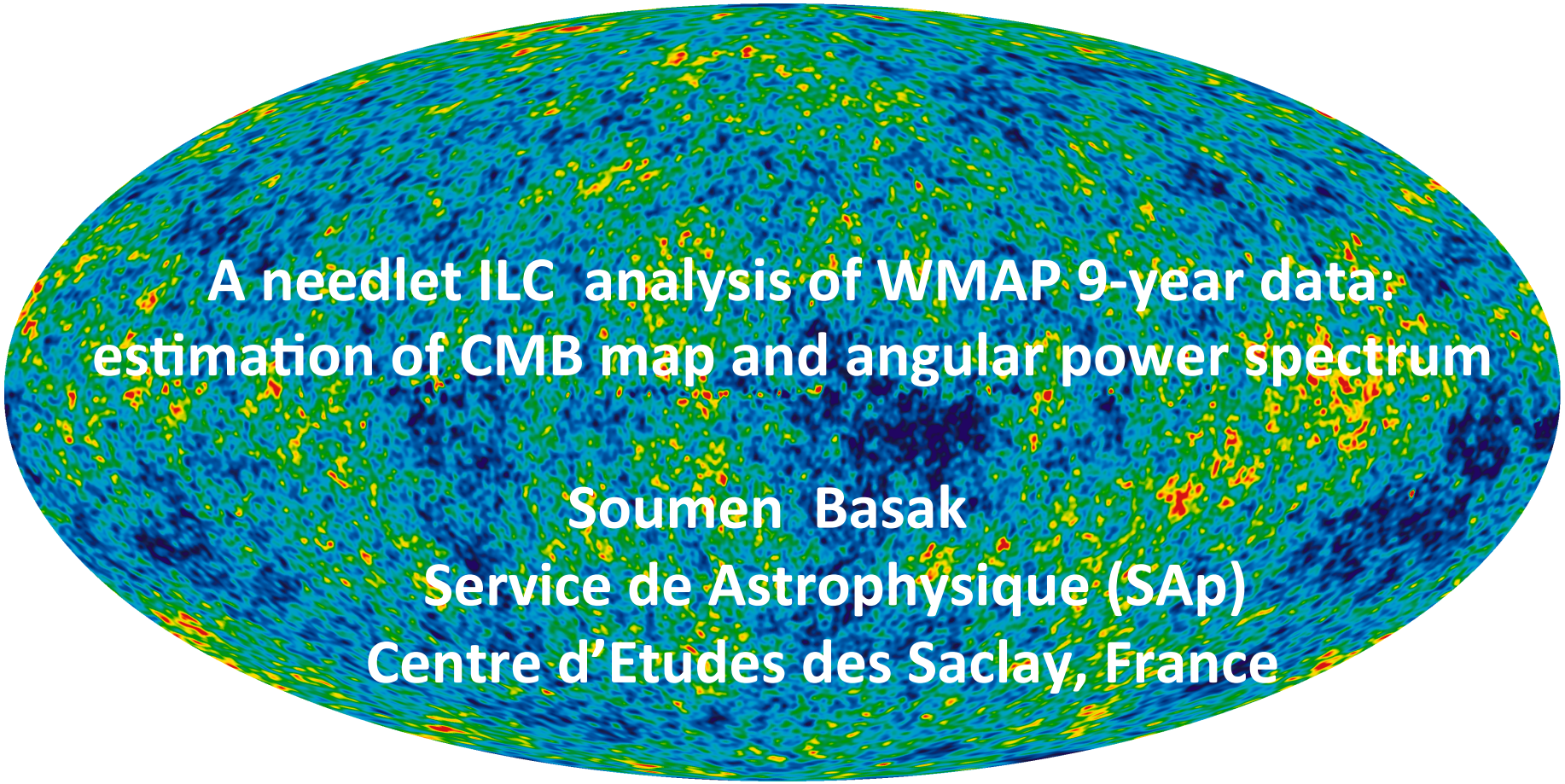


A needlet ILC analysis of WMAP 9-year data: estimation of CMB map and angular power spectrum

Soumen Basak
Service de Astrophysique (SAp)
Centre d'Etudes des Saclay, France

CMB : Cosmic Microwave Background

WMAP : Willkinson Microwave Anisotropy Probe

Collaborator :
Jacques Delabrouille
Laboratorie APC, Paris, France.

arXiv: 1204.0292
Journal ref. : to appear in MNRAS

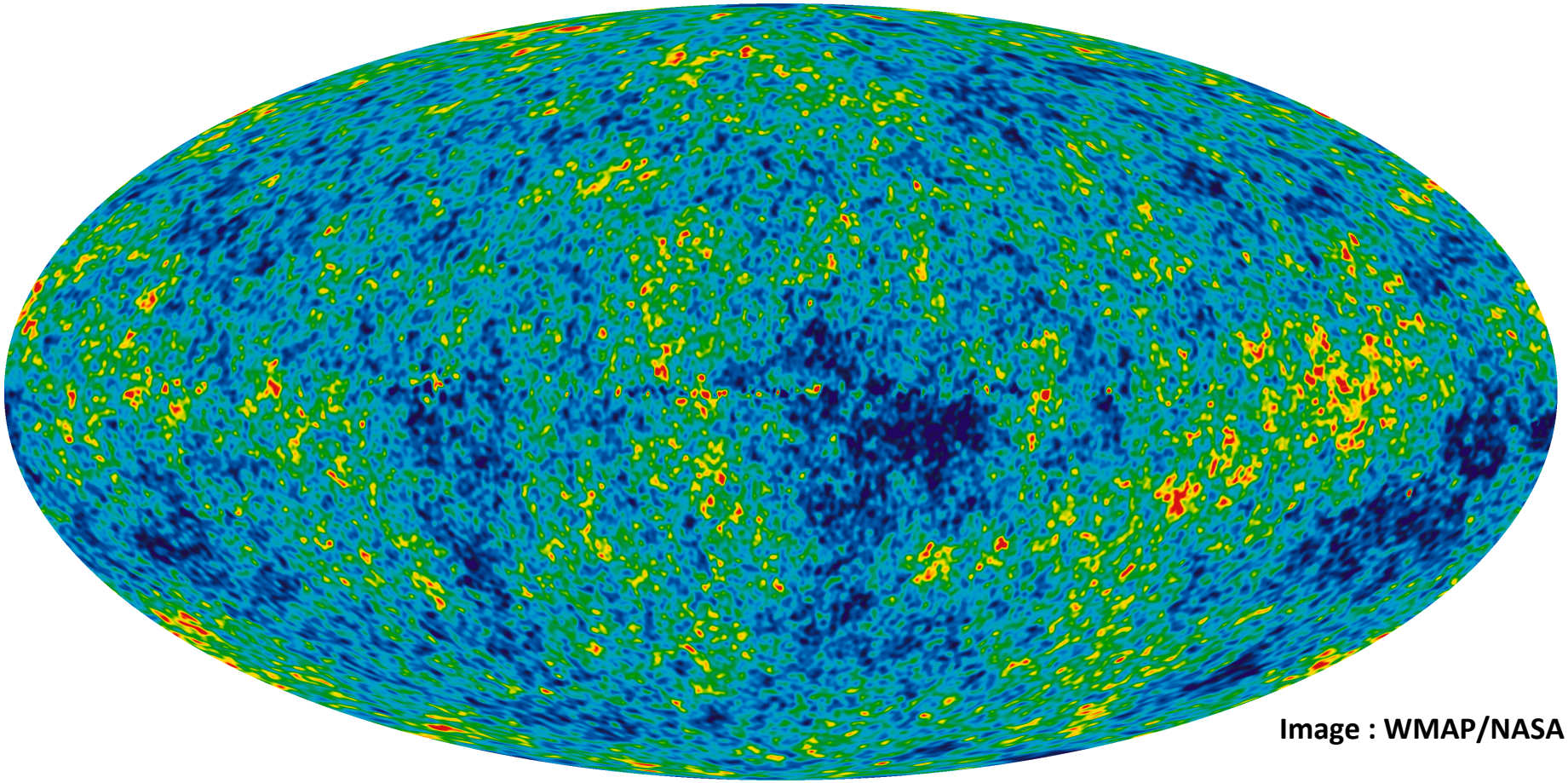


Image : WMAP/NASA

An accurate snapshot of oldest light in our Universe

Originated around 380,000 years after Universe came into existence

High temperature

Low temperature

Baby picture of our Universe

Expanding Universe

Hubble's observations (in 1929) :

- **Distant galaxies in every direction are going away from us.**
- **Galaxies that are farther away are moving faster.**

Edwin Hubble

100-inch Hooker telescope

Hubble's law : $v = H_0 d$

- **v = Relative velocities of galaxies**
- **H_0 = Hubble's constant 70 Km/sec/Mpc**
- **d = distance from earth**

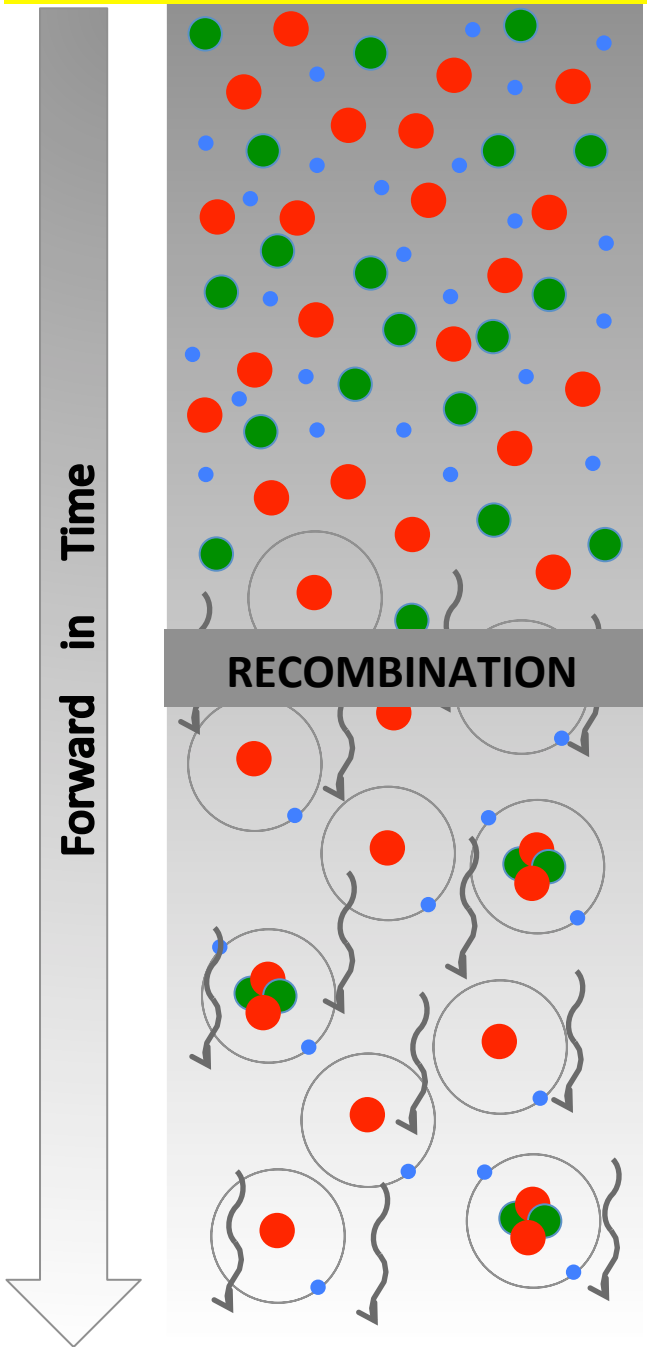
Cosmological principle :

- **There is no preferred direction or location in our Universe as, on the largest cosmic scales, Universe is homogeneous and isotropic.**

Universe is expanding

Early Universe was very dense and hot state

Basic facts about CMB (Origin)



Proton Neutron Electron Photon

Prior to recombination :

- Universe was opaque (high optical depth) as photons were strongly coupled with free electrons through electromagnetic interactions.

