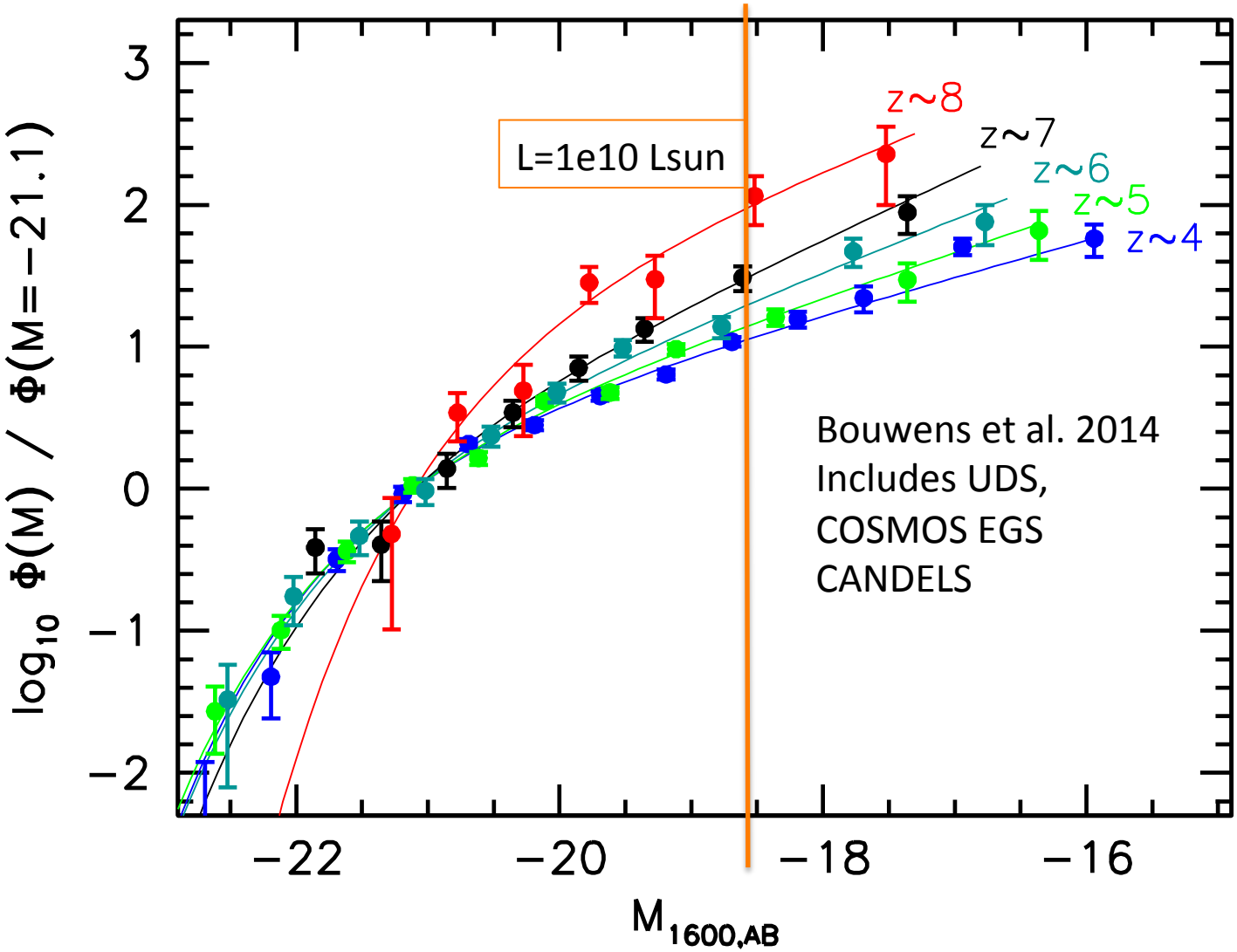
Probing the EoR with Tomographic Intensity Mapping in the Far-IR through Millimeter

