# Large surveys of dusty galaxies at high redshift with AtLAST

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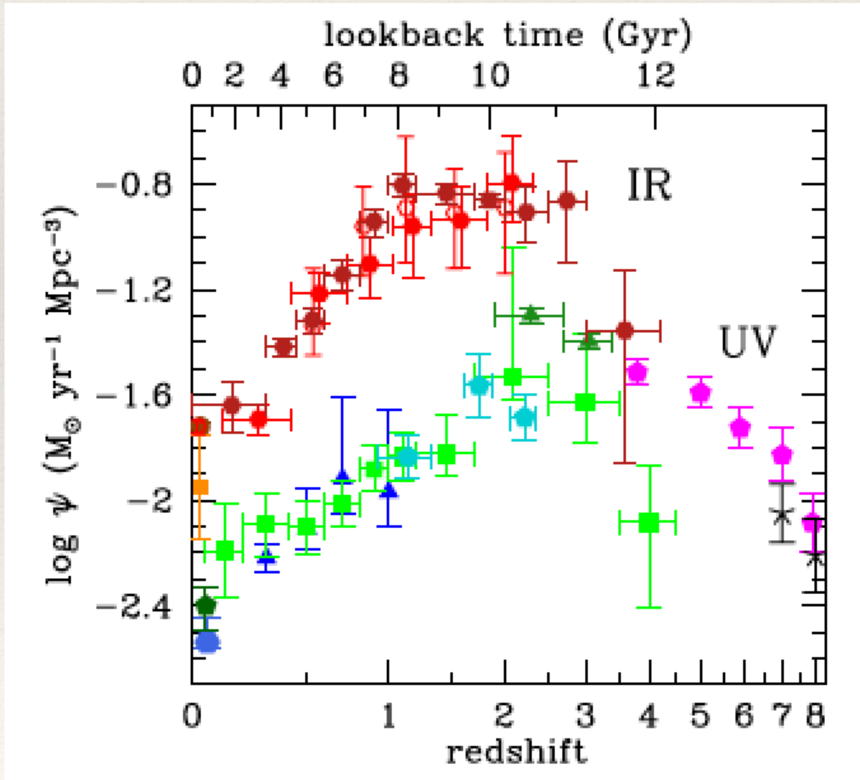
LAM

# The high-redshift dusty Universe

- Final frontier in piecing together a coherent picture of cosmic history relates to the period 6<z<15
  - Earliest stars and galaxies began to shine
  - The intergalactic medium transitioned from a neutral to a fully ionized gas
- The two are connected (e.g., Planck collaboration 2016, Robertson+2015)

- Another remarkable result :
  - Realization that the SFR at redshifts z>1 is higher than at present by about an order of magnitude
  - >half of the energy produced since the surface of last scattering has been absorbed and reemitted by dust (in Dusty Star-Forming Galaxies, DSFG)




Madau & Dickinson, 2014

# The high-redshift dusty Universe

- Two fundamental questions AtLAST has to address:
  - What is the contribution of the dust-enshrouded star formation at z>3?
  - What is the role of DSFG in shaping the reionization?
- In particular:
  - When did the Universe produce dust? What is the history of star formation?
  - How the ISM in typical galaxies matures from a nearly primordial, dust-free state at z~8 to the dust- and metallicity-enriched state observed at z~4?
  - From gas to stars: what are the processus of regulation of star-formation?

# Observing the high-redshift dusty Universe

- Continuum: $L_{IR}$ ( SFR), dust mass, dust temperature
- Lines CII, OIII, NII, OI, CI, CO (and many others… )
  - Redshifts
  - Gas mass reservoirs
  - Gas cooling rate
  - Metallicities
  - Shocks & AGN activity

| | |
|---|---|
| $CII_{158}$ | PDRs, diffuse HI, diffuse ionized gas, HII regions |
| $OI_{63}$ | Warm and / or dense PDRs |
| $OIII_{88}$ | High-excitation ionized gas |
| $NII_{122,205}$ | Low-excitation ionized gas |
| $CI_{370,\ 609}$ | Cold molecular gas |
| CO | Molecular gas |

- Clustering (lines or continuum):
  - How galaxies populate dark-matter halo?
  - What is the typical halo mass scale of star formation?
  - Role of the cosmic web in shaping galaxy properties

# Observing the high-redshift dusty Universe

- In the (sub-)mm, galaxies are so faint and numerous, compared to the angular resolution achievable, that confusion plagues observations substantially.
  - Limited to the brightest galaxies
  - Béthermin+2017: clustering + low-angular resolution:
    - Number counts measured by Herschel at 350 and 500µm between 5 and 50 mJy are biased towards high values by a factor ~2

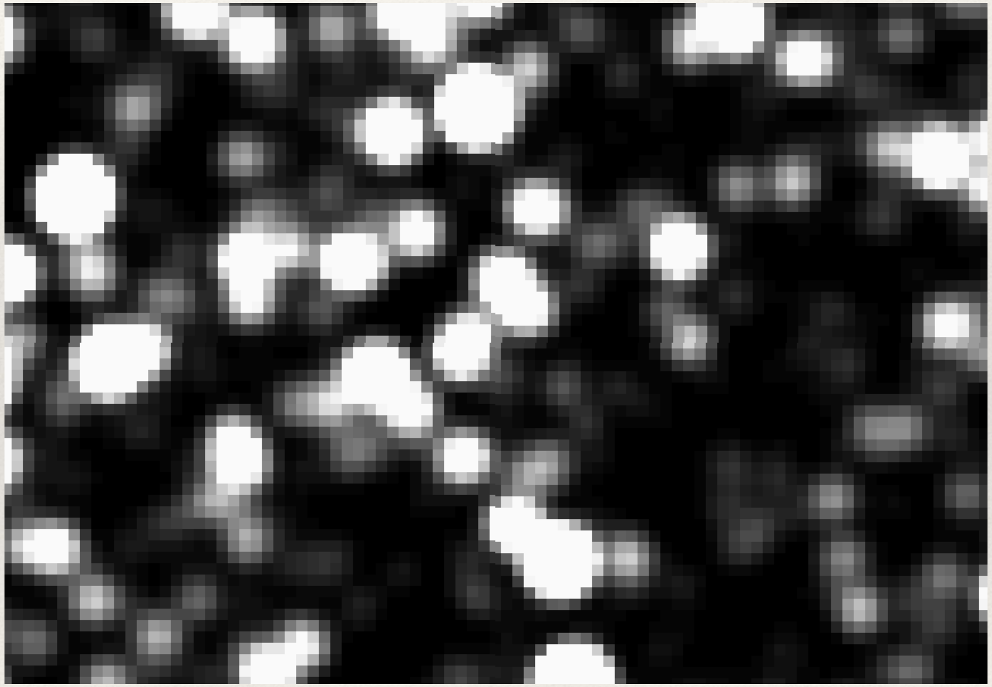
- Blind surveys with the ALMA interferometer can see fainter DSFGs but are detecting only a handful of galaxies at z>4 because of its limited mapping speed.

