CONCERTO at APEX:

a new (sub-)millimeter spectrometer dedicated to line intensity mapping

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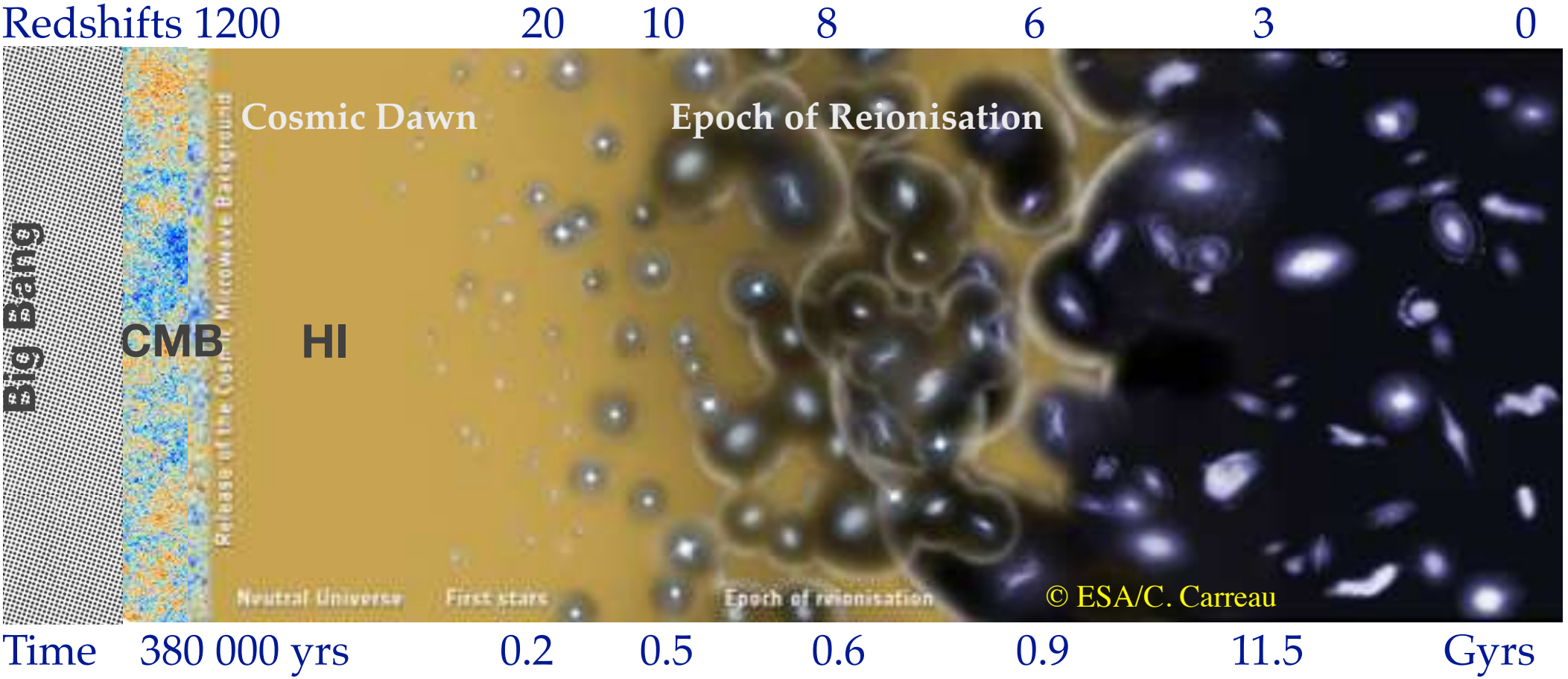
CPPM

Jan 2023

Why embark on the construction of a new instrument ?

Cosmic dawn and the Epoch of Reionization



From recombination to reionisation

… a very brief history of the Universe

Epoch of Reionization: When?

- The Planck breakthrough (Planck collaboration 2016, XLVI & XLVII; 2018 VI):
  - Scattering optical depth due to free electrons:

$$\tau(z) = \int_{t(z)}^{t_0} n_e \sigma_T \, c dt$$

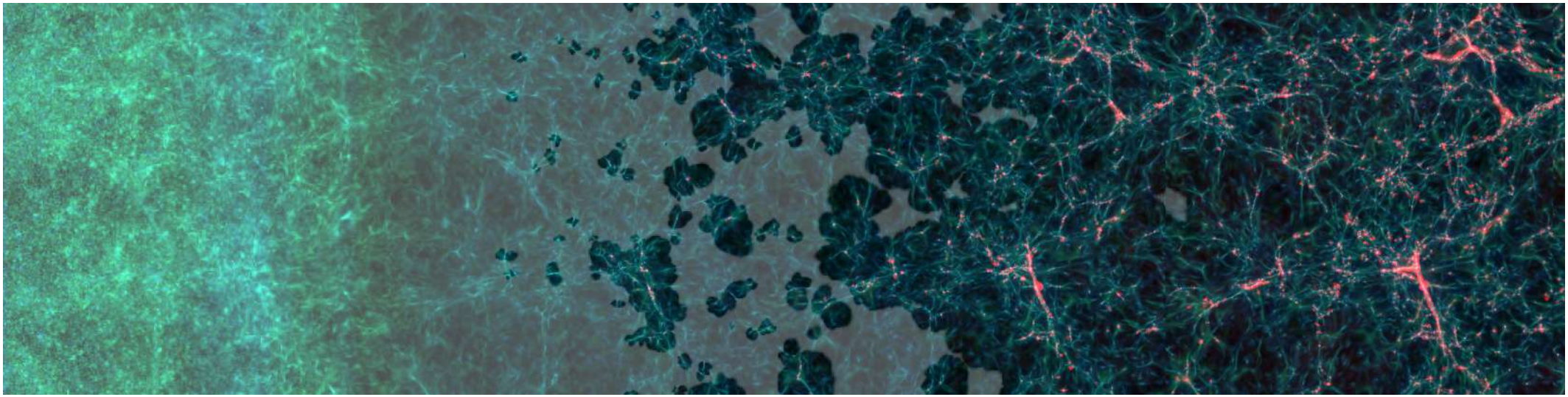
n_e is the number density of free electrons
σ_T is the Thomson scattering cross section

  - $\tau = 0.054 +- 0.007$ (Previously WMAP: $0.089 +-0.014$)
  - Average redshift of reionization: z~8
  - Universe is ionized at less than the 10% level at z>10.
- From the quasars absorption along the LoS: reionization ends at z~6

=> Reionization is extremely rapid and at our fingerprints!

We have now a reasonable handle of when….

The Epoch of Reionisation: what and how?



EMMA simulation, D. Aubert & N. Deparis

… But what and how?…… we don't really know!

Stellar populations vs black holes, IMF in first galaxies, role of supernovae and radiative feedback, metal pollution, efficiency of star formation, IGM structures, UVB evolution etc..

Galaxy candidates have been found out to z~13. Are these the stellar populations responsible for the reionization?

The Epoch of Reionisation: galaxy candidates

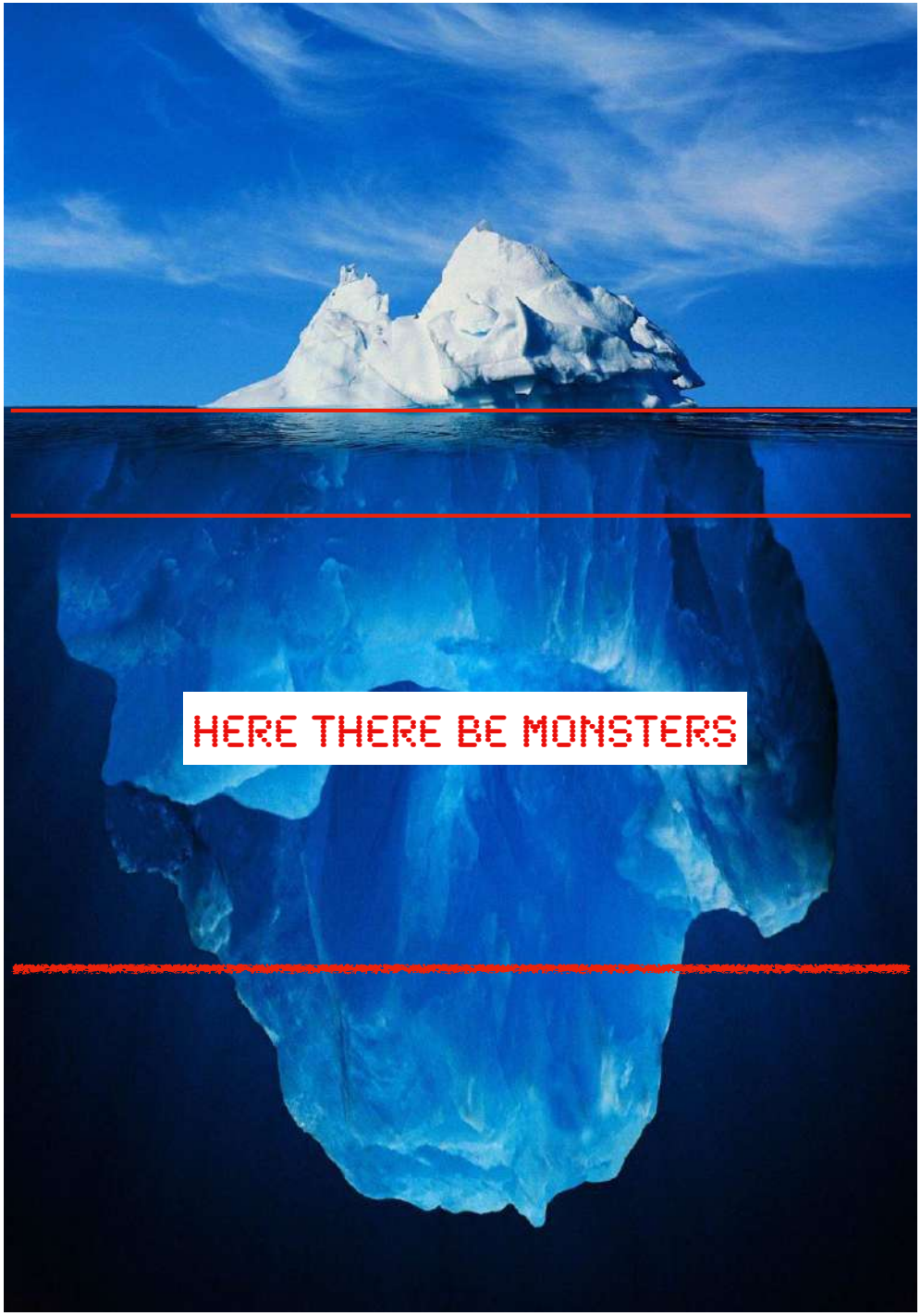
@ z=8

Hubble limit

JWST limit

Hidden population of faint and abundant galaxies?

Complete reionisation



M_{AB}=-22

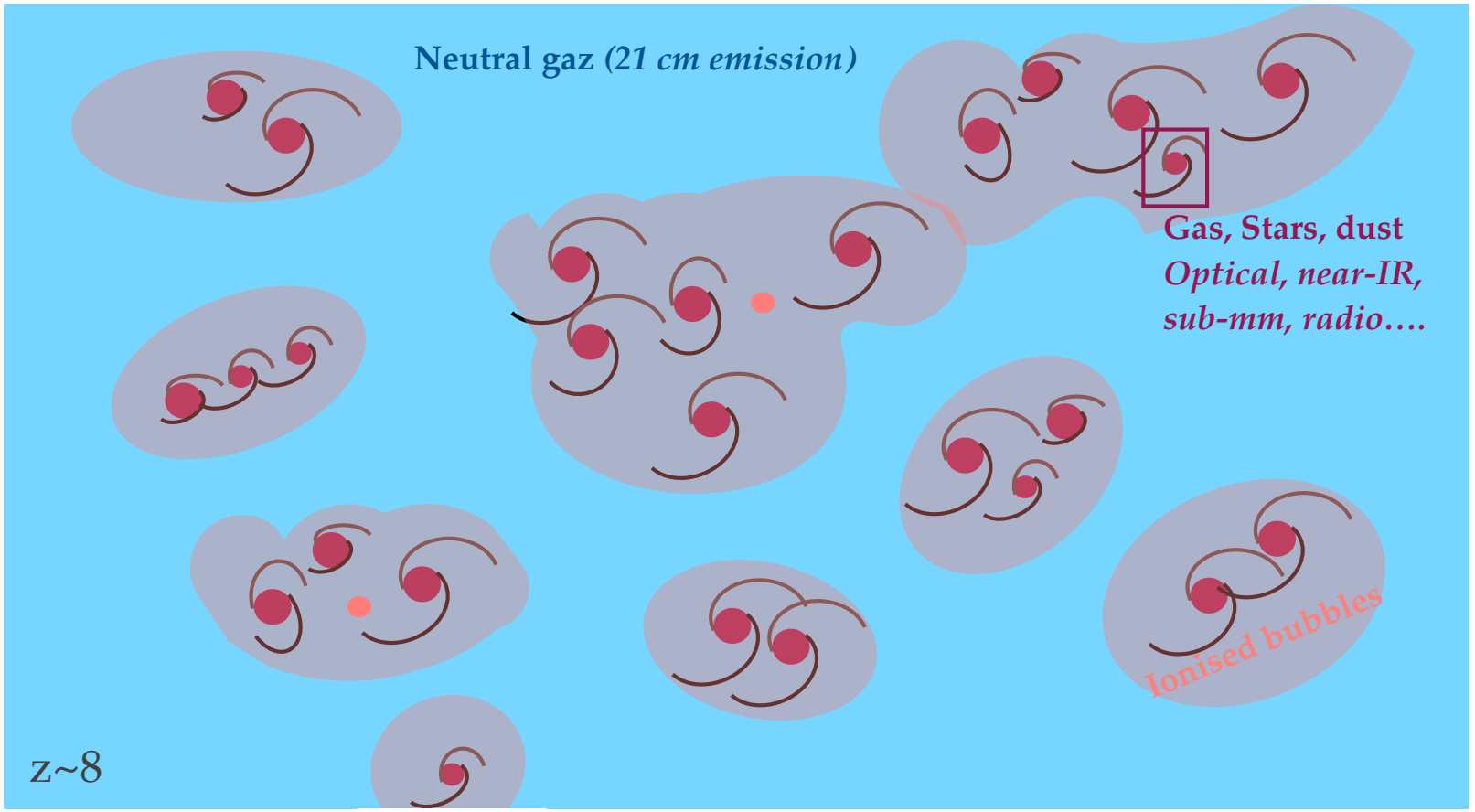
M_{AB}=-18

M_{AB}=-14

M_{AB}=-10

Idea: Mesinger

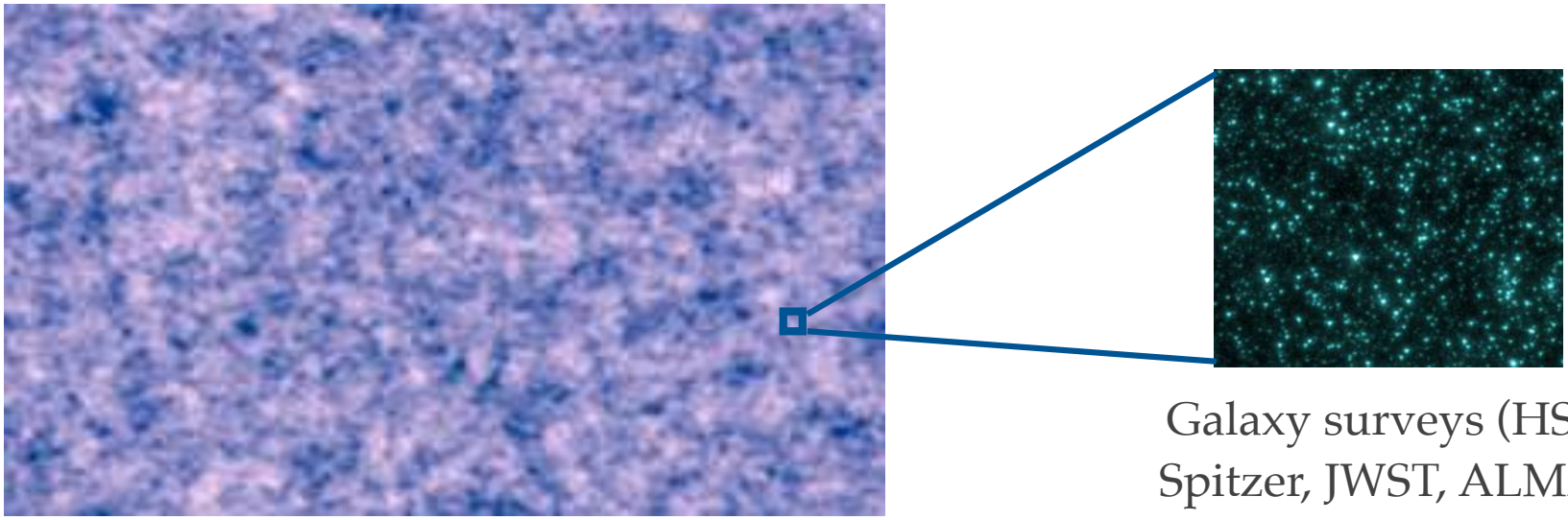
Observing the Epoch of Reionisation



Intensity mapping: basic idea

Measuring the large-scale fluctuations in the emission from a large number of unresolved sources

Intensity mapping: basic idea



Intensity mapping
(confusion-limited surveys)

Galaxy surveys (HST,
Spitzer, JWST, ALMA)

Intensity mapping:

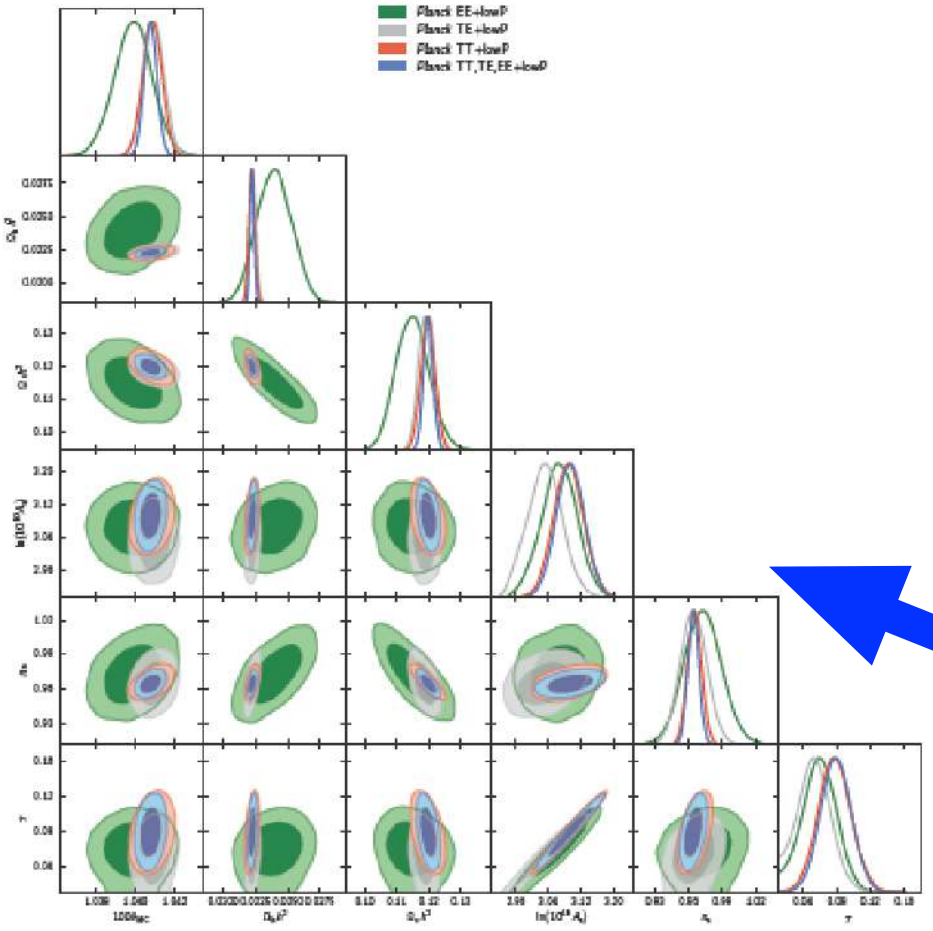
- measure angular fluctuations in the brightness of the sky at a particular frequency

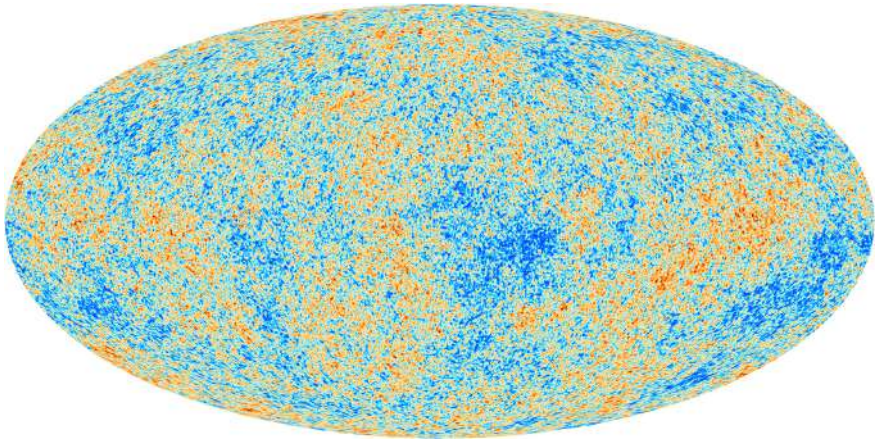
- naturally sensitive to the radiation from faint sources and from the diffuse intergalactic medium

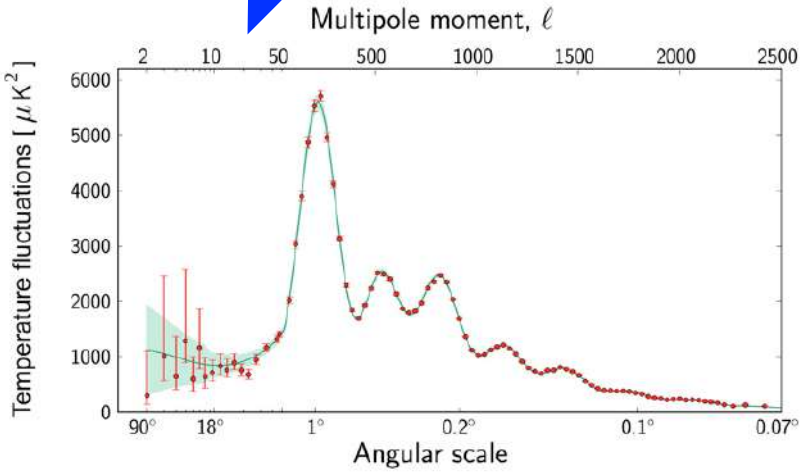
- basic tool : **angular power spectrum**; intensity fluctuations are used to reconstruct the power spectrum of matter fluctuations

2D intensity mapping: CMB

Cosmic Microwave Background, z=1100





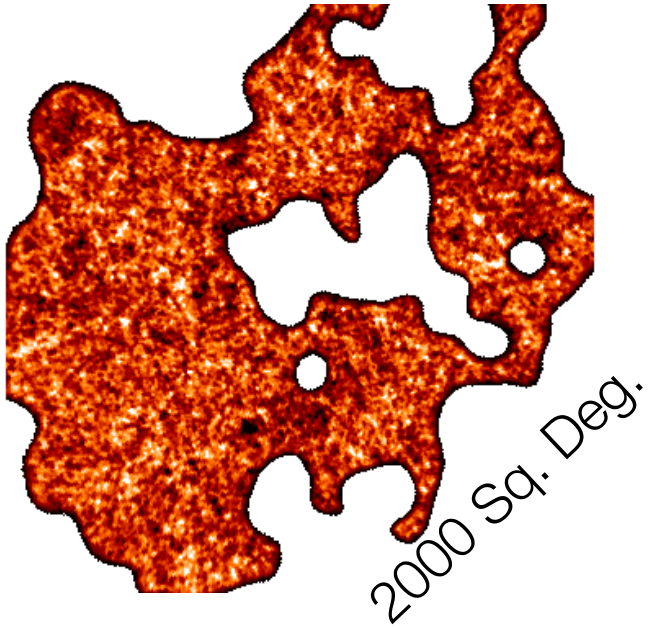


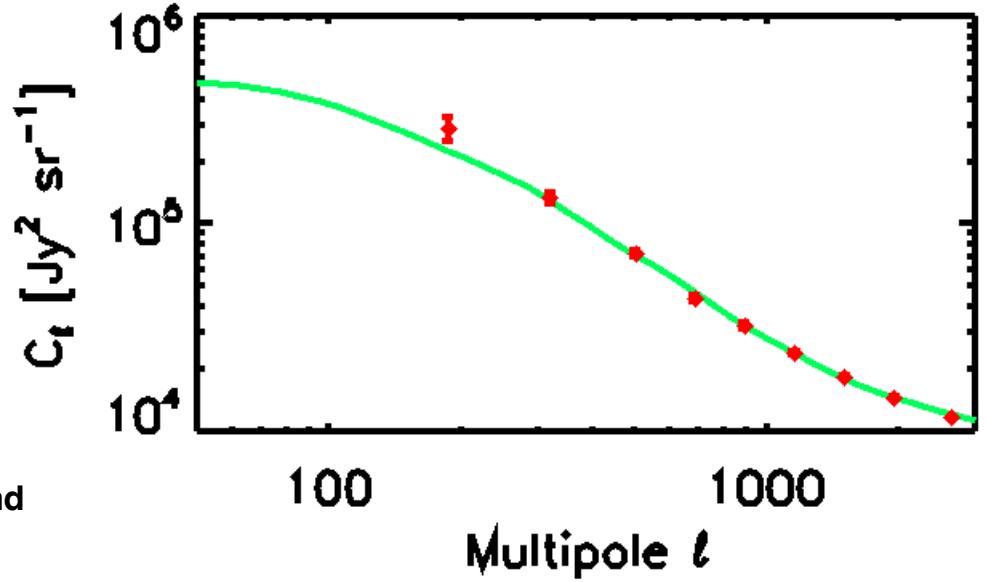
Planck 2013 results. XVI. Cosmological parameters
Planck 2015 results XIII. Cosmological parameters
Planck 2015 results IX. Diffuse component separation: CMB maps
Planck 2015 results XI. CMB power spectra, likelihoods, and robustness of parameters

2D intensity mapping: CIB

Cosmic Infrared Background

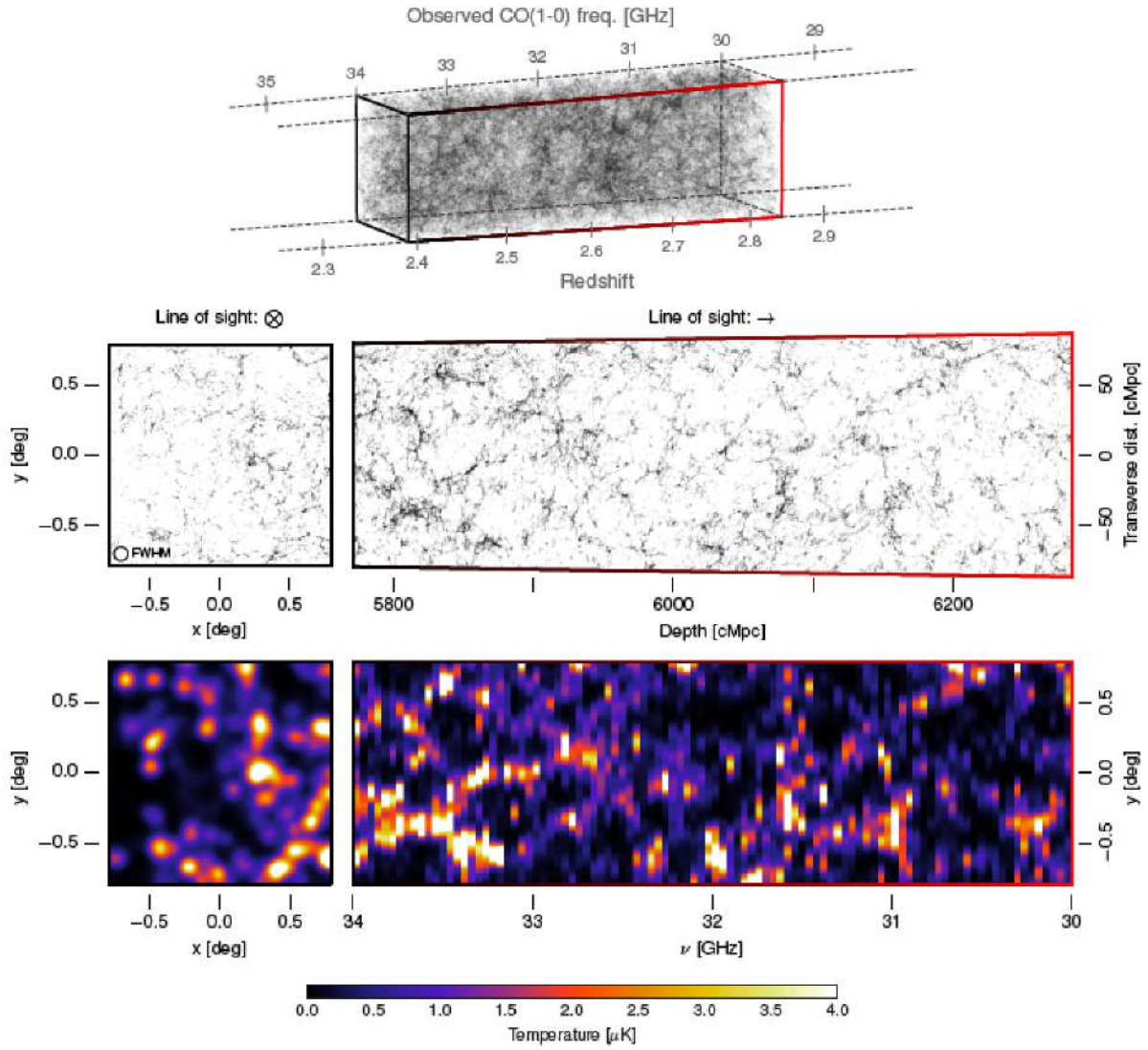
Cumulative far-IR emission from all galaxies throughout cosmic history (all z)





Planck 2013 results. XXX. Cosmic infrared background measurements and implications for star formation

Line intensity mapping (3D)



- Brightness temperature fluctuations on the sky in 3D
- Retain redshift information

$\Rightarrow \delta\nu = 1.5$ GHz corresponds to $\delta z = 0.05$ for [CII] at z=7

Li+2015

Line intensity mapping (3D)

- Lines:
  - CO, [CII], HI, Lyα
- Epoch of Reionization
  - Reasonable handle of when did reionization occur. But what and how?… we don't really know.
  - Evolution of the ionisation structure in the intergalactic medium and reionization sources
  - Ionized regions (bubbles) are large: >20 Mpc, ~20′ at z~9
- Mapping structures at lower redshift & galaxy evolution
  - Density of cold gas versus cosmic time
  - SFRD over cosmic time
  - Star formation efficiency
  - Galaxy assembly
  - Constrain faint populations missing from traditional galaxy surveys

CONCERTO*

A new spectrometer to map the intensity fluctuations of the [CII] line (z>5.2)

LAM, Institut Néel, LPSC, IPAG
And European/Chilean partners (science)

https://mission.lam.fr/concerto/

*CarbON CII line in post-rEionisationand ReionisaTiOn epoch

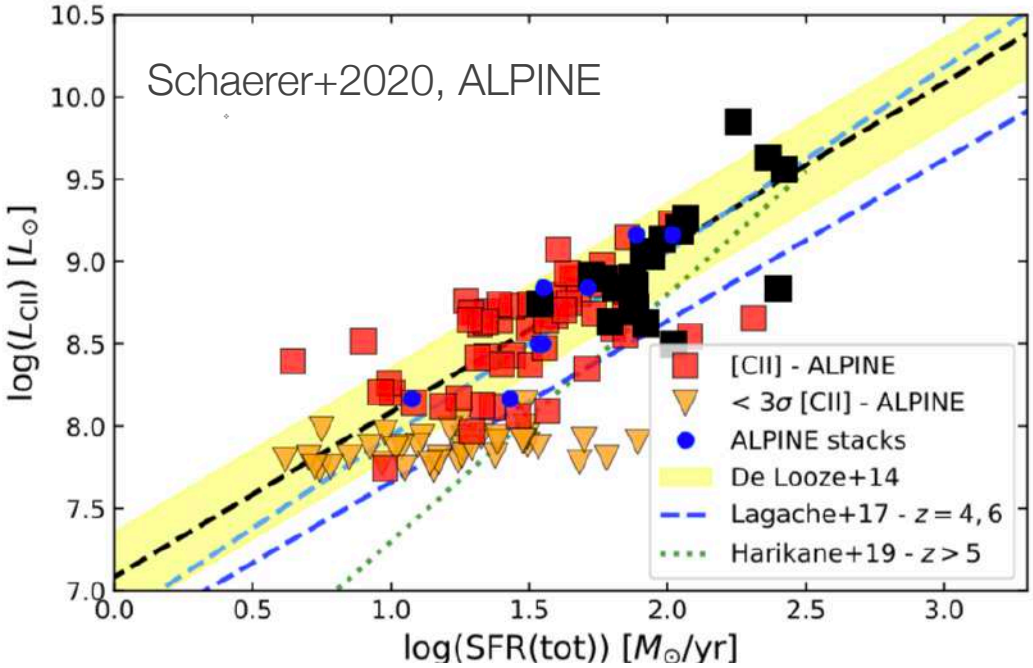
Why [CII]?

- One of the brightest emission lines in the spectra of galaxies
- Redshifted into the sub-mm and mm atmospheric windows for 4.5<z<9
  - APEX/FLASH , ALMA, NOEMA, detect [CII] at very high redshift, pointing on known objects
- Extinction free tracer of star formation
- One of the most valuable tracers of dusty star formation at high redshift (e.g. Lagache, Cousin, Chatzikos, 2018)

ALPINE/ALMA

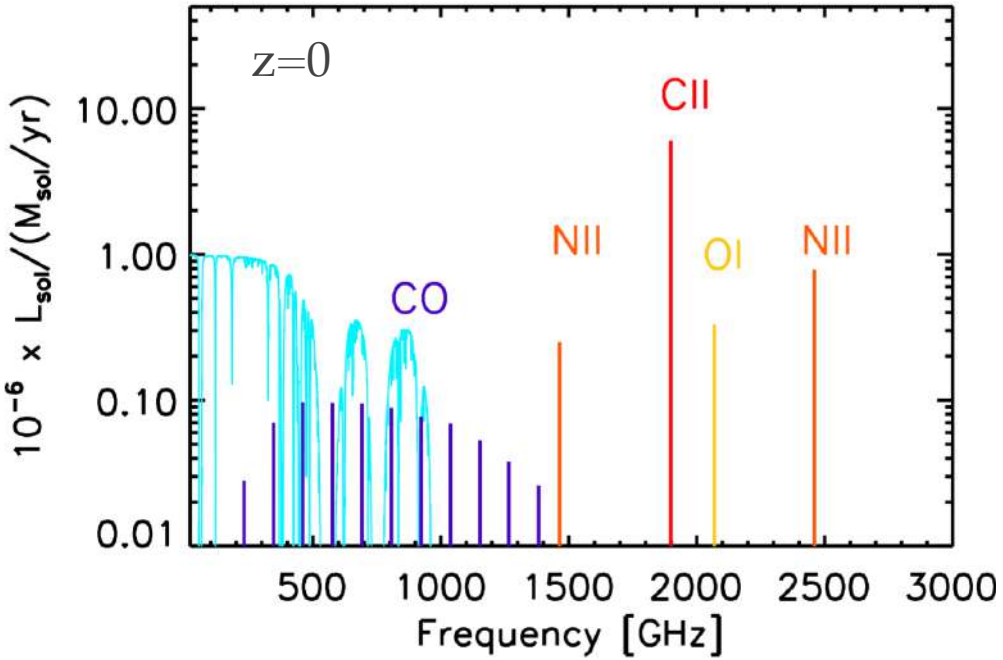
- 118 UV-selected star-forming galaxies at $4.4 < z < 5.9$

