Exploration of High Redshift Galaxies through Intensity Mapping

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SMA Science in the Next Decade
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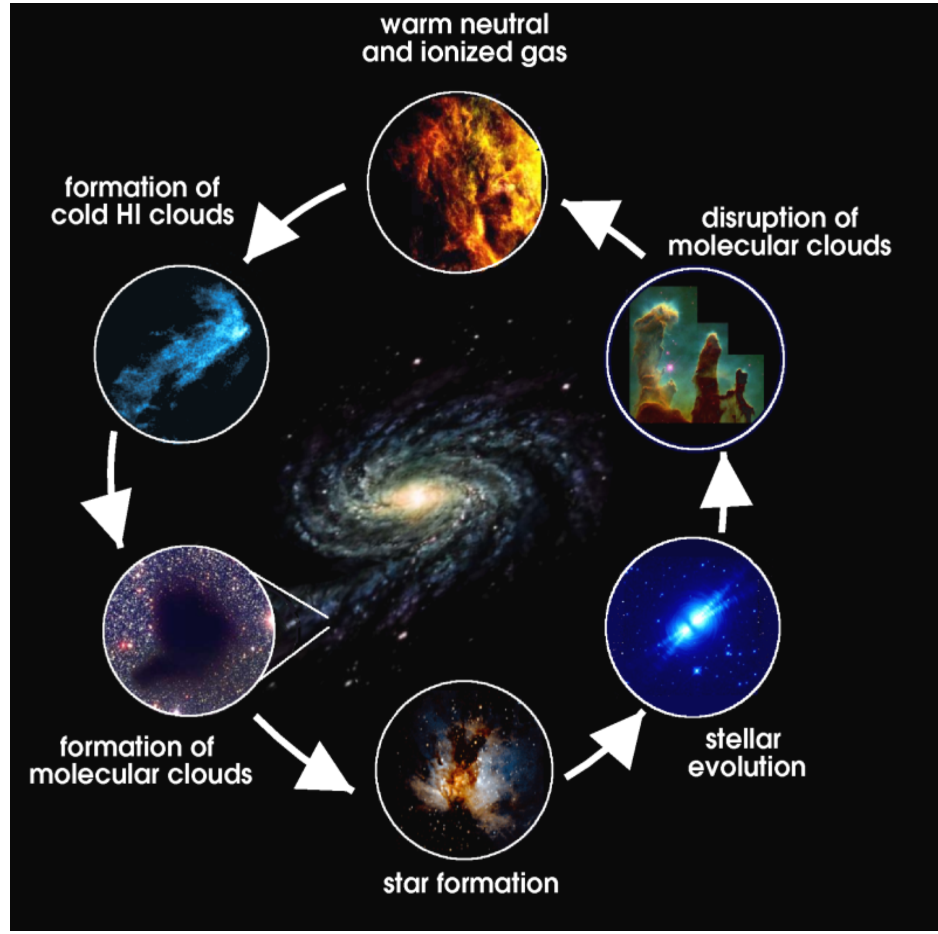
Exploring the Early Universe

Molecular gas, as the fuel for star formation, is a vital component of galaxies, and plays a crucial role in their evolution.

CO and [CII] are two of the principle tracers used for cold gas within galaxies.

