Detection and physics of distant galaxy clusters via the Sunyaev-Zel'dovich effect

PhD Seminar – April 11, 2024

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COSMO-ML team

Supervisors : Juan F. Macias-Perez & Nario Kuno

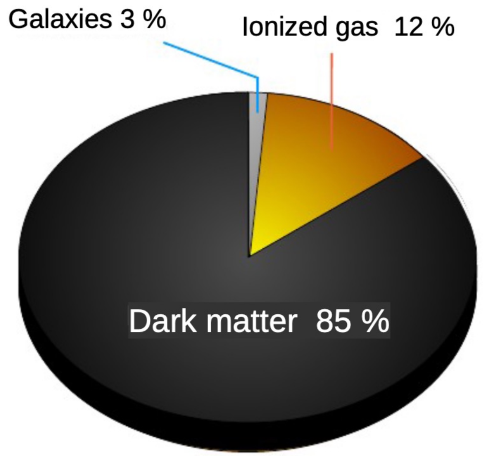
Part of the UGA-Tsukuba Double Degree Program

Outline

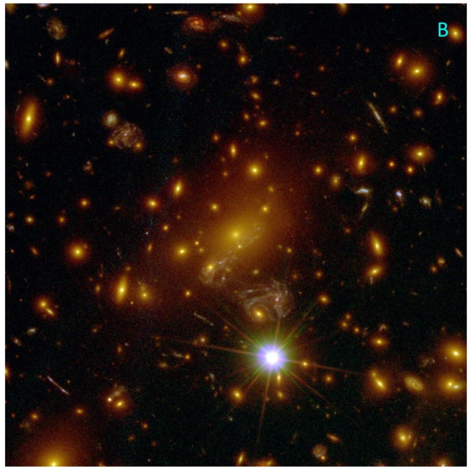
- Cluster of galaxies
- Galaxy clusters blind detection with NIKA2
- Galaxy clusters observation with the Tsukuba-Grenoble 100 GHz camera at Nobeyama
- Conclusion

Galaxy clusters

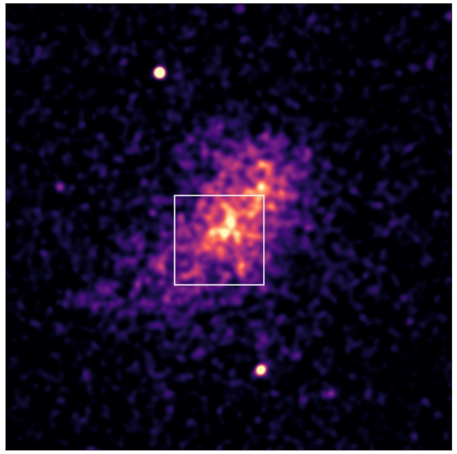
- Largest gravitationally bound structures in the Universe
- 3 main components :
  - Dark Matter : Optical & IR via lensing
  - Intra Cluster medium (ICM) : X-ray & SZ
  - Galaxies : Optical & IR
- $M \in 10^{13} - \text{few } 10^{15} M_\odot$ and $0 < z < 3$



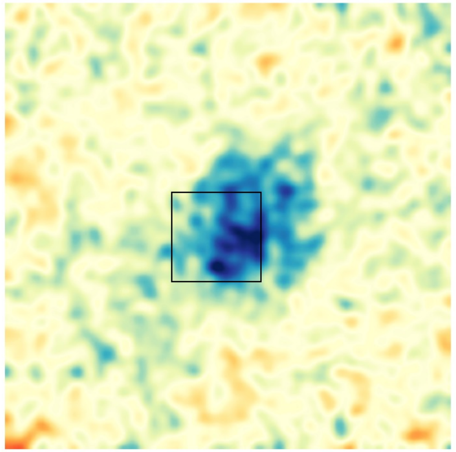
Optical
(flux and density of galaxies,
lensing background galaxies)



X-ray
(Bremsstrahlung)



Millimeter
(Inverse Compton scattering)



MACSJ1149.5+2223 observed at different wavelengths

Sunyaev-Zel'dovich effect

CMB spectral distortion from Inverse Compton scattering with clusters' hot electrons in the ICM

- Very distinct spectrum
- Compton parameter : $y = \frac{\sigma_T}{m_e c^2} \int P_e dl$
- **SZ effect is redshift independent (not affected by cosmological dimming)**

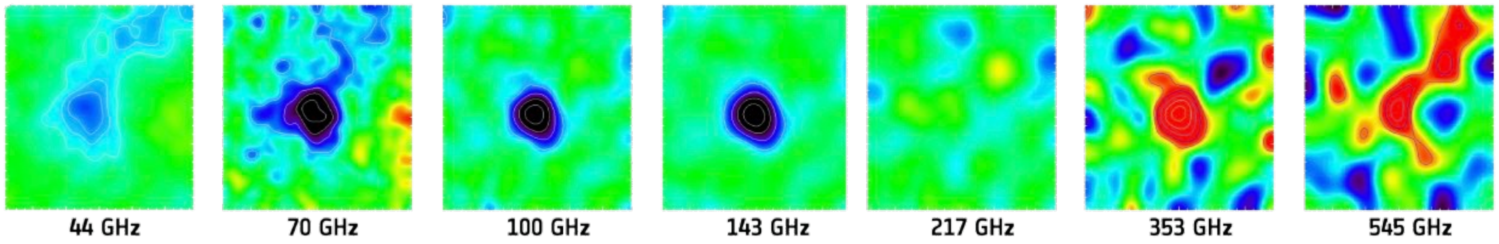
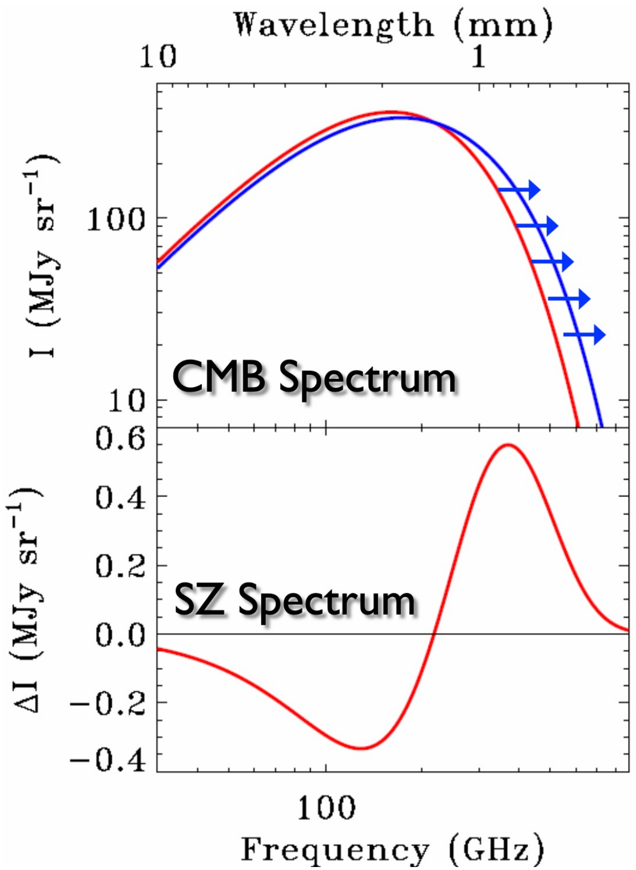
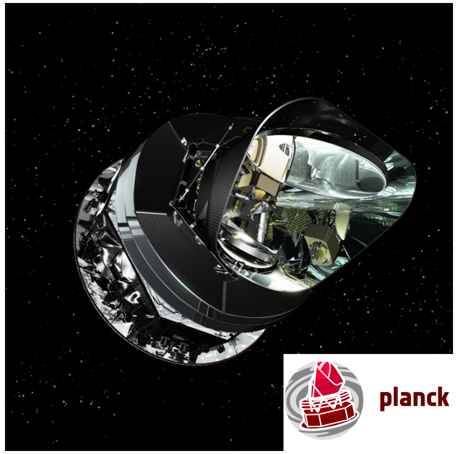


