Mapping the intracluster medium temperature in the era of NIKA2 and MUSTANG-2

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In collaboration with: The NIKA2 and MaDCoWS cluster teams

mm Universe @NIKA2 — June 28, 2021

Formation of galaxy clusters

Impact of Mergers and Feedback on ICM temperature

Mapping the ICM temperature at high redshift

Joint X-ray / SZ analyses of MaDCoWS clusters

Mapping ICM temperature without X-rays

Detecting the rSZ effect

Conclusions / Perspectives

Bridging the gap between Chandra—XMM and Lynx—Athena

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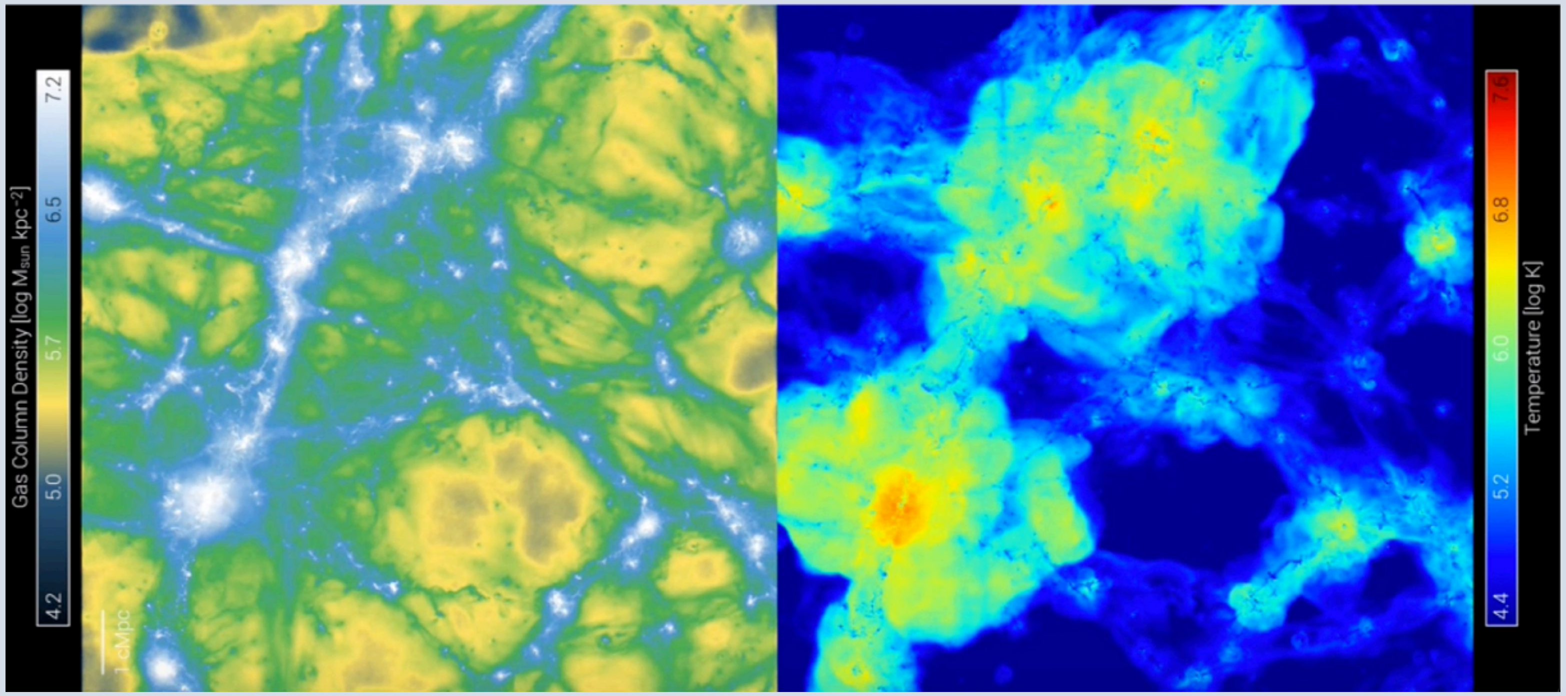

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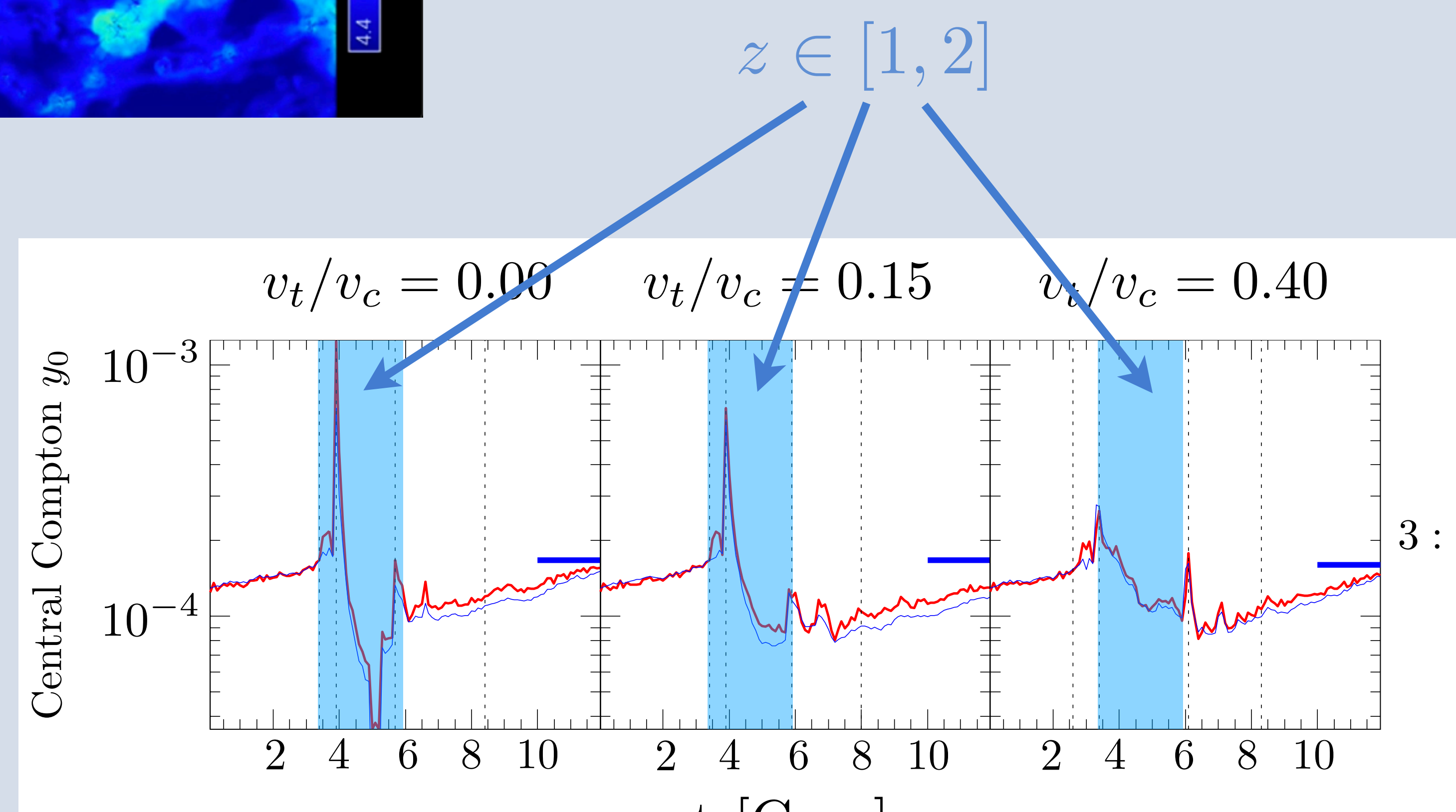
Growth of galaxy clusters:

- Smooth accretion of surrounding material
  ⟶ **linear regime**
- Merger events with substructures + Stabilization of gravitational collapse
  ⟶ **non-linear regime**



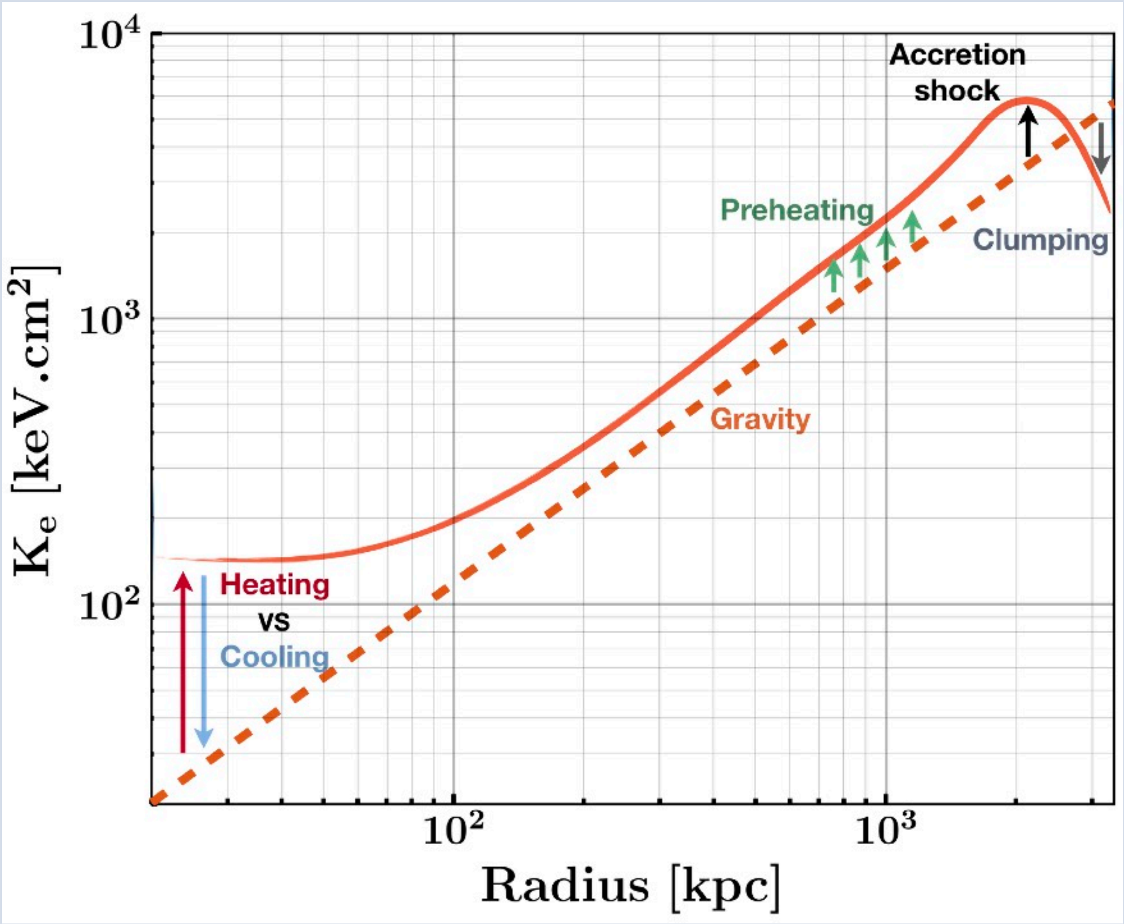
Poole *et al.*, MNRAS (2007)

Galaxy cluster mergers and SZ effect:

- Large variations of Compton parameter with time
- ICM pressure most rapidly evolving at $1 < z < 2$

> Analysis of ICM thermodynamic properties at $z > 1$ essential to understand structure formation

Constraining cluster models with ICM observations

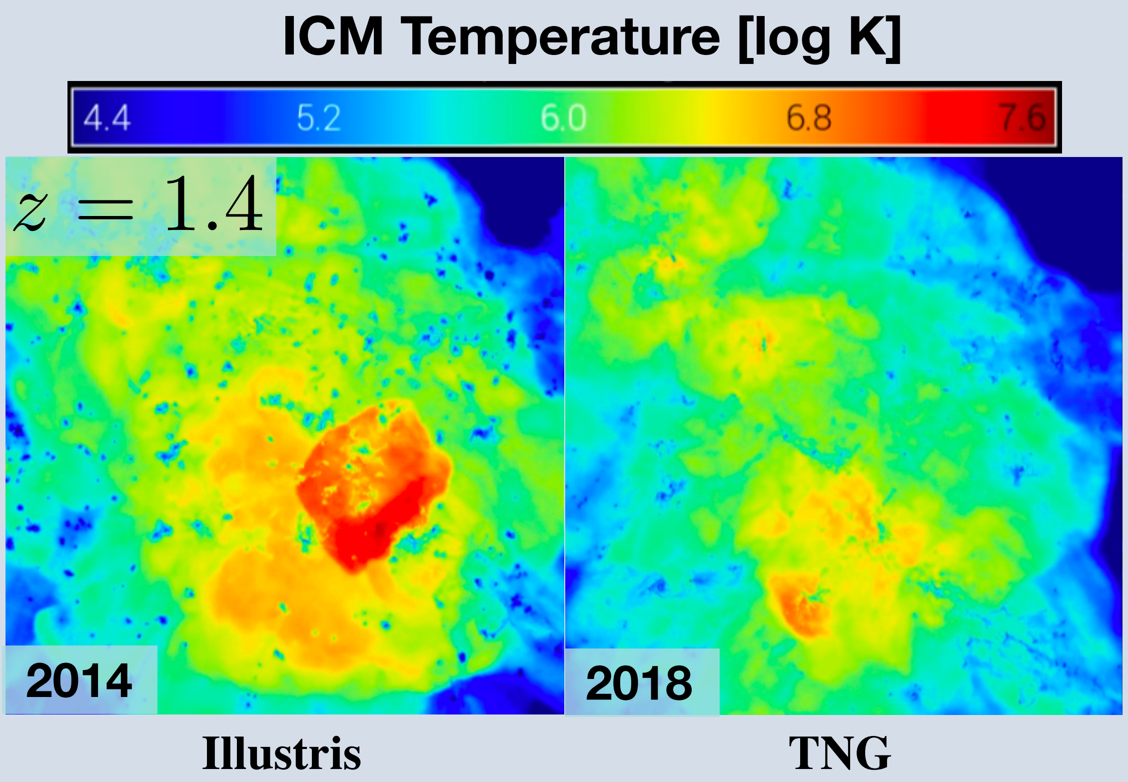


Radial distribution of gas entropy:

