First Sunyaev-Zel'dovich mapping of a galaxy cluster with NIKA2

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on behalf of the NIKA2 collaboration

Enigmass meeting - December 07

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I - Cosmology from SZ observations of galaxy clusters

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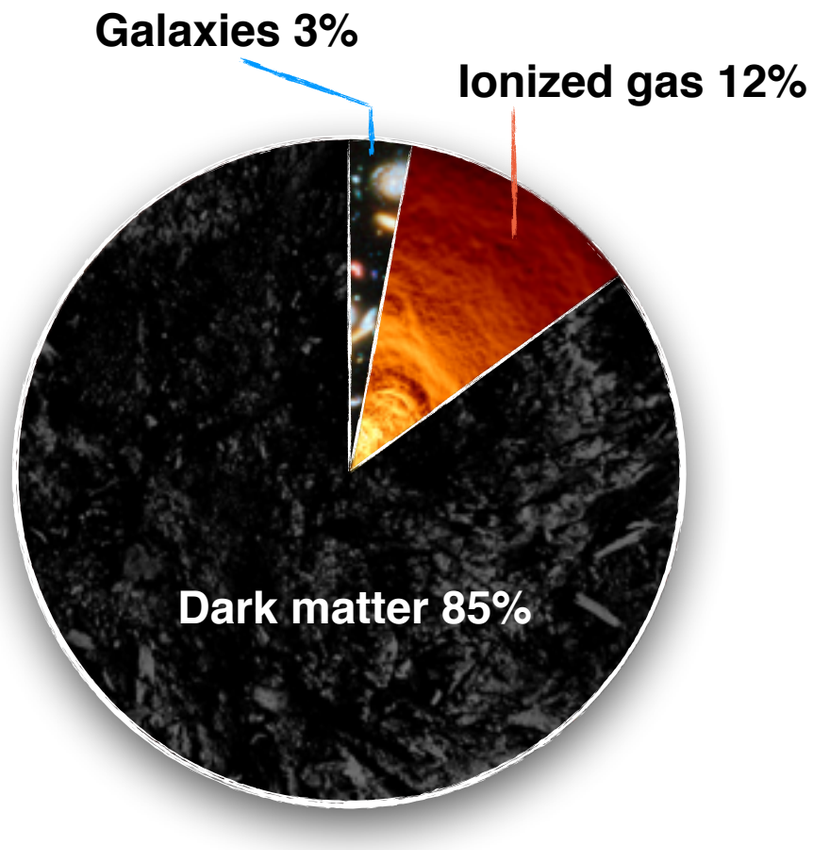
Cosmology with galaxy clusters

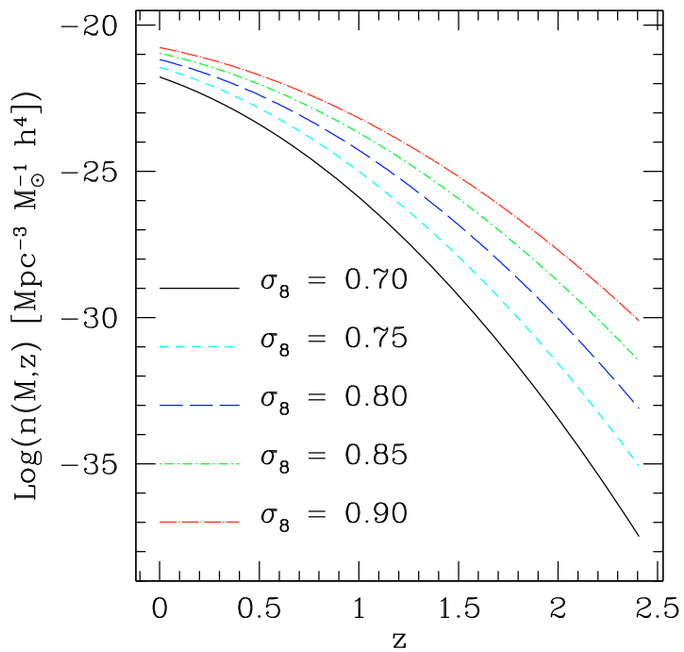


$M_{\rm tot} \sim 10^{14} - 10^{15} M_\odot$

$z \in [0, 3]$

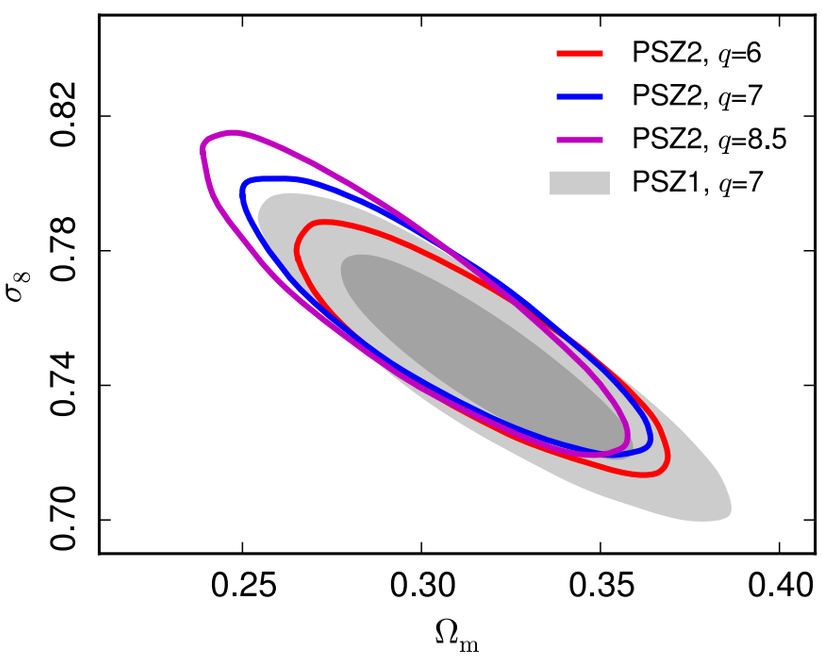
- **Galaxy clusters:**
  - Largest gravitationally bound objects in the Universe
  - Dark matter dominated
  - Intracluster medium (ICM):
    Baryonic matter - hot ionized gaz $\sim 5 - 10$ keV
- Powerfull probe for cosmology from the study of the mass function $\dfrac{dn}{dMdz}$
- **Constraints on cosmological parameters:** Ω_m , σ_8

Mass function



C. Fedeli, *et al.*, A&A **486** (2008)

Cosmological parameters



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

Total mass of galaxy clusters

- Estimate the total mass for each cluster in cosmological surveys

→ **Scaling relation** to link the observable to the cluster mass

- Need to calibrate the scaling relation on a representative cluster sample

- Mass estimate under the hydrostatic equilibrium hypothesis:

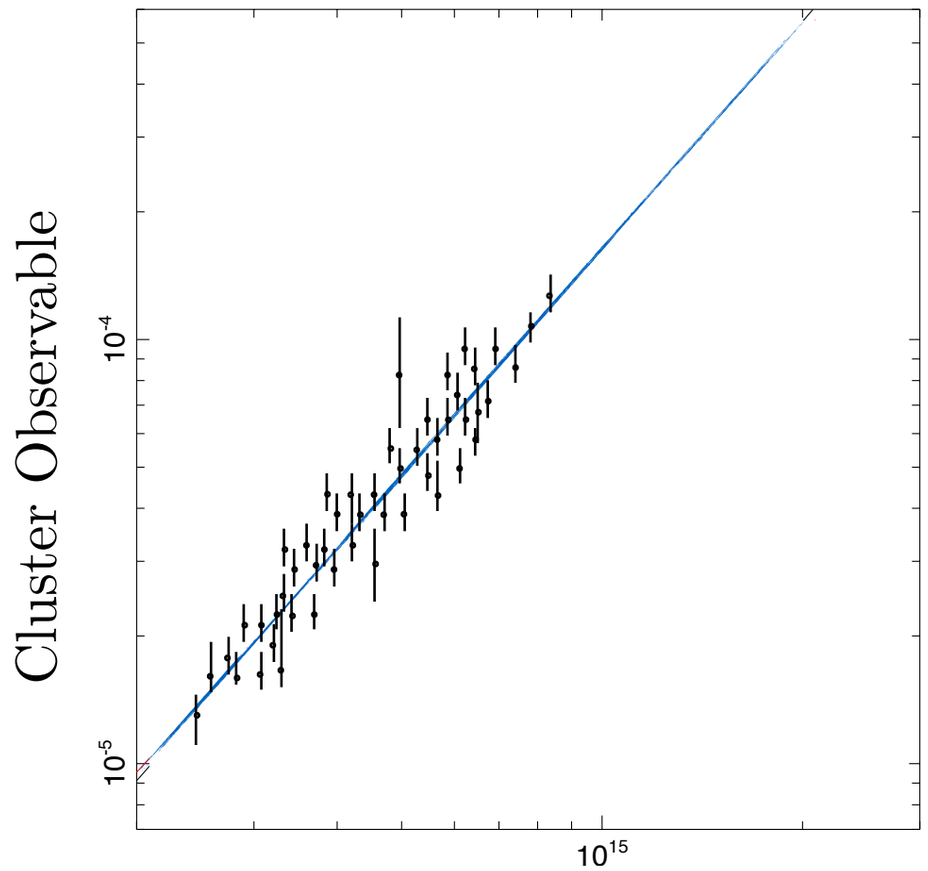
$$M_{\rm HSE}(r) \propto \frac{r^2}{n_e(r)} \times \frac{dP_e(r)}{dr}$$

ICM pressure

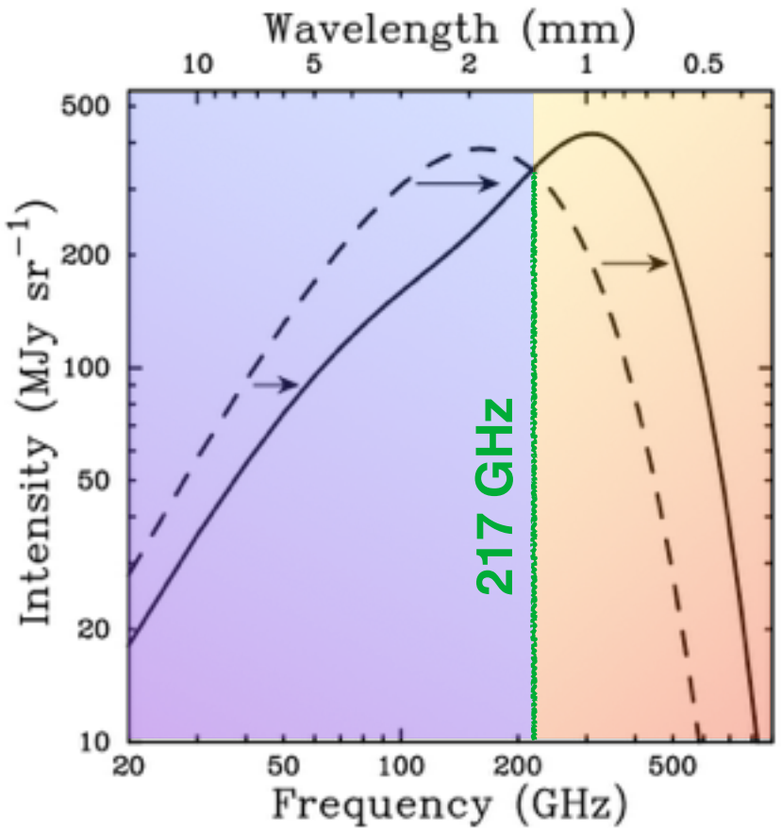
ICM density

→ Need to estimate the **density** and **pressure** distributions within the ICM

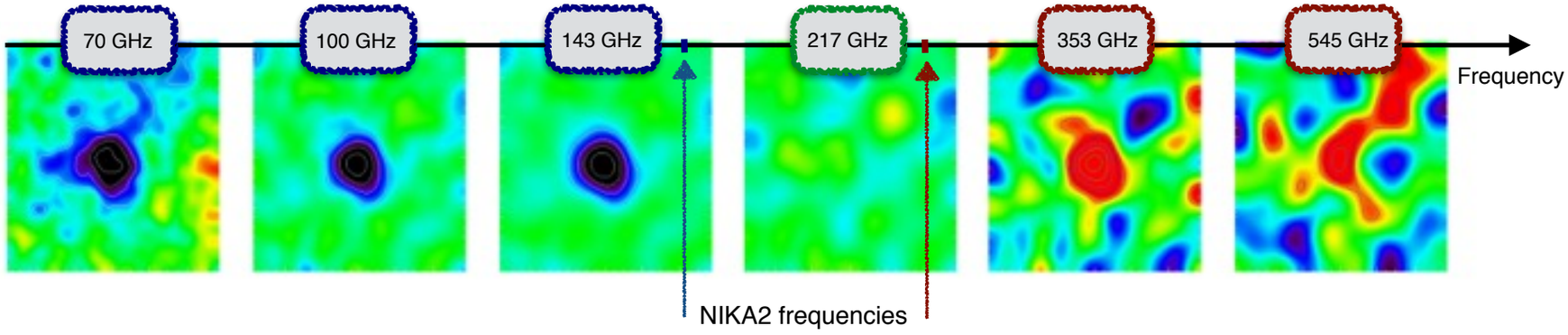
Scaling relation



The Sunyaev-Zel'dovich effect



Carlstrom *et al.* ARA&A (2002)



