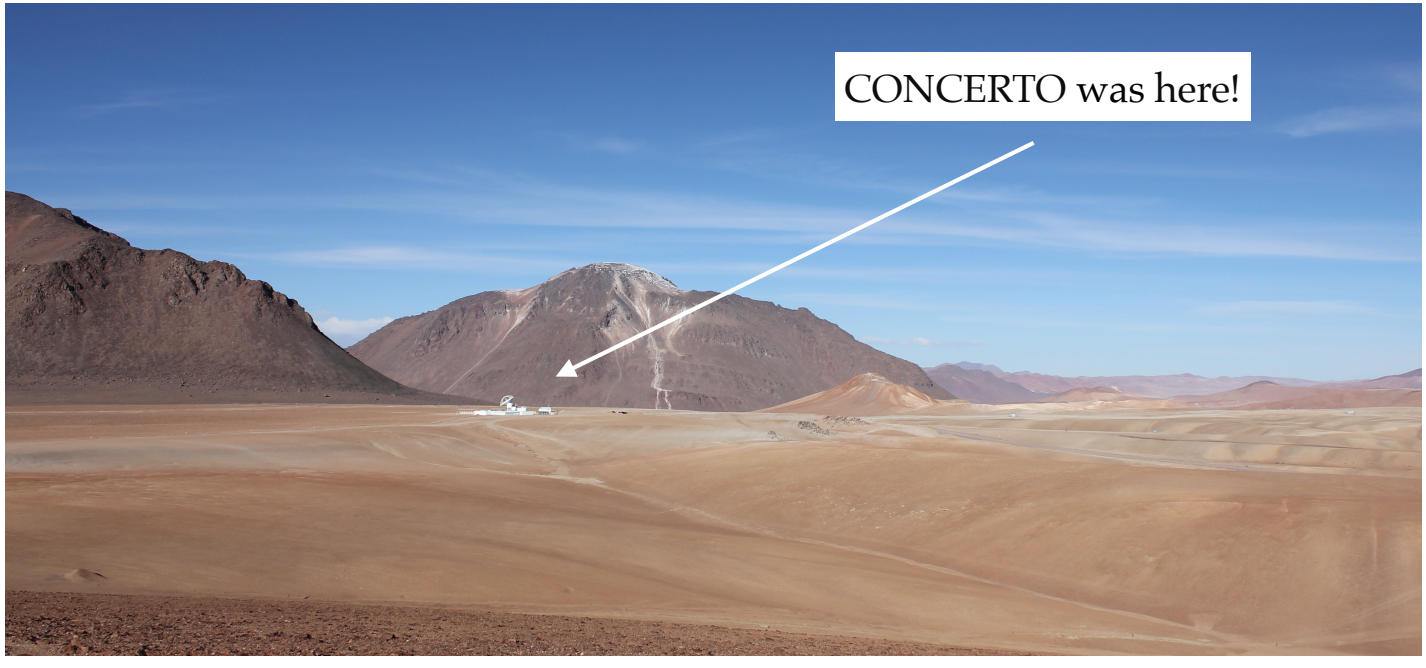
Status of [CII] Intensity Mapping in the Era of CONCERTO

Guilaine Lagache (LAM)
On behalf of the CONCERTO collaboration

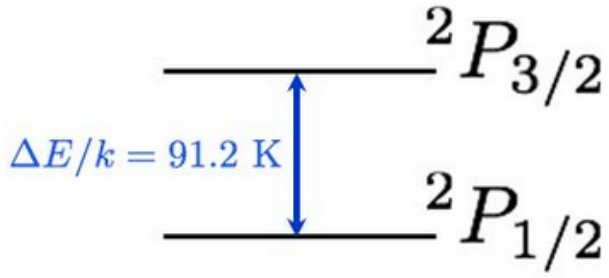


LIM 2025 - Annecy
LAPTh, 2-6 June

The [CII] line

A little Physics

- Low ionisation potential (11.3 eV) of carbon => [CII] is the dominant form of Carbon under a large variety of conditions
- [CII] has only two fine structure levels in the ground electronic state.
  - Fine structure line at 157.74 μm



Fine structure of the ground state of C+

- Excitation of the [CII] fine structure transition can be via collisions with hydrogen molecules, atoms, and electrons
  - e.g., for the WNM and WIM conditions the critical density for excitation of [CII] by H atoms is 1300 cm^{-3}, and for electrons 45 cm^{-3}

The [CII] line

A little Physics

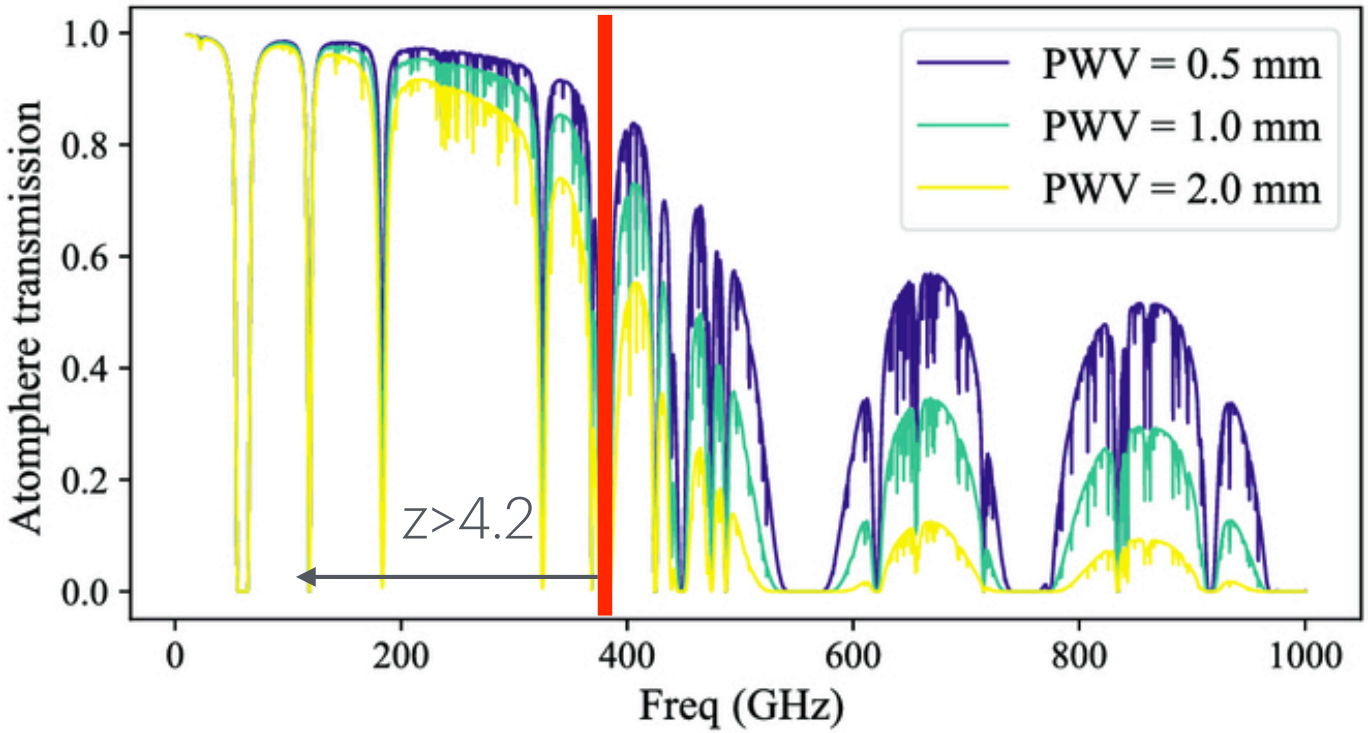
- [CII] at high z originates mainly from PDR (& CNM)
- One of the most valuable tracers of dusty star formation at high redshift
- Excellent coolant for neutral gas in PDRs, and a good probe of the stellar radiation fields
- Extinction free tracer of star formation
- One of the brightest emission lines in the spectra of galaxies with $L[CII]/L_{FIR}$ ~0.1-0.3%

The [CII] line

Observations

Li+2025

<u>Ground-based experiments:</u>
sub-mm and mm windows (z>4.2)
Pointed obs: ALMA, NOEMA, (APEX)
LIM: CONCERTO, *TIME, FYST, TIFUUN*



<u>Balloon experiments :</u>
LIM: *TIM (0.5<z<1.7), EXCLAIM (2.5<z<3.5)*

<u>(Old) space experiments :</u>
All sky: FIRAS; **Pointed obs:** ISO, Herschel

[CII] intensity mapping

Experiments

- **PAST:**
  - CONCERTO (Observation July 2021 - Dec 2022 ; removed from the telescope in May 2023): 1.4 Sq. Deg. — R~100-300 — z>5.2
- **ON SKY:**
  - TIME (obs@ARO-12m 2024-2026) — 1.3° x 0.′45 — R~100 — 5<z<9
- **IN DEVELOPMENT:**
  - FYST/EoR Spec — 1 year after FYST first light — 2x5 Sq. Deg — R~100 — 3.5<z<8
  - TIM — Test Flight in 2024 — 0.2 Sq. Deg — R~250 — 0.5<z<1.6
  - EXCLAIM — Flight planned in 2025 — 300 Sq. Deg — R~500 — 2.5<z<3.5
  - TIFUUN — 2027-2029 — 1 Sq. Deg. — R~500 — 5.3<z<6.6 & 10.2<z<12.6

The [CII] line

Observations

- First detection at high z in a QSO at z=6.42 (Maiolino+2005)

- [CII] is now « routinely » detected with ALMA and NOEMA:
  - 10 LBGs at z~5-6 (Capak+2015)
  - 75 galaxies at z~5-6 from the ALPINE LP (Bethermin+2020)
  - ~40 galaxies at z=6.4-7.7 from the REBELS LP (Bouwens+2021)

    => <200 LBGs + SMG today

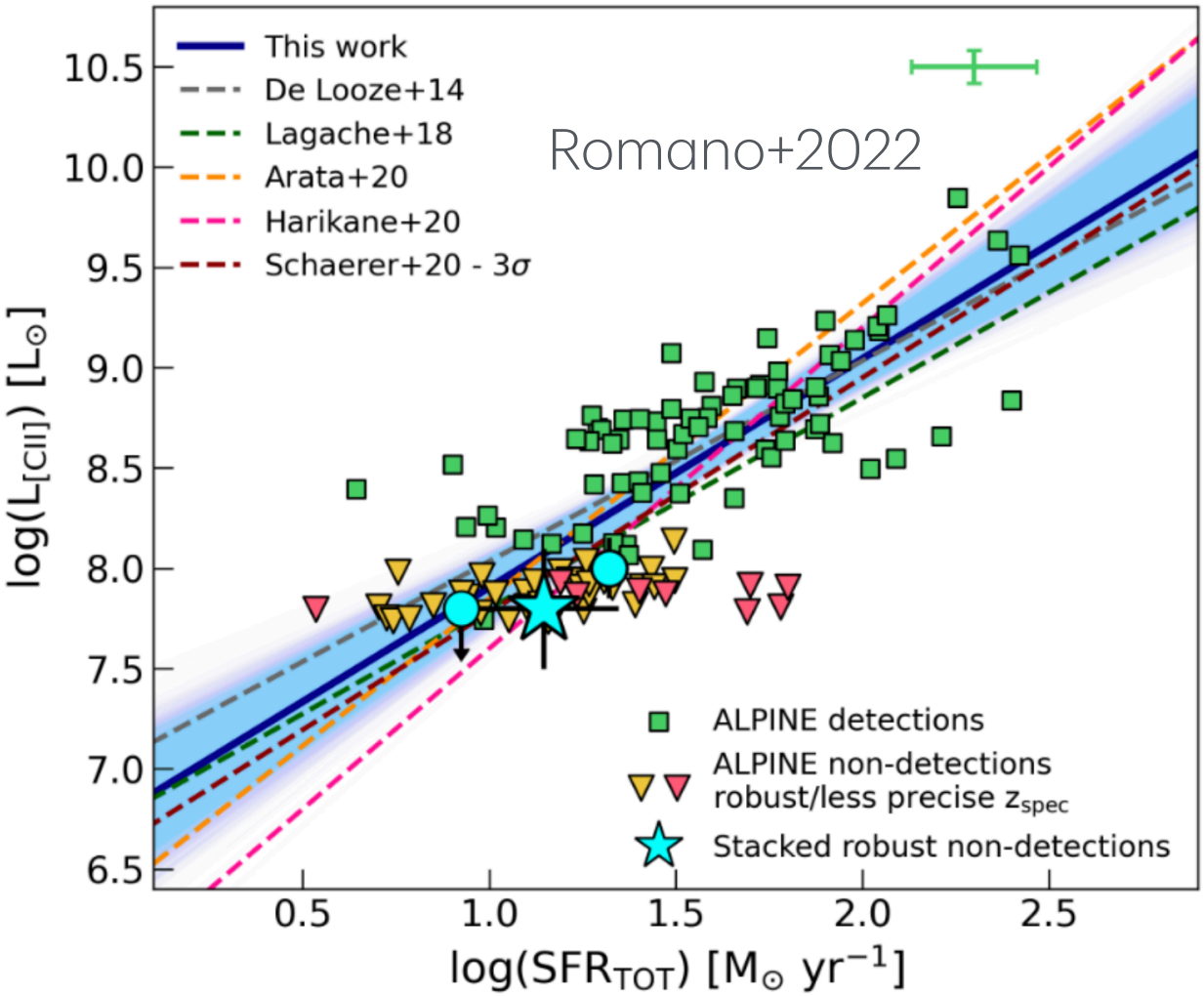
    - Most distant measurements:
      - Galaxy at z=8.3 (Bakx+2022)
      - QSO at z=7.2 (Fujimoto+2022)

- Blind survey: ALMA ASPECS (6<z<8): cross-correlation with LBGs and LAE => no detection (Uzgil+2021)

