Tomography of Cosmic Reionization Through [CII] Intensity Mapping at Redshifts 3.5-9 with CCAT-p

CCAT-p

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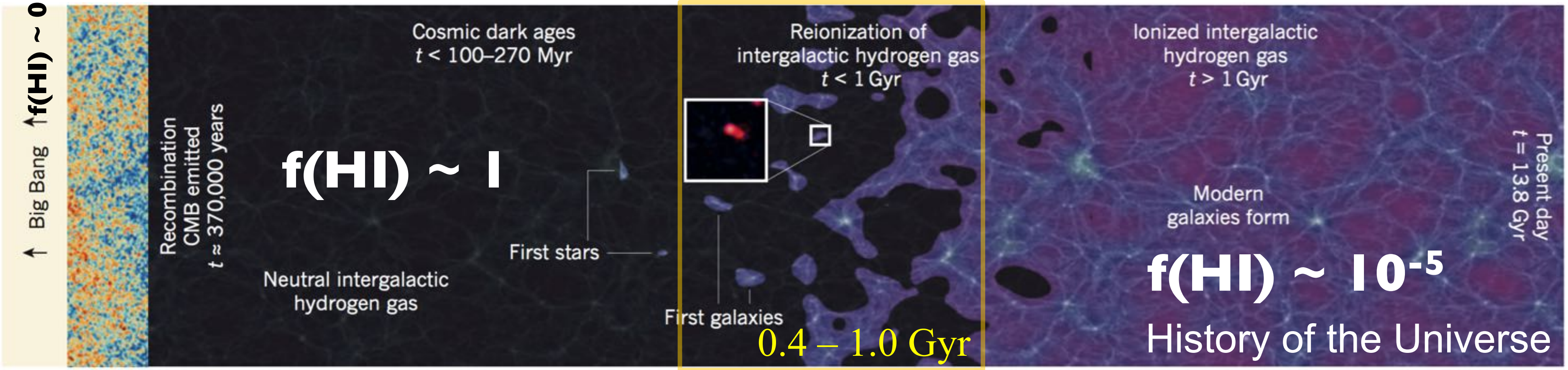
Epoch of Cosmic Reionization (EoR)



z ~ 6 to 12

The cosmic "Dark Ages" are ended by the first sources of ionizing UV photons in the universe: the *first stars* and in particular, the *first galaxies*.

These sources drive the *"Epoch of Reionization" (EoR)*, after which the intergalactic medium (IGM) is largely ionized until present day.

Today, we know that galaxies exist at least out to redshifts 8-10 based on few bright examples.

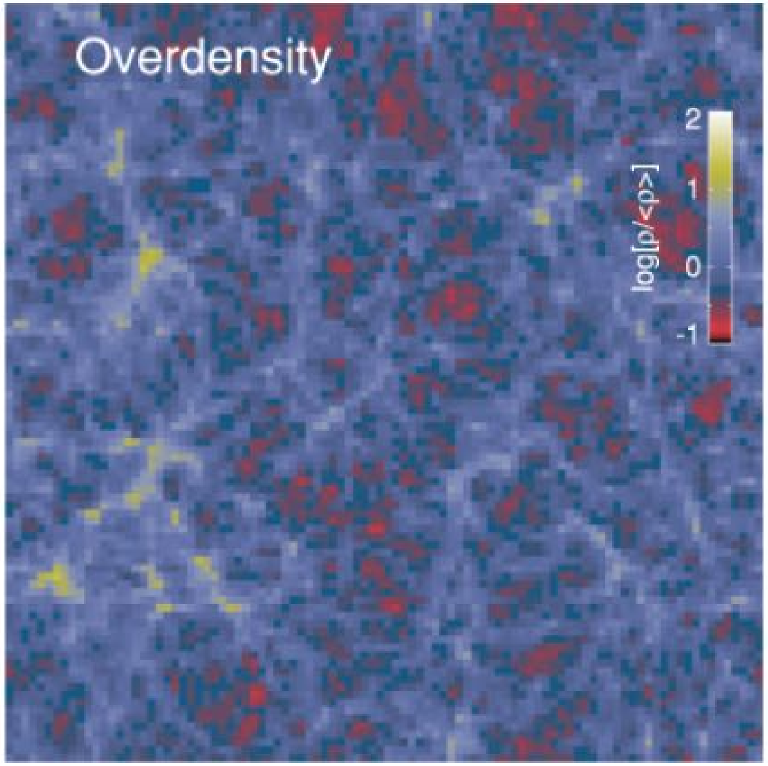
➢ Need to systematically explore the EoR as a signpost of cosmic structure formation

<u>Main challenge:</u> UV lum.fct.; most numerous EoR galaxies are too faint to be detected individually

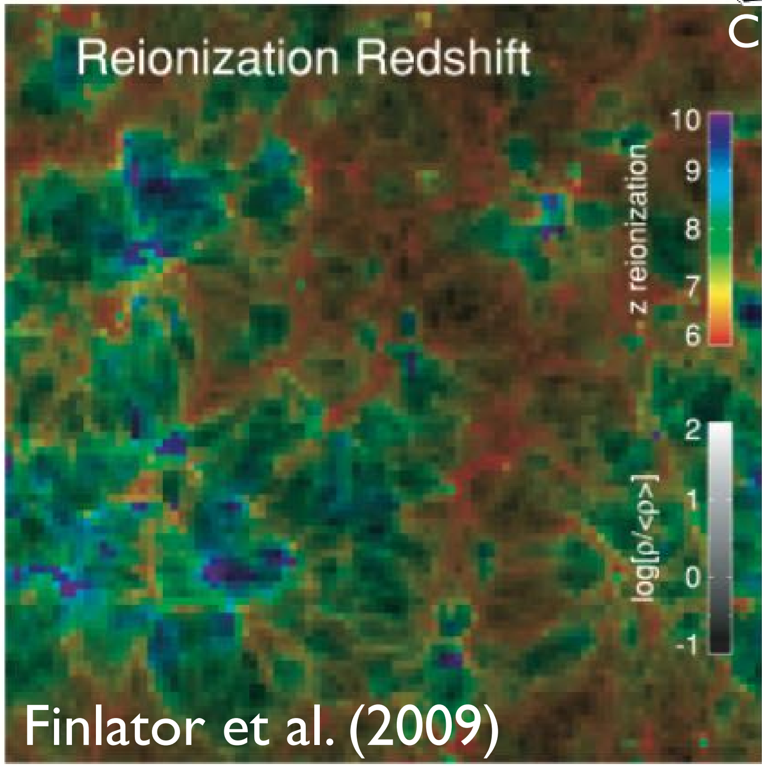
<u>Solution:</u> measure *aggregate* emission on large scales via **Intensity Mapping (IM)**

Robertson et al. (2010); Riechers (2013)

Simulations of Cosmic Reionization



(a) Overdensity $\rho/\bar{\rho}$ at $z = 6.49$.



(b) Redshift of reionization, defined as the redshift at which the hydrogen neutral fraction first dips below 10^{-3}.

Re-ionization does *not* occur instantaneously, because mean free path of ionizing photons depends on local IGM density structure. Overdense regions re-ionize first, then voids, then moderate-density structures

