Cosmology with galaxy clusters

The Sunyaev-Zel'dovich effects to probe the formation of distant clusters

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Séminaire OCA
Nice - 23/05/2017

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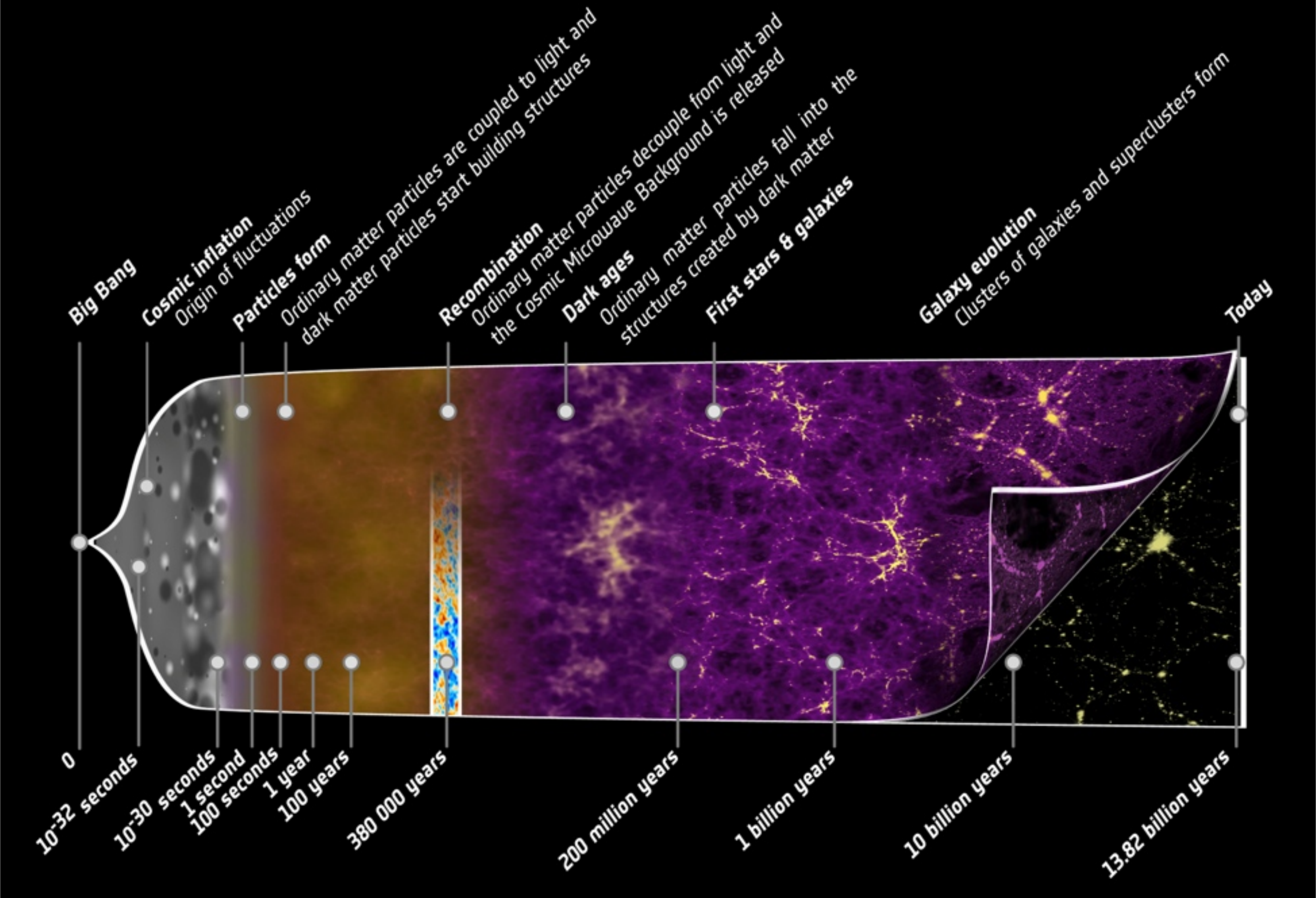

[Credit: ESA - C. Carreau]

What is the nature of dark matter?

What is the cause of the accelerating expansion of the Universe?

What is the correct description of gravity on cosmological scales?

What is the origin of the fluctuations that led to the structures we observe today?

How does the baryonic matter co-evolve with the dark matter?

Outline

1. **Clusters of galaxies as cosmological probes**
    1. Testing cosmology with massive halos
    2. The Sunyaev-Zel'dovich effects
    3. Current status and limitations of SZ cluster cosmology
2. **Pushing observations at high redshift with NIKA**
3. **Mapping the gas velocity in clusters**
4. **Conclusions and perspectives**

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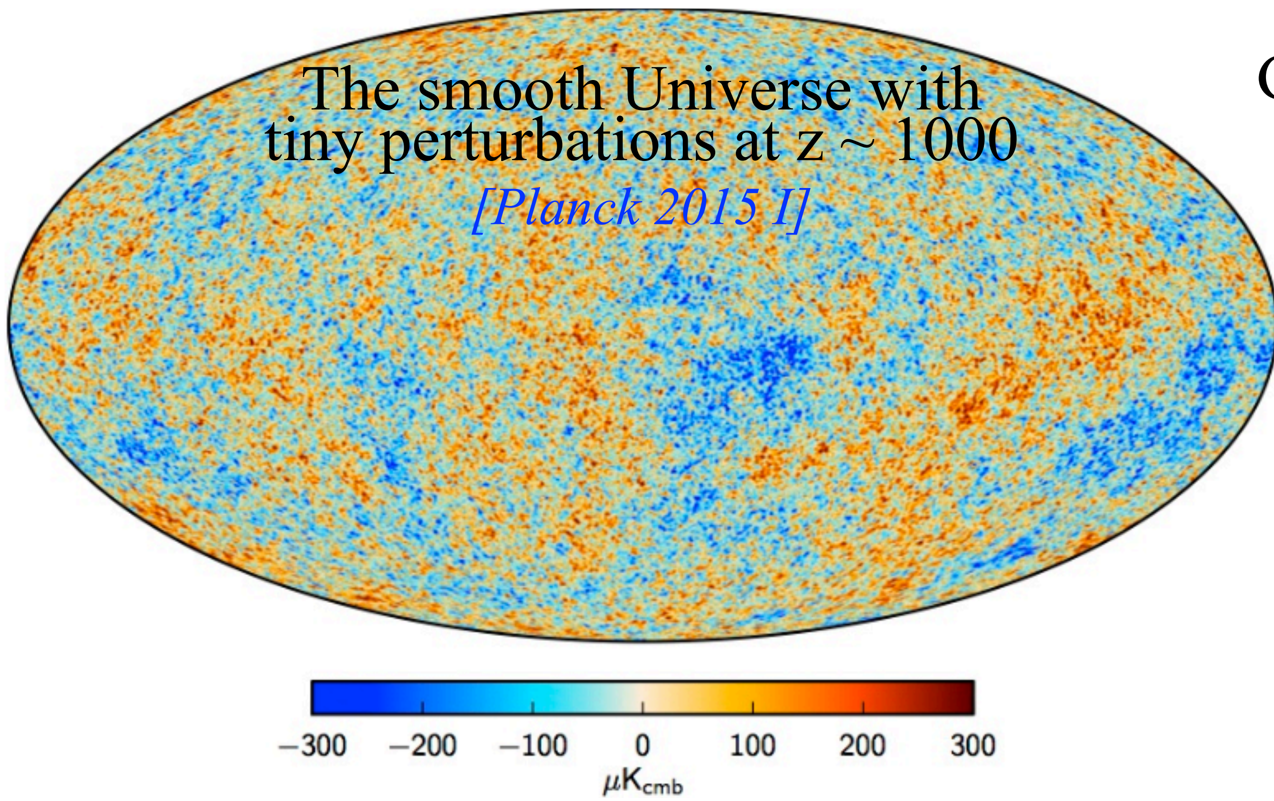
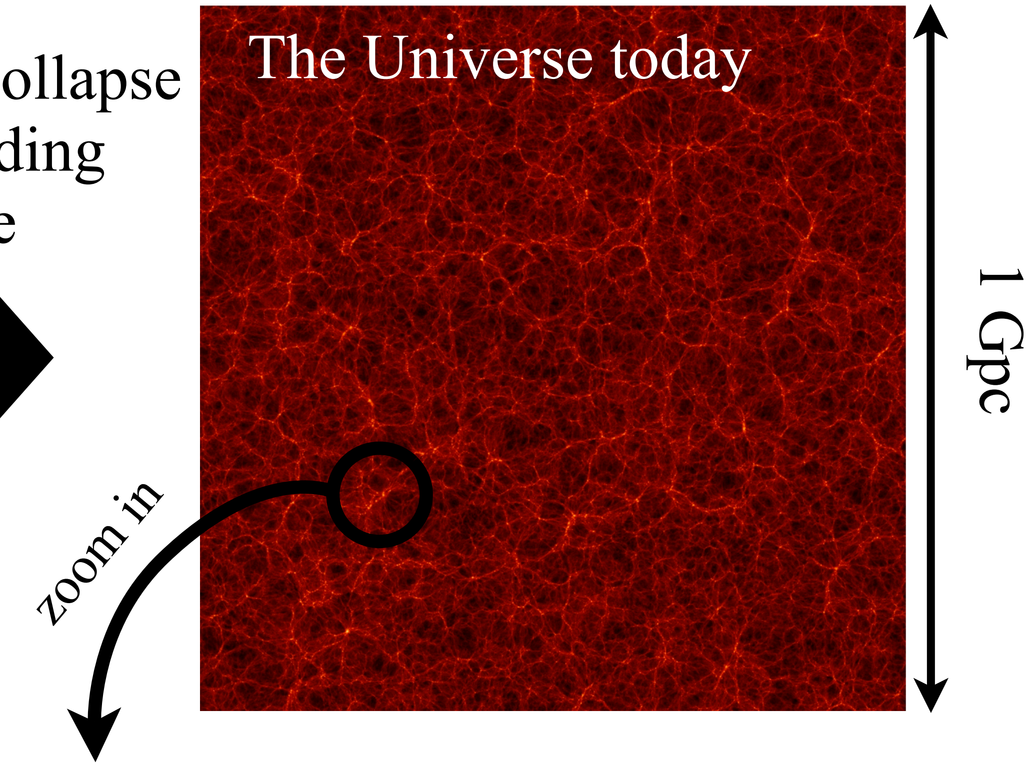
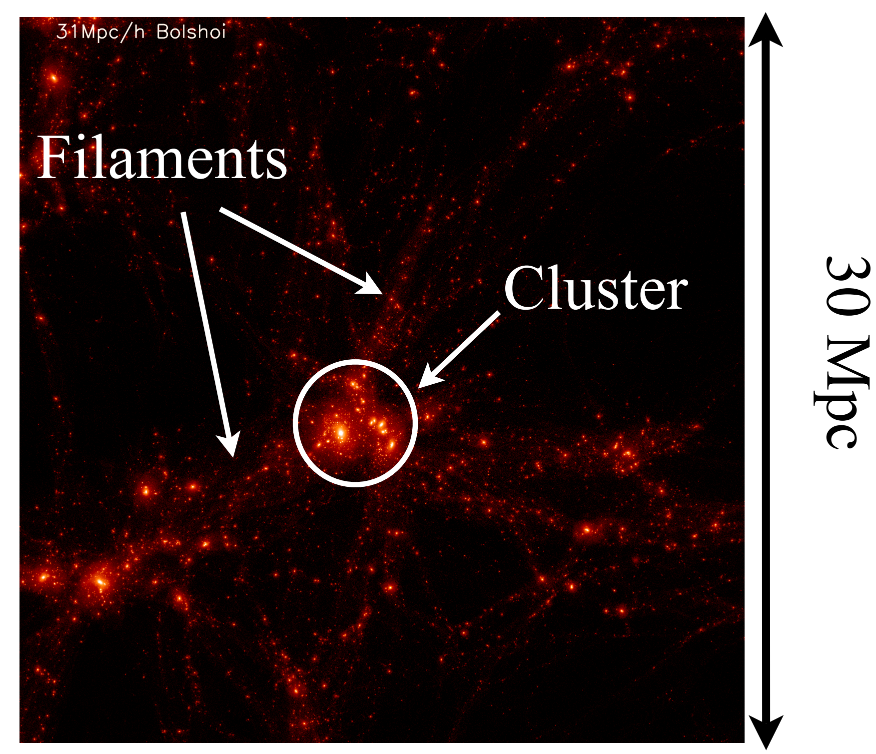
From primordial fluctuations to galaxy clusters: tracing the matter distribution



Gravitational collapse in an expanding Universe

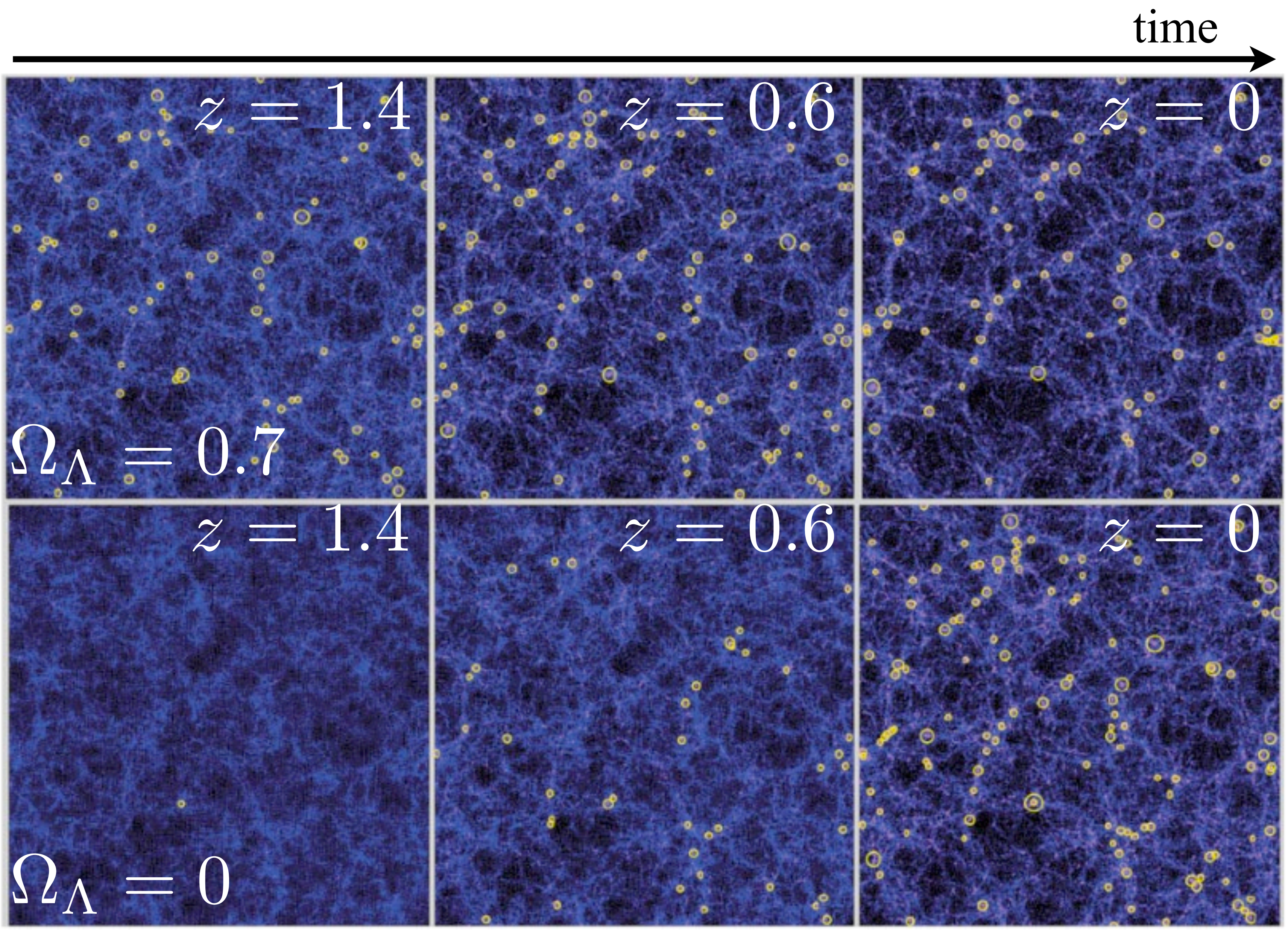




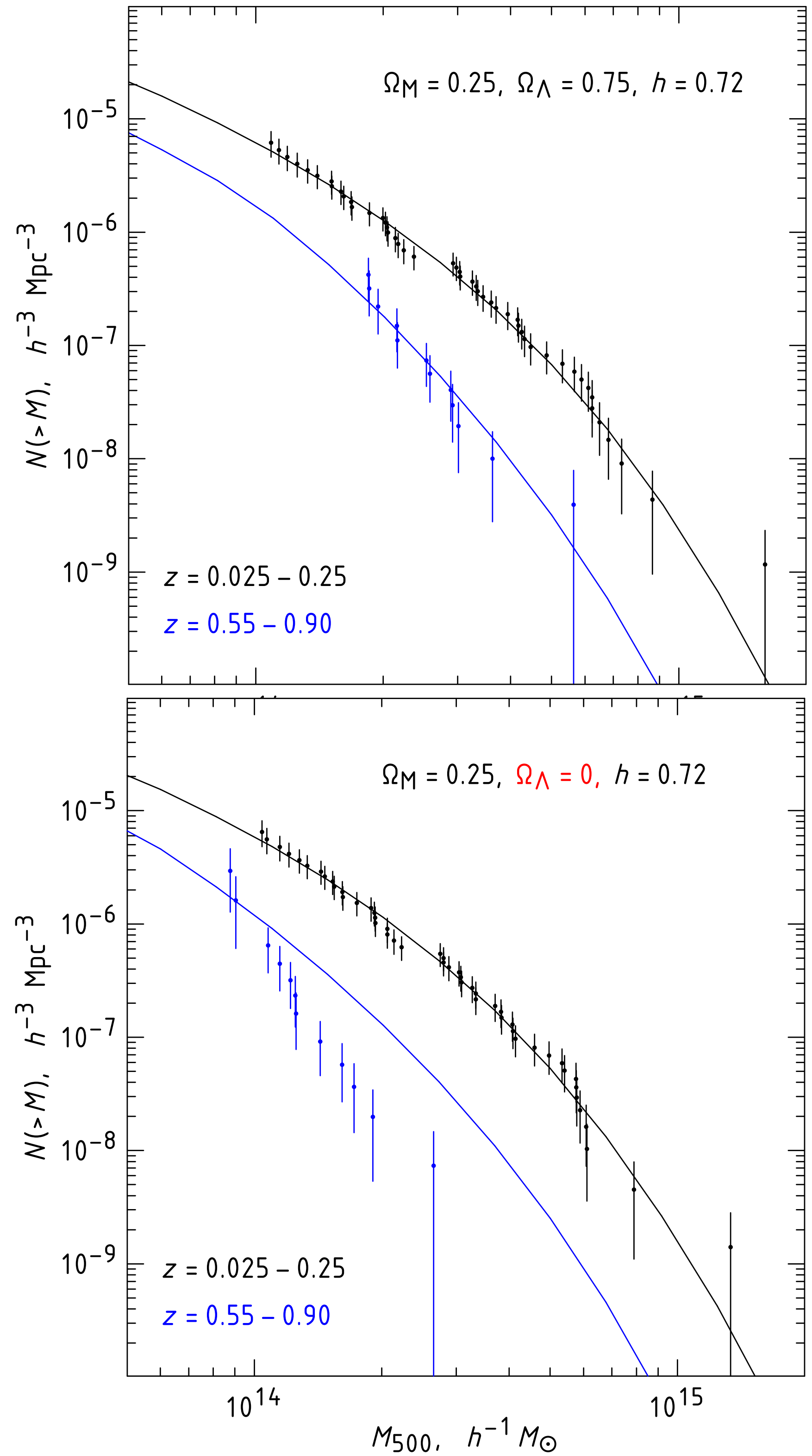
[www.multidark.org]

