# Exploring the dusty star-formation in the early Universe using CIB and [CII]-line intensity mapping

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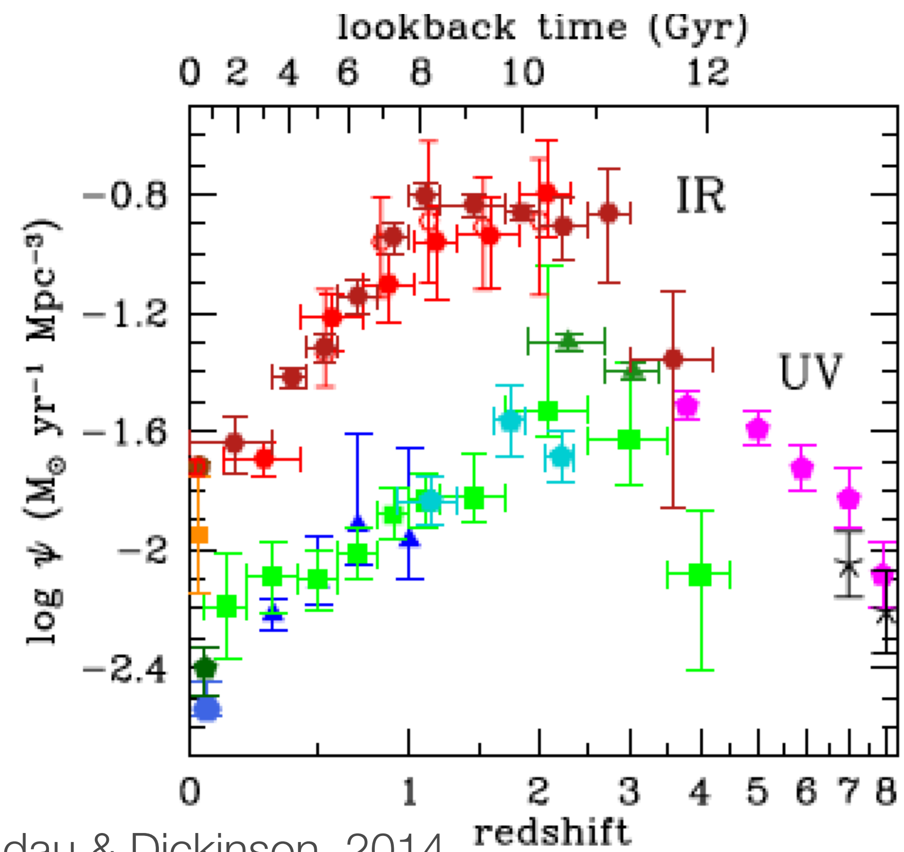
# Dusty star formation at 0<z<4

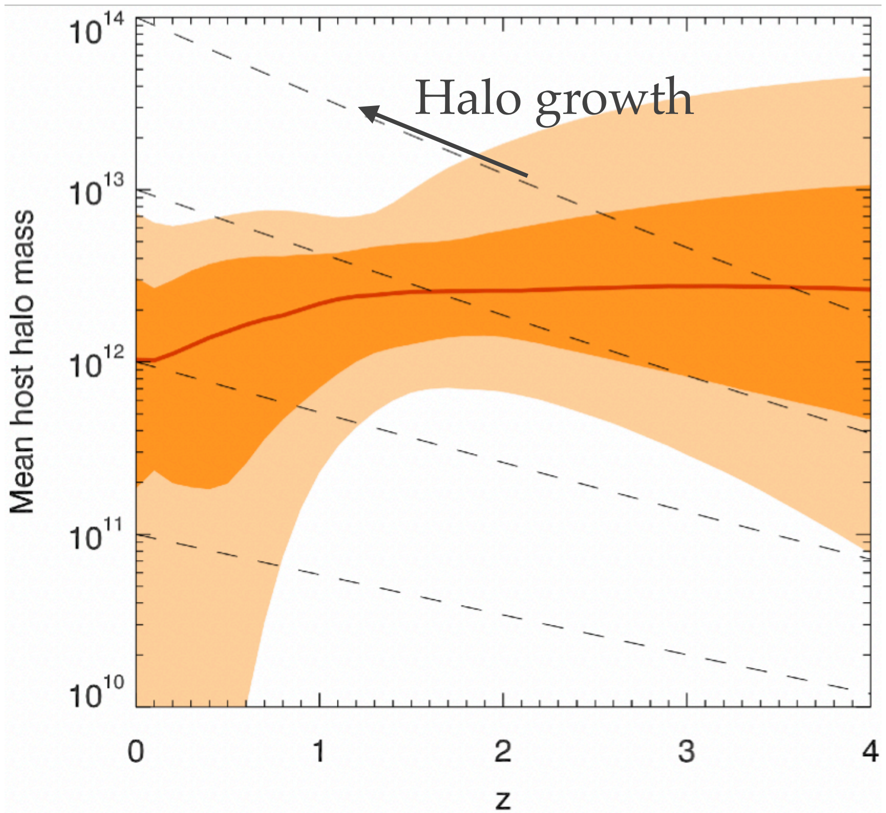
- One of the most pressing questions of modern Cosmology: How the clumpy structured universe that we see today evolved from the smoothly distributed matter that existed during the dark ages?
- Dusty star-forming galaxies (DSFG) are participating to this major change.
- DSFG are critical players in the assembly of stellar mass and the evolution of massive galaxies at high redshift up to z=4

*Cosmic Star Formation Rate Density*



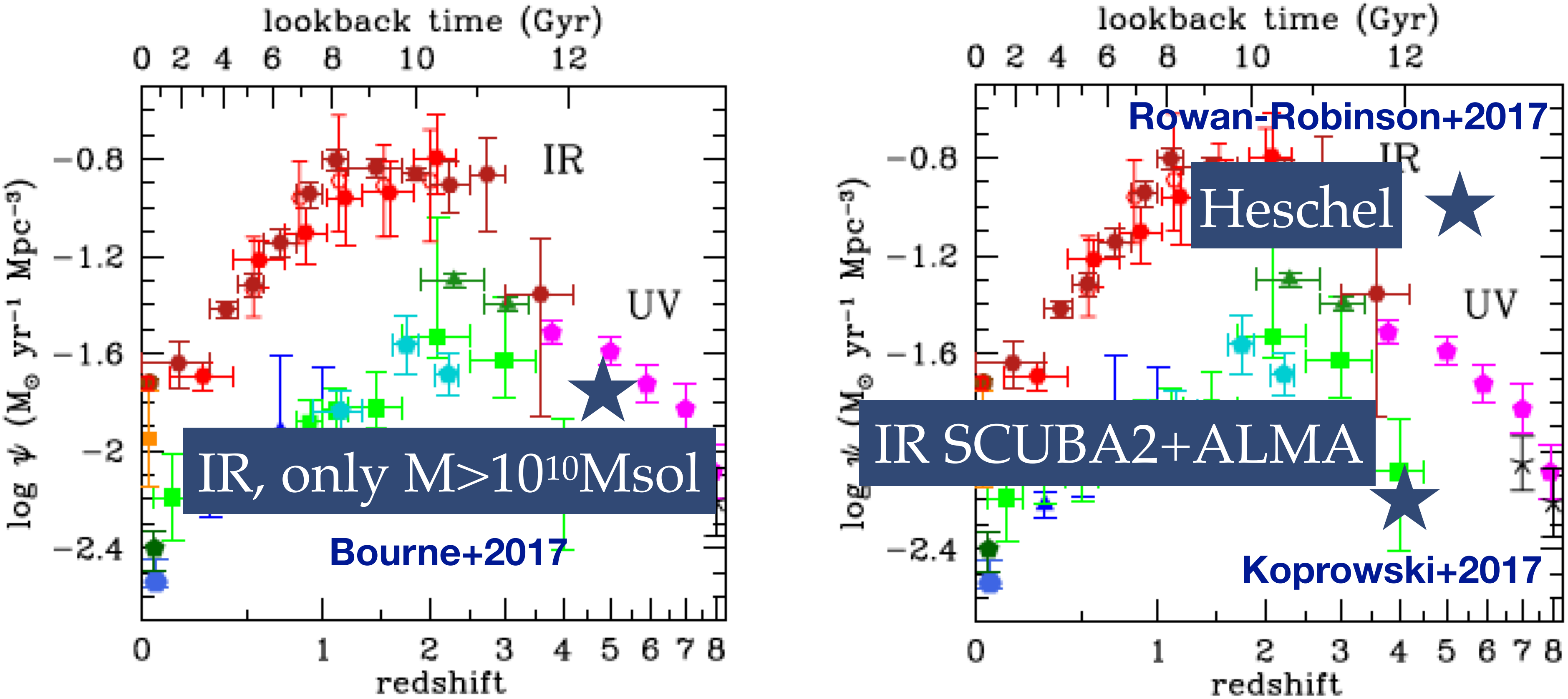

Madau & Dickinson, 2014

*Halo near $10^{12}$ Msol are the most efficient at forming stars*




Adapted from Planck XXX 2013 (M. Béthermin)

