Blind detection of galaxy clusters in the COSMOS field via the SZ effect

mm Universe 2025 – June 24, 2025

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Galaxy cluster blind detection

Sunyaev-Zel'dovich effect

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

- Very distinct spectrum

- Compton parameter : $y = \frac{\sigma_T}{m_e c^2} \int P_e dl$

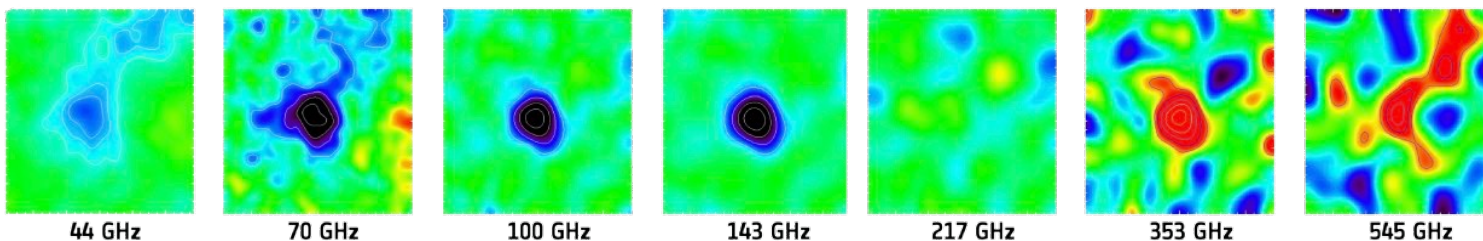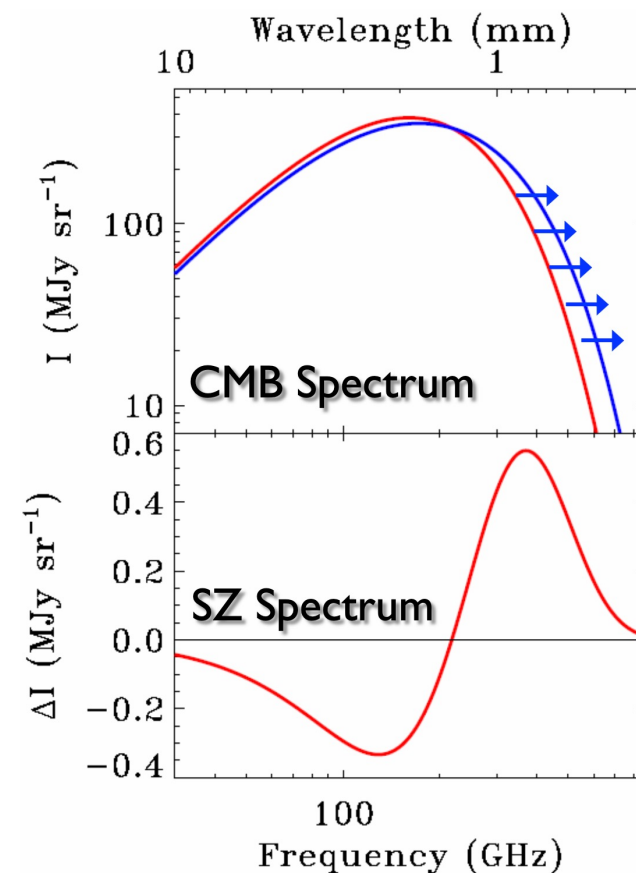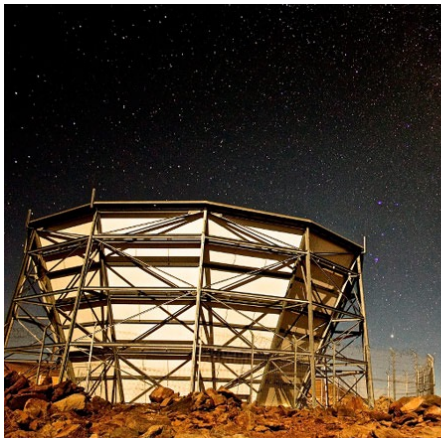- **SZ effect is redshift independent (not affected by cosmological dimming)**
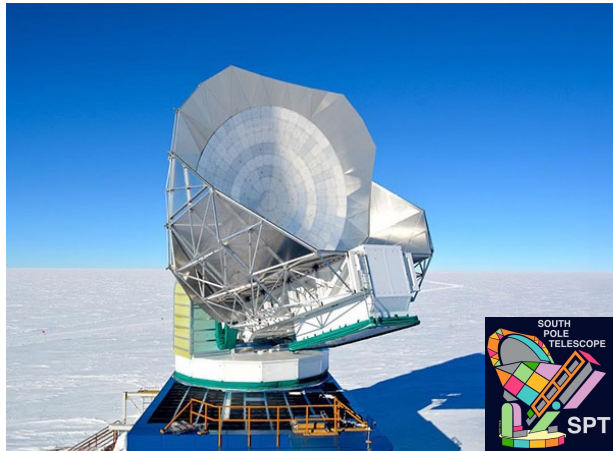
Image credit: ESA / HFI & LFI Consortia

A2319 Cluster observed by Planck

Millimeter large SZ surveys

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

Kornoelje et al 2025

Distribution in the mass-redshift plane of all the clusters published in the Planck, SPT, and ACT catalogs
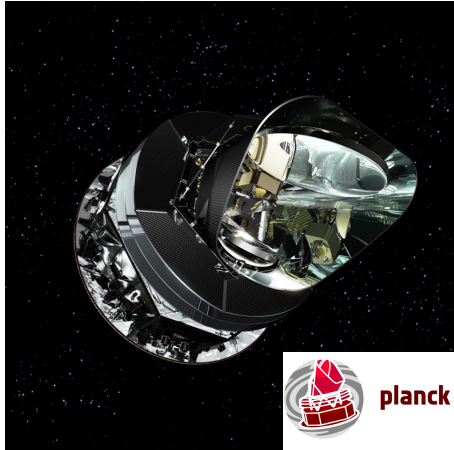
R_{500} : radius at which the mean cluster density is 500 times the critical density of the Universe

