

Cartography of the ICM properties of a massive on-going merger at $z = 1.2$

Florian Ruppin

Observing the millimeter Universe with the NIKA2 camera

M. McDonald (MIT), M. Brodwin (UMKC), A. Gonzalez (UF), E. Moravec (UF),
A. Stanford (UC) & the [NIKA2](#) collaboration



Content

- I - Mapping the most massive clusters at $z > 1$**
- II - NIKA2 and *Chandra* observations of MOO J1142+1527**
- III - Multi-wavelength analysis: ICM morphology**
- IV - Multi-wavelength analysis: ICM profiles**
- V - Cartography of the ICM properties**

Content

I - Mapping the most massive clusters at $z > 1$

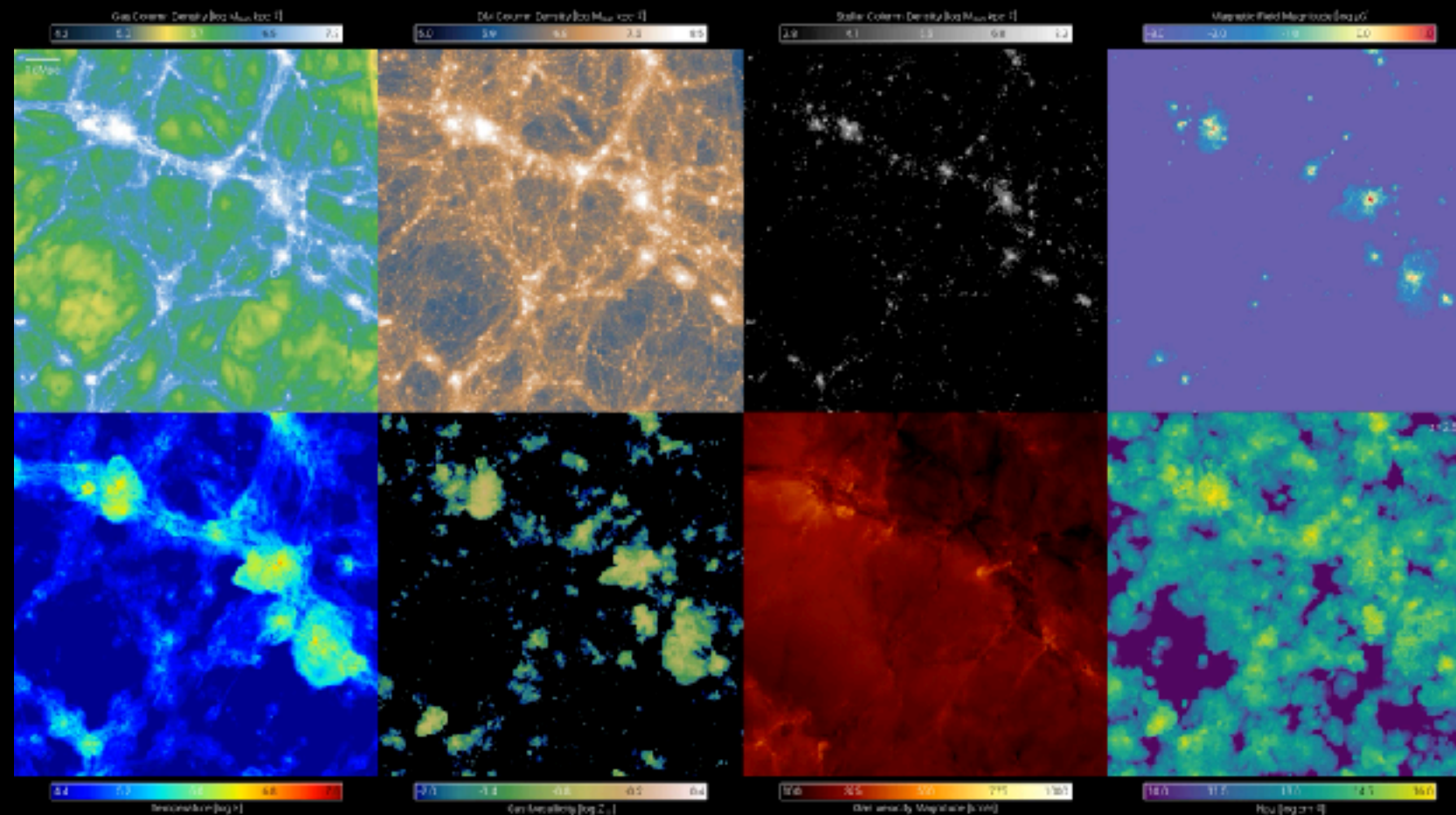
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Mapping the most massive clusters at $z > 1$



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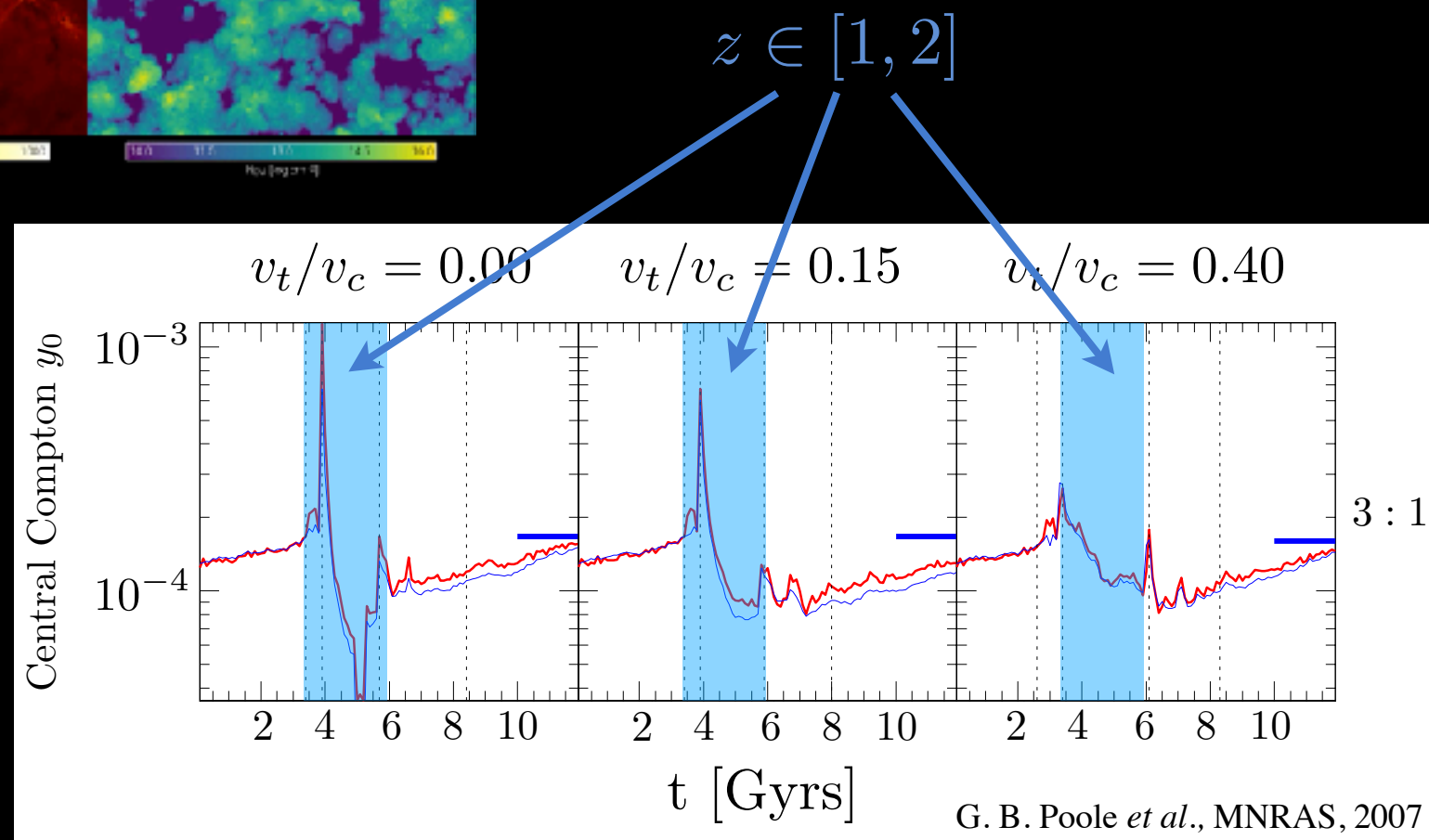
Galaxy cluster mergers and SZ effect:

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

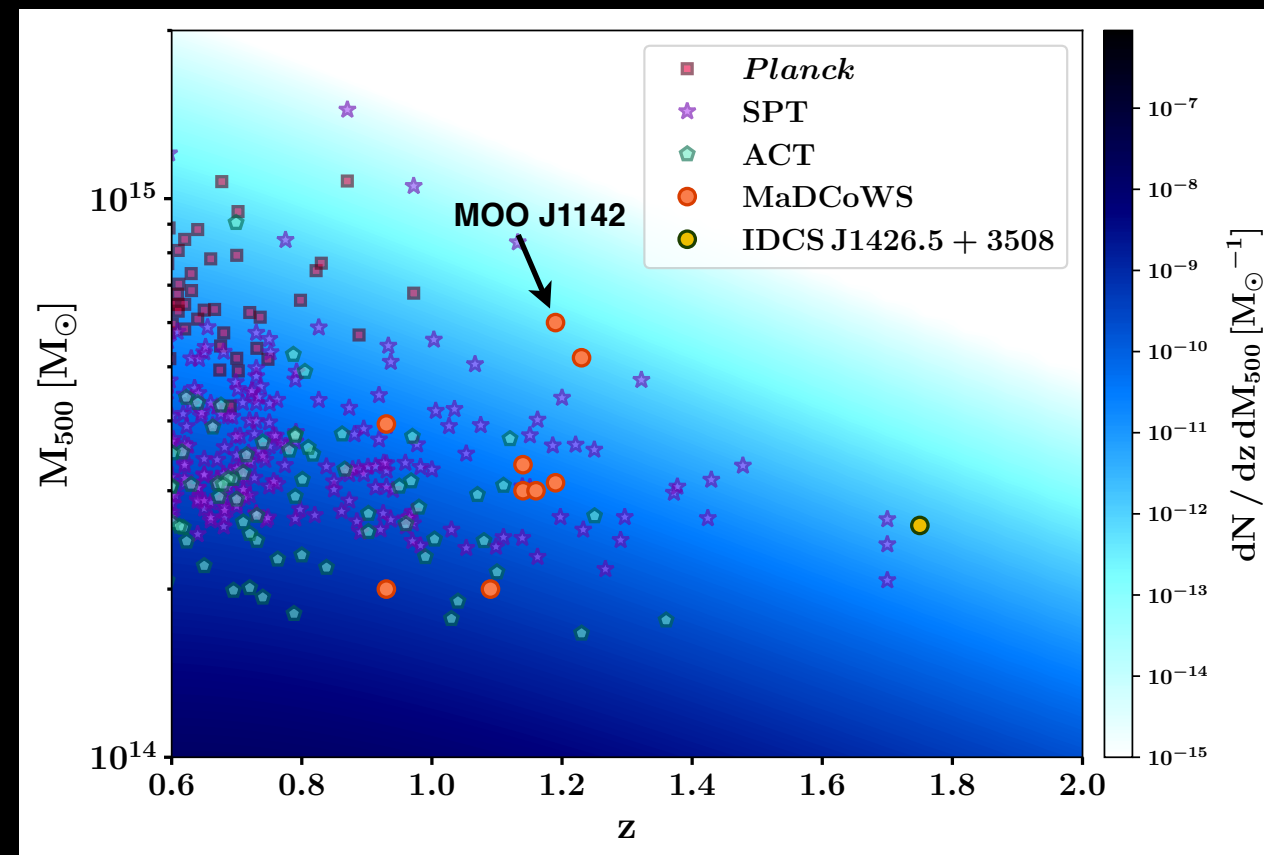
Analysis of ICM thermodynamic properties at $z > 1$
essential to understand structure formation

Growth of galaxy clusters:

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



Mapping the most massive clusters at $z > 1$



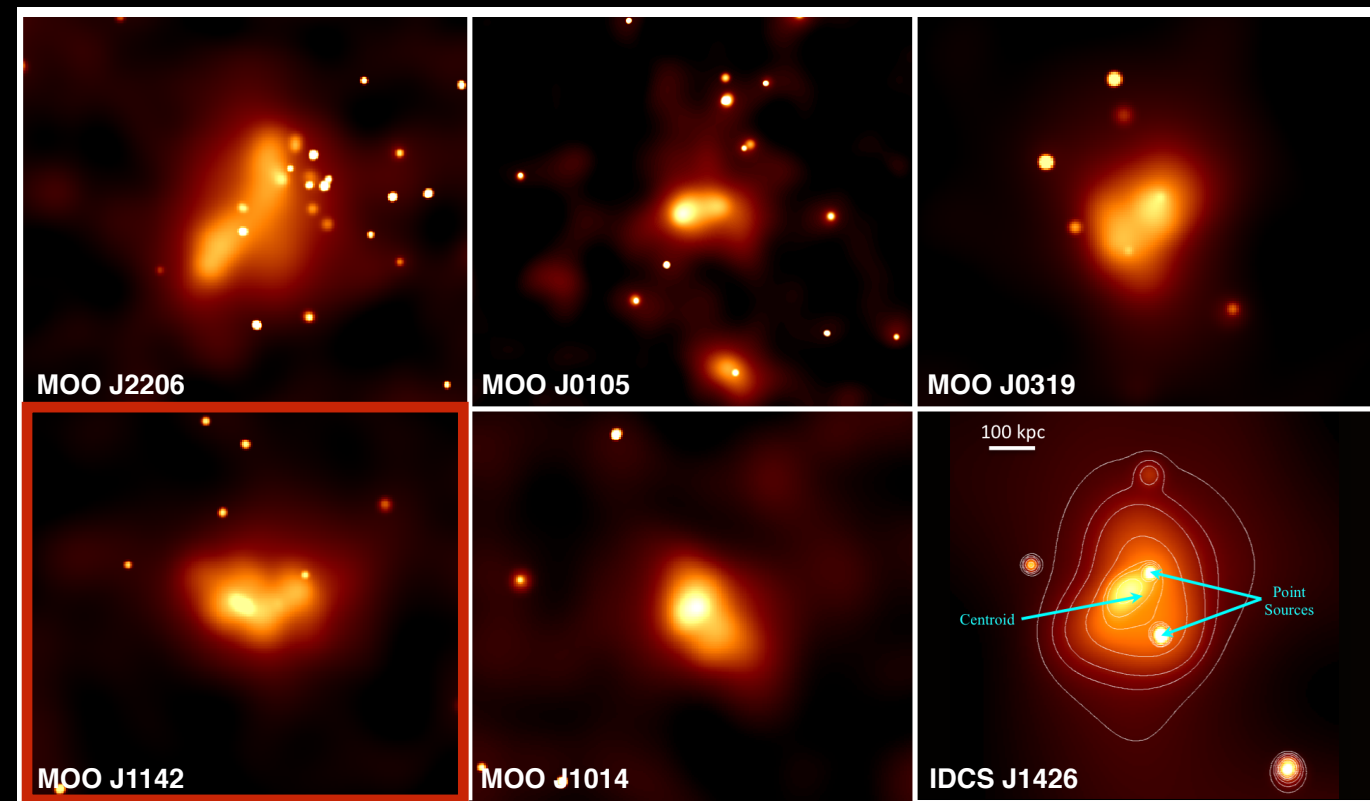
Large program of X-ray and SZ observations at $z > 1$:

