SZ effect : a foreground for early CMB spectral distortions

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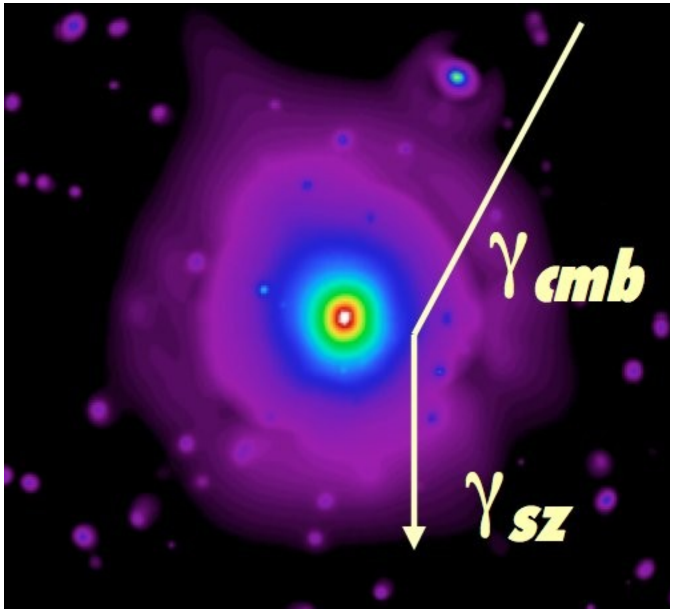
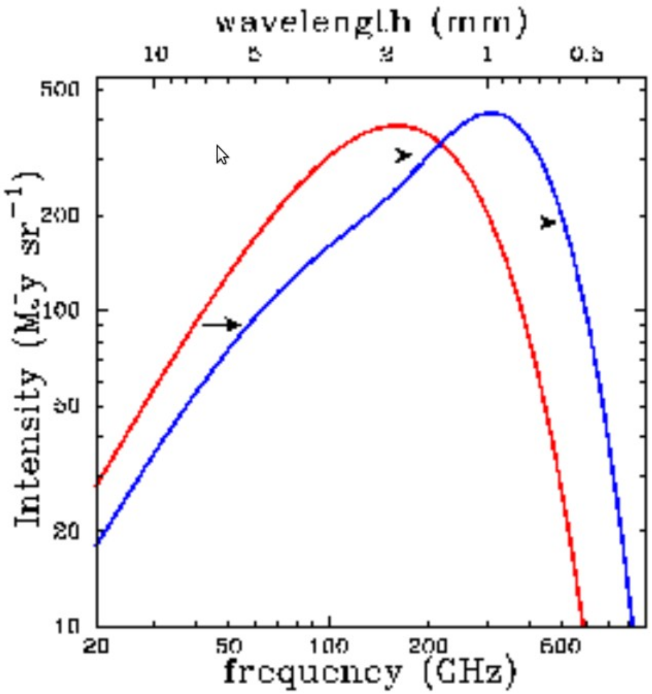
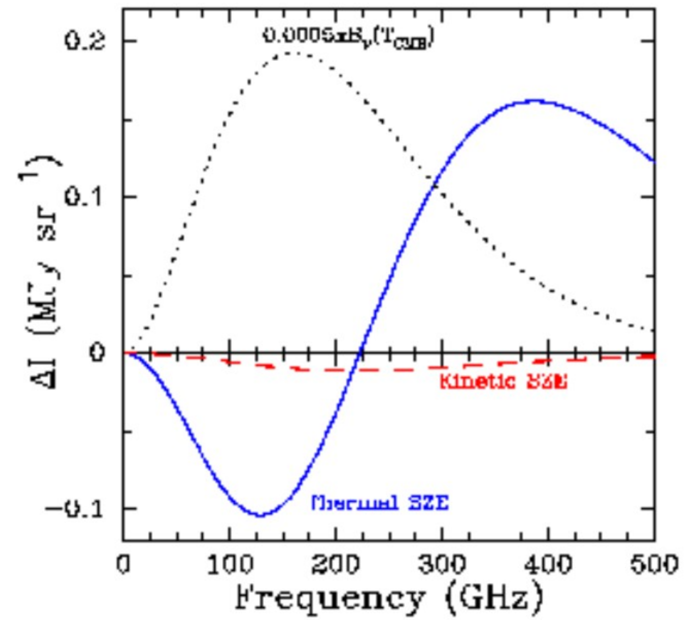
The University of Manchester

CMB spectral distortions from cosmic baryon evolution
Raman Research Institute, Bangalore
July 11-16, 2016

Thermal Sunyaev-Zeldovich effect







y-distortion: inverse Compton scattering of CMB photons by hot gas of electrons in galaxy clusters

Sunyaev & Zeldovich, 1972

- SZ effect does not depend on redshift!

  → robust detection of distant galaxy clusters

- SZ effect scales as $\mathbf{n_e}$ (density of electrons) where X-ray brightness scales as $(\mathbf{n_e})^2$

  → robust probe of the baryon physics in the cluster outskirts

But other CMB spectral distortions !

Planck blackbody distribution

$$\boxed{n_{Pl}(x) = \frac{1}{(e^x - 1)}, \qquad x = h\nu/kT}$$

Bose-Einstein distribution

$$\boxed{n_{BE}(x) = \frac{1}{(e^{x+\mu} - 1)}, \qquad x = h\nu/kT}$$

Chemical potential

- **y-type** distortions (SZ) in late universe

$$n \approx n_{Pl} + y\frac{xe^x}{(e^x - 1)^2}\left(x\frac{e^x + 1}{e^x - 1} - 4\right)$$

spectral signature

impact on CMB of LSS after Recombination epoch ($0 < z < 10^4$)

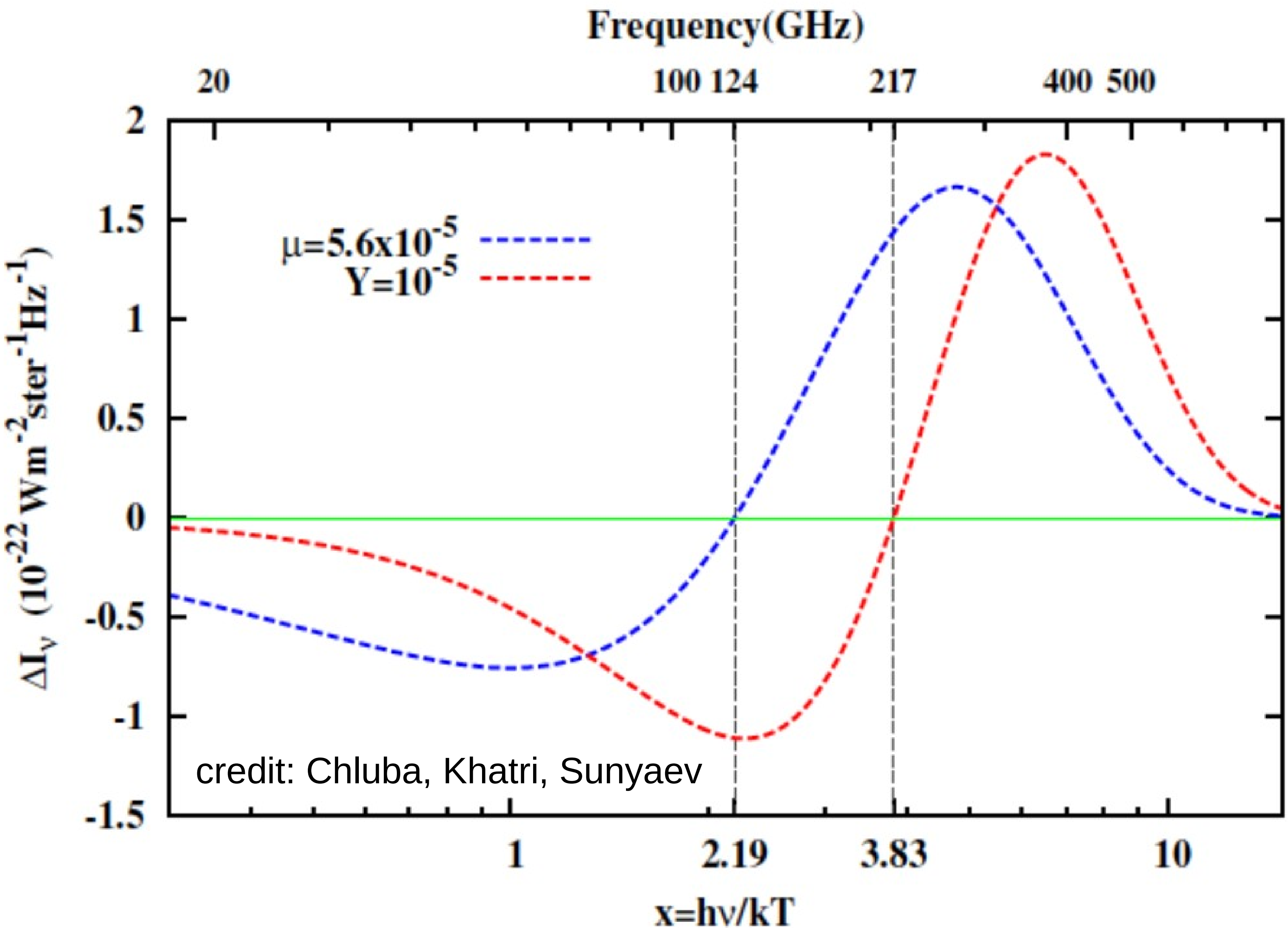
- **μ-type** distortions in early universe

$$n_{BE} \approx n_{Pl} + \mu\frac{e^x}{(e^x - 1)^2}\left(\frac{x}{2.19} - 1\right)$$

spectral signature

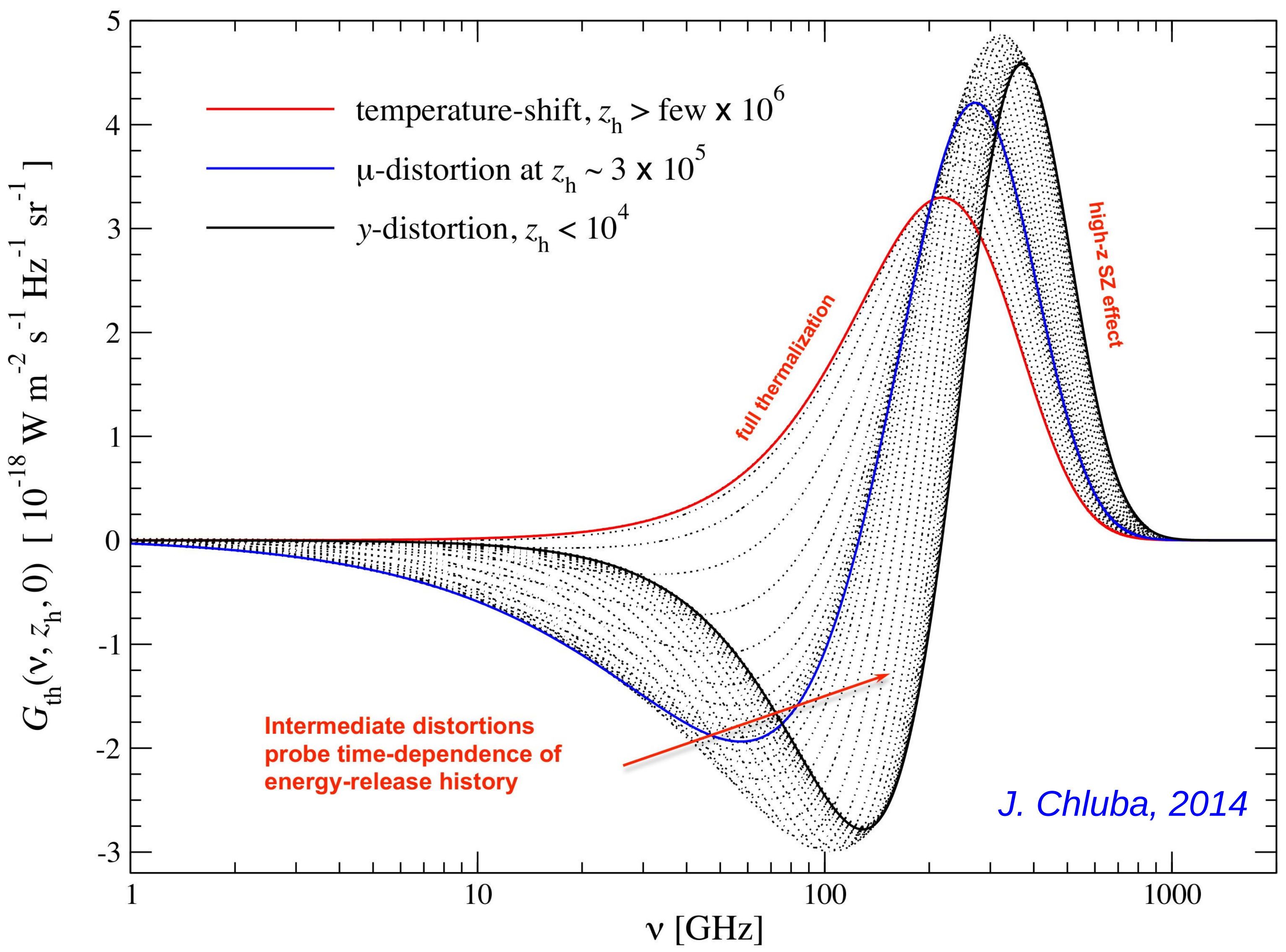
impact on CMB of energy injections before Recombination epoch ($z > 10^5$)

2 components with distinct spectral signatures

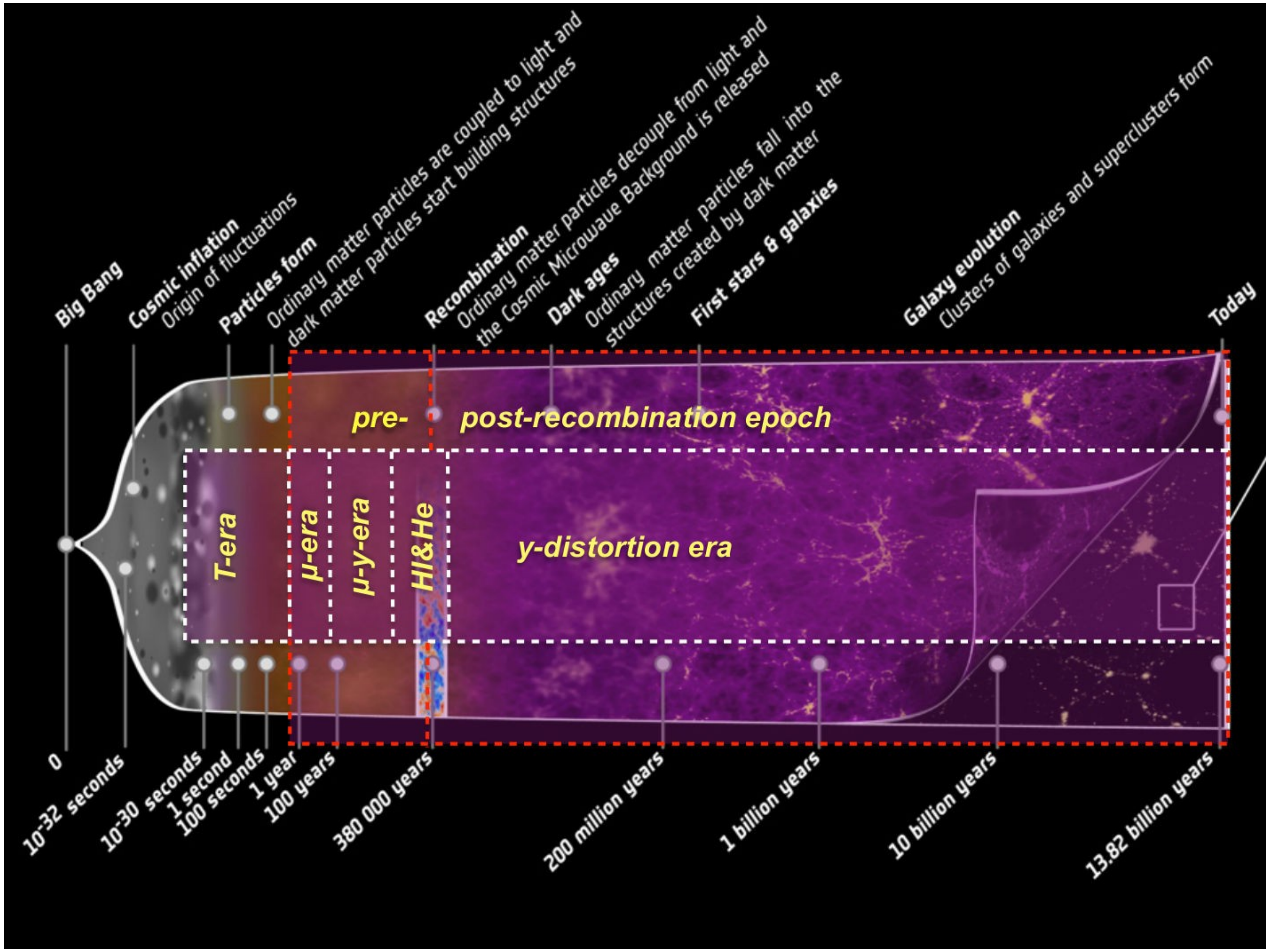


Component separation is doable !

Multiple CMB spectral distortions



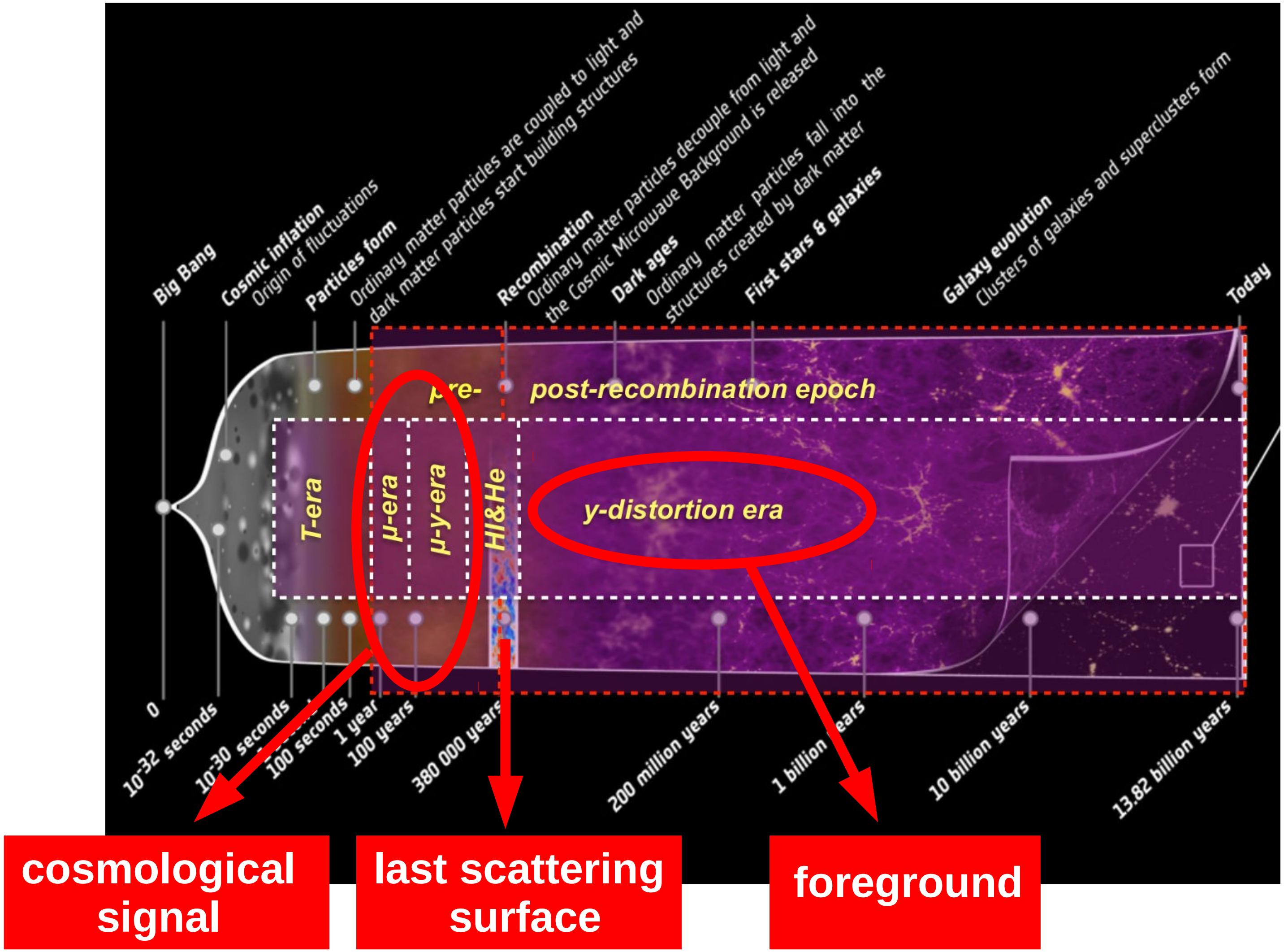
Cosmic history of CMB spectral distortions



