Intensity Mapping of Molecular Gas in the Early Universe

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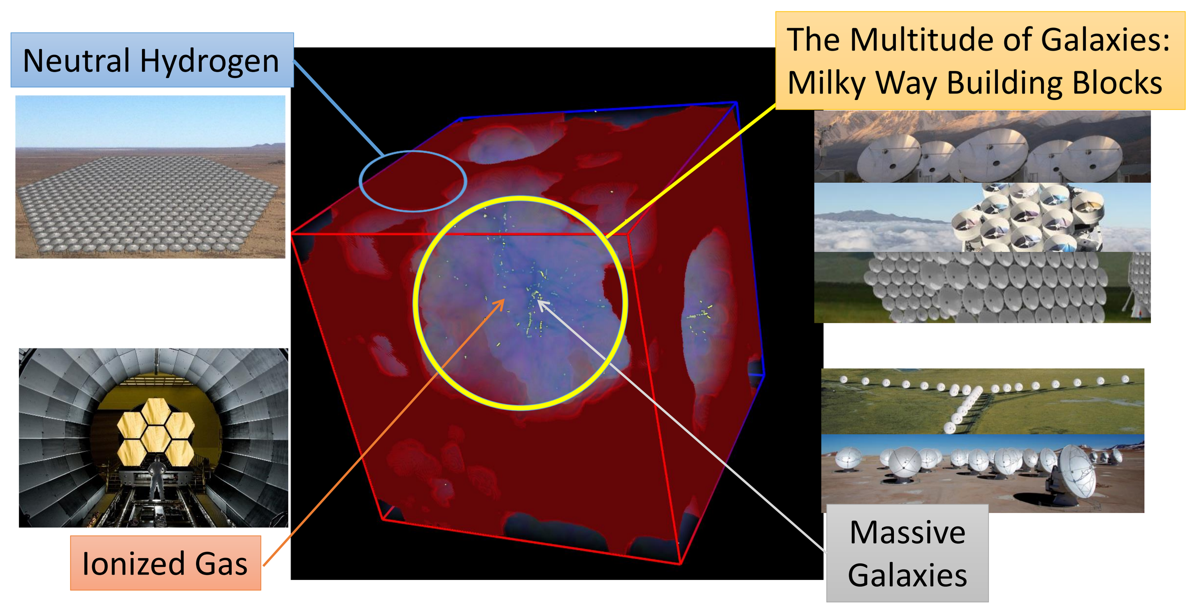
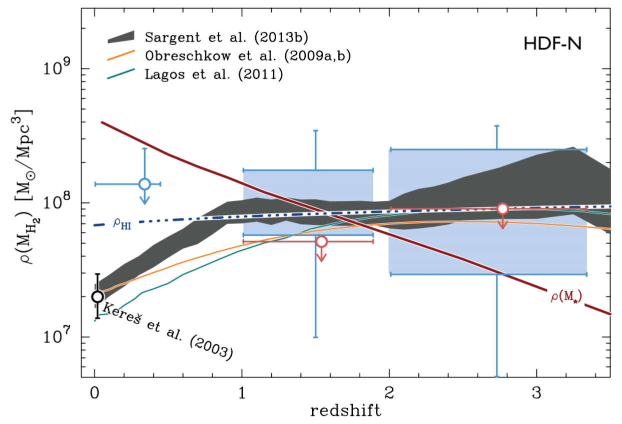
Tracking the Evolution of Cosmic Structure and Galaxies



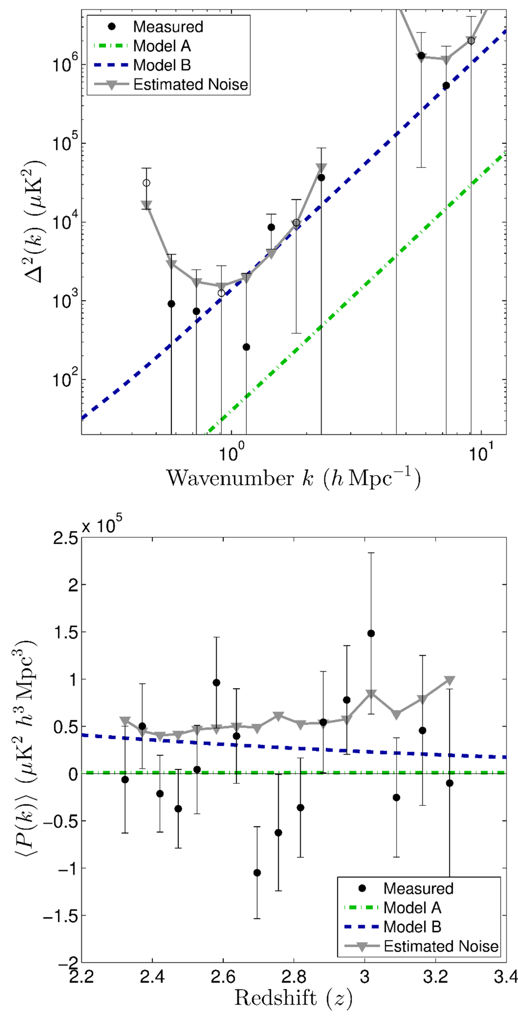
Above: A new generation of instruments will allow for detailed studies of the high-redshift Universe, though ELVA and ALMA will only be able to detect the most massive and luminous of galaxies at $z \sim 3$. Intensity mapping offers a path towards detecting the large population of "normal" (less massive) systems in the early Universe.



