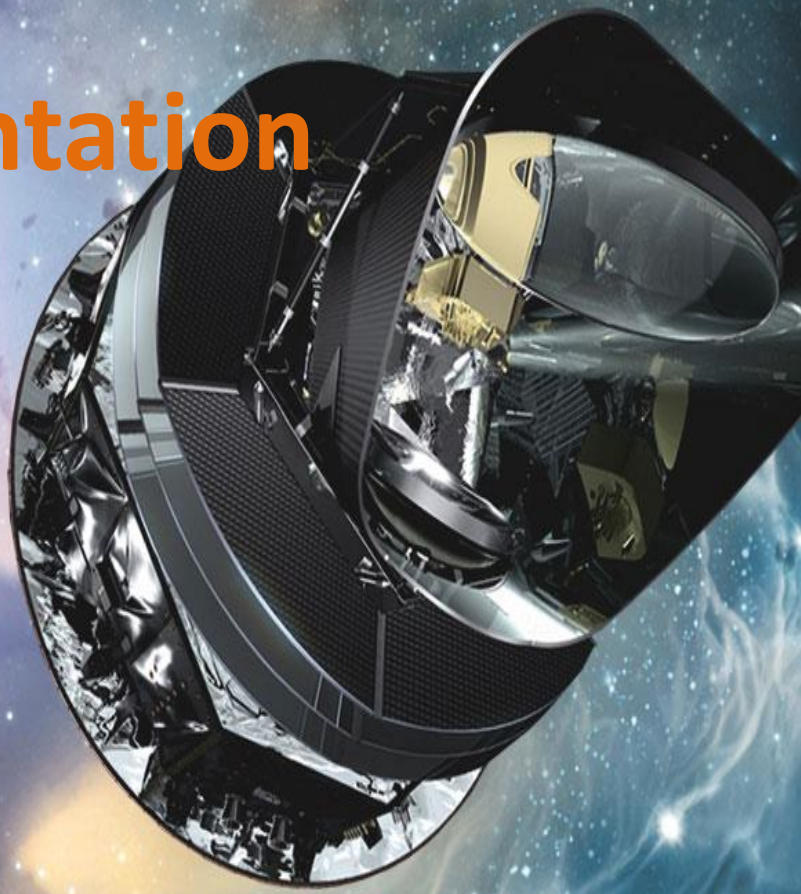
Space Instrumentation

ELEC-E4220 (5 cr)

Teachers: Anne Lähteenmäki

Esa Kallio

Guests



Today 10.11.2020

- ESA's Cosmic Vision Science Programme
- Lifecycle of a space mission: researcher's view
- Case study: the Planck satellite
- Space debris

ESA

ESA SPACE MISSIONS

ESA's COSMIC VISION

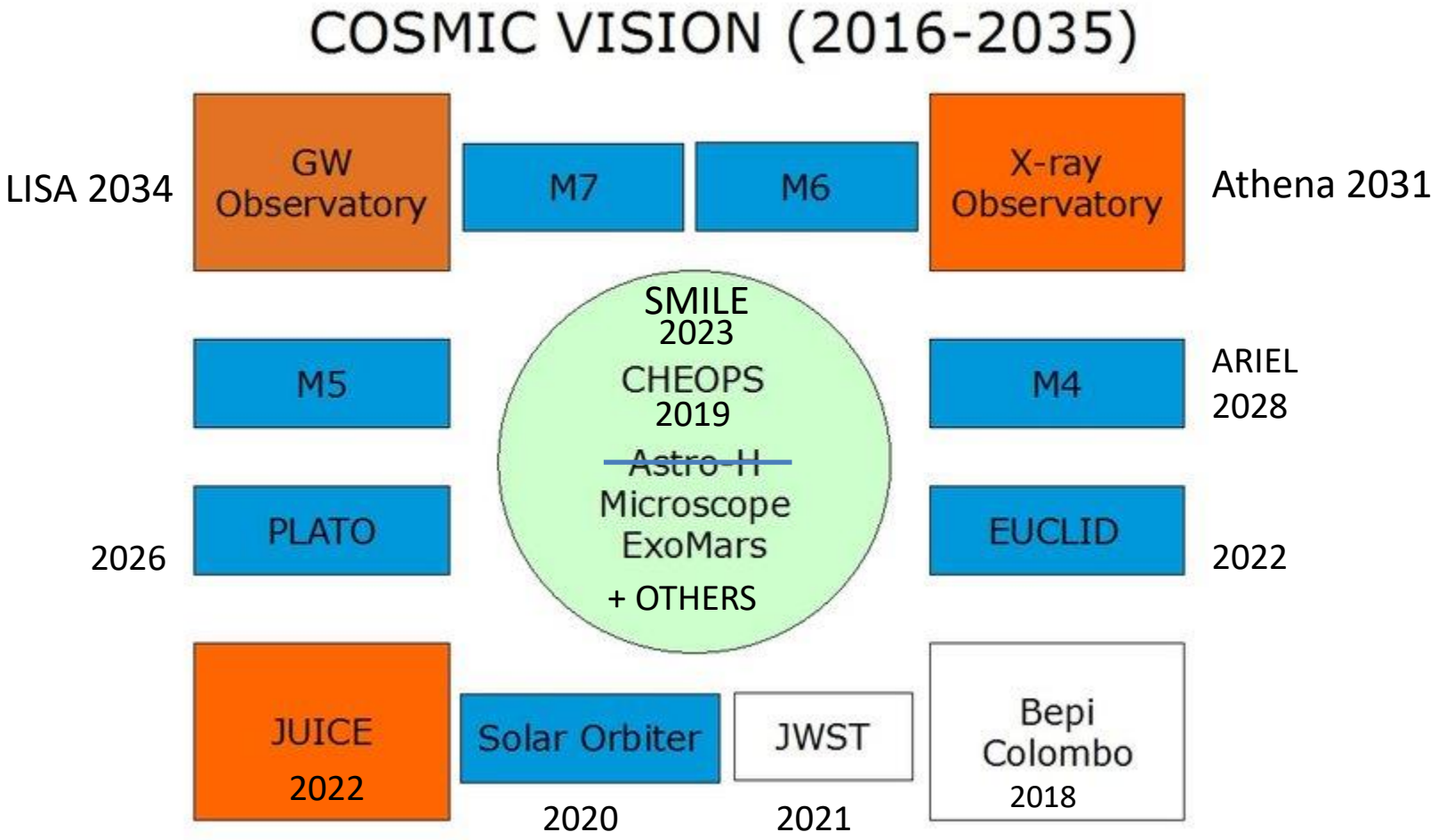
- Horizon 2000 (1985-2005)
- Horizon 2000+ (2005-2015)
- Cosmic Vision (2015-2025)
- Three categories
  - Small (S), Medium (M), Large (L)
  - Scientific goals, cost, and development time

- *What are the conditions for planet formation and the emergence of life?*
- *How does the Solar System work?*
- *What are the physical fundamental physical laws of the Universe?*
- *How did the Universe originate and what is it made of?*

Cosmic vision themes

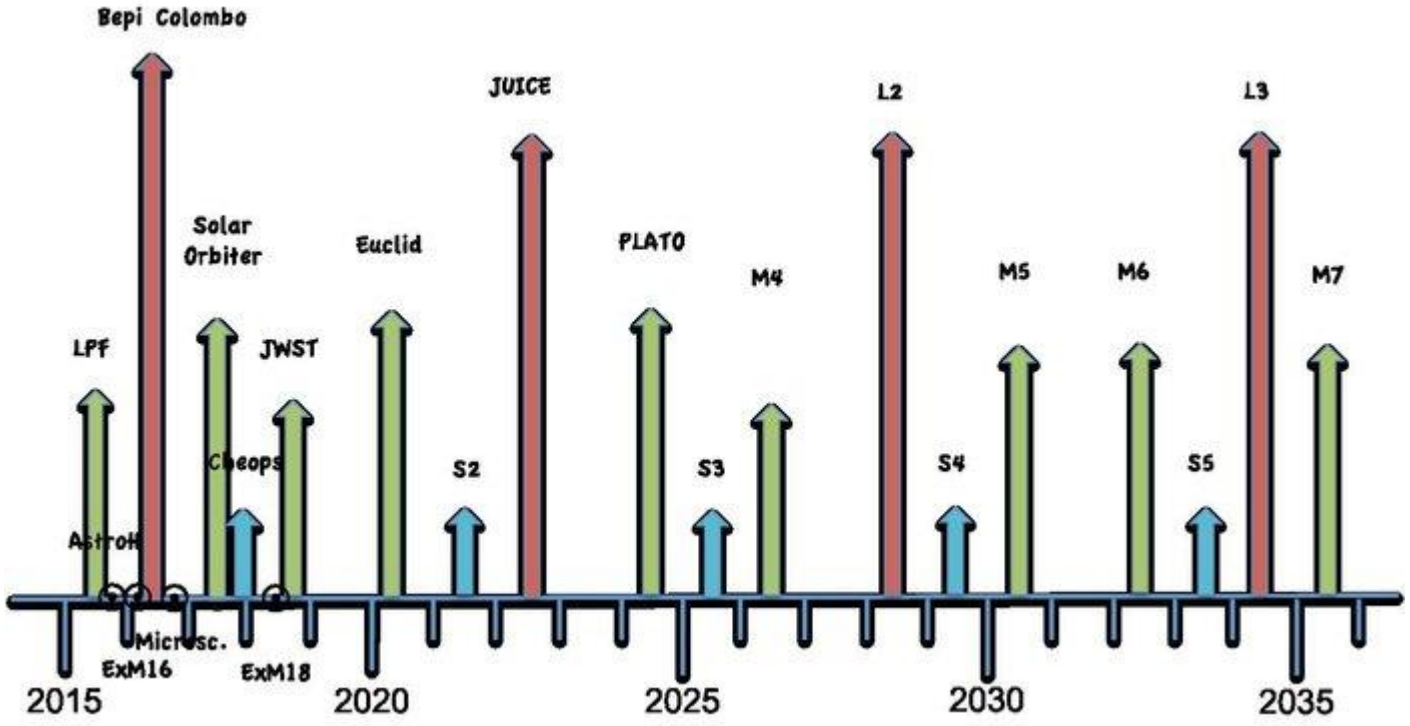
- The Hot and Energetic Universe
- The Gravitational Universe
- Planets and Life
- The Solar System
- Fundamental Laws
- The Universe

Science Programme Committee SPC



Additional reading:
sci.esa.int/cosmic-vision/46510-cosmic-vision/
www.esa.int/Our_Activities/Space_Science/How_a_mission_is_chosen

Cosmic Vision timeline



- ESA missions:

  https://sci.esa.int/s/ABne4NA

- For NASA missions see http://www.nasa.gov/missions

Sun	Solar System	Astrophysics	Fundamental Physics
IMPLEMENTATION			
	[2022] JUICE	[2026] PLATO [2022] Euclid [2021] JWST	
OPERATIONS / POST-OPERATIONS			
[2020] Solar Orbiter [2009] PROBA2 [1995] SOHO	[2018] BepiColombo [2016] ExoMars TGO & Schiaparelli [2004] Rosetta [2003] Mars Express [2003] Double Star [2000] Cluster	[2019] CHEOPS [2013] Gaia [2002] INTEGRAL [1999] XMM-Newton [1990] Hubble	
LEGACY			
[1990] Ulysses	[2005] Venus Express [2003] SMART-1 [1997] Cassini-Huygens [1985] Giotto	[2009] Planck [2009] Herschel [1995] ISO [1989] Hipparcos [1983] EXOSAT [1978] IUE [1975] Cos-B	[2015] LISA Pathfinder

Space in Finland …or Finland in space?

