NIKA2
a millimeter camera
for cluster cosmology

J.F. MACÍAS-PÉREZ
on behalf of the NIKA2 collaboration
Clusters of galaxies

- Formed by gravitational collapse at the intersection of cosmic filaments, correspond to massive dark matter halos
  - Self-similar scenario: clusters are scaled copies one of each others
  - However, baryonic physics plays a significant role
- First observed by Zwicky in 1930’s who inferred that their total mass was larger than the sum of its luminous components
- Largest gravitationally bound structures in the Universe
  - Dominated by dark matter
  - Most baryonic matter is in the form of gas, the Inter Cluster Medium (ICM)
  - Galaxies count for only 3 % of the total mass
- Total mass $10^{13}$- $10^{16} \text{M}_\odot$, redshift $0 < z < 3$
Cosmology with clusters

Cluster distribution in mass and redshift depends on cosmological parameters
Sunyaev-Zeldovich effect

- $tSZ = \text{CMB spectral distortion from interaction with clusters' hot electrons}$
- $kSZ = \text{CMB Doppler shift from bulk motion of electrons (typically } \sim tSZ/10)$

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

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

$\Rightarrow$ Pressure

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

$\Rightarrow$ Velocity $\times$ density

No cosmological diming

$\Rightarrow$ $SZ = \text{probe for intracluster gas}$

[Image of Sunyaev-Zeldovich effect with associated equations and diagrams]

[Graph showing $\Delta I_\nu/I_0$ vs. GHz with $tSZ$, $kSZ$, and $tSZ + kSZ$ curves]

[Image of El Gordo with CMB and observer]

[J.F. Macías-Pérez - LPSC  DSU 2019 - Buenos Aires]
tSZ cluster cosmology

- Catalogue of 1653 tSZ detected clusters
- Redshift: optical follow-up
- Hydrostatic mass by combining tSZ flux and X-ray data: $Y_{500} - M_{YX} (M_{HS})$
- Characterisation of the hydrostatic-total mass bias via simulations: $M_{HS} = (1-b) M_{tot}$

Number of clusters as function of redshift and mass is very sensitive to cosmology

2-σ tension between CMB and tSZ (cluster observable) derived cosmological parameters
Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, ...

J.F. Macías-Pérez - LPSC  
DSU 2019 - Buenos Aires
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High redshift evolution?

- Planck can only resolve low redshift clusters

- High redshift clusters are at the early stages of formation and may not behave like low redshift ones: merging processes and shocks, undefined outskirts, evolution of scaling relations, non hydrostatic equilibrium, etc

Multi-wavelength high resolution observations of high redshift clusters are needed to identify possible evolution of cluster properties with redshift
The NIKA2 camera

Dual band mm KID camera operating and 150 and 260 GHz

Specific optical system to obtain the widest field

Dilution cryostat: 180 mK nominal temperature

Arrays of 1140 (616) KIDs: 8 (4) independent feedlines with up to 200 KID each

<table>
<thead>
<tr>
<th>Frequency</th>
<th>150 GHz</th>
<th>260 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td># KIDs</td>
<td>616 (553)</td>
<td>2 x 1140 (960)</td>
</tr>
<tr>
<td>FOV diameter</td>
<td>6.5 arcmin</td>
<td>6.5 arcmin</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>8 ± 1 mJy/s^{1/2}</td>
<td>33 ± 2 mJy/s^{1/2}</td>
</tr>
<tr>
<td>Angular res.</td>
<td>17.7 arcsec</td>
<td>11.2 arcsec</td>
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20 boxes (one per feedline) arranged in 3 crates (one per array)

300 multiplexing factor
NIKA2 is a perfect instrument for the tSZ effects in clusters of galaxies

- Wide-field: size of PLANCK beam
- High resolution: 17 times better than Planck

Two frequency bands, negative & zero tSZ signal

[Ruan et al. (2013)]
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

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

[NIKA2 collaboration, 2017]
NIKA SZ pilot sample for cluster physics

RX J1347.5-1145 (z=0.45) | CL J1226.9+3332 (z=0.89) | MACS J1423.9+2404 (z=0.55)

perfect test target | very high-z | relaxed (and foreground point sources)

MACS J0717.5+3745 (z=0.54) | PSZ1 G046.13+30.75 (z=0.57) | PSZ1 G045.85+57.71 (z=0.61)

complex morphology | Planck SZ-discovered: follow-up

MACS J0717-3745 tSZ 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

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

*gas pressure*  
*gas velocity and density*  

[Adam & NIKA collaboration, 2016]

