The NIKA2 Sunyaev-Zeldovich Large Program

Precise galaxy cluster physics for an accurate cluster-based cosmology

Laurence Perotto on behalf of the NIKA2 collaboration

The NIKA2 Sunyaev-Zeldovich Large Program

- Cosmology with Galaxy clusters
  - Implication of high-angular resolution SZ mapping of galaxy clusters
- Why NIKA2 is well-suited for SZ ?
- The Sunyaev-Zel'dovich Large Program
  - Main science goals & products
  - Status of the observations
  - Status of the analysis
  - First results
  - On-going studies and prospectives

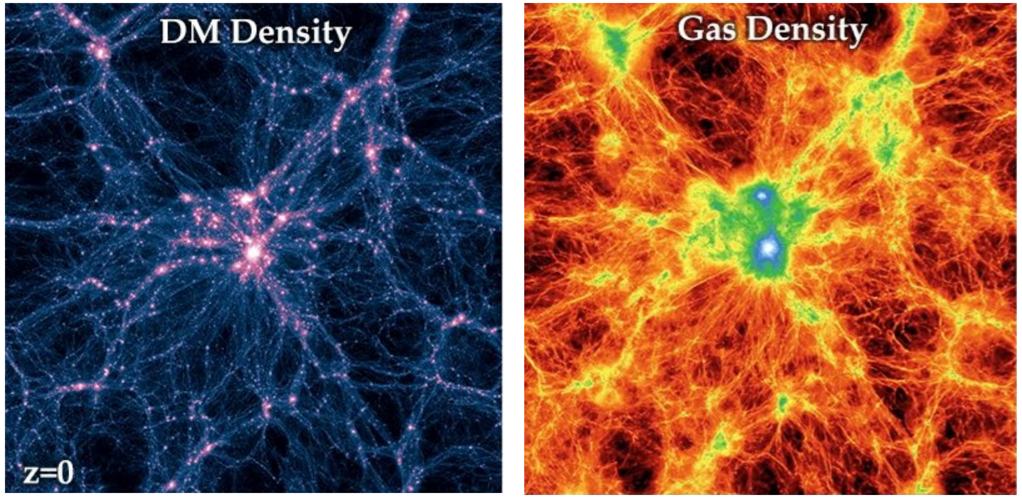
Cosmology with Galaxy clusters

Peaks of the matter density
at the intersection of the filaments of the cosmic web

- Masse M = 10^{13} - 10^{16} M_{sun}
- Redshift $0 < z < 3$

Composition:
- 85% Dark matter halo
- 12% hot ionised gas = the Intra-Cluster Medium (ICM)
- 3% galaxies

Illustris



Scale-invariant (self-similar) : they are all built from the same universal model

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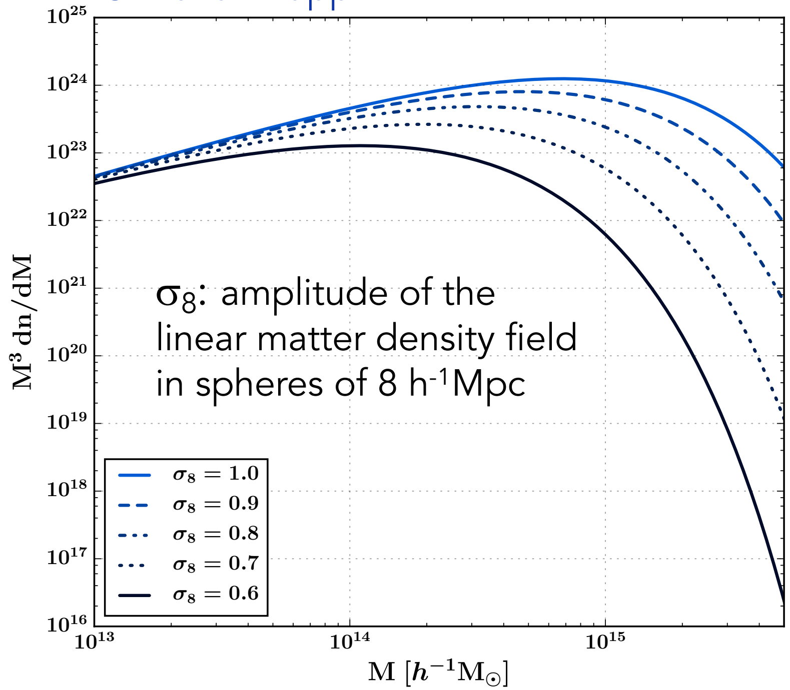


Cosmological probes based on galaxy clusters

- Gas fraction as a standard ruler $f_{gas} \sim \dfrac{\Omega_b}{\Omega_m}$
- Cluster clustering : the spatial distribution
- **Number count** : the numerical distribution in intervals of mass and redshift

$$\frac{d^2N}{dM\,dz} \sim \int d\Omega \frac{d^2V}{dz\,d\Omega}\frac{dn}{dM}$$

Galaxy clusters are tracers of the matter density field over cosmic evolution

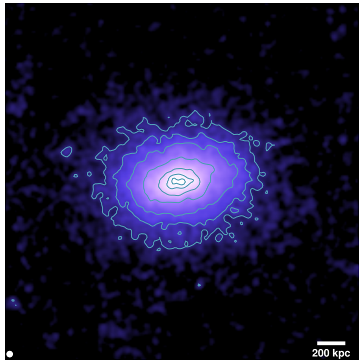
Cluster observables

Optical/IR

Stellar light of the galaxies

Strong and Weak lensing
Richness
Velocity dispersion

X-ray



The ICM is a strong X-ray emittor:

Temperature ≥ 10^7 K (~ 1 keV)

- Photometry

Bremsstrahlung of the electrons

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

3D radial profile of the density $n_e(r)$

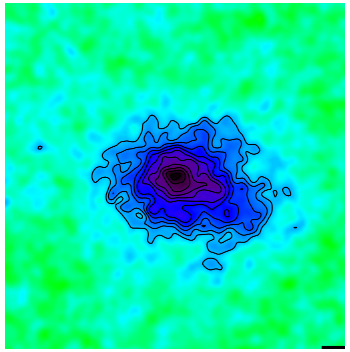
- Spectrometry

Line emission of the metal elements

3D radial profile of the temperature

Sunyaev-Zel'dovich Effect

Sunyaev&Zel'dovich 1970



Inverse Compton scattering of the CMB photon on the ICM electrons

- Spectral distortion

→ Independent of the redshift

- The amplitude of the effect

$$y = \frac{\sigma_T}{m_e c^2} \int P_e\, dl$$

→ Deprojection : 3D radial pressure profile : P_e (r)

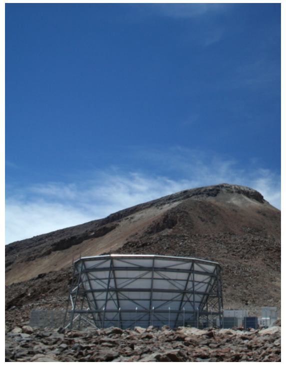
- The integrated Compton parameter

$$Y_{500} = \frac{\sigma_\mathrm{T}}{m_e c^2}\, 2 \int_0^{R_{500}} P_e(r) dl(r)$$

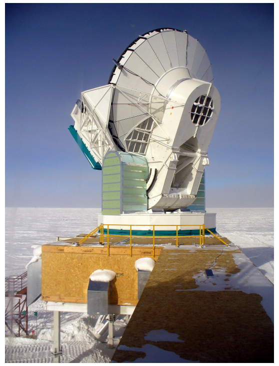
Sunyaev-Zel'dovich effect measurements

Catalogues of several thousands of clusters detected via the SZ effect

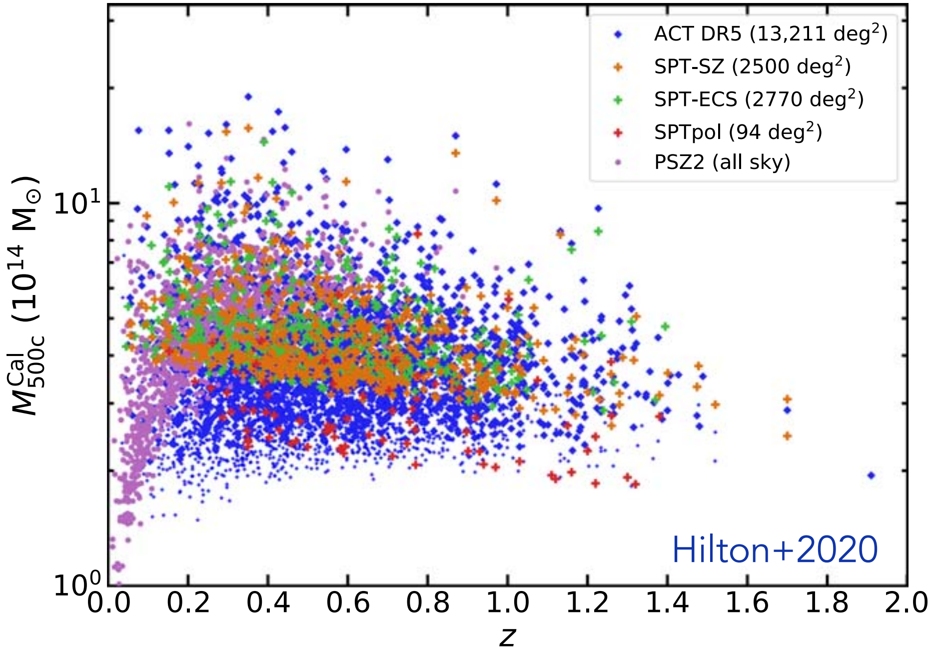
Planck satellite



Atacama Cosmology Telescope (ACT)

