The inner structure of galaxy clusters seen through the Sunyaev-Zel'dovich effects with NIKA

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(new member of the Astro - γ group)

LLR seminar
Palaiseau - 03/12/2018

What is the nature of dark matter?

What causes the accelerating expansion of the Universe: Λ, dark energy, modified gravity?

co-evolution

Dark matter (simple) ⟷ **Gas and galaxies (not simple)**

How does the baryonic matter co-evolve with dark matter during structure formation?

[Illustris simulation]

Outline

1. Clusters of galaxies as cosmic laboratories
2. Resolving the inner structure of the hot gas with NIKA
3. Mapping the gas pressure and velocity in clusters
4. Non-thermal processes in clusters
5. Summary

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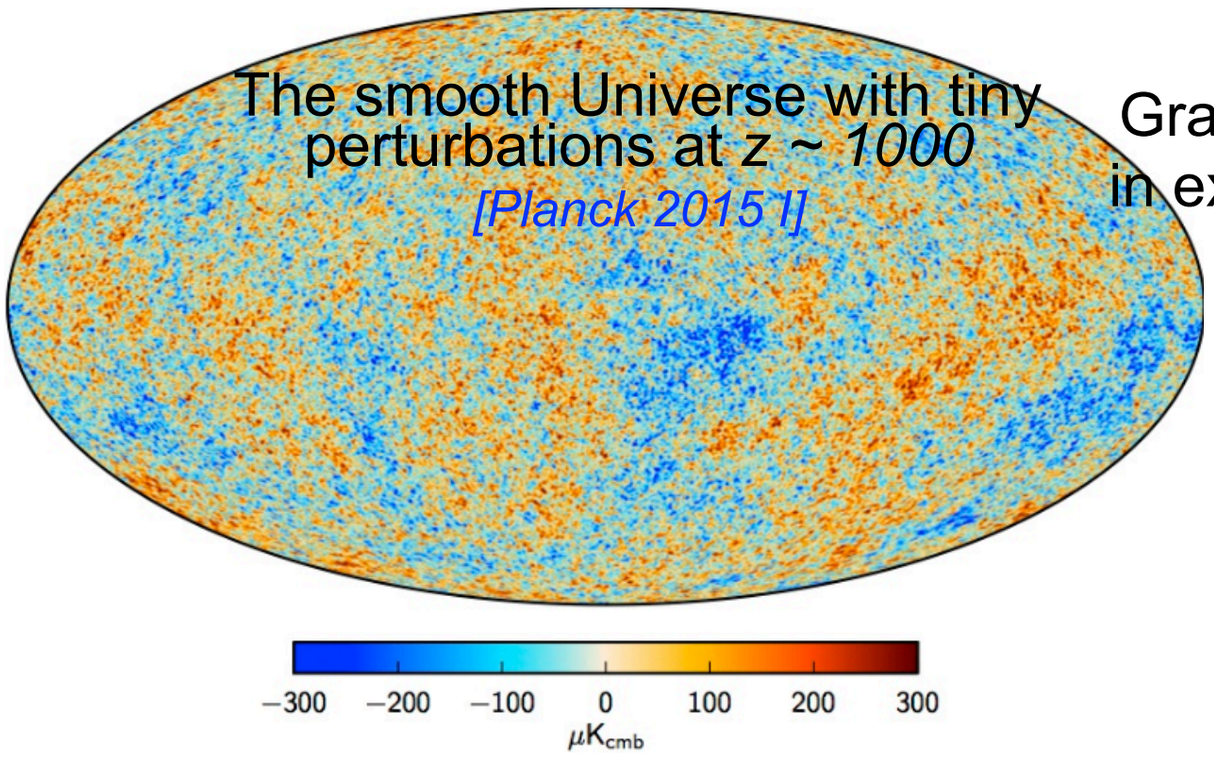
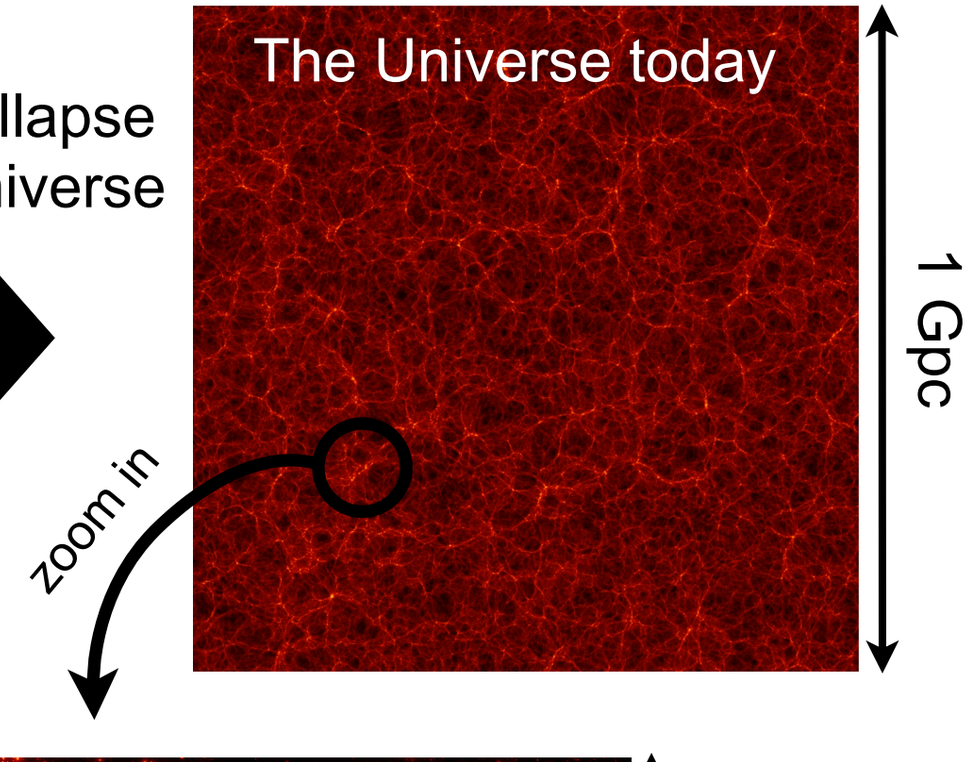
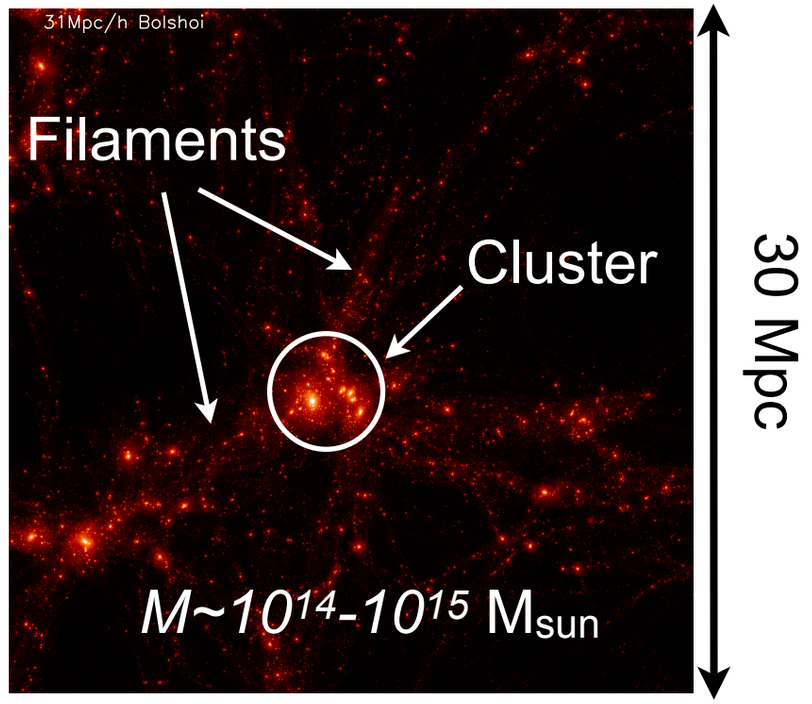
From primordial fluctuations to galaxy clusters



Gravitational collapse in expanding Universe

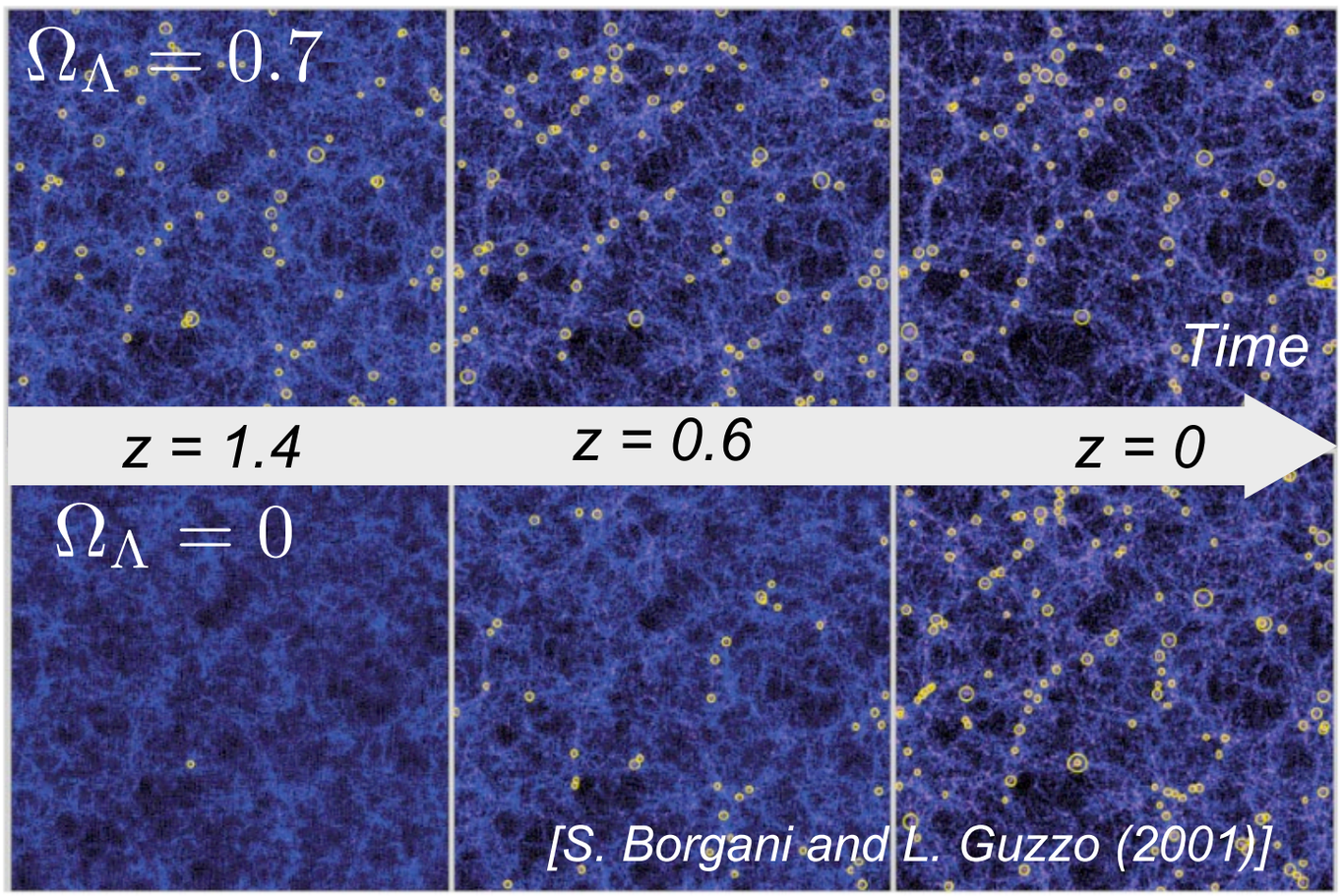


Galaxy clusters are peaks in the matter density field



[www.multidark.org]

Cosmology with galaxy cluster number count



Survey detection — *Model*

$$\frac{dN}{dz} = \int \chi(z, M) \frac{d^2 N}{dz dM} dM$$

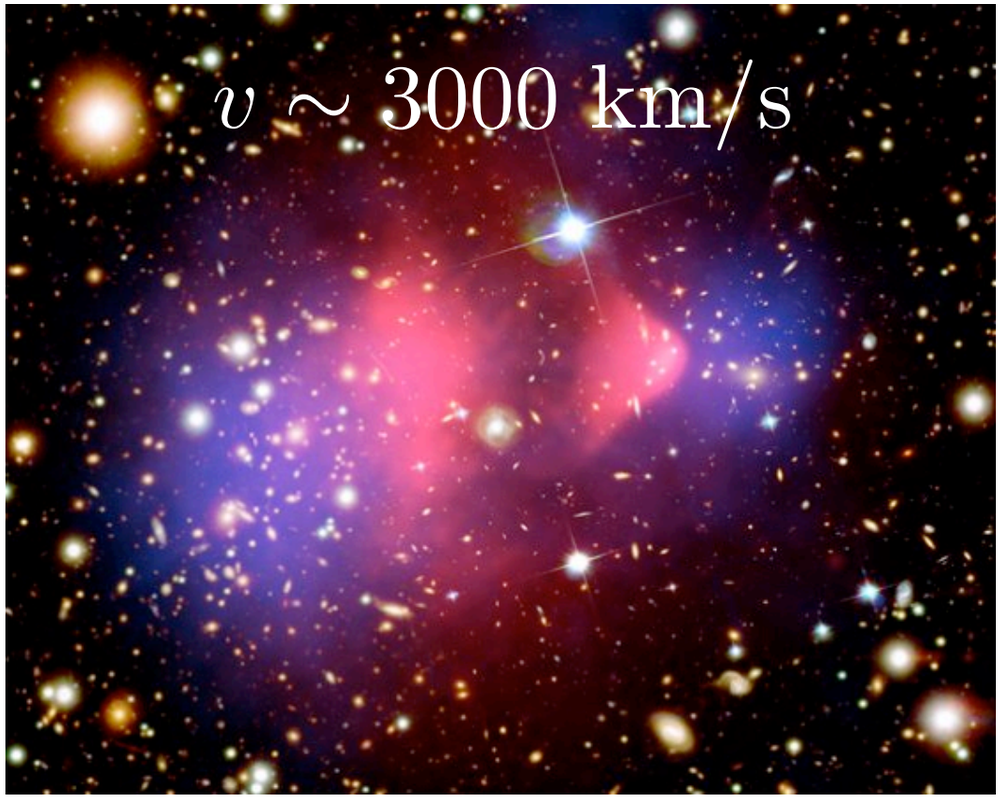
Selection function — *Mass-obs. relations*

Sensitive to geometry, dark matter/energy and gravitation

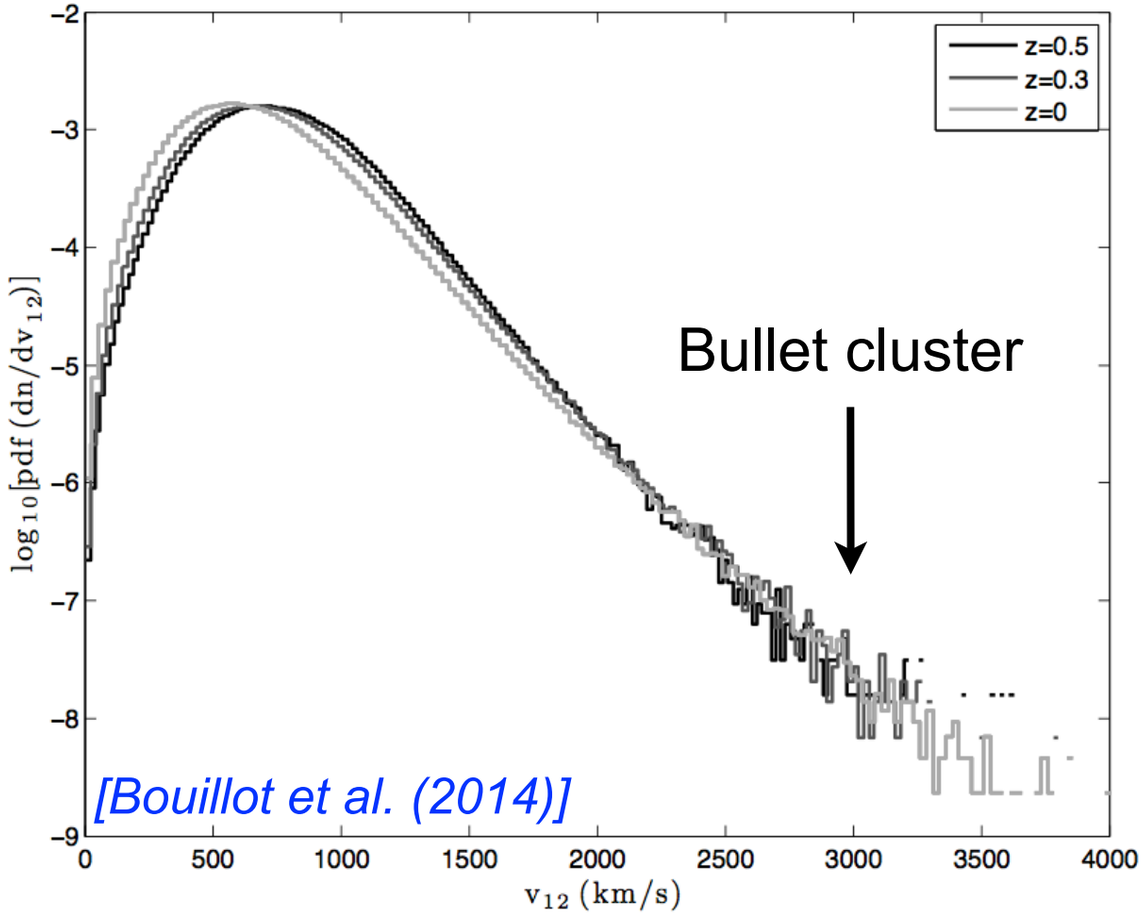
Key ingredients: mass + observational properties

Cosmology with galaxy cluster bulk velocities

1. Peculiar **velocity count** of large samples *[e.g., Bhattacharya & Kosowsky (2008)]*
2. Large velocities of **merging** cluster **pairs** *[e.g., Thompson & Naganime (2012)]*

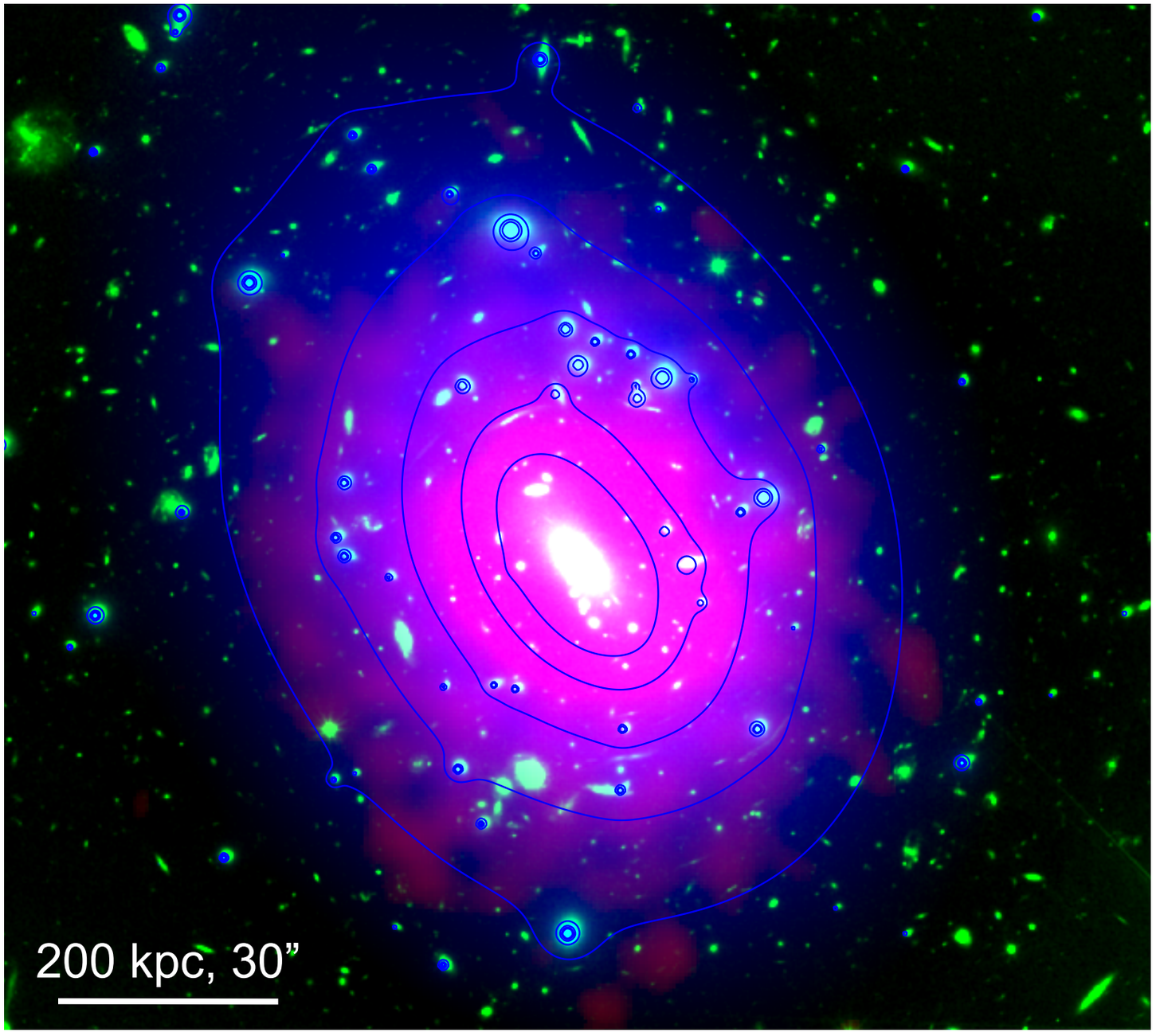


[Markevitch et al., Clowe et al.]