Galaxy clusters are the peaks in the matter density field

Cosmology with galaxy cluster number count



[Borgani & Guzzo (2001)]



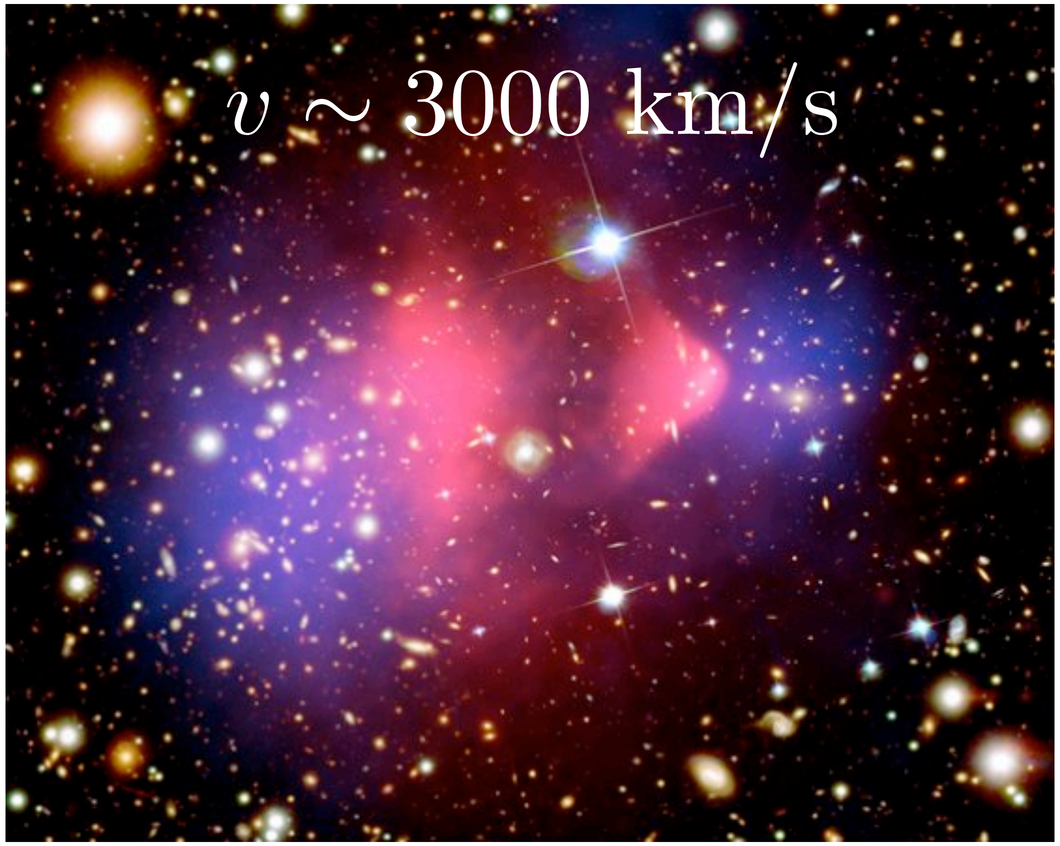
[Vikhlinin et al. (2009)]

Sensitive to both gravity and geometry

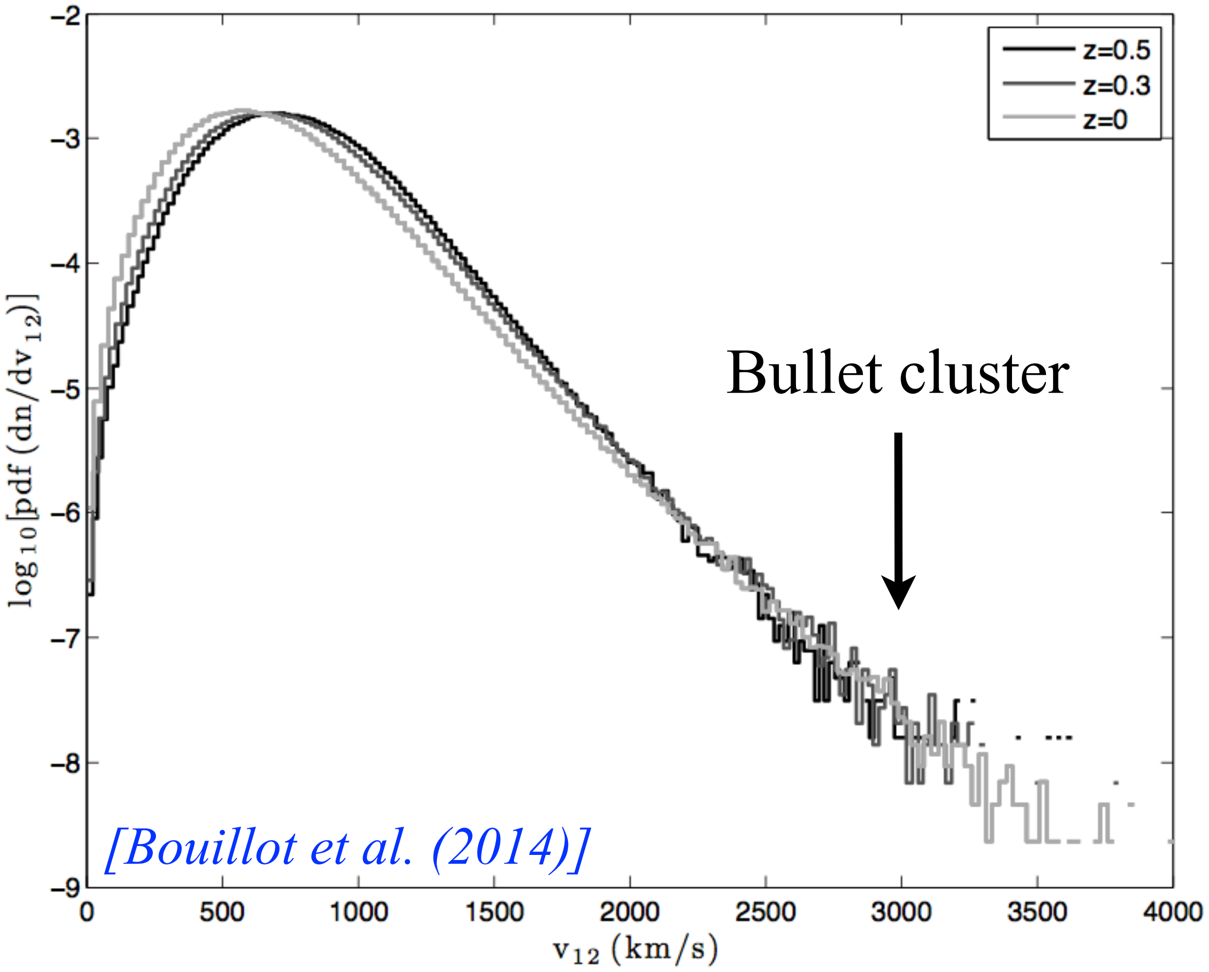
What is the true mass of clusters?

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.]

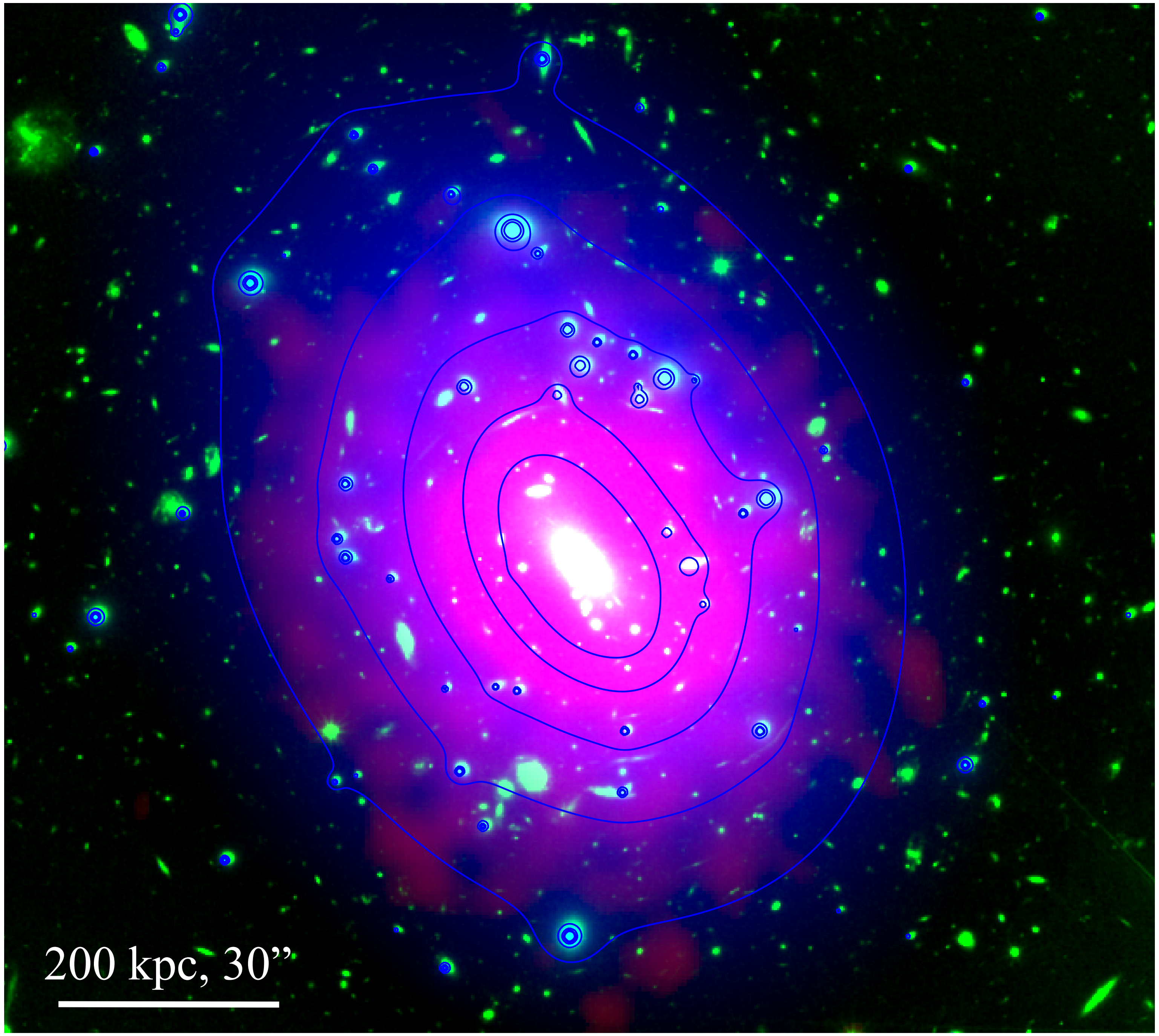


[Bouillot et al. (2014)]

Again, sensitive to both gravity and geometry

What is the true peculiar velocity of clusters?

Observing clusters of galaxies



Galaxies (~3%)
- Optical & NIR

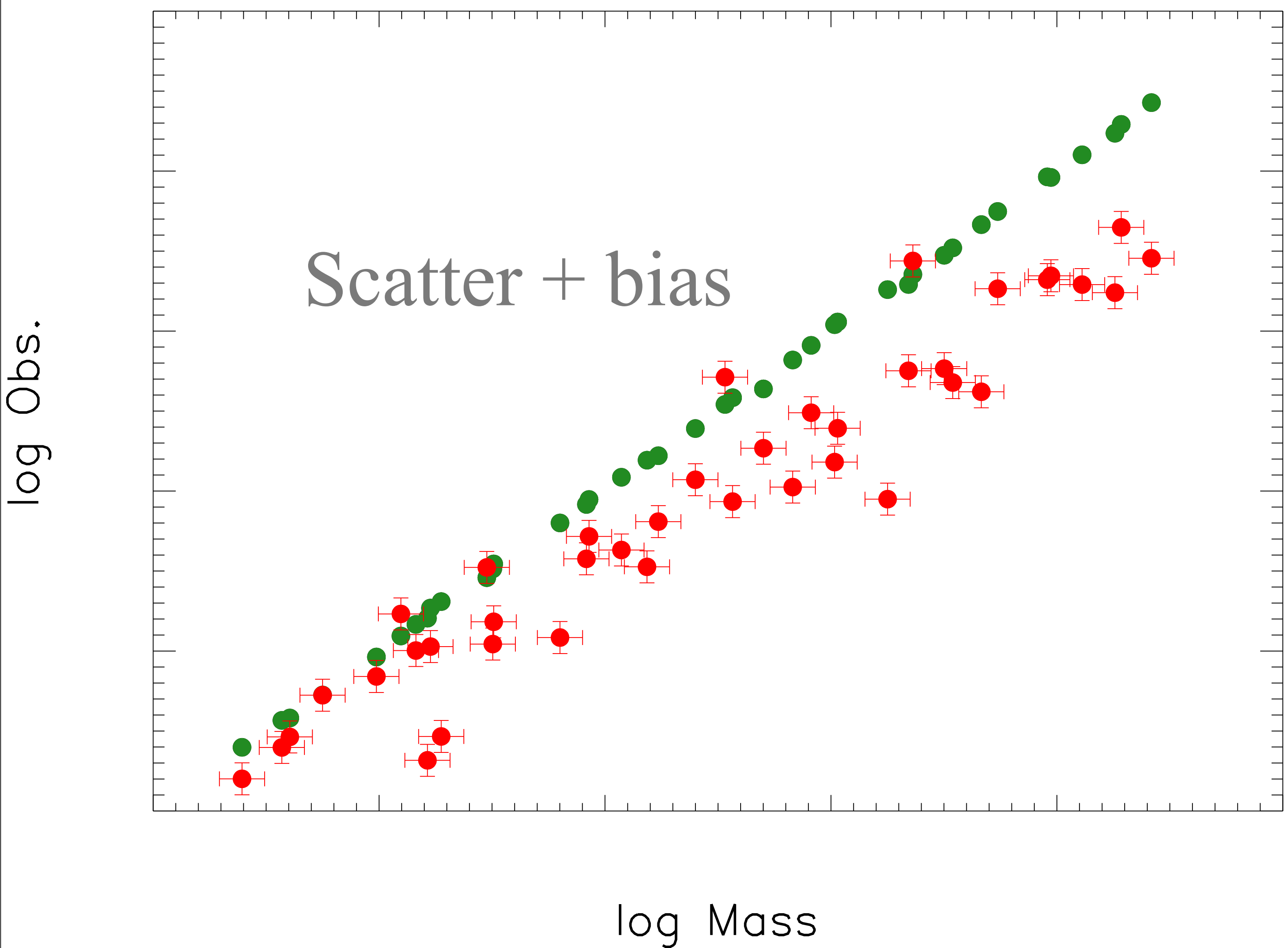
Hot inonized gas (~12%)
- X-ray
- Sunyaev-Zel’dovich
- Radio

Dark matter (~85%)
- Lensing from galaxies

We need to rely on baryonic tracers

Linking cluster observables to their underlying total matter distribution

We cannot measure the mass (or the velocity) for every cluster in a survey:
need scaling relations



Perfect cluster population

Gravity is scale free - power law relations between observables *[Böhringer et al. (2012)]*

e.g., $k_{\mathrm{B}}T \propto (H(z)M)^{2/3}$

Real life

Internal structure & environment
Non-gravitational processes
Evolution effects (M, z)
Observational biases
...