The [CII] line

[CII] - SFR correlation

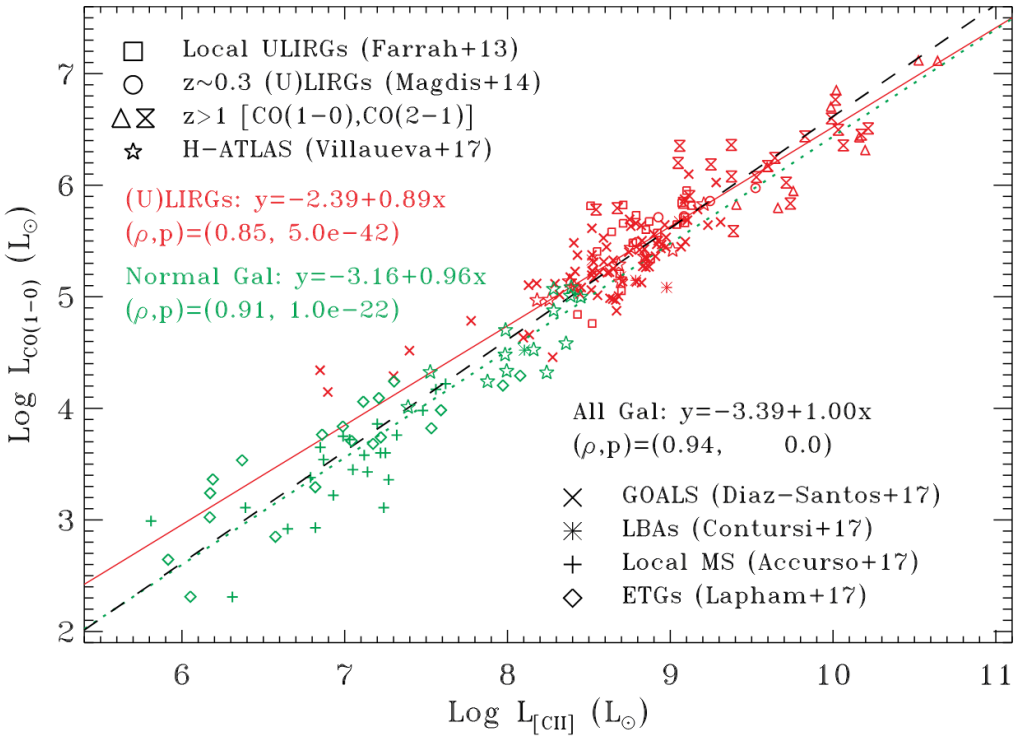
ALPINE sample, z~5-6



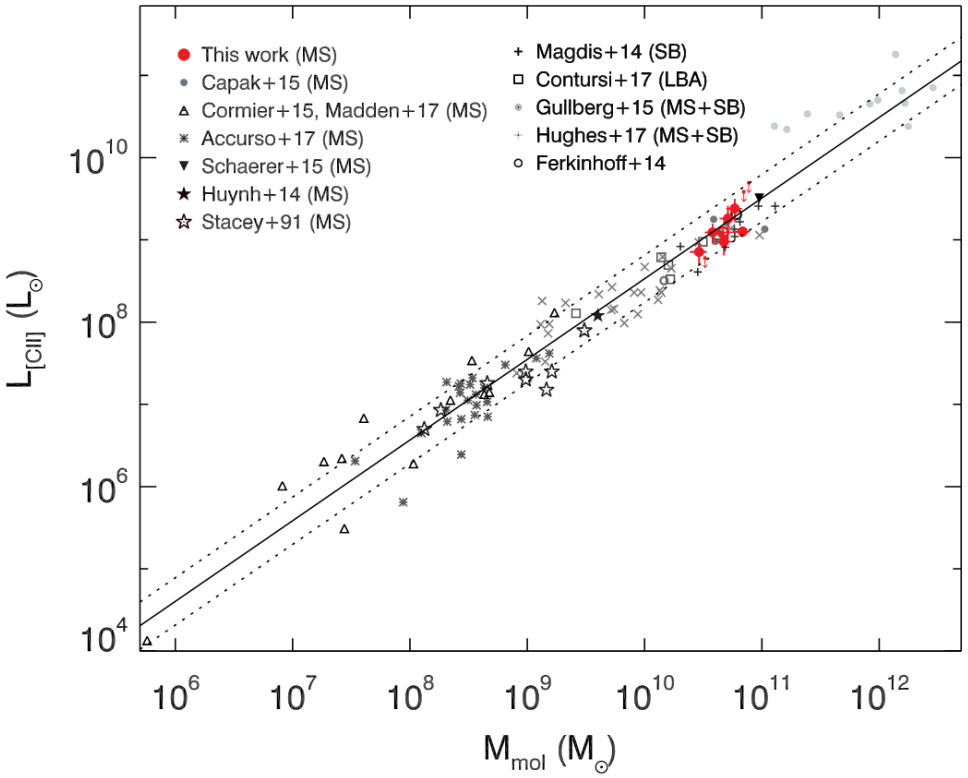
- No redshift evolution of the LCII-SFR relation?
- No [CII] deficit in luminous galaxies at high z?

The [CII] line

Total molecular gas mass tracer



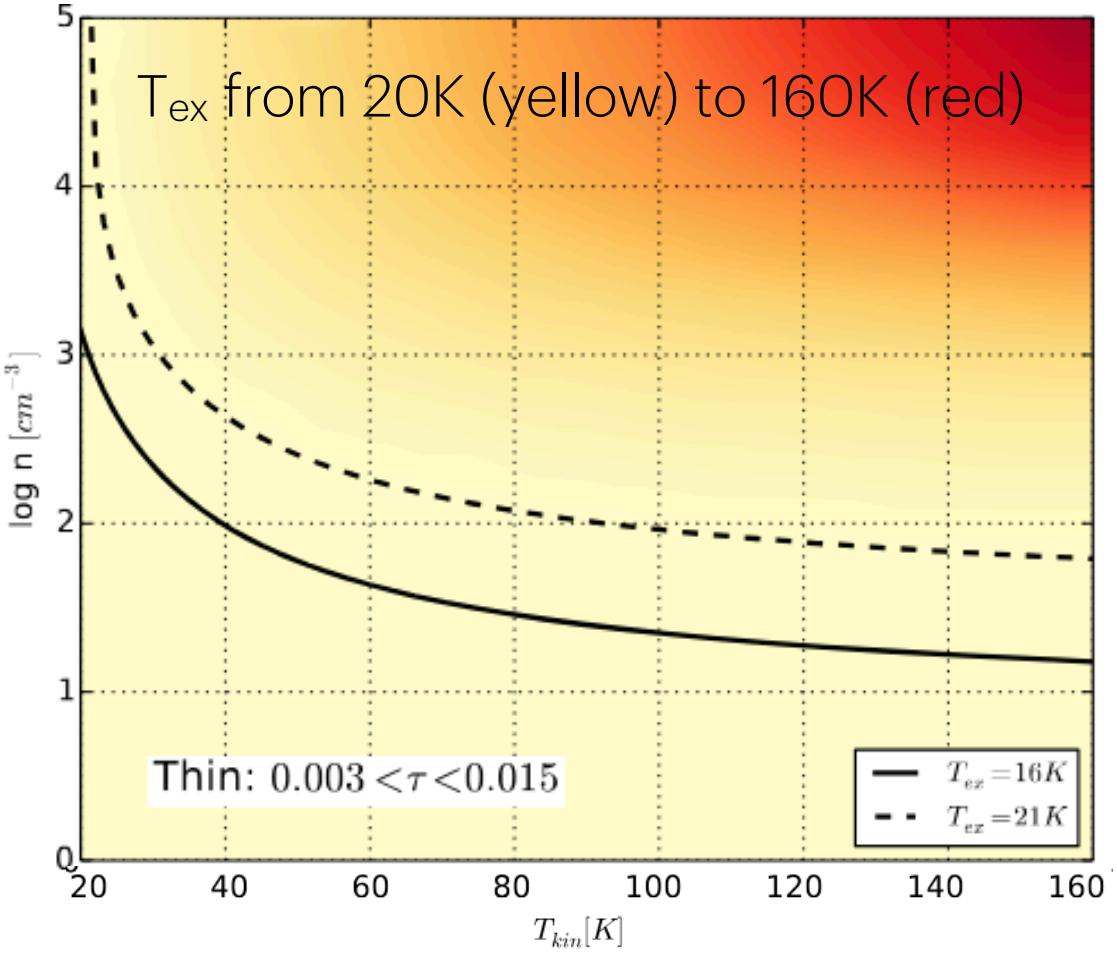
Zhao+2024



Zanella+2018

The [CII] line

Effect of T_{CMB} increase



Lagache+2018; Vallini+15

The T_{CMB} increases as (1+z) hence at high z it becomes a stronger background against which we observe the [CII] line.

CMB temperature at z=5.0 and z=6.7 => [CII] emission is suppressed for kinetic temperature below the lines T_{ex}=16K and T_{ex} = 21K.

This suppression affects mostly the cold neutral medium (T_{kin} ~50-120 K, n ~20-200 cm^{-3}).

[CII] line intensity mapping

And in cross-correlation with galaxies and CIB, CO & other lines

- SFR(D), relation between dark-matter halo mass & SF
- Dust production
- Average physical characteristics of the ISM of distant galaxies
- Gas mass density
- [CII]xHI: physics during EoR, including the ionized bubble sizes and the mean ionization fraction

Great! => Let's go for [CII] LIM

CONCERTO*

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

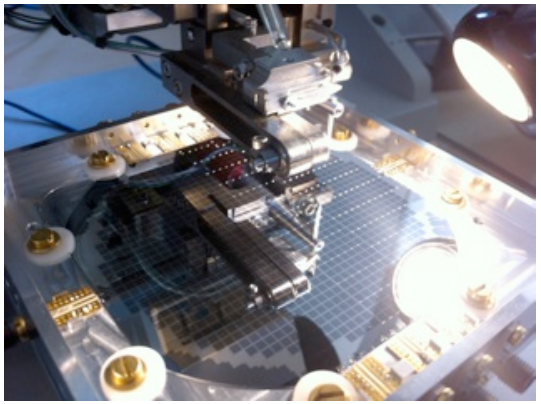
LAM, Institut Néel, LPSC, IPAG

And European/Chilean partners (science)

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

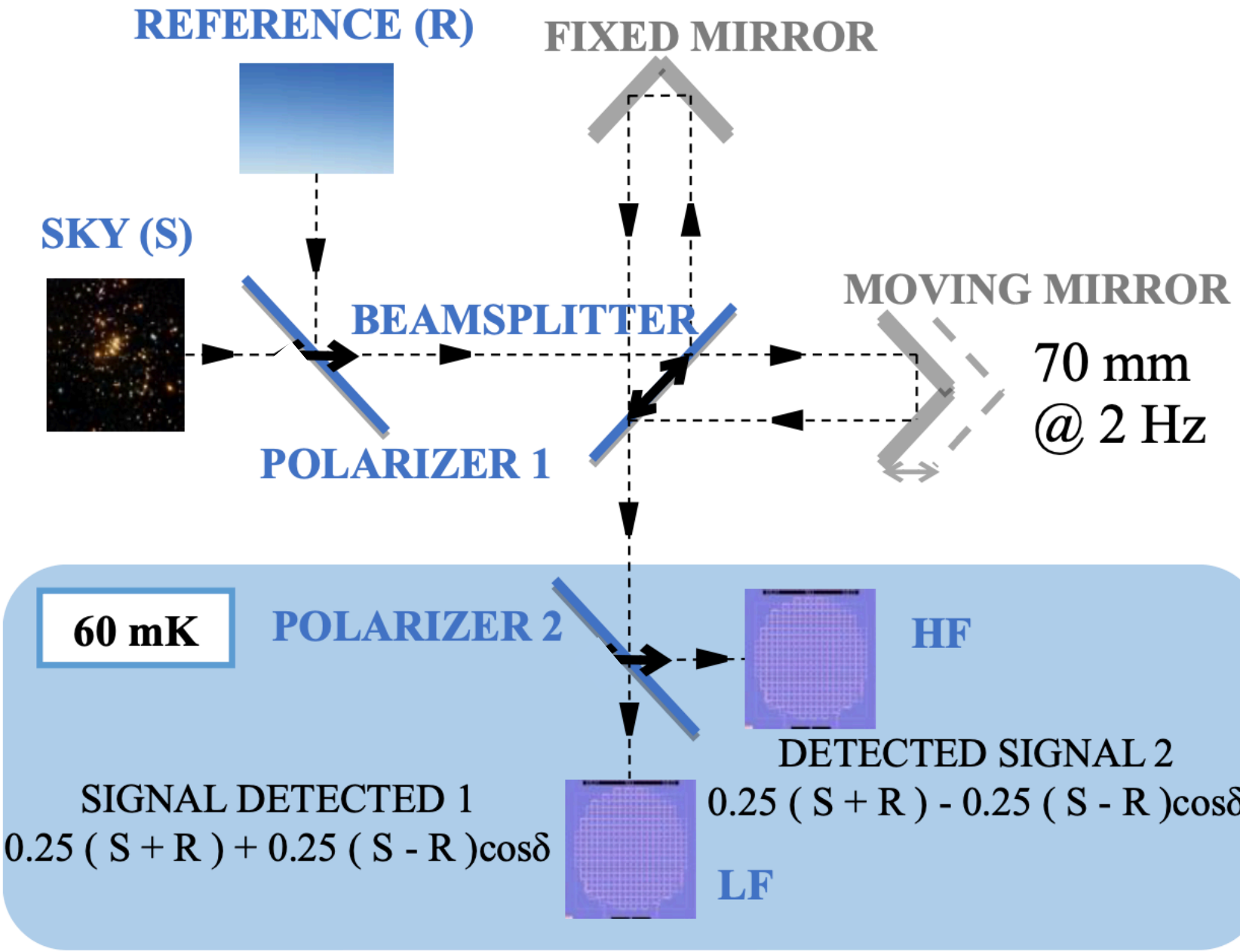
*CarbON CII line in post-rEionisationand ReionisaTiOn epoch

CONCERTO instrument



- **Focal plane:**
  - Kinetic Inductance Detectors (as NIKA2 IRAM camera)
  - FOV D=18'6, two arrays of 2,152 pixels
- **Cryostat:**
  - Closed-circle ^{3}He-^{4}He dilution - 100mK
- **Martin-Puplet interferometer** (like a Michelson interferometer but with a movable mirror)
  - Outside the cryostat
  - Spectral resolution ($\nu/\delta\nu$): 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=25'' at 300 GHz
  - Frequency range: two arrays, 195-310 GHz for the HF and 130-270 GHz for LF
  - Installation: April 2021 — Scientific observations: from July 2021 to December 2022

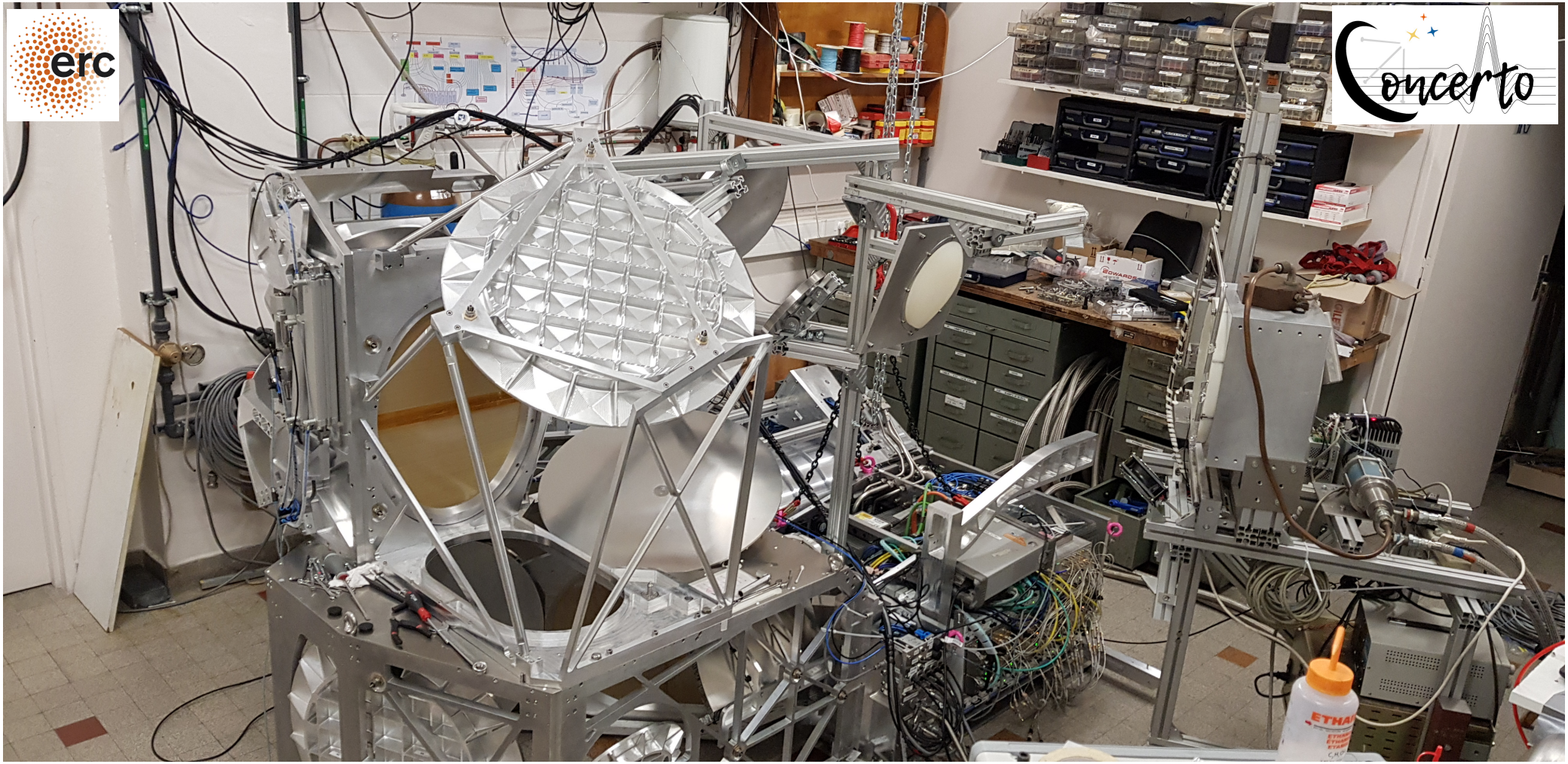
CONCERTO MPI



Slide from A. Fasano

Complete instrument (20/10/20)

