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NIKA2: a millimeter camera for cluster cosmology

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the NIKA2 collaboration

Outline

I. Cluster cosmology with the Sunyaev-Zeldovich (SZ) effect

II. The NIKA2 and NIKA mm cameras

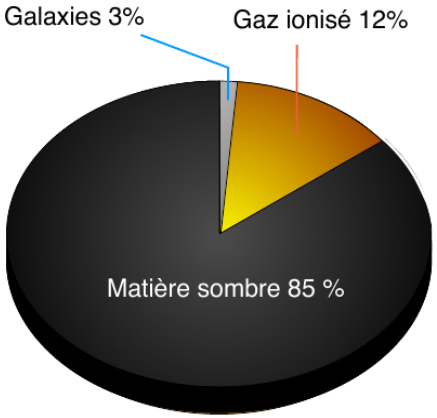
III. NIKA SZ pilot sample

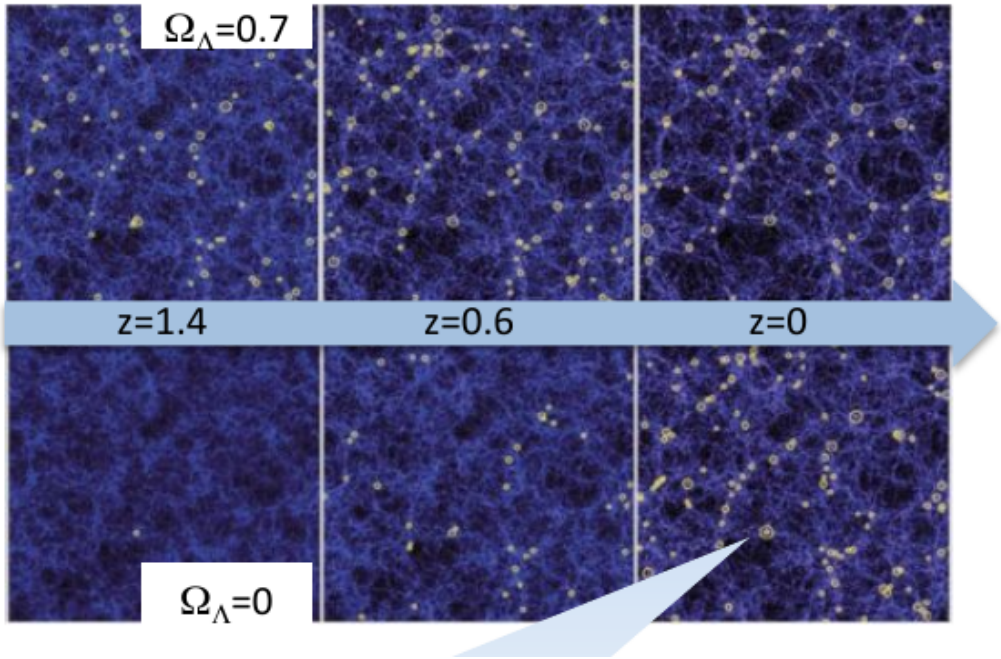
IV. NIKA2 SZ Large program

V. Conclusions

Clusters of galaxies and cosmology

- Largest gravitationally bound structures in the Univers
- Formed by gravitational collapse at the intersection of cosmic filaments, correspond to massive dark matter halos
  - Self-similar scenario: clusters are scaled copies one of each others
  - However, baryonic physics in the intercluster medium (ICM) plays a significant role
- Total mass 10^{13}-10^{16} $M_{\odot}$, redshift $0 < z < 3$
- Mass and redshift distribution of clusters is sensitive to cosmological parameters
- Various cluster observables:
  - Optical and infra-red emission: light from galaxies
  - X-ray emission: free-free emission from ICM e-
  - Sunyaev-Zeldovic effect: Inverse Compton of CMB photons and hot ICM e-
  - Radio halos: non-thermal emission



