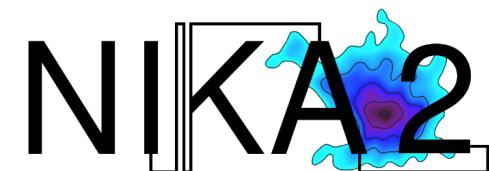


Cluster cosmology with the NIKA2 SZ Large Program

F. Mayet

on behalf of the NIKA2 Collaboration



Outline



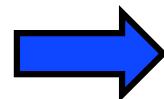
1. SZ Cluster cosmology
The need for high-resolution SZ observations
2. The NIKA2 SZ large program (2018-2023)
Follow-up of 45 Planck(ACT)-detected clusters
3. Observation of 2 clusters NIKA2
Impact of high-resolution SZ observations
F. Ruppin *et al.*, A&A 2018
F. Kéruzoré *et al.*, A&A 2020

SZ Cluster cosmology

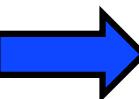


- Cosmology can be probed with **surveys** of clusters with **known masses**
→ Abundance of galaxy clusters with mass and redshift depends on **cosmological parameters**
- Cosmology with the Sunyaev-Zel'dovich (SZ) effect
 - SZ signal
 - is a mass proxy
 - is redshift independent
 - has a clear spectral signature
 - SZ can be used to **detect** a large numbers of clusters in CMB surveys (*Planck*, SPT, ACT...)

Cluster detection Mass calibration Number counts

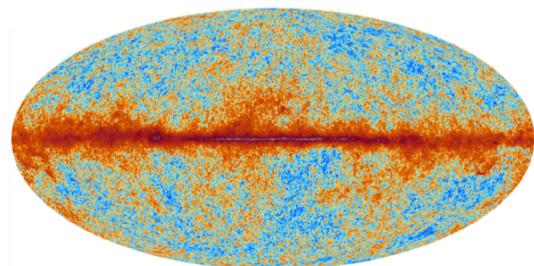


Mean pressure profile



Scaling relation

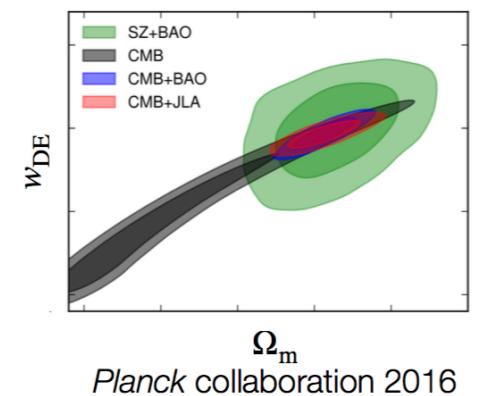
Mass function



Planck @ 143 GHz,
Planck collaboration 2018

Cluster	Obs. Y
#1	Y_1
#2	Y_2
#3	Y_3
#N	Y_N

Cluster	Mass M
#1	M_1
#2	M_2
#3	M_3
#N	M_N



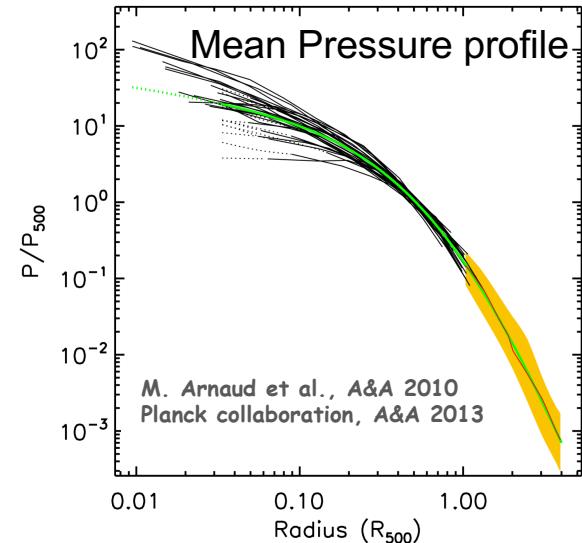
Planck collaboration 2016

Cluster cosmology - tools



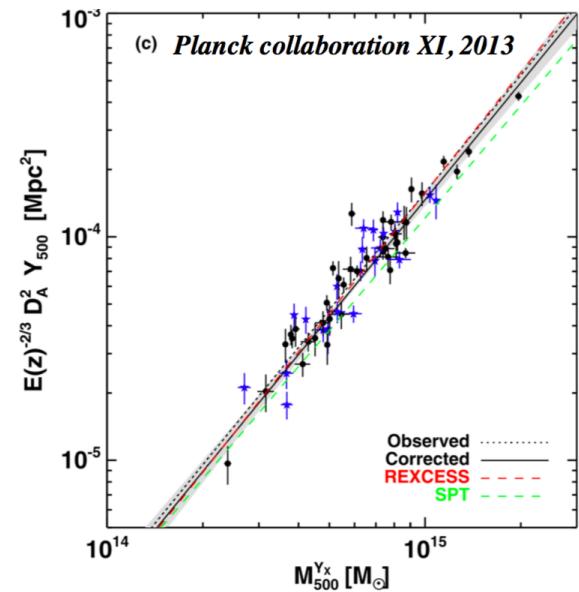
Mean pressure profile $\mathbb{P}(r)$

- Needed for SZ cluster detection J.B. Melin *et al.*, A&A 2006
- Self-similarity hypothesis
→ applied to the whole population
- So far, mostly measured at low-z with
 - low-resolution SZ
 - X-rays



SZ-mass scaling relation

- Needed to estimate the mass of each cluster in a survey
 - links the integrated SZ signal to the cluster mass
 - Usually calibrated with
 - weak lensing, Boquet *et al.* (SPT), A&A 2019
 - X-ray masses, Planck collaboration, A&A 2016
- applied to the whole population



Cluster cosmology – Hydrostatic mass



Hydrostatic mass

in the framework of the hydrostatic equilibrium hypothesis...