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

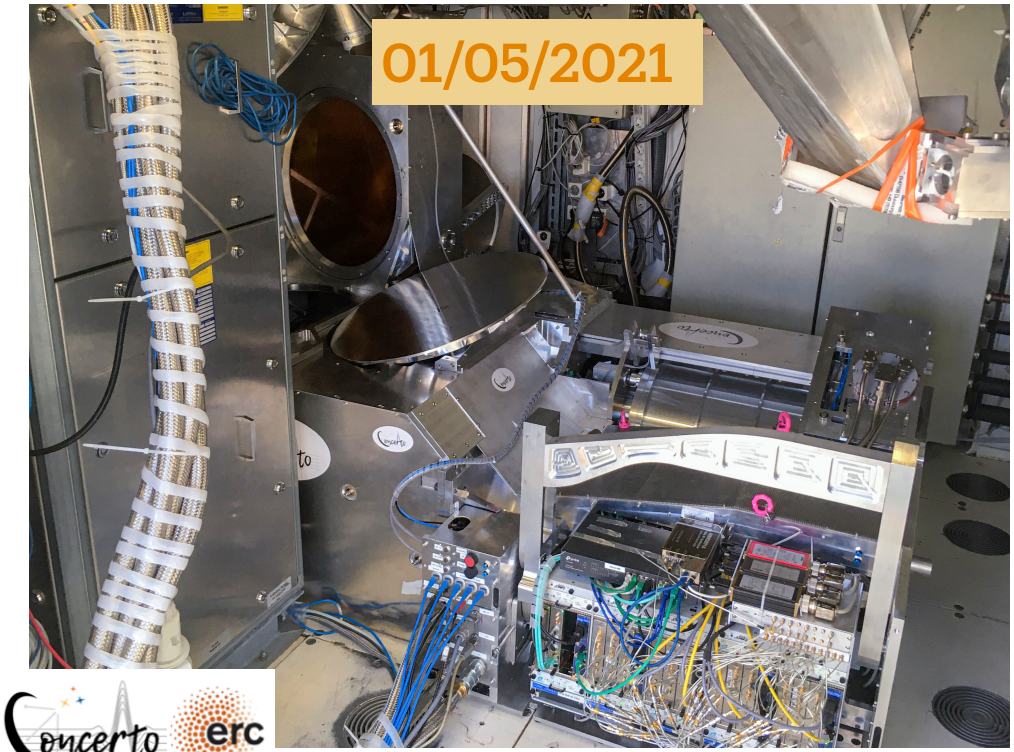


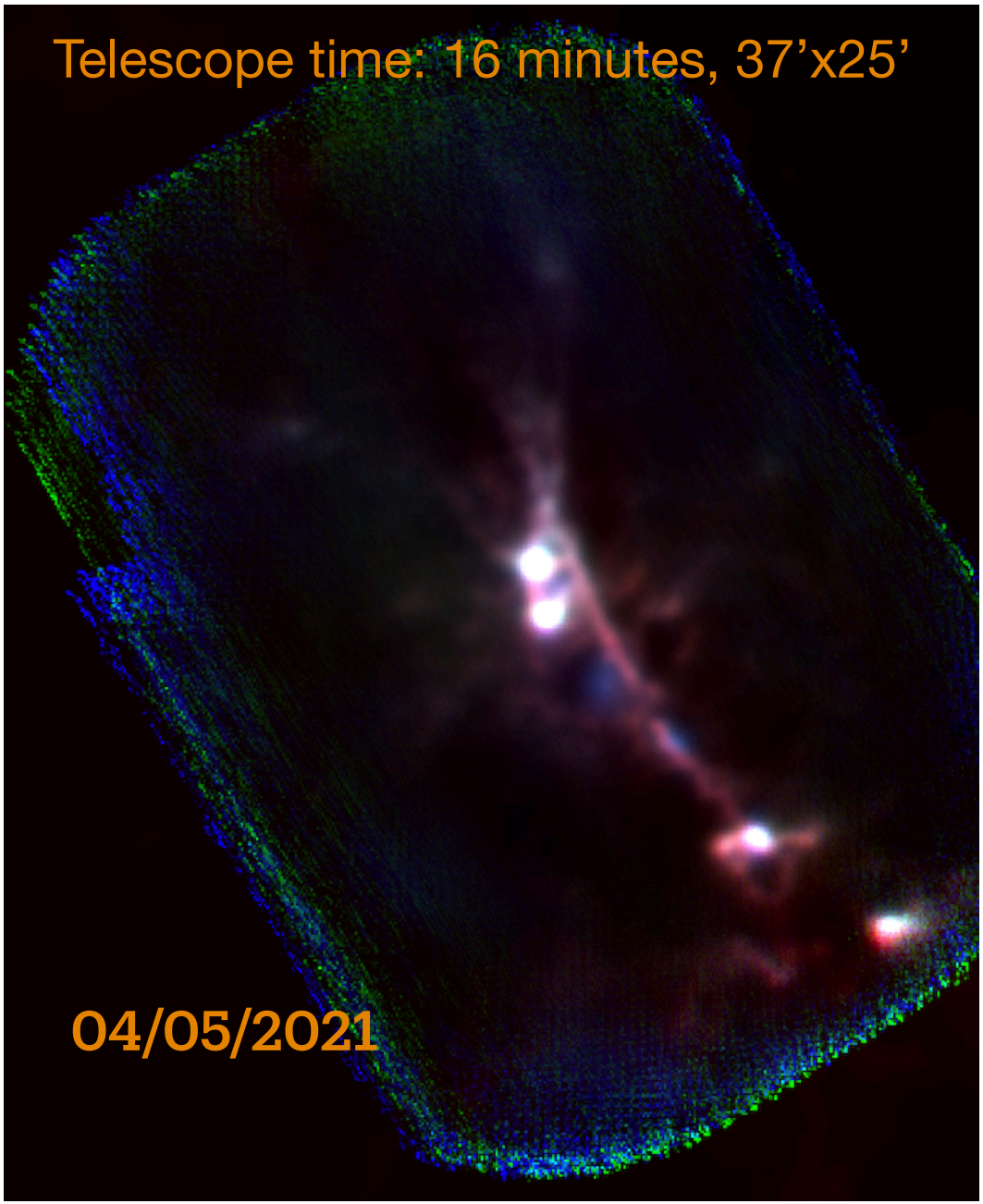
“A wide field-of-view low-resolution spectrometer at APEX: Instrument design and scientific forecast”

The CONCERTO collaboration, A&A 642, 2020

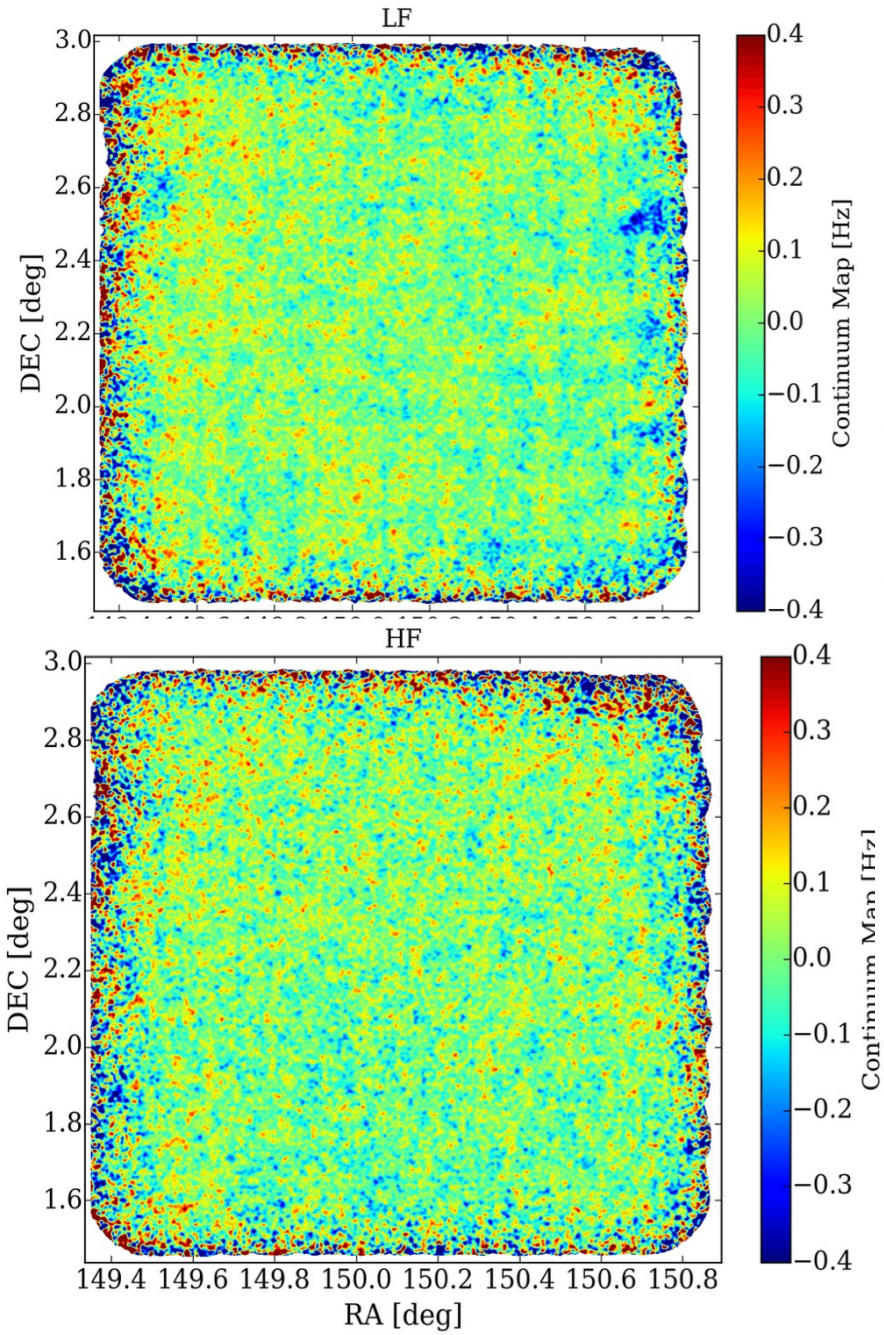
A fast track installation and commissioning

(ESO withdrawal from APEX on Dec 2022)



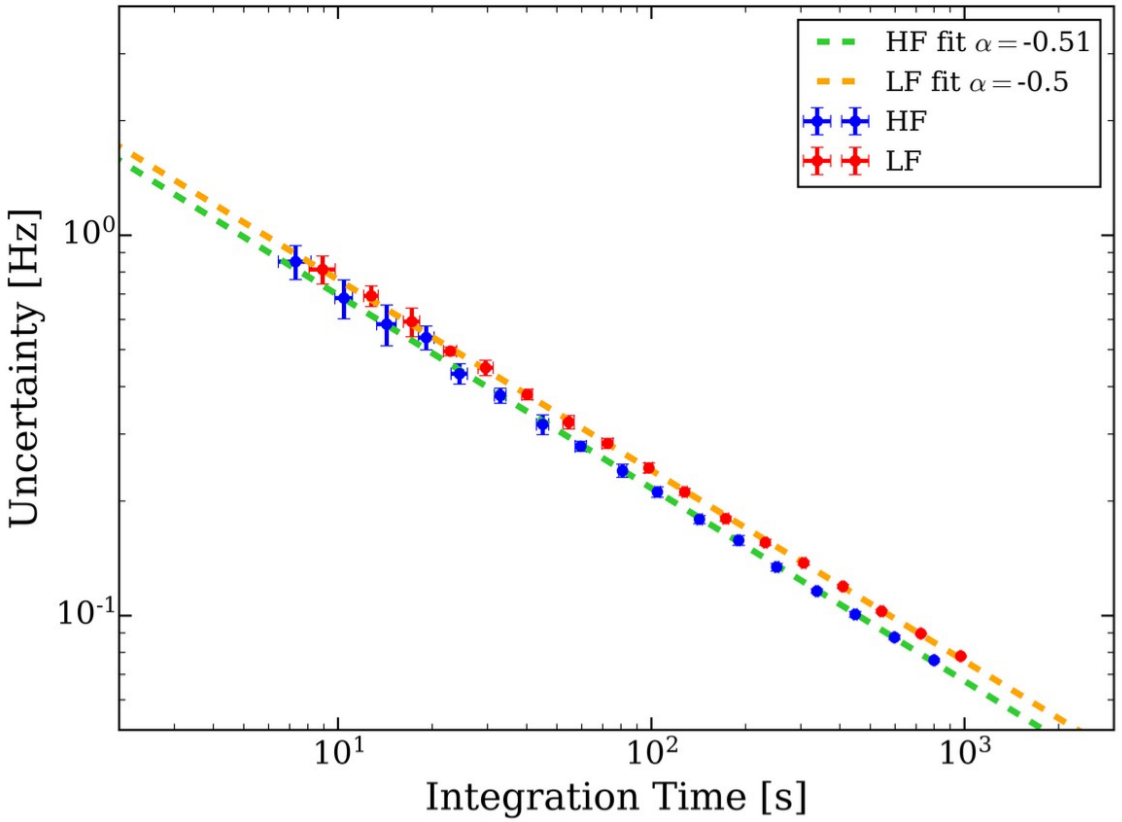


Continuum mode: noise levels



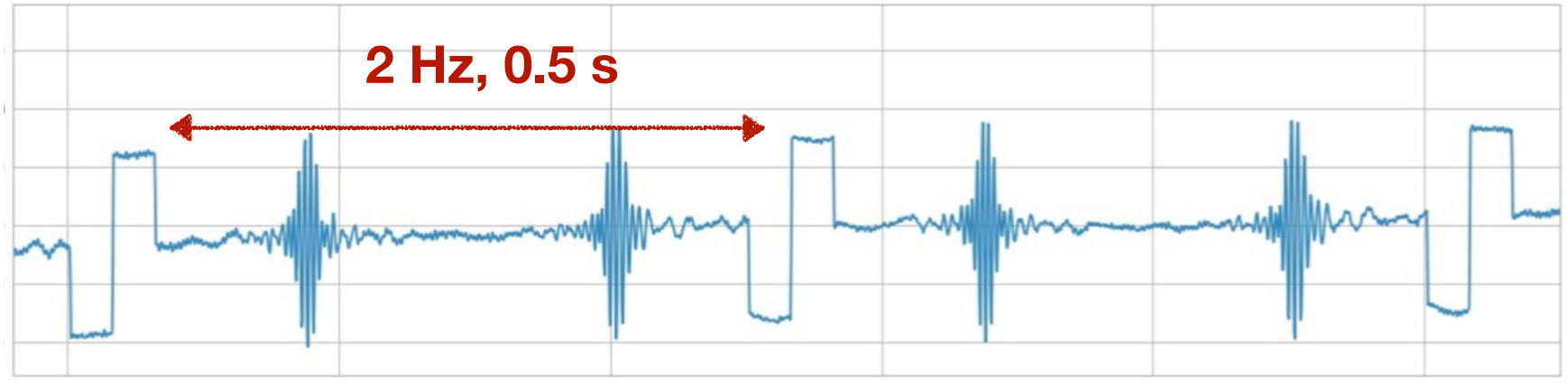
COSMOS field — 1.4 deg² (792 h)