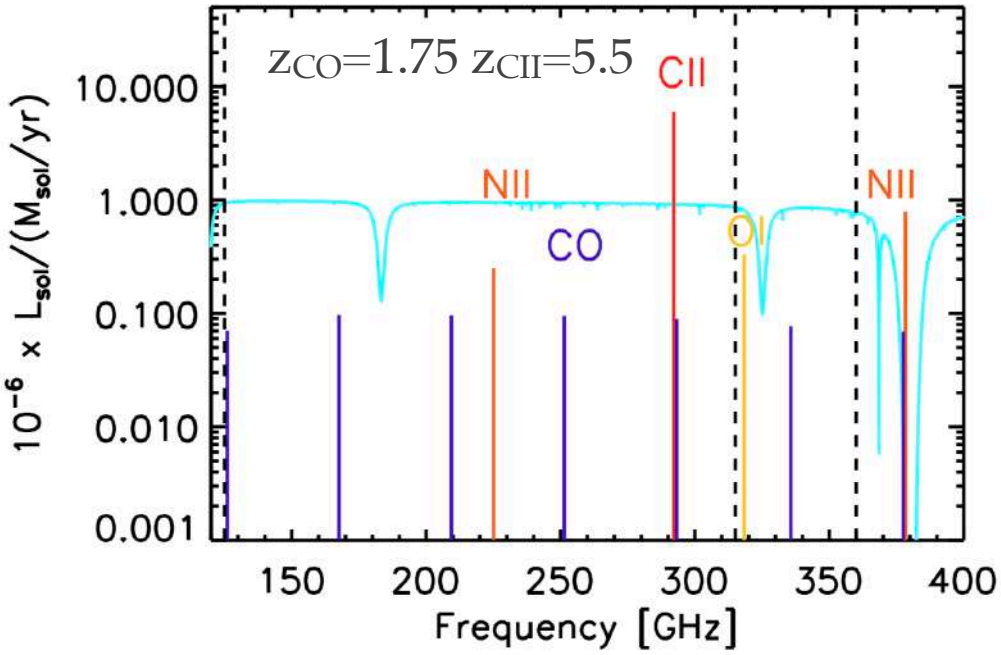
- 75 detected in [CII]



In the mm: [CII], CO, [CI] and dust continuum

CONCERTO= 130 - 310 GHz (2307-958 microns)

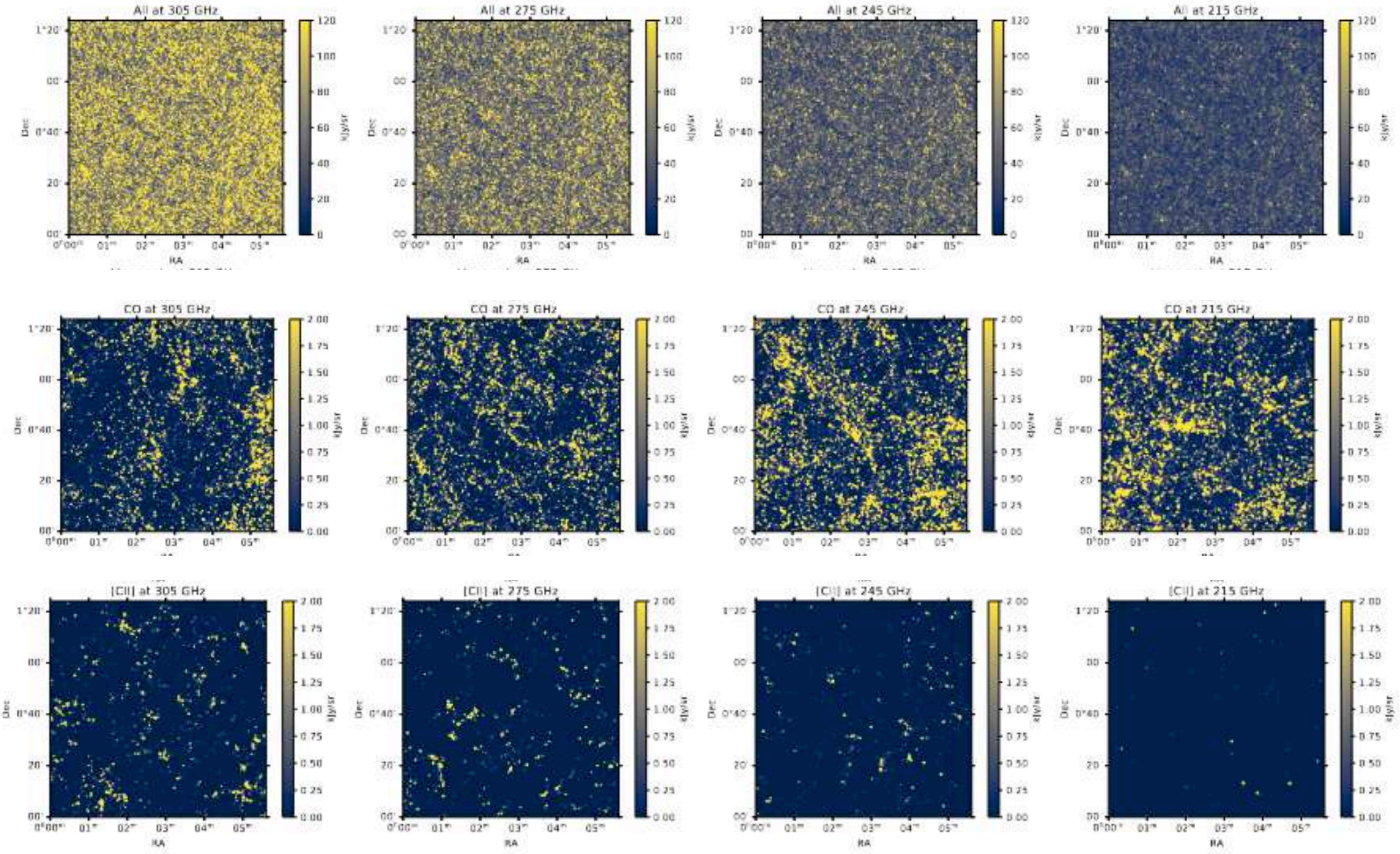




Power spectrum of CO~[CII] at z~5-6

Power spectrum of CO>[CII] by factor 10 to 1000 at z>6

[CII]/CO intensity mapping



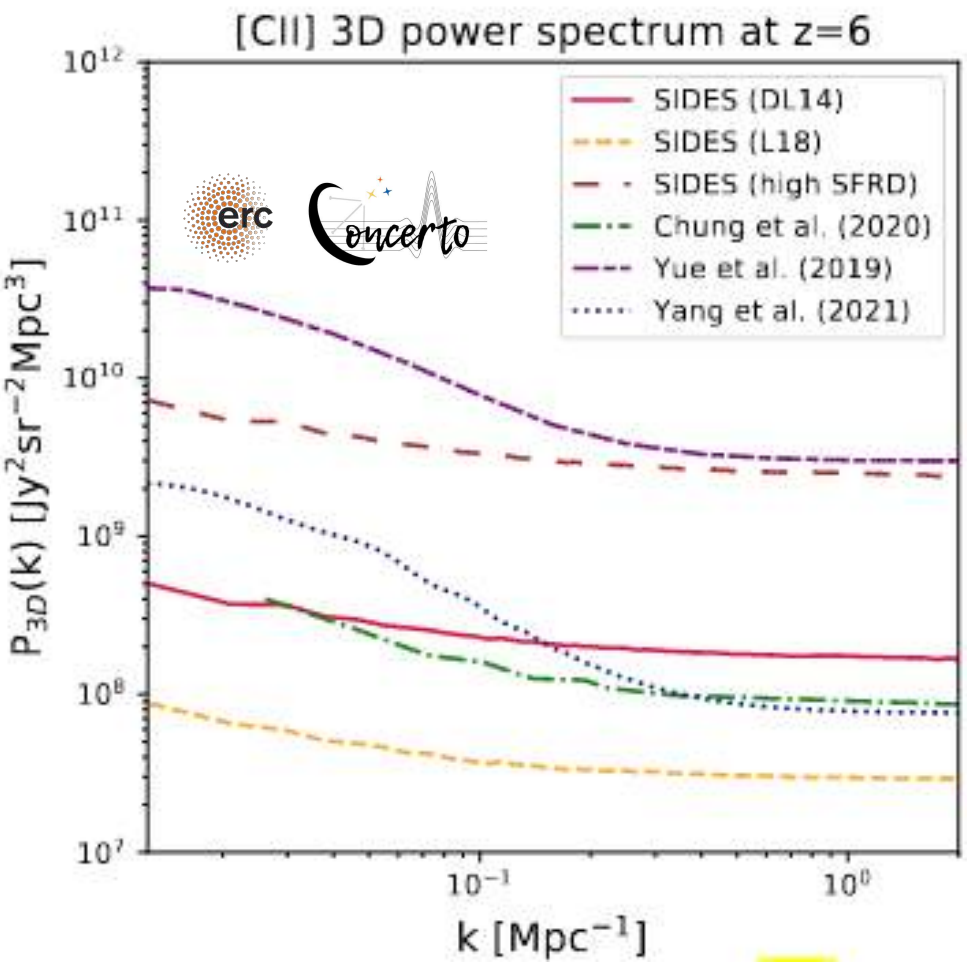
z=5.2

z=7.8

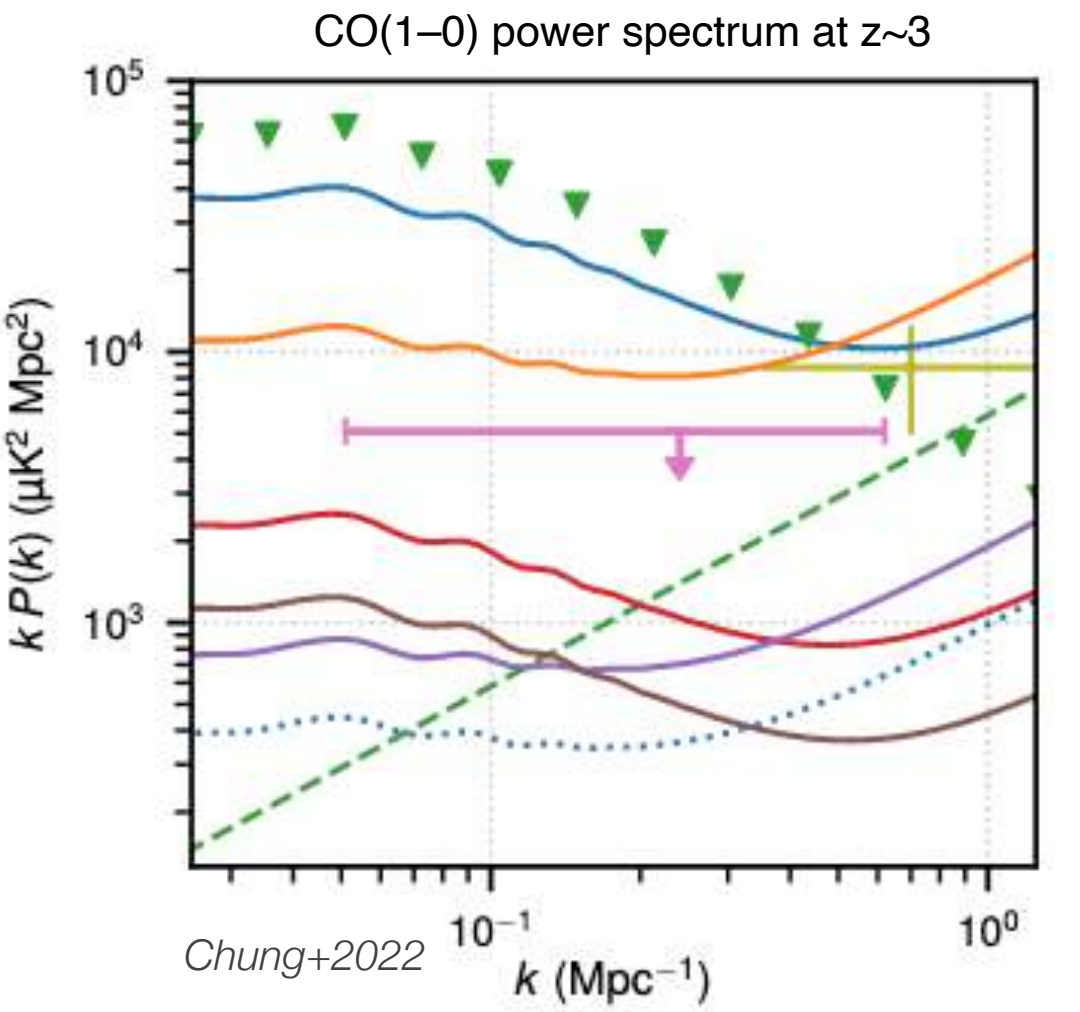
2 Sq. Deg.: Bethermin+2022

117 Sq. Deg.: Gkogkou+2022

[CII]/CO power spectra



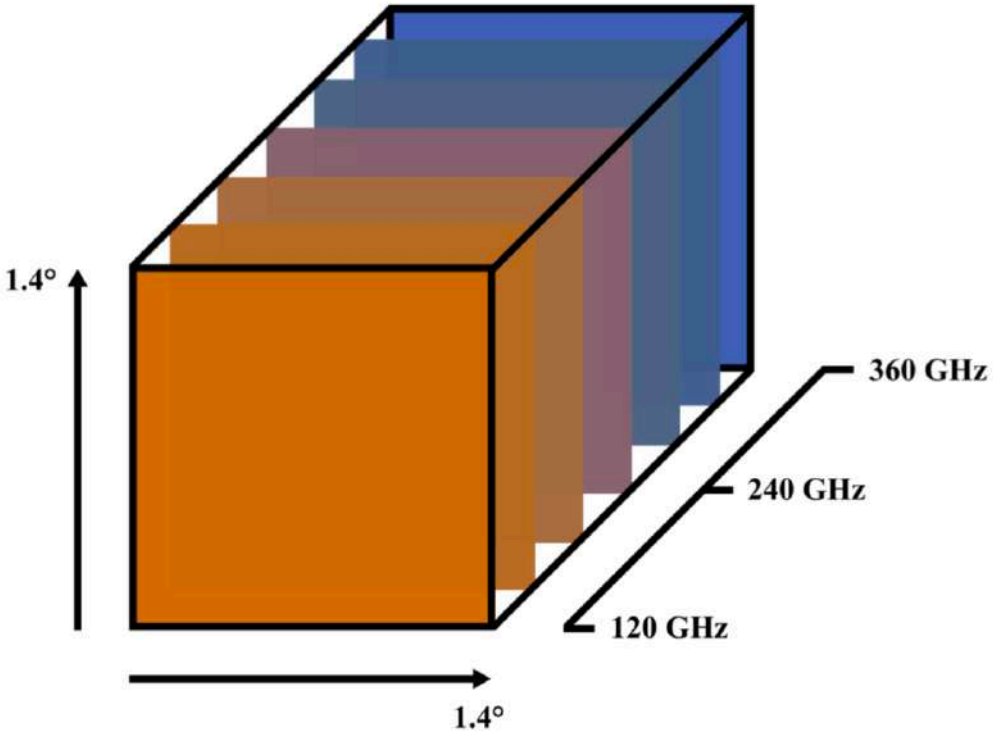
Béthermin+2022



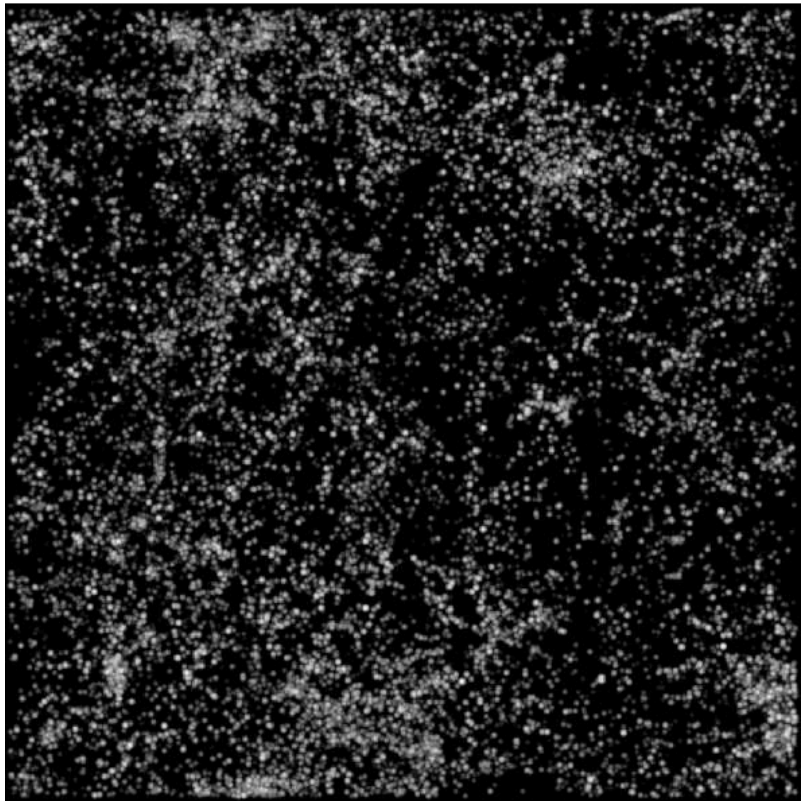
Chung+2022

The [CII] intensity mapping survey

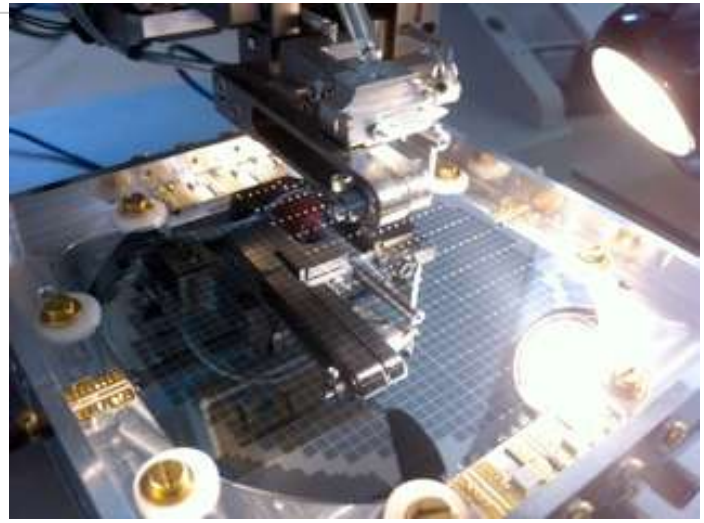
- 1.4 Sq. Deg., ~900 hours, COSMOS field
- The survey will provide a spatial-spectral data cube in which intensity is mapped as a function of sky position and redshift.
- The 3-D fluctuations are then studied in Fourier space with the power spectrum.



