Charting the Molecular Gas of the Universe Across Cosmic Time

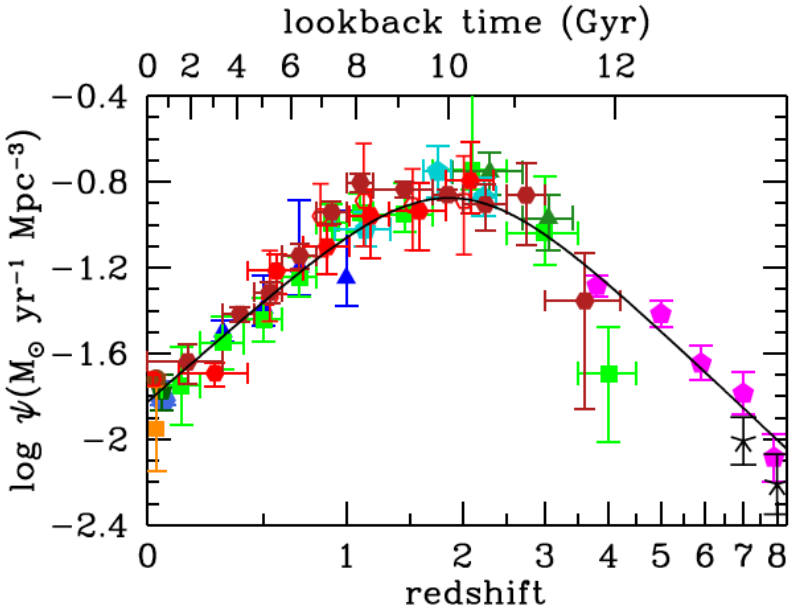
Garrett "Karto" Keating
Submillimeter Array Fellow
Smithsonian Astrophysical Observatory

garrett.keating@cfa.harvard.edu

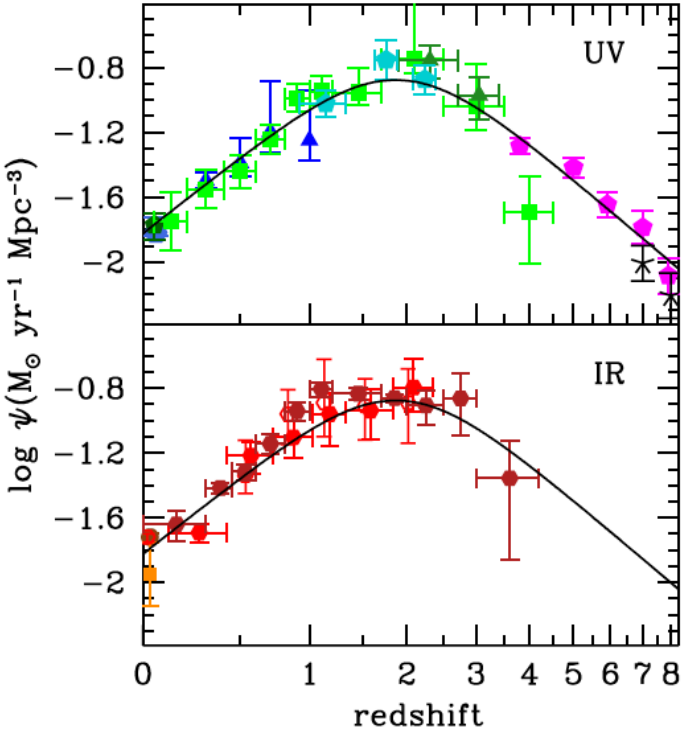
NEROC Symposium
November 8th, 2017

Exploring the Early Universe

Our knowledge of the star-formation history of the Universe has grown dramatically in the last two decades…



