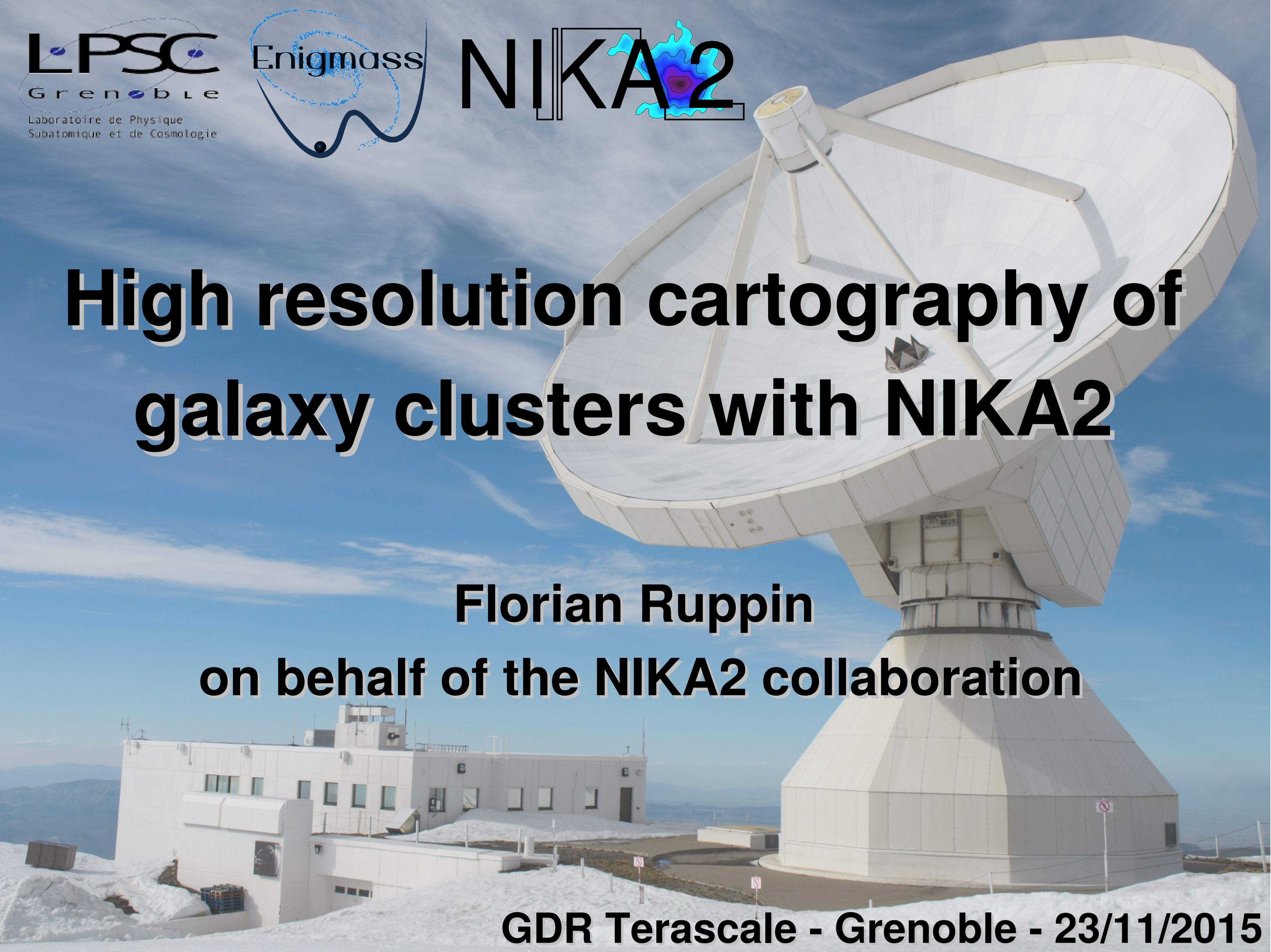


High resolution cartography of galaxy clusters with NIKA2

Florian Ruppin
on behalf of the NIKA2 collaboration

GDR Terascale - Grenoble - 23/11/2015

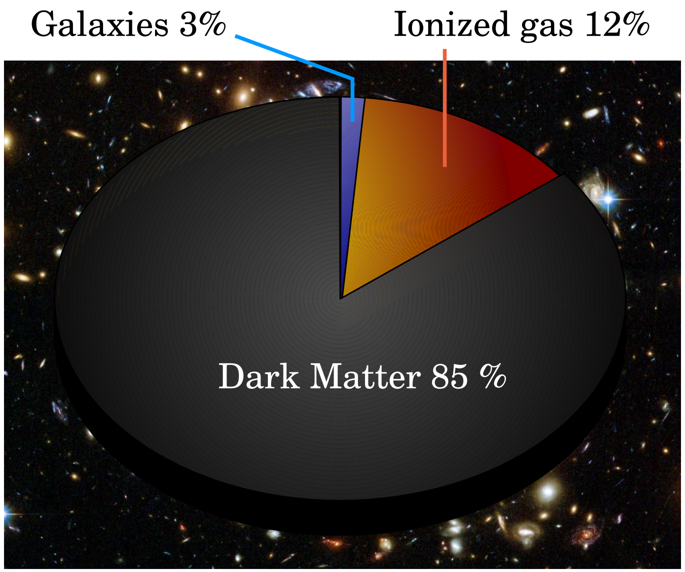
NIKA2

This work has been done in collaboration with:

R. Adam, M. Arnaud, B. Comis, J-F. Macias-Perez, F. Mayet, L. Perotto, E. Pointecouteau, G. Pratt

Contents

Generalities on galaxy clusters



- **Galaxy clusters:**
  - largest gravitationally bound objects in the Universe
  - dark matter dominated
  - Intracluster medium (ICM): baryonic matter content dominated by ionized gas

$$M \sim 10^{14} - 10^{15}\ M_{\odot}$$
$$z \in [0.004 - 2.07]$$

- Powerful probe for cosmology and dark matter study

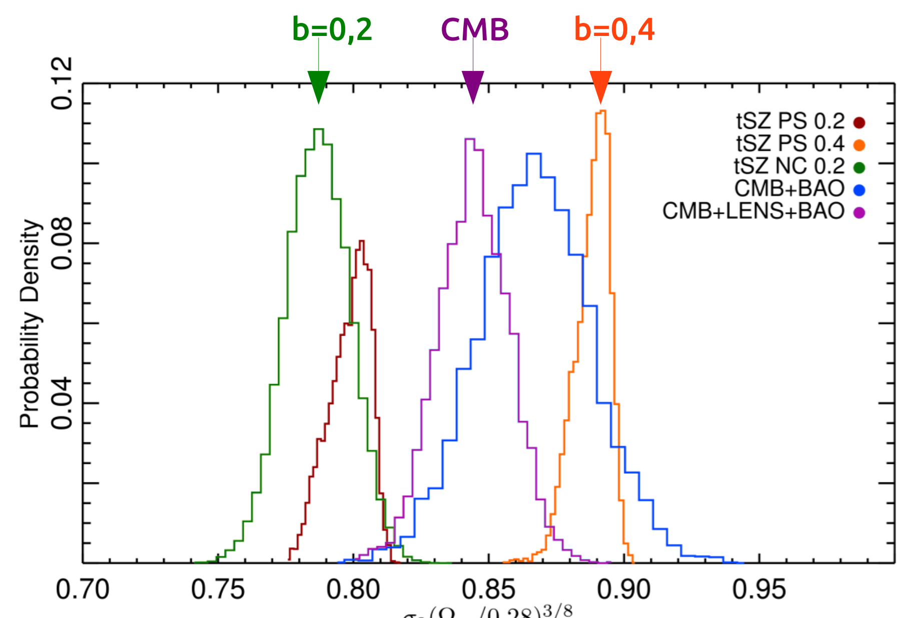
- **Constraints on $\Omega_{\rm b}$ and $\Omega_{\rm CDM}$**

  If baryonic mass fraction in galaxy clusters representative of the matter content in the universe

- **Tensions between CMB and galaxy cluster cosmological parameters estimations**

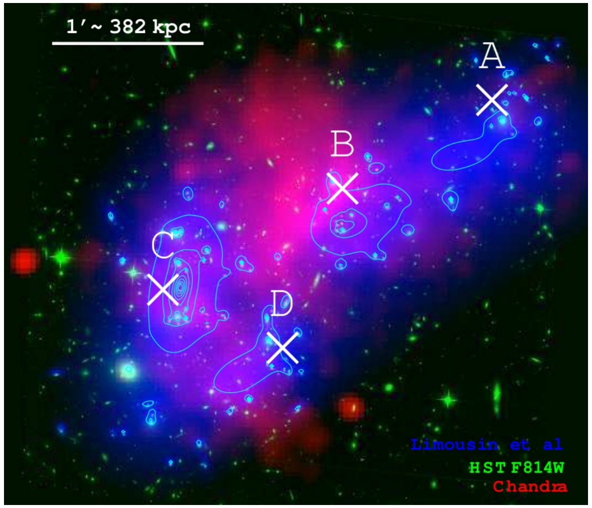
$$M_{tot} = (1-b)M_{HSE}$$

→ Must characterize precisely the hydrostatic bias



Planck 2015 results. XXII. (2015)

