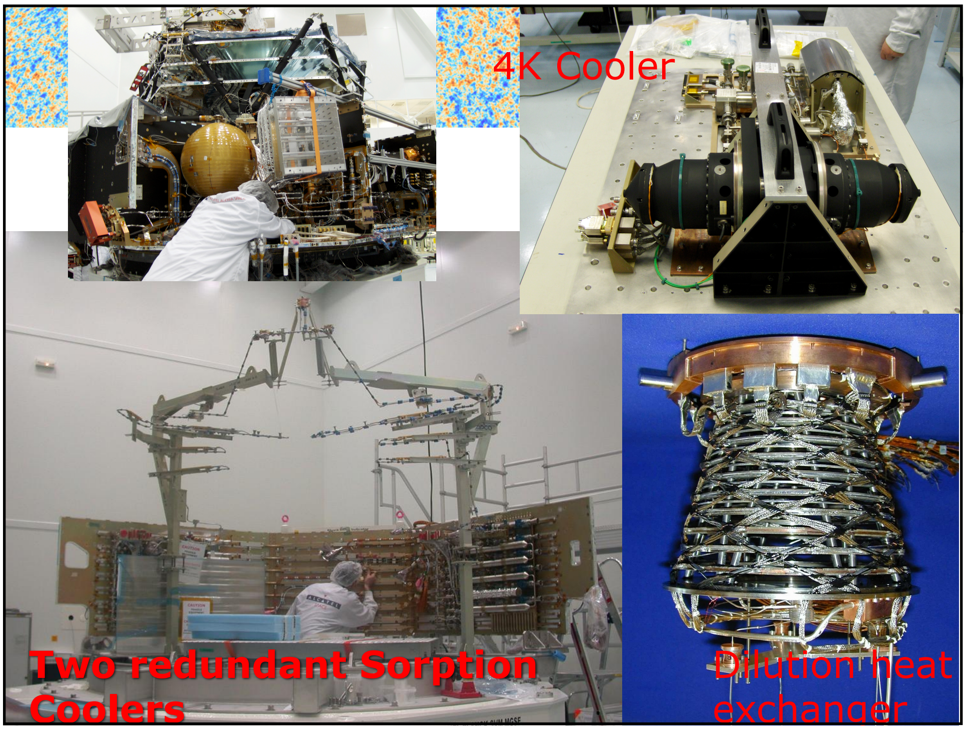

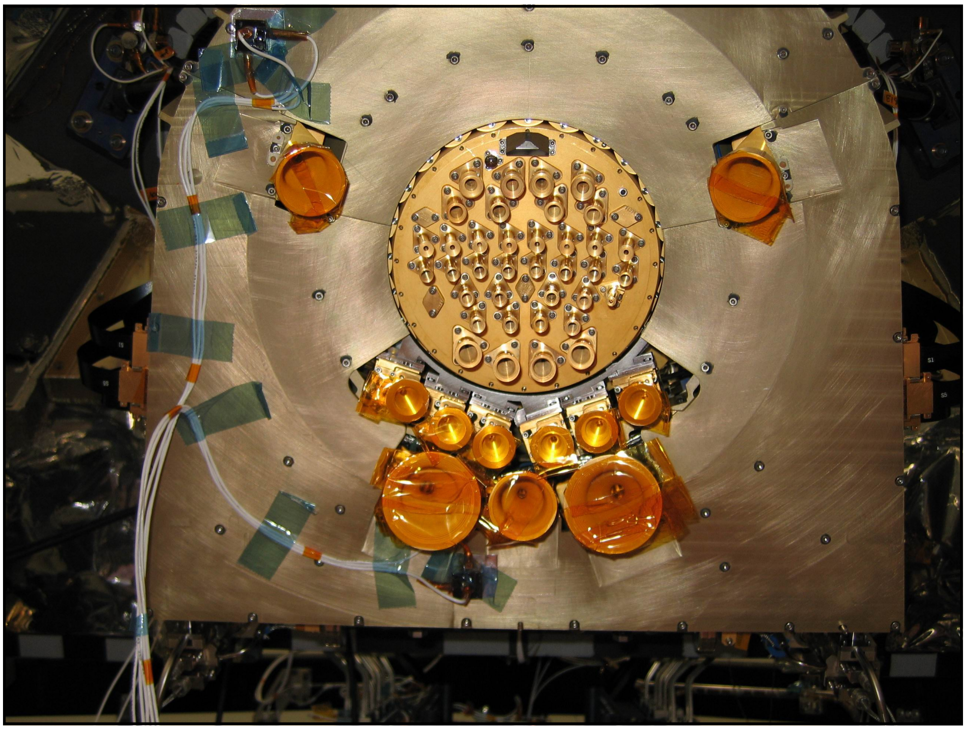

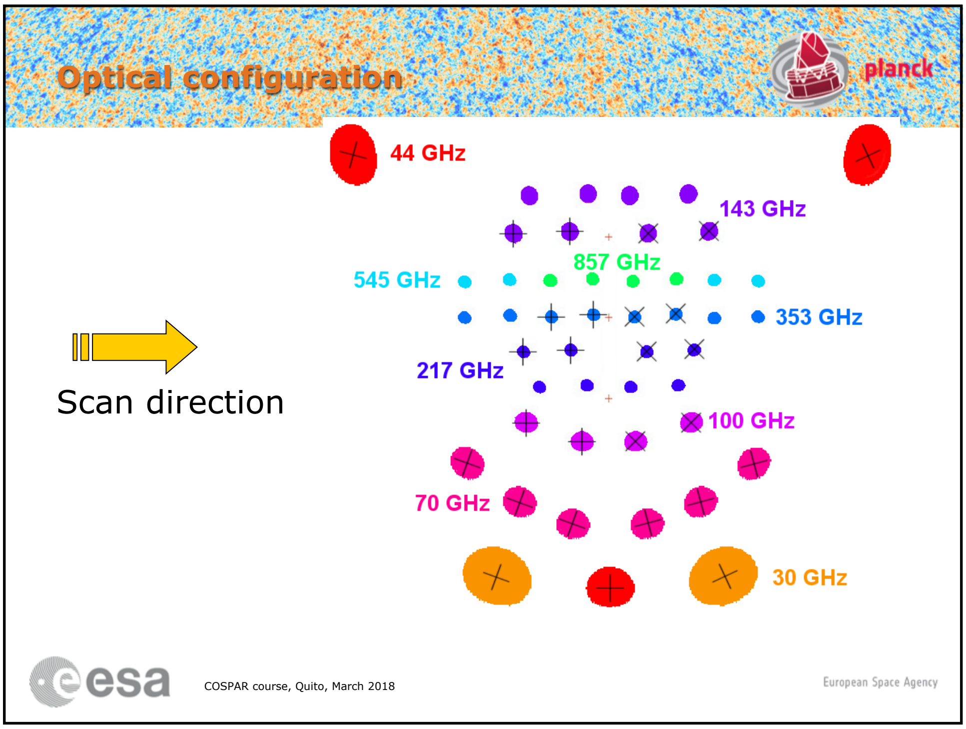
Optical configuration
planck
44 GHz
143 GHz
857 GHz
545 GHz
353 GHz
217 GHz
Scan direction
100 GHz
70 GHz
30 GHz
esa
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Polarization Basics

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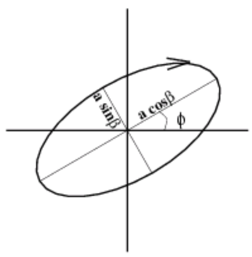
1. In general, light is partly polarised
    a. Part of it is unpolarised
    b. Part of it is polarised
2. Polarised light requires four quantities to fully represent it



An ellipse can be represented by 4 quantities:

1. size of minor axis
2. size of major axis
3. orientation (angle)
4. sense (CW, CCW)

Polarization Basics

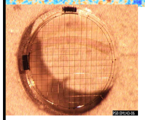
planck

1. Mathematically, it can be represented in different ways
    a. Field components
    b. Geometric ellipse components
    c. (Jones) vectors
    d. **Stokes parameters**
    e. …
2. Four maps to represent emission
    a. We can mostly ignore V