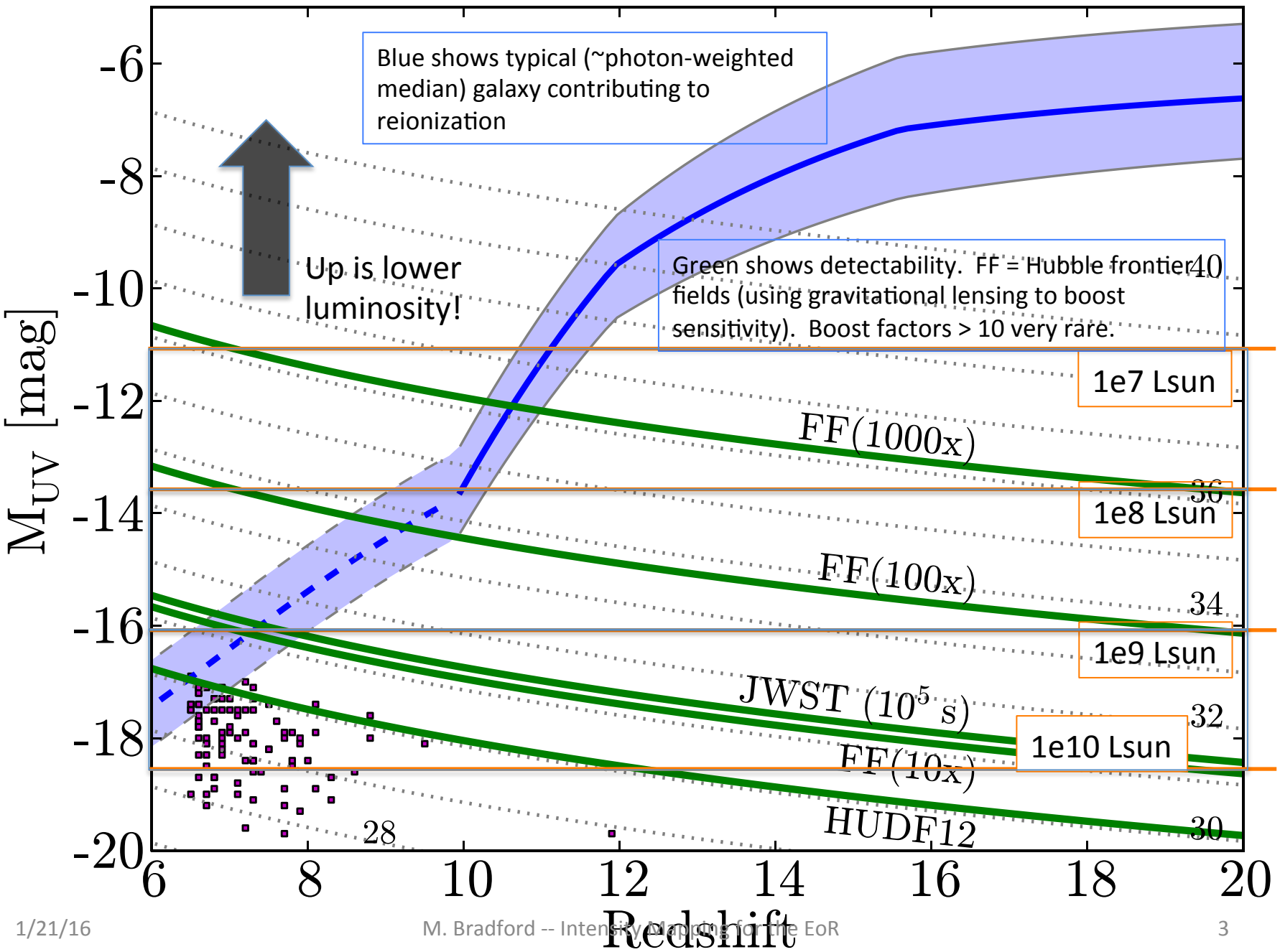
Matt Bradford

Typical EoR Photon Originates in a Faint Galaxy



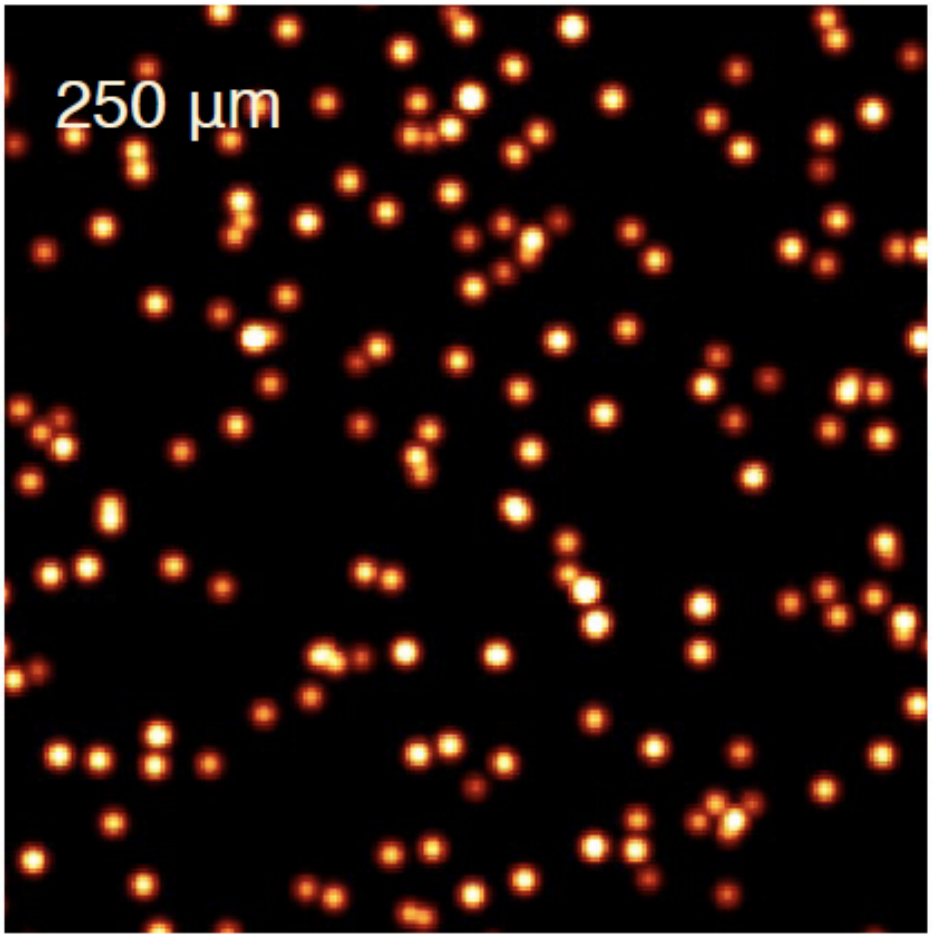
- Faint galaxies more important as we look back through reionization.
- The highest redshifts have divergent total light integrals.

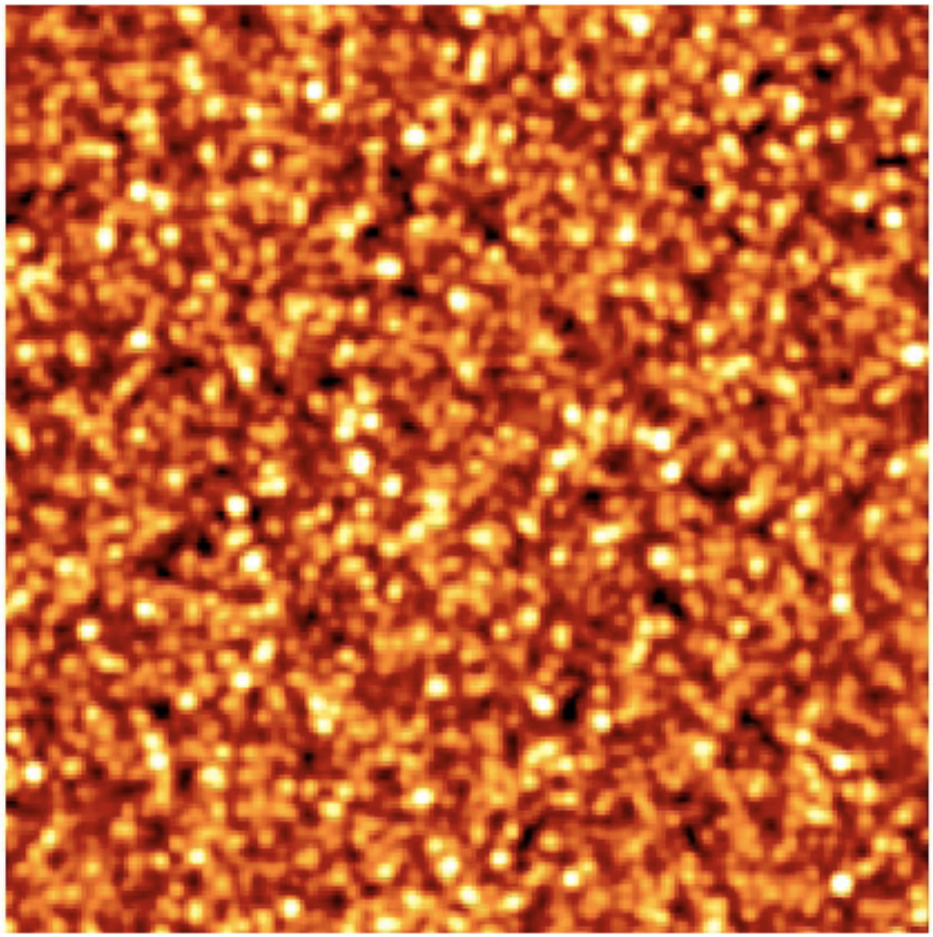
Example Reionization Galaxy Model – Wise et al., 2014



How to access the full population?

Measure clustering via maps, instead of discrete sources.

