Cluster cosmology
with the **NIKA2 camera**
at the IRAM **30-m telescope**

F. Mayet
on behalf of the NIKA2 Collaboration

Outline

1. Cluster cosmology
   The need for high-resolution SZ observations

2. The NIKA2 camera
   A perfect tool for SZ science

3. The NIKA2 SZ large program (2017-2022)
   Follow-up of 50 Planck-discovered clusters

4. First cluster observation with NIKA2
   Impact of high-resolution SZ observations

Cluster cosmology – Introduction

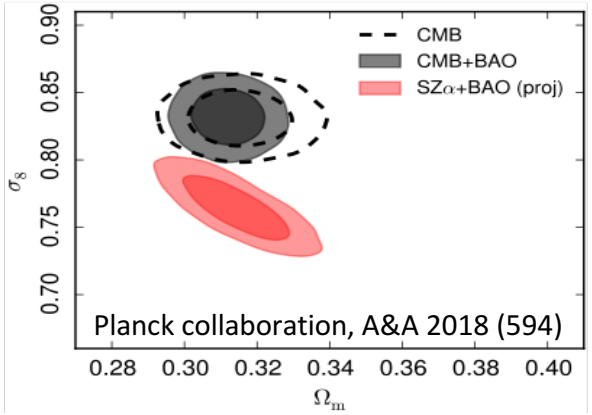
Cosmological parameters

→ **Tension** between CMB and cluster results

- New physics

  large-scale structure formation, neutrinos, …

- Insufficient knowledge of cluster physics



Estimating cosmological parameters with clusters of galaxies

- A large **cluster sample**: ~2000 clusters identified by their SZ signal by Planck, ACT and SPT
- Methods: **cluster count** $\frac{d^2n}{dMdz}$, SZ power spectrum $C_\ell^{\rm SZ}$
- Inputs
  - Universal **pressure profile** *P(r)*
  - **Scaling relation** relating the observable and the cluster mass

  → estimated with a sample of clusters at low redshift (0.2)

  → may evolve with z, may depend on internal structure and dynamical state.

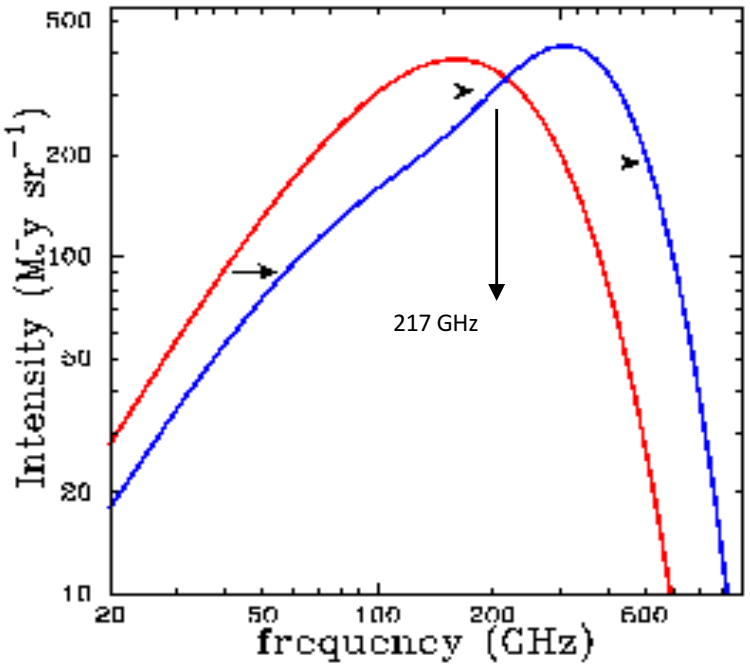
Cluster mass

- Estimated from observables : X-rays (density), **SZ effect** (pressure), ..

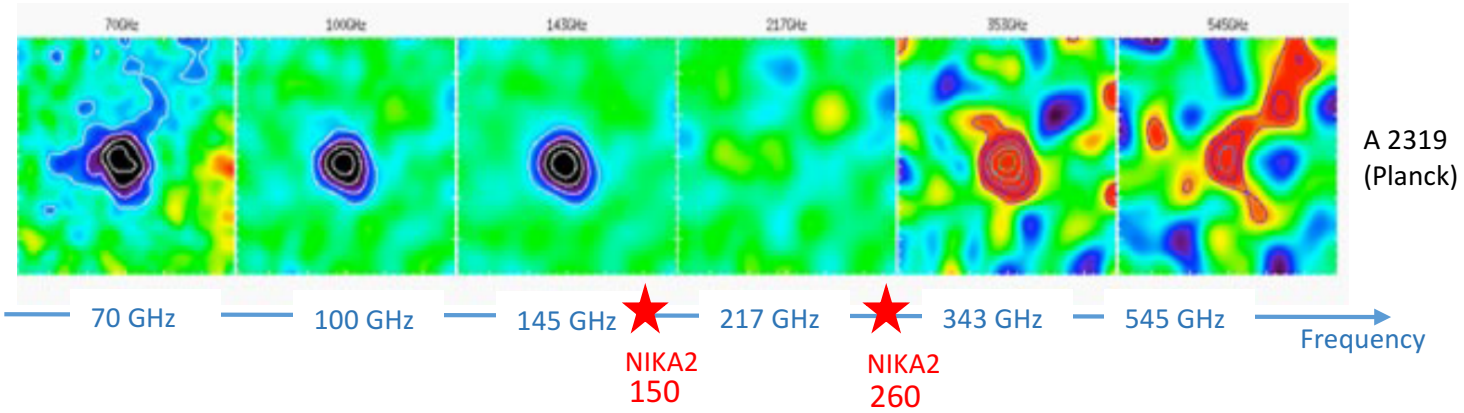
Cluster cosmology – SZ effect

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 (high-z clusters)
- SZ signal: Compton parameter $y \propto \int P_e d\ell$
  → characterization of the electronic pressure in the ICM
  → radial profiles (1D) or maps (2D)
- Integrated SZ signal $Y_\Delta \propto \int_0^{R_\Delta} Pe\, d^3r$
  → related to the mass via the scaling relation
  → unresolved observations



A cluster as seen by Planck



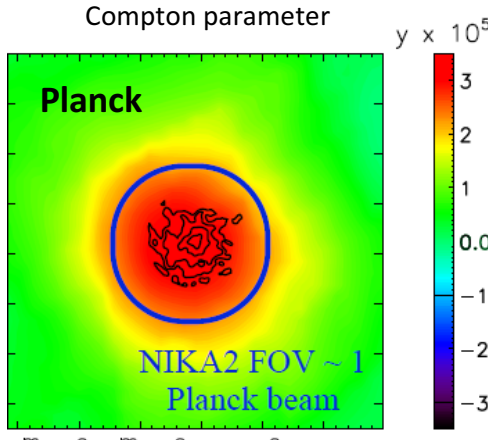
A 2319 (Planck)

Cluster cosmology – SZ effect

High-z clusters are not resolved by Planck

Planck beam = NIKA2 field of view

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



High-resolution SZ observations

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

→ This will open a **new era** for the **use of clusters to constrain cosmological models**