During recombination (t ~ 380,000 years) :

- Subatomic particles combine to form neutral atom at the time of recombination (T~3000 °K)

After recombination :

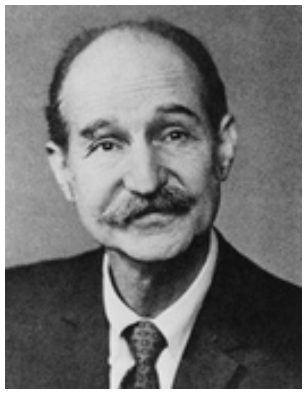
- Universe became transparent (low optical depth) as photons could travel freely without being scattered by neutral atoms. These photons, reaching us today, form Cosmic Microwave Background (CMB) radiation.

Basic facts about CMB (Prediction and Discovery)

Prediction :

CMB has been predicted by Ralph Alpher, Robert Herman and George Gamow in 1948.

Ralph Alpher



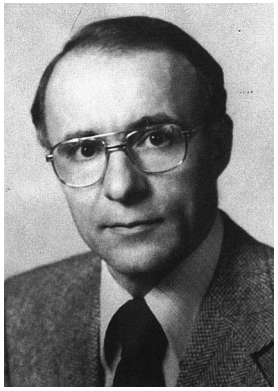
Robert Herman

George Gamow

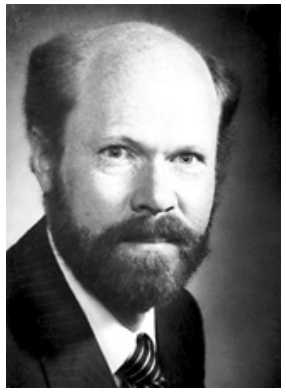
Predicted Temperature : 5-10 °K

Discovery :

CMB has been discovered by Arnow Penzias and Robert Wilson at Bell Labs in 1965.



Arnow Penzias



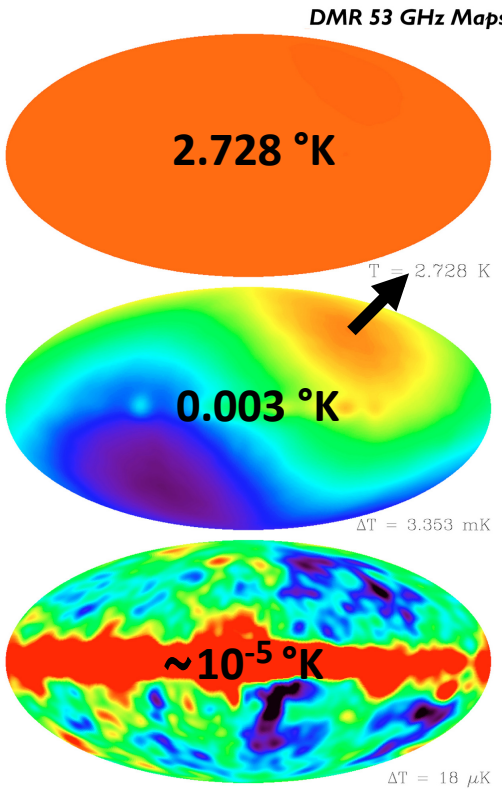
Robert Wilson

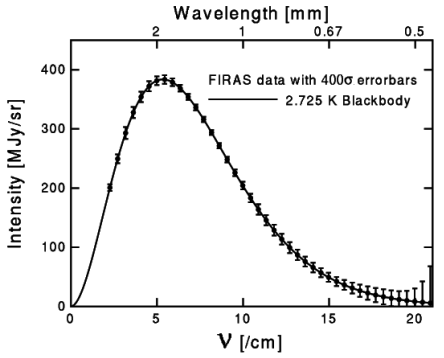
Nobel Prize 1978

Measured Temperature : 3.5 °K

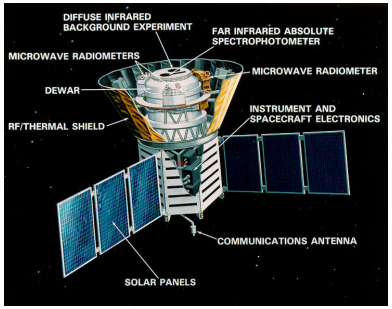
Cosmic Background Explorer (COBE) satellite mission

- Black-body spectrum with corresponding temperature of 2.728 °K (- 270.72 °C) because matter and radiation were in thermal equilibrium.
- Uniform over the sky on large angular scales (greater than 7°) because matter density in early Universe was uniform as well.
- Dipole anisotropy (~10^{-3} °K) because of motion of earth in the rest frame of
- Fluctuations or anisotropy (~10^{-5} °K) on small angular scales (smaller than 7°).
- Fluctuations resulted from inhomogeneity in mater density in the early Universe.
- Inhomogeneity in mater density in early Universe give rise to observed large scale structure in the galaxy distribution.





Black body spectrum



COBE Satellite

John Mather

George Smoot

Nobel Prize 2006

List CMB experiments in last 25 years (after COBE satellite mission)

Ground-based :

- **ACBAR, ACME, ACT, AMI, AMiBA, APACHE, ATCA, BEAST, BICEP, BIMA, CAPMAP, CAT, CBI, CG, COSMOMAS, DASI, KUPID, MAT, POLAR, Python, QUaD, SK, SPT, Tenerife, VSA.**

Balloon-born :

- **Archeops, ARGO, BAM, BEAST, BOOMERANG, FIRS, MAXIMA, MSAM, PIQUE, QMAP, TopHat.**

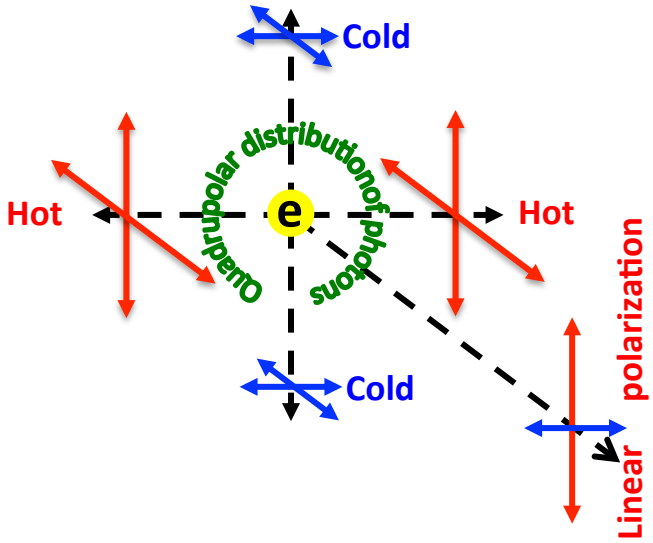
Satellite :

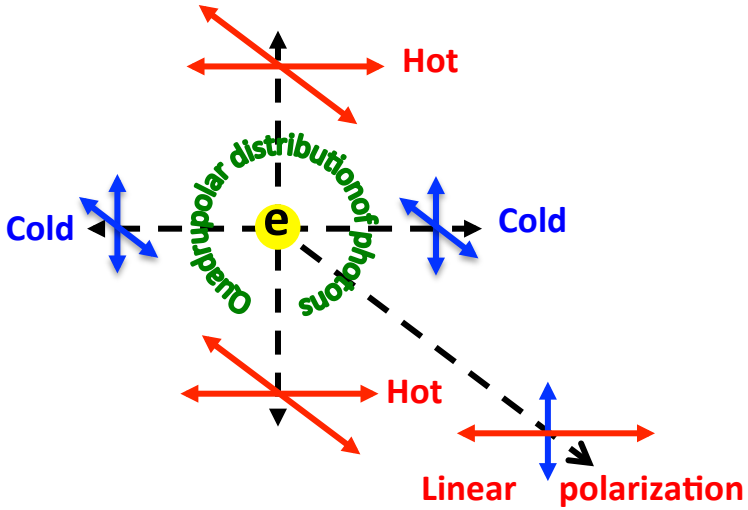
- **WMAP, Planck.**

- ✓ **Observed the sky in various angular scales and frequencies.**
- ✓ **Measurements of CMB agrees extremely well the predictions of cosmology.**

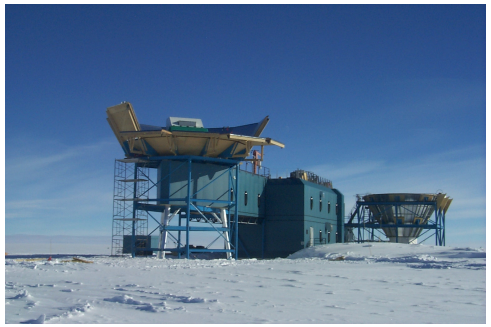
Basic facts about CMB (Linear Polarization)

CMB is linearly polarized due to Thomson scattering of quadrupolar distribution of unpolarized photons with free electrons at the time of recombination and reionization.



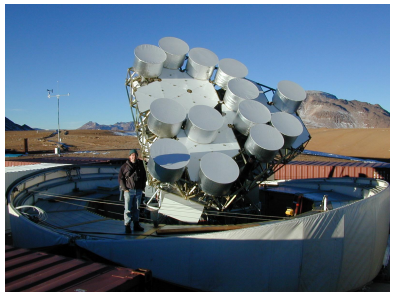


CMB Polarization is first detected by Degree Angular Scale Interferometer (DASI) experiment at South-pole in 2002 and is confirmed by subsequent experiments.

