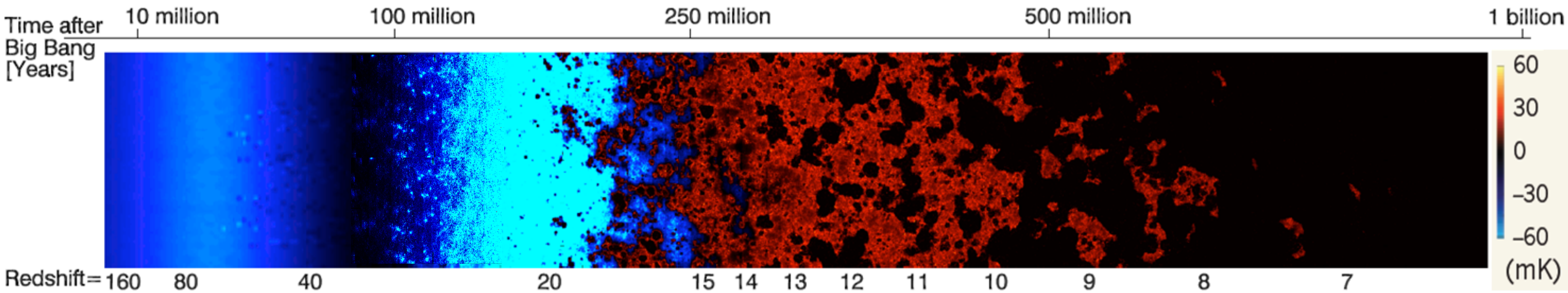
Supporting the revolution through cross-correlations

Mário G. Santos (UWC, SKA-SA)

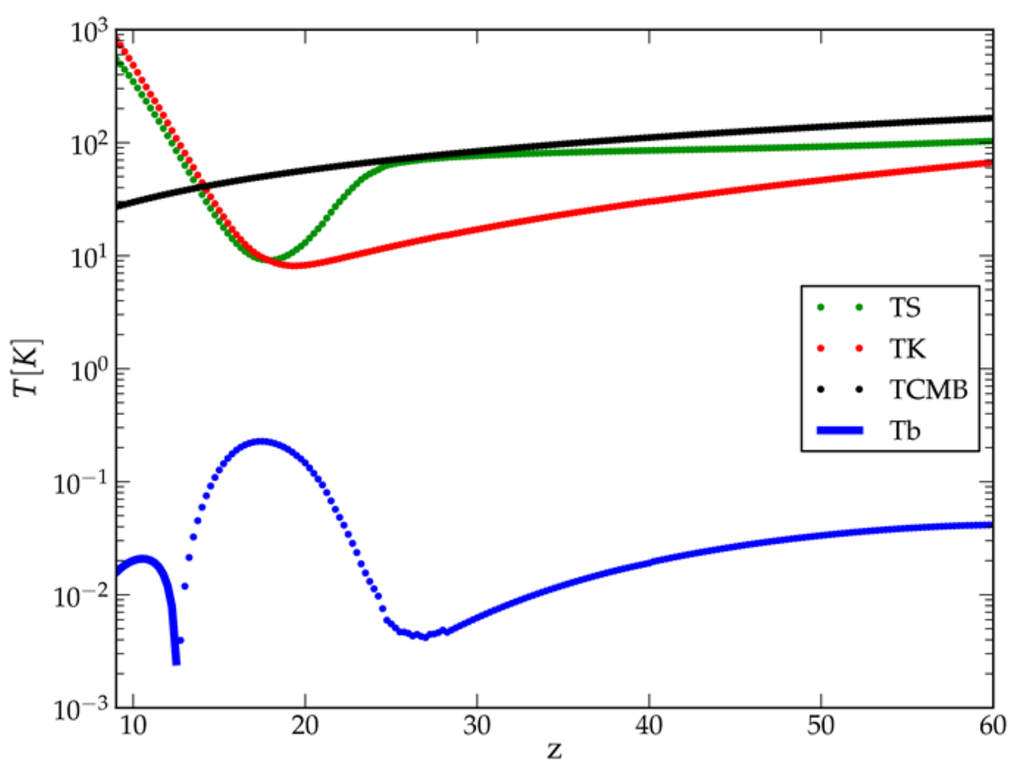
"Preparing for the 21-cm cosmology revolution", Irvine, October, 2015

21cm signal: a great (best?) probe of the EoR…



In *Pritchard & Loeb (2010)*, using simulations from *Santos et al., 2008, ApJ, 689, 1*

- Full picture of the evolution of the Universe during galaxy formation
- Sensitive to:
  - IGM Gas density
  - IGM temperature
  - ionization fraction
  - Star formation rate
  - Lyman-α flux



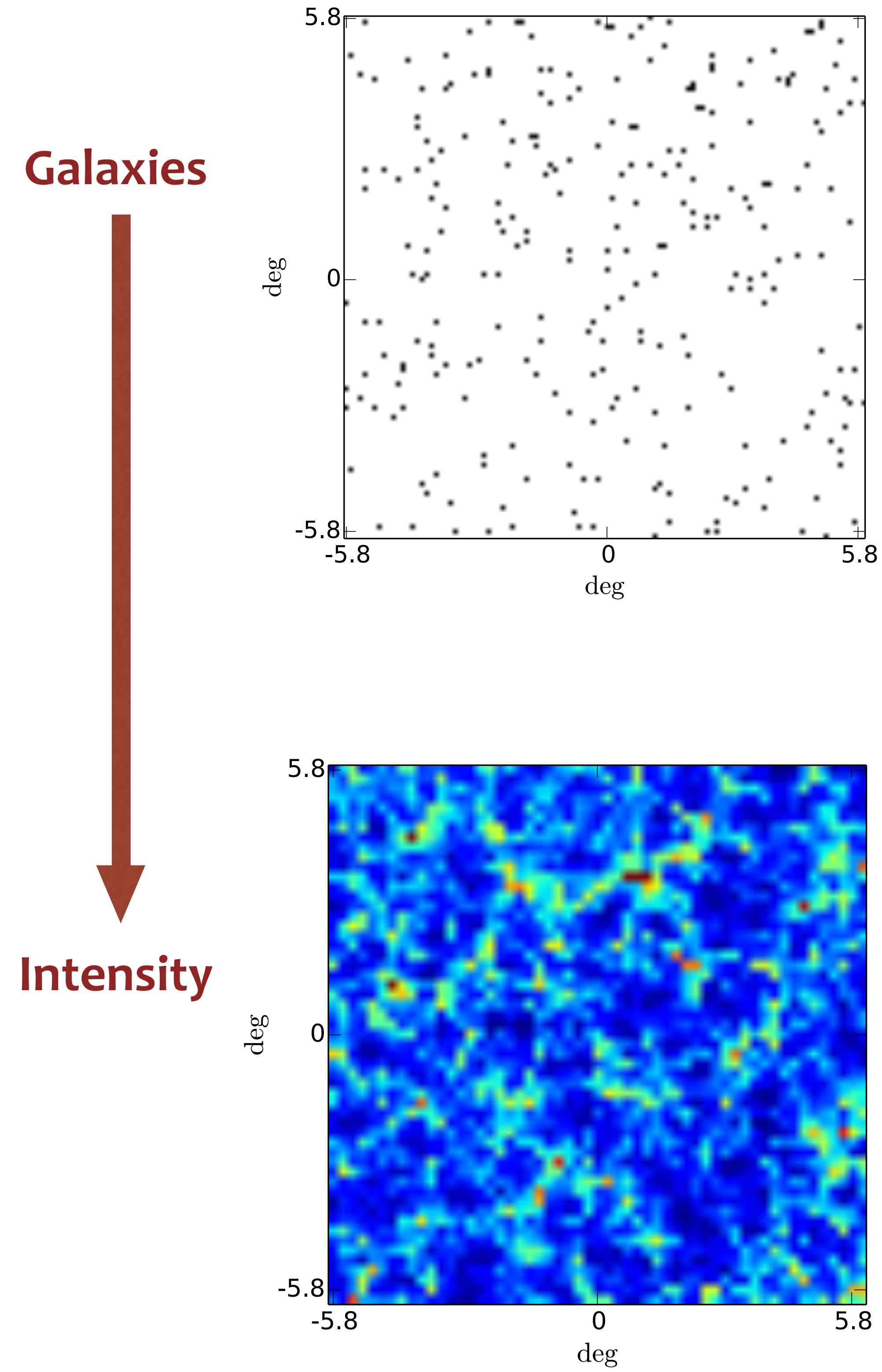
Temperature evolution with redshift

Adding other lines…

- Complementary picture of the EoR (Galaxies versus IGM)
- Cross-correlation can help to beat 21 cm foregrounds and radio calibration issues
- Most relevant at $z \lesssim 10$
- Lines:
  - CO
  - CII
  - Lyman-α

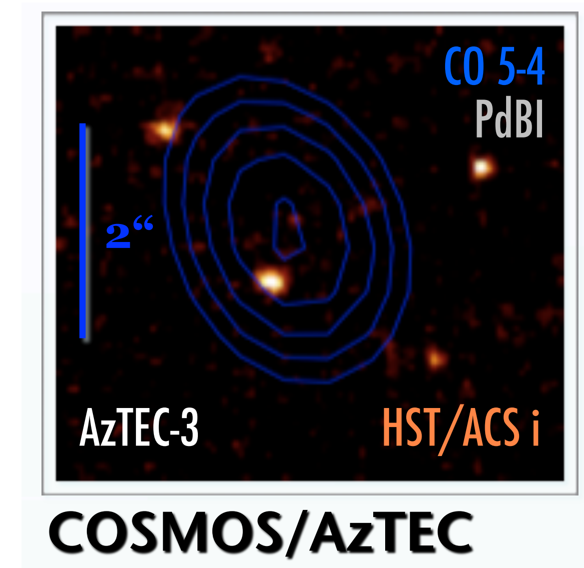
The intensity mapping

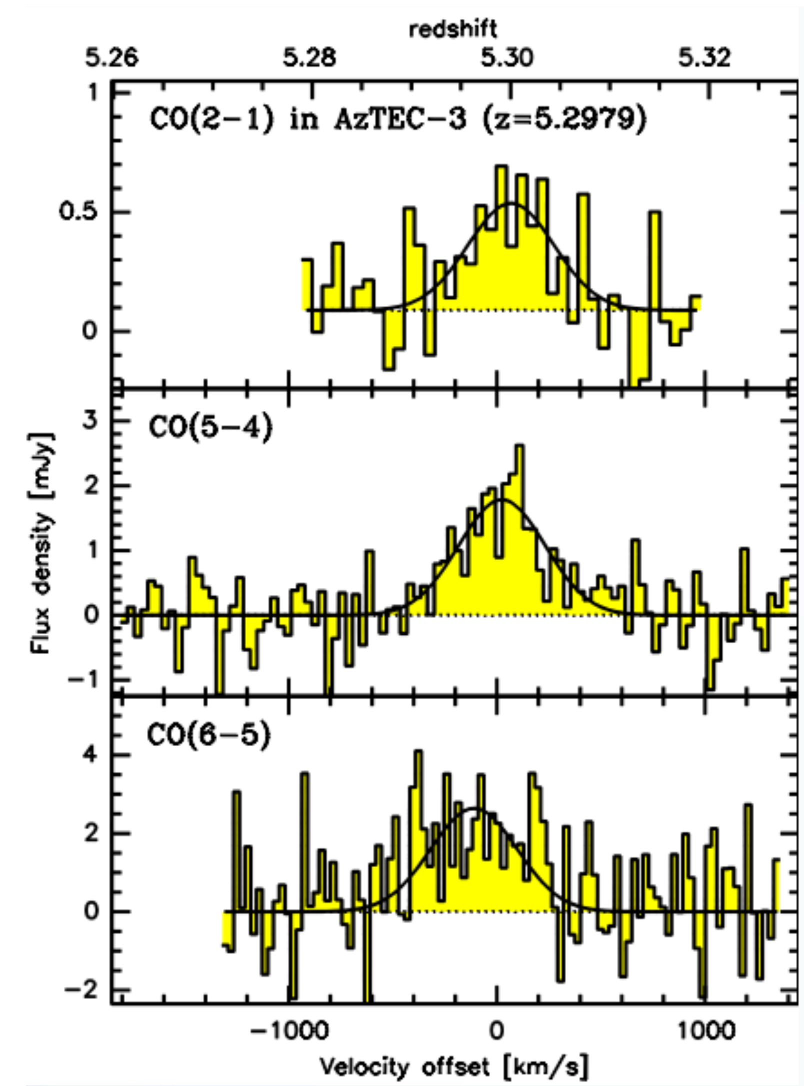
- How to probe these lines?
- Hard to make a large galaxy survey at high redshifts
- Give up detecting galaxies
- Look instead at the integrated line emission from many galaxies in one big pixel



