High-resolution SZ imaging
of **clusters** of galaxies
with **NIKA2** at the **IRAM 30-m telescope**

F. Mayet
on behalf of the NIKA2 Collaboration

Outline

NIKA2

1. The NIKA2 camera
   and the NIKA pathfinder

2. Why high-resolution SZ imaging of clusters ?

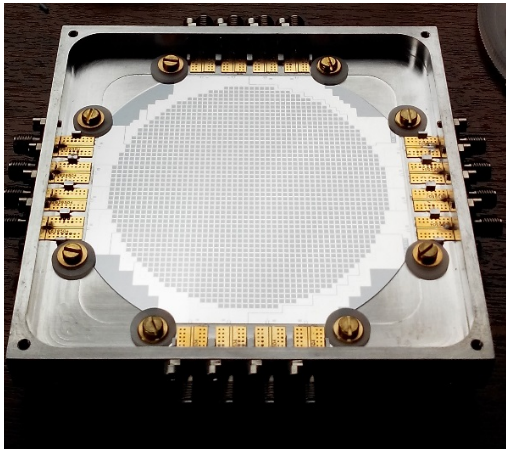
3. One example of SZ observations with NIKA
   - a Planck-discovered cluster

4. The NIKA2 SZ large program (2017-2022)
   - Follow-up of 50 Planck-discovered clusters
   - First cluster observation with NIKA2

High-resolution SZ imaging of clusters of galaxies with **the NIKA2 camera** at the IRAM 30-m telescope

NIKA2

NIKA2 LEKID array (260 GHz)



The NIKA2 camera

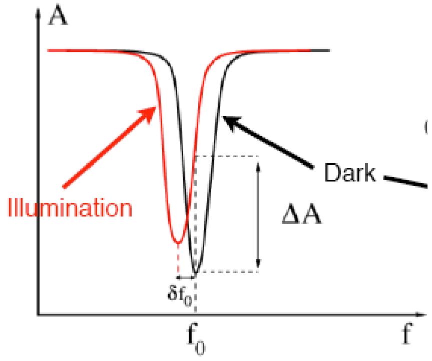
NIKA2

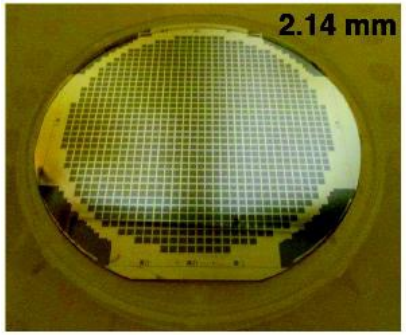
- KID-based camera
  Kinetic Inductance Detectors
  High quality factor superconducting resonators
  Frequency shift proportional to the incoming optical power
- Operated at 150 mK
- Dual-band: 150 and 260 GHz (3 arrays)
- Wide field of view: 6.5 arcmin – 2896 valid detectors
- High angular resolution: 17.7 and 11.2 arcsec
- State-of the art sensitivity: 6 and 20 mJy.s$^{1/2}$ (at null opacity)

(Polarization capabilities at 260 GHz)

These values are measured performance : see R. Adam et al., arXiv:1707.00908

Transfer function





NIKA

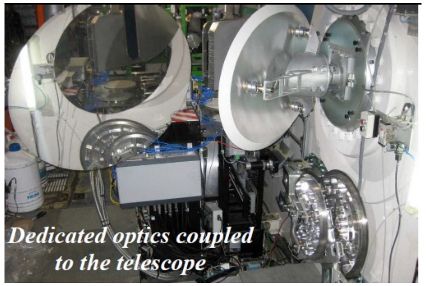
- a pathfinder for NIKA2
- operated at IRAM-30m telescope from 2014 to 2015
- Field of view: 1.8 arcmin (356 detectors)

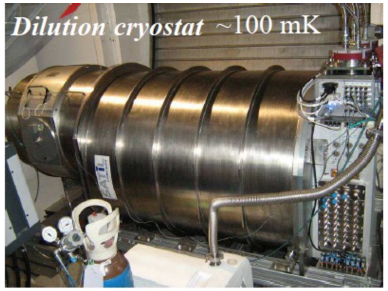
The NIKA2 camera

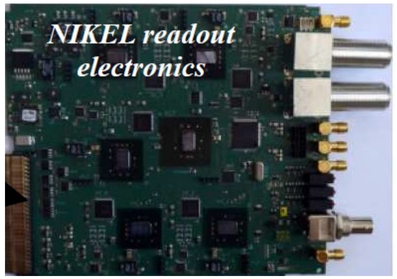
IRAM 30-m telescope
at Pico Veleta (Spain)

The NIKA2 camera has been built by the NIKA2 Collaboration

- 14 laboratories
- 110 members of the collaboration



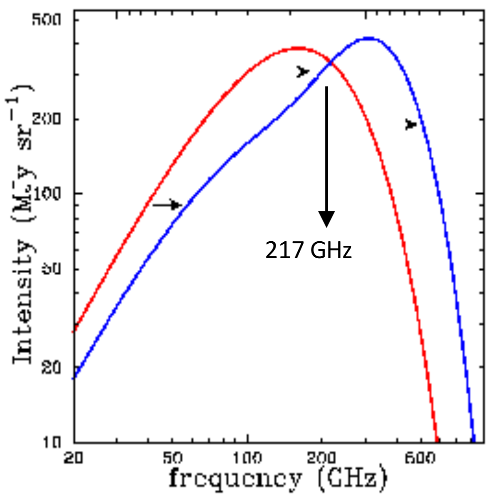


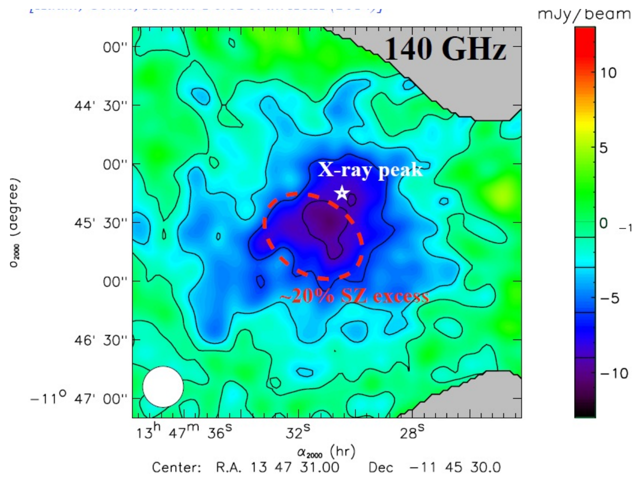


The NIKA2 camera

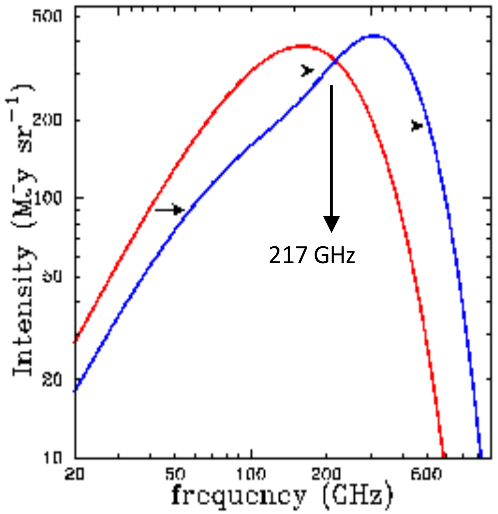
- has been installed in Sep. 2015 at the **IRAM-30m telescope** (Granada, Spain)
- has been **commissioned in 2017**
- **is opened to the scientific community for the next decade**