**=> High mapping-speed continuum and spectroscopic galaxy surveys with a large single-dish telescope**

# Confusion-limited survey with a 25-m dish at 350 microns

- Confusion noise = 105 μJy RMS (after excluding 5σ sources)
- This corresponds to a SFR-limit of:
  9 $M_\odot$/yr at z=2
  30 $M_\odot$/yr at z=4
  92 $M_\odot$/yr at z=6
  (for >5σ detections)
- BUT, very hard to reach confusion limit on large patches at this wavelength
  AND not optimal at z>4

Simulation assuming a 25-m and no instrumental noise



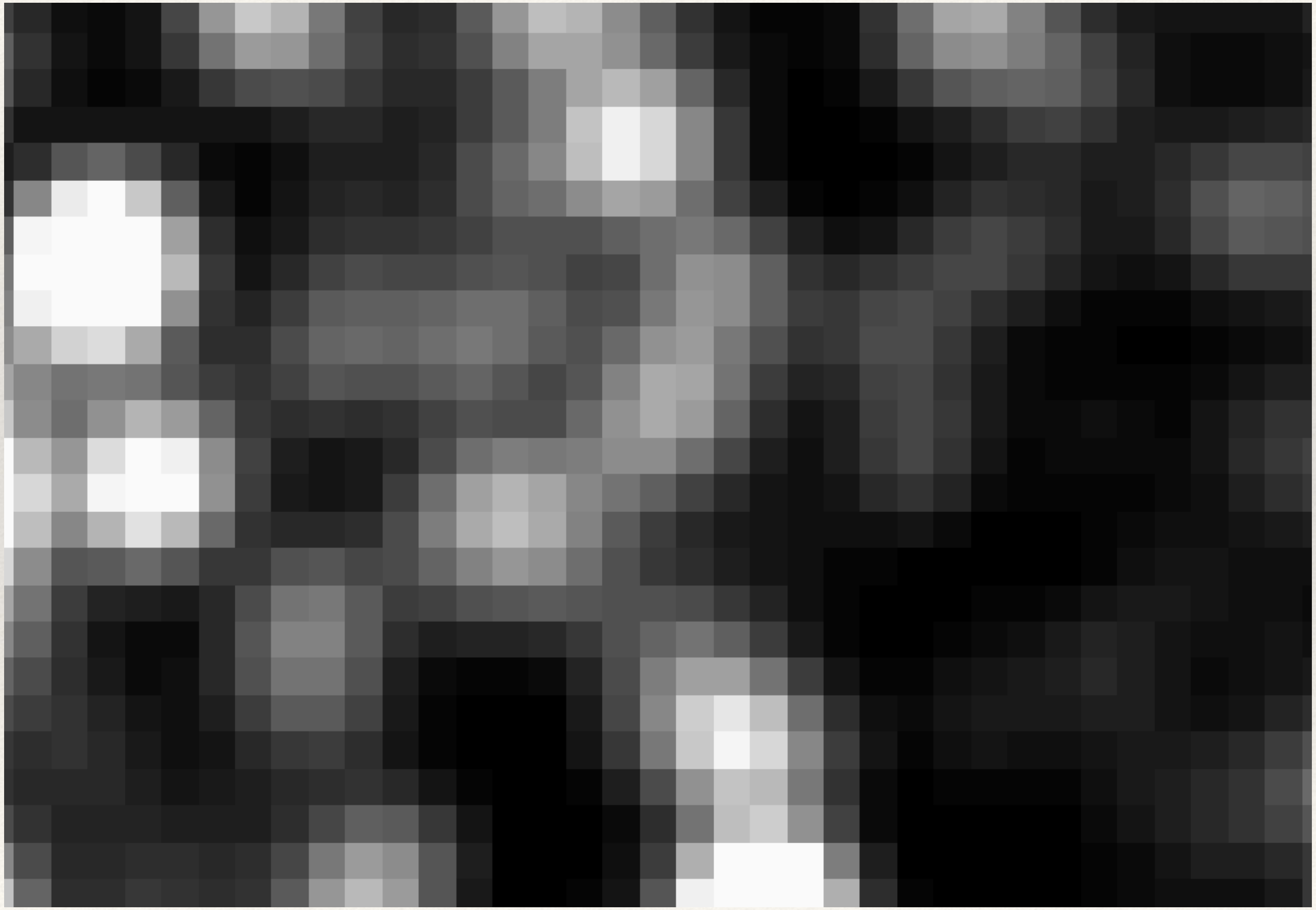
=> some blending, but easy to distinguish most of individual sources

