Hot Gas Induced Signal in WMAP's First Year Data

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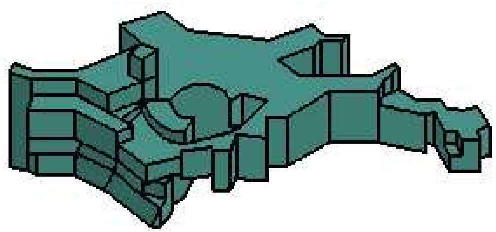


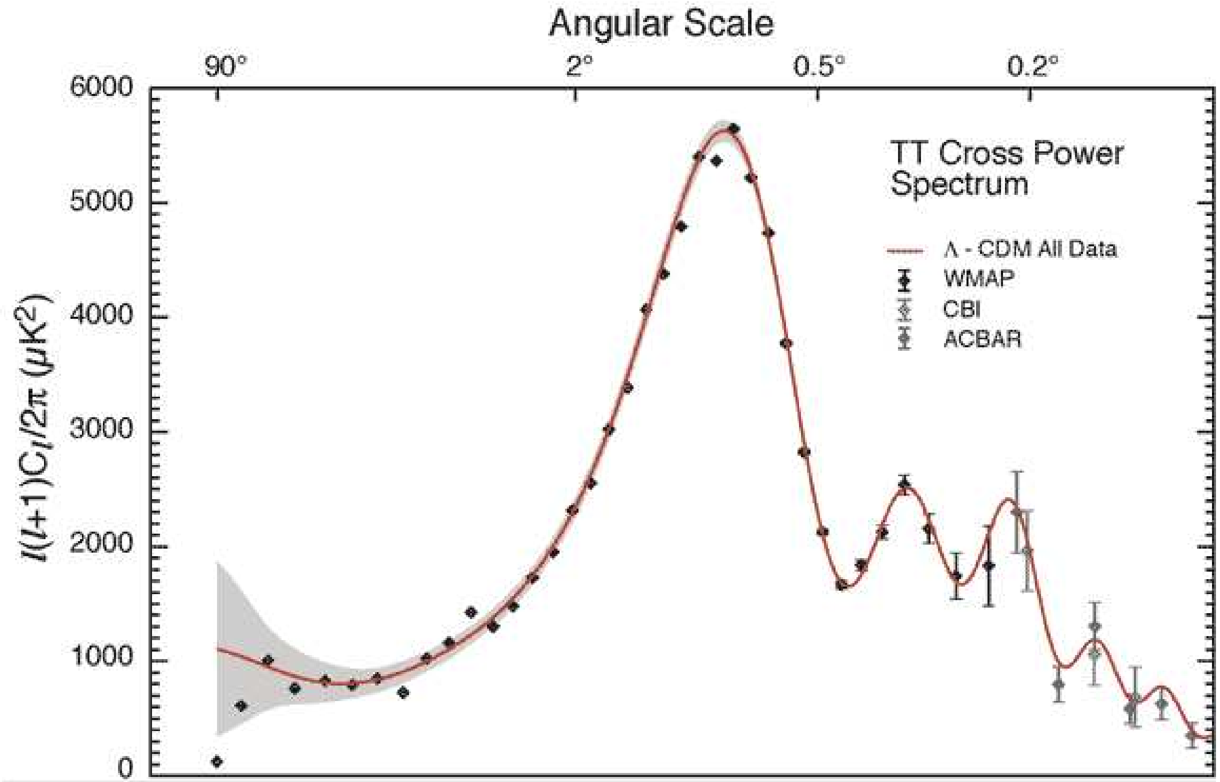
Summary:

- General Introduction
- The statistical method used
- The procedure
- The results
- The tests
- Conclusions

Intro: CMB Temperature Fluctuations

$$\delta T(\theta,\phi) = \sum_{l,m} a_{l,m}[\Omega_m, \Omega_b, h, n_s, ...]\, Y_{l,m}(\theta,\phi)$$

CMB Power Spectrum: $C_l \equiv \langle |a_{l,m} a^*_{l,m}| \rangle$



Secondary Fluctuations

- Reionization
- Rees-Sciama effect: $\frac{\delta T_{RS}}{T_0} = -\frac{2}{c^2} \int d\eta \, \dot{\phi}(\eta)$
- Gravitational lensing
- Spectrum distortion after inverse Compton scattering with plasma: **thermal Sunyaev-Zel'dovich effect, (tSZ)**.

$$\frac{\delta T_{tSZ}}{T_0} \simeq g(\nu) \int d\mathbf{r} \; \sigma_T n_e(\mathbf{r}) \frac{k_B T_e(\mathbf{r})}{m_e c^2}$$

- ...

Thermal Sunyaev-Zel'dovich Effect

$$\frac{\delta T_{tSZ}}{T_0} \simeq g(\nu) \int d\mathbf{r}\; \sigma_T n_e(\mathbf{r}) \frac{k_B T_e(\mathbf{r})}{m_e c^2} \simeq g(\nu) \frac{\sigma_T}{m_e c^2} \int d\mathbf{r}\; p_e(\mathbf{r})$$

Comptonization parameter: $y \equiv \int d\mathbf{r}\; \sigma_T n_e(\mathbf{r}) \frac{k_B T_e(\mathbf{r})}{m_e c^2}$

- As it distorts the CMB Black Body spectrum, it is frequency dependent. **At WMAP's frequencies, $g(\nu) < 0$.**
- It measures integrated pressure along the LOS.

$\Rightarrow$ The tSZ effect on the CMB will be our tool to trace the presence of hot, ionized gas in cosmological scales.

Goals:

- Estimate the amount of tSZ signal present in WMAP data
- Identify the sources generating tSZ signal in WMAP data
- Constraints on Ω_{baryon}?