SZ effect X-rays

$$K_e(r) = P_e(r)/n_e(r)^{5/3}$$

- Shape and amplitude: energy inputs in the ICM



ICM temperature map:

SZ effect X-rays

$$k_B T_e(x,y) = P_e(x,y)/n_e(x,y)$$

- Thermalization of merging substructures with the main halo
- AGN feedback / shock fronts / turbulence

Need high-angular resolution X-ray/SZ observations at $z > 1$

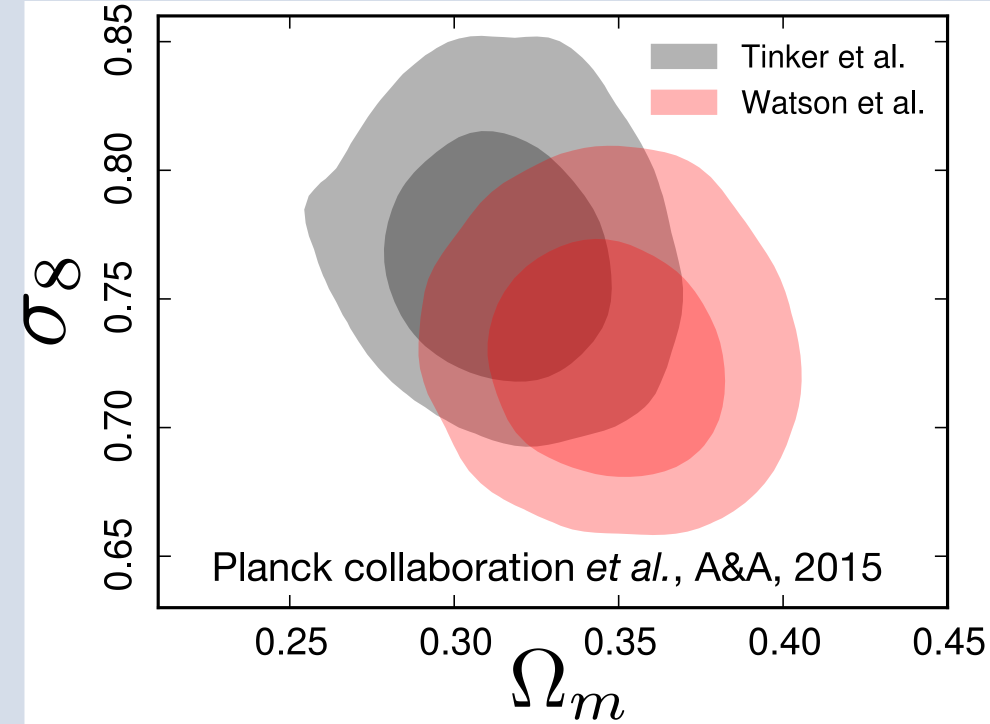
→ Improvement of ICM models

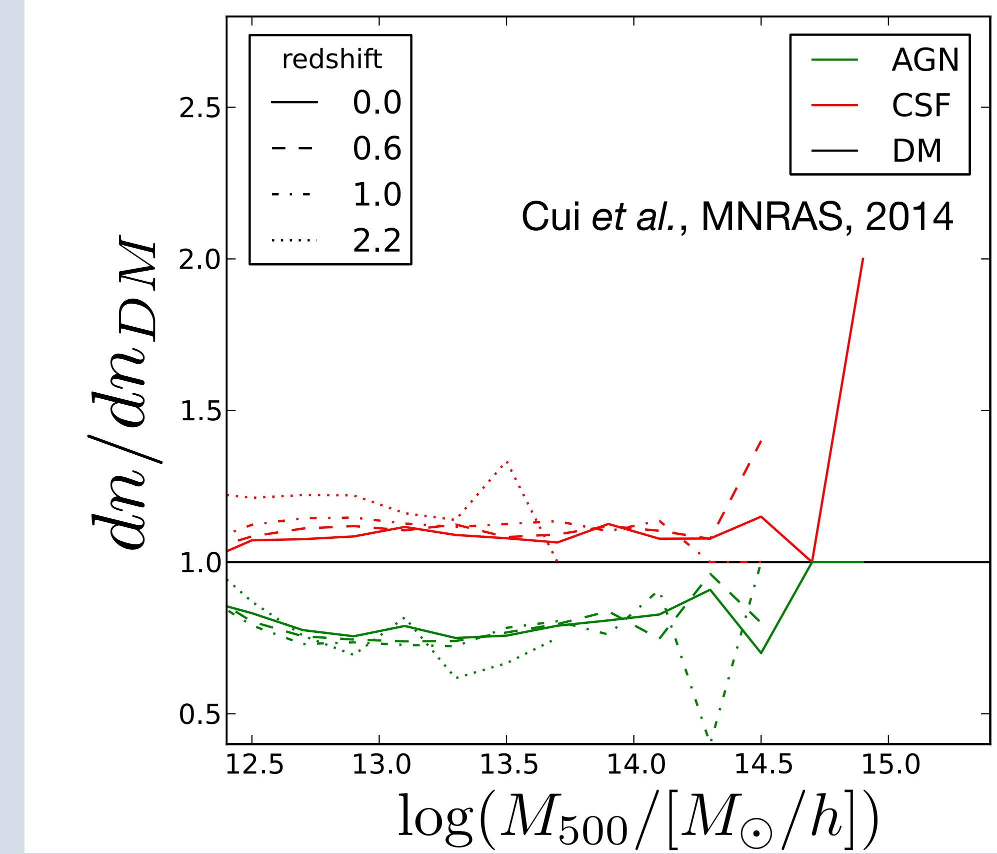
Systematics on the cluster mass function

Mass function: $\frac{dn}{dM_{500}}$

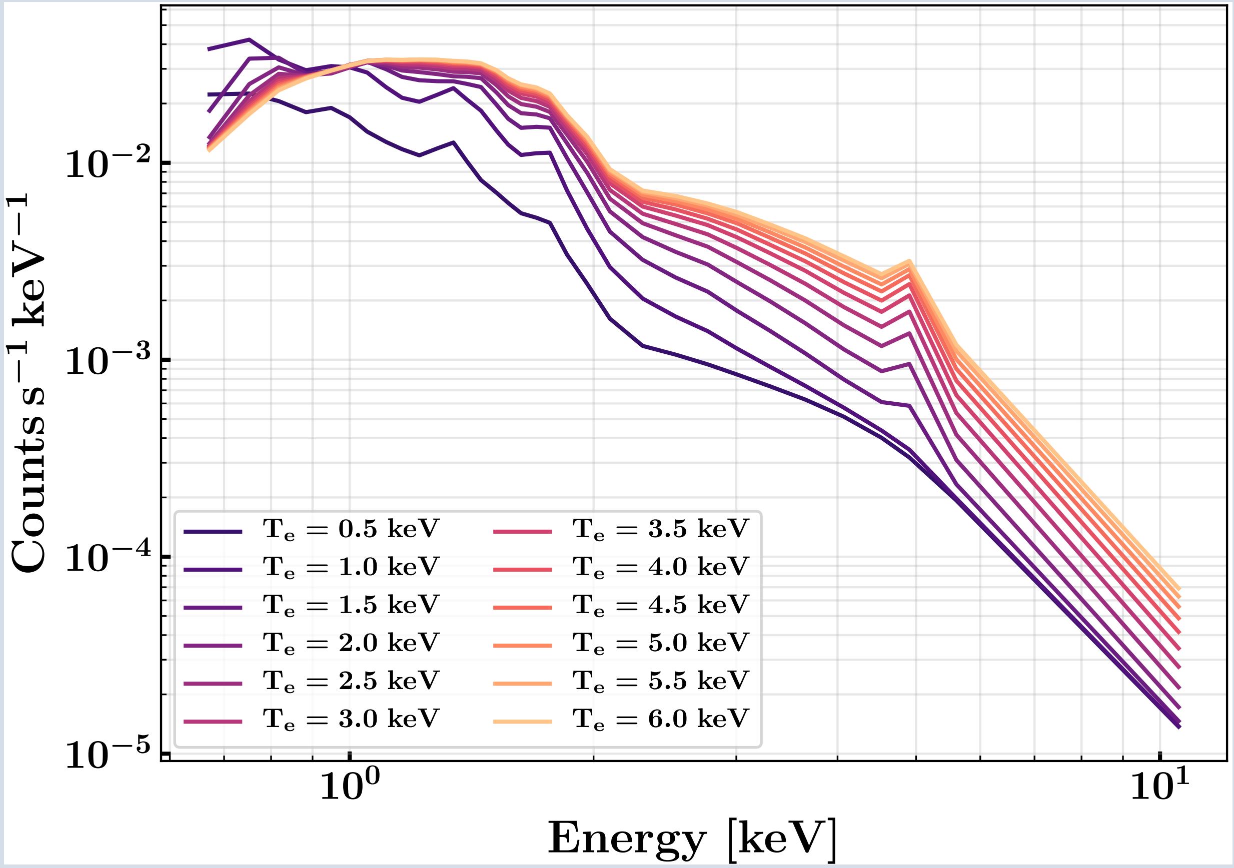
- Calibrated from numerical simulations *(mostly N-body)*
- Cosmological impact *(significant for next generation surveys)*
- Hydrodynamic simulations: different cluster abundance
  Impact of gas properties and feedback on cluster abundance
- Not enough knowledge on: - AGN feedback
  - heat dissipation within the ICM

→ Observational priors to improve cosmological simulations



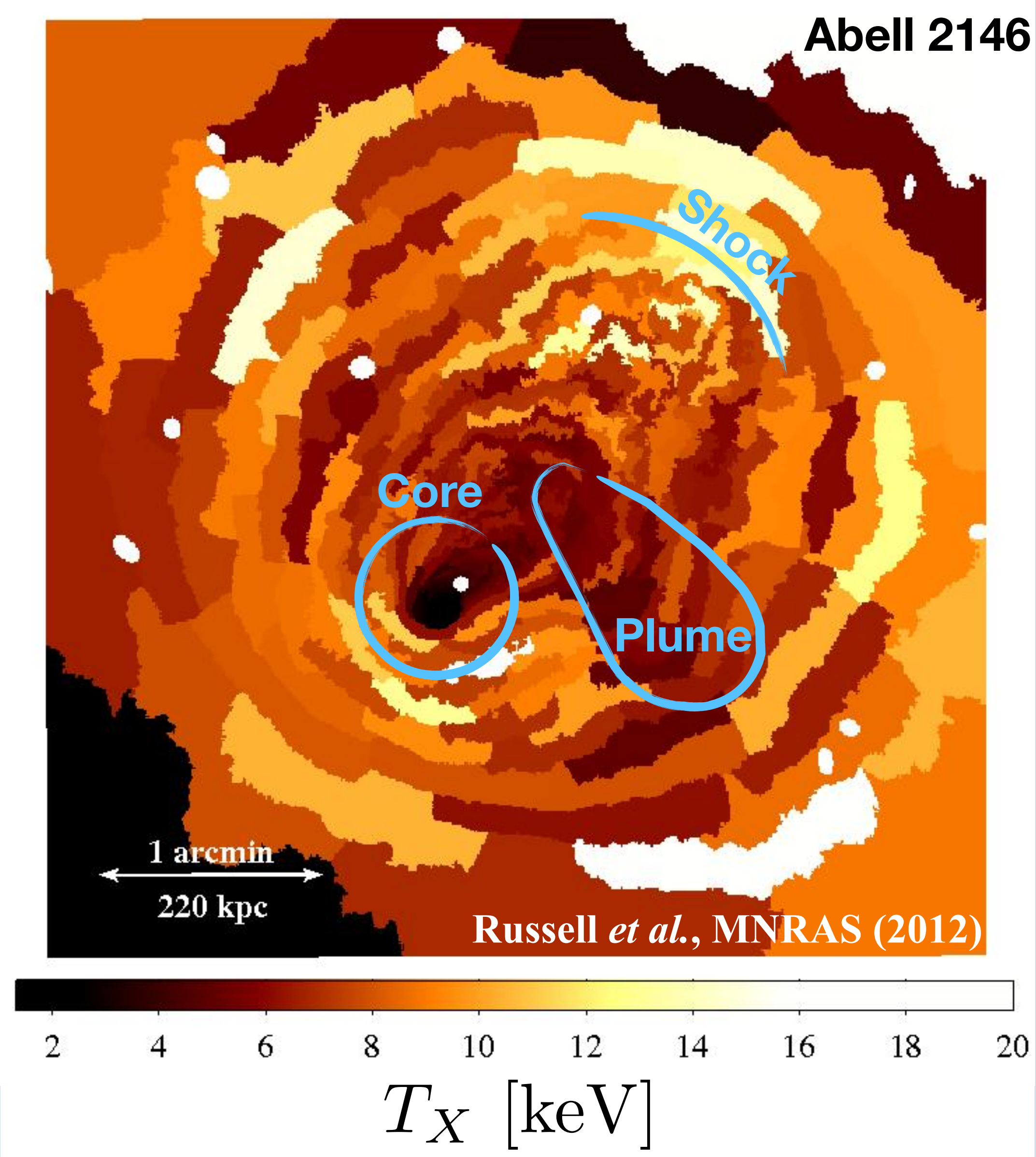


Mapping the ICM temperature with X-ray observations



X-ray temperature:

- Parameter of a model of the measured X-ray spectrum



- Degeneracy with: - hydrogen column density
  - ICM density and metallicity
- Potential calibration bias *(difficult to correct in space)*
- Need ~ 1000 counts for a good estimate of T_X

