Cluster cosmology
with the **NIKA2 SZ Large Program**

F. Mayet
on behalf of the NIKA2 Collaboration

Outline

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

3. The NIKA2 SZ large program (2018-2023)
   Follow-up of 45 Planck(ACT)-discovered clusters

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

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

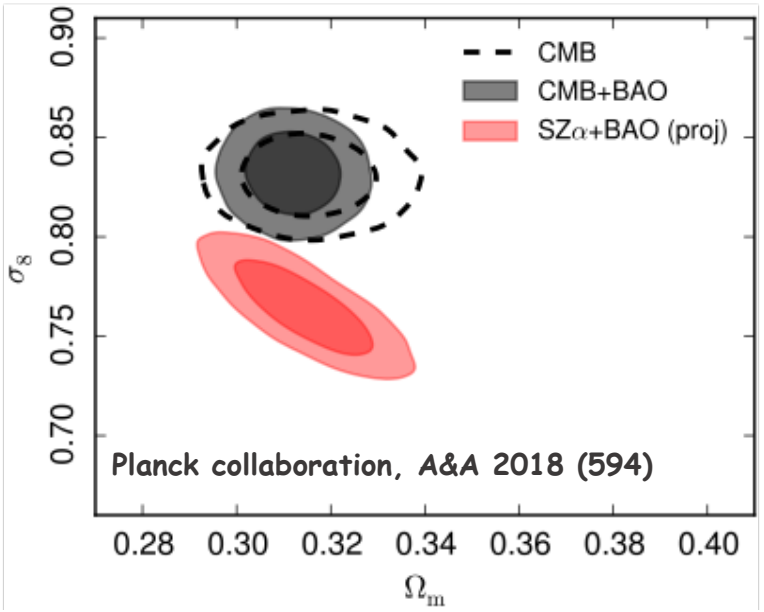
Cluster cosmology – Cosmological parameters

After Planck: high-precision cosmological era

However …

Tension between CMB and cluster results

- σ_8 Amplitude of the linear power spectrum @ 8 h^{-1} Mpc
- Ω_m Matter density



Explanation

- New physics ?

  large-scale structure formation, neutrinos, …

- Insufficient knowledge of cluster physics, *e.g.* a wrong estimate of
  - the hydrostatic bias parameter L. Salvati *et al.*, A&A 2018
  - **the scaling relation**
  - **the mean pressure profile** F. Ruppin *et al.*, arXiv:1905.05129

⇨ **a better understanding of cluster physics is needed**

Cluster cosmology - methods

Cosmological survey (Planck, ACT, SPT

→Two methods

1) **Cluster count** $\frac{d^2n}{dMdz}$

→ use a cosmological cluster sample (2000 clusters**)**

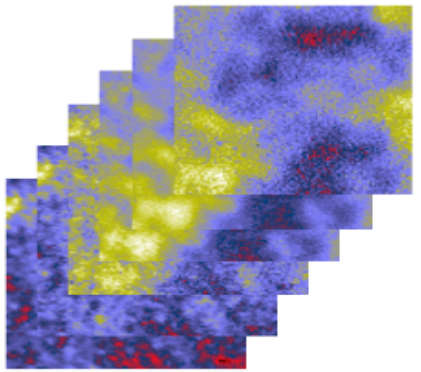
→ build a catalog (mass, redshift)

→ count the number of clusters per **redshift** and **mass** bin

→ compare with prediction of the cosmological model

Planck Collaboration, A&A 2011 & 2014

Planck maps



J.B. Melin *et al.*, A&A 2006

2) **SZ power spectrum** $C_\ell^{\rm SZ}$

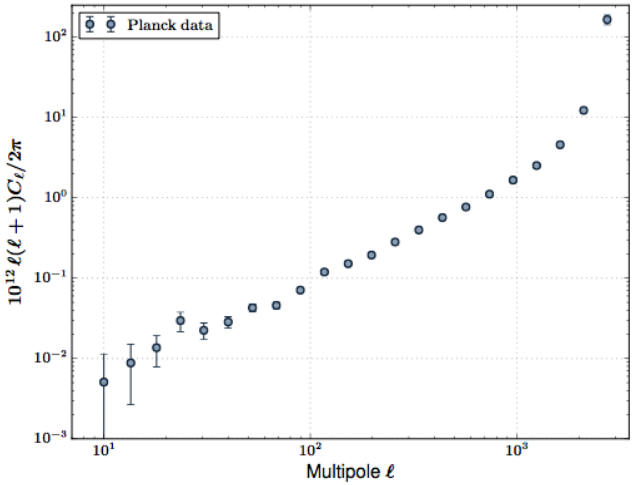
→ use a SZ map (full sky**)**

→ compute the power spectrum

→ compare with prediction of the cosmological model

Planck Collaboration, A&A 2014

SZ power spectrum



⇨ **two tools are needed**

Cluster cosmology - tools

Information needed for each cluster, *e.g.* cluster count $\frac{d^2n}{dMdz}$

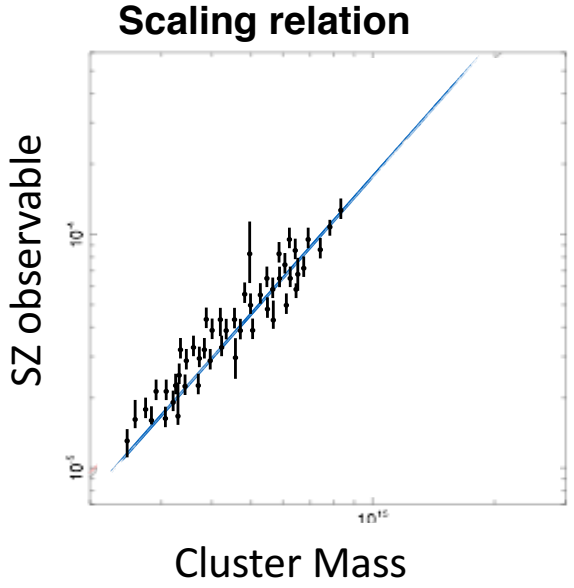
- redshift (optical follow-up)
- **cluster mass** … must be infered from the **SZ observable**

Integrated Compton parameter $$Y_{500} \propto \int_0^{R_{500}} P_e d^3r$$

R_{500} : radius of a sphere contening 500 times the critical density

Y_{500} is the only information for a cosmological survey

⇒ a **scaling relation** is needed to estimate the cluster mass



Cluster cosmology – scaling relation

The scaling relation must be **calibrated**

… with a cluster sample that is **representative** of the whole population

… for which both the observable (Y_{500}) and the mass is known

$$M_{\rm HSE}(r) \propto \frac{r^2}{n(r)} \times \frac{{\rm d}P(r)}{{\rm d}r}$$

with the hypothesis of HydroStatic Equilibrium

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

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

Nota Bene

X-ray spectrocopy also provides the Temperature

→ Pressure directly from X-ray observations $(P_e \propto n_e T_e)$

→ Great … but very time consuming at high redshift (prohibitive)

Useful for comparison when known

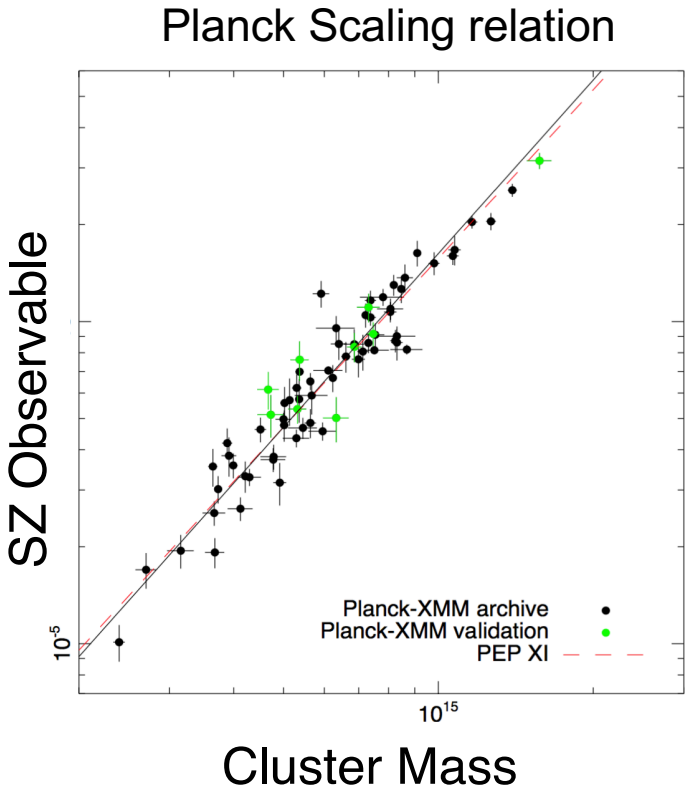
Cluster cosmology – scaling relation

Currently, the scaling relation is **calibrated** with

- 71 clusters
- Redshift below 0.45
- Mass from X-ray observation only (with spectroscopy)

Planck Collaboration et al., A&A 2016

  - → Planck scaling relation
  - → applied to the whole population



However, the scaling relation may **depend** on the

- redshift range
- dynamical state (merger)
- morphology (departure from sphericity)

To study this tool

- High-resolution observation of sample of clusters is needed
- →NIKA2 SZ Large Program

Cluster cosmology – mean pressure profile

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

→ another tool to exploit a (cosmological) cluster survey

For instance,

In cluster count analyses: $\mathbb{P}(r)$ is needed to measure the integrated SZ flux of each cluster

J.B. Melin et al., A&A 2006

Self-similarity

Once scaled (masse and radius), clusters of galaxies are supposed to be self-similar

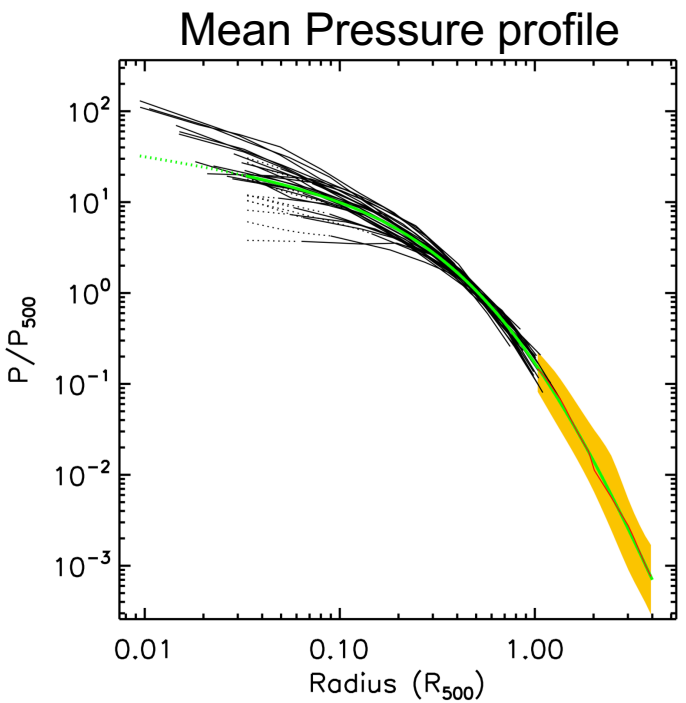
⇨ $\mathbb{P}(r)$ may be applied to the whole population

