LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

Enigmass

HFI PLANCK
a look back to the birth of Universe

NIKA

Astrophysics and Cosmology with galaxy clusters from Sunyaev-Zel'Dovich observations

Rémi Adam

Enigmass Cosmology meeting
LAPP (Annecy) - 19/06/2014

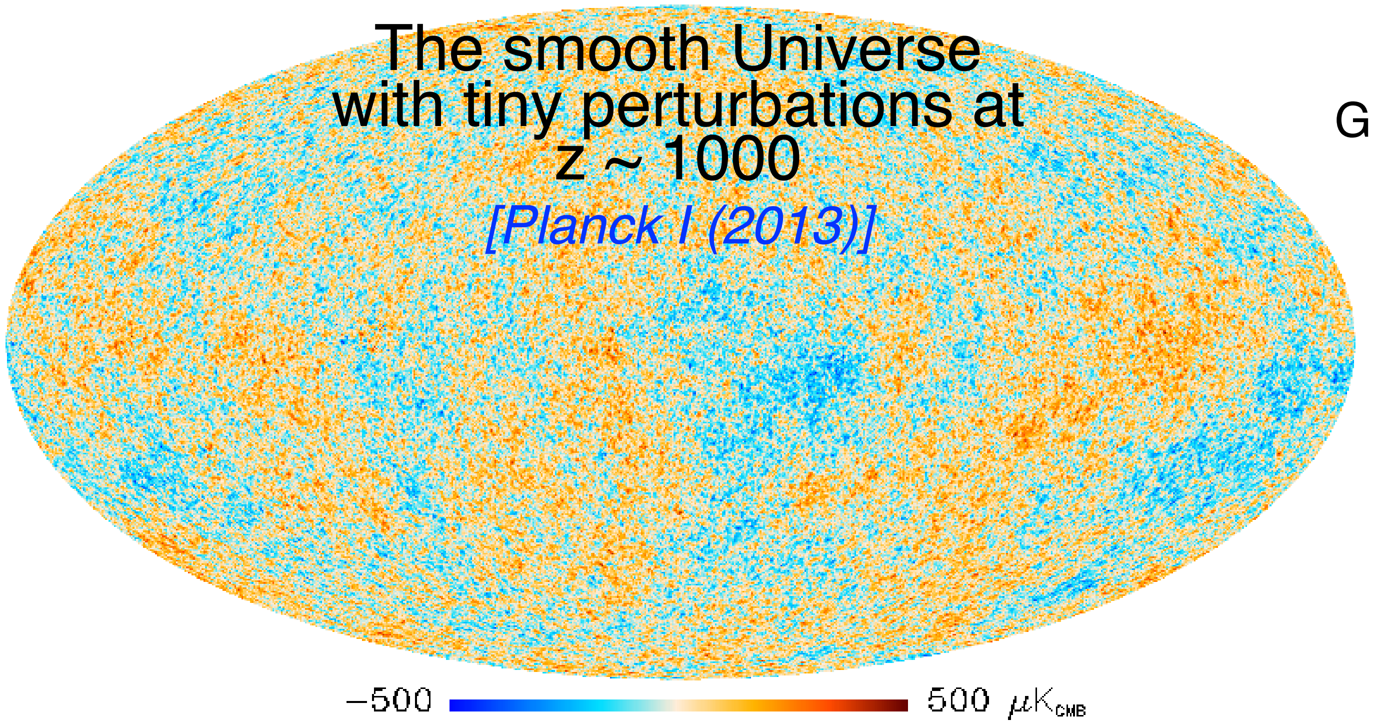
[MACS J0717+3745 - Ma et al. (2009)]

Outline

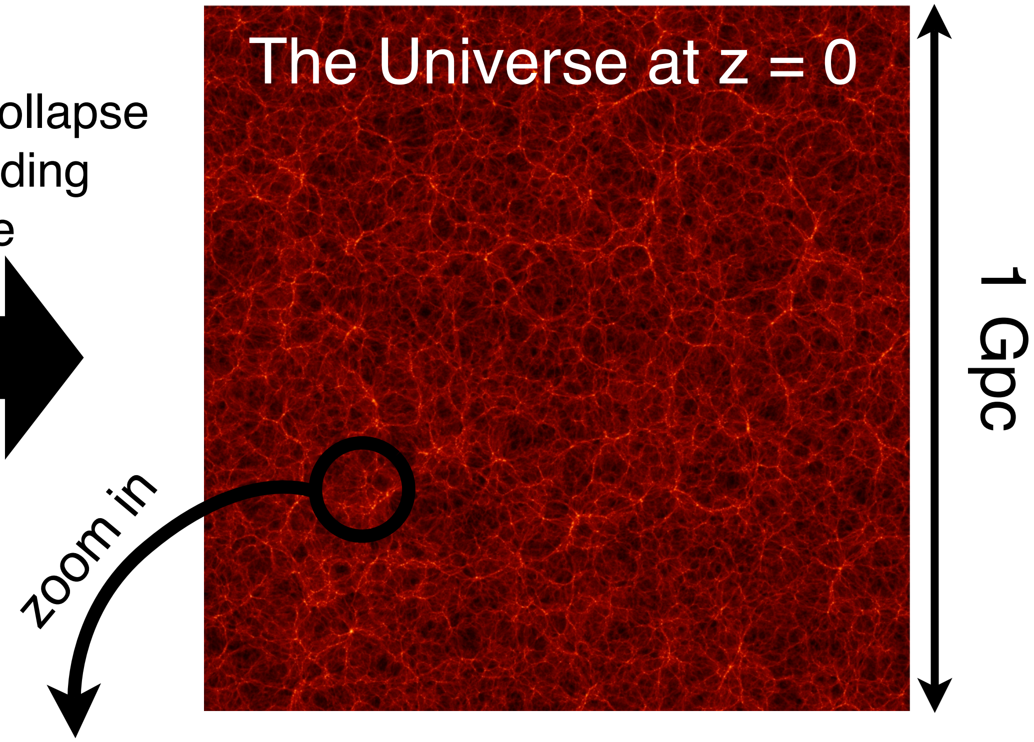
1. **Galaxy clusters** as cosmological probes
2. Cosmology from the **Sunyaev-Zel'dovich** effect
3. Looking at high-redshift clusters with **NIKA**
4. Probing the **IntraCluster Medium**
5. Conclusions, perspectives and **NIKA2**

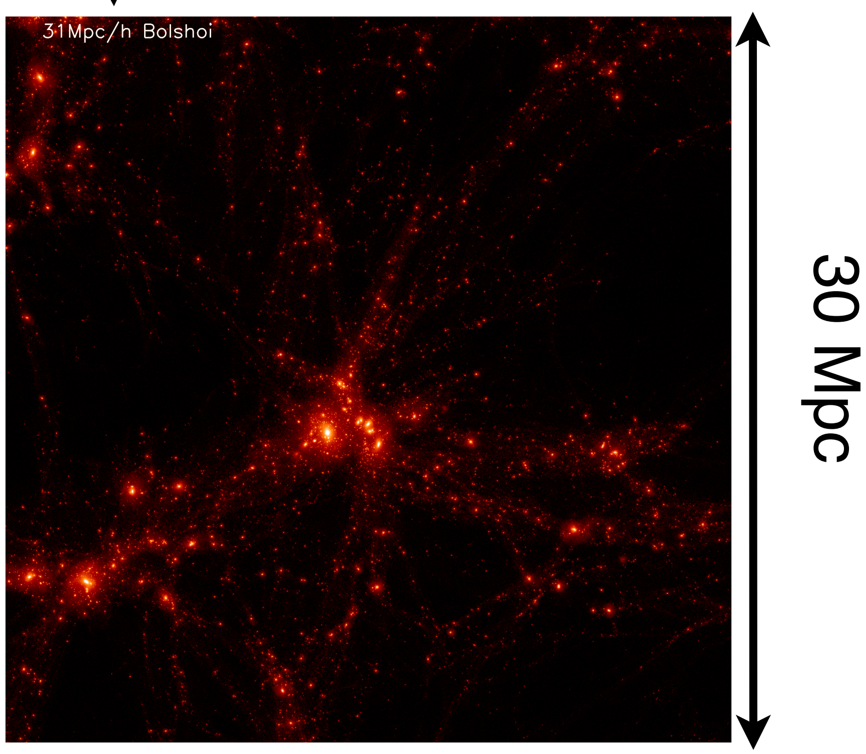
Galaxy clusters as cosmological probes

From primordial fluctuations to galaxy clusters



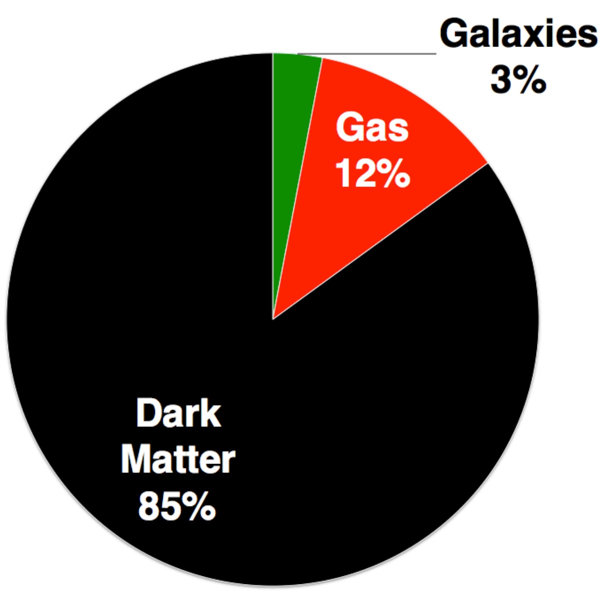
Gravitational collapse in an expanding Universe





MultiDark simulations [www.multidark.org]

The galaxy cluster recipe:



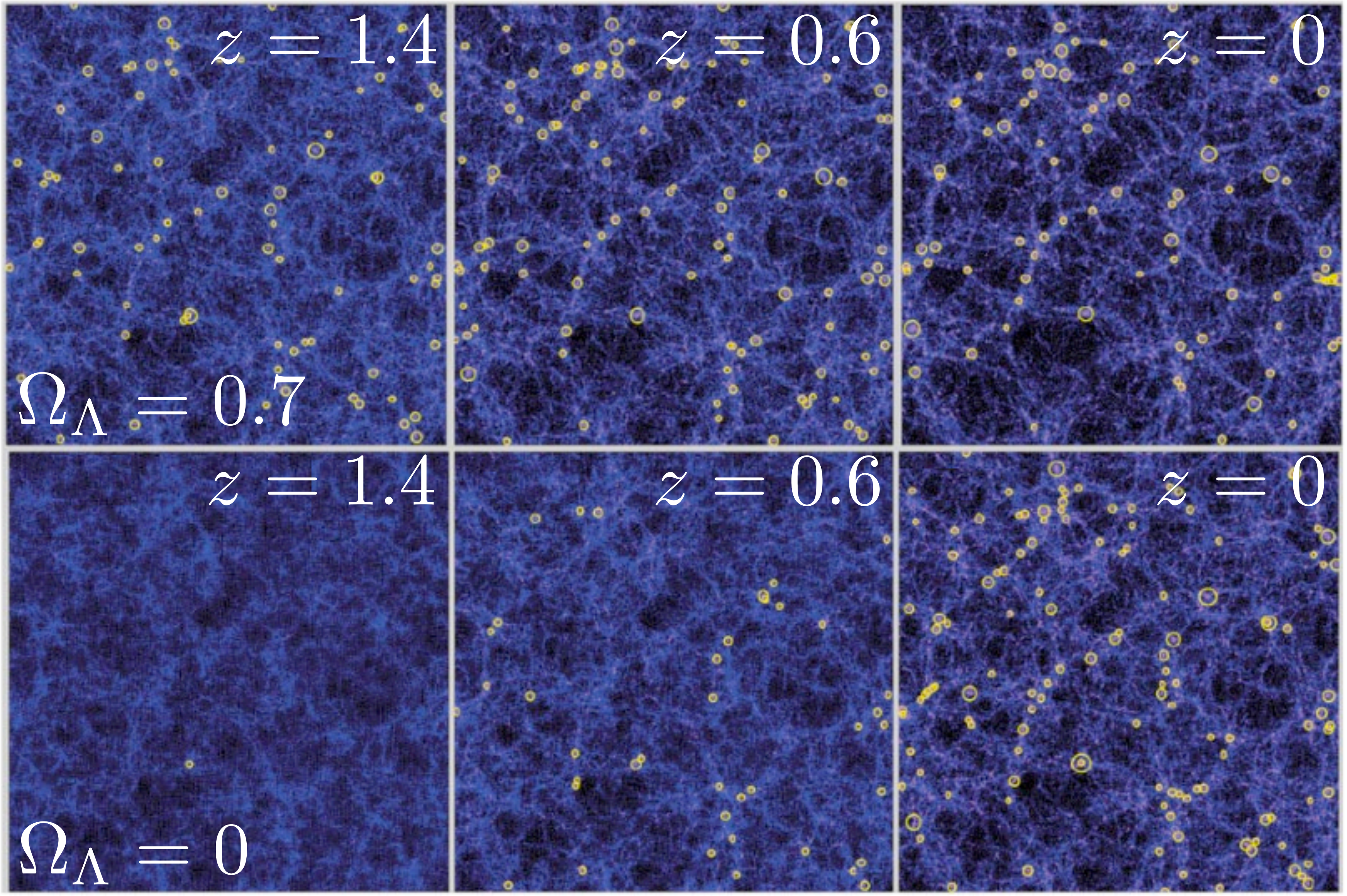
➡ **Clusters form hierarchically at the intersection of filaments**

Testing cosmology with massive halos

- Cluster number counts are very sensitive to cosmology via *[see Planck XX (2013)]* :
  - Matter content
  - Initial density distribution
  - Expansion history of the Universe

- Observables have to be related to the mass

Growth of structure simulation in a flat Universe



[S. Borgani and L. Guzzo (2001)]

➡ **Galaxy clusters are a powerful probe for cosmology, if one can measure their masses**

Galaxy clusters observables

Optical & infrared:

- 100-1000 **galaxies** per cluster
- Velocity dispersion
- **Lensing mass** (dark matter)

  $M_{\rm tot} \sim 10^{14} M_\odot$
- Dusty galaxies

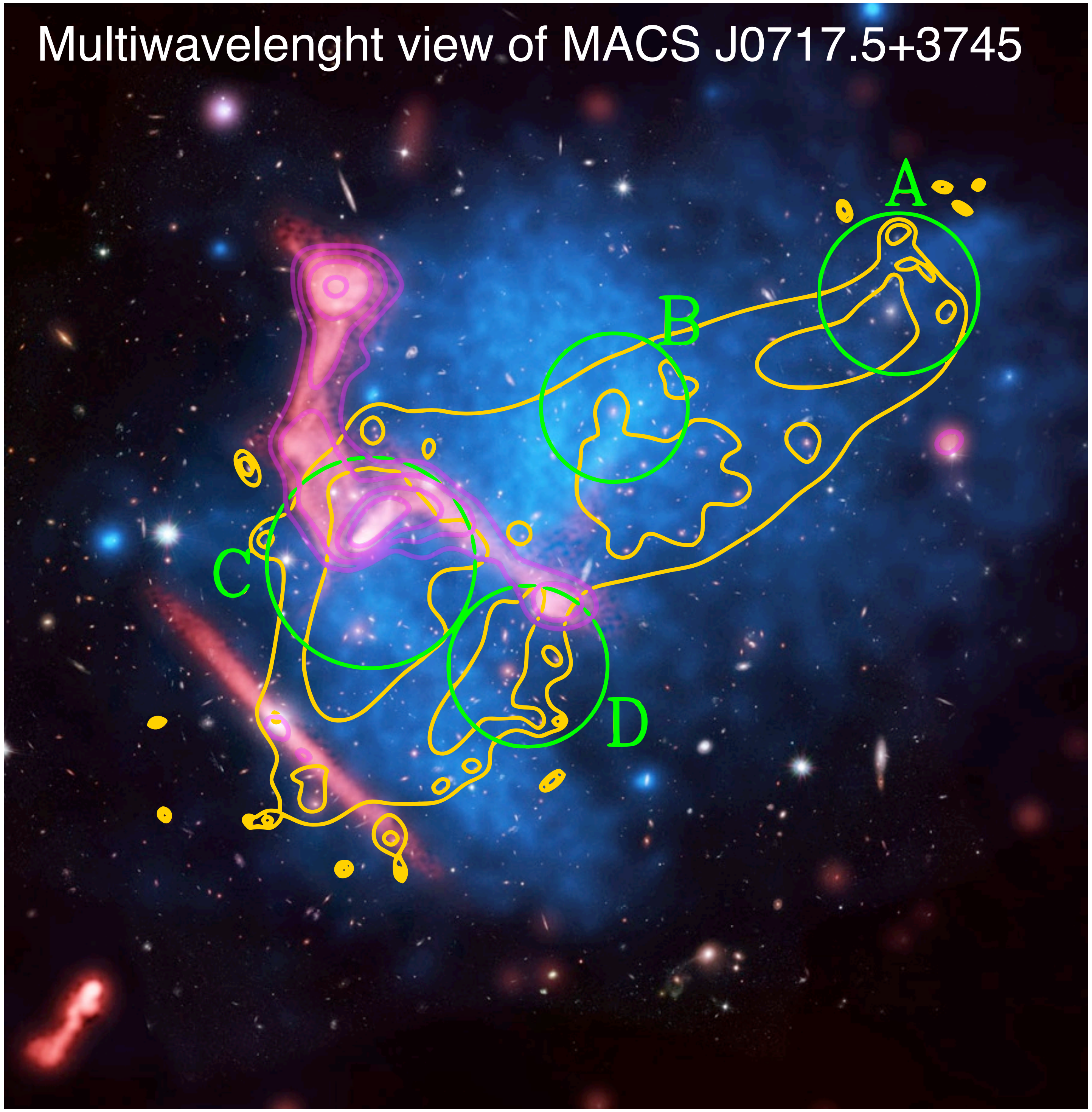
X-ray:

