Instituto de Física de Cantabria

UNIVERSITY OF CAMBRIDGE
Astrophysics Group
Cavendish Laboratory

Kavli Institute for Cosmology Cambridge

Constraints on inflationary models of the Universe based on CMB data

Andrés Curto Martín
Enrique Martínez González

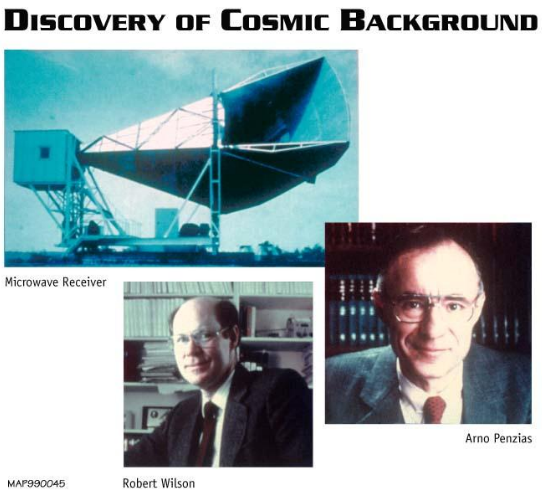
8th RES User Conference, Santander, 23/Sept/2014

Overview

- Cosmology using CMB data
  - Historical overview.
  - Physics of inflation.
- Principal codes and algorithms
  - Non-Gaussian simulator.
  - Minkowski functionals.
  - Wavelets.
- Implementation and use of RES
  - Main codes.
- Major results throughout the use of RES
  - Characterisation of systematic errors.
  - Constraints on primordial non-Gaussianity.

Cosmic Microwave Background

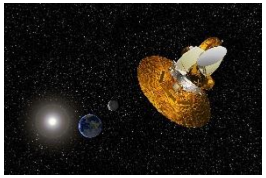
- 1920’s and 1930’s: Big Bang theory - Lemaître, Hubble, etc.
- 1946. Theoretical proposal of black body radiation at T<20 K.
- 1964. The CMB is detected.



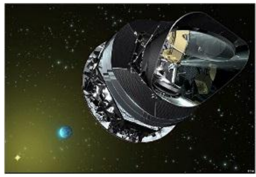
- 1970’s and 1980’s: First satellites dedicated to study the CMB: COBE (US) and RELIKT-1 (URSS).
- 1989-1992. COBE discovers the anisotropies of the CMB.
- 2001-2012. Multiple ground based, balloon-borne experiments and the WMAP satellite (NASA) study the anisotropies in detail.
- 2009-2014. The Planck satellite (ESA) produces the most precise maps of the CMB anisotropies and their polarisation.