Universal Pressure Profile

⇨ $\mathbb{P}(r/R_{500}) = P_e(r)/P_{500}$

gNFW $$P_e(r) = \frac{P_0}{\left(\frac{r}{r_p}\right)^c + \left[1 + \left(\frac{r}{r_p}\right)^a\right]^{\frac{b-c}{a}}}$$

$P_0, a, b, c, \ldots$ parameters that defines $\mathbb{P}(r)$

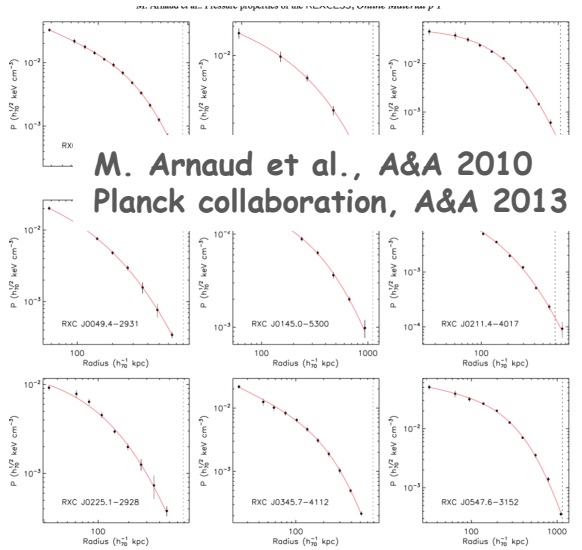


M. Arnaud et al., A&A 2010
Planck collaboration, A&A 2013

Cluster cosmology – mean pressure profile

Currently, the most widely used profile has been evaluated with

- 33 clusters
- @ low redshift (z<0.2) and high mass (>$10^{14}\,M_{\odot}$)
- Profiles obtained with X-ray information only (spectroscopy)



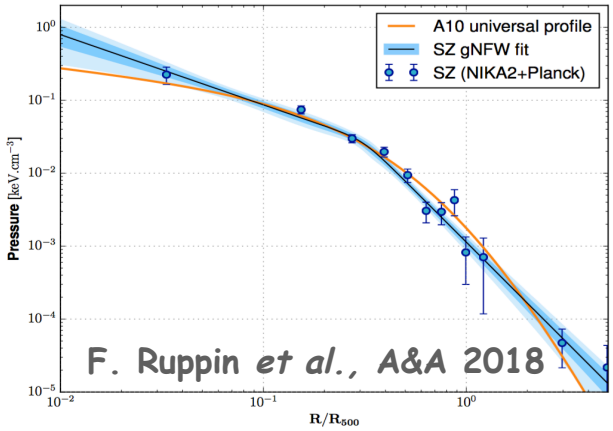
However, the mean pressure profile may **depend** on the

- redshift range
- dynamical state (merger→**overpressure**)
- morphology (departure from sphericity)

Validity of self-similarity

at high redshift ?

Departure from self-similarity ?



To study this tool

- High-resolution observation of sample of clusters is needed
- →NIKA2 SZ Large Program

Cluster cosmology – conclusion

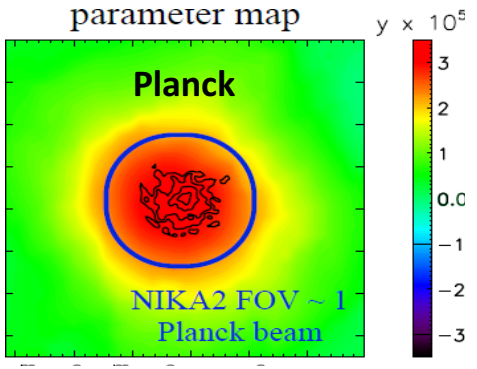
To assess results in cluster cosmology

The scaling relation and the mean pressure profile
must be studied with a
cluster sample covering
a wide range in mass up to high redshift (z~1)

High-resolution SZ observations are needed
to study the intra-cluster medium:

- dynamical state (merger)
- morphology (departure from sphericity)

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



Planck beam = NIKA2 field of view

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

⇨ NIKA2

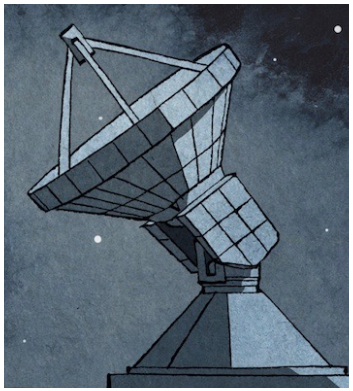
The NIKA2 SZ large program (2018-2023)

a follow-up of 45 Planck-discovered 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 SZ LP: team

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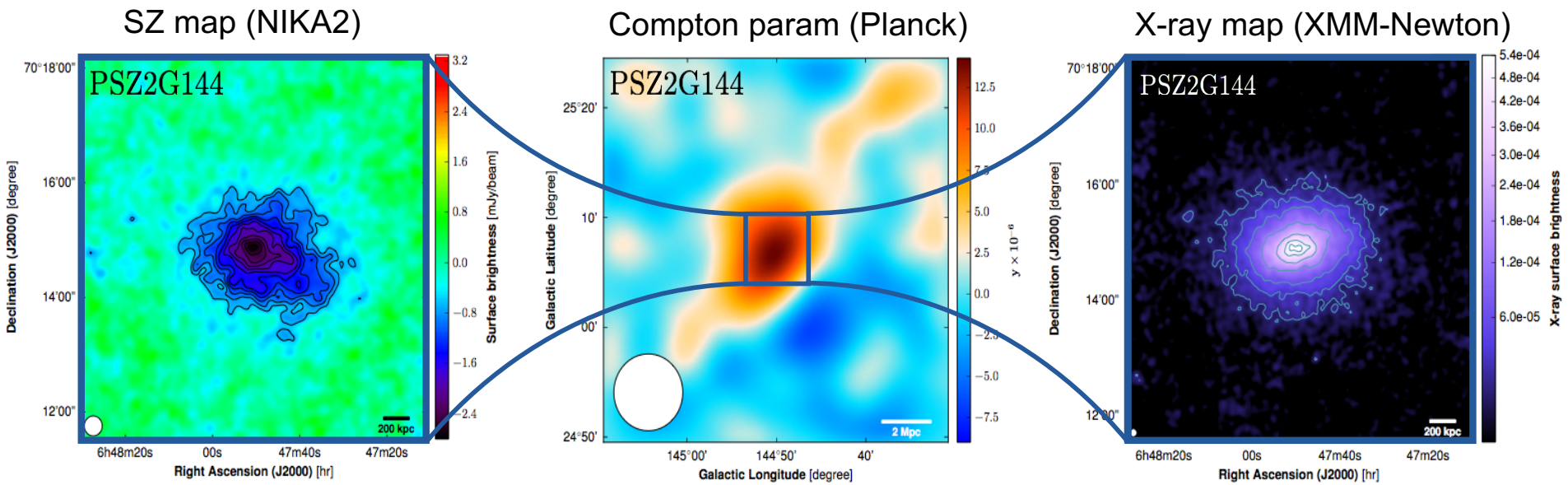
Thank you to the whole team for:

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

NIKA2 SZ LP: data & methods



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

} thermodynamic profiles

Mass profile $$M(r) \propto \frac{1}{n(r)} \times \frac{\mathrm{d}P}{\mathrm{d}r}$$ ⇒ **Cluster mass (M_{500})**

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

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

NIKA2 SZ LP: SZ & X-ray synergy

High-resolution SZ observations must be combined with X-ray observations

→ thermodynamic studies

- Profiles: Pressure, Density, Mass, Entropy
- Integrated quantities: R_{500}, Y_{500}, M_{500}

→ **LPSZ products**

→ Multi-probe view of clusters

- SZ, X-ray, optical, radio data
- N-body simulation

→ **Information on: merging events, shocks, …**

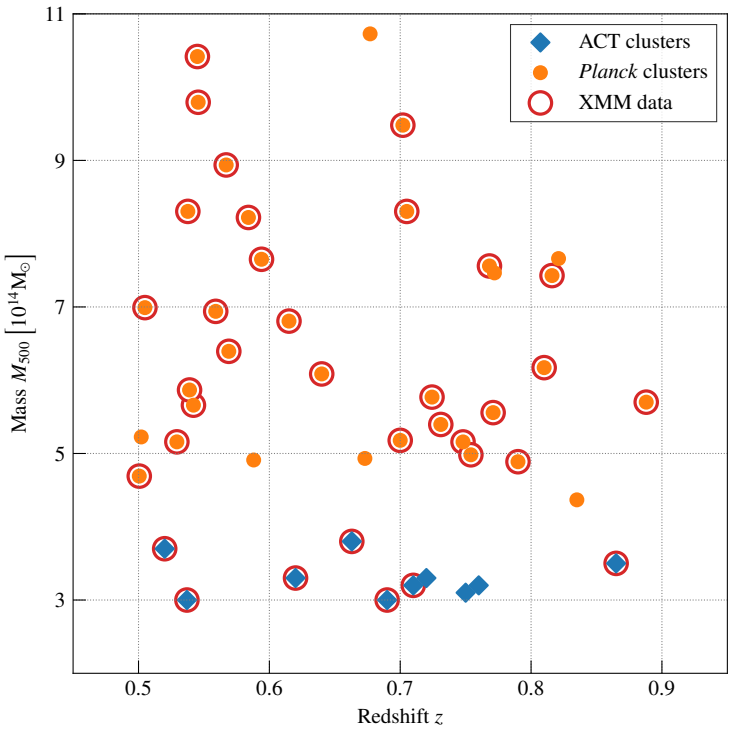
⇨ NIKA2 LPSZ requires a synergy between X-ray and SZ and also optical data, simulation, …

NIKA2 SZ LP: sample

The LPSZ sample

- 45 SZ-selected clusters
  - 10 from ACT catalog
  - 35 from Planck catalog
- 38 with X-ray data

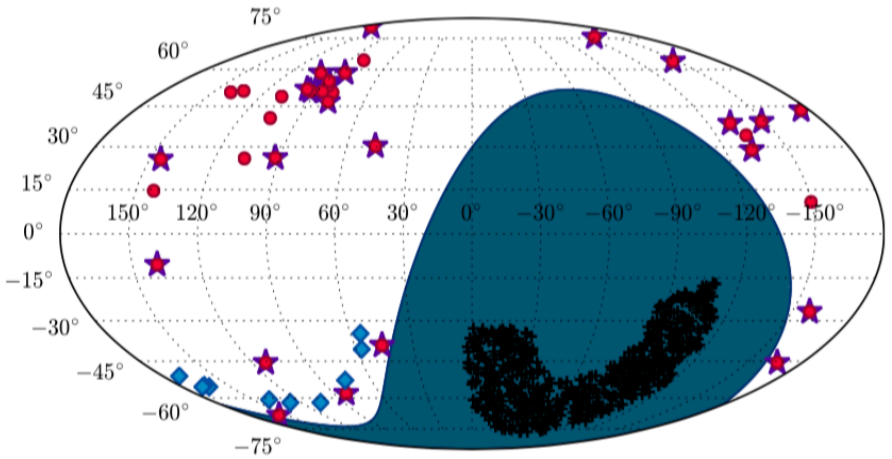
  →XMM-Newton follow-up in progress
- 19 have been observed with NIKA2