Right: Current constraints on the molecular gas density at $z < 3.5$. Current constraints for $z > 2$ are weak due to the difficulty in detecting high-redshift normal star-forming galaxies. (Figure taken from Walter et al., 2014)

- CO is a very powerful tracer for studying molecular gas and star formation.
- Normal star-forming galaxies at the peak of cosmic star formation ($z \sim 2$) difficult to detect individually.
  - Intensity mapping offers a way to detect these galaxies statistically.
- CO intensity mapping as a tool for probing the majority of star-forming galaxies at $z \sim 3$
  - "Shot-noise" power most sensitive to L_* / Milky Way progenitors.
  - "Cluster" power also sensitive to "Milky Way Building Block" galaxies.
- CO intensity mapping can also probe structure formation at $z \sim 3$ (large-scale structure; redshift-space distortions)

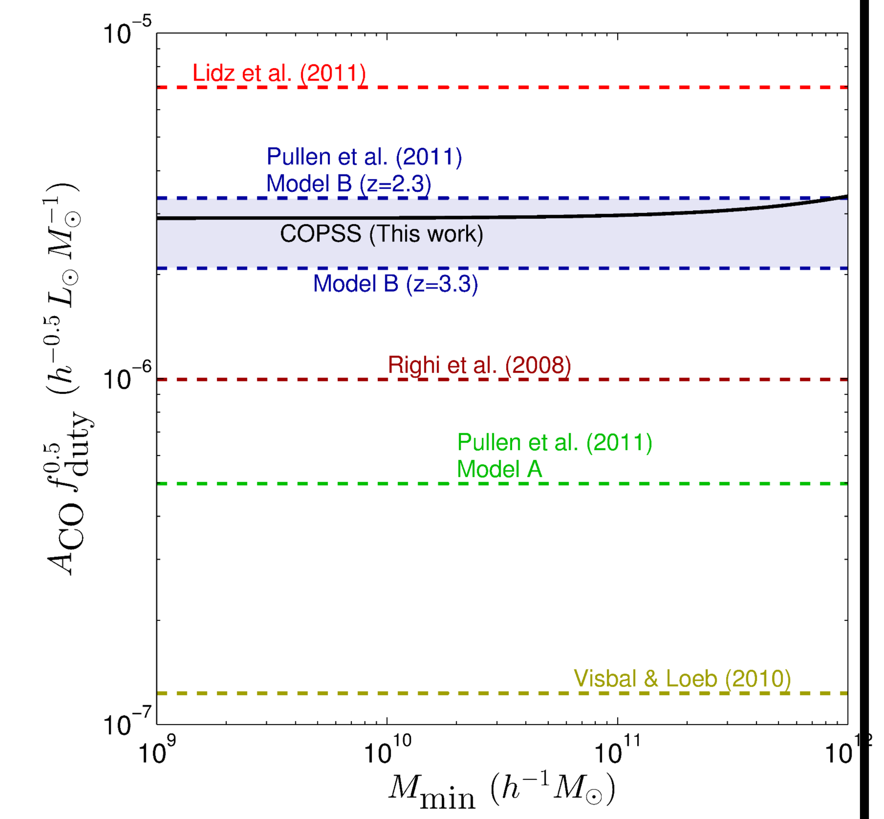
Pathfinder Analysis with Existing SZA Data