COBE

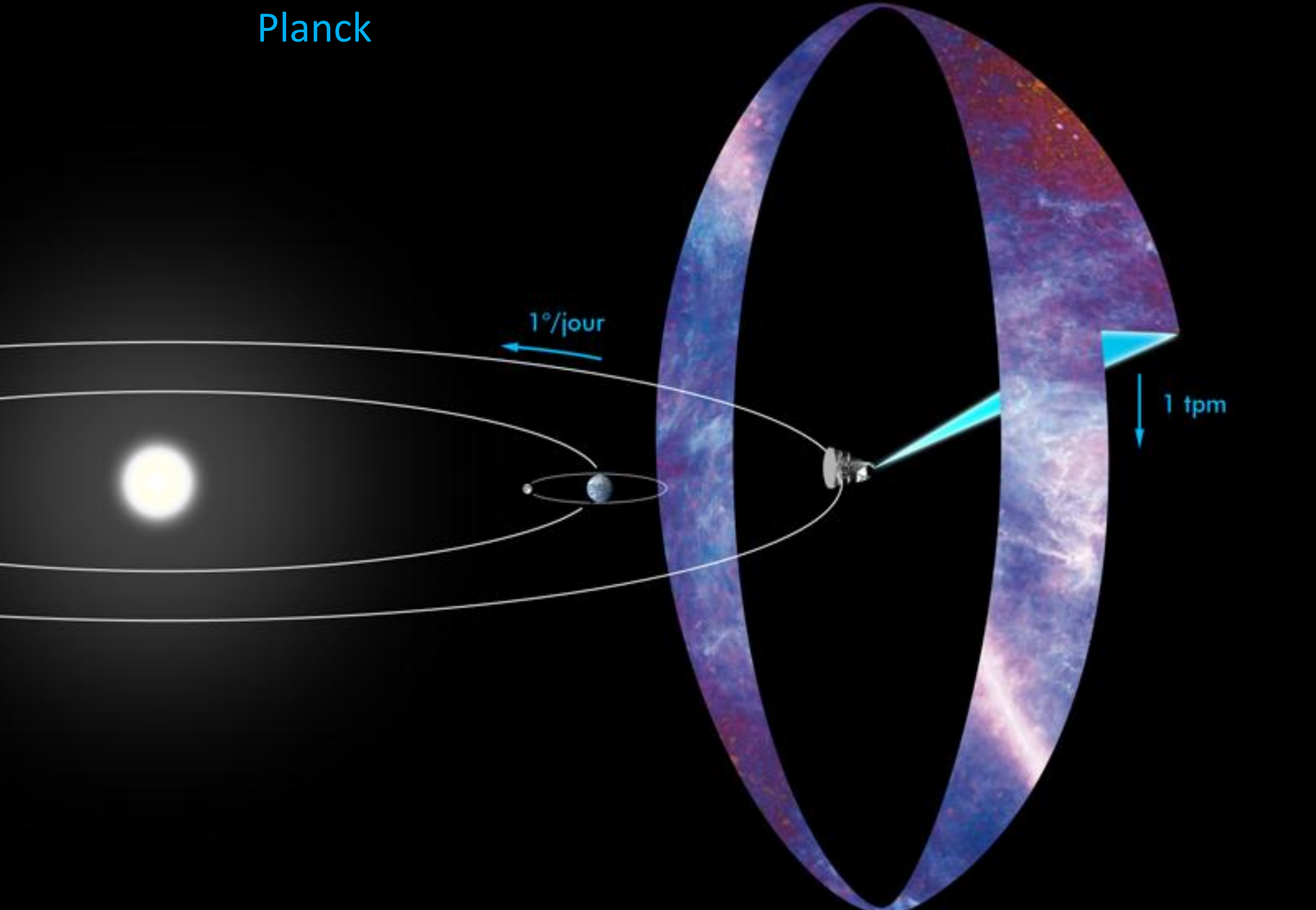
WMAP

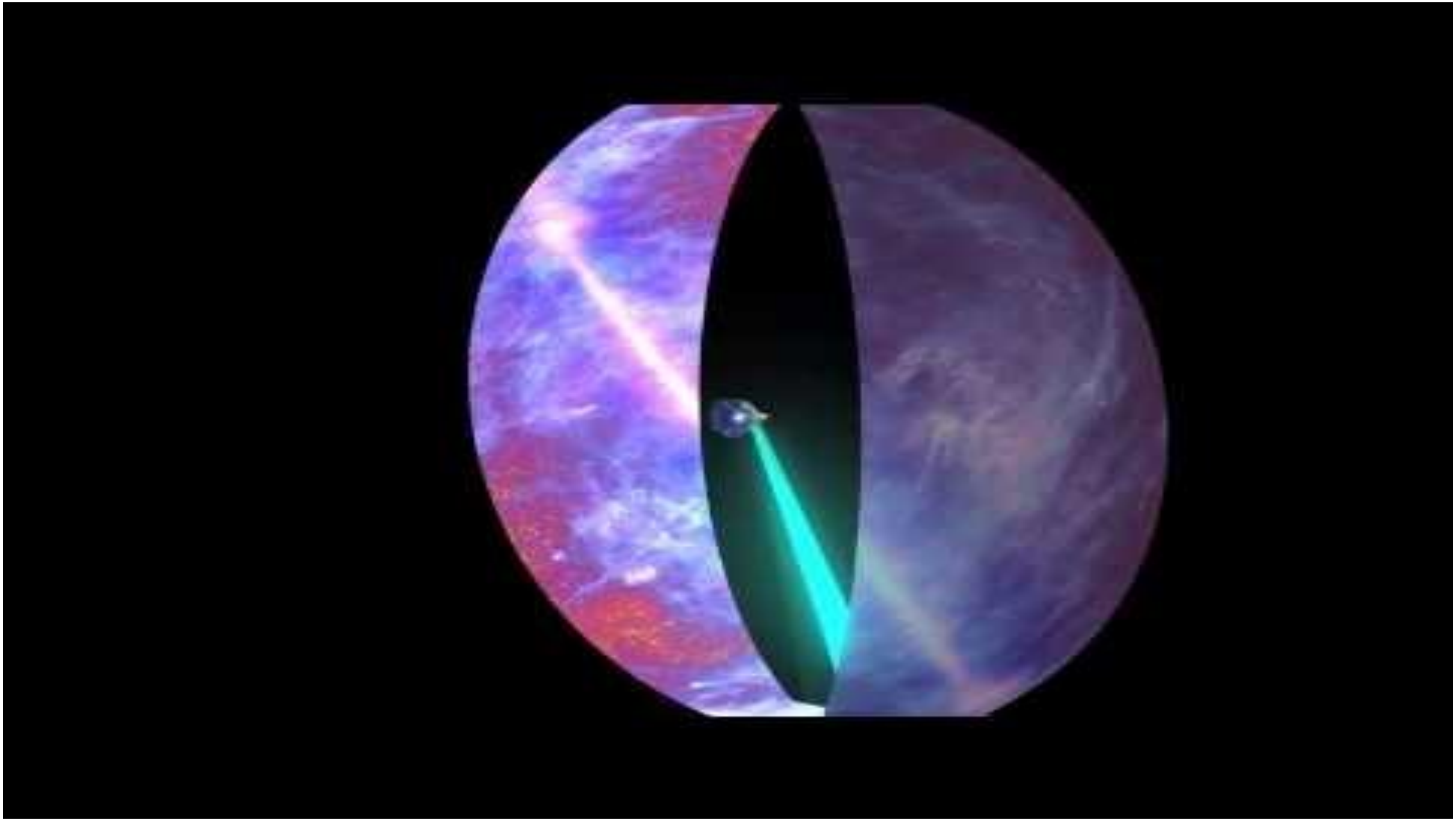


PLANCK



Planck

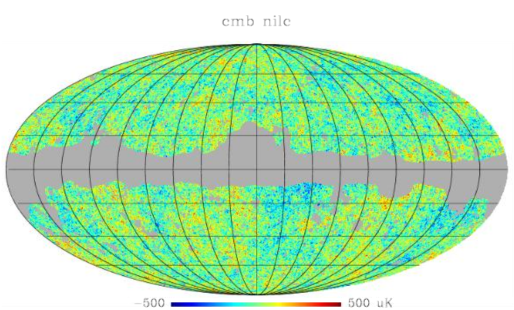




Planck satellite

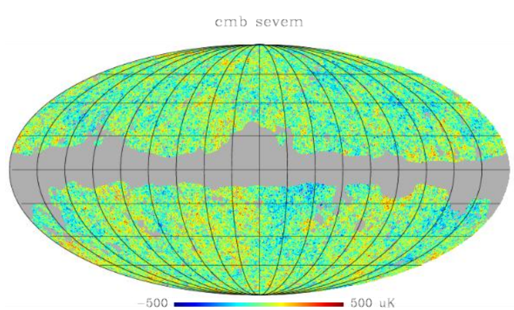
- A project designed in the early 1990's.
- Two instruments to measure the anisotropies in the frequency range between 30 to 857 GHz.
- Maximum angular resolution of 5 arcmin.

