Far-IR fine-structure-line tomography of the epoch of reionization

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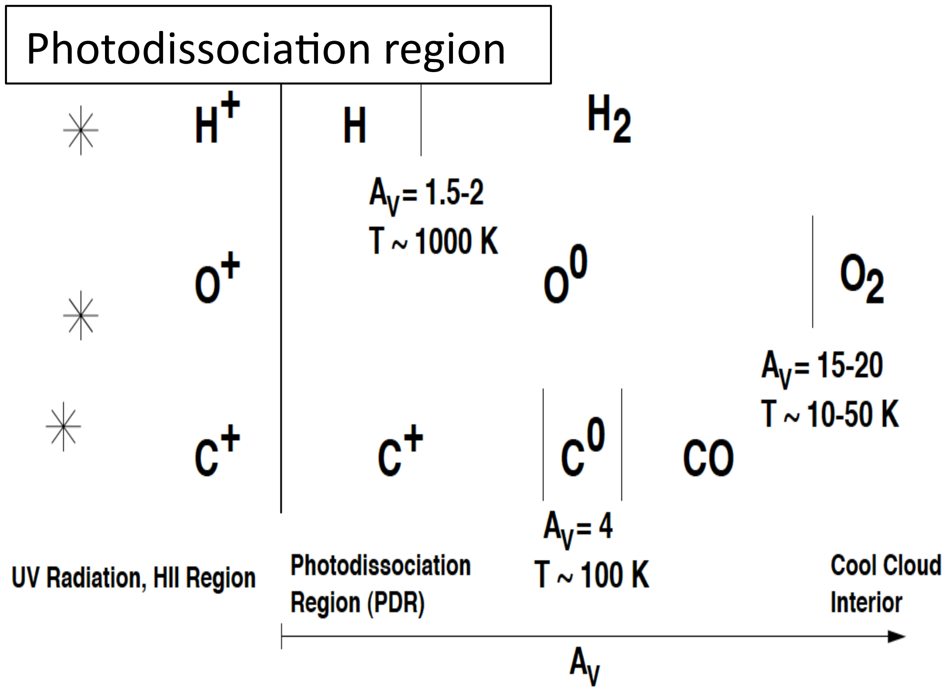
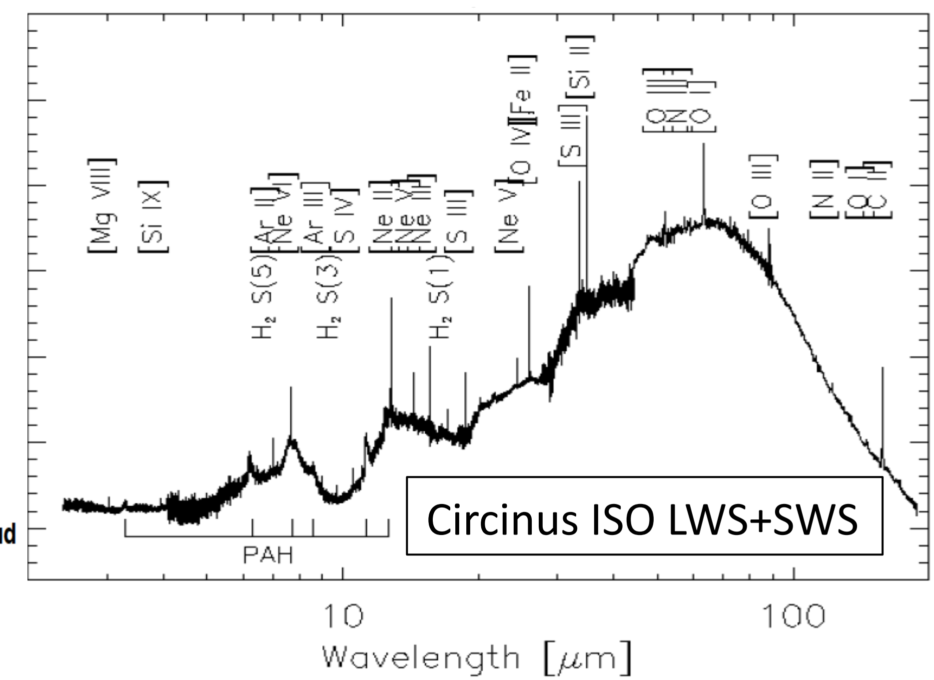
KISS 1st Billion Years Workshop

- C+ astrophysics and radiometry
- C+ mean intensity and power spectra -> Y. Gong, A. Cooray et al. calculation
- Approaches to a millimeter-wave C+ mapper
- Prospects for other fine-structure lines from space

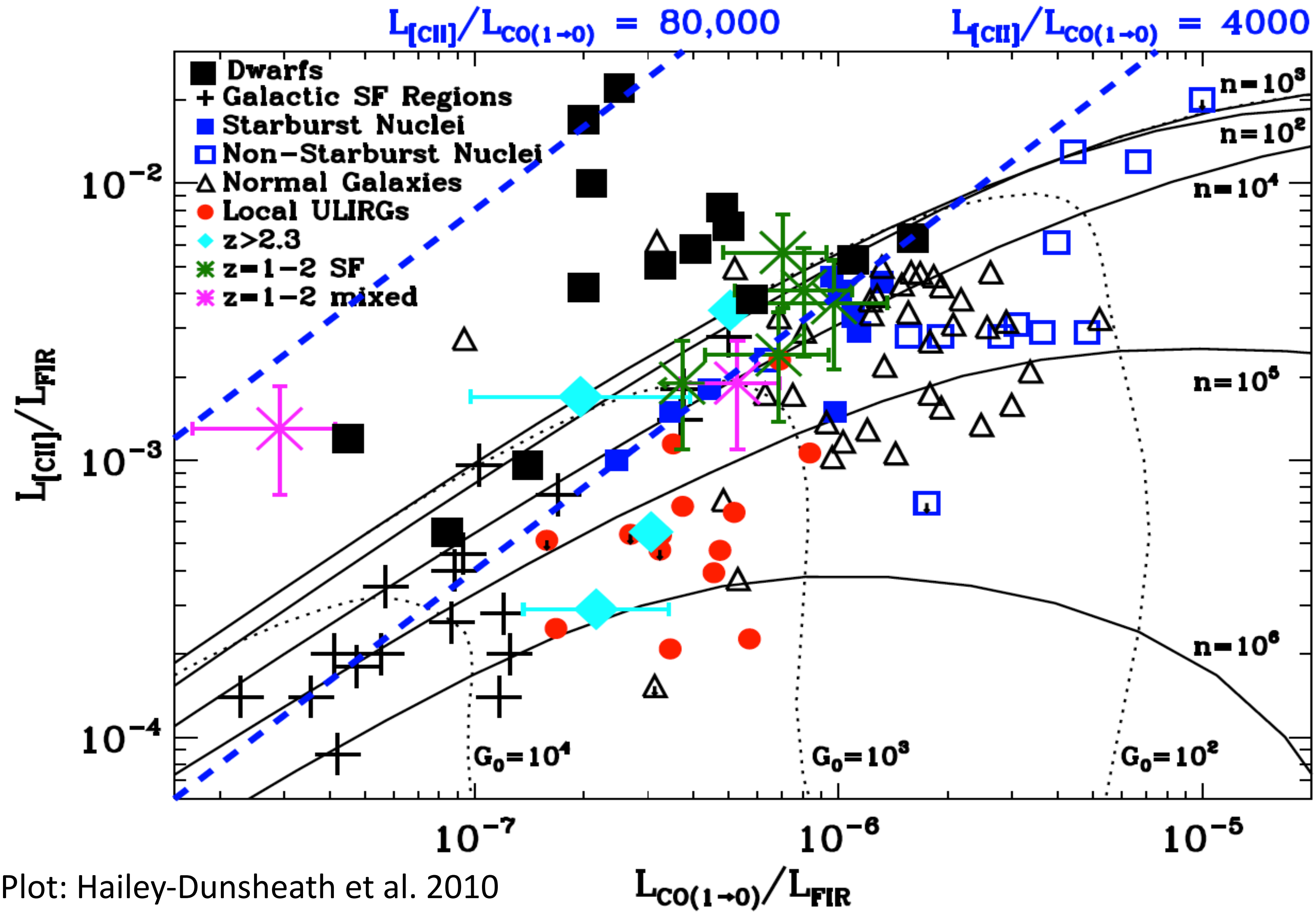
C+ and fine-structure lines in galaxies





- C+ ionization potential 11.6 eV, so it exists in neutral gas where much of the energy is input into the interstellar medium.
  - Easily thermalized with a critical density of 3e3 H_2 cm^{-3} or ~50 e^- cm^{-3}
  - Dense photo-dissociation regions: regions, C-ionizing photon density is set by dust extinction
    - C+ carries a large fraction of the gas cooling (30-50%, (of the 1% of the total))
  - Among the most luminous spectral line in the spectra of galaxies.
    - -> less dust to gas means more C+.
- Also traces diffuse ionized gas.