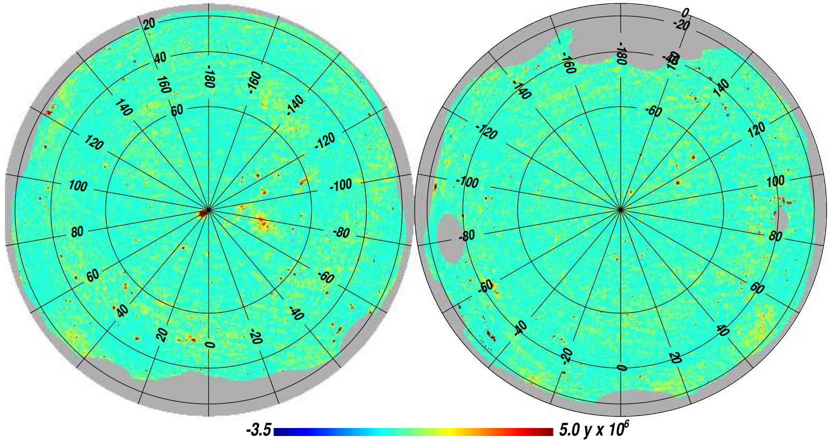


South Pole Telescope (SPT)



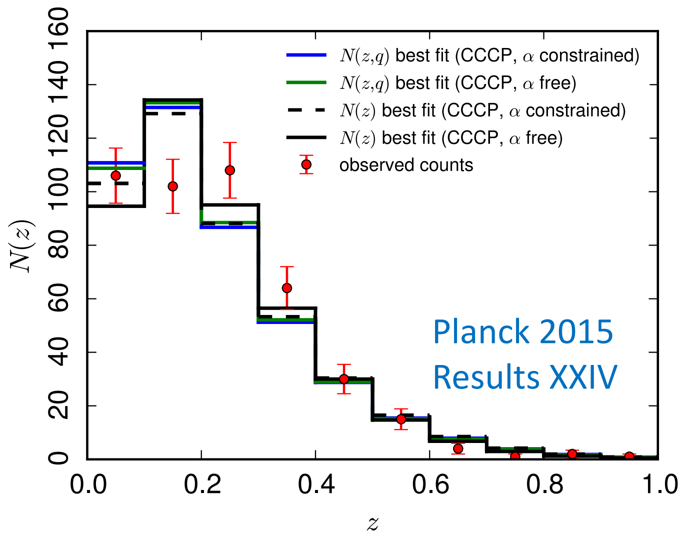
- PSZ2: ~2000 clusters via the SZ effect
- ACT DR5:
  - > 4000 confirmed clusters at $z_{med} \approx 0.5$
  - > 200 of which are at z > 1
- SPT: ~ 350 confirmed clusters at $z_{med} \approx 0.5$ Huang+2020 Bleem+2020

Full-sky map of the Compton parameter



Cosmological probes from SZ measurements

Cluster count



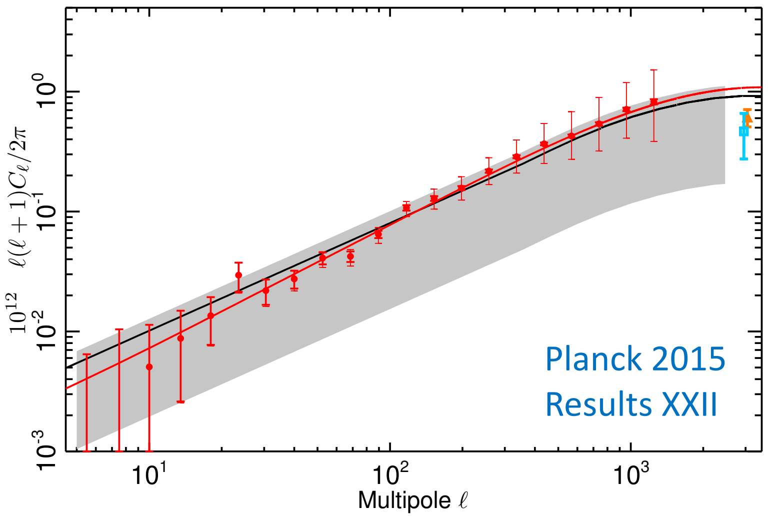
$$\frac{dN}{dz} = \int d\Omega \int dM_{500}\ \hat{\chi}(M_{500}, z, \mathbf{x}) \frac{dN}{dM_{500}dzd\Omega}$$

Selection function

$Y_{500} - M_{500}$ scaling relation

Spatial distribution:

Measure of the angular power spectrum of the y-map



$$C_\ell^{1\text{halo}} = \int_0^{z_{\max}} dz \frac{dV_c}{dzd\Omega} \int_{M_{\min}}^{M_{\max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2$$

Comoving volume and Mass function

2D Fourier transform of the

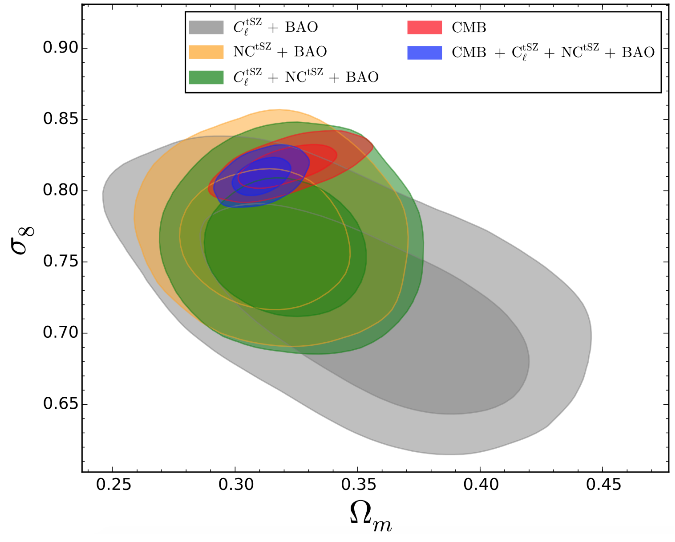
mean pressure profile

Cluster-based vs CMB-based cosmological results

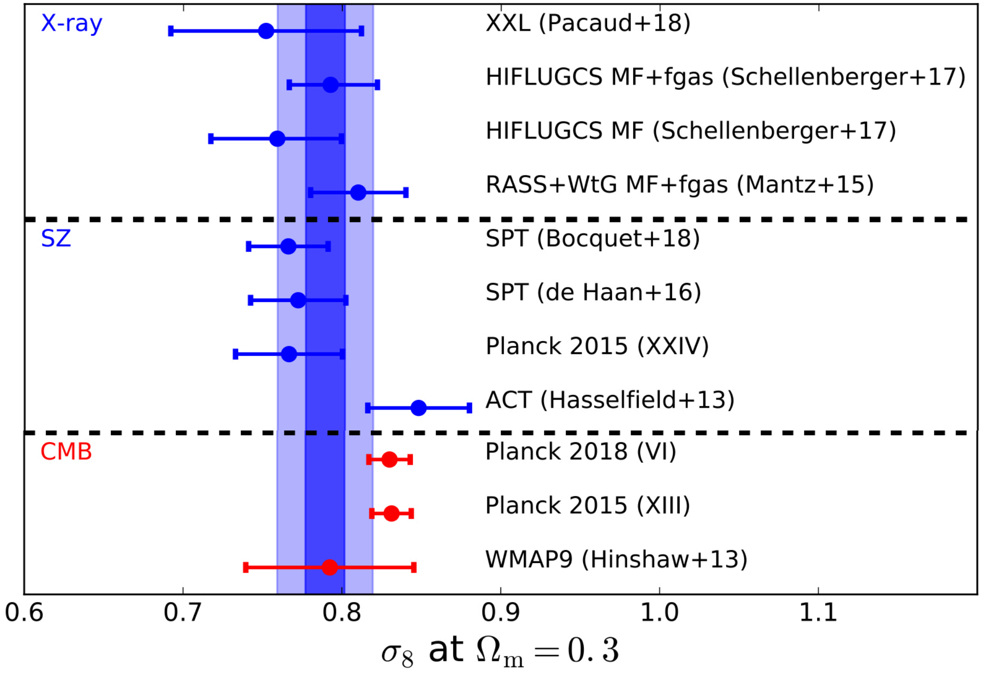
- SZ-based cosmology favored low-vallue of the amplitude of the linear matter density field w.r.t primary CMB cosmology
- Trend towards low-σ8 from cluster cosmology at all wavelengths

Planck cosmological constraints

Salvati+2018



Pratt et al. ISSI review (2019)



Most likely explanation: cluster-based cosmology may be impacted by the lack of knowledge on the cluster physics

First task: ascertain the accuracy of the tools needed for cluster cosmology (Y-M relation and mean pressure profile)