A 2319 (*Planck*)

- **Thermal Sunyaev-Zel'dovich effect** (SZ)

  Sunyaev & Zel'dovich CoASP (1972)

  Inverse Compton scattering of CMB photons on hot ICM electrons

  → CMB photons acquire energy

  Study of the ICM from its imprint on the CMB (spectral distorsion)

  → SZ effect is redshift independent

- SZ effect amplitude given by the Compton parameter:

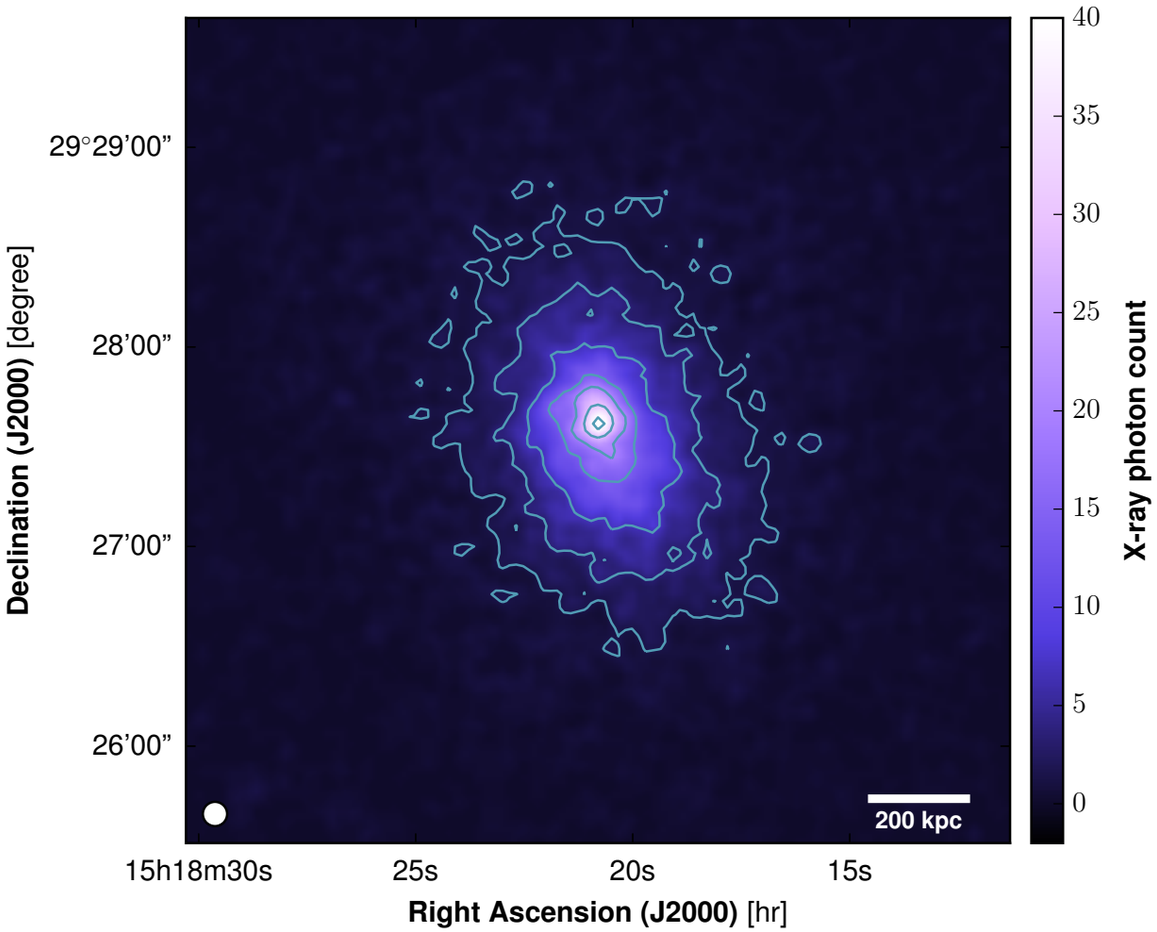
$$y_{\rm SZ} \propto \int_{\rm LOS} P_e \, dl$$

→ Characterize the electron **pressure** within the ICM

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

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

X-ray emission from the ICM



- **X-ray:**

Bremsstrahlung radiation from electrons of the ICM

→ tracer of the electronic gas **density**

$$S_X \propto \frac{1}{(1+z)^4} \int n_e^2 \Lambda \, dl$$

Challenging observations at high z due to cosmological dimming

ICM **temperature** from X-ray spectroscopy

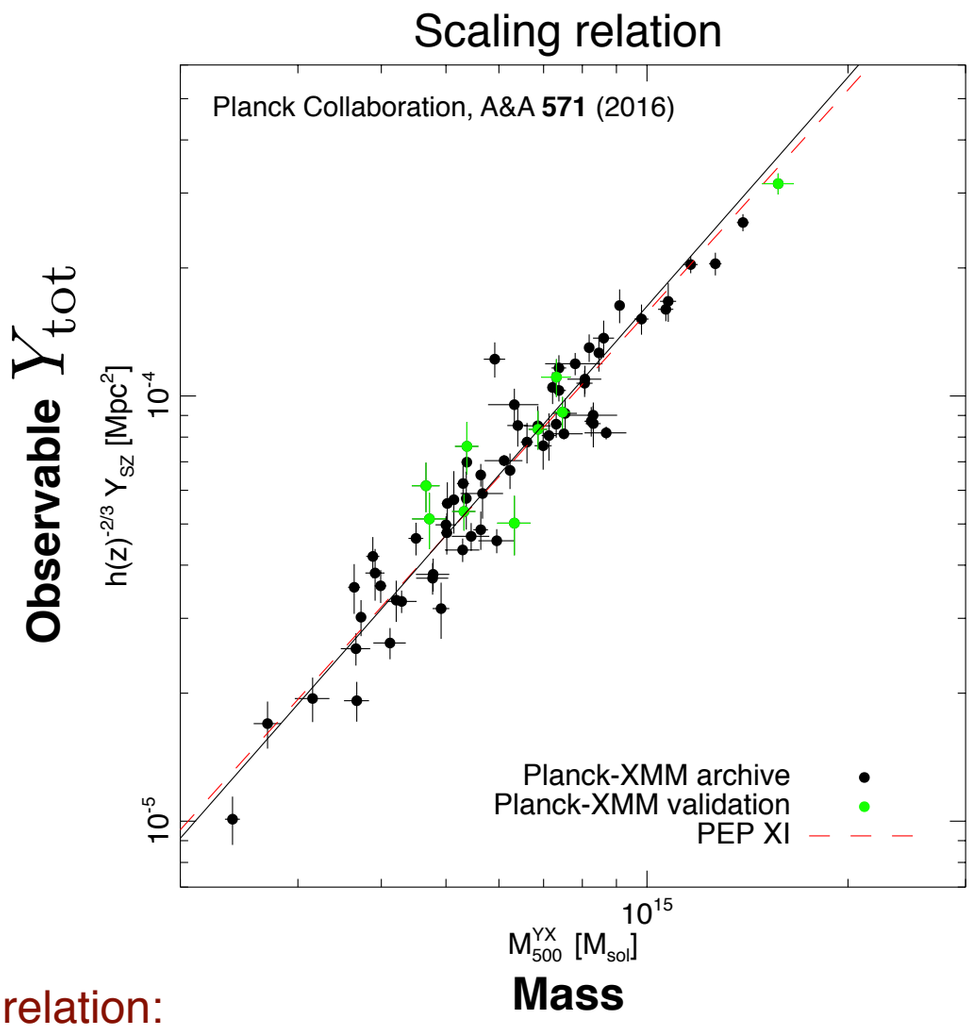
→ Possible to estimate the ICM **pressure** at low z from the ideal gas law: $P_e = n_e \times T_e$

→ Hydrostatic mass from X-ray only observation

Major drawback: X-ray spectroscopy is time consuming ⟶ prohibitive at high z

Cosmology with the *Planck* catalog

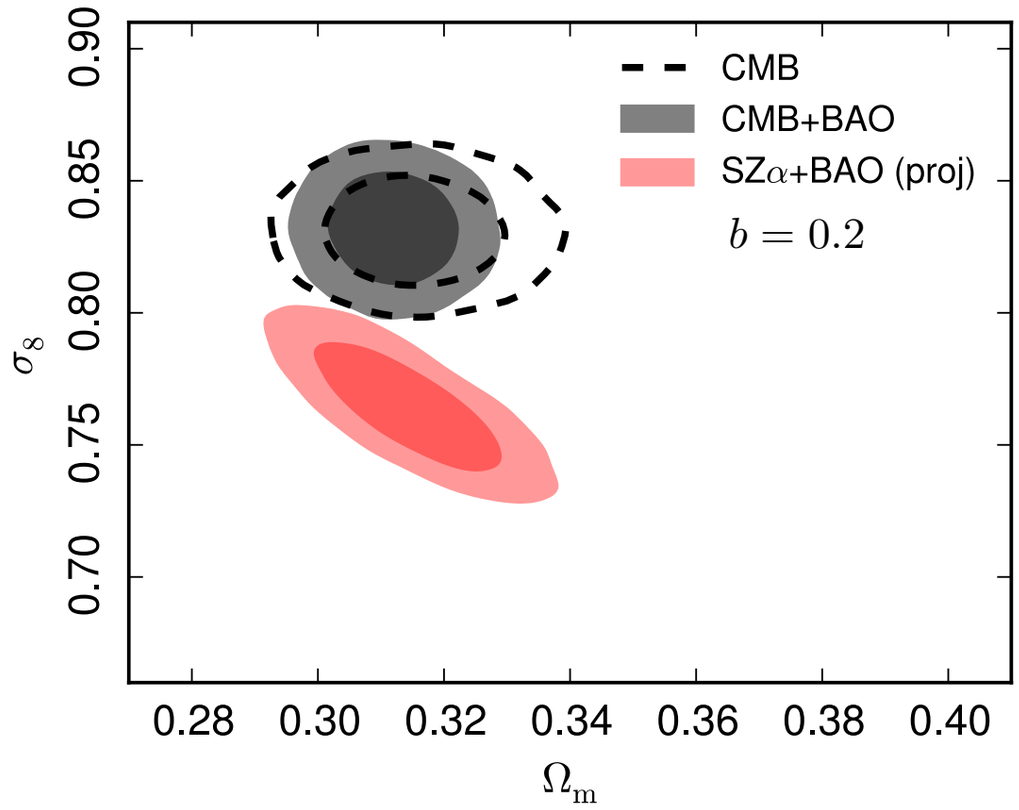
- ***Planck* Catalog**
  1653 galaxy clusters detected from SZ effect with $z \in [0, 0.9]$
- Scaling relation: link the SZ observable to the cluster mass



- Calibration of the scaling relation:
  - Redshift lower than 0.3
  - Mass and Compton parameter estimated from X-ray observations ($P_e = n_e \times T_e$)
  - Integration up to R_{500}

Cosmology with the *Planck* catalog

- **Tension between CMB and cluster constraints of cosmological parameters**

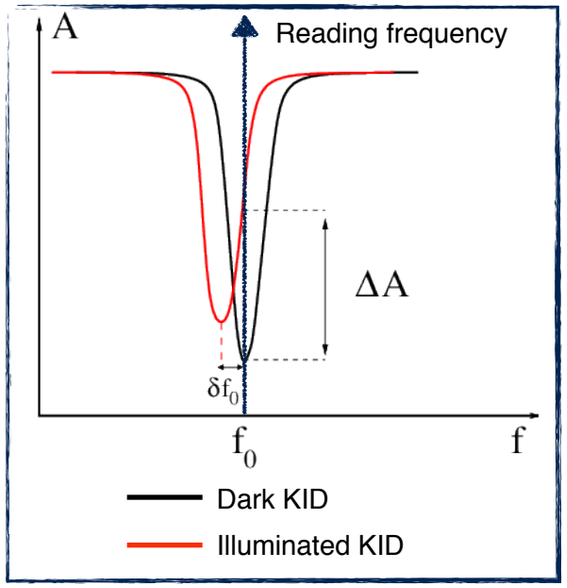


Planck Collaboration, A&A **594** (2016)

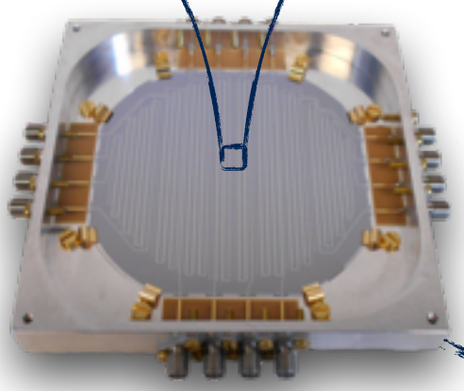
- Bias and systematics:
  - Hydrostatic equilibrium hypothesis
    $M_{\rm HSE} = (1-b)M_{\rm tot}$ $\qquad b:$ hydrostatic bias
  - Insufficient knowledge of the bias and Y_{500} for $z \gtrsim 0.3$
  - Angular resolution of *Planck* (10 arcmin) is too low