Key ingredients: clusters peculiar velocities

Observing clusters of galaxies



Galaxies (~3%)
- Optical & NIR

Hot ionized gas (~12%)
- X-ray
- (sub-)millimeter (SZ)
- radio
- γ-rays?

Dark matter (~85%)
- lensing (galaxies/CMB)

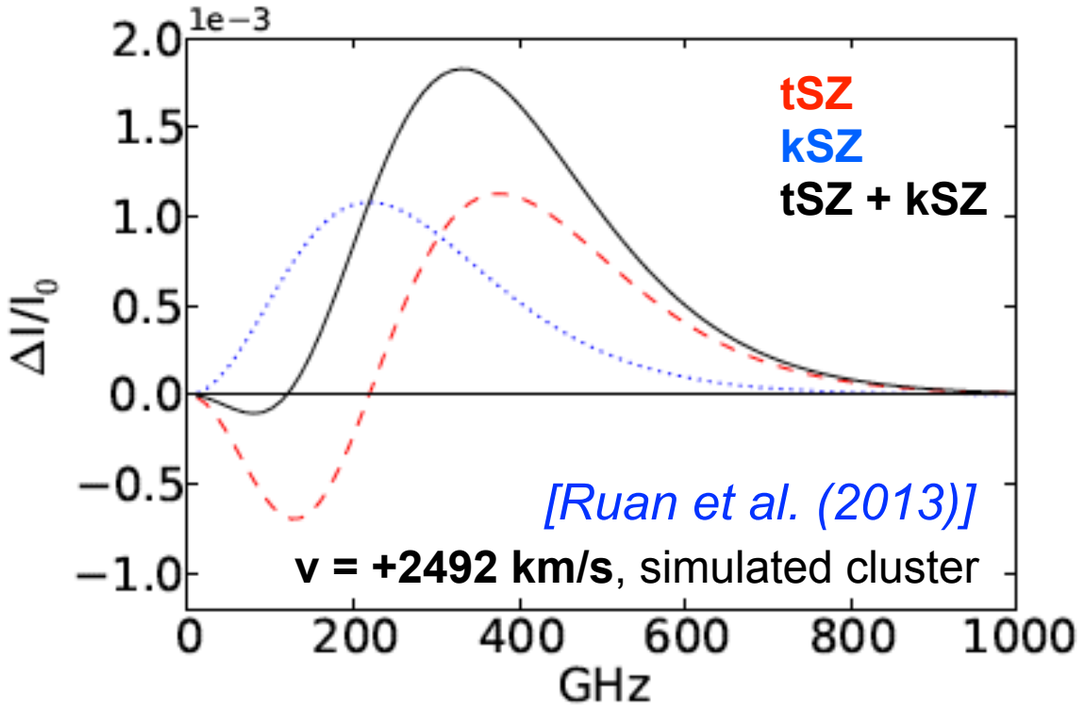
We need to rely on baryonic tracers

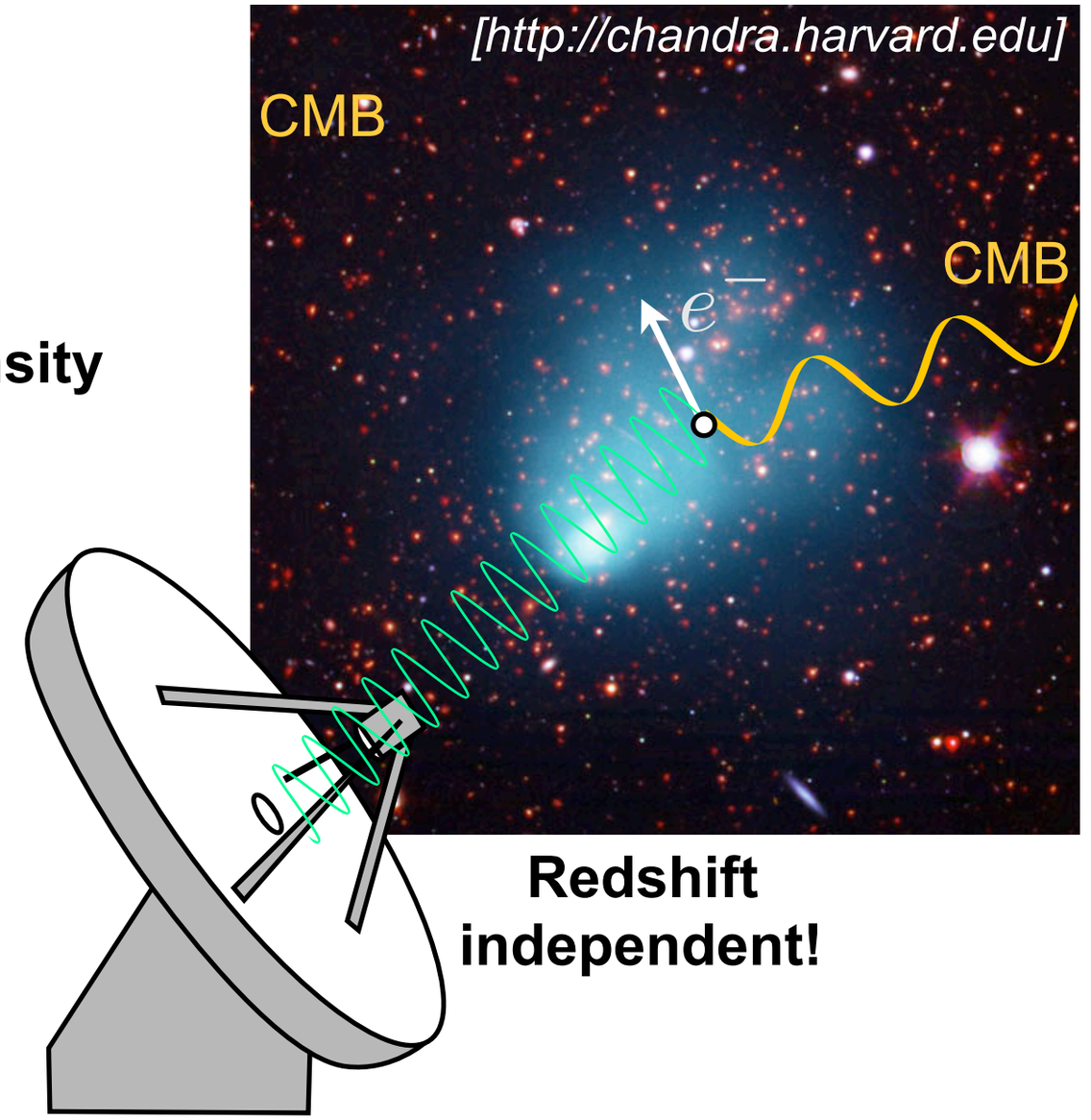
Looking at clusters using the SZ effects

- **tSZ** = CMB spectral distortion from interaction with clusters' hot electrons
- **kSZ** = CMB Doppler shift from bulk motion of electrons (typically ~ tSZ/10)

$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

$$\begin{cases} y_{\mathrm{tSZ}} = \dfrac{\sigma_{\mathrm{T}}}{m_e c^2} \displaystyle\int P_e \, d\ell & \Rightarrow \textbf{Pressure} \\ y_{\mathrm{kSZ}} = \sigma_{\mathrm{T}} \displaystyle\int \frac{-v_z}{c} n_e \, d\ell & \Rightarrow \textbf{Velocity x density} \end{cases}$$





Redshift independent!

The SZ effects are probes for intracluster gas

Astrophysics & cosmology with the SZ effects

➡ tSZ pressure ~ total mass
➡ kSZ momentum ~ velocity

Cluster Cosmology

Growth of structures
Universe expansion history
Large scale velocity flow

Control in detection & mass determination

➡ **Cosmological parameters**
[Allen et al. (2011), for a review]

Astrophysical models

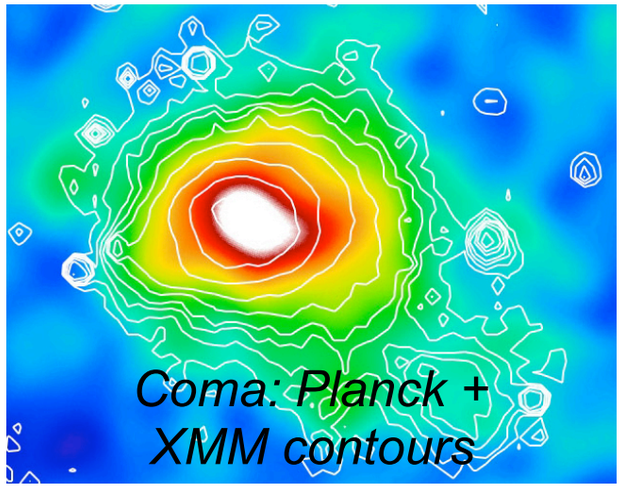
Cluster Astrophysics

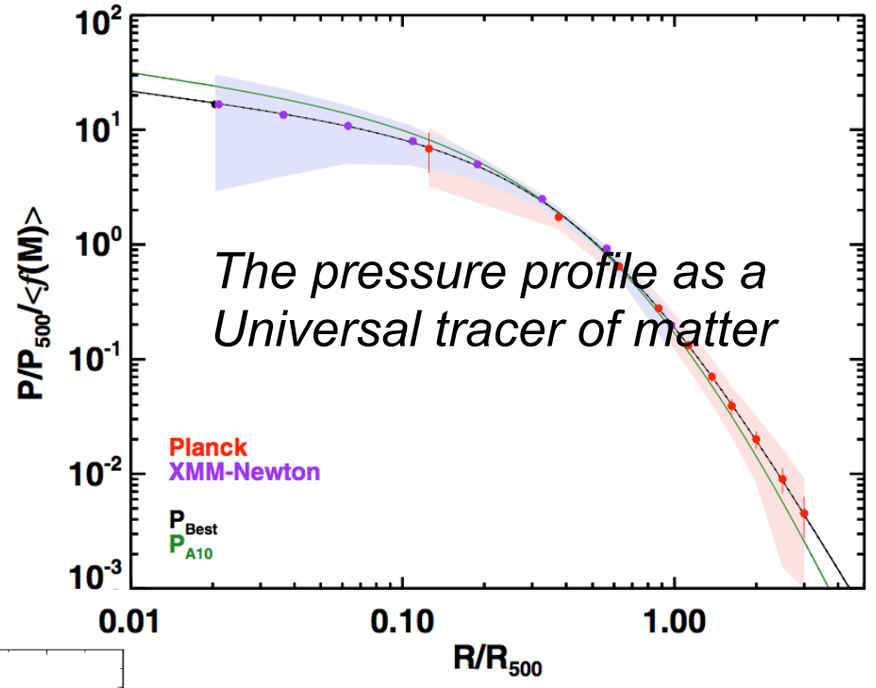
Gas, galaxies and dark matter interplay
Shock heating / turbulence
Feedback
Gas clumping
...

➡ **Observational properties (e.g. pressure distribution)**
[Mroczkowski et al. (2018), for a SZ review]

Status after Planck and ground based SZ surveys

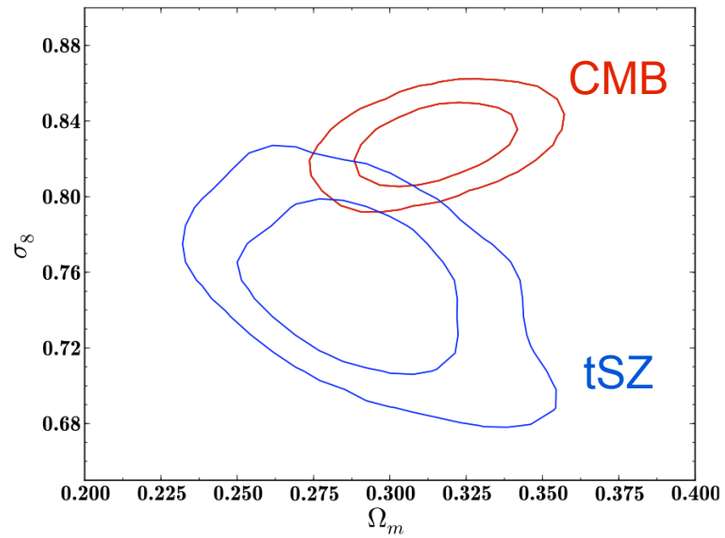
- Formalism & first detection (70's)
[Sunyaev & Zel'dovich (1970)]
- First (statistical) kSZ detection
[Hand et al. (2012)]





- All-sky catalog (1653 objects) & map
[Planck XXIX (2013), XXVII & XXII (2015)]
- Detailed study of nearby clusters
[Planck V, VIII, X (2013)]
- Number count
[Planck XX (2013), Planck XXIV (2015)]
- See also results by SPT, ACT, ...

- CMB & local Universe tensions



Misunderstanding of cluster?
Hint for missing physics?
Statistical fluctuation?

➡ *Need to explore the SZ signal **inner structure***
*at **high z** with high angular resolution follow-ups*

Huge progress, but new fundamental questions

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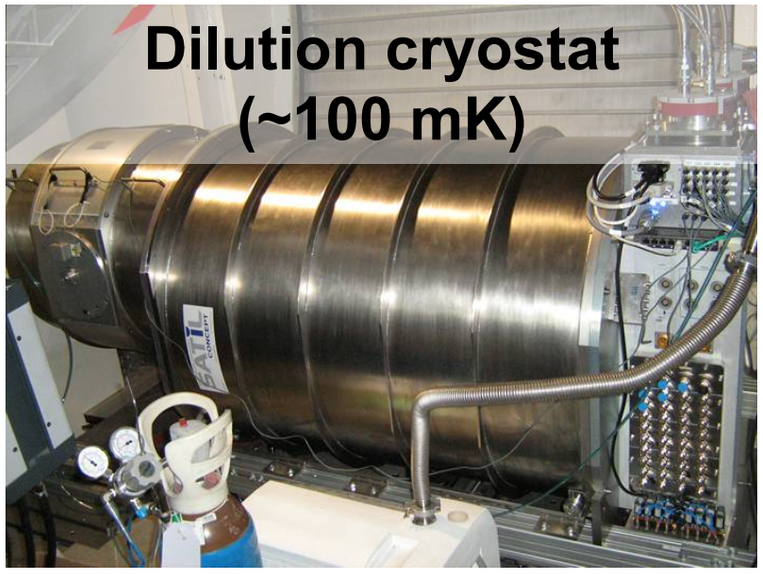
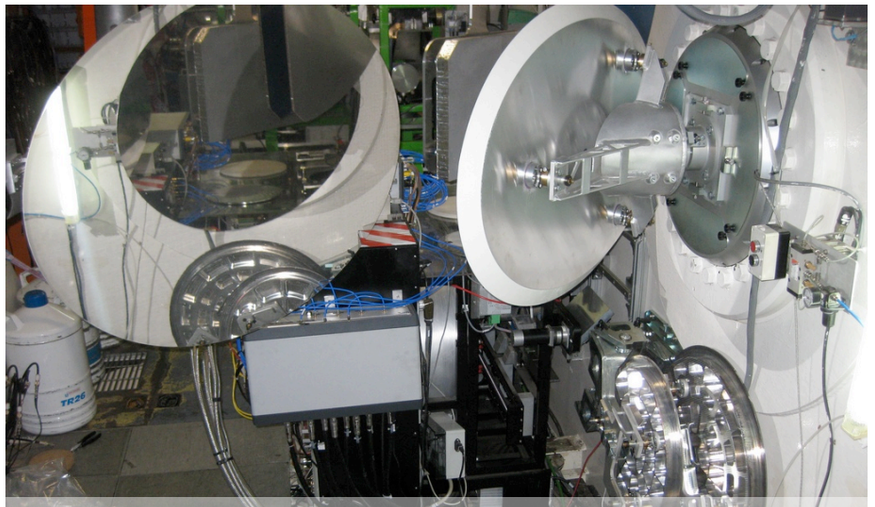
NIKA2: the New IRAM KIDs Array

KID detectors arrays
150 & 260 GHz

Dilution cryostat
(~100 mK)





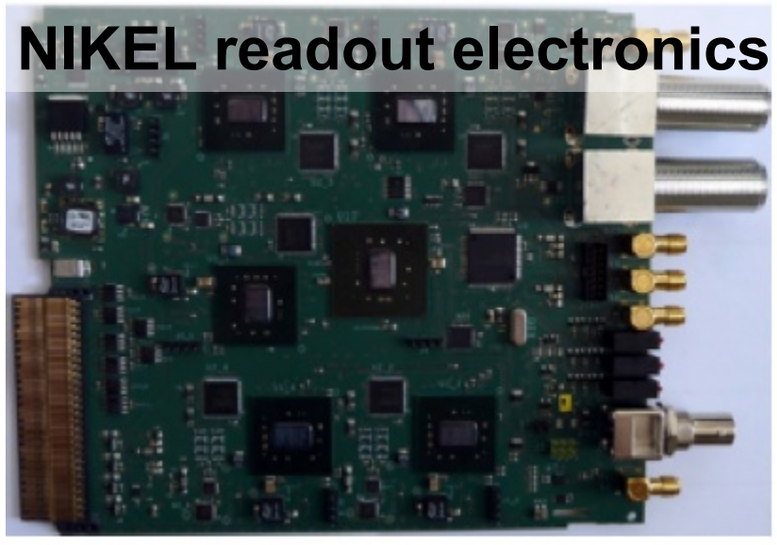
Dedicated optics coupled to the telescope (6.5’ FoV)