High-resolution Sunyaev Zel'dovich imaging of clusters of galaxies with **NIKA2** at the **IRAM 30-m telescope**





Sunyaev Zel'dovich (SZ) Effect

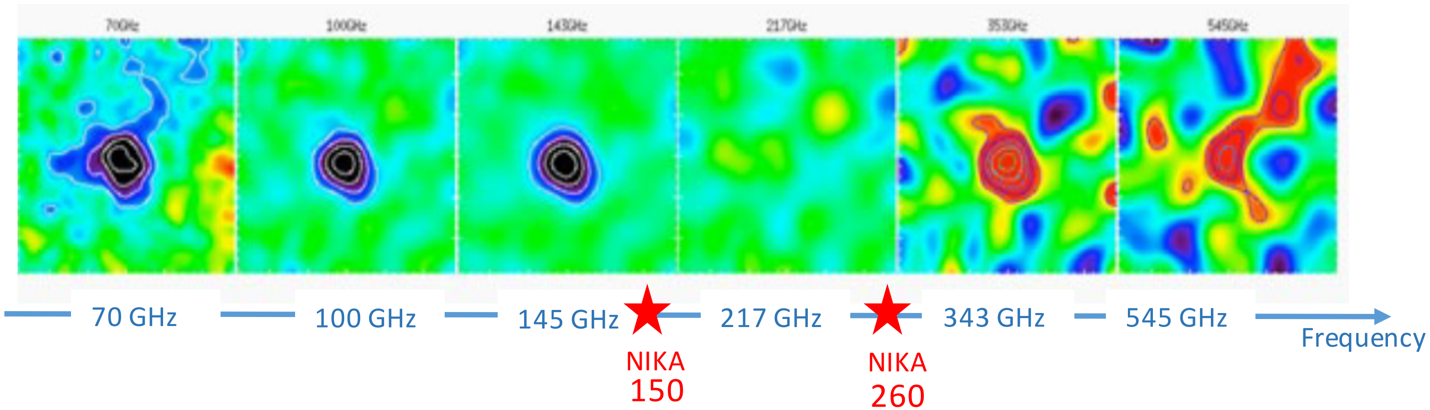


Thermal Sunyaev Zel'dovich effect (SZ)

- Inverse Compton scattering of CMB photons on hot electrons of the intra-cluster medium (ICM)
- Spectral distorsion of the CMB spectrum
  →SZ effect is redshift-independant
  →Observation of high-z clusters
- SZ signal: Compton parameter $y \propto \int P_e d\ell$
- SZ effect → characterization of the electronic pressure in the ICM

A cluster as seen by the Planck satellite

A 2319
(Planck)



Why high-resolution SZ imaging of clusters ?

Cosmology with clusters of galaxies

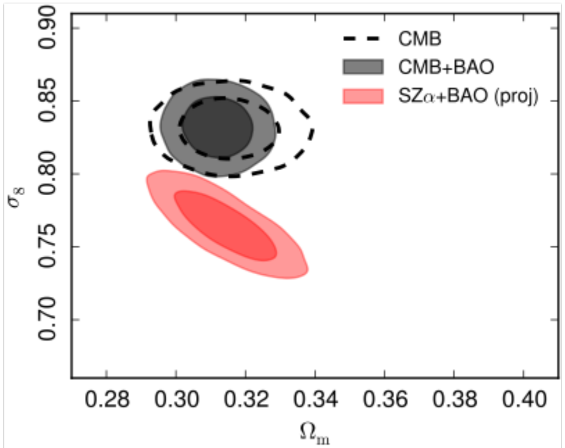
- **Catalog** of ~2000 clusters identified by their SZ signal by Planck, ACT and SPT
  → The cluster mass is evaluated from the observable (X, SZ, …)
  → need to calibrate the relation between the Mass and the Observable

$$\boxed{M_{\rm meas} = (1-b)M_{\rm true}}$$

where b is the hydrostatic bias
it includes hydrostatic equilibrium hypothesis, absolute calibration, …

$$M_{\rm meas} = M_{\rm X}, M_{\rm SZ}, \ldots$$

- **Tension** between CMB and Cluster estimation of cosmological parameters
  … most probably due to
  - the estimation of the total mass of the cluster
  - the scatter around the Mass-Observable relation that may
    → evolve with z,
    → depend on the internal structure and dynamical state.



Planck Collaboration, A&A **594** (2016)

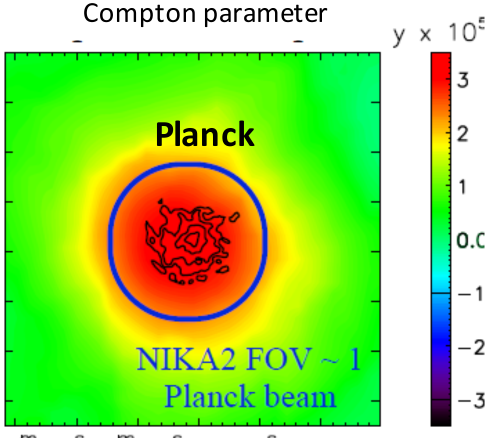
Why high-resolution SZ imaging of clusters ?

NIKA2

High-resolution SZ observations

- are needed to study the intra-cluster medium:
  dynamical state (merger) & morphology (departure from sphericity)
- must be combined with other probes (X-ray, lensing)
  → multi-probe analysis of clusters

→ This will open a **new era** for the use of clusters to study cosmology.



NIKA2 field of view = Planck beam

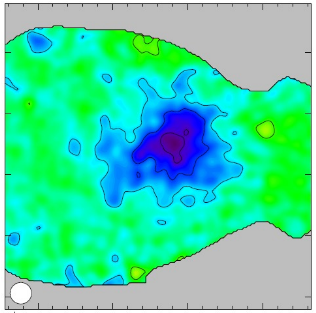
NIKA2 is able to **resolve inner structures** smoothed by the Planck beam.

