Clusters of galaxies with GIS KIDS cameras

J.F. Macías-Pérez
on behalf of Grenoble GIS KIDS

KISS

Outline

I. Clusters of galaxies and the Sunyaev-Zeldovich effect

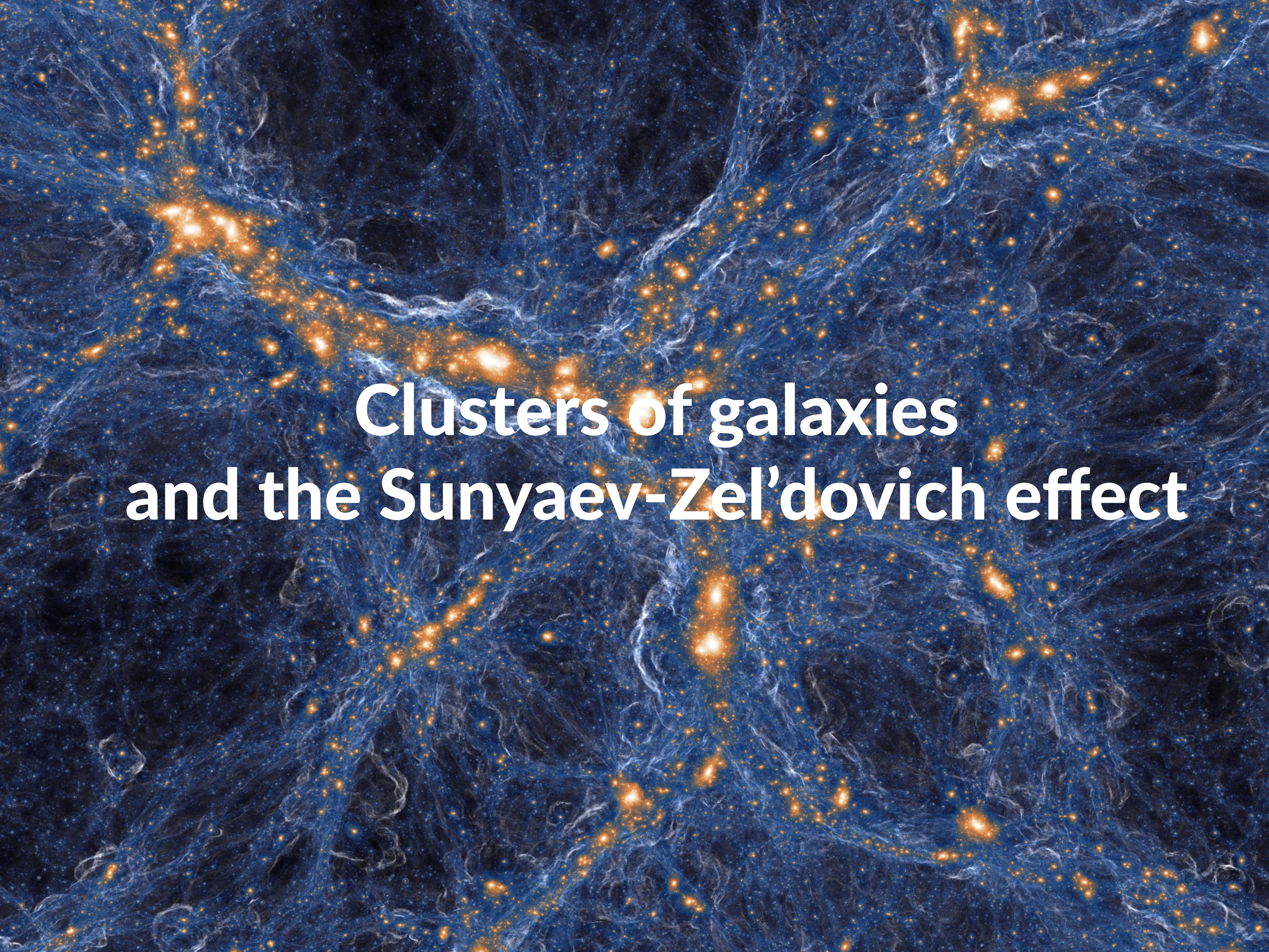
II. KID technology for SZ

III. KID cameras and spectrometers for SZ

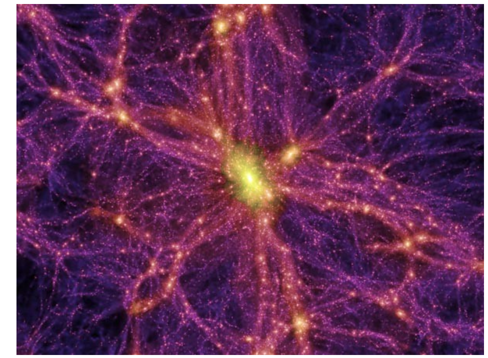
IV. SZ with NIKA2

V. The CRESZENDO project

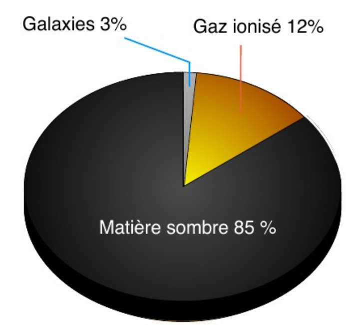
Clusters of galaxies and the Sunyaev-Zel'dovich effect

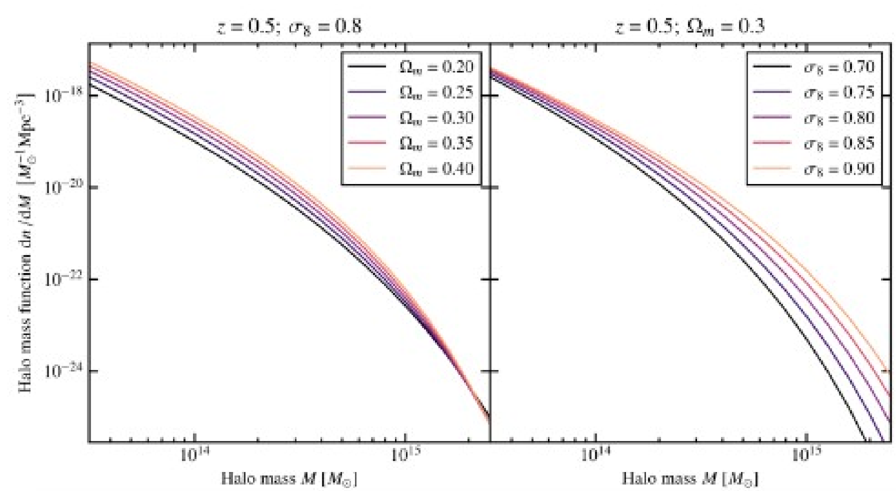


Clusters of galaxies

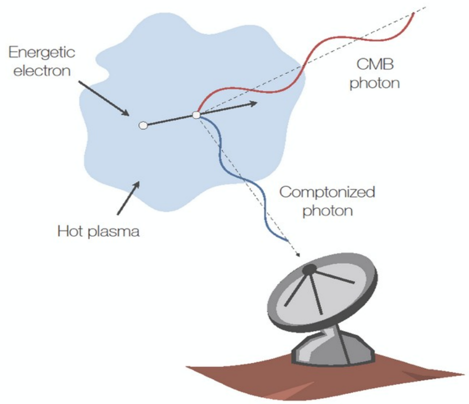


- Formed by gravitational collapse at the intersection of cosmic filaments, correspond to massive dark matter halos
- Largest gravitationally bound structures in the Universe
  - Dominated by dark matter – lensing effects
  - Most baryonic matter is in the form of gas, the Inter Cluster Medium (ICM) – X-ray & SZ emisision
  - Galaxies count for only 3 % of the total mass - optical and IR observations
- Total mass 10^{13}- 10^{16} $M_\odot$, redshift $0 < z < 3$
- Cosmological probe of choice – need to measure precisely their mass accounting for baryonic physics





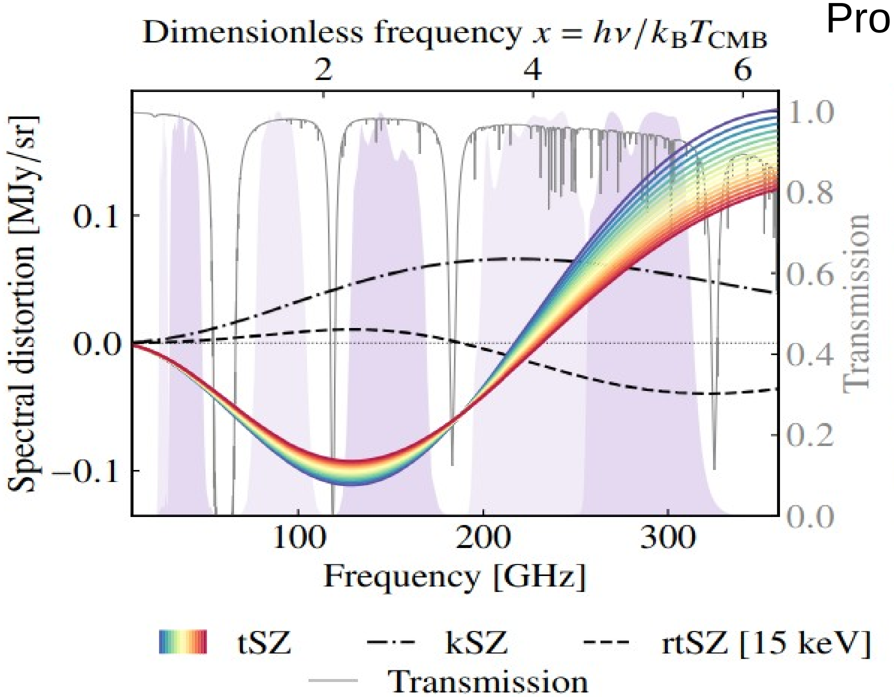
Sunyaev-Zel'dovich (SZ) effect

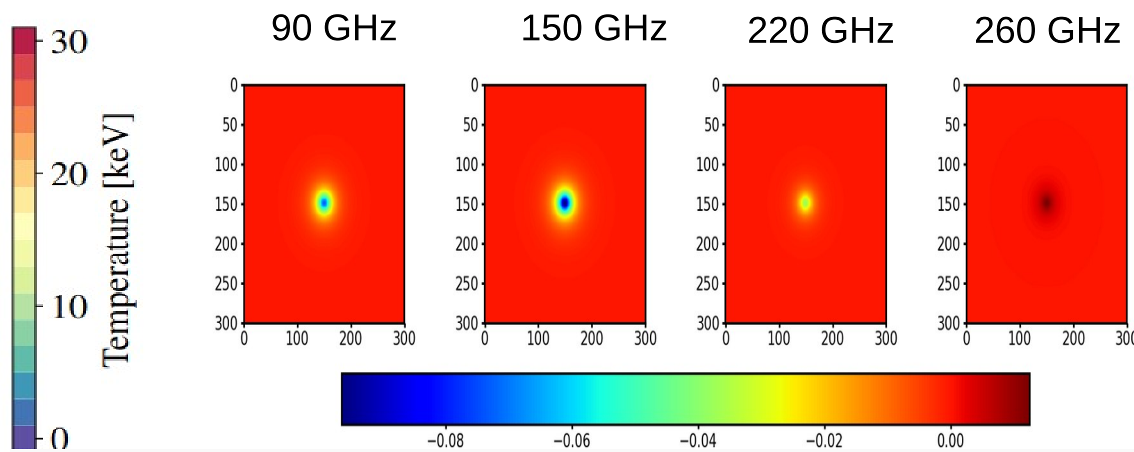


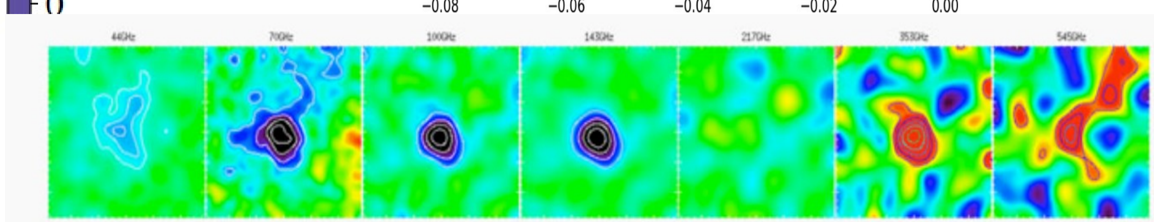
Inverse Compton scattering of hot electrons on CMB photons

- Thermal SZ : $$y_{tSZ} = \frac{\sigma_T}{m_e c^2} \int P_e d\ell$$
- Kinetic SZ : $$y_{kSZ} = \sigma_T \int \frac{-v_z}{c} n_e d\ell$$

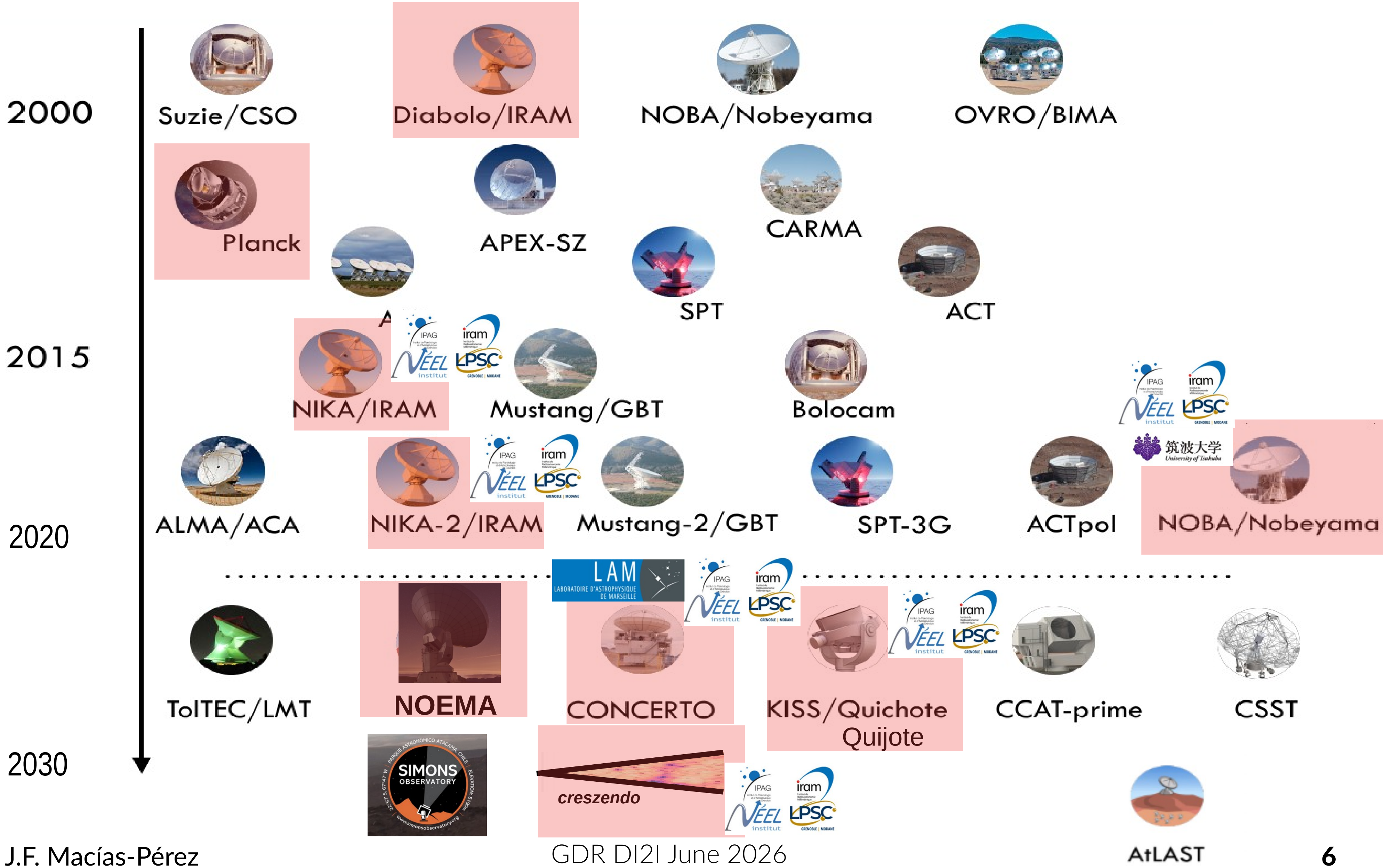
No affected by cosmological dimming
Probes pressure, temperature, mass and cluster velocity





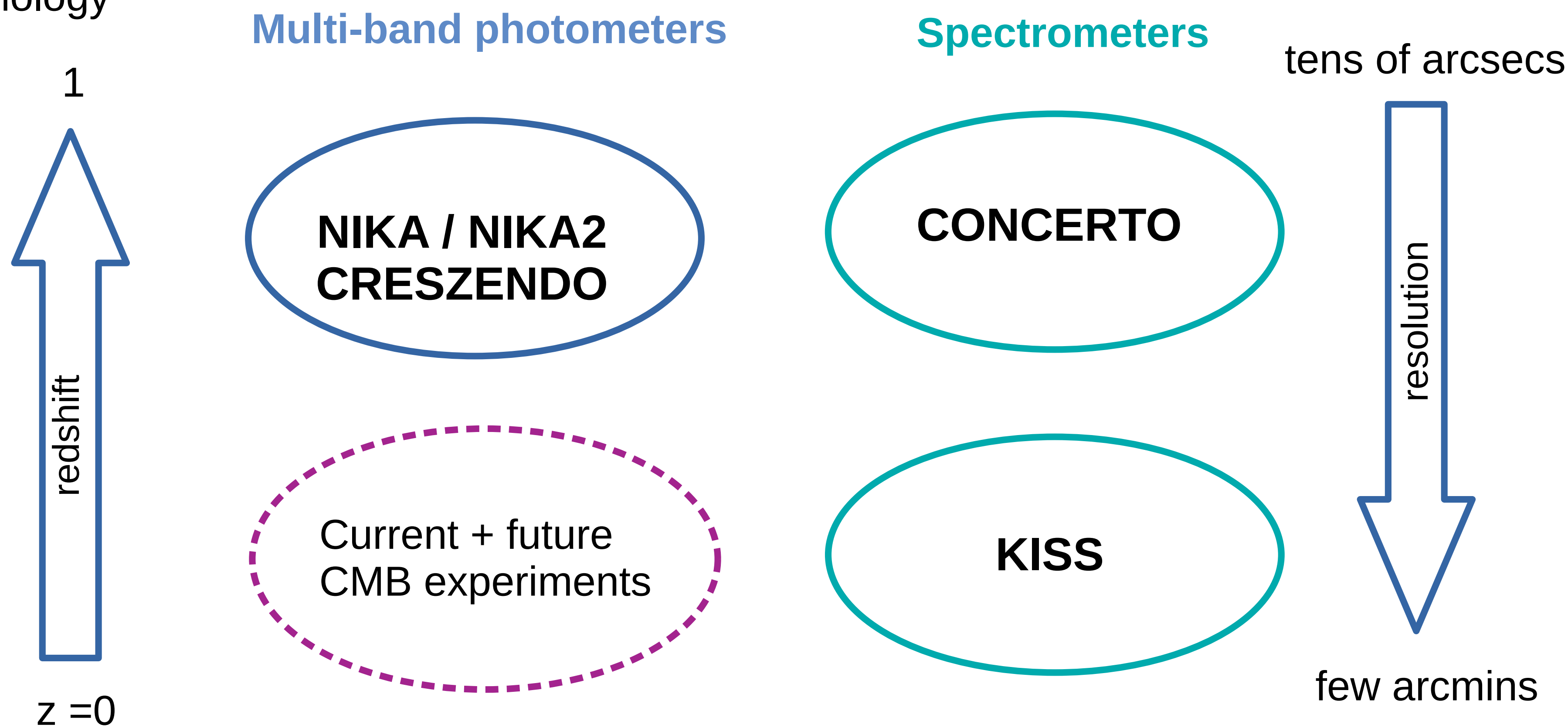


SZ observations

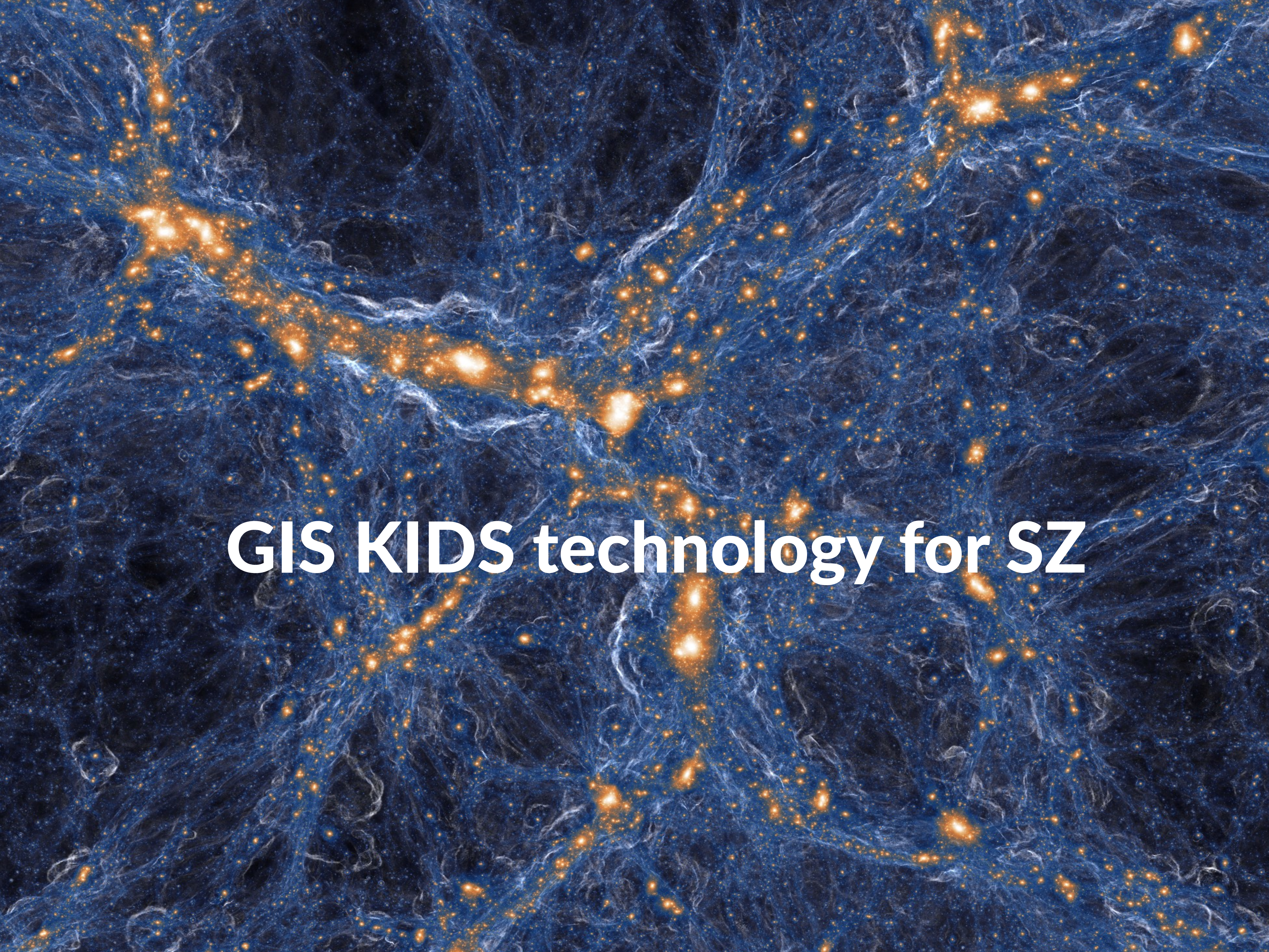


Our SZ science approach

Develop new instruments to carry out complementary SZ observations targeting cluster physical properties (mass, velocity, temperature, dynamical state, ..) at low and high redshift and cosmology



