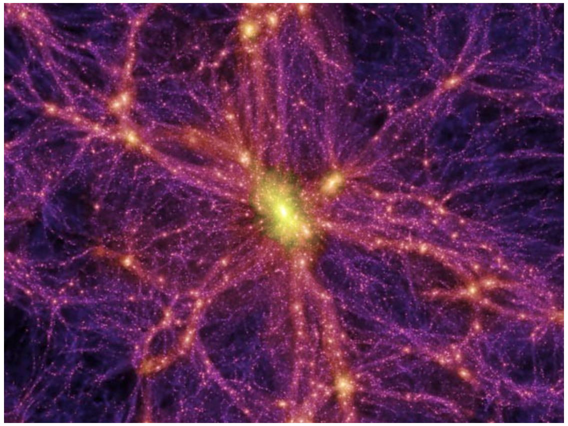
NIKA2
a millimeter camera for cluster cosmology

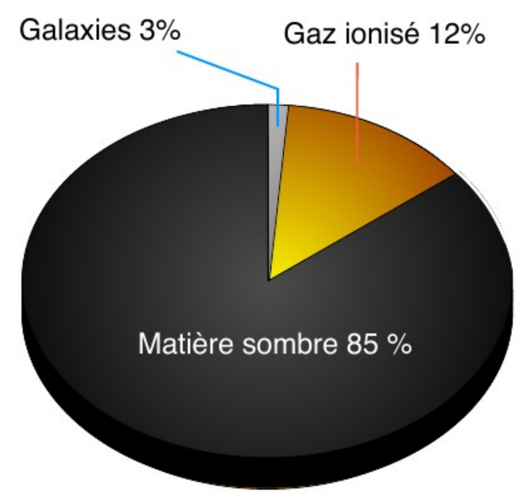
J.F. MACÍAS-PÉREZ

on behalf of the NIKA2 collaboration

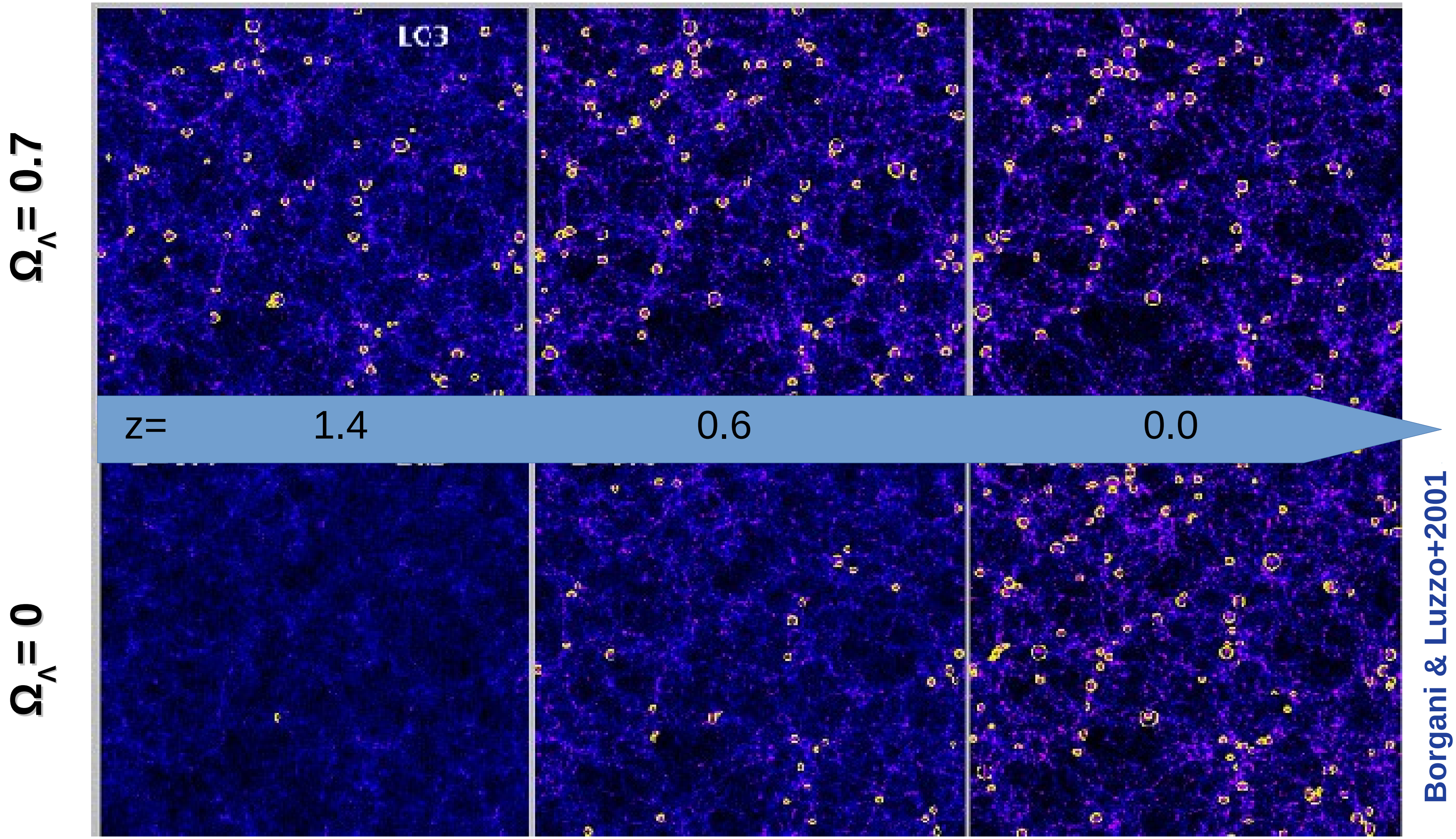
Clusters of galaxies



- 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 plays a significant role
- First observed by Zwicky in 1930's who inferred that their total mass was larger than the sum of its luminous components
- Largest gravitationally bound structures in the Universe
  - Dominated by dark matter
  - Most baryonic matter is in the form of gas, the Inter Cluster Medium (ICM)
  - Galaxies count for only 3 % of the total mass
- Total mass 10^{13}- 10^{16} $M_{\odot}$, redshift $0 < z < 3$



Cosmology with clusters



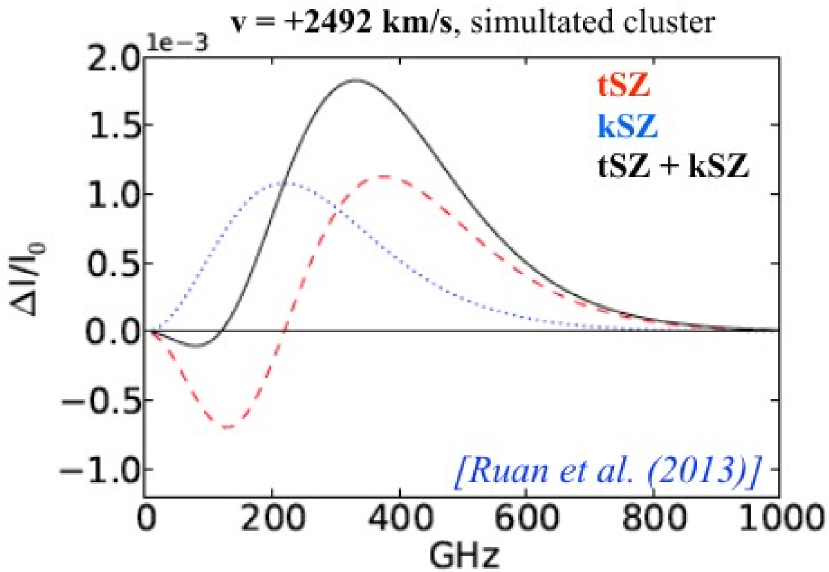
Cluster distribution in mass and redshift depends on cosmological parameters

