NIKA and NIKA2: from the pathfinder KID camera to the ultimate mm-wave imaging/polarimetry at the 30-meters Pico Veleta telescope

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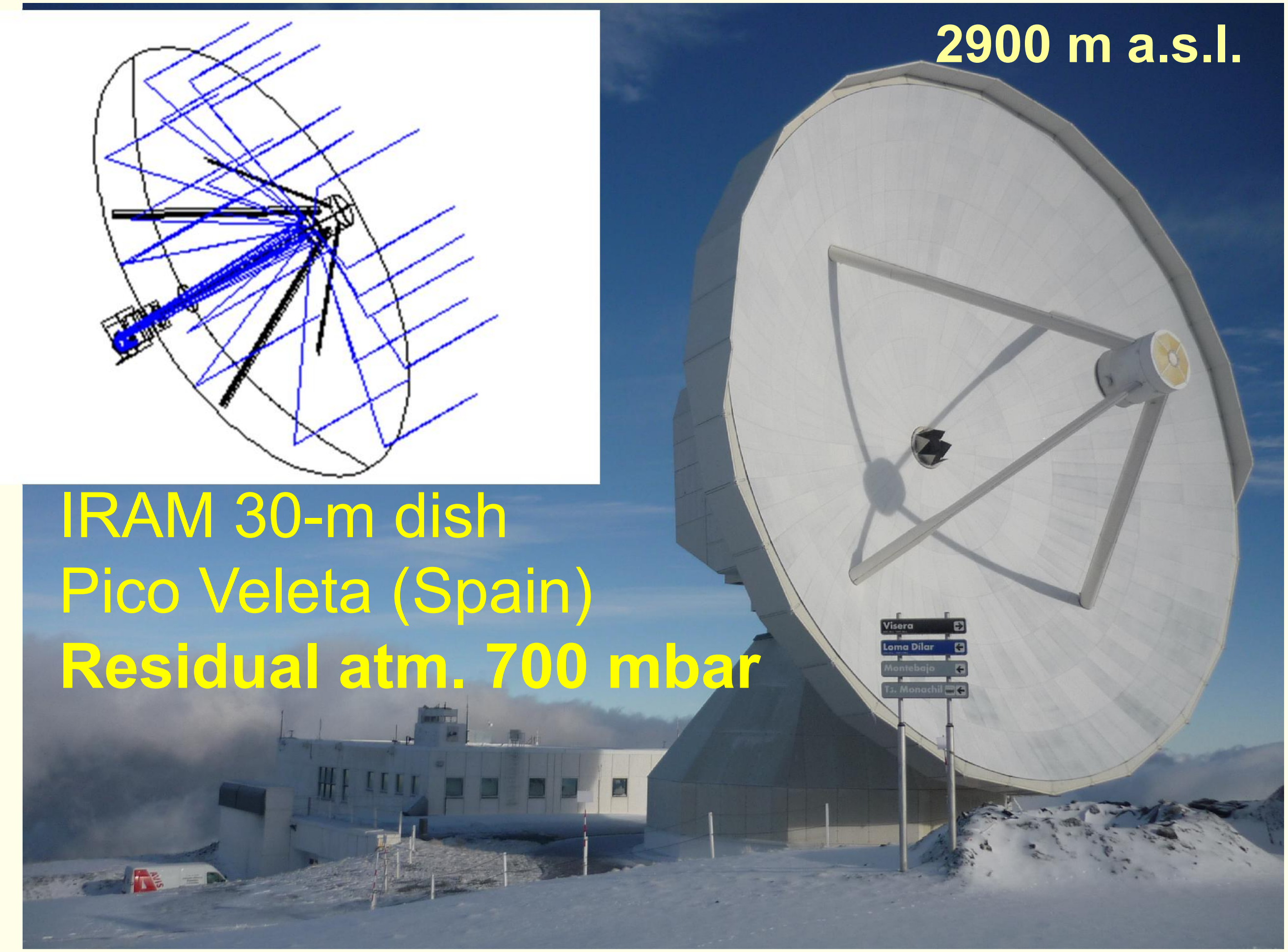
Institut Néel – LPSC – IPAG – IRAM (Grenoble)
For the NIKA2 collaboration

Other collaborations including APC (M. Piat, A. Tartari, D. Prele and the mm group)

"Our" mm-wave telescope



Working Bands:

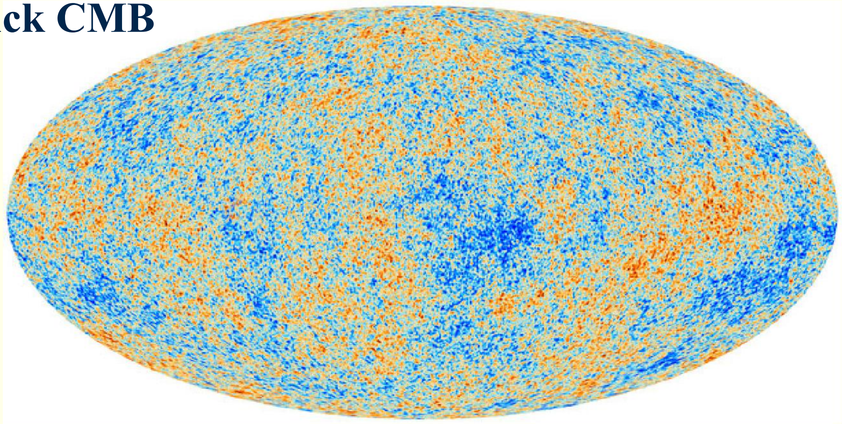
3mm (100GHz)
2.05mm (146 GHz)
1.25mm (240 GHz)
0.87mm (345 GHz)

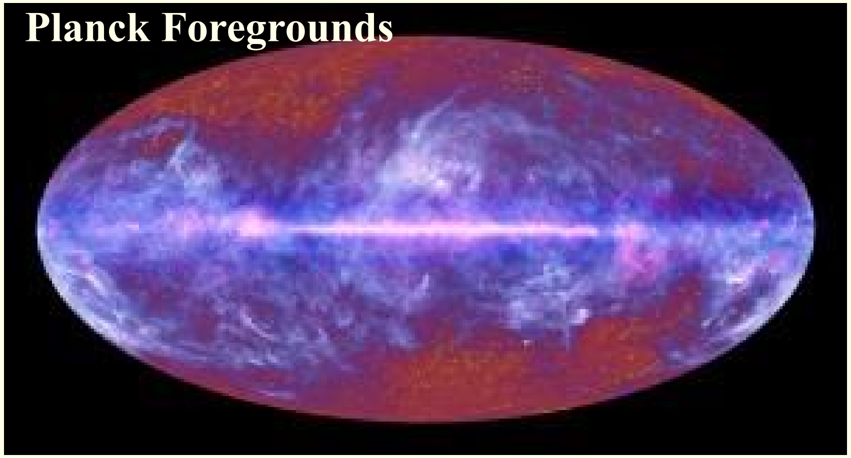
IRAM, based in Grenoble, was founded in 1979 by the French CNRS, the German MPG (Max-Planck-Gesellschaft) and the Spanish IGN (Instituto Geográfico Nacional).

IRAM = Institute for Millimetric RadioAstronomy

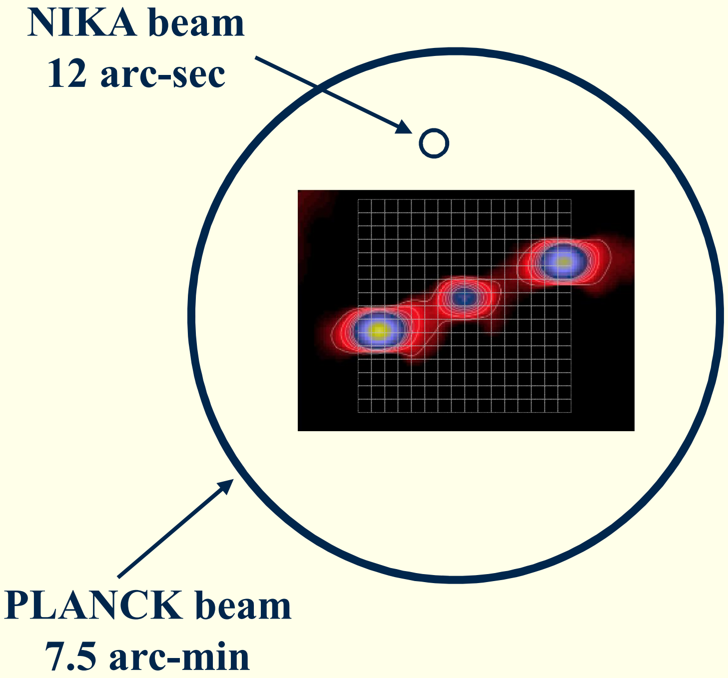
Sensitivity + Angular resolution

Planck CMB





The faintest compact sources seen by Planck are detected in $T_{integration}$ < 1 sec by NIKA-2



Ultra-sensitive cameras

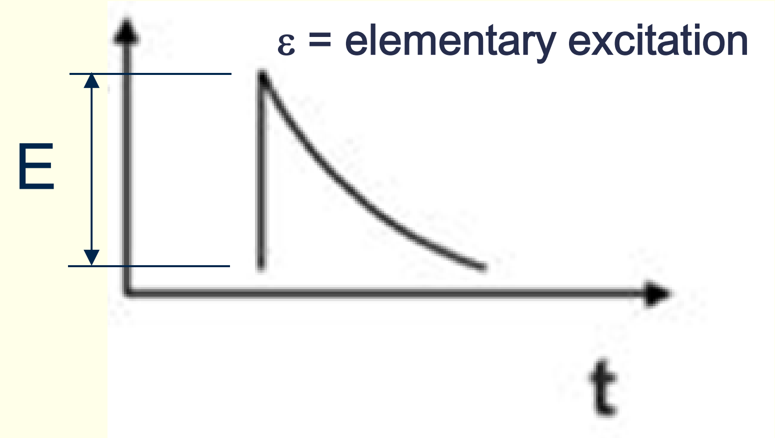
SUB-KELVIN DETECTORS REQUIRED

NEEDS:

- detecting/measuring **tiny amounts** of power (e.g. $aW/Hz^{0.5}$)
- build **thousands pixels** cameras ≡ efficient **multiplexing**

Why low temperatures ?

Whole point is to reduce the energy associated to the "elementary excitation".



$\Rightarrow$ N = E/ε
$\Rightarrow$ √N = √ E/ε
$\Rightarrow$ Energy Resolution ∝ √ ε
$\Rightarrow$ ε to be MINIMIZED

→ Cooper-pair-breaking detectors (gap ≈ 3.5·kT_c)

→ Bolometers (phonon energy ≈ kT)

Big advantage of bolometers: working temperature is a "free" parameter

Big advantage of pair-breaking detectors: design not driven by thermal constrains

Independent "practical" limitation: multiplexing

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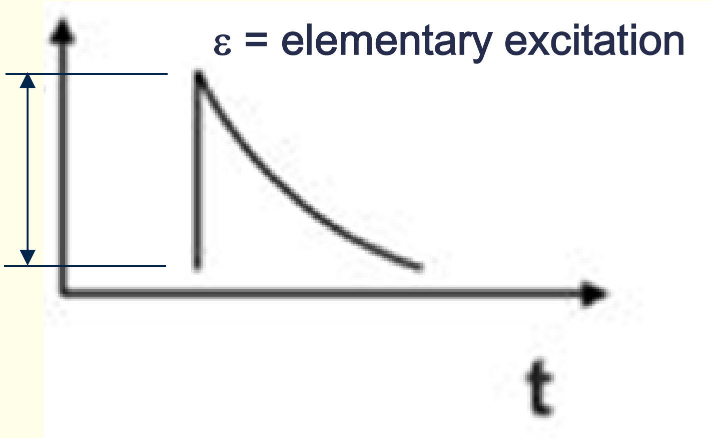
Whole point is to reduce the energy associated to the “elementary excitation”.



$\Rightarrow N = E/\varepsilon$

$\Rightarrow \sqrt{N} = \sqrt{E/\varepsilon}$

$\Rightarrow$ Energy Resolution $\propto \sqrt{\varepsilon}$

$\Rightarrow$ ε to be MINIMIZED

→ Cooper-pair-breaking detectors (gap ≈ $3.5 \cdot kT_c$) $T_{base} << T_c$

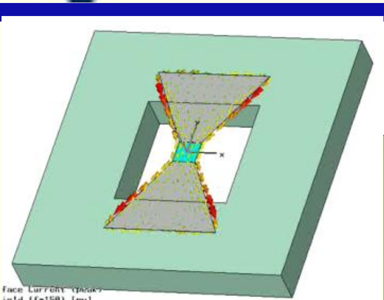
→ Bolometers (phonon energy ≈ kT)

Big advantage of bolometers: working temperature is a “free” parameter

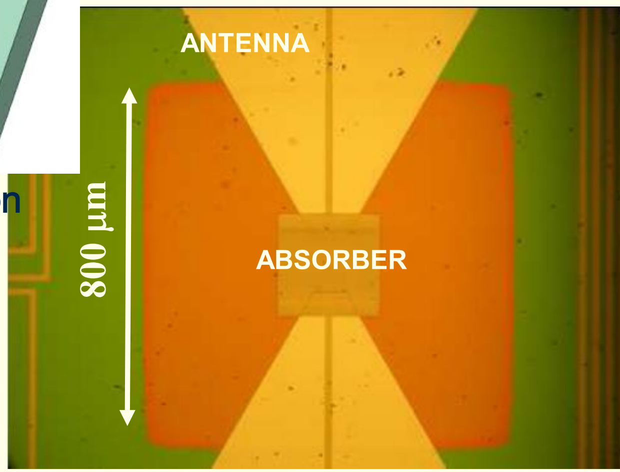
Big advantage of pair-breaking detectors: design not driven by thermal constrains

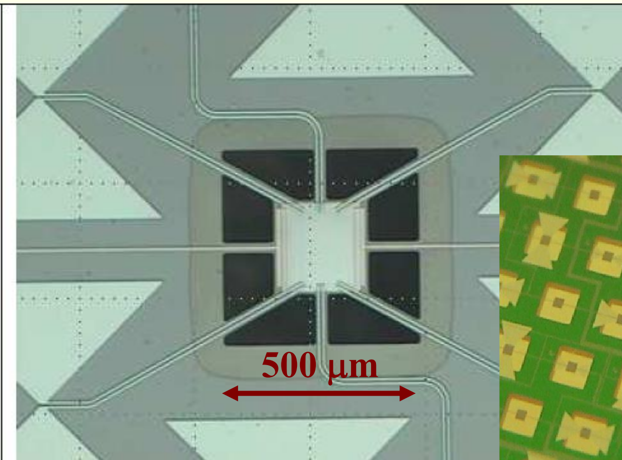
Independent “practical” limitation: multiplexing

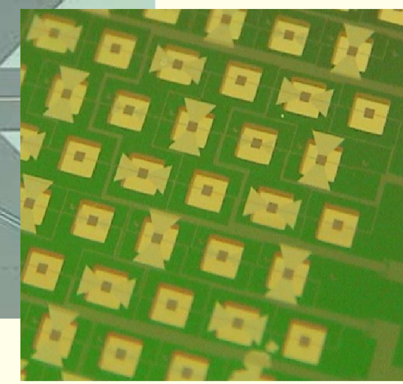
Classical approach: bolometers



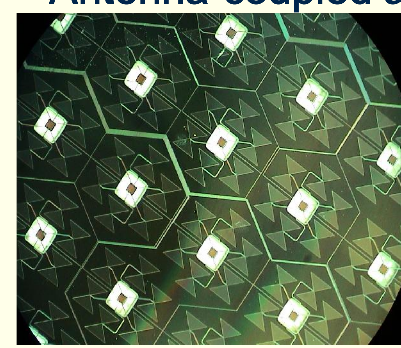
3-D EM simulation







Antenna-coupled arrays



Developed successfully by a large number of groups Worldwide, including CNRS and CEA as well (e.g. LETI, Irfu, CSNSM-IEF, APC, CRTBT)

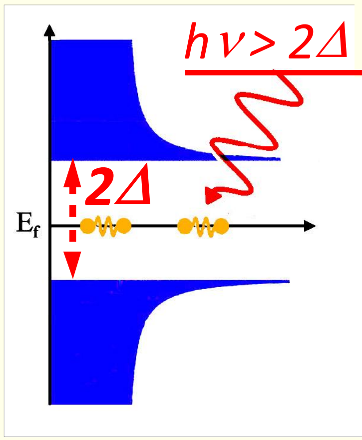
→ some practical limitations:

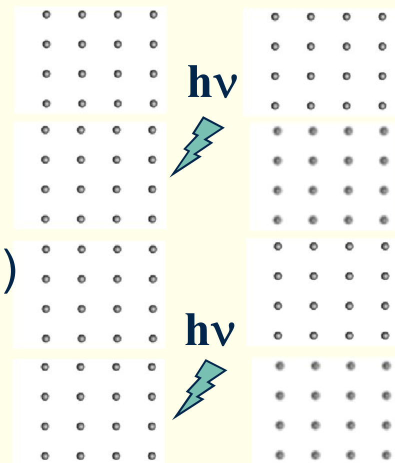
slow (thermal), complex, <u>multiplexing not so easy</u>

Other approach: Cooper-pairs counting

Δ (gap) ~ 10^{-23} J (0.1 meV)

$h\nu > 2\Delta$ ~ 100 GHz (e.g. Al)





DARK
(more CP)

$P = N \cdot h\nu$

LIGHT
(less CP)