$P(r)$ Pressure profile (from SZ observation) $y_{SZ} \propto \int_{\text{LOS}} P_e d\ell$

$n(r)$ Density profile (from X-ray observation) $S_X \propto \frac{1}{(1+z)^4} \int n_e^2 \Lambda d\ell$

→ Hydrostatic mass profile

$$M_{\text{HSE}}(r) \propto \frac{r^2}{n(r)} \times \frac{dP(r)}{dr}$$

But unresolved SZ-surveys only measure **integrated quantities**

$$\text{SZ signal} \quad Y_{500} \propto \int_0^{R_{500}} P_e d^3 r$$

}

scaling relation

Cluster mass $M_{500} = M_{\text{HSE}}(R_{500})$

Cluster cosmology – cluster sample

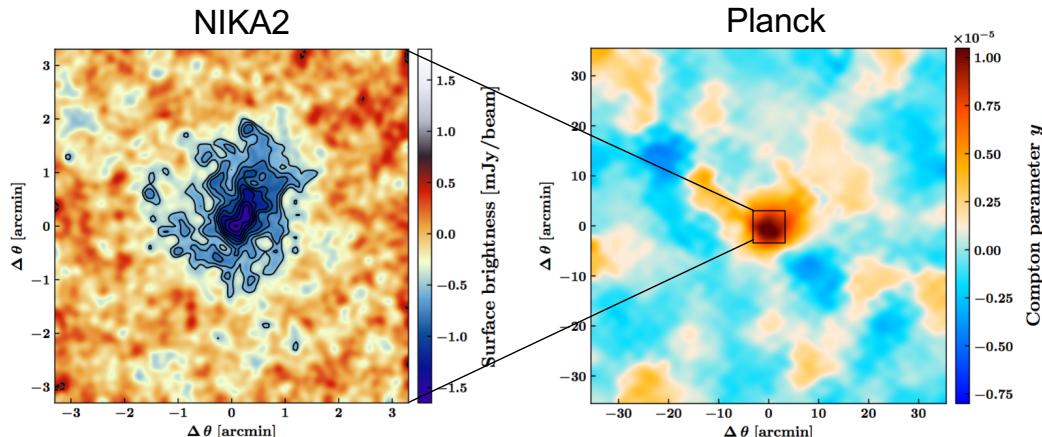


To assess results in SZ cluster cosmology

The scaling relation and the mean pressure profile must be studied with a **cluster sample**

Cluster sample must

- **be representative** of the whole population
- cover a wide range in mass up to high redshift ($z \sim 1$)
- be observed in SZ & X-ray (NIKA2 and XMM-Newton) with high resolution
→ maps, profiles and integrated quantities : Y_{500} , M_{HSE}



a disturbed cluster (MUSIC simulation)

Planck beam \approx NIKA2 field of view

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

F. Ruppin et al., A&A 2019

Detector wish list for SZ science

- High angular resolution
→ to resolve inner 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

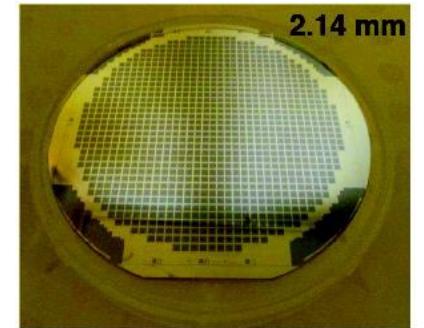
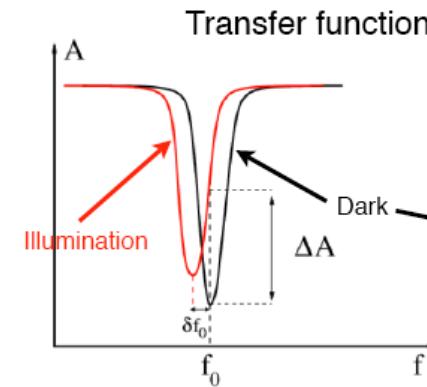
L. Perotto *et al.*, A&A 2020



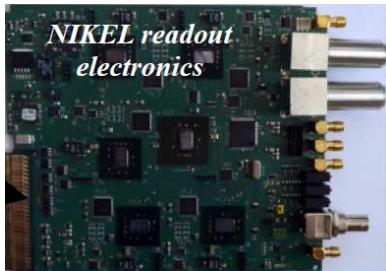
NIKA2

- KID-based camera
Kinetic Inductance Detectors
High quality factor superconducting resonators
Frequency shift proportional to the incoming optical power
- installed at the IRAM 30m telescope
- Operated at 150 mK
- Dual-band: 150 and 260 GHz (3 arrays)
- Wide field of view: 6.5 arcmin – 2466 valid detectors
- High angular resolution: 17.6 and 11.1 arcsec
- State-of the art sensitivity: 9 and 30 mJy.s^{1/2} (at null opacity)
→ high S/N observation of clusters in 2 to 15 hours

*These values are measured performance: see L. Perotto *et al.*, A&A 2020*



The NIKA2 camera



Readout electronics



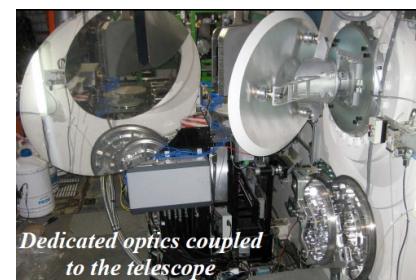
KID detector

The NIKA2 camera has been built by the **NIKA2 Collaboration**

- 14 laboratories
- 110 members of the collaboration



Dilution cryostat



Dedicated optics coupled to the telescope

IRAM 30-m telescope
at Pico Veleta (Spain)

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**



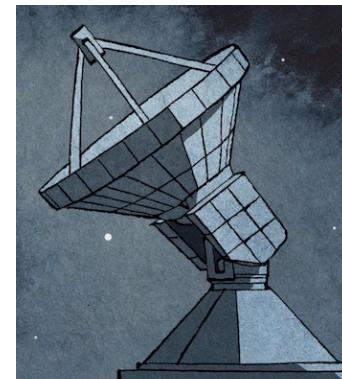
The NIKA2 Sunyaev Zel'dovich Large Program (LPSZ)

a follow-up of 45 Planck(ACT)-detected clusters

- One of the 5 Large Programs of the NIKA2 Guaranteed time
- 300 hours of observations to observe 45 clusters