Status and difficulties

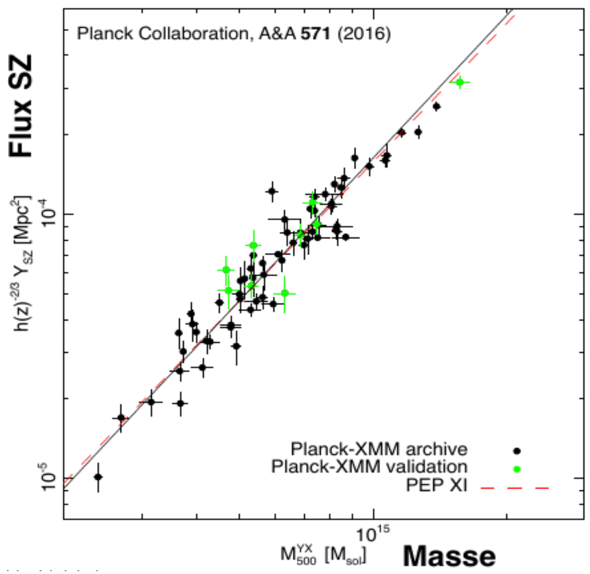
Status: the universal (average) properties of the galaxy clusters are measured from samples of closeby and massive clusters

Y_{500} – M_{500} scaling relation

- Infered from 20 clusters at z<0.2 observed in X-ray only

$$-\frac{G(1-b)M_{\mathrm{HSE,X}}}{r^2} = \frac{1}{\{\rho_{\mathrm{gaz}} = \mu m_p n_{\mathrm{gaz}}\}}\frac{dP_{\mathrm{gaz}}}{dr}$$

- Calibrated using nearby clusters observed in SZ and X-ray

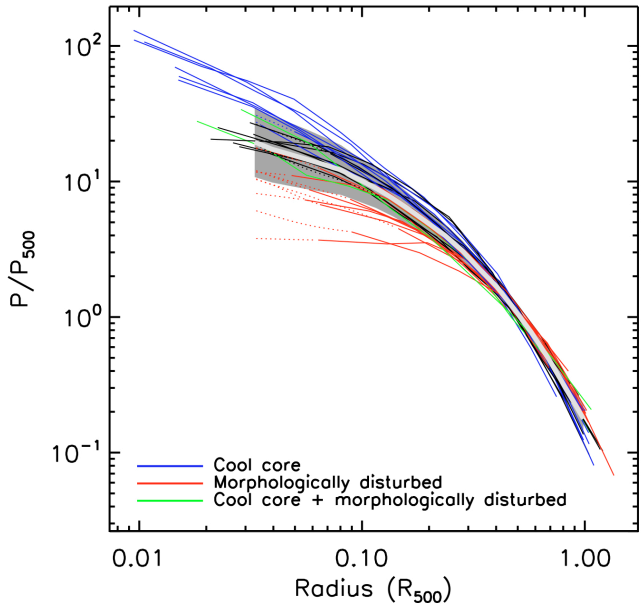


Arnaud+2010,
Planck coll. 2013

Mean pressure profile

- Measured using 33 clusters at z<0.2 observed in X-ray

$$P_{\mathrm{gaz}} = k_{\mathrm{B}}\, n_{\mathrm{gaz}} T_{\mathrm{gaz}}$$



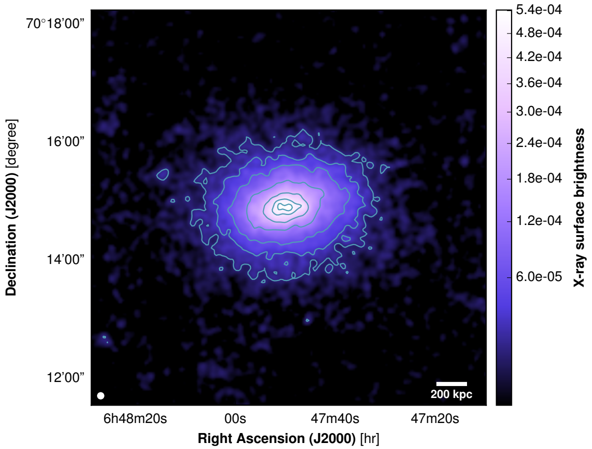
Pratt+2010,
Arnaud+2010

Difficulties : Precise temperature measurements requires very high-quality spectroscopic data (prohibitive integration time for distant low-mass clusters)

Cluster mass measurements with high-angular resolution SZ mapping

Mapping the SZ effect with the same angular resolution as the X-ray observatories to fully exploit the X-ray/SZ synergy

X-rays



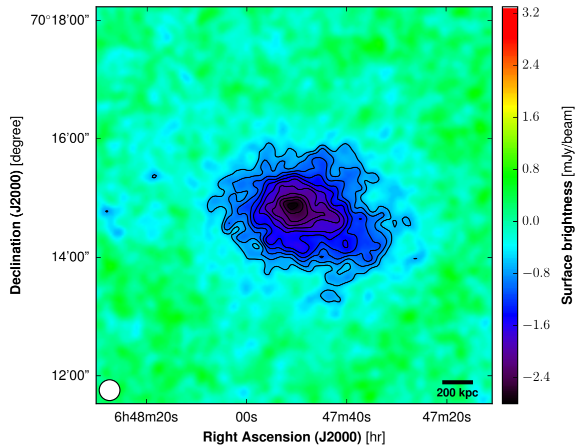
$$S_X = \frac{1}{(1+z)^4} \int n_e^2(l)\, \Lambda\, dl$$

(High-quality Spectroscopy $T_e(r)$)

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

SZ

Ruppin+2018
Kéruzoré+2020



$$y = \frac{\sigma_T}{m_e c^2} \int P_e(l) dl$$

Independent of redshift

- The Hydrostatic mass profile is measured from a direct observable of the gas pressure
- « bypass » of the X-ray spectroscopy : measurement of temperature profile at high-z $k_{\mathrm{B}} T_e(r) = \frac{P_e(r)}{n_e(r)}$

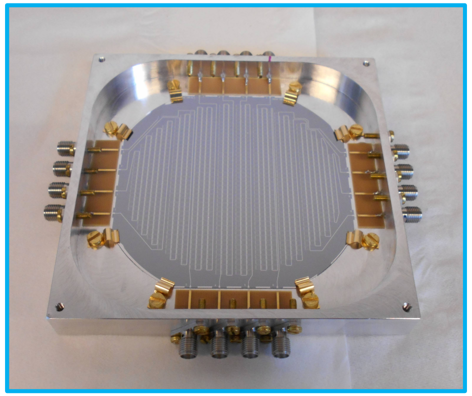
This programme requires an experience such as **NIKA2** !

NIKA2 in a nutshell

A millimetric continuum camera of 2 900 Kinetic Inductance Detectors (KID), operating at 150 and 260 GHz, installed at the IRAM 30-meter telescope, and operating since 2017

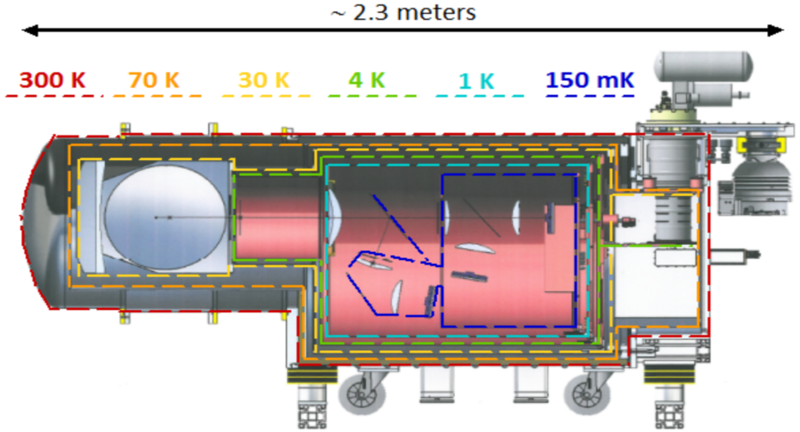
Adam et al. (2018) A&A 609, A115
Perotto et al. (2020) A&A 637, A71

Thousands KID-based camera…



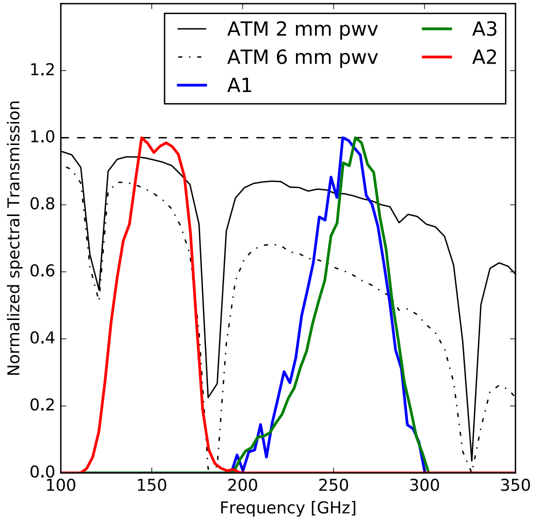
One of the two 1140 KID arrays at 260 GHz