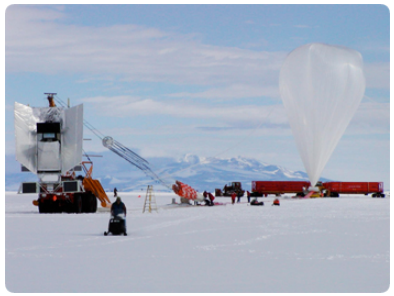


DASI (2002)

WMAP (2003)



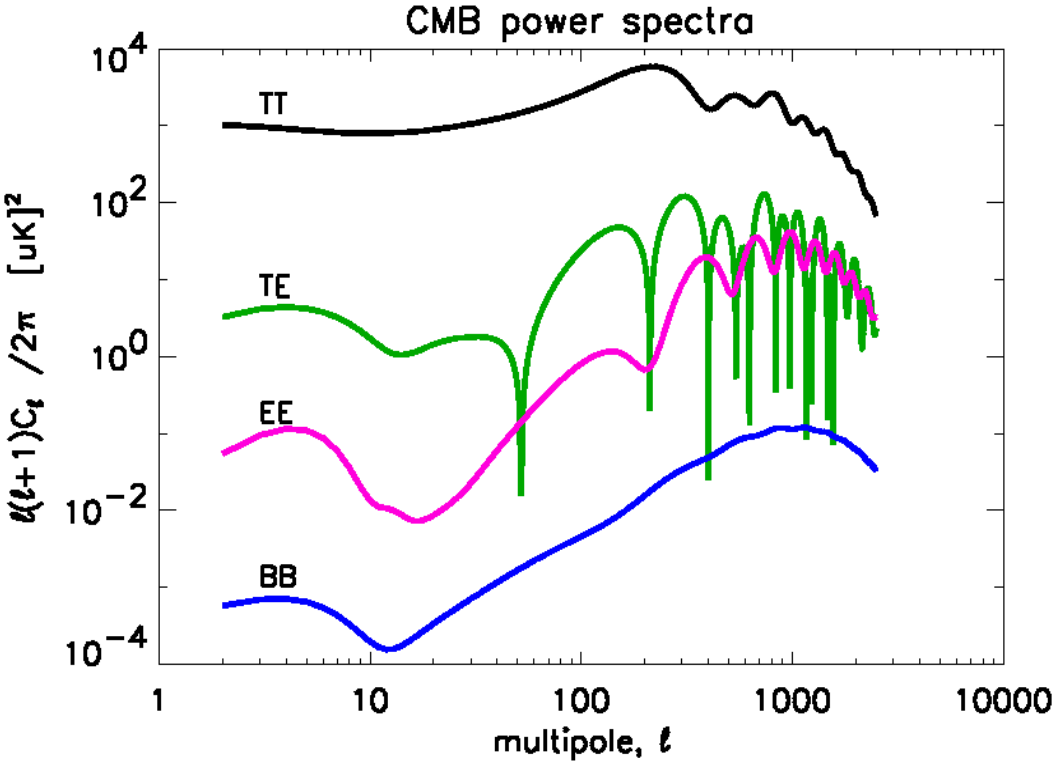
CBI (2004)



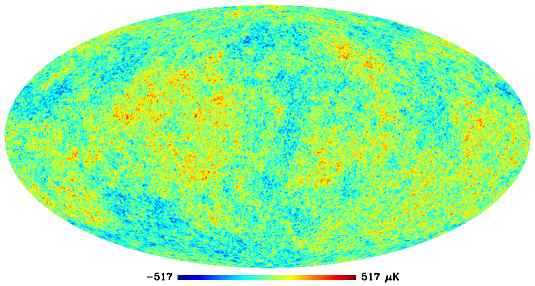
BOMERANG (2005)

Motivation of our work

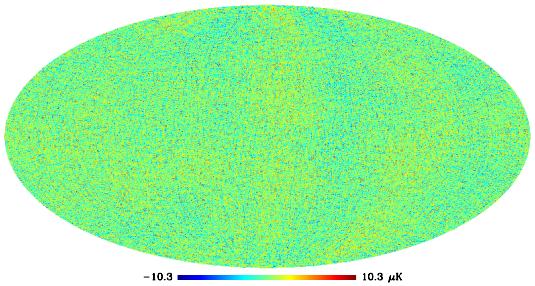
- Accurate measurement of CMB angular power spectra as they are very sensitive to initial conditions, geometry, matter contents, expansion rate etc. …….



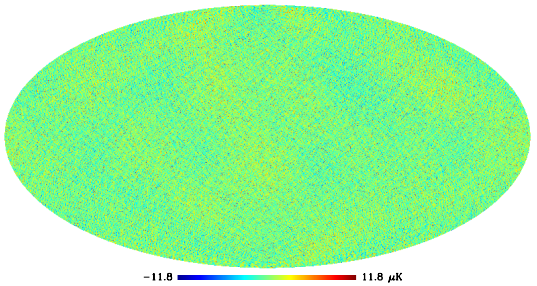
- Accurate estimation of CMB temperature anisotropy and polarization



CMB-T



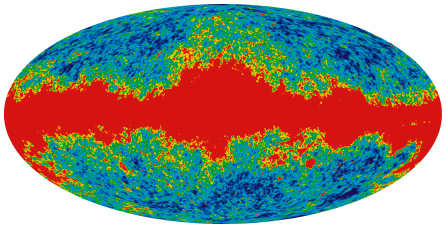
CMB-Q



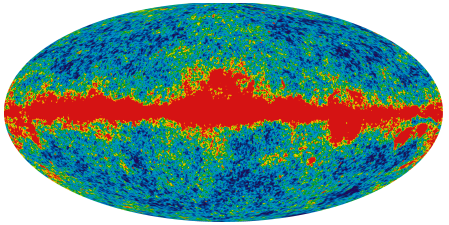
CMB-U

Multi-frequency observations from WMAP

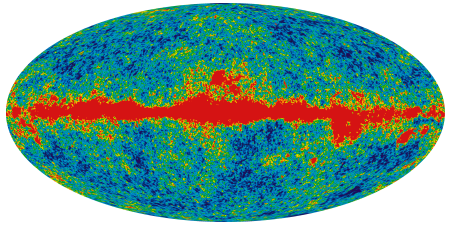
K band (23 GHz)



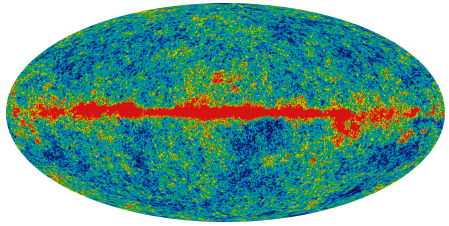
Ka band (33 GHz)



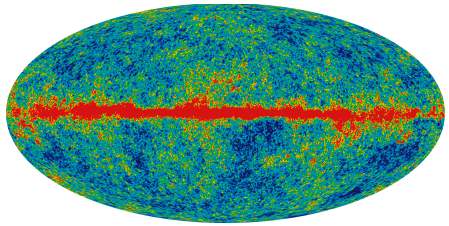
Q band (41 GHz)



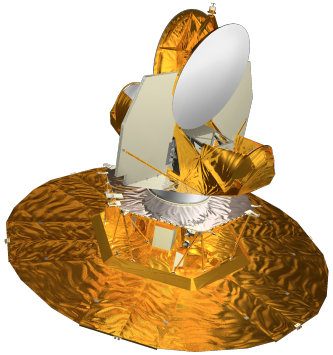
V band (61 GHz)



W band (94 GHz)



Wilkinson Microwave Anisotropy Probe (WMAP)



WMAP Satellite

Delta II space shuttle

Launch date : June 30, 2001

Duration of Observation : 9 Years

Pixelization : HEALPix (Nside = 512)

Number of Pixels : $12 \times (\text{Nside})^2 = 3145728$

Data : 10 sky (difference assembly) maps per year

K1 Ka1 Q1 Q2 V1 V2 W1 W2 W3 W4

Multi-frequency observations from WMAP

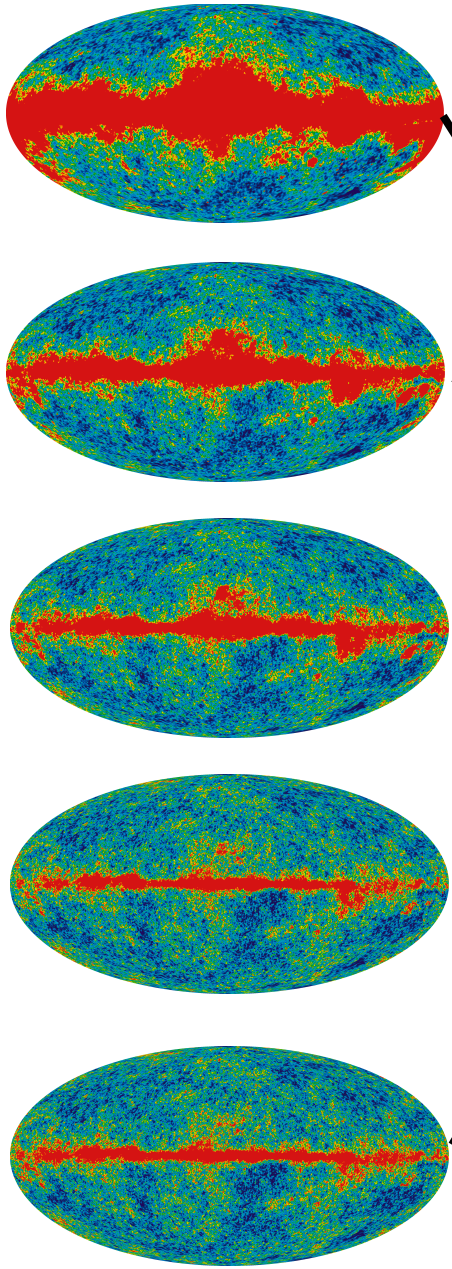
K band (23 GHz)

Ka band (33 GHz)

Q band (41 GHz)

V band (61 GHz)

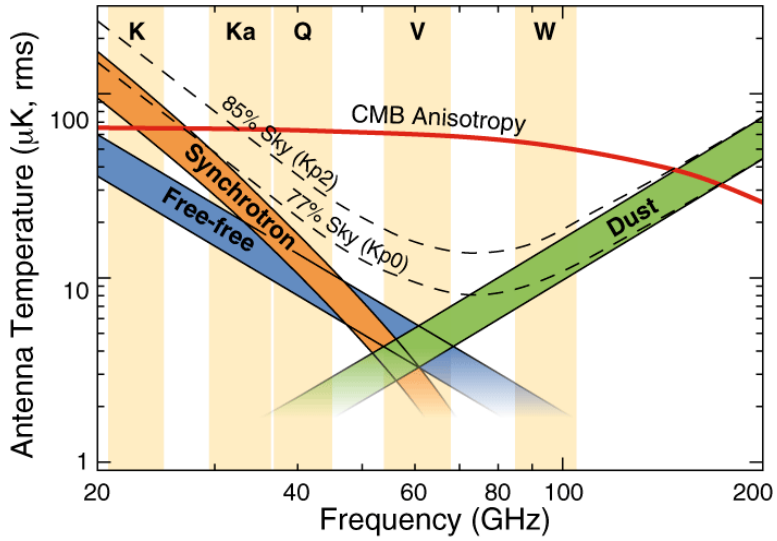
W band (94 GHz)



Objective of our work :

- **Estimation of CMB from multi-frequency observations by removing of contaminants (Foreground emissions and Instrumental Noise) is the primary objective of our work.**

Sky = CMB + Foreground + Noise



Internal linear combination (ILC) in spherical wavelet domain

ILC in pixel domain

- ILC weight can be varied in pixel domain

ILC in spherical harmonic domain

- ILC weight can be varied in harmonic domain

Tegmark, de Oliveira-Costa, & Hamilton 2003; Eriksen et al. 2004; Saha, Jain & Souradeep 2006; Souradeep, Saha & Jain 2006; Saha, Prunet, Jain & Souradeep 2008; Samal et al. 2010; Saha 2011; Souradeep 2011.