Combination of Planck and NIKA2 data

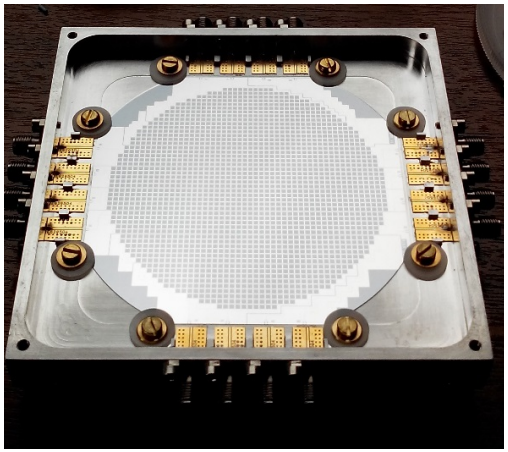
Probe the intra-cluster medium at all angular scales (core and outskirts)

The NiKA2 camera

A perfect tool for SZ science

R. Adam *et al.*, A&A 2018

NIKA2 LEKID array (260 GHz)



Detector wish list for SZ science

- High angular resolution
  → to resolve ICM structures
- High sensitivity
  → to reduce integration time
- Large Field of View
  → to map the whole cluster
- More than one frequency band
  → below and above 217 GHz

The NIKA2 camera

R. Adam *et al.*, A&A 2018

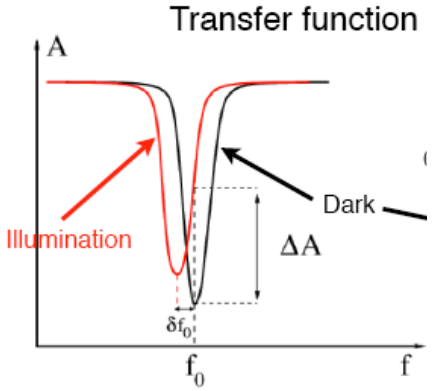
NIKA2

- KID-based camera

  Kinetic Inductance Detectors

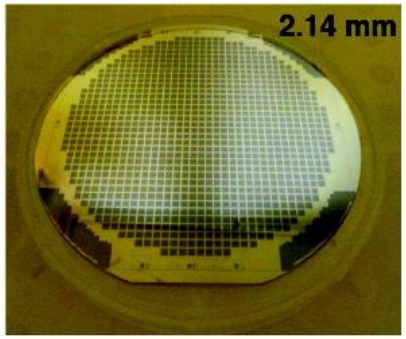
  High quality factor superconducting resonators

  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 detectors
- High angular resolution: 17.7 and 11.2 arcsec
- State-of the art sensitivity: 8 and 33 mJy.s$^{1/2}$ (at null opacity)

  → high S/N observation of clusters in 2 to 15 hours

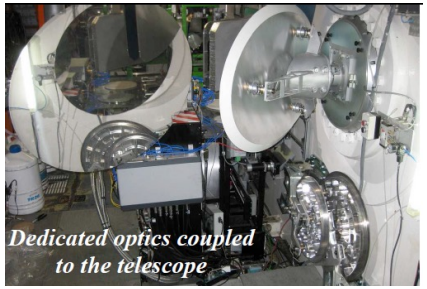


These values are measured performances : see R. Adam et al., A&A 2018

The NIKA2 camera

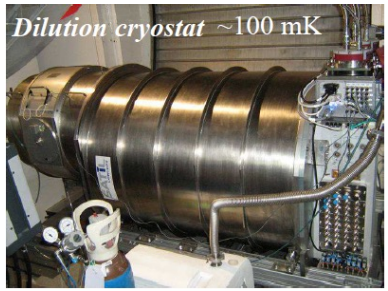
R. Adam *et al.*, A&A 2018

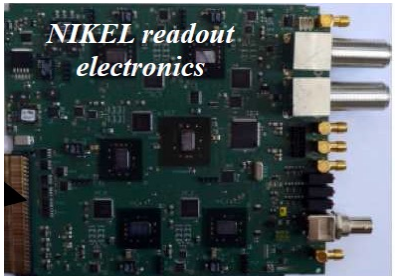
IRAM 30-m telescope
at Pico Veleta (Spain)



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**

The NIKA2 SZ large program (2017-2022)

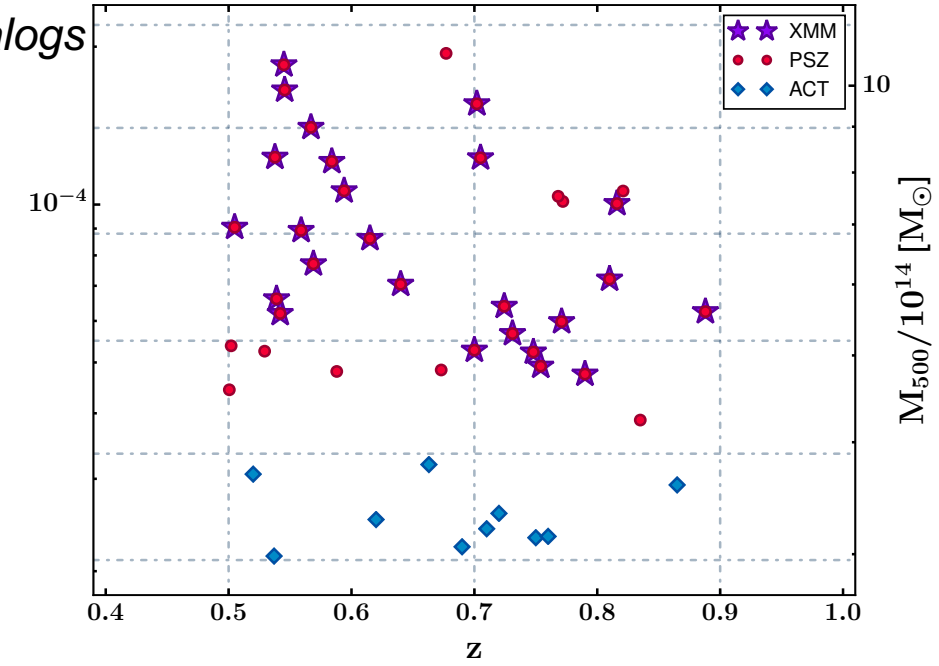
a follow-up of 50 Planck-discovered clusters

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

The NIKA2 SZ large program

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 X-ray data

→Thermodynamic properties of the ICM

Pressure, density, temperature, mass, entropy

Expected outputs

- A representative cluster sample,

→ *cluster properties as function of their dynamical states (mergers) & morphology (sphericity)*