# Dusty star formation at z>4?

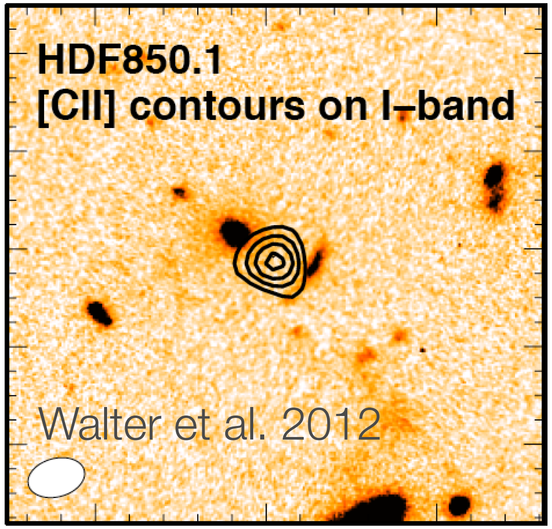


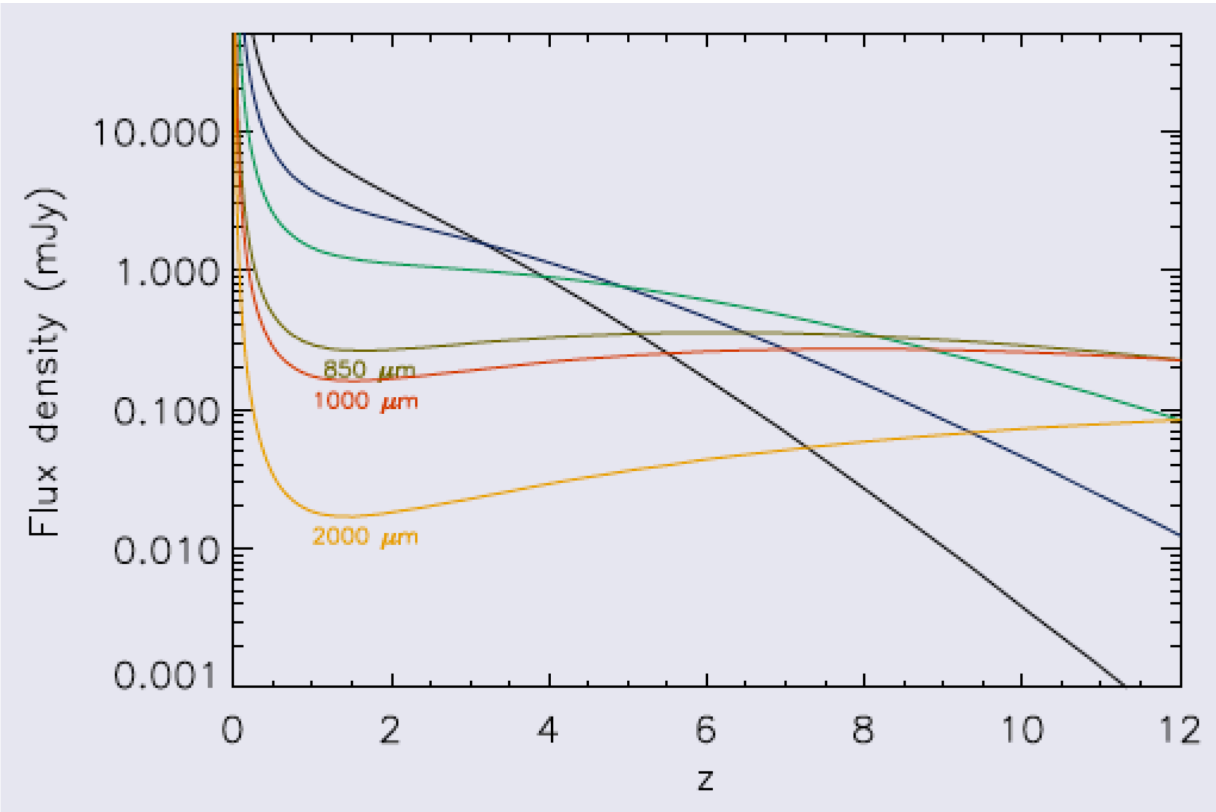

- Laporte+2017: z=8.4, $M_{dust}$=6x10$^{6}$, $L_{IR}$=1.0x10$^{11}$ (20 Msol/yr)
- Watson+2015: z=7.5, $M_{dust}$=4x10$^{7}$, $L_{IR}$=6.2x10$^{10}$ (9 Msol/yr)
- Strandet+2017: z=6.9, $M_{dust}$=3x10$^{9}$, $L_{IR}$=2.2x10$^{13}$ (2200 Msol/yr)

# Observing the dusty star formation at z>4

Observe the dusty star-formation at high redshift => you need (sub-)mm experiments

Discovered in 1998 (SCUBA surveys)
Redshift z=5.2 in 2012!



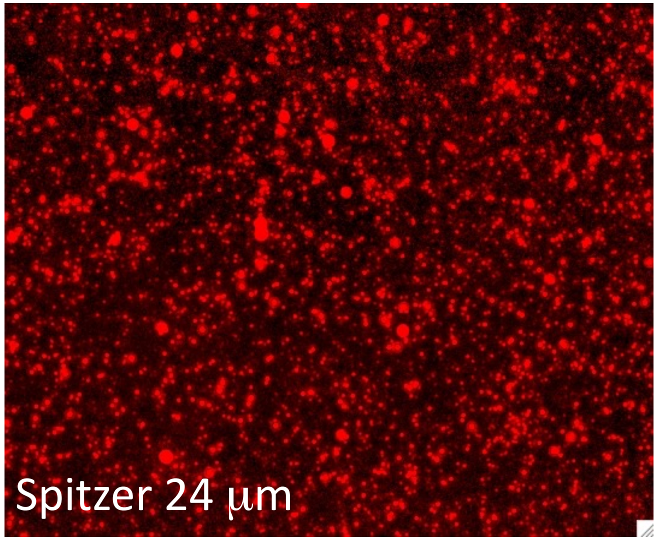



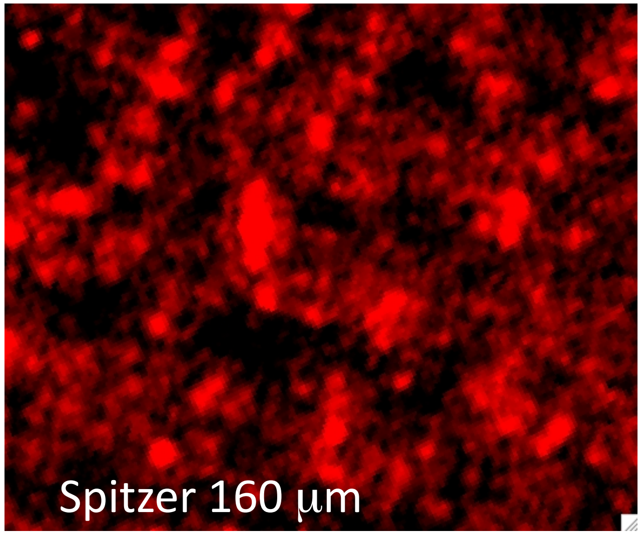

Negative K-correction: the magic of high-z sub-mm and mm window !

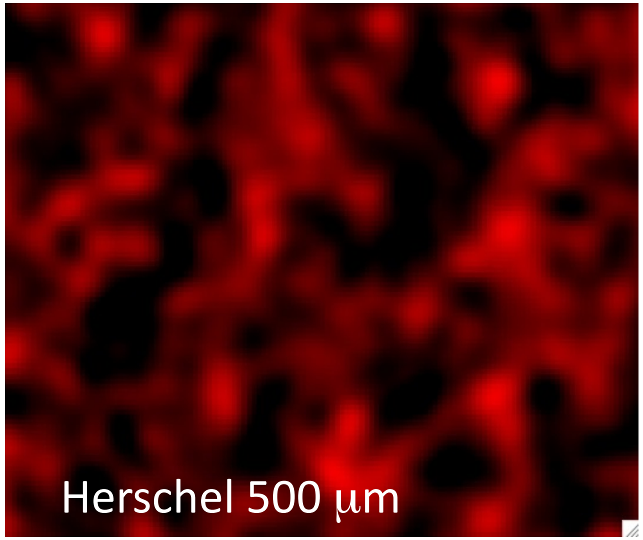
# Observing the dusty data formation at z>4

In the (sub-)millimeter, galaxies are so faint and numerous, compared to the angular resolution achievable, that confusion plagues observations substantially.

=> Fluctuations in the background (CIB)




Individual galaxies

CIB is resolved at ~6%
Intensity Mapping
(CIB fluctuations)

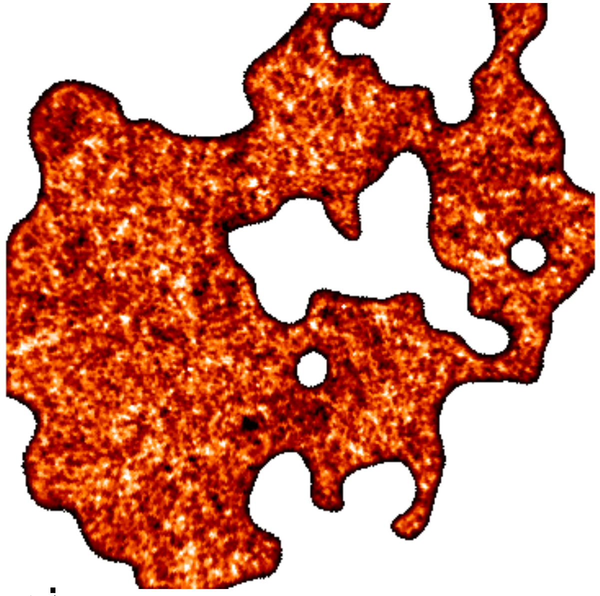
Dust-continuum blind surveys with the ALMA interferometer can see fainter DSFGs but are detecting only a handful of galaxies at z>4 because of its limited mapping speed.