C+ / CO 1-0 in galaxies



Plot: Hailey-Dunsheath et al. 2010

Madden et al, 2011: Dwarf galaxies added

C+ / CO radiometry comparison

- For typical galaxies, C+ has antenna temperature which is at least 0.4 x that of CO 1-0, 2-1
  - C+ luminosity is conservatively 1600 times higher than 1-0. $L \sim T \times \nu^3$.
  - Low-luminosity, low metallicity systems have higher C+ / CO by 3-10x. Dust extinction is less important, allows more gas to be photo-dissociated.
- Bolometer spectrometer at 250 GHz will have NET of 0.8 to 2.5 mK $sec^{1/2}$ per R=600 bin
- Scaling from 1 uK in CO (per the report, Carilli, Gong et al.), detecting 0.4 uK in C+ requires 1000 to 10,000 hours.
- An instrument with 10-20k detectors deployed in a combination of spectral and spatial multiplexing is tractable now, even larger arrays are on the horizon.
- Results in a detection in a few-thousand hour experiment.

C+ mean intensity calculations Gong et al.

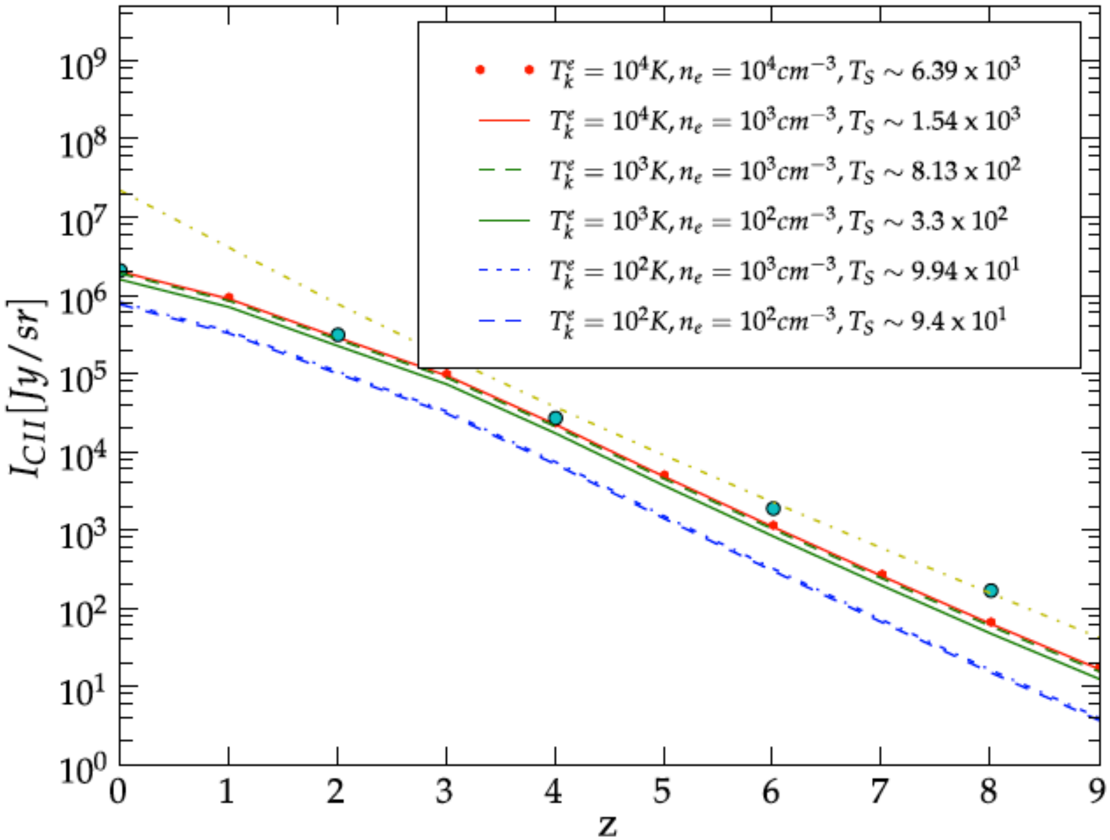
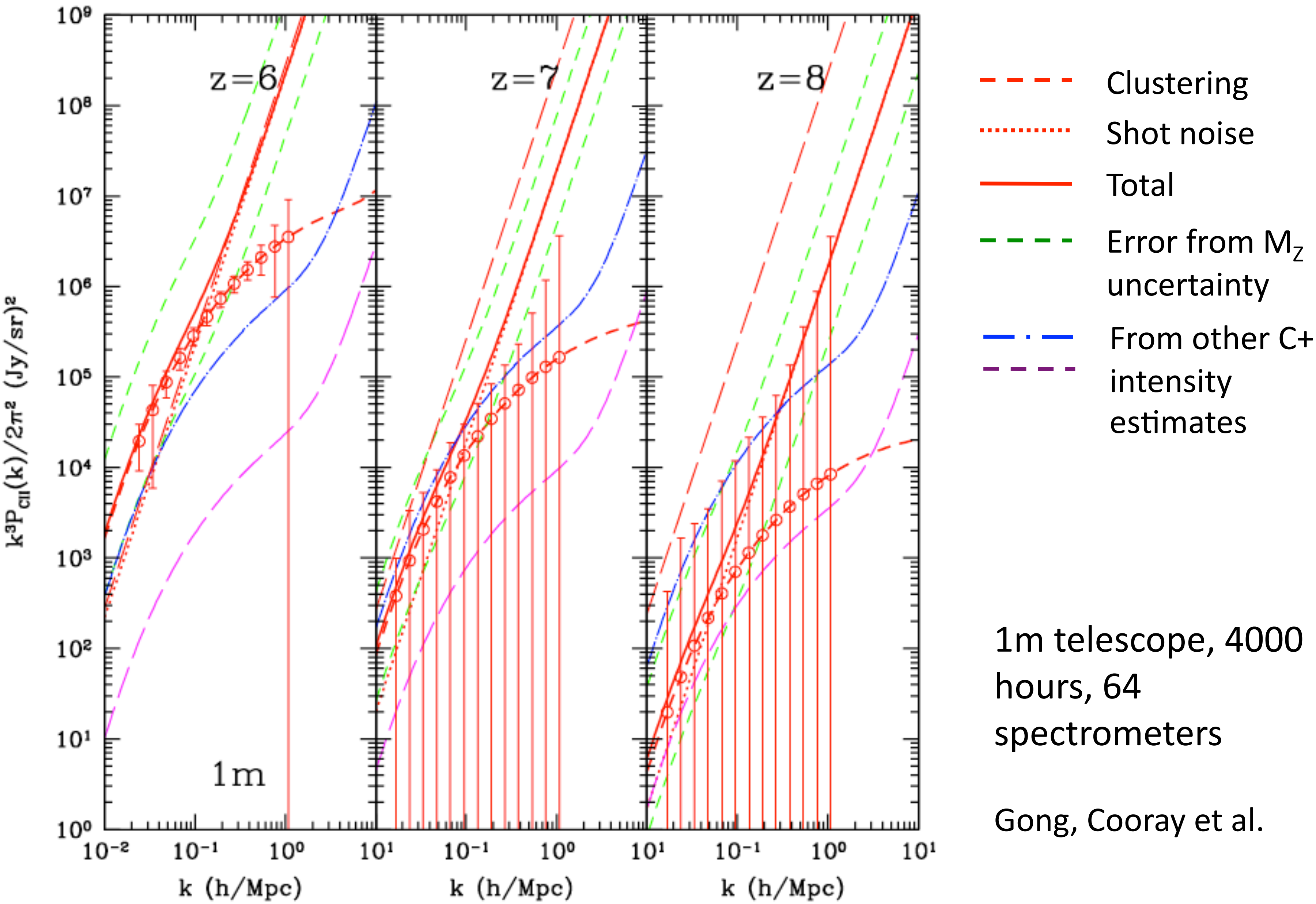


FIG. 7.— The mean intensity of CII emission line from the outputs obtained from the De Lucia & Blaizot (2007) simulation at several different redshifts. The yellow dotted line is our analytic result, and the blue spots are obtained from the simulation with the hot and warm gas contributing to the $L_{\rm CII}$. The yellow line and the blue spot were calculated with $n_{\rm e} = 10^3$ cm^{-3} and $T_{\rm k}^{\rm e} = 10^4$ K. The other lines are derived from the simulation assuming only the hot gas contributes to the $L_{\rm CII}$.

- Analytic, via first principals
  - $Z/Z_{solar} = 10^{-0.5z}$
  - 30% of gas in galaxies is above critical density.
- Via simulation using semi-analytic models of galaxy formation
  - Assumptions about which components contribute to C+
- Matches scaling from star formation history and C+ at 1e-3 to 1e-2 of total co-moving luminosity density.