- Universal pressure profile,
- Scaling law: SZ-mass

} for the first time at high redshift

→ tools to re-analyze Planck cluster data

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

First cluster observation with NIKA2

Impact of high-resolution observations

F. Ruppin *et al.*, A&A 2018

First cluster observation - maps

SZ target

F. Ruppin *et al.*, A&A 2018

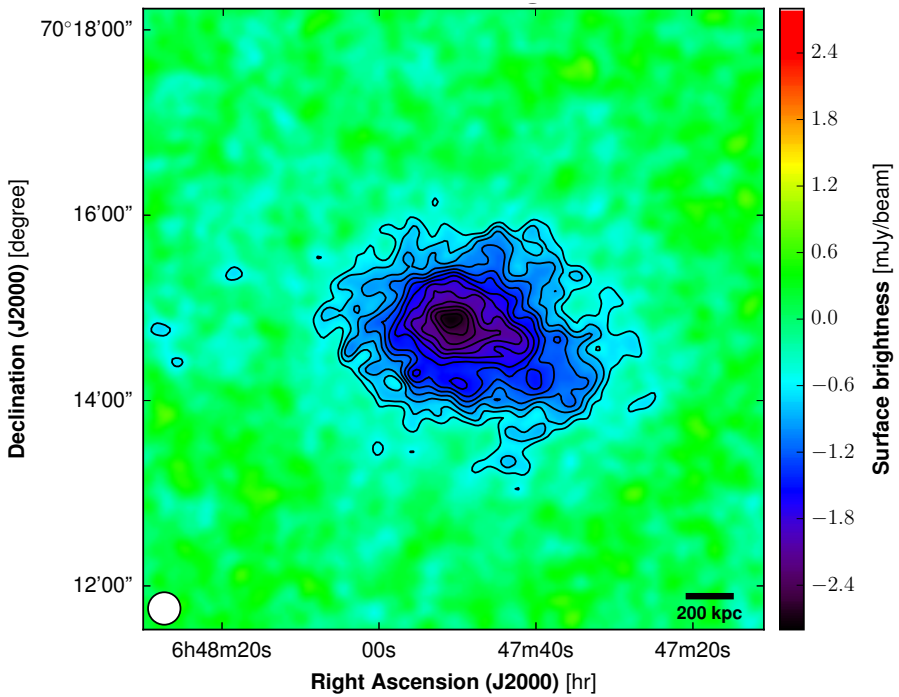
- PSZ2G144: a cluster from the NIKA2 LP sample (Planck catalogue)
- z = 0.58
- $M_{500} = 7\times10^{14} M_{\odot}$ (Y proxy)
- X-ray data: deep XMM-*Newton* exposure (~ 60 ksec) :
  - density (photon count)
  - temperature (spectroscopy)

(time consuming)

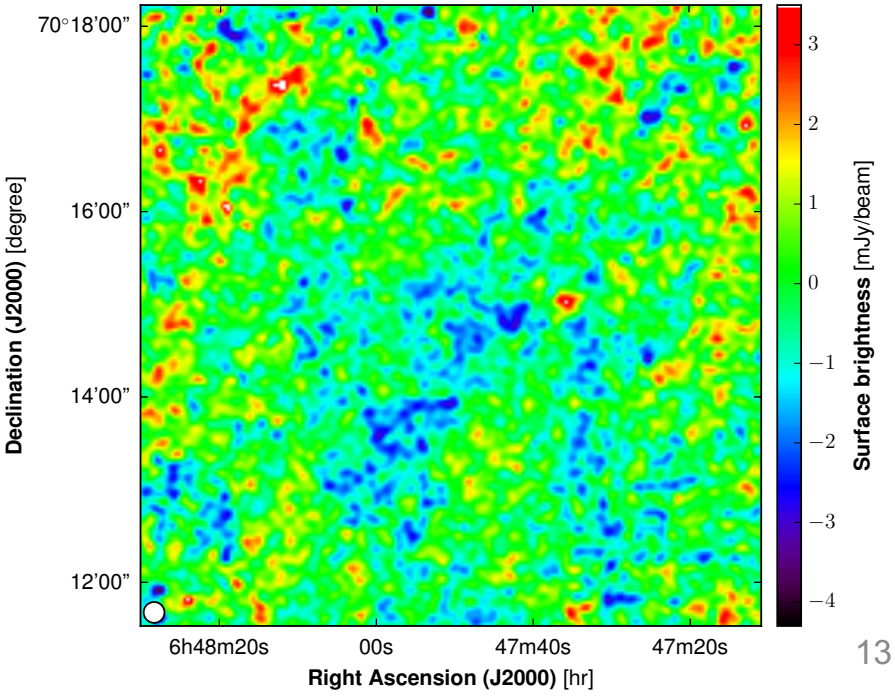
Observations in April 2017

- Effective observation time: 11 hours
- Mean opacity : 0.3 @ 2mm *(bad weather)*

NIKA2 – 150 GHz



NIKA2 – 260 GHz



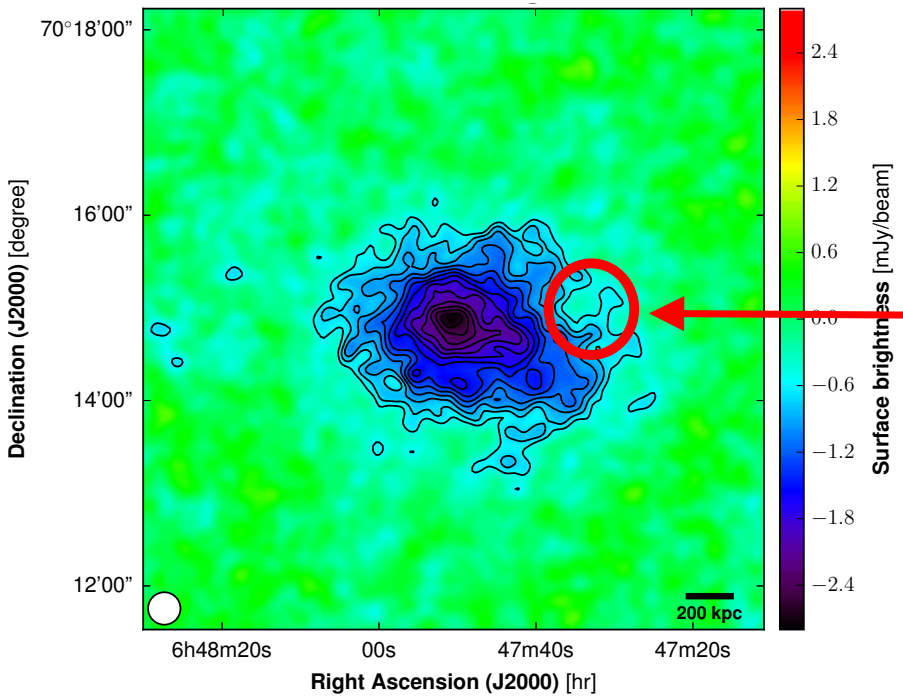
First cluster observation – point source removal

F. Ruppin *et al.*, A&A 2018

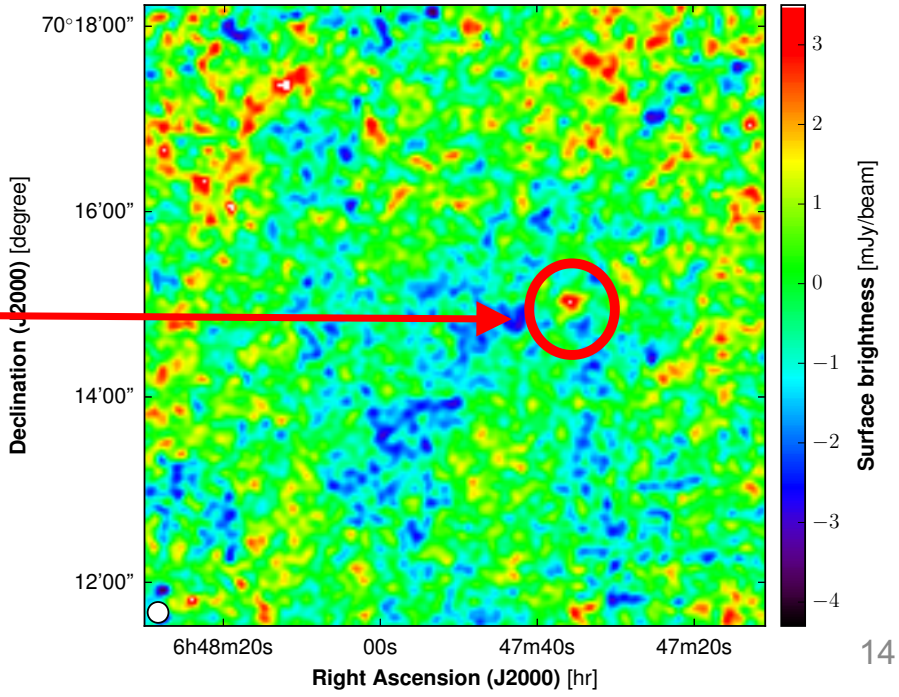
Dual-band observation

- no SZ signal is expected at 260 GHz (for this noise elevel)
- 260 GHz map is used to identify point sources that may compensate SZ signal at 150 GHz