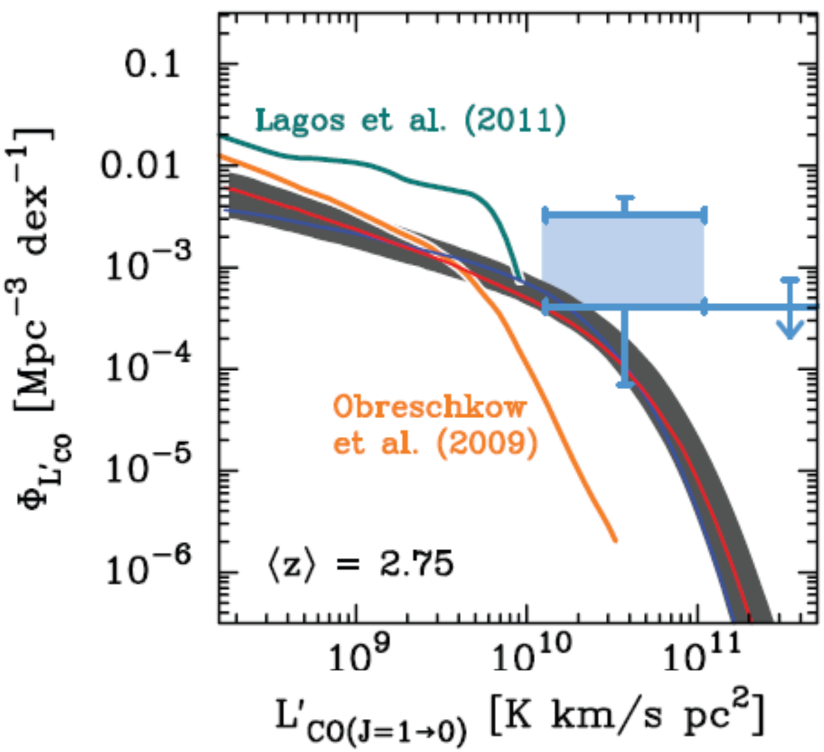


Kulesa, C. 2011, Bolatto et al., 2013

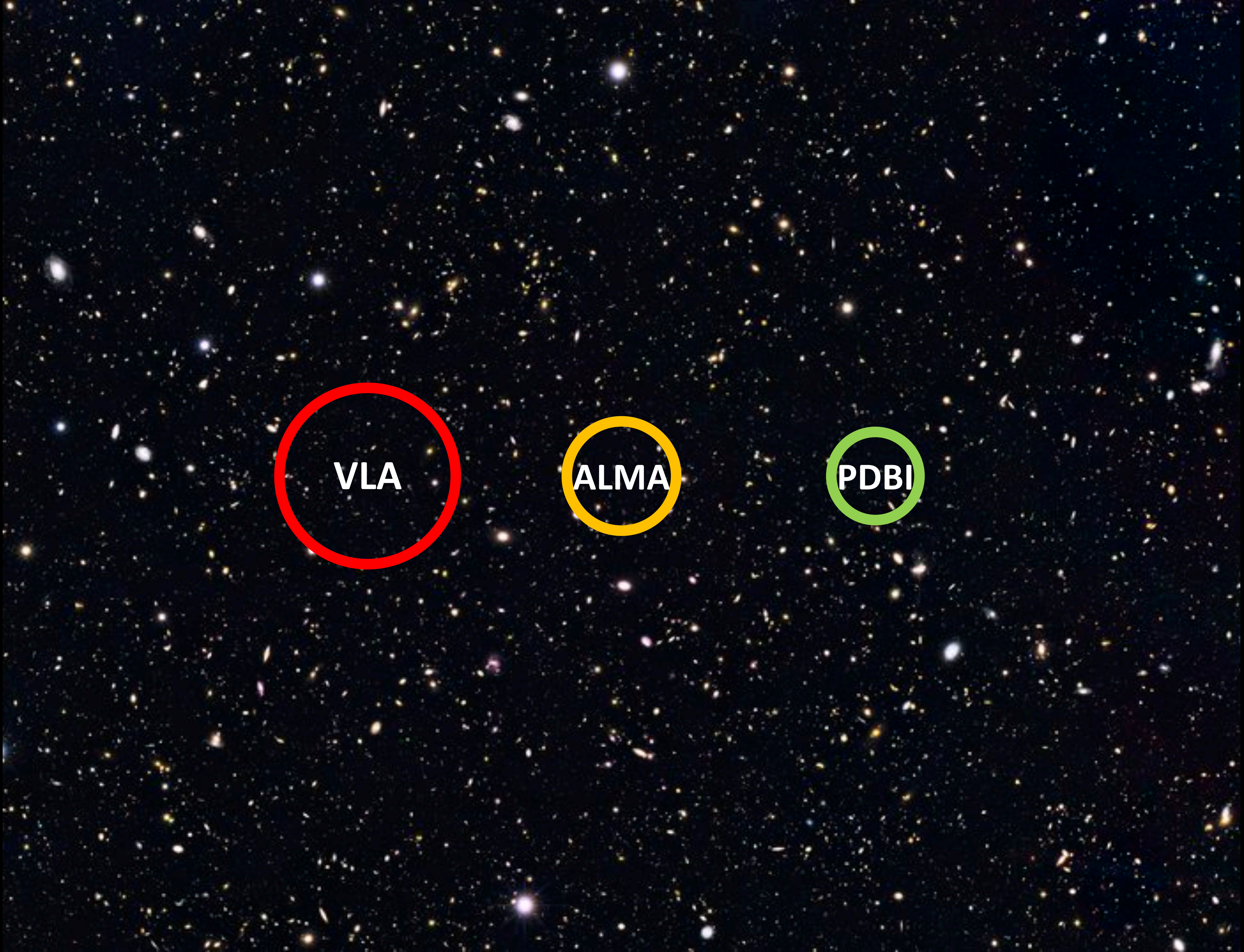
CO Luminosity Function

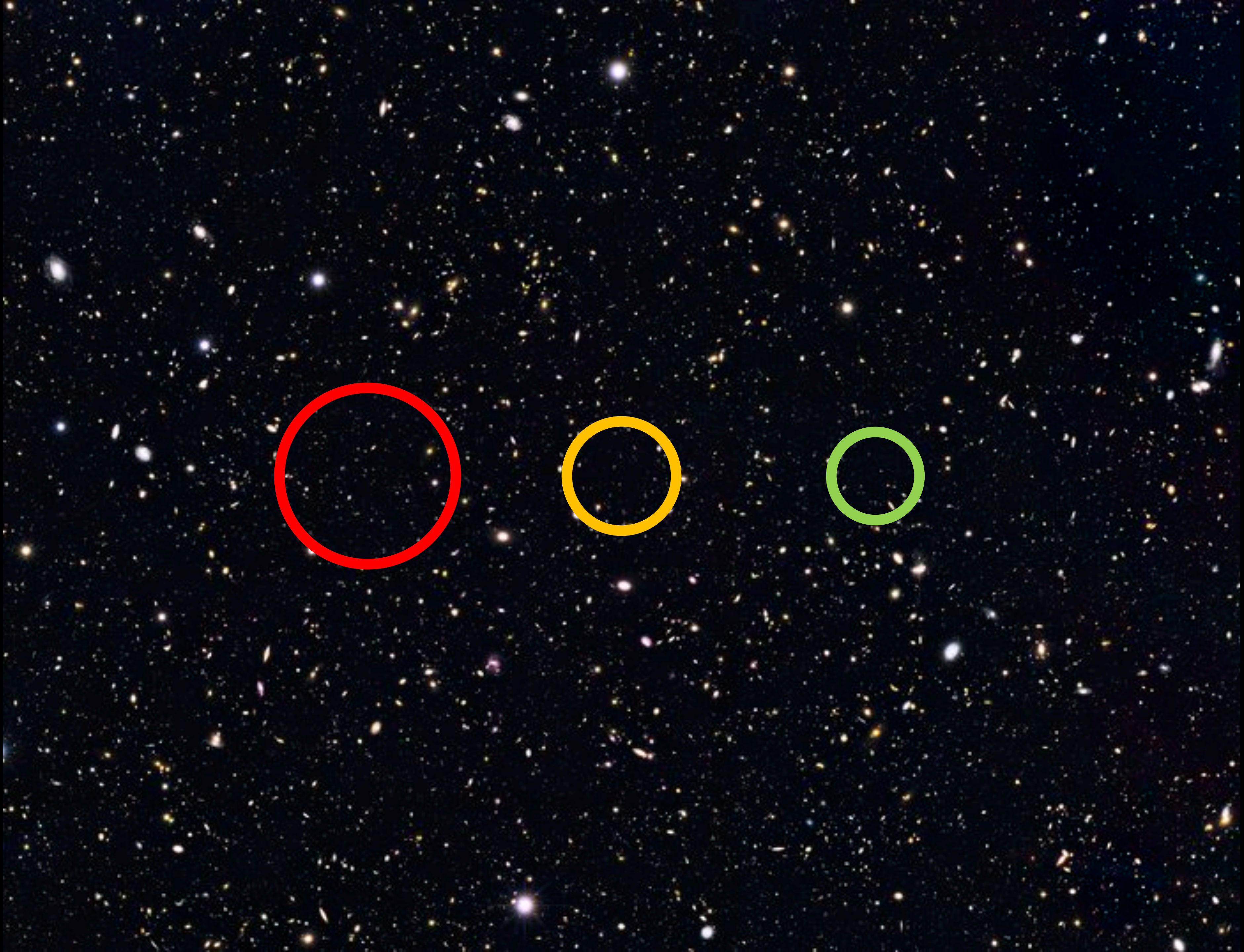
Measuring CO/[CII] emission from a broad population of galaxies is important for measuring the abundance and evolution of molecular gas.

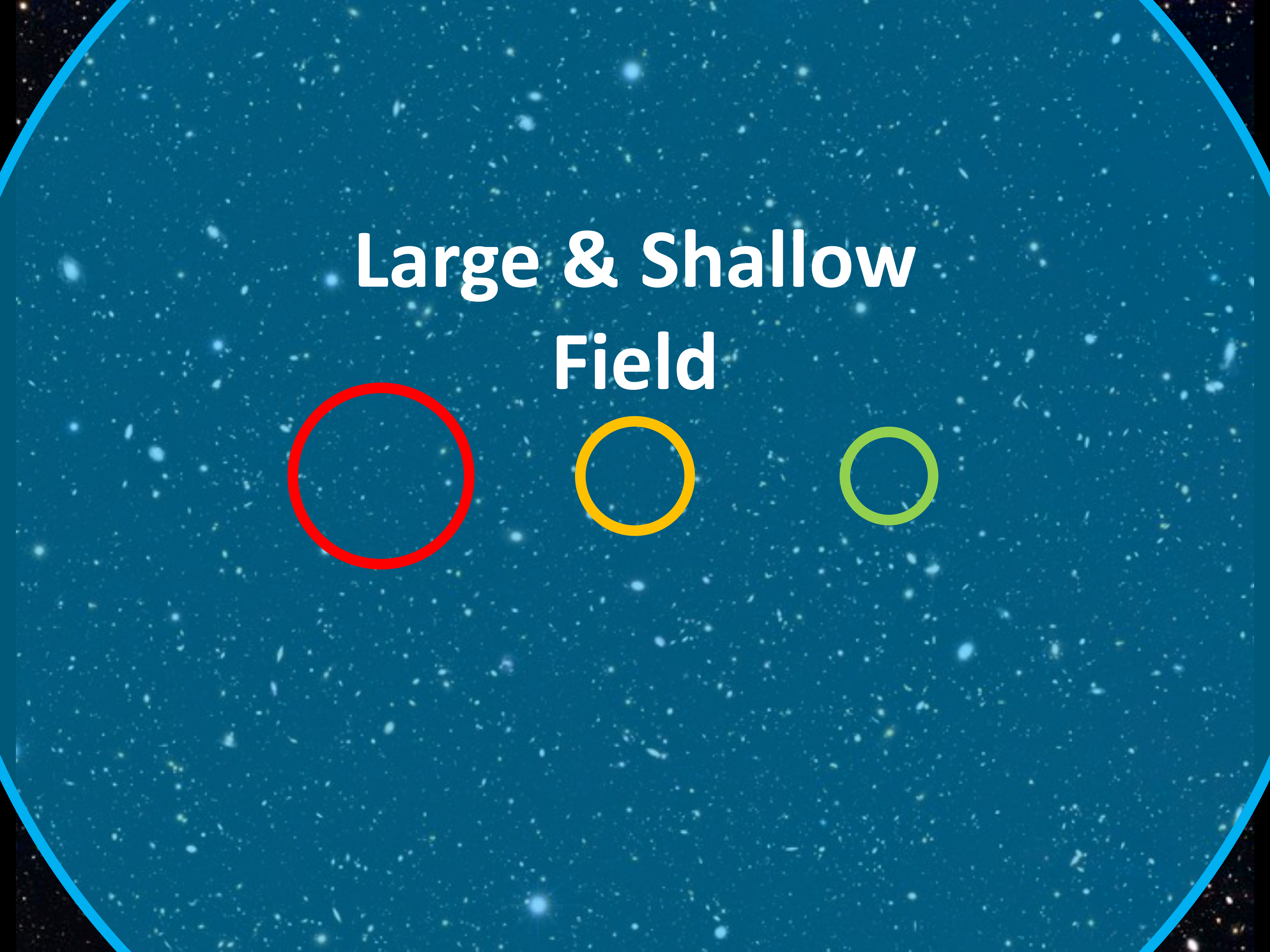
Constraints on CO at $z \sim 3$ are the product of 100 hours integration time with PdBI. *Even with this deep a measurement, these constraints are very weak!*