Simulations of Cosmic Reionization

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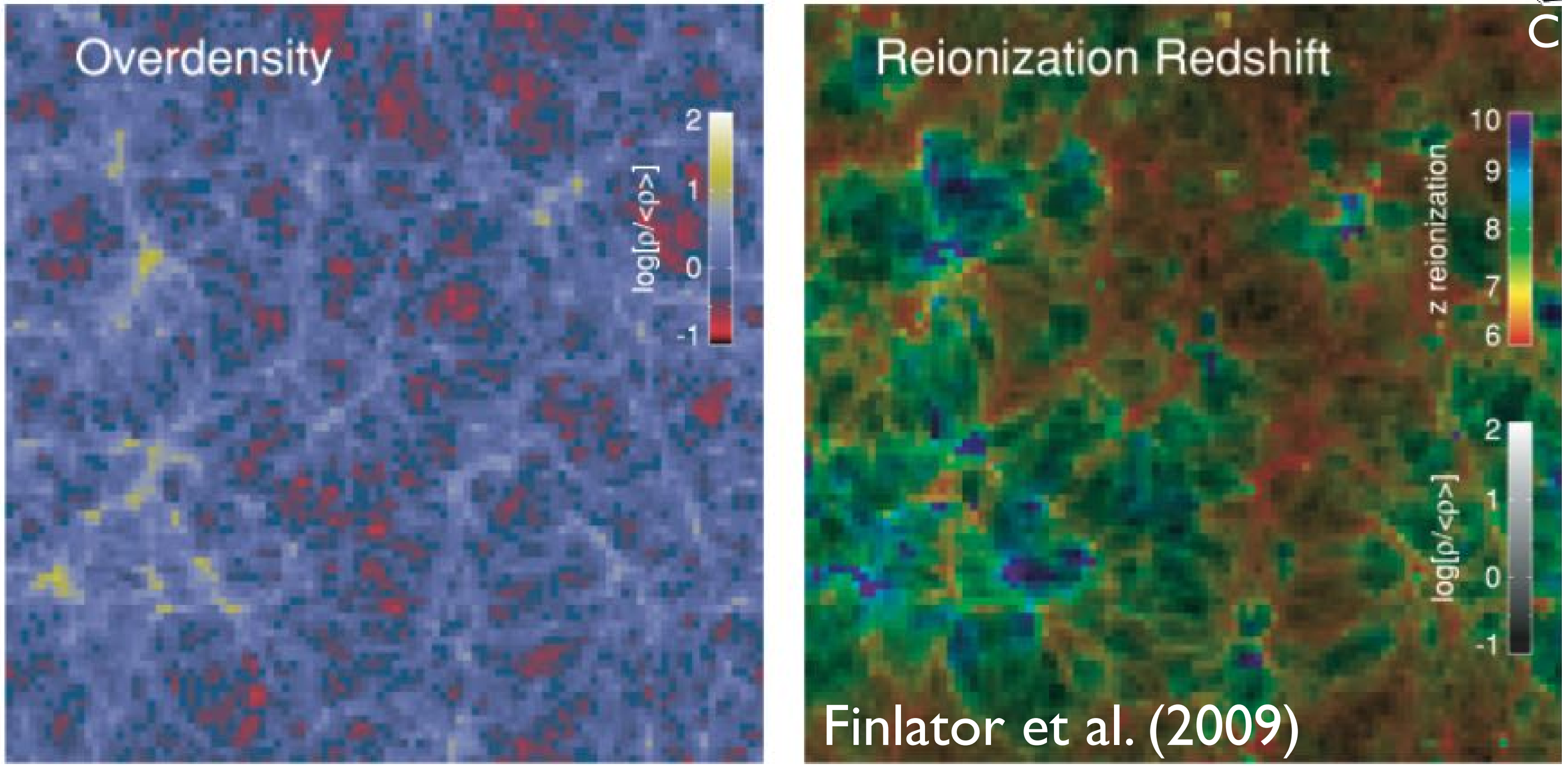

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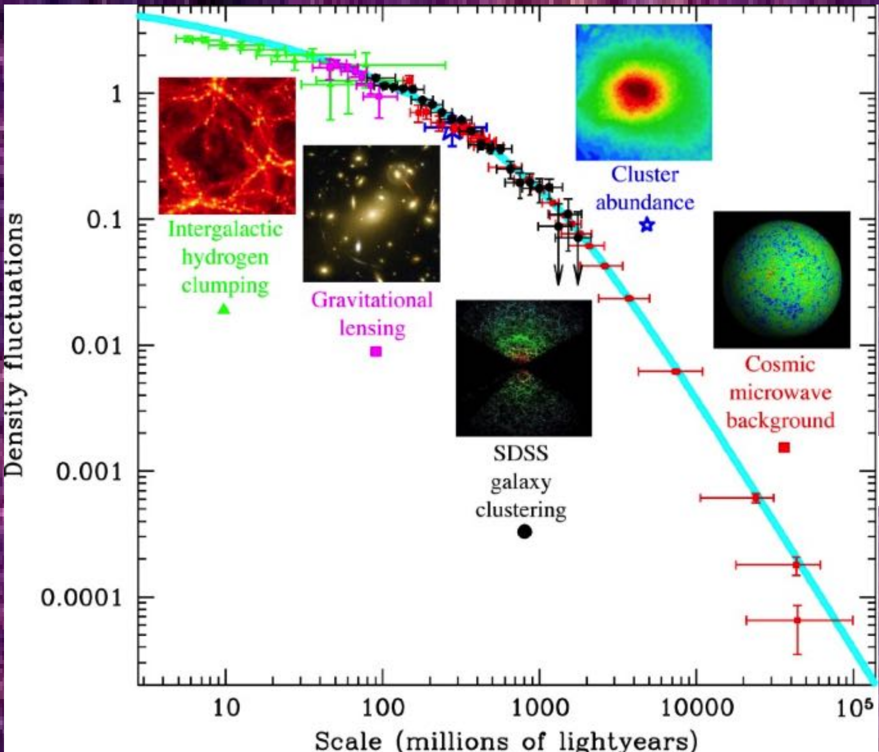
⇒ *galaxy clustering drives the evolution*

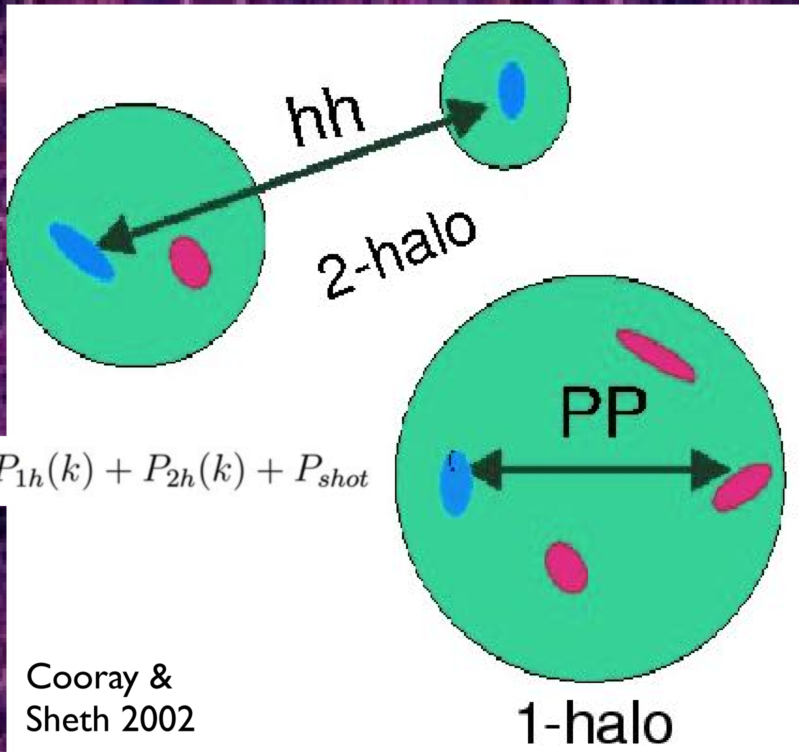
⇒ *need to map signal spatially and as f(redshift)*

Measurement of a Clustering Signal ("Fluctuations"): Relationship Between Dark Matter and Galaxies