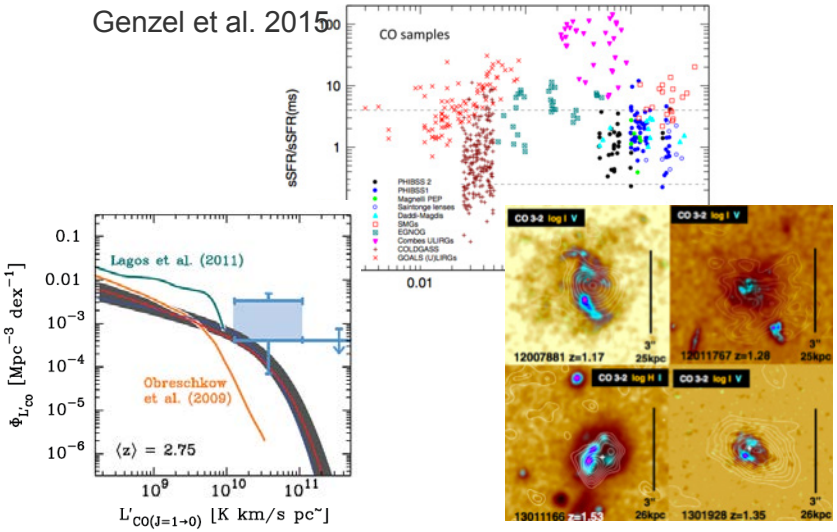
Madau and Dickinson, 2014



The New Frontier of Cold Gas

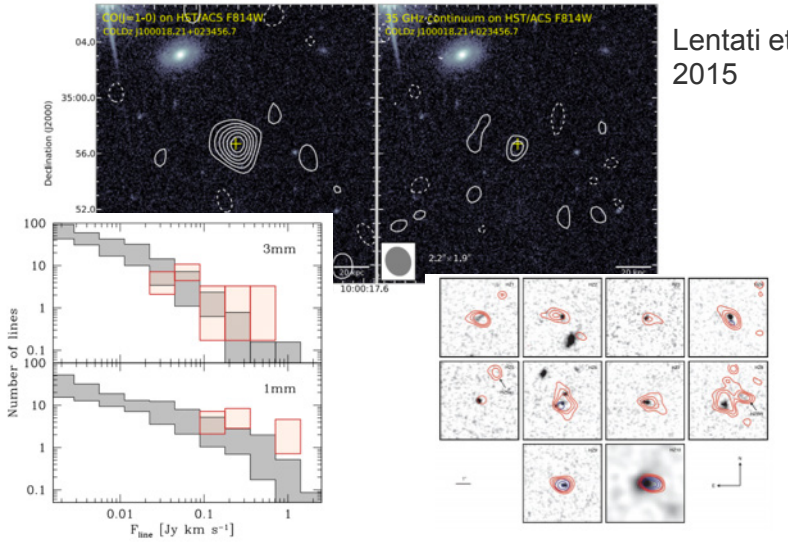
Current instruments have yielded dozens of high-redshift CO and [CII] detections…

Genzel et al. 2015



Walter et al. 2014

Tacconi et al. 2013



Lentati et al. 2015

Walter et al. 2016

Capak et al. 2015

…but what are the prospects for wide-field, wideband surveys to measure emission arising from *millions or billions* of galaxies?

Why Wide-Field?

Molecular Gas is incredibly complex:
CO, [CII] is dependent on chemistry, feedback, etc.; understanding how its ties to molecular gas requires both detailed studies *and* large, statistical samples

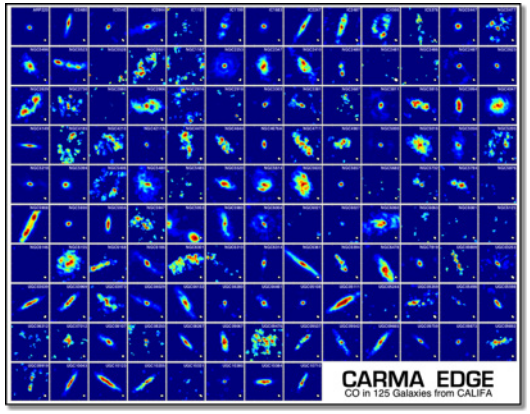
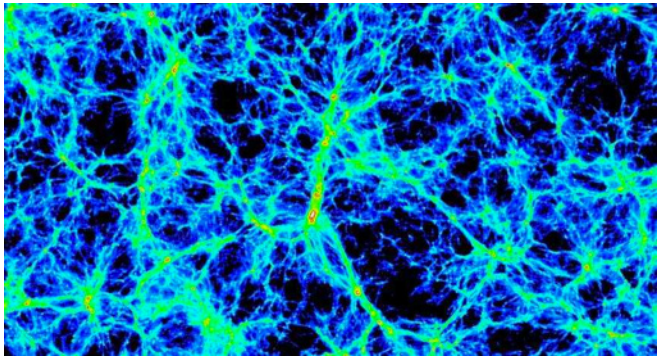


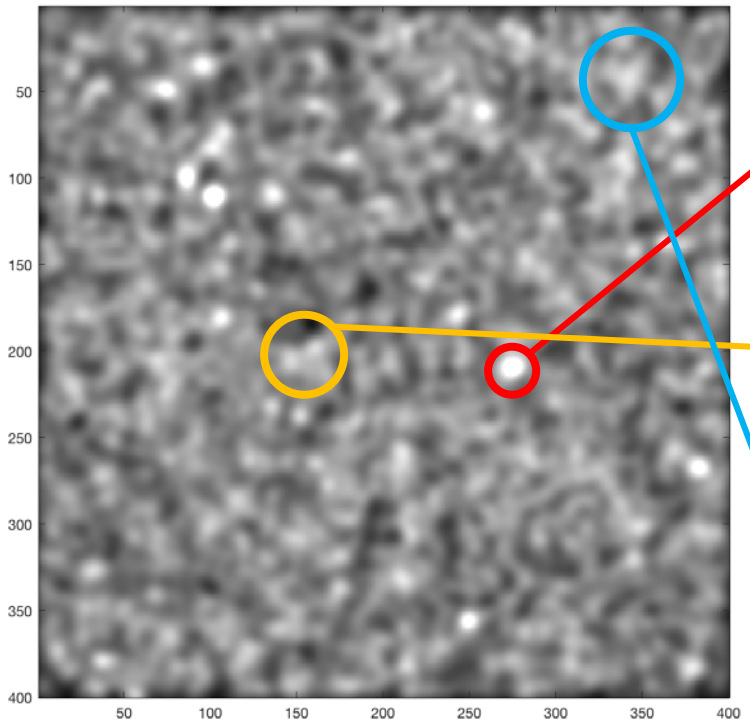
Image Credit: Alberto Bolatto



Cosmological applications:
Multiple cosmology-related measurements require $\gg 1\ \mathrm{deg}^2$

A wealth of full-sky/large-area data:
Entering an era of large, multi-wavelength full sky surveys (photo + spec)