Combination of Planck and NIKA2 data

Study of the intra-cluster medium at all scales (core and outskirts)

SZ observations with NIKA

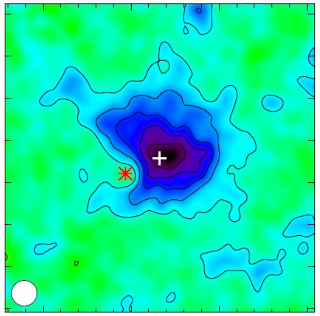
RXJ1347



well-known

R. Adam et al., A&A 2014

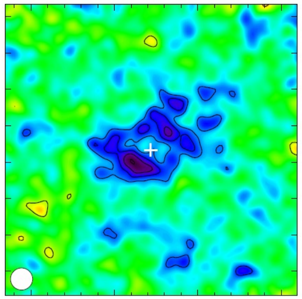
CLJ1227



high-z

R. Adam et al., A&A 2015

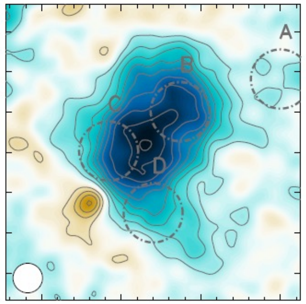
MACSJ1424



point-source removal

R. Adam et al., A&A 2016

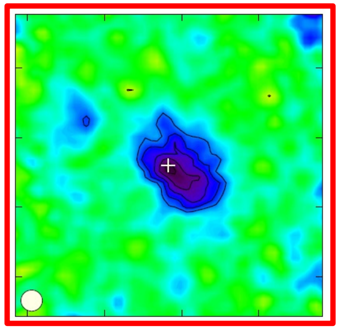
MACSJ0717



disturbed cluster

R. Adam et al., A&A 2017

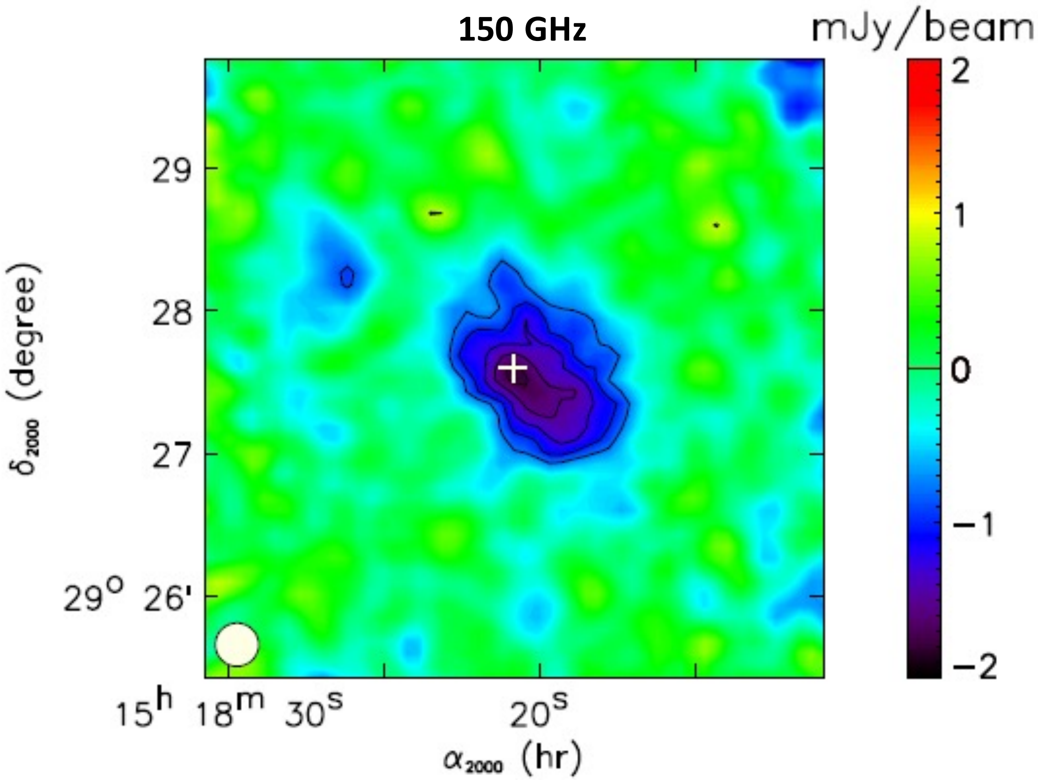
PSZ1G045



Planck-discovered

F. Ruppin et al., A&A 2017

Planck-discovered cluster: PSZ1G045



Obs. time: 5.5 h
F. Ruppin *et al.*, A&A 2017

PSZ1G045

- first Planck follow-up with NIKA
- z= 0.6

PSZ1G045 as seen by NIKA

- SZ peak at 7σ
- SZ and X-ray peaks: well aligned
- *260-GHz map:*
  no significant SZ signal,
  no point sources

A pilot study done with NIKA to prepare the NIKA2 SZ program

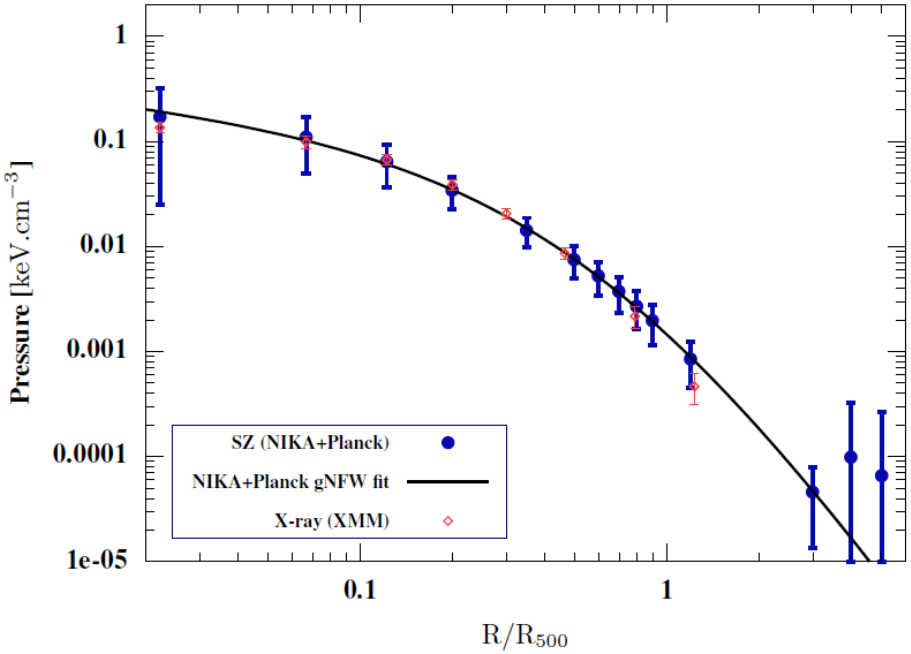
Planck-discovered cluster: PSZ1G045

Obs. time: 5.5 h
F. Ruppin *et al.*, *A&A* 2017

MCMC analysis based on a non-parametric model

Data = NIKA and Planck

- Constrain the values of the pressure from the cluster core to its outskirts



Deprojection of the electronic pressure distribution

- Agreement with X-ray data (with spectroscopy... but time consuming)
- Typical of the output product of the NIKA2 Large program