Dark matter constraints from clusters

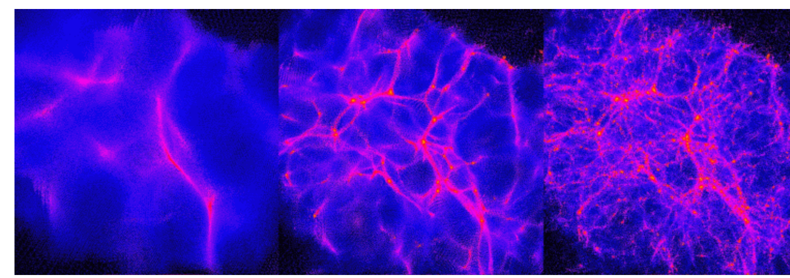


MACSJ0717.5+3745
Credit: J. Sayers

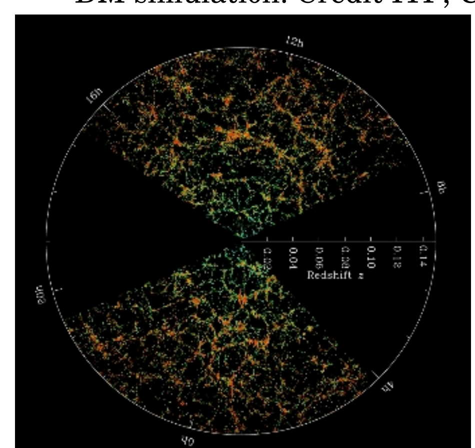
1E 0657-558 (Bullet Cluster)
M. Markevitch et al., D. Clowe et al.

- Observations of shifts between baryonic matter and DM in highly disturbed systems
- Identification of DM structures

Hot DM **Warm DM** **Cold DM**



DM simulation: Credit ITP, University of Zurich



Observations: Credit: M. Blanton & SDSS Collaboration

➡ Constraints on the DM halo astrophysics

- **Need high resolution cartography**

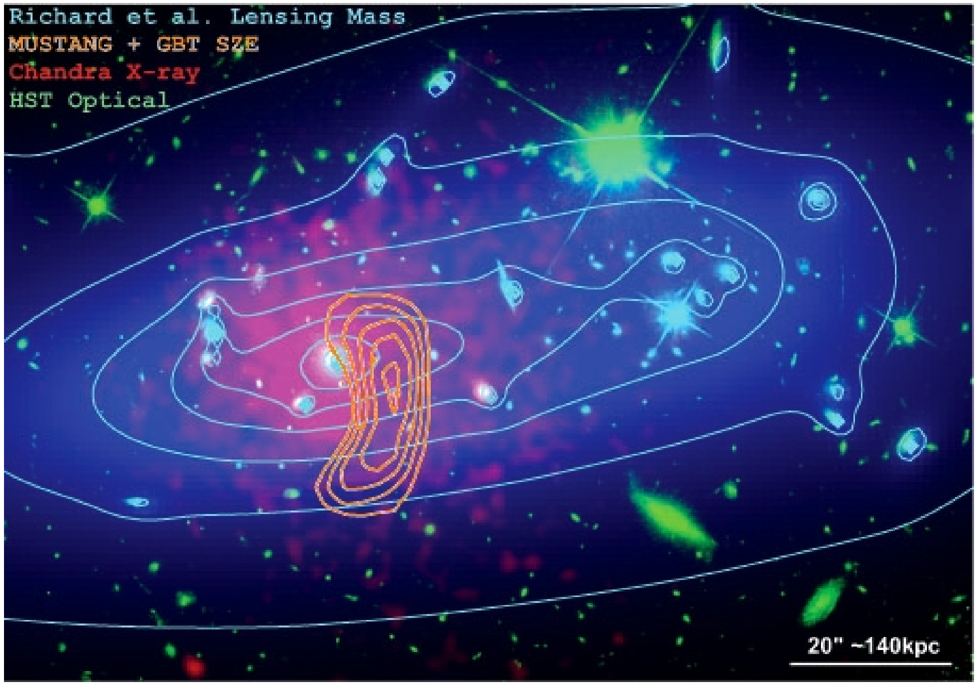
- Comparison between the observed halo number density as a function of redshift and outputs from N-body simulations

➡ Constraints on the DM particle mass range

- **Need observations in a wide redshift range**

Multi-probe analysis of clusters

- **Optical:**
  - Stellar emission of light
  - Spatial distribution of galaxies
    → Dynamical state of the cluster
  - Richness (number of galaxies) and galaxy velocity distribution
    → Estimation of the total mass



Composite image of MACS0744
Credit: Phil Korngut and Brian Mason

- **X-ray:**
  - Bremsstrahlung radiation from electrons of the ICM
    → tracer of the electronic gas density

  ICM temperature from spectroscopy → time consuming

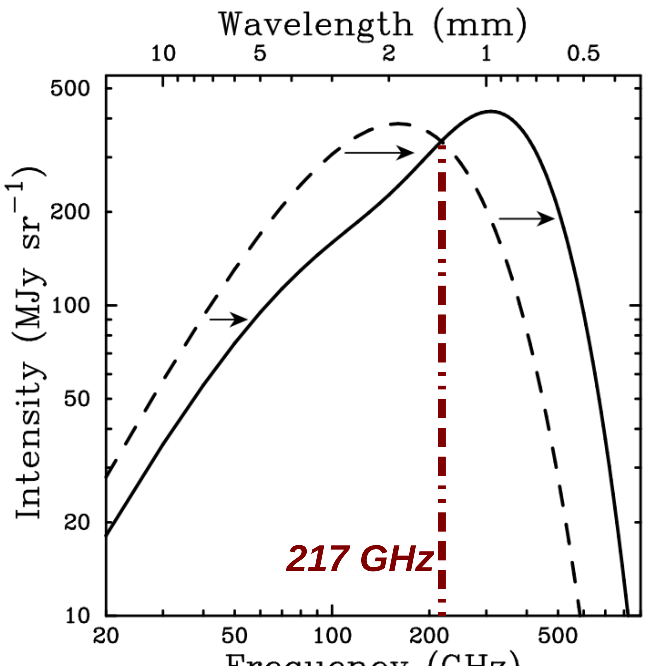
$$S_X \propto \frac{1}{(1+z)^4} \int n_e^2 \Lambda dl$$

- **Lensing:**

  Strong: surface mass distribution in the central regions

  Weak (small background galaxies distortion): total mass distribution around the cluster

The Sunyaev - Zel'dovich effect



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

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

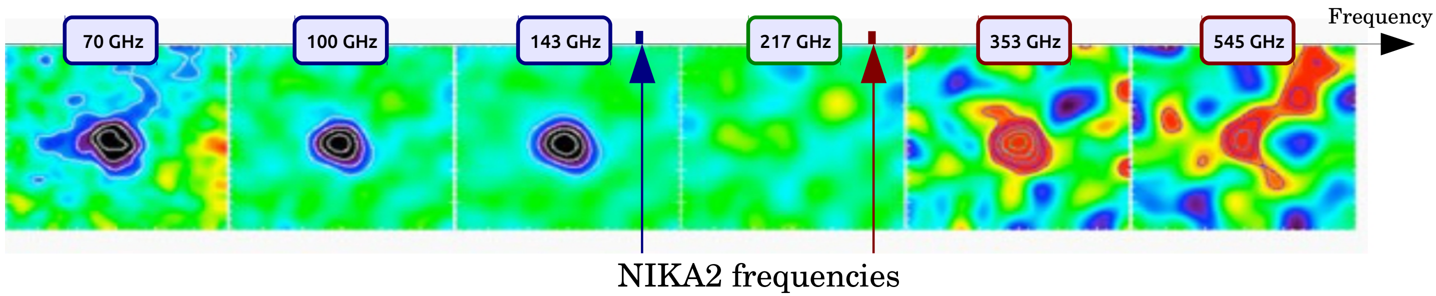
  Inverse Compton scattering of CMB photons on hot ICM electrons

  → CMB photons acquire energy

- Spectral distortion of the CMB

  → SZ effect is redshift independent

A 2319 (Planck)



