A full sky, low foreground, high resolution CMB map from WMAP

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Outline

- Motivations
- Our method
- CMB Results
- Comments
- Conclusion

Why do we need a clean CMB map ?

- For power spectrum estimation ?
  - Not really (see, e.g. the SMICA method)

Delabrouille et al. MNRAS, 346, 1089
Cardoso et al. astro-ph 0803.1814

  - Power spectrum can be estimated on cut sky (clean regions)
- As a clean CMB template
  - For calibration of upcoming experiments
  - For subtraction from observations (for other science)
- For non gaussianity studies...
- For correlation searches (ISW)...
- For topology, stationarity...
- To look for DMA haze (see Finkbeiner's and de Boer's talks)...

A CMB map wish-list

- Sky coverage : as complete as possible !
  - Pretty damn good separation needed in the galaxy !
  - Proper handling of contamination by strong point sources

- Map resolution : best possible
  - Currently WMAP W-channel for full sky maps
  - Next: data fusion? but issue of beam uniformity…

see *Faÿ et al. astro-ph 0807.1113*

- Minimum error variance
  - Minimise $(\underline{s} - s)^2$
  - Trade-off between resolution and integrated error

- Well characterised beam and noise

Why do we need *one more* clean CMB map ?

NAME	resolution	data used	Reference
WILC1	1°	1-yr	Bennett et al. (2003)
TILC1	W channel	1-yr	Tegmark et al. (2003)
EILC1	1°	1-yr	Eriksen et al. (2004)
WILC3	1°	3-yr	Hinshaw et al. (2007)
EGS3	3°	3-yr	Eriksen et al. (2007)
PILC3	1°	3-yr	Park et al. (2007)
TILC3	W channel	3-yr	
WILC5	1°	5-yr	Gold et al. (2008)
KILC	1°	5-yr	Kim et al. (2008)
TILC5	W channel	5-yr	

Bonaldi et al. (2007)
Maino et al. (2007)
Saha et al. (2007)

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obsolete (WILC1, TILC1)

obsolete (WILC3)

obsolete (TILC3)

EGS3: 3° resolution
not full sky
(model-dependent)

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1° resolution

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not full sky
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OK ?

1 ° resolution

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Internal Linear Combination

- Advantages
  - Very few (and safe) asumptions:
    - CMB emission law
    - Decorrelation between CMB and (foregrounds + noise)
  - Very easy to implement (multichannel linear filter)

$$W_{ilc} = \frac{a^t \hat{R}^{-1}}{a^t \hat{R}^{-1} a}$$

  - No model of foregrounds and noise needed

- Drawbacks
  - No model of foregrounds and noise used
  - Thus, errors not easily characterised
  - Biased (due to the use of empirical correlations in the filter)

Internal Linear Combination

Quick reminder...

- $y = as + n$ (or $y = s + n$ in CMB units)

m maps y_i

m maps of noise

one CMB map

- ILC: $\underline{s} = \Sigma\, w_i\, y_i$ with $\Sigma\, w_i\, a_i = 1$

  such that the variance of $\underline{s}$ is minimal

ILC and GLS

- Data : $y = as + n$

- ILC: $w = a^t \underline{R}_y^{-1} / [a^t \underline{R}_y^{-1} a]$

$$R_y = [R_n + aa^t \sigma_s^2]$$

$$\rightarrow \quad a^t R_y^{-1} \propto a^t R_n^{-1}$$

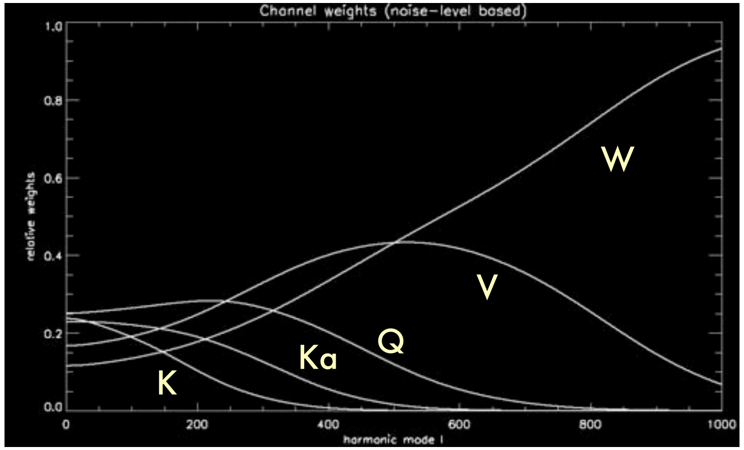
- GLS: $a^t R_n^{-1} / [a^t R_n^{-1} a] = a^t R_y^{-1} / [a^t R_y^{-1} a]$

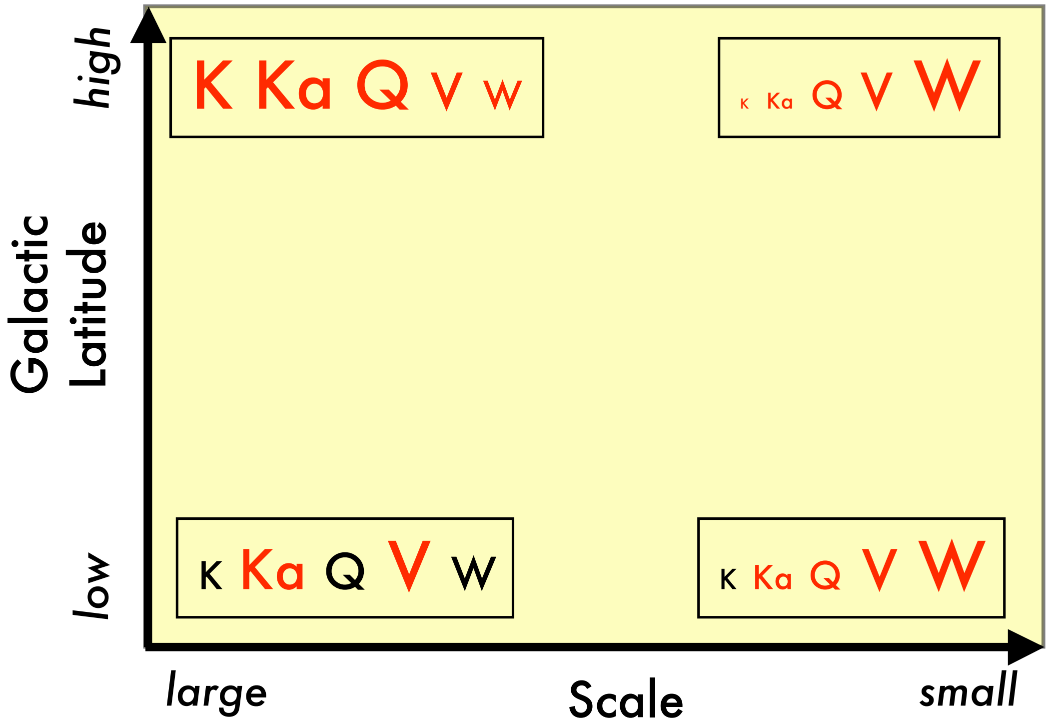
$$\underline{R}_y = \text{estimate of } R_y$$

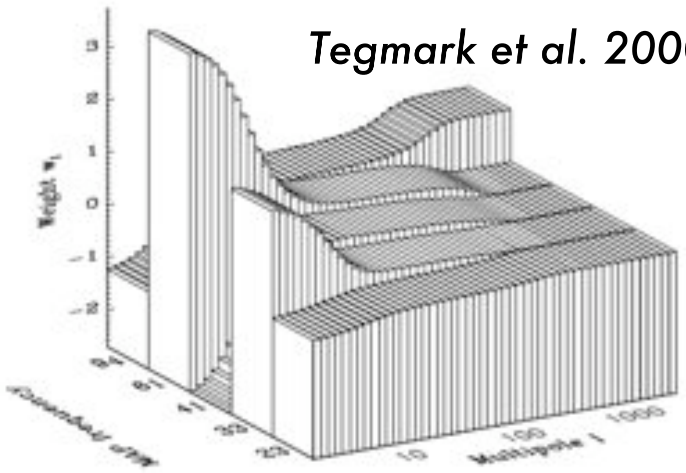
- <u>CONSEQUENCE</u>: The ILC is equivalent to an implementation of the "optimal" GLS using empirical estimates of correlation matrices !

How to "weigh" WMAP channels ?

