NIKA2 commissioning, first results & cosmology program with galaxy clusters

Laurence Perotto on behalf of the NIKA2 Collaboration

53rd Rencontres de Moriond
17-24 Mars 2018
La Thuile
NIKA2: a high-resolution millimetric camera

Part I: Cosmological motivations for high-resolution observation of high redshift clusters

Part II: NIKA2 instrument, commissioning and performance

Part III: NIKA2 Cosmology program with galaxy clusters & First results
Galaxy Cluster observables

Largest bound structures

- Self-similarity
- Multi-component

80% DM 3% galaxies 17% gas (ICM)

\[ M_{tot} \approx 10^{13} - 10^{15} M_\odot \]
\[ 0 < z < 3 \]

Intra-Cluster Medium (ICM) observables

- X-rays:
  - Bremsstrahlung emission from electrons of the ICM
    - photometry \( \rightarrow \) density mapping
    - spectroscopy \( \rightarrow \) temperature

- Sunyaev Zel’dovich (SZ) effects,
  - Inverse Compton scattering of the CMB on hot electrons in the ICM
    - thermal SZ (tSZ)
    - kinetic SZ (kSZ), due to bulk velocity of the cluster; subdominant

See previous talks:
- Laura Salvati
- Alain Blanchard
- Boris Bolliet
- ....
Thermal Sunyaev Zel’dovich effect

- Inverse Compton scattering of the CMB photons on the hot dense ionised gas = the Intra-Cluster Medium (ICM)

- Spectral distortion of the CMB black body spectrum

\[
\frac{\Delta I_\nu}{I_0} = f_\nu \, y_{\text{t SZ}}
\]

- Amplitude of the SZ = Compton parameter

\[
y_{\text{t SZ}} = \frac{\sigma_T}{m_e c^2} \int P_e d\ell
\]

- Observer velocity \( v = +2492 \text{ km/s} \), simulated cluster

- Planck HFI/LFI consortium

Galaxy clusters, a valuable cosmological probe, are cleanly detected via thermal SZ up to high redshift

 SZ = probe for intracluster gas

Planck

El Gordo

[http://chandra.harvard.edu]
There are many SZ instruments observing clusters from ground based telescope, and from space.

- PLANCK, SPT, ACT: catalogs of about 2000 SZ-detected clusters
- Strong experimental efforts to reach higher angular resolution: NIKA2, ALMA, MUSTANG, BOLOCAM, ...
**SZ Cluster Cosmology: methods & assumptions**

**Cosmological Observables**

- **SZ cluster number counts**
  
  ![Graph](https://via.placeholder.com/150)

- **Compton parameter power spectrum**
  
  ![Graph](https://via.placeholder.com/150)

**Ingredients to model cluster physics:**

- mass function from hydrodynamical simulation
- pressure profile
- a scaling relation between the SZ observable and the mass of the cluster

**Calibration**

- Pressure profile and scaling relation calibrated from tSZ and X-rays low-redshift clusters

**See Laura Salvati’s & Boris Bolliet’s talks**
Results:

- tension between CMB and SZ derived cosmologies
- also true for other SZ experiments (SPT, ACT) and other cluster observables

*See talks from Laura Salvati, Alain Blanchard, Ziad Sakr, Boris Bolliet*

Several investigation routes:

- impact of cosmological parameters that affect the growth of structures (mnu, w), modified gravity, etc.
- impact of complex cluster physics on the mass estimation (deviation from self-similar scenario, non-thermal pressure, redshift evolution, etc.)

Need of a more robust calibration of the mass-observable as function of :

- redshift
- cluster internal matter distribution

*High angular resolution observations of high redshift clusters are now required for accurate cosmology with clusters*
NIKA2: a high-angular resolution millimeter imager

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NIKA2 & the NIKA2 collaboration

- NIKA2: resident instrument operated at the IRAM 30-m telescope, Pico Veleta (2800 m), Sierra Nevada, Spain
- NIKA2 Collaboration: Involving 150 people in 18 institutes (NIKA2 consortium + IRAM, Institut Radio millimétrique)
NIKA2 experimental overview

A dual-band camera of thousands of Kinetic Inductance Detectors (KID) operated at the IRAM 30-meter telescope.

A multi-thousand KID camera...

...operating at 150mK...

Design of the cryogenic stages

...observing in 2 channel bands at 150 and 260 GHz...

Measured spectral transmission

IRAM 30m telescope at Pico Veleta, 2800m, Spain

One of the two 1140 KID arrays at 260 GHz

...with an angular resolution < 20 arcsec and a large (6.5 arcmin) field of view...

...and mapping the polarisation at 260GHz

NIKA2 project timeline

NIKA Pathfinder

- October 2009: First light with 69 KIDs at 150GHz
- October 2010: Technical run with dual-band 356 KIDs camera
- 2011-2014: 7 technicals campaigns
- February 2014: NIKA opened to the community (3 campaigns)

NIKA2 commissioning

- First light in October 2015
- First campaign with a complete readout electronic in January 2016
- 10 commissioning campaigns (about 60 days)
- Upgrade in September 2016
- Avril 2017: commissioning successively finished, Science Verification Phase
- September 2017: IRAM End-of-commissioning review

NIKA2 is now opened to the community for the next decade

- October 2017: First Open Pool
- Winter 2018: 3 open pools in January, February and March (13-21)
- 2018-2028: resident instrument at IRAM 30-m telescope
Optics & bandpasses

Primary & secondary mirrors

Dedicated warm optics (inside the receiver cabin)

Cold optics (inside the cryostat)

- 150 GHz: bandwidth = 40 GHz: fill in the 2 mm atmospheric window to maximise the responsivity
- 260 GHz: bandwidth = 50 GHz: robustness against average weather condition

- 30-m aperture:
  - maximal angular resolution: 16 at 150 GHz and 9 at 260 GHz
  - usable FoV of 6.5 arcmin

Arrays of ~ 1000 detectors are needed
Kinetic Inductance Detectors & Multiplexing

KIDs are superconducting RLC resonators, operated at 150 mK ($< T_c$)

Incoming radiation changes the kinetic inductance (Cooper pair breaking)

Raw data are variation of the resonance frequency

Natural frequency multiplexing capabilities

**Pixel size (1 F lambda)**
- 2.8 mm at 150 GHz
- 2 mm at 250 GHz

**260 GHz**: 2 arrays of 1140 KIDs connected by 8 feed-lines

**150 GHz**: array of 616 KIDs connected by 4 feed-lines

M. Calvo et al. (2016) arXiv:1601.02774

20 NIKEL readout electronic boxes: NIKA dedicated readouts, multiplexing factor = 200;

O. Bourrion et al. (2016) arXiv:1602.01288

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**Dual Polarisation**
Roesch et al. (2012) arXiv:1212.4585

Films: thin Al (18÷25 nm)

Incoming Radiation

Capacitor
Inductance ($L_0 + L_f$)

Amplitude

Pixel size (1 F lambda)
- 2.8 mm at 150 GHz
- 2 mm at 250 GHz

transmission feed-line carrying 200 tones in ... out

260 GHz:
- 2 arrays of 1140 KIDs connected by 8 feed-lines

150 GHz:
- array of 616 KIDs connected by 4 feed-lines

M. Calvo et al. (2016) arXiv:1601.02774

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Focal Plan Geometry

- Matching the KID frequency tones to positions on the sky is needed for each observation campaign.
- We use deep integration scans of about 20' toward bright point sources to perform individual maps per KID.
- From these maps, we derive i) KIDs positions on the FoV, ii) beam properties, iii) inter-calibration.

- The full 6.5 arcmin diameter FoV is covered.
KID selection

- All the (2,900) built KIDs are responsive! Some of them are affected by cross-talk or their frequency tuning is lost during a scan.
- We perform a KID selection from a series of quality criteria for several beam-map scans.

KID position colour-coded as a function of the number of times they met the selection criteria (from red = valid for all selections to green = valid in one selection).

- Fraction of ‘valid’ (=stables in at least 2 scans) KIDs: 84% at 260 GHz and 90% at 150 GHz.
Beam Pattern

- Full beam pattern

- Observed features:
  - main beam
  - error beams
  - diffraction ring
  - M2 quadrupod arms
  - other spikes

- Main beam: average angular resolution
  
  2D Gaussian of FWHM:  
  - \(11.2''\) at 260 GHz
  - \(17.7''\) at 150 GHz

  \[\text{better than specifications}\]

- Beam efficiency: \(BE = \frac{\Omega_{MB}}{\Omega_{true}}, \ r_{\text{max}} = 250''\)  
  - 55\% at 260 GHz and 75\% at 150 GHz

  \[\text{in agreement with expectations}\]
Noise properties

- Dominant noise is the atmospheric fluctuations:
  - inducing strong 1/f noise spectrum
  - As it is seen by all the detectors, it can be decorrelated

- After decorrelation, correlated noise residuals from the atmosphere and the electronics at sub-dominant level in the maps

...which do not affect the noise scaling down with integration time: we checked that the flux uncertainties reduce as $1/\sqrt{t}$
Stability & Sensitivity

**Stability**

- Absolute Calibration using Planets [Moreno 2010, Bendo 2013]
- Photometry checks using secondary calibrators monitored at PdB

Calibration uncertainties:
7% at 260 GHz and 5% at 150 GHz

**Sensitivity**

- NEFD: Noise Equivalent Flux density \[ \text{NEFD} = \sigma(\text{Flux}) \sqrt{t_{\text{center}}} \]

  > Useful to predict the required observation time to reach a given SNR at the center of the map

  \begin{align*}
  \text{NEFD} & [\text{mJy.s}^{1/2}] : 33 \text{ at } 260 \text{ GHz and } 8 \text{ at } 150 \text{ GHz} \\
  \text{Mapping speed} & : m_s = \eta_{\text{valid}} \frac{\text{FoV}}{\text{NEFD}^2}
  \end{align*}

  > better estimator of the mapping capabilities

  Mapping speed [arcmin²/h/mJy²] :
  75 pm 5 at 260 GHz and 1350 pm 75 at 150 GHz

  > mJy sources can be detected in < 1h of integration time!

\[ \text{Pluto (4.8 mJy at 150GHz): } \sigma(\text{Flux}) = 0.3 \text{ mJy in } 1.44 \text{ hours over 150 arcmin}^2 \]
NIKA2 performance

<table>
<thead>
<tr>
<th></th>
<th>150 GHz</th>
<th>260 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of detectors</td>
<td>616 (553)</td>
<td>2x 1140 (960)</td>
</tr>
<tr>
<td>FoV diameter</td>
<td>6.5’</td>
<td>6.5’</td>
</tr>
<tr>
<td>Angular resolution: FWHM</td>
<td>17.7 ± 0.1 arcsec</td>
<td>11.2 ± 0.1 arcsec</td>
</tr>
<tr>
<td>Sensitivity: NEFD</td>
<td>8 ± 1 mJy.s$^{1/2}$</td>
<td>33 ± 2 mJy.s$^{1/2}$</td>
</tr>
</tbody>
</table>


NIKA2 is well adapted for SZ observations of intermediate and high redshift clusters

- Two frequency bands, negative & zero tSZ signal
- Large FOV: size of PLANCK beam
- High resolution: 17 times better than Planck
NIKA2: a high-angular resolution millimeter imager

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NIKA Pathfinder SZ pilot studies

- High-resolution SZ mapping capabilities have been demonstrated using NIKA = 1/10 NIKA2
- Breakthrough results have been obtained

### SZ-related publications

- First SZ observation with KIDs
  Adam et al. (2014) arXiv:1310.6237
- High-redshift thermodynamics with X-rays+SZ
  Adam et al. (2015), arXiv:1410.2808
- Point source removal
  Adam et al. (2016) arXiv:1510.06674
- Detection of high-z lensed galaxies
  Adam et al. (2015, 2017a)
- First map of the kinetic SZ
  Adam et al. (2017a) arXiv:1606.07721
- First map of the temperature with SZ
  Adam et al. (2017b) arXiv:1706.10230
- Non-parametric pressure profile
  Ruppin et al. (2017) arXiv:1607.07679
- Sub-structure measures: SZ+RHAPSODY-G
First mapping of the kinetic SZ effect

**Target**
- multiple merger MACS J0717.5+3745, \( z = 0.55 \)

**NIKA data**
- about 13h during Winter 2015
- good weather conditions (\( \text{tau}_{\text{atm}} \) about 0.09 at 150GHz)

**Point source removal**
- thanks to high-quality radio, optical, IR data
- foreground sources + high-z lensed galaxies

**First map of the kSZ**
- use both 150 and 260 GHz maps to separate tSZ from kSZ
- temperature from X-ray spectroscopy

\[
y_{kSZ} = \sigma_T \int -v_z n_e dl
\]

**resolved map of the gas velocity**
- using X-ray data from XMM-Newton
- using a gas model

\[
\hat{v}_z = -\frac{y_{kSZ}}{\int n_e dl}
\]
NIKA2 Guaranteed Time Cluster Cosmology Large Program

High-resolution mapping of a large sample of high-redshift Galaxy Clusters via SZ effect

- 300 hours of Guaranteed Time for SZ observation
- 50 clusters at $0.5 < z < 1$
- Representative sample: selected from PLANCK and ACT SZ catalogs
- X-ray follow-up with XMM-Newton

Main objectives:

- In-depth study of ICM (Intra-cluster medium)
- Thermodynamic properties: pressure, density, temperature, mass profiles
- Mass-tSZ scaling relation

Expected outputs:

- Constraints on the redshift evolution of scaling laws, pressure profile, hydrostatic bias
- Constraints on variation of cluster properties with morphology (departure from sphericity), dynamical state (impact of mergers)

Prospectives:

- Improvement of the cosmological constraints drawn from SZ-clusters
- Calibration of mass-observable scaling for Euclid high-z clusters
First mapping of a NIKA2 Cluster

Target:
- PSZ2-G0144.83+25.11
- $z = 0.58 \quad M_{500} = 7.8 \times 10^{14} M_\odot$

NIKA2 data:
- 11h of integration time on source
- April 2017: poor weather conditions (opacity of 0.3 at 150GHz)

Well-known cluster:

Young et al. 2014

Mustang

Sayers et al. 2013

Bolocam

Planck collaboration et al. 2016

Planck

Angular resolution of 9"
FOV: 42"
Green Bank Telescope

Angular resolution of 58"
FOV: 8 arcmin
Caltech Submillimeter Observatory

Angular resolution of 7' (y-map)
FOV: Full sky
Space: Lagrangian point L2
First NIKA2 Cluster: raw maps

- 13.5 sigma measurement at peak
detection up to 1.5 arcmin (>10Mpc)
- over-pressure south-west extension
- 4sigma point source detection
First NIKA2 Cluster: raw maps

- 13.5 sigma measurement at peak detection up to 1.5 arcmin (>10Mpc)
- over-pressure South-West extension

**Point source removal**

- we use Herschel observations from
  - PACS (0.10 and 0.16 mm)
  - SPIRE (0.25, 0.35 and 0.50 mm)

  to model point source emission in NIKA2 150GHz band
First NIKA2 Cluster: pressure profile

- Pressure profile using a non-parametric deprojection, Ruppin et al. (2017)
- The over-pressure extension is masked out

NIKA2 + Planck

NIKA2 + Planck + Mustang

- Compatible with X-ray derived pressure profile
- Not Compatible with profile derived from Mustang+Bolocam combination, Young et al. (2014)

Cluster dynamical state impact on the tSZ flux
Impact on Y_{500} (integrated quantity used for calibrating the mass-observable scaling law)
Implication on Cluster cosmology

- Significant difference between the pressure profiles obtained with and without masking the over-pressure region
- Impact on the integrated quantities used for the calibration of the tSZ-mass scaling relation

<table>
<thead>
<tr>
<th></th>
<th>With mask (unbiased)</th>
<th>Without mask (biased)</th>
</tr>
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<tbody>
<tr>
<td>$R_{500}$ [kpc]</td>
<td>1107 ± 30</td>
<td>1342 ± 61</td>
</tr>
<tr>
<td>$Y_{500}$ [$\times 10^{-4}$ arcmin$^2$]</td>
<td>8.06 ± 0.46</td>
<td>13.31 ± 0.85</td>
</tr>
<tr>
<td>$M_{500}$ [$\times 10^{14}$ $M_\odot$]</td>
<td>6.95 ± 0.56</td>
<td>12.42 ± 1.43</td>
</tr>
</tbody>
</table>

- Significant deviation from the universal pressure profile obtained from a sample of low-redshift clusters

Wrong estimate of the value of $Y_{500}$ → cluster masses in cosmological analyses
Summary

High-resolution SZ observation of high-z clusters is a key tool for cluster cosmology.

NIKA2: a unique dual-band, large (6.5 arcmin) FoV, high (< 20'') angular resolution experiment.

- Commissioned and opened to the community since October 2017.

NIKA2 SZ Large Program (2018-2023, 300 h of guaranteed time)
- High-resolution tSZ mapping of 50 clusters
- X-ray follow-up (XMM-Newton & Chandra)

- Main expected output: constraints on redshift evolution of the pressure profile and the mass-observable relation.

Promising results obtained from the analysis of the first NIKA2 cluster.
- Impact of the dynamical state on the estimated integrated quantities.

- + 10 clusters have been observed during the Winter 2018 campaign.