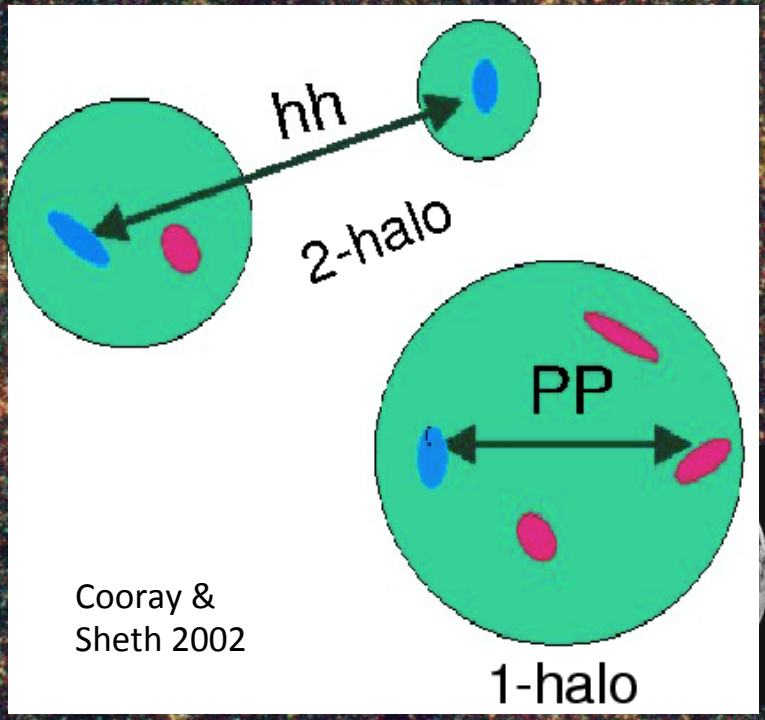




$S > 20$ mJy : 1,200/deg^2 $S < 20$ mJy : 480,000/deg^2

Intensity Mapping

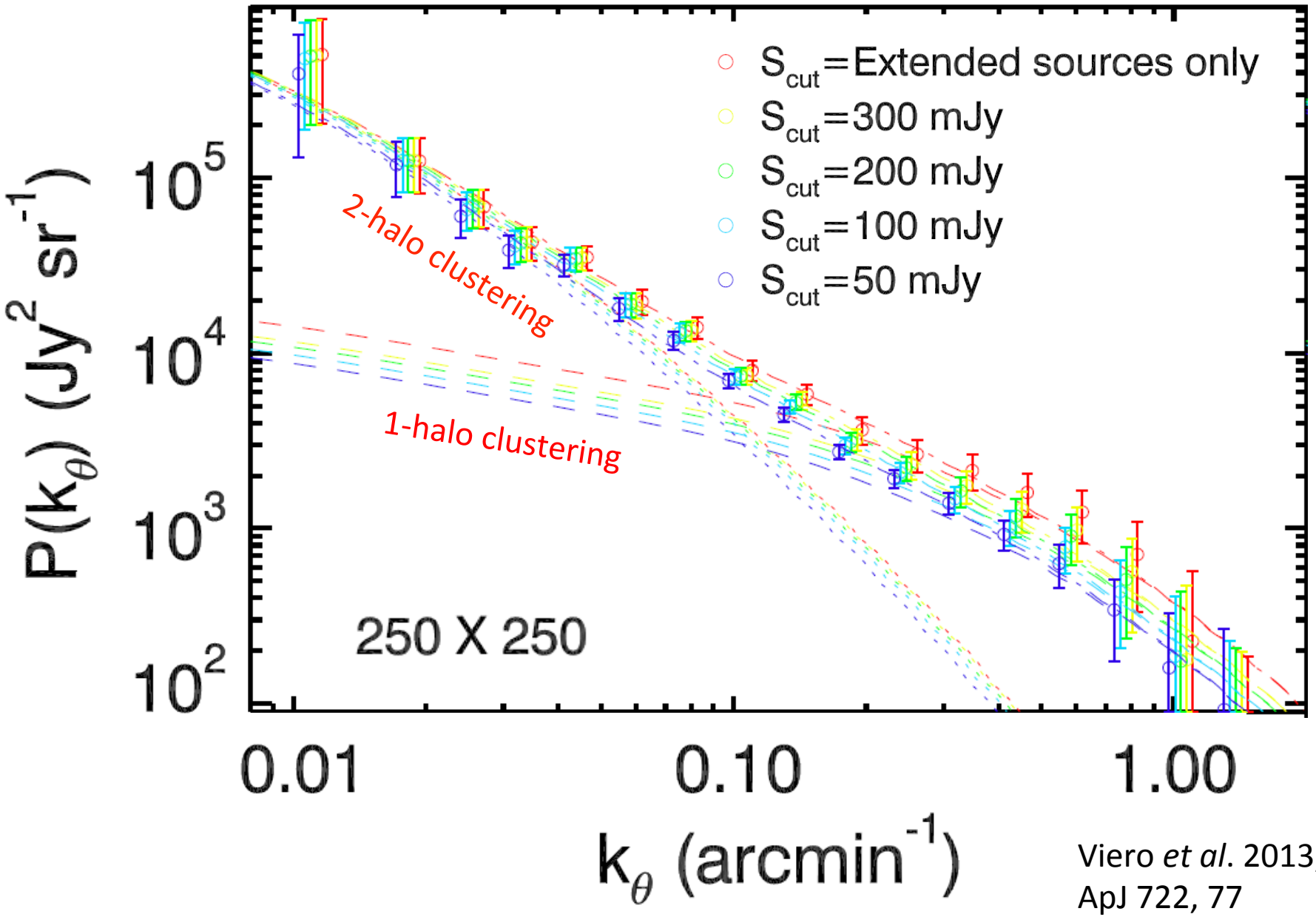
HerMES Lockman Survey Field with Herschel SPIRE: 250, 350, 500 microns



Cooray & Sheth 2002

3.6°

2-D Spatial Power Spectrum of Hershel SPIRE Maps



Viero *et al*. 2013, ApJ 722, 77

2-D Spatial Power Spectrum of Hershel SPIRE Maps

Fitting 2-D auto- and cross-spectra (under various depth flux cuts) to halo models

Table 5
Model 2: Best-fit Parameters and Corresponding Correlation Matrix

Parameter	$\log(M_{\rm min})$	$\log(M_{\rm peak})$	T	T_z	β	$\sigma^2_{L/m}$	$\log(L_0)$	η
$\log(M_{\rm min})$	10.1 ± 0.5	-0.02	0.20	-0.27	-0.10	0.02	0.26	-0.25
$\log(M_{\rm peak})$	...	12.3 ± 0.5	0.21	-0.01	-0.23	-1.00	-0.18	0.20
T	...	...	20.7 ± 1.2	-0.66	-0.92	-0.21	0.76	-0.56
T_z	...	...	...	0.2 ± 0.0	0.38	0.01	-0.81	0.89
β	...	...	...	...	1.6 ± 0.1	0.23	-0.53	0.31
$\sigma^2_{L/m}$	...	...	...	...	...	0.3 ± 0.0	0.18	-0.20
$\log(L_0)$	...	...	...	...	...	...	-1.8 ± 0.1	-0.90
η	...	...	...	...	...	...	...	2.4 ± 0.1

SED parameters

L-M relation

z-evol.

Find:
Minimum halo mass to support star formation: Log ~ 10.1
Halo mass of peak star formation efficiency: Log ~ 12.3
Some constraints on redshift evolution.

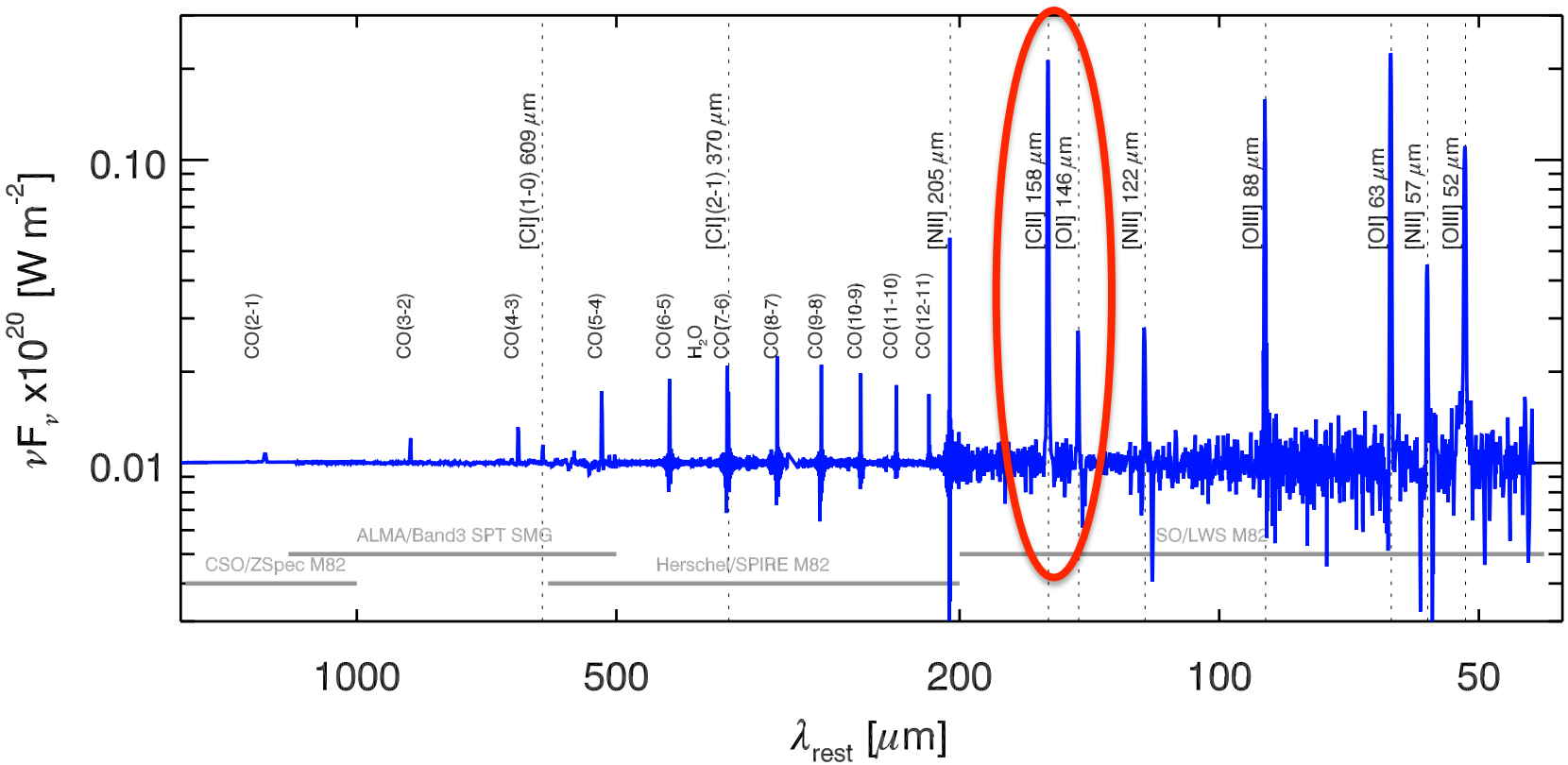
BUT:
2-D broad-band dataset averages over all redshifts: EOR signal buried by 'foregrounds'