If there were no foregrounds →







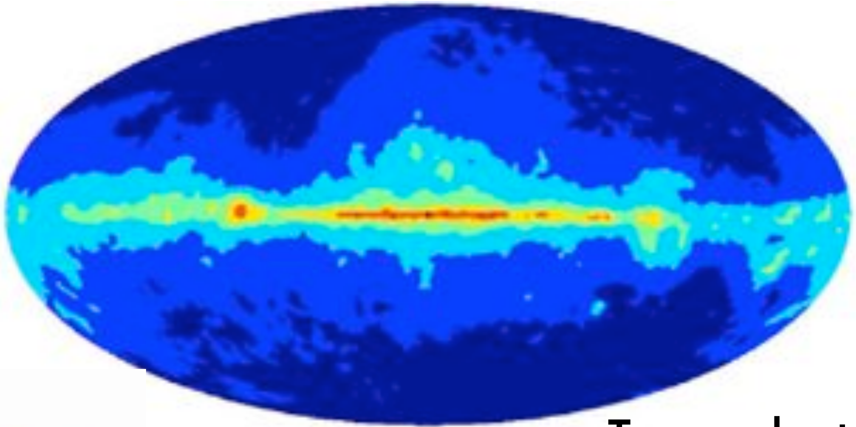
Tegmark et al. 2000

Conclusions of this

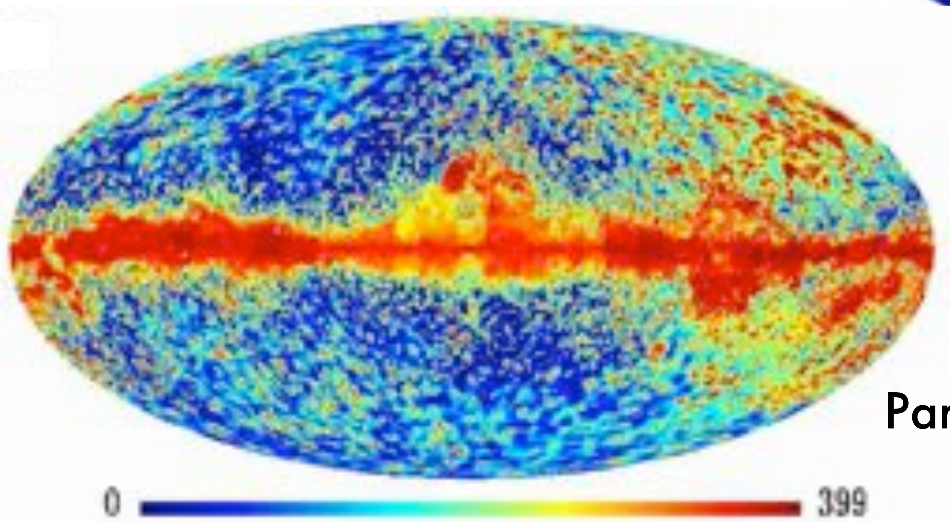
- Weights depend on scale
  - Foregrounds are strong on large scales
  - Noise (and Point Sources) dominate on small scales
  - WMAP channels have different resolutions
- Weights depend on sky position
  - Noise-weighted average where foregrounds are negligible
  - Subtract foregrounds where they dominate

Localisation ?

WMAP: 11 zones



Tegmark et al.:
9 zones



Park et al.: 400 zones

Conclusions of this

- Find a natural way to adapt to local conditions
  - Local in pixel space
  - Local in harmonic space

- There is sufficient motivation for yet another CMB map !

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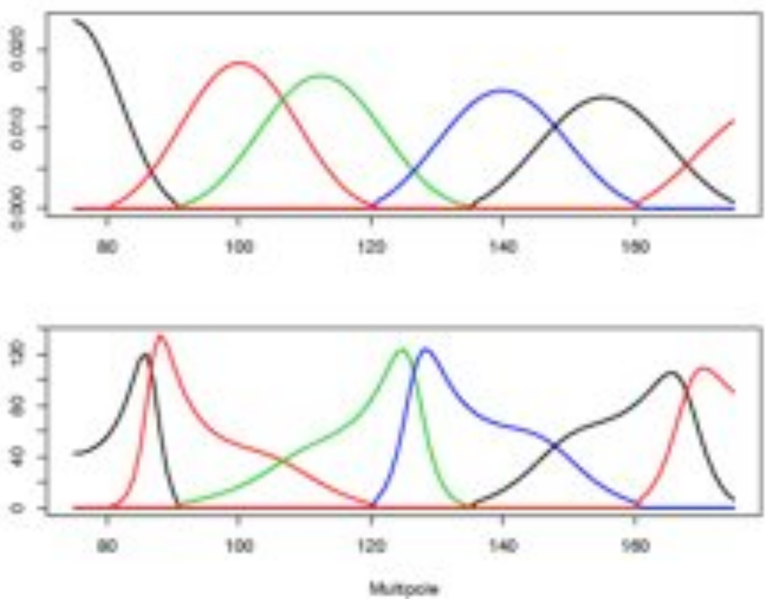
Spherical needlets

- Basic idea: decompose maps on a set of functions which are localised in space and in scale (*Guilloux et al. astro-ph/0706.2598*)



Analysis windows

Free choice

- of the bands;
- of the shapes.

Synthesis windows

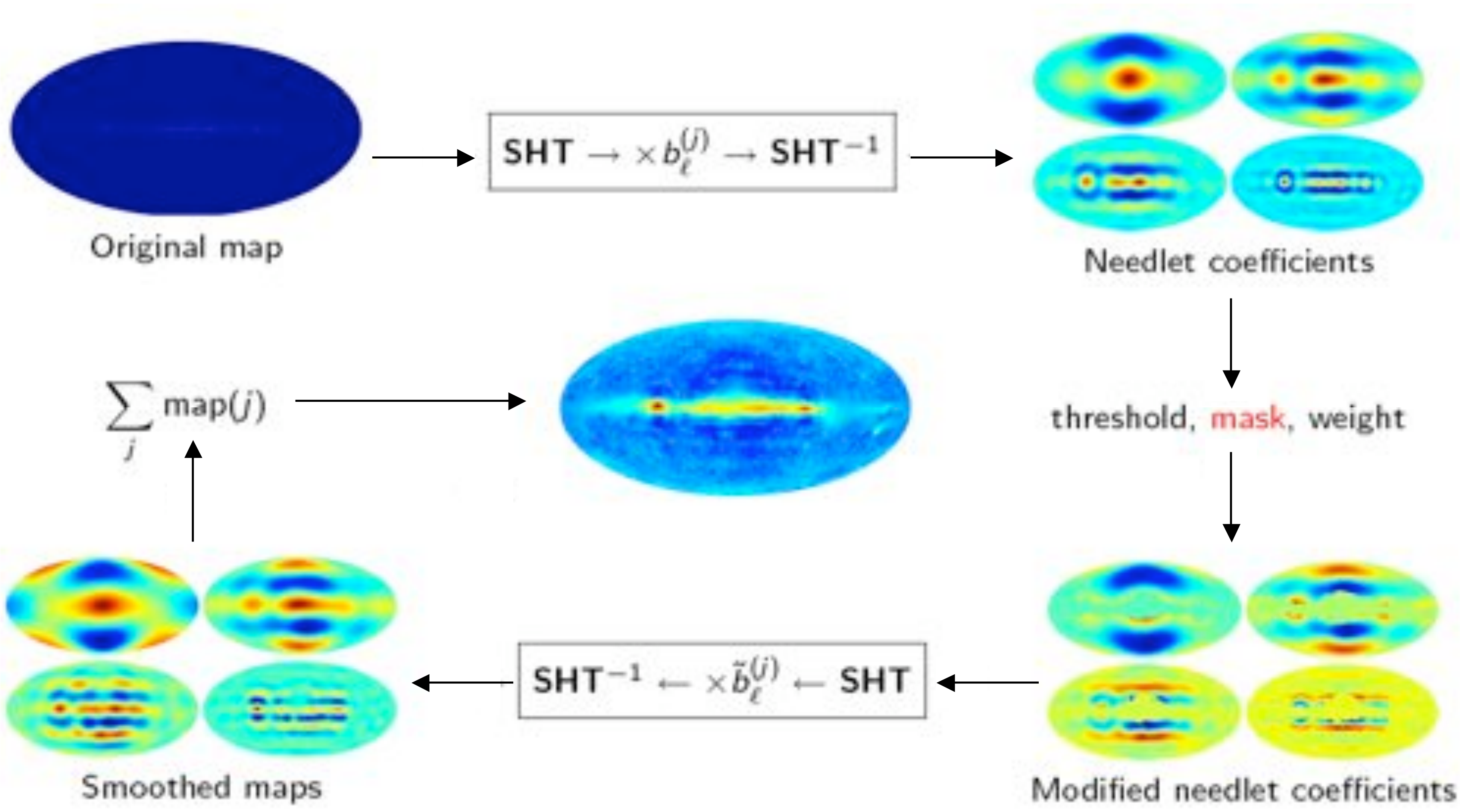
$$\tilde{b}_\ell^{(j)} = \frac{b_\ell^{(j)}}{\sum_{j' \in \mathcal{J}} \left(b_\ell^{(j')}\right)^2}$$