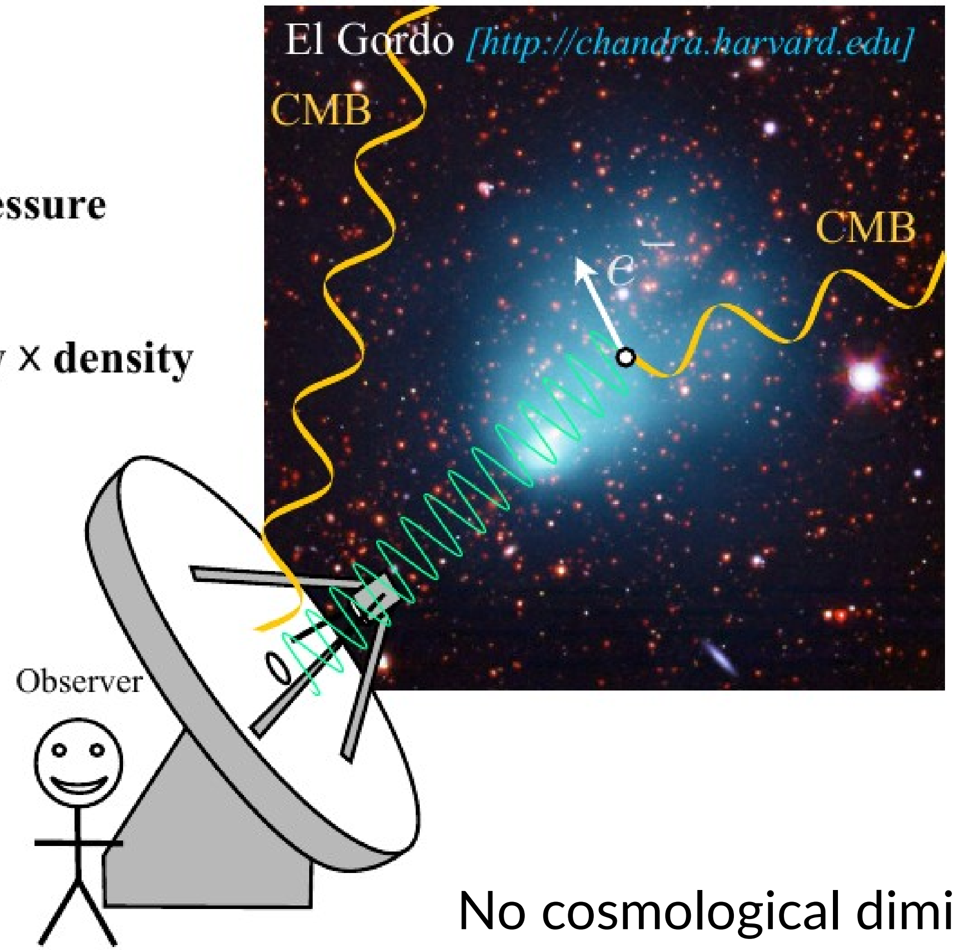
Sunyaev-Zeldovich effect

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

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

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



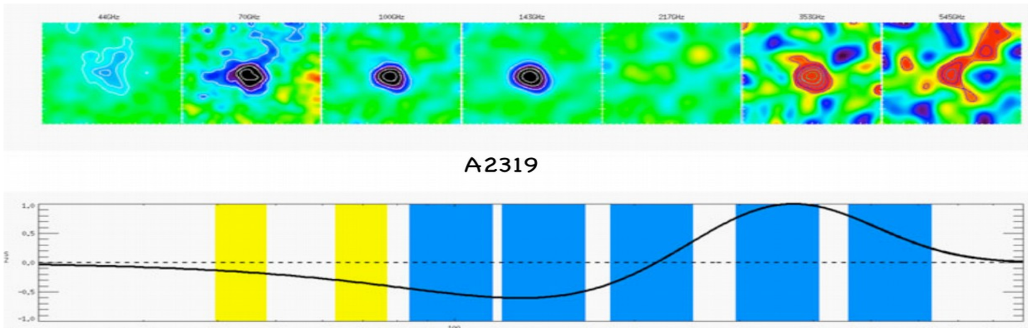


No cosmological diming

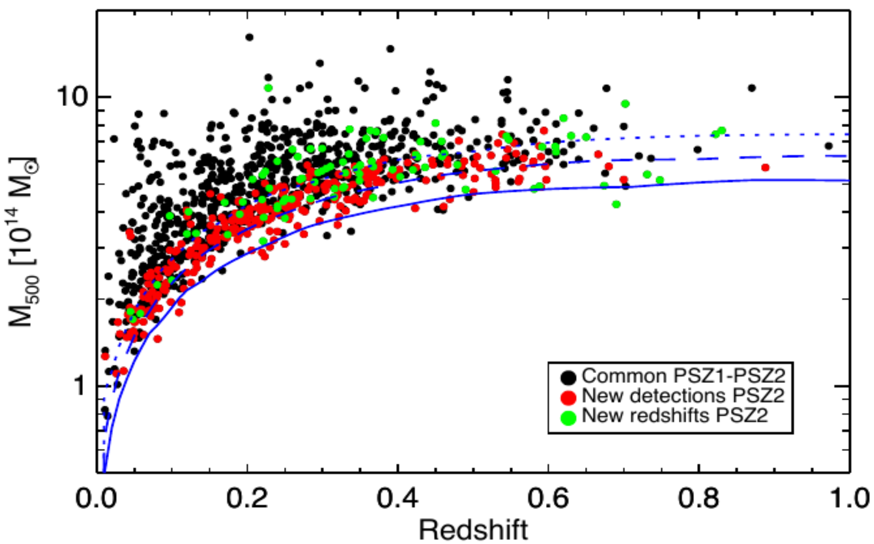
➡ **SZ = probe for intracluster gas**

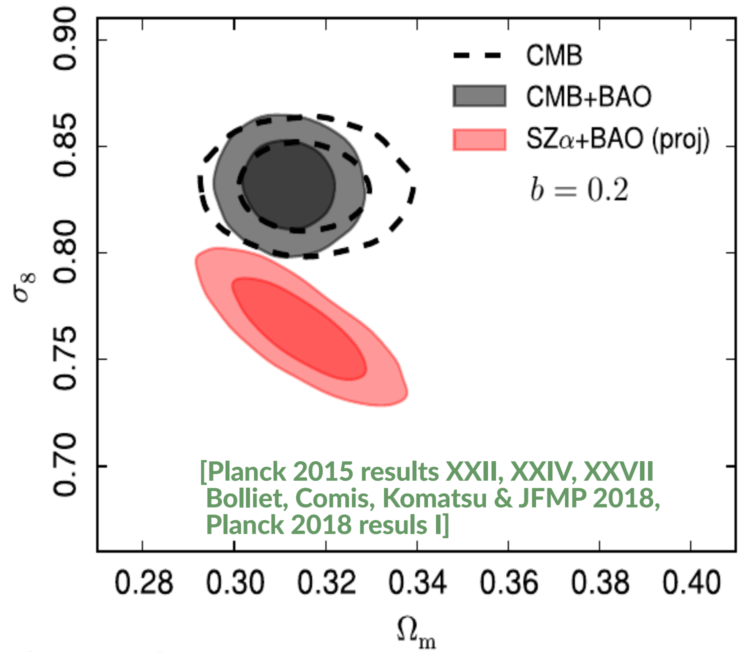
tSZ cluster cosmology

- 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: $M_{HS} = (1\text{-}b)\ M_{tot}$