Uncertainty on the SZ signal reduced by a factor 2 (with respect to Planck)

$$Y_{500} = (5.61^{+0.68}_{-0.59})\times 10^{-4}\,\mathrm{armin}^2$$

Planck-discovered cluster: PSZ1G045

NIKA2

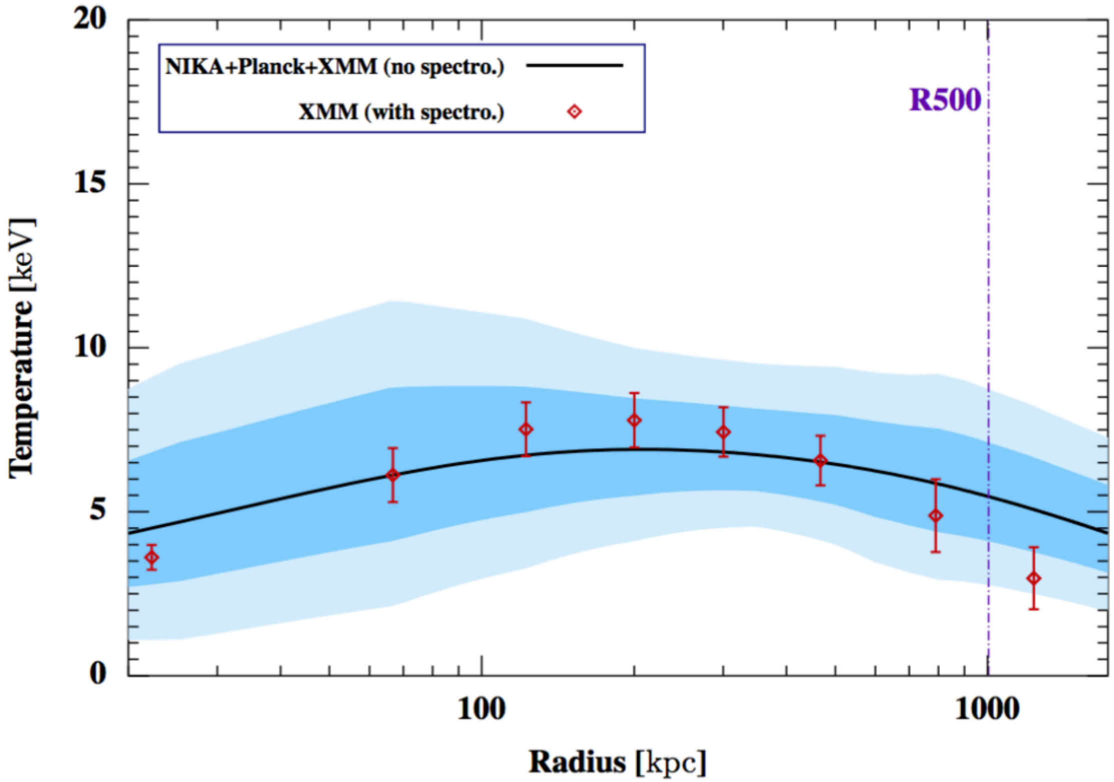
Obs. time: 5.5 h
F. Ruppin *et al.*, A&A 2017

Combined analysis

Data: Planck+NIKA+XMM
→ A multi-probe study
→ **Thermodynamic properties** of the cluster
Pressure, Temperature, Entropy, Mass profiles

Temperature profile

$$\mathrm{k_B}T(r) = \frac{P(r)}{n(r)}$$



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F. Ruppin *et al.*, A&A 2017

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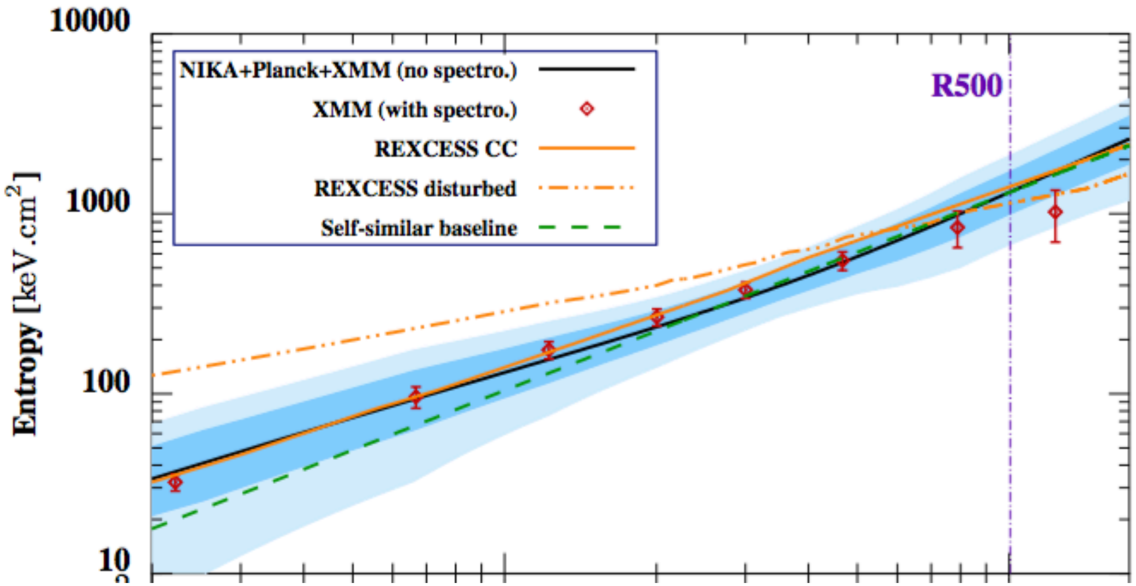
Entropy profile

$$\boxed{K(r) = \frac{P(r)}{n(r)^{5/3}}}$$



→PSZ1G045 is a **cool-core** cluster.

Planck-discovered cluster: PSZ1G045

NIKA2

Obs. time: 5.5 h
F. Ruppin *et al.*, A&A 2017

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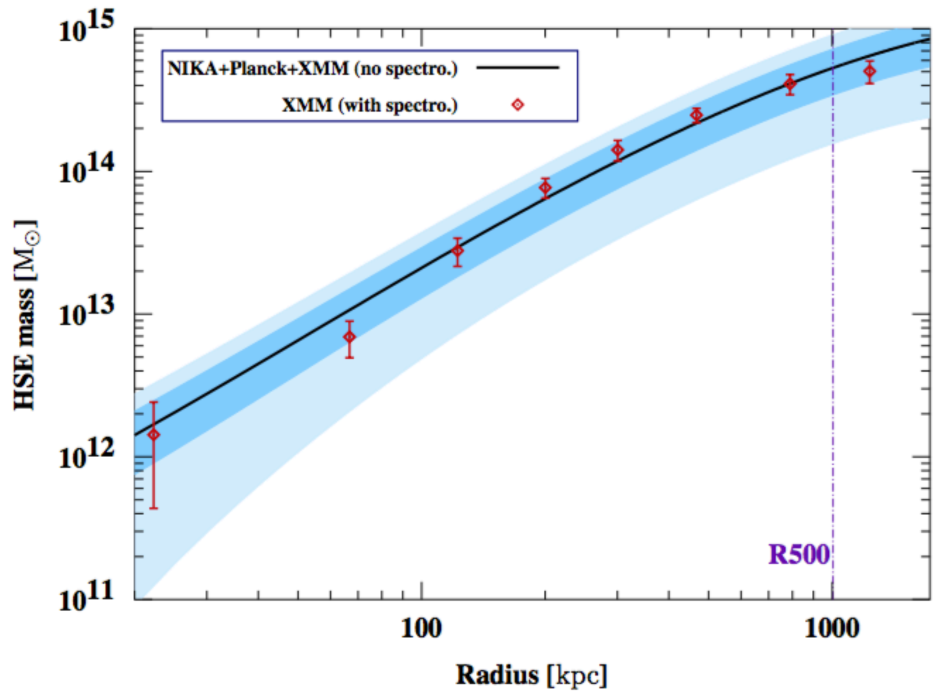
Mass profile