Commonly Used Statistical Methods:

$$\mathbf{T} = \mathbf{T}_{cmb} + \alpha\mathbf{M} + \sum_i c_i \mathbf{F}^i + \mathbf{N},$$

- Method i):

$$\chi^2 = (\mathbf{T} - \alpha\mathbf{M})\mathcal{C}^{-1}(\mathbf{T} - \alpha\mathbf{M})^T$$

$$E[\alpha] = \frac{\mathbf{T}\mathcal{C}^{-1}\mathbf{M}^T}{\mathbf{M}\mathcal{C}^{-1}\mathbf{M}^T}$$

$$\mathcal{C} =< (\mathbf{T} - \alpha\mathbf{M})^T(\mathbf{T} - \alpha\mathbf{M}) >$$

- Method ii):

$$\chi^2 = \sum_{ij} \left[C_{TM}(\theta_i) - \alpha C_{MM}(\theta_i)\right] \times \pi_{ij}^{-1} \left[C_{TM}(\theta_j) - \alpha C_{MM}(\theta_j)\right]$$

$$E[\alpha] = \frac{\sum_{ij} C_{TM}(\theta_i)\pi_{ij}^{-1}C_{MM}(\theta_j)}{\sum_{ij} C_{MM}(\theta_i)\pi_{ij}^{-1}C_{MM}(\theta_j)}$$

α **will be our tSZ statistic!**

Comparing the two methods...

- Errors go like $\sim 1/\sqrt{N_{pix}}$ for method $i)$ and like $\sim 1/\sqrt{N_{pairs}} \sim 1/N_{pix}$ for method $ii)$.
- Both assume $\langle \mathbf{T}_{cmb} \rangle = 0$. *One may have to force it by hand!*
- Possible systematics are more intuitive in method $i)$. For this method, however, one must invert a matrix which cannot be too large.

$\Rightarrow$ **We shall use method** $i)$

Previous Works (I):

- Banday et al (1996). **COBE** data (7°) $\Rightarrow$ no detection.
- Rubiño-Martín, Atrio-Barandela & Hernández-Monteagudo (2000). **Tenerife** data (5°) $\Rightarrow$ no detection.
- Bennett el al (2003). **WMAP** data (0.21°):
  - Some clusters are seen (COMA)
  - Cross-correlation with XBAC (Ebeling et al.1996) gives 2.5σ detection.
- Diego, Silk & Sliwa (2003): **WMAP** and ROSAT $\Rightarrow$ no detection.
- Bough & Crittenden (2003): **WMAP** and HEAO-1, NVSS $\Rightarrow$ ISW detection at 2-3σ

Previous Works (and II):

- Fosalba & Gaztañaga (2003), Fosalba, Gaztañaga & Castander (2003): **WMAP** and APM, SDSS galaxy surveys. Evidence of ISW in the large scales and of tSZ in the small scales.
- Hernández–Monteagudo & Rubiño–Martín (2004), [HMRM]: 2–5σ detections on X-ray based Galaxy Cluster Catalogues
- Myers et al. (2004): they claim to have found *diffuse* tSZ emission up to $\sim 0.5^0$–1^0 scales: Is Ω_{baryon} higher than expected?

HMRM (I)

$\alpha \pm \sigma_\alpha$, (μK), [Kp0]

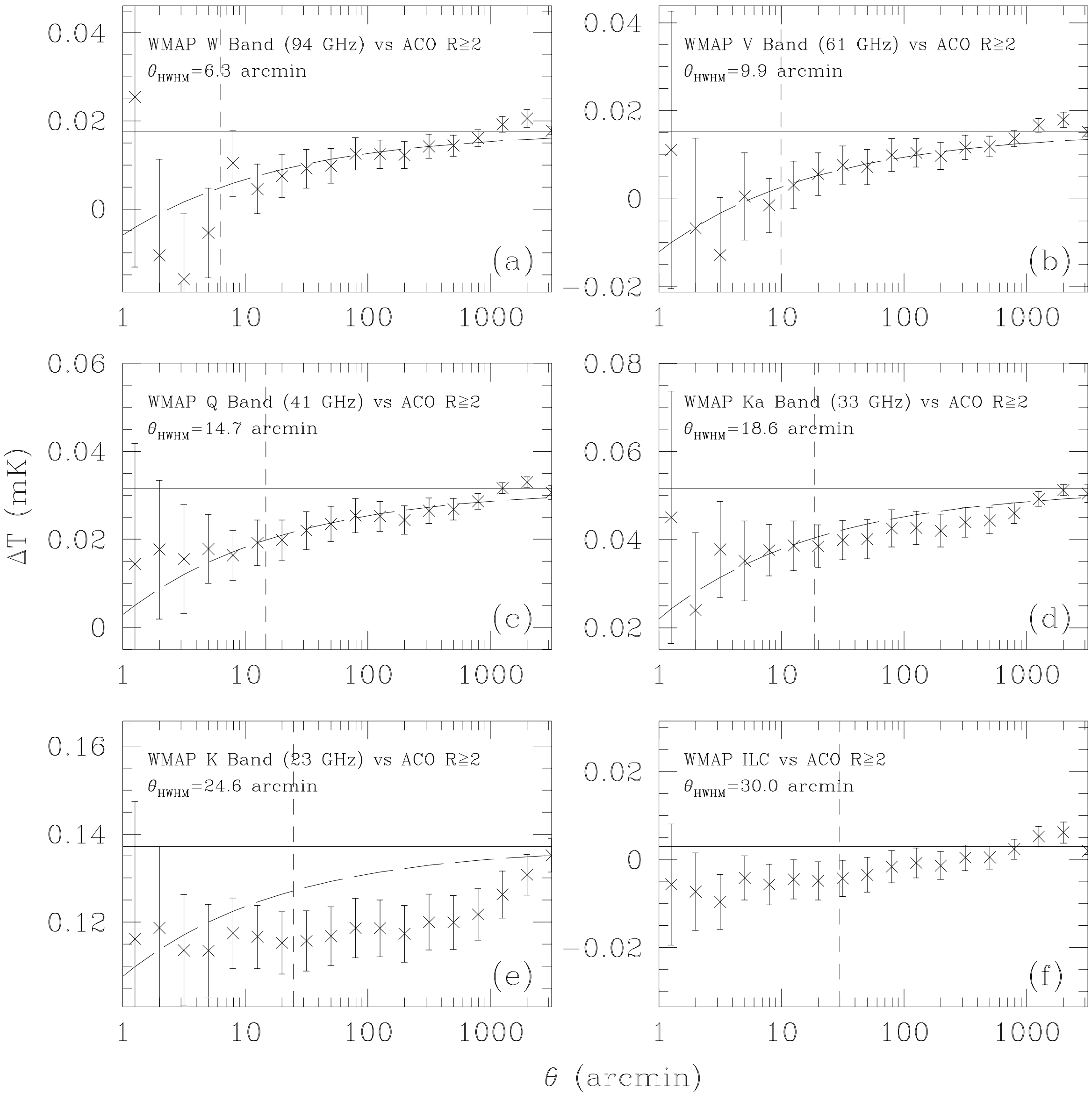
Template		W	R-W	T03	R-T03
ACO (cal)	ν_1	20.34 ± 6.83	18.57 ± 6.84	-1.32 ± 4.75	5.21 ± 4.82
	ν_2	17.21 ± 11.26	13.23 ± 11.32	-2.40 ± 7.60	2.72 ± 7.64
	ν_3	32.35 ± 28.69	12.46 ± 28.54	24.36 ± 18.10	-1.49 ± 18.27
ACO (n=1)	ν_1	13.44 ± 6.65	13.89 ± 6.64	0.54 ± 3.78	-0.35 ± 3.84
	ν_2	16.22 ± 10.80	11.31 ± 10.85	-3.41 ± 7.03	-0.08 ± 7.14
	ν_3	20.69 ± 28.13	-23.49 ± 27.96	5.36 ± 17.29	-35.93 ± 17.56
ACO (n=2)	ν_1	6.93 ± 6.02	9.83 ± 6.05	-0.54 ± 3.13	-2.72 ± 3.22
	ν_2	2.76 ± 10.91	4.72 ± 11.07	-6.81 ± 6.27	-3.99 ± 6.54
	ν_3	16.47 ± 28.41	-29.00 ± 28.50	5.19 ± 17.36	-30.98 ± 18.00
APM (n=1)	ν_1	-3.37 ± 8.94	-2.22 ± 8.93	-5.67 ± 4.16	-3.89 ± 4.15
	ν_2	-2.19 ± 15.96	6.15 ± 15.95	-7.57 ± 10.40	-11.41 ± 10.42
	ν_3	3.77 ± 31.99	29.28 ± 32.05	-3.05 ± 21.92	2.82 ± 22.09
APM (n=2)	ν_1	-5.58 ± 5.74	1.57 ± 5.76	-3.24 ± 2.55	-3.69 ± 2.58
	ν_2	-10.63 ± 12.45	9.96 ± 12.45	-9.62 ± 6.27	-9.10 ± 6.30
	ν_3	-0.54 ± 31.73	36.01 ± 31.78	-13.10 ± 19.49	-3.33 ± 19.95