X-ray temperature map: only feasible for massive low-redshift clusters with current instruments

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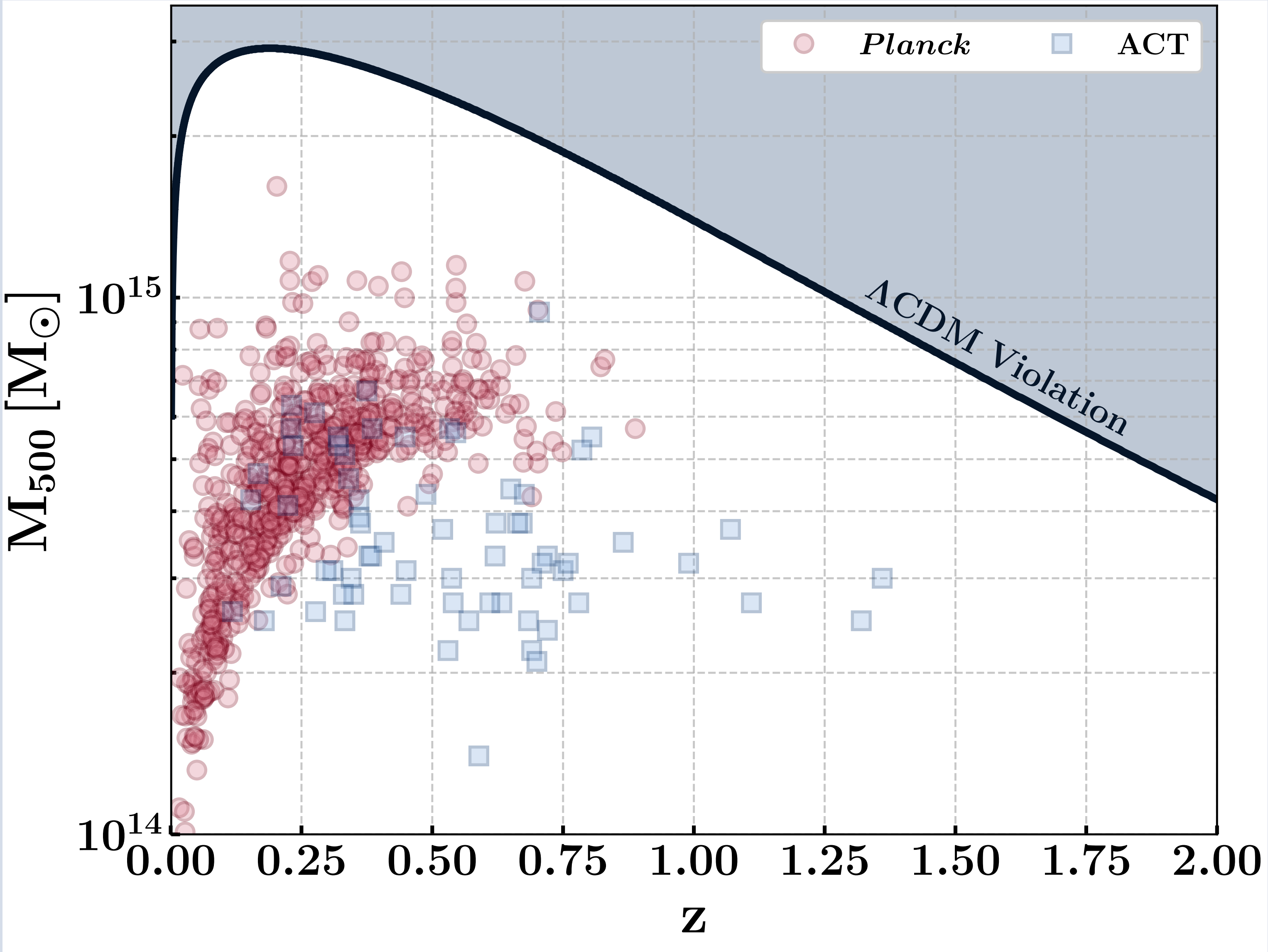
Building a sample of z > 1 galaxy clusters

SZ-detected clusters observable by NIKA2 and MUSTANG-2 ($\delta > -10^\circ$)

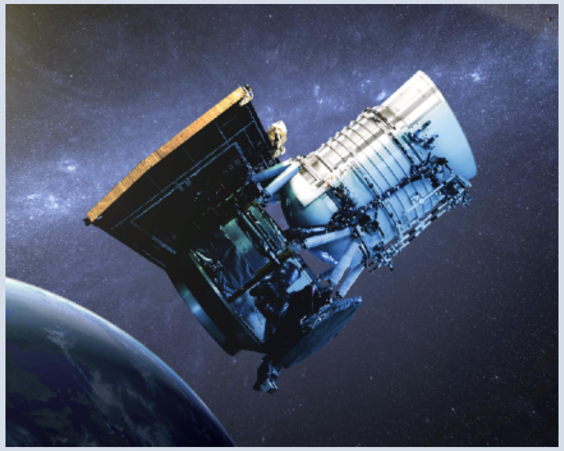
- No Planck-detected clusters at $z > 1$
- Only 4 ACT-detected clusters at $z > 1$ *(in 2019)*

Need to consider optical / IR selection to build our sample



MaDCoWS survey: massive clusters at high redshift

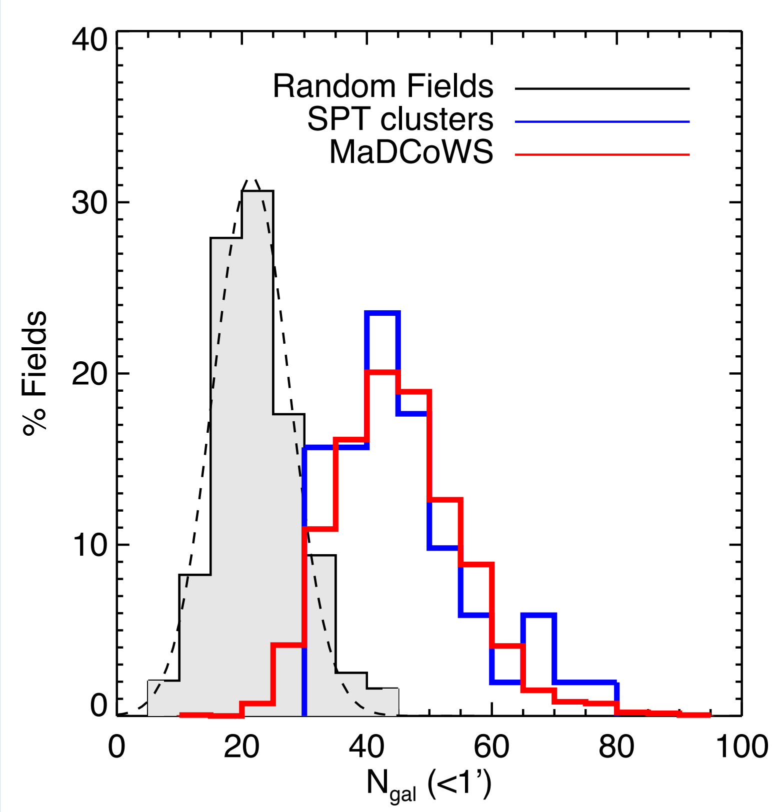
MaDCoWS: The Massive Distant Clusters of WISE survey



- WISE: Wide-field Infrared Survey Explorer
- All-sky survey at $3.4, 4.6, 12,$ and $22\ \mu\mathrm{m}$
- Cluster detection: galaxy overdensities using WISE and optical data *(PZWav)*
- Confirmation: - Gemini + Keck spectroscopy → redshift
  - CARMA → SZ mass *(scaling relation)*

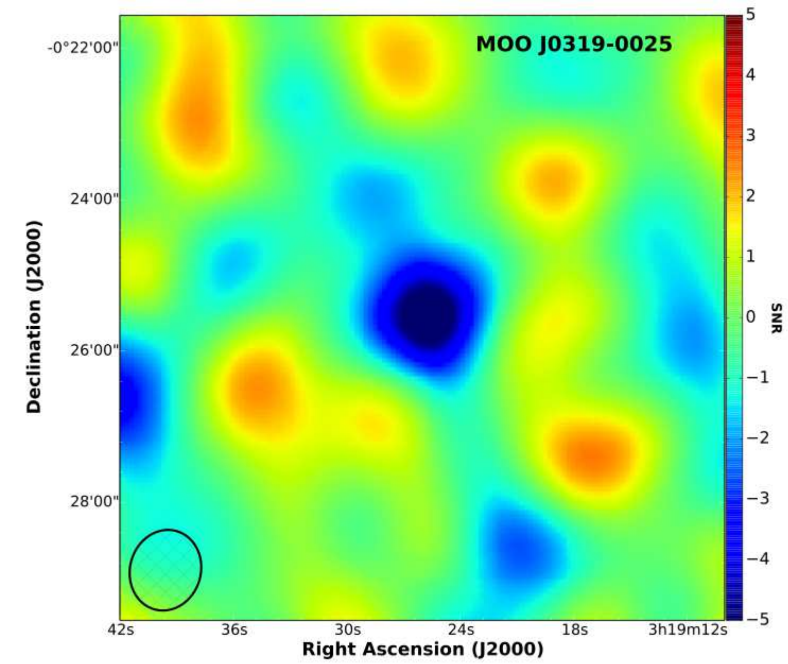
MaDCoWS

2433 density peaks in the WISE—Pan-STARRS region

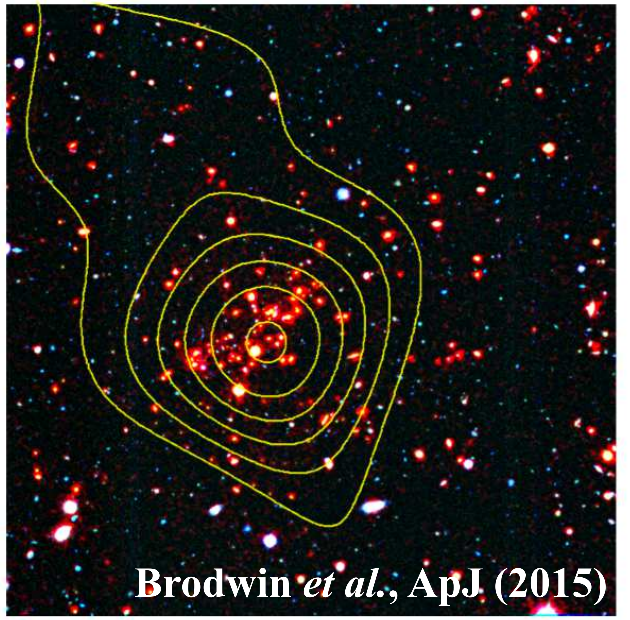


Gonzalez *et al.*, ApJS (2019)

CARMA



Gemini/GMOS-N + *Spitzer*/IRAC



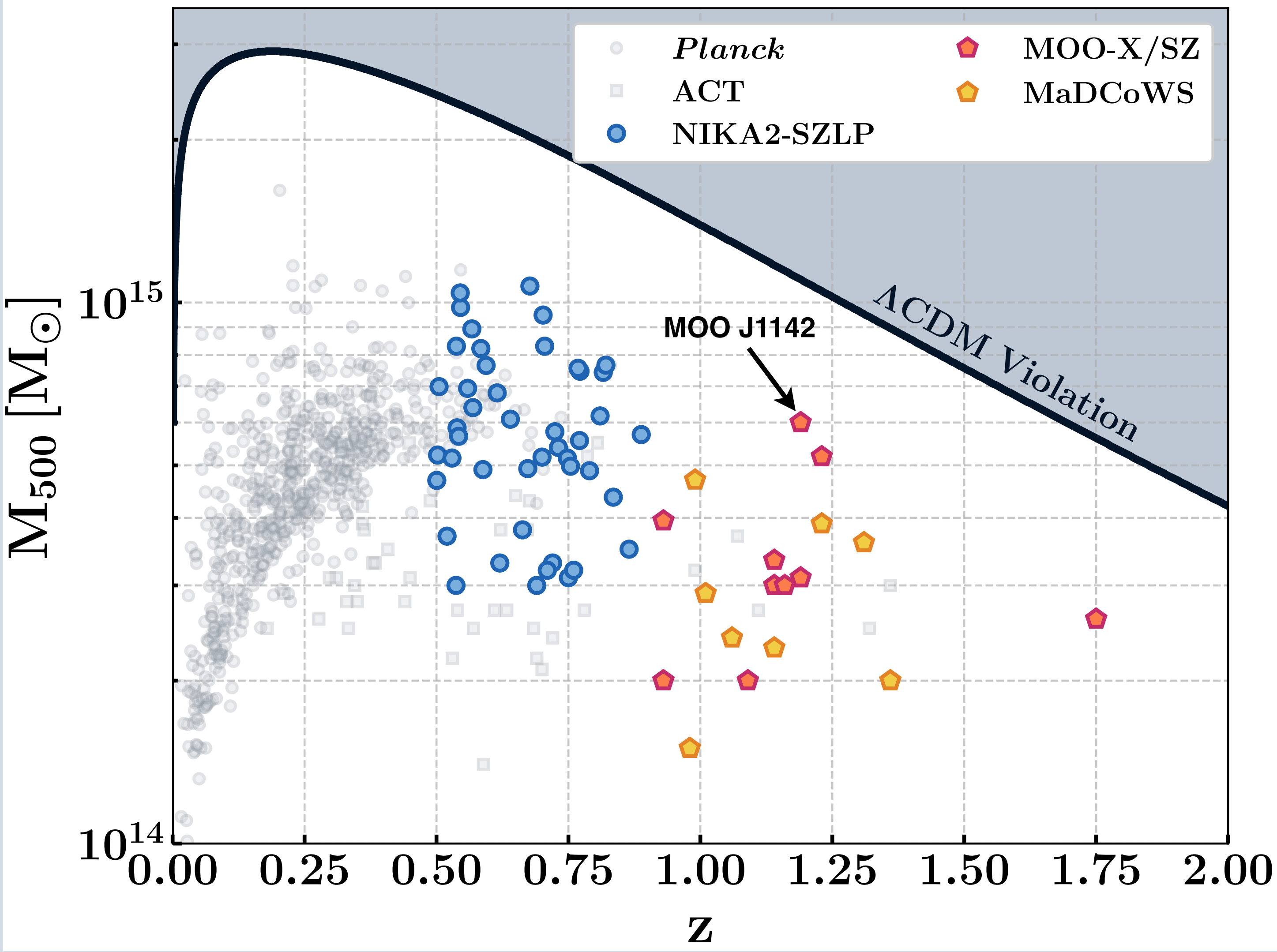
Observing clusters at z > 1 with NIKA2

X-ray and SZ observations at z > 1:

- Sample of 10 clusters

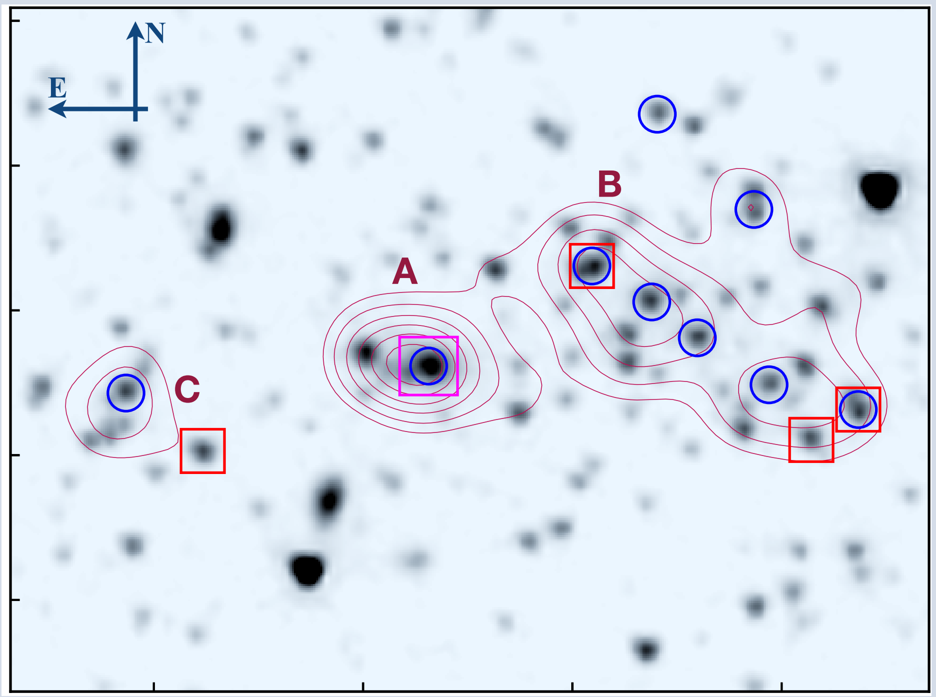
3 MOO-X/SZ proposals:
- OT with NIKA2: MOOJ1142 *(observed by Chandra)* ✓
- OT with NIKA2: 5 clusters observed by *Chandra* ✓
- LP with *Chandra*: 4 clusters observed by MUSTANG2 ✓

Goal: Study merger dynamics and evolution of ICM thermodynamic properties **at z > 1**



Most massive cluster known at z > 1.2

in Infrared



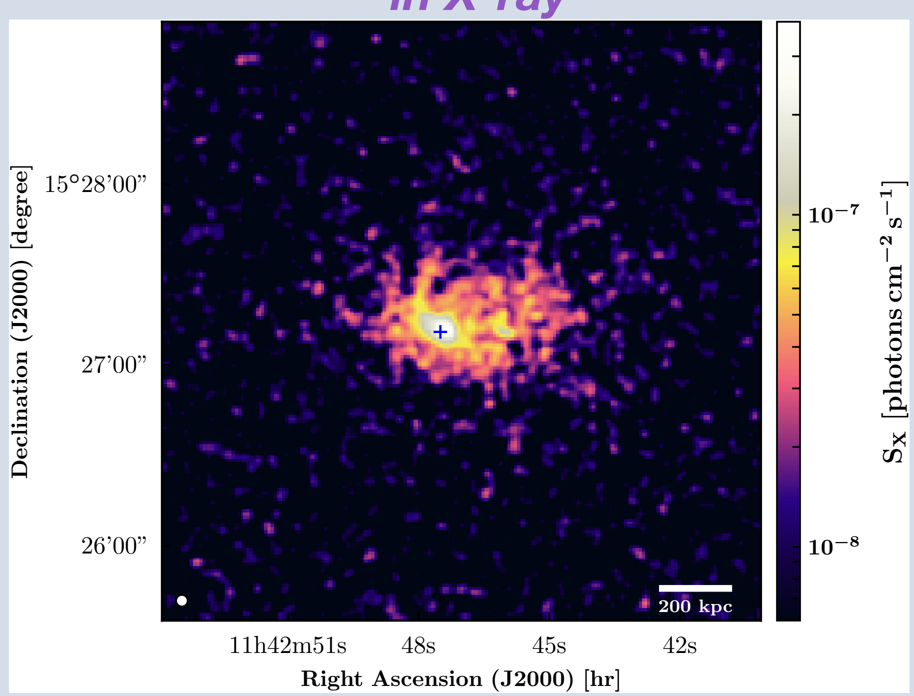
The case of MOO J1142: merging galaxy cluster at z = 1.2

- High-angular resolution follow-ups:
  - In IR with *Spitzer* (IRAC $3.6\ \mu m$)
  - In X-ray with *Chandra* (ACIS-I)
  - In SZ with NIKA2
- Two main galaxy structures A and B
- X-ray peak coincides with brightest cluster galaxy (A)

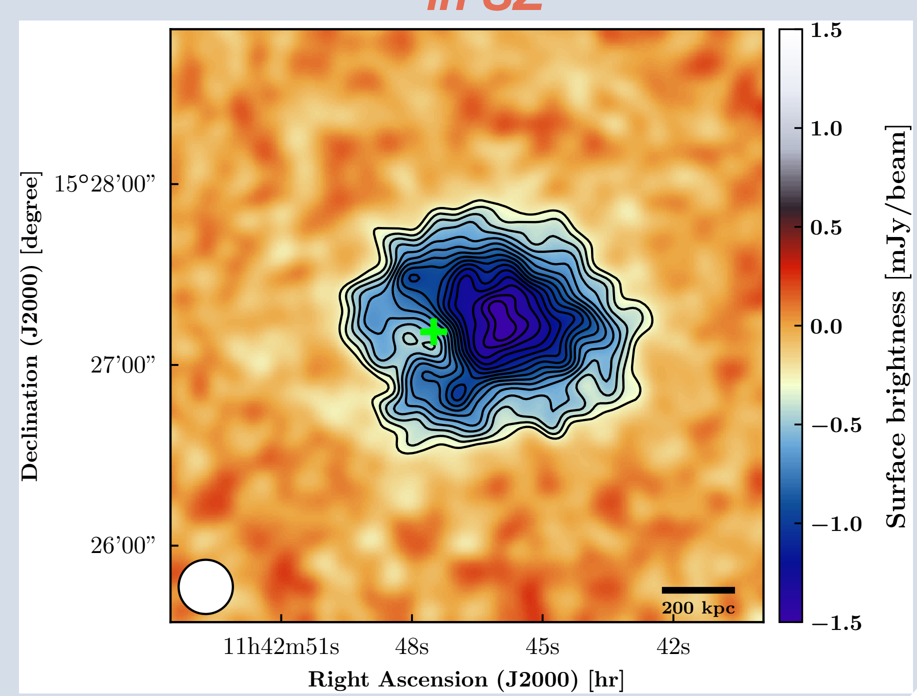
- Radio source at the X-ray peak *(cancel SZ signal)*
- SZ peak between A and B

Merging cluster with a cool-core

in X-ray



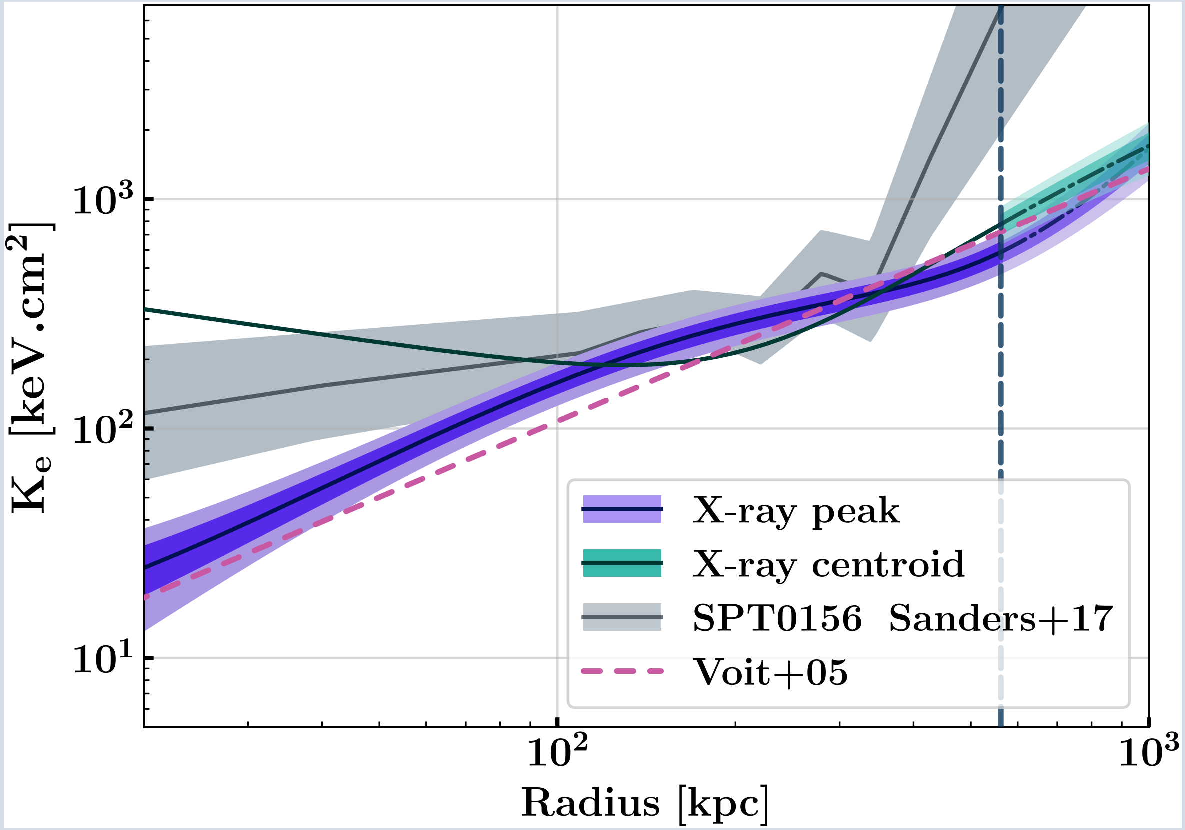
in SZ



ICM entropy profile and temperature map

NIKA2 Chandra

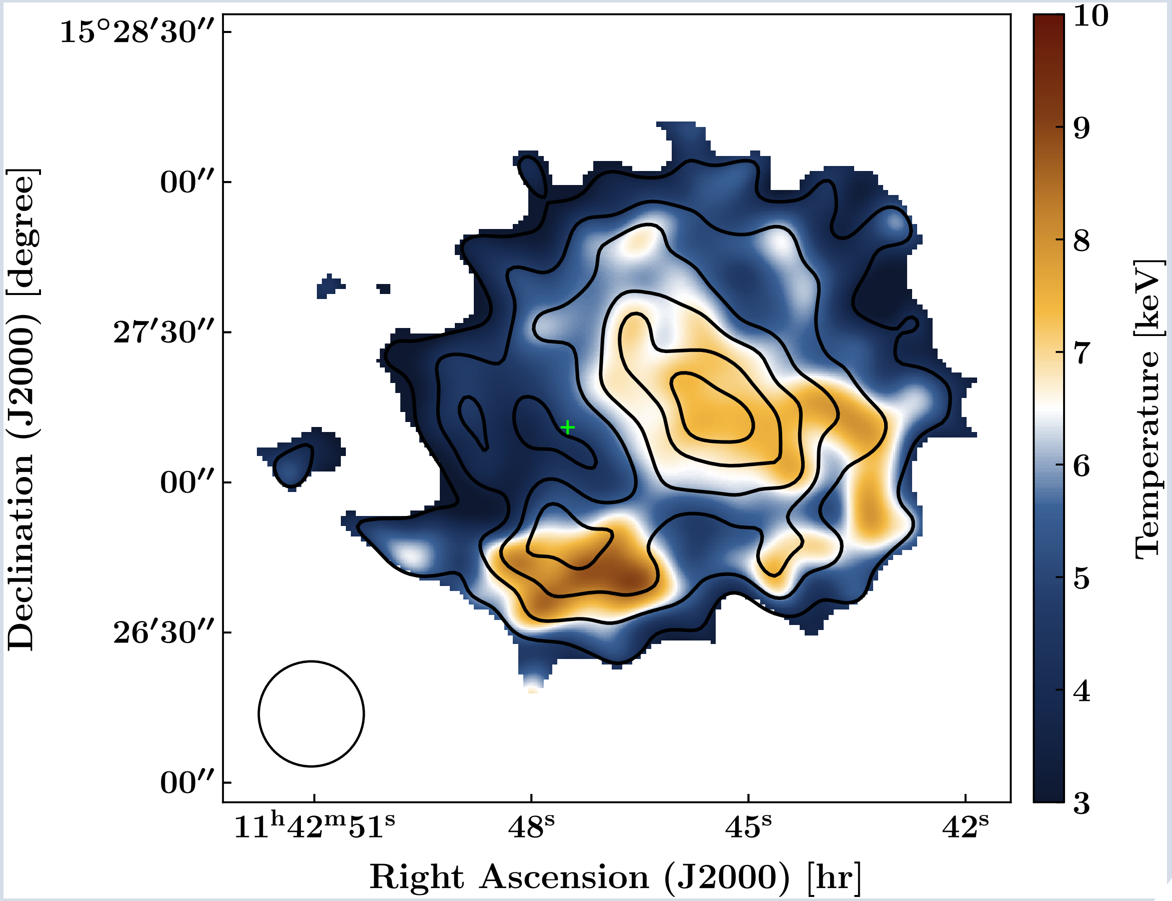
Entropy: $K_e(r) = P_e(r)/n_e(r)^{5/3}$



- **X / SZ pipeline**: joint analysis of NIKA2 and *Chandra* data
- Entropy profiles + temperature maps