Extracting Galaxy Emission



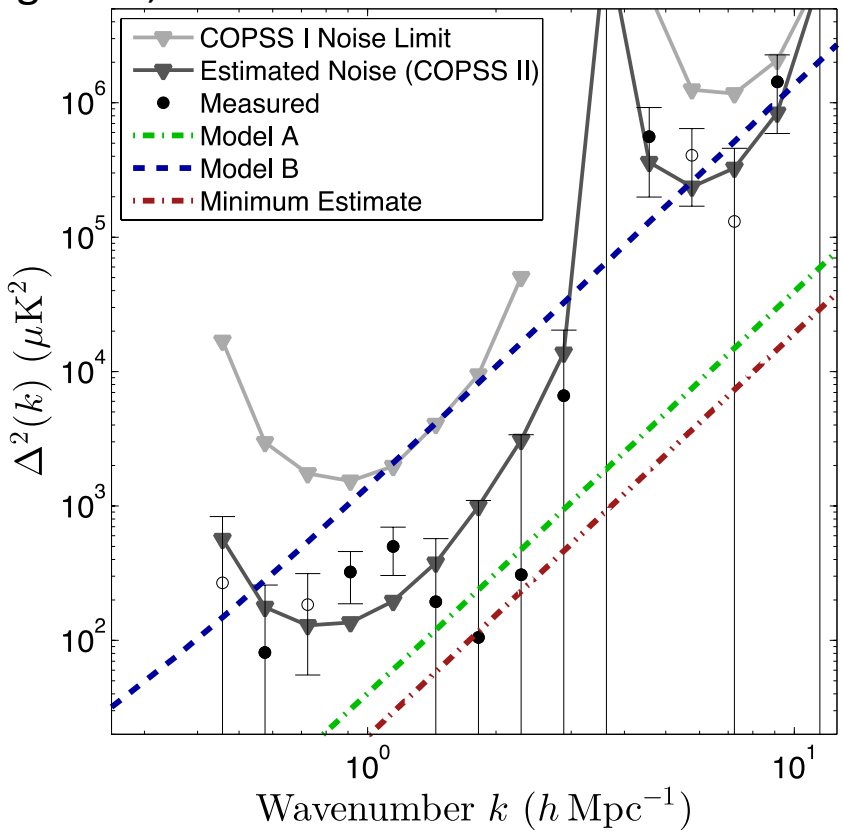
Direct Detection: Faint objects can be prohibitively expensive.

Source Stacking: Needs ancillary data

Intensity Mapping:
Excellent for faint sources, requires strong control of systematics.

Extracting Galaxy Emission

Keating et al., 2016



Intensity mapping is a tool for better leveraging wider, shallower datasets

Intensity Mapping:
Excellent for faint sources, requires strong control of systematics.

- On smaller scales ($< 1'$), it measures contributions from individual galaxies
- On larger scales ($> 1'$), it probes contributions from the cosmic web

Think Big, Go Small!

SZA Dishes

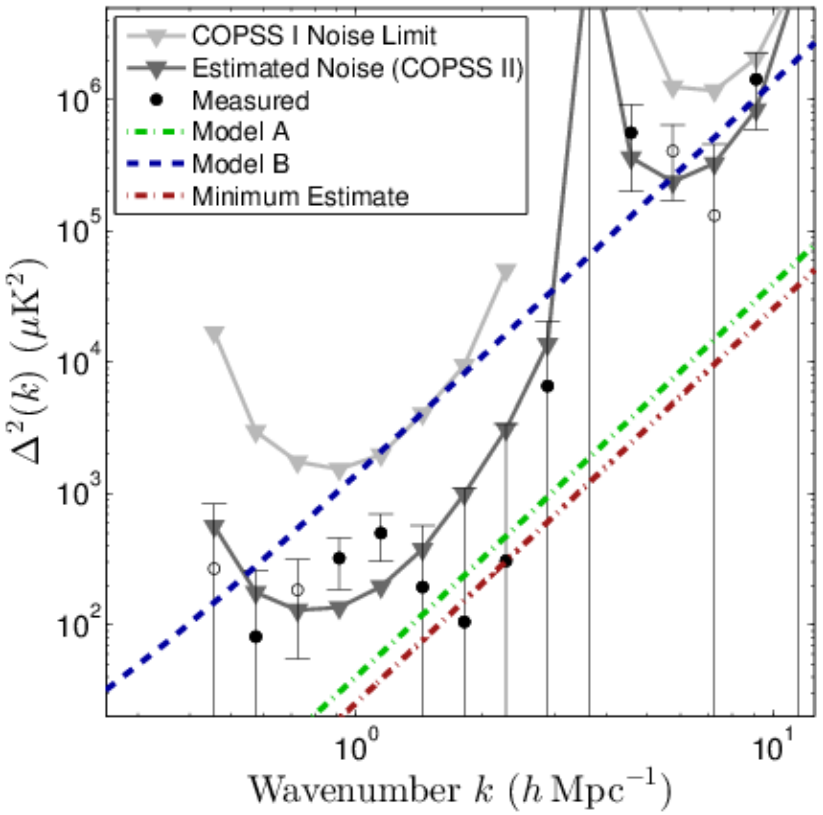
The CO Power Spectrum Survey (COPSS)

COPSS Collaborators:

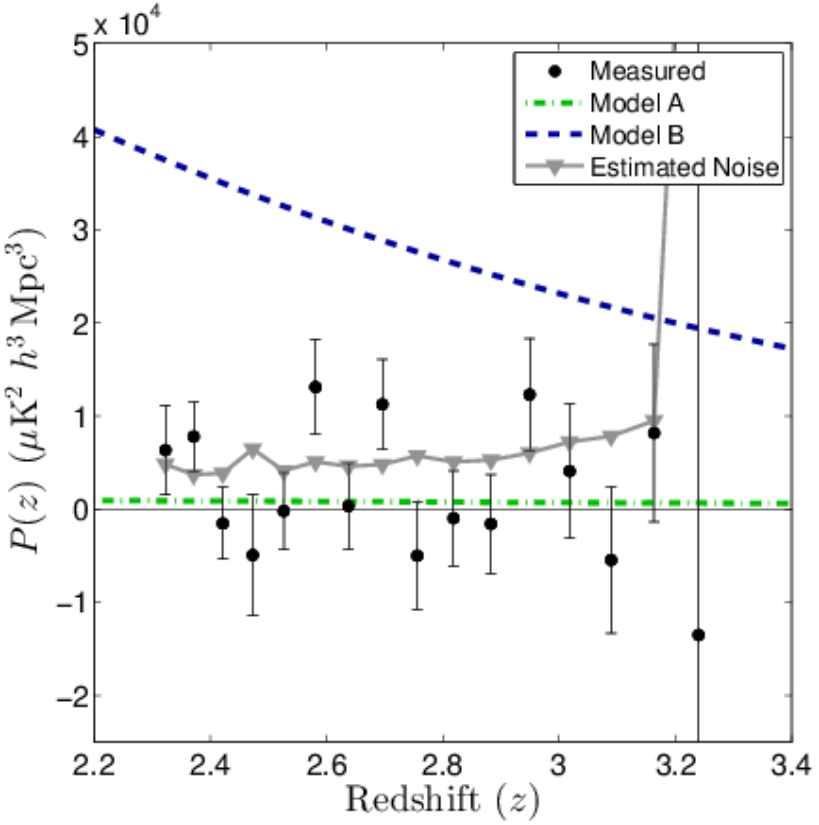
Karto Keating (PI; SAO, formerly Berkeley/UCPD)
Geoff Bower (ASIAA)
John Carlstrom (Chicago)
Tzu-Ching Chang (ASIAA)
Dave Deboer (Berkeley)
Chris Greer (Arizona)
Carl Heiles (Berkeley)
James Lamb (CalTech)
Erik Leitch (CalTech)
Dan Marrone (Arizona)
Amber Miller (Columbia)
Stephan Muchovej (CalTech)
Dick Plambeck (Berkeley)
David Woody (CalTech)

Primary Survey Results

CO Power Spectrum



CO Redshift Evolution

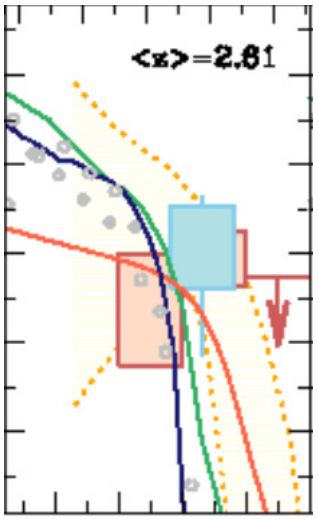


First (tentative) detection! $P_{\mathrm{CO}} = 3.0^{+1.3}_{-1.3} \times 10^3\ \mu\mathrm{K}^2\ (\mathrm{Mpc}/h)^3$

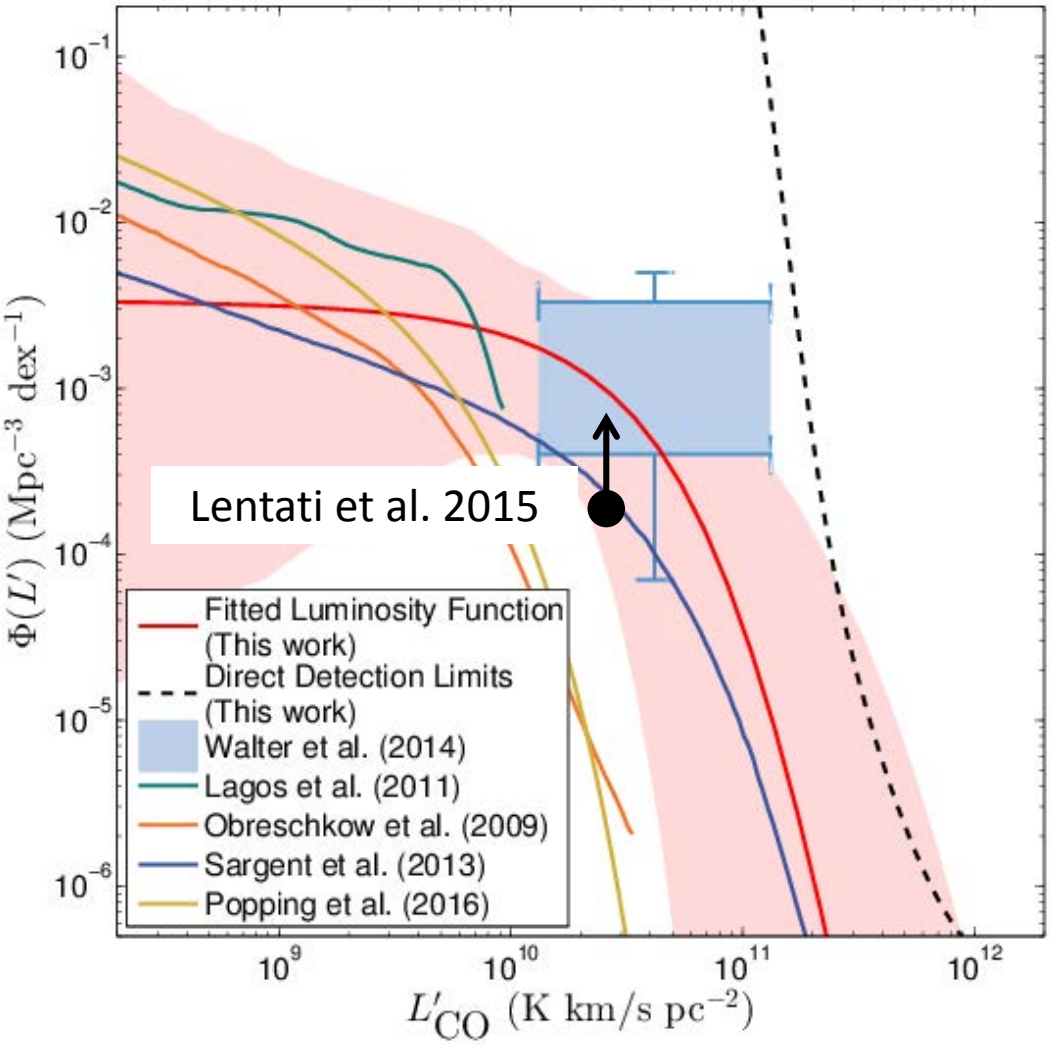
Weak evidence ($\sim 1\sigma$) of increasing power with decreasing redshift.