For this we need large arrays of detectors in the millimeter domain

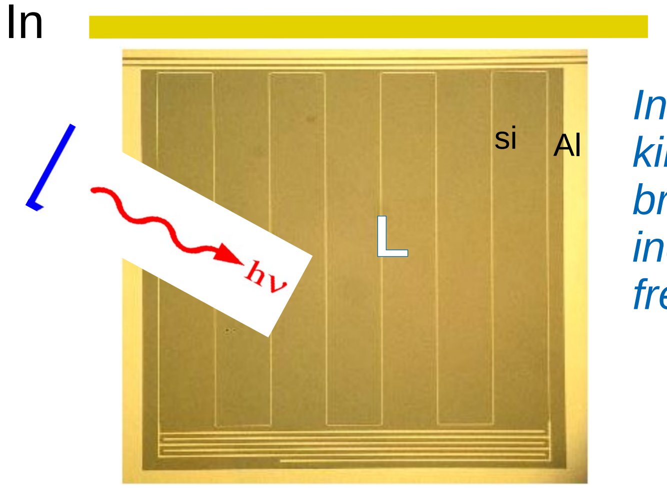


GIS KIDS technology for SZ

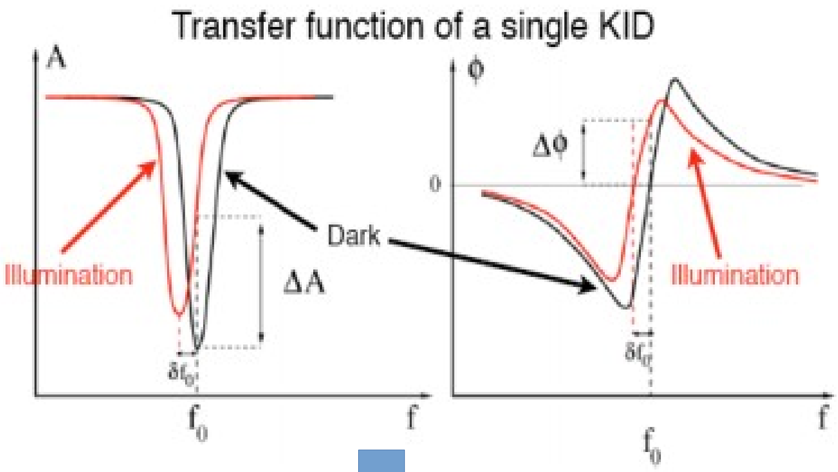
Kinetic Inductance Detectors (KIDs)

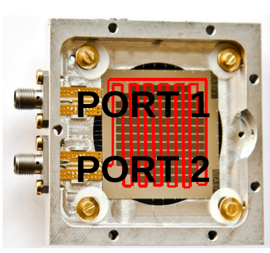
KIDs are superconducting RLC resonators operated at $T_b \sim 100\ \mathrm{mK}\ \ll\ T_c \sim 1.5\ \mathrm{K}$

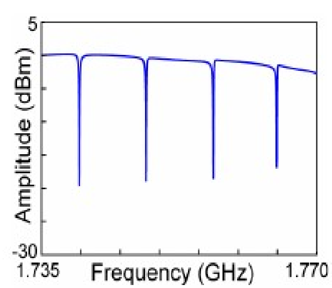
We concentrate on LEKIDs



Incoming light changes kinetic inductance by breaking Cooper pairs and induces a resonance frequency shift







Monfardini, Benoit, Bideaud et al. 2011

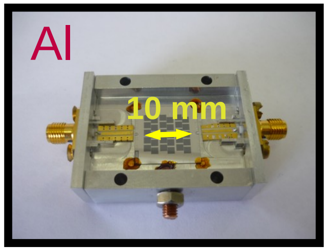
KIDs a are good alternative to bolometers

- Fast detectors, time constant << 1 ms
- Relatively simple fabrication procedure
- Natural frequency domain multiplexing
- Simultaneous real-time readout

GIS KIDs developments (Institut Néel, LPSC, IPAG, IRAM)

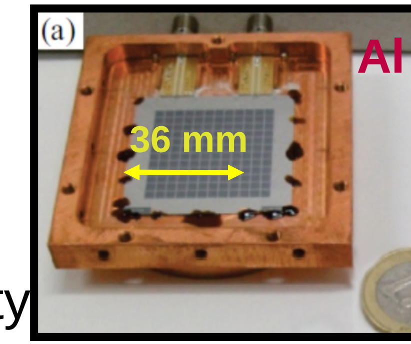
2000
KID Concept
(Caltech-JPL)

NIKA0
2009

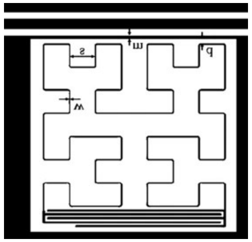


30 pixels

NIKA1
2010-2013

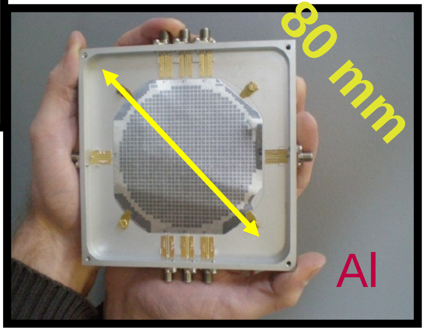


300 pixels



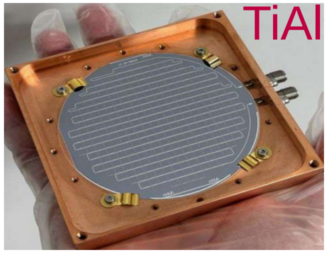
Hilbert geometry (dual polarisation)

NIKA2
2014-2017

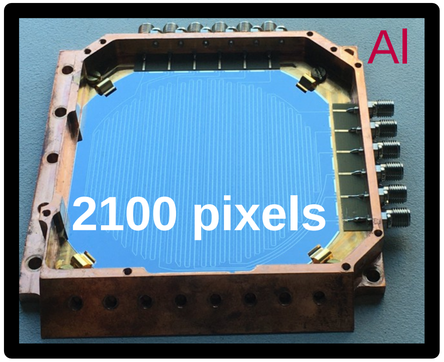


1100 pixels

NOBEYAMA
2025



CONCERTO
2019-2020



2008
Grenoble “join” the KID community

2009
30 pixels → NIKA0 (first ever KID camera)

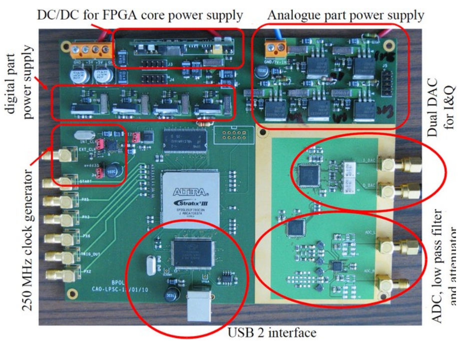
2014 - 2017
- Background-limited **(NEP < 10^{-17} W/$Hz^{0.5}$)**
- Readout line 2.5 m long !! Litho !!
- Al high-quality, uniform thickness film (≈10nm)

2019 – 2020
- 2100 background limited detectors

[Monfardini+2010, 2011, Adam+2019, Concerto collaboration+2020,]

GIS Readout developments

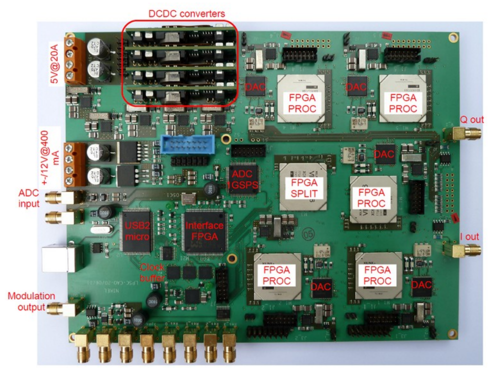
2011: NIKEL proto



128 pixels
500 MHz bandwidth
external RF

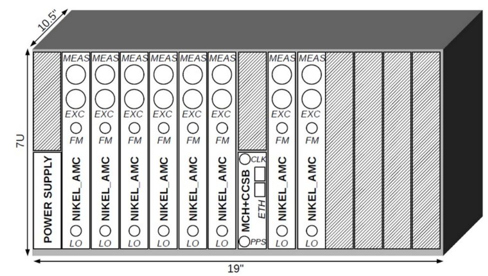
See presentation from J. Bounmy this morning

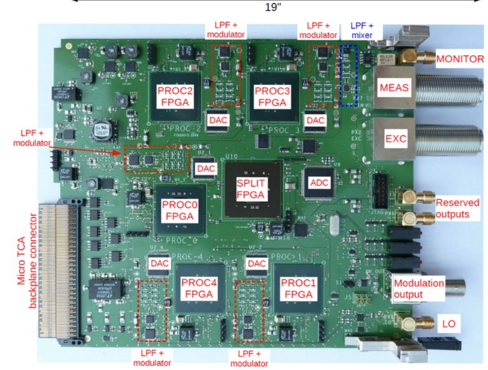
2012: NIKEL (NIKA)



400 pixels
500 MHz bandwidth
external RF

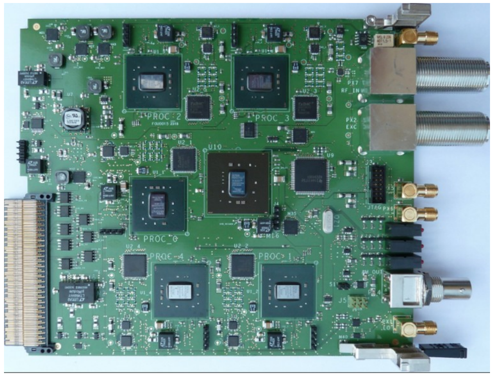
2016: NIKEL AMC (NIKA2/KISS)





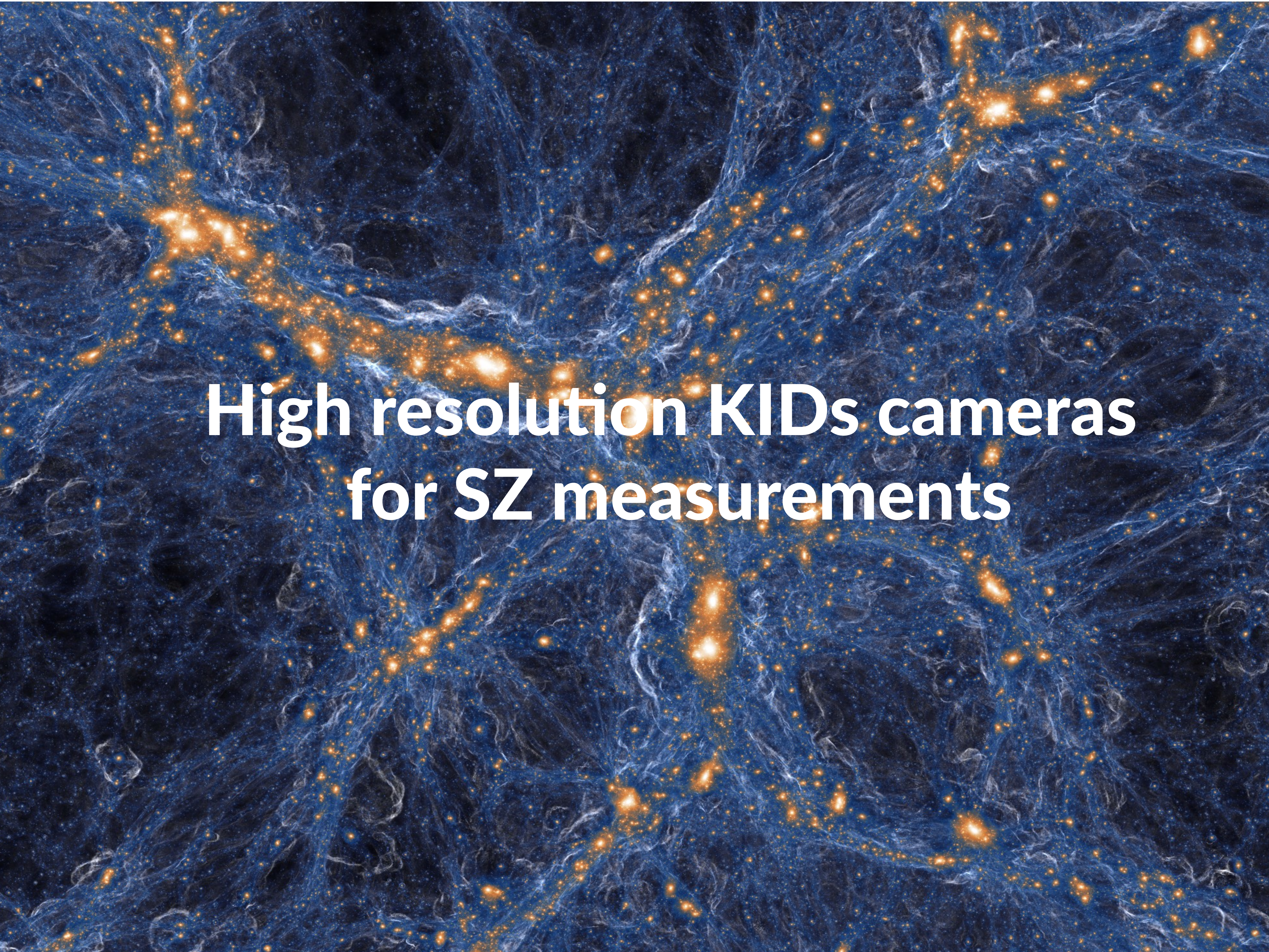
400 pixels
500 MHz bandwidth
RF in the board
Compact crate with up to 10 boards

2020: NIKEL AMC v2 (CONCERTO)



400 pixels
1 GHz bandwidth
30 watts power

[Bourrion+2011, 2012, 2016, 2022, Bounmy+2022]



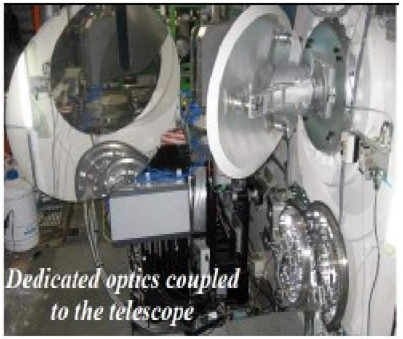
High resolution KIDs cameras for SZ measurements

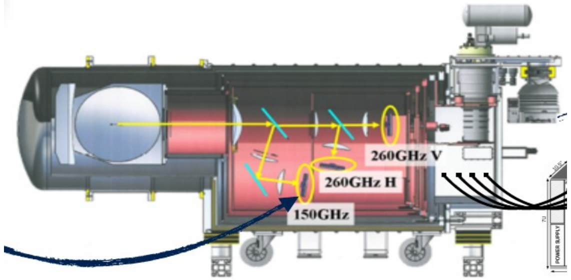
The NIKA2 camera

Dual band mm camera made of Kinetic Inductance Detector (KID) arrays

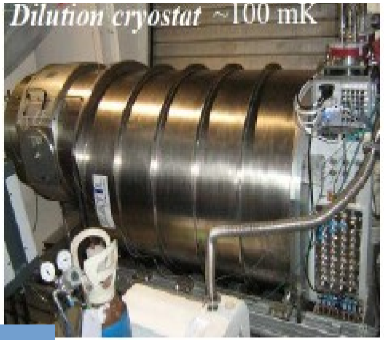
Resident instrument open to the astrophysical community

IRAM 30-m telescope
at Pico Veleta (Spain)





PI: A. Monfardini
PS : JFMP

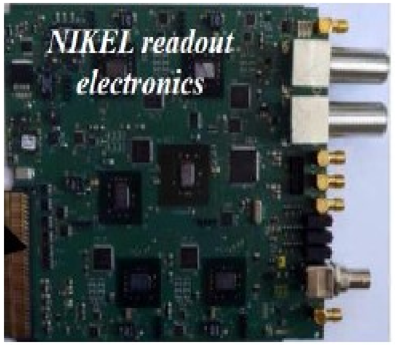


Arrays of 1140 (666) KIDs:
8 (4) independent feedlines
with up to 200 KID each

[Adam+ NIKA2 collaboaration 2019, Perotto + NIKA2 collaboration 2020, & mm conference proceedings]

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

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



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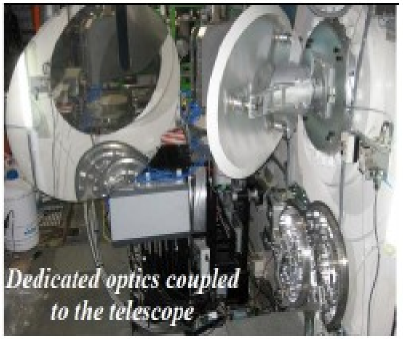

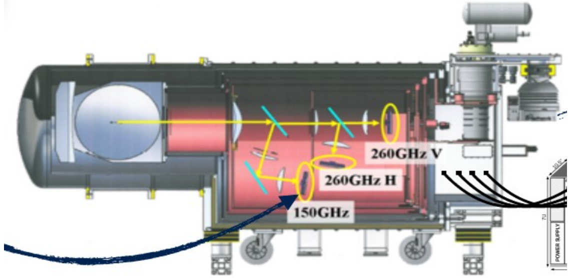

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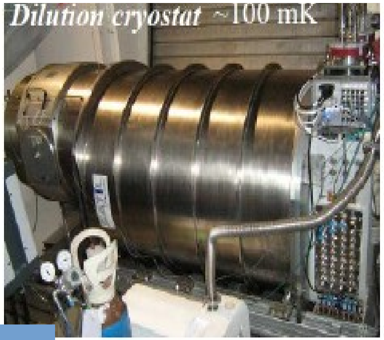

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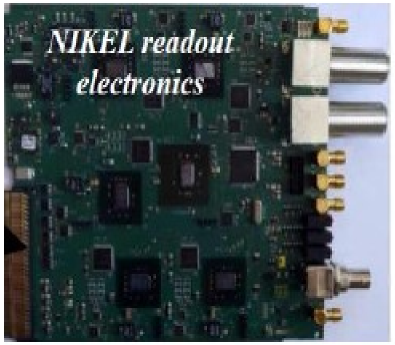
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	8±1 mJy/s$^{1/2}$	15±2 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

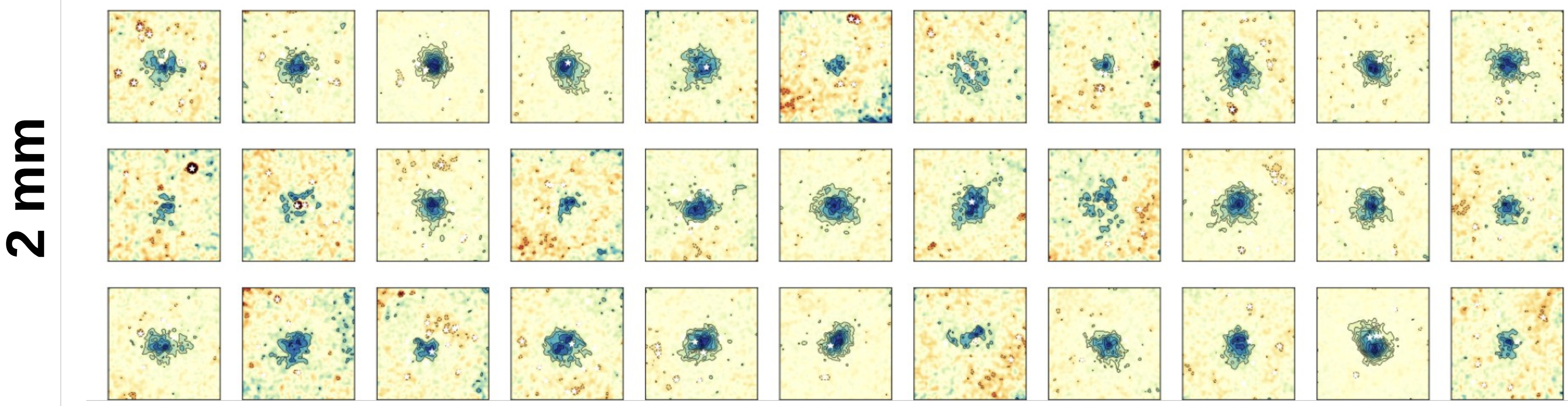
20 boxes (one per feedline) arranged in 3 crates (one per array)