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

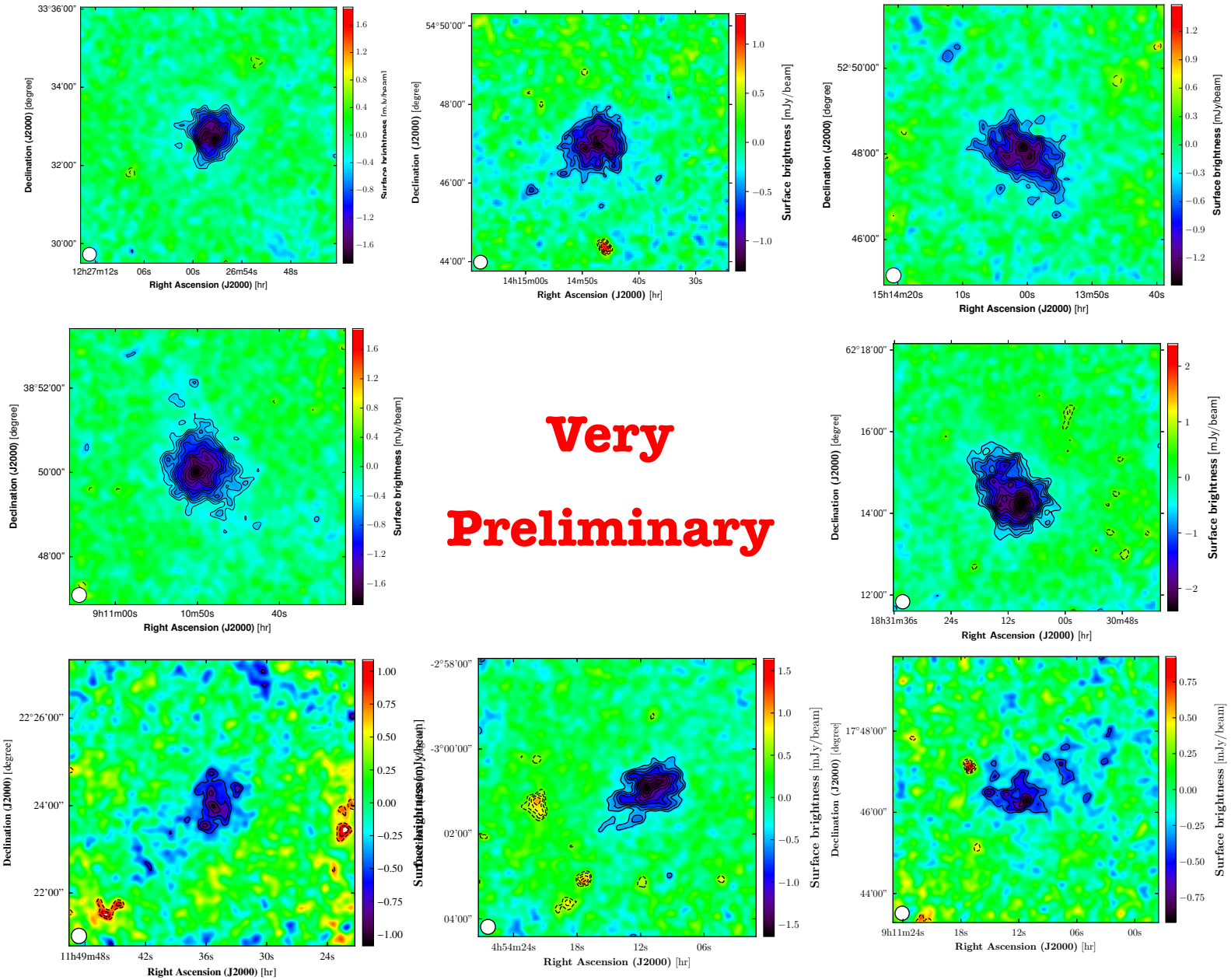


from F. Ruppin PhD thesis

NIKA2 SZ LP: status

Bin	0.5-0.7	0.7-0.9
5 (high mass)	PSZ2 G155.27-68.42 PSZ2 G111.61-45.71 PSZ2 G228.16+75.20 PSZ2 G209.79+10.23	~~PSZ2 G138.61-10.84~~
4	PSZ2 G183.90+42.99 PSZ2 G211.21+38.66 PSZ2 G045.32-38.46 PSZ2 G144.83+25.11 PSZ2 G201.50-27.31	PSZ2 G091.83+26.11 ~~PSZ1 G140.10+50.09~~ ~~PSZ1 G224.73+33.65~~ PSZ2 G141.77+14.19 PSZ1 G080.66-57.87
3	PSZ2 G212.44+63.19 PSZ2 G094.56+51.03 PSZ2 G193.31-46.13 PSZ2 G046.13+30.72 PSZ2 G099.86+58.45	PSZ2 G084.10+58.72 PSZ2 G086.93+53.18 PSZ2 G160.83+81.66 PSZ1 G226.65+28.43 PLCK G227.99+38.11
2	PSZ2 G081.02+50.57 ~~PSZ2 G106.15+25.75~~ PSZ2 G108.27+48.66 PSZ2 G133.59+50.68 PSZ2 G080.64+64.31	PSZ2 G104.74+40.42 PLCK G079.95+46.96 PSZ2 G088.98+55.07 PSZ2 G087.39+50.92 PSZ2 G097.52+51.70
1 (low mass)	ACT-CL J0219.8+0022 ACT-CL J2152.9-0114 ACT-CL J0240.0+0116 ACT-CL J2302.5+0002 ACT-CL J0223.1-0056	ACT-CL J0018.2-0022 ACT-CL J0058.0+0030 ACT-CL J2130.1+0045 ACT-CL J0119.9+0055 ACT-CL J0215.4+0030

NIKA2 SZ LP: very first maps



NIKA2 SZ LP: products

- **Products**
  - SZ maps @ high angular resolution
  - Thermodynamic profiles
  - Integrated quantities Y_{500}, M_{500}

  } for each cluster

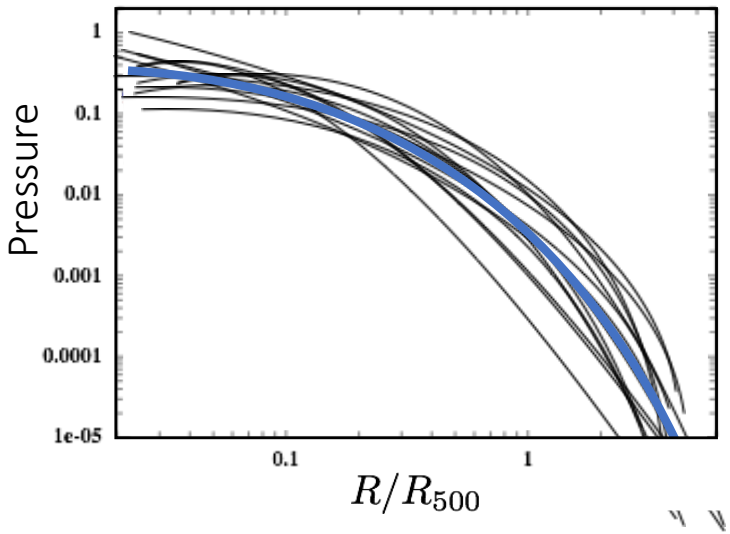
⇨ **A cluster catalog**

  - **Mean pressure profile**
  - **Scaling relation** $Y_{500} - M_{500}$

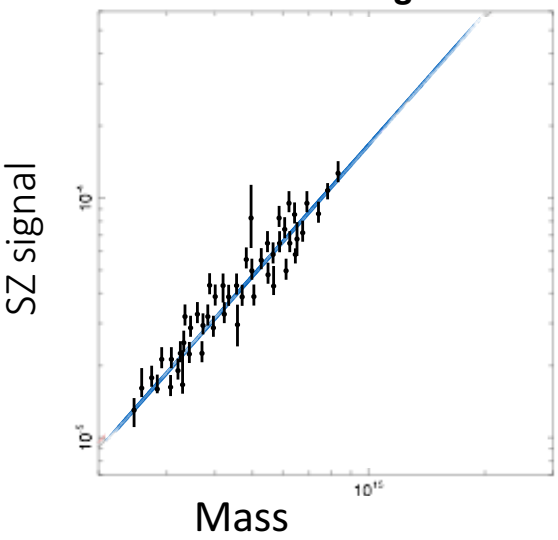
  } with the full sample

⇨ **Tools for cluster cosmology**

NIKA2 mean Pressure profile



NIKA2 scaling relation

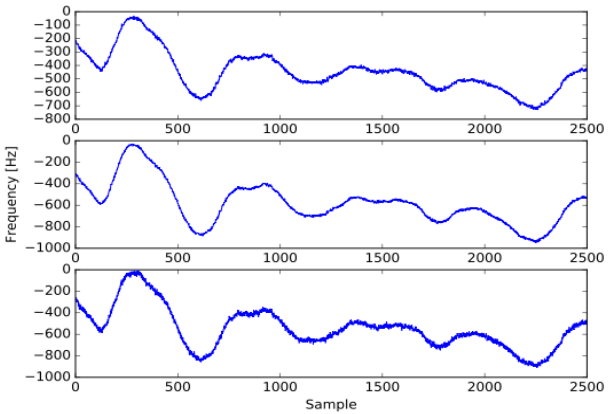


⇨ **Re-analyze cosmological survey (Planck)**

NIKA2 SZ LP: pipeline

slide from F. Ruppin PhD thesis

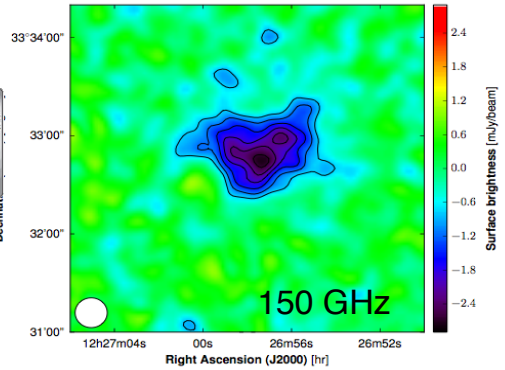
NIKA2 raw data



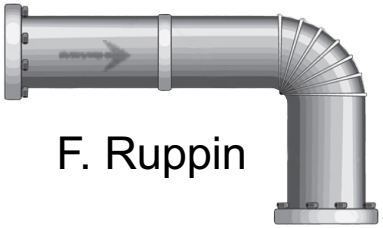
NIKA2 pipeline

(NIKA2 collab.)

