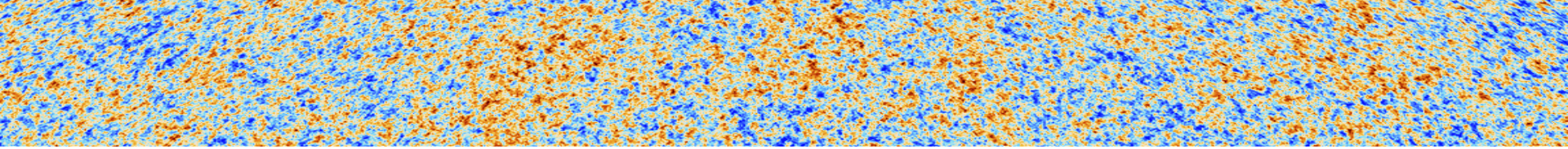


Sunyaev Zel'dovich Signal

Pasquale Mazzotta

Universita' di Roma "Tor Vergata"

"Initial" list of collaborators

Senior Researchers

1. Borgani S.
2. Bourdin H.
3. De Gasperis G
4. Mazzotta P.
5. Rasia E.

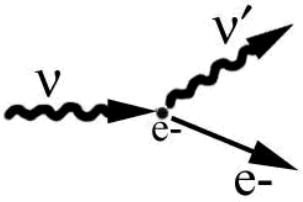
PhD Strudents

1. Baldi. A. S.
2. Kozmanyan. A.

Sunyaev Zel'dovich effect

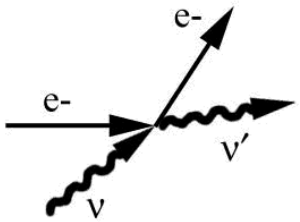
CMB+CLUSTERS

Compton scattering



$\nu' < \nu$

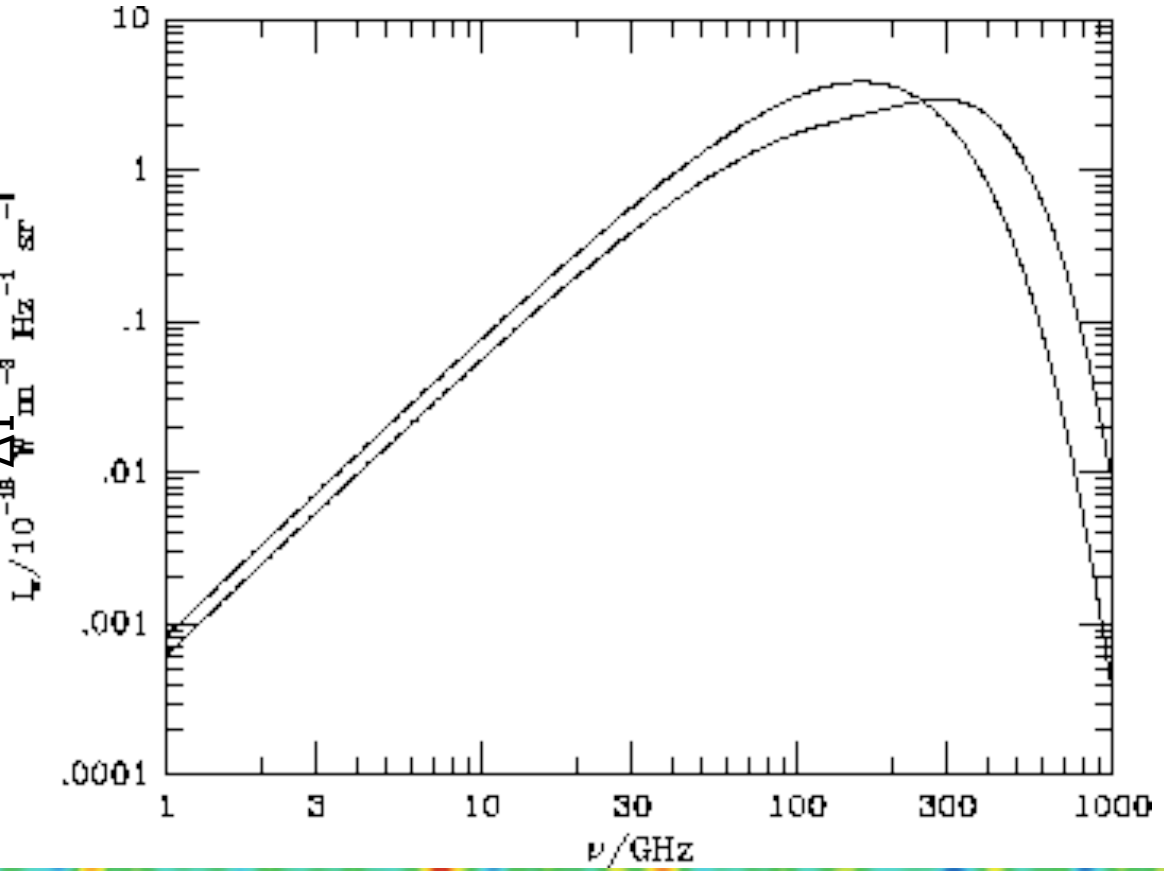
Electron is initially at rest
e- gains energy
Inverse Compton scattering



$\nu' > \nu$

High energy e- initially
e- loses energy

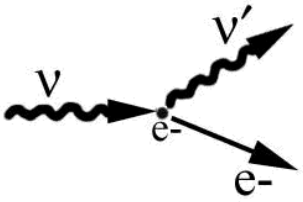
SZ effect (Sunyaev & Zel'dovich 1969)



Sunyaev Zel'dovich effect

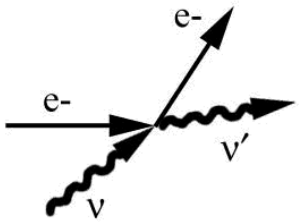
CMB+CLUSTERS

Compton scattering



$\nu' < \nu$

Electron is initially at rest
e- gains energy
Inverse Compton scattering



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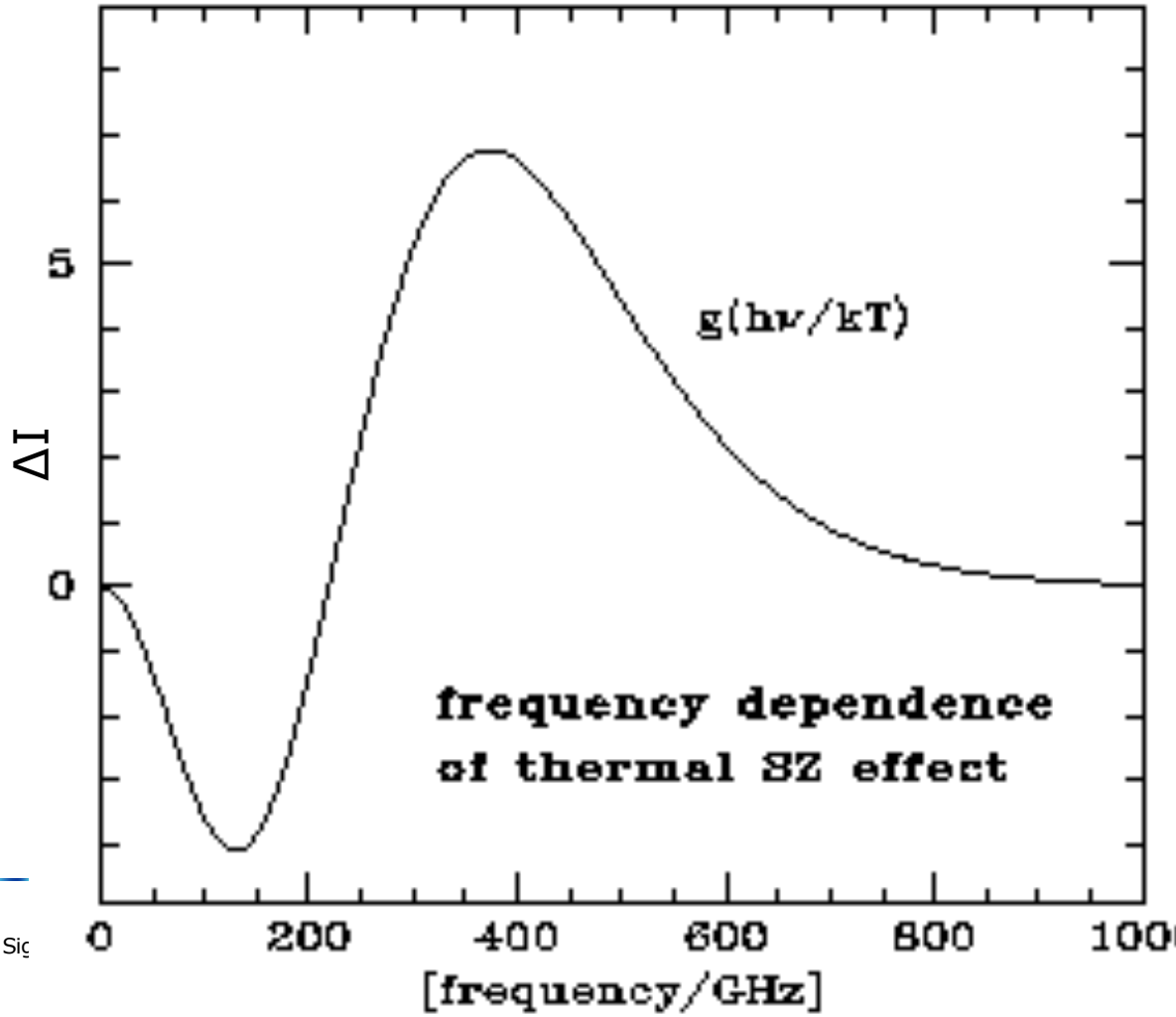
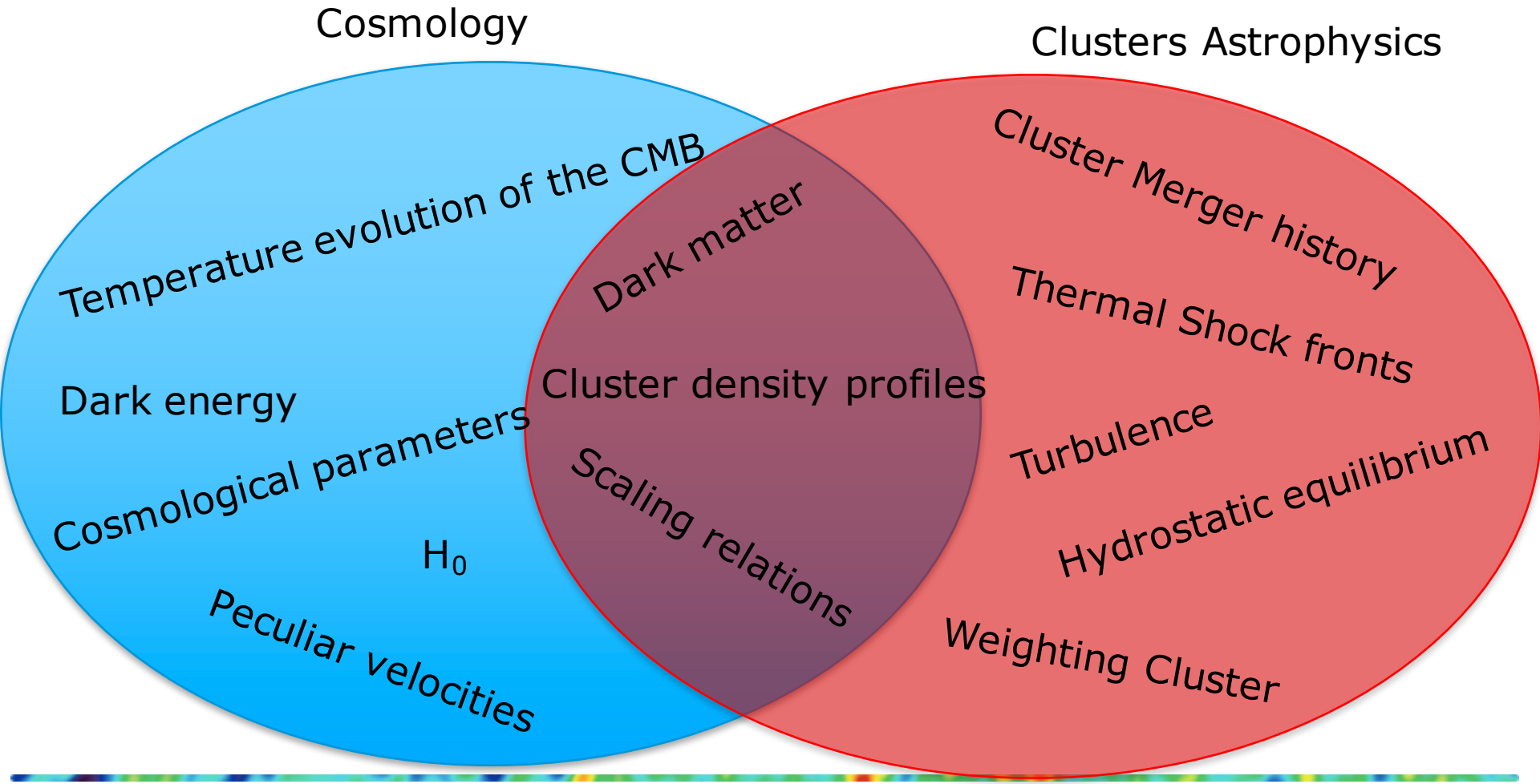
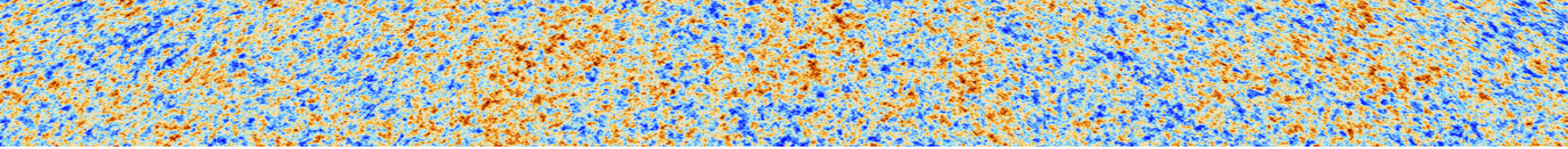
SZ effect (Sunyaev & Zel'dovich 1969)