Viero *et al*. 2013, ApJ 722, 77

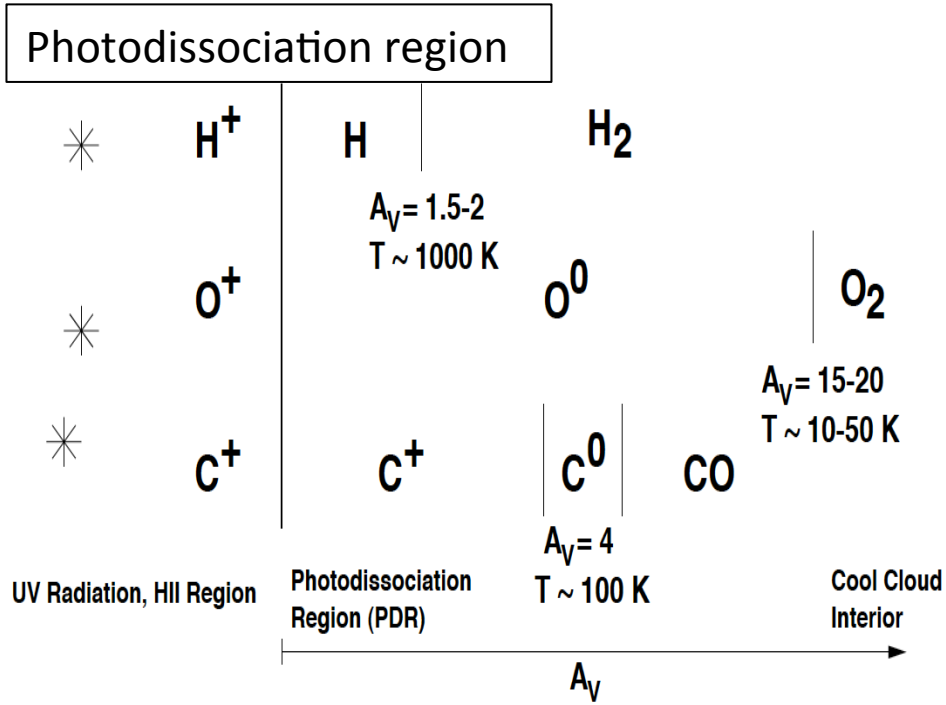
3-D Intensity Mapping of Spectral Lines

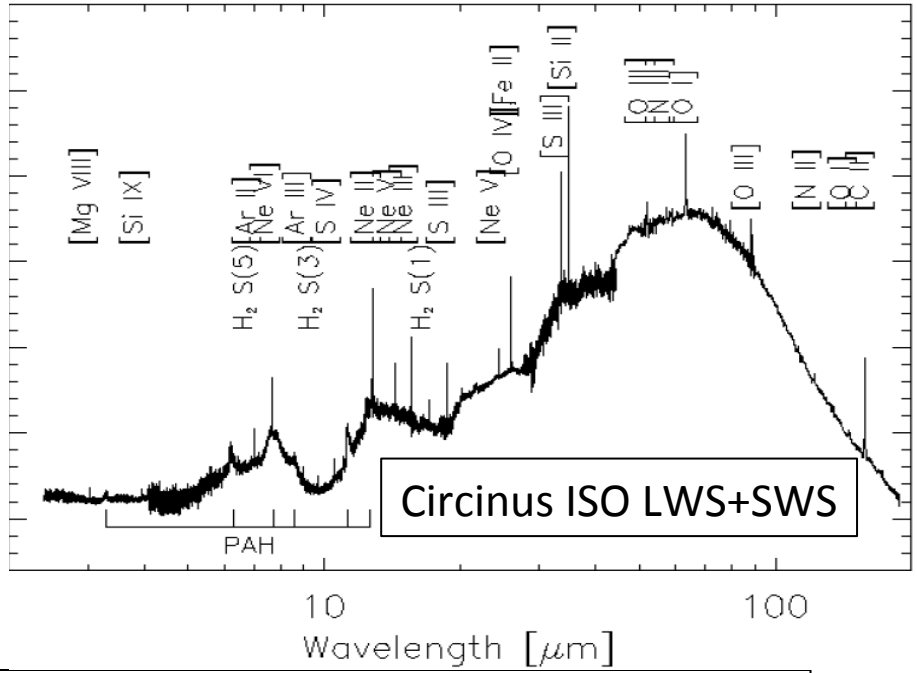
- Provides automatic redshift information.
- 3rd dimension adds additional modes to the dataset.
- Still carries sensitivity to the full population.
- Measurement is with a moderate-R, high-throughput spectrometer
- CII 158-micron fine-structure especially useful.