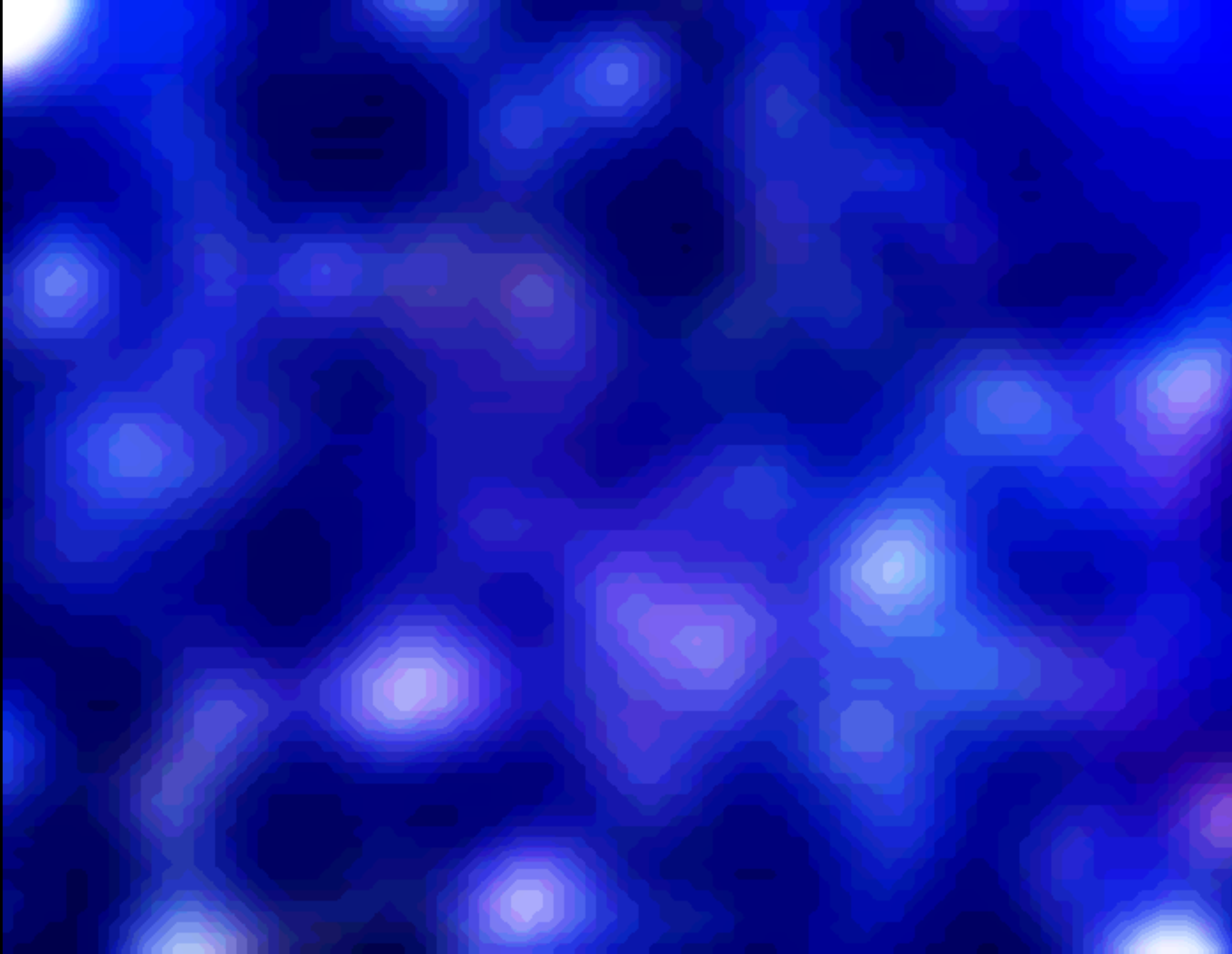


Walter et al., 2014


VLA
ALMA
PDBI

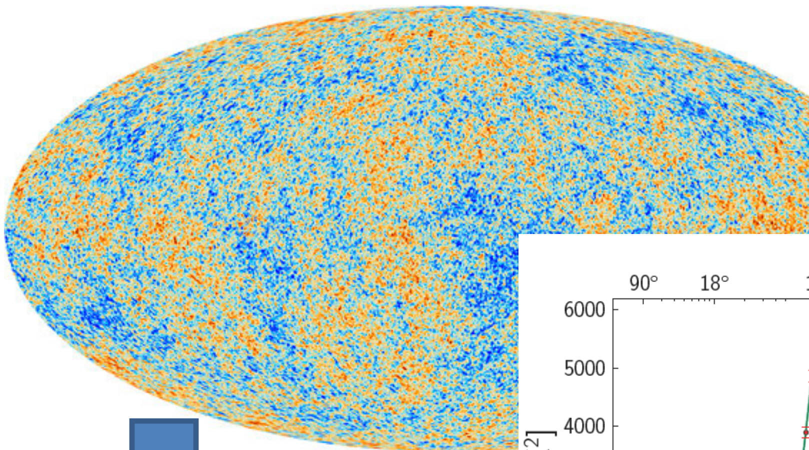



Large & Shallow
Field



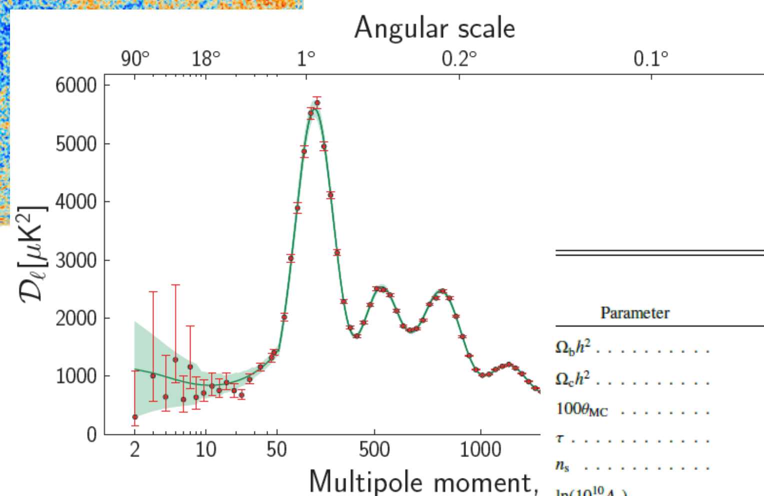
CMB Power Spectrum Analysis

CMB Observed



Intensity mapping shares a common methodology with CMB power spectrum production and analysis.

Statistics Derived



2PCF & $\mathcal{F}(k)$

Properties Determined

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10}A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

Theory & Models

Planck Collaboration, 2011-I

Think Big, Go Small!

SZA Dishes

The CO Power Spectrum Survey (COPSS)

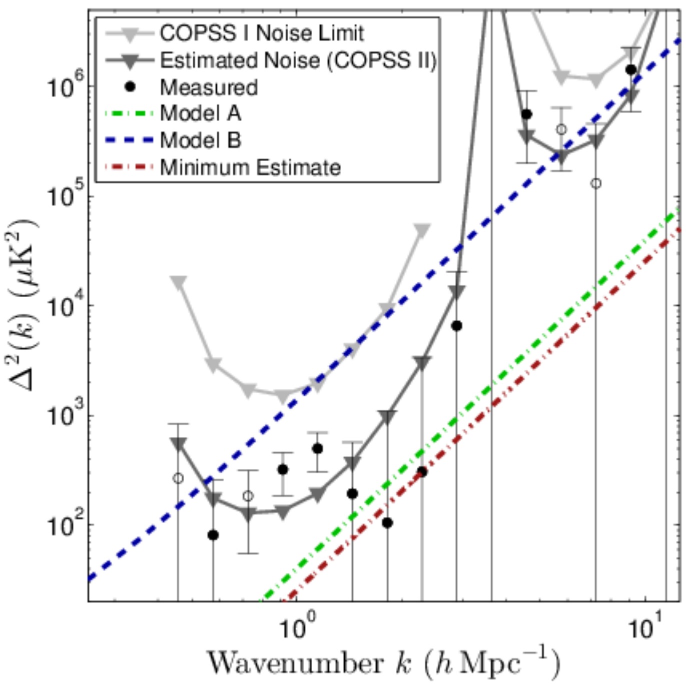
COPSS Collaborators:

Karto Keating (PI; SAO, formerly Berkeley/UCPD)

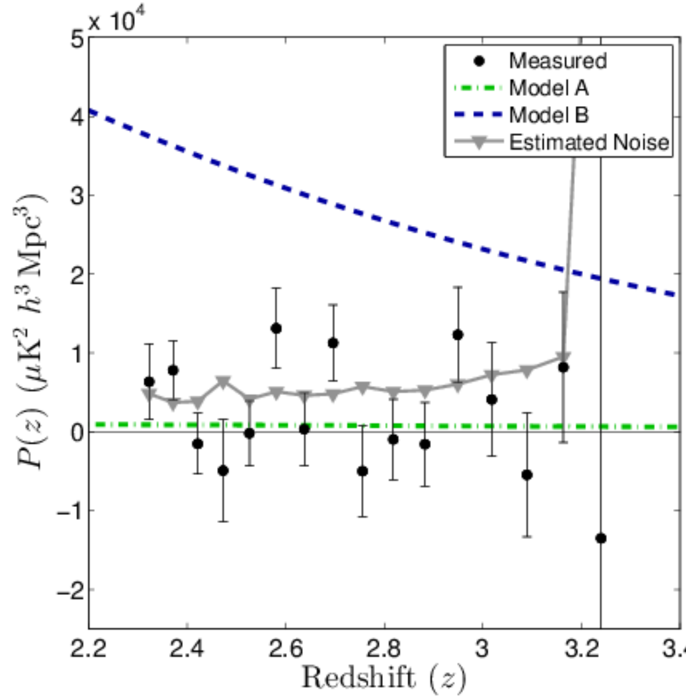
Geoff Bower (ASIAA)
John Carlstrom (Chicago)
Tzu-Ching Chang (ASIAA)
Dave Deboer (Berkeley)
Chris Greer (Arizona)
Carl Heiles (Berkeley)
James Lamb (CalTech)
Erik Leitch (CalTech)
Dan Marrone (Arizona)
Amber Miller (Columbia)
Stephan Muchovej (CalTech)
Dick Plambeck (Berkeley)
David Woody (CalTech)

Primary Survey Results

CO Power Spectrum



CO Redshift Evolution



First (tentative) detection! Power spectrum for CO constrained to $P_{\mathrm{CO}} = 3.0^{+1.3}_{-1.3}{\times}10^3\ \mu\mathrm{K}^2\ (\mathrm{Mpc}/h)^3$, $P_{\mathrm{CO}} > 0$ to 98.9% confidence. Weak evidence ($\sim 1\sigma$) of increasing power with decreasing redshift.

