Cosmic Microwave Background

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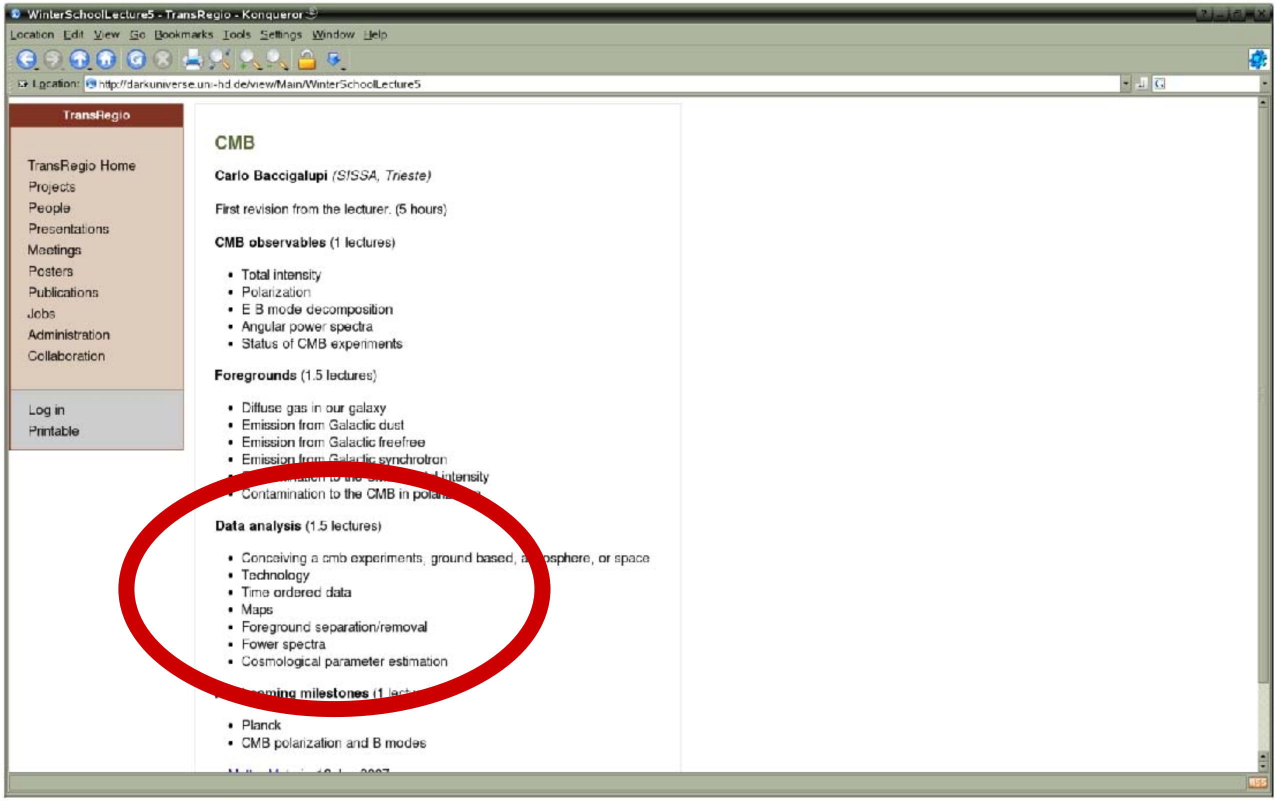
CMB lectures at TRR33, see the complete program at darkuniverse.uni-hd.de/view/Main/WinterSchoolLecture5

These lectures are available in pdf format at people.sissa.it/~bacci/work/lectures

CMB data analysis

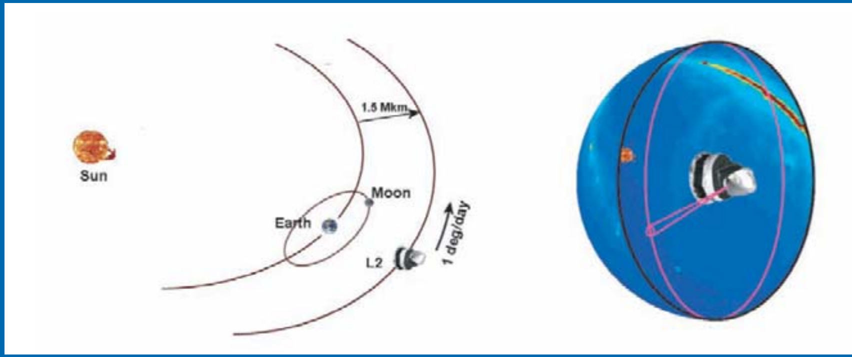


Outline

- Basics of CMB data analysis
- Instrumental design
- Time ordered data
- Map-making
- Component separation
- Suggested lectures

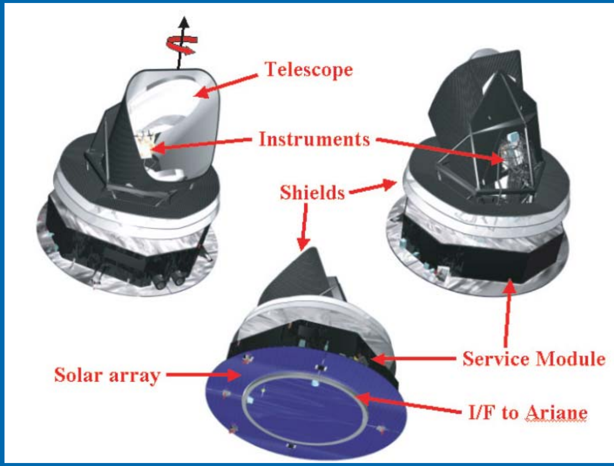
CMB data analysis: a fantastic information compression