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

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

IRAM telescope

Monfardini+ 17, Bourrion+ 16, Adam+ 18

NIKA2 KIDs array and readout board

150 GHz

260 GHz

44 GHz   70 GHz   100 GHz   143 GHz   217 GHz   353 GHz   545 GHz

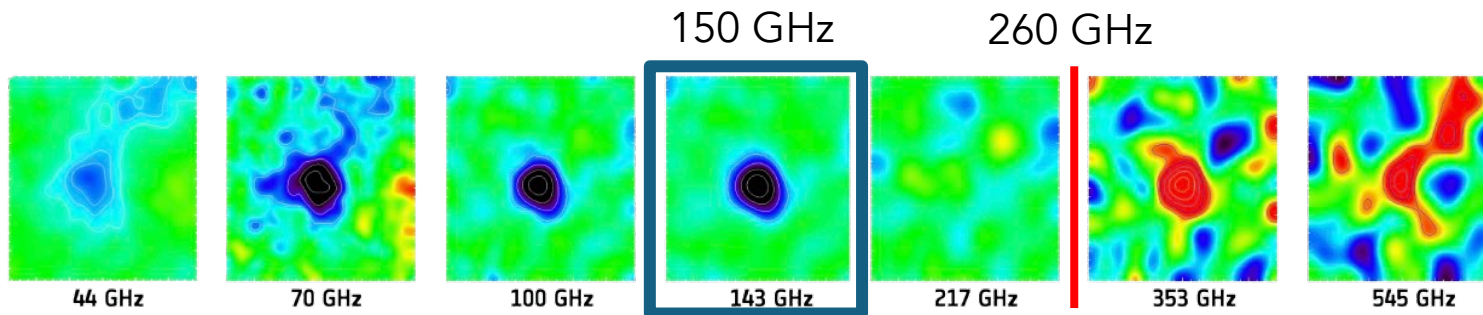A2319 Cluster observed by Planck

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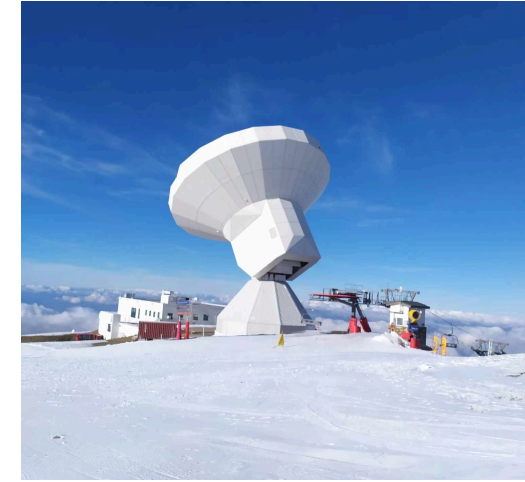- Operating since 2015, we dispose of 1300h of guaranteed time

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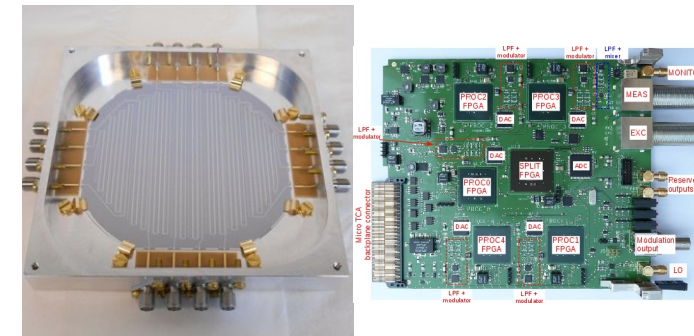**Powerful instrument to study the tSZ effect in high redshift clusters**

(see Alice and Fred's talk on NIKA2 LPSZ results)

Blind cluster detection in deep NIKA2 fields

- Data acquired by the NIKA2 Cosmological Legacy Survey (N2CLS) Large Program

- ~195 hours of deep field observations of the well-known COSMOS field

- ~1400 arcmin^2 (~0.4 deg^2) field

- Used for the detection of high redshift galaxies (*Bing+2023, Berta+2025*) – see Stefano's talk

Objective : Blindly detect galaxy clusters with NIKA2
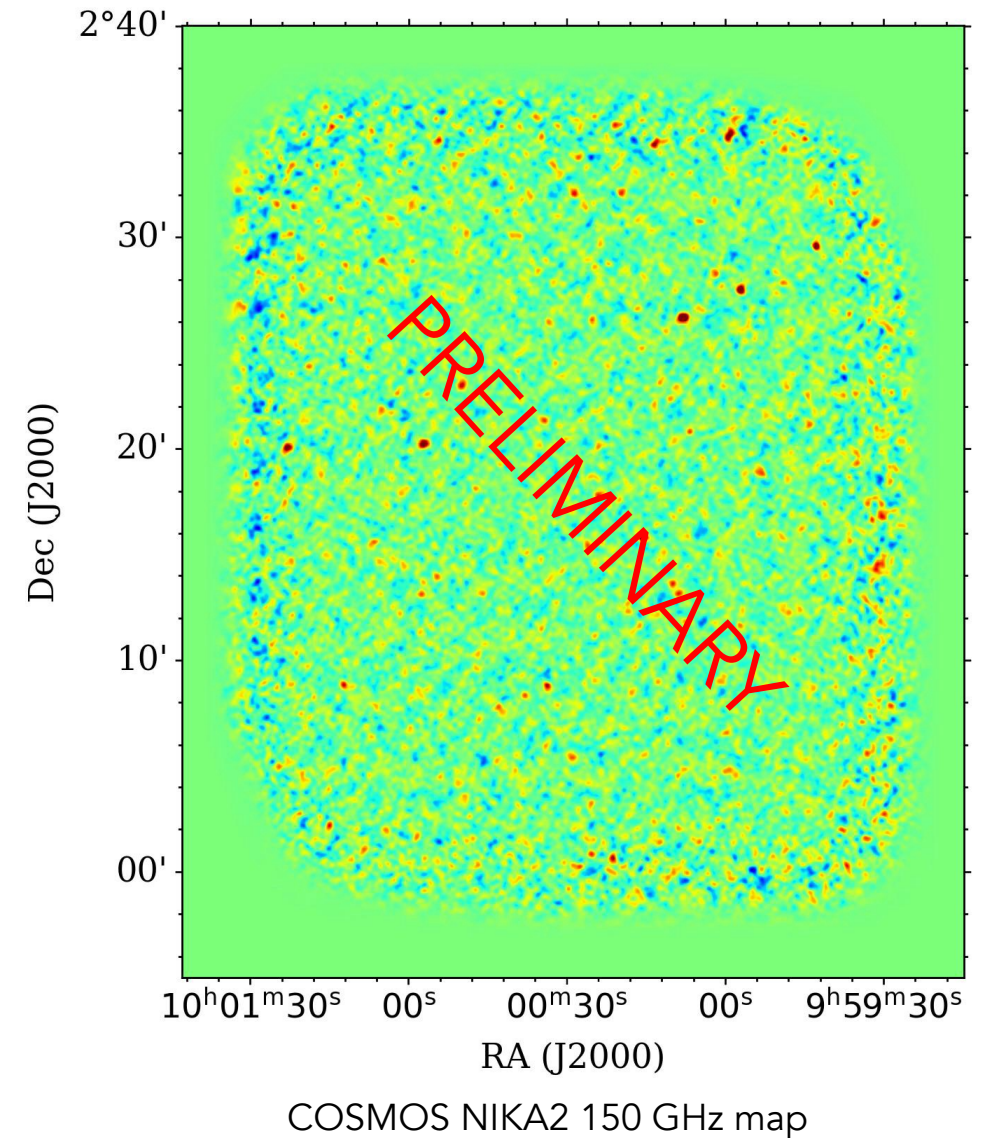
COSMOS NIKA2 150 GHz map

Galaxy cluster blind detection

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)

- Single frequency match filter: 260 GHz data not sensitive to the tSZ effect - used for masking point sources (mainly dusty galaxies)

Maps

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

Spatial template   Noise

Matched Filter (Fourier space)

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

Package *pymf* from Erler et al. 2019

Blind cluster detection

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

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

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

2. Filter the map with different template sizes

–> 5 parameters : P_0 amplitude

r_p, a transition radius/ steepness

3. Find peaks in the filtered map above a signal-to-noise ratio (SNR) threshold of 4

c, b internal/ external slopes

Blind cluster detection

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We have 16 cluster candidates after these 3 steps