PI: F. Mayet

coPI: L. Perotto



NIKA2 LPSZ: team



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Jose Alberto RUBINO MARTIN



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Charles ROMERO



Rémi ADAM



Alexandre BEELEN



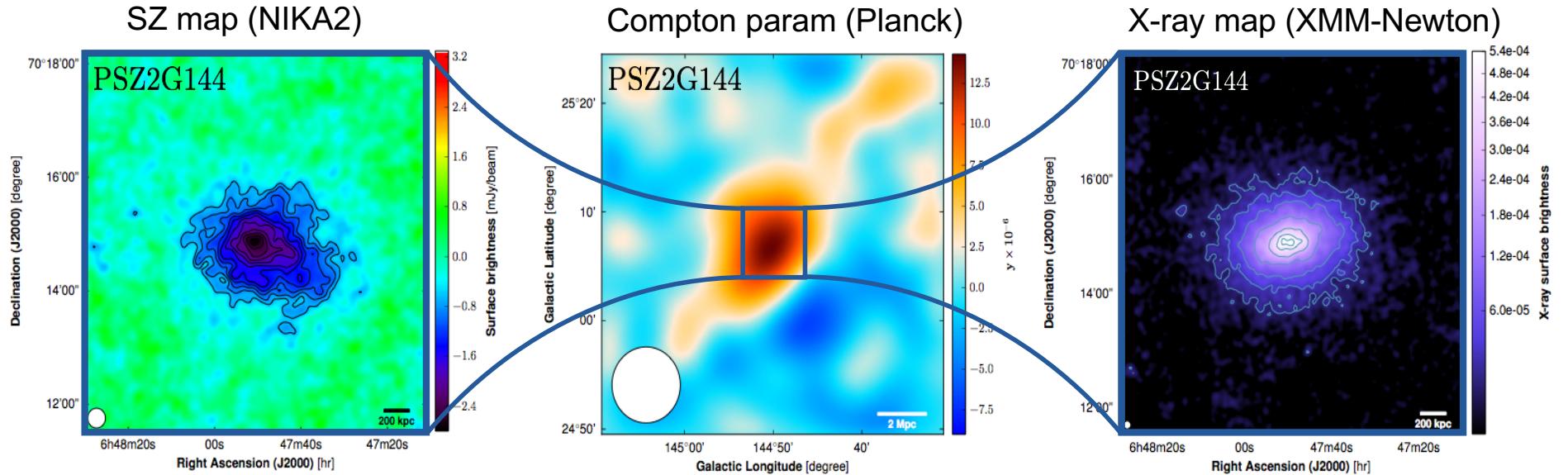
Nabila AGHANIM
Marian DOUSPIS

Chiara FERRARI

Thank you to the whole team for:

commissioning, SZ observations, NIKA2 pipeline, SZ pipeline, X-ray data, optical data, simulation, cosmological studies, ...

NIKA2 LPSZ: data & methods



- NIKA2+Planck → **Pressure profile** $P(r)$
 - XMM-Newton → **Density profile** $n(r)$
- thermodynamic profiles

Mass profile

$$M(r) \propto \frac{1}{n(r)} \times \frac{dP}{dr}$$



Cluster mass (M_{500})

Temperature profile

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

Entropy profile

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

NIKA2 LPSZ: products



for each cluster

- SZ & X-ray @ high angular resolution
- Thermodynamic profiles : P, n, M, ...
- Integrated quantities : R_{500} , Y_{500} , M_{500}



a cluster catalog

→ Multi-probe view of clusters

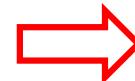
- SZ, X-ray, optical, radio data
- Hydrodynamical simulation (synthetic twin sample)

→ Information on: merging events, shocks, ...

→ study of induced-systematics

with the full sample

- Mean pressure profile
- Scaling relation



Tools for SZ cluster cosmology

in the range

- $z = 0.5 - 0.9$
- $M_{500} = (3 - 10) \times 10^{14} M_\odot$

NIKA2 LPSZ: cluster sample

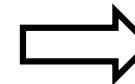
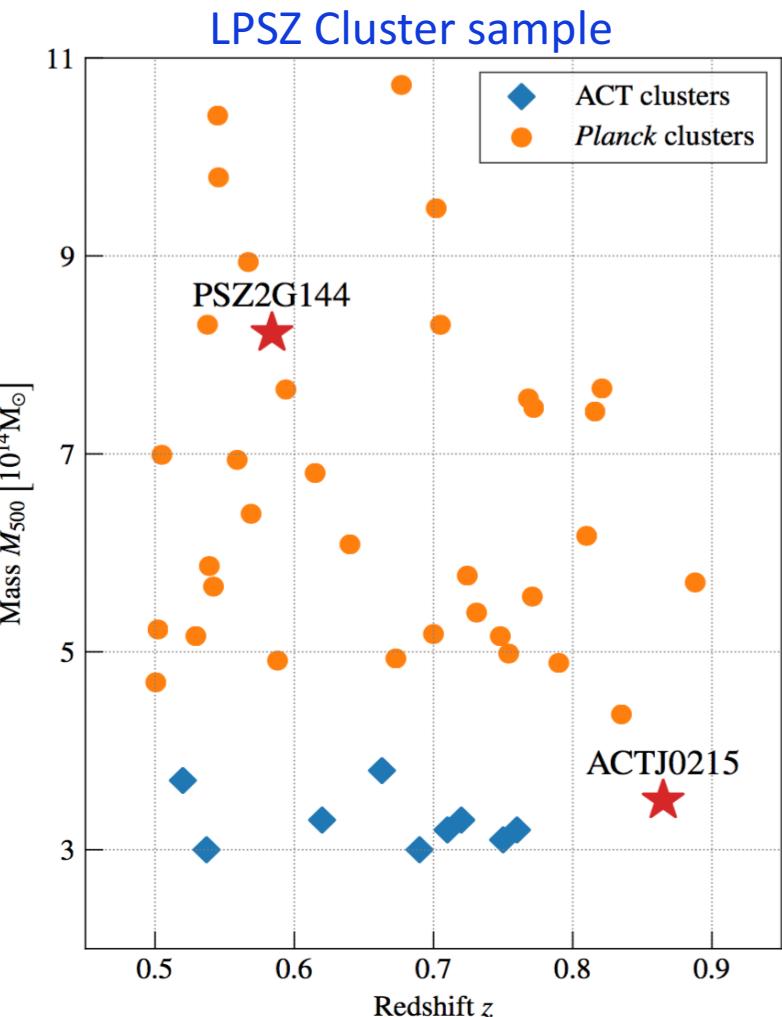


The LPSZ sample

- 45 SZ-selected clusters
 - 10 from ACT catalog
 - 35 from Planck catalog
- 38 with X-ray data
→XMM-Newton follow-up in progress
- 20 have been observed with NIKA2

Constraints

- the sample must be representative
- Warning:
- selection function
 - data analysis
 - data quality : S/N=3 on $P(r)$ @ R_{500}
 - some clusters look (in X-ray images)
 - very diffuse,
 - double/triple