IRAM 30m telescope
~15” FWHM

NIKA2

[NIKA collaboration (2018)]

NIKEL readout electronics

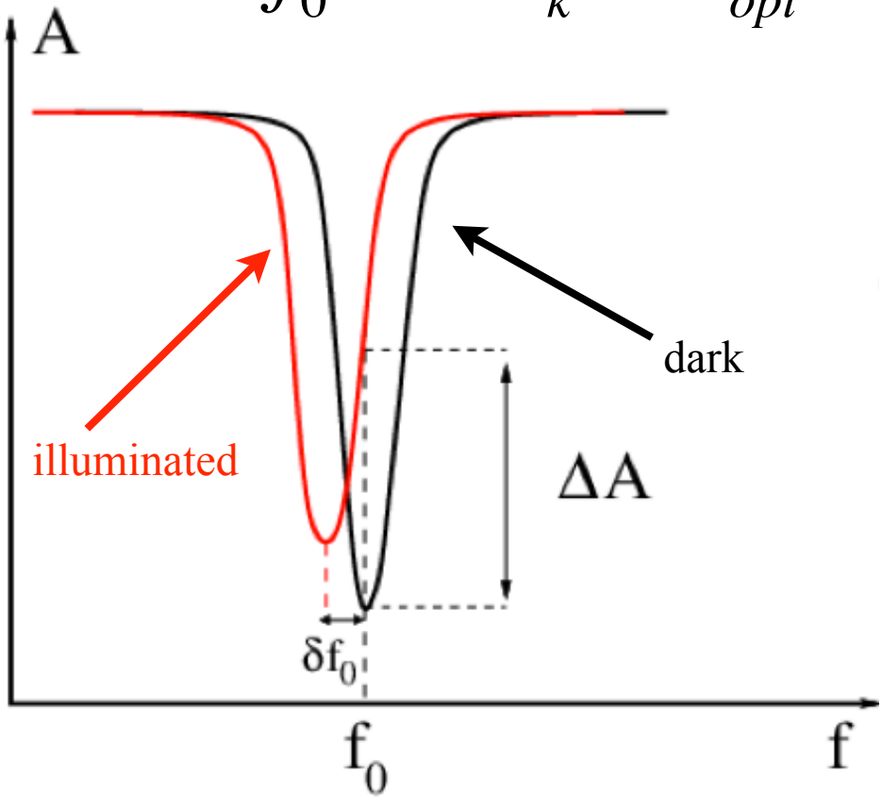


Large FoV+high resolution+SZ bands: excellent for resolving clusters

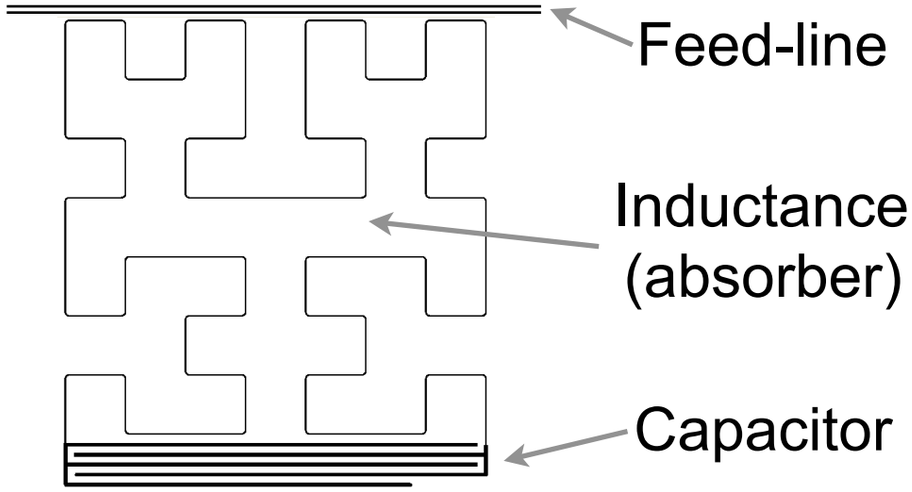
Kinetic Inductance Detectors (KIDs)

- KIDs are high-Q superconducting RLC resonators
- Absorbed photons change the kinetic inductance by breaking Cooper pairs

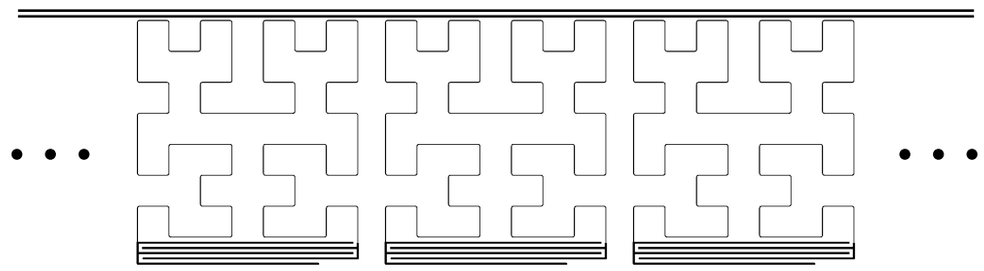
$$\delta f_0 \propto \delta L_k \propto P_{opt}$$



Single KID: *Al* on *Si* wafer *[Roesch et al. (2012)]*

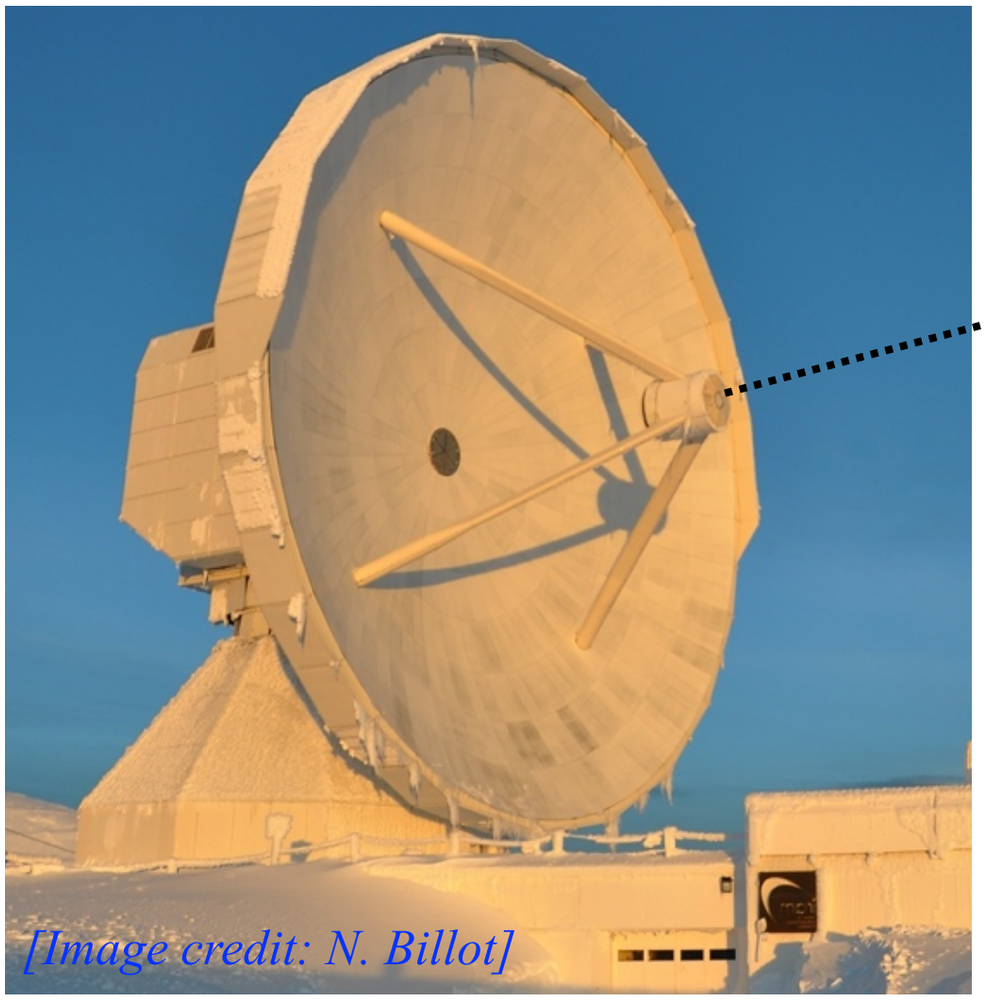


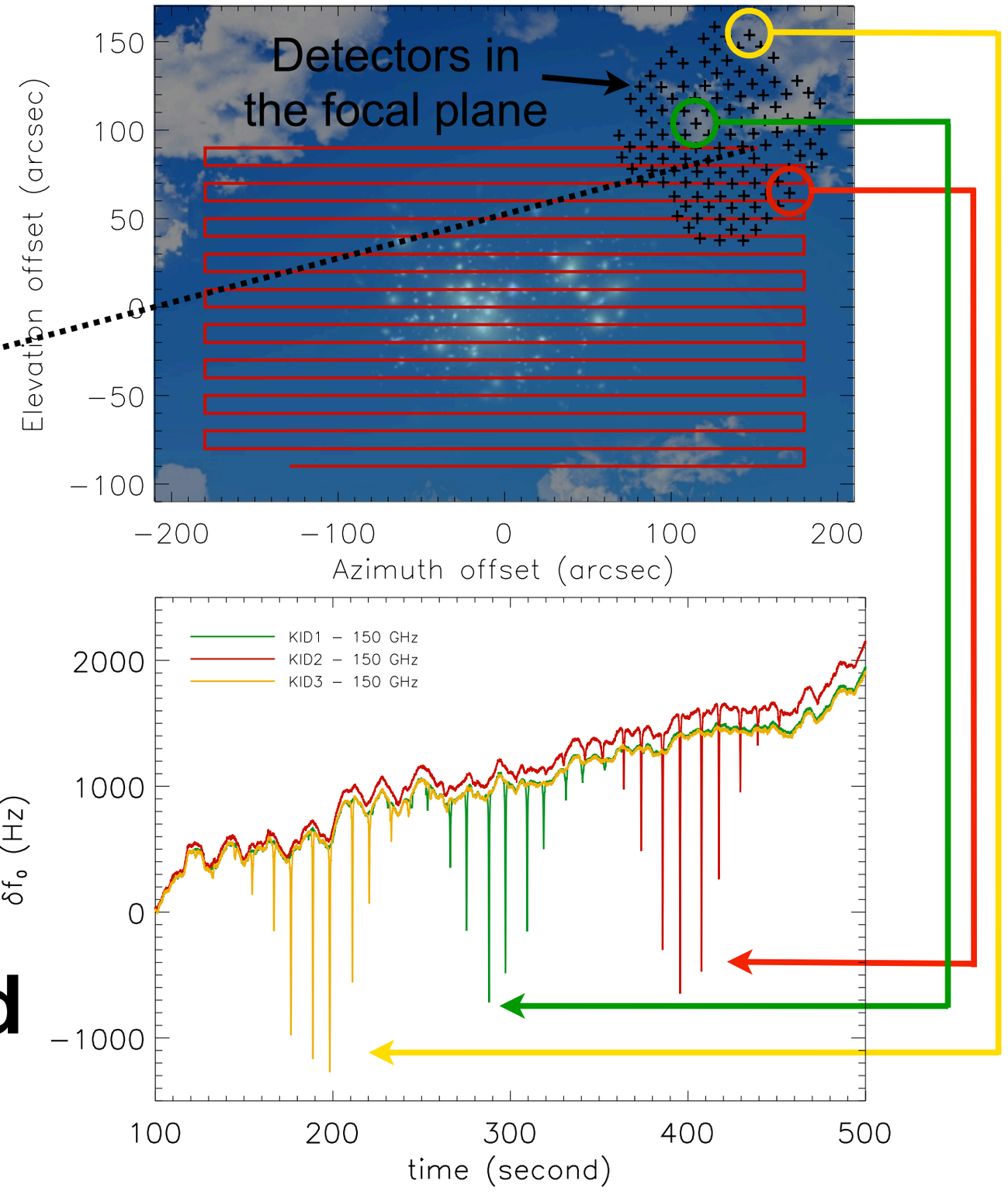
Building an array of KIDs



Excellent solution for large detector arrays

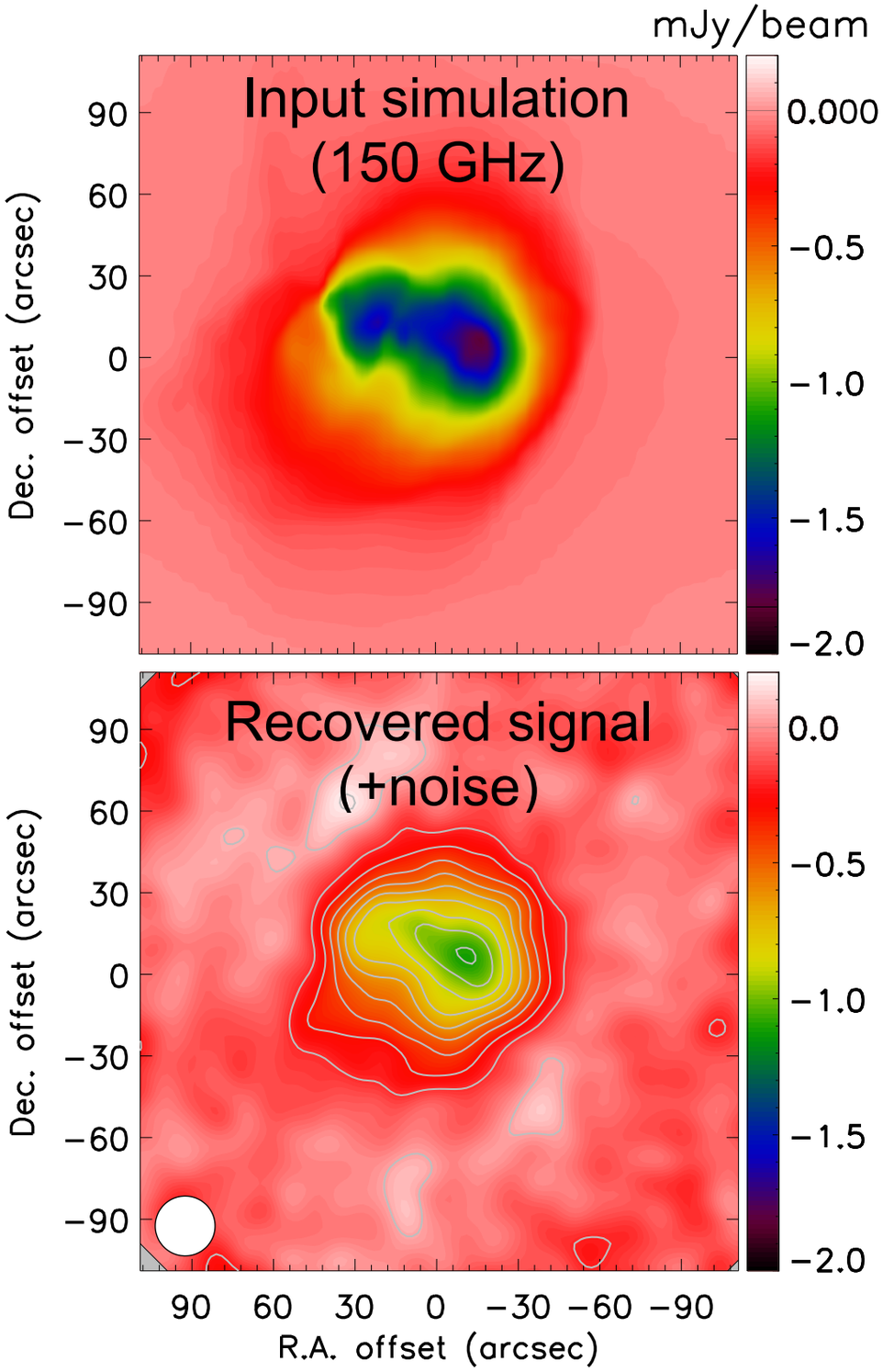
Observations at the telescope





Goal: remove correlated noise, keep the signal

Mapmaking and calibration

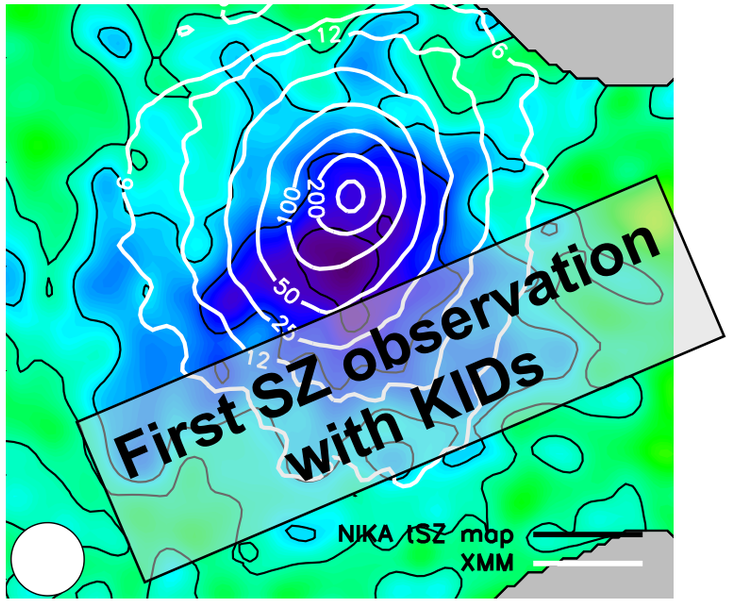


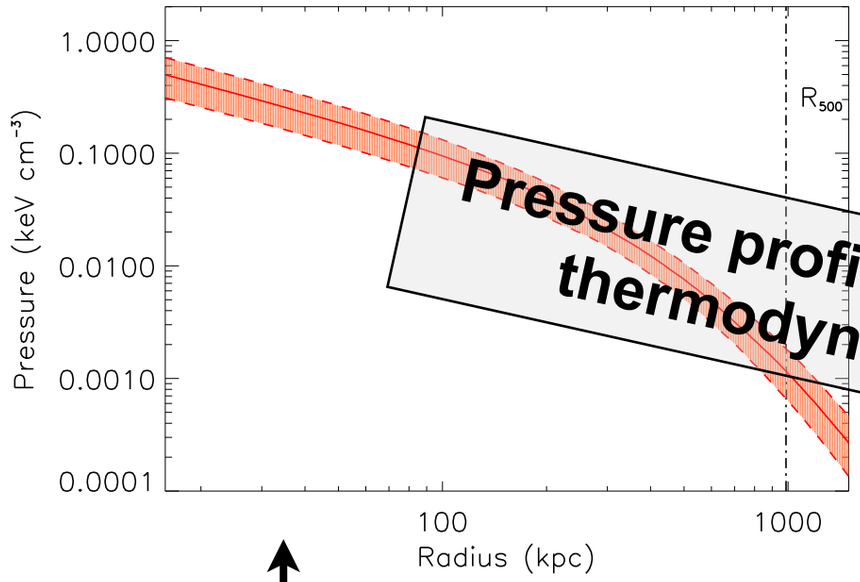
Correlated noise removal by combining detector timelines: Trade-off between noise & filtering

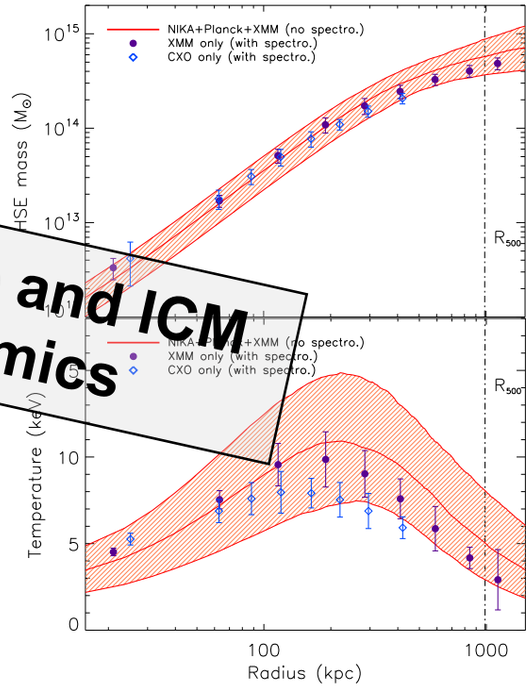
[Adam et al. (2014-16), Catalano et al. (2014)]