*From SIDES simulations (Bethermin+2017)*

# How size impacts the confusion level?

## 850 microns

Simulation assuming a 25-m and no instrumental noise

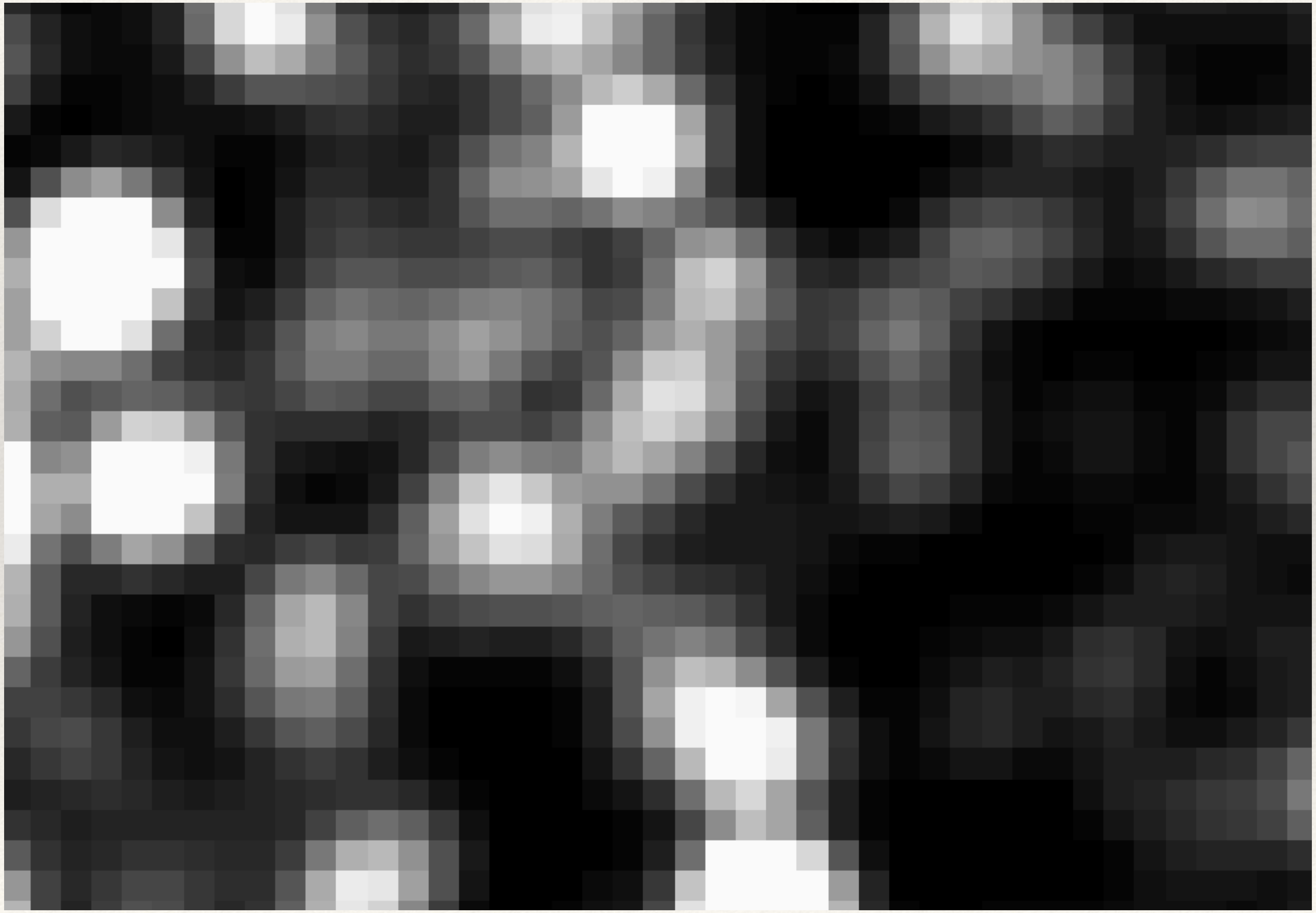


*From SIDES simulations (Bethermin+2017)*

# How size impacts the confusion level?

## 850 microns

Simulation assuming a 30-m and no instrumental noise

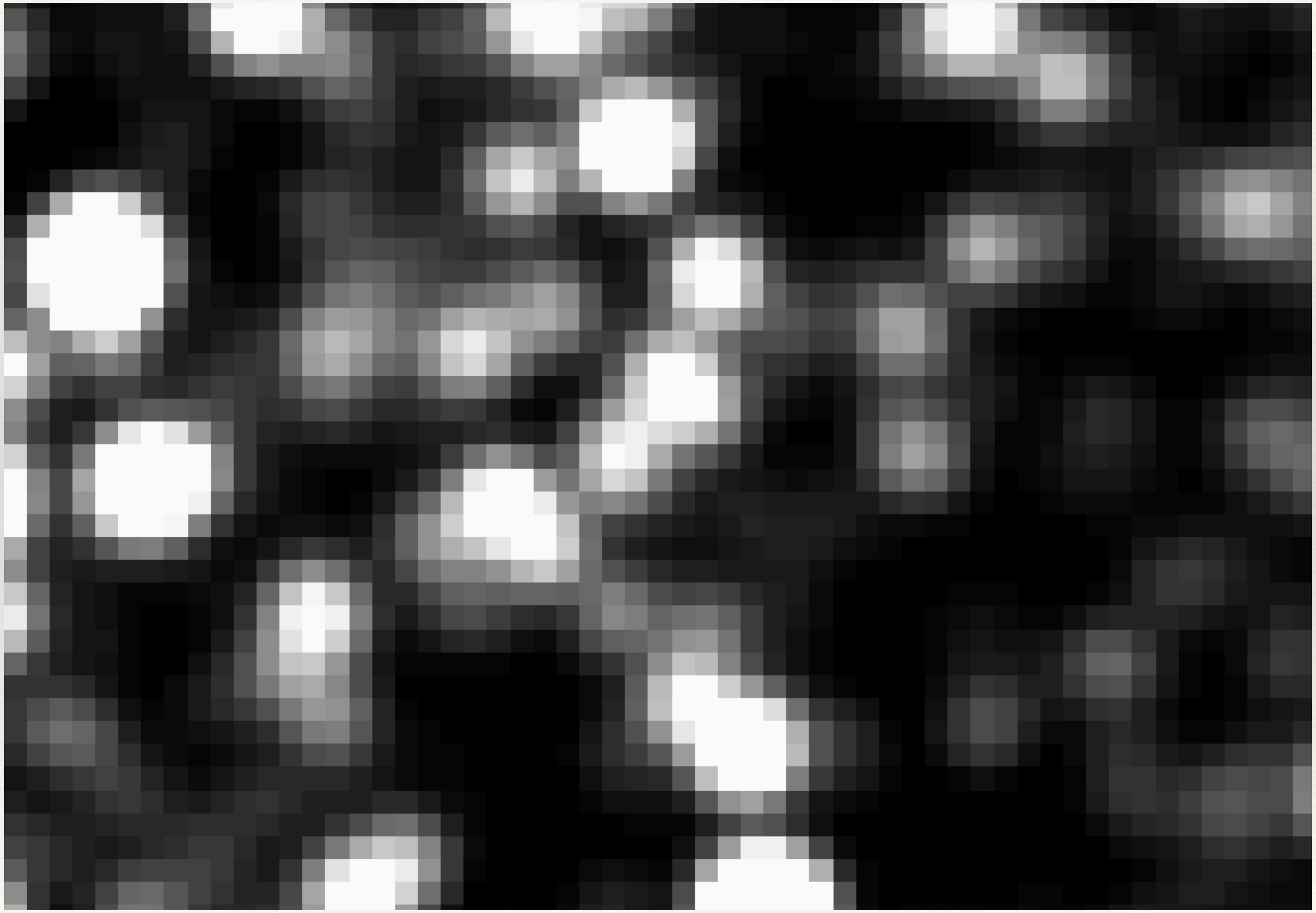


*From SIDES simulations (Bethermin+2017)*

# How size impacts the confusion level?

## 850 microns

Simulation assuming a 40-m and no instrumental noise

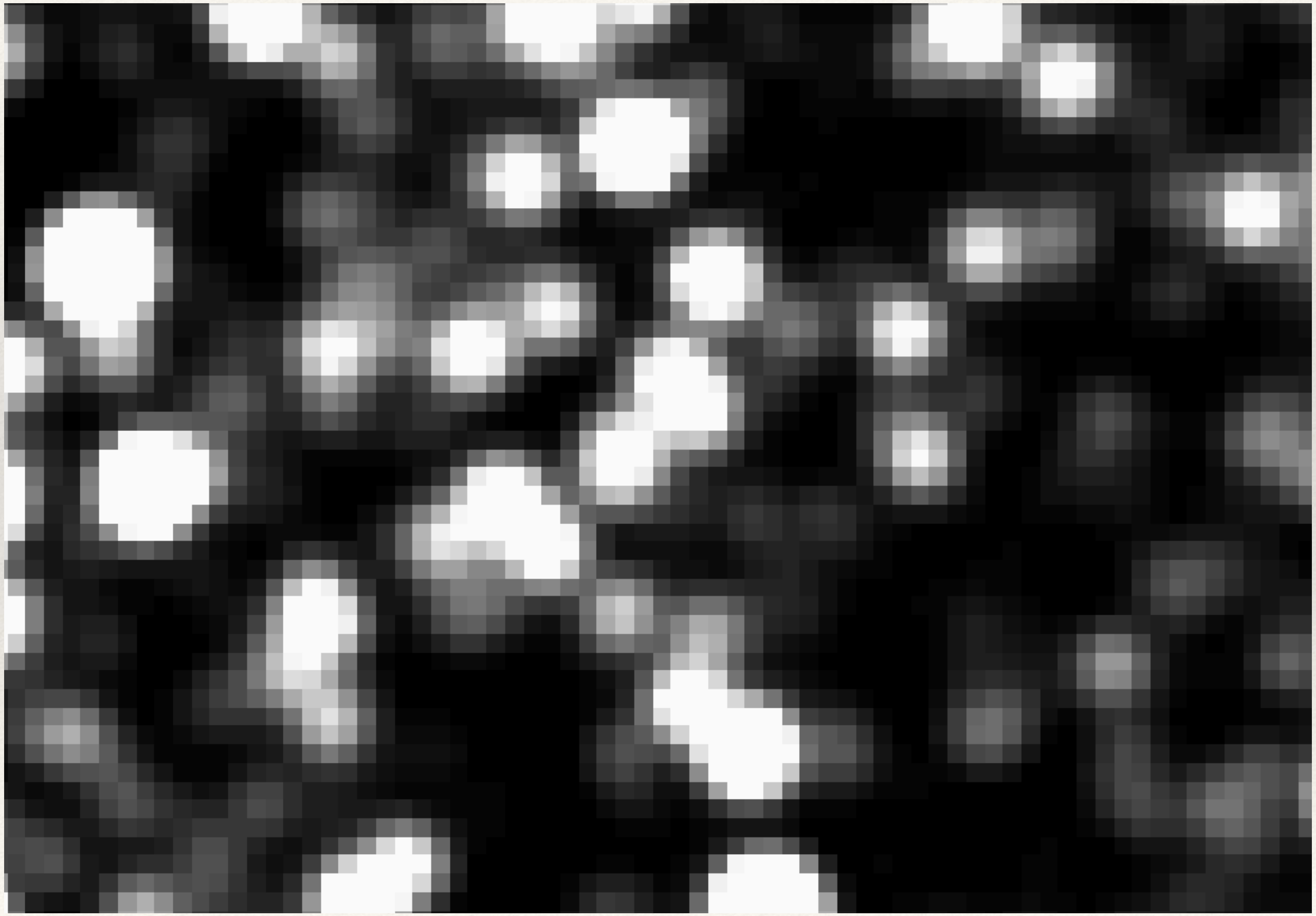


*From SIDES simulations (Bethermin+2017)*

# How size impacts the confusion level?

## 850 microns

Simulation assuming a 50-m and no instrumental noise



*From SIDES simulations (Bethermin+2017)*

# SFR limit versus telescope size (for a 850 μm survey)

- Negative K-correction: similar SFR limit for z=2-6.
- From 25m to 50m: confusion limit 5 times lower.
- 40-50m: able to detect the obscured SFR of the typical LBGs (a few tens of $M_\odot$/yr)

| | 25 m | 30 m | 40 m | 50m |
|---|---|---|---|---|
| 1σ confusion μJy/beam | 152 | 107 | 57 | 32 |
| 5σ SFR limit at z=2 ($M_\odot$/yr) | 80 | 56 | 30 | 17 |
| 5σ SFR limit at z=6 | 108 | 76 | 40 | 22 |