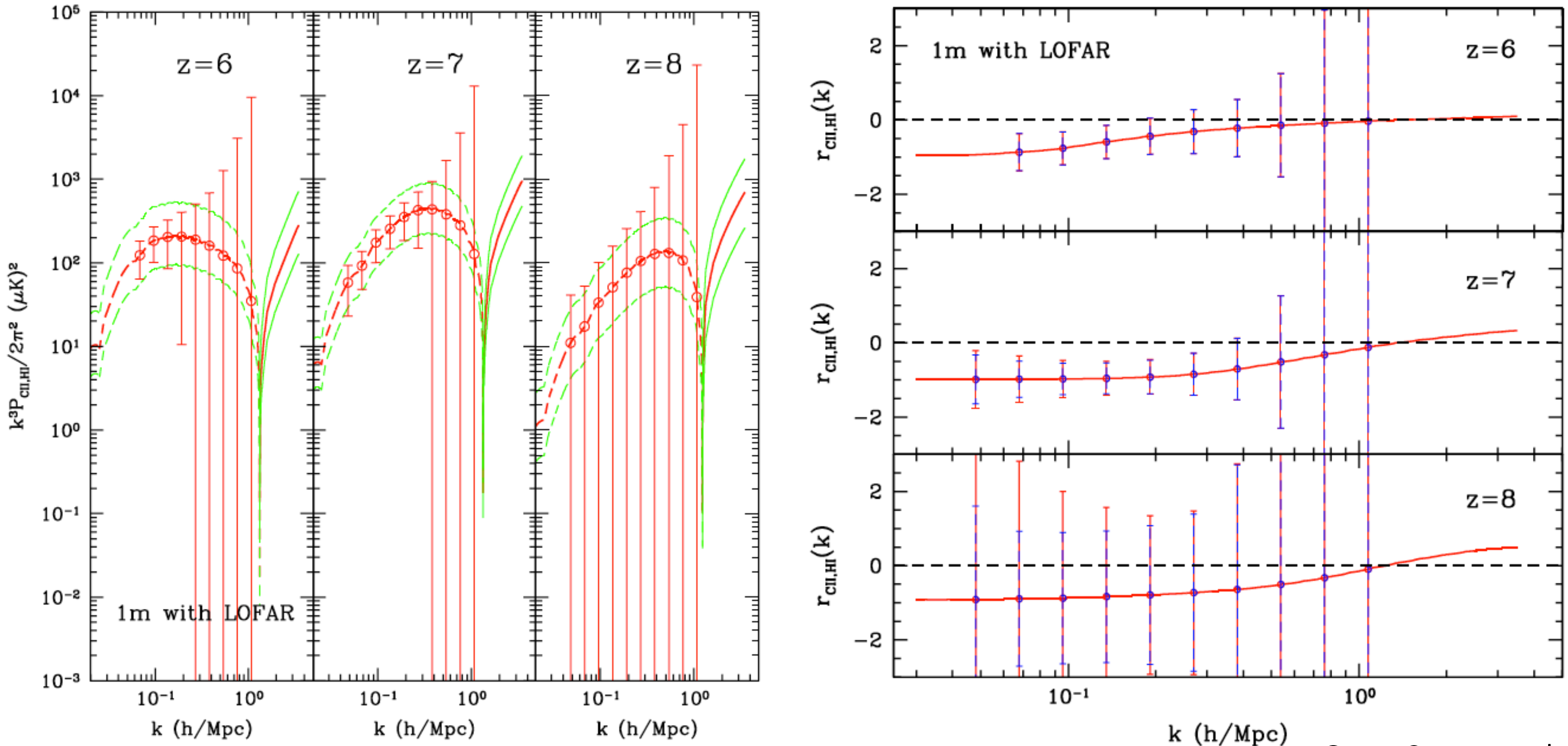
C+ power spectra



1m telescope, 4000 hours, 64 spectrometers

Gong, Cooray et al.

C+ / 21 cm cross spectra & correlation



Gong, Cooray et al.

- C+, 21 cm anticorrelated on large scales (matter density correlated with ionization fraction)
- Correlated on large scales where you average over multiple ionized bubbles
- Transition scale is a related to ionizing bubble size, requires ~10 m telescope at λ=1mm

C+ mapper instrument parameters

TABLE 1
EXPERIMENTAL PARAMETERS FOR A POSSIBLE CII MAPPING INSTRUMENT.

Aperture diameter (m)	1	3	10
Survey Area (deg^2)	16	16	16
Total integration time (hours)	4000	4000	4000
Free spectral range (GHz)	185–310	185–310	185–310
Freq. resolution (GHz)	0.4	0.4	0.4
Number of bolometers	20,000	20,000	20,000
Number of spectral channels	312	312	312
Number of spatial pixels	64	64	64
Beam size[a] (FWHM, arcmin)	4.4	1.5	0.4
Beams per survey area[a]	2.6×10^3	2.3×10^4	2.6×10^5
$\sigma_{\rm pix}$: Noise per detector sensitivity[a] (Jy$\sqrt{\rm s}$/sr)	2.5×10^6	2.5×10^6	2.5×10^6
$T_{\rm pix}$: Integration time per beam[a] (hours)	100	11	1.0
$z = 6$ $V_{\rm pix}$ (Mpc/h)^3	216.5	23.7	2.1
$z = 7$ $V_{\rm pix}$ (Mpc/h)^3	332.4	36.8	3.3
$z = 8$ $V_{\rm pix}$ (Mpc/h)^3	480.0	53.1	4.7
$z = 6$ $P_N^{\rm CII}$ (Jy/sr)^2 (Mpc/h)^3	3.7×10^9	3.7×10^9	3.6×10^9
$z = 7$ $P_N^{\rm CII}$ (Jy/sr)^2 (Mpc/h)^3	5.7×10^9	5.8×10^9	5.7×10^9
$z = 8$ $P_N^{\rm CII}$ (Jy/sr)^2 (Mpc/h)^3	8.3×10^9	8.4×10^9	8.1×10^9

[a] values computed at 238 GHz, corresponding to CII at $z = 7$.