Any cosmological interpretation requires the control of cluster formation processes

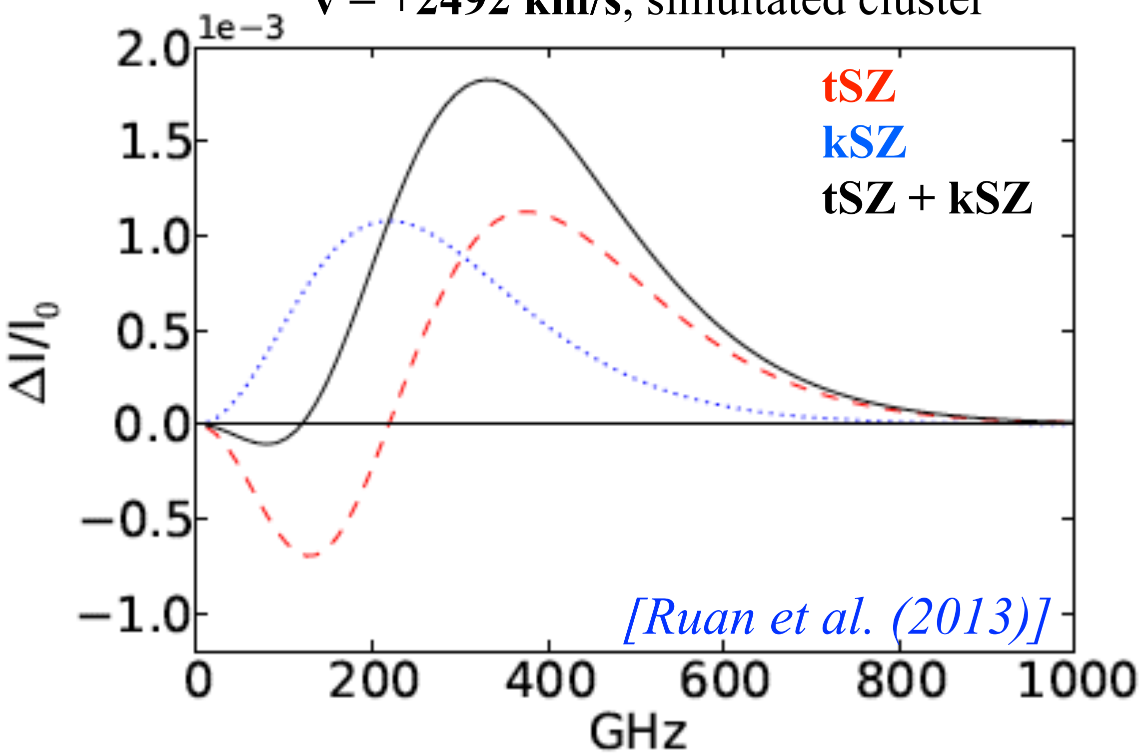
Looking at clusters using the SZ effects

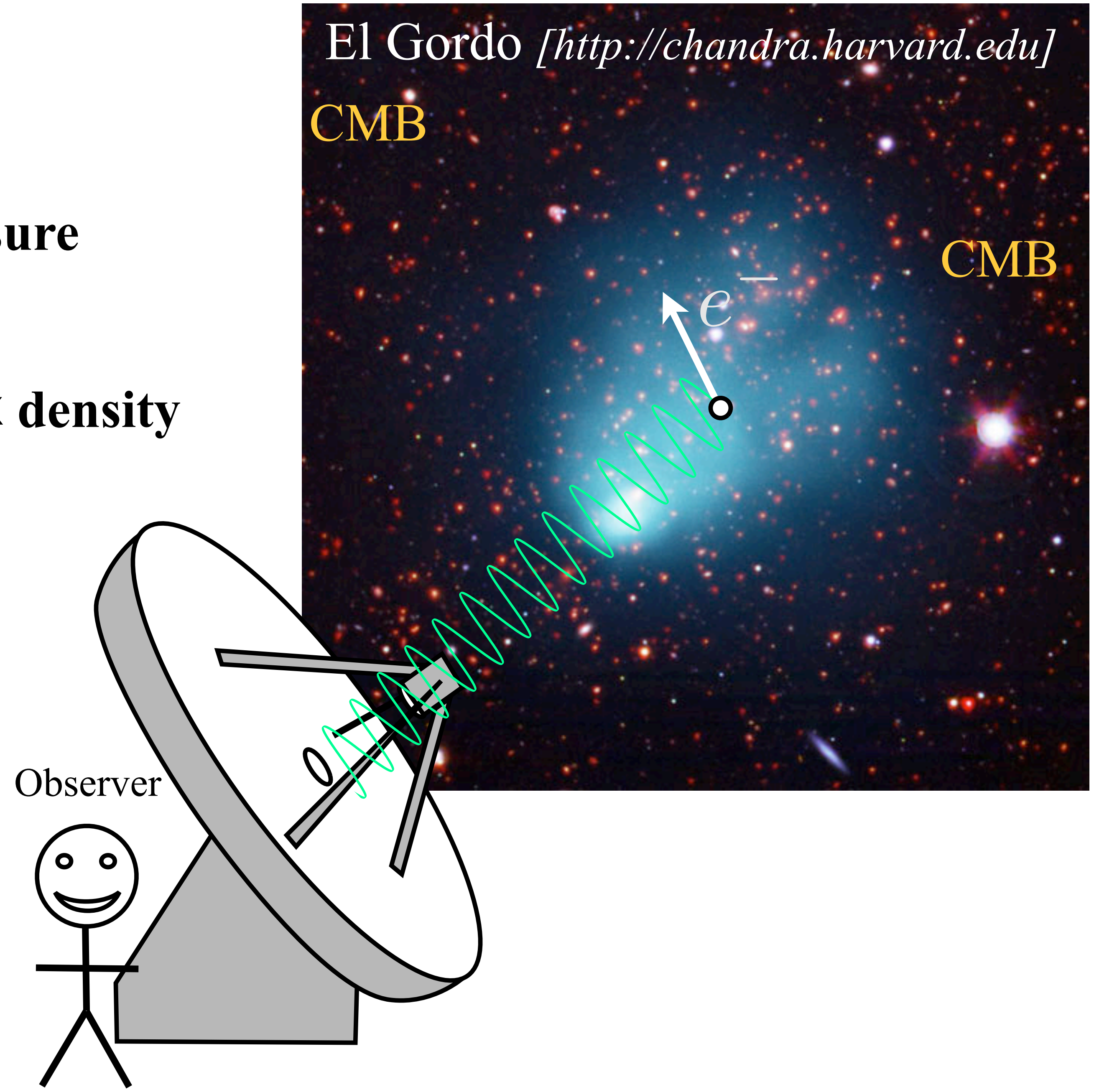
- **tSZ** = CMB spectral distortion from interaction with clusters' hot electrons
- **kSZ** = CMB Doppler shift from bulk motion of electrons (typically ~ tSZ/10)

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

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

v = +2492 km/s, simultated cluster





SZ = probe for intracluster gas

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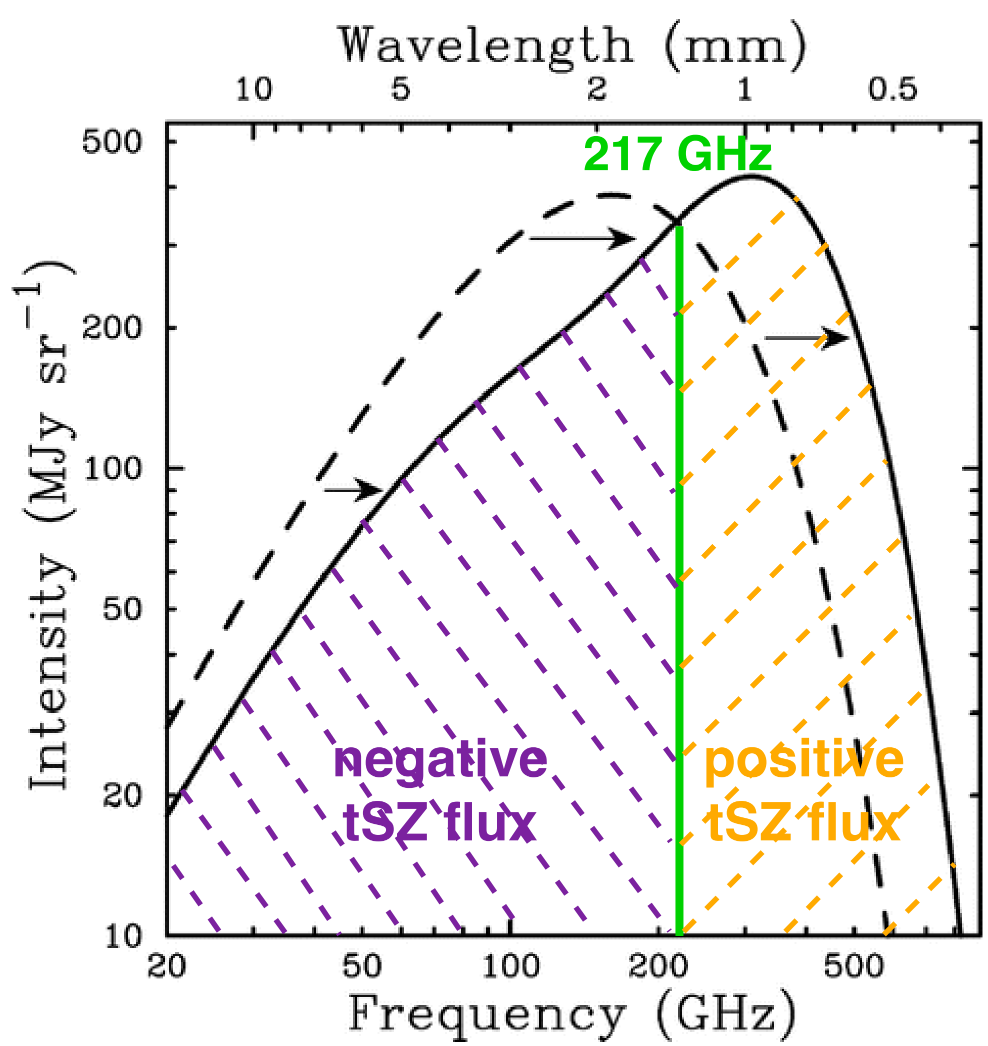
tSZ only here *[Sunyaev & Zeldovich (1980)]*



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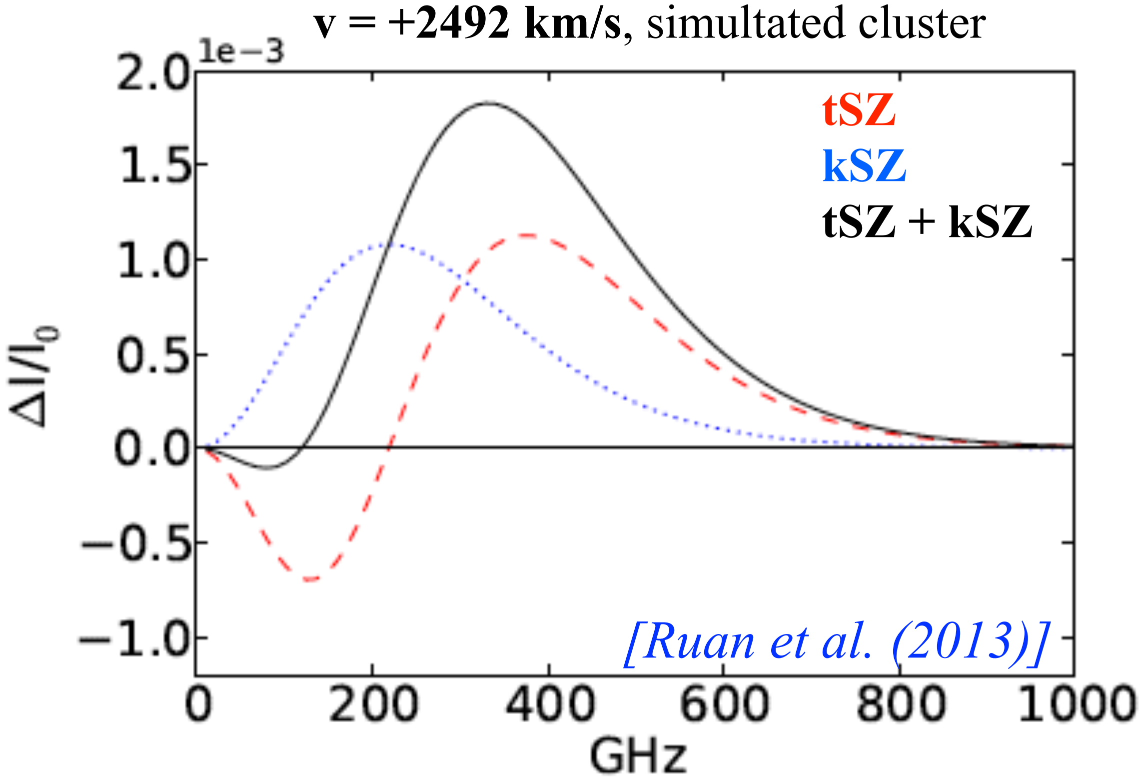

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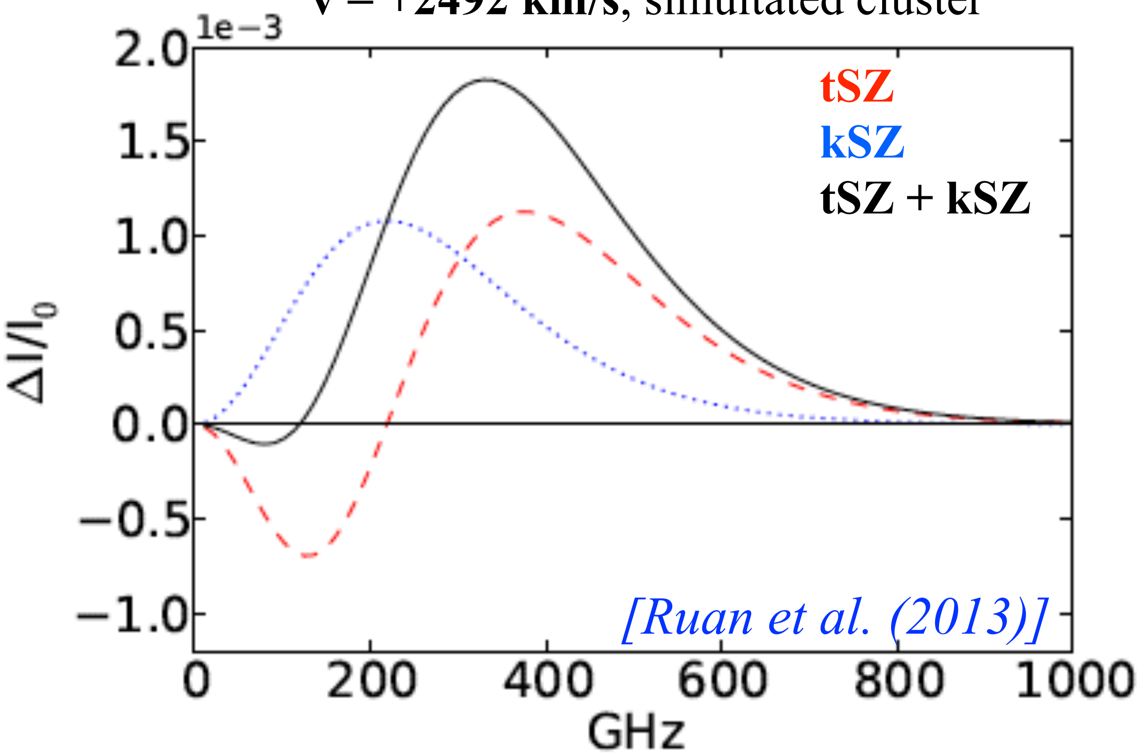
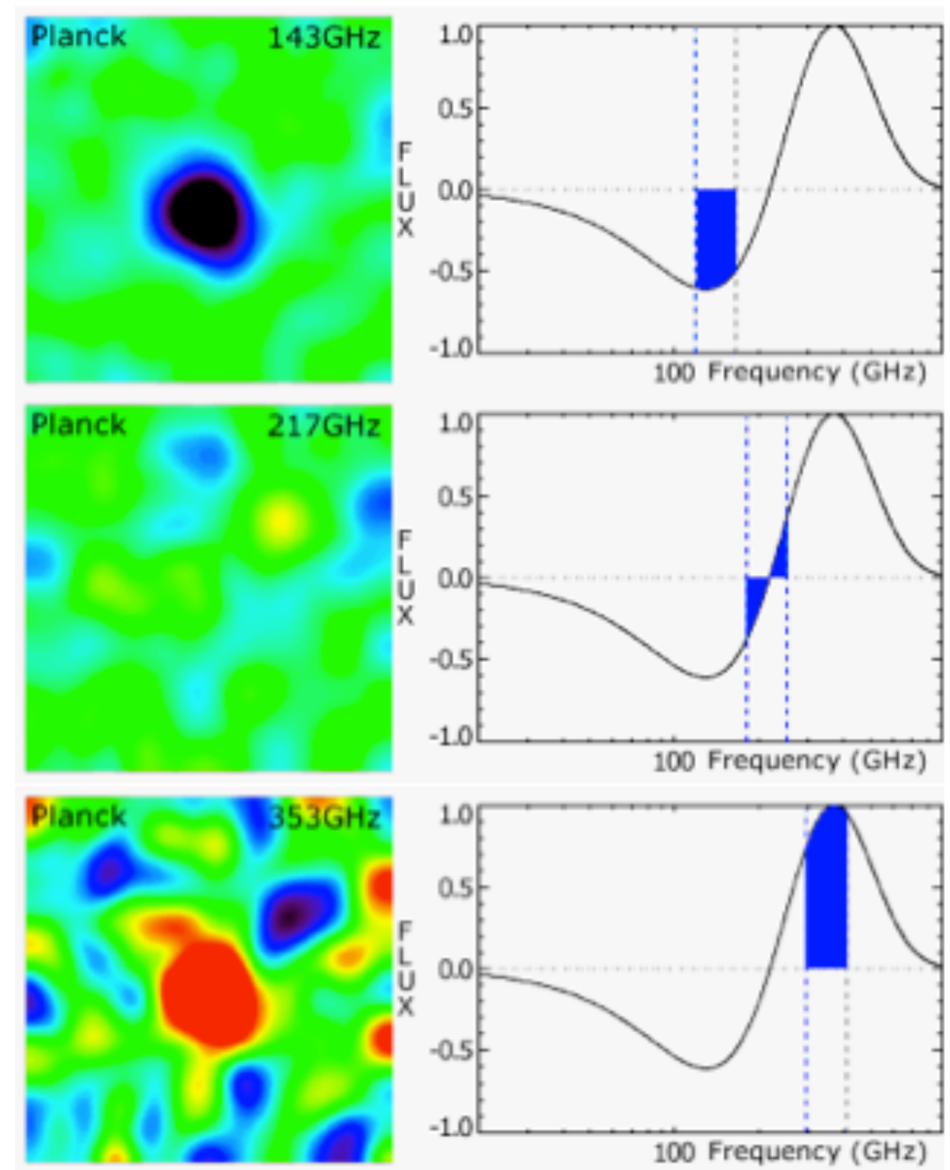