NIKA2 – 150 GHz



NIKA2 – 260 GHz



First cluster observation – point-source removal

F. Ruppin *et al.*, A&A 2018

Point-source removal

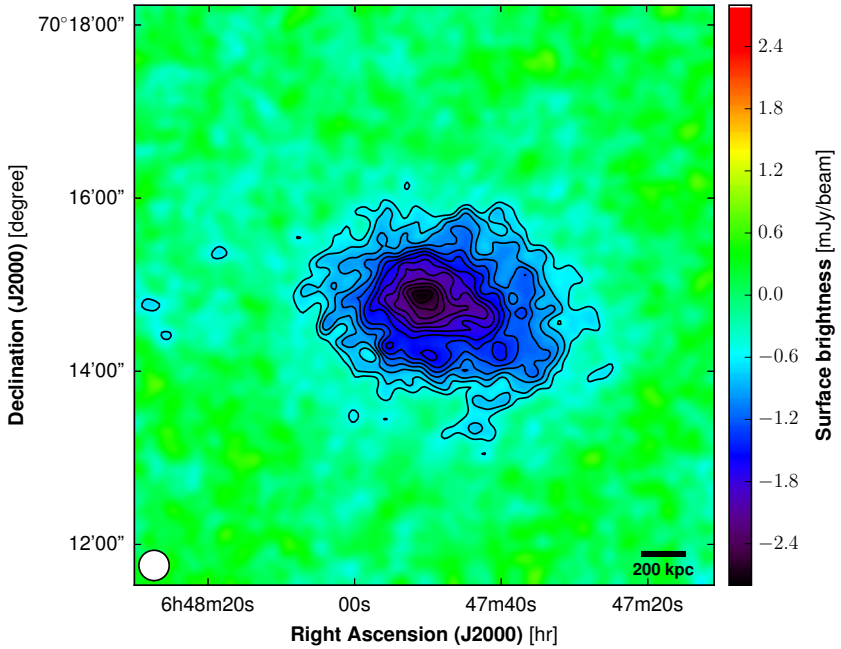
Data: Herschel (0.1 to 0.5 mm) and NIKA2 data (260 GHz, 1 mm)

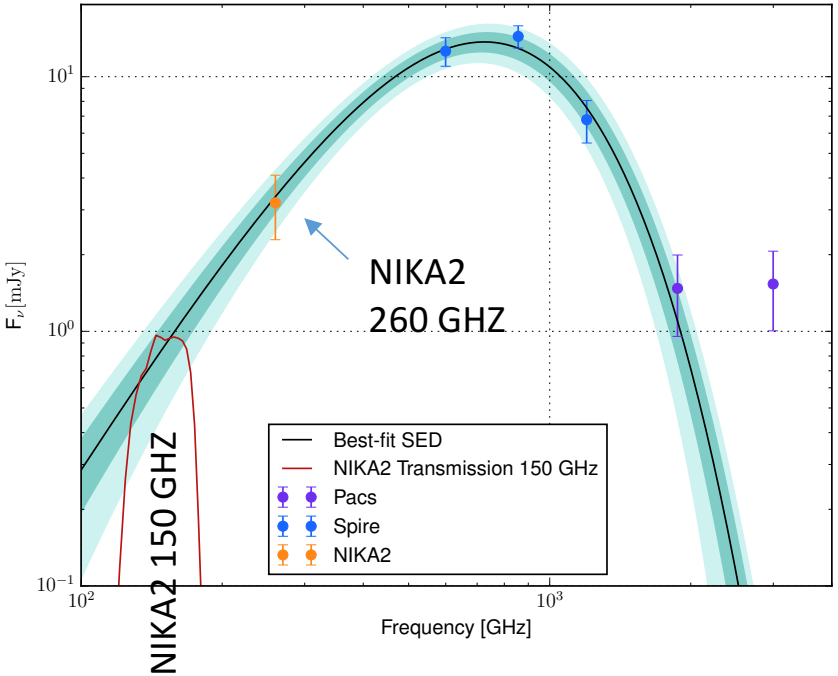
→ fit of the Spectral Energy Distribution of the source