Foreground dominates at low Galactic latitudes while noise dominates on high Galactic latitudes

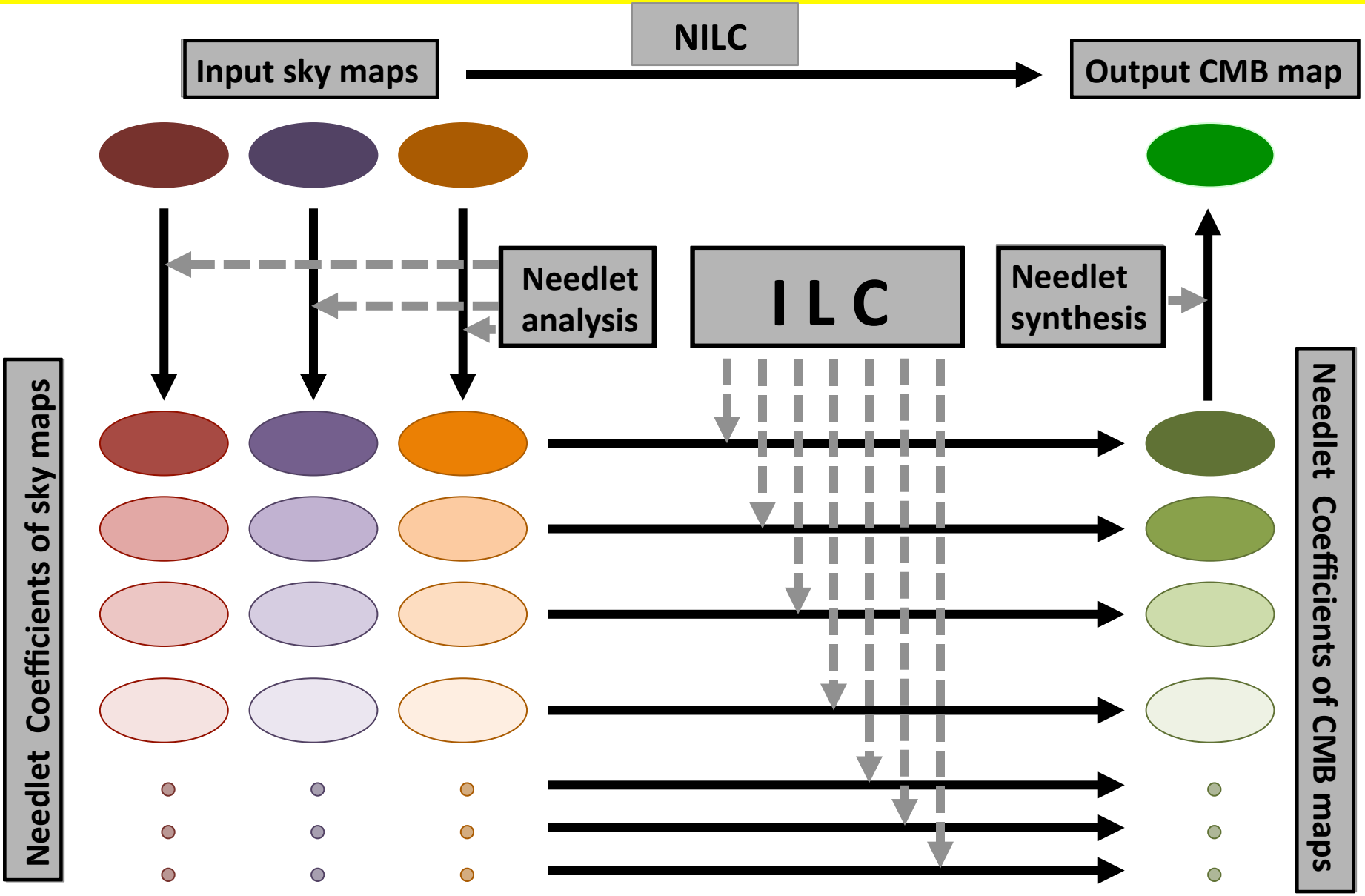
Foreground dominates at large angular scales while noise dominates on small angular scales

ILC in wavelet domain

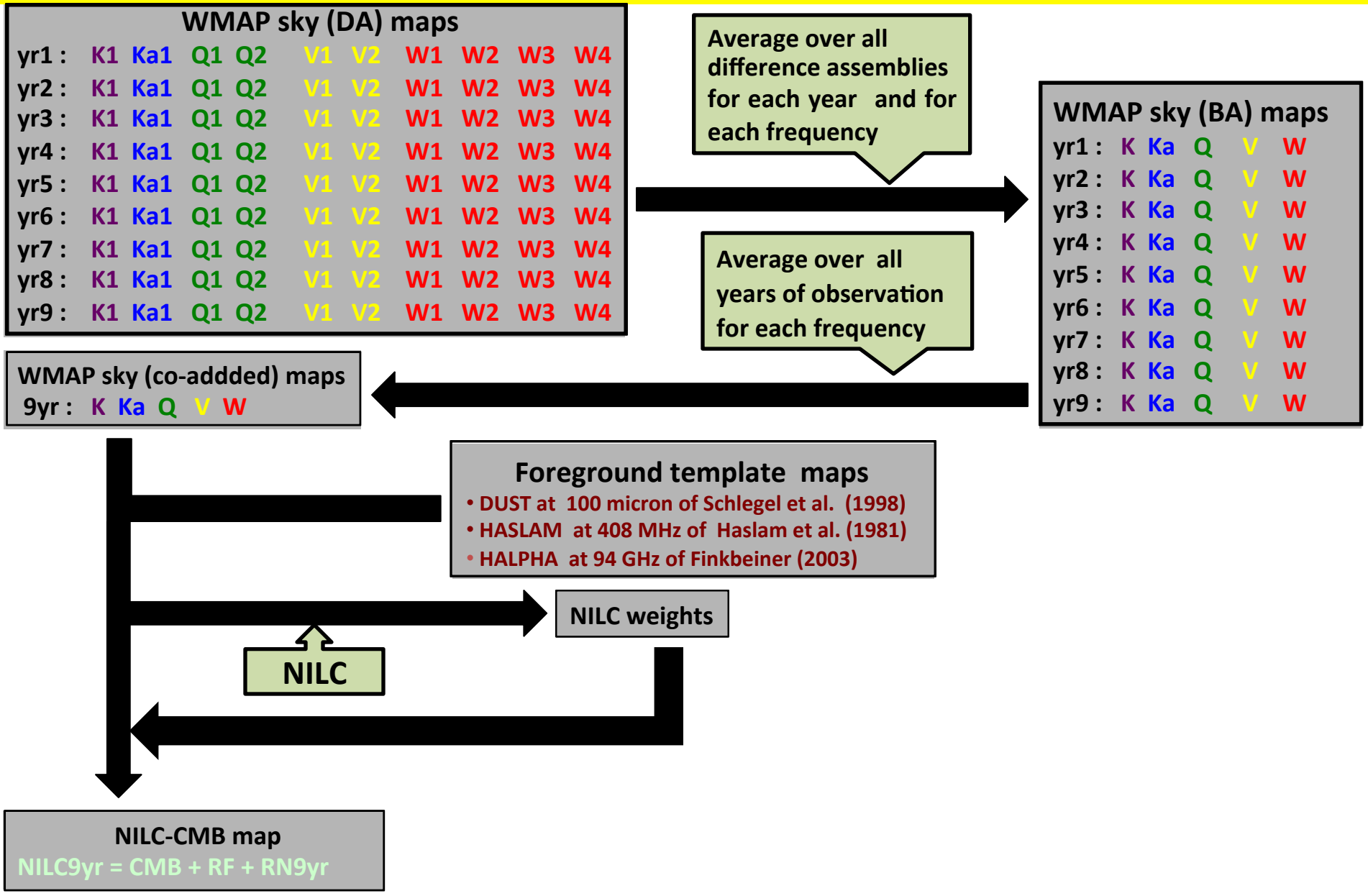
- ILC weight can be varied in pixel and harmonic domain simultaneously

Delabrouille et al. 2008, Basak & Delabrouille 2011, Basak & Delabrouille 2013

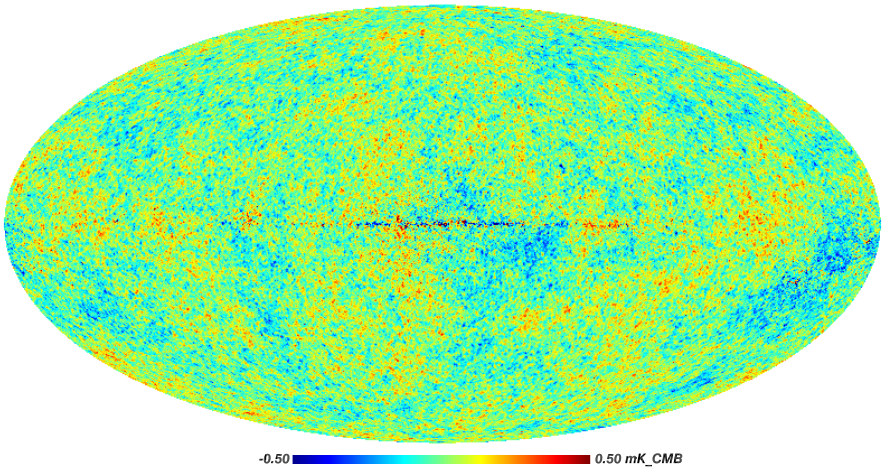
Needlet Internal linear combination (NILC)