- **Gas density** from bremsstrahlung
- **Temperature** from spectroscopy
- $T_g \sim 10^8$ K
- **Mass** from **hydrostatic** equilibrium

Radio:

- **Non-thermal emmission**
- Radio point source

➡ **Detailed physical understanding from multi-wavelength approach**



[van Weeren et al. (2013) + Mroczkowski et al. (2012)]

What can we learn from clusters
Astrophysical and Cosmological interplay

Improved masses determination

Cluster Astrophysics

Shocks heating, MHD turbulence
Dynamical/thermodynamical state
Radiative cooling
Star and black hole formation
Feedback from compact sources (AGN)
Dust content
Clumping
...
[e.g. S. Allen et al. (2011)]

Improved constraints on astrophysical models

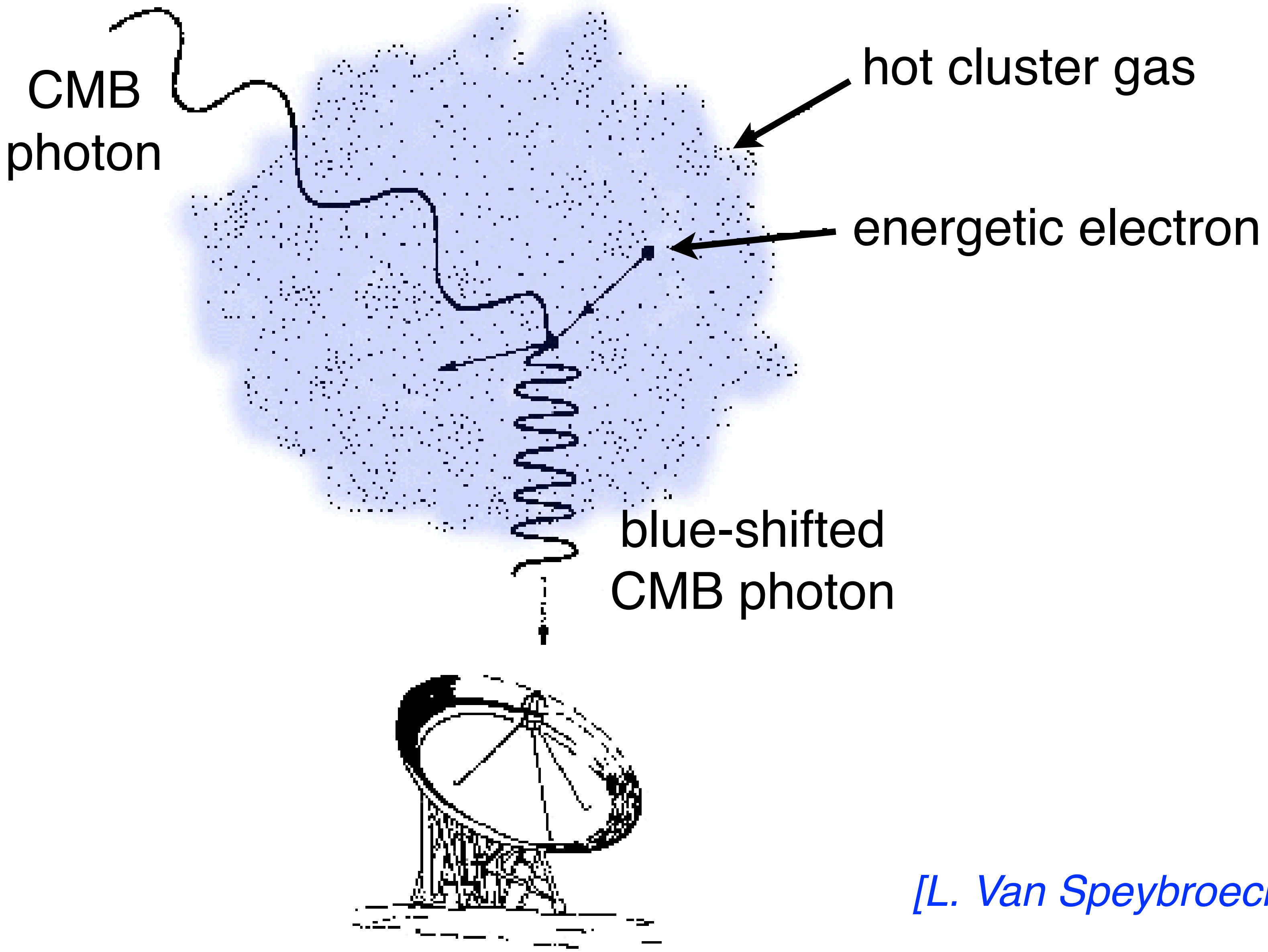
Cluster Cosmology

Growth of structures
Universe expansion history

➡ **Deep astrophysical understanding of cluster is necessary for cosmology**

Cosmology from the Sunyaev-Zel'dovich effect

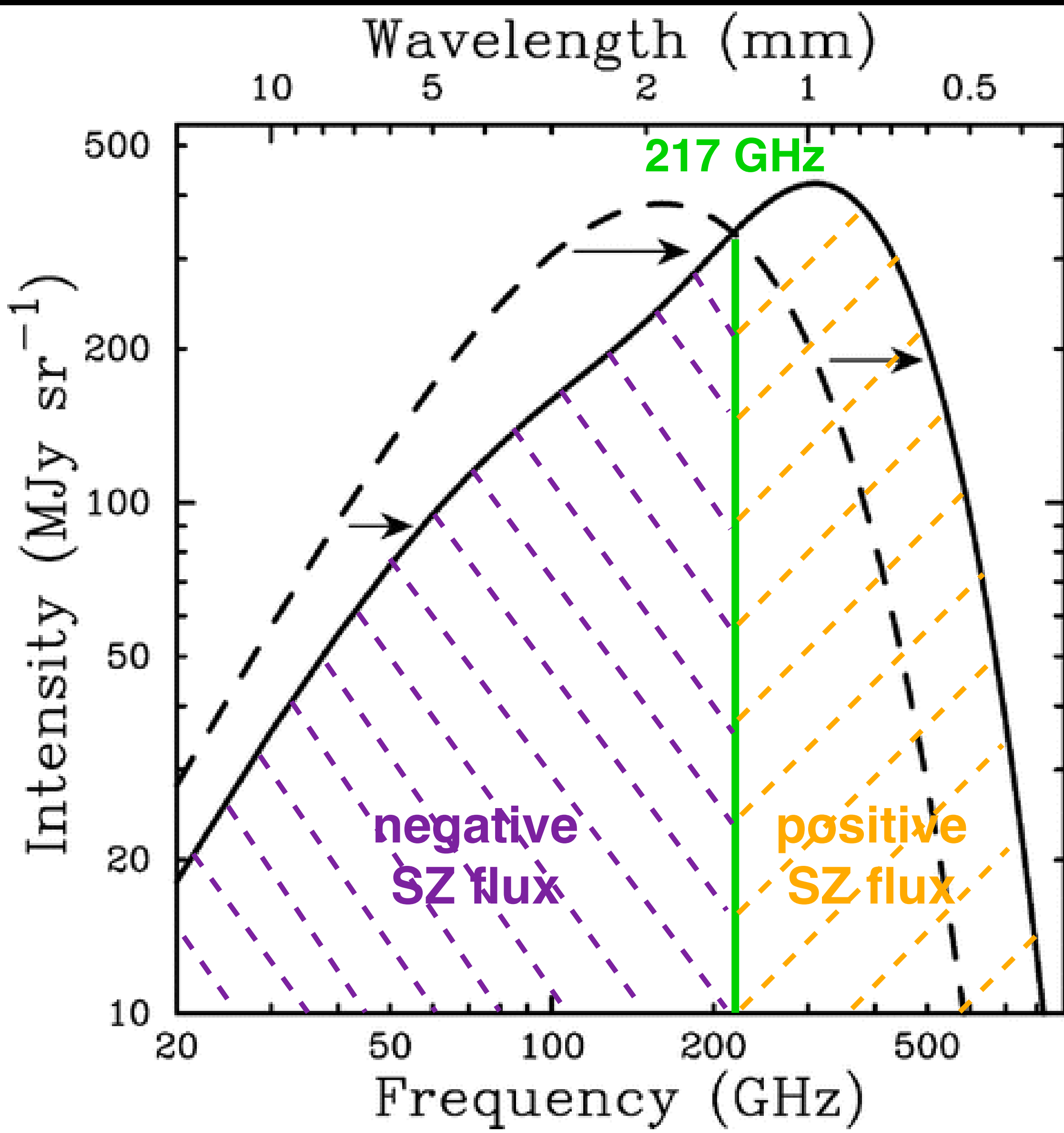
Another observable: the Sunyaev-Zel'Dovich effect



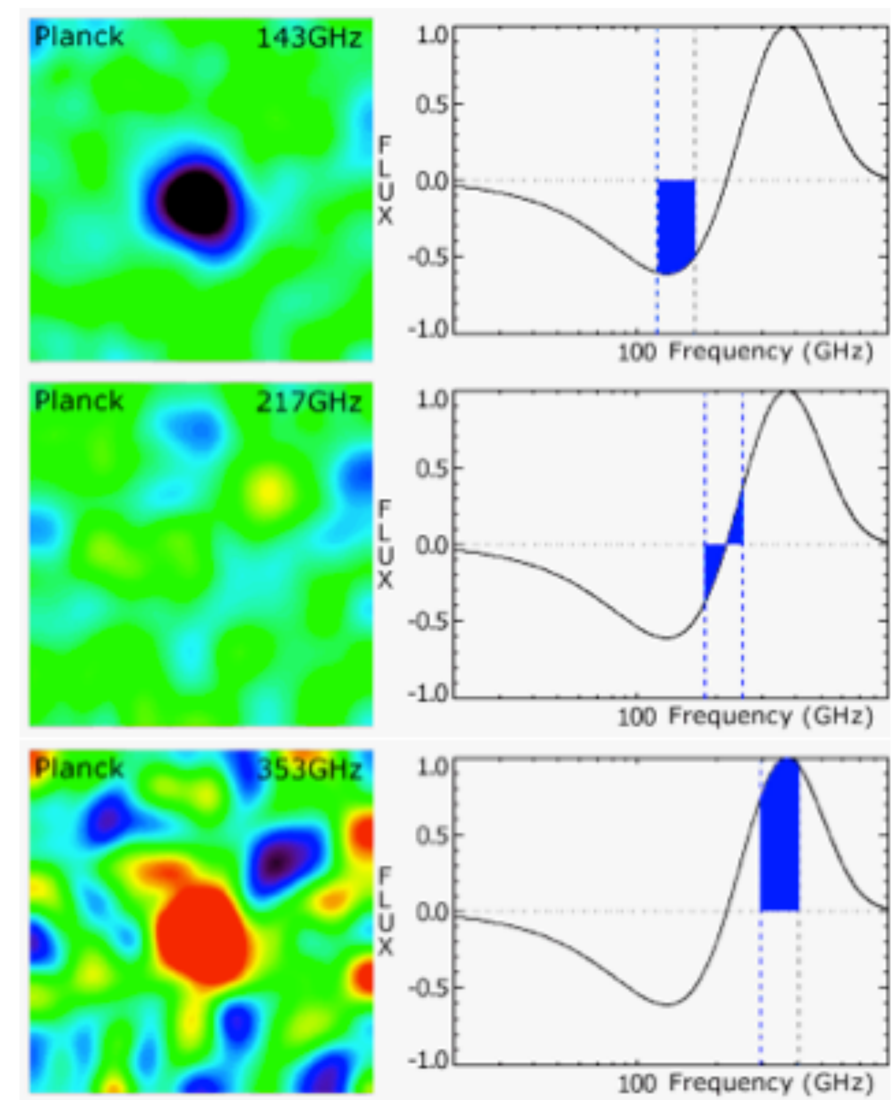
[L. Van Speybroeck]

➡ **The SZ effect is the inverse Compton scattering of CMB photons on hot electrons in clusters**

Probing pressure with the thermal Sunyaev-Zel'Dovich effect (tSZ)



[J. E. Carlstrom et al. (2002)]



[ESA HFI/LFI consortia]

- tSZ = CMB spectral distortion caused by electronic pressure
- No redshift dependence

$$\frac{\Delta I_{tSZ}}{I_0} = \left(f(\nu) + \delta_{tSZ}(T_e, \nu)\right) \frac{\sigma_T}{m_e c^2} \int P_e dl$$