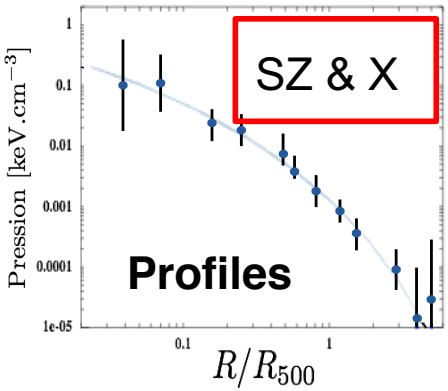
SZ map



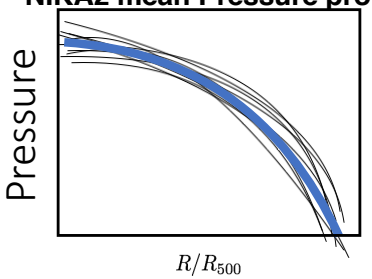
SZ pipeline



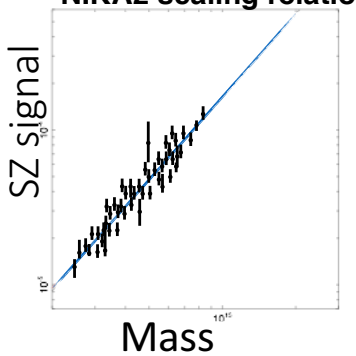
F. Ruppin



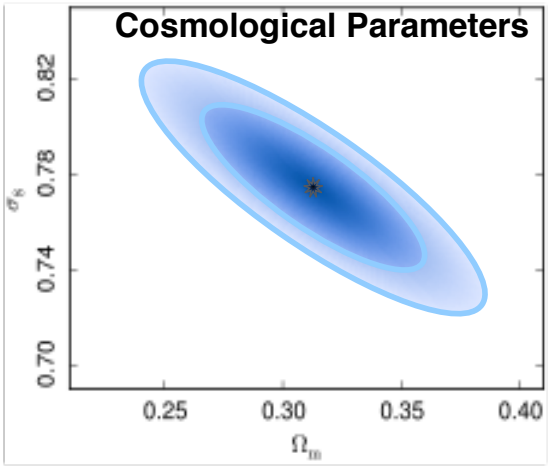
NIKA2 mean Pressure profile

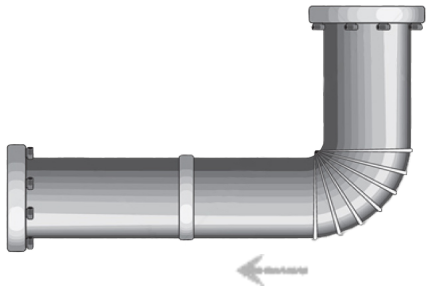


NIKA2 scaling relation



Cosmology





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

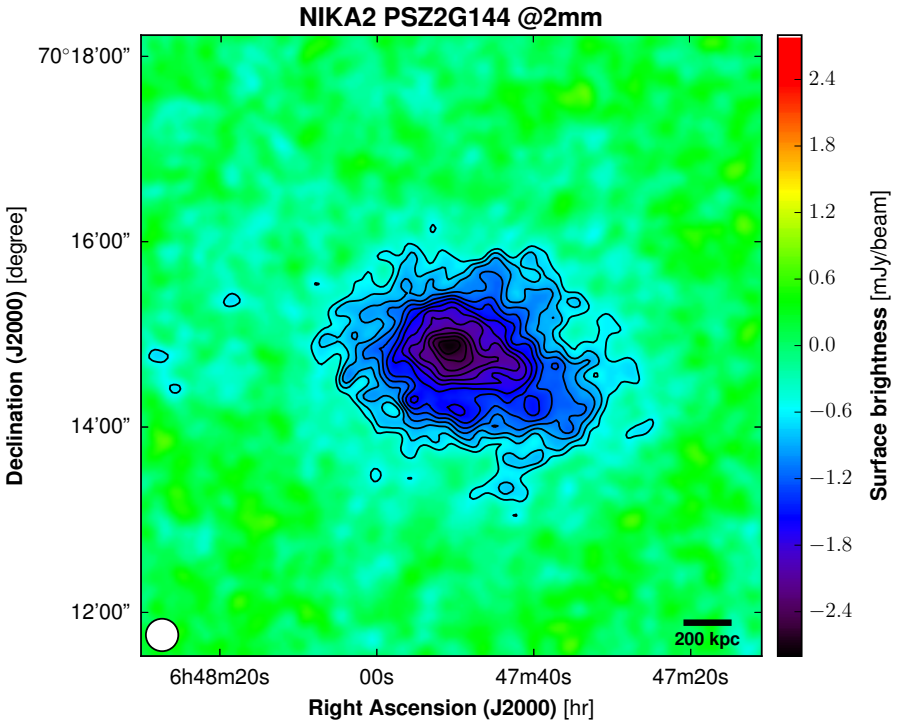
- PSZ2G144: a cluster from the NIKA2 LP sample (Planck catalogue)
- z = 0.58
- $M_{500} = 8.22 \times 10^{14} M_{\odot}$ (Y proxy)
- X-ray data: deep XMM-*Newton* exposure (~ 60 ksec) :
  - density (photon count)
  - temperature (spectroscopy)

(time consuming)

Observations in April 2017

- Effective observation time: 11 hours *(5.5 times more than requested) – Science verification*
- Mean opacity : 0.3 @ 2mm *(bad weather)*

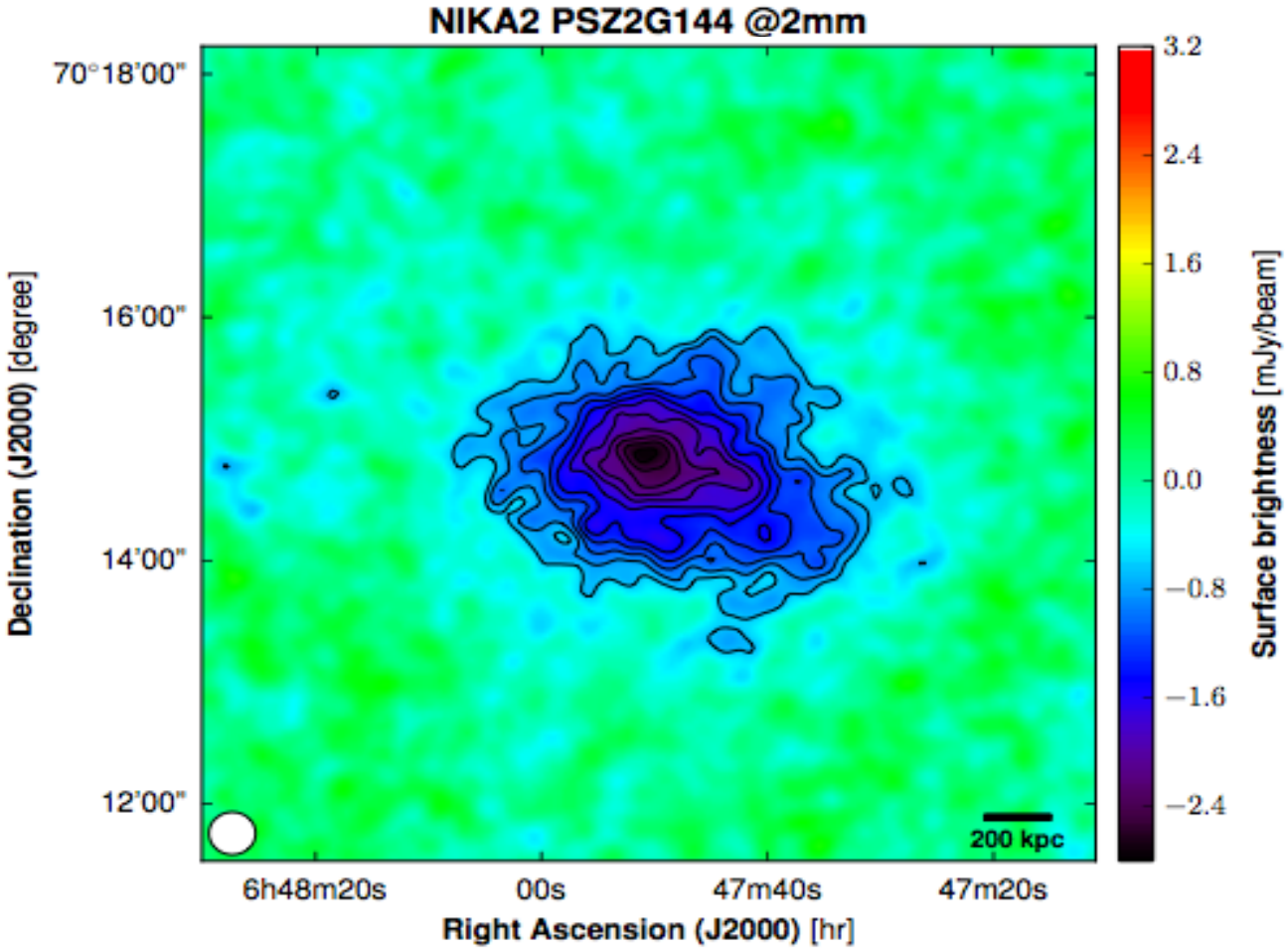
NIKA2 – 150 GHz



- SZ peak: 13.5σ
- SZ signal up to 1.4 arcmin
- Noise: 203 μJy/beam

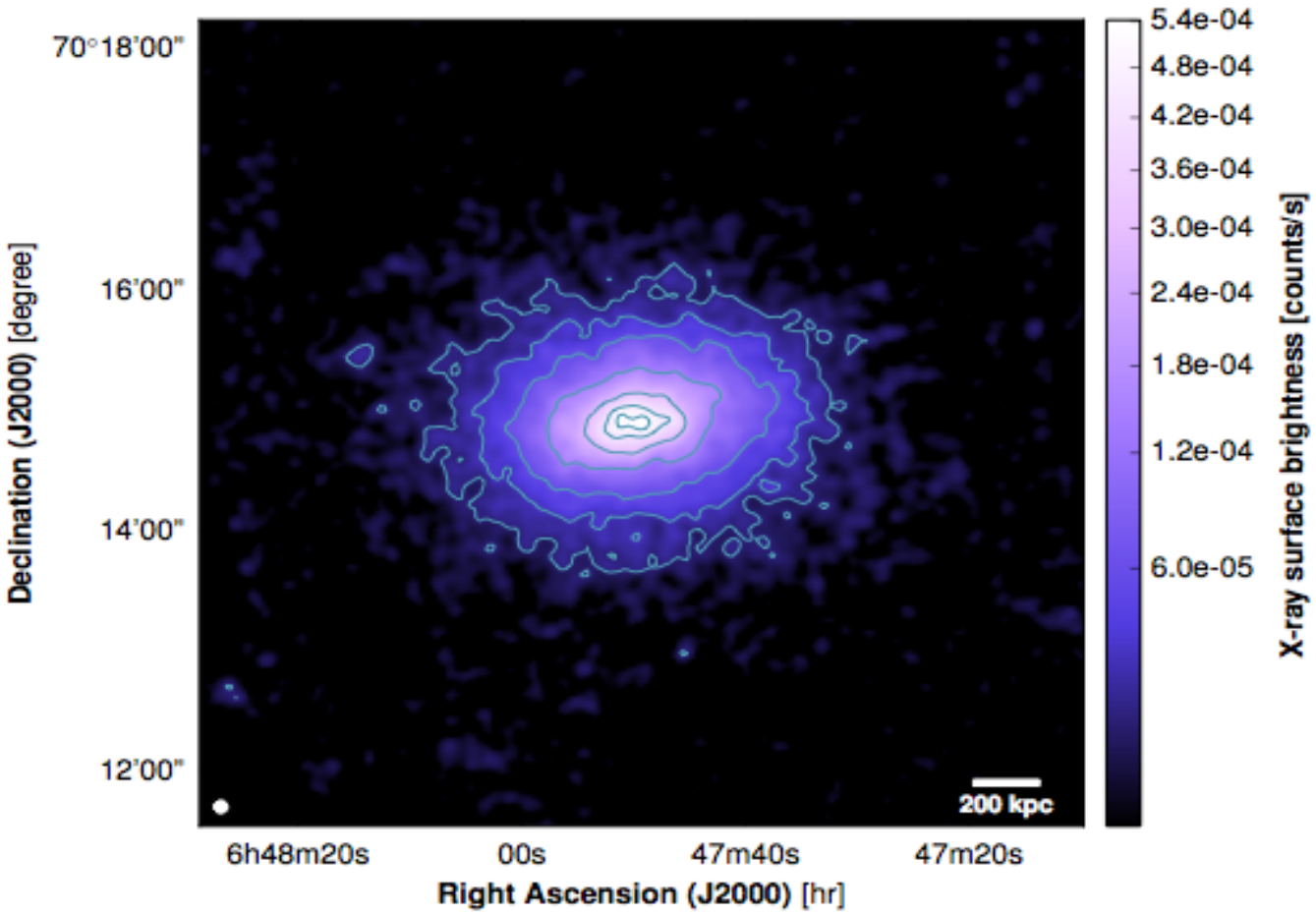
First cluster observation – comparison with X-ray