…cooled at 150 mK…



Design of the cryogenic stages

… operating at 150 and 260 GHz …



Measured spectral transmission

IRAM 30-meter telescope at Pico Veleta, 2870m, Spain

…with an angular resolution < 20'' and an instantaneous field of view of 6.5' in diameter…

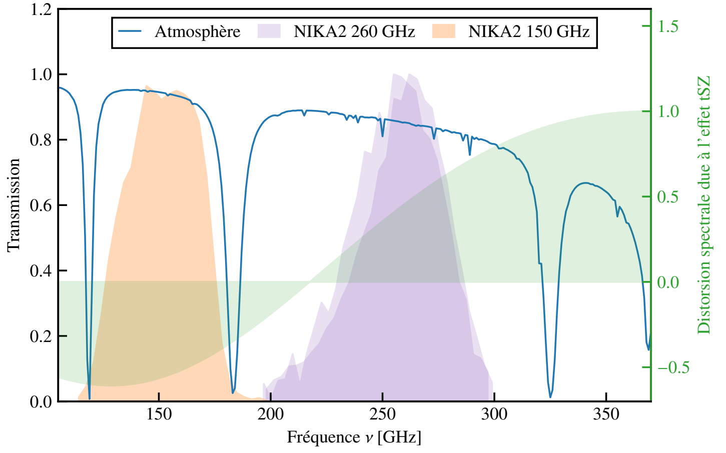
(…and sensible to polarization at 260GHz)

Performance well-suited for SZ mapping

	150 GHz	260 GHz
FOV diameter	6.5‘	6.5’
Angular resolution: FWHM	17.6’’ ± 0.1’’	11.1’’ ± 0.2’’
RMS calibration uncertainties	3%	6%
Absolute calibration uncertainties	5%	5%
Systematic uncertainties	<1%	<1%
Sensitivity: NEFD	9 ± 1 mJy.s$^{1/2}$	30 ± 3 mJy.s$^{1/2}$
Mapping speed arcmin^2 /mJy^2 / hours	1388 ± 174	111 ± 11

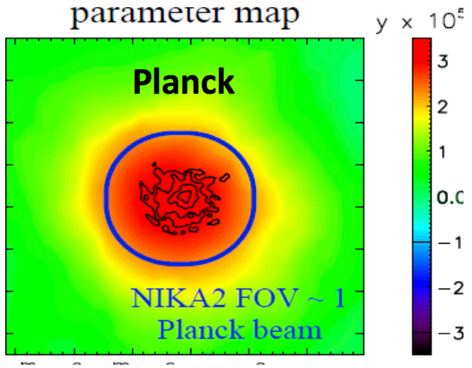
Perotto+2020

F. Kéruzoré’s PhD Thesis



Two frequency bands to observe the SZ decrement and a slight positive signal

Capabilities to simultaneously resolve high-redshift clusters while mapping the clusters’ outskirts



Stability and high sensitivity

- at 150 GHz to map clusters including low-mass ones
- at 260 GHz to detect and remove point sources

The NIKA2 Sunyaev-Zeldovich Large Program

- Cosmology with Galaxy clusters
  - Implication of high-angular resolution SZ mapping of galaxy clusters
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- The Sunyaev-Zel'dovich Large Program
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The Sunyaev-Zeldovich Large Programme

High angular resolution thermal SZ mapping of a representative sample of galaxy clusters for Cosmology

- 300 hours of Guaranteed Time at the IRAM 30-m telescope
- PI : Frédéric Mayet, coPI : Laurence Perotto
- 45 clusters at $0.5 < z < 0.9$
- Follow-up of Planck and ACT (Atacama Cosmology Telescope)
- Representative: selected in mass and redshift in the Planck and ACT catalogues
- X-ray observation available (XMM-Newton and Chandra)

Main goals

- Mean pressure profile (and thermodynamical properties of the Intra-cluster medium)
- Y-M scaling relation
- Probe the low-mass and high-redshift clusters

➡ Provide the community with tools to improve the accuracy of Cosmology with galaxy clusters

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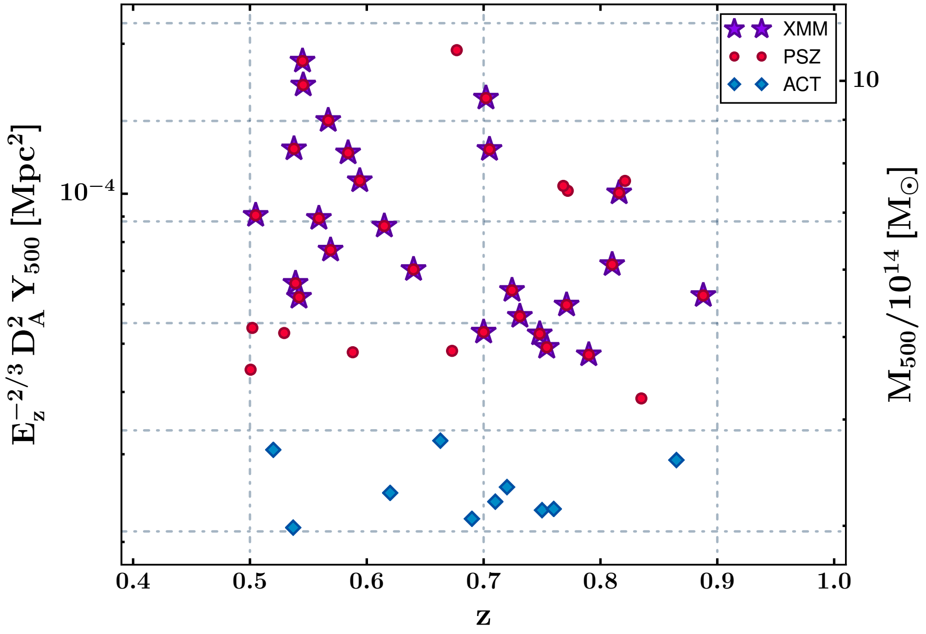
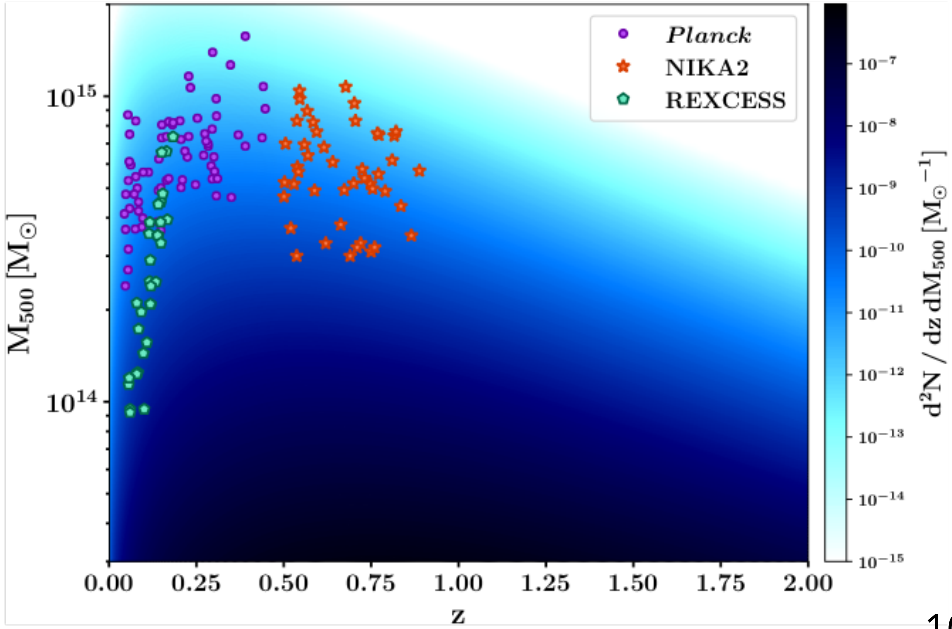


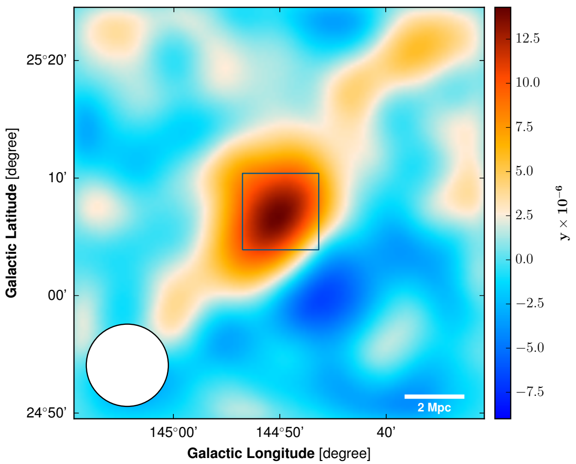


The Sunyaev-Zeldovich Large Programme

NIKA2 = First generation of SZ experiments for exploiting the synergy between X-rays and SZ at the same angular resolution