Number of clusters as function of redshift and mass is very sensitive to comology





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, ...

tSZ cluster cosmology

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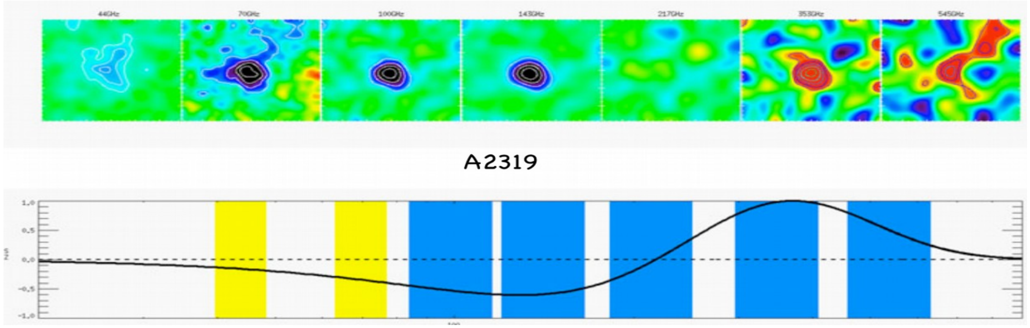

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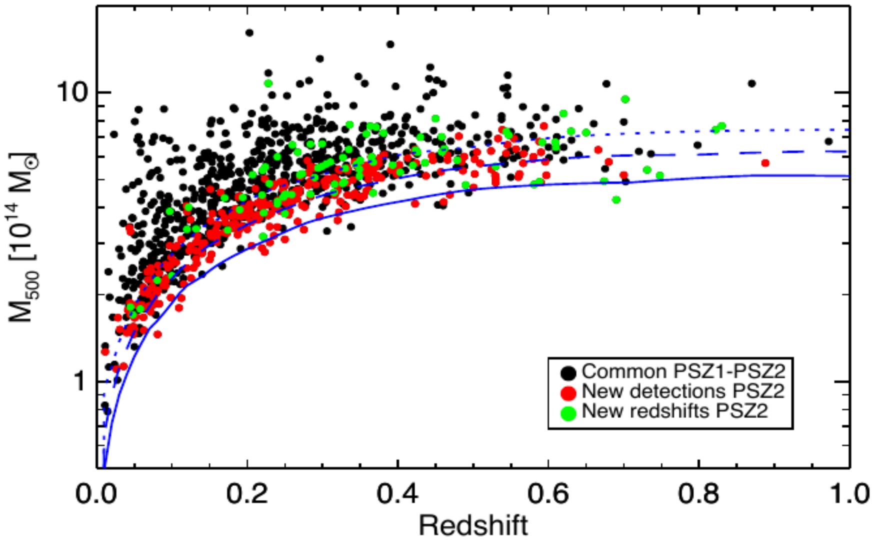
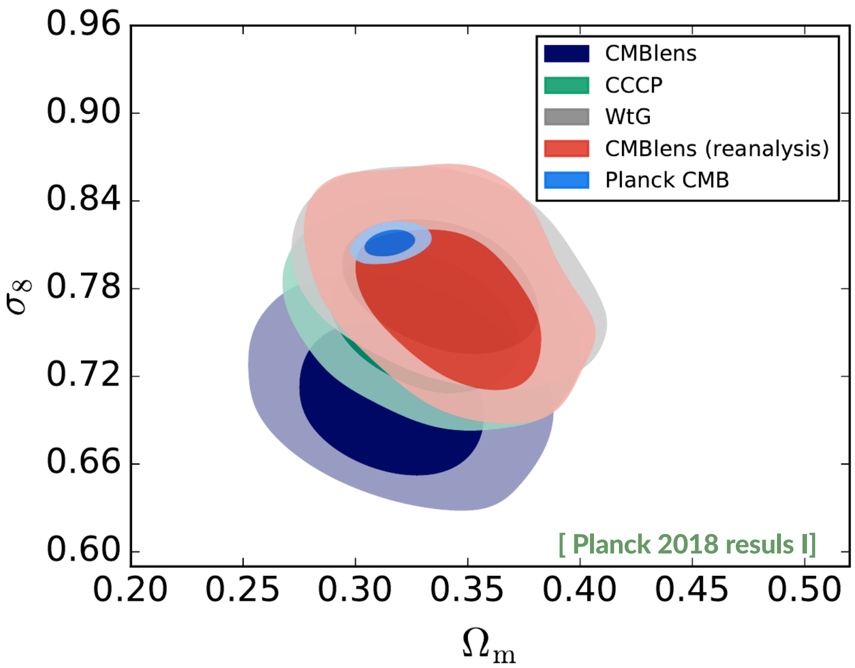




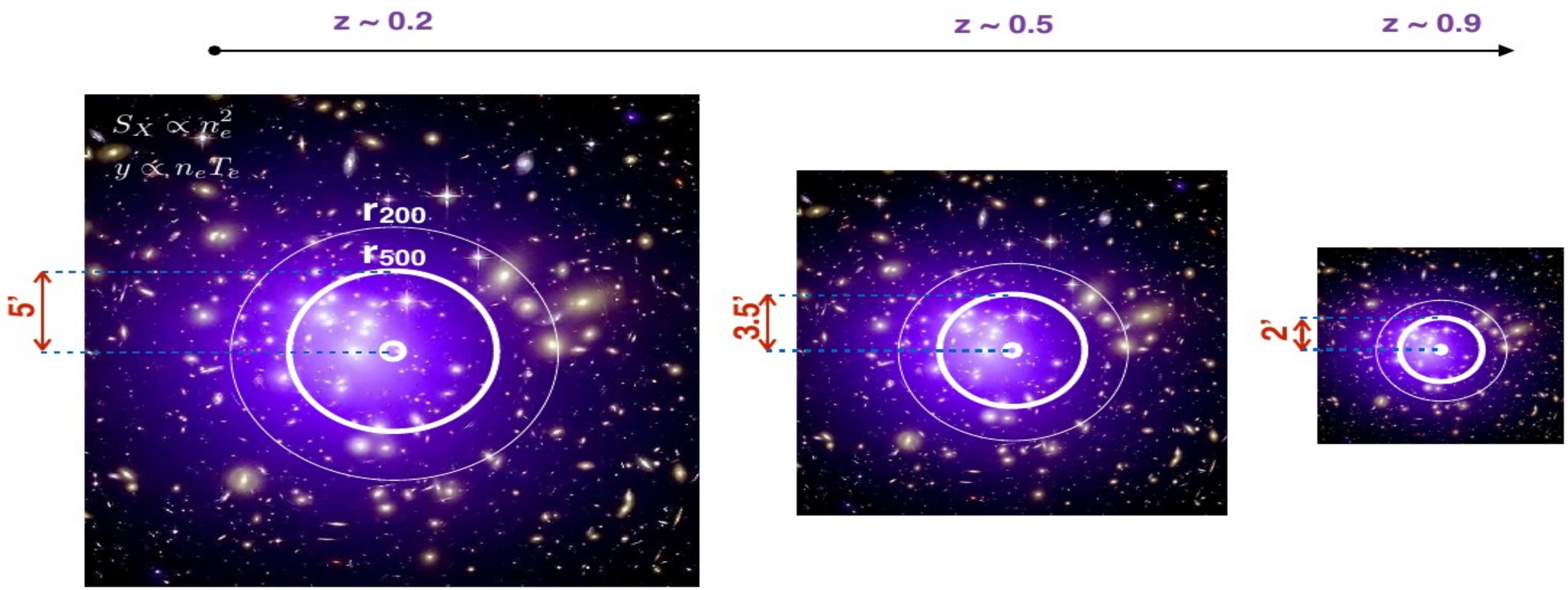
2-σ tension between CMB and tSZ (cluster observable) derived cosmological parameters

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

High redshift evolution ?