# 2D intensity mapping: CIB

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

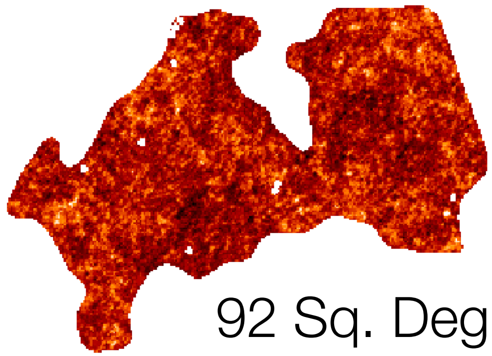
## Component separation:

- Galactic dust, CMB, point sources
- On maps:
  - Galactic dust and CIB: ~similar SED, ~similar power spectra, no particular features
  - See Planck XLVIII (2016) for an attempt using GNILC
  - Need a template for dust emission
    - HI maps: Penin+12 (Spitzer + IRAS) and Planck collaboration XVIII (2011) and XXX (2013) from 143 to 3000 GHz
- On power spectra:
  - Herschel/SPIRE: Viero+13 - 70 Sq. Deg.
  - Planck 353, 545, 857GHz: Mak+17 - 20,000 Sq. Deg.



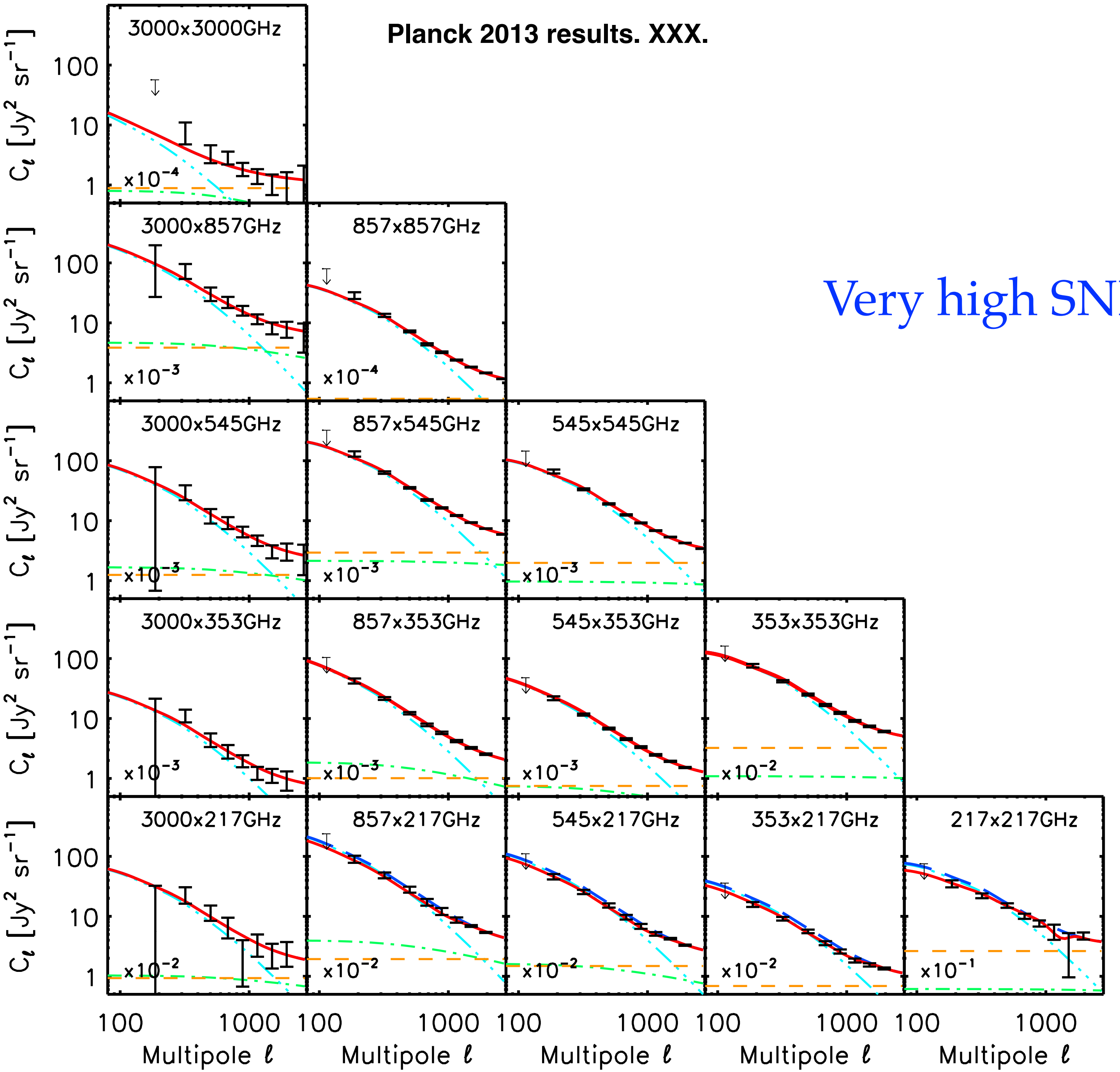
2000 Sq. Deg.

Planck 2013 results. XXX.



92 Sq. Deg.

# 2D Intensity mapping: CIB




Very high SNR!

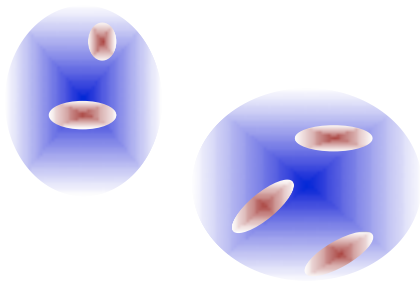
# 2D Intensity mapping: CIB

## Models for power spectra:

- Need to assume the cosmology
- Linear scales:

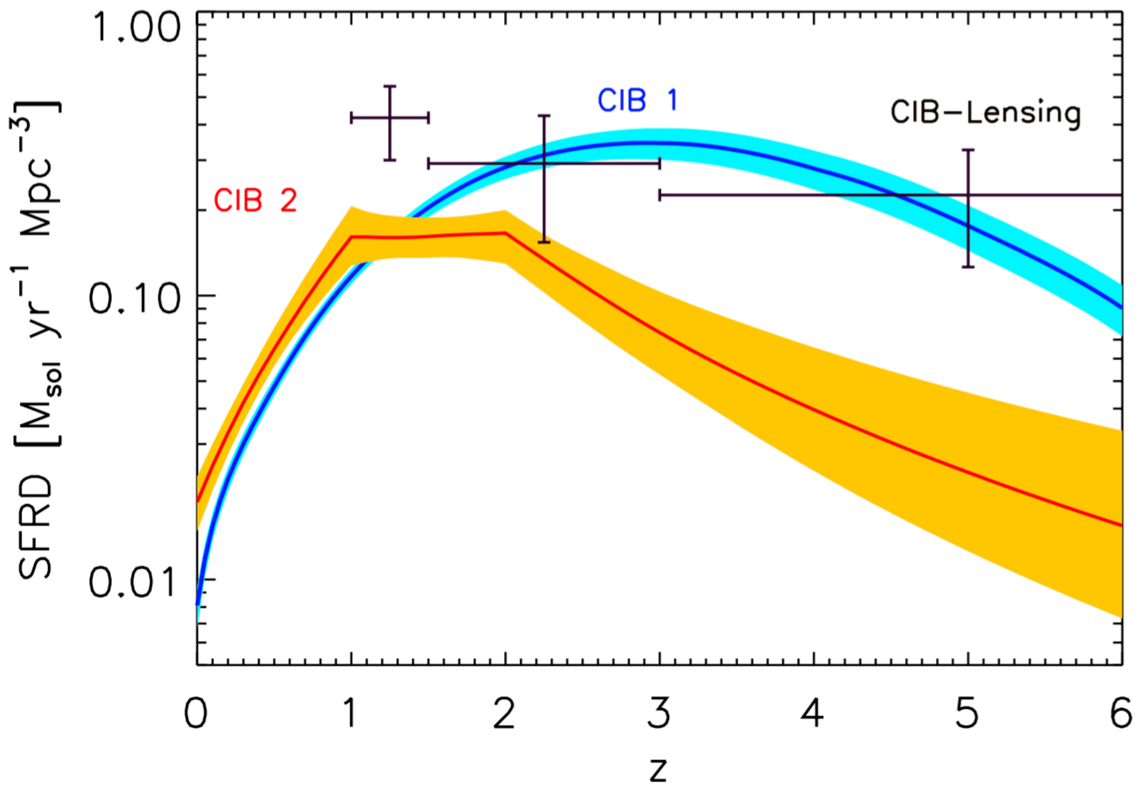
$$C^{2h}_{\ell,\nu,\nu'} = \int \frac{\mathrm{d}z}{\chi^2}\frac{\mathrm{d}\chi}{\mathrm{d}z} a^2 b^2_{\mathrm{eff}}(z)\,\bar{j}(\nu, z)\,\bar{j}(\nu', z)\,P_{\mathrm{lin}}(k = \ell/\chi, z).$$

  - Need to assume DSFG SEDs
  - Strong degeneracies (beff, j)
- Halo Occupation Distribution:
  - Assume L-M relation for centrals and satellites
    - SEDs, Mmin, functional form of the SFR-M, redshift evolution
  - 1h contribution quite small!