- Instruments and science typically funded nationally:
  - Academy of Finland (research projects, research fellows etc)
  - Business Finland (used to be Tekes; technology, instruments, Finland's ESA representative along with the Ministry of economic affairs and employment)
- ESA funds project management, launch, operations etc.
- Finland pays ESA fees yearly (approx. 20 MEUR).
  - Full member since 1995.
- Other space-related organizations
  - The Finnish space committee (Avaruusasiain neuvottelukunta, ANK), Committee on Space Research COSPAR, ESO

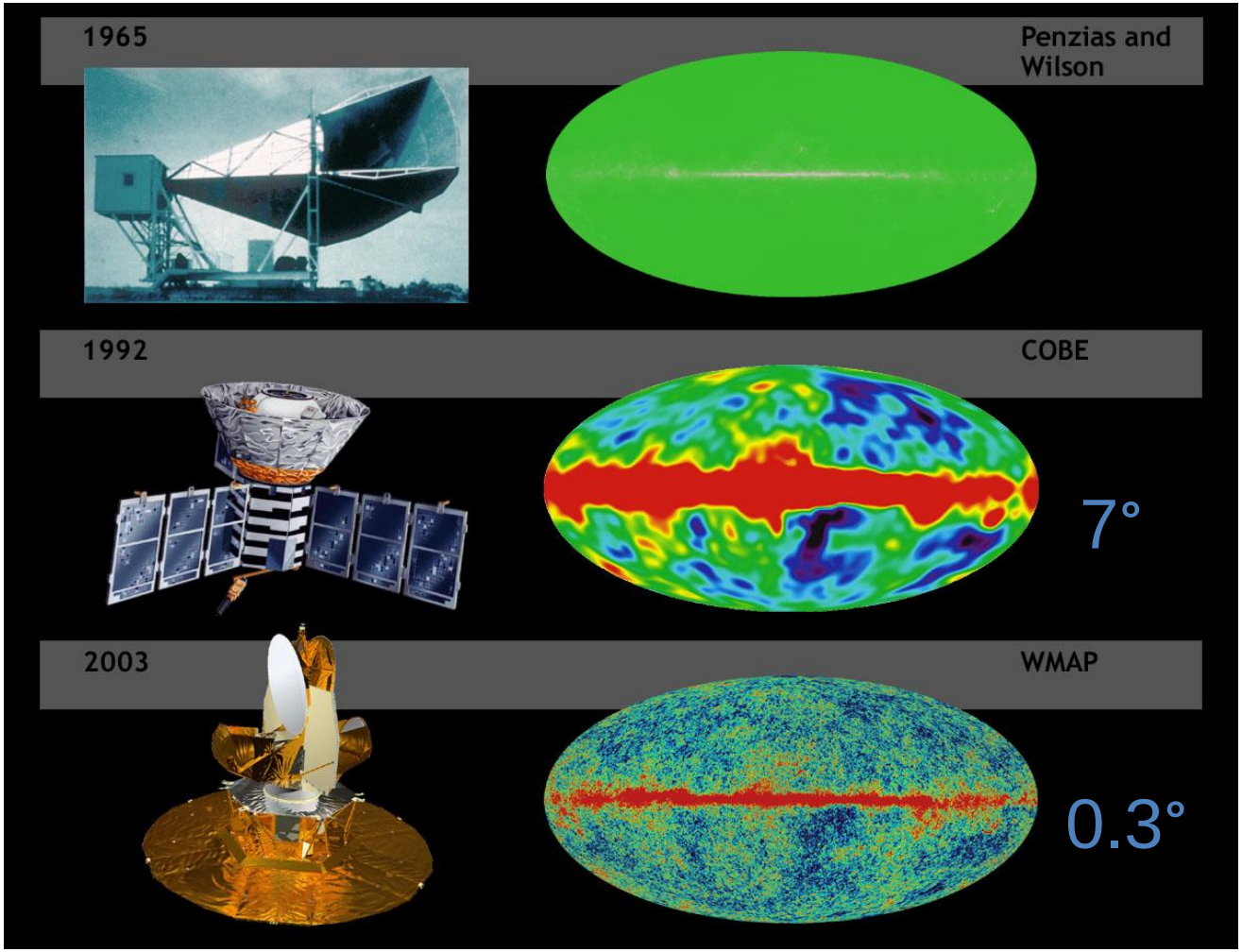
- Space researchers: universities, institutes etc.
  - Astronomy, space physics, Earth observation, space technology …
- Aalto-satellites

(+ Private companies…)

