Charting Molecular Gas Across Cosmic Time

"Waste No Photon"

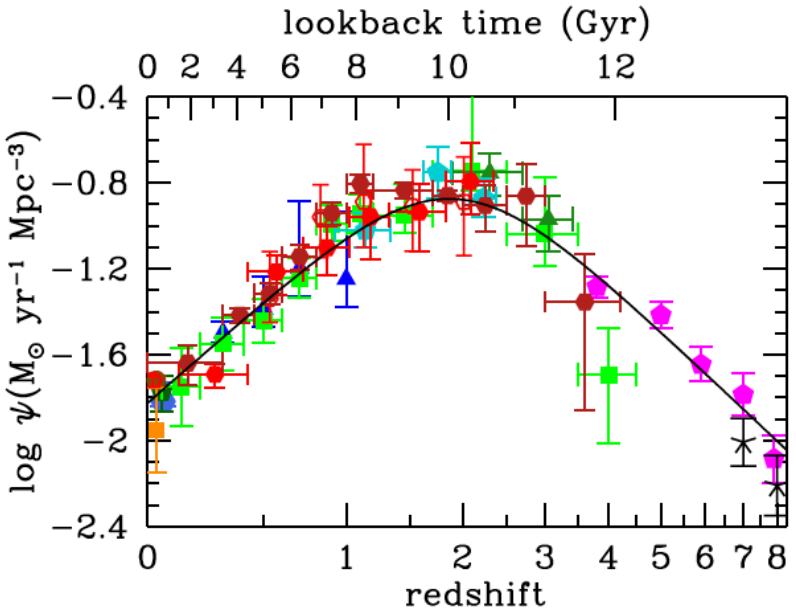
Garrett "Karto" Keating (CfA)
on behalf of the mmIME Collaboration:
Geoff Bower (ASIAA), Tzu-Ching Chang (ASIAA), Anastasia Fialkov (Cambridge), Attila Kovacs (CfA)
Avi Loeb (CfA), Natalie Mashian (Pomona), Dan Marrone (Arizona), Wei-Hao Wang (ASIAA)