- Planck can only resolve low reshift clusters

- High redshift clusters are at the early stages of formation and may not behave like low redshift ones: merging processes and shocks, undefined outskirts, evolution of scaling relations, non hydrostatic equilibrium, etc



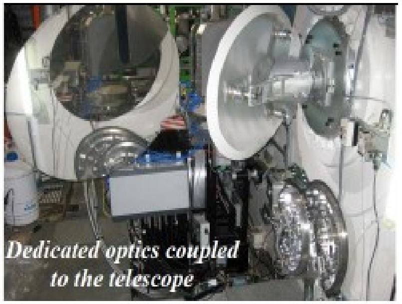
Multi-wavelength high resolution observations of high redshift clusters are needed to identify possible evolution of cluster properties with redshift

The NIKA2 camera

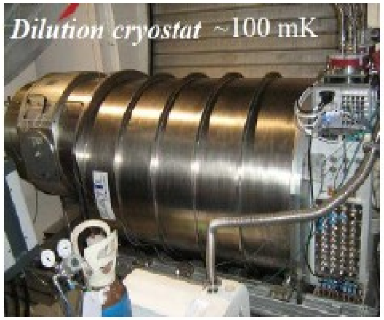
Dual band mm KID camera operating and 150 and 260 GHz

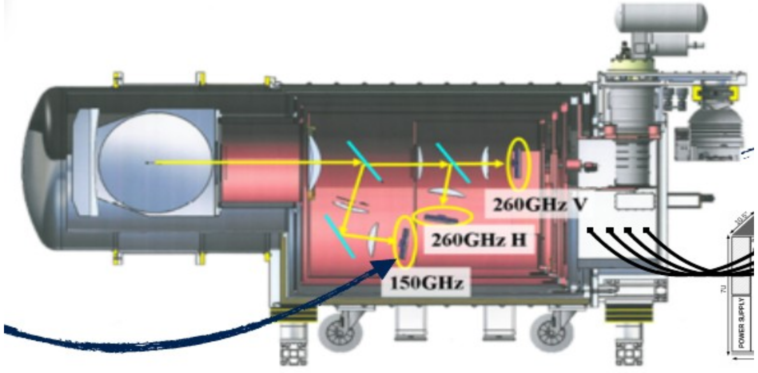
IRAM 30-m telescope
at Pico Veleta (Spain)

Specific optical system to
obtain the widest field



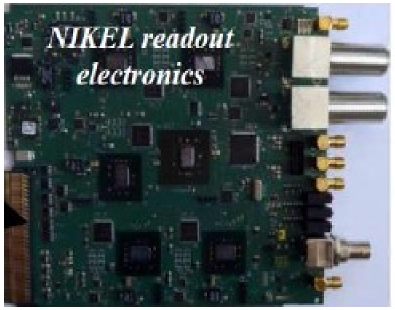
Dilution cryostat:
180 mK nominal
temperature





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

300 multiplexing factor



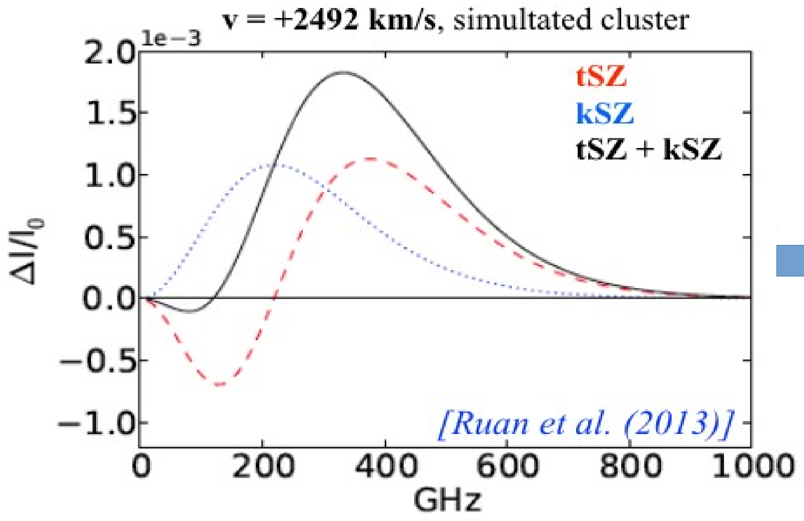
20 boxes (one per feedline)
arranged in 3 crates (one per
array)

NIKA2

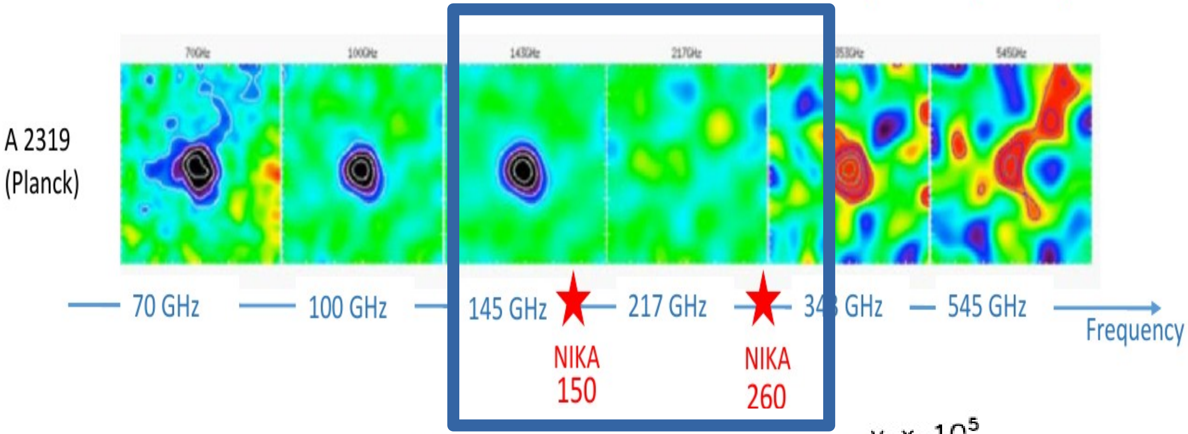
Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	8±1 mJy/s$^{1/2}$	33±2 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