NIKA2 Chandra

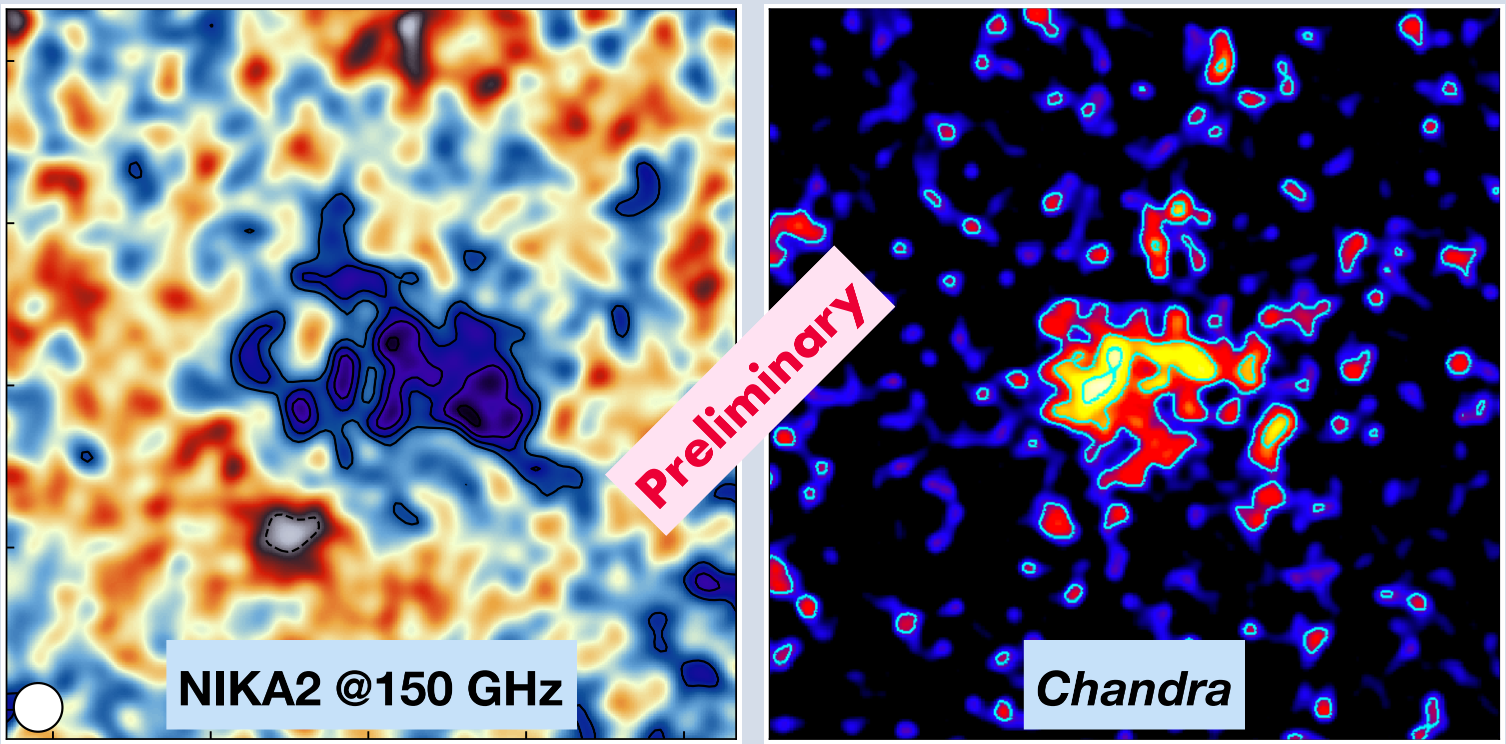
Temperature: $k_B T_e(x,y) = P_e(x,y)/n_e(x,y)$



- Entropy: profile 3 times more constrained than X-ray results
- Temperature: constrain merger dynamics + cool core

F. Ruppin *et al.*, ApJ 893, 74 (2020)

Mapping the ICM temperature in a cluster sample at z > 1

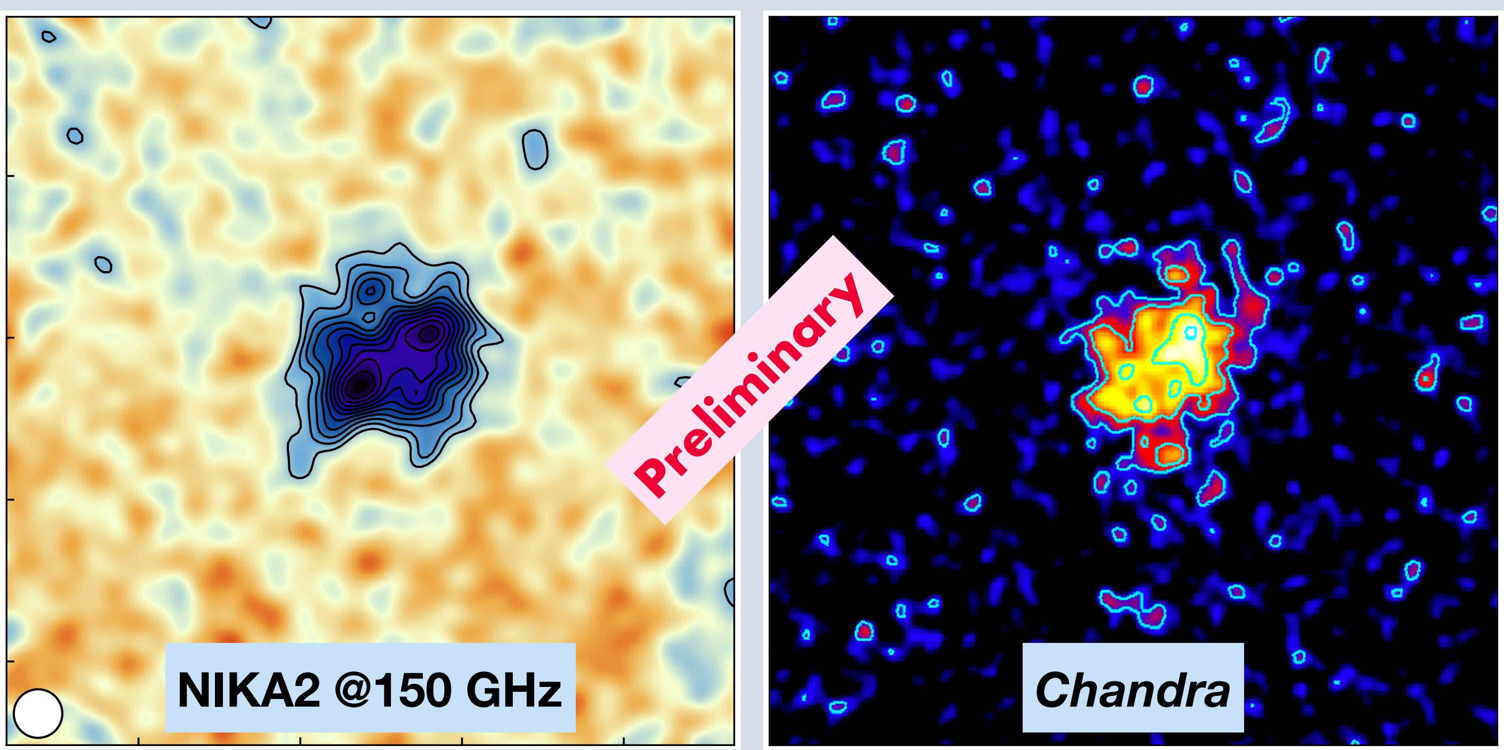


MOO J0105+1323

$$z = 1.14$$

$$M_{500} = 3.3 \times 10^{14}\ \mathrm{M}_{\odot}$$

- Elongated ICM morphology
- Over-pressure region in the west



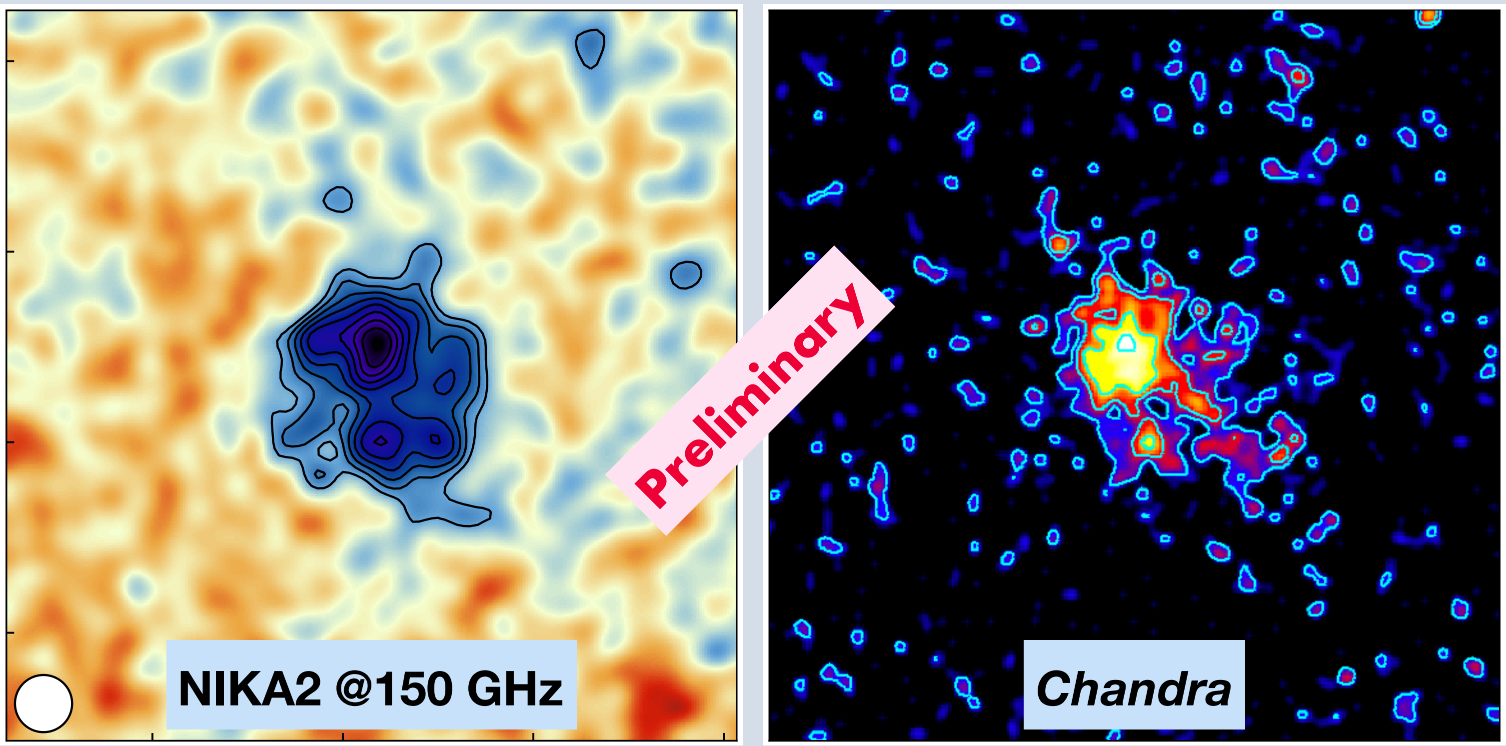
MOO J0319-0025

$$z = 1.19$$

$$M_{500} = 3.1 \times 10^{14}\ \mathrm{M}_{\odot}$$

- Clear bimodal ICM morphology
- South-east peak: high-pressure / low-density
- Hint of a third peak in the north