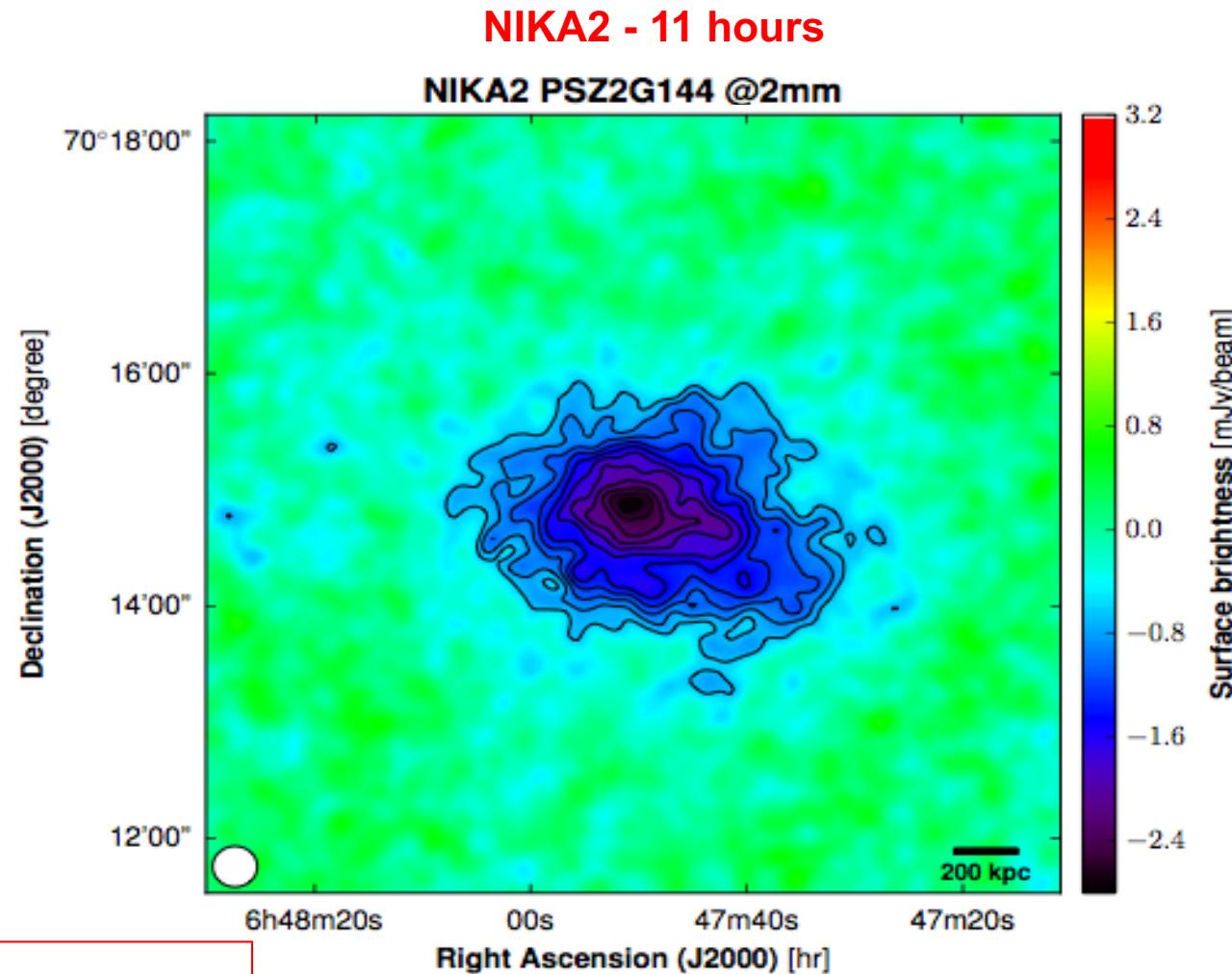
Study of two extreme clusters

First cluster observations with NIKA2

Impact of high-resolution observations

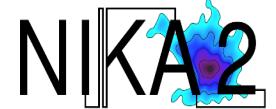
- First cluster observed with NIKA2: PSZ2G144
F. Ruppin *et al.*, A&A 2018
 - **High mass, low redshift** : $z = 0.58$ & $M_{500} = 8.22 \times 10^{14} M_\odot$ (Y proxy)
 - Long observation time (Science verification) → high SNR
- Second cluster: ACTJ0215
F. Kéruzoré *et al.*, A&A 2020
 - **Low mass, high redshift** : $z = 0.86$ & $M_{500} = 3.5 \times 10^{14} M_\odot$ (Y proxy)
 - Not detected by *Planck*
 - Standard LPSZ observations