CO line

- Rotational emission lines from CO molecules
- Tracer of molecular gas in galaxies (fuel for star formation)
- CO (1-0)
  - 2.6 mm (115.3 GHz)
  - 14.4 GHz at z=7
- CO(2-1)
  - 1.3 mm (230.5 GHz)
  - 28.8 GHz at z=7
- Works:
  - Righi et al. (2008) - angular power spectrum/CMB
  - Visbal & Loeb (2010) - low redshift
  - Gong et al. (with M. Santos, 2011) - 3d P(k) during EoR
  - Carilli (2011)
  - Lidz et al. (2011)

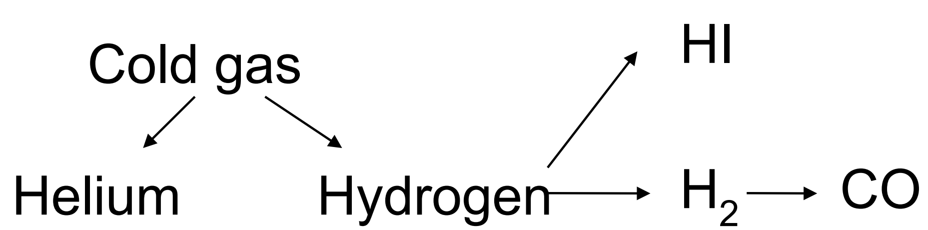




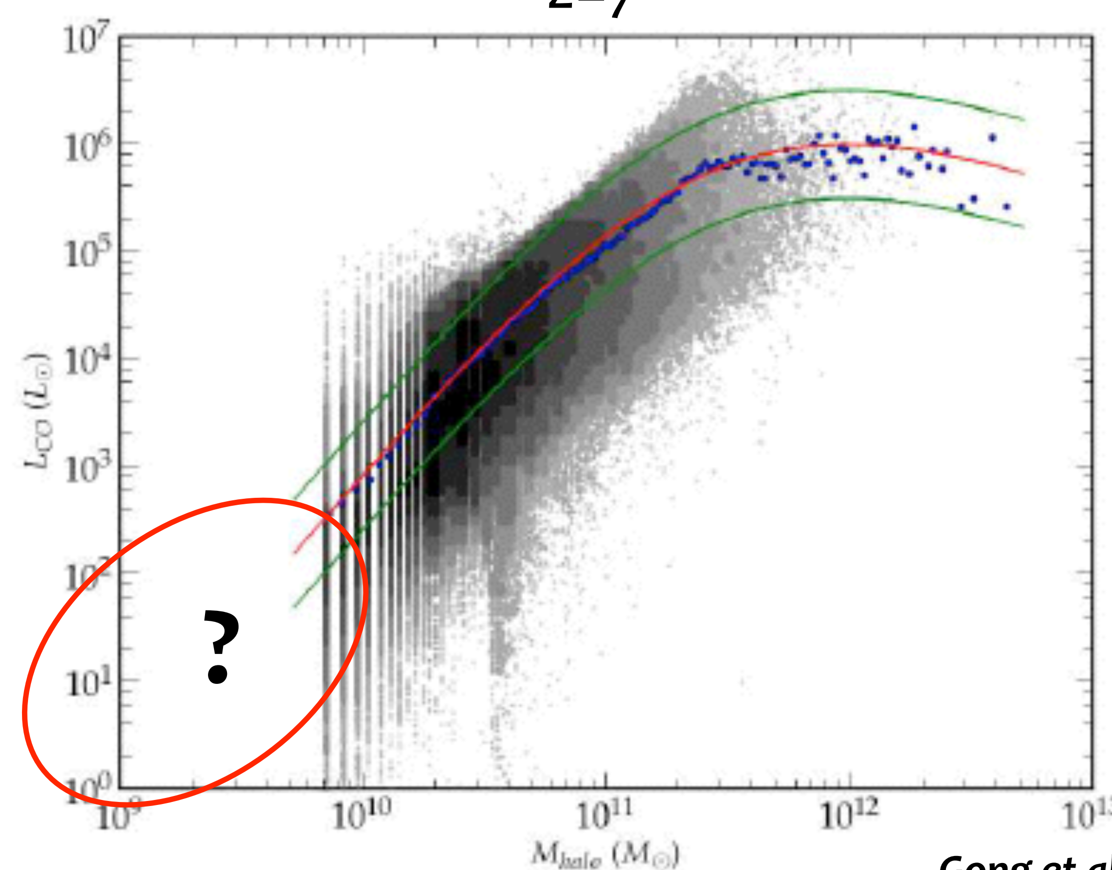
CO at z~5.3 (EVLA)
Riechers et al. 2010
ID: Capak et al. 2010

CO signal estimation

- Use direct relation between luminosity and halo mass (not SFR!)
- Calibrate with simulations from Obreschkow et al. (2009):
  - Millennium simulation
  - Galaxy catalog (De Lucia & Blaizot)



z=7



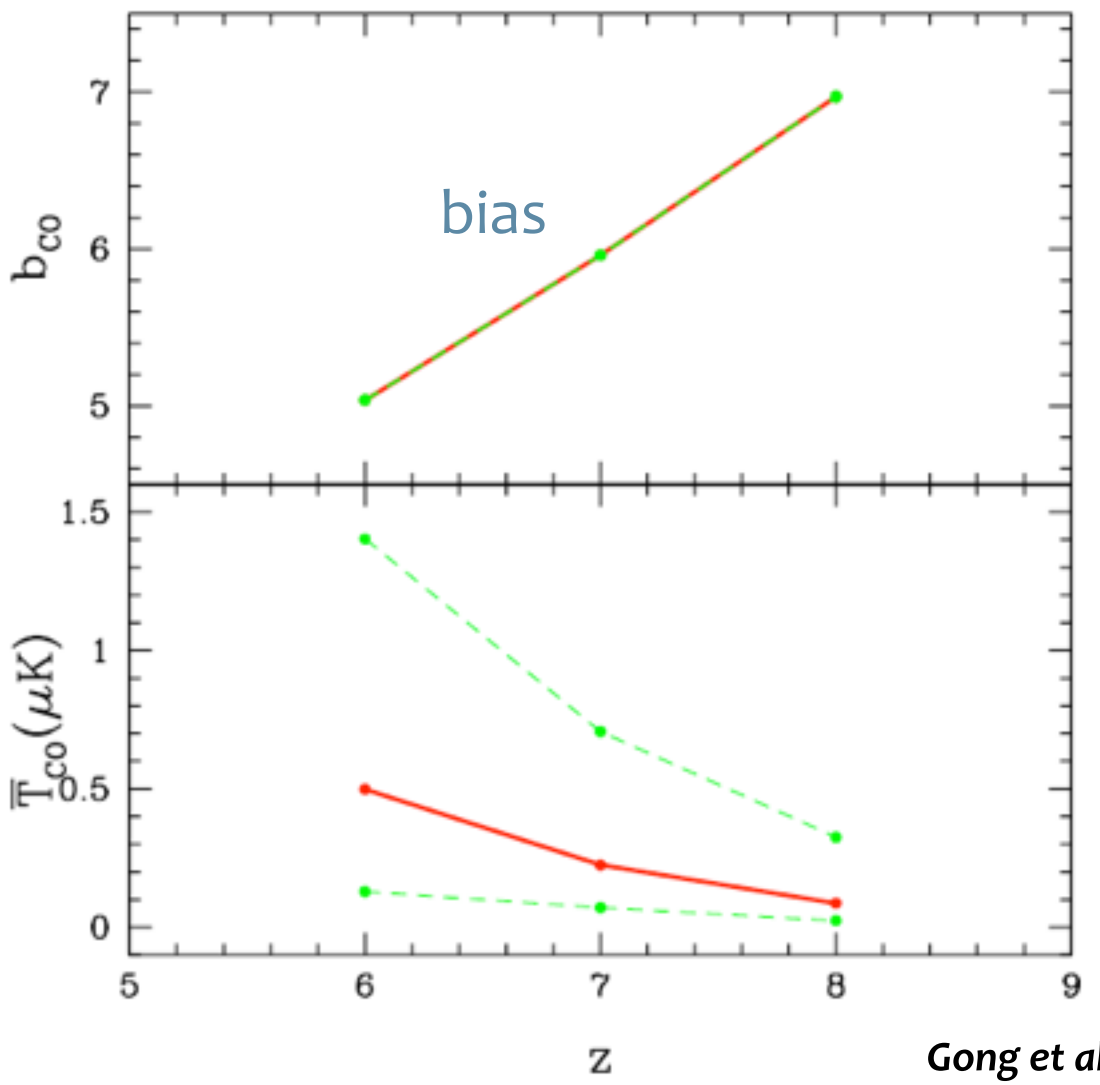
Gong et al. (2011)