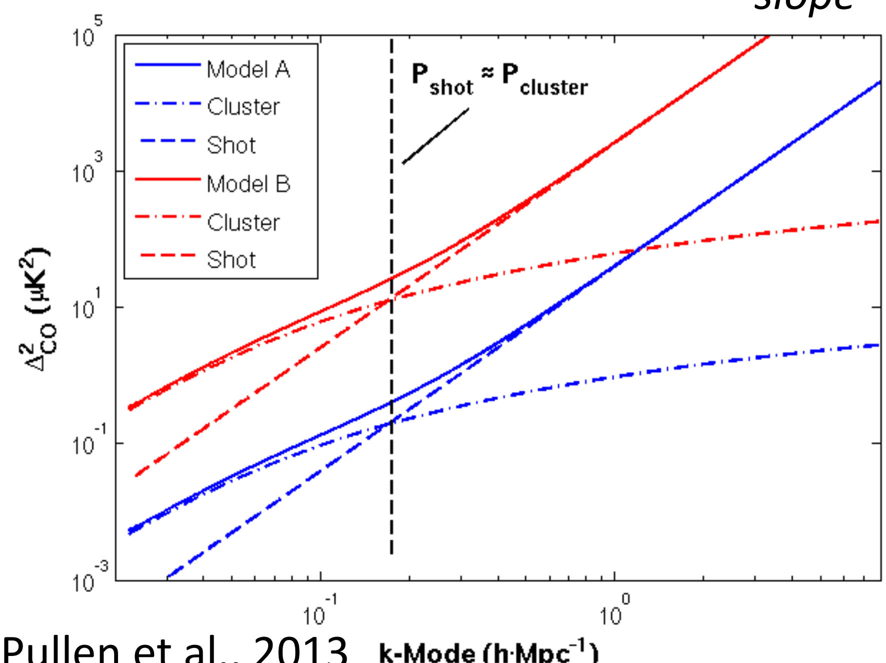
Keating et al., 2016

A Tale of Two Regimes

Luminosity function of the form

$$\Phi_{CO}(L) = \phi^* \left(\frac{L}{L_*}\right)^{\alpha} e^{-L/L_*}\, dL \quad L > L_{min}$$

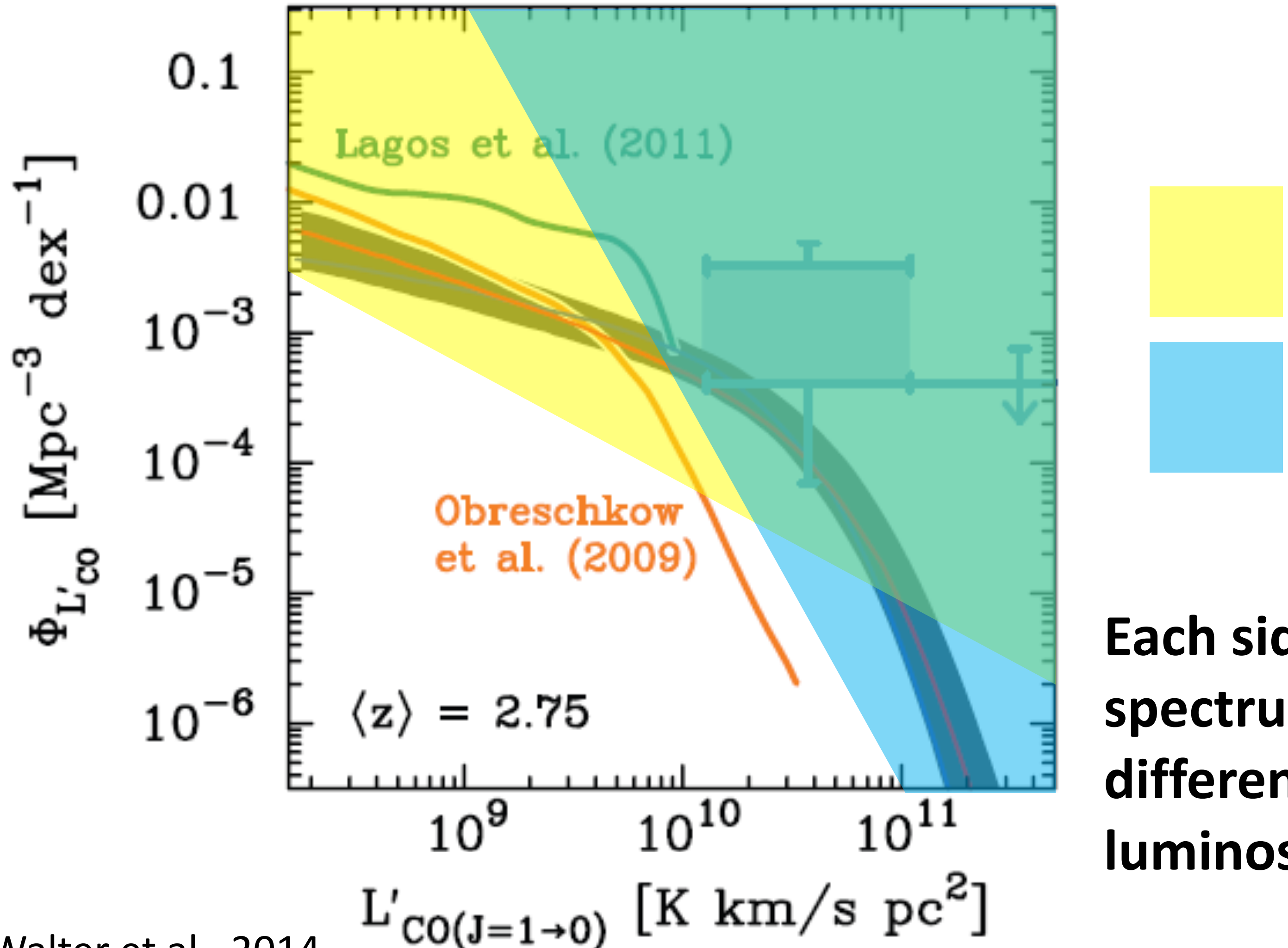
Normalization *Low L slope* *High L Cutoff* *Low L Cutoff*



Pullen et al., 2013

- **Clustering Power**: Sensitive to the broad population of galaxies (one molecule, one vote!)
- **Shot Power**: Sensitive to "luminous-but-common" systems, i.e., Milky Way-like galaxies.

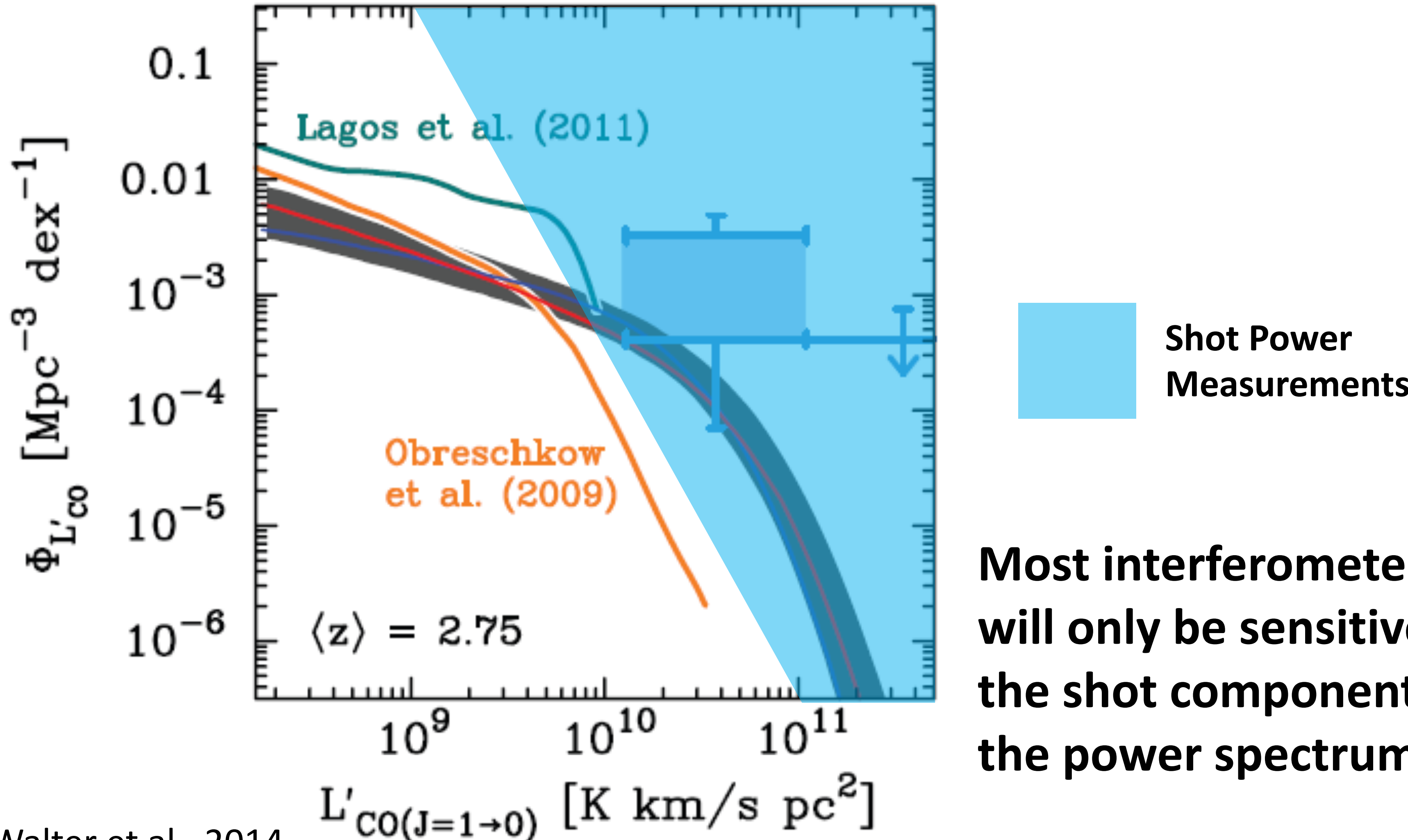
CO Luminosity Function



Walter et al., 2014

Each side of the power spectrum measures a different moment of the luminosity function