NILC



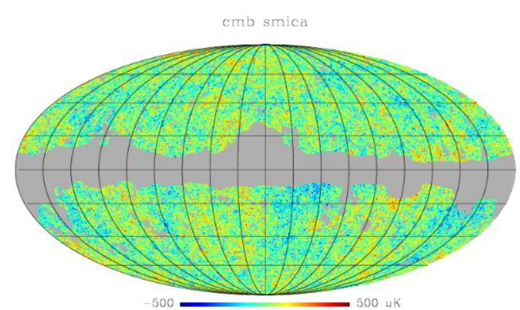
France

SEVEM



IFCA

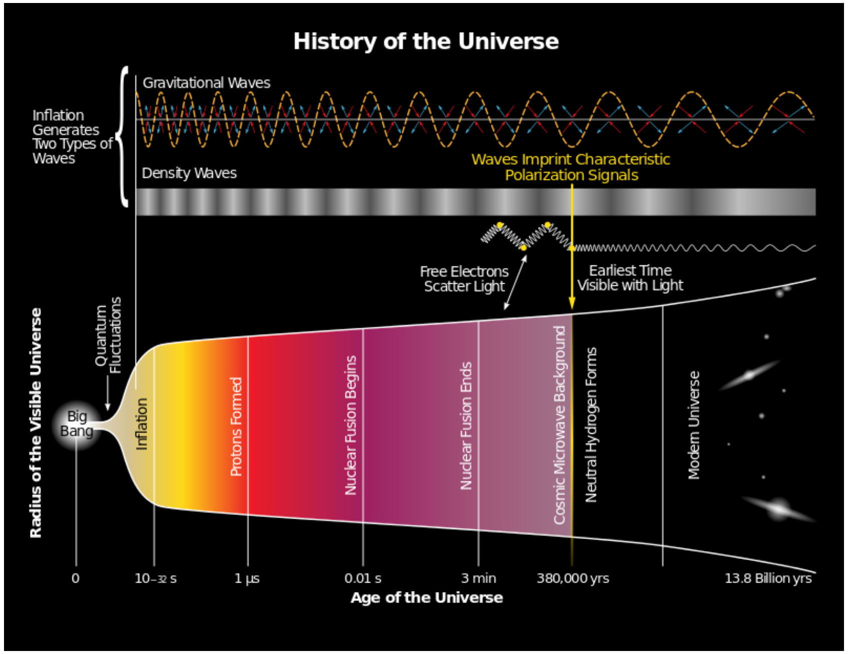
SMICA

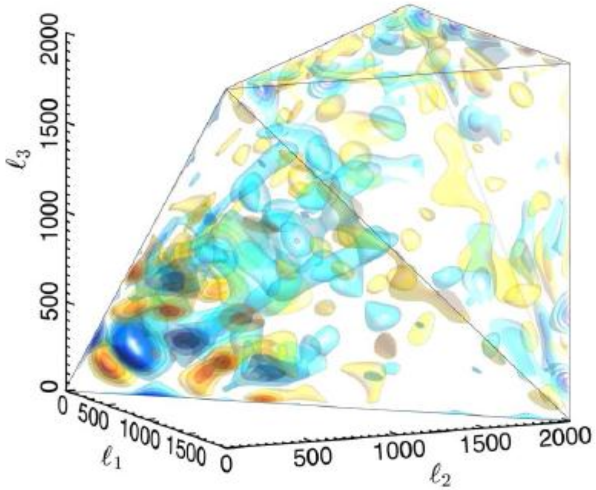


France

Physics of Inflation

- The inflationary scenario solves fundamental problems of the Big Bang such as the initial conditions.
- CMB in general agreement with inflation but there are many models.
- The statistical properties of the CMB anisotropies are powerful observables to find the best models.
- Many models predict non-Gaussian imprints in the CMB anisotropies.
- We try to measure the third order moment of the anisotropies: the bispectrum.
- The bispectrum is characterised by its amplitude: the non-linear coupling parameter f_{nl}.



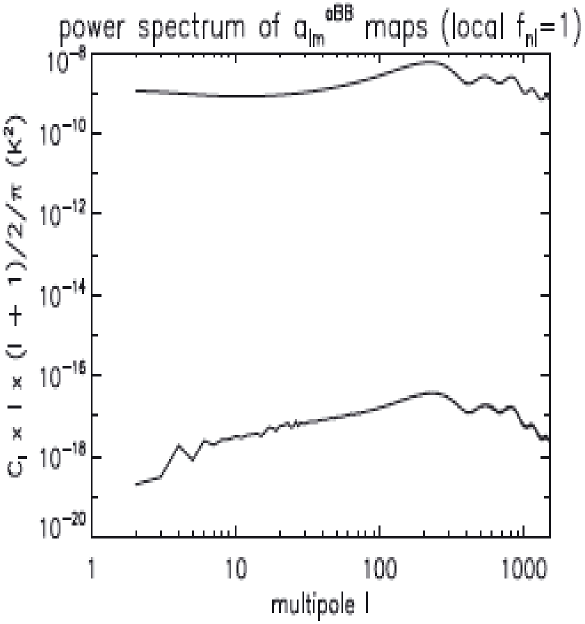


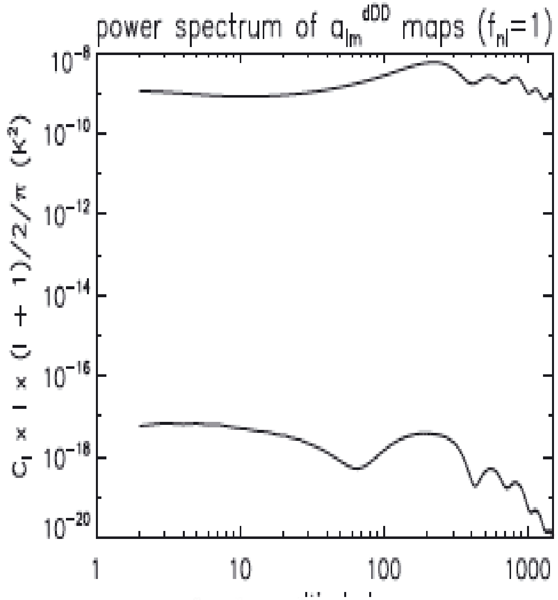
Planck 2013 CMB bispectrum

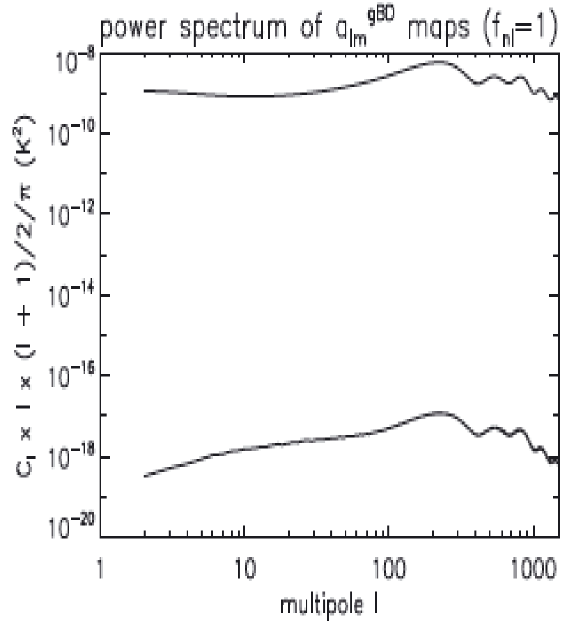
Principal codes

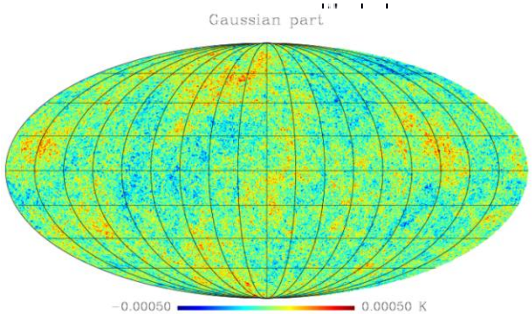
- Non-Gaussian simulator
  - Simulate non-Gaussian features in the CMB anisotropies that mimic possible imprints from inflation.
- Minkowski functionals
  - Topological tool widely used by the CMB community.
- Wavelets
  - Filter the CMB maps preserving properties of both the real and harmonic space.