$$M(r) \propto \frac{1}{n(r)} \times \frac{\mathrm{d}P}{\mathrm{d}r}$$

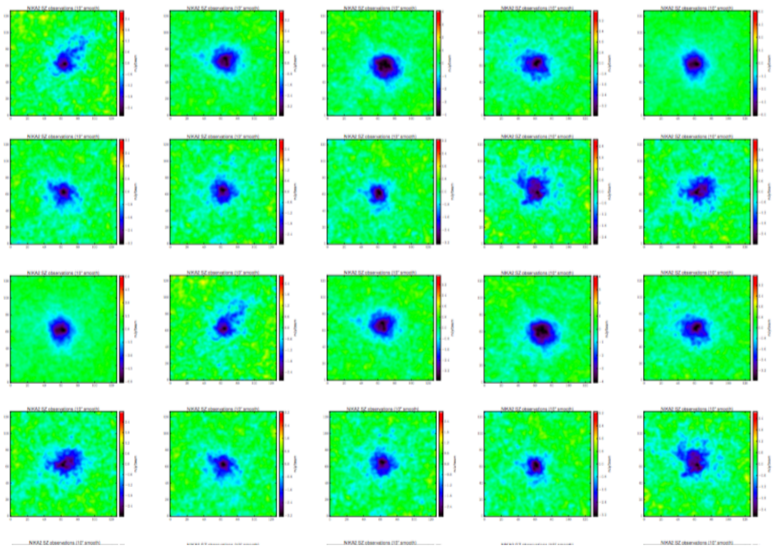


→PSZ1G045 is **a massive** cool-core cluster.

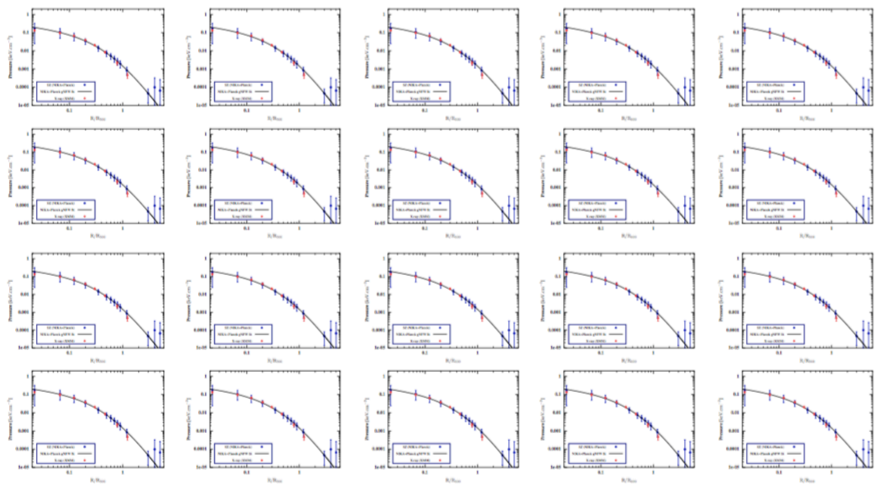
$$M_{500} = (5.4^{+2.6}_{-3.0})\times 10^{14}\,M_{\odot}$$

The NIKA2 SZ large program (2017-2022)

- One of the 5 Large Programs of the NIKA2 Guaranteed time
- 300 hours of observations to observe 50 clusters



SZ maps



Pressure profiles

The NIKA2 SZ large program (2017-2022)

NIKA2 cluster sample

- 50 clusters up to z=1 from P*lanck & ACT catalogs*
- XMM-Newton follow-up *(X-ray data)*

Goals

- In-depth study of the intra-cluster medium
- Combination with ancillary data (X-ray, *lensing*)

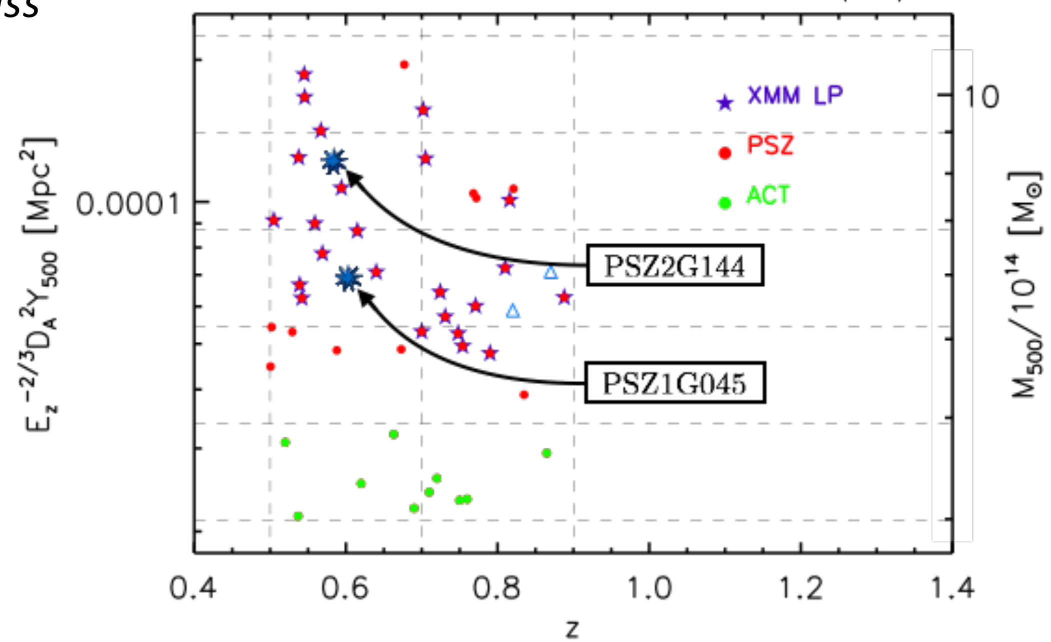
→**Thermodynamic properties of the ICM**

Pressure, density, temperature, entropy, mass

Expected outputs

- Redshift evolution of
  - *pressure profile,*
  - *scaling law*
  - *the hydrostatic bias*
- Cluster properties as function of
  - *dynamical states (mergers)*
  - *morphology (sphericity)*