Continuum-subtracted far-IR to mm-wave spectrum of M82 – J. Vieira



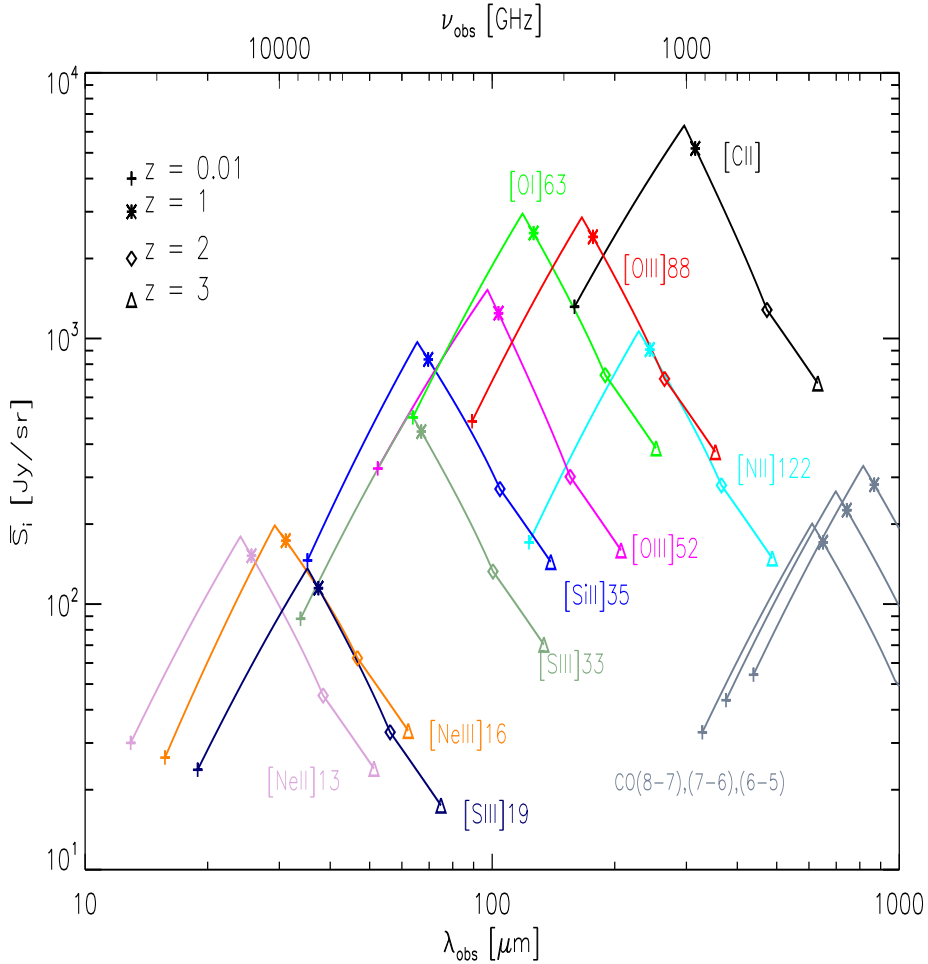
C+ and fine-structure lines in galaxies

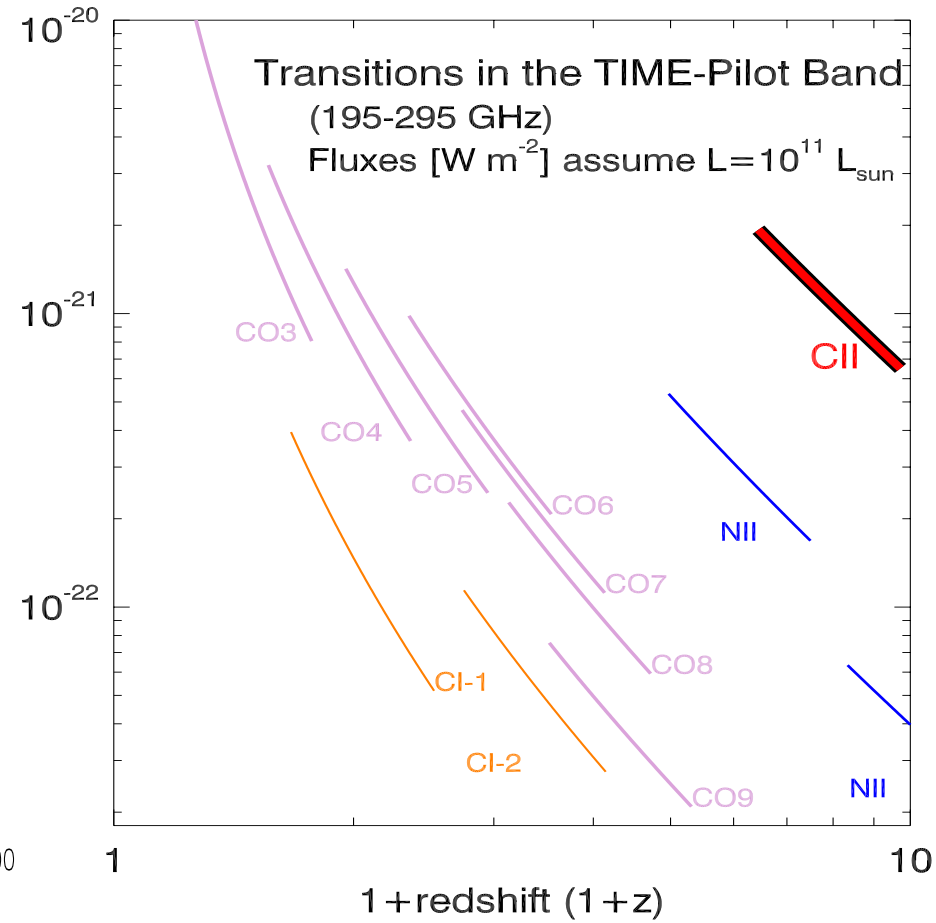




- C+ ionization potential 11.6 eV, so it exists in neutral gas where much of the energy is input into the interstellar medium.
  - Easily thermalized with a critical density of 3e3 H_2 cm^{-3} or ~50 e^- cm^{-3}
  - Dense photo-dissociation regions: regions, C-ionizing photon density is set by dust extinction
    - 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+ to far-IR
- Also traces diffuse ionized gas.

Spectral lines accessible for intensity mapping





Line Intensities at intermediate redshift. CII relatively isolated and bright for a given galaxy luminosity. Uzgil et al.

But CO from intermediate redshift galaxies an important source of variance because luminosity density is higher.

TIME-Pilot Collaboration

Caltech / JPL

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Jonathon Hunacek
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Patrick Koch
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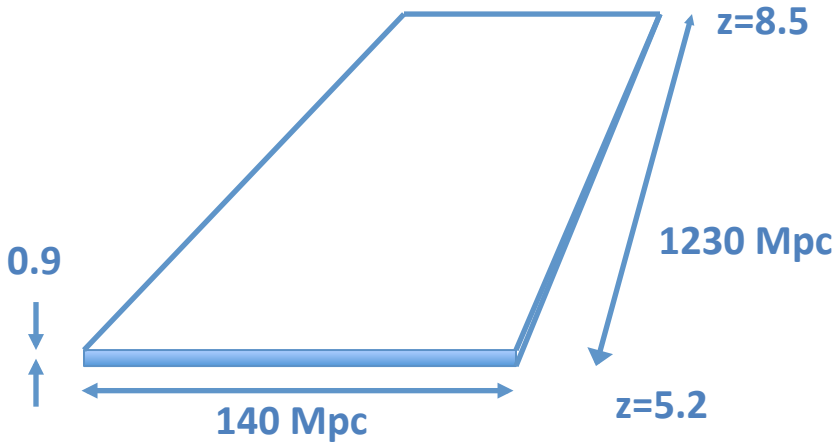
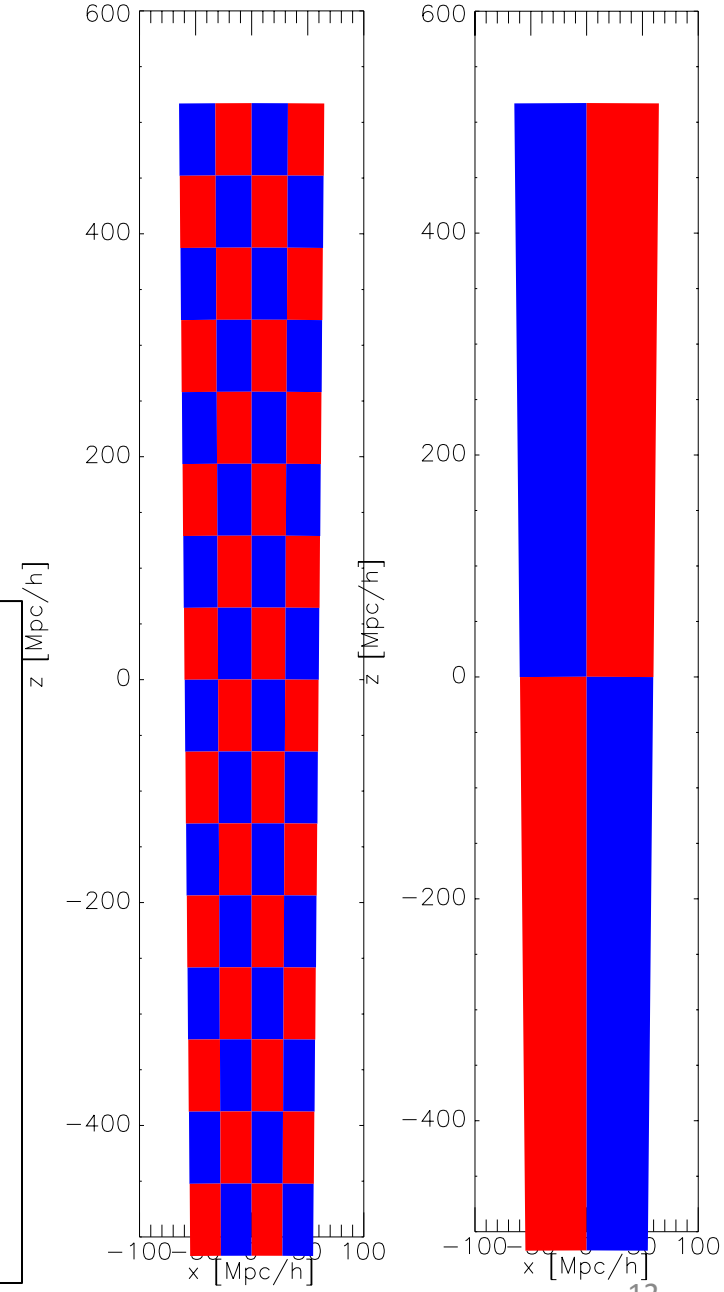
Yan Gong