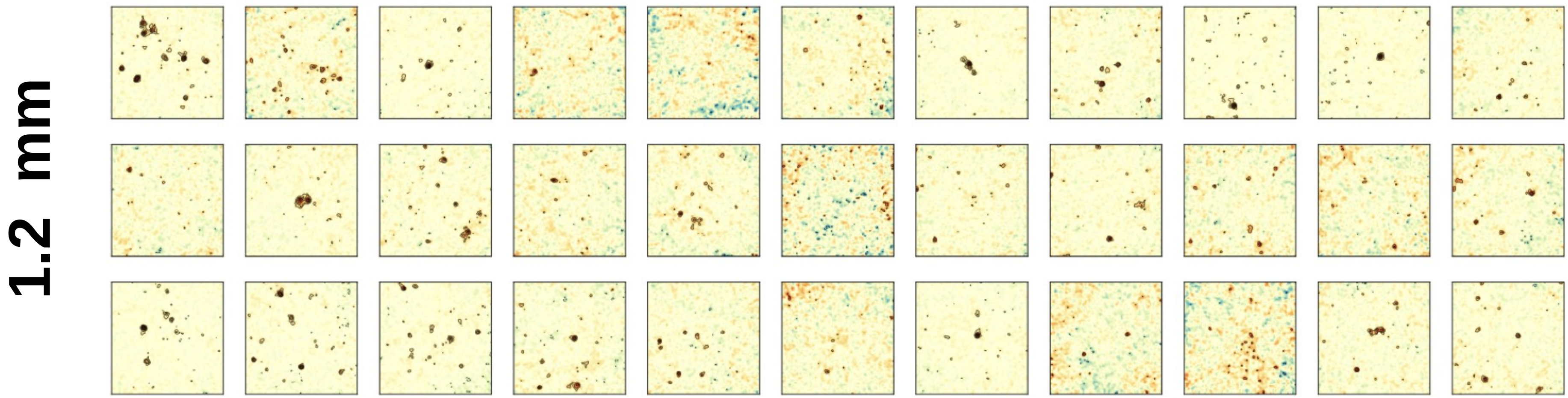
Observed NIKA2 LP SZ clusters

- tSZ selected clusters from Planck and ACT catalogues
- 300 hours NIKA2 observations
- 33 high redshift clusters 0.5 < z < 0.9

- Universal pressure profile
- Mass-SZ scaling relations
- Cosmological constraints



Hundreds of mm sources detected, excess with respect to expected number counts

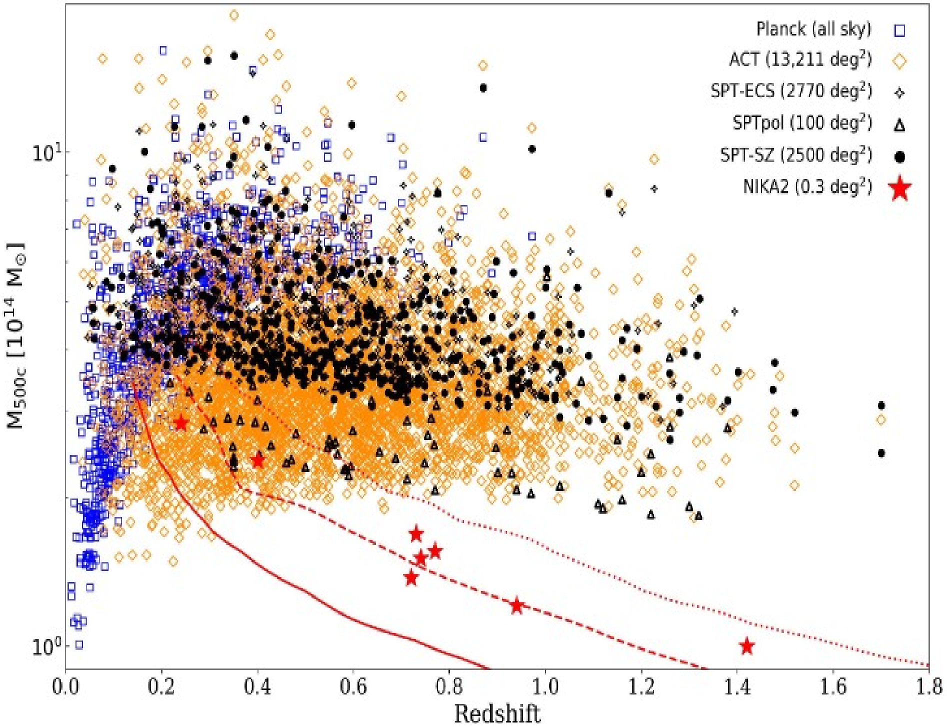


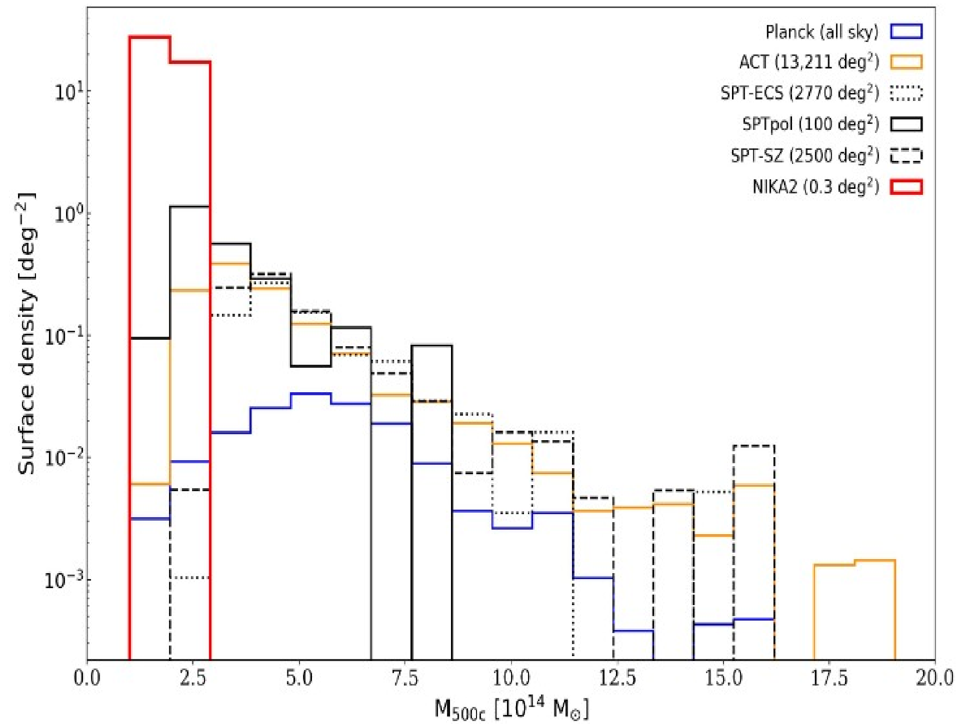
Hanser+2026 a,b,c; Moyer-Anin+2026; Desert+2026; Adam+2026;

NIKA2 detected clusters

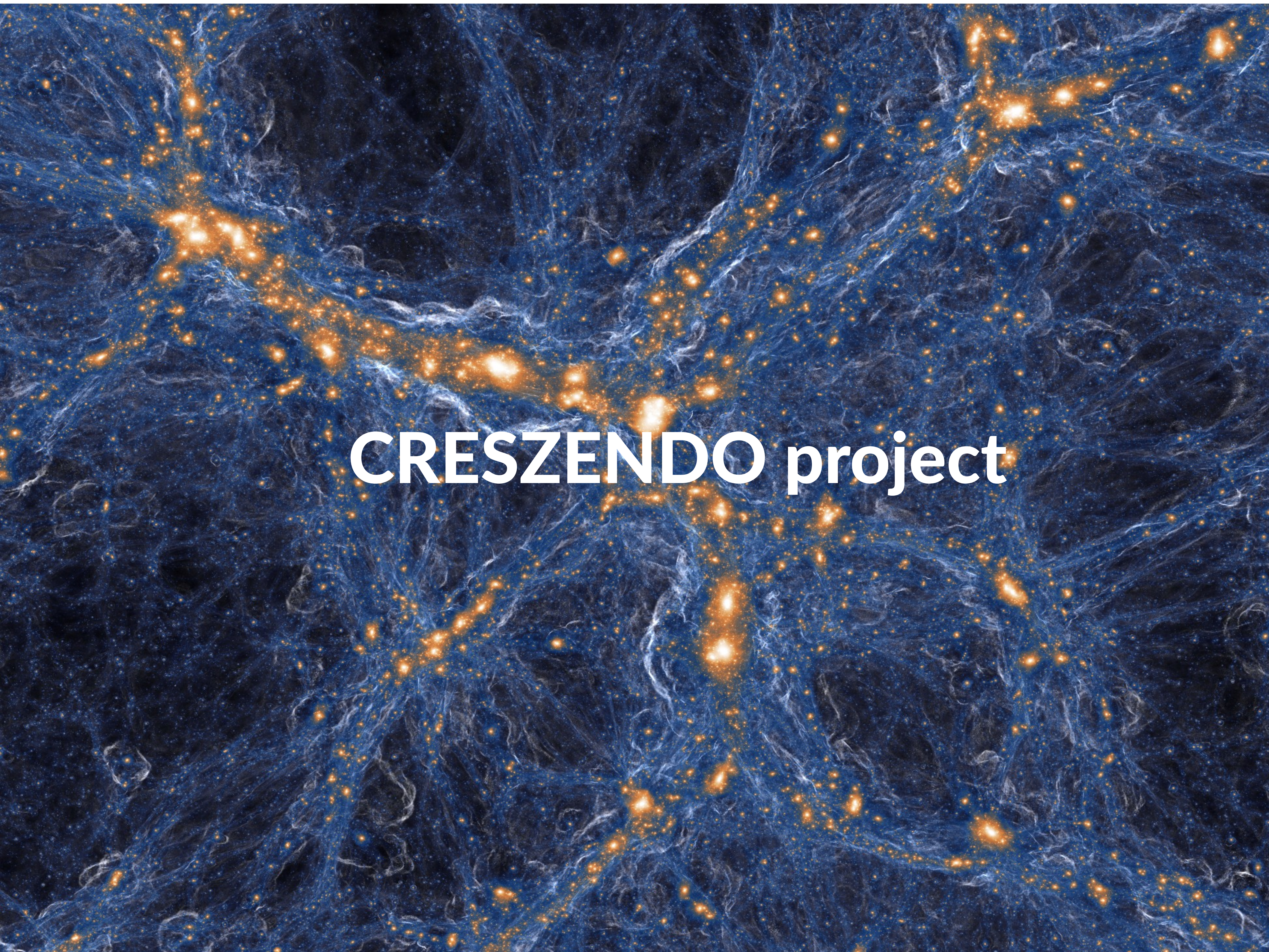
- N2CLS 200 hours of observations
- 0.3 deg2 survey of the sky
- Blind cluster detection analysis

- First high resolution tSZ cluster detection
- Sensitive to low mass and low redshift
- Highest density of low mass clusters





Cherouvier+2026; Lagache+2026; Bing+2025, Bethermin+2026,Berta+2026



CRESZENDO project

CRESZENDO in a nutshell

Scientific Objectives

- Study reionization epoch via diffuse kSZ observations: directly measure patchy reionization and its duration
- Characterize cosmic flows via kSZ in galaxy clusters – measure velocity along the line-of-sight
- Unveil the cosmic web via direct tSZ observations and t-kSZ cross-correlations with LSS
- Detect high redshift and low mass galaxy clusters via tSZ : establish full population of clusters and compare to LSS and X-rays ones

Observations

- 4000 hours of observations
- Two surveys of the Northern sky centered on Euclid Deep Field North (EDFN)
  - A shallow survey (few 10s to 100 deg^2) survey for clusters detection and cross-correlations
  - A (very)-deep survey (few deg^2) survey for patchy reionisation

Instrument

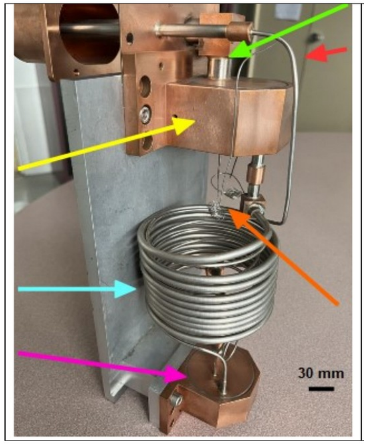
Millimeter wavelength camera installed at the 30 m IRAM telescope

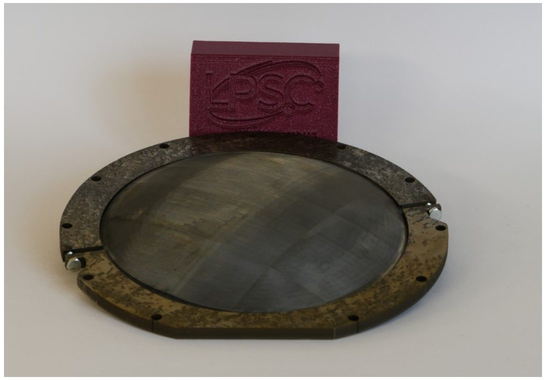
- 4 frequency bands 90, 150, 220 and 260 GHz
- High-resolution (from 25 to 10 arcsec) with large FOV (12 arcmin)
- State of art sensitivity : 3, 5, 10, 12 mJy.s$^{1/2}$
- 18000 KIDs detectors in total with Al and TiAl technology

Instrument

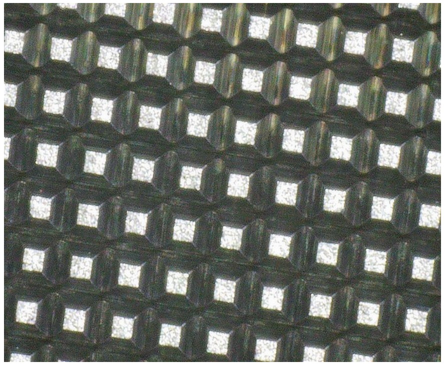
creszendo

- Reuse NIKA2 cyrostat
- Update: telescope mirrors, cryogenic system, internal optics, KIDs arrays, cold amplifier, readout electronics, acquisition system

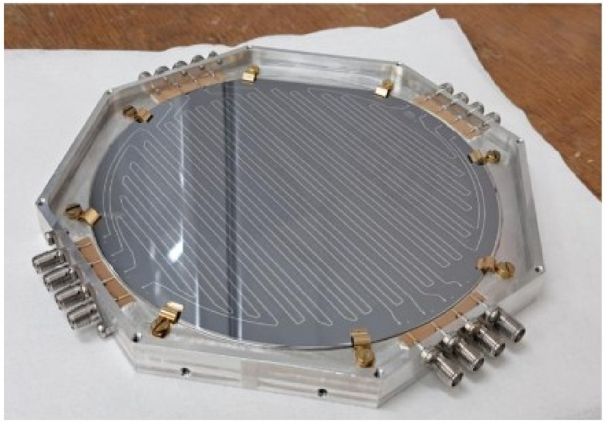


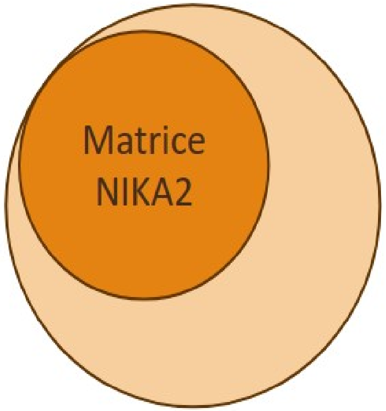


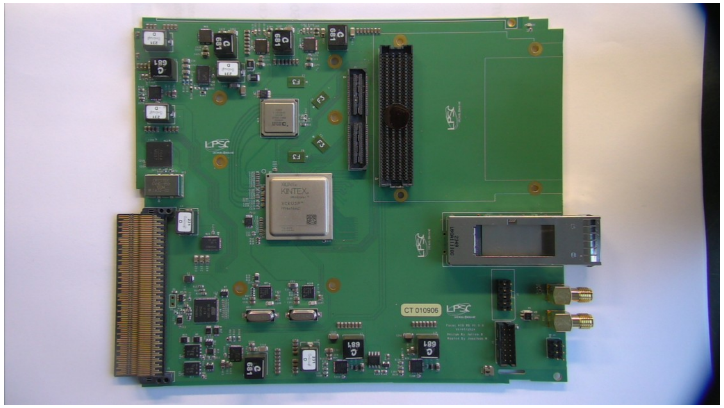
up to 8000 KIDs
Al and TiAl



1.5 GHz (2 GHz goal) bandwidth
900 detectors per board



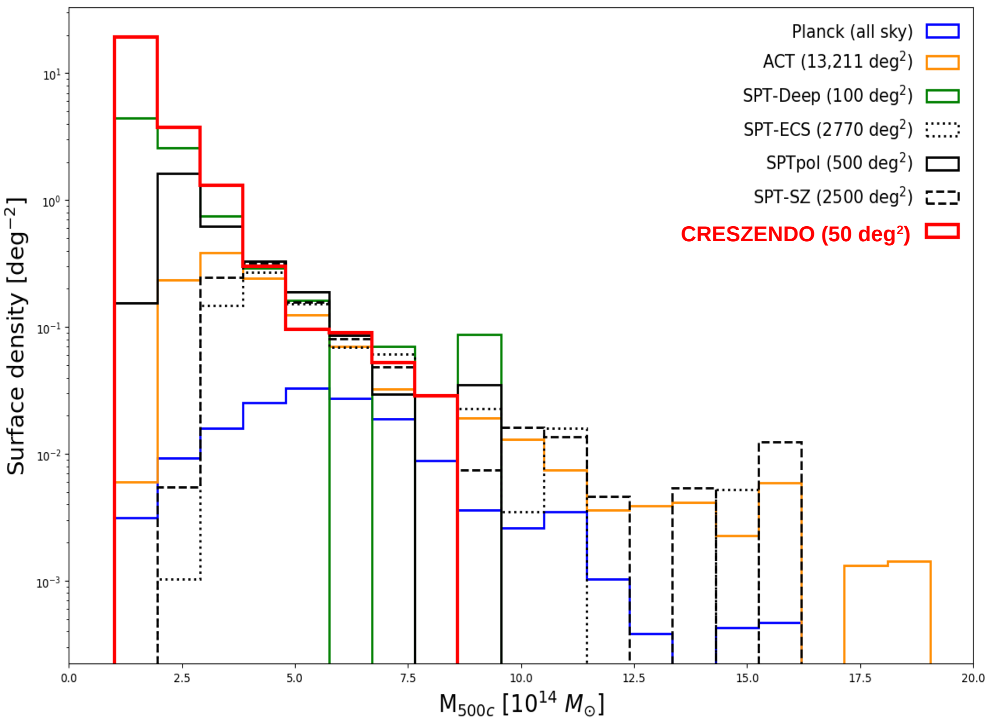


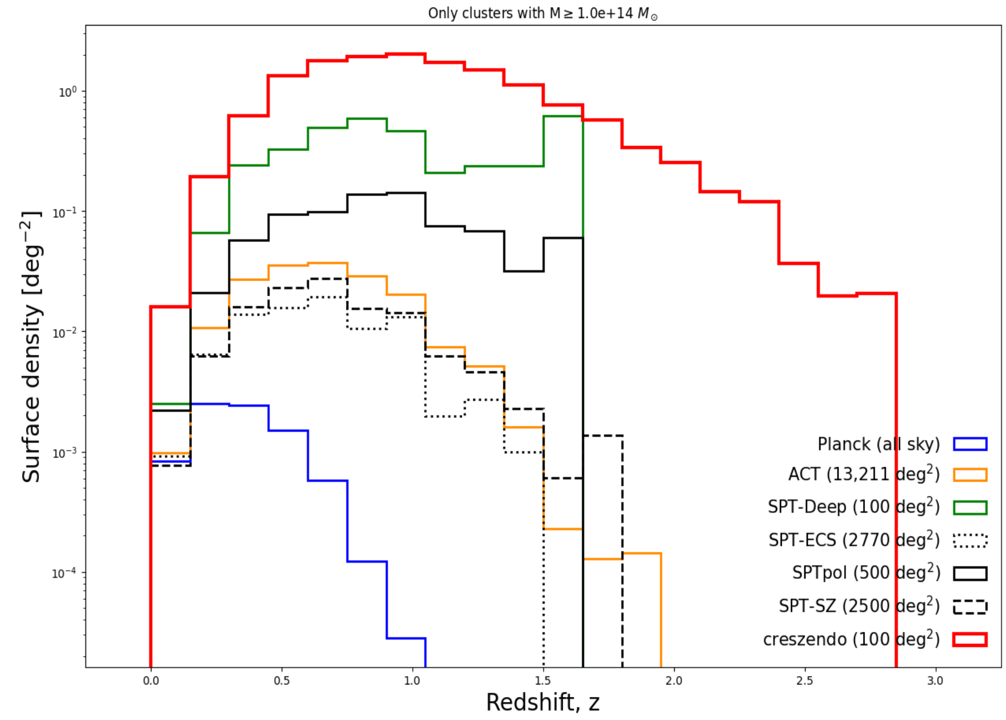


Cluster detection and cosmology

creszendo

- Able to blindly detect about 9000 clusters
- High-resolution allows us to detect cluster at very low mass and very high redshift
- Able to directly measure cluster masses