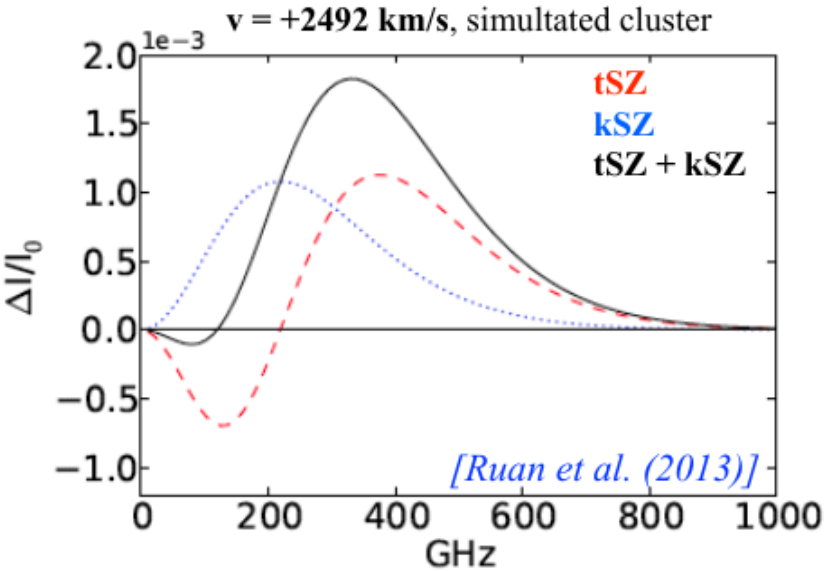


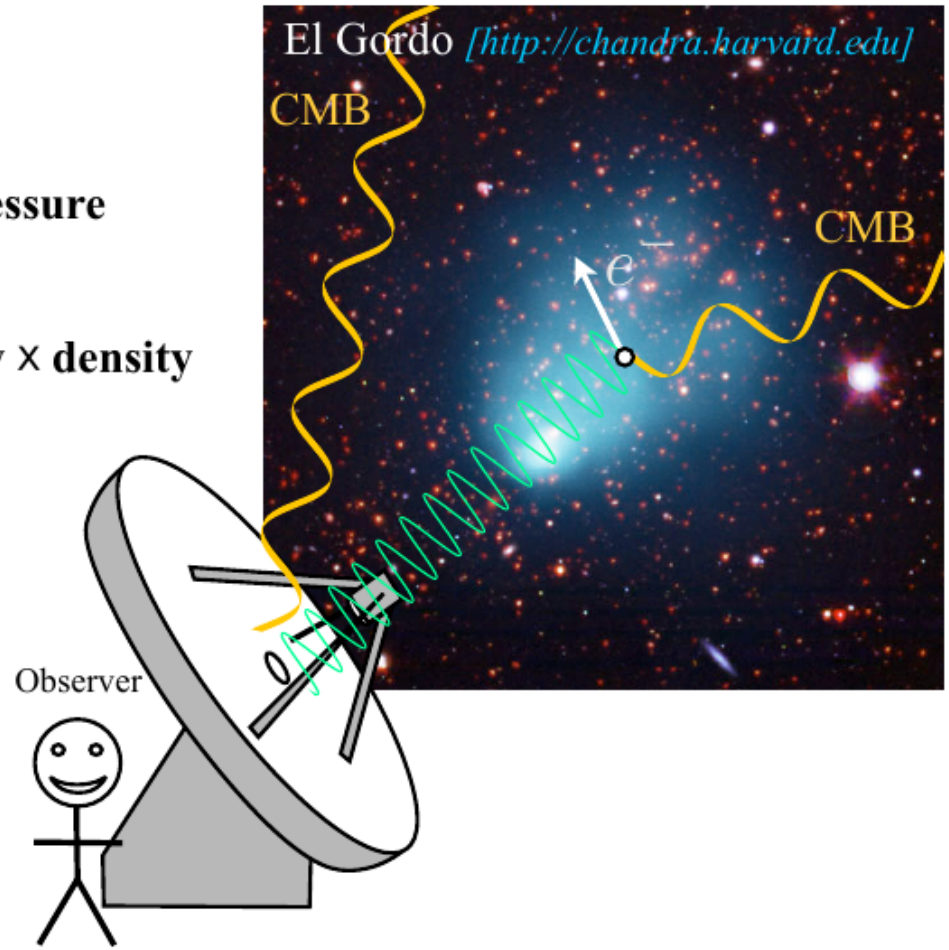
Sunyaev-Zeldovich effect

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

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

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

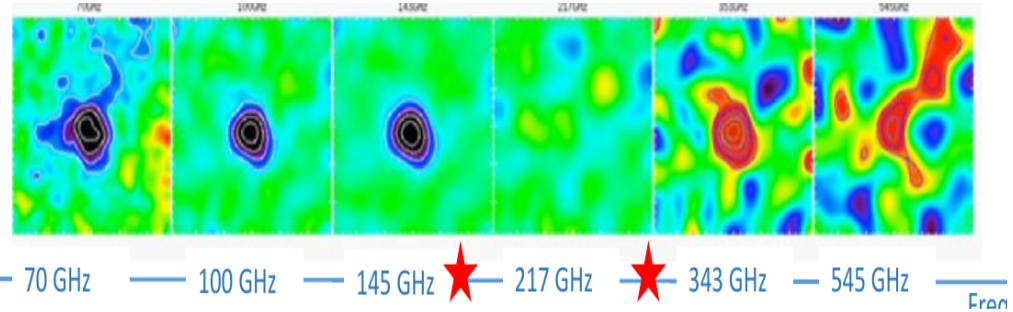




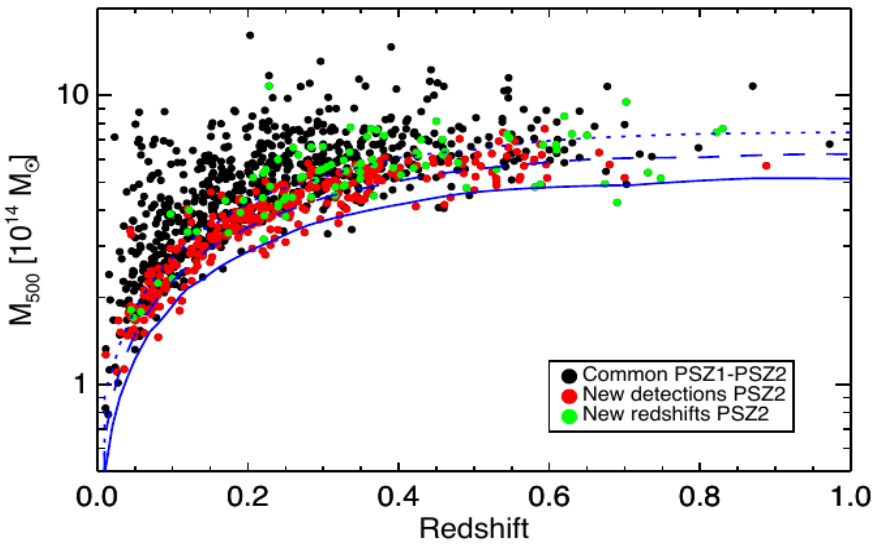
➡ **SZ = probe for intracluster gas**

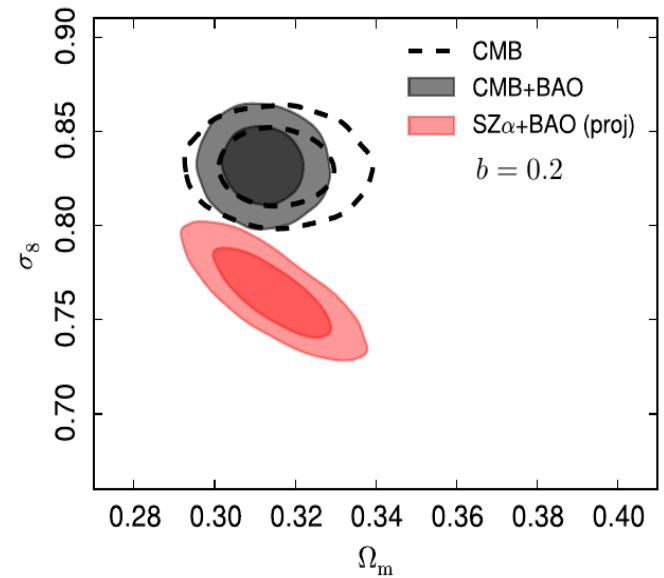
tSZ cluster cosmology

- Catalogue of 1653 tSZ detected clusters
- Redshift : optical follow-up
- Hydrostatic mass by combining tSZ flux and X-ray data : Y_{500} – M_{YX} (M_{HS})
- Charaterisation of the hydrostatic-total mass bias via simulations: $M_{HS} = (1-b)\, M_{tot}$



[Planck 2015 results XXII, XXIV, XXVII]





2-σ tension between CMB and tSZ (cluster observable) derived cosmological parameters

Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, ...