- SZ effect amplitude given by the Compton parameter:

$$y \propto \int P_e dl$$ → Characterize the electron pressure within the ICM

- Study of the ICM via its effect on the CMB

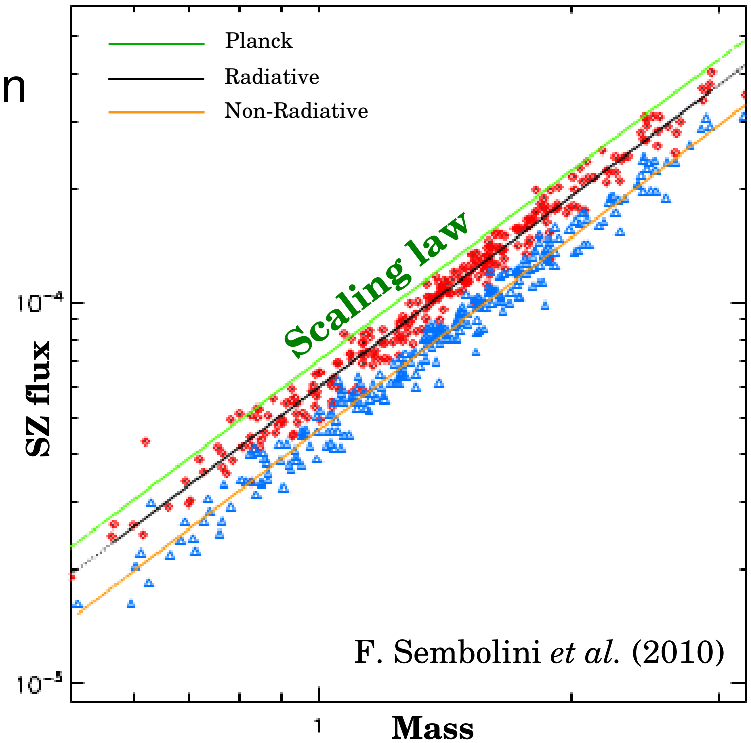
The Sunyaev - Zel'dovich effect

- Integrated Compton parameter ⇢ Thermal pressure ⇢ Hydrostatic mass

- Total mass estimation requires hypothesis:
  - Hydrostatic equilibrium
  - Dynamics dominated by gravitational processes

⇢ Bias and scatter on the **SZ flux – total mass** relation

Planck Vs MUSIC simulations

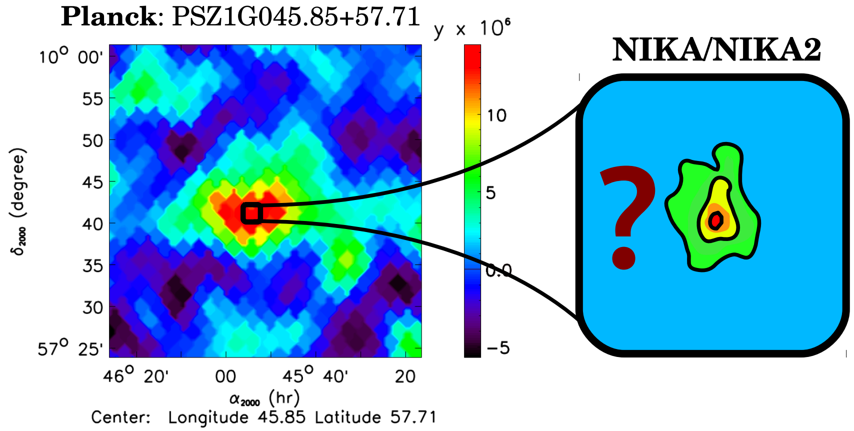


- Complementarity between SZ, X-ray, optical / lensing → fully characterize the ICM

- Need high resolution cartography to map precisely the ICM structures especially at high redshift

The NIKA2 camera and its prototype

- Planck : catalog of ~2000 galaxy clusters identified by their SZ signal



- IRAM 30-meter telescope (Pico Veleta, Spain)

→ Resolution of ~15 arcsec

30 times better than Planck resolution (~10 arcmin)

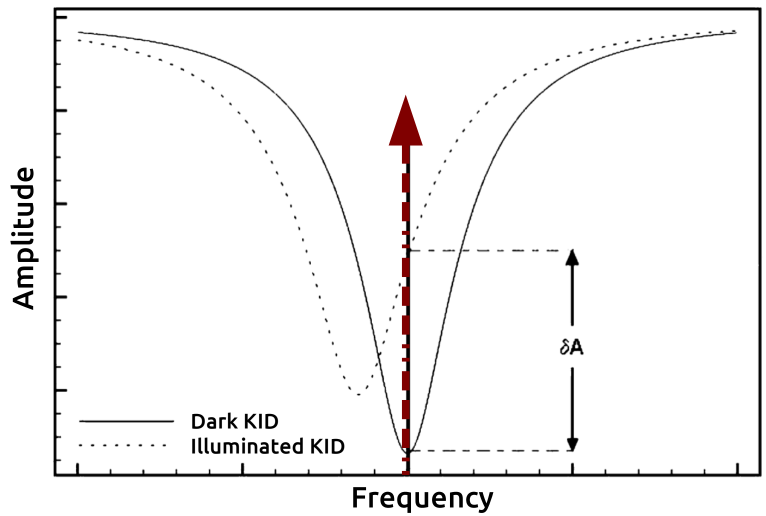
- NIKA (prototype): 300 pixel camera
  1.5 arcmin field of view
- NIKA2 (final instrument): 3500 pixel camera
  6.5 arcmin field of view

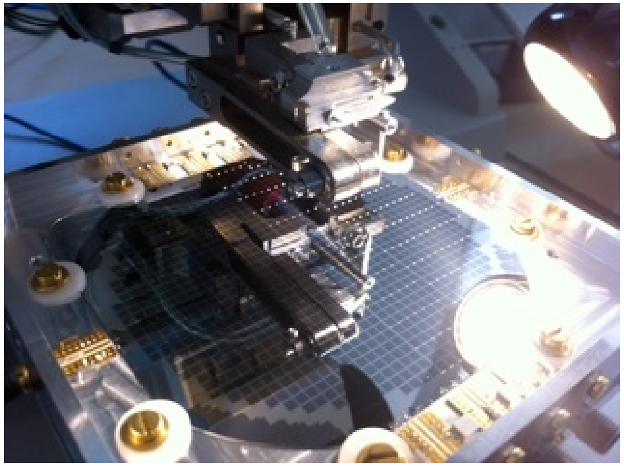
- Dual band instrument:
  - 150 GHz
  - 260 GHz

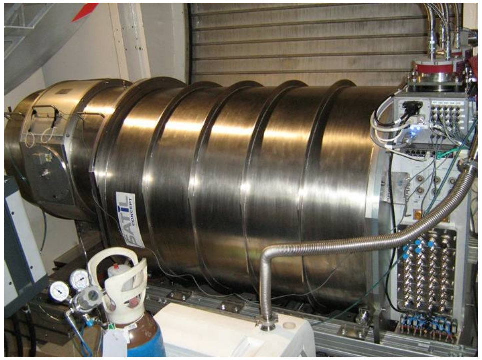
→ Ideal for the SZ effect

→ **SZ cartography of Planck discovered galaxy clusters**

The NIKA2 camera and its prototype







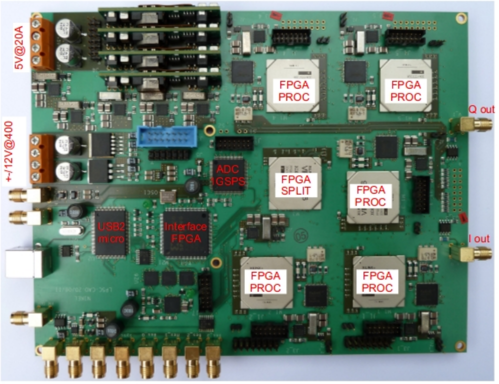
- Kinetic Inductance Detectors (KIDs):
  High quality factor superconducting resonators

- Resonance frequency shift proportional to the incoming optical power

- Need to cool down the resonators below their critical temperature

$\Rightarrow T \sim 100 \text{ mK} \ll T_c \simeq 1.2 \text{ K}$

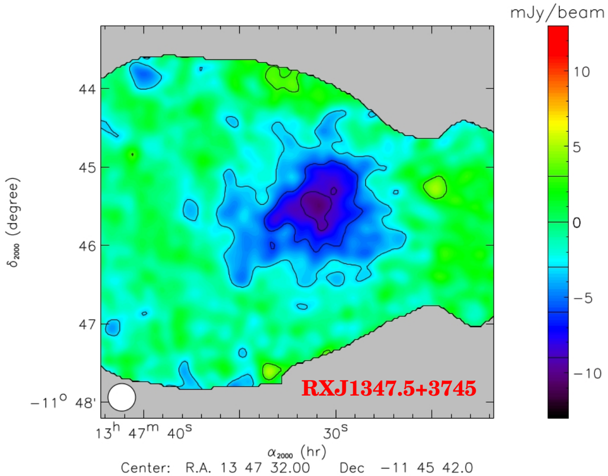
- KIDs frequency shifts measured at a given acquisition frequency by dedicated fast electronics