Density fluctuations on different scales



Halo Clustering Model



$$P(k) = P_{1h}(k) + P_{2h}(k) + P_{shot}$$

Cooray & Sheth 2002

An Example of Intensity Mapping

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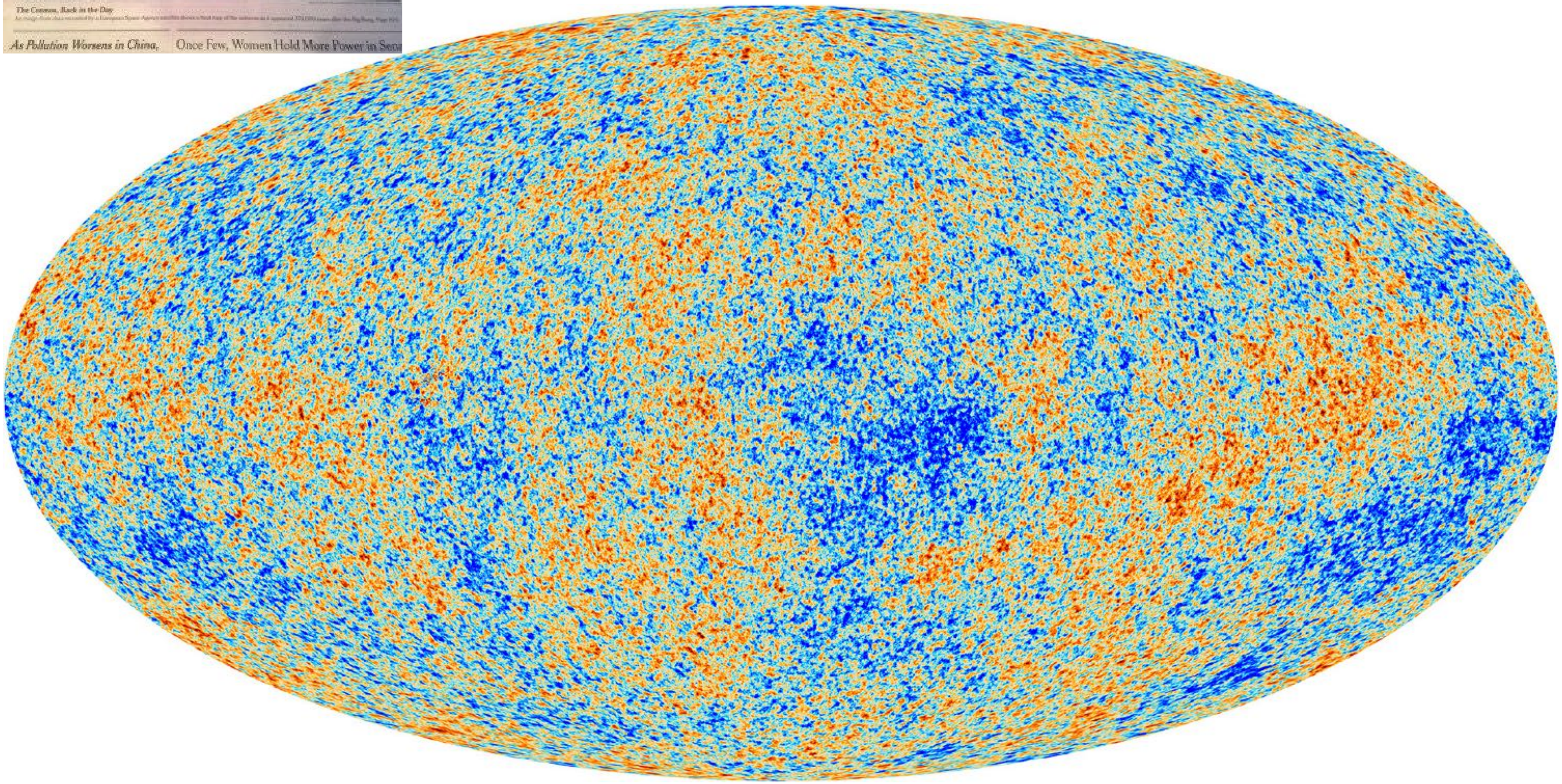
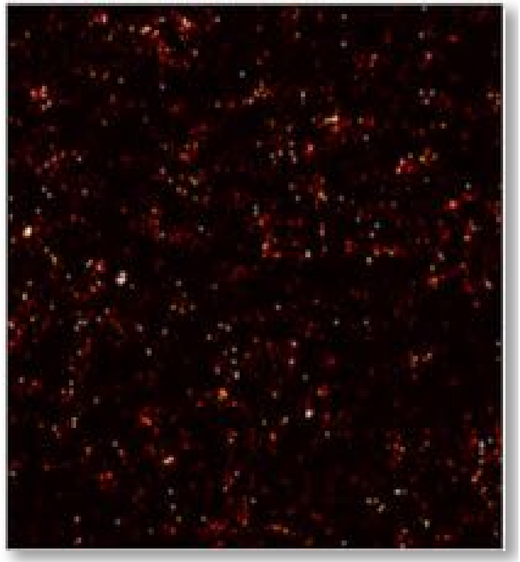


Key difference: require spectral line measurements to get *redshifts* = cosmic time snapshot
→ instead of 2D-picture, obtain full 3D-mapping of the sky over large regions

3-D Intensity Mapping

Sky map at z

Intensity map at z



- No need to resolve individual source
- Measure the collective emission from many sources
- Map large volume and faint sources at high z economically
- Astrophysical and cosmological applications from structure formation to measurement of SFRD of the universe at $z > 2$

[CII] Intensity Mapping in the EoR: Rationale

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Map out EoR at redshifts that will remain largely inaccessible to best optical tracers

Measure clustering signal of galaxies at redshifts z=6-8 in the 158 μm [CII] line, a tracer of star formation activity in galaxies (i.e., early galaxy assembly)

Understand the *topology* and *timescale* of reionization, i.e., how and when galaxies first formed, the *properties of sources* of reionization

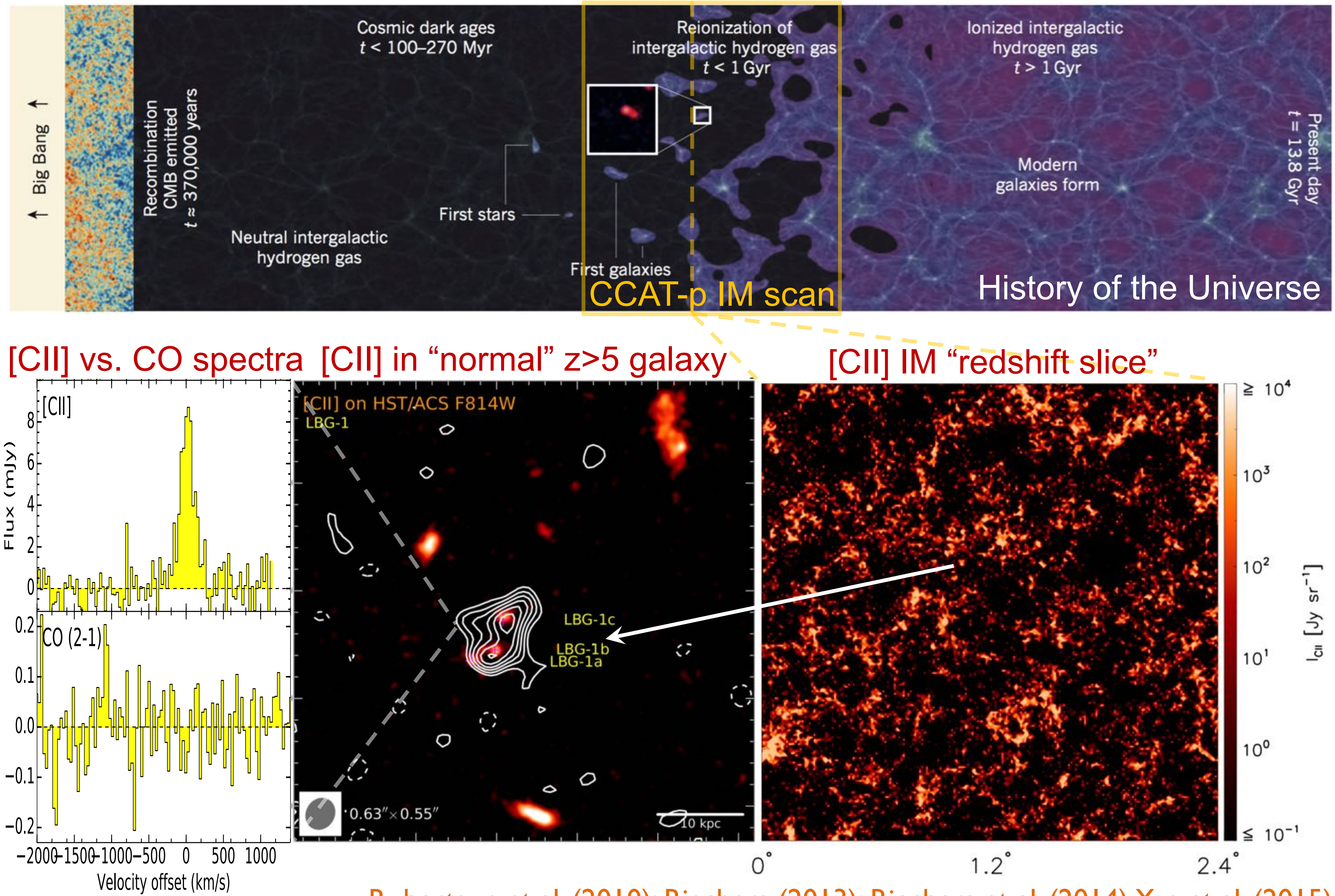
Understand if there is enough star formation to produce enough UV photons to cause and maintain reionization within the first billion years