Filtered NIKA2 150 GHz map with a cluster template the size of the beam
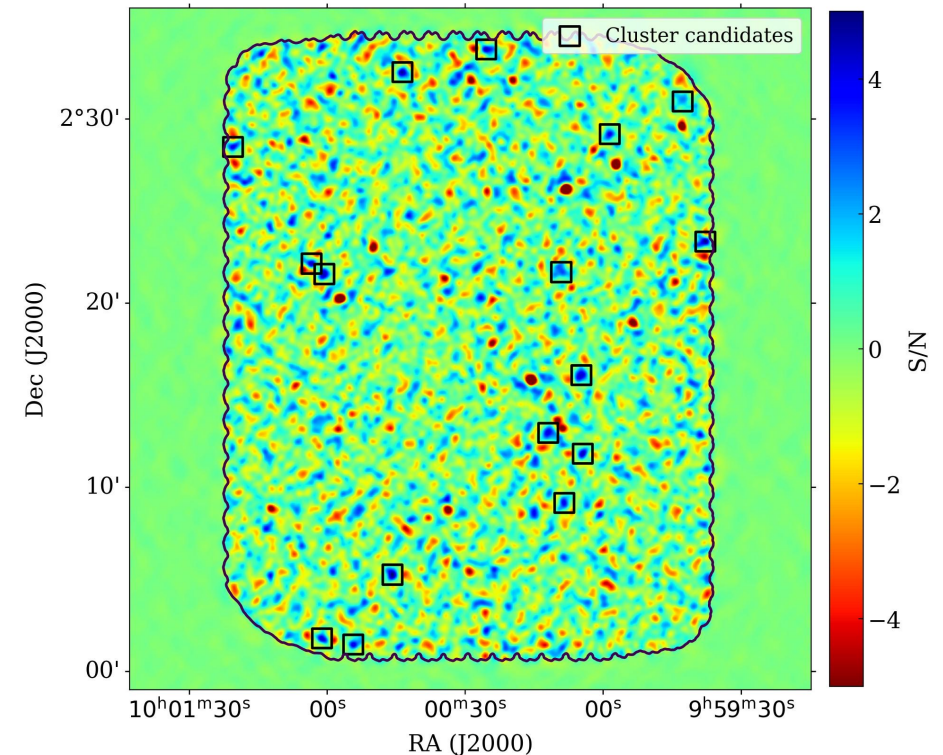
Candidate clusters have a positive SNR (negative sign accounted for in the filter) !

Cluster candidates validation
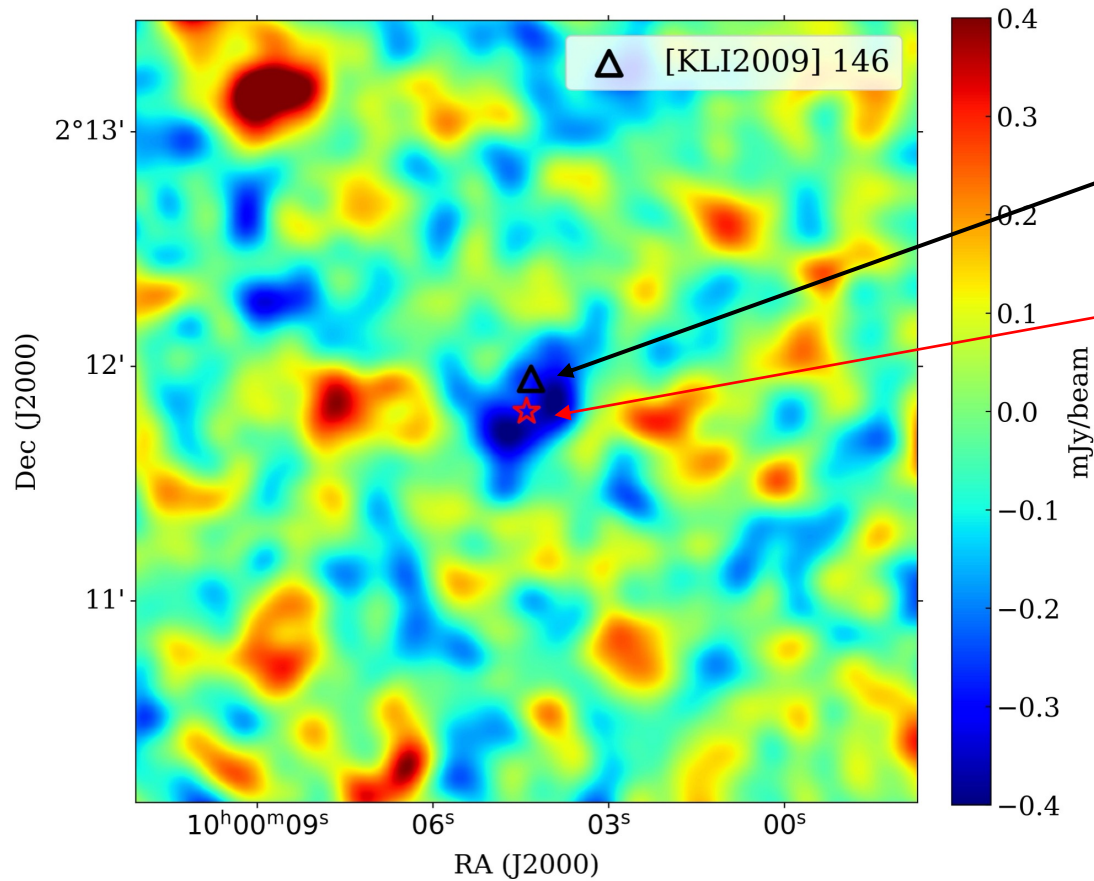
150 GHz NIKA2 map

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

Optically (spectro redshift) detected cluster

Cluster candidate

- Clear negative signal in the map

- Match with a high redshift cluster at z ~ 0.94 :
  - [KLI2009] 146

8 of our 16 detections match with a previously detected cluster

Spectro and photo redshift catalogs
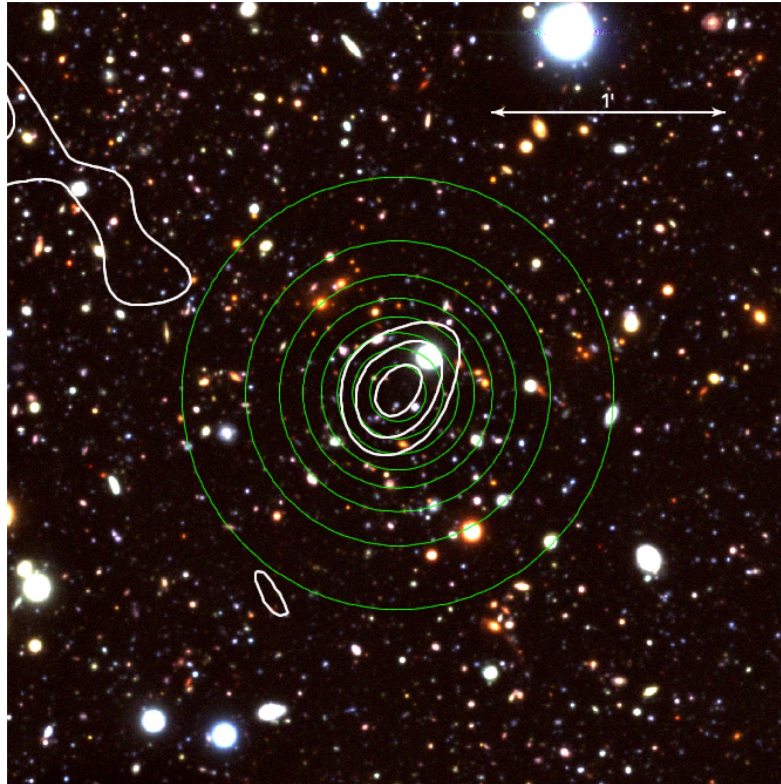
HSC *gri* map with SNR contours (white)
and best-fit tSZ model (green)