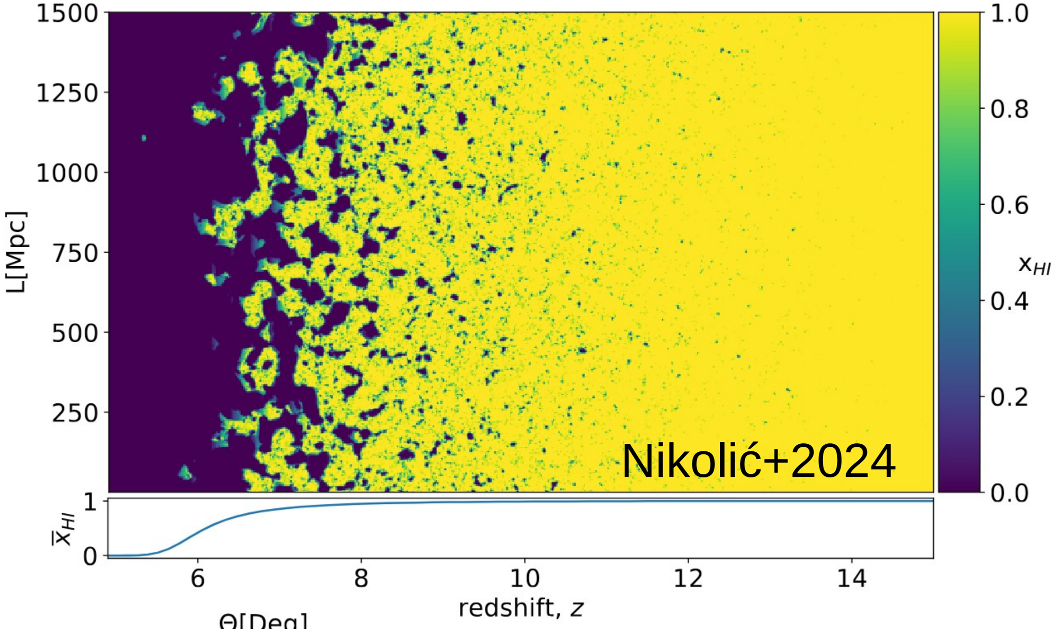


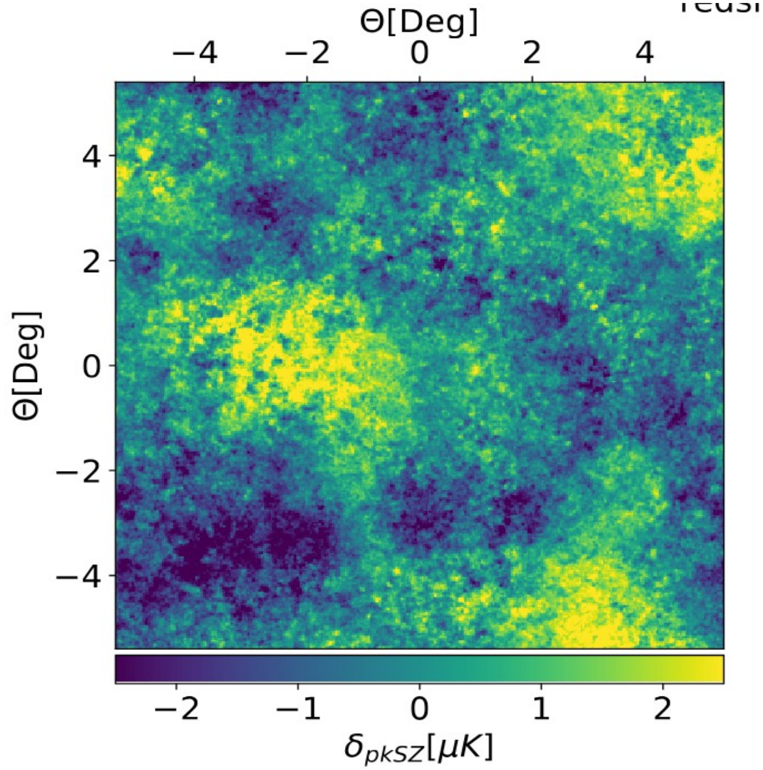
Strong synergies with Euclid cluster and cosmological studies

Reionization

creszendo

Reionization physics will imprint in CMB via kSZ :
patchy + homogeneus reionization





We can measure both reionzation redshift and duration – complements CMB EE modes measurements at very large angular scales and LSS observations (Ly-alpha)

Reionization

creszendo

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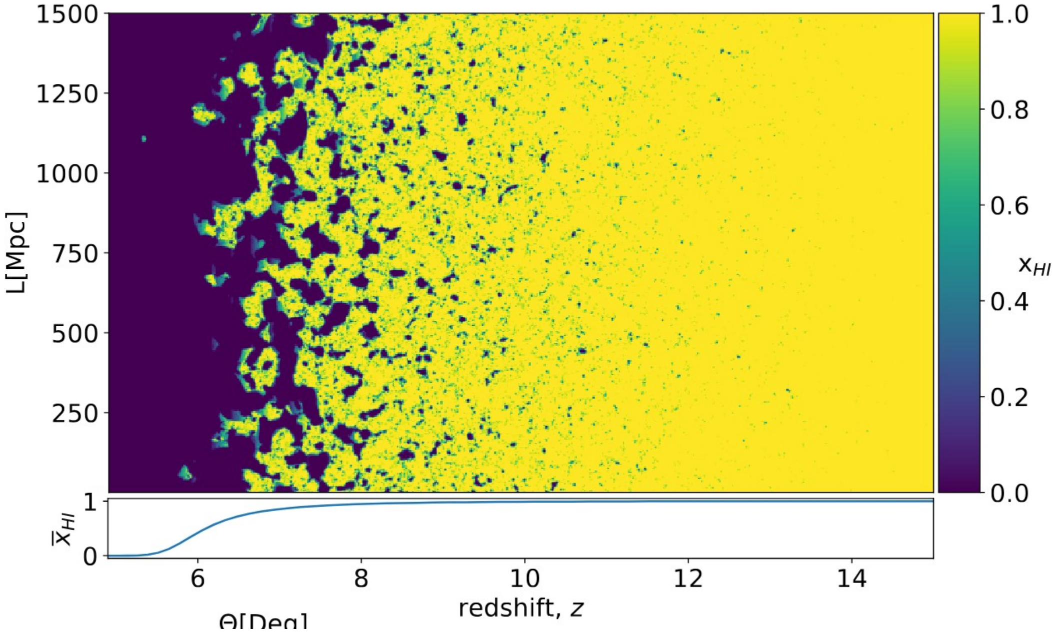
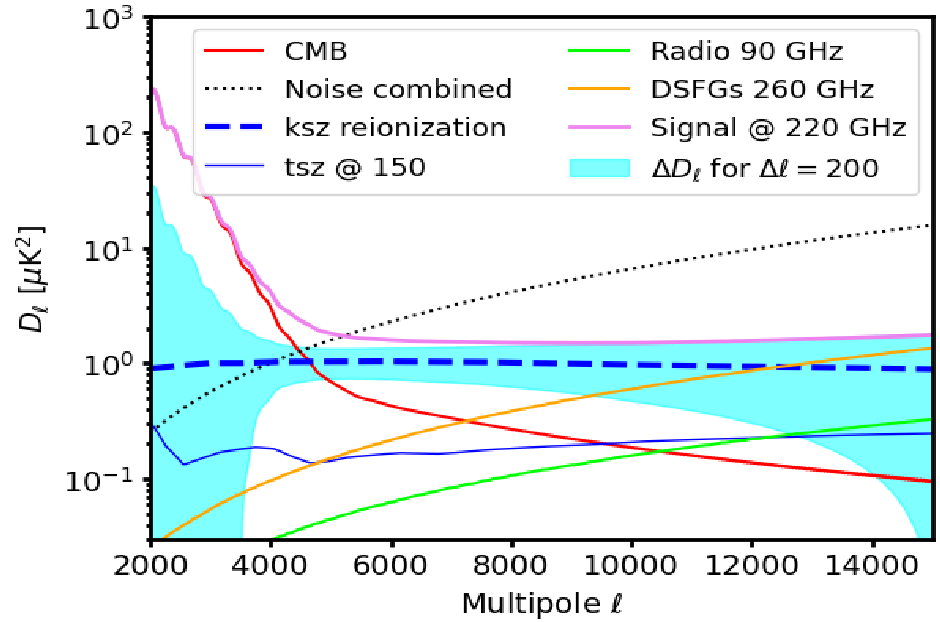




We can measure both reionzation redshift and duration – complements CMB EE modes measurements at very large angular scales and LSS observations (Ly-alpha)

CONCLUSIONS

- Current science drivers in mm astronomy and cosmology needs high sensitivity and wide-field multi-color observations with large arrays of detectors

- KIDs have achieved sufficient technical maturity to be a credible option to build those large arrays (tens of thousands pixels) of photon noise limited detectors

- Cluster physics and cosmology via the SZ effect are a target of choice for KID cameras

- NIKA first, and now NIKA2 and Tsukuba-Grenoble have demonstrated that KID based mm cameras can achieve state-of-art performance for SZ science.

- Ground-based mm spectrometers with KIDs, like CONCERTO, have been operated successfully

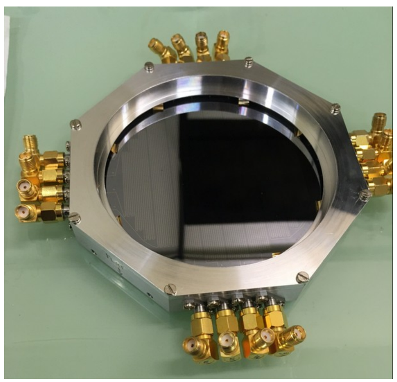
- GIS KIDS activities try to tackle new challenges in CMB and SZ science : e.g. KAIROS and CRESZENDO projects

A lot of new instrumental developments

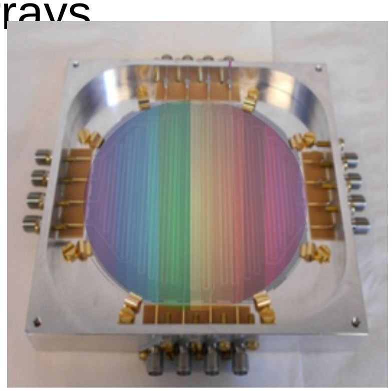
- New challenges on CMB and cluster physics

- Simultaneous selected line spectroscopy and continuum

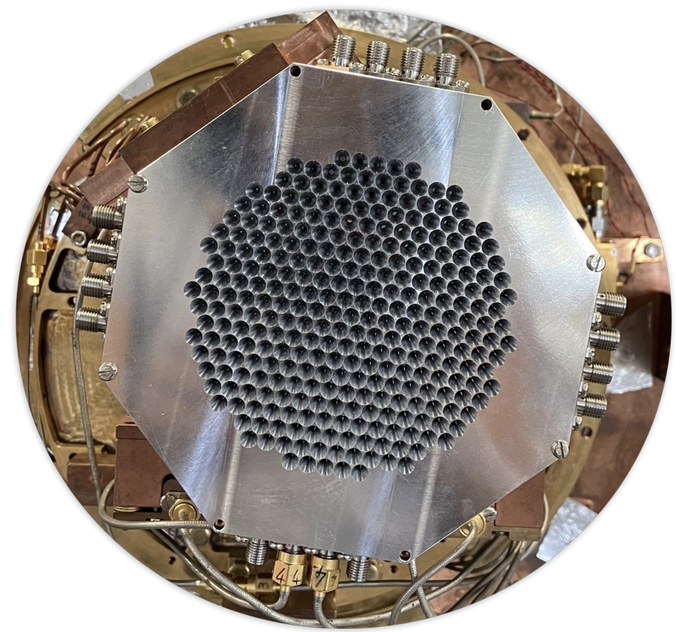
8000 KID arrays



Multichroic KID arrays



300 HYPKIDs



larger multiplexing factor with new readout electronic

800 pixels for 1 GHz

Coating + silicon lens

typically structure between 20-50 µm
Depth between 100-200 µm
On 3D surface

Increase in optical efficiency
Improved sensitivity

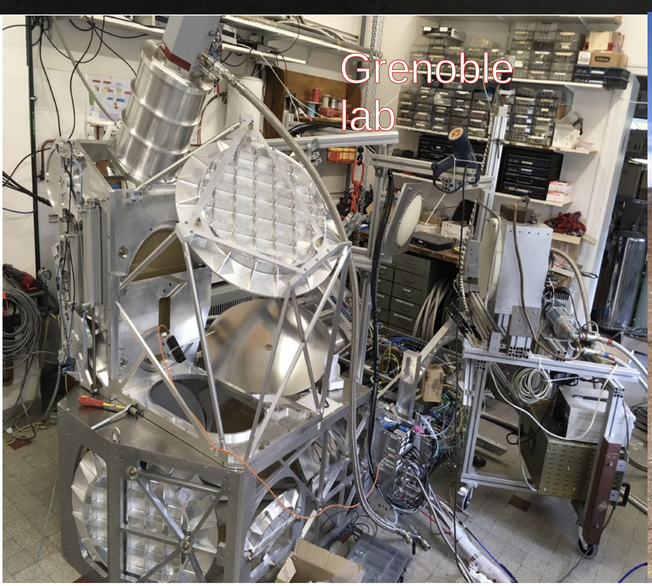
CONCERTO

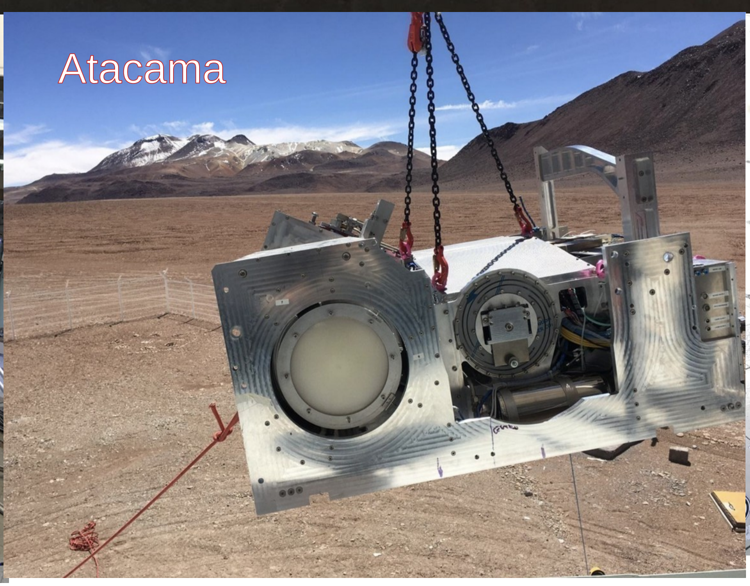
Funded by: ERC Advanced Grant January 2019
P.I. : Guilaine Lagache (LAM)
Co-PIs IN and LPSC

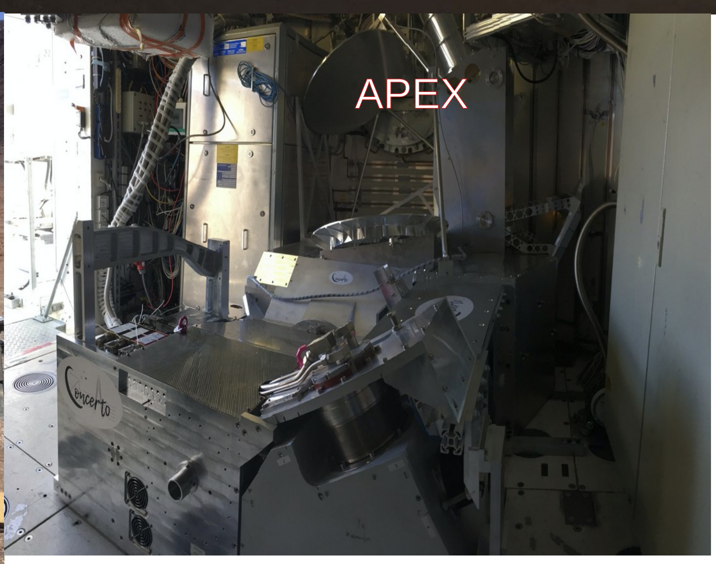
- Spectro-Interferometer (spectral resolution R > 100)
- Observing from 120 GHz to 350 GHz at 12 m APEX Tel.
- Large Field of View (20 arcmin)- LEKID Technology
- Collaboration LAM - Inst. Néel - LPSC – IPAG - Chile

CONCERTO collaboration, A&A 2022, Monfardini+2022

- Observations of [CII] @ z>5
- **Separating SZ effects**
- Galactic emission SED



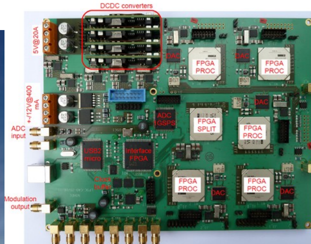


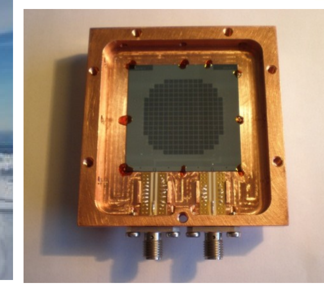


Installation during COVID-19 pandemic !

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



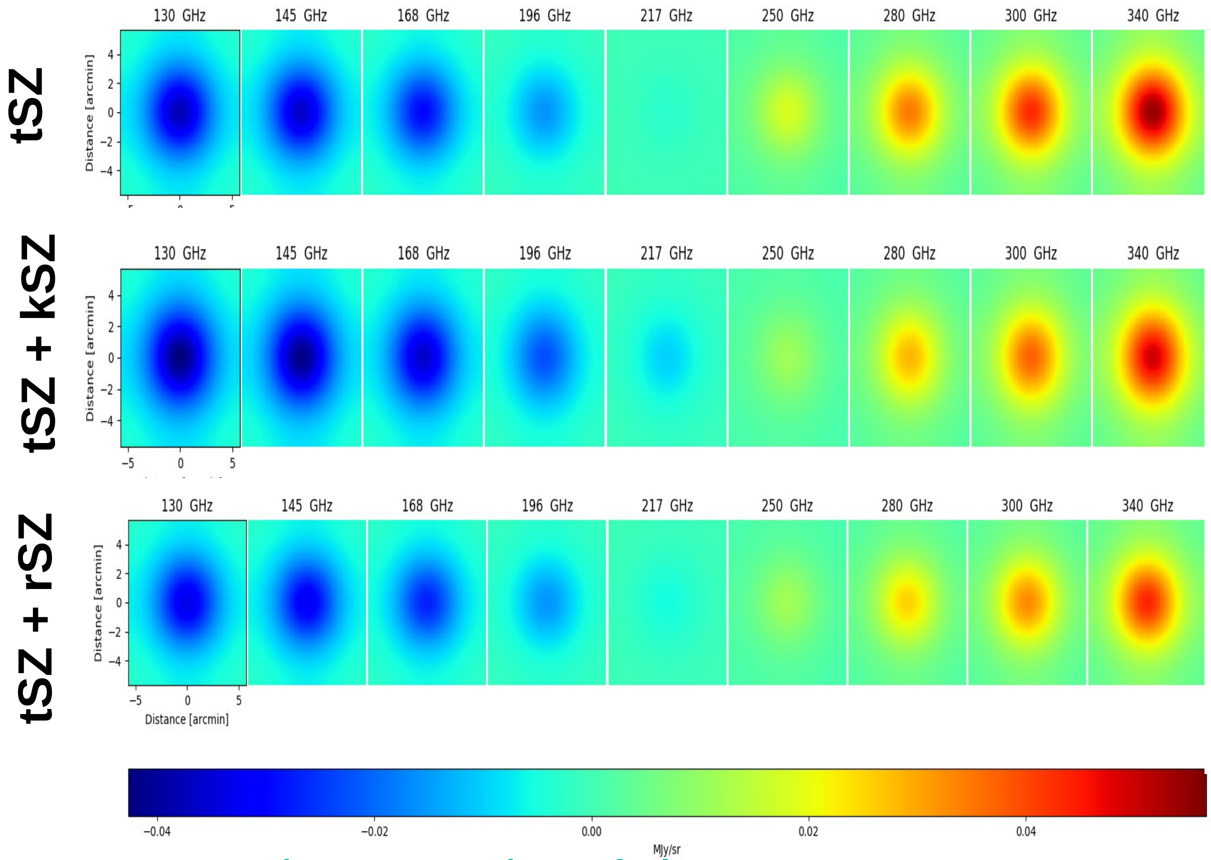


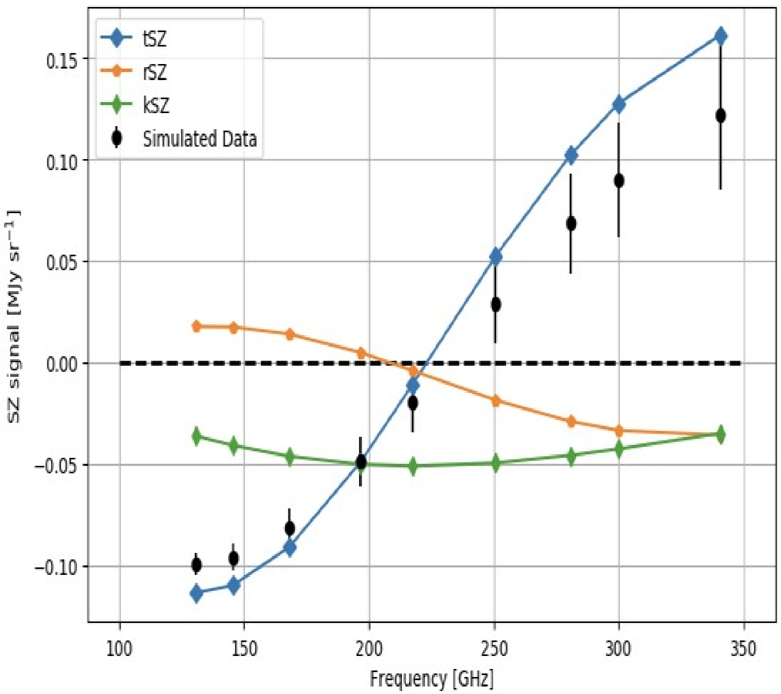
NIKA	150 GHz	260 GHz
# KIDs	132	224
FOV diameter	1.8 arcmin	2.0 arcmin
Sensitivity	14 mJy/s$^{1/2}$	40 mJy/s$^{1/2}$
Angular res.	18 arcsec	12 arcsec

[Calvo & NIKA collaboration, 2012, Adam & NIKA collaboration, 2014, Catalano & NIKA collaboration 2014]

Spectral imaging SZ science

SZ effect for a simulated cluster at redshift z = 0.4, with a mass of 10^{15} M_{sun} and a temperature of 20 keV, which is moving at 1000 km/s towards the observer.