→ Short-cut to some results expected from HI 21cm surveys with full SKA

[CII] 158 μm:

- Tracer of UV field in star-forming regions, redshifted to ~1 mm at EoR redshifts
- Much stronger signal than HI 21cm and much simpler foregrounds
- Not subject to IGM absorption like Ly-α 1216 A and others
- Not subject to steep metallicity dependence like CO rotational lines

[CII] Intensity Mapping in the EoR



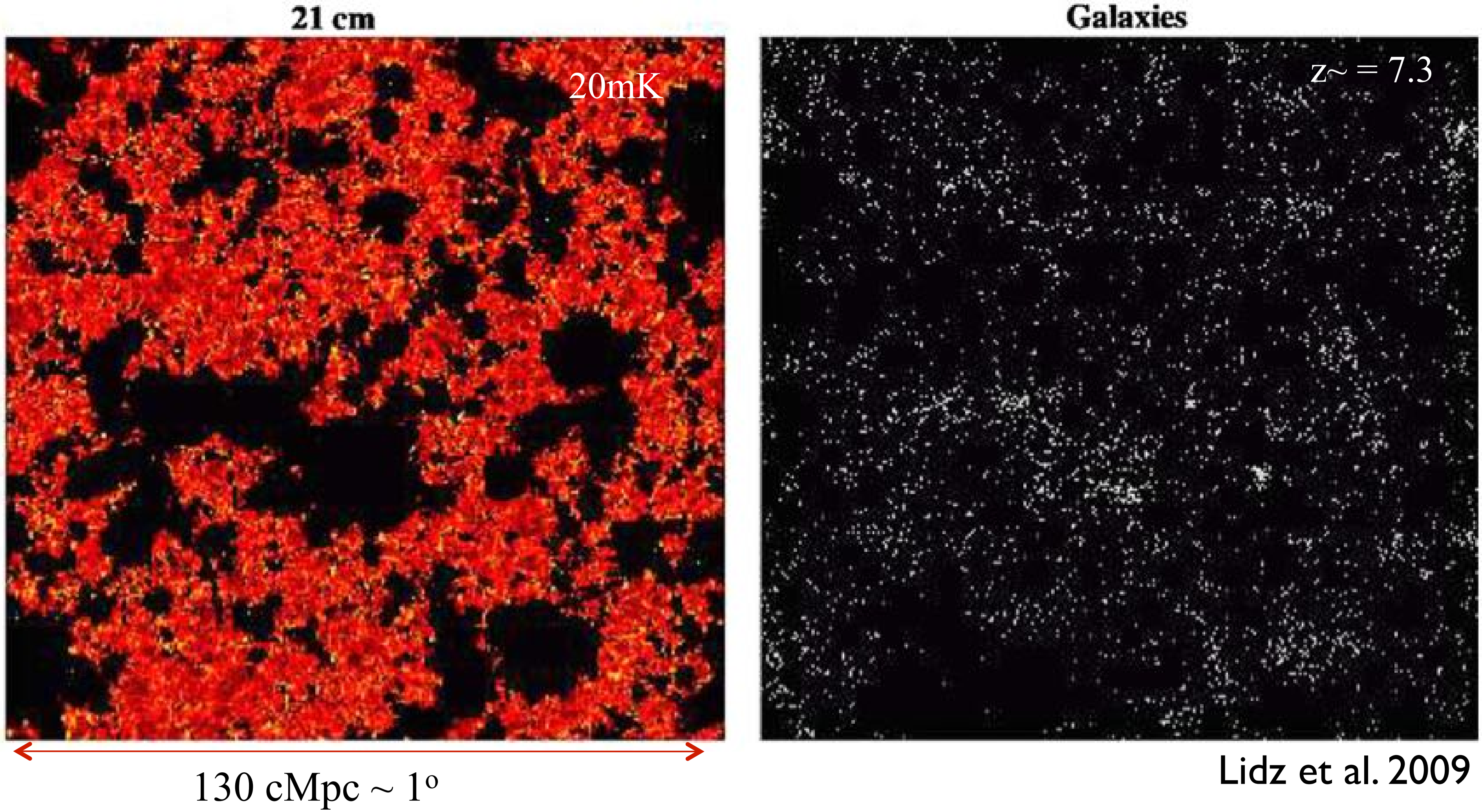
Robertson et al. (2010); Riechers (2013); Riechers et al. (2014), Yue et al. (2015)

HI vs [CII]: "Inverse" views of large-scale structure during EoR

Neutral intergalactic medium (det. in HI 21cm line) = consequence

• Galaxies which drive re-ionization (detected in [CII] line) = sources

→ will detect [CII] signal in already ionized regions ("holes" in HI map)



Lidz et al. 2009

Simulated Sky in [CII] to z~9

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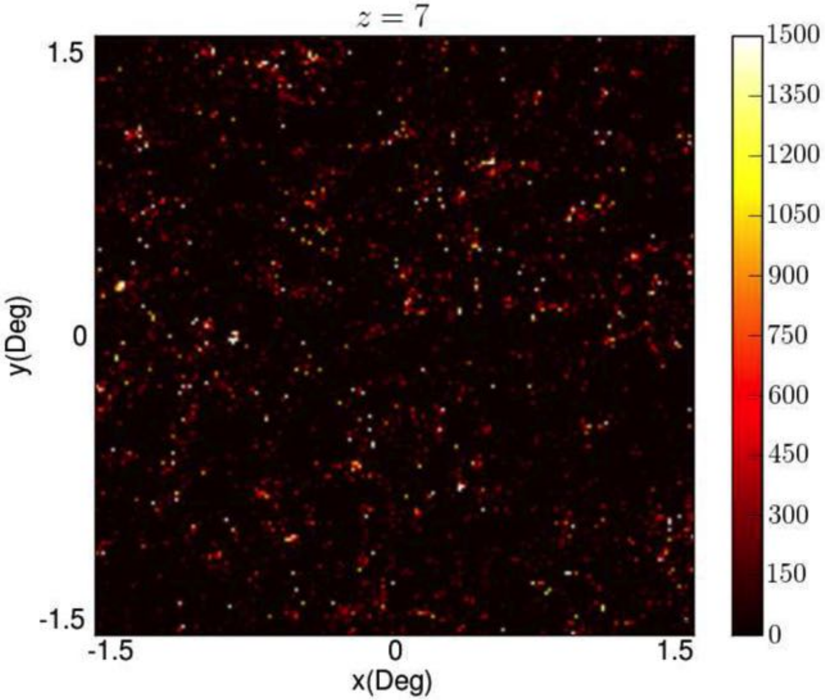