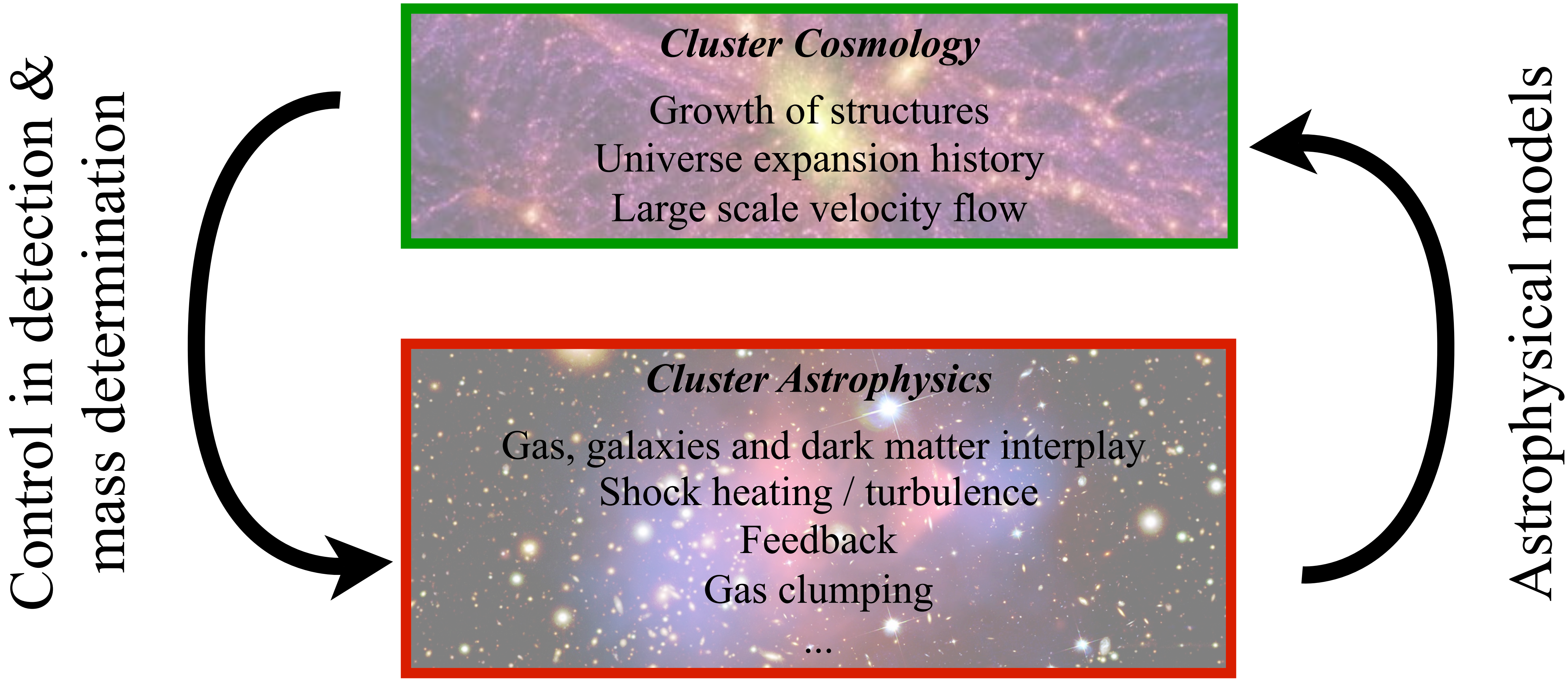
tSZ only here *[ESA HFI/LFI consortia]*



SZ = probe for intracluster gas

Cosmology with the SZ effects

➡ tSZ pressure ~ total mass
➡ kSZ momentum ~ velocity



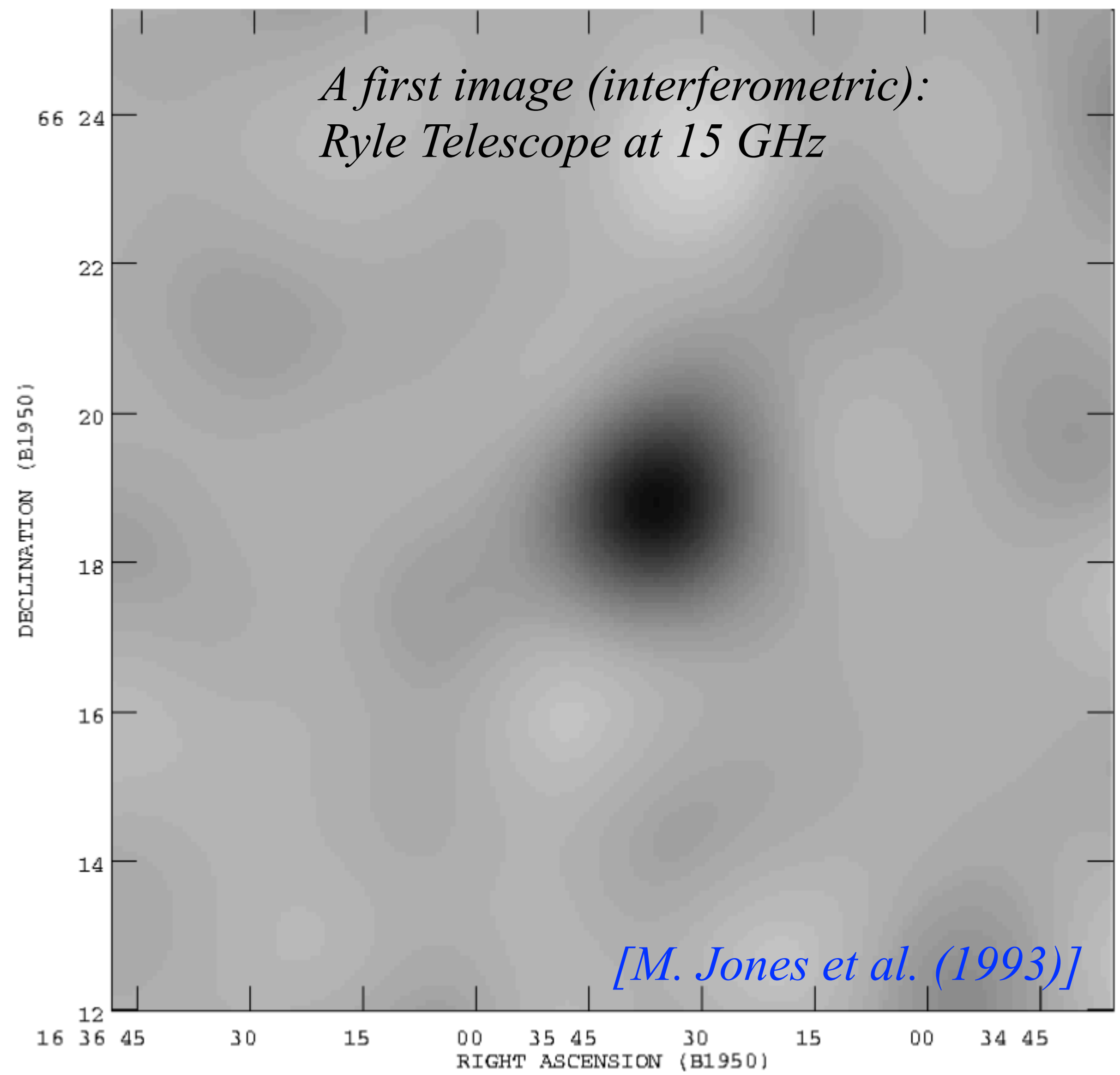
SZ = excellent tracers of the matter distribution

SZ status after Planck (and other surveys)

- Formalism in the early 70's
[Sunyaev & Zel'dovich (1970)]
- First tSZ detections in the 70's
- First (statistical) kSZ detection
[Hand et al. (2012)]

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

- Tensions between CMB & local Universe



Huge progress & new fundamental questions

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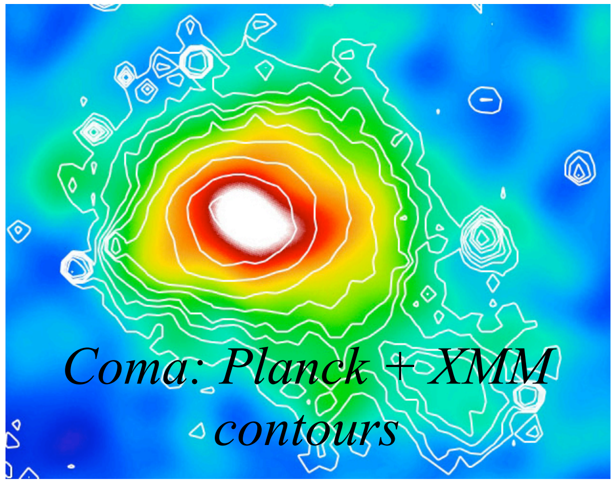
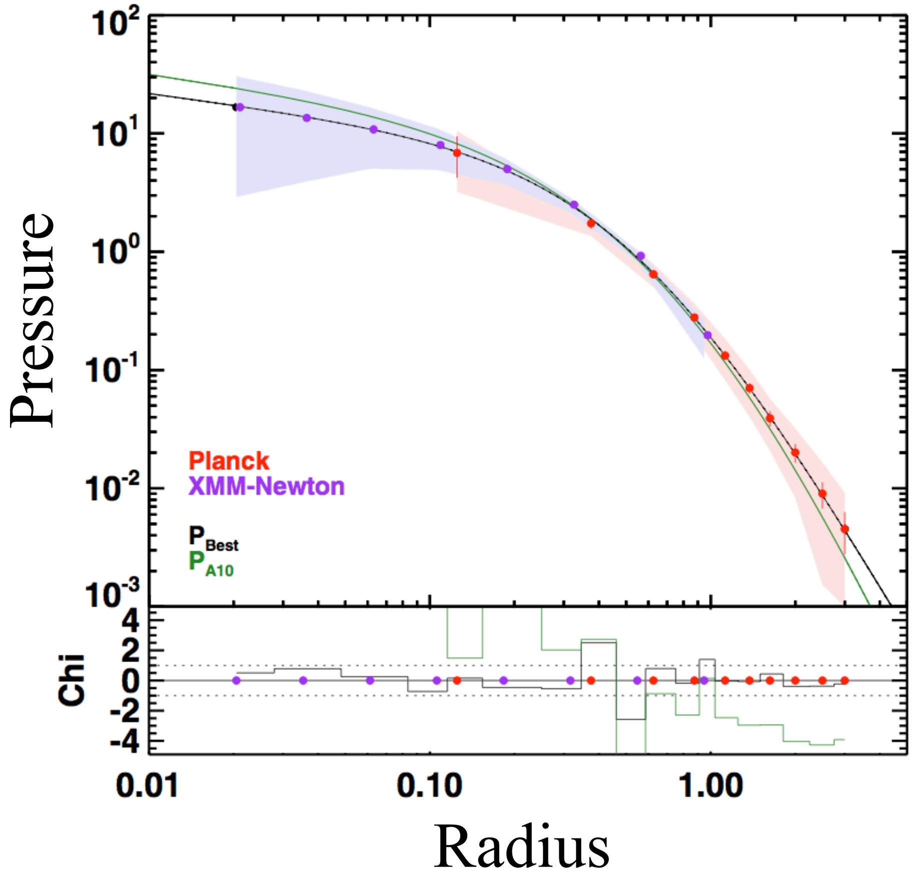


The pressure profile as a Universal tracer of matter



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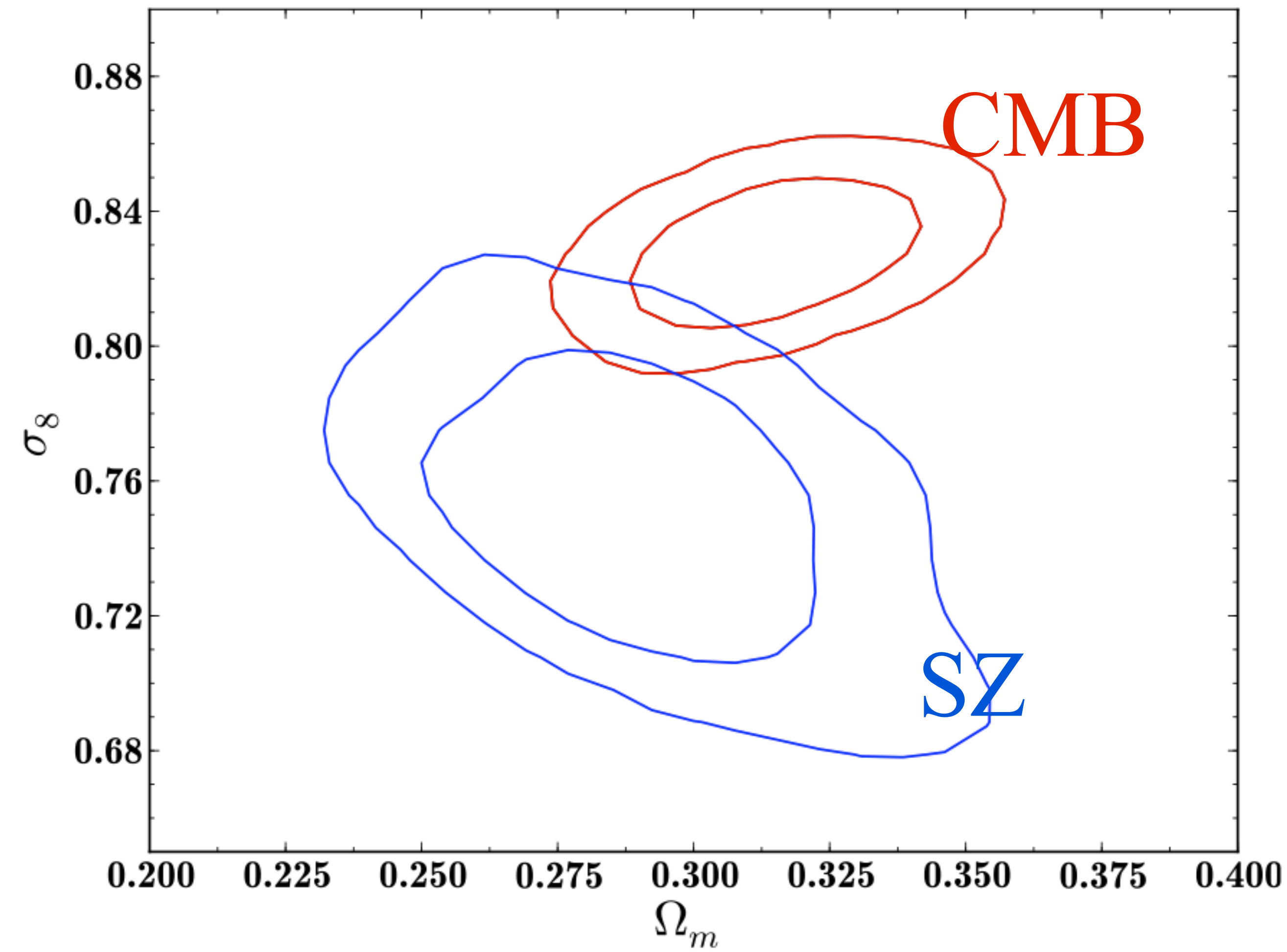

Misunderstanding of cluster physics?
Hint for new physics? Neutrino masses?
Statistical fluctuation?