HMRM (II)

$\alpha \pm \sigma_\alpha$, (μK), [Kp0]

Template		W	R-W	T03	R-T03
BCS	ν_1	**-18.10 ± 5.30**	6.61 ± 5.37	**-8.44 ± 2.50**	-2.76 ± 2.57
	ν_2	**-29.87 ± 11.40**	16.66 ± 11.62	**-19.00 ± 6.63**	-8.25 ± 6.81
	ν_3	**-64.06 ± 31.78**	19.59 ± 31.96	**-39.30 ± 18.43**	-12.30 ± 18.62
NORAS	ν_1	**-10.95 ± 5.47**	8.12 ± 5.44	**-10.47 ± 2.64**	4.12 ± 2.69
	ν_2	-15.04 ± 11.06	18.17 ± 10.97	**-17.89 ± 6.50**	3.79 ± 6.60
	ν_3	-29.65 ± 29.16	42.09 ± 28.51	**-49.54 ± 17.30**	1.50 ± 17 .37
de Grandi	ν_1	-3.75 ± 3.05	-0.32 ± 2.98	**-7.24 ± 1.32**	-0.14 ± 1. 29
	ν_2	2.10 ± 10.45	2.75 ± 10.27	**-21.49 ± 5.19**	5.31 ± 5.01
	ν_3	6.37 ± 28.68	-27.48 ± 28.47	**-48.58 ± 17.72**	25.55 ± 17 .41
PSPC	ν_1	5.52 ± 4.31	2.98 ± 3.92	0.24 ± 1.89	-0.06 ± 1.73
	ν_2	12.94 ± 12.20	11.11 ± 11.22	-0.56 ± 6.68	1.18 ± 6.1 1
	ν_3	17.87 ± 33.01	26.42 ± 29.55	-1.32 ± 19.89	-5.13 ± 17.75
Vogues	ν_1	0.50 ± 2.44	1.12 ± 2.37	0.34 ± 1.07	0.19 ± 1.05
	ν_2	14.91 ± 8.78	11.10 ± 8.61	3.47 ± 4.07	0.86 ± 4 .05
	ν_3	45.18 ± 31.03	37.81 ± 30.22	10.09 ± 18.51	1.57 ± 18.23

Myers et al., (2004)



The Procedure

- Our basic assumption: ***galaxies trace the distribution of hot gas***

$$\Rightarrow \delta T_{tSZ}(\mathbf{n}) \propto N_{gal}(\mathbf{n})$$

- We shall focus method *i)* on those pixels sets having higher projected galaxy density

$$\chi^2 = (\mathbf{T} - \alpha\mathbf{M})\mathcal{C}^{-1}(\mathbf{T} - \alpha\mathbf{M})^T$$

$$E[\alpha] = \frac{\mathbf{T}\mathcal{C}^{-1}\mathbf{M}^T}{\mathbf{M}\mathcal{C}^{-1}\mathbf{M}^T}$$

$$\mathcal{C} = < (\mathbf{T} - \alpha\mathbf{M})^T(\mathbf{T} - \alpha\mathbf{M}) >$$