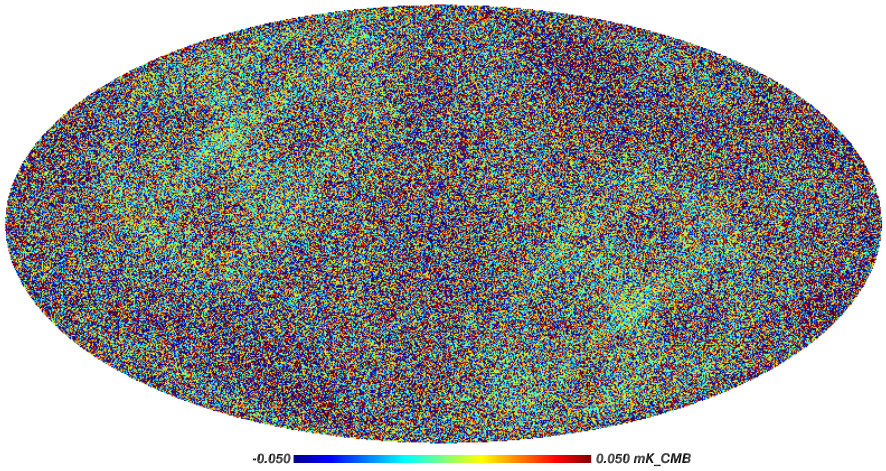
Implementation of NILC on WMAP 9-year data :



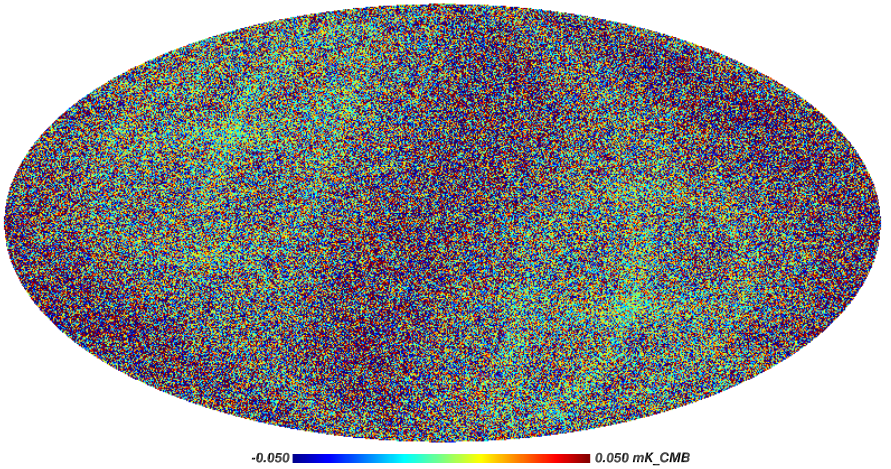
NILC estimate of CMB (FWHM : 13.2 arcmin NSIDE : 512)



NILC-T-CMB



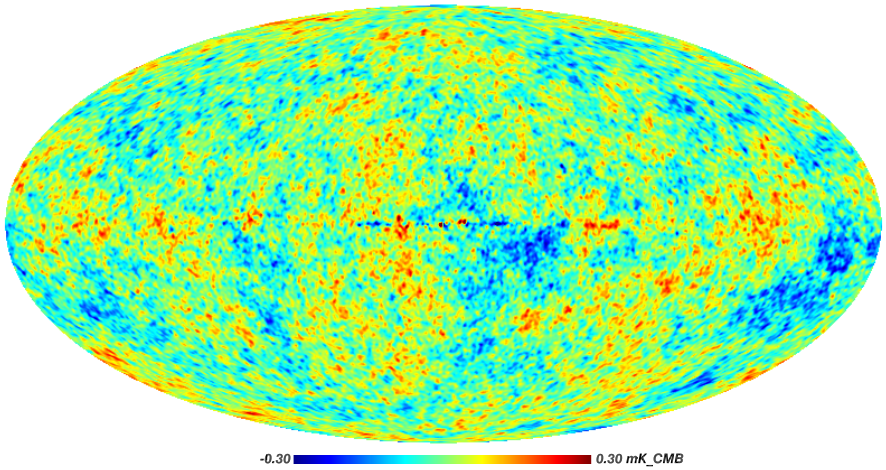
NILC-Q-CMB



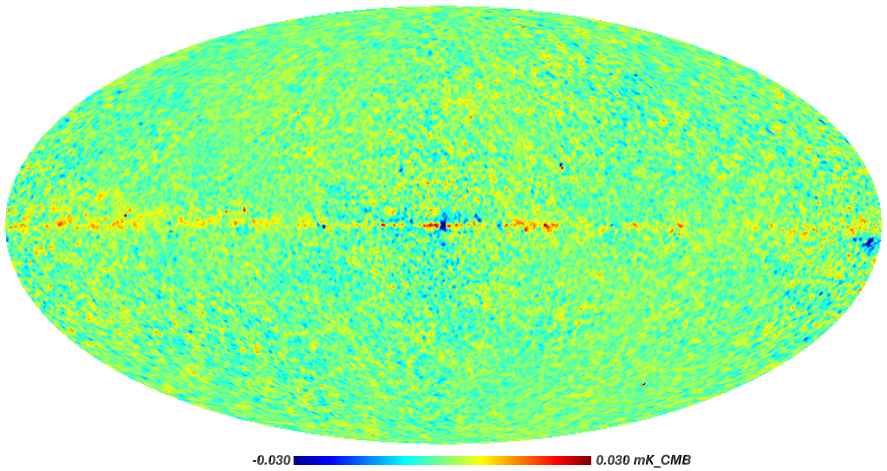
NILC-U-CMB

arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

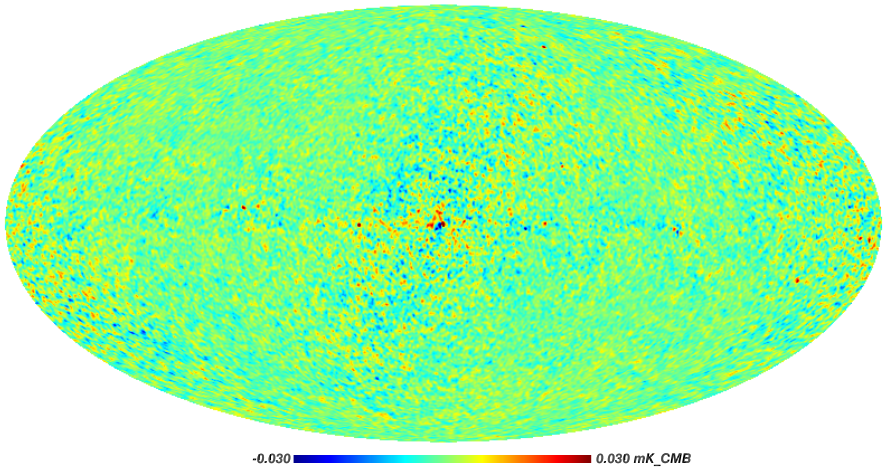
NILC estimate CMB (FWHM : 60 arcmin)