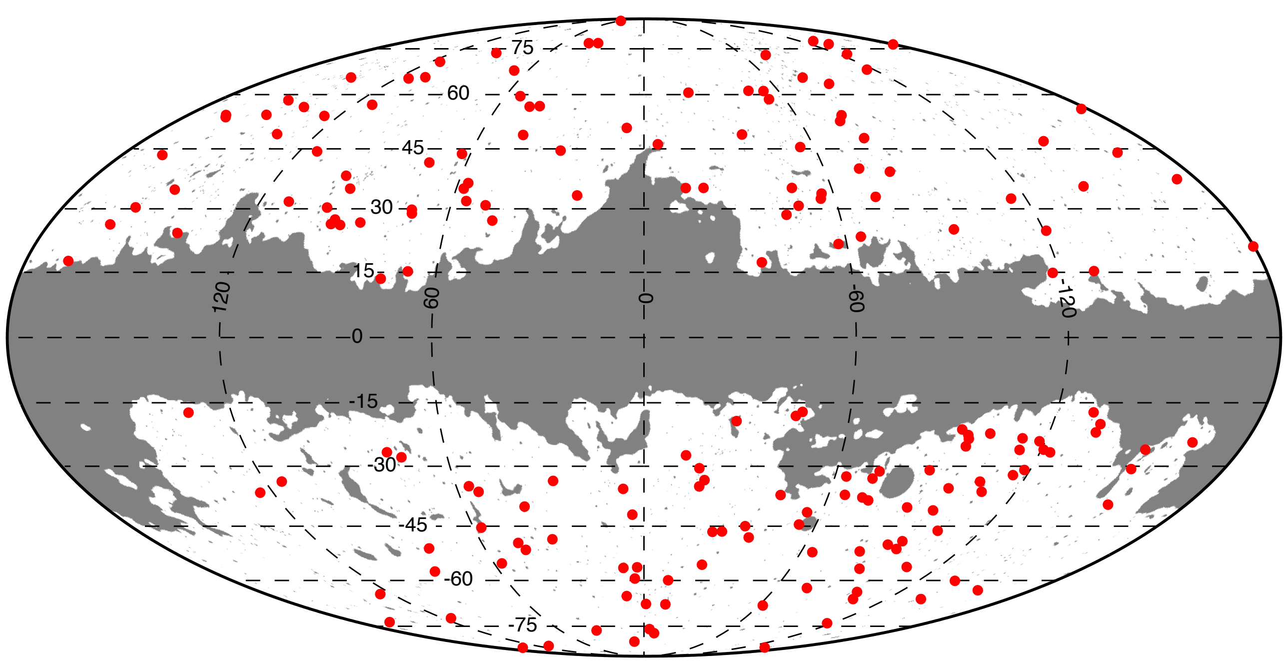
Compton parameter y: tSZ amplitude

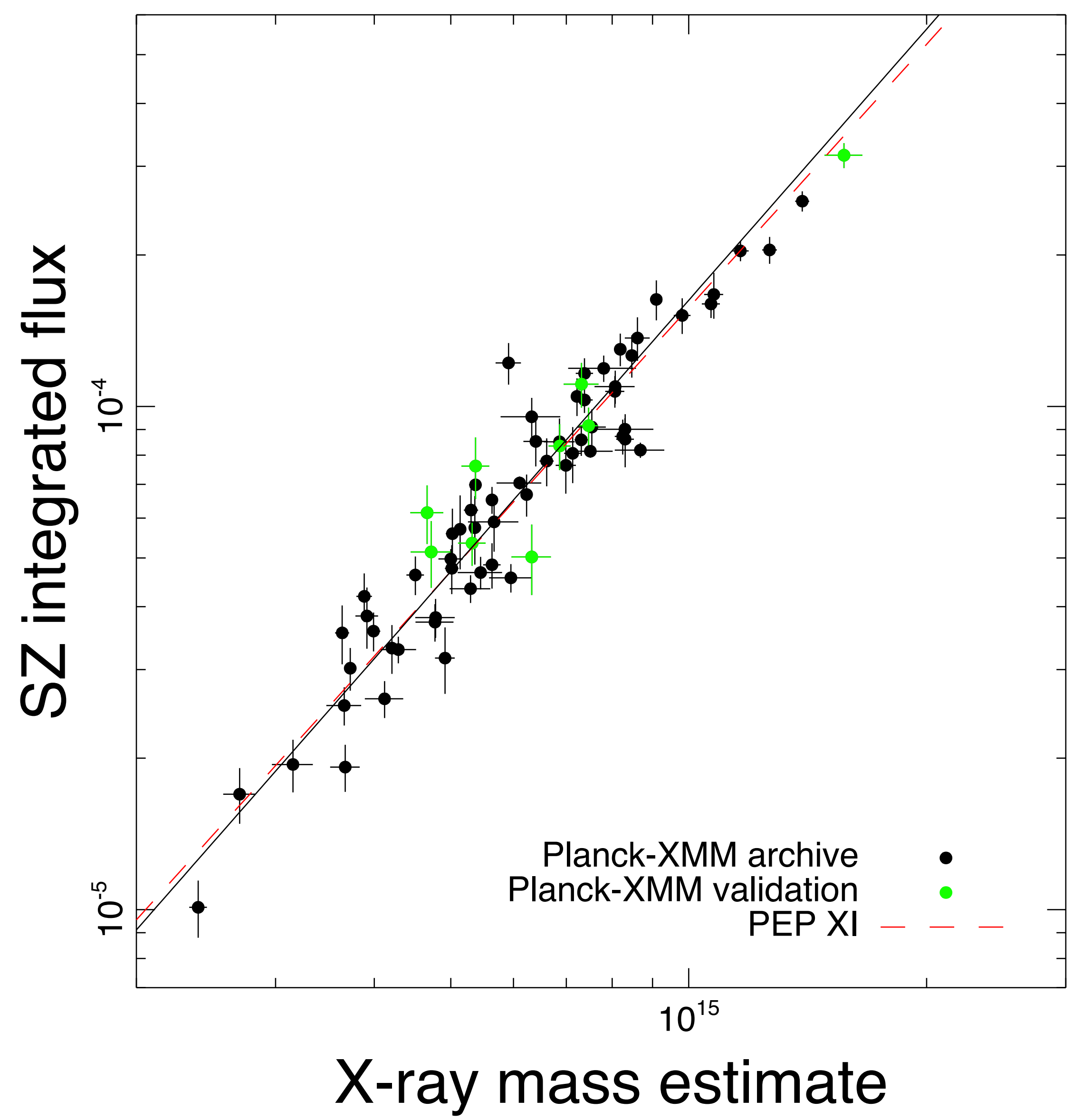
➡ **The tSZ effect probes the pressure in clusters**

State-of-the-art Planck cosmological SZ results
Cluster counts sample [Planck XX (2013)]

$$SZ_{flux} \rightarrow \text{thermal pressure} \rightarrow \text{thermal energy} \rightarrow \text{hydrostatic mass}$$

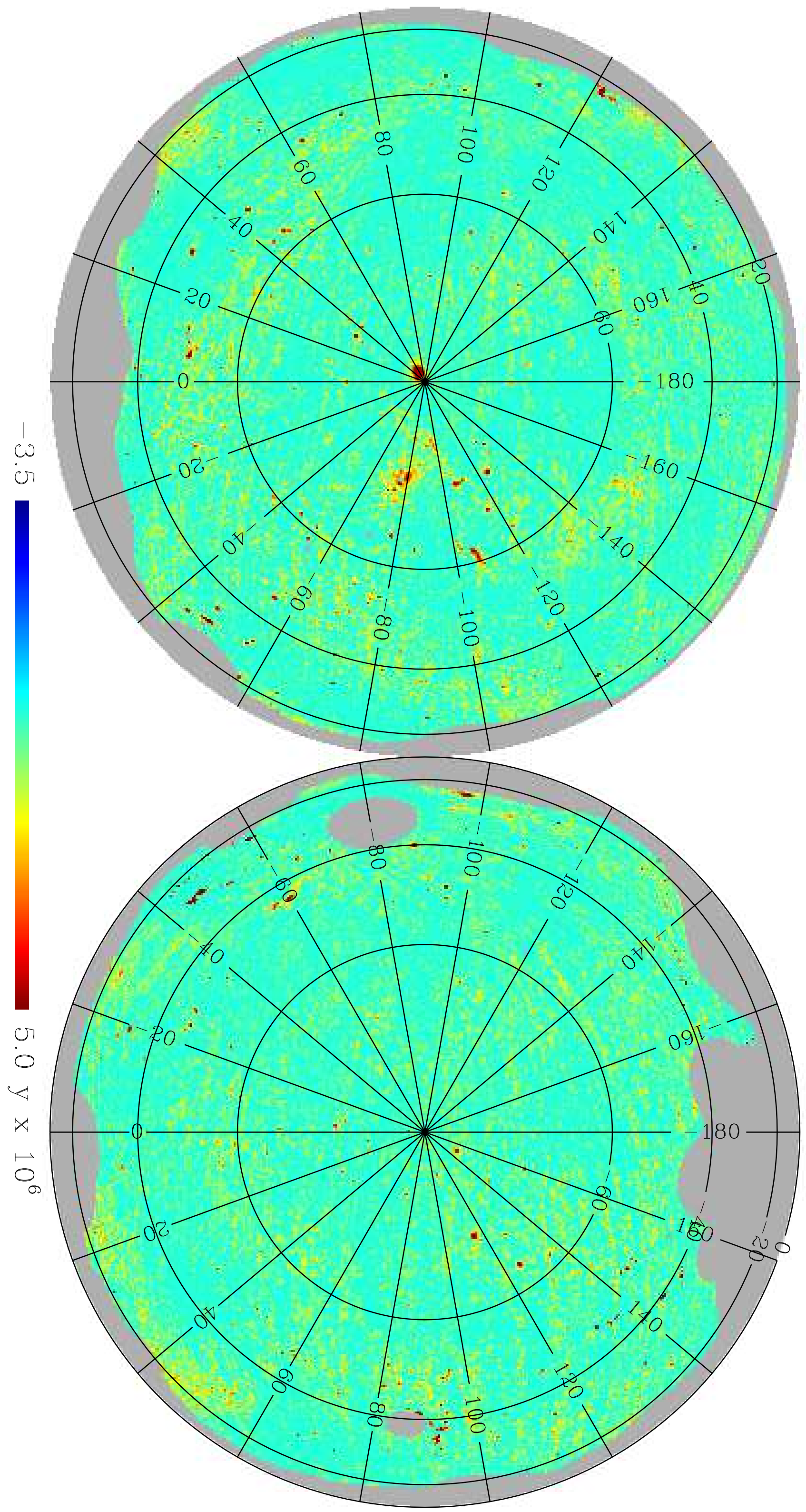
- Selected sample from a compromise between purity and large number of clusters
- Considered only the cleanest 65% of the sky
  - ➡ 189 clusters out of 1227 [Planck XXIX (2013)], with S/N > 7
  - ➡ 188 clusters with known redshift
  - ➡ 71 of them were used to calibrate the mass



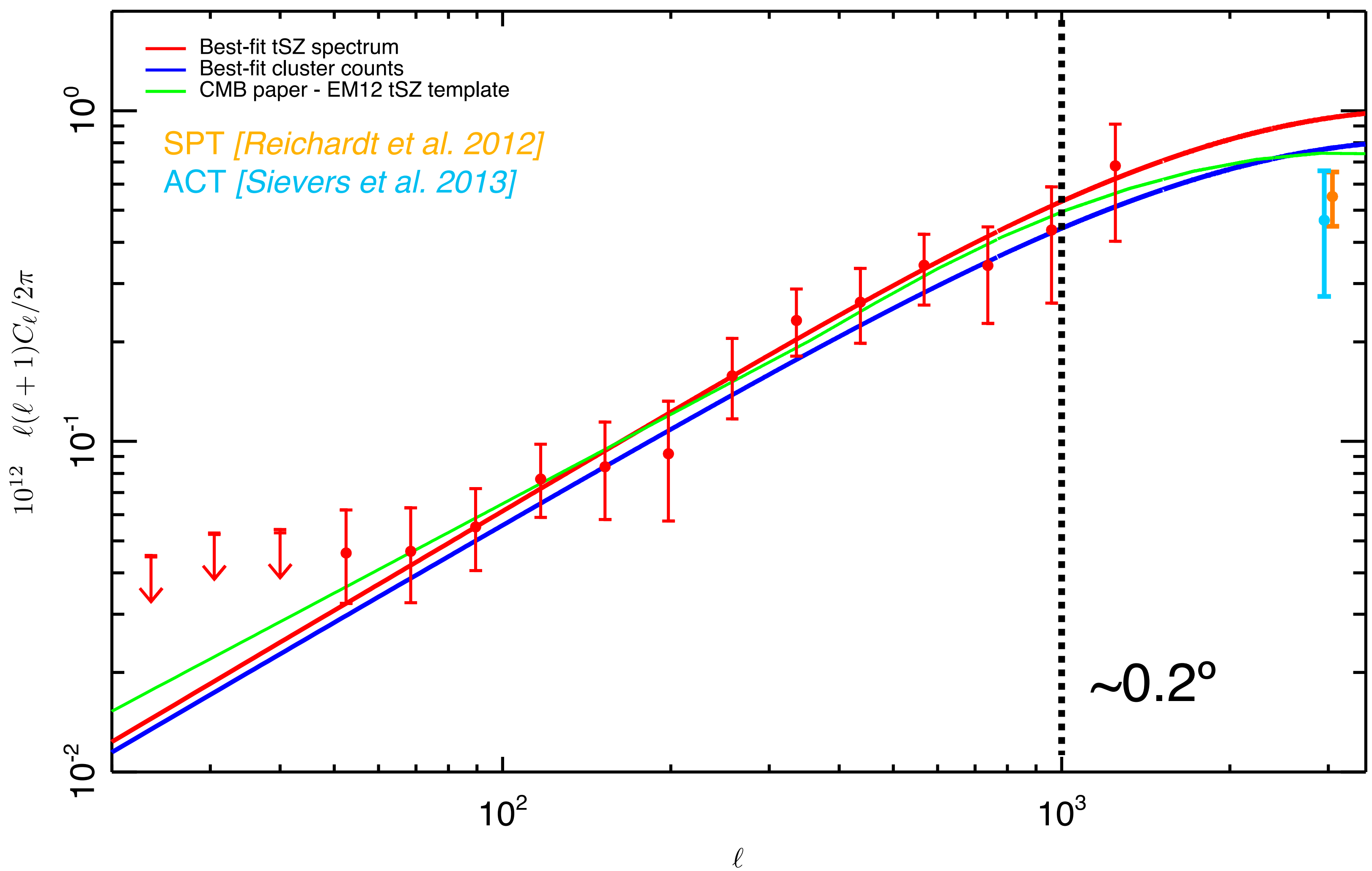


➡ **Well characterized SZ selected sample**

State-of-the-art Planck cosmological SZ results
Compton *y* parameter map *[Planck XXI (2013)]*

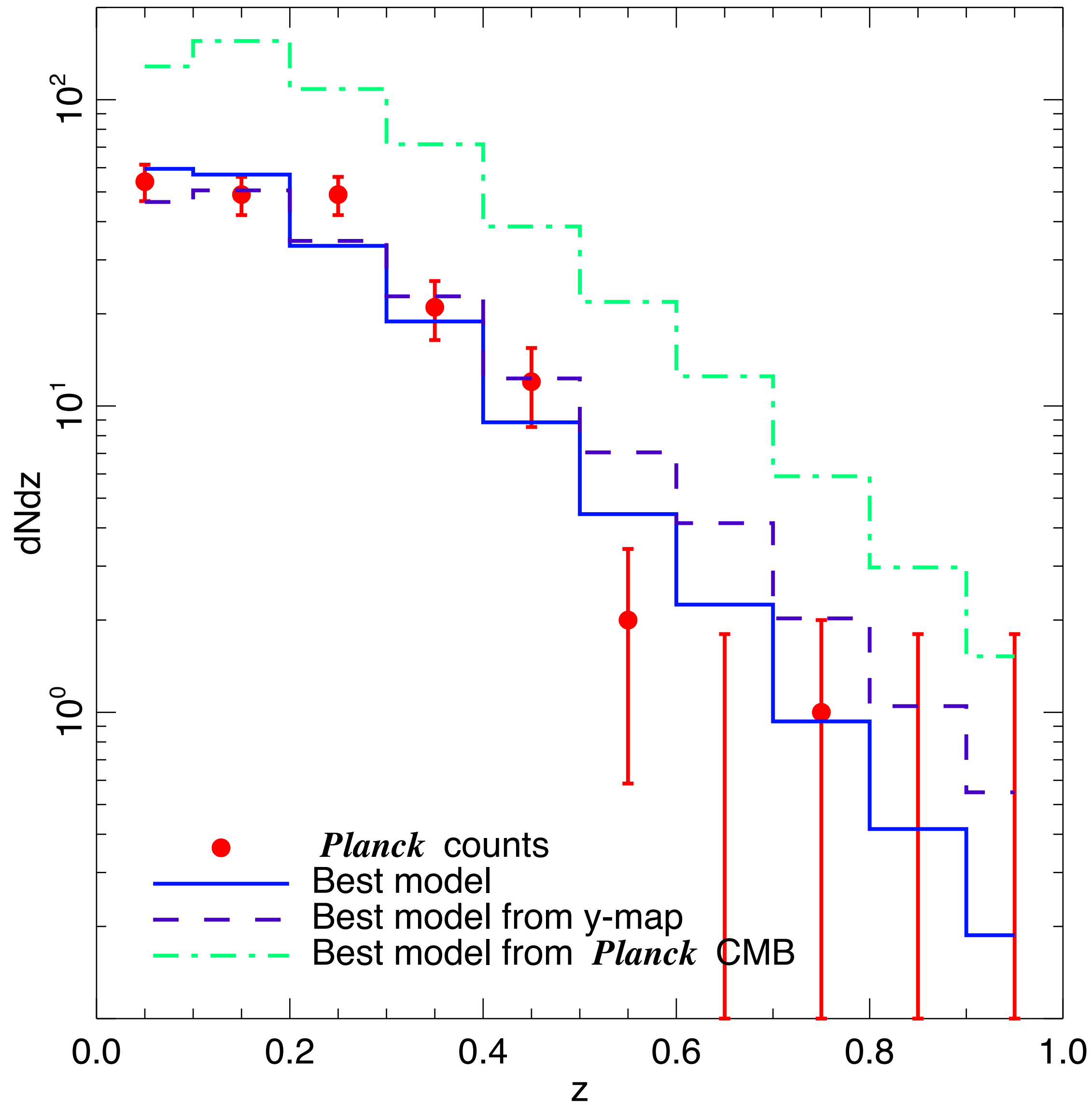


- Use Planck HFI channels to extract the Compton *y map* *[Remazeilles et al. (2011), Hurier et al. (2013)]*
- Compute the power spectra (account for foregrounds contamination)
- Compare to expected models (sensitive to matter distribution)

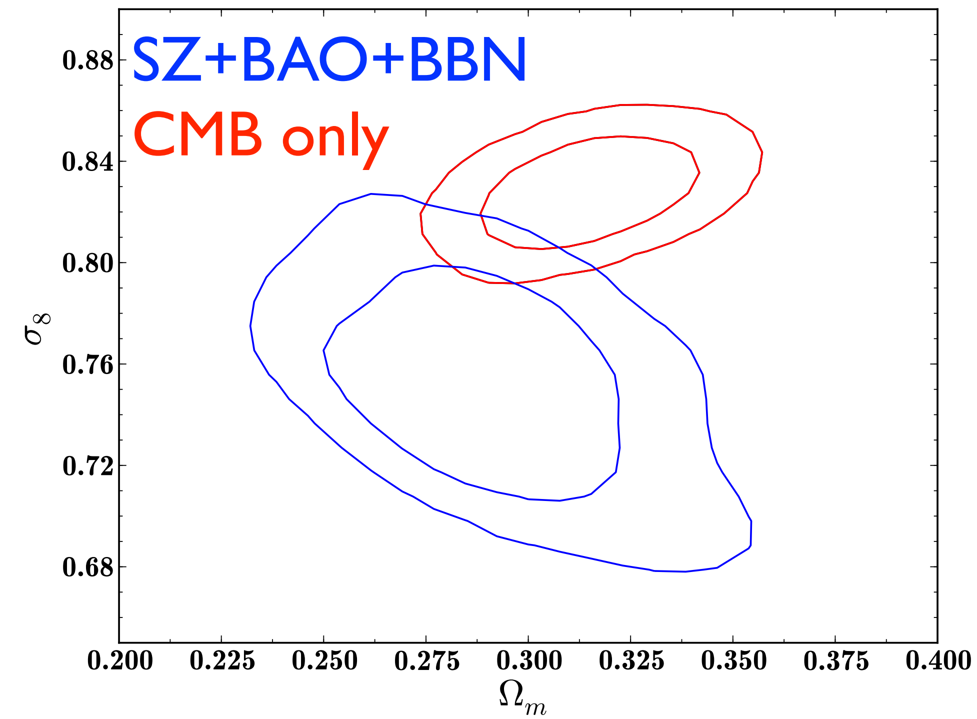


➡ **First tSZ power spectrum at these scales**

State-of-the-art Planck cosmological SZ results
Constraints on cosmology



[Planck XX (2013)]