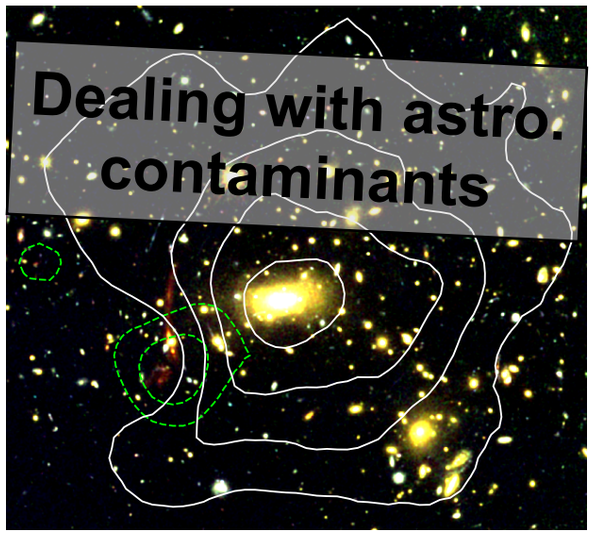
- ☑ Angular + spectral transmission measured
- ☑ Noise covariance matrix from MC realizations
- ☑ Transfer function characterized using simulations

The maps can be used quantitatively for science

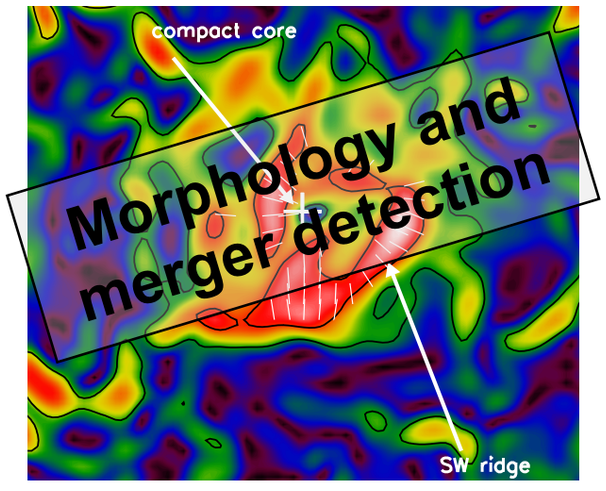


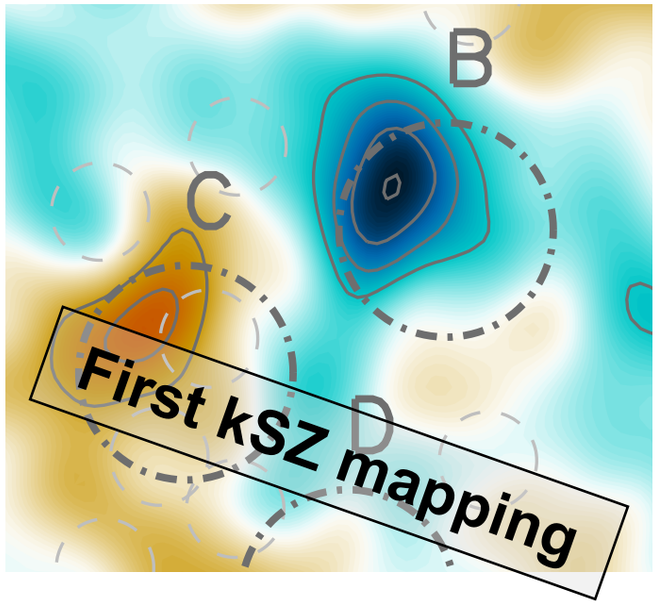


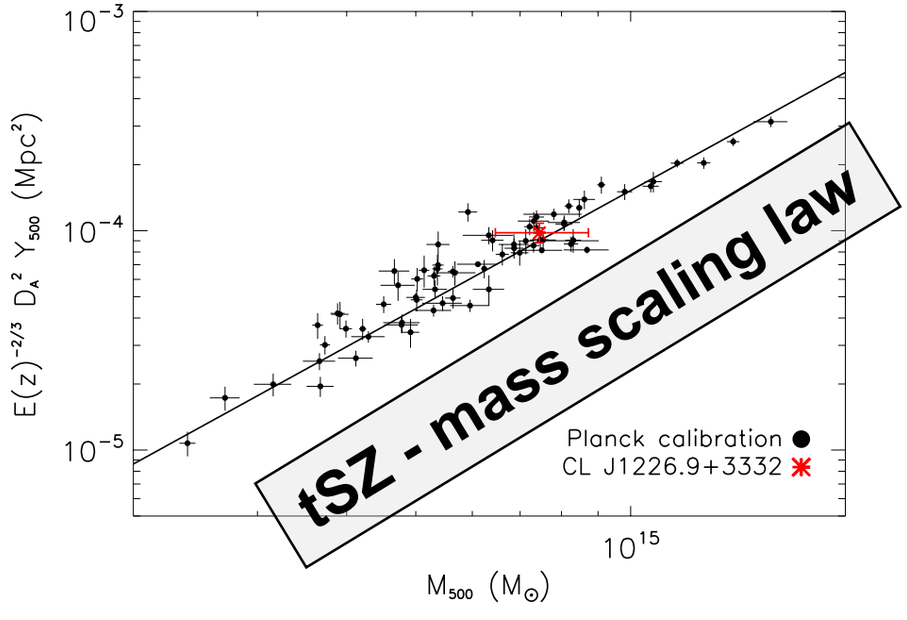


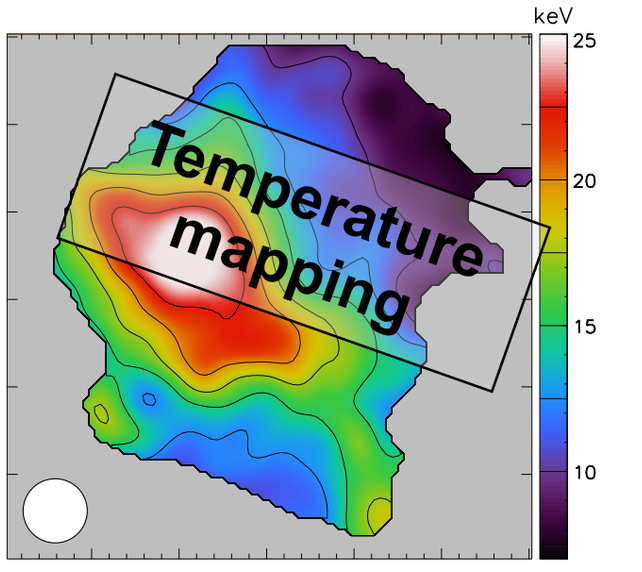


NIKA SZ: A pilot sample to prepare NIKA2 observations









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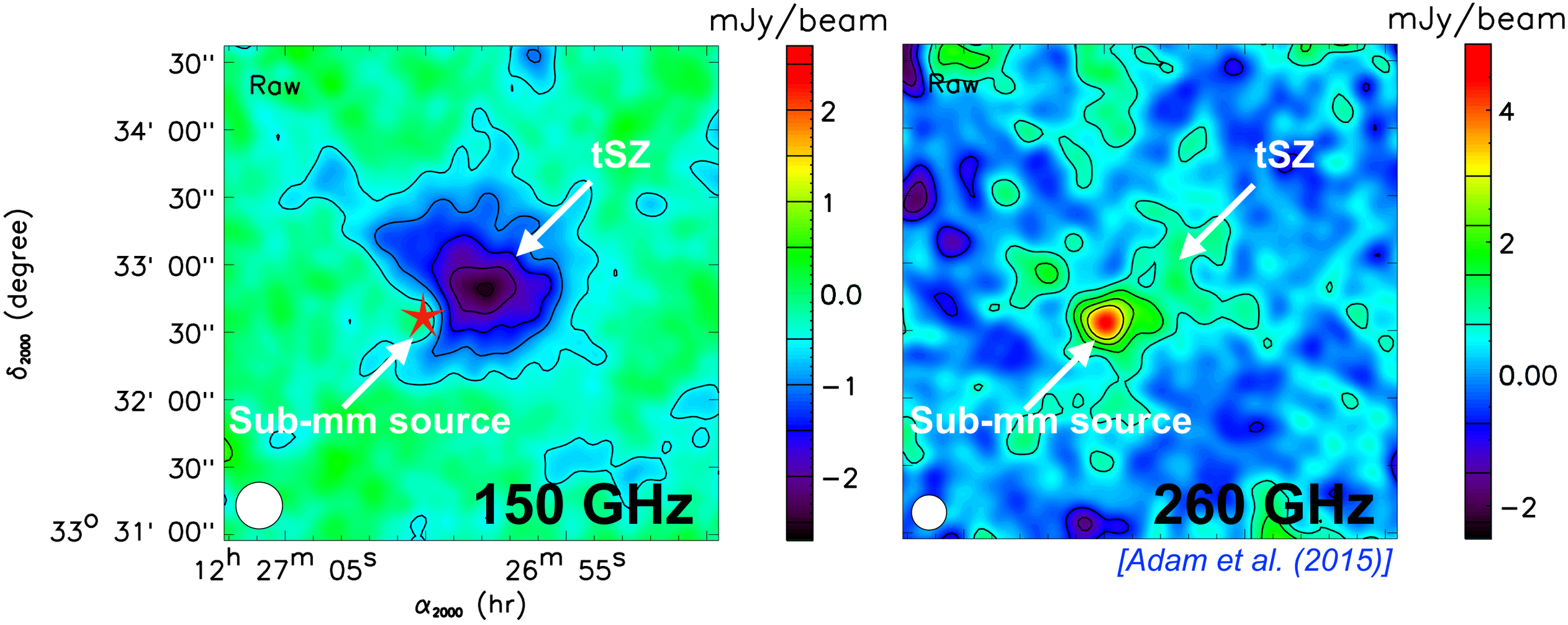
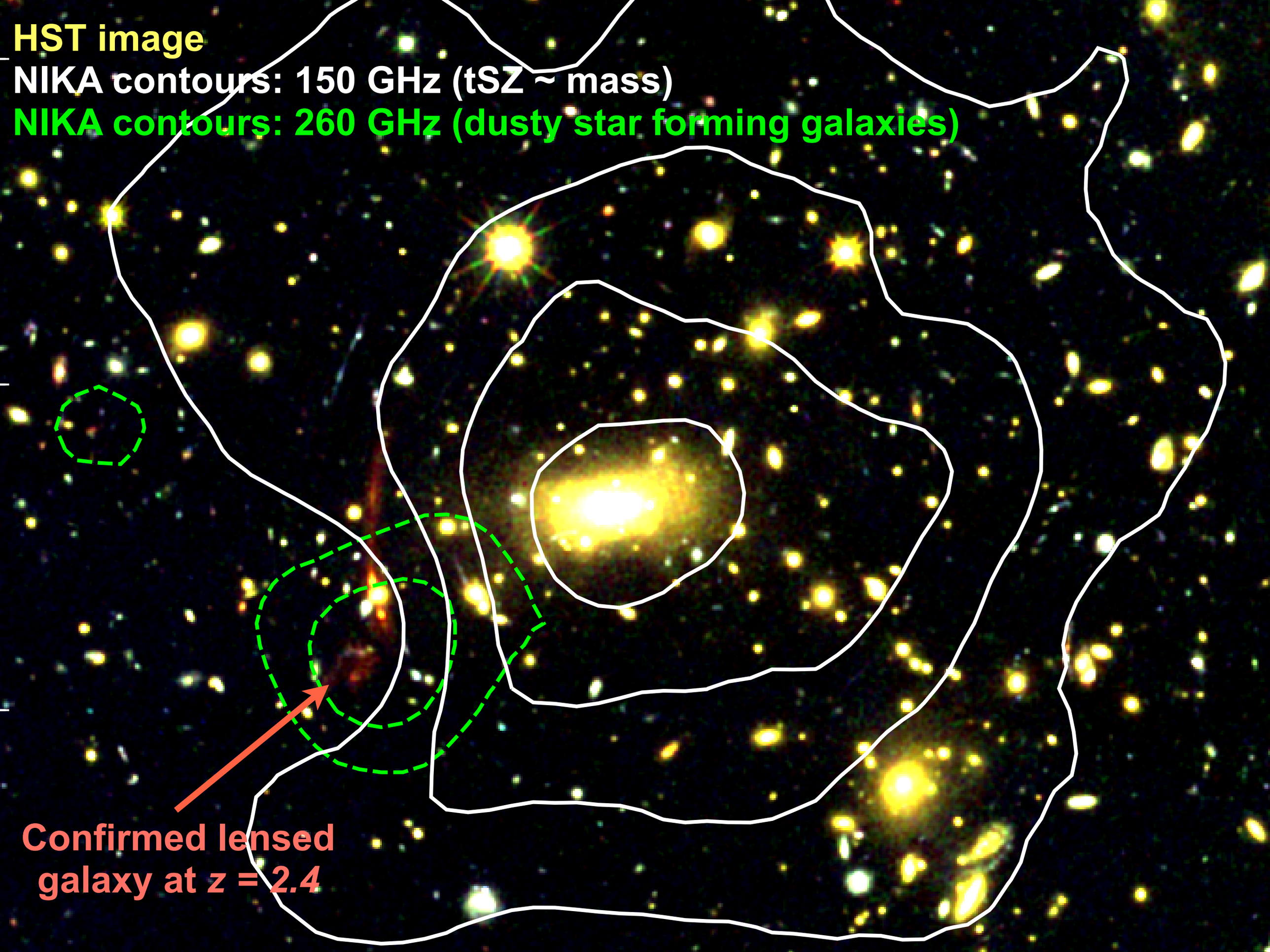
A first look at the maps

CL J1226.9+3332 at z = *0.89*



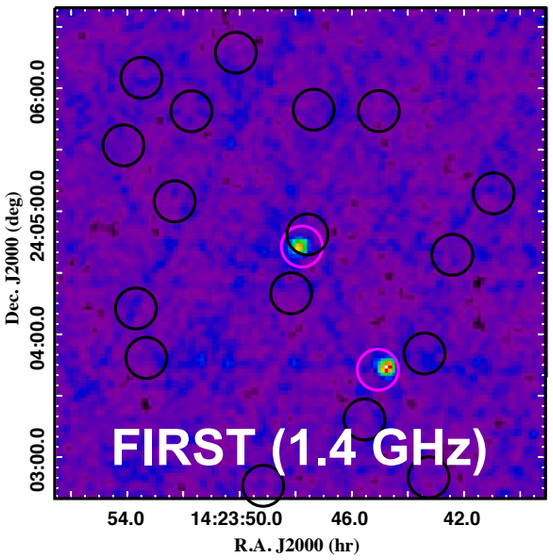
[Adam et al. (2015)]

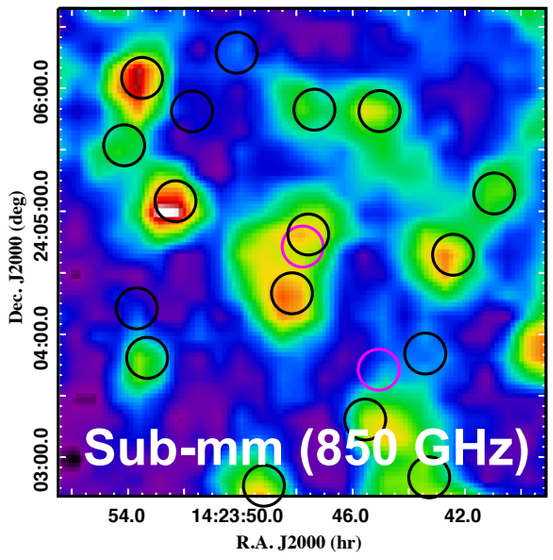
Sub-mm and radio galaxies can bias the SZ signal

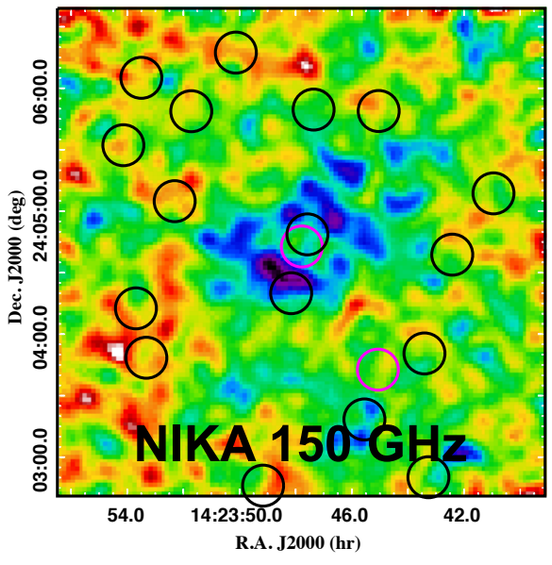

HST image
NIKA contours: 150 GHz (tSZ ~ mass)
NIKA contours: 260 GHz (dusty star forming galaxies)
Confirmed lensed
galaxy at z = 2.4