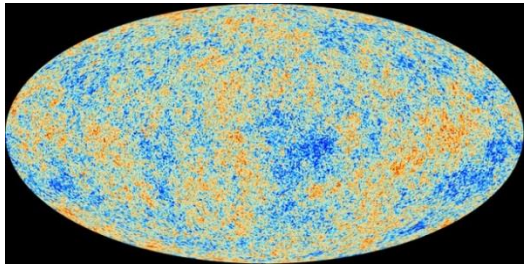
COSMOLOGICAL MISSIONS

- A short recap

CMB missions

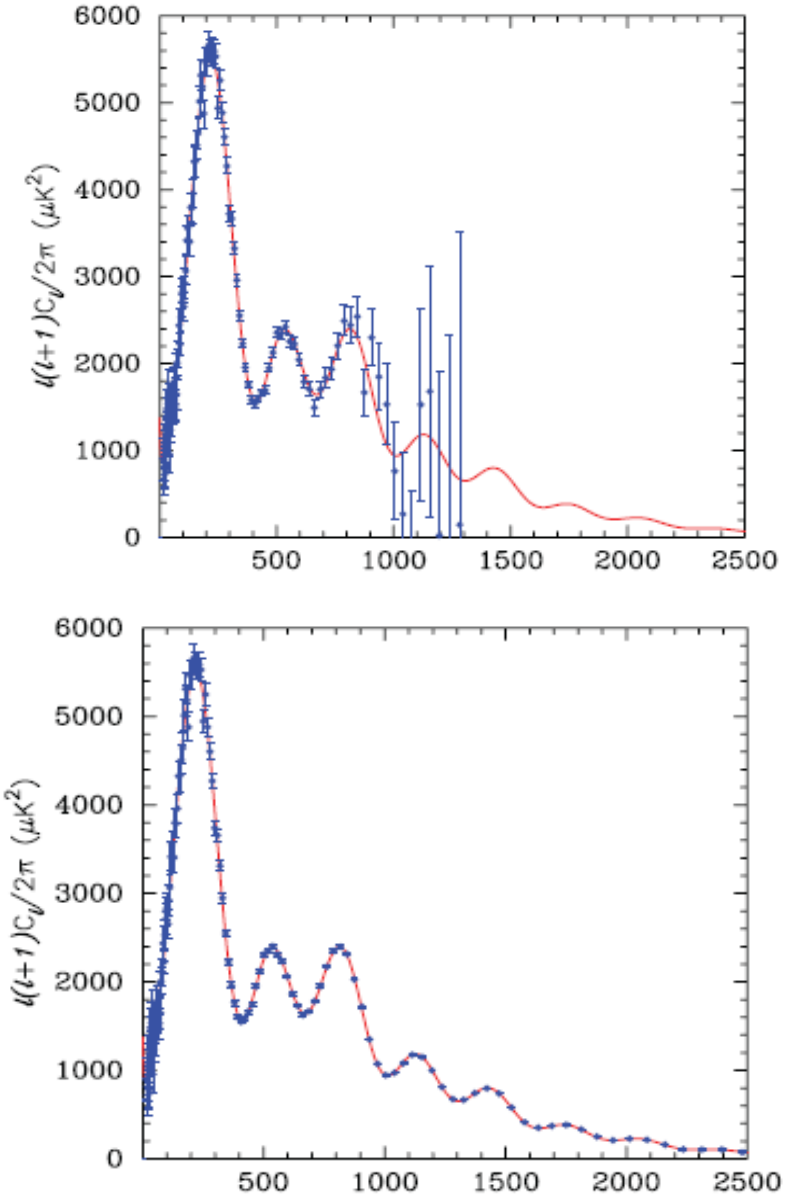


2013 Planck
5’ - 30’

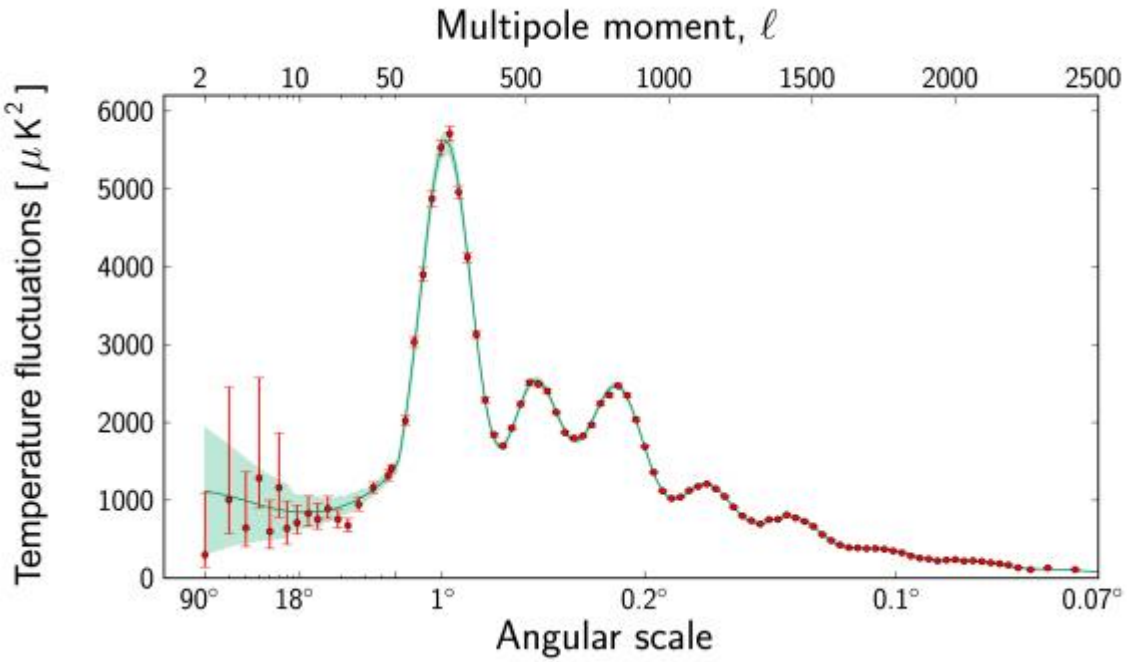


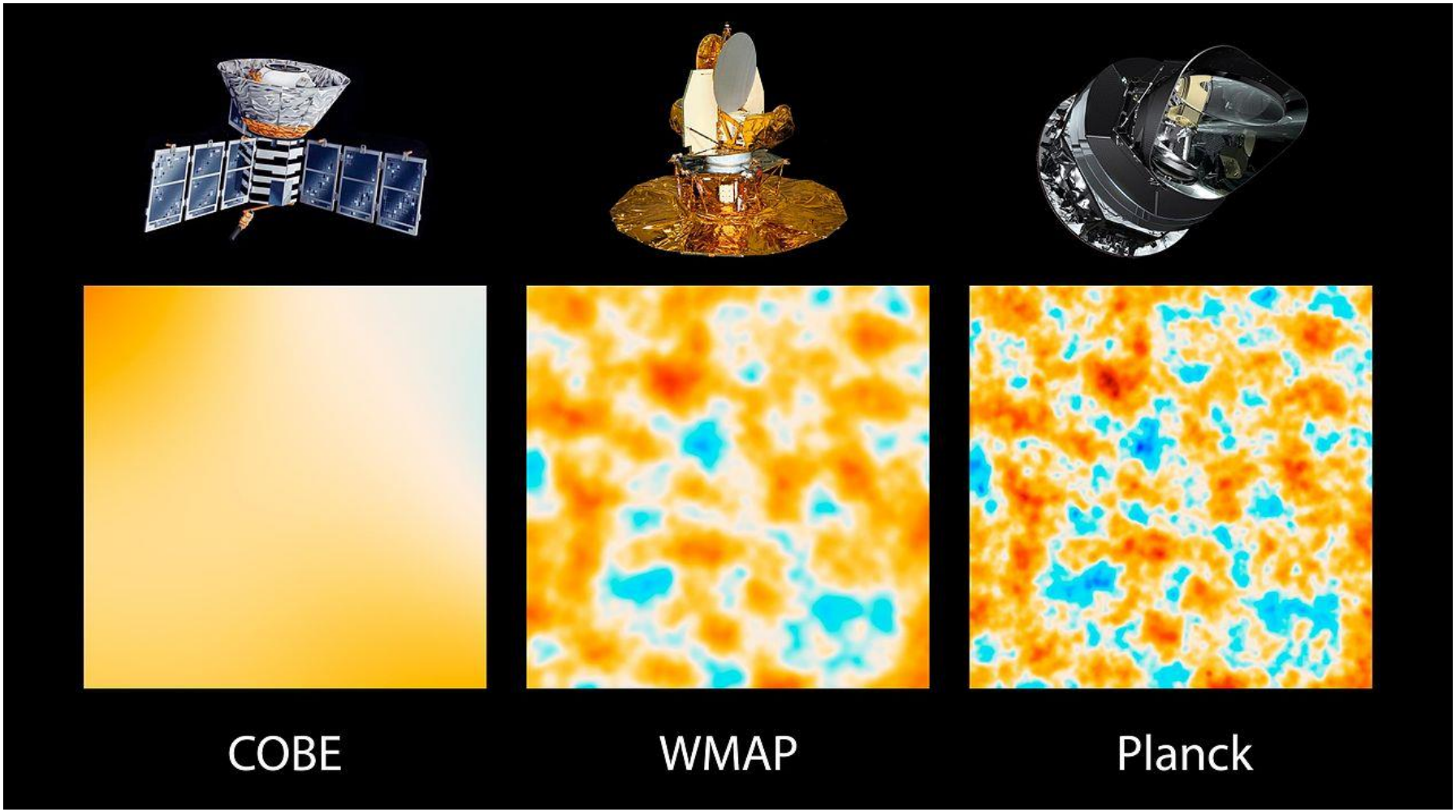
The supremacy of Planck

- Cosmological parameters with supreme accuracy and tiny errors
  - higher resolution (14’ vs. 5’)
  - higher sensitivity, also polarization (10^{-5} vs. 10^{-6})
  - more frequencies (5 vs. 9)



Angular power spectrum

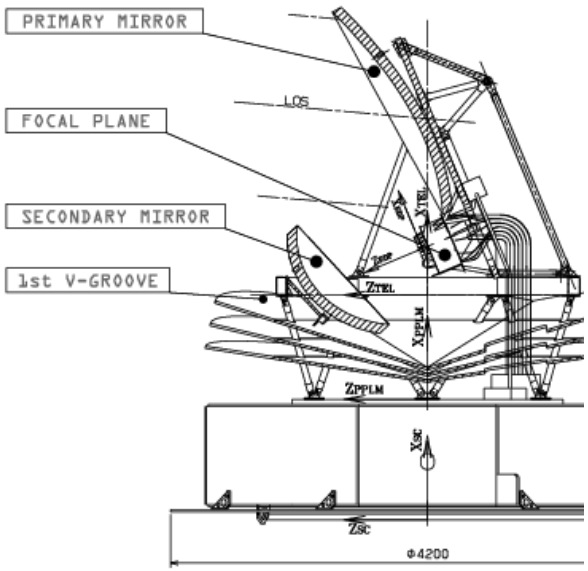



COBE
WMAP
Planck

PLANCK SATELLITE

Planck

- Measured the cosmic microwave background (CMB) temperature anisotropies with an unprecedented accuracy and sensitivity
- Frequencies 30 – 857 GHz (9)



Payload

- Two instruments:
  - Low Frequency Instrument LFI (30 – 77 GHz)
  - High Frequency Instrument HFI (100 – 857 GHz)
- Telescope
  - Off-axis tilted Gregorian
  - 1.9 x 1.5 m paraboloid
  - surface accuracy <10 µm RMS
  - FOV 8° at its widest
- Total size
  - 4.2 x 4.2 m
  - 1900 kg

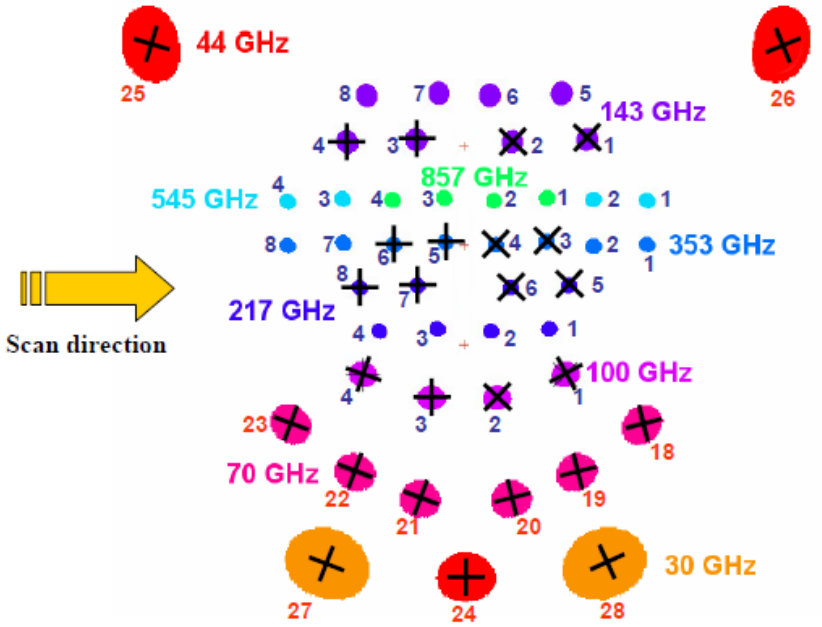
HFI (100 – 857 GHz)

- Array of microwave detectors using bolometers (52) in which the incoming radiation is absorbed in a grid, and the resulting increase in temperature is then measured.
- Cooled to 0.1 K.
- HFI Consortium led by principal investigator from France.

LFI (30 – 77 GHz)

- Array of radio receivers (22) using high electron mobility transistor mixers.
- Sky signal and 4 K blackbody reference loads compared.
- Cooled to 20 K.
- LFI Consortium led by principal investigator from Italy.

Elimination of systematic effects!


44 GHz
25
26
143 GHz
857 GHz
545 GHz
353 GHz
217 GHz
100 GHz
70 GHz
23
18
22
21
20
19
27
24
28
30 GHz
Scan direction

Estimated Instrument Performance Goals

Telescope	1.5 m (proj. aperture) aplanatic; shared focal plane; system emissivity 1%								
	Viewing direction offset 85° from spin axis; Field of View 8°								
Instrument	LFI			HFI					
Center Freq. (GHz)	30	44	70	100	143	217	353	545	857
Detector Technology	HEMT LNA arrays			Bolometer arrays					
Detector Temperature	~20 K			0.1 K					
Cooling Requirements	H_2 sorption cooler			H_2 sorption + 4 K J-T stage + Dilution cooler					
Number of Unpol. Detectors	0	0	0	0	4	4	4	4	4
Number of Linearly Polarised Detectors	4	6	12	8	8	8	8	0	0
Angular Resolution (FWHM, arcmin)	33	24	14	9.5	7.1	5	5	5	5
Bandwidth (GHz)	6	8.8	14	33	47	72	116	180	283
Average $\Delta T/T_I$* per pixel#	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
Average $\Delta T/T_{U,Q}$* per pixel#	2.8	3.9	6.7	4.0	4.2	9.8	29.8		

* Sensitivity (1σ) to intensity (Stokes I) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

\# A pixel is a square whose side is the FWHM extent of the beam.

* Sensitivity (1σ) to polarised intensity (Stokes U and Q) fluctuations observed on the sky, in thermodynamic temperature ($x10^{-6}$) units, relative to the average temperature of the CMB (2.73 K), achievable after two sky surveys (14 months).