Understanding mass-observable relation

- Cluster cosmology requires accurate mass and matter distribution estimates
- Two complementray approaches :

WL masses	vs	baryonic mass proxies
no bias !!?		unknown bias
large scatter		low scatter

Weak lensing provides absolute mass normalisation

Many observational efforts :
CCCP, Weighing the Giants, 400d WL, CFHTLenS, 400d WL, LoCuSS, WISCy

LSST + EUCLID 2021 -->

$Y - M_{tot}$ & $P(r)$

bias, scatter, evolution **vs** dynamics, z

Cluster detection

X-rays : e-ROSITA
SZ : SPT-3G (2016-2019), Advanced ACTPOL

Scaling relations

X-rays : XMM, Chandra
SZ : **NIKA2 (2017-2021),** MUSTANG2 (2018),

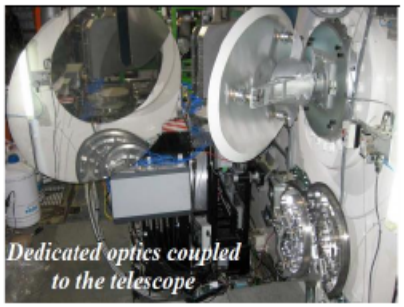
Mainly low redshift cluster data available, and we expect some evolution with redshift

Multi-wavelength high resolution observations of high redshift clusters are needed

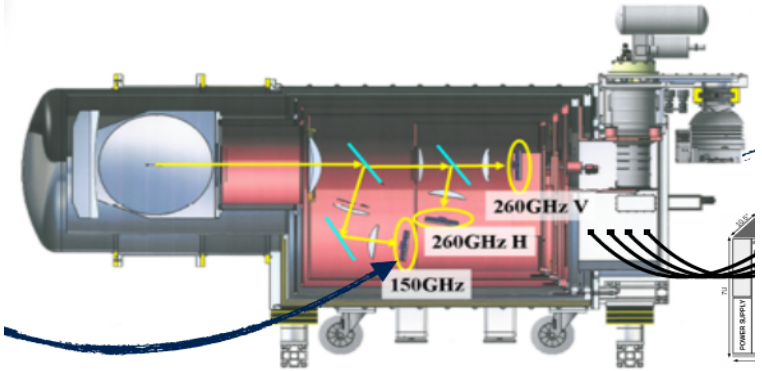
The NIKA2 camera

Dual band mm KID camera operating and 150 and 260 GHz

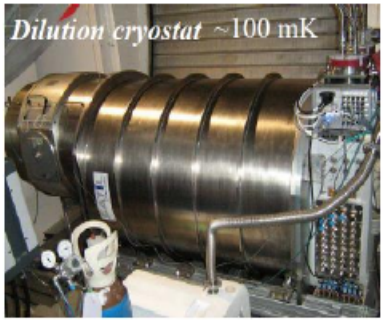
IRAM 30-m telescope
at Pico Veleta (Spain)



Specific optical system to obtain the largest FOV

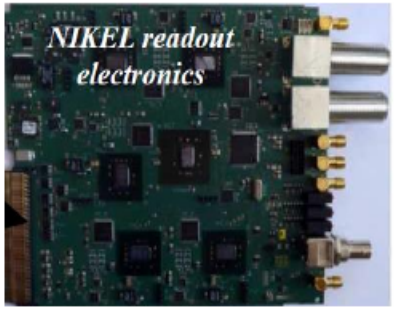


Dilution cryostat:
180 mK nominal temperature



Arrays of 1140 (616) KIDs:
8 (4) independent feedlines
with up to 200 KID each

300 multiplexing factor



20 boxes (one per feedline) arranged in 3 crates (one per array)

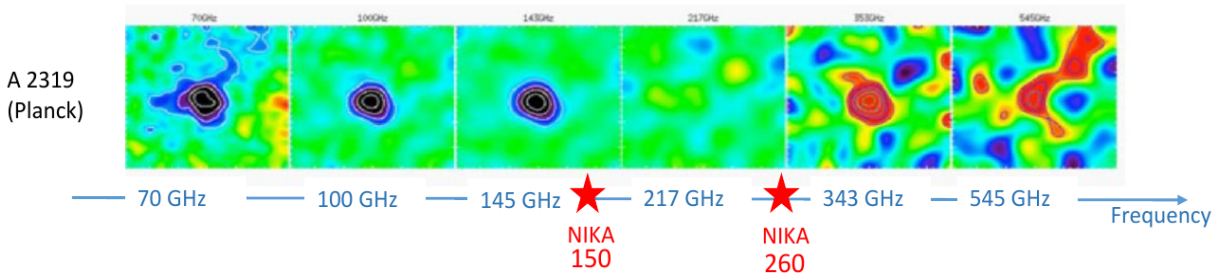
The NIKA2 camera

- September 2015 : installation at IRAM
- October 2015 : First lights
- September 2016 : complete instrumental setup
- April 2017 : commissioning succesfully finished ; performance better than expected
- Open to for public observations for at least one decade from now

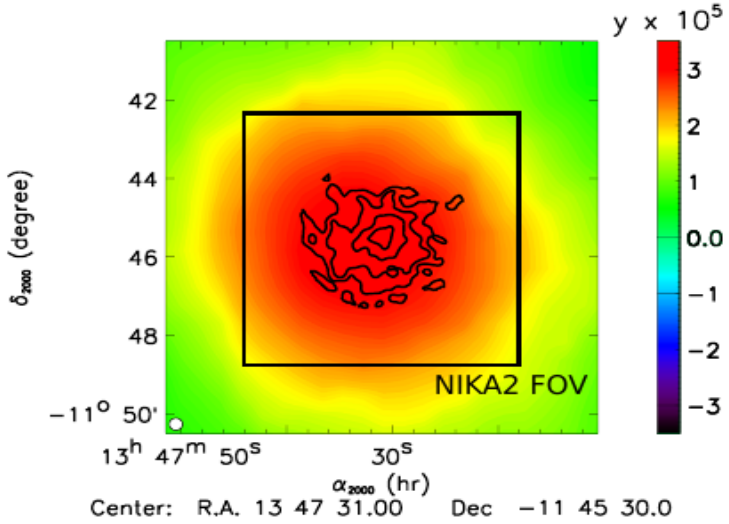
Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	6 mJy/s$^{1/2}$	20 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

[NIKA collaboration, 2017]