The needlets are axisymmetric functions defined by

$$\psi_k^{(j)}(\xi) = \sqrt{\lambda_k^{(j)}} \sum_{\ell=0}^{\ell_{\max}} h_\ell^{(j)} L_\ell(\xi \cdot \xi_k^{(j)}),$$

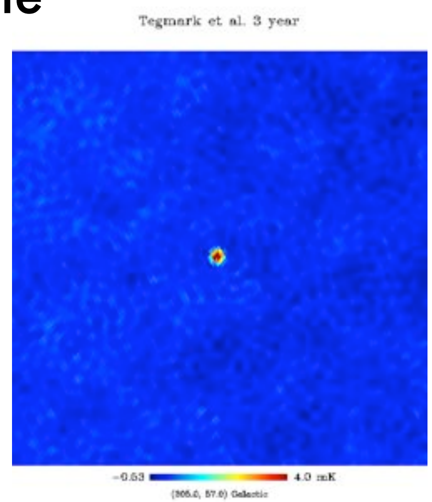
$$\forall \ell \in \mathbb{N}, \sum_j \tilde{b}_\ell^{(j)} b_\ell^{(j)} = 1$$

Using spherical needlets



Our work

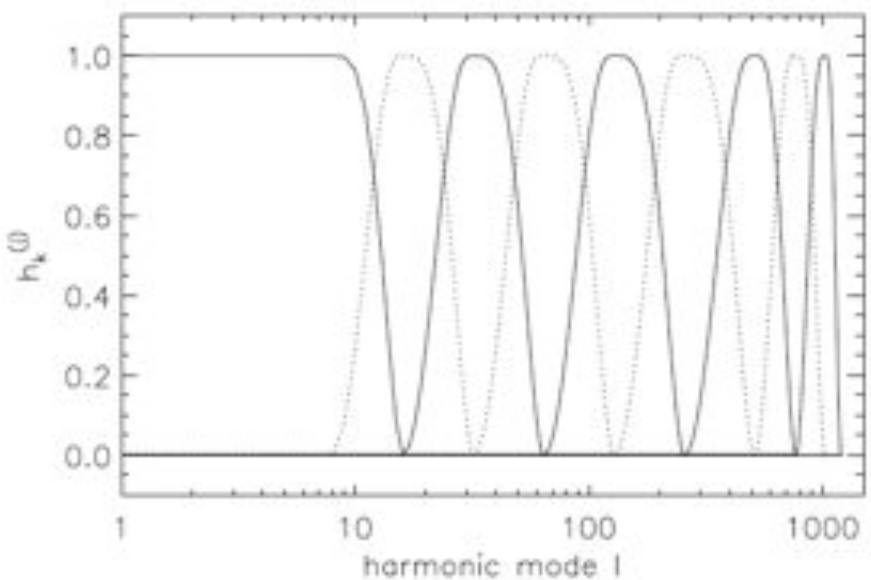
- A full resolution "ILC" using the decomposition of the observations on a needlet frame



- Refinements
  - Subtract strongest point sources
  - Mask 11 compact regions in the galaxy (0.058% of sky)
  - Use the IRIS 100 micron map as an additional observation
- A full characterisation of the outputs
  - Noise properties
  - Bias
  - Beams

Spectral bands for needlet decomposition

- Compute a_{lm}
- Multiply by spectral window
- Go back to pixel space
- Get needlet coefficient maps



Band (j)	ℓ_{min}	ℓ_{max}	nside(j)
1	0	15	8
2	9	31	16
3	17	63	32
4	33	127	64
5	65	255	128
6	129	511	256
7	257	767	512
8	513	1023	512
9	769	1199	512

Table 3. Spectral bands used for the needlet decomposition in this analysis. Needlet coefficient maps are made at different values of nside, given in the last column.

→ 9 maps per channel at different nside

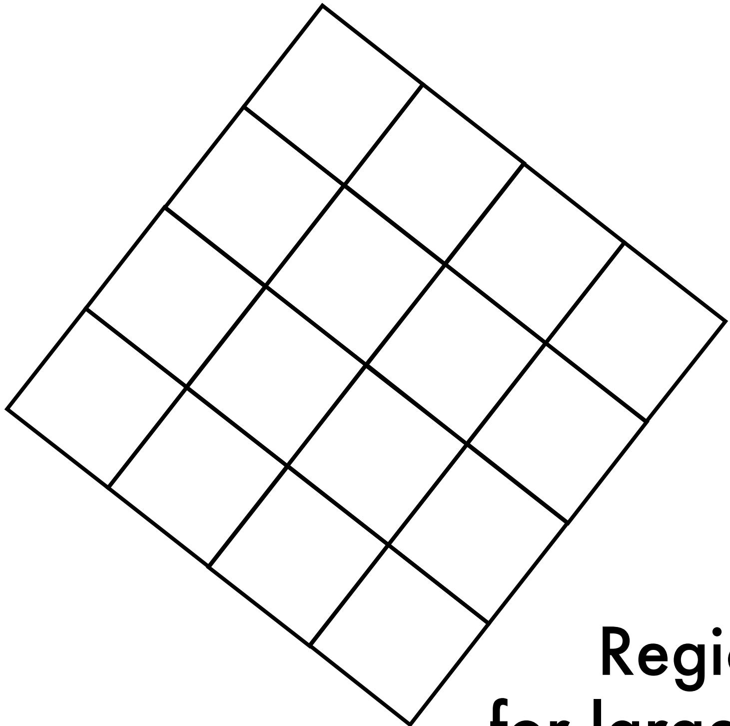
Our work (cont'd)

- Needlet coefficent maps are Healpix maps - at different nsides !
- We can use all the Healpix tools to compute map statistics locally...
- The easiest is to use the udgrade facility to compute correlations in larger healpix pixels (e.g. 32x32, 64x64)

