Detection of distant galaxy clusters with the NIKA2 camera via the SZ effect

CMB France #6 – December 19, 2024

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and the NIKA2 collaboration

Outline

I. Context

II. Cluster candidates detection

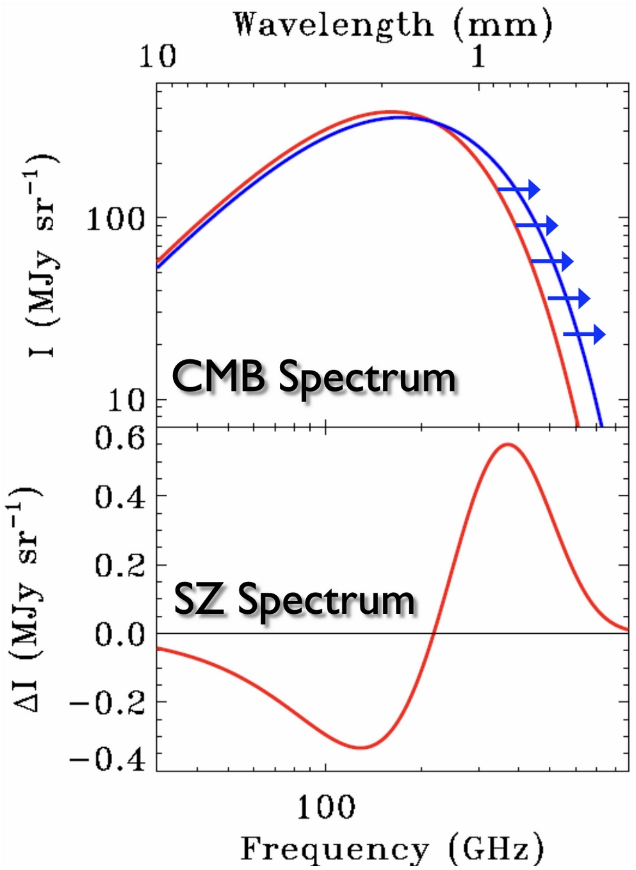
III. Cluster candidates properties

IV. Cluster sample characterization

Sunyaev-Zel'dovich effect

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

- Very distinct and characteristic spectrum
- Integrated Compton parameter is a proxy of cluster mass
- **SZ effect is redshift independent (not affected by cosmological dimming)**



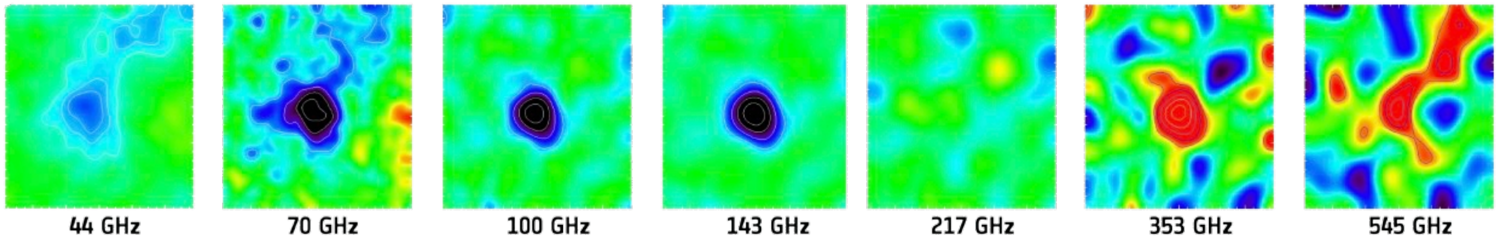
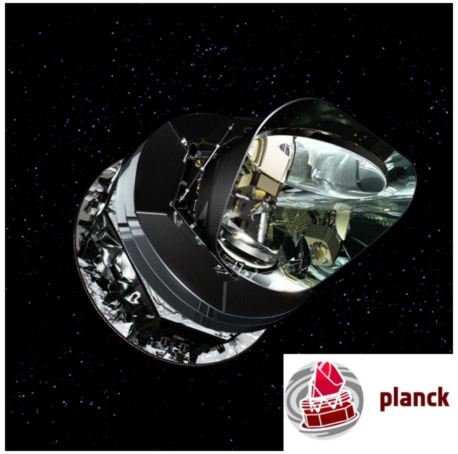
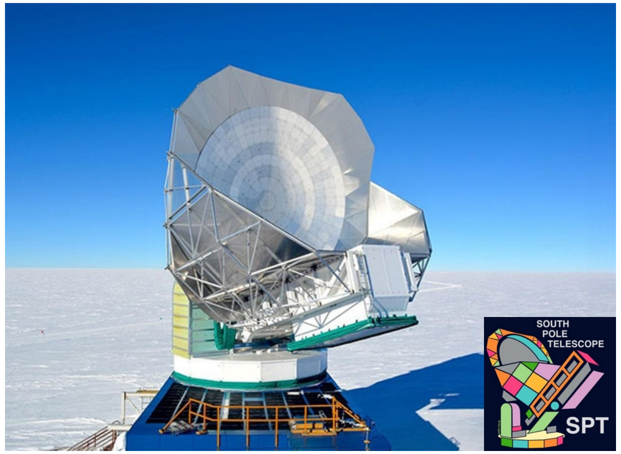


Image credit: ESA / HFI & LFI Consortia

A2319 Cluster observed by Planck

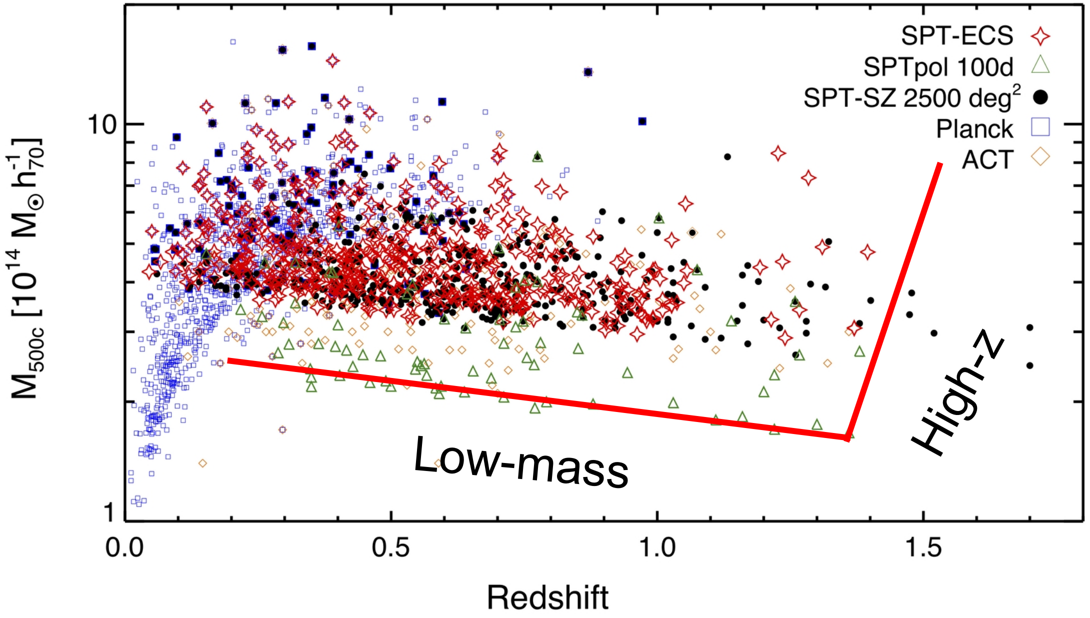
Millimeter large SZ surveys





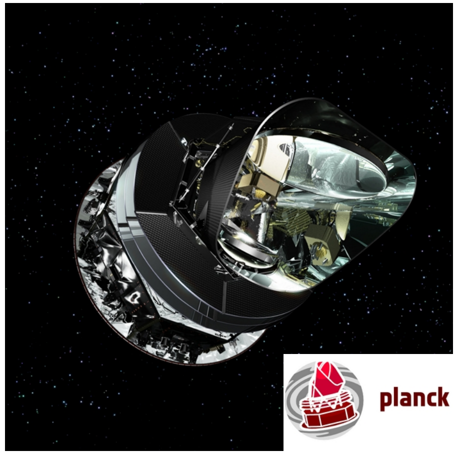
R_{500} : radius at which the mean cluster density is 500 times the critical density of the Universe