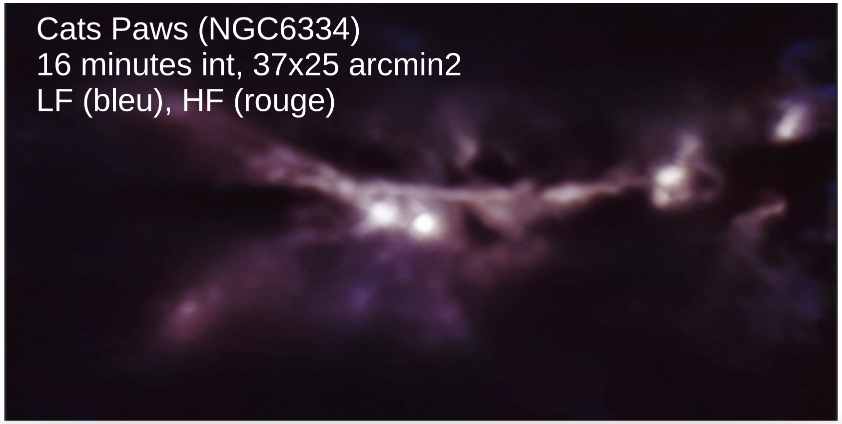


CONCERTO collaboration, A&A 2022

Direct mapping of cluster pressure, temperature and velocity distributions via the tSZ, kSZ and relativistic corrections

First CONCERTO results

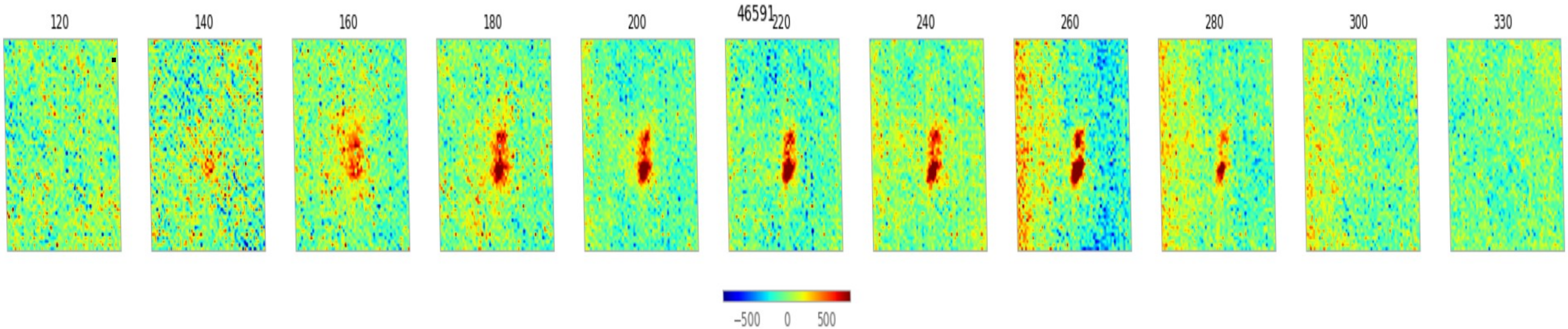
Successful commissioning in continuum



	Array HF	Array LF
Effective Frequency for Uranus [GHz]	262.2	224.9
Frequency range[a] [GHz]	195-310	130-270
Number of designed detectors	2152	2152
Fraction of valid detectors[b] [%]	72.5	78.2
$FWHM_1$[c] [arcsec]	27.1±0.1	29.6±0.1
$FWHM_2$[d] [arcsec]	35.9±6.1	38.1±5.1
Solid Angle Ω[e] [sr]	$3.44\pm0.10\times10^{-8}$	$3.87\pm0.07\times10^{-8}$
Jy-to-Hz conversion factor[f] [Hz/Jy]	19.45	25.55
Absolute calibration uncertainty[g] [%]	3.0	3.4
White noise [Hz/ $\sqrt{Hz}$]	2.24	2.21
α noise vs. integration time	-0.50	-0.50
NET [mK/ $\sqrt{Hz}$]	1.7±0.1	1.6±0.1
NEFD[h] [mJy·$s^{1/2}$]	118±3	99±2

Hu et al, A&A, 2024

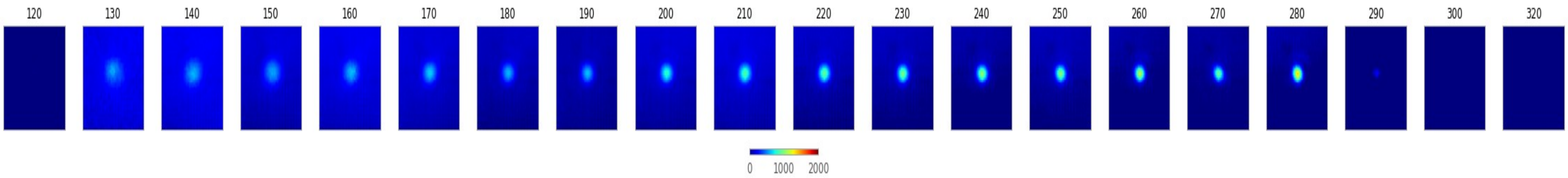
First spectroscopic maps on Orion Nebula (pilot diffuse emission project) and Galactic Plane

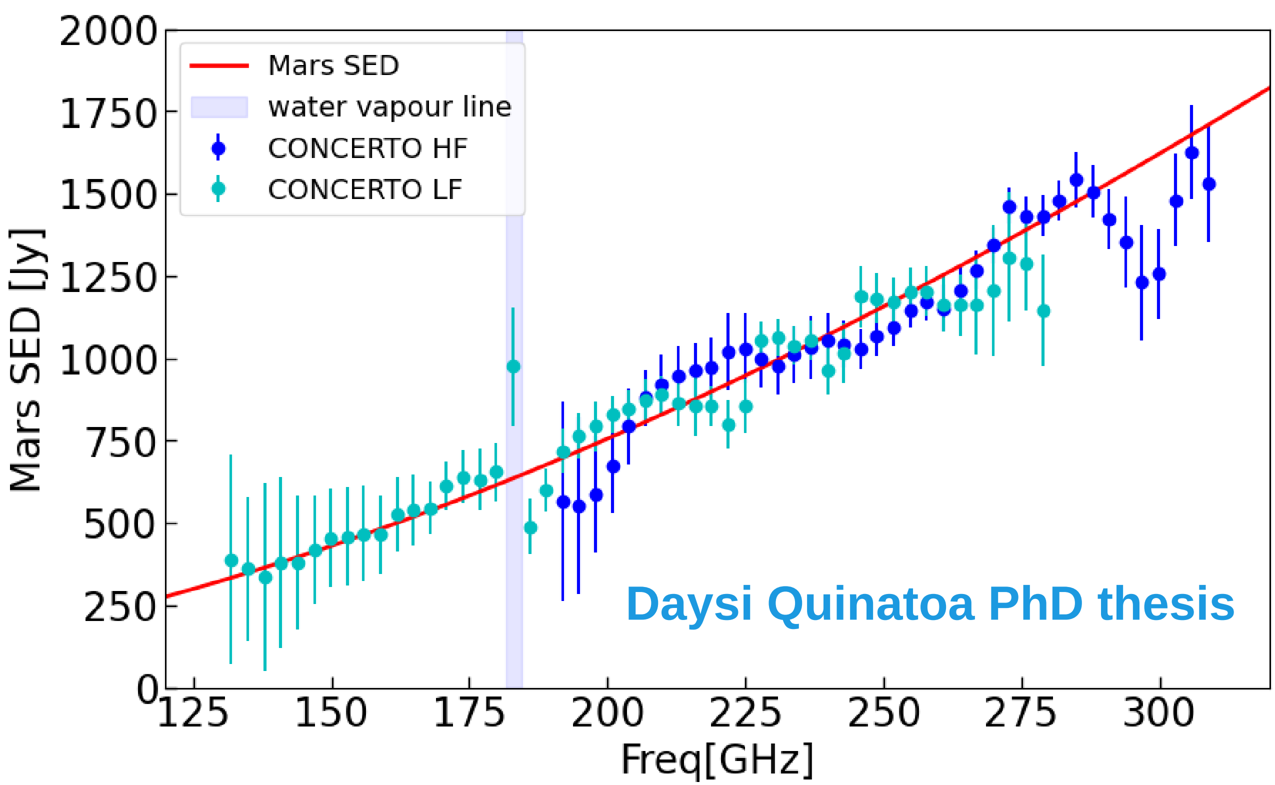


Sensitivity as expected, need still to work more on spectroscopic data processing pipeline & SZ specific analyses

Significant contribution from Valparaiso

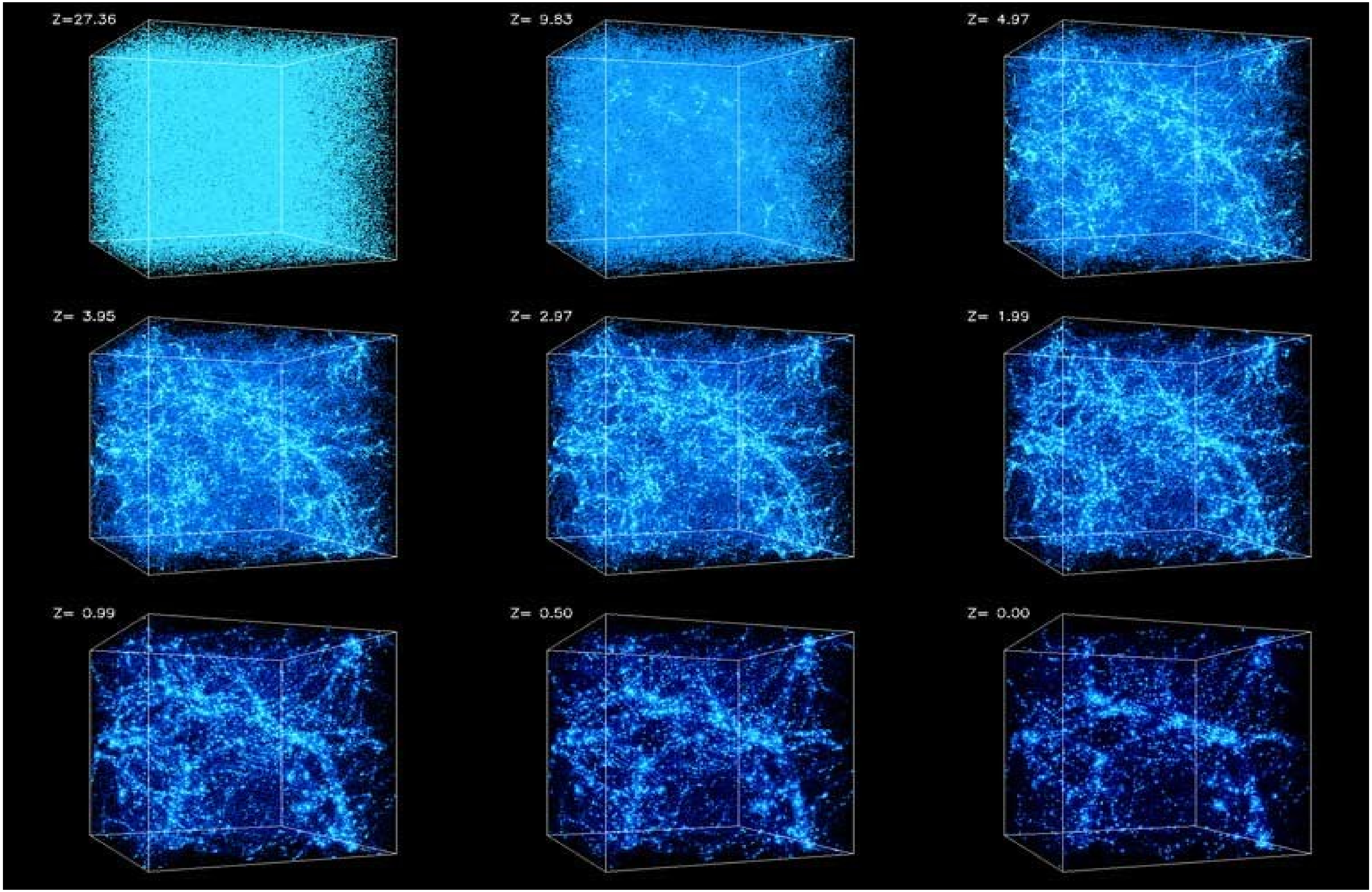
In charge of the spectroscopic calibration using planet observations





- Observations in good agreement with instrument model
- Full calibration products delivered to the CONCERTO collaboration !
- Further testing ongoing

Large scale structure formation



Credit: Center for Cosmological Physics

Cluster observables and physics

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

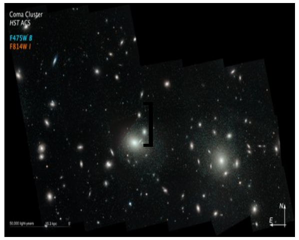
Pressure, mass, shocks:
- Compton parameter

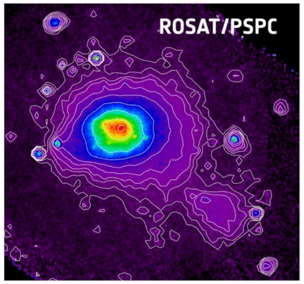
Radio emission

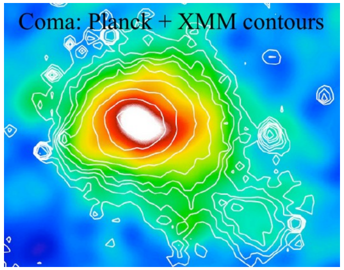
Non thermal emission from accelerated particles

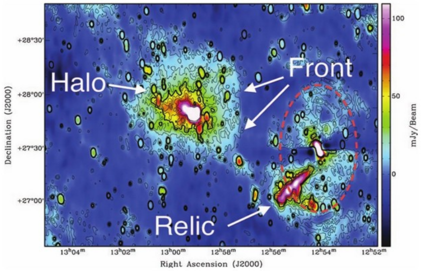
Shocks:
- Surface brightness

Cluster physics from multi-wavelength observations









Coma cluster

Sunyaev-Zel'dovich (SZ) effect

Two main components:

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

thermal SZ: CMB spectral distortion induced by inverse Compton interaction of CMB photons with clusters hot electrons

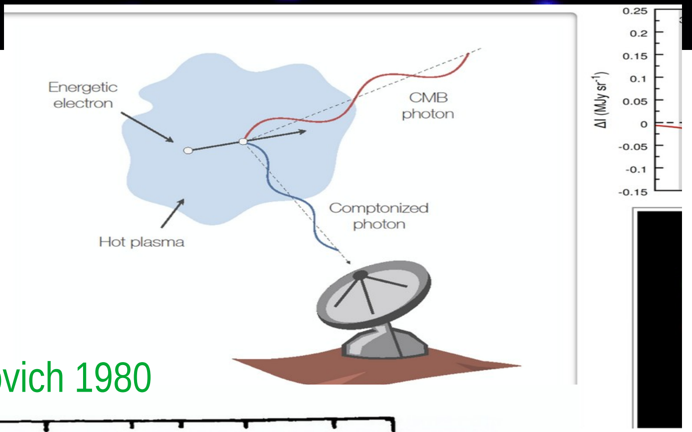
$$y_{tSZ} = \frac{\sigma_T}{m_e c^2} \int P_e d\ell$$

Kinetic SZ: CMB Doppler shift from bulk motion of cluster electrons (about tSZ/10)

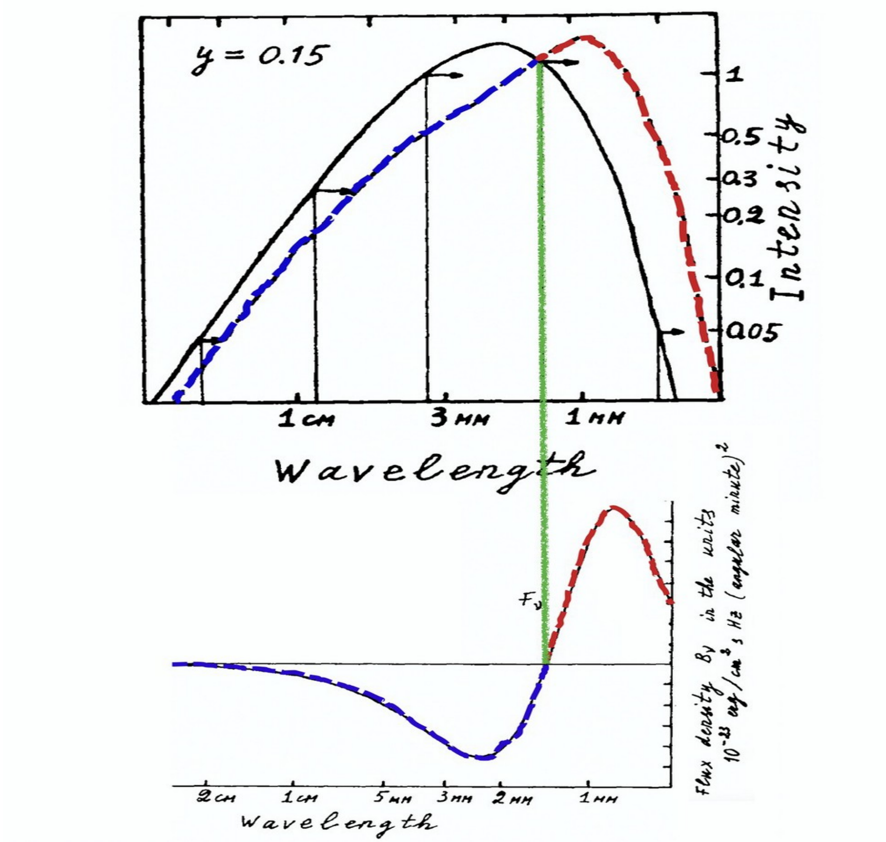
$$y_{kSZ} = \sigma_T \int \frac{-v_z}{c} n_e d\ell$$