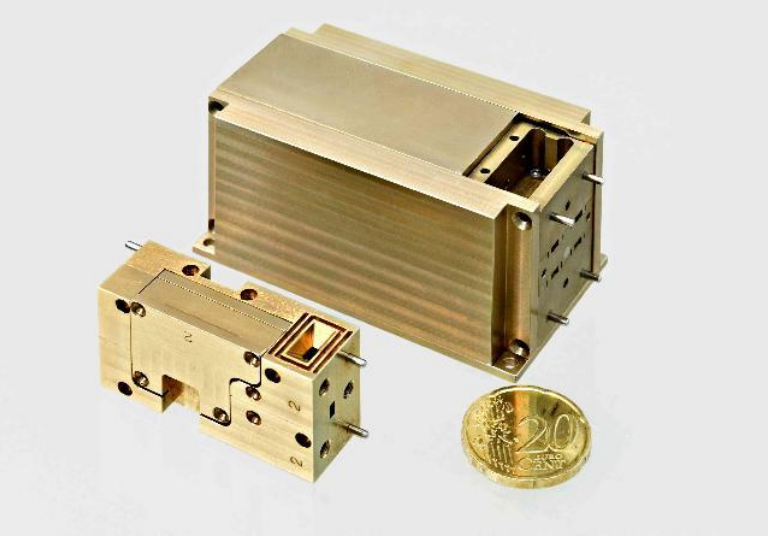
PLANCK

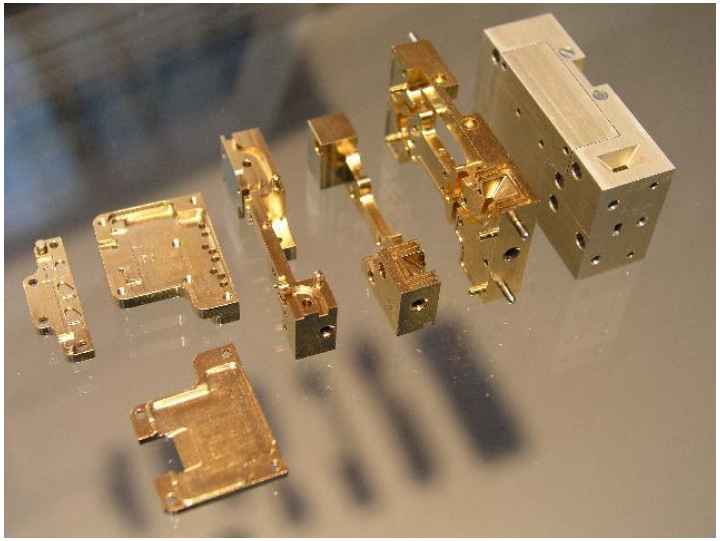
Table last updated Feb. 2004

esa ASTROPHYSICS

70 GHz receivers

- Designed and built in Finland by Millilab, DA Design (Ylinen, Elektrobit Microwave), Metsähovi

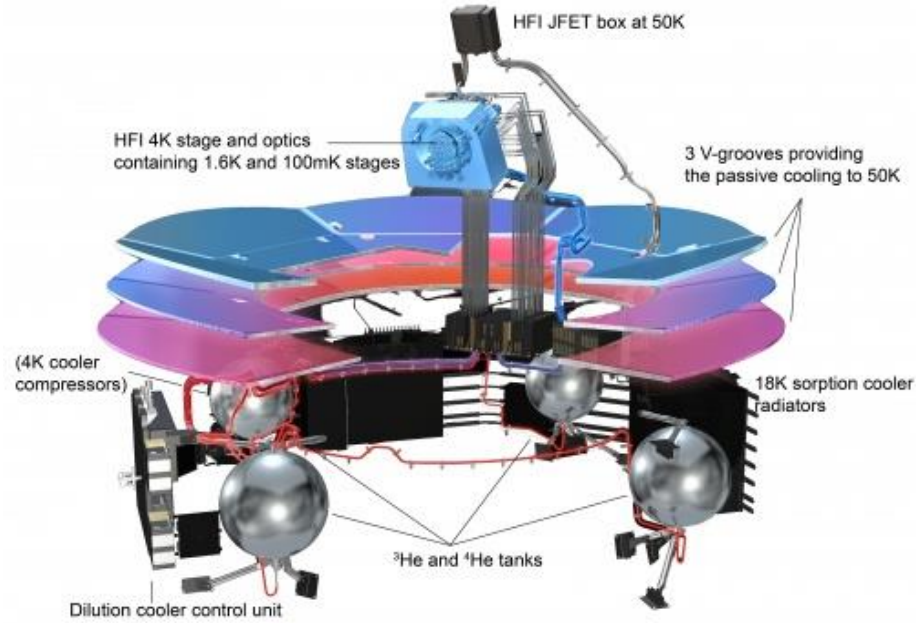


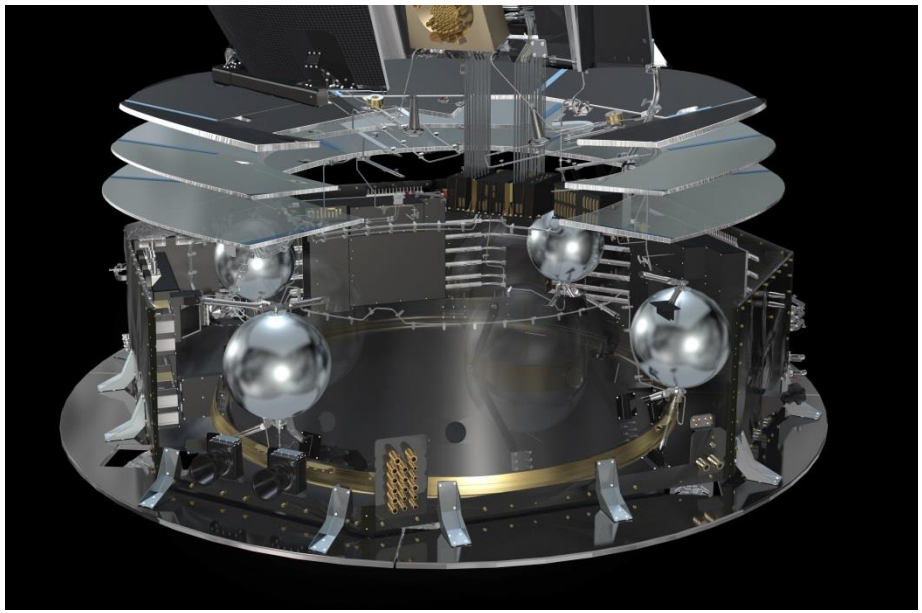


Cooling

- Passive radiative cooling down to 45 K
  - Also thermal isolation of instruments and telescope from the warm spacecraft bus.
- Active Cryocoolers 20 & 0.1K
  - Closed-cycle hydrogen sorption cooler for LFI.
  - Chain of three cryo-coolers for HFI.
    - LFI cooler (18 K)
    - Joule-Thomson cooler (4 K)
    - $^{3}He^{4}He$ dilution cooler (0.1 K)

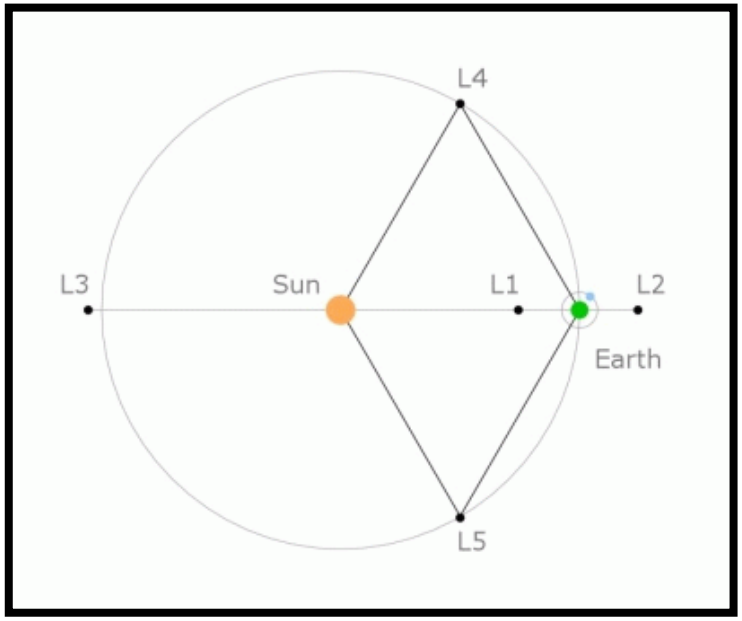
Vibration?