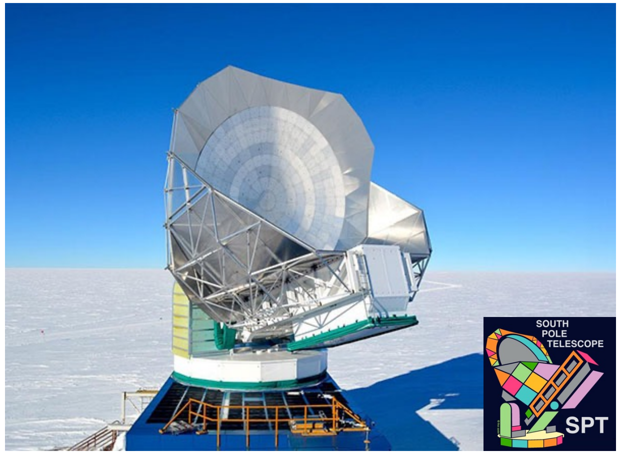
Image credit: ESA / HFI & LFI Consortia

A2319 Cluster observed by Planck



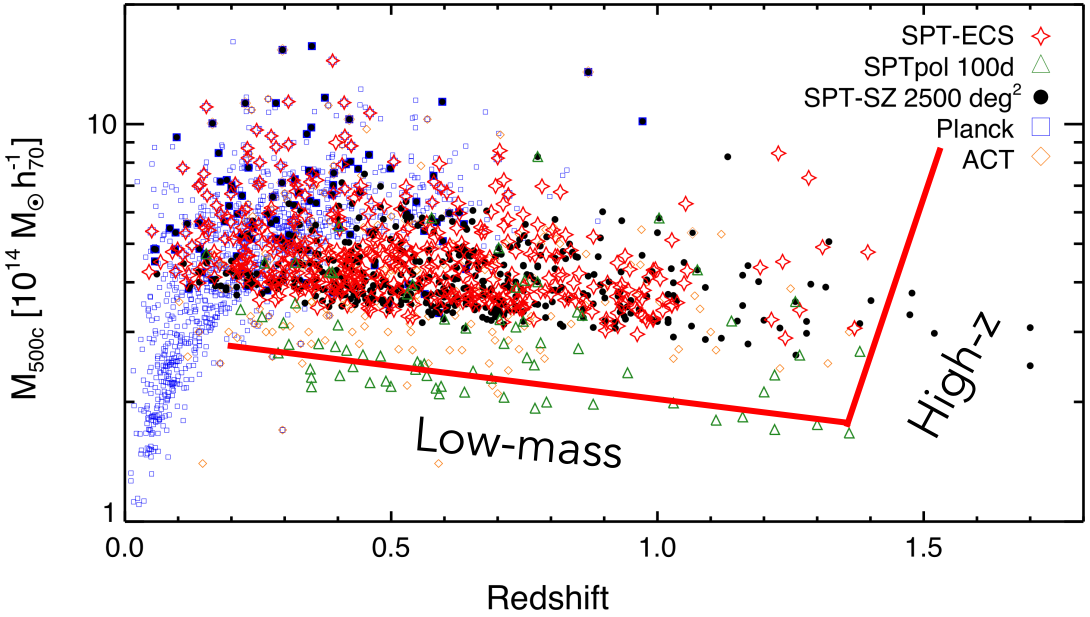
Millimeter large SZ surveys





- Catalog of thousands of SZ clusters from previous millimeter large surveys (Planck, ACT, SPT)

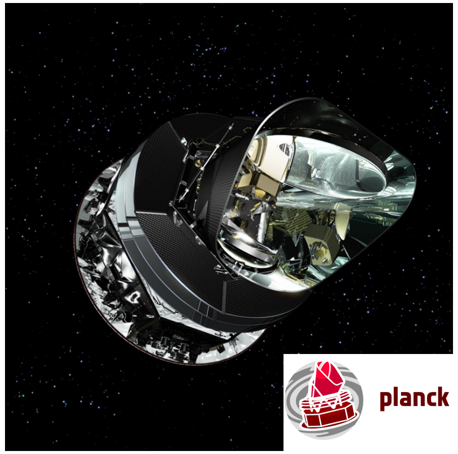
- But they have relatively poor resolutions
  - ~5 arcmin for Planck
  - ~1 arcmin for SPT and ACT

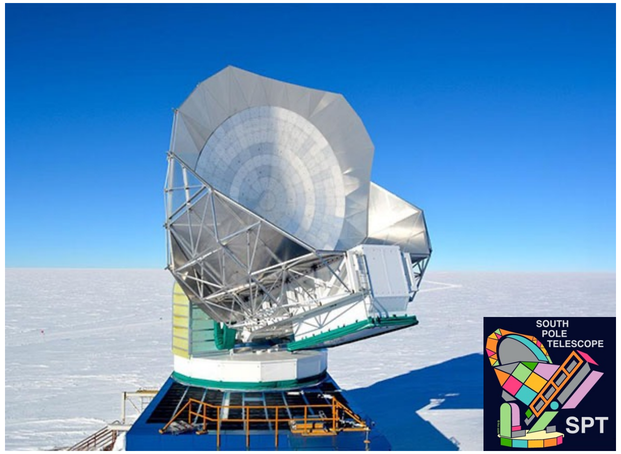


Distribution in the mass-redshift plane of all the clusters published in the Planck, SPT, and ACT catalogues.

R_{500} : radius at which the mean cluster density is 500 times the critical density of Universe

Millimeter large SZ surveys





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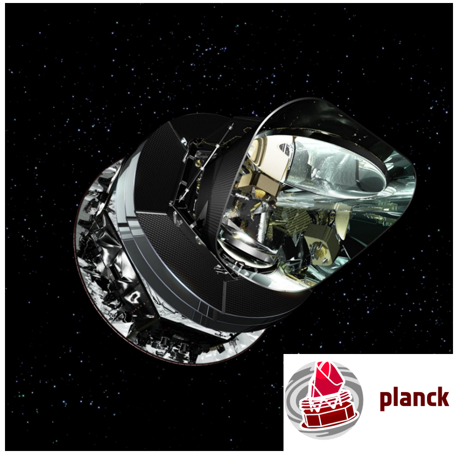
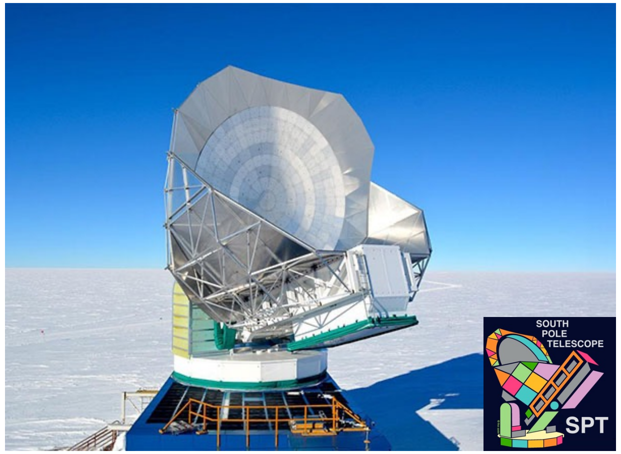
Why study low mass high redshift clusters ?

- Verify structure formation and self similarity :
  - What is the real definition of a cluster ?
  - Impact of departure from self similarity on scaling relations for cosmology (see Alice's talk)

Millimeter large SZ surveys





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R_{500} : radius at which the mean cluster density is 500 times the critical density

We need high angular resolution to detect low mass/high redshift clusters

NIKA2

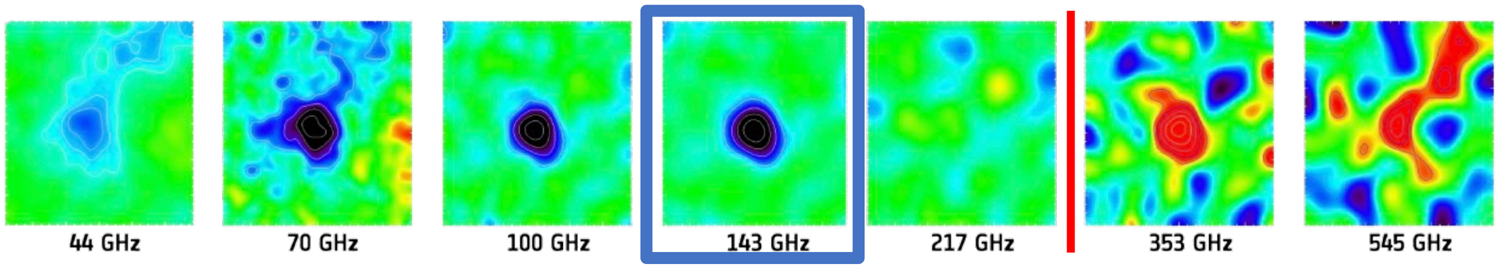
- Dual band millimeter camera of 2 900 Kinetic Inductance Detectors (KIDs) installed at the IRAM 30m telescope
- Built in Grenoble GIS KIDS (LPSC, Institut Néel, IPAG, IRAM)
- Operating since 2015, we dispose of 1300h of guaranteed time

IRAM telescope

Observing band	150 GHz	260 GHz
Field of view [arcmin]	6.5	6.5
Angular resolution [arcsec]	17.6 ± 0.1	11.1 ± 0.2
Mapping speed [$arcmin^2.mJy^{-2}.h^{-1}$]	1388 ± 174	111 ± 11