- A typical CMB probe takes records of the sky radiation with a hundreds of Hz per second per detector, from weeks to years
- Maps contain tens of millions of resolution elements
- C_l are a few thousands
- Cosmological parameters are a few

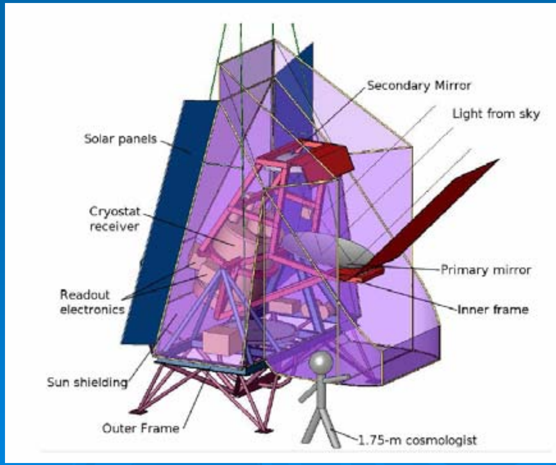


Instrumental design

Planck



- The telescope is made by a primary and a secondary mirror
- The light proceeds to the focal plane and the detectors, which may be radiometers at low frequencies, measuring the total flux, or bolometers at high frequencies, meauring the sky temperature as very sensitive thermometers
- The data are stored onboard if possible due to load and data size constraints
- A telemetry system sends the sky signal as well as detector data to the ground

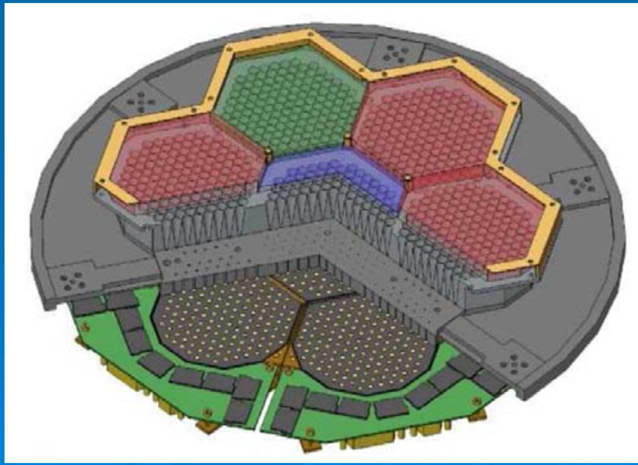


EBEx, courtesy of the EBEx collaboration

Time ordered data

- The focal plane contains all detectors and records the sky signal with typical frequency of hundreds of Hz depending on the technology
- Beam: at each point, the radiation is collected from a finite solid angle, it has to be reconstructed in flight in order to control its systematics
- Noise: it has a typical 1/frequency shape, making it highly correlated from sample to sample in the timestreams
- Calibration: instrument units must be converted into CMB ones, which is usually done at this stage by means of known and strong sources, either the CMB dipole or a point-like object, or measuring the signal induced by the motion of the probe
- Glitches: cosmic rays, or detector malfunctioning causes saturation in some elements in the timestreams that need to be removed

Planck focal plane, courtesy of the Planck collaboration



EBEx focal plane, courtesy of the EBEx collaboration

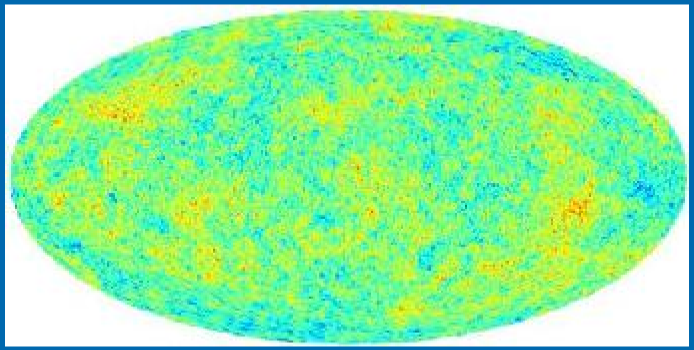
Map-making

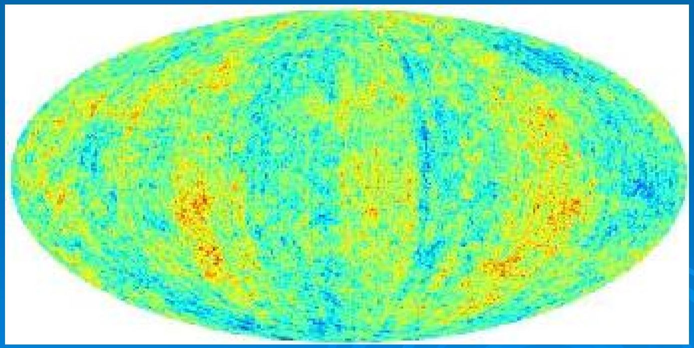
$$d=Pm+n$$

- d: a column vector (time samples)
- P: pointing matrix (time samples, sky directions)
- m: sky map column vector (sky directions)
- n: noise column vector (time samples)
- Given d and the available information on the noise properties, the equation above must be inverted for m