garrett.keating@cfa.harvard.edu

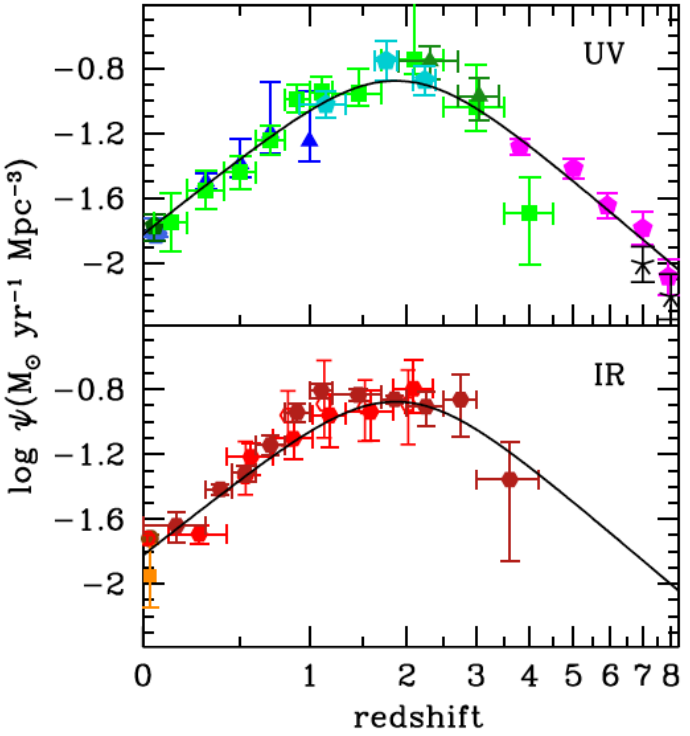
2019 SMA Workshop
November 4th, 2019

Exploring the Early Universe

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

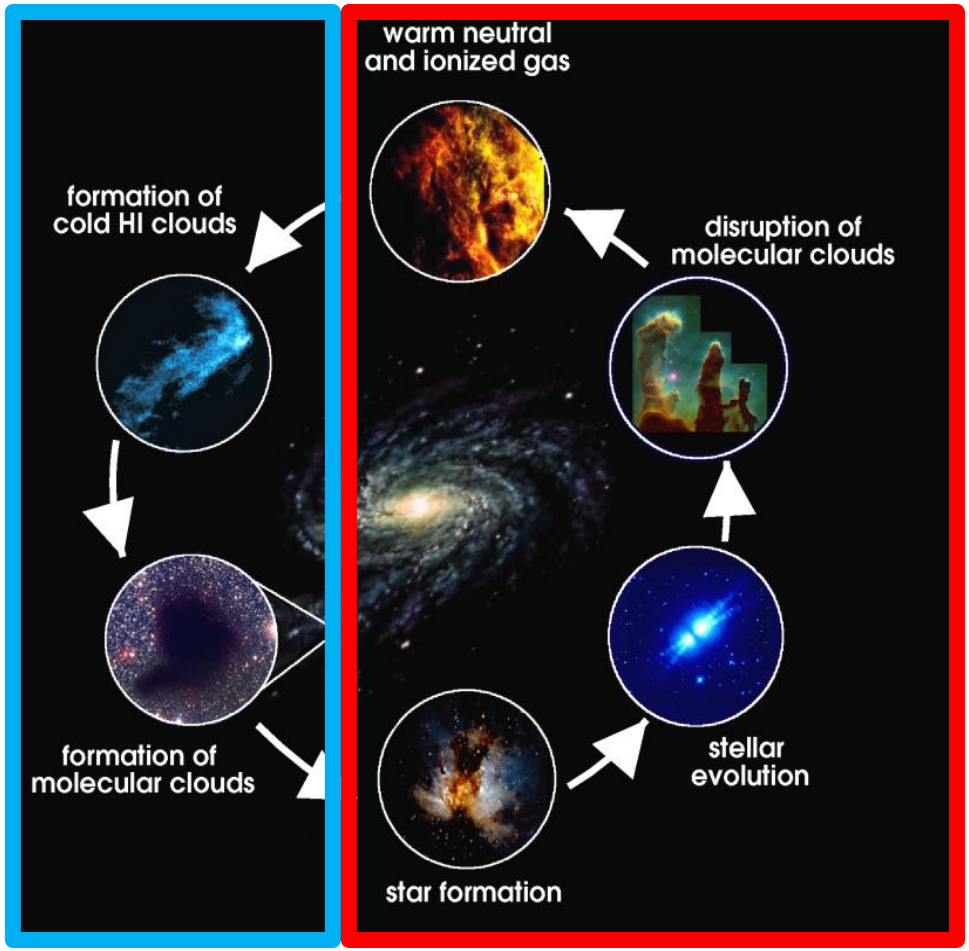


Madau and Dickinson, 2014



Exploring the Early Universe

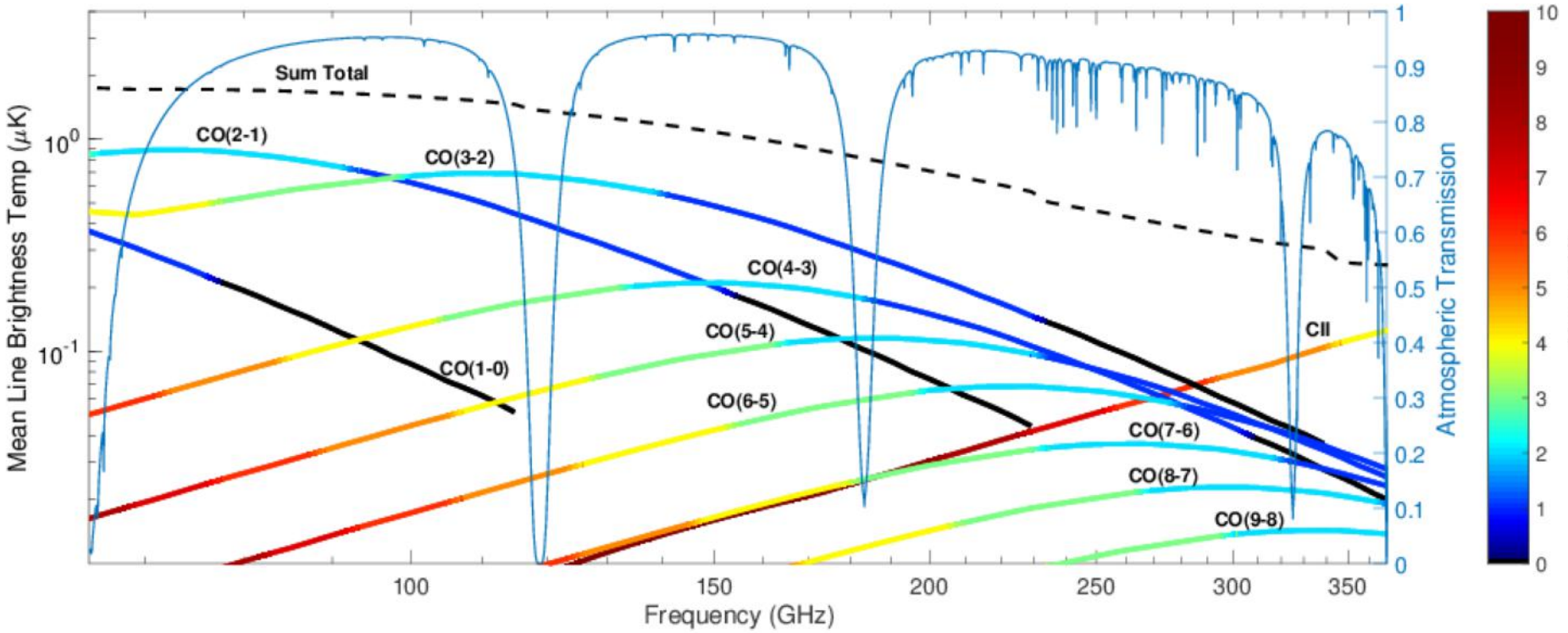
…but we'd like to know more about the **colder**, denser gas that feeds star-formation.



Most high-redshift data comes from the **warmer**, more diffuse regions of galaxies…

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

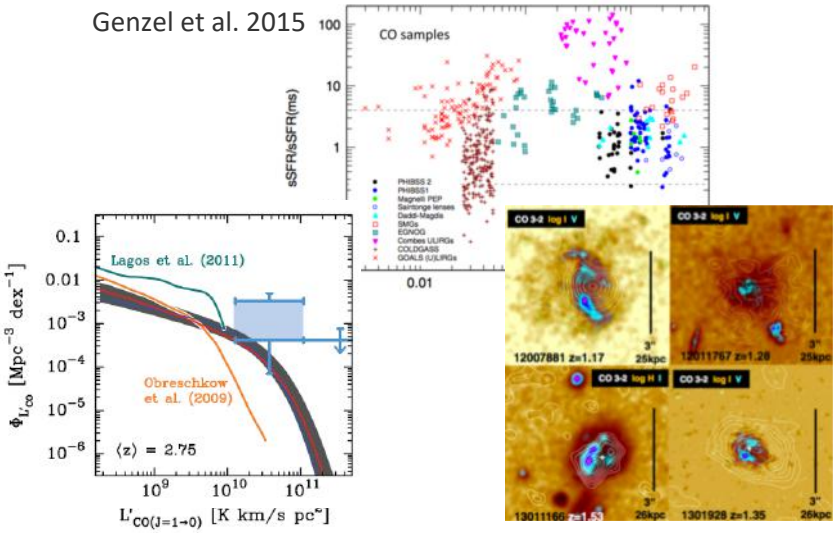
Lines in the (sub-)mm window



The New Frontier of Cold Gas

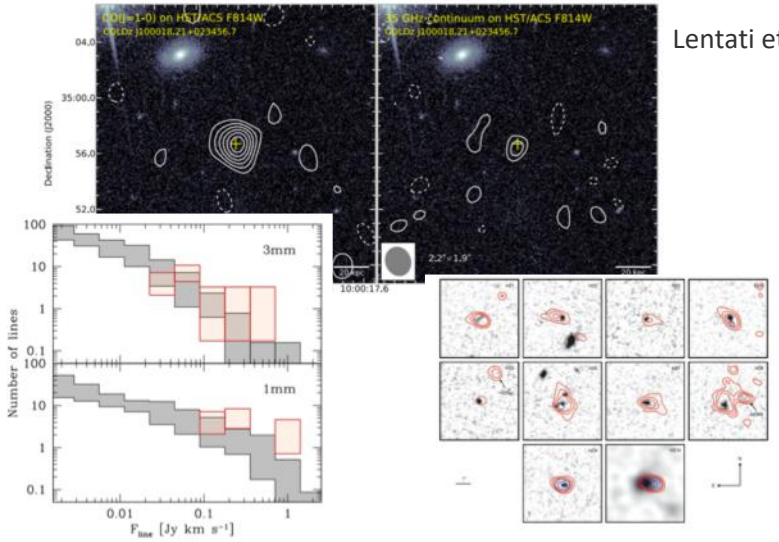
Current instruments have yielded dozens of high-redshift CO and [CII] detections…

Genzel et al. 2015



Walter et al. 2014

Tacconi et al. 2013



Walter et al. 2016

Lentati et al. 2015

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 Large Volume Surveys?

Understanding the complexity of molecular gas

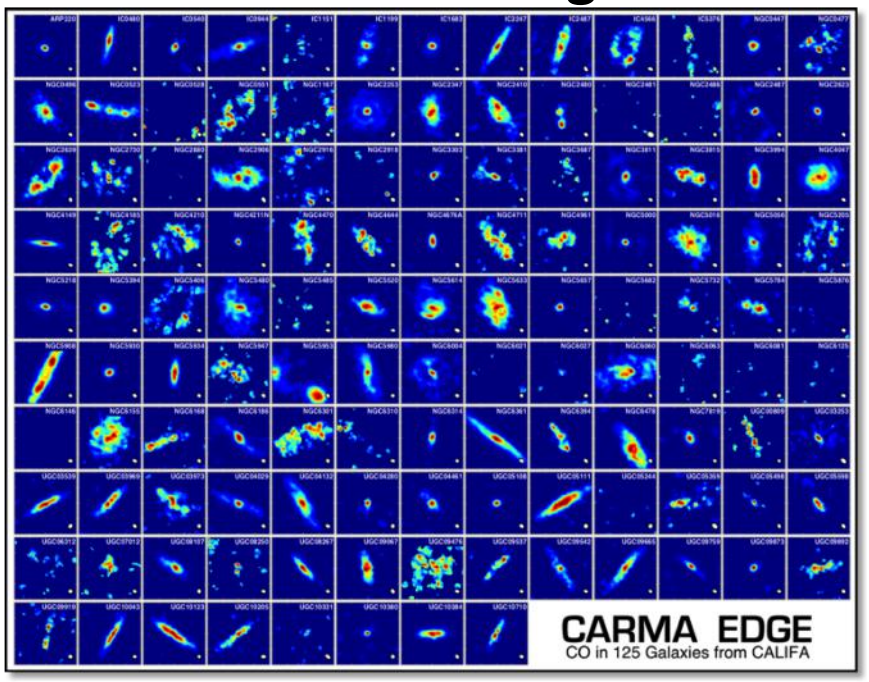
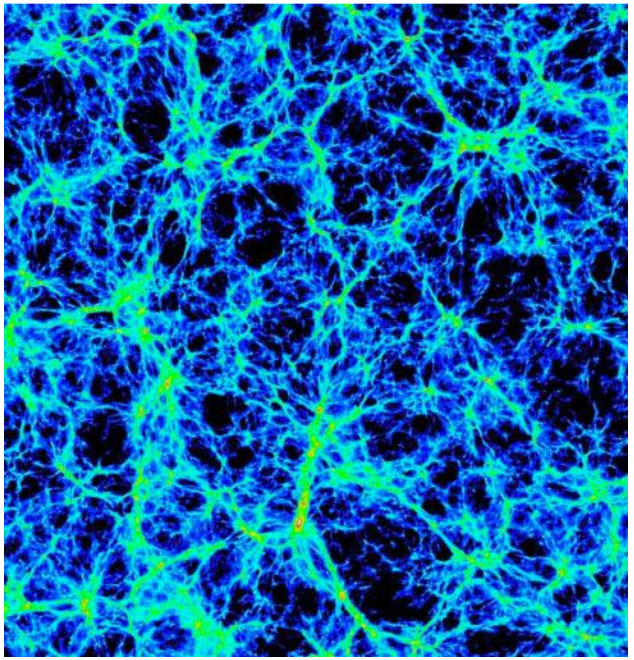