J. Chluba, 2014

- **CMB spectral distortions = interactions between CMB photons and (dark) matter**
- CMB spectral distortions open a new window toward very early universe
  to watch behind the last scattering surface !
- Late-time **y-type** distortion (SZ effect) is a **foreground** to early-time **μ-type** distortion

y-distortions : a foreground to μ-type distortions



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- **CMB spectral distortions = interactions between CMB photons and (dark) matter**
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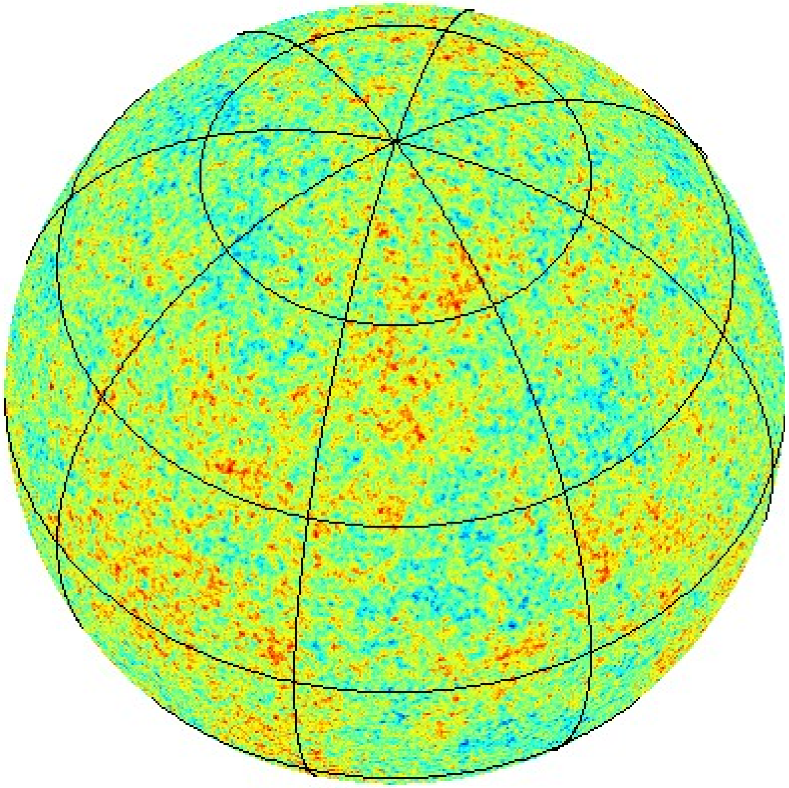
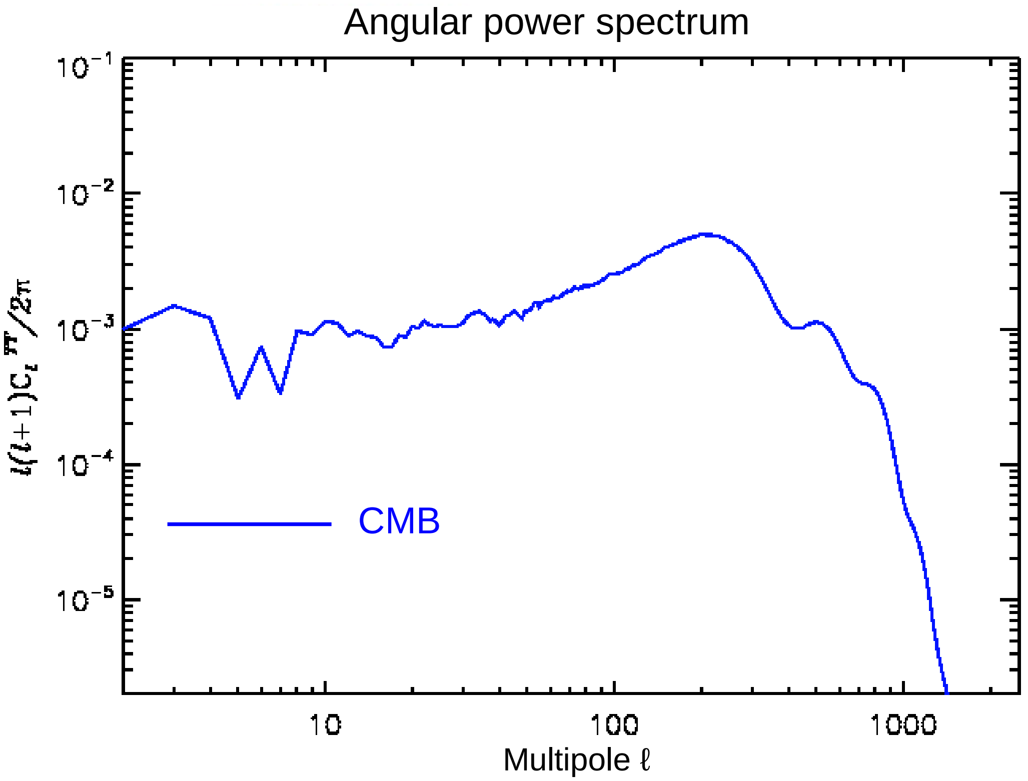
Component separation : the problem





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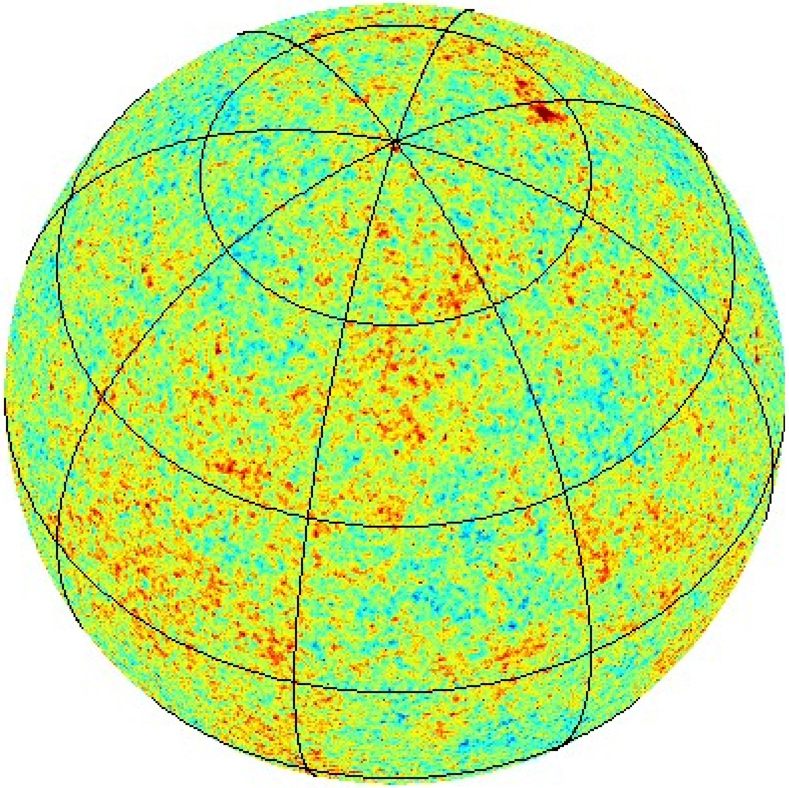

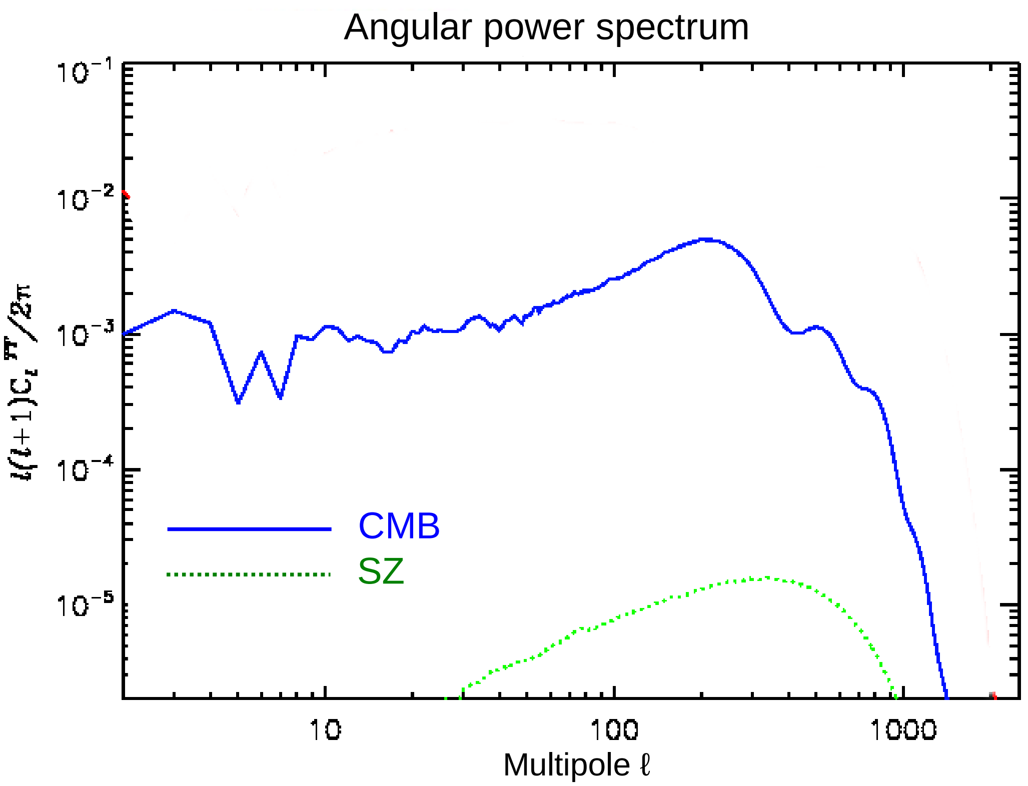

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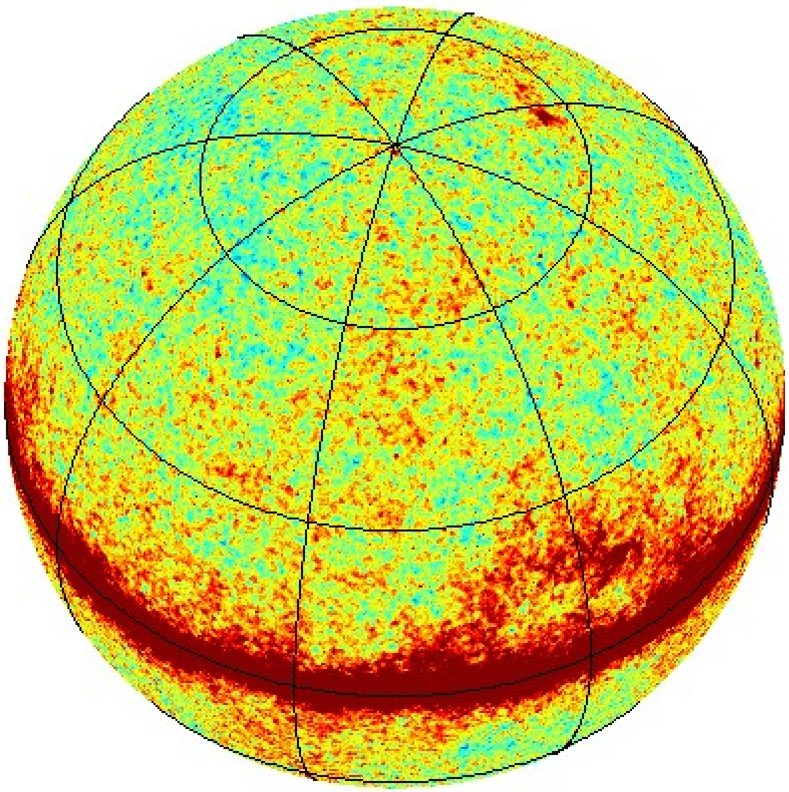
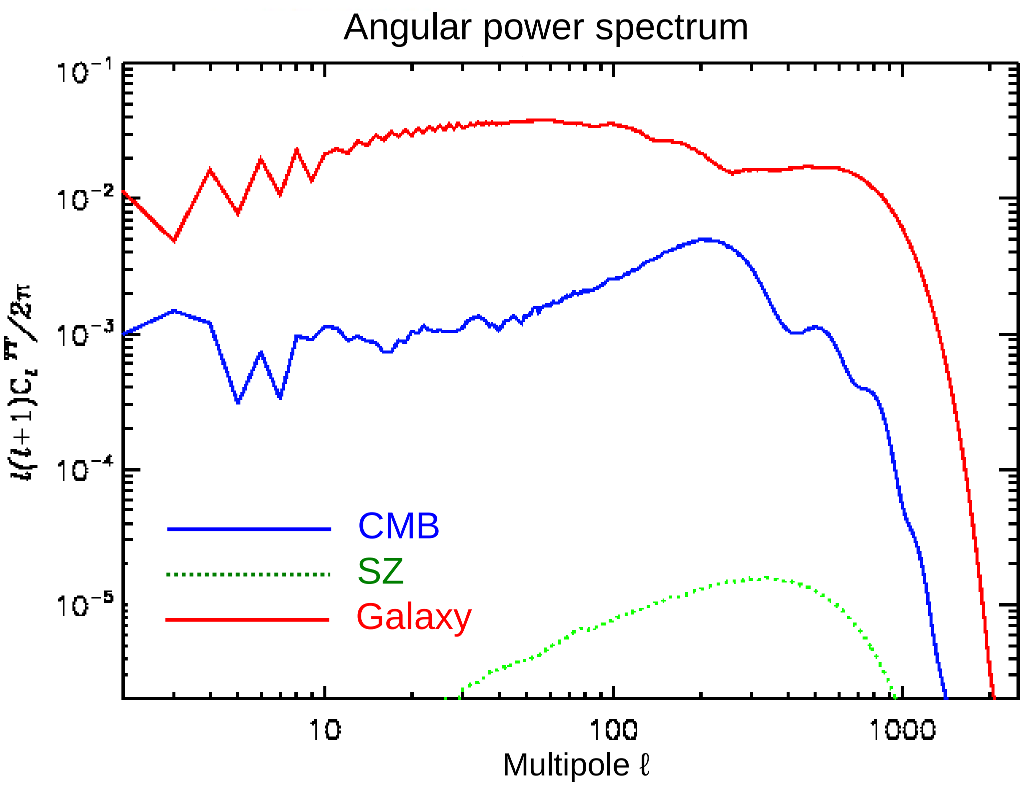
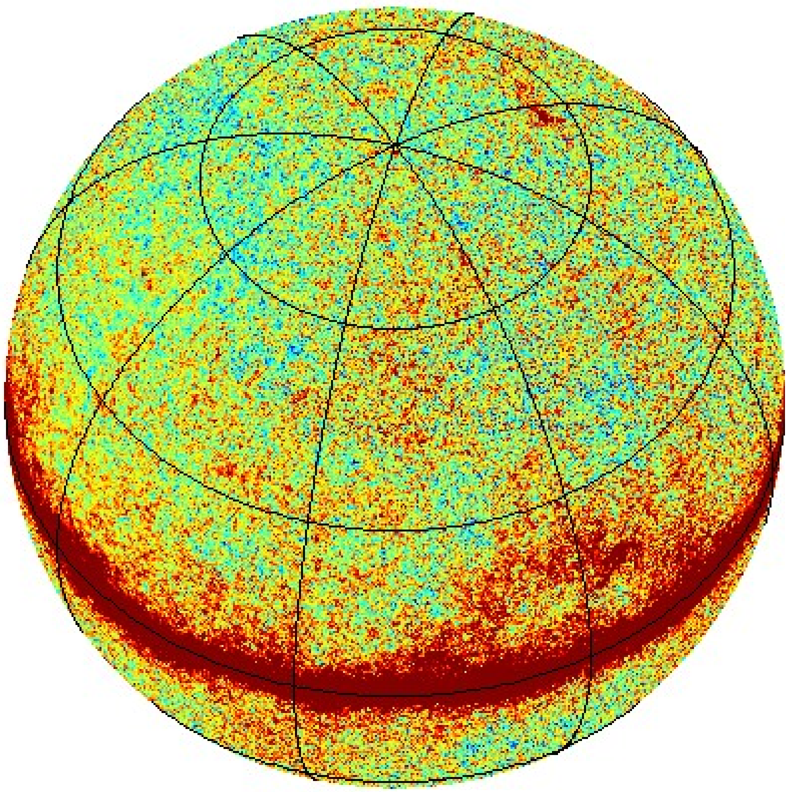
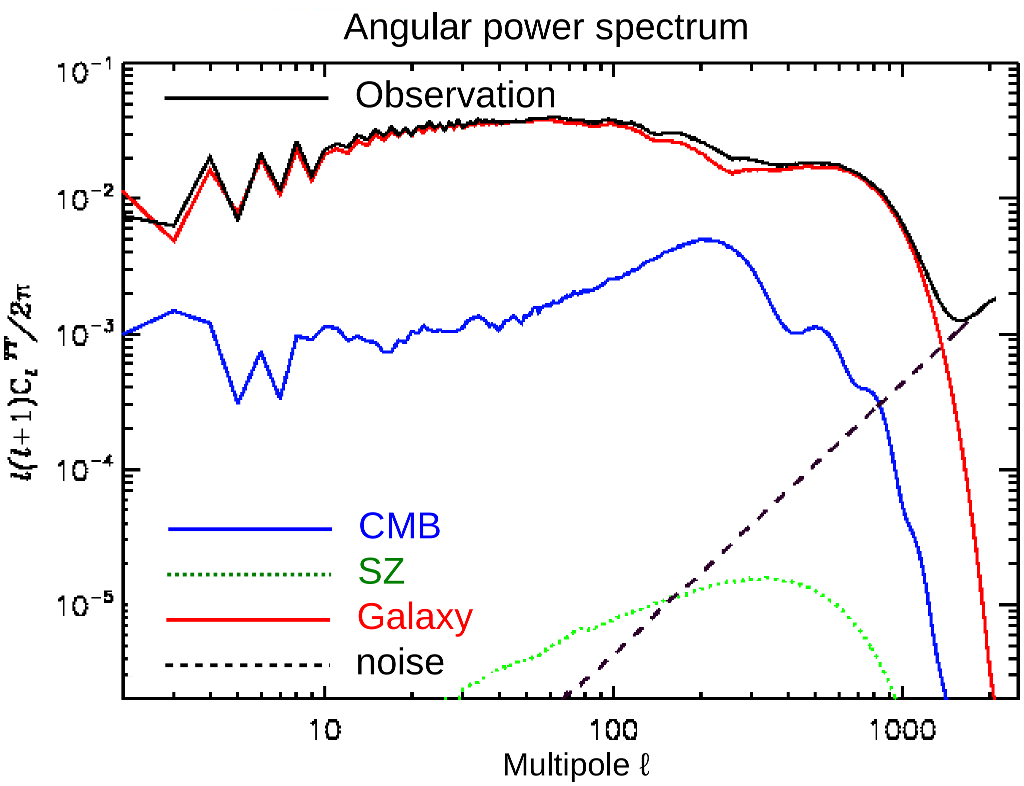
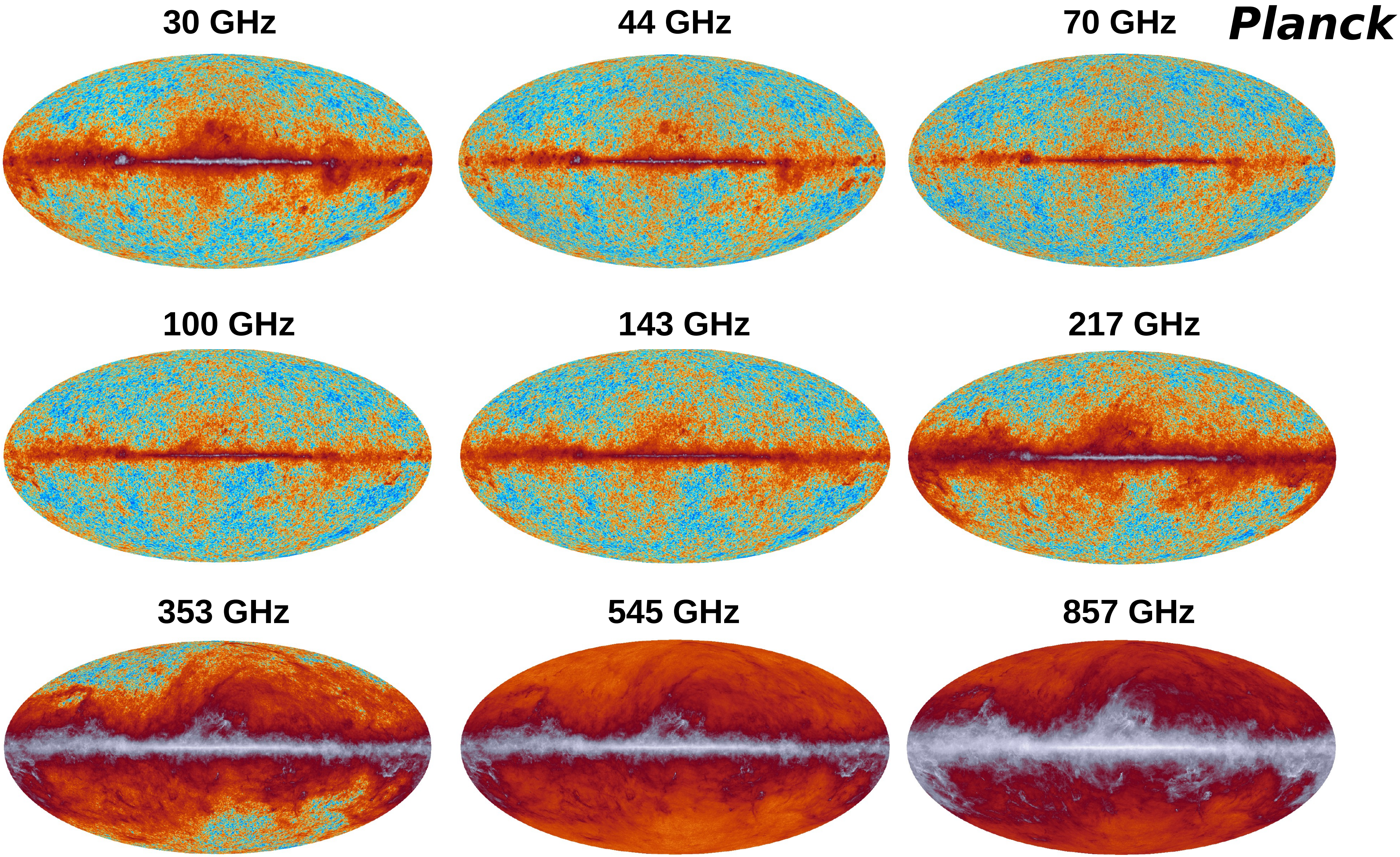