Perotto et al. 2020

- Large field of view
- High angular resolution
- High sensitivity



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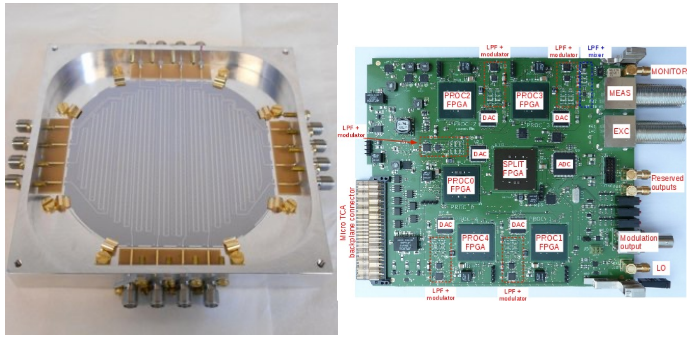

NIKA2 KIDs array and readout board

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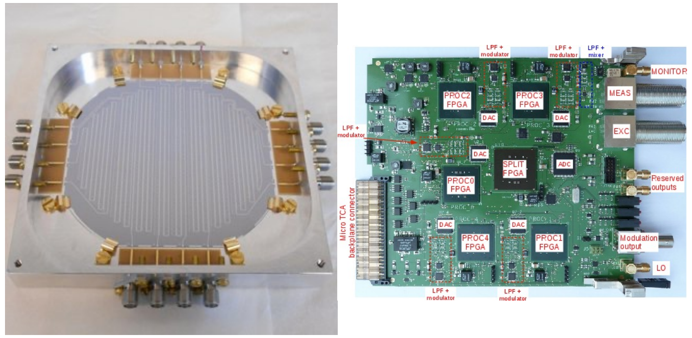

NIKA2 KIDs array and readout board

Powerful instrument to study the tSZ effect in high redshift clusters

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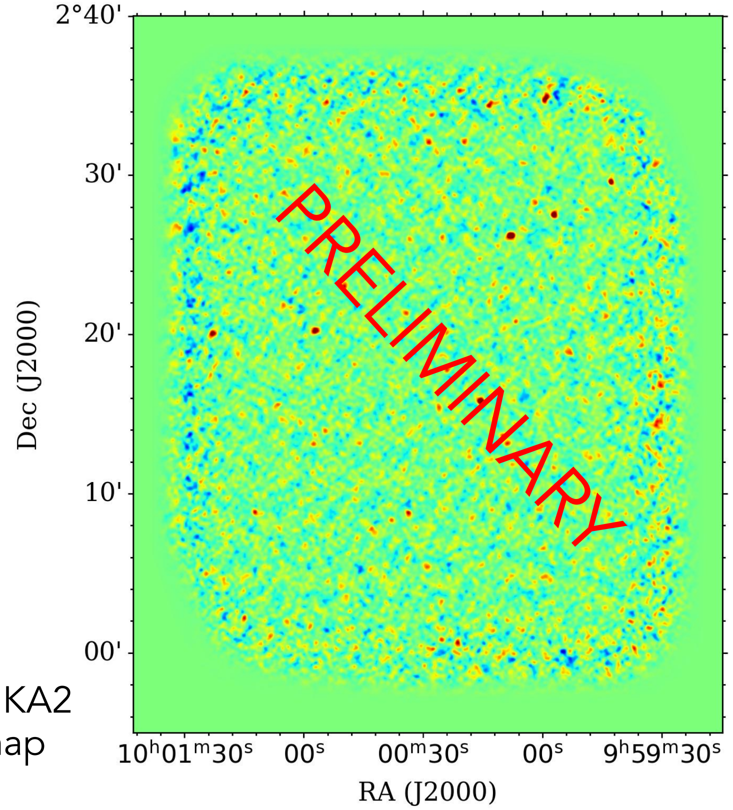
Blind cluster detection in deep NIKA2 fields

- Data acquired by the NIKA2 Legacy Survey (N2CLS) Large Program
- ~195 hours of deep field observations of the well-known COSMOS field
- ~1400 arcmin^2 field
- Used for the detection of high redshift galaxies (*Bing et al 2023, 2024*)

Objective : Blindly detect galaxy clusters with NIKA2

- I worked on 3 maps of the COSMOS field
- 3 different data reduction processes optimized for different purposes
- Will present results for one of them



COSMOS NIKA2 150 GHz map

Blind cluster detection : Matched Filter technique

- Used in the construction of previous large surveys (Planck ,SPT, ACT) cluster catalogs
- Enhances the SNR of sources with a well-known spatial template (e.g galaxy clusters)
- Will be used in future experiments (Simons Observatory, etc…)

Maps

$$\boldsymbol{M}(\vec{x}) = \boldsymbol{S}(\vec{x}, \theta_c) + \boldsymbol{N}(\vec{x})$$

Spatial template Noise

Matched Filter (Fourier space)

$$\boldsymbol{\Psi}(\vec{k}) = \left[\boldsymbol{S}(\vec{k})^T \boldsymbol{C}(\vec{k})^{-1} \boldsymbol{S}(\vec{k})\right]^{-1} \boldsymbol{S}(\vec{k}) \boldsymbol{C}(\vec{k})^{-1}$$

Package *pymf* from Erler et al. 2019

Blind cluster detection

$$y \propto \int P_e \, dl$$

1. Use a Compton 2D profile as template
   - From gNFW pressure profile (*Nagai et al. 2007)*
   - With *Arnaud et al. 2010 (A10)* parameters

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

2. Filter the map with different template sizes as done for Planck

–> 5 parameters : P_0 amplitude

r_p, a transition radius/ steepness

c, b internal/ external slopes

3. Find peaks in the filtered map above a Signal-to-Noise Ratio (SNR) threshold of 4

Blind cluster detection

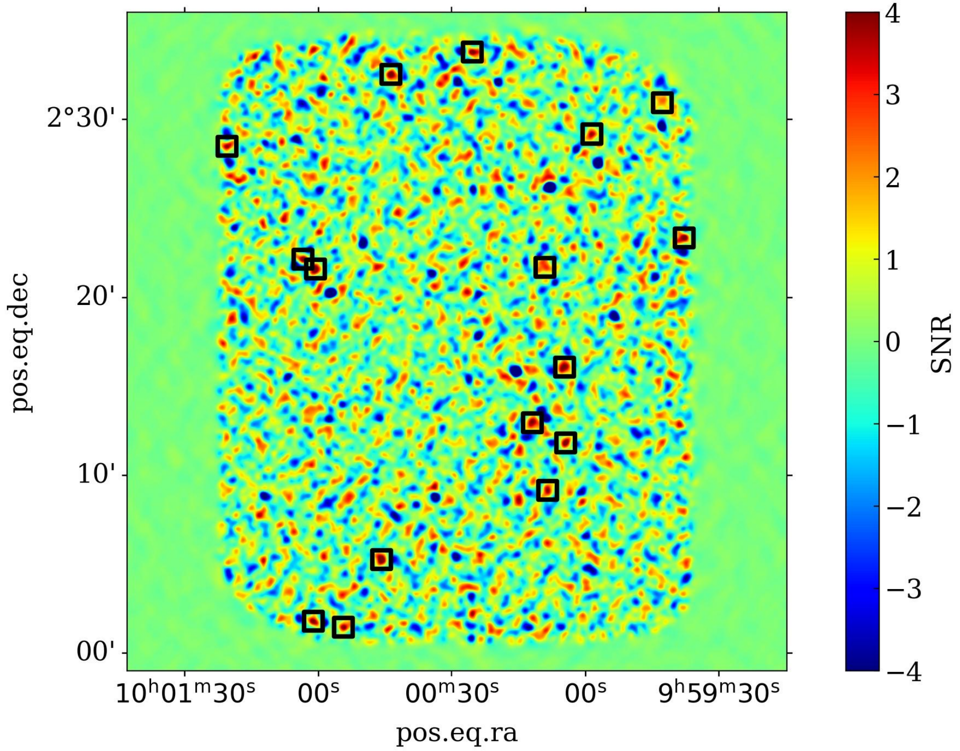
1. Use a Compton 2D profile as template
   - From gNFW pressure profile (*Nagai et al. 2007)*
   - With *Arnaud et al. 2010 (A10)* parameters