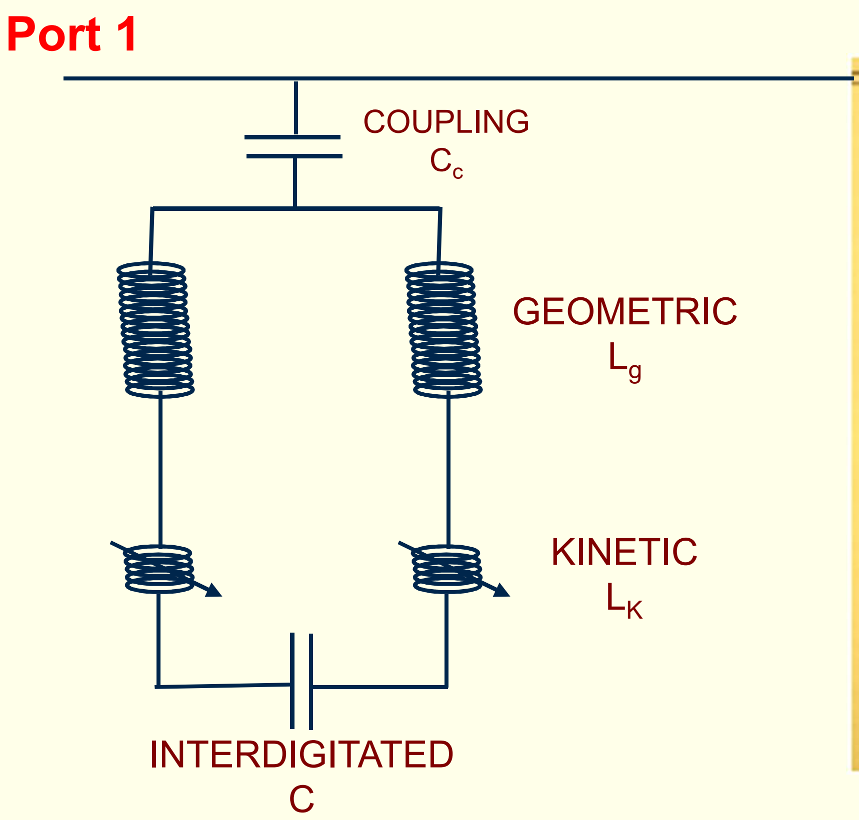
GOAL: count the Cooper pairs … to deduce how many are missing

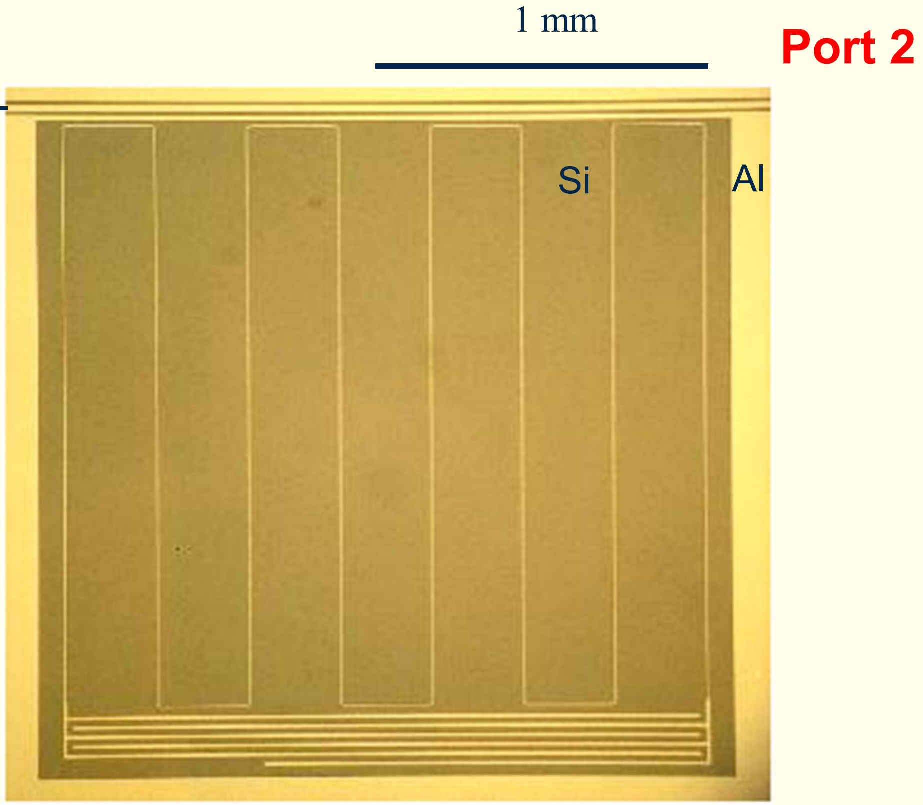
HOW: measure their total kinetic energy

→ MEASURE THE INDUCTANCE OF A FILM

Resonators for sensitive L measurement

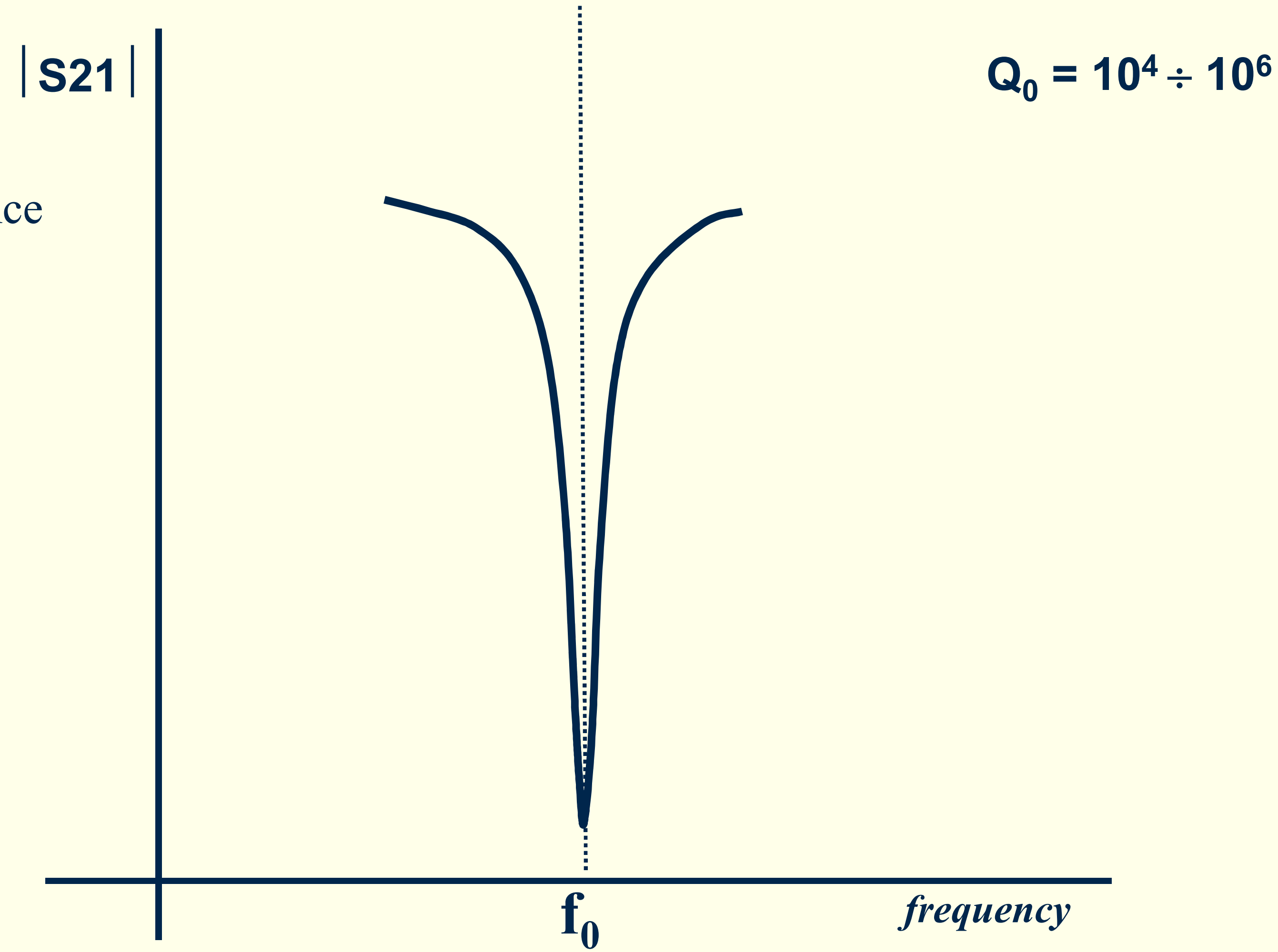
ORIGINAL IDEA: JPL-Caltech (2001) – P. Day, J. Zmuidinas





Kinetic Inductance Detector

DARK:
- $T << T_c \sim 1$ K
- deep & sharp resonance
- frequency → f_0



Kinetic Inductance Detector

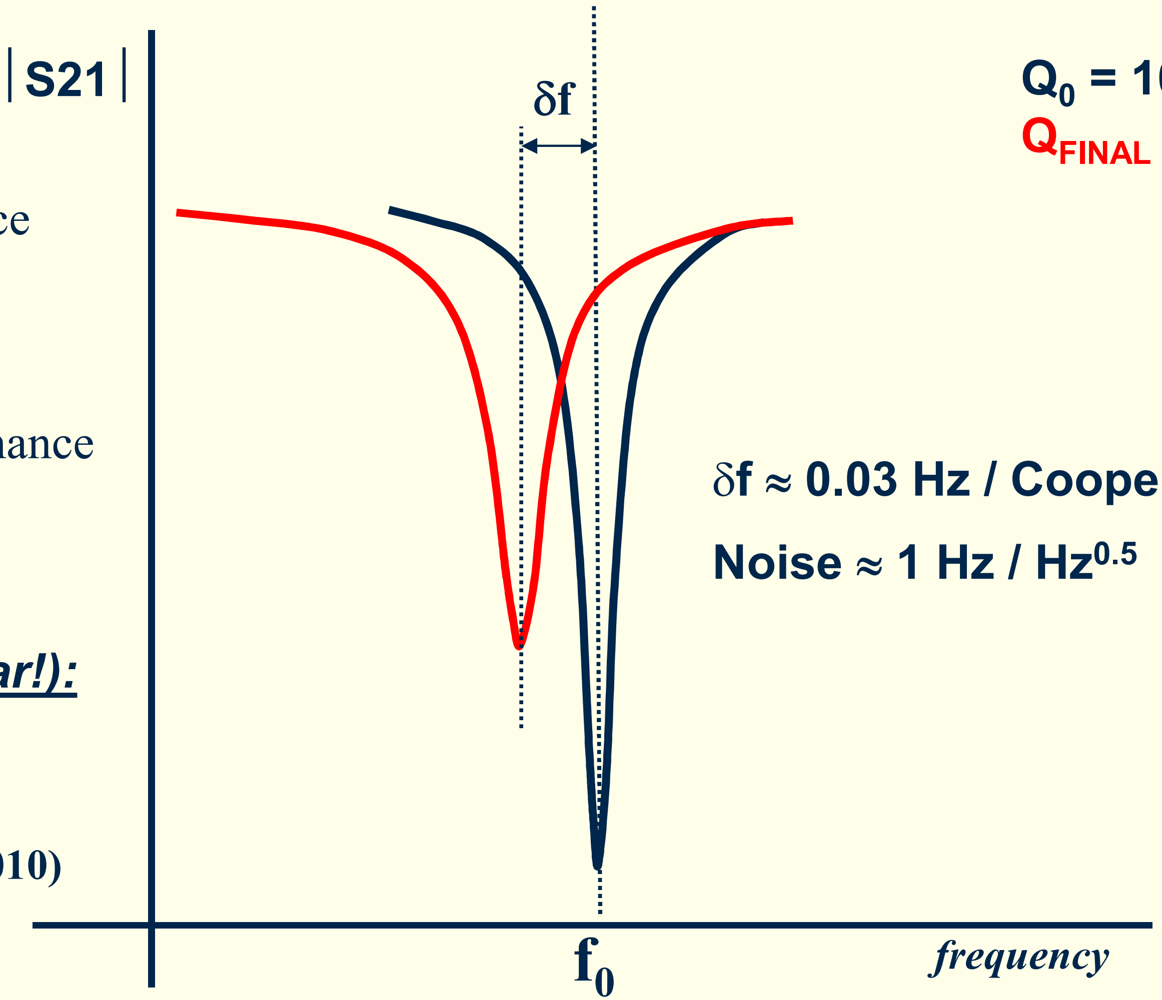
DARK:
- $T << T_c \sim 1$ K
- deep & sharp resonance
- frequency → f_0

LIGHT:
- shallow & broad resonance
- frequency → $f_0 - \delta f$

Large dynamics (linear!):

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

APL 96, Issue 26, 263511 (2010)



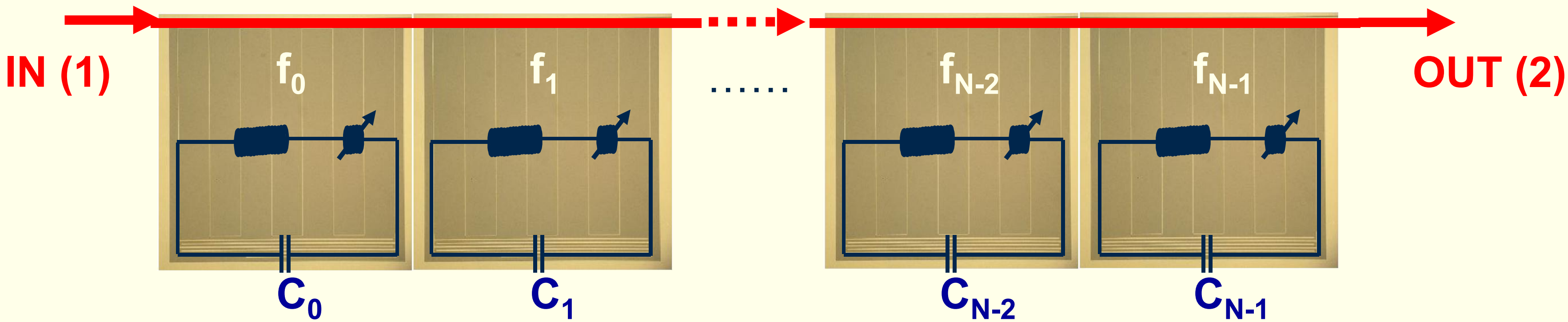
$Q_0 = 10^4 \div 10^6$

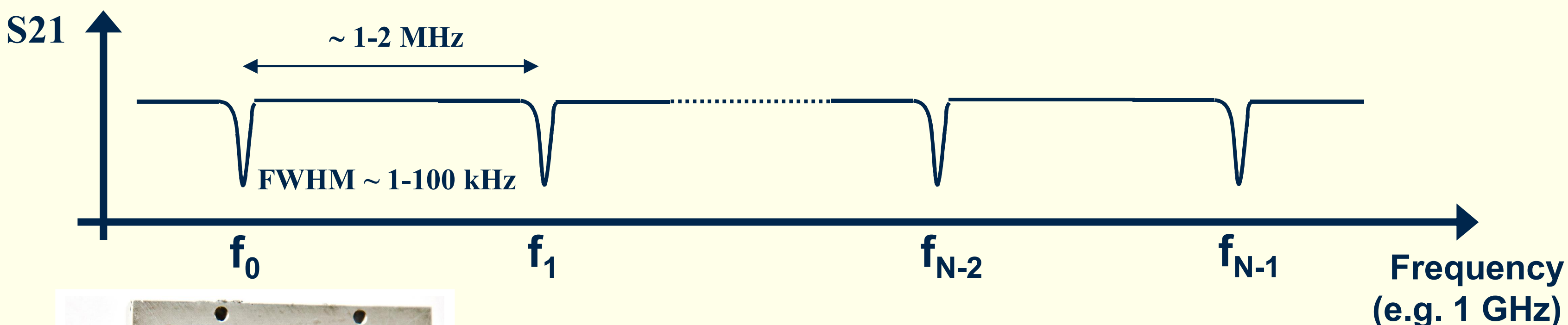
$Q_{FINAL} < Q_0$

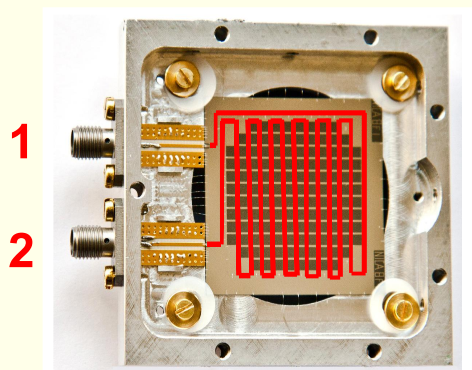
$\delta f \approx 0.03$ Hz / Cooper Pair

Noise ≈ 1 Hz / $Hz^{0.5}$

Multiplexing KID







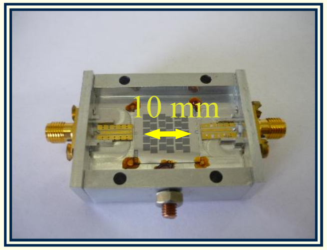
→ **Natural f-domain multiplexing**

→ **High MUX factor** (<u>hundreds-thousands</u>)

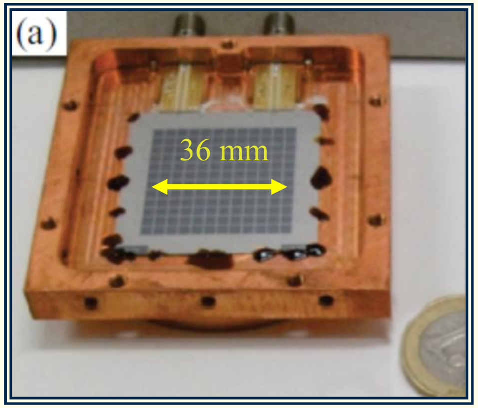
KID arrays made in Grenoble

Astronomy & Astrophysics 521, A29 (2010)
The Astrophysical Journal Suppl. 194 (2011)
Astronomy & Astrophysics, in preparation