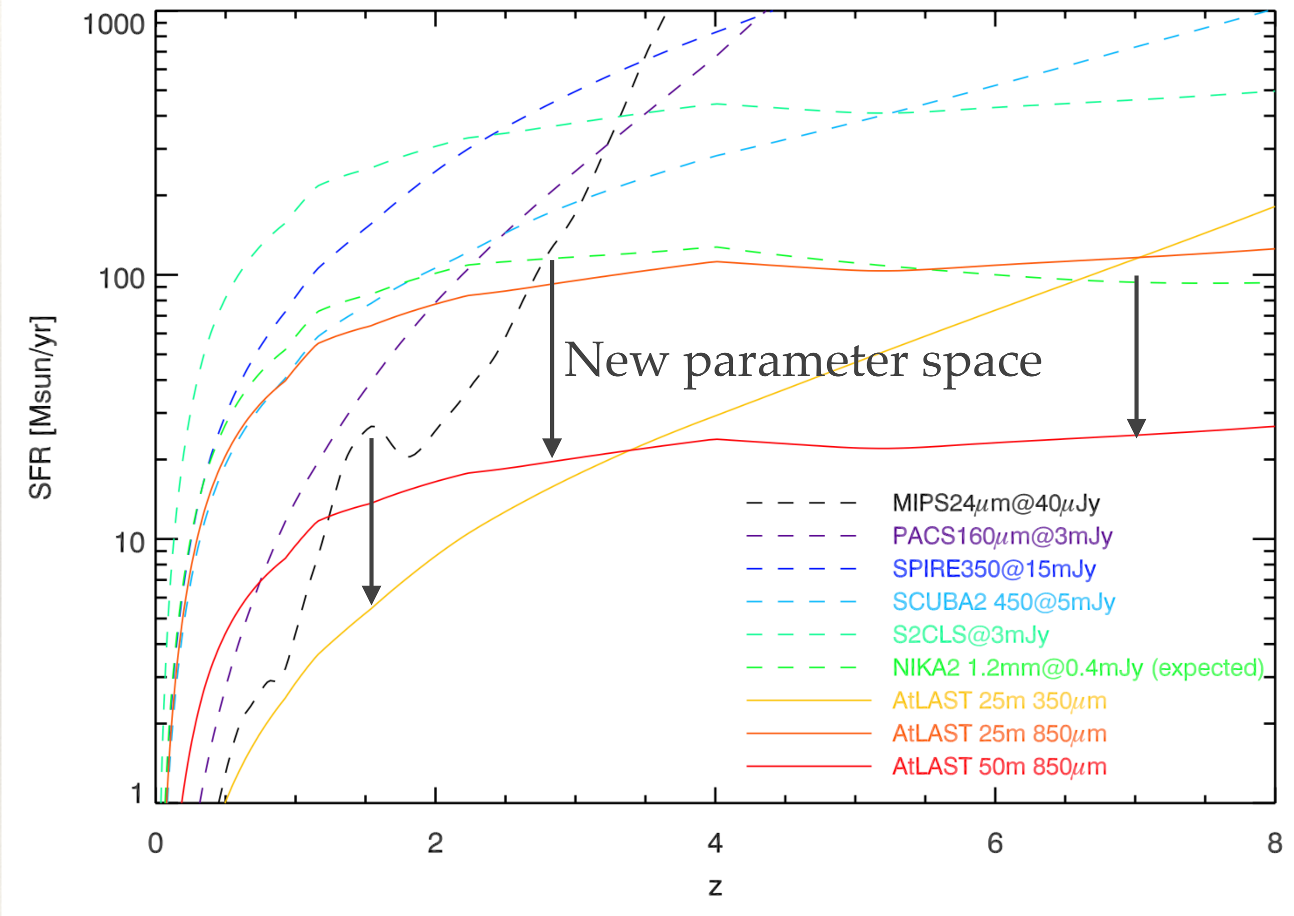
# Comparison with current single-dish surveys

- z≤3: 350 µm at confusion is spectacular
  => ~3-10 times deeper than mid-IR with Spitzer and much more direct tracer of SFR

- z≥3: 850 µm is the best channel
  - if 50 m: 5 times deeper than NIKA2 and 20 than S2CL