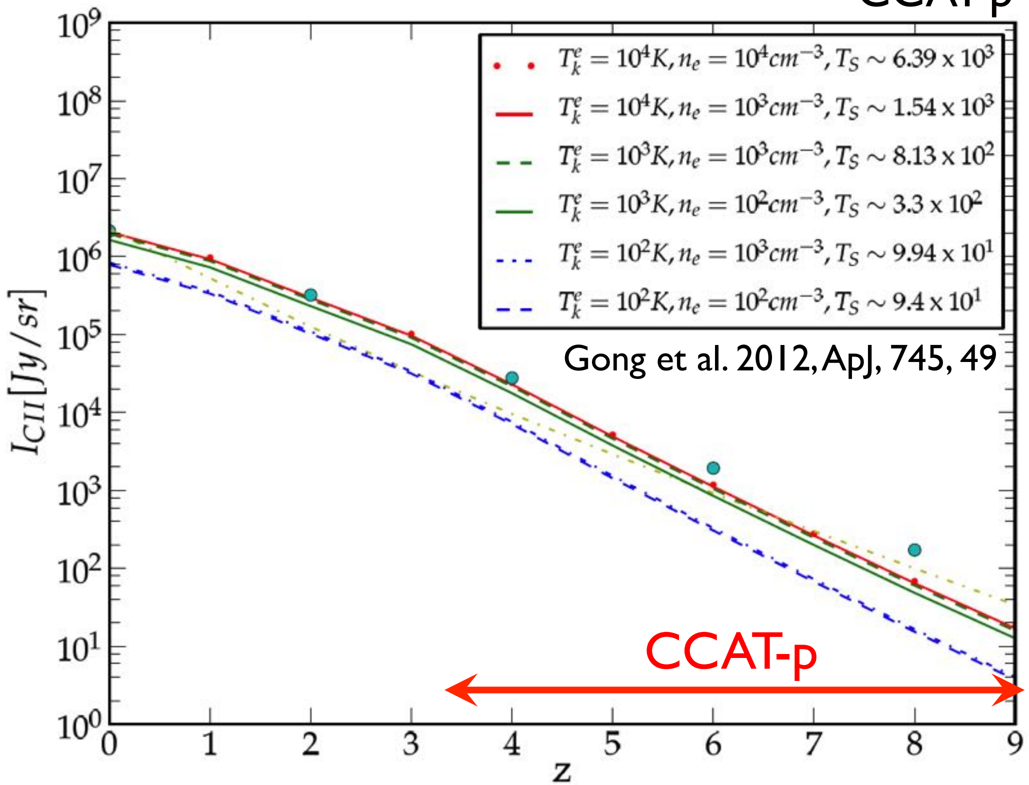

- [CII] serves as a tracer of star formation
- The clustering signal traces *total luminosity*
  => unlike a flux-limited galaxy survey
- Use [CII] to spatially trace star formation during the re-ionization epoch

Simulated [CII] Power Spectrum Measurements at z=6-8

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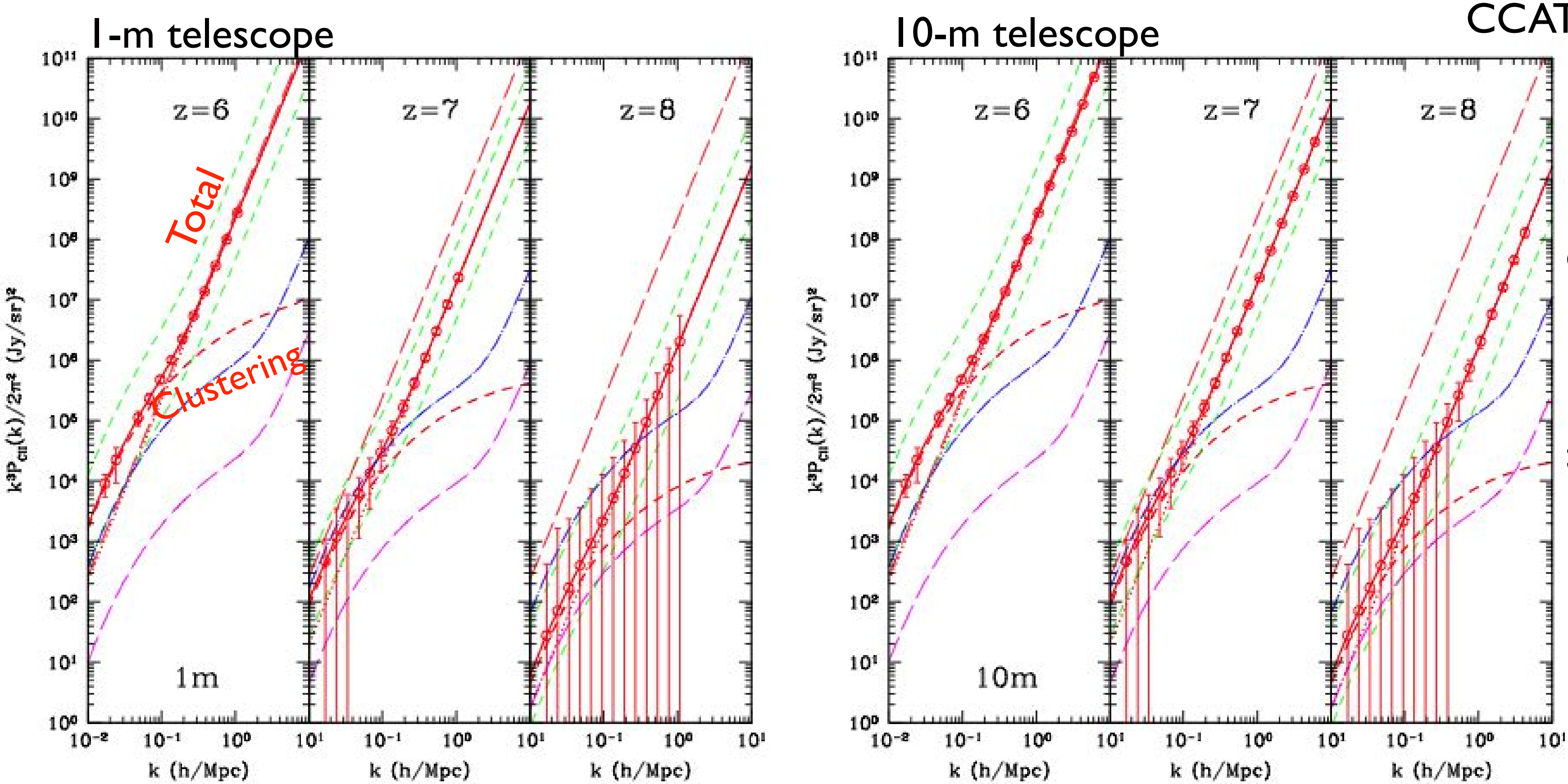

Gong et al. 2012, ApJ, 745, 49

Quality of measurement scales with telescope size, but only weakly.

Reason:

Larger Telescope has more collecting area = *point source* sensitivity

However, also has smaller beam, so the *signal per resolution element* gets weaker

Ideal choice: resolution close to clustering scales at z~6-8, close to 1' @1mm

HI - [CII] Cross-Correlation: Ionized Bubbles

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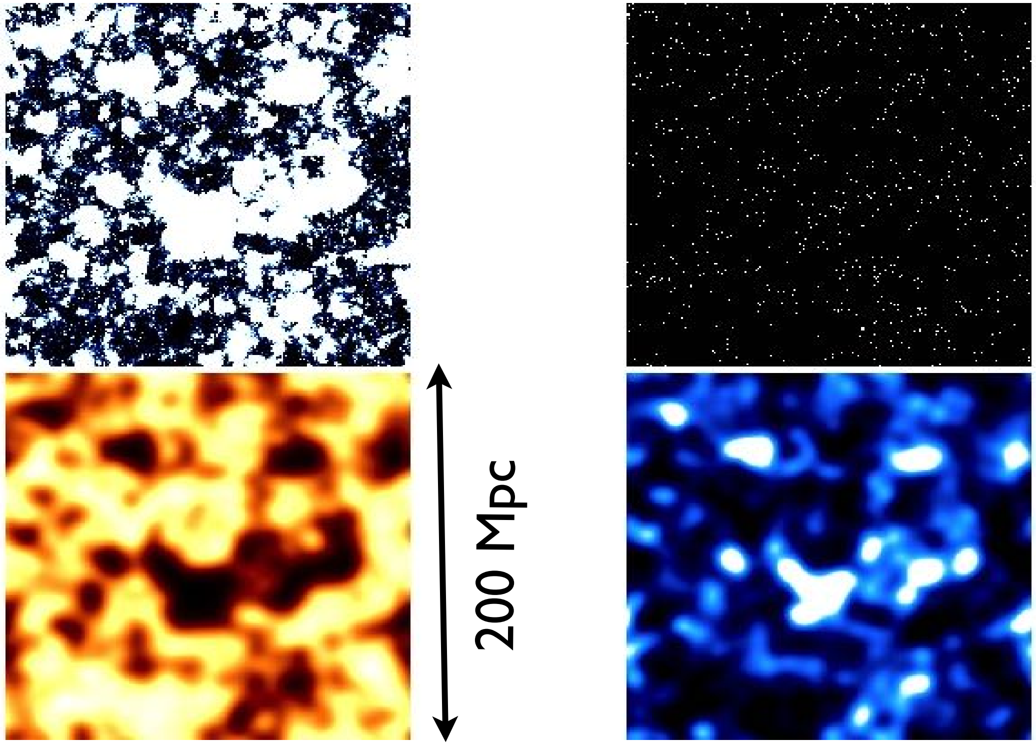
- 21 cm and galaxy emission should be anti-correlated on large scales.
- Confirm cosmological origin of putative 21 cm signal.
- Cross-correlation sensitive to bubble sizes.

