TSUKUBA GLOBAL SCIENCE WEEK 2018

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Astrophysics and cosmology with KID cameras

J.F. Macías-Pérez – LPSC
on behalf of the Grenoble KID collaboration

LPSC Grenoble

NÉEL institut

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

iram Institut de Radioastronomie Millimétrique

The KID collaboration at Grenoble

Alessandro MONFARDINI – Director of research
Alain BENOIT – Director of research (Emeritus)
Sébastien TRIQUENAUX – Research engineer
Martino CALVO – Research engineer
* Aurélien BIDEAUD – Research engineer (postdoc)
* Johannes GOUPY – Research expert (postdoc)
* Alessandro FASANO - PhD Started 10/2017

Juan MACIAS-PEREZ – Director of research
Andrea CATALANO – Researcher
Olivier BOURRION – Research engineer
Frédéric MAYET – Lecture
Laurence PEROTTO – Researcher
* Florian RUPPIN – PhD Started 10/2015

Karl SCHUSTER – Director
Eduard DRIESSEN – Scientist
Samuel Leclerq - Scientist
* Shibo SHU – PhD Started 10/2016

François-Xavier DESERT – Astronomer / Director
Nicolas PONTHIEU – Researcher
* Aina ANDRIANASOLO – PhD Started 10/2016

Outline

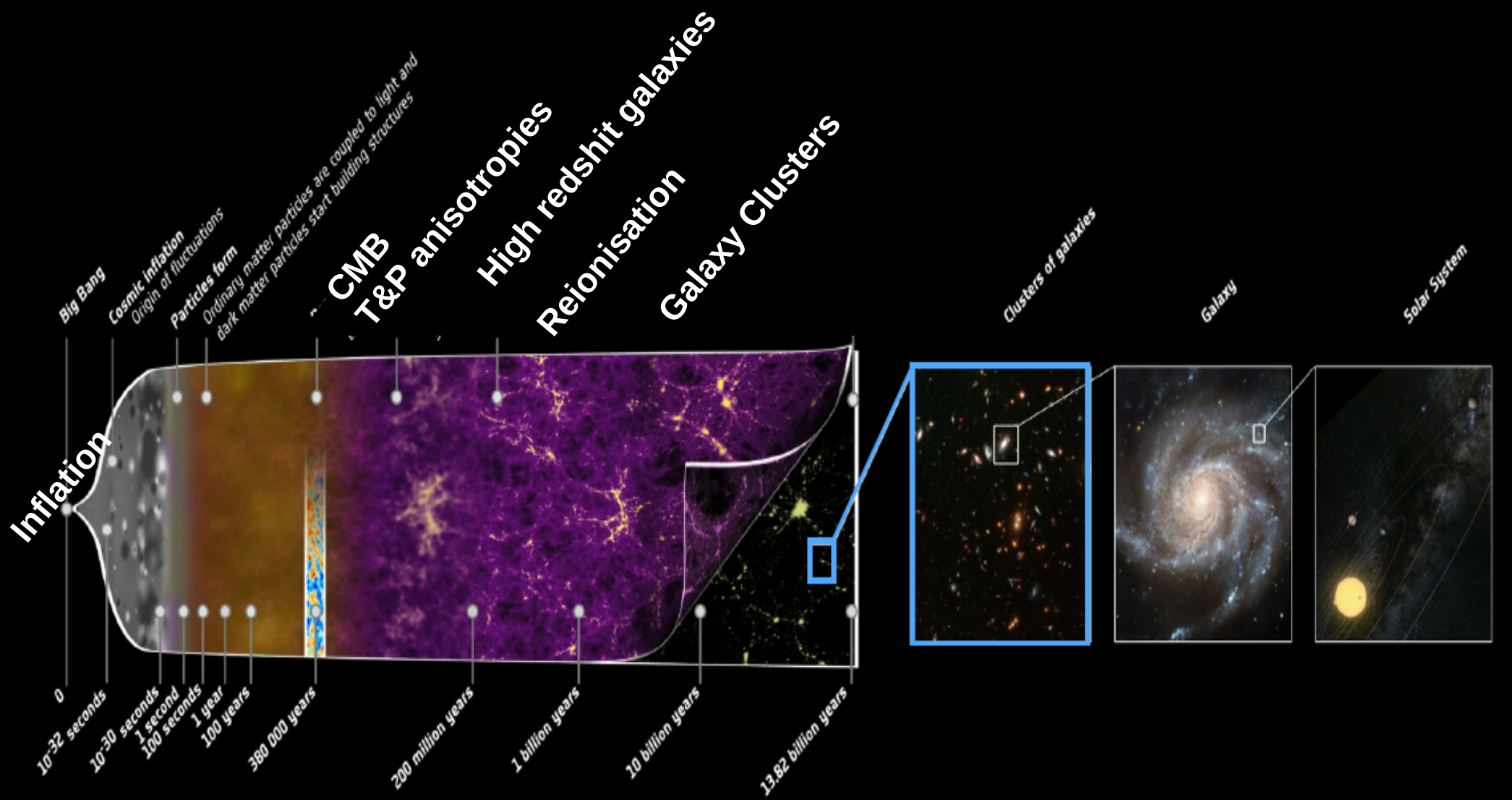
I. From cosmology/astrophysics challenges to instrumental requirements at mm wavelengths

II. Kinetic Inductance Detectors for the new generation of mm cameras

III. The NIKA2 camera for cluster cosmology

IV. Large wide-field mm spectroscopy with KIDs

Brief history of the Universe



Main science drivers at mm wavelenths

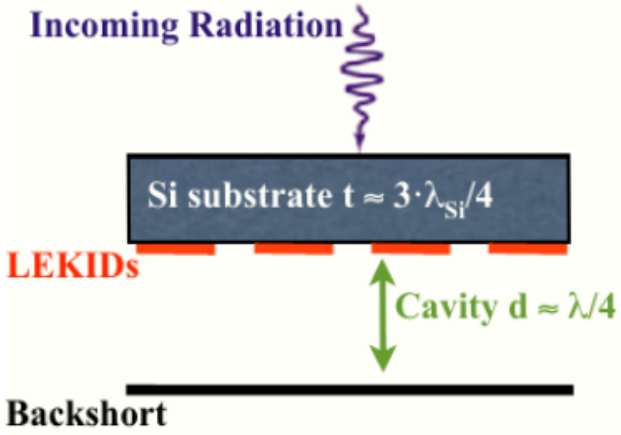
- Detection of primordial CMB B-modes polarisation anisotropies (primordial grativational waves) to measure the energy scale of inflation
- Detailed measurement of the Sunyaev-Zeldovic effect in clusters of galaxies to obtain independent and complementary cosmological constraints
- Deep observations of distant galaxies in cosmological fields (COSMOS, GOODS, etc) to the confusion limit
- Detailed understanding of the reionization processes (stellar mass function) at high redshift via spectroscopic observations
- Multi-color continuum observations of Galactic and extra-Galactic sources at high resolution over a wide-field to measure the dust mass and infer star formation

From science to technological requirements

	Requirements
B-Modes **Spectral distortions**	high sensitivity for low r values multi-frequency for foreground removal Wide-field high sensitivity spectroscopic camera
SZ Effect	high resolution, high sensitivity mapping of distant clusters spectroscopy measurements of nearby clusters mapping thermodynamic properties
Re-ionisation	measurements of molecules lines at high red-shift high sensitivity mapping large sky areas

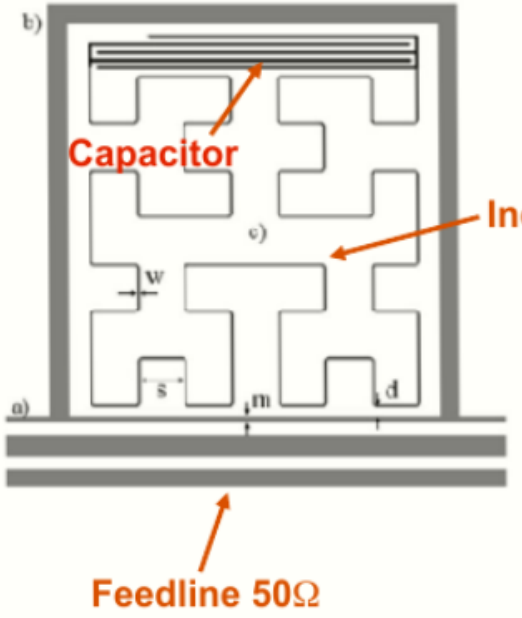
Large high sensitivity detector arrays are needed !!

Kinetic Inductance Detectors (KID)



Dual Polarisation
(3rd-order Hilbert pattern)

Roesch, M. et al. 2012, ArXiv 1212.4585



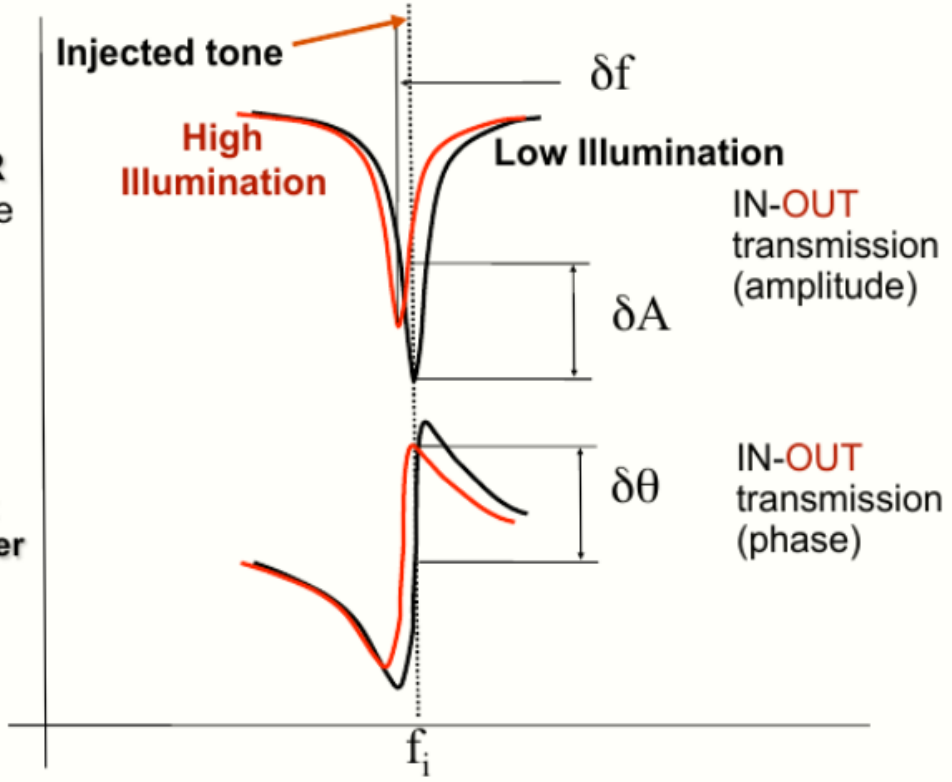
The incoming photons break Cooper pairs (supercurrent carriers) in a superconducting LC resonator → measurable signals

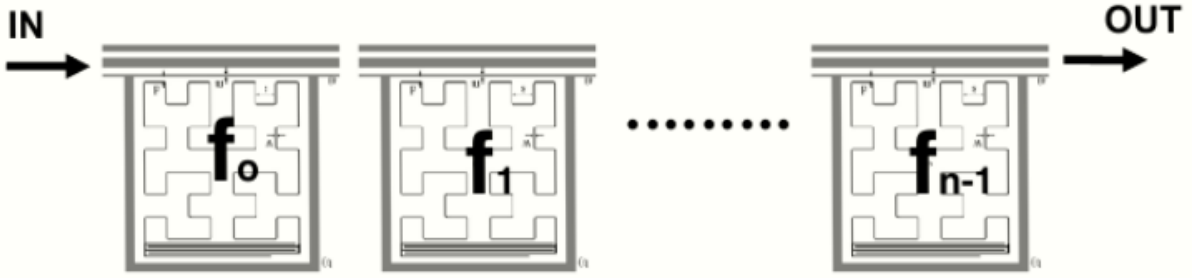
Dark, T << T_c

Light: **increase in R**
Change in amplitude (ΔA) and phase

$\delta f \propto \delta L_K \propto \delta P$

δf = frequency shift
δP = incoming power





Why KIDs?

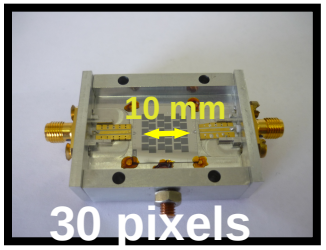
- ✔ Direct multiplexing (300 detectors or more)
- ✔ Can adapt to low and high background: from ground to satellite experiments
- ✔ Fast response (time constant << 1 ms)
- ✔ *Not too sensitive to comic-rays hits*
- ✔ Large spectral coverage: frequency range from 70-1000 GHz
- ✔ High sensitivity in intentsity and in polarisation
- ✔ Cheap to fabricate and if possible to do it at home

Brief Grenoble KID+readout history

2000
KID Concept
(Caltech-JPL)

NIKA0

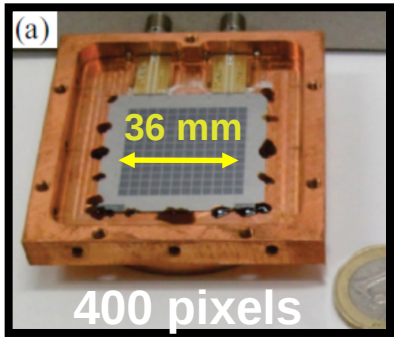
2009



NIKA1

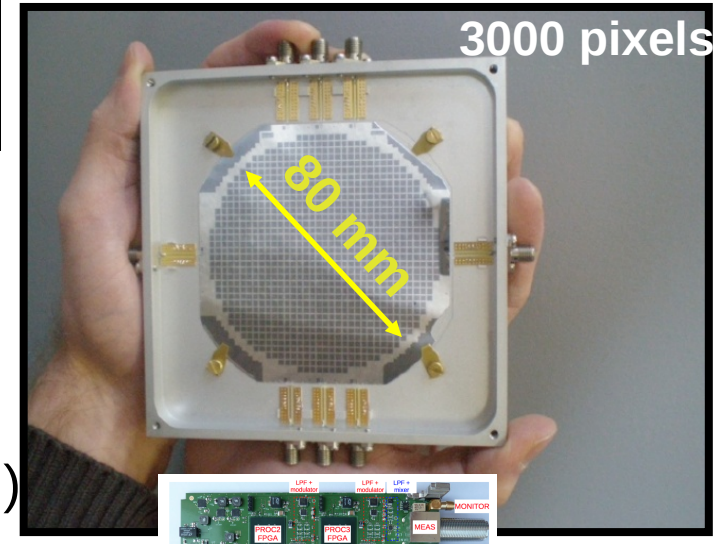
x 2

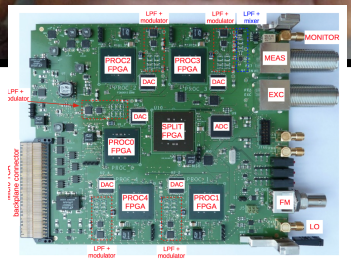
2010-2013



NIKA2

2014-2017





x 20

2008

We “join” the KID community

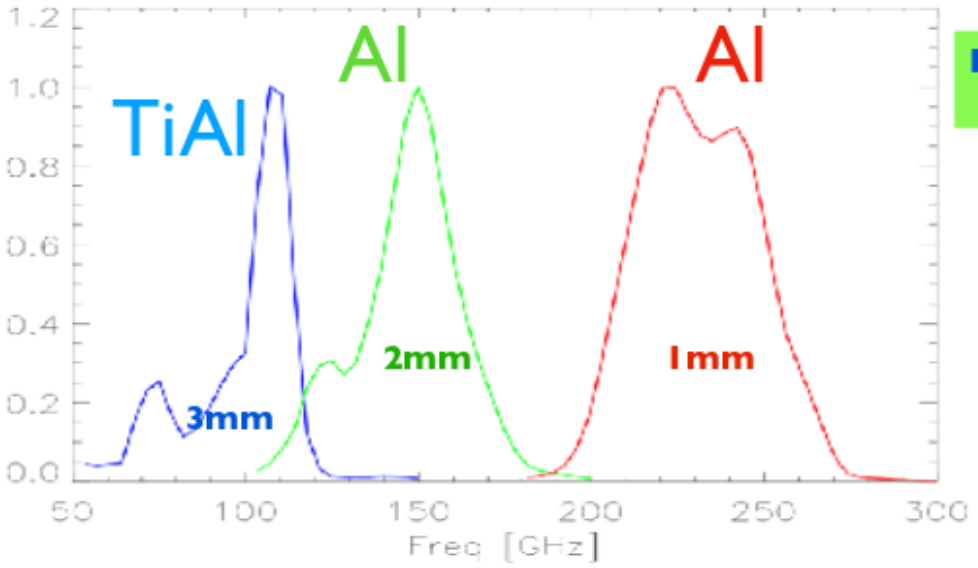
2009

30 pixels → NIKA0 (first ever KID camera)

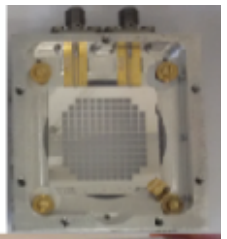
2014 - 2017

- Background-limited **(NEP < 10^{-17} W/$Hz^{0.5}$)**
- Readout line 2.5 m long !! Litho !!
- Al high-quality, uniform thickness film (≈10nm)

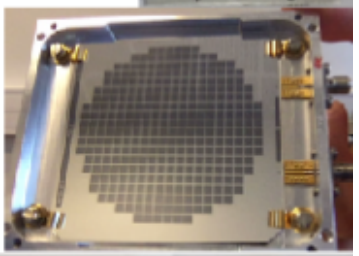
KID spectral response

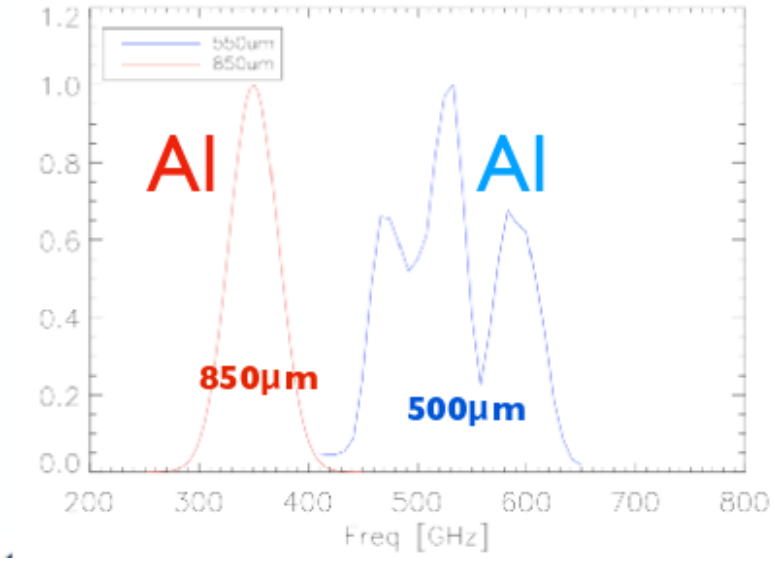


LEKID Demonstrators for space (132pix)
3mm - 2mm - 1mm - 850µm - 500µm

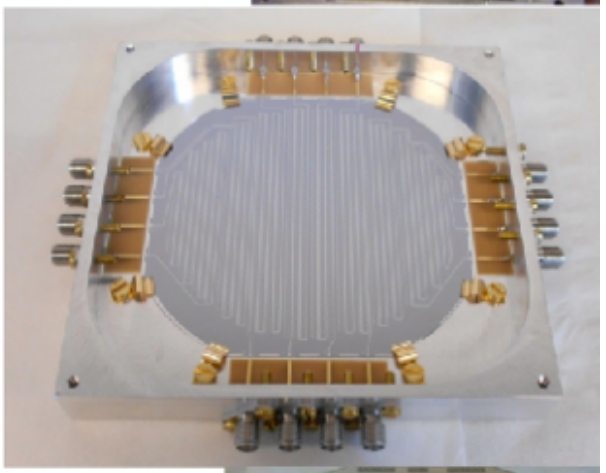


LEKID Array for KISS Interferometer (300pix) TiAl@3mm

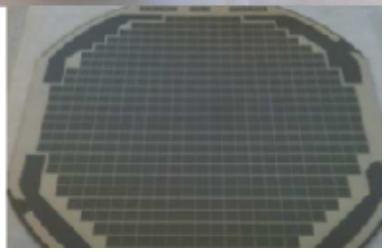




LEKID Array for NIKA2 (2000pix) Al@3mm

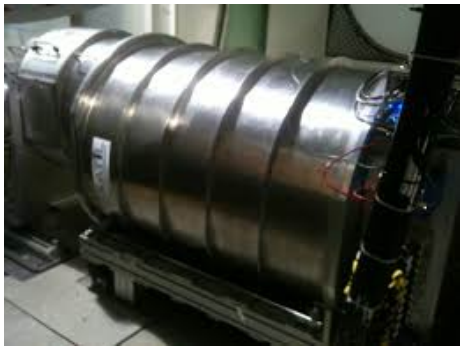


LEKID Array for Ballon (500 pix) Al@500µm

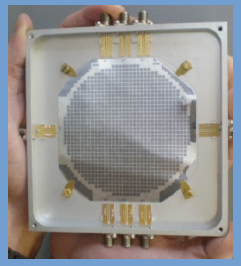


A bit more than just KID arrays

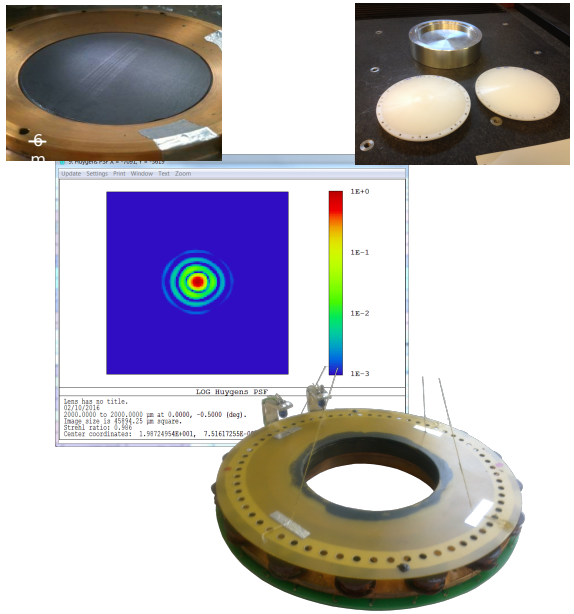
Cryogenics



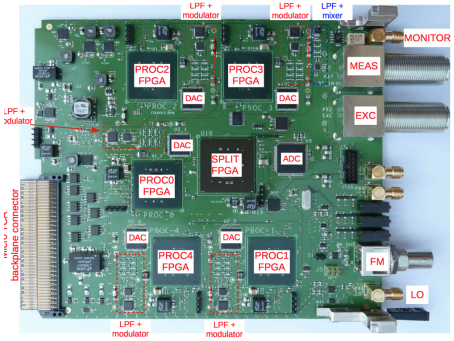
KID array



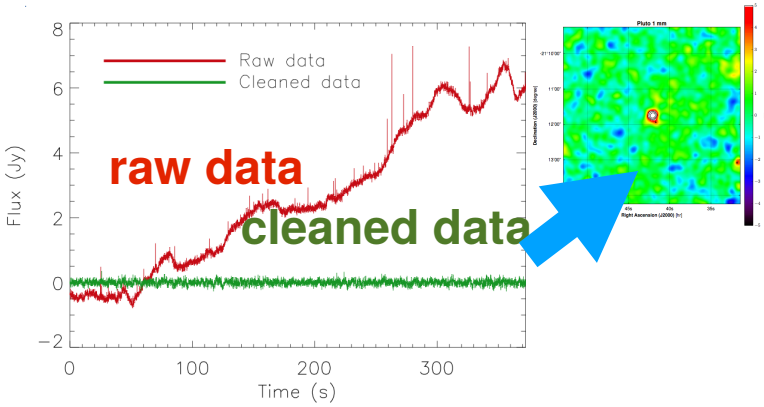
Optics



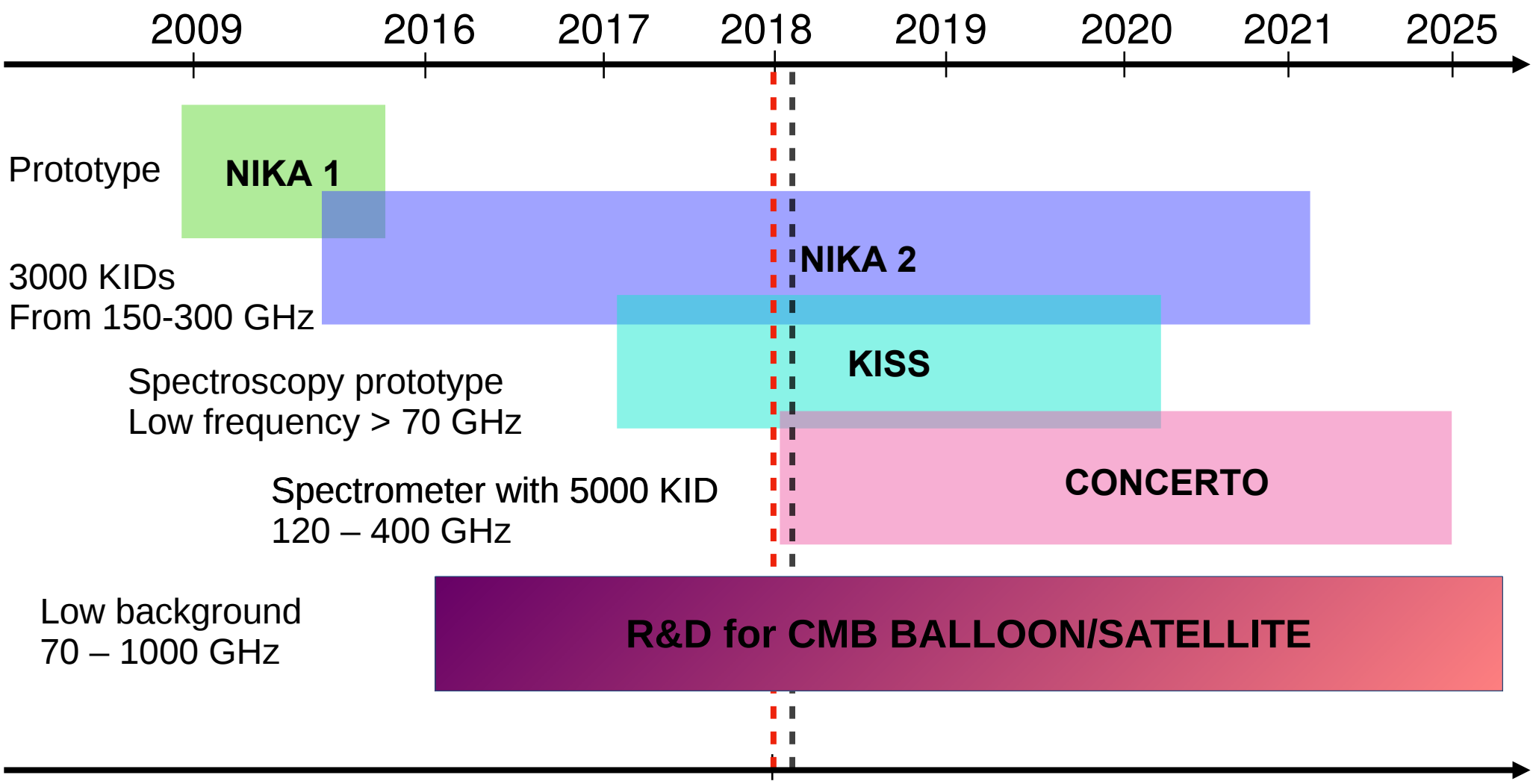
Electronics



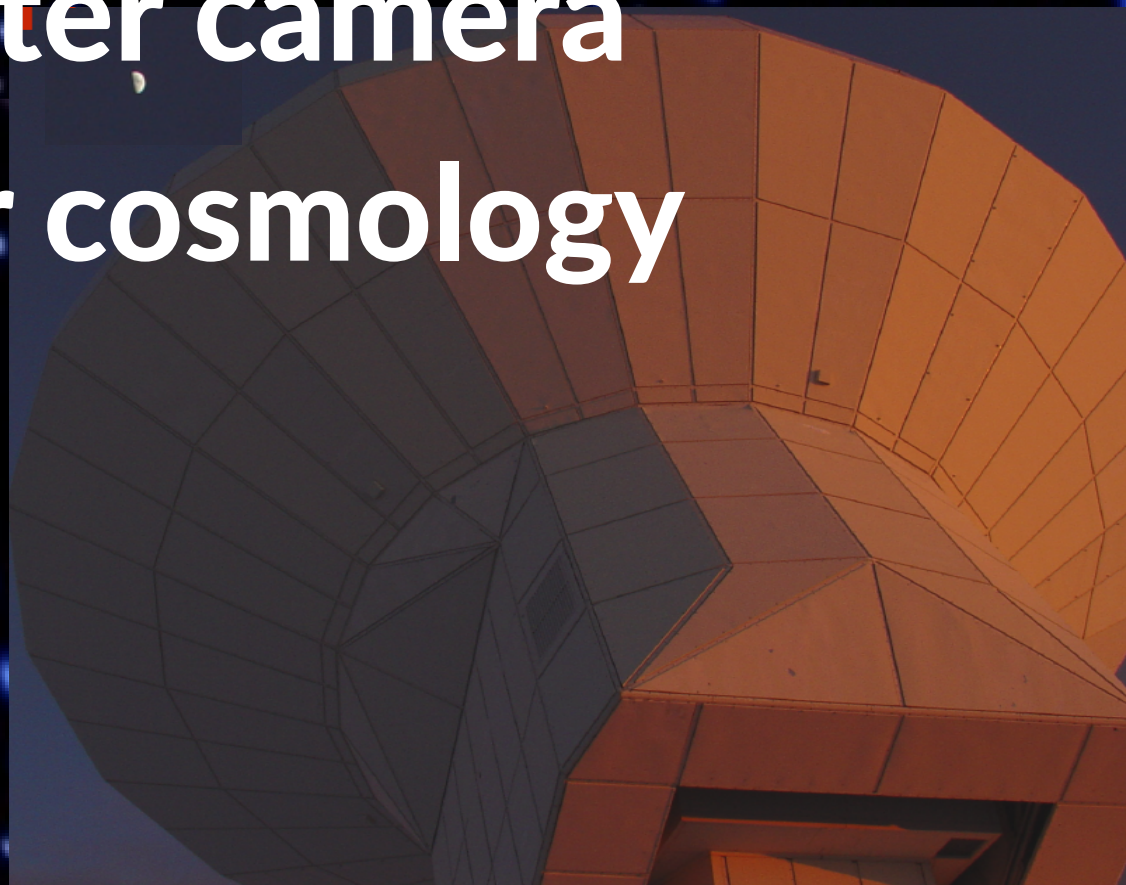
Data analysis



Technical developments driven by instruments



NIKA2
a millimeter camera
for cluster cosmology



NIKA

http://ipag.osug.fr/nika2

Benoît Alain
Calvo Martino
Barria Emilio
Bres Guillaume
Donnier-Valentin Guillaume
Exshaw Olivier
Garde Gregory
Goupy Johannes
Grollier Maurice
Hoaurau Christophe
Leggeri Jean-Paul
Levy-Bertrand Florence
Monfardini Alessandro
Triqueneaux Sebastien
D'Addabbo Antonio

Bacmann Aurore
Ceccarelli Cecilia
Désert François-Xavier
Hily-Blant Pierre
Ponthieu Nicolas

Billot Nicolas
Gueth Frédéric
Hermelo Israel
Kramer Carsten
Navarro Santiago
Sievers Albrecht
Adane Amar
Coiffard Grégoire
Leclercq Samuel
Pety Jerome
Schuster Karl
Zylka Robert

Adam Rémi
Angot Julien
Bourrion Olivier
Catalano Andrea
Comis Barbara
Dargaud Guillaume
Macias-Perez Juan-F.
Geraci Calogero
Mayet Frédéric
Menu Johann
Pelissier Alain
Perotto Laurence
Ritacco Alessia
Roni Samuel
Roudier Sébastien
Scordillis Jean-Pierre
Tourres Damien
Vescovi Christophe

Abergel Alain
Aghanim Nabila
Aumont Jonathan
Beelen Alexandre
Boulanger François
Bracco Andrea
Dole Hervé
Douspis Marian
Martino Joseph
Miniussi Antoine
Pajot François
Soler Juan

André Philippe
Arnaud Monique
Aussel Hervé
Daddi Emanuele
Duc Pierre-Alain
Elbaz David
Galliano Frederic
Konyves Vera
Lebouteiller Vianney
Madden Suzanne
Maury Anaelle
Melin Jean-Baptiste
Motte Frederique
Pratt Gabriel
Revéret Vincent
Rodriguez Louis

Savini Giorgio

Belier Benoît

Omont Alain
Roussel Hélène

Bernard J.-Ph.
Dernyk Karine
Hugues Annie
Montier Ludovic
Paradis Deborah
Pointecouteau Etienne
Ristorcelli Isabelle

Ade Peter
Bideaud Aurélien
Castillo Edgard
Davies Jonathan
Doyle Simon
Eales Steve
Mauskopf Phil
Parise Berangere
Pascale Enzo
Peretto Nicolas
Tucker Carole

Bethermin Matthieu

D'Addabbo Antonio
de Petris Marco

Lagache Guilaine

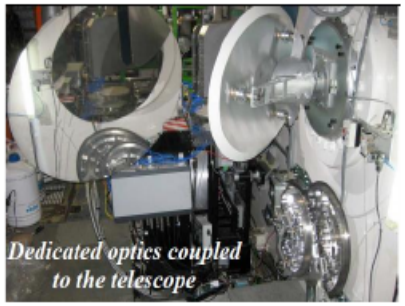
also financed by

The NIKA2 camera

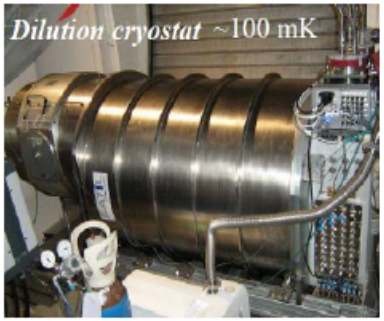
Dual band mm KID camera operating and 150 and 260 GHz

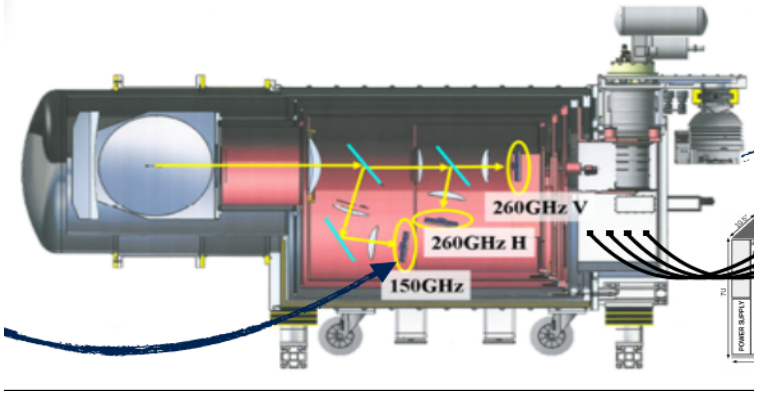
IRAM 30-m telescope
at Pico Veleta (Spain)

Specific optical system to obtain the widest field



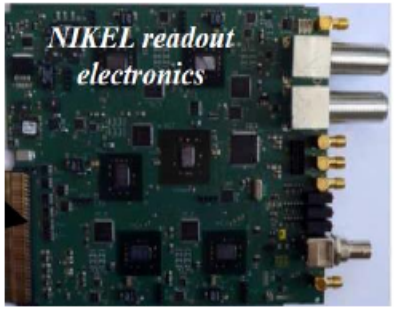
Dilution cryostat: 180 mK nominal temperature





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

300 multiplexing factor



20 boxes (one per feedline) arranged in 3 crates (one per array)

The NIKA2 camera

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

Frequency	150 GHz	260 GHz
# KIDs	616 (553)	2 x 1140 (960)
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	8±1 mJy/s$^{1/2}$	33±2 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

[NIKA collaboration, Adam et al, 2018]

Science with NIKA2

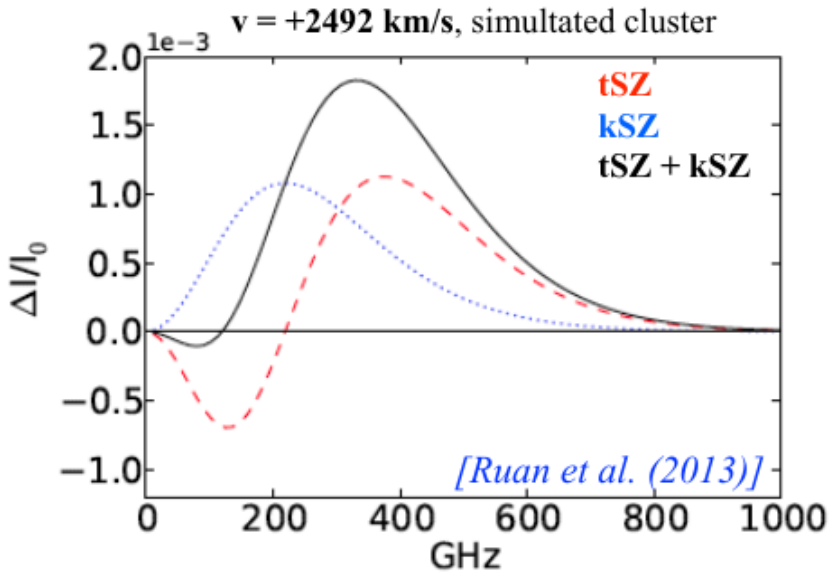
- Multi-purpose camera open to the astrophysical community
- Open time observations for at least one decade (already 4 campaings)
- The NIKA2 collaboration has been awarded 1300 hours of GT shared between 5 Large programs for astrophysics and cosmology:
  - Galactic studies in intensity and polarisation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

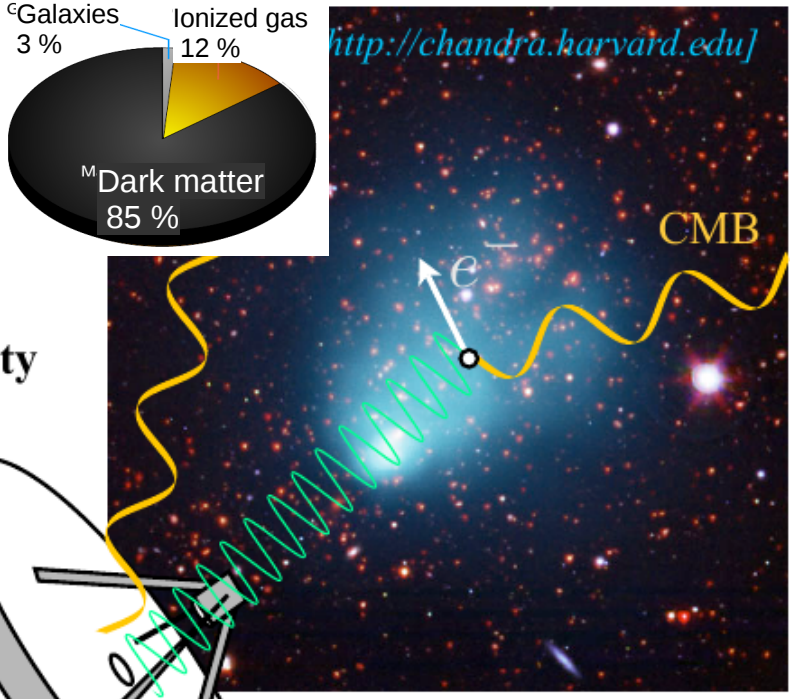
Sunyaev-Zeldovich effect

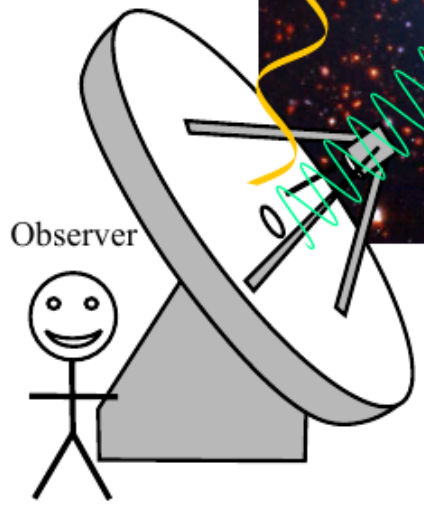
- **tSZ** = CMB spectral distortion from interaction with clusters' hot electrons
- **kSZ** = CMB Doppler shift from bulk motion of electrons (typically ~ tSZ/10)

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

$$\begin{cases} y_{\rm tSZ} = \dfrac{\sigma_{\rm T}}{m_e c^2} \displaystyle\int P_e \, d\ell & \Rightarrow \text{Pressure} \\ y_{\rm kSZ} = \sigma_{\rm T} \displaystyle\int \dfrac{-v_z}{c} n_e \, d\ell & \Rightarrow \text{Velocity x density} \end{cases}$$





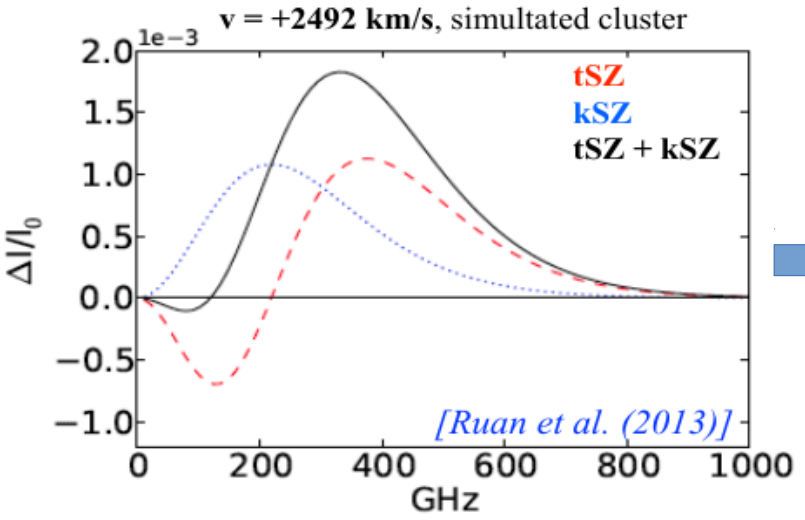


No cosmological diming

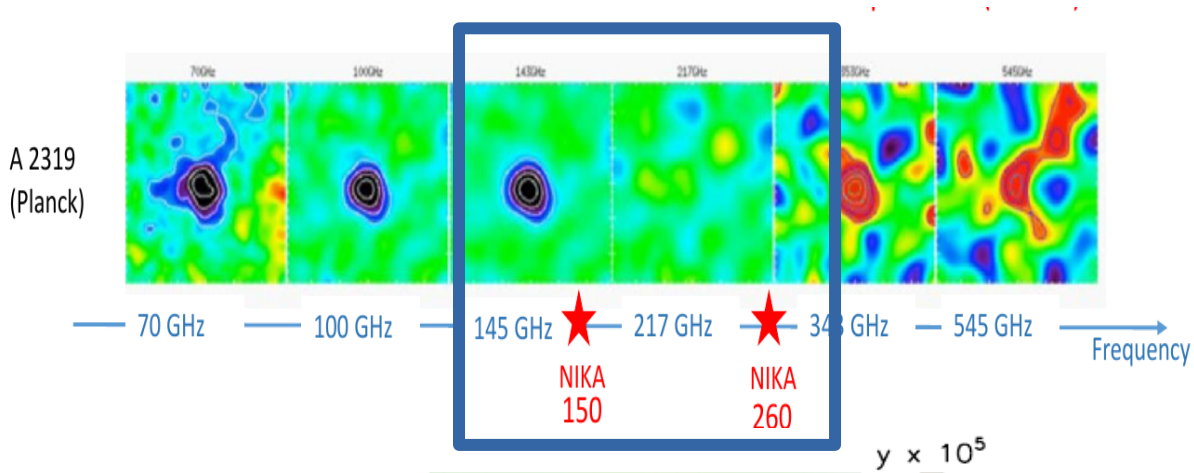
➡ **SZ = probe for intracluster gas**

SZ effect with NIKA2

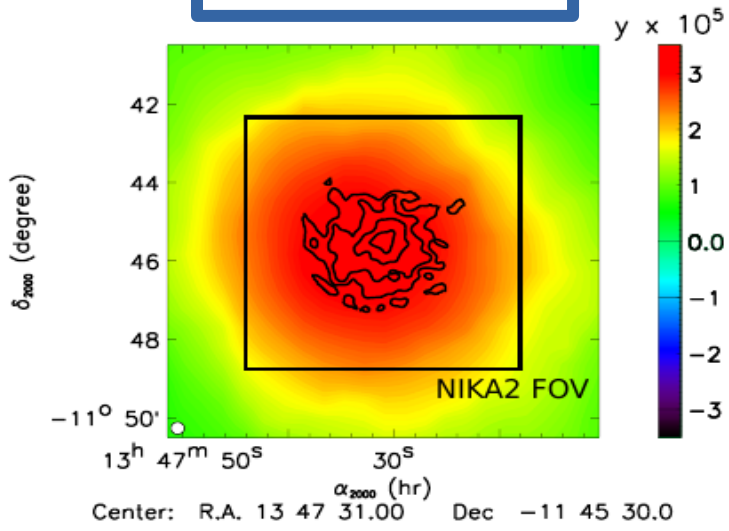
NIKA2 is a perfect instrument for the tSZ effects in clusters of galaxies



Two frequency bands, negative & zero tSZ signal

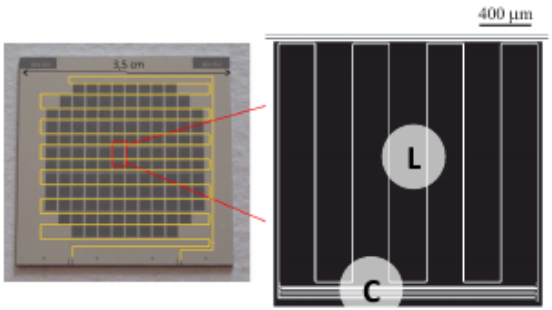


- Wide-field: size of PLANCK beam
- High resolution : 17 times better than Planck



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



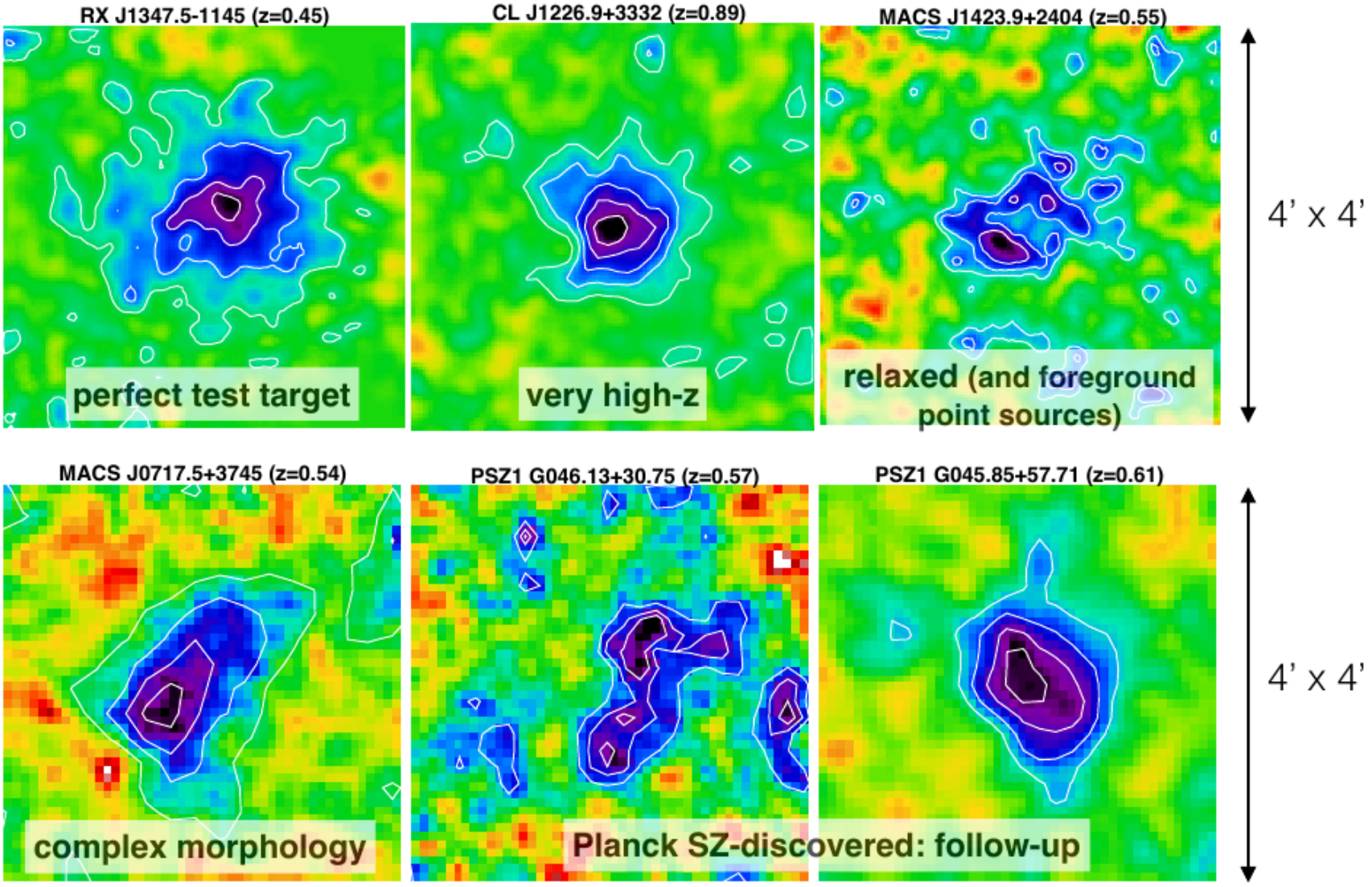
NIKA	150 GHz	260 GHz
# KIDs	132	224
FOV diameter	1.8 arcmin	2.0 arcmin
Sensitivity	14 mJy/s$^{1/2}$	40 mJy/s$^{1/2}$
Angular res.	18 arcsec	12 arcsec

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

NIKA2	150 GHz	260 GHz
# KIDs	616	2 x 1140
FOV diameter	6.5 arcmin	6.5 arcmin
Sensitivity	6 mJy/s$^{1/2}$	20 mJy/s$^{1/2}$
Angular res.	17.7 arcsec	11.2 arcsec

[NIKA2 collaboration, 2017]

SZ pilot sample for cluster physics



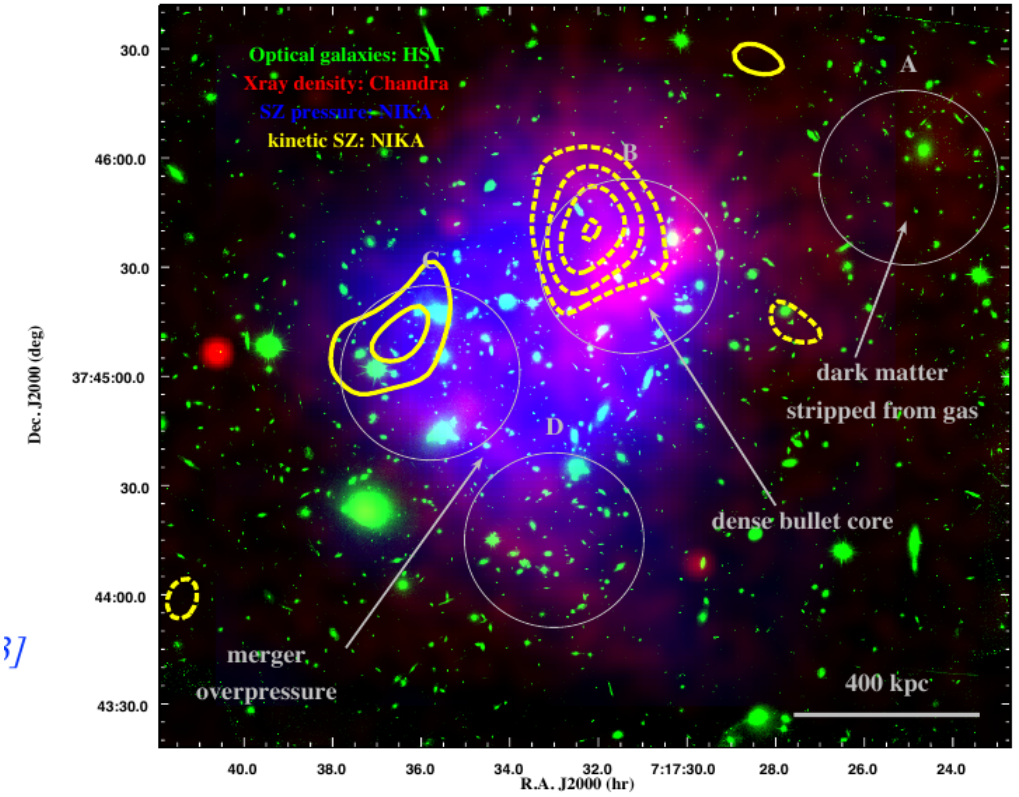
[Adam & NIKA collaboration, 2014, 2015.2016,2017 Ruppin & NIKA collaboration 2017, Romero & NIKA collaboration 2017]

MACS J0717-3745 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

MACS J0717-3745



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

spectral dependencies

gas pressure — *gas velocity and density*

[Adam & NIKA collaboration, 2016]

MACS J0717-3745 and kSZ

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  + High quality X-ray, optical and IR data
- However, mapping kSZ is very challenging:

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  Degeneracy relativistic tSZ and kSZ
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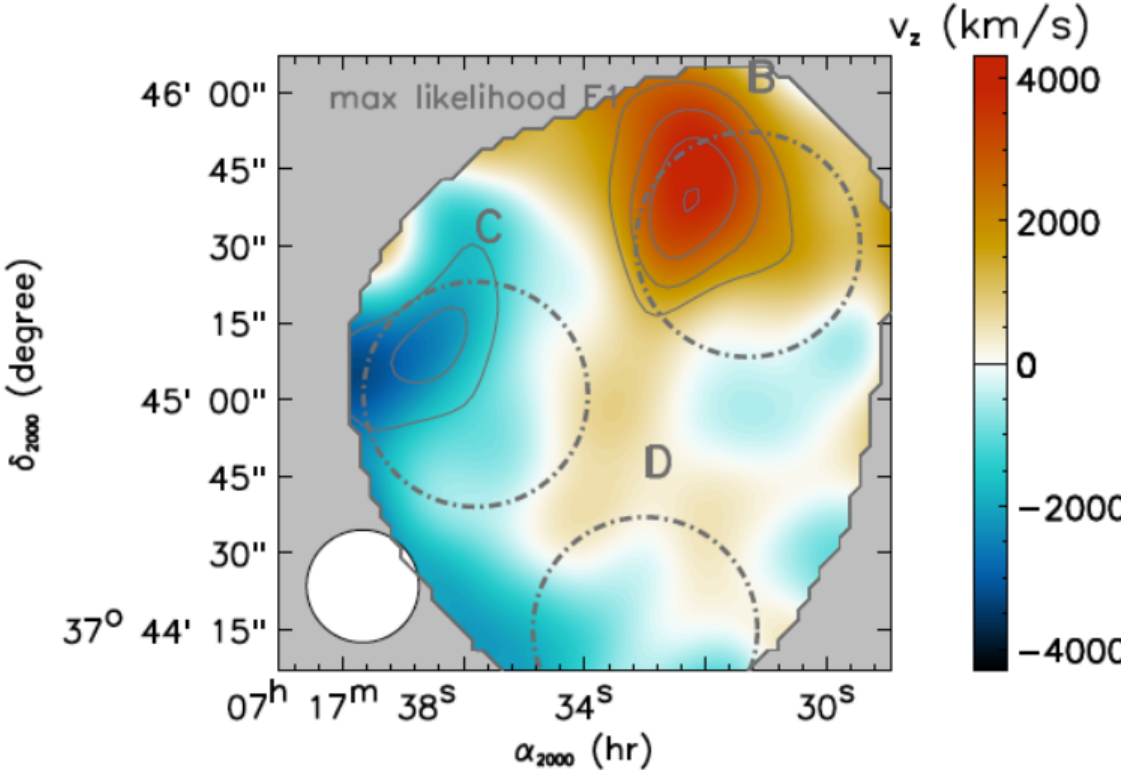
spectral dependencies

gas pressure

gas velocity and density

MACS J0717-3745



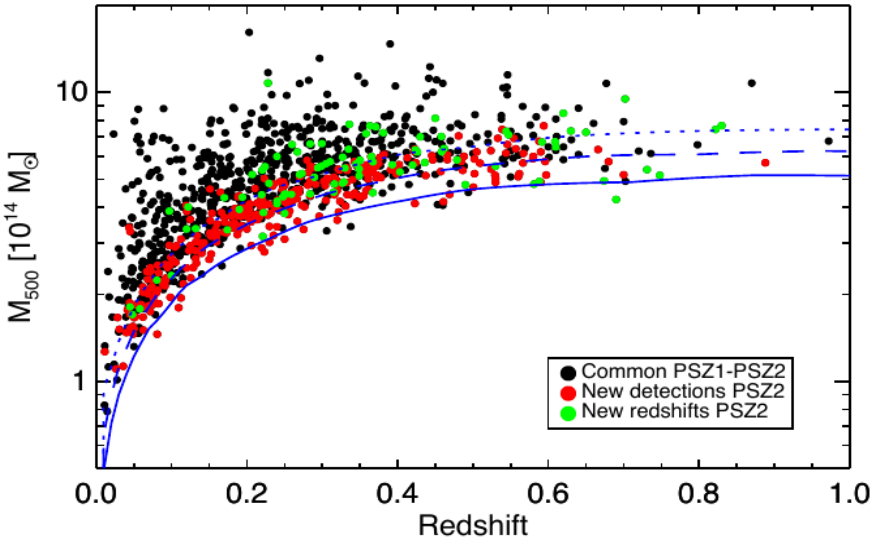
First direct mapping of kSZ emission

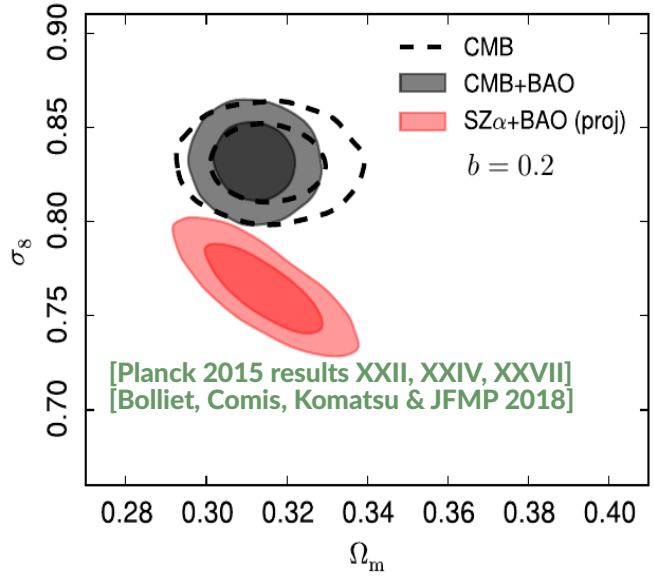
[Adam & NIKA collaboration, 2016]

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})
- Charaterisation 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 comology

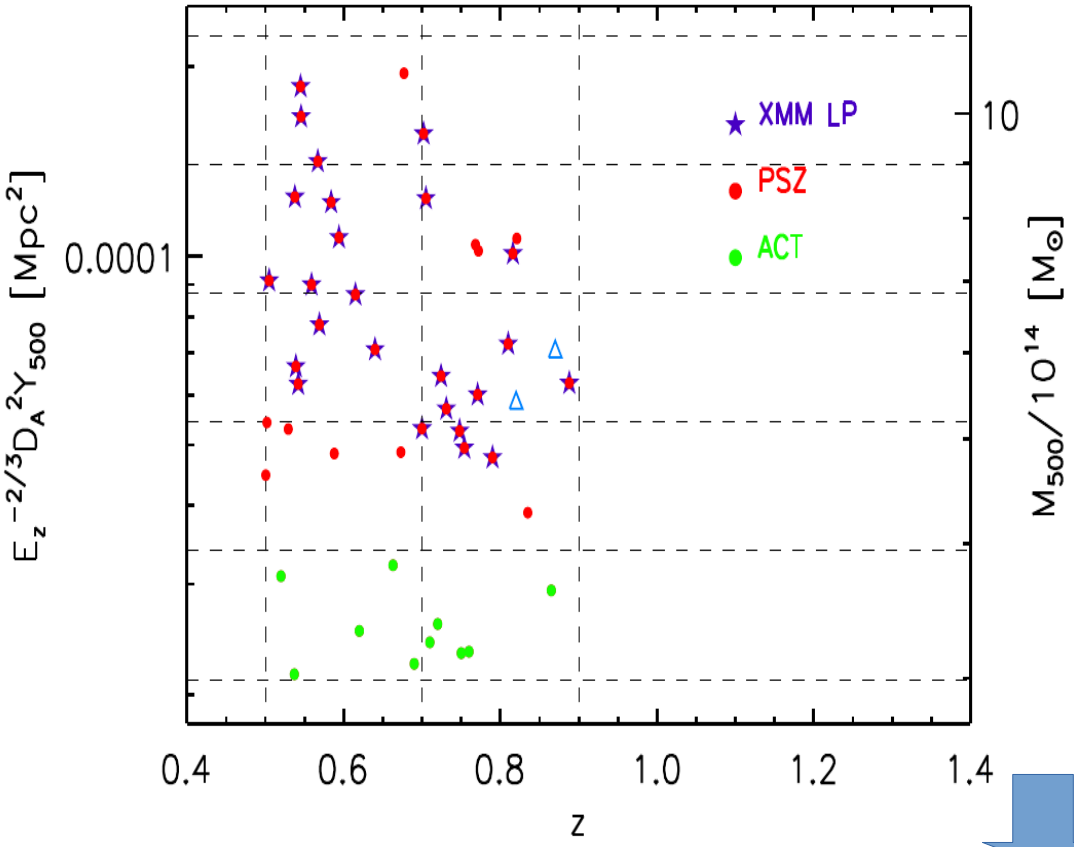




2-σ tension between CMB and tSZ (cluster observable) derived cosmological parameters

Need to understand cluster physics: hydrostatic bias, condition for hydrostatic equilibrium, shocks in the ICM, non thermal pressure, ...

NIKA2 SZ Large program



One of the 5 NIKA2 LP (1300h 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

- In-depth study of ICM
- Thermodynamic properties: pressure, density, temperature and entropy profiles
- Mass – tSZ flux relationship

Redshift evolution of:

- Thermodynamic quantities profiles
- Scaling laws and hydrostatic bias

Variation of cluster properties with:

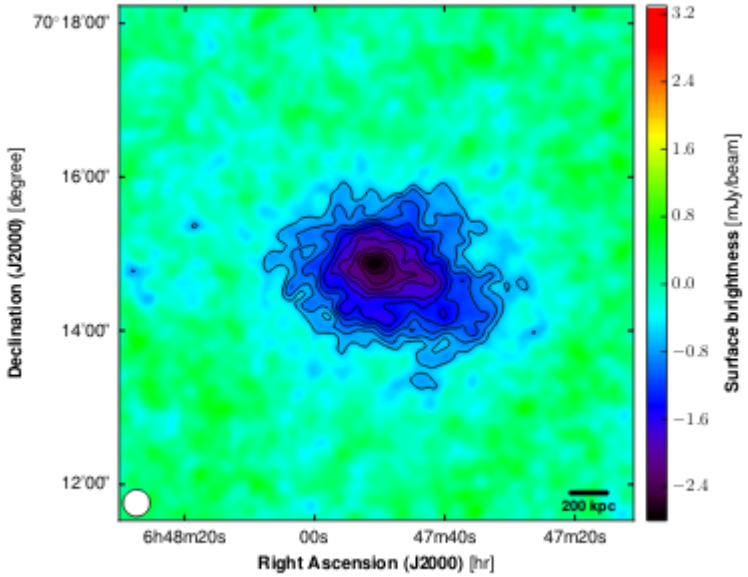
- Dynamical state (mergers)
- Morphology (ellipticity)

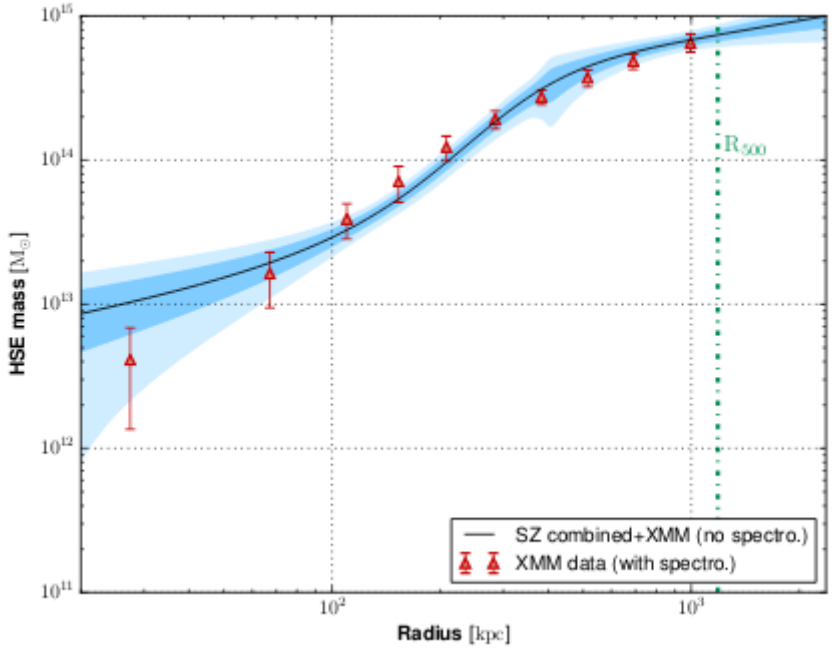
[JFMP & NIKA2 collaboration 2017, arXiv:171107088]

First NIKA2 SZ cluster

PSZ2 G144 [Ruppin et al, AA, 2018]

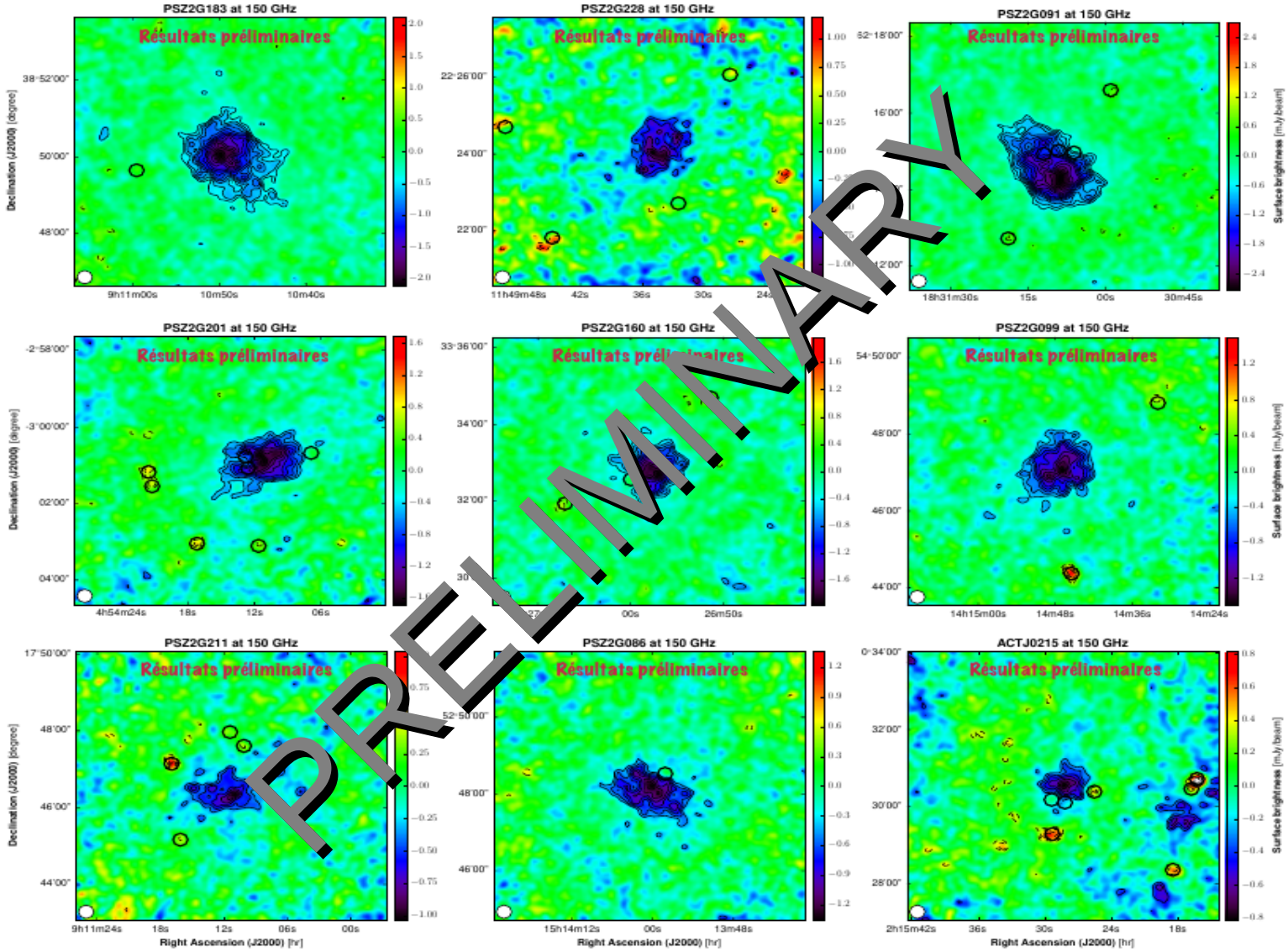
- Planck tSZ detected cluster at redshift, z = 0.58, high mass M_{500} = 7.8 x 10^{14} $M_{\odot}$
- 11h observations with NIKA2 in poor weather conditions (atmospheric opacity 0.3@225 GHz)
- Already observed: SZ – MUSTANG & Bolocam, X-rays - XMM





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

Observed NIKA2 LP clusters



Coming soon

KISS

Measure physical properties of nearby cluster via the SZ effect

Low resolution MP spectrometer from 70 to 260 GHz

600 KIDs @ QUIJOTE telescope in Teide Observatory

Installation expected in November 2018

CONCERTO

Intensity mapping of CII lines at high redshift to measure SFR + detection of clusters with SZ

Low resolution MP spectrometer from 120 to 350 GHz

5000 KIDs @ APEX telescope in Atacama

Installation expected in 2021

Summary and conclusions

- Current science drivers in mm astronomy and cosmology needs high sensitivity and wide-field multi-color observations with large arrays of detectors
- KIDs have achieved sufficient technical maturity to be a credible option to build those large arrays (tens of thousands pixels) of photon noise limited detectors
- NIKA first and now NIKA2, have demonstrated that KID based mm cameras can achieve state-of-art performance for astrophysics and cosmology
- Cluster physics and cosmology via the SZ effect are a target of choice for KID cameras
- We are developping a new generation of KID based mm spectrometers that should be on the sky very soon
- KID based mm instruments are emerging: AMKID, Olympo, DESHIMA, MUSCA, GroundBird, KISS, Concerto, MKIDs for Nobeyama (Nitta-san talk)