300 GHz — CO+[CII]

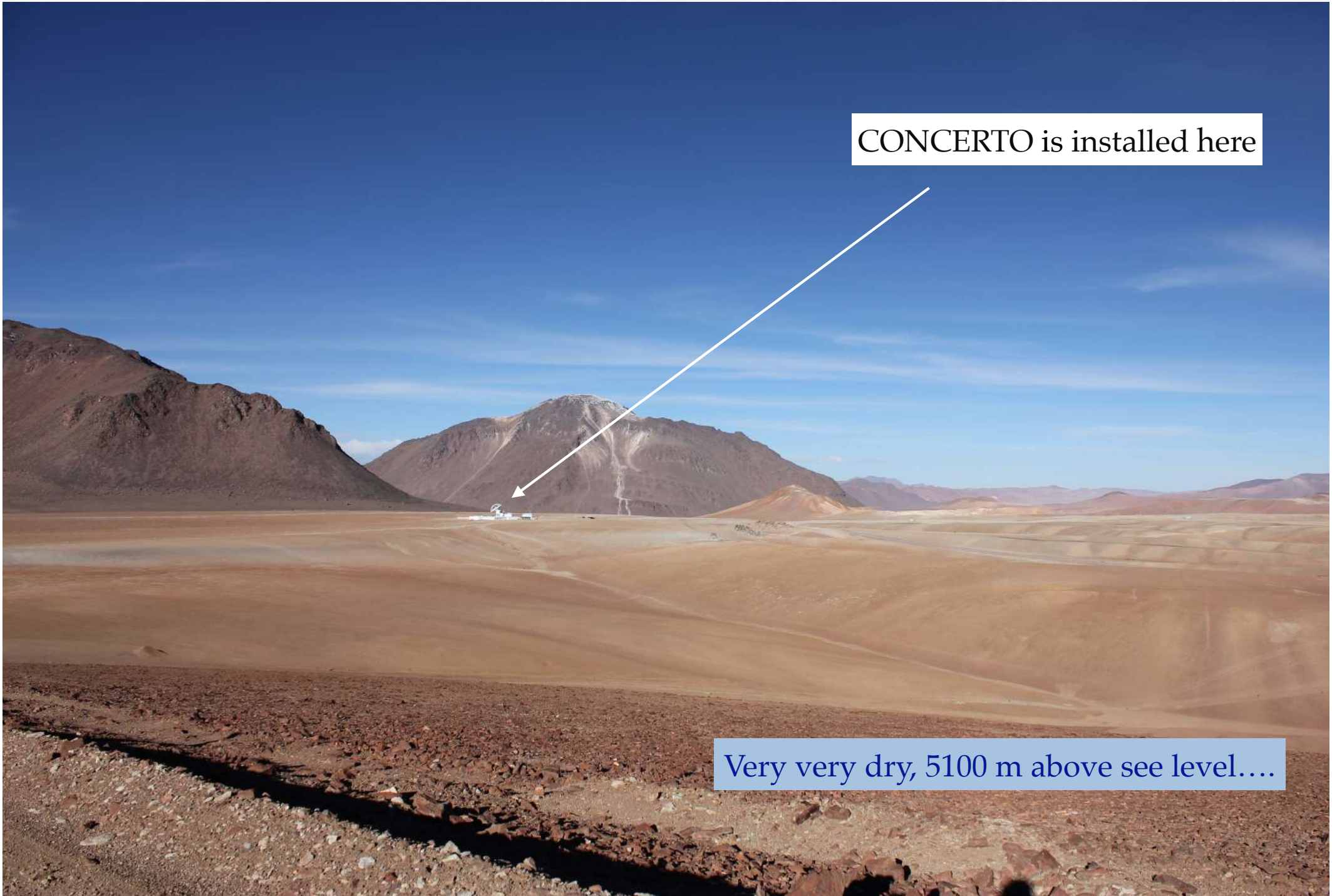


CONCERTO instrument



- Focal plane:
  - Kinetic Inductance Detectors (KID)
  - Success of the NIKA2 IRAM camera
  - FOV D=18'6, fλ sampling => arrays of 2,152 pixels
- Cryostat:
  - Closed-circle 3He-4He dilution - 100mK
  - The 4K stage (required for initiating the 3He-4He dilution) is achieved using a standard two-stages pulse-tube
- Martin-Puplet interferometer (like a Michelson interferometer but with a movable mirror)
  - Outside the cryostat
  - Spectral resolution (ν/δν): R=100 to 300
  - Perform continuously path interferograms at a frequency of few Hertz or more (2-5Hz)
    - Faster than most of the sky noise - only possible with KIDS
  - "Nominal": 4 interferograms for all pixels of the matrix every second
- A « sub-mm » antenna:
  - APEX telescope, in a very dry area, θ=23" at 305 GHz
  - Frequency range: two arrays, 195-310 GHz for the HF and 130-270 GHz for LF

CONCERTO @ APEX

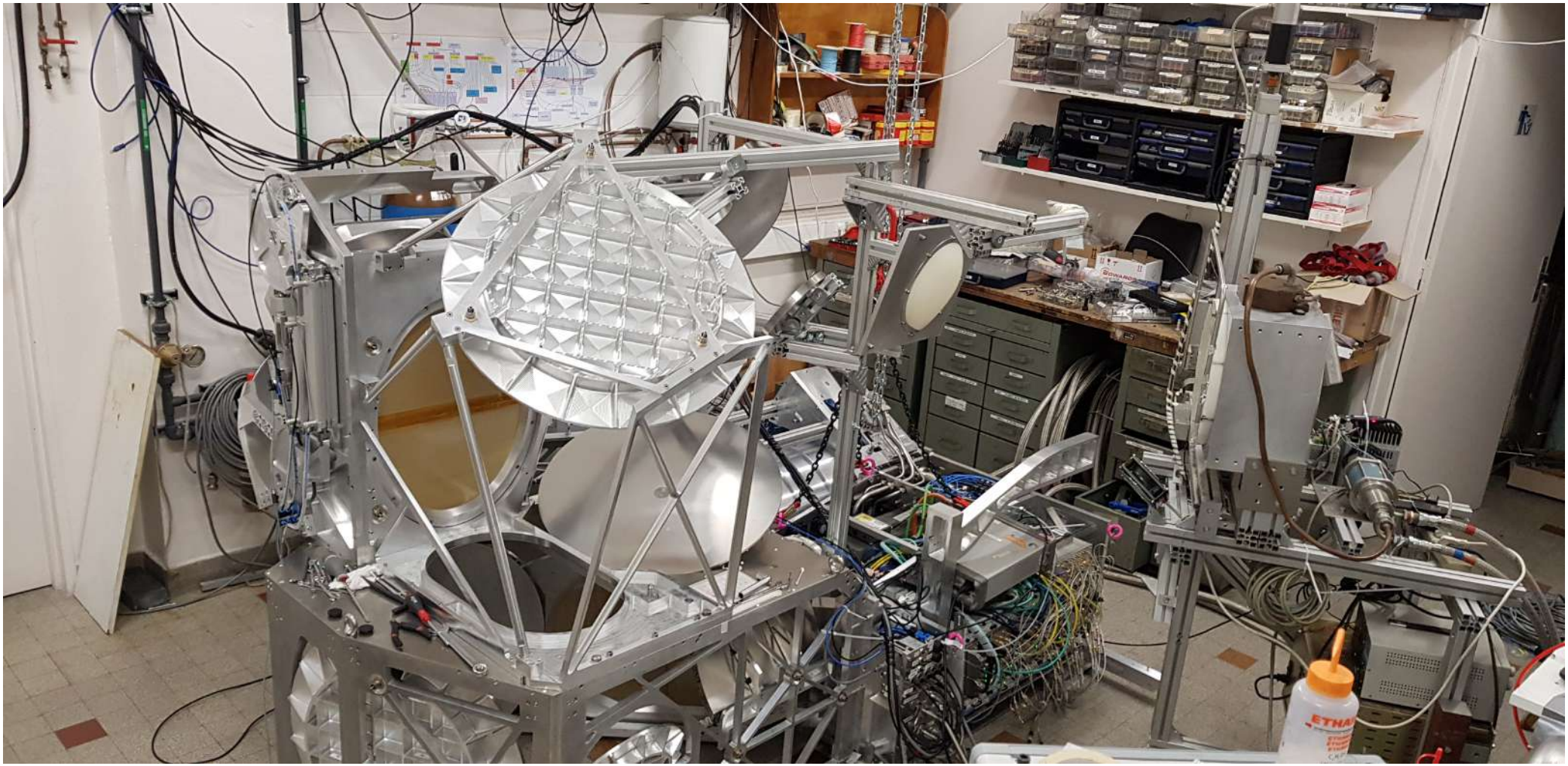


Project history

- Funded by:
  - A*MIDEX University Foundation (2018-2021)
  - ERC AdvGt LAM@Marseille and Institut Néel@Grenoble (2019-2024)
  - And support from our labs
- Visit in Chile in Apr 2018
- Preliminary Design Review (Feb. 2019)
- June 2019: the cryostat is being built
- Critical Design Review: Jan 2020 / Final Design Review: Feb 2020
- In Lab intense “observing” campaign: ~1rst/11/2020 - 20/02/2021
- 01/03/2021: CONCERTO left Grenoble
- Papers, papers and papers (mission, shipment, etc) - I recommend: https://www.ulisse.cnrs.fr/concerto-apex-separes-de-12-000-km/ !
- Installation at APEX started on April, 2021, the 6th

CONCERTO: instrument is complete! (20/10/20)

ERC approval: Feb 2018 — PDR: Feb 2019 — FDR: Feb 2020 — Installation: April 2021



"A wide field-of-view low-resolution spectrometer at APEX: Instrument design and scientific forecast"

The CONCERTO collaboration, A&A 642, 2020

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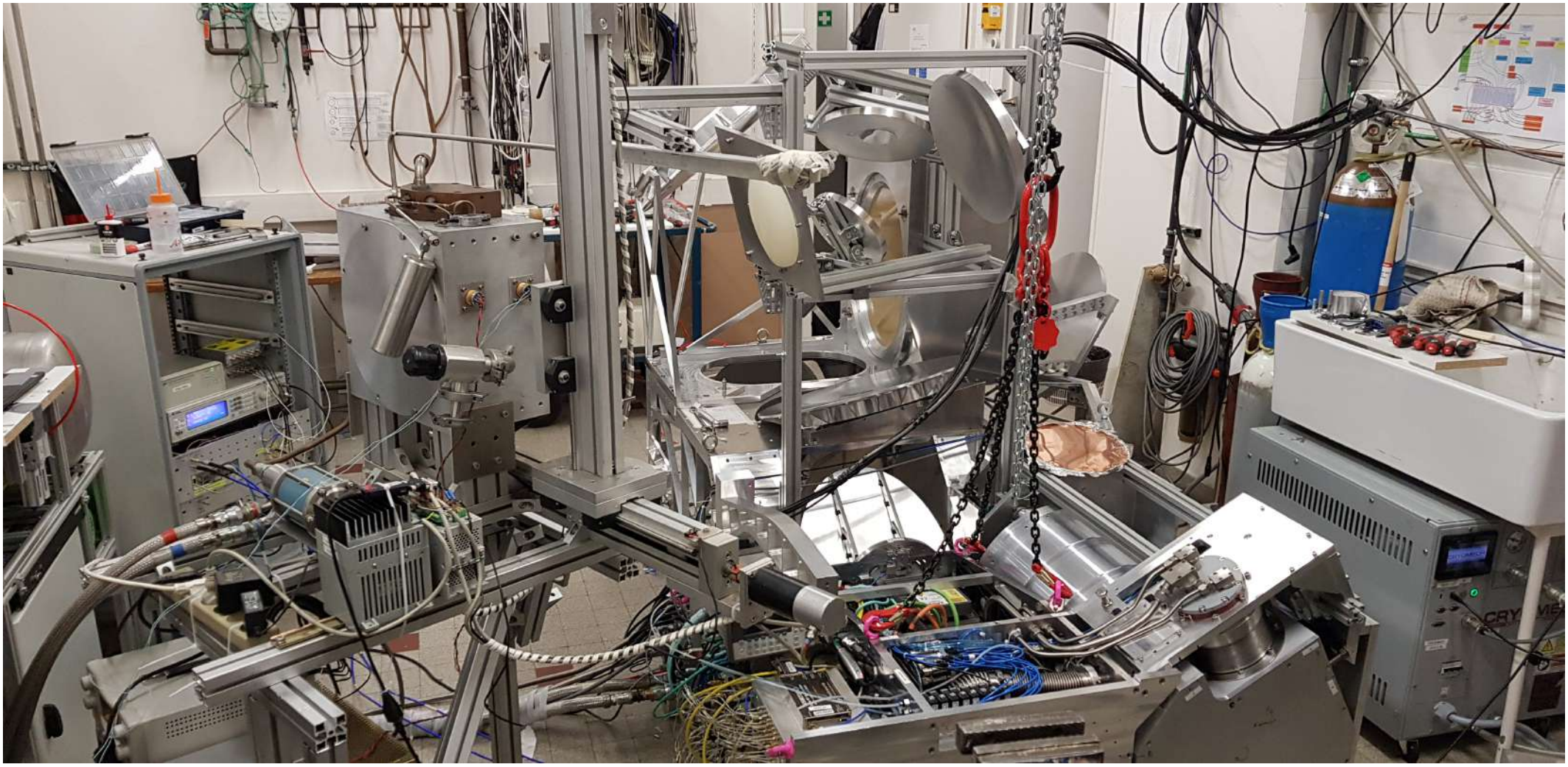
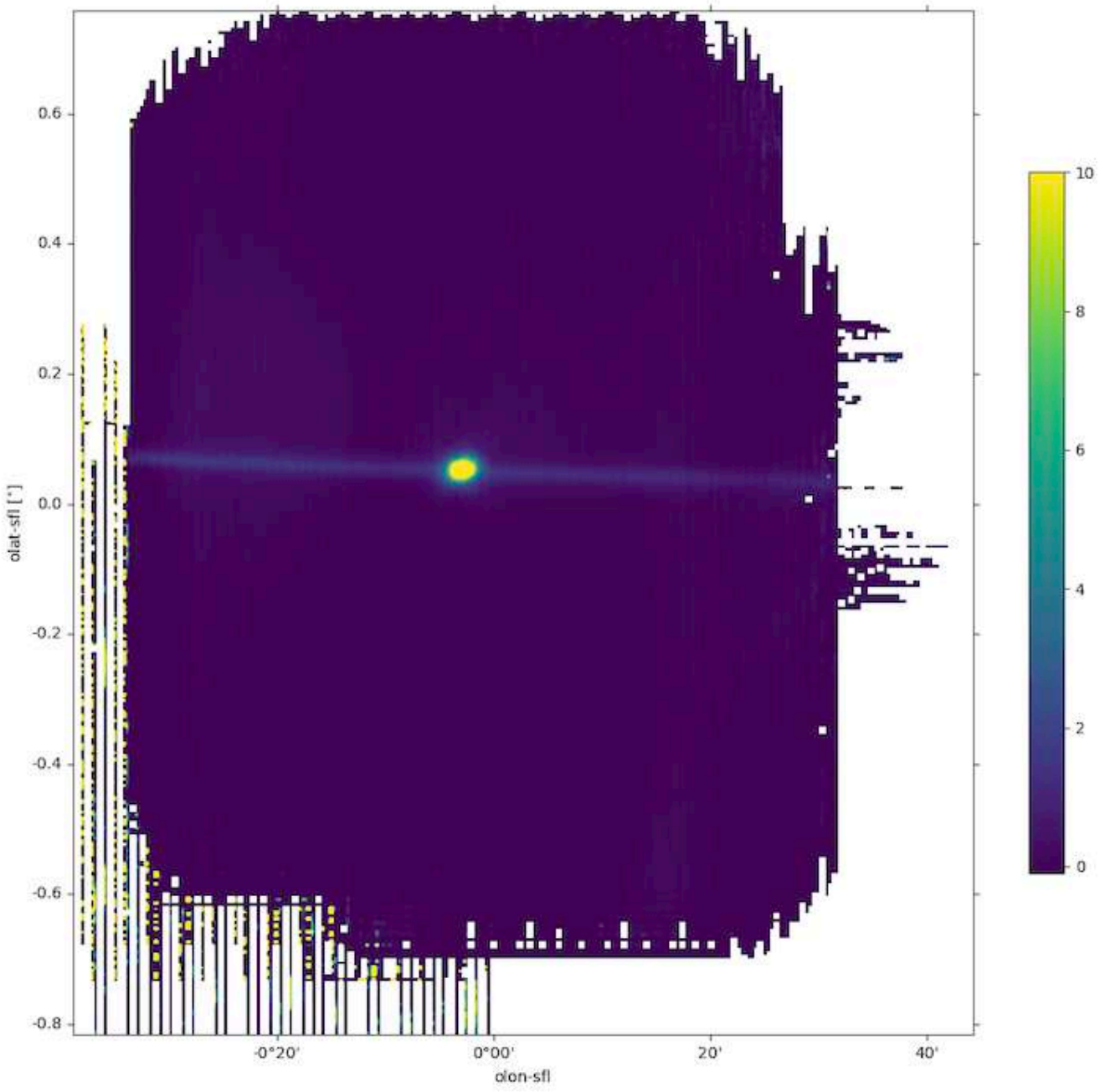


"A wide field-of-view low-resolution spectrometer at APEX: Instrument design and scientific forecast"

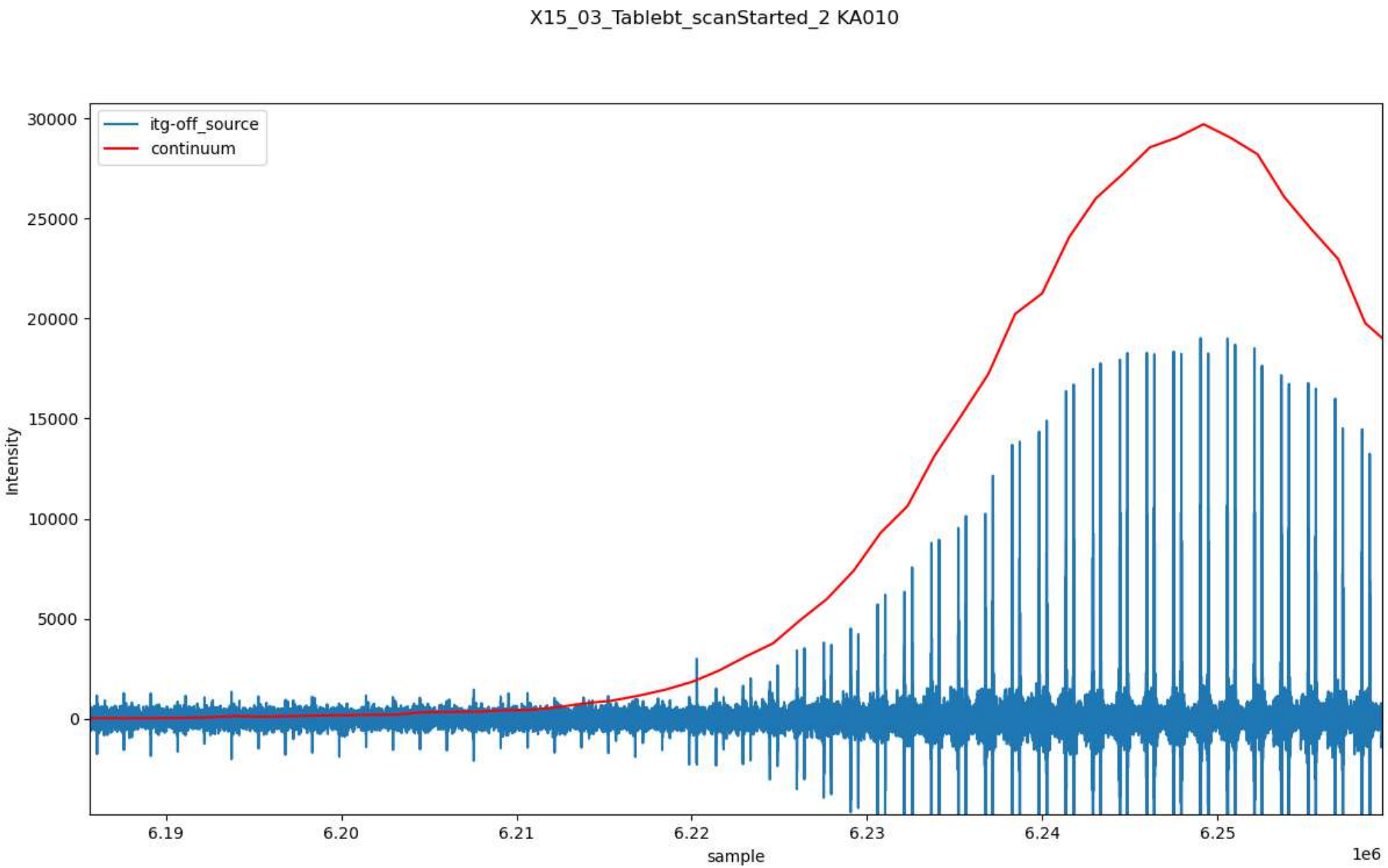
The CONCERTO collaboration, A&A 642, 2020

CONCERTO: First light in lab!