No affected by cosmological diming

Probe for inter-cluster gas, mass and velocity tracer



Sunyaev & Zel'dovich 1980



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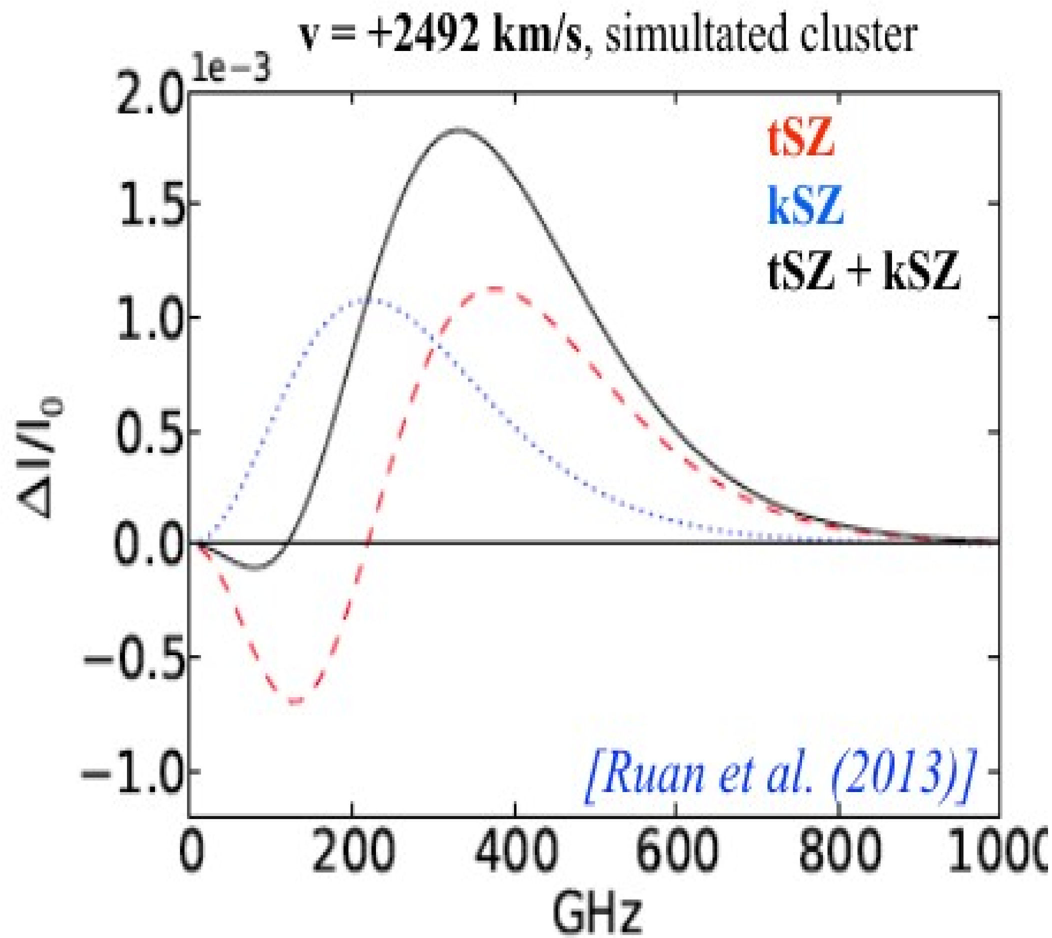
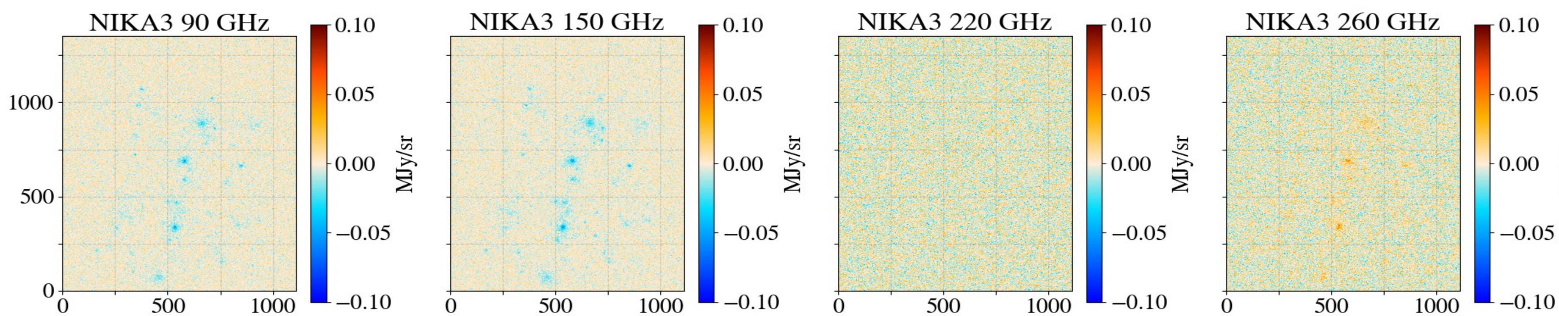
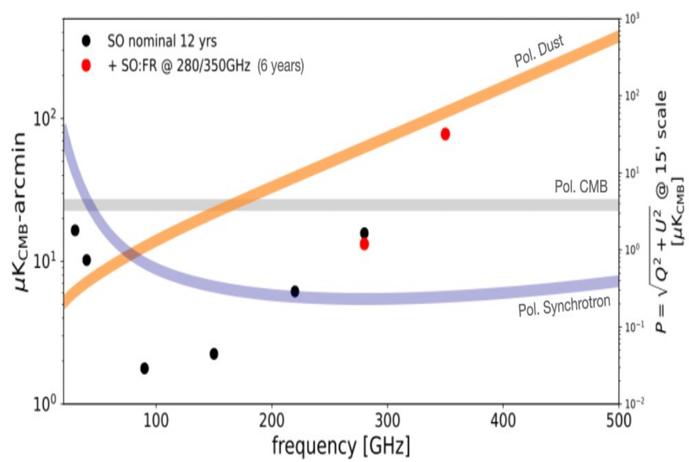


(possible) next generation of experiments with GIS KIDs

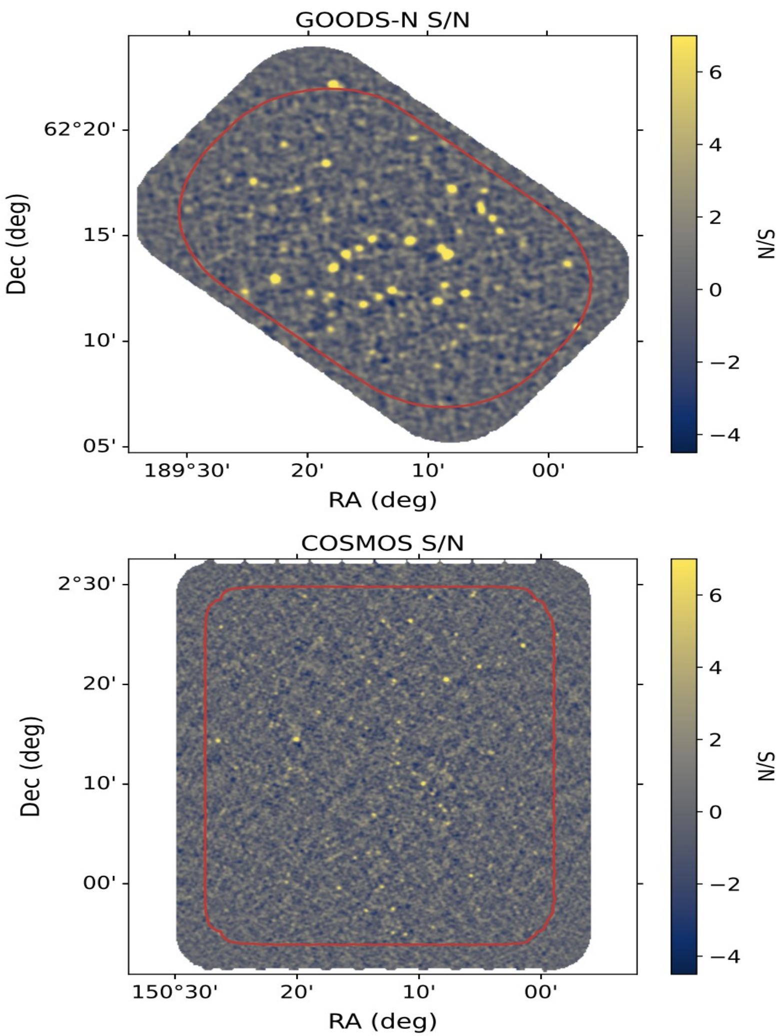
- Upgrade of NIKA2 to target individual kSZ measurements and follow-up of clusters from current and future CMB experiments and LSS from Euclid and The Rubin Vera Observatory
- Converting CONCERTO into a “simultaneous line spectroscopy and continuum instrument”
- 15-m telescope for a high-resolution large sky survey for CMB lensing, clusters and high redshift sources
- SAT (small aperture telescope) for Simons Observatory (S0) targeting high frequency and dust decontamination



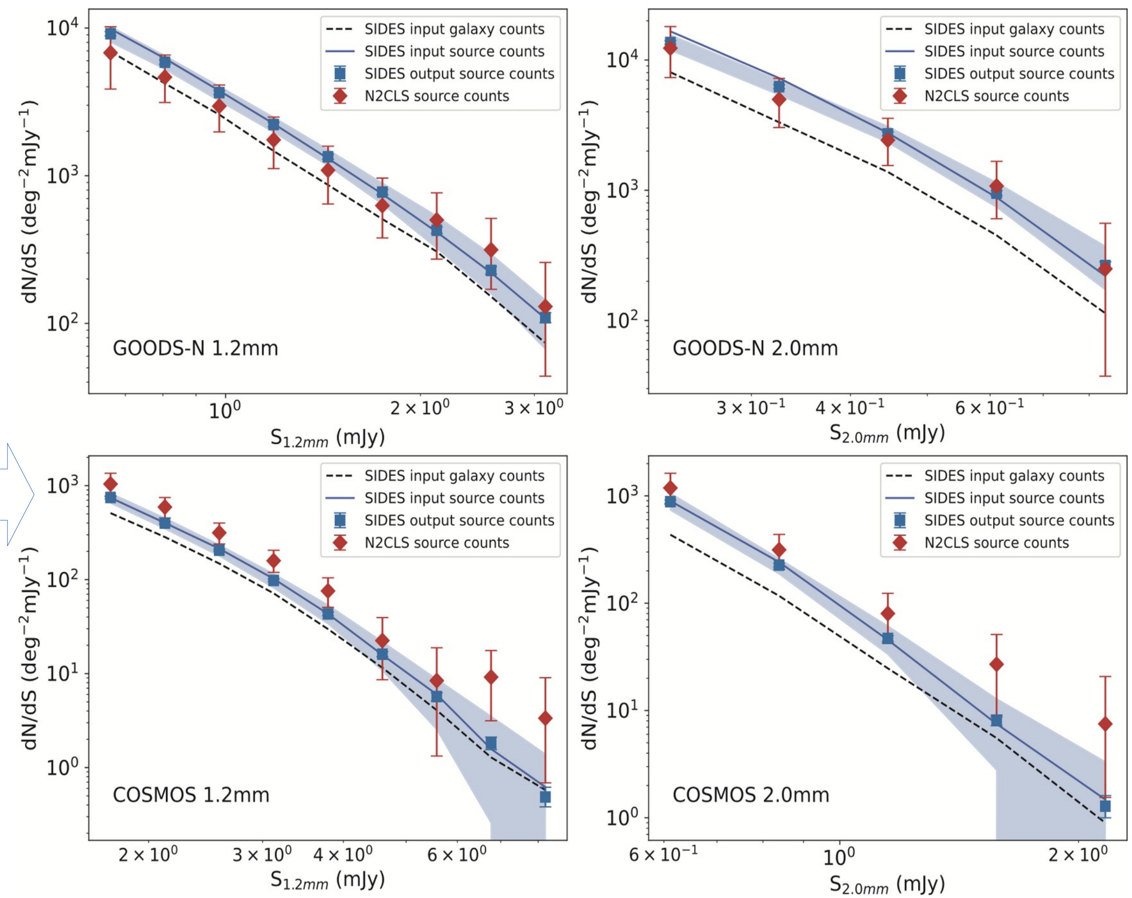


mm high redshift galaxies

Deep observations of the COSMOS and Goods North fields



Precise number counts measurements

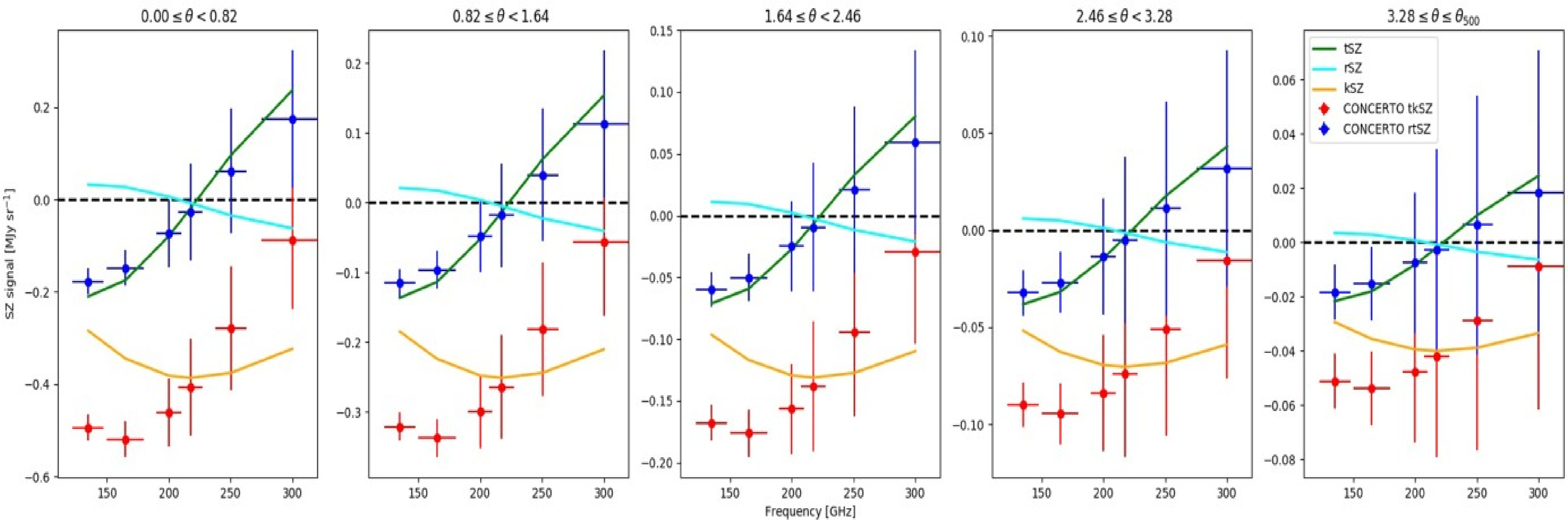


Bing+2023, A&A, 677, A66

CONCERTO SZ performance

SZ effect for a simulated cluster at redshift z = 0.4, with a mass of 10^{15} M_{sun}
and a temperature of 20 keV, which is moving at 1000 km/h towards the observer.

Concerto collaboration+2022.



Four clusters observed with CONCERTO for more than 300 hours on source

Sunyaev-Zeldovich (SZ) effect

$$\Delta I_\nu^{th} + \Delta I_\nu^{kin} + \Delta I_\nu^{rel} + \Delta I_\nu^{non-th} + \Delta I_\nu^{pol} + \Delta I_\nu^{m-scat}$$