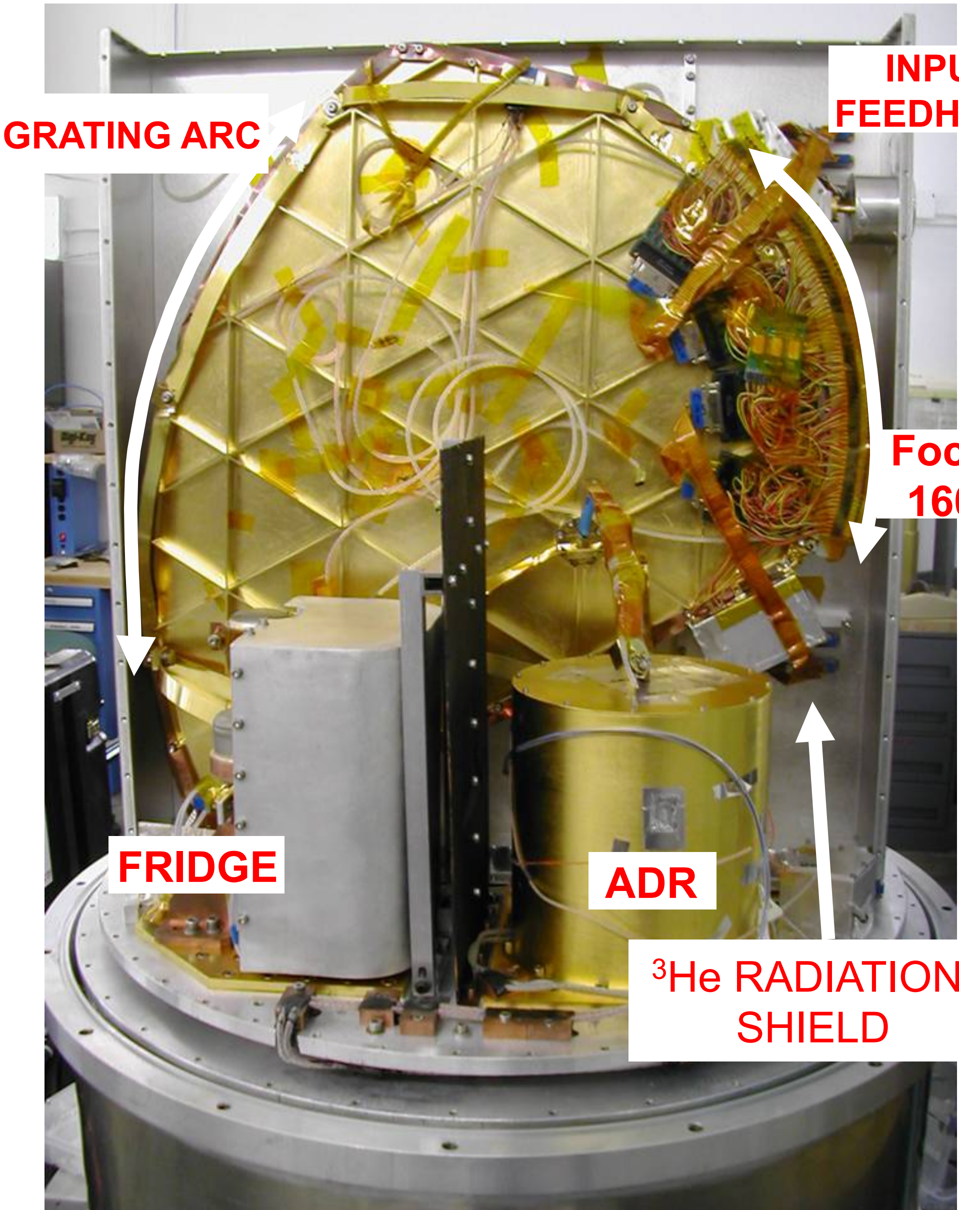
4.8 Mpc comoving at z=7

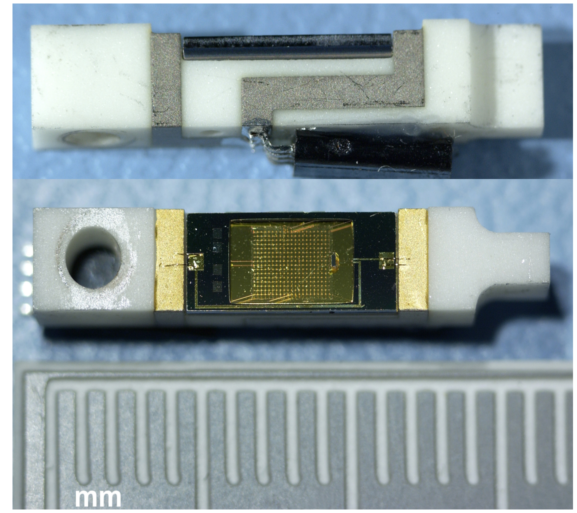
4.5 Mpc comoving at z=7

75 Mpc^3 comoving at z=7

- R=600 spectral bin well-matched to an ~arcminute angular scale.
- Large aperture (e.g. 10m or CCAT) does not improve sensitivity to mean intensity, but provides coverage to high l.
- 20 kilopixels a reasonable target.

Instrument approaches: Z-Spec, a proof of concept





Individually mounted SiN bolometers

<u>Z-Spec Team</u>

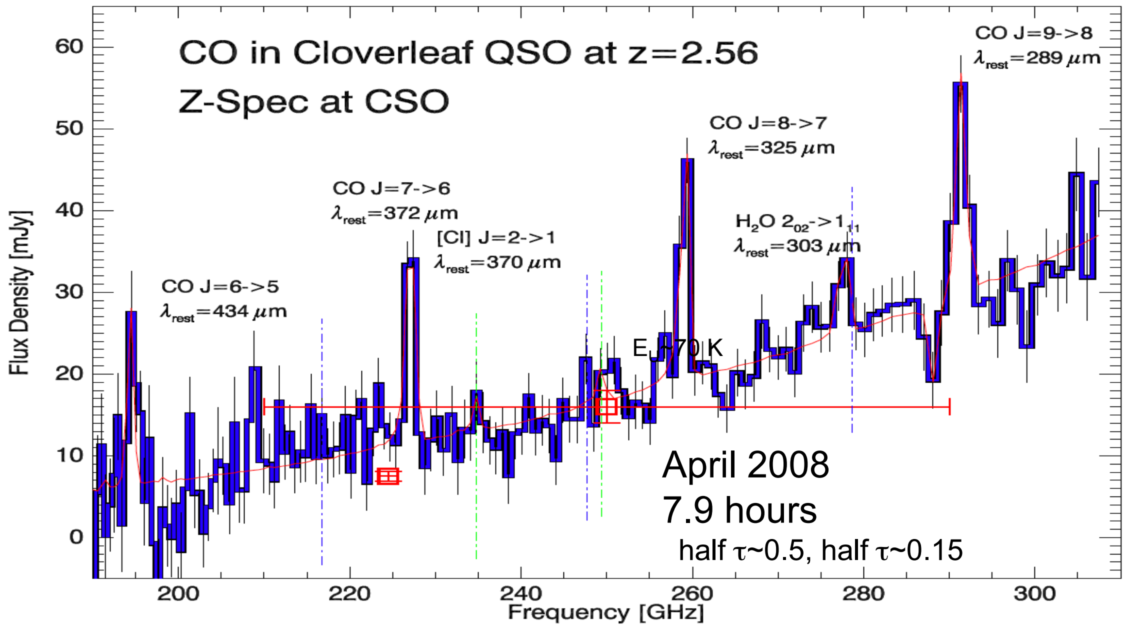
Matt Bradford, Jamie Bock, Hien Nguyen, Bret Naylor, Jonas Zmuidzinas (JPL & Caltech)

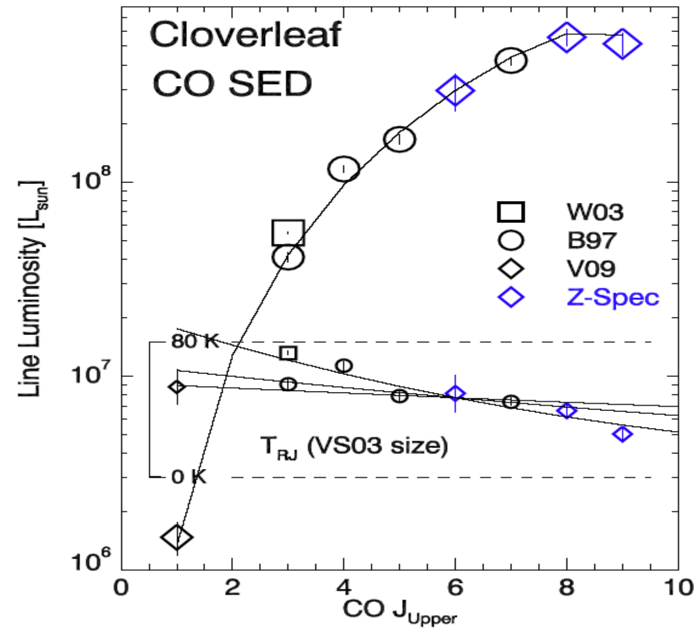
Jason Glenn, Lieko Earle, Phil Maloney (CASA, University of Colorado)

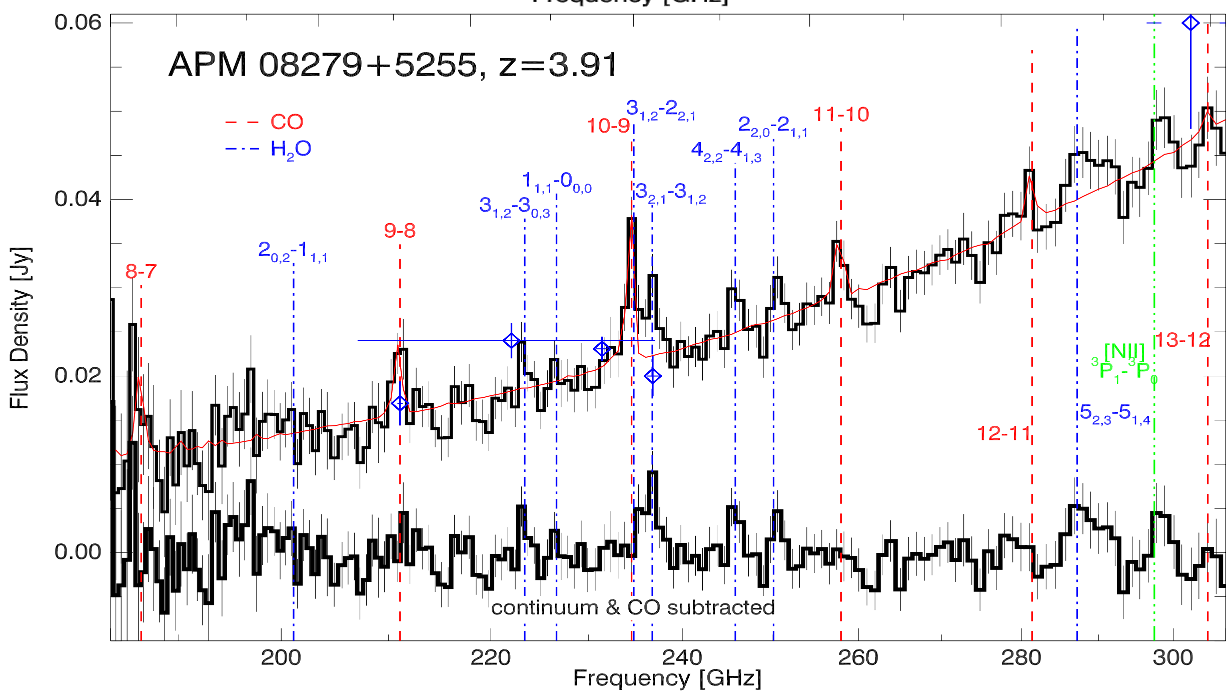
James Aguirre, Kim Scott, Roxanna Lupu (U. Penn)