Assume "experimental pixel" is large enough to include a large number of galaxies - average:

$$L_{CO}(M) = L_0(M/M_c)^b(1+M/M_c)^{-d}$$

Parameters depend on redshift

CO intensity



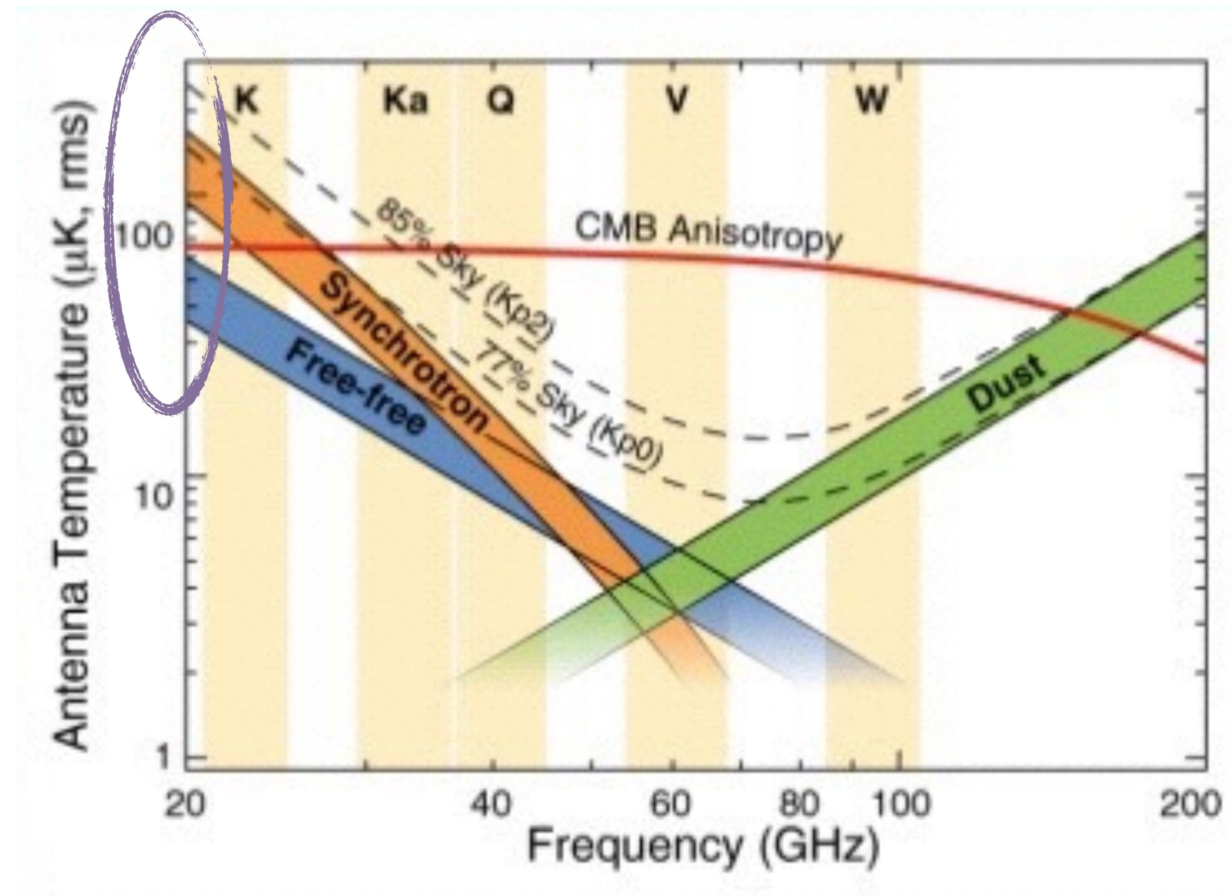
Gong et al. (2011)

- Uncertainties…
  - Amount of cold gas in galaxies
  - Excitation temperature of the gas (local radiation field: bursty galaxies? IMF?)
  - CMB radiative transfer (e.g. excitation temp. larger than CMB? ~ 30K)
  - Metallicity
  - Optical depth of molecular clouds
  - Geometry of star-forming gas (discrete clouds or smooth medium?)

- Mean CO(1-0) brightness from z=7 is about **0.1 to 1** micro-Kelvin
- Consistent with Carilli et al. (2011) scaling argument

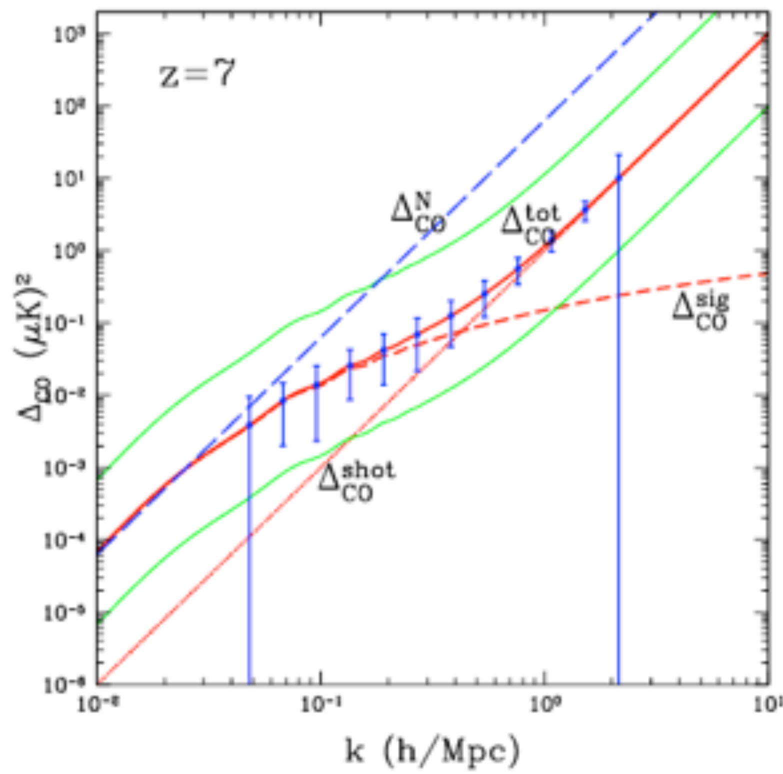
Foregrounds?

- higher CO lines will be weaker (higher z)
- Stronger contamination from the galactic synchrotron, free-free emission, CMB (~ 100 μK)
- No obvious contaminants from other strong lines (HCN?)
- Use frequency smoothness of foregrounds to clean the maps

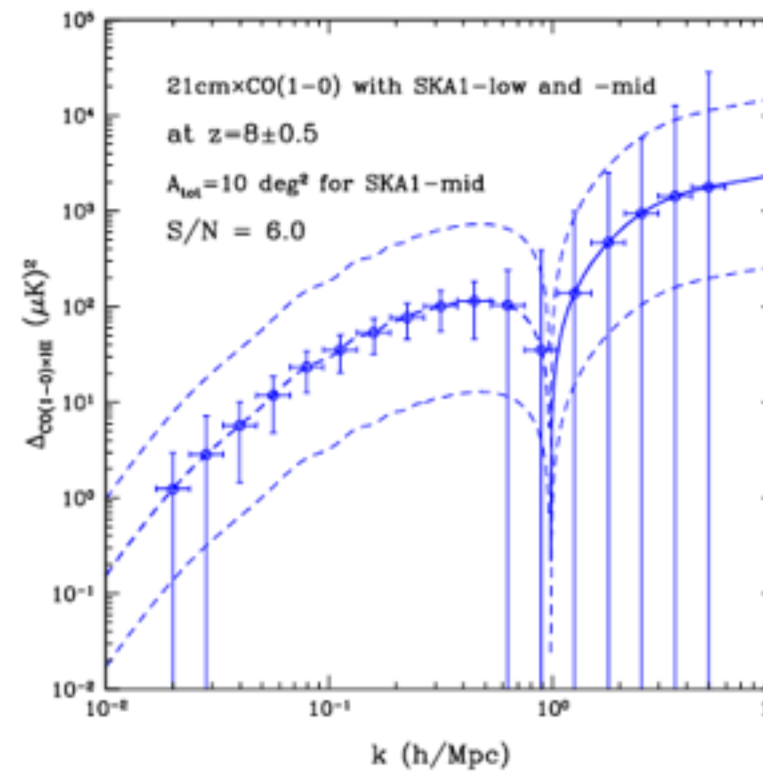


Experiments…

- Experimental setup:
  - Interferometer ~ 15 GHz
  - FoV ~ 5 deg^2
  - A_{tot} = 385 m^2
  - Bandwidth = 1 GHz
  - Spectral resolution = 30 MHz
  - 1000 elements - D=70 cm
  - T ~ 20 K
  - core with 25 m diameter
  - ~ 2000 hours



CO(1-0) line detected with S/N ~ 20 σ (optimistic scenario)



SKA1-MID (auto-correlation) x SKA1-LOW

Chang et al., arXiv:1501.04654

Very hard to measure even with SKA1-MID! (too sparse/ not sensitive enough…)

CII

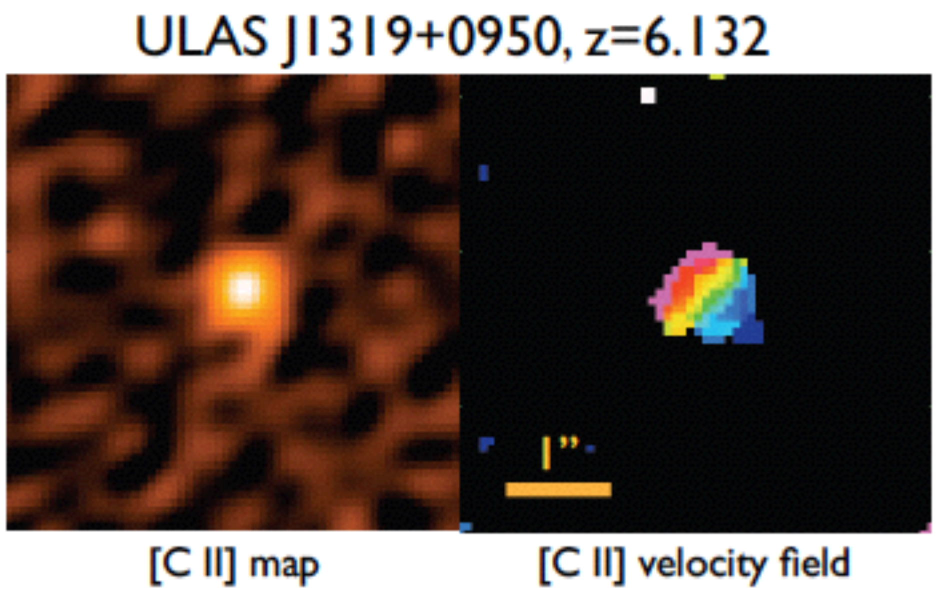
- Ionisation: 11.26 eV
- Fine structure line: $^2P_{3/2} \longrightarrow {}^2P_{1/2}$
- 157.7 µm (1900 GHz)
- **238 GHz** at z=7 (1.3 mm)
- ~ 0.5% of FIR
- Stronger than CO:

$$L_{CII} \sim 1622\, L_{CO(1-0)}$$

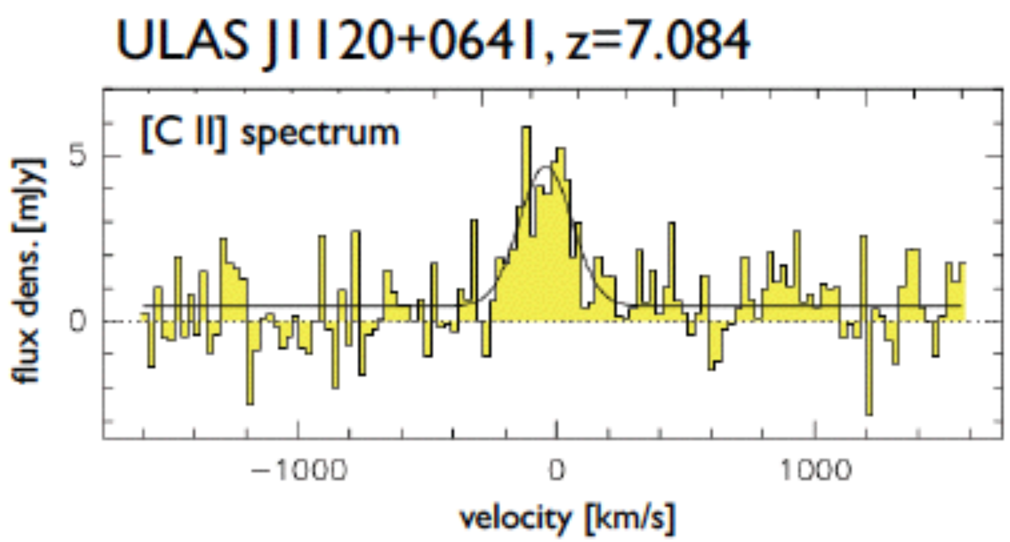
$$L_{CII} \sim 10^4\, L_{CO(1-0)}$$

Stacey et al. (2010)
Breuck et al. (2011)