# 2D Intensity mapping: CIB

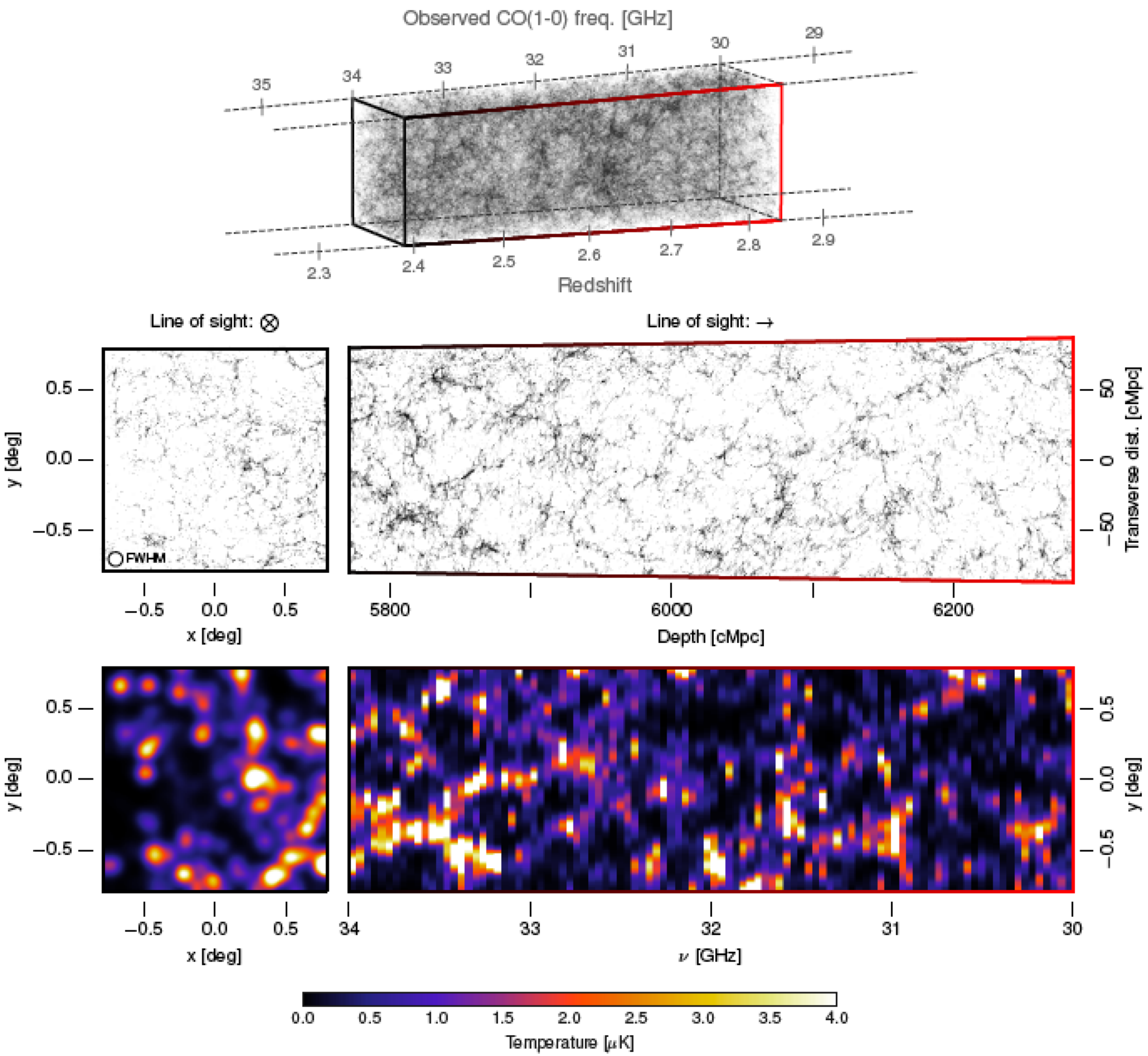
SFRD derived from different CIB models




Planck collaboration, 2014

- Problem of degeneracies as the redshift distribution of the mean emissivity is unknown
- Improve using all constraints together (e.g., galaxy counts, SED measurement — e.g. Béthermin et al. 2013) or putting strong priors (Maniyar et al. 2017)
- Impossible to isolate the high-redshift signal in the CIB (z>4)

# Line intensity mapping (3D)




Li+2015

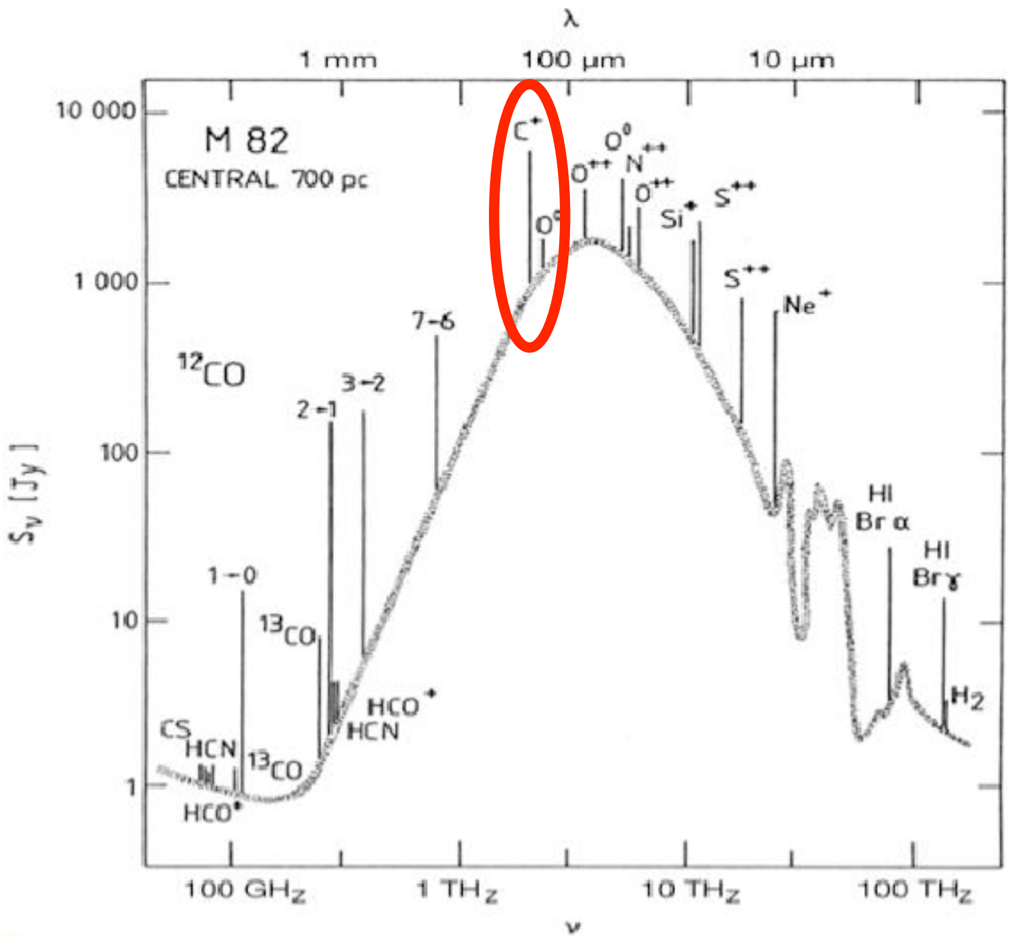
Answer the questions of whether dusty star-formation contributes to early galaxy evolution, and whether dusty galaxies play an important role in shaping cosmic reionization

## [CII]-line intensity mapping experiments

CONCERTO
Time-Pilot
CCAT-p

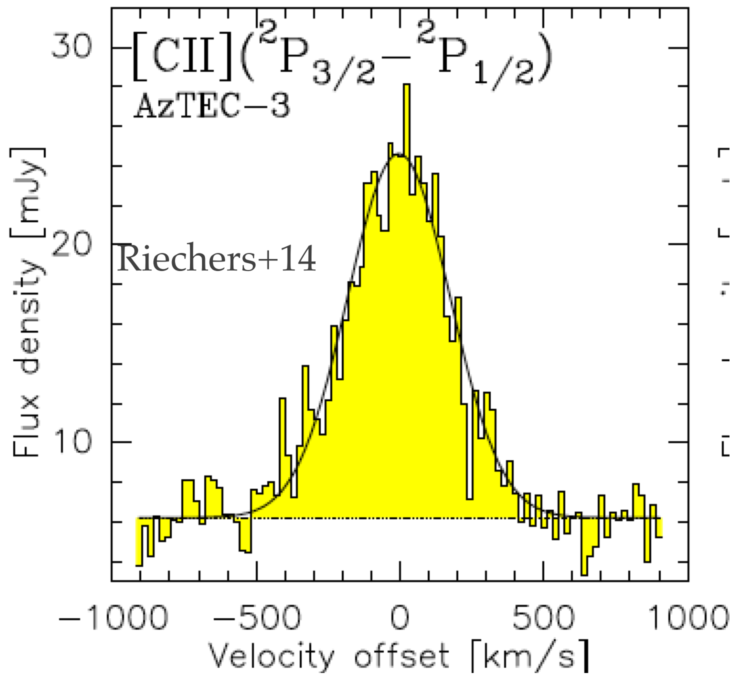
# Line intensity mapping : why [CII]?