The 2MASS XSC Catalogue

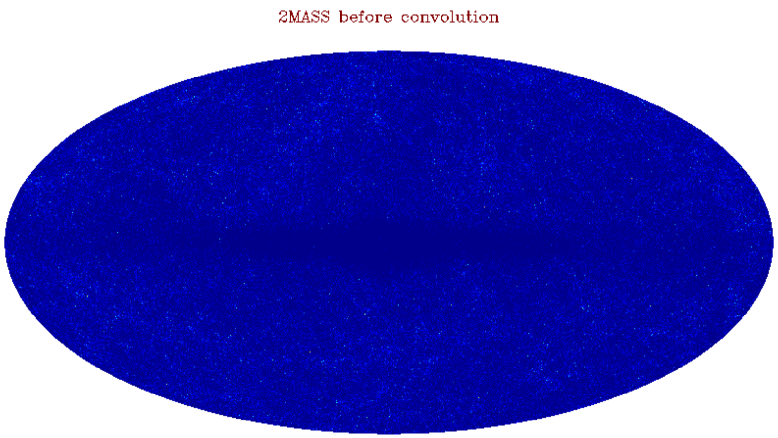
- 2 Micron All Sky Survey (2MASS), Extended Source Catalogue (XSC), contains around $\sim 1,600,000$ objects, most of which are $z < 0.1$.
- It is based on infra-red bands: J, H and K
- It is an *all sky survey* particularly insensitive to dust absorption

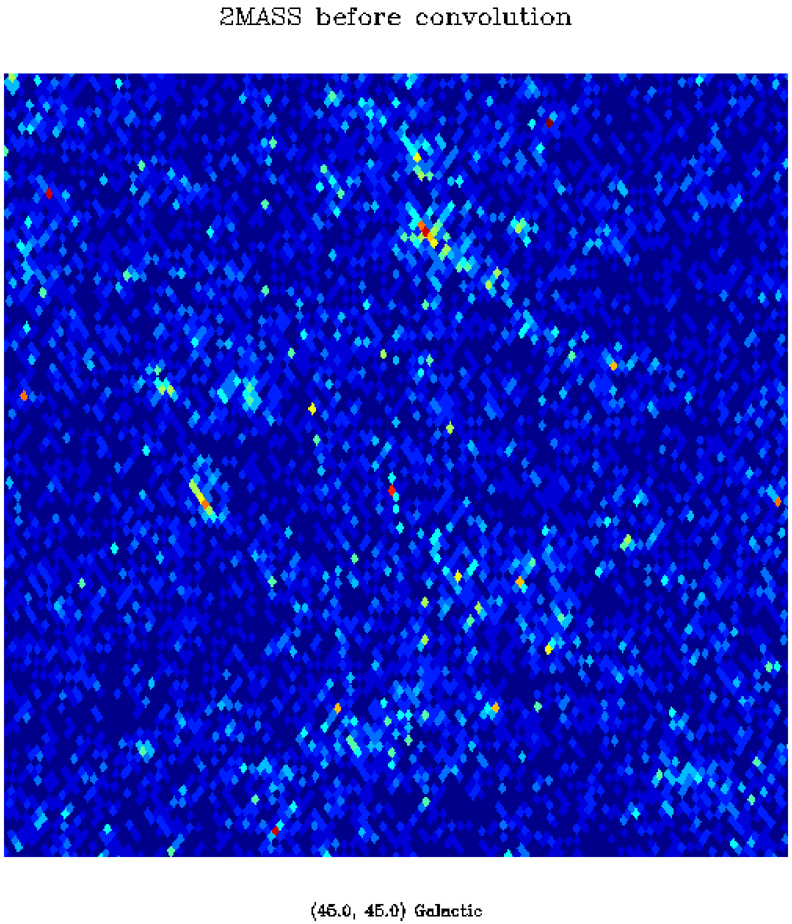
$\Rightarrow$ good tracer of galaxies in the **Zone of Avoidance**

Processing the catalogue, (I)

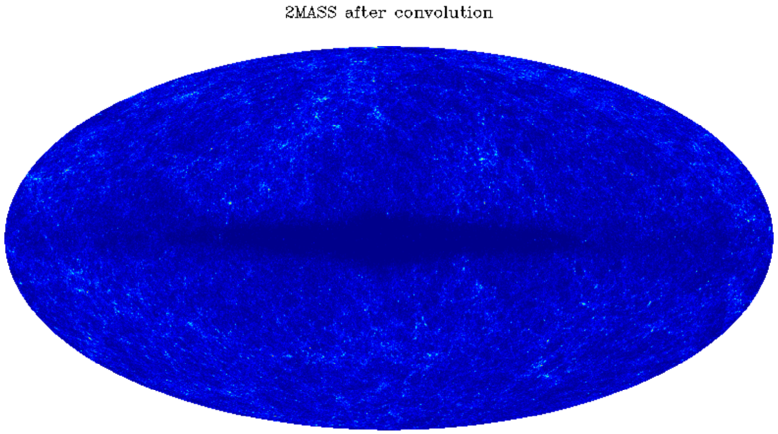
- We asign to each pixel a value equal to the number of galaxies contained in such pixel.
- We convolve the resulting catalogue with a noise-weighted average of the beams of each of the four difference assemblies of WMAP's W band.
- We filter the catalogues with the Kp0 mask.