2. Filter the map with different template sizes as done for Planck

3. Find peaks in the filtered map above a SNR threshold of 4

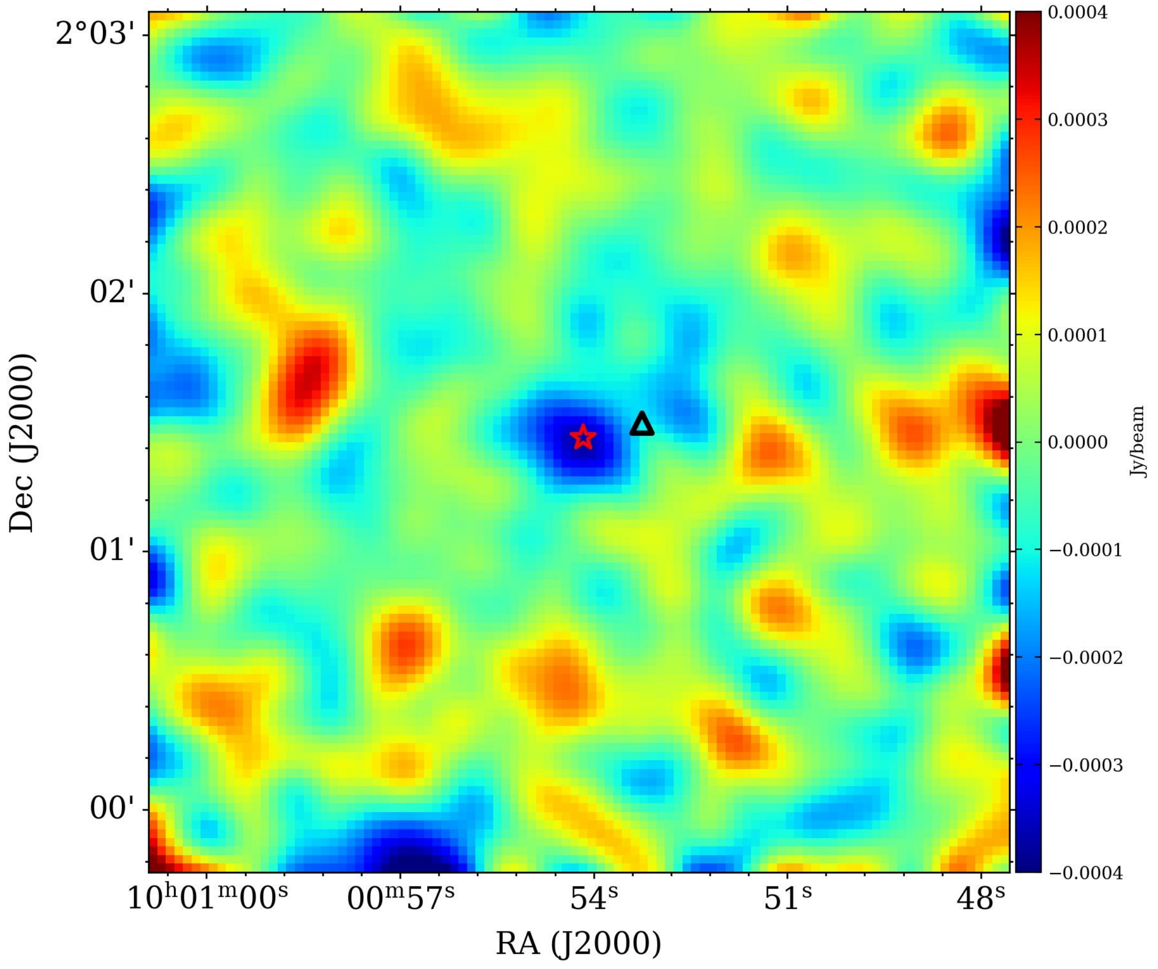
We have 16 cluster candidates after these 3 steps

Filtered NIKA2 150GHz map with a cluster template the size of the beam



Candidate clusters have a positive SNR (negative sign accounted for in the filter) !

Cluster candidates matching



150 GHz NIKA2 map

- Search cluster catalogs in the literature to find possible matches with our candidates

Red star : Cluster candidate

Black triangle : Optically (peak in galaxy density) detected cluster

- Clear negative signal in the map
- Match with a high redshift cluster at z ~ 1.42 :
  - [SCC2012] 1517

8 of our 16 detections are matched with a previously detected cluster

Cluster candidate sample

Candidate Name	RA °	DEC °	SNR	z	θ_{500} arcmin	Y_{500} 10^{-5} arcmin^2	M_{500} 10^{14} $M_{\odot}$	Matching cluster Name (distance [″], reference)
NIKA2-CL J100045.8+020514.3	150.1907	2.0873	5.31	–	Size	tSZ Flux	Mass	–
NIKA2-CL J095937.7+022320.4	149.9071	2.3890	5.00	0.740±0.029				ALH J0959.38+0223.03 (17.8″, 8)
NIKA2-CL J100004.7+021604.4	150.0194	2.2679	4.97	–				–
NIKA2-CL J100043.6+023232.4	150.1818	2.5423	4.87	–				–
NIKA2-CL J100025.3+023346.4	150.1056	2.5629	4.67	0.72±0.02				[BMH2011] 124 (11.5″, 10, 26)
NIKA2-CL J100100.6+022134.4	150.2524	2.3596	4.67	0.769±0.01				[SCC2012] 0788 (9.1″, 39)
NIKA2-CL J100004.4+021148.4	150.0183	2.1968	4.60	0.94±0.05				[KLI2009] 146* (8.7″, 24)
NIKA2-CL J100103.4+022208.4	150.2641	2.3690	4.54	–		?		–
NIKA2-CL J100011.9+021256.5	150.0494	2.2157	4.48	0.24±0.08				XMMXCS J100012.3+021246.7 (11.7″, 29)
NIKA2-CL J100101.1+020146.6	150.2546	2.0296	4.30	–				–
NIKA2-CL J100054.3+020126.4	150.2262	2.0240	4.28	1.423±0.014				[SCC2012] 1517 (16.0″, 39)
NIKA2-CL J100009.1+022140.3	150.0378	2.3612	4.27	–				–
NIKA2-CL J095942.6+023056.5	149.9277	2.5157	4.08	0.73±0.02				DESI 2353000051 (12.0″) 46
NIKA2-CL J100120.5+022828.2	150.3353	2.4745	4.07	–				–
NIKA2-CL J100008.4+020908.3	150.0350	2.1523	4.04	–				–
NIKA2-CL J095958.5+022910.4	149.9938	2.4862	4.01	0.397±0.010				[SCC2012] 0270 (14,8″, 39)

8 of our 16 detections are matched with a previously detected cluster or group of galaxies