- Lack of massive high redshift clusters in SZ catalogs
- Use Optical/IR detected clusters
 - MaDCoWS and IDCS surveys *Brodwin et al., ApJ, 2015*
- Sample of 10 clusters at $0.93 < z < 1.75$
- Combine highresolution X-ray and SZ observations

Submitted 3 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 $z > 1$



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NIKA2 and *Chandra* observations of MOO J1142+1527

1 - NIKA2 SZ maps and point source contamination

2 - Chandra X-ray map and spectrum

NIKA2 and *Chandra* observations of MOO J1142+1527

1 - NIKA2 SZ maps and point source contamination

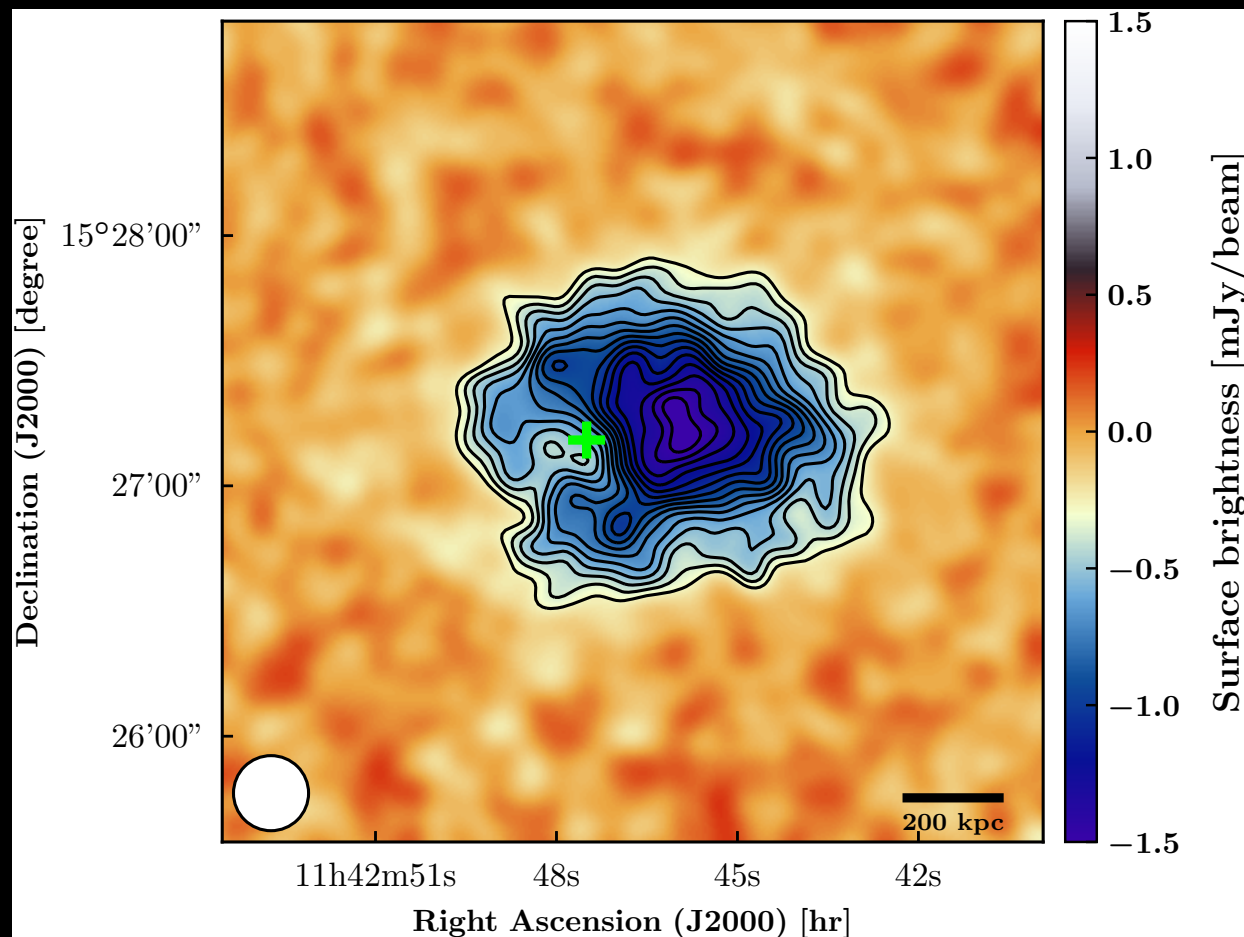
2 - Chandra X-ray map and spectrum



- NIKA2 observations of MOO J1142+1527 in October 2017 during 10.4 hours
- Pointing center: SZ peak found by CARMA (*lower angular resolution*)
- Weather conditions: quite stable, $\tau_{150\text{ GHz}} = 0.19$

NIKA2 SZ maps

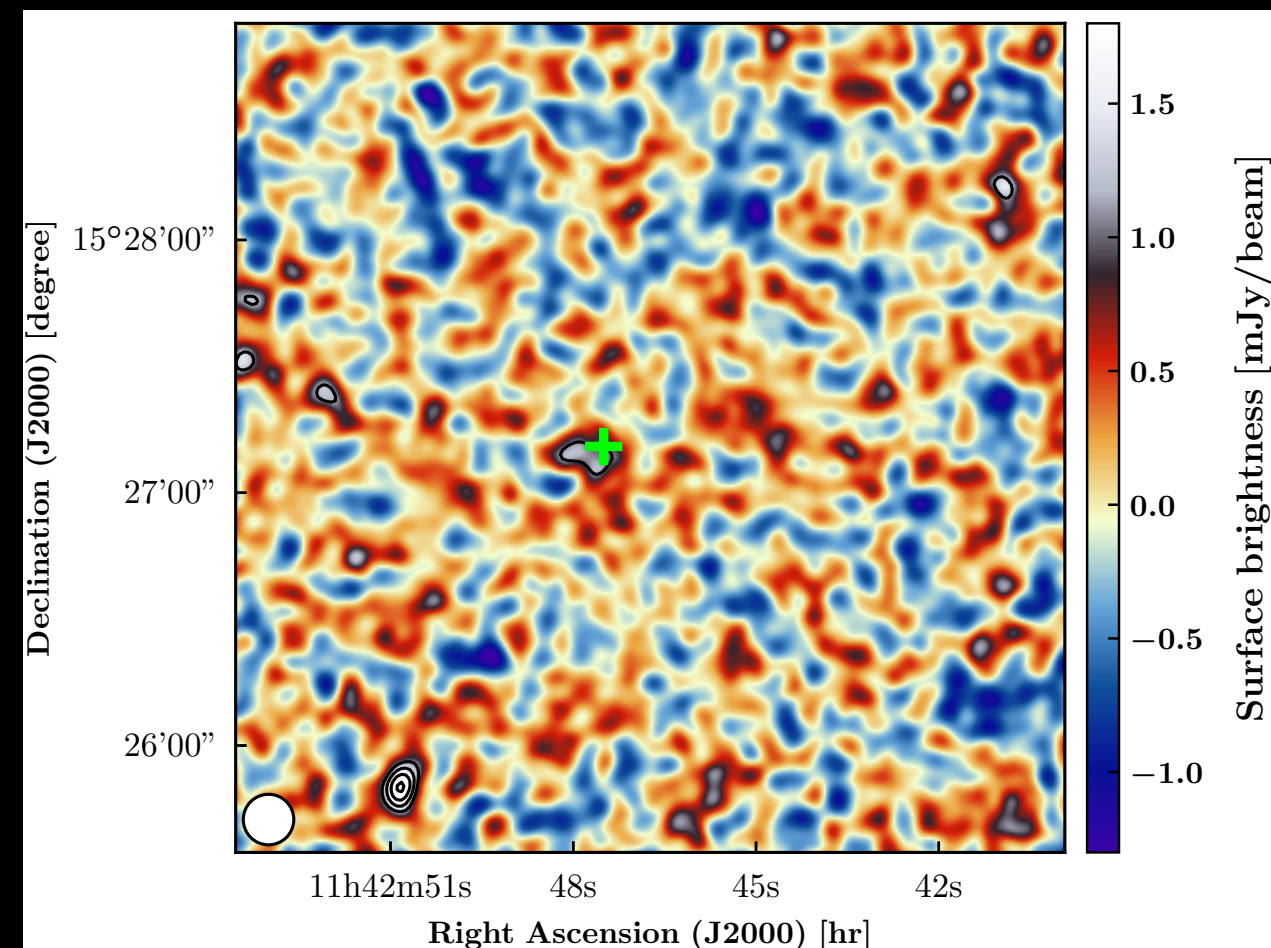
NIKA2 map at 150 GHz



At 150 GHz:

- Mapping the SZ signal at high significance
peak SNR = 17 and SNR > 3 up to 1 arcmin from pointing center
- ICM morphology: elliptical with an E-W orientation
compatible with CARMA results → *Gonzalez et al., ApJL, 2015*
- Signal contamination from point source East of SZ peak

NIKA2 map at 260 GHz



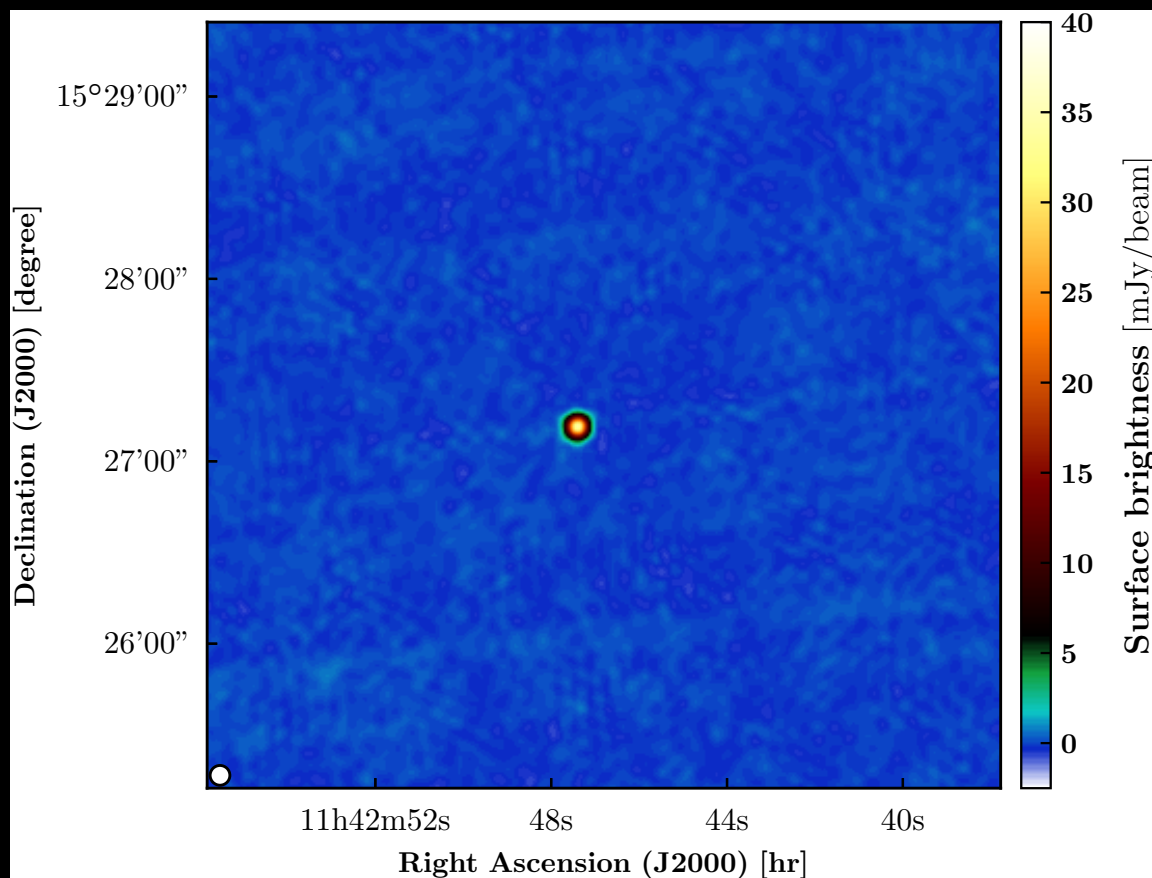
At 260 GHz:

- Point source detected with peak SNR = 4
position compatible with radio source found in FIRST survey
- No significant SZ signal detected (expected given noise)

Need to characterize radio source contamination
before pressure profile extraction

Radio source contamination at 150 GHz

FIRST map at 1.4 GHz



- Model the SED of the source using a power law:

$$F_{\nu} = F_{1 \text{ GHz}} \left(\frac{\nu}{1 \text{ GHz}} \right)^{\alpha_{\text{radio}}}$$