Component separation : the problem







Strategy: combine multi-frequency observations in order to separate the components on the sole basis of their distinct spectral, spatial, statistical properties

Standard Internal Linear Combination (ILC)

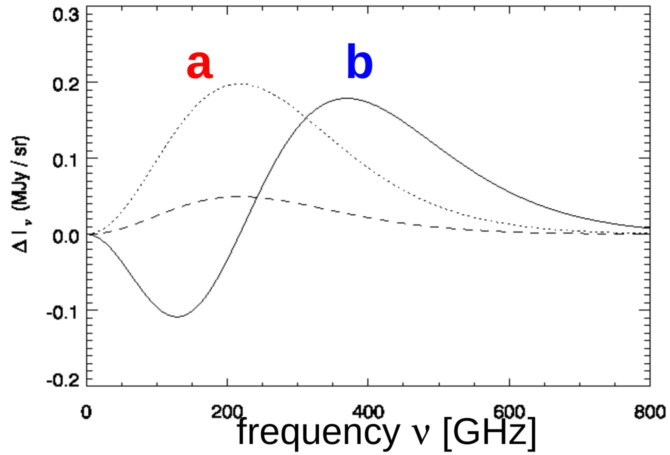
observation "noise"

$$X_\nu(p) = a_\nu S_{CMB}(p) + b_\nu S_{SZ}(p) + N_\nu(p)$$

$$\hat{S}(p) = \sum w_\nu x_\nu(p)$$

where
$$\begin{cases} \text{variance } \langle \hat{s}^2 \rangle \text{ minimum} \\ \sum w_\nu a_\nu = 1 \end{cases}$$

spectral emission laws

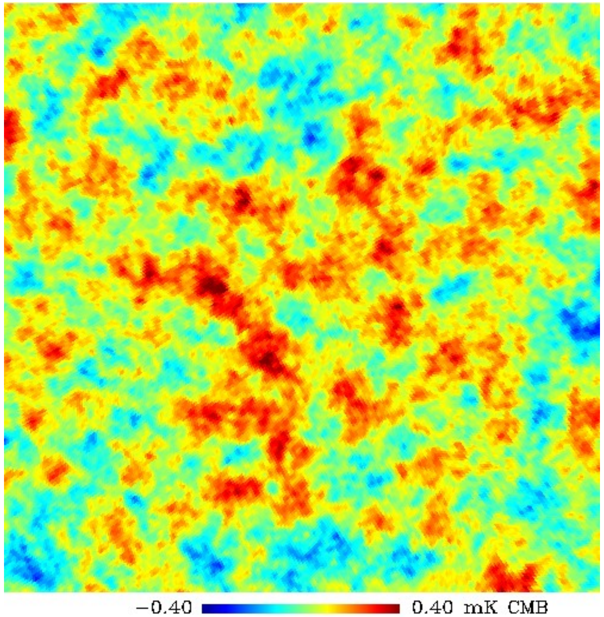


standard ILC

$$\boxed{W = \frac{a^T C^{-1}}{a^T C^{-1} a}}$$

Benett et al, 2003, Tegmark et al, 2003
Eriksen et al, 2004, Delabrouille et al, 2009

CMB (+ KSZ) reconstruction



Standard Internal Linear Combination (ILC)

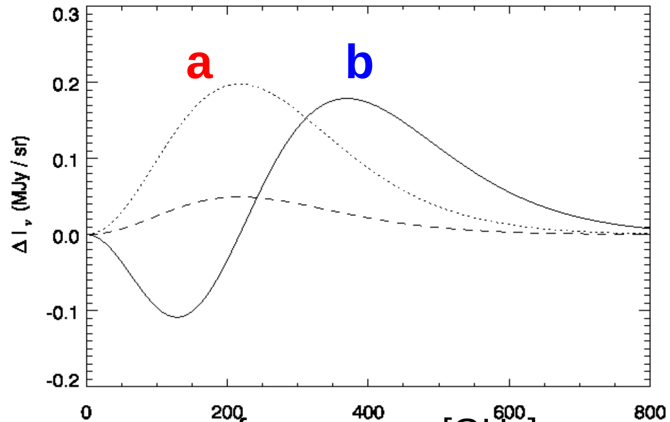
observation　　　　　　　　　　　　　　　　　　　　　　　　“noise”

$$X_\nu(p) = \color{red}{a_\nu}\, \color{black}{S}_{\color{red}{CMB}}(p) + \color{blue}{b_\nu}\, \color{black}{S}_{\color{blue}{SZ}}(p) + N_\nu(p)$$

$$\hat{S}(p) = \sum w_\nu\, x_\nu(p)$$

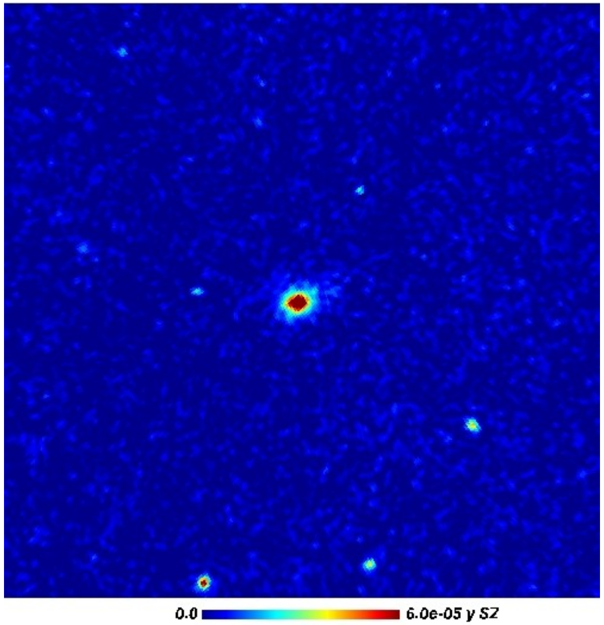
where
$$\begin{cases} \text{variance } \langle \hat{s}^2 \rangle \text{ minimum} \\ \sum w_\nu\, \color{blue}{b_\nu} \color{black}{= 1} \end{cases}$$

spectral emission laws



frequency ν [GHz]

Thermal SZ reconstruction

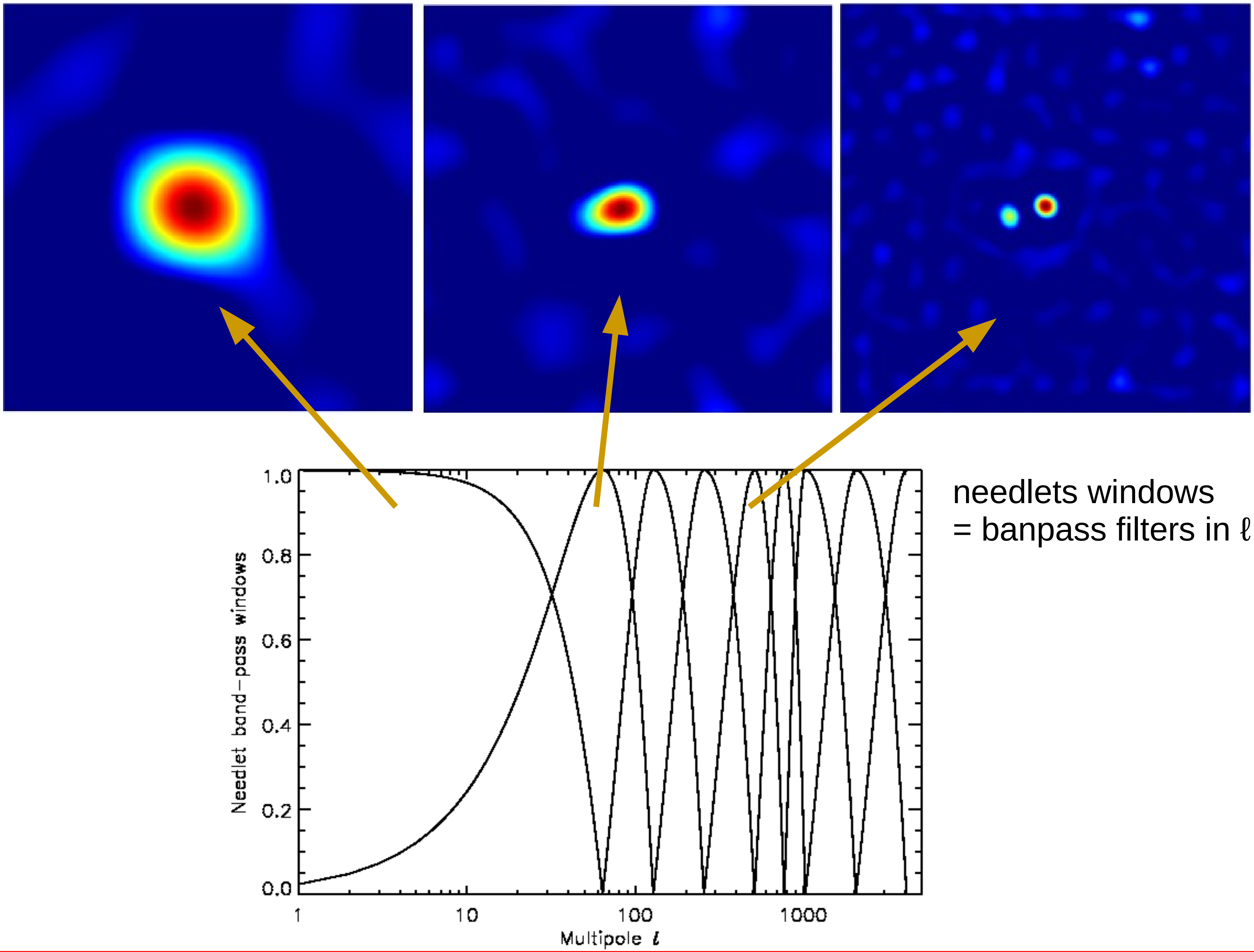


standard ILC

$$\boxed{W = \frac{\color{blue}{b^T} \color{black}{C^{-1}}}{\color{blue}{b^T} \color{black}{C^{-1}} \color{blue}{b}}}$$

Benett et al, 2003, Tegmark et al, 2003
Eriksen et al, 2004, Delabrouille et al, 2009
Remazeilles et al. 2011, 2013

Wavelet based ILC method : NILC



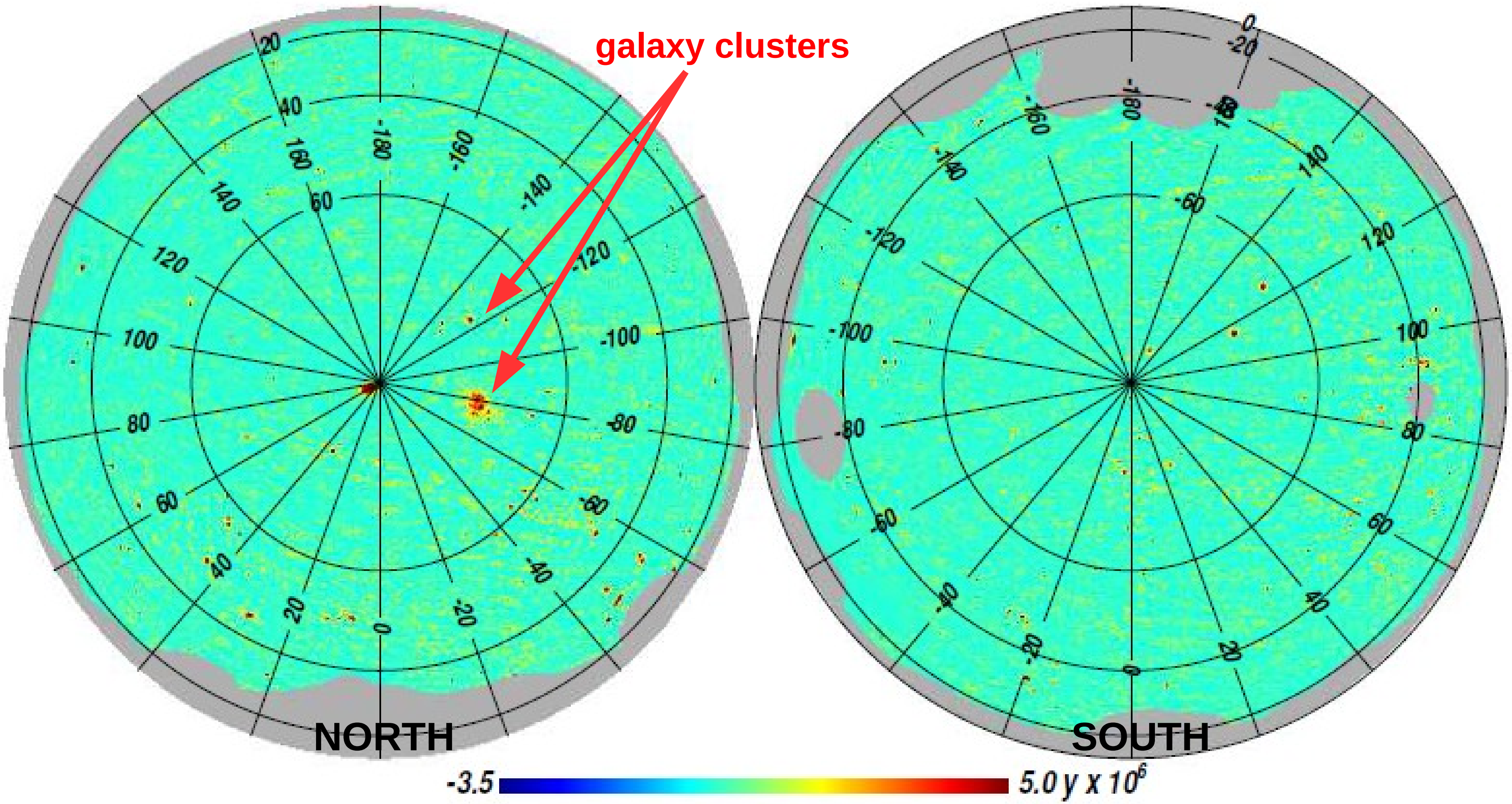
needlets windows
= banpass filters in ℓ

Wavelets (needlets) can adapt the component separation to the local conditions of contamination, in both (harmonic) ℓ-space and (real) pixel space

Planck Sunyaev-Zeldovich all-sky map

"Planck 2015 Results. XXII. A map of the thermal Sunyaev-Zeldovich effect" A&A accepted (2016)

Planck 2015 released !



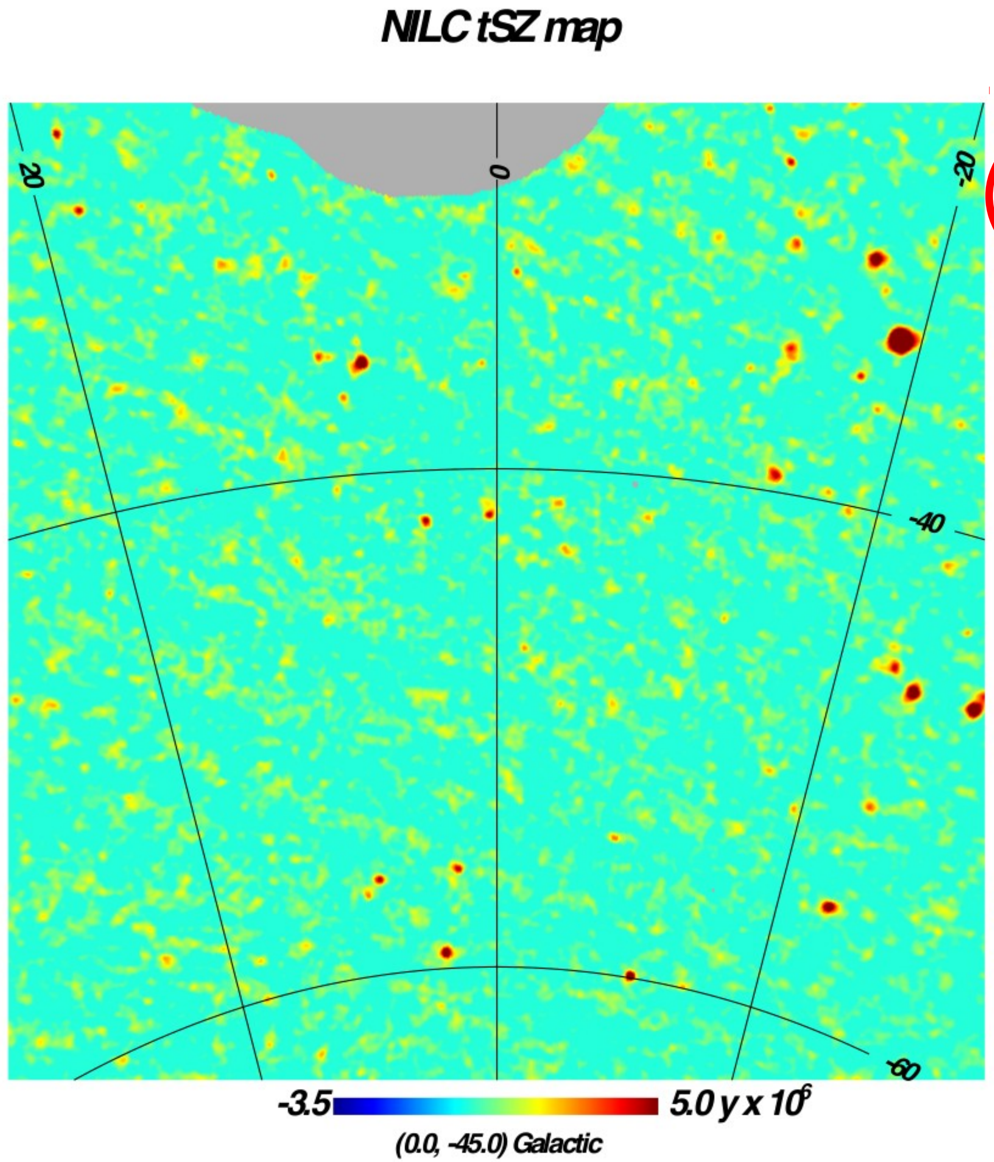
NILC

wavelet-based component-separation method

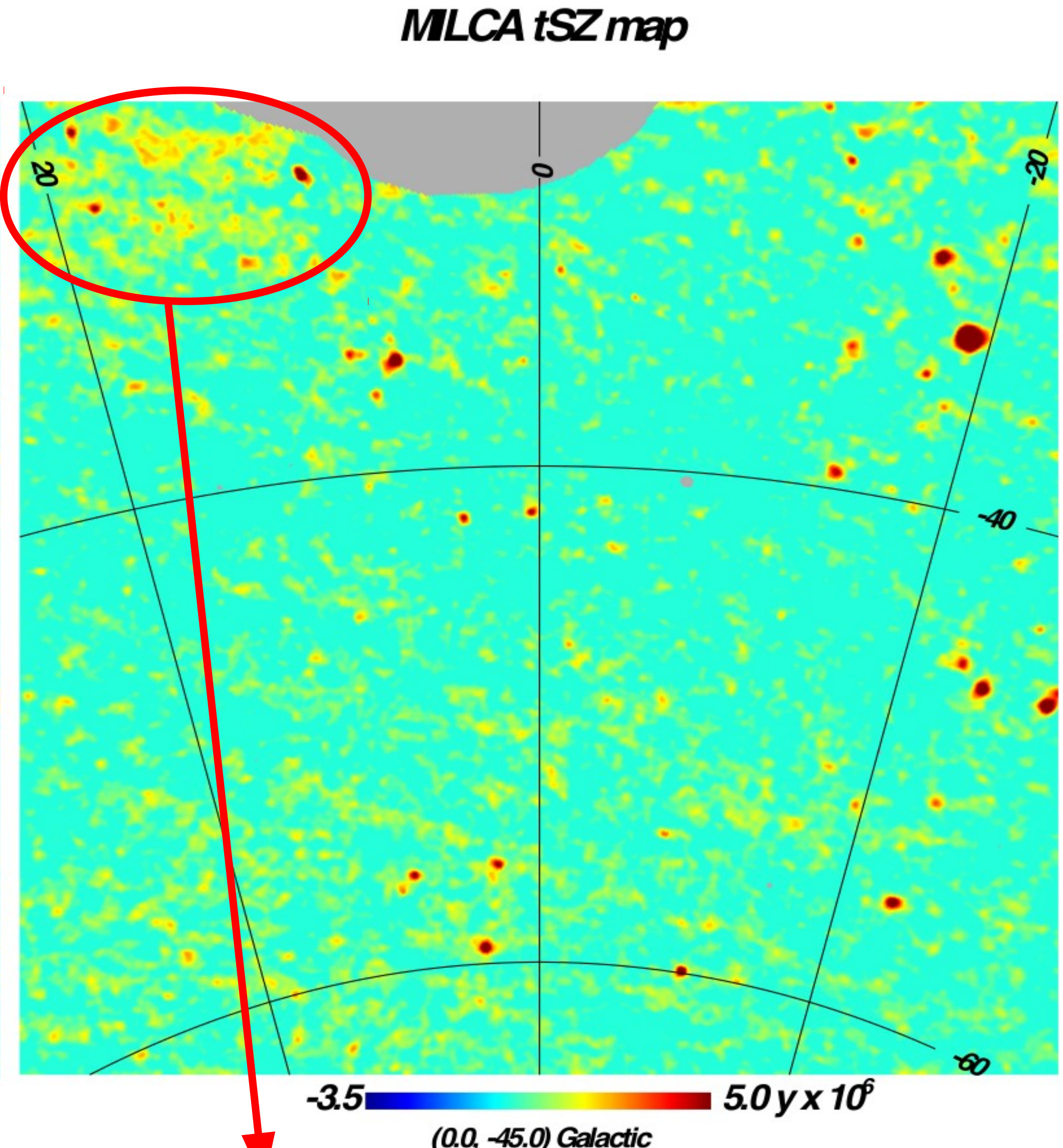
Remazeilles, *Delabrouille, Cardoso, MNRAS 2011*
Remazeilles, *Aghanim, Douspis, MNRAS 2013*