Keating et al., 2016

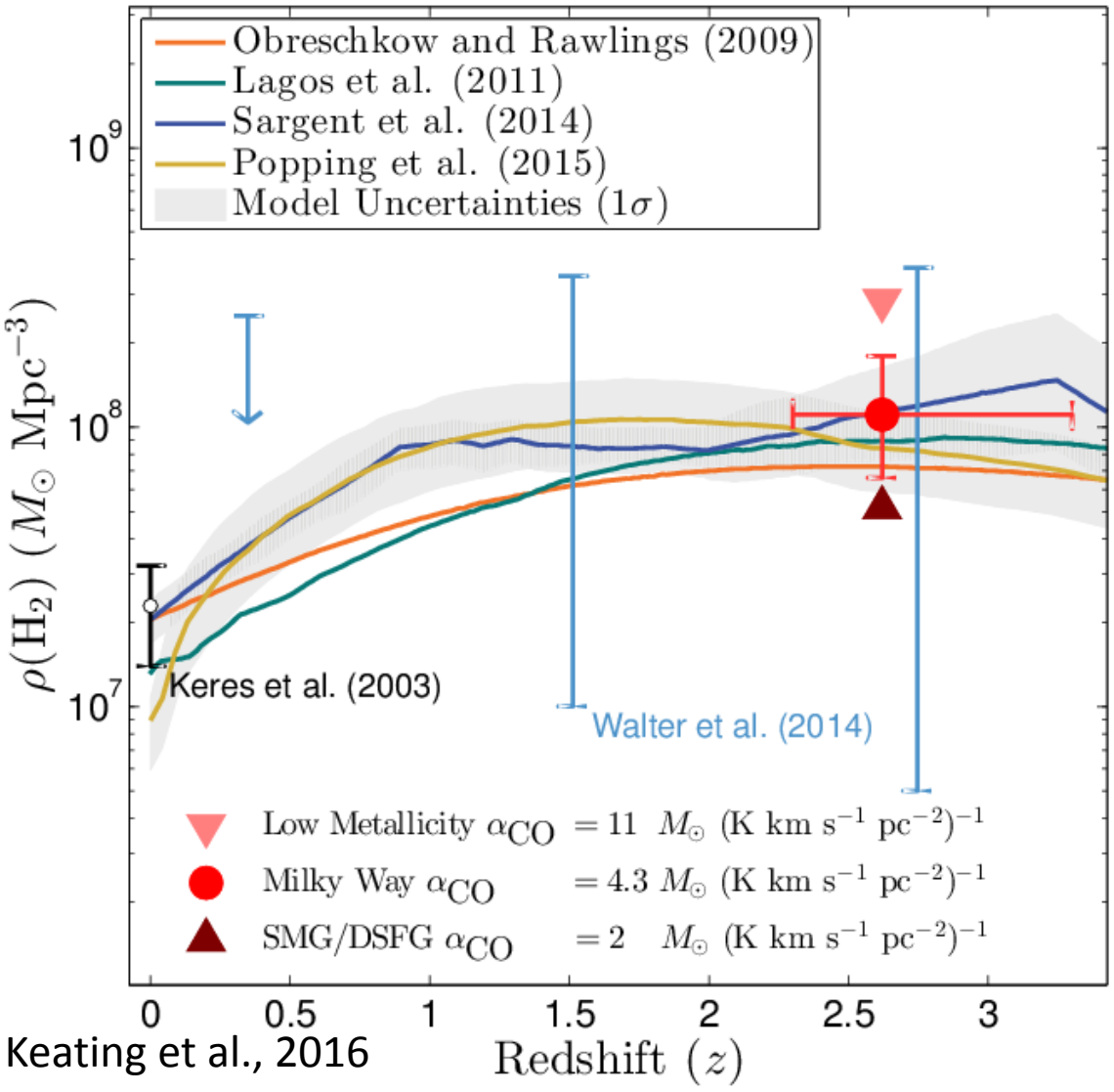
The CO Luminosity Function



Results from ALMA (Decarli et al. 2016) in agreement with COPSS!