[Planck XX (2013)]

- Good agreement between *y*-map and cluster number counts
- Tension with CMB constraints

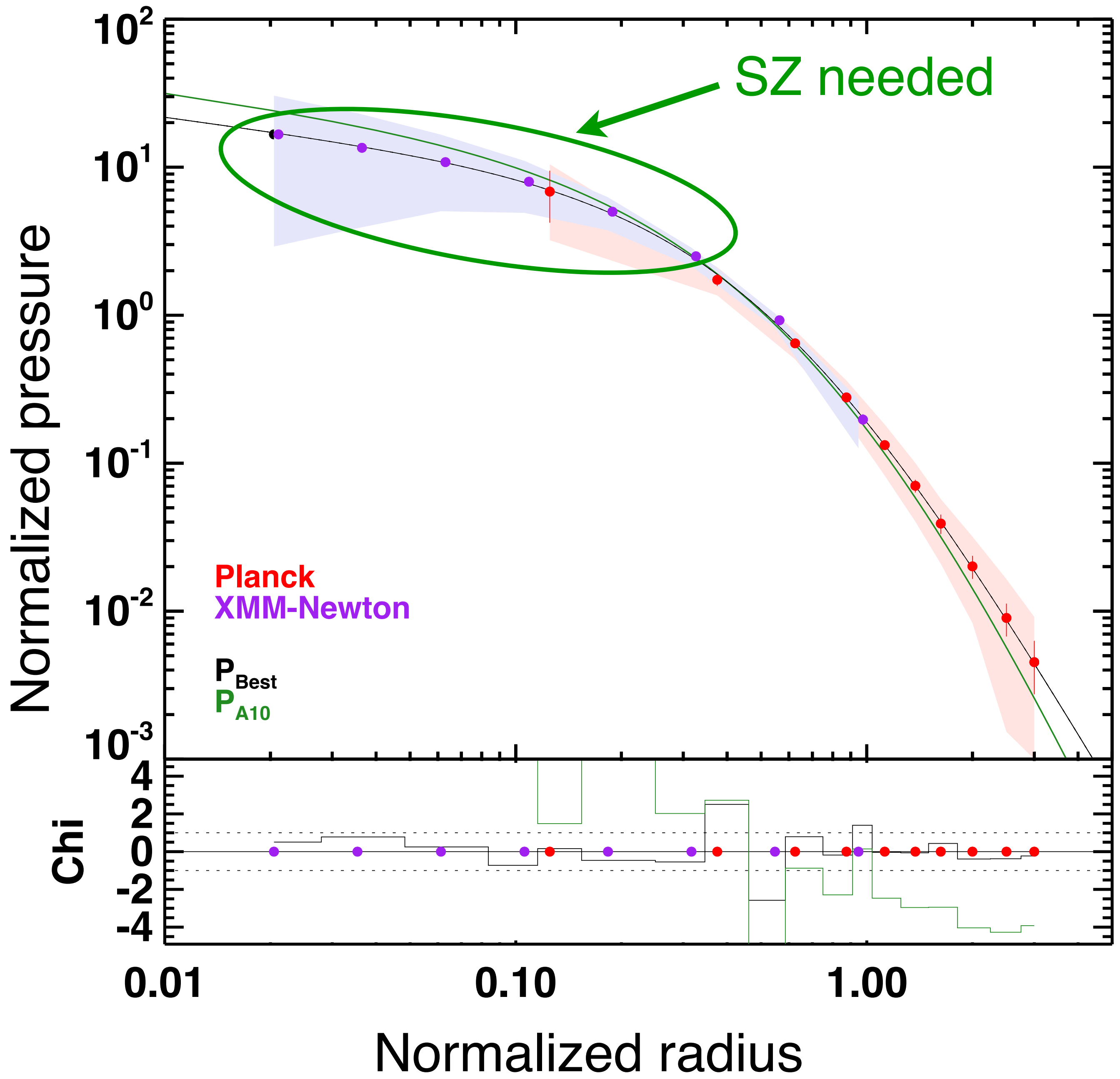
WARNING: physical model dependences

➡ Pressure profile, gas physics, mass function, mass bias, ...

➡ **Galaxy clusters need further investigation**

State-of-the-art Planck cosmological SZ results
Improvements

- **Bias** due to departure from equilibrium to be handled
- Need to look at clusters in **details** to calibrate the pressure (*i.e.* mass) distribution at small scales
- Need to look at **high-z** clusters to calibrate the pressure profile as a function of redshift



[Planck intermediate V (2013)]

➡ **High-resolution SZ observations are required (+ multi-wavelength)**

Looking at the high redshift Sunyaev-Zel’dovich clusters with NIKA

Towards high-angular resolution SZ observations
The next generation of mm-wavelength instruments

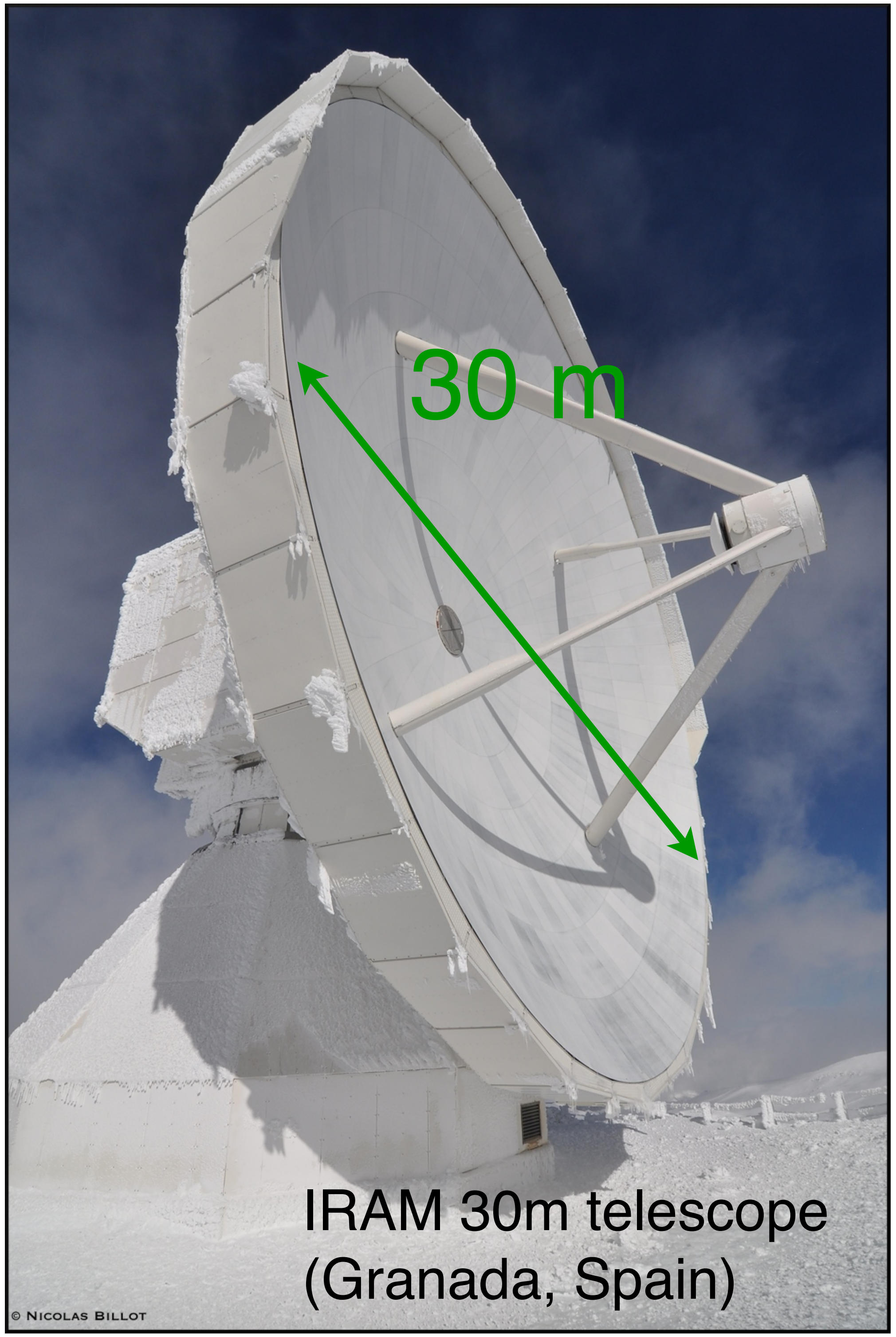
How to improve high-resolution SZ observations?

Reduce the noise → 1. ~~Space/ballon experiments~~ → Low resolution

Increase statistics → 2. Use more detectors

Kinetic Inductance Detectors (KIDs) offer an alternative to bolometers for large array instruments

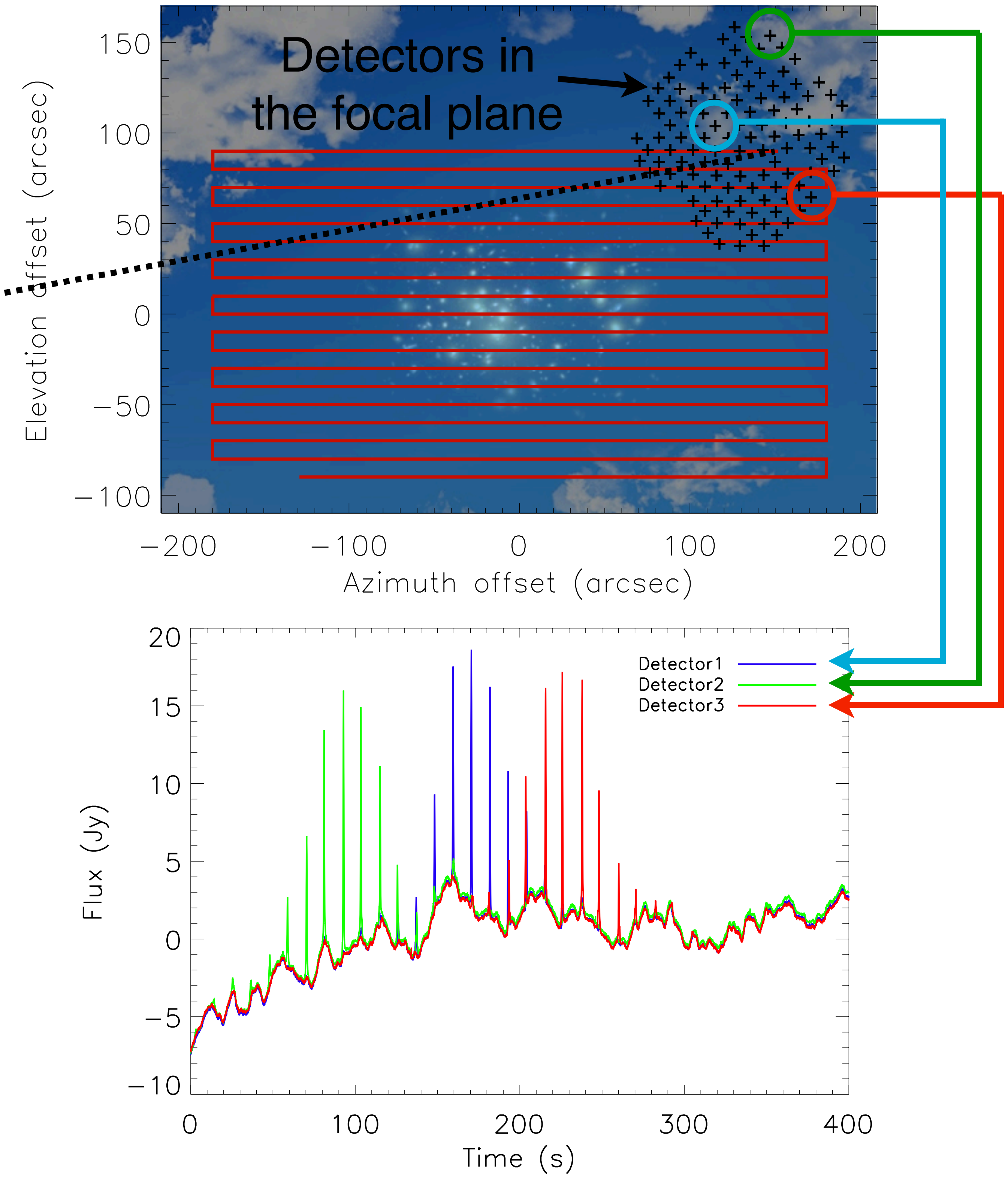
The New IRAM KID Arrays (*NIKA*):
➡ Developed in Grenoble (Neel+IRAM+LPSC+IPAG)



[N. Billot]

From raw data to maps: scanning the sky

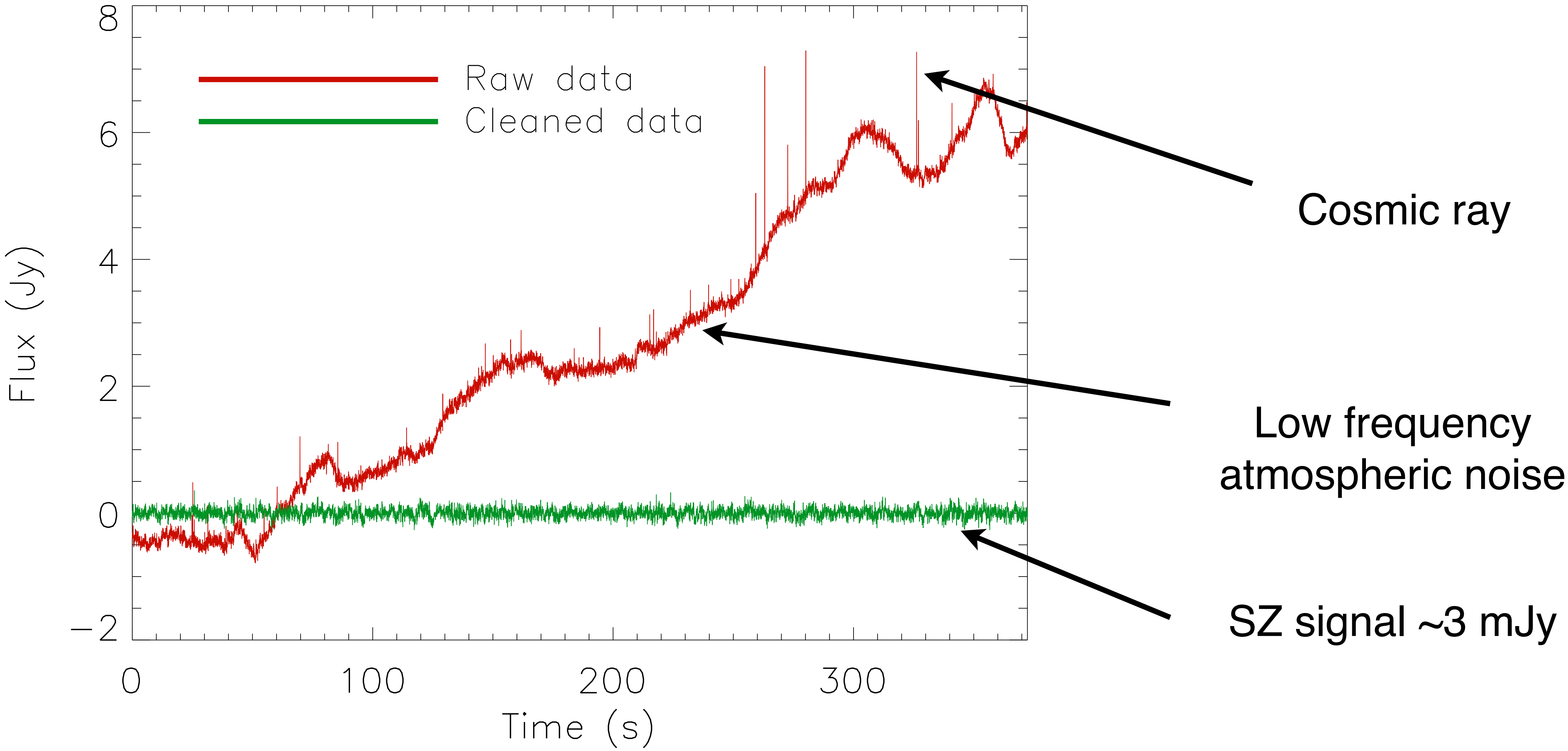
[N. Billot]