Hu+2024



Noise integrates down as expected

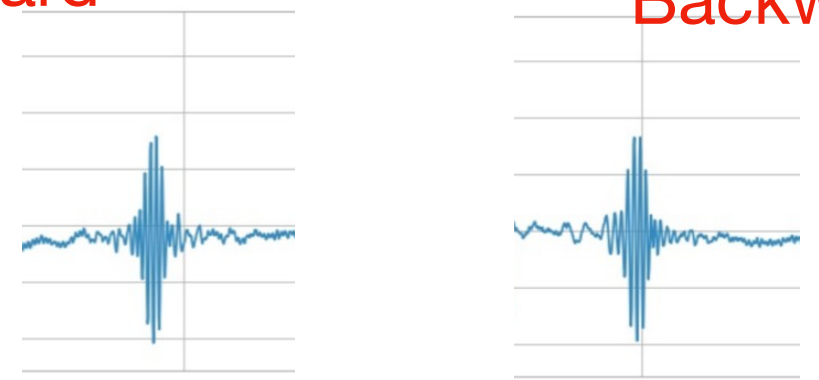
Interferograms



Forward

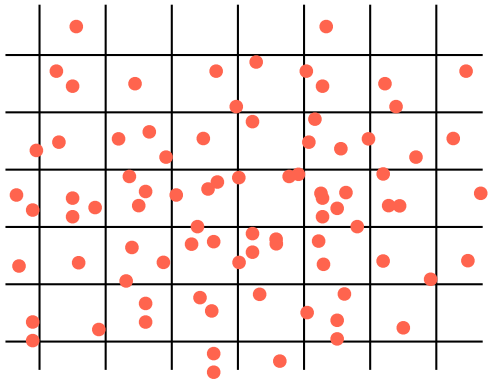
Flip horizontally

Backward



Grid spacing typically 4”

Regridding

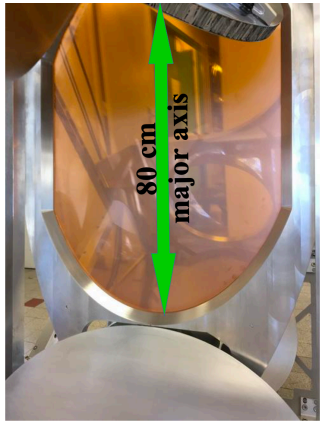


0.2 s each, or 7” moving at 34”/s

Slide from A. Lundgren

Systematics

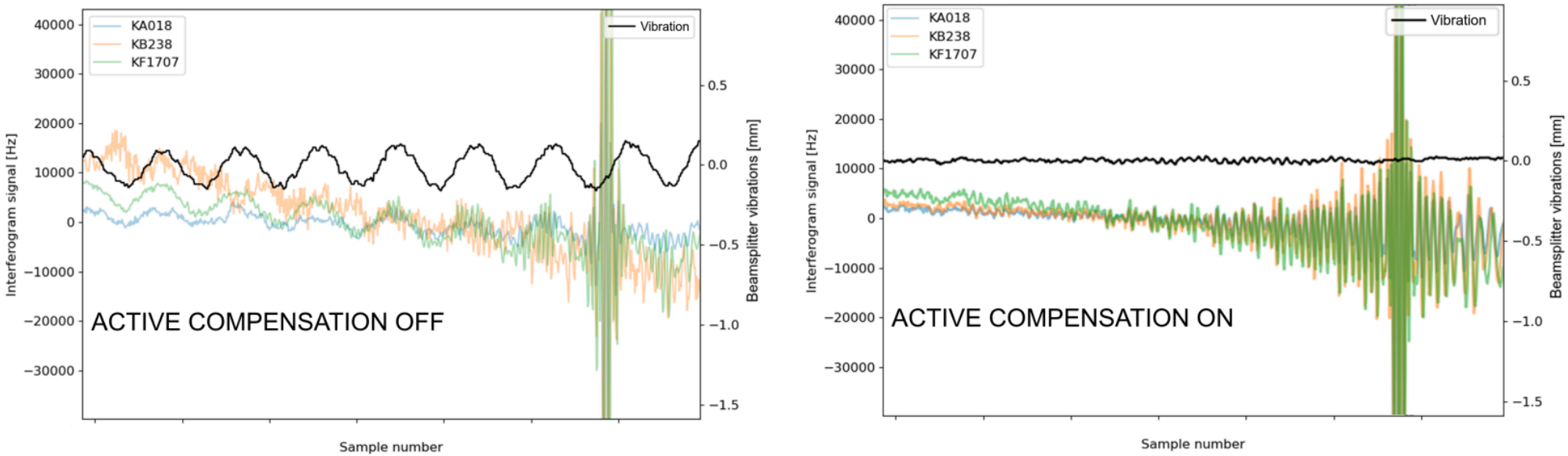
Beamsplitter membrane vibration



Oscillations due to acoustic noise

Solution was to install (Dec 2021) a series of devices that measure and mitigate the vibration (speaker pointing towards the membrane+laser)

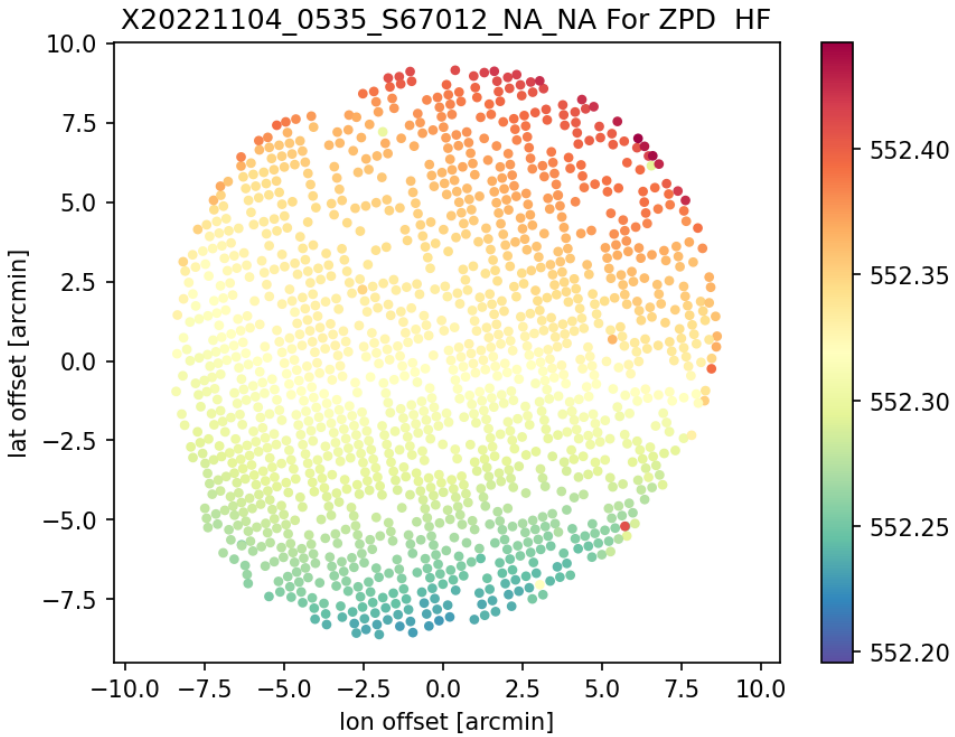
=> correction of these vibrations by propagating a correcting sound wave



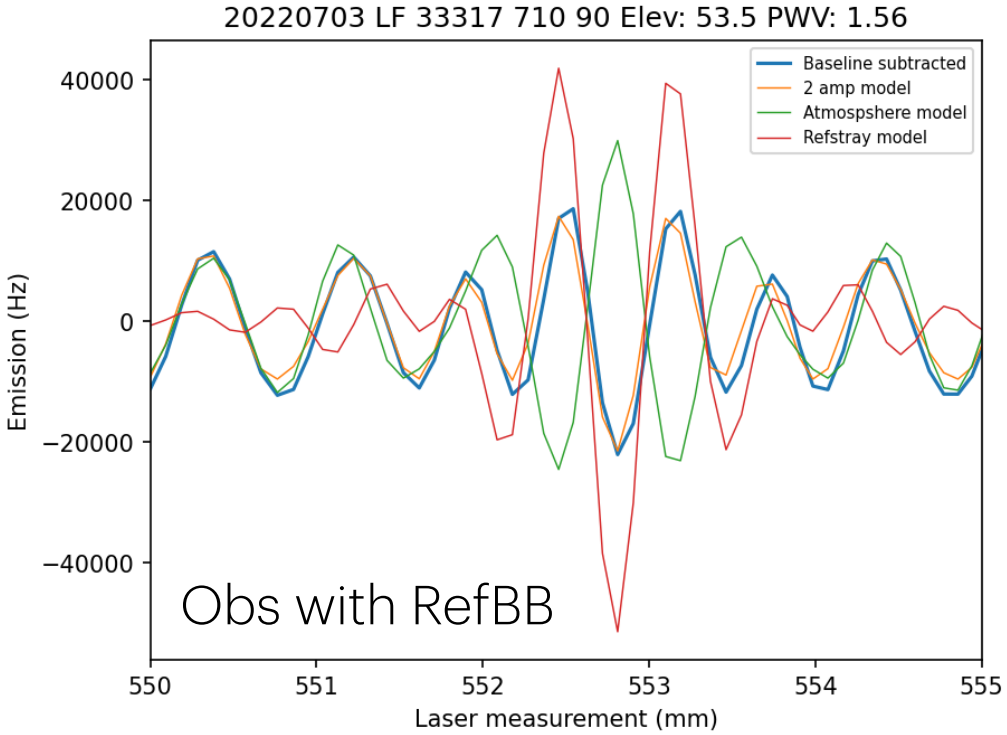
Fasano+2022

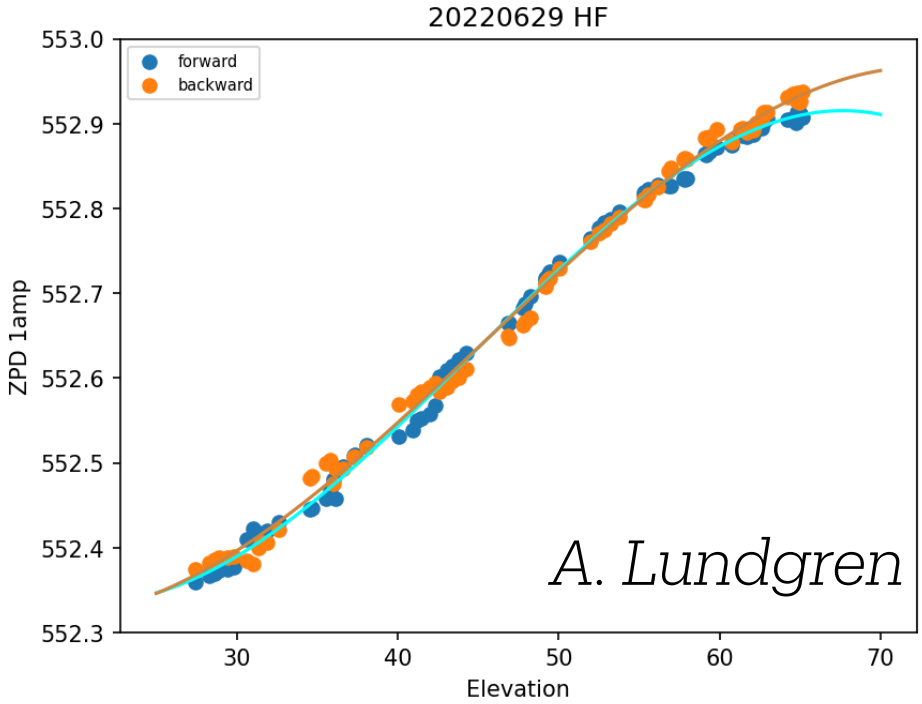
Systematics

Zero Path difference (ZPD)



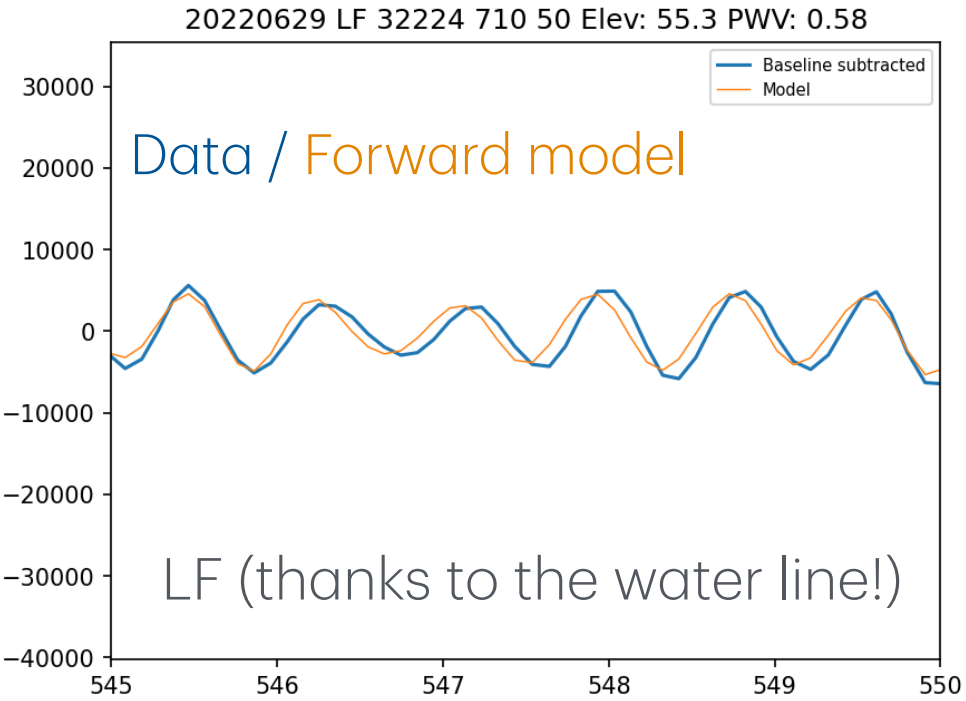
ZPD depends on location on the array, elevation, mirror movement direction, and which array