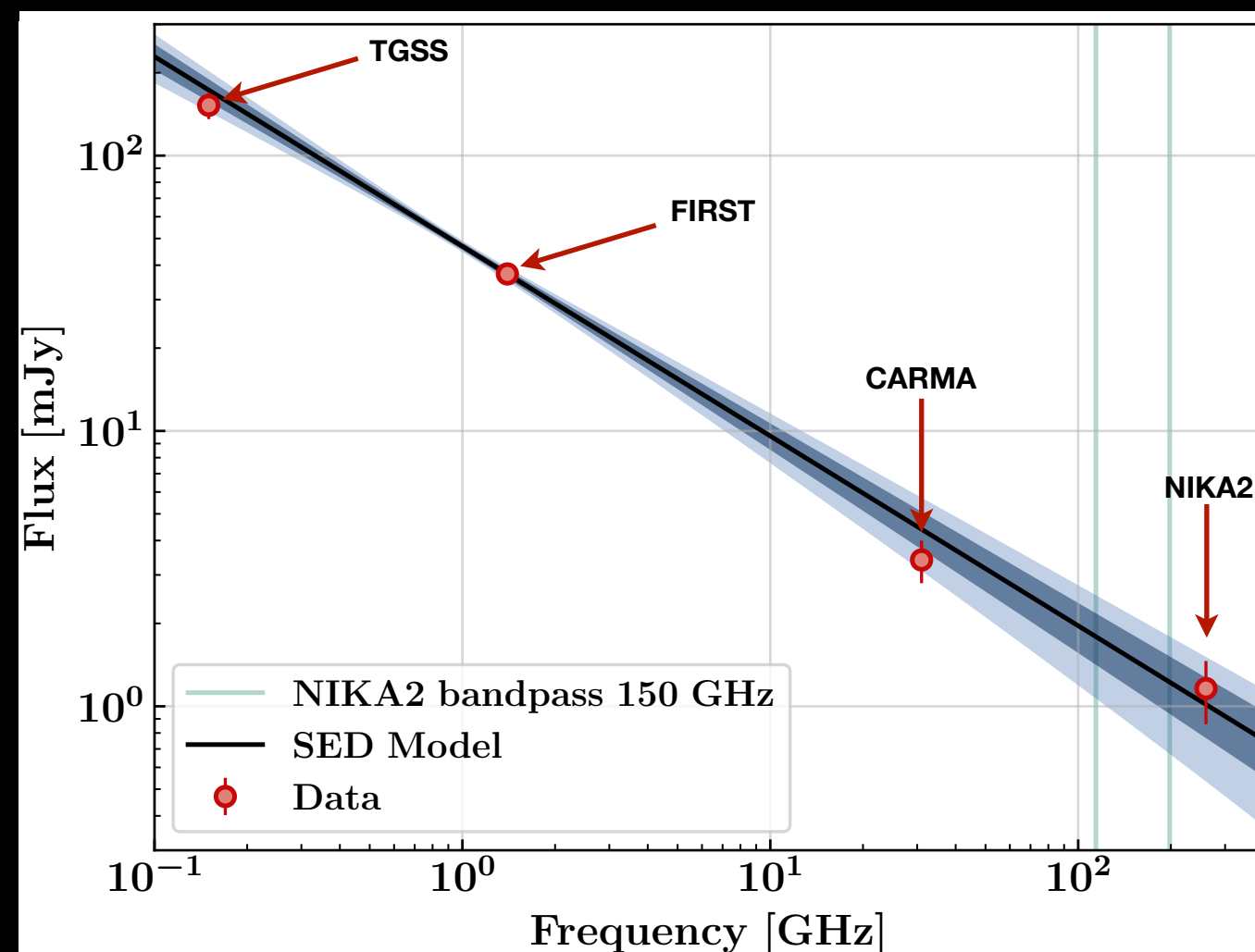
- Estimate flux at 150 GHz:
integration of best-fit SED in NIKA2 bandpass

$$F_{150 \text{ GHz}} = 1.5 \pm 0.3 \text{ mJy}$$

Prior on the source flux in SZ deprojection analysis

- Known flux densities at different frequencies:
 - TGSS at 153 MHz
 - FIRST at 1.4 GHz
 - CARMA at 31 GHz
- Additional data point at 260 GHz from NIKA2 (source fit)

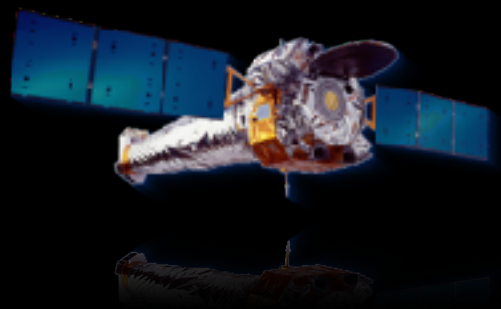
Radio source SED



NIKA2 and *Chandra* observations of MOO J1142+1527

1 - NIKA2 SZ maps and point source contamination

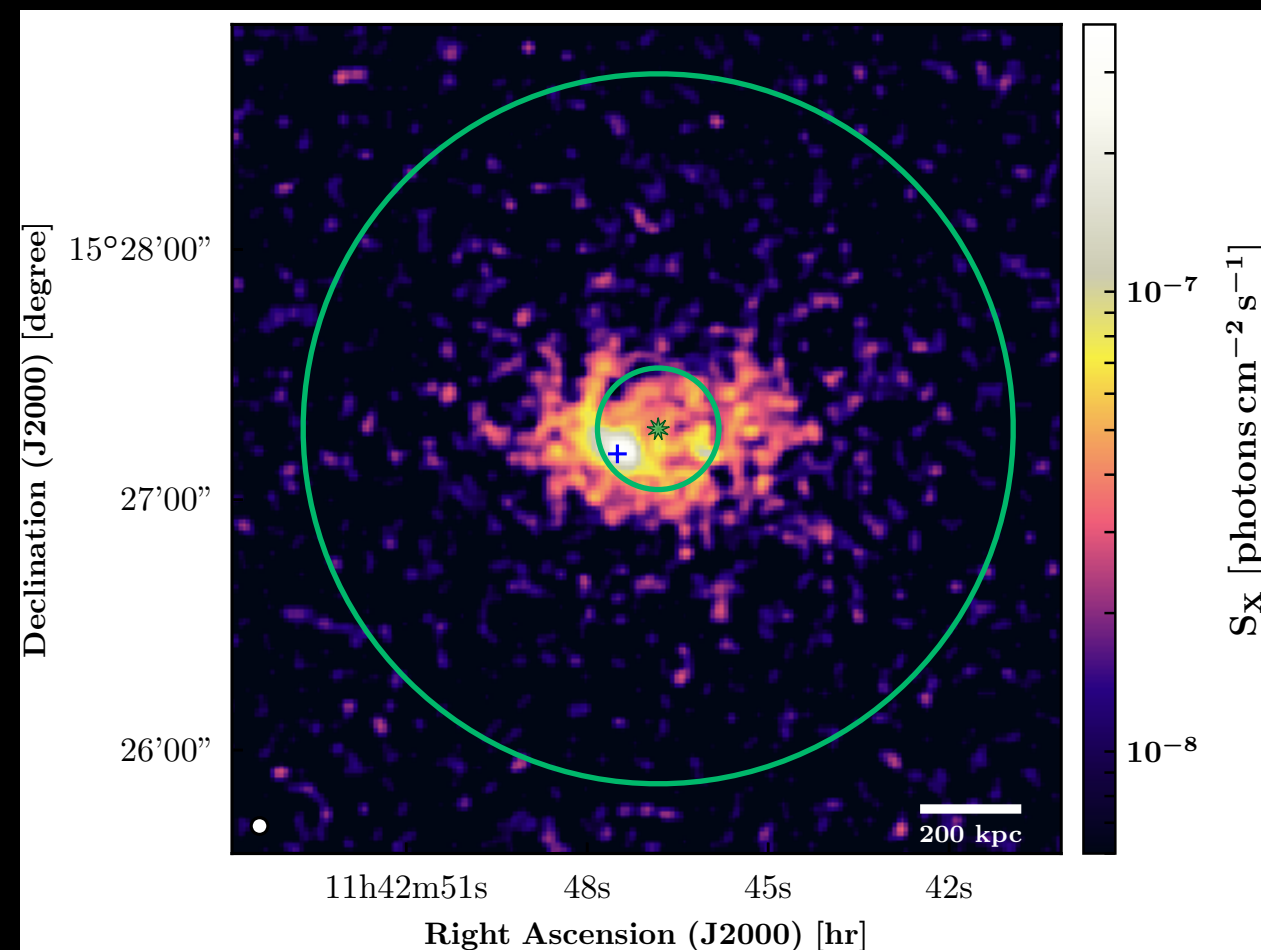
2 - Chandra X-ray map and spectrum



- *Chandra* observations of MOO J1142+1527 in February 2017, PI: A. Stanford
- ACIS-I filtered exposure: 40.3 ks → ~1700 counts in cluster region

Chandra raw data

Chandra X-ray map



Cluster morphology:

- Elliptical diffuse X-ray emission (*similar to NIKA2 SZ*)
- X-ray peak at the same location as radio source

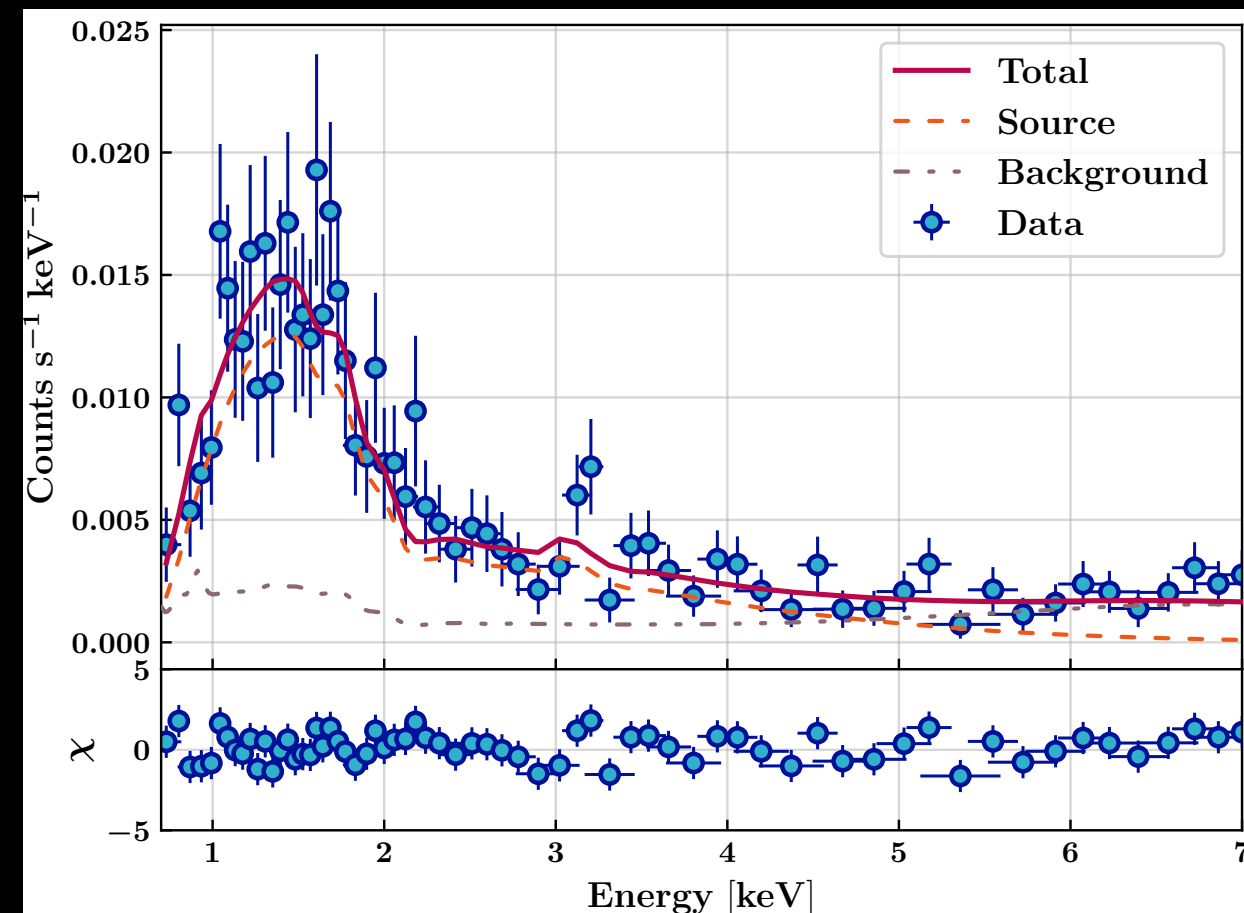
X-ray spectrum:

- Use events in annulus centered on large scale centroid with $0.15R_{500} < r < R_{500}$
- Joint fit background + cluster emission:
Galactic absorption (PHABS) $\times$ source (APEC) + bkg (APEC + p-law)

Event list cleaning: CIAO software v4.10 and CALDB v4.8.0

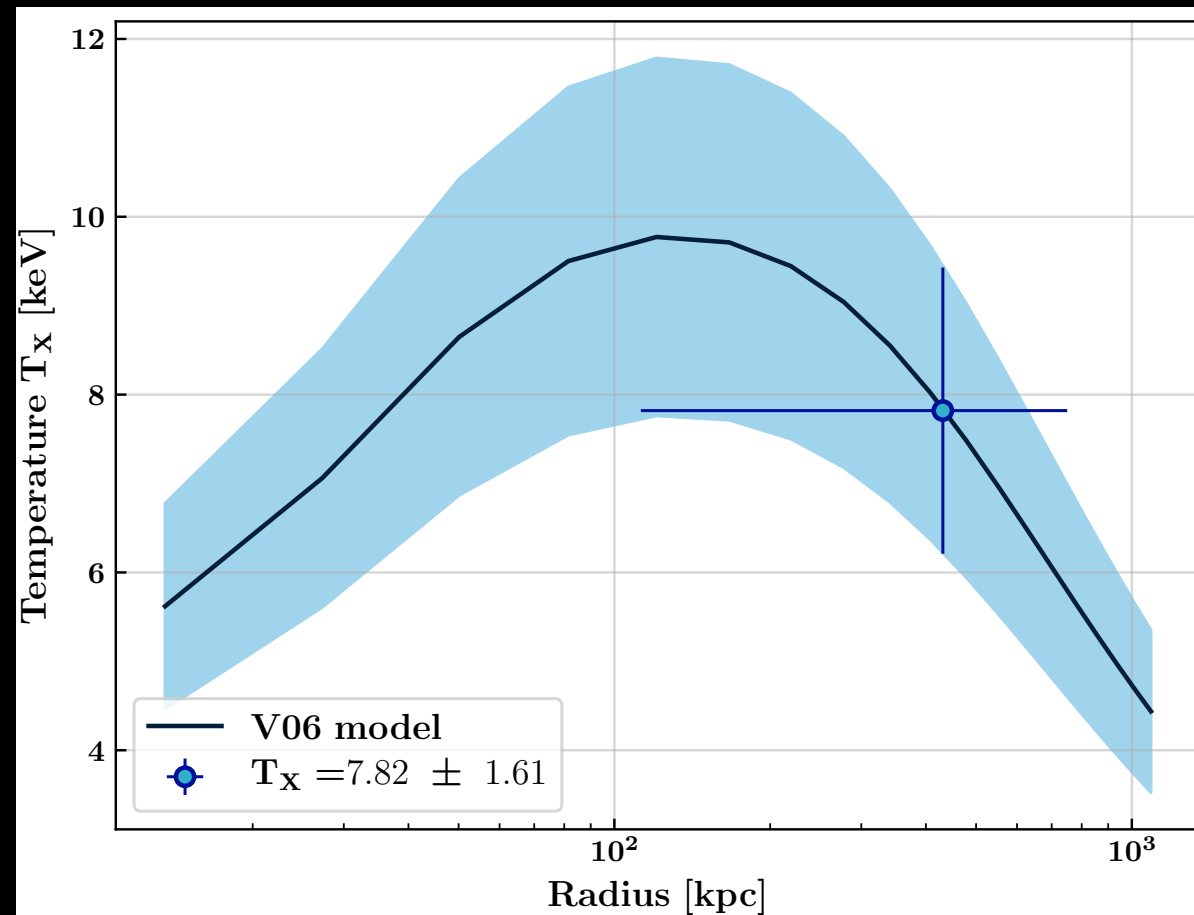
- Reprocess event list + Remove flares from lightcurves
- Compute exposure map in broad band [0.5,7] keV
- Identify point sources using wavelet decomposition
- Match blanksky background to count rate in [9,12] keV