Cosmic Molecular Gas

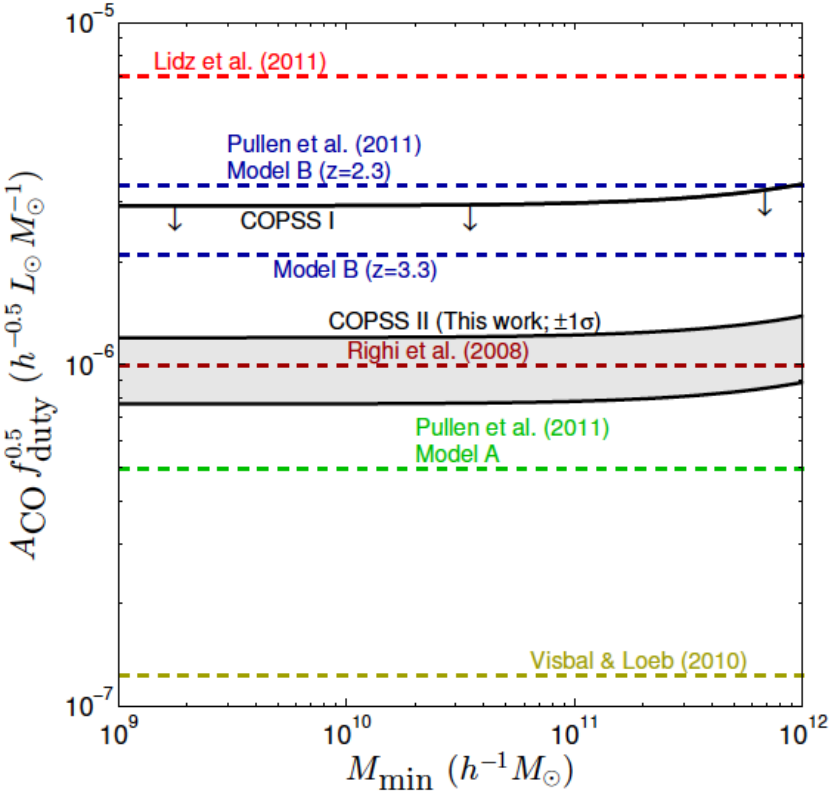


Keating et al., 2016

Current State of Cold Gas Surveys

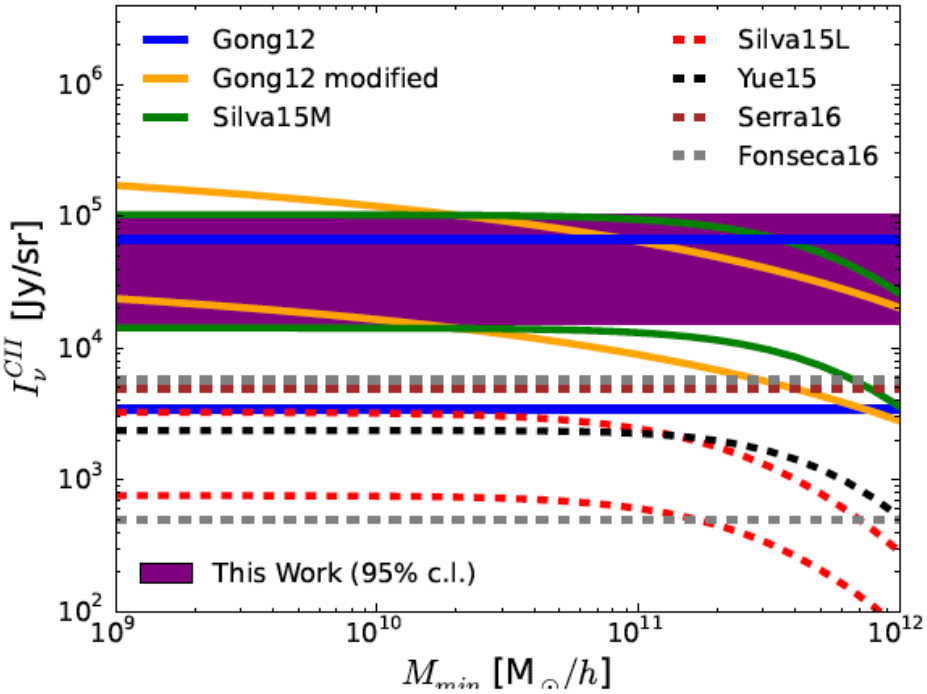
Progress in Intensity Mapping

CO at $z \sim 3$



Keating et al., 2016

[CII] at $z \sim 3$

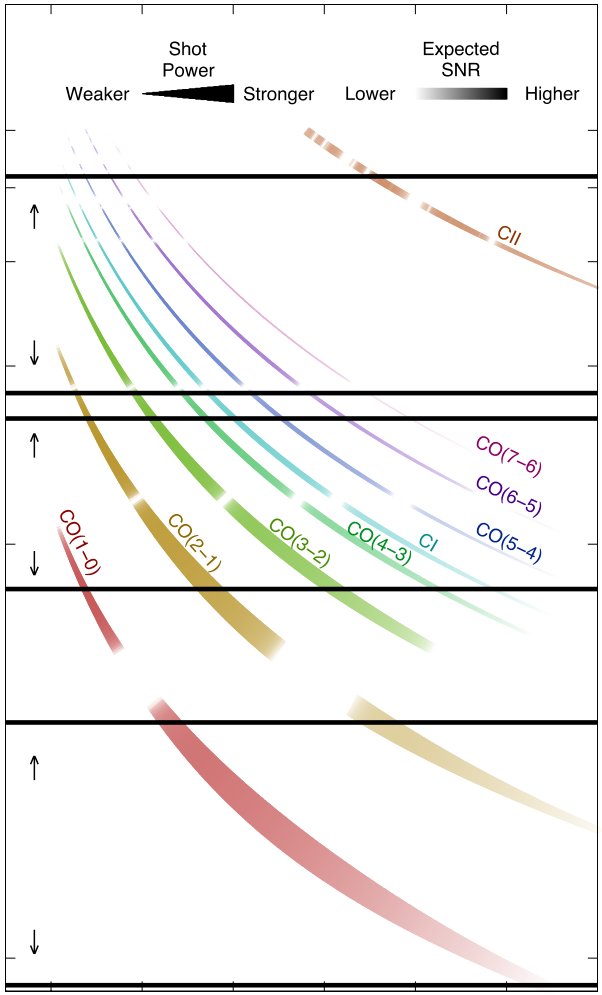


Pullen et al., 2017

Future CO/[CII] Intensity Mapping

The Millimeter Intensity Mapping Experiment (mmIME):

"It only looks like there's nothing there"



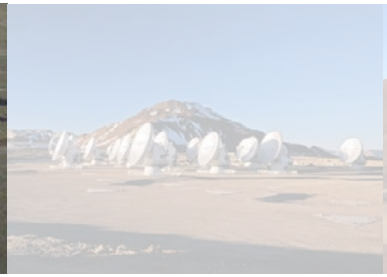
VLA (1cm) **ACA/ALMA (3mm)** **SMA (1mm)**

VLA, ACA and SMA are **well-suited** for intensity mapping cross-correlation studies!