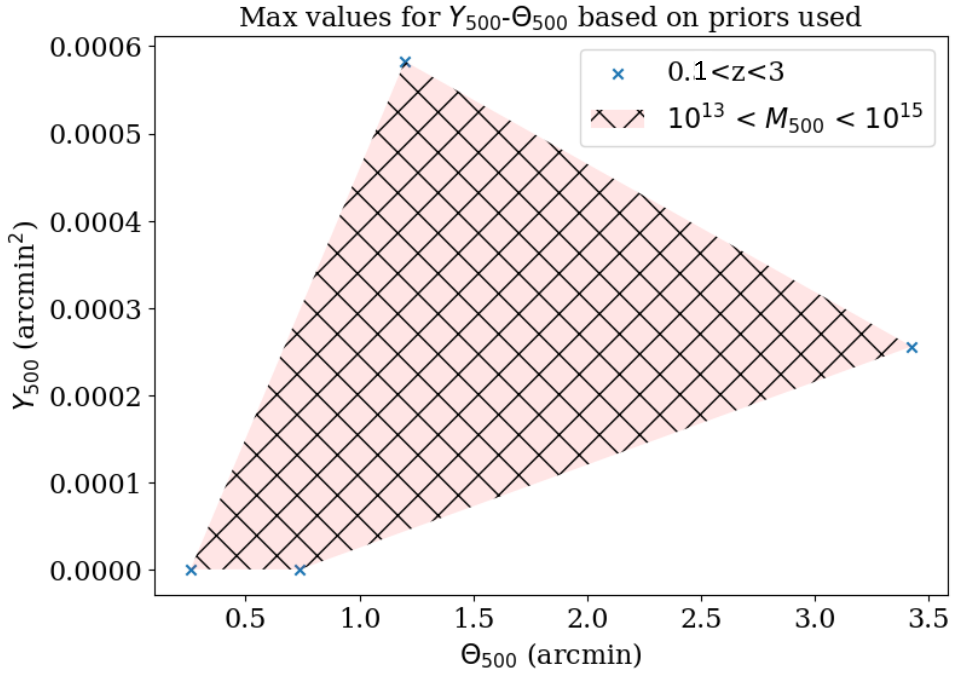
Y_{500}-θ_{500} measurements

$$M_{500} - z \leftrightarrow Y_{500} - \theta_{500}$$

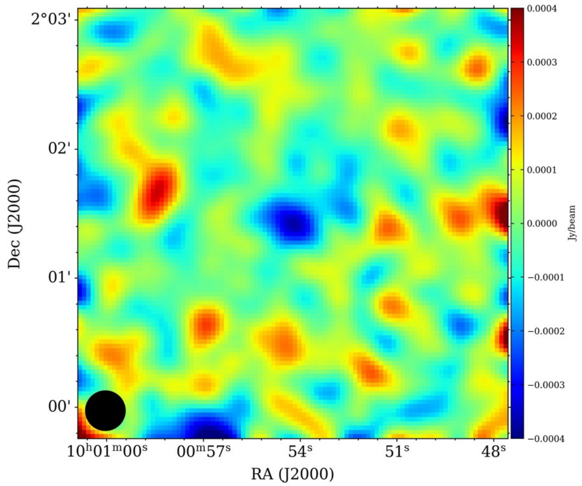
Mass Redshift tSZ Flux Size

Hypothesis : Clusters are self similar

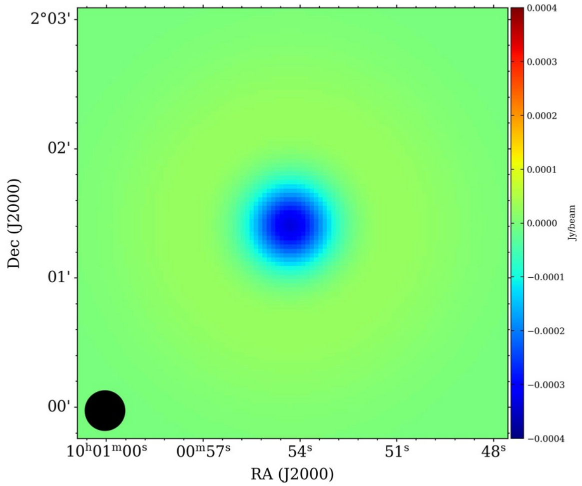
- Fit a cluster model using MCMC sampling, with 2 free parameters M_{500} and z to find Y_{500}-θ_{500}
- Model : integrated gNFW pressure profile model (*Nagai et al. 2007*) with fixed parameters as in Arnaud 2010
- Account for transfer function of data reduction
- Flat priors on M_{500} and z



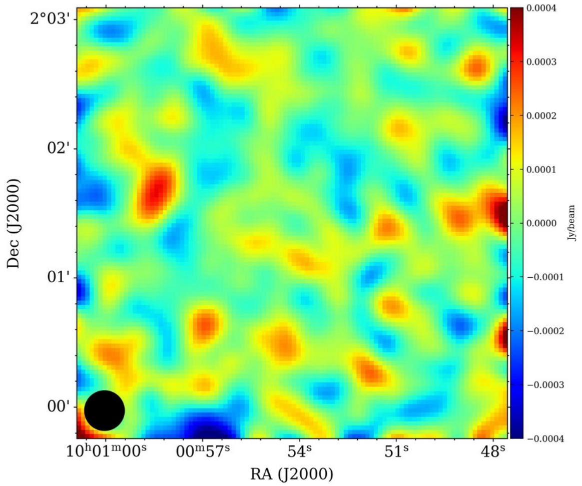
Zoom in on NIKA2-CL J100054.3+020126.4 (z ~1.42)



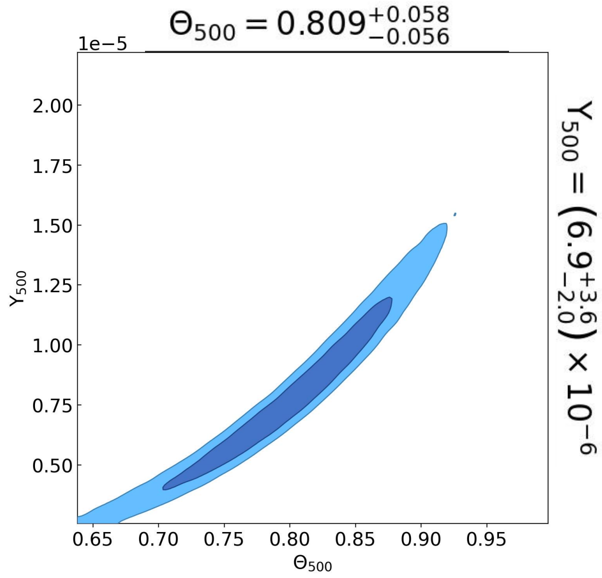
NIKA2 150 GHz map



Best-fitting model



Residual map



Integrated quantities corner plot

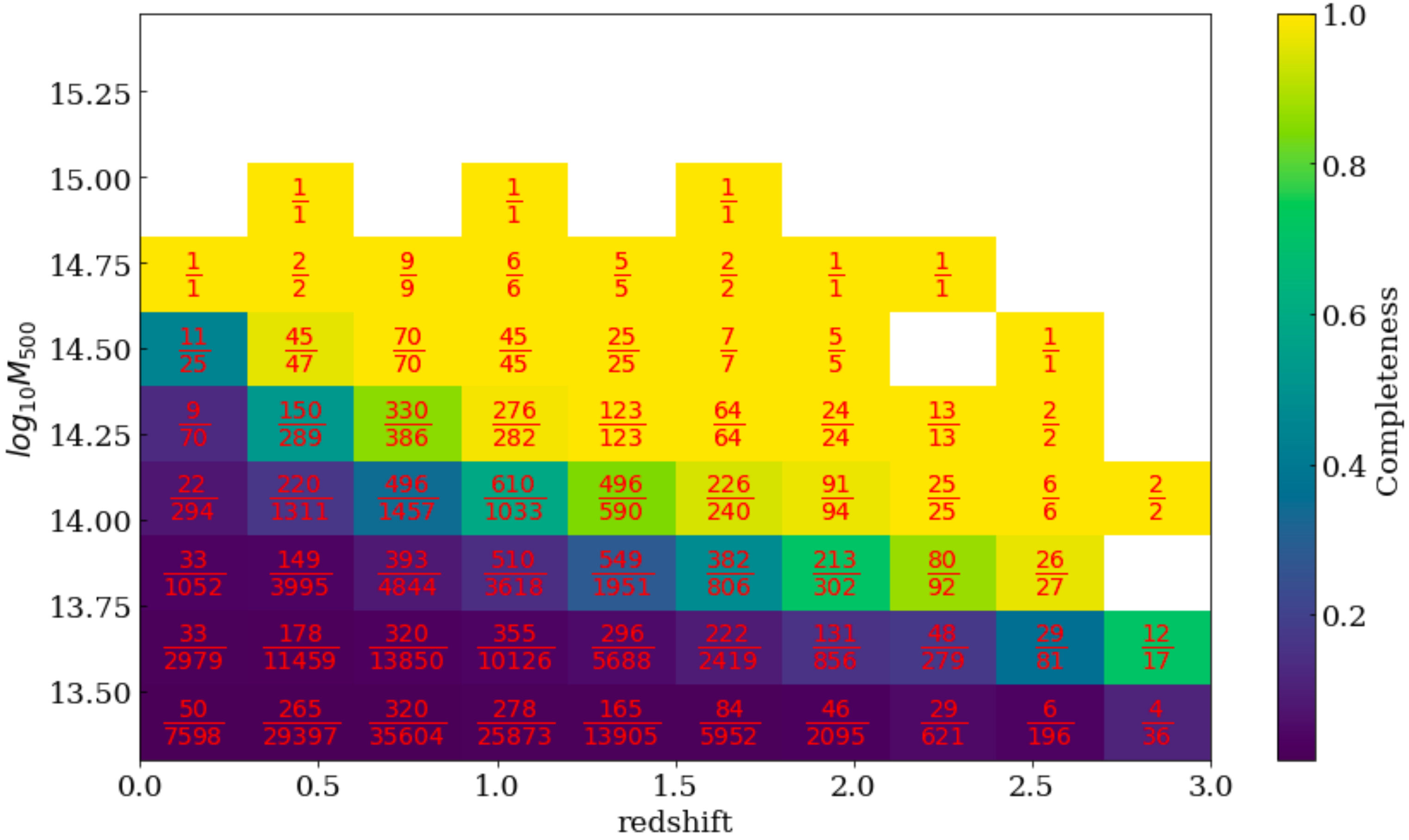
- We can fix the redshift for candidates with a known counterpart
- Possible to get a mass estimation in this case

$$M_{500} = 1.03^{+0.19}_{-0.24} \times 10^{14}\, M_{\odot}$$

For a Planck like scaling relation (*Arnaud et al. 2010*)