Chandra X-ray spectrum



Chandra surface brightness profile and temperature

Chandra spectroscopic temperature

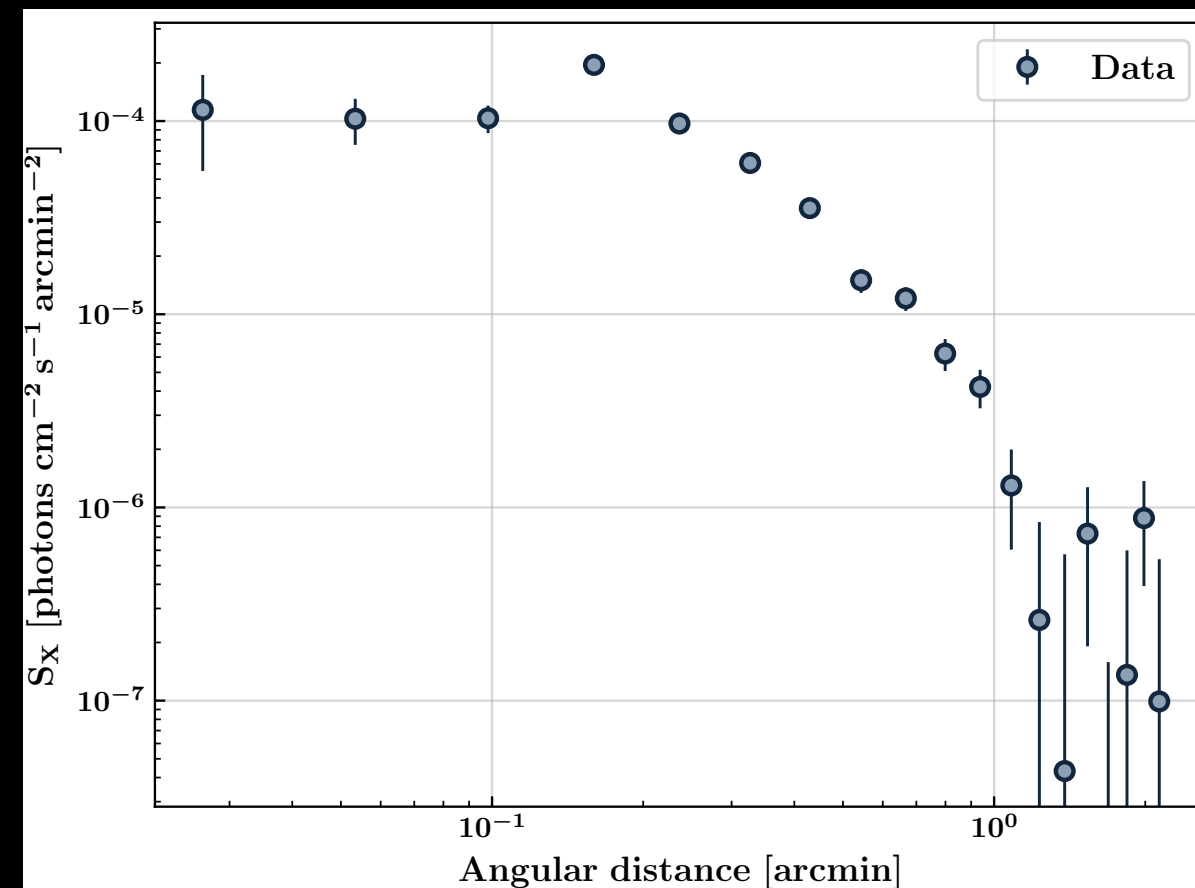


- Mean ICM spectroscopic temperature: $T_X = 7.82 \pm 1.61$ keV
- First estimate of temperature profile:
Fit universal temperature profile from Vikhlinin *et al.*, ApJ, 2006

- Extract X-ray surface brightness profile from event list after point source and background subtraction

X-ray surface brightness profile + temperature profile
→ ingredients for emission measure profile

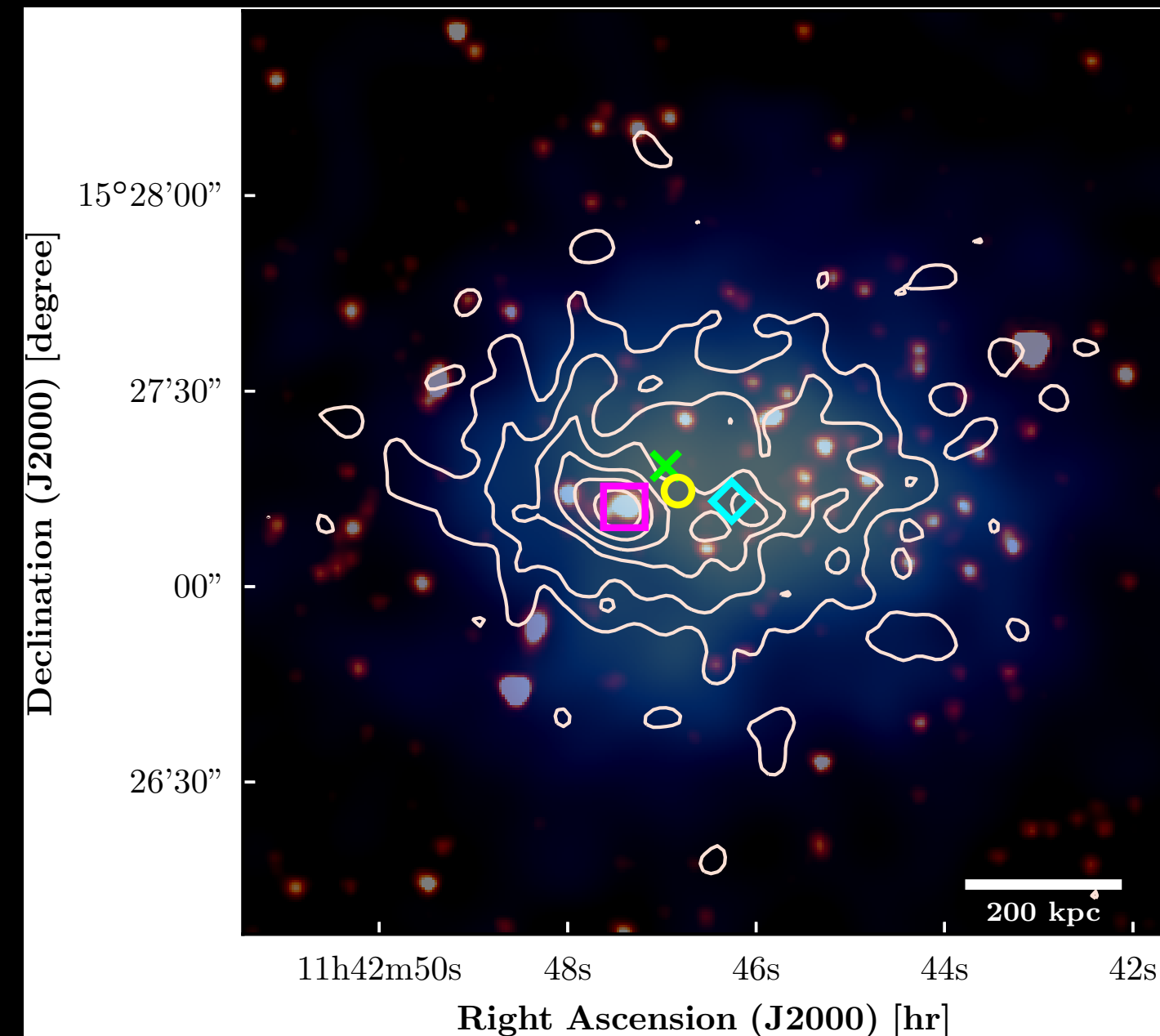
Chandra X-ray surface brightness profile



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Multi-wavelength analysis: ICM morphology

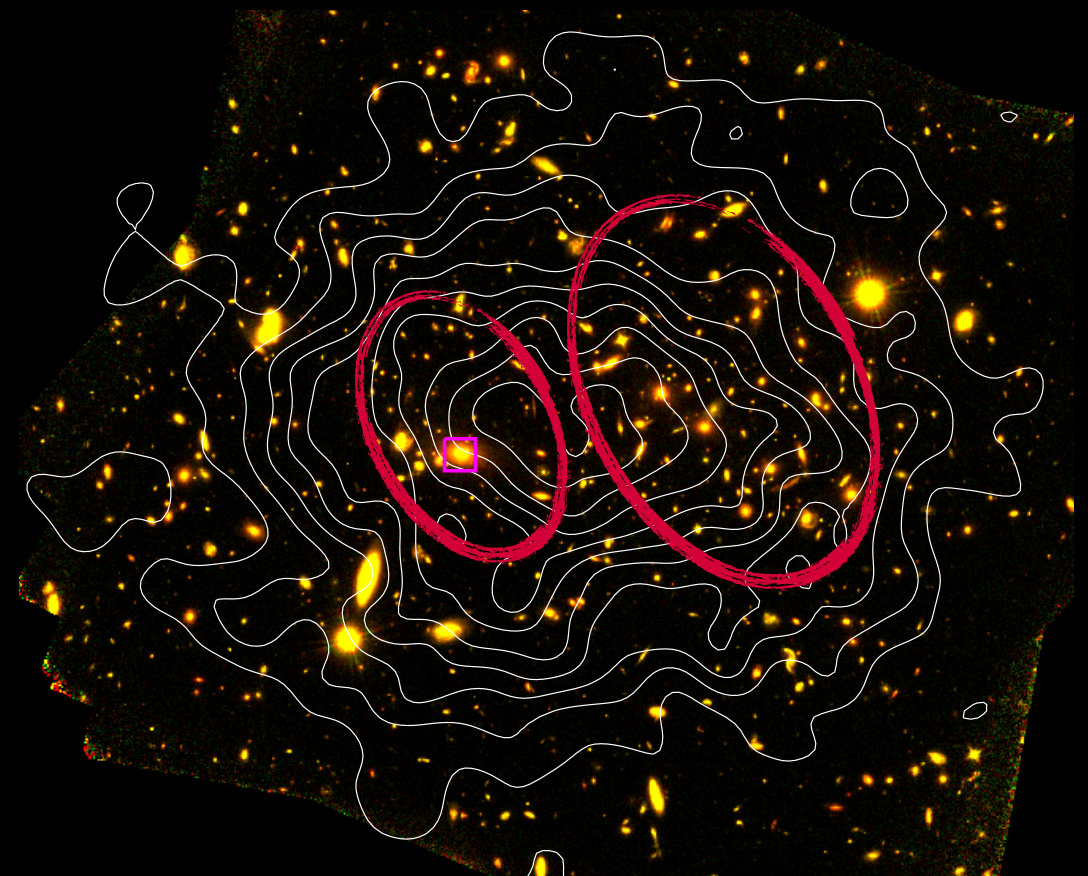


- Bimodal galaxy distribution seen in Optical/Infrared by *Hubble* and *Spitzer*

MOO J1142 = Massive on-going merger

- *Chandra* X-ray peak + radio source + BCG
- *Chandra* X-ray large-scale centroid
- ◇ NIKA2 SZ peak **before** point source removal
- × NIKA2 SZ peak **after** point source removal

- Separation between X-ray and SZ peak positions: ~100 kpc
- SZ peak close to X-ray centroid



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Multi-wavelength analysis: ICM profiles

1 - NIKA2 pressure profile

2 - Chandra density profile

3 - Temperature - entropy - mass profiles

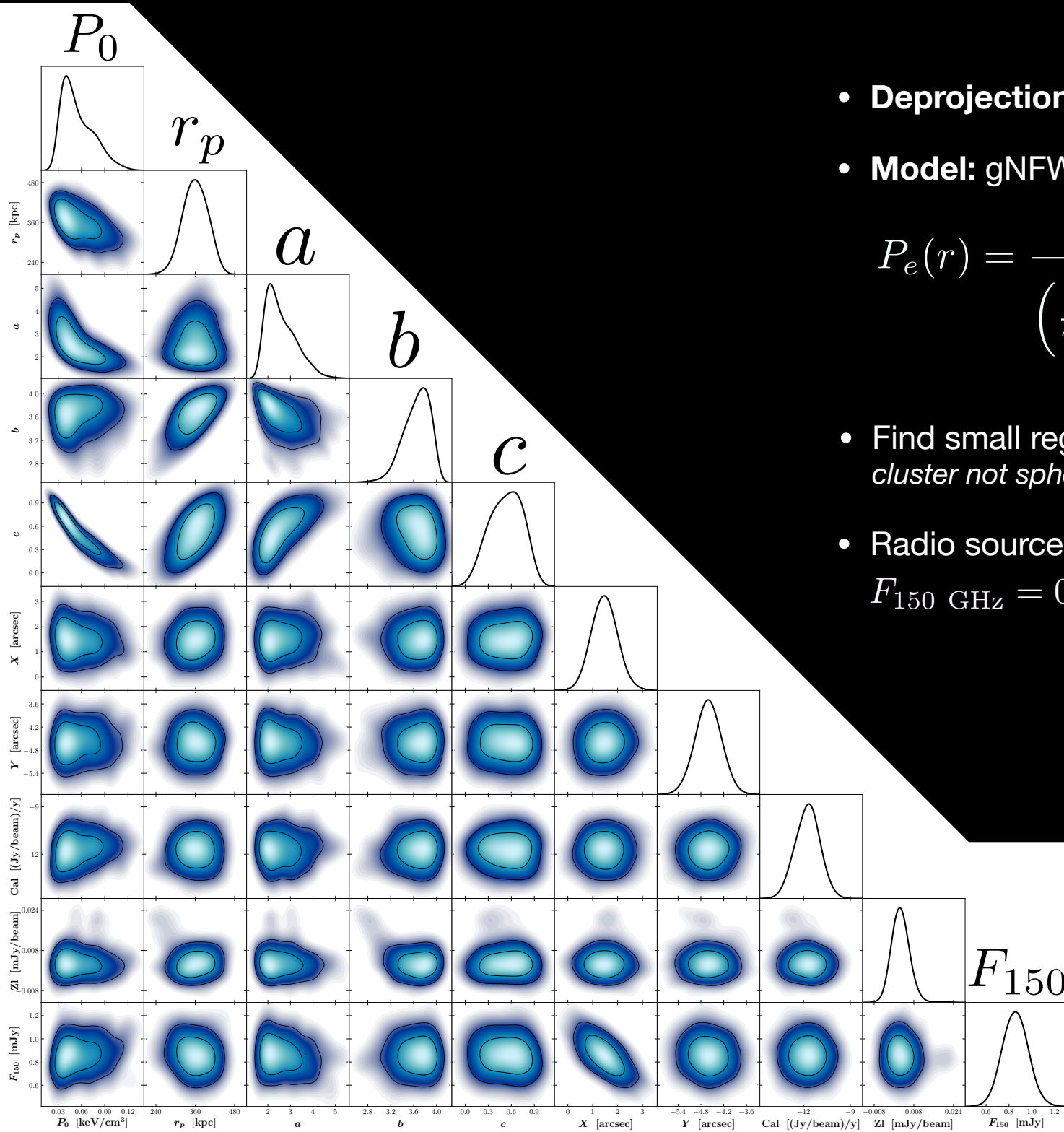
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NIKA2 SZ MCMC analysis