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

→ Corrected map at 150 GHz

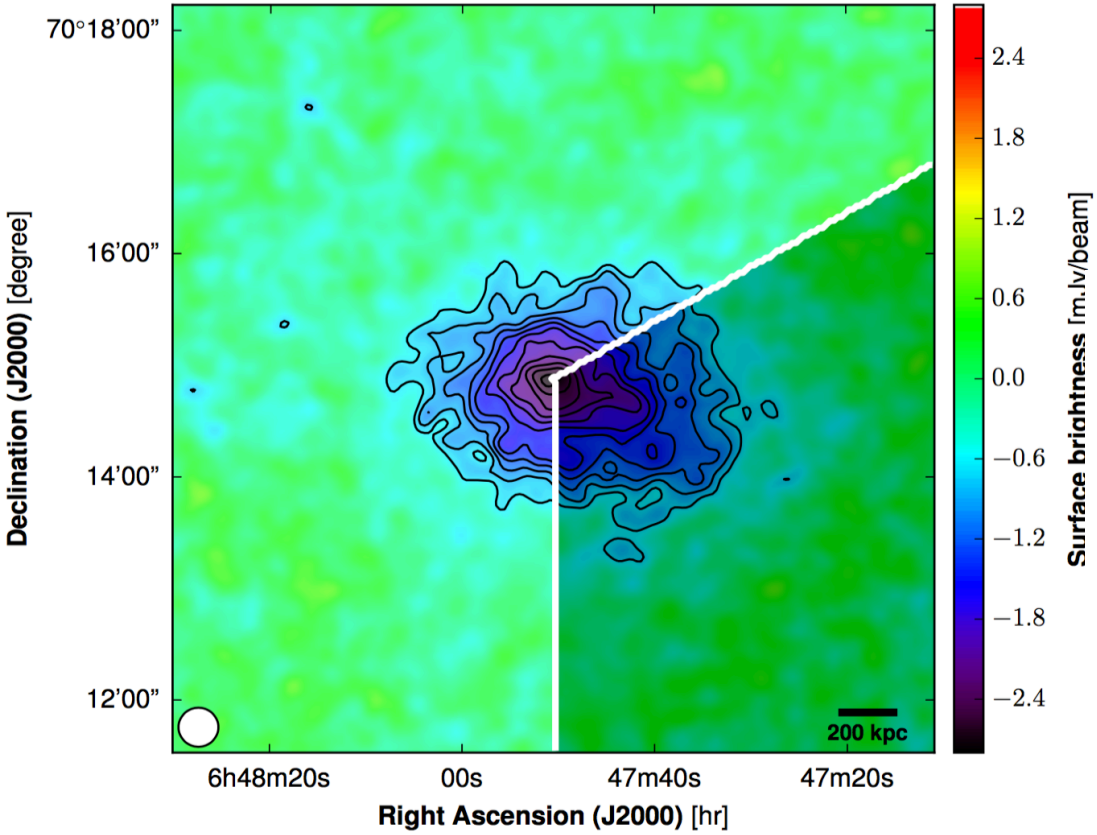
NIKA2 – 150 GHz - **corrected**

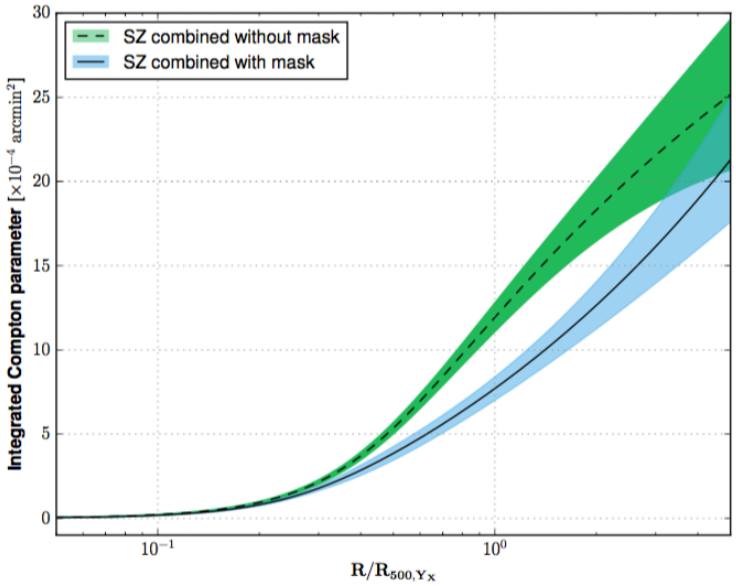




First cluster observation – overpressure region

F. Ruppin *et al.*, A&A 2018





Discovery of an overpressure region

→ should impact integrated SZ signal and mass

→ highlight the need for high-resolution observations

this cluster is not resolved by Planck

First cluster observation – pressure profile

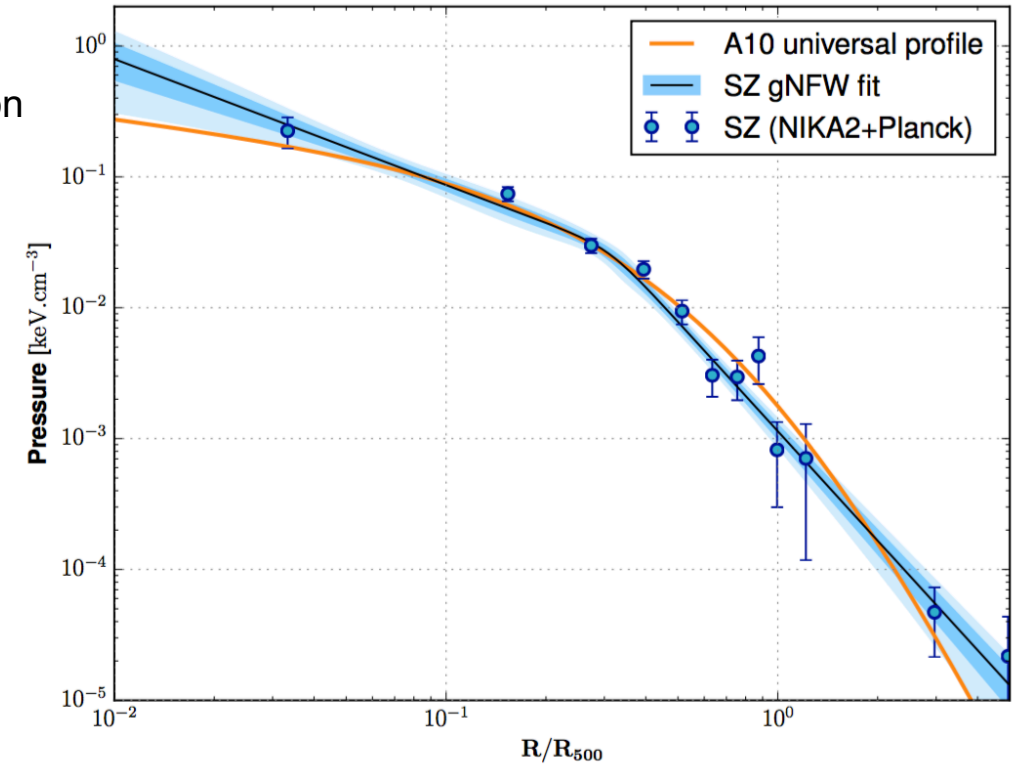
F. Ruppin *et al.*, A&A 2018

MCMC analysis based on a non-parametric model

Data = NIKA2 and Planck

→ **Deprojection** of the electronic pressure distribution

→Comparison with Universal Pressure Profile



- Small departure from the Universal Pressure Profile
  - → no conclusion can be drawn from a single cluster
- NIKA2 Large program will allow us to
  - establish a Universal pressure profile at high z
  - study its redshift evolution

First cluster observation – thermodynamics

Combined analysis

F. Ruppin *et al.*, A&A 2018

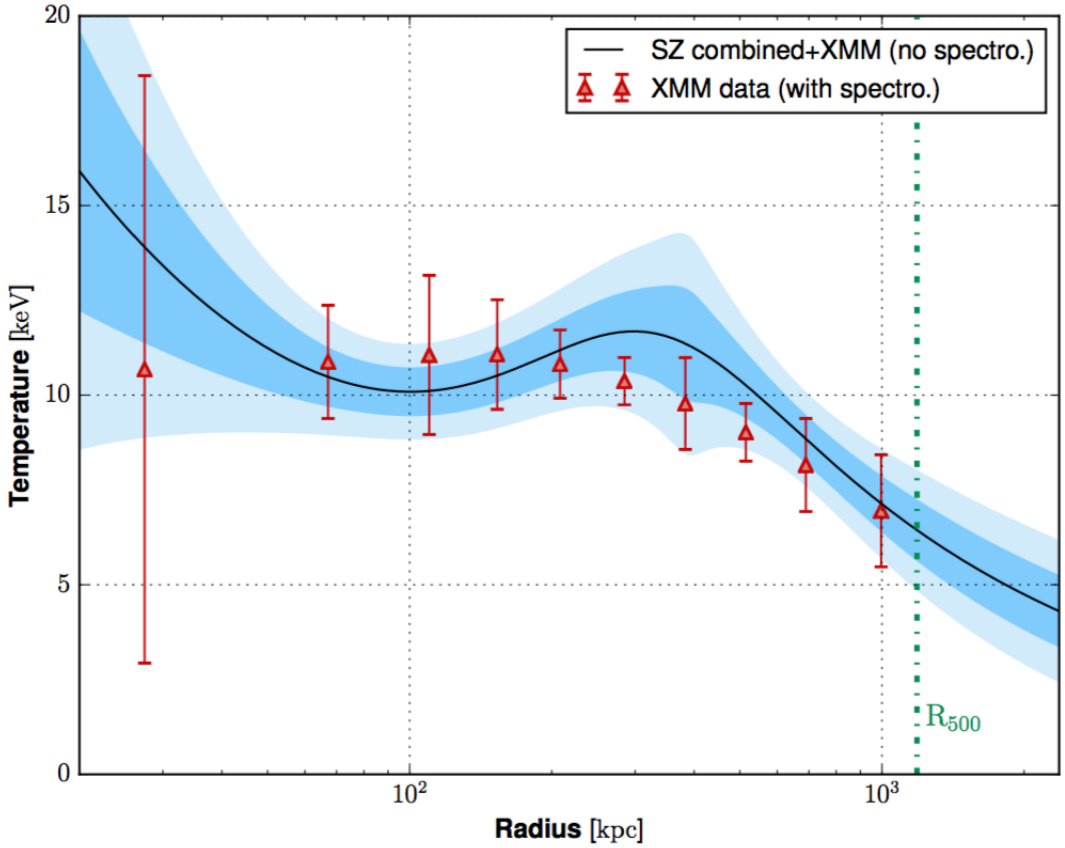
Data = SZ and X-ray (XMM)