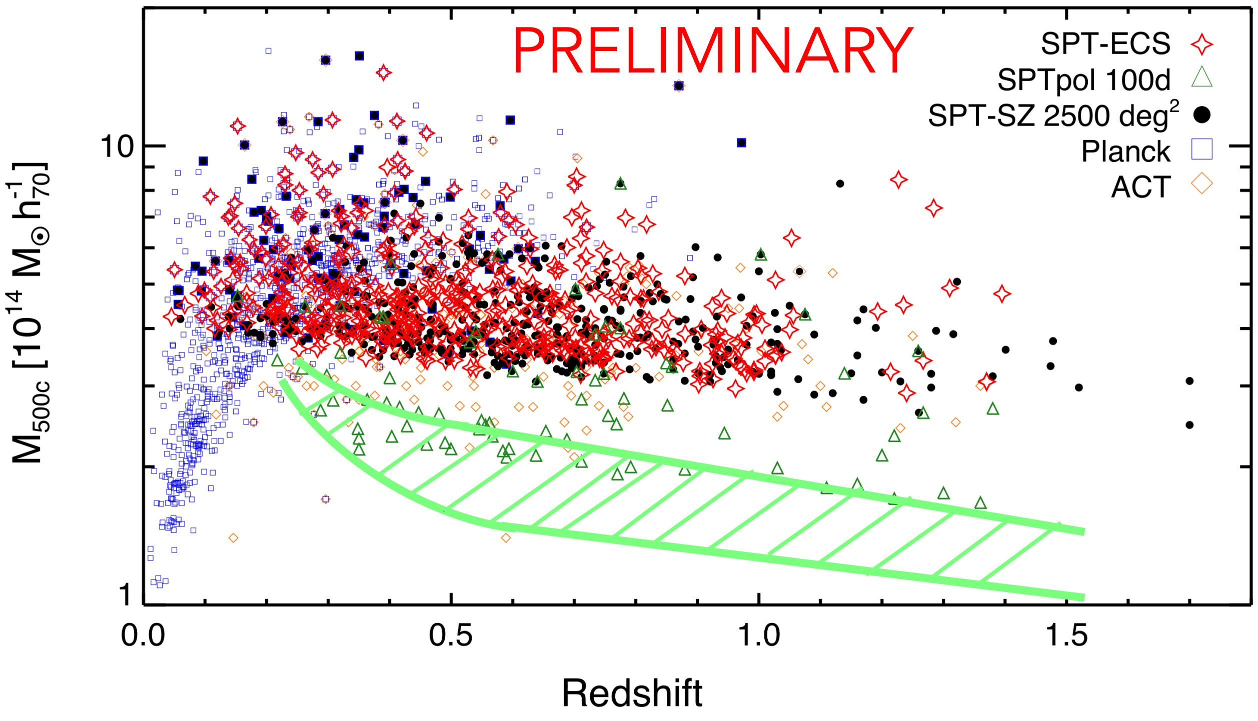
Cluster sample characterization

- 1000 simulations of expected number of clusters in COSMOS in a certain (M_{500}, z) range + noise
- Purity : Percentage of true detection in the sample
  - We reach a purity of 70% at SNR ~4.3
- Completeness : Fraction of true cluster detected
  - Yellow-green region : able to detect clusters in this mass-redshift range



Completeness

Very high resolution blind cluster detection



- Very promising results
- Validated NIKA2 catalog properties (purity and completeness) with simulations
- Future crosscheck on future large surveys catalog (e.g. Euclid, Vera Rubin)

We can blindly detect galaxy clusters with NIKA2

Need follow up observations to characterize cluster properties

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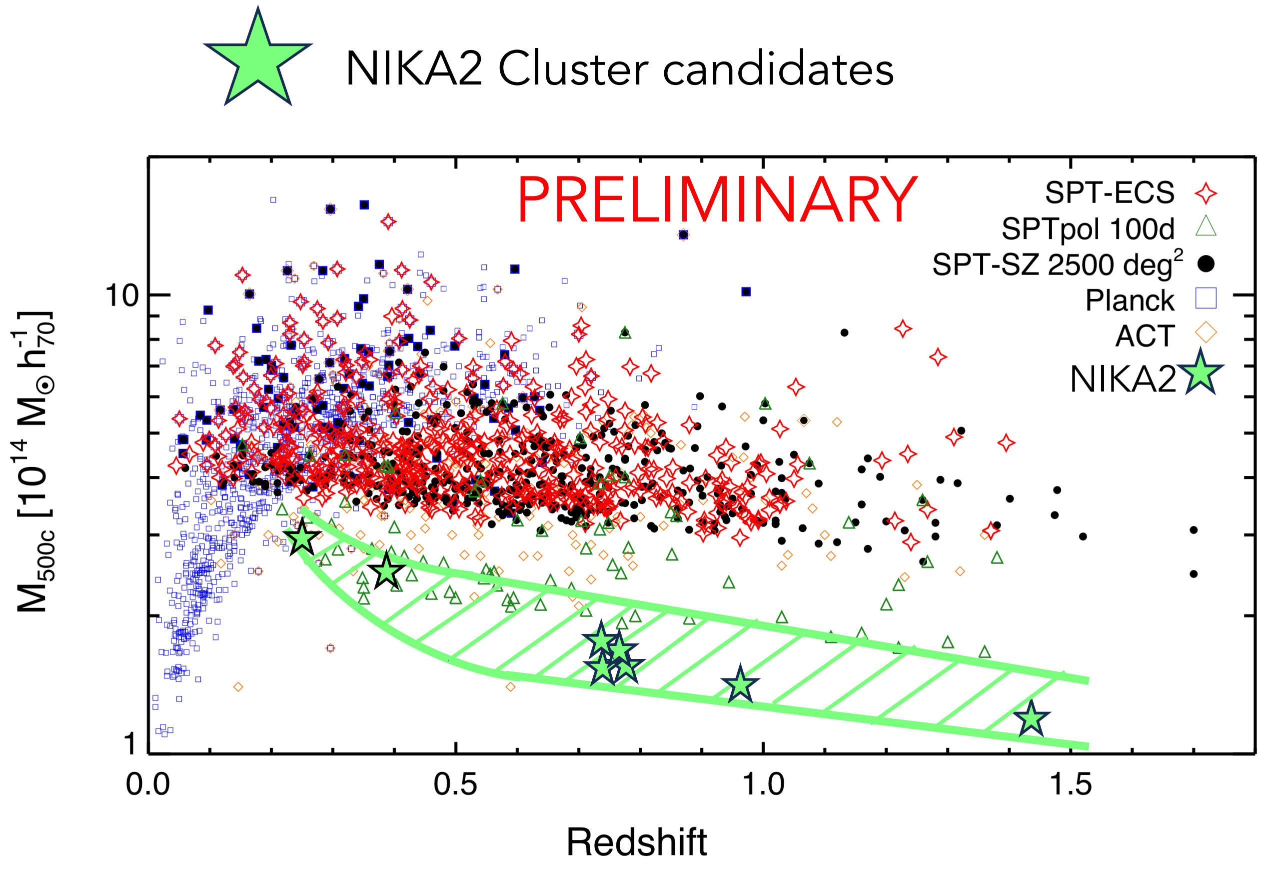

Mass estimates are in accordance with the region of interest derived from simulations

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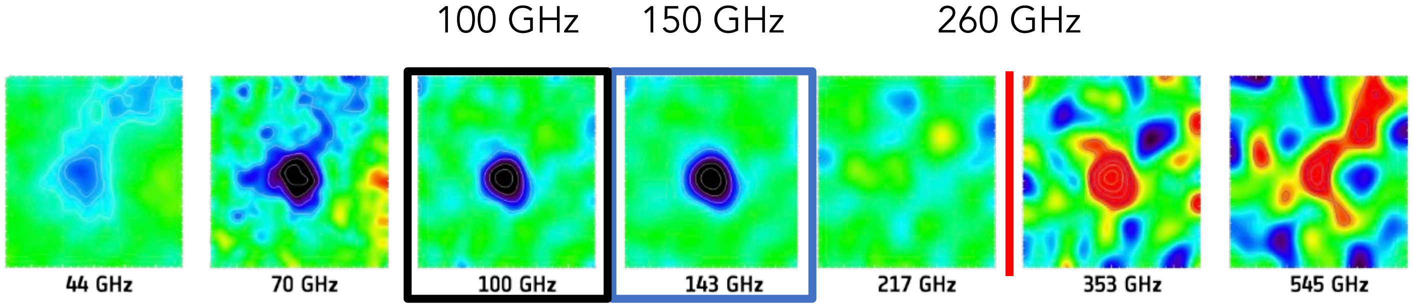
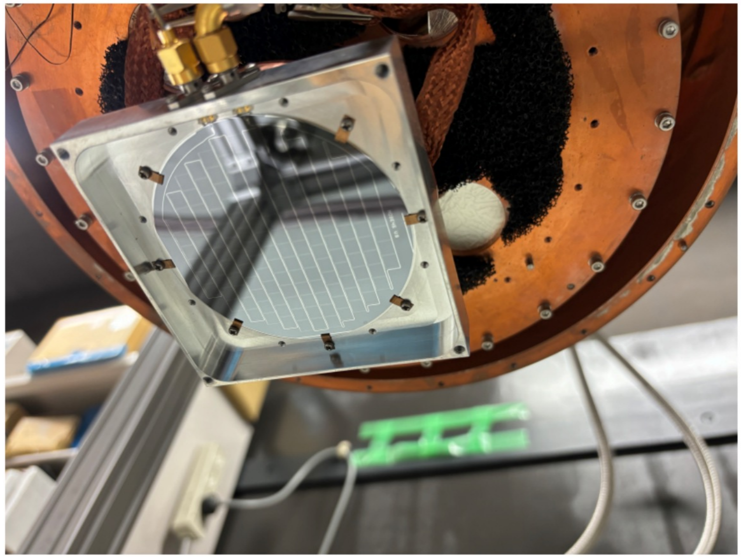
Tsukuba-Grenoble 100 GHz camera