16 November 2020



CONCERTO: efficiency in lab



From Alex Beelen

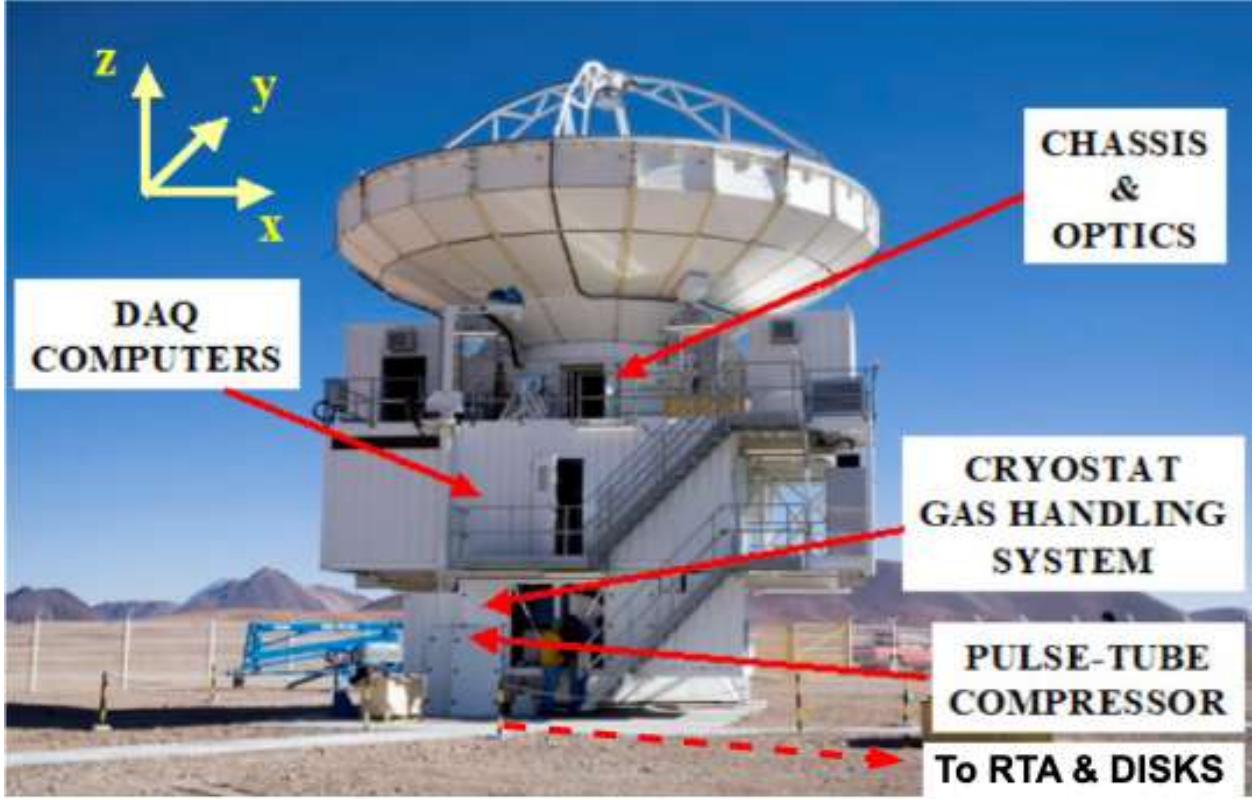
Installation and commissioning

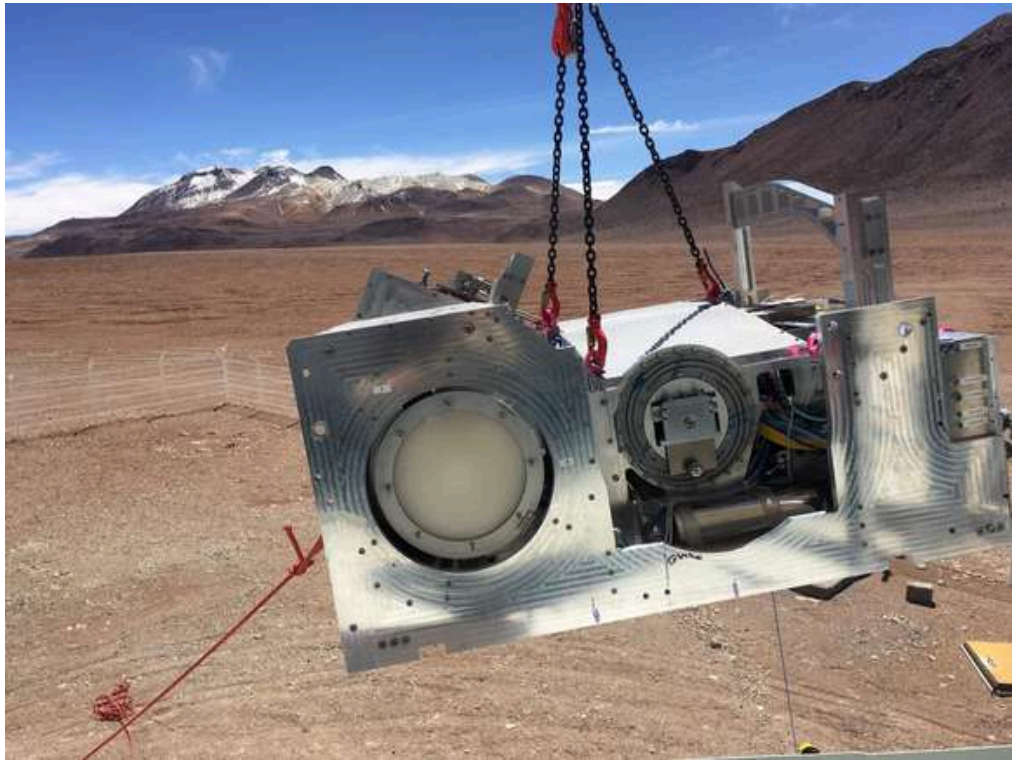
Shifts APEX « Feb 2020 », « O », « P », « Q » and « R »

(Feb. 2020 plus 25/03/2021 to 06/05/2021)

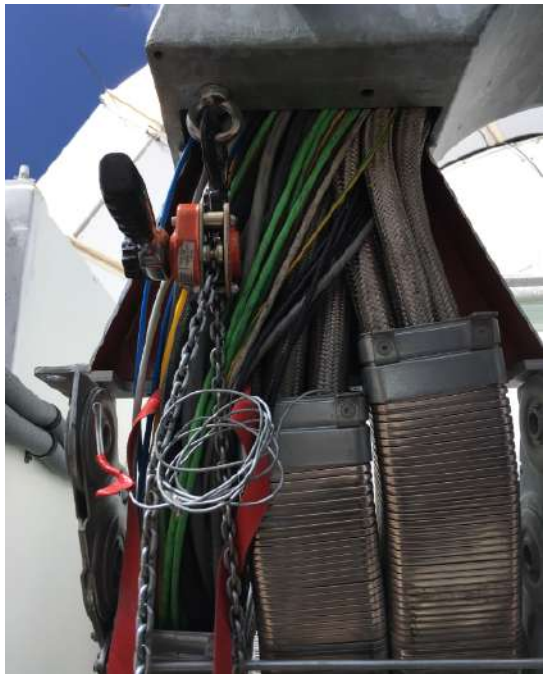
Slides (from A. Monfardini)

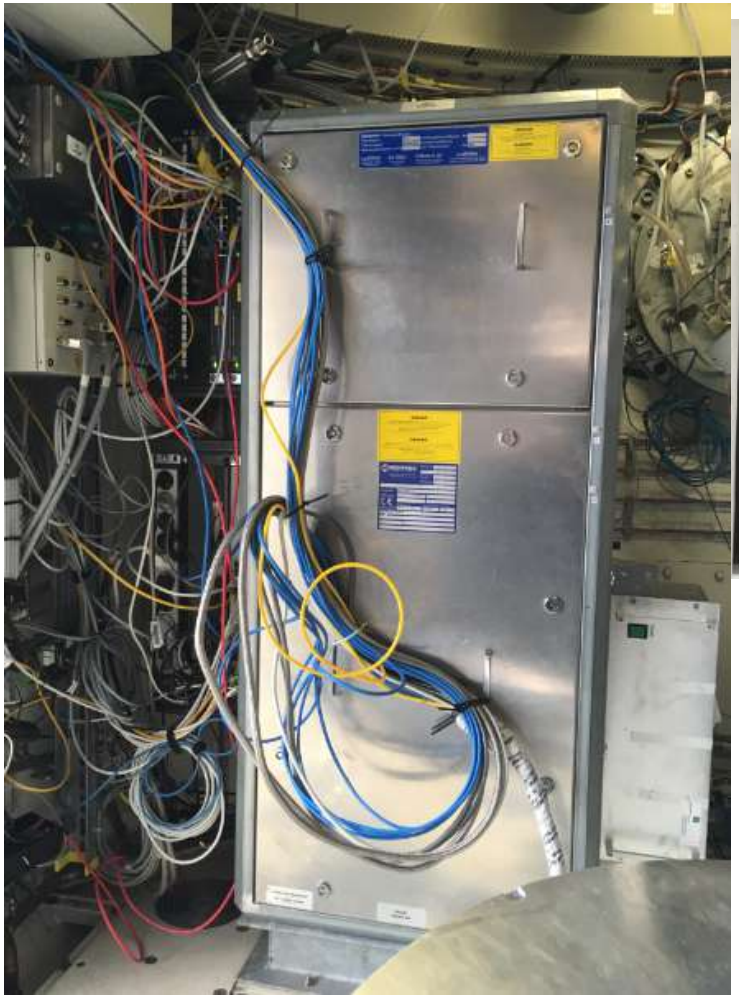
presented at the APEX board on May the 6th


z
y
x
CHASSIS
&
OPTICS
DAQ
COMPUTERS
CRYOSTAT
GAS HANDLING
SYSTEM
PULSE-TUBE
COMPRESSOR
To RTA & DISKS



Pre-installation (February 2020)





Preparation of all the links (electrical, network, pneumatic, helium, vacuum..) in the telescope tower

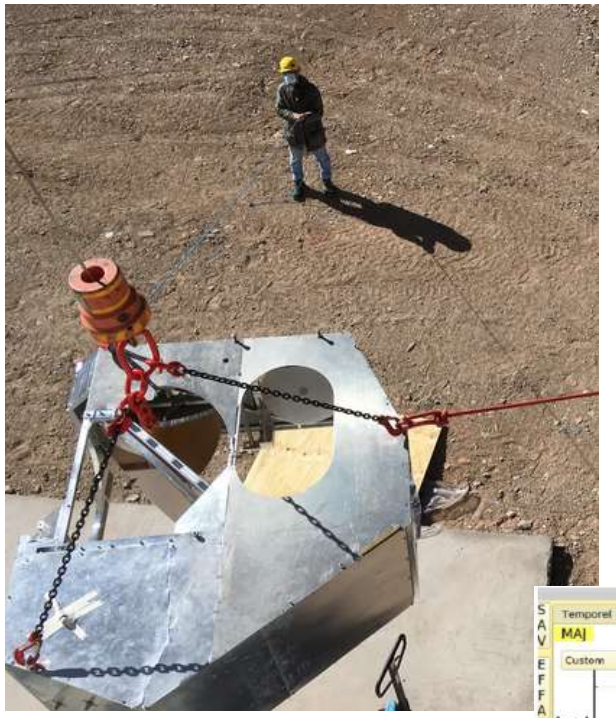
Shift « O » - 25/03/2021 to 04/04/2021

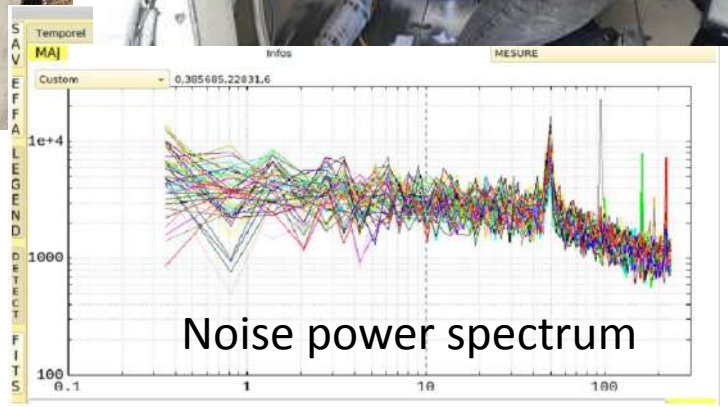
Boxes reception and storing — Opening boxes 4 AND 5 to extract compressor, gas handling system and bars

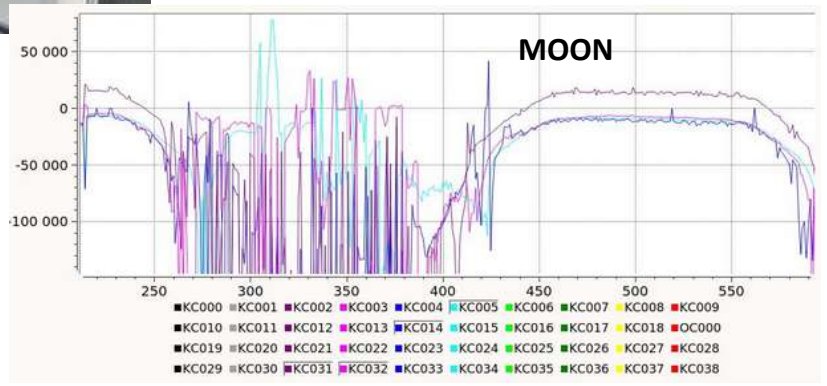
MORE: Preparation of plugs, rough test of bars, placing of the PT compressor and gas handling system in the compressors room …

Thanks to all the APEX engineers for their help!

Shift « P » - 06/04/2021 to 15/04/2021





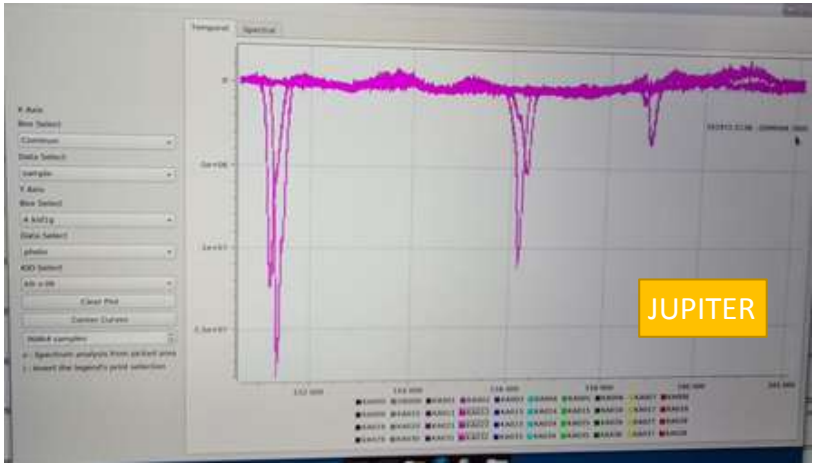


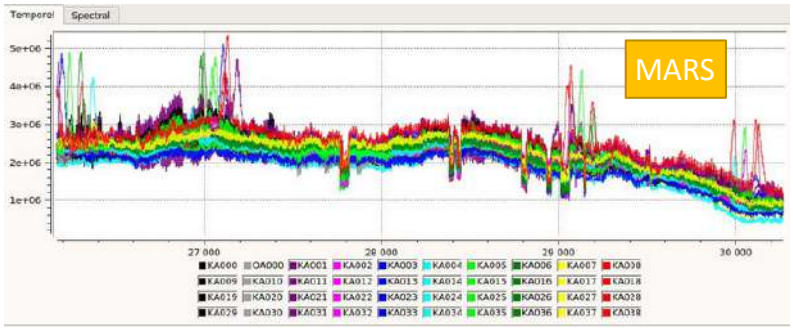
MOSTLY: Unpacking, installation in the C-cabin, instrumentations and compressors containers, connection, cooling-down, first technical light on Sky and Moon, running underground cables

→Cryostat cold, resonances OK, noise floor OK, 50Hz noise observation (not present with cap), seen response from Skydip, observation of the Moon.