Mapping the ICM temperature in a cluster sample at z > 1

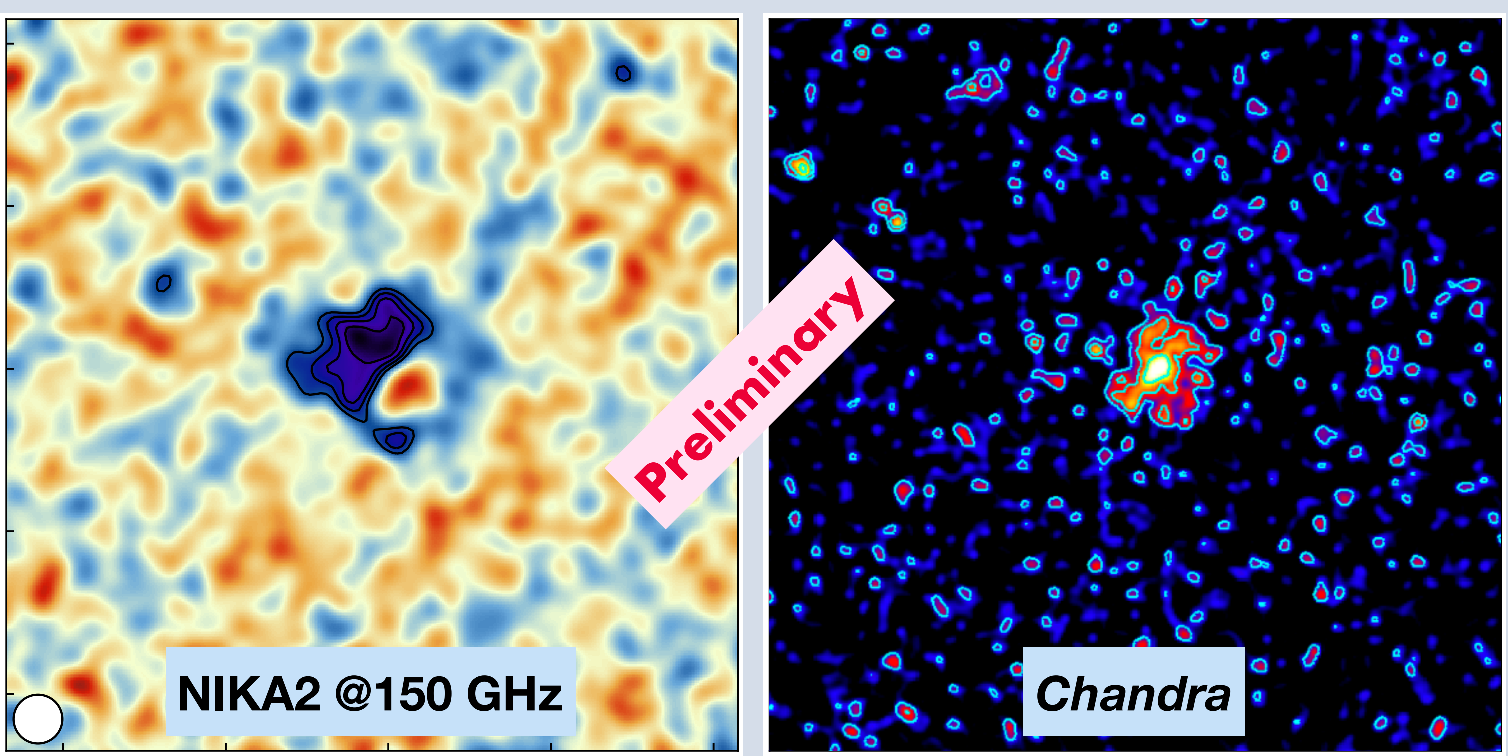


MOO J1014+0038

$z = 1.23$

$M_{500} = 5.2 \times 10^{14}\ \mathrm{M}_{\odot}$

- X-ray and SZ peaks at same location
- Clear merging features in the southwest



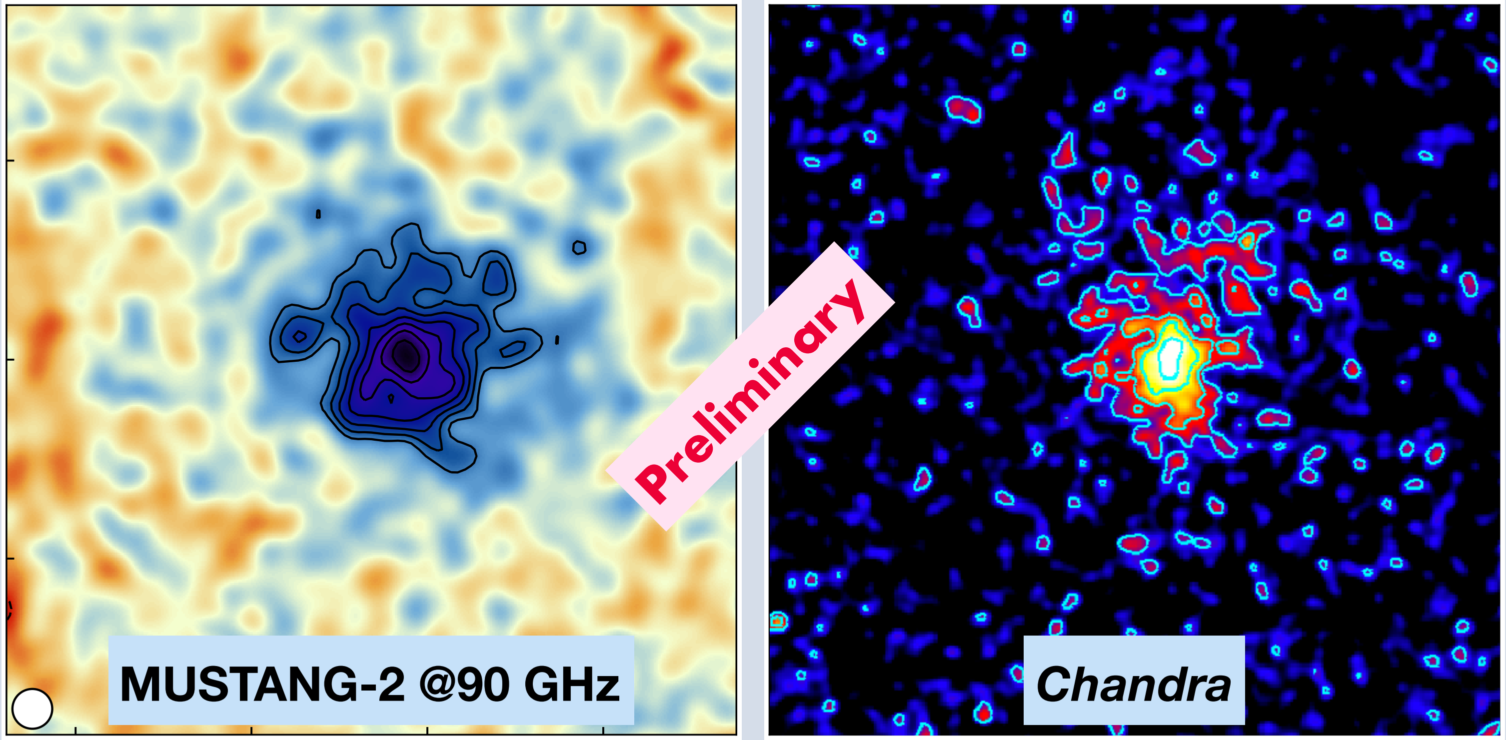
IDCS J1426+3508

$z = 1.75$

$M_{500} = 2.6 \times 10^{14}\ \mathrm{M}_{\odot}$

- Contamination by radio AGN
- X-ray peak between SZ peak and AGN
- NIKA2 map similar to MUSTANG-2 one *(slightly more extended signal)*

Mapping the ICM temperature in a cluster sample at z > 1

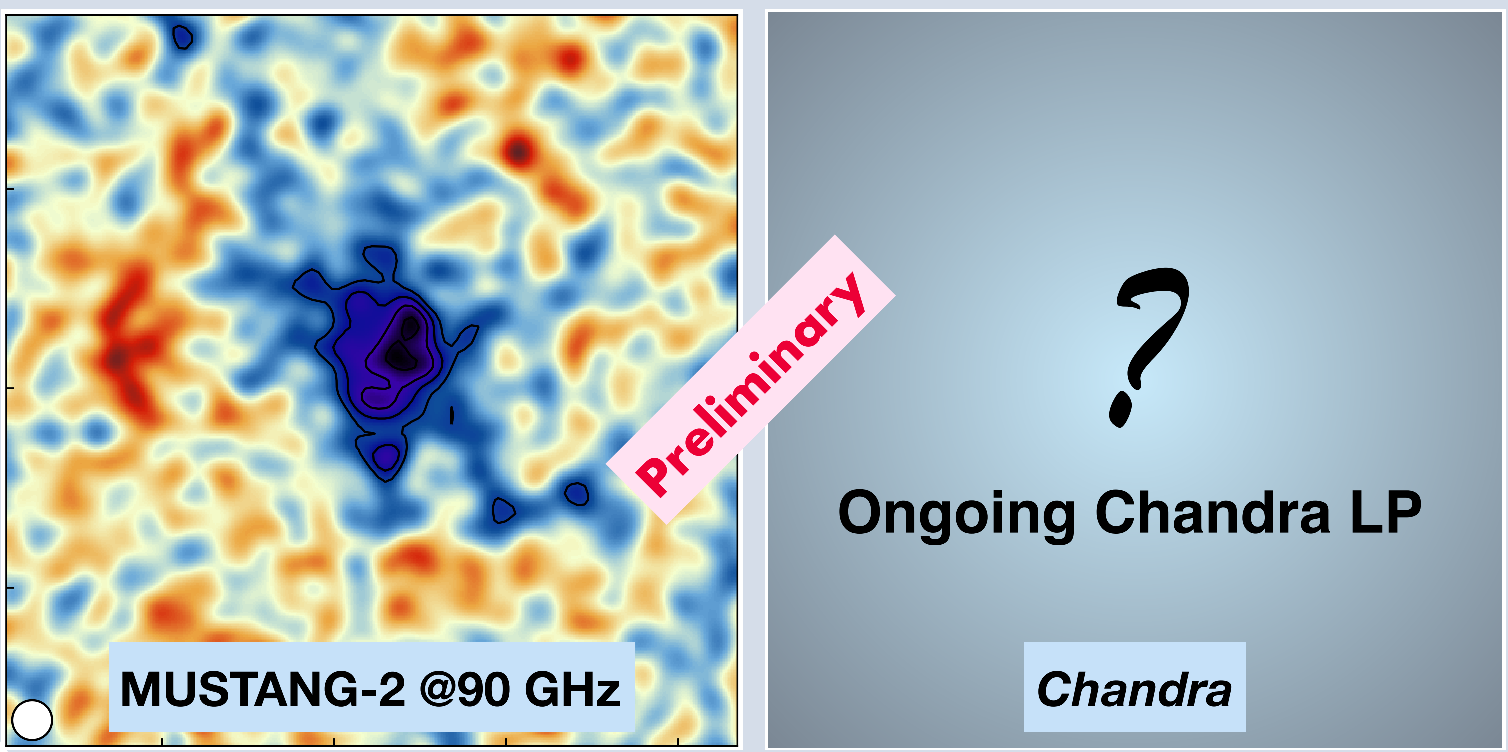


MOO J1046+2758

$$z = 1.16$$

$$M_{500} = 4.0 \times 10^{14}\ \mathrm{M}_{\odot}$$

- Only cluster with a relaxed morphology
- Hints of cold gas in the north



MOO J1059+5454

$$z = 1.14$$

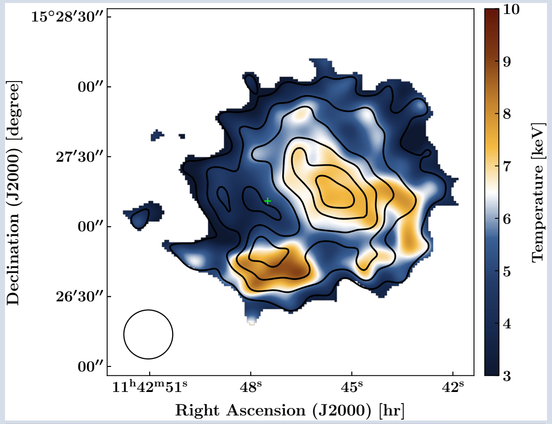
$$M_{500} = 3.0 \times 10^{14}\ \mathrm{M}_{\odot}$$

- Not observed with *Chandra* yet *(scheduled)*
- ICM elongated in the N-S direction
- Hints of a disturbed core

On-going studies based on MOO-X/SZ sample

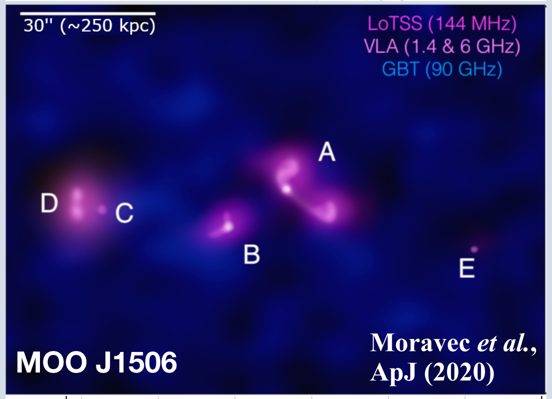
Combine *Chandra* and NIKA2 / MUSTANG-2 data at the map level:

- Correlate temperature / entropy fluctuations with galaxy distribution
  - ⟶ merger dynamics at $z > 1$



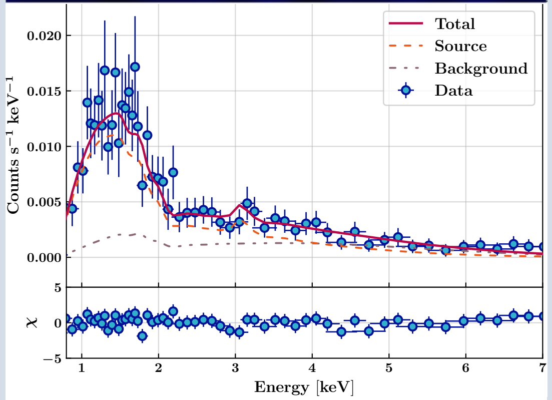
Cross-correlation with radio data:

- Connection between ICM thermodynamic properties and AGN radio emission
  - ⟶ AGN feedback at $z > 1$



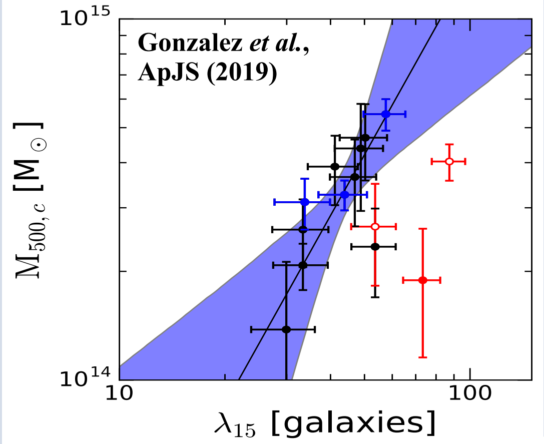
Use X-ray spectroscopic information:

- Fix ICM temperature to the SZ / X-ray one to estimate ICM metallicity
  - ⟶ Metal enrichment at $z > 1$