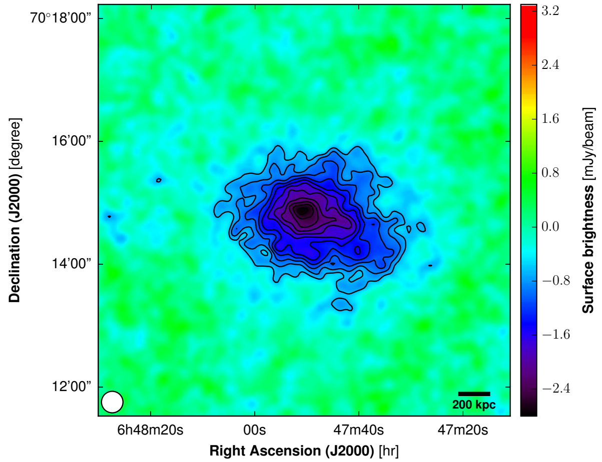
PSZ2 G144@

Planck



$$\mathcal{D}_A^2\, Y_{500} = 4\pi \frac{\sigma_T}{m_e c^2} \int_0^{R_{500}} r^2 P_e(r)\, \mathrm{d}r$$

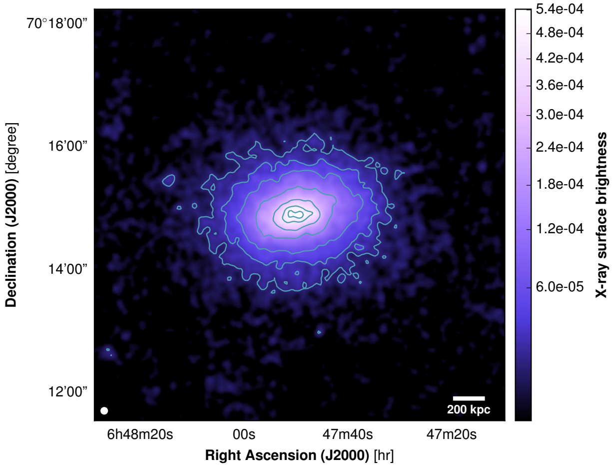
NIKA2



Ruppin+2018

$$y = \frac{\sigma_T}{m_e c^2} \int P_e(l) dl$$

XMM-Newton



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

Deep integration-time spectroscopy $T_e(r)$

- Full characterization of the Intra-Cluster Medium from the core to the outskirts
- Hydrostatic equilibrium Mass profile from a direct observable of the gas pressure
- Gas temperature profile of high-redshift clusters

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

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

The LP-SZ Team

…gathers specialists of all key domains for Galaxy clusters studies (27 people, 13 institutits)

- *NIKA2*
- *SZ*
- *X-rays*
- *Simulation*
- *Optical*
- *Radio*

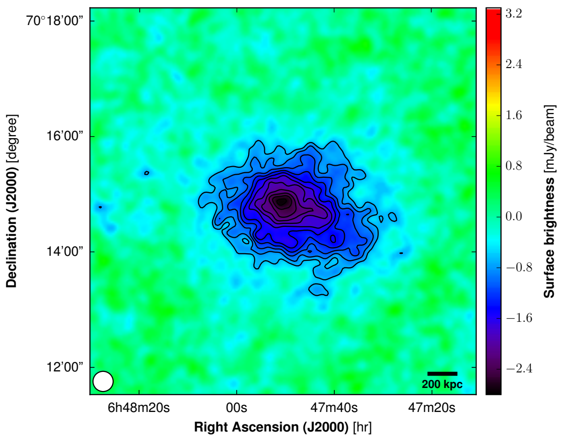
Nicolas PONTHIEU
François-Xavier DESERT
Laurence PEROTTO
Juan MACIAS-PEREZ
Miren MUNOZ-ECHEVERRIA
Florian KERUZORE
Frédéric MAYET
Emmanuel ARTIS
Rémi ADAM
Florian RUPPIN
Charles ROMERO
Etienne POINTECOUTEAU
Nicolas CLERC
Nabila AGHANIM
Marian DOUSPIS
Jean-Baptiste MELIN
Monique ARNAUD
Gabriel PRATT
Iacopo BARTALUCCI
Hervé AUSSEL
Alexandre BEELEN
Marco DE PETRIS
Aishwarya PALIWAL
Gustavo YEPES
Rafael BARRENA DELGADO
Antonio FERRAGAMO
Jose Alberto RUBINO MARTIN
Chiara FERRARI

MADRID

NIKA2 LP-SZ first results

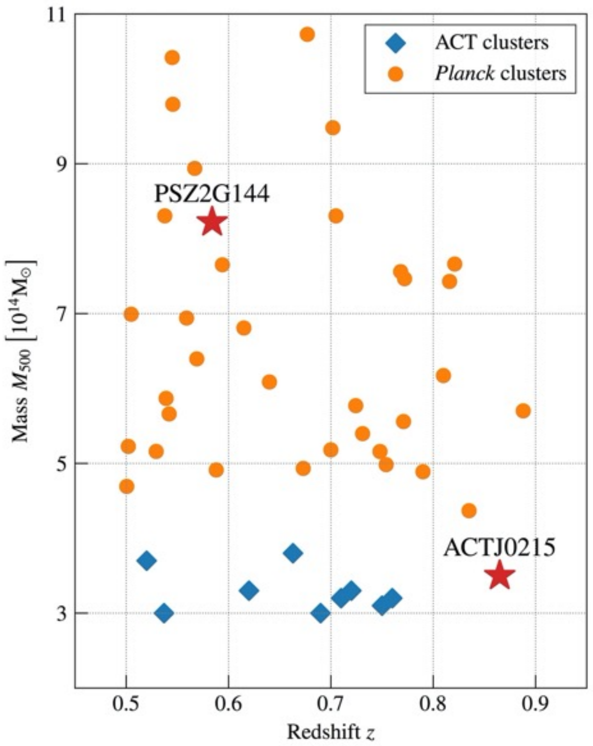
The demonstrator : PSZ2 G0144

- PSZ2-G0144.83+25.11
- $z = 0.58 \quad M_{500} = 7.8 \times 10^{14} M_\odot$
- Science verification, April 2017
- t_obs = 11h = 5 x t_LPSZ
- Atmospheric opacity ≈0.3 at 150 GHz



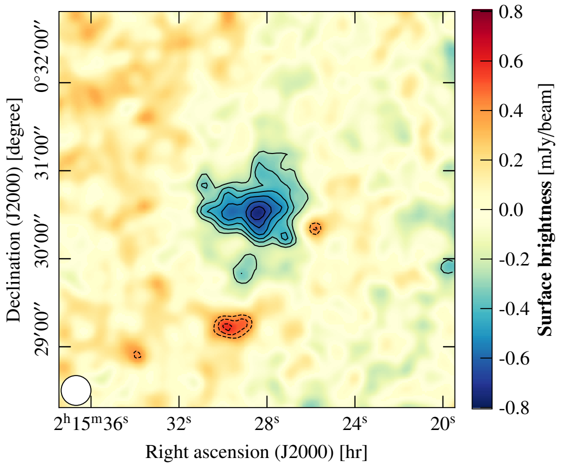
- 13.5 sigma measurement at peak
- Thermal SZ sigma detected up to1.5’ (> 0.5 Mpc)

Ruppin et al. (2018) A&A 615 A112



The *challenging* : ACT-CL J0215

- ACT-Cl J0215
- $z = 0.865 \quad M_{500} = 3.5 \times 10^{14} M_\odot$
- N2R14, January 2018
- t_obs = 9h = t_LPSZ
- Atmospheric opacity ≈0.2 at 150 GHz



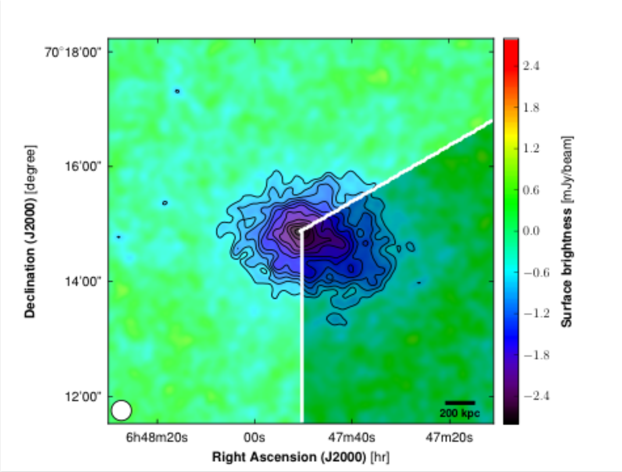
- 9 sigma measurement at peak
- SNR > 3 in a disk of 1 arcmin square

Kéruzoré et al. (2020) A&A 644 A93

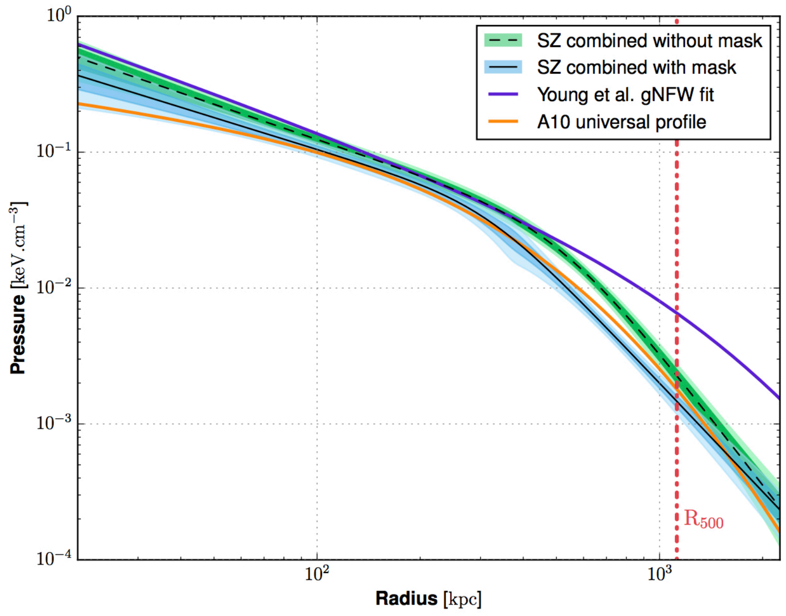
PSZ2-G144: Implication for the LP-SZ Cosmology Program