Bourrion *et al.* Journ. of Instr. (2012)

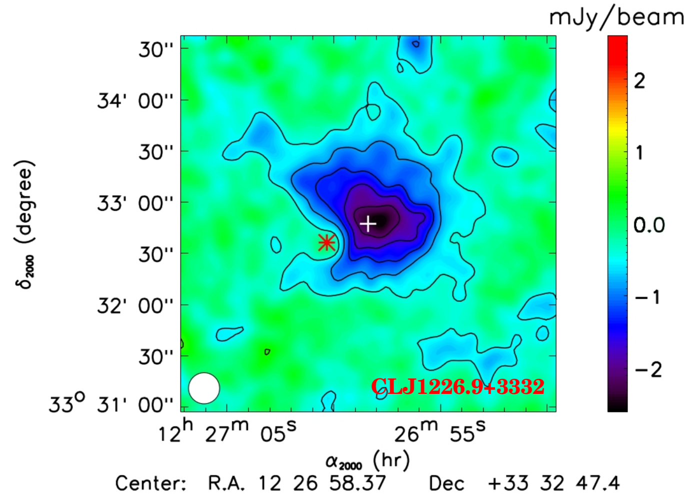
Results from the NIKA prototype

Well know on-going merger



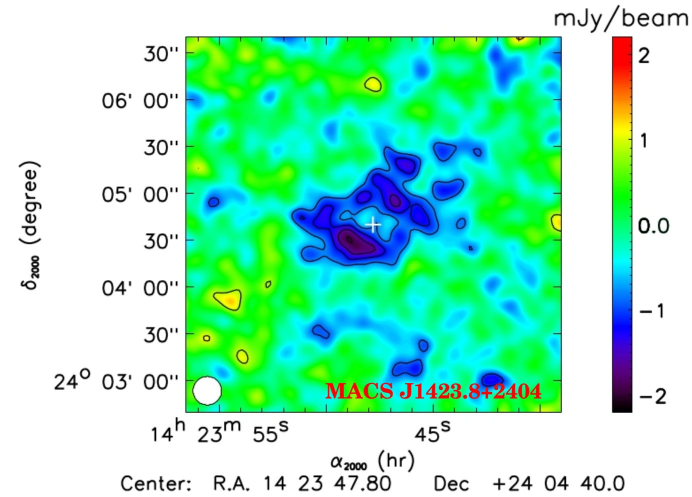
Adam *et al.* A&A (2014)

High redshift cluster (z=0.89)



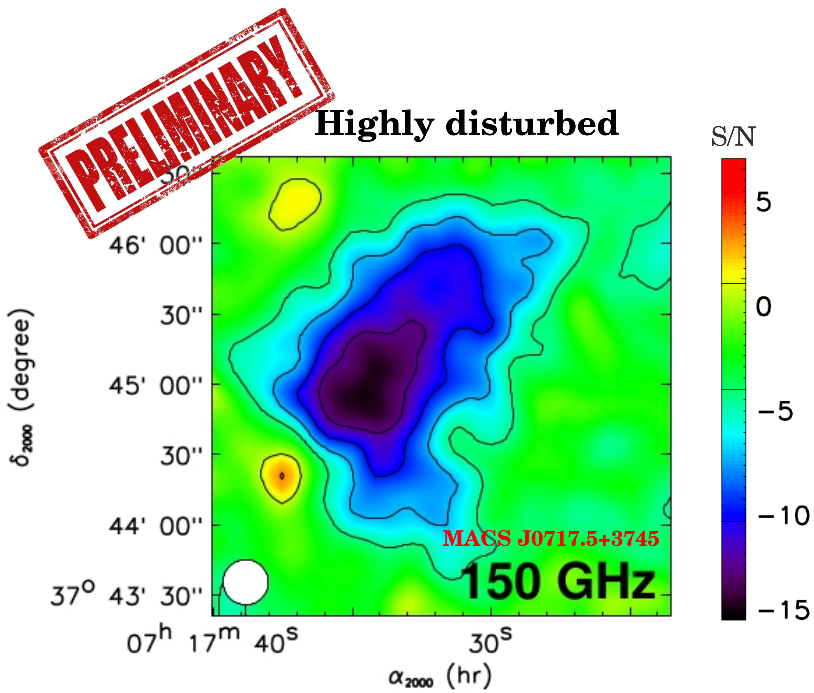
Adam *et al.* A&A (2015)

Point source contamination

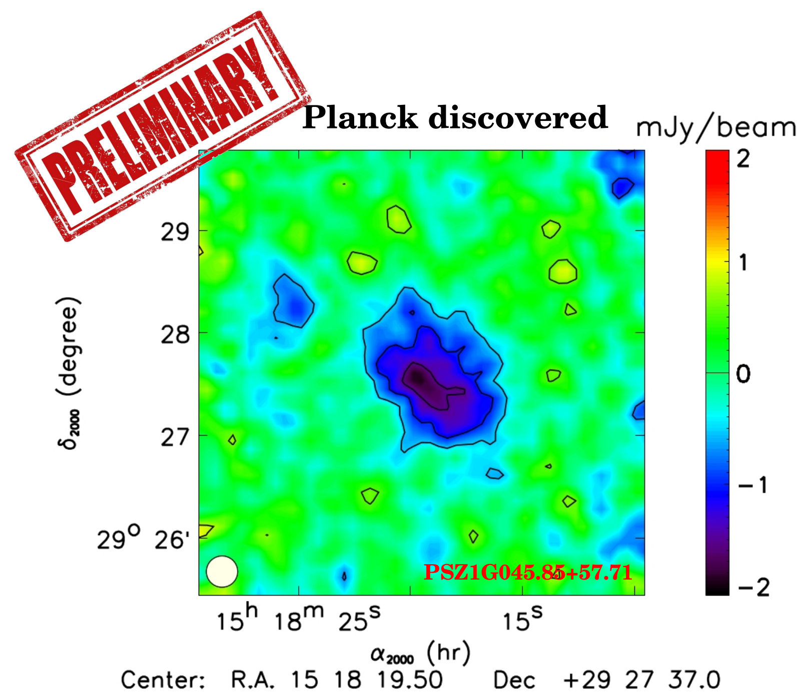


Adam *et al.* arXiv (2015)

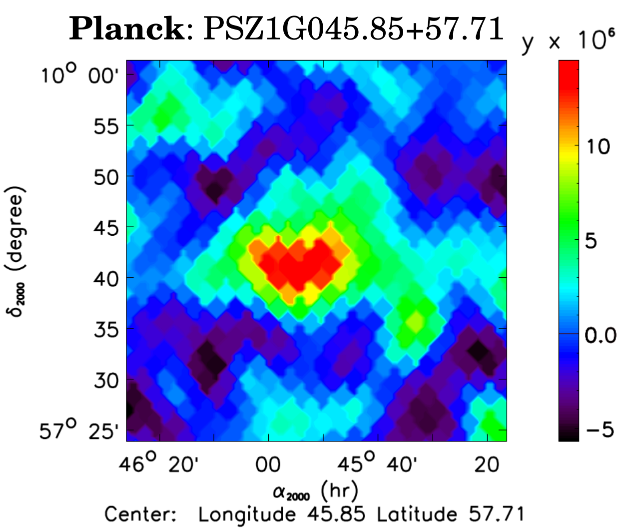
Highly disturbed

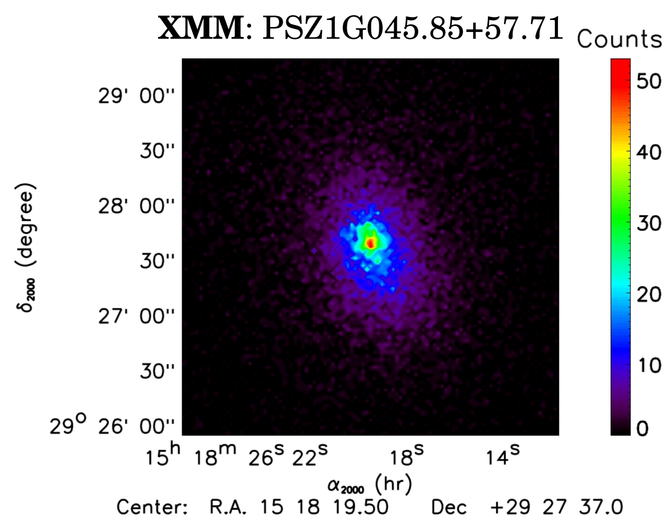


Planck discovered



Follow-up of a Planck-discovered cluster





- Planck-discovered cluster

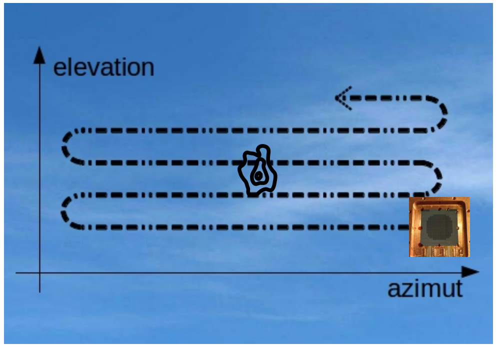
  ➡ Low angular resolution

- Redshift: 0.61
- Cluster already observed by XMM (2012)