  - if 25 m: depth of NIKA2, but the strength might be the mapping speed

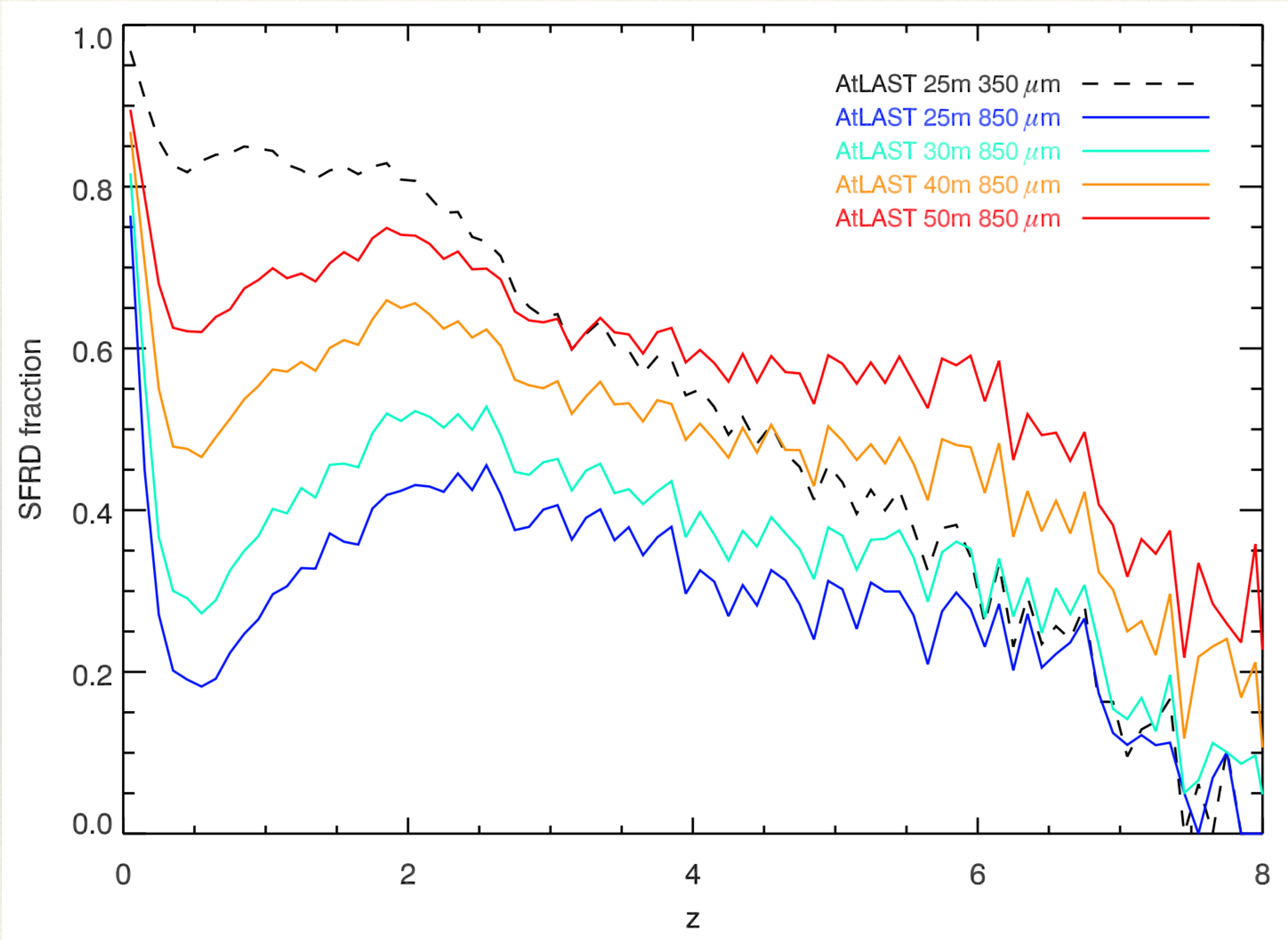
SFR limit versus z



# Resolved fraction of the SFRD at the confusion

- ≥40m at 850μm: galaxies detected at >5σ explain >50% of the SFRD up to z~6

- A 25m at 350μm, ~85% of the SFRD at z≤2, but the fraction decreases dramatically above.



# 2D and 3D intensity mapping

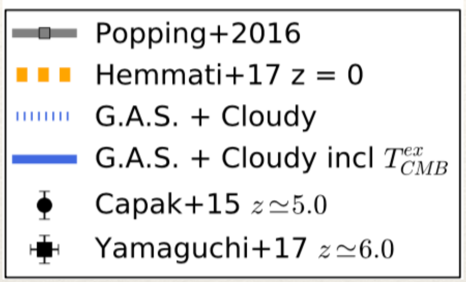
- Large-scale spatial fluctuations on the collective emission from all the sources emitting in one frequency band (2D) or in some convenient spectral lines (3D)
- 2D: Cosmic Infrared Background anisotropies
  - Herschel and Planck (Viero+13, Planck collaboration +11, +13)
  - Problem of degeneracies as N(z) is unknown, hard to isolate the high-redshift signal
- 3D: bright lines (HI, CO, Lya, CII)
  - Redshift information is retained ($\delta\upsilon \sim$1GHz)
  - Low-angular resolution redshift surveys (confusion limited)
  - CII: one of the brightest emission lines in the spectra of galaxies, extinction free tracer of star formation, redshifted into the relatively transparent sub-millimeter and millimeter atmospheric windows for $4 < z < 9$

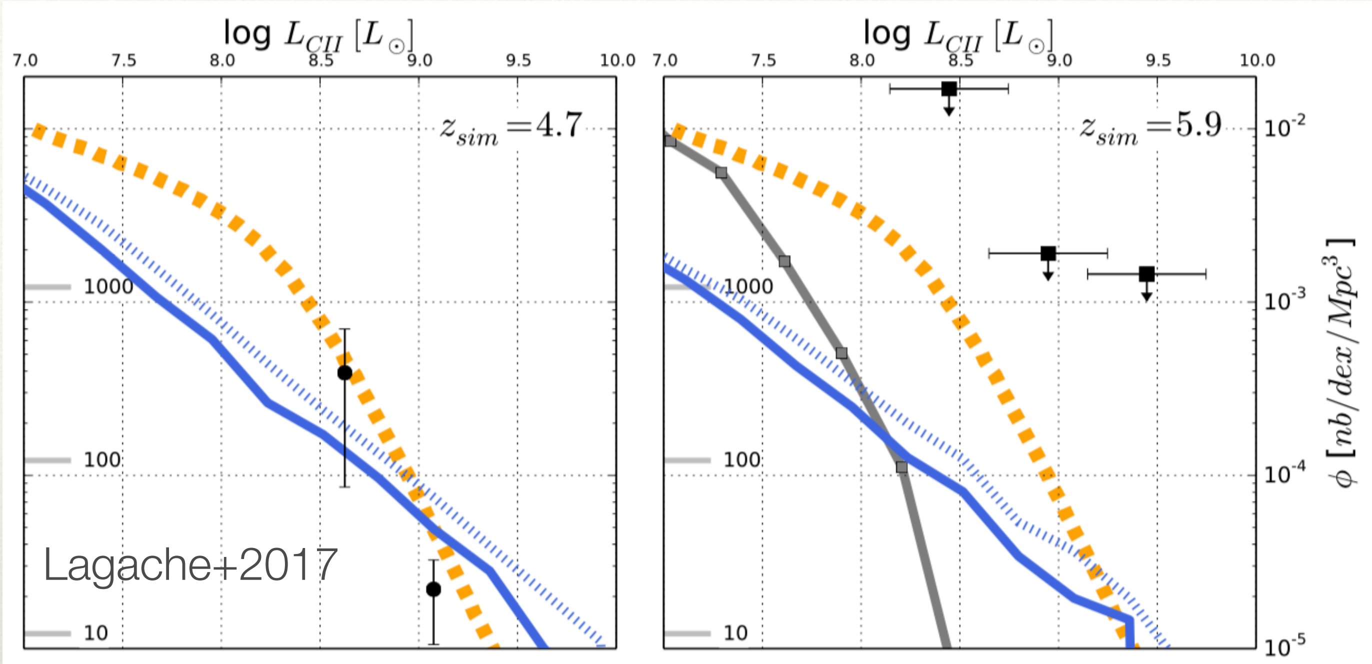
# CONCERTO (CarbON CII line in post-rEionization and ReionizaTiOn epoch)