Investigations with SZ Observations

SZ observations as powerful tools (just some keywords)





Optimized SZ Signal Extraction

Component separation

Frequency maps $\longrightarrow I = As + N$

Emitting sources

Instrumental noise

Mixing matrix

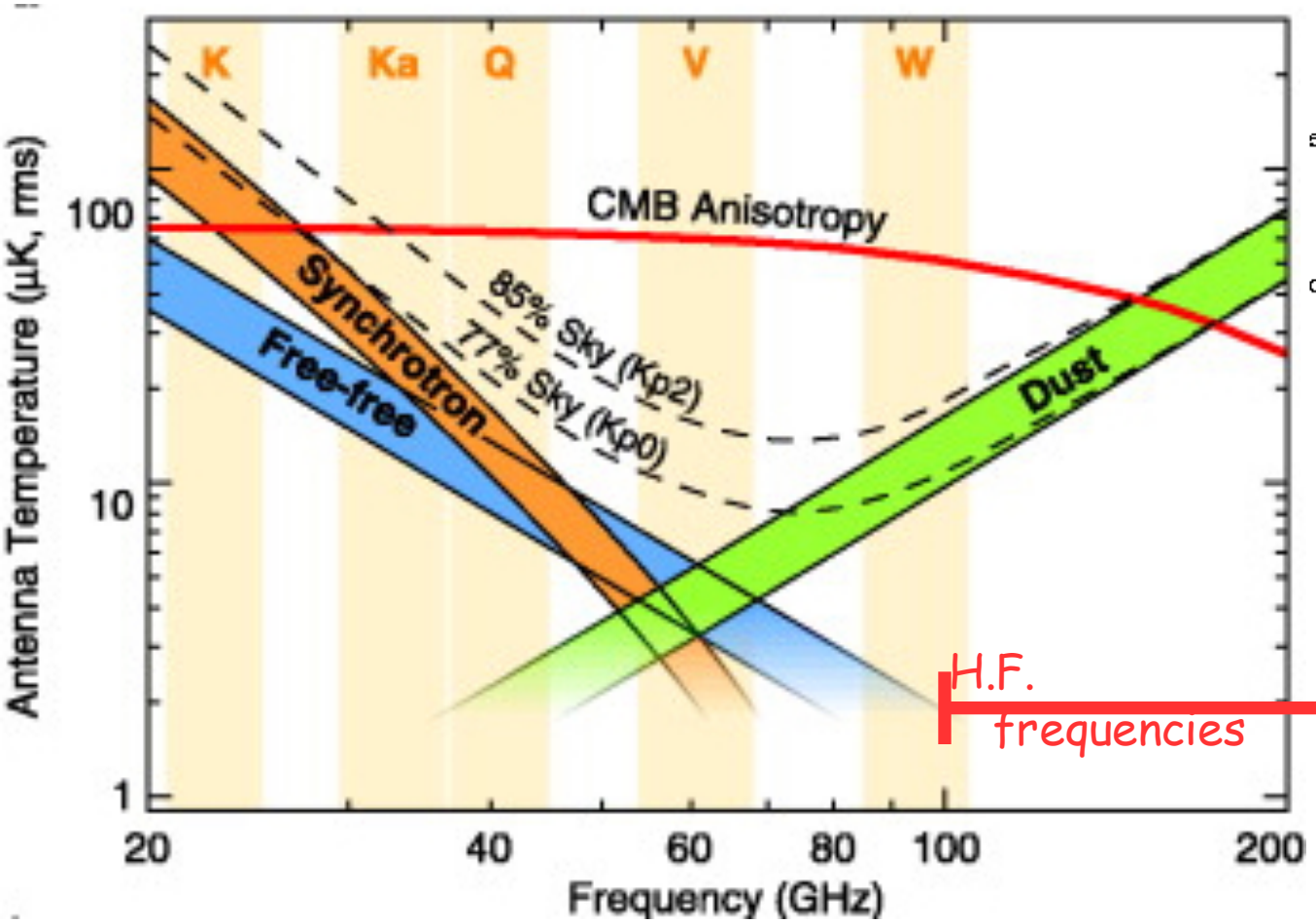
1. For $\nu > 100$ Ghz:

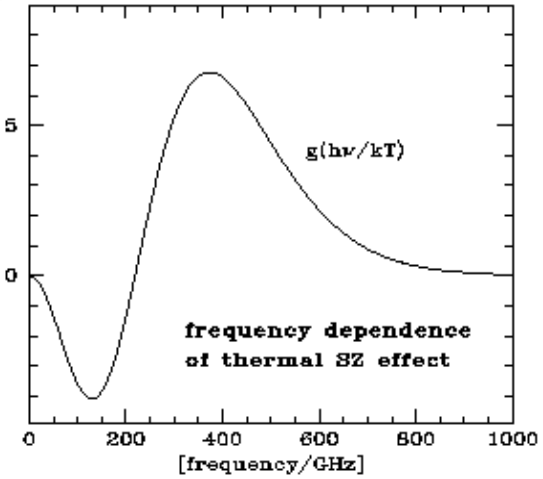
$$I(k,l,\nu) = R(\nu) \times \left[A_{SZ}(k,l) f_{SZ}(\nu) + A_{dust}(k,l) f_{dust}(\nu) + A_{CMB}(k,l) \right]$$

$$f_{dust} \propto \nu^{\beta} B_{\nu}(\nu, T)$$

$$f_{SZ}(\nu) = \left[\left(\frac{h\nu}{kT} \right) \frac{\exp(h\nu/kT + 1)}{\exp(h\nu/kT - 1)} - 4 \right]$$

Foreground components in the H.F. frequency range





CMB vs foreground anisotropy as seen by WMAP (Bennett et al., 03)

The Goal

i) Study the outskirts of clusters of galaxies;
ii) Identify and reconstruct anisotropic features in the atmosphere of clusters of galaxies from SZ observations