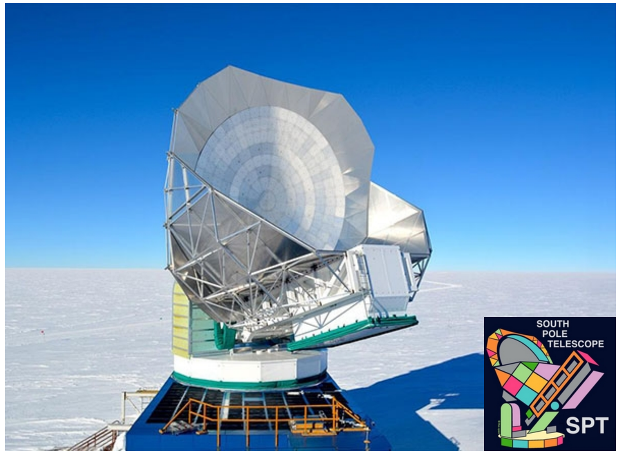
- Catalog of thousands of SZ clusters from previous millimeter large surveys (Planck, ACT, SPT)
- But they have relatively poor resolutions
  - ~5 arcmin for Planck
  - ~/<1 arcmin for ACT and SPT



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

Millimeter large SZ surveys





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

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 by GIS KIDS (LPSC, Institut Néel, IPAG, IRAM)
- Operating since 2015, we dispose of 1300h of guaranteed time

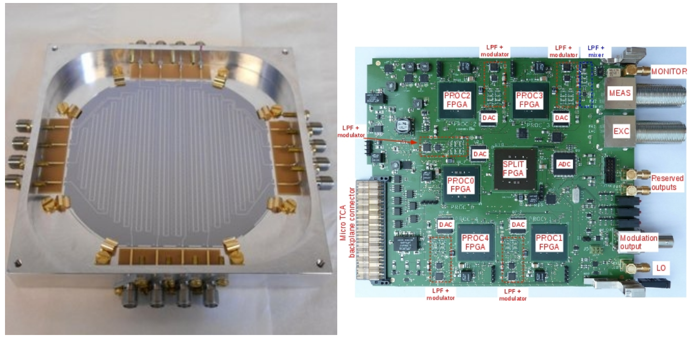
Observing band	150 GHz	260 GHz
Field of view [arcmin]	6.5	6.5
Angular resolution [arcsec]	17.6 ''	11.1''
Mapping speed [arcmin^2.mJy^{-2}.h^{-1}]	1388	111

Perotto et al. 2020

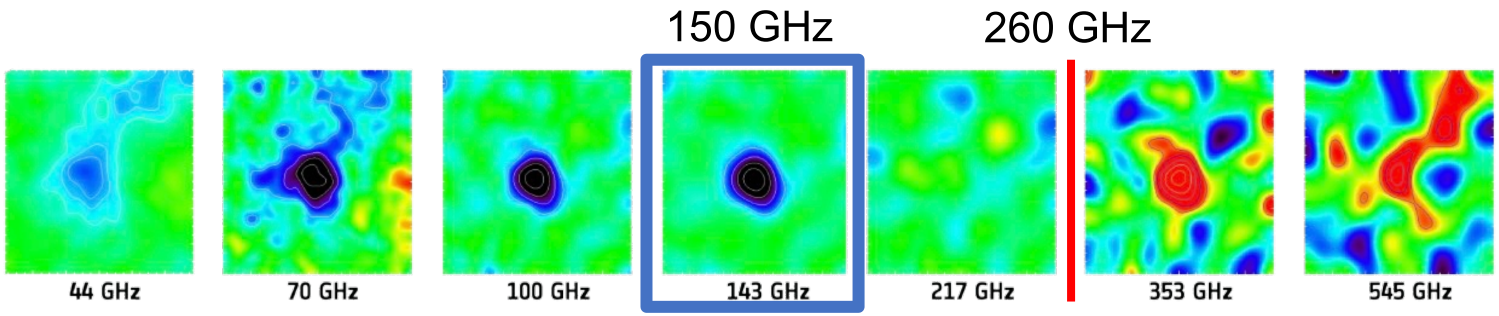
- Large field of view
- High angular resolution
- High sensitivity

IRAM telescope

Monfardini+ 17, Bourrion+ 16, Adam+ 18



NIKA2 KIDs array and readout board

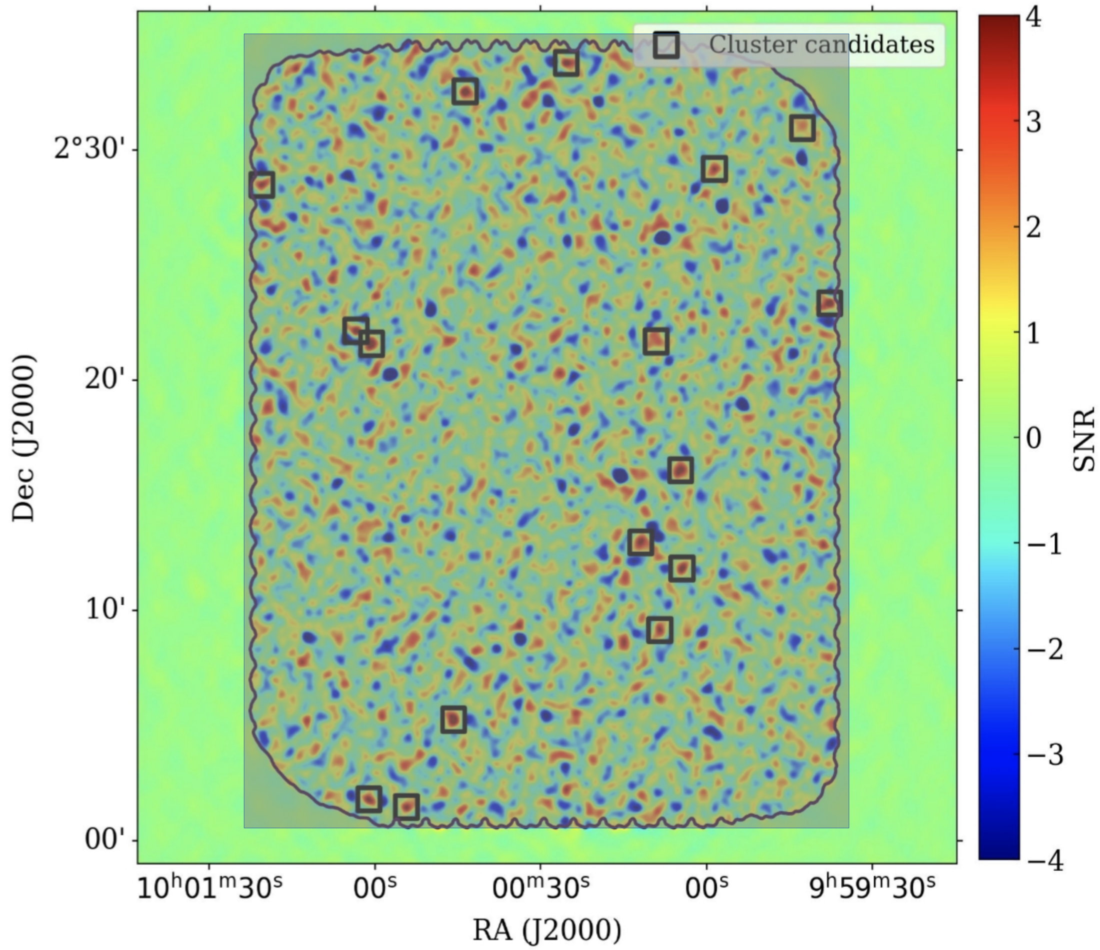


A2319 Cluster observed by Planck

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



COSMOS NIKA2 150 GHz map

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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)