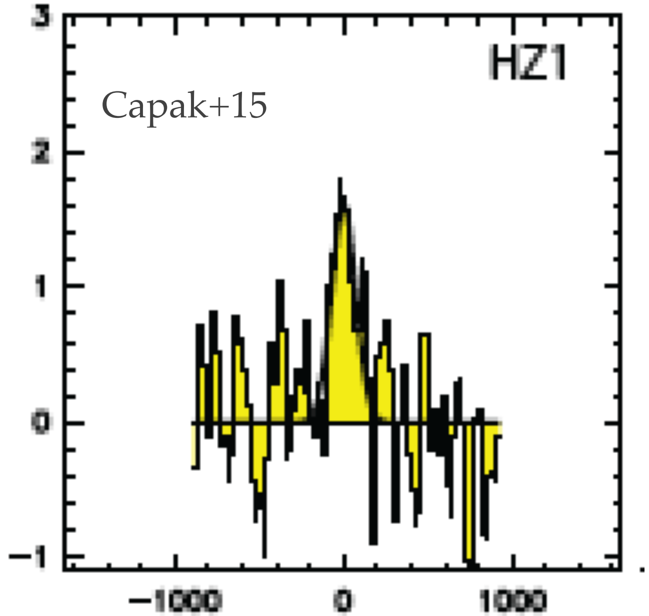
- One of the brightest emission lines in the spectra of galaxies (at 157.7 μm rest frame), with $L_{[CII]}/L_{FIR}$ ~0.1-0.3%
- One of the most valuable tracers of dusty star formation at high redshift
    - [CII] at high z originates mainly from PDR (& CNM)
- Excellent coolant for neutral gas in PDRs, and a good probe of the stellar radiation fields
- Extinction free tracer of star formation
- Conveniently, [CII] is redshifted into the sub-millimeter and millimeter atmospheric windows for 4.5<z<9



# Line intensity mapping : why CII?

- ALMA, NOEMA, APEX/FLASH detect [CII] at very high redshift, pointing on known objects
  - ~35 star-forming galaxies at z>4.5 (LBGs and SMGs)
- Few objects, different selection biases, time consuming
- ALMA is good at “case studies”, but we need to look at the overall population too, i.e. large volume surveys.



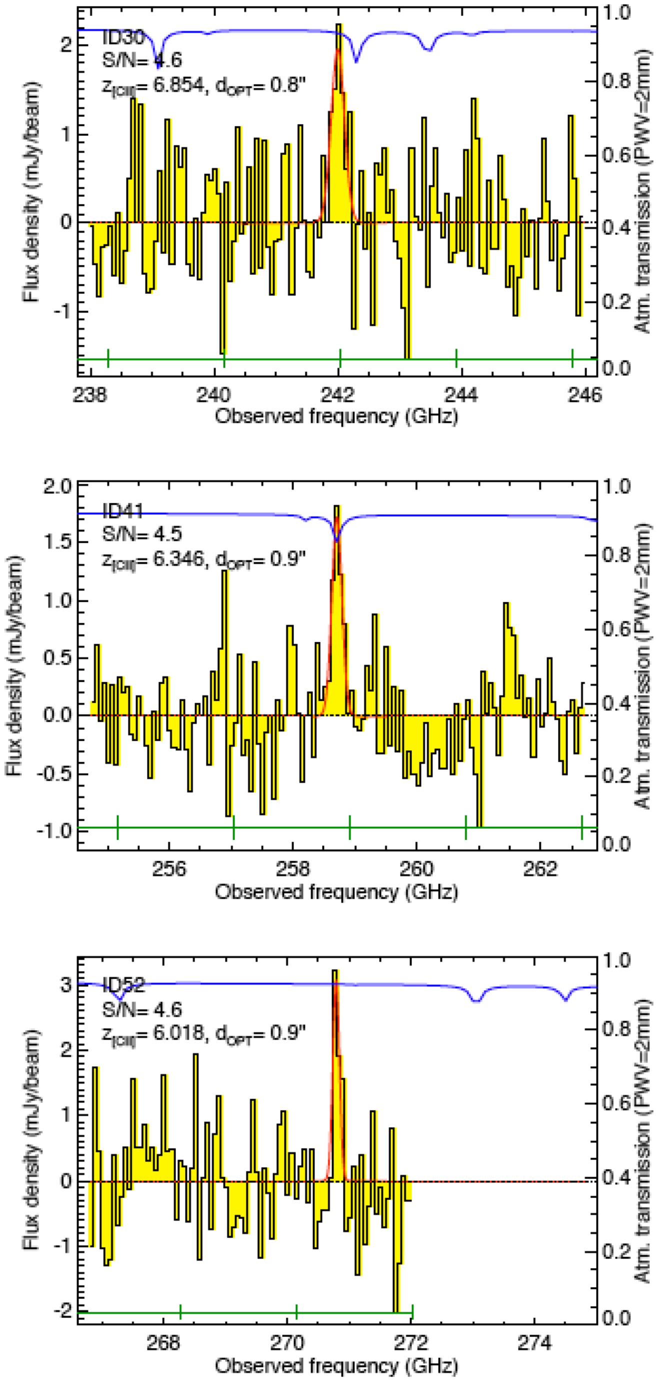



# Line intensity mapping : why CII?

Aravena+16

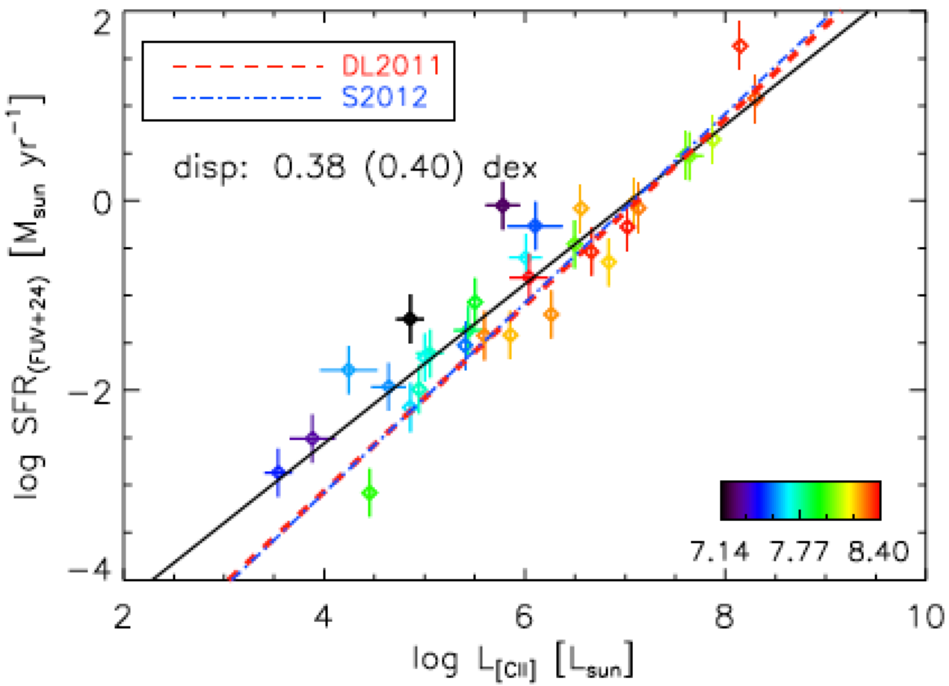
- ALMA ASPEC survey (Walter et al. 2016) in UDF:
  - 1 Sq. arcmin, 40h of ALMA time
  - full frequency scans in band 3 (84-115 GHz) and band 6 (212-272 GHz)
  - [CII] at 6<z<8
  - 14 [CII] line emitting candidates, 60% of the candidates are expected to be spurious
  - LP accepted for 4 Sq. arcmin

- [CII] intensity mapping
  - complements such efforts beautifully, providing maps on several-degree scale
  - provides an unbiased view of the distribution of CII-emitting gas that is difficult to assemble from targeted measurements of individual galaxies