Image Credit: Alberto Bolatto

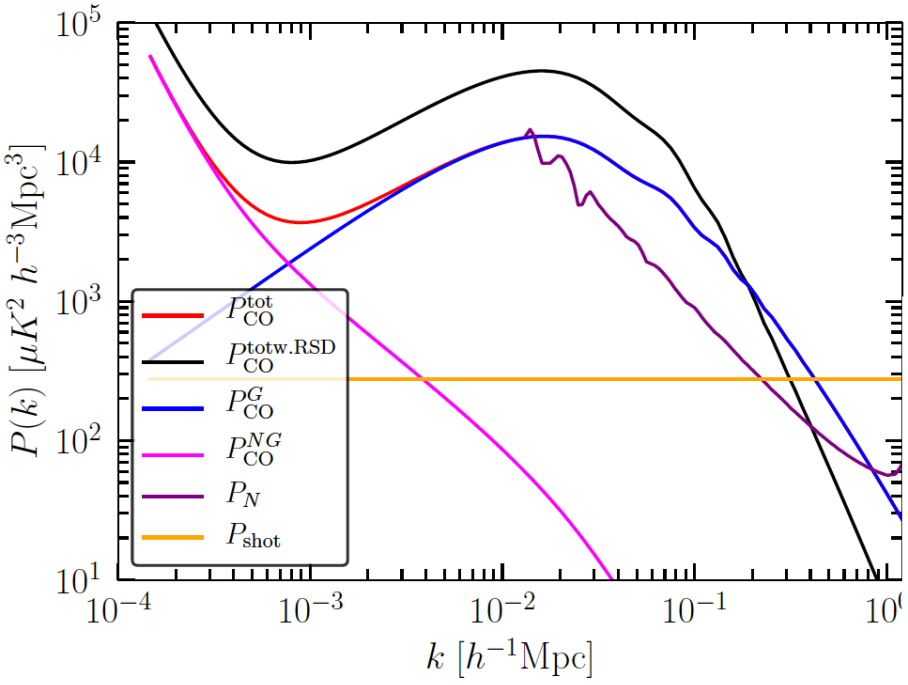
Cosmological applications at high redshift

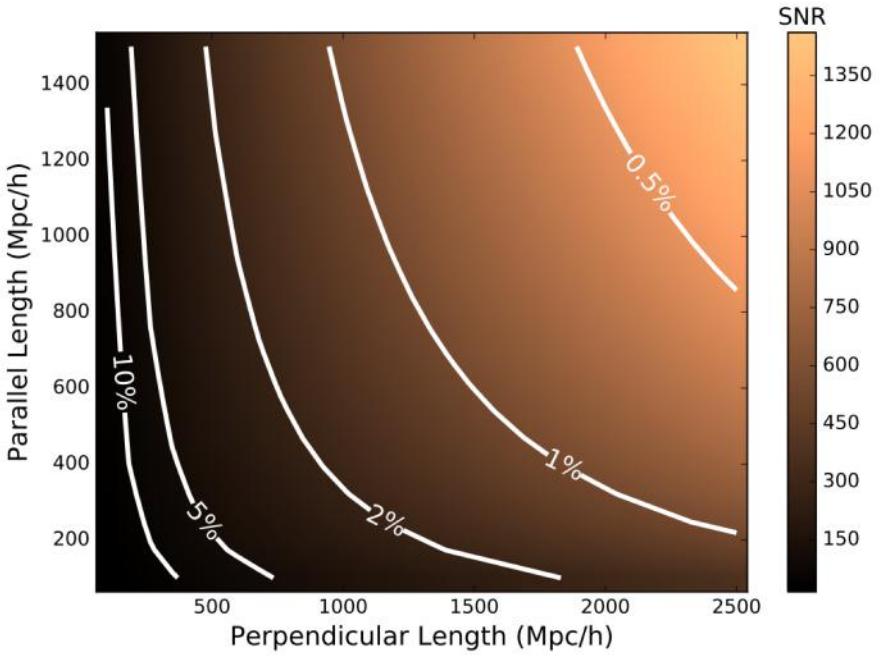


A wealth of existing and upcoming high-redshift extragalactic data

Constraining Cosmology

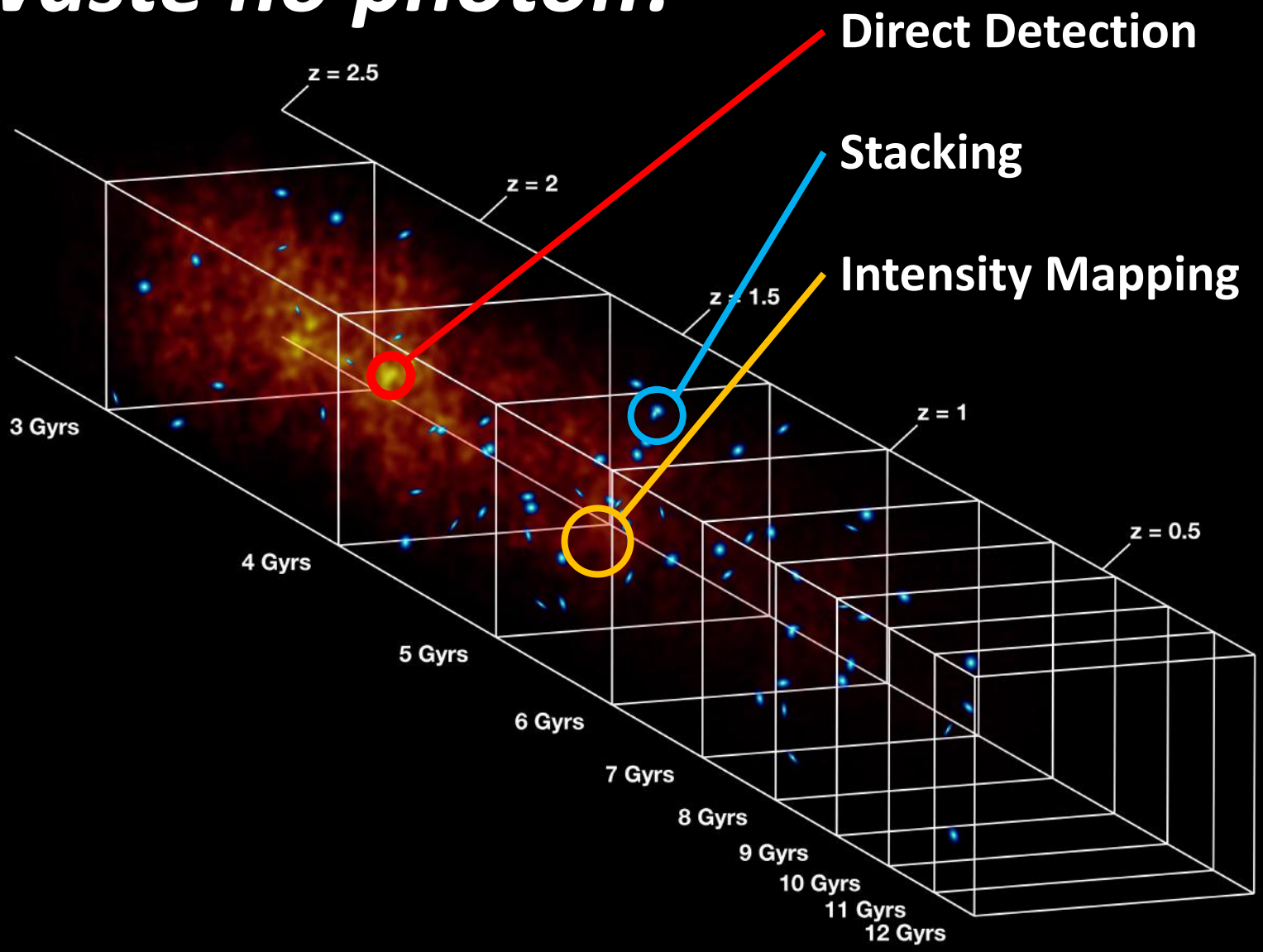
Moradinezhad Dizgah & Keating, 2019





Karkare & Bird, 2018

Waste no photon!



What's in a name?