- Works:
  - Basu et al. 2004
  - Visbal & Loeb 2010
  - **Gong et al. 2012 (M Santos)**
  - **Silva et al. 2015 (M Santos)**

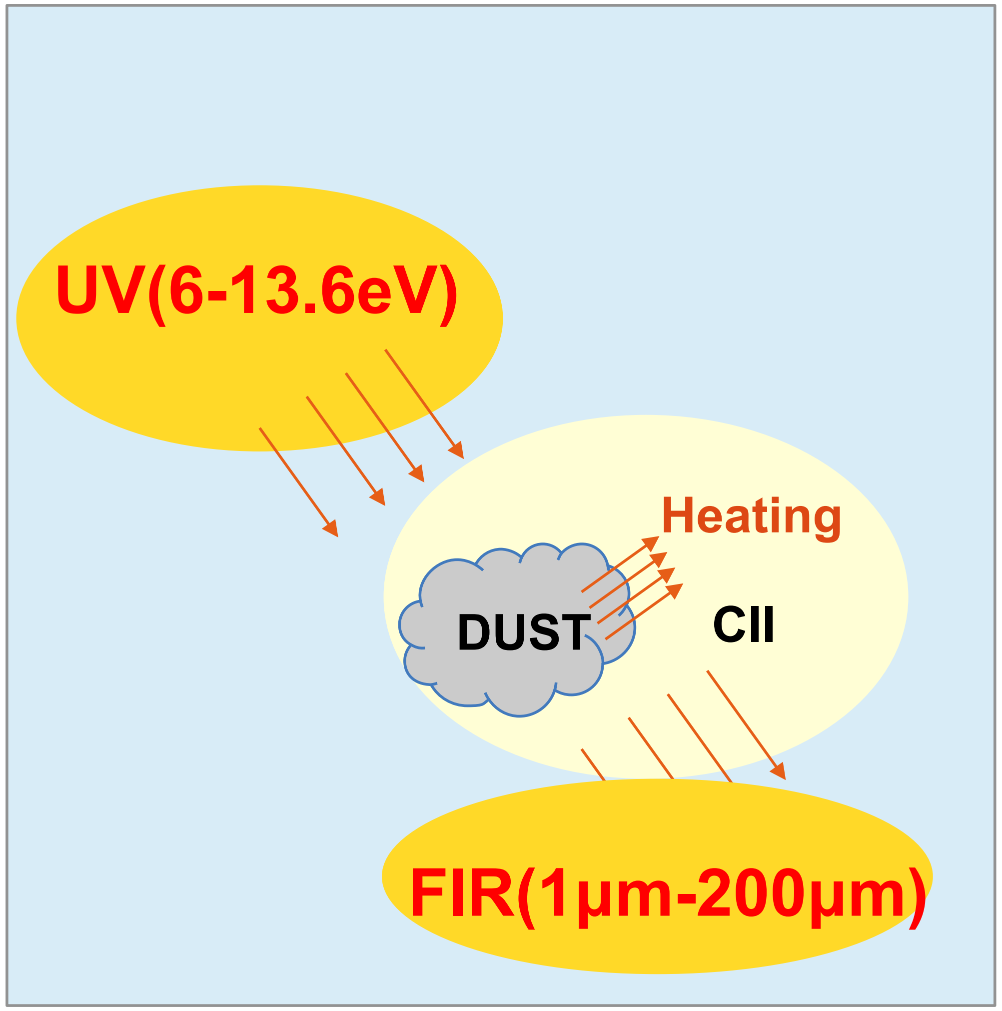


Wang et al. 2013 (ALMA)



Venemans et al. 2012 (PdBI)

CII



- Main contribution from PDRs (photo-dissociation regions)
- HII regions (hot gas) only contribute a few percent
- Relate to star formation rate:

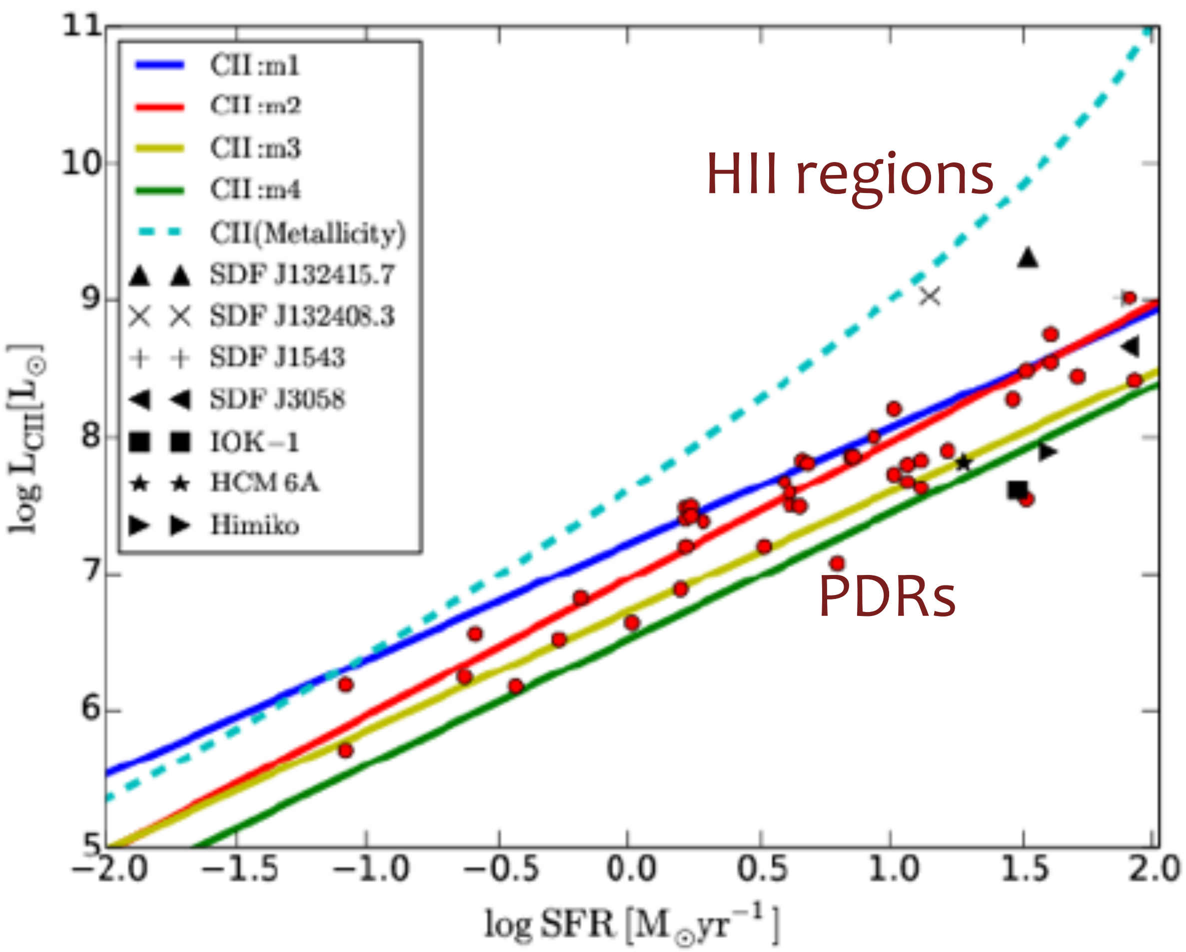
$$L_{\mathrm{CII(M,z)}}\,[\mathrm{L}_\odot] = 0.003 \times L_{\mathrm{FIR}}$$

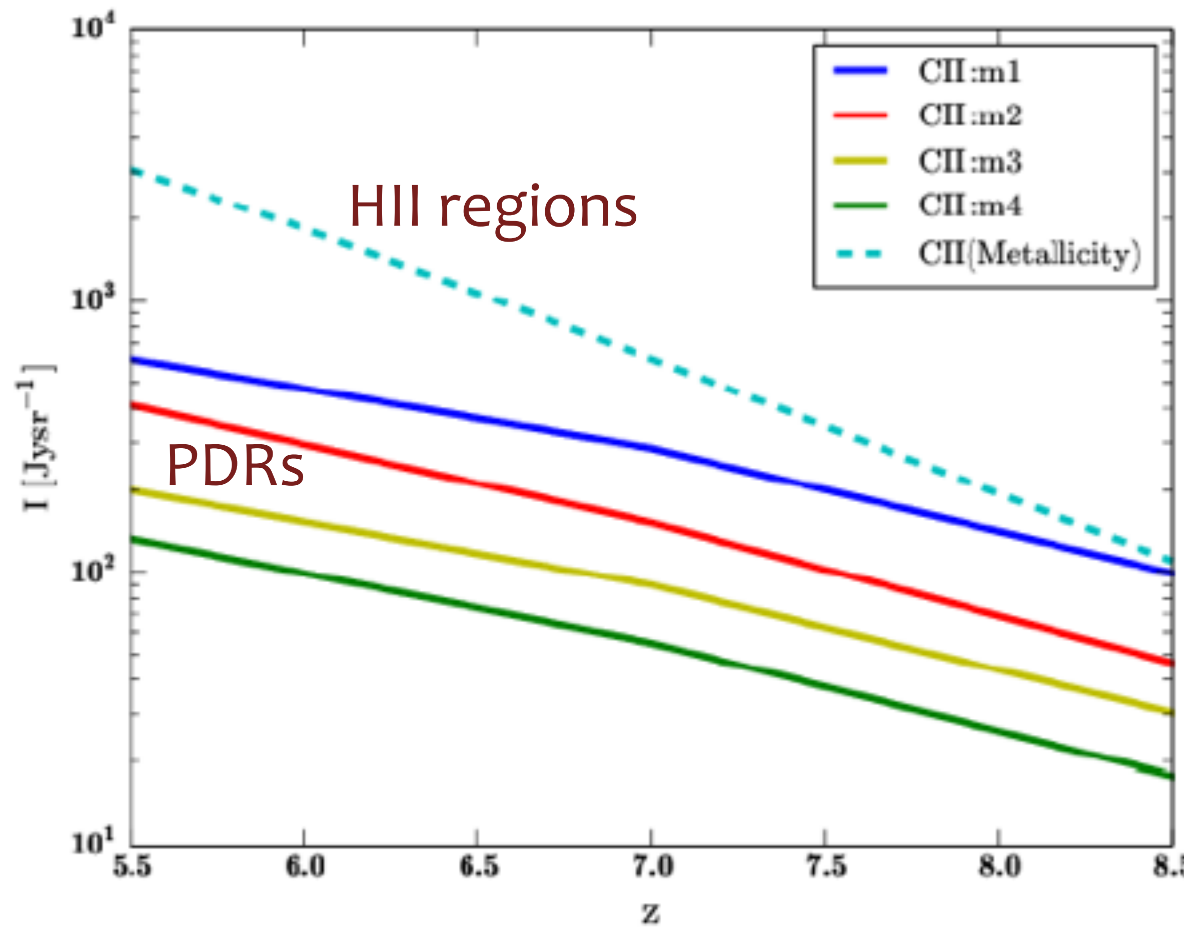
(Boselli et al. 2002)
Local Universe

$$\mathrm{L_{FIR}}[\mathrm{L}_\odot] = 3.07 \times 10^9 \mathrm{SFR}[\mathrm{M}_\odot \mathrm{yr}^{-1}]$$