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

Adapted 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

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

–> 5 parameters : P_0 amplitude

r_p, a transition radius/ steepness

c, b internal/ external slopes

Blind cluster detection

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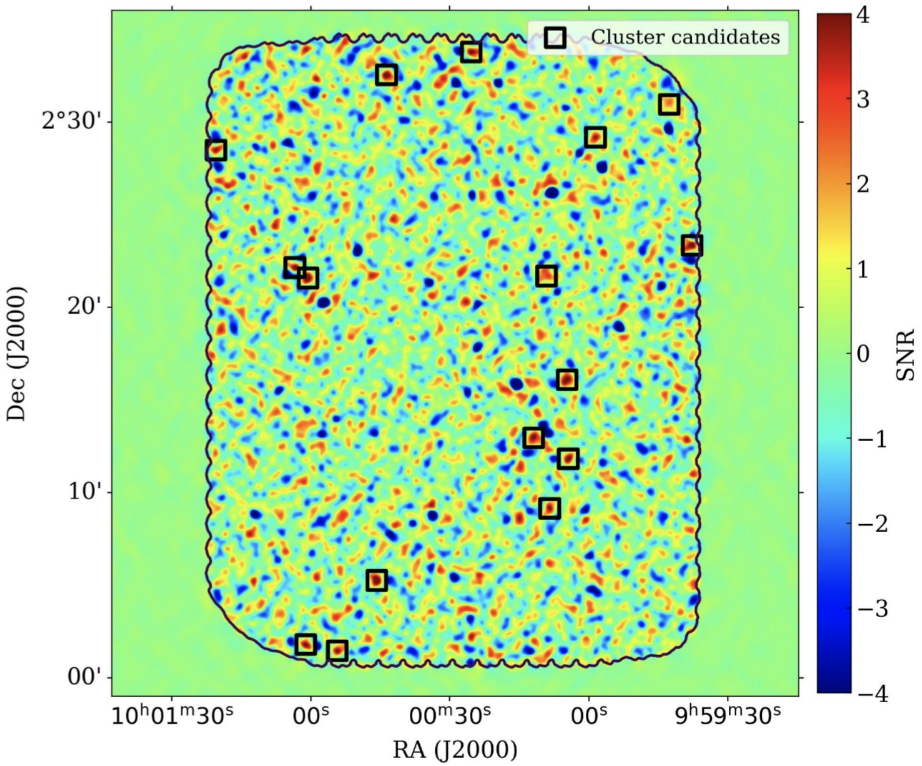
   - With *Arnaud et al. 2010 (A10)* parameters

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**

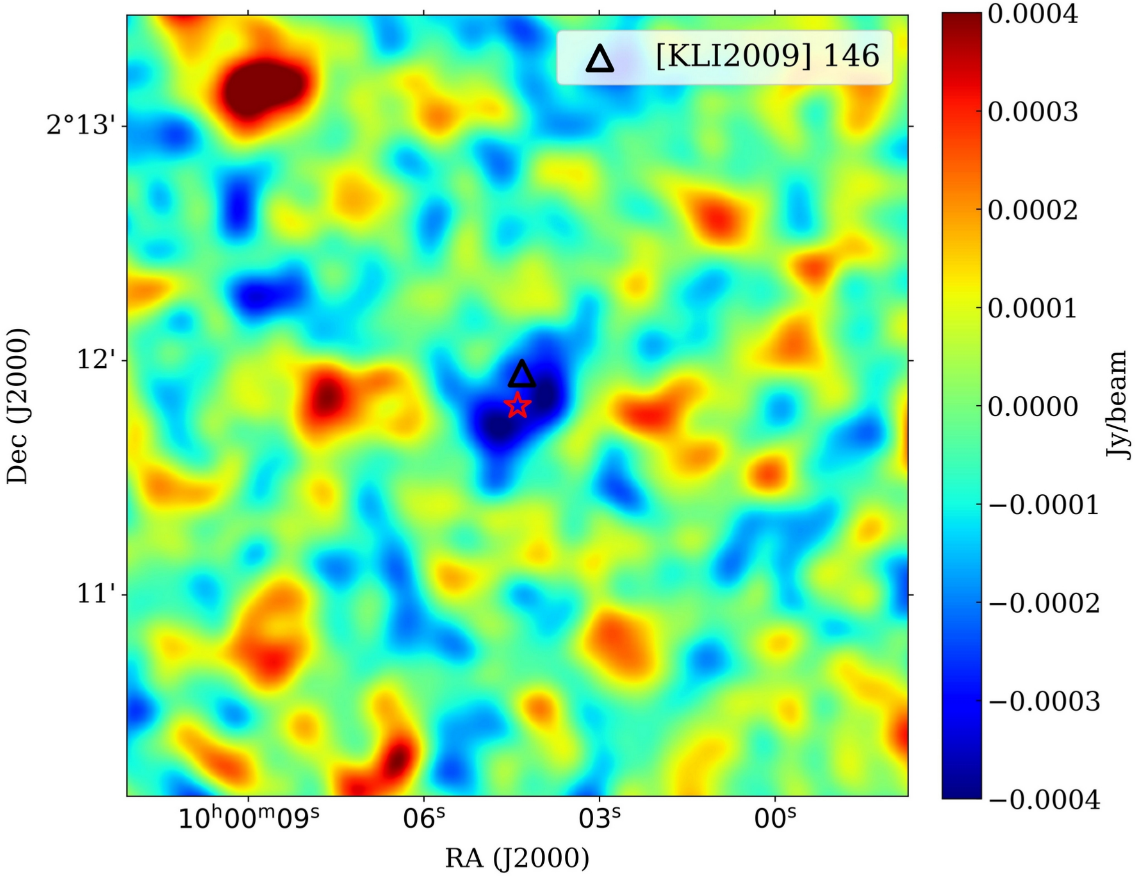
We have 16 cluster candidates after these 3 steps