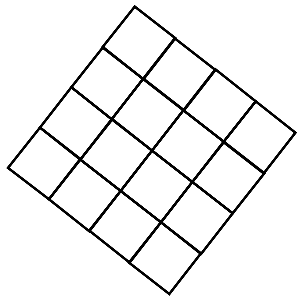
Local filtering

Using local needlet coefficient covariance matrices

$$W_{ilc} = \frac{a^t \hat{R}^{-1}}{a^t \hat{R}^{-1} a}$$



Region
for large scale



Region
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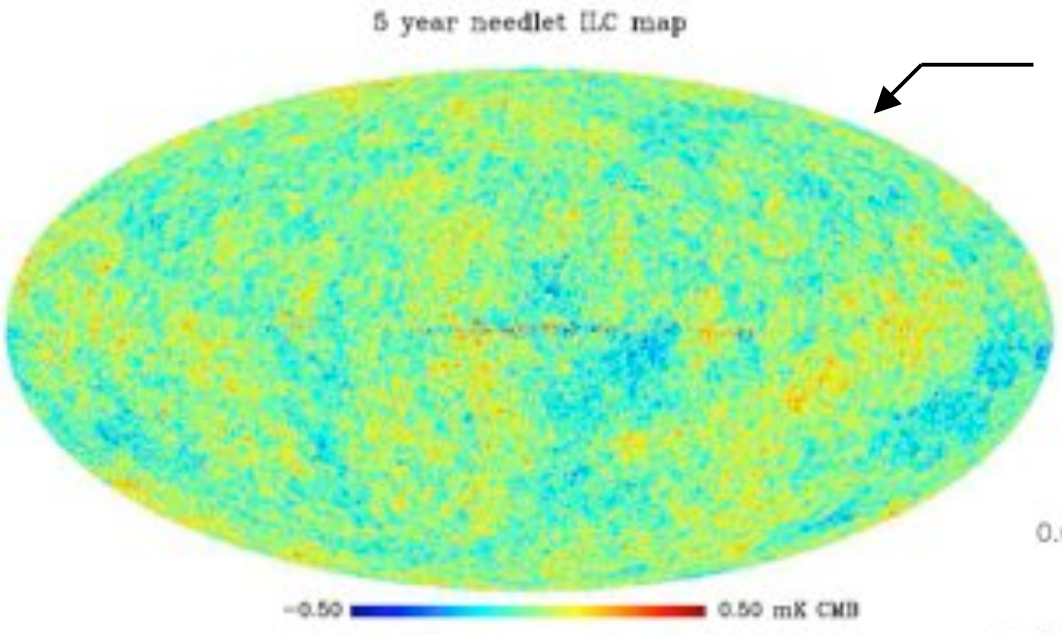
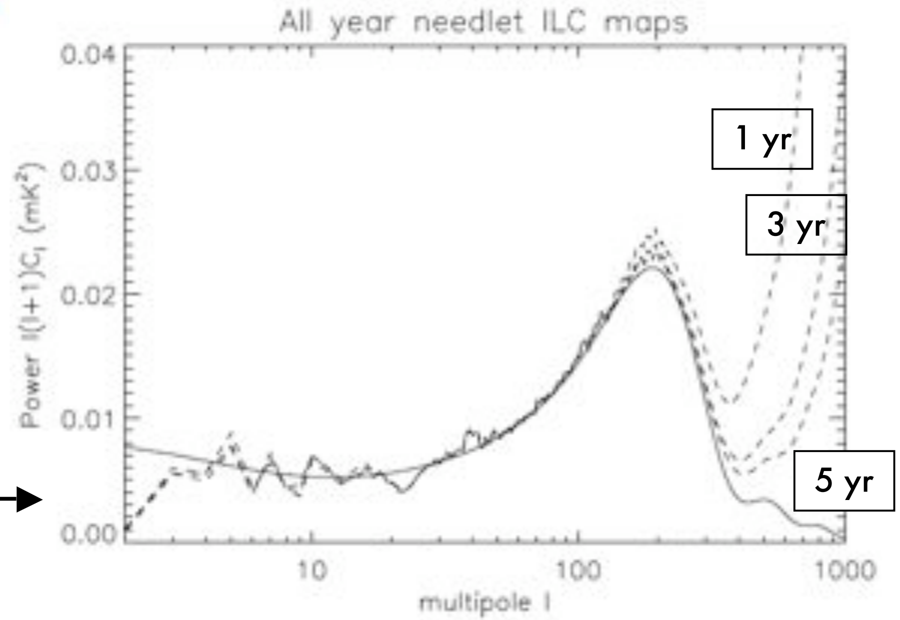
Result



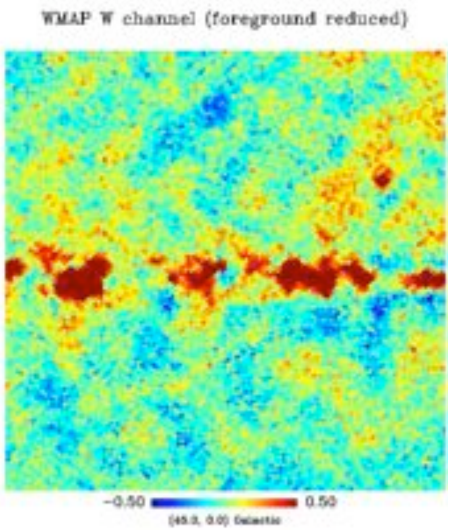
Map synthetised from the filtered needlet coefficients

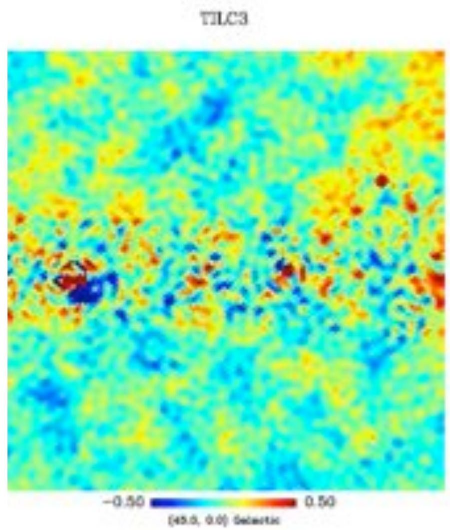
All sky power spectrum



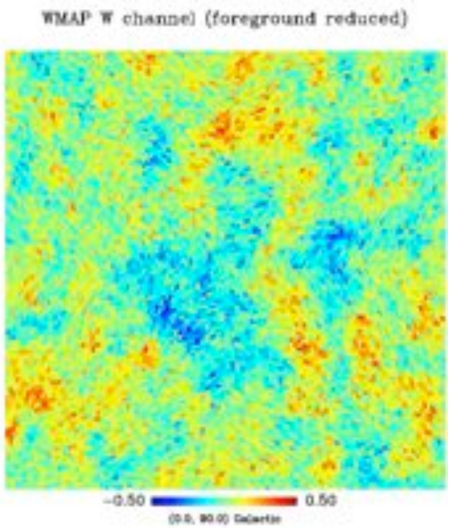
Comparison with other maps

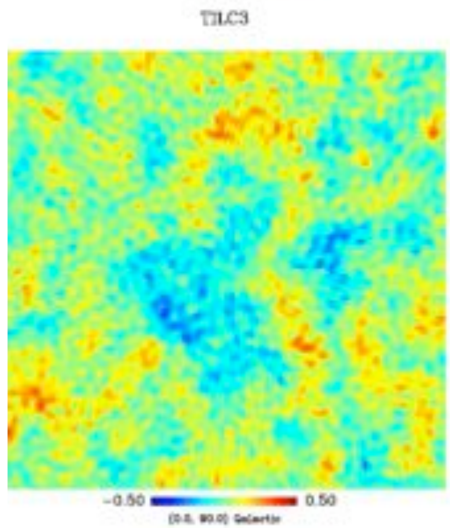
WMAP foreground reduced





Galactic plane





Galactic pole

Tegmark et al. ILC (3 year)