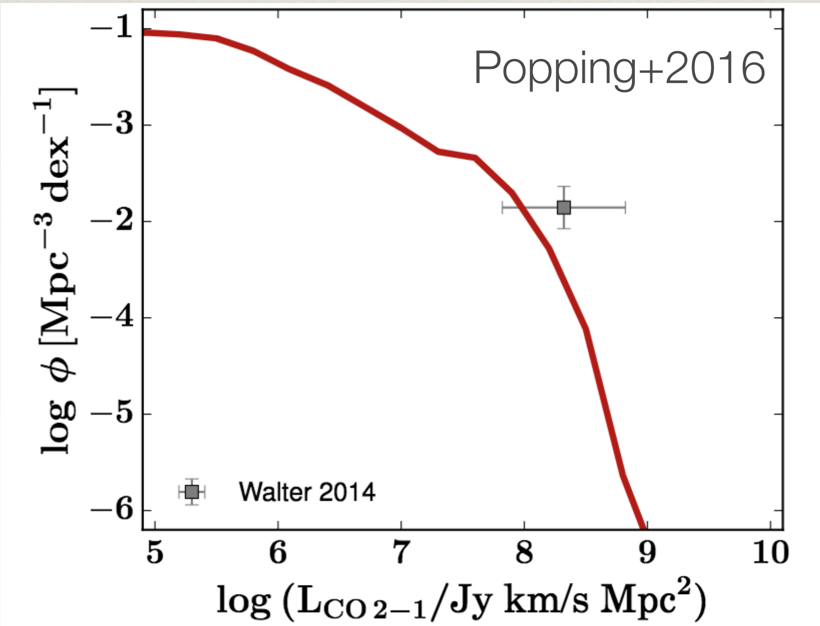
- Focal plane:
  - KIDS, following the success of the NIKA2 IRAM camera
  - Cooled to 150 mK thanks to a closed-circle 3He-4He dilution cryostat
  - FOV D~15′, f$\lambda$ sampling => two arrays of 1,500 pixels
  - Frequency range: (150)200 - 360 GHz
- Martin-Puplet interferometer (like a Michelson interferometer but with a movable mirror)
  - Spectral resolution ($\nu/\delta\nu$): R=100 to 300
  - At least one spectrum for all pixels of the matrix every second
- CONCERTO @ APEX: $\theta$=20″ for CII at z=5
- Primary goal: CII intensity mapping and CII-bright emitting galaxy luminosity function at 4.5<z<8.5 + CO intensity mapping at z<2
- But rich ancillary science, from the ISM of our Galaxy to the hot gas and velocity flows in galaxy clusters
- Testing the pathfinder (KISS instrument) and recent funding to quick start the instrument building