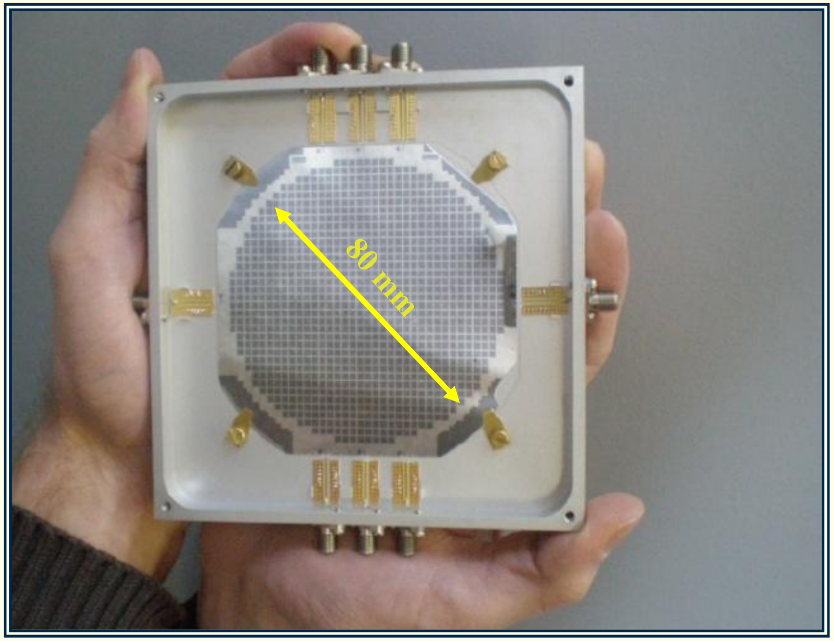
2009



2010-2013



2014-2017

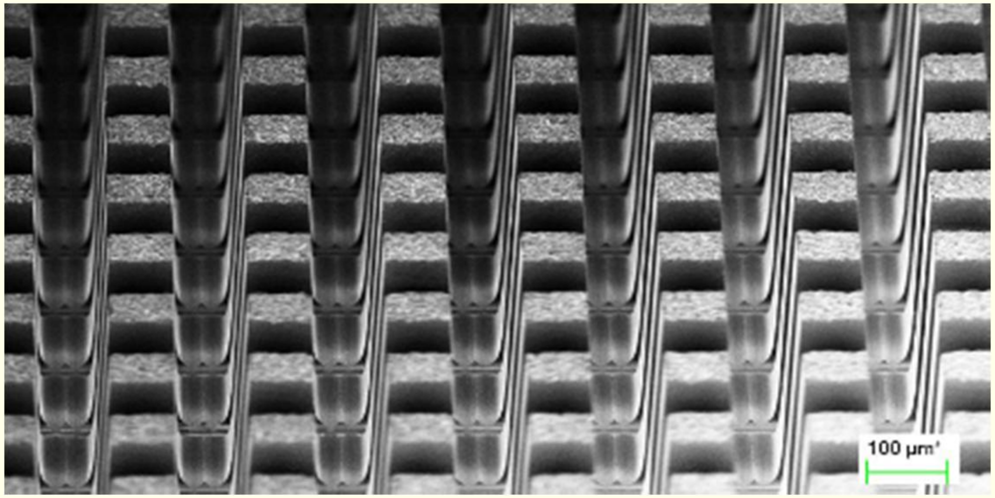


2008:
- single pixel

2009:
- 30 pixels, detectors noise dominated

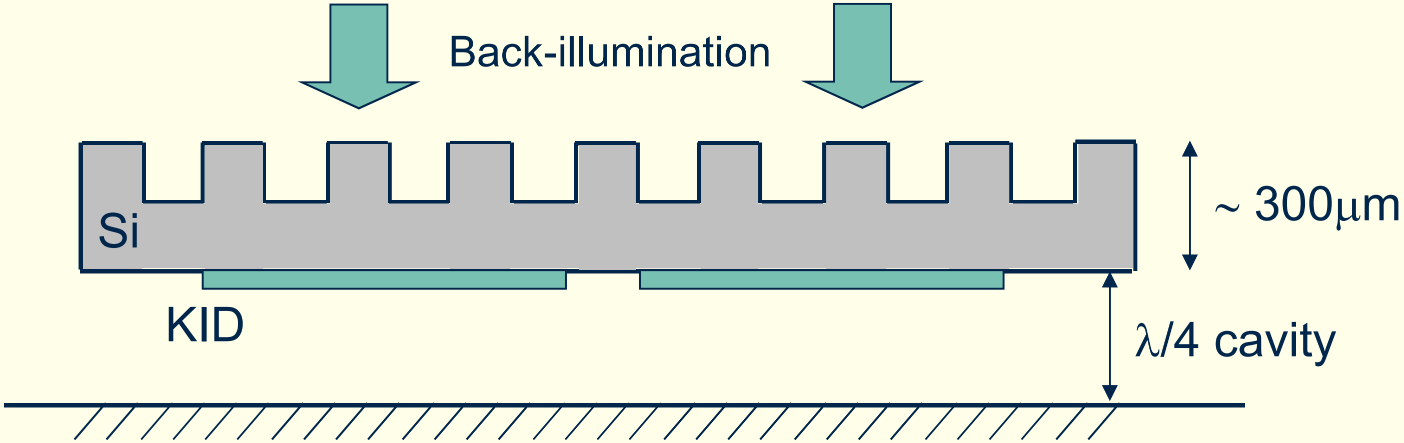
2014 - 2016:
- Background-limited (10^{-17} W/$Hz^{0.5}$)
- Readout line 2.5 m long !! Litho !!
- Al high-quality film (t = 10-20 nm)

Technology tricks, an example



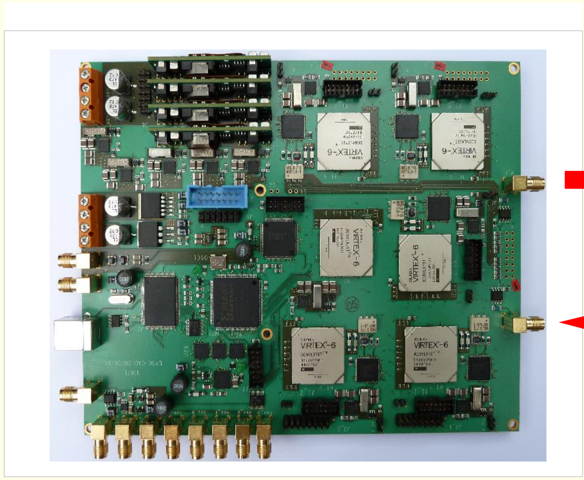
Micromachined anti-reflecting layer

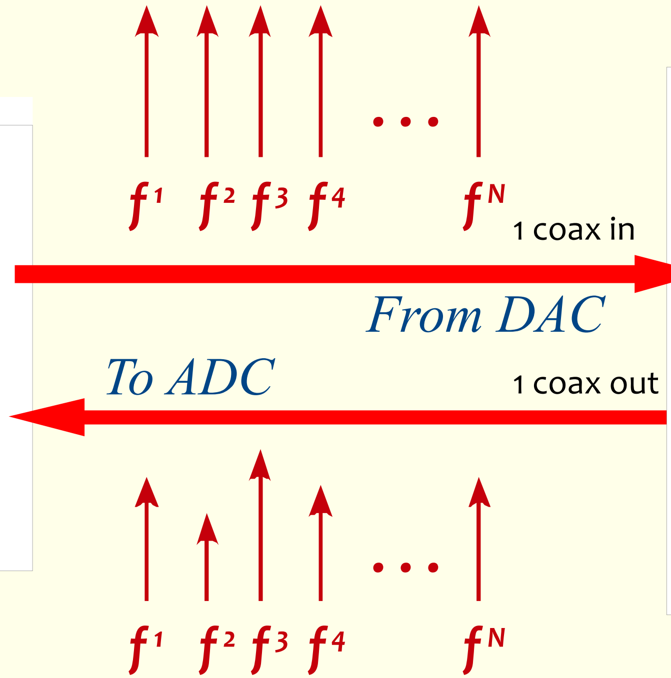
Journal of Low Temperature Physics, LTD16 Proceedings

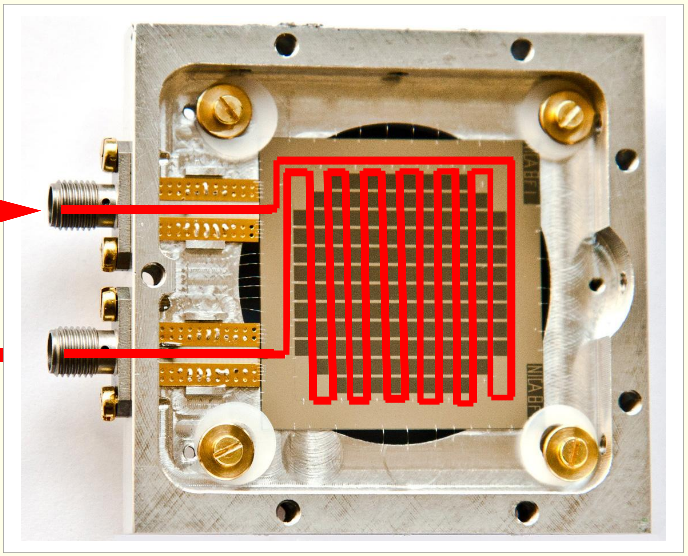


Lumped Element Kinetic Inductance Detectors

FPGA readout electronics







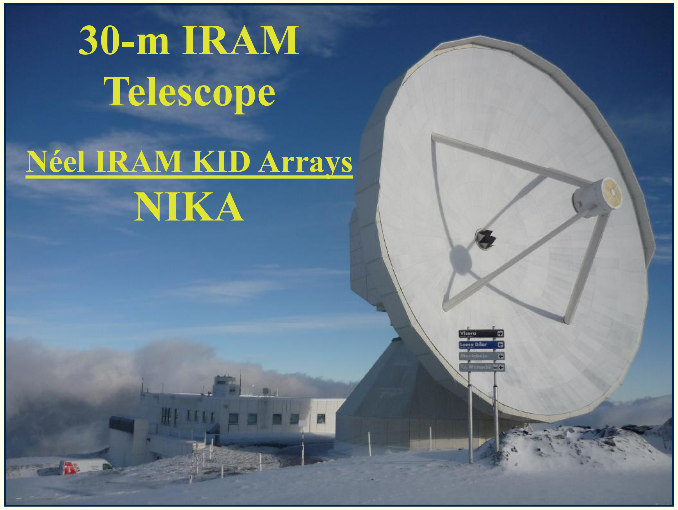
400 channels/board
.. simultaneous 1KHz
..no dead readout time

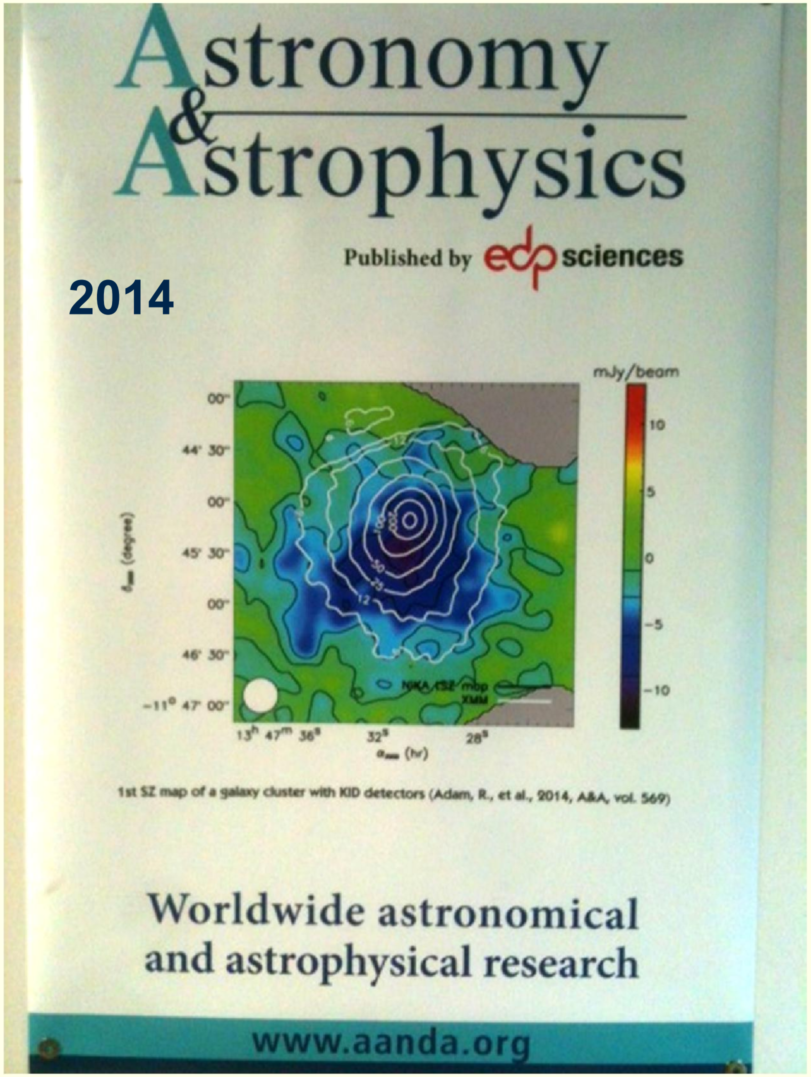
Single IN/OUT line for hundreds pixels

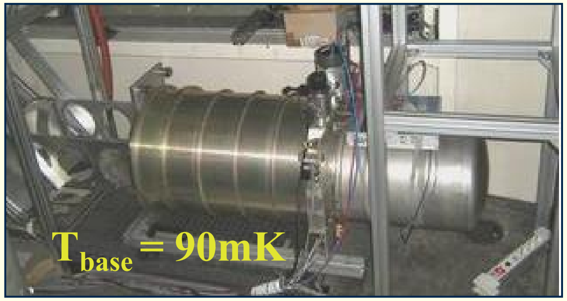
Journal of Instrumentation 7, Issue 07, 7014 (2012)
Journal of Instrumentation 8, Issue 12, C12006 (2013)
Journal of Instrumentation, submitted, arXiv:1602.01288

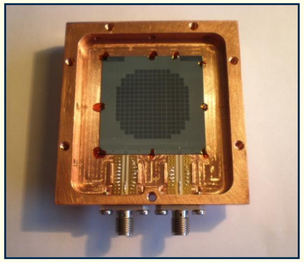
Instruments

The KID international pathfinder (2010-15)