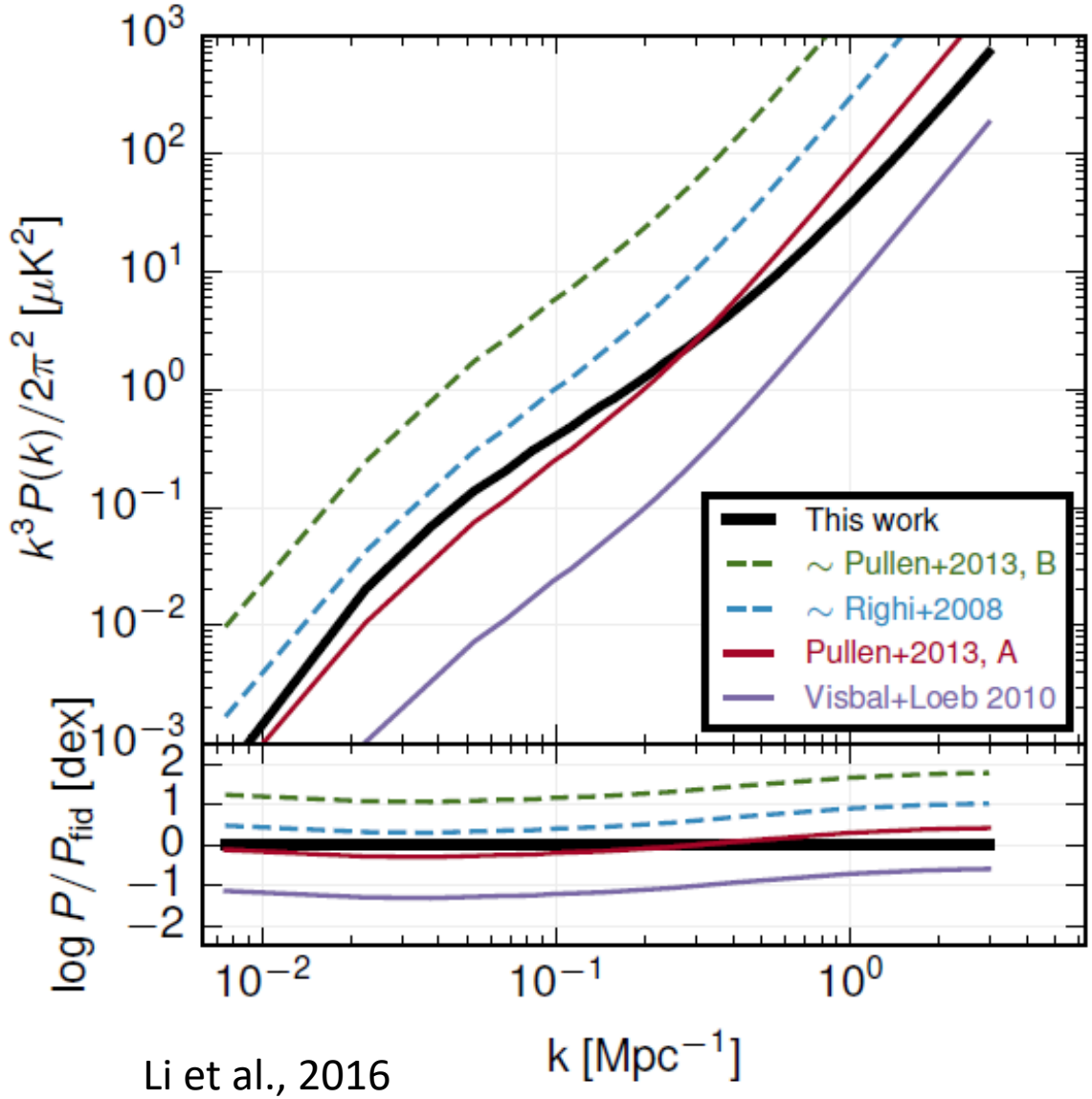
Intensity Mapping

^Line

≠

Making Maps of ^Line Intensity

The CO Power Spectrum

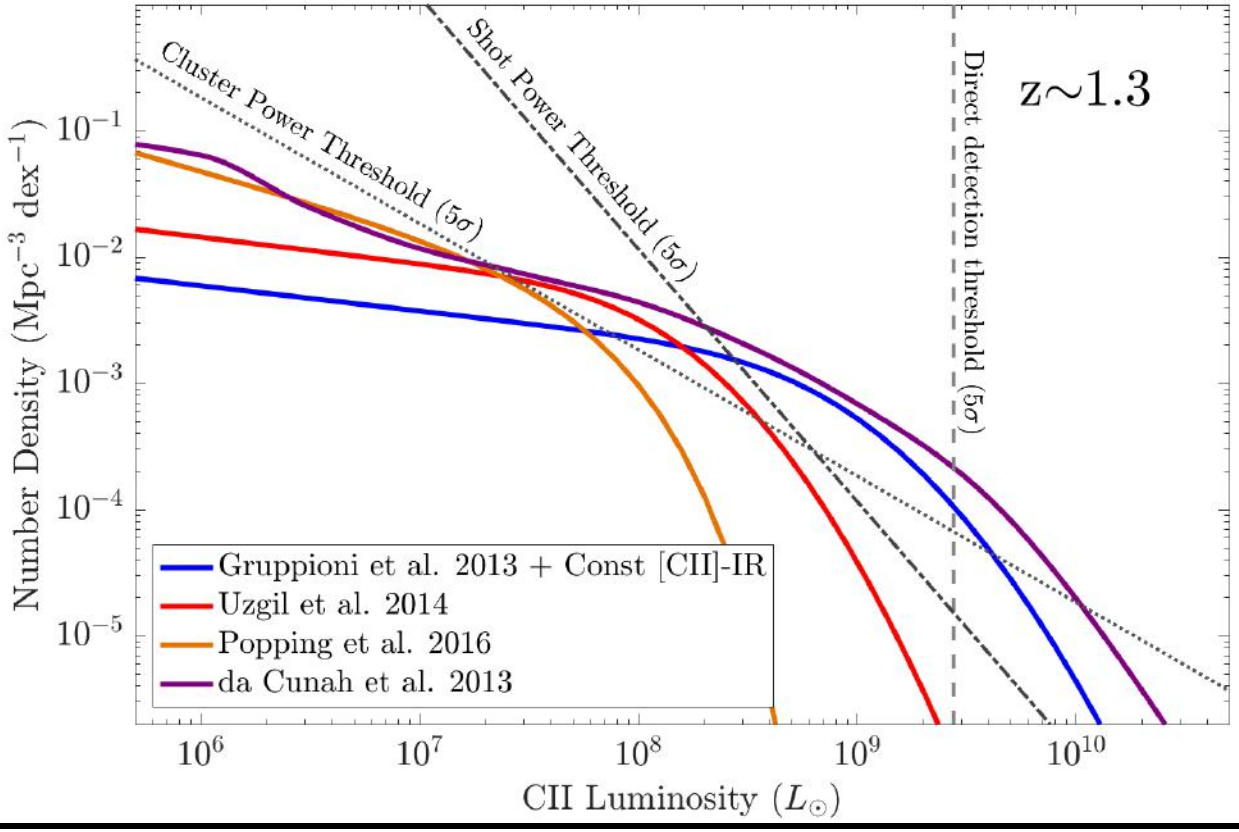


Li et al., 2016

The Luminosity Function

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

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



Cluster Power

Shot Power

Direct Detection

Think Big, Go Small!

SZA Dishes

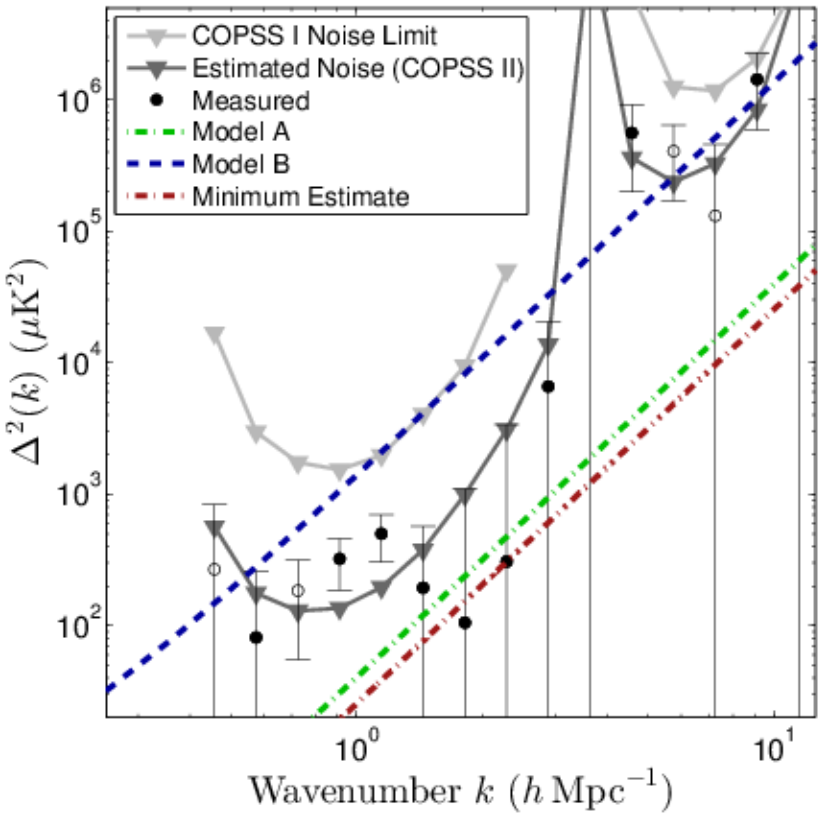
The CO Power Spectrum Survey (COPSS)