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

Huge progress & new fundamental questions

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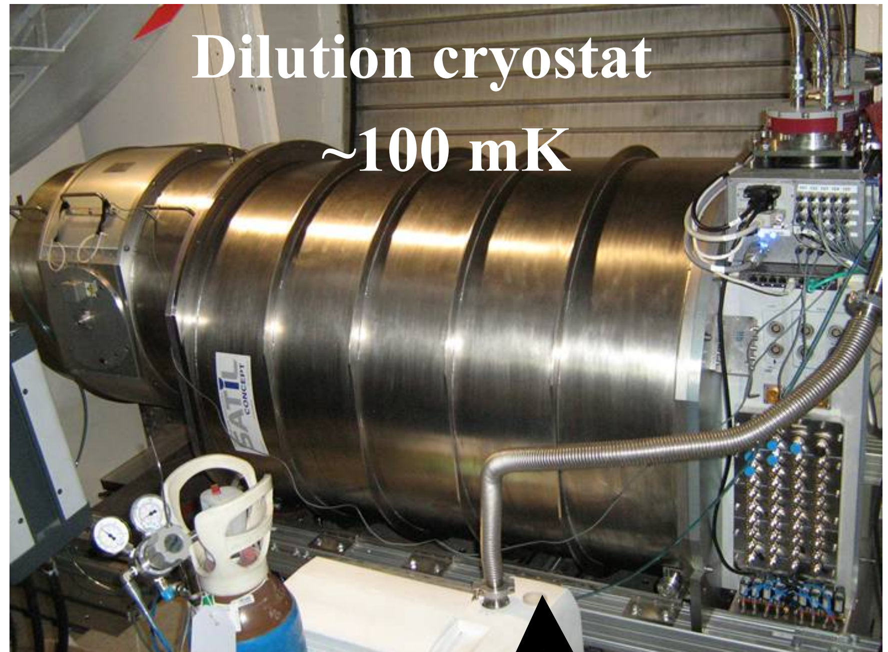
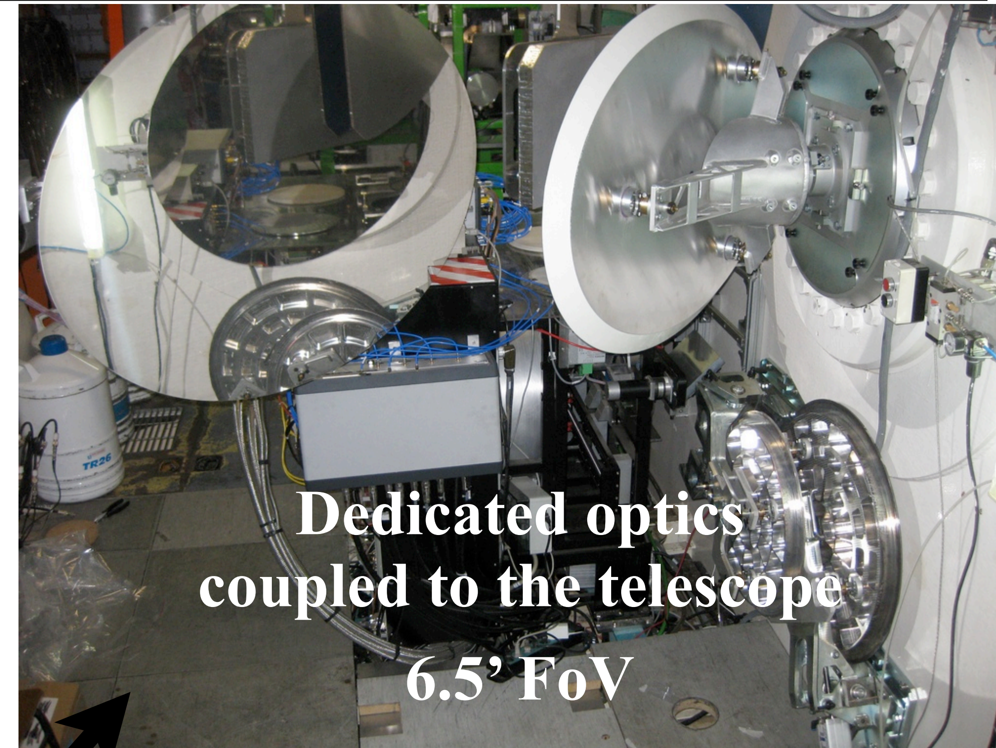
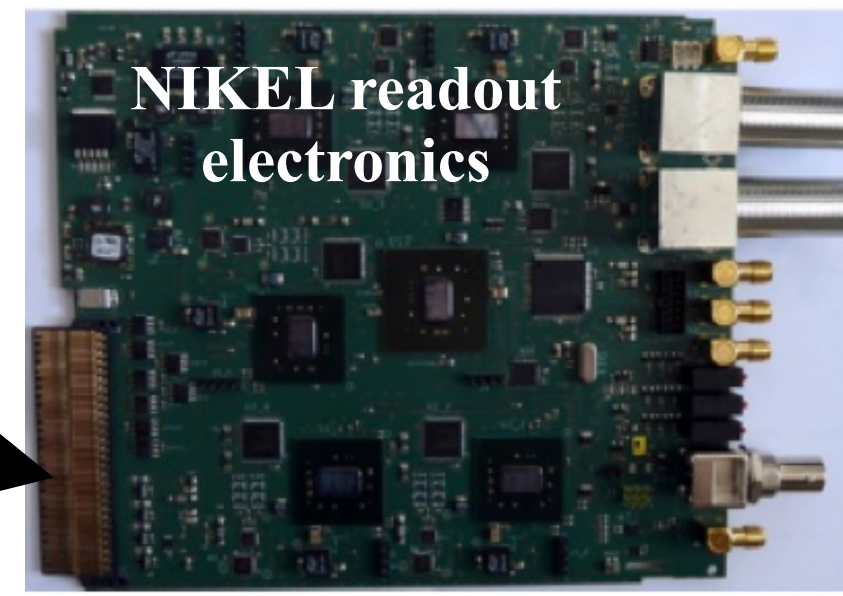
NIKA2: the next generation millimeter wave continuum instrument at the IRAM 30m telescope



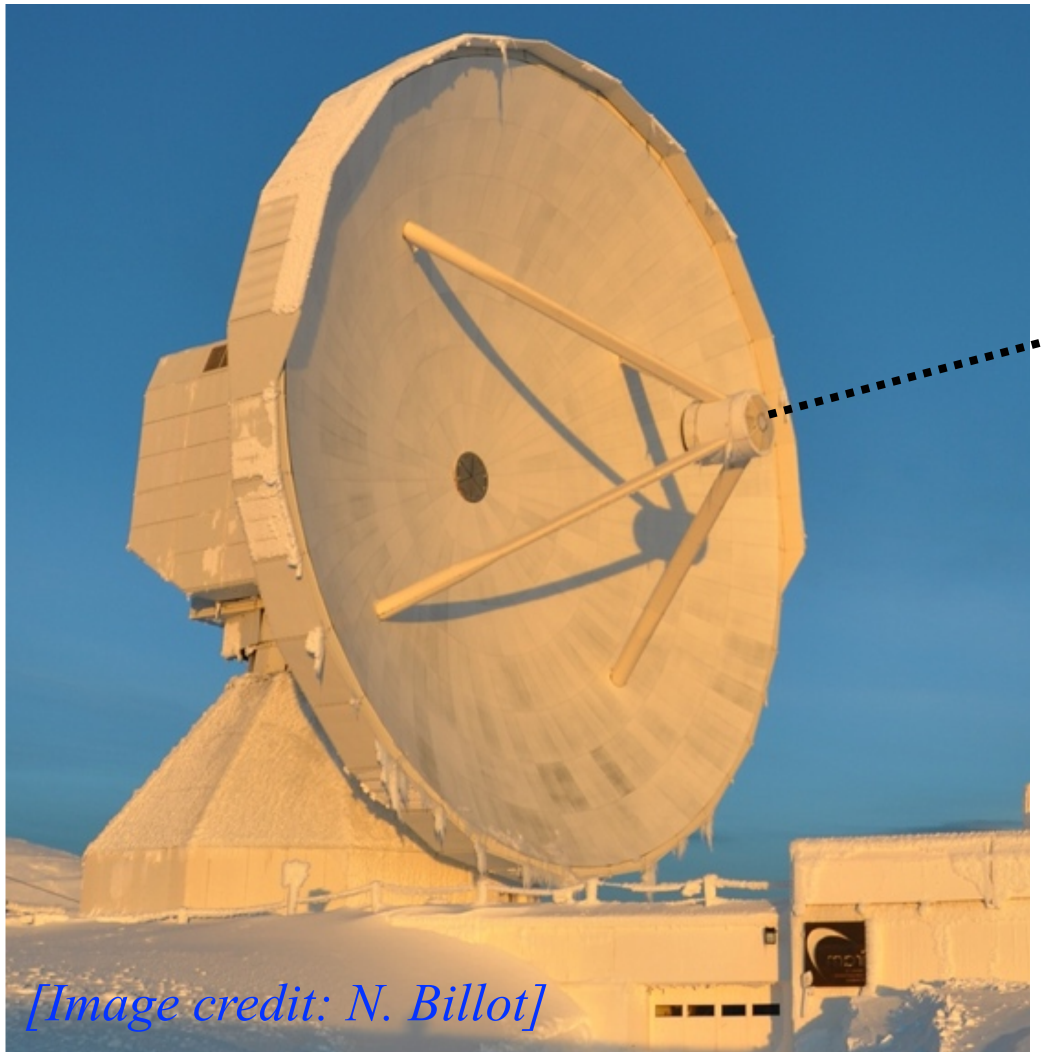


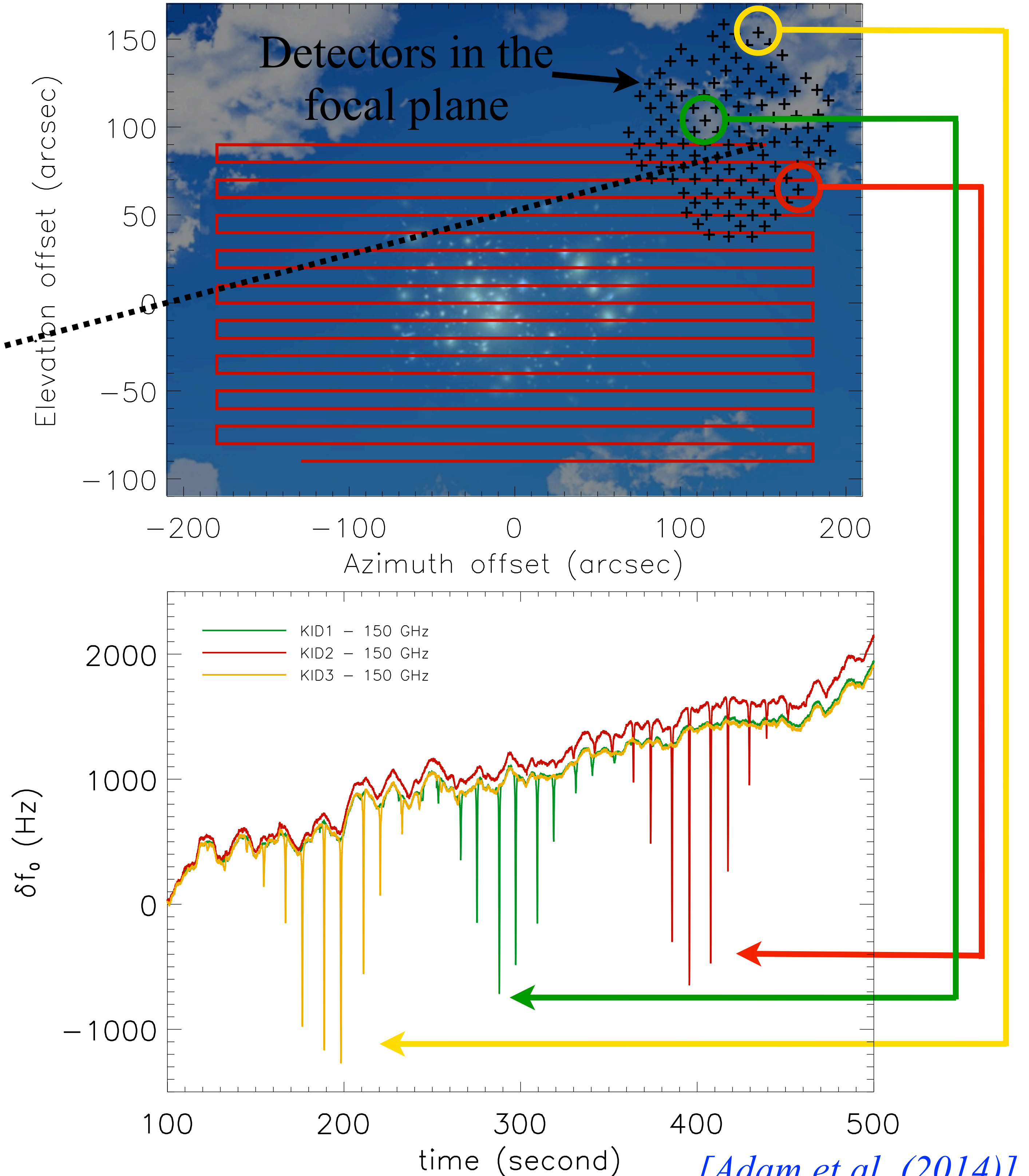
NIKA2



Large FOV+high resolution+SZ bands: perfect for high z clusters

Observations at the telescope



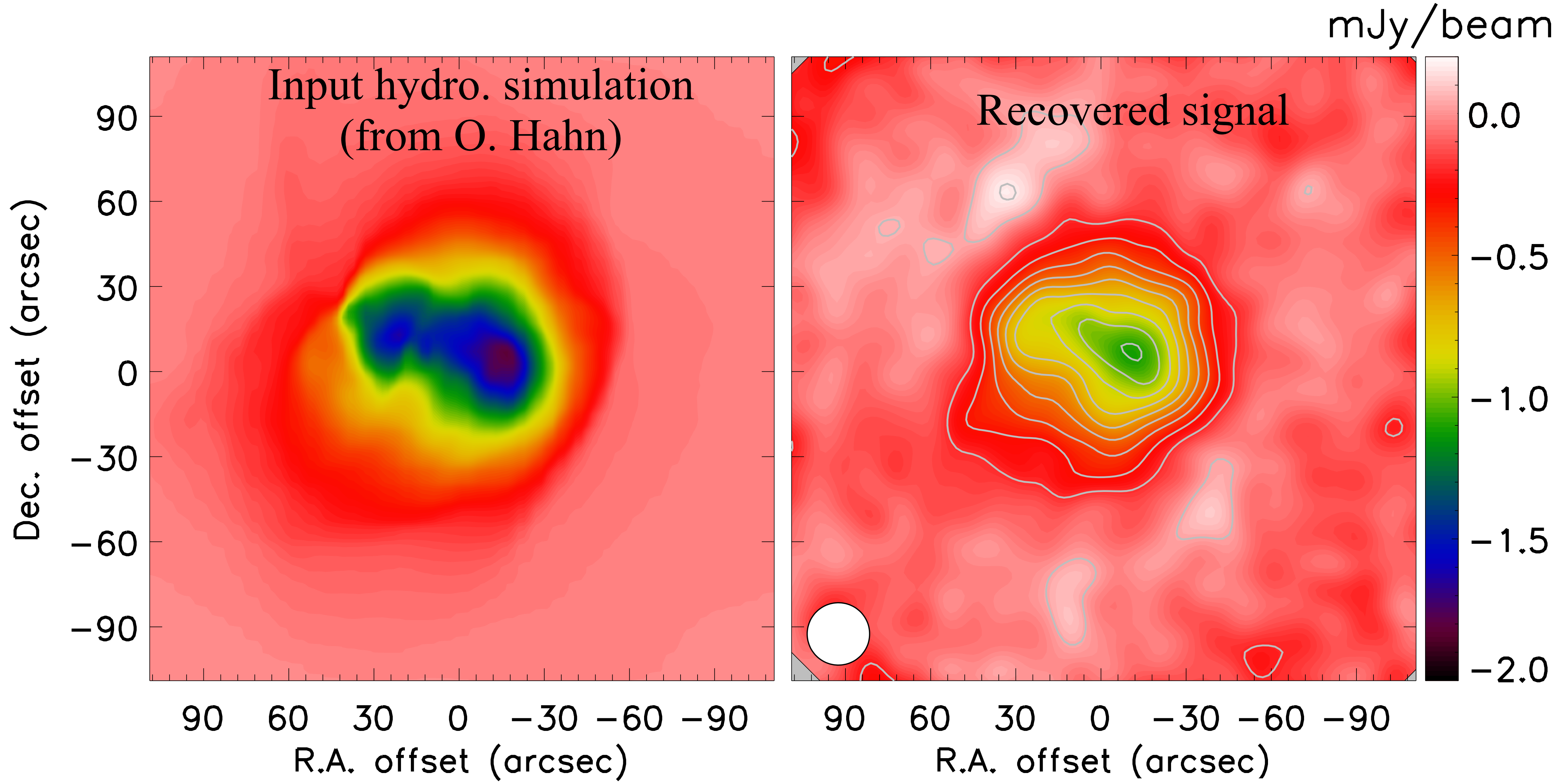


[Adam et al. (2014)]