- In most case, redshift estimates are found at the peak of redshift distribution

- Some unidentified candidates also have well-defined redshift peaks

Normalized spectroscopic (blue) and photometric (red) redshift counts within a 1 arcmin radius

Cluster candidate sample

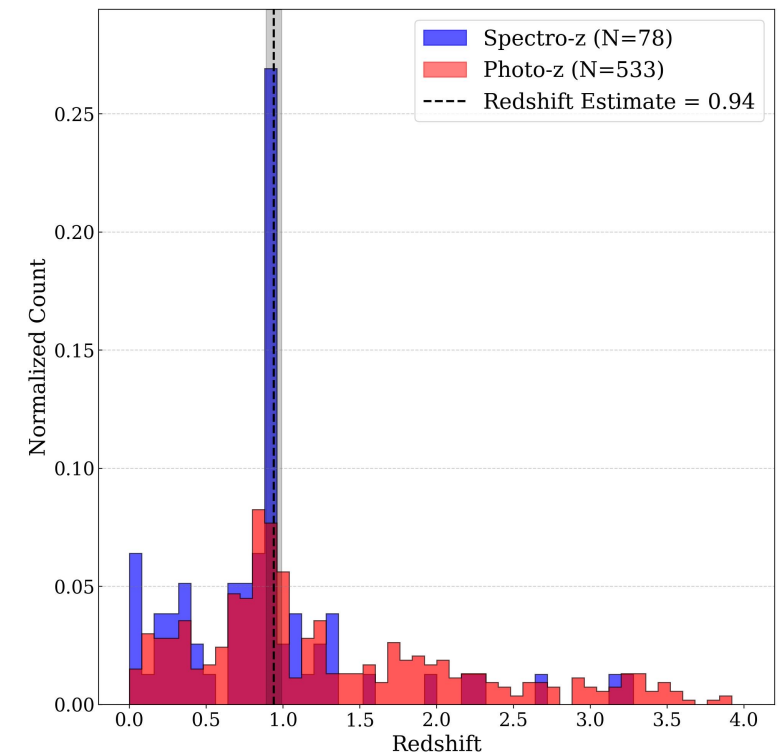| Candidate Name	RA °	DEC °	S/N	z	θ_{500} arcmin	Y_{500} 10^{-5} arcmin^2	M_{500} 10^{14} M$_\odot$	Matching cluster name (distance [''])
NK2-CL J100045.8+020514.3	150.1907	2.0873	5.31	–	Size	tSZ Flux	Mass	–
NK2-CL J095937.7+022320.4	149.9071	2.3890	5.00	0.74±0.03 (p)				ALH J0959.38+0223.03 (17.8'')
NK2-CL J100004.7+021604.4	150.0194	2.2679	4.97	–				–
NK2-CL J100043.6+023232.4	150.1818	2.5423	4.87	–				–
NK2-CL J100025.3+023346.4	150.1056	2.5629	4.67	0.72±0.02 (p)				[BMH2011] 124 (11.5'')
NK2-CL J100100.6+022134.4	150.2524	2.3596	4.67	0.77±0.01 (p)				[SCC2012] 0788 (9.1'')
NK2-CL J100004.4+021148.4	150.0183	2.1968	4.60	0.94±0.05 (s)				[KLI2009] 146* (8.7'')
NK2-CL J100103.4+022208.4	150.2641	2.3690	4.54	–		?		–
NK2-CL J100011.9+021256.5	150.0494	2.2157	4.48	0.24±0.08** (p)				XMMXCS J100012.3+021246.7 (11.7'')
NK2-CL J100101.1+020146.6	150.2546	2.0296	4.30	–				–
NK2-CL J100054.3+020126.4	150.2262	2.0240	4.28	1.42±0.01 (p)				[SCC2012] 1517 (16.0'')
NK2-CL J100009.1+022140.3	150.0378	2.3612	4.27	–				–
NK2-CL J095942.6+023056.5	149.9277	2.5157	4.08	0.73±0.02 (s)				DESI 2353000051 (12.0'')
NK2-CL J100120.5+022828.2	150.3353	2.4745	4.07	–				–
NK2-CL J100008.4+020908.3	150.0350	2.1523	4.04	–				–
NK2-CL J095958.5+022910.4	149.9938	2.4862	4.01	0.40±0.01 (p)				[SCC2012] 0270 (14,8'')

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

Galaxy cluster blind detection

I. Context

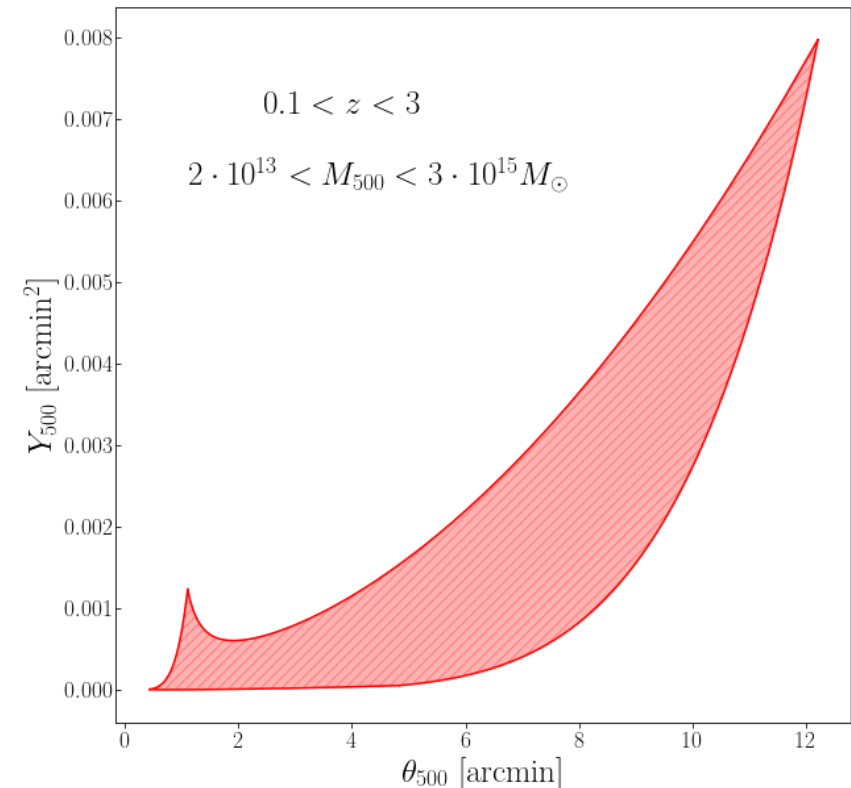II. Cluster candidates detection

III. Cluster candidates properties

IV. Cluster sample characterization

Y_{500}-θ_{500} measurements

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

Mass   Redshift   tSZ Flux   Size

- 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

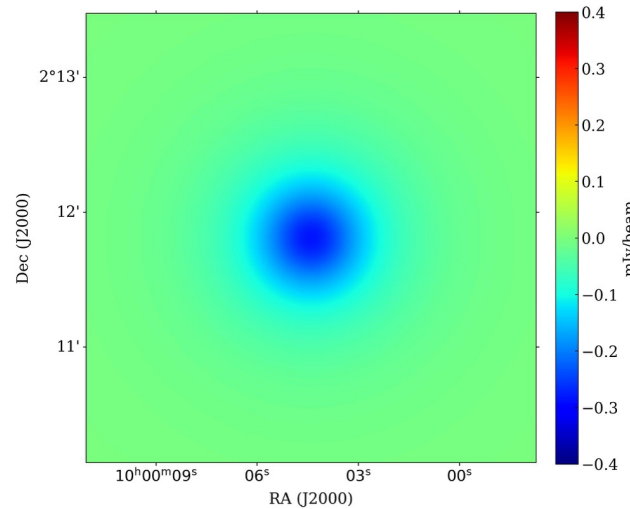- Flat priors on M_{500} and z (unless known)