Planck SZ map: NILC vs MILCA

Remazeilles et al., MNRAS 2011



Hurier et al., A&A 2013

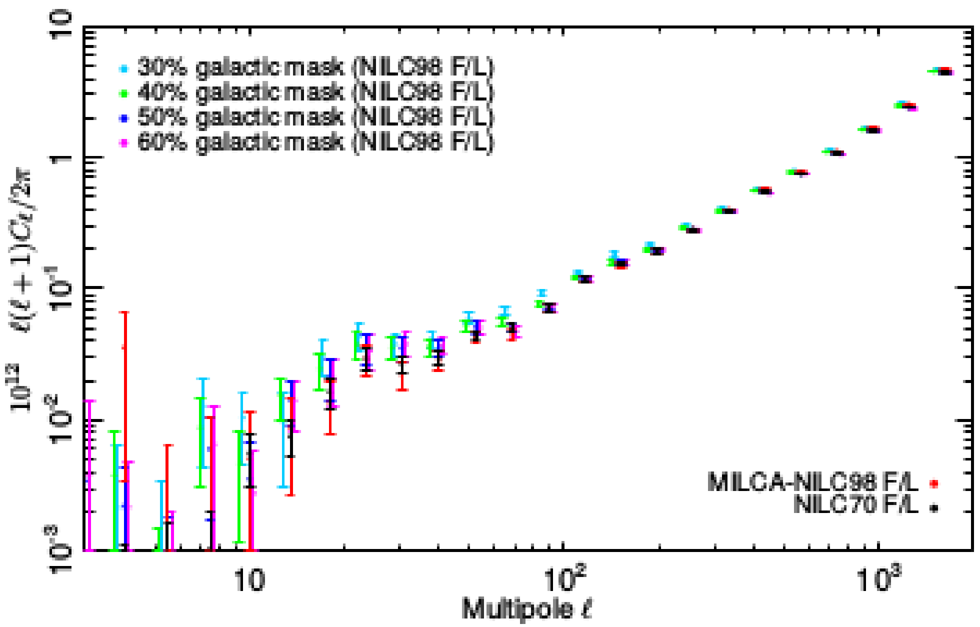


"Planck 2015 Results. XXII. A map of the thermal Sunyaev-Zeldovich effect" A&A accepted (2016)

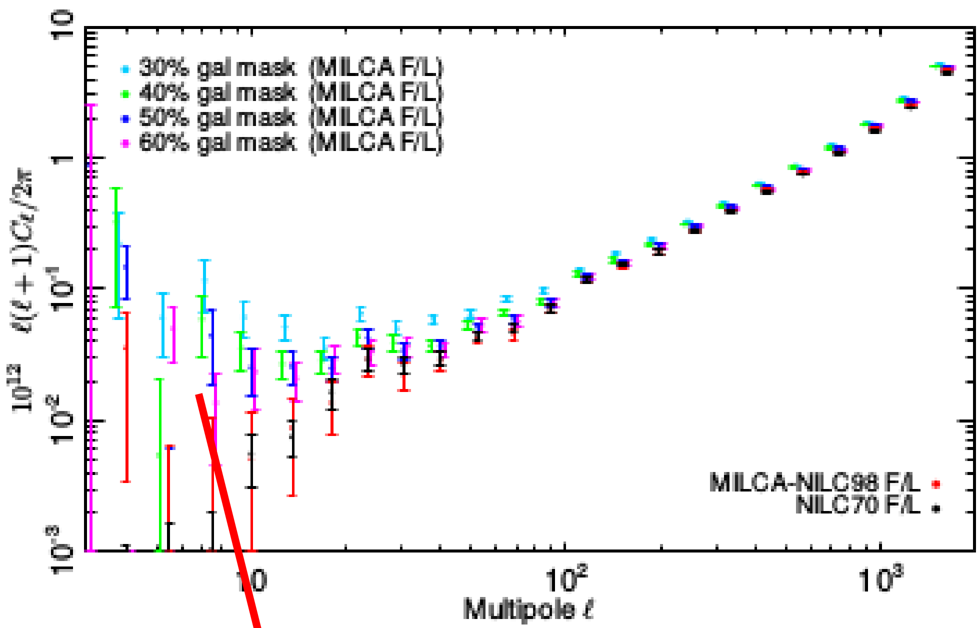
More foreground residuals

Planck SZ power spectrum: NILC vs MILCA

NILC



MILCA



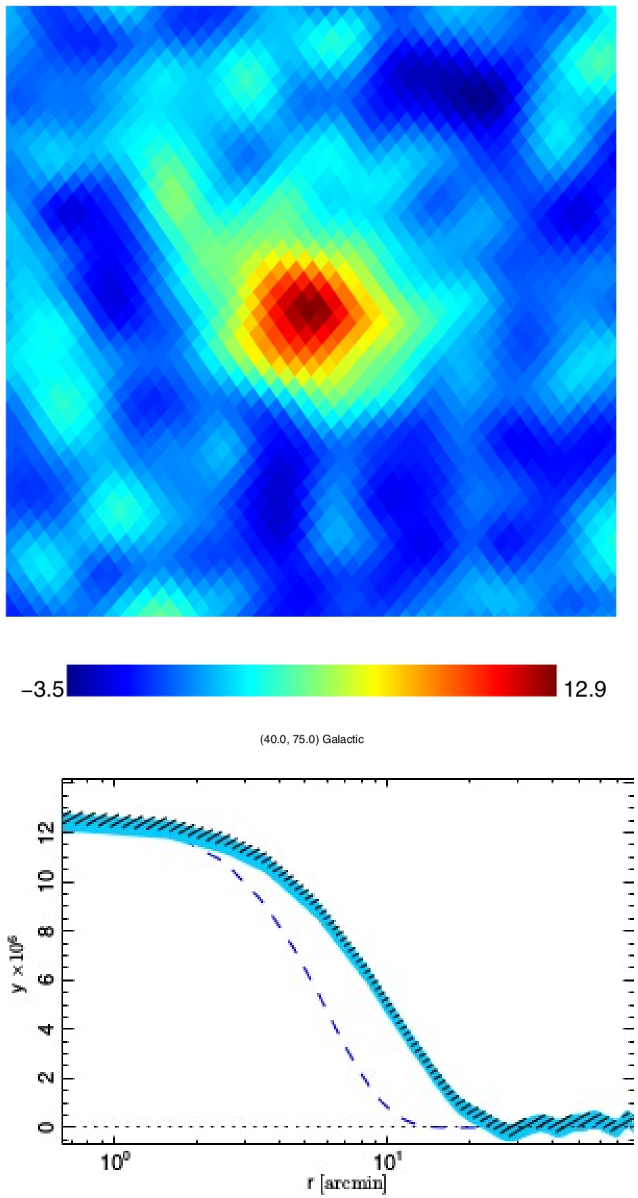
"Planck 2015 Results. XXII. A map of the thermal Sunyaev-Zeldovich effect" A&A accepted (2016)

more Galactic foreground contamination on large scales

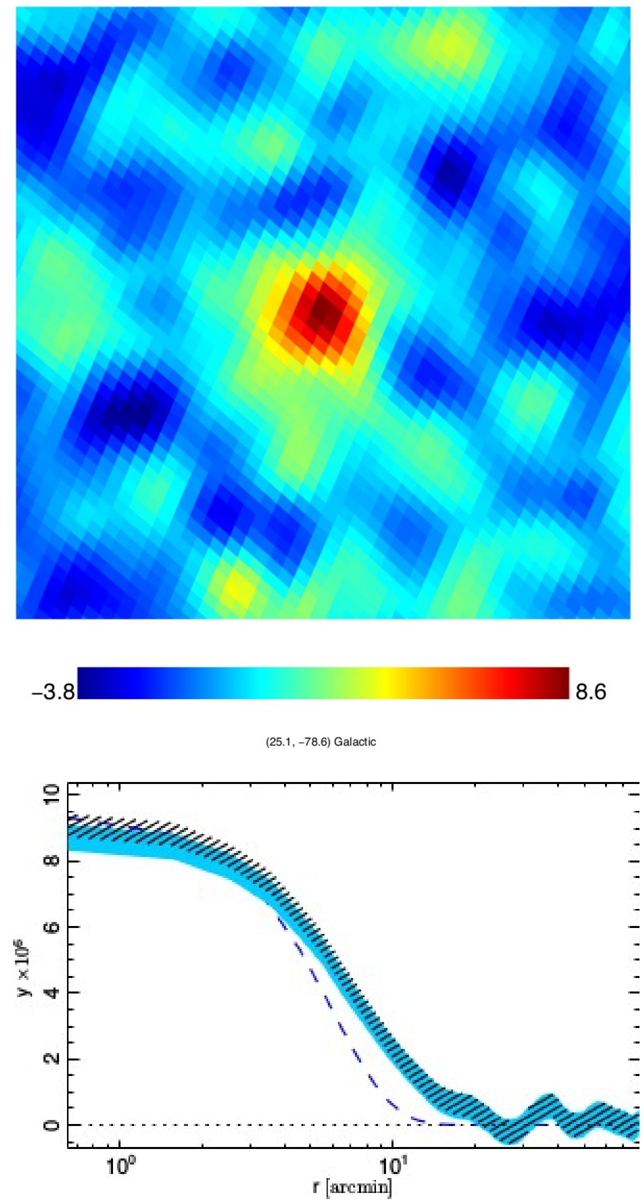
Both SZ maps are released by the *Planck* Collaboration:
http://pla.esac.esa.int/pla/

Planck SZ clusters in NILC y-map

Unlike matched filters, NILC is blind: it does not make assumptions on cluster profiles !



NILC y-map

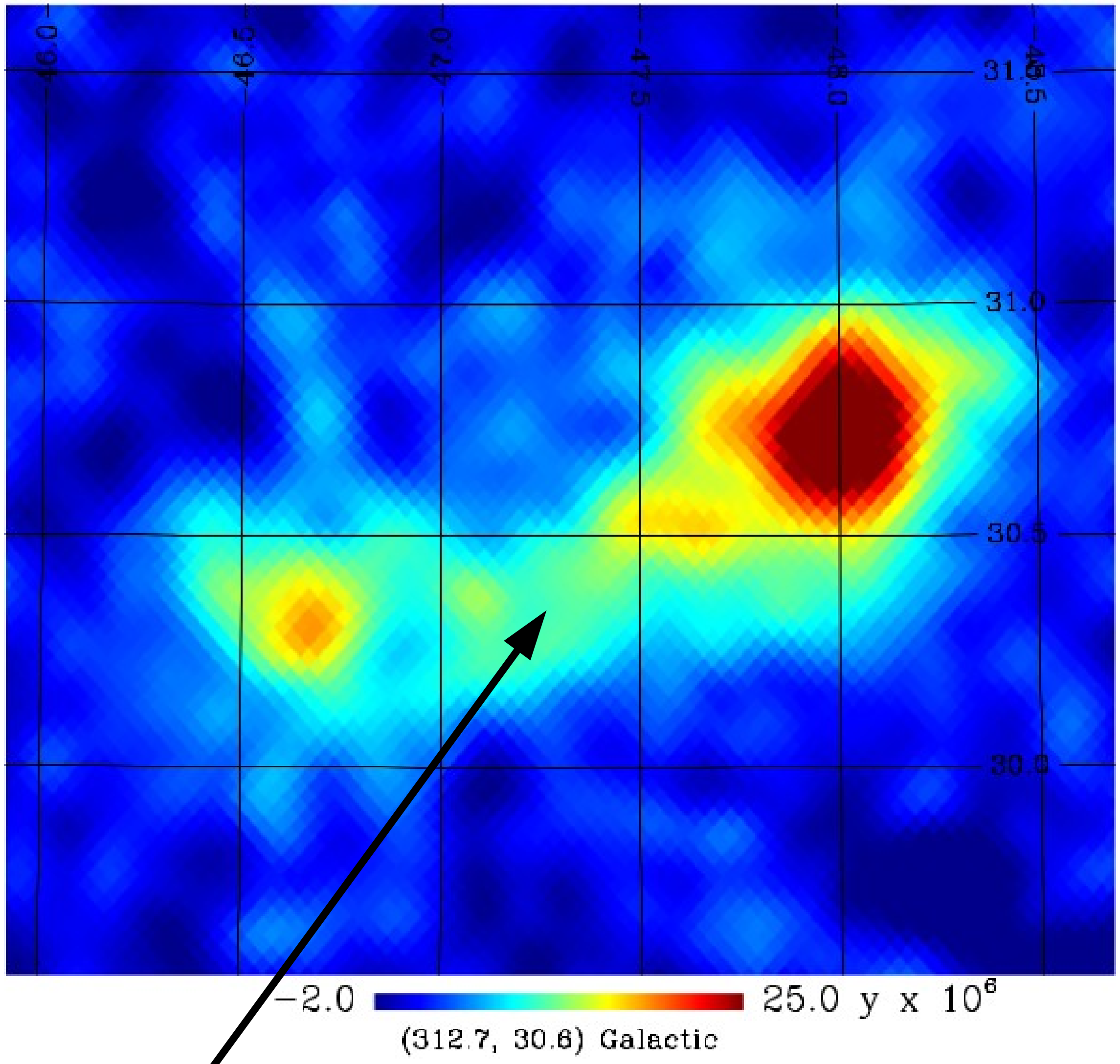


"Planck 2015 Results. XXII. A map of the thermal Sunyaev-Zeldovich effect" A&A accepted (2016)

Merging systems: Shapley supercluster

NILC y-map

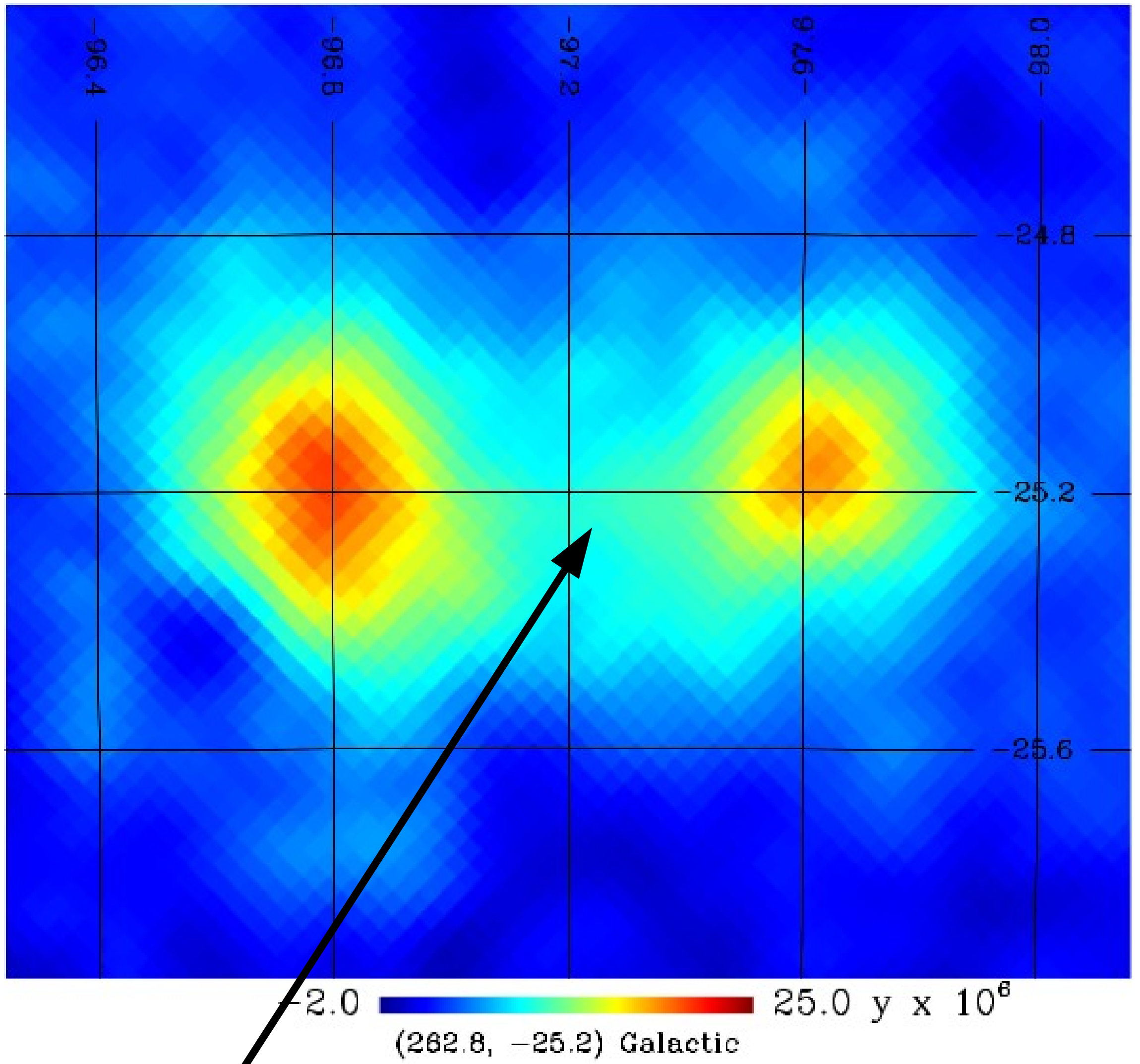
Planck 2015 results. XXII. A&A accepted (2016)



Thermal SZ probes the cluster outskirts (WHIM), which may account for the missing baryons in the universe

Merging systems: A3395 - A3391

NILC y-map

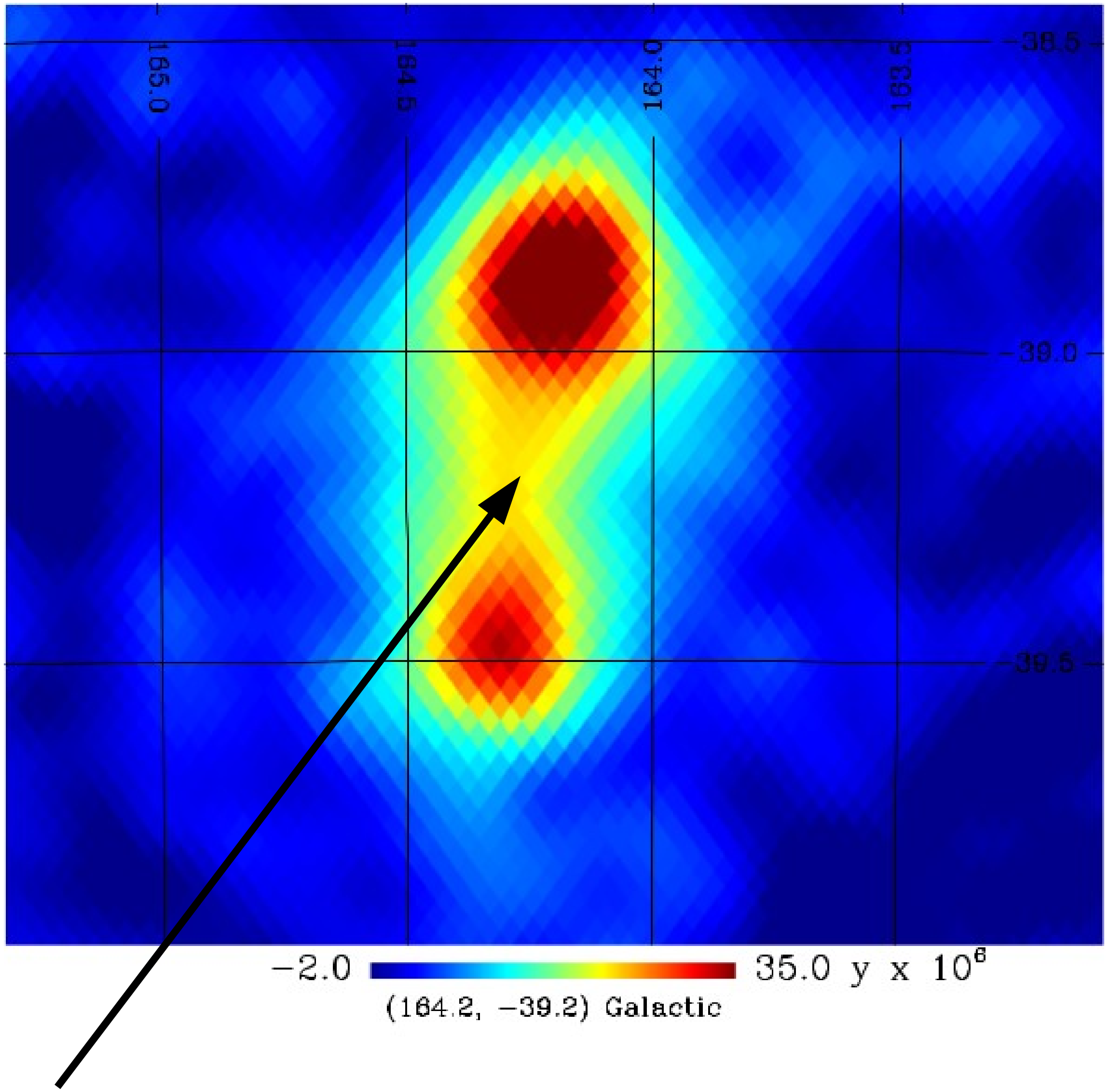


Planck 2015 results. XXII. A&A accepted (2016)