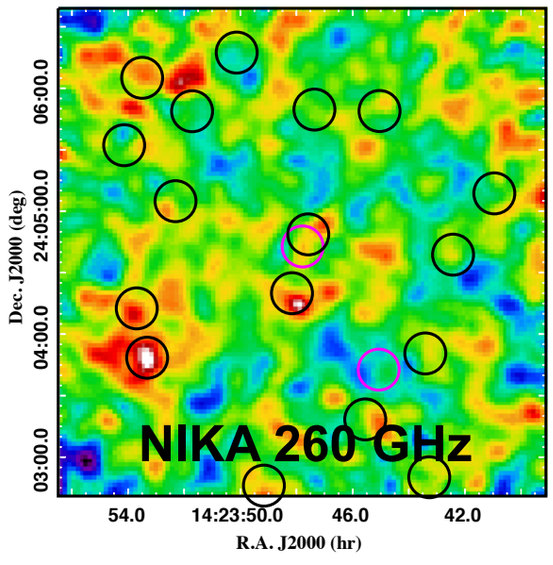
Cleaning the ‘contaminant’ galaxies

The test case MACS J1423.8+2404 at *z=0.54*



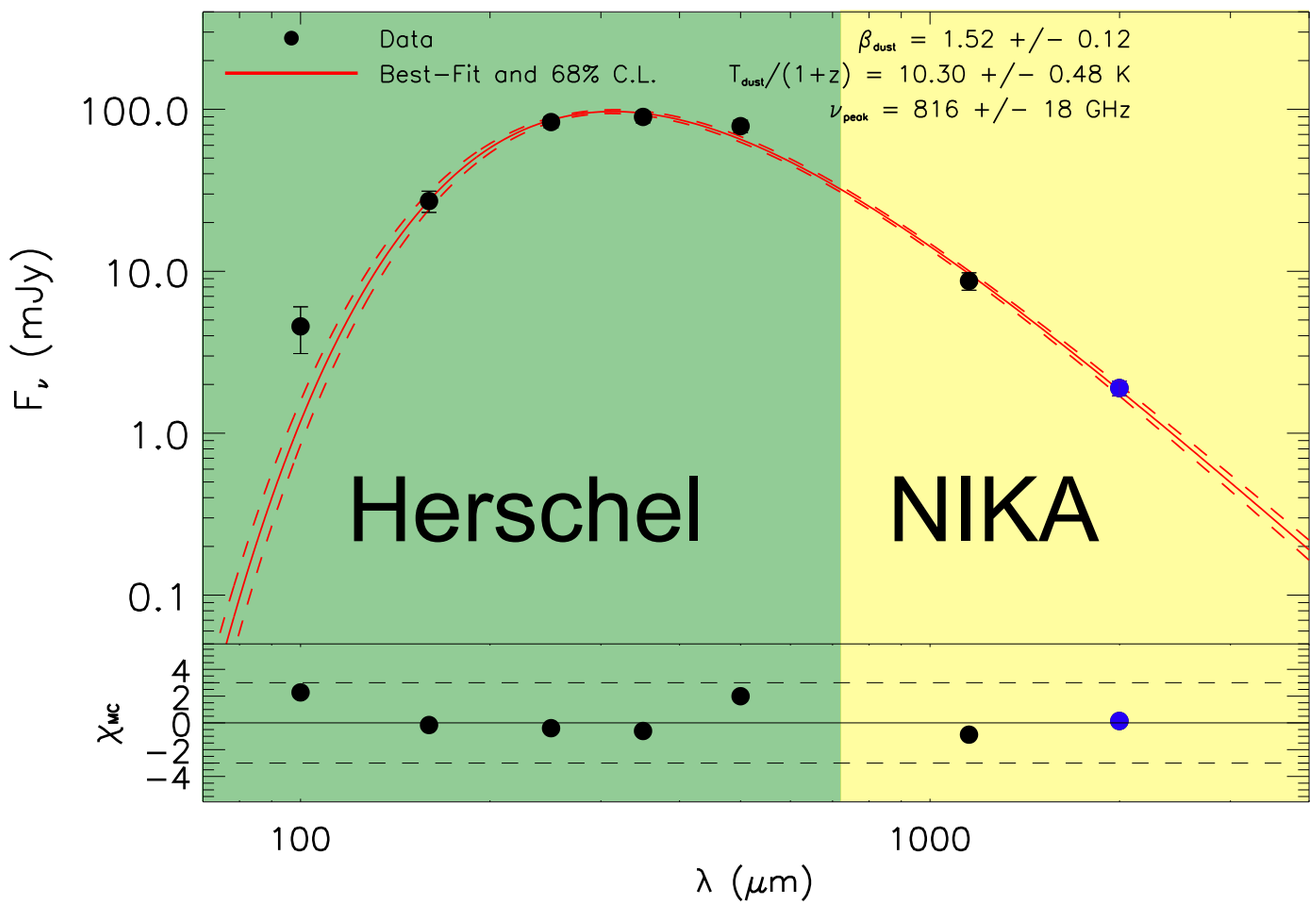






[Adam et al. (2016)]

Multi-wavelength dust & radio SED fitting



It is crucial to account for contaminant sources

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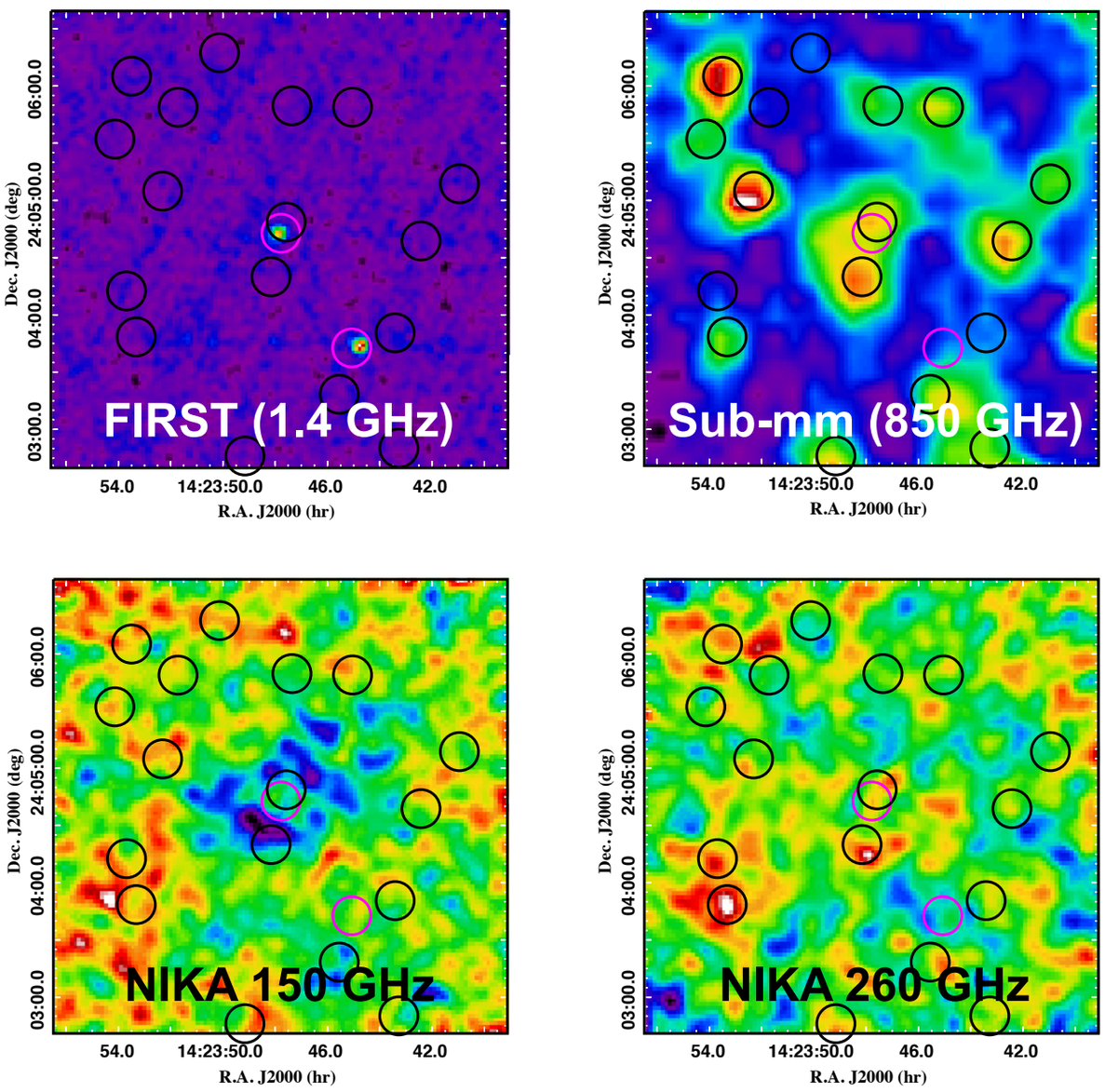
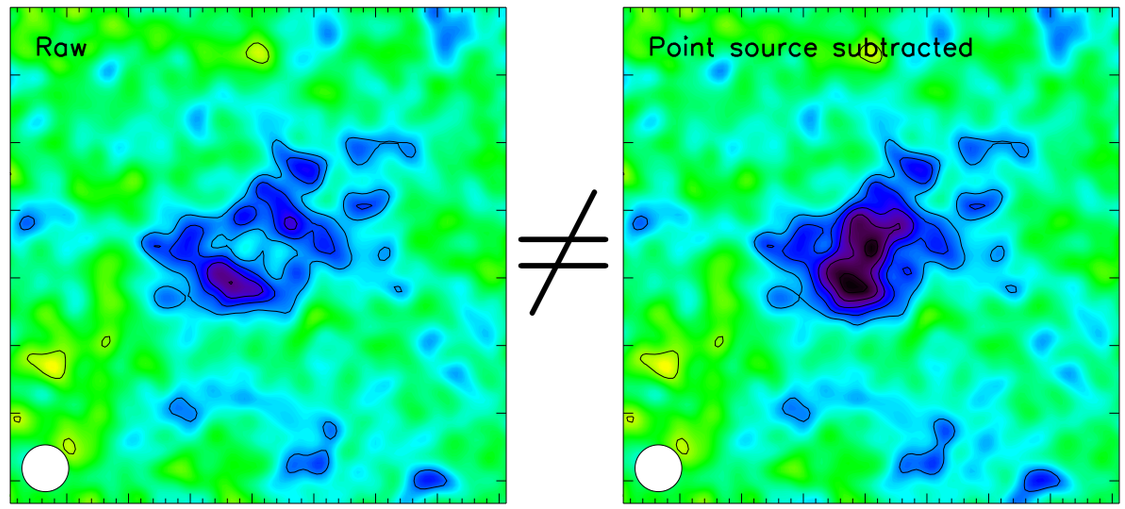
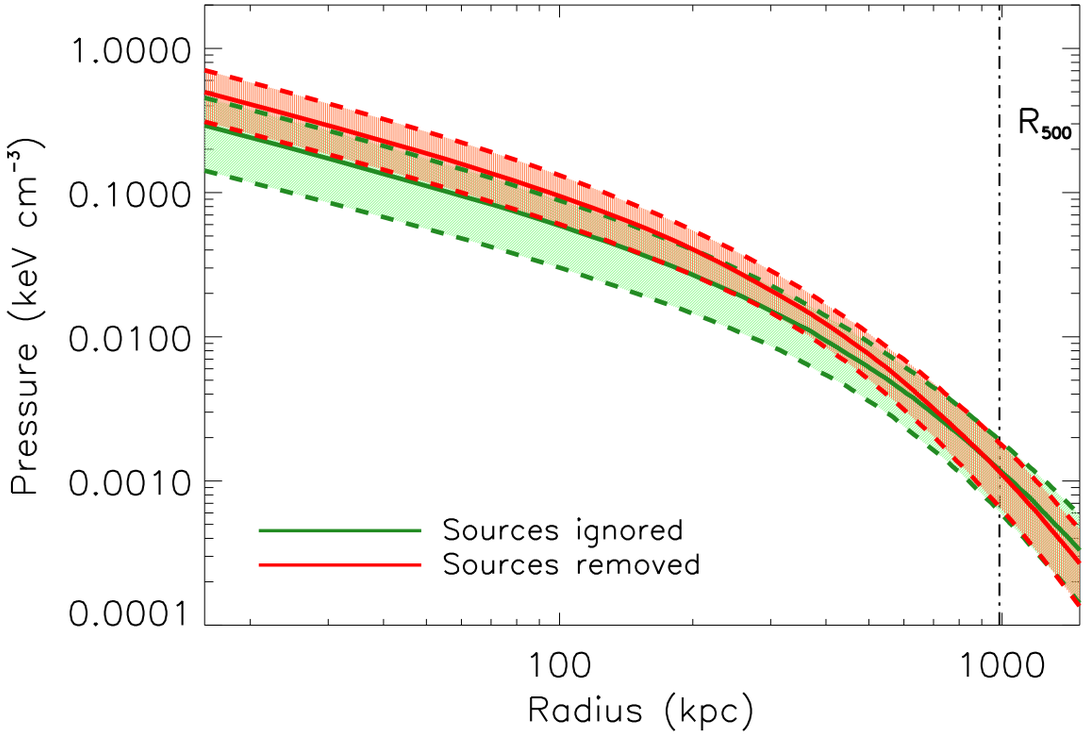


[Adam et al. (2016)]

1. Morphology

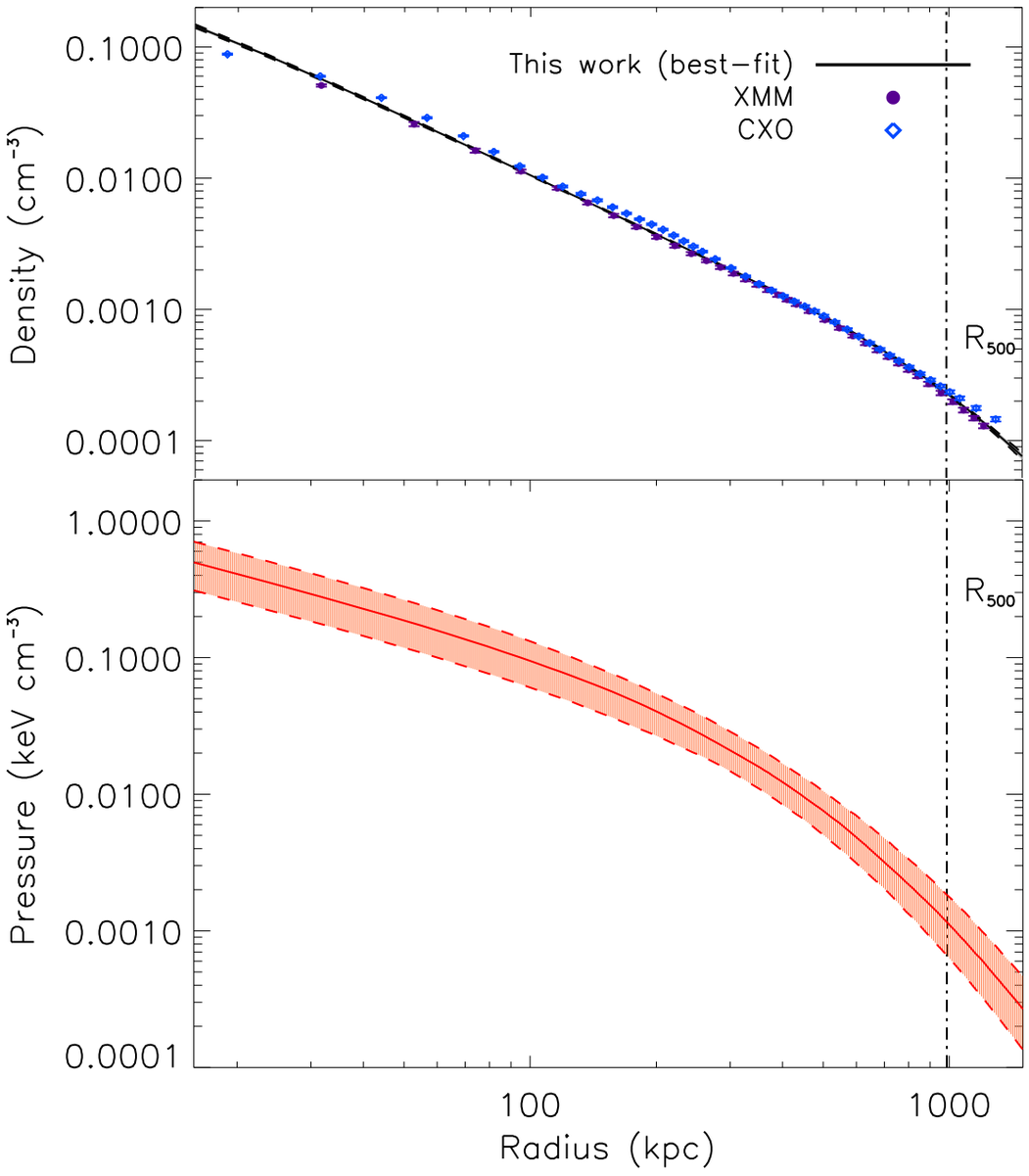


2. Pressure profile



It is crucial to account for contaminant sources

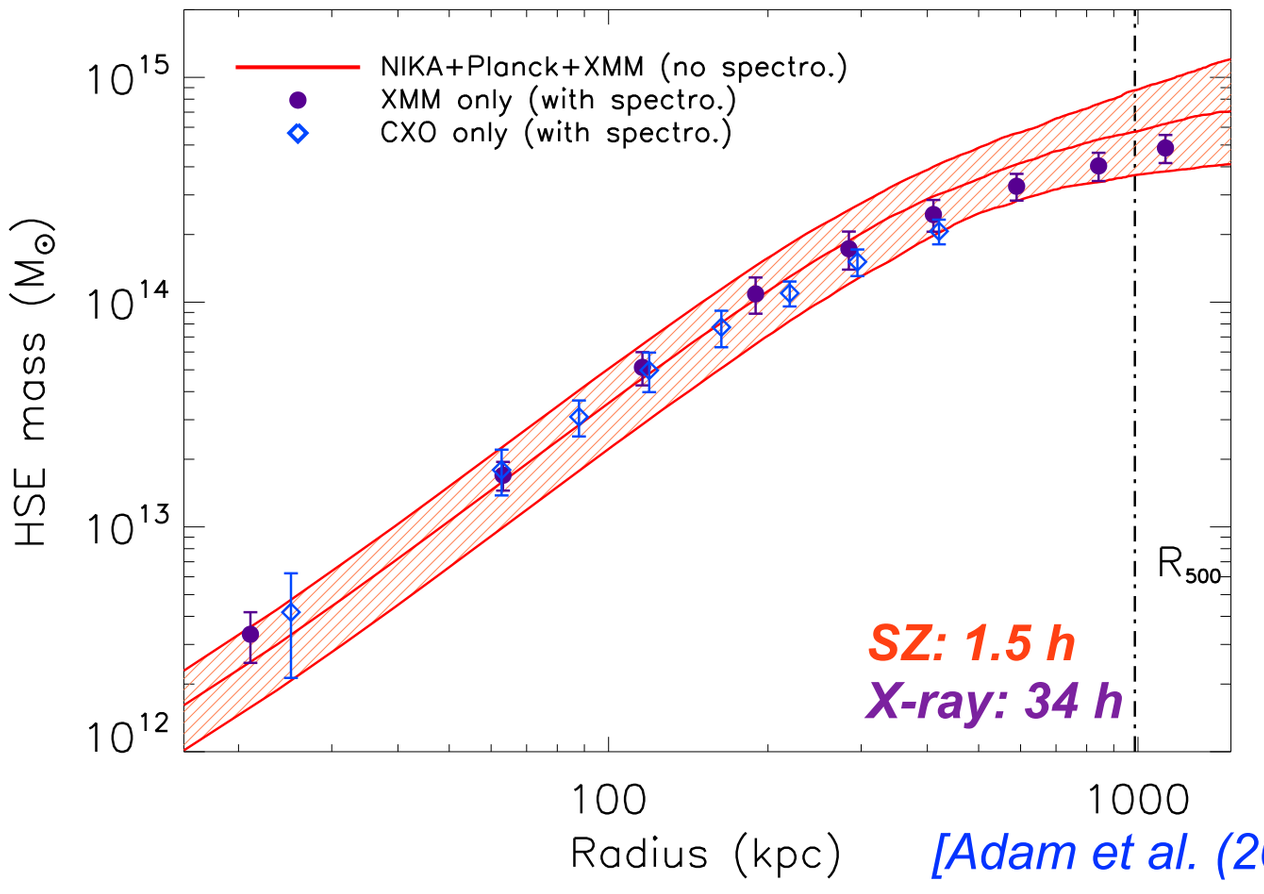
Extracting the hydrostatic mass from tSZ+X-ray



$$M_{\rm HSE}(r) = -\frac{r^2}{\mu_{\rm gas} m_{\rm p} n_{\rm e}(r) G} \frac{{\rm d}P_{\rm e}(r)}{{\rm d}r}$$

tSZ measurement

Cheap from X-ray



[Adam et al. (2016)]

➡ Access to the mass, the SZ flux, and the cluster dynamics (morphology)