➡ **The signal is modulated by the scanning strategy**

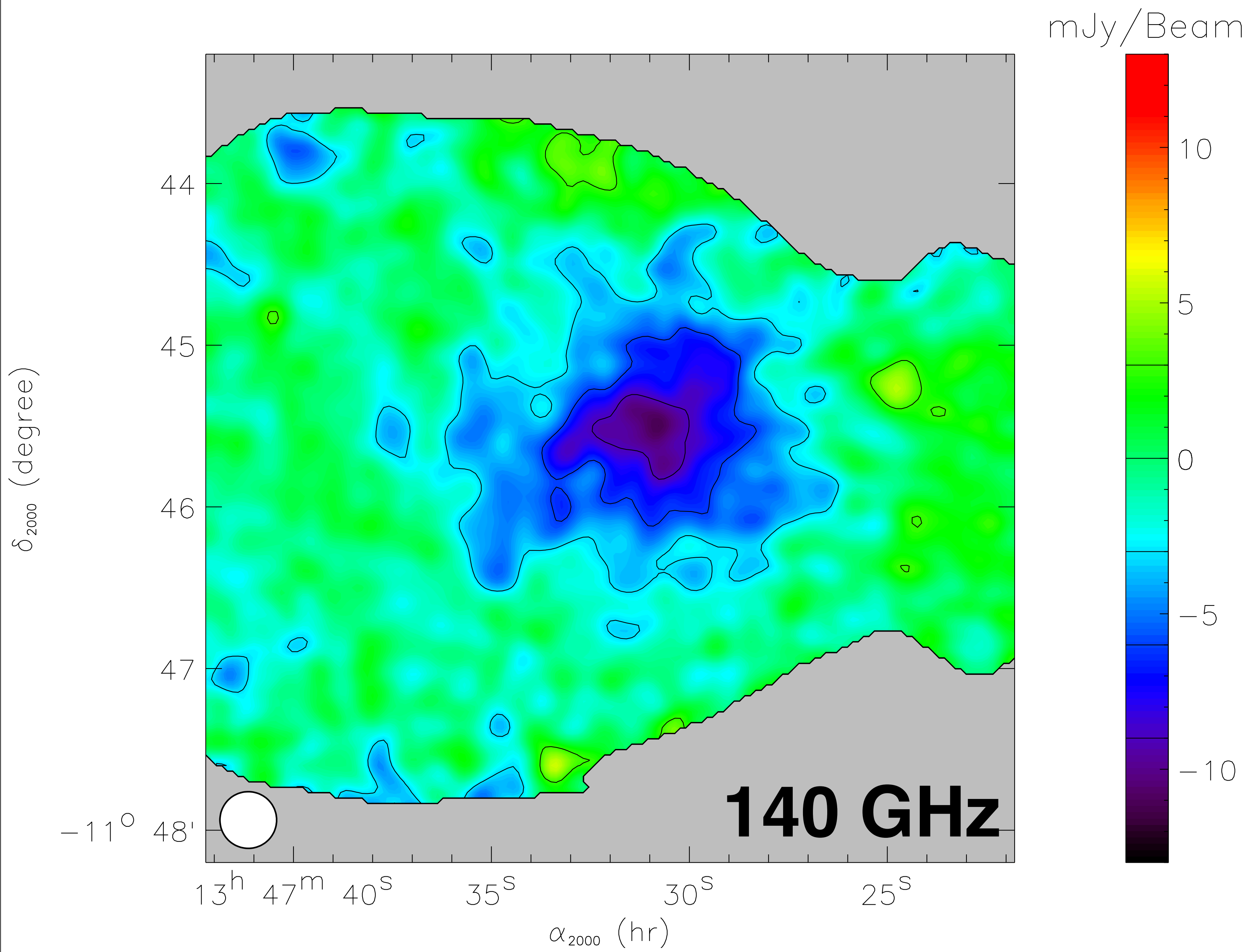
From raw data to maps: atmospheric noise removal

$$d(t) = P_{\vec{r}(t)}\ \mathrm{Flux}_{SZ}(\nu) + A(t,\nu) + E(t) + N(t)$$



➡ **The correlated noise is removed combining the detectors timelines**

The first NIKA tSZ map
RX J1347.5+3745 (z=0.45)

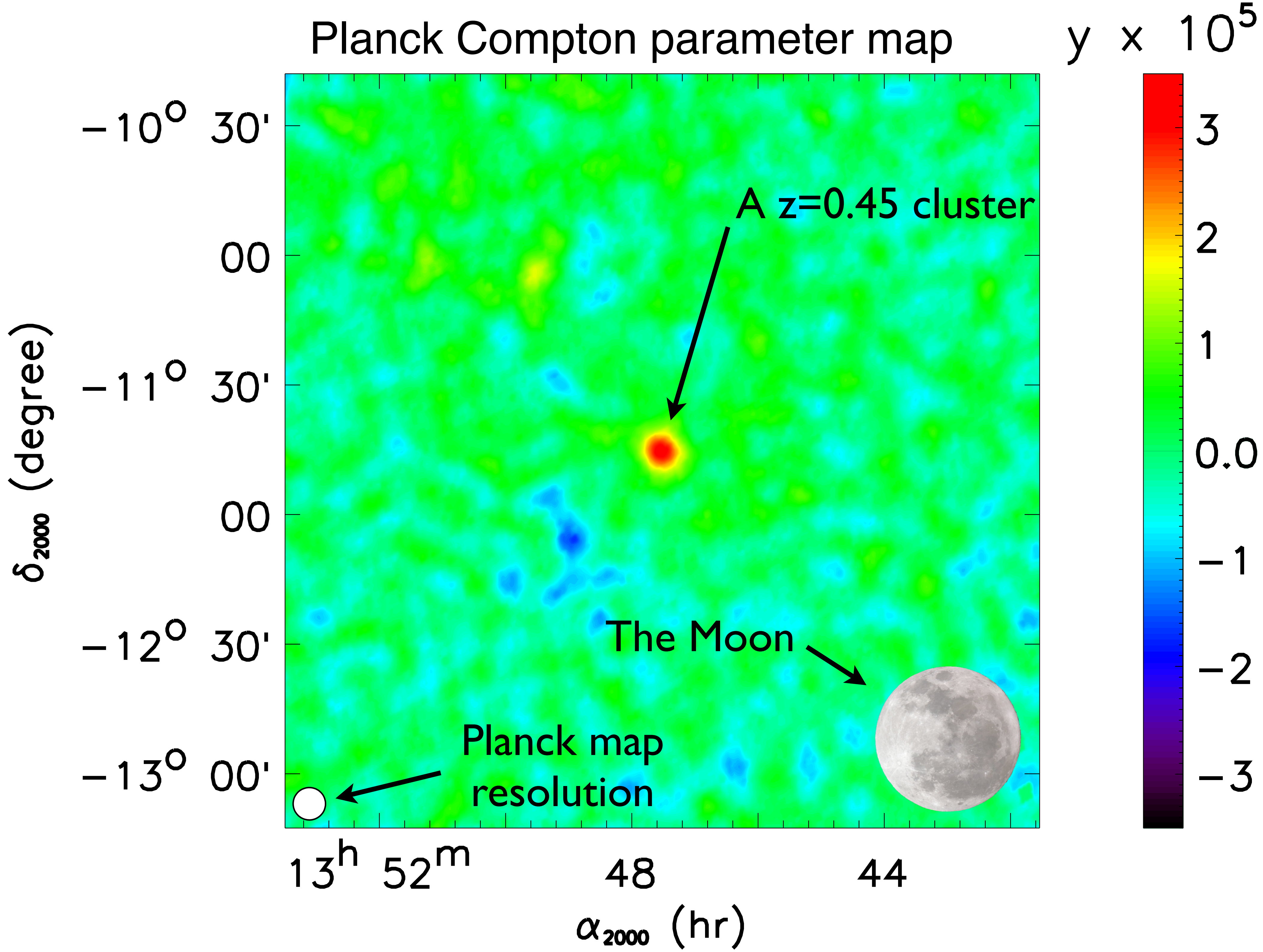


- Observation performed in November 2012
- Dual-band common-mode decorrelation from the 240 GHz channel
- Large scales are recovered
- Integration time: 5h47min

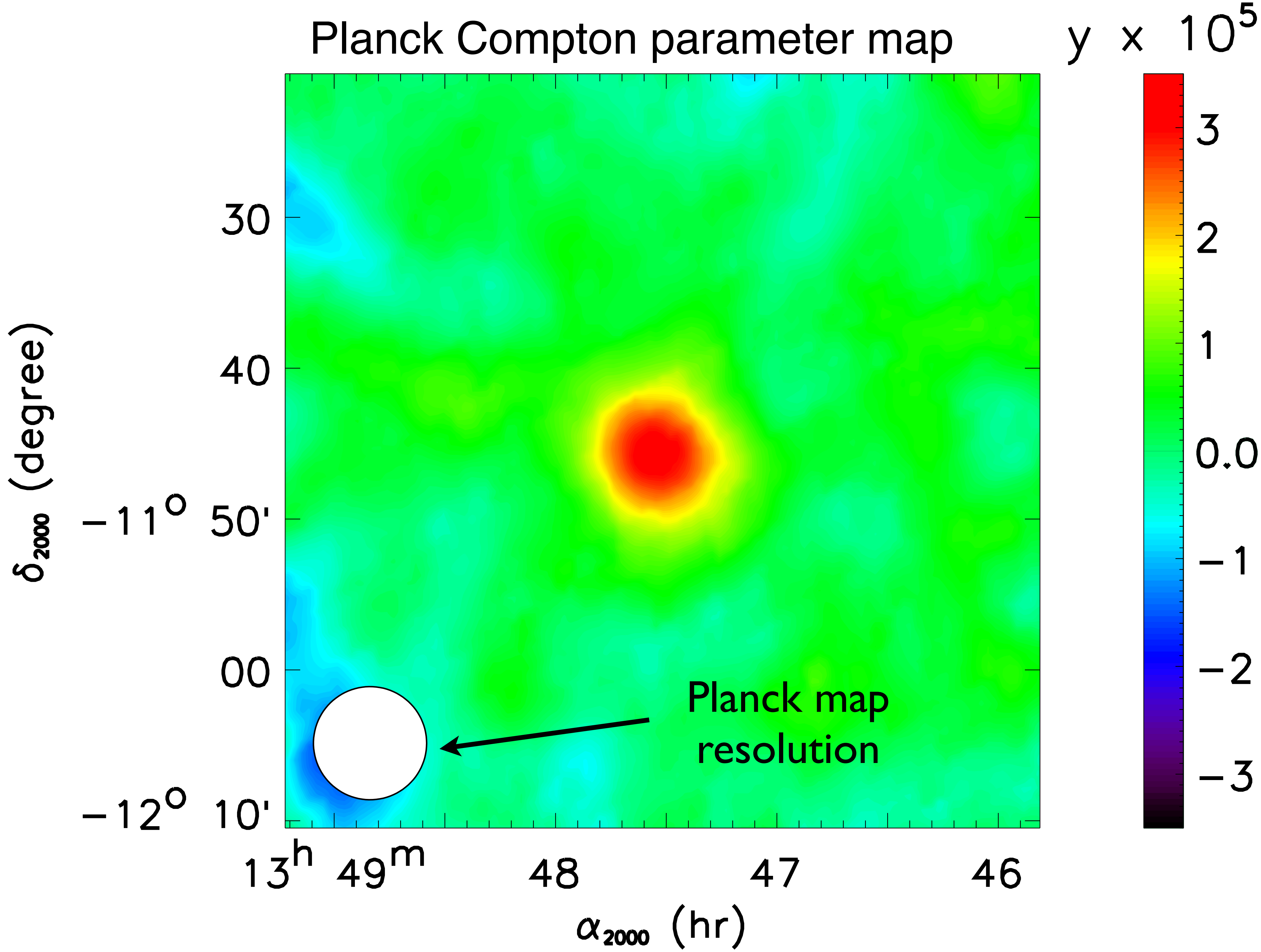
➡ **The first SZ observation with KIDs, using the *NIKA* prototype**

[R. Adam, B. Comis, J. F. Macías-Pérez et al. (2013)]

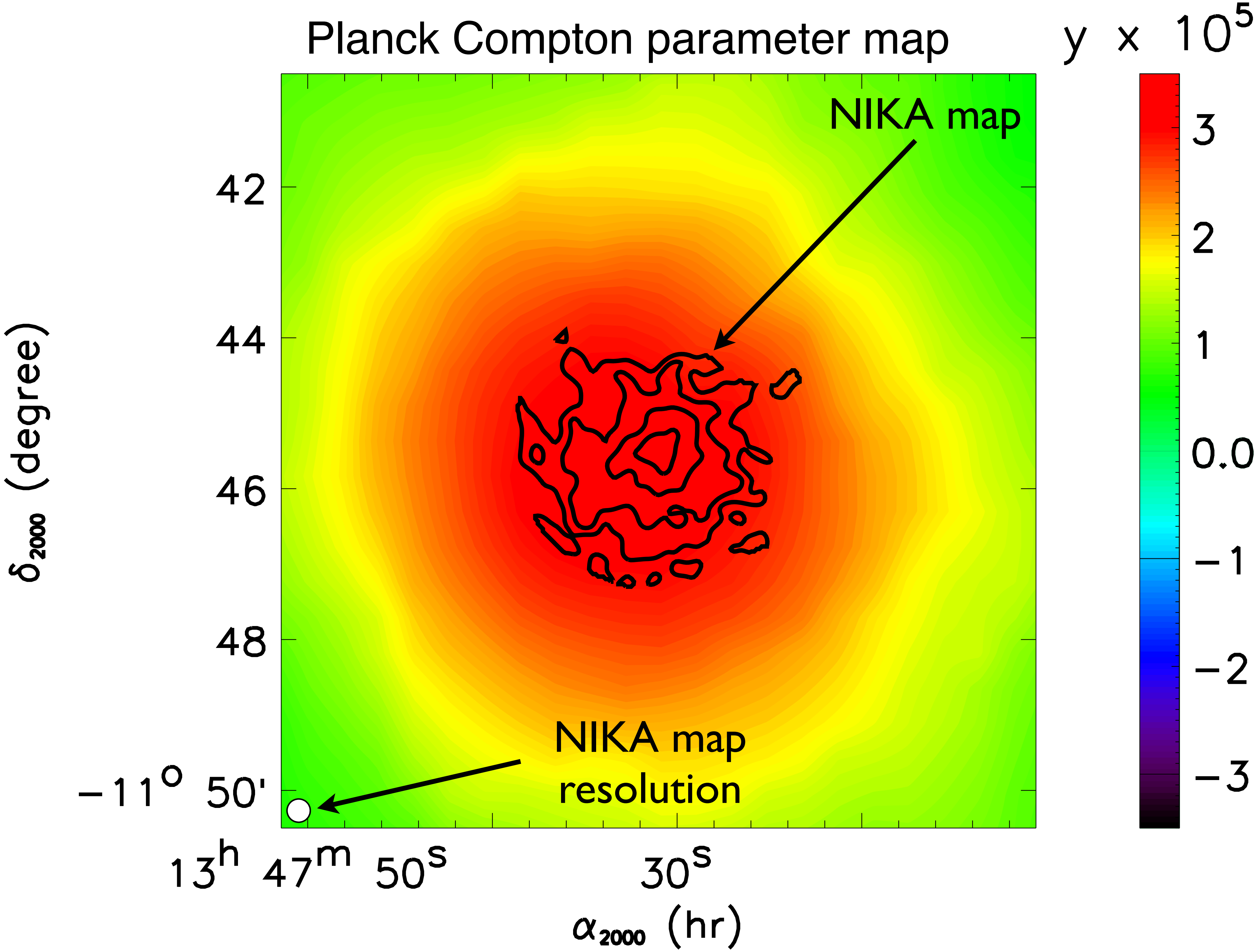
Looking at high-z cluster with Planck and NIKA:
A typical Planck SZ map