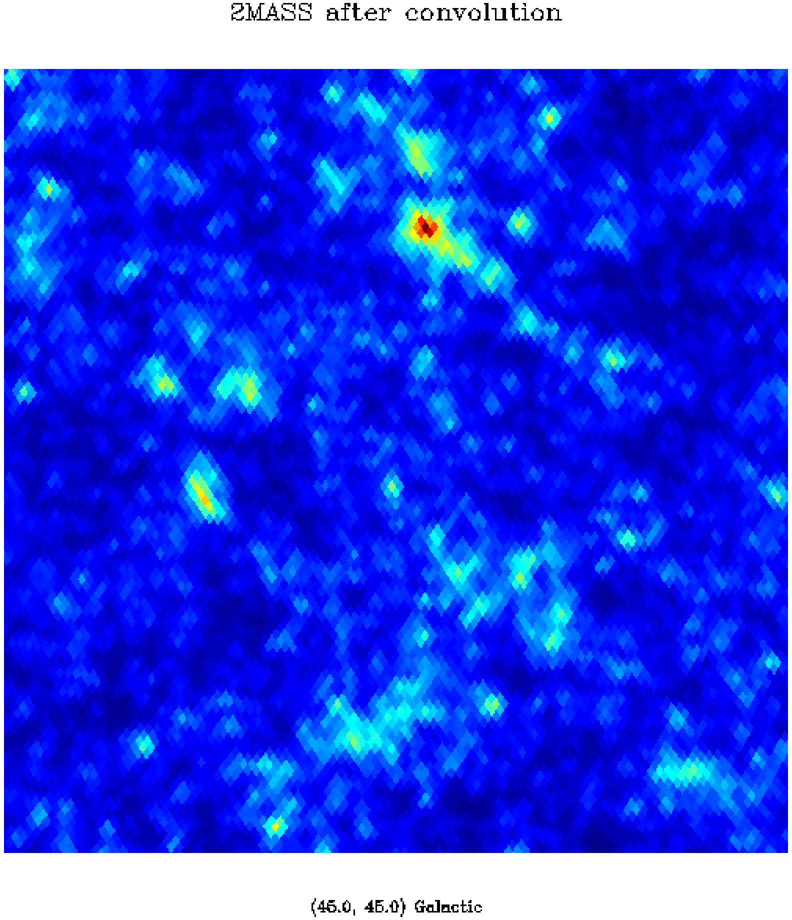
2MASS before convolution





2MASS after convolution





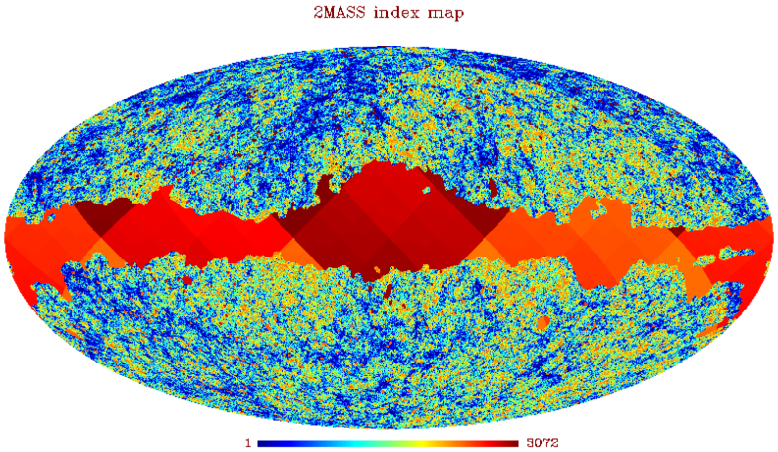
Processing the catalogue, (II)

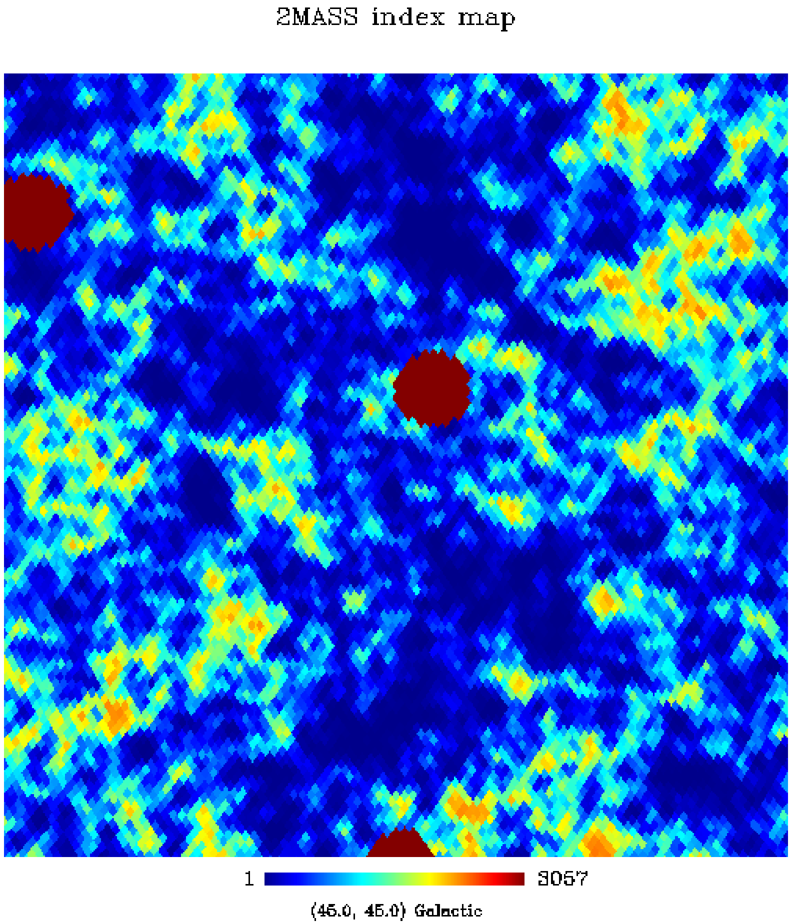
- We divide the template in a number of patches (N_{patch}) of $N_{pix\ patch}$ pixels each, so $N_{pix\ total} = N_{patch} \times N_{pix\ patch}$.
- $N_{pix\ patch} =$ 64, 128, 256, 512, 1024 and 2048
- We choose our patches in such a way that *first* patches have *brightest* (in the sense of *highest* galaxy density) pixels.