  PI : M. Arnaud

- NIKA observation of PSZ1G045.85+57.71 in November 2014:

  - Scanning strategy: On The Fly



➡ Time Ordered Information

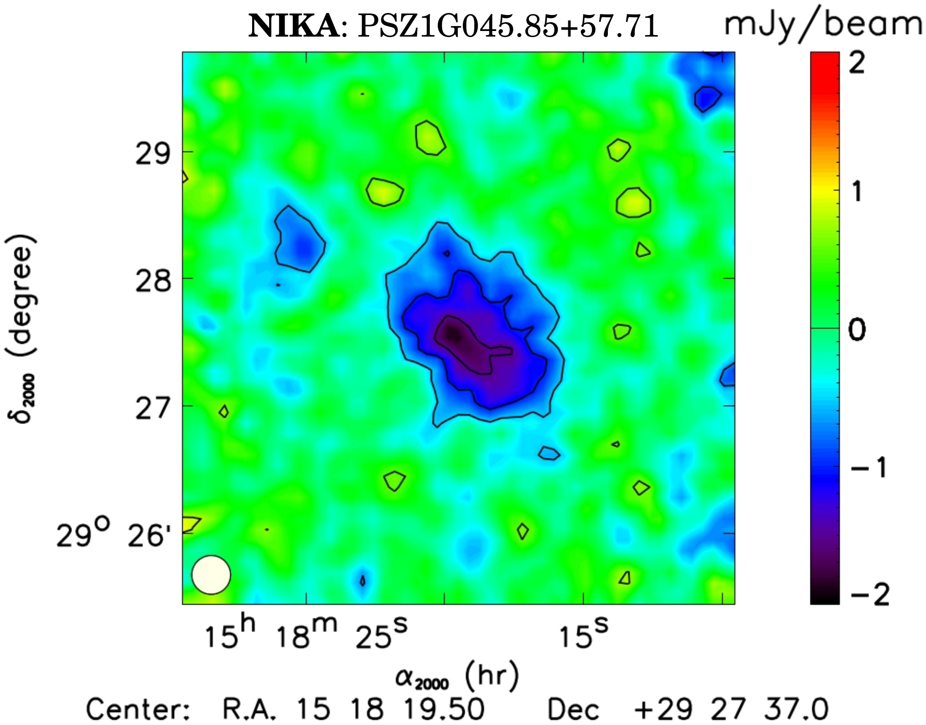
➡ Atmospheric noise subtraction

  - 5 h 45 min of observation
  - Mean opacities: 0,27 at 260 GHz
    0,21 at 150 GHz

    → Not too bad weather

  - Calibration uncertainties: 10,6 % at 260 GHz
    8,5 % at 150 GHz

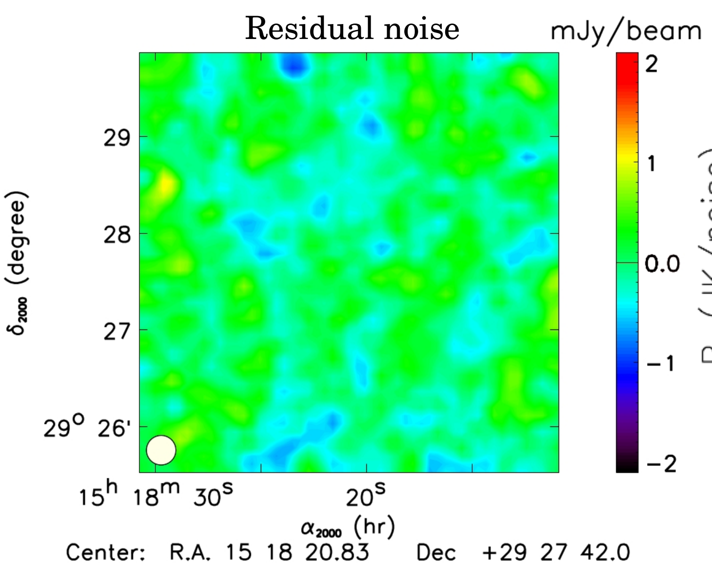
NIKA tSZ map of PSZ1G045.85+57.71

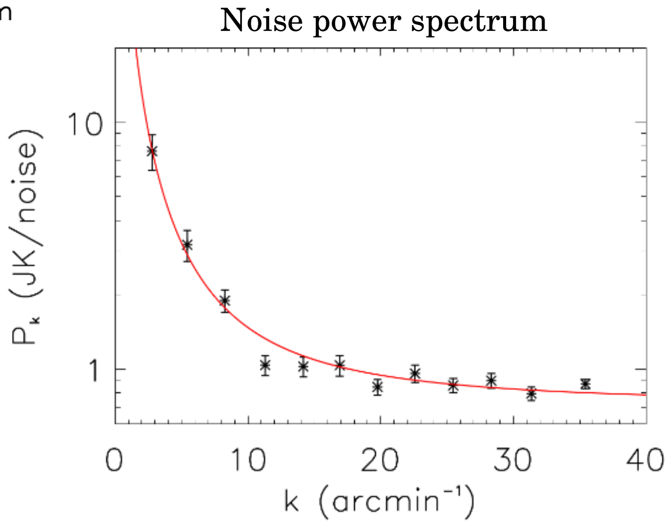


- Final SZ map computed by the coaddition of all the scans analyzed at 150 GHz
- Residual noise estimation by computing null maps:
  - semi-difference of the coadded maps from two subsamples

    → Residual noise power spectrum

    → Estimation of the noise covariance matrix





- S/N contours computation

SZ pic identified at 7 sigma

Modeling of the ICM thermodynamics

- **Multi-probe** analysis of the ICM:
  - NIKA SZ map
  - XMM data
  - Planck integrated Compton parameter

- **<u>Main goal</u>**: Characterize the ICM by estimating $P_e(r)$, $n_e(r)$, $T_e(r)$, $M_{HSE}(r)$

- **Physical model** of the cluster thermodynamics

Pressure: Generalized Navarro, Frenk and White model (gNFW) :

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

All the parameters are free except c (Planck)

Planck intermediate results V. A&A (2013)

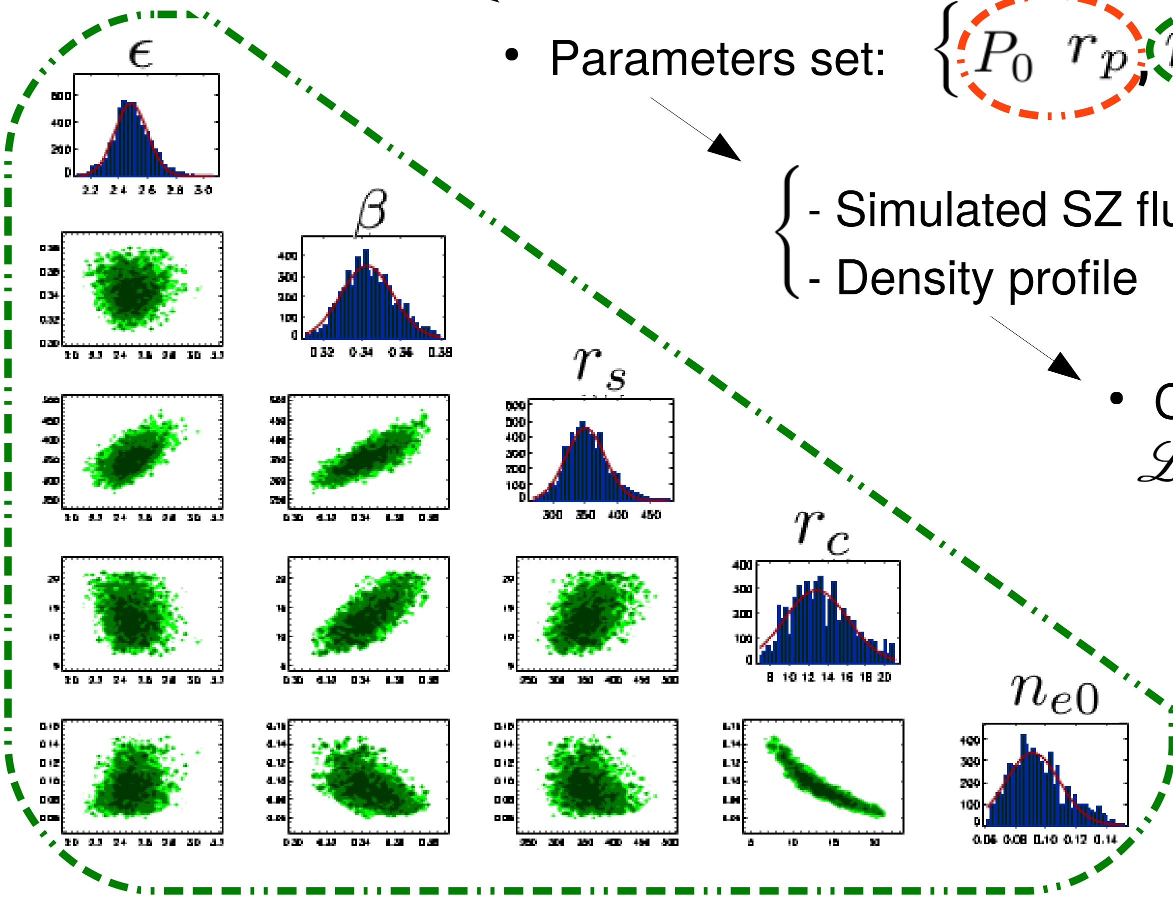
Density: Simplified Vikhlinin model (SVM) :