Thermal SZ probes the cluster outskirts (WHIM), which may account for the missing baryons in the universe

Merging systems: A339 - A401

NILC y-map

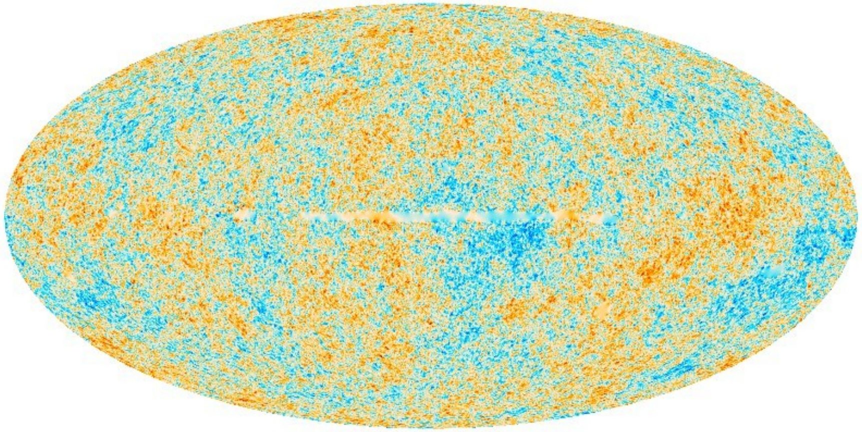


Planck 2015 results. XXII. A&A accepted (2016)

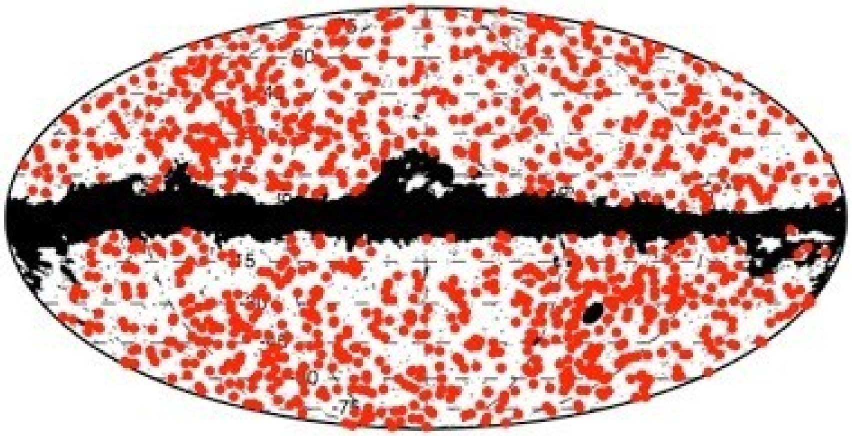
Thermal SZ probes the cluster outskirts (WHIM), which may account for the missing baryons in the universe

SZ residuals in the *Planck* CMB map

Released *Planck* CMB map

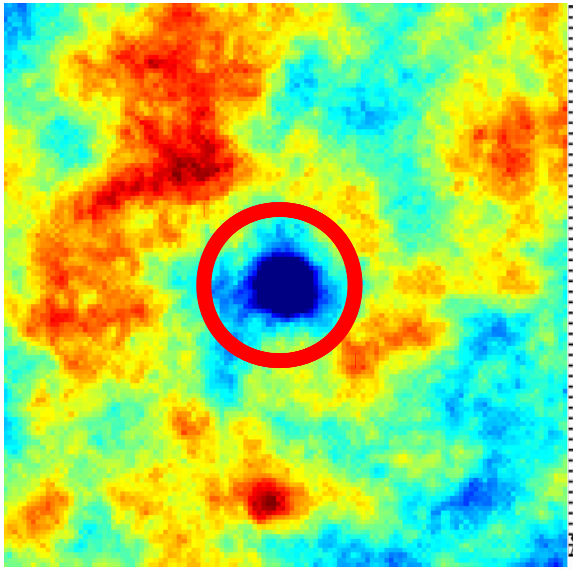


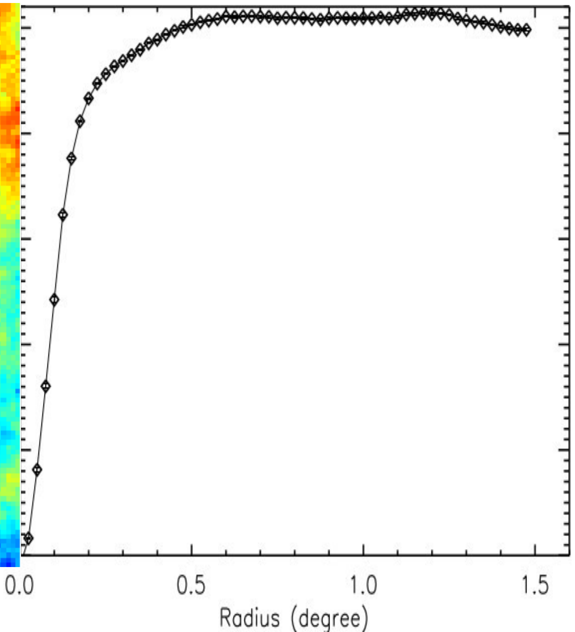
Planck cluster catalogue



Let's stack the *Planck* CMB map in direction of galaxy clusters :

residual SZ in CMB !
(LSS)





Standard Internal Linear Combination (ILC)

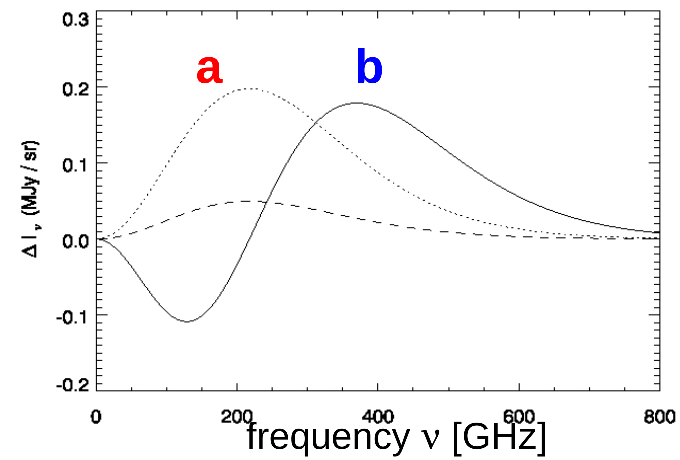
observation "noise"

$$X_\nu(p) = a_\nu S_{CMB}(p) + b_\nu S_{SZ}(p) + N_\nu(p)$$

$$\hat{s}(p) = \sum w_\nu x_\nu(p)$$

$$\text{where} \begin{cases} \text{variance } \langle \hat{s}^2 \rangle \text{ minimum} \\ \sum w_\nu a_\nu = 1 \end{cases}$$

spectral emission laws

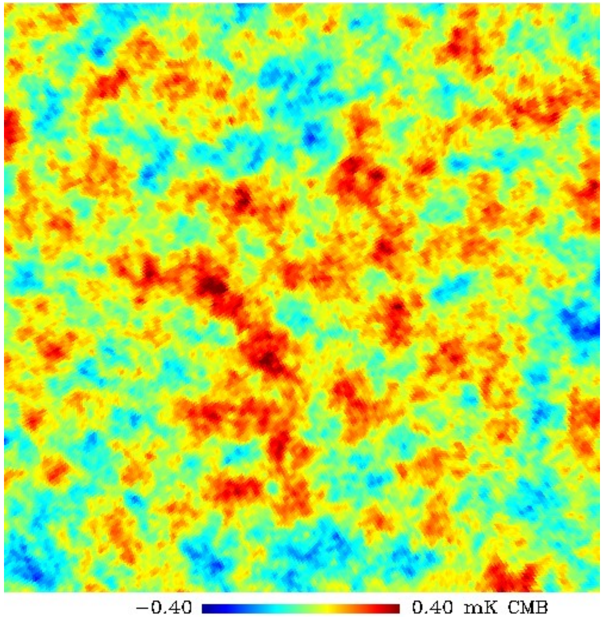


standard ILC

$$\boxed{W = \frac{a^T C^{-1}}{a^T C^{-1} a}}$$

Benett et al, 2003, Tegmark et al, 2003
Eriksen et al, 2004, Delabrouille et al, 2009

CMB (+ KSZ) reconstruction



Constrained Internal Linear Combination

observation "noise"

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where
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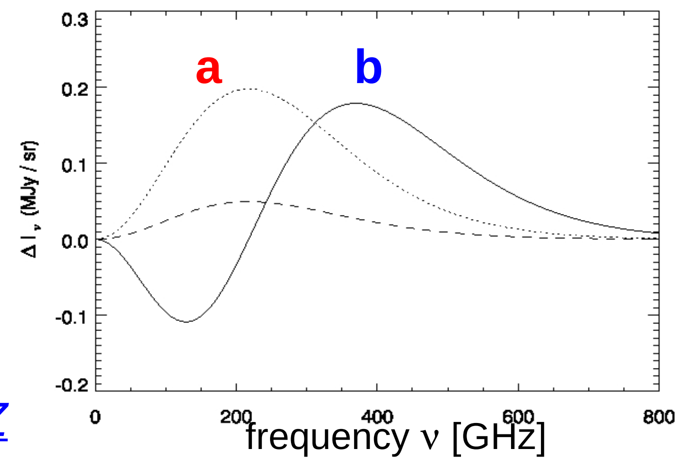
extra constraint
to kill the thermal SZ

spectral emission laws



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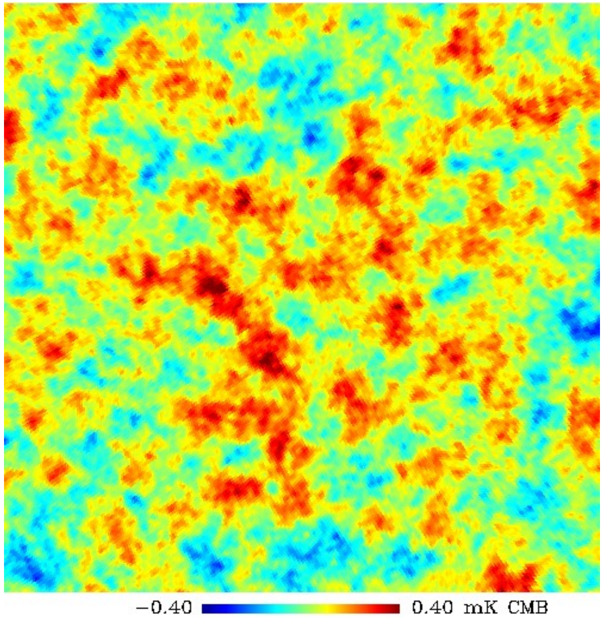


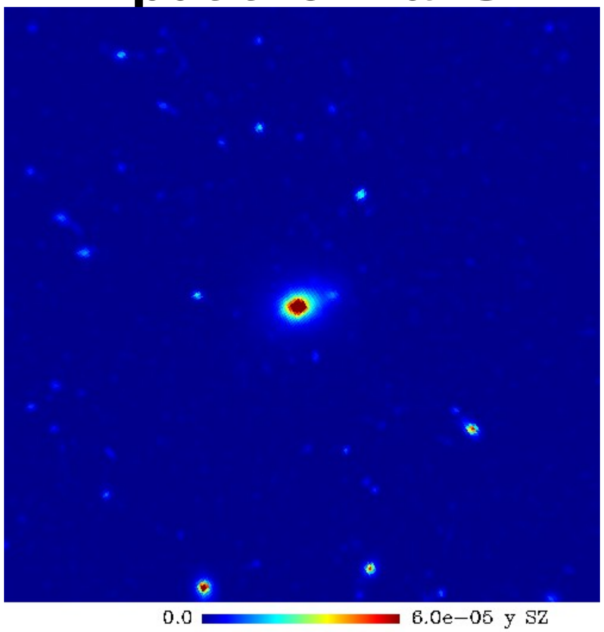
Constrained ILC

$$\boxed{W = \frac{(b^T C^{-1} b)\, a^T C^{-1} - (a^T C^{-1} a)\, b^T C^{-1}}{(a^T C^{-1} a)(b^T C^{-1} b) - (a^T C^{-1} b)^2}}$$

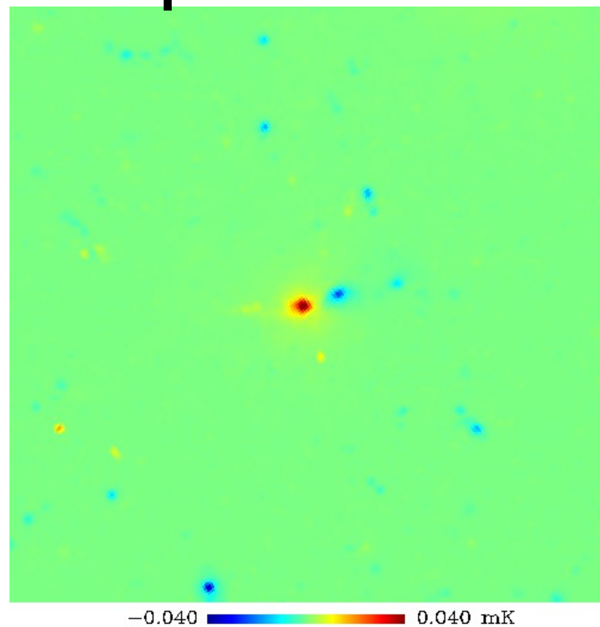
Remazeilles, Delabrouille, Cardoso, *MNRAS, 2011*

Standard ILC

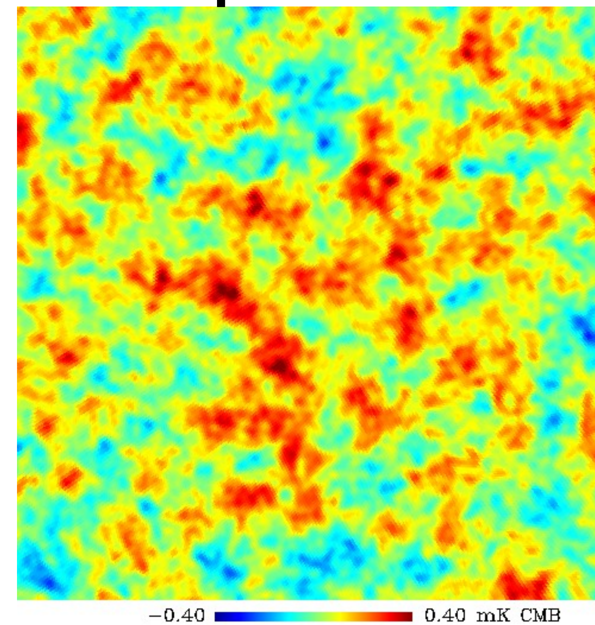
input thermal SZ



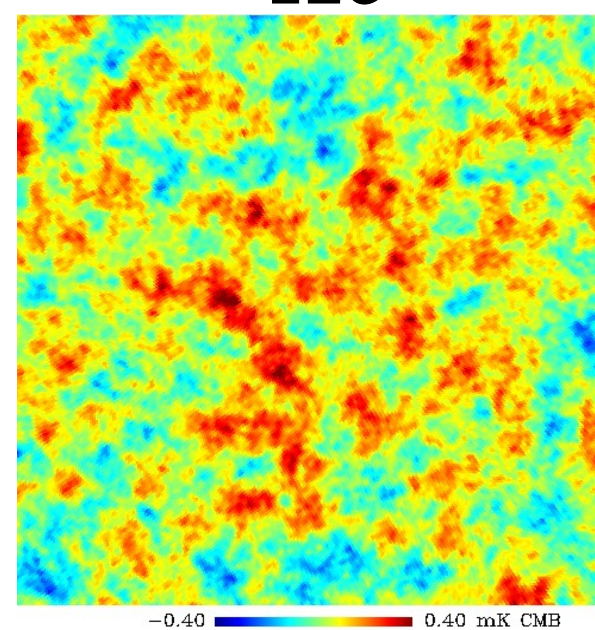
input kinetic SZ



input CMB



ILC



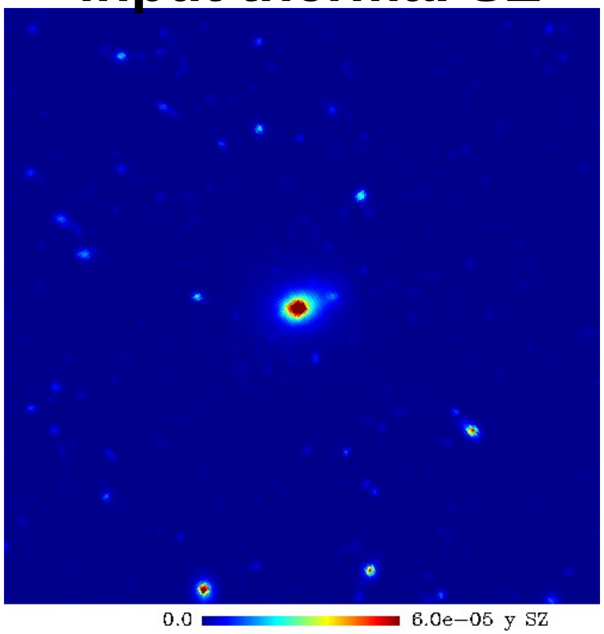
Standard ILC

$$W = \frac{a^T C^{-1}}{a^T C^{-1} a}$$

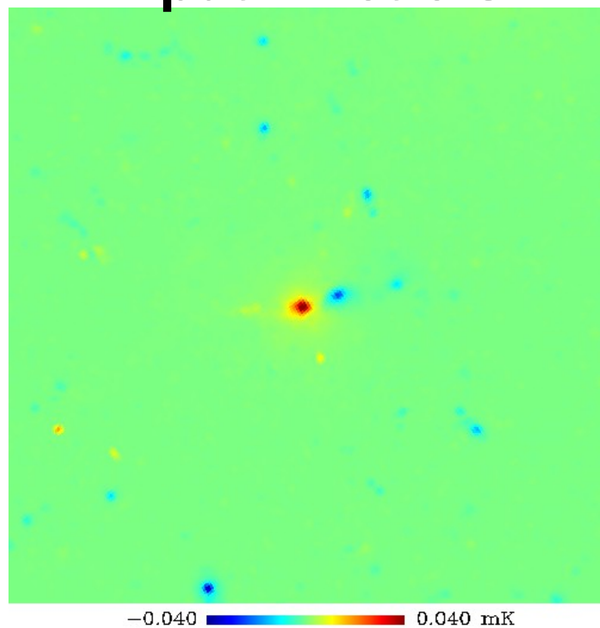
Bennett et al., 2003, Tegmark et al., 2003, Eriksen et al., 2004, Delabrouille et al., 2009

Standard ILC

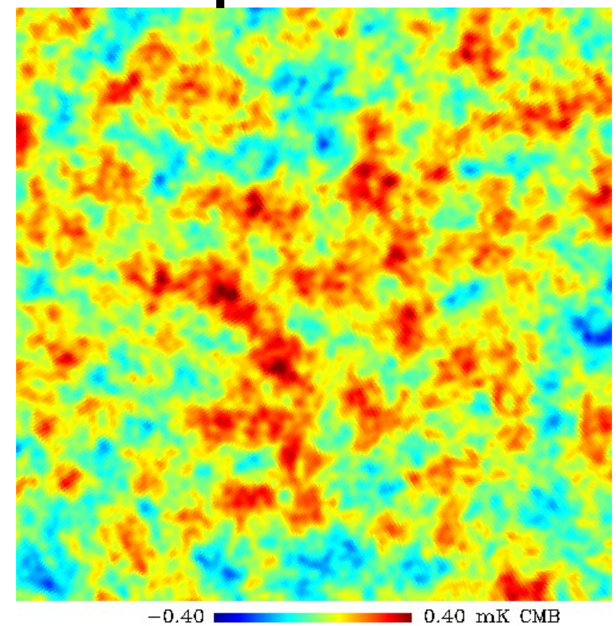
input thermal SZ



input kinetic SZ

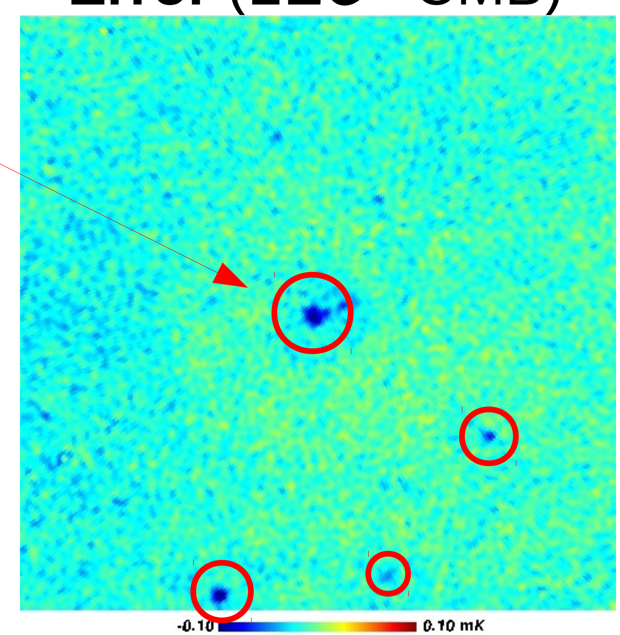


input CMB



Error (ILC - CMB)

thermal SZ residuals !
(clusters in the CMB)