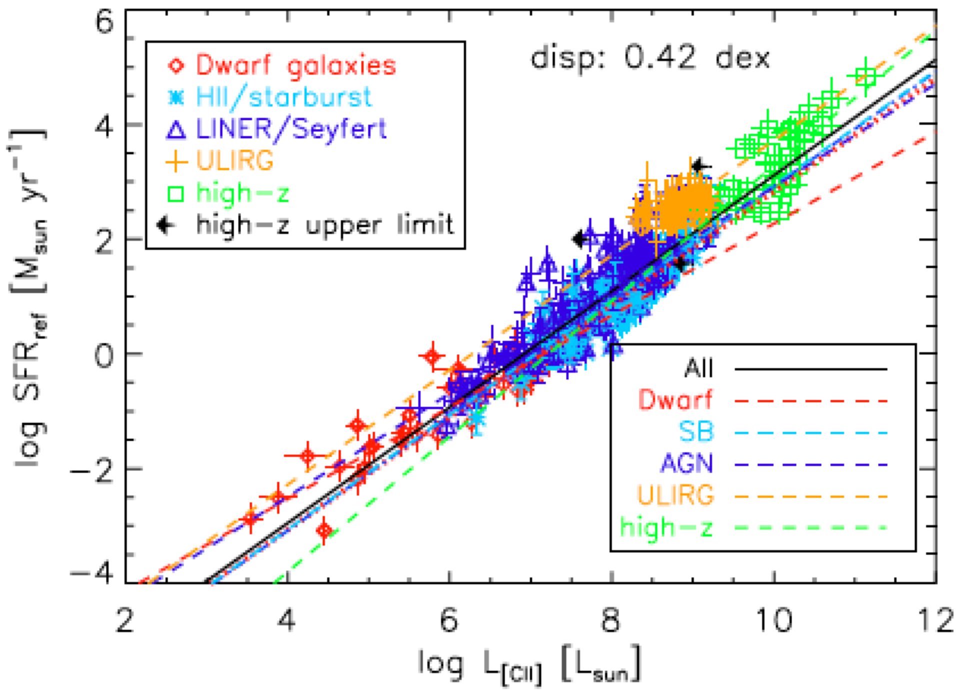


# CII at high redshift: a good tracer of SFR?

**Low-metallicity dwarf galaxies**




**Different galaxy populations**

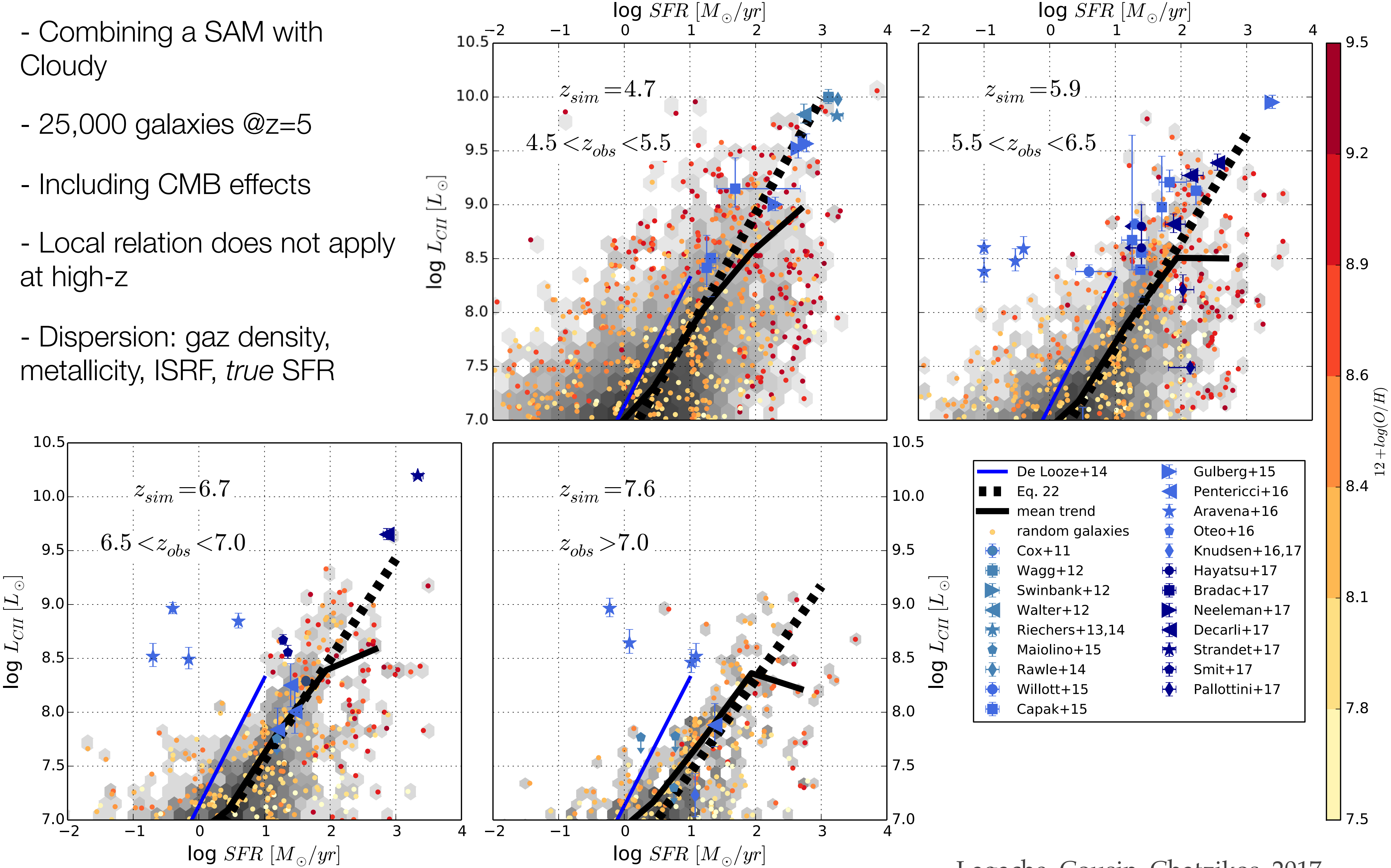



**Caveat: SFR not homogeneously determined**

De Looze+2014 (see also Herrera-Camus+2014)

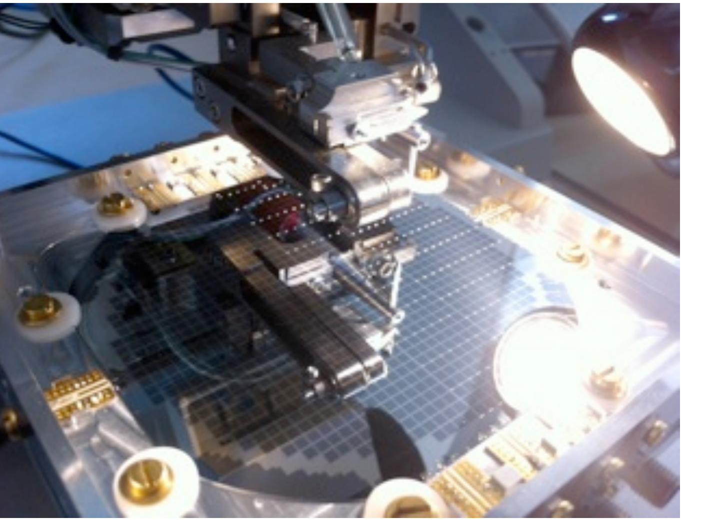
# CII at high redshift: a good tracer of SFR?

- Combining a SAM with Cloudy
- 25,000 galaxies @z=5
- Including CMB effects
- Local relation does not apply at high-z
- Dispersion: gaz density, metallicity, ISRF, *true* SFR