ILC algorithms not optimized for imaging purposes

Spatial resolution not tuned to the S/N level

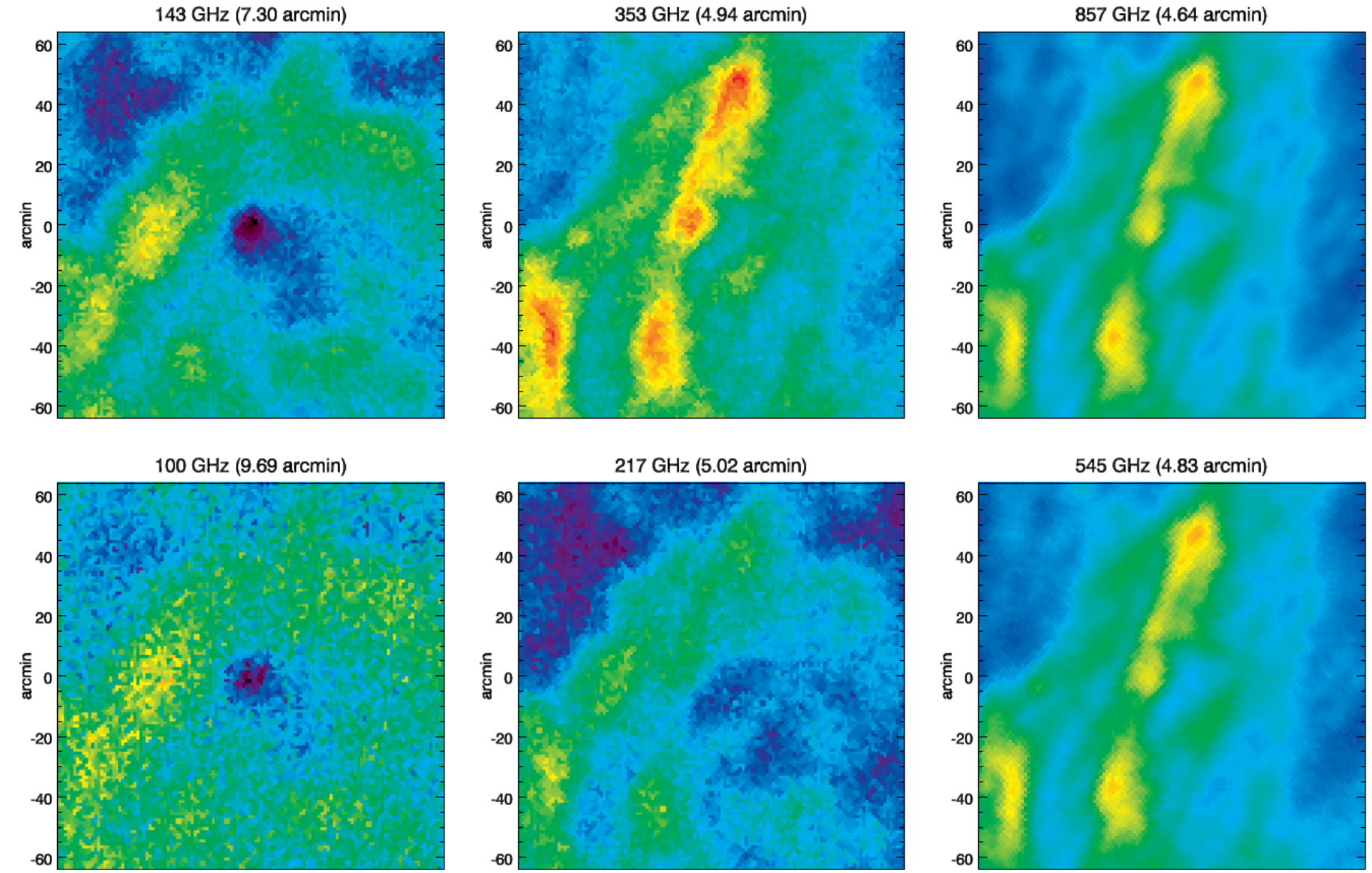
Our proposed solution

Algorithm of component separation with independent multiscale analysis on each component. In particular, wavelet on CMB and curvelet on Dust and SZ.

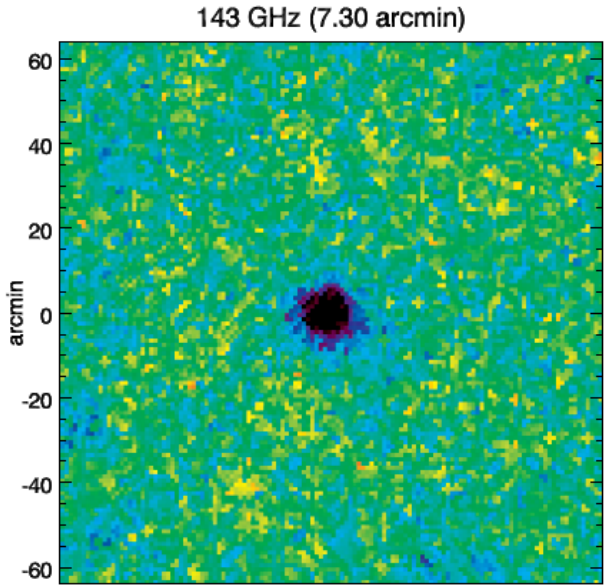
Highlights of the method

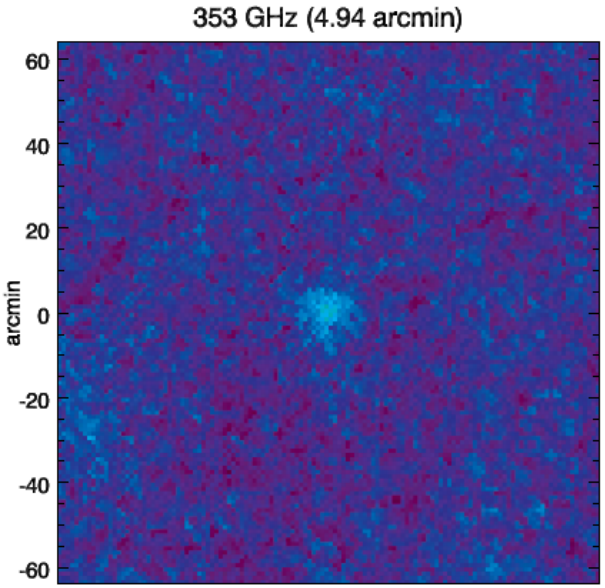
1) Each frequency map is treated independently at itz own maximum angular resol.
2) Fully parametric component separation
3) Accurate reconstructions of features also in low S/N regime
4) Image deconvolution that approaches the highest resolution of freq. maps used
5) Curvelet analysis: optimized to detect anisotropic feature in dust and SZ components (Note that: wavelet GMCA is optimized for isotropic features)

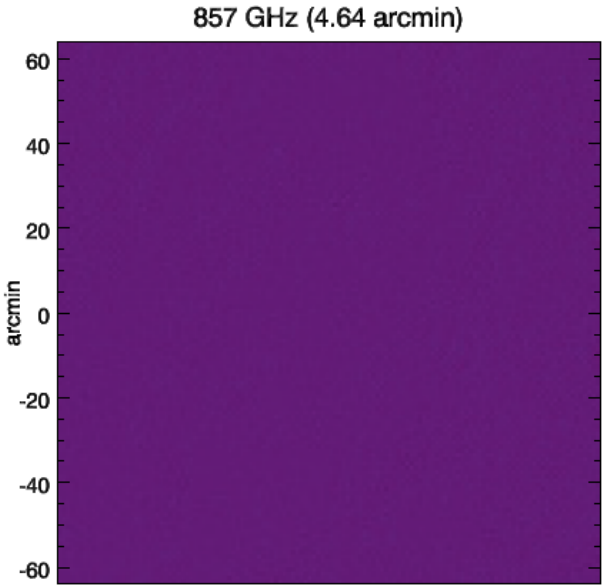
Extraction of SZ in each Planck Freq. Map (A2163)

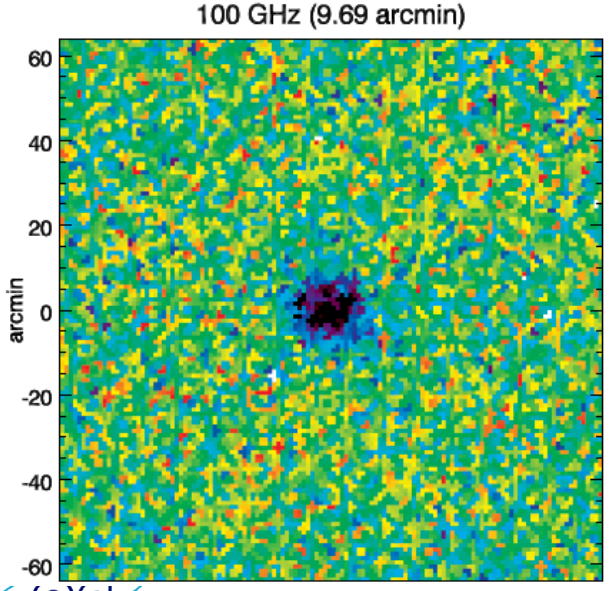


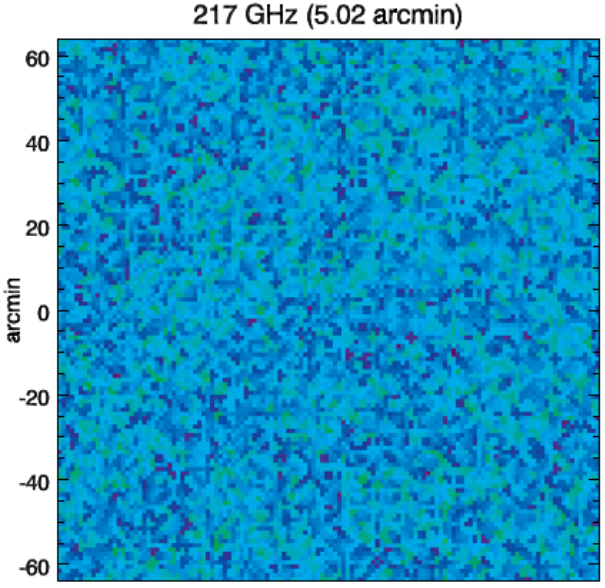
Extraction of SZ in each Planck Freq. Map (A2163)

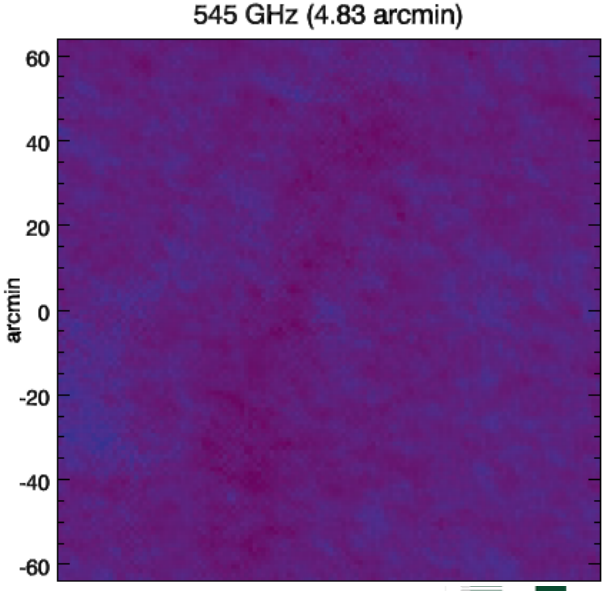












Component estimate

Uniform template (χ^2 estimate):