Possible values of $Y_{500} - \theta_{500}$ based on priors used

$0.1 < z < 3$

$2 \cdot 10^{13} < M_{500} < 3 \cdot 10^{15} M_{\odot}$

Zoom in on NK2-CL J100004.4+021148.4 (z~0.94)
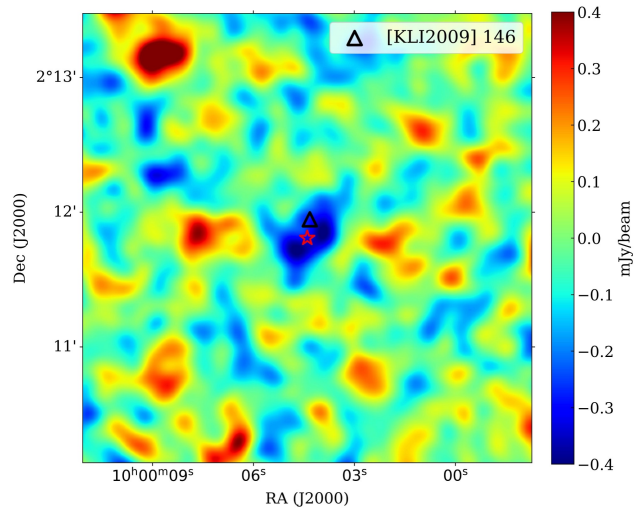
NIKA2 150 GHz map

Best-fit tSZ model

Residual map

$\Theta_{500} = 1.10^{+0.09}_{-0.10}$

$Y_{500} = (2.10^{+0.91}_{-0.78}) \times 10^{-5}$
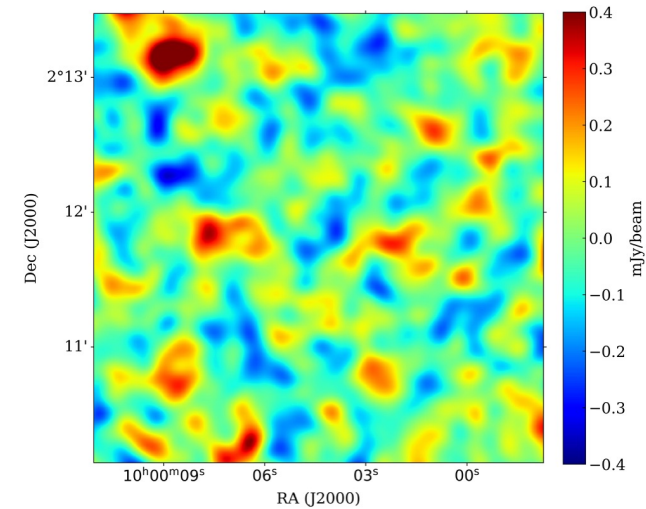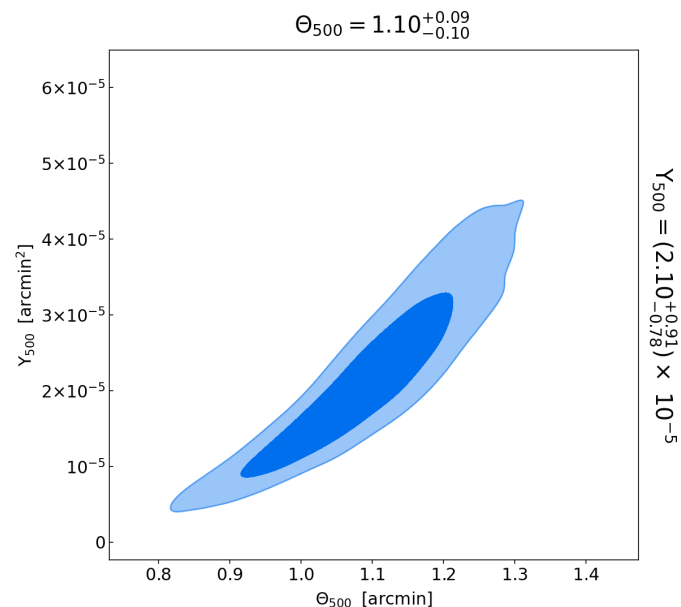
- We can "fix" the redshift for candidates with a known counterpart

- Possible to get a mass estimation in this case

$$M_{500} = 1.21^{+0.27}_{-0.27} \times 10^{14}\ M_{\odot}$$

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

(see Alice's talk on NIKA2 scaling relation)

Galaxy cluster blind detection

I. Context

II. Cluster candidates detection

III. Cluster candidates properties

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Cluster sample characterization

- Realistic simulations of expected number of clusters in COSMOS in a certain (M_{500}, z) range + noise

- Incorporation of the SIDES sky model (*Béthermin et al 2017*)

- Purity : Percentage of true detection in the sample
  - We reach a purity of ~50% at SNR > 4.0