Kennicutt (1998) +Cardiel et al. (2003)

CII average intensity





Silva et al. (M Santos), ApJ, 2015

$$\log10(L_{\rm CII}[{\rm L}_\odot]) = a_{\rm LCII} \times \log10(\psi[{\rm M}_\odot]) + b_{\rm LCII},$$

$$\psi(M,z) = M_0 \times \left(\frac{M}{M_a}\right)^a \left(1 + \frac{M}{M_b}\right)^b$$

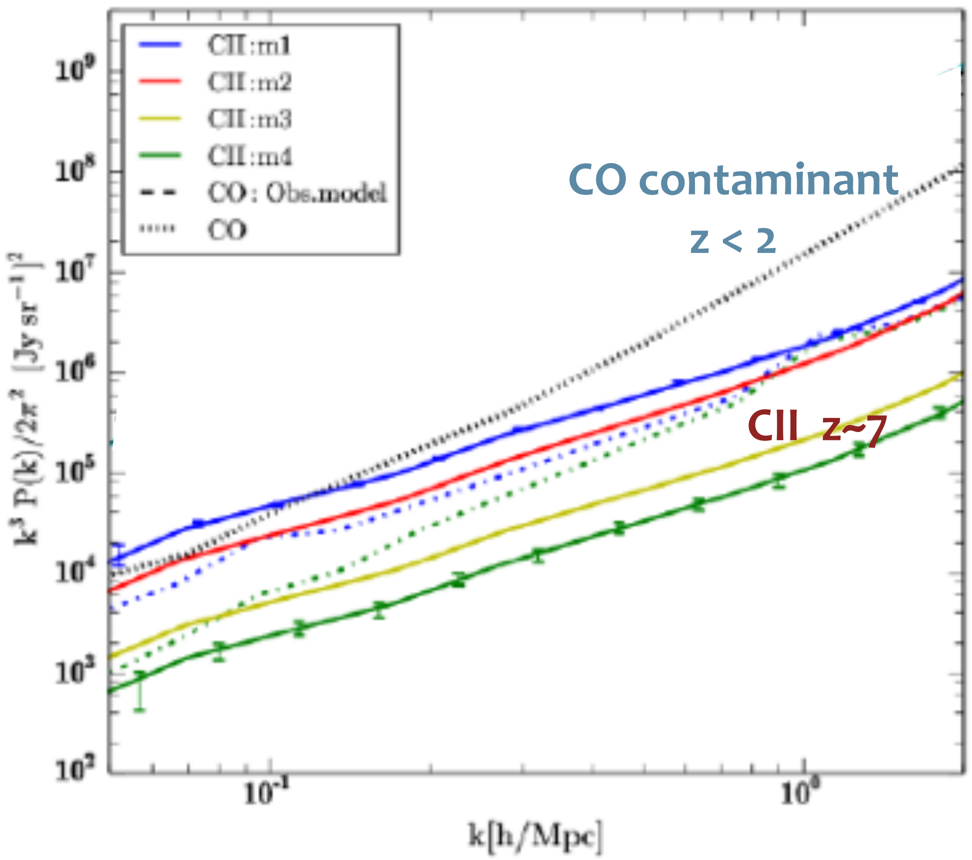
- SFR from simulations (Guo et al. 2011, De Lucia & Blaizot 2007)

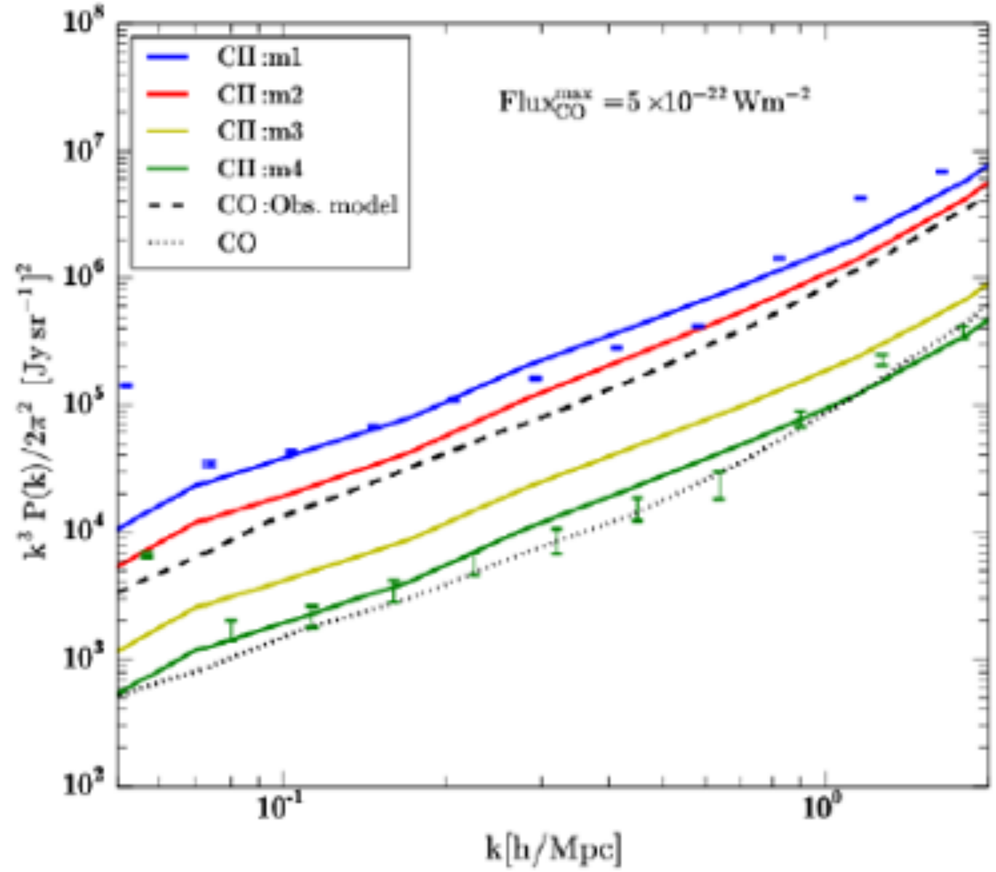
CII

- Signal CII (200 GHz - 300 GHz) ~ **300 Jy/sr**
- Line emission:
  - CO(J=2-1),… ,CO(J=10-9) → Intensity larger than the CII signal (~ 10^3 Jy/sr)
    - (from z<2 galaxies)
  - OI[145μm], NII[122μm], NII[205μm] and CI[610μm] → Intensity smaller than the CII signal
- Continuum emission:
  - Stellar emission
  - Free-free
  - Free-bound
  - Two photon
  - **Dust emission ~ 10^5 Jy/sr**
  - Emission from the Milky Way

→ Spectrally smooth components can be removed along each line of sight
Yue et al. 2015

CII





- Left: CO will dominate CII for most models
- Need to mask the 3d pixels which have strong CO contamination - use low z galaxy survey with CO or a CO tracer such as SFR (or AB magnitudes in the K filter)
- Right: masking pixels with CO fluxes below 5×10^{-22} W/m^2. Less than 10% pixels masked for a typical CII experiment (resolution: 0.5 GHz, 0.5 arcmin)
- Note: tests done using semi-numerical simulations - 3d observational cone generated. CII power spectrum includes effect of masking

CII experiment

- This is "microwave"! Use bolometers…

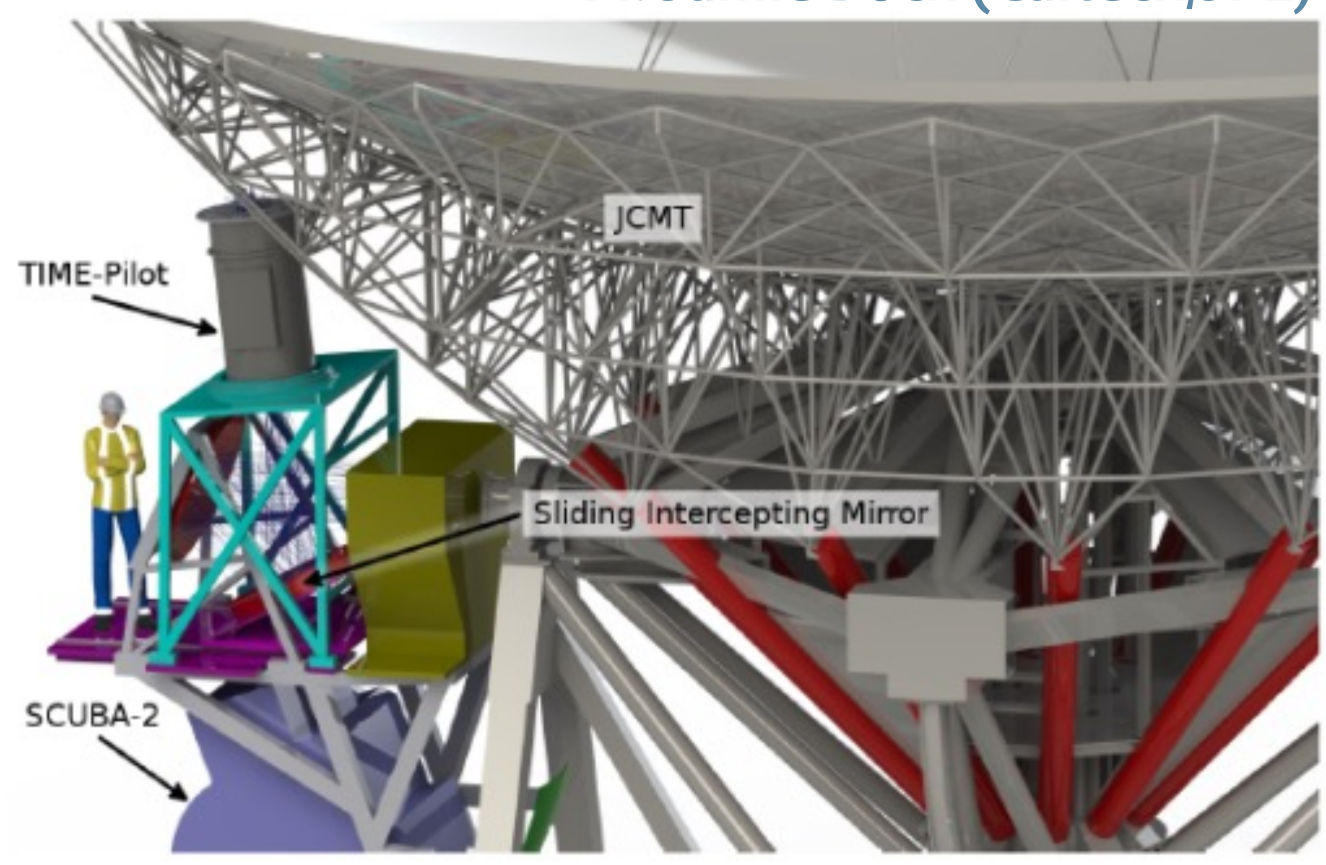
Instrument	CII-Stage I	CII-Stage II
Dish size (m)	10	10
Survey area A_s (arcmin^2)	78×0.5	600×600
Instantaneous FOV (arcmin^2)	13.6×0.5	25.6×0.4
Freq. range (GHz)	200 - 300	200 - 300
Frequency resolution (GHz)	2	0.4
Number of Spectrometers	32	64
Total number of bolometers	1600	16000
On-sky integration time (hr)	1000	2000
NEFD on sky (mJy $\sqrt{\text{sec}}$)	65	5