Top: Power spectrum result from Keating et al. 2015

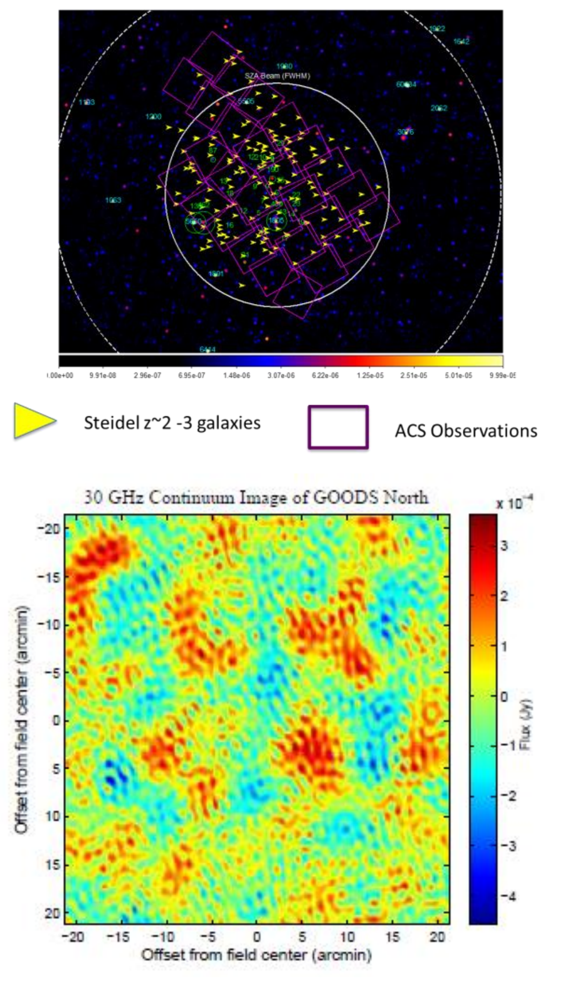
Bottom: Measured power as a function of redshift

- Data collected with the Sunyaev-Zel'dovich Array (SZA)
  - Original analysis performed by Sharp et al. (2010)
  - 8 elements, 3.5m diameter (6 in compact config + 2 outriggers)
  - Frequency coverage from 27-35 GHz, covering the CO(1-0) transition between $z = 2.3 - 3.3$
  - Sensitivity to spatial modes between $k = 0.5 - 2\ h^{-1}$ Mpc
  - 880 hours integration time on spent on 44 fields.
- Final results presented in Keating et al. 2015 (submitted)
  - $P_{CO} < 2.6 \times 10^4\ \mu K^2\ h^{-3}\ \mathrm{Mpc}^3$
  - $\rho_{H_2}(z \sim 3) < 2.8 \times 10^8\ M_\odot\ \mathrm{Mpc}^{-3}$



Above: Constraints on A_{CO}, the light-to-halo mass ratio, versus M_{min}, the minimum halo mass required for CO emission, where f_{duty} is the duty cycle of CO emission.

The CO Power Spectrum Survey (COPSS) with CARMA



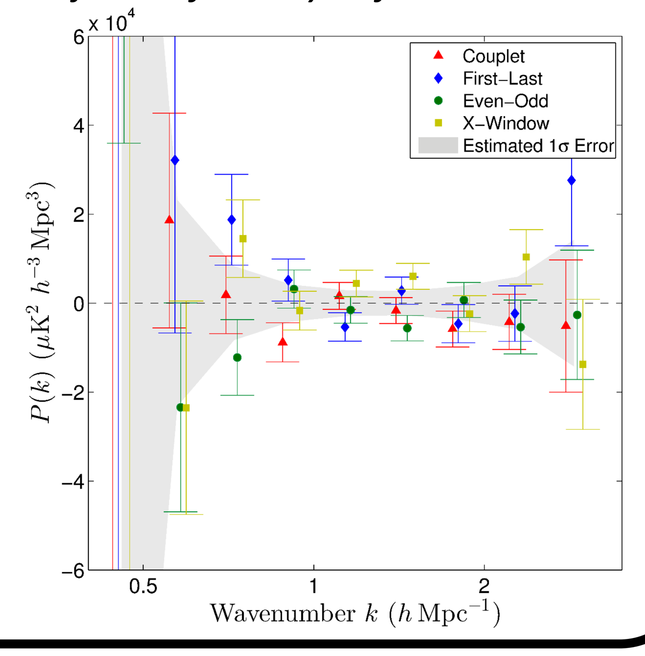
Top: The GOODS-N field, along with positions of galaxies at $z \sim 3$ with spectroscopic redshifts

Bottom: The 30 GHz continuum image of GOODS-N from COPSS data.