SZ-mass calibration vs dynamical state and *z*

Substructure and merger detection

Application to RHAPSODY-G simulations

Gaussian Gradient Magnitude filter

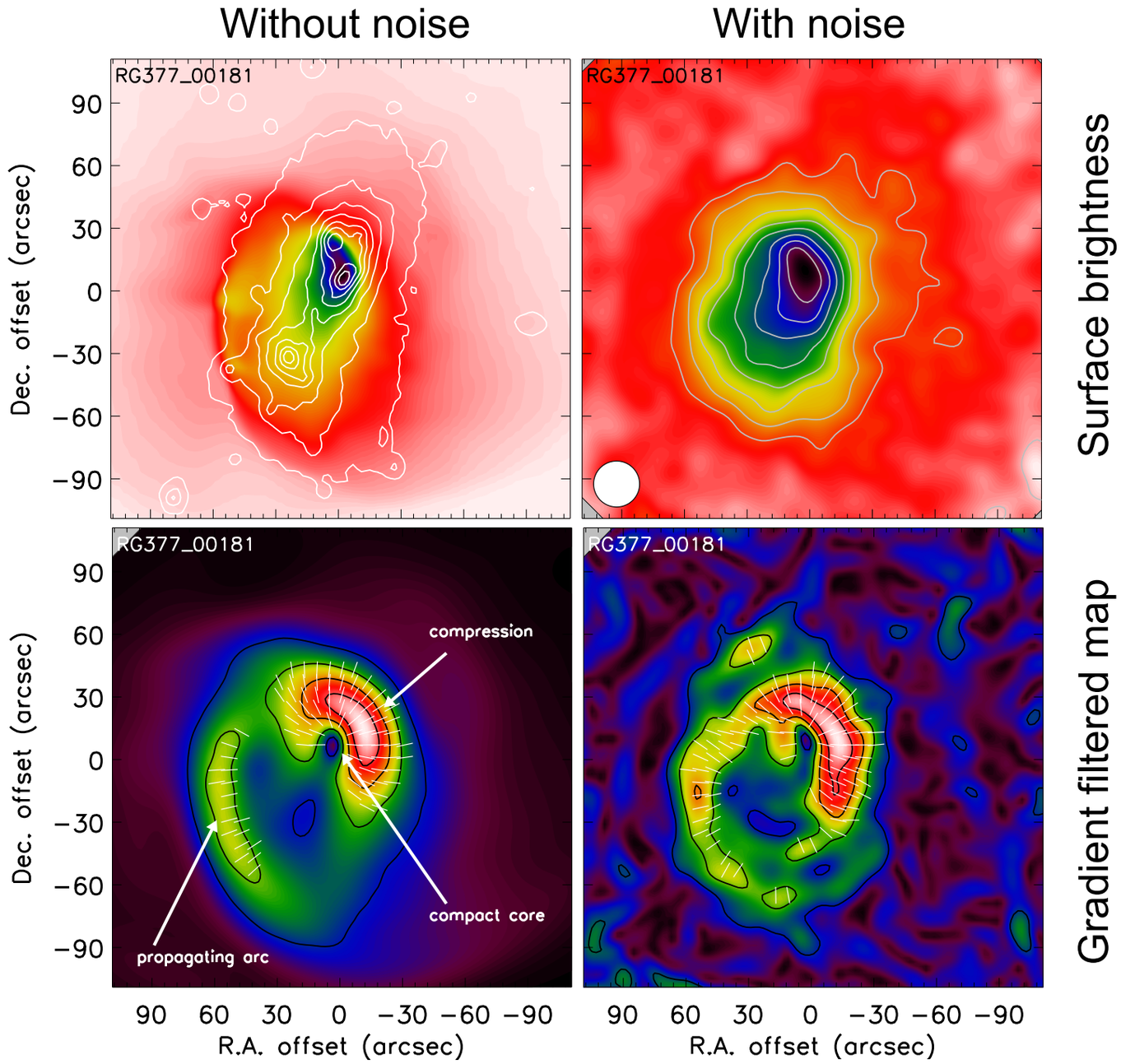
Used in X-ray analysis

[e.g., Sanders et al. (2016)]

1. Gaussian filter of the map at scale θ
2. Compute the gradient magnitude

➡ Pick up **discontinuities** at scale θ, connected to cluster formation history

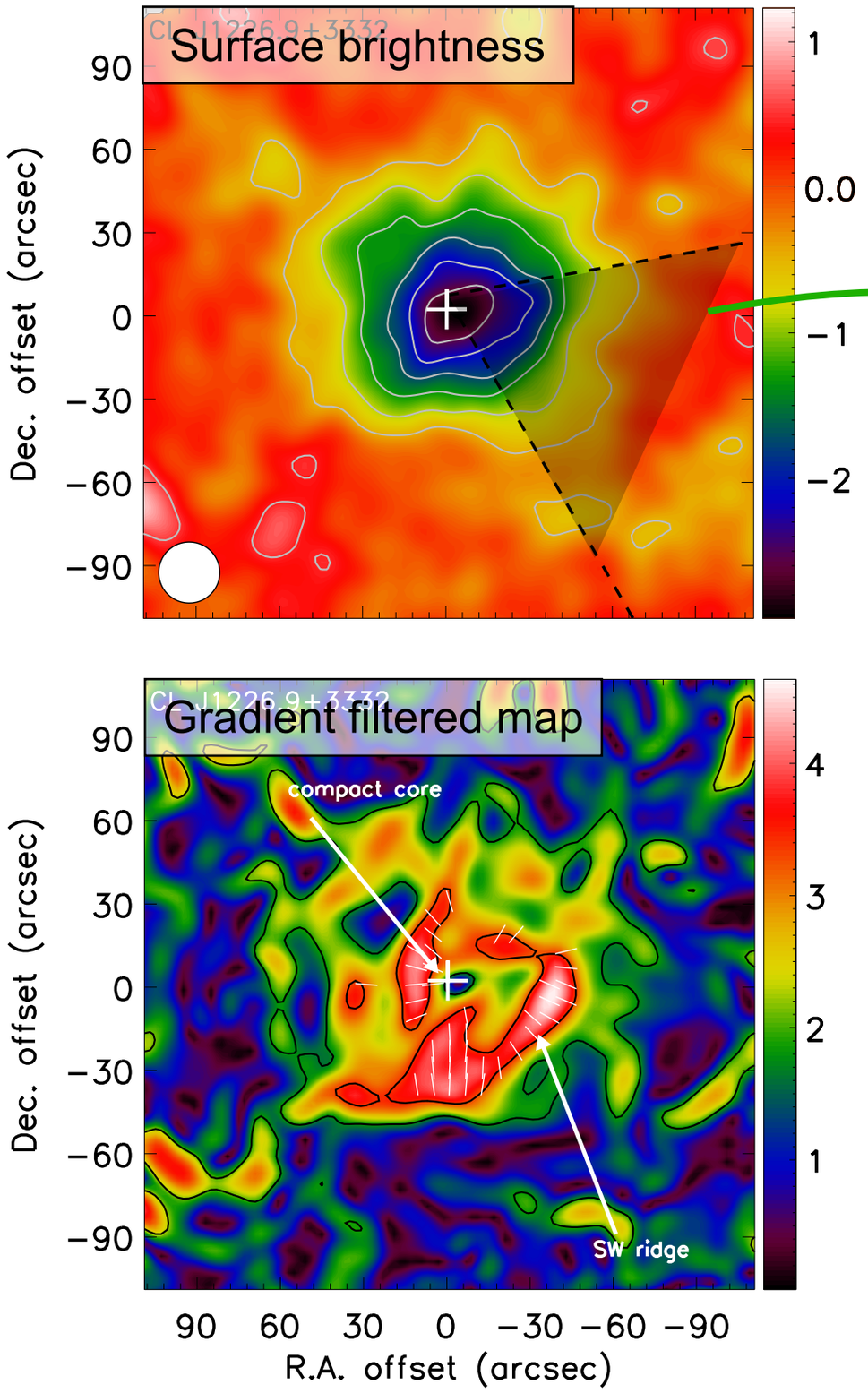
[Adam et al. (2018)]



New tools for dynamical state estimates in SZ

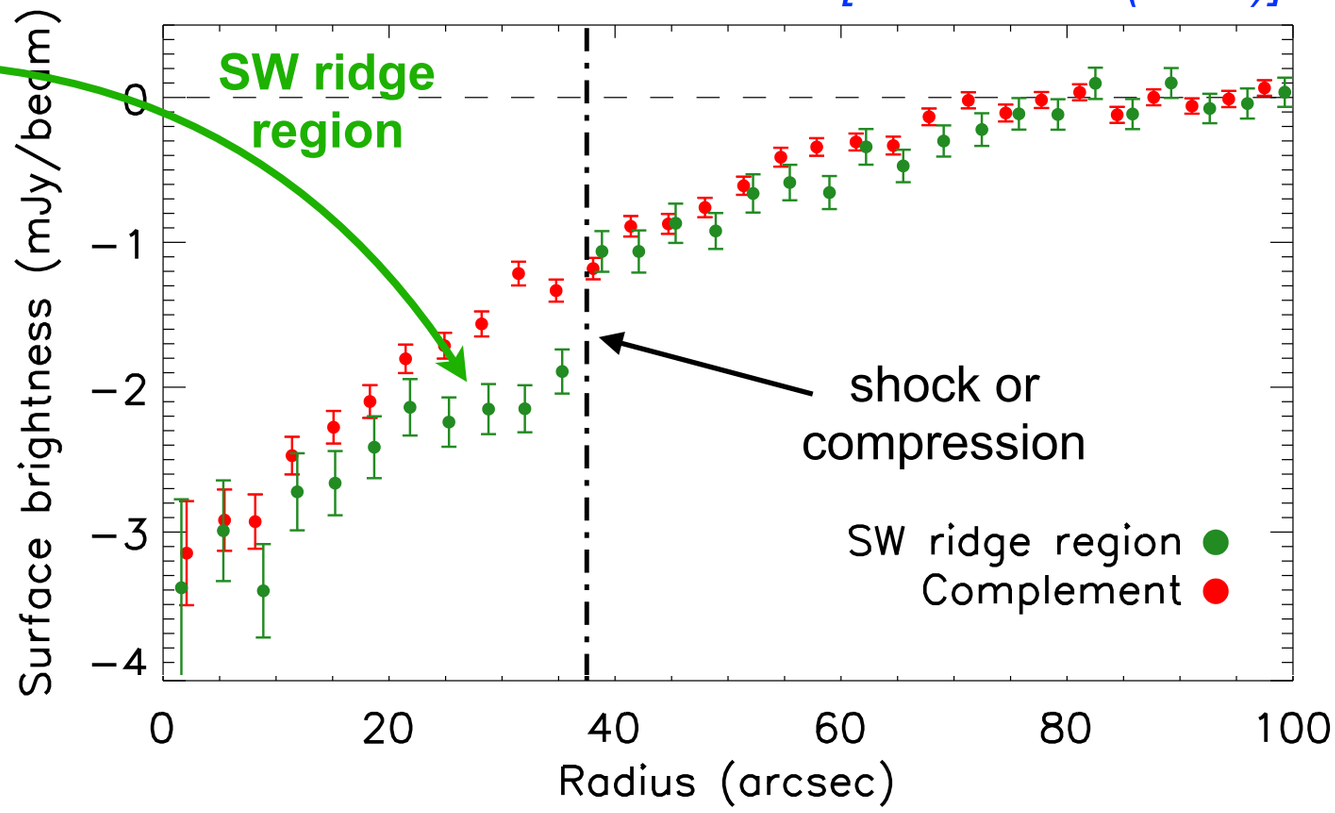
Substructure and merger detection

Application to the NIKA sample



The case of CL J1226.9+3332 at $z = 0.89$

[Adam et al. (2018)]



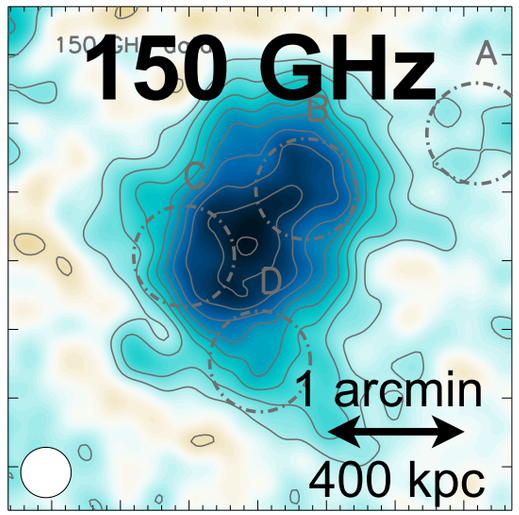
Identification of a merging event in the south-west

First kSZ mapping towards a galaxy cluster

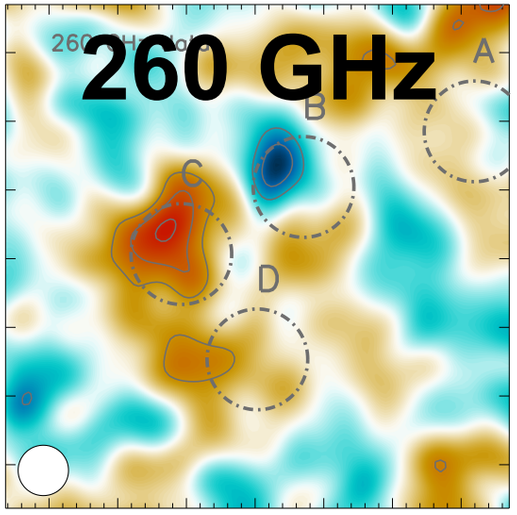
Extracting the signal

High sensitivity + high angular resolution
+ systematics removal required

➡ **Very challenging to measure**



&



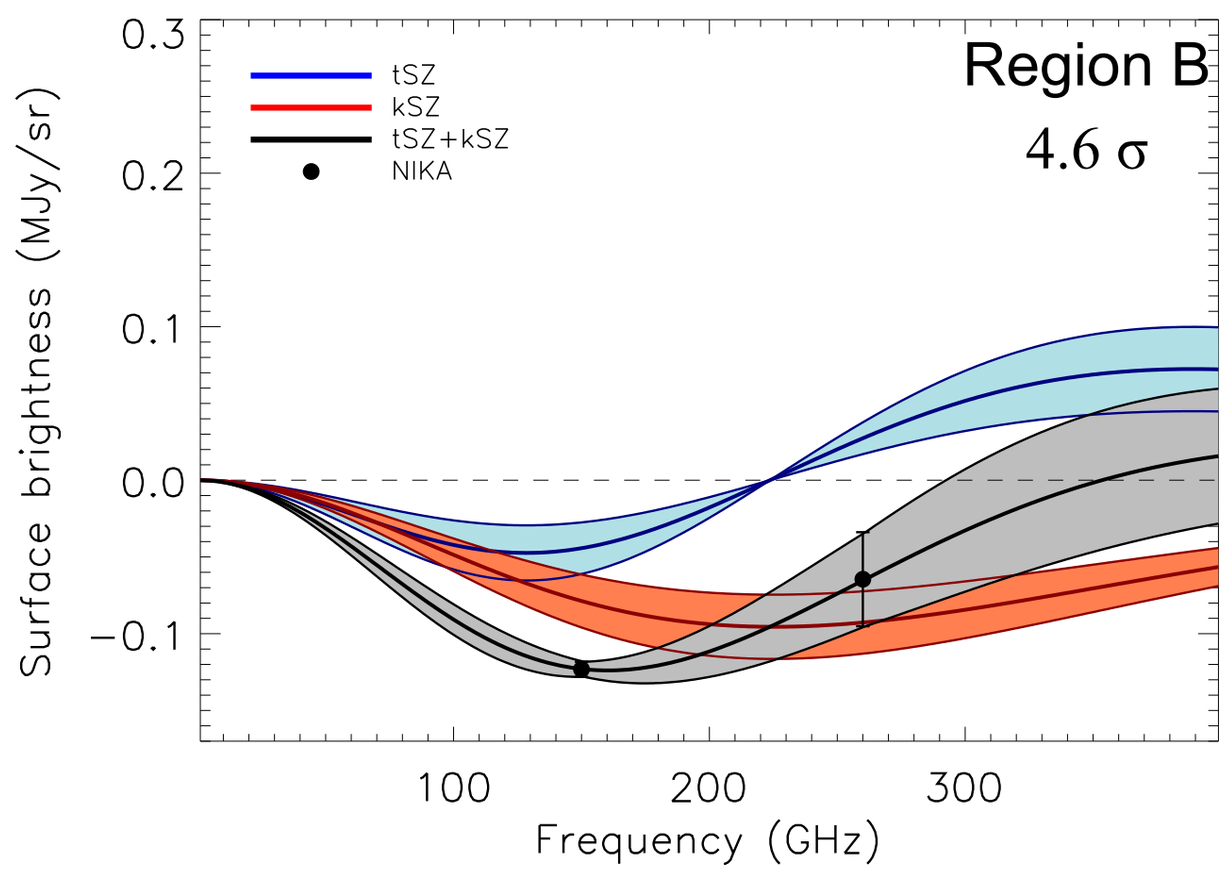
spectral dependencies

$$\frac{\Delta I_\nu}{I_0} = f_\nu \, y_{\mathrm{tSZ}} + g_\nu \, y_{\mathrm{kSZ}}$$

gas pressure *gas velocity x density*

➡ Separate kSZ and tSZ with 2 bands
See also the first detection by Bolocam
[Sayers et al. (2013)]

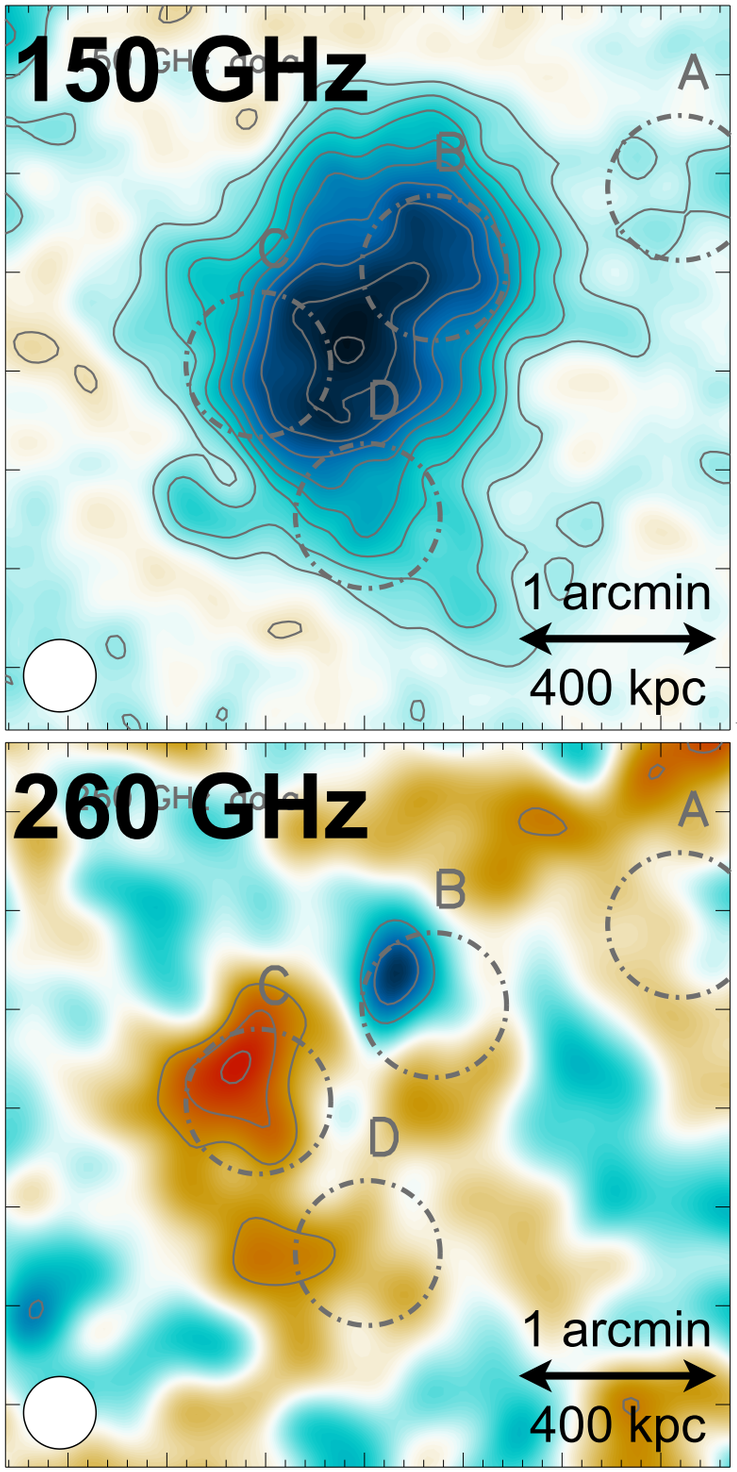
[Adam et al. (2017)]