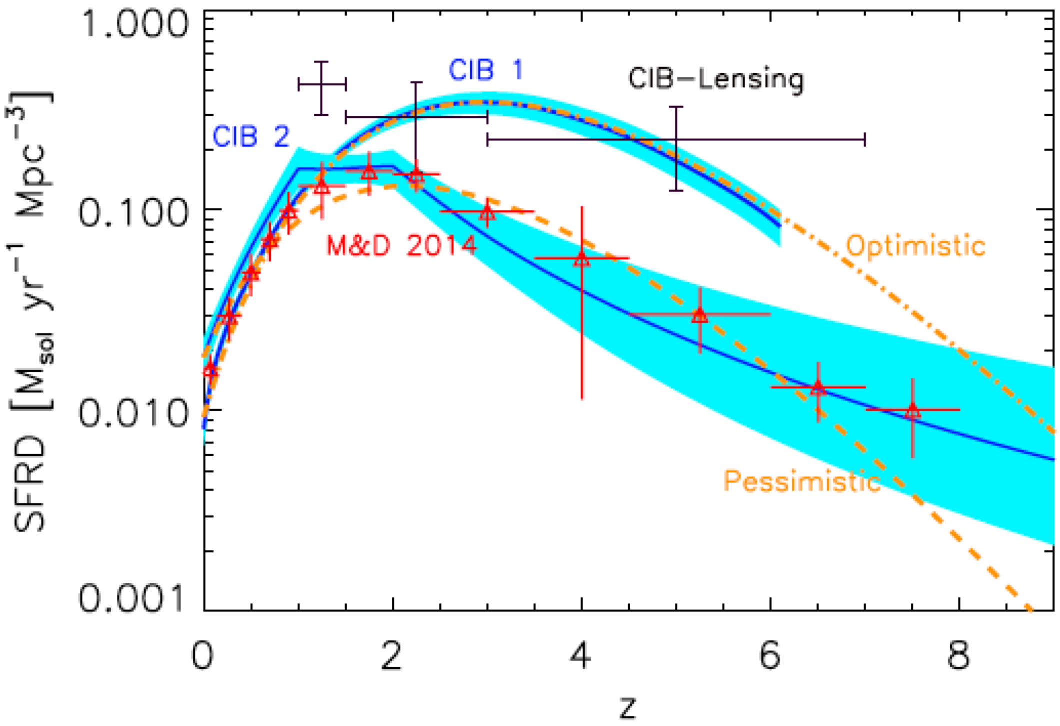

Lagache, Cousin, Chatzikos, 2017

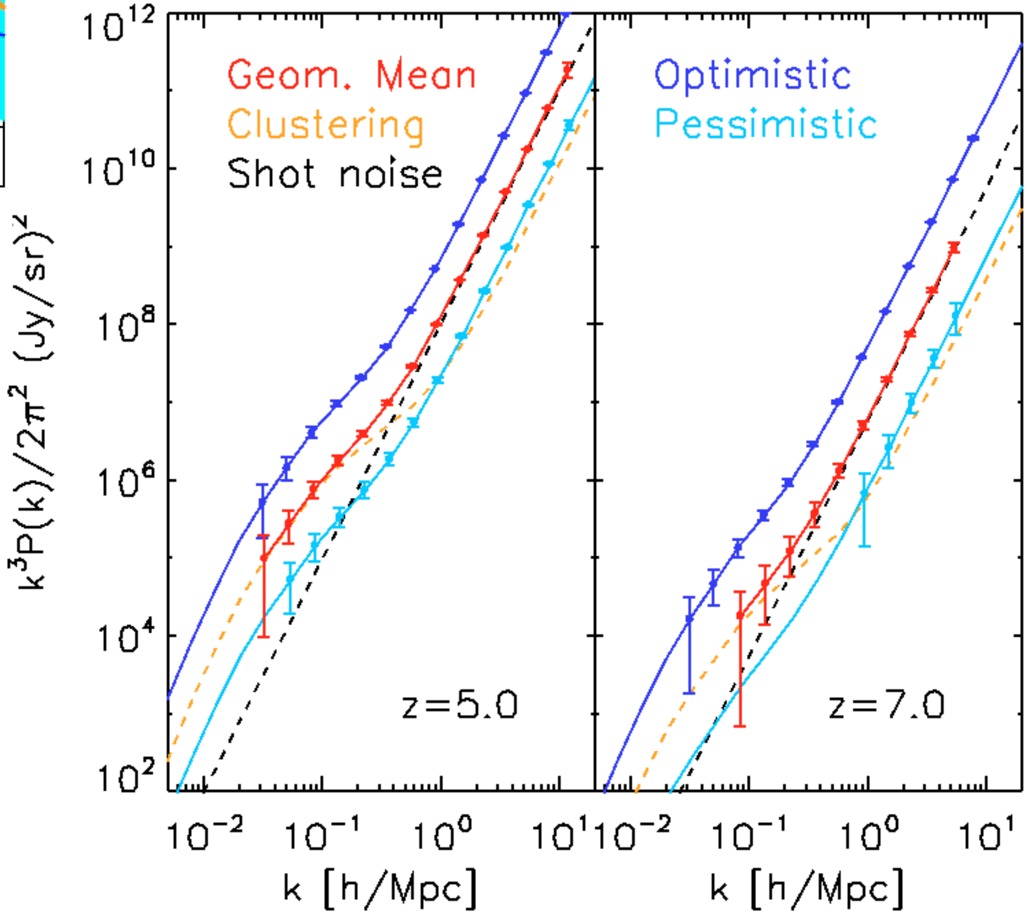
# CONCERTO: instrument



- Focal plane:
  - Kinetic Inductance Detectors (KID)
  - Success of the NIKA2 IRAM camera
  - FOV D=12', fλ sampling => arrays of 1,500 pixels
- Cryostat:
  - Closed-circle 3He-4He dilution - 150mK
  - 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
  - At least one spectrum for all pixels of the matrix every second
- A « sub-mm » antenna:
  - Frequency range: 200 - 360 GHz
  - APEX telescope

# CONCERTO: predictions




Survey of 2 Sq. deg.
1,200 hours of observations

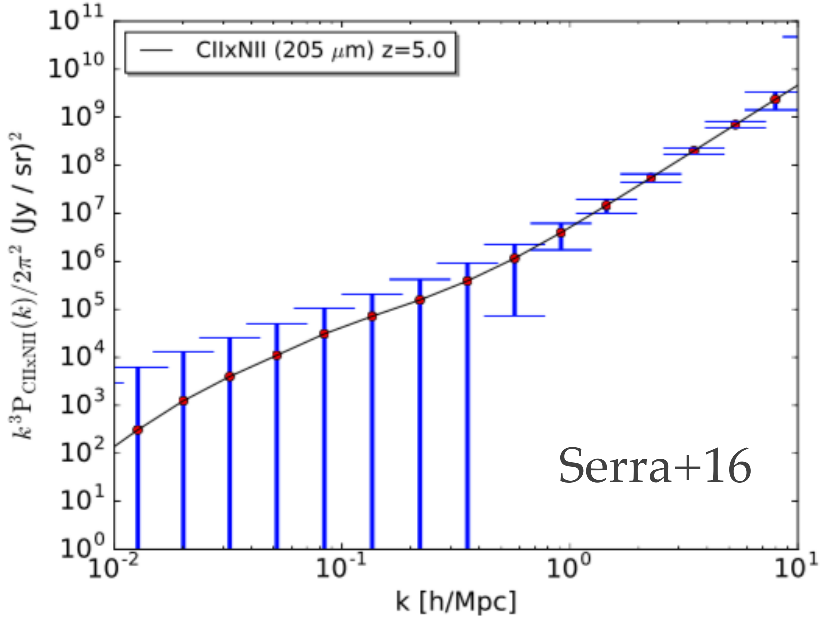
# CONCERTO: what is expected to be learned ?

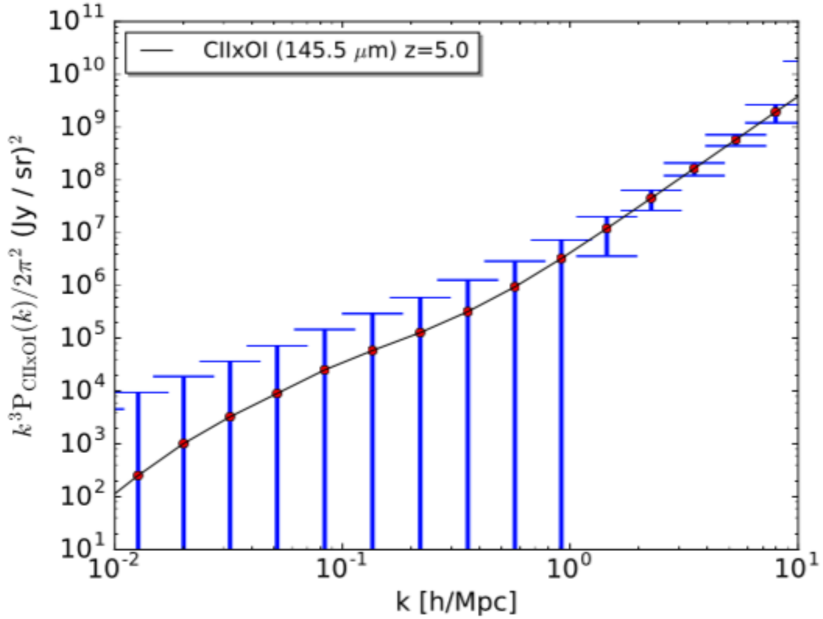
*Answer the questions of whether dusty star-formation contributes to early galaxy evolution, and whether dusty galaxies play an important role in shaping cosmic reionization*

- Clustering power spectra
    - «Dusty» SFRD for z>4.5
    - [CII] luminosity- Mh relation
    - Typical halo mass scale of SF galaxies
- Shot noise
    - Measure the weighted dark-matter halo mass integral of the [CII] luminosity function
    - Constrain number counts of [CII]-emitters as a function of redshift
- From individually detected sources:
    - Measure the bright-end of the luminosity function (very model dependent)

# CONCERTO: what is expected to be learned ?

- Cross-correlations within CONCERTO:
  - Cross-power spectra of the [CII] line with the [OI] (145 μm) line, and the [NII] lines (122 μm and 205 μm)
  - [NII] line ratio: good electron density tracer of the low-density ionized gas in HII regions
  - [NII] (205 μm)/[CII] can be used as an indicator of the amount of [CII] emission coming from the ionized medium
  - [OI] (145 μm)/[CII]: ISRF and the mean density of PDRs