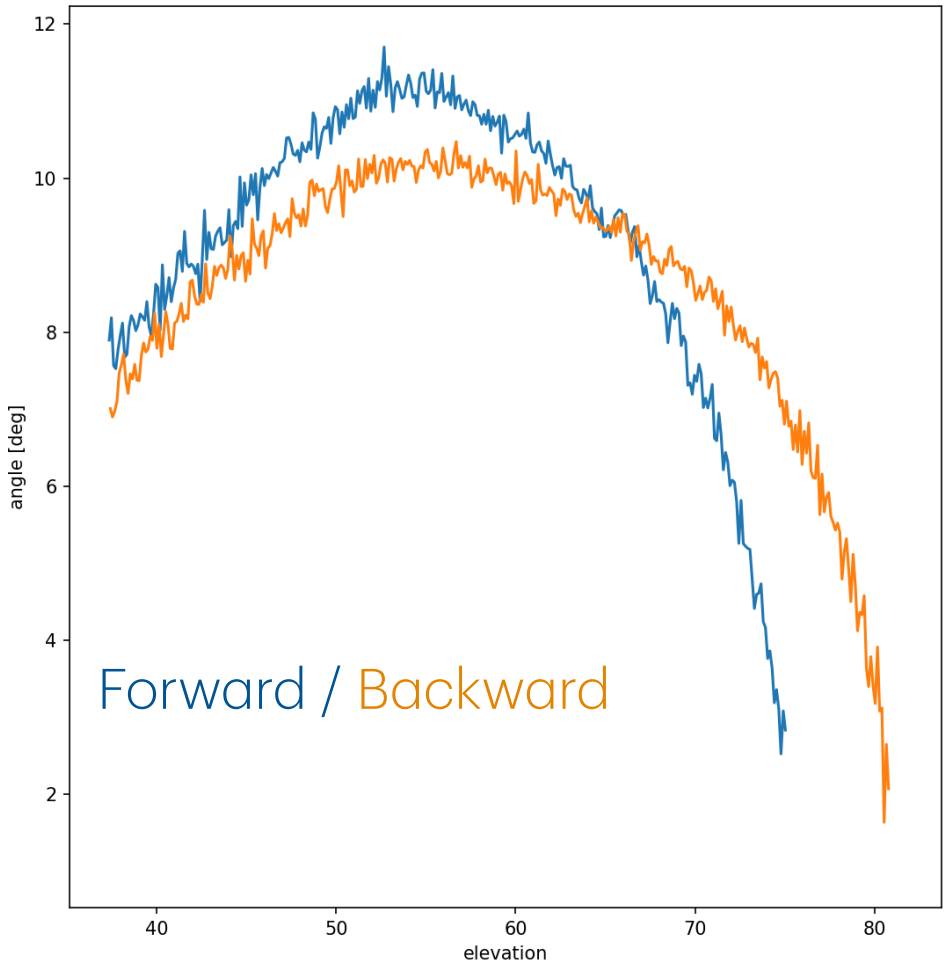


Systematics

Stretching of the Optical Path Difference (OPD) — **Debated!**



Far from ZPD

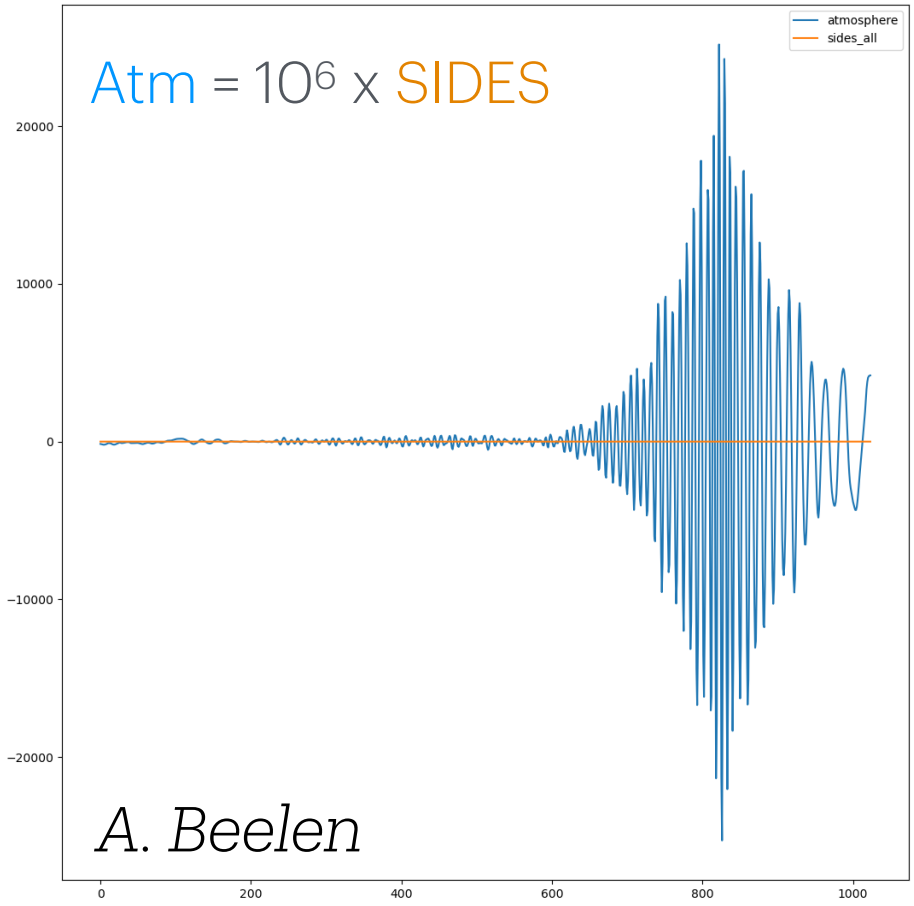


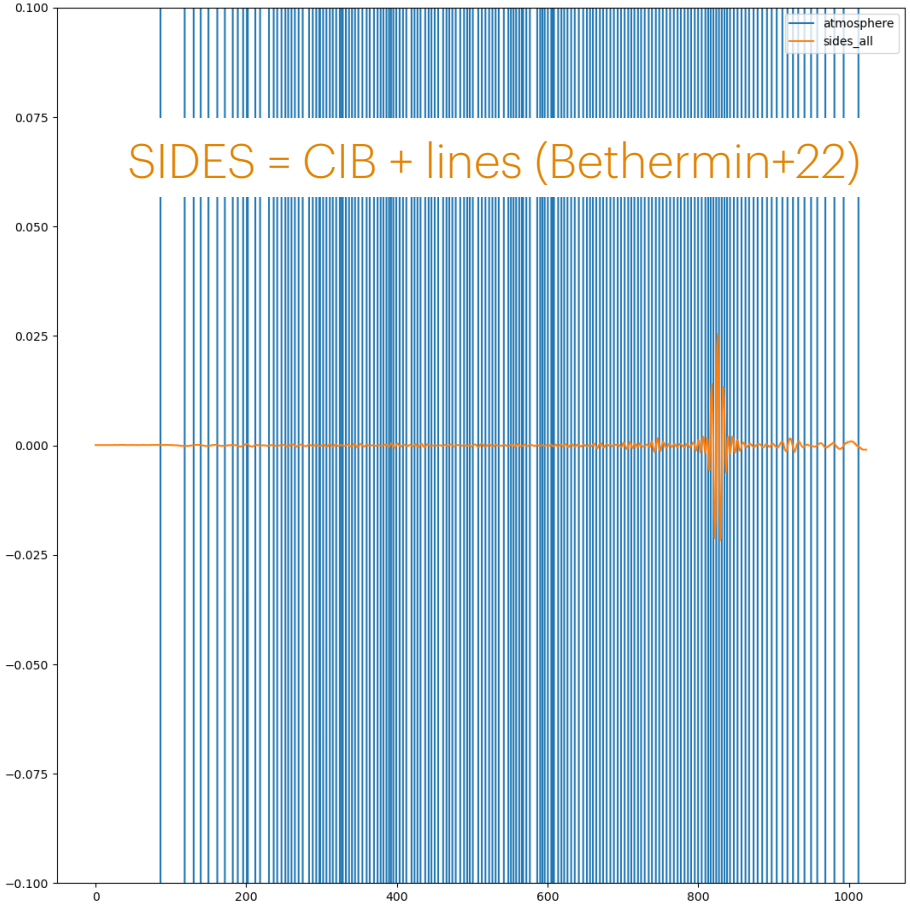
Converting the stretch into angles

A. Beelen

Systematics

Atmospheric emission (when RefBB)

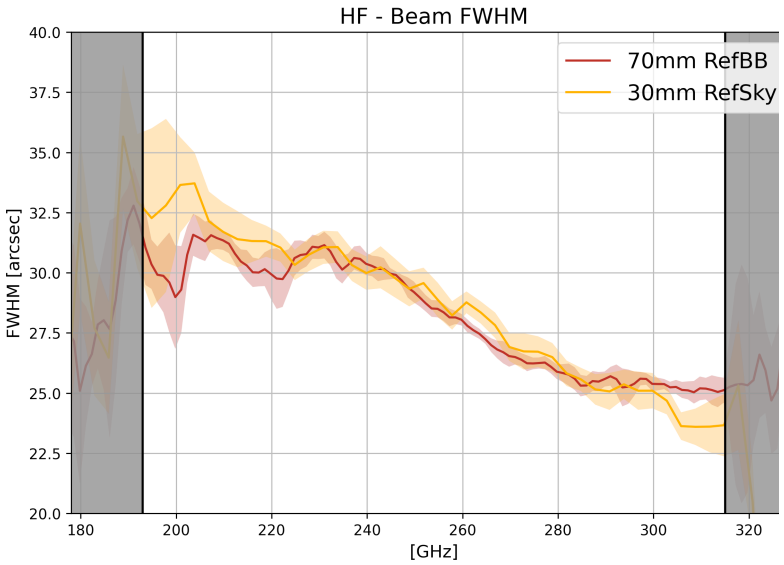


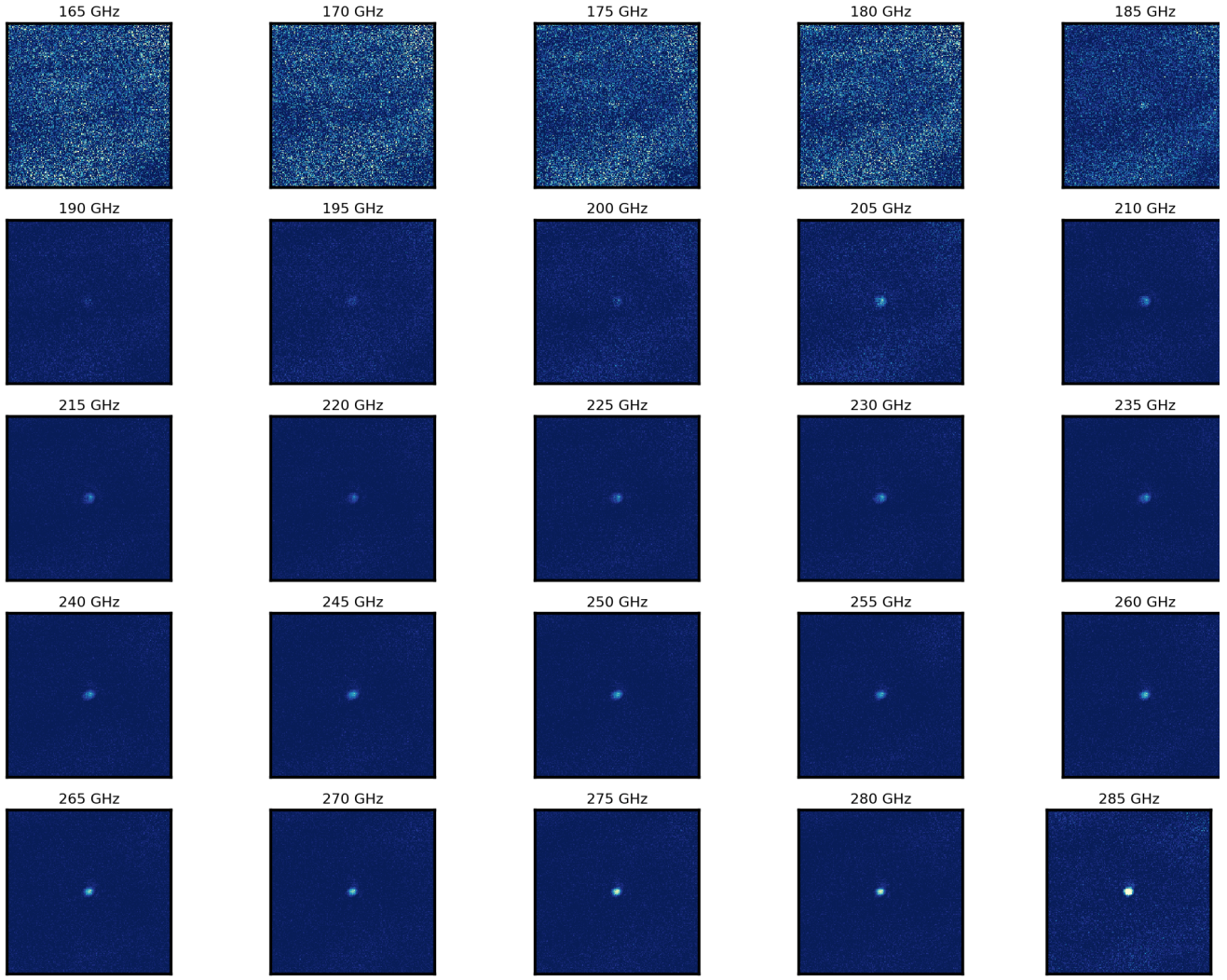


Common mode removal, filtering

=> Full instrument model to correct for pipeline TF (Fasano+ to be submitted)