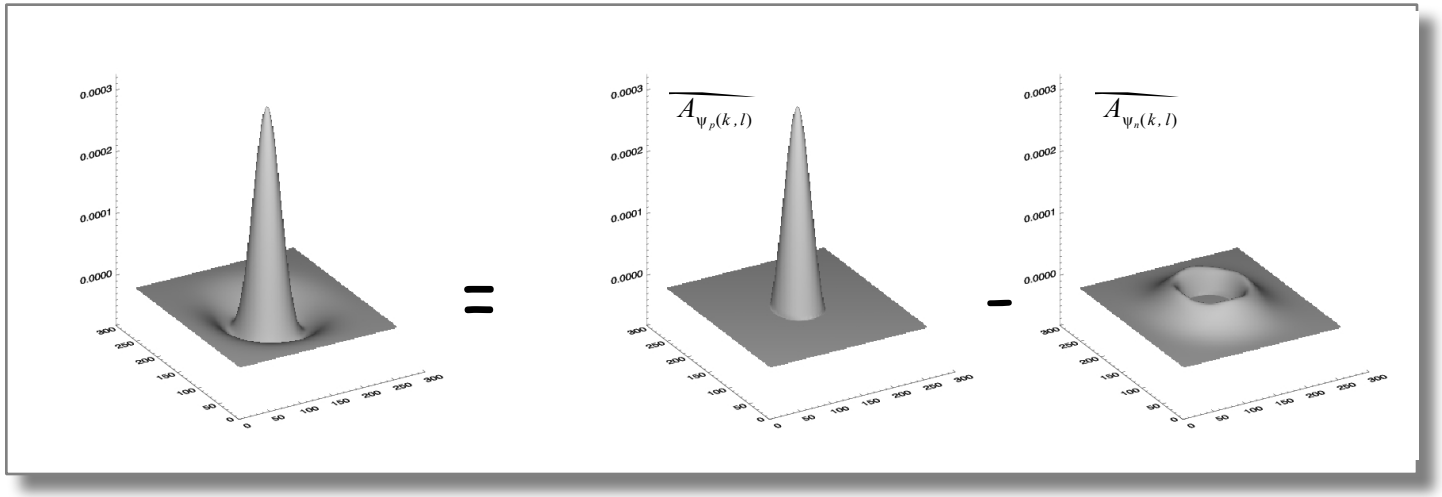
$$\chi^2 = \sum_{i,j} \frac{\left[I(i-k, j-l, \nu) - y(i-k, j-l, \nu) \right]^2}{\sigma^2(i-k, j-l, \nu)}$$

Spatially variable template (weighted χ^2 estimate):

$$w\chi^2 = \sum_{i,j} w(i,j) \frac{\left[I(i-k, j-l, \nu) - y(i-k, j-l, \nu) \right]^2}{\sigma^2(i-k, j-l, \nu)}$$

(Inspired by the work on the weighted maximum likelihood; Deledalle, 2009)

Component imaging: wavelet transform



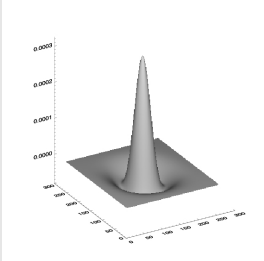
$$W(k,l,a) = \frac{1}{2} \times \left[\widehat{A_{\psi_p}(k,l)} - \widehat{A_{\psi_n}(k,l)} \right]$$

$$dW(k,l,a) = \frac{1}{2} \times \sqrt{\widehat{\sigma^2_{A_{\psi_n}}(k,l)} + \widehat{\sigma^2_{A_{\psi_p}}(k,l)}}$$

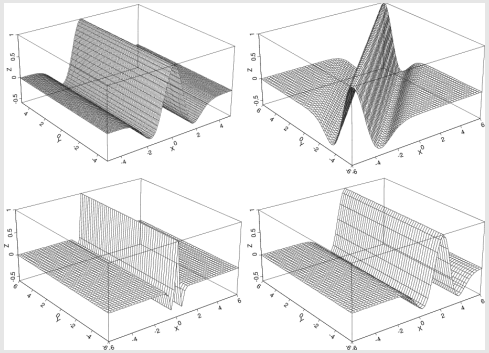
Variance stabilized transform: $W'(k,l,a) = \frac{W(k,l,a)}{dW(k,l,a)}$

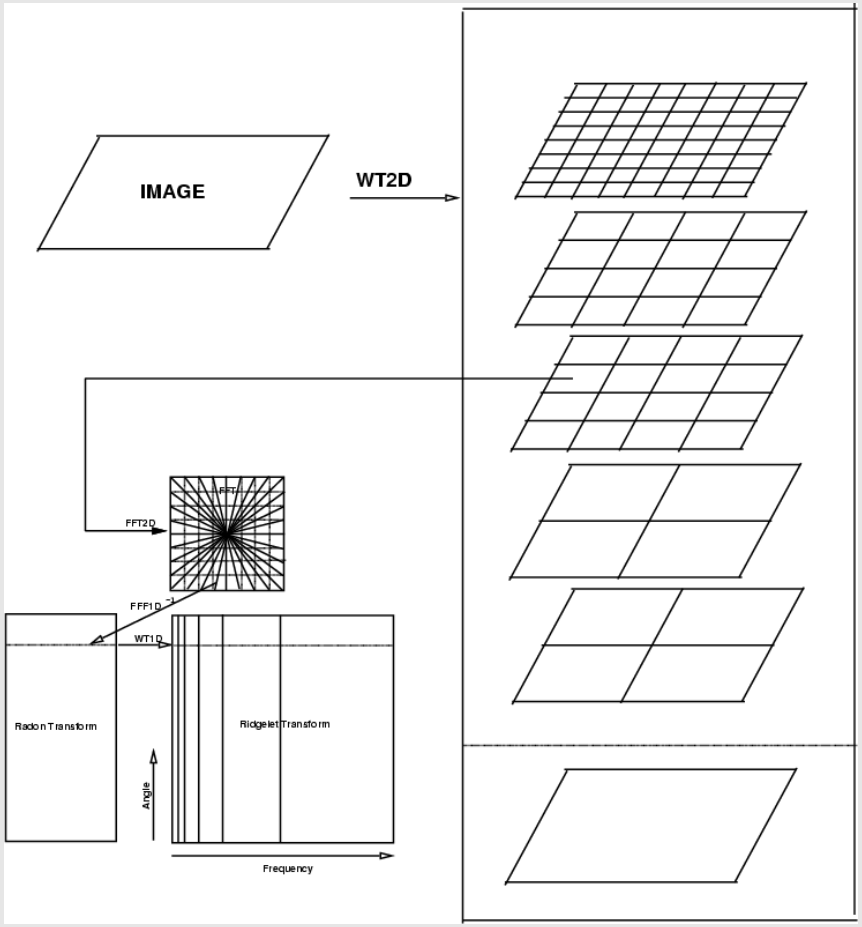
Component imaging: curvelet transform

B3-spline (à trous) wavelet analysis



Ridgelet analysis





Starck, Donoho and Candès, 03

Component restoration: denoising + deconvolution

Image denoising (wavelet and curvelet transform thresholding):

$$\widetilde{\boldsymbol{A}_o}(k,l) = f\left[argmin\left(w\chi^2[\boldsymbol{I}_o]\right)\right] = \begin{bmatrix} R_W \bar{W}[1+A_{CMB}(k,l)] \\ R_C \bar{C}[A_{dust}(k,l)] \\ R_C \bar{C}[\log(1+A_{SZ})(k,l)] \end{bmatrix}$$

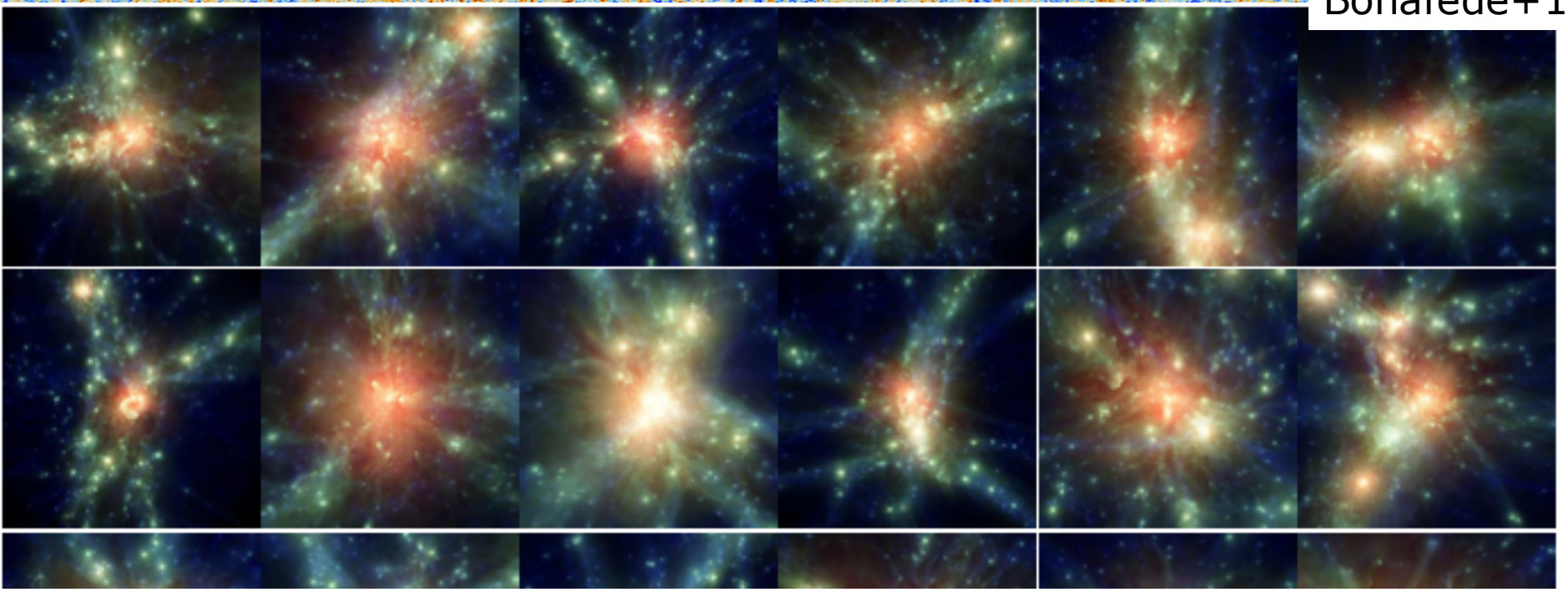
Image restoration -Van-Cittert deconvolution within the *multiresolution support of* **A_n** *(Murtagh et al., 95)-:*

$$P * \boldsymbol{A}_n = argmin\left(w\chi^2[P * \boldsymbol{I}_n]\right)$$

$$\boldsymbol{R}_n(x,y) = \boldsymbol{A}_o(x,y) - [P * \boldsymbol{A}_n](x,y)$$

$$\boldsymbol{A}_{n+1} = \boldsymbol{A}_n + \alpha\, \boldsymbol{R}_n(x,y)$$

Zoom-in simulated clusters (24) and groups (5)