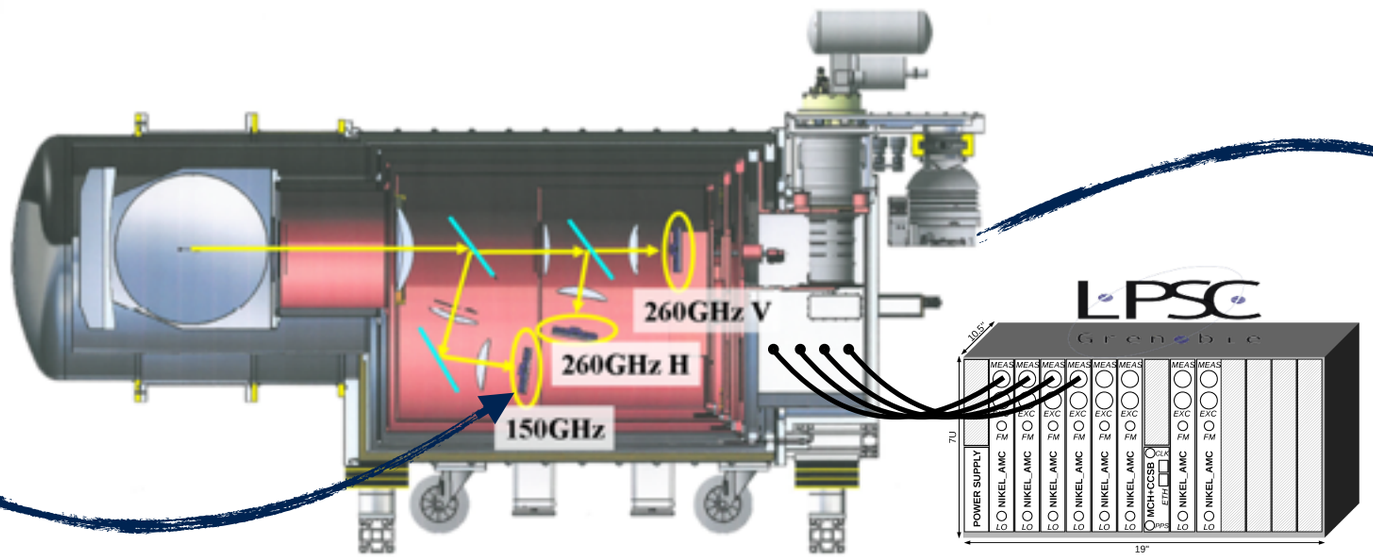
→ **Calibration of the scaling relation from SZ observations at high angular resolution at high redshift**

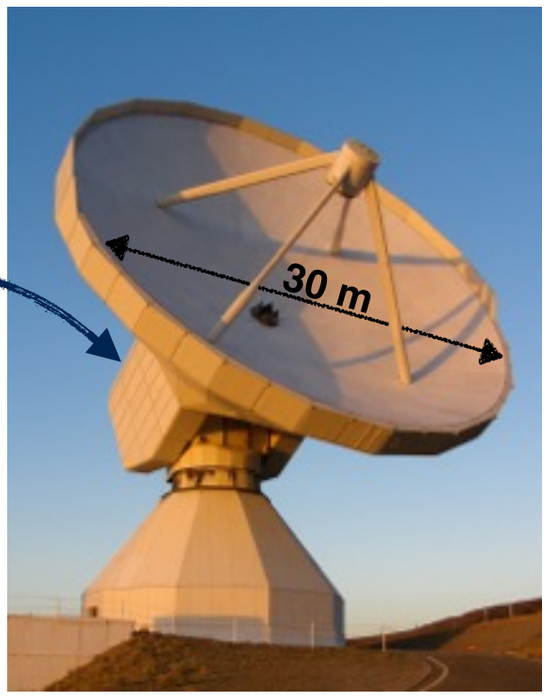
The NIKA2 camera



- Kinetic inductance detectors (KIDs):
  - Superconducting resonators
  - Value of the kinetic inductance depends on the number of Cooper pairs
  - Variation of the resonance frequency proportional to the incoming intensity
- Observation frequencies: → 150 GHz - Negative SZ signal; → 260 GHz - Slightly positive SZ signal
- Fast electronics to read multiplexed KIDs (LPSC)
  Cryostat to cool down the KIDs at a base temperature of 150 mK
- Installation at the IRAM 30-m telescope
- Ready and commissioned







NIKA2 characteristics for SZ mapping

Measured NIKA2 performance:

Frequencies	150 GHz	260 GHz
Number of KIDs	616	2×1140
Field of view	6.5 arcmin	
Sensitivity	8 mJy.s$^{1/2}$	30 mJy.s$^{1/2}$
Angular resolution	17.7 arcsec	11.2 arcsec

Adam *et al.* 2017

→ ~ Size of the *Planck* beam

→ Very high mapping speed

→ 25 times better than the *Planck* resolution

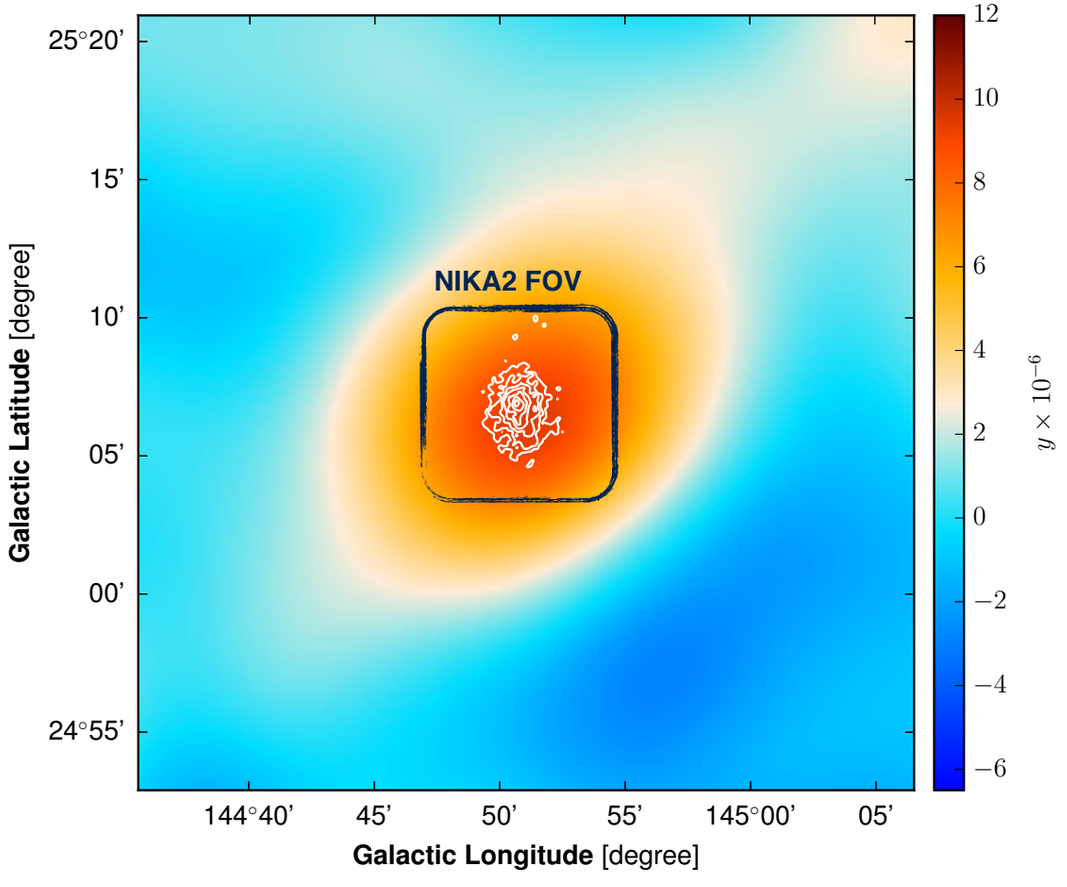
- The NIKA2 performance will enable to:

  Map the **SZ signal to large radii** (comparable to X-ray data)

  Resolve inner structures smoothed by the Planck beam

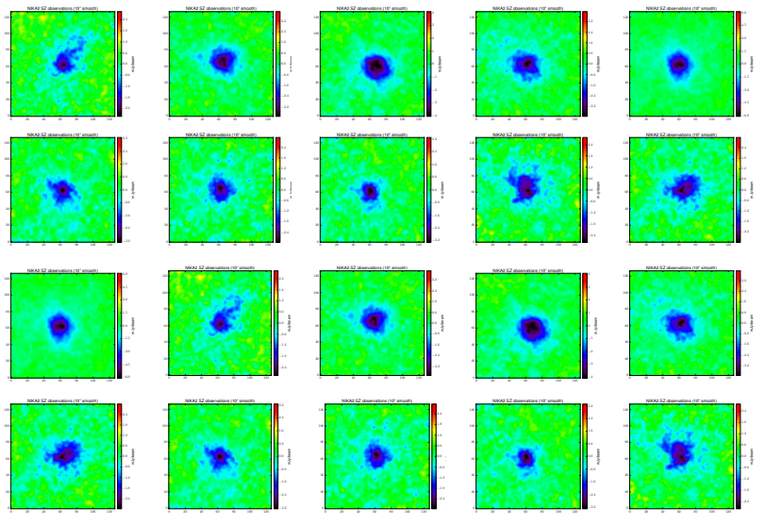
- NIKA2 SZ analysis pipeline ready and tested with NIKA1 data:

  Pathfinder of NIKA2 with a smaller FOV (~ 1.8 arcmin)



SZ observations with NIKA2

- **NIKA2 SZ large program:**



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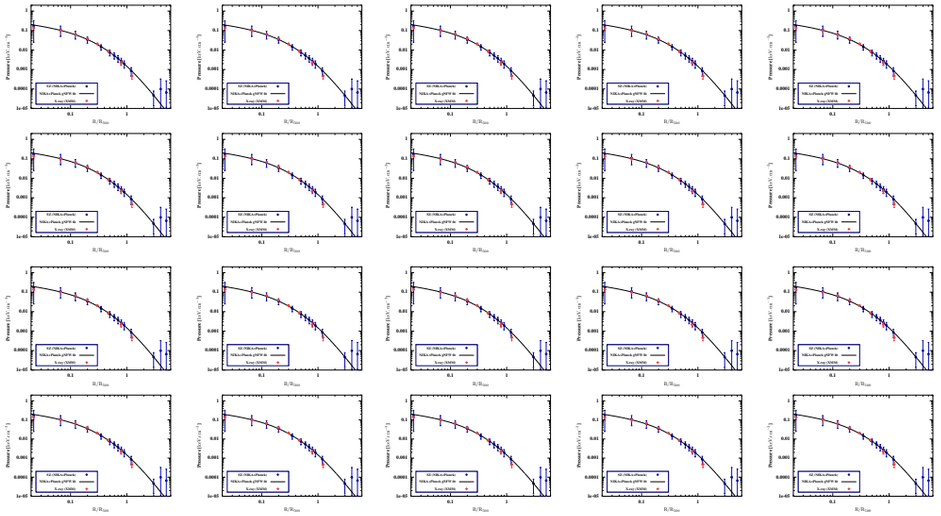
50 SZ surface brightness maps



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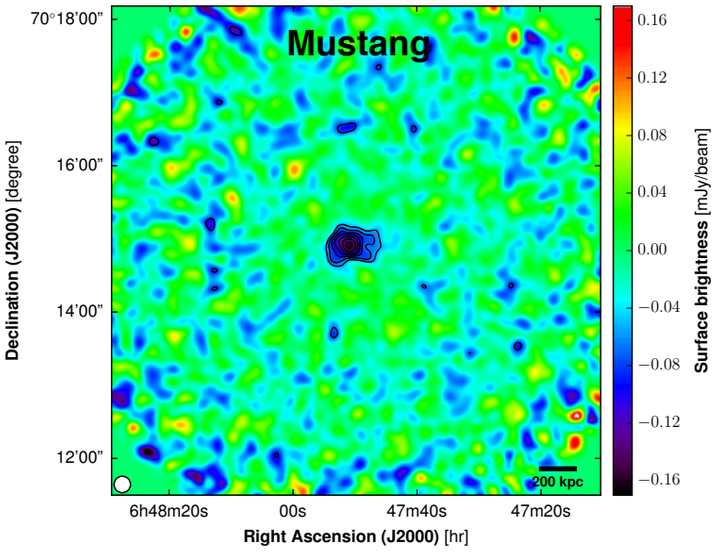
50 highly constrained pressure profiles