Ruppin et al. (2018) A&A 615 A112

Evidence of an over-pressure region



Significative impact on the pressure profile

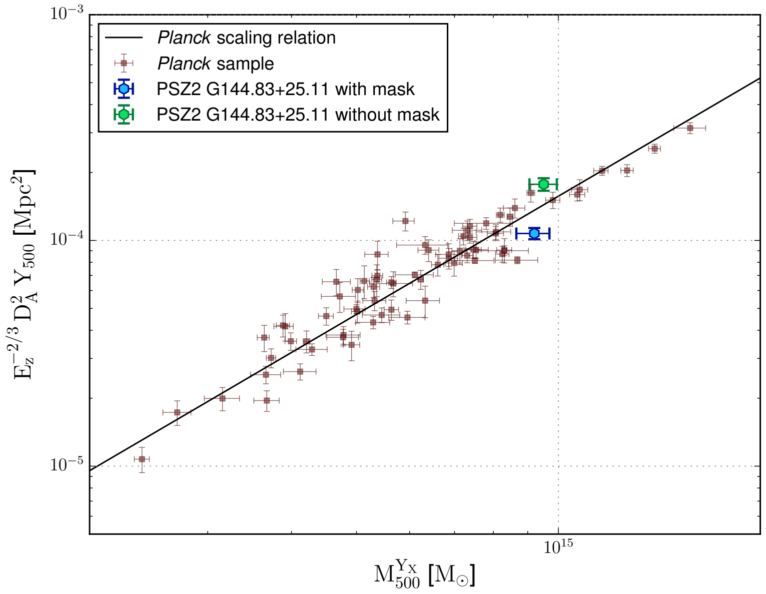


Impact on the hydrostatic mass profile

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

and on the integrated quantities Y_500 and M_500 used to relate the observable to the mass

$$M_{500} = \int_0^{R_{500}} M_{\mathrm{HSE}}(r) dr$$

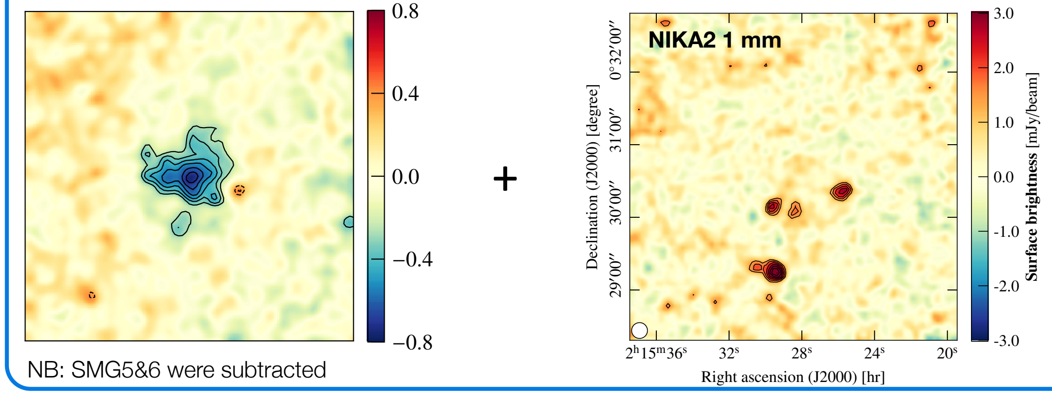


Sensitivity to the intrinsic dispersion of the Mass-Observable relation

ACT-Cl-J0215: Impact of point sources

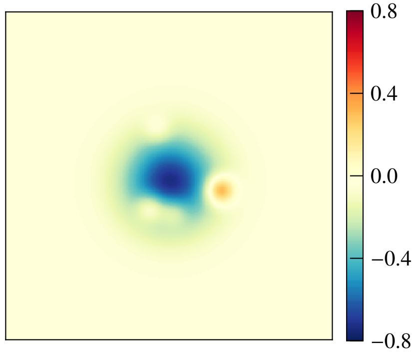
Kéruzoré et al. (2020) A&A 644 A93

NIKA2 data

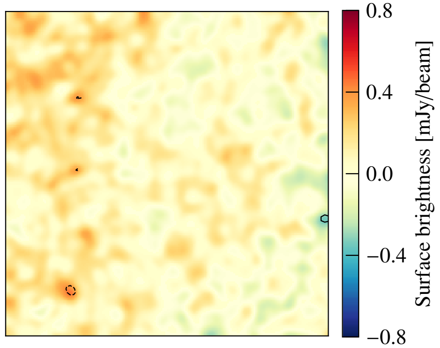


NB: SMG5&6 were subtracted

Best fit

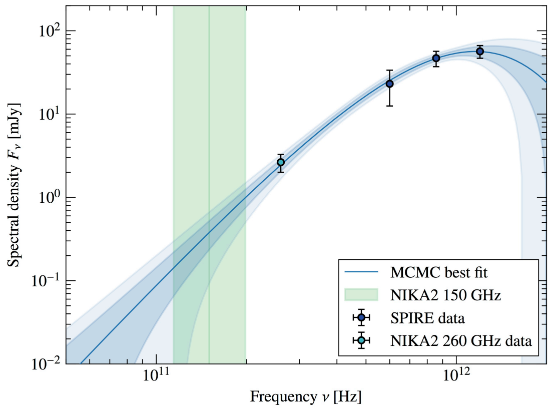


Residuals = data — best fit

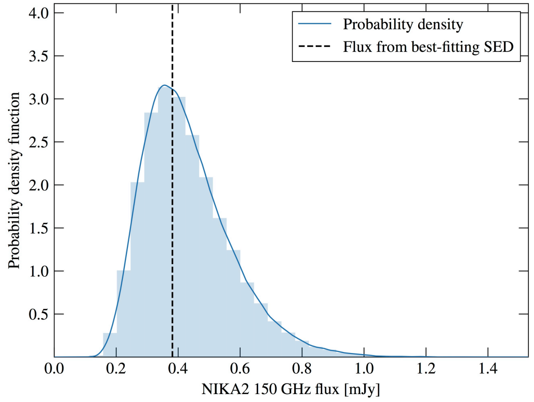


SPIRE @ Herschel

SED fit of SMG2



150 GHz flux of SMG2



Fit of the point source flux in the 150 GHz band from NIKA2@260GHz + SPIRE@600, 800, 1200 GHz

Probability distribution of the point source flux at 150 GHz

Miren Muñoz-Echeverría's talk #1

Joint model

- tSZ signal projected from a gNFW pressure profile (Nagai+2007)
- Point sources

MCMC fit using the probability distribution of the point source fluxes as prior

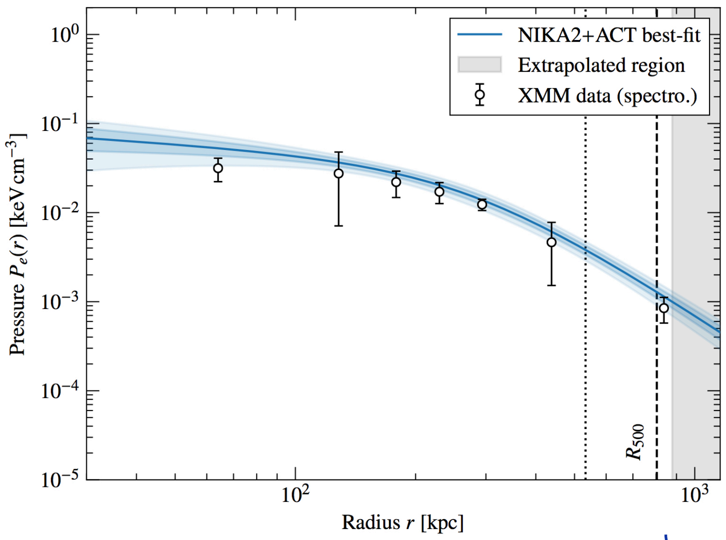
➡ Unbiased pressure profile estimate

➡ The uncertainties on the estimation of point source fluxes are well-propagated

ACT-Cl-J0215: implication for the LP-SZ cosmology program

Kéruzoré et al. (2020) A&A 644 A93

Pressure profile with NIKA2+ACT



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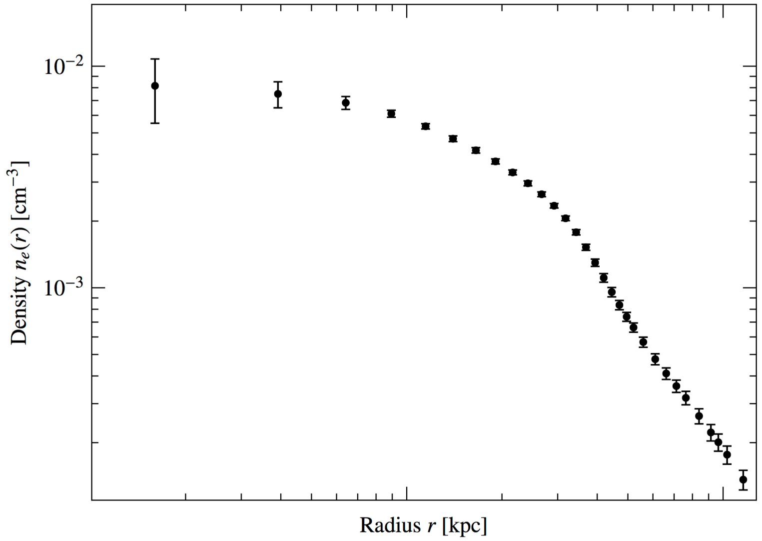