NILC-T-CMB



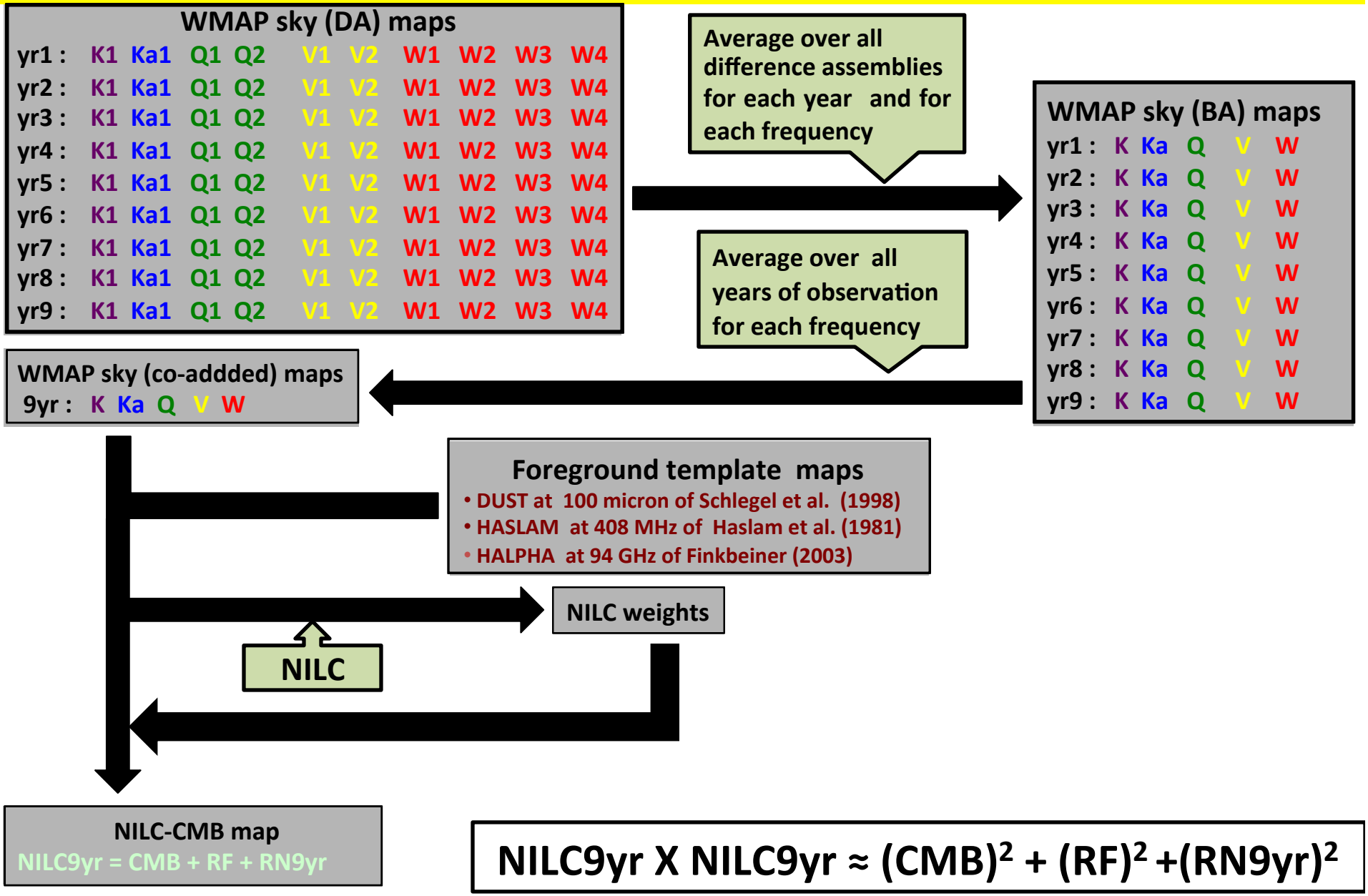
NILC-Q-CMB



NILC-U-CMB

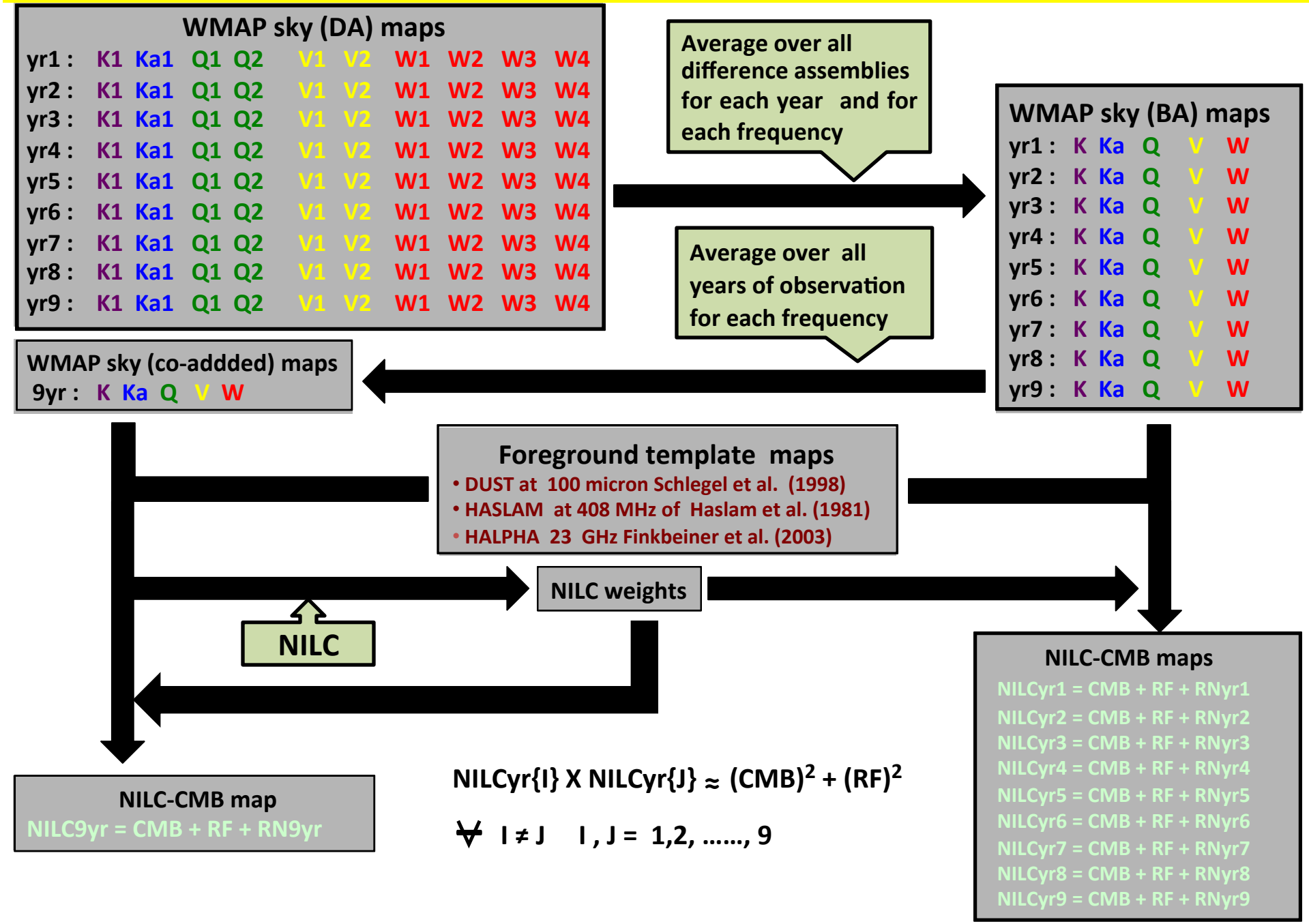
arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

Implementation of NILC on WMAP 9-year data :



$$\text{NILC9yr X NILC9yr} \approx (\text{CMB})^2 + (\text{RF})^2 + (\text{RN9yr})^2$$

Implementation of NILC on WMAP 9-year data :

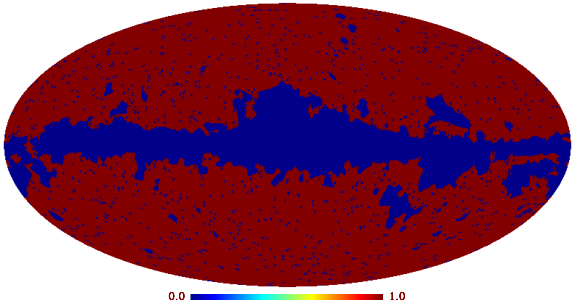


NILC estimate angular power spectrum (C^{XY}) of CMB

NILC-CMB maps

NILCyr1 = CMB + RF + RNyr1
NILCyr2 = CMB + RF + RNyr2
NILCyr3 = CMB + RF + RNyr3
NILCyr4 = CMB + RF + RNyr4
NILCyr5 = CMB + RF + RNyr5
NILCyr6 = CMB + RF + RNyr6
NILCyr7 = CMB + RF + RNyr7
NILCyr8 = CMB + RF + RNyr8
NILCyr9 = CMB + RF + RNyr9

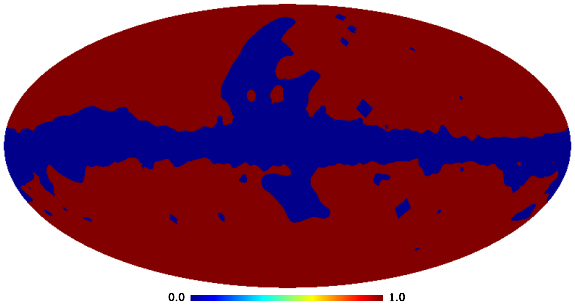
Residual Foreground = Residual Galactic Foreground + Residual Point Sources



Temperature mask

Master analysis to correct for the mask.

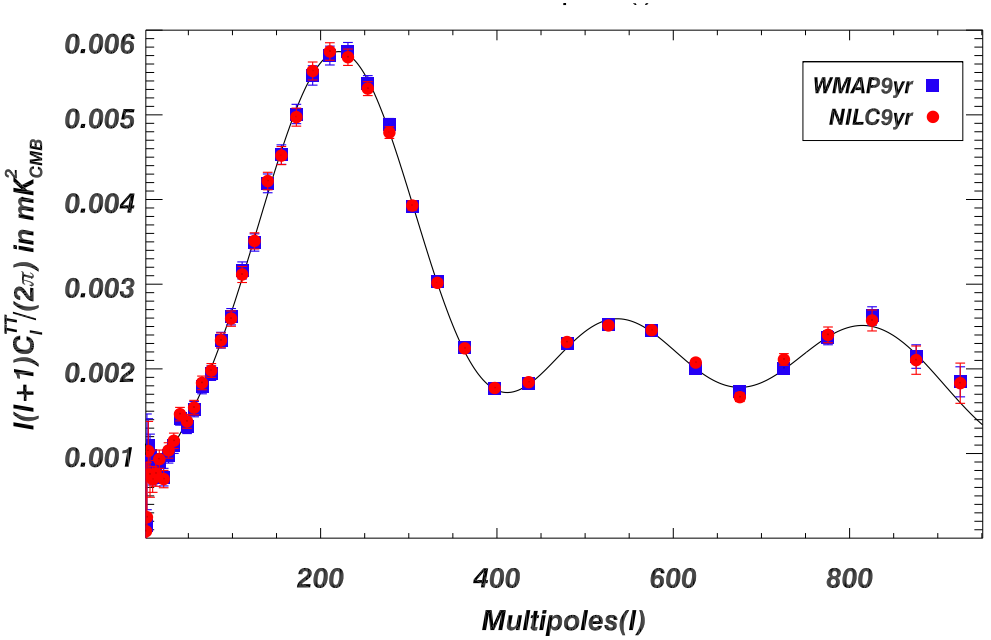
Hivon et al. 2002



Polarization mask

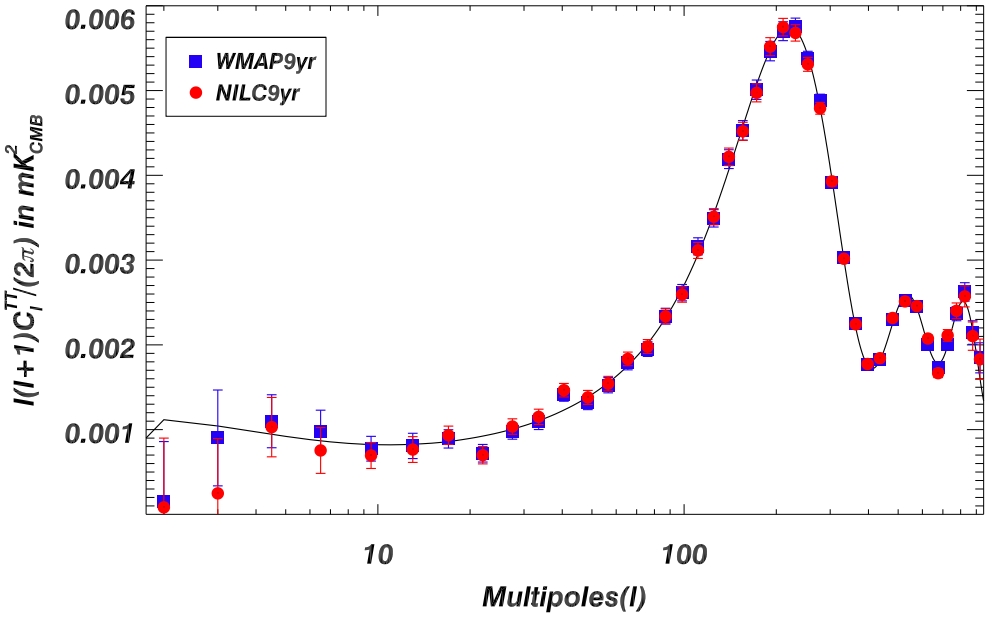
$$\text{Power spectrum} = \left(\sum_{I \neq J} \text{NILCyr}\{I\} \times \text{NILCyr}\{J\}\right) \Big/ \left(\text{All possible cross-year correlations}\right)$$