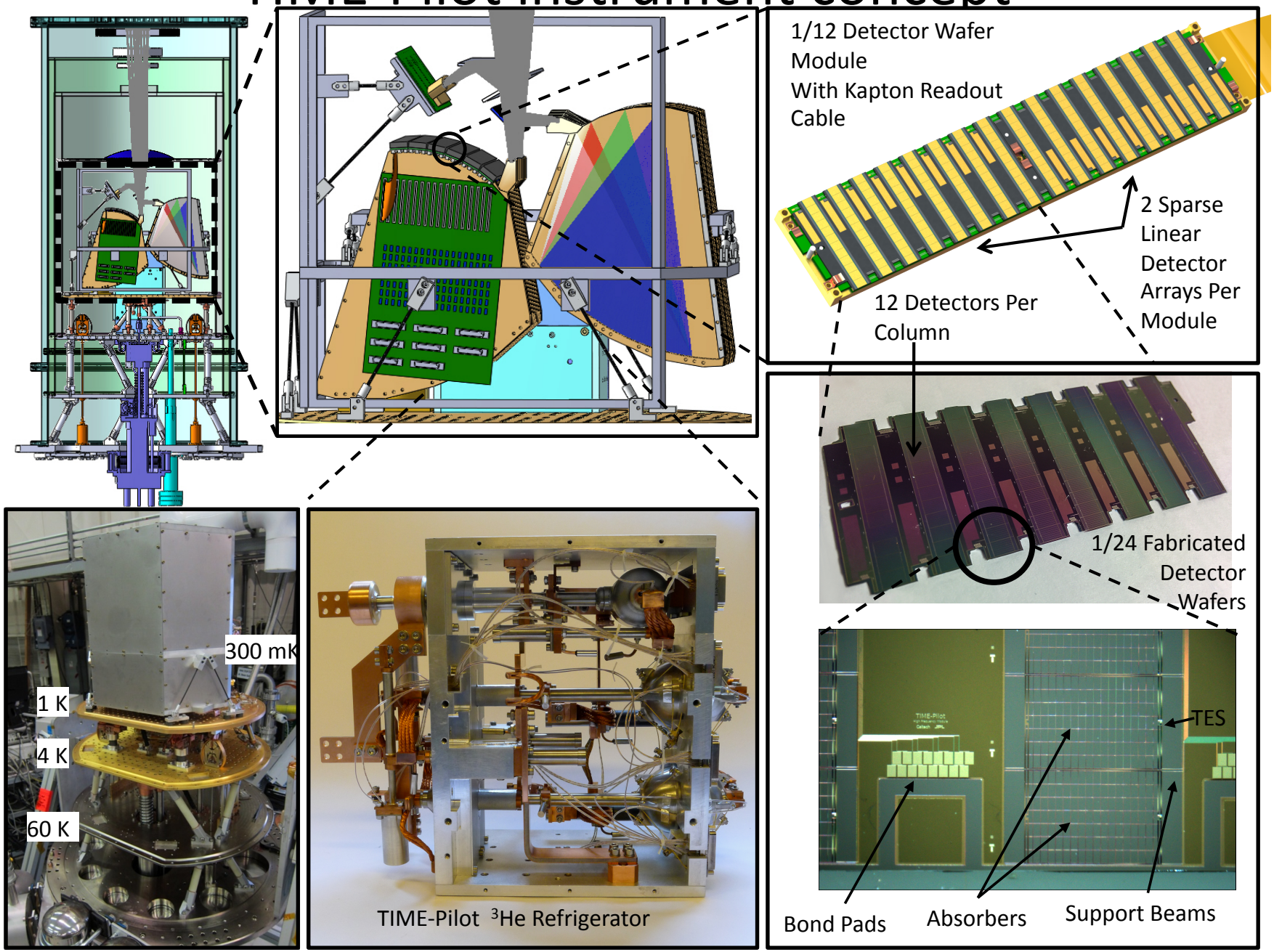
TIME-Pilot survey geometry and instrument modes.



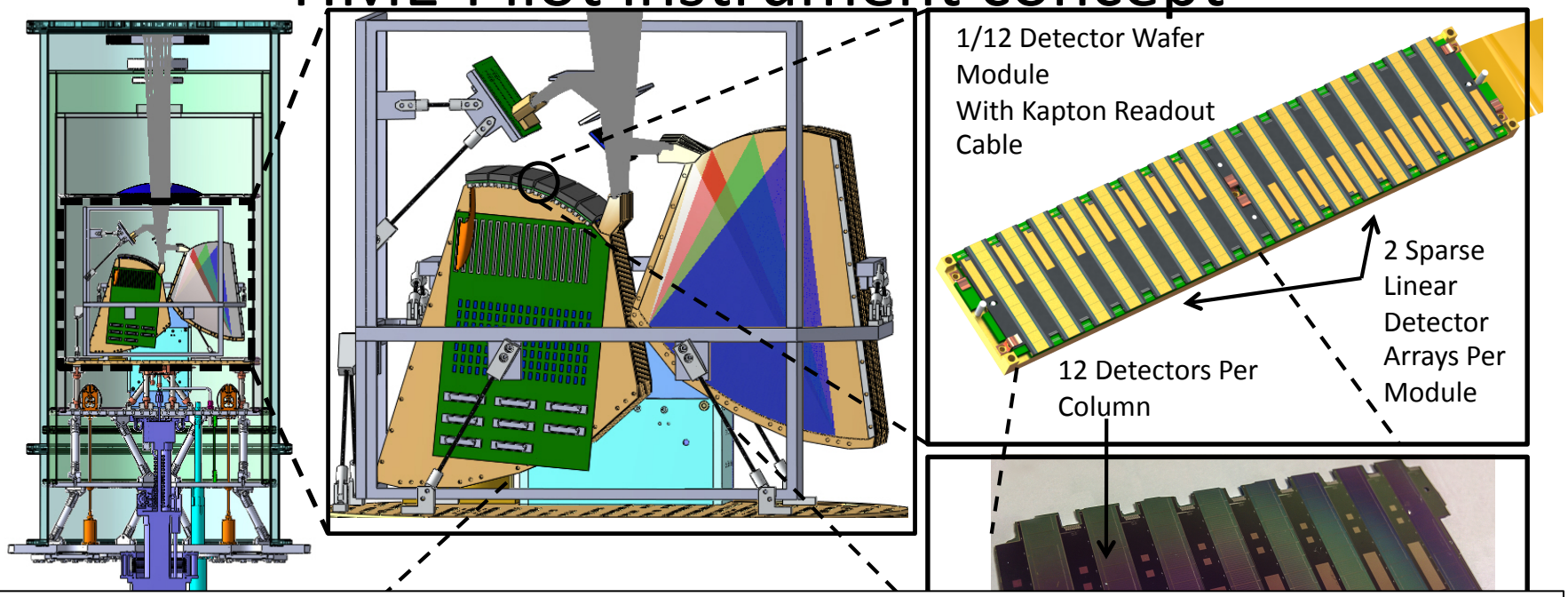
- Want to maximize per-pixel sensitivity – go deep with small area. But need to sample small k, drives to large size (don't want to rely on spectral direction solely).
- Our approach: 156-beams wide x 1 beam-thick rectangle on the sky (140 Mpc x 0.9 Mpc on the CSO).
- Spectral coverage mapped into comoving coordinates gives large z direction: 195 to 318 GHz is z=5.0 to 8.7, a total of 1440 Mpc.