J.F. Macías-Pérez - LPSC  

DSU 2019 - Buenos Aires
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\[
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\]

- **spectral dependencies**
  - gas pressure
  - gas velocity and density

[Adam & NIKA collaboration, 2016]

First direct mapping of kSZ emission

[Adam & NIKA collaboration, 2016]
Follow-up of Planck clusters

**CLJ1226.29+33.32, \( z = 0.89 \)**

**PSZ1 G045.85+57.71, \( z = 0.61 \)**

First non-parametric reconstructions of high redshift cluster pressure profiles

J.F. Macías-Pérez - LPSC  
DSU 2019 - Buenos Aires
NIKA2 SZ Large program

One of the 5 NIKA2 LP (1300 h in total)
- **300 hours** of tSZ observation
- **50 high redshift clusters** $0.5 < z < 1.0$
- tSZ selected clusters from Planck and ACT catalogues

Ancillary data
- X-ray follow-up with XMM
- Optical data using GranTeCan
- MUSIC hydrodynamic simulations

Main goals

Redshift evolution of:
- Cluster thermodynamic quantities
- Scaling laws (mass - tSZ) and hydrostatic bias

Variation of cluster properties with:
- Dynamical state (mergers)
- Morphology (ellipticity)

[Comis+2016, Mayet+2017,JFMP+ 2017 ]
First NIKA2 SZ cluster

PSZ2 G144  [Ruppin et al, AA, 2018]

- Planck tSZ detected cluster at redshift, $z = 0.58$, high mass $M_{500} = 7.8 \times 10^{14} M_\odot$
- 11h observations with NIKA2 in poor weather conditions (atmospheric opacity 0.3@225 GHz)
- Already observed: SZ – MUSTANG & Bolocam, X-rays - XMM

Detailed characterization of the cluster pressure profile – overpressure found
Hints of dependence of the hydrostatic mass bias with cluster physics
Observed NIKA2 LP clusters

Very promising results, detailed analysis on going

Very Preliminary
Conclusions

- High resolution SZ resolution observations of high redshift clusters are needed to check possible redshift evolution of cluster properties and their impact on cosmology.
- NIKA high resolution tSZ observations has been extremely successful covering a large number of scientific cases.
- NIKA has provided first direct mapping of the kSZ effect opening a new window in cluster physics and cosmology.
- First NIKA2 observations have proved to be of high quality.
- Detailed analysis of PSZ2G144 NIKA2 tSZ map have shown cluster dynamical state is key for understanding the mass-tSZ relation.
- NIKA2 SZ LP will provide unprecedented view of high redshift cluster allowing for accurate cluster cosmology.
The "standard" cosmological model
Cluster observables: detect them and/or measure their physical properties

**Visible and IR emission**
Light from stars in galaxies

**X-ray emission**
Free-free emission from free electrons in the ICM

**Sunyaev-Zeldovich effect**
Interaction of hot electrons in the ICM with CMB photons

**Radio emission**
Non thermal emission from accelerated particles

**Mass:**
- Richness (number of galaxies)
- Luminosity profile
- Velocity dispersion
- Gravitational lensing

**Density, temperature, entropy, mass:**
- Surface brightness
- Spectroscopy

**Pressure, mass, shocks:**
- Compton parameter

**Shocks:**
- Surface brightness
A bit of tSZ cluster cosmology theory

Cluster number counts

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

Universe volume

Catalogue selection function

\[ \frac{dN}{dz \, dM_{500} \, d\Omega} \]

Cluster’s Mass function
Cluster cosmology requires accurate mass and matter distribution estimates. Two complementray approaches:

- Weak lensing provides absolute mass normalisation.
  - LSST + EUCLID 2021 -->

- Baryonic mass proxies have unknown bias and low scatter.
  - X-rays: e-ROSITA.
  - SZ: SPT-3G (2016-2019), Advanced ACTPOL.

Mainly low redshift cluster data available, and we expect some evolution with redshift. Multi-wavelength high resolution observations of high redshift clusters are needed.
The NIKA2 camera

- September 2015: installation at IRAM
- October 2015: First lights
- September 2016: complete instrumental setup
- April 2017: commissioning successfully finished; performance better than expected

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Science with NIKA2

- Multi-purpose camera open to the astrophysical community
- Open time observations for at least one decade (already 4 campaigns)
- The NIKA2 collaboration has been awarded 1300 hours of GT shared between 5 Large programs for astrophysics and cosmology:
  - Galactic studies in intensity and polarisation
  - Nearby and distant galaxies
  - Clusters of galaxies

[NIKA2 collaboration: Adam+2018, Perotto+2019]