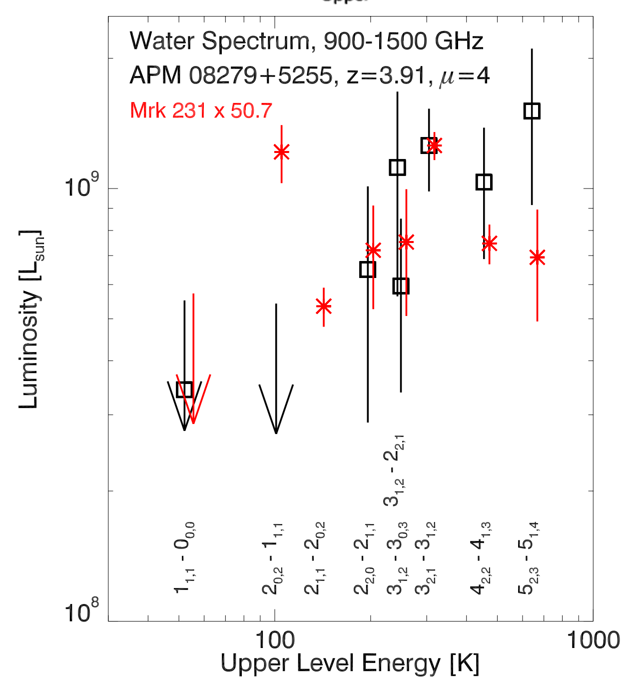
Hideo Matsuhara (ISAS / JAXA)