Purity as a function of SNR
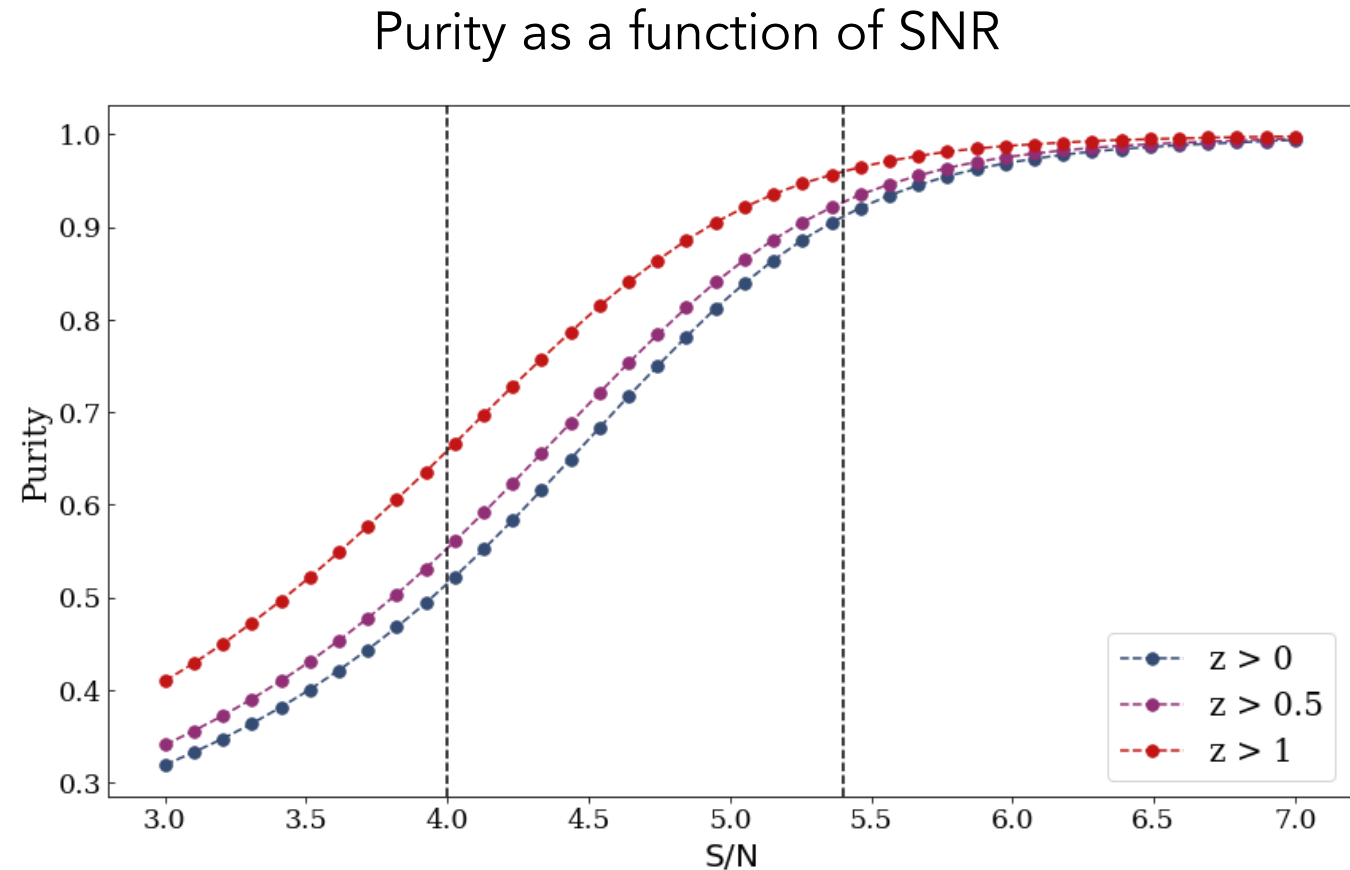
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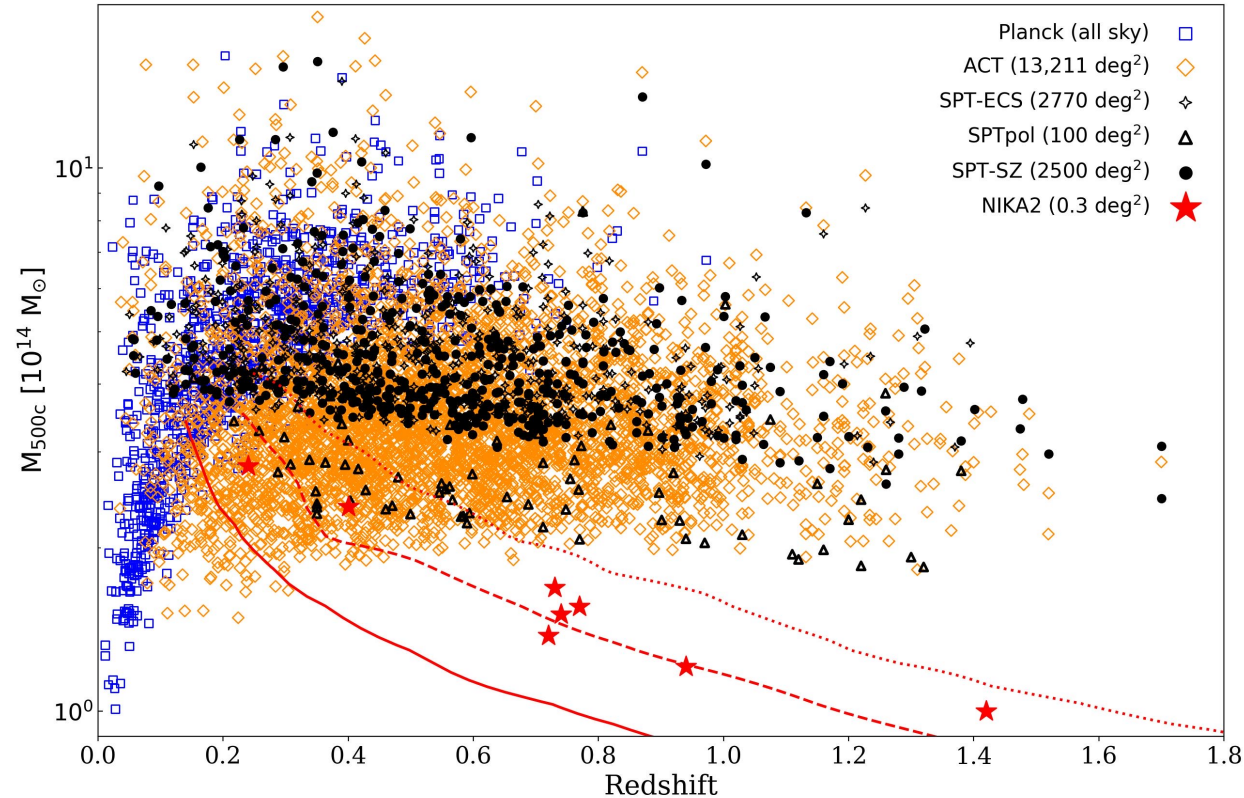 - We reach a purity of ~50% at SNR > 4.0

- Completeness : Fraction of true cluster detected
  - We reach 80% completeness at all redshift for $M_{500} \sim 1.8 \times 10^{14} M_{\odot}$

Completeness as a function of mass
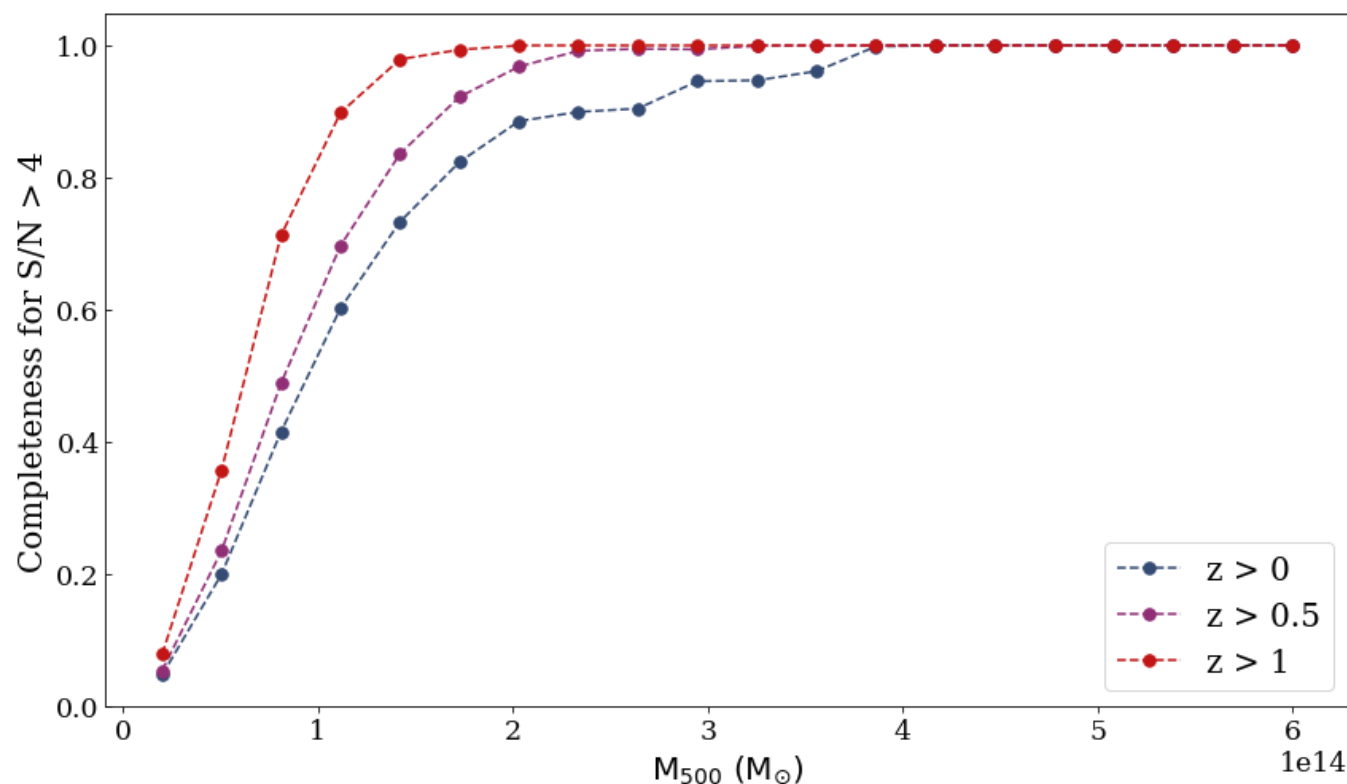
Very high resolution blind detection