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

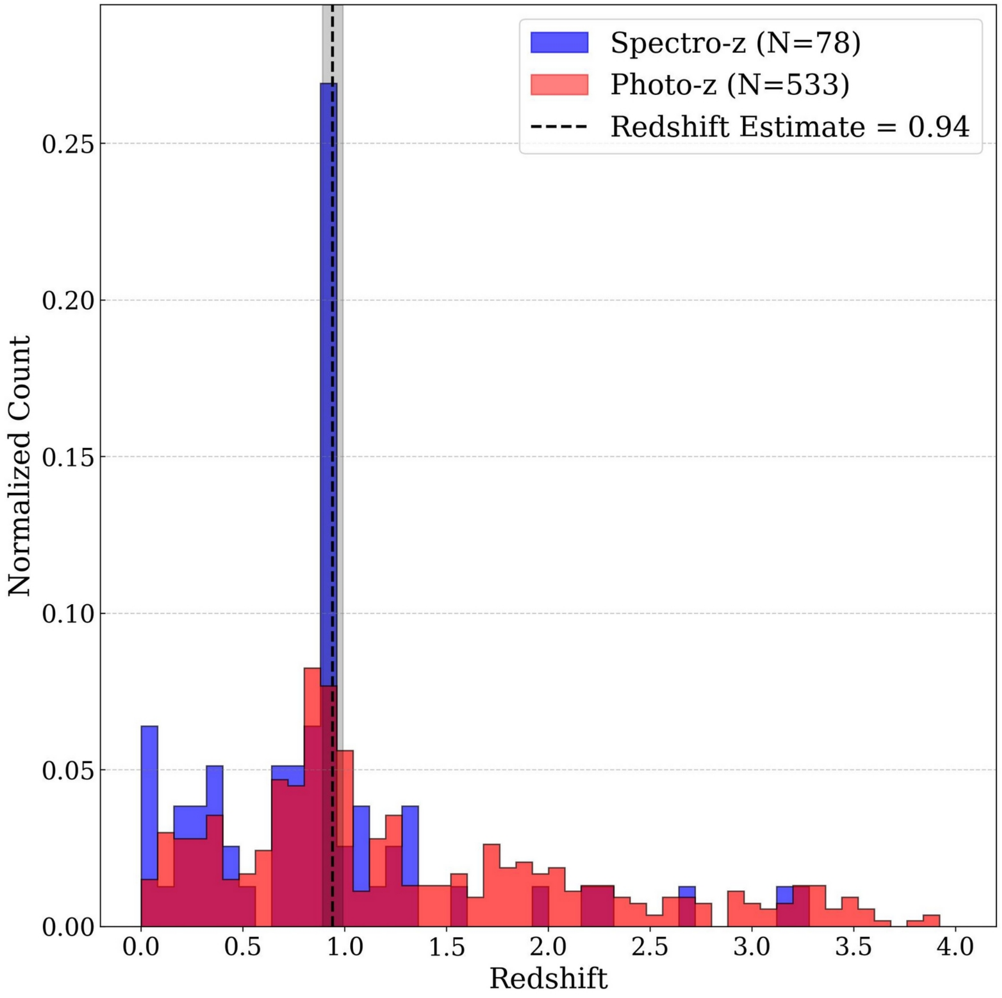
Red star : Cluster candidate

Black triangle : Optically (spectro redshift) detected cluster

- Clear negative signal in the map
- Match with a high redshift cluster at z ~ 0.94 :
  - [KLI2009] 146

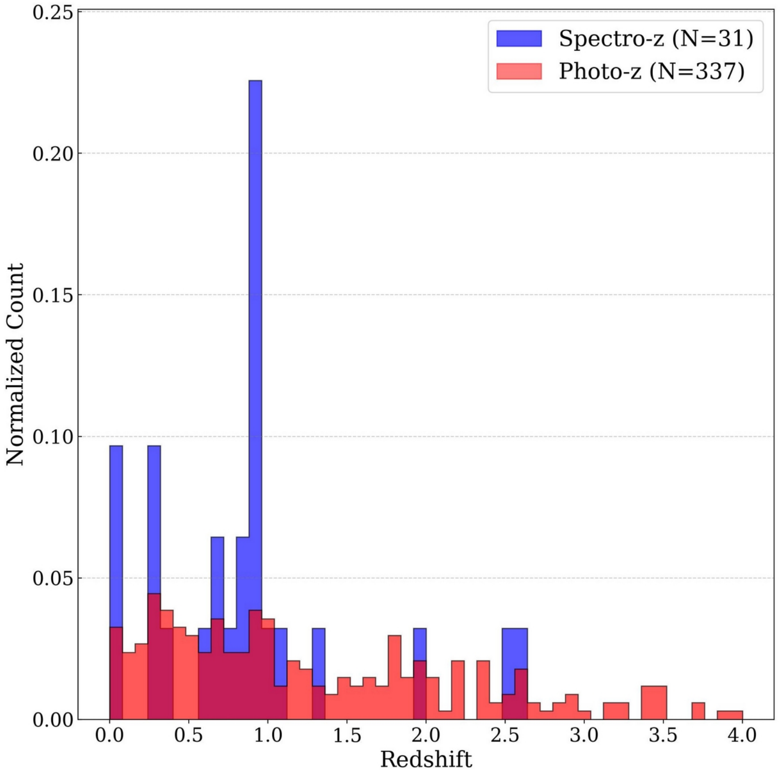
8 of our 16 detections are matched with a previously detected cluster

Spectro and photo redshift catalogs



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

- In most case, redshift estimates are found at the peak of redshift distrib
- Some unidentified candidates also have well-defined redshift peaks



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

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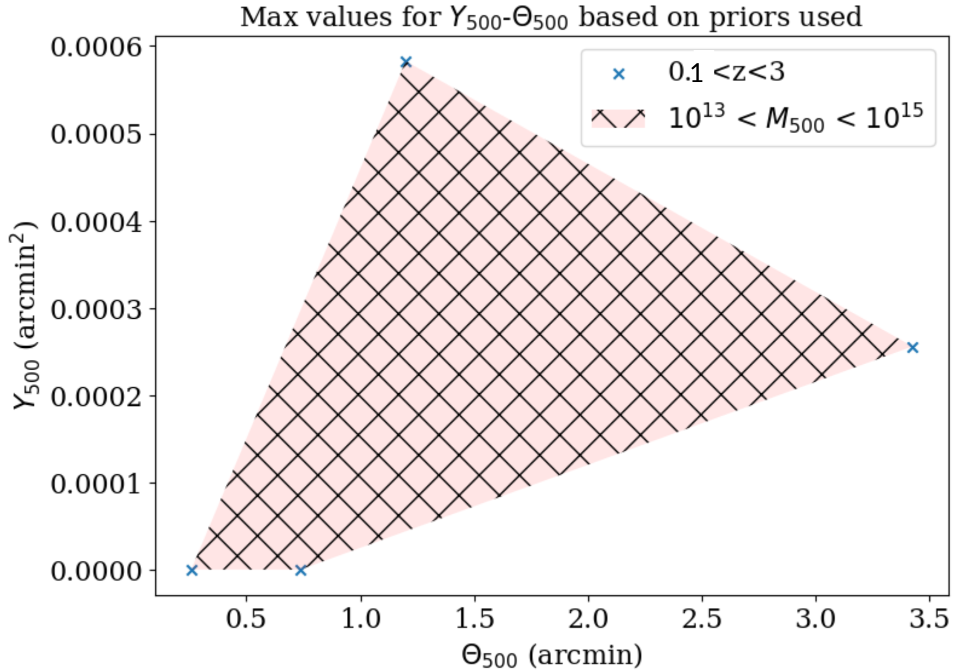
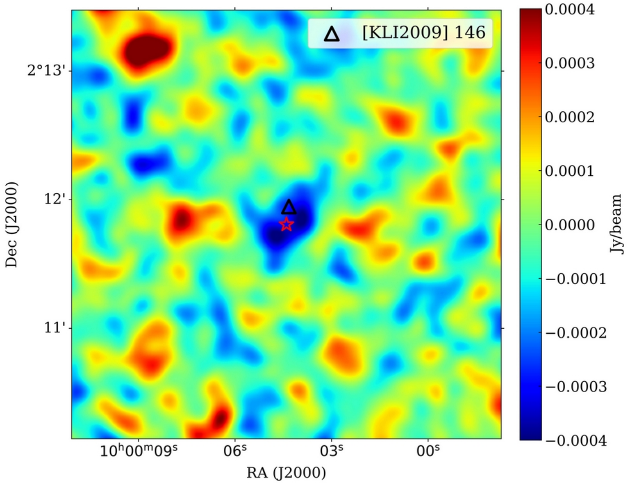
Y_{500}-$_{500}$ measurements

Mass Redshift tSZ Flux Size

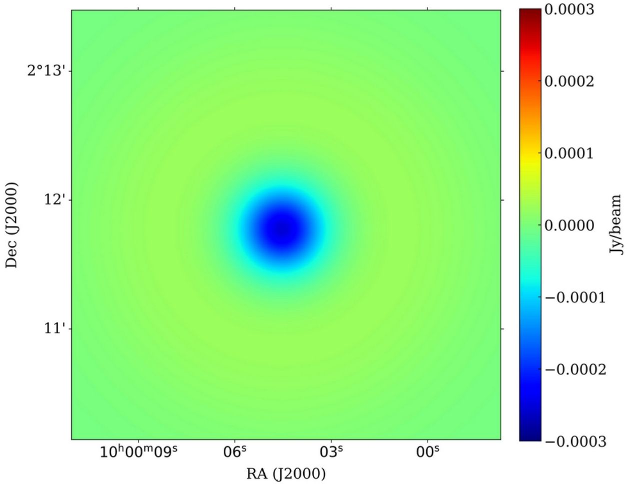
- Fit a cluster model using MCMC sampling, with 2 free parameters M_{500} and z to find Y_{500}-$_{500}$
- Model : integrated gNFW pressure profile model (*Nagai et al. 2007*) with fixed parameters as in Arnaud 2010
- Account for transfer function of data reduction
- Flat priors on M_{500} and z