Comis *et al.* (2016)



Significant improvements on the use of clusters of galaxies to draw cosmological constraints

First cluster observation with NIKA2

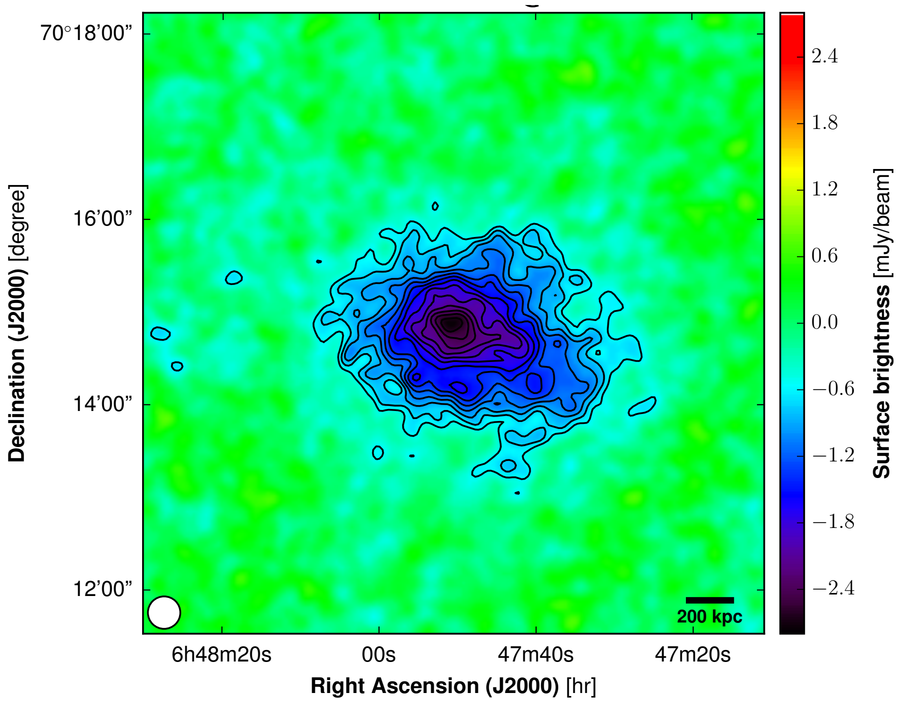
SZ target: PSZ2G144 (PI: F. Ruppin)

- A cluster from the NIKA2 LP sample (Planck catalogue)
- z = 0.58
- $M_{500} = 7\times10^{14} M_{\odot}$ (Y proxy)
- X-ray data: deep XMM-*Newton* exposure (~ 60 ksec).

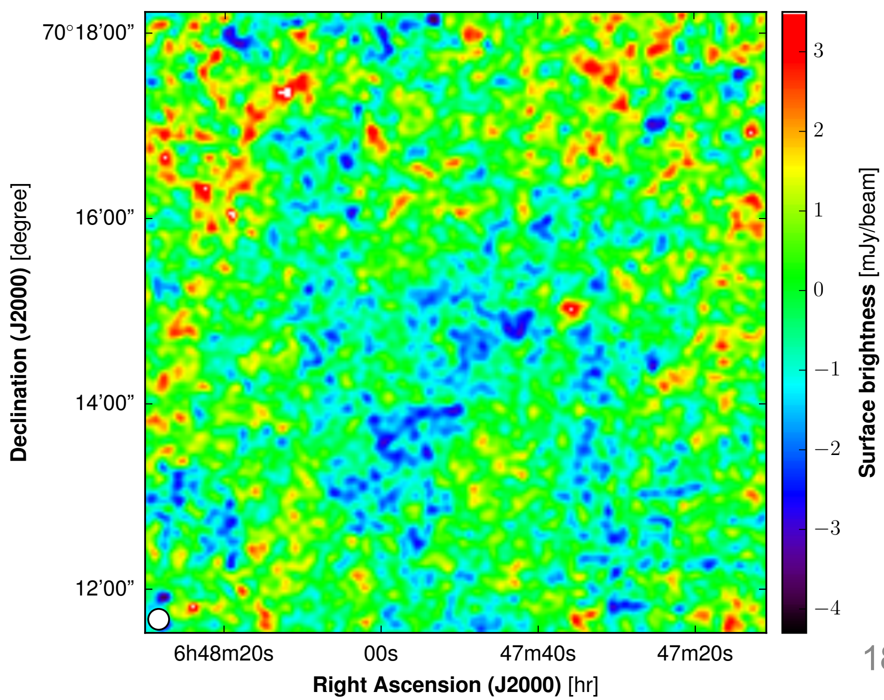
Observations in April 2017

- Effective observation time: 11 hours
- Mean opacity : 0.3 @ 2mm *(bad weather)*
- Mean elevation : 41,4°

NIKA2 – 150 GHz



NIKA2 – 260 GHz



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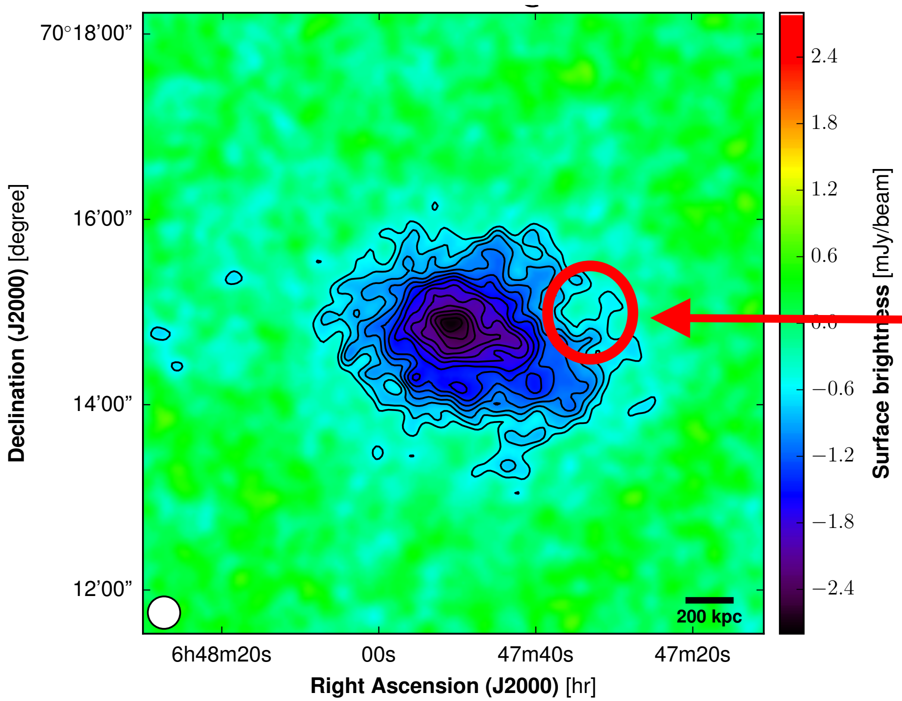
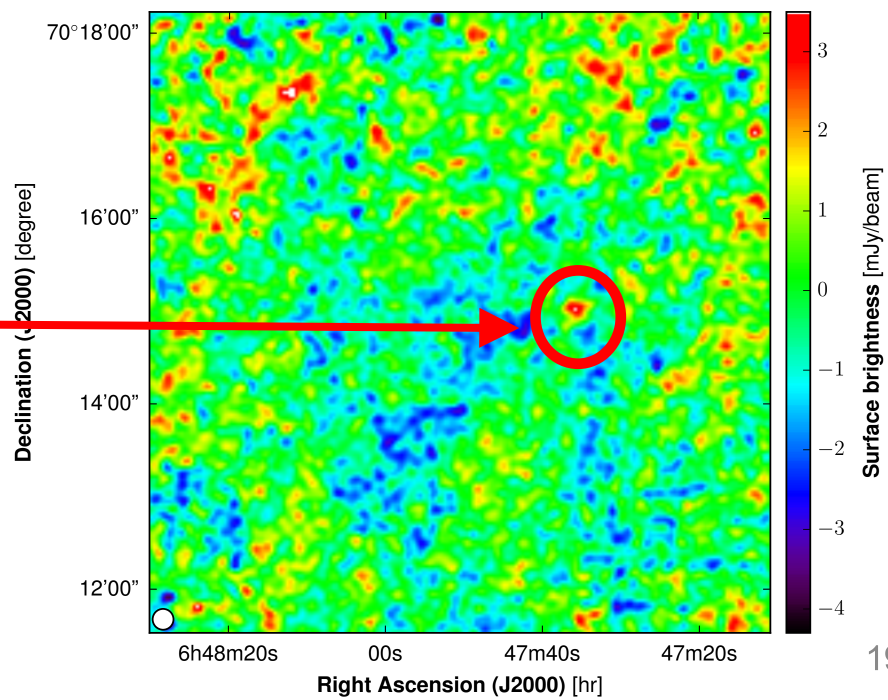