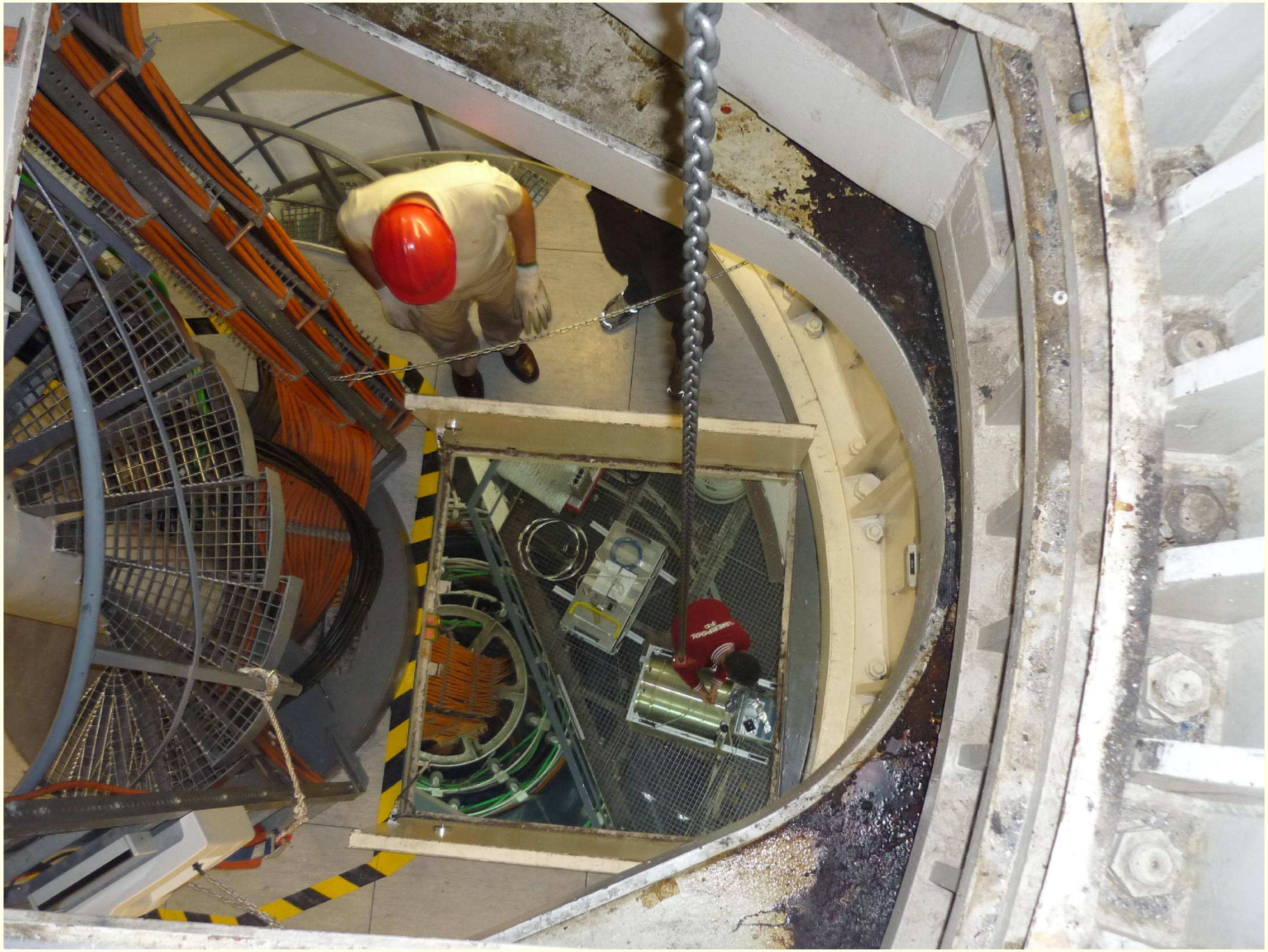




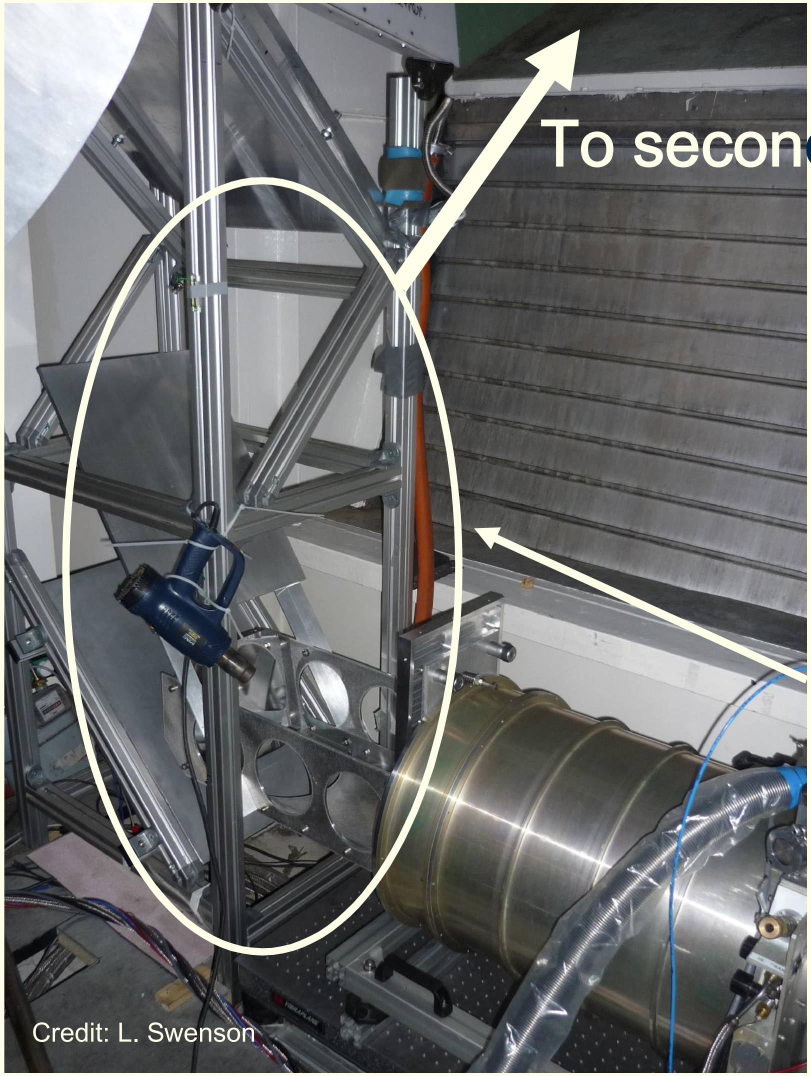
120 - 300 GHz

DUAL-BAND, 356 pixels total

... not in clean-room today ?



« NIKA0 » (2009) installed



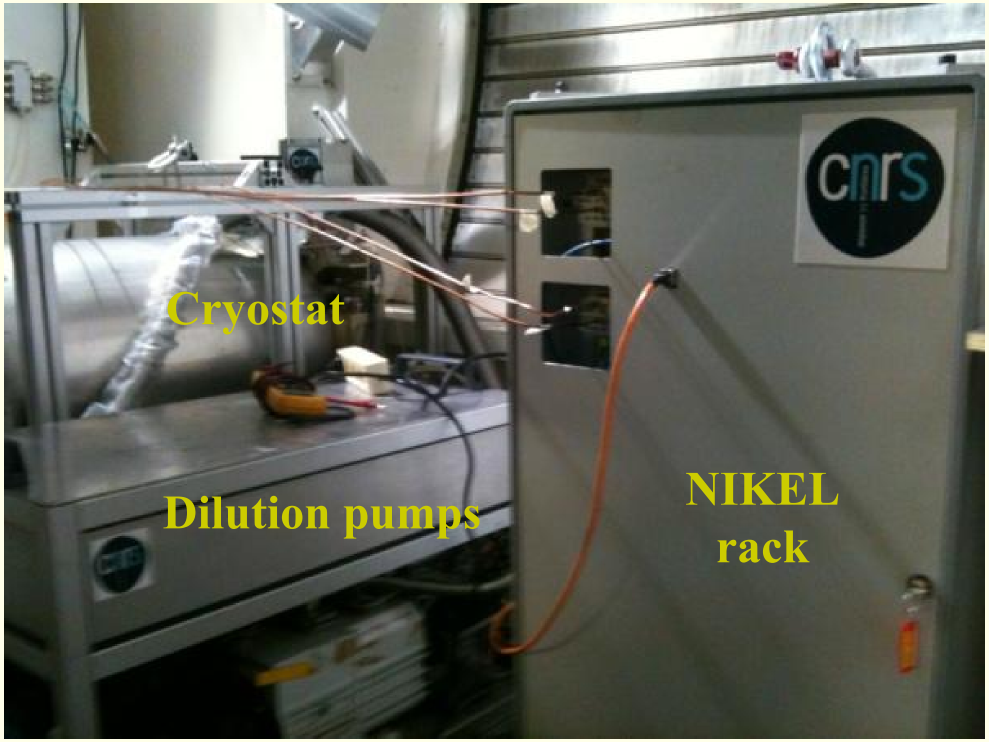
To secondary mirror

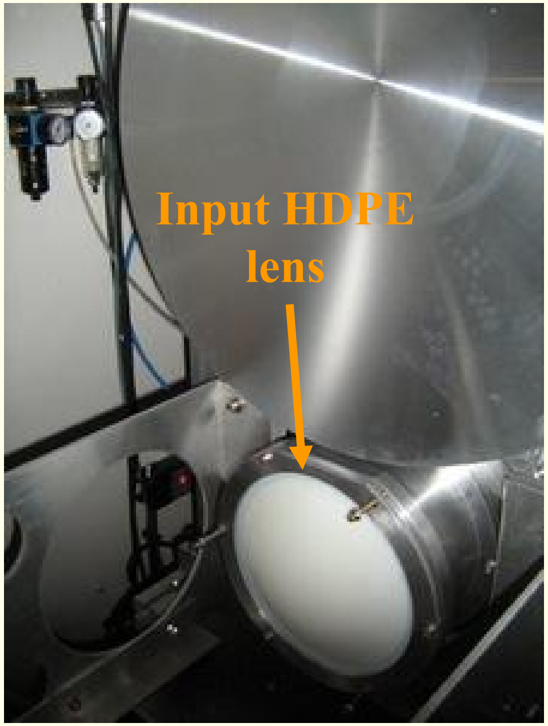
… through this hole

interface optics

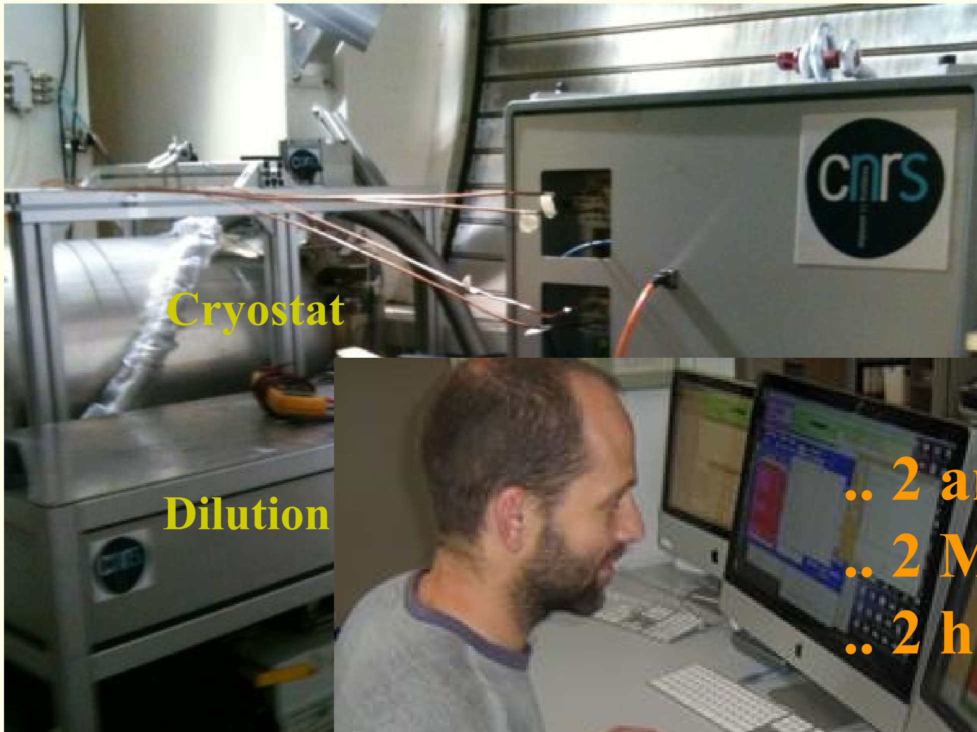
Cryostat (containing KID arrays)

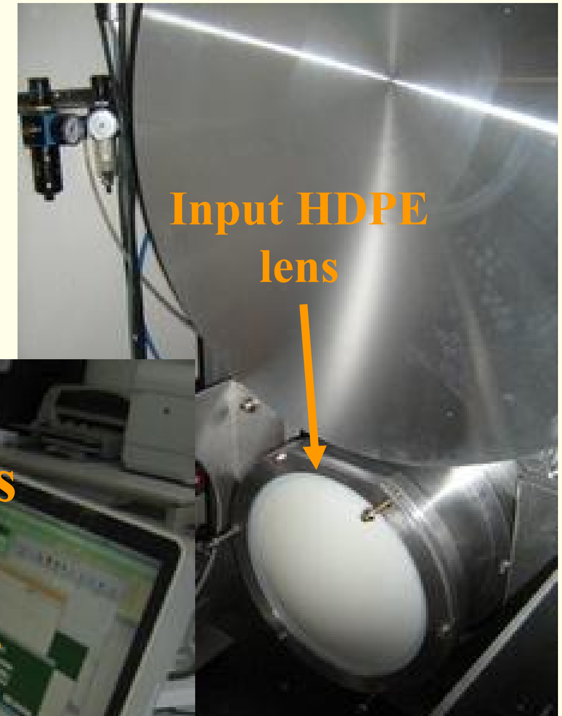
NIKA at the 30m





NIKA at the 30m





Our first run in October 2009

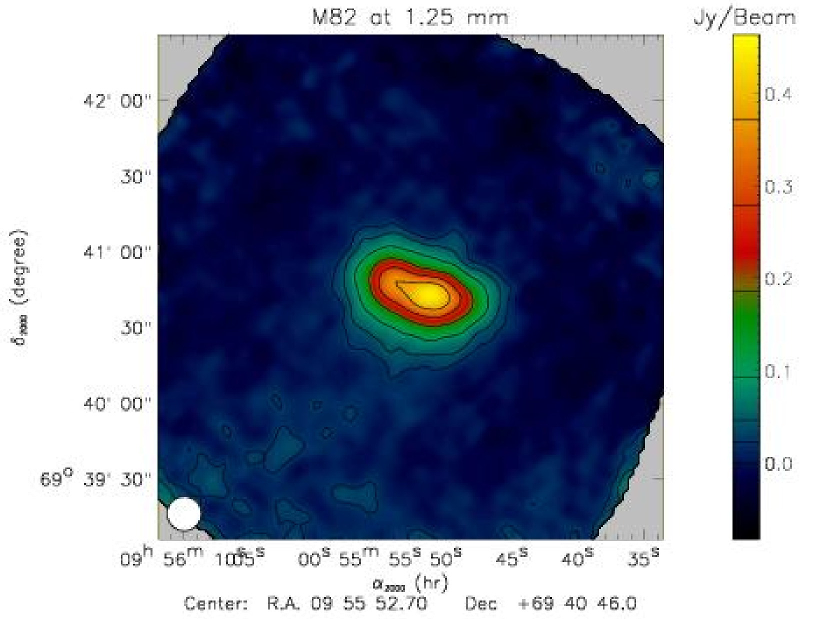
Jochem Baselmans
Simon Doyle
Loren Swenson
Alain Benoit
Philippe Camus
Aurelien Bideaud
François-Xavier Désert
Andrey Barishev
Stephen Yates
myself
…

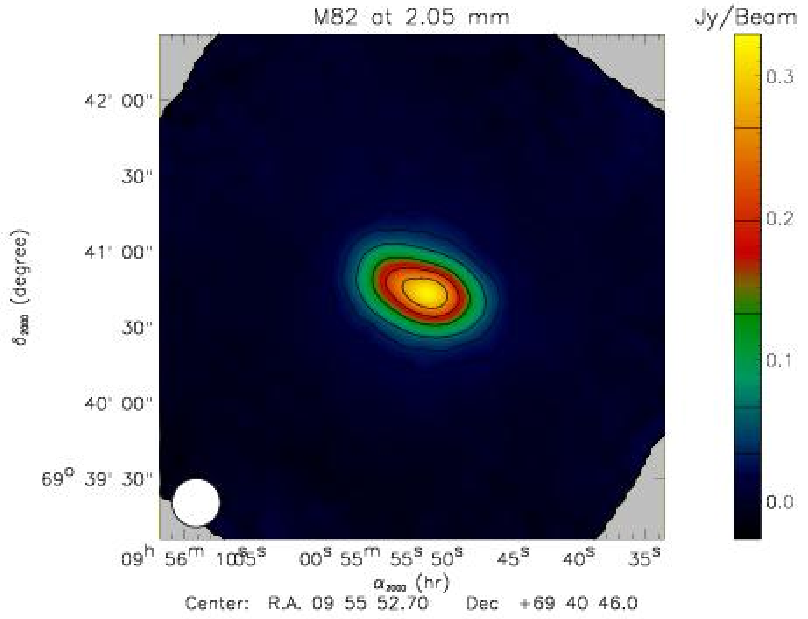
Everybody wanted to witness the first KID array on the Sky

Astronomy and Astrophysics 521, A29 (2010)

Nearby galaxies mapping/spectrum

June 2013 – run 6 **Exposure time ≈ 18 min. under very poor observing conditions (τ_{225} = 0.8)**