- **Deprojection** of NIKA2 SZ signal at 150 GHz using MCMC analysis

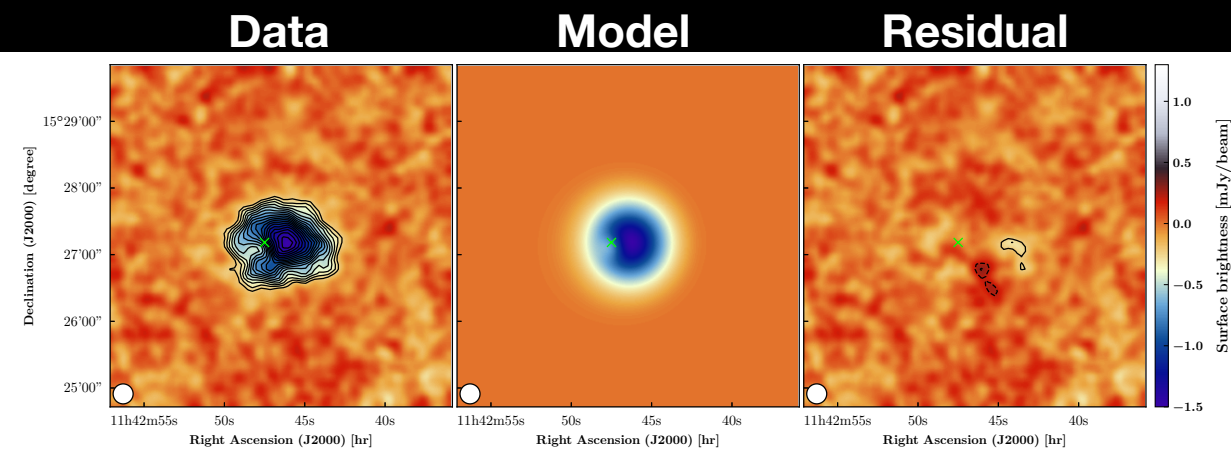
- **Model:** gNFW pressure profile + 2D Gaussian (radio source)

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

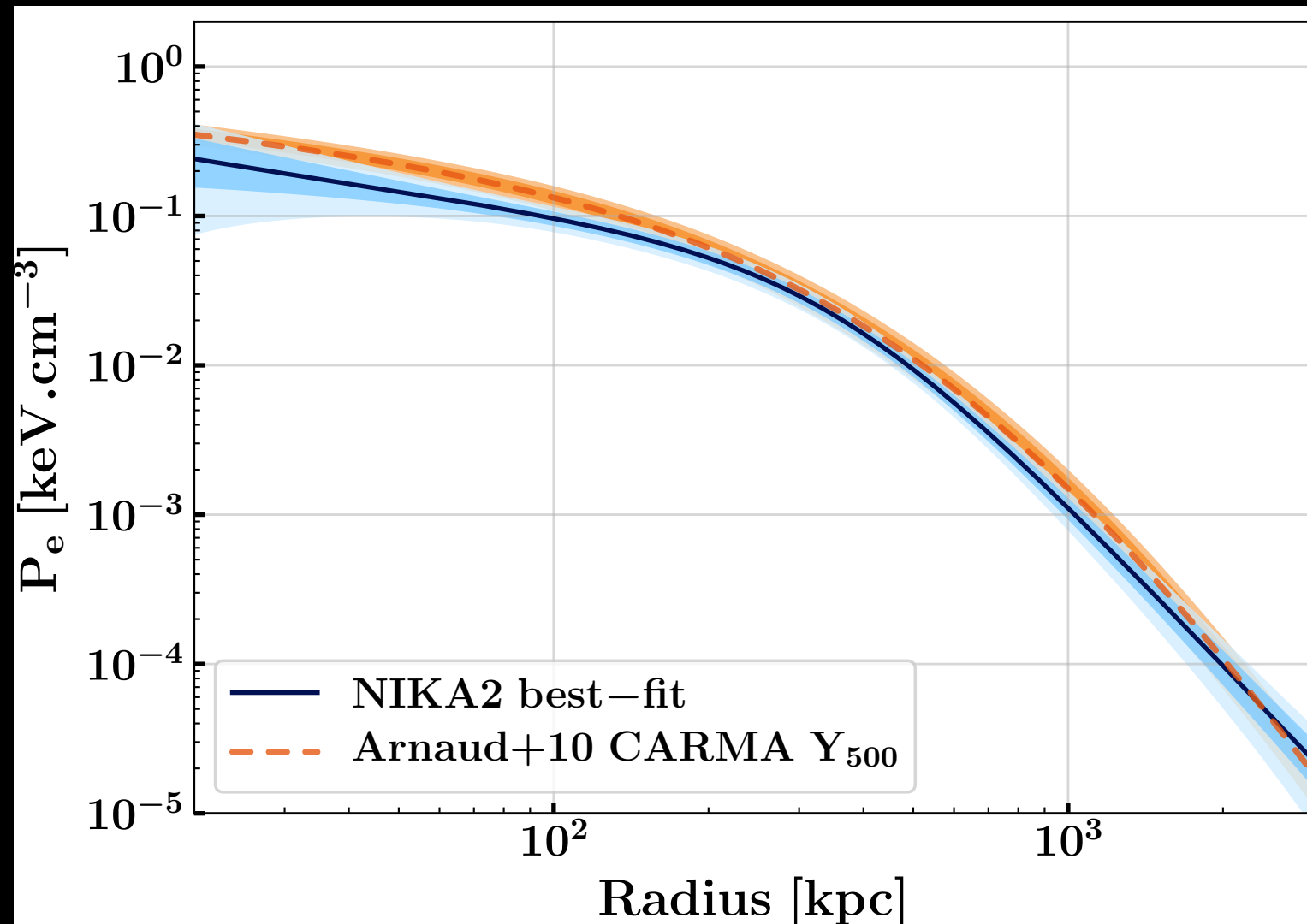
- Find small regions with 3 sigma residuals after best-fit subtraction
cluster not spherical

- Radio source flux compatible with the expected one (*from SED*)

$$F_{150 \text{ GHz}} = 0.95 \pm 0.13 \text{ mJy}$$



NIKA2 Pressure profile



- Pressure profile highly constrained from cluster center to R_{500} (extrapolation begins for $r \gtrsim 800 \text{ kpc}$)
- **Comparison with universal profile:** (Arnaud et al., A&A, 2010)
Integrated Compton parameter from CARMA $Y_{500} = (3.8 \pm 0.5) \times 10^{-4} \text{ arcmin}^2$
Pressure profile from A10 using $Y_{500}-M_{500}$ scaling relation

Small deviations with respect to A10 profile (single cluster)

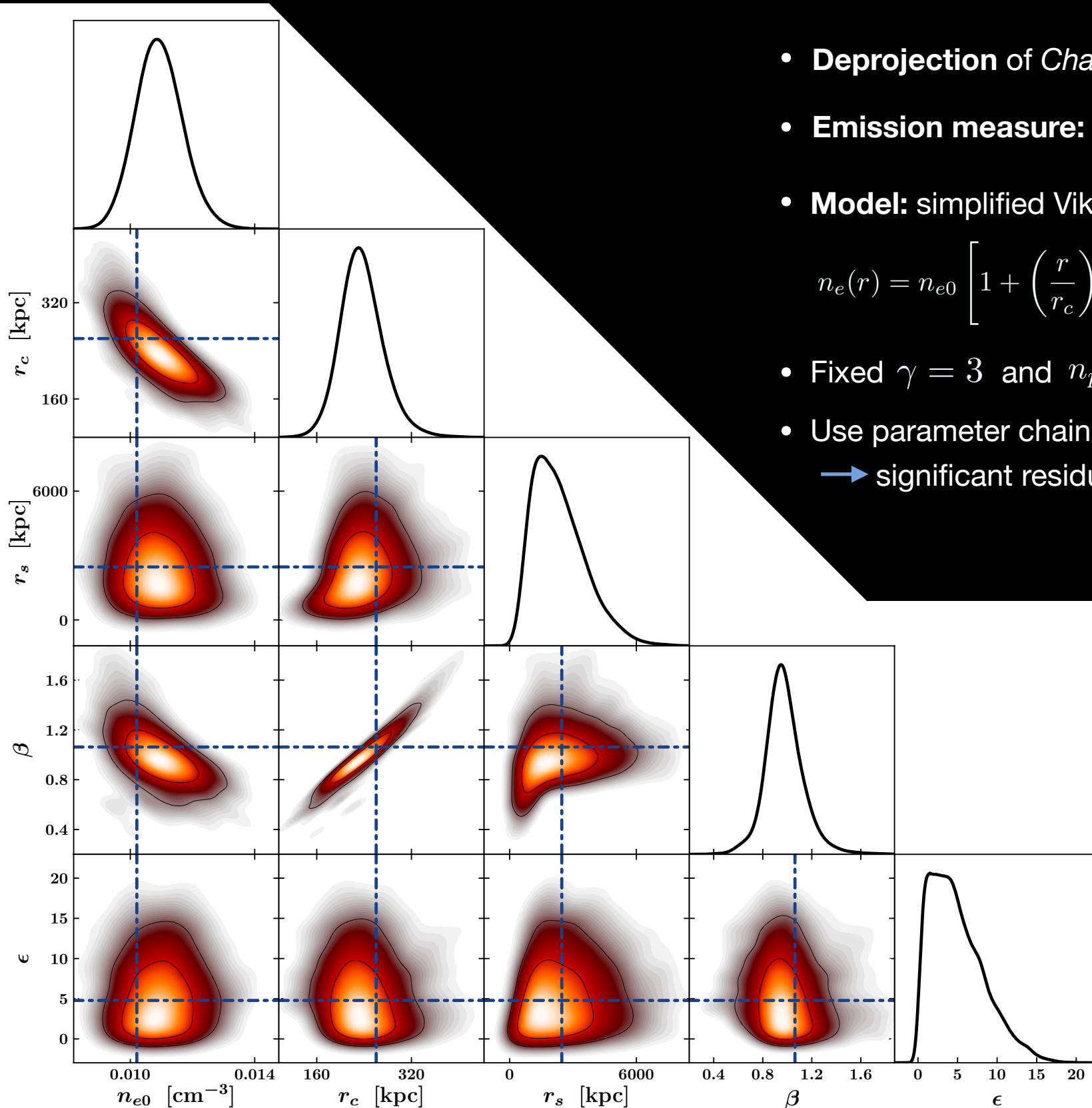
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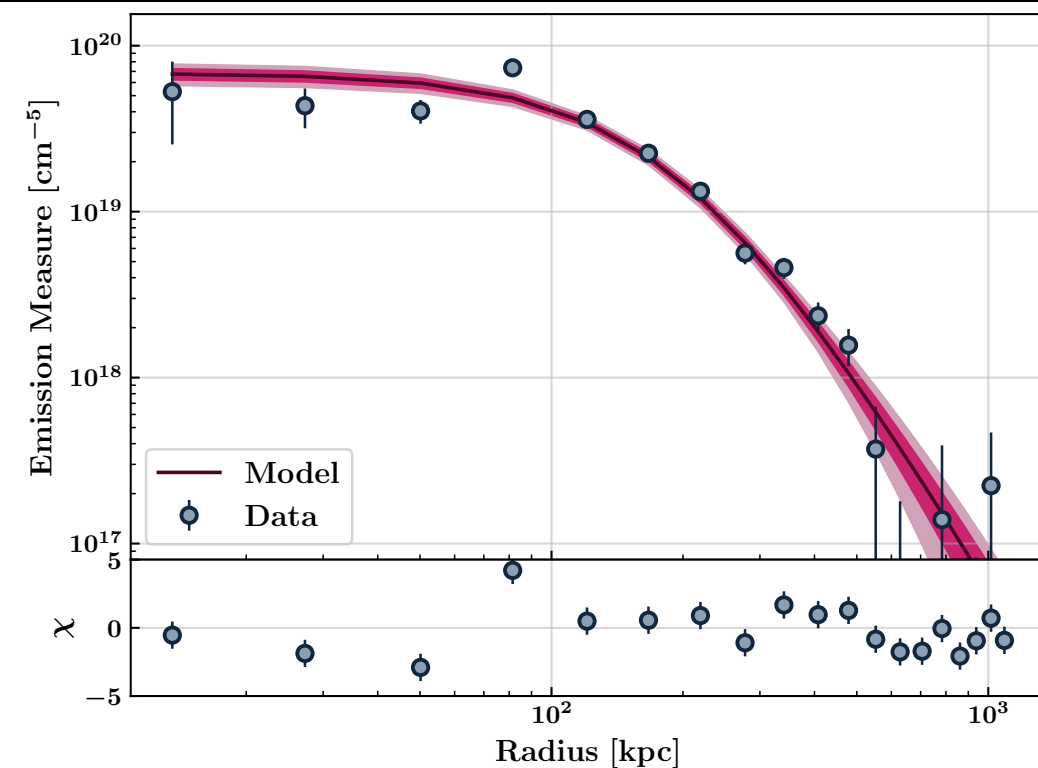
Chandra X-ray MCMC analysis