Need to deal with the correlated noise

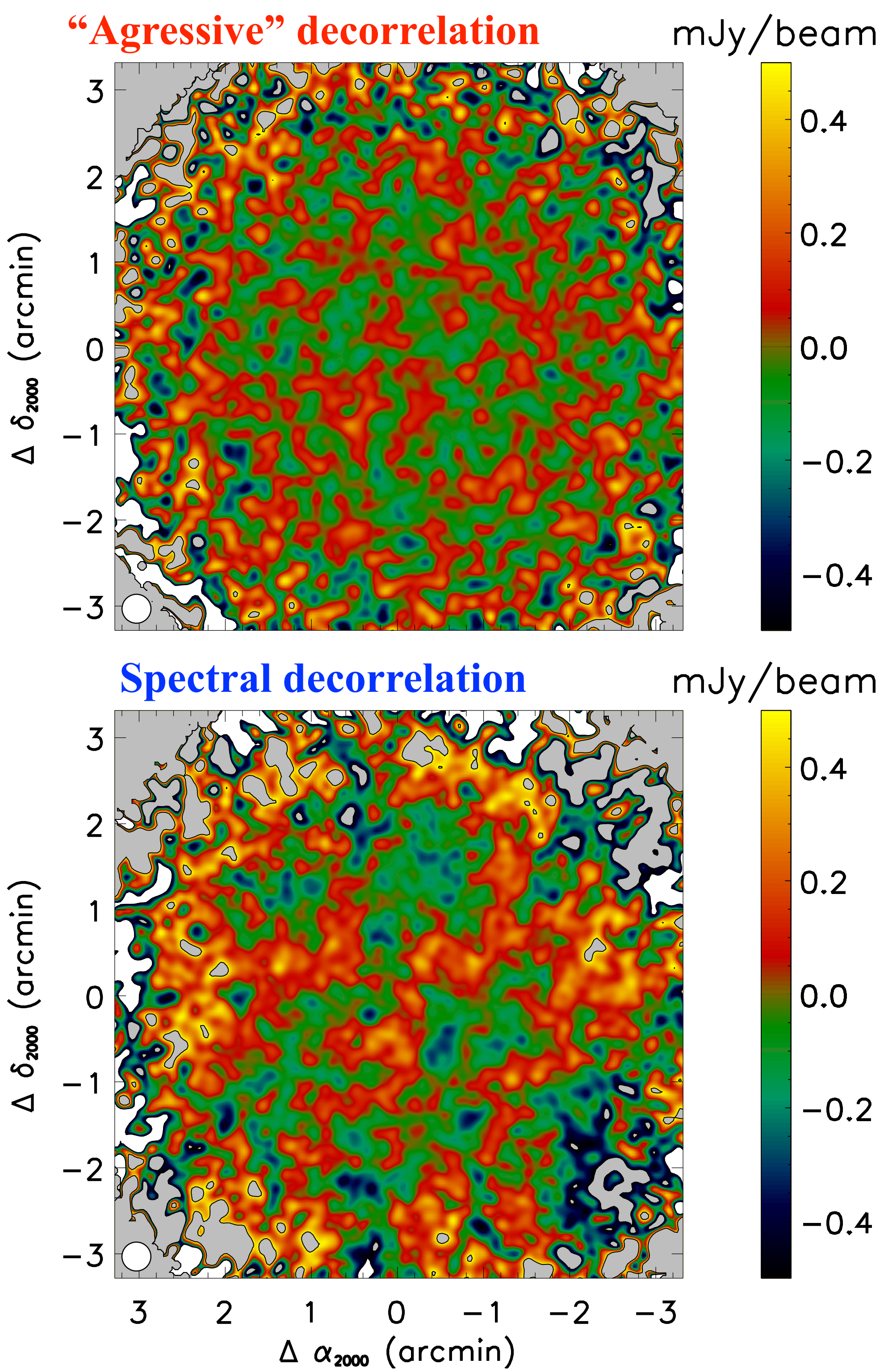
Data reduction: mapmaking from raw data

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

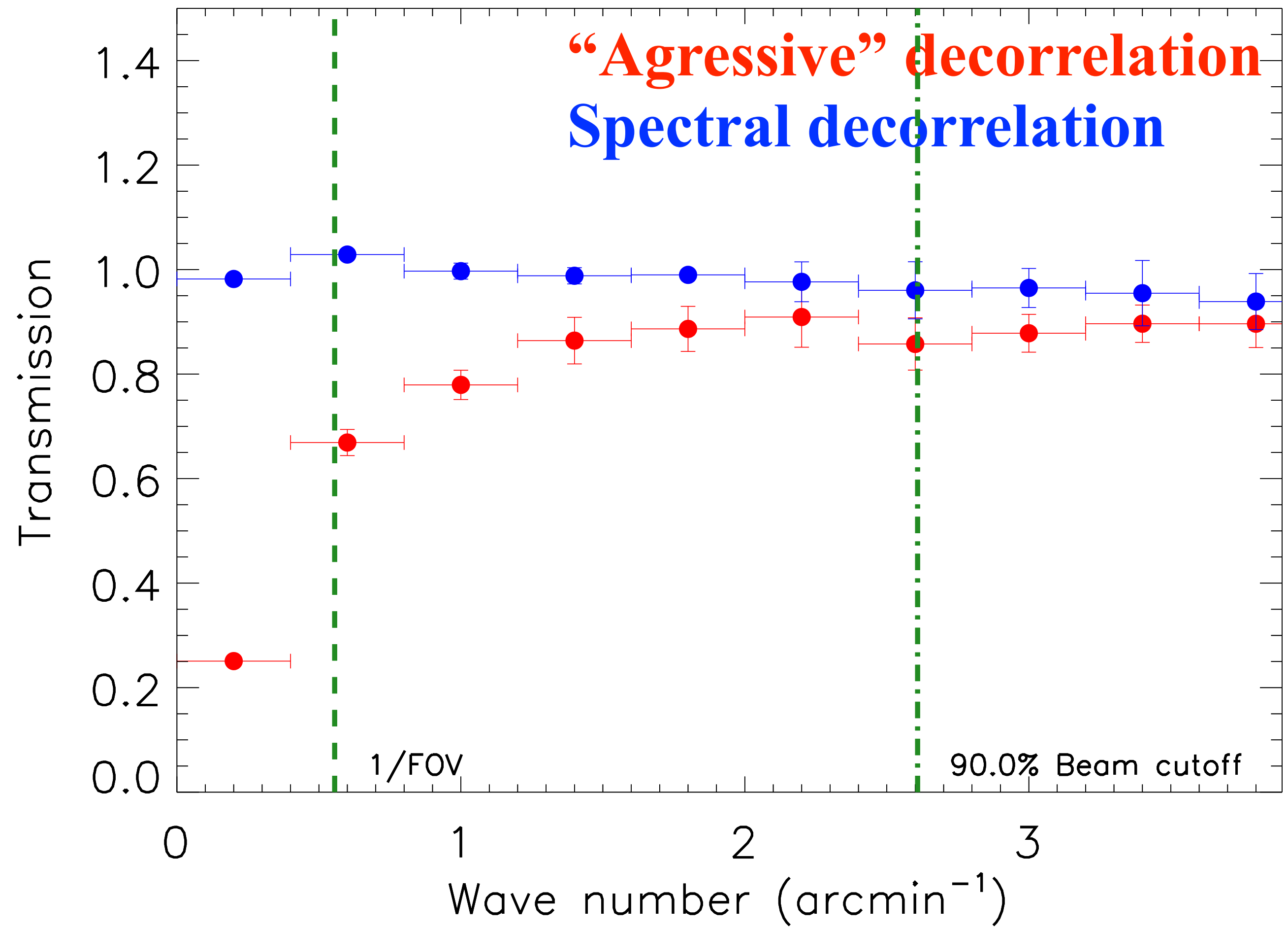


The processing affects the reconstructed signal

Calibration of the maps

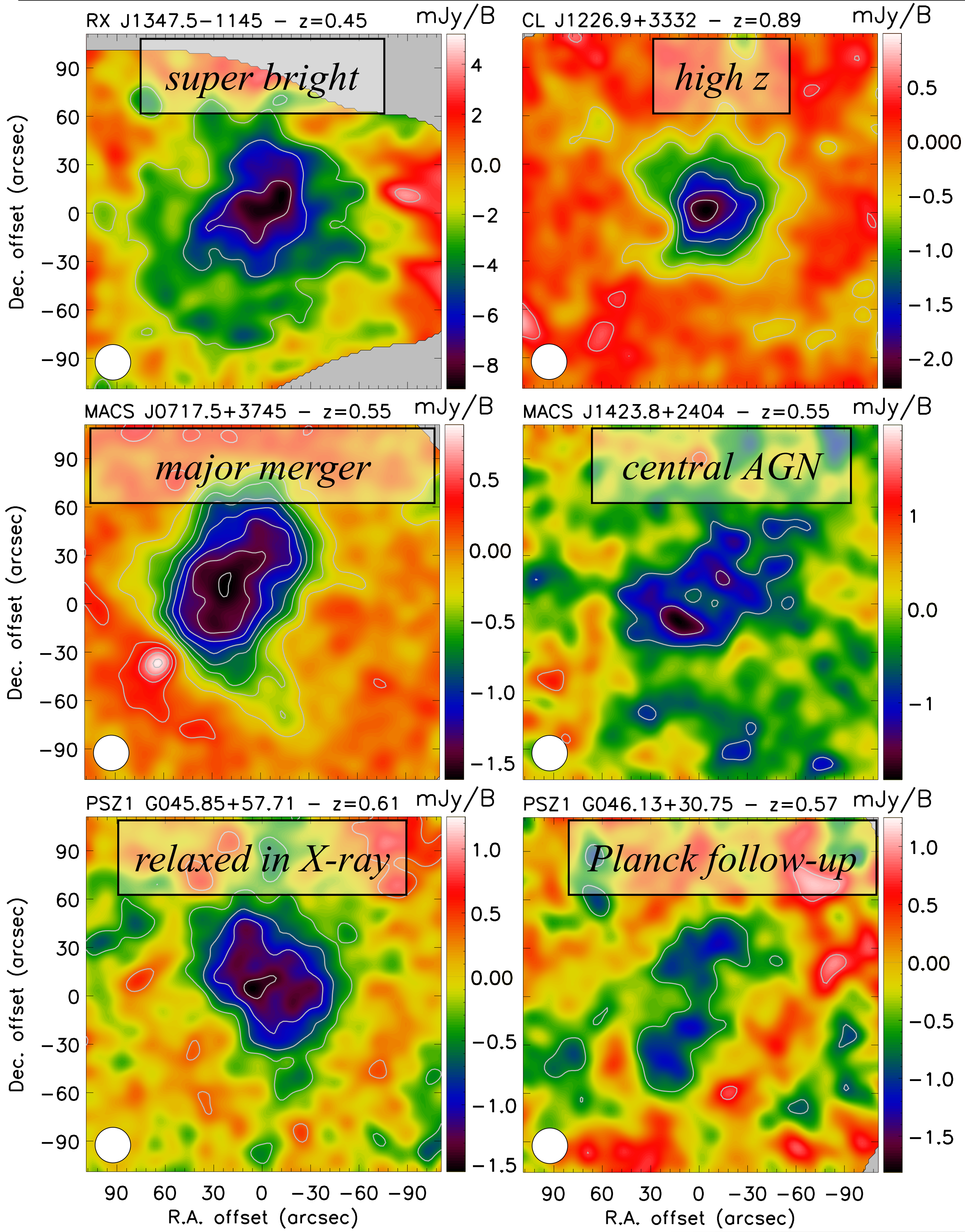


- ☑ Angular + spectral transmission measured *[Adam et al. (2014), Catalano et al. (2014)]*
- ☑ Transfer function characterized using simulations *[Adam et al. (2015)]*
- ☑ Noise covariance matrix from MC realizations *[Adam et al. (2016)]*



The maps can be quantitavely used to extract the SZ information

The NIKA cluster sample (at 150 GHz)



A pilot sample to prepare the NIKA2 observations

- ☑ First SZ observation with KIDs detectors
  [Adam et al. (2014)]
- ☑ High z thermodynamics reconstruction with tSZ+X
  [Adam et al. (2015, 2016), Ruppin et al. (2017)]
- ☑ Dealing with astrophysical contaminants
  [Adam et al. (2016)]
- ☑ Detection and follow-up of high z lensed galaxies
  [Adam et al. (2015, 2017)]
- ☑ A first image of the kSZ effect
  [Adam et al. (2017)]
- ☑ A first temperature mapping from SZ imaging
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- ☑ Merger detection: NIKA versus RHAPSODY-G simu.
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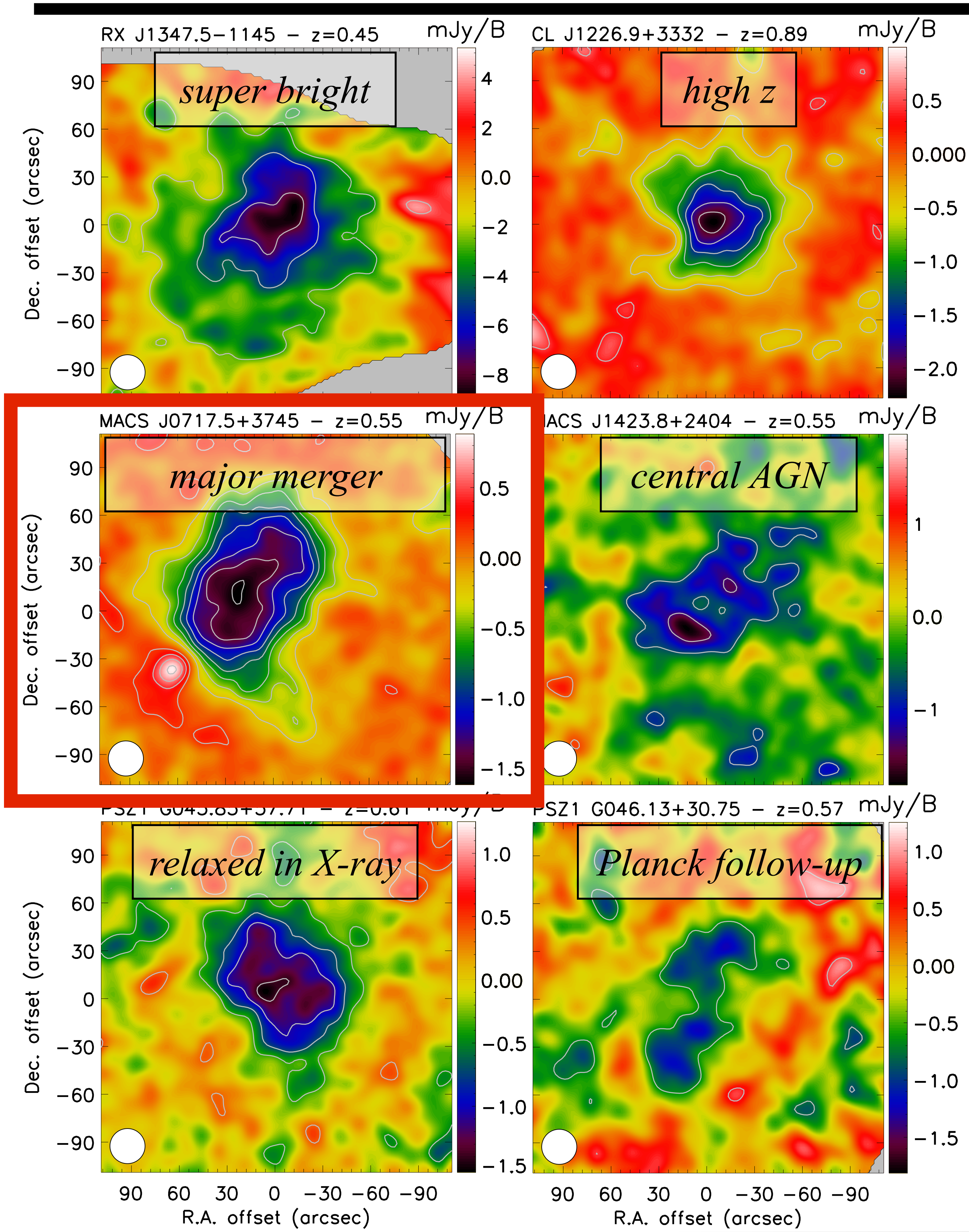