SZ effect with NIKA2

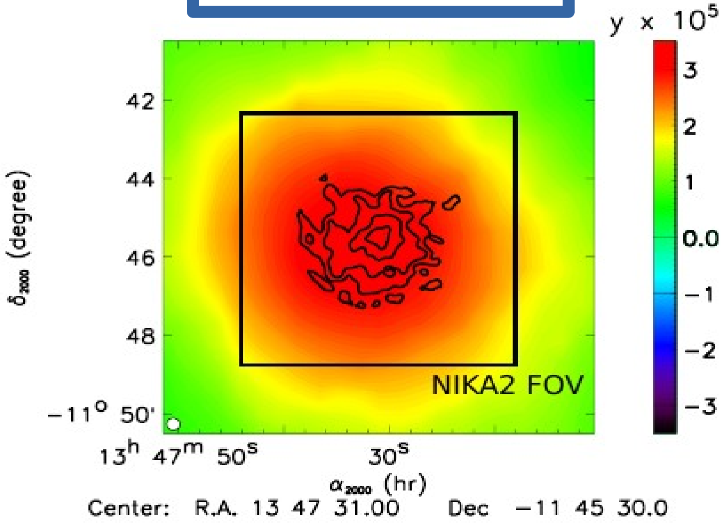
NIKA2 is a perfect instrument for the tSZ effects in clusters of galaxies



Two frequency bands, negative & zero tSZ signal

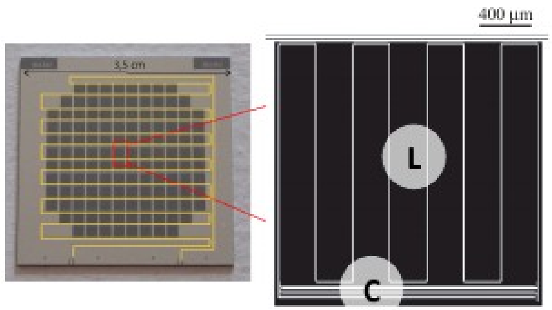


- Wide-field: size of PLANCK beam
- High resolution : 17 times better than Planck



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



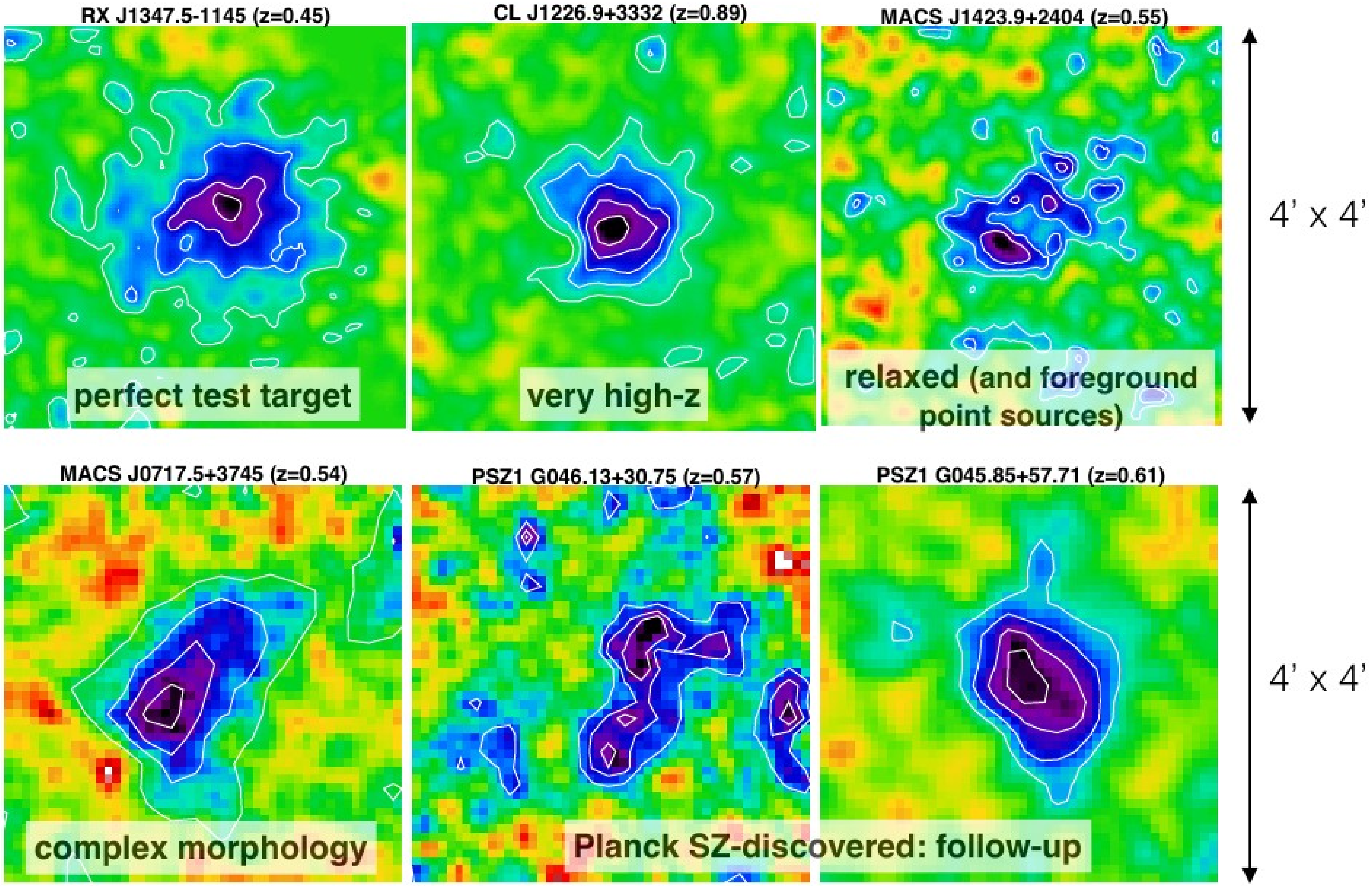
NIKA	150 GHz	260 GHz
# KIDs	132	224
FOV diameter	1.8 arcmin	2.0 arcmin
Sensitivity	14 $mJy/s^{1/2}$	40 $mJy/s^{1/2}$
Angular res.	18 arcsec	12 arcsec

[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 for cluster physics



[Adam & NIKA collaboration, 2014, 2015,2016,2017 Ruppin & NIKA collaboration 2017, Romero & NIKA collaboration 2017]

MACS J0717-3745 tSZ 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

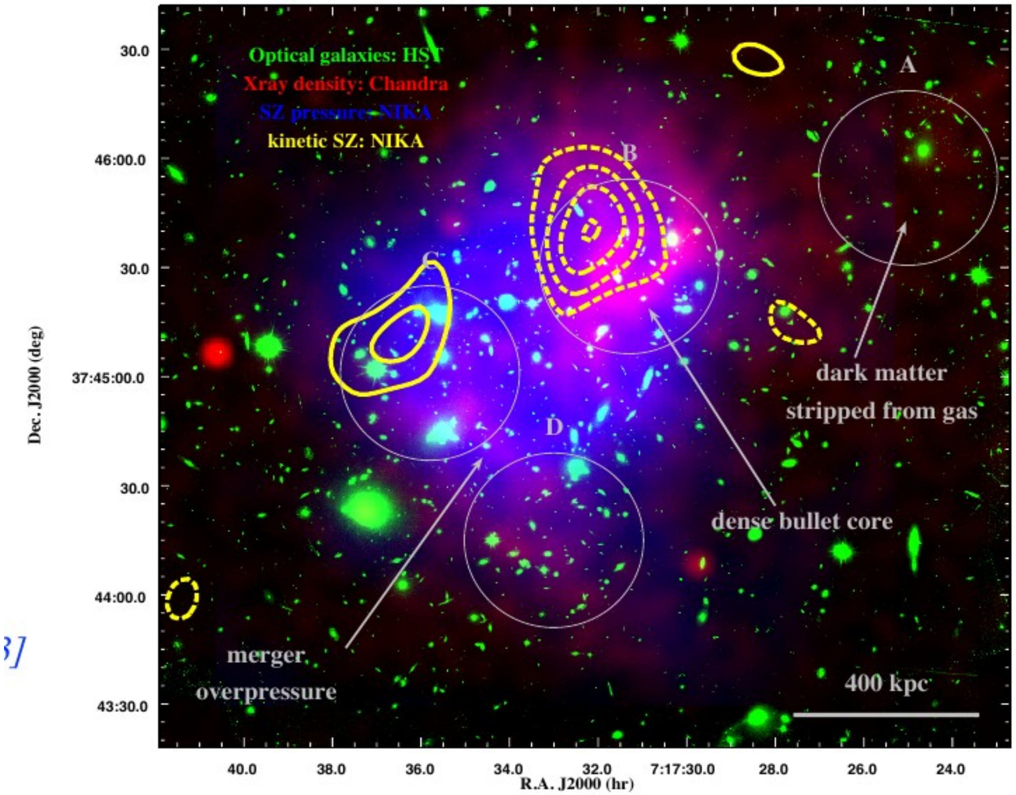
- Use the two NIKA channel maps
  + temperature map from X-rays