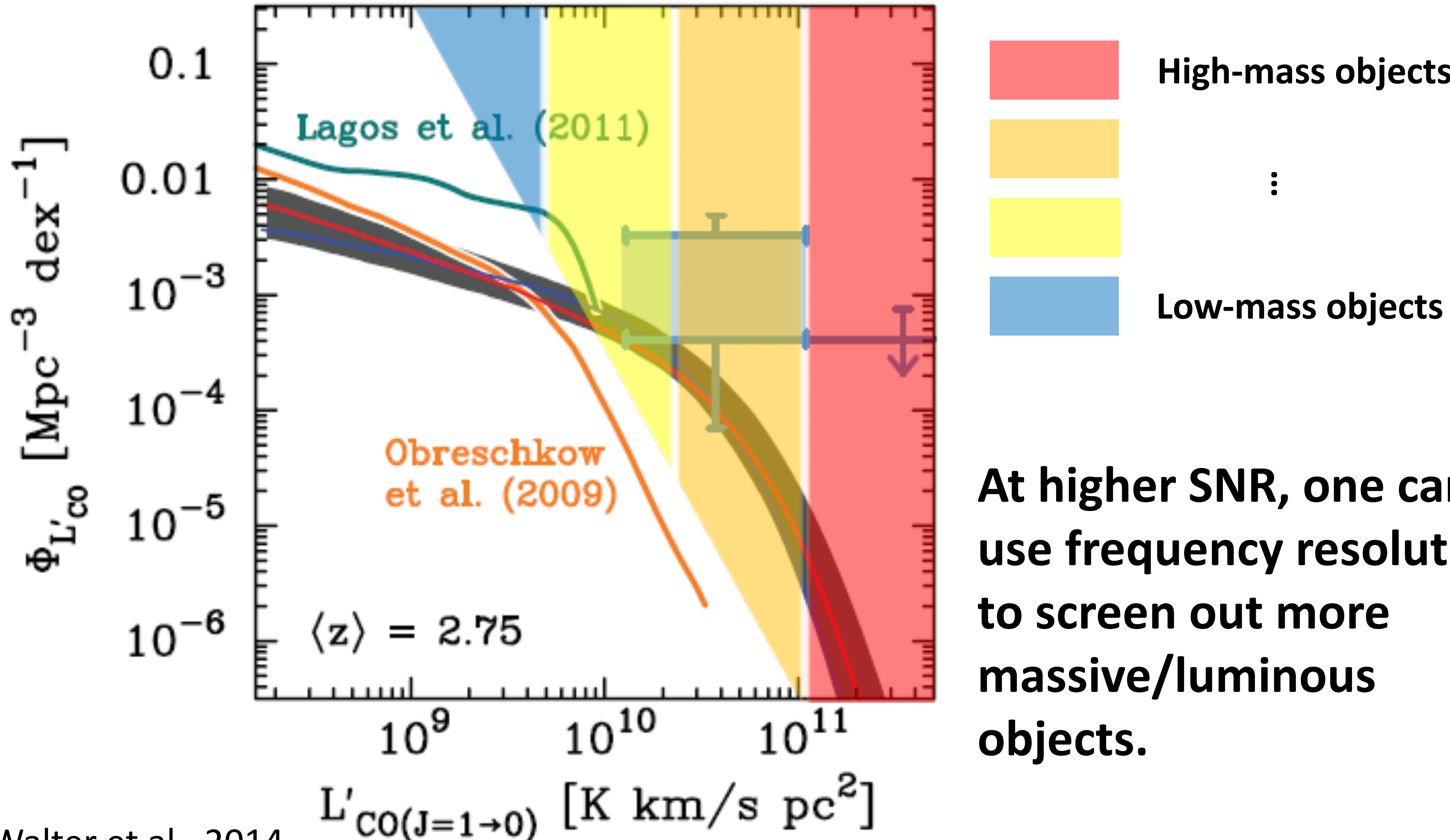
CO Luminosity Function



Walter et al., 2014

Most interferometers will only be sensitive to the shot component of the power spectrum

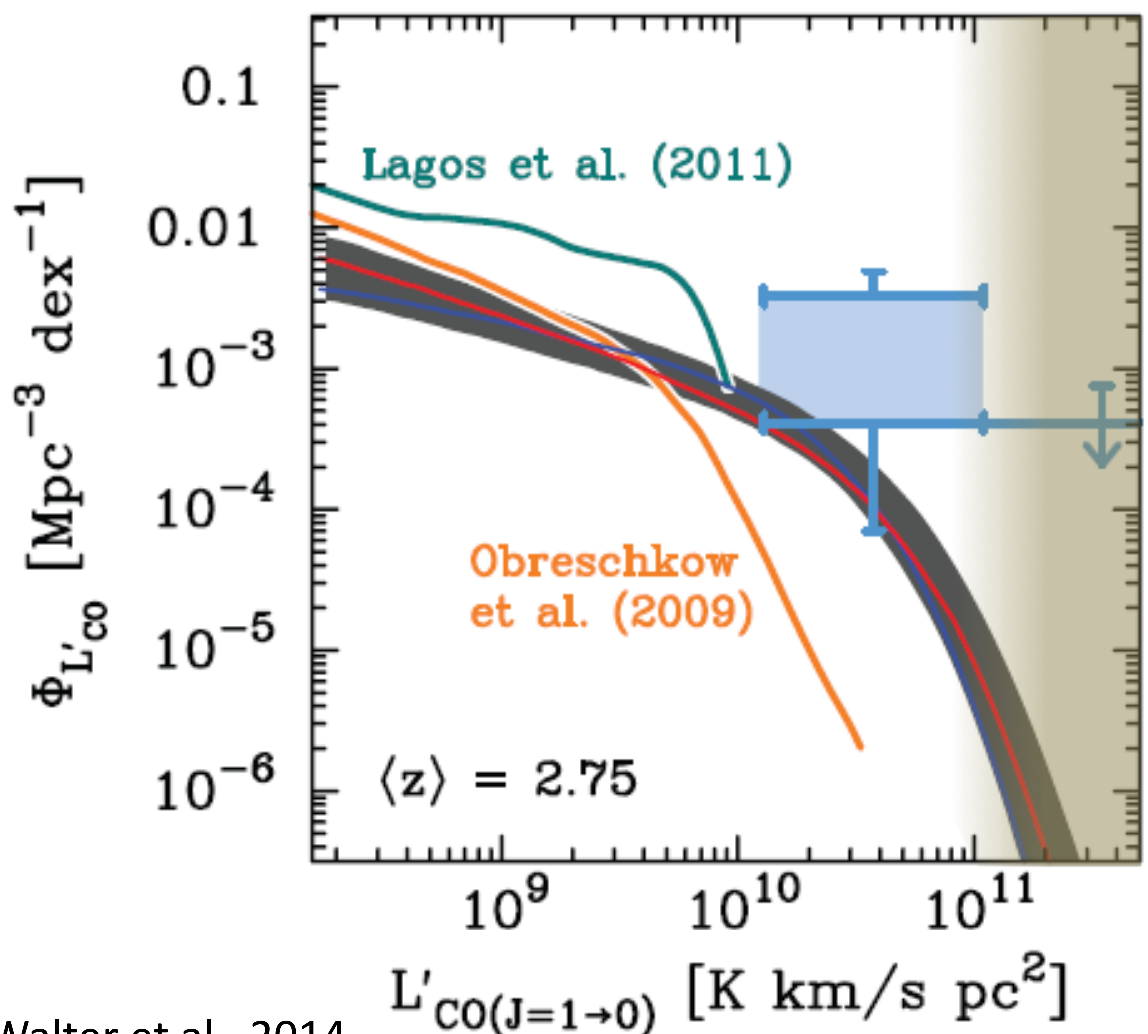
CO Luminosity Function



Walter et al., 2014

At higher SNR, one can use frequency resolution to screen out more massive/luminous objects.