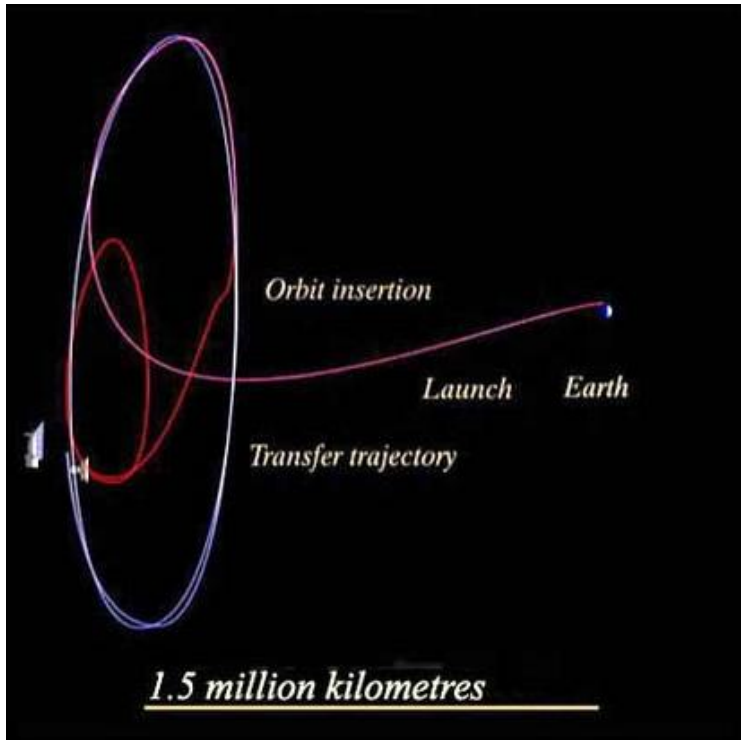


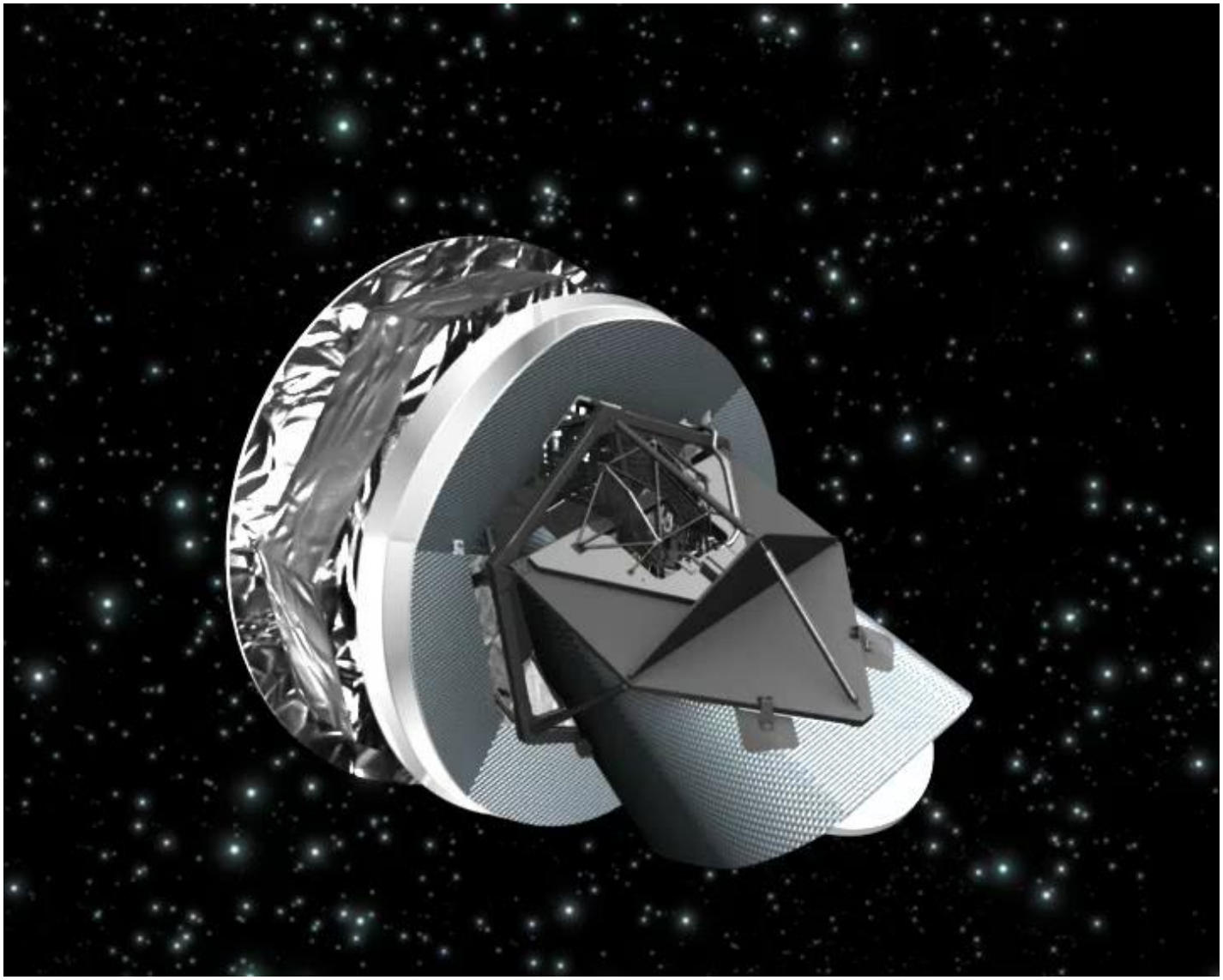


Orbit

- ~4 months to reach L2
- Anti-Sun pointing:
  - Line-of-sight 85° to the spin axis
  - Optimal thermal conditions, minimal straylight (Earth, Sun, Moon, communications…)
- One sky ring per minute, one degree per day.
- Whole sky (>95%) covered once in 6 months.
  - Several timescales.







LAUNCH CAMPAIGN

- Instruments put together and tested in Europe, then shipped to launch site at Kourou, French Guiana.
- Further testing and integration of the satellite (solar panels, launcher…) on site.

Integration of payload to launcher

(This is not Planck.)

Planck and Herschel ready for launch

Ariane 5 rollout 13.5.2009

Launch pad


esa
ariane
CENTRE DE LANCEMENT N°3

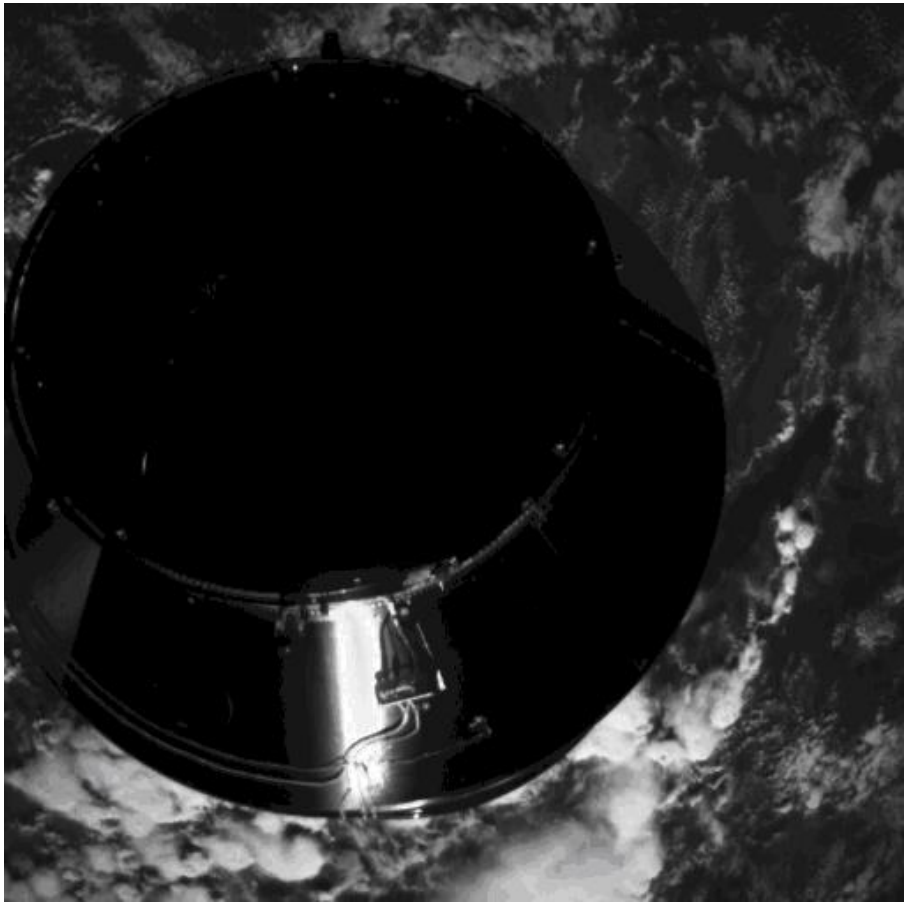

18 02 58
- 19 09 02
arianespace
Service & Solutions


arianespace
Service & Solutions

Launch 14.5.2009

Separation of Planck and Herschel

- 26 min after launch
- At the height of 1150 km



PLANCK SCHEDULE & ORGANIZATION

The beginning

- Response to a call for proposals for 3rd medium-sized (M3) missions in ESA's Horizon 2000 Science Programme in 1993:
  - COBRAS (Cosmic Background Radiation Anisotropy Satellite)
  - SAMBA (Satellite for Measurement of Background Anisotropies)
- Phase A (=feasibility) study February 1996.
  - Results in a preliminary design & industrial contacts.

Mission lifetime cycle

Phase 0	Mission analysis and identification
Phase A	Feasibility
Phase B	Preliminary Definition
Phase C	Detailed Definition
Phase D	Qualification and Production
Phase E	Utilisation
Phase F	Disposal

”The Redbook” 1996

- Planck’s Phase A study
  - The scientific case (32 pages)
  - From observations to scientific information (28 pages)
  - The model payload (20 pages)
  - The mission (11 pages)
  - The Spacecraft (8 pages)
  - Project management (4 pages)
- Launch foreseen in 2003 (-> 2009)

Acceptance & implementation

- Accepted 1996.
- Announcement of Opportunity (AO) for instruments 1997, accepted 1999.
- Invitation to Tender for spacecraft and launch 2000.

”The Bluebook”2005

- Planck’s scientific programme according to the Planck Baseline Scientific Programme call for proposals
  - The Planck mission (overview, 19 pages)
  - Primary CMB anisotropies (41 pages)
  - Secondary anisotropies (20 pages)
  - Extragalactic sources (23 pages)
    - The astrophysics of quasars and blazars (3 pages)
  - Galactic and solar system science (22 pages)

Planck schedule

- Horizon 2000 Science Programme call 1993
- Phase A study report 1996
- Metsähovi gets involved 1997
- The baseline scientific programme 2005
- Launch 14.5.2009
- First all-sky scan winter 2009 – 2010, …
- Early Release Compact Source Catalog (ERCSC) in January 2011 together with a set of Planck Early Results

- Extended mission (HFI & LFI) until end of 2011
- Extended mission (LFI only) until mid-2013
- Planck Results released 2013 and 2015
- Planck Intermediate Results since 2011
- Operations stopped 23.10.2013
- More results to come…

The end

- Nominal lifetime of 15 months was exceeded: 4.5 years!
- 14.1.2012 HFI ran out of coolant; LFI went on taking data.
- All science operations ended 3.10.2013.
- Safe disposal:
  - Disposal trajectory away from L2, on a ”parking” orbit drifting away from Earth.
  - Burning remaining fuel off.
  - Re-programming of software to avoid automatic reactivation.
  - Disconnecting batteries.
  - Switch off transmitters: ”*We will witness the silencing of Planck and we will never receive a signal from her again*.”
- Operations stopped 23.10.2013.

Planck Collaboration

- Planck Science Team
  - *"A group of scientists whose general task is to monitor and advise on all aspects of Planck which may affect its scientific objectives."*
- Instrument Consortiums (LFI & HFI)
- Telescope Consortium
- Data Processing Centres (LFI & HFI)
- Science Working Groups (7; cosmology & foregrounds)
- Core teams
- Individual: Planck Associates, Planck Scientists, Planck Co-Investigators
- Planck Editorial Board
  - Publication of results

Rules and policies
Documentation

So what did we do all those years before we actually got the data?

- Helped in eliminating CMB foregrounds.
- Formulated extragalactic points sources' science case.
- Went to a lot of meetings and got to know a lot of great people.
  - Official Planck meetings
  - Planck national meetings
  - Tekes Planck LFI 70 GHz steering group

- Also… wrote a lot of tedious reports, memorandums of understanding, policies…
- Wrote a lot of justifications for the science cases.
- Wrote a lot lof funding proposals and reports to funding agencies.

PLANCK DATA

Planck data

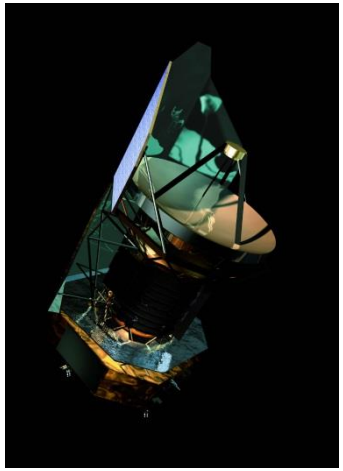
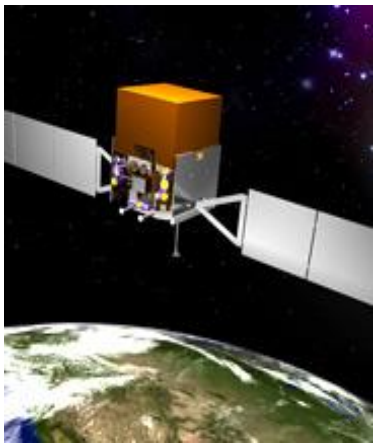
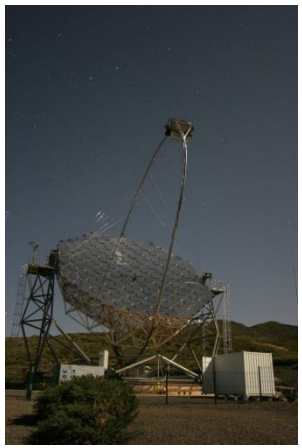
- Data transferred to Earth once a day (Mission Operations Centre, MOC, in Darmstadt, Germany).
- Data processing has 4 levels:
  - level 1: telemetry processing, instrument control, time-ordering of data.
  - level 2: data reduction and calibration, QDS.
  - level 3: astrophysical and cosmological component maps (LFI & HFI).
  - level 4: generation of the final data products (LFI & HFI).