# AtLAST lines survey

CII luminosity functions at z~5-6



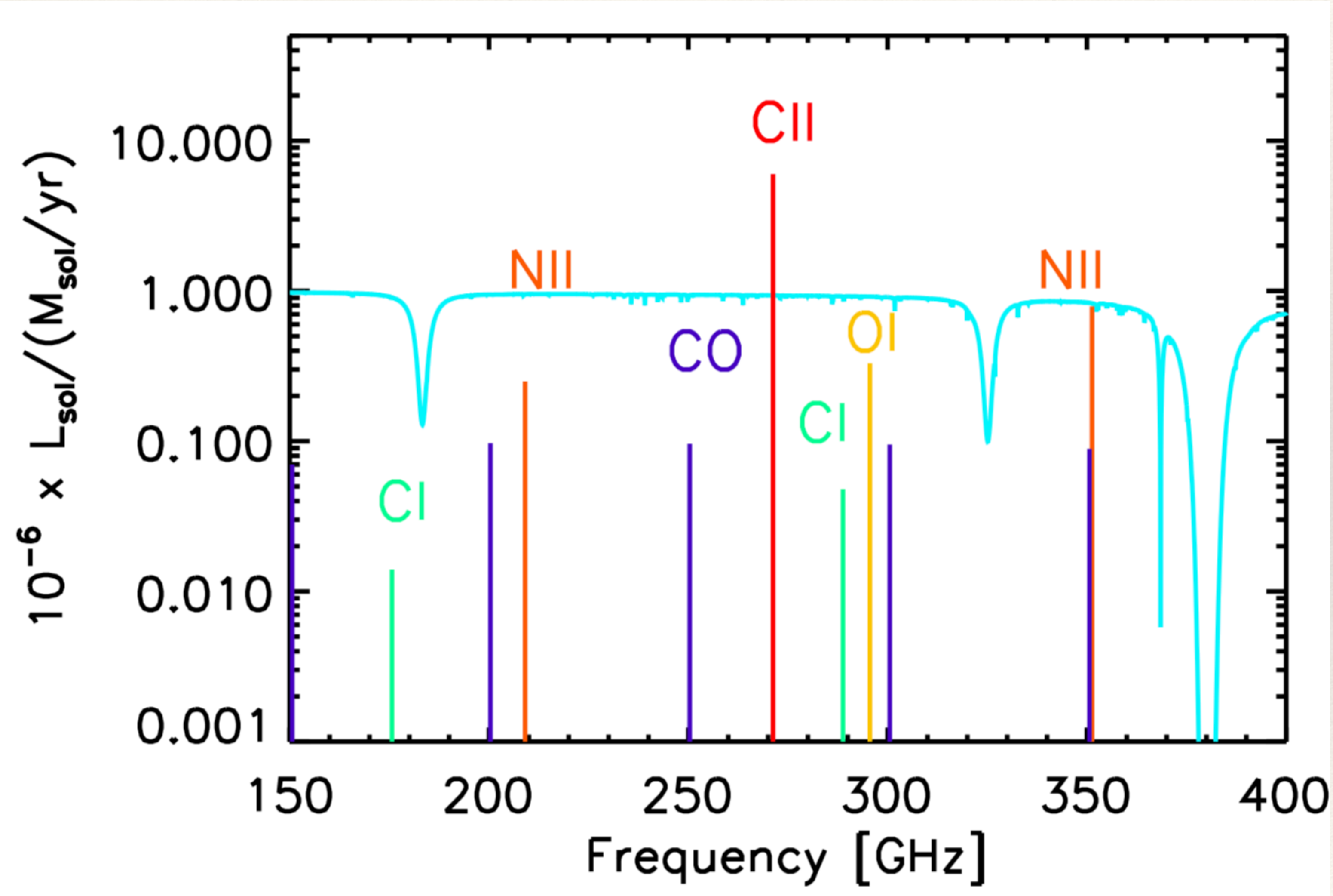




CO luminosity function at z=1.5

# AtLAST lines survey

## Low frequencies

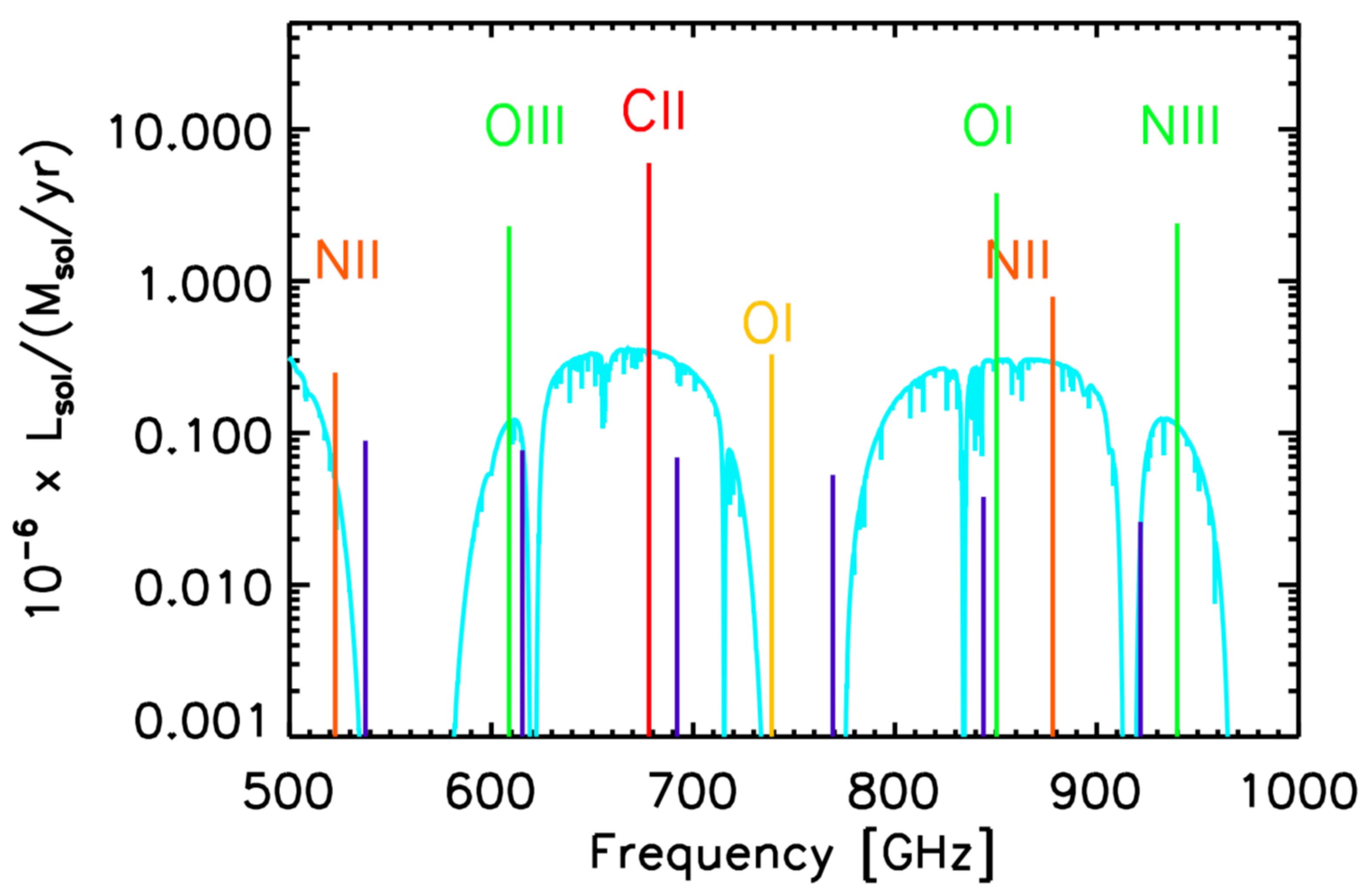



**Chajnantor**
**pwv:1mm**

**zCO=1.3**
**zCII, NII, OI=6.0**
**zCI=1.8**

# AtLAST lines survey (high frequencies)

## High frequencies




Chajnantor
pwv:1mm

zCO=0.5
zCII, NII=1.8
zOIII, OI, NIII=4.6

# Conclusion

- Cover large areas, high mapping-speed (large FOV ~1 deg)
- Continuum surveys:
  - z<3: 350 μm, D>25m, θ<2.5", confusion 1σ<105 μJy/beam
  - z>3: 850 μm, D>40m, θ<5.3", confusion 1σ<57 μJy/beam
    - obscured SFR of the typical LBGs at z=6!

    => High redshift dusty Universe: simultaneous 750μm, 850μm, 1.1mm, 1.3mm imaging
- Line surveys: Cover a wide frequency band
  - ex: CII luminosity function at z>4 and CII in reionisation
    - $1\sigma = 10^6 L_\odot$ at z=7 => S δv = 0.8 Jy km/sec
  - @238 GHz (i.e. CII at z=7 )
    - R=750 => δz=0.01 & δv=400 km/sec