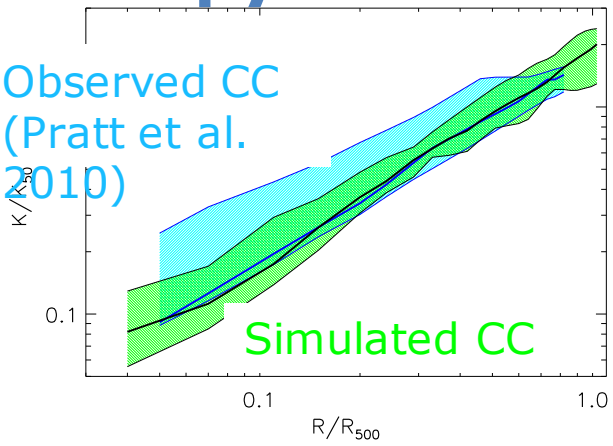
GADGET3 with recent improvements (Beck et al. 2015)

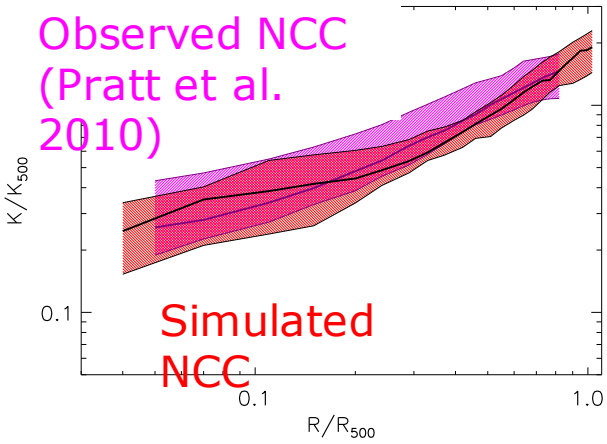
Cooling, Star Formation, Stellar Feedback
AGN feedback with cold and hot accretion

Metal production from SNII, SNIa, AGB:
C, Ca, O, N, Ne, Mg, S, Si, Fe, Na, Al, Ar, Ni

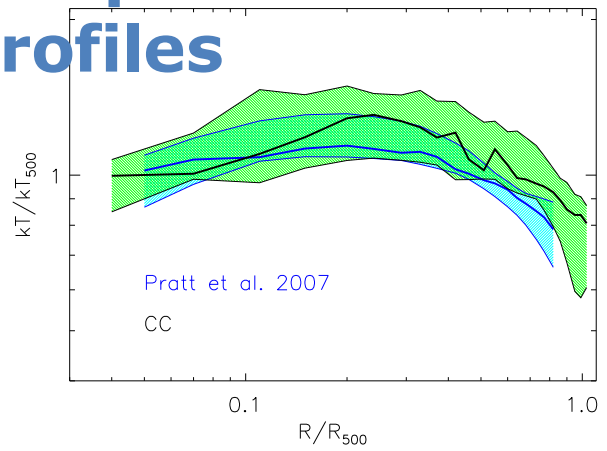
Realistic Entropy and Metallicity Profiles (Rasia et al. 2015, Biffi et al. 2017)
No bias of hydrostatic-equilibrium mass in the core of CC (Biffi et al. 2016)
Agreement with Observations of Pressure Profile and of clumpiness

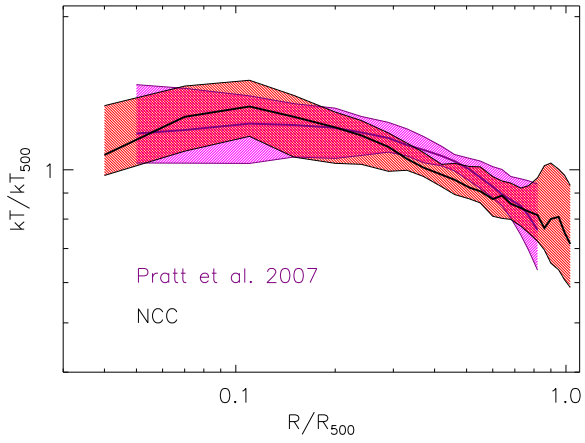
Entropy Profiles





Temperature Profiles

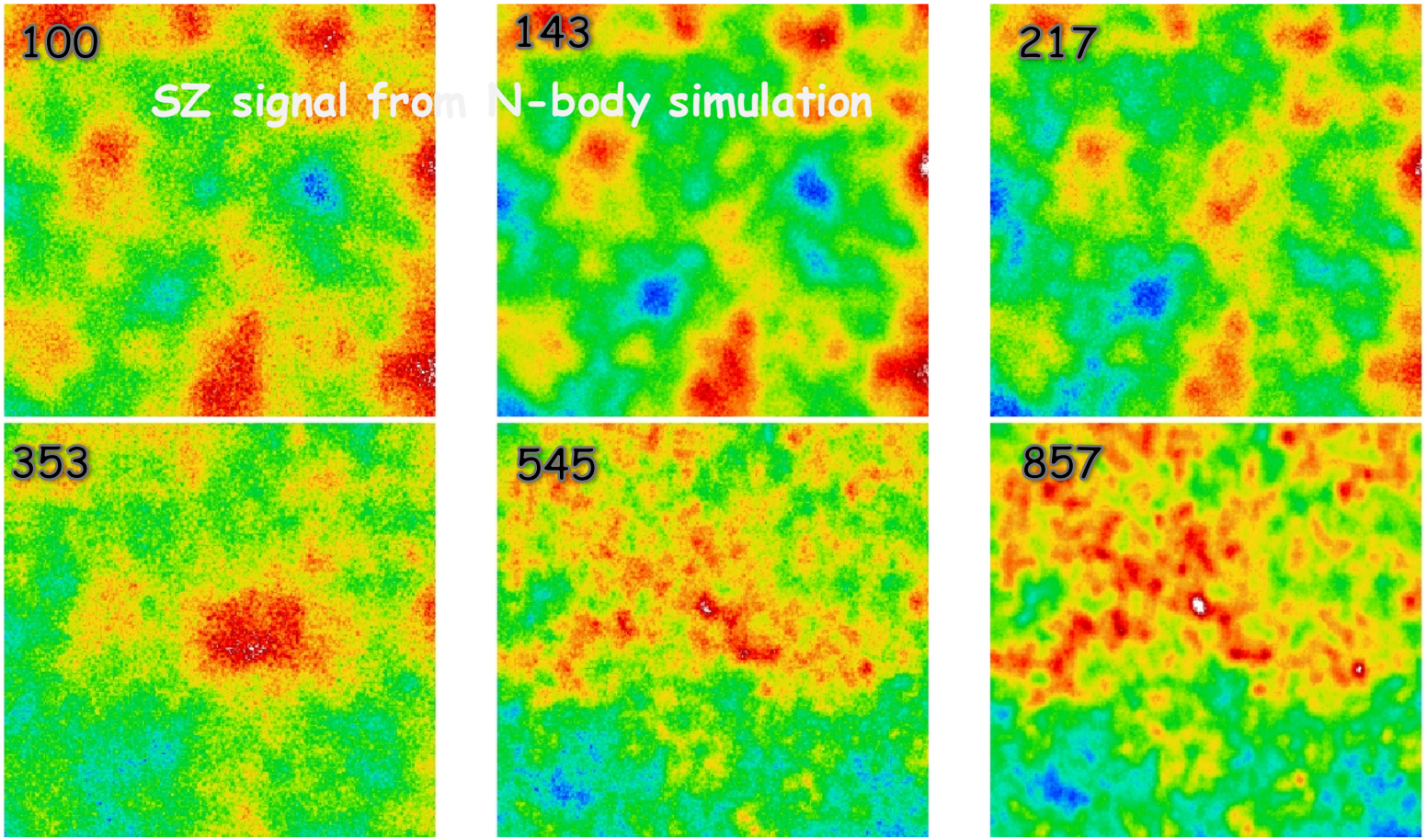




Rasia et al 2015

Simulation of a Merging cluster with Strong Thermal Shock

Mock HFI frequency maps @ (l=270 b=-60)