Cosmological impact:

- Estimate hydrostatic masses and compare with richness-derived masses
  - ⟶ Redshift evolution / selection bias at $z > 1$



Detailed ICM physics in a sample of z > 1 clusters

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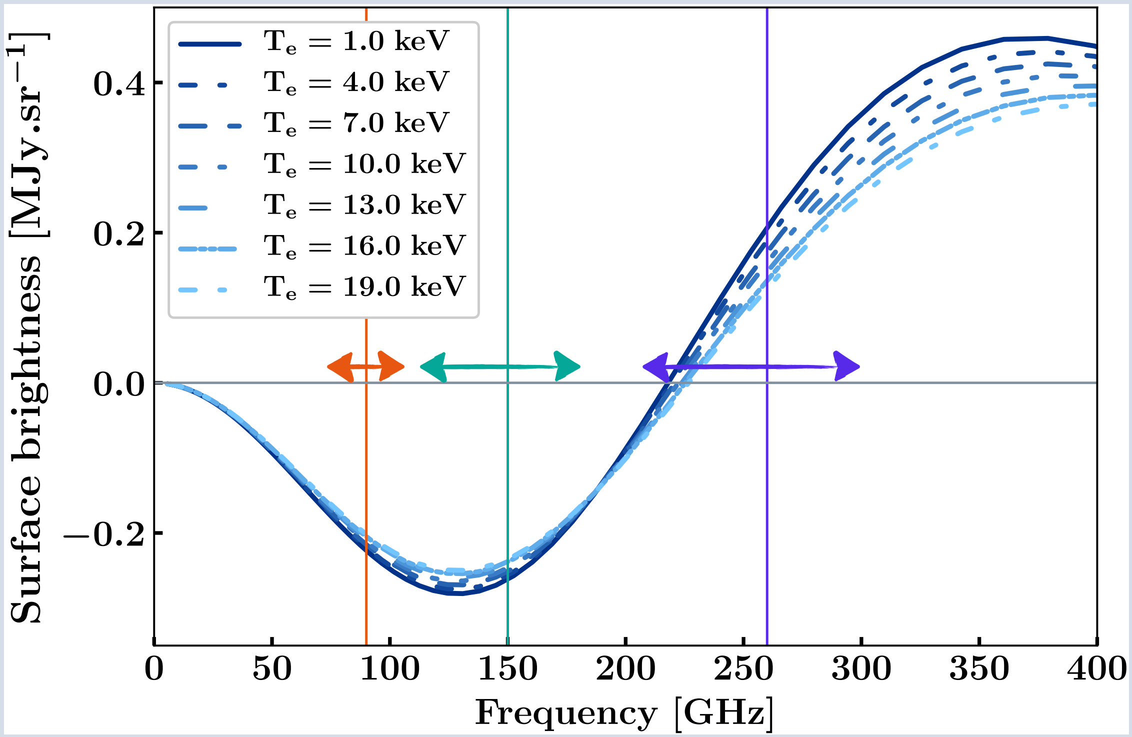
Relativistic corrections to the SZ effect

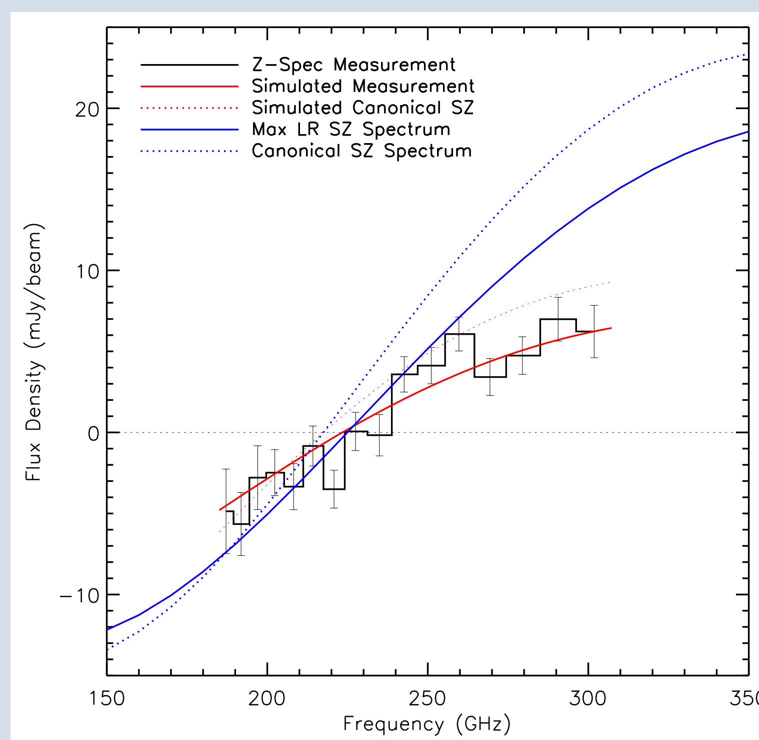


Sunyaev-Zel'dovich effect:

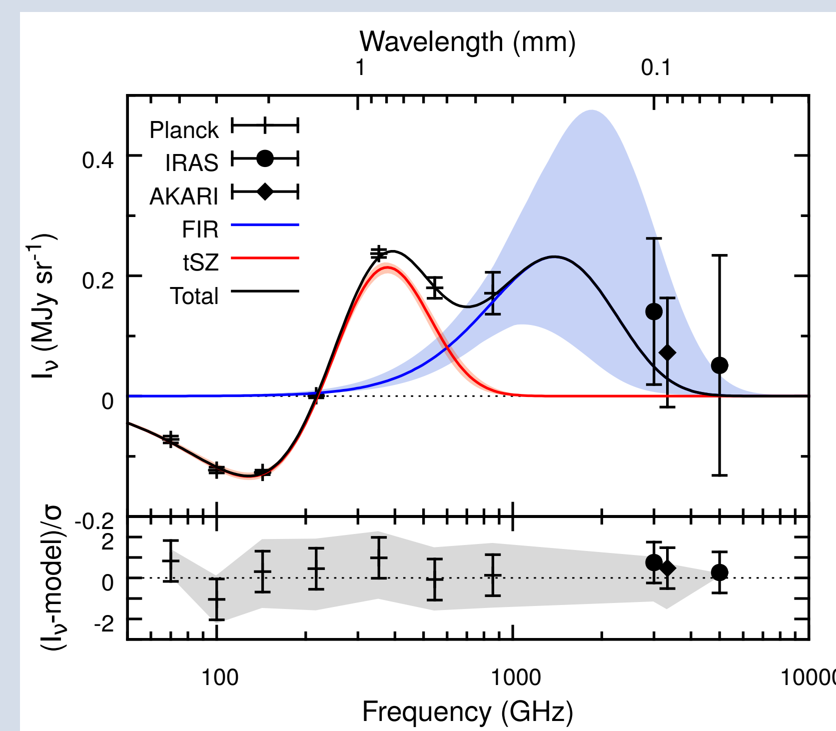
- Depends on three variables: - Compton parameter
  - ICM bulk velocity along the LoS
  - ICM electron temperature
- ICM temperature: relativistic corrections change the shape of the spectrum
- Relativistic corrections: either neglected or deduced from X-ray

Existing detections of rSZ:

- Null-frequency with Z-Spec
  → Mean ICM temperature of a massive cluster
- Stacking analysis of *Planck* clusters
  → Mean ICM temperature of a cluster sample



Zemcov *et al.*, ApJ (2012)



Erler *et al.*, MNRAS (2019)

RXJ1347–1145: the best candidate to map rSZ

Mapping the rSZ effect: Instrument selection

- Need high angular resolution + large field-of-view

→ NIKA2 and MUSTANG-2 are the best instruments

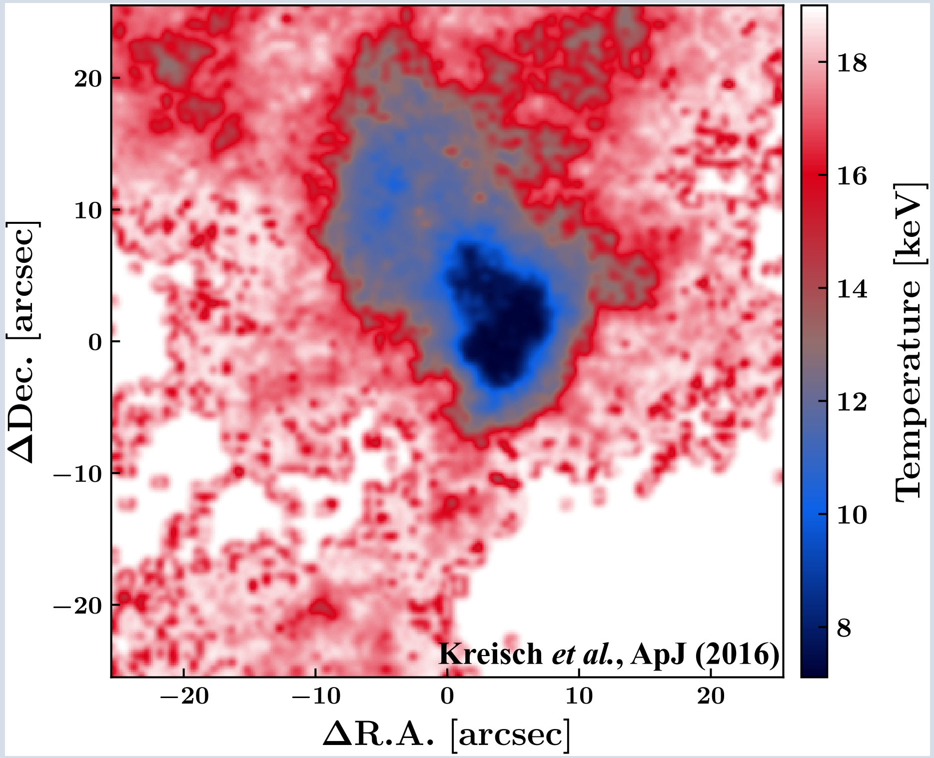
Mapping the rSZ effect: Cluster selection

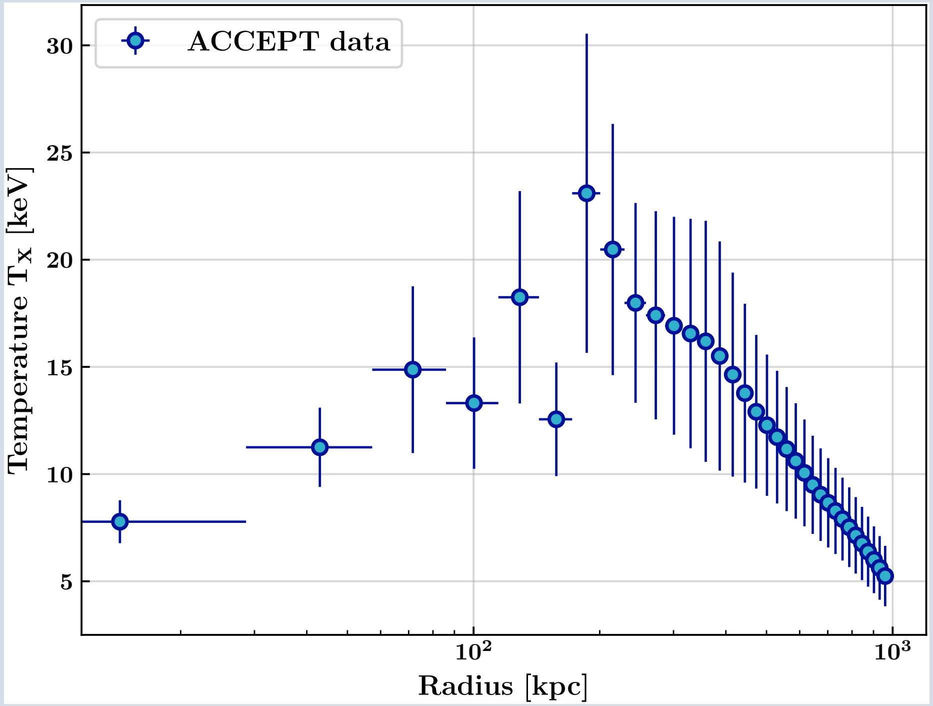
- Need a cluster with high-enough declination *(NIKA2 + MUSTANG-2)*
- Need a massive cluster *(Compton parameter)*
- Need large temperature variations *(rSZ detection)*

RXJ 1347–1145

- Most SZ luminous cluster in the sky
- X-ray temperature variations from 7 to 20 keV
- Intermediate redshift of $z = 0.45$ *(number of resolution elements)*

Ideal source to **map the rSZ effect** for the first time





MUSTANG-2 and NIKA2 maps of RXJ1347−1145

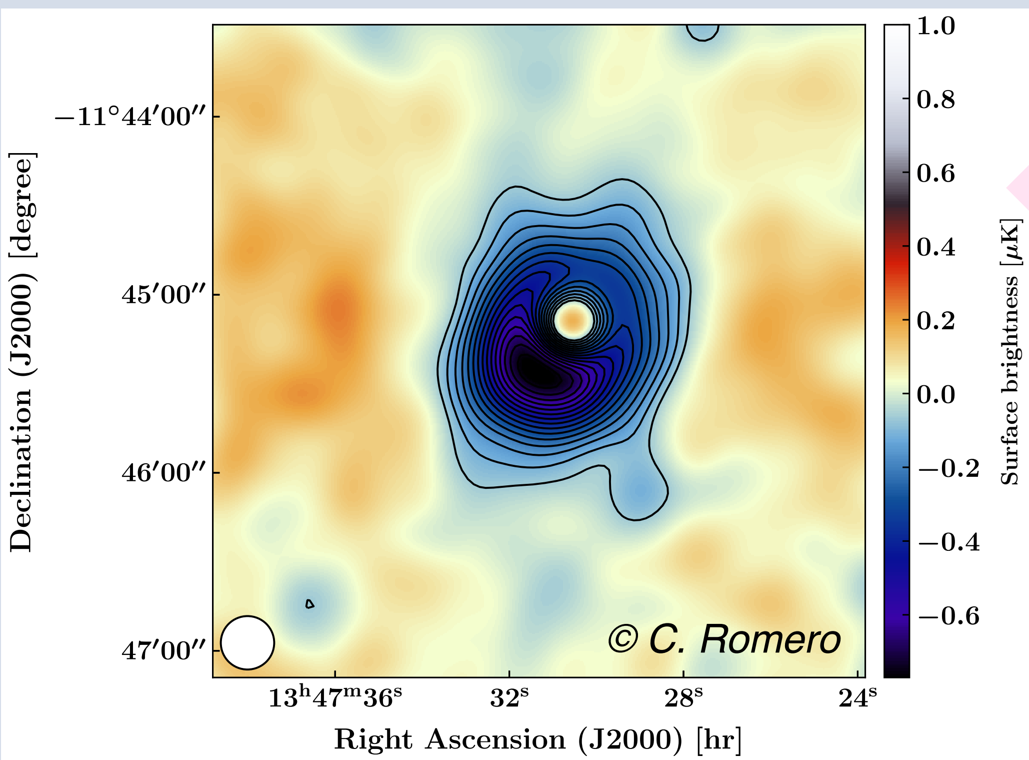
MUSTANG-2:

- Observed for 2 hours during commissioning phase
- Data analysis with MIDAS pipeline C. Romero *et al.*, ApJ (2020)

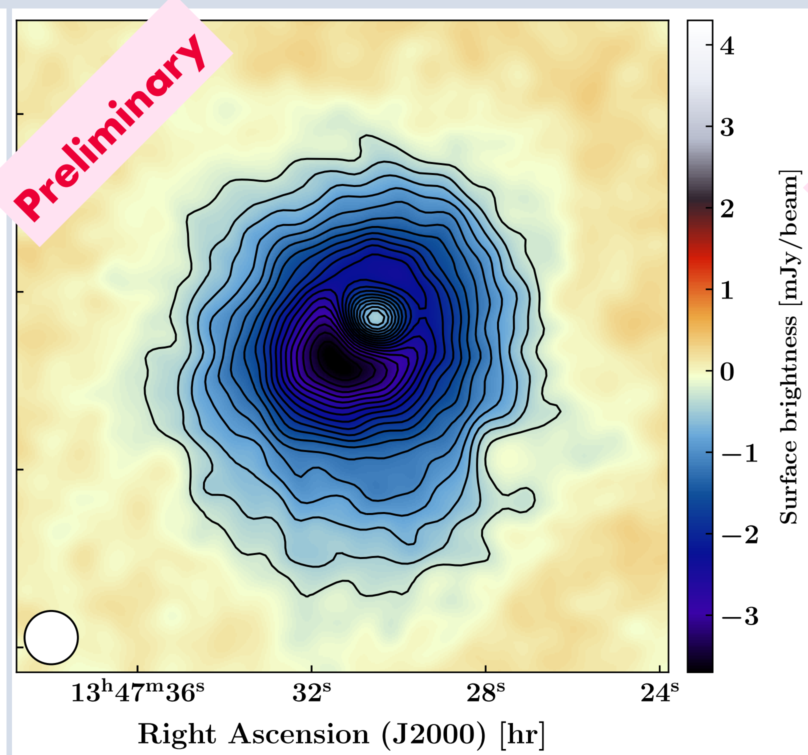
NIKA2:

- Observed for 24 hours during dedicated Open Time program *(completed in March 2021)*
- Preliminary analysis with standard NIKA2 pipeline → SZ signal is detected at 260 GHz

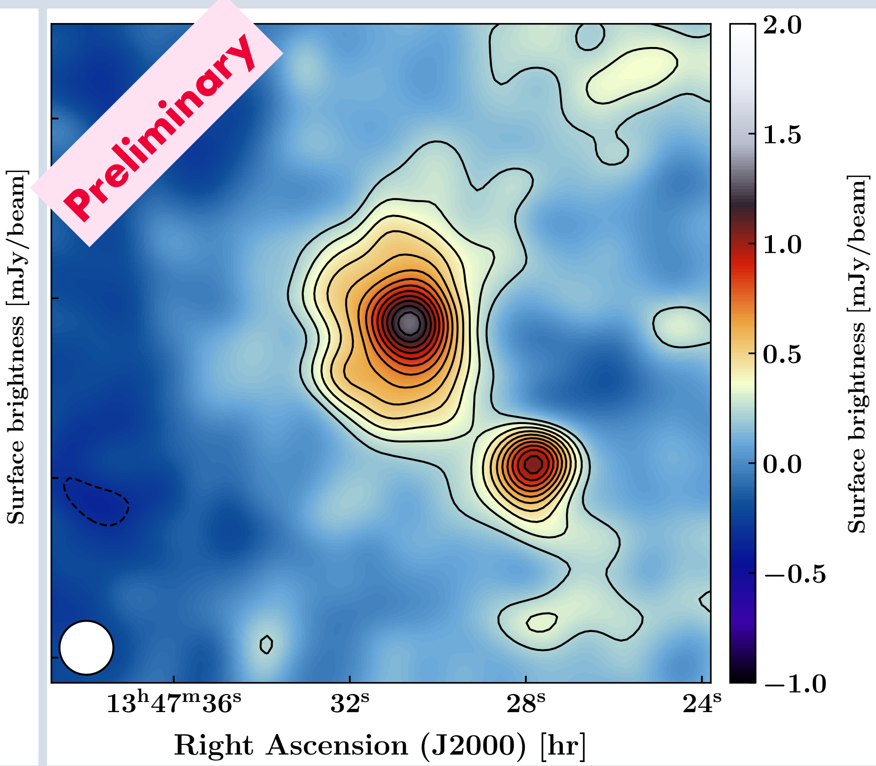
MUSTANG-2 @90 GHz



NIKA2 @150 GHz



NIKA2 @260 GHz



High quality data in the three bands: very promising

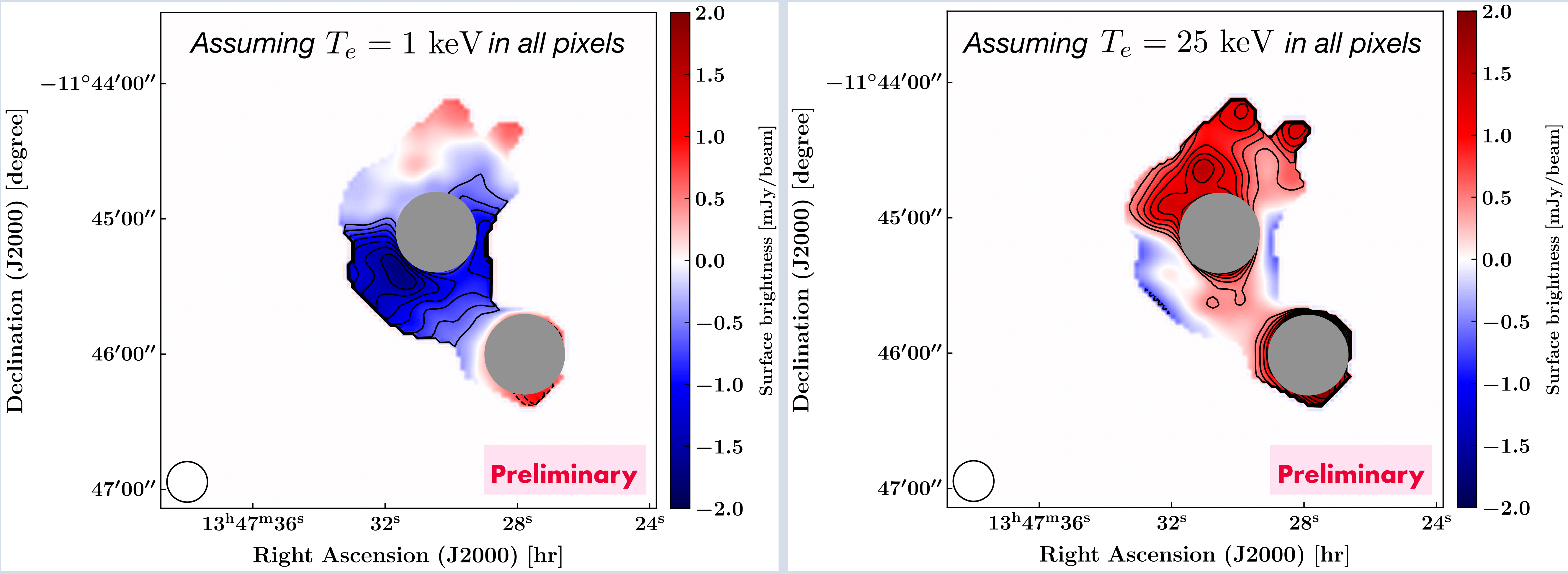
F. Ruppin *et al.*, in prep. (2021)

Detecting the relativistic corrections to the tSZ effect

Thermal SZ effect: $\frac{\Delta I_{tSZ}(\nu)}{I_0} = y\, f(\nu, T_e)$

Implications for NIKA2: $\Delta I_{tSZ}(150\ \mathrm{GHz}) - \Delta I_{tSZ}(260\ \mathrm{GHz})\, \frac{f(150\ \mathrm{GHz}, T_e)}{f(260\ \mathrm{GHz}, T_e)} = 0$ *(If we know the temperature map of the cluster)*

Experiment: Compute residual map assuming **constant ICM temperature** across the FoV



Significant residuals for constant ICM temperature → **rSZ is detected**

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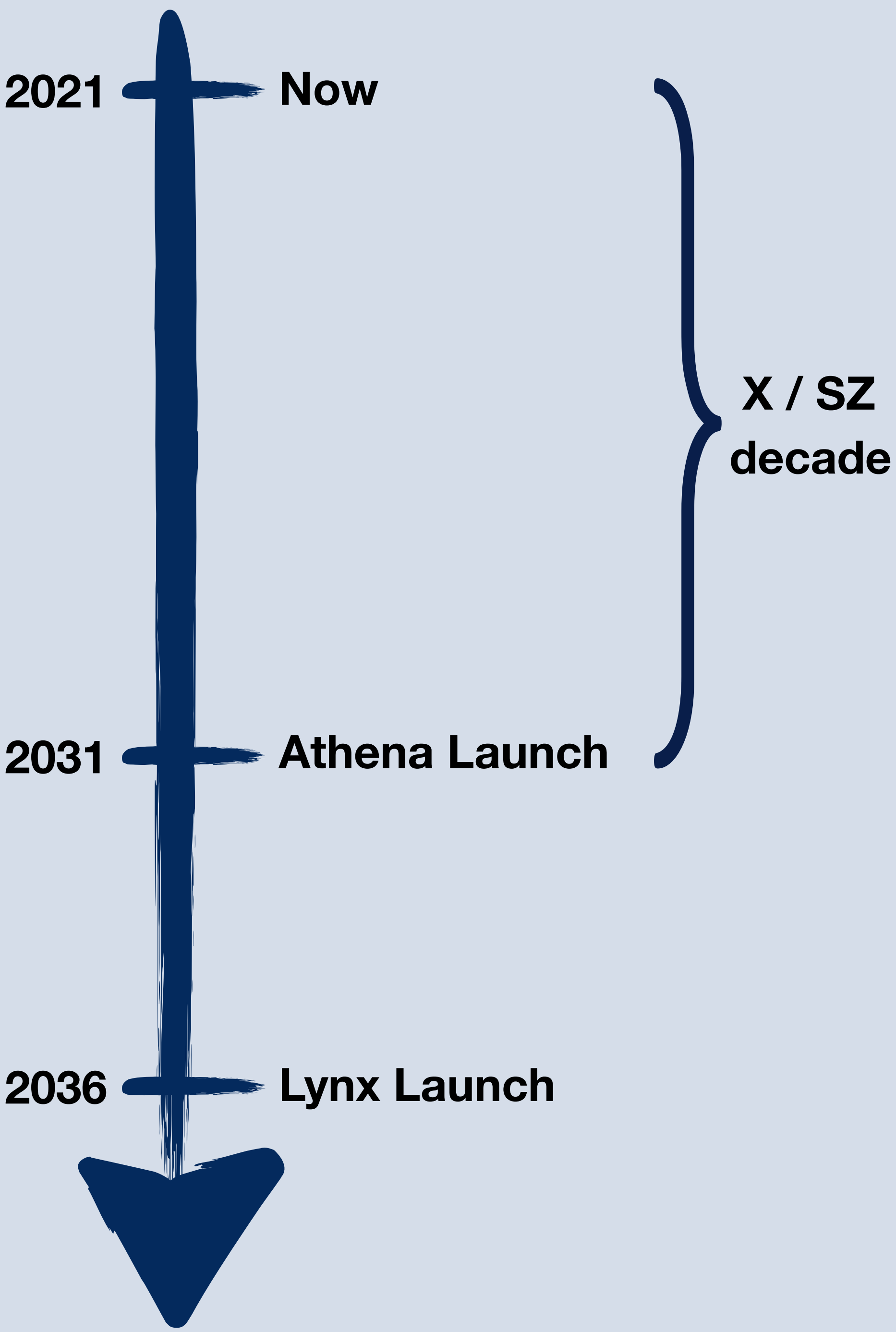

Mapping the ICM temperature:

- Better understanding cluster formation *(mergers + feedback)*
- Improve hydrodynamical simulations *(cosmology)*

Current limitations:

- Mapping → high sensitivity + high angular resolution
- Unfeasible with X-rays at $z \gtrsim 0.5$ with current instruments

Solutions:

- Joint X-ray / SZ analyses: characterize $z \sim 1.5$ clusters as well as we did with X-rays at $z \sim 0.5$
- SZ spectroscopy: rSZ detections will become common in the 2020s

(see next talks + A. Fasano and A. Catalano's talks on Friday)

Use SZ to map ICM temperature in the 2020s: **extend our knowledge of cluster physics**