Comparison with other maps

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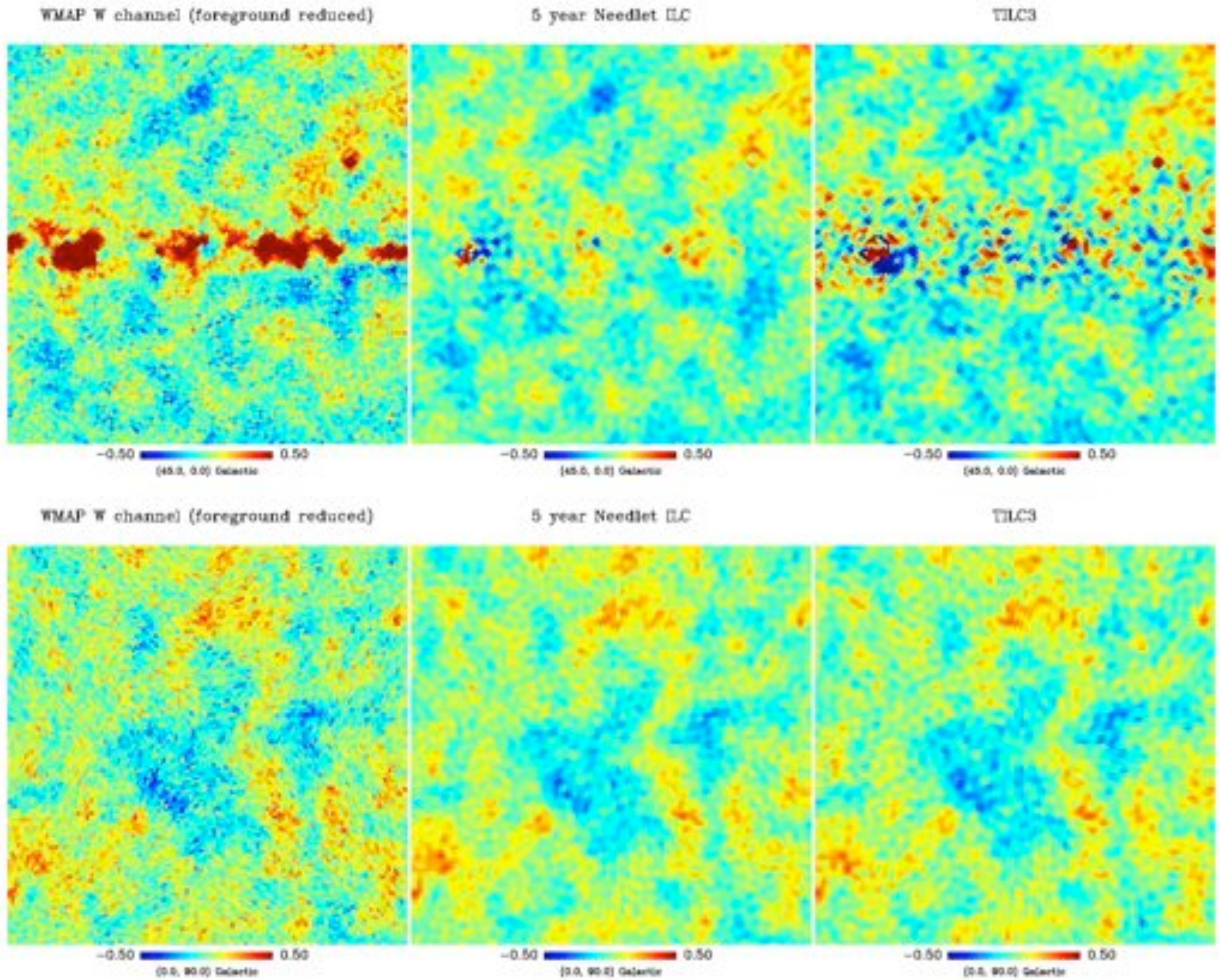
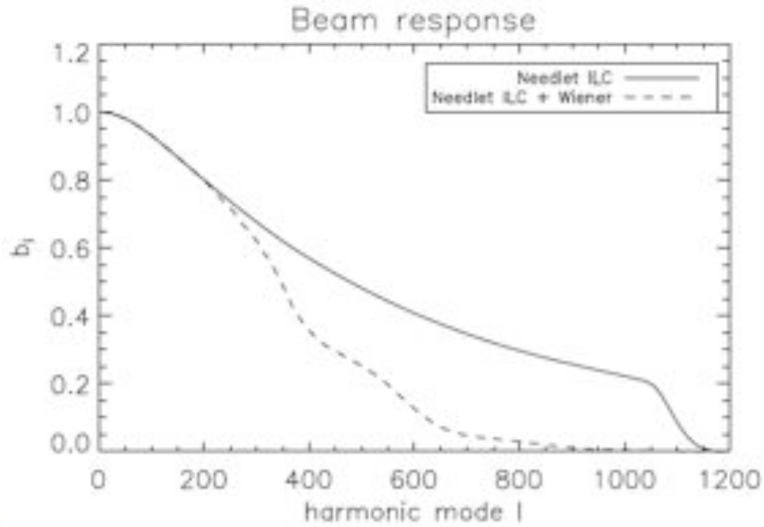


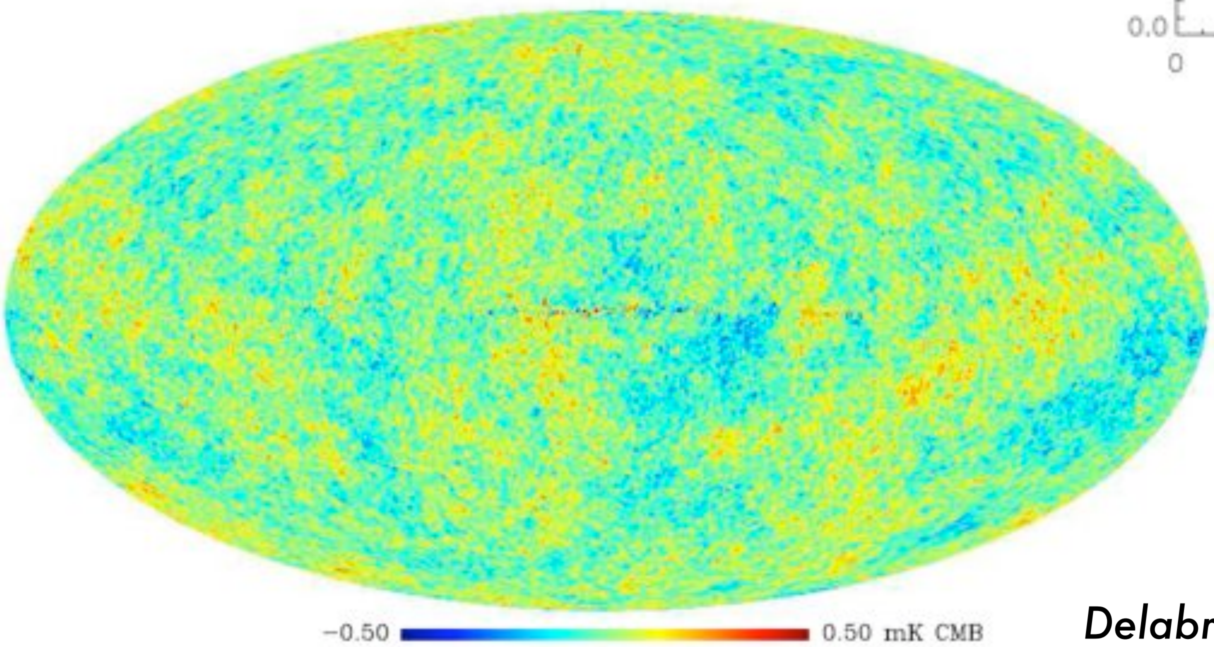
Tegmark et al. ILC (3 year)

Can we do better ?

- Yes ! Wiener filter



5 year needlet ILC map + harmonic Wiener filtering



Delabrouille et al. astro-ph/0807.0773

Can we do even better ?

- Yes !
- Optimize bands
  - Spectral bands can be optimized for the data set
  - They could also be different at low and high gal. latitude
- Optimize zones for estimation of covariances
  - Again, the size of the zones could depend on gal. latitude
- One could "model" the covariances to reduce the "ILC bias"
- One could use more "ancillary" data (not only IRIS)
- One could do localised Wiener filtering (at the price of inhomogeneous equivalent beam)

So why did we stop here ?

- Good reason
  - We wanted to develop a method which uses as little fine-tuning as possible. Here, the processing is almost fully blind, no manual adjustment of any parameter.

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- Ugly reason
  - We will improve our map only if it happens to be useful for the upcoming scientific analyses :-D (optimisation for specific purpose)

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Polarisation ?

- Nothing prevents using the same method for making polarisation maps
  - Compute a_{lm}^E and a_{lm}^B
  - For each independently:
    - Make a needlet decomposition
    - Implement the ILC in local regions
    - Reconstruct E map and B map
  - Not done on WMAP data because low S/N
  - Succesfully tried on Planck simulations (for E)
  - Ongoing work

Non CMB components ?

- The same method can be used to extract other components
  - Spectral emission law known
  - Uncorrelated with the other emissions