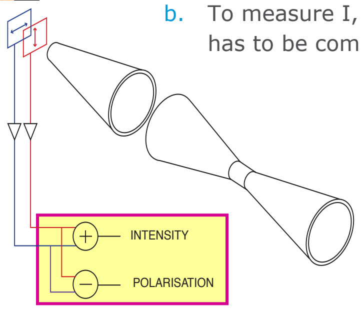
$$S_0 = I = E_{0x}^2 + E_{0y}^2$$
$$S_1 = Q = E_{0x}^2 - E_{0y}^2$$
$$S_2 = U = 2E_{0x}E_{0y}\cos\varepsilon$$
$$S_3 = V = 2E_{0x}E_{0y}\sin\varepsilon$$

• Linear polarization	$Q \neq 0, U \neq 0, V = 0$
• Circular polarization	$Q = 0, U = 0, V \neq 0$
• Fully polarized light	$I^2 = Q^2 + U^2 + V^2$
• Partially polarized light	$I^2 > Q^2 + U^2 + V^2$
• Unpolarized light	$Q = U = V = 0$

Basics: detection

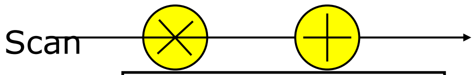


1. Detectors can also be "polarised": they are sensitive only to certain types of polarisation
   a. In LFI and HFI, most detectors are linearly polarised
   b. To measure I, Q, and U, data from several detectors has to be combined



Both bolometers in a PSB pair share the same optics but have different readouts

- Each PSB ***pair*** measures (I & U) or (I & Q)
- Two pairs, rotated by 45°, together measure (I, U, Q)

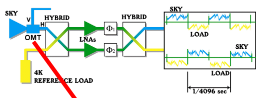


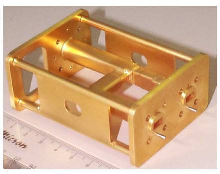
$I = E_x^2 + E_y^2$ $\quad Q = E_x^2 - E_y^2$

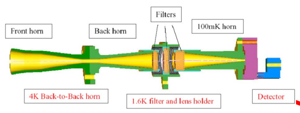
$U = 2E_xE_y$

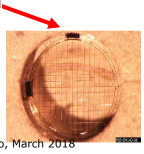
Note: Planck does not measure V !

Polarisation Measurement with LFI and HFI

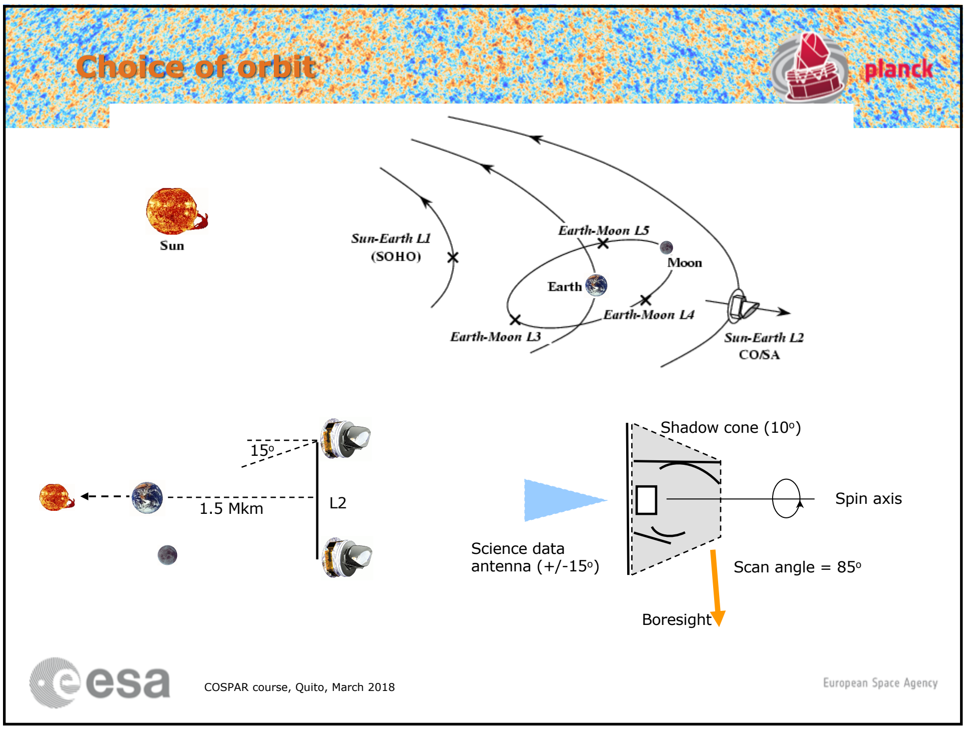








1. Principle is the same for both LFI and HFI
2. Polarisation separation mechanism is different
   a. LFI: Ortho-mode Transducer separates two orthogonal polarisations
   b. HFI: Orthogonally oriented grids select polarisation and deliver to separate thermistors