- A multi-probe study
- **Thermodynamic properties** of the cluster

*Pressure, **Temperature**, Mass, Entropy profiles*

Temperature profile

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



- Compatible with spectroscopy estimate
- ~11 keV in the cluster core

→ disturbed cluster

First cluster observation – thermodynamics

Combined analysis

F. Ruppin *et al.*, A&A 2018

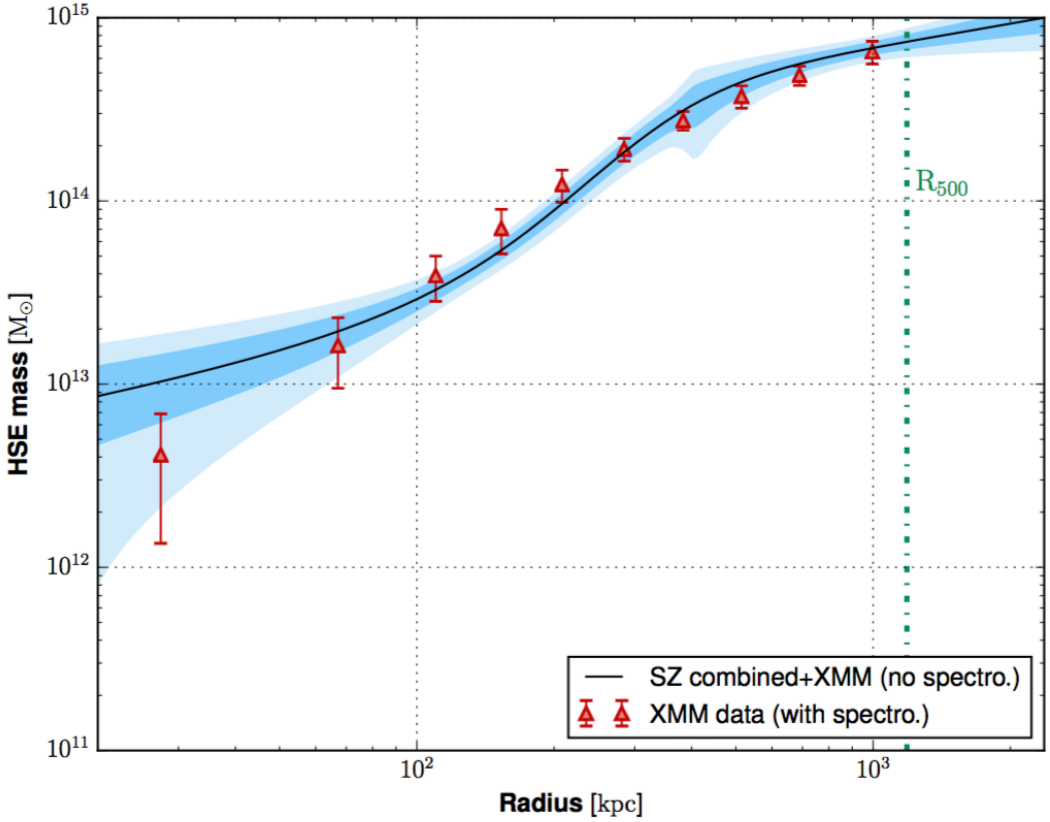
Data = SZ and X-ray (XMM)

- A multi-probe study
- **Thermodynamic properties** of the cluster

*Pressure, Temperature, **Mass**, Entropy profiles*

Mass profile

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



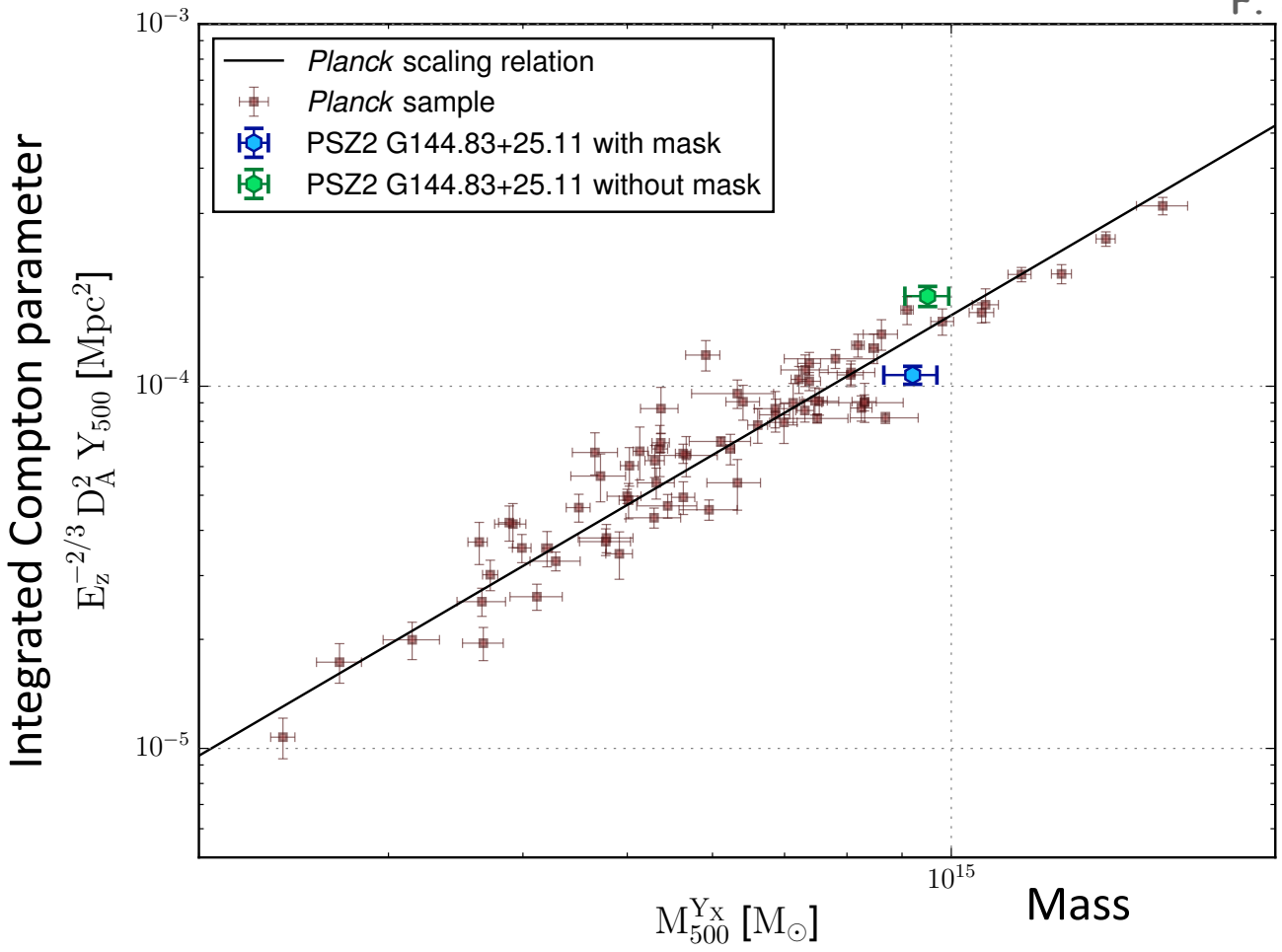
Estimation of integrated quantities

- Cluster Mass
- Integrated Compton parameter (Y)