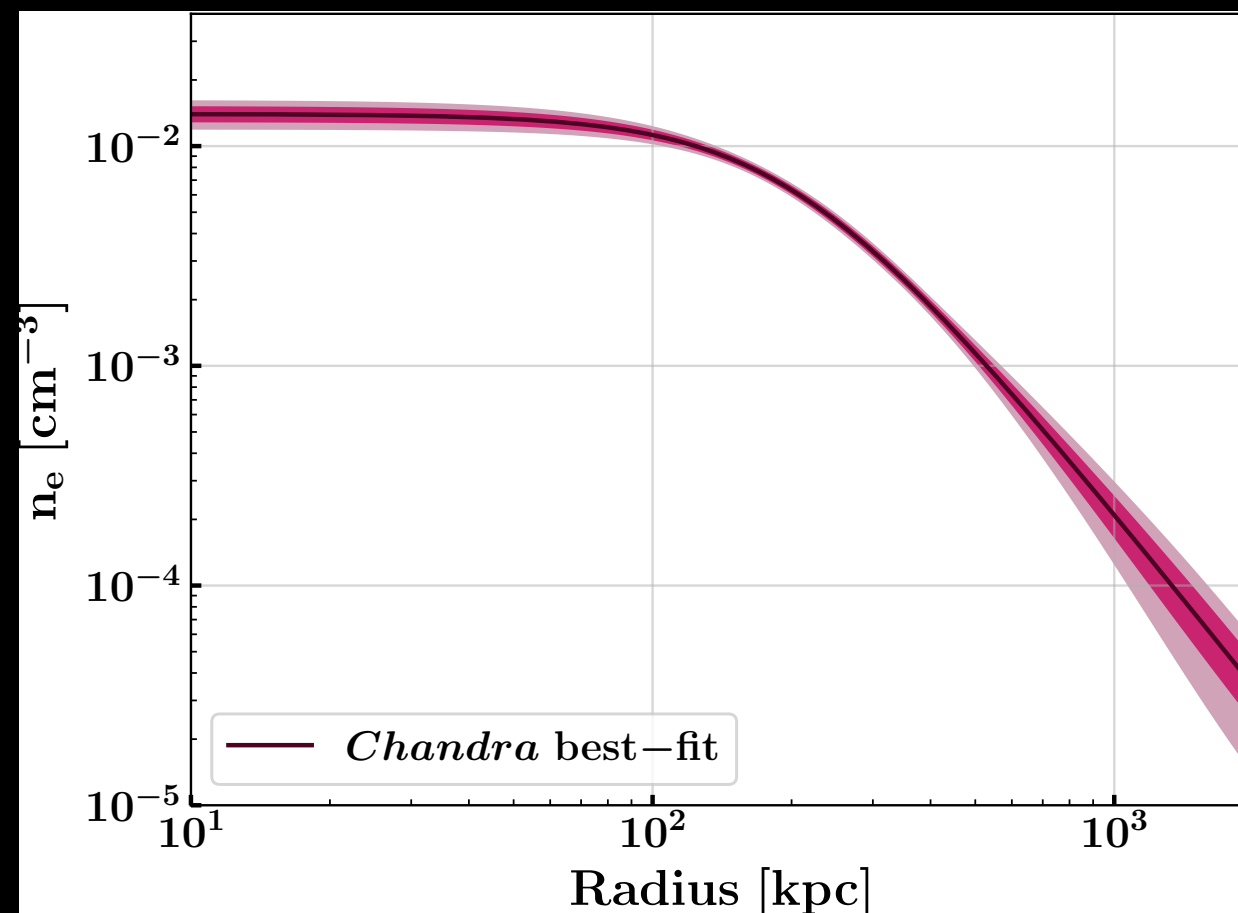
- **Deprojection** of *Chandra* emission measure profile using MCMC analysis
- **Emission measure:** $EM(r) = \int n_e n_p dl$
- **Model:** simplified Vikhlinin model for the electron density

$$n_e(r) = n_{e0} \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2} \left[1 + \left(\frac{r}{r_s} \right)^\gamma \right]^{-\epsilon/2\gamma}$$
- Fixed $\gamma = 3$ and $n_p = n_e/1.199$
- Use parameter chains to estimate uncertainties
 - significant residuals at X-ray peak position (*expected*)

Chandra emission measure profile



Chandra density profile



- Density profile constrained from cluster center up to R_{500}
- Density profile used to estimate maps of averaged ICM thermodynamic properties:

Average density along the LOS: $\bar{n}_e = \frac{1}{\ell_{\text{eff}}} \int n_e dl$ *Computed from Chandra surface brightness map*

Average pressure along the LOS: $\bar{P}_e = \frac{1}{\ell_{\text{eff}}} \int P_e dl$ *Computed from NIKA2 Compton parameter map*

Effective electron depth:

$$\ell_{\text{eff}} = \frac{\left(\int n_e dl \right)^2}{\int n_e^2 dl}$$

Multi-wavelength analysis: ICM profiles

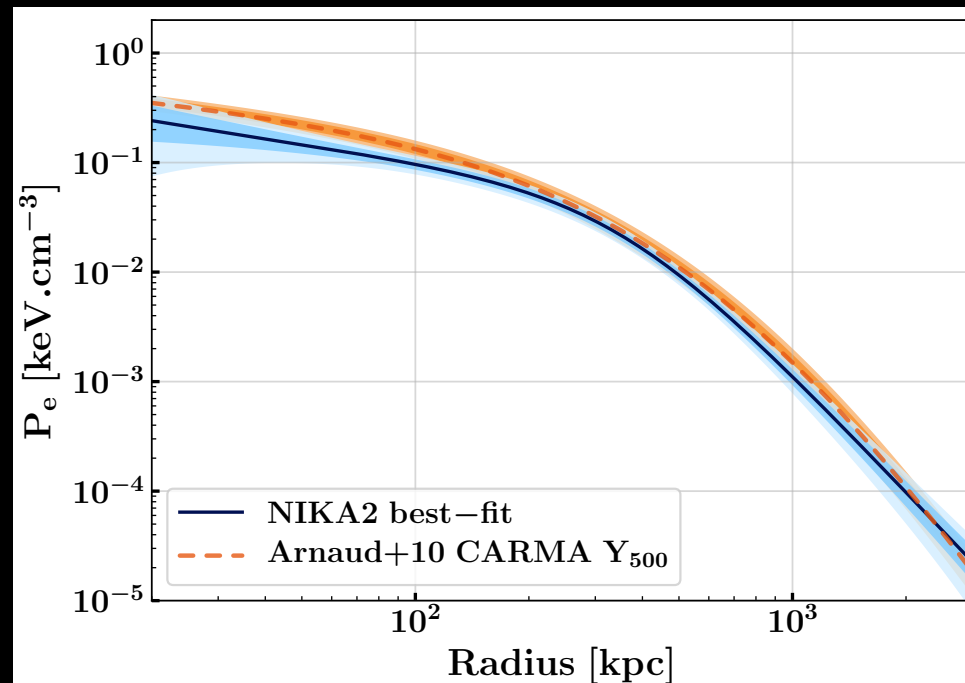
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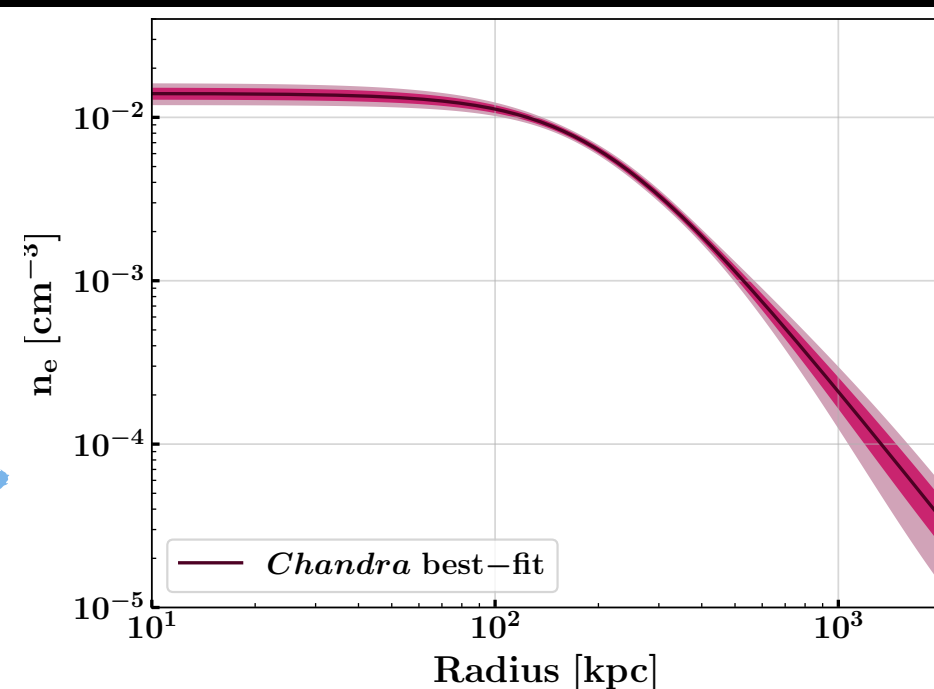
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Temperature and Entropy profiles

NIKA2 pressure profile



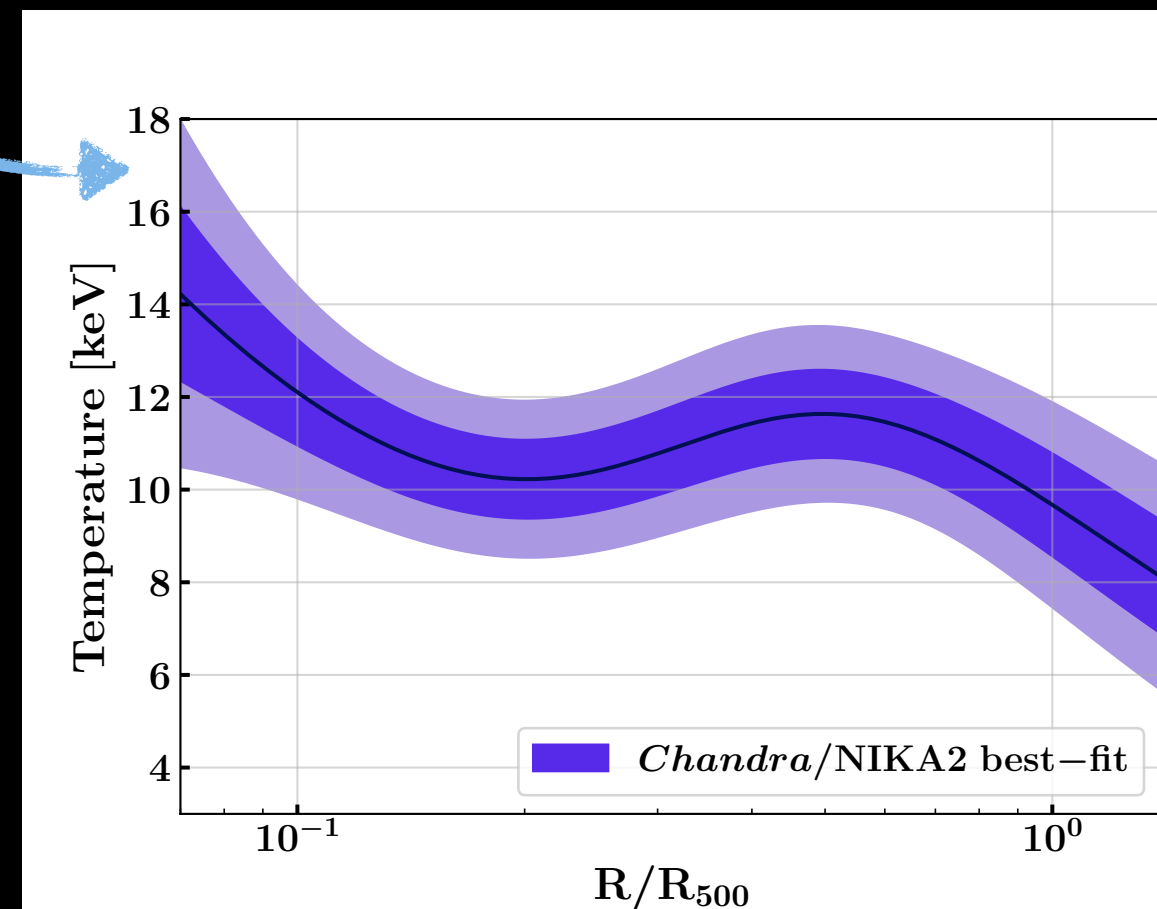
Chandra density profile



$$k_B T_e(r) = \frac{P_e(r)}{n_e(r)}$$

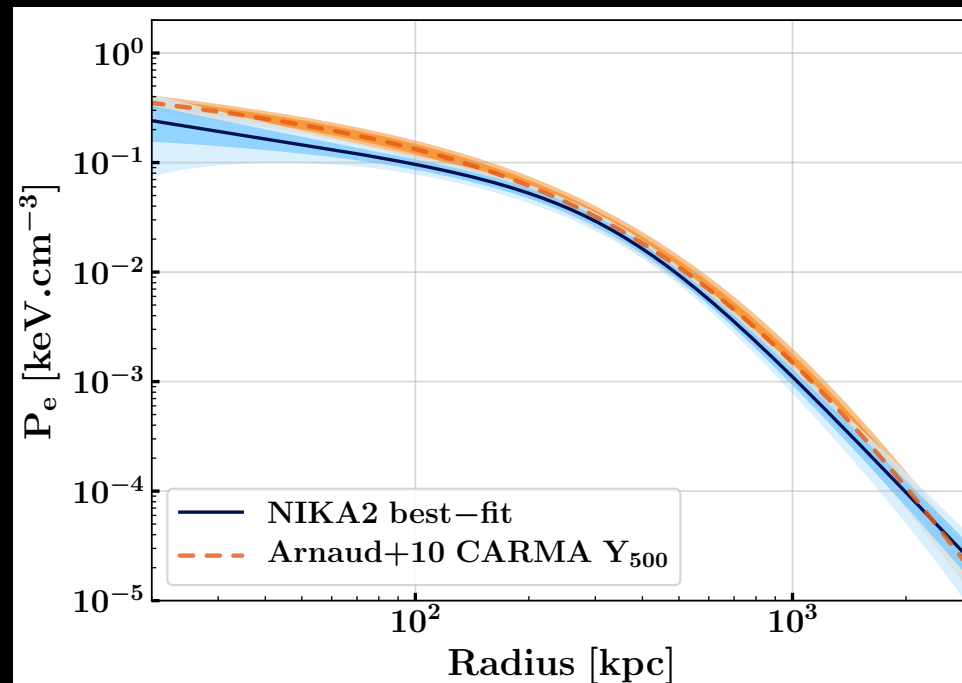
Temperature profile:

- Compatible with constant up to ~700 kpc from X-ray centroid
- High temperature core: consistent with merging event (*disturbed core*)