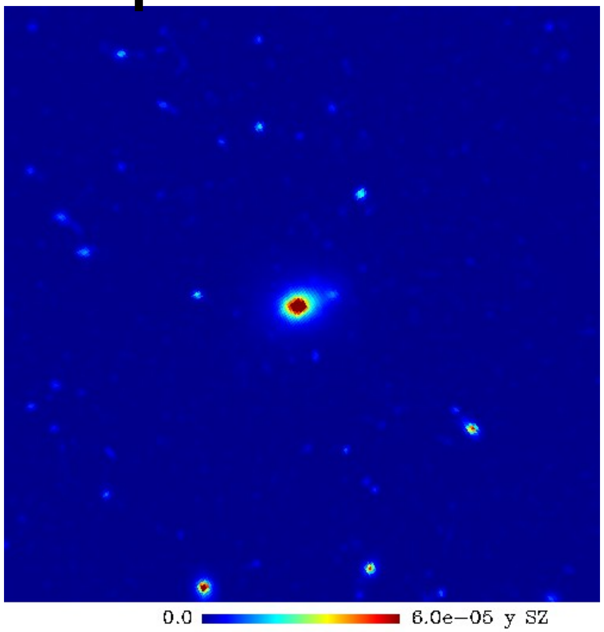
Standard ILC

$$W = \frac{a^T C^{-1}}{a^T C^{-1} a}$$

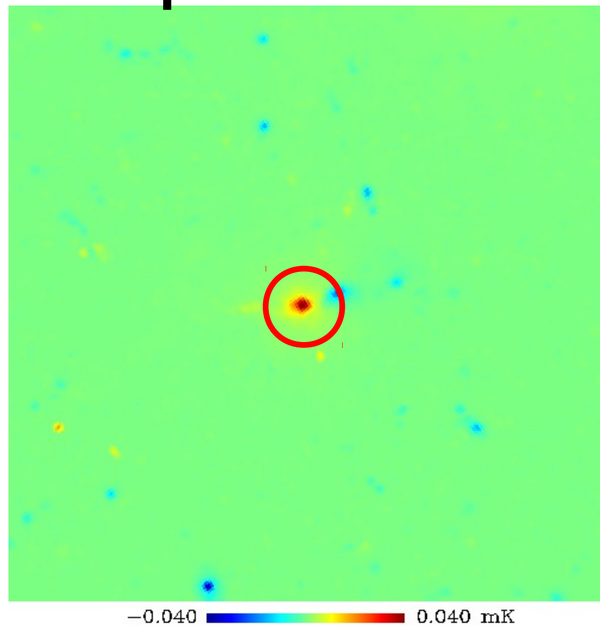
Bennett et al., 2003, Tegmark et al., 2003, Eriksen et al., 2004, Delabrouille et al., 2009

Constrained ILC

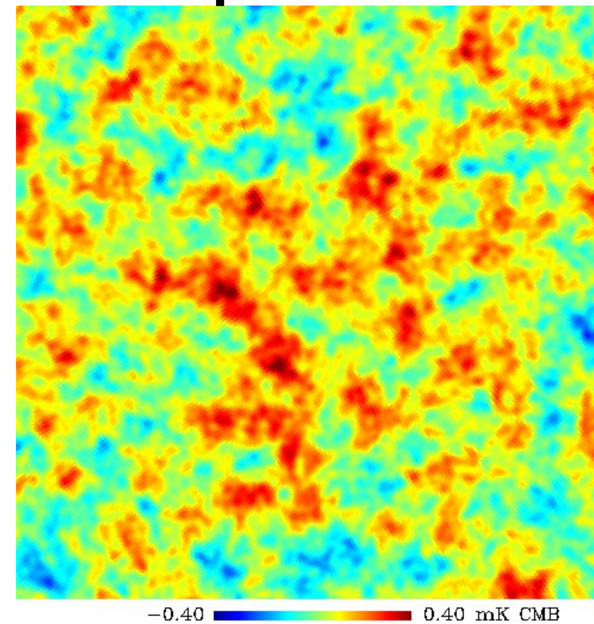
input thermal SZ



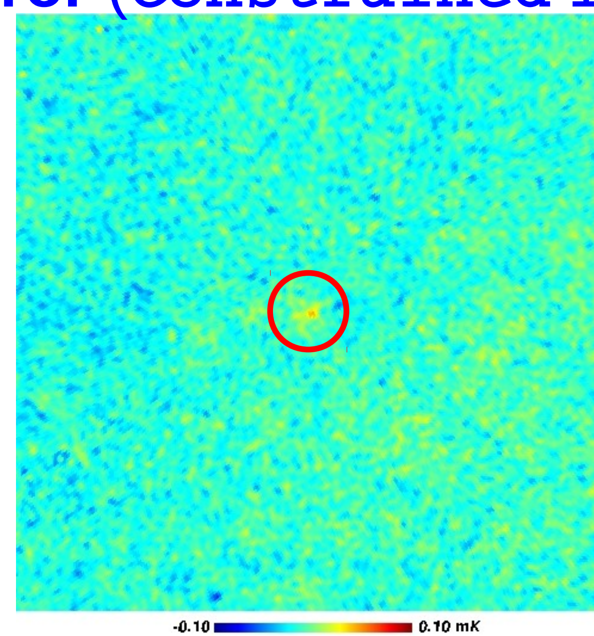
input kinetic SZ



input CMB



Error (Constrained ILC)

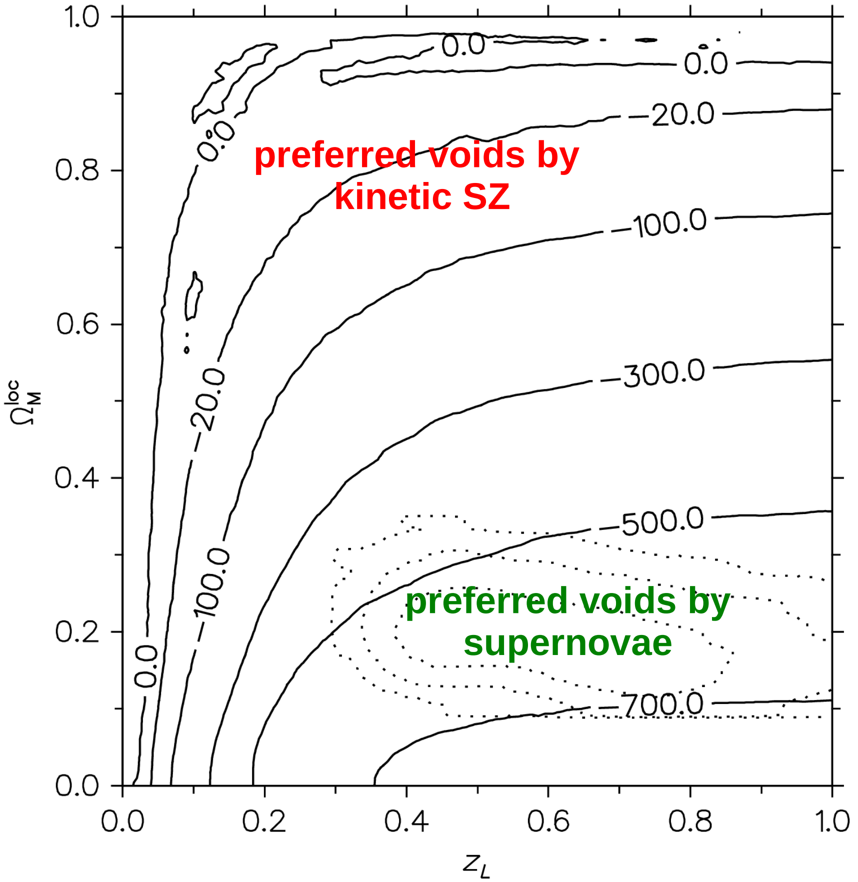


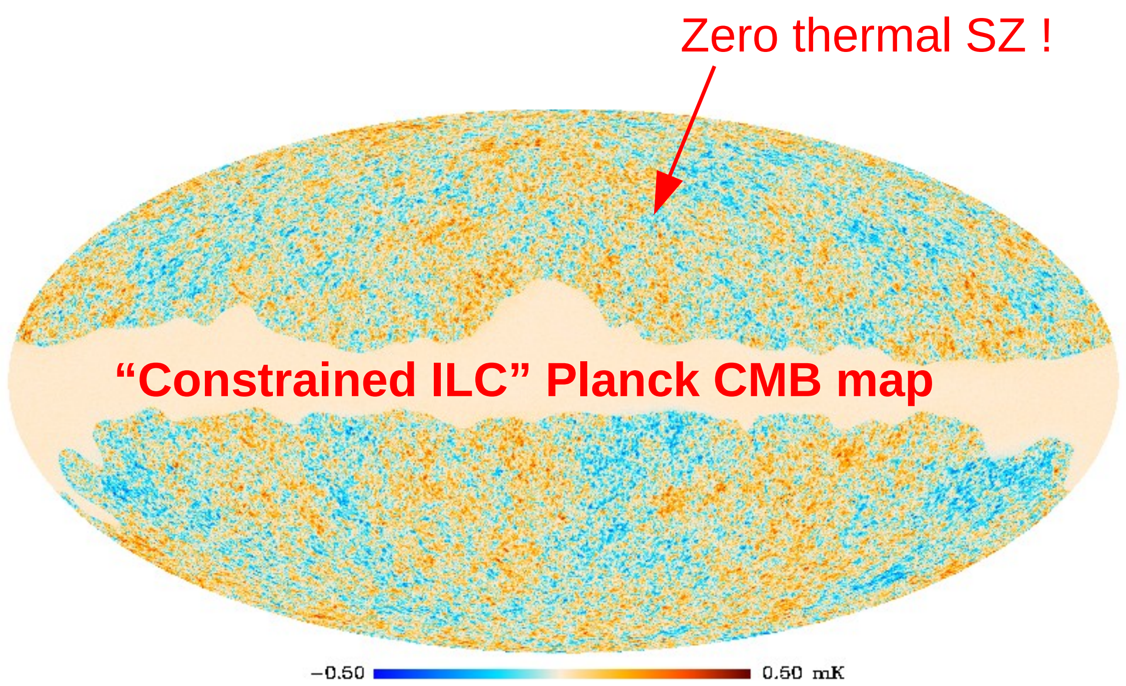
<u>Constrained ILC</u>

$$W = \frac{(b^T C^{-1} b) a^T C^{-1} - (a^T C^{-1} a) b^T C^{-1}}{(a^T C^{-1} a)(b^T C^{-1} b) - (a^T C^{-1} b)^2}$$

Remazeilles, Delabrouille, Cardoso, MNRAS, 2011

A “Constrained” CMB map to detect kinetic SZ





An inhomogeneous universe (local void) can mimic the accelerated expansion without dark energy !

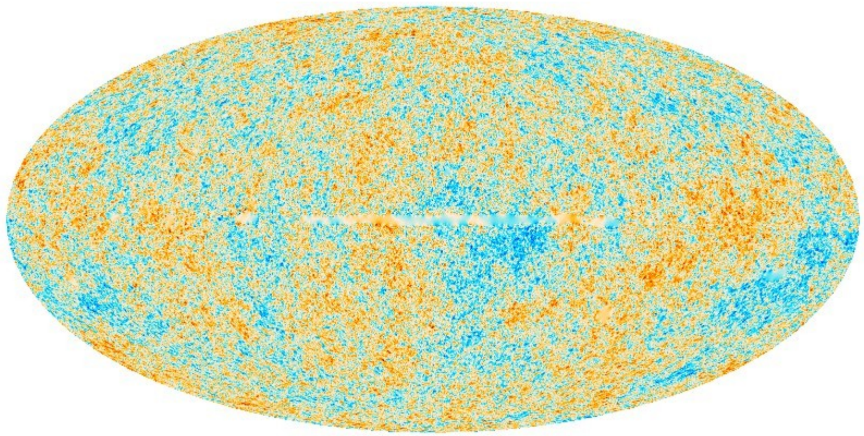
Incompatible void models :

- *“ Universe is homogeneous up to Gpc scales ”*
- *“ Universe is consistent with dark energy ”*

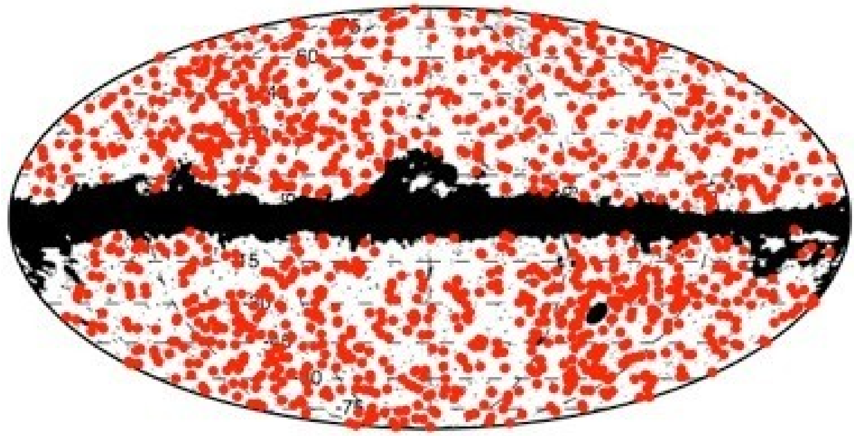
***Planck collaboration**, “Planck intermediate results. XIII. Constraints on peculiar velocities,” A&A 561, A97 (2014)*

SZ residuals in the *Planck* CMB map

Released *Planck* CMB map

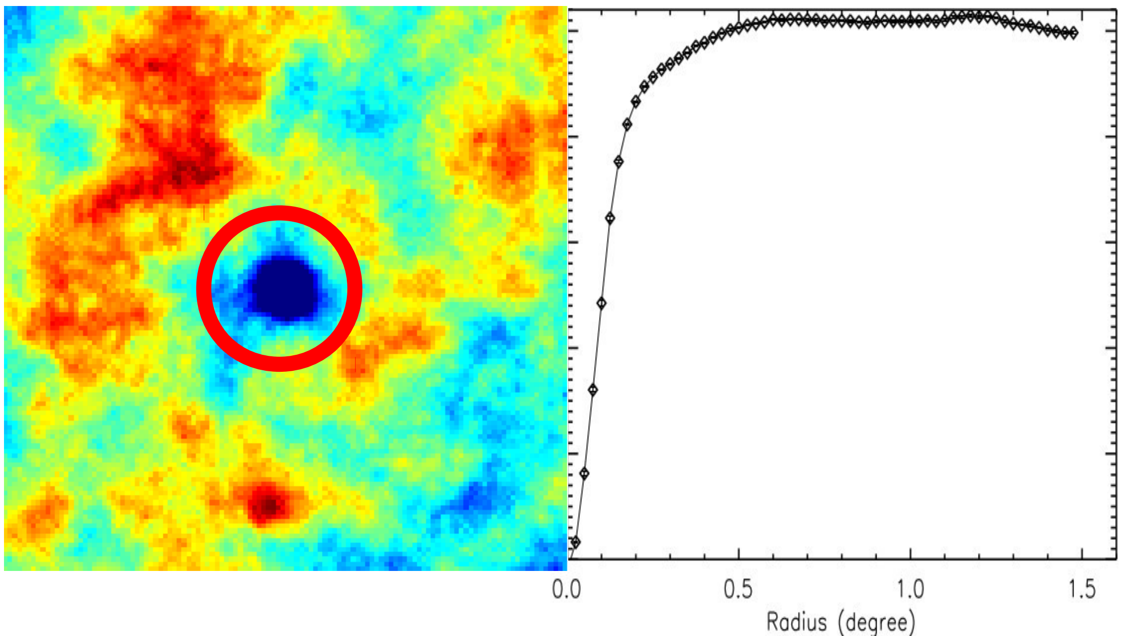


Planck cluster catalogue



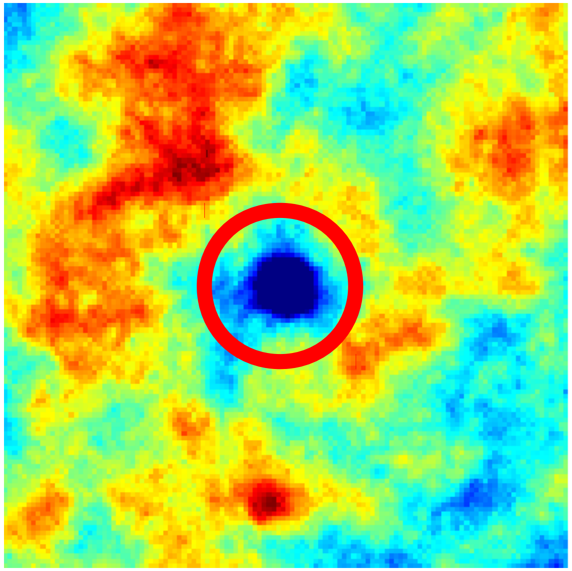
Let's stack the *Planck* CMB map in direction of galaxy clusters :

residual SZ in CMB !
(LSS)

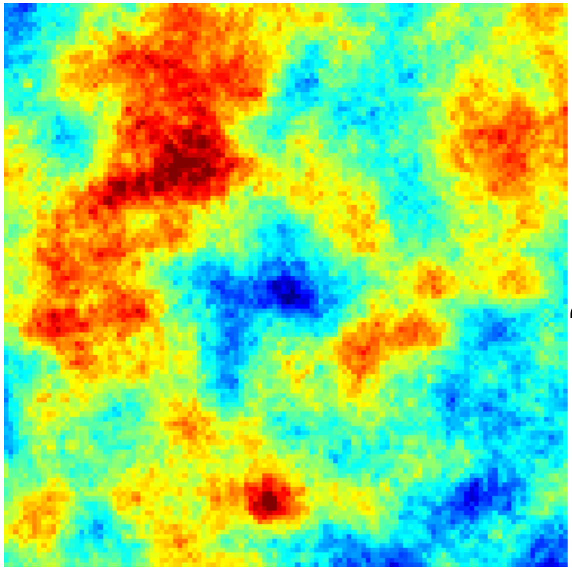


How to kill SZ foregrounds in CMB ?

Stacking CMB Planck 2015

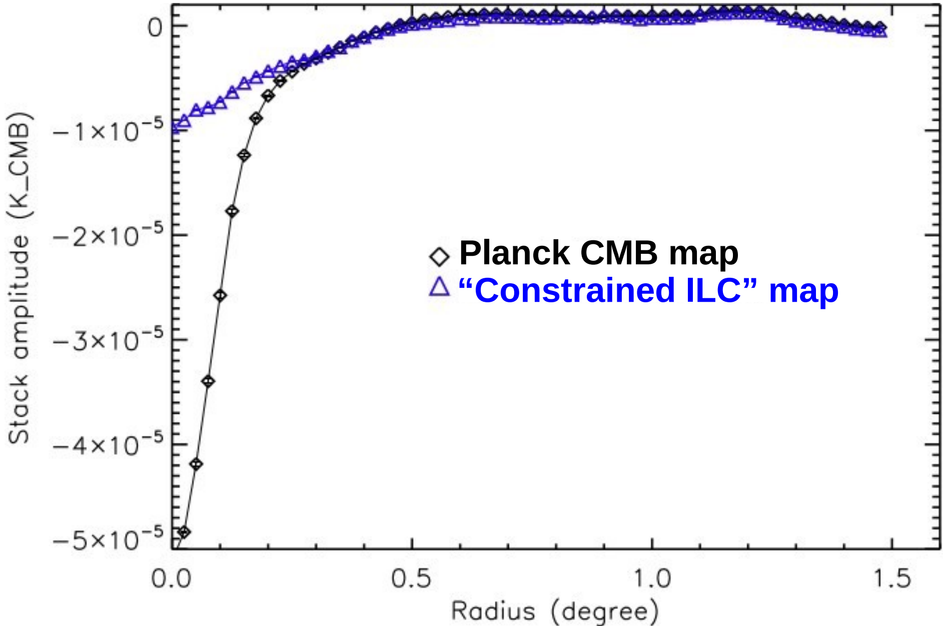


Stacking "Constrained ILC" CMB



Remazeilles et al., MNRAS 2011

Absence of SZ residuals in the "Constrained ILC" CMB map



"Constrained" CMB map is recommended for

- LSS x CMB correlations
- Kinetic SZ
- **μ-distorsions !**

μ-type distortion temperature fluctuations

- Fluctuations of **μ-type** distortions may result from **non-Gaussianity**
  Pajer & Zaldarriaga, 2012

- **Khatri & Sunyaev, 2015:**

  μ-type x CMB : $\ell\,(\ell+1)\,C_\ell^{\mu \times T} / 2\pi \approx 2.4 \times 10^{-17} f_{NL}$

  μ-type x μ-type : $\ell\,(\ell+1)\,C_\ell^{\mu \times \mu} / 2\pi \approx 6.12 \times 10^{-24} (f_{NL})^2$

$k_S \sim 46 - 10^4$ Mpc^{-1}

$k_L \sim 10^{-3}$ Mpc^{-1}

First extraction of μ-distortion fluctuations

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Constraints on μ-distortion fluctuations and primordial non-Gaussianity from Planck data