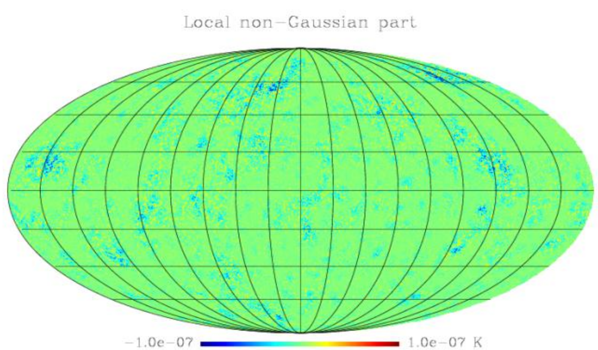
Non-Gaussian simulations

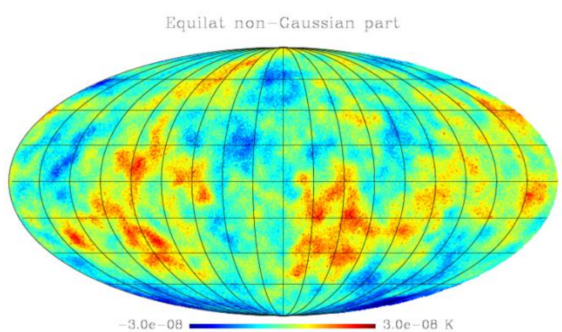


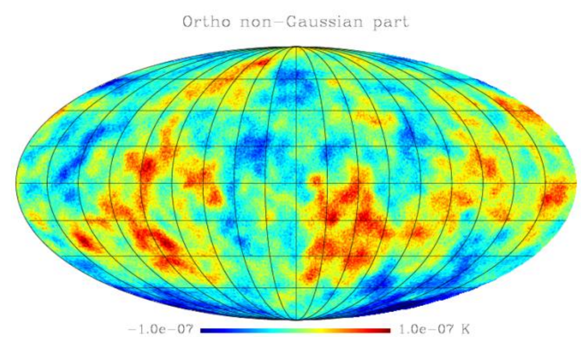






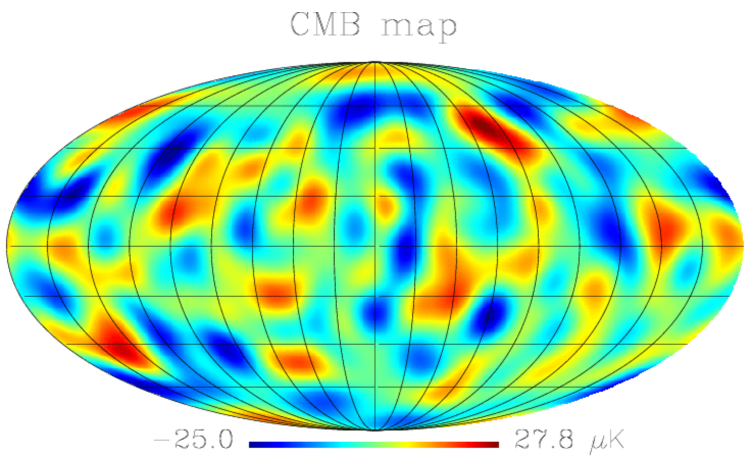


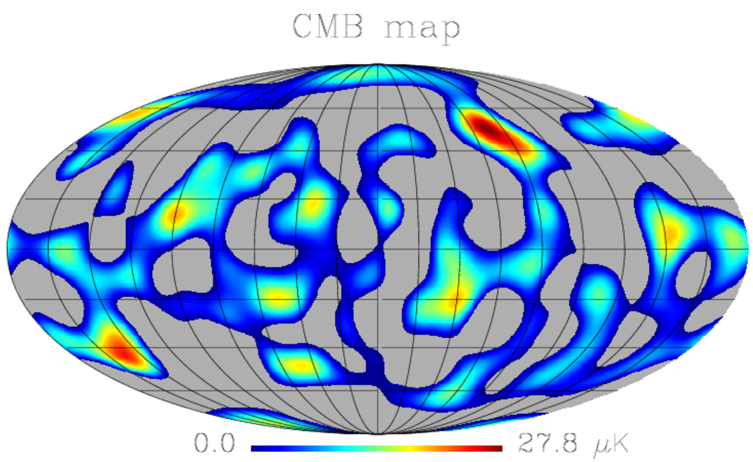




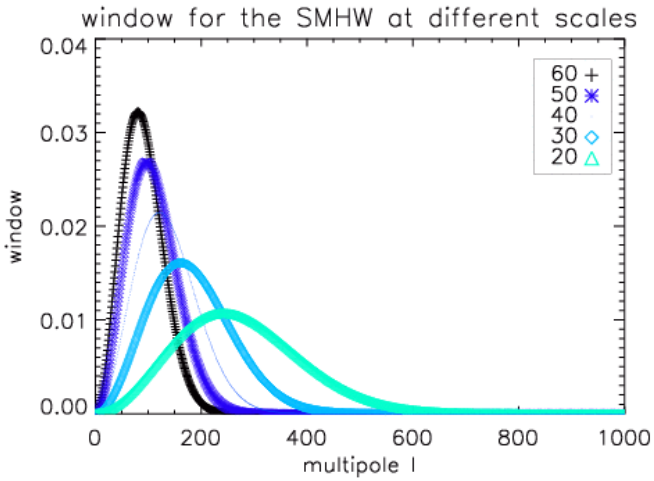
Minkowski functionals

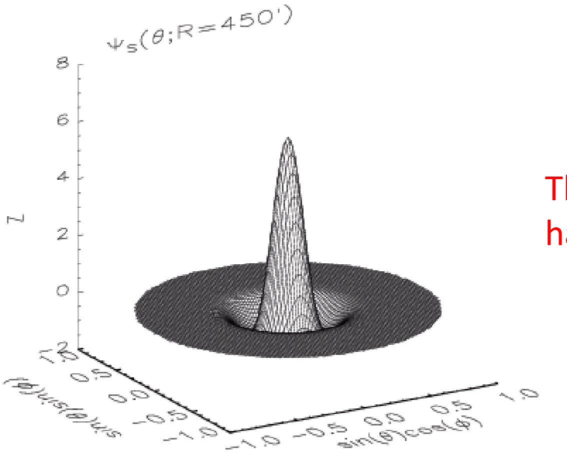
- Area: A(ν)
  - The area of the hot spots above a given threshold (ν)
- Contour Length : C(ν)
  - The perimeter of the hot spots above a given threshold (ν)
- Genus : G(ν)
  - Number of hot spots (> ν) minus number of cold spots (< ν)