Z-Spec and bright quasars: high-z multiline studies

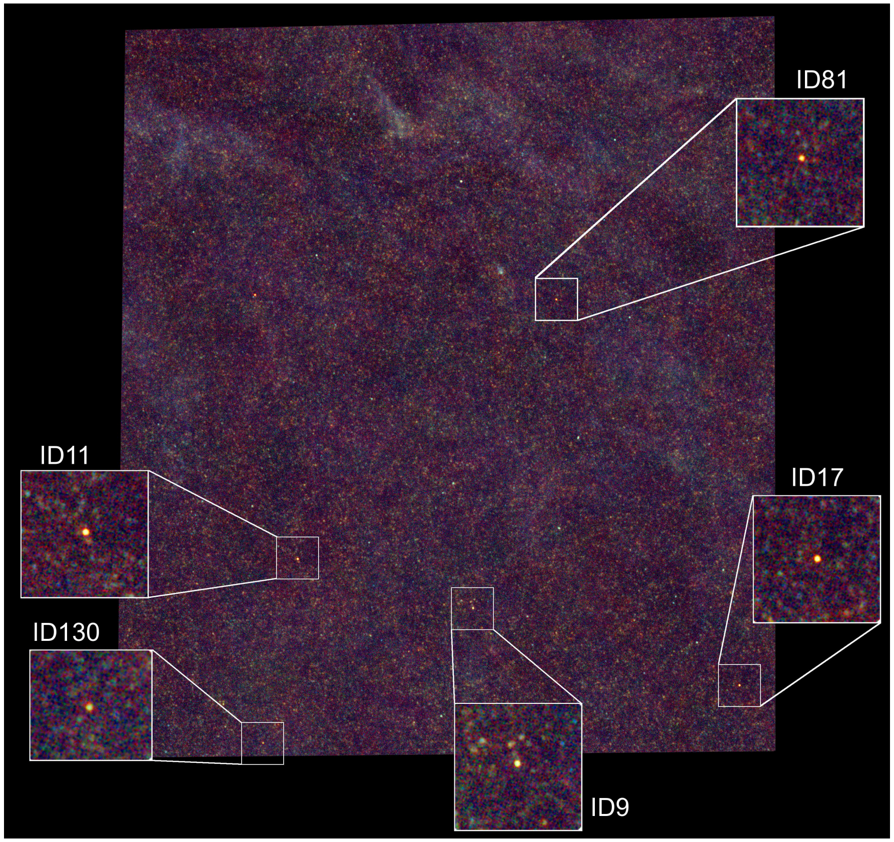


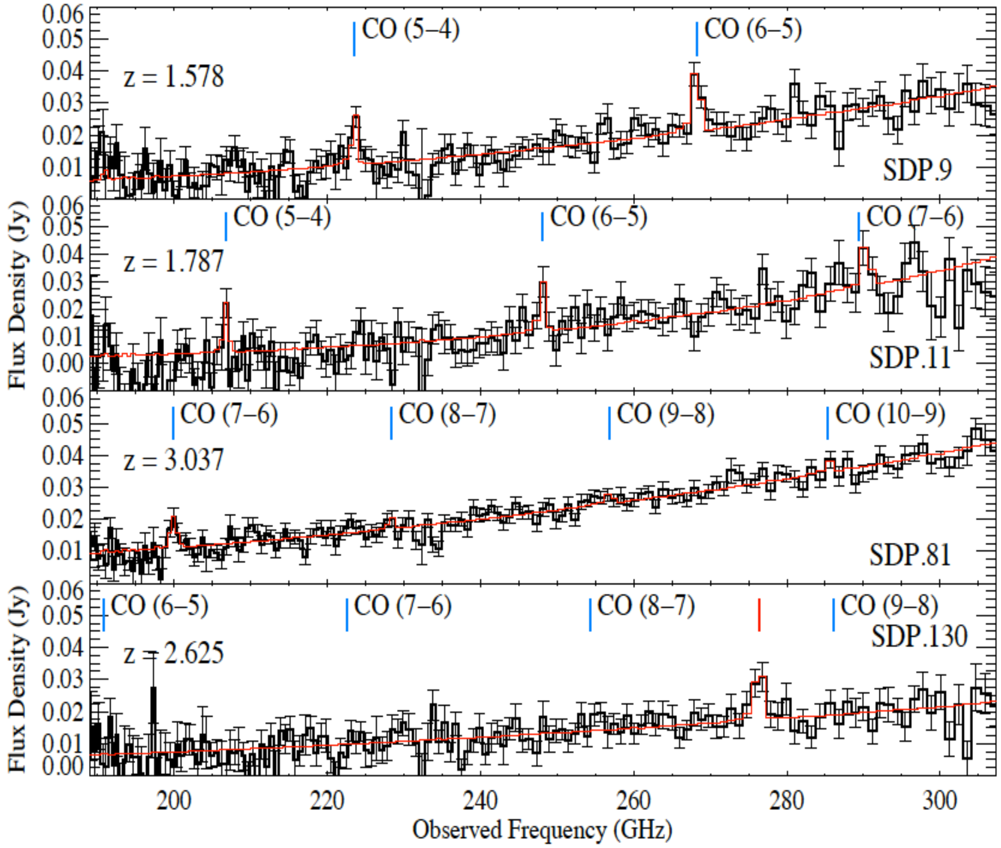






Herschel follow-up: early CO redshifts from the CSO

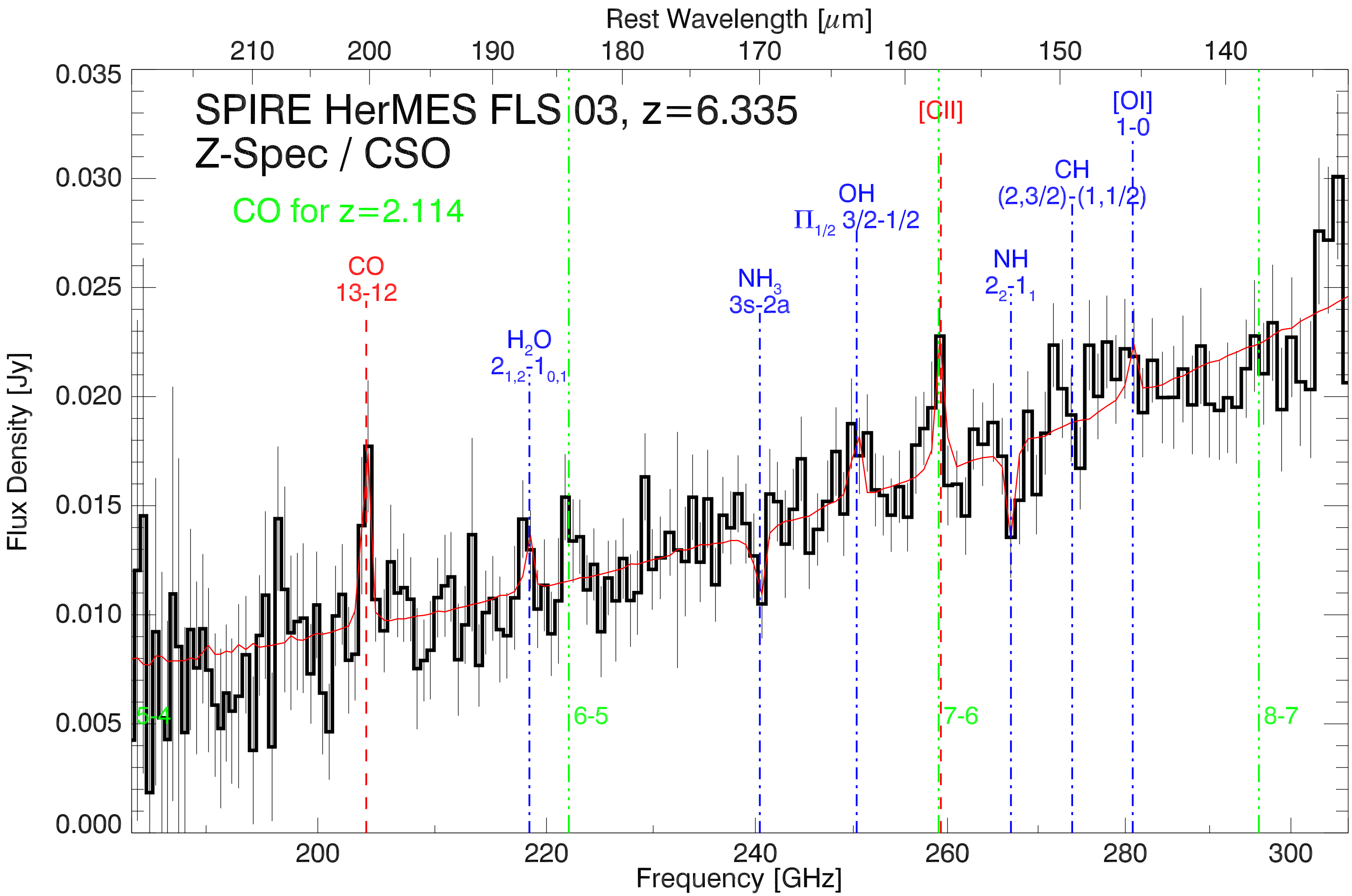




Negrello et al. 2010: Images from the H-Atlas SPIRE 3-color survey. The bright sources appear to be lensed far-IR bright galaxies.

Lupu et al., 2011. Z-Spec / CSO spectra of these sources, measuring redshifts with CO ladder, confirming high redshift thus lensing in these sources. Measurements made in spring 2010. CO excitation modeling shows that gas in these sources ≤ 100 K.
See also Scott et al., 2011.

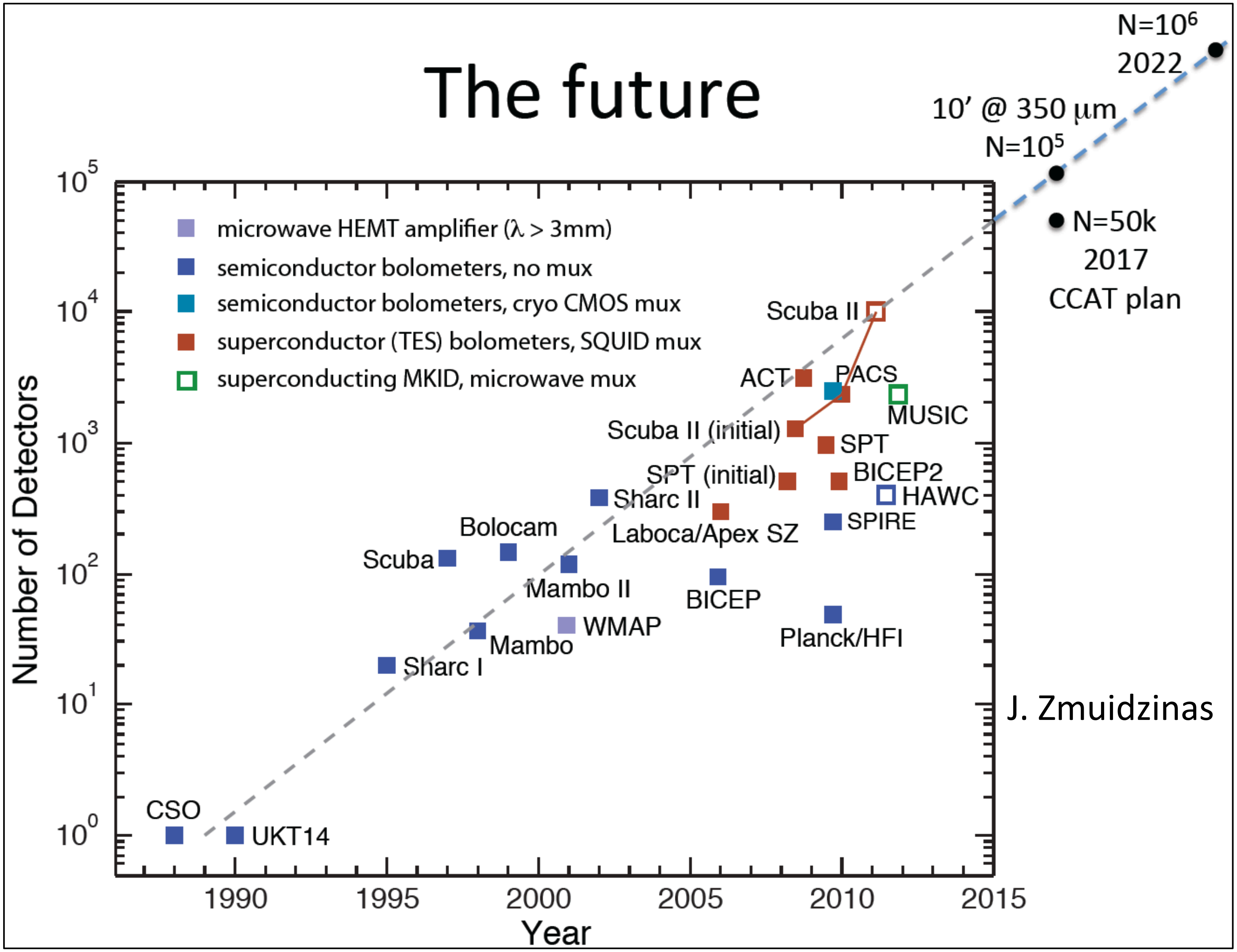
Z-Spec reaching z=6.3



Redshift discovered with CARMA

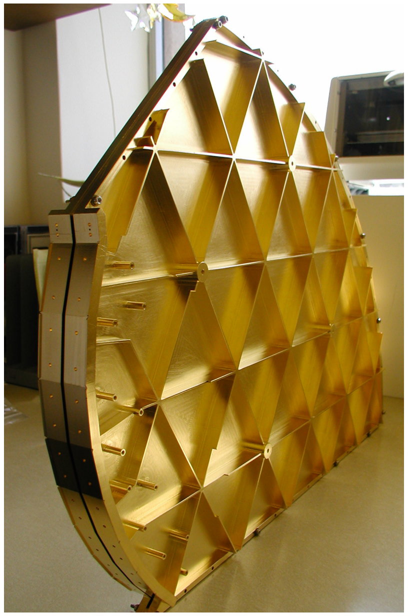
Joint paper in progress, Riechers et al.