Choice of orbit
planck
Sun
Sun-Earth L1
(SOHO)
Earth-Moon L5
Moon
Earth
Earth-Moon L4
Earth-Moon L3
Sun-Earth L2
COSA
15°
1.5 Mkm
L2
Shadow cone (10°)
Spin axis
Science data
antenna (+/-15°)
Scan angle = 85°
Boresight
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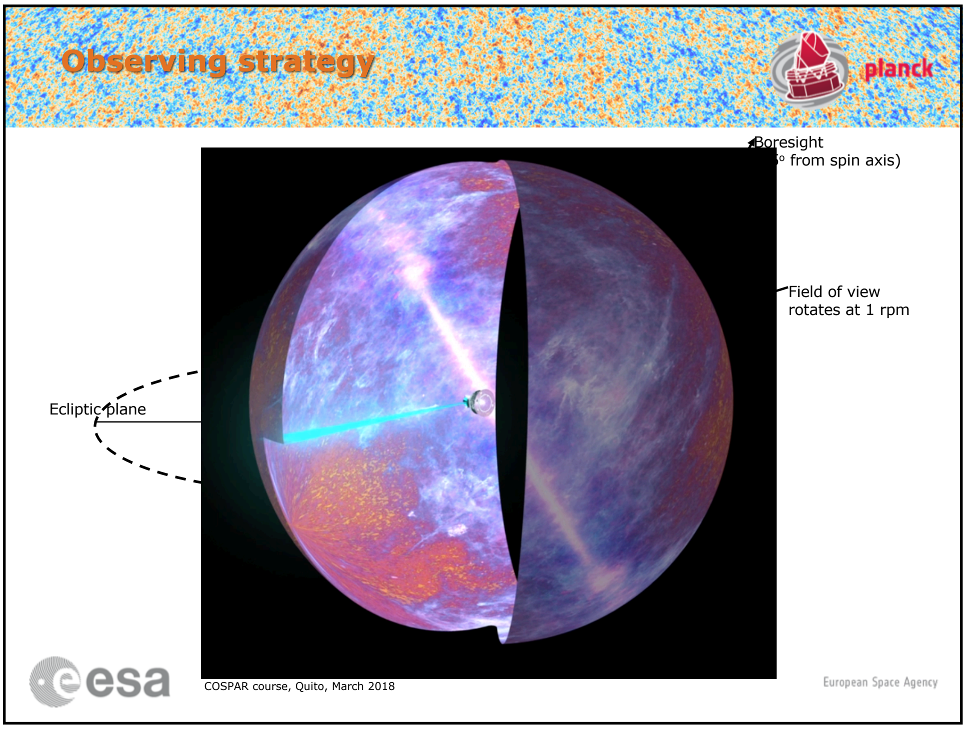
Observing strategy
planck
Boresight
° from spin axis)
Field of view
rotates at 1 rpm
Ecliptic plane
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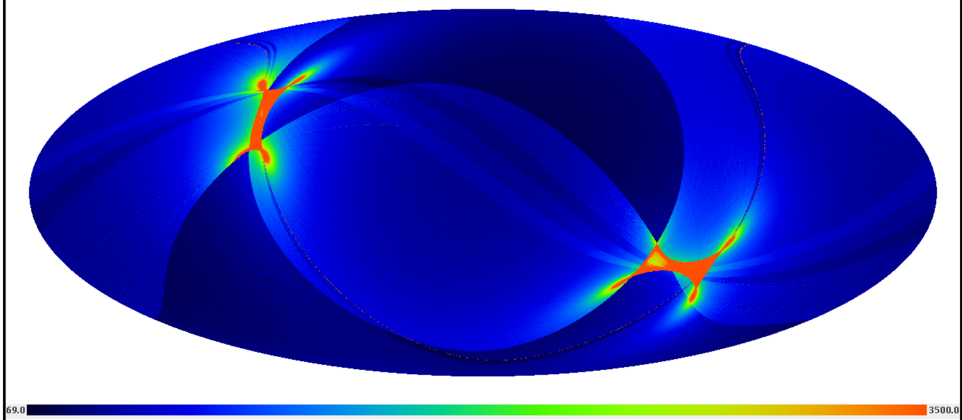
Integration time @ 353 GHz