Density profile with XMM-Newton

	ACT	XMM-*Newton*	NIKA2+XMM
R_{500} [kpc]	877.8 ± 46.2	780.9 ± 19.8	810.1 ± 41.9
$\mathcal{D}_A^2\, Y_{500}$ [10^{-5} Mpc^2]	4.07 ± 1.13	–	3.76 ± 0.39
M_{500} [10^{14} $M_\odot$]	3.5 ± 0.8	2.48 ± 0.70	3.79 ± 0.58
	Hasselfield+2013	Bartalucci+2018	

➡ Precision improvement on Y_500 w.r.t. ACT

➡ Precision improvement on M_500 w.r.t.
- ACT (using a Y500-M500 scaling law)
- and XMM-Newton !

Status of the LPSZ observations

- Total observed hours
  - From 2017 Summer Semester to 2020 Winter Semester
  - 170 hours out of 300

- Status of the observation of the cluster sample

45 clusters

- 31 already observed
- 3 started
- 7 scheduled (including 4 ACT clusters)
- 4 ~~non-confirmed~~ (not a cluster)

Bin	0.5-0.7	0.7-0.9
5 (high mass)	PSZ2 G155.27-68.42 PSZ2 G111.61-45.71 PSZ2 G228.16+75.20 PSZ2 G209.79+10.23	~~PSZ2 G138.61-10.84~~
4	PSZ2 G183.90+42.99 PSZ2 G211.21+38.66 PSZ2 G045.32-38.46 PSZ2 G144.83+25.11 PSZ2 G201.50-27.31	PSZ2 G091.83+26.11 ~~PSZ1 G140.10+50.09~~ ~~PSZ1 G224.73+33.65~~ PSZ2 G141.77+14.19 PSZ1 G080.66-57.87
3	PSZ2 G212.44+63.19 PSZ2 G094.56+51.03 PSZ2 G193.31-46.13 PSZ2 G046.13+30.72 PSZ2 G099.86+58.45	PSZ2 G084.10+58.72 PSZ2 G086.93+53.18 PSZ2 G160.83+81.66 PSZ1 G226.65+28.43 PLCK G227.99+38.11
2	PSZ2 G081.02+50.57 ~~PSZ2 G106.15+25.75~~ PSZ2 G108.27+48.66 PSZ2 G133.59+50.68 PSZ2 G080.64+64.31	PSZ2 G104.74+40.42 PLCK G079.95+46.96 PSZ2 G088.98+55.07 weak PSZ2 G087.39+50.92 PSZ2 G097.52+51.70 warning
1 (low mass)	ACT-CL J0219.8+0022 ACT-CL J2152.9-0114 ACT-CL J0240.0+0116 – 77% ACT-CL J2302.5+0002 – 50% ACT-CL J0223.1-0056	ACT-CL J0018.2-0022 ACT-CL J0058.0+0030 ACT-CL J2130.1+0045 – 3% ACT-CL J0119.9+0055 ACT-CL J0215.4+0030

Status of the LPSZ analysis pipeline

Both observation and analysis of the clusters must be homogeneous to preserve the representativity of the sample

- From raw data to SZ maps
  - Perform a noise decorrelation…

Time Ordered Information of each KID k have correlated components of atmospheric and electronic origins

$$d_k(t) = A_{tp}S_p + N^{\mathrm{atm}}(t) + N^{\mathrm{elec}}_{k \in \mathrm{box}}(t) + N_k(t)$$

  - …While preserving the large angular scales

The angular scales filtering induced by the pipeline is modeled using a transfer function

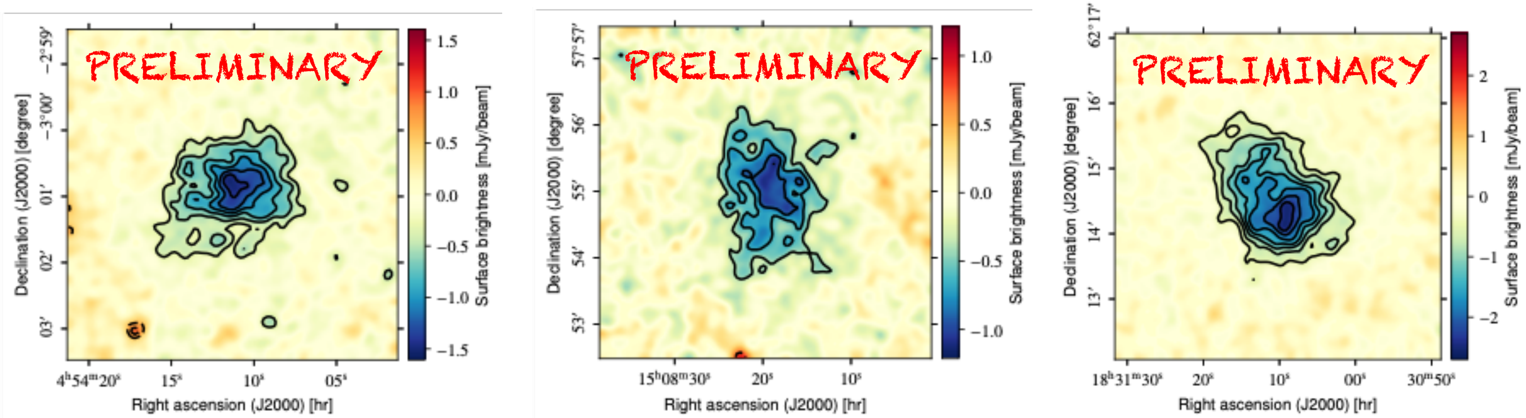
in … Pipeline … out

$$TF = \frac{< \tilde{M}^{\mathrm{out}} \tilde{M}^{\mathrm{in}} >}{< |\tilde{M}^{\mathrm{in}}|^2 >}$$

➡ Find an optimal trade-off between noise subtraction and induced filtering

Miren Muñoz-Echeverría's talk #1

- Control of the systematics: dealing with complex morphology

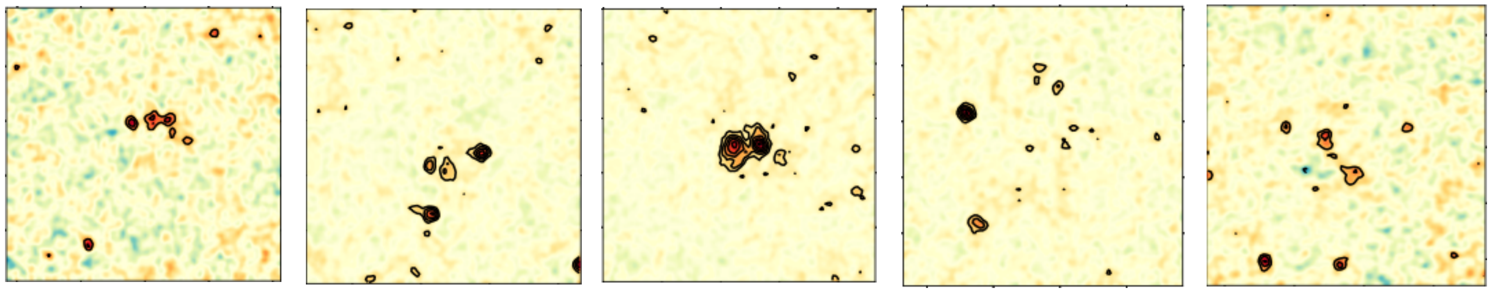


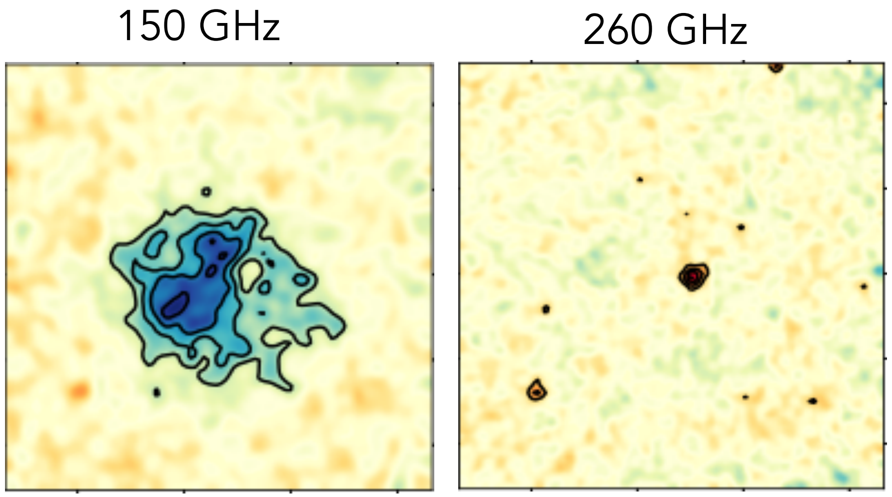
Emmanuel Artis'talk #1

Status of the LPSZ pipeline

- Point source detection and removal
  - Main contaminant: backgroup lensed galaxies, members, foregrounds
  - Fluxes need to be estimated : use archival data + follow-ups ?
  - Nice by-product of the LP-SZ : Release of a catalogue of point sources including high-z lensed galaxies candidates