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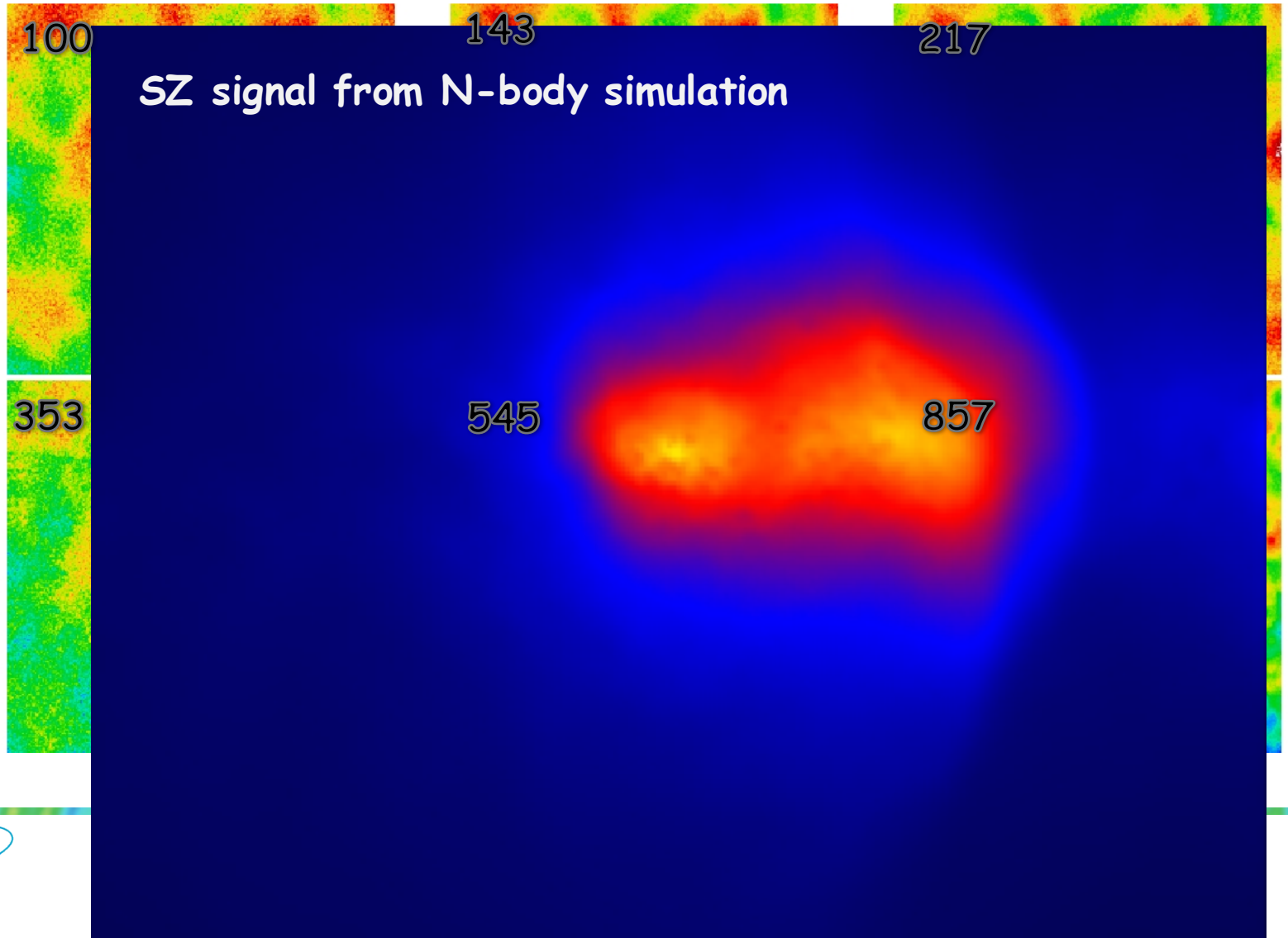
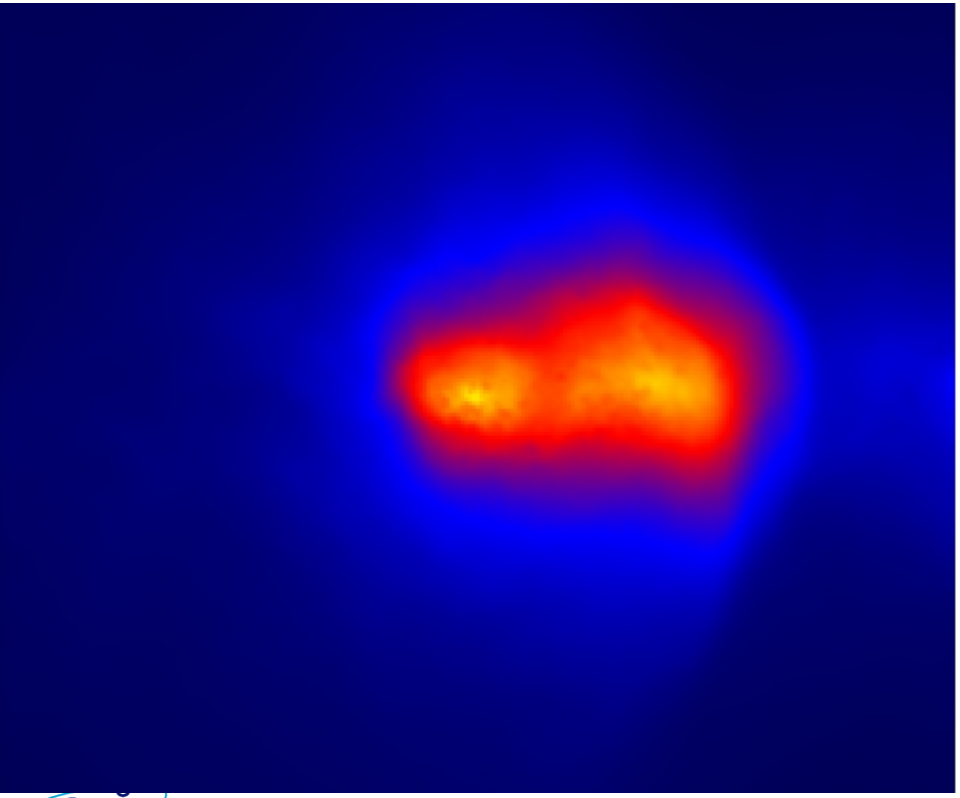