Karto Keating (PI; CfA/SAO)

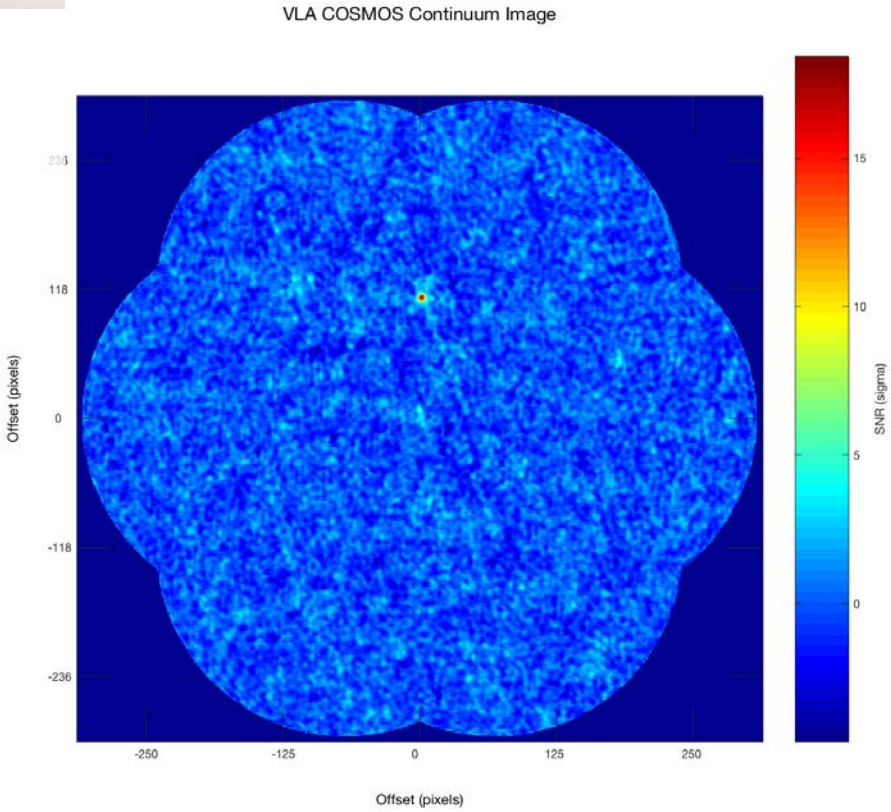
Geoff Bower (ASIAA)
Tzu-Ching Chang (ASIAA)
Anastasia Fialkov (CfA)
Avi Loeb (CfA)
Natalie Mashian (CfA)
Dan Marrone (Arizona)
Wei-Hao Wang (ASIAA)

Recent Progress with mmIME



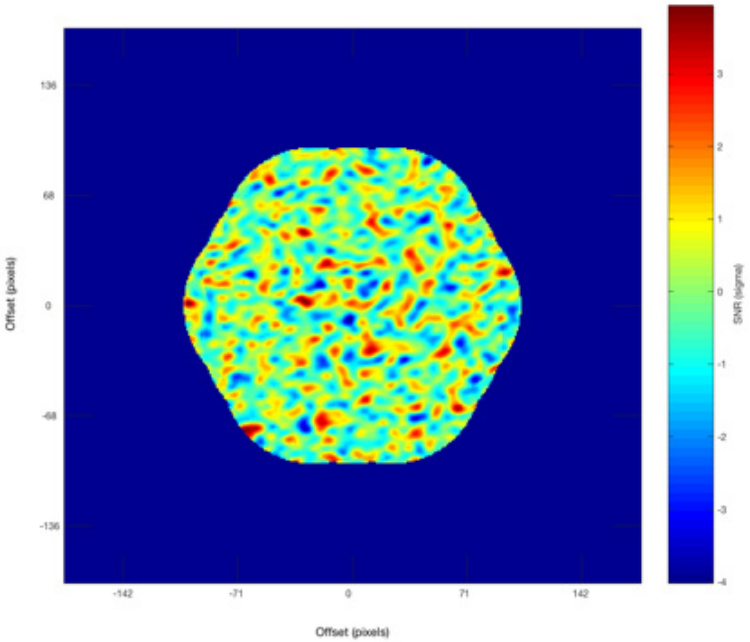
VLA (1cm) ACA/ALMA (3mm) SMA (1mm)

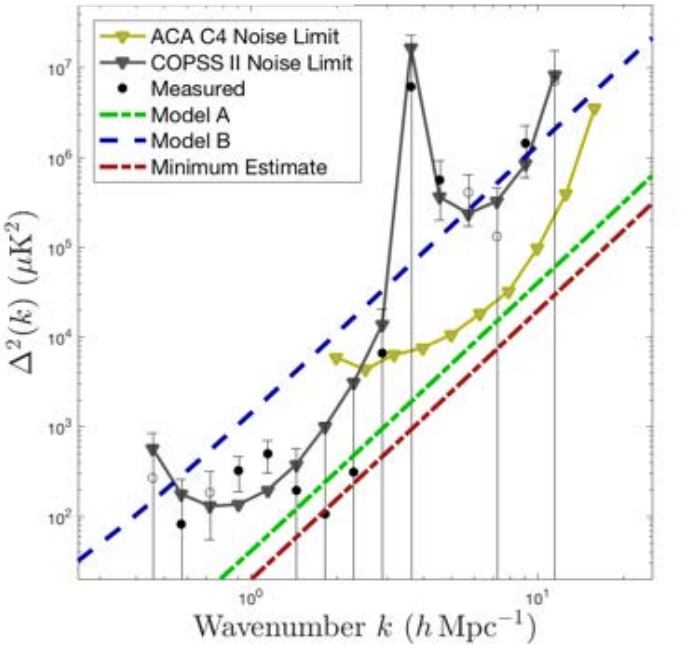
Presently analyzing a 500 hour VLA legacy project, targeting CO in GOODS-N and COSMOS.