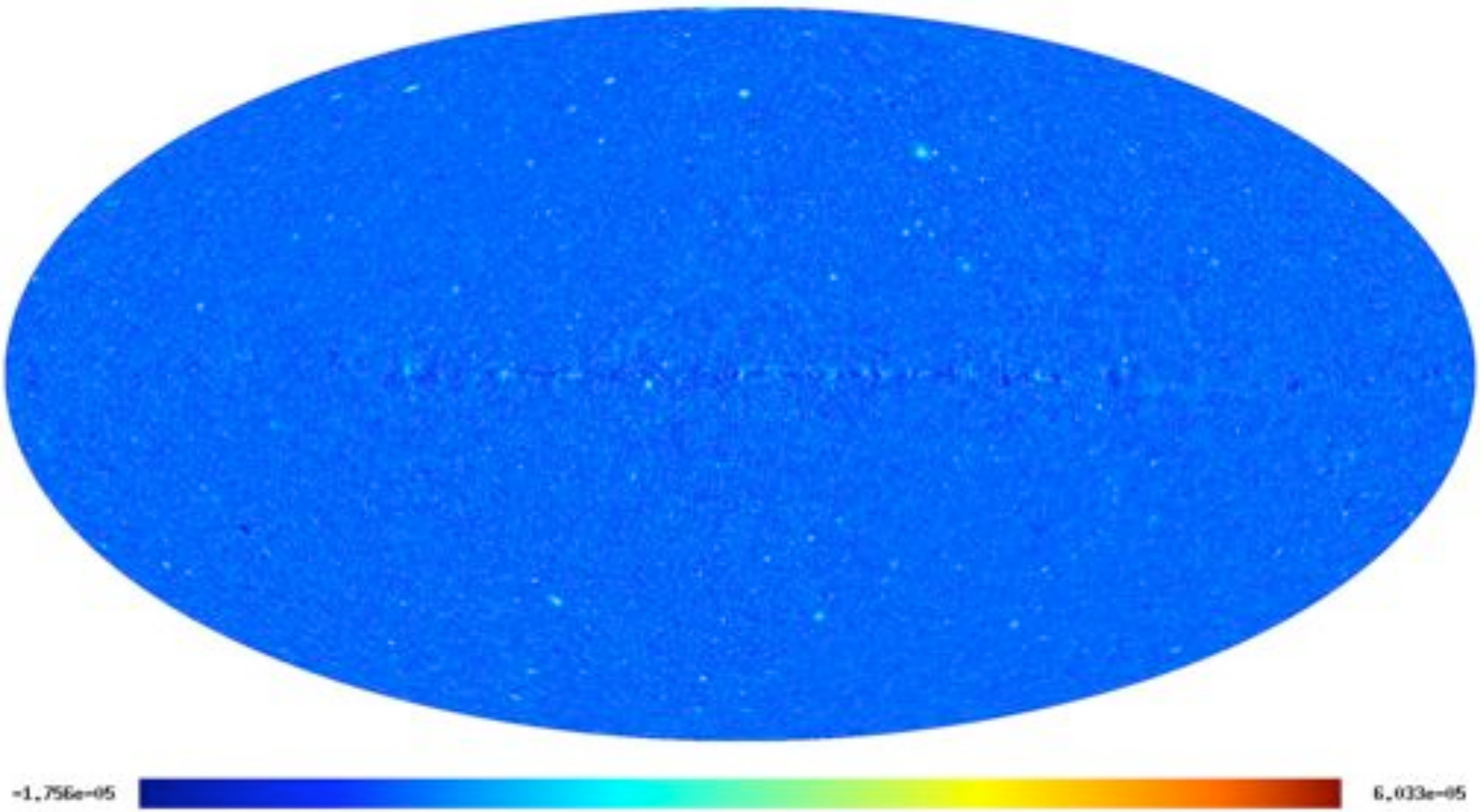
- Not suited for galactic foregrounds (sorry)...

- Succesfully tested for extracting the thermal SZ emission on Planck simulations
  - "data" from WG2 "challenge 2" (or WG5 "SZ challenge")

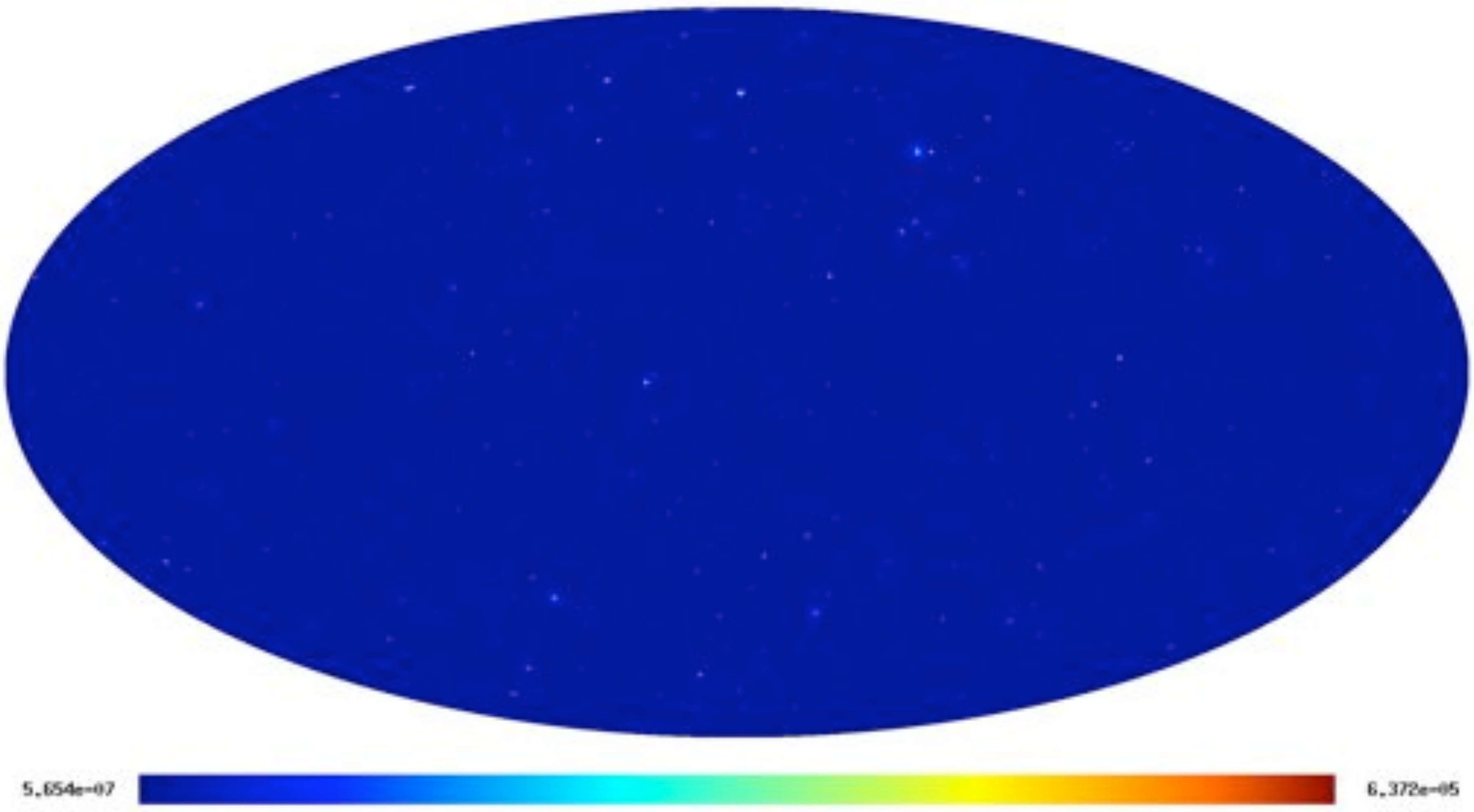
(Delabrouille et al. in preparation)

(Leach et al. astro-ph/0805.0269)