First cluster observation – comparison with X-ray

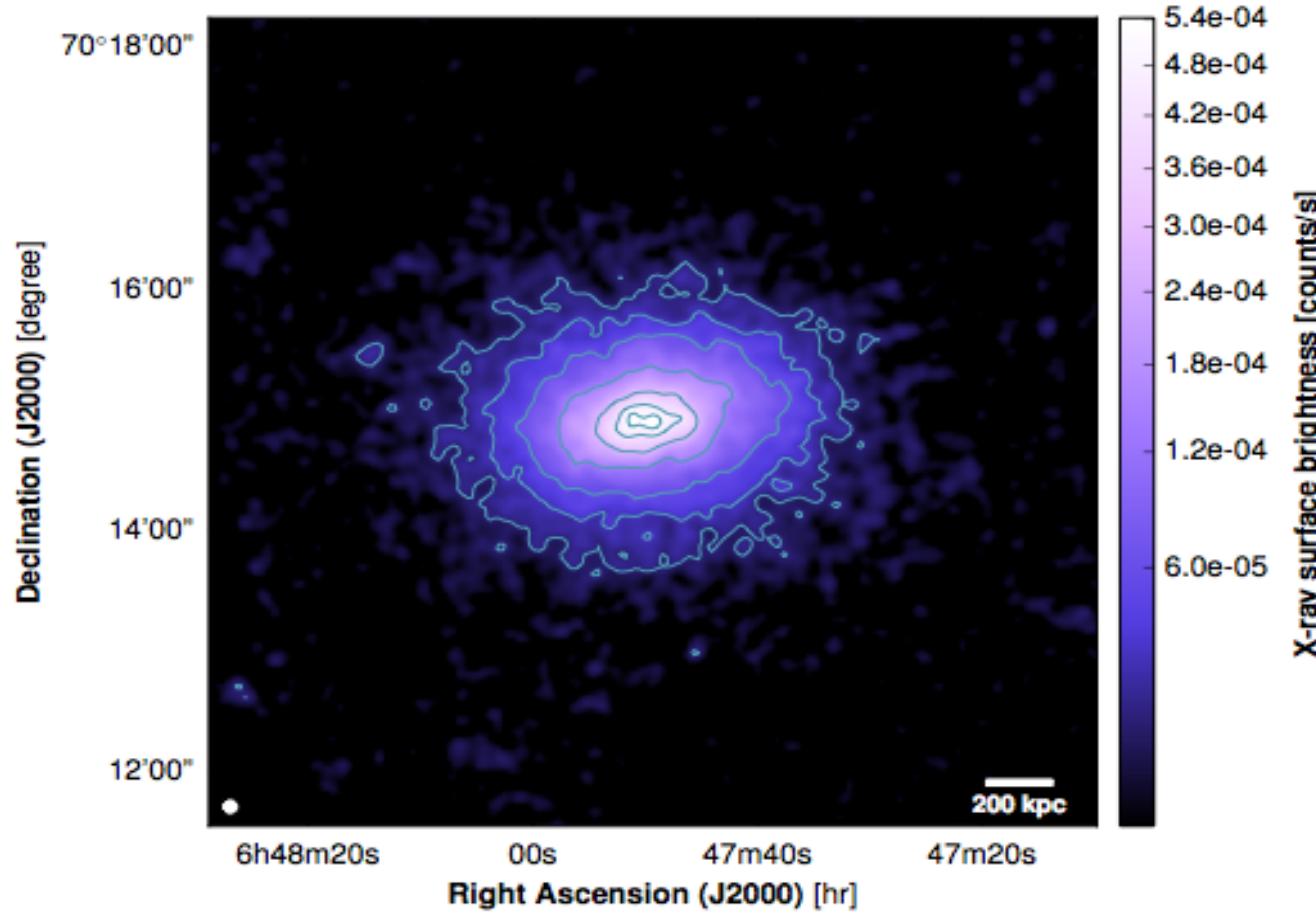


- SZ peak: 13.5σ
- SZ signal up to 1.4 arcmin
- Noise: $203 \mu\text{Jy}/\text{beam}$

First cluster observation – comparison with X-ray



XMM-Newton – 60 ks = 16.6 hours

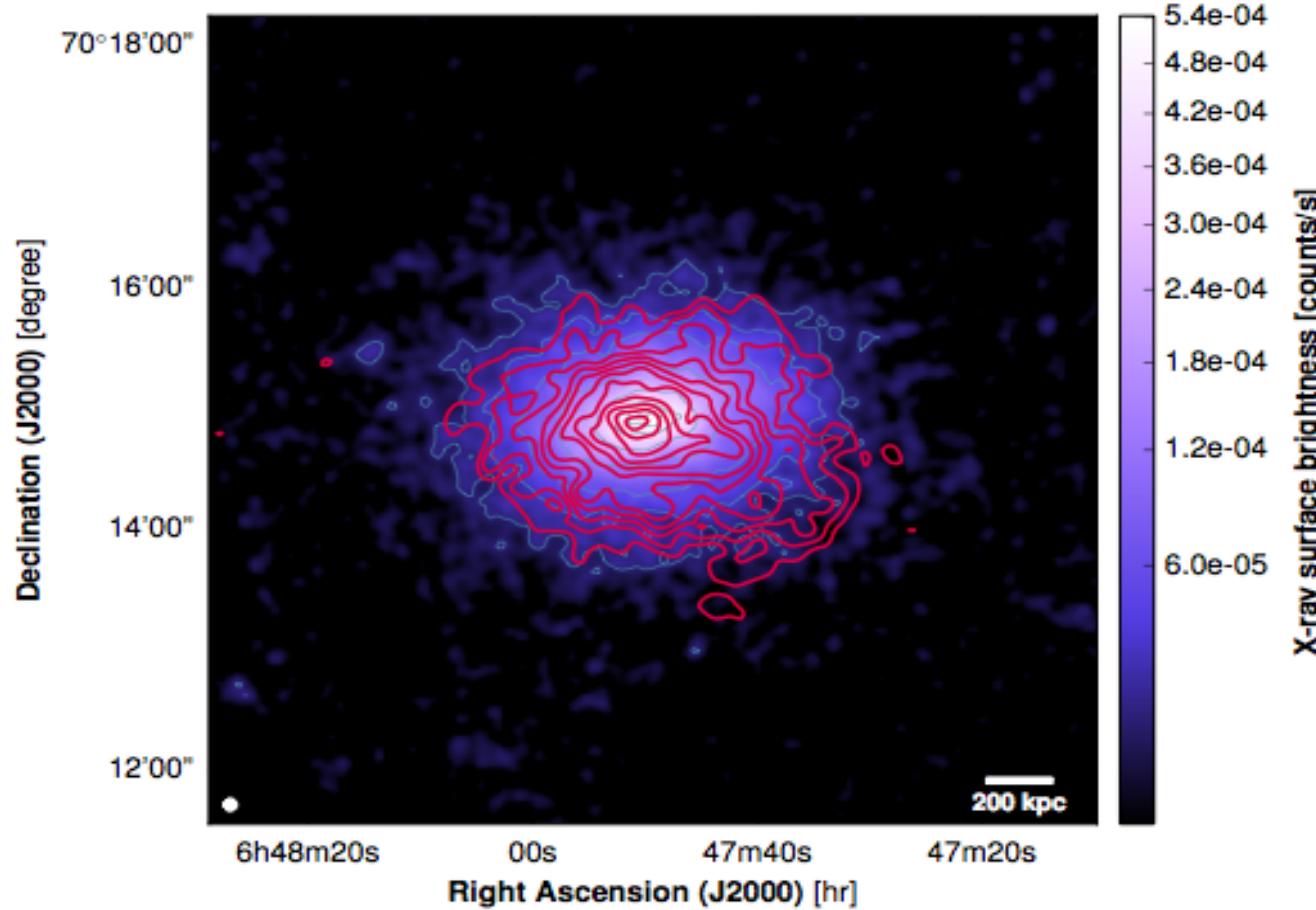


It is crucial to have good X-ray data
in order to perform a thermodynamic study (mass)