Reason: Cross-spectrum turns over on scale of bubbles around (groups of) galaxies.



e.g., Lidz et al. 2011

HI - [CII] Cross-Correlation: Ionized Bubbles

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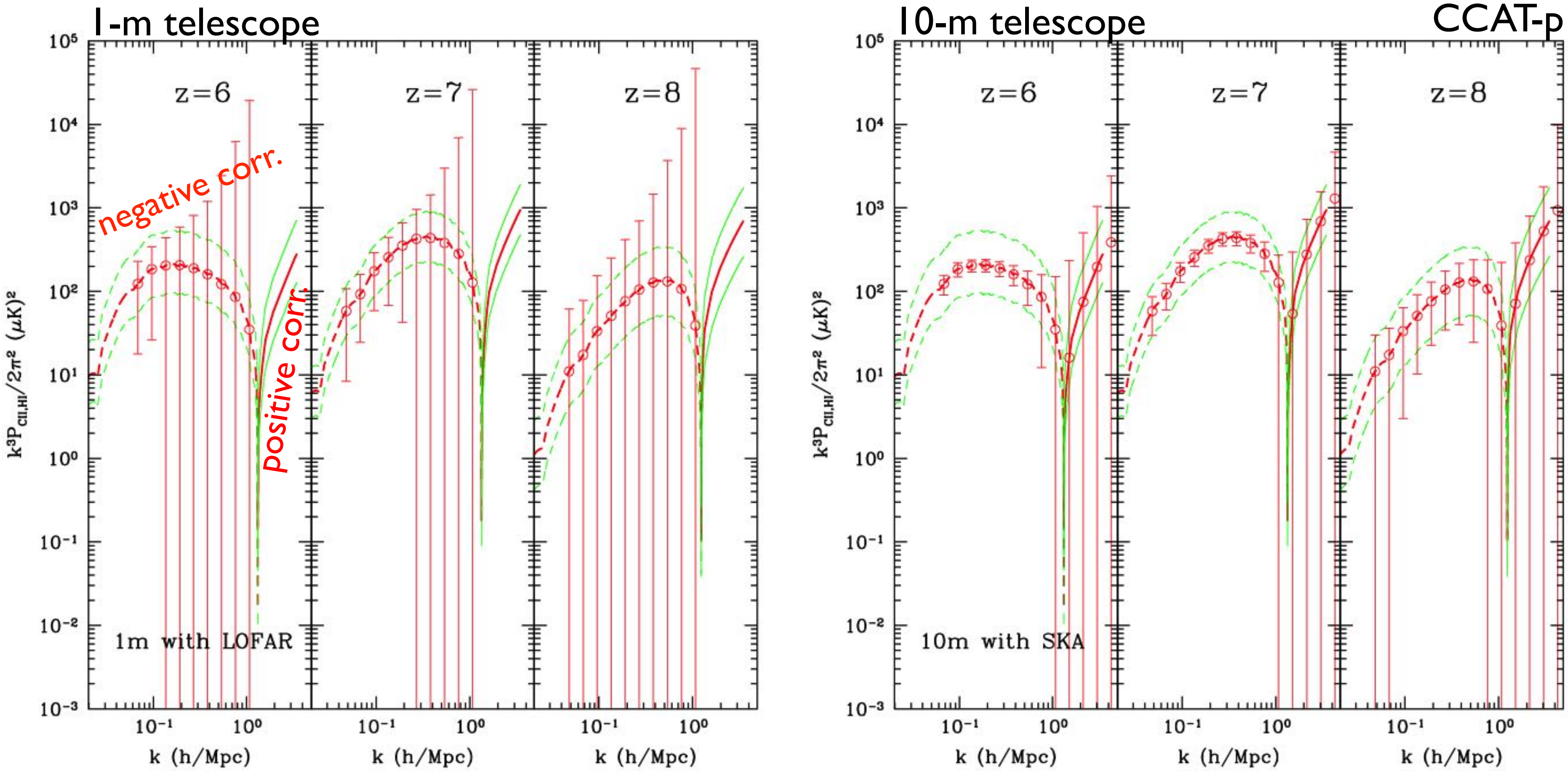

HI-[CII] cross power spectrum:
dashed line: negative correlation (ionization fraction vs. matter density)
solid line: positive correlation (matter density auto-correlation on small scales)

Gong et al. 2012, ApJ, 745, 49

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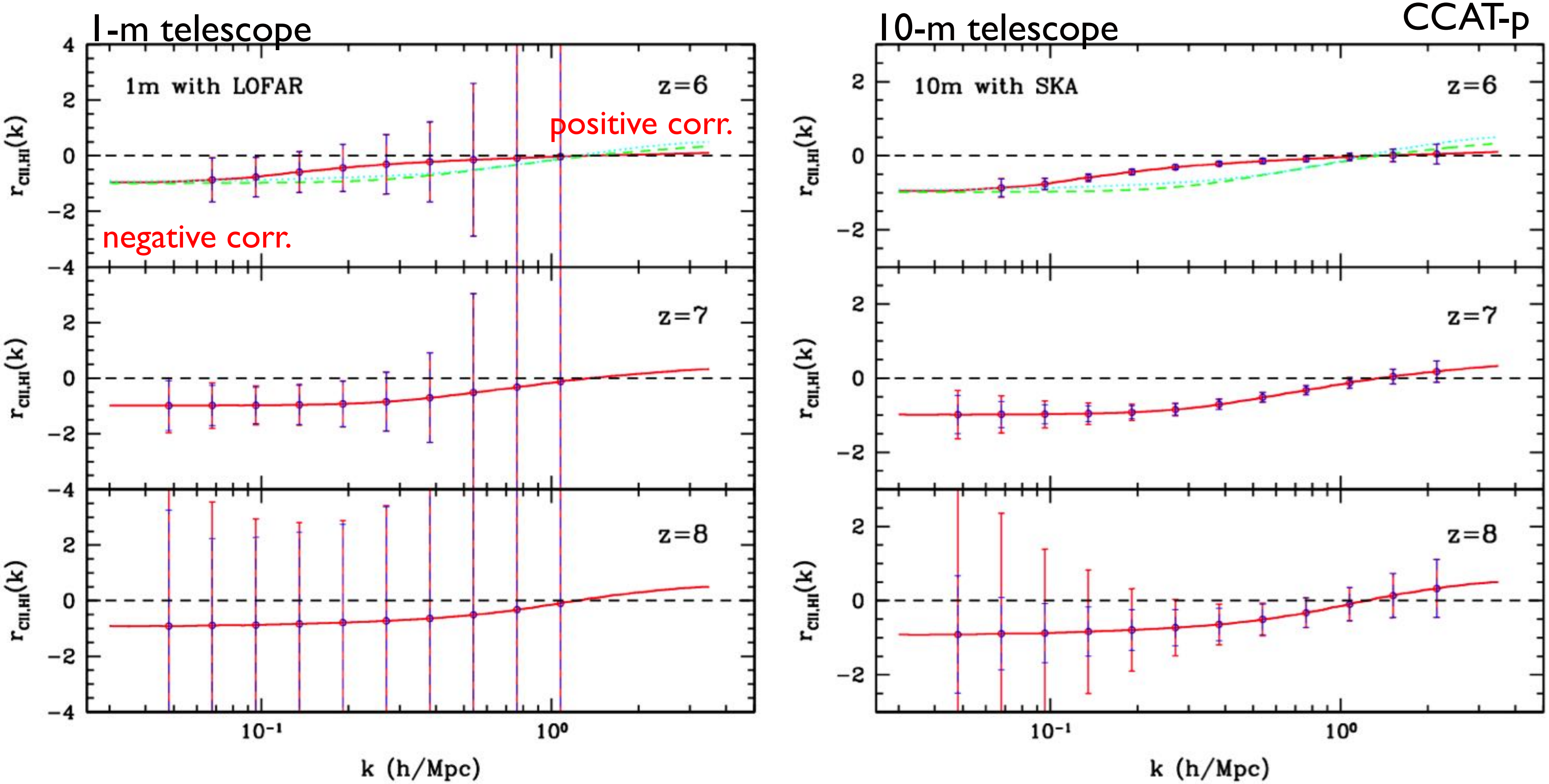