First observation of a cluster of the NIKA2 SZ large program: PSZ2 G144.83+25.11

Previous observations of PSZ2G144

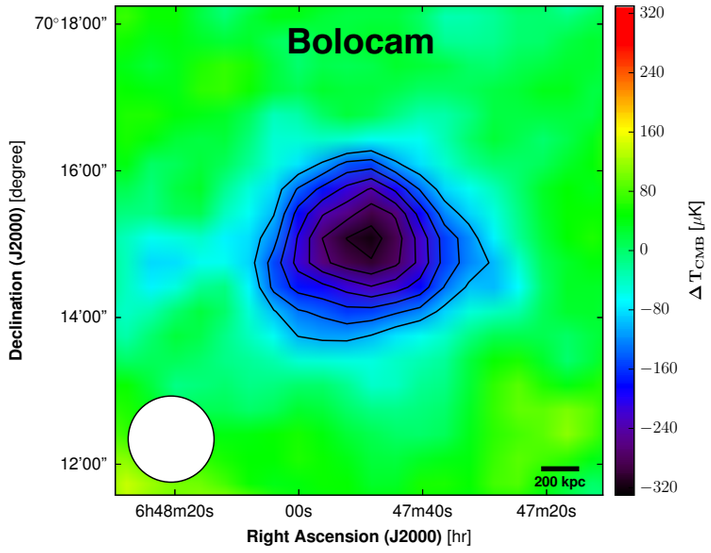
- SZ target: $z = 0.58$
- Already observed: **SZ** - Mustang, Bolocam, *Planck*, AMI ⟶ Constraints on $Y_{\rm tot}$
  X-ray - XMM-*Newton* and Chandra ⟶ ICM electron density profile
  Optical / Infrared - Hubble and Herschel ⟶ Point source contamination and lensing

Young *et al.* 2014



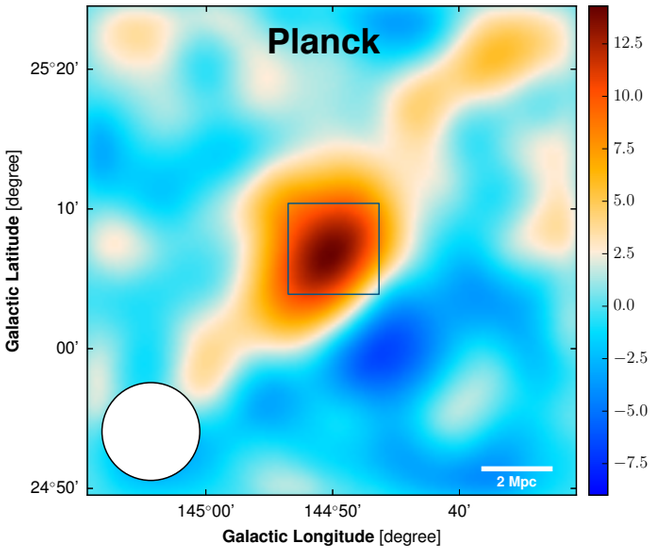
Angular resolution of 9”
FOV: 42”
Green Bank Telescope

Sayers *et al.* 2013



Angular resolution of 58”
FOV: 8 arcmin
Caltech Submillimeter Observatory

Planck collaboration *et al.* 2016



Angular resolution of 7’
FOV: Full sky
Space: Lagrangian point L2

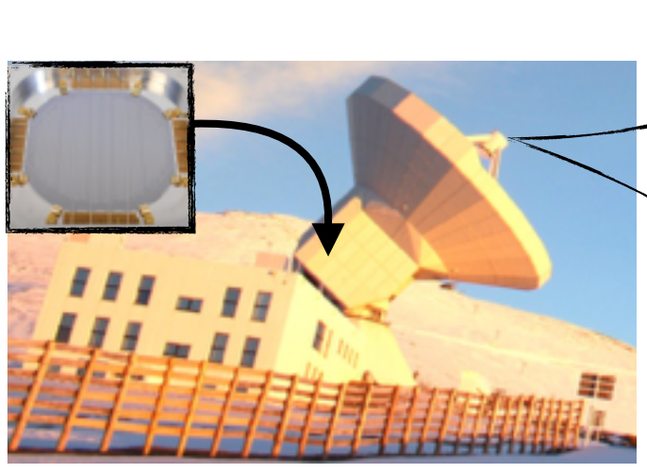
well known cluster

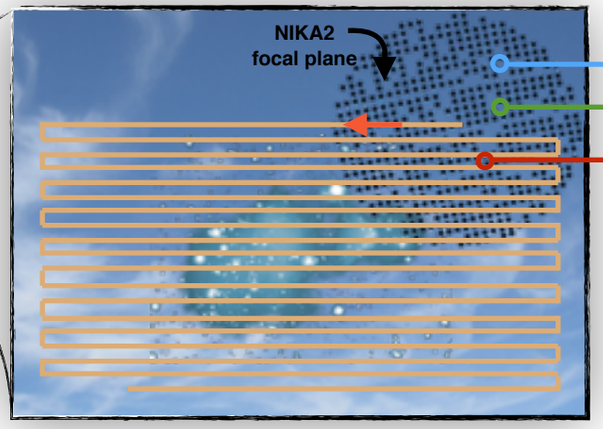
Ideal target to start the NIKA2 SZ large program

SZ observations of PSZ2G144 with NIKA2

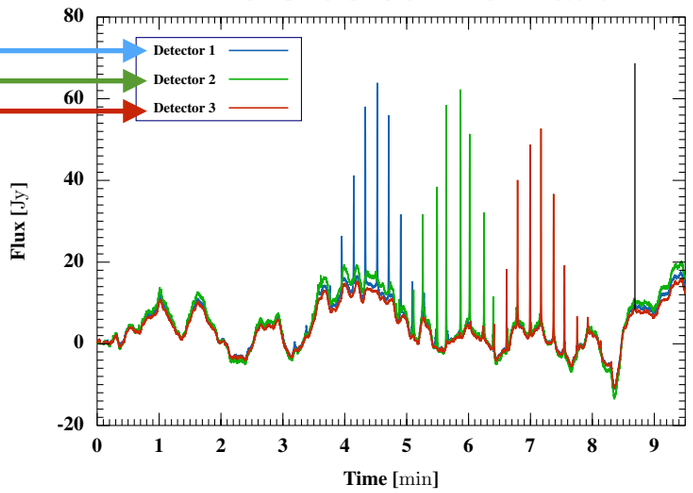
- **NIKA2 SZ observations in April 2017:** Effective observation time of 11h
  Mean opacity of 0.3 at 150 GHz
  (poor weather conditions but stable opacity)
  Mean elevation of 41.4°

- **Data calibration:** Neptune scans taken at the same opacity (mean elevation of 38.2°)



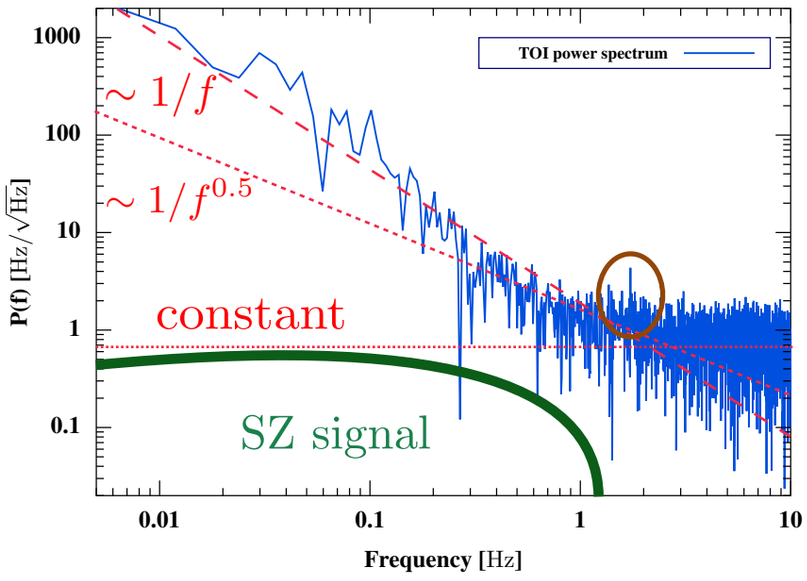


Time **O**rdered **I**nformation



$$d_k(t) = \underbrace{P_t \times S(\nu, x, y)}_{\text{SZ Signal}} + \underbrace{A(\nu, t)}_{\text{Atmosphere}} + \underbrace{E_k(t)}_{\text{Electronics}} + \underbrace{N_k(t)}_{\text{Detector}} + \underbrace{G_k(t)}_{\text{Glitches}} + \underbrace{C_k(t)}_{\text{Vibrations}}$$

Pointing matrix



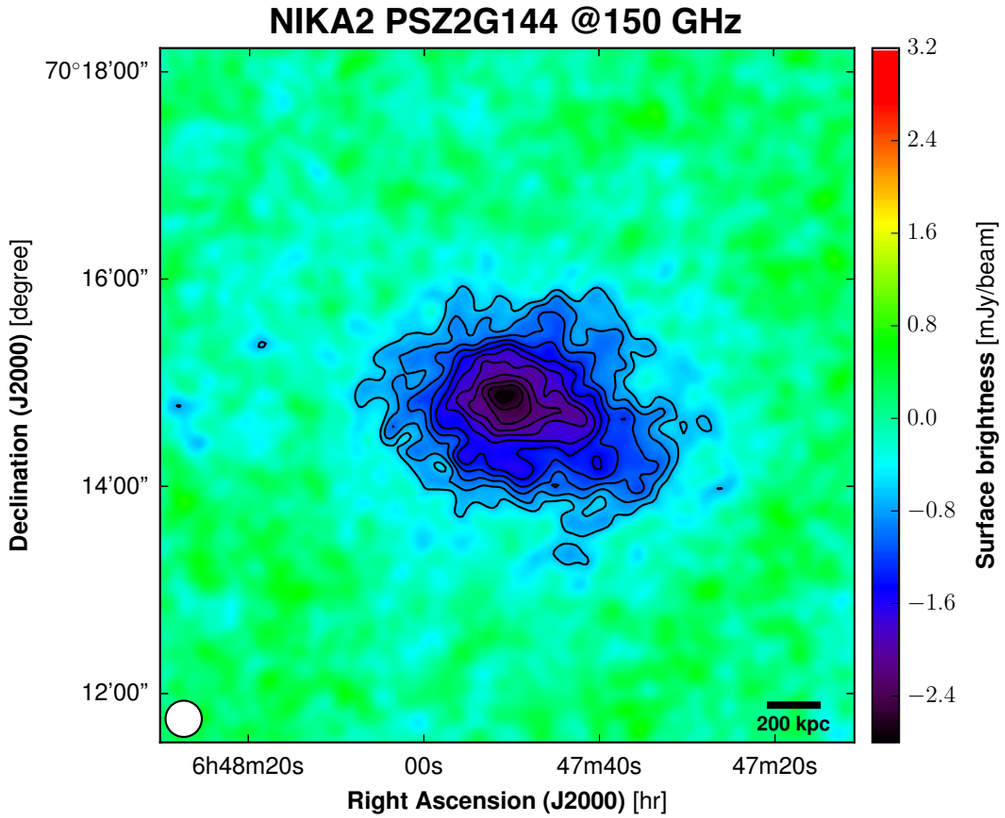
- Atmospheric emission (grey body) is the main contaminant

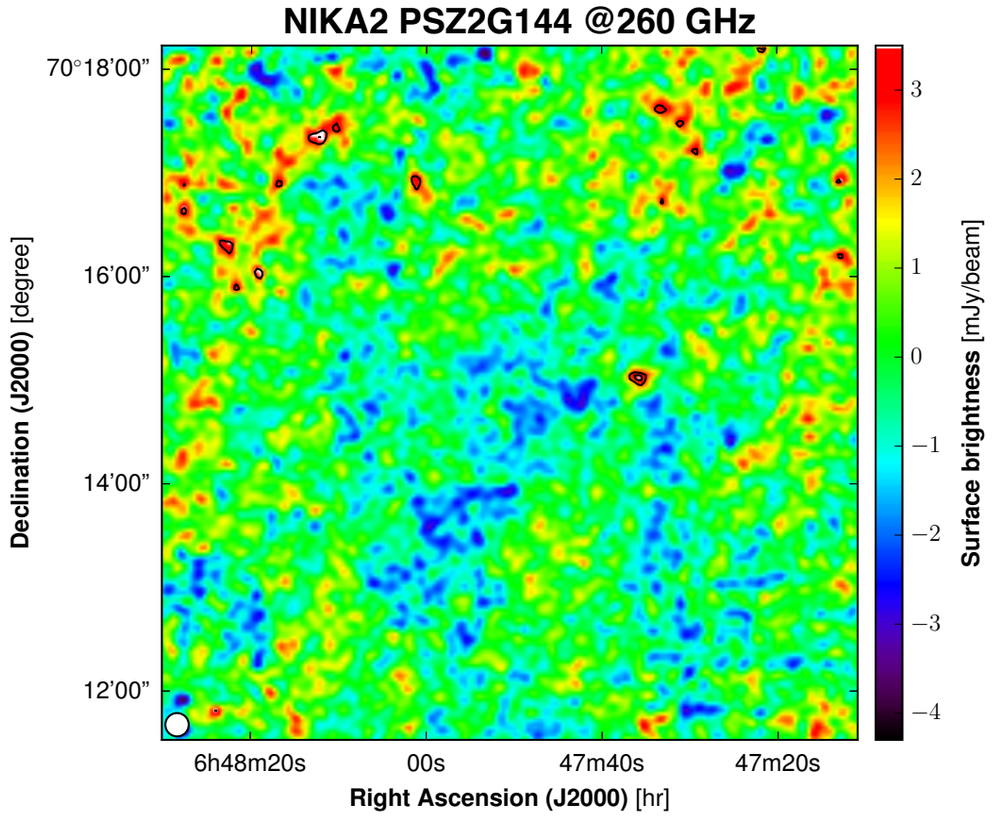
- Decorrelation method: compromise between residual noise on the map and signal filtering ⟶ iterative estimation of the common mode