NIKA2 - 11 hours



First cluster observation – comparison with X-ray

XMM-Newton – 60 ks = 16.6 hours

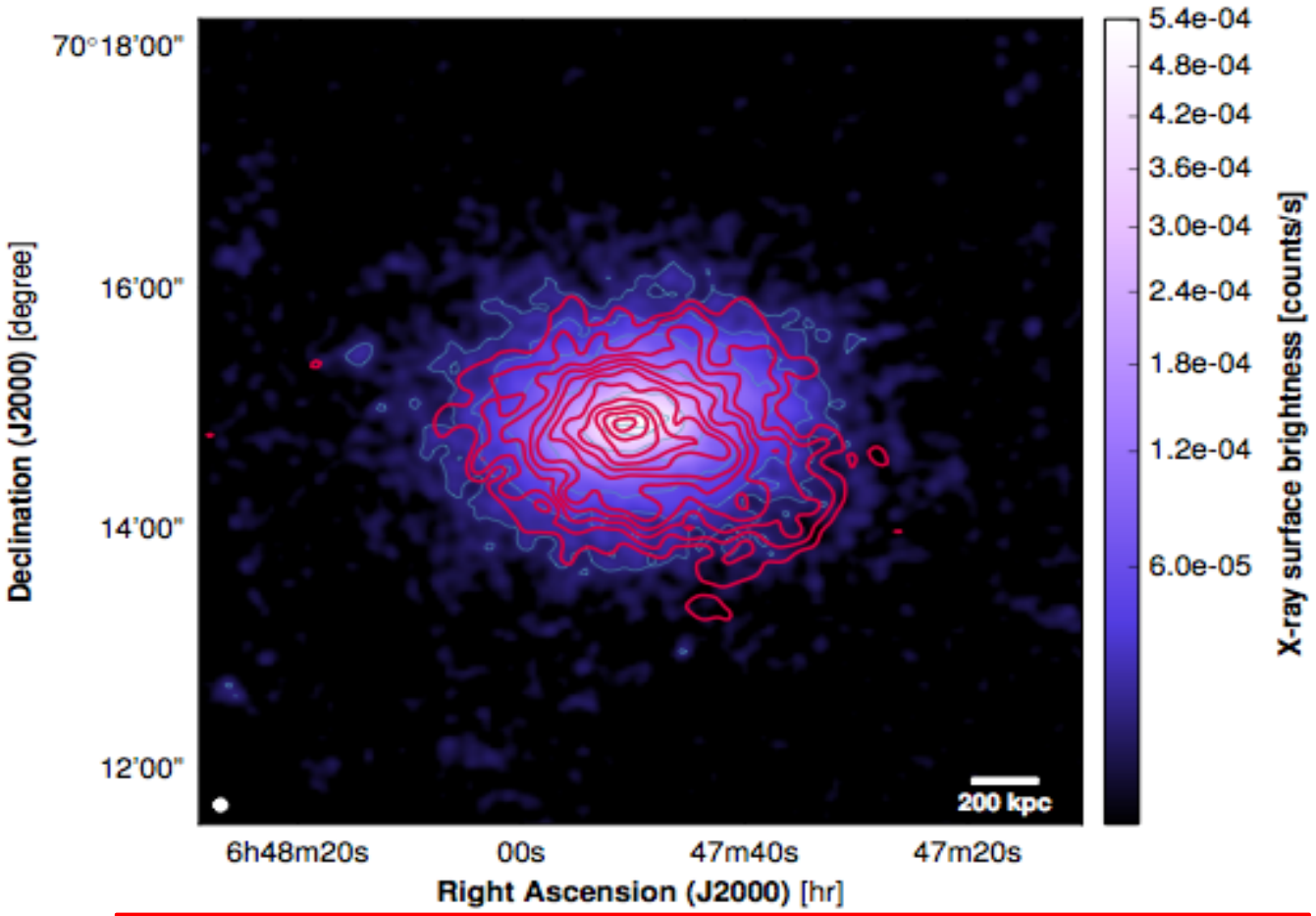


It is crucial to have good X-ray data

in order to perform a thermodynamic study (mass)

First cluster observation – comparison with X-ray

- map: XMM-Newton
- contours: NIKA2



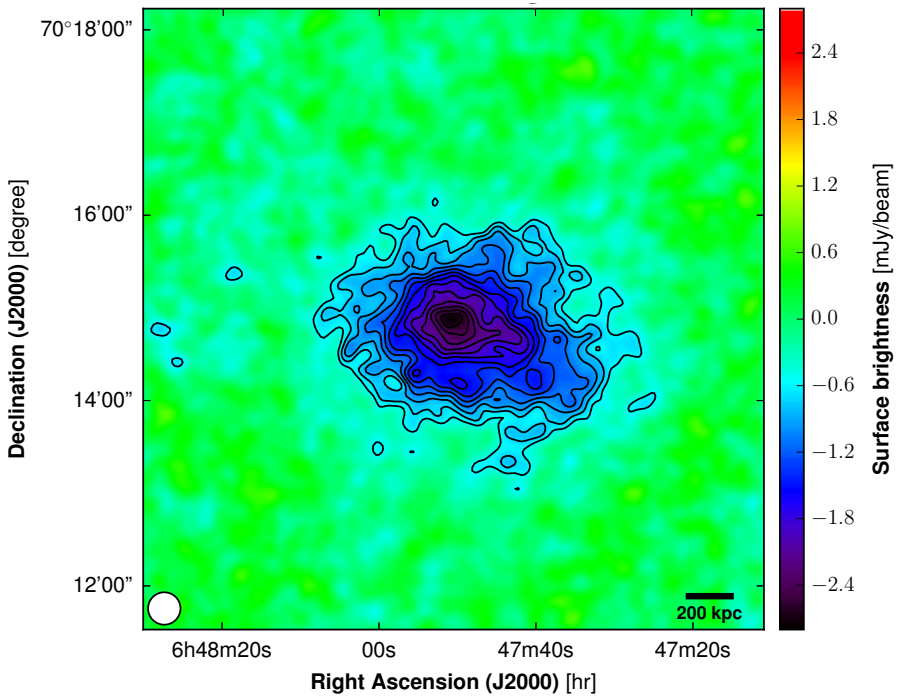
- NIKA2 and XMM extension are comparable
- For the first time, we have SZ and X-ray data at the same level

First cluster observation - maps

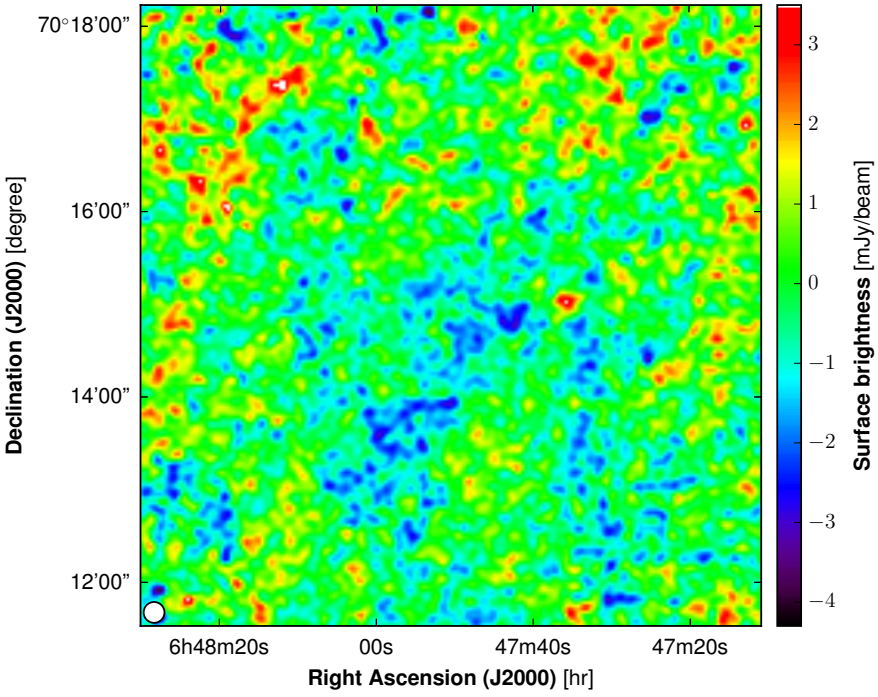
Dual-band observation

- no SZ signal is expected at 260 GHz (for this noise level)
- Noise: 933 μJy/beam
- 260 GHz map is used to identify point sources that may compensate SZ signal at 150 GHz

NIKA2 – 150 GHz



NIKA2 – 260 GHz



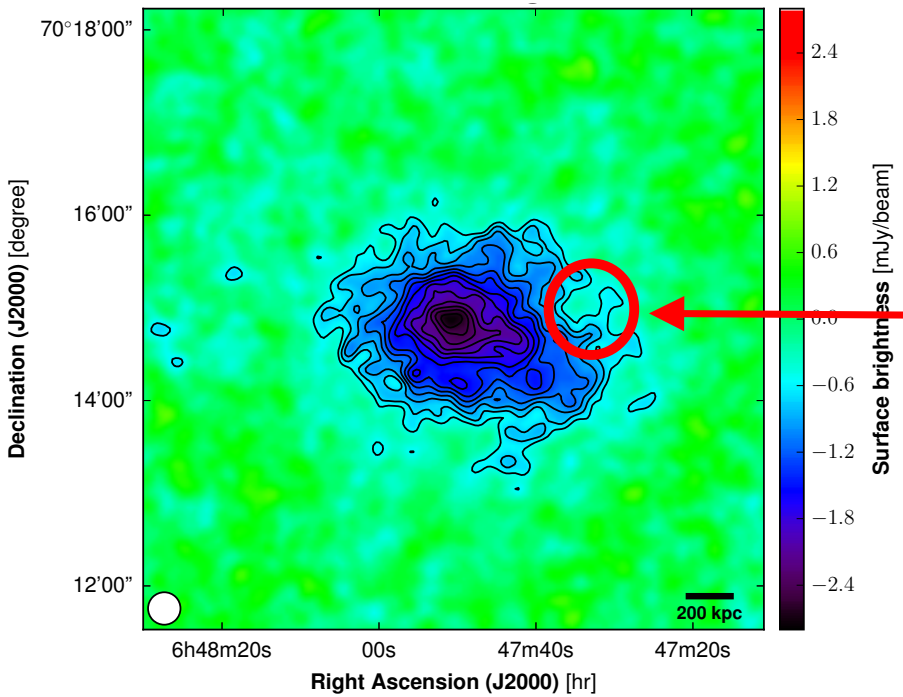
First cluster observation – point-source removal