Thermal

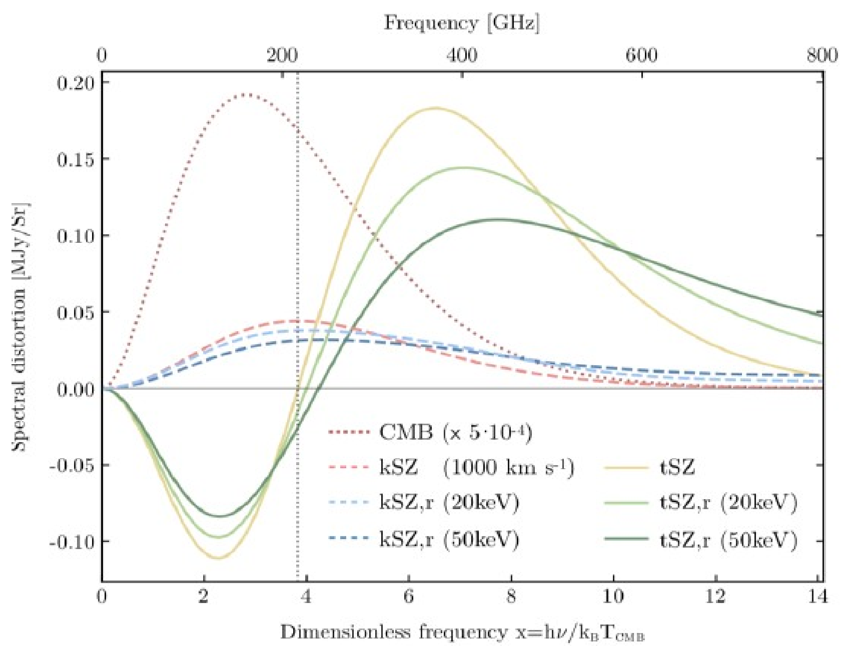
Kinetic

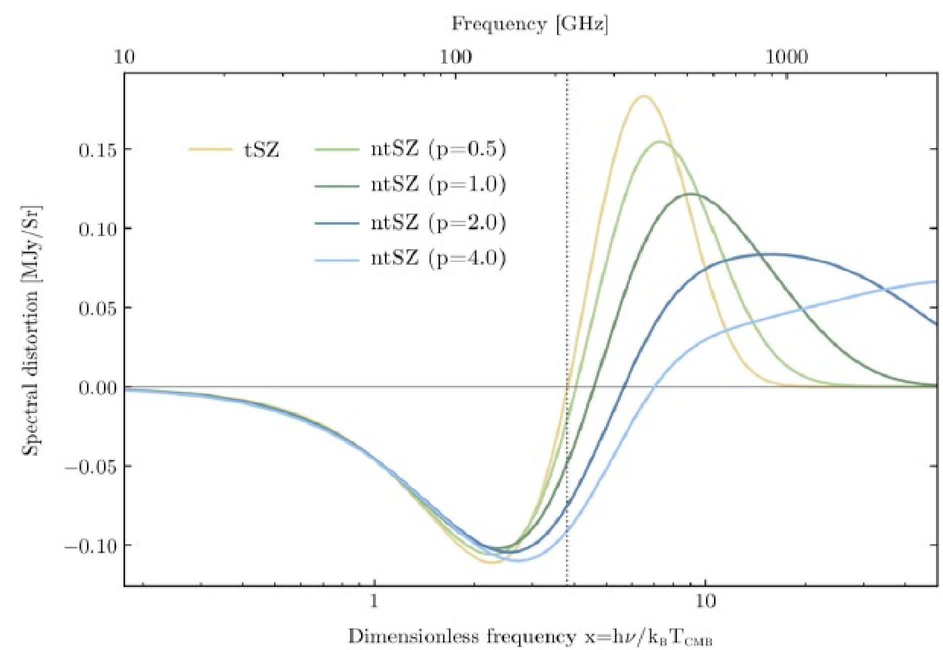
Relativistic corrections

Non-thermal

Polarised

Multiple Scattering



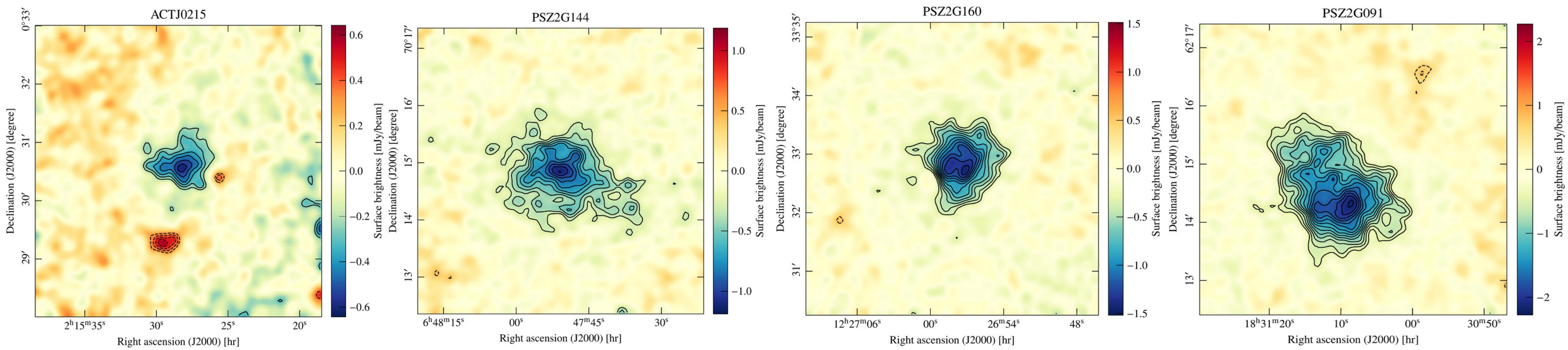


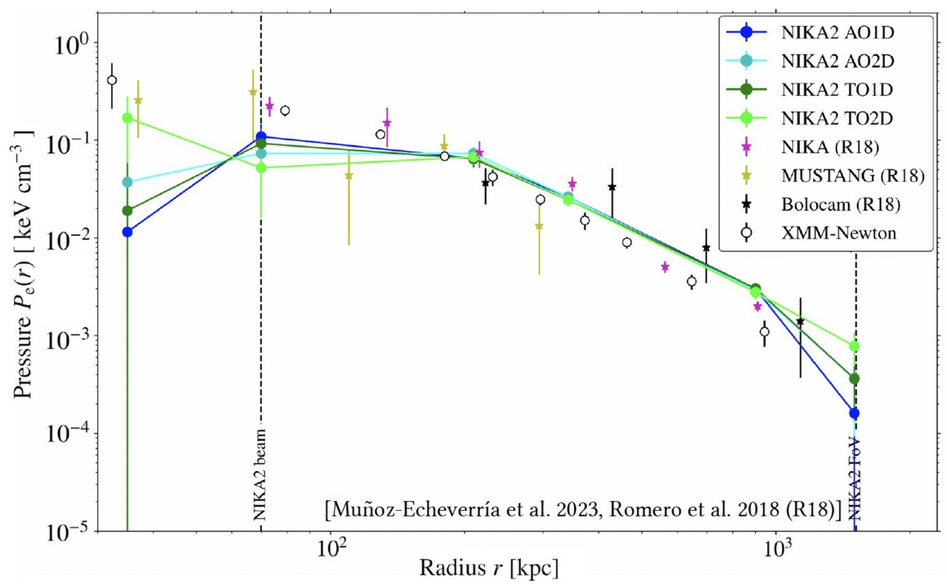
Mroczkowski+2019

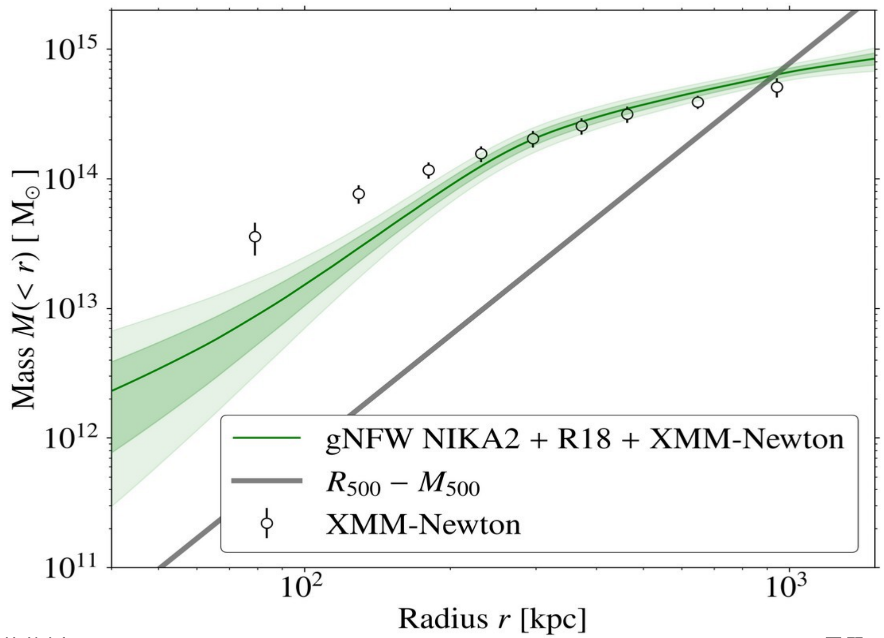
Observed NIKA2 LP SZ clusters

4 clusters already published individually

Ruppin+2018, Kéruzoré+2020, Muñoz-Echeverría+2022, Artis+2022







Observed NIKA2 LP SZ clusters

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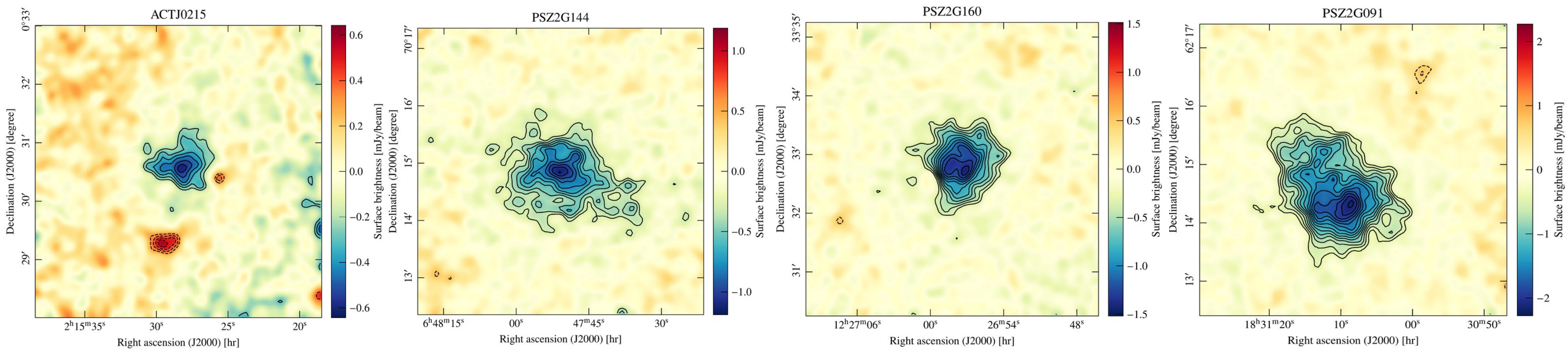
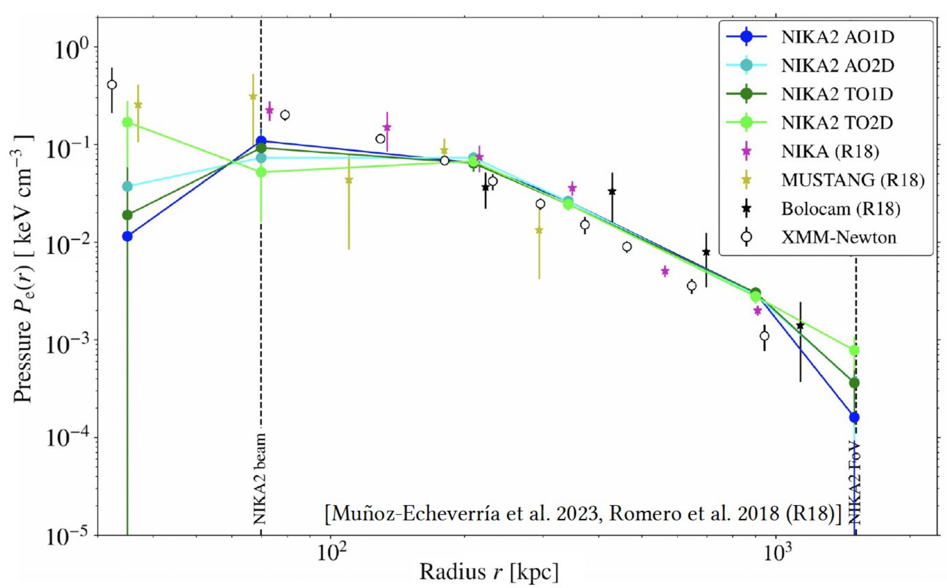
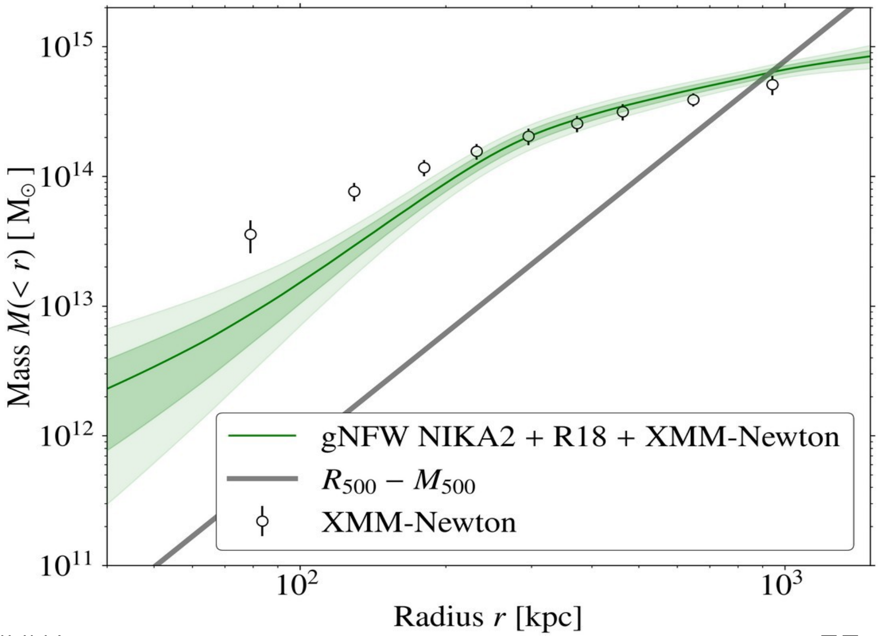


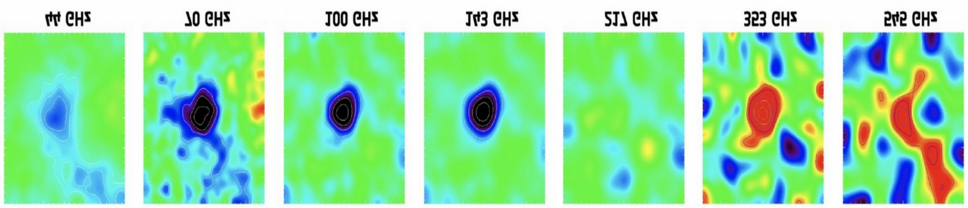


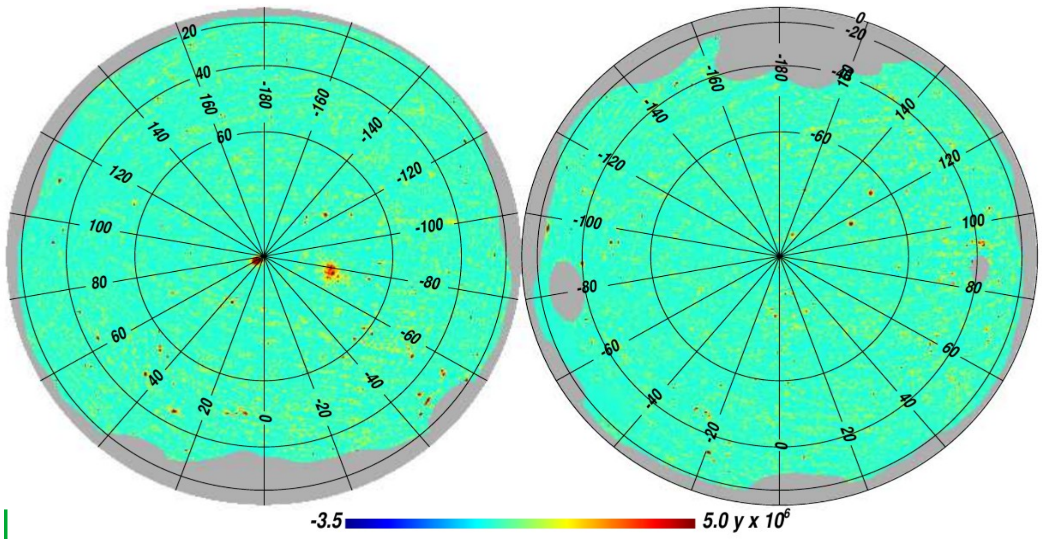


SZ cluster detection and cosmology (Planck example)

Cluster detection

Use tSZ unique spectral signature combined with expected cluster morphology





Planck 2015 results: XXII, XXIV and XXVII

Cluster number counts

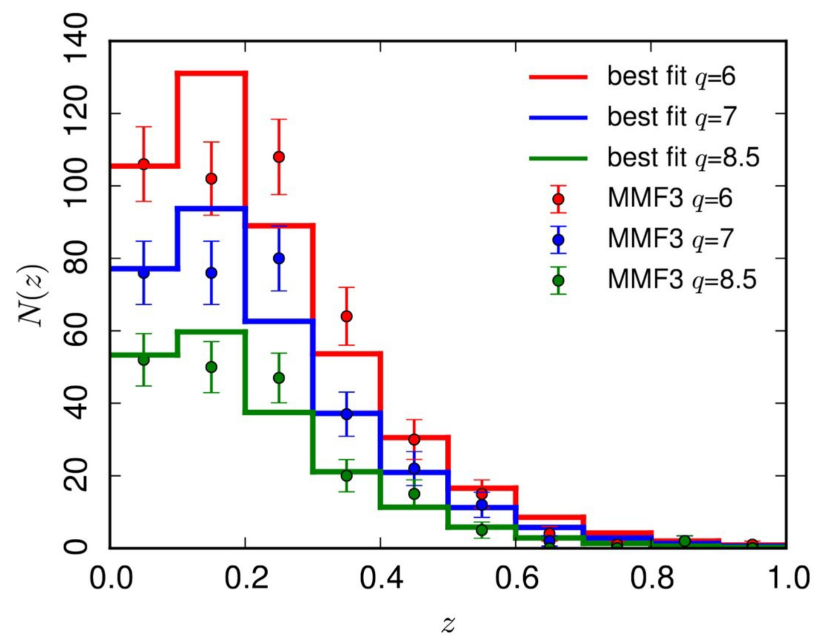
cosmology

Instrumental performance

cosmology

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

measurements



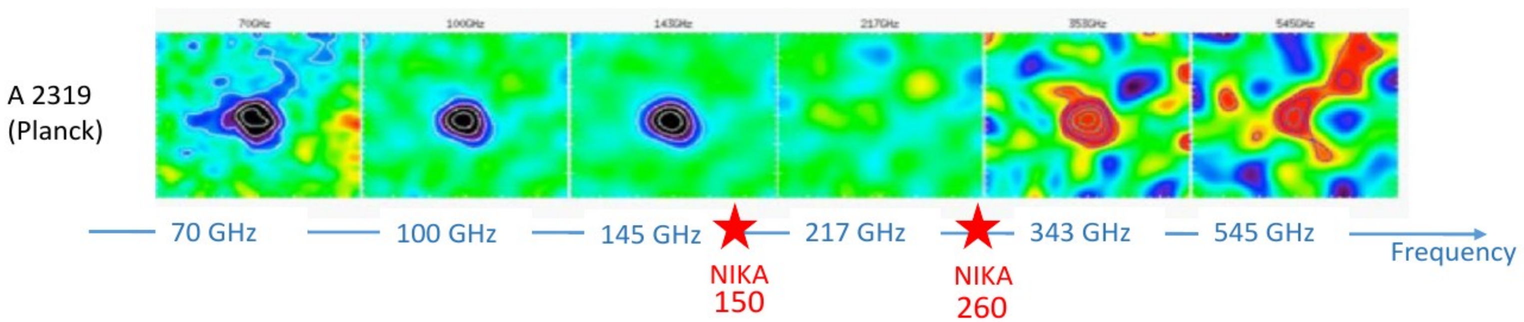
Limited by knowledge of the **cluster mass** that can not be measured directly

SZ with NIKA/NIKA2

NIKA1/2 well adapted for SZ observations of intermediate and high redshift clusters

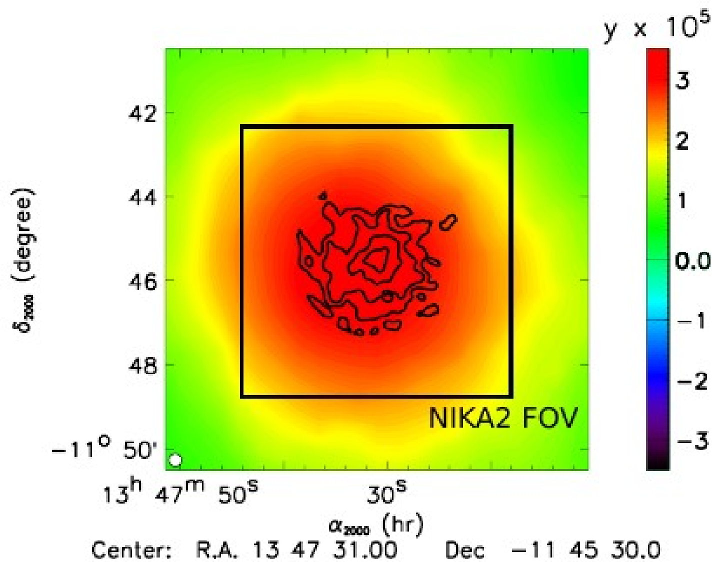
Ideal spectral coverage

Simultaneous mapping of SZ and possible contaminants



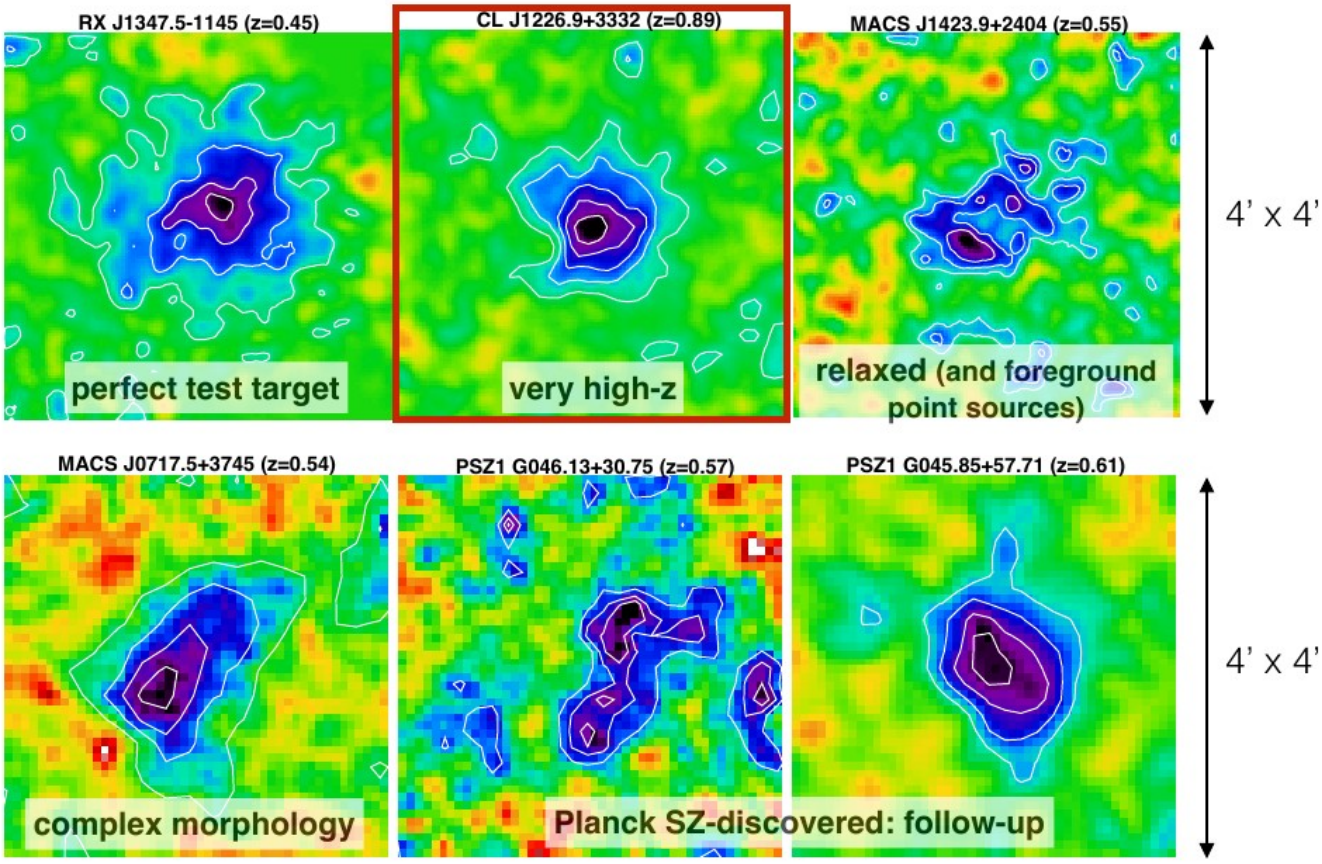
High resolution and large FOV

23 times more resolved than Planck
Can map both cluster inner regions and outskirts



The NIKA cluster sampe

A sample of 6 clusters selected in terms of physical properties



- First ever science relevant observations with KIDs
- Pressure profiles reconstruction
- Temperature map by combining X-ray and tSZ
- Direct kSZ measurements

[Adam+ 2014, Adan+2015, Adam+2016, Ruppin+2017,Adam+2017, MP+2020, Romero+2018, Adam+2018]

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

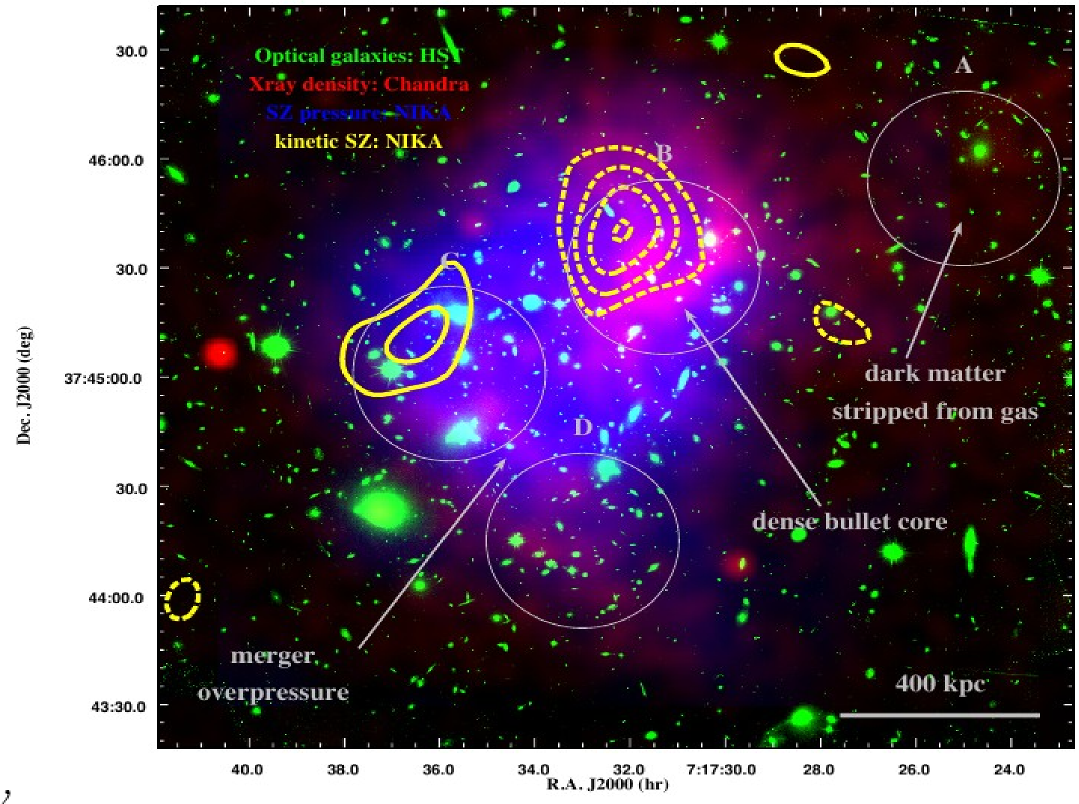
- Use the two NIKA channel maps
  + temperature map from X-rays