Looking at high-z cluster with Planck and NIKA:
No departure from a point source



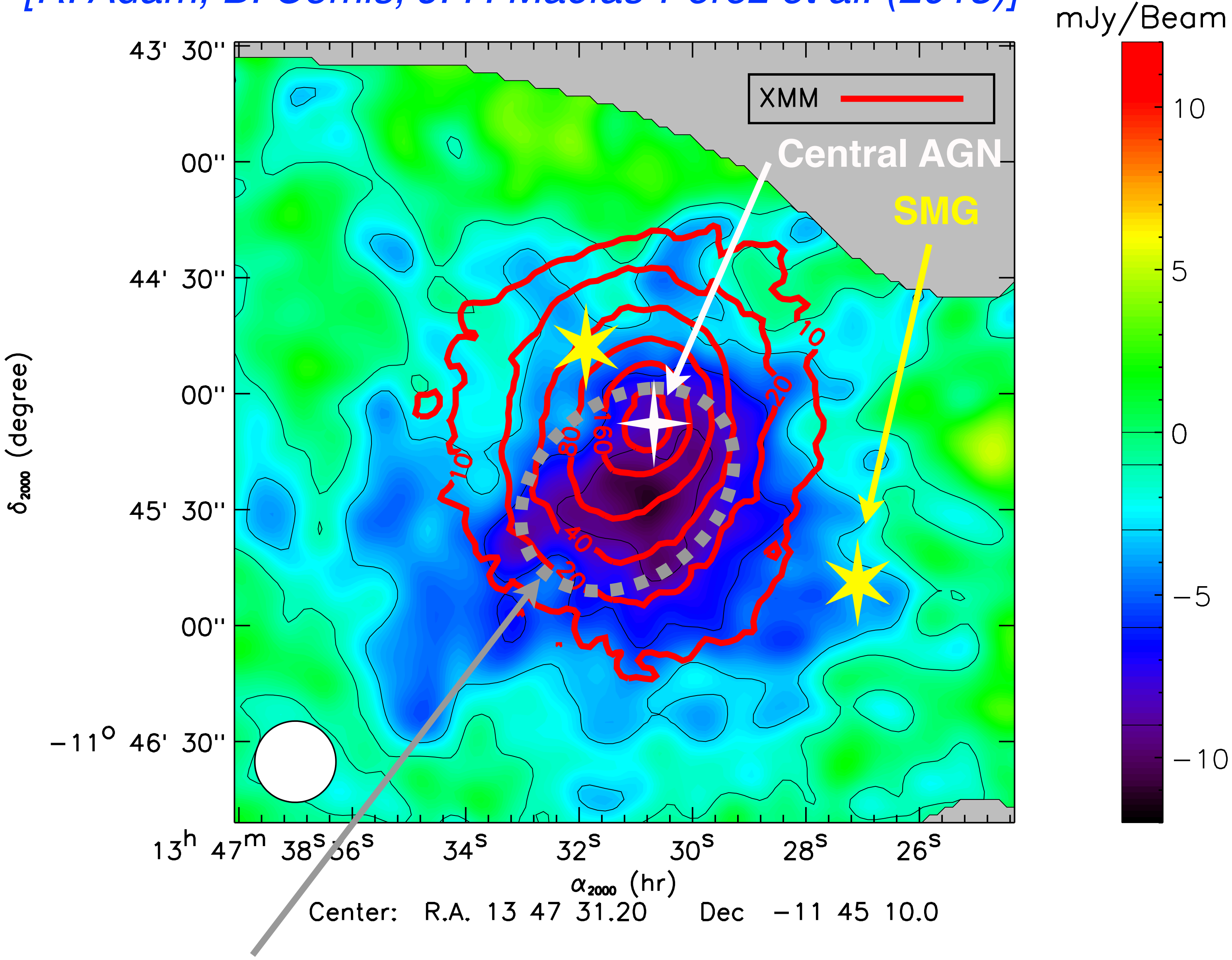
Looking at high-z cluster with Planck and NIKA:
Imaging the cluster signal at higher resolution



Probing the IntraCluster medium using Sunyaev-Zel'dovich data

RX J1347.5+3745 (z=0.45):
Complementarity of resolved (sub)millimeter, X-ray, radio and optical data

[R. Adam, B. Comis, J. F. Macías-Pérez et al. (2013)]



Radio halo at the shock location
[C. Ferrari et al. (2011)]

- The X-ray emission is due to bremsstrahlung from hot electrons

$$\mathrm{X\ ray} \propto n_e^2 \sqrt{T_e}$$

$$\mathrm{SZ} \propto P_e \propto n_e T_e$$

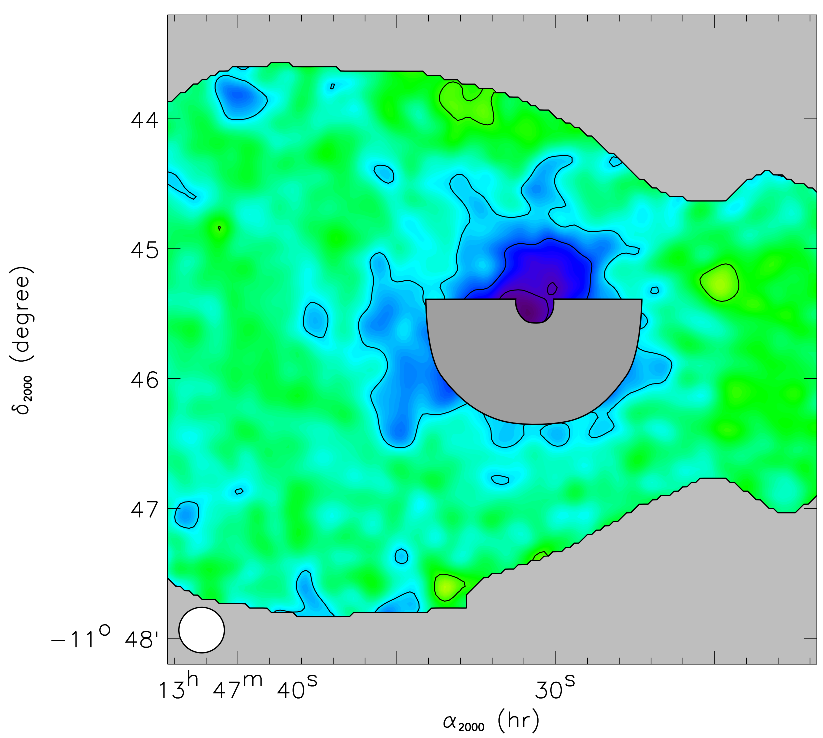
- SZ is well adapted for the **measurement of shocks**
- RX J1347.5-1145 is an ongoing merger (strong SE extension)
- Multiwavelength observations provide a complete picture of the cluster

➡ **Detection and SZ mapping achieved**

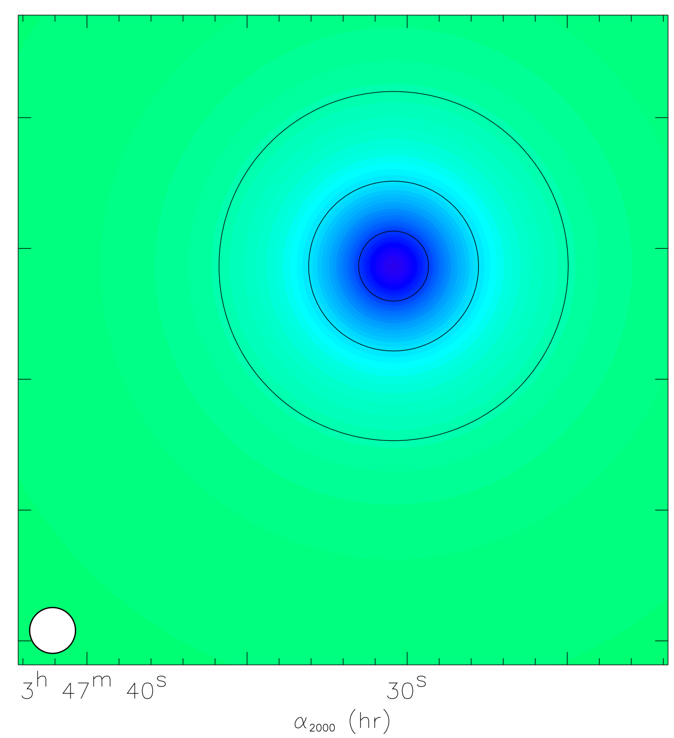
RX J1347.5+3745 (z=0.45):
SZ characterization of the merger overpressure

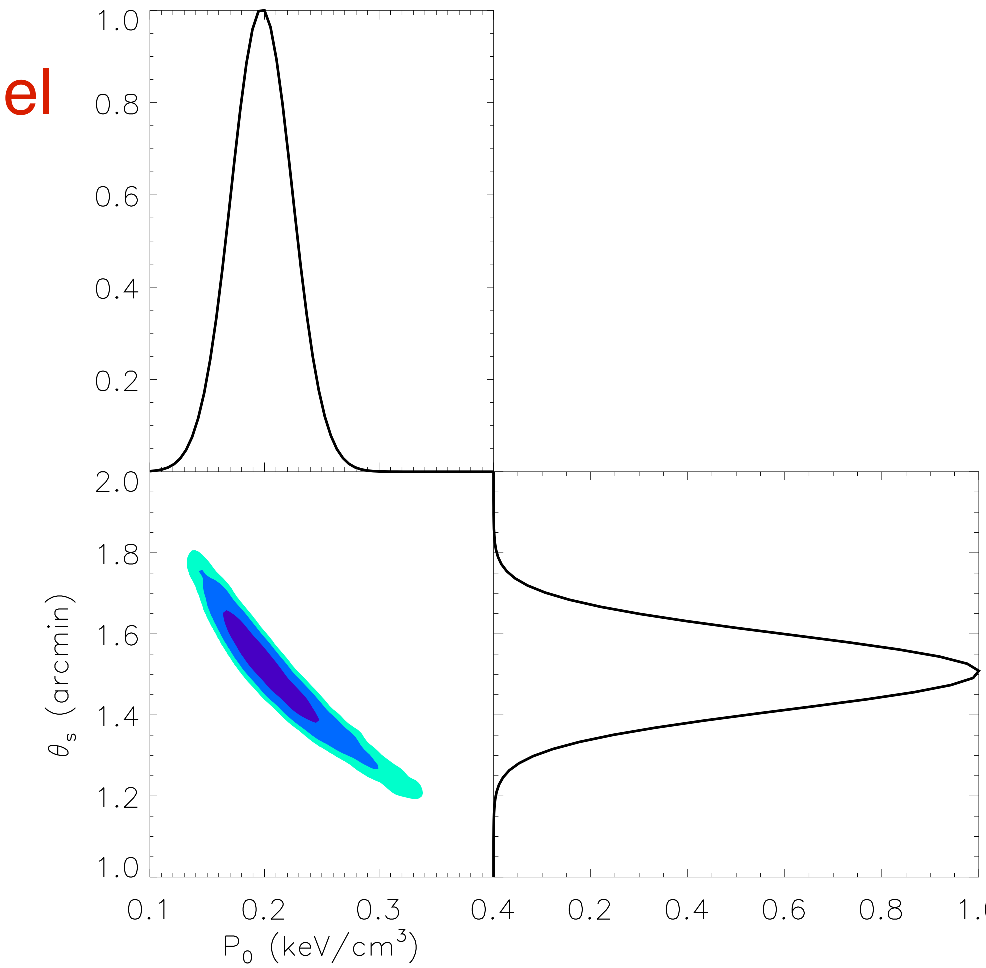
We fit the relaxed North region of RX J1347.5-1145 using a gNFW **pressure profile** parametrization *[D. Nagai et al. (2007)]*

NIKA data



X-ray centered best fit model





$$P(r) = \frac{P_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{\frac{\beta-\gamma}{\alpha}}}$$

Slopes fixed to:

[M. Arnaud et al. (2010)]

$\alpha = 1.2223$

$\beta = 5.4905$

$\gamma = 0.7736$

RX J1347.5+3745 (z=0.45):
SZ characterization of the merger overpressure

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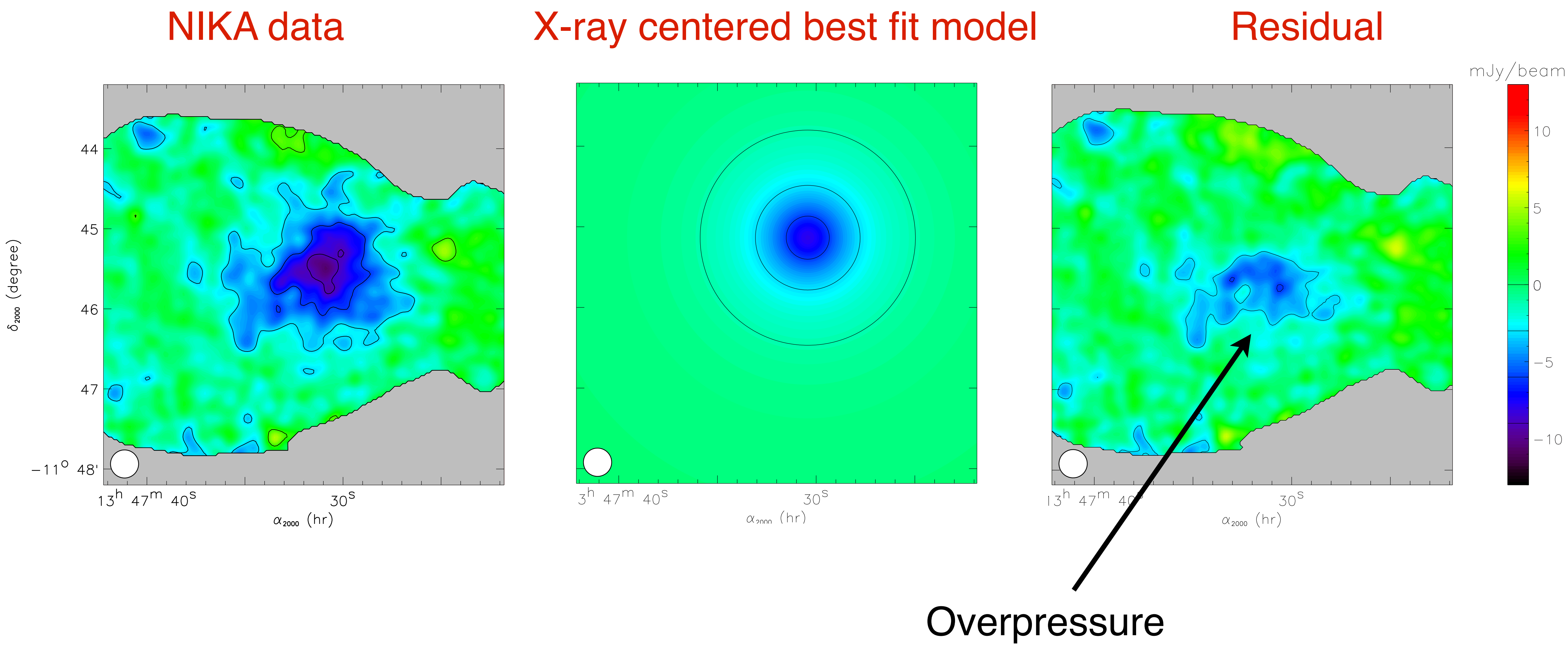


➡ RX J1347.5-1145 = relaxed cool-core + merger (20%)

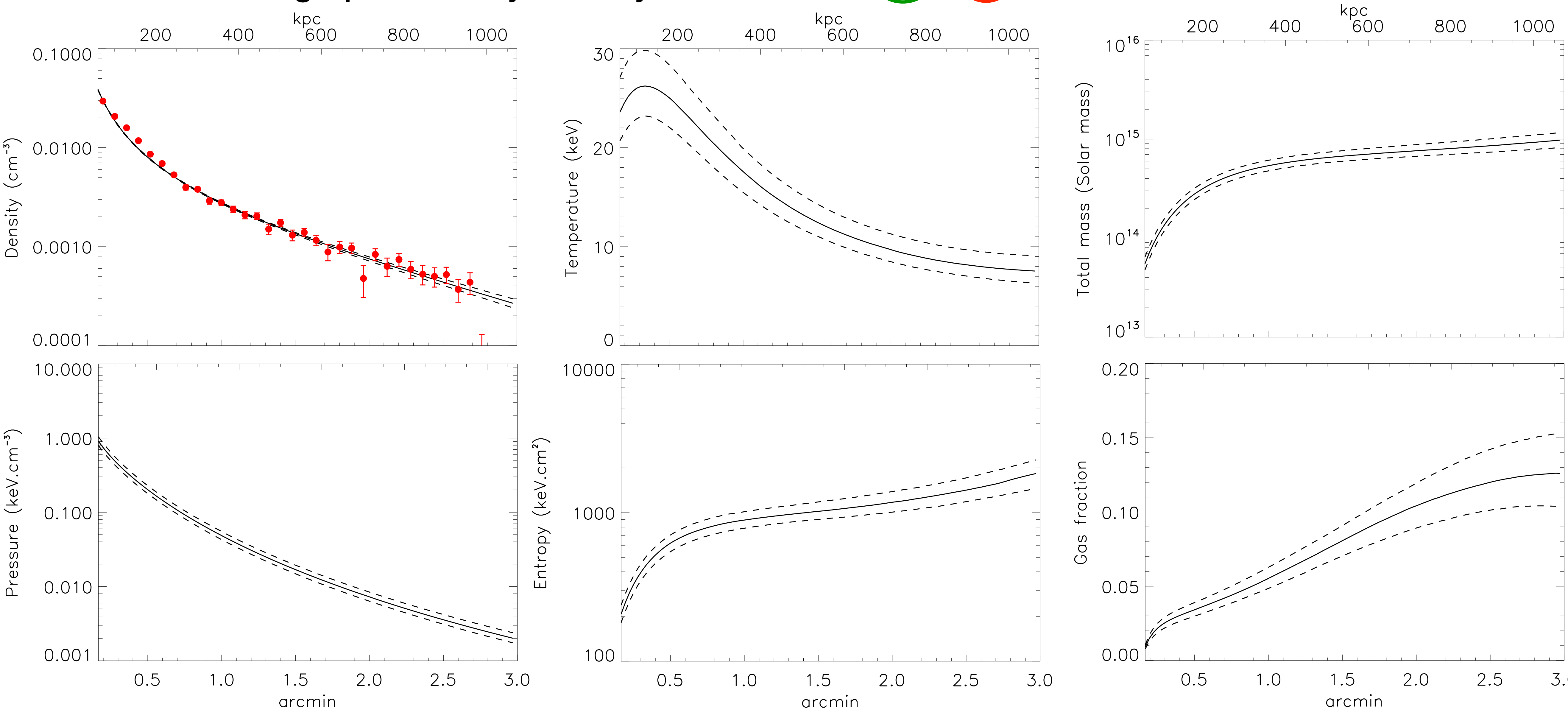
RX J1347.5+3745 - z=0.45 (PRELIMINARY): IntraCluster Medium measurement with SZ and X-ray