$$n_e(r) = n_{e0} \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2} \left[1 + \left(\frac{r}{r_s}\right)^\gamma\right]^{-\epsilon/2\gamma}$$

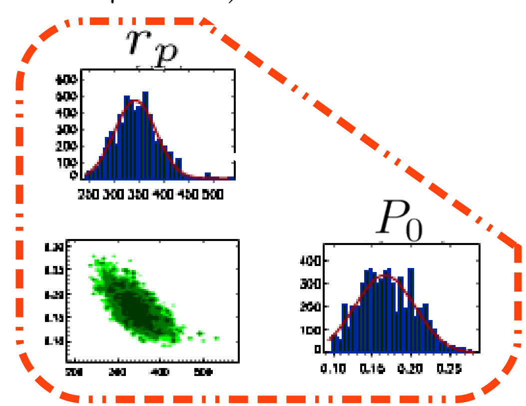
All the parameters are free except γ

Modeling of the ICM thermodynamics

- Markov Chain Monte Carlo analysis (MCMC)
- Metropolis-Hasting algorithm
- Efficient sampling of the parameter space
  - Parameters set: $\{P_0 \ r_p, n_{e0}, r_c, r_s, \beta, \epsilon\}$
    - Simulated SZ flux map
    - Density profile
      - Comparison with the data $\mathscr{L}(model|data)$



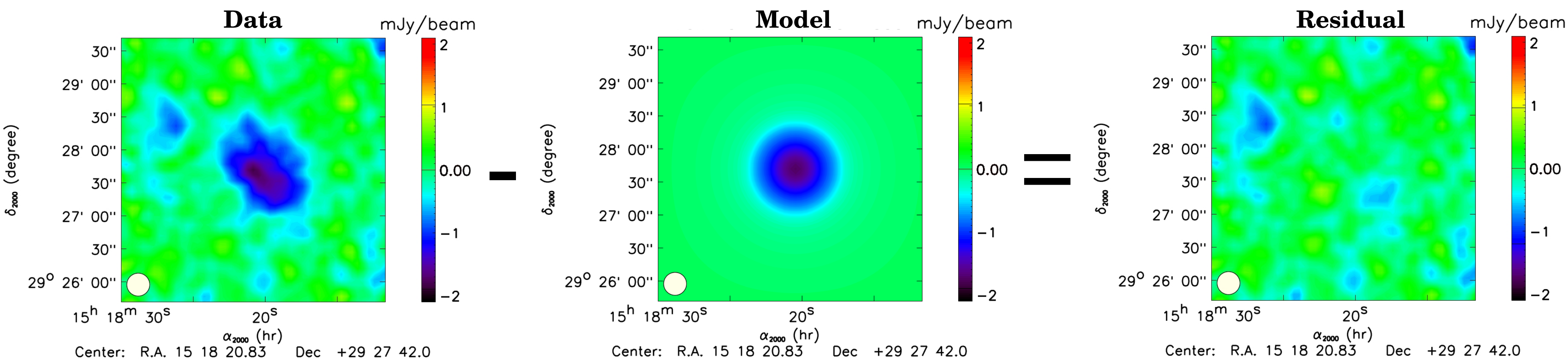
Density



Pressure

Modeling of the ICM thermodynamics

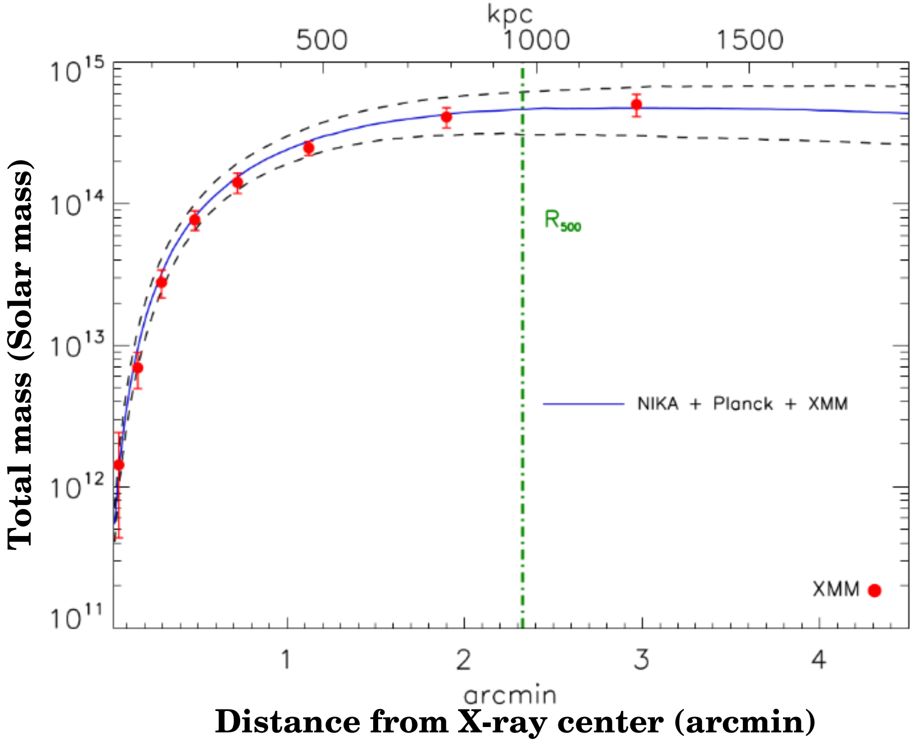
- **Maximum likelihood:** pressure model ➤ SZ brightness map model



- No apparent substructure in the residual
- Deviations from sphericity are consistent with residual noise
- Reduced χ^2 is good

➤ PSZ1G045 well described by a spherical model

Mass and dark matter fraction profiles



- Hydrostatic equilibrium
  → mass profile:

$$M_{HSE}(r) \propto -r^2 \frac{1}{n_e(r)} \frac{dP_e(r)}{dr}$$

- Characteristic radius:

$$R_{500} = (956 \pm 62)\ \text{kpc}$$

- Integrated hydrostatic mass:

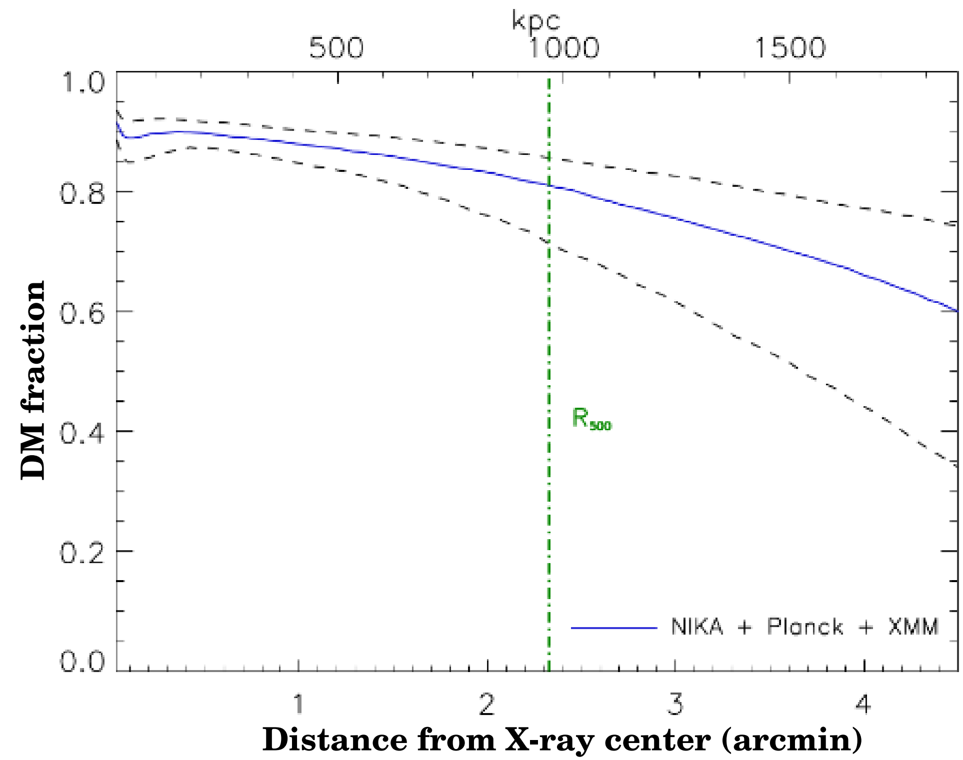
$$M_{HSE,500} = 4,61^{+0,96}_{-0,84} \times 10^{14}\ \mathrm{M}_\odot$$

- Integrated Compton parameter:

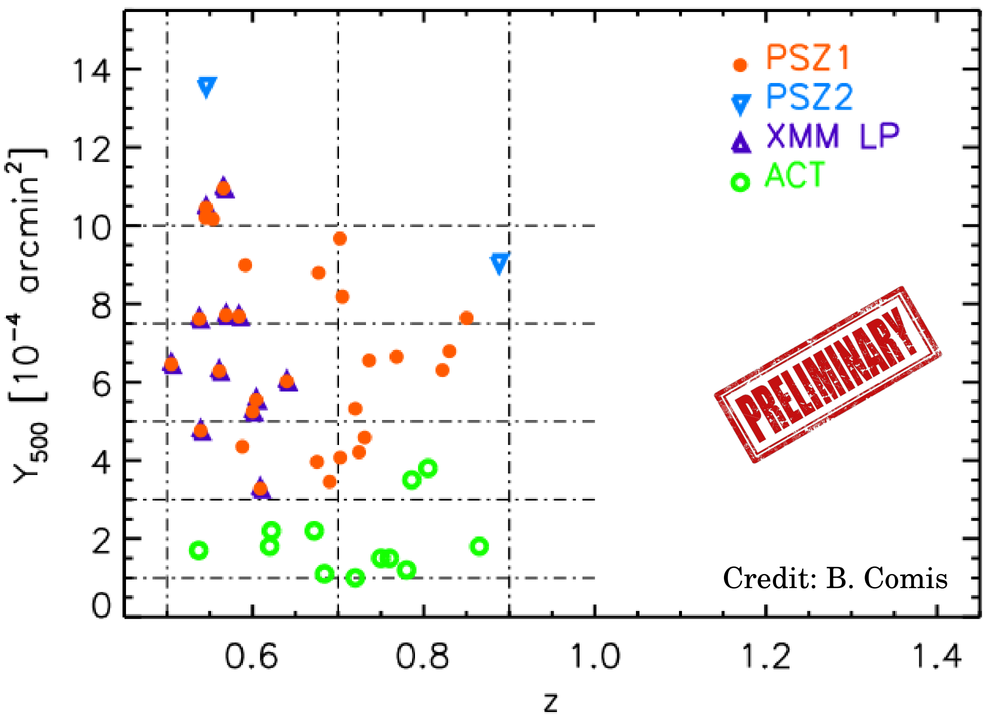
$$Y_{tSZ}(R_{500}) = 5,15^{+0,80}_{-0,73} \times 10^{-4}\ \text{arcmin}^2$$

- Dark matter fraction profile

→ Baryon to DM ratio fairly constant within the virial radius



NIKA2 SZ large program



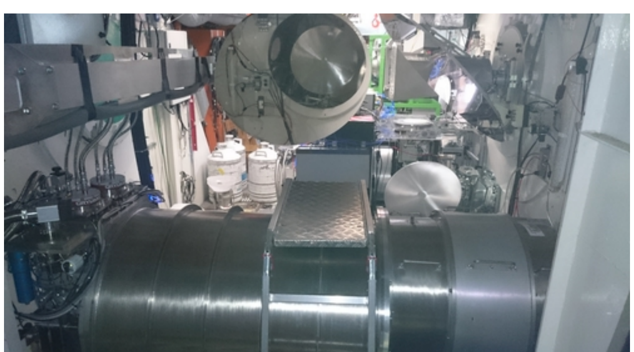
- 300 hours dedicated to SZ with NIKA2
- Observation of ~ 50 clusters:
  - 2 redshift bins
  - wide range of masses
- Program based on the Planck and ACT catalogs
- Combine NIKA2 data with other probes to fully characterize the selected clusters

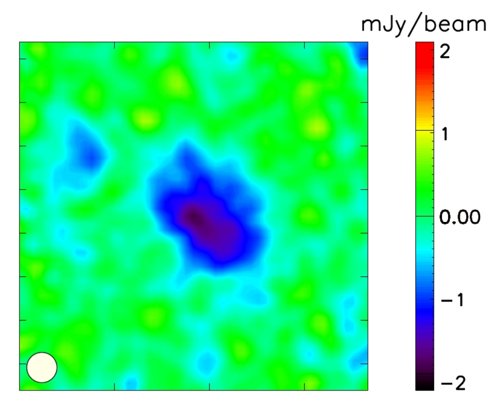
- **Aims:**
  - Study the redshift evolution of the scaling law relating the SZ flux to the total mass
  - Characterize the evolution of galaxy clusters dynamical state with redshift
  - Study the impact of non-gravitational processes on the total mass estimation

Constraints on galaxy cluster formation and dynamics → Dark matter study

Summary and Conclusions

- Several unknowns in the dark matter driven large scale structure formation scenario:
  - Properties of the dark matter halos
  - Influence of non-gravitational processes in the ICM
- NIKA have proved to be a well suited camera for SZ galaxy cluster observation.
- **Detailed cartography** of the pressure distribution in galaxy clusters
- **First light** in NIKA2 in October / November 2015 → ready to start NIKA2 SZ observations in 2016
- **Multi probe analysis** of NIKA2 SZ large program selected clusters
  → better understanding of the mass distribution in the Universe