COPSS Collaborators:

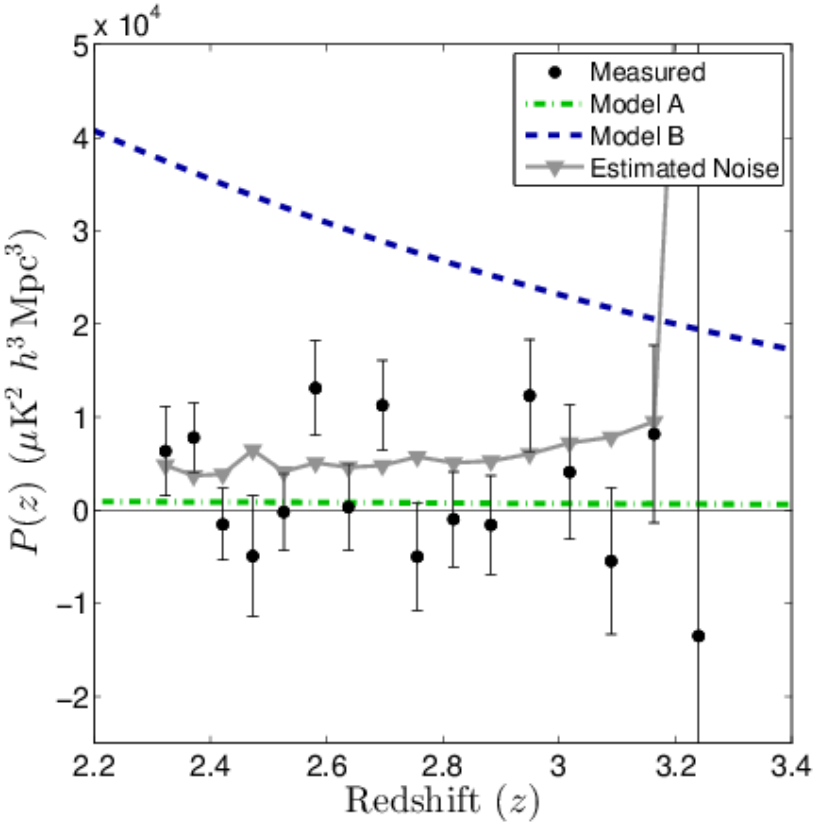
Garrett 'Karto' Keating (PI; formerly Berkeley/UCPD)
Geoff Bower (ASIAA)
John Carlstrom (Chicago)
Tzu-Ching Chang (ASIAA)
Dave Deboer (Berkeley)
Chris Greer (Arizona)
Carl Heiles (Berkeley)
James Lamb (CalTech)
Erik Leitch (CalTech)
Dan Marrone (Arizona)
Amber Miller (Columbia)
Stephan Muchovej (CalTech)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

Primary Survey Results

CO Power Spectrum



CO Redshift Evolution

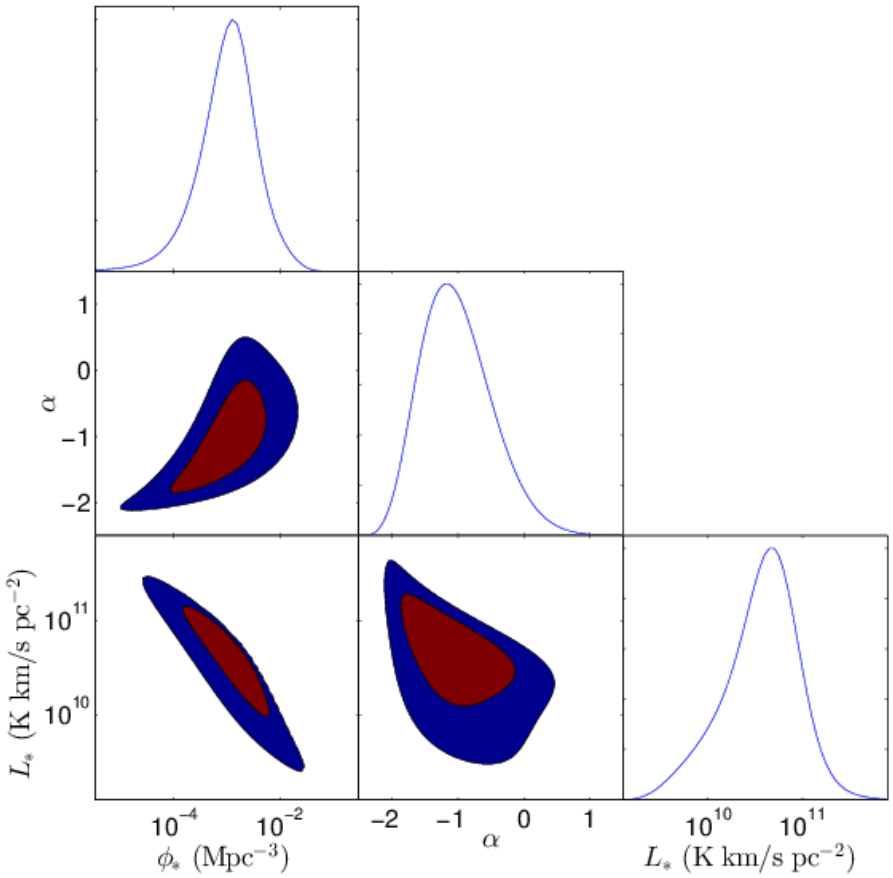


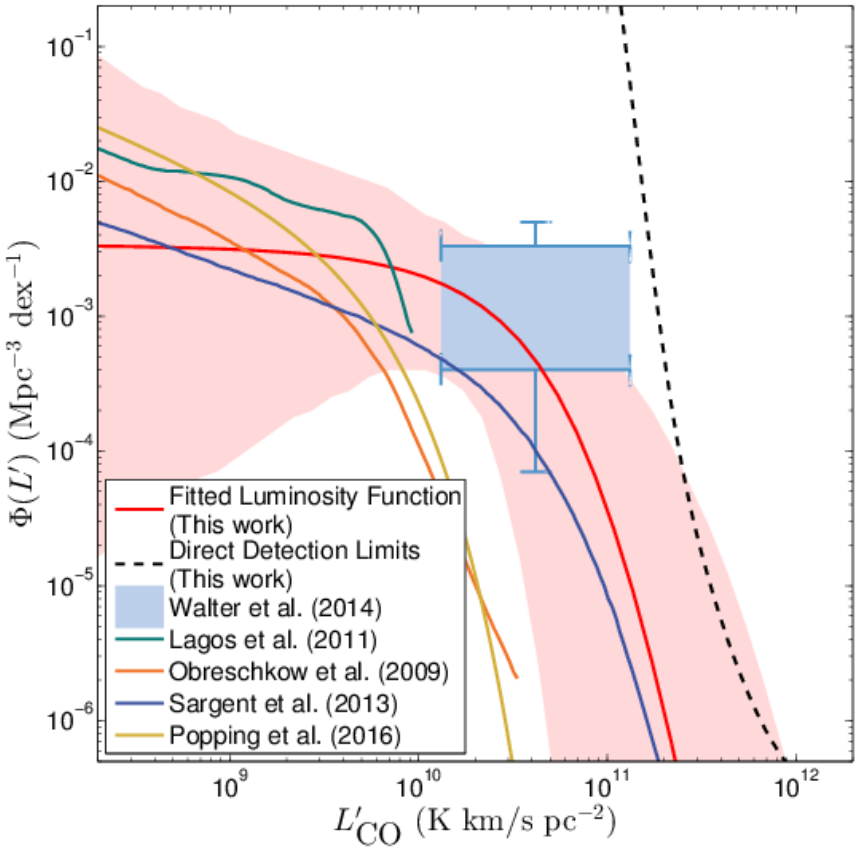
First (tentative) detection! $P_{\mathrm{CO}} = 3.0^{+1.3}_{-1.3} \times 10^3\ \mu\mathrm{K}^2\ (\mathrm{Mpc}/h)^3$