Silva et al. 2015

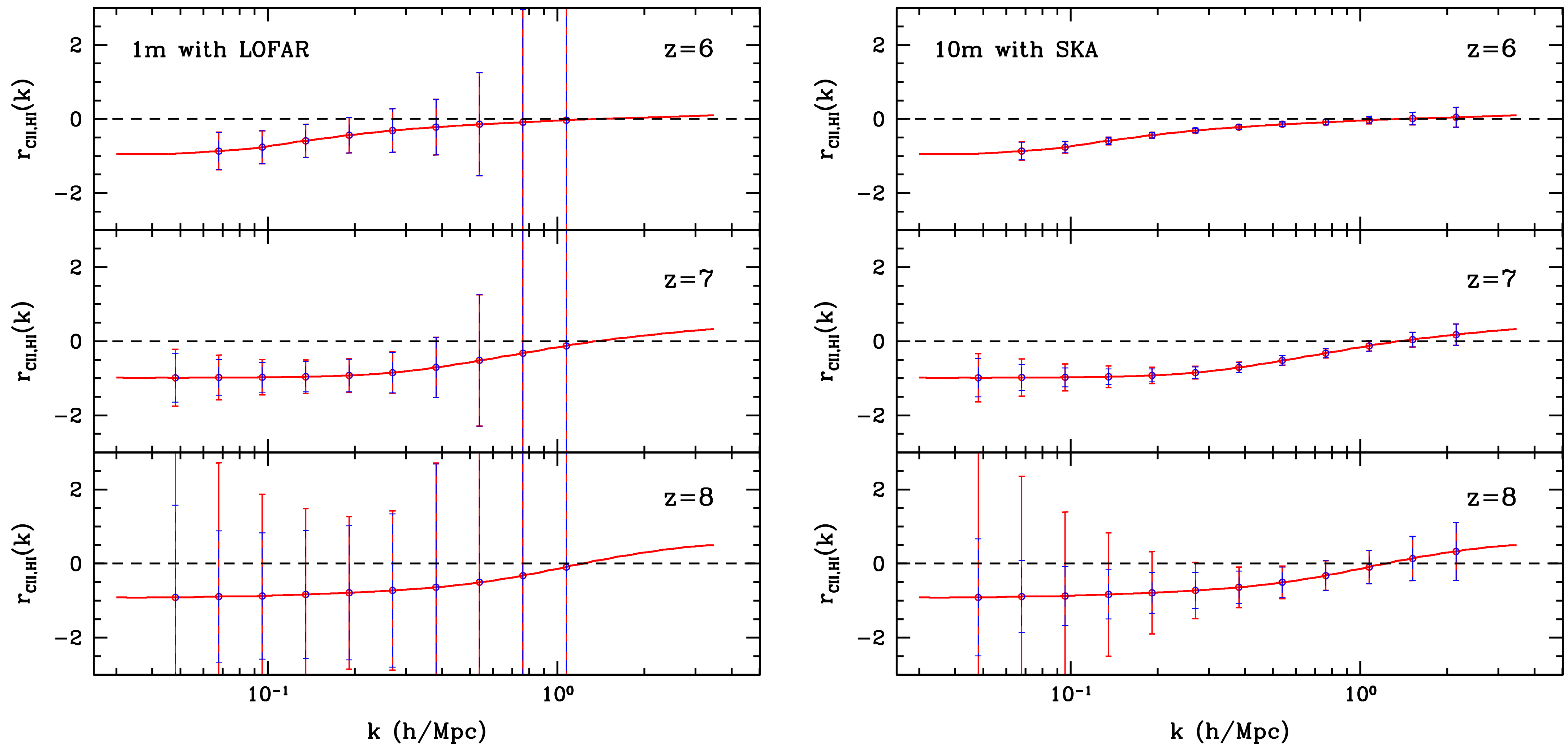
- ALMA total power array? (4 dishes, not interferometer) - not sensitive enough…
- Note: power spectrum of "single dish" survey does not depend on dish size!

- **TIME-Pilot:** a first detection machine
  - 1840 bolometers
  - 32 spectrometers
  - ν = 183 – 326 GHz
  - $\nu/\Delta\nu$ = 100
  - 240 hours on the sky at JCMT

PI: Jamie Bock (Caltech/JPL)



CII-21cm cross-correlation



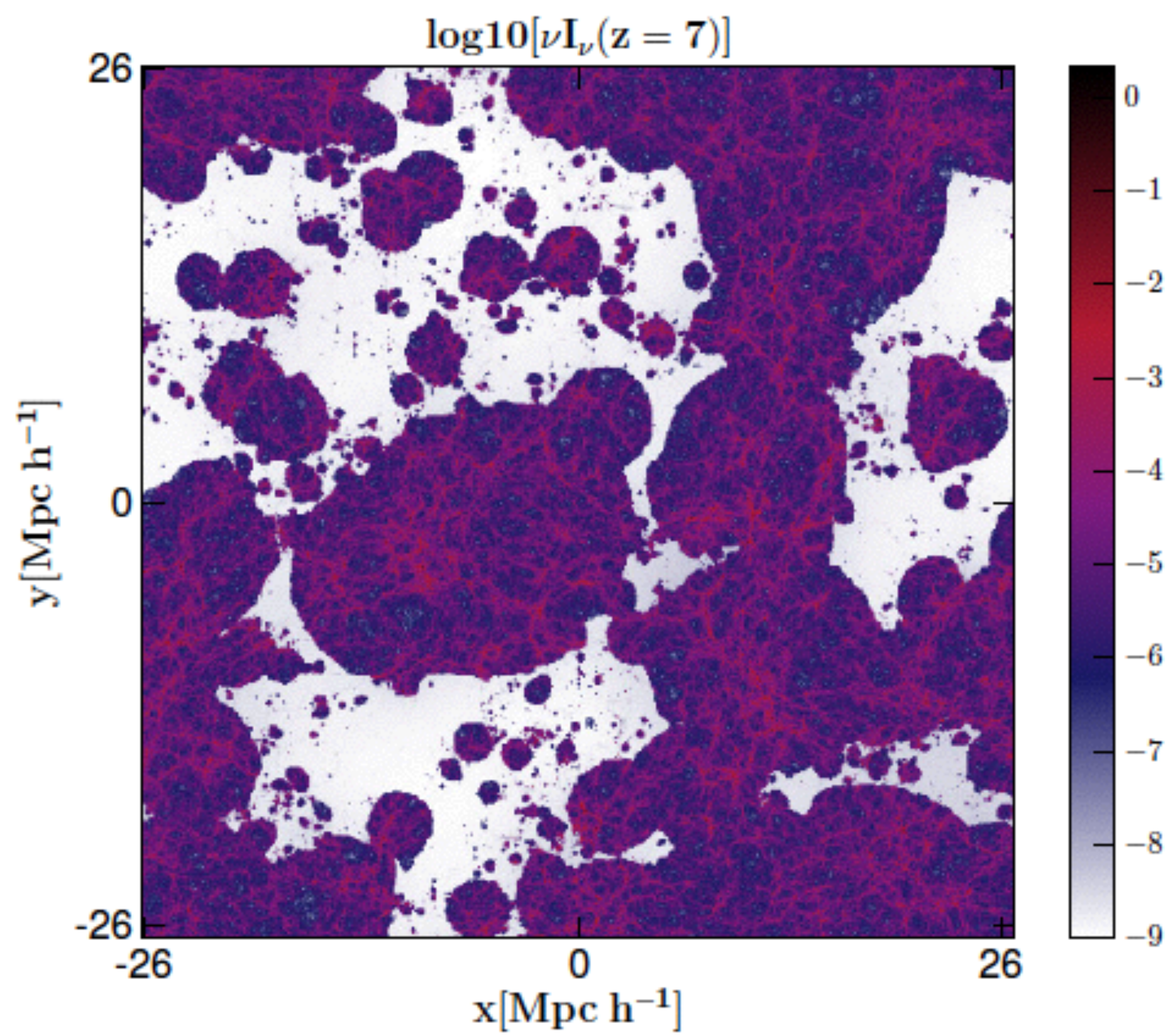
- Transition from negative to positive related to typical bubble size
- The cross-correlation helps to remove contaminants and improve measurements related to the ionized fraction and the number of CII galaxies in each ionization bubble, all as a function of redshift.