iram
Institut de Radioastronomie Millimétrique

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

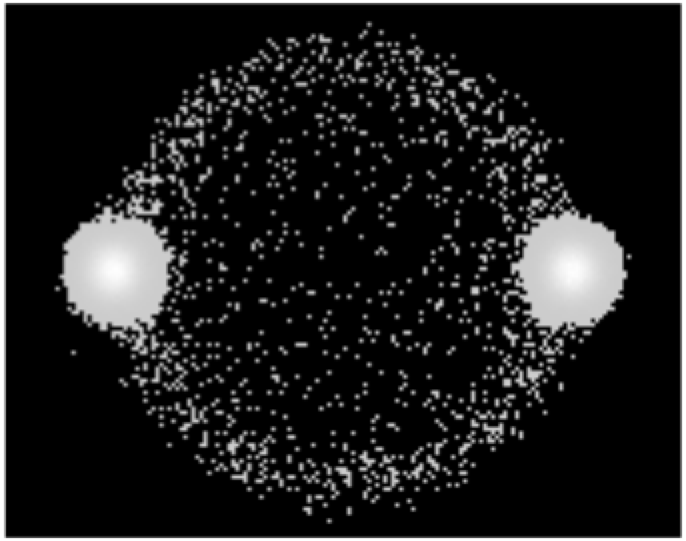
NÉEL institut

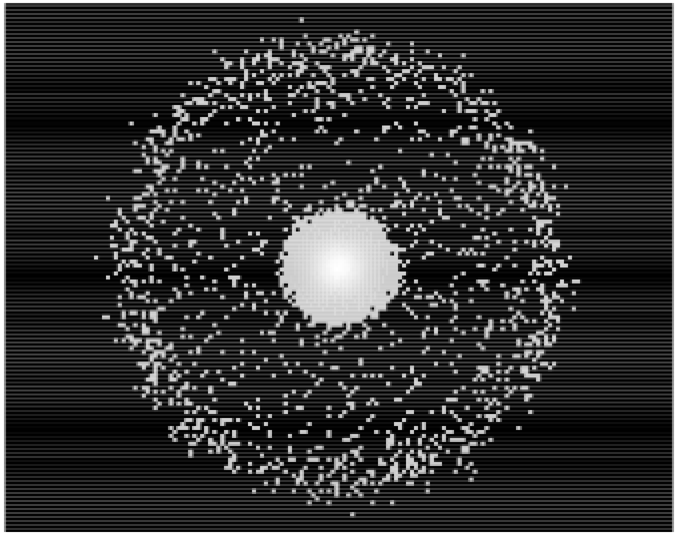
A. Abergel, R. Adam, A. Adane, A. D'Addabbo, P. Ade, N. Aghanim, P. André, J. Angot, M. Arnaud, J. Aumont, H. Aussel, A. Bacmann, E. Barria, A. Beelen, B. Belier, A. Benoît, J-P. Bernard, M. Bethermin, A. Bideaud, N. Billot, F. Boulanger, O. Bourrion, A. Bracco, G. Bres, V. Buat, D. Burgarella, M. Calvo, E. Castillo, A. Catalano, C. Ceccarelli, G. Coiffard, B. Comis, A. Coulais, M. Cousin, E. Daddi, G. Dargaud, J. Davies, K. Demyk, F-X. Désert, H. Dole, G. Donnier-Valentin, M. Douspis, S. Doyle, P-A. Duc, S. Eales, D. Elbaz, O. Exshaw, F. Galliano, G. Garde, C. Geraci, J. Goupy, M. Grollier, F. Gueth, I. Hermelo, P. Hily-Blant, M. Hoaurau, A. Hugues, V. Konyves, C. Kramer, G. Lagache, V. Lebouteiller, S. Leclercq, J-P. Leggeri, J-F. Lestrade, F. Levy-Bertrand, J-F. Macias-Perez, S. Madden, J. Martino, A. Maury, P. Mauskopf, F. Mayet, J-B. Melin, J. Menu, A. Miniussi, A. Monfardini, L. Montier, F. Motte, S. Navarro, A. Omont, F. Pajot, D. Paradis, B. Parise, E. Pascale, A. Pelissier, N. Peretto, L. Perotto, M. de Petris, J. Pety, E. Pointecouteau, N. Ponthieu, G. Pratt, V. Revéret, I. Ristorcelli, A. Ritacco, L. Rodriguez, S. Roni, S. Roudier, H. Roussel, F. Ruppin, G. Savini, K. Schuster, J-P. Scordillis, A. Sievers, J. Soler, D. Tourres, S. Triqueneaux, C. Tucker, C. Vescovi, R. Zylka

Université Grenoble Alpes
cnrs — dépasser les frontières
Agence Nationale de la Recherche ANR
erc
Enigmass
UCL
CEA — De la recherche à l'industrie — Saclay
IAP
l'Observatoire de Paris
Cardiff University — Prifysgol Caerdydd
irap — astrophysique & planétologie
Sapienza Università di Roma
LAM — Laboratoire d'Astrophysique de Marseille
IAS — Institut d'Astrophysique Spatiale — Orsay
ESO

DM self-interaction

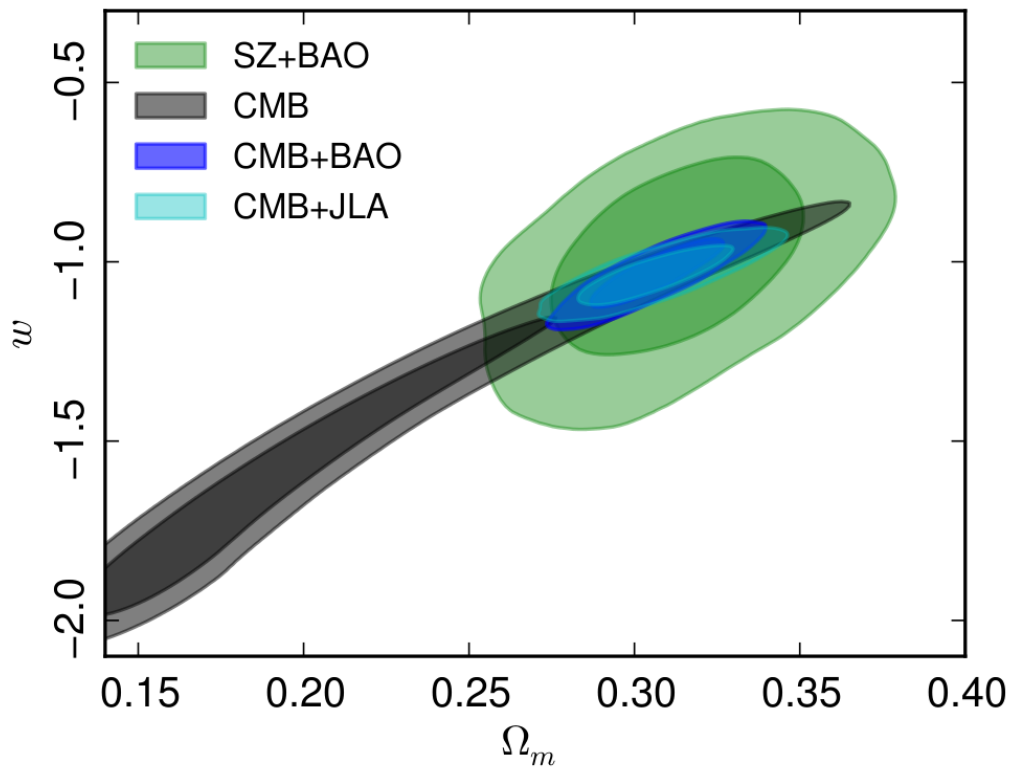
- Simulated merger dynamics with self-interacting DM
- 2 main parameters:
  - relative importance of kinetic versus gravitational effects during the collision $k = |E_{kinetic}/E_{mutual\ gravity}|$
  - effective DM-DM particle scattering strength parameter $a \approx \frac{\sigma_{DM}}{m_{DM}} M_{\Sigma}$





Y, Mishchenko1 and C-R. Ji arXiv (2015)

Cosmological probes



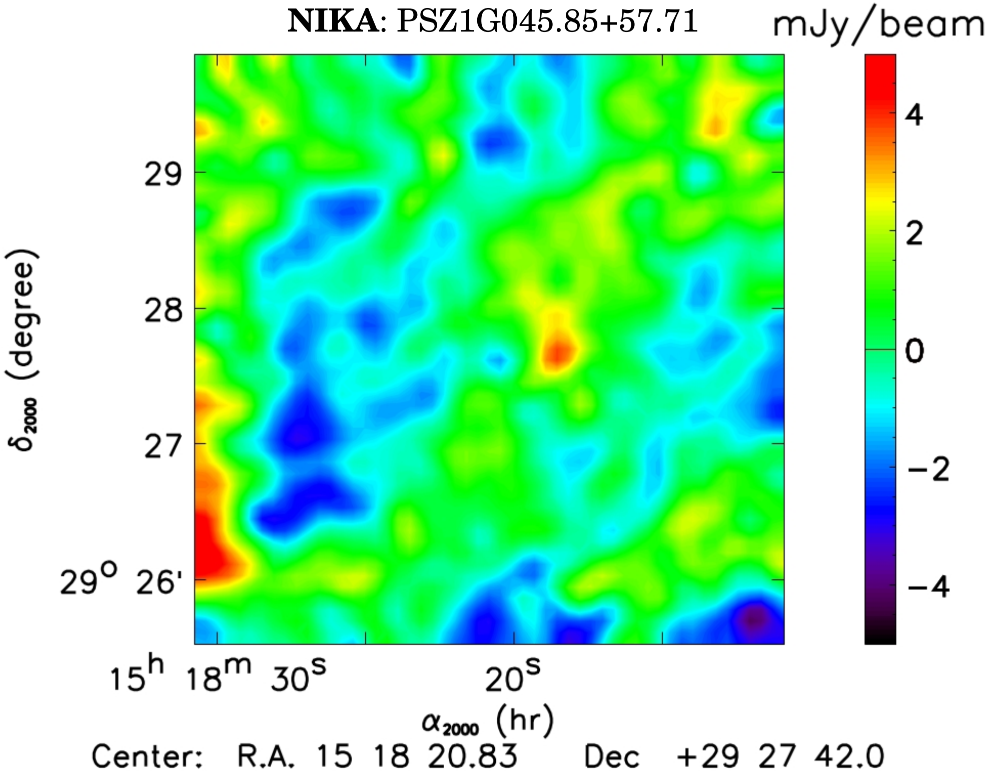
- Analysis of the CMB temperature anisotropy power spectrum

  → Cosmological parameters

- Degeneracies !

  → We must combine a large number of cosmological probes

PSZ1G045 coadded map at 260 GHz



- Coaddition of all the scans analyzed at 260 GHz

- The observed structures are consistent with residual noise (null map)

➡ We focus on the 150 GHz SZ map