NILC estimate angular power spectrum (TT) of CMB

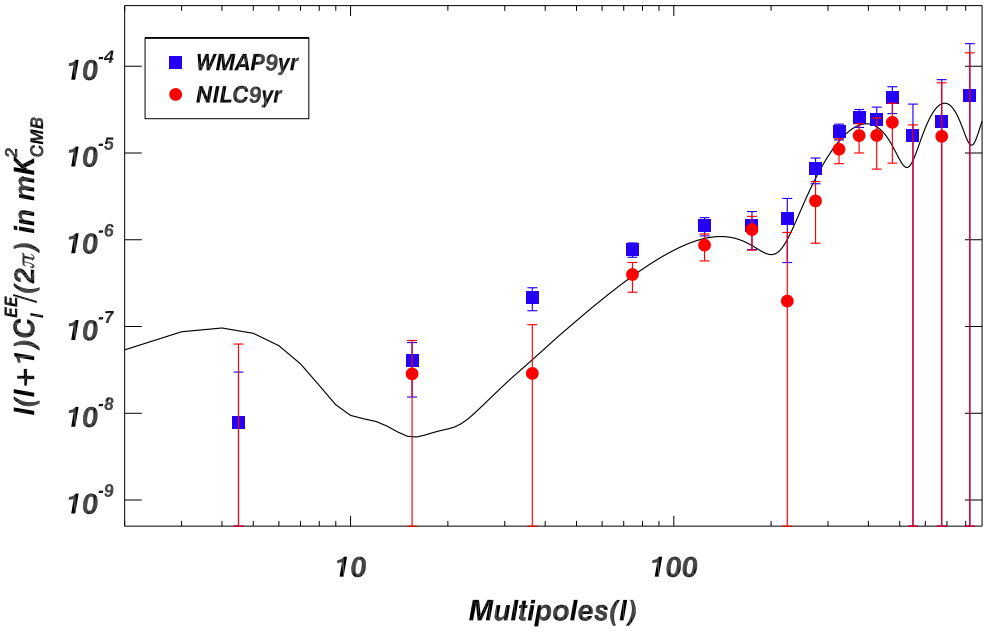


arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

- **Excellent agreement with WMAP 9-year best-fit theory spectrum.**
- **Excellent agreement with WMAP 9-year spectrum**

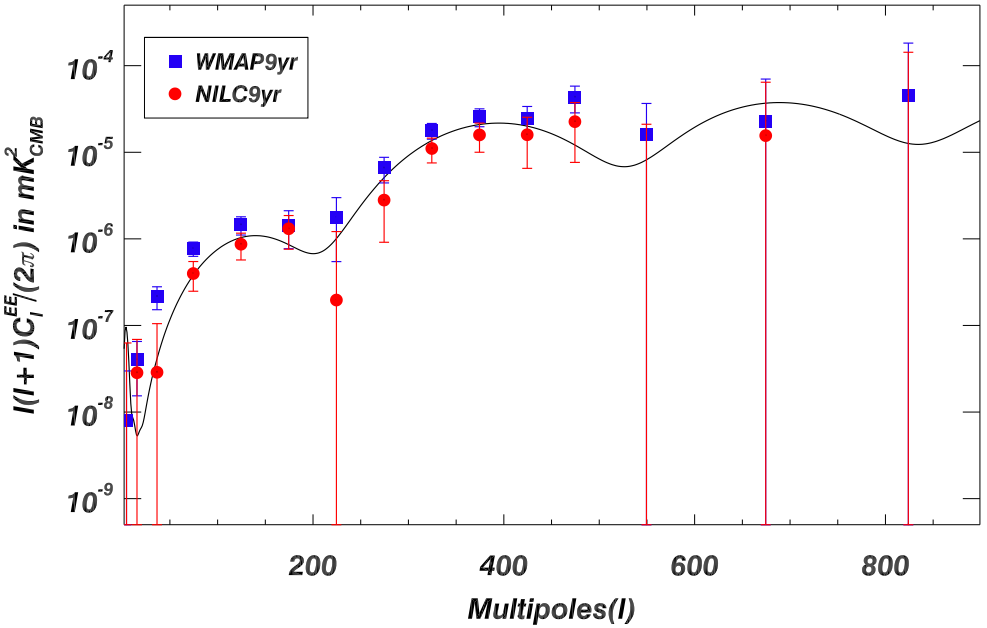


NILC estimate angular power spectrum (EE) of CMB

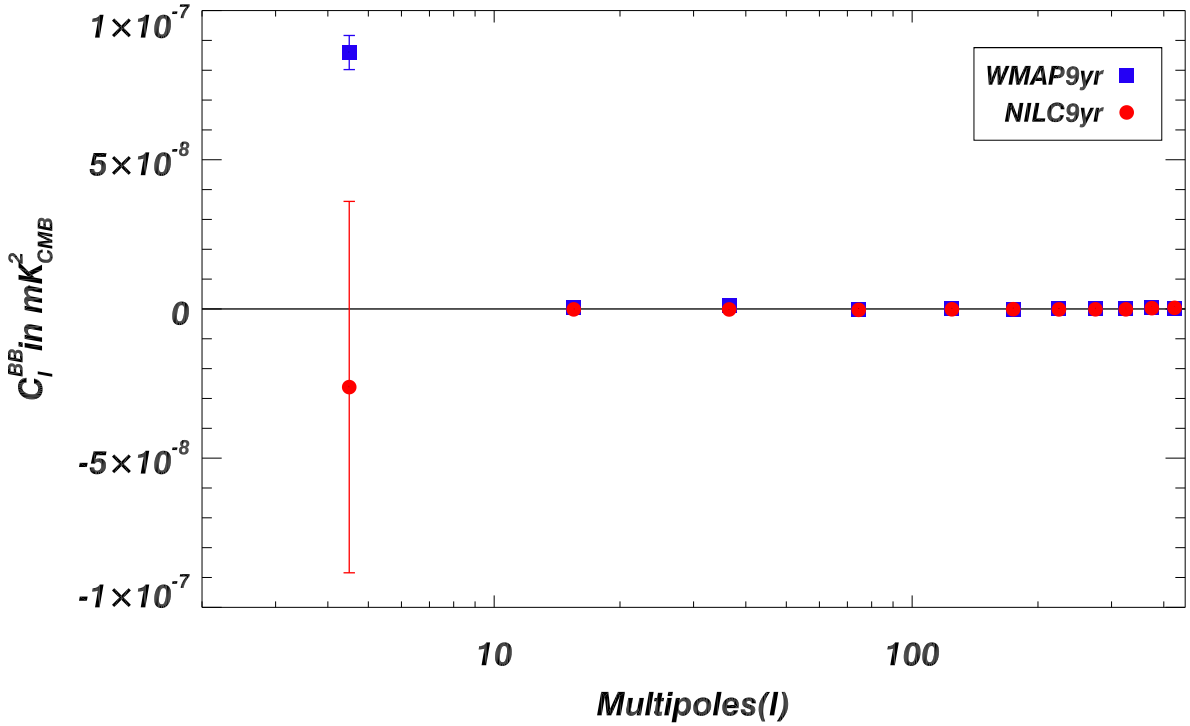


arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

- Excellent agreement with WMAP 9-year best-fit theory spectrum.
- Systematically lower than WMAP 9-year spectrum



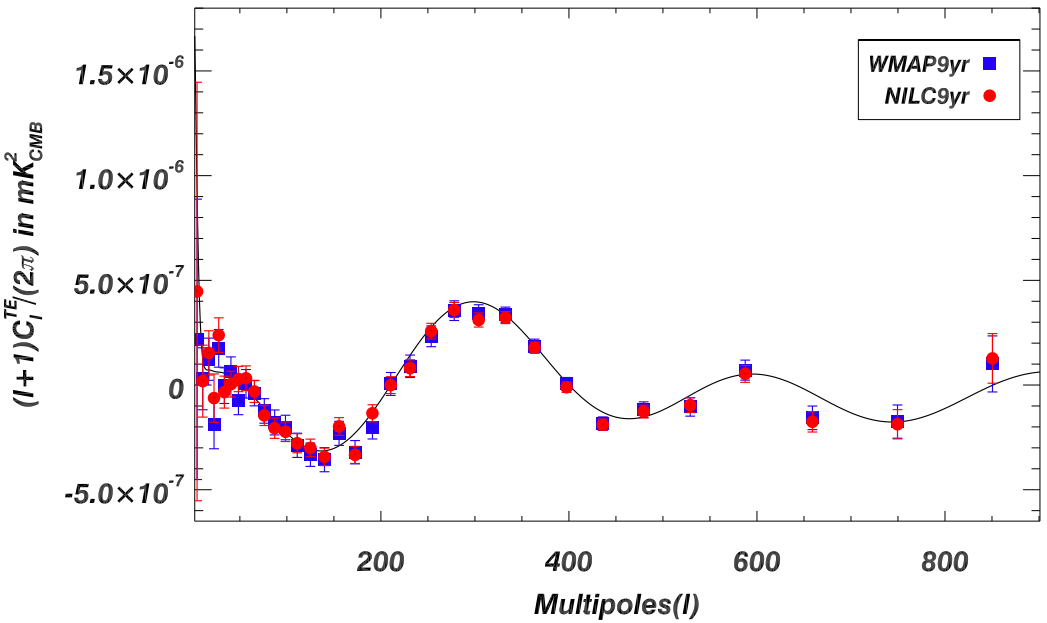
NILC estimate angular power spectrum (BB) of CMB



- No detection of B-mode of CMB polarization.
- WMAP 9-year measurement shows extra power at large angular scales.