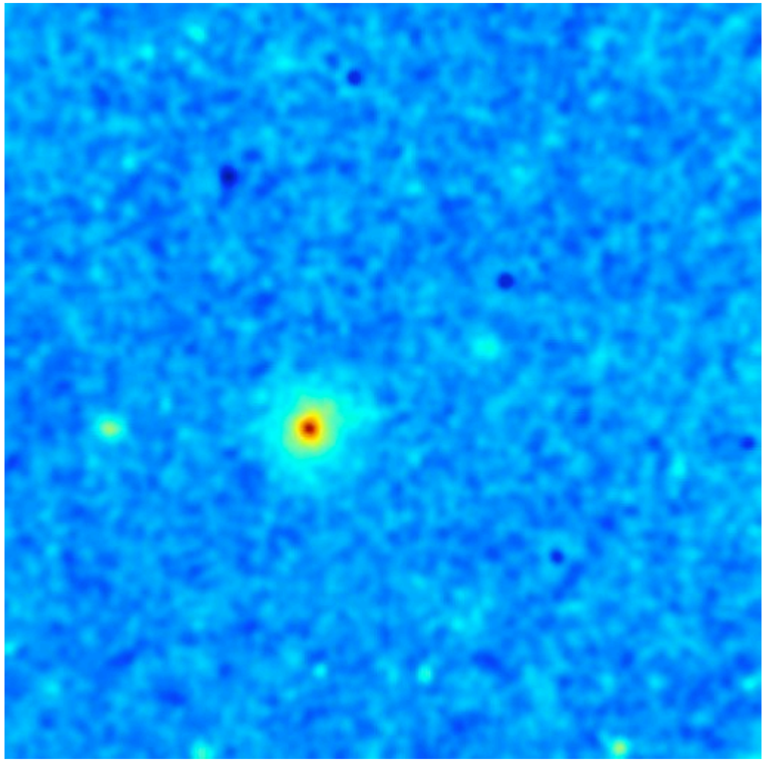
Recovered all-sky SZ map



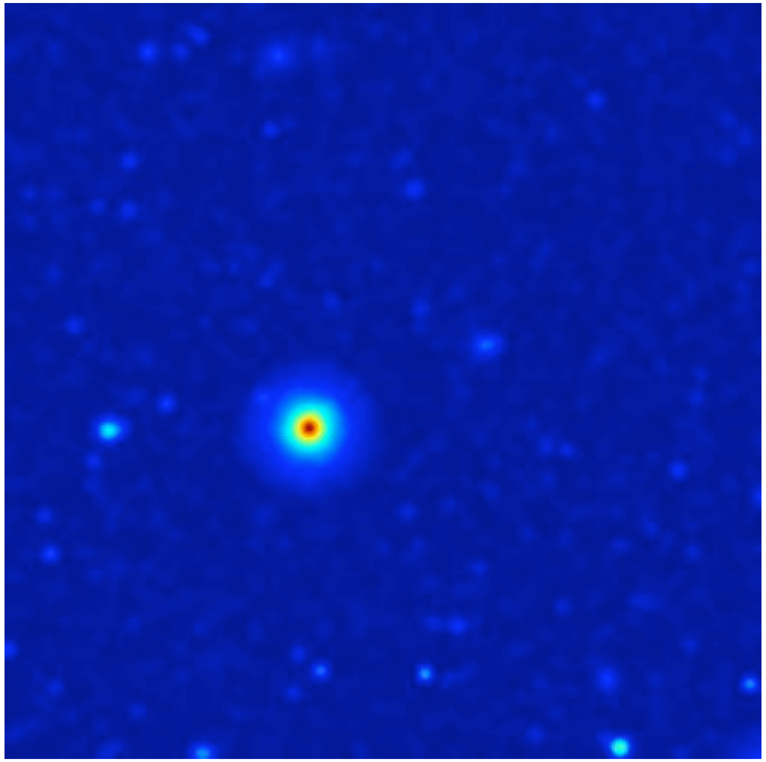
Input all-sky SZ map



Coma region

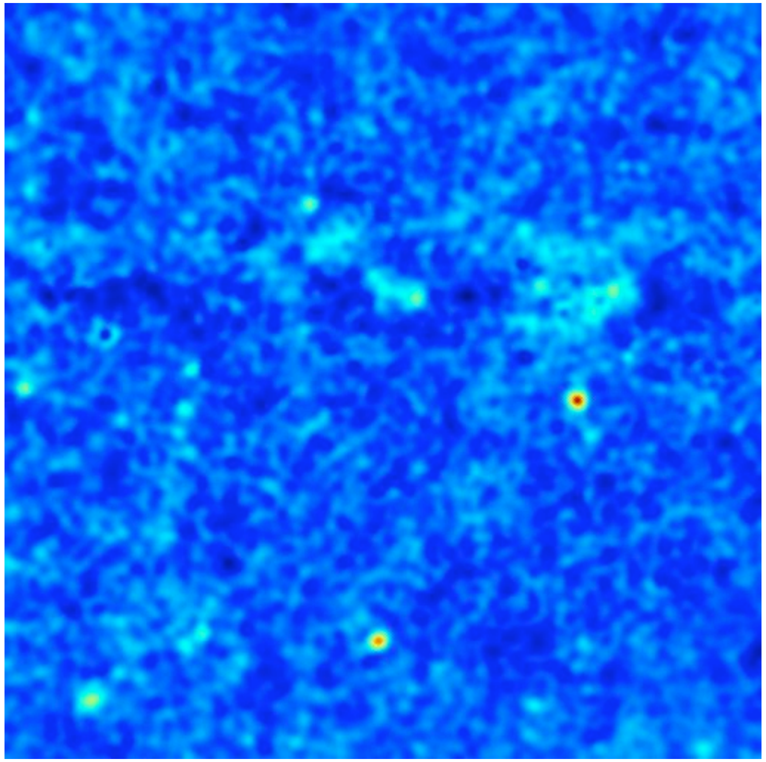


Output map

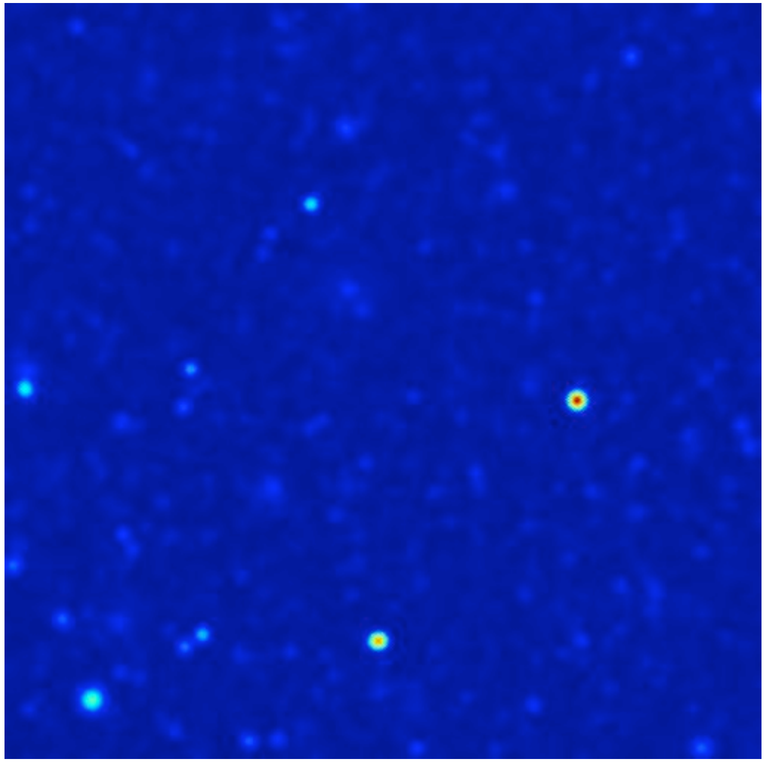


Input map

Galactic plane region !