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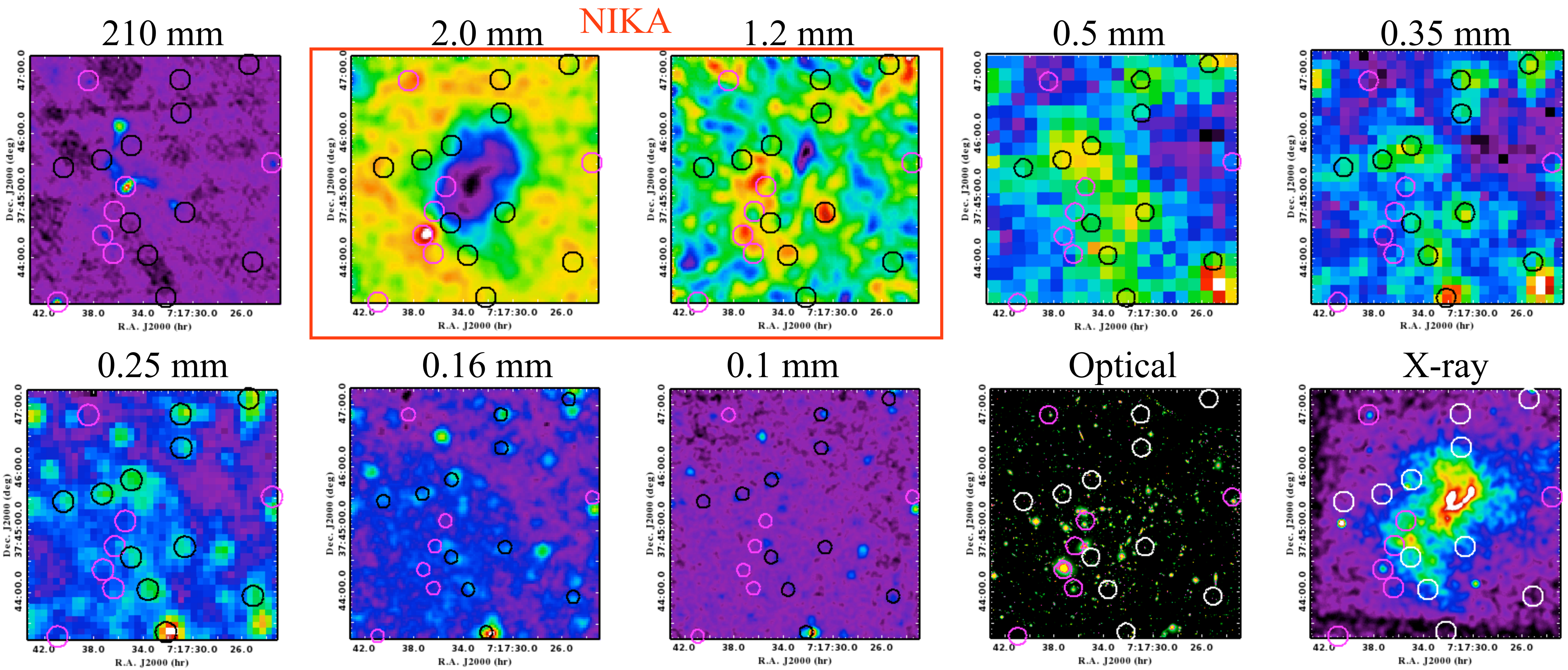
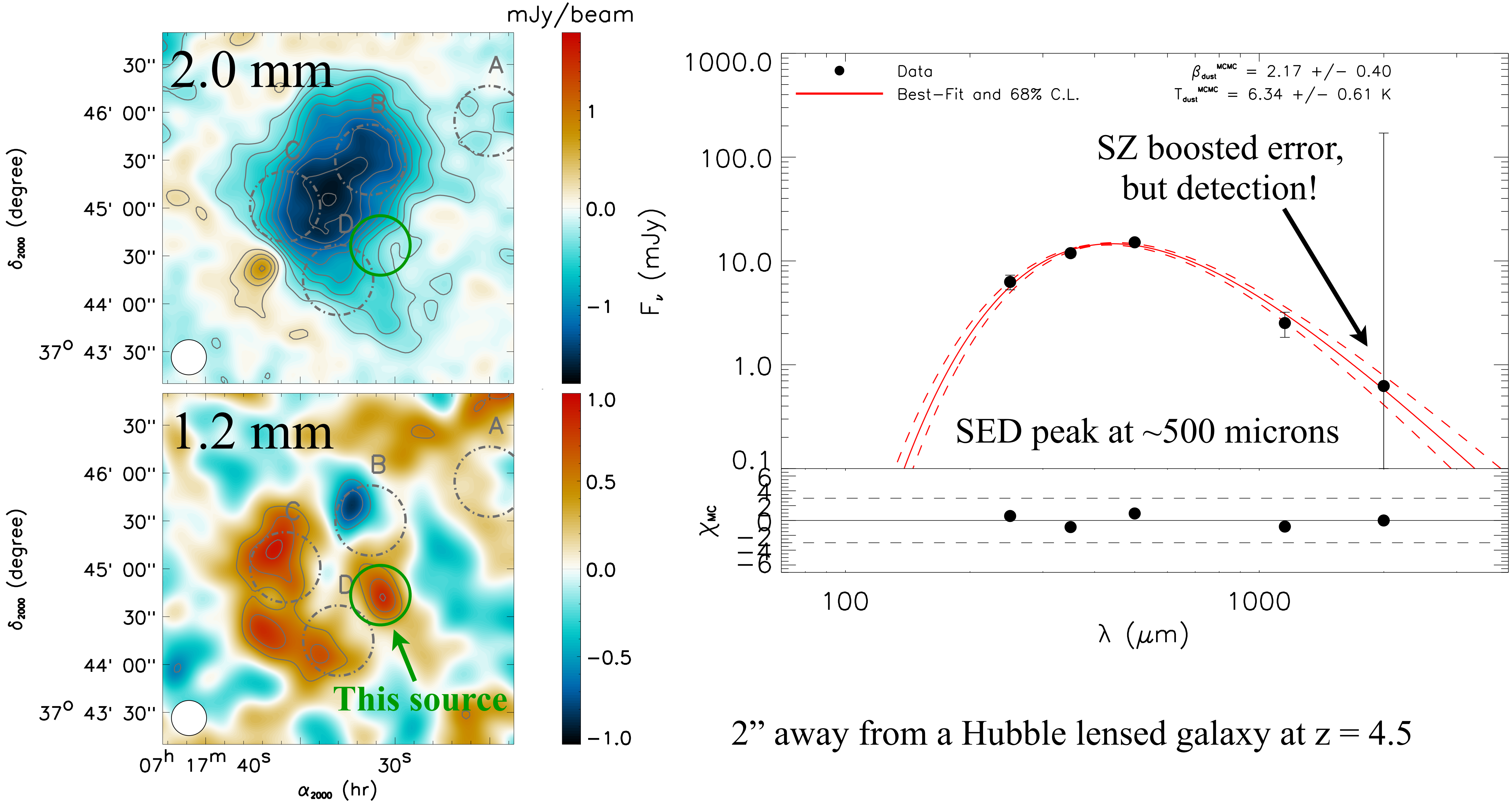
MACS J0717.5+3745 from radio to X-ray: removing the “contaminants”



- Radio emission (litterature + FIRST & NVSS)
- IR emission (Herschel)

Cleaning with multi-wavelength SED modeling

MACS J0717.5+3745: Detection of a lensed galaxy at z ~ 4.5



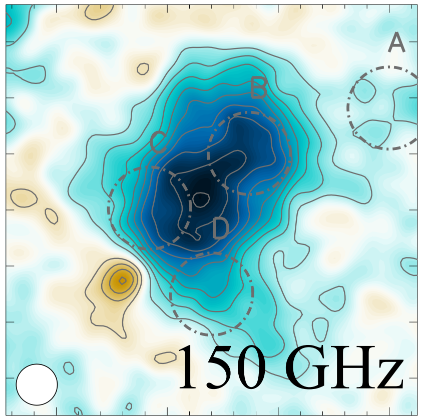
2" away from a Hubble lensed galaxy at z = 4.5

Follow-up proposed with NOEMA

Extracting the kinetic SZ signal

High sensitivity + high angular resolution
+ systematics removal required

➡ Very challenging to measure



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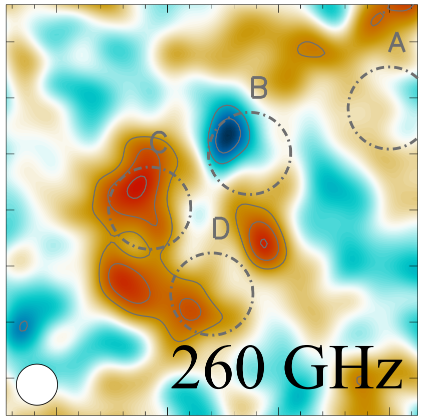
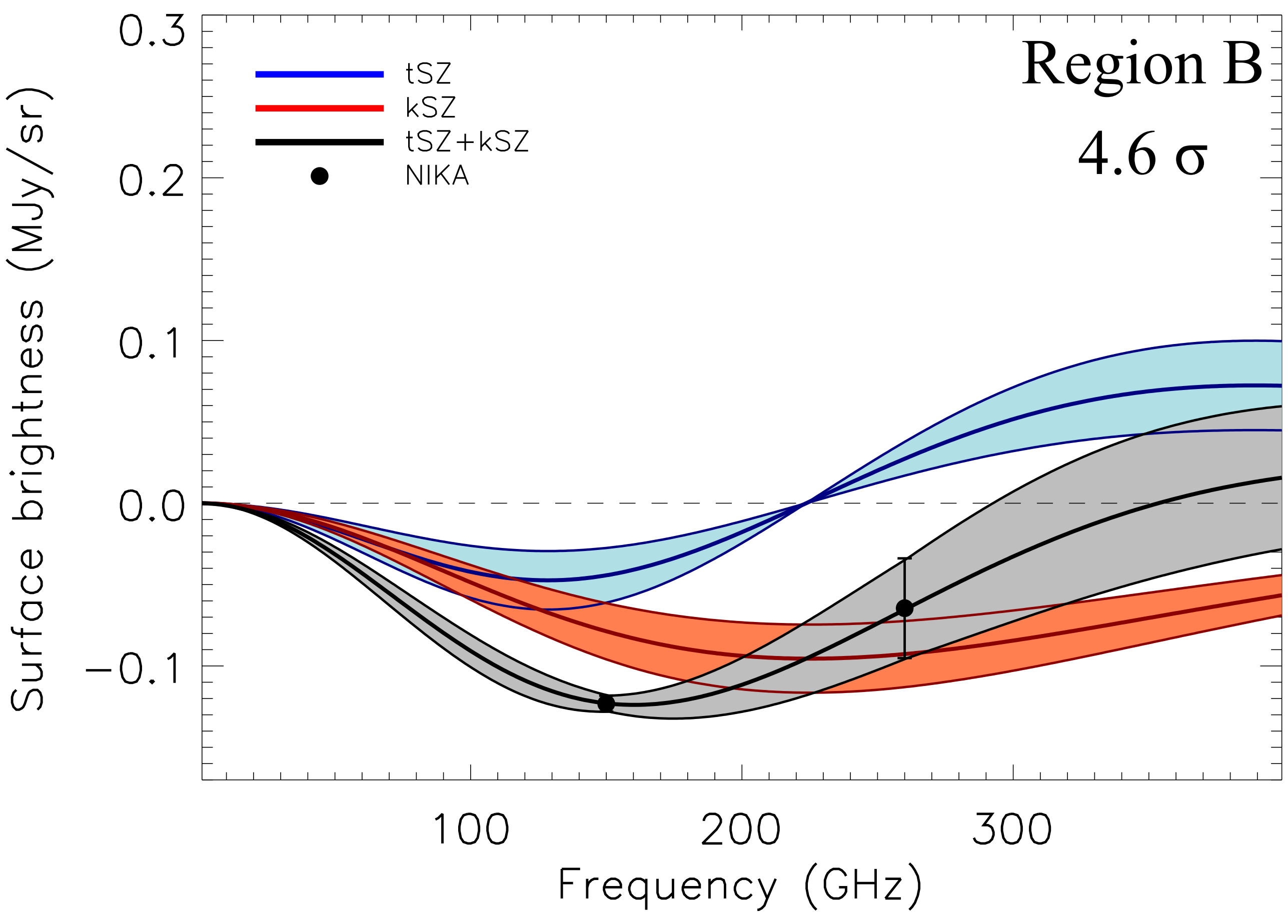


spectral dependencies

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

gas pressure *gas velocity and density*



➡ Separate kSZ and tSZ with 2 bands

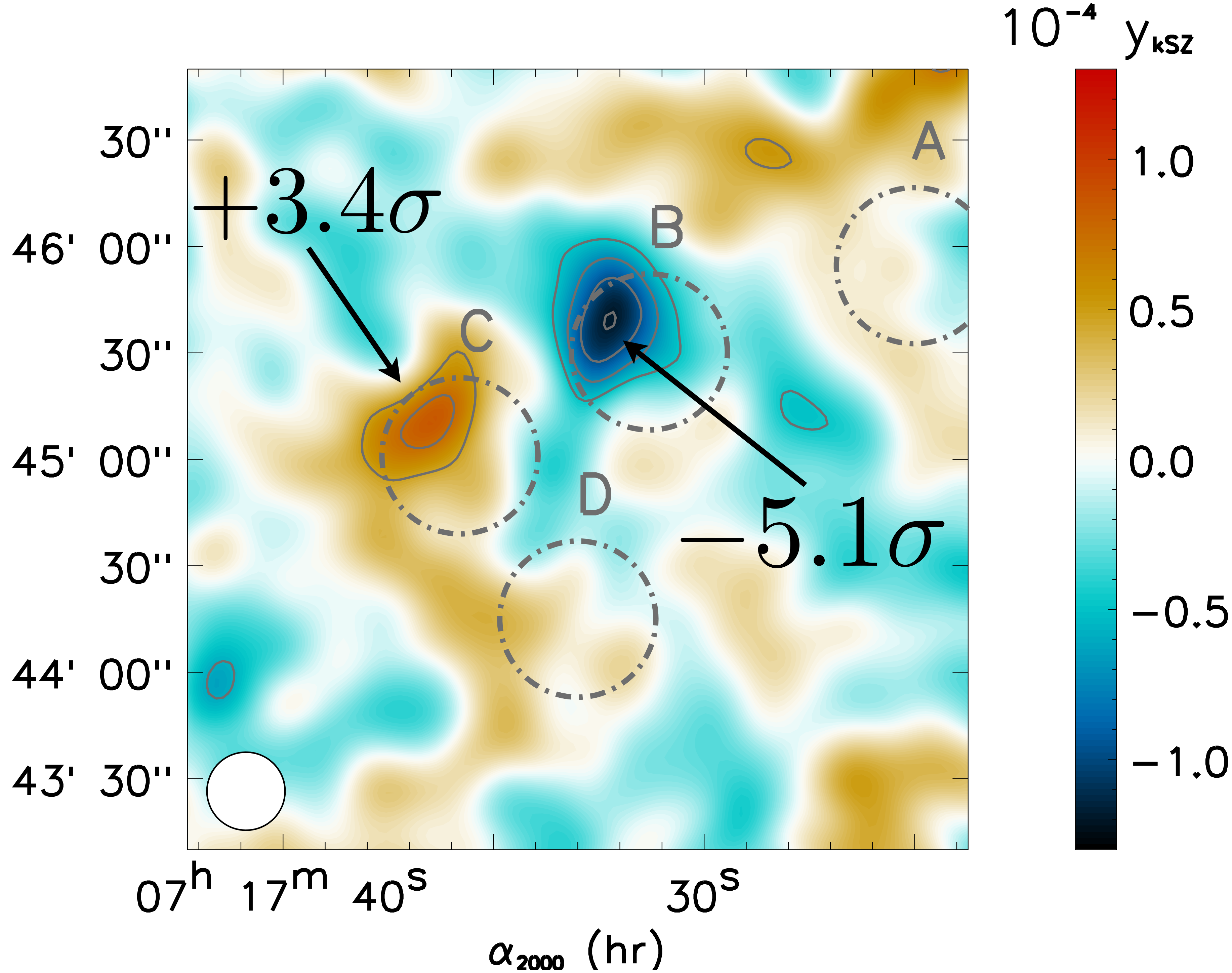
We detect kSZ signal !

Imaging the kinetic SZ effect: a first kSZ map

We also get a map of y_{tSZ} and y_{kSZ}

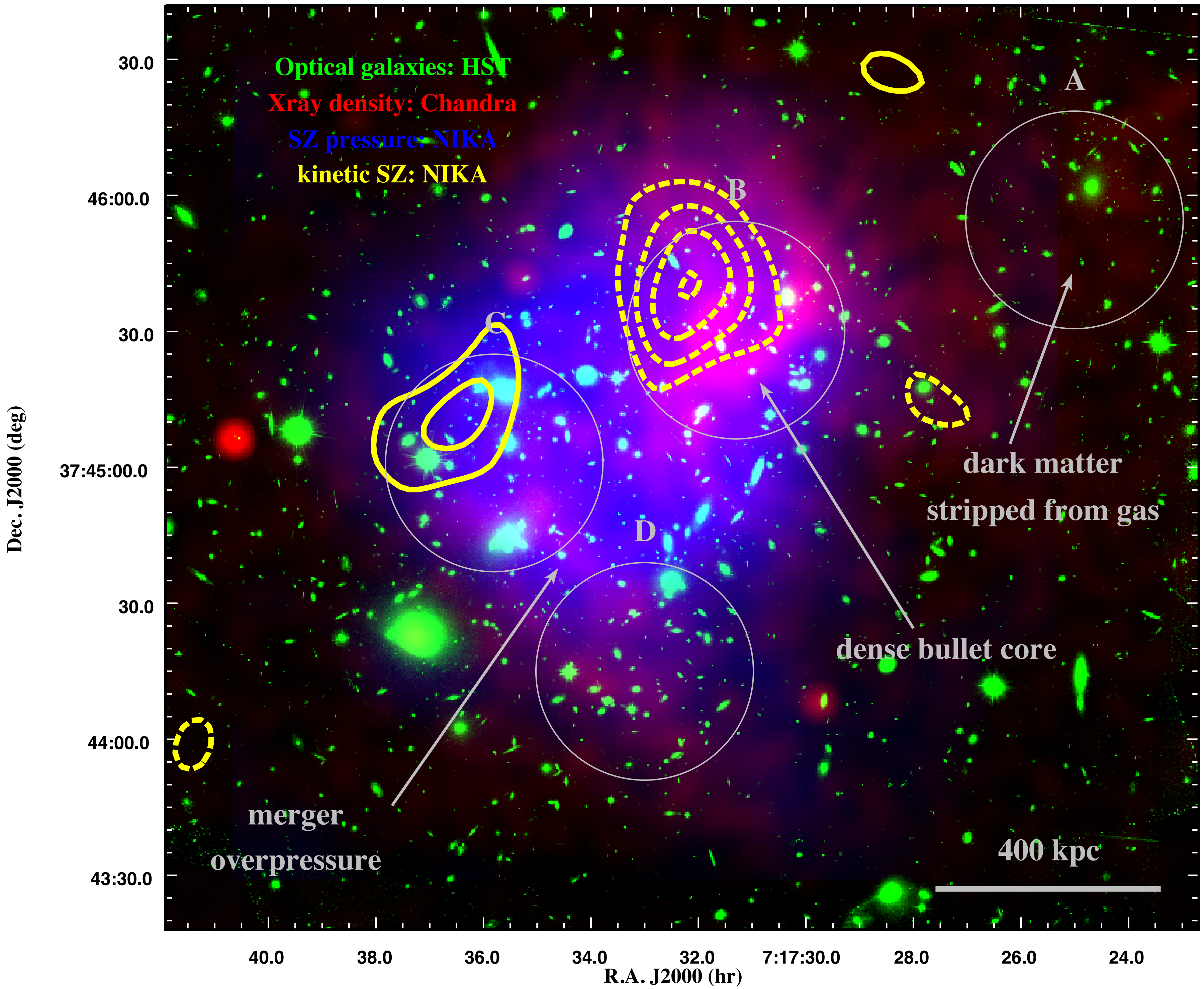
y_{kSZ} = velocity x density

- First detection by Bolocam *[Sayers et al. (2013)]*
- First imaging by NIKA *[Adam et al. (2017)]*