CO Luminosity Function



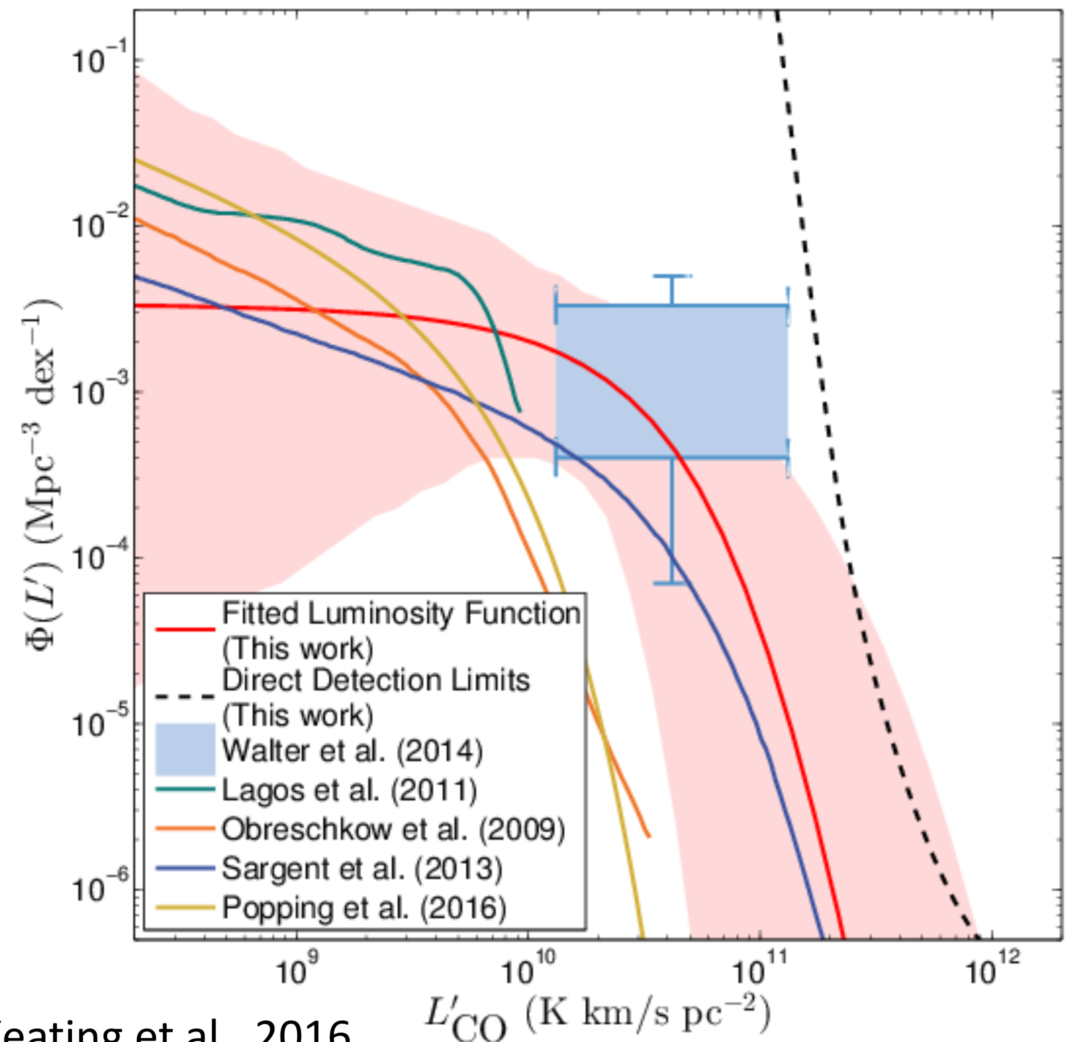
Walter et al., 2014

Imaging Constraints

Direct imaging can also be used with intensity mapping experiments to search for rarer objects.

Luminosity Function Constraints

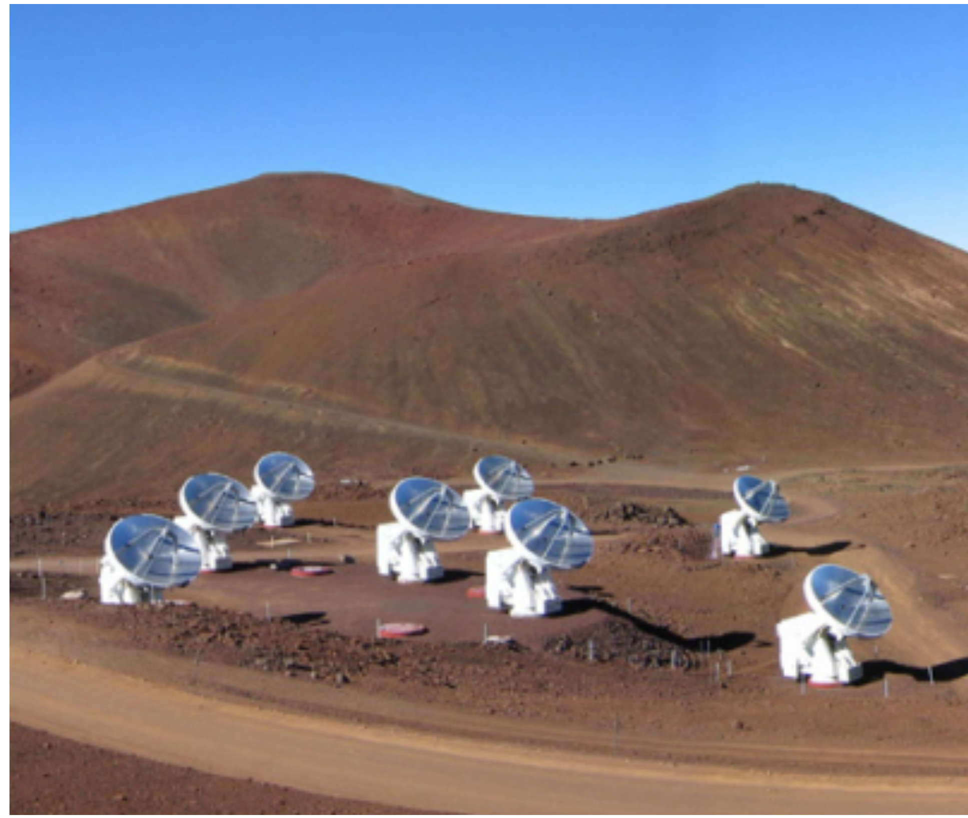
Luminosity function constraints can be significantly enhanced by direct detection experiments, ***even when few sources are detected.***



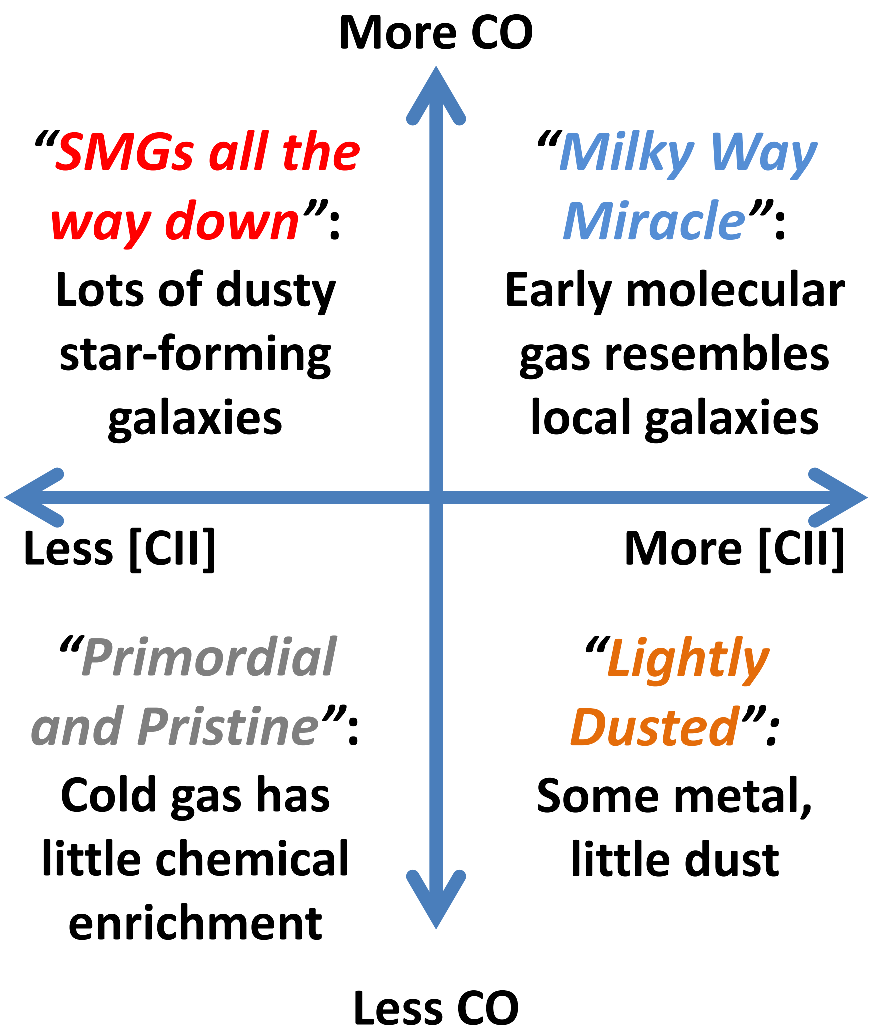
Keating et al., 2016

Suitability of the SMA

- Compact nature means individual emitters not resolved (OPTIMAL)
- Smaller dishes/relatively larger field of view (OPTIMAL)
- Full SWARM correlator coming online (OPTIMAL)
- Broad frequency coverage (OPTIMAL)
- Only shot power component can be measured (NEUTRAL)