  $\Rightarrow$ ***Smaller*** **index corresponds to** ***higher*** N_{gal}

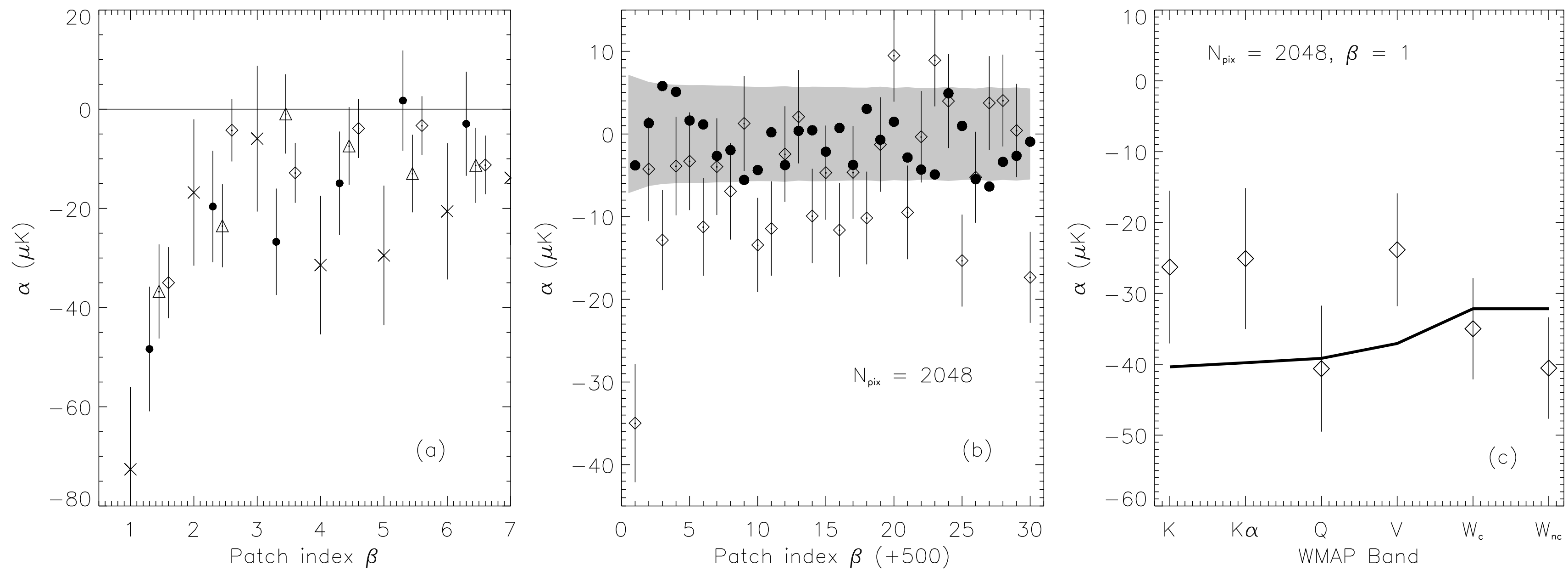
- We apply our method $i)$ separately for each of these patches, (note that, due to the required matrix inversion, $N_{pix\ patch}$ cannot be too big).

Index maps for 2MASS





Results (I)



(a)
(b)
(c)
N_{pix} = 2048
N_{pix} = 2048, β = 1
α (μK)
Patch index β
Patch index β (+500)
WMAP Band
K
Kα
Q
V
W_c
W_{nc}

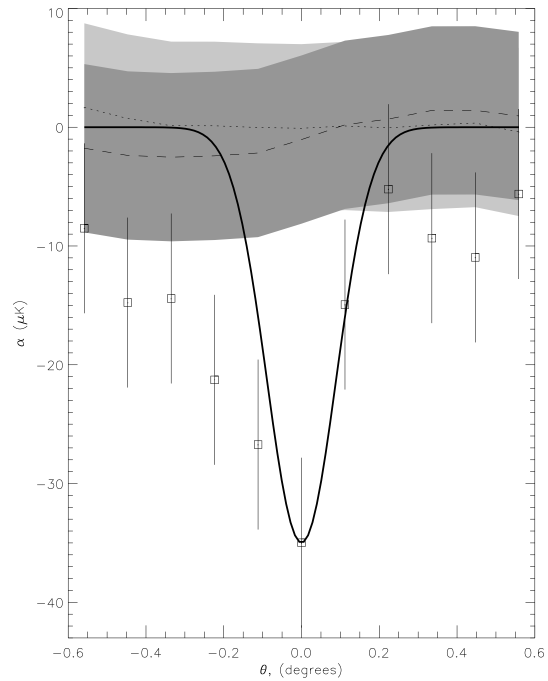
Results (Ib)

- Evidence for temperature decrements is found in ~ 180 sq-degrees in the sky. The amplitude of the decrement is correlated to the projected galaxy density.
- High statistical significance ($\simeq 5\sigma$) in ~ 26 sq-degrees:

$$-35 \pm 7\ \mu\text{K}.$$

- Decrements are spectrally compatible with tSZ effect.
- Foregrounds are likely to be irrelevant

Results (II)



- Angular extension of the sources is $\sim 20 - 30$ arcmins, (in dissagreement with Myers et al. (2004), who claimed $\sim 1^0$).
- Foregrounds do *not* compromise our results.

What generates this tSZ signal?

We cross correlated the 2048 densest pixels giving rise to a 5σ decrement with optical and X-ray based galaxy cluster catalogues:

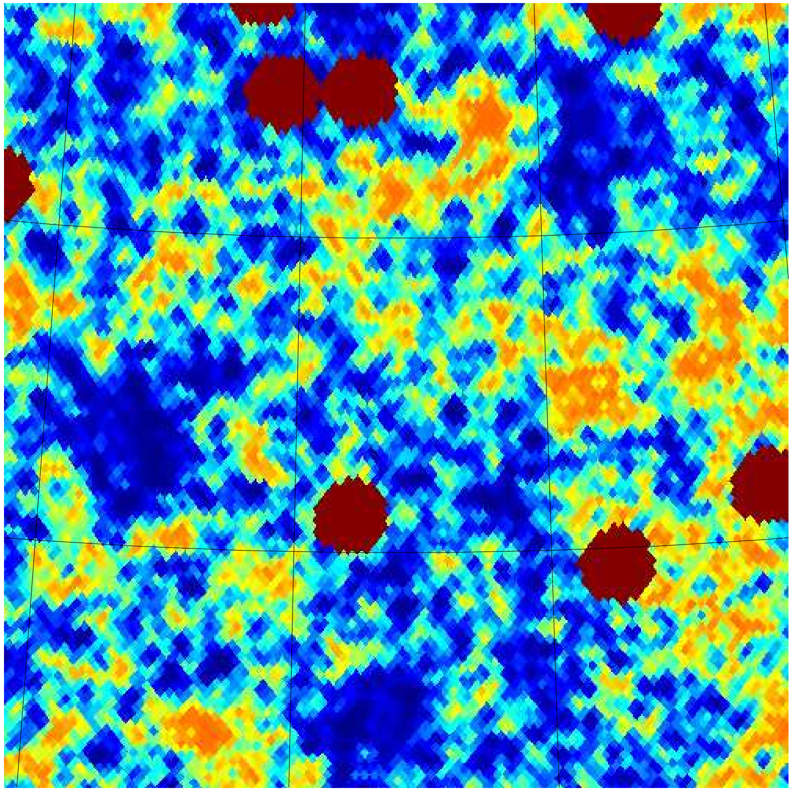
- 1625 pixels in ACO catalogue
- 589 pixels in XBAC (Ebeling's) catalogue
- 525 pixels in NORAS catalogue
- 267 pixels in de Grandi catalogue
- 223 pixels in APM catalogue