Reconstructed map of the Simulated Cluster

SZ signal from N-body simulation

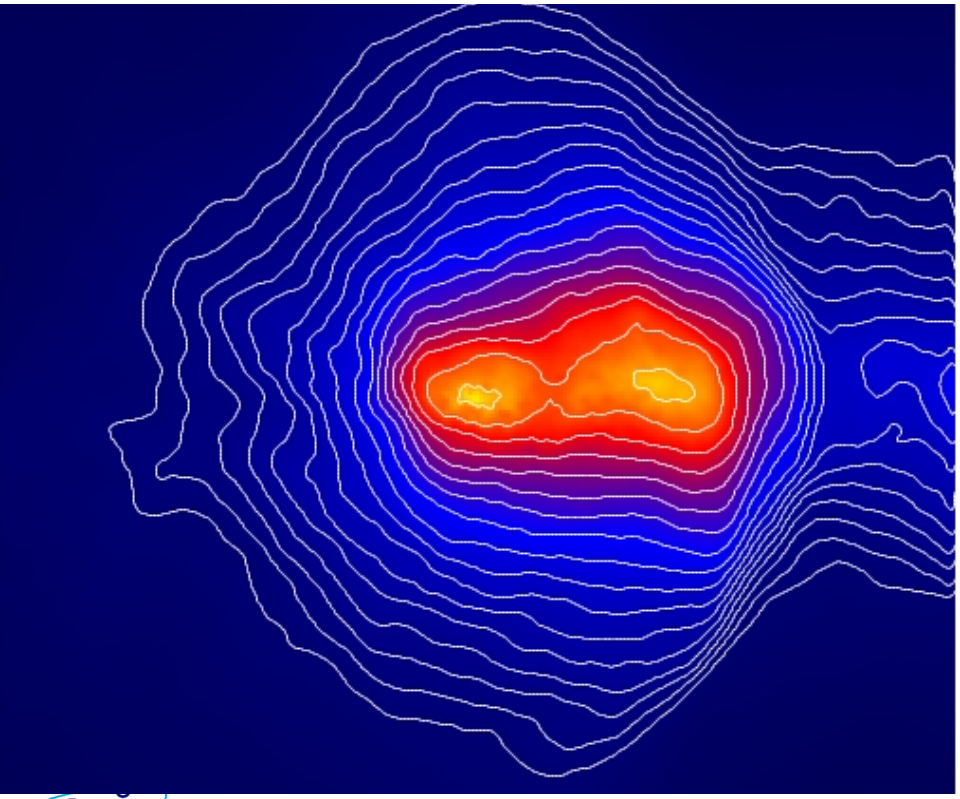


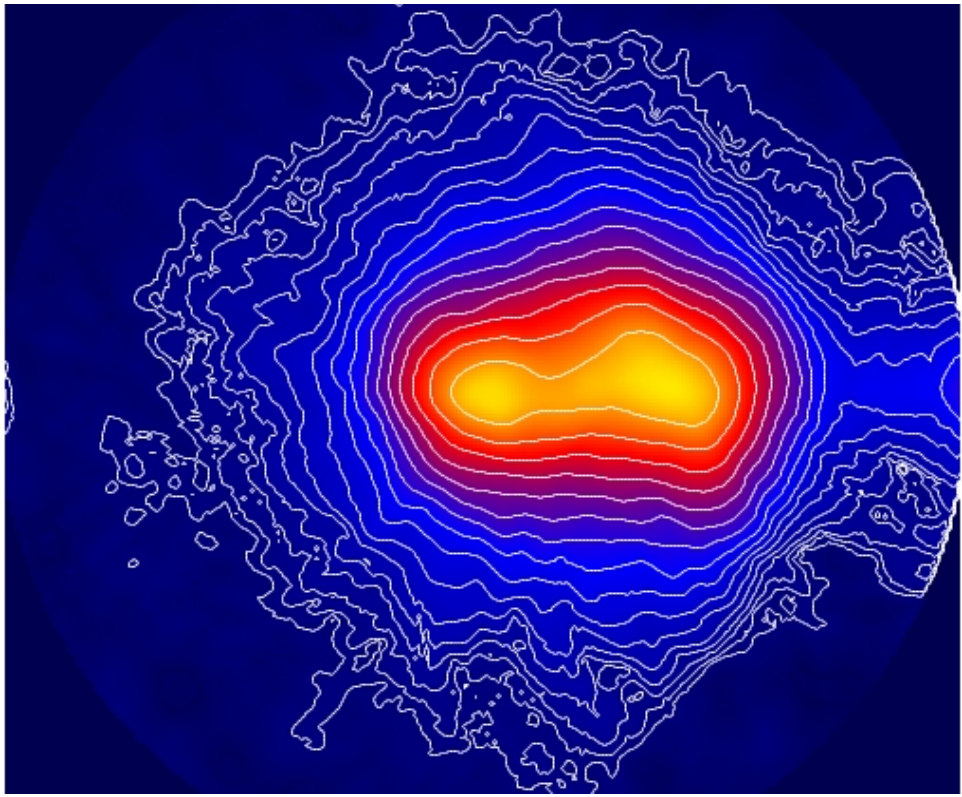
Restored Mock Planck Observation

Reconstructed map of the Simulated Cluster

SZ signal from N-body simulation

Restored Mock Planck Observation





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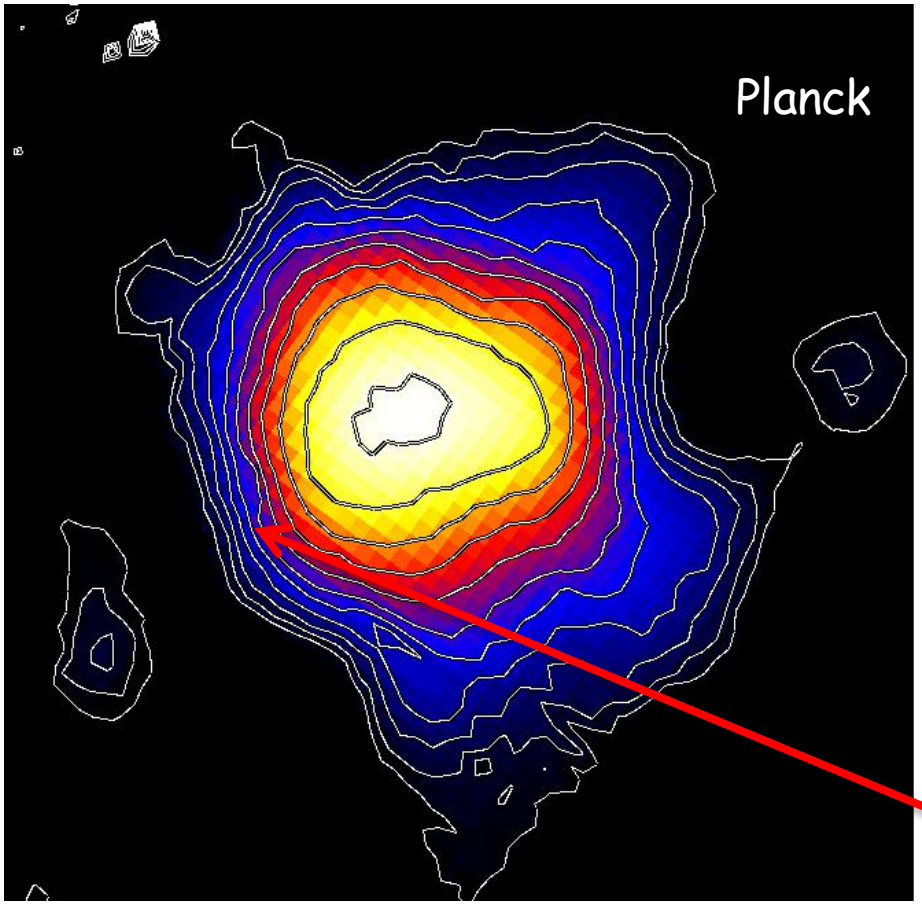
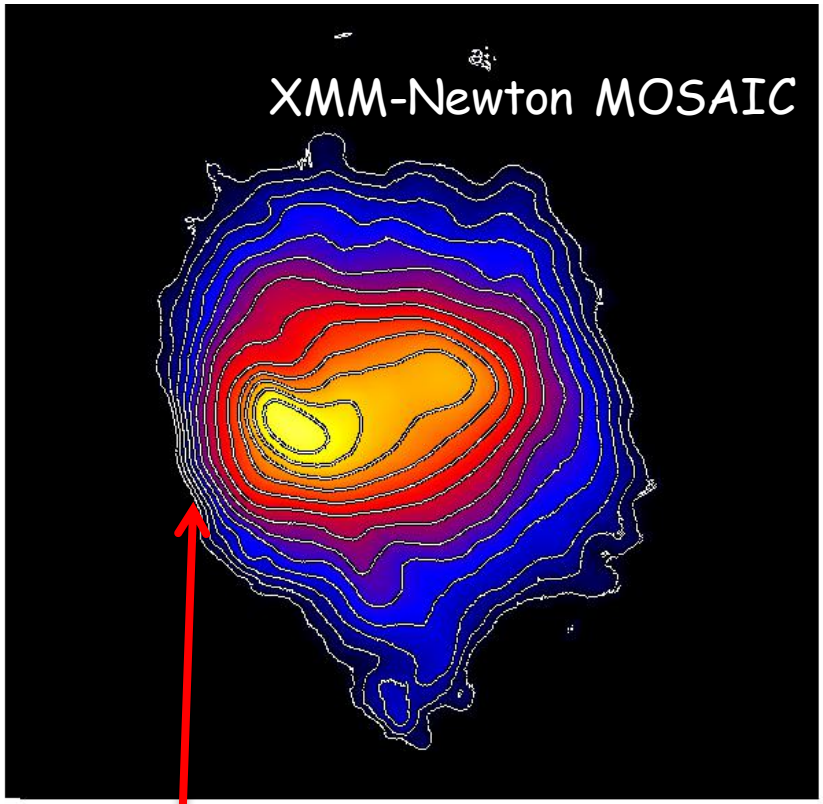
Spectral-imaging algorithm at work on real data

- Use the Planck 2015 full release frequency maps
- Test case: Abell 754
  - l= 239.32668
  - b=24.79898
- Not negligible level of dust contamination !

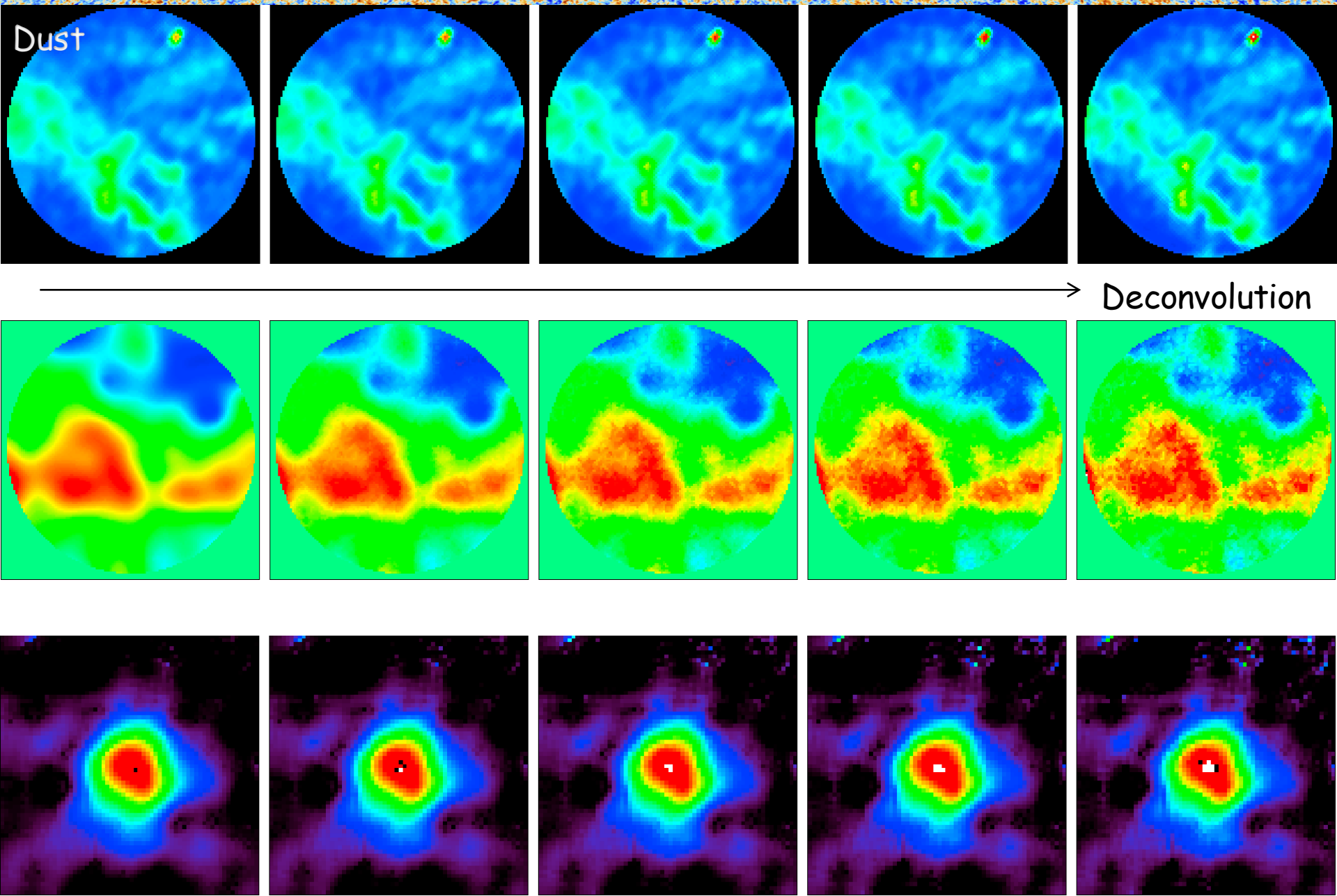
SZ and X-ray Image of A754

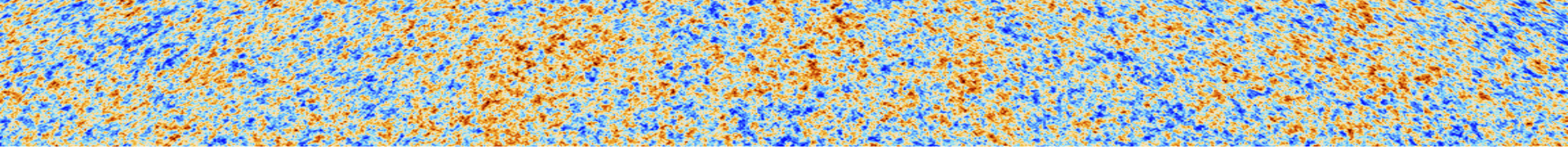




Schock (Macario et al. 2011)

Component separation: A754





“Visual” comparison with some

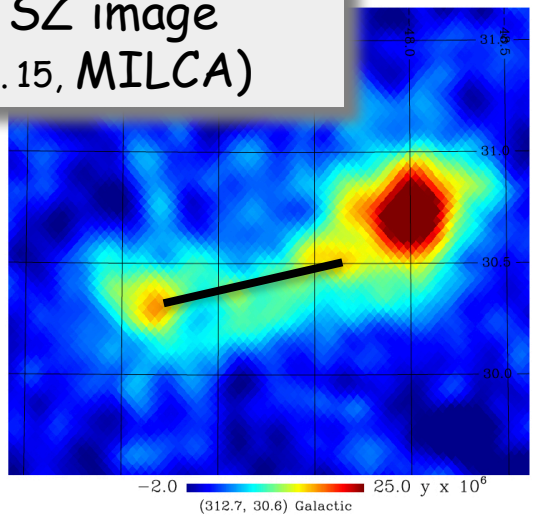
SZ imaging

ILC algorithms:

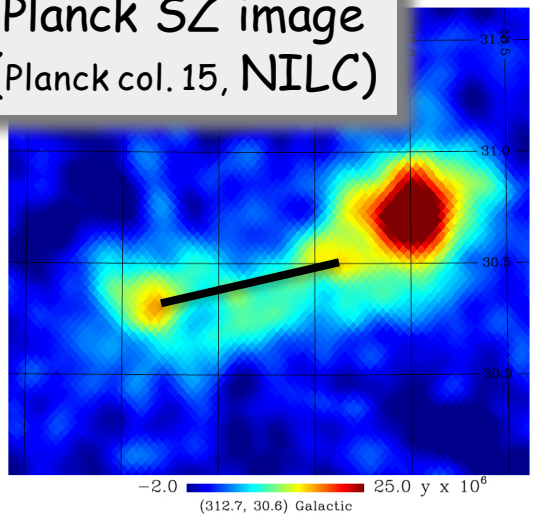
SZ v.s. X-ray images

Shapley supercluster core

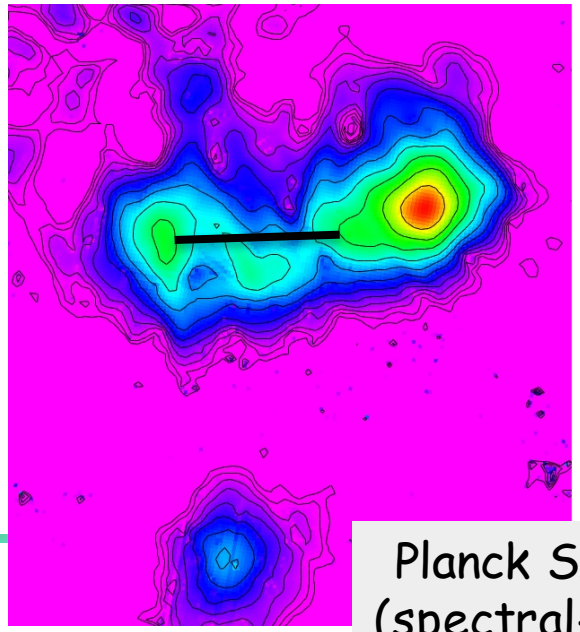
Planck SZ image
(Planck col. 15, MILCA)



Planck SZ image
(Planck col. 15, NILC)



Extracted from the Planck full sky SZ-map
(Planck 2015 results XXII)



Planck SZ image
(spectral-imaging)