  - level S: simulations.

Quick Detection System (QDS)

- Software package that looks for unusual and interesting point sources in the time-ordered data stream of Planck within a week from the observations.
  - First scientific data that can be exploited.
  - Testing the performance of the satellite.



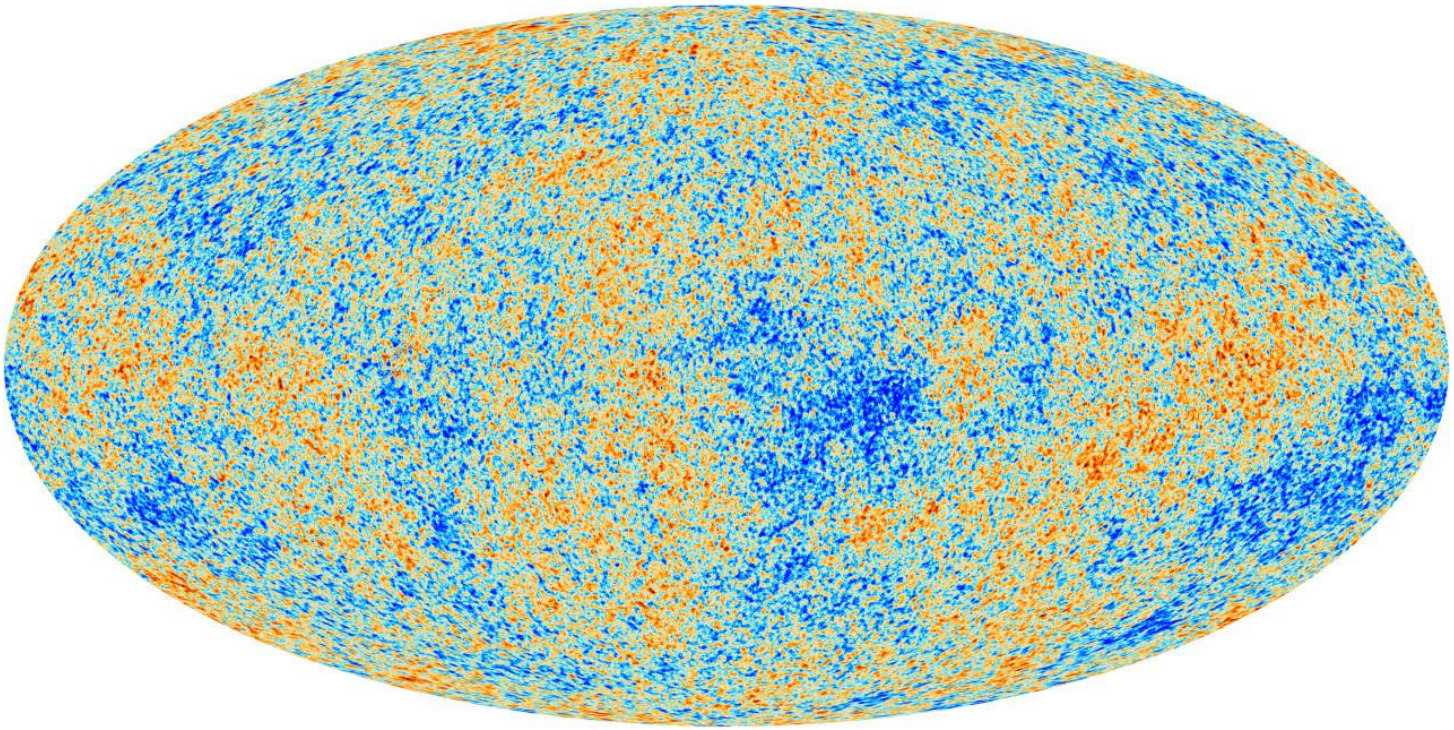





How can I use Planck data?

- Data products in Planck Legacy Archive
  - All-sky frequency & component maps, catalogs, cosmology
  - Auxiliary information
- Everything else in calibrated time-ordered format
  - Need software/algorithm for making sense out of it.

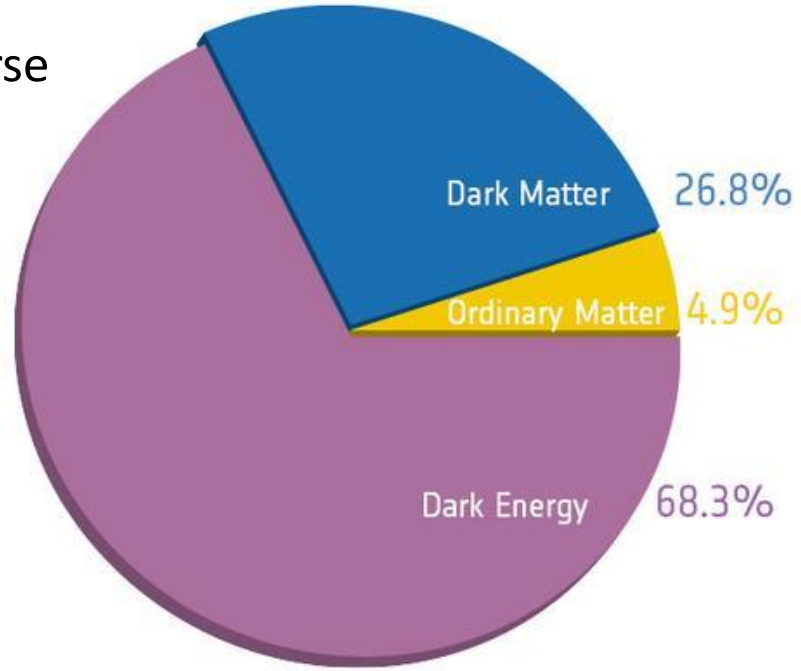
PLANCK SCIENCE

Cosmology



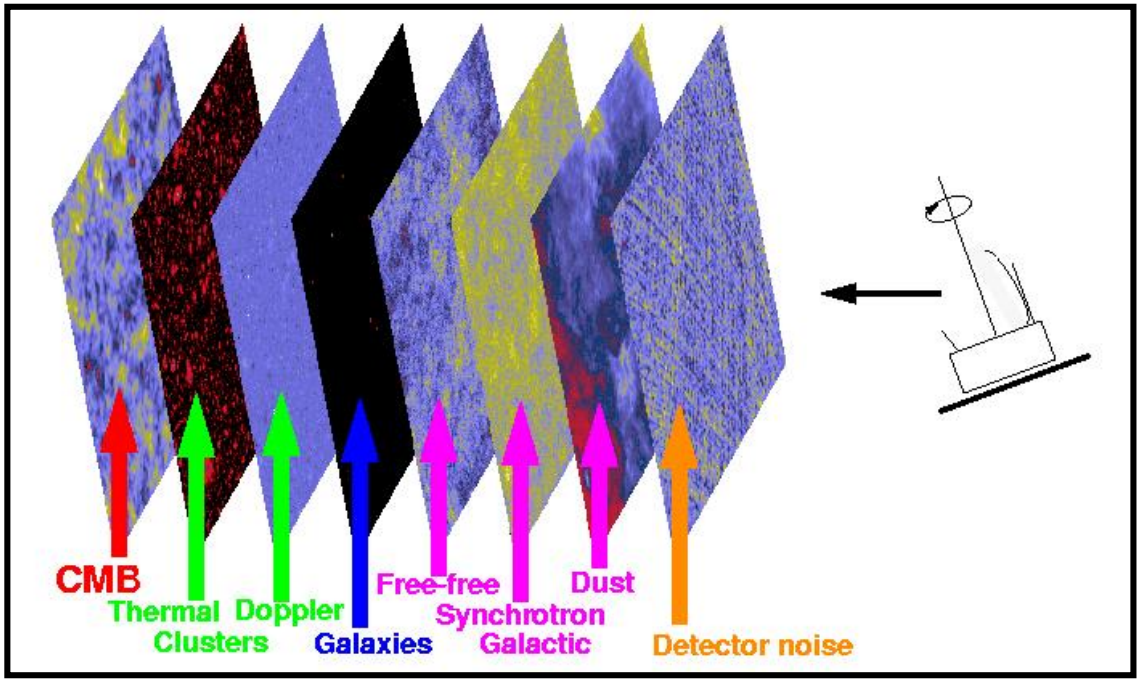
Cosmology

- Accurate determination of cosmological parameters.
  - For example, the Hubble constant.
- Tests of inflationary models of the early universe.
- Nature of primordial fluctuations.
  - Formation of structure in the Universe
- Nature of dark energy.



More on CMB on the Radio Astronomy course!

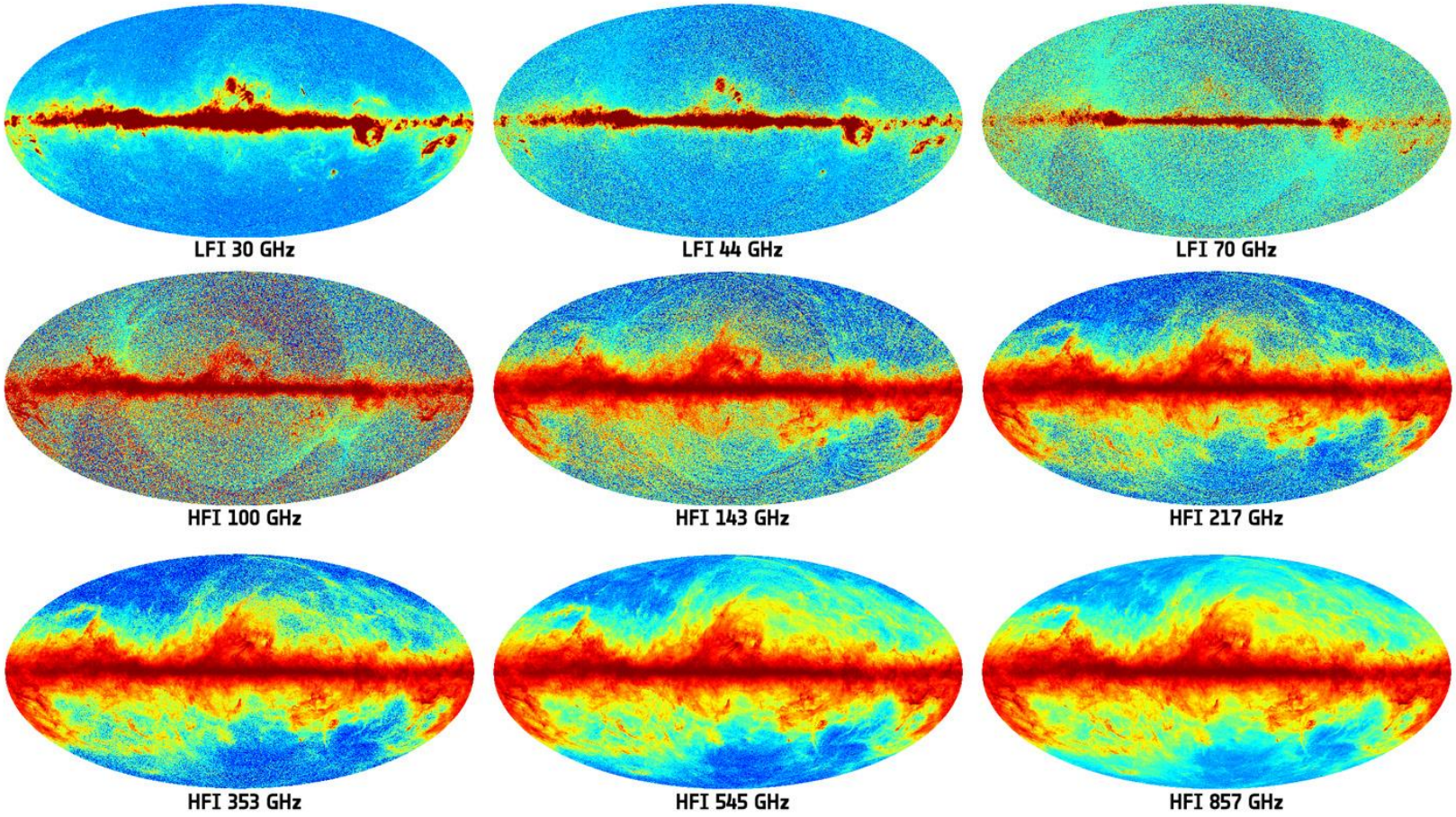
Planck foregrounds



- Radio emission also from other sources in front of the CMB.
- Identification and elimination of contaminating foreground radio sources requires observations at several frequencies.
- ”Garbage for cosmologists = science for astronomers!”