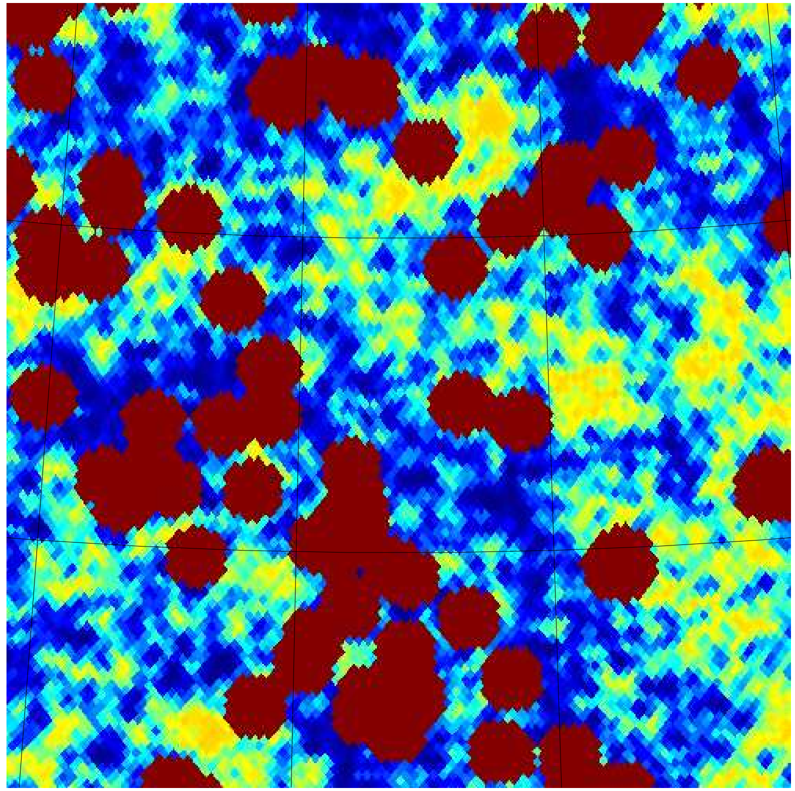
Is there diffuse gas causing tSZ?

We masked out pixels belonging to all known galaxy clusters:

- For cluster with known core radii (r_c), we removed all pixels within $r_v = 10 \cdot r_c$
- For clusters with known redshift, we assumed $r_v = 1.7$ Mpc.
- For clusters without redshift, we removed all pixels within a 30 arcmin radius from cluster center.