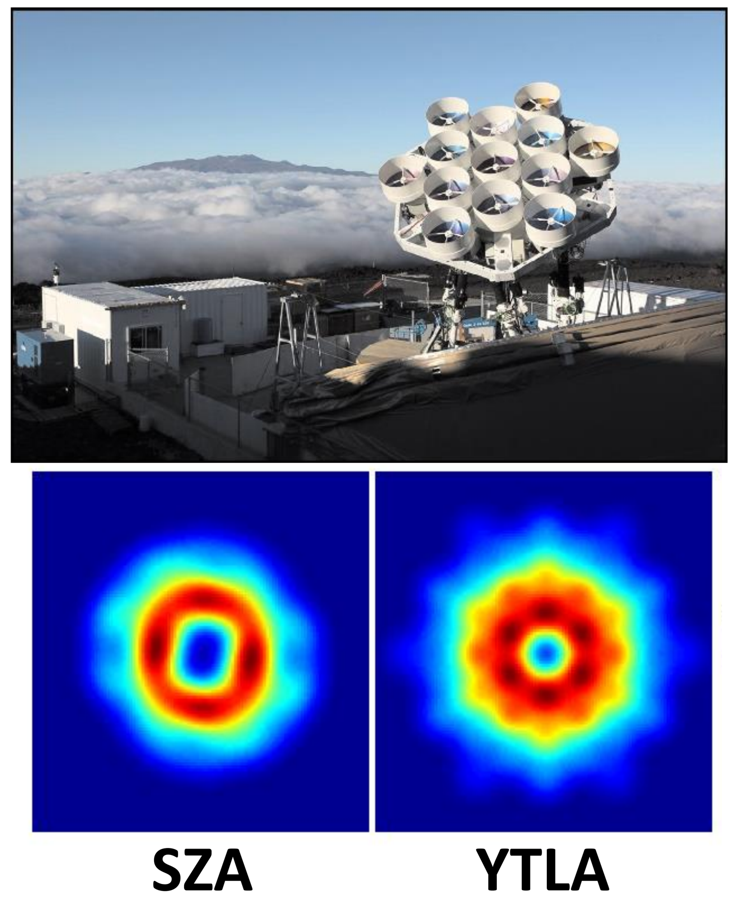
- Observations focused on CO intensity mapping conducted from 2013-2015
  - 5000 hours total observing time
  - Ultra-compact configuration (no outrigger antennas) – double the sensitivity per hour.
  - 12 primary fields, including GOODS-N, AEGIS, Q2343 – targets with opportunities for optical cross-correlation.
- Analysis approaching completion
  - Sensitivity expected to be 20 times greater than what was achieved with Sharp 2010 dataset.
  - Jackknife tests suggest data contamination is not an issue.

Above: The Sunyaev-Zel'dovich Array (SZA), in Owens Valley, CA.

Below: Current results from jackknife analysis from COPSS.



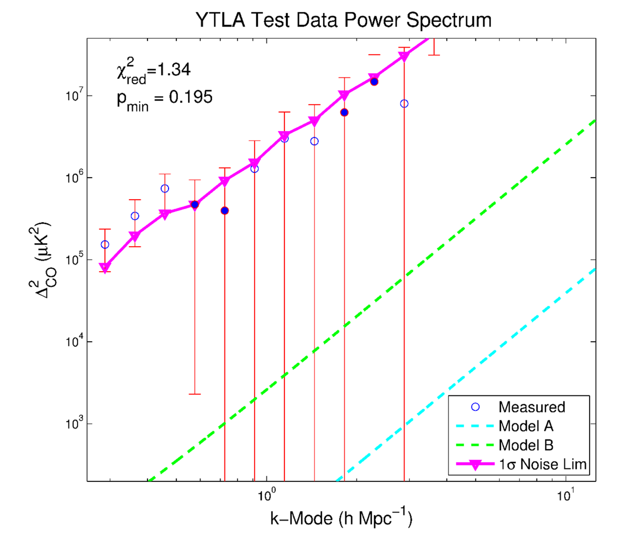
Future CO Intensity Mapping Efforts with the YTLA



Top: The Yuan T. Lee Array (YTLA), located atop Mauna Loa, HI.

Bottom: A comparison of the synthesized apertures for the SZA and the YTLA. Similar UV coverage and complementary frequency coverage allow for cross-correlation between the SZA and YTLA possible.

- Observations focused on CO intensity mapping conducted from 2013-2015
  - Frequency coverage between 86-102 GHz
  - Covers CO(3-2) ($z = 2.3 - 3.0$) and CO(2-1) ($z = 1.3 - 1.7$) transitions.
  - Sensitivity to spatial modes between $k = 0.4 - 2\ h^{-1}$ Mpc
- Commissioning currently underway
  - New digital correlator, 4 GHz w/ 8192 spectral channels
  - Surveys to begin in 2016
- Future plans to install 1-cm receivers
  - Will allow for sensitivity to spatial modes down to $k = 0.1\ h^{-1}$ Mpc, where cluster−power is expected to dominate.



Above: A power spectrum measurement of the CO(3-2) transition, using commissioning data.

Bottom: Estimated sensitivity of planned YTLA surveys.