Co-adding map-making

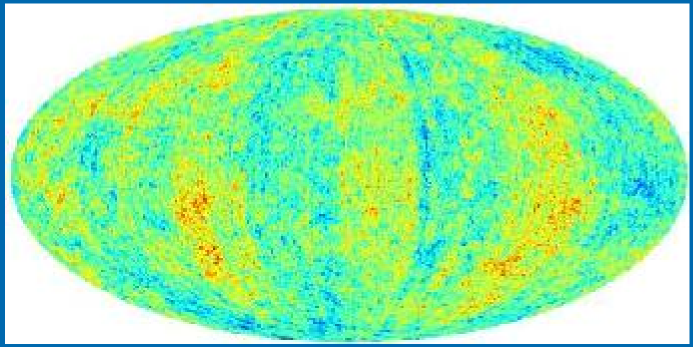
- A very good knowledge of the matrix P is usually available
- Co-addition means simply assigning the time samples to the corresponding direction in the sky
- For small scale observations this may work, for all sky it doesn't as the detector noise has a finite correlation length in time, and produces stripes on the co-added map

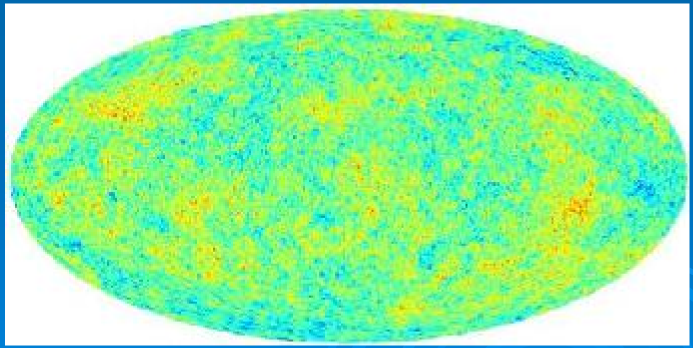




Destriping map-making

- Approximate stripes as constant offsets
- Estimate the offsets using redundancy, i.e. points in which different circles from different detectors intersect
- Subtract them out





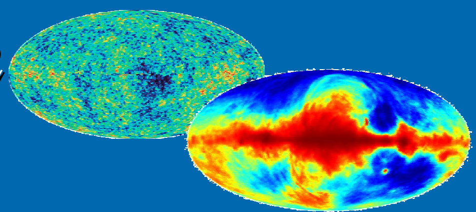
Maximum likelihood map-making

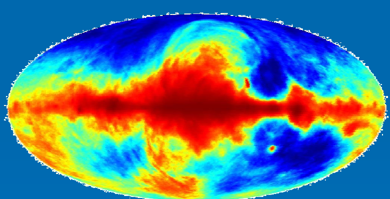
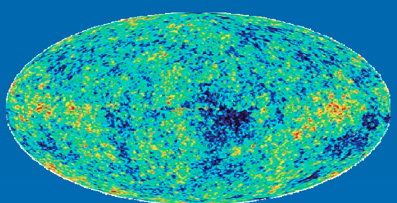
$$d = Pm + n \qquad \boxed{m = (P^T N^{-1} P)^{-1} P^T N^{-1} d}$$

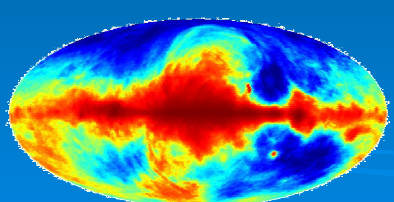
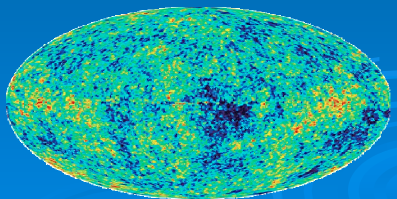
- $N = \langle nn^T \rangle$: noise correlation matrix (time samples, time samples)
- N^{-1}: inverse of N (time samples, time samples)
- A substantial computational challenge for Planck, feasible only for supercomputing facilities like the NERSC in Berkeley, running on thousands of processors for hours for a single total intensity map
- Feasible for experiments flying for much less than one year, and mapping a limited part of the sky

Stompor et al. 2002

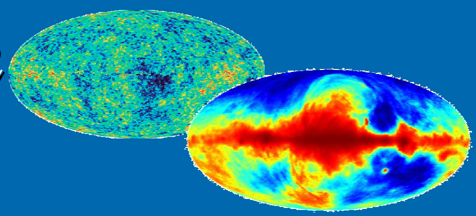
Component separation



$x_1 = a_{11}$  $+ a_{12}$  $+ n_1$

$x_2 = a_{21}$  $+ a_{22}$  $+ n_2$

Component separation

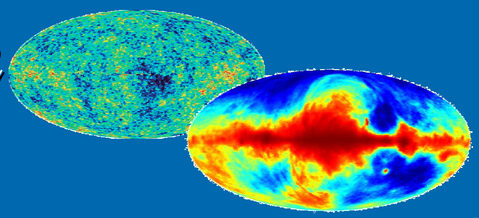


$$x_1 = a_{11} \quad s_1 \quad + a_{12} \quad s_2 \quad + n_1$$

$$x_2 = a_{21} \quad s_1 \quad + a_{22} \quad s_2 \quad + n_2$$

Component separation

s_2



s_1

ν_1

ν_2

$$x = As + n$$

Invert for s!