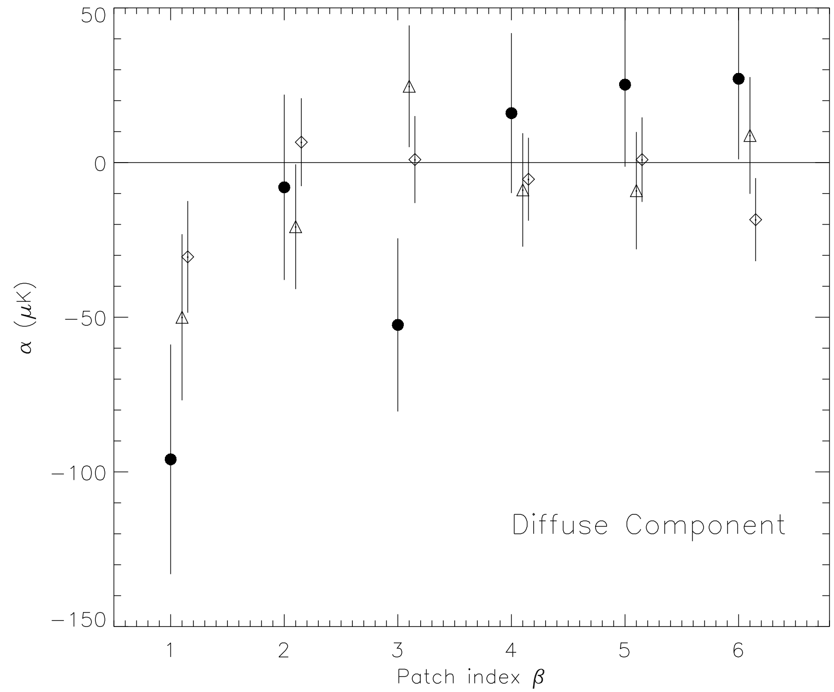
Effect of masking on our index map





$\Rightarrow$ We remove ~ 4000 sq-degrees from the analysis

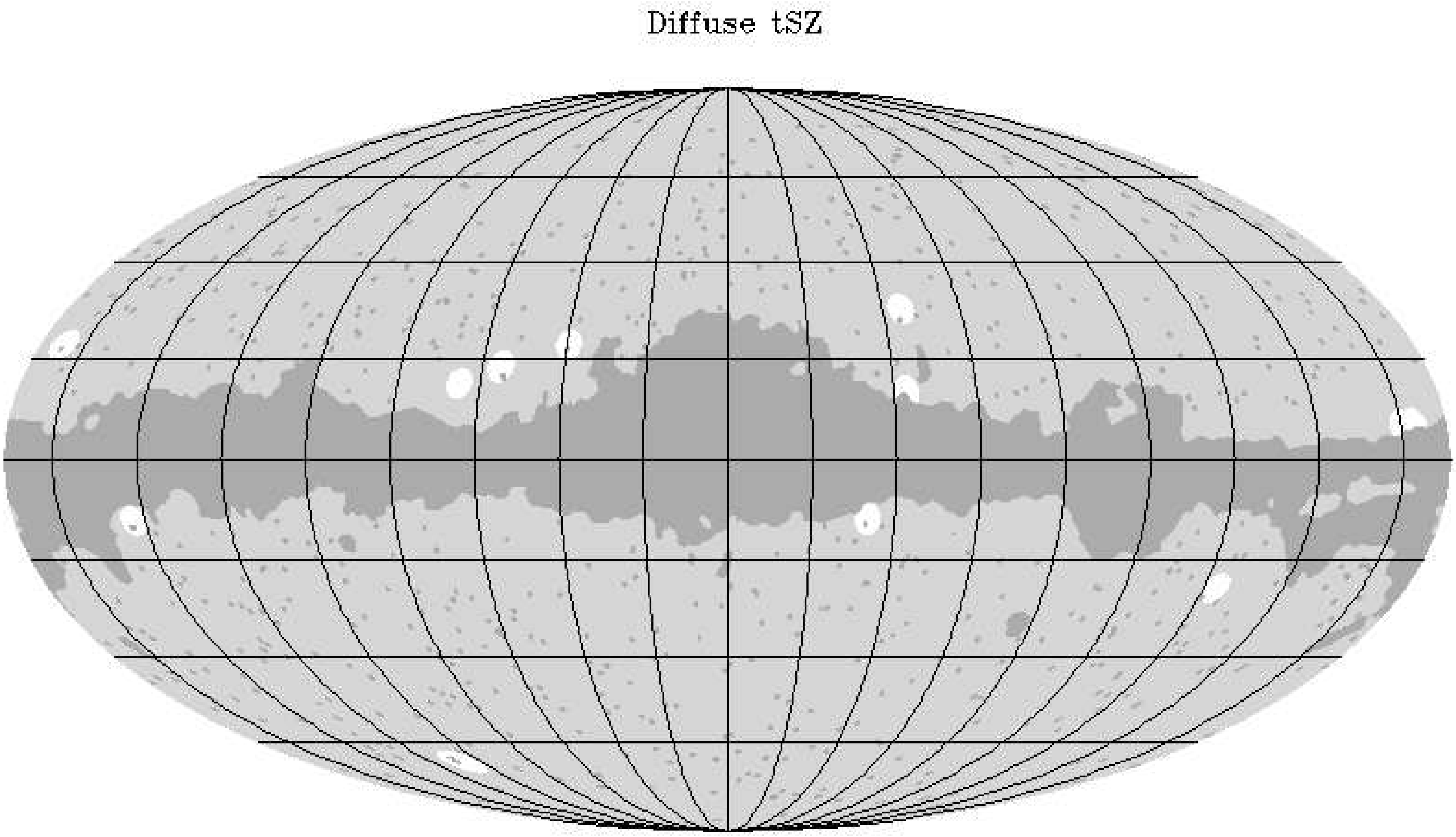
tSZ non-associated to known GC's:



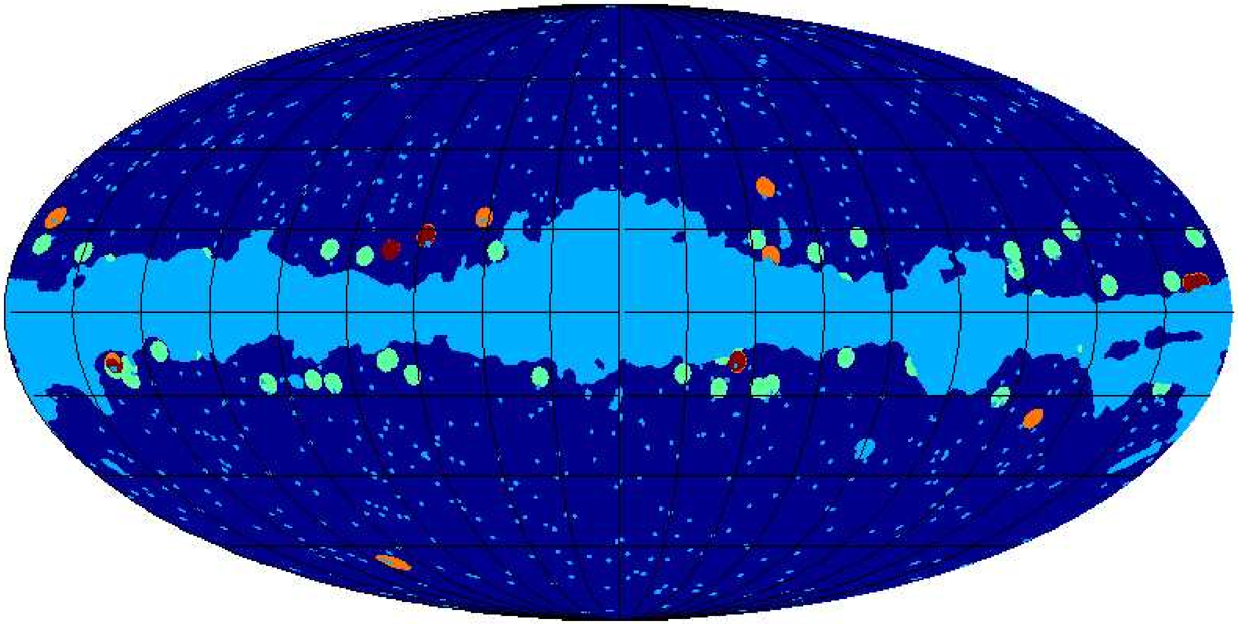
- For the remaining 64 brightest pixels, we find $\alpha = -96 \pm 37\,\mu$K (2.6σ).
- This detection dillutes as more pixels are included

Where is this signal coming from?

From the Zone of Avoidance! (ZoA):



Coincidence with CIZA catalogue



45 of the 64 pixels belong to 5 different galaxy clusters present in the CIZA catalogue

The remaining pixels fail to give a significant tSZ detection.

Conclusions

In WMAP's first year data ...

- ... there are ~ 26 sq-degrees with an average tSZ decrement of $-35 \pm 7\ \mu$K
- ... there is evidence for tSZ signal in ~ 180 sq-degrees in the sky.
- ... most of the tSZ decrements are associated to galaxy clusters, whose typical angular size is 20–30 arcmins.
- ... there is tSZ signal coming from *at least* five different galaxy clusters placed in the ZoA.
- we have found *no* significant evidence for tSZ associated to structures like filaments and sheets in supercluster scales.