	With mask	Without mask
R_{500} [kpc]	1107 ± 30	1342 ± 61
Y_{500} [$\times 10^{-4}$ arcmin^2]	8.06 ± 0.46	13.31 ± 0.85
M_{500} [$\times 10^{14}$ $M_\odot$]	6.95 ± 0.56	12.42 ± 1.43

First cluster observation – scaling relation

F. Ruppin *et al.*, A&A 2018



- First comparison of a NIKA2 cluster with the Planck scaling relation
- Highlight the impact of overpressure regions on integrated quantities (scatter)

Conclusions

- High-resolution SZ observation of high-z clusters is a key issue for cluster cosmology.

- The NIKA2 camera is installed at the IRAM 30m telescope
  and opened to the scientific community

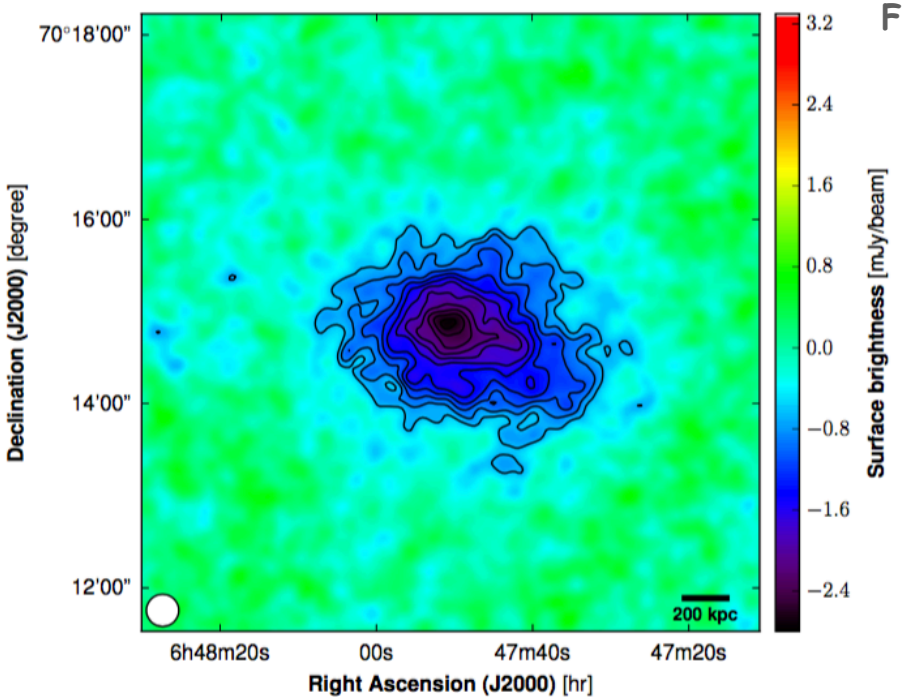
- NIKA2 SZ Large Program: 50 clusters to be observed in the forthcoming years.

- **First cluster observed with NIKA2**
  Impact of high-resolution observations on cluster property estimates (mass)