NIKA2 is well adapted for SZ observations of intermediate and high redshift clusters

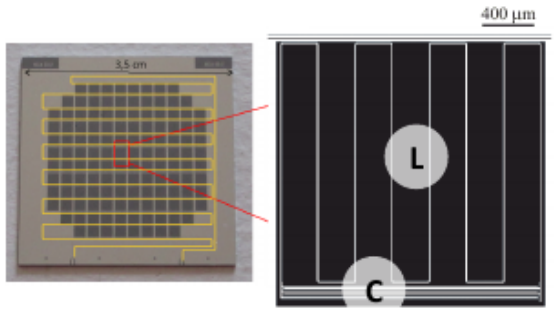


- Two frequency bands, negative & zero tSZ signal
- Large FOV : size of PLANCK beam
- High resolution : 17 times better than Planck



The NIKA camera

- prototype of NIKA2
- operated at the IRAM 30 m telescope from 2009-2014
- Dual band camera with 336 KIDs
- Polarisation capabilities in both bands
- First KID based camera to provide scientific grade results



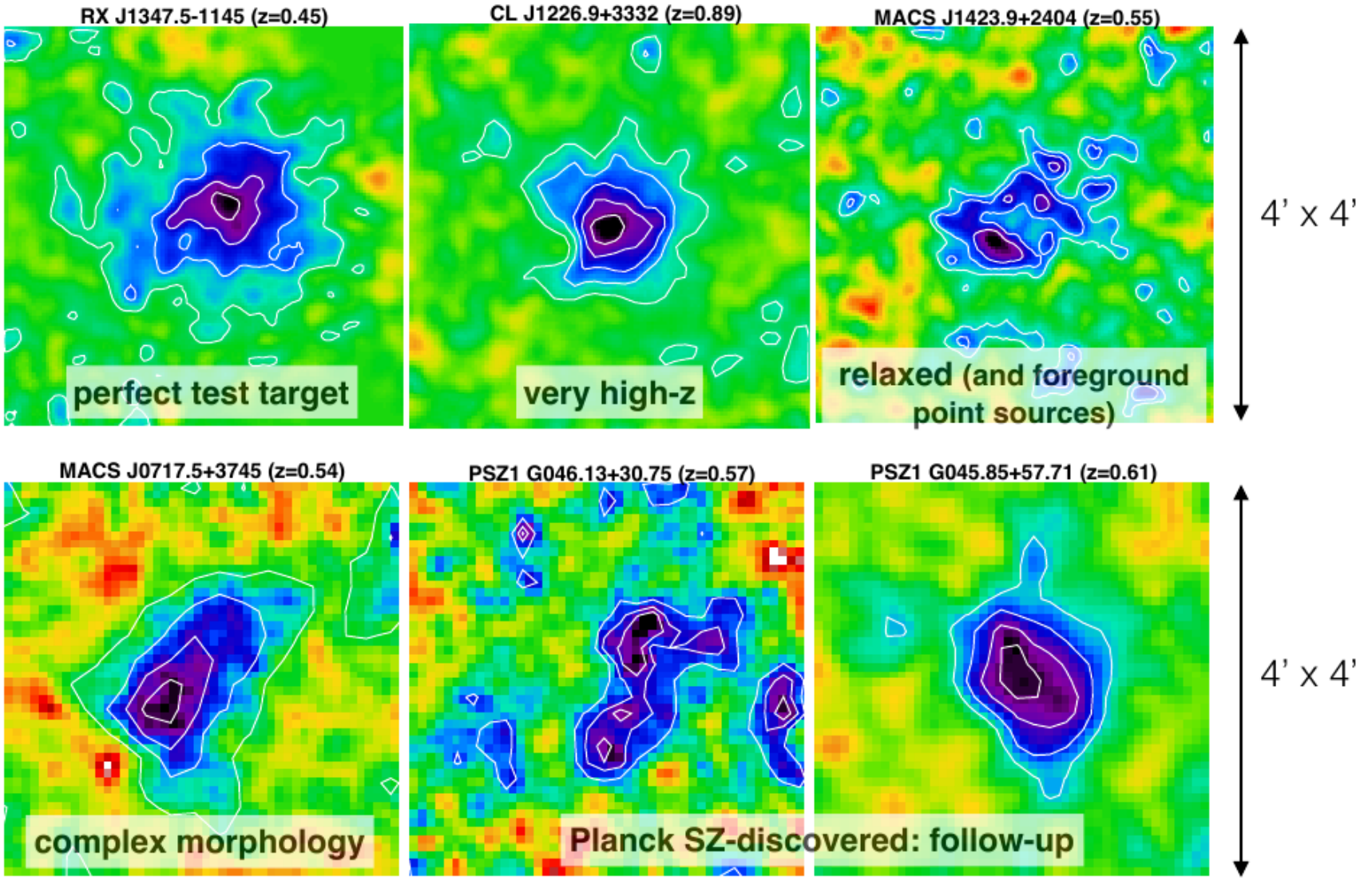
NIKA	150 GHz	260 GHz
# KIDs	132	224
FOV diameter	1.8 arcmin	2.0 arcmin
Sensitivity	14 mJy/s$^{1/2}$	40 mJy/s$^{1/2}$
Angular res.	18 arcsec	12 arcsec

[Adam & NIKA collaboration, 2014, Catalano & NIKA collaboration 2014]

NIKA2	150 GHz	260 GHz
# KIDs	616	2 x 1140
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	6 mJy/s$^{1/2}$	20 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

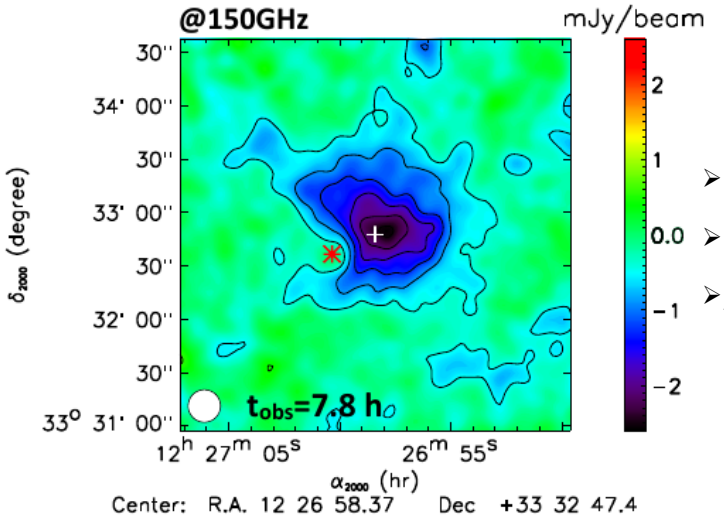
[NIKA2 collaboration, 2017]