Intensity mapping with the Ly-

- Line: 1215.7 Å
- 0.97 μm at z=7 (NIR)
- Galaxy contributions:
  - Recombinations
  - Excitations/decays
  - gas cooling (gravitational collapse)
  - Ly-α emission from stars
- IGM contributions:
  - Recombinations
  - Excitations/decays
  - Scattering of Ly-n photons from galaxies

α SFR

T_K, x_i

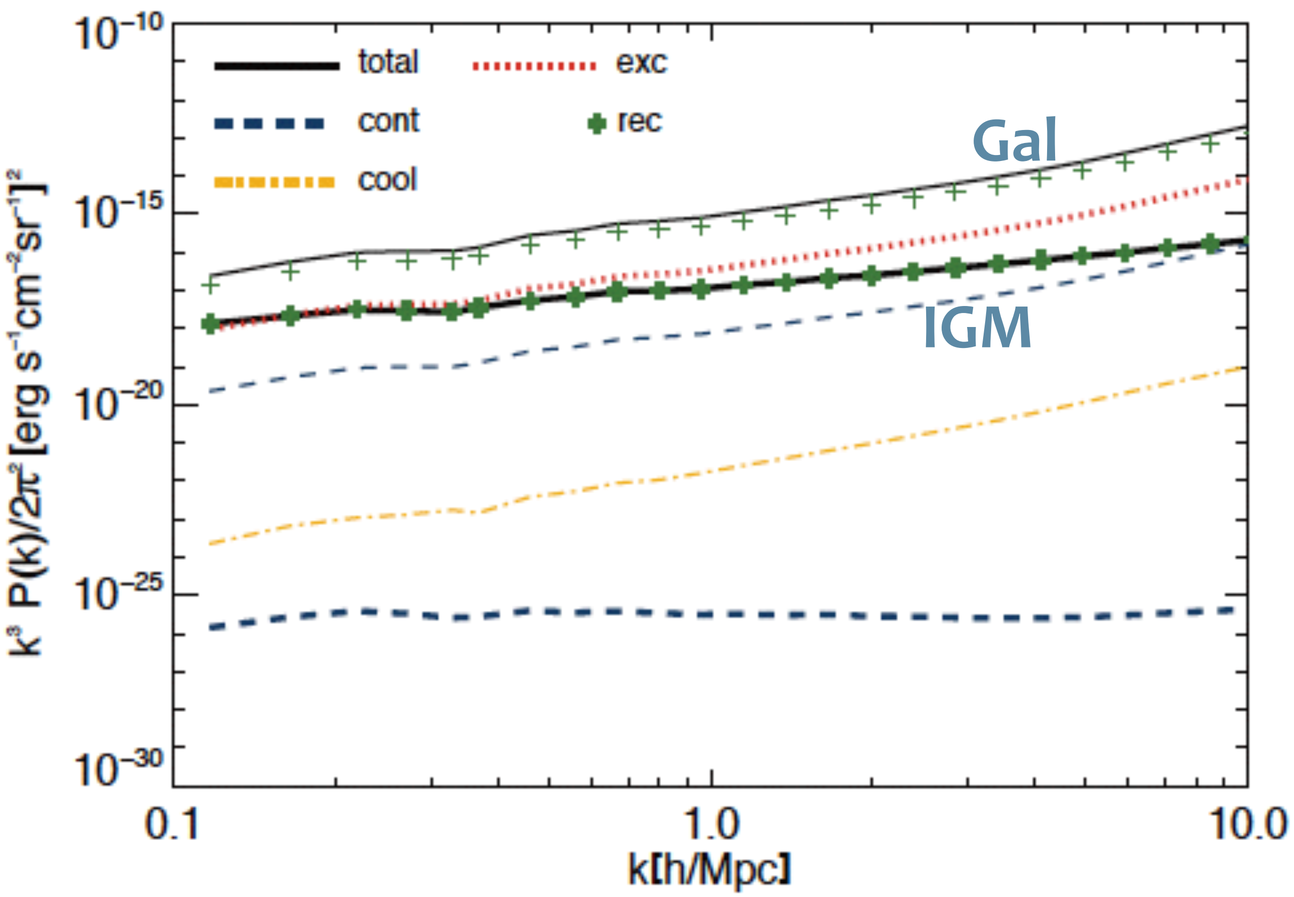


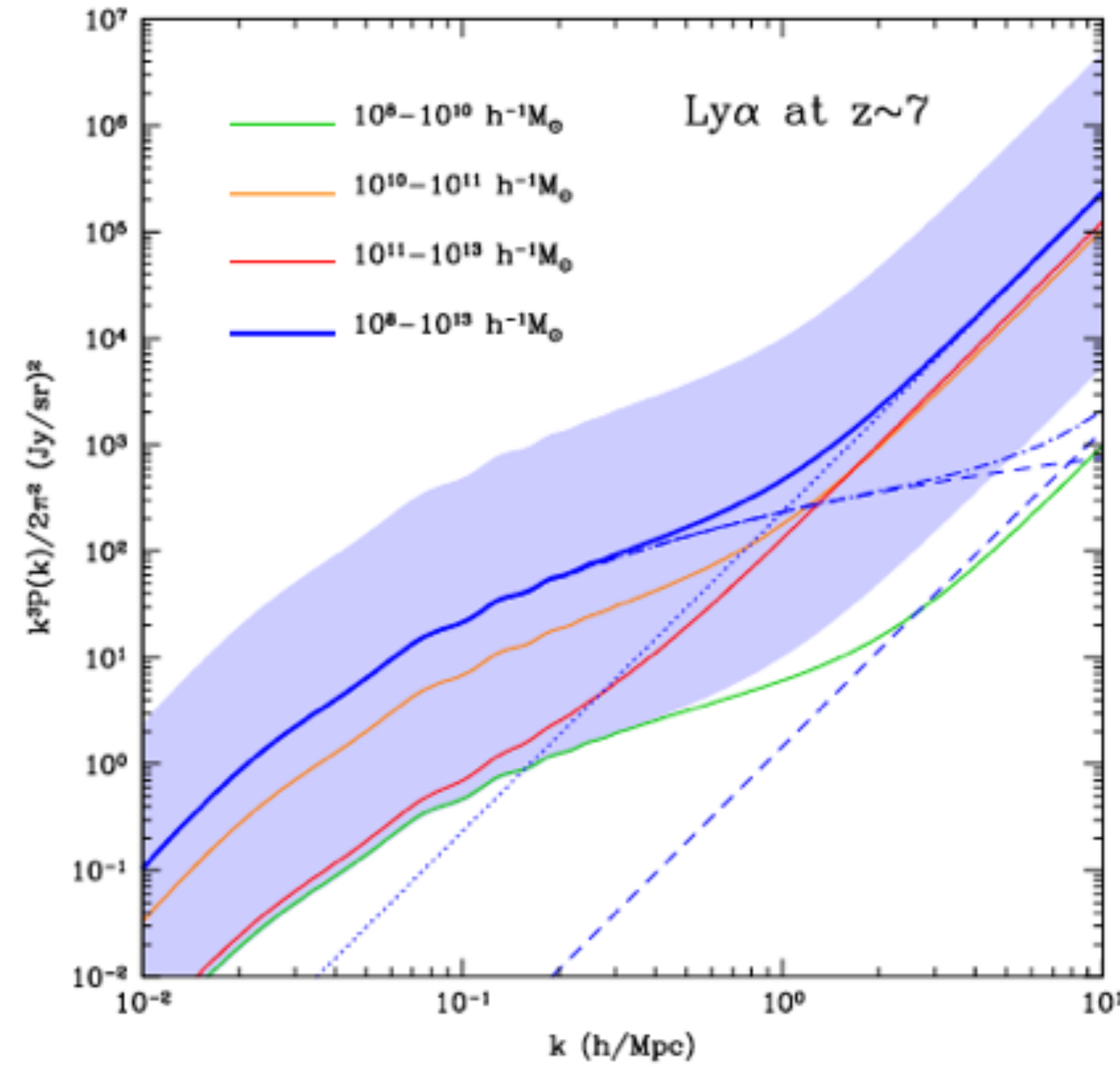
Total Ly-α intensity from galaxies and the IGM in erg s^{-1} cm^{-2} sr^{-1} at redshift 7

M. B. Silva et al. (M. Santos, 2013)
Gong et al. (M. Santos, 2014)

(see also Pullen et al. 2014)