PRELIMINARY





PRELIMINARY

…

- Estimation of the thermodynamical profiles: Pressure, Temperature, HSE Mass
  - Coming soon! PANCO2: the second Pipeline for the Analysis of NIKA2 Cluster Observation
  - MCMC-based fast estimator of the thermodynamical profiles of the intracluster medium

Florian Kéruzoré's talk #1

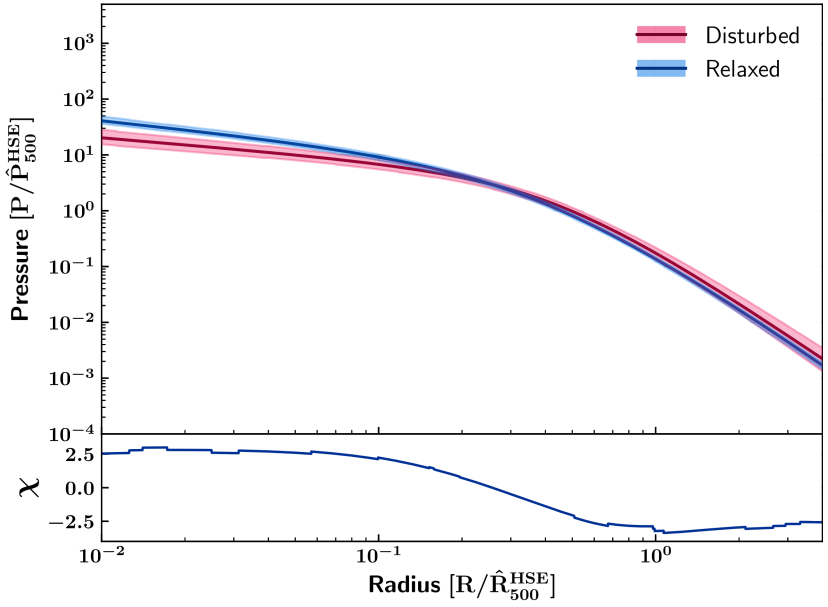
- Statistical analysis tools for Cosmology :

how to measure an unbiased scaling relation and to estimate the intrinsic dispersion ?

Florian Kéruzoré's talk #2

Validation and forecasts on simulation

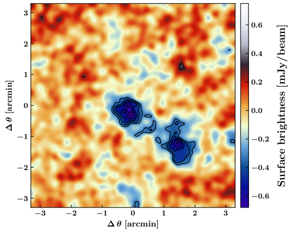
Ruppin et al, A&A, 631, A21, 2019

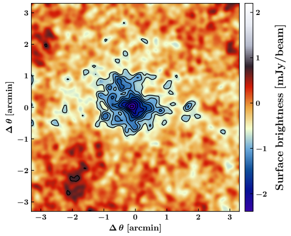


- The MUSIC LP-SZ twin sample

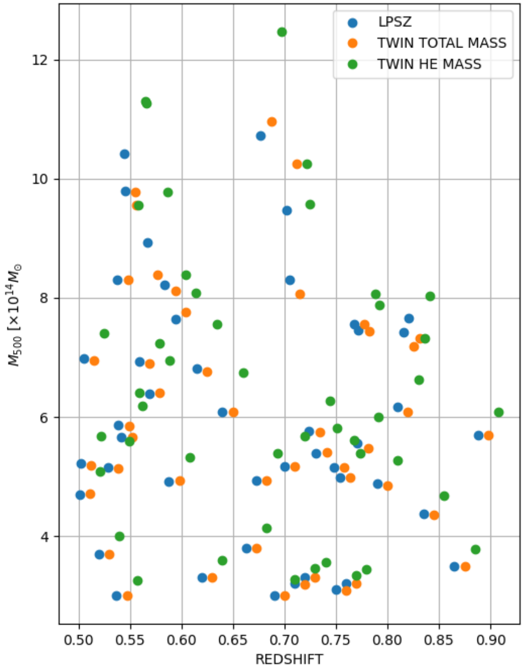
MUSIC, Marenostrum MUltidark SImulations of galaxy Clusters
Sembolini et al. 2013

Selection based on morphology: disturbed relaxed





- The 300th LP-SZ twin samples



The Three Hundred Project, zoomed hydrodynamical simulation centered on the 324 most massives haloes of the Multidark-Planck simulation at z=0, Cui+2018, MNRAS, 480, 2898-2915

Selection of the NIKA2 LPSZ 300th twin samples

Aishwarya Paliwal's talk

Mock observations in X-ray, SZ, Optical, lensing

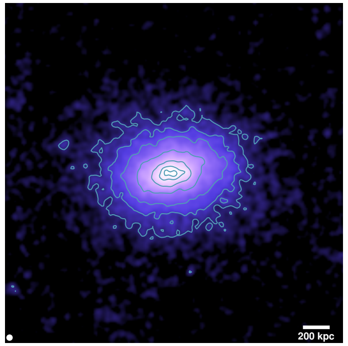
- Test novel methods on realistic simulation, assess the impact of dynamical state, z-evolution
- Forecast NIKA2 LP-SZ uncertainties on scaling laws and biases (Y-M, M_{HSE}-M, Richness-M)
- Forecast NIKA2 LP-SZ capability to measure f_{gas}, H_0

Multi-wavelength analysis

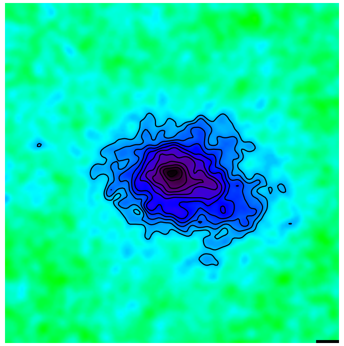
Building a consistent picture of the cluster physics to gain accuracy on the mass estimates

HSE bias

X-ray



SZ



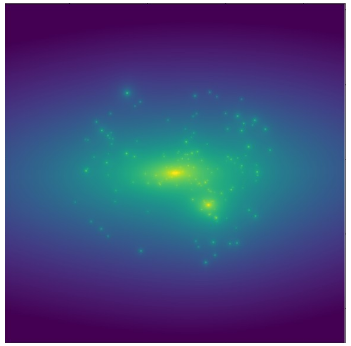
Scaling laws

- Thermal ICM properties

  Hydrostatic Equilibrium mass

  Substructures and fluctuations

Physical origin of HSE bias



Lensing

- Line-of sight integrated mass density

  M_lens

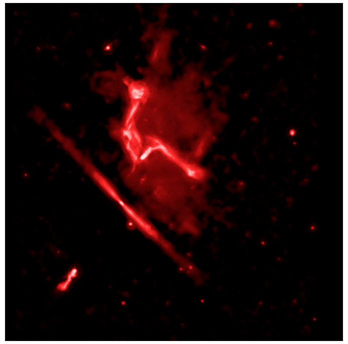
Miren Muñoz-Echeverría's talk #2

Optical

About 50% of the LP-SZ sample have deep integration optical data (SDSS, PanStarrs)
van der Burg et al., 2018, A&A, 618, A140

- Richness

  Radial velocity -> Dynamical mass



Radio

- Non-thermal ICM properties

  Turbulence, AGN feedback, Shocks

Summary

- Galaxy clusters are cosmological probes sensitive to the growth of structures over cosmic evolution
- Fully exploiting clusters to set constraints on Cosmology requires better knowledge of cluster physics and in particular, accurate estimate of their mass and universal properties
- To that aim, resolved SZ + X-ray is a must : estimation of the mass as a function of the cluster properties (morphology, dynamical state) up to high redshifts
- NIKA2 is key to realise this program: SZ mapping at the same quality level as X-ray data
- The **LPSZ**: A Guaranteed-Time Large Program dedicated to the resolved SZ mapping of a representative sample of 45 clusters at $0.5 < z < 0.9$ (300 hours, PI: F. Mayet, co-PI: L.Perotto)
- The resolved SZ capabilities were demonstrated with NIKA the pathfinder / First results of NIKA2 clusters are promising !
- We will deliver the mean pressure profile and the Y-M scaling relation as main products (+the maps, all thermodynamical profiles and the codes)
- In addition to X-ray/SZ, we will combine with lensing, optical photometry/spectrometry, radio data to gain a consistent picture of the cluster physics → more implication on Cosmology