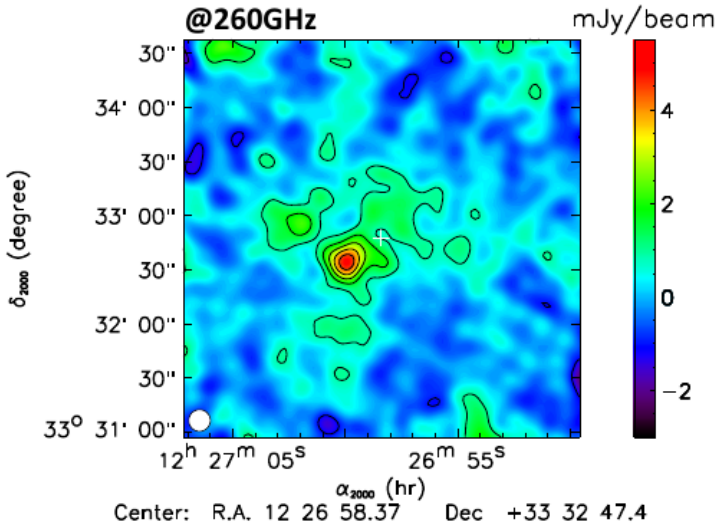
NIKA SZ pilot sample



[Adam & NIKA collaboration, 2014, 2015.2016,2017]Ruppin & NIKA collaboration 2017]

High redshift cluster (z=0.89)

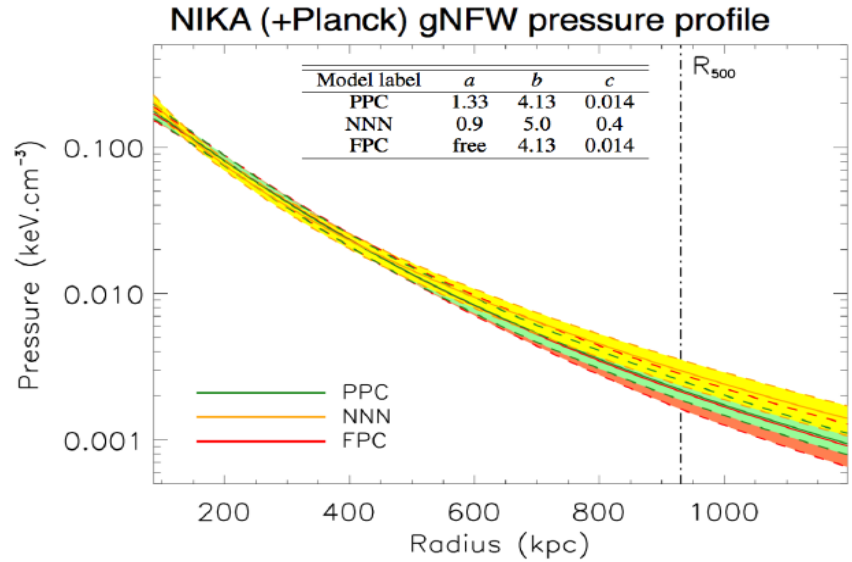


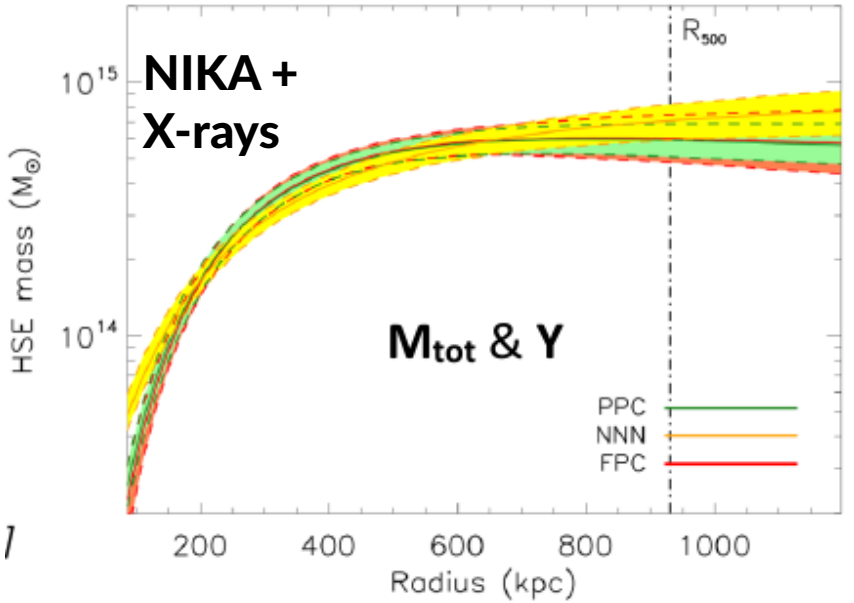


CL1226.8+3332

- Relaxed and massive
- 18-σ peak detection
- Strong point source

Measure cluster thermodynamic properties and HSE mass





[Adam & NIKA collaboration, 2015]

MACS J0717-3745 and kSZ

- High sensitivity NIKA data (12 hours on source)
  + High quality X-ray, optical and IR data

- However, mapping kSZ is very challenging:

  Complex system (5 subclusters
  Foreground emission
  Degeneracy relativistic tSZ and kSZ