Combining CO and [CII] Results



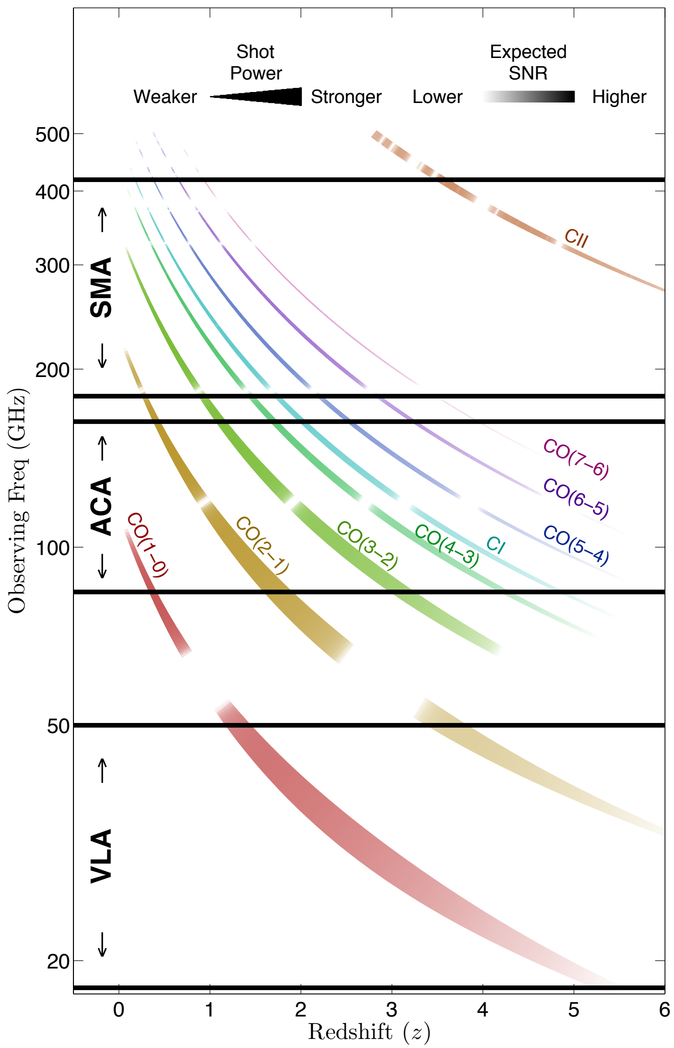
- Combined constraints on CO/[CII] luminosity functions give insights into "luminous-but-common" galaxies

- Combined data can also allow for more robust estimates of cosmic H_2 density

Future CO/[CII] Intensity Mapping

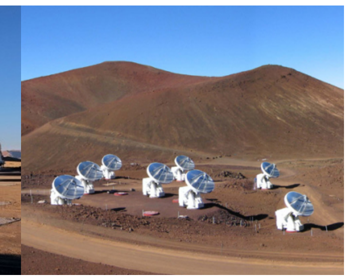
The Millimeter Intensity Mapping Experiment (mmIME):

“It only looks like there’s nothing there”



VLA (1cm)

ACA/ALMA (3mm)



SMA (1mm)

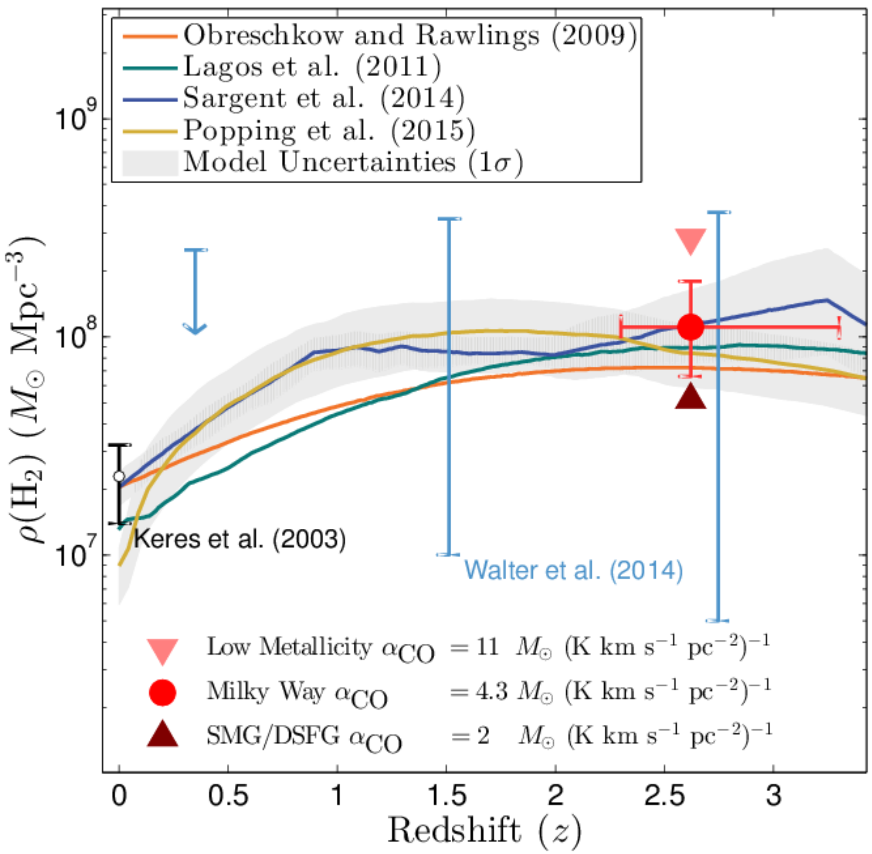
VLA, ACA and SMA are **well-suited** for intensity mapping cross-correlation studies!

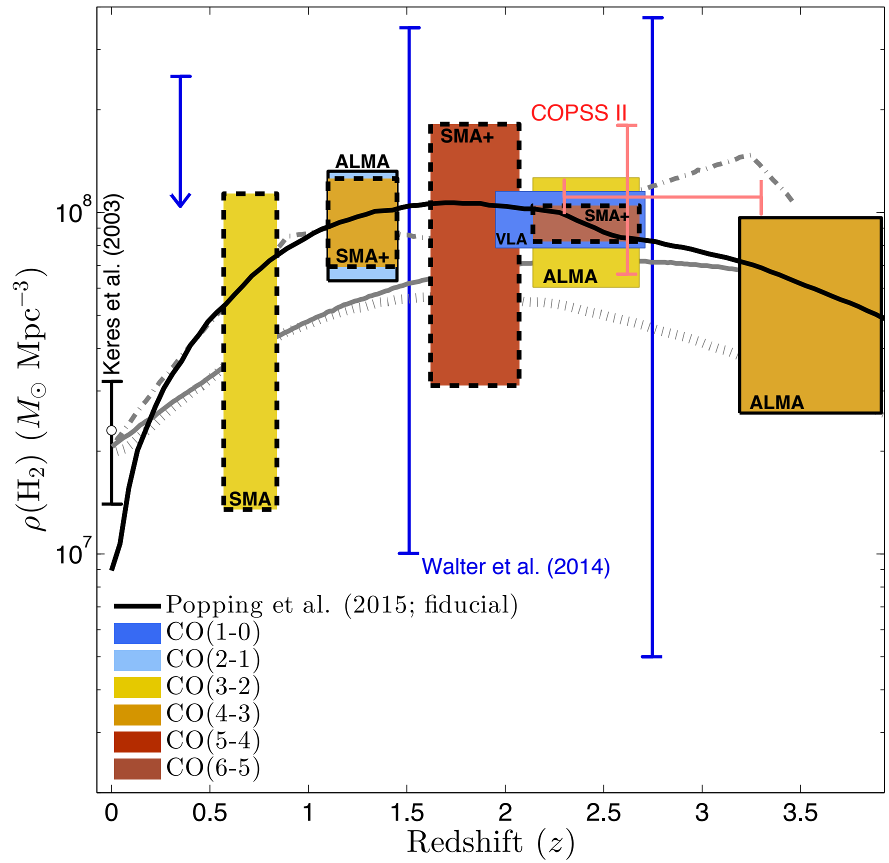
Karto Keating (PI; CfA/SAO)

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

Cosmic Molecular Gas

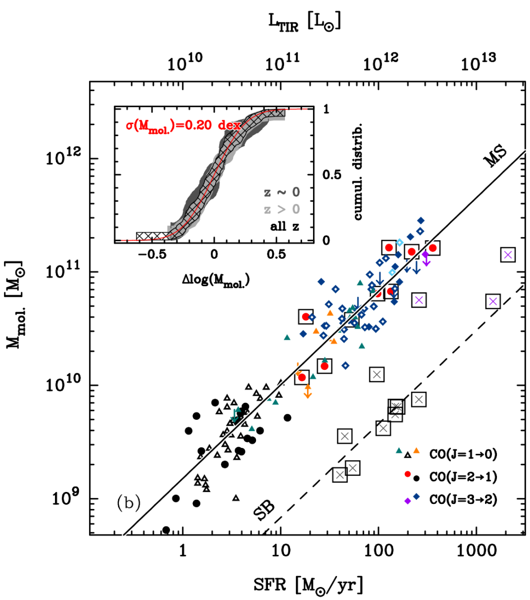
Keating et al., 2016





Can use CO to constrain cosmic molecular gas abunduance out to $z \sim 5$ (and may be able to use [CII] to constrain $\rho(\mathrm{H_2})$ at higher redshift).