- 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

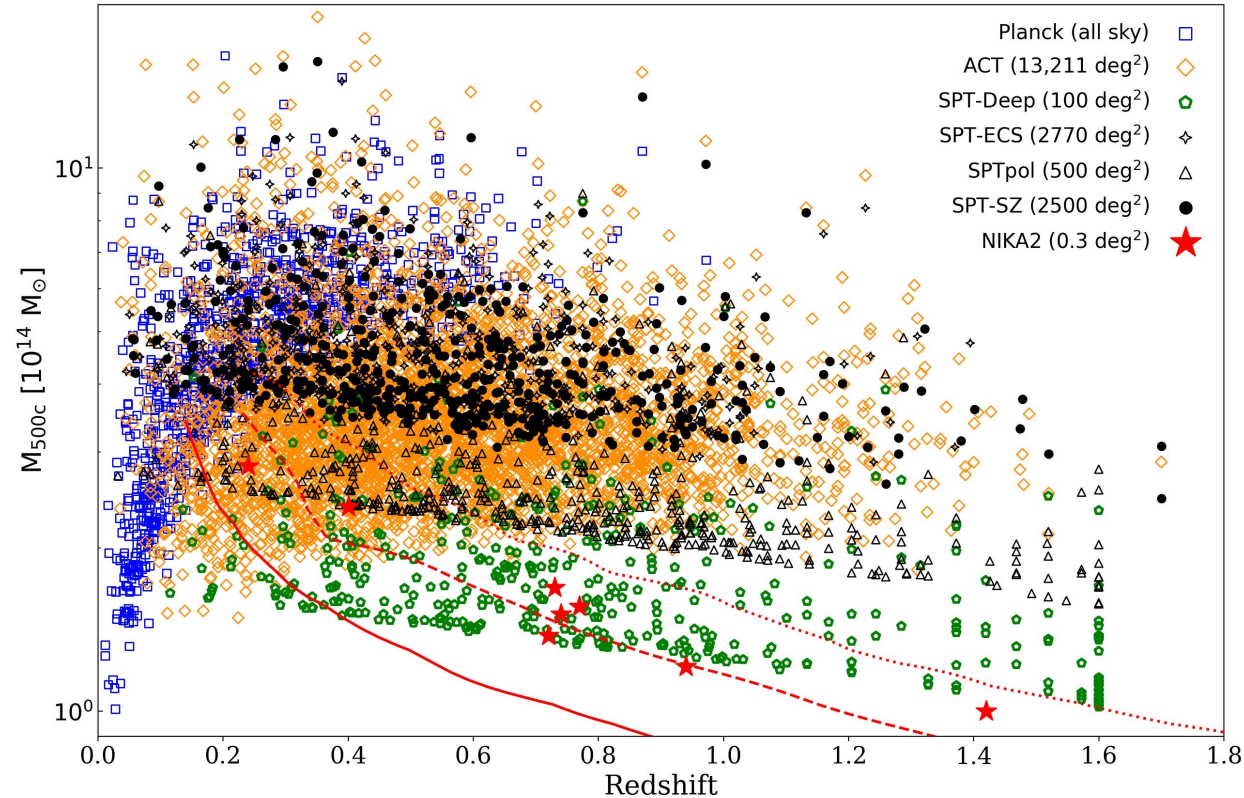# Very high resolution blind detection

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Conclusion and perspectives

- First blind detection of galaxy clusters at sub-20 arcsec resolution

  - ✓ 16 candidates, 8 with a known counterpart
  - ✓ Median redshift of the sample: z ~ 0.74, Median mass: $M_{500} \sim 1.54 \times 10^{14} M_{\odot}$

  - ✓ Accepted for publication in A&A (Arxiv: 2506.18231)

- Follow-up observations

  - ✓ Accepted NOEMA (4'' resolution) proposal will target highest redshift candidate (z~1.42)
  - ✓ Nobeyama 45m telescope with the Grenoble-Tsukuba 100 GHz KIDs camera

- Good prospects for a high-resolution survey of the Northern sky

  - ✓ Upgrades of NIKA2 (extra frequency bands and larger FoV) to cover a larger area
 - ✓ A new instrument placed on a 13m telescope to cover thousands of deg^2 (see Mateo's poster)