- Use the two NIKA channel maps
  + temperature map from X-rays

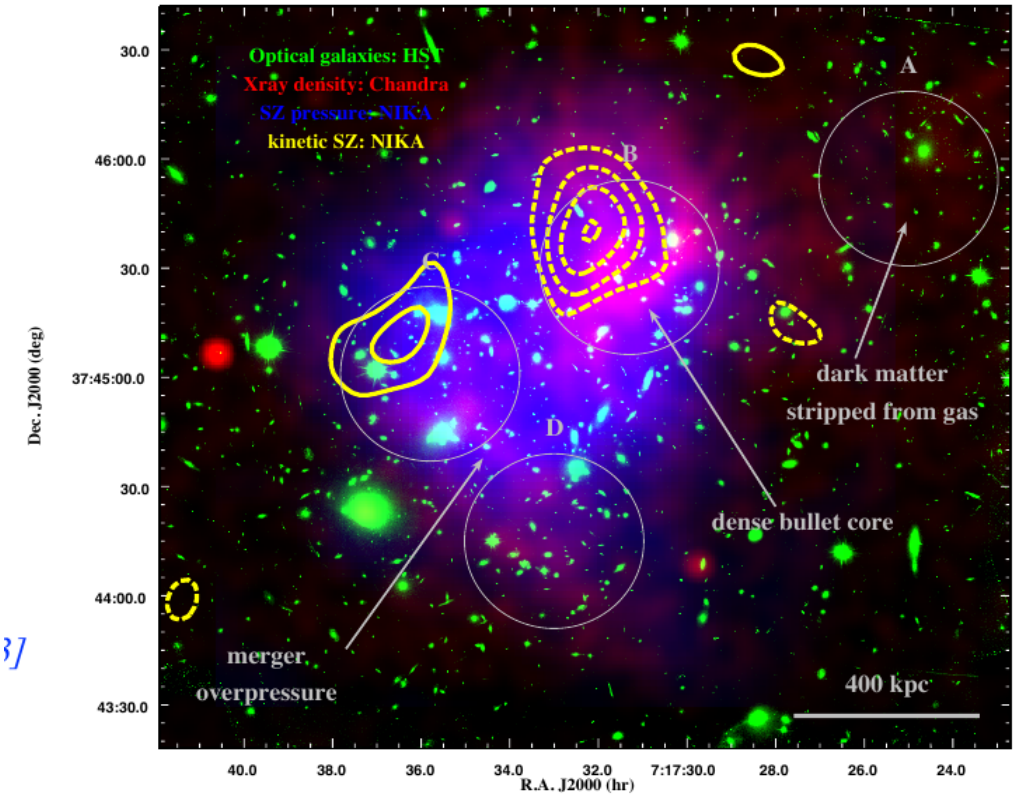
$$\frac{\Delta I_\nu}{I_0} = f_\nu \; y_{\mathrm{tSZ}} + g_\nu \; y_{\mathrm{kSZ}}$$

spectral dependencies

gas pressure

gas velocity and density

MACS J0717-3745



[Adam & NIKA collaboration, 2016]

kSZ mapping with NIKA

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  + High quality X-ray, optical and IR data
- However, mapping kSZ is very challenging:

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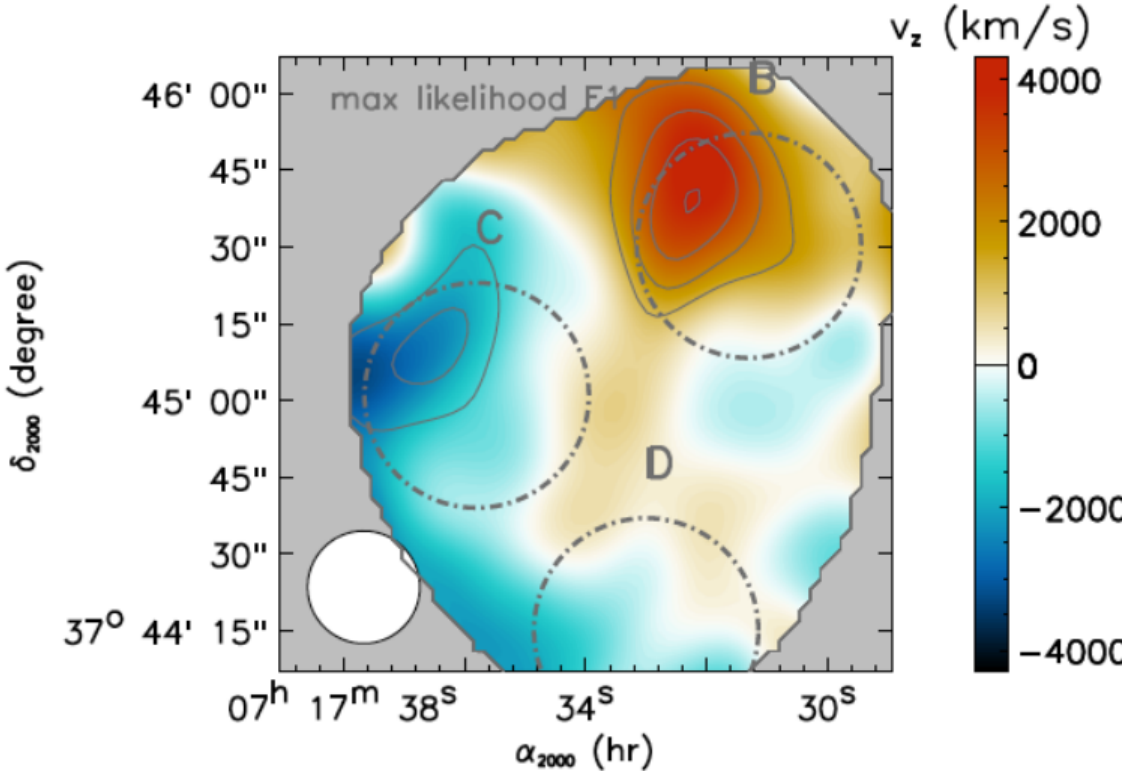
$$\frac{\Delta I_\nu}{I_0} = f_\nu \, y_{\rm tSZ} + g_\nu \, y_{\rm kSZ}$$

spectral dependencies

gas pressure

gas velocity and density

MACS J0717-3745 velocity map



First direct mapping of kSZ emission

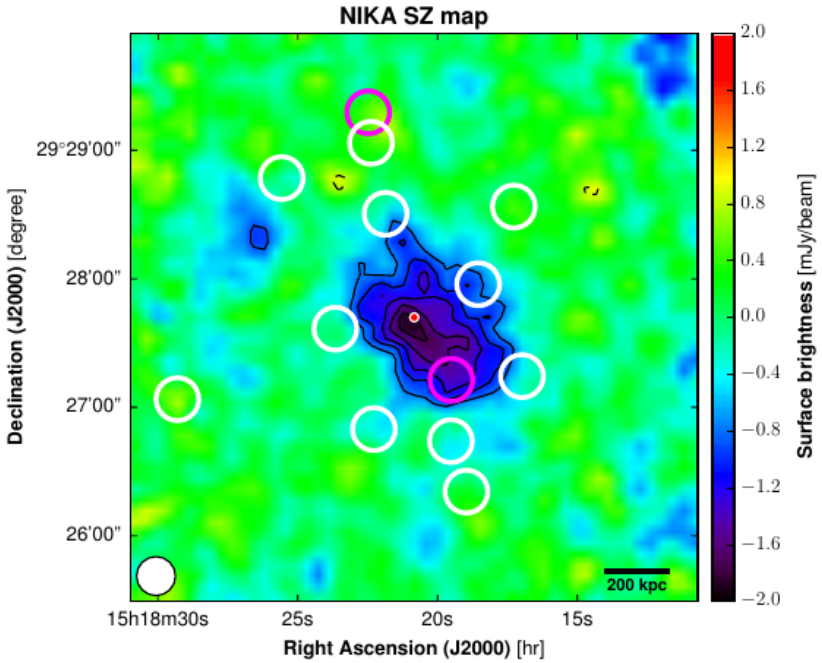
[Adam & NIKA collaboration, 2016]