Characterization of the raw maps

- **NIKA2 raw map at 150 GHz:**
  Significant negative tSZ signal up to ~1.4 arcmin
  Noise RMS at the map center (21”): $203\ \mu\mathrm{Jy/beam}$
  tSZ peak significance of 13.5σ

- **NIKA2 raw map at 260 GHz:**
  No significant tSZ signal detection (expected given the noise RMS)
  Noise RMS at the map center (13”): $933\ \mu\mathrm{Jy/beam}$
  Point source detected at 4σ





Very promising results for this first NIKA2 SZ observation

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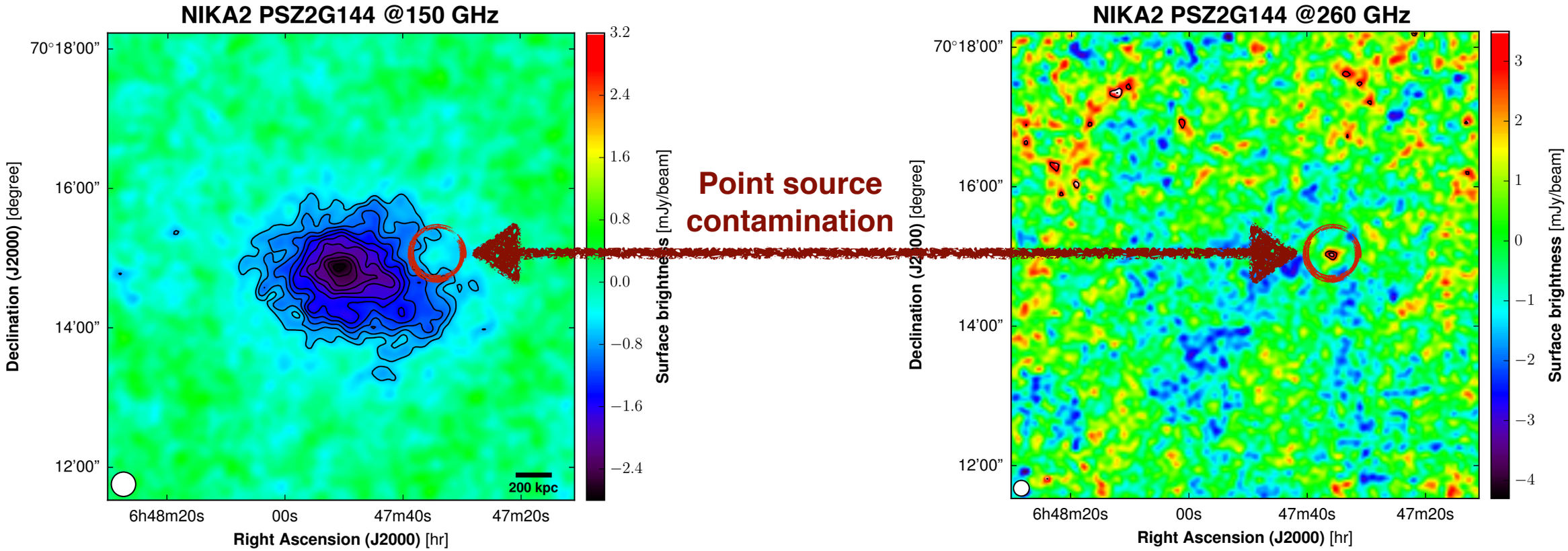

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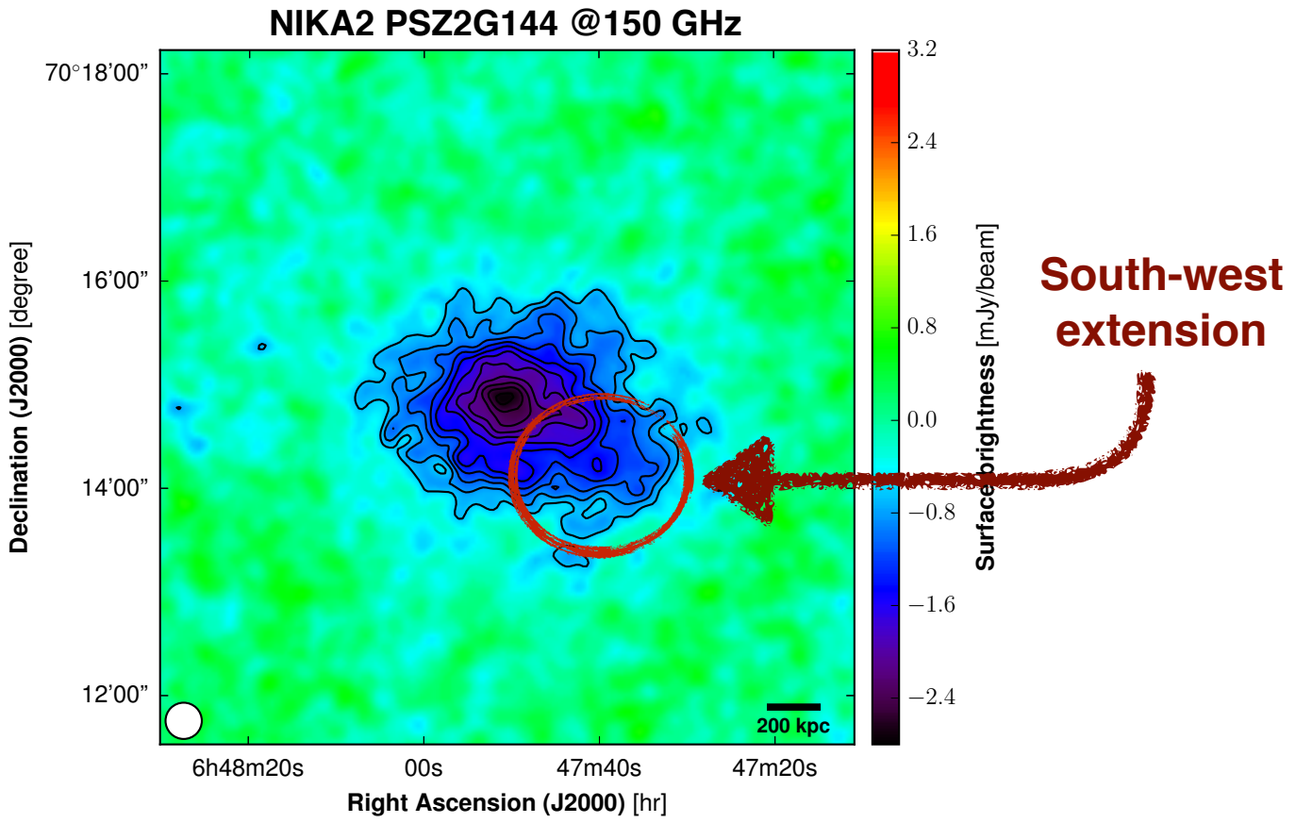
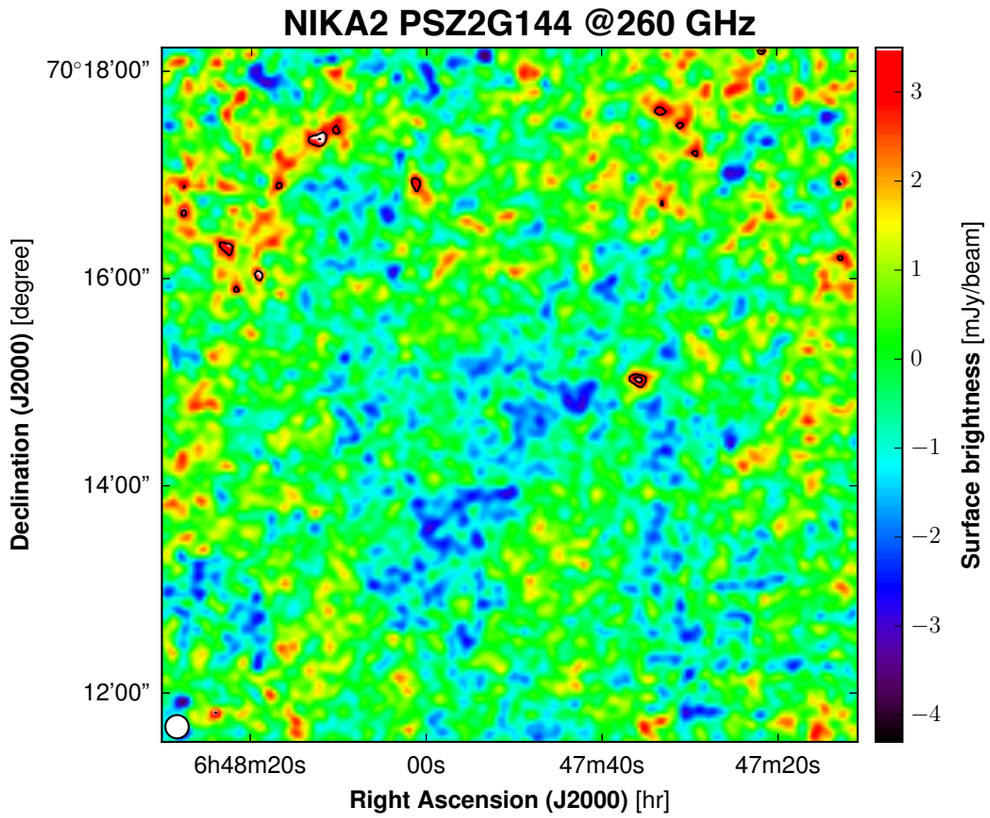
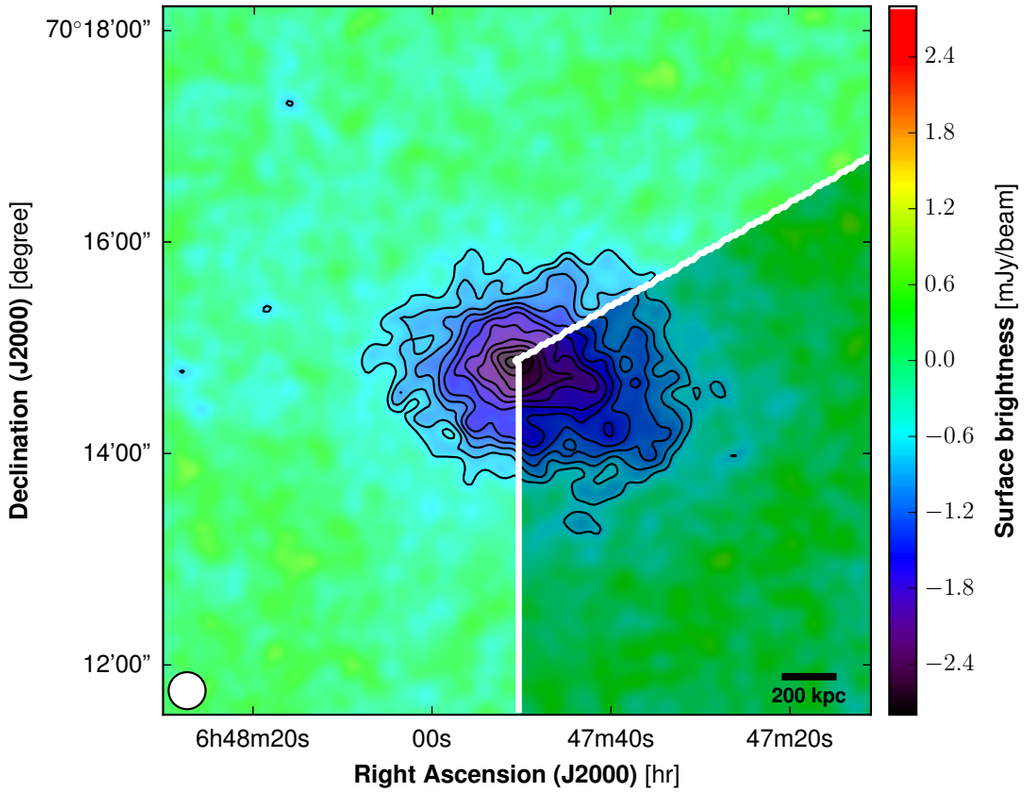