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

Keating et al., 2016

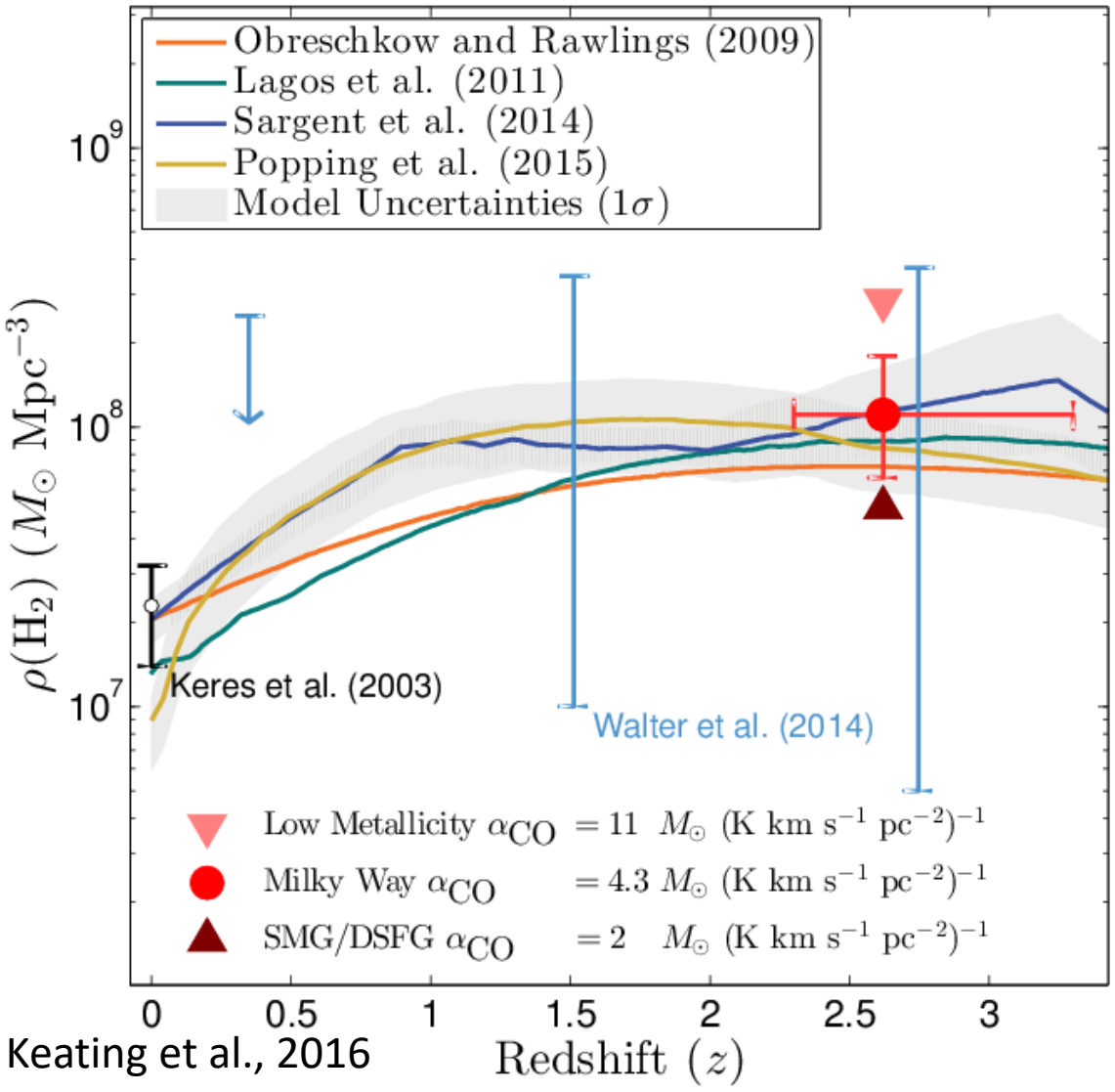
The CO Luminosity Function





Keating et al., 2016

Cosmic Molecular Gas

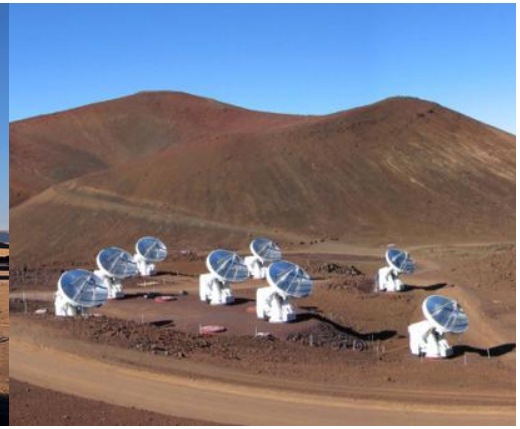


Keating et al., 2016

Millimeter Intensity Mapping

VLA @ 1cm

ACA (ALMA) @ 3mm



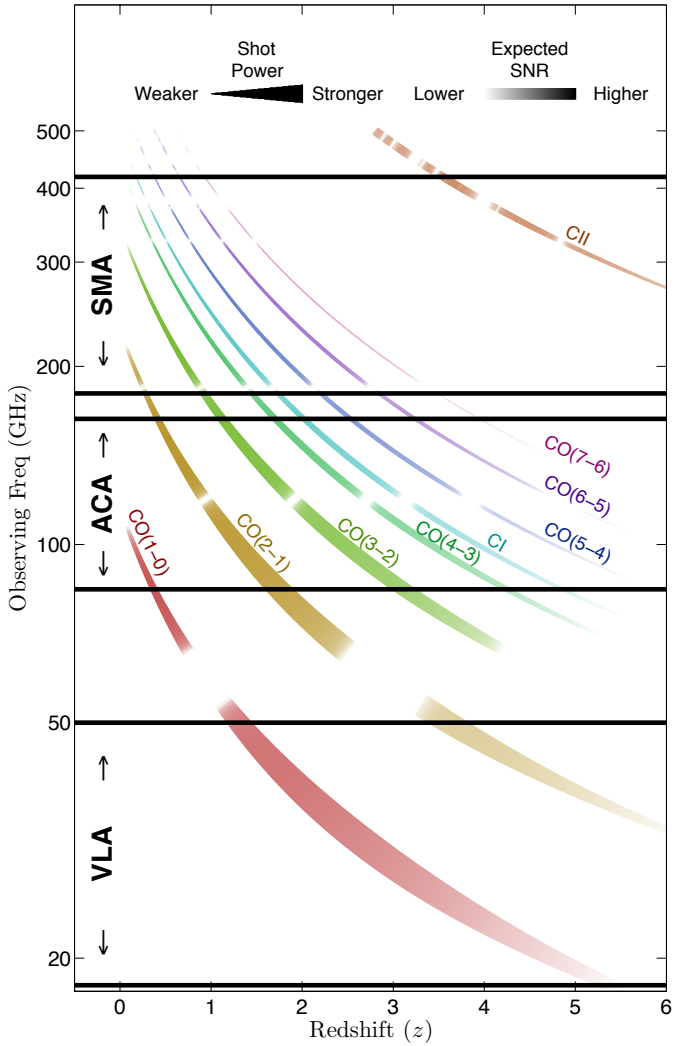
SMA @ 1mm

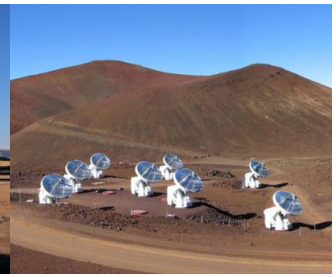
VLA, ACA and SMA have similar primary beam sizes and UV-coverage – **well-suited for cross-correlation!**

Millimeter Intensity Mapping

The Millimeter Intensity Mapping Experiment (mmIME):

"It only looks like there's nothing there"