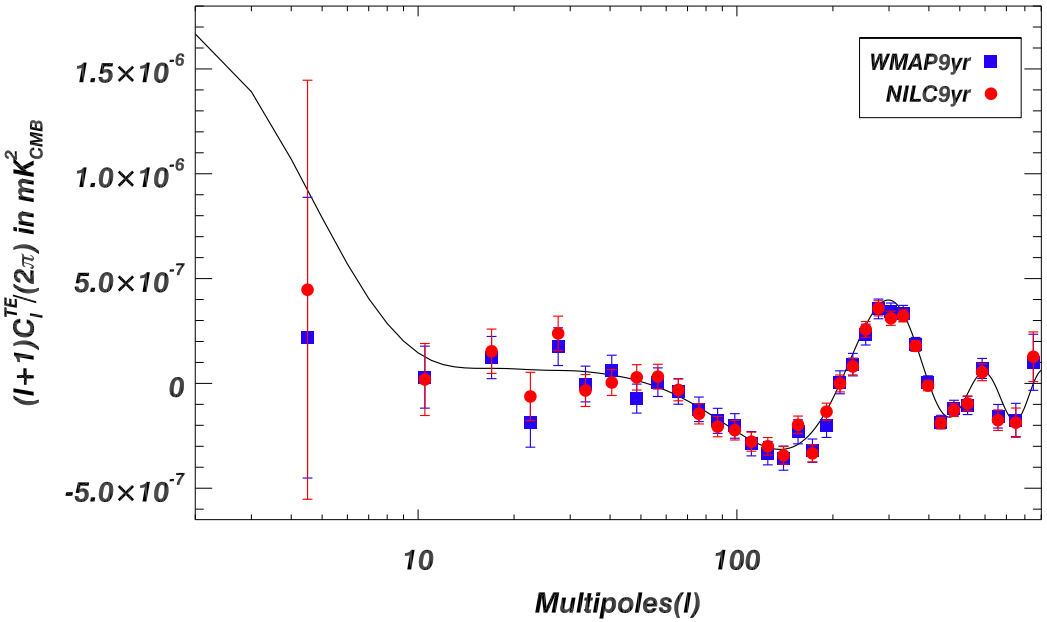
arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

NILC estimate angular power spectrum (TE) of CMB

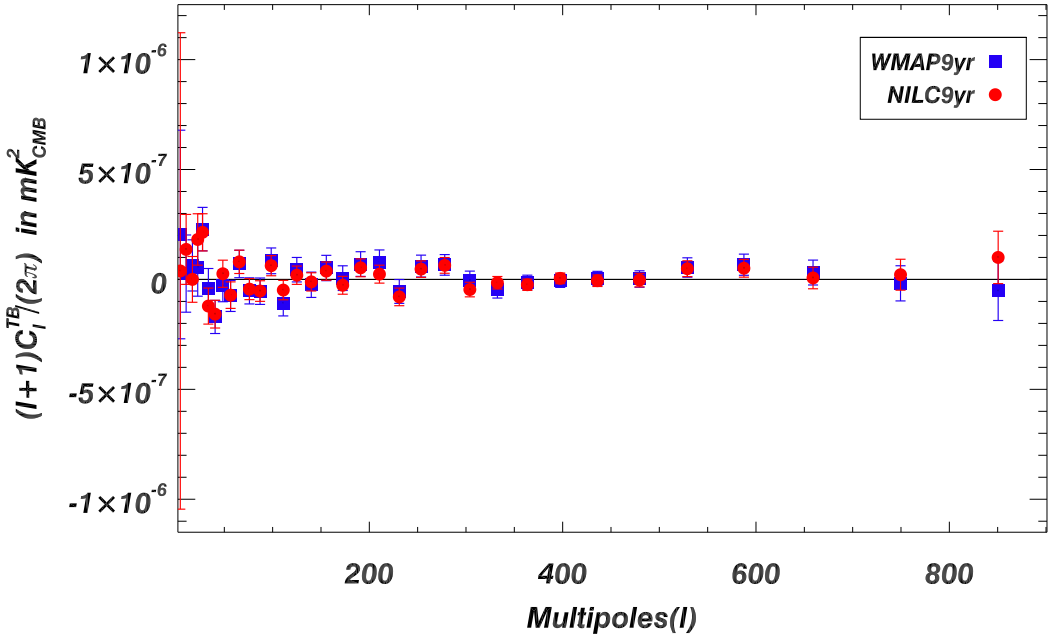


arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

- **Excellent agreement with WMAP 9-year best-fit theory spectrum.**
- **Excellent agreement with WMAP 9-year spectrum**

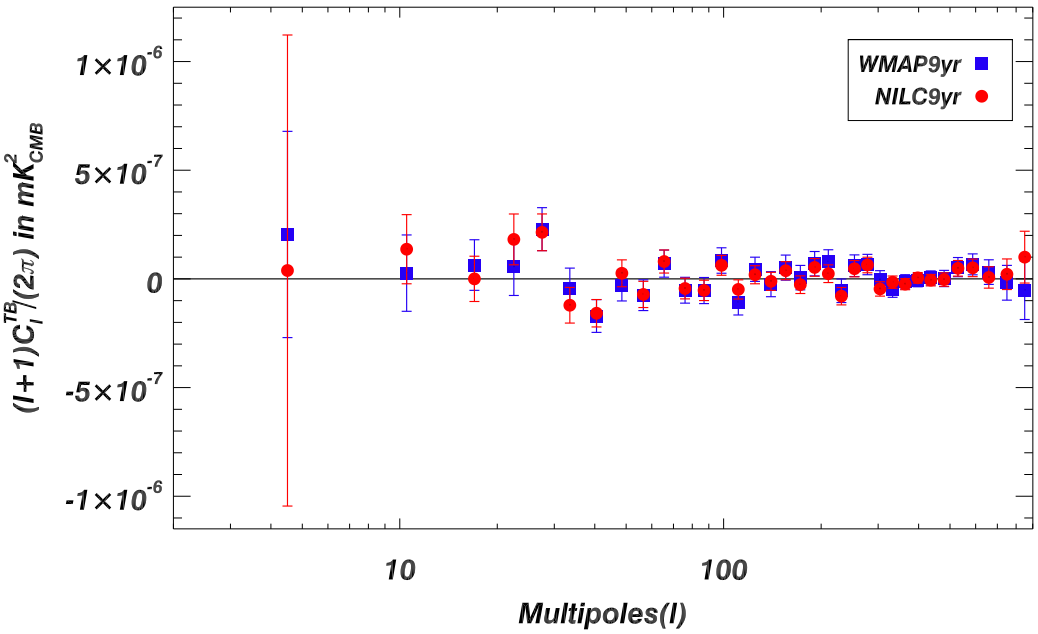


NILC estimate angular power spectrum (TB) of CMB

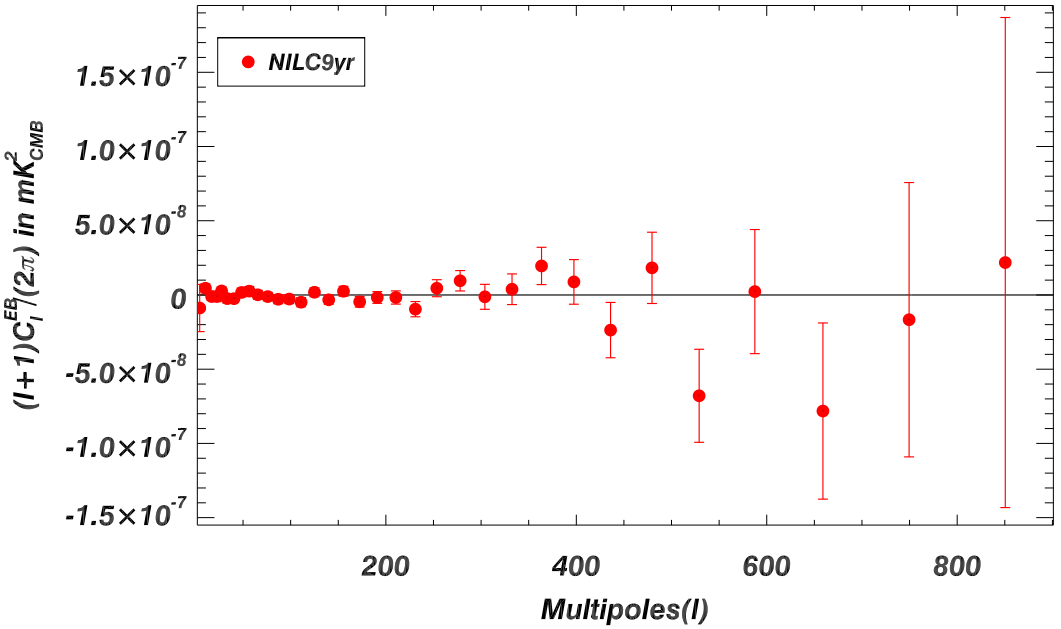


arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

- **Compatible with zero as predicted by theory**

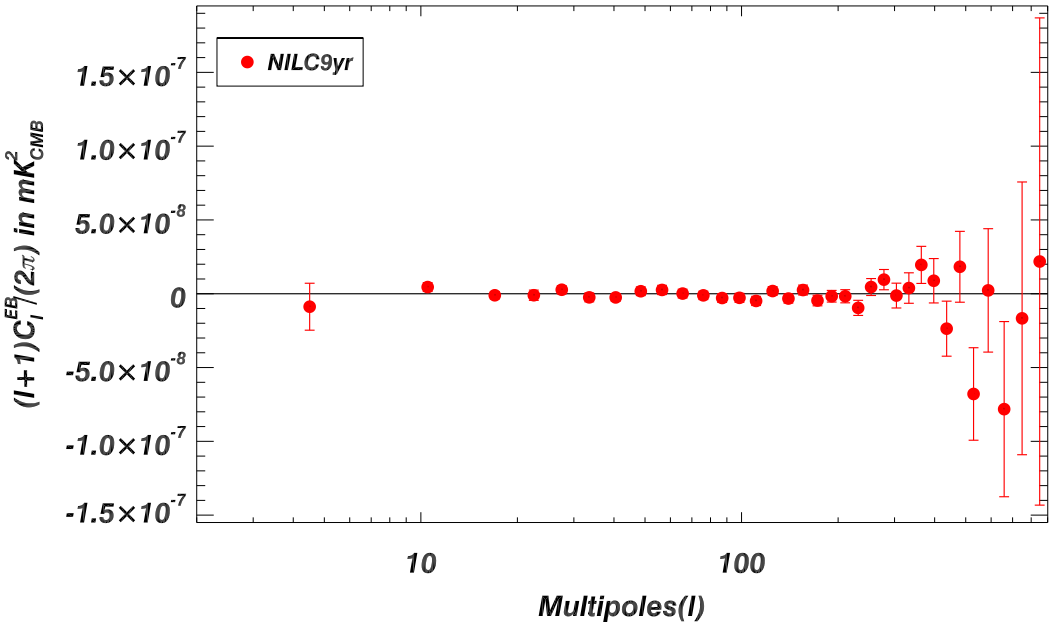


NILC estimate angular power spectrum (EB) of CMB



arXiv ref. : arXiv: 1204.0292
Journal ref. : to appear in MNRAS

- **Compatible with zero as predicted by theory**



SUMMARY

Context :

- Cosmic microwave background (CMB) anisotropies provide a snapshot of what the Universe looked like at the moment of recombination.
- Precisely measured CMB angular power spectra is considered as goldmine for understanding and describing our Universe .

Aim :

- Estimation CMB map and angular power spectrum from WMAP 9-year data by removing foreground emissions and instrumental noise.

Method :

- We have used Internal Linear Combination of WMAP sky maps on a frame of spherical wavelets (Needlets) to estimate the CMB.
- Needlets allow localized filtering both in pixel and harmonic domain due to their unique localization property.

Results :

- We have obtained low-foreground CMB map and angular power spectrum.
- Our measurement of angular power spectrum agrees remarkably well with the theoretical predictions.
- In case of EE and BB spectrum, our measurement agrees better with theory than the measurements of WMAP collaborations.

THANK YOU