Mars: Beams and absolute photometric calibration





FWHM varies as expected

Beam + Mars size + flattening for

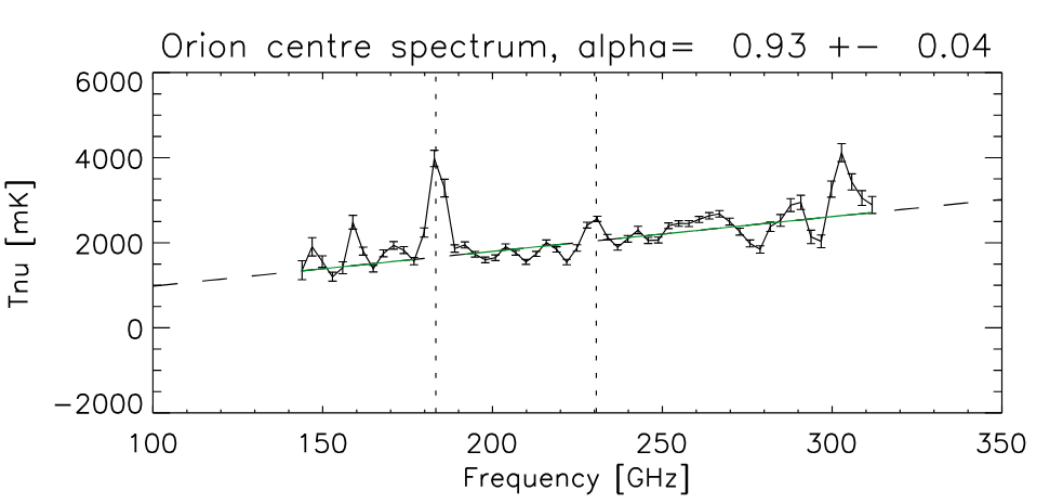
$\nu >$ 260 GHz by design

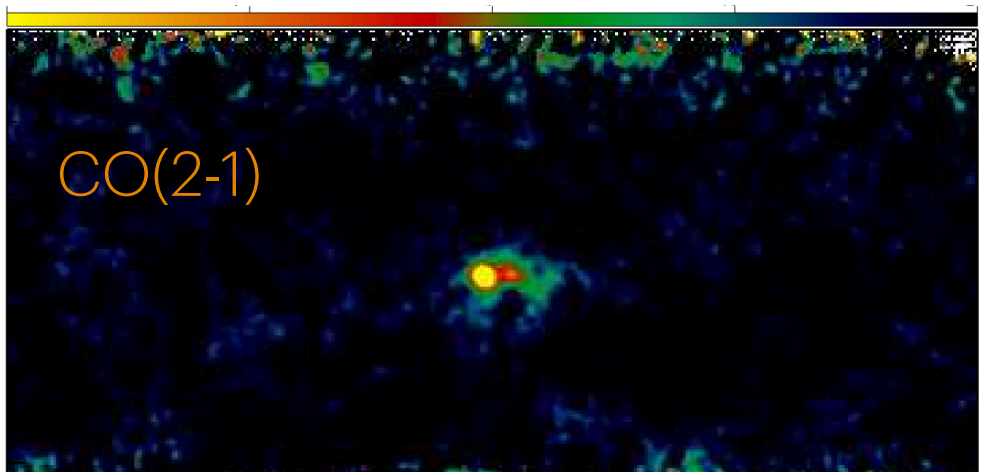
Absolute calibration better than 15%

C. Dubois, D. Quinatoa

Continuum, CO and Water vapour maps of the Orion Nebula

First millimetre spectral imaging with CONCERTO





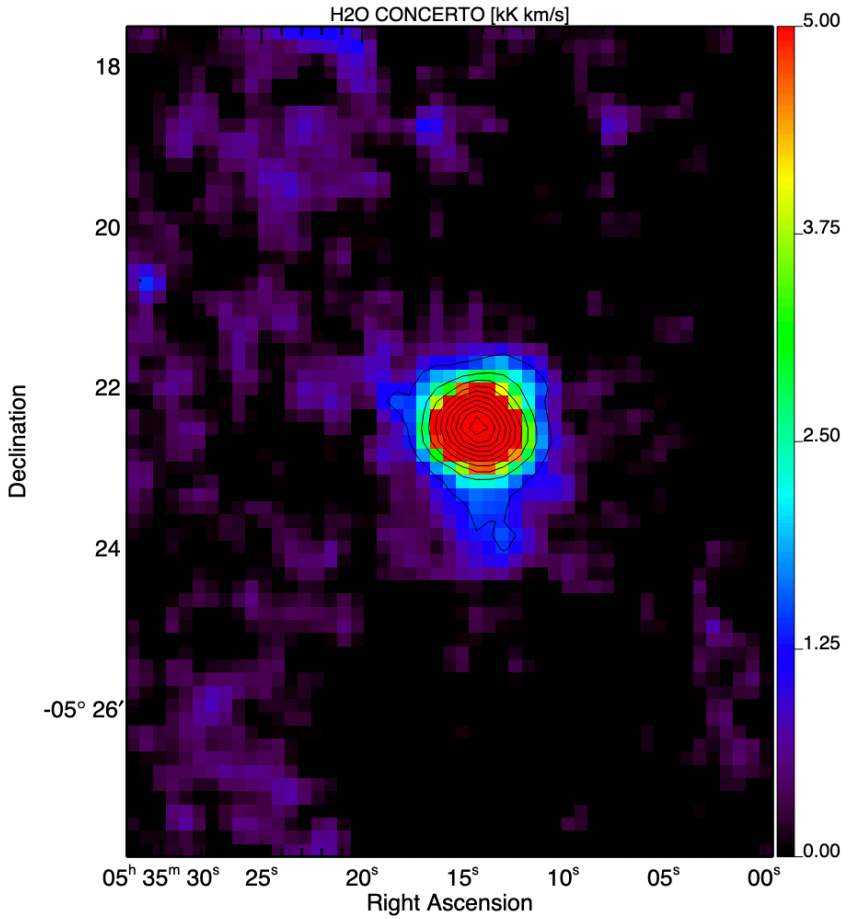


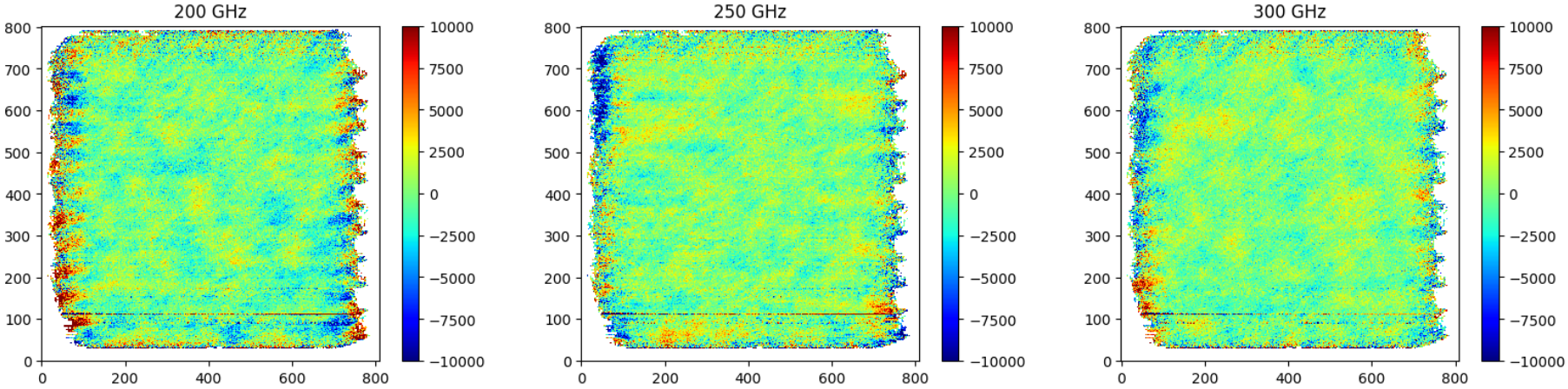
Fig. 11. Map of H_2O line integrated intensity in Orion, after a convolution (by a 20 arcsecond Gaussian kernel) to reach a resolution of 40 arcseconds, with a focus on the Orion Center. The maximum intensity (saturated in this figure) is 14 kK km s^{-1}. The contours represent the signal-to-noise ratio from 3 by steps of 3.

Désert+2025

[CII] LIM: COSMOS field

- 1.4 deg^2, 792 hours (650 hours on field) ; on site and remote observations
  - 146 hours from 2021 (before active compensation of vibrations)
- Rectangular and spiral on-the-fly scans in a raster scanning pattern, totalling 1522 scans (72 scans excluded due to poor quality)
- Final spectral resolution: 2.5 GHz (from 130 to 310 GHz)
- 90 Tb of data (x5 uncompressed)
- Precipitable water vapour pwv=0.83±0.63
- ..... hope to derive an upper bound with meaningful constraints

One scan (preliminary)



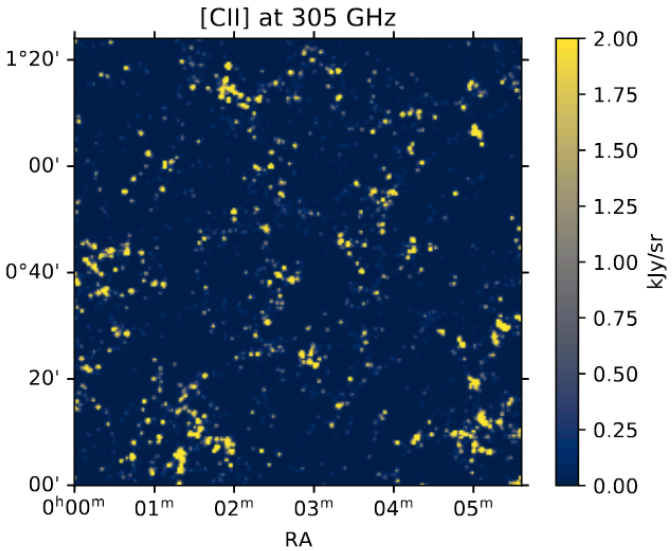
(Other) Challenges for [CII] line intensity mapping

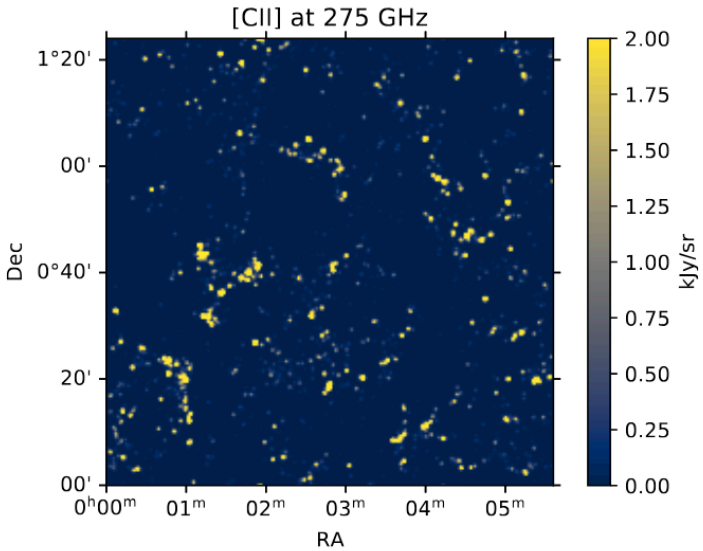
Excluding data reduction & systematics

The signal is very weak

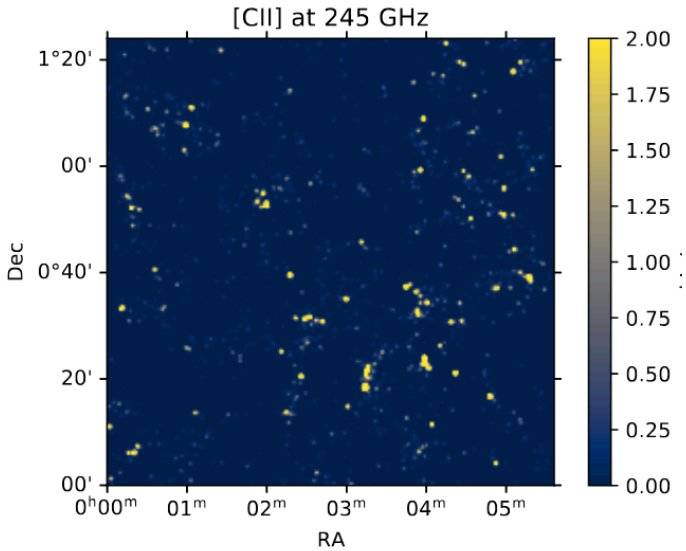
- Interferogram timelines: 10^{6} times weaker than atmospheric noise
- Power spectrum: $10^{2\text{-}3}$ times weaker than CIB fluctuations
- Power spectrum: ~same level as (or 10x weaker than) CO + CI interlopers
- Need other summary statistics than P(k)