spectral dependencies

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

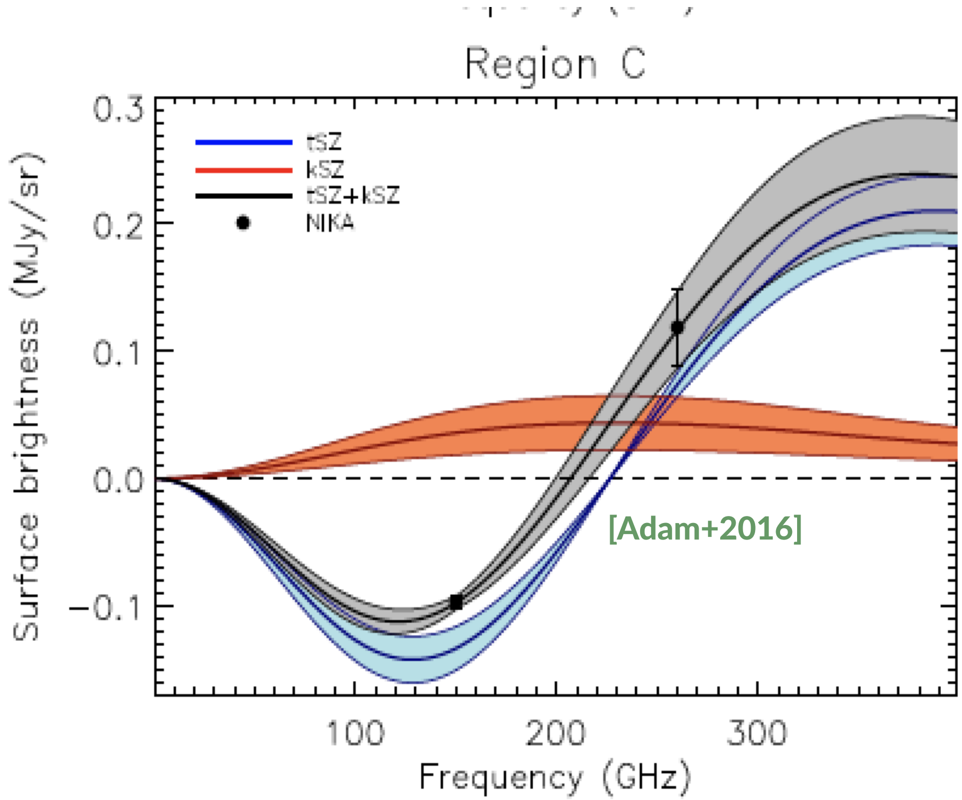
gas pressure *gas velocity and density*

MACS J0717-3745

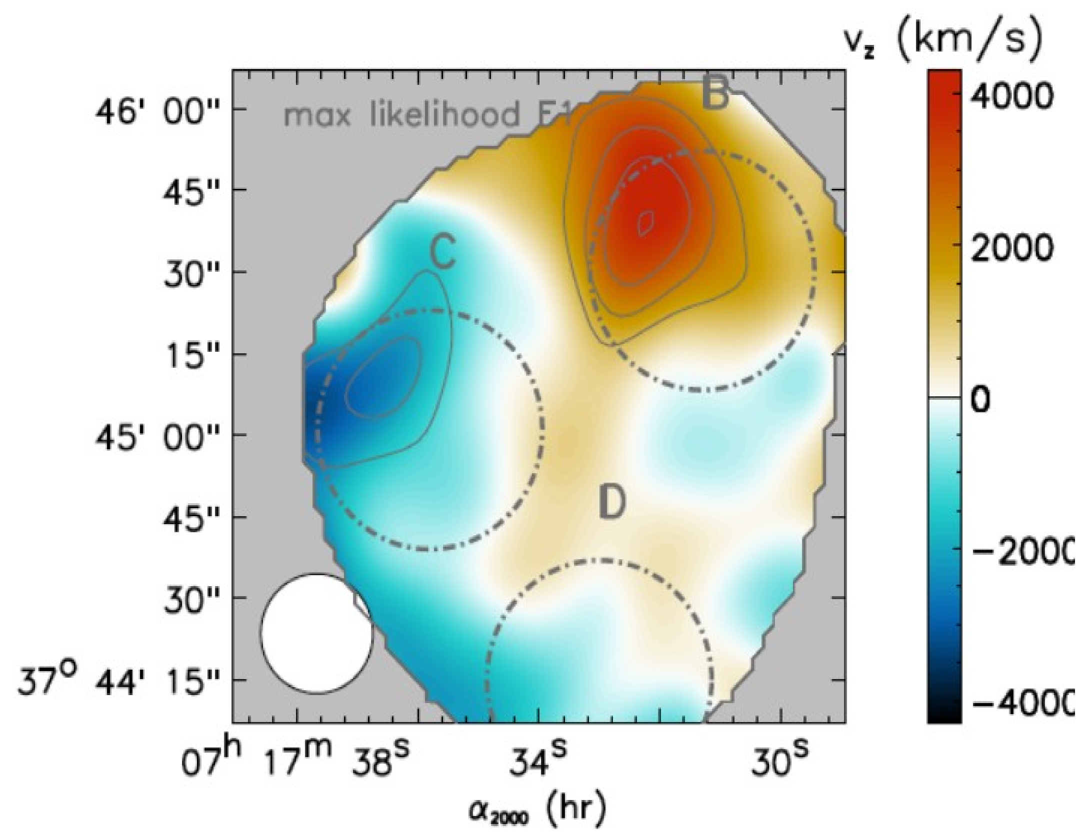


kSZ mapping with NIKA

Disentangling SZ & kSZ contributions



Velocity map reconstruction



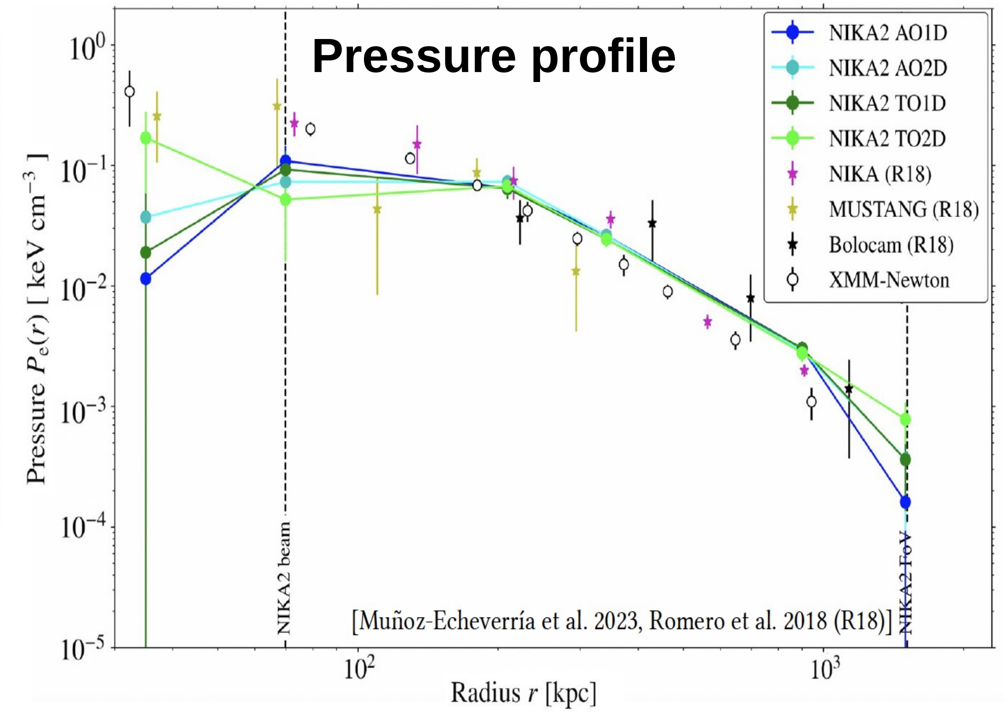
First direct mapping of kSZ emission

Pressure profiles and hydrostatic mass

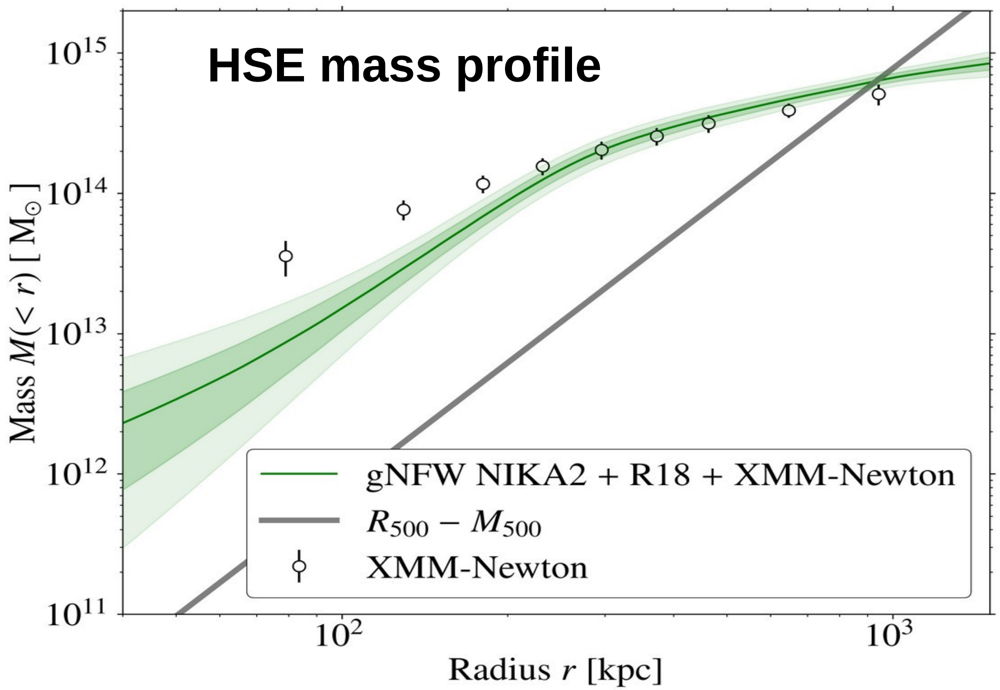
- Pressure profiles and hydrostatic (HSE) mass estimates for 4 individual clusters already have been published

Ruppin+2018, Kéruzoré+2020, Muñoz-Echeverría+2022, Artis+2022

From NIKA2 150 GHz maps

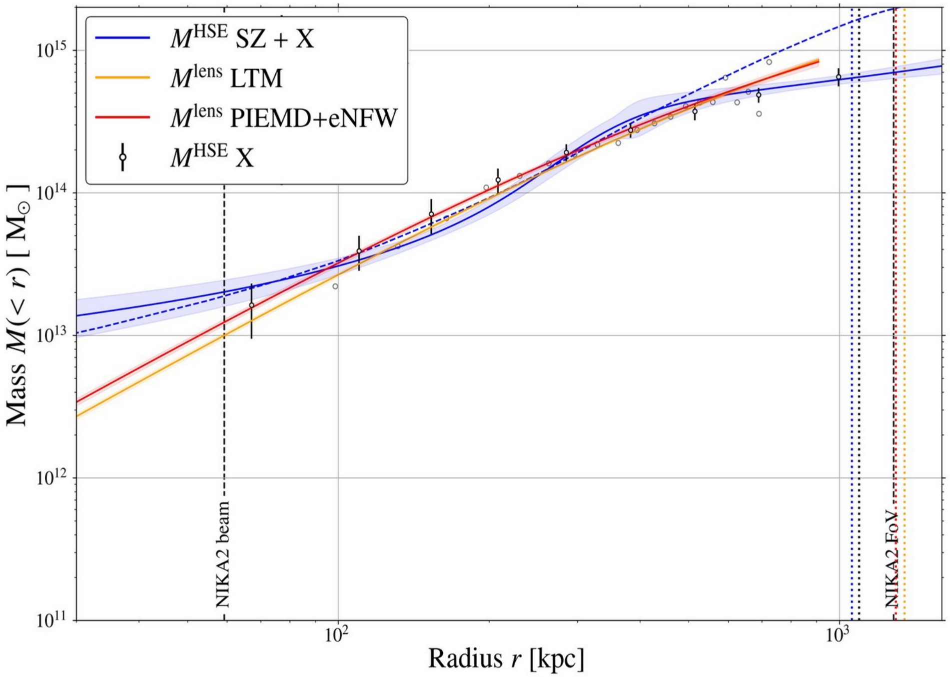


From combined X-ray and tSZ analysis

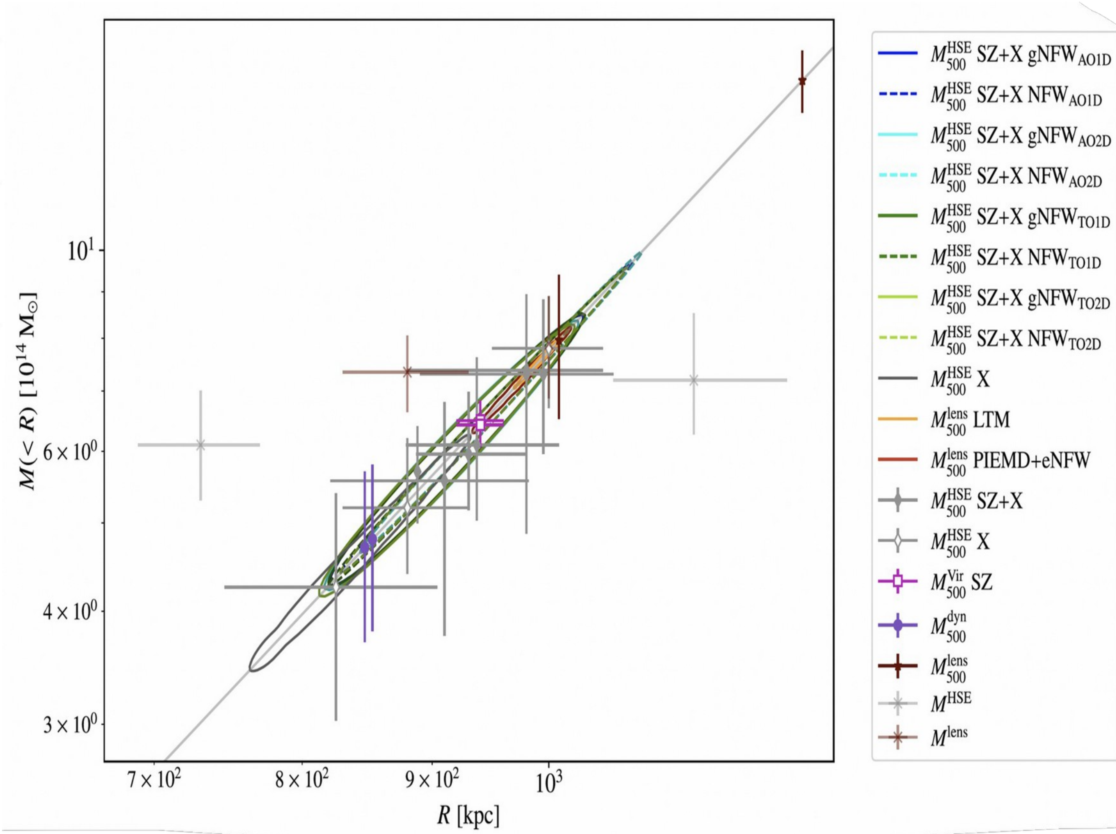


Can directly measure the hydrostatic mass of clusters on resolved profiles

tSZ and lensing masses



Can compare HSE and lensing mass to estimate possible bias and systematics

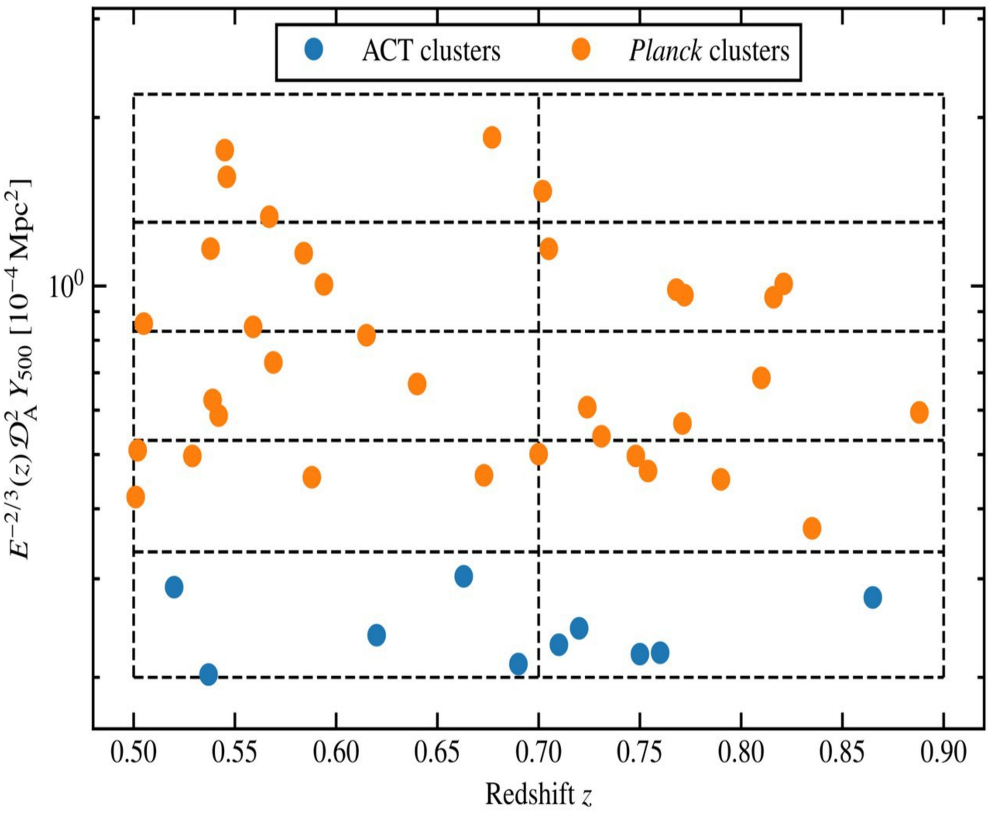


Dispersion on mass estimates is significantly larger than the error-bars quoted by individual analyses

Ferragamo+2021, Muñoz-Echeverría+2023

NIKA2 SZ Large program

[Comis+2016, MP+2017, Mayet+2020, Kéruzoré+2021]



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

- **300 hours** of tSZ observation
- **33 high redshift clusters 0.5 < z < 0.9**
- tSZ selected clusters from Planck and ACT catalogues

Ancillary data

- X-ray follow-up with XMM
- Optical data using GranTeCan
- The Three Hundreds hydrodynamic simulations

Main goals

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

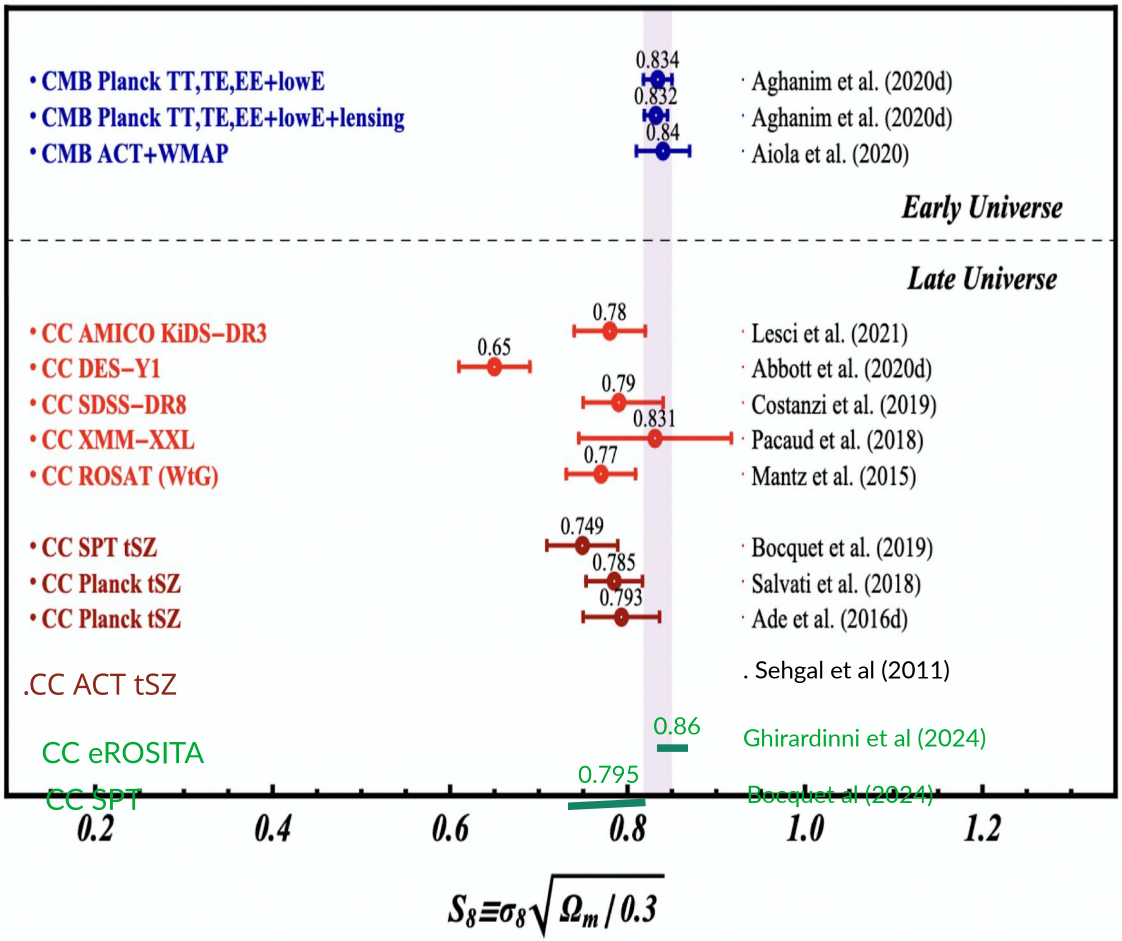
Redshift evolution of:

- Thermodynamic quantities profiles
- Scaling laws and hydrostatic bias

Variation of cluster properties with:

- Dynamical state (mergers)
- Morphology (ellipticity)

SZ cluster detection and cosmology



Discrepancy with CMB cosmology

- New physics?
- Systematics on CMB ?
- Systematics on cluster analysis:

  Bias in mass estimates
  Wrong modeling of clusters properties

High resolution observations of clusters at intermediate and high redshift are mandatory !