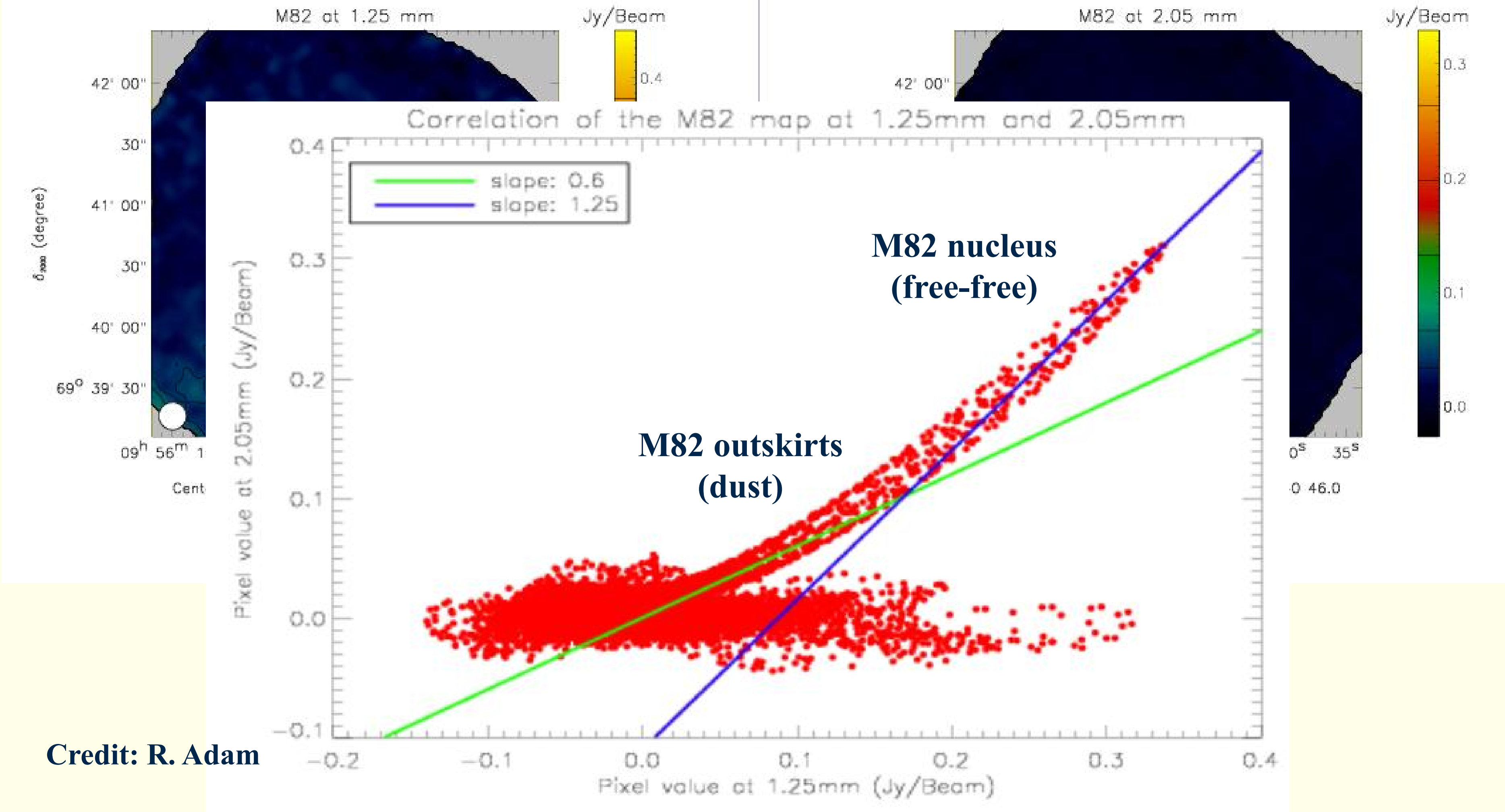




Credit: R. Adam

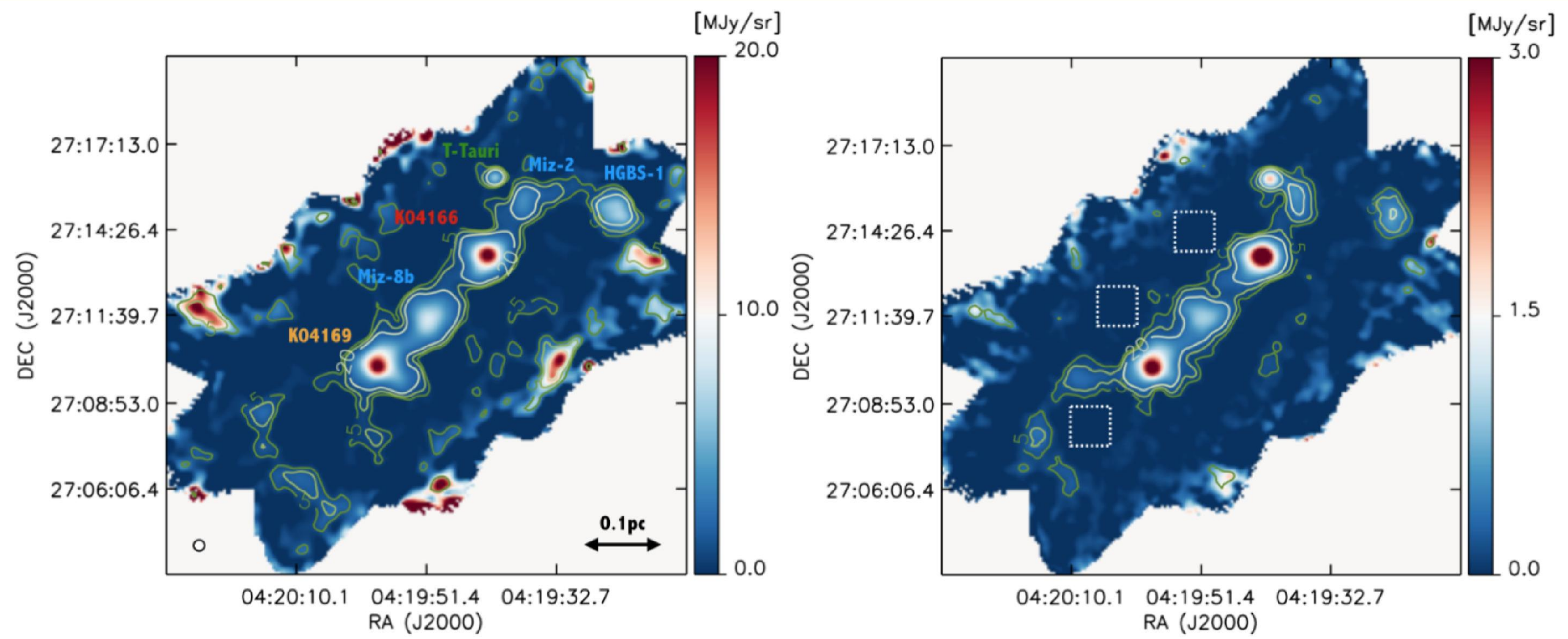
Nearby galaxies mapping/spectrum

June 2013 – run 6 Exposure time ≈ 18 min. under very poor observing conditions (τ_{225} = 0.8)



Credit: R. Adam

Galactic Science – an example



Credit. Andrea Bracco (Irfu)

Submitted to A&A

NIKA1 polarisation

ORION OMC-1 molecuar cloud is the closest site of OB star formation

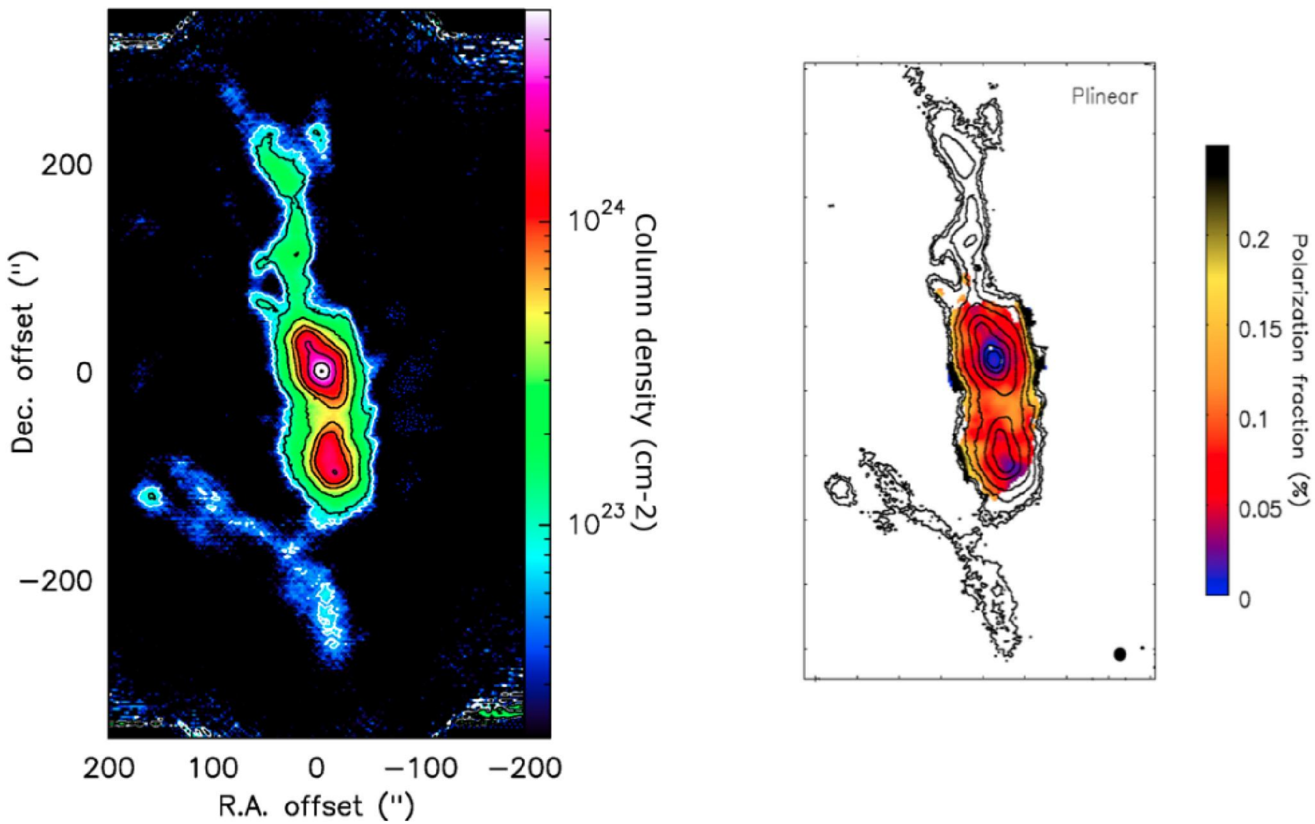


Figure 15. Column density map (left) obtained from the intensity map *I* at 1.15 mm. For comparison the polarization fraction is reported on the right panel of the figure.

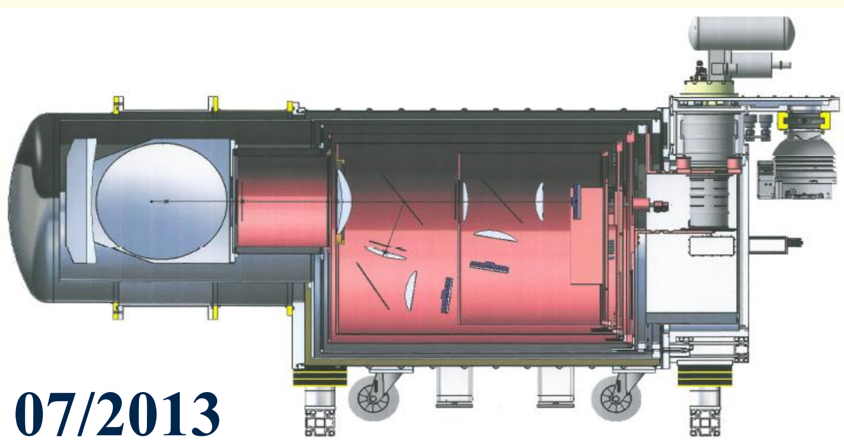
Astronomy & Astrophysics 599, A34 (2017)

NIKA2: ultimate mm imaging

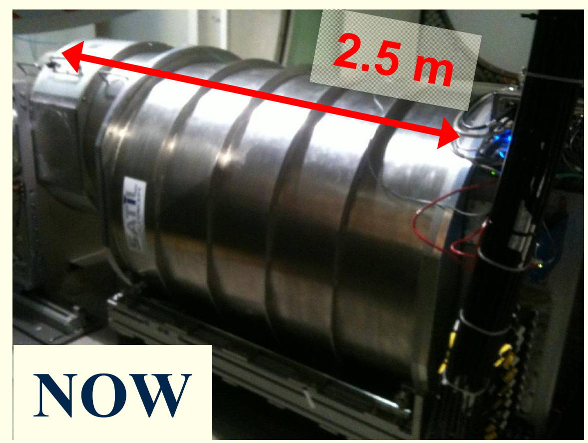
→ **10 times bigger** (and efficient) than NIKA
→ 3,300 pixels, **three arrays**
→ Imaging + **Polarisation** (120 - 300 GHz)

The **NIKA2 team** includes more than 80 people

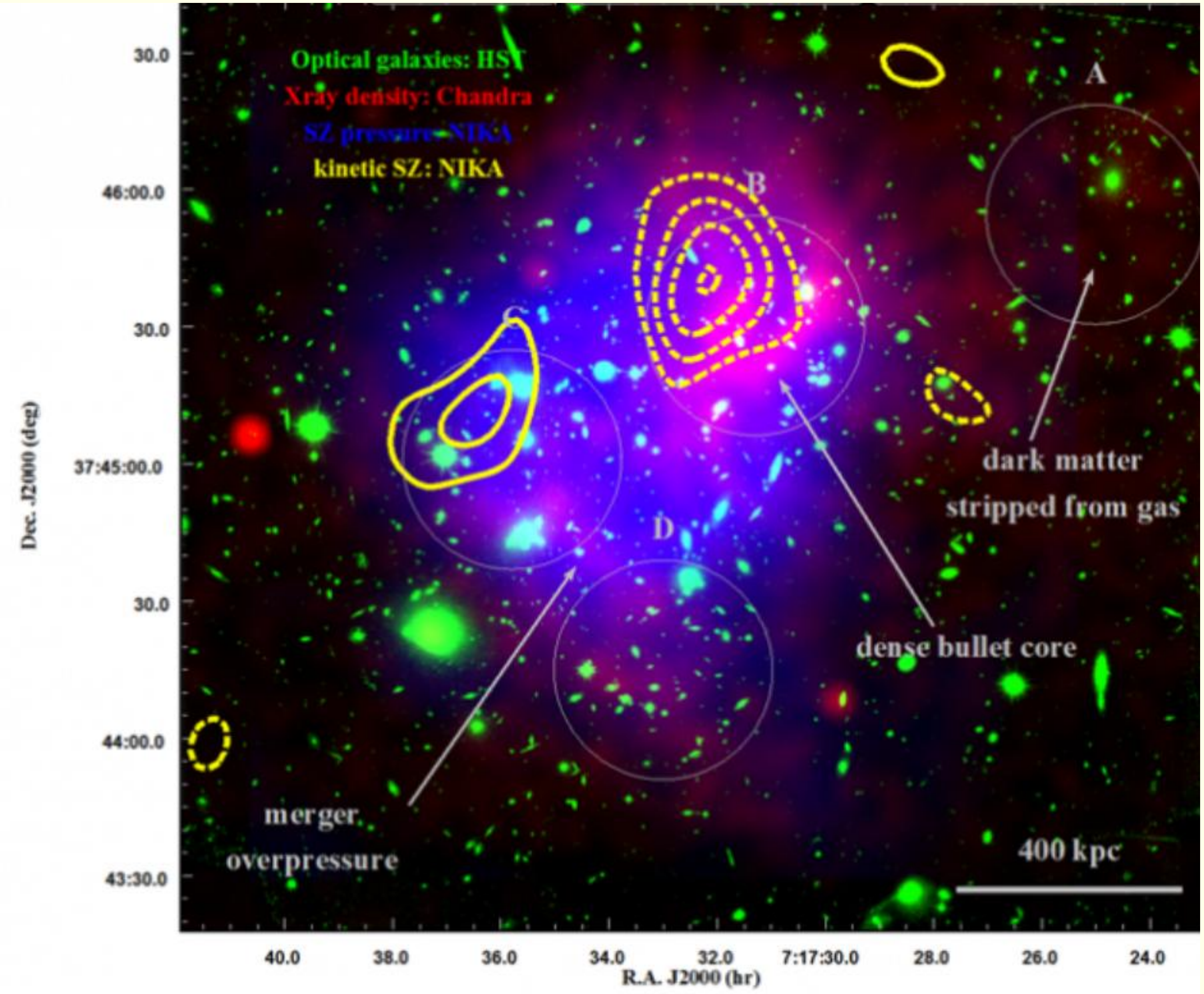
Cryostat 1.3 tons, fully remote control, ≈ m^3 at 150mK, possible thanks to … Alain Benoit



→



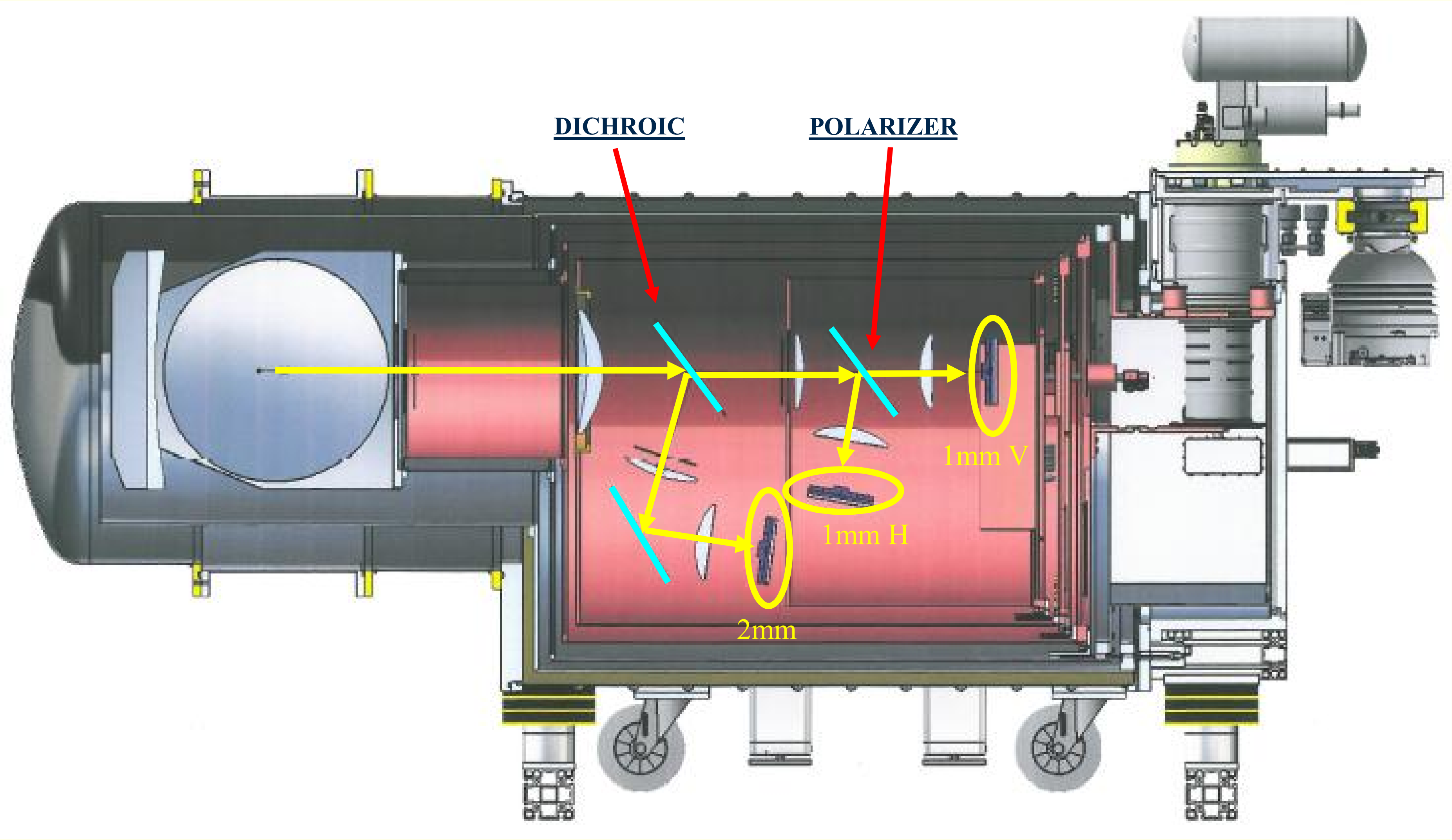
The latest NIKA achievement: kinetic map of the intergalactic medium