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

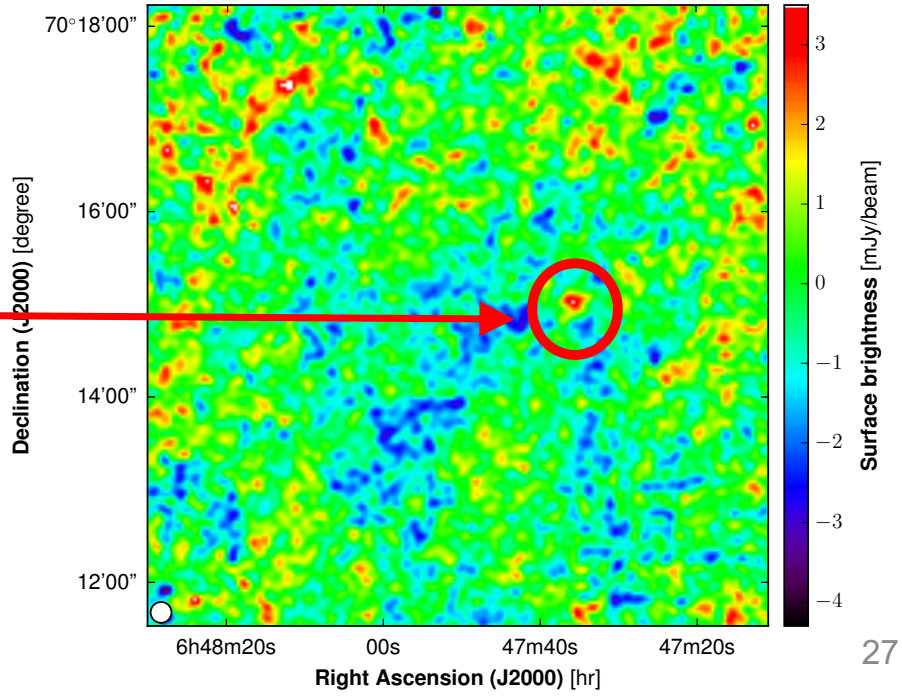
Dual-band observation

- no SZ signal is expected at 260 GHz (for this noise elevel)
- Noise: 933 μJy/beam
- 260 GHz map is used to identify point sources that may compensate SZ signal at 150 GHz
- One source detected at 4σ, 1.3 arcmin from the center

NIKA2 – 150 GHz



NIKA2 – 260 GHz



First cluster observation – point-source removal

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

Point-source removal

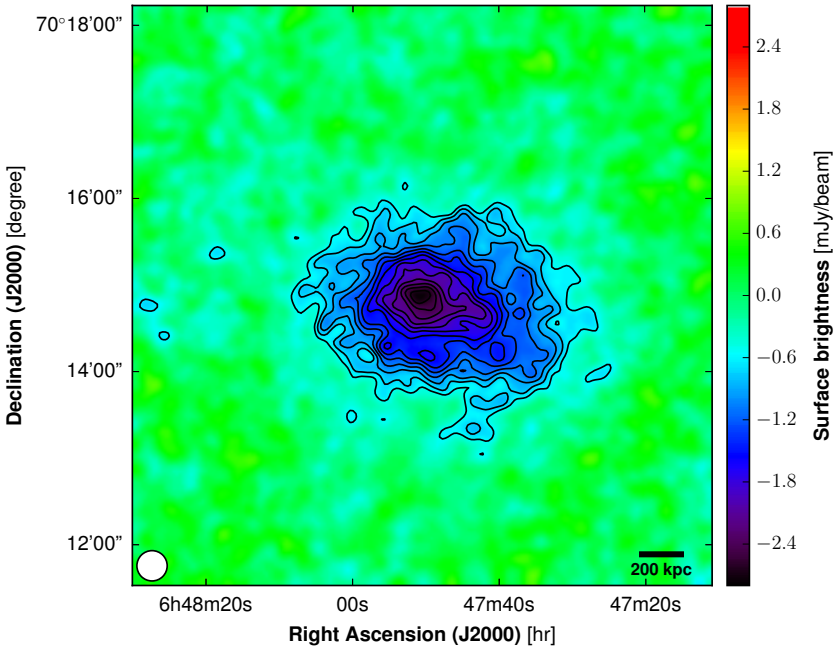
Data: Herschel (0.1 to 0.5 mm) and NIKA2 data (260 GHz, 1 mm)

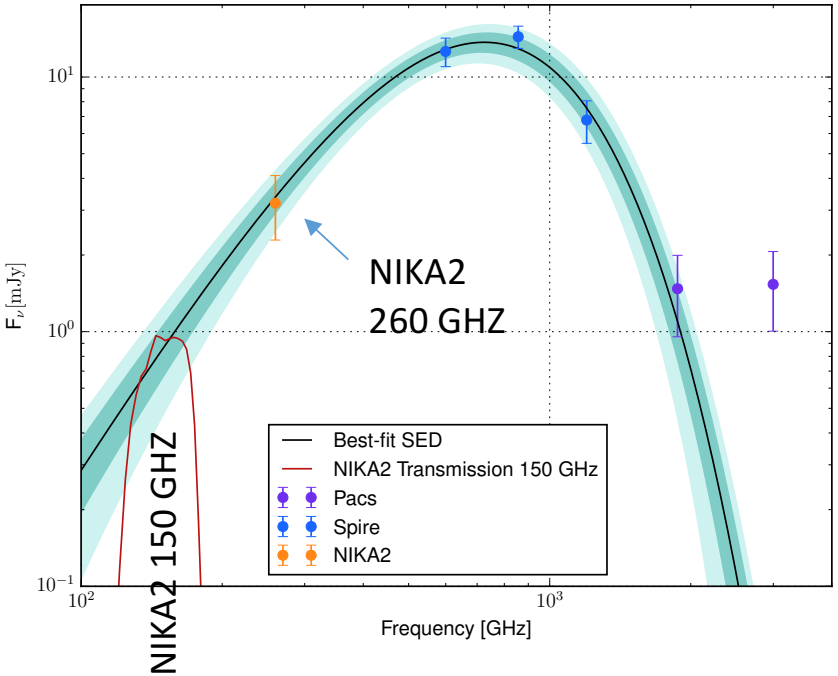
→ fit of the Spectral Energy Distribution of the source