Calibration

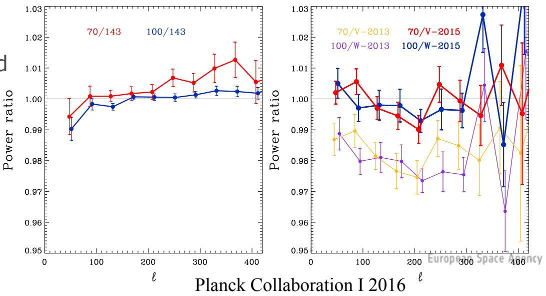
1. No on-board standards
2. External photometric calibrators:
   - ~~a. FIRAS (0.1% on CMB temperature)~~
   - b. CMB dipole (~3 mK amplitude, known to ~10 μK)
   - c. CMB dipole modulation with orbital motion (~0.3 mK amplitude, known with very high accuracy)
   - d. Planets (Mars, Saturn)
3. Precise determination of beam patterns:
   - a. main beam and mid-sidelobes using outer planets
   - b. far-side lobes using scanning strategy and models
4. No polarised calibrators on the sky

Calibration accuracy

planck

- The Planck temperature frequency maps are exquisitely calibrated !
  - Absolute calibration accuracy is as low as ~0.1% (100-143 GHz) *at the largest angular scales*
  - The Solar dipole amplitude is determined by Planck to 0.06% (0.02º in direction); worst residual 0.2% at 217 GHz
  - Relative calibration between 70 and 217 GHz <0.3% (0.5% when including 353 GHz) *at intermediate angular scales*
  - The 545 and 857 GHz maps are calibrated on planets
    - The relative calibration is ~1%, but the absolute calibration is driven by the model uncertainty of 5%

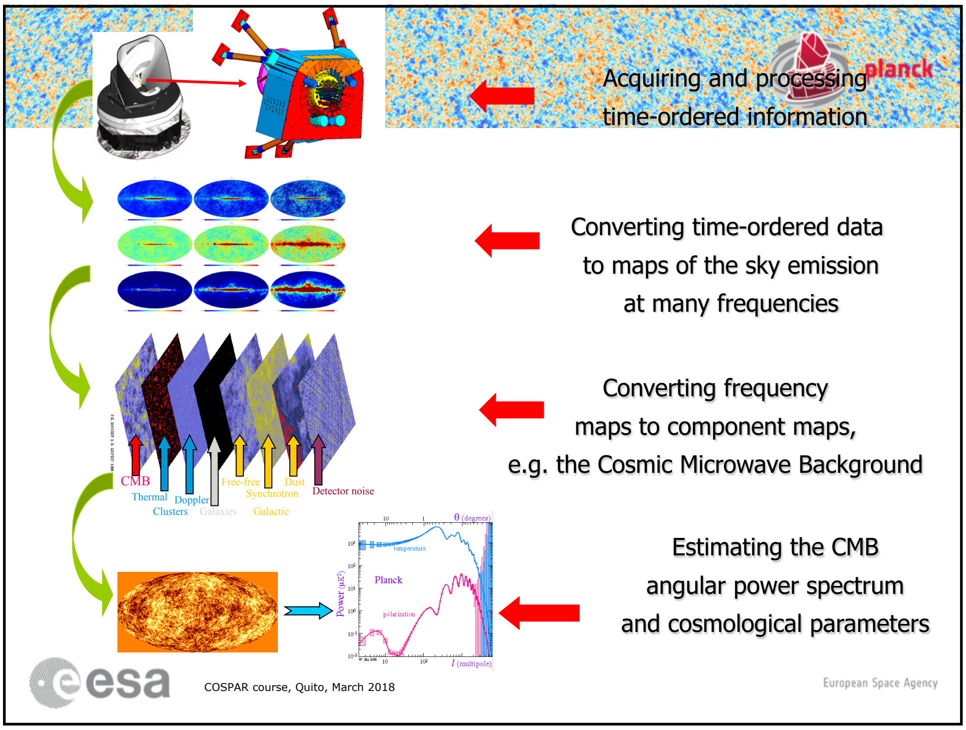
- Planck has the potential to become a calibration standard for many ground- and space-based observatories
  - See E.g. cross-calibration with SPIRE, VLA (PIPXLV, Bertincourt et al 2016)