The **IntraCluster Medium can be characterized** using a combined **SZ (NIKA+Planck)** and **X-ray (Chandra)** MCMC:

1. Assuming hydrostatic equilibrium
2. Assuming ideal gas law
3. Assuming spherical symmetry

$$\frac{dP}{dr} = -\frac{G\,\rho_{gas}(r)\,M_{tot}(r)}{r^2}$$

$$P = n\,k_B T$$

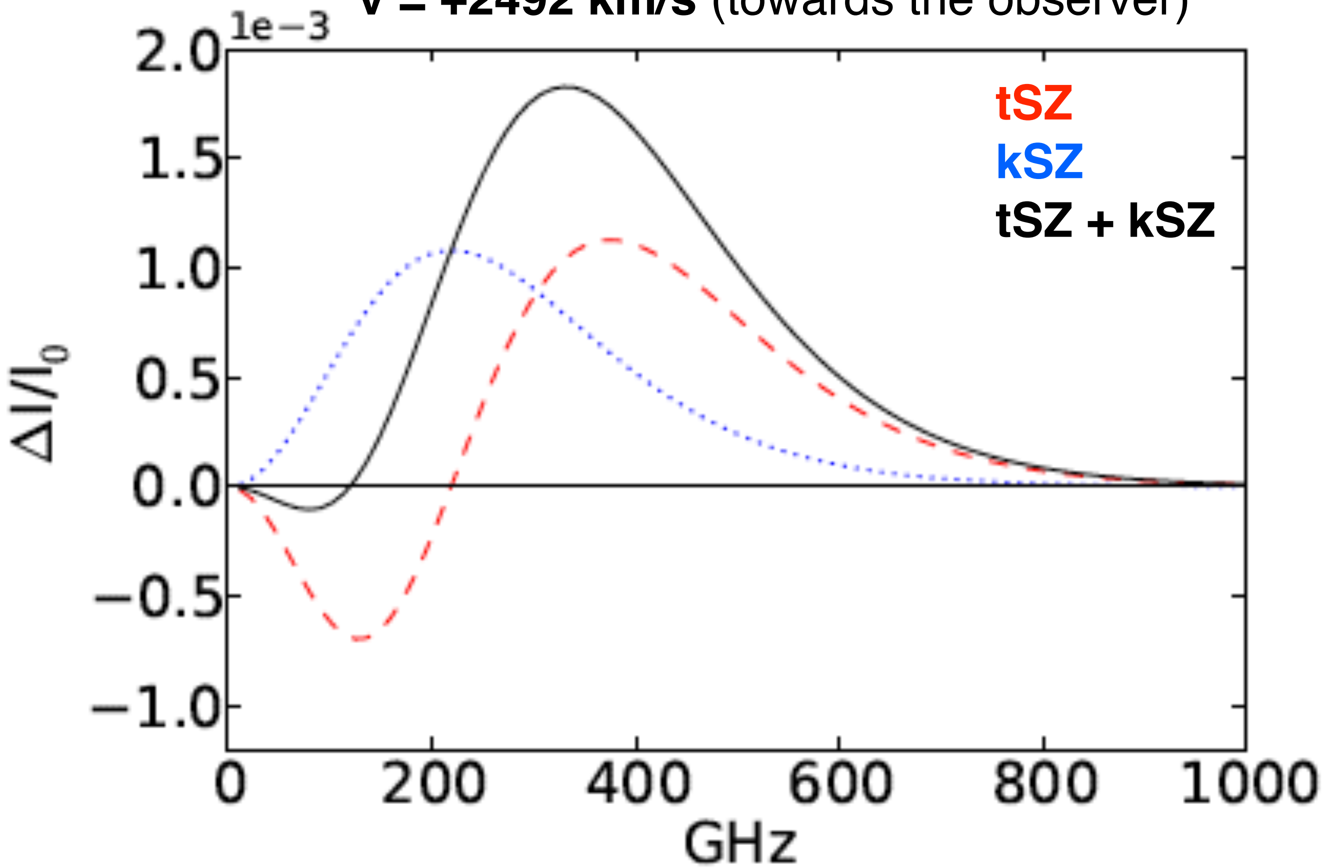


Probing velocities with the kinematic Sunyaev-Zel'Dovich effect (kSZ)

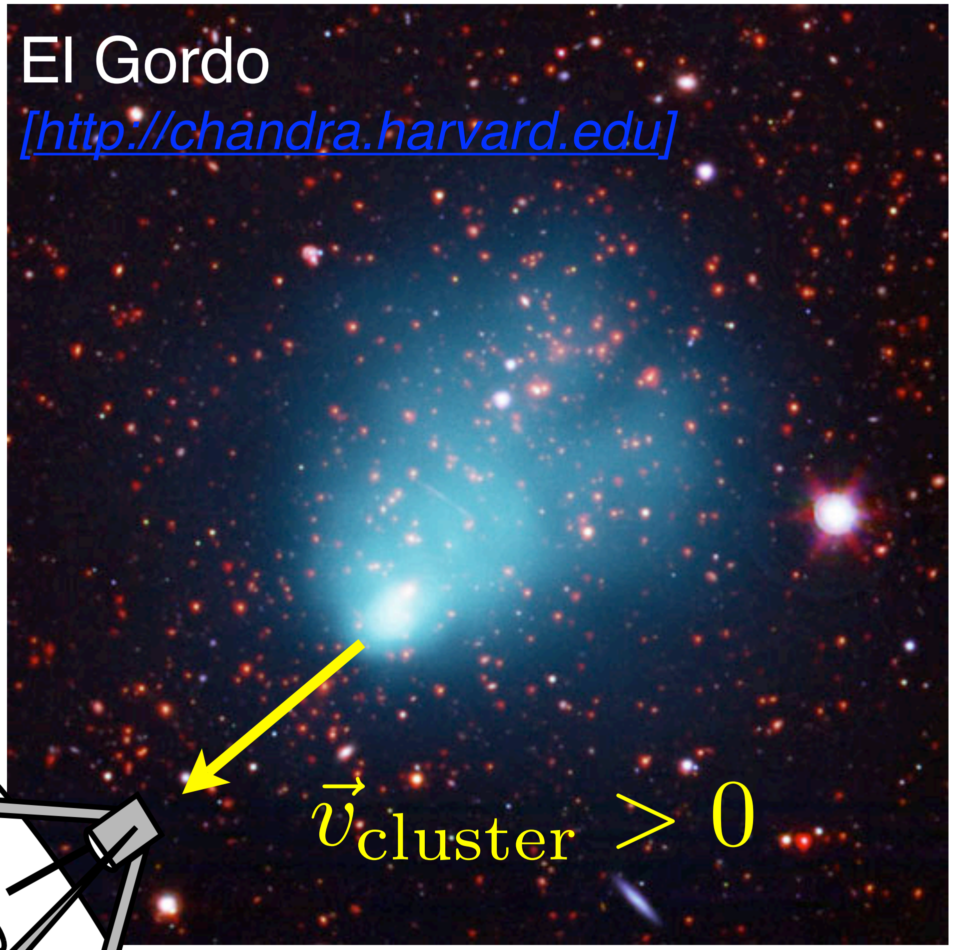
- kSZ = CMB Doppler shift induced by the bulk motion of the cluster electrons
- Amplitude typically 10 times smaller than tSZ

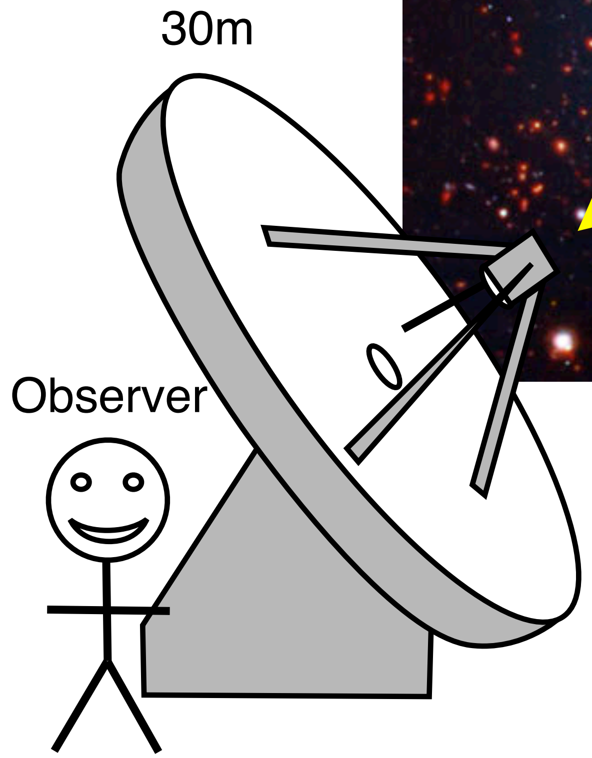
$$\frac{\Delta I_{kSZ}}{I_0} = (g(\nu) + \delta_{kSZ}(T_e, \nu, v))\, \sigma_T \frac{v}{c} \int n_e dl$$

v = +2492 km/s (towards the observer)



[Simulation - J. J. Ruan et al. (2013)]



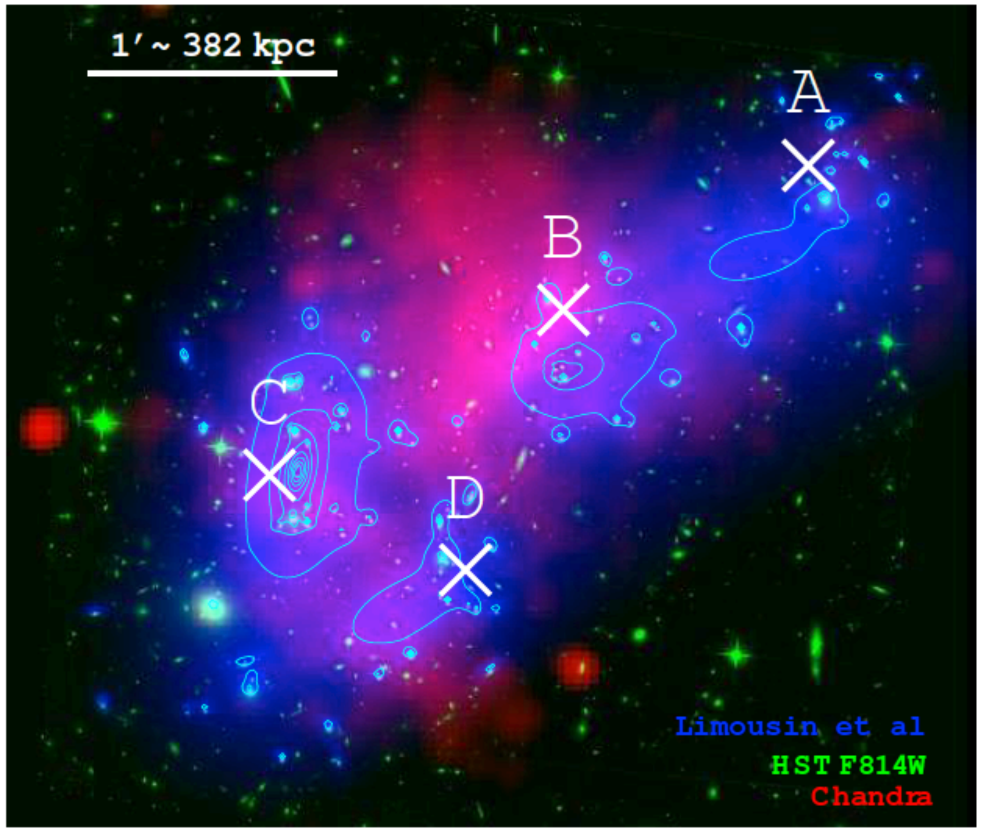


➡ **The kSZ effect probes the line-of-sight velocity in clusters**

MACS J0717.5+3745 - z=0.55: First attempt to measure cluster gas velocity distibution

An exceptionally disturbed cluster

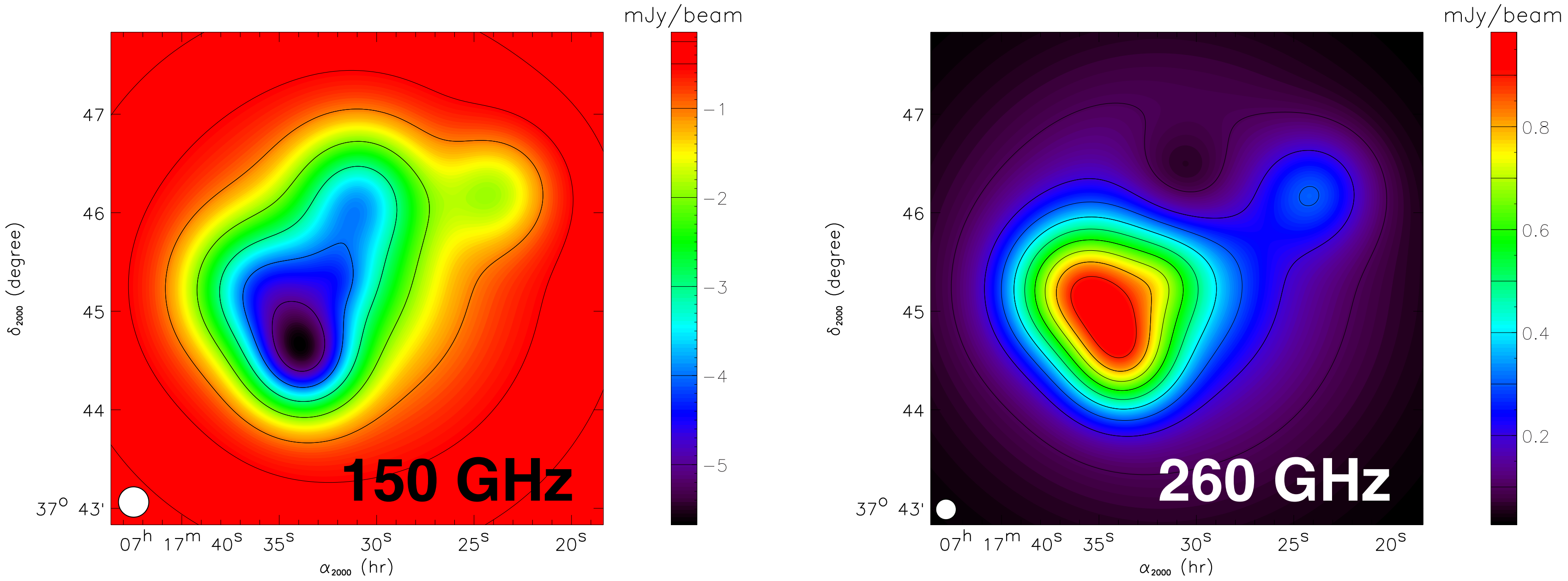
- Triple merger
- 4 optically identified groups
- Temperature up to 30 keV
- Line-of-sight velocities up to -3000 km/s (sub-cluster B)



First kSZ detection by Bolocam using a parametric model + X-ray data
[J. Sayers, T. Mroczkowski et al. (2013)]