spectral dependencies

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

gas pressure — *gas velocity and density*

MACS J0717-3745



[Adam & NIKA collaboration, 2016]

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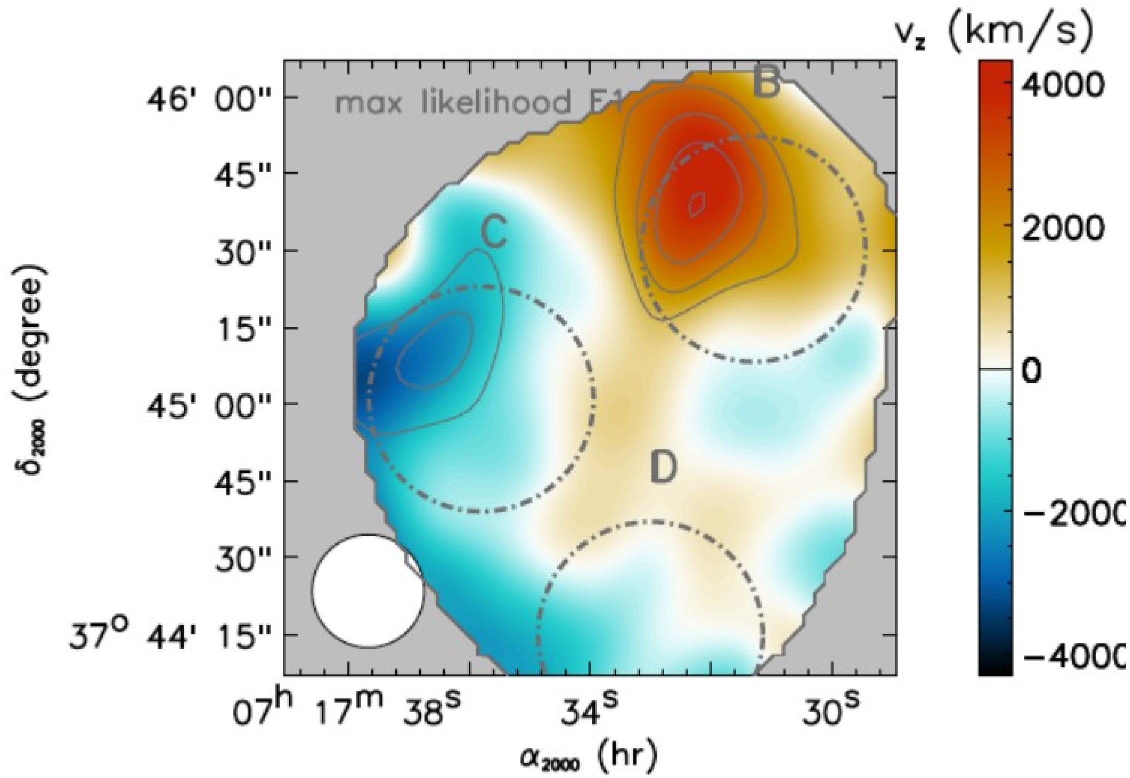
[Adam & NIKA collaboration, 2016]

MACS J0717-3745 velocity map

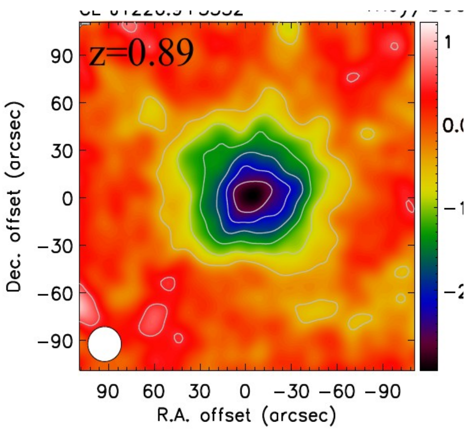


First direct mapping of kSZ emission

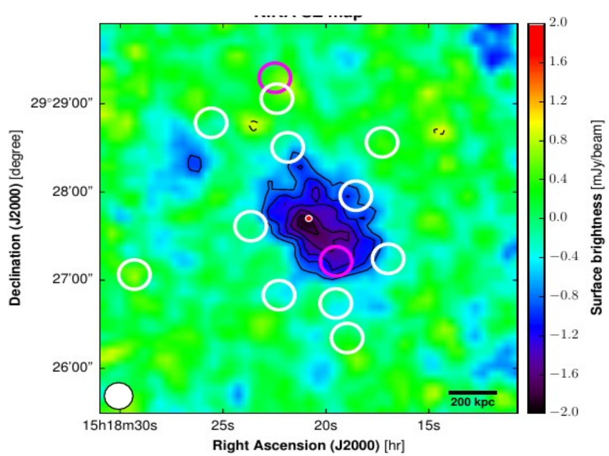
[Adam & NIKA collaboration, 2016]