NIKA2 – 260 GHz



First cluster observation with NIKA2

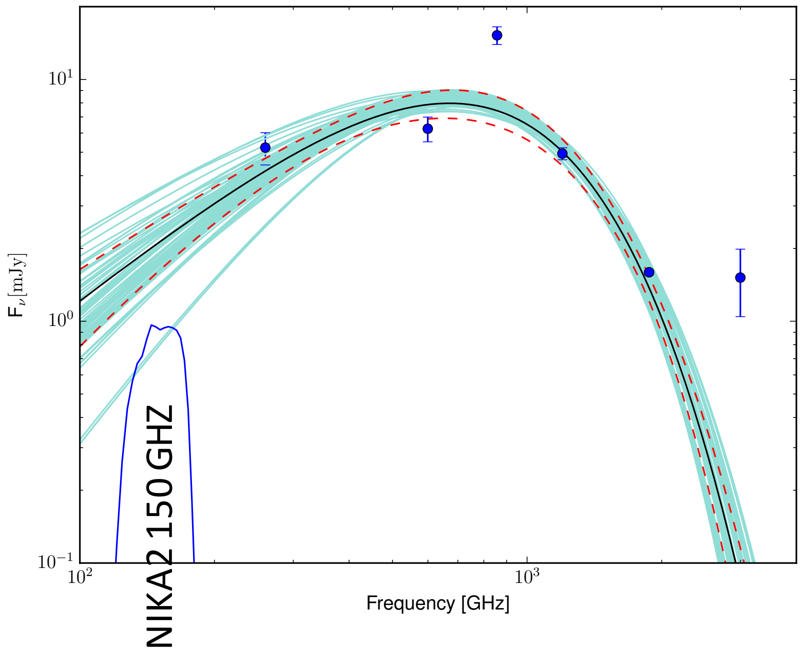
Point source removal

Data: Herschel (0.1 to 0.5 mm) and NIKA2 data (260 GHz, 1 mm)

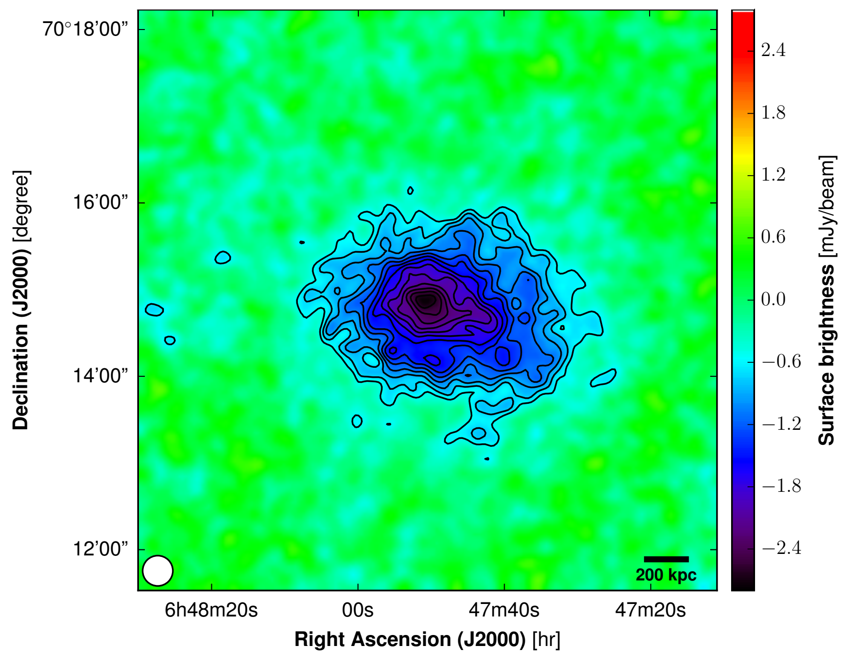
→ fit of the Spectral Energy Distribution of the source

→ estimation of the flux at 150 GHz (2mm)