We detect kSZ signal

First kSZ mapping towards a galaxy cluster

Gas momentum map

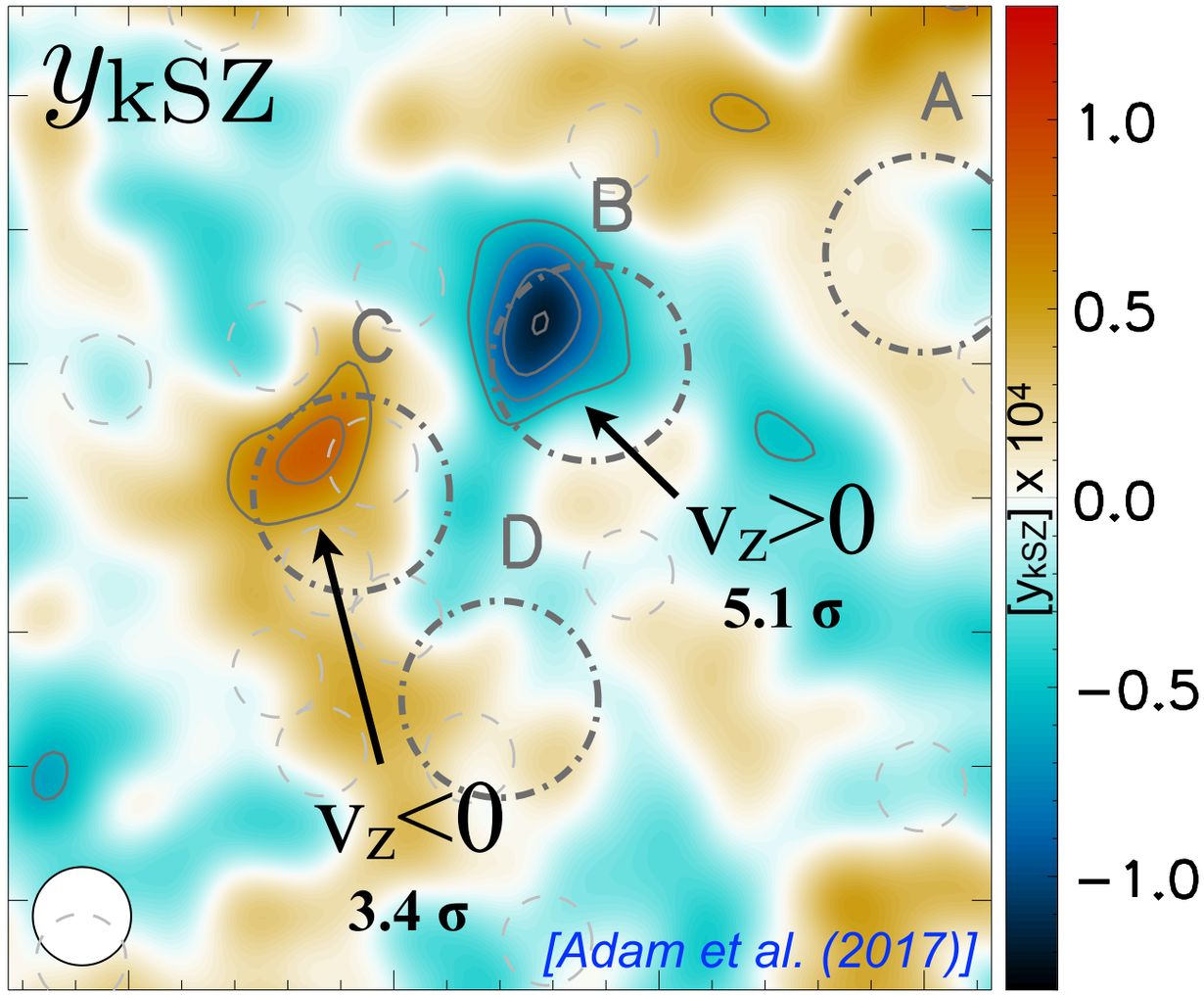


$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

spectral dependencies

gas pressure

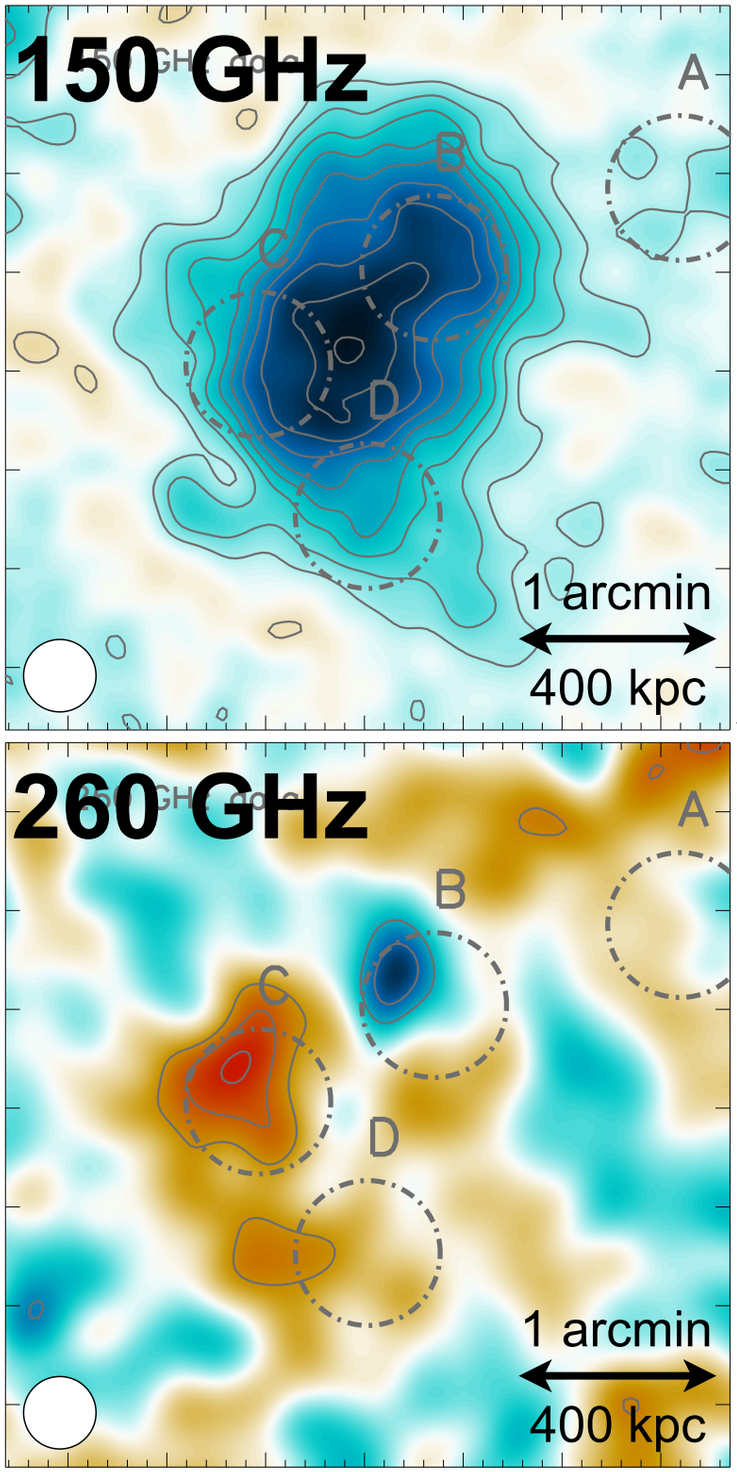
gas density+velocity



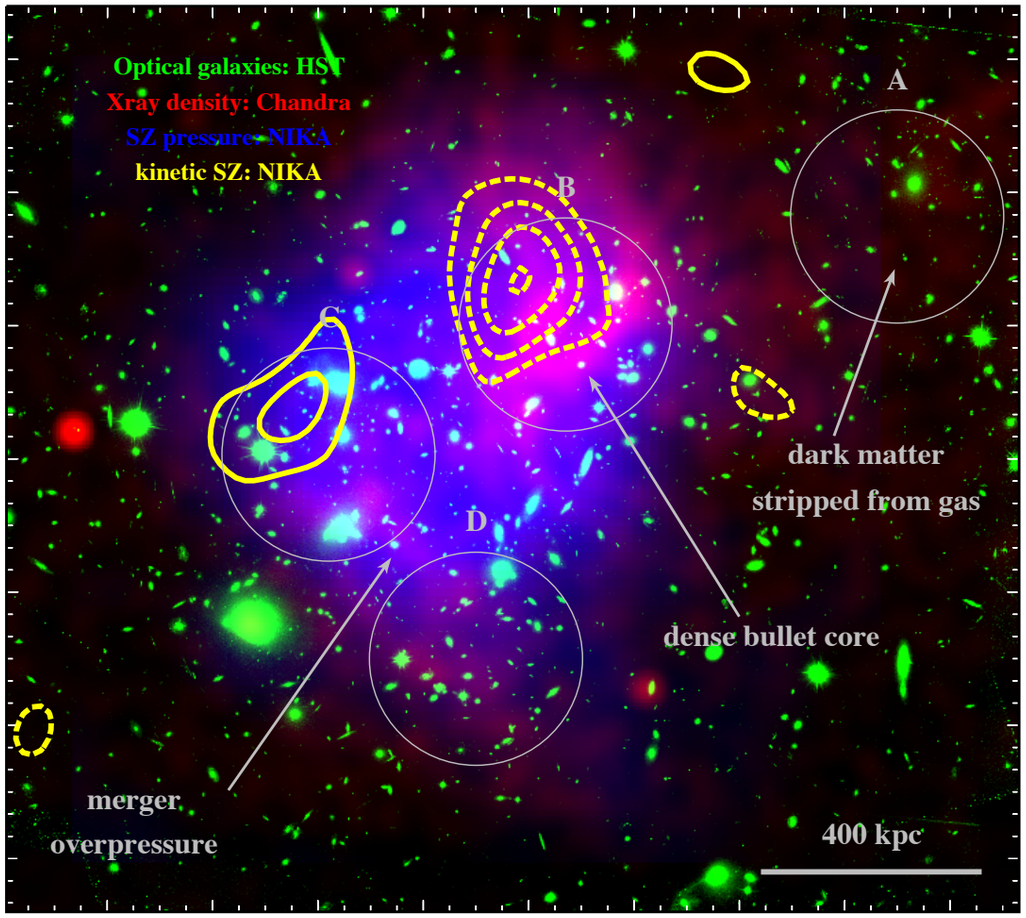
We can even get a kSZ map

First kSZ mapping towards a galaxy cluster

Multi-wavelength comparison



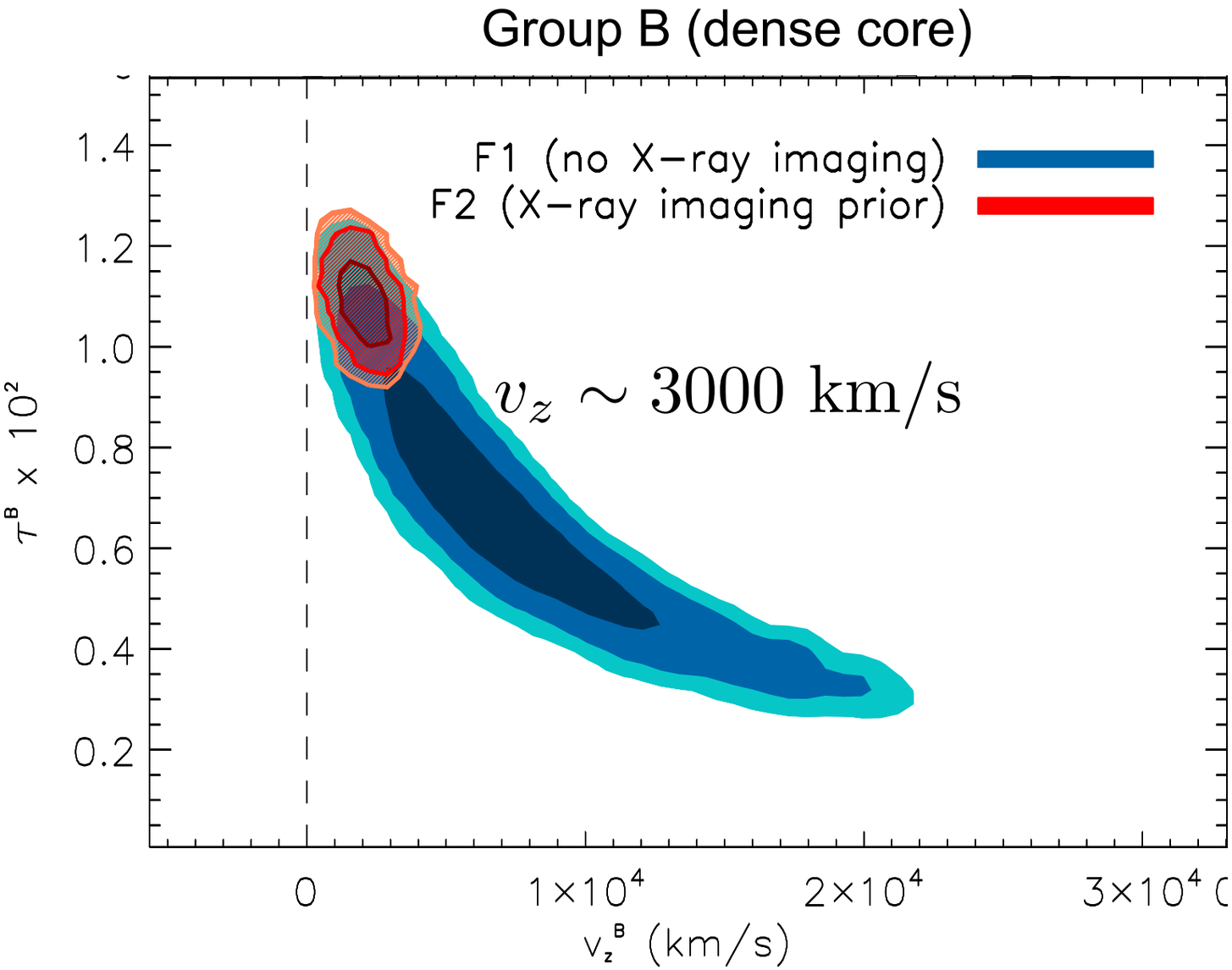
To be compared with multi-wavelength data



Bimodal signal from 2 main merging subclusters

First kSZ mapping towards a galaxy cluster

Constraints on the gas velocity



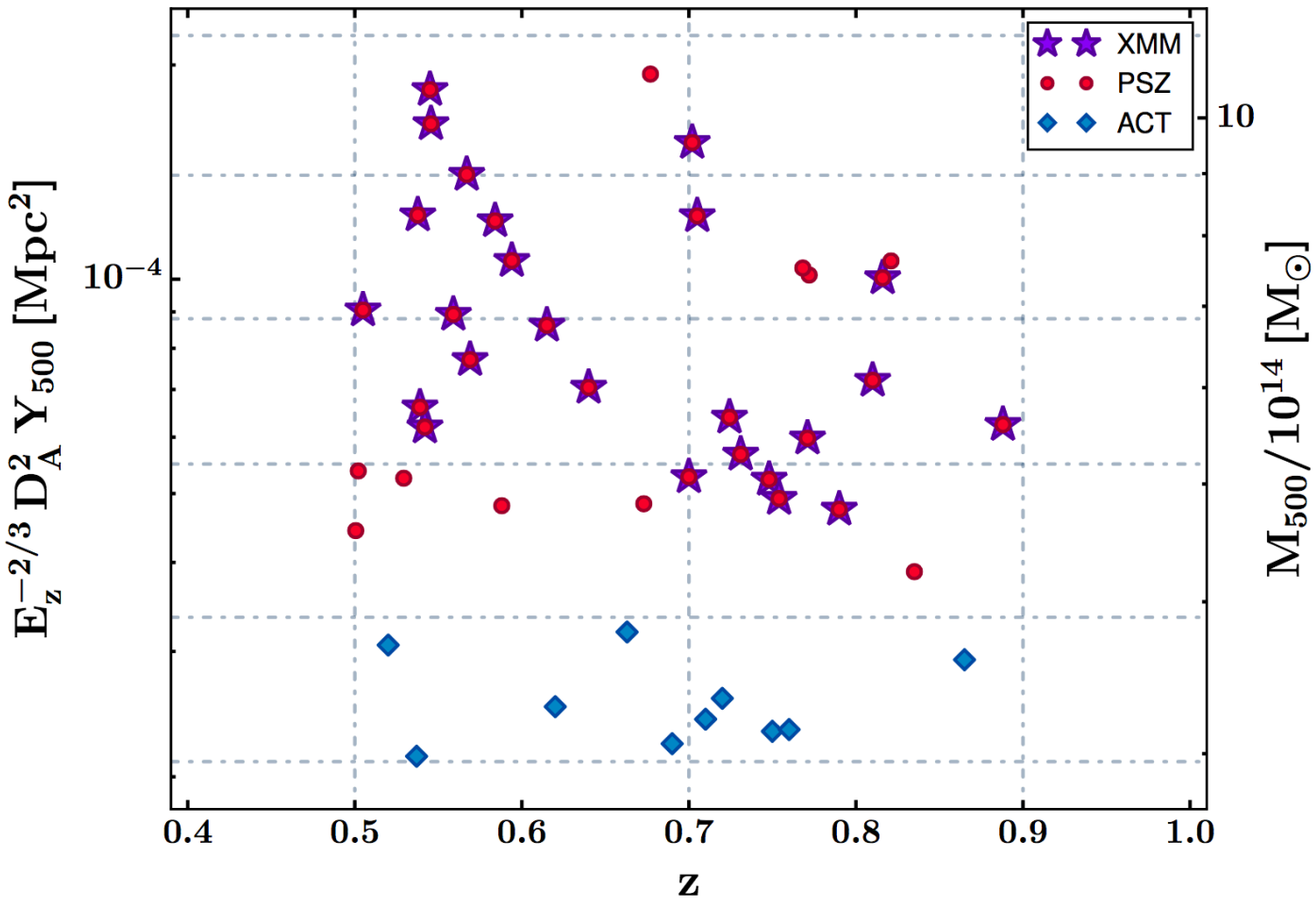
$$y_{\mathrm{kSZ}} = v_z \times \tau$$

(velocity x density)

- Fit for a density model
- Need an external gas constraint from X-ray (T_x)

Exceptionally large v_z, but fine with ΛCDM

The NIKA2 guaranteed time SZ large program



- High resolution observations of 50 clusters
  - *0.5 < z < 0.9*, $M_{500} > 3 \times 10^{14}$ M_{sun}
- Planck/ACT tSZ selected
  - representativity
- Combinaison to XMM data
  - Full thermodynamics
- 300 hours of guaranteed time
  - 10 clusters observed so far