[Adam & NIKA collaboration, 2016]

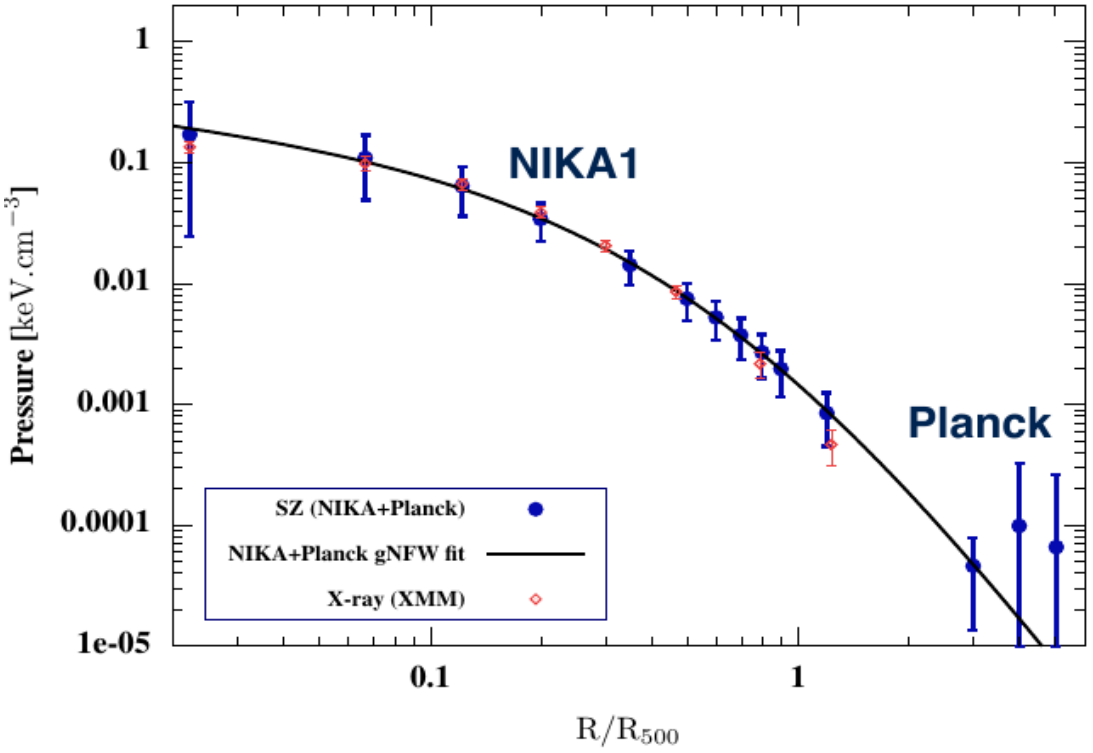
Follow-up of Planck clusters

PSZ1 G045.85+57.71

- Planck tSZ detected cluster at high redshift, z = 0.61
- 5h41m observations with NIKA1 in moderate weather conditions

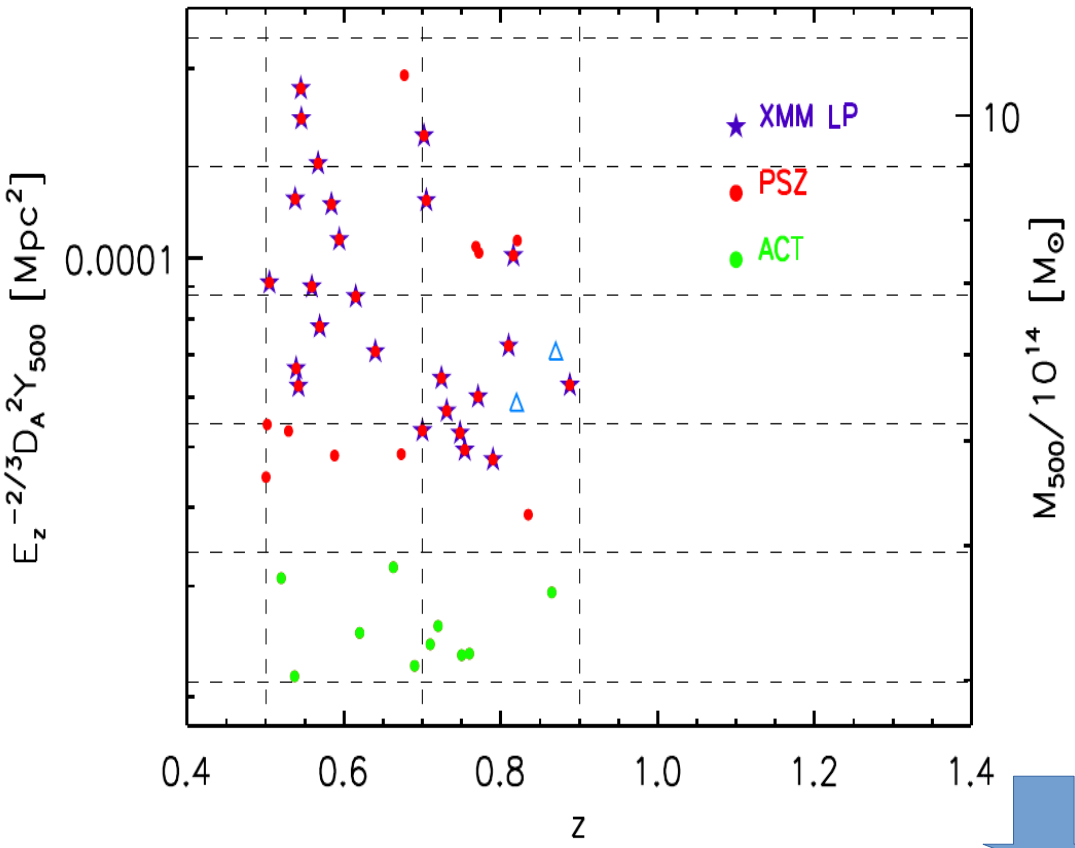


[Ruppin & NIKA collaboration, 2017]