Growth in mm direct detector formats

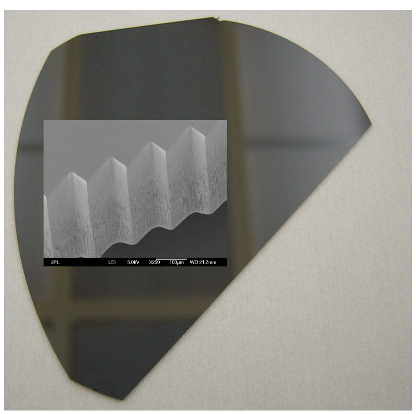


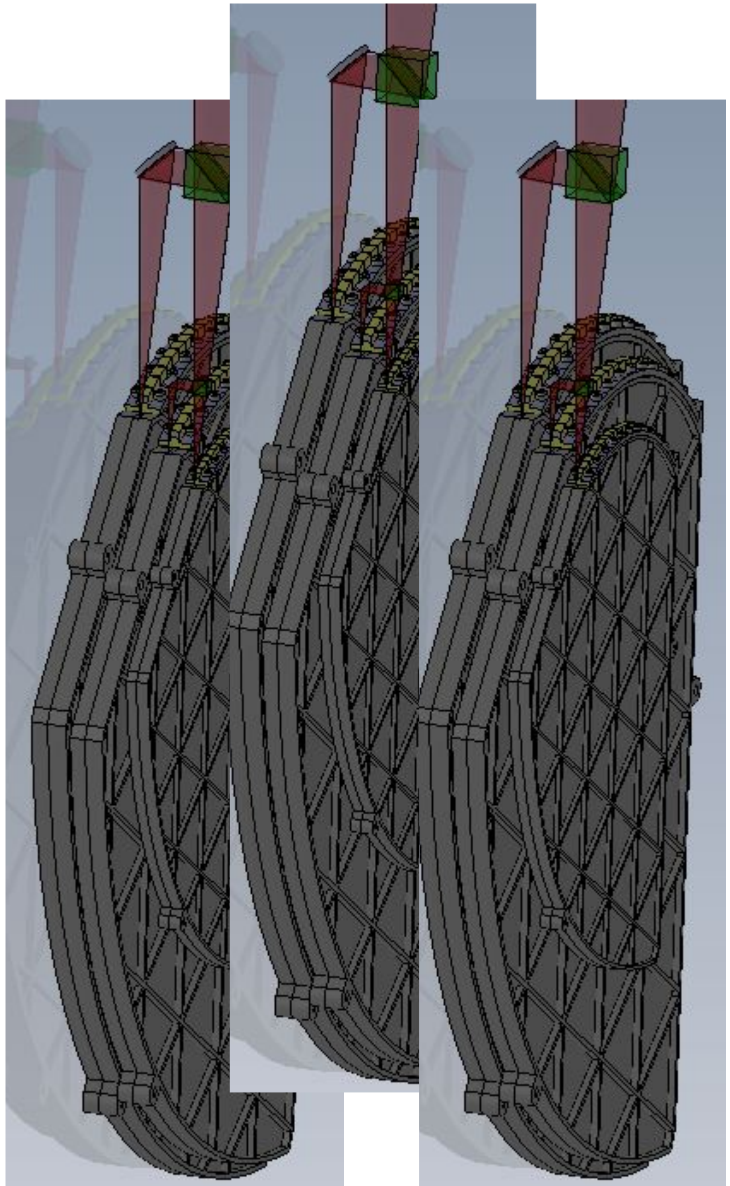
10^5 pixels in a decade, if we can afford them -> MKIDs offer low-cost multiplexing

Toward large-format spectrometers -> a simple approach



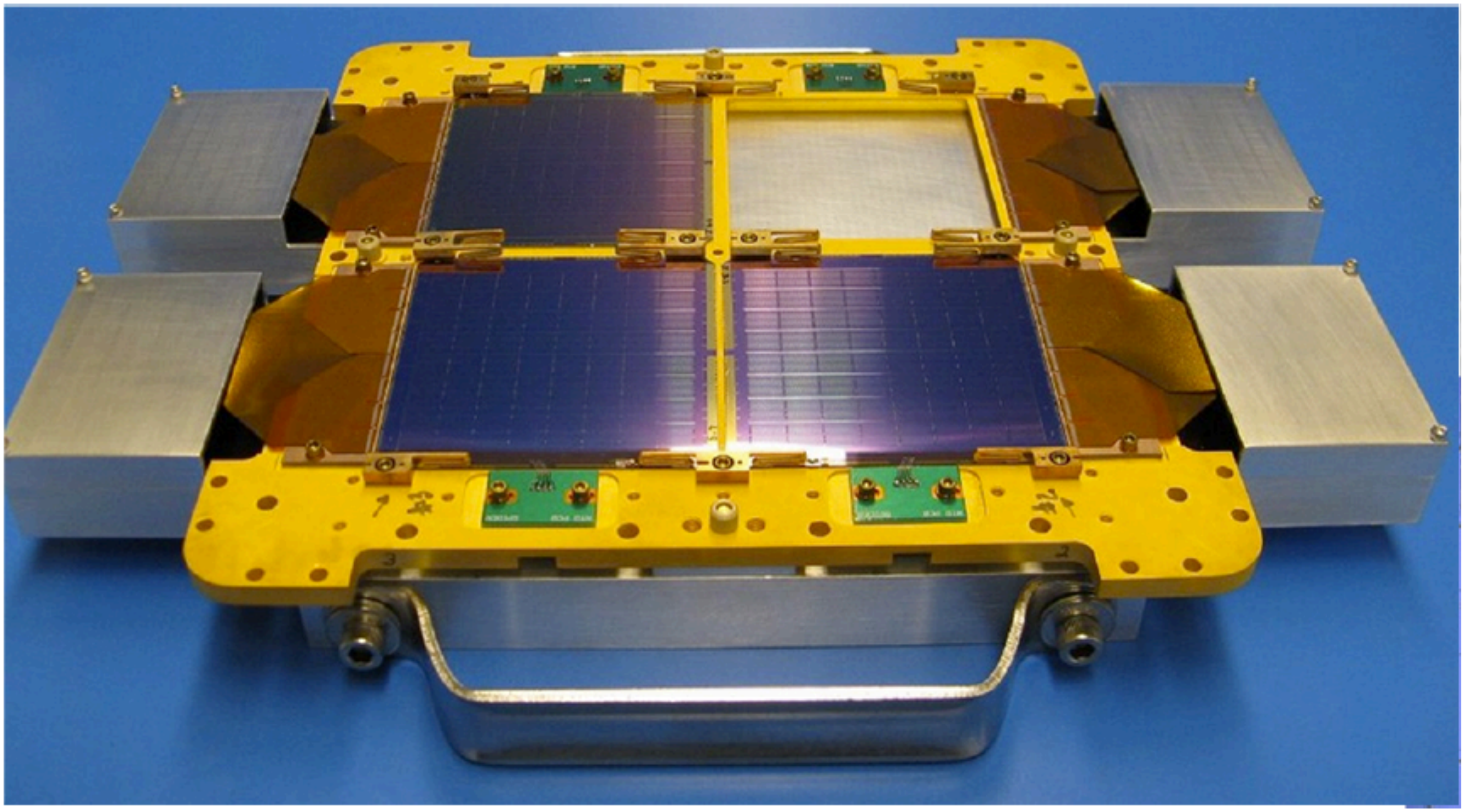
Silicon WaFIRS development.





- 3 Bands per beam, each a WaFIRS module with matched horns & detectors.
- All couple instantaneously to a single point source -> use polarizer and dichroic filters.
- Cooled to 100 mK, detector NEP ranging from 2e-18 to 3e-17.
- ~1000 detectors per 3-band unit.
- R=700-1000,
- except 1 mm band: R=400-500 due to size limitation, can use second polarization with staggered channel spacing.
- Silicon devices coming!
- Size: 75 cm by 60 cm.
- Width ~5 cm, can stack 12-15.
- Array in ~2-D in the ~1m cryostat cryostat.
- Front end for CCA is set of warm quasioptical, elbowed-arm feed Seiffert / Goldsmith. (not require for reionization experiment).