z=5.2



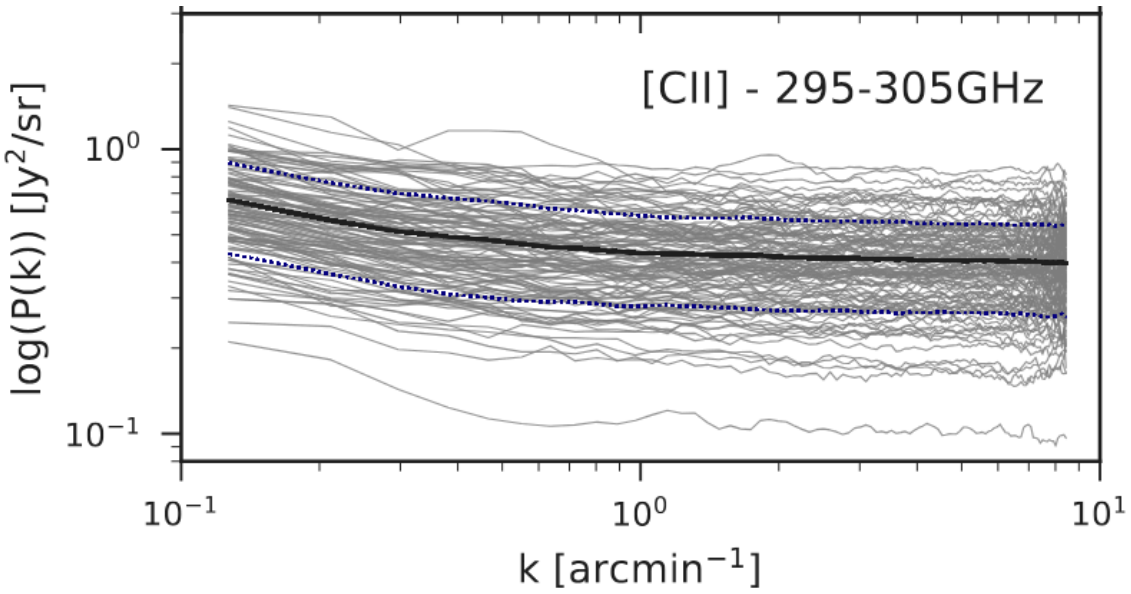


z=6.8

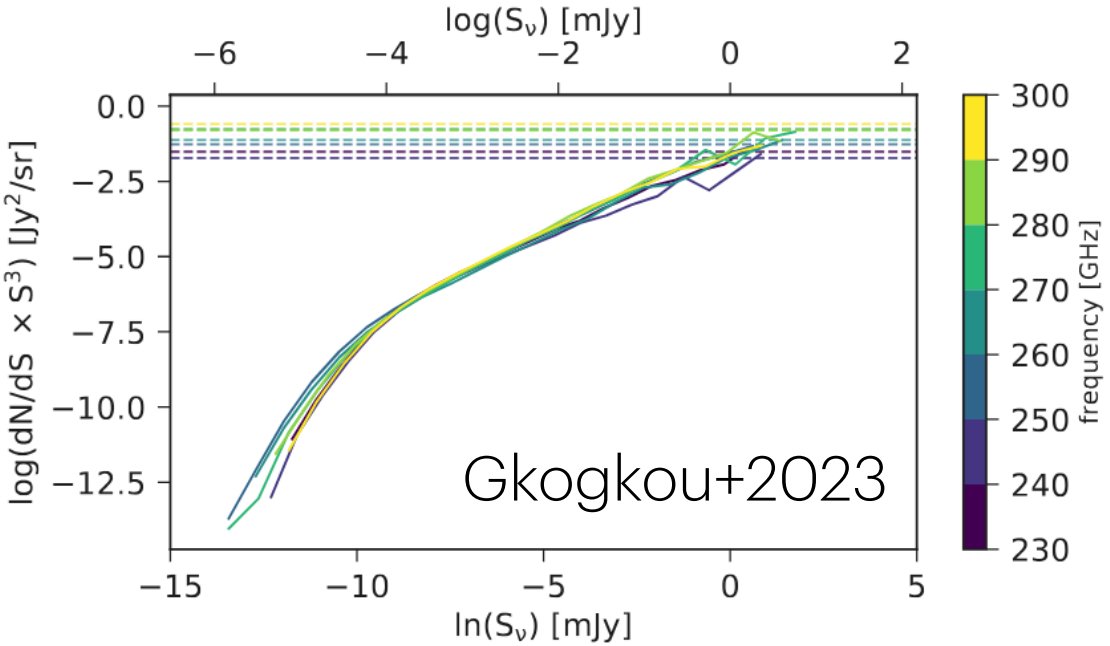


Béthermin+2022

The shot noise is very high and not well-behaving



117 power spectra on 1 Sq. Deg. fields

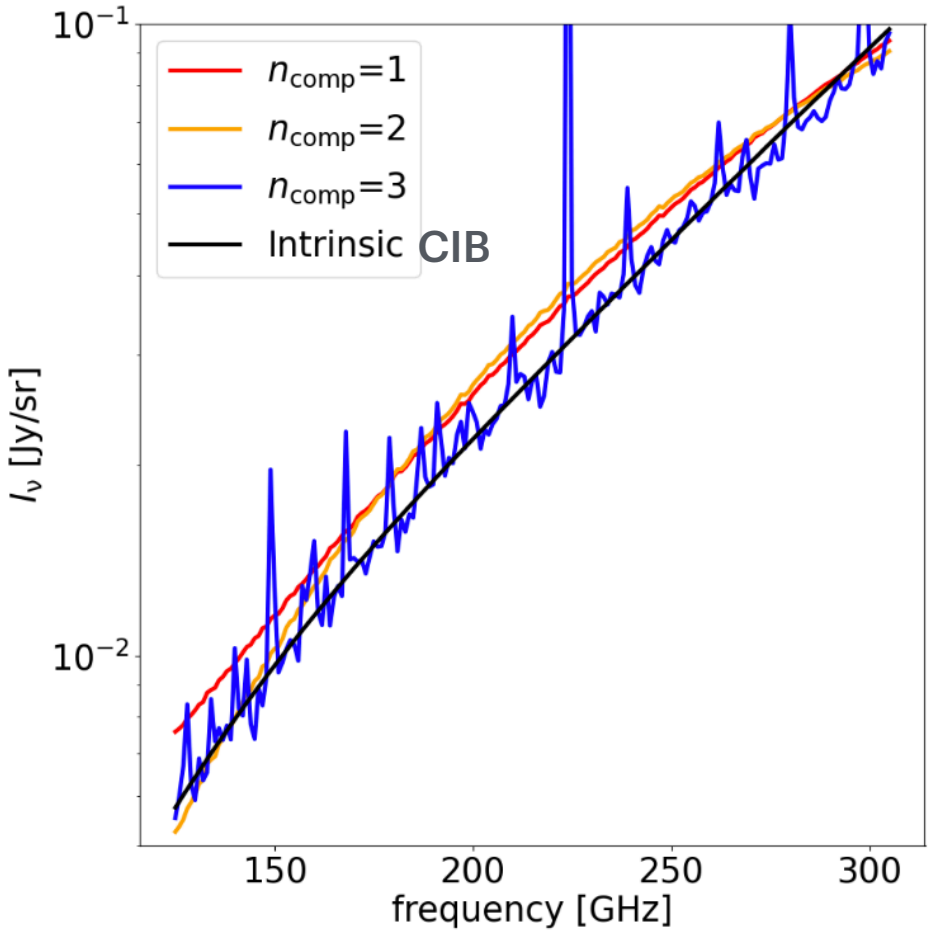


Contribution to the shot noise (as a function of fluxes)

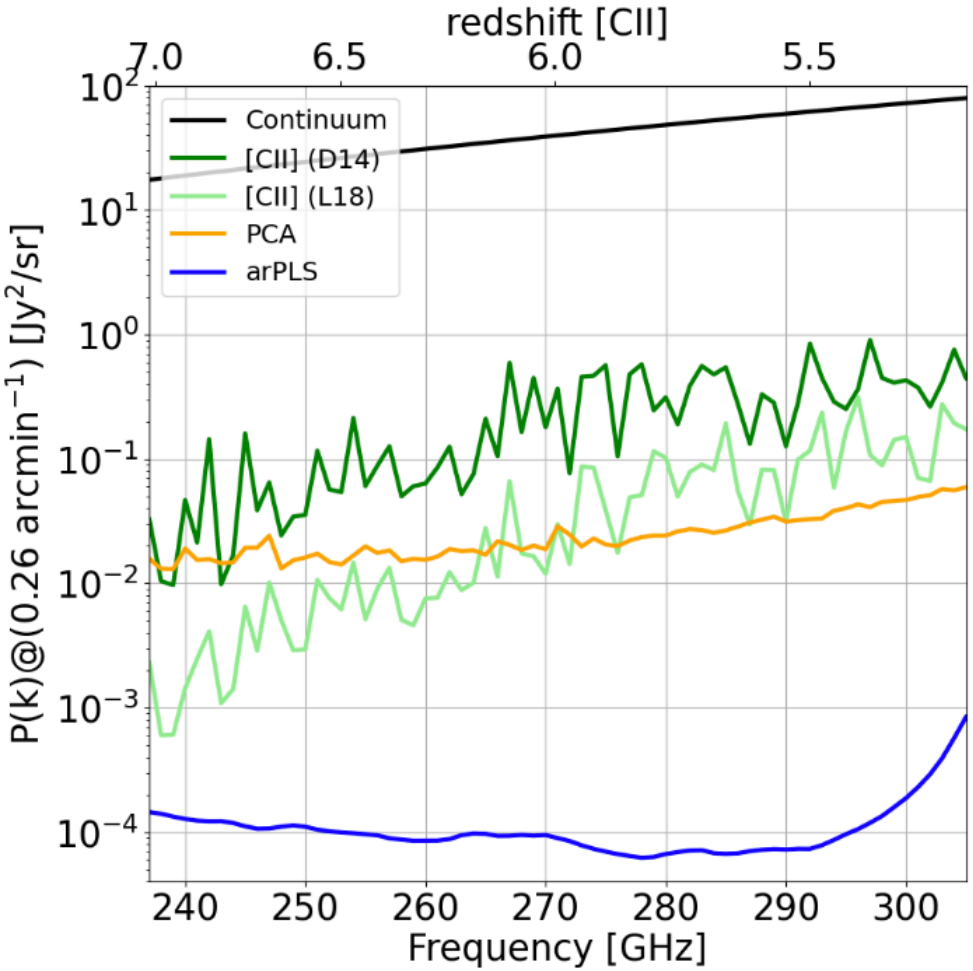
Unlike for the CIB: shot noise always dominated by the brightest sources

Component separation

Continuum (CIB)



PCA



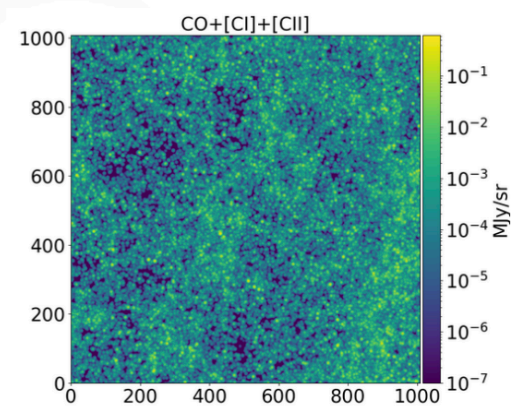
ArPLS (iterative smooth baseline estimator)

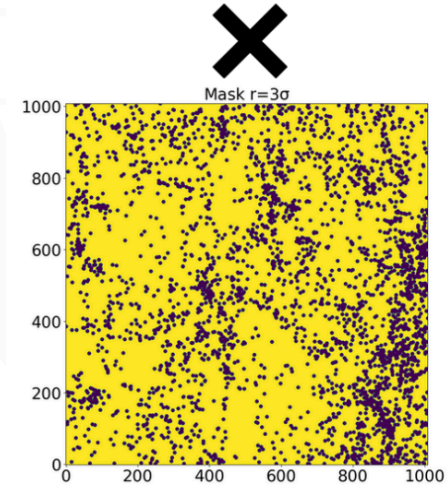
Van Cuyck+2023

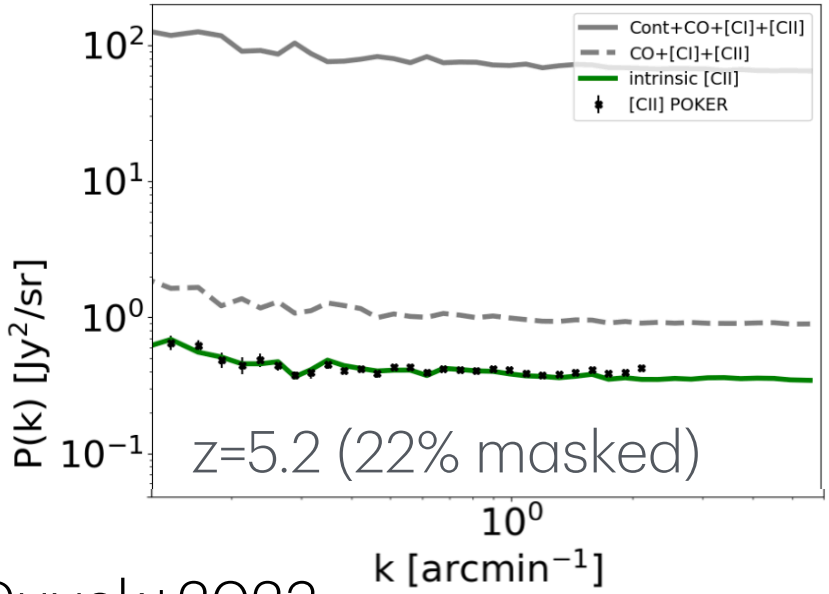
Component separation

Lines (interlopers)

- Masking (e.g. Silva+15,+21; Breysse+15; Van Cuyck+23; Karoumpis+24)
- Anisotropies of interlopers projected on the [CII] frame (e.g. Lidz & Taylor16; Gong +20; Cheng+20)
- Cross-correlations (e.g., Chang+15; Switzer+19; Chung+19; Comaschi+16) — including internal cross-co.
- Deep learning (Moriwaki+20,21: Halpha at z=1.3-2.4)







Van Cuyck+2023

Modeling

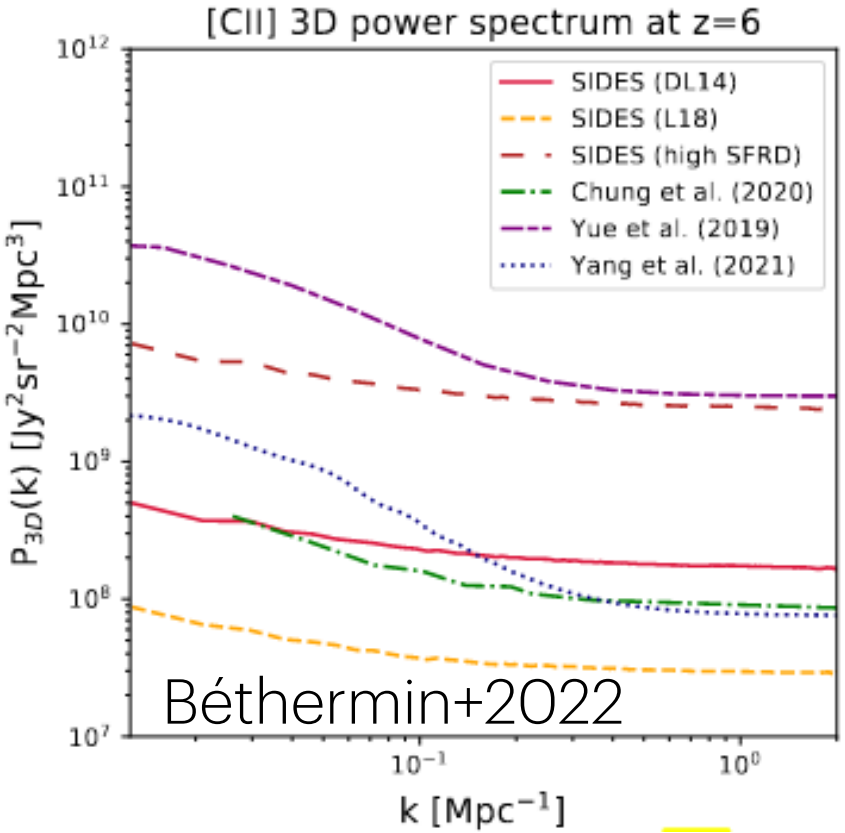
high-z [CII]

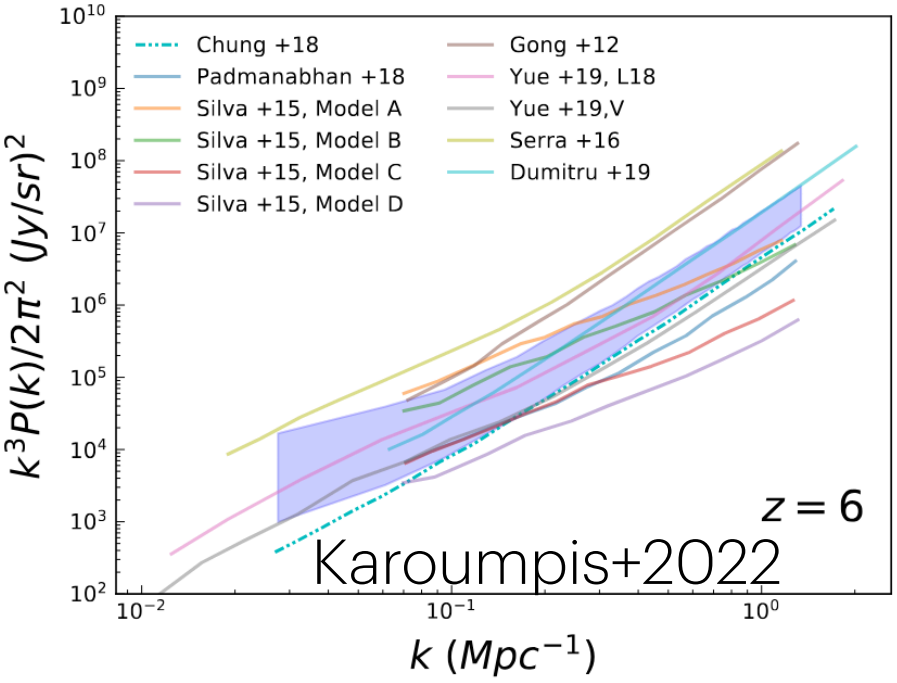
- Analytical models: Dark-matter distribution (HOD) + empirical scaling relations (e.g., Gong+12, Serra+16, Yue&Ferrara+19, Yang+22)