→ Corrected map at 150 GHz

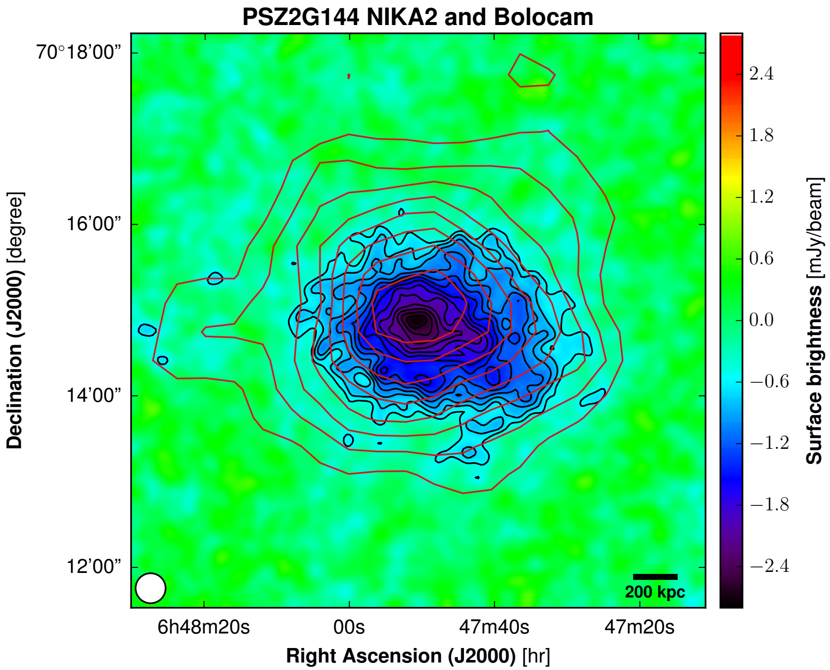


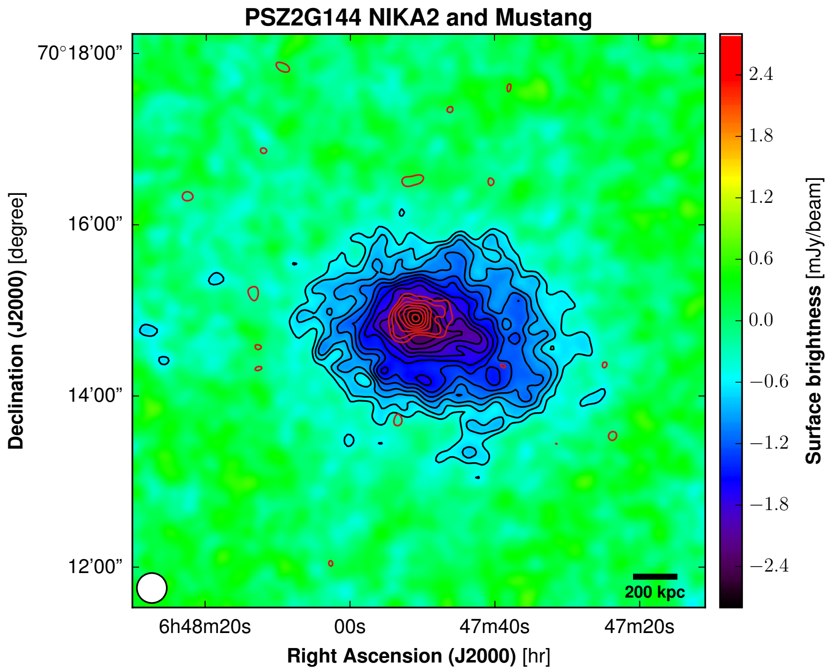
NIKA2 – 150 GHz - corrected



First cluster observation with NIKA2

Comparison with Bolocam and Mustang





Bolocam at 140 GHz
Angular resolution: 58"
FOV: 8'
Caltech Submillimeter Observatory

NIKA2 at 150 GHz
Angular resolution: 18"
FOV: 6.5'
IRAM 30-m Telescope

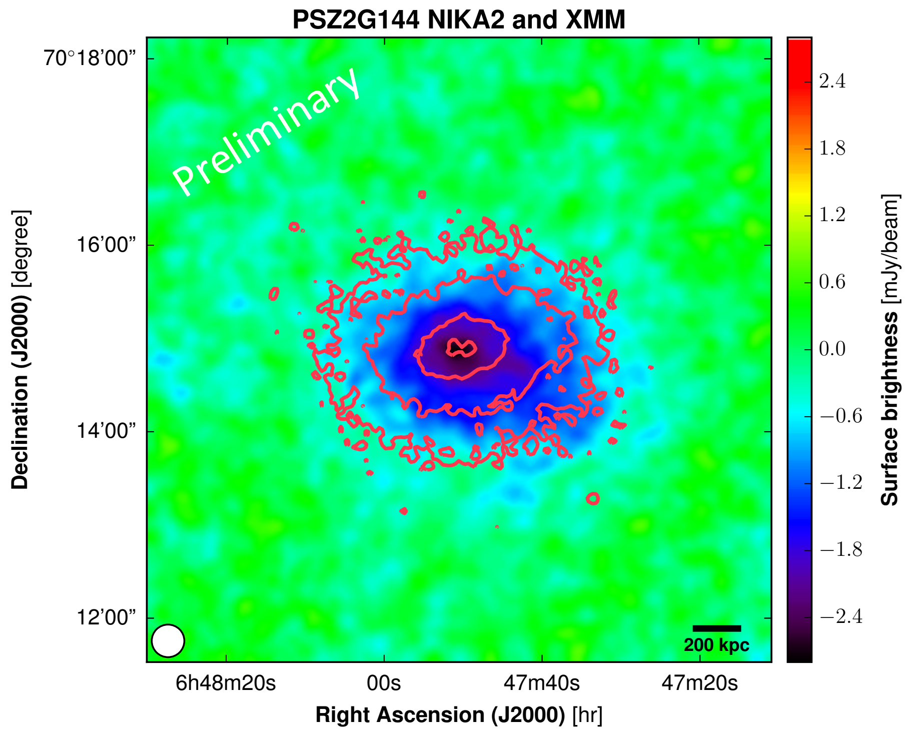
MUSTANG at 90 GHz
Angular resolution: 9"
FOV: 42"
Green Bank Telescope

With a **large FOV** and a **high angular resolution**,
NIKA2 brings **valuable information**
in the field of SZ imaging of clusters

C. Romero et al., A&A 2015
S. R. Dicker *et al.*, Proc. SPIE 2008
J. Glenn *et al.*, Proc. SPIE 1998
F. Ruppin et al. , to be submitted (soon)

First cluster observation with NIKA2

Comparison with XMM-Newton data



SZ and X-ray data present comparable quality (e.g. cluster extension)

→ Optimal for a combined analysis

- 1D (profiles)
- 2D (maps)

→ very promising results

Conclusions

- High-resolution SZ observation of high-z clusters is a key issue for cosmology.
- NIKA2 SZ Large Program: 50 clusters to be observed in the forthcoming years.
- **The NIKA2 camera is installed at the IRAM 30m and commissioned.**
  opened to the scientific community
- **First cluster observed with NIKA2 : promising results**

R. Adam, P. Ade, N. Aghanim, P. André, M. Arnaud, H. Aussel, R. Barrena Delgado, I. Bartalucci, A. Beelen, A. Benoît, A. Bideaud, N. Billot, O. Bourrion, M. Calvo, A. Catalano, N. Clerc, G. Coiffard, B. Comis, M. De Petris, F.-X. Désert, M. Douspis, S. Doyle, C. Ferrari, J. Goupy, C. Kramer, G. Lagache, S. Leclercq, J.-F. Lestrade, J.F. Macías-Pérez, P. Mauskopf, F. Mayet, J.-B. Melin, A. Monfardini, E. Pascale, L. Perotto, G. Pisano, E. Pointecouteau, N. Ponthieu, G. Pratt, V. Revéret, A. Ritacco, C. Romero, H. Roussel, J. A. Rubino Martin, F. Ruppin, K. Schuster, A. Sievers, S. Triqueneaux, C. Tucker, R. Zylka