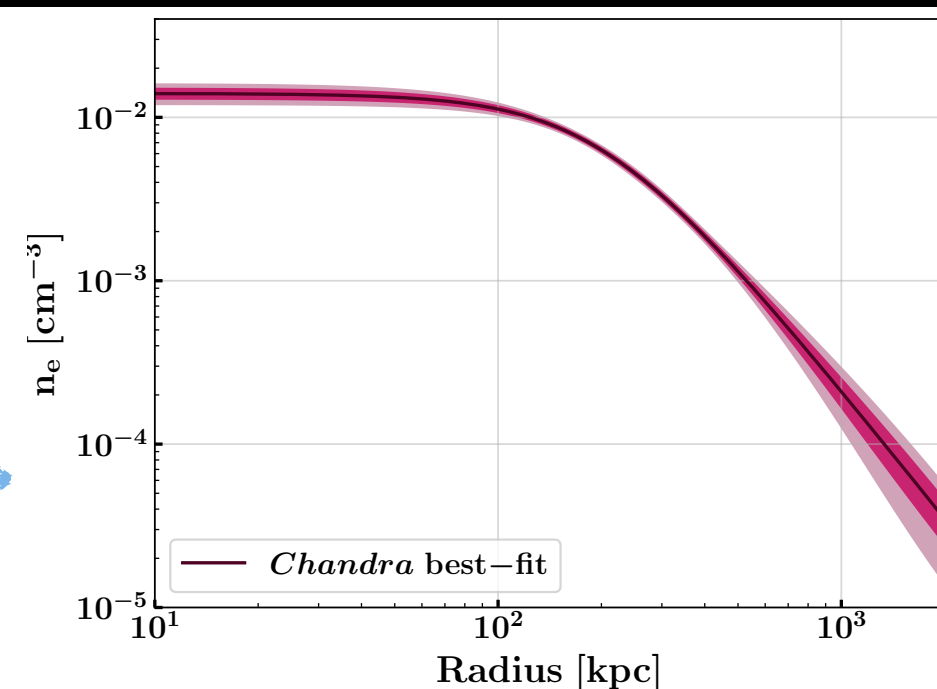


Temperature and Entropy profiles

NIKA2 pressure profile



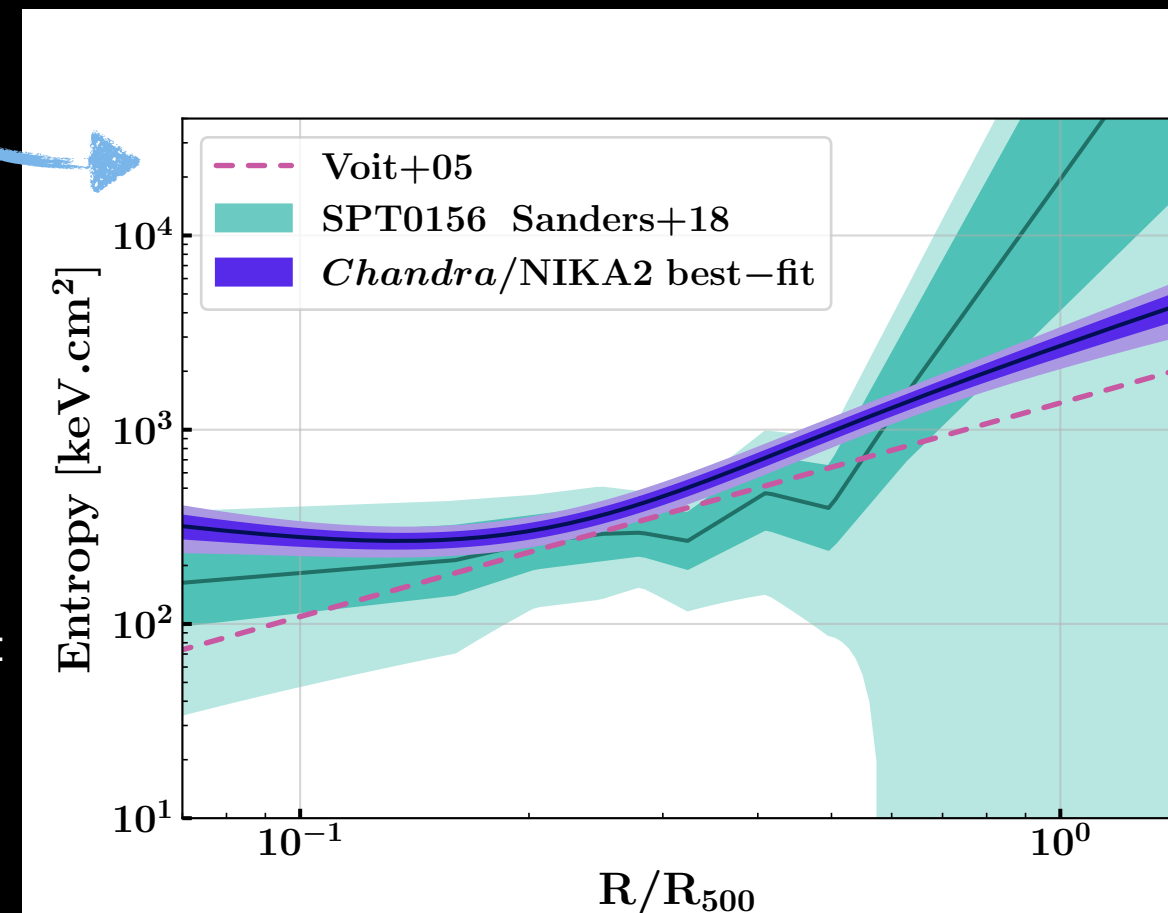
Chandra density profile



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

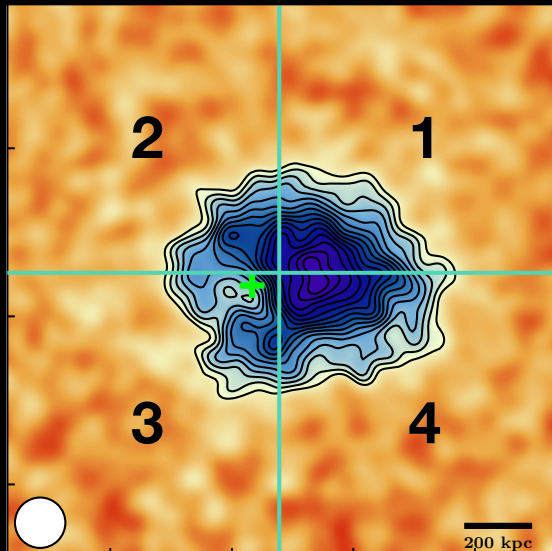
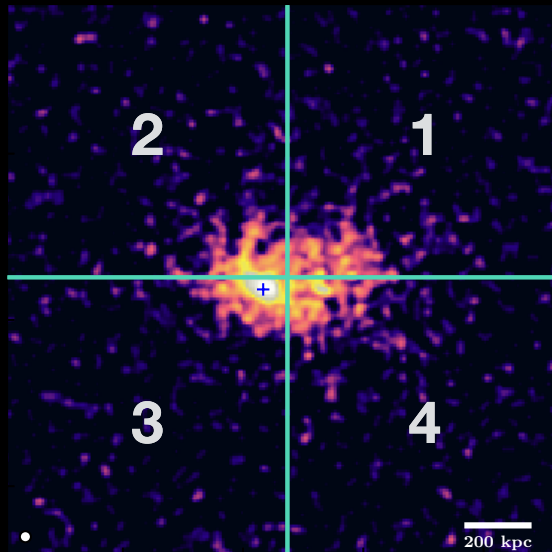
Entropy profile:

- High entropy core: plateau up to $\sim 0.2R_{500}$ (*disturbed core*)
- Outer slope compatible with self-similar expectation
- Exceptional constraints on the entropy profile at this very high redshift



Systematic effect on HSE mass

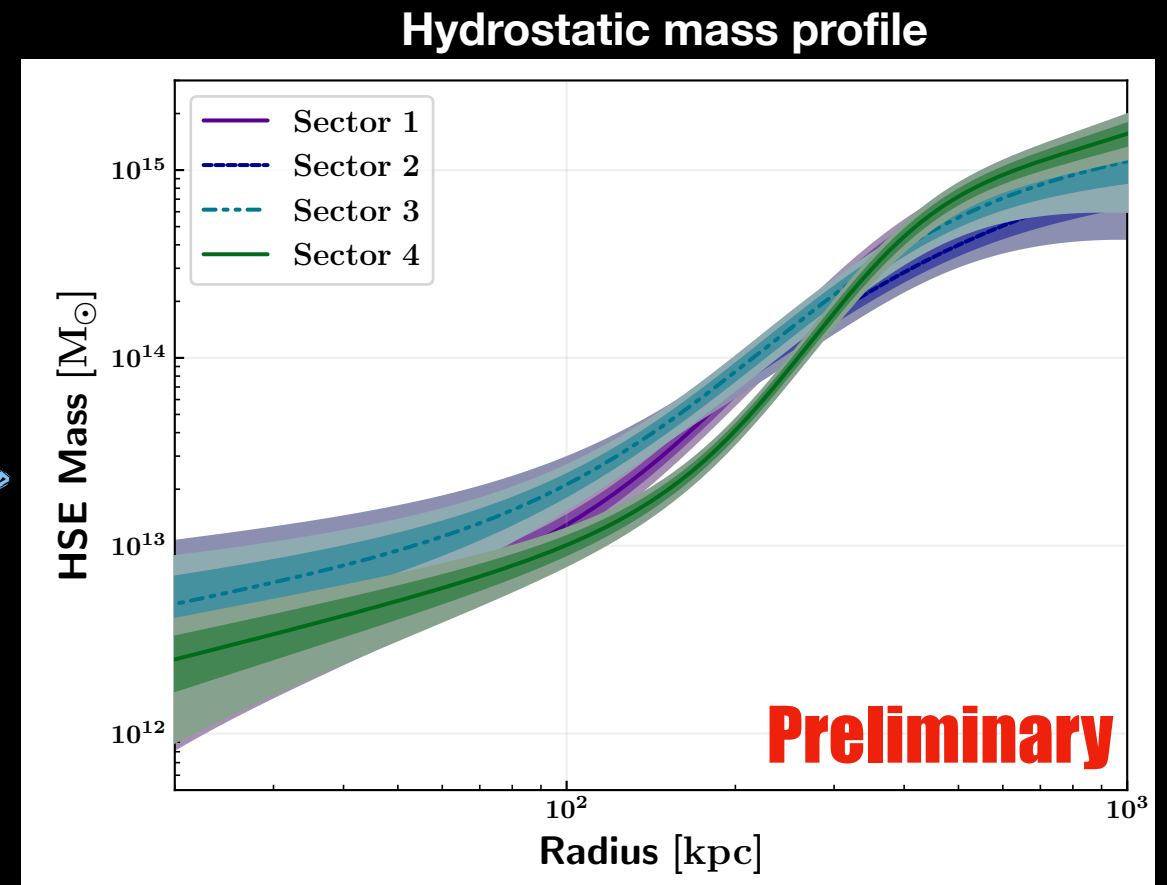
- **Observation:** MOOJ1142 is a disturbed cluster → not in hydrostatic equilibrium
- **Goal:** Estimate systematic effect from cluster merger on HSE mass estimate



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

ICM density ICM pressure

Joint MCMC analysis



$$M_{500}^{HSE} = [9.3 \pm 1.3(\text{stat}) \pm 3.5(\text{syst})] \times 10^{14} M_{\odot}$$

Cluster merger → increase relative uncertainty on the mass from 15% to 50%

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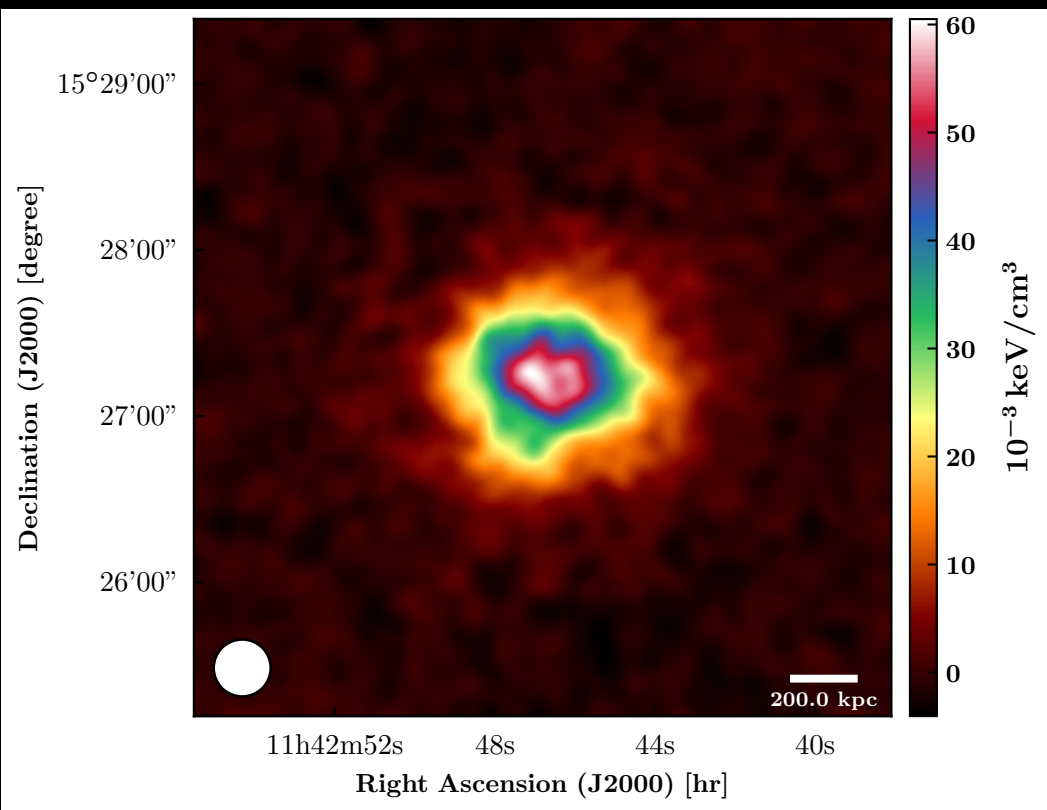
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Following the methodology of Adam et al., A&A, 2017

Mapping ICM pressure and density

MOO J1142 pressure map



Pressure map: $\bar{P}_e = \frac{1}{\ell_{\text{eff}}} \int P_e dl = \frac{m_e c^2}{\sigma_T} \frac{y_{\text{tSZ}}}{\ell_{\text{eff}}}$

y_{tSZ} : Compton parameter map from NIKA2 observations at 150 GHz
After transfer function deconvolution + point source subtraction