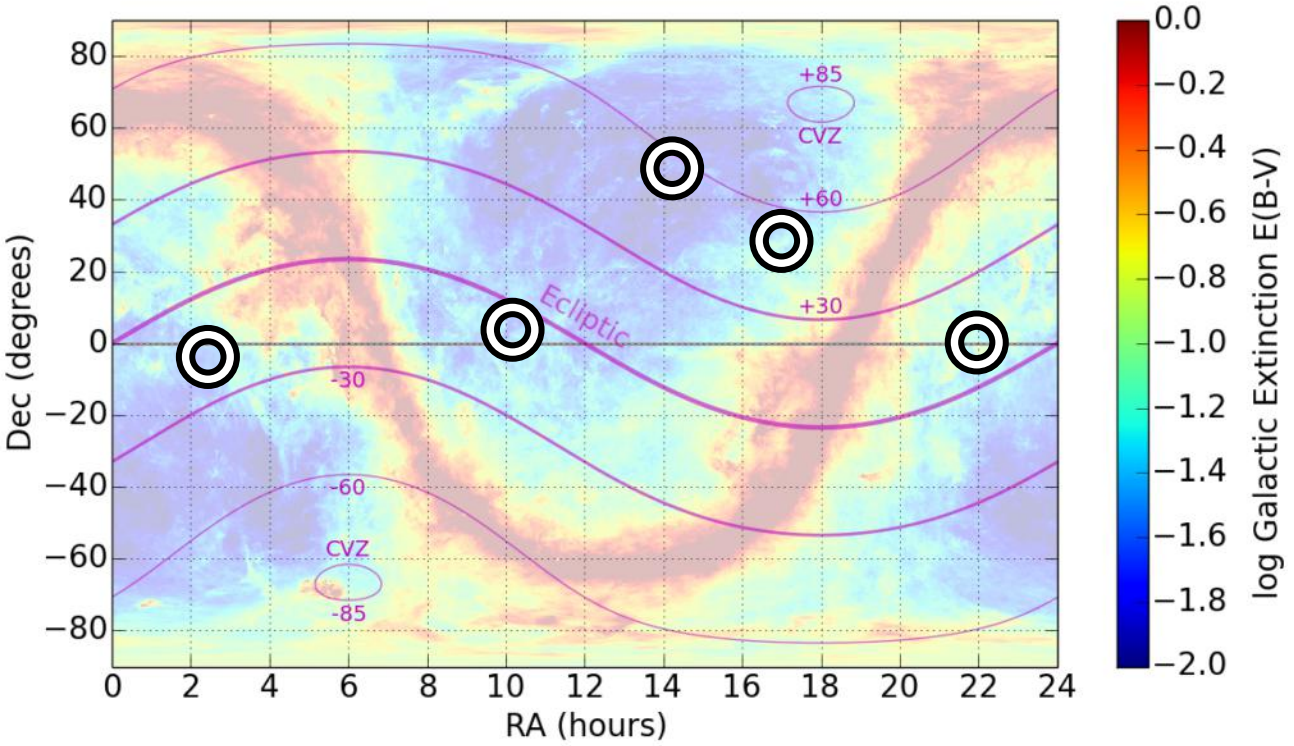


VLA (1cm) **ACA/ALMA (3mm)** **SMA (1mm)**

Garret 'Karto' Keating (PI; CfA)

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

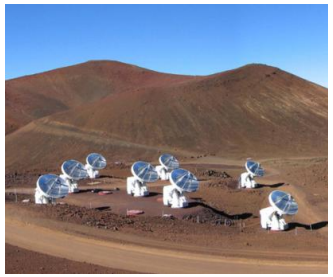
mmIME Survey Targets



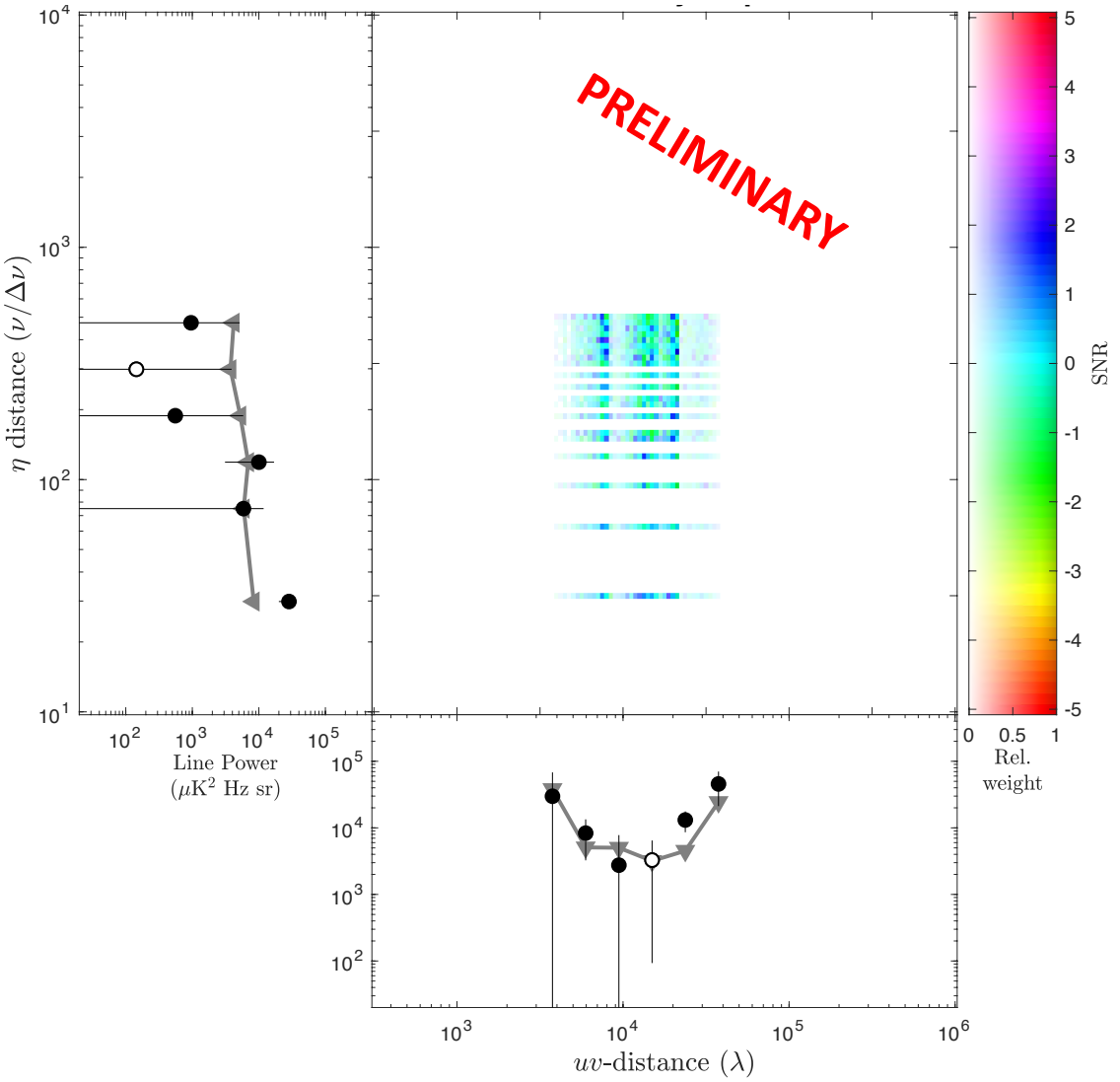
Stage I:

- Appx. 600 hours
- 5 target regions *(SXDS, COSMOS, AEGIS, VIPERS, DEEP2)*
- 192-242 GHz*
- 50 sq. arcmin
- ~ 0.5 mJy cont
- ~ 3 Jy km/sec line
- Power sensitivity of $6\times10^2\ \mu\mathrm{K}^2\ \mathrm{Hz\ sr}$