TIME-Pilot instrument concept



TIME-Pilot instrument concept

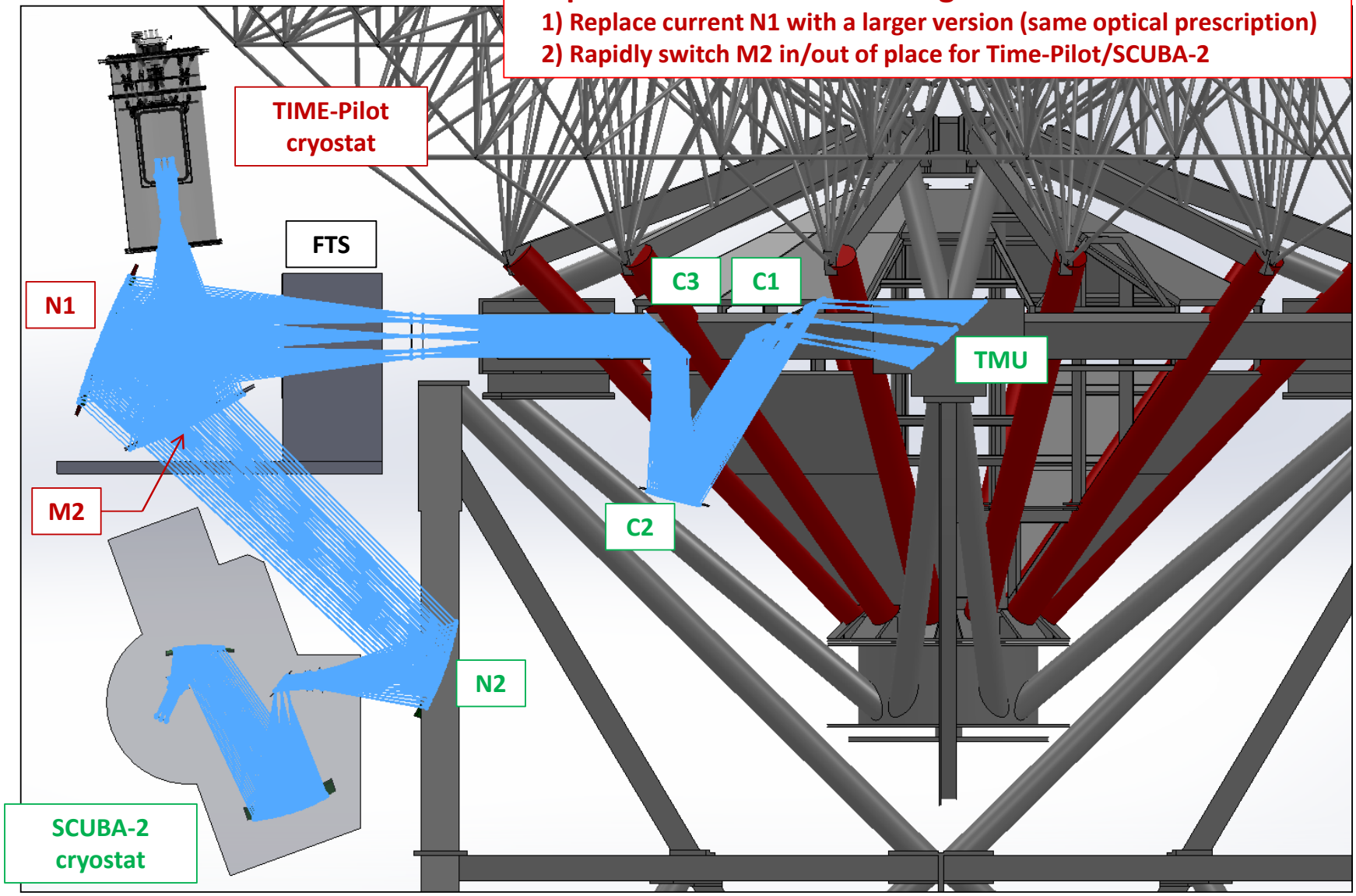


- 32 waveguide grating spectrometers
  - As used in Z-Spec
  - R=100, 60 detectors each covering 186-324 GHz.
  - At least 42 channels each for science, up to 18 can be atmospheric monitors.
- 1800 absorber-coupled TES bolometers
  - time-domain (NIST) SQUID MUX, as per SCUBA-2, BICEP-2.
  - NEP of 3e-18 well in hand after BLISS / SPICA development.
- Novel 'slab' survey geometry with most of low-k information coming from spectral dimension.
  - Requires careful deconvolution between instrument modes and astrophysical k bins.

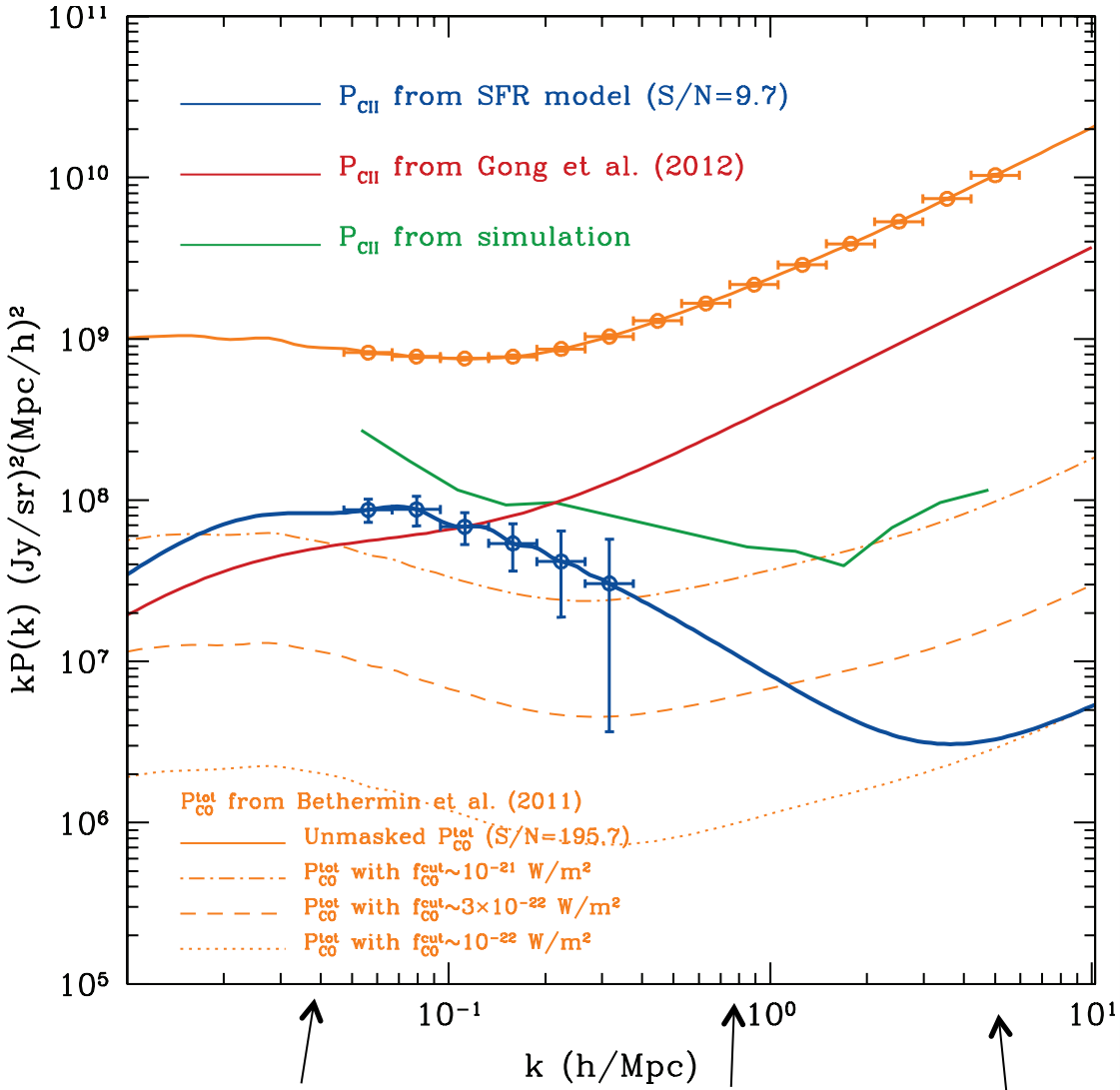
Operation of TIME-Pilot at JCMT

Proposed Time-Pilot Mounting Scheme:

1) Replace current N1 with a larger version (same optical prescription)
2) Rapidly switch M2 in/out of place for Time-Pilot/SCUBA-2