Component separation

$$x = As + n$$

- Non-blind approach: use prior knowledge on A and s in order to stabilize the inversion, likely to be suitable for total intensity
- Blind approach: do not assume any prior either on A or s, likely to be used in polarization
- Parametrization: introduce extra ``cosmological parameters” parametrizing the foreground unknowns, and fit the data with those in, marginalizing afterwards, prosmising results in total intensity, to be tested in polarization
- Relevant literature from Brandt et al. 1994, to Stivoli et al. 2006, successful applications to COBE, BEAST, WMAP

Independent Component Analysis (ICA)

- Assume statistical independence between different astrophysical emissions
- Their superposition tends to be close to Gaussianity
- Reverse the process with linear combinations of the signals at different frequencies, extremizing the non-Gaussianity
- Each extremum corresponds to one independent component

See Baccigalupi et al., 2004, and references therein

Component separation: ICA

Pixels or Modes

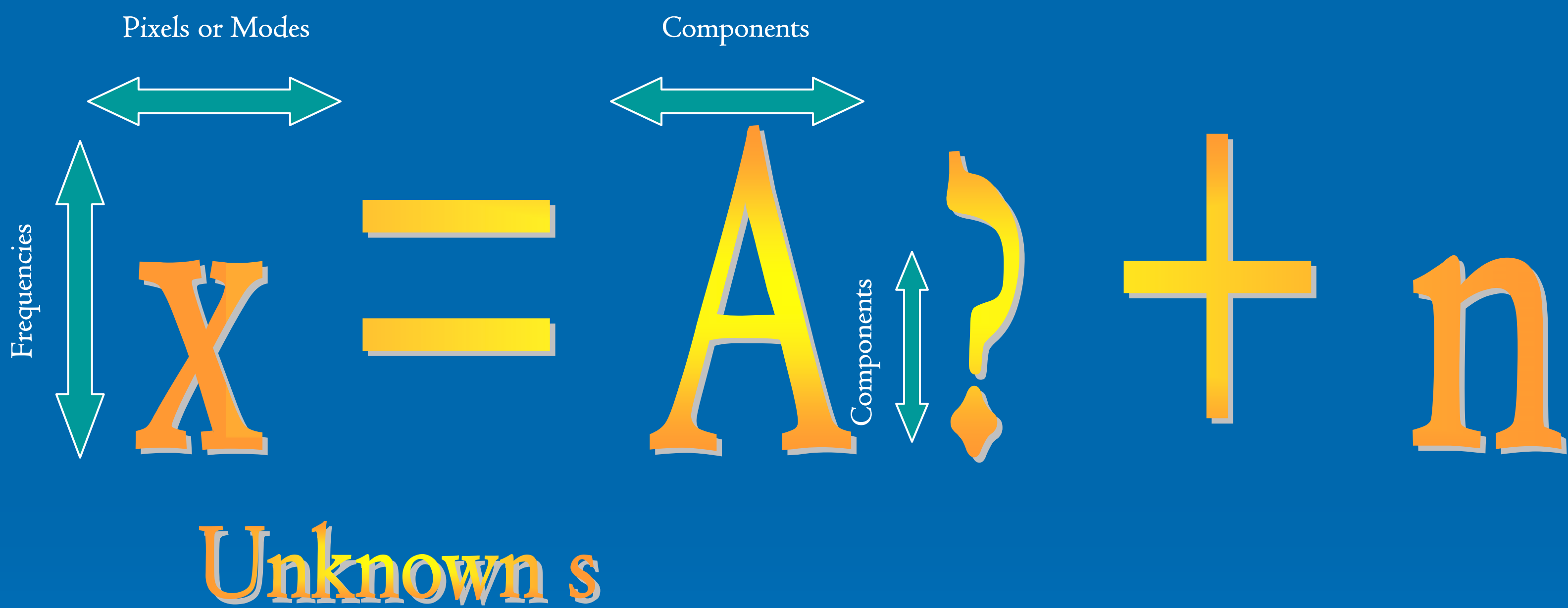
Components

Frequencies

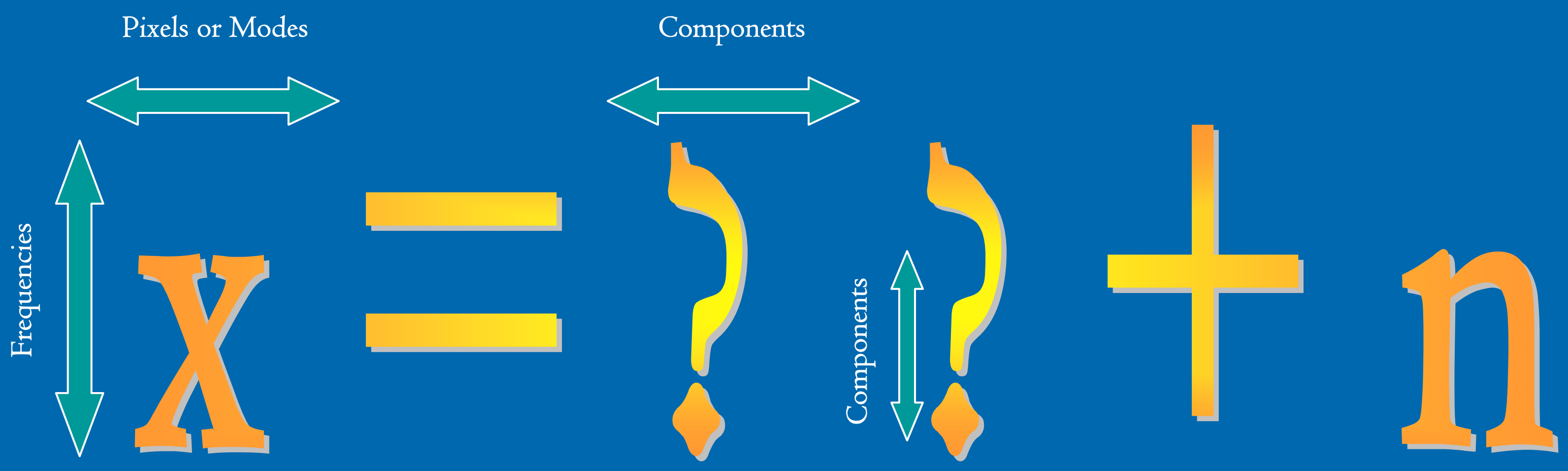
Components

$$x = A s + n$$

Component separation: ICA



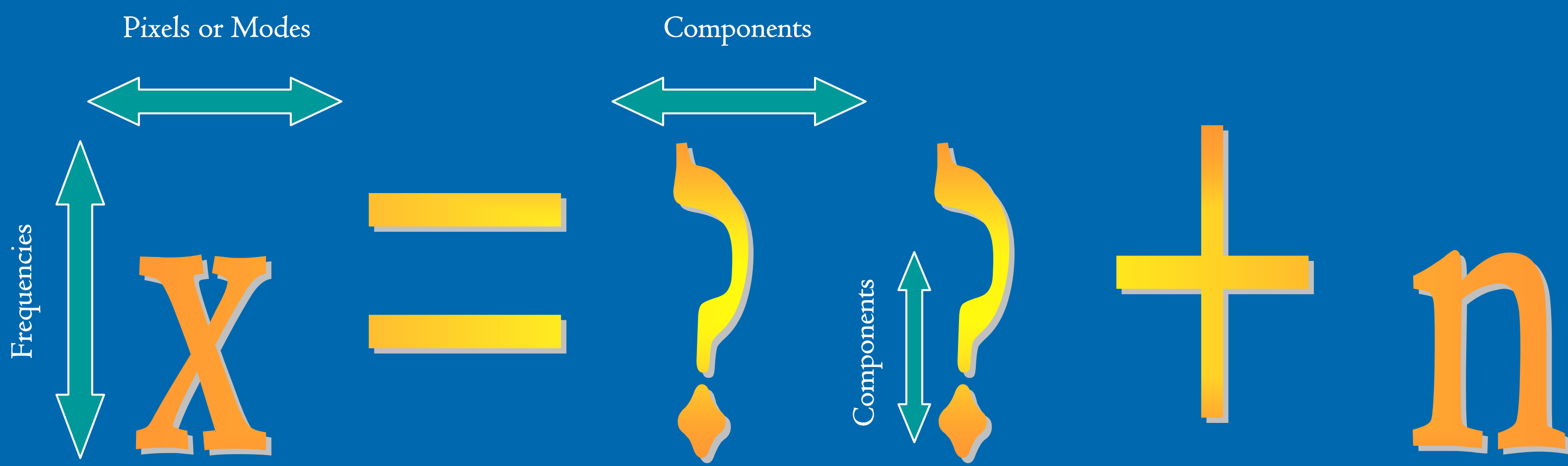
Component separation: ICA



Unknown s

Unknown A

Component separation: ICA



Unknown s

Unknown A

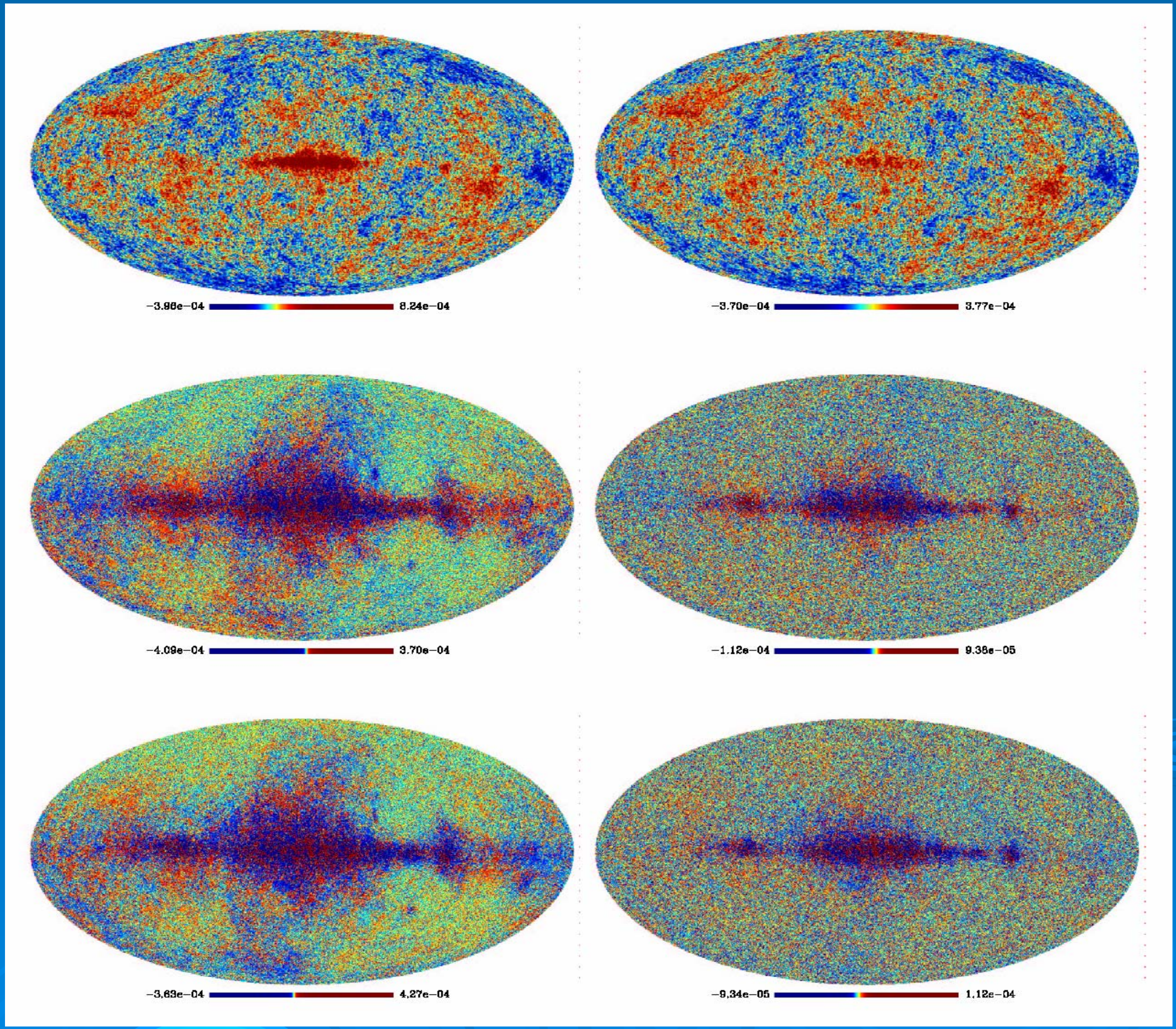
Find s!