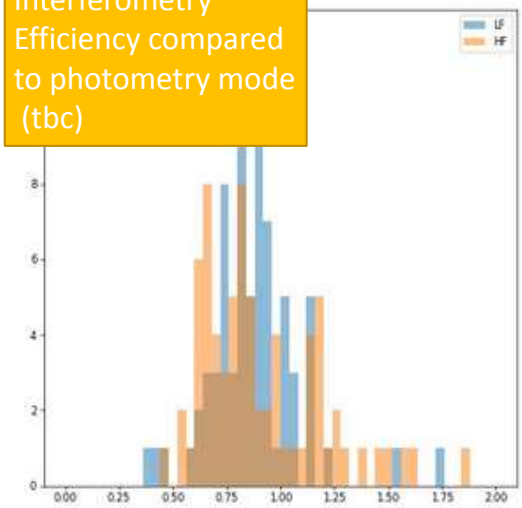
Shift « Q » - 17/04/2021 to 25/04/2021

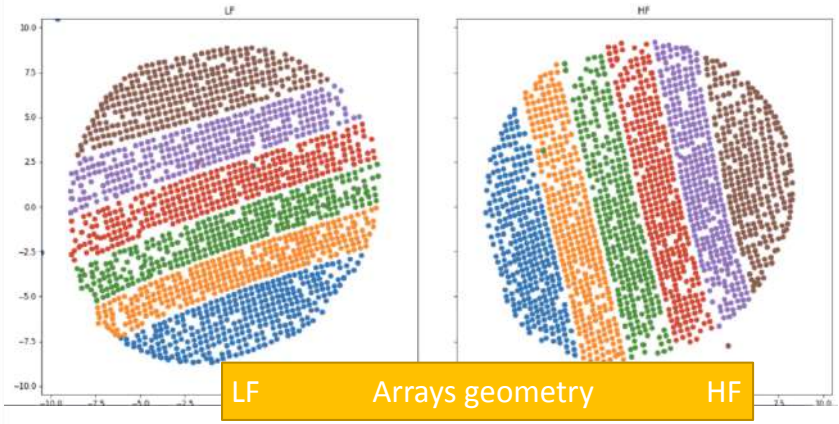
Electronics maintenance

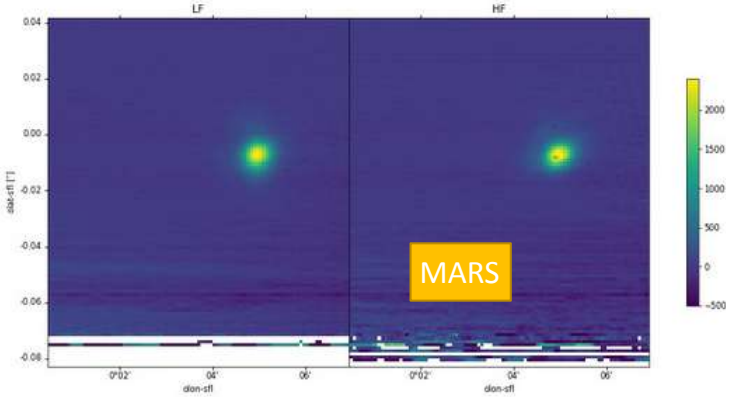




Interferometry Efficiency compared to photometry mode (tbc)





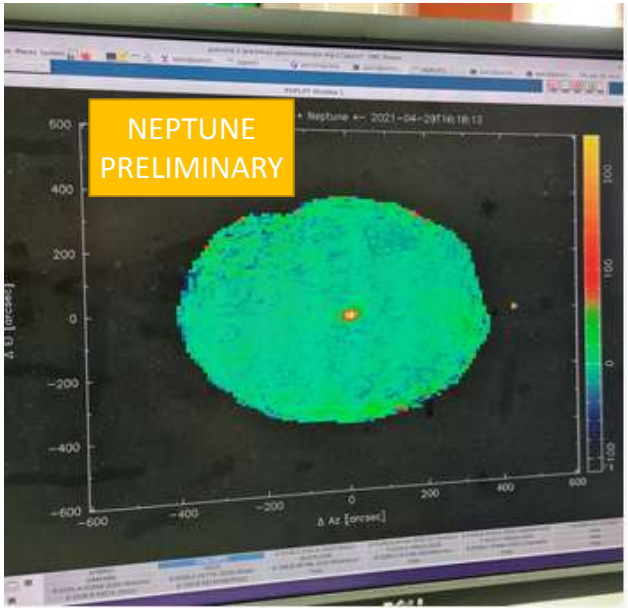


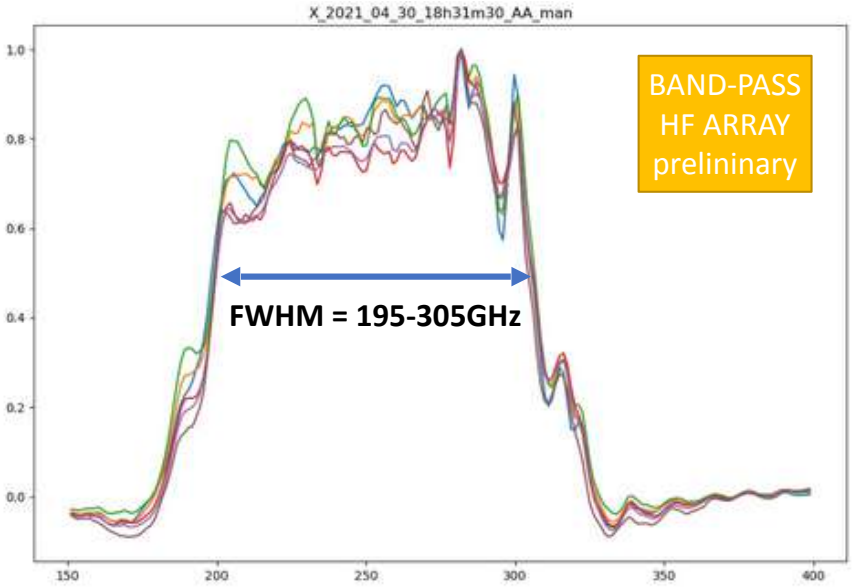
MOSTLY: installation in servers room, detectors settings, alignments, fixing various electronics problems, first focussed light, investigation of 50Hz noise, geometries, DAQ debug etc.

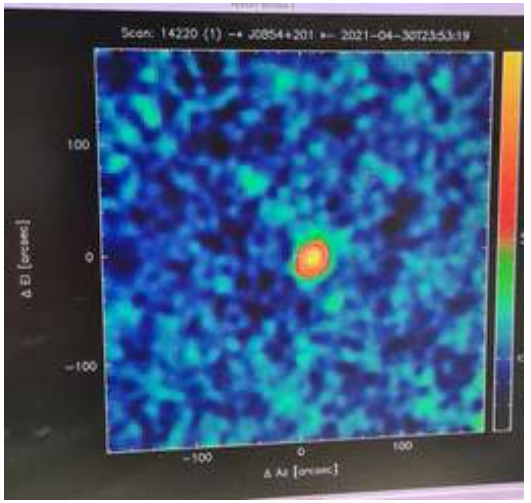
→Identified the MENERGA origin for part of the 50Hz noise, seen Jupiter and Mars, detectors response OK, fixed problems on electronics, interferometry is good, geometries

…

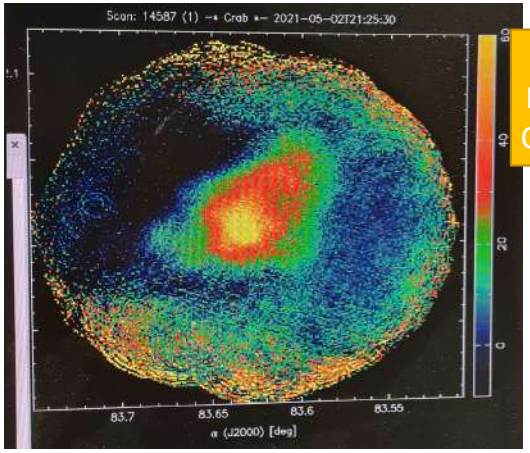
Shift « R » - 27/04/2021 to 06/05/2021







J0854+201 – 2.5Jy @233GHz
Pointing scan 35 seconds
(start of pointing run)

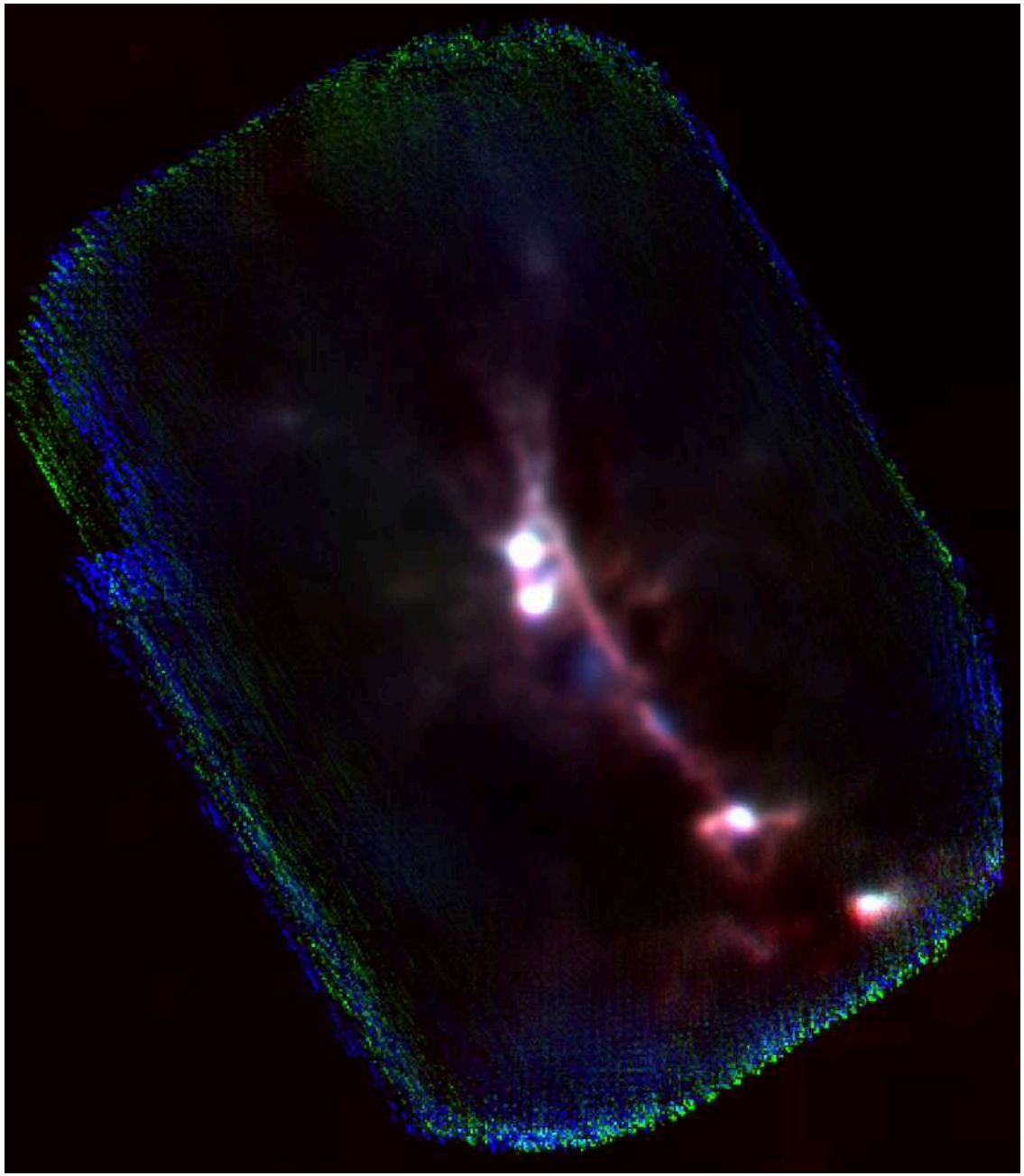


MOSTLY: observations, investigation of 50Hz noise, software, data analysis, pointing model

→Observed some fainter and extended sources, focus, bandpass HF is OK, bandpass LF on-going, pointing model…

→Demonstrating remote observations

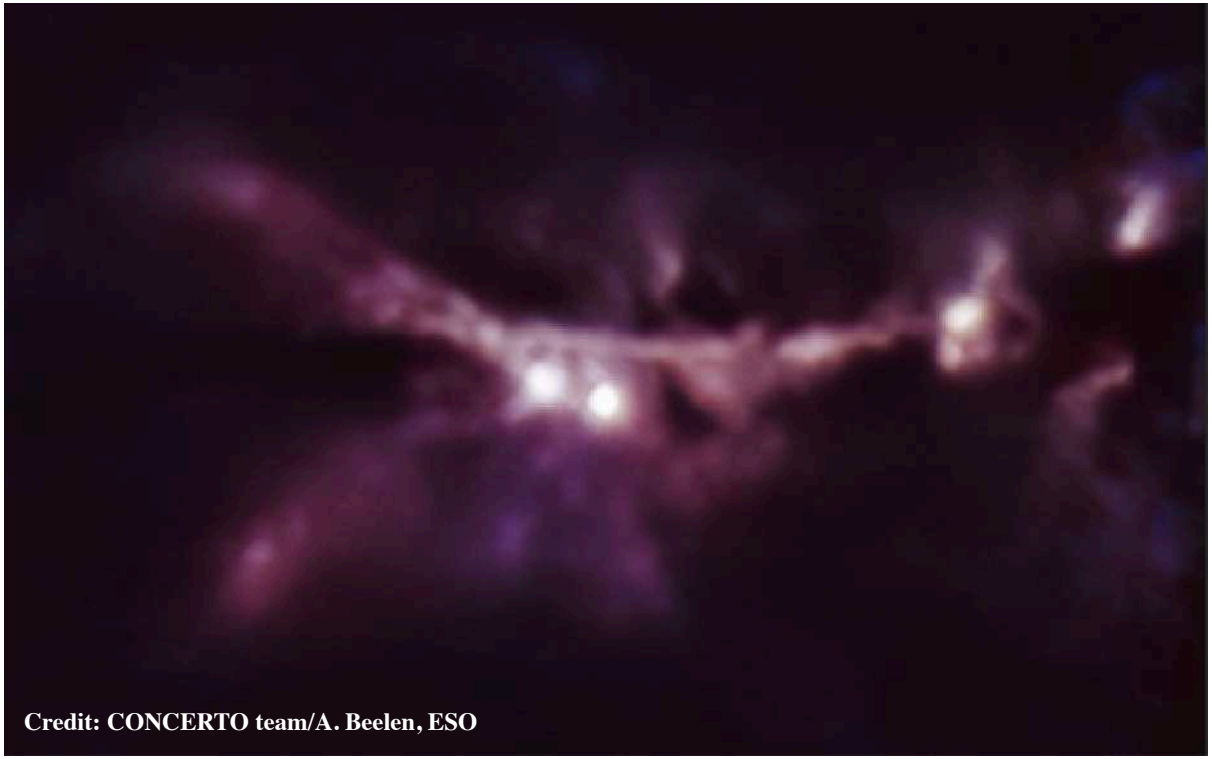
NGC6334 – Mapping demonstration (4 May)



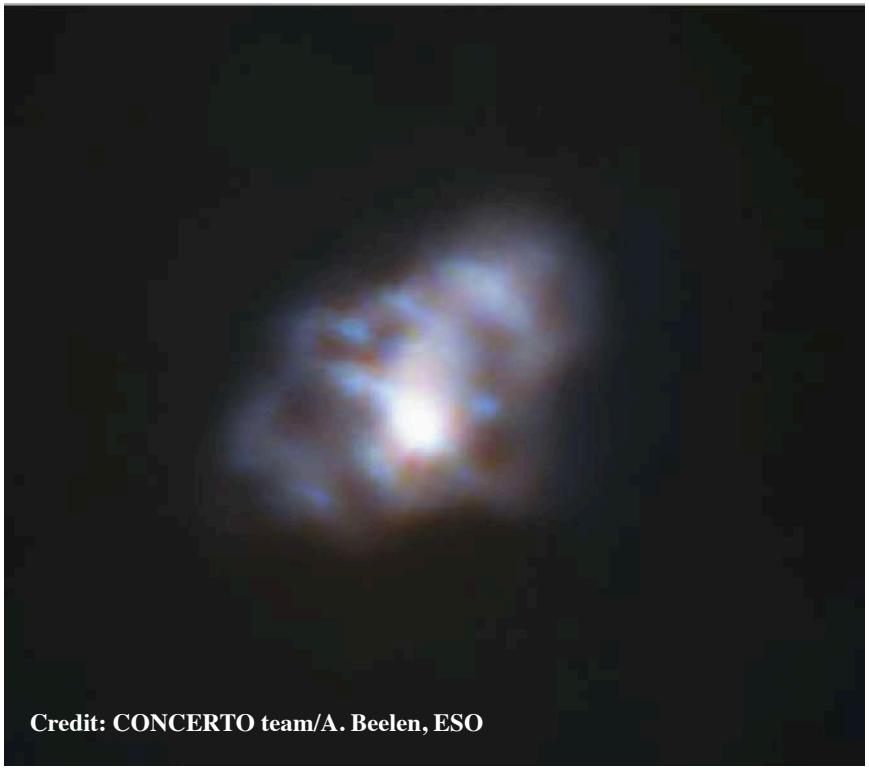
Telescope time: 16 minutes, 37'x25'

→ Quickly demonstrating the mapping potential in imaging. All the fainter structures in this map are confirmed by existing Artemis, Herschel, SCUBA observations

From Alex Beelen

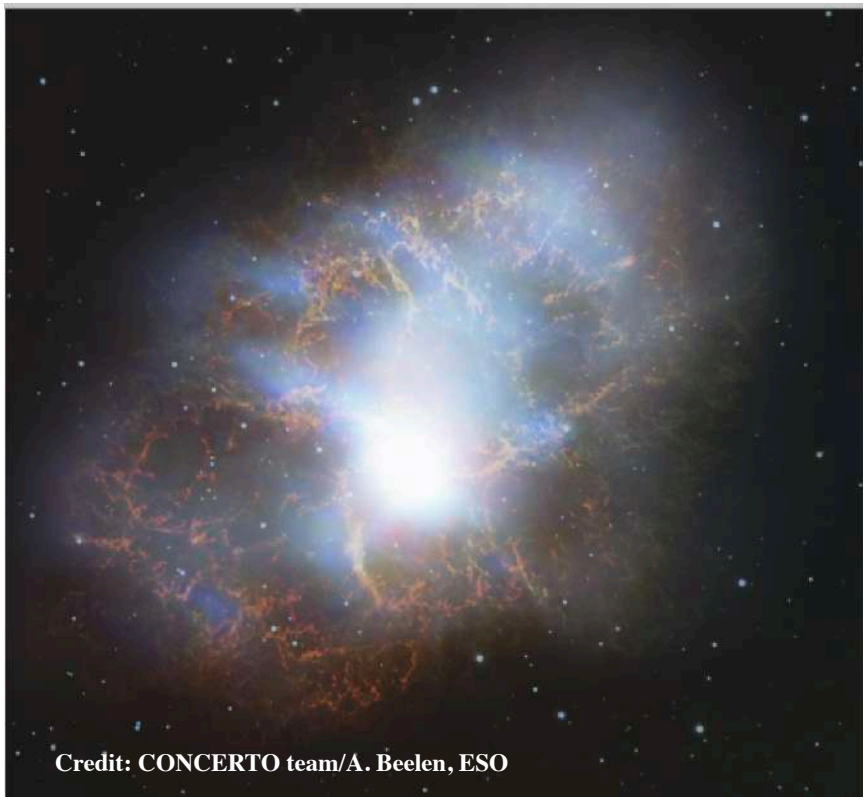


Credit: CONCERTO team/A. Beelen, ESO



Credit: CONCERTO team/A. Beelen, ESO

Credit: ESO/J. Emerson/VISTA Acknowledgment: Cambridge Astronomical Survey Unit



Credit: CONCERTO team/A. Beelen, ESO

SUCCESS !! A human adventure….