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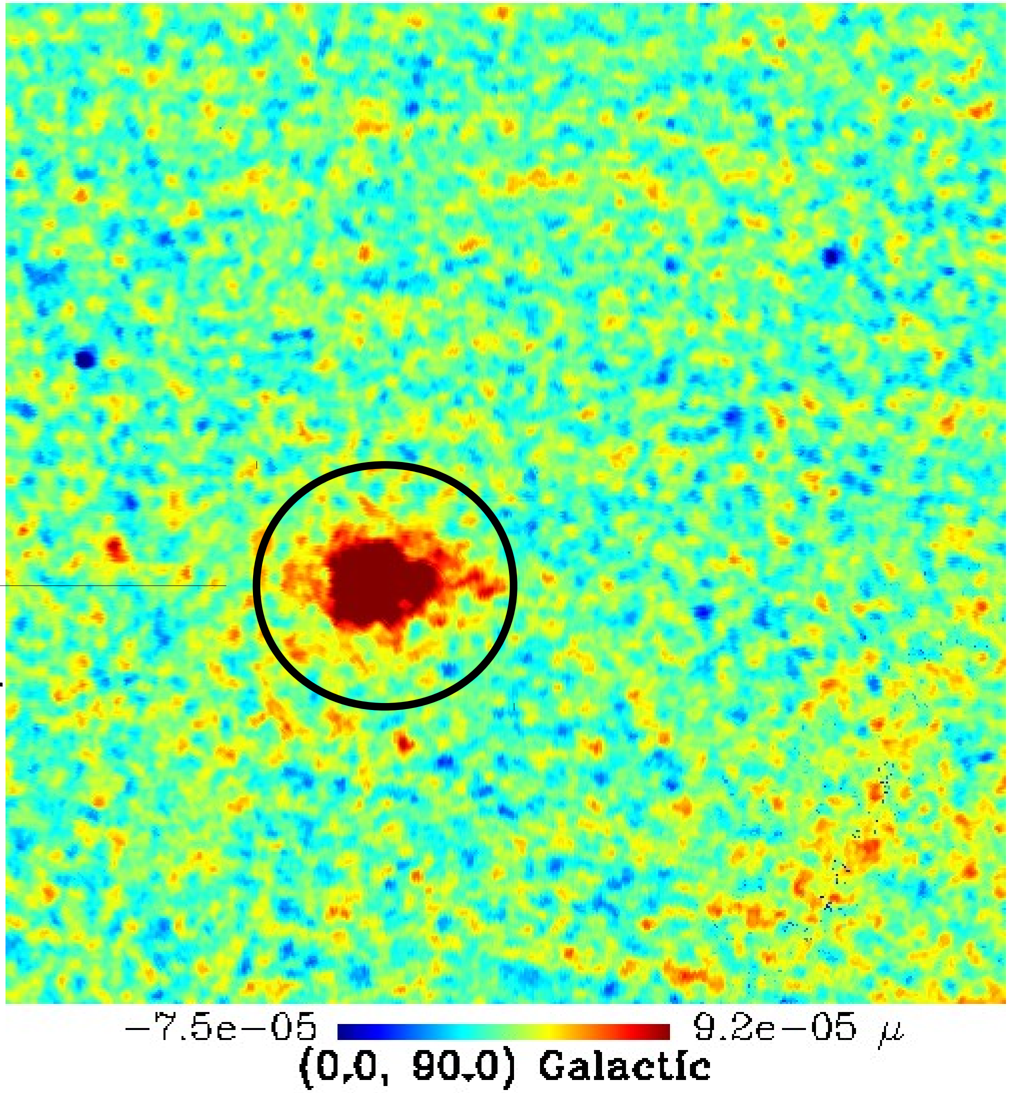
Abstract. We use the Planck HFI channel maps to make an all sky map of μ-distortion fluctuations. Our μ-type distortion map is dominated by the y-type distortion contamination from the hot gas in the low redshift Universe and we can thus only place upper limits on the μ-type distortion fluctuations. For the amplitude of μ-type distortions on $10'$ scales we get the limit on root mean square (rms) value $\mu_{\rm rms}^{10'} < 6.4 \times 10^{-6}$, a limit 14 times stronger than

JCAP09(2015)0

Map of μ-type distortion fluctuations from Planck data

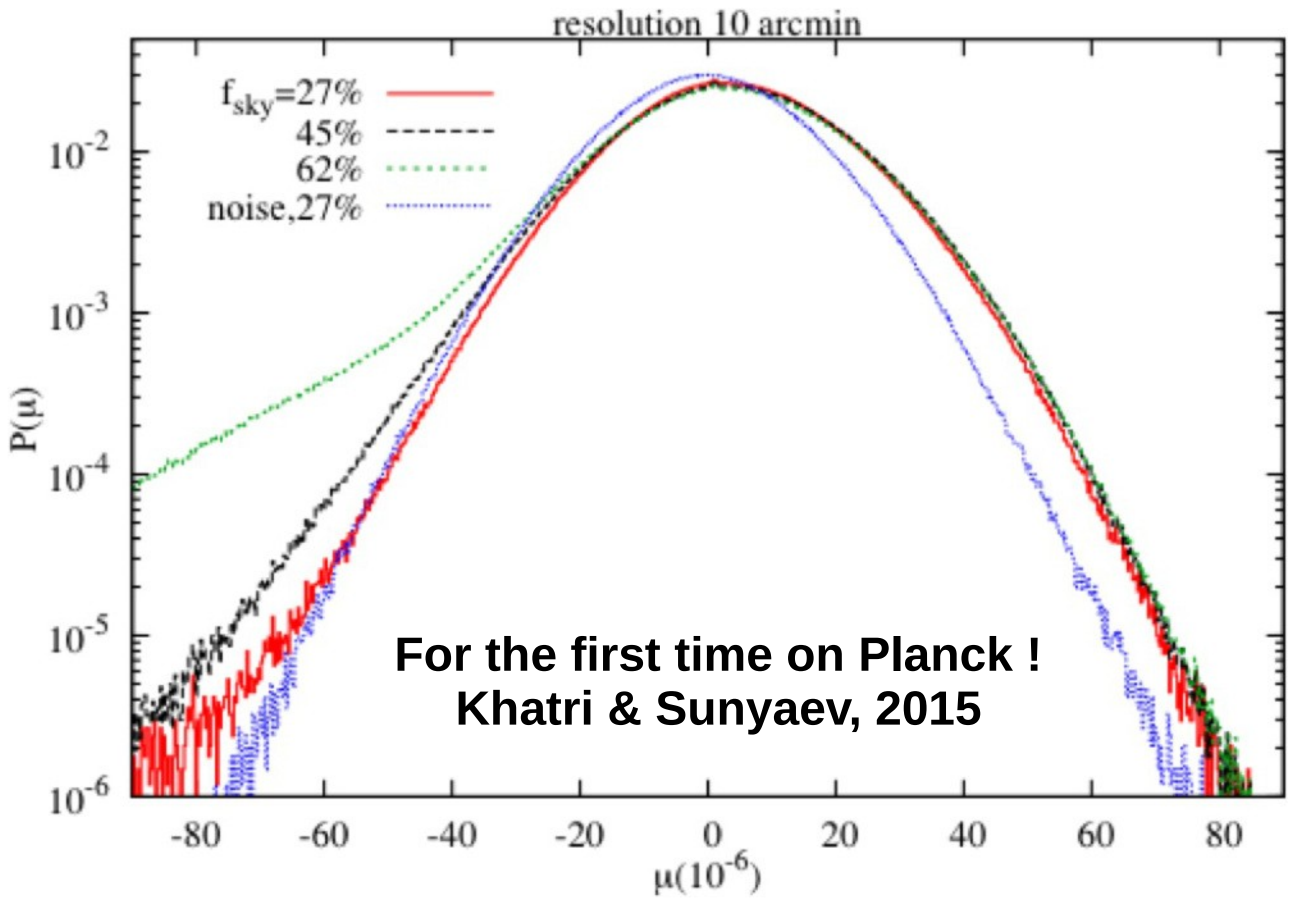
Khatri & Sunyaev (2015)
http://wwwmpa.mpa-garching.mpg.de/~khatri/muresults/



<u>Parametric LIL</u>

y-type distortion (SZ)
foreground residuals
in direction of Coma cluster

1D PDF of μ-type distortion fluctuations from Planck



A parametric fitting method (LIL) was applied to Planck data

Khatri & Sunyaev, 2015: $\langle\mu\rangle < 6.4 \times 10^{-6}$ at 10' resolution

Fixsen et al, 1996 (COBE/FIRAS): $\langle\mu\rangle < 90 \times 10^{-6}$

Extraction of μ-type temperature fluctuations

- Parametric methods (e.g. LIL) are model-dependent

  Slight incorrect modelling of Galactic foregrounds may strongly impact / bias the
  the reconstruction of such a faint μ-type distortion signal (similar to CMB B-modes)

- The alternative solution I propose: **Constrained ILC + wavelets**

  - Constrained ILC is a **blind method** (no assumptions about Galactic foregrounds)

  - Constrained ILC both **recovers μ-type distortion** and **kills SZ/y-type foreground,** while minimizing other foregrounds and noise

  - Any serious component separation should be performed in **wavelet space** to deal with **local conditions of contamination both over the sky and over the scales**

    e.g., <u>Galactic dust</u> localized in the Galactic plane and dominant on large angular scales
    <u>Instrumental noise</u> unlocalized on the sky and dominant on small angular scales
    <u>SZ</u> is localized on clusters and dominant on small angular scales

Separating CMB spectral distortions ?

- **y-type** distortions (SZ) in late universe

$$n \approx n_{Pl} + y \frac{xe^x}{(e^x-1)^2}\left(x\frac{e^x+1}{e^x-1} - 4\right)$$

spectral signature

Impact on CMB of LSS *<u>after</u>* *Recombination ($0 < z < 10^4$)*

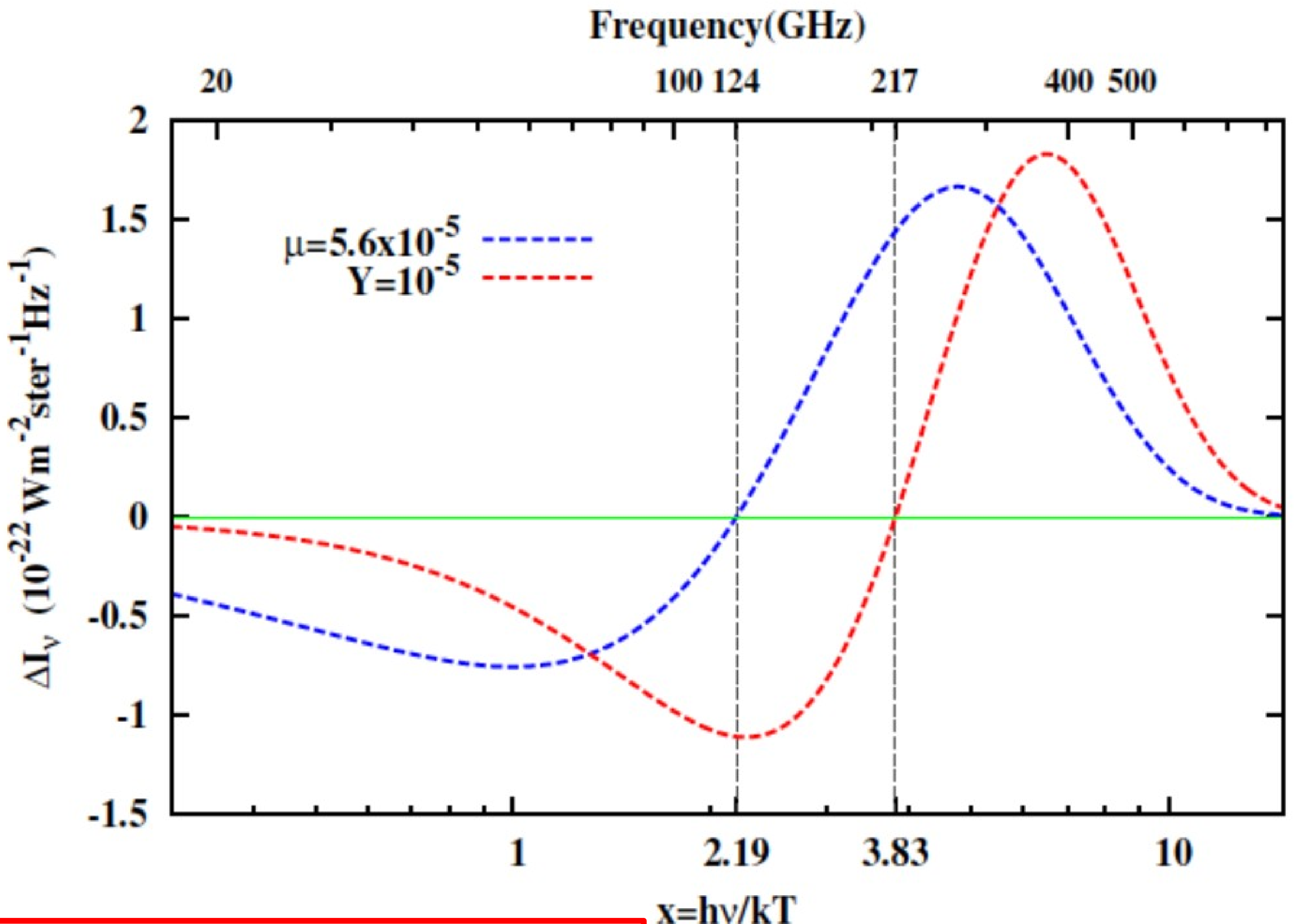
- **μ-type** distortions in early universe

$$n_{BE} \approx n_{Pl} + \mu \frac{e^x}{(e^x-1)^2}\left(\frac{x}{2.19} - 1\right)$$

spectral signature

Impact on CMB of energy injections *<u>before</u>* *Recombination ($z > 10^5$)*

2 components with distinct spectral signatures



We can apply the Constrained ILC !

Chluba, Khatri, Sunyaev

Constrained Internal Linear Combination

observation — "noise"

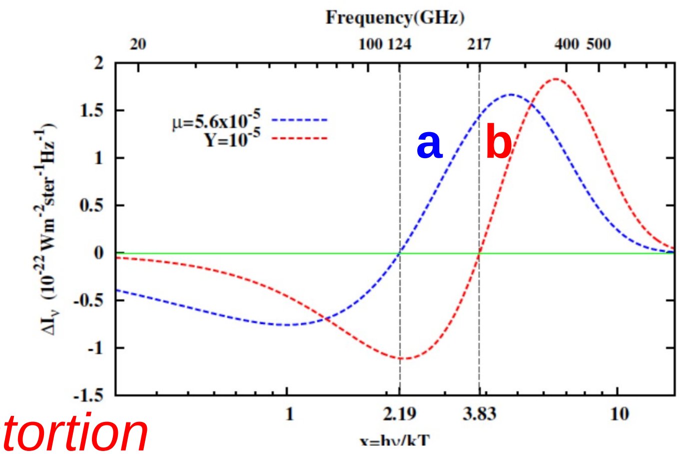
$$X_\nu(p) = {\color{blue} a_\nu\, \mu(p)} + {\color{red} b_\nu\, y_{SZ}(p)} + N_\nu(p)$$

$$\hat{s}(p) = \sum w_\nu\, x_\nu(p)$$

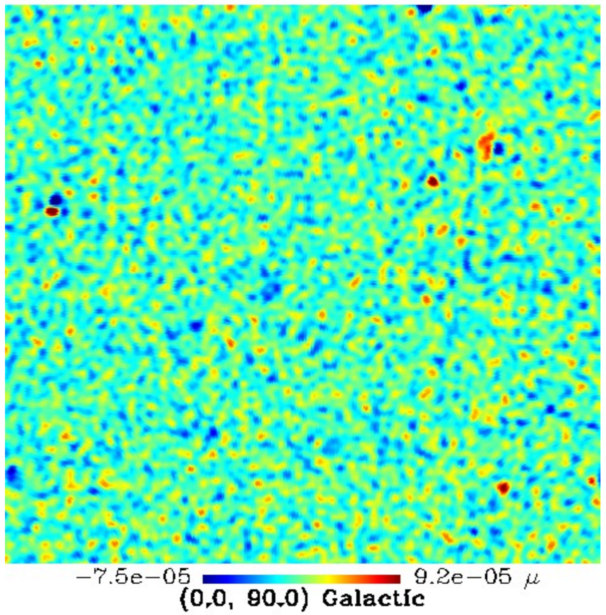
where
$$\begin{cases} \text{variance } \langle \hat{s}^2 \rangle \text{ minimum} \\ \sum w_\nu\, {\color{blue} a_\nu} = 1 \\ \sum w_\nu\, {\color{red} b_\nu} = 0 \end{cases}$$

extra constraint
to kill the SZ / y-distortion

spectral emission laws



μ-distortion reconstruction



Constrained ILC

$$\boxed{W = \frac{({\color{red} b}^T C^{-1} {\color{red} b})\, {\color{blue} a}^T C^{-1} - ({\color{blue} a}^T C^{-1} {\color{blue} a})\, {\color{red} b}^T C^{-1}}{({\color{blue} a}^T C^{-1} {\color{blue} a})({\color{red} b}^T C^{-1} {\color{red} b}) - ({\color{blue} a}^T C^{-1} {\color{red} b})^2}}$$

Remazeilles, Delabrouille, Cardoso, MNRAS, 2011

CMB distortions: Remazeilles et al, in prep. 2016

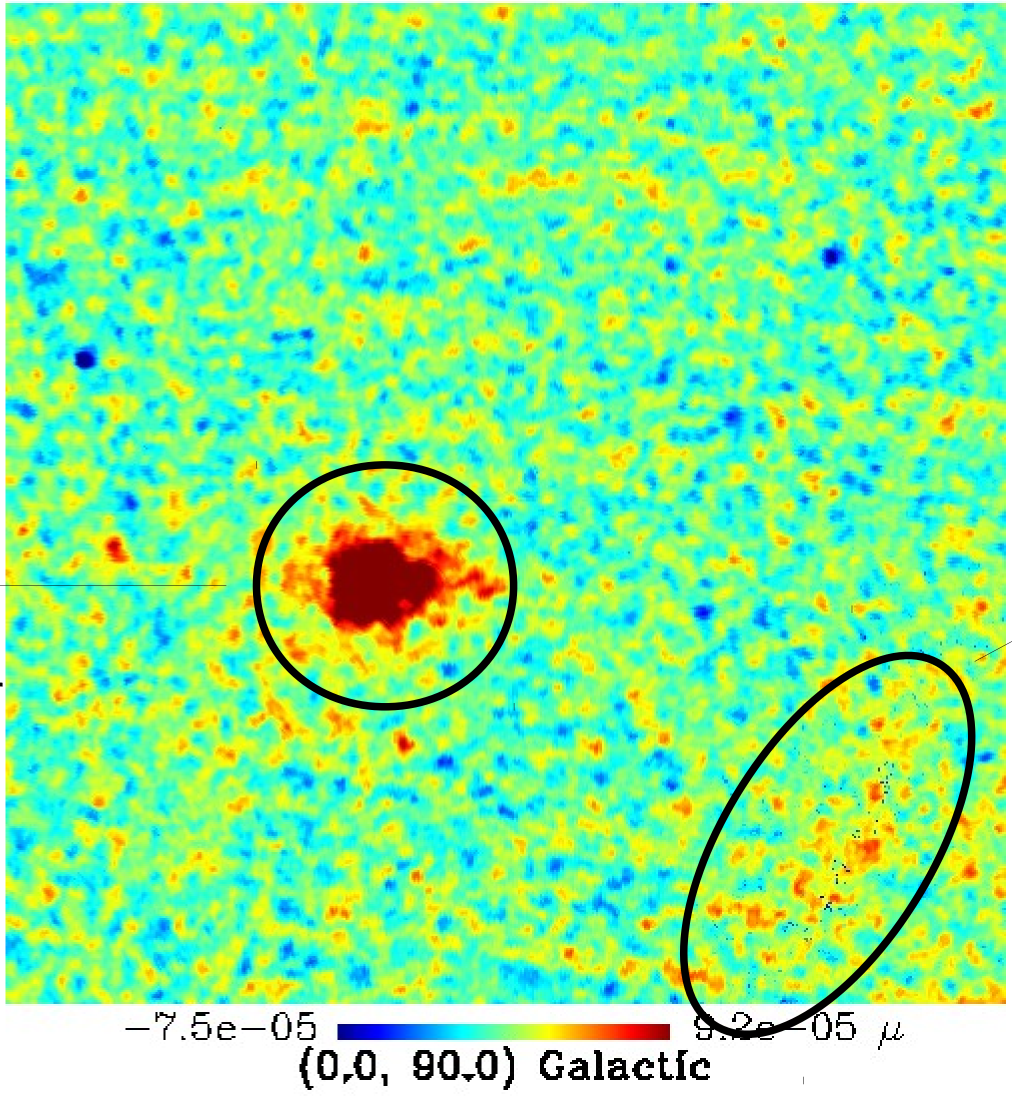
Map of μ-type distortion fluctuations from Planck data