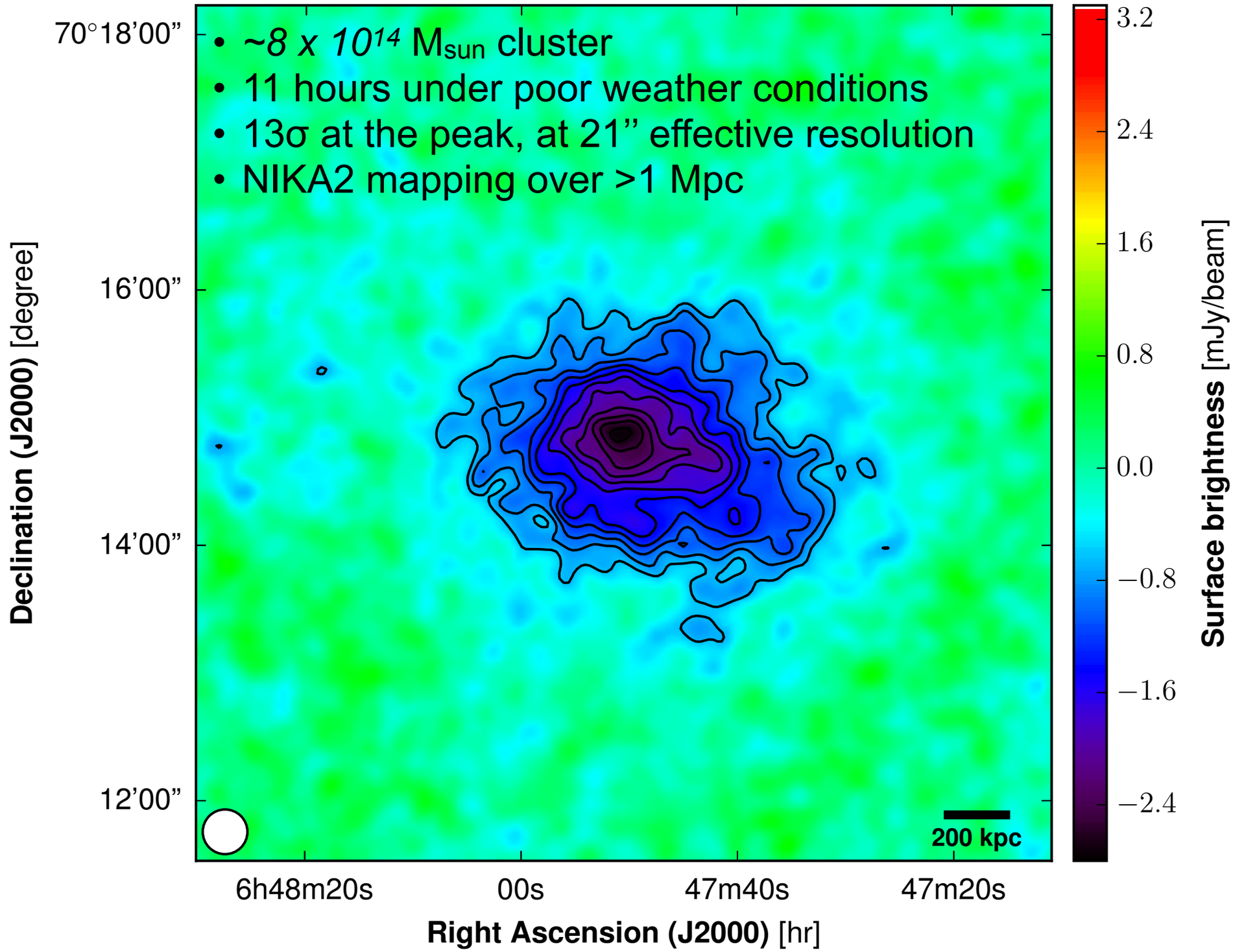
➡ In depth population study of the ICM

➡

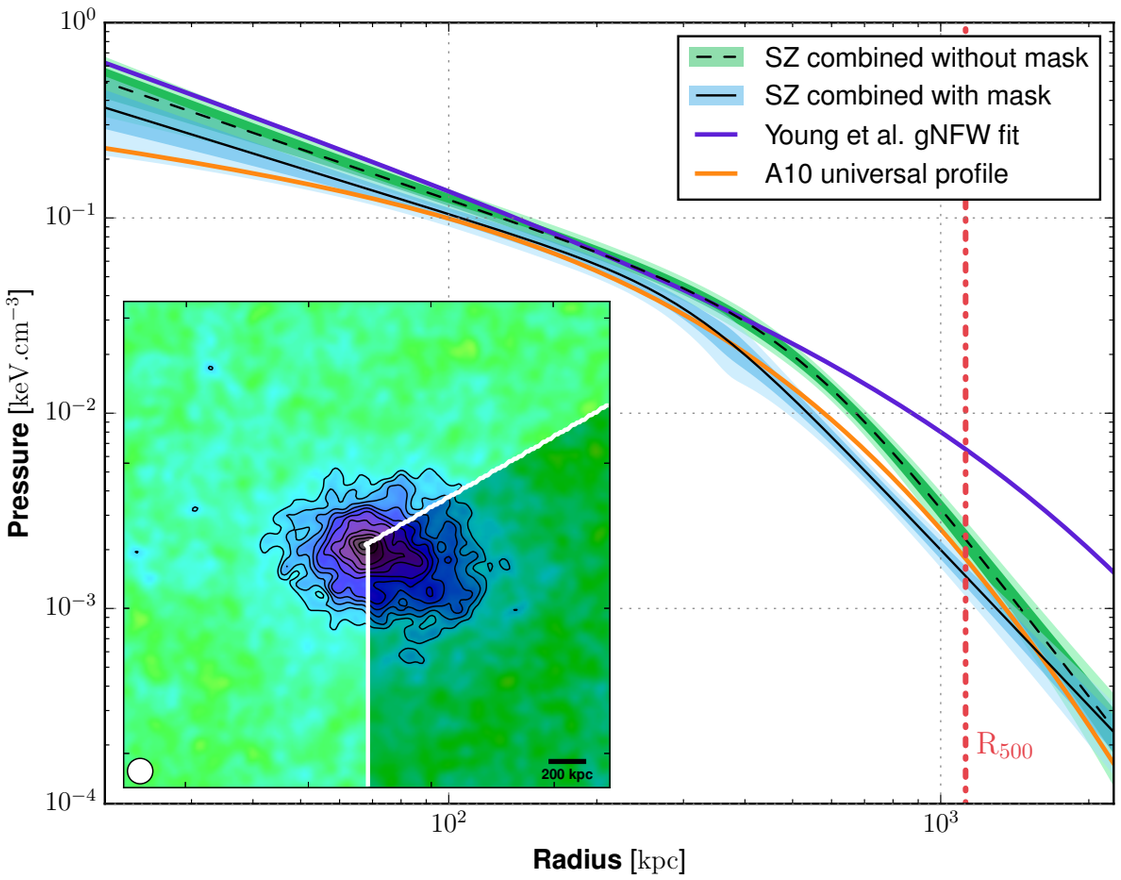
- Redshift evolution of the ICM properties and scaling relations
- Dependence on cluster dynamical state

First NIKA2 results from the SZ large program

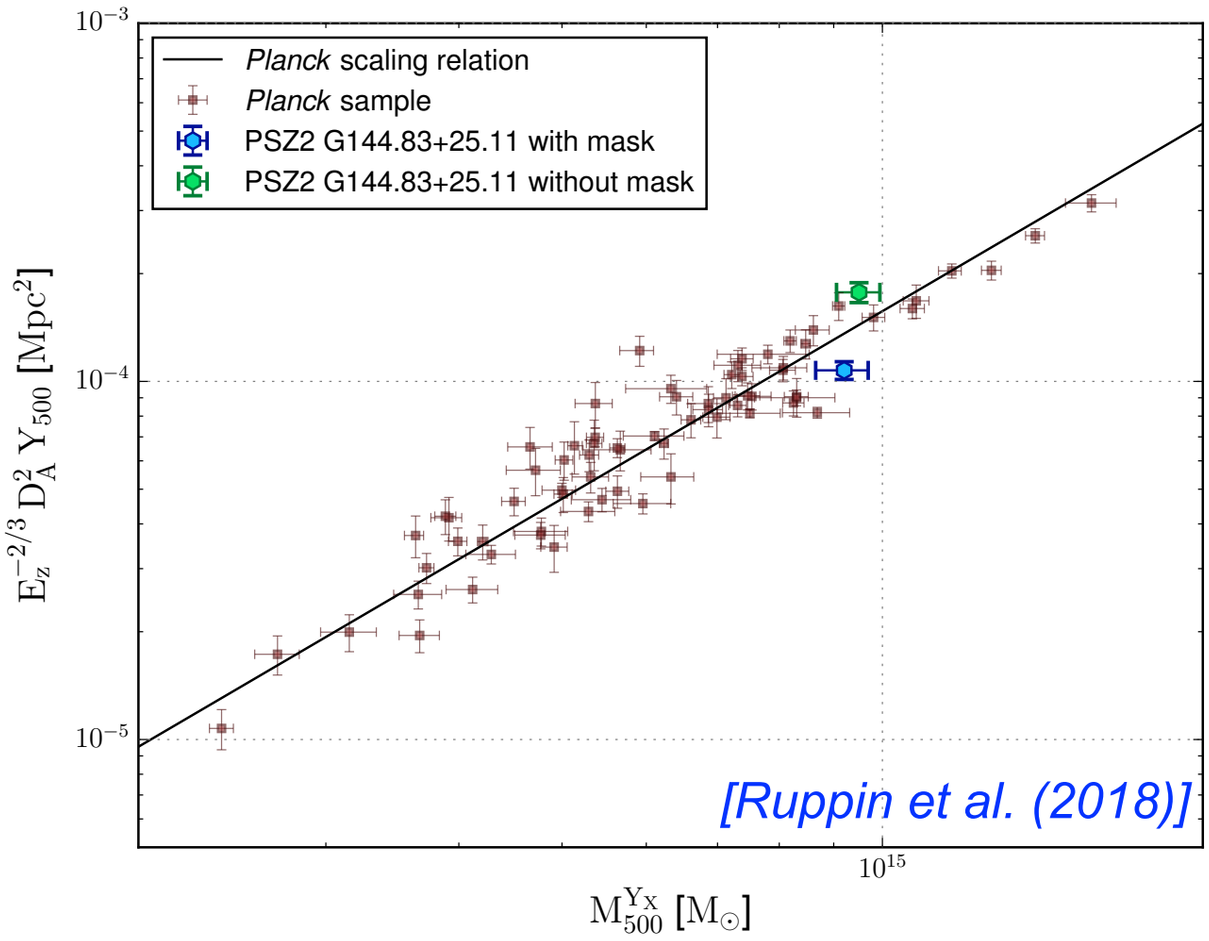
MACS J0647+7015 (z = *0.58*) at 150 GHz *[Ruppin et al. (2018)]*



Implication of substructures on the pressure profile and the SZ - mass scaling relation



- Identification of disturbed region:
  - induces significant deviations from the 'universal profile'
  - boost of the SZ flux by >60%



Strong impact of inner structure on Y-M relation

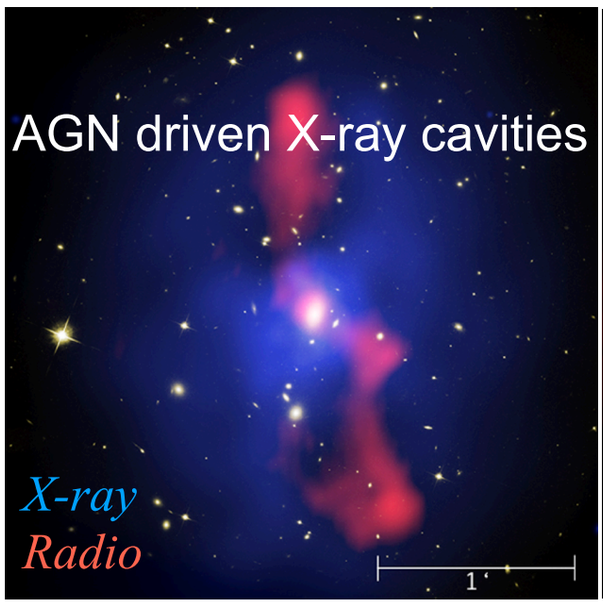
Outline

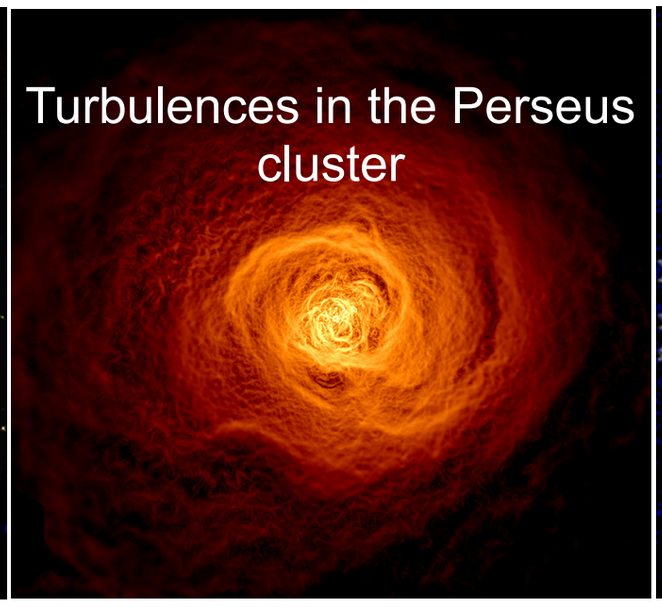
1. Clusters of galaxies as cosmic laboratories
2. Resolving the inner structure of the hot gas with NIKA
3. Mapping the gas pressure and velocity in clusters
4. **Non-thermal processes in clusters**
5. Summary

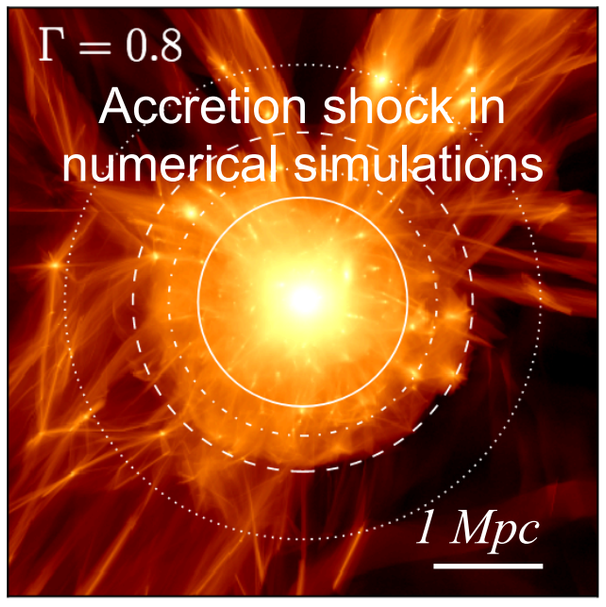
Non-thermal physics in clusters

Clusters host extreme environments at different scales

Few kpc	10-100 kpc	0.1-1 Mpc	Few Mpc
AGN outburst in central galaxies	*Gas sloshing, smooth accretion, AGN energy injection*	*Major merger*	*Large scale structure accretion from filaments*







[Chandra press release] *[Walker, et al. (2017)]* *[Markevitch (2010)]* *[More et al. (2015)]*

➡ Many implications for the gas physical properties and clusters evolution

Unique probe of high energy processes

γ-ray emission from galaxy clusters

➡ γ-ray emission is expected in clusters and could provide unique information on non-thermal physics

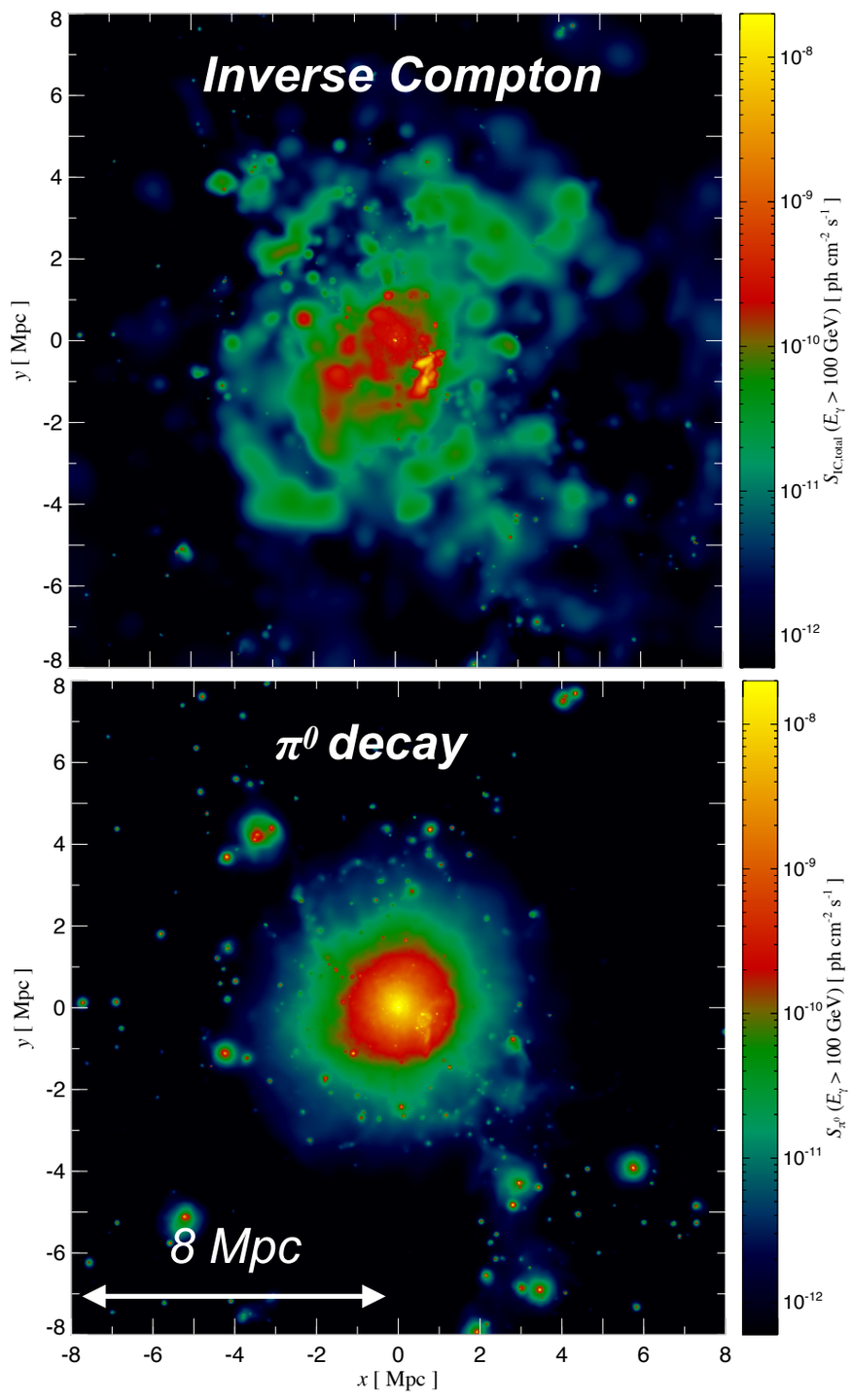
[Brunetti & Jones (2014)]

- Understanding particle acceleration
  - Differentiate leptonic vs hadronic mechanism
  - The role of AGNs, turbulences and shocks

- Targets for indirect dark matter searches
  - Require a good understanding of the background
  - and the control of the dark matter internal structure

New window on cluster astrophysics with CTA?

Simulation of a massive cluster in γ
[Pinzke & Pfrommer (2010)]



Outline

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Summary

The SZ effect in the Planck era

- The SZ effects are excellent astro. & cosmological probes
- After Planck, need high resolution follow-up: substructure, high z, kSZ

Status of SZ imaging

- Pathfinders such as NIKA have established great capabilities
- SZ imaging: test case demo. (ICM studies, kSZ, lensed galaxies…)

Next steps

- Pathfinders studies to be applied on cosmo. samples with NIKA2
- Multi-wavelength synergies are still under development
- Large optical surveys in dev.: robust mass determination is crucial
- Next γ-ray telescopes: new window on non-thermal clusters physics?