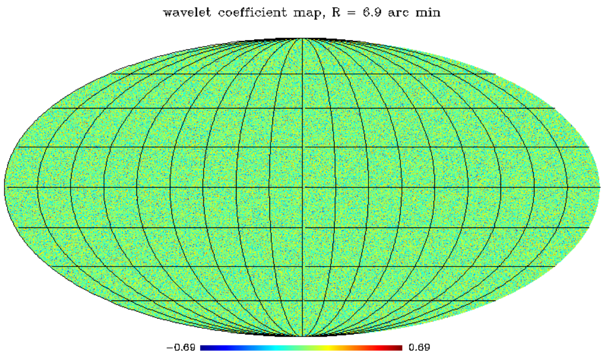


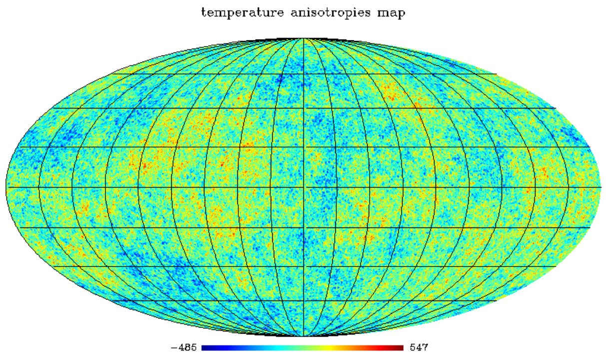
f_{nl} estimates using wavelets

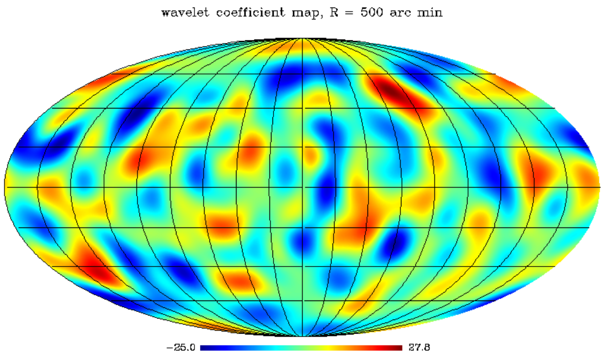




The spherical Mexican hat wavelet



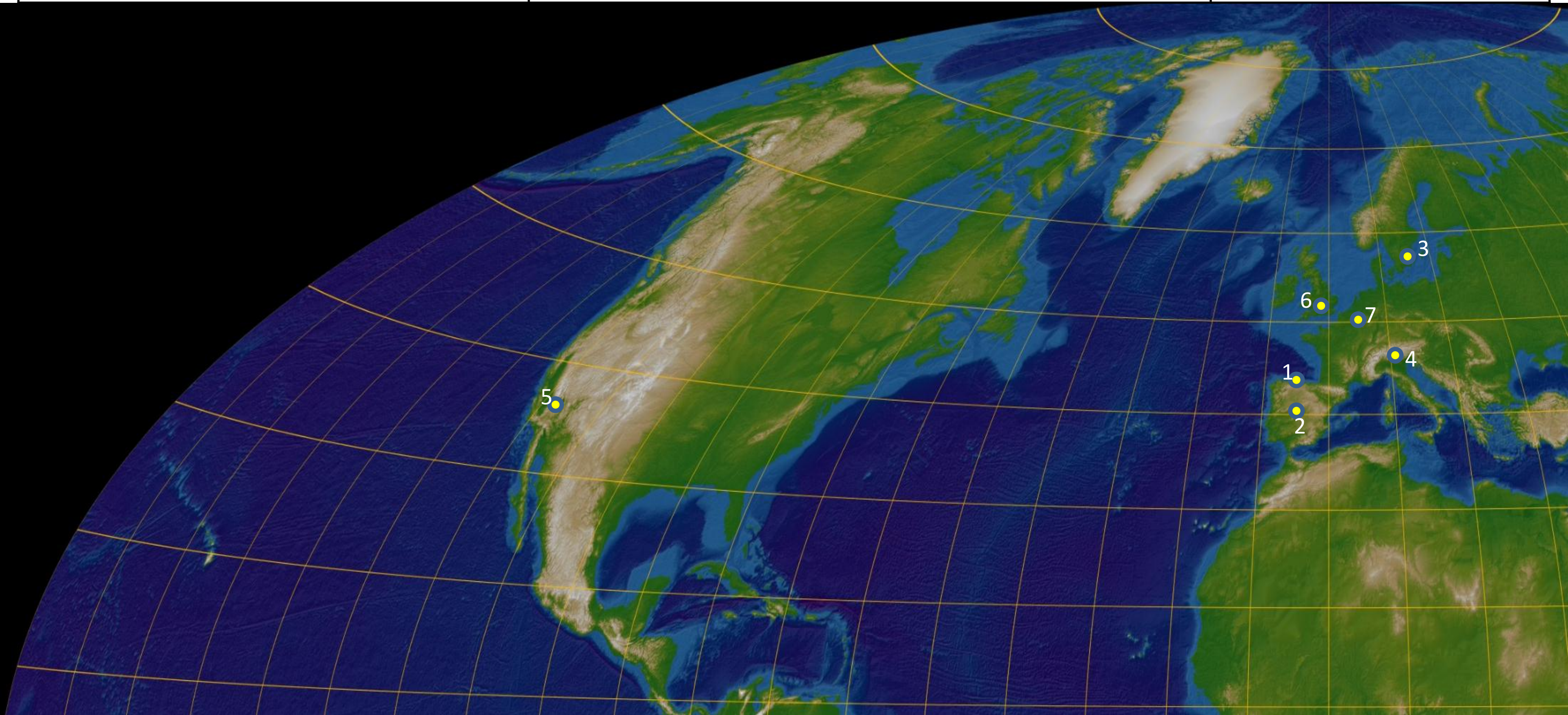


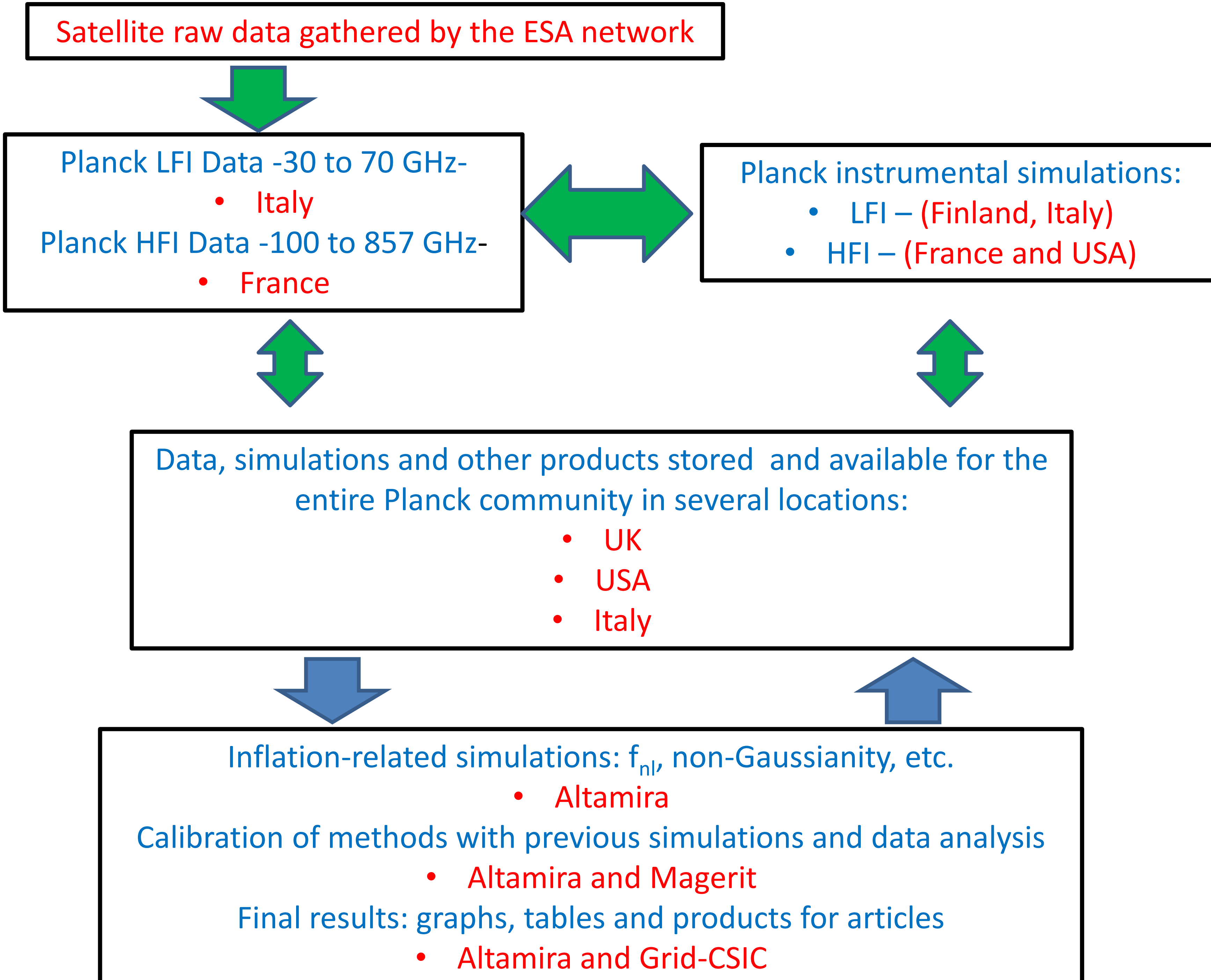


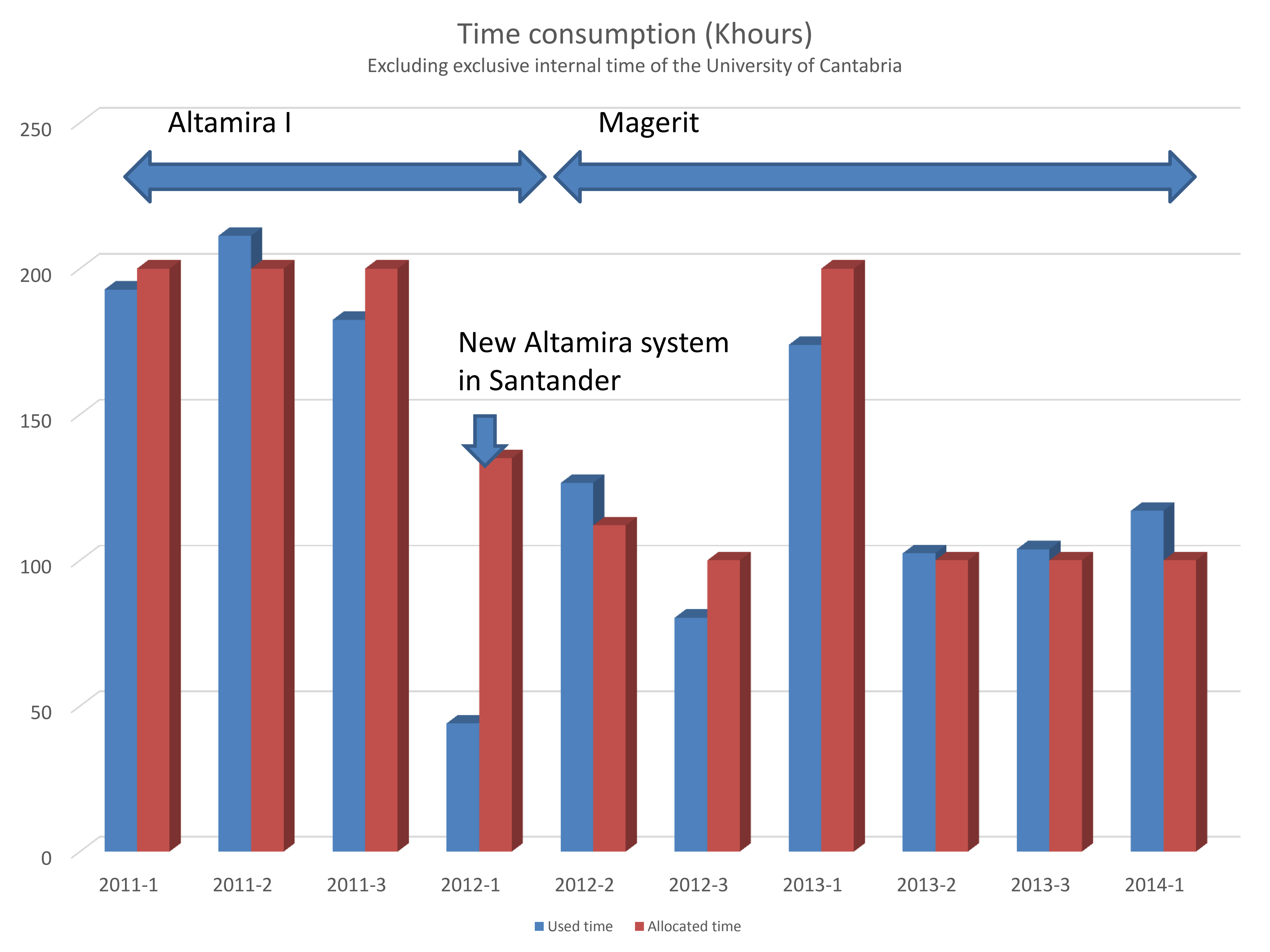
Properties of the software

- Generation of CMB simulations
  - One single non-Gaussian map at Planck resolution requires approx. 10 hours using 32 CPUs (data measured with Altamira).