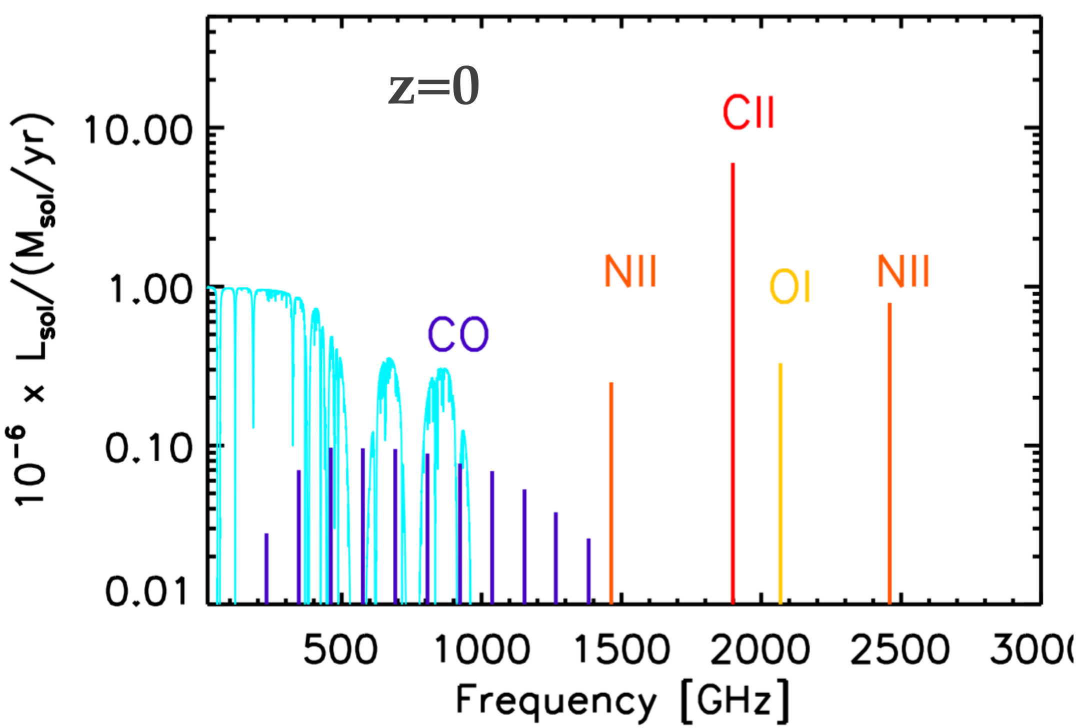



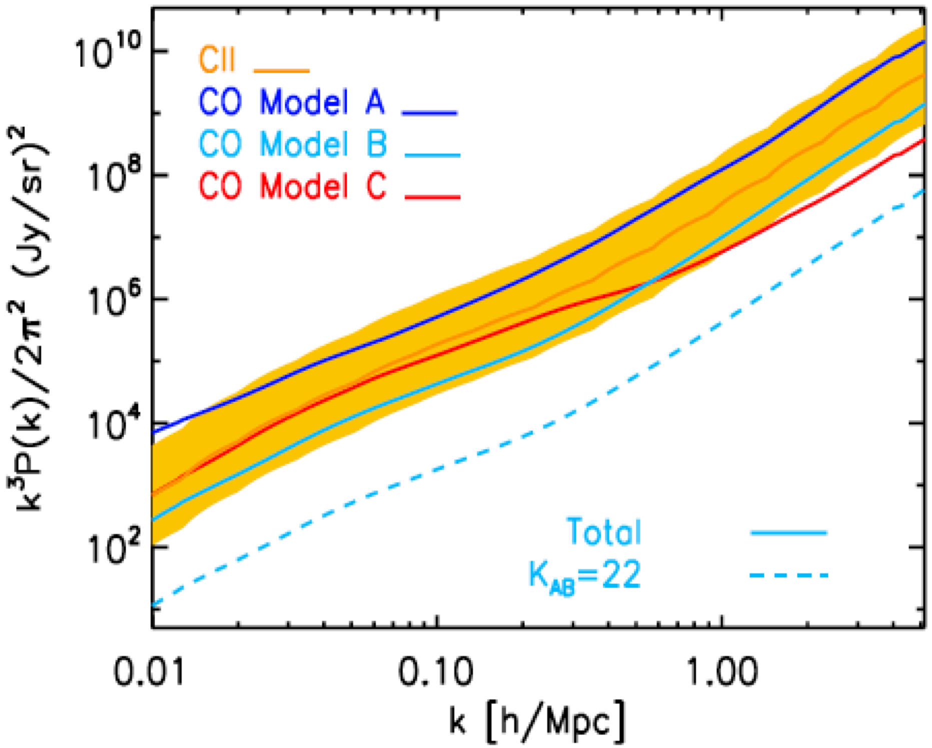
# CONCERTO: what is expected to be learned ?

- Cross-correlations with external data sets:
  - With galaxies from deep surveys:
    - An other estimate of star formation rates in z~4-7 galaxies
    - When did the Universe produce dust?
  - With HI:
    - Correlation negative on large scales when the correlation between the ionization fraction and the matter density dominates and positive on small scales when the matter density auto-correlation is dominating
    - Capture physics during EoR, including the ionized bubble sizes and the mean ionization fraction

# CONCERTO: what is expected to be learned ?

- CO emission at z<1.9 (for the rotational levels up to J=5)



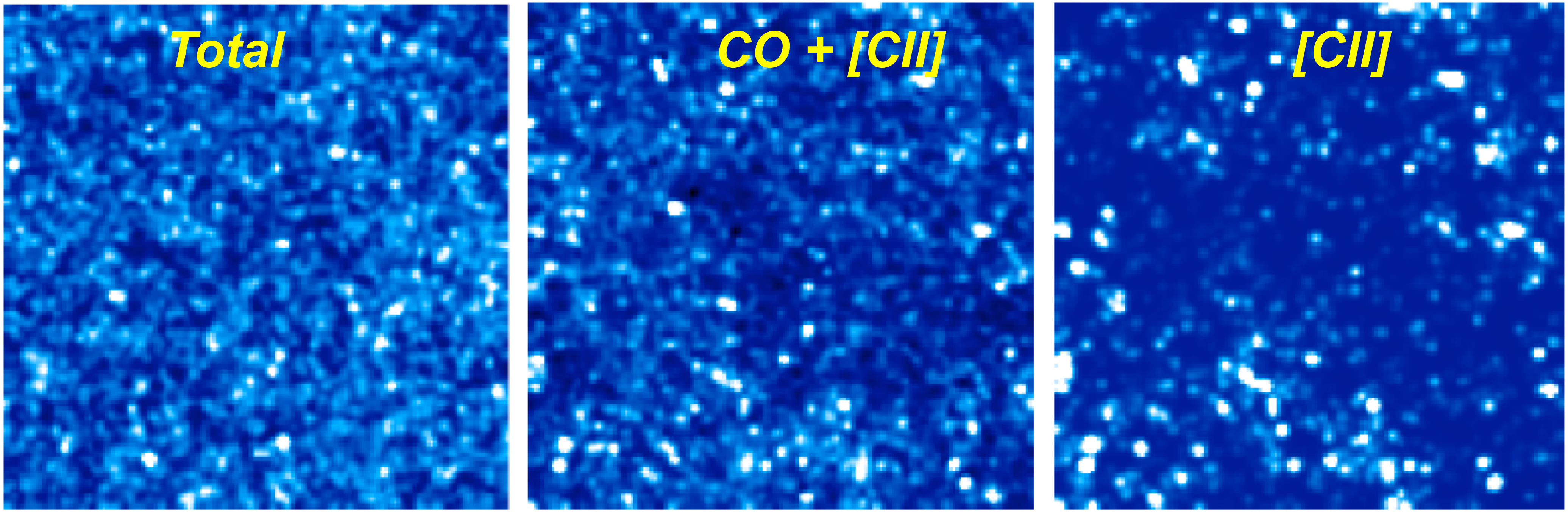




CII z=6
CO(3-2) z=0.27
CO(4-3) z=0.69
CO(5-4) z=1.12
CO(6-5) z=1.54

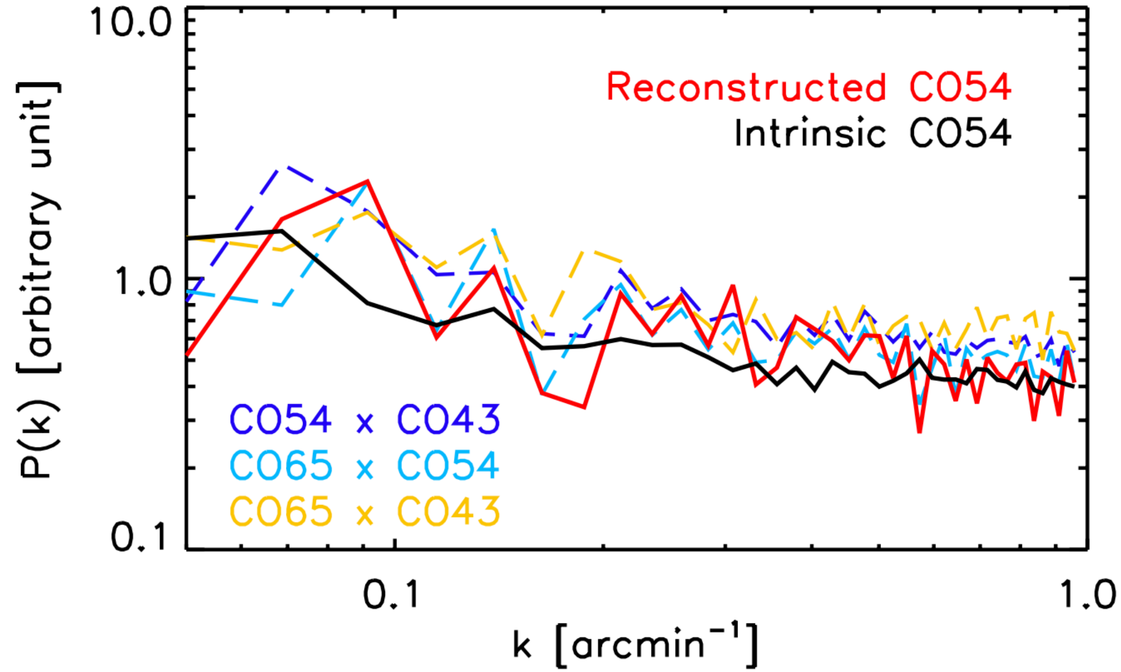
CO :
- Models A and B are from Silva+15
- Model C from Cheng+16

# CONCERTO: contamination

*1.4x1.4 degrees CONCERTO simulated sky maps at z=5.5±0.1*




From Bethermin et al. (2017)




*First tests for CONCERTO*
*The CO(5-4) contamination at z=1.12 of the [CII] at z=6*

# CONCLUSIONS

- Intensity mapping: promising for dusty star-formation at high z

- CIB: different models can fit equally well the CIB data while giving notably different answers on high-z SFRD

- HI experiments will trace the reionization of the intergalactic medium, but they will not observe the young stars responsible for it.

- We propose as an alternative to map the star formation at redshift 4.5<z<8.5 using intensity mapping of the [CII] 157.7 micron line.

  *Naoki: [OIII] at z>8.9 could be the next step…*

- With CONCERTO and Time-Pilot, we will map the star formation at z>4.5, and in the end of EoR
  - And probe the gaz content of galaxies at z~1-2 (with the CO lines)

# But of course the CIB and its fluctuations are useful…

## for Cosmology, large-scale structures and galaxy evolution…

Hansen+2013, Reichardt+2012, Dunkley+2013, Planck collaboration 2015, XI & XIII, George+2015, Crawford+2014, Ilic+2011, van Engelen+2014, Manzotti+2017, Lacasa+2014, Knox+2001, Sherwin & Schmittfull 2015, Lagache+2007, Hall+2010, Gispert+2000, Lagache+2005, Glenn et al. 2011, Penin+2012, Béthermin+2013, Planck collaboration XVIII 2011, Amblard+2011, Miville-Deschênes+2002, Renault+2001, Viero+2013, Thacker+2013, Puget+1996, Lagache+2000, Planck collaboration XXX 2013, Shang+2012, Béthermin+2012, Schmidt+15, Mak+2017, Hauser+98, Dole+2006, Song+2003, Holder+2013, Jauzac+2011, Planck collaboration XVIII 2013, Serra+2014, Viero+2009, Fixsen+1998, Thacker+2014, Hincks+2013, Planck collaboration XVIII 2013 Addison+2012, Planck collaboration 2015 XXIX, Matsuura+10, Simard+2015, Cowley+2015, Wu+2017, Larsen+2016