Very promising results for this first NIKA2 SZ observation

Over-pressure region

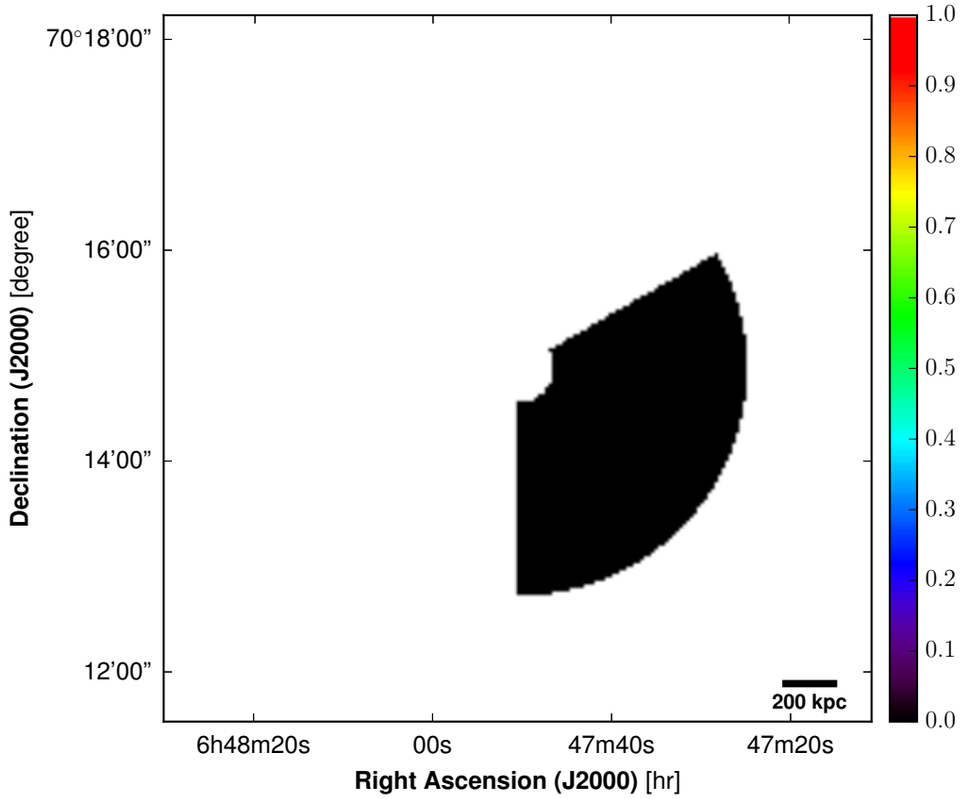


- Best sector that encloses the over-pressure region

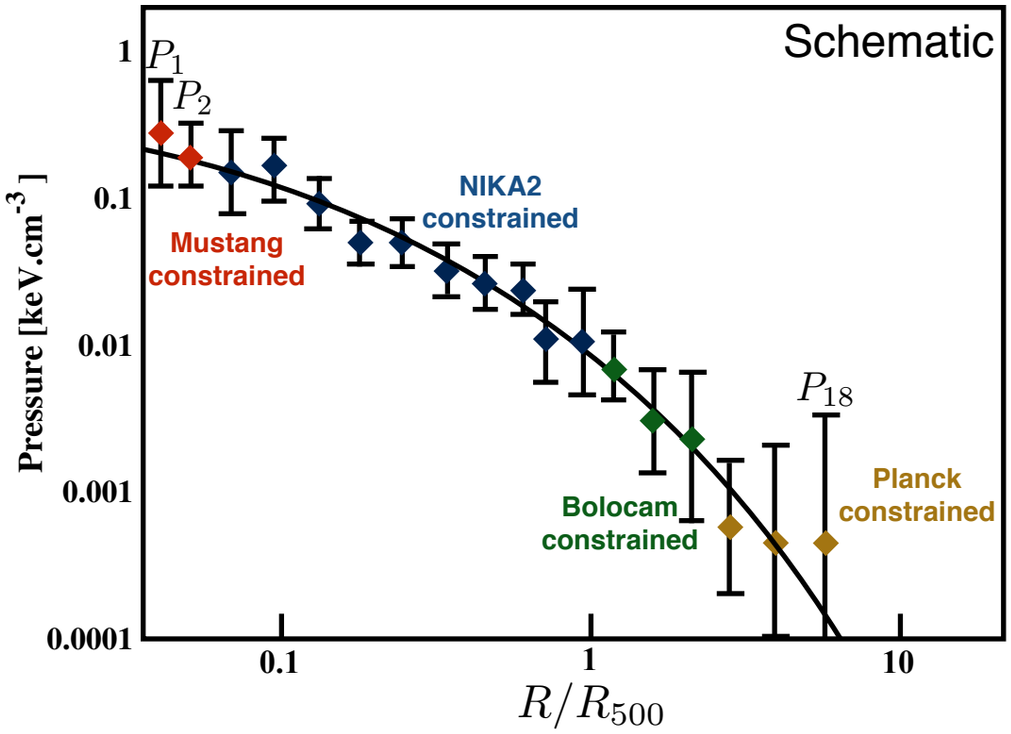
- ICM characterization with and without masking the over-pressure region

→ Systematic effect induced by the ICM perturbation ?

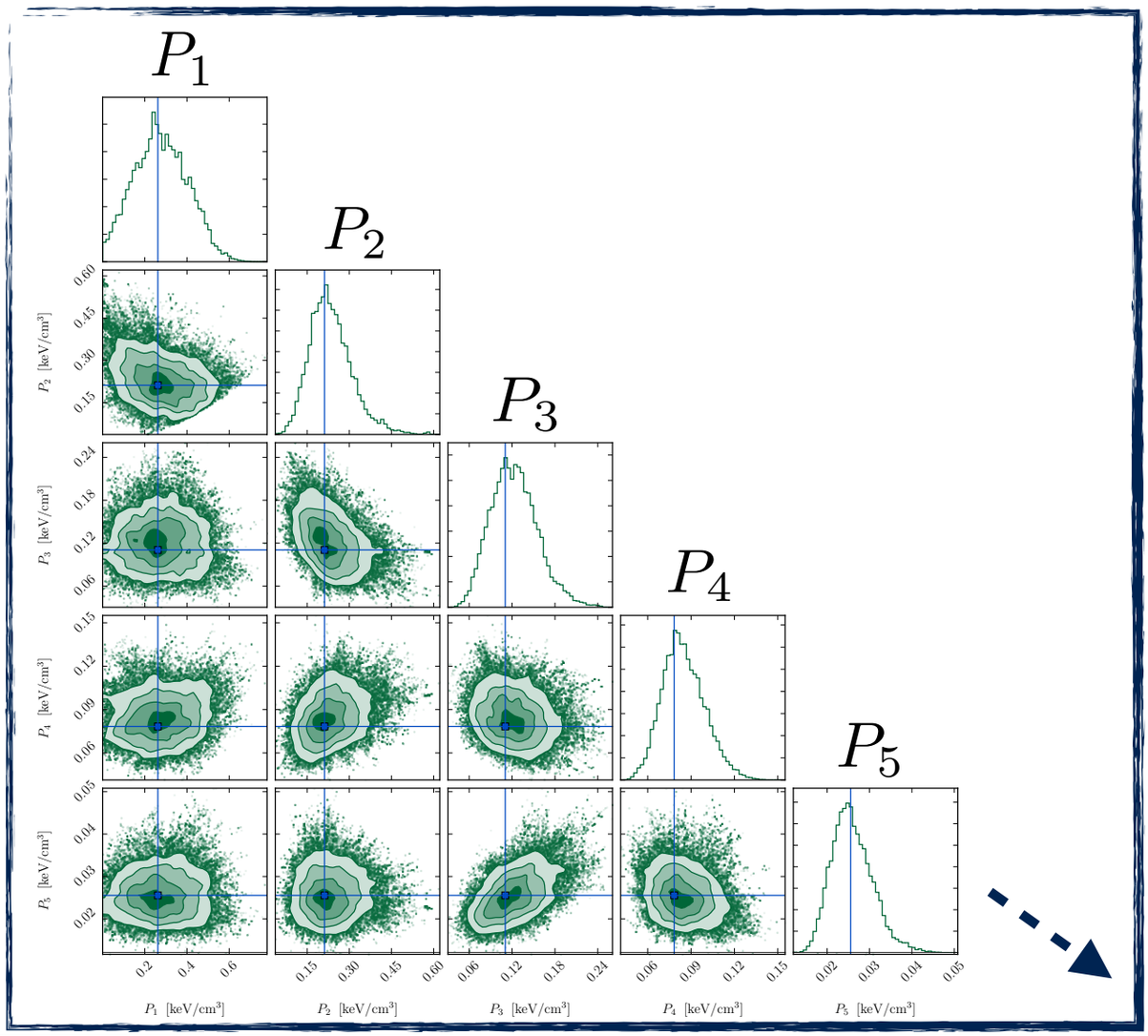
Final mask used for the ICM analysis



MCMC - non-parametric deprojection

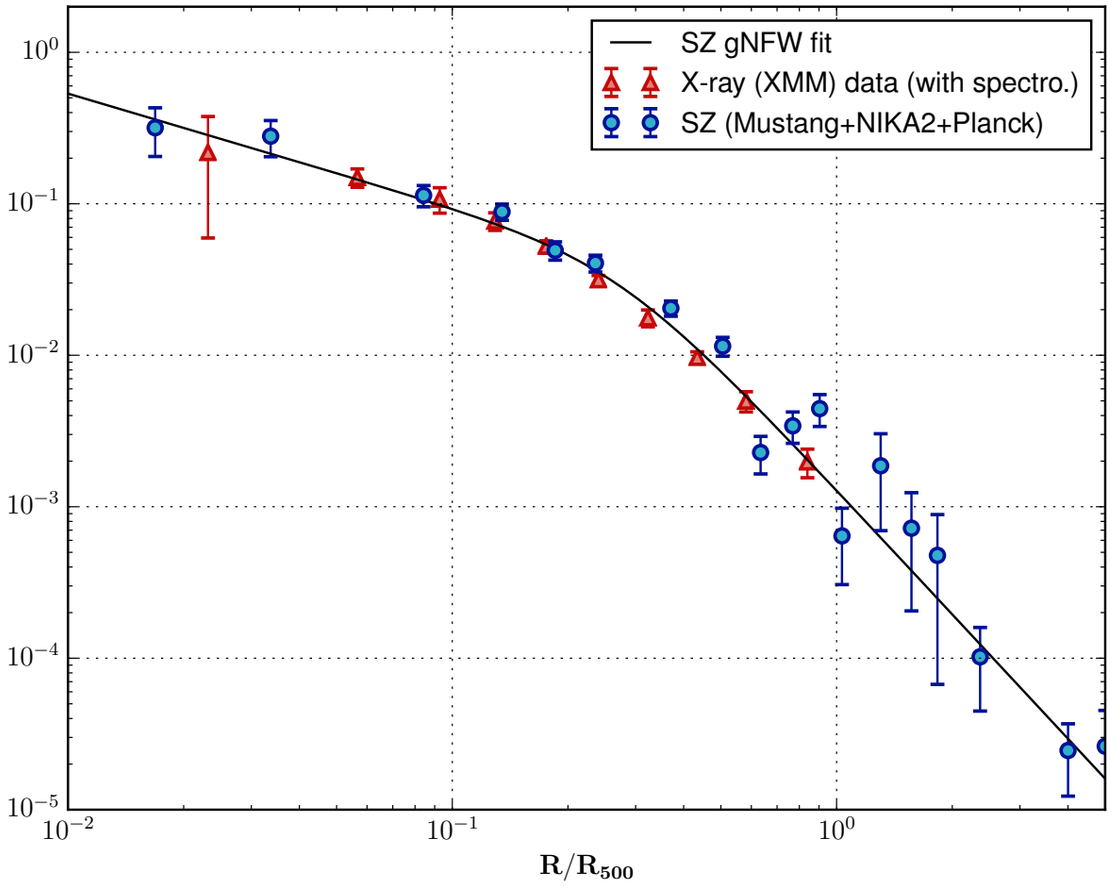


- **Goal:** Study the impact of the over-pressure on the ICM profiles
- **Methodology:** Constrain the pressure profile from a multi-probe analysis (Mustang, NIKA2, Bolocam, *Planck*, XMM-*Newton*)
- **Non-parametric** spherical model of the pressure profile
  18 constrained points
  interpolation with a power law between the points



- Markov Chain Monte Carlo analysis (MCMC):
  - Sampling of the pressure in each bin
  - Integration of the pressure profile along the line of sight
    SZ surface brightness map model
  - Comparison with the Mustang, Bolocam, NIKA2 and *Planck* SZ maps (*Likelihood function*)
- Strong correlations between neighboring points
  Taken into account in the error bar estimation

ICM profiles (Masking the over-pressure region)