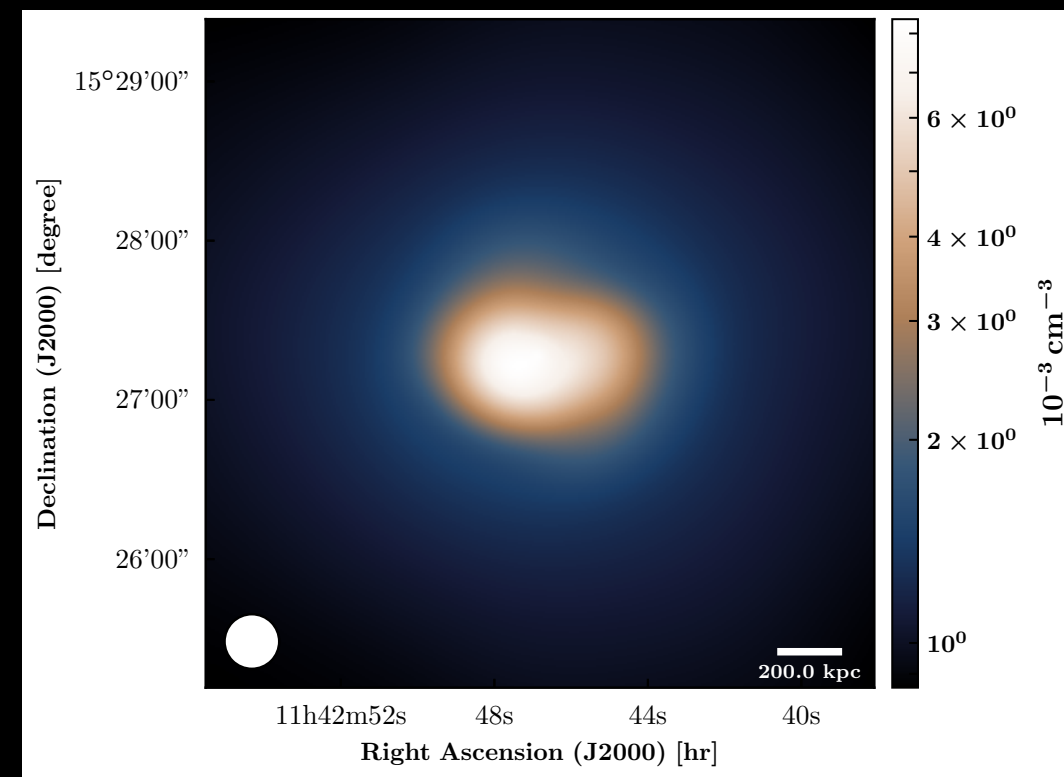
ℓ_{eff} : Effective electron depth from *Chandra* density profile

Density map: $\bar{n}_e = \frac{1}{\ell_{\text{eff}}} \int n_e dl = \frac{1}{\sqrt{\ell_{\text{eff}}}} \sqrt{\frac{4\pi (1+z)^4 S_X}{\Lambda(T_e, Z)}}$

S_X : Surface brightness map from *Chandra* observations
After exposure correction + background and point source subtraction

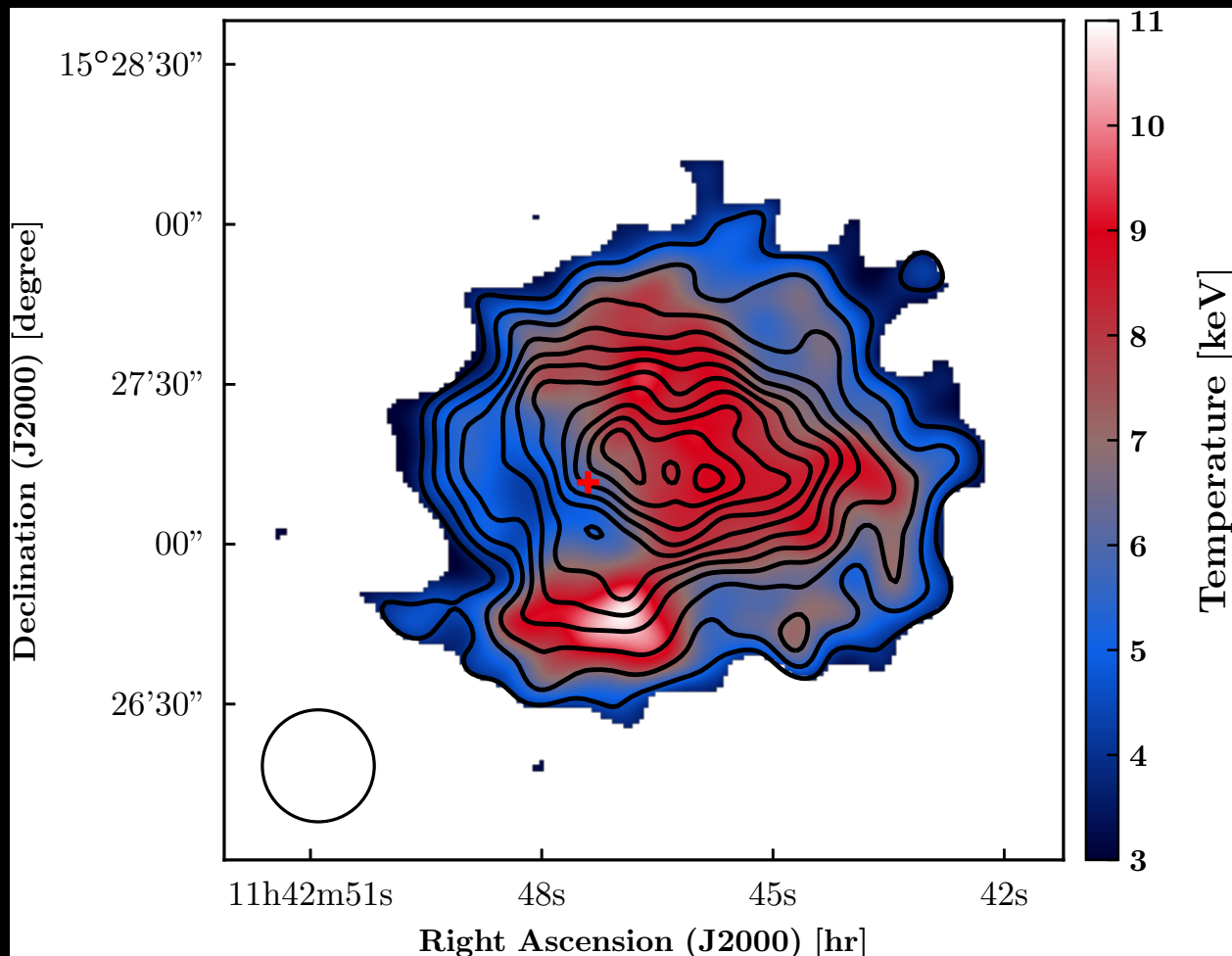
$\Lambda(T_e, Z)$: Map of the cooling function
Using mass weighted temperature profile + $0.3 Z_{\odot}$

MOO J1142 density map



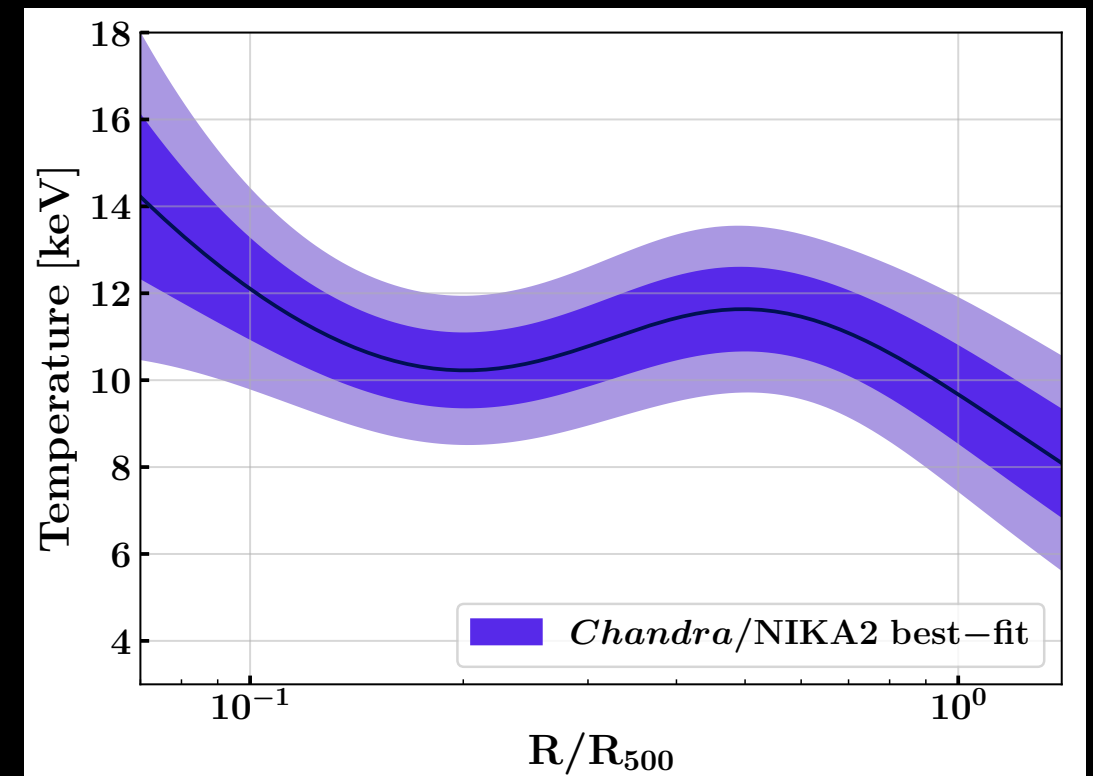
Mapping ICM temperature

Temperature map



VS

Temperature profile

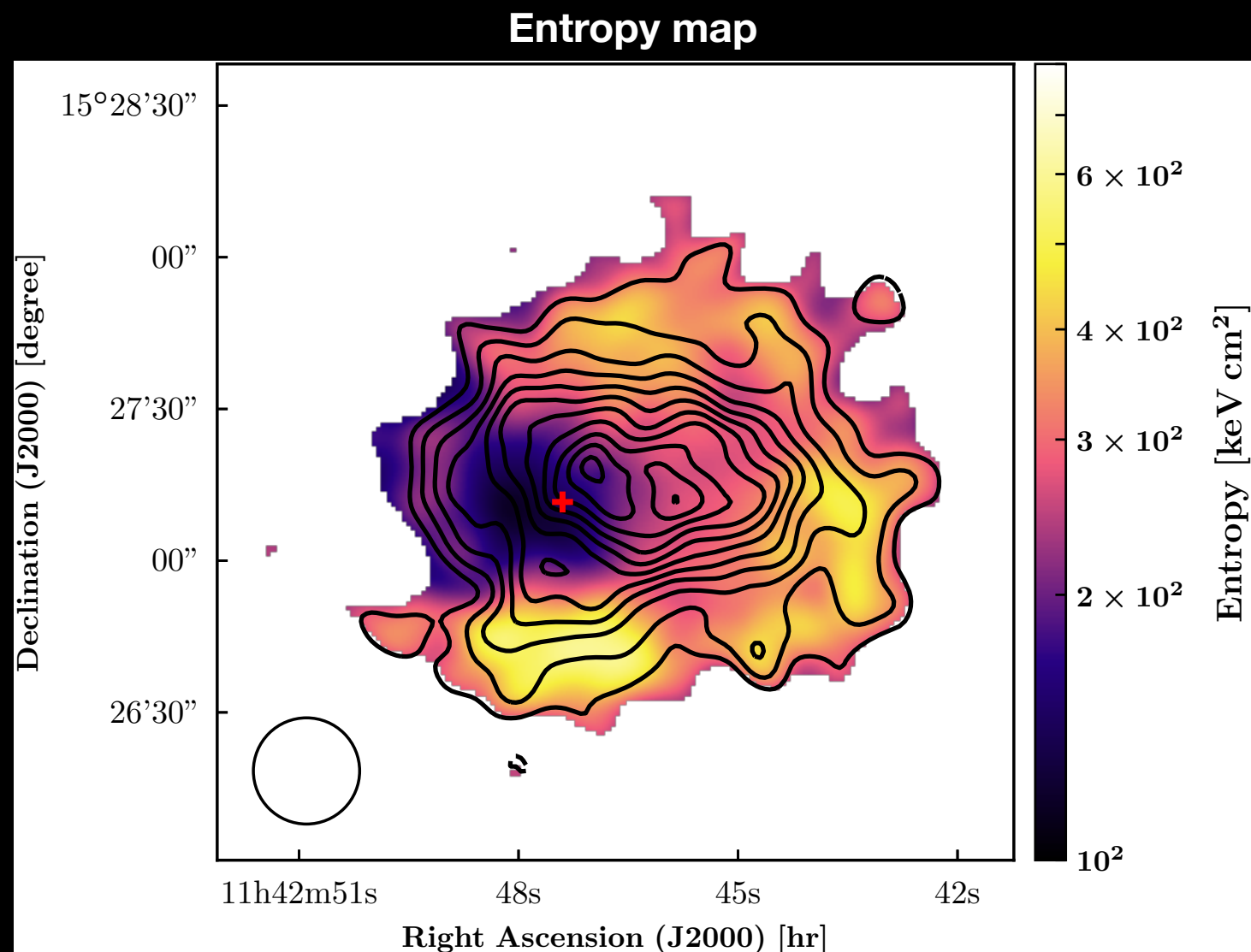


Temperature map: $\bar{T}_e = \bar{P}_e / \bar{n}_e$

- Low temperature core at the X-ray peak + High temperatures in the south and west regions
- Better understanding of temperature profile shape (*using centroid*)

Additional information on spatial distribution of temperature for disturbed clusters

Mapping ICM entropy



- Relatively low entropy core at the BCG position + High entropy in the south and west regions
- Offset between low-entropy core and cluster centroid → consistent with merger activity

Cluster cool core not completely disturbed by merger activity

Conclusions / Perspectives

- First joint analysis of high angular resolution SZ and X-ray data at $z > 1$
 - Large leap forward on the constraints on the temperature and entropy profiles at $z > 1$
- MOO J1142+1527 = on-going merger although not obvious from SZ signal
 - Large impact on the HSE mass estimate (*not in hydrostatic equilibrium at all*)
- Mapping the ICM thermodynamic properties: very relevant for this particular cluster (*first time at $z > 1$*)
 - Find high temperature/entropy regions in the south and west

Future analyses:

- Repeat same analysis procedure for the 10 clusters of our program
- Study evolution of thermodynamic profiles
- Study properties of cluster mergers at $z > 1$

SZ/X-ray analyses → begin studying high redshift and low mass clusters before next generation X-ray satellite is launched

Thank you



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