CONCERTO is a completely crazy project!

One and a half years later….

Low resolution spectroscopic surveys

- CONCERTO is offering a generic access to a large FoV and low-frequency resolution spectroscopic instrument.

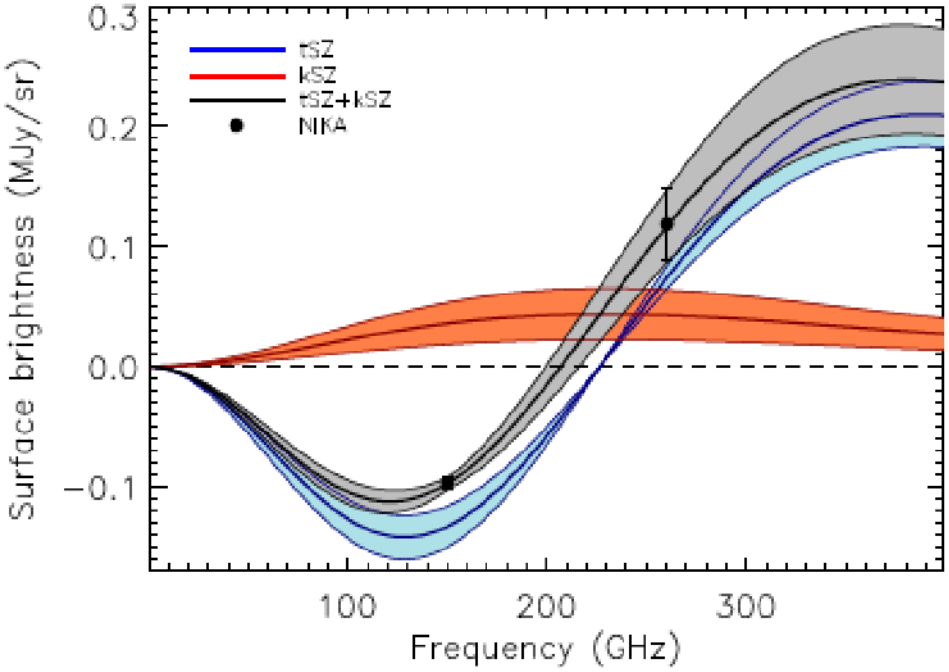
- After ground-based sub-mm experiments, Herschel and Planck: from broad-band photometry to spectroscopy
  - Very complementary to the high resolution mode of the SPIRE/Herschel FTS ($\delta\nu$=1.2 GHz, 191-671 microns) but with a FoV >20 times larger.

- A Multi-purpose instrument:
  - Galaxy clusters: SZ and gravitationally lensed high-redshift galaxies
  - Local and high-redshift galaxy surveys
  - Star-forming regions and high-latitude cirrus clouds
  - Solar system planets

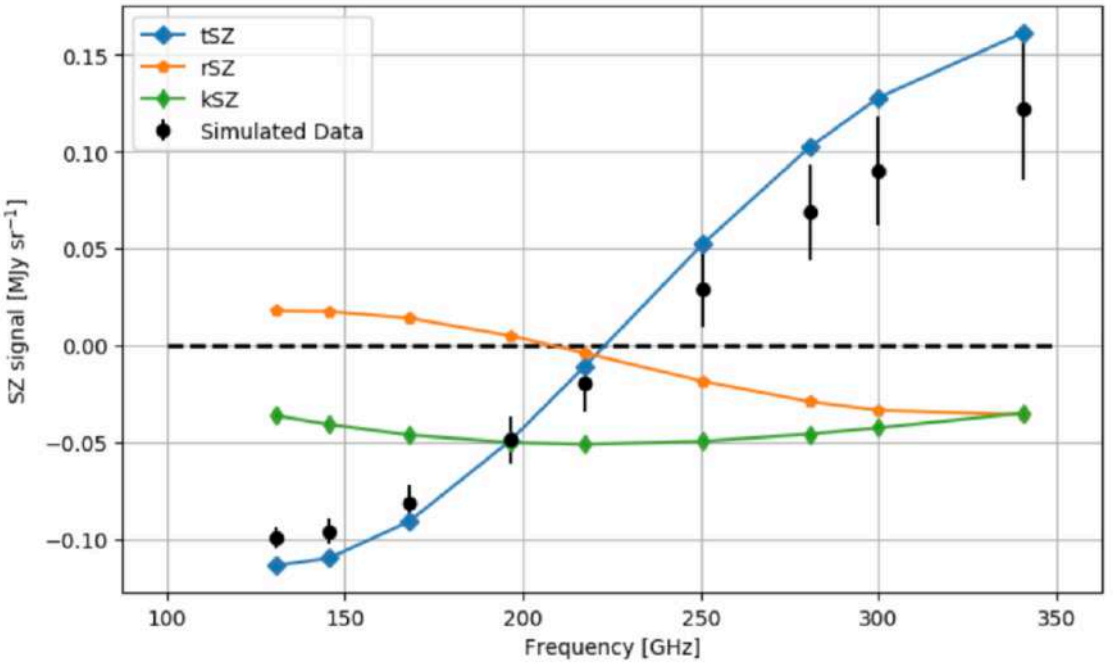
- Our main scientific interest: Intensity mapping of the [CII] line at z>5

Galaxy clusters (SZ)

- CONCERTO enable an accurate separation of the tSZ, kSZ and relativistic corrections, as well as the extraction of the SZ signals from the other astrophysical components
- FOV well adapted for medium to high-z clusters & angular resolution matters (sub-structures, mergers)



Adam et al. 2016
NIKA1 observations of MACS J0717.5+3745



z=0.5, M=10^{15} M_{sol}, 20 hours

Observations

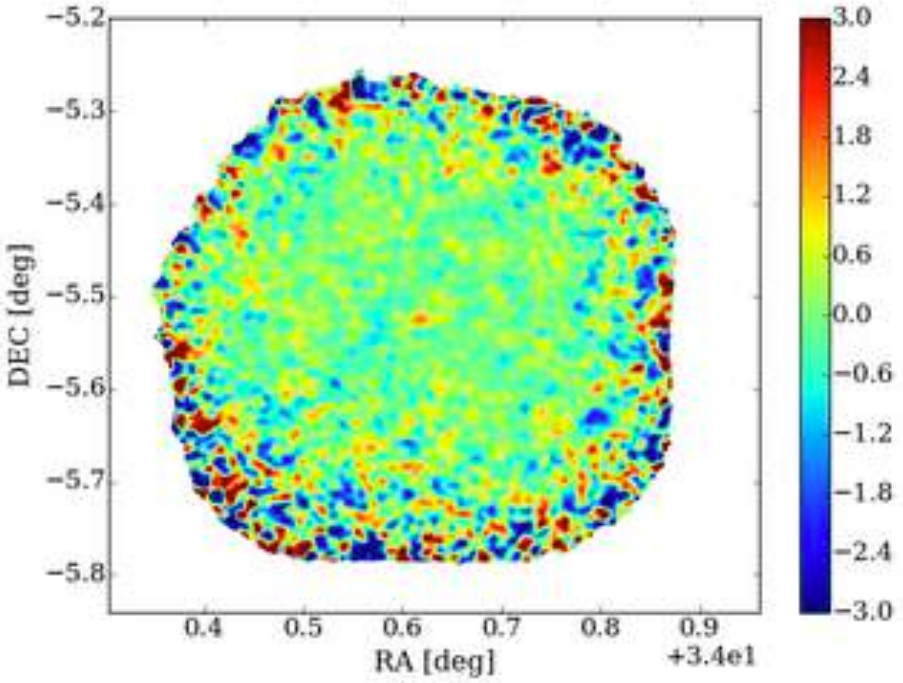
- First “astro” observations during commissioning: AS2UDS (24/06), RXCJ1206 (26/06)
- From July to December 2021: 5 remote observing runs and 1 on site. **Routine observations!**
- Start again on April 20, 2022: 7 observing runs + 5 remote
- 3 weeks in April 2023

- Simple procedures to start and prepare the instrument before starting the observations. Takes less than 15 minutes. Operating and monitoring the instrument is very smooth: APEX_manager and interface with instrument setup (acquisition) and quick look (signal, PSD)

- P108: Observations of 2 galaxy clusters
  - RXJ1347: ESO Open time + Abell 2744: CL time
- P109: 7 proposals (ESO) + 1 (CL) submitted
  - 2 ESO were accepted (PIs: Annie Zavagno and Emmanuel Artis for 110.5 hours) + 1 CL
- P110: 6 proposals (ESO for 265 h) submitted
  - Clusters - Galactic - SMC: All accepted and already observed
- **+ COSMOS field (Large Program):**
  - Starting the OSO+CL+ESO LP on the COSMOS field on 15/07/2021
  - So far: 700/800 hours (ESO+OSO) + 65 hours (CL) = 765 hours

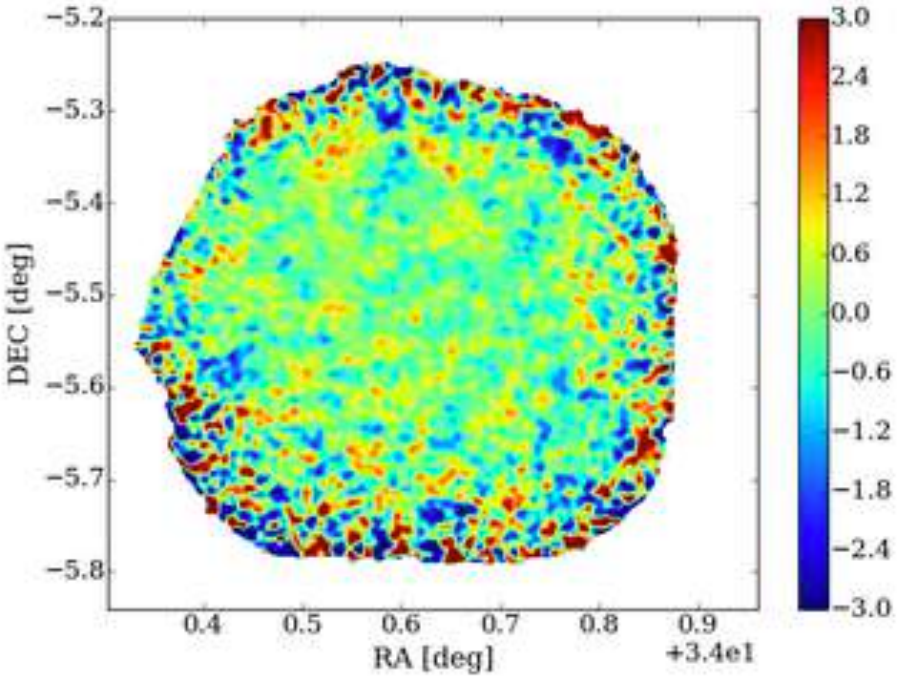
AS2UDS

HF



SNR = 3.3 - 4.6

LF



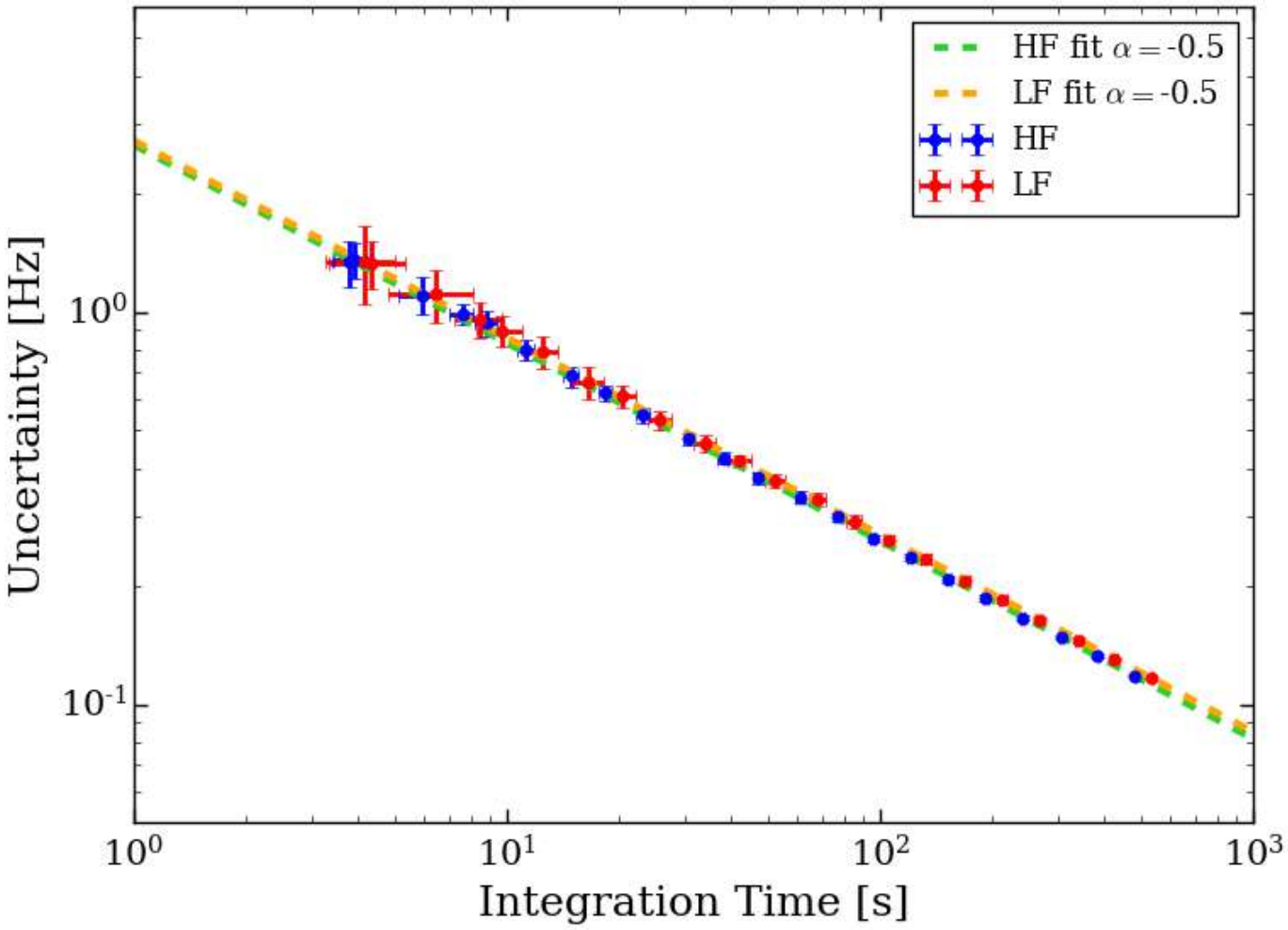
SNR = 2.9 - 3.7

Expected flux at 1.2mm (250 GHz): 13.6-15.2 mJy

=> Should see the source at 3.3-3.7 sigma.

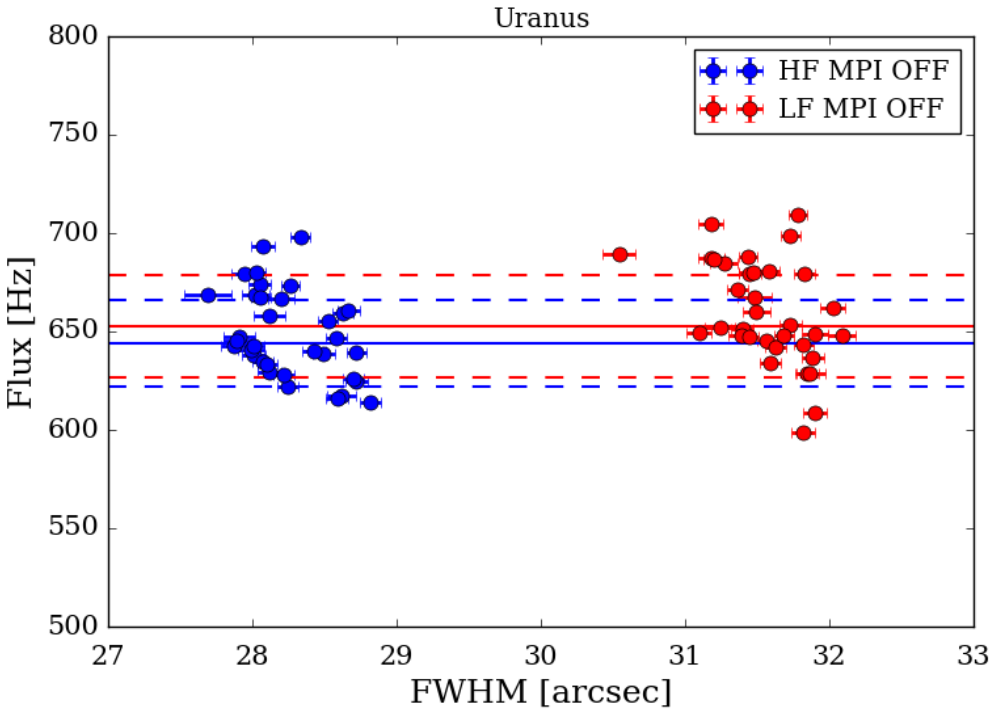
Sensitivity measured on sky (photometric mode) perfectly in line with expectations.

rms (per pix, 2021 data)