First non-parametric reconstruction of the pressure profile for high redshift cluster

NIKA2 SZ Large program



One of the 5 NIKA2 LP (1300h in total)

- **300 hours** of tSZ observation
- **50 high redshift clusters 0.5 < z < 1.0**
- tSZ selected clusters from Planck and ACT catalogues

Ancillary data

- X-ray follow-up with XMM
- Optical data using GranTeCan
- MUSIC hydrodynamic simulations

Main goals

- In-depth study of ICM
- Thermodynamic properties: pressure, density, temperature and entropy profiles
- Mass – tSZ flux relationship

Redshift evolution of:

- Thermodynamic quantities profiles
- Scaling laws and hydrostatic bias

Variation of cluster properties with:

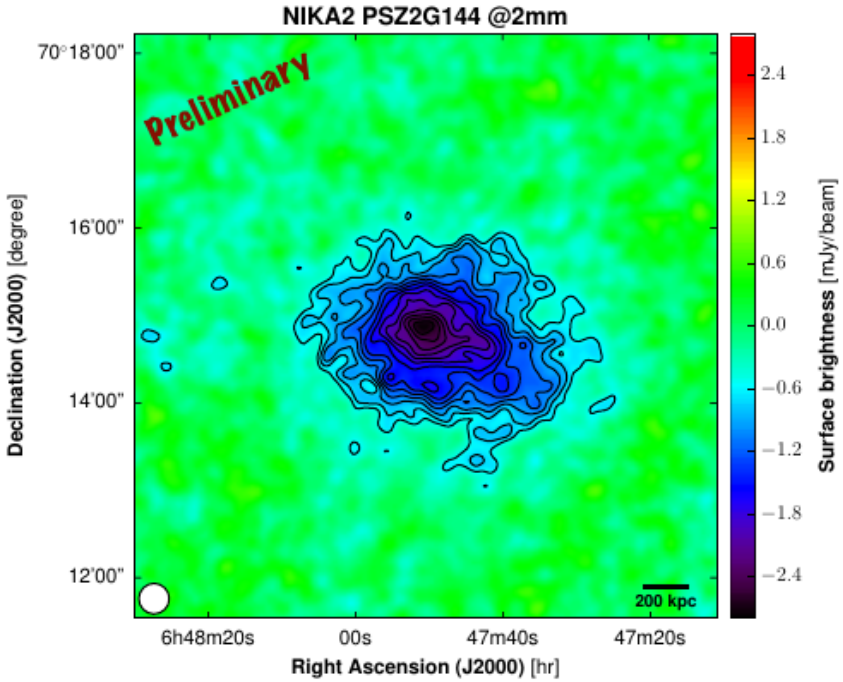
- Dynamical state (mergers)
- Morphology (ellipticity)

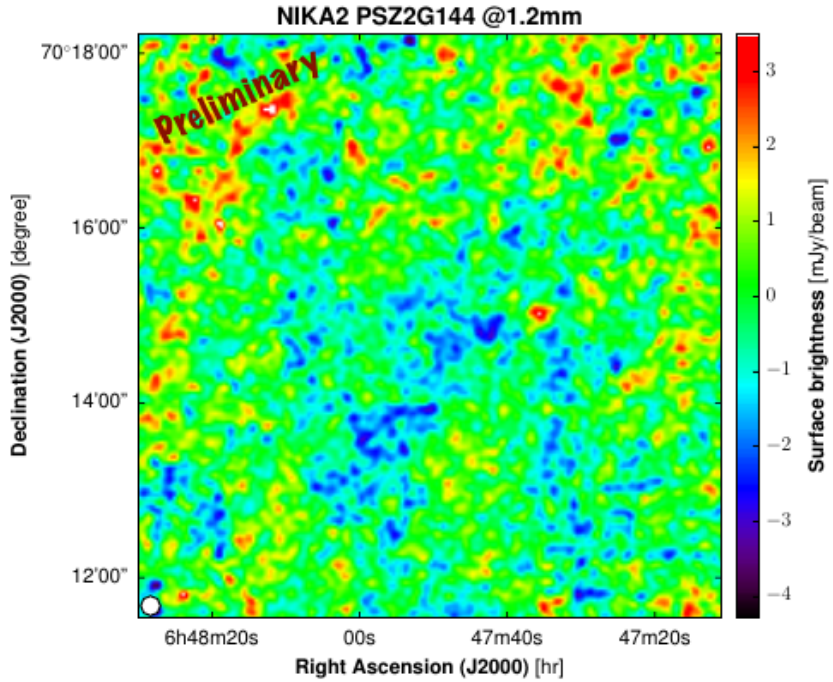
First NIKA2 SZ LP cluster

PSZ2 G144

- Planck tSZ detected cluster at redshift, z = 0.58, high mass M_{500} = 7.8 x 10^{14} $M_{\odot}$
- 11h observations with NIKA1 in poor weather conditions (atmospheric opacity 0.3@225 GHz)
- Already observed: SZ – Mustang & Bolocam, X-rays - XMM

[Ruppin et al, 2018]





Very promising results, detailed analysis on going

Conclusions

- Clusters of galaxies provide a cosmological probe of choice
- SZ effect opens a new window for the detection, study and cosmological use of clusters of galaxies
- Recent CMB experiments like Planck, ACT and SPT have released large catalogs of tSZ detected clusters making SZ cosmology possible
- SZ cluster cosmology, as for any other cluster observable, is limited by the knowledge of the mass-observable scaling relations
- High resolution SZ resolution observations of high redshift clusters are needed to check possible redshift evolution of cluster properties
- NIKA2, installed at the Pico Veleta 30 m telescope, is the largest mm camera to-date and will provide high resolution SZ observations of clusters via dedicated large program
- The success of the pilot SZ sample observations with NIKA, the NIKA2 prototype, points to the feasibility of the NIKA2 SZ LP
- We just finished NIKA2 commissioning and first SZ results are very promising

NIKA

http://ipag.osug.fr/nika2

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