New window for cluster formation from kSZ mapping

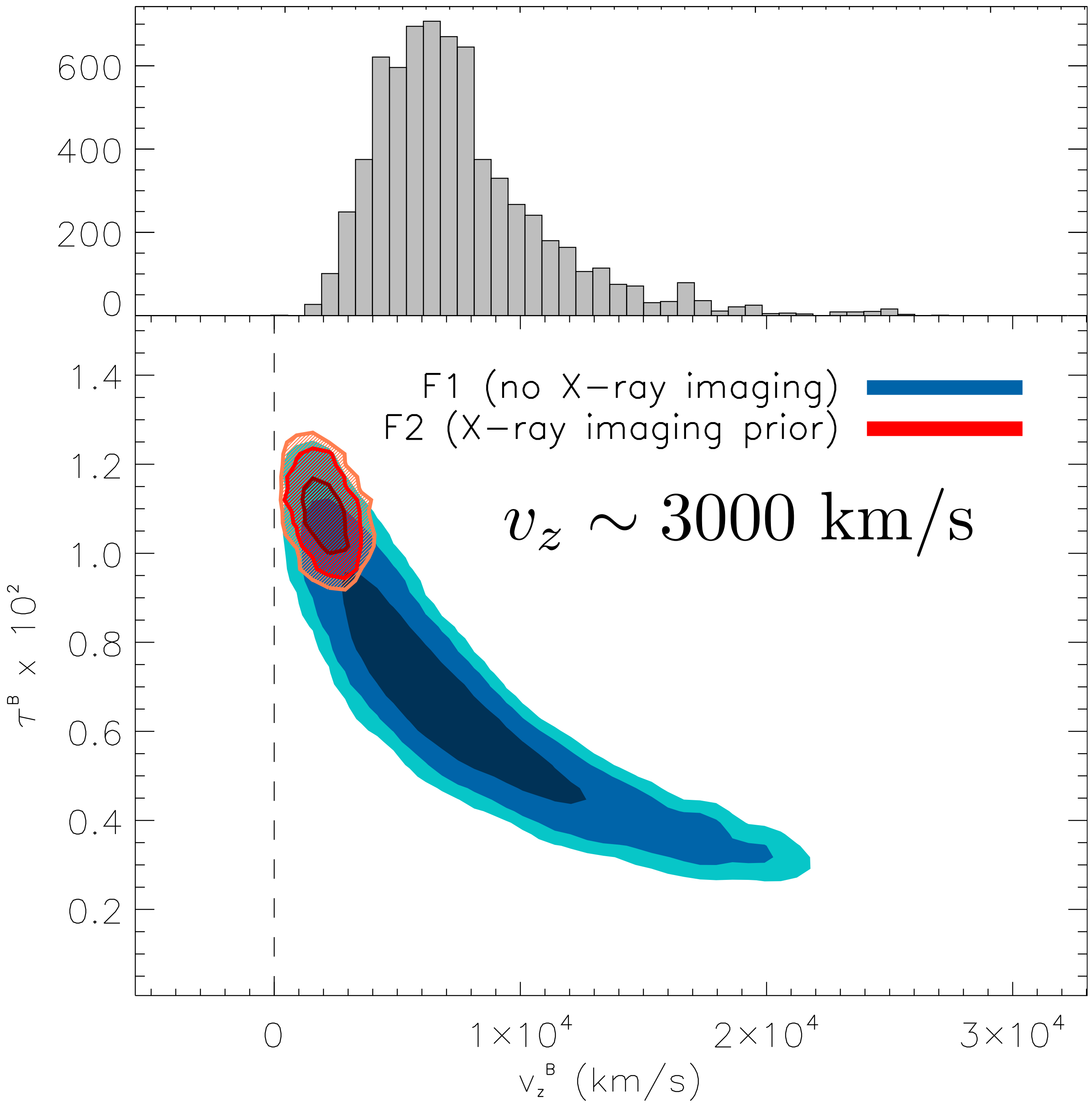
Comparison to multi-wavelength data



A complex structure associated to 2 main sub-clusters

Constraints on the gas line-of-sight velocity

E.g., group B



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

(velocity x density)

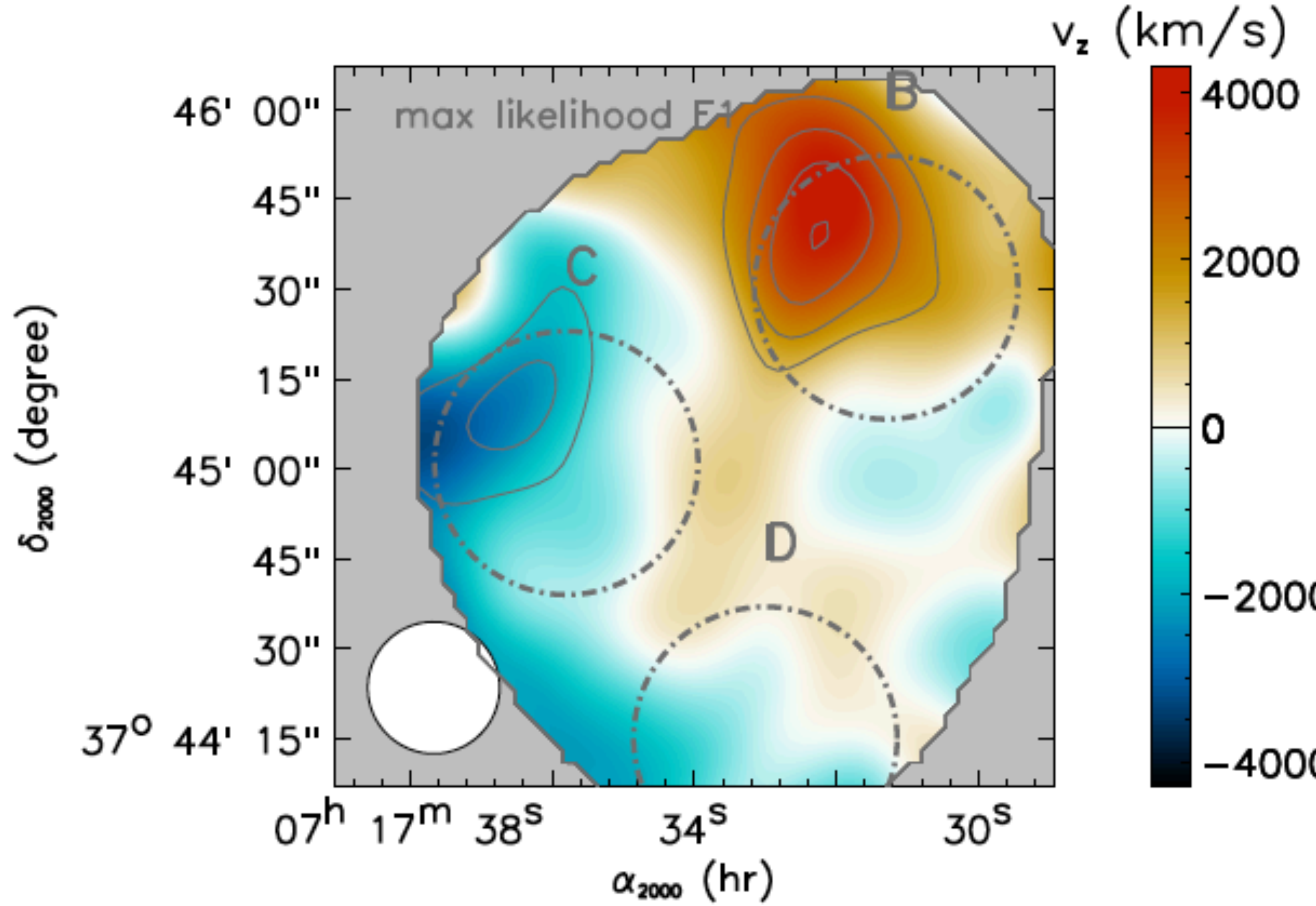
- Need an external gas constraint from X-ray (T_x)
- Fit for a density model

Exceptionally large v_z, but fine with ΛCDM

Mapping the gas line-of-sight velocity

The kSZ effect is the only known way to measure velocities at cosmological distances

➡ We get an absolute gas velocity map, relative to the CMB!



A new way to probe the assembly of distant clusters

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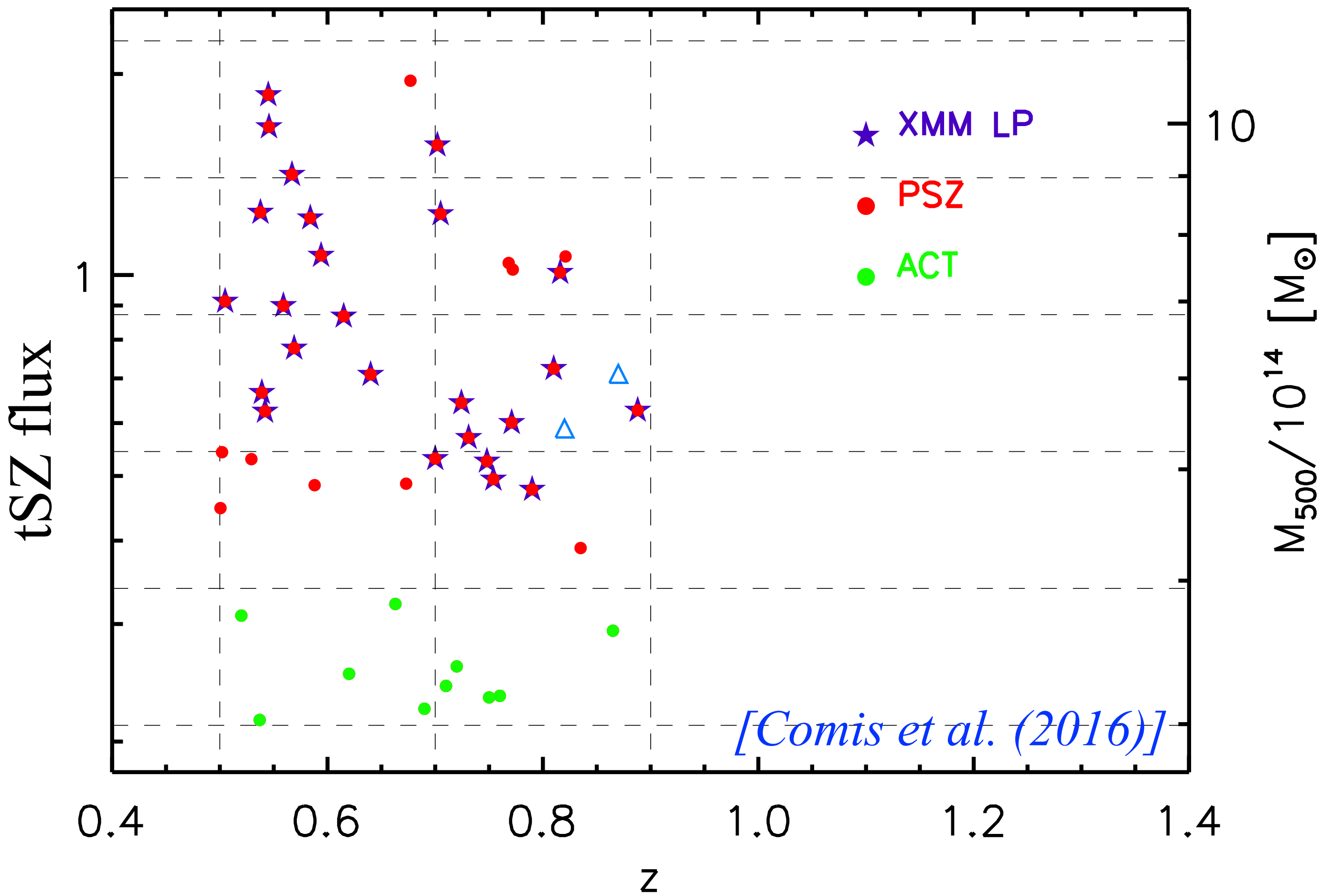
The NIKA2 SZ large program

SZ large program

- **300 hours** dedicated for SZ
- ~ **50 clusters** at **0.5 < z < 1**
- Planck/ACT clusters: **representativity**
- Combine NIKA with **Planck**, **X-ray, optical, radio, submm** and other datasets



Main goals

- Calibrating the **tSZ flux** as a **mass** proxy and its **evolution** with redshift
- Characterize the **structural properties** and clusters dynamical state
- kSZ imaging in individual clusters

NIKA2 perf. demonstrated, observations have started

Conclusions

The SZ effect in the Planck era

- The SZ effects are excellent astro. & cosmo. probes
- Planck/SPT/ACT have pushed the field to a new era
- Need high angular resolution follow-up: substructure, high z, kSZ

Status of SZ imaging

- Pathfinders such as NIKA have established great capabilities
- SZ imaging: test case demonstration and outstanding results

Next steps for SZ cluster cosmology

- Pathfinders studies to be applied on cosmological samples (e.g., NIKA2)
- Next generation CMB experiments in prep.: huge potential for kSZ

Next steps for cluster cosmology

- Large optical/NIR surveys should soon revolutionize cluster cosmology
- Robust mass determination to percent level, up to high z, will be crucial


Thanks!

Cosmology with cluster count

Observations
(survey, e.g. Planck, LSST, Euclid)

Halo mass function and
volume elements from theory

$$\frac{dN}{dz} = \int d\Omega \int \hat{\chi}(z, M, \vec{n}) \frac{dN}{dz dM d\Omega} dM$$

Survey selection function (purity/completness):
➡ control systematics in detection
(e.g. signal shape versus redshift)

Mass observable relation:
➡ control systematics in sample mass determination

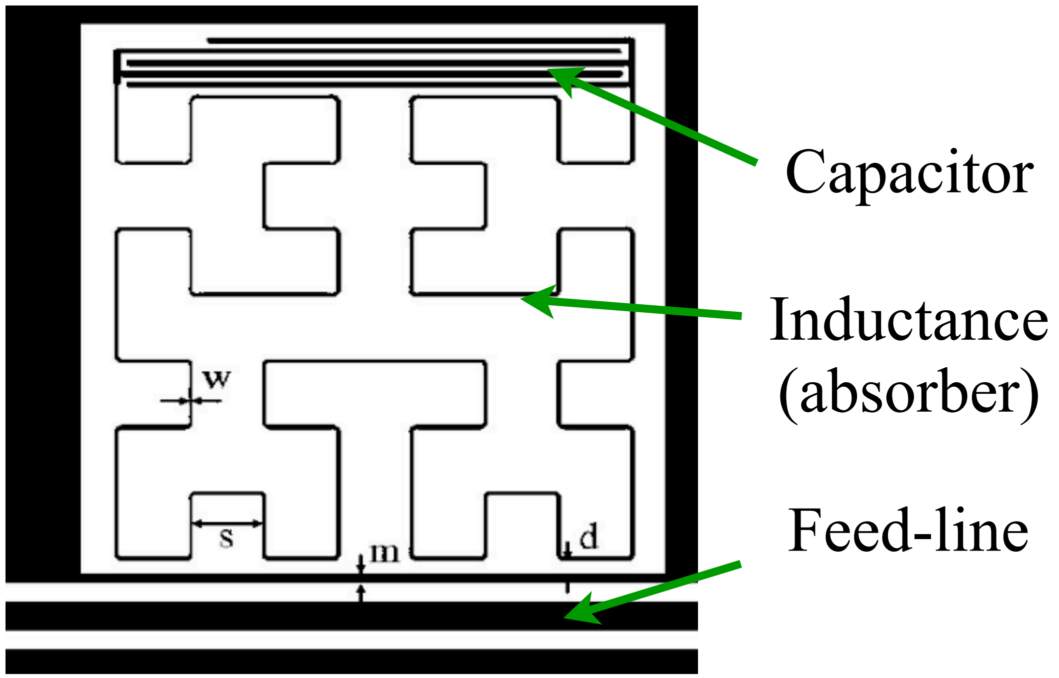
➡ Robust cosmological parameters estimation requires control on cluster physics

NIKA2: kinetic inductance detectors (KID) development

- KID = superconducting LC resonator
- Absorbed photons change the kinetic inductance by breaking Cooper pairs

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

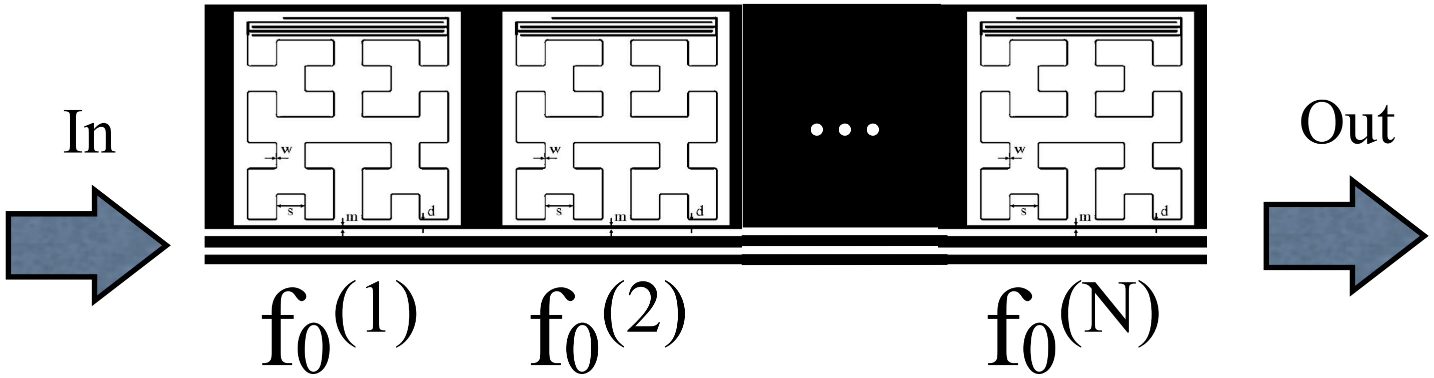
[Monfardini et al. (2013)]



☑ KIDs linearity checked in laboratory
[Calvo et al. (2013)]

☑ Up to N=400 tones per electronic box
[Bourrion et al. (2012)]

☑ Detector cross-talk limited



KIDs are competitive detectors

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

Sub-structures detections in high redshift SZ imaging