Component separation: ICA

Experience the Magic

An example of the ICA performance

Mix CMB & Synchrotron at 50 & 80 GHz, 3 arcmin resolution, all sky, noiseless



T

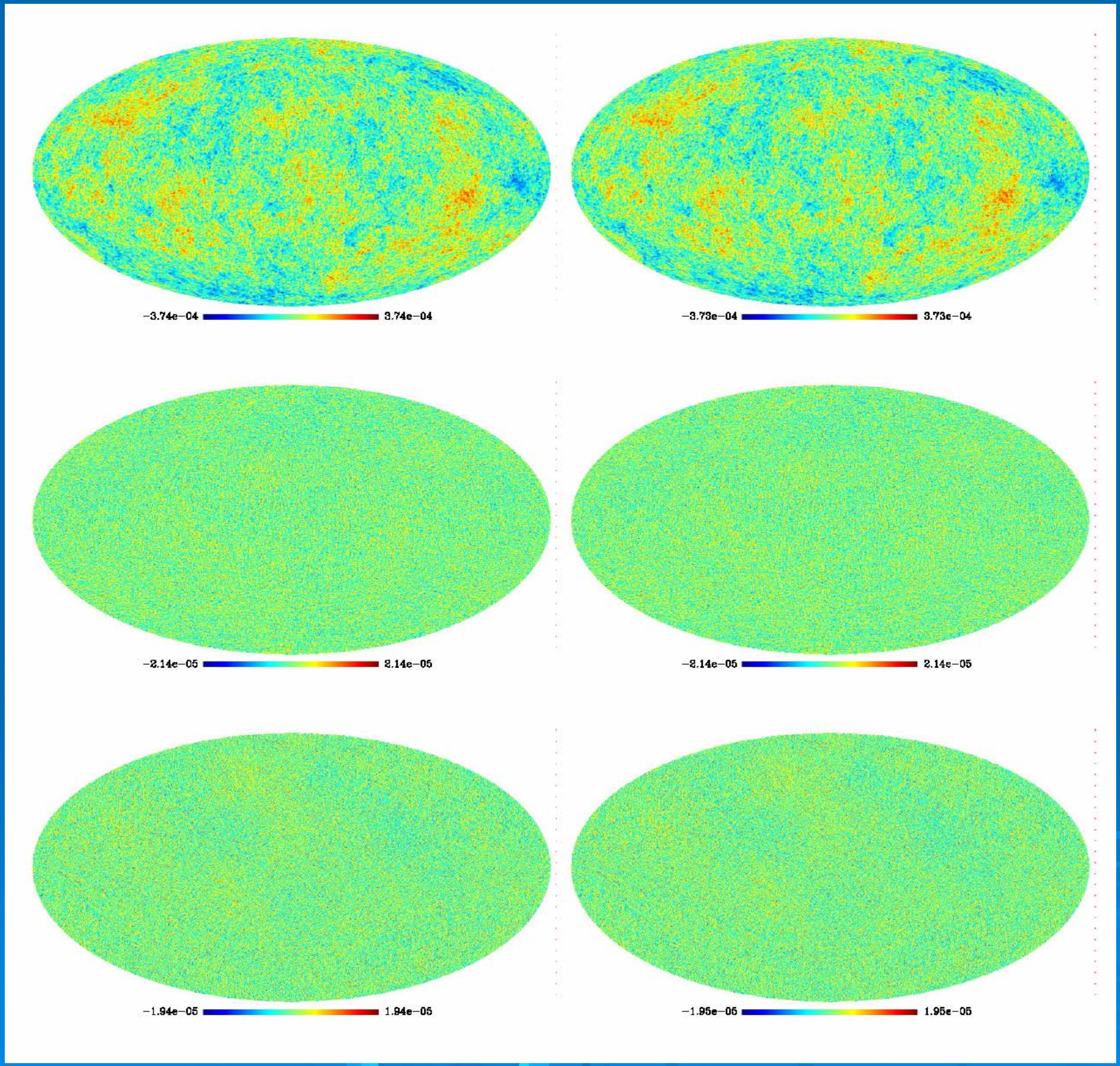
Q

U

50 GHz

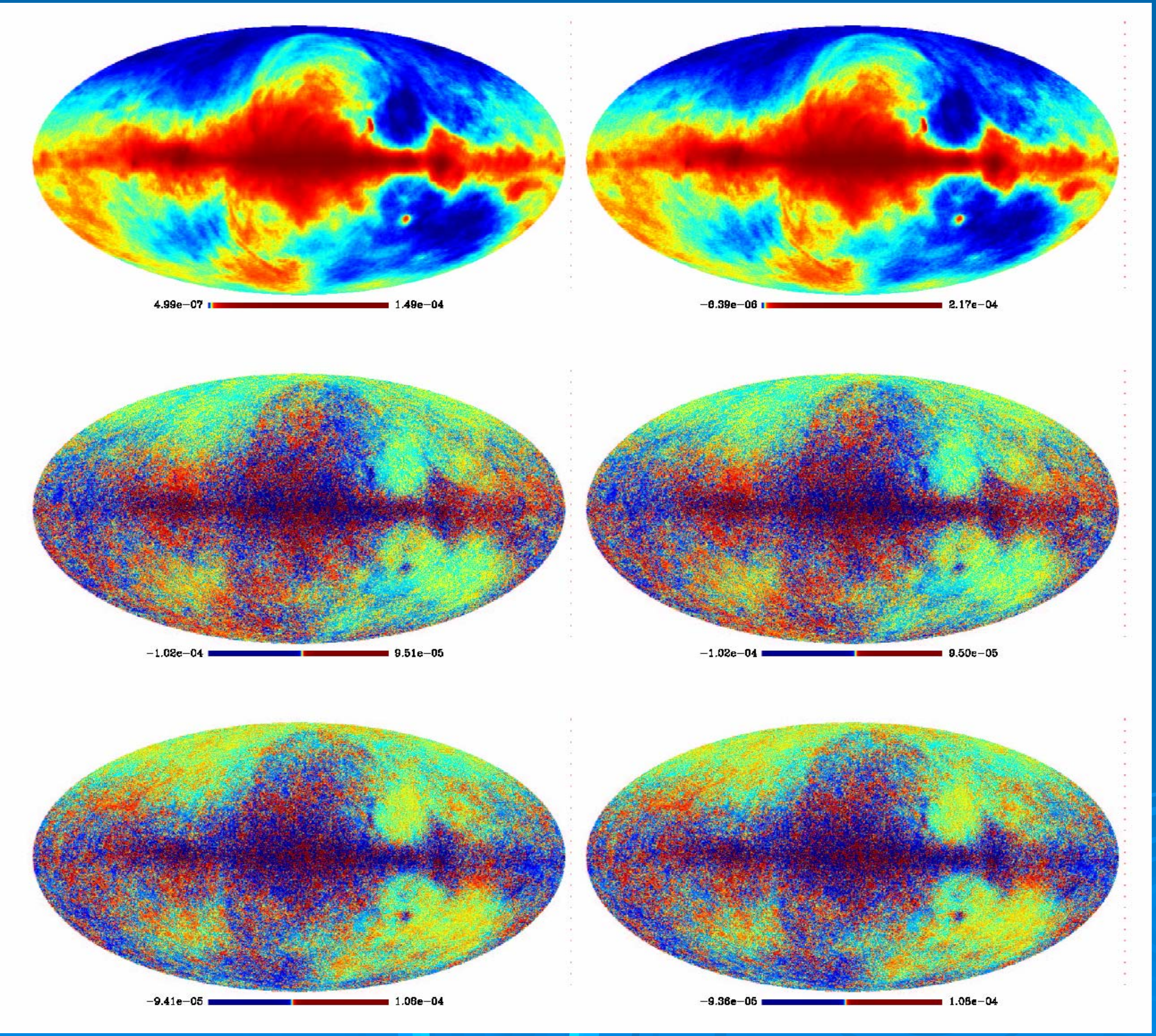
80 GHz

An example of the ICA performance



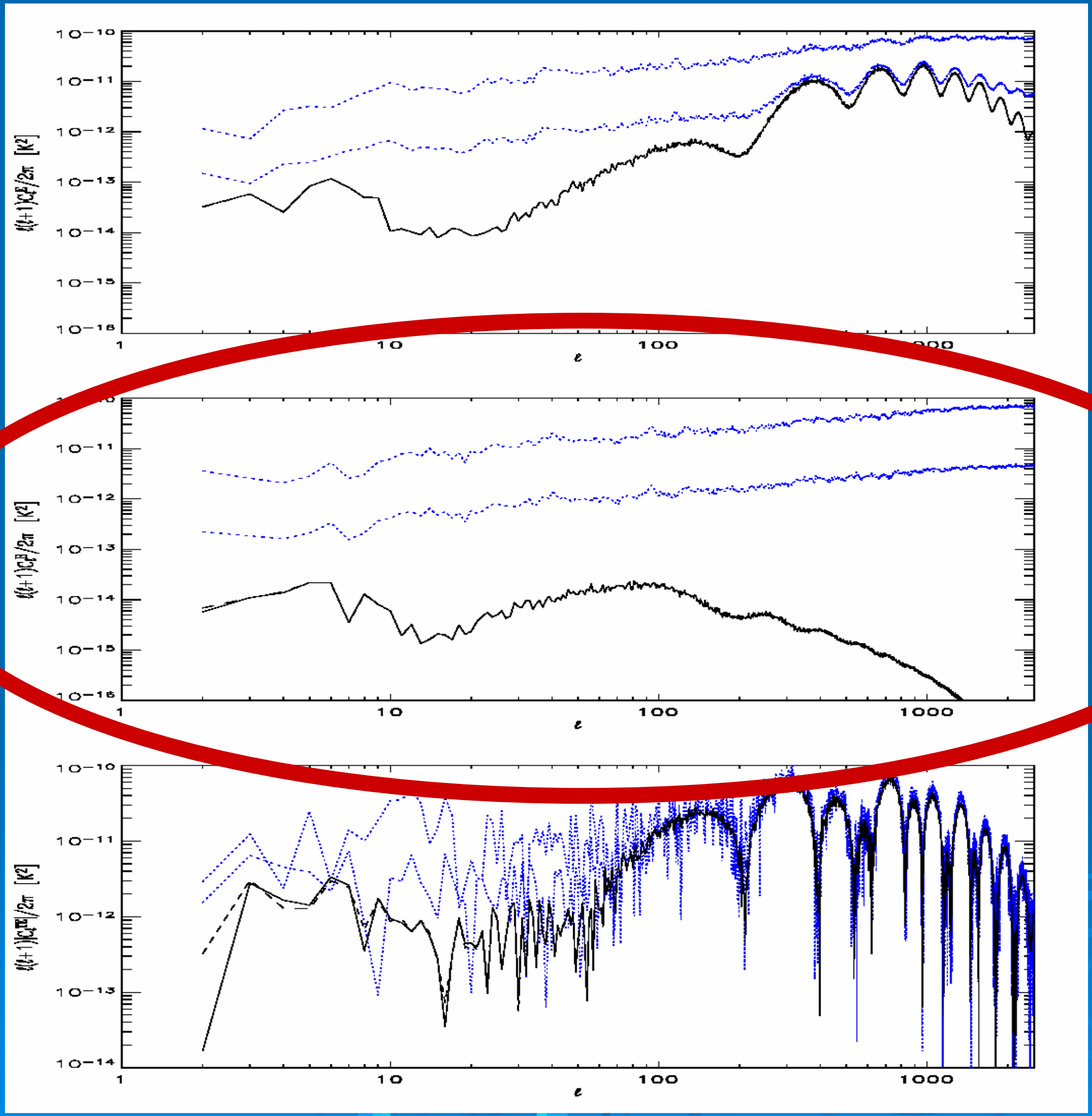