TIME-Pilot Dataset – Expected Sensitivity



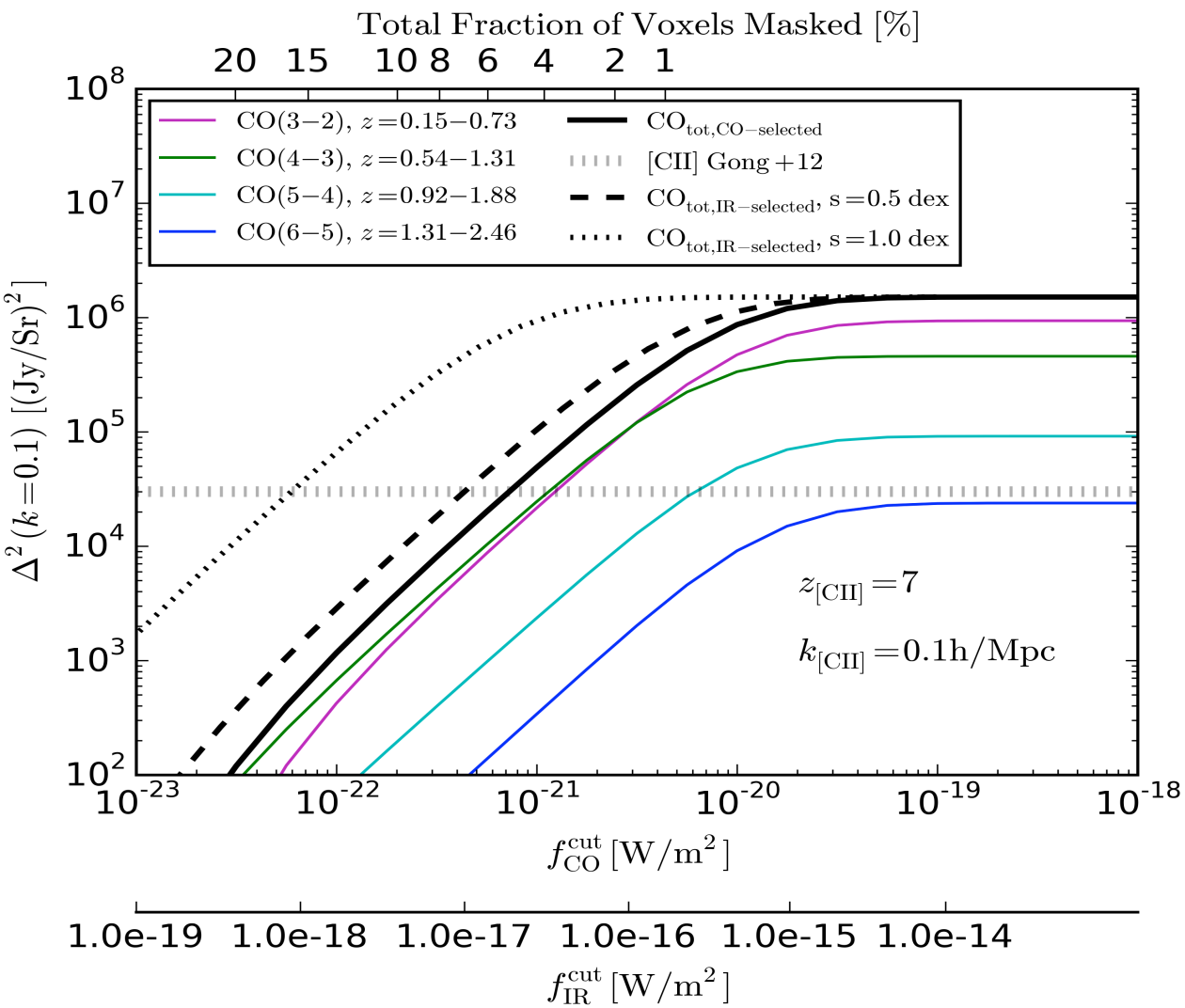
Halo-halo clustering (linear term, encodes total CII emission)

Inter-halo clustering

Shot noise

- [CII] autocorrelation spectra over the full TP band.
- [CII] EoR signal strength not known, consider various models.
  - Constant SFR
  - Gas physics calculation
  - Millennium sim x 3e-3
- Error bars correspond to 240 hours on sky w/ JCMT.
- CO from z ~ 0.5 to 3 (multiple lines) is dominant signal in raw map (shown referred to CII survey geometry), but can be masked using galaxy catalogs.
- Cross correlations at CO frequencies with galaxy surveys can provide a CO census

Masking of low-z CO Galaxies



Amplitude of linear term: CO dominates raw variance in slab

But can remove CO signal by selecting based on total IR luminosity.

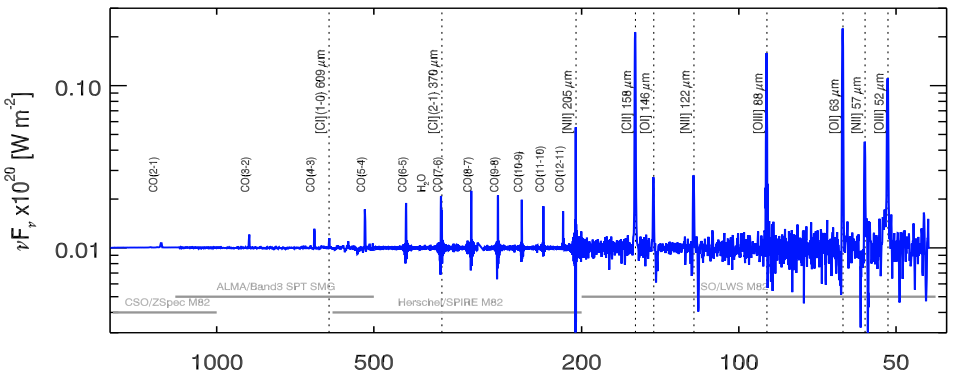
- Includes scatter in IR / CO luminosities)
- Reaches down to about 1e9 Lsun galaxy.

Only ~10% of survey voxels need to be removed. ~700 galaxies.

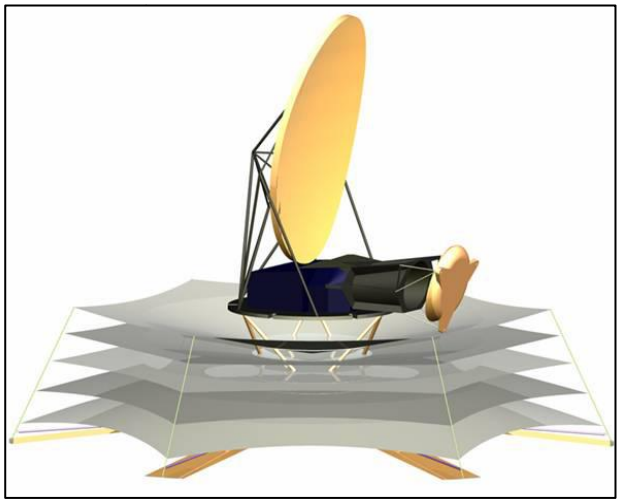
Need to tie optical / near-IR fluxes to total IR luminosity.

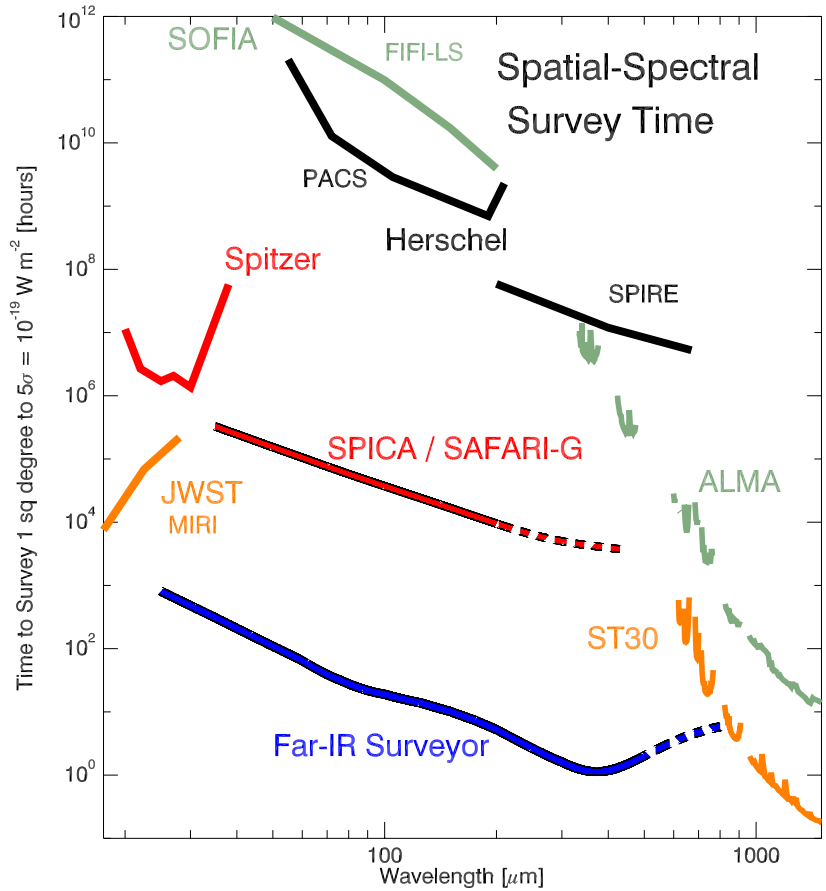
Also will need the 700 redshifts.

Far-IR Intensity Mapping from Space



CALISTO: single dish concept for far-IR Surveyor





- Far-IR lines of O++, N++, and N+ measure the ionization state and metallicity of the gas.
- SPICA and FIR Surveyor (single-dish) can measure these lines galaxies in the Universe's first billion years, comparable to JWST and ALMA in sensitivity. Will have ~100 moderate-R spectrometer 'pixels', all at background limit. Excellent for intensity mapping. Single-dish system the community choice for Surveyor in June meeting. (FIR session this evening.)
- SPICA currently under development for Cosmic Visions M5 proposal. 2.5 meter aperture, SAFARI R=300 grating spectrometer with R=3000 etalon mode. SPICA poster Friday.