Planck Collaboration I 2016

The moment of glory – 14 May 2009

planck



Acquiring and processing
time-ordered information
planck
Converting time-ordered data
to maps of the sky emission
at many frequencies
Converting frequency
maps to component maps,
e.g. the Cosmic Microwave Background
CMB
Thermal
Doppler
Clusters
Galaxies
Free-free
Synchrotron
Dust
Galactic
Detector noise
Planck
temperature
polarization
Power (μK²)
l (multipole)
θ (degrees)
Estimating the CMB
angular power spectrum
and cosmological parameters
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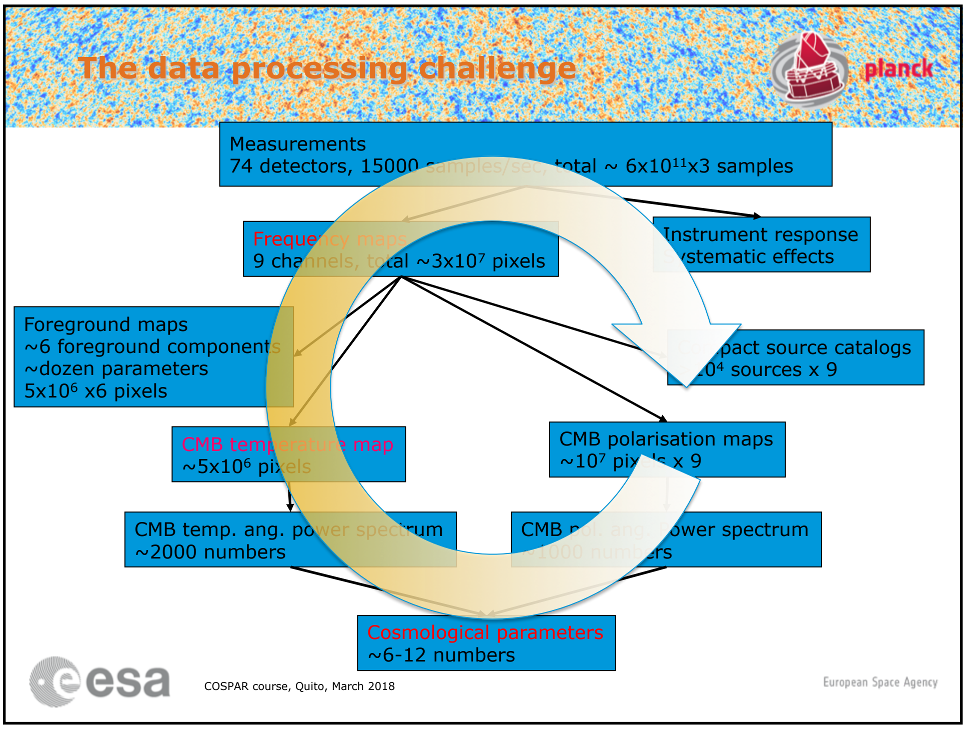

The data processing challenge
planck
Measurements
74 detectors, 15000 samples/sec, total ~ 6x10¹¹x3 samples
Frequency maps
9 channels, total ~3x10⁷ pixels
Instrument response
systematic effects
Foreground maps
~6 foreground components
~dozen parameters
5x10⁶ x6 pixels
pact source catalogs
10⁴ sources x 9
CMB temperature map
~5x10⁶ pixels
CMB polarisation maps
~10⁷ pixels x 9
CMB temp. ang. power spectrum
~2000 numbers
CMB pol. ang. power spectrum
~1000 numbers
Cosmological parameters
~6-12 numbers
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Limitations