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

→ Corrected map at 150 GHz

NIKA2 – 150 GHz - **corrected**

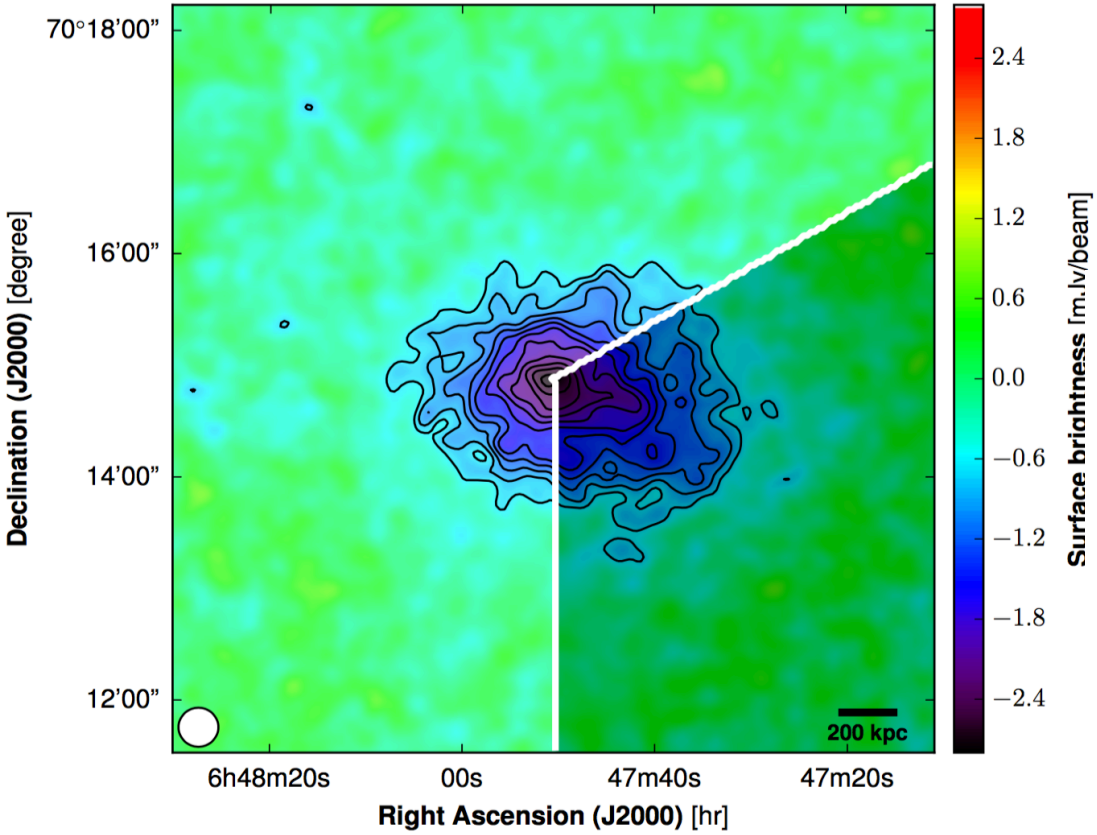


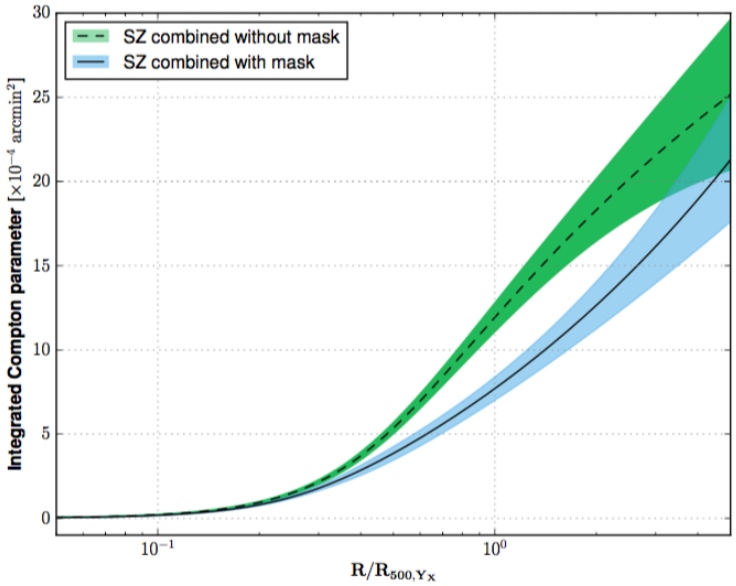


see talk by F. Kéruzoré, this session

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

MCMC analysis based on a non-parametric model

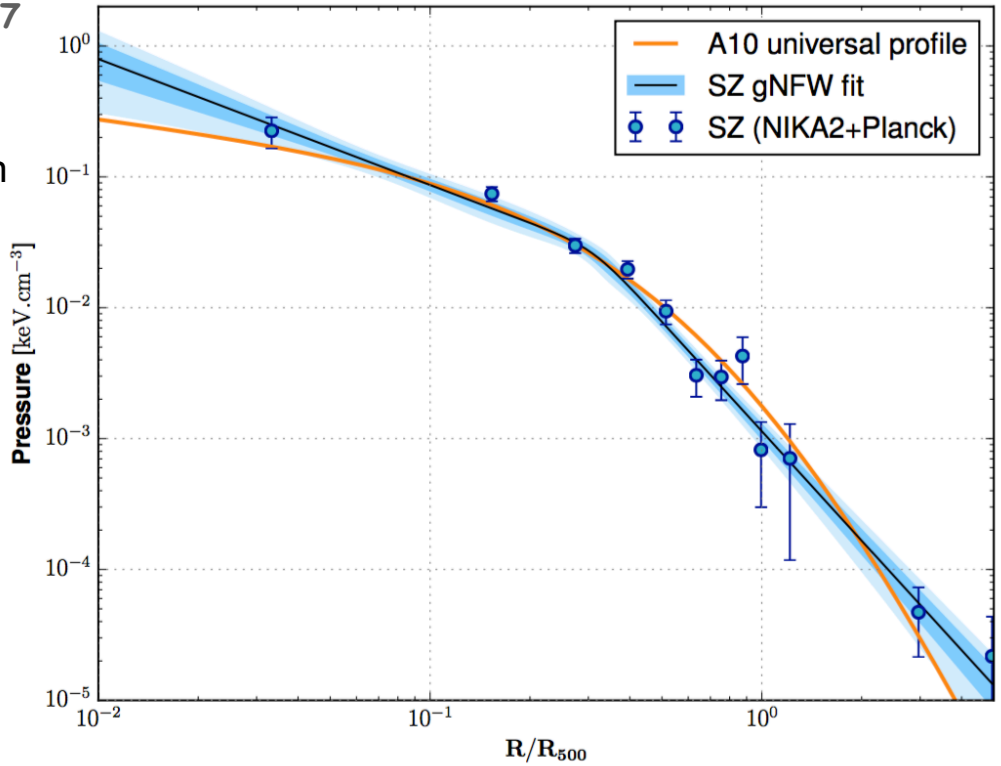
F. Ruppin *et al.*, A&A 2017

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

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

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

Combined analysis

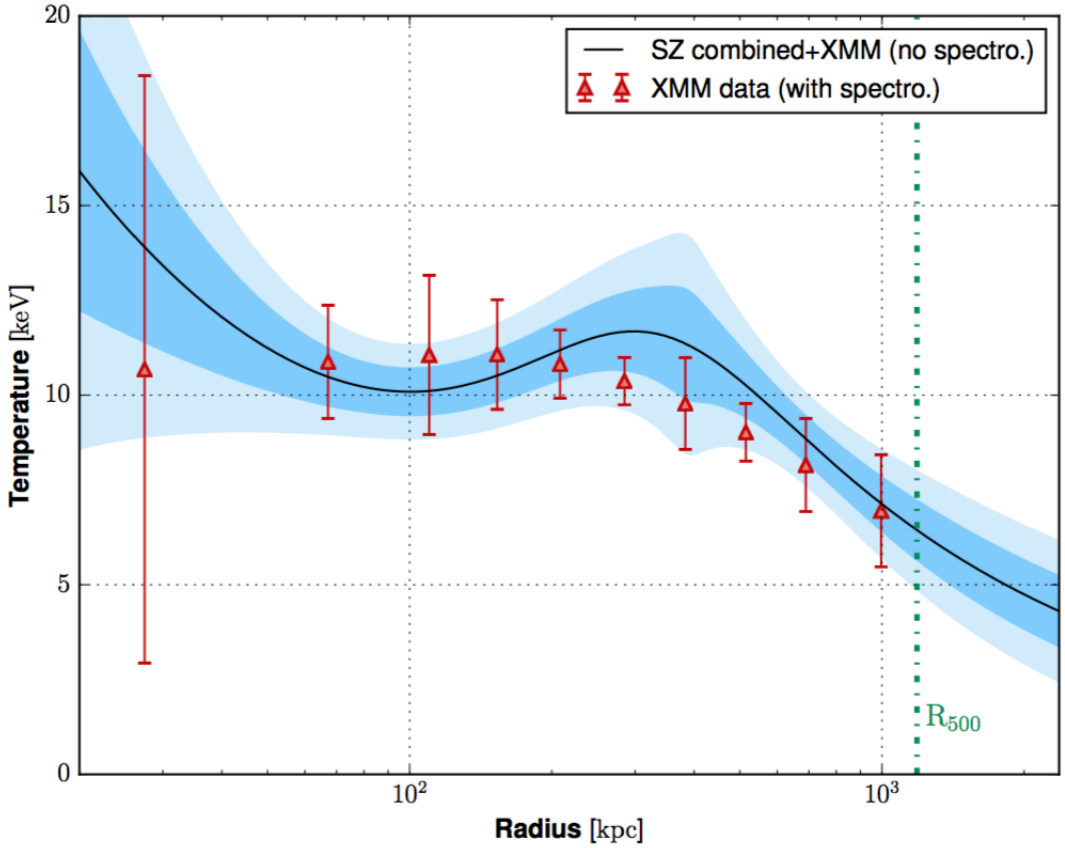
Data = SZ and X-ray (XMM)

- 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

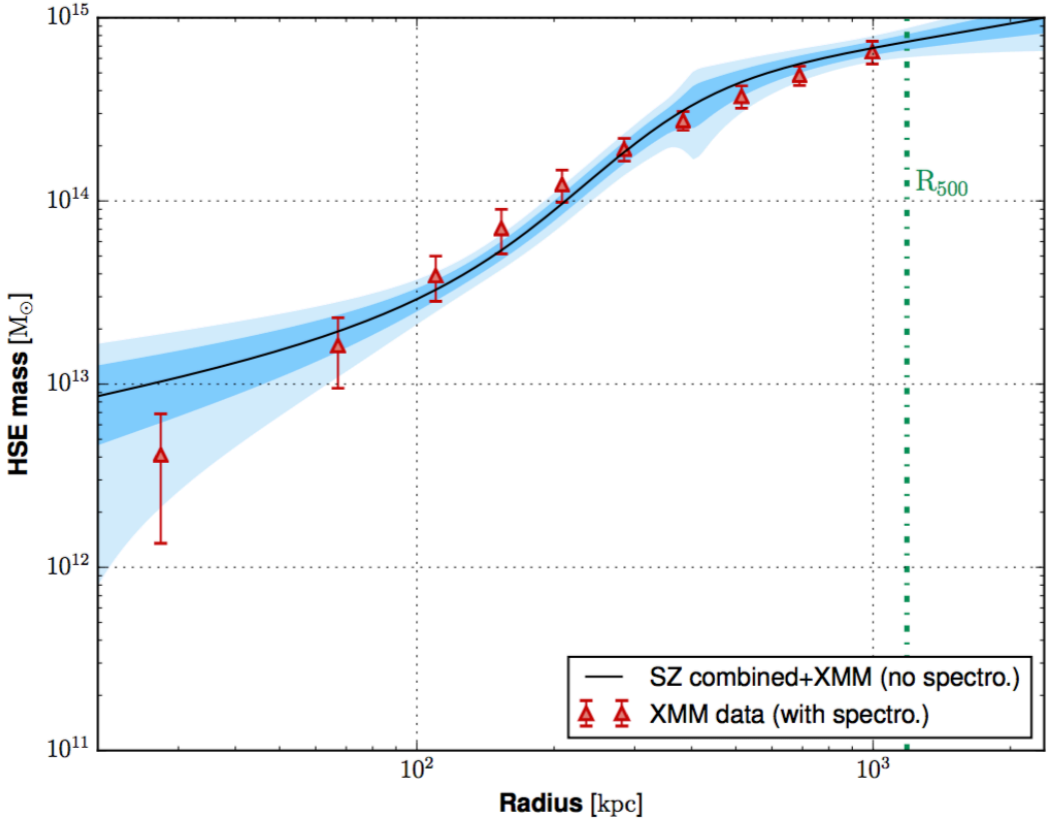
Data = SZ and X-ray (XMM)

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

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

Mass profile

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



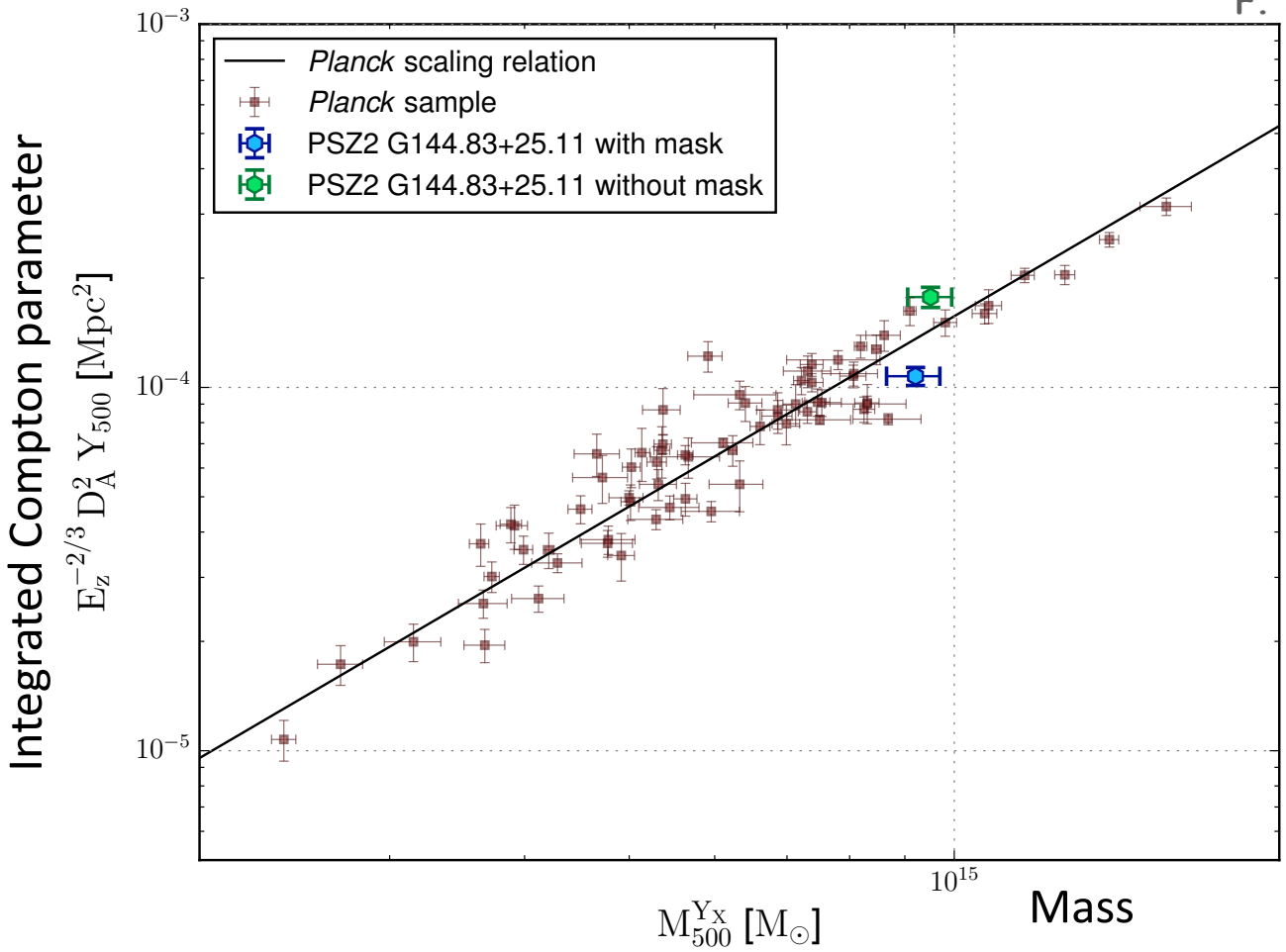
Estimation of integrated quantities

- Cluster Mass
- Integrated Compton parameter

	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)

→ very good result … but relatively long observation time !