Recent Progress with mmIME

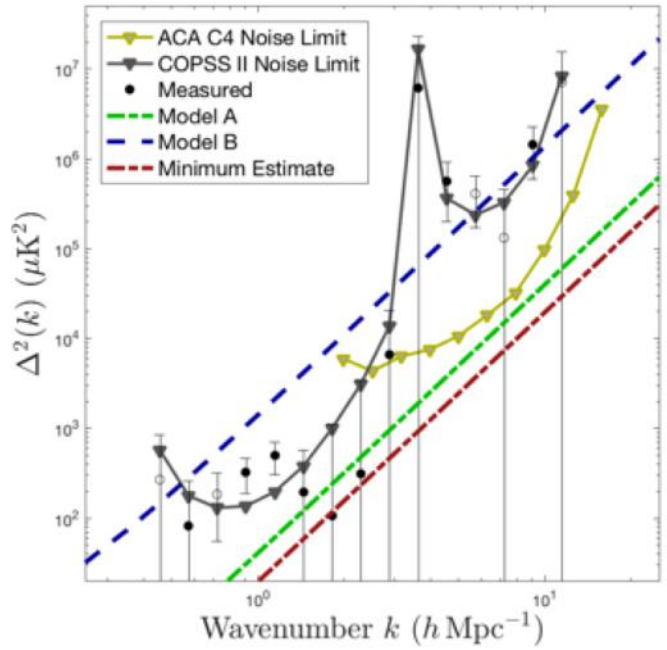


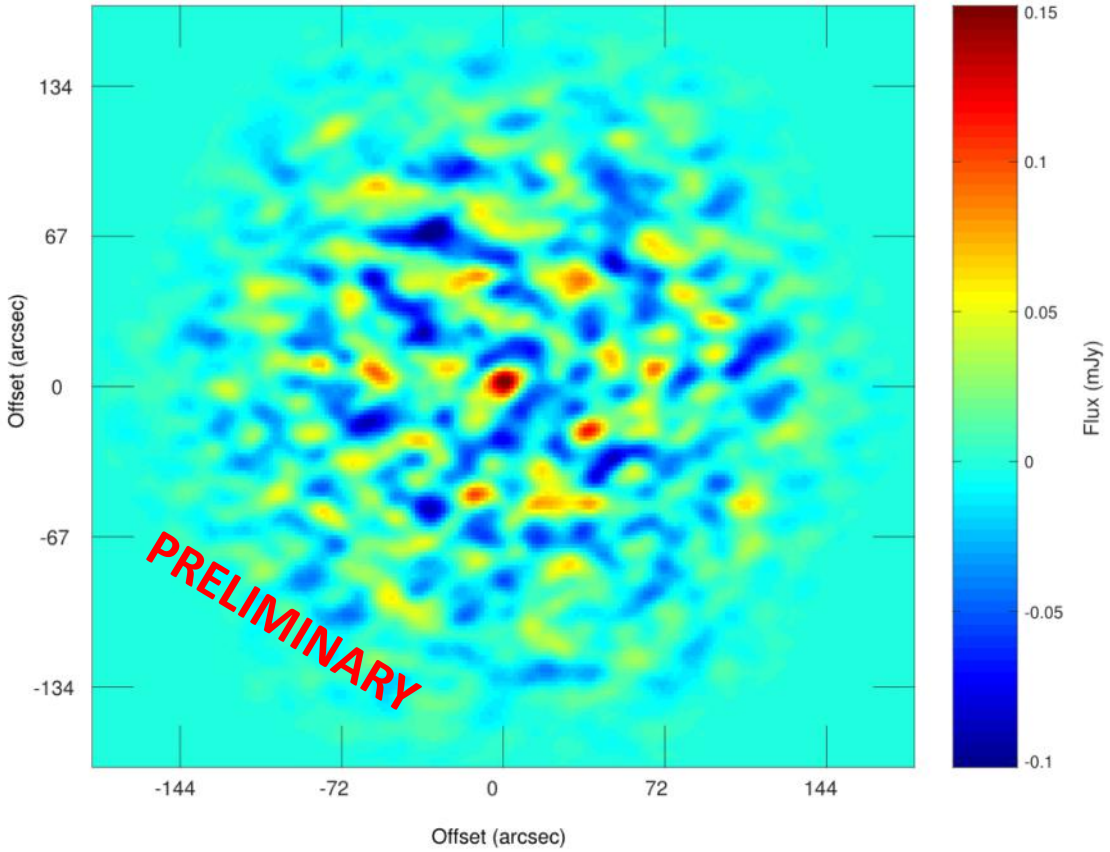
SMA
(1mm)



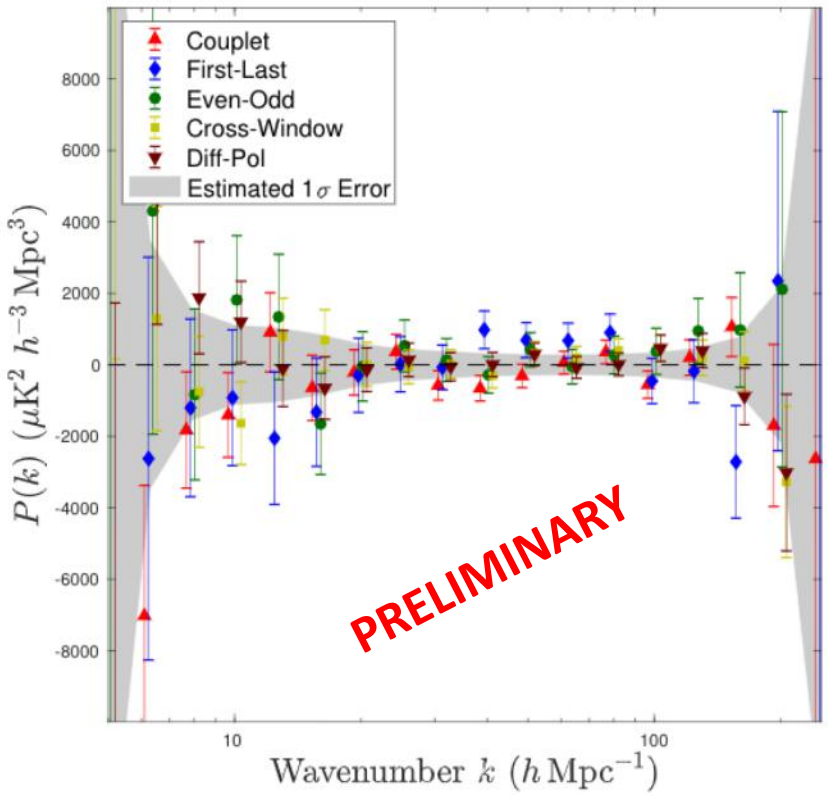
Recent Progress with mmIME

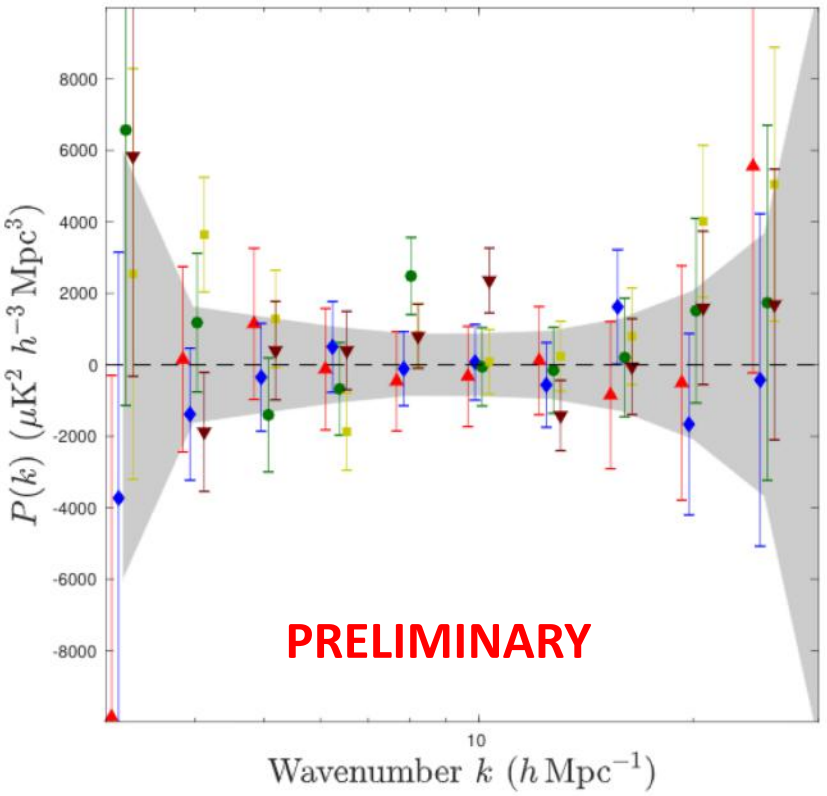
ACA/ALMA (3mm)





Recent Progress with mmIME