- We want to measure *very* faint (polarized) signals
- The enemies are
  - Systematic effects
    - Instrumental
    - Scanning
  - Astrophysical sources of "noise"
  - Data processing pipelines, e.g. map-making, component separation
- So far it has been possible to deal with all of this on a one-by-one basis – beyond Planck this is no longer viable
- There is increasing reliance on Monte-Carlo simulations - high-performance computing

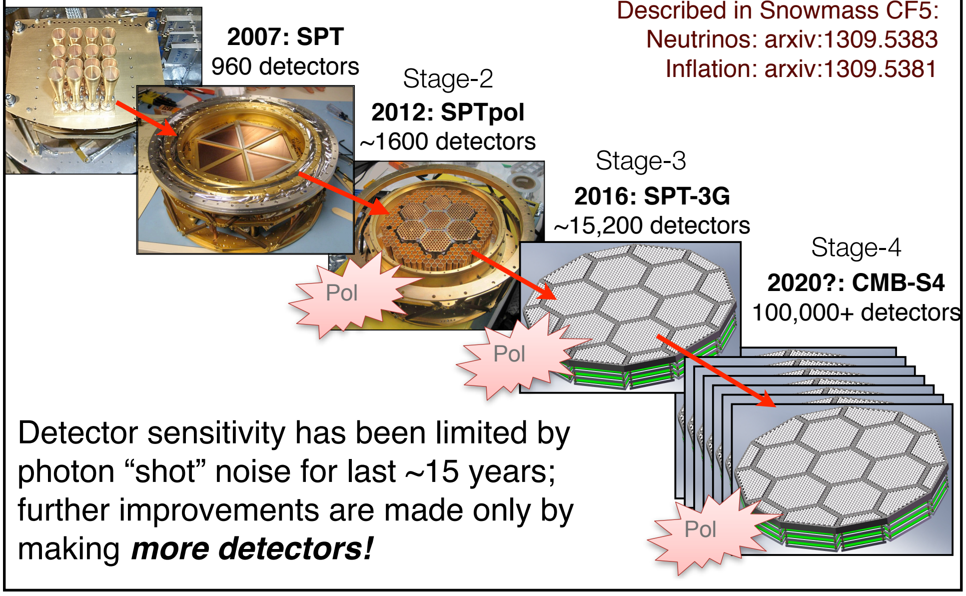
Summary

Three generations of CMB observations from space

- COBE
  - DMR: the first detection of CMB anisotropies
  - FIRAS: still the best measurement of the temperature of the CMB; absolutely calibrated all-sky spectro-photometric maps 30-3000 GHz
  - DIRBE: all-sky maps 1.2 -240 μm
- WMAP: all-sky maps 23 - 94 GHz
- Planck: all-sky maps 30 – 857 GHz
  - Currently the flagship CMB data source
  - Maps of diffuse galactic foregrounds
  - Catalogues of galactic and extragalactic compact sources

Evolution of CMB Focal Planes

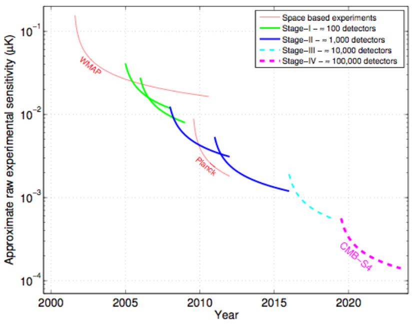
CMB Stage-4 Experiment
Described in Snowmass CF5:
Neutrinos: arxiv:1309.5383
Inflation: arxiv:1309.5381

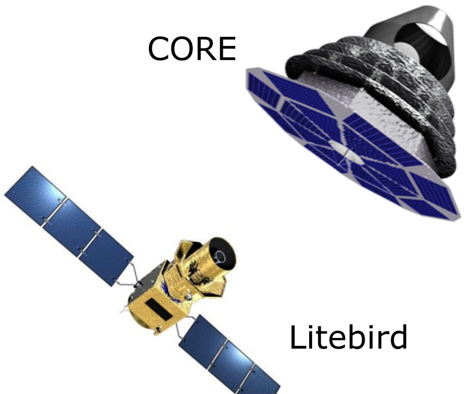


Detector sensitivity has been limited by photon "shot" noise for last ~15 years; further improvements are made only by making ***more detectors!***

The next frontier: CMB polarization

planck





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