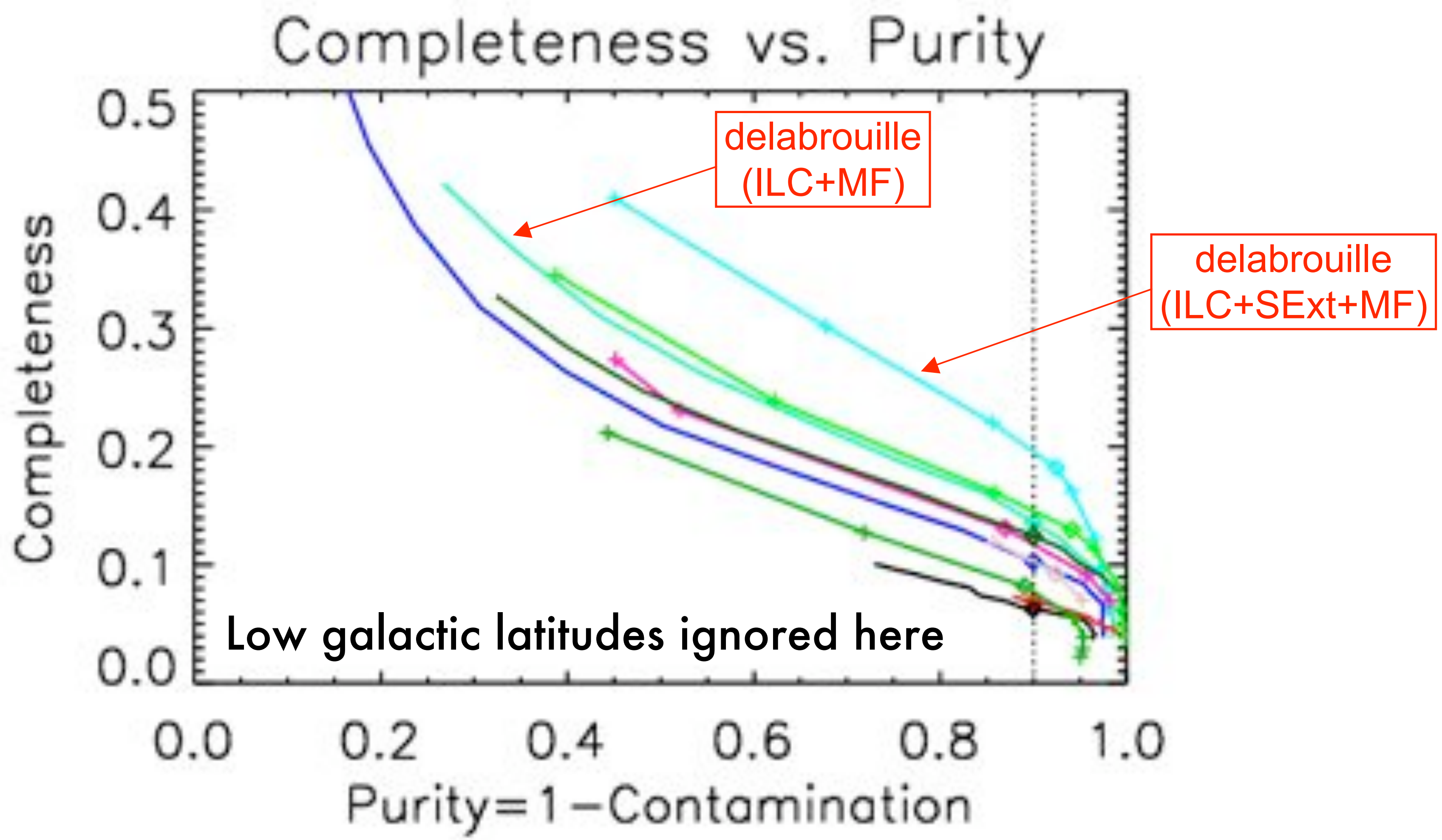


Output map



Input map

Preliminary result of Planck SZ challenge



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Conclusion

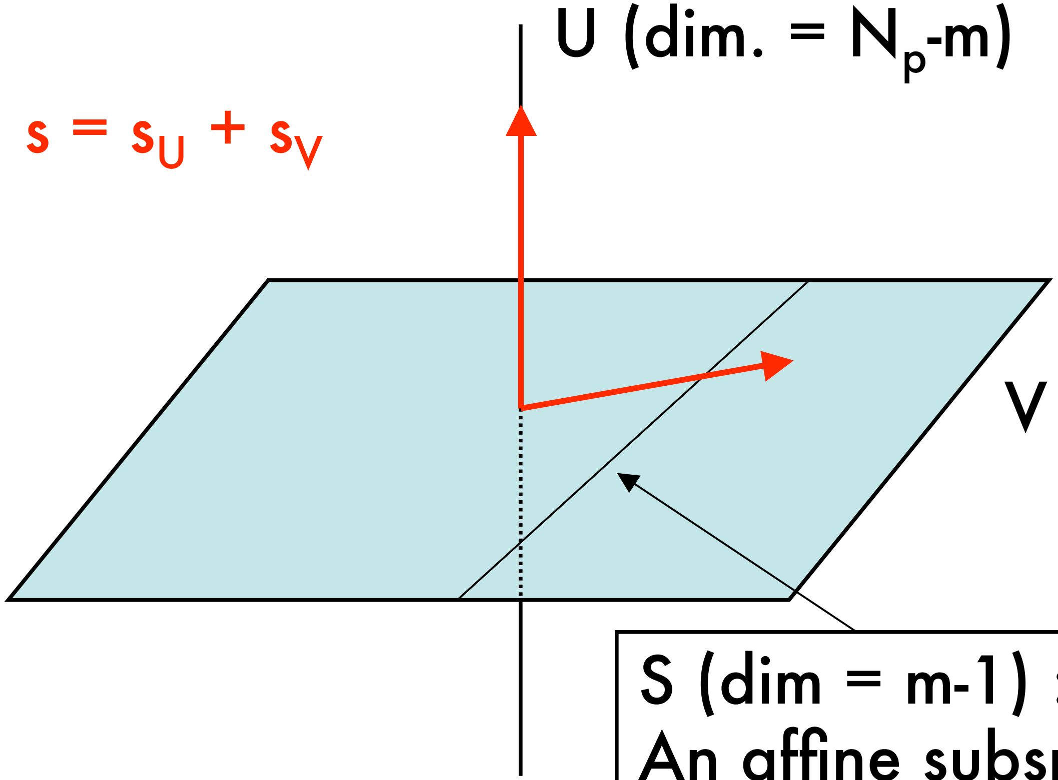
- An effective, versatile method for extracting CMB and SZ from multifrequency observations
- Application to simulated Planck observations
  - A very clean SZ map
- Application to WMAP data for CMB
  - A clean, high resolution CMB map (post-analysis is ongoing)
  - A Wiener-filtered version
  - (Nearly-)complete characterisation of the error available
  - Data (soon) available
    http://www.apc.univ-paris7.fr/APC_CS/Recherche/Adamis/cmb_wmap-en.php
  - In the mean time, collaborations welcome

The End

Bias problem

- The bias issue: a geometrical illustration
  - $y_i = s + n_i$
  - y_i, s and n_i can be considered as elements of a N_p-dimensional vector space W
  - The m vectors n_i are in general independent. They span an m-dimensional subspace V of W

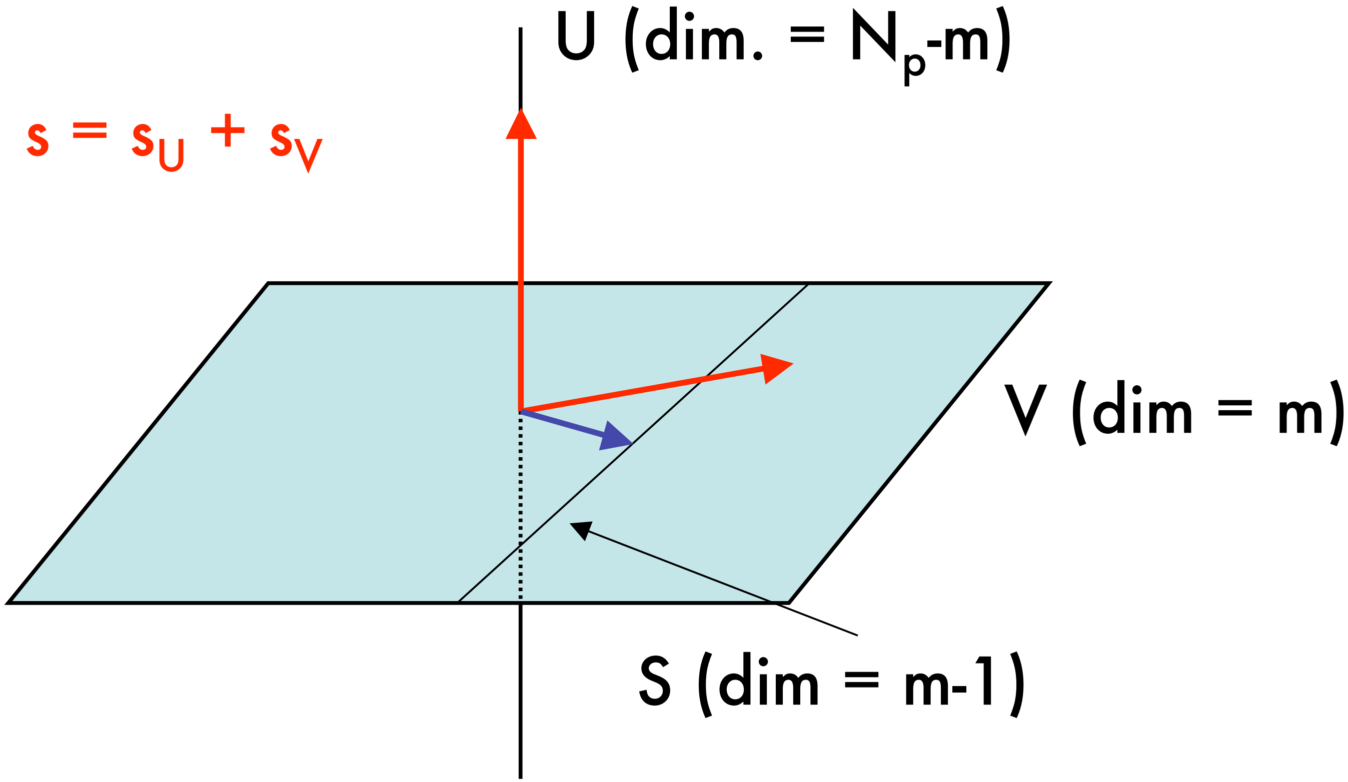
The ILC bias: geometric illustration



$W = U \oplus V$

S (dim = m-1) :
An affine subspace of V spanned by the restriction to V of the linear combinations $s_V + \Sigma\, w_i\, n_i$

The ILC bias: geometric illustration



Minimizing the norm of $\Sigma\, w_i\, y_i$ results in the "cancellation" of the CMB parallel to S (m-1 directions out of a total of N_p) !

Consequences

- Trade-off between
  - localisation (implementation of ILC in small domains)
  - bias
- (keep m << N_p)
- How to do better?
  - De-bias if we know a priori something about n_i
  - Implement filters locally, but regularise covariance estimations using priors and models (e.g. SMICA)
  - Etc…