Conclusions

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

  → but also on **cluster physics**

- **First cluster observed with NIKA2**

  → Impact of high-resolution observations on cluster property estimates (mass)

  → First step toward a

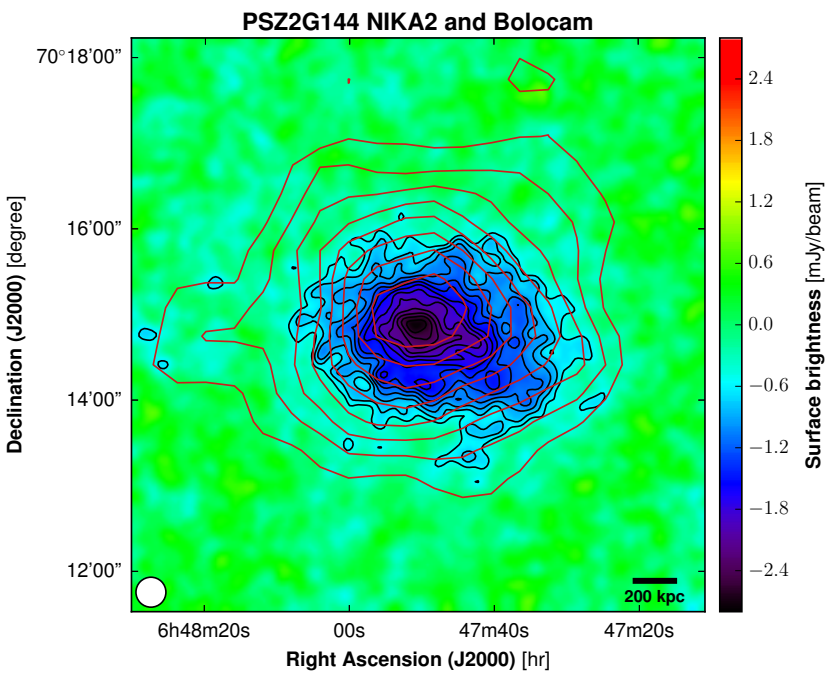
  - NIKA2 mean pressure profile
  - NIKA2 scaling relation

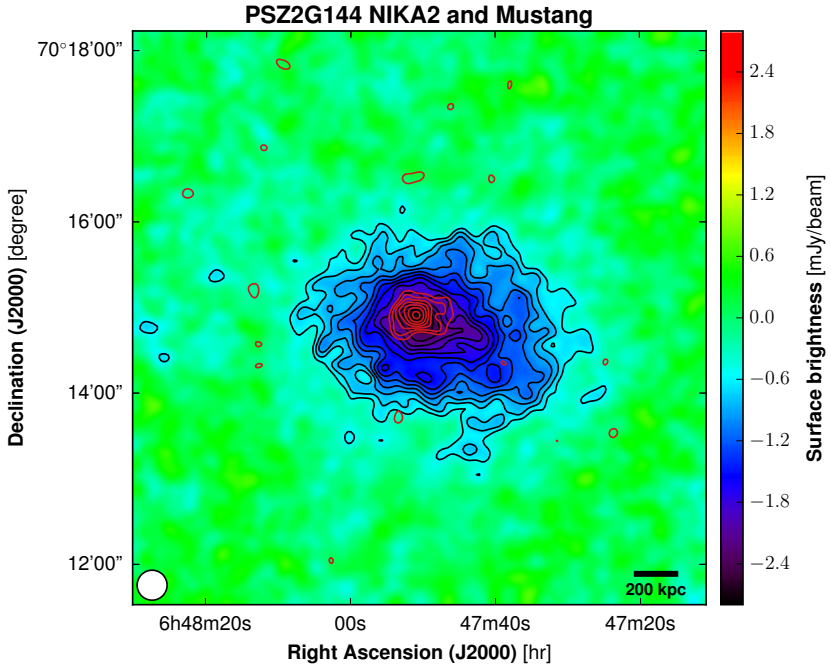
→ *see talk by F. Kéruzoré (2nd cluster of the LPSZ)*

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

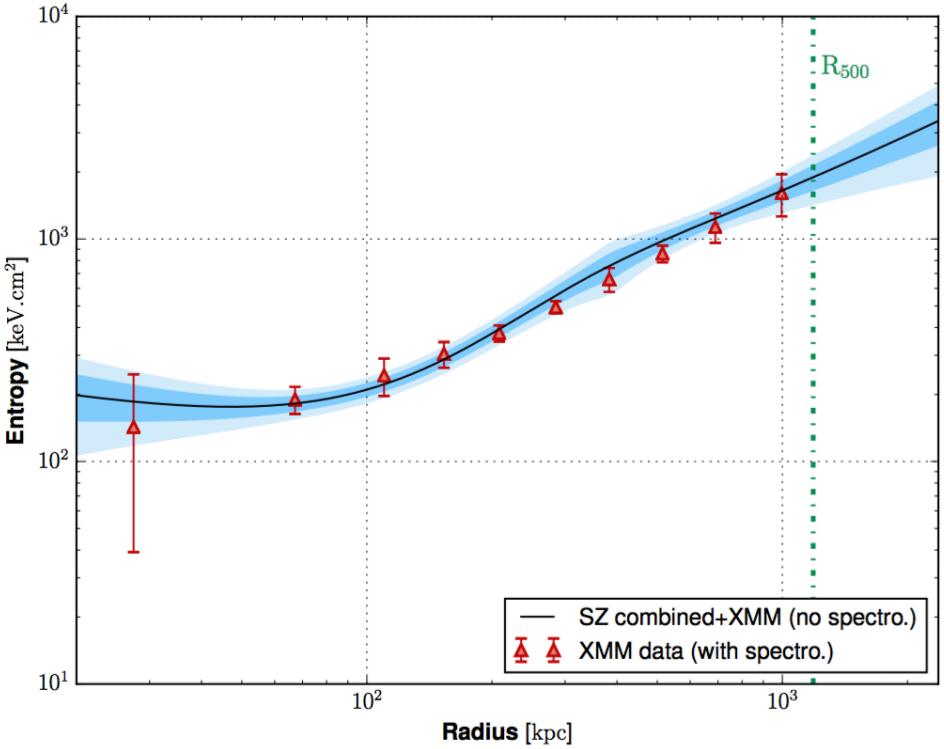
→ A multi-probe study

→ **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

Cluster cosmology - methods

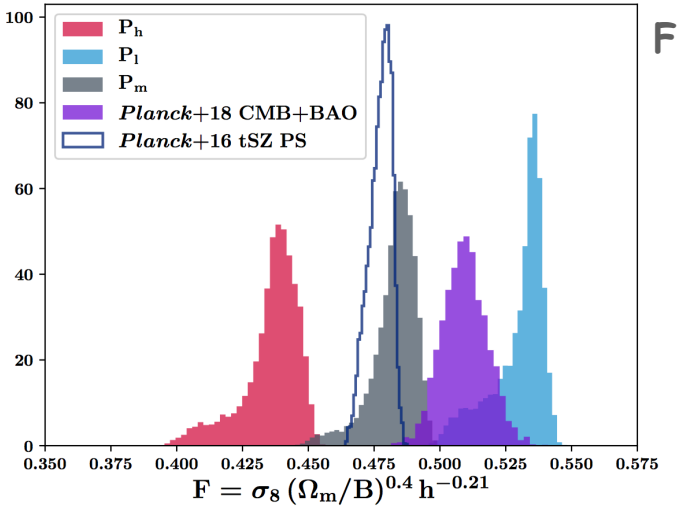
- **Methods**
  - **Cluster count** $\frac{d^2n}{dMdz}$
  - **SZ power spectrum** $C_\ell^{\rm SZ}$

- Very sensitive to cosmological parameters… but
  High degeneracy between σ_8, Ω_m, h and B the hydrostatic bias

$$F = \frac{\sigma_8 \Omega_m^{0.40}}{B^{0.40} h^{0.21}}$$

B. Bolliet *et al.*, MNRAS 2018

→the only parameter that is directly constrained with clusters

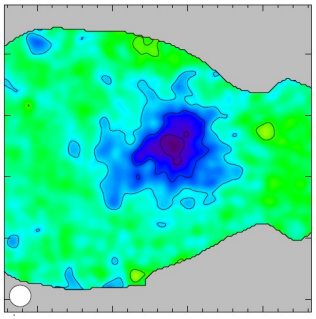


F. Ruppin *et al.*, arXiv:1905.05129

see talks by F. Ruppin & B. Bolliet, Thursday morning

SZ observations with NIKA

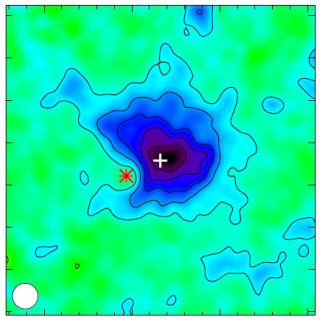
RXJ1347



well-known

R. Adam et al., A&A 2014

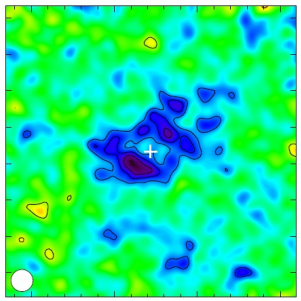
CLJ1227



high-z

R. Adam et al., A&A 2015

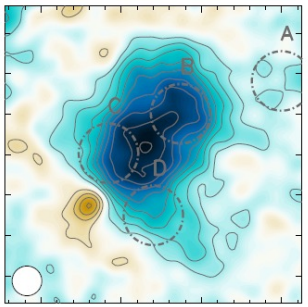
MACSJ1424



point-source removal

R. Adam et al., A&A 2016

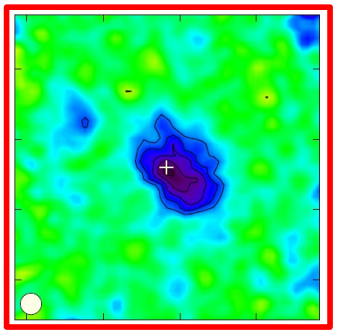
MACSJ0717



disturbed cluster

R. Adam et al., A&A 2017

PSZ1G045



Planck-discovered

F. Ruppin et al., A&A 2017