F. Ruppin *et al.*, A&A 2018

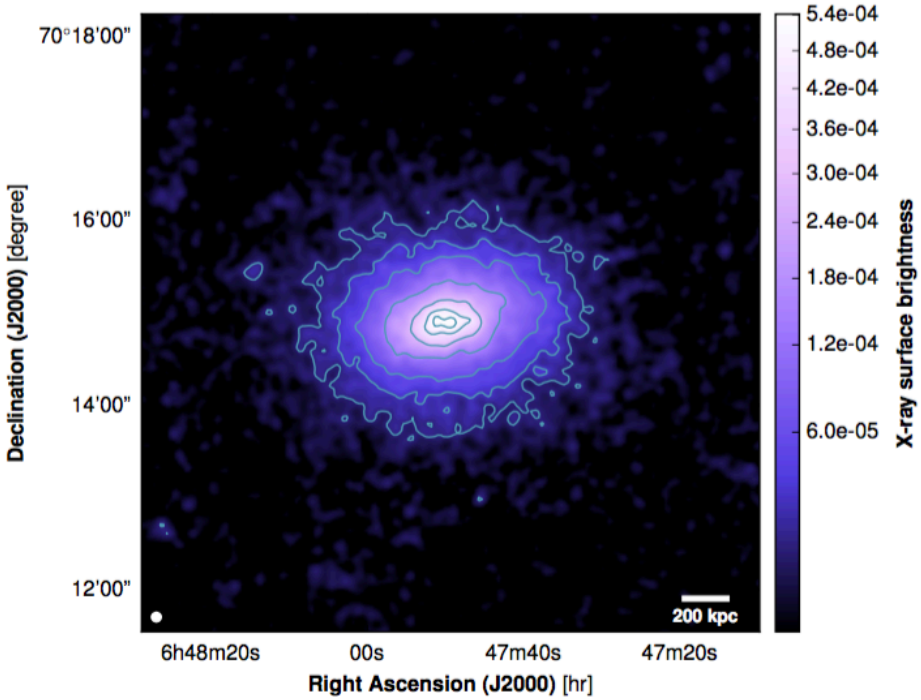
NIKA2

SZ → Pressure



XMM-Newton

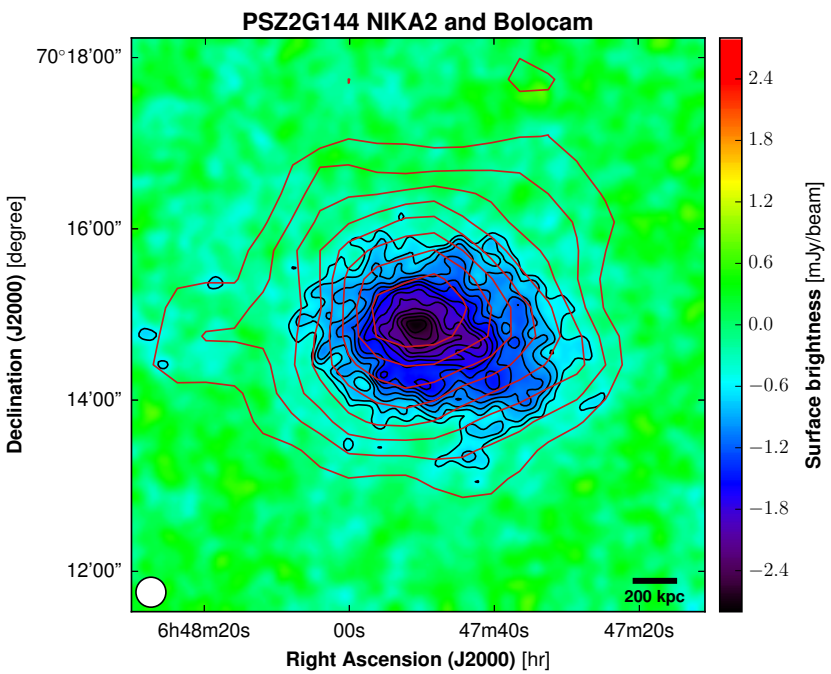
photo count → density

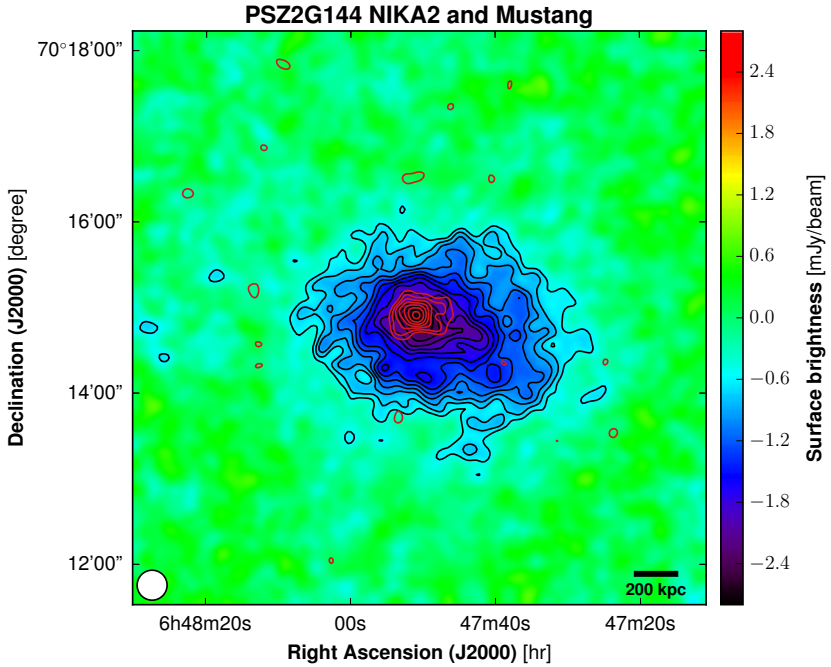


First cluster observation - comparison

Comparison with Bolocam and Mustang

F. Ruppin *et al.*, A&A 2018





Bolocam at 140 GHz
Angular resolution: 58”
FOV: 8’
Caltech Submillimeter Observatory

NIKA2 at 150 GHz
Angular resolution: 18”
FOV: 6.5’
IRAM 30-mTelescope

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 – thermodynamics

Combined analysis

F. Ruppin *et al.*, A&A 2018

Data: Planck+NIKA+XMM

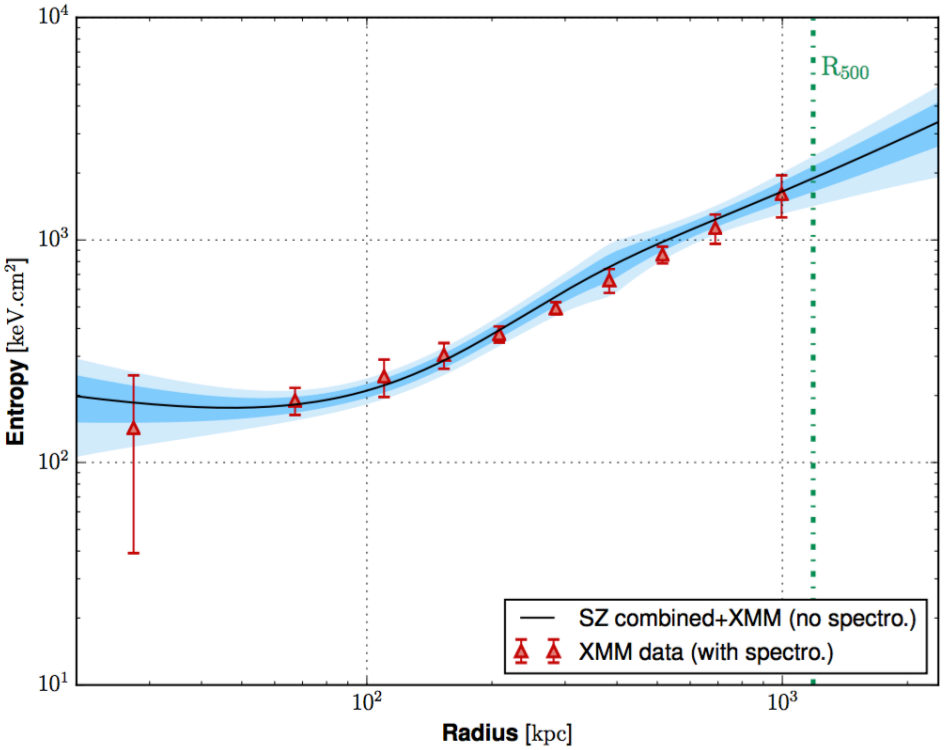
→ A multi-probe study

→ **Thermodynamic properties** of the cluster

Pressure, Temperature, Entropy, Mass profiles

Entropy profile

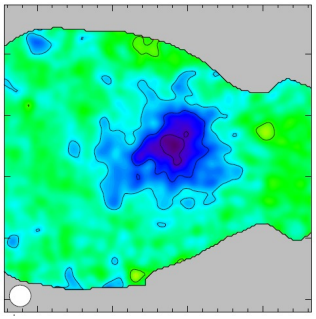
$$K(r) = \frac{P(r)}{n(r)^{5/3}}$$



Entropy is contant in the core
→ disturbed core

SZ observations with NIKA

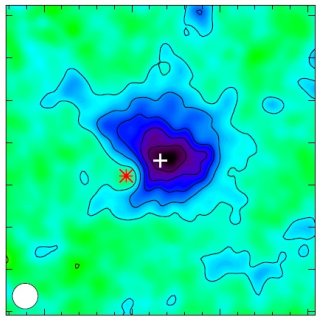
RXJ1347



well-known

R. Adam et al., A&A 2014

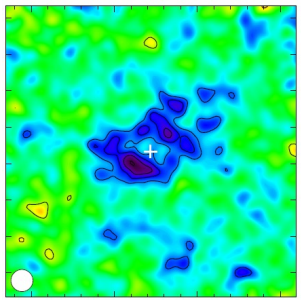
CLJ1227



high-z

R. Adam et al., A&A 2015

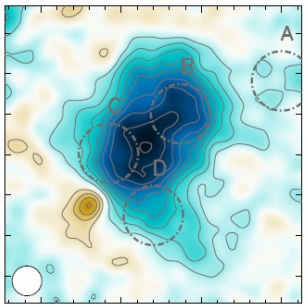
MACSJ1424



point-source removal

R. Adam et al., A&A 2016

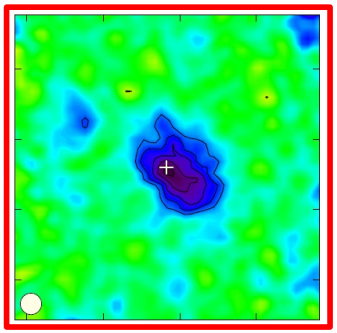
MACSJ0717



disturbed cluster

R. Adam et al., A&A 2017

PSZ1G045



Planck-discovered

F. Ruppin et al., A&A 2017