Simulations of the expected SZ signal

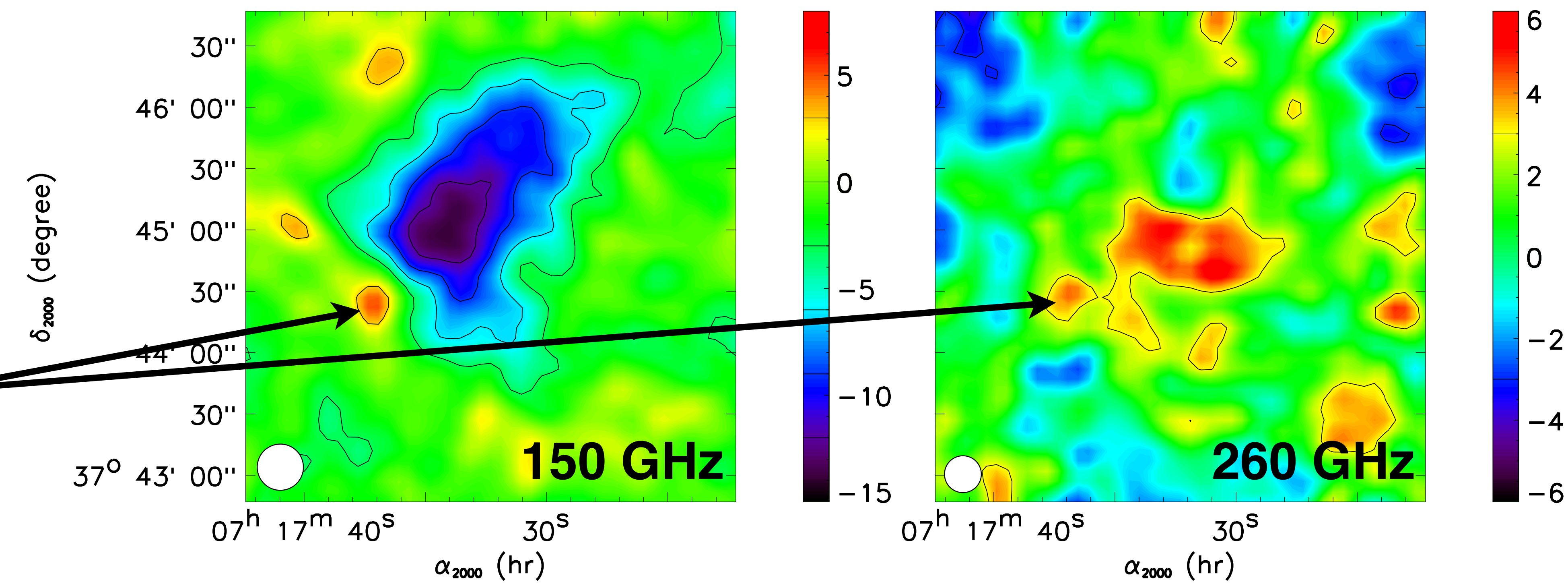
- Thermal SZ
- Kinematic SZ (*i.e.* SZ from line-of-sight velocity)
- Relativistic corrections



MACS J0717.5+3745 - z=0.55 (PRELIMINARY): First attempt to measure cluster gas velocity distibution

NIKA data

- 5.3h on source shown here (SNR)
- Detection of a foreground galaxy



Simulations of the expected SZ signal

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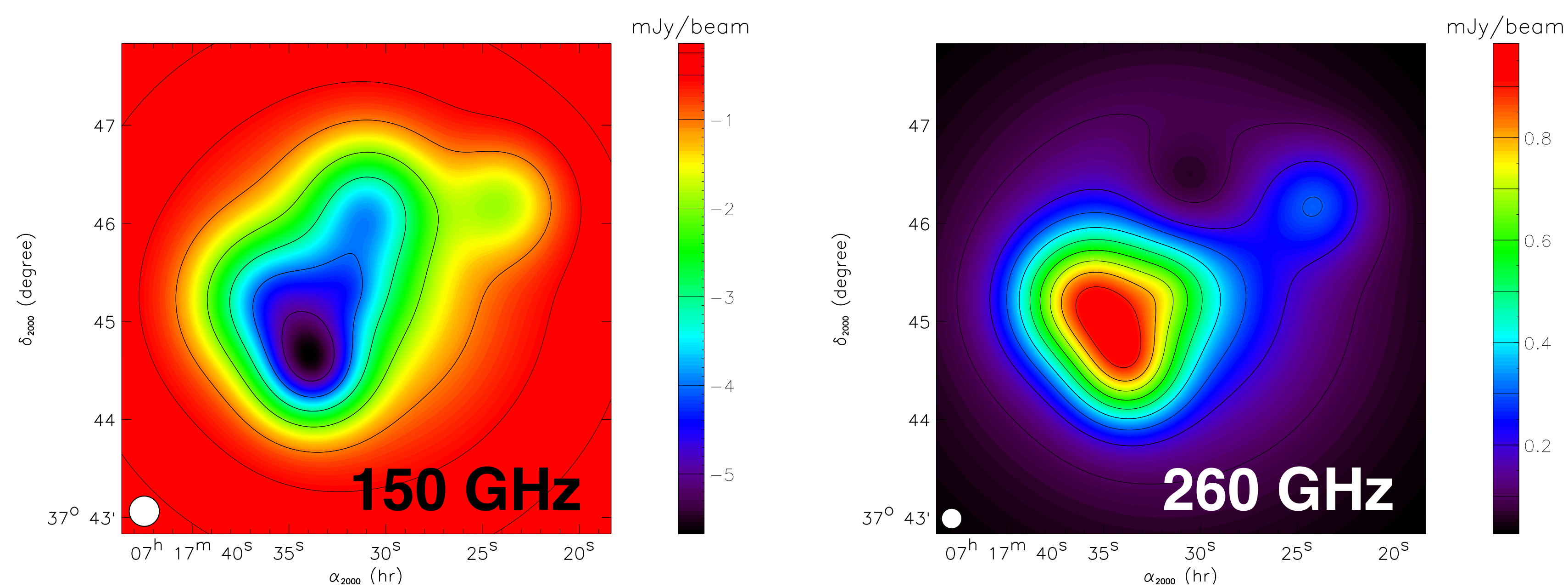
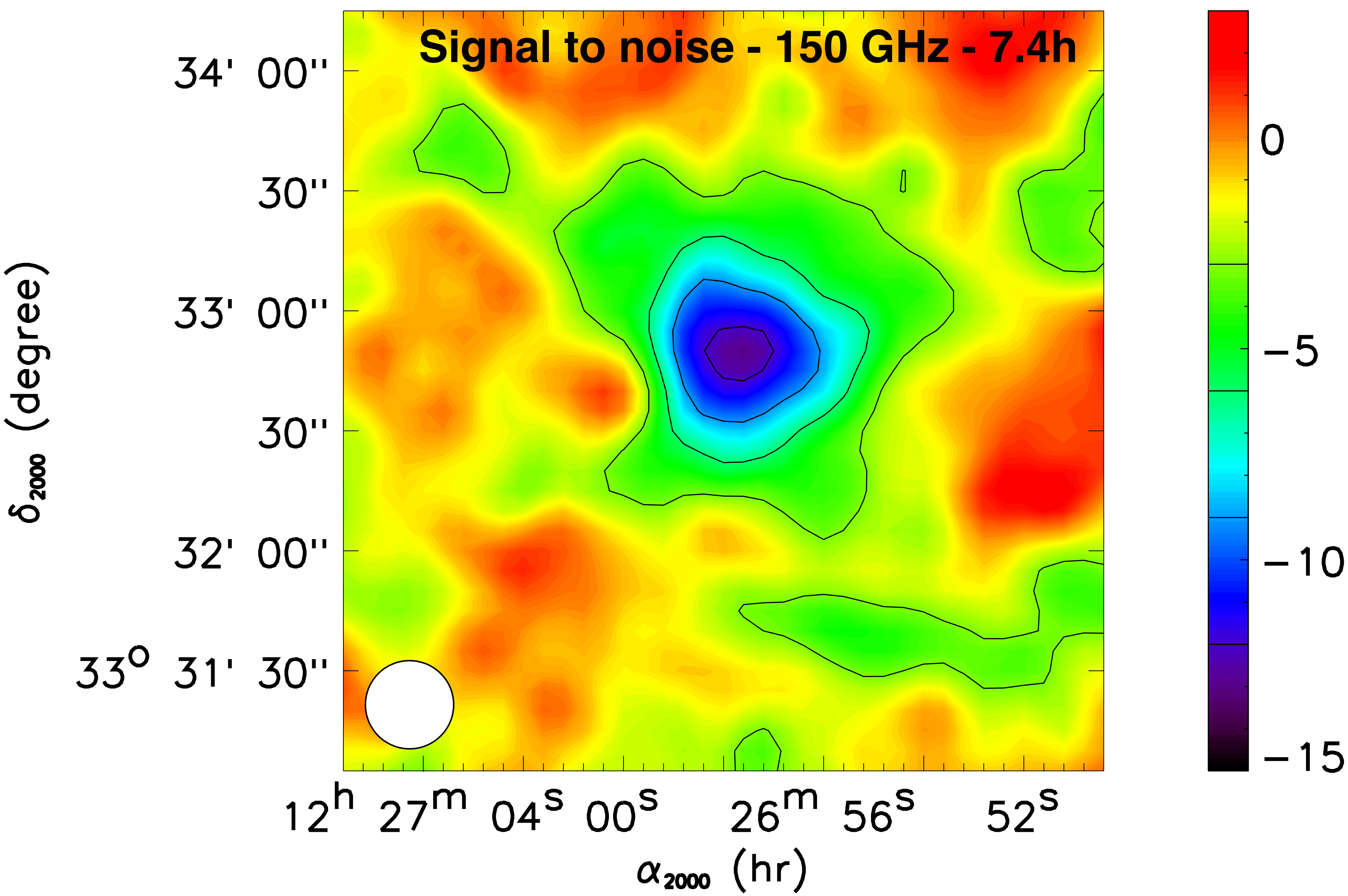


➡ **SZ mapping of a very disturbed cluster at 150 and 260 GHz**

CL J1226.9+3332 - z=0.89 (PRELIMINARY):
A massive high-redshift cluster (preliminary)



Goal

- Test observations of high-z clusters for *NIKA2*
- Measure the pressure distribution at high-z

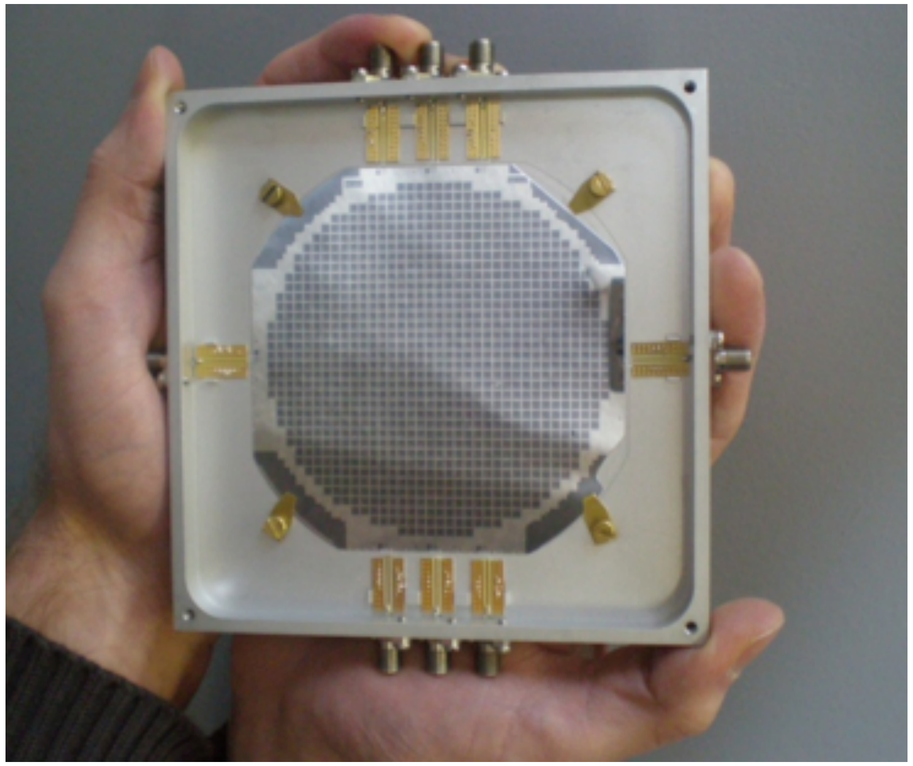
➡ **SZ mapping of a high-redshift cluster**

Conclusions, perspectives and NIKA2

NIKA2
Large Sunyaev-Zel'dovich programs

NIKA2 (prototype)

- 5000 (300) detectors at SZ frequencies: 150 and 260 GHz
- 6.5 (2) arcmin instantaneous field-of-view
- State-of-the-art sensitivities (similar)
- High angular resolution (similar)



1000 pixels KIDs array

SZ large program

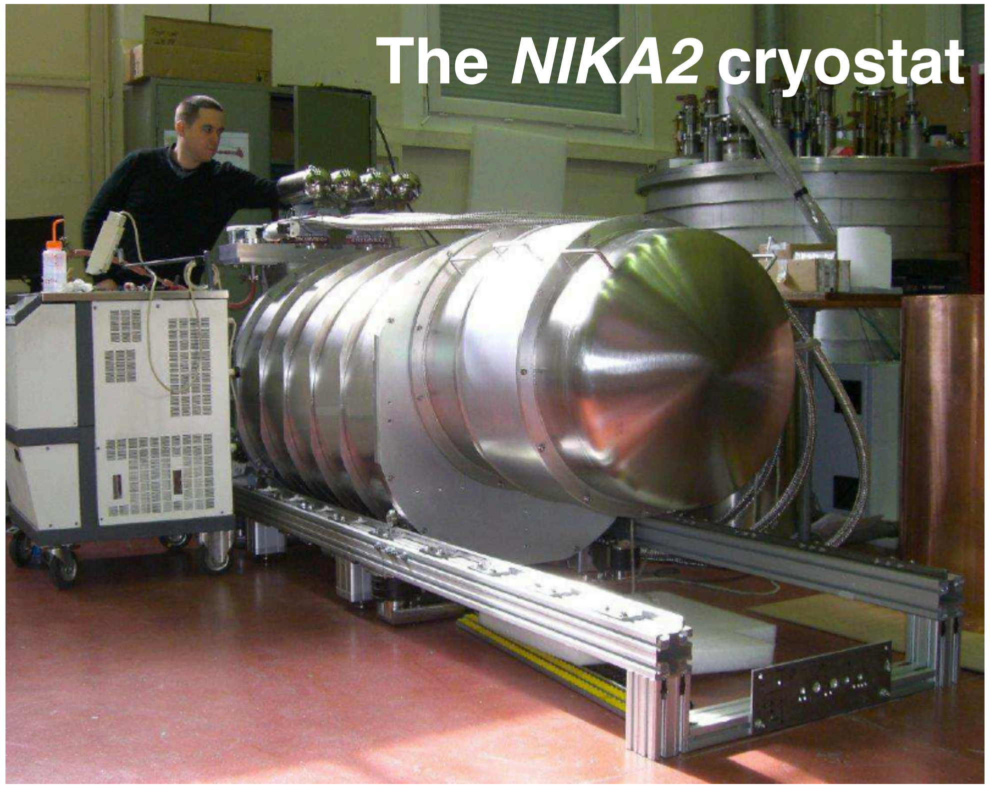
- 300 hours dedicated for SZ
- Observe more than 50 clusters in the range z = 0.5 - 1.5
- Planck/ACT (unresolved) clusters are a working basis to define a **representative sample**
- Combine SZ with multiwavelength data

SZ goal

- Calibrating the **SZ flux** as a **mass** proxy and its **evolution** with redshift (pressure profile)
- Characterize the **structural properties** and clusters dynamical state
- Measure kinematic SZ in individual clusters

Conclusions and perspectives

- SZ observations of galaxy clusters are powerful and complementary to traditional methods
- NIKA has demonstrated its capability for SZ observations up to high-redshifts
- *NIKA2* construction: ongoing
- Cosmological *NIKA2* SZ large programs in preparation



Work in progress

Planck

- Next data delivery in October 2014
- Improved SZ catalogue

NIKA

- February 2014 data to be analysed in details
  - Possible kSZ mapping (for the first time)
  - High-z pressure profile
- More *NIKA* SZ observations planned in November 2014
  - Pilot project for *NIKA2*
  - Another cluster for kSZ

http://ipag.osug.fr/nika2

R. Adam, A. Adane, P. Ade, P. André, A. Beelen, B. Belier, A. Benoît, A. Bideaud, N. Billot, N. Boudou, O. Bourrion, M. Calvo, A. Catalano, G. Coiffard, B. Comis, A. D'Addabbo, F.-X. Désert, S. Doyle, J. Goupy, C. Kramer, S. Leclercq, J. F. Macías-Pérez, J. Martino, P. Mauskopf, F. Mayet, A. Monfardini, F. Pajot, E. Pascale, L. Perotto, E. Pointecouteau, N. Ponthieu, V. Revéret, L. Rodriguez, F. Ruppin, G. Savini, K. Schuster, A. Sievers, C. Tucker, R. Zylka