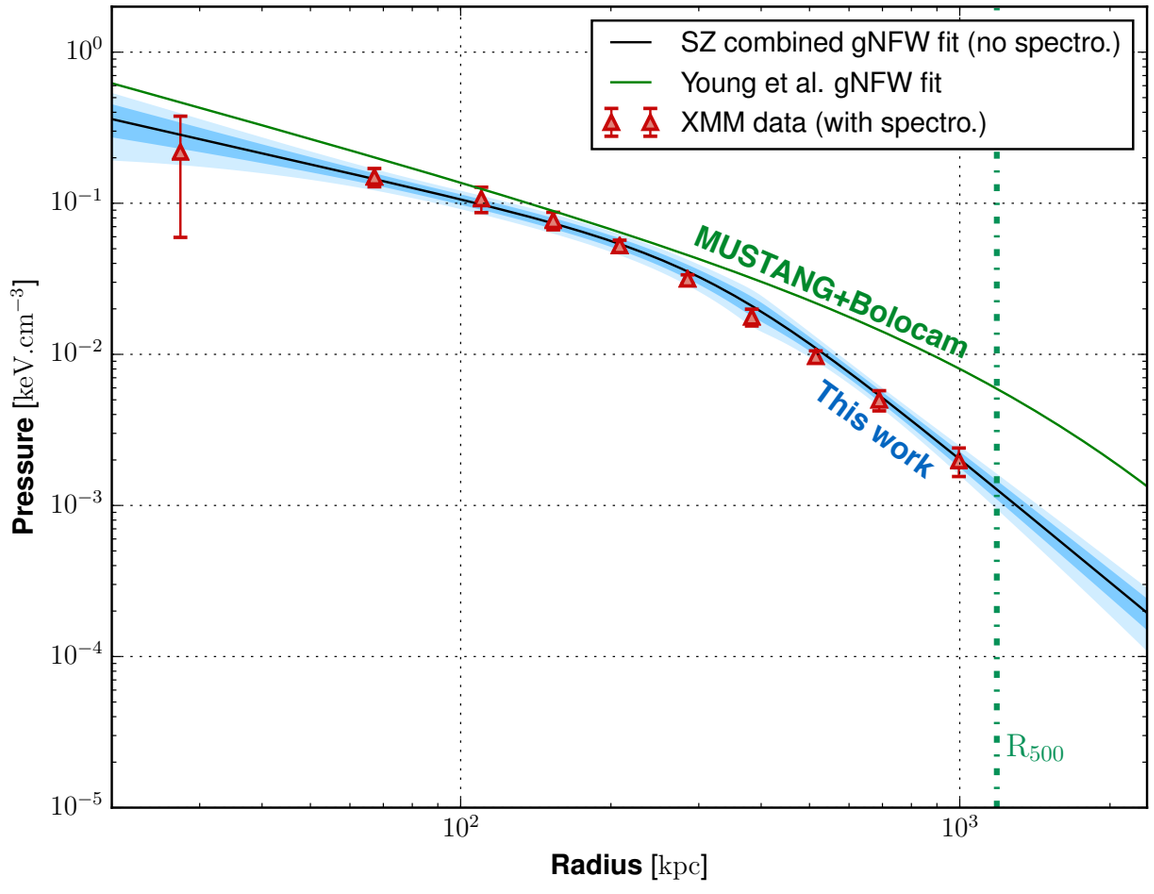


- **Pressure profile** at maximum Likelihood:
- Constraints on the pressure from the cluster center to its outskirts
- Compatibility with the pressure profile given by XMM-*Newton*
- Not compatible with the pressure profile from Young *et al.* 2014
  Over-pressure region not taken into account

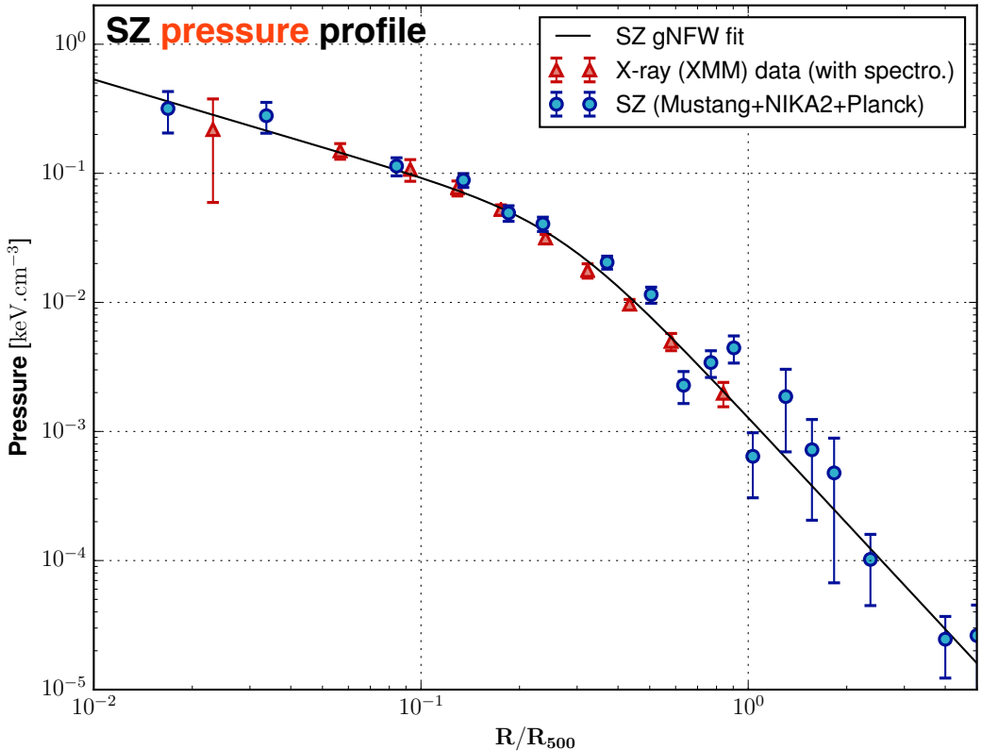
- **Estimates of Y_{500}**

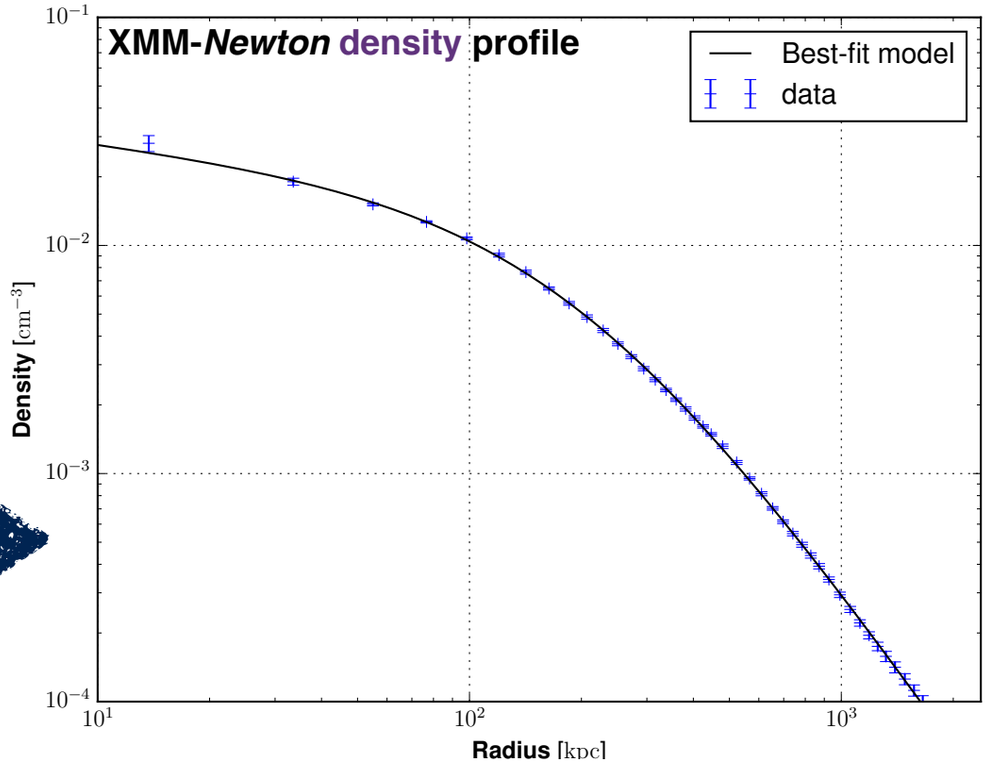
	Y_{500} [$\times 10^{-4}$ arcmin^2]
XMM-*Newton*	7.44
NIKA2	8.06 ± 0.46
MUSTANG+Bolocam	20.3

→ **impact of ICM perturbations on the tSZ flux**

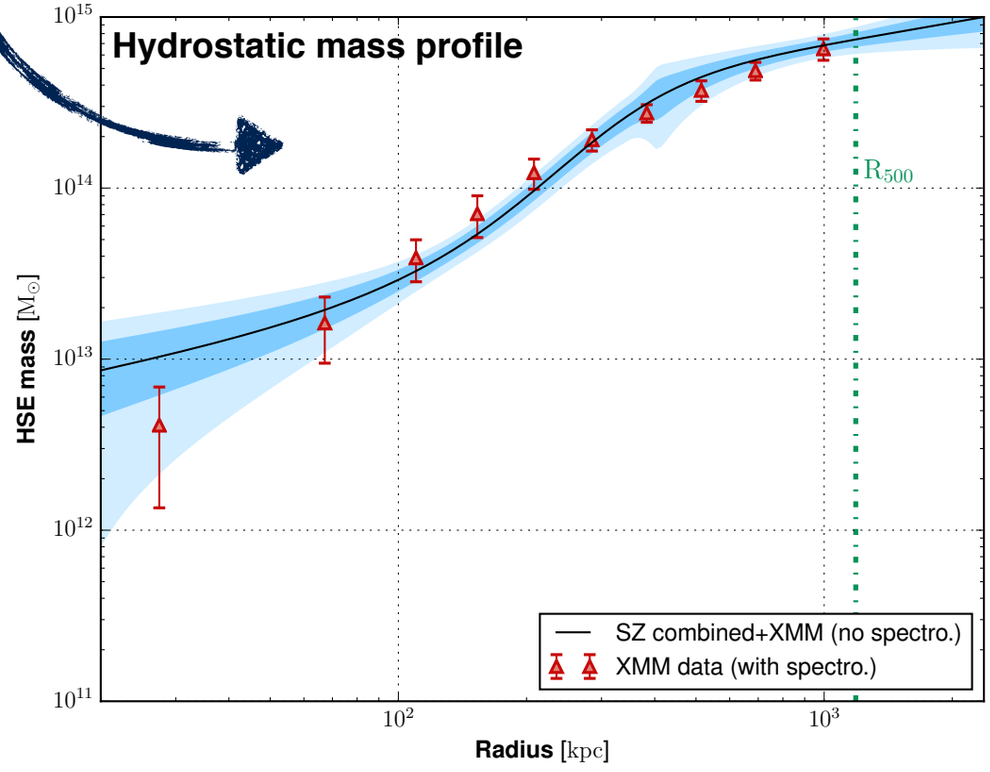


ICM profiles (Masking the over-pressure region)



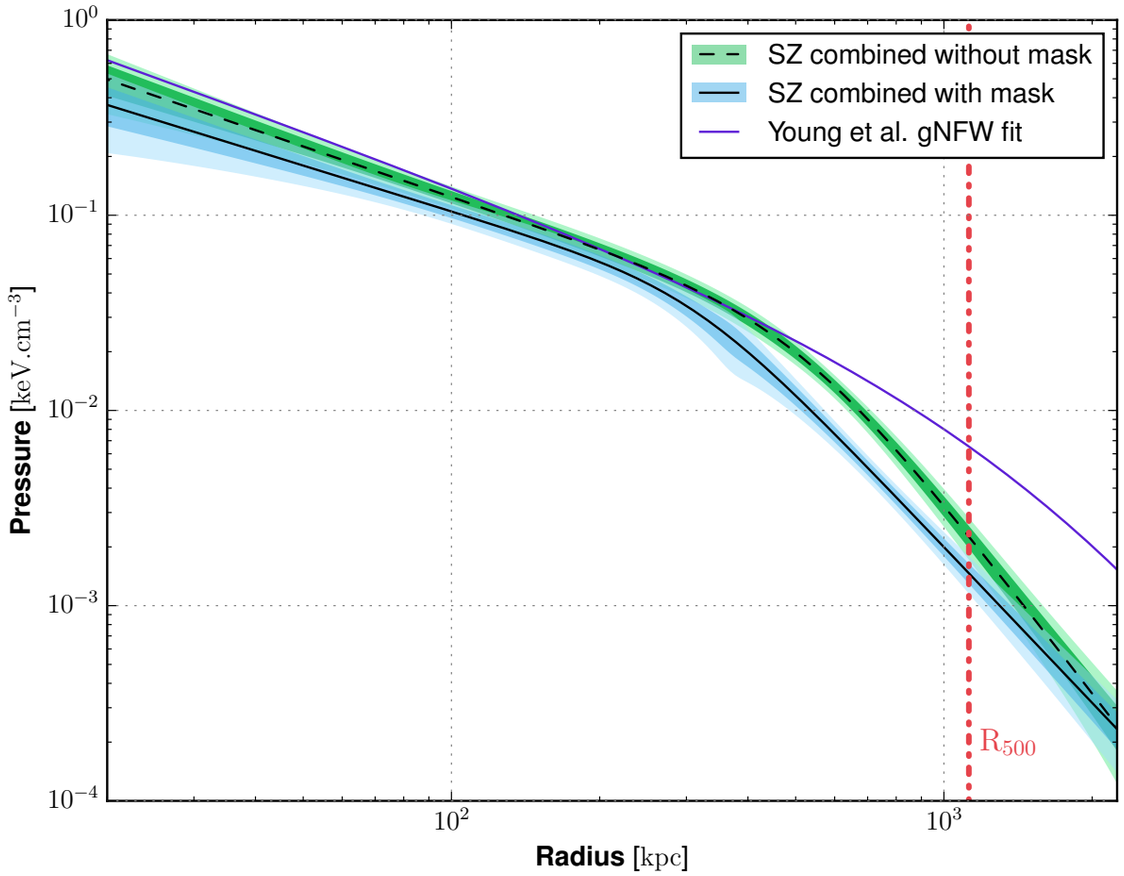


$$M_{\rm HSE}(r) \propto \frac{r^2}{n_e(r)} \times \frac{dP_e(r)}{dr}$$



- Constraints on the **ICM thermodynamic properties**:
  - Mass profile obtained without spectroscopy
    compatible with XMM-Newton (with spectro.)