Khatri & Sunyaev (2015)

http://wwwmpa.mpa-garching.mpg.de/~khatri/muresults/

Parametric LIL

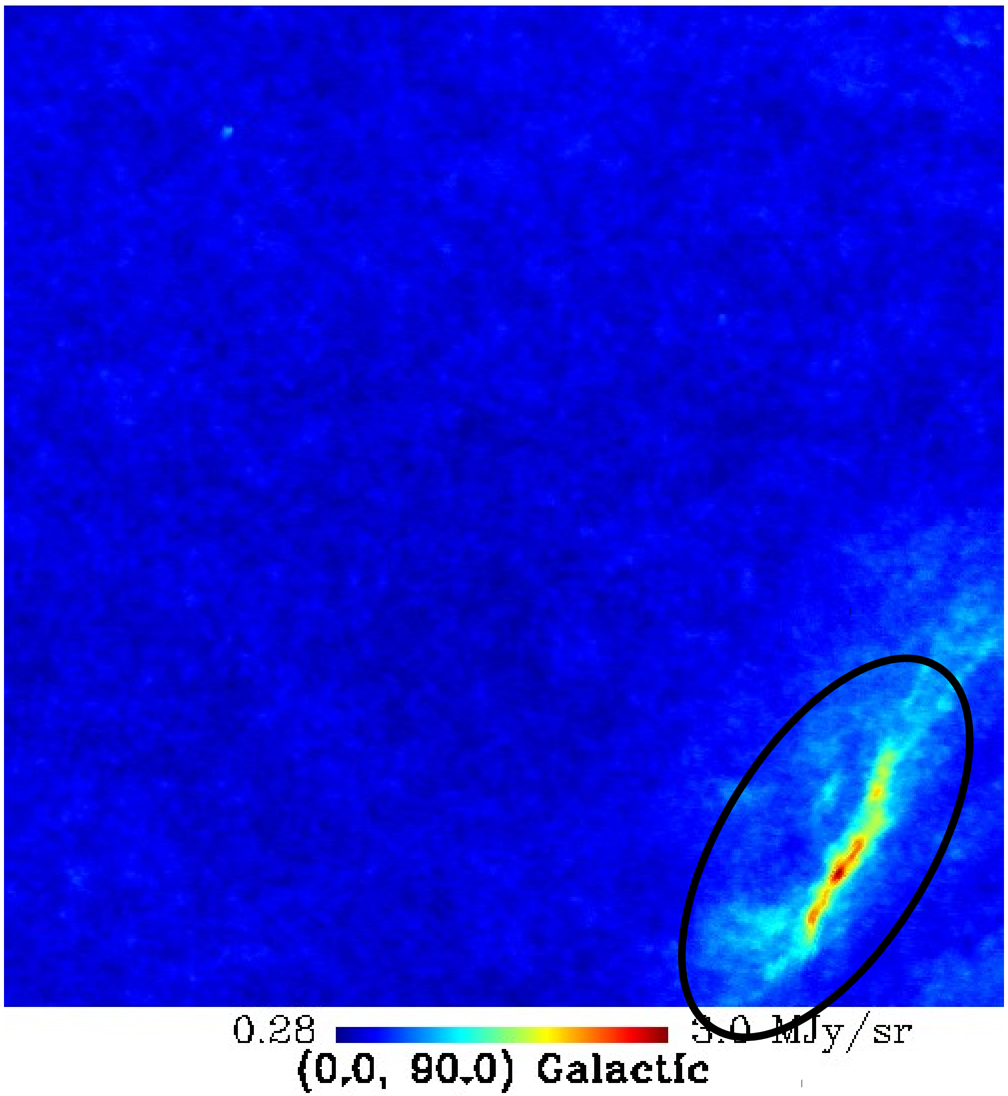
y-type distortion (SZ) foreground residuals in direction of Coma cluster



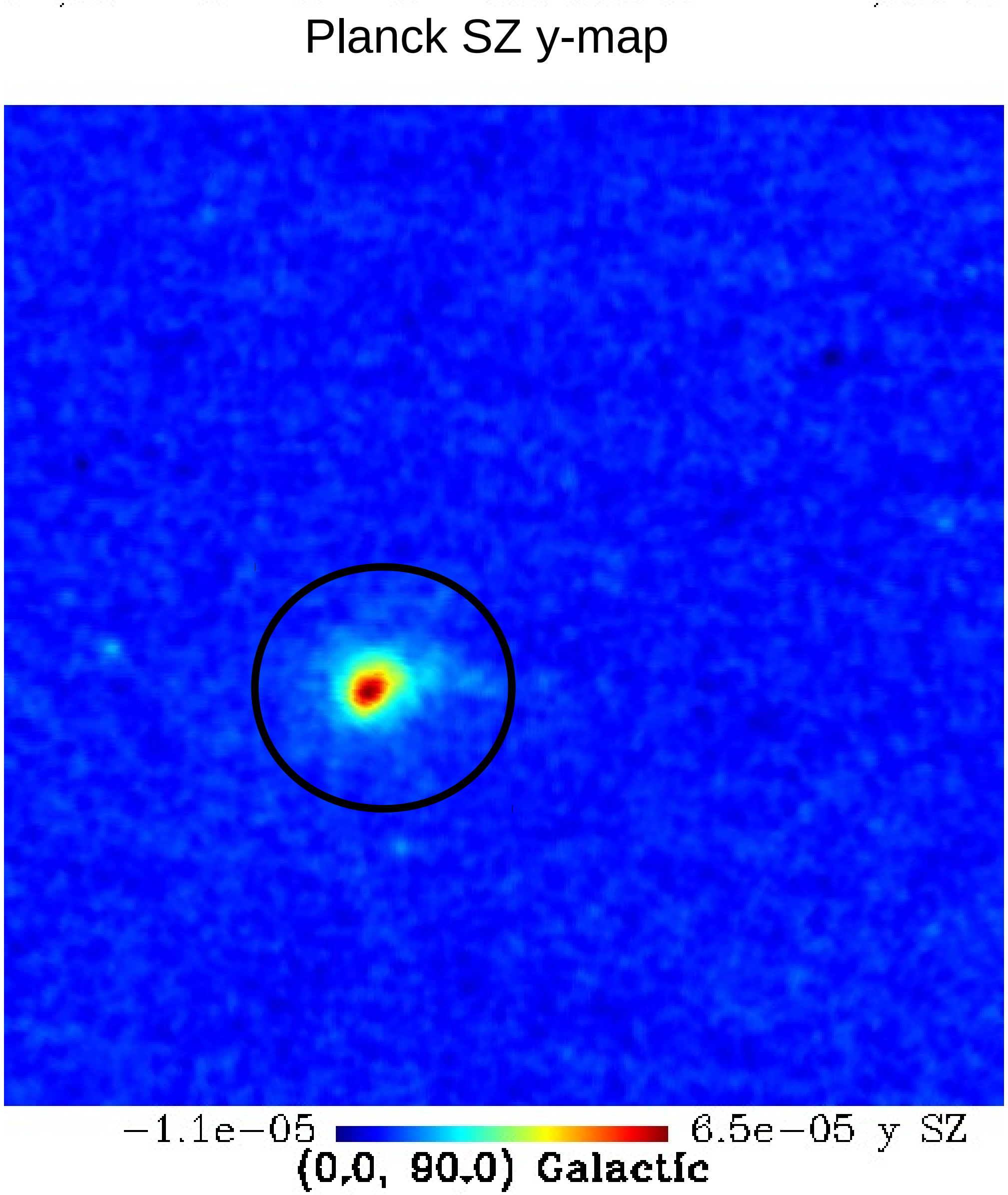
Galactic dust residuals

Check foreground residuals

Planck 545 GHz map: Galactic thermal dust



Check foreground residuals



Map of μ-type distortion fluctuations from Planck data

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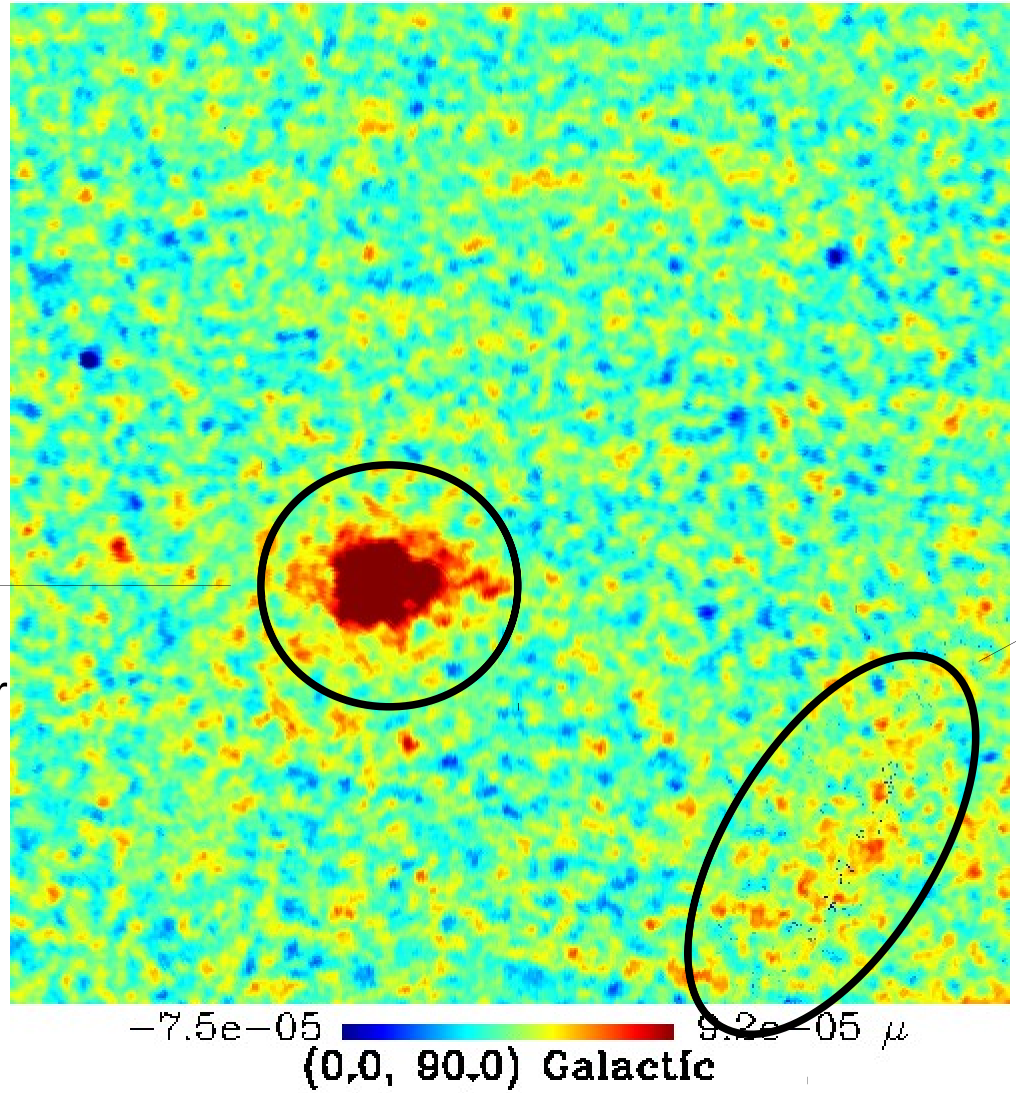
Parametric LIL

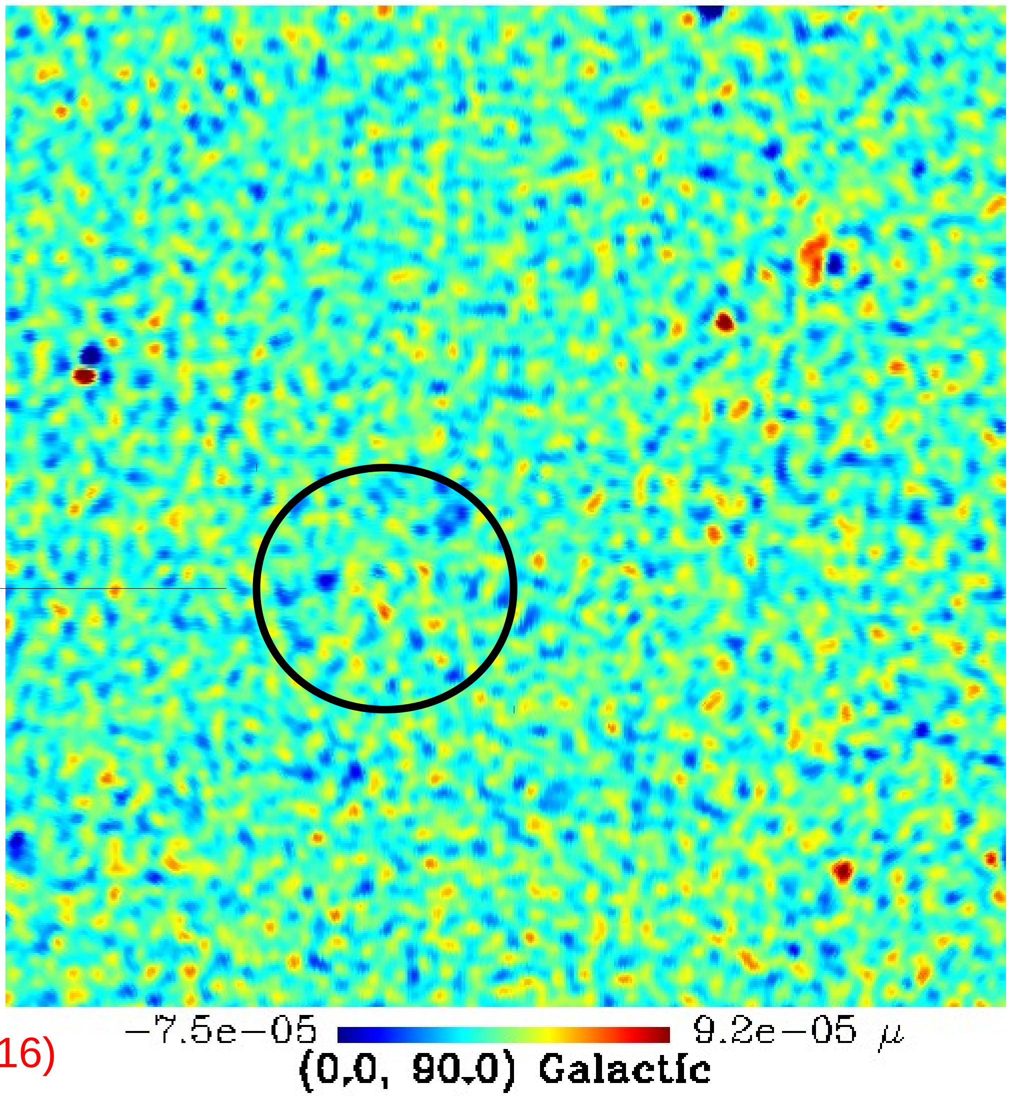


y-type distortion (SZ) foreground residuals in direction of Coma cluster

Galactic dust residuals

Map of μ-type distortion fluctuations from Planck data

Constrained NILC μ-type distortion map



<u>"Constrained NILC"</u>

Remazeilles et al, MNRAS 2011

No more residuals of SZ y-type !

(at the cost of noise)

Preliminary exercise !

Remazeilles et al, in prep (2016)

Conclusions

- **CMB spectral distortions** open a **new window to pre-recombination physics**, (dark) matter x CMB interactions behind the last scattering surface

- The **Constrained ILC** component-separation method **can disentangle** high-z **μ-type distortions** and low-z **y-type distortions** (SZ foreground)

  It offers <u>unit response to μ-type</u> distortion and <u>zero response to y-type</u> distortion !

- **Large number of frequencies** (e.g *PIXIE*, *COrE*) will help the Constrained ILC in minimizing other foregrounds

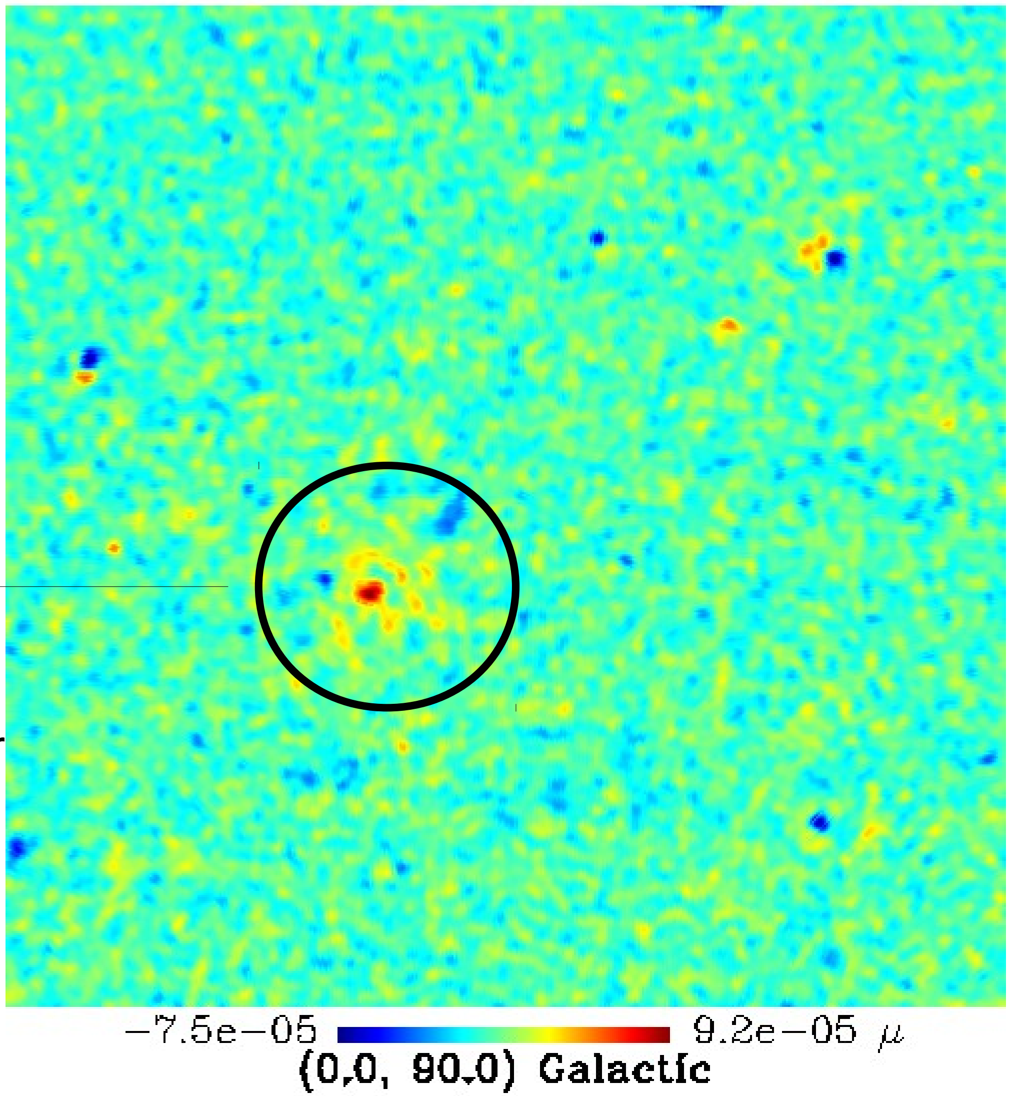
- **Sky simulations of CMB spectral distortions are essential !** e.g., within the Planck Sky Model (PSM) software

Thank you !

Backup slides

Map of μ-type distortion fluctuations from Planck data

NILC μ-type distortion map

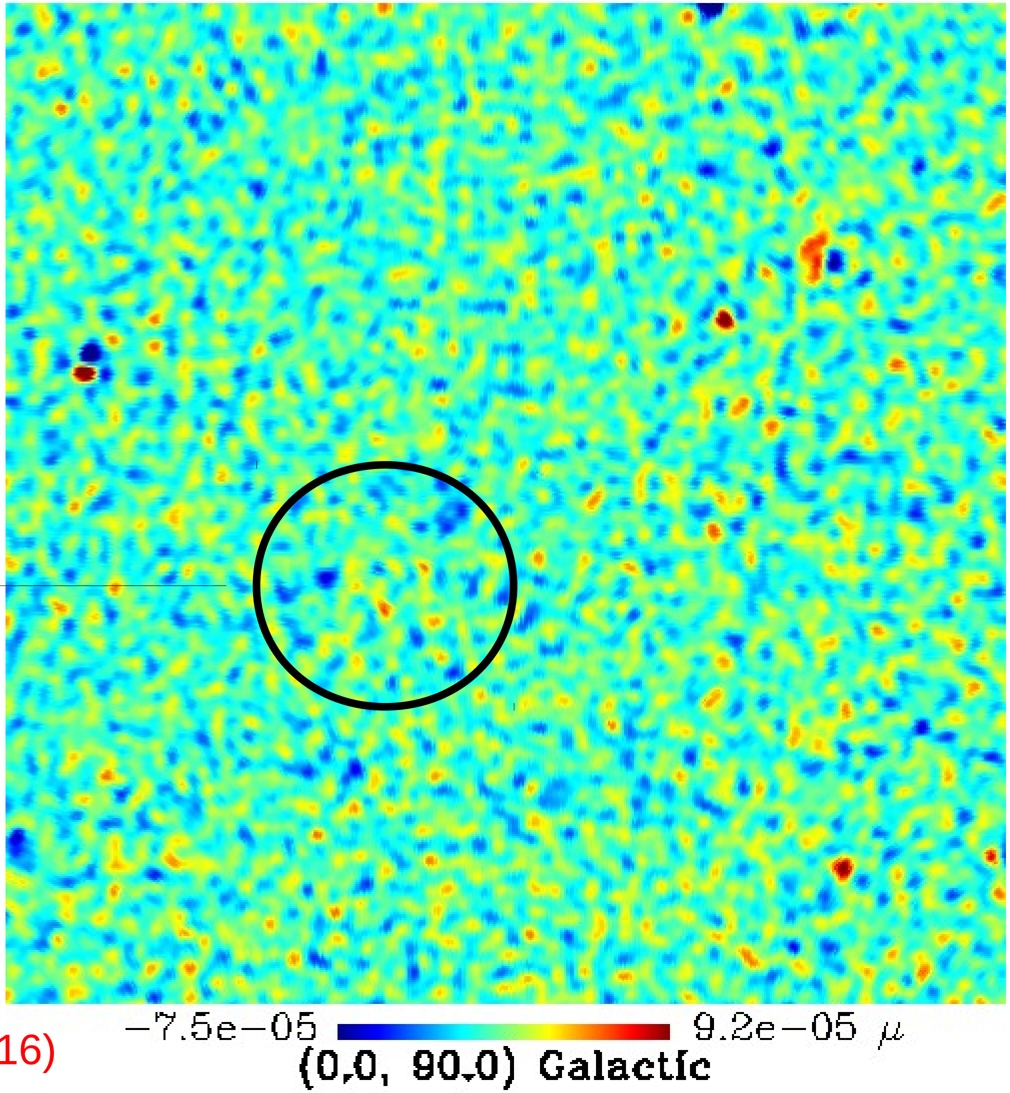


<u>“Standard NILC”</u>

Still
y-type distortion (SZ)
foreground residuals
in direction of Coma cluster

Map of μ-type distortion fluctuations from Planck data

Constrained NILC μ-type distortion map



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Remazeilles et al, MNRAS 2011

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(at the cost of noise)

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Remazeilles et al, in prep (2016)