- Collaboration between the University of Tsukuba and Grenoble GIS KIDS (LPSC, Institut Néel, IPAG, IRAM)
- Tsukuba-Grenoble 100 GHz KIDs array camera : 126 detectors
  - KIDs fabricated in Grenoble
  - Cryostat and electronics from Tsukuba/Grenoble
- Goal : Install and commission the camera at Nobeyama 45m telescope
  - High resolution : 18''
  - Equivalent resolution w.r.t NIKA2
  - Complementary observations at 100 GHz of our cluster candidates

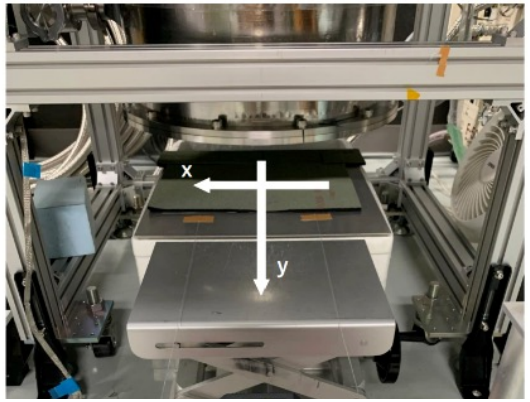




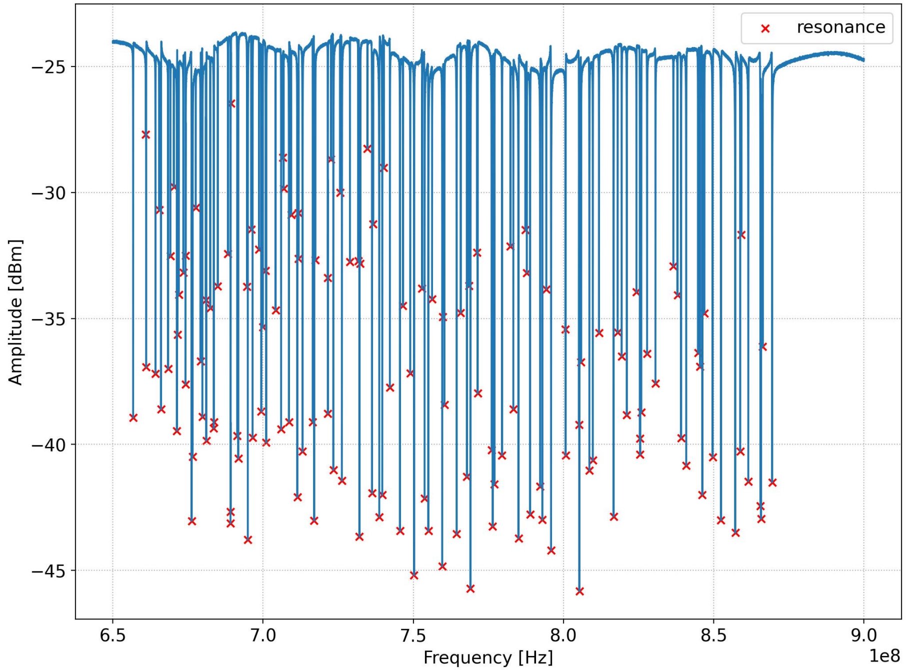
Picture of the KIDs array installed in the lab in Japan

Grenoble 100 GHz KIDs array

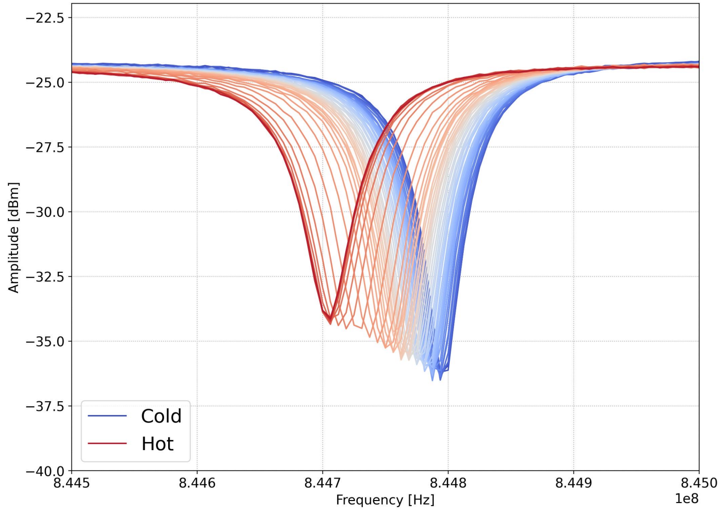
- KIDs are superconducting resonators (see Sofia & Mounir presentations)
- Resonance frequency shifts depending on the energy of the incident photon $\delta f \propto \delta L_k \propto -\delta P_{\text{opt}}$
- My work :
  - Electronic modelisation and comparison of LPSC and Tsukuba readout
  - Perform lab measurement campaign in Japan
  - Grenoble KIDs array characterization