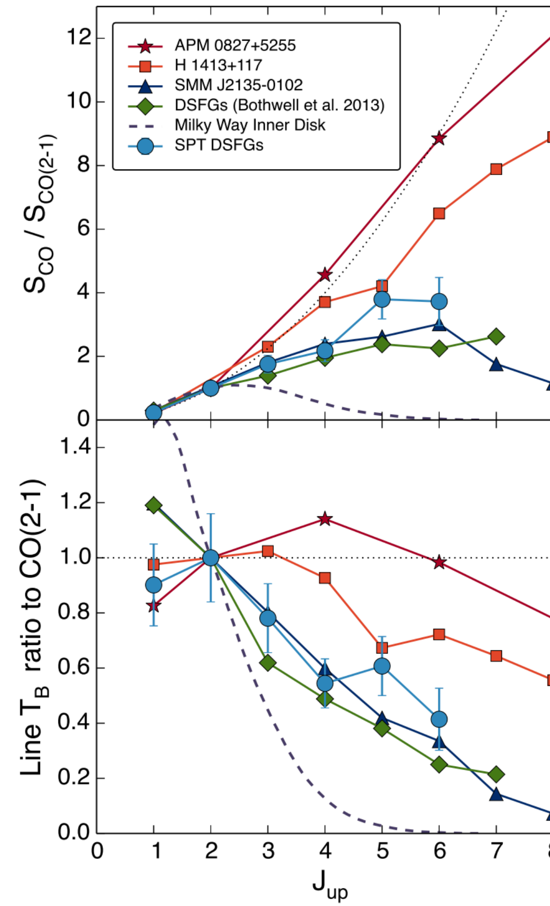
Cross-Correlation Studies



Sargent et al., 2014

With a more limited measurement, can use models to estimate fraction of starburst/IR-luminous galaxies at high redshift.

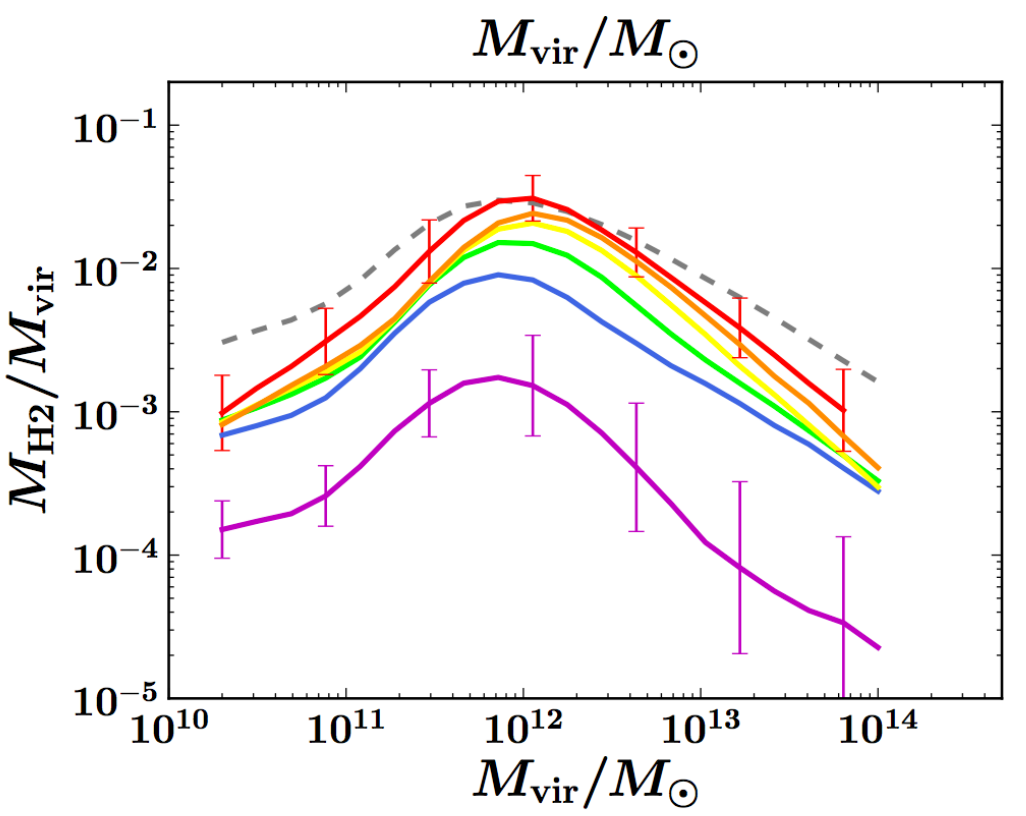
With a deeper integration, one can measure individual line ratios, probe physical conditions of the molecular gas



Spilker et al., 2014

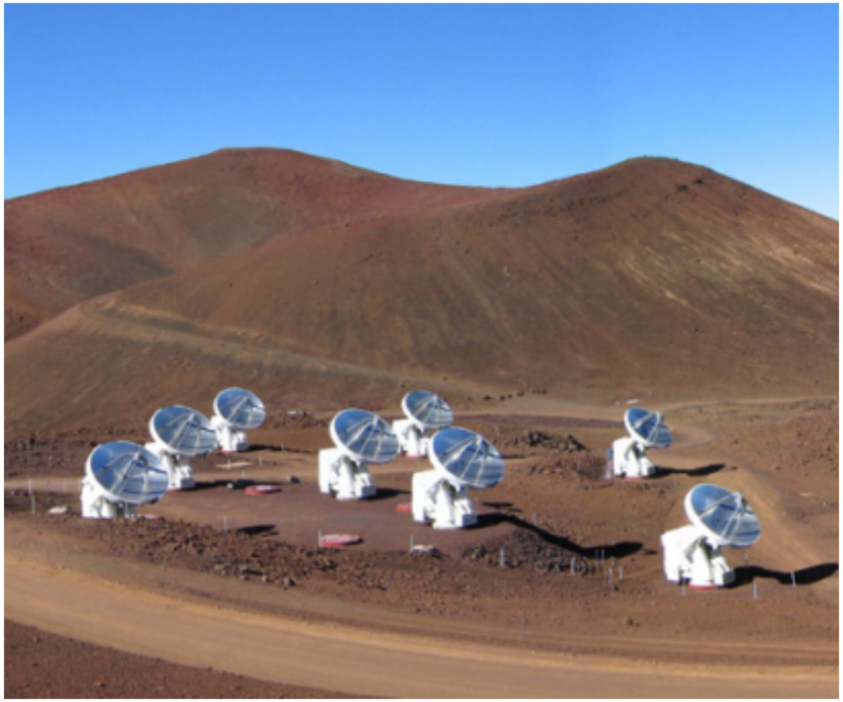
High-mass Halo Gas Abundance

With a deeper integration, one can constrain the moderate/high-mass scaling relationship for CO/[CII] luminosity and molecular gas abundance.



Popping et al., 2015

Planning for the future



The sensitivity of intensity mapping experiments depends on:

- System Temperature ($\propto T_{\mathrm{sys}}^2$)
- Bandwidth ($\propto B$)
- Configuration ($\propto R^{1/2}$)
- Systematics control ($\sim 20\%$?)

Other notes:

- Since the survey should be blind, choice of target fields is flexible
- Broad frequency coverage is a major boost for SMA IM studies
- Dual-pol doubles (!) sensitivity, affords extra systematics check

Science Forecast and Conclusions

- Intensity mapping studies with the SMA will be a powerful probe for molecular gas over a broad range of cosmic history
- SMA upgrade would enable searches at much higher redshift
- Upgrade would also allow for detailed studies of physical gas conditions and onset of quiescence in the early Universe

Pilot Survey (up to 100 hrs)	Existing Array (up to 1,000 hrs)	Upgraded Array (up to 10,000 hrs)
- First detection/ confirmation of result from COPSS - Molecular gas density at $z \sim 1, 2, 3$ - Constraints on CO SLED at $z \sim 2$	- [CII] from $4 \leq z \leq 6$ - CO from $0.2 \leq z \leq 3$ - Molecular gas density from $z \sim 1 - 5$ - CO SLED constraints from $z \sim 1 - 3$ - Fraction of starburst-like objects as a function of redshift	- [CII] from $4 < z < 10$ - CO SLED from $z \sim 0.5 - 6$ - [CI]/[NII]/[OI] cross-correlation studies - Physical gas conditions - High-mass scaling relationships/history of quiescence - Molecular gas density from $z \sim 0.2 - 8$