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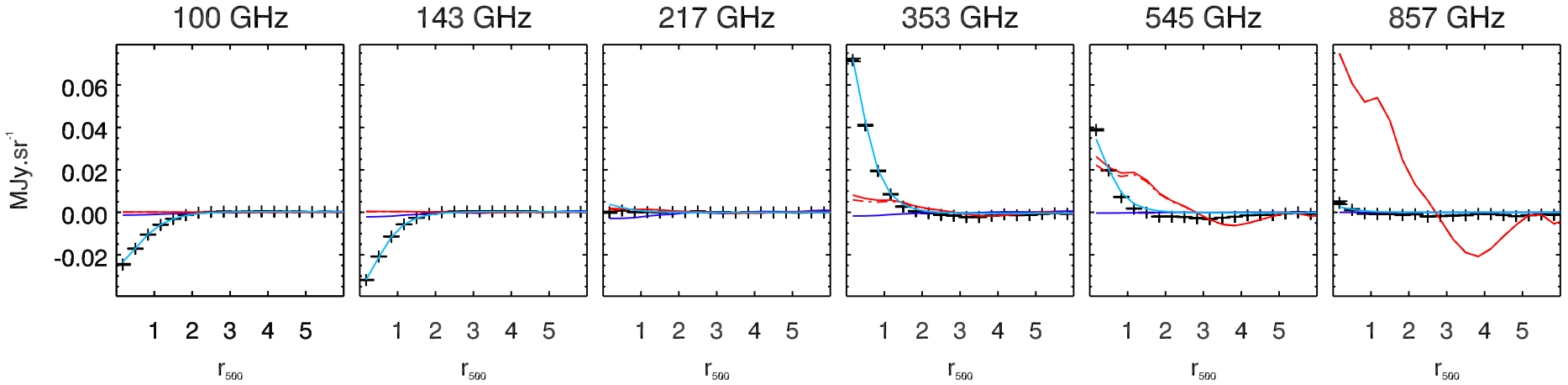
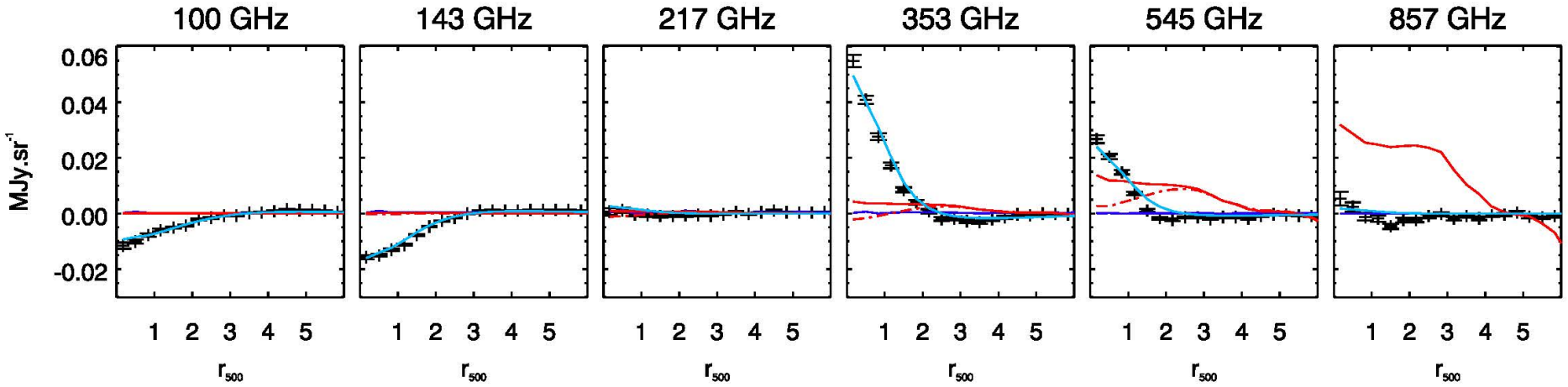
Stacked radial profiles of Planck Clusters

Low redshift sample z<0.5

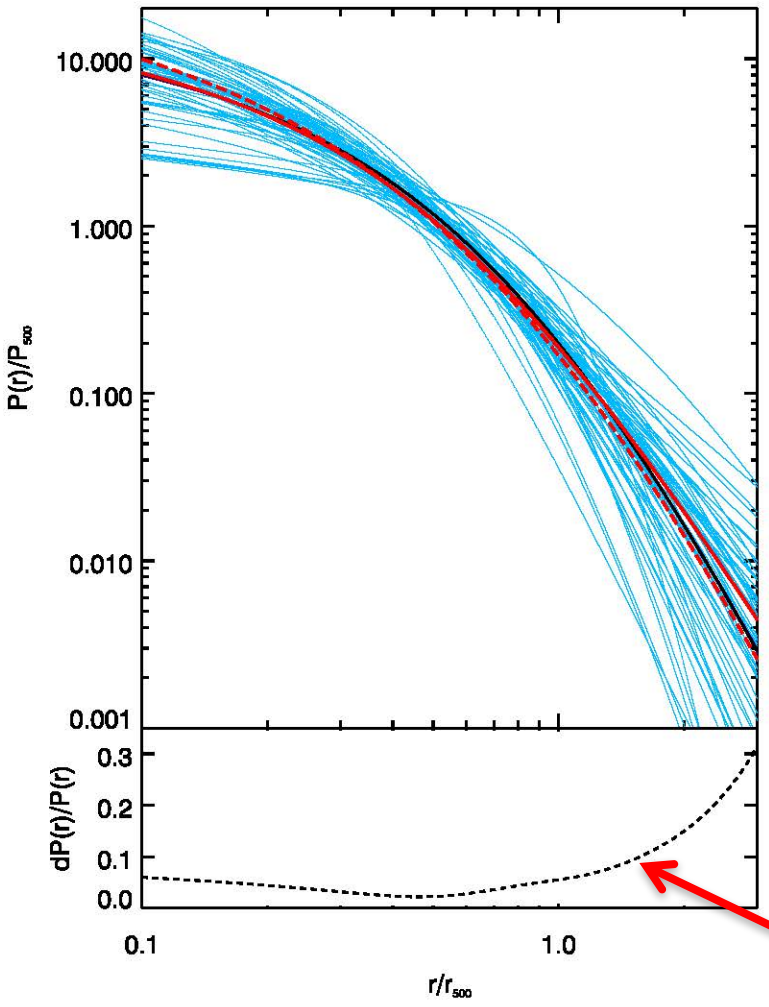


High redshift sample 0.5<z<1

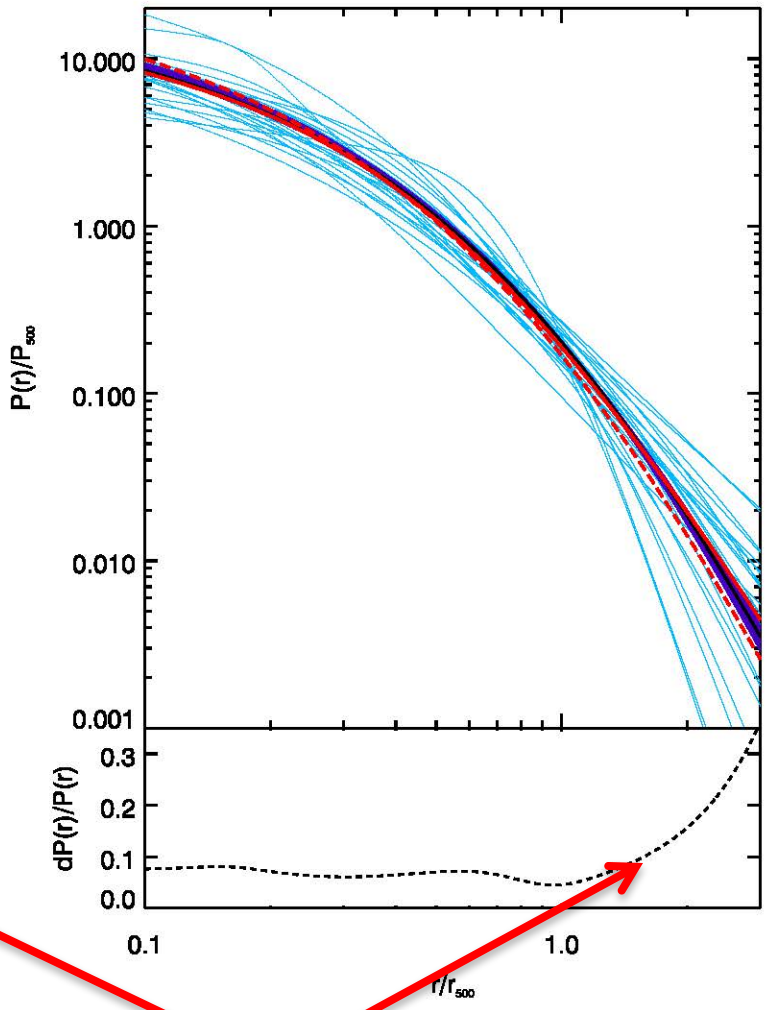


Mass scaled gas pressure profiles

Low redshift sample z<0.5



High redshift sample 0.5<z<1



Similar Scatter, consistent with simulations

Conclusions 1/2

- SZ Observations have opened a new and promising window of investigation related to the clusters of galaxies, large scale structure and cosmology.
- To significantly improve in almost of the studies, beside increasing the sensitivity of future experiments, we necessarily need to find better ways to extract the SZ signal which include better ways to model and subtract the foreground components.
- In the ASI/COSMOS framework we presented a new approach for the spectral-imaging analysis of the SZ emission from clusters of galaxies.
- It uses denoising and deconvolution "protocols" and allows to implement wavelet (for the CMB) and curvelet (for Dust and SZ) transform

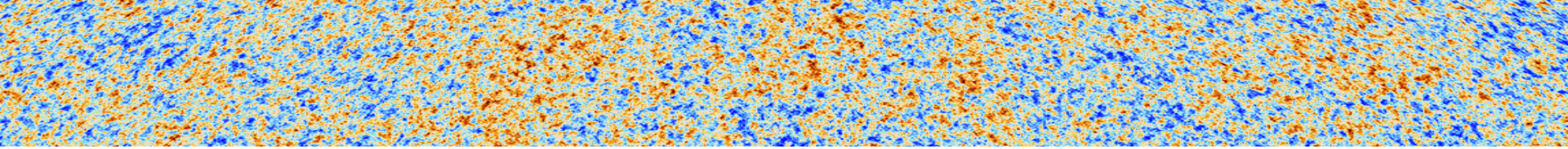
Conclusion 2/2

- One of the pros: use of the full spatial resolution at each frequency channel.
- The proposed approach is instrument flexible: one can easily add in the analysis frequency maps from other SZ experiments (e.g. Olimpo, SPT, Core+)
- It is needed only:

  Frequency map

  Noise map

  Frequency response and beam
- N-body simulations are essential



Thank you