Lab measurement setup



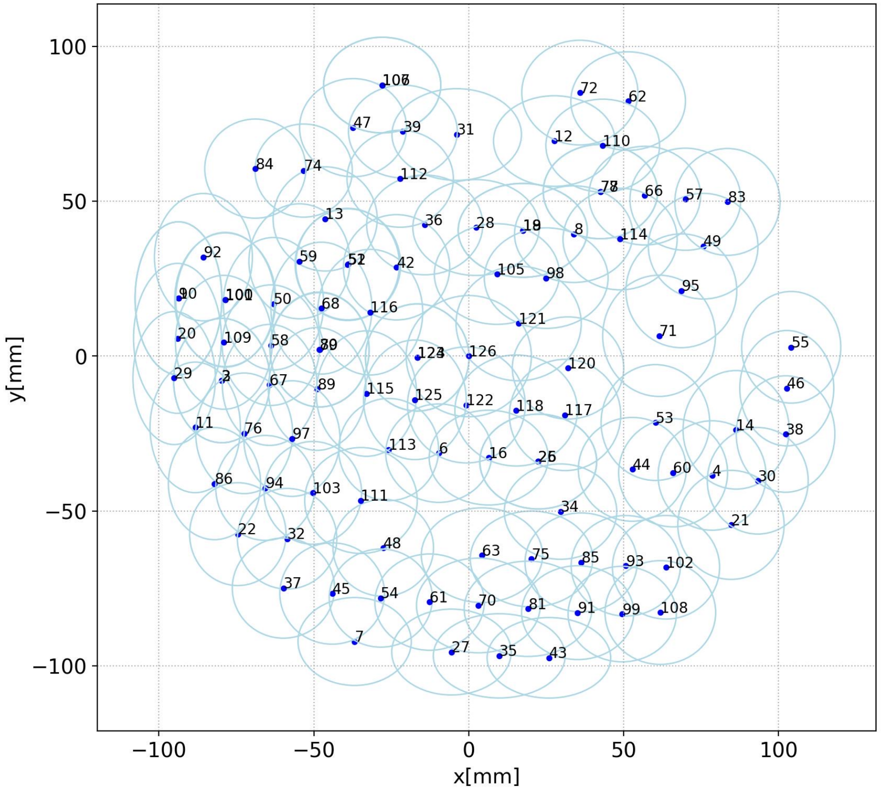
Transmission line



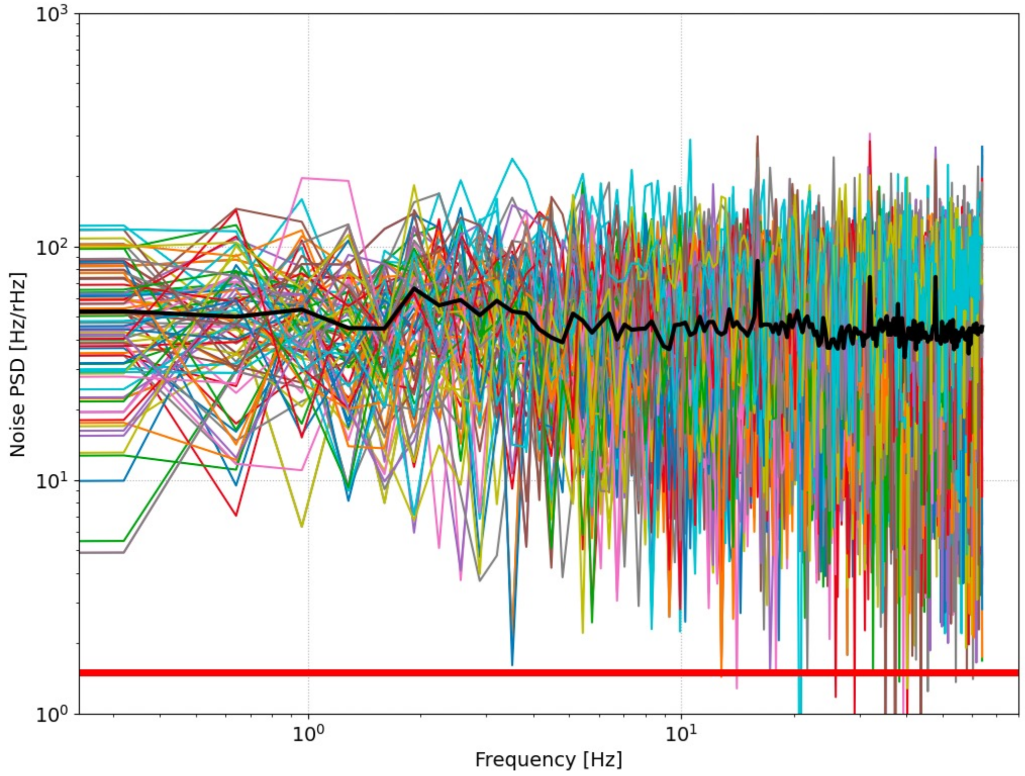
Example of the frequency shift of a KID detector

Grenoble KIDs array characterization

< FWHM > ~ 34.5 mm



Geometry of the KIDs array



40 Hz/rHz

1.5 Hz/rHz

Sensitivity measured during the campaign

- We find larger beams and lower sensitivity w.r.t. to measurements in Grenoble
- Setup, cold LNA, optic or readout electronics problem

Conclusion and perspectives

- First blind detection of galaxy clusters at high angular resolution
  - ✓ 16 candidates, 8 with a known counterpart
  - ✓ Mapping the mass-redshift region of interest
  - o Paper in preparation

- Preparing observations at the Nobeyama telescope
  - ✓ Characterization of the Grenoble-Tsukuba LEKIDs array to prepare upcoming observations
  - o Assembling a new NIKEL electronic
  - o Proposal in progress, 50h of observations requested
  - o Ongoing work to understand why the detectors' performance are worse than expected

o Follow-up observations with NOEMA interferometer at higher resolution (4'')

Blind detection of galaxy clusters with the NIKA2 camera via the Sunyaev-Zeldovich effect

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April 4, 2024

ABSTRACT

Clusters of galaxies, formed at the latest stages of structure formation, constitute unique cosmological probes and are sensitive to cosmological parameters related to structure formation like σ_8 and Ω_m. With the advent of large CMB surveys like those from the Planck satellite, the ACT and SPT telescopes, we now have access to a large catalog of galaxy clusters detected at millimeter wavelength via the thermal Sunyaev-Zeldovich (tSZ) effect. However, they do not offer the high angular resolution needed to detect the lowest mass high redshift clusters. This could be achieved by using millimeter cameras operated in large millimeter telescopes like for example the NIKA2 camera installed in the IRAM 30–m telescope in Pico Veleta, Spain. We use the existing 150 GHz data from the NIKA2 Cosmological Legacy Survey (N2CLS) Large Program for blindly search for galaxy cluster in the well-known COSMOS field across a 877 $arcmin^2$ region centred on $(R.A., Dec.)_{J2000}$ = (10h00m28.81s, +02d17m30.44s). We first develop a dedicated data reduction pipeline to construct NIKA2 maps at 150 (2mm) and 260 GHz (1.2 mm), and compute the pipeline transfer function via simulations. Then, we use a matched-filter algorithm on the NIKA2 150 GHz map to extract cluster candidates assuming a universal pressure profile to model the expected cluster tSZ signal. For each candidate we derive an estimate of the SNR, and of the tSZ signal in the $Y_{500} - \theta_{500}$ plane. We compute the purity and completeness of the sample by applying the previous algorithm to 1000 simulated maps of the expected cluster tSZ signal in the COSMOS field including point sources and instrumental noise derived from null maps. Finally, we cross-match the cluster candidates with existing cluster catalogs as part of the validation process, which also includes comparisons to optical and infrared galaxy catalogs. We obtain a total 16 cluster candidates from which 7 have either an optical or X-ray cluster (group of galaxies) counterpart. This is the first blind detection of clusters of galaxies at mm wavelength at high resolution. For candidates for which estimates of the redshift are available we derive their mass by modeling the cluster tSZ signal with a universal pressure profile via a MCMC analysis. From this analysis we confirm that NIKA2 and the IRAM 30–m telescope should be sensitive to the lowest mass clusters at intermediate and high redshift.

Conclusion and perspectives

- First blind detection of galaxy clusters at high angular resolution
  - ✓ 16 candidates, 8 with a known counterpart
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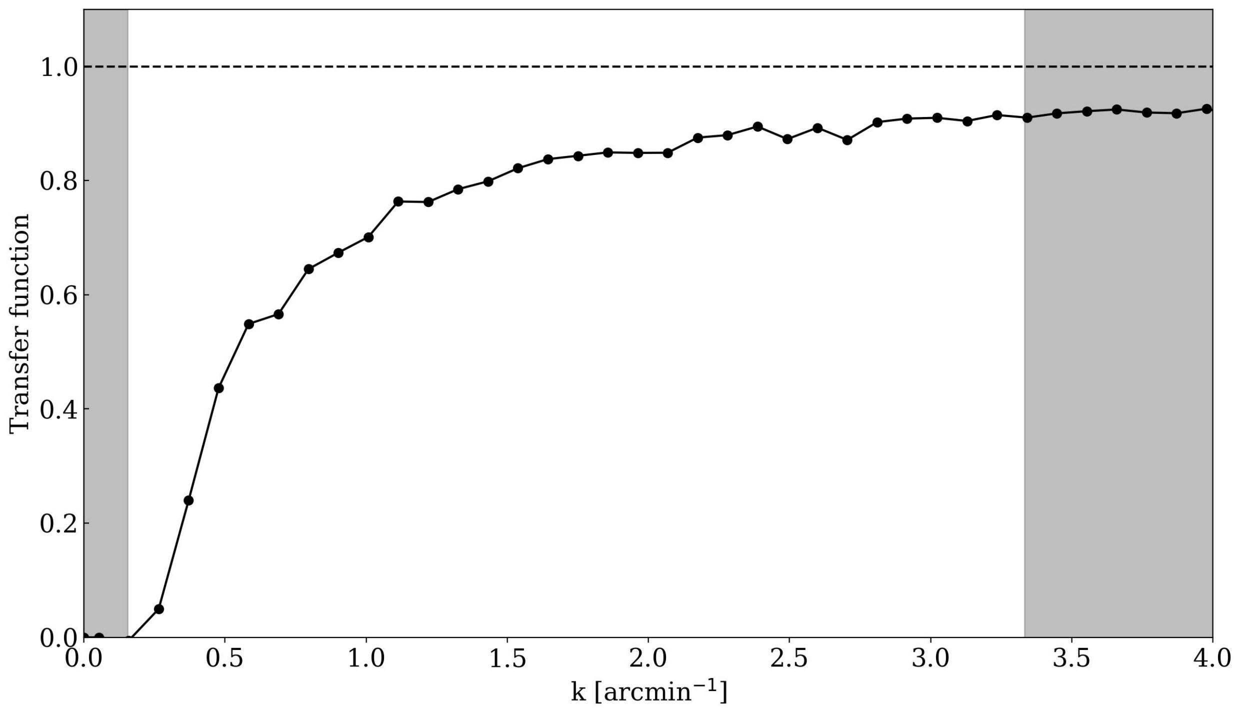
Backup

Transfer function

- Transfer function computed from simulated white noise signal

- Analysis optimised for point sources – explains why clusters seem to be so compact

- Future work needed for better cluster detection and characterization



Transfer function of the 2mm NIKA2 data