Backup

Cluster candidate sample

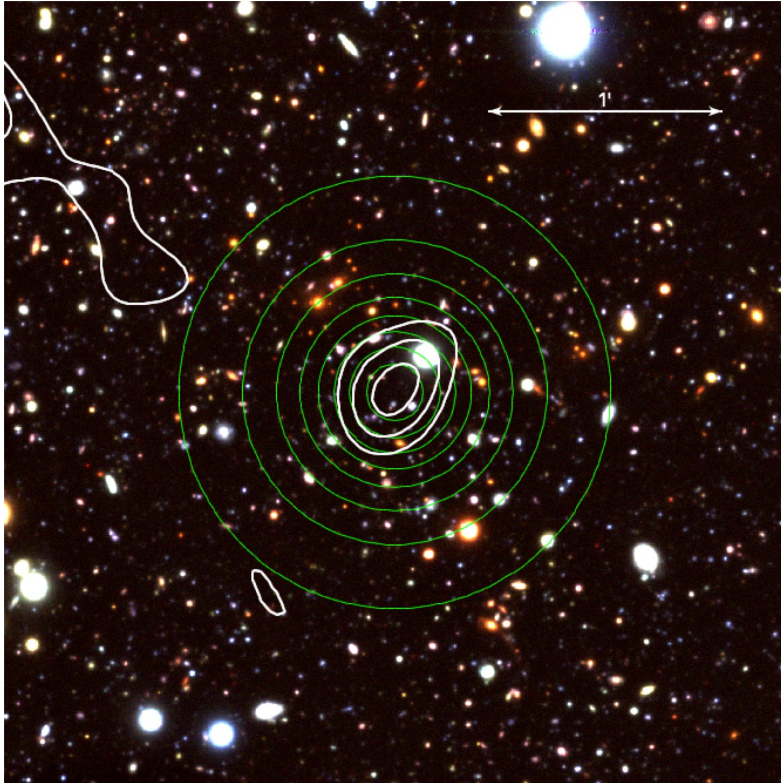| Candidate Name	RA °	DEC °	S/N	z	θ_{500} arcmin	Y_{500} 10^{-5} arcmin^2	M_{500} 10^{14} M$_\odot$	Matching cluster name (distance [''])
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NK2-CL J095937.7+022320.4	149.9071	2.3890	5.00	0.74±0.03 (p)	$1.38^{+0.12}_{-0.13}$	$3.35^{+1.77}_{-1.34}$	$1.51^{+0.40}_{-0.38}$	ALH J0959.38+0223.03 (17.8'')
NK2-CL J100004.7+021604.4	150.0194	2.2679	4.97	–	$0.92^{+0.62}_{-0.29}$	$1.95^{+2.65}_{-0.88}$	–	–
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NK2-CL J100100.6+022134.4	150.2524	2.3596	4.67	0.77±0.01 (p)	$1.36^{+0.09}_{-0.11}$	$3.47^{+1.42}_{-1.25}$	$1.56^{+0.33}_{-0.34}$	[SCC2012] 0788 (9.1'')
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NK2-CL J100011.9+021256.5	150.0494	2.2157	4.48	0.24±0.08** (p)	$3.79^{+2.11}_{-1.01}$	$28.20^{+69.45}_{-16.79}$	$2.83^{+1.55}_{-0.88}$	XMMXCS J100012.3+021246.7 (11.7'')
NK2-CL J100101.1+020146.6	150.2546	2.0296	4.30	–	$0.71^{+0.44}_{-0.16}$	$0.96^{+0.83}_{-0.29}$	–	–
NK2-CL J100054.3+020126.4	150.2262	2.0240	4.28	1.42±0.01 (p)	$0.81^{+0.05}_{-0.06}$	$1.56^{+0.62}_{-0.53}$	$1.00^{+0.21}_{-0.21}$	[SCC2012] 1517 (16.0'')
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NK2-CL J095958.5+022910.4	149.9938	2.4862	4.01	0.40±0.01 (p)	$2.52^{+0.22}_{-0.23}$	$12.24^{+6.22}_{-4.77}$	$2.38^{+0.61}_{-0.57}$	[SCC2012] 0270 (14,8'')

Transfer function

- Transfer function computed from simulated white noise signal

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

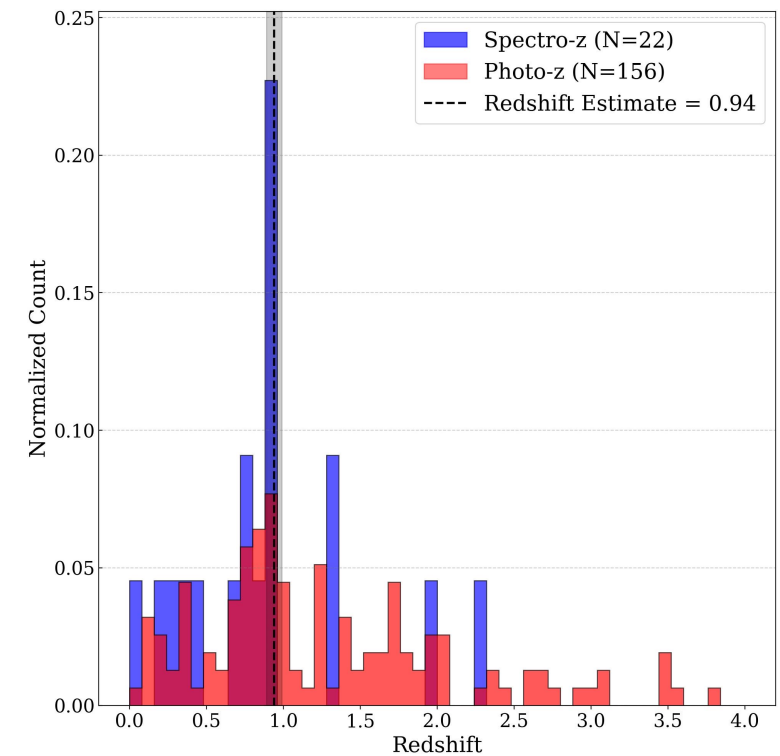- Future work needed for better cluster detection and characterization
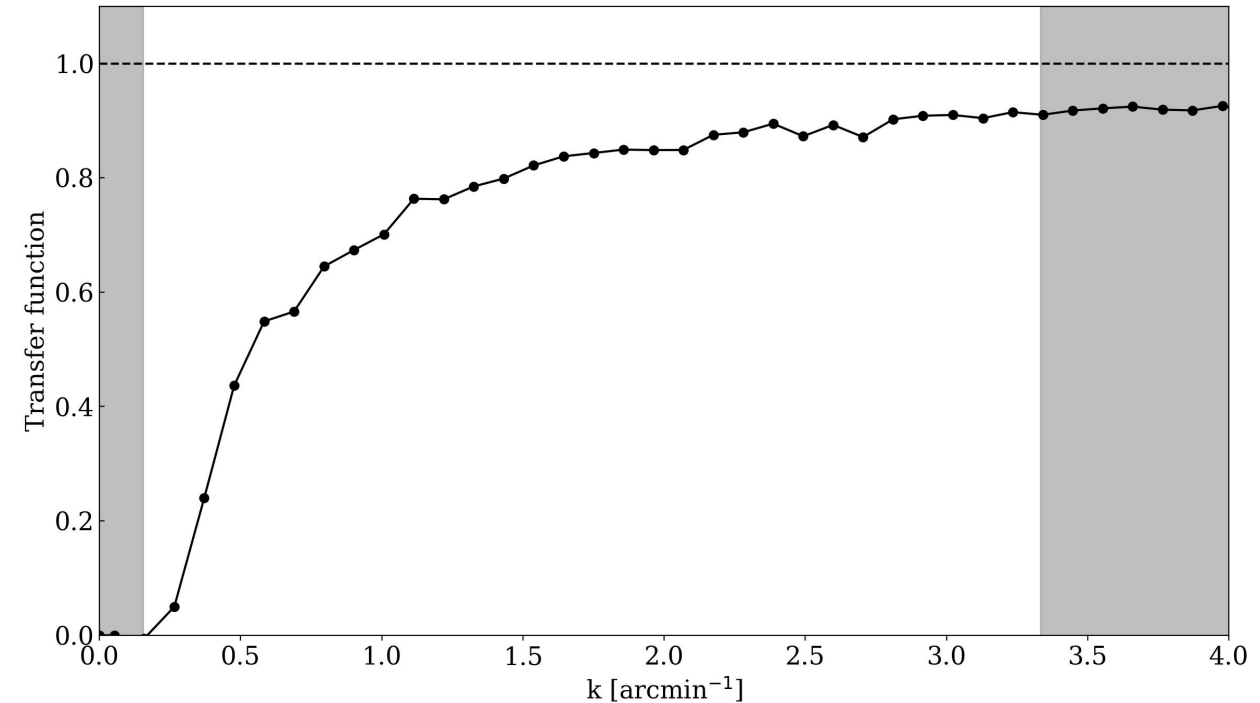
Transfer function of the 2mm NIKA2 data

Spectro and photo redshift catalogs

HSC *gri* map with SNR contours (white)
and best-fit tSZ model (green)

- In most case, redshift estimates are found at the peak of redshift distribution

- Some unidentified candidates also have well-defined redshift peaks

Normalized spectroscopic (blue) and photometric (red) redshift
counts within a 1 arcmin radius