Lya signal

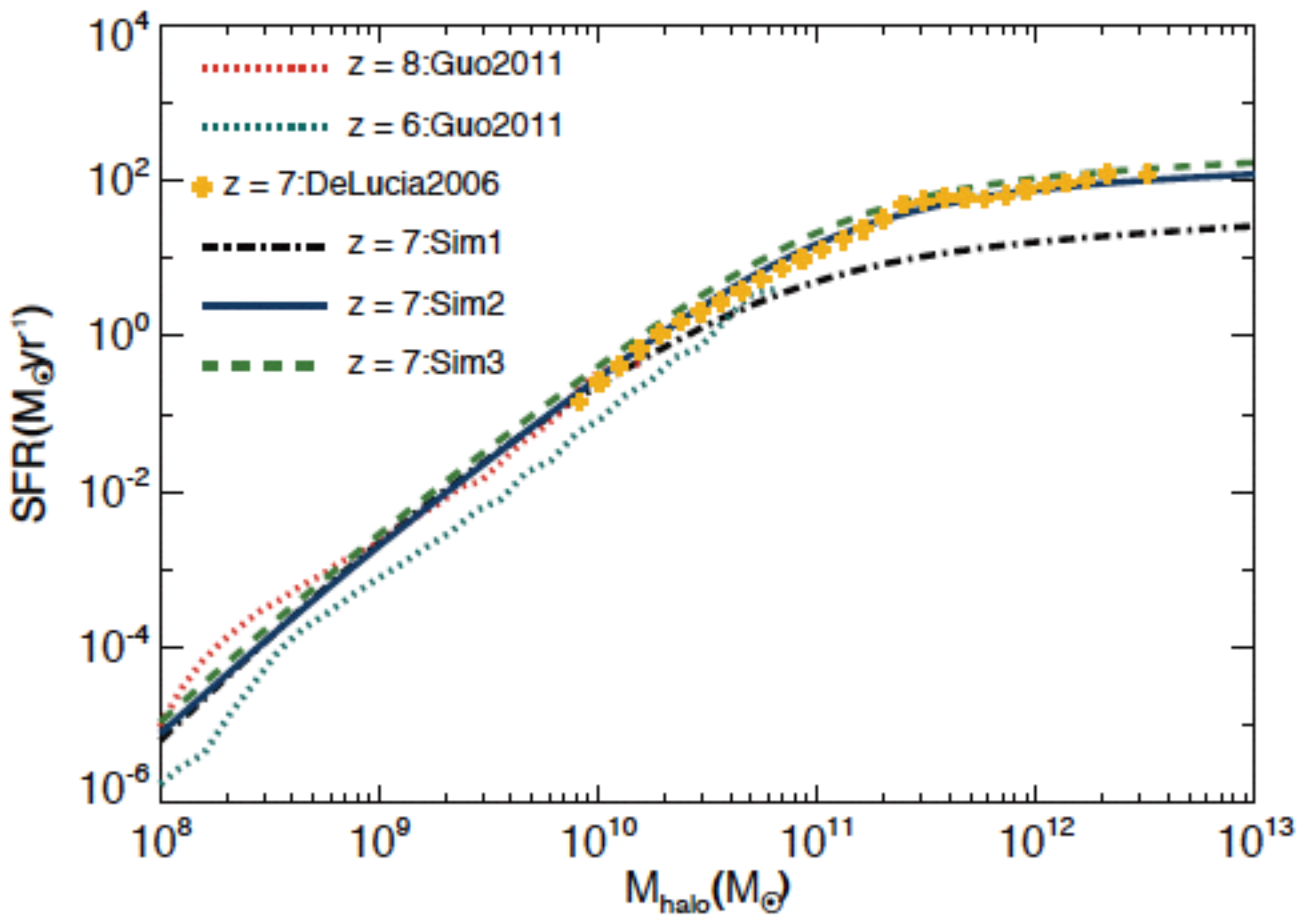


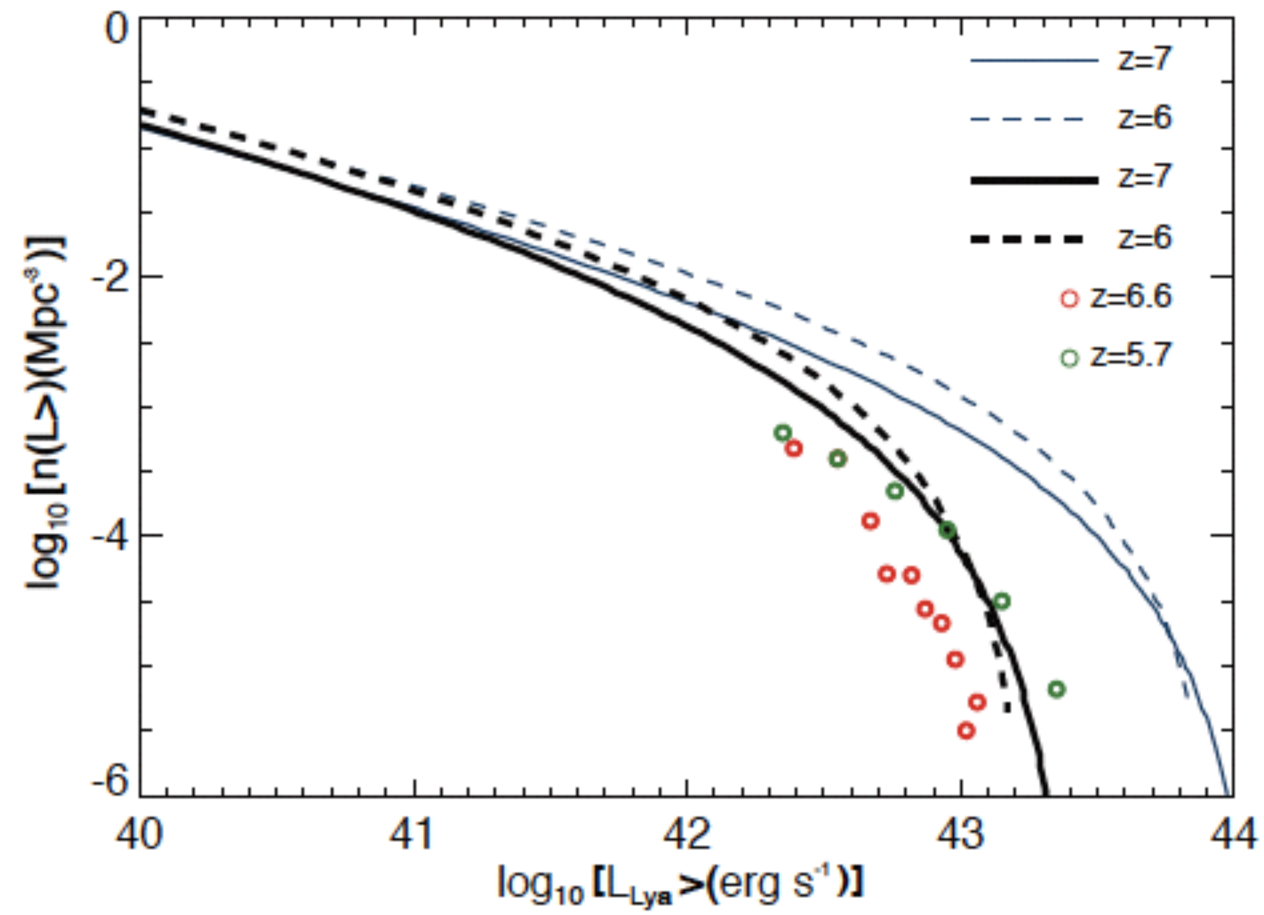


- Galaxy emmission dominates over IGM
- Recombinations are the main contribution
- Calculations using fully consistent semi-numerical simulations

- Large uncertainty in the relation (SFR, UV escape fraction, Lya escape fraction)
- Dominated by 10^{10} - 10^{11} M_{sun} halos!!

Signal calculated using fully consistent EoR simulations

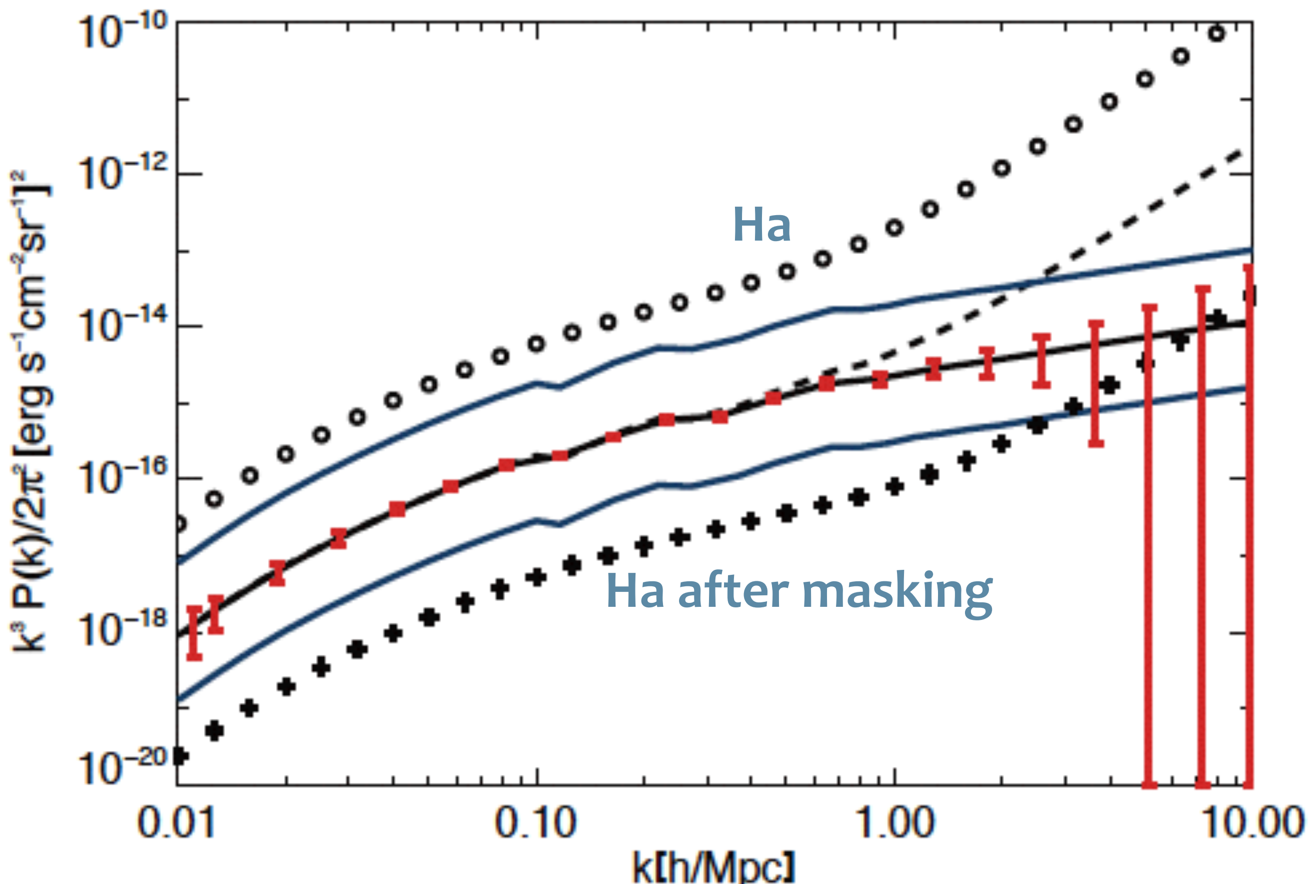




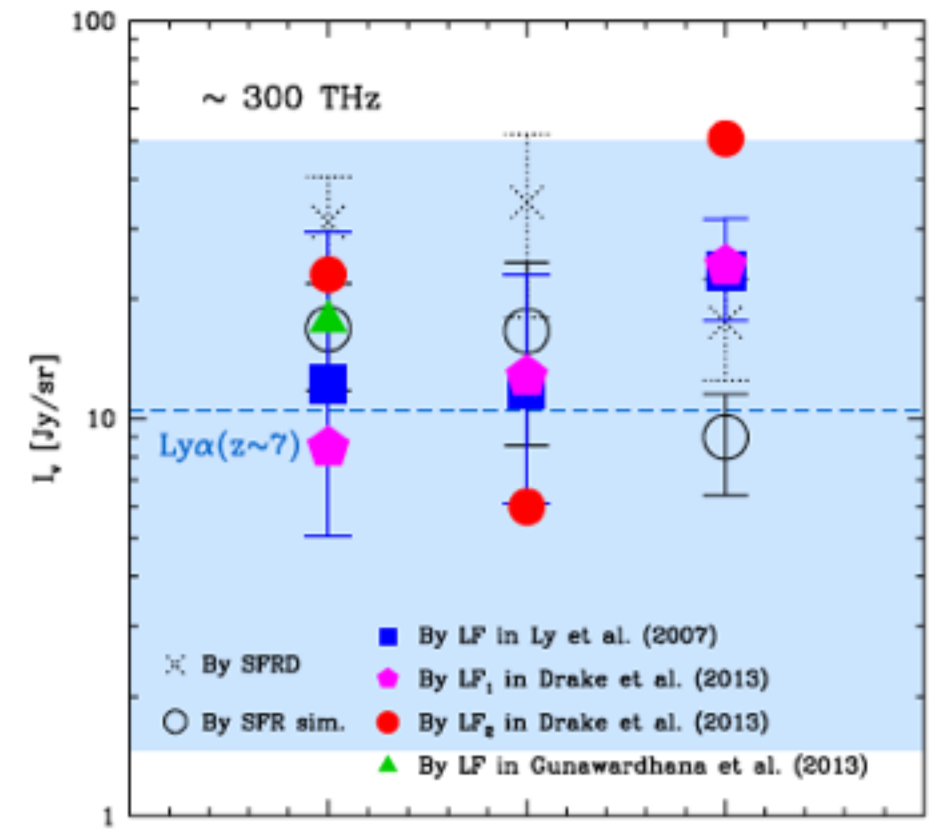
- **SFR needs to produce right optical depth and also the right luminosity function**
- Lower SFR model (left dot-dashed) fits better the luminosity functions (right, solid) from Shimasaku et al. (2006) and Kashikawa et al. (2006)
- 21cm simulation gives optical depth of ~0.066

Code: Simfast21 (https://github.com/mariogrs/Simfast21)

Lya observations



M. B. Silva et al. (2013)



Gong et al. (2014)

- Observations in the near infrared (~ 1 μm) - need to go to space: 20 cm aperture; R ~200 - 300 (about 50 channels) ; 2048x2048 HgCdTe detector array (10 arcsec); Survey area ~ 20 deg^2
- Main contaminants: Ha, OIII and OII lines at low z
- Need to mask pixels with fluxes above 1.4x10^{-20} W/ m^2 (about 3% of pixels)

Conclusions

- Intensity mapping of molecular and atomic lines other than 21 cm, such as CO, CII and Ly-α can provide new insights into the epoch of reionization.
- Cross-correlation with the 21 cm signal will help remove contaminants (and confirm the detection!) and improve our understanding of the connection between galaxy properties and the IGM
- **CO line**: Probe of cold gas. Low foreground contamination but hard to measure.
- **CII line**: Connected to SFR during reionization. Contaminated by CO but possible to measure with small instrument (< 10% masking). **Possibly our best bet from the ground.**
- **Lya line**: Dominated by recombinations in galaxies. Connect directly to UV emission budget during reionisation. Contaminated by Ha, OII, OIII. Possible to measure with small NIR space mission (~ 3% masking) - see SPHEREx…