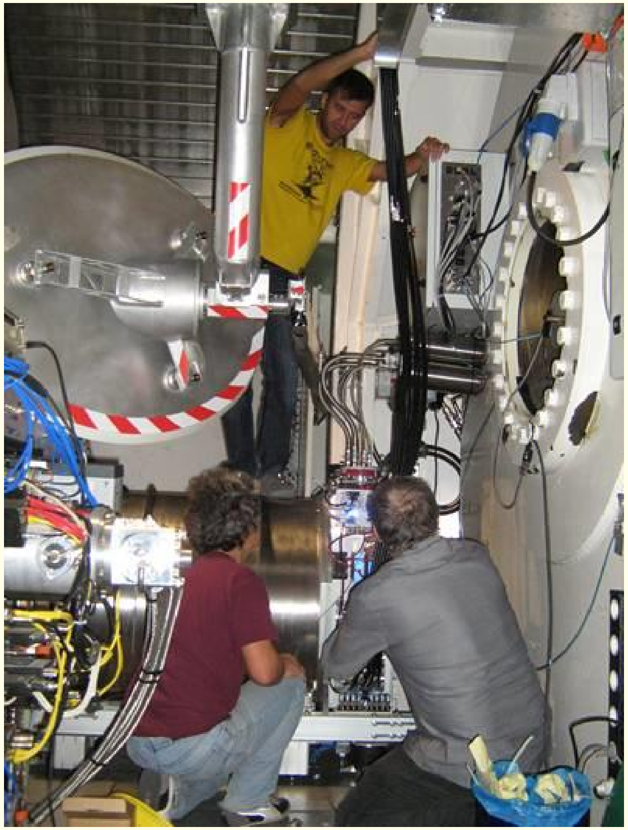
The largest g-bound objects, building blocks of our Universe, are the **clusters of galaxies**. They are mainly made of **dark matter and hot ionized gas**. Only a few percent of the mass is contained in galaxies. These mergers are **the most energetic events since the Big Bang** and they are fundamental to understand.

Astronomy & Astrophysics 598, A115 (2017)

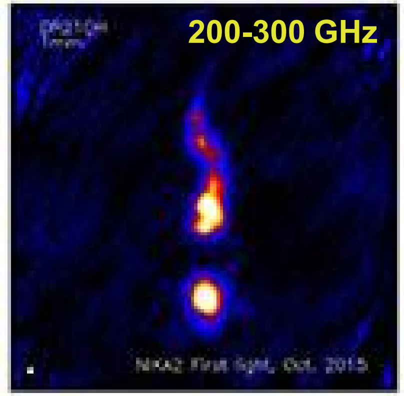
The NIKA-2 instrument (2015-2025)

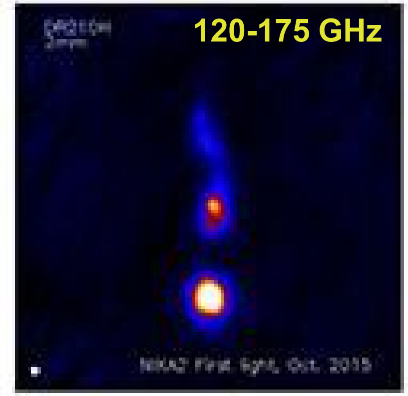


NIKA2 first light



Succesful installation achieved in September 2015



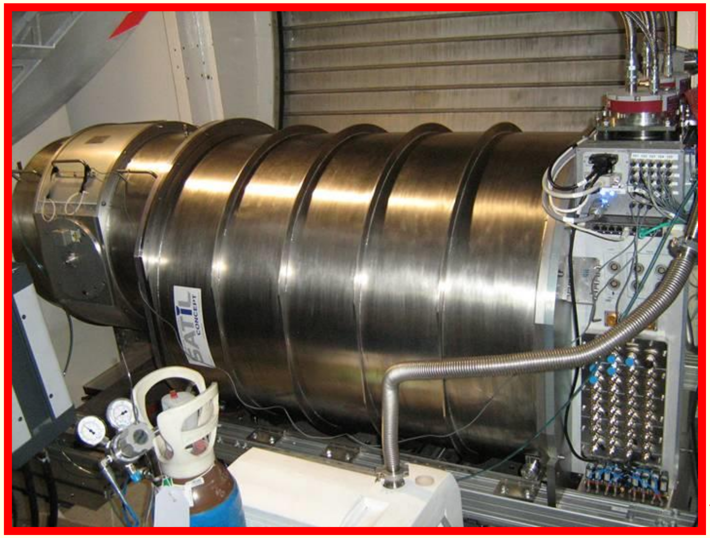


First NIKA2 images taken on DR21OH, a star-forming region in the dense molecular cloud Cygnus X.

State-of-the-art instrument

The combination telescope + NIKA2 allows a gain in mapping-speed of a **factor 50** compared to previous generation instruments.

The NIKA2 setup



The cryostat in the receivers cabin

60 meters of pipes

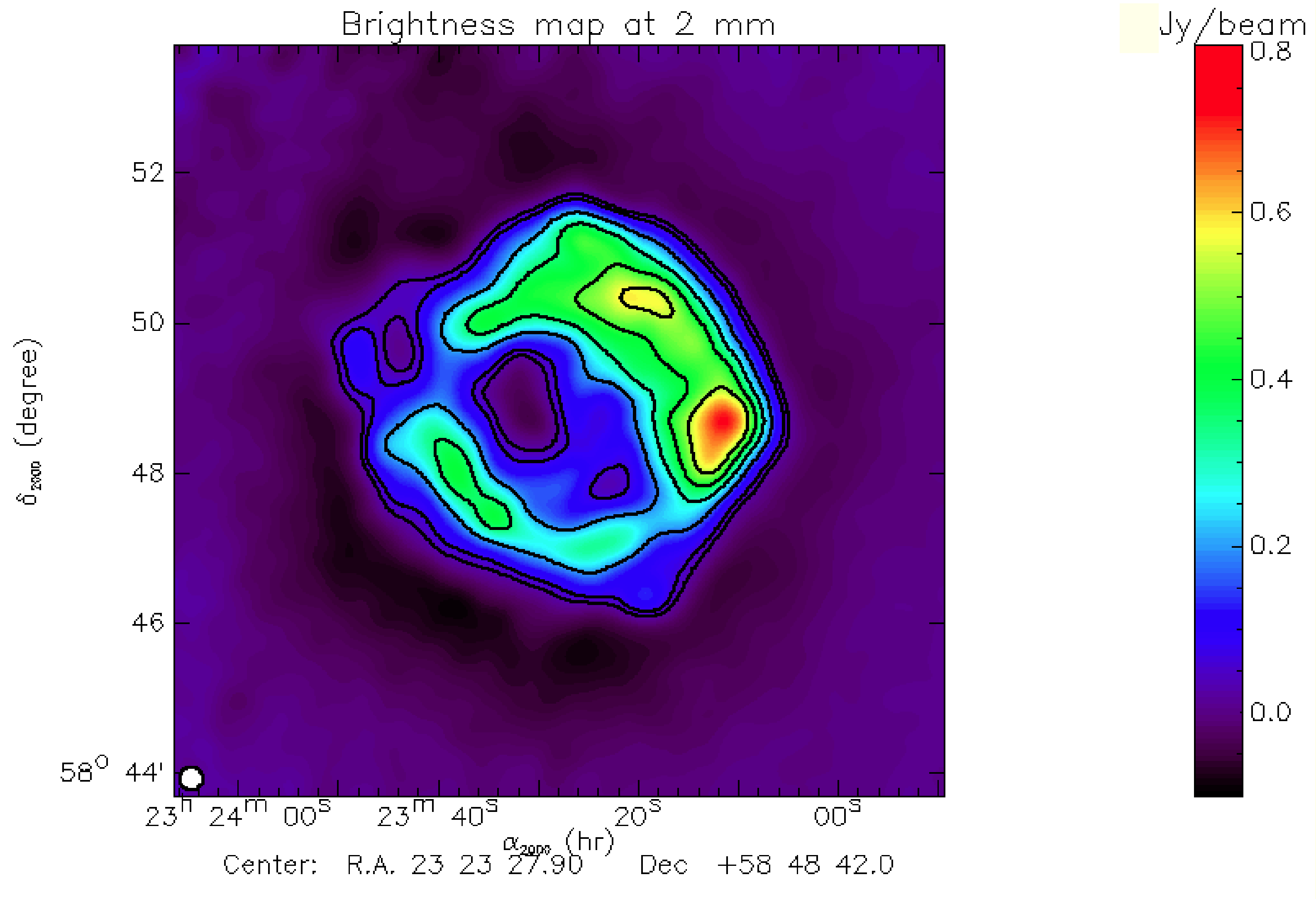
The dilution gas handling in the basement

The 40 COAX cables

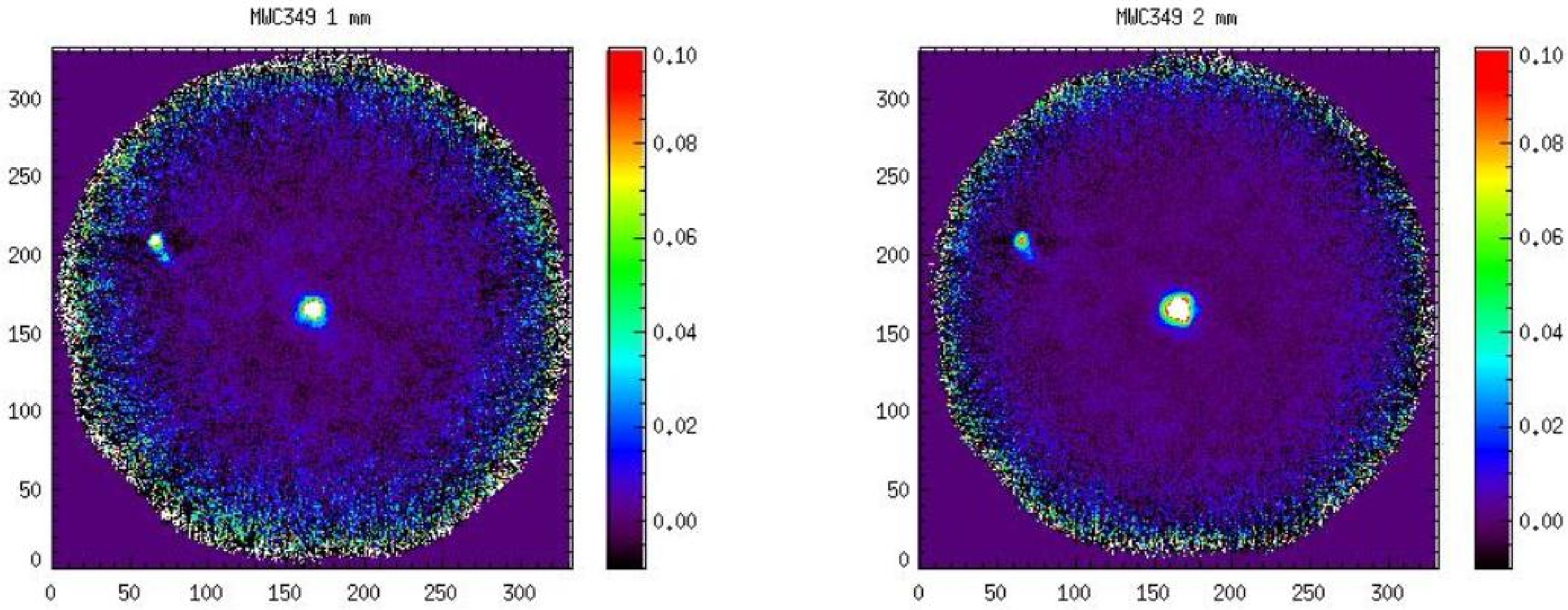
NIKA2 figures:

- 3000 pixels over 3 arrays
- 1.2 tons; 2.5 m long; 3000 pieces
- Two Pulse Tubes
- Fully remote control
- Completely cryogen free
- Base T ≈ 150 mK