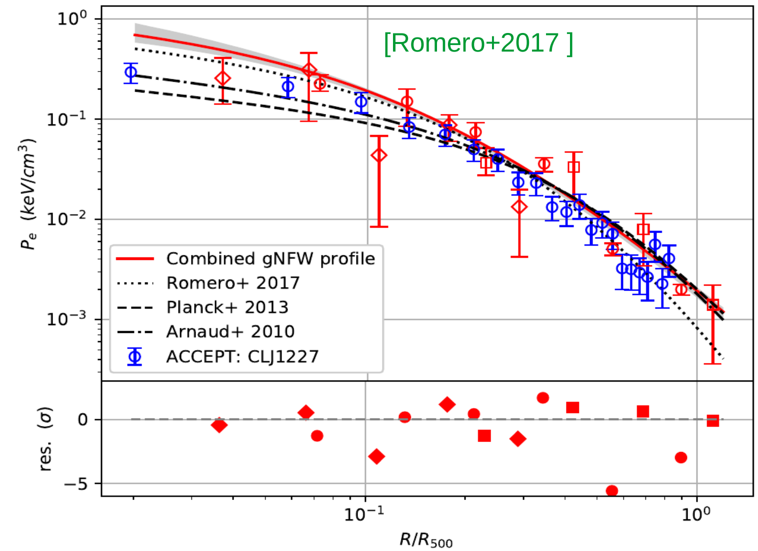
Follow-up of Planck clusters

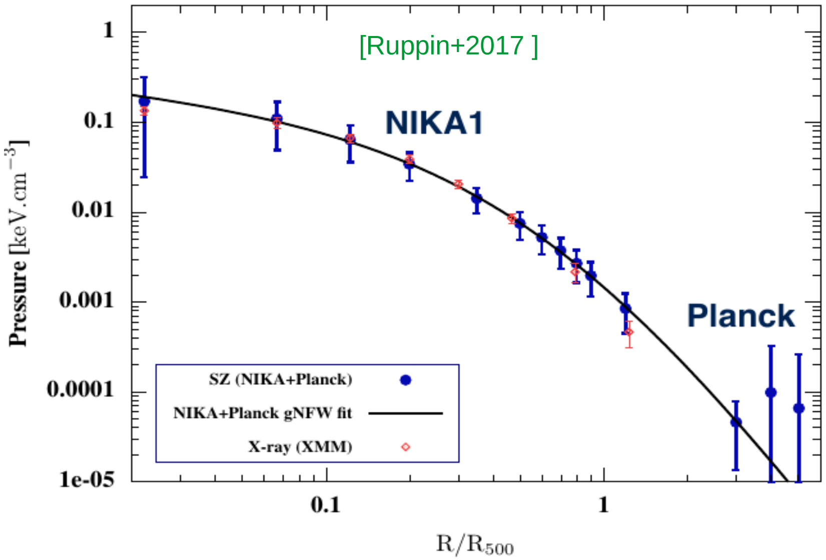
CLJ1226.29+33.32, z = 0.89



PSZ1 G045.85+57.71, z = 0.61

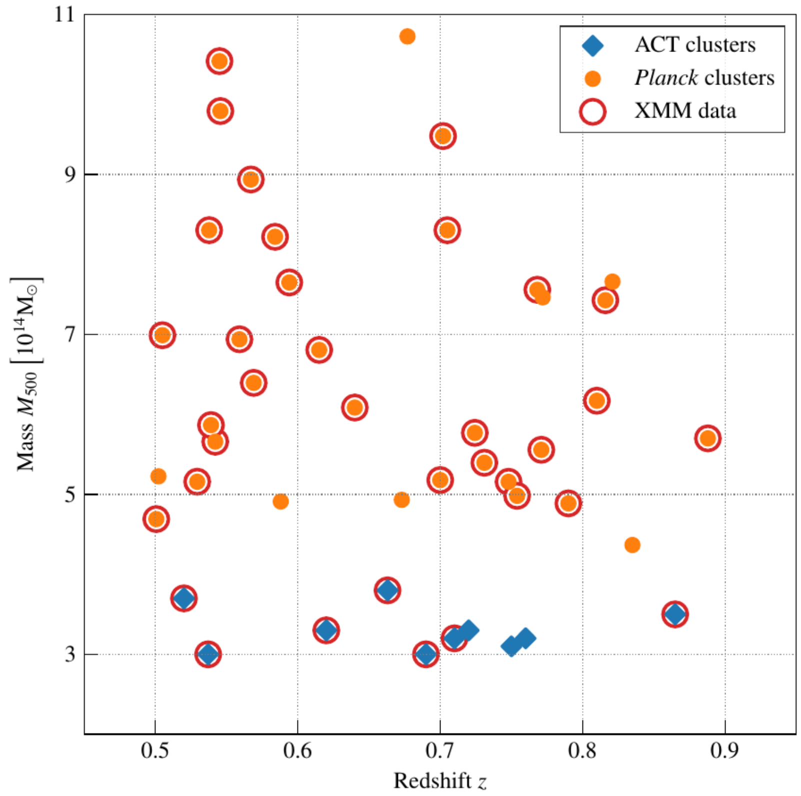






First non-parametric reconstructions of high redshift cluster pressure profiles

NIKA2 SZ Large program



One of the 5 NIKA2 LP (1300 h 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

Redshift evolution of:

- Cluster thermodynamic quantities
- Scaling laws (mass - tSZ) and hydrostatic bias

Variation of cluster properties with:

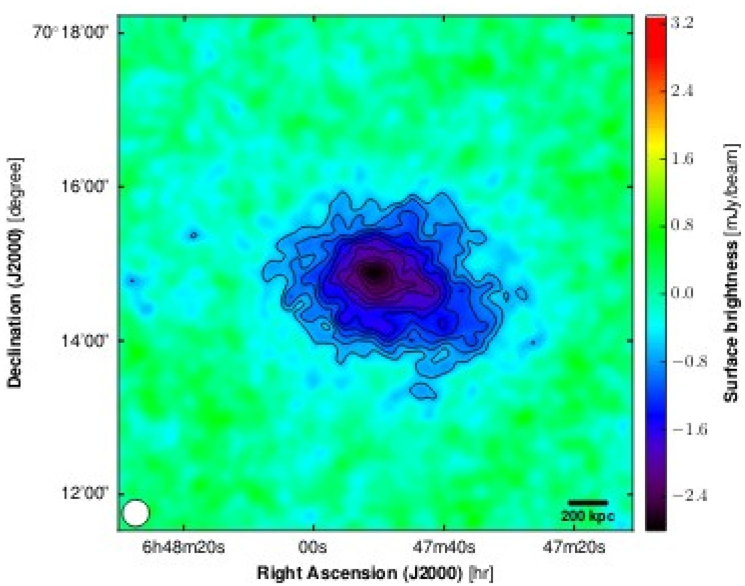
- Dynamical state (mergers)
- Morphology (ellipticity)

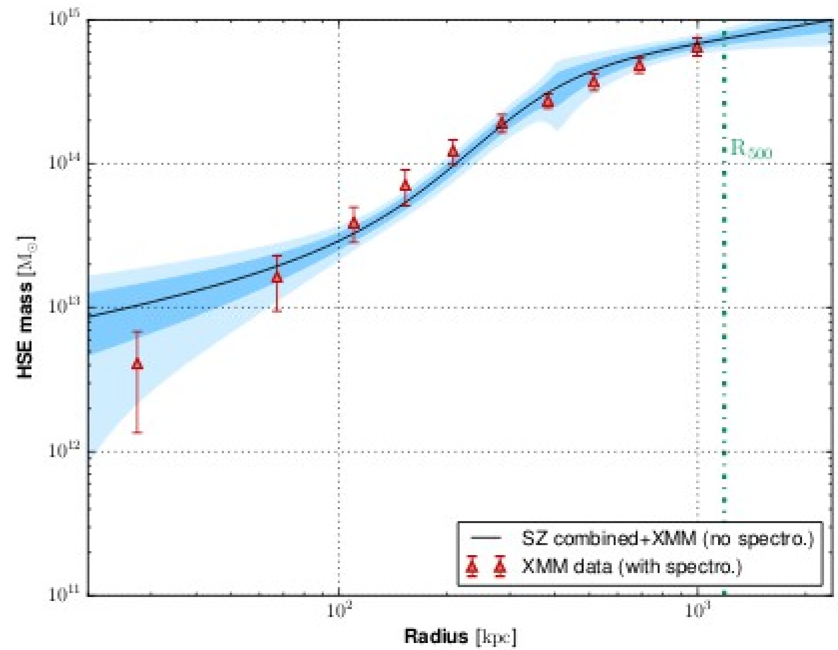
[Comis+2016, Mayet+2017,JFMP+ 2017]

First NIKA2 SZ cluster

PSZ2 G144 [Ruppin et al, AA, 2018]