Full 512-pixel array, similar to on sky now

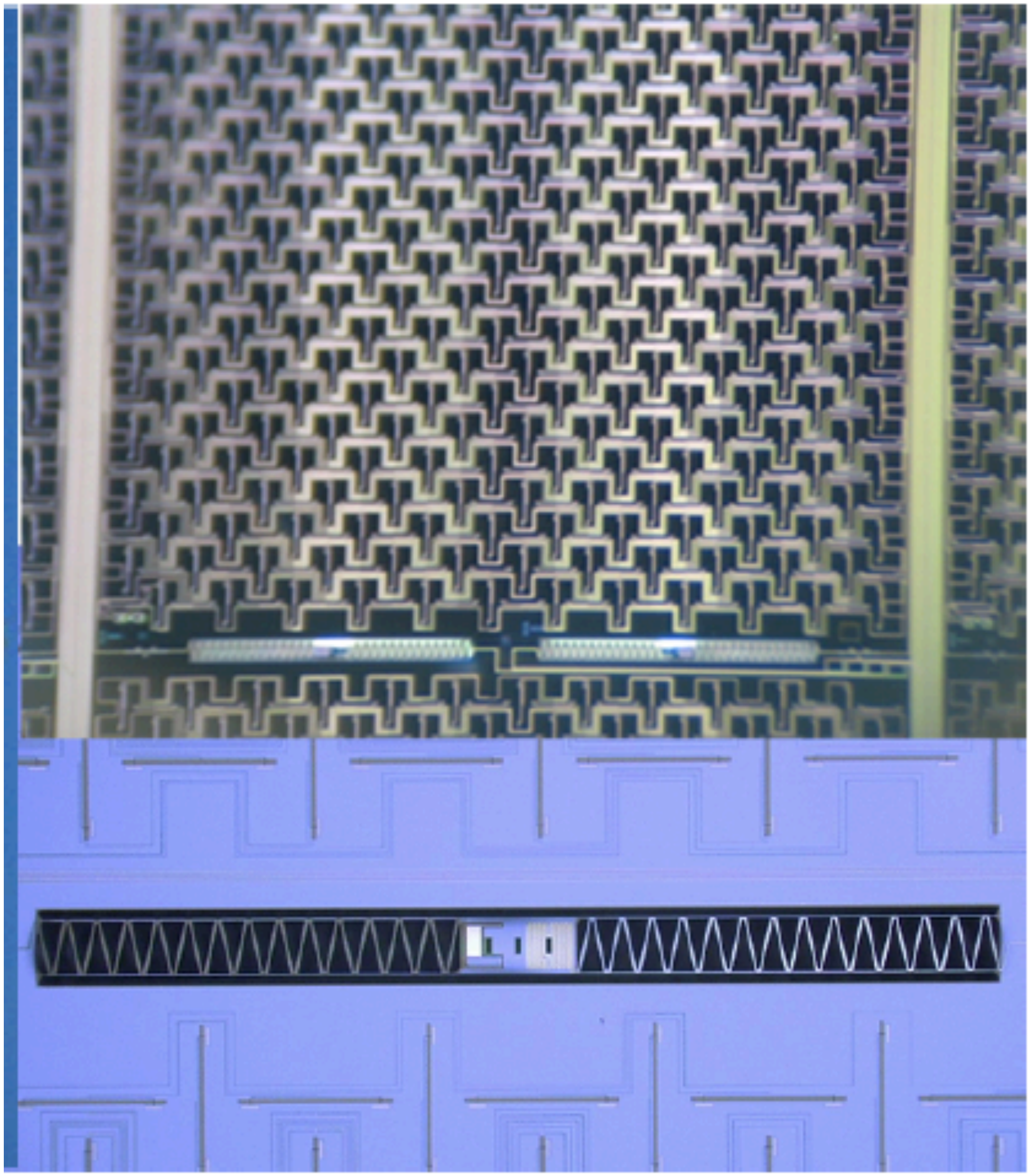


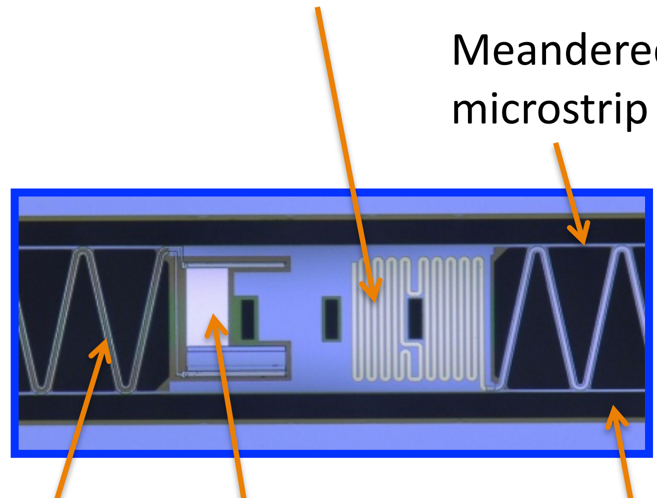
SPIDER, J. Bock et al.

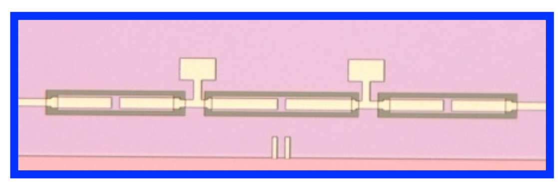
- 150 GHz focal plane, 4 wafers, 2x 64 pixels each.
- Each pixel has a phased array of 12 x 12 slots for both polarizations
- Microstrip combiner trees bring signal to two TESes on island
  - Each slot tapped at two positions

Antenna-coupled bolometer arrays

J. Bock et al.

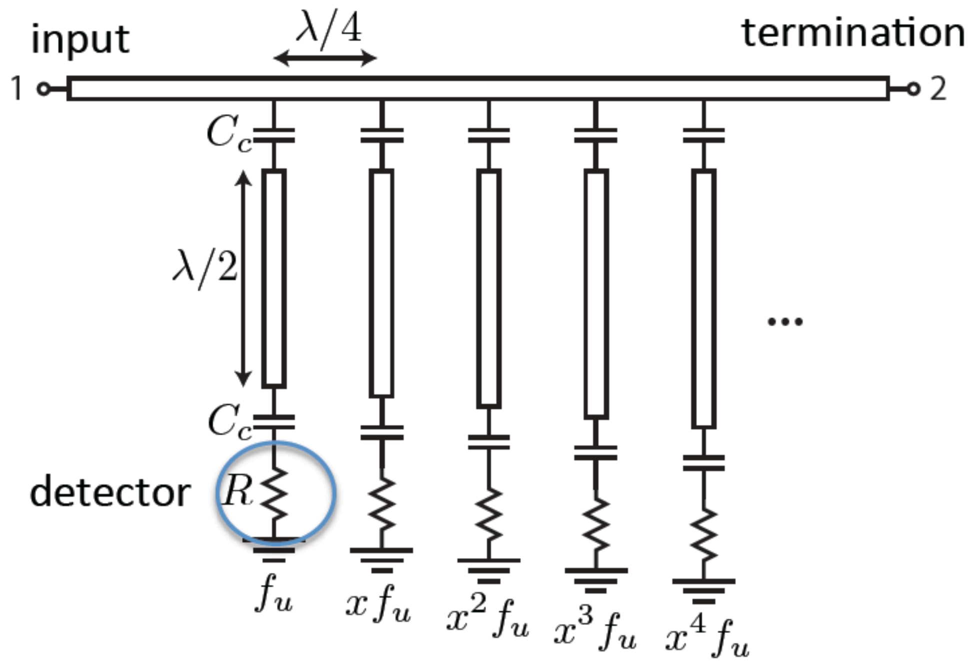


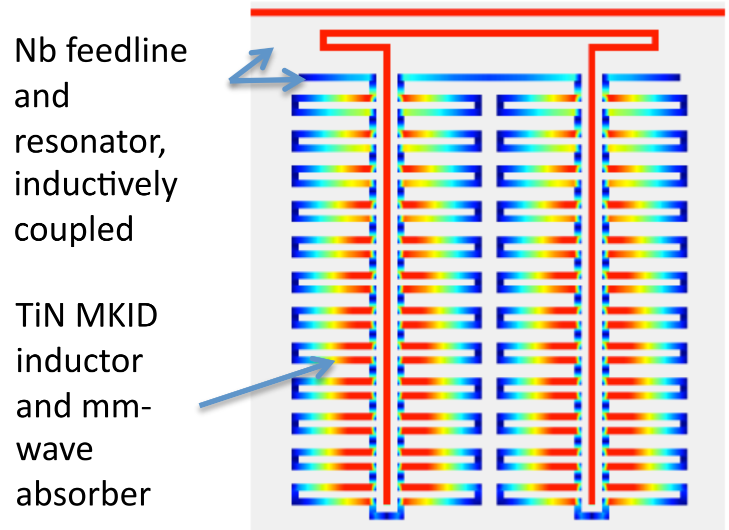


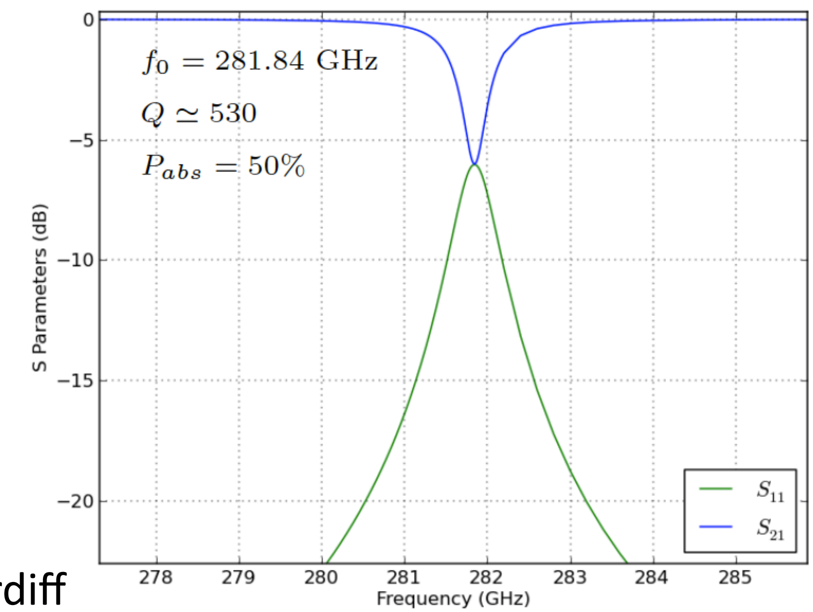


Toward large-format spectrometers

SuperSpec, a filter-band spectrometer in superconducting microstrip







Entire 190-300 GHz 500-channel spectrometer in a 1 cm chip!
Kovacs and Zmuidzinas 2010,
Paving the way to 1000-10,000 element spectrometer arrays!

P. Barry, P. Mauskopf, Cardiff

Reionization measurements from space

- Cold telescope has ~20 x lower NEP out to ~300 microns than at 1 mm on the ground, so 400 times faster per beam for the same line luminosity.
- NeII 12.8 μm, SiII 34.3 μm ~1/3 of C+, FeII 26 μm may be important at low metallicity
- BLISS on SPICA could potentially take a stab at e.g. NeII, even with a small number of beams.
- A dedicated 100 –beam system on a small cold telescope could offer a dramatically better measurement than a few-kilo-pixel system the ground.