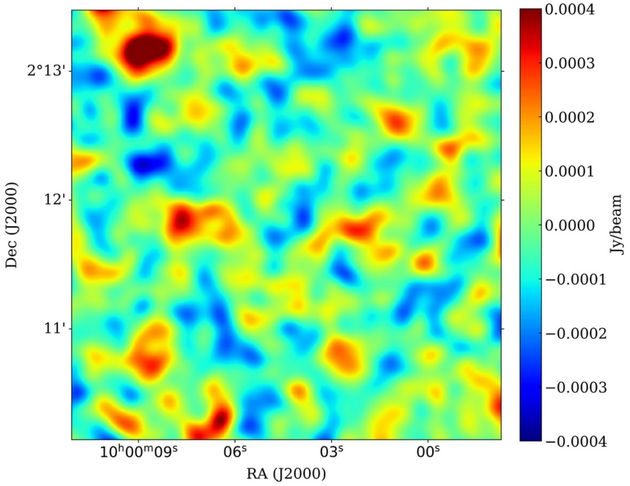
Zoom in on NIKA2-CL J100004.4+021148.4 (z ~0.94)



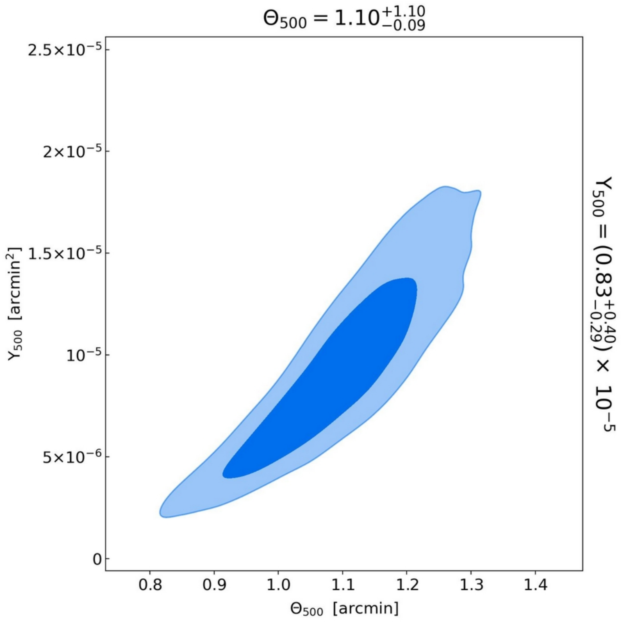
NIKA2 150 GHz map



Best-fitting model



Residual map



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

$$M\,500 = 1.16^{+0.33}_{-0.23} \times 10^{14}\, M_\odot$$

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

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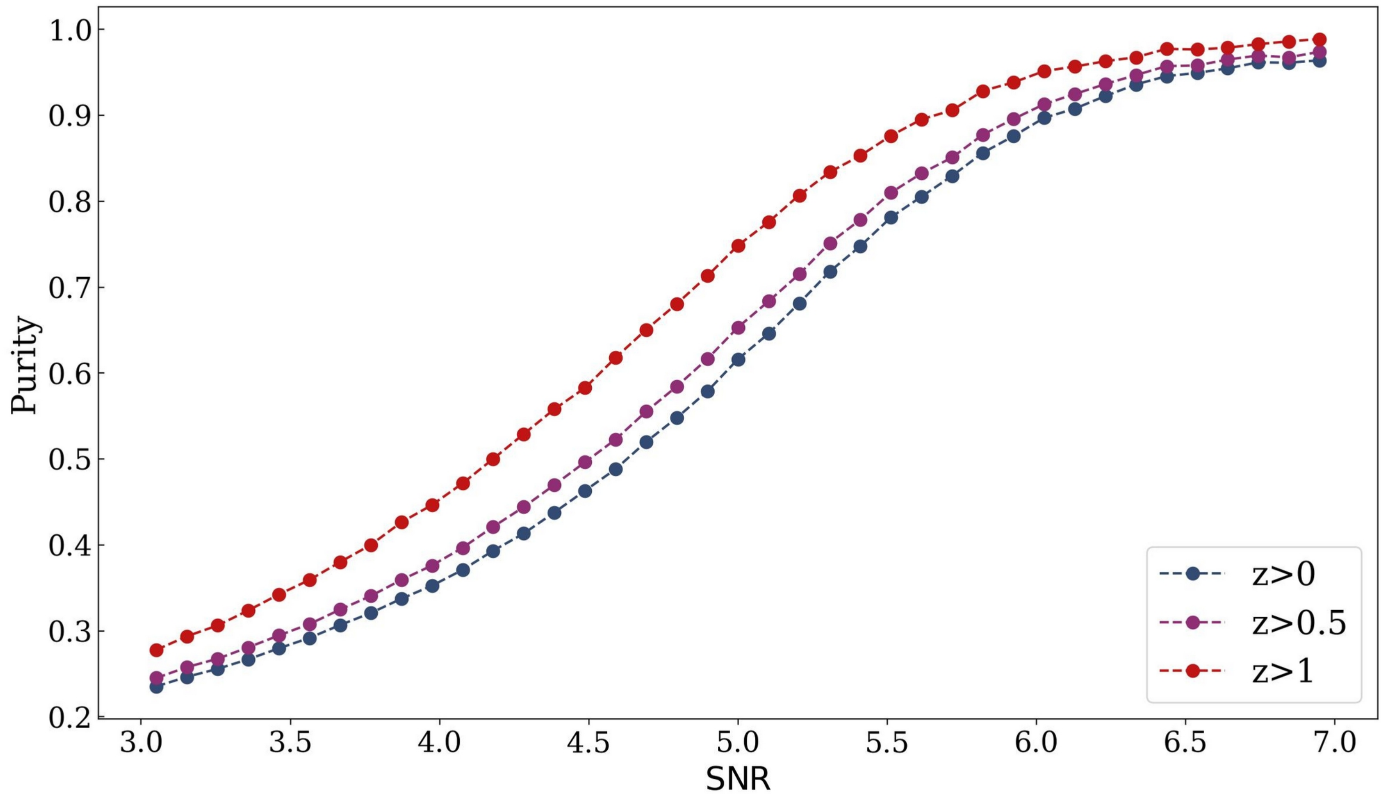
Cluster sample characterization

- 1000 simulations of expected number of clusters in COSMOS in a certain (M_{500}, z) range + noise + point sources

- Purity : Percentage of true detection in the sample
  - We reach a purity of **60% at SNR ~5.0**

- Completeness : Fraction of true cluster detected
  -



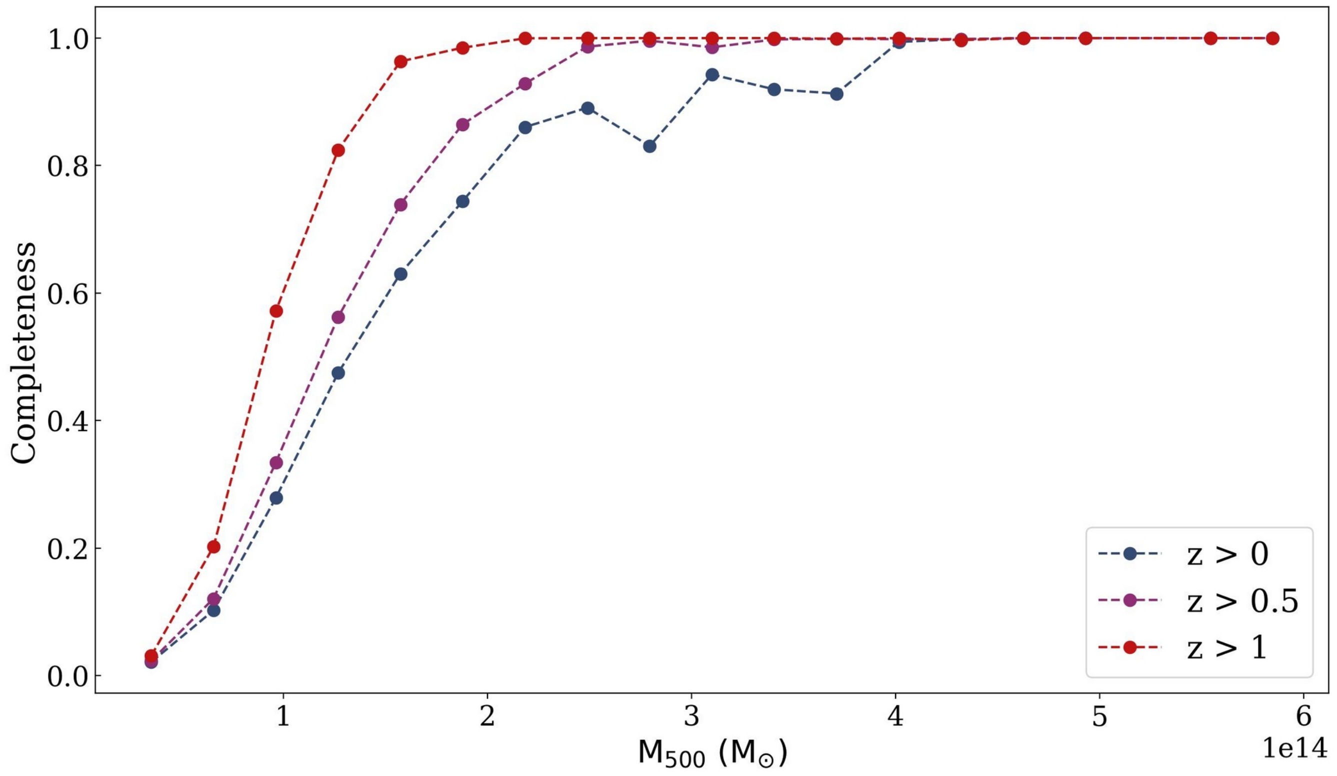
Purity as a function of SNR

Cluster sample characterization

- 1000 simulations of expected number of clusters in COSMOS in a certain (M_{500}, z) range + noise + point sources

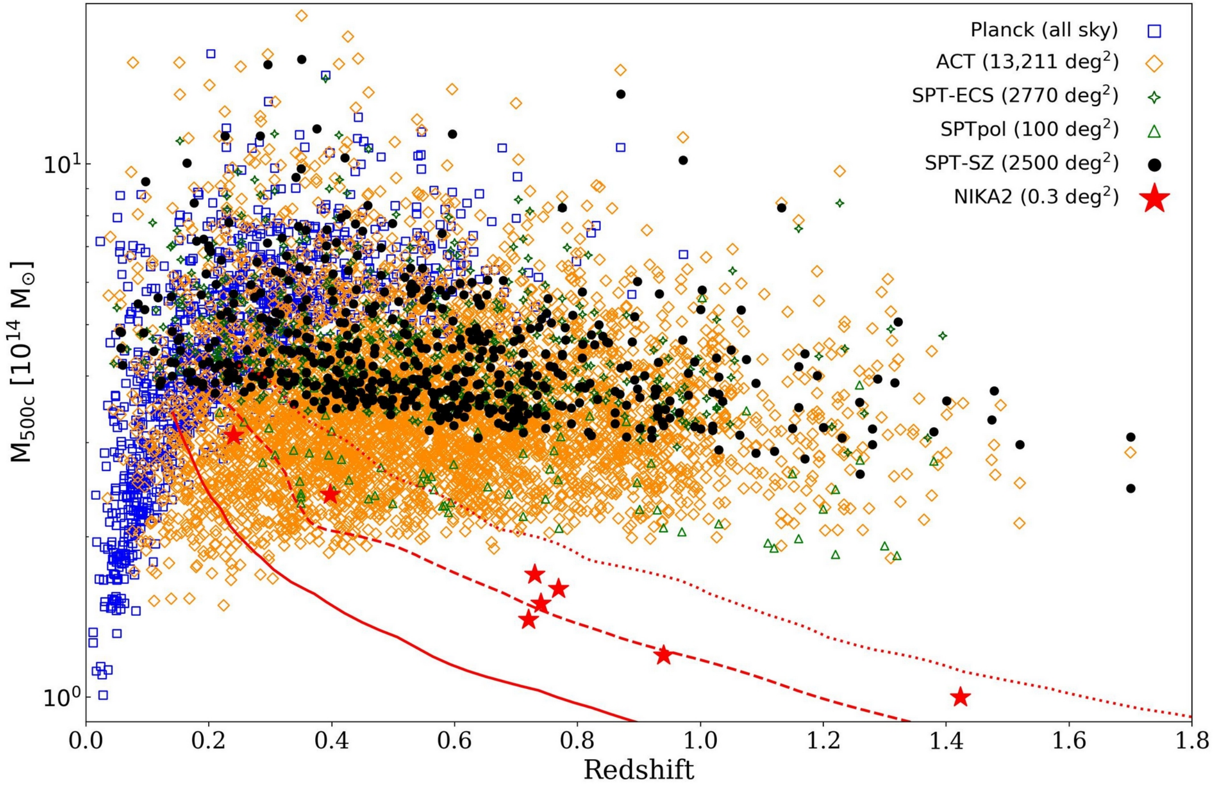
- Purity : Percentage of true detection in the sample
  - We reach a purity of 60% at SNR ~5.0

- Completeness : Fraction of true cluster detected
  - able to detect clusters in this mass-redshift range



Completeness as a function of mass

High resolution blind cluster detection



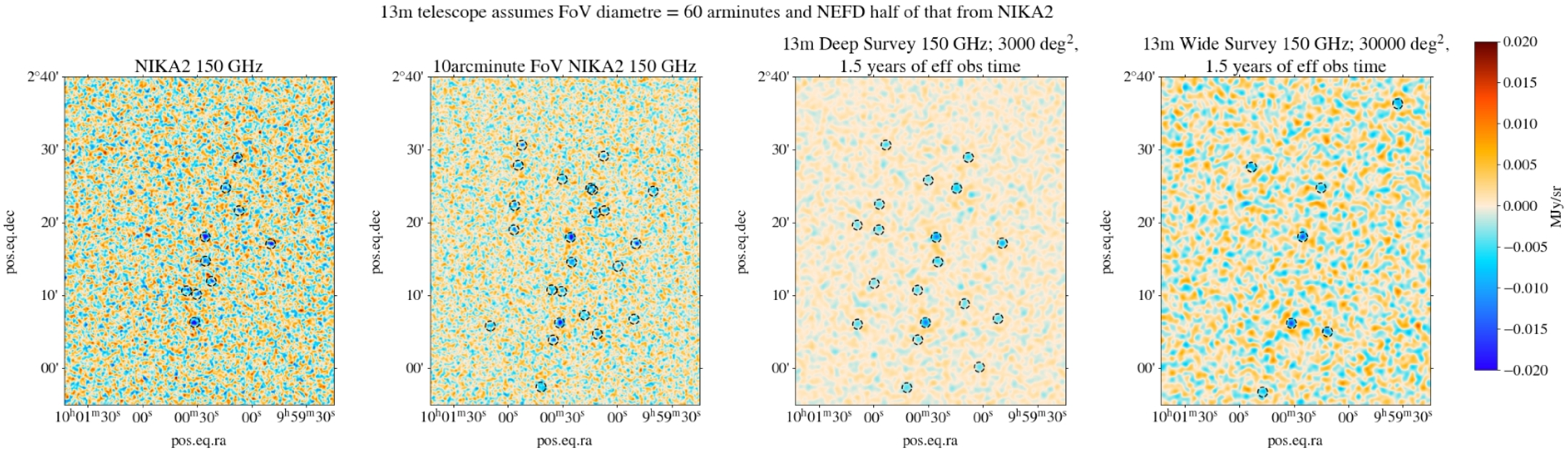
- Very promising results
- Validated NIKA2 catalog properties (purity and completeness) with simulations
- Future crosscheck on future large surveys catalog (e.g. Euclid, Vera Rubin)

We can blindly detect galaxy clusters with NIKA2

Need follow up observations to characterize cluster properties

Conclusion and perspectives

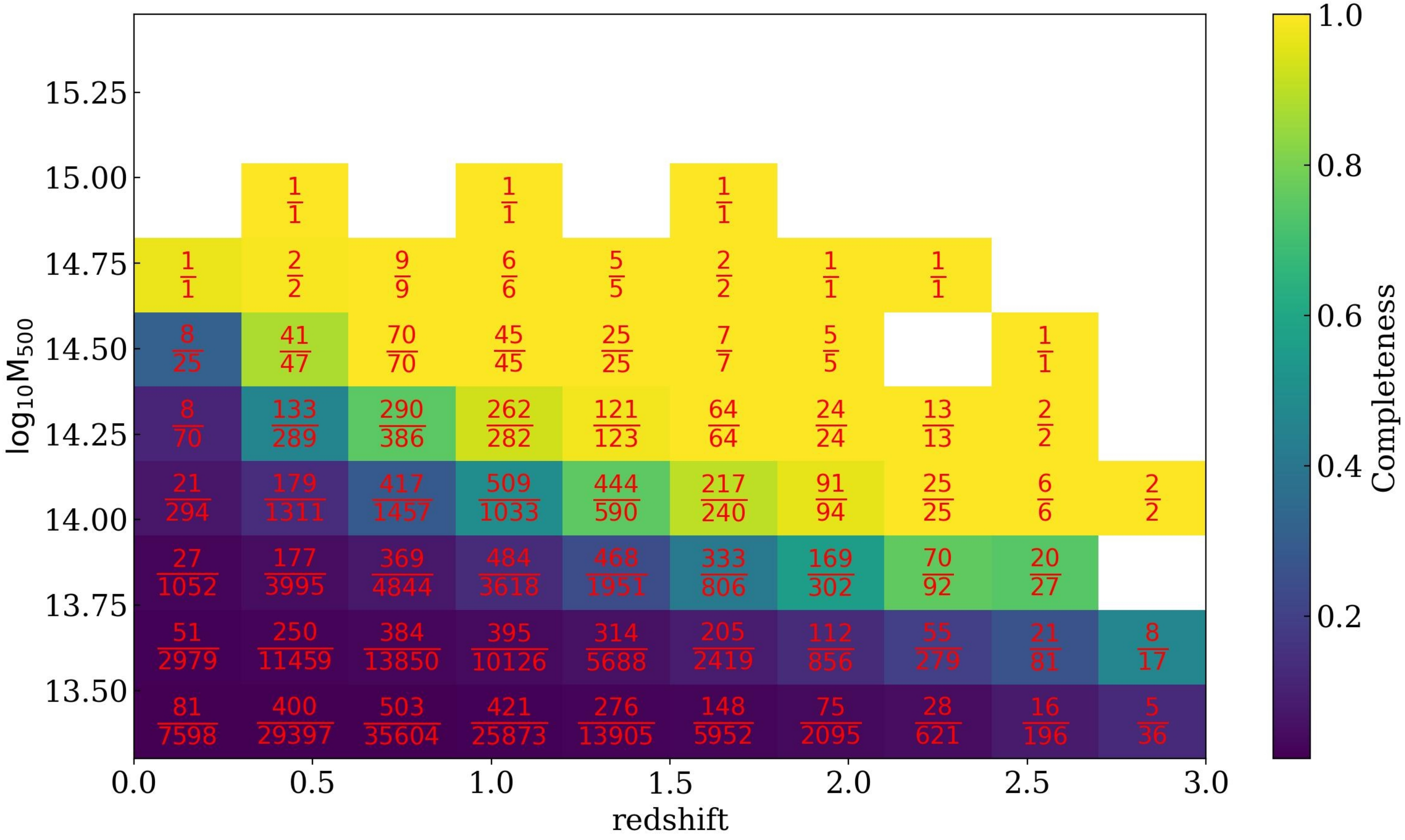
- First blind tSZ detection of galaxy clusters at very high angular resolution
  - ✓ 16 candidates, 8 with a known counterpart
  - ✓ Median redshift of the sample : z ~ 0.74, Median mass : M_{500} ~ 1.2 10^{14} M
- Good prospects for a high-resolution survey of the North of the sky
  - ✓ Upgrades of NIKA2 (extra frequency + larger FOV) to cover a larger area (tens of deg^2)
  - ✓ A new 13(15)-m telescope to cover thousands of deg^2 (new generation of Event Horizon telescope ?)



Backup

Cluster sample characterization

- 1000 simulations of expected number of clusters in COSMOS in a certain (M_{500}, z) range + noise + point sources
- Purity : Percentage of true detection in the sample
  - We reach a purity of 60% at SNR ~5.0
- Completeness : Fraction of true cluster detected
  - Yellow-green region : able to detect clusters in this mass-redshift range



Completeness

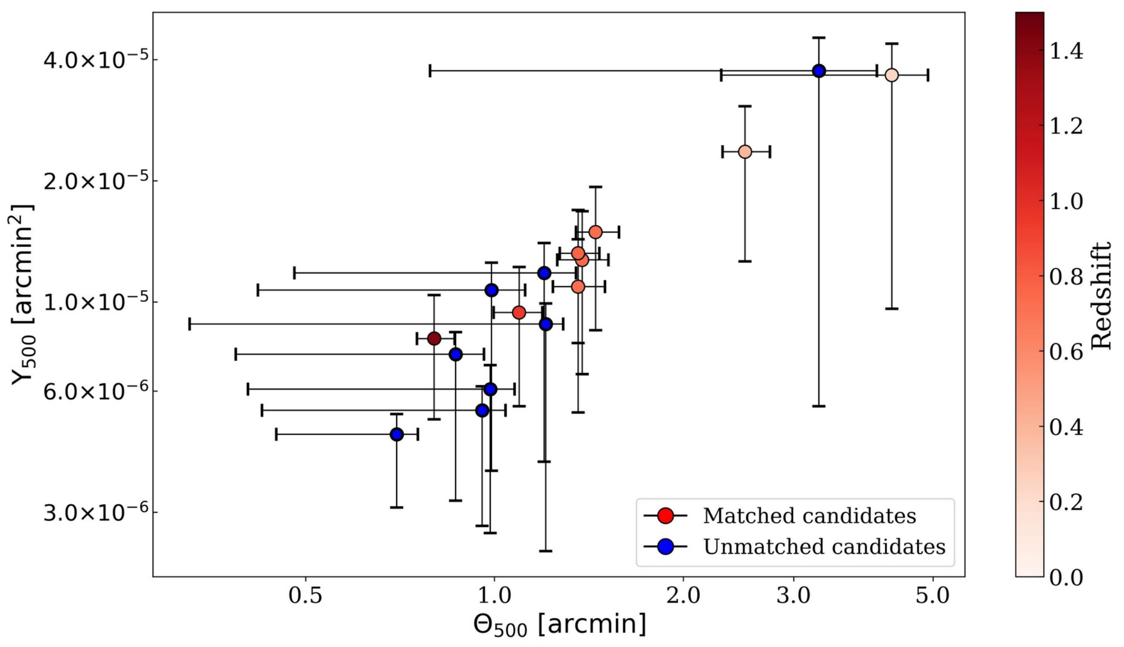
Conclusion and perspectives

- First blind detection of galaxy clusters at high angular resolution

  ✓ 16 candidates, 8 with a known counterpart

  ✓ Mapping the mass-redshift region of interest

  ✓ Median redshift of the sample : z ~ 0.74
  ✓ Median mass : M_{500} ~



Y_{500} - Θ_{500} estimates for each candidate

Cluster candidate sample

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NIKA2-CL J095937.7+022320.4	149.9071	2.3890	5.00	0.740±0.029	$1.42^{+0.10}_{-0.15}$	$1.08^{+0.62}_{-0.43}$	$1.44^{+0.47}_{-0.32}$	ALH J0959.38+0223.03 (17.8″, 8)
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NIKA2-CL J100043.6+023232.4	150.1818	2.5423	4.87	–	$0.48^{+0.31}_{-0}$	$0.51^{+0.37}_{-0.28}$	–	–
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NIKA2-CL J100009.1+022140.3	150.0378	2.3612	4.27	–	$1.7^{+2.4}_{-1.0}$	$1.6^{+3.0}_{-1.1}$	–	–
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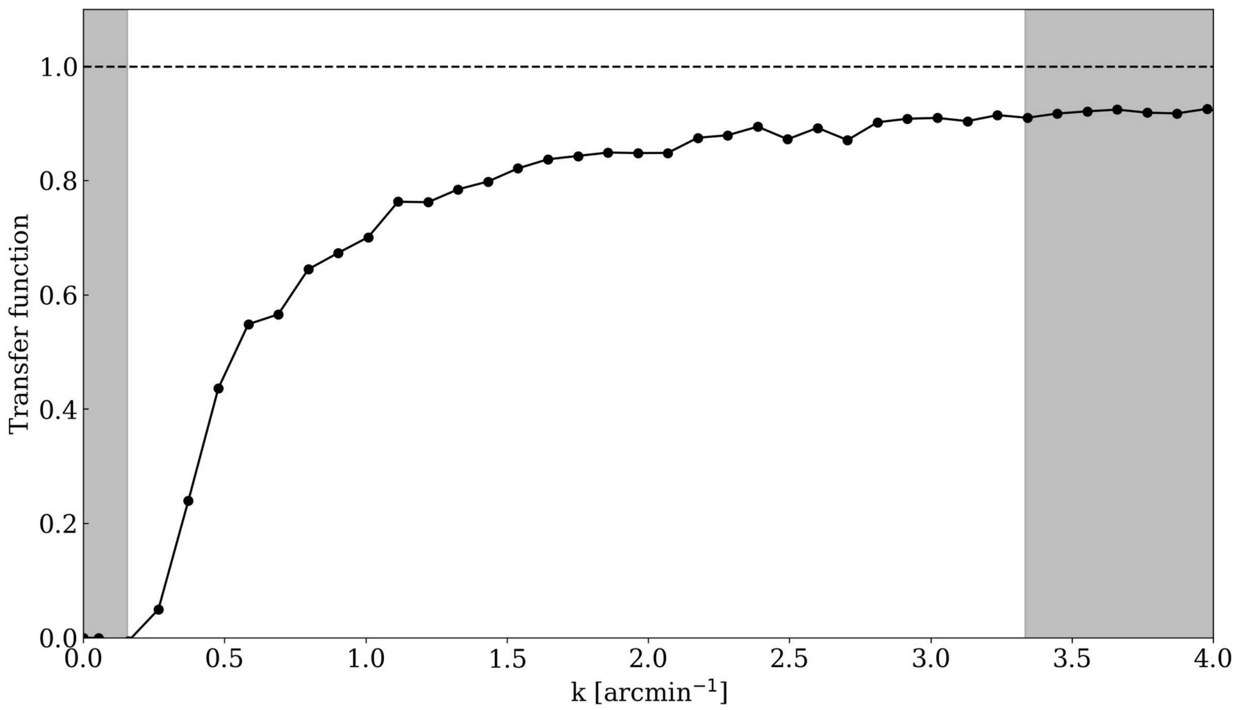
NIKA2-CL J095958.5+022910.4	149.9938	2.4862	4.01	0.397±0.010	$2.52^{+0.25}_{-0.20}$	$1.94^{+1.18}_{-0.70}$	$2.40^{+0.59}_{-0.61}$	[SCC2012] 0270 (14,8″, 39)

Transfer function

- Transfer function computed from simulated white noise signal

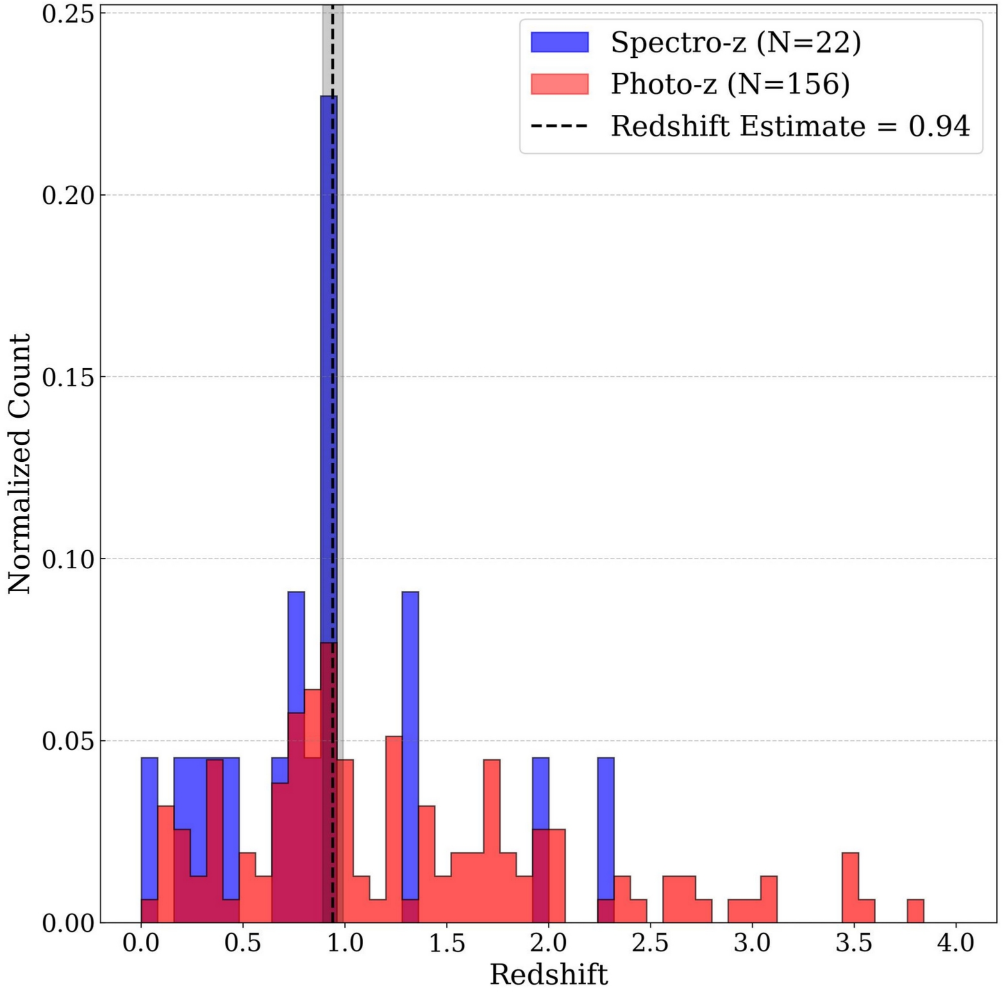
- Analysis optimised for point sources – explains why clusters seem to be so compact

- Future work needed for better cluster detection and characterization



Transfer function of the 2mm NIKA2 data

Spectro and photo redshift catalogs



Normalized spectroscopic (blue) and photometric (red) redshift counts within a 30 arcsec radius

- In most case, redshift estimates are found at the peak of redshift distrib
- Some unidentified candidates also have well-defined redshift peaks