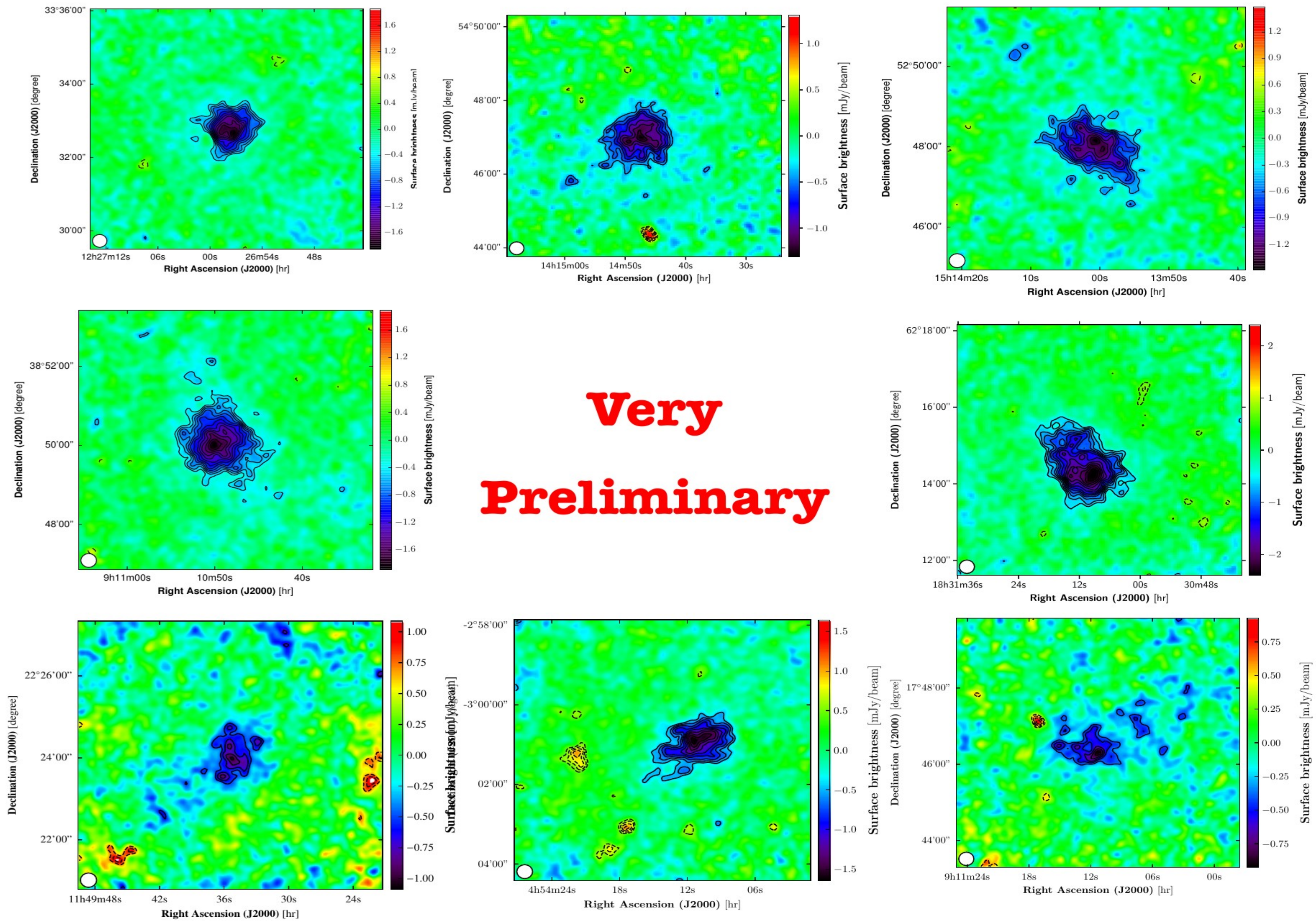
- Planck tSZ detected cluster at redshift, z = 0.58, high mass M_{500} = 7.8 x 10^{14} $M_{\odot}$
- 11h observations with NIKA2 in poor weather conditions (atmospheric opacity 0.3@225 GHz)
- Already observed: SZ – MUSTANG & Bolocam, X-rays - XMM





Detailed characterization of the cluster pressure profile – overpressure found
Hints of dependence of the hydrostatic mass bias with cluster physics

Observed NIKA2 LP clusters



Very promising results, detailed analysis on going

Conclusions

- High resolution SZ resolution observations of high redshift clusters are needed to check possible redshift evolution of cluster properties and their impact on cosmology
- NIKA high resolution tSZ observations has been extremely successful covering a large number of scientific cases
- NIKA has provided first direct mapping of the kSZ effect opening a new window in cluster physics and cosmology
- First NIKA2 observations have proved to be of high quality
- Detailed analysis of PSZ2G144 NIKA2 tSZ map have shown cluster dynamical state is key for understanding the mass-tSZ relation
- NIKA2 SZ LP will provide unprecedented view of high redshift cluster allowing for accurate cluster cosmology

NIKA http://ipag.osug.fr/nika2

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Lagache Guilaine

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Cluster observables

Cluster observables: detect them and/or measure their physical properties

Visible and IR emission

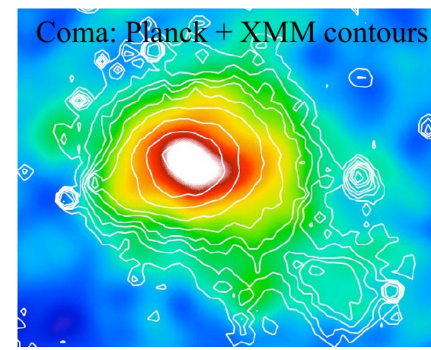
Light from stars in galaxies

Mass:
- Richness (number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing

X-ray emission

Free-free emission from
free electrons in the ICM

Density, temperature, entropy, mass:
- surface brightness
- spectroscopy



Sunyaev-Zeldovich effect

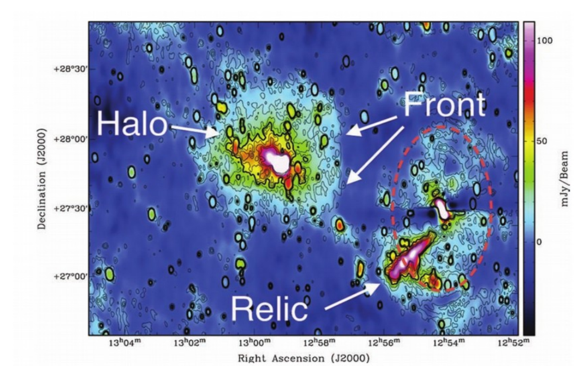
Interaction of hot electrons in
the ICM with CMB photons

Pressure, mass, shocks:
- Compton parameter

Radio emission

Non thermal emission from
accelerated particles

Shocks:
- Surface brightness



A bit of tSZ cluster cosmology theory

Cluster number counts

Catalogue selection function

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

Universe volume

Cluster's Mass function

Need for accurate cluster masses

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

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

- September 2015 : installation at IRAM
- October 2015 : First lights
- September 2016 : complete instrumental setup
- April 2017 : commissioning succesfully finished ; performance better than expected

Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	8±1 mJy/s$^{1/2}$	33±2 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

[NIKA2 collaboration: Adam+2018, Perotto+2019]

Science with NIKA2

- Multi-purpose camera open to the astrophysical community
- Open time observations for at least one decade (already 4 campaings)
- The NIKA2 collaboration has been awarded 1300 hours of GT shared between 5 Large programs for astrophysics and cosmology:
    - Galactic studies in intensity and polarisation
    - Nearby and distant galaxies
    - Clusters of galaxies