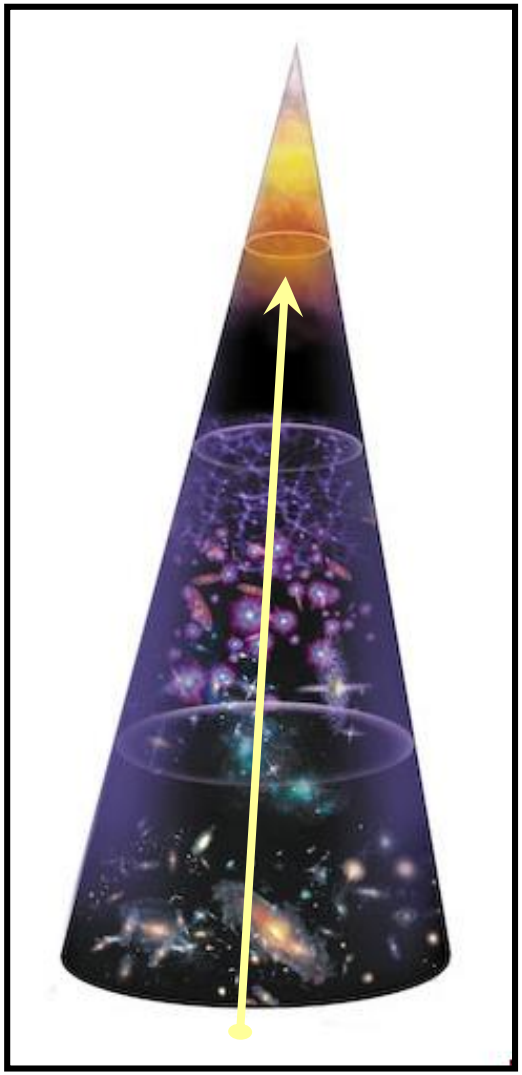
1. Cleaning the foregrounds off the CMB maps.
2. Scientific research of the foregrounds.

Planck all-sky foreground maps

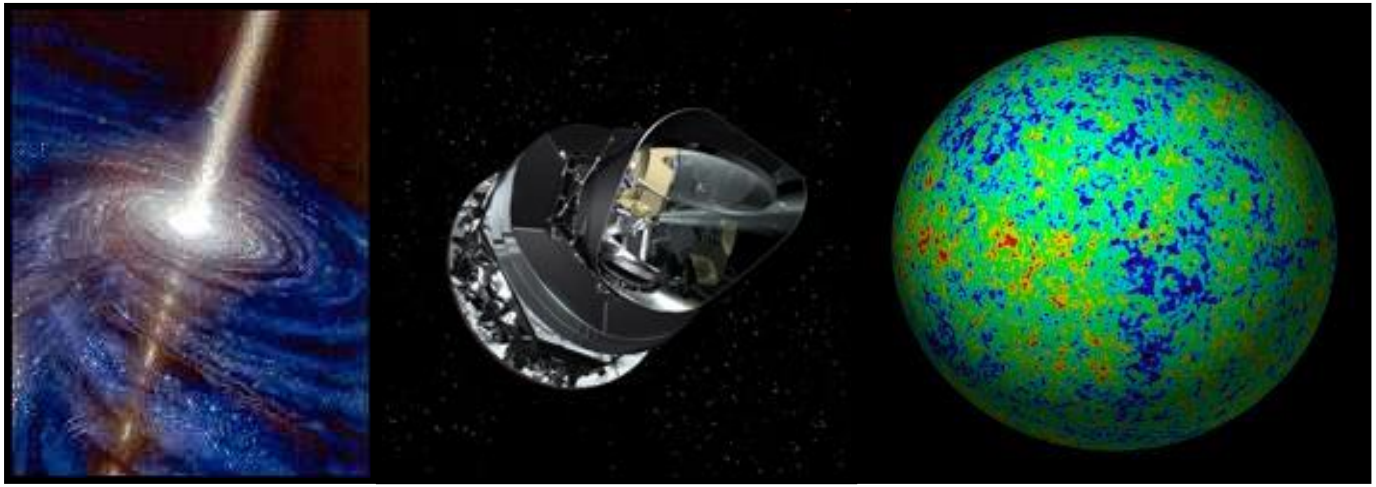


Planck science in Finland

- Dept. of Physics, Univ. of Helsinki
  - Cosmology
  - Local interstellar matter; cold cores of molecular clouds; nearby molecular clouds; star formation; structure of the Galaxy
- Aalto University Metsähovi Radio Observatory & Tuorla Observatory, Univ. of Turku
  - Quasars, BL Lac and GPS sources; statistics of radio sources; galaxy clusters, Sunyaev-Zel'dovich effect



Why were we so excited about Planck?



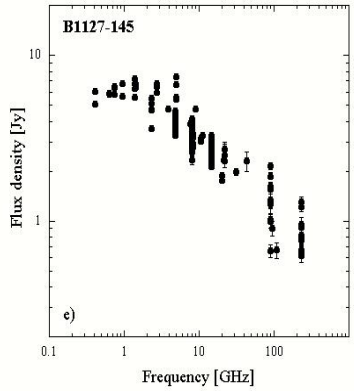
Extragalactic point sources

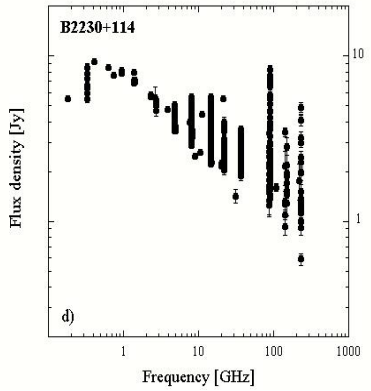
- No all-sky surveys at high radio frequencies.
  - WMAP, 400 / 500 sources, >0.7 Jy
  - AT20G, 6000 sources, >40 mJy
- Relatively few observations even of individual sources at high radio frequencies.

- Wide selection of sources with diverse physical characteristics.

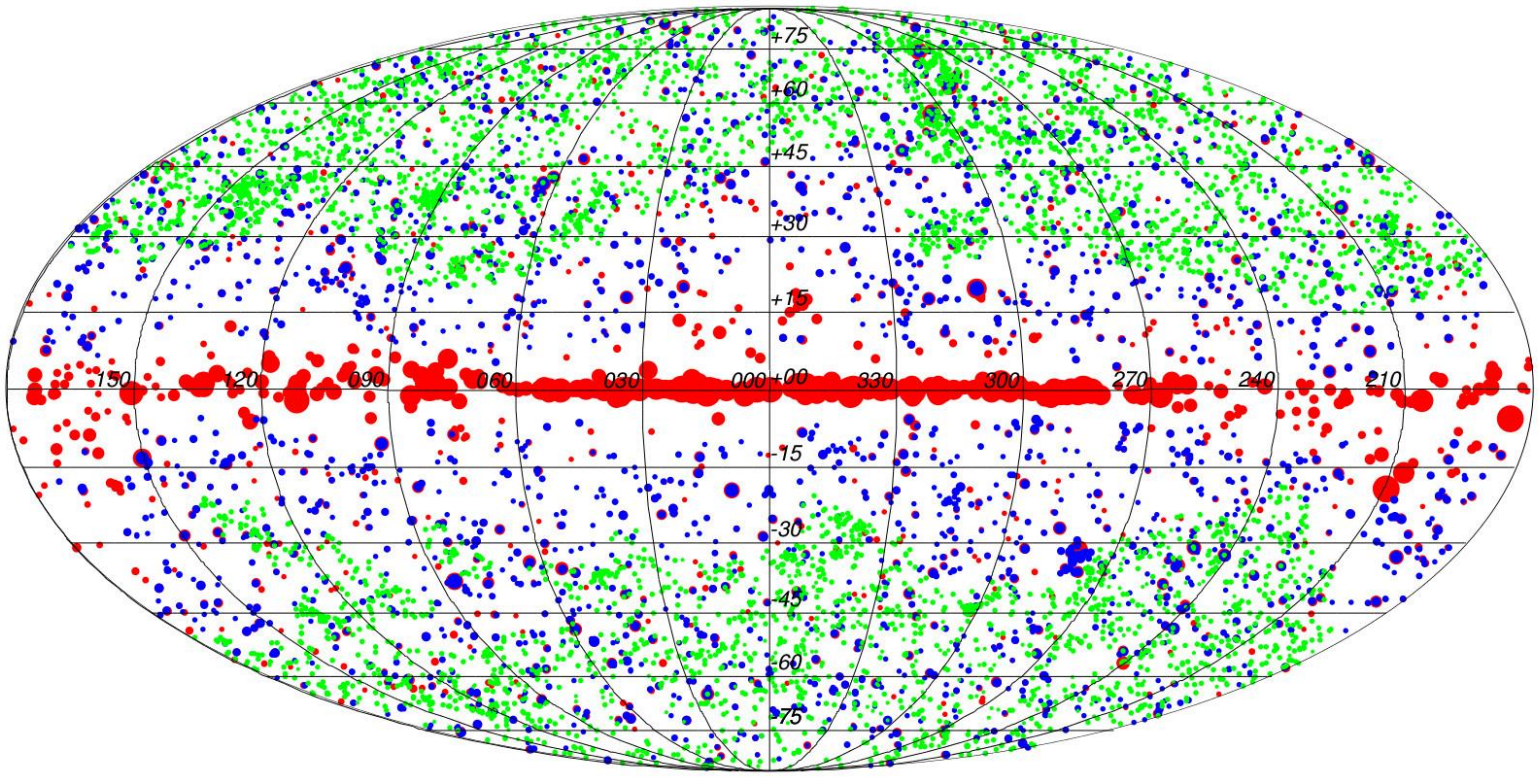
From Planck we get…

- …the most complete radio source catalogs ever at high radio frequencies (depending on detection limit).
  - Complete samples of all classes of radio sources.
  - Variability at several time scales.
  - Simultaneous data (from Planck and multifrequency campaigns).