Cas A – $T_{INT} \approx 10$ minutes

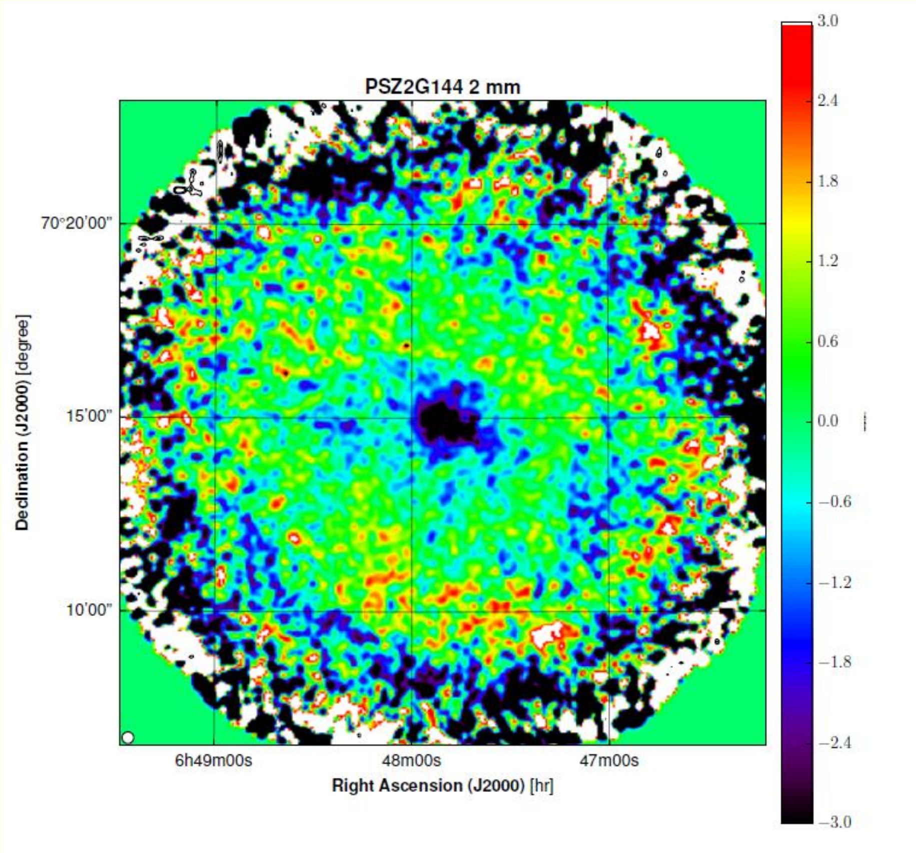


MWC349 – Last week

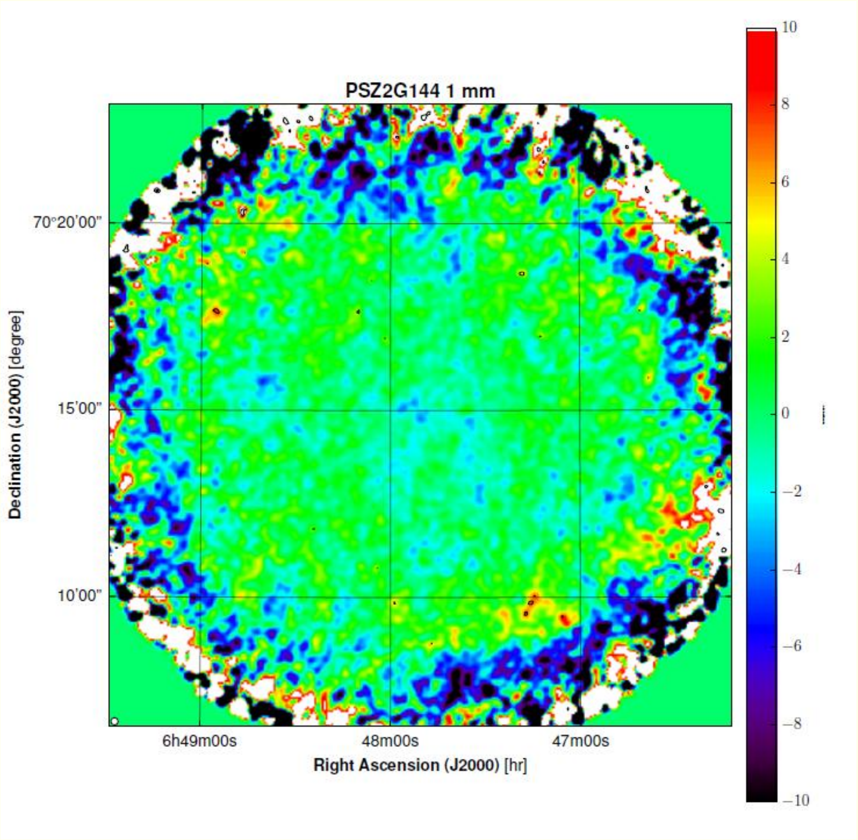


A galaxy cluster (SZ) in real time

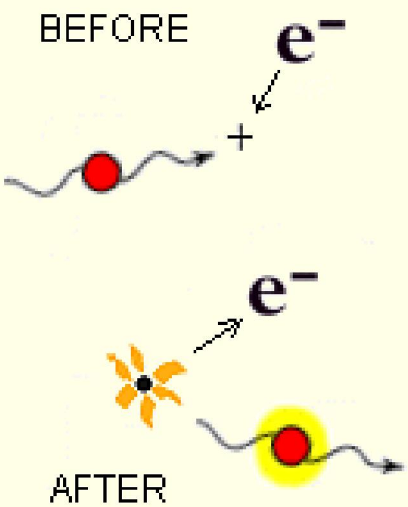
SZ minimum → 150 GHz

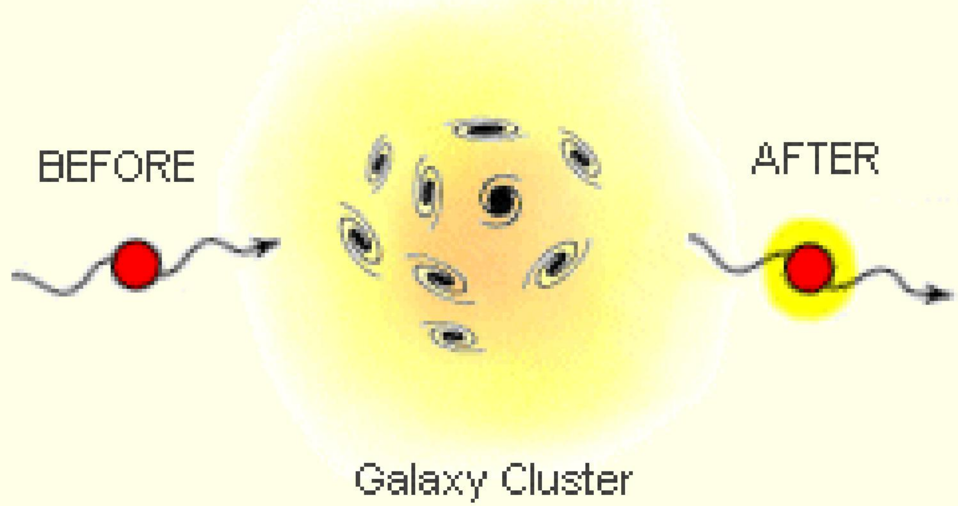


SZ « almost zero » → 250 GHz



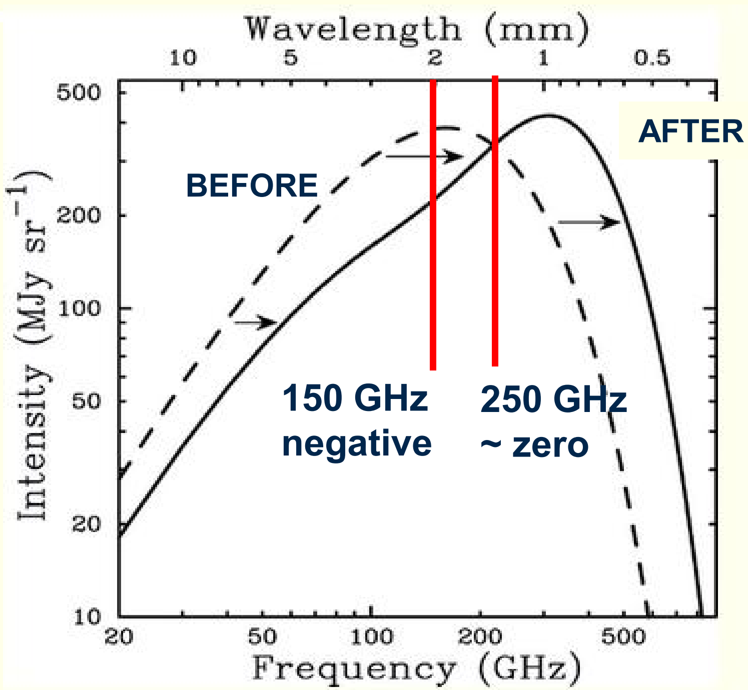
The SZ effect





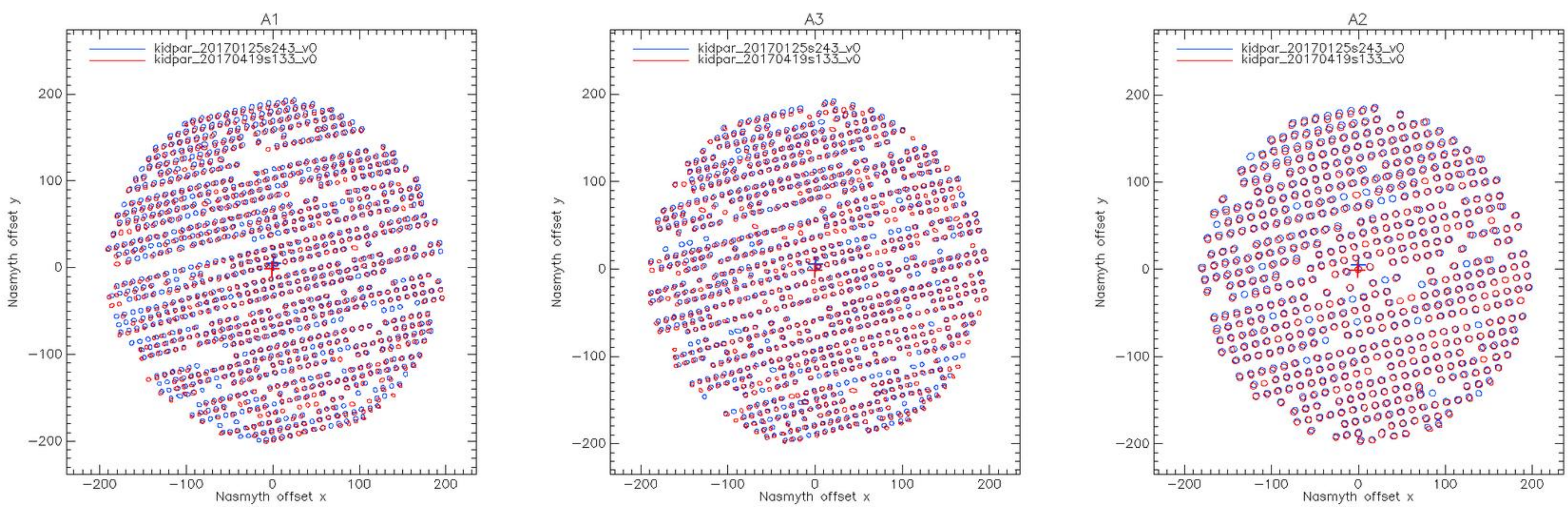
$R_{eff} \sim 5Mpc$

$n_e \sim 10^{-3} cm^3$



NIKA2 performance

250 GHz → 1140 x 2 pixels **150 GHz → 616 pixels**



On average, **90% of the pixels are identified** (e.g. 94% on the 2mm array)

However, **only around 80% of the pixels exhibit very good S/N.**

FHWM are around 11 arc-sec at 250 GHz and 17 arc-sec at 150 GHz

The sensitivity is **better than the ambitious goals at 150 GHz**, approaching this goal (and **much better that the specifications**) **at 250 GHz**.

NIKA2 schedule

September 2012 → Project kick-off (start designing cryostat etc.)

September 2015 → Installation (1k pixels warm readout)

January 2016 → Complete readout for 3kpixels

September 2016 → hardware upgrade (new dichroic from Cardiff, new and more sensitive 150 GHz array)

April 2017 → Last « intensity » commissioning run (enough data)

April 2017 → First « science verification » run

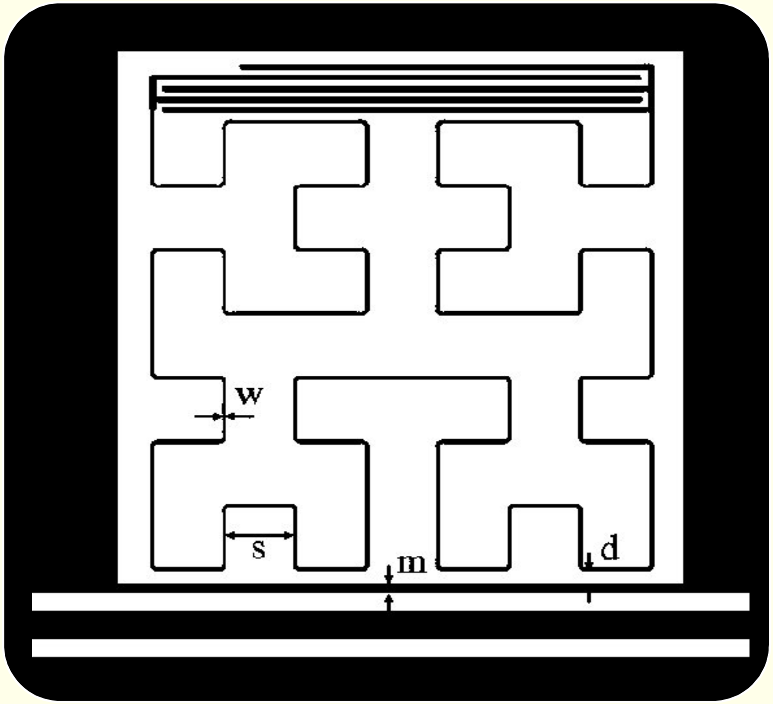
June 2017 → First « polarisation commissioning » run

From the next Winter, if the IRAM software is ready, open to astronomers via competitive calls.

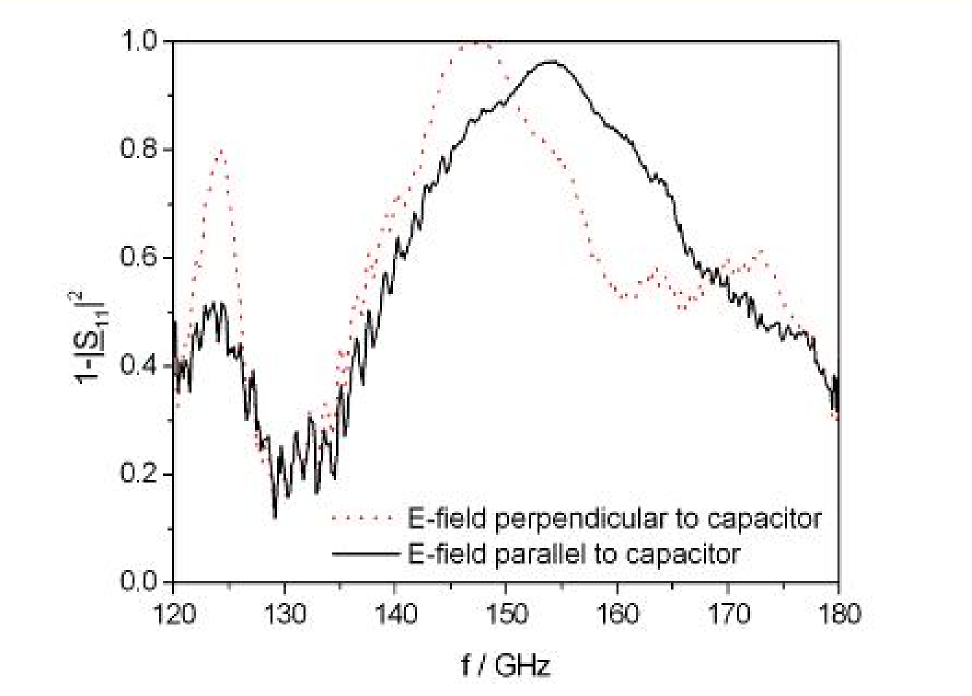
The NIKA/NIKA2 pixel design

GOAL: efficiently absorb both polarisations

SOLUTION: Hilbert fractal curve (3rd order)



M. Roesch et al., arXiv:1212.4585

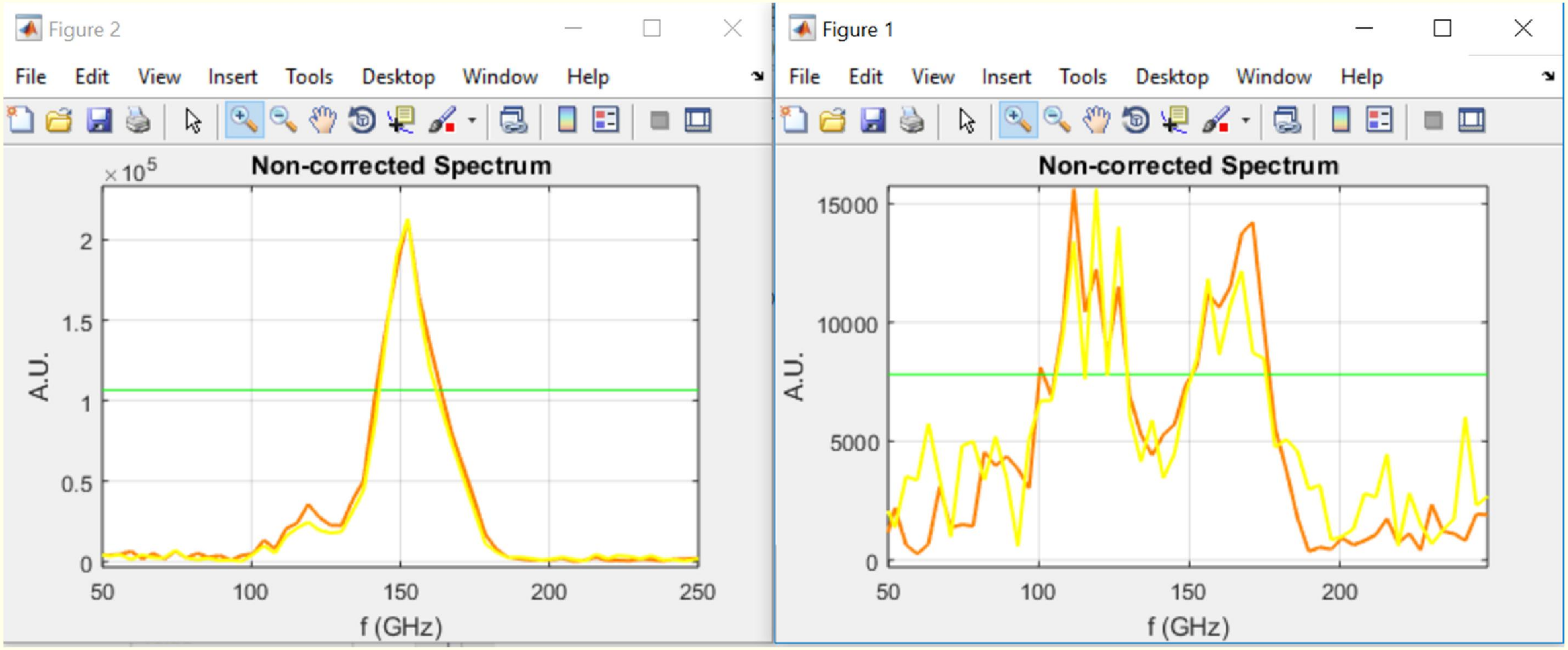


Film: thin Al (12÷25nm)

Polarization on-chip

Activity driven by APC – mostly was driven by the CORE program

Polarization on-chip



Cross-polarisation of the order of 2-5%, best values 2% at 150 GHz

Encouraging even if not yet in the wanted range (<1% for a large band)

Beyond NIKA2 ?

KID in Space ?
Spectroscopic functions ?