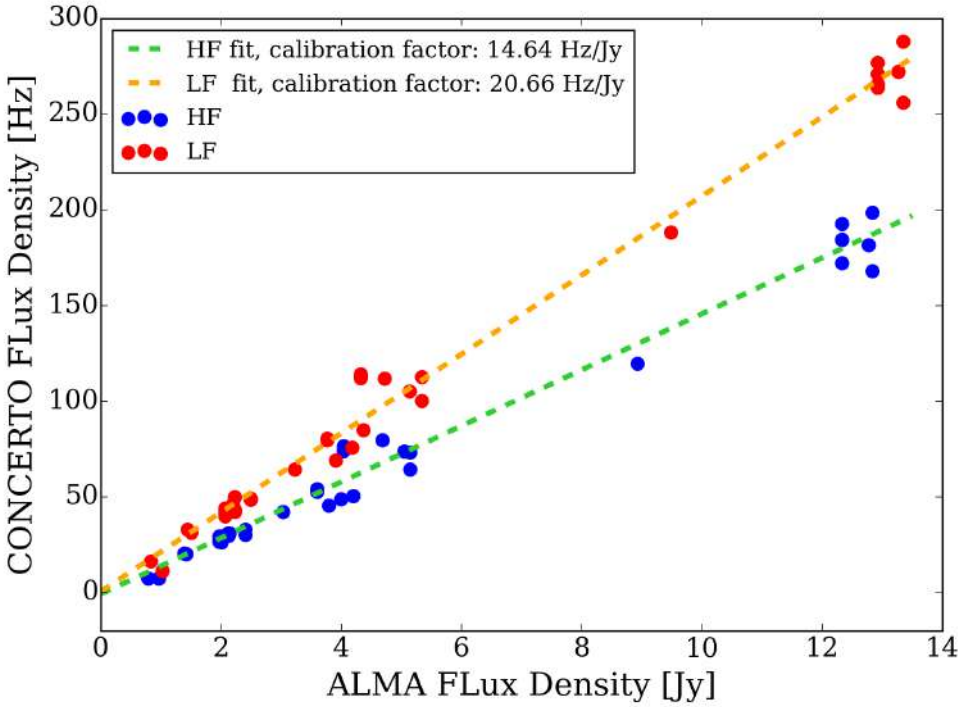


From Wenkai Hu

Absolute photometric calibration



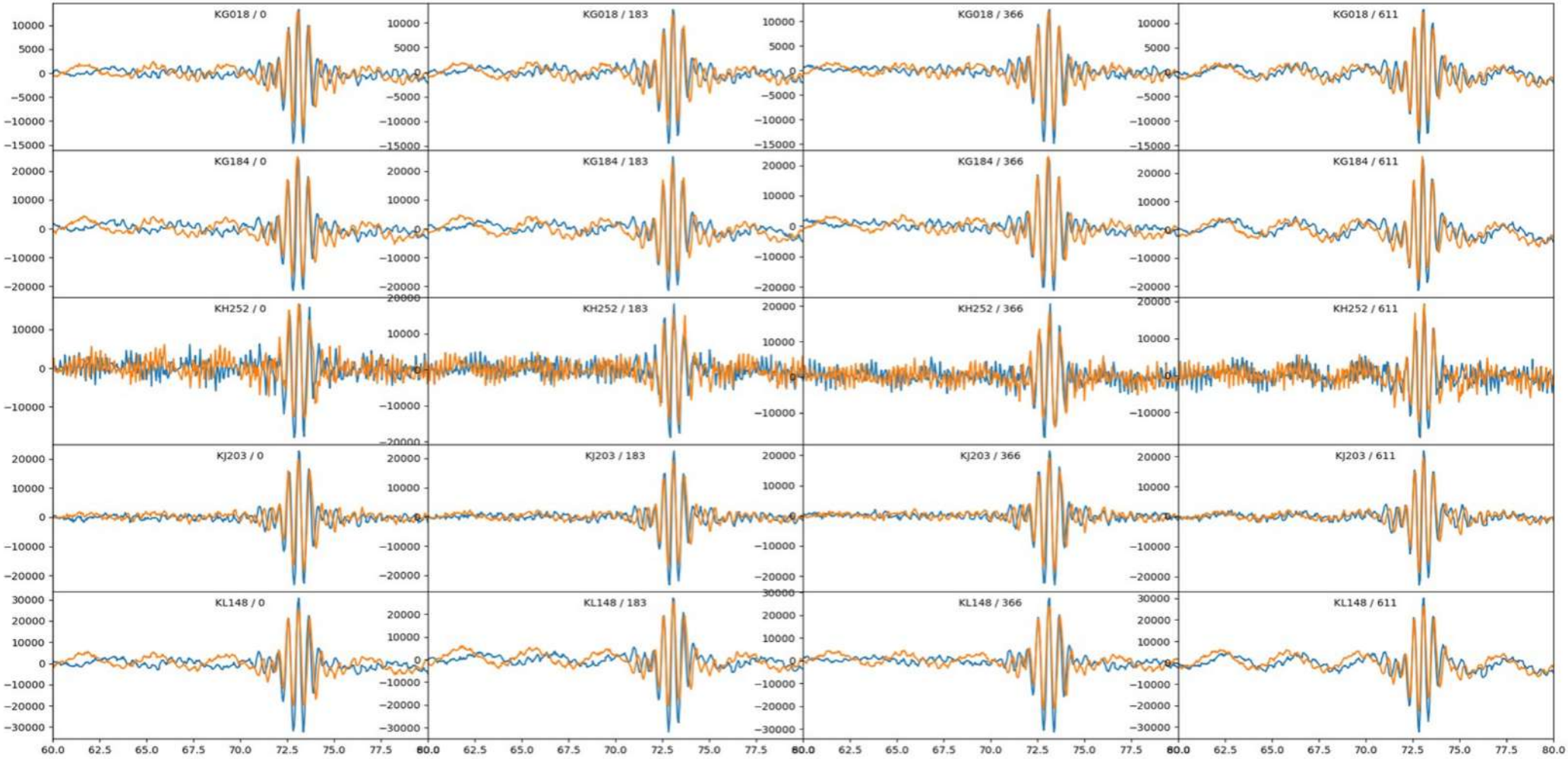
Quasars (ALMA)



From Wenkai Hu

A strong systematic effect

- KIDS timelines show strong 47ish Hz noise

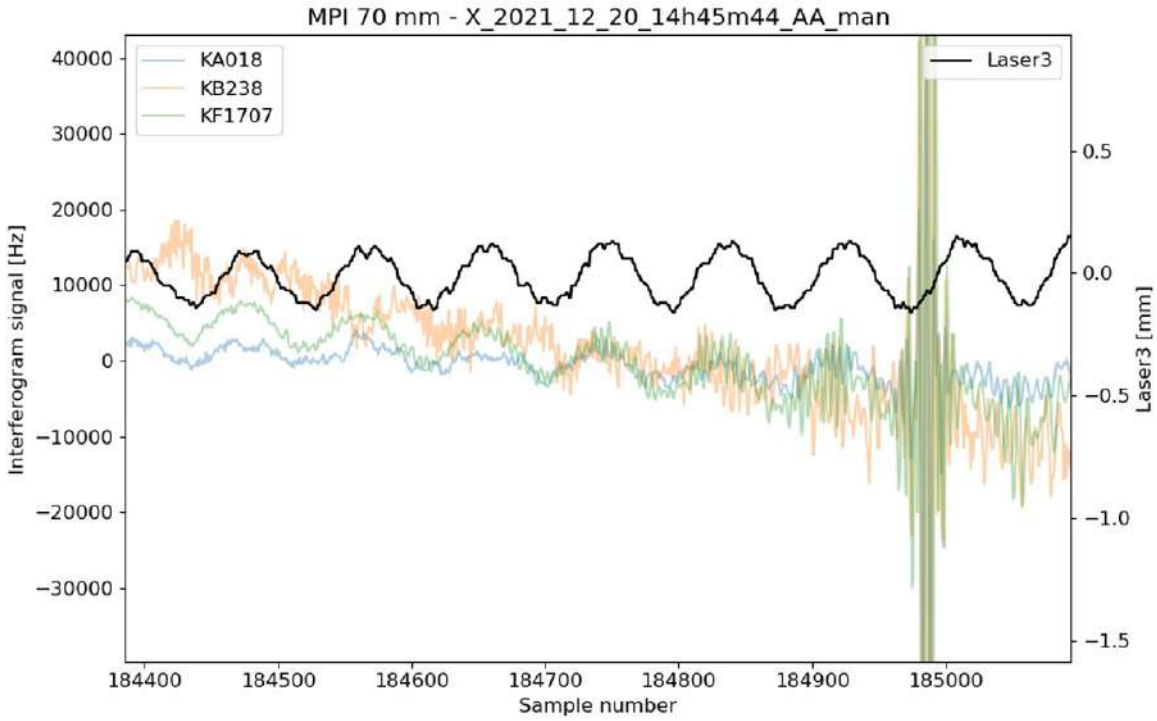


A strong systematic effect

Acoustic vibrations/deformation of the polariser could explain it all!

- The main laser is not measuring the actual optical difference
  - Problems to get the zero-path difference of the interferograms
- Additional noise in the KIDS timeline:
  - Suppression of the noise when MENERGA is off
  - Additional noise when MPI is on

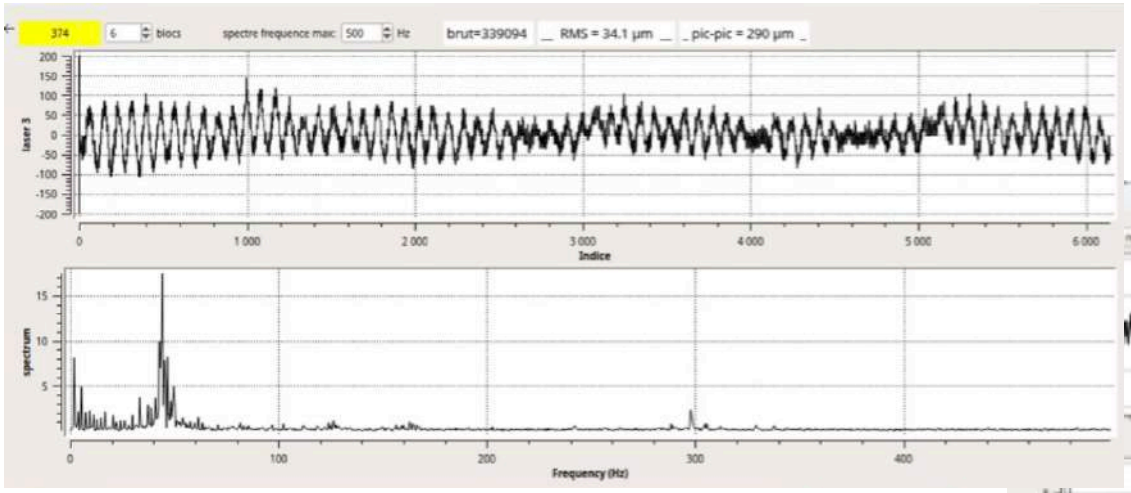
A new laser!
(Dec 2021)

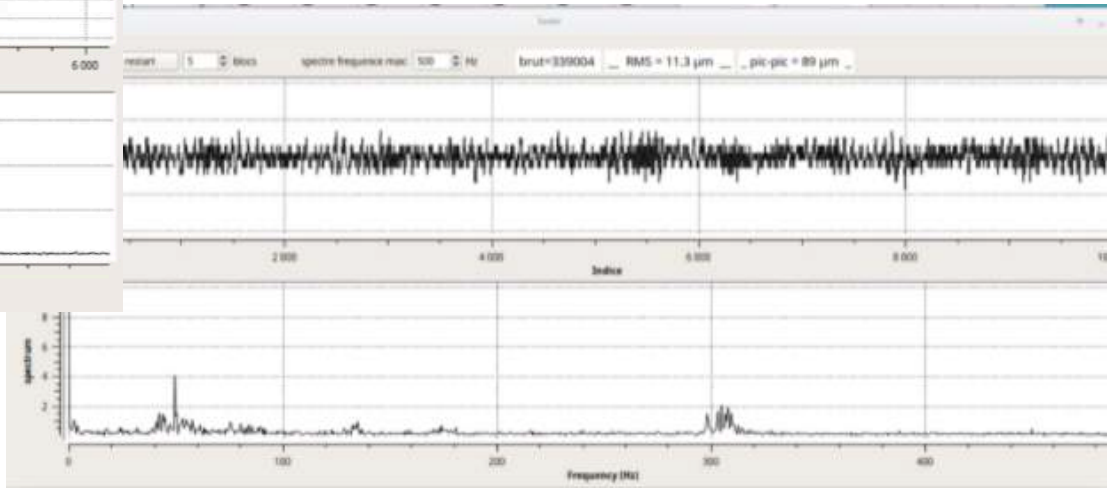


Polariser vibrations - Counter Action

Installation of a speaker pointing towards the membrane (Jan 2022)

- Can excite the membrane
  - Allows us to derive KIDS response to membrane displacement
  - Allows us to derive effective correction to OPD
- Can be use in close-control loop to reduce membrane vibration
    - Decrease membrane rms by x3 (limited by the laser precision)





One and a half years later….

We got a hand on the first and **strongest systematic effect** impairing our ability to derive spectra with confidence.

With Laser3, sensitivity in spec already within a factor of 2.

Observing, observing, observing …. in hurry because of the end of CONCERTO in Dec 2022 (May 2023).

….. 180 To of data to analyse

Last Call for ESO Observing Time on APEX

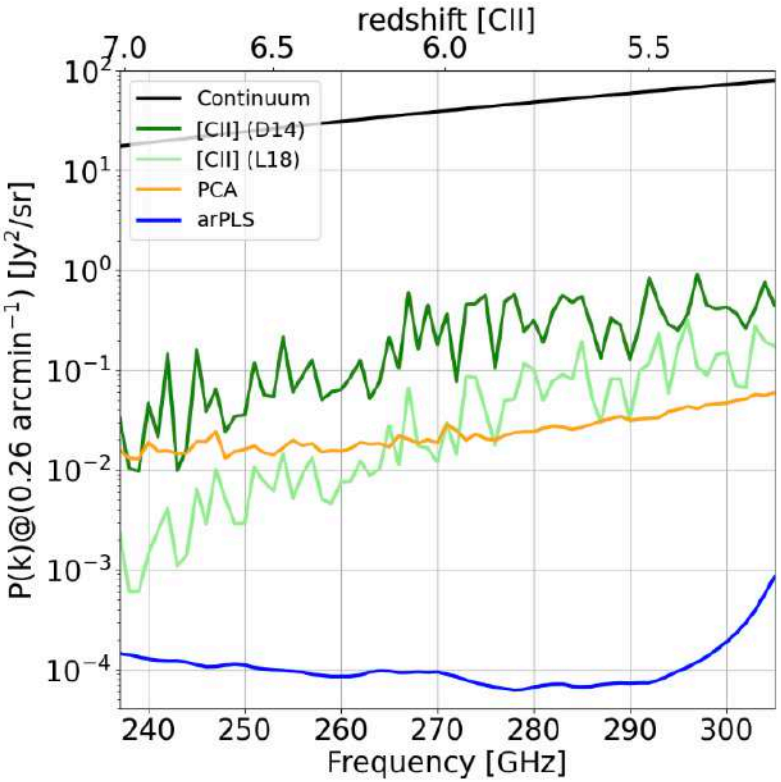
Published: 25 Feb 2022

One and a half years later….

Preparing the interpretation of the [CII] LIM survey:

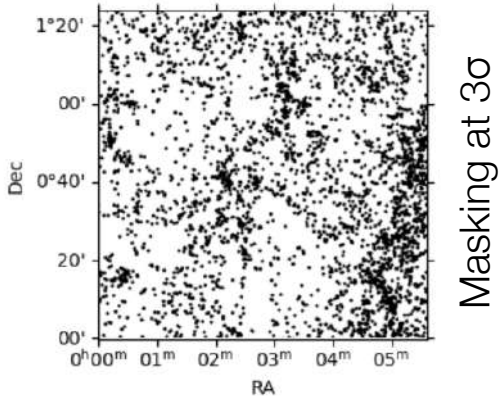
- Modelling the [CII] and CO power spectra
- Component separation

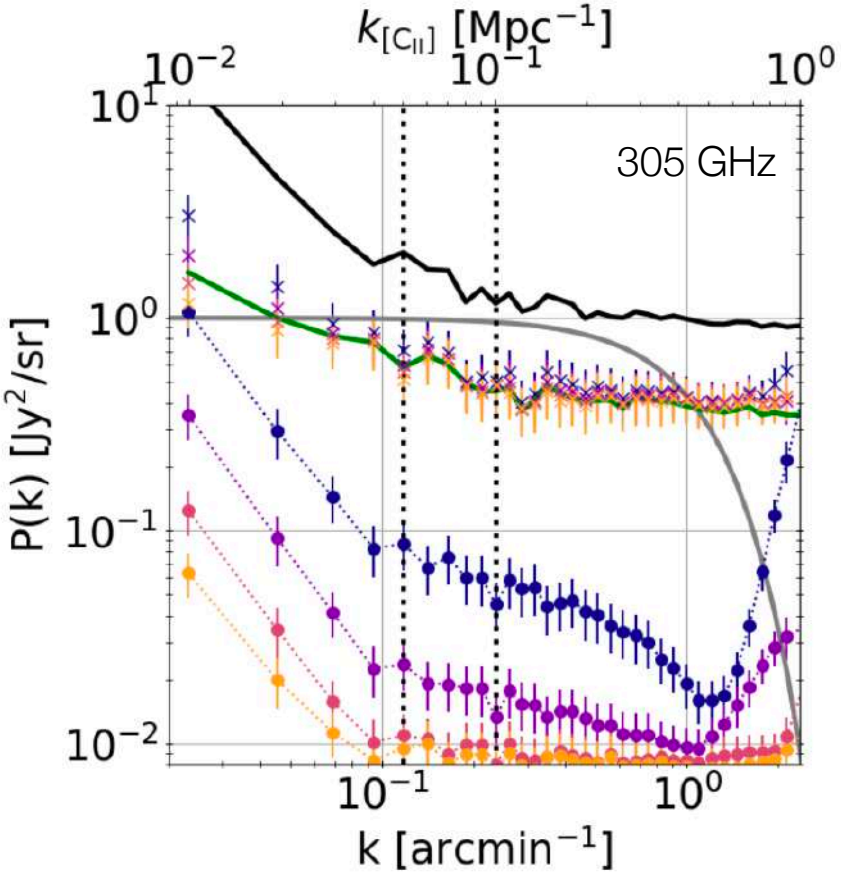
Removing the continuum (CIB)



Van Cuyck et al. 2023

Removing the CO contaminaation





CONCLUSIONS

- We have constructed and installed a low-resolution (up to $\delta v = 1.5$ GHz) spectrometer operating between 130 and 305 GHz.

- Our main interest: map in 3D the specific intensity due to CII-line emission, a technique known as « Intensity Mapping »
  - With the CII-dedicated CONCERTO survey, we will map the star formation at $z>5.1$, and in the end of epoch of reionisation

- CONCERTO @ APEX is (was) a unique combination to :
  - study galaxy cluster physics
  - probe the gas content of galaxies (CO, CI, CII, NII, OI lines), the efficiency of star formation
  - measure the dust mass and emissivity
  - study the structure of molecular clouds

CONCERTO team

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Infrastructure: J.-C. Lambert (LAM), T. Fenouillet (LAM)

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Admin: L. Todorov (LAM, Marseille), C. Vannier (LPSC, Grenoble)

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