- Dark-matter only simulations combined with semi-analytical models (e.g. Moradinezhad Dizgah+22, Béthermin+22, Gkogkou+23, Sun+23)

- Cosmological-volume hydrodynamical simulations (e.g., Kannan+22; Karoumpis+22 (coupled with empirical relations))

Discrepancy of a factor ~100 (at z=6)

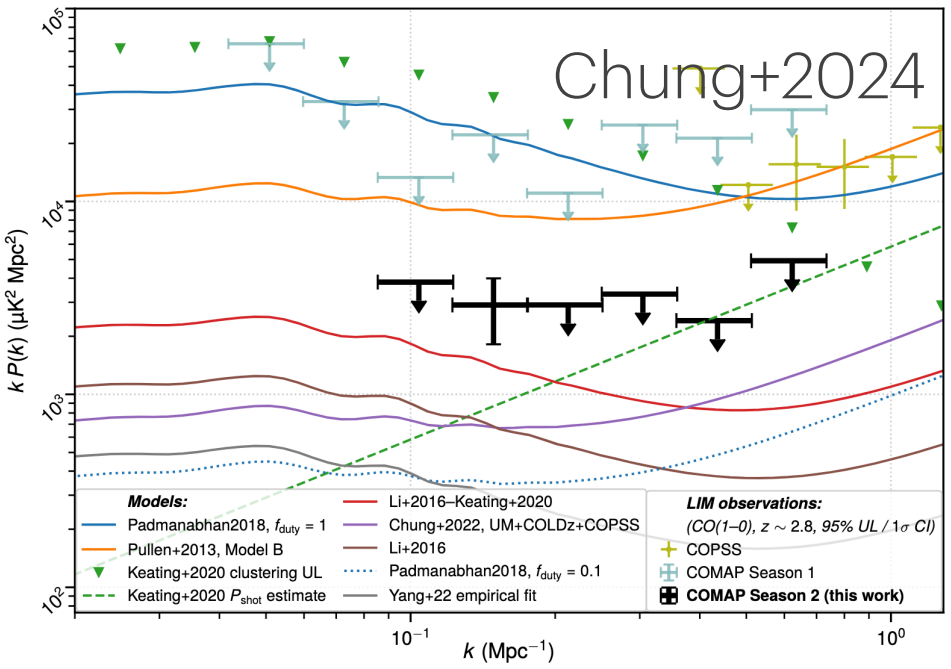




Modeling

Low-z CO contamination: also quite uncertain

CO(1–0) power spectrum at z~3



So hard.....

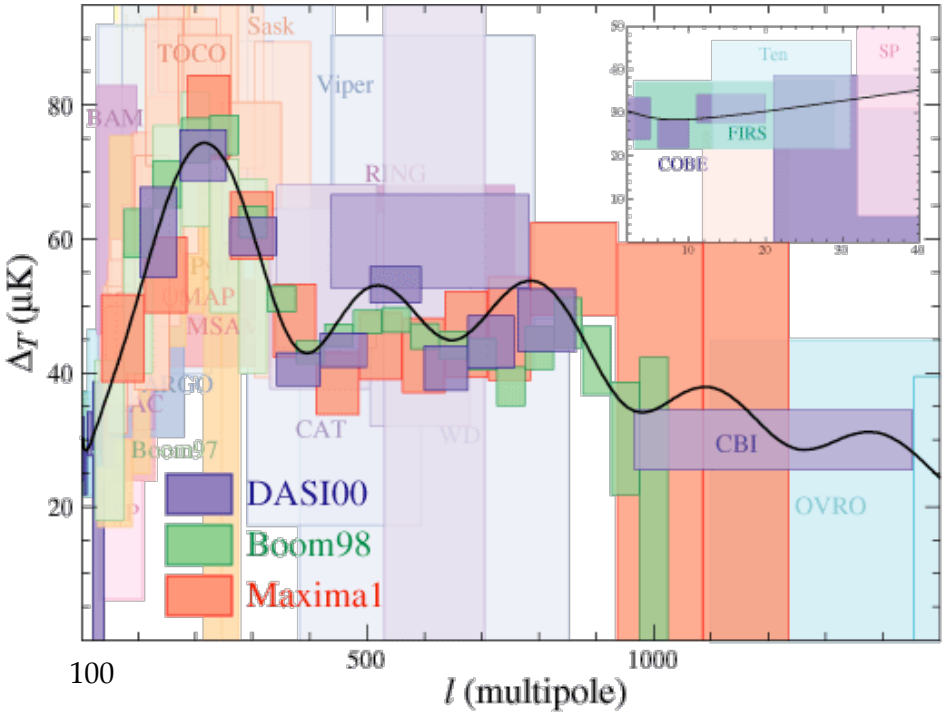
- Redshift evolution of scaling relations?
- Power of intensity mapping is to probe objects too faint for individual detections: validity of scaling relations outside the range of measurements?
- At high z: CMB background
- Radiative transfer, chemical enrichment, multiphase ISM, including resolved HII, PDR and molecular regions, metal and dust production and distributions, and precise radiation field intensities.
- Large cosmic variance (for [CII]: Gkogkou+23)
- Optimal extraction of key physical parameters?

Conclusion

- [CII] line: need to increase the sample size for individual galaxies
- CONCERTO:
  - First [CII] IM experiment (observations in 2021 & 2022)
  - Hope to get a meaningful upper limit on the [CII] power spectrum
  - Currently investigating Gal x CO interlopers at $0.5<z<3$
- Numerous challenges
  - Measurements but also component separation & modelling
- Good luck for the next generation of [CII] intensity mapping experiments!

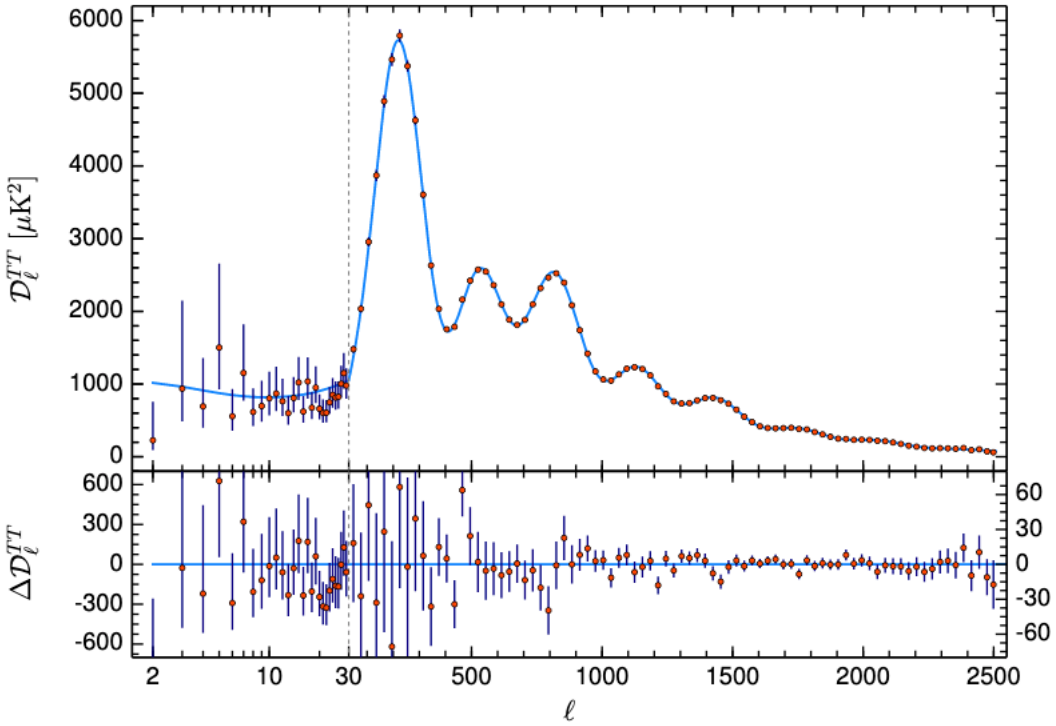
Be patient!

CMB in 2001



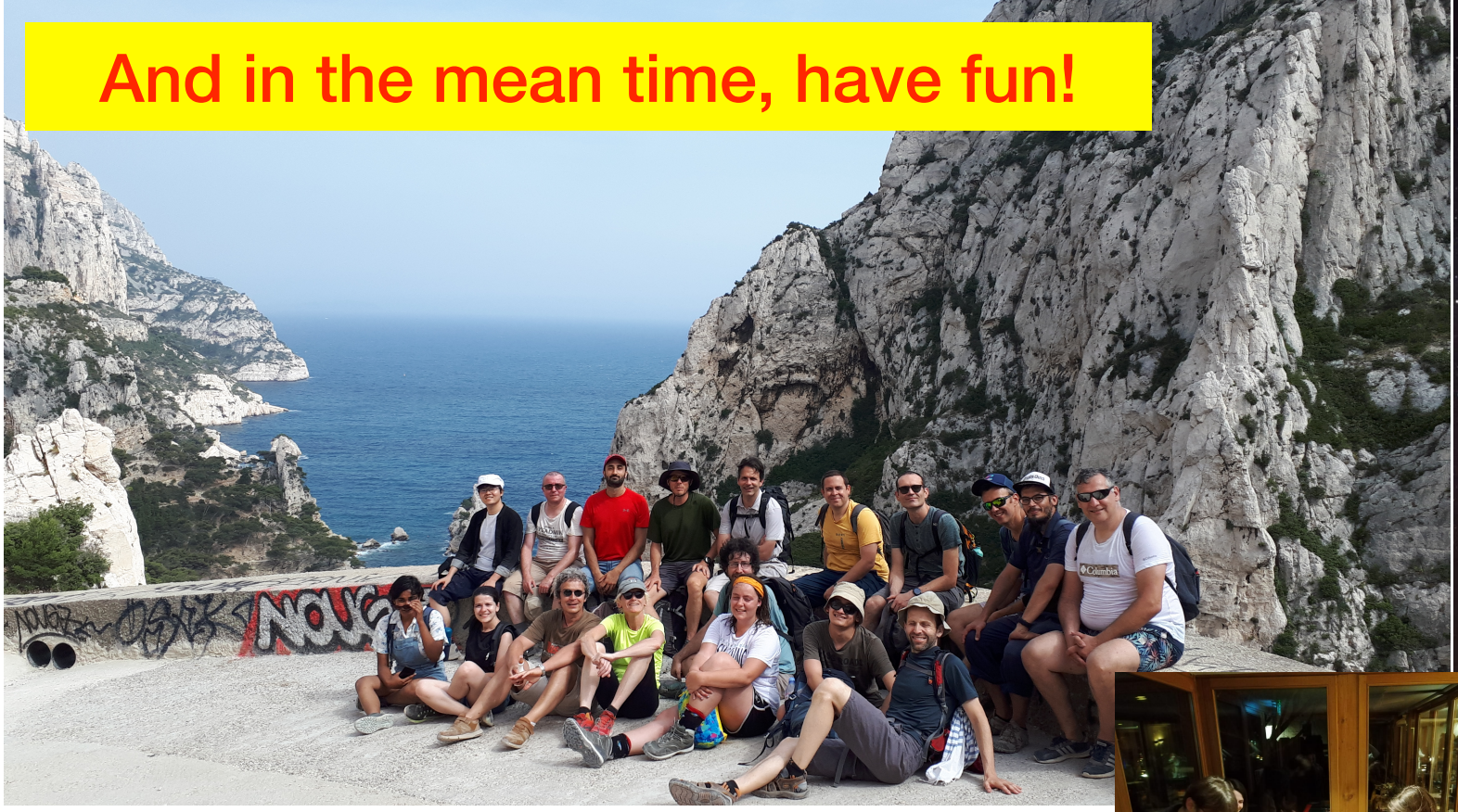
Wayne Hu

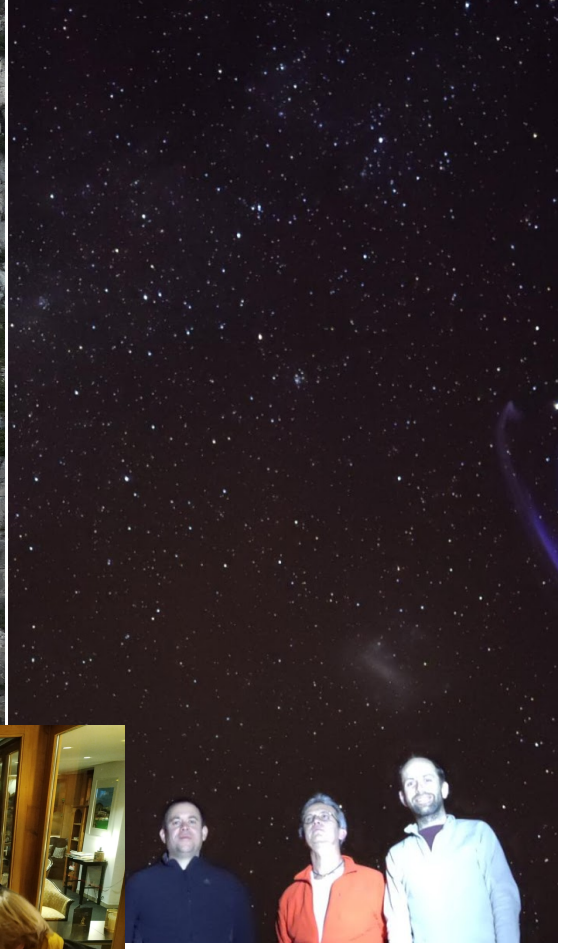
CMB in 2018



Planck collaboration 2018
Credits: ESA

And in the mean time, have fun!





Part of the CONCERTO collaboration

SIDES: Main structure

Dark-matter halos (M_{halo})

Abundance Matching

Galaxies ($M_{stellar}$)

Passive galaxies

Star forming galaxies

Empirical Scaling relations

M_* - SFR
SFR – L_{IR}
$L_{CO(1-0)}$ - L_{IR}
$L_{[CII]}$ - SFR
$L_{[CI]}$ - $L_{CO(X-Y)}$

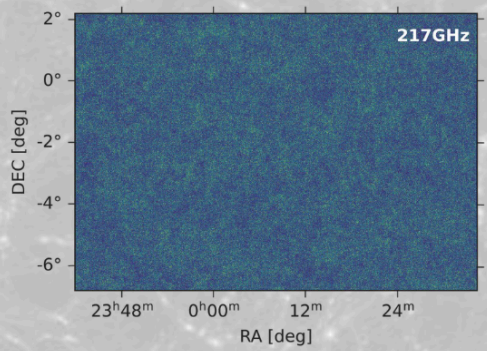
SFR

L_{IR}

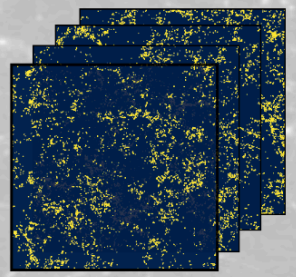
L_{CO}, $L_{[CII]}$, $L_{[CI]}$

map maker

cube maker



Continuum emission
Planck 217GHz



Continuum
[CII] emission
CO emission
[CI] emission

Code publicly available:
https://gitlab.lam.fr/mbethermin/sides-public-release

Catalogs publicly available:
https://cesamsi.lam.fr/instance/sides/home

Béthermin et al. (2017)
Béthermin, Gkogkou et al. (2022)