First cluster observation – comparison with X-ray

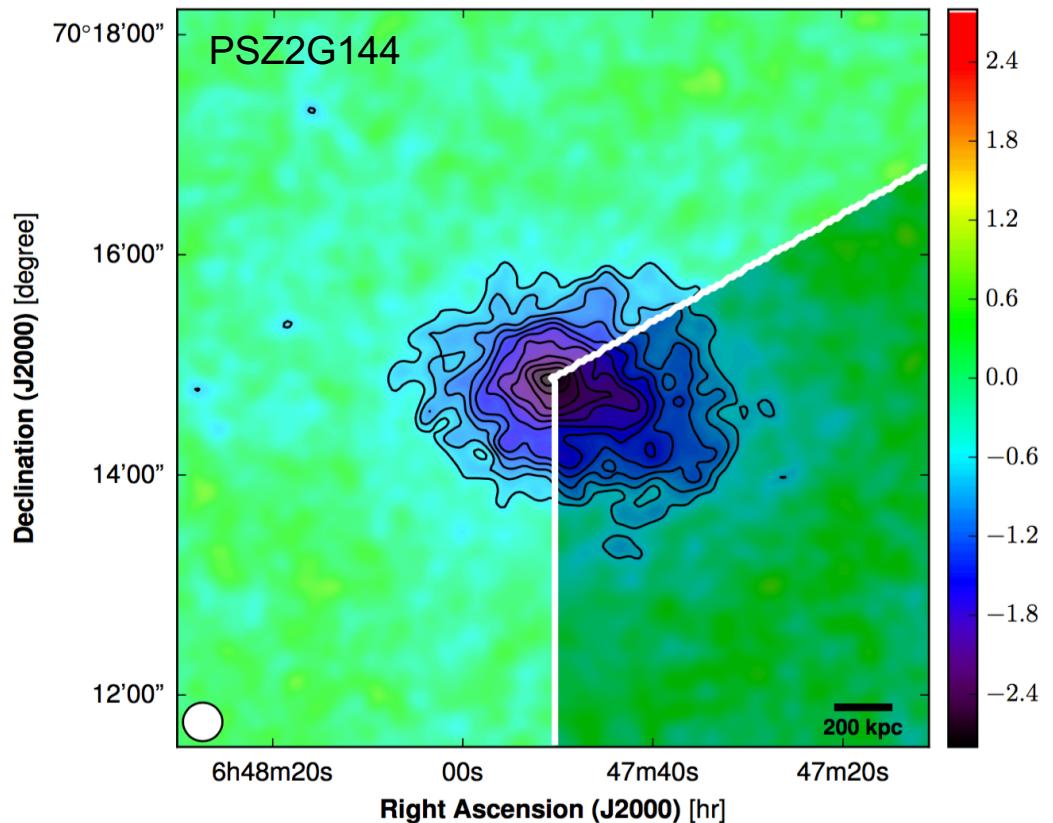


- map: XMM-Newton
- contours: NIKA2

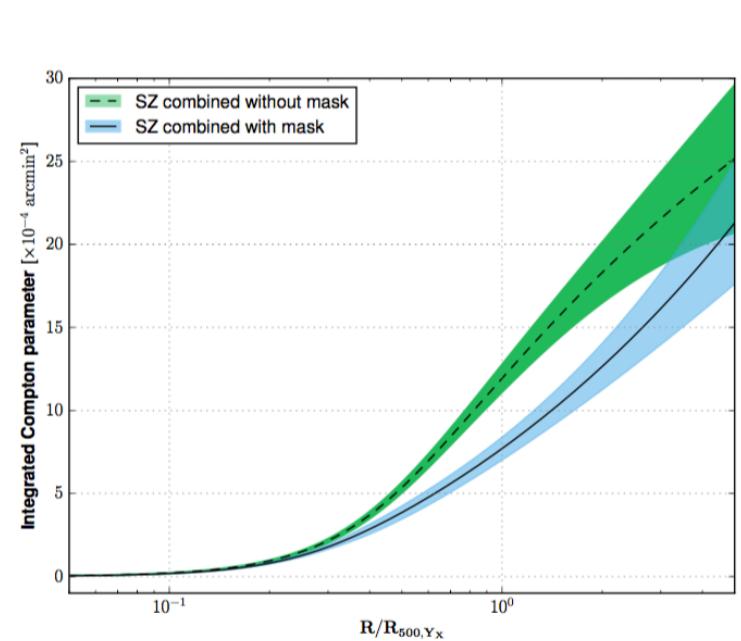


- NIKA2 and XMM extension are comparable
- For the first time, we have SZ and X-ray data at the same level

First cluster observation – overpressure region



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



Discovery of an overpressure region

- does impact integrated SZ signal and mass
- highlight the need for high-resolution observations

this cluster is not resolved by Planck

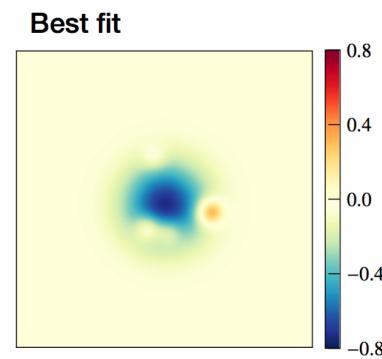
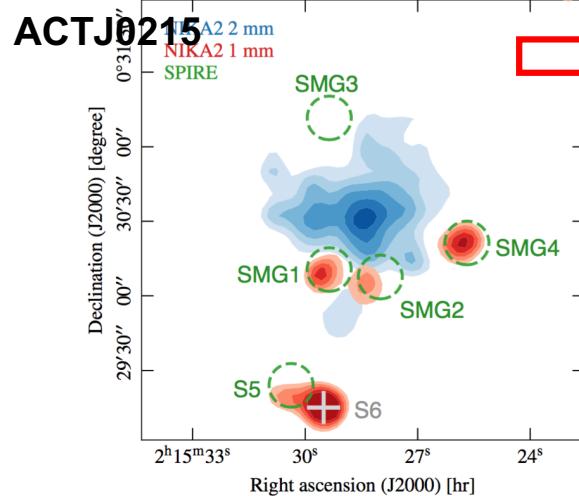
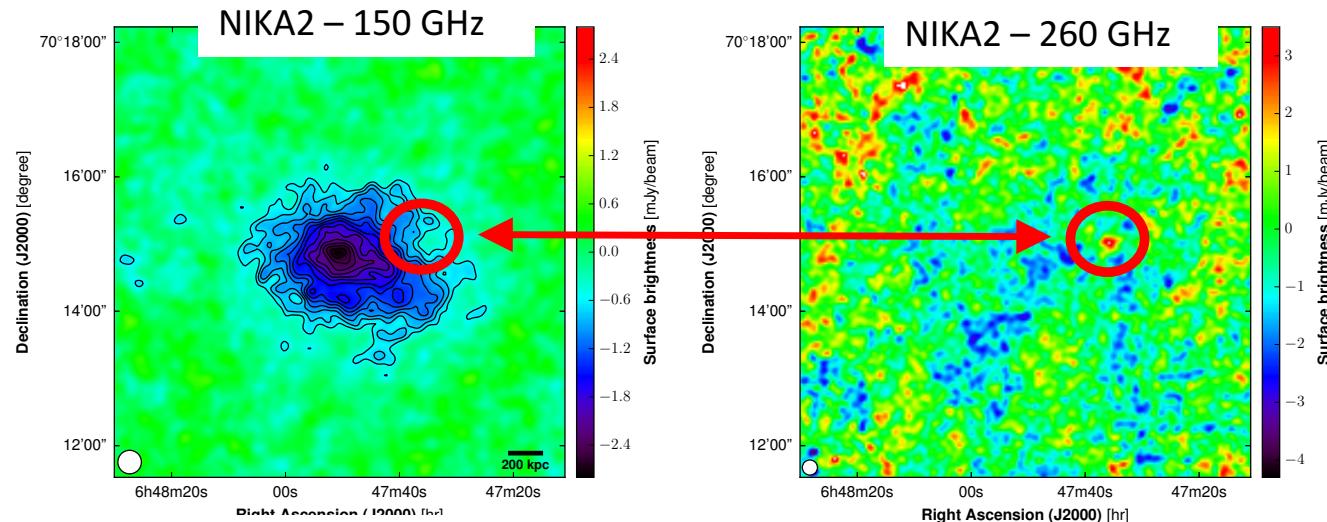