  - We need approx. 1000 simulations to perform Monte Carlo statistics.
- Minkowski Functionals
  - The estimation of the MF takes 3 hours for T and 12 hours for the polarization mode (Planck resolution).
- f_{nl} estimation with wavelets
  - The total process takes approx. 25000 hours (Planck resolution, only T).
  - Parallelised code.

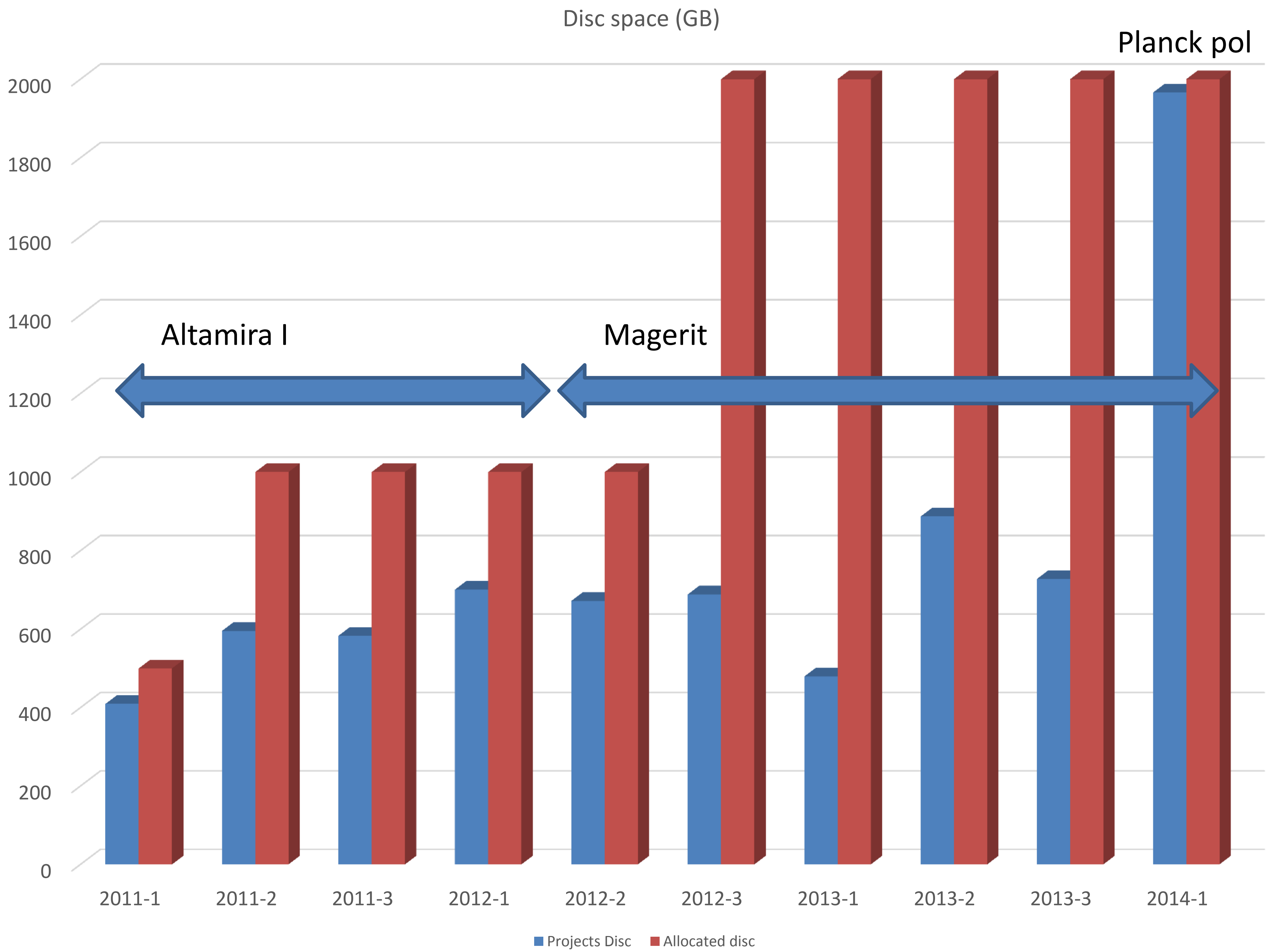
System	Organization	Location
1. Altamira	IFCA & RES (0.6 Mhours in RES + internal UC time)	Santander (Spain)
2. Magerit	U. Politécnica Madrid & RES (0.7 Mhours in RES)	Madrid (Spain)
3. Sisu & Louhi	IT Center For Science (PRACE DECI-7 project of 2.5 Mhours led by a Finish group; 0.5 Mhours for us)	Helsinki (Finland)
4. Ironthrone	Planck LFI	Trieste (Italy)
5. Hopper & Carver	NERSC (0.5 Mhours within a USA Planck project)	California (USA)
6. Cosmos & Universe	U. Of Cambridge (~0.1 Mhours within Planck)	Cambridge (UK)
7. Magique	Planck HFI	Paris (France)