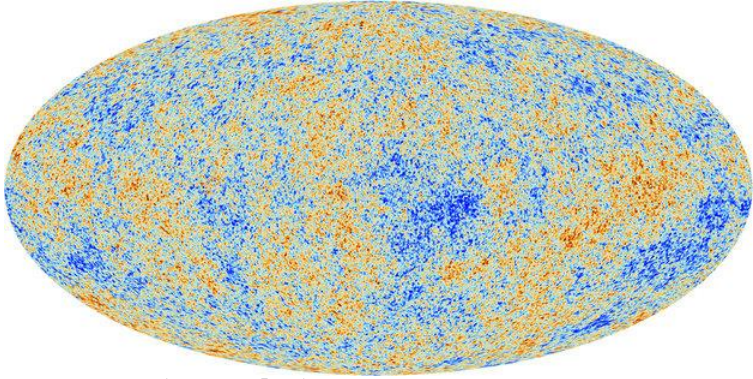


The second *Planck* catalogue of compact sources



esa

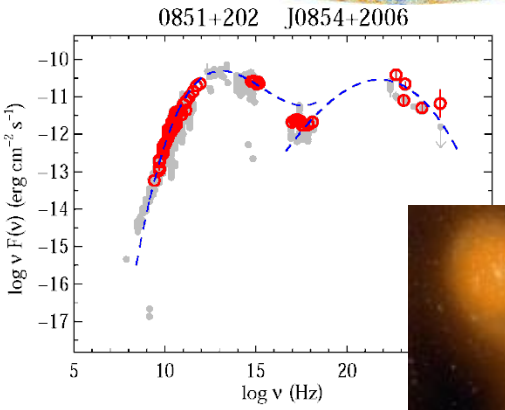
D/SCI(96)3
February 1996

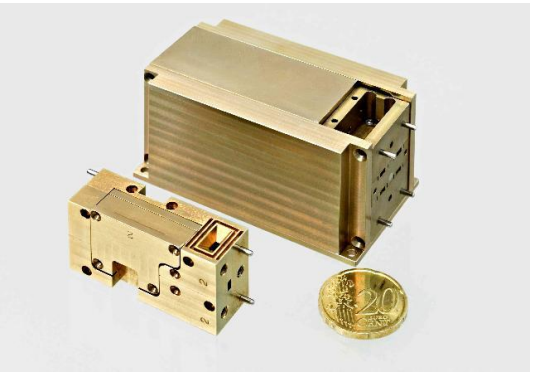


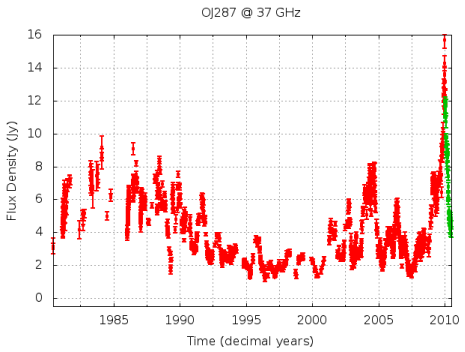
COBRAS/SAMBA

A Mission Dedicated to Imaging the Anisotropies of the Cosmic Microwave Background

REPORT ON THE PHASE A STUDY







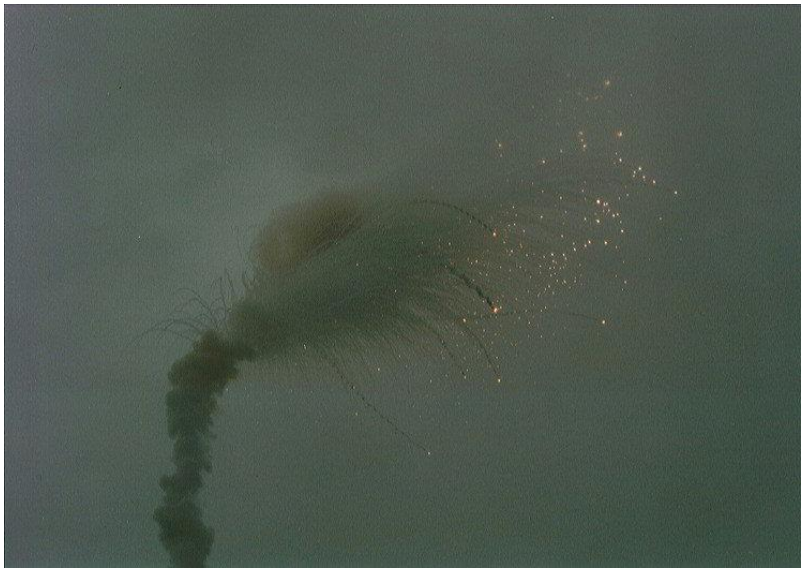
Planck links

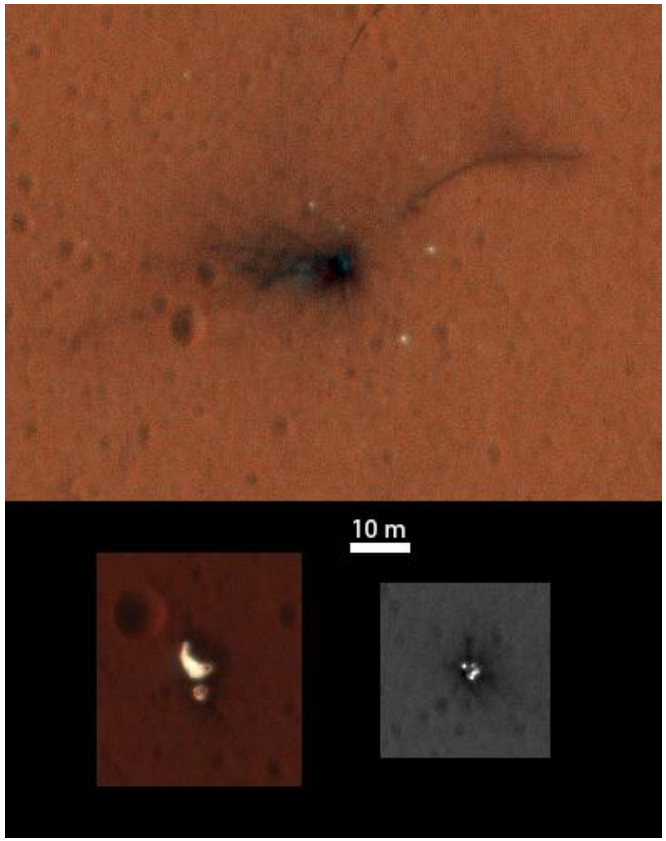
- Planck Science Team home: http://www.cosmos.esa.int/web/planck
  - Access to data via the Planck Legacy Archive (PLA)
  - Access to Planck publications

- The Bluebook: http://www.cosmos.esa.int/web/planck/publications#PlanckProgramme
- Planck mission history and the Redbook: http://www.cosmos.esa.int/web/planck/mission-history

What if…

- Something goes wrong
  - Launch
  - Operations
  - Instruments
  - Funding



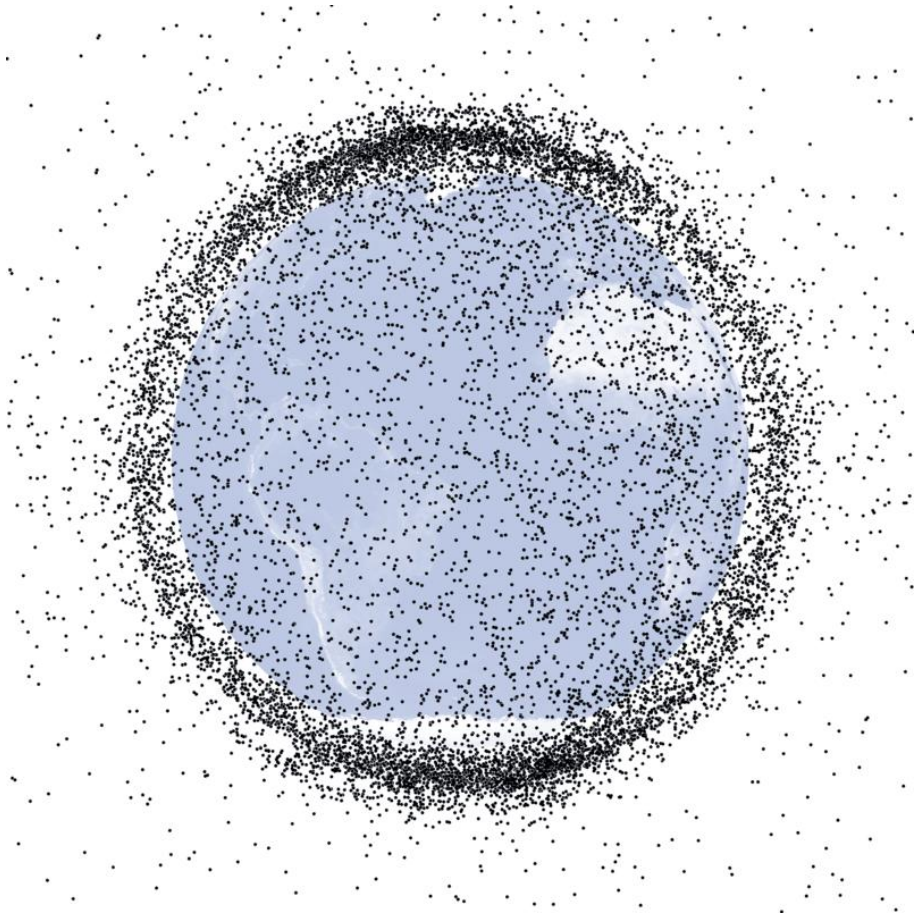


Space debris

- >5500 launches, 9600 satellites, 5500 remain, ~2300 operational now.
- >22 300 tracked objcts in orbit, in reality probably over 30 000 large pieces and **millions** of small pieces.
- Future: 57 000 planned launches until 2029!

- Discards, disintegration, pollutants
- Collisions, explosions, missile tests etc produce more and more debris.
- Most will finally reenter the atmosphere: burn or crash? However, this will take time…

- Kessler syndrome



- Thinking ahead:
  - Good design (no risk), active debris removal, deorbiting to graveyard orbit or reentry, passivation.

NEXT STEPS

- Project plan deadline TODAY at 23.59.

- Continue project work, next help session Thu 12.11. at 12-13. If you have questions, be there. If you are all clear, no need to attend.

- **Next lecture Tue 17.11 at 14-16**
  - **Dr. Karri Koljonen : High energy space missions I. X rays.**