input output

An example of the ICA performance



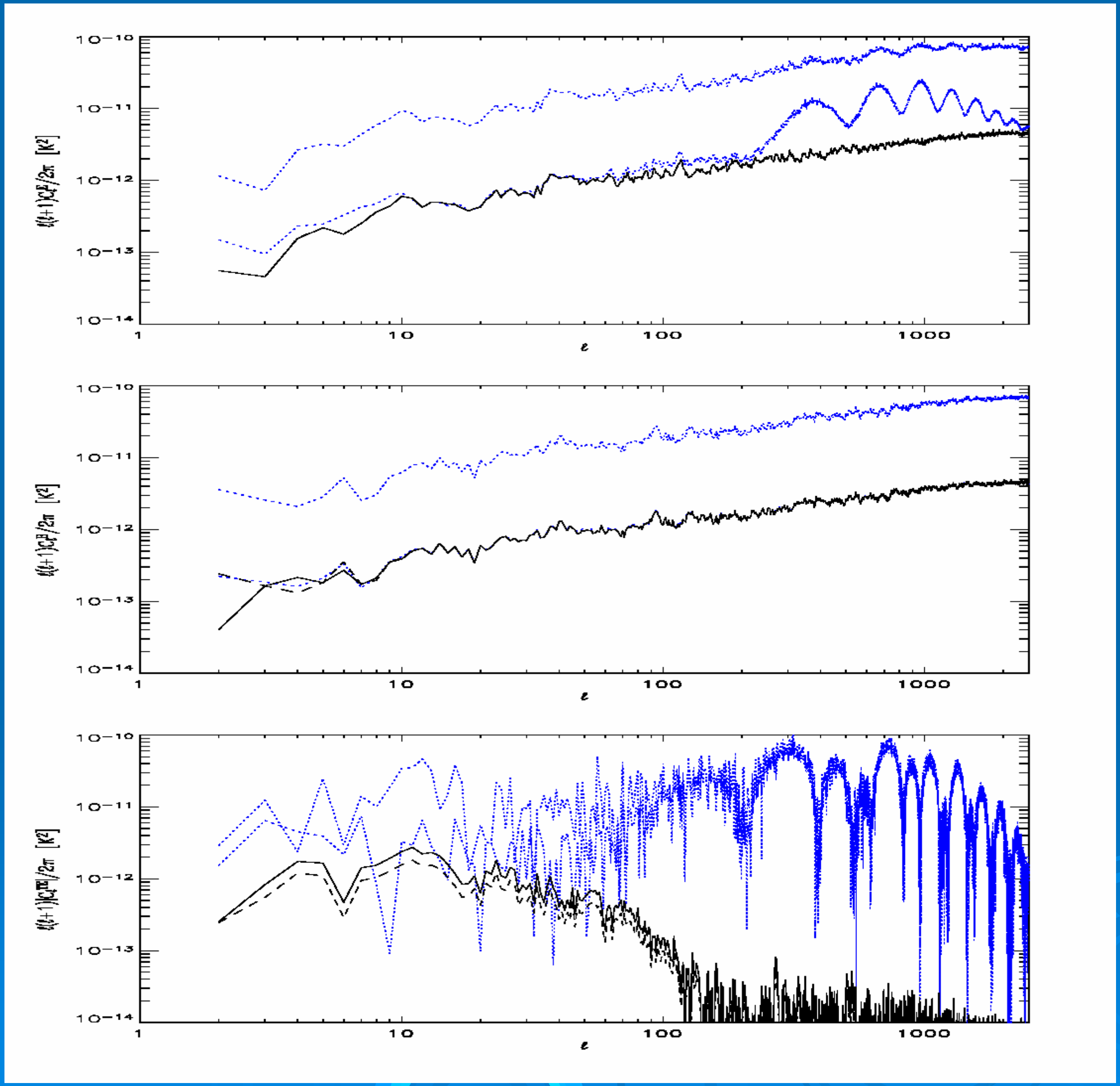
input output

An example of the ICA performance



Blue: sky at the two frequencies. Black solid (dashed): CMB output (input)

An example of the ICA performance



Blue: sky at the two frequencies. Black solid (dashed): synchrotron output (input)

Suggested reading

- The Planck blue book is available at http://www.rssd.esa.int/Planck
- Oxley et al. 2005 for a description of EBEx
- Stompor et al. 2002 and references therein for map-making
- Stivoli et al. 2006 and references therein for component separation and the latest application of ICA to the recovery of B modes of CMB polarization