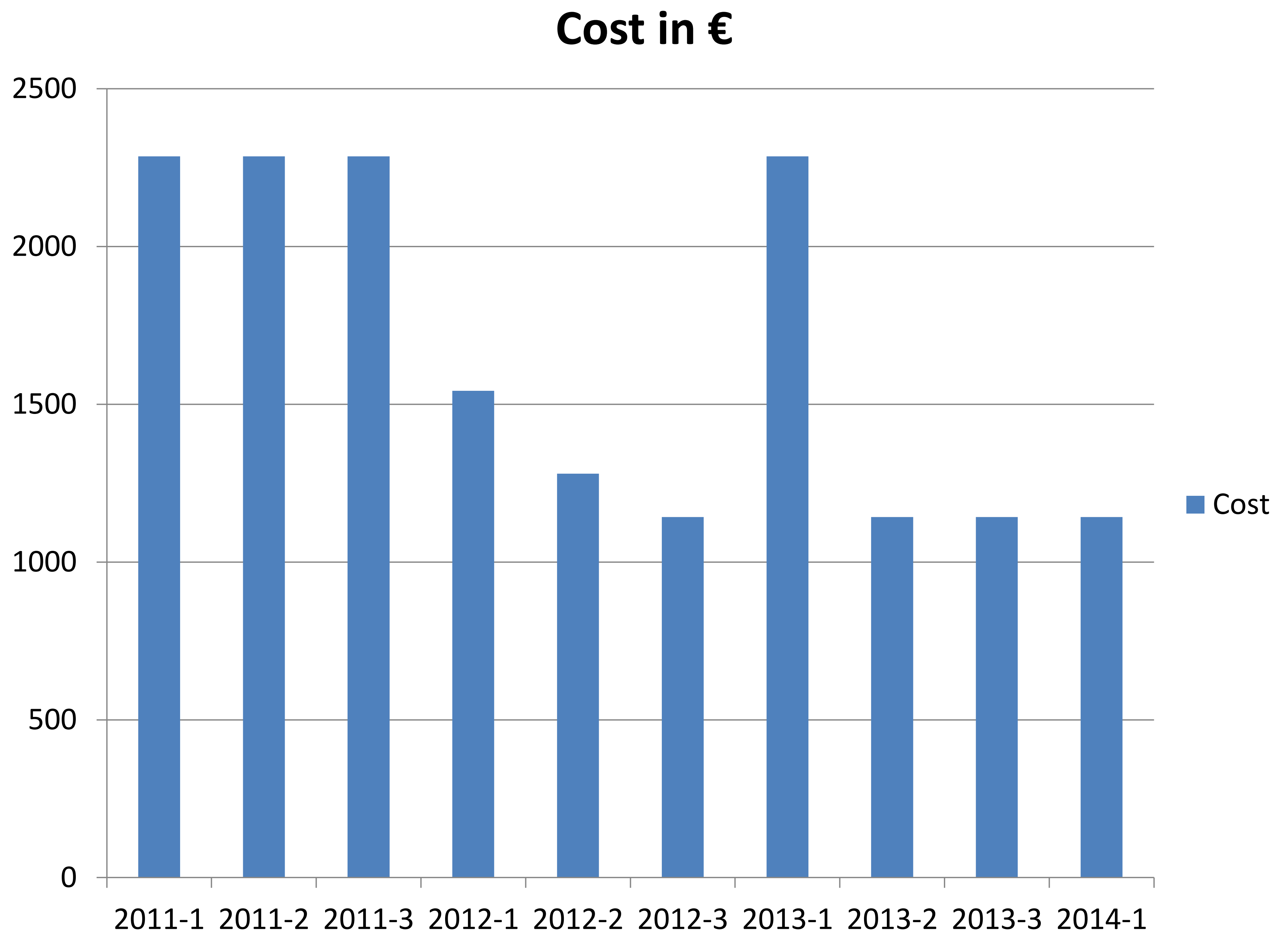

Satellite raw data gathered by the ESA network
Planck LFI Data -30 to 70 GHz-
• Italy
Planck HFI Data -100 to 857 GHz-
• France
Planck instrumental simulations:
• LFI – (Finland, Italy)
• HFI – (France and USA)
Data, simulations and other products stored and available for the entire Planck community in several locations:
• UK
• USA
• Italy
Inflation-related simulations: f_{nl}, non-Gaussianity, etc.
• Altamira
Calibration of methods with previous simulations and data analysis
• Altamira and Magerit
Final results: graphs, tables and products for articles
• Altamira and Grid-CSIC



Time consumption (Khours)
Excluding exclusive internal time of the University of Cantabria
Altamira I
Magerit
New Altamira system
in Santander
250
200
150
100
50
0
2011-1
2011-2
2011-3
2012-1
2012-2
2012-3
2013-1
2013-2
2013-3
2014-1
Used time
Allocated time



Disc space (GB)
Planck pol
Altamira I
Magerit
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2011-1
2011-2
2011-3
2012-1
2012-2
2012-3
2013-1
2013-2
2013-3
2014-1
Projects Disc
Allocated disc


Cost in €
2500
2000
1500
1000
500
0
Cost
2011-1
2011-2
2011-3
2012-1
2012-2
2012-3
2013-1
2013-2
2013-3
2014-1

Principal Scientific Results

- "Planck 2013 results. III. LFI systematic uncertainties", (arXiv:1303.5064).
  - Statistical characterisation of the systematic errors presents in the data maps by performing different tests of non-Gaussianity.
- "Planck 2013 results. XXIII. Isotropy and Statistics of the CMB", (arXiv:1303.5083).
  - Study of the Isotropy and statistics properties of the CMB maps using wavelets and Minkowski functionals.
- "Planck 2013 results. Constraints on primordial non-Gaussianity", (arXiv:1303.5084).
  - The measurement of the amplitude of the primordial bispectrum present in the Planck data using wavelets.

Future steps

- Planck polarised maps coming soon.
- Maps and companion papers to be published in November/December 2014.
- Planck legacy products by mid-2015.
- Important questions open
  - Is Bicep2 a primordial detection of B mode directly related to the gravitational waves of the Big Bang?