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Ancillary Science Goals

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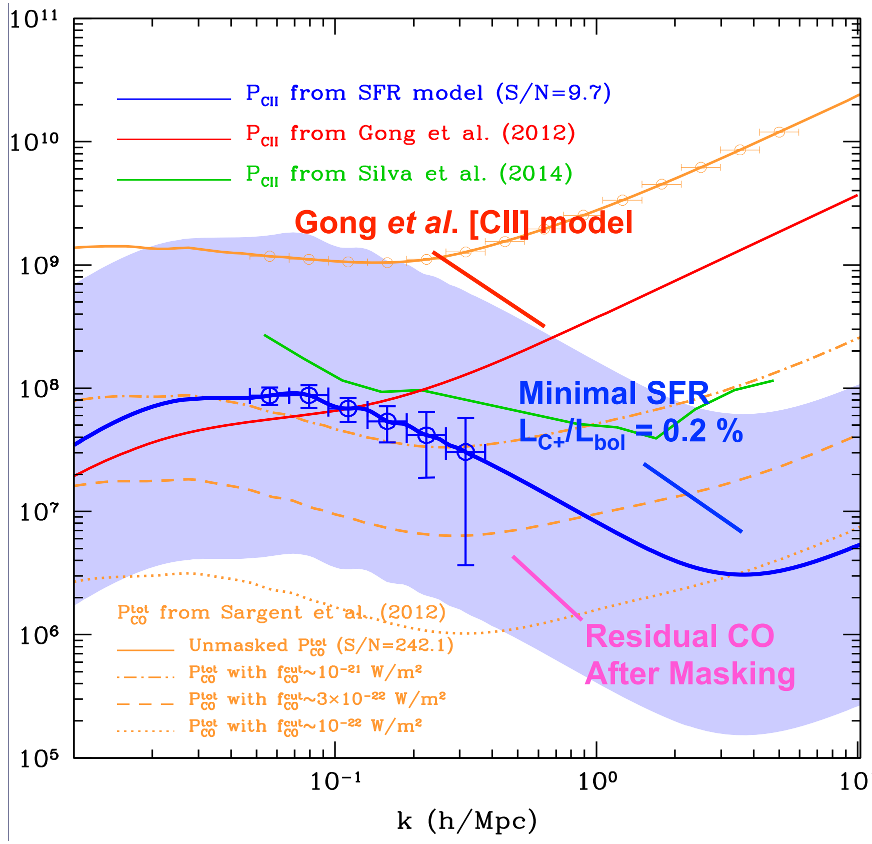

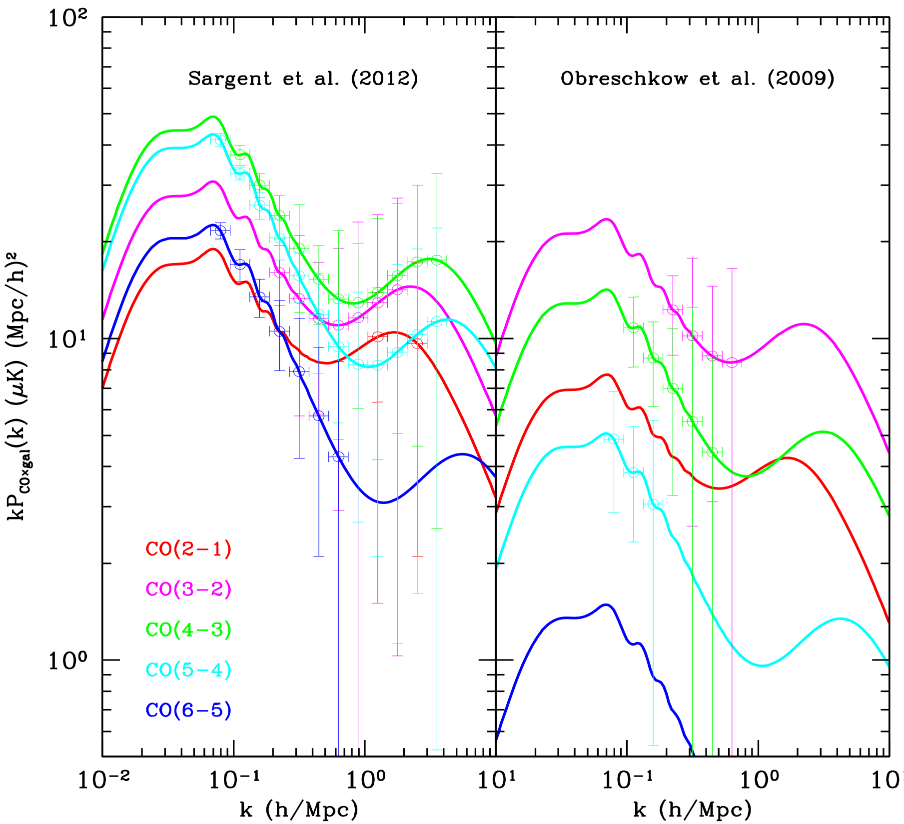

EoR science:

- Detect [CII] clustering & Poisson fluctuations to address models
- Also detect [OIII] 88μm at highest z: cross-correlation w/ other FS lines

Peak epoch of galaxy formation science:

- Detect CO "foregrounds" & clustering
- ISM content of galaxies at intermediate z
- Detailed study as foregrounds/masking

updated from Gong et al. 2012

Simulated Survey: Parameters

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	CCAT-p	
Aperture Diameter (m)	**6**	
Survey area (deg^2)	16	*e.g., deep HyperSC fields: COSMOS, UDS*
Total integration time (hr)	**4000**	*~1.5yr (8-10hr/day)*
Spectral range (goal; GHz)	185-440	*minimum: 210-275*
Frequency resolution (GHz)	0.4	
Number of detectors (spectral x spatial)	**20000**	
Beam FWHM size* (arcmin)	0.75-1	
Beams over survey area*	9.4×10^4	
Noise per detector sensitivity* ($Jy\ s^{1/2}$ / sr)	2.5×10^6	
Integration time per beam* (hr)	3	
Volume per pixel $(Mpc\ h^{-1})^3$: z=6	7.5	
z=7	9.2	
z=8	13.4	
Fluctuation power spectrum P_N^{CII} $(Jy\ sr^{-1})^2$ $(Mpc\ h^{-1})^3$: z=6	5.4×10^9	
z=7	4.9×10^9	
z=8	4.4×10^9	

*: *Values at 238 GHz (CII at z=7)*

predictions based on models by Gong et al. 2012, ApJ, 745, 49

CCAT-prime: An Ideal Intensity Mapping Telescope

CCAT-p

6-m telescope has ~1' = 45" beam for [CII] at z~7 (~240 GHz)
→ ideal to probe few arcmin/Mpc clustering scales at EoR over >10 deg^2

Requirement:

- moderate spectral resolution (~0.5 GHz, dz~0.01), wide-bandwidth multi-element spectroscopy covering [CII] at z=6-8 (z=3.3-9.3): continuous coverage of 1mm (+760/850μm) atmospheric windows
- Rapid spectral+spatial mapping speed on deg-scales critical to be feasible
  → Using Fabry-Perot Interferometer on 4000-pix *quad-color* TES camera
- Sensitivity at a premium: high site, very low emissivity telescope *essential*
  - ~1.5x reduced sky emissivity compared to ALMA site
  - <2% telescope emissivity with off-axis design