Recent Progress with mmIME

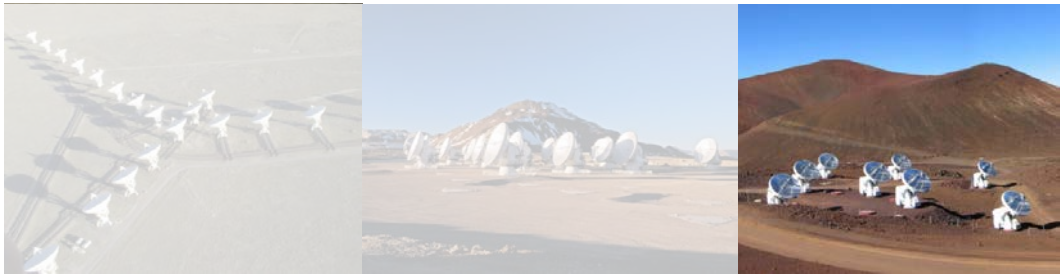
VLA (1cm) ACA/ALMA (3mm) SMA (1mm)





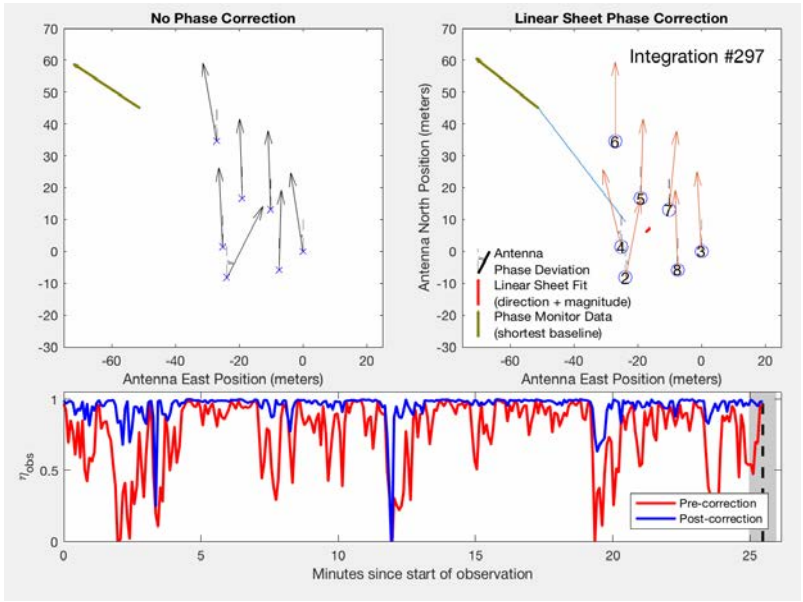
ACA completed a 40 hour survey in Cycle 4, targeting VLA region in COSMOS in Band 3

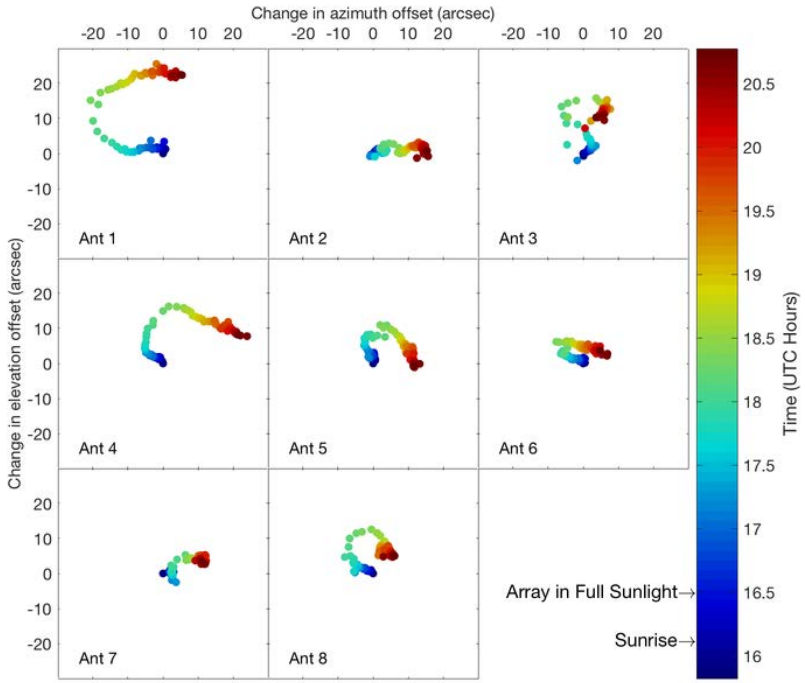
Recent Progress with mmIME



VLA (1cm) ACA/ALMA (3mm) SMA (1mm)

SMA conducted a 100 hour pilot study, now studying prospect of daytime observing





Comments and Questions

Concluding points:

- **The cold gas of typical high-redshift galaxies a critical piece of the star-formation puzzle of the early Universe**
- **Intensity mapping of CO/[CII] offers an inexpensive way to probe cold gas, that would otherwise be difficult to detect directly**
- **The first generation of experiments and instruments are coming online now, *stay tuned!***