Impact of the over-pressure region

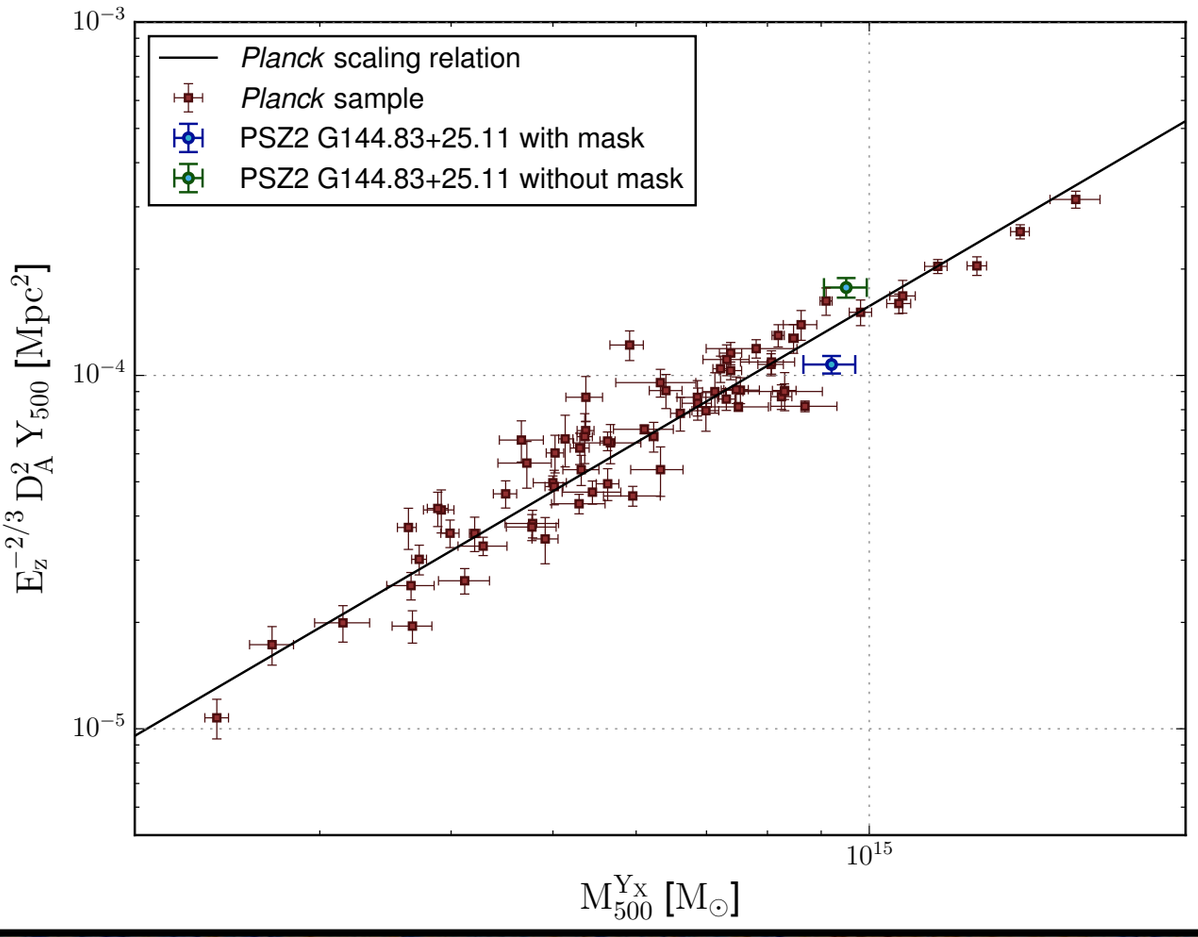


- Significant deviation from the universal pressure profile
  obtained from a sample of low-redshift clusters

Wrong estimate of the value of Y_{500}
⟶ cluster masses in cosmological analyses

- Significant difference between the pressure profiles obtained with and without masking the over-pressure region
- Impact on the integrated quantities used for the calibration of the tSZ-mass scaling relation

	With mask (unbiased)	Without mask (biased)
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



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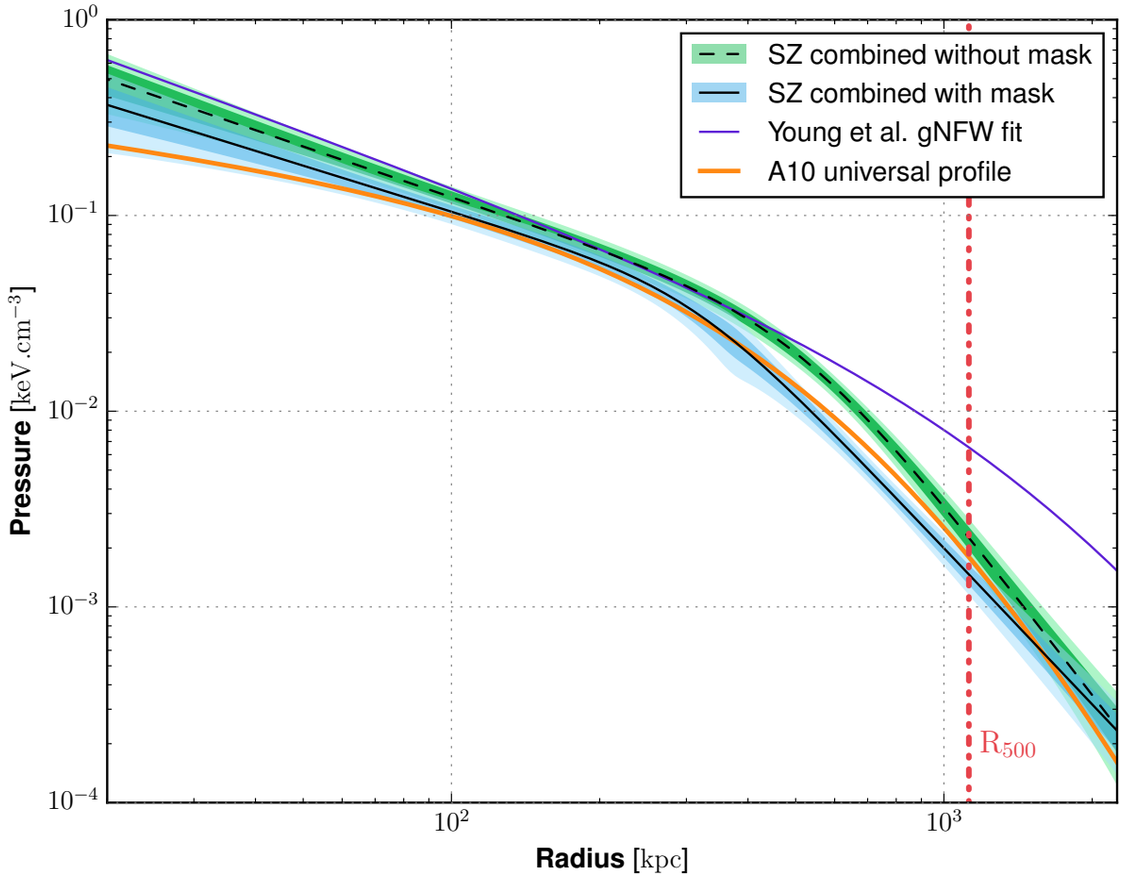

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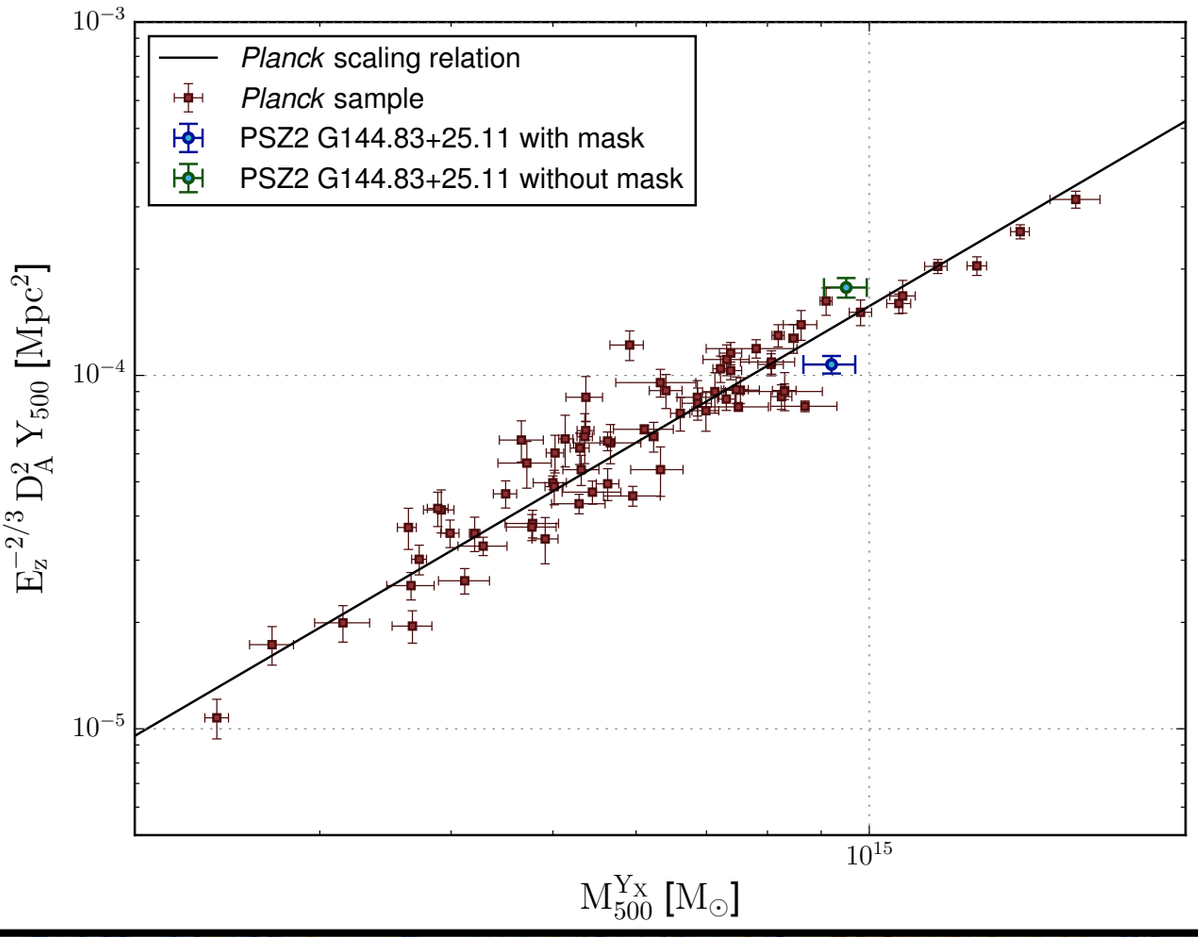

Conclusions

- **Cosmology studies based on SZ-selected cluster samples:**
  - Potentially biased by misunderstood astrophysical processes at intermediate and high redshifts

    → High angular resolution SZ observations at high redshift are essential

- **NIKA2 SZ large program:**
  - High angular resolution SZ observations of 50 clusters at high redshift in the forthcoming years

    → Redshift evolution of the pressure profile and $Y_{500} - M_{500}$ scaling relation

- **First SZ observations with NIKA2:**
  - Mapping of the tSZ signal up to 1.4 arcmin at high angular resolution

    → { High potential for the identification of disturbed ICM regions
    High constraining power of the pressure profile in the intermediate regions of the ICM

  - Tight constraints on the ICM thermodynamic properties (SZ + X-ray)

    → Impact of the gas dynamics on the integrated quantities used for cosmology

The NIKA2 SZ large program has started and the first results are very promising

Thank you