  → Overall ~20 – 100x mapping speed for EoR IM wrt. APEX, JCMT, LMT

Mapping speed for same instrument: CCAT-p/co-eval telescopes

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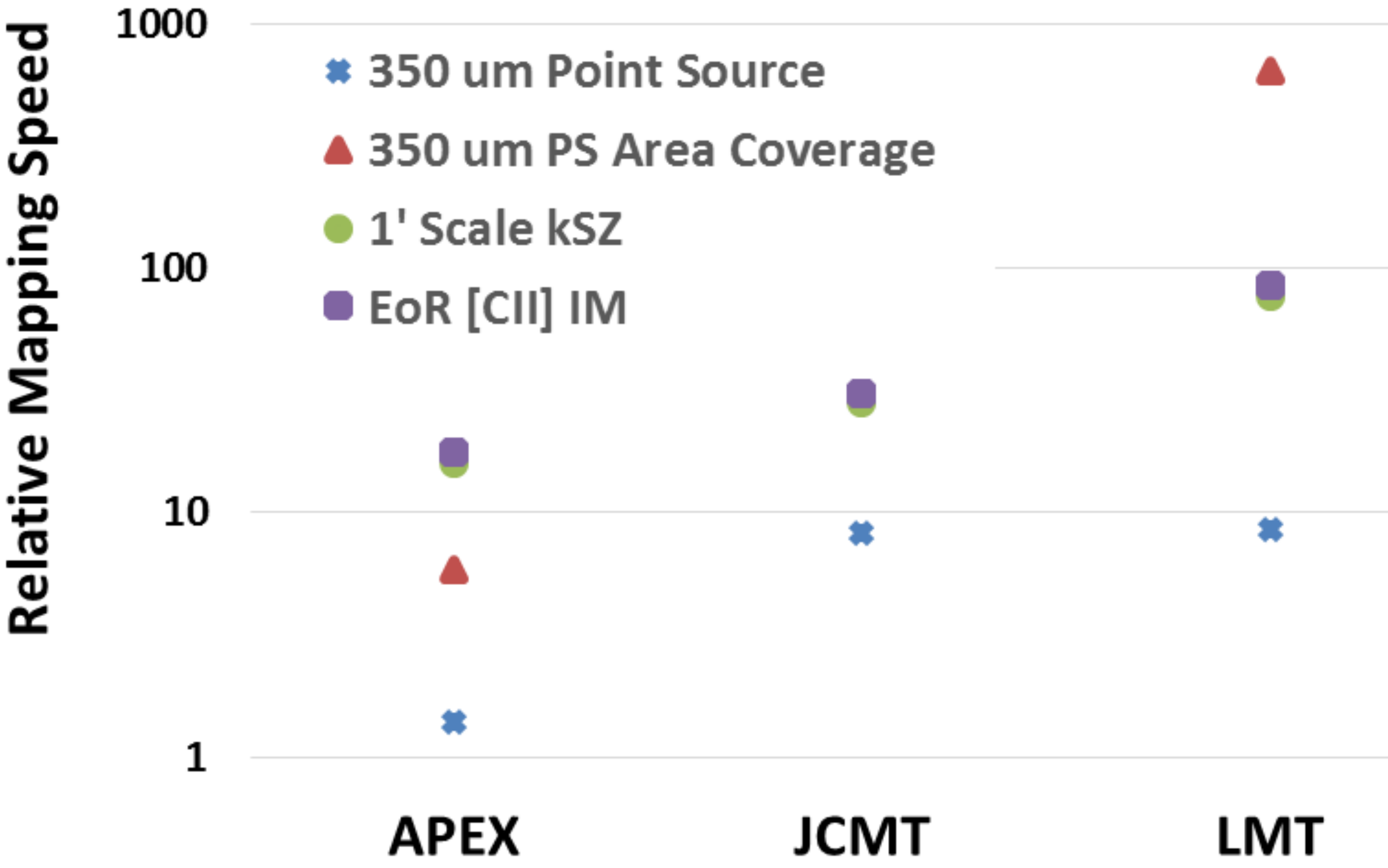
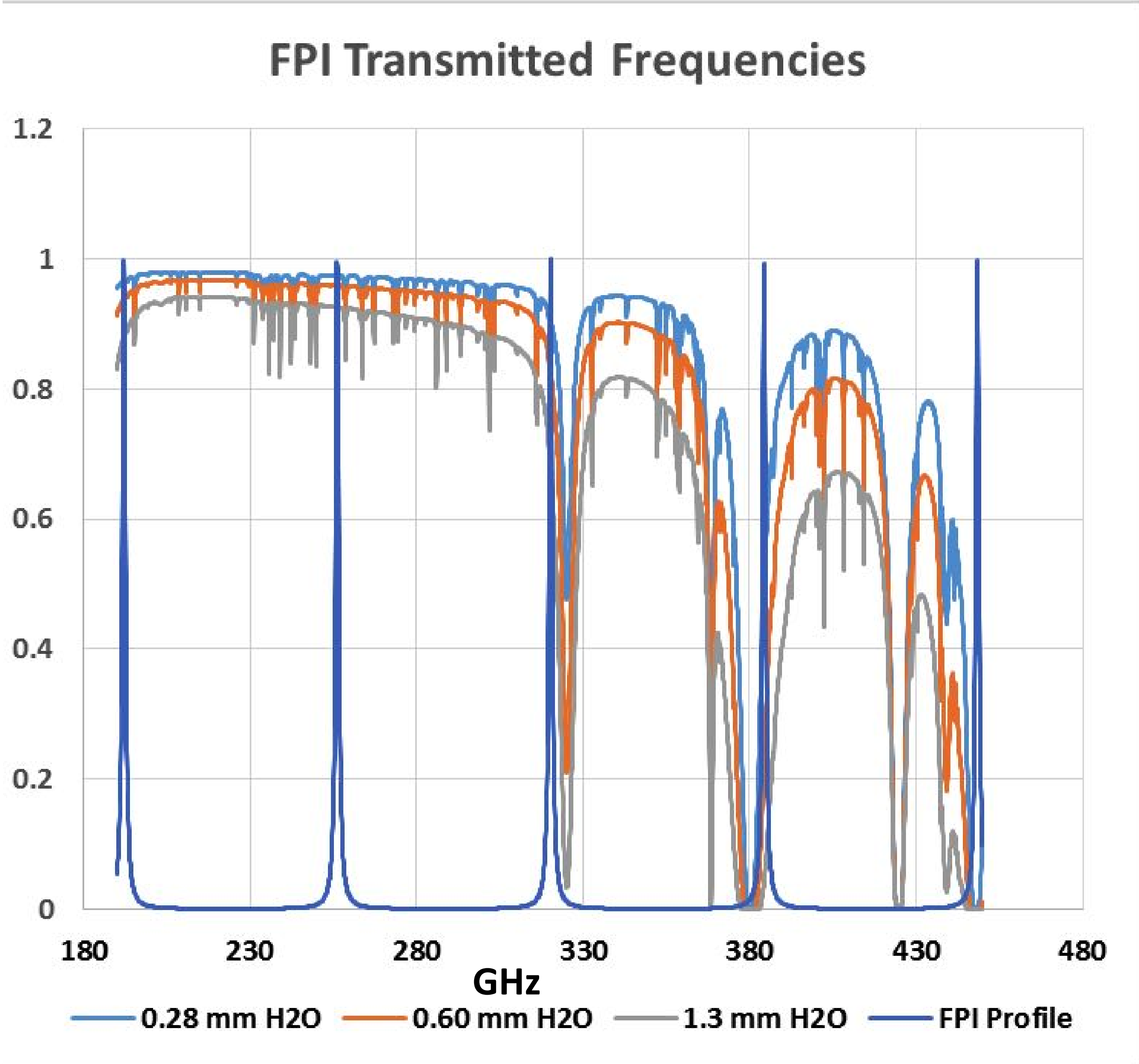


courtesy: G. Stacey



FPI Transmitted Frequencies
1.2
1
0.8
0.6
0.4
0.2
0
Transmission
180
230
280
330
380
430
480
GHz
0.28 mm H2O
0.60 mm H2O
1.3 mm H2O
FPI Profile

CCAT-p

Summary

CCAT-p

- EoR is the last unexplored epoch of galaxy evolution & structure formation
- CCAT-p will map out the topology of cosmic reionization through the clustering of star-forming galaxies, as observed in the [CII] 158 μm line
- Cross-correlation with HI 21cm will yield ionized bubble sizes
- Rich ancillary science: cold gas content of mid-z galaxies; [OIII] 88 μm IM
- Feasible with novel instrument design and low-transmission telescope at exceptional site
- Expected: dedicated ~4000 hr, 3-5 year survey, starting 2021