First cluster observations - maps

Dual-band observation

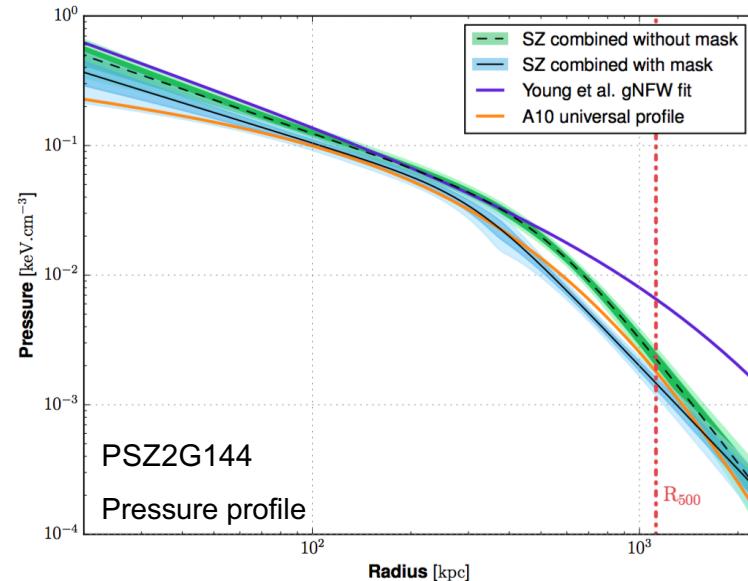
- no SZ signal is expected at 260 GHz (for this noise level)
- 260 GHz map is used to identify **point sources** that may compensate SZ signal at 150 GHz

PSZ2G144



MCMC analysis
 Model : NIKA2 150 GHz map
 $=$
 ICM SZ signal + **point source contamination**
 $(+ \text{noise})$

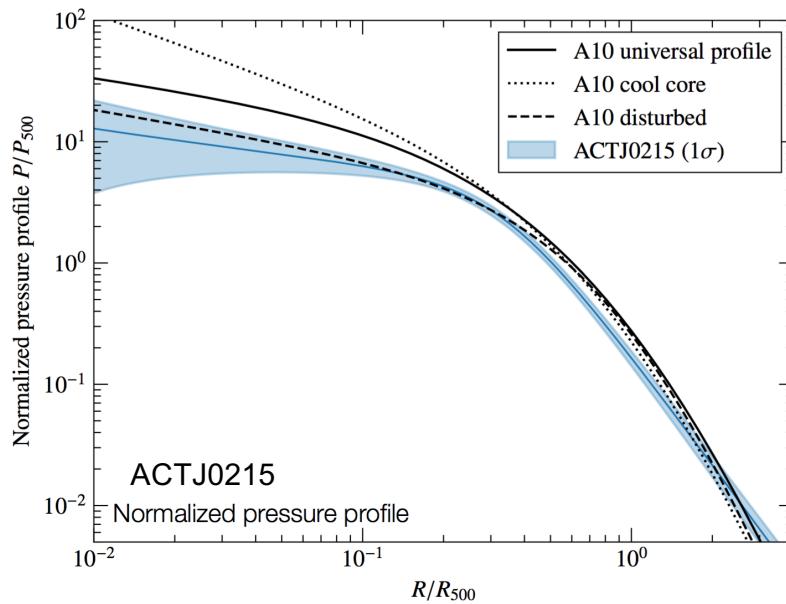
First cluster observations – pressure profiles



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

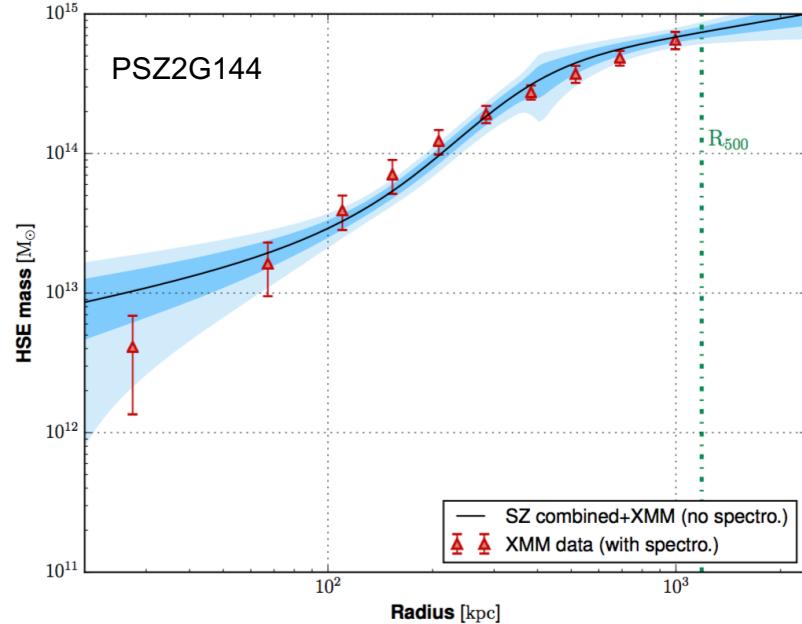
- significant differences w/wo overpressure (outer part)
 3σ between 500 and 900 kpc
- impact of the overpressure region
- comparison with A10 profile

M. Arnaud *et al.*, A&A 2010



- departure form universal profile
- compatible with disturbed A10 profile

First cluster observations – mass profiles

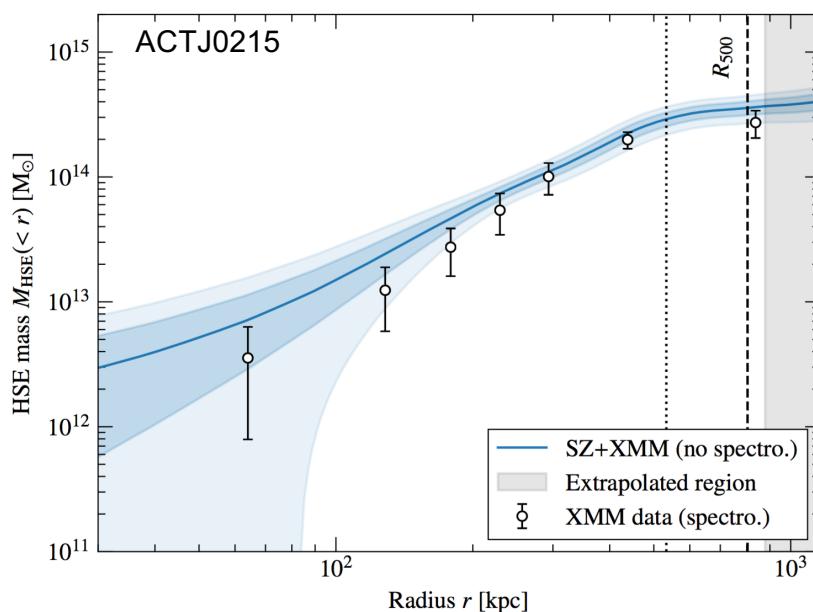


F. Ruppin *et al.*, A&A 2018

Mass profiles

- LPSZ : density (XMM) & Pressure (NIKA2)
- XMM-only : density & Temperature (XMM)

X-ray spectroscopy also provides the Temperature
 → Pressure directly from X-ray observations
 → Great ... but very time consuming at high redshift (prohibitive)



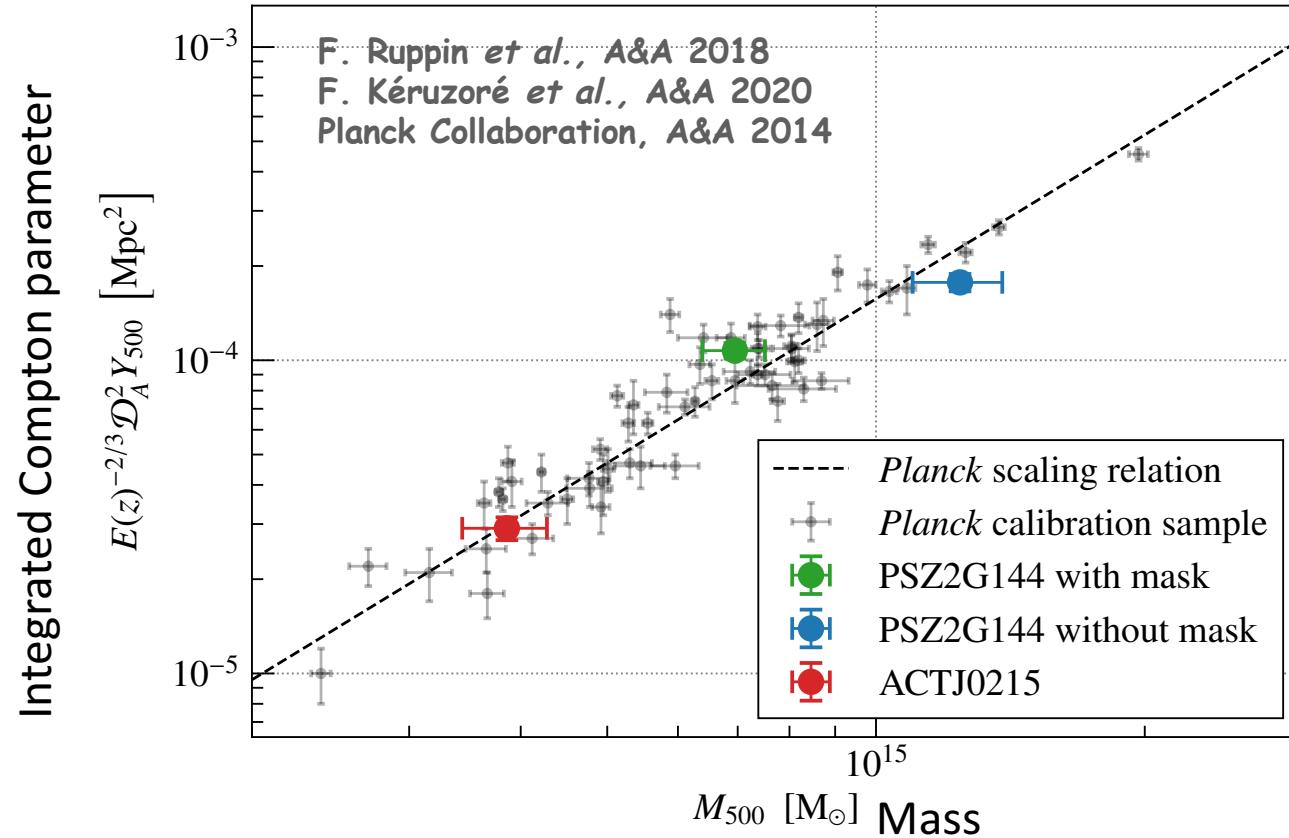
in both cases



- mass profiles are in good agreement
- estimation of M_{500}

However, no conclusions can be drawn with 2 clusters...

First cluster observations – scaling relation



- First comparisons of the NIKA2 clusters with the Planck scaling relation
- High-resolution SZ → study of systematics
→ biases & dispersions as a function of overpressure, relaxatin state, non-sphericity, ...

Conclusions



- High-resolution SZ observation of high-z clusters is a key issue for SZ cluster cosmology.
- NIKA2 SZ Large Program: 45 clusters to be observed in the forthcoming years.
 - SZ (NIKA2) and X-ray (XMM-Newton) will have
 - impact on SZ **cluster cosmology**
 - but also on **cluster physics**
- **First clusters observed with NIKA2**
 - Impact of high-resolution observations on cluster property estimates (mass)
 - First step towards a
 - NIKA2 mean pressure profile
 - NIKA2 scaling relation

{ in the range

- $z = 0.5 - 0.9$
- $M_{500} = (3 - 10) \times 10^{14} M_\odot$