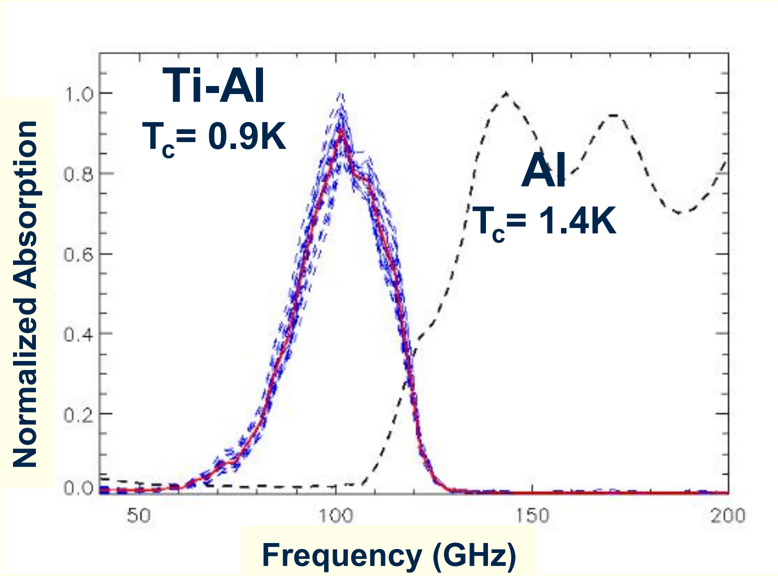
…. here just an example

Extending the sensitivity range

NEW MATERIALS (gap engineering)

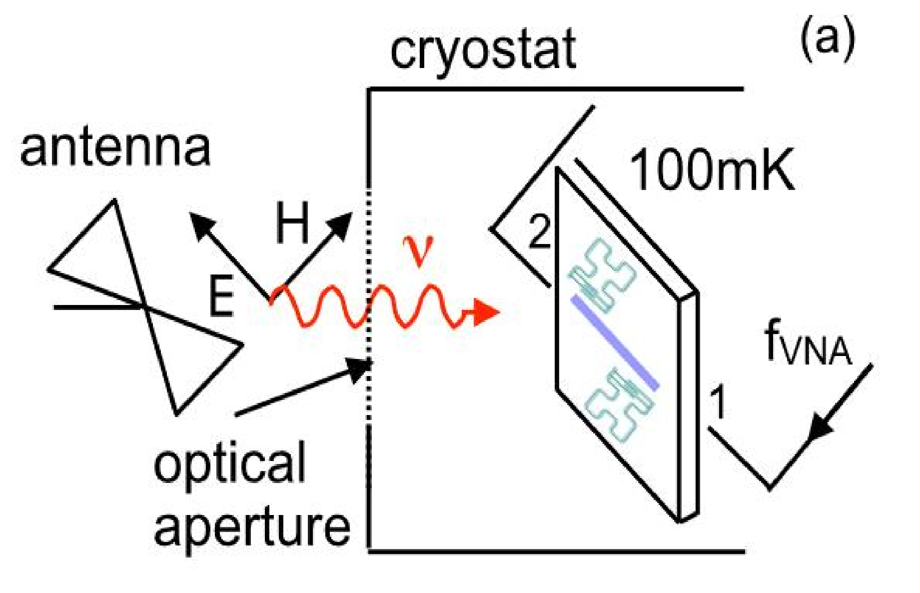
- Build our **preferred gap** to have access to lower frequencies
- **Maximize the Kinetic Inductance**

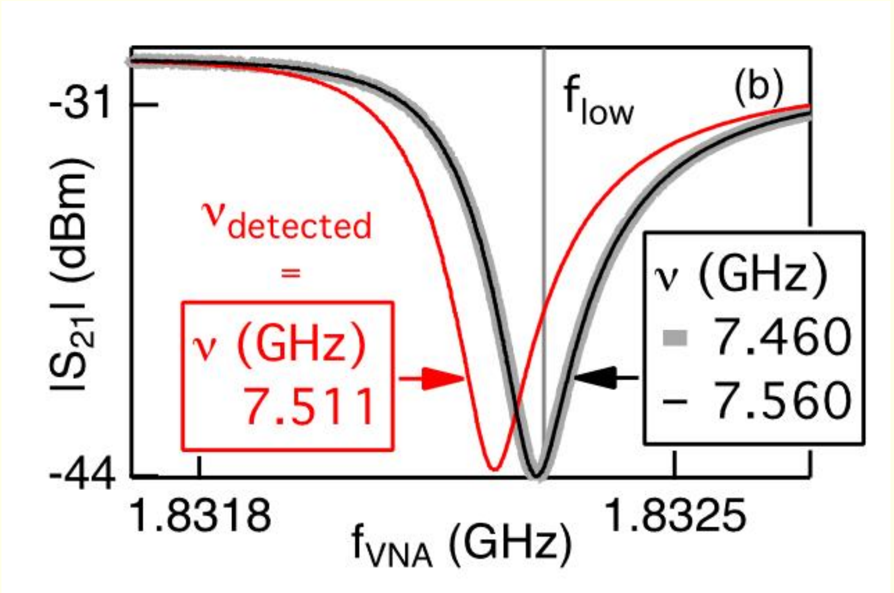
→ Exploring/synthesizing **new superconducting materials** (elements, alloys, multilayers)



→ **Ongoing collaborations with e.g. CSNSM, Karlsruhe etc.**

Sub-Gap KID - SKID

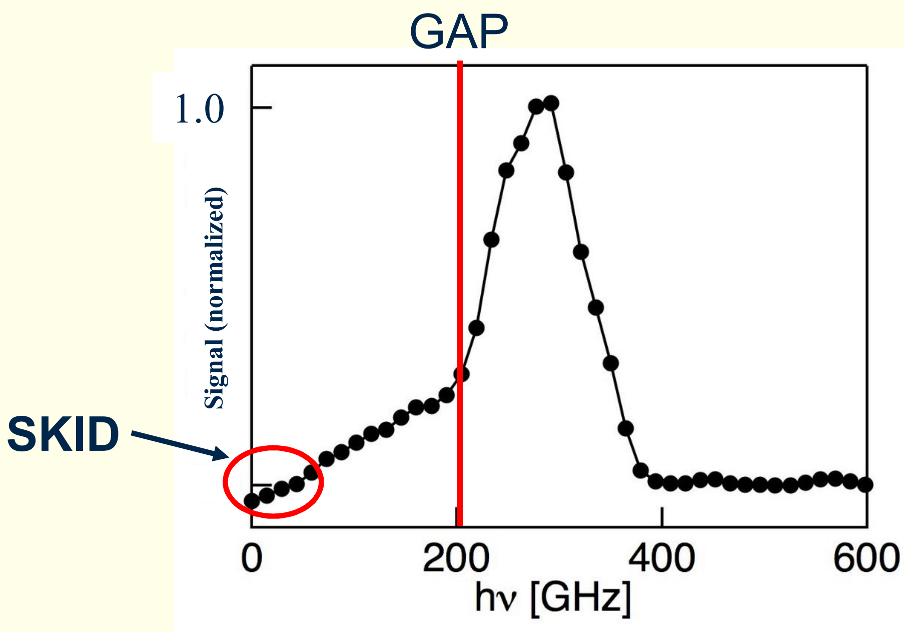


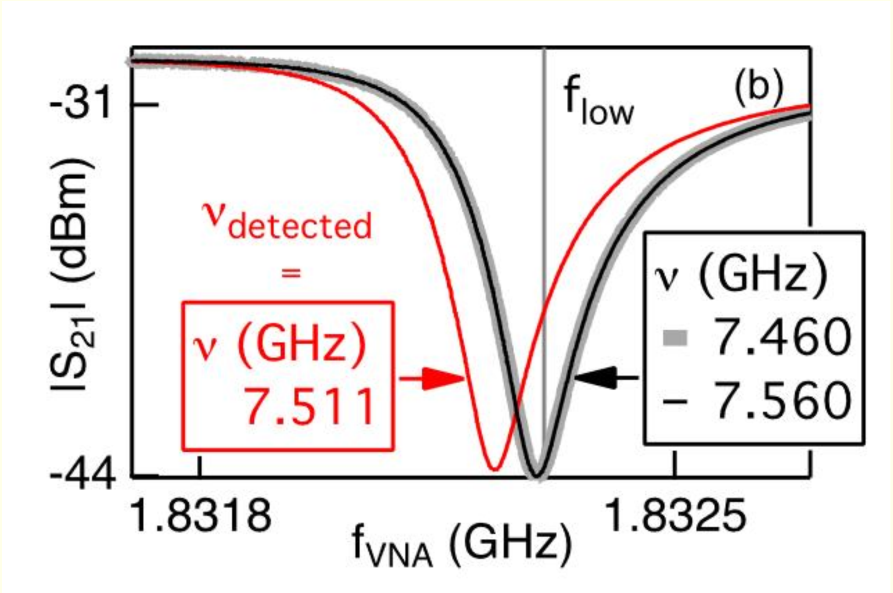


O. Dupré ….. and F. Levy-Bertrand, Supercond. Sci. Technol. 30 045007 (2017)

- Physics discussions ongoing (e.g. plasma modes, inter-gap states, L_s non-linearity etc.)
- **Prototype 22 GHz spectrometer for atmospheric studies** (collaboration IRAM)

Sub-Gap KID - SKID





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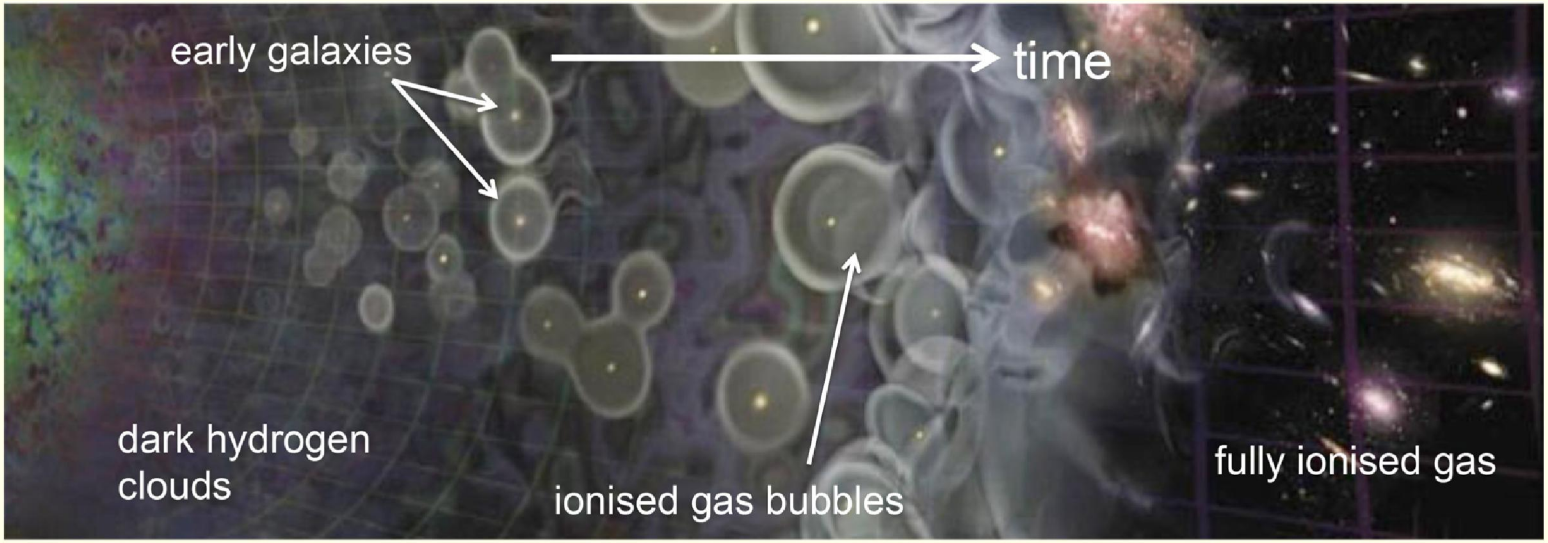
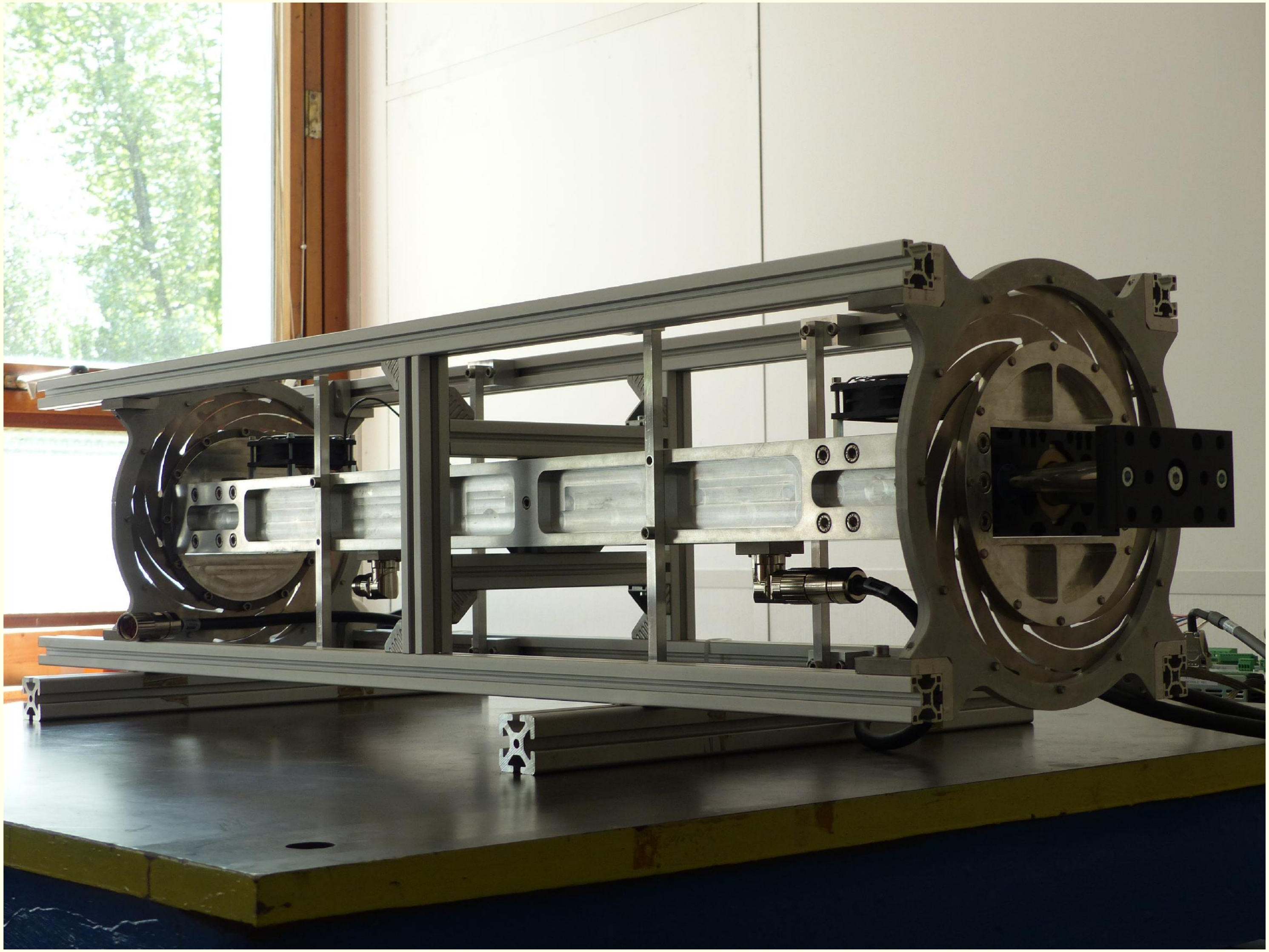
The CONCERTO instrument

Adding in front of the cryostat a fast interferometer allows multiplexing the spectral dimensions in the time-domain.



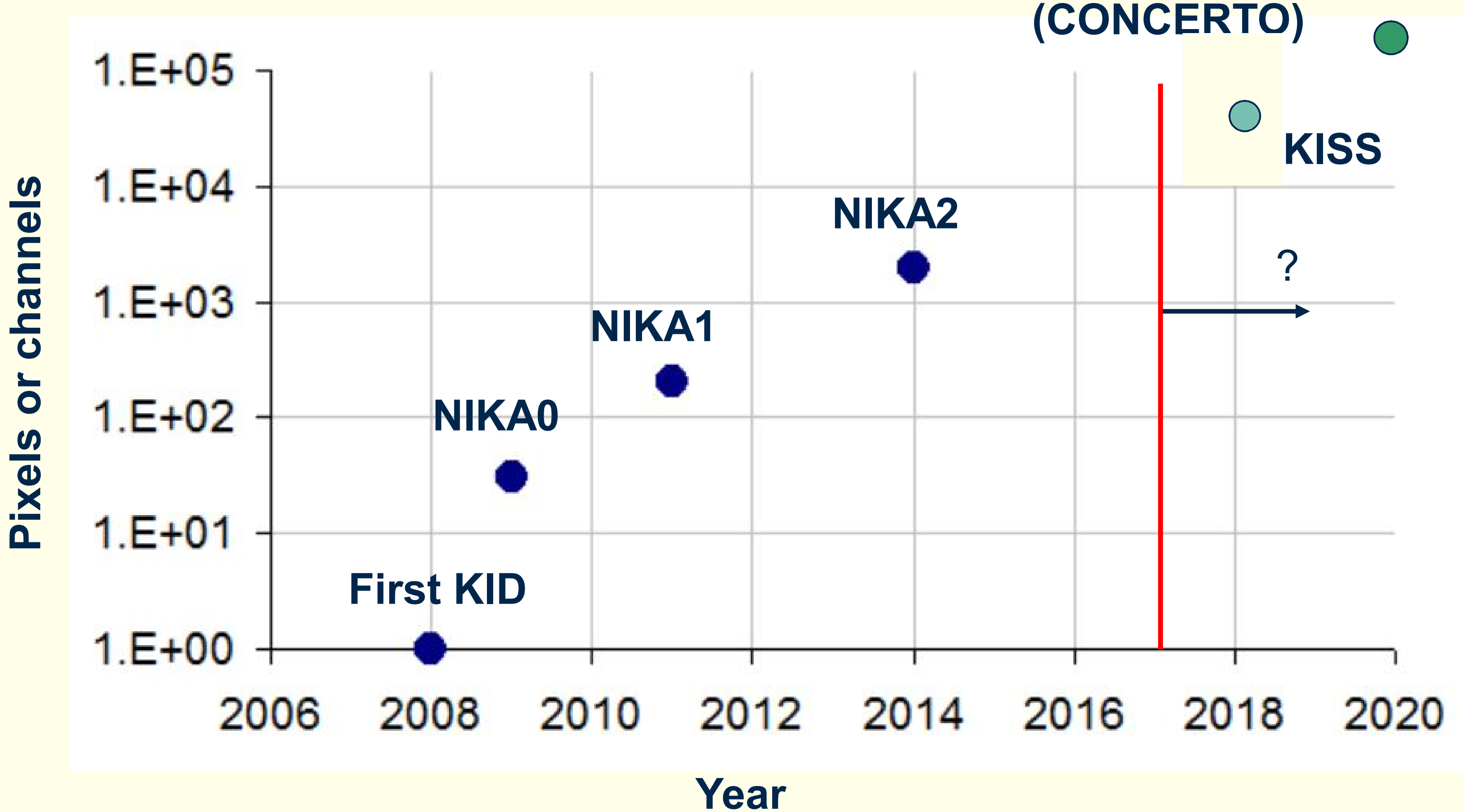
Intensity mapping of fluctuations of the (red-shifted) [CII] line emission. Instead of resolving the individual galaxies, measuring fluctuations on large sky regions and in a wide band.

The work has started



The NIKA-CONCERTO Moore's law

Large FoV spectro-imaging ≡ $2 \cdot 10^5$ pixels (CONCERTO)



Thanks

Just a bunch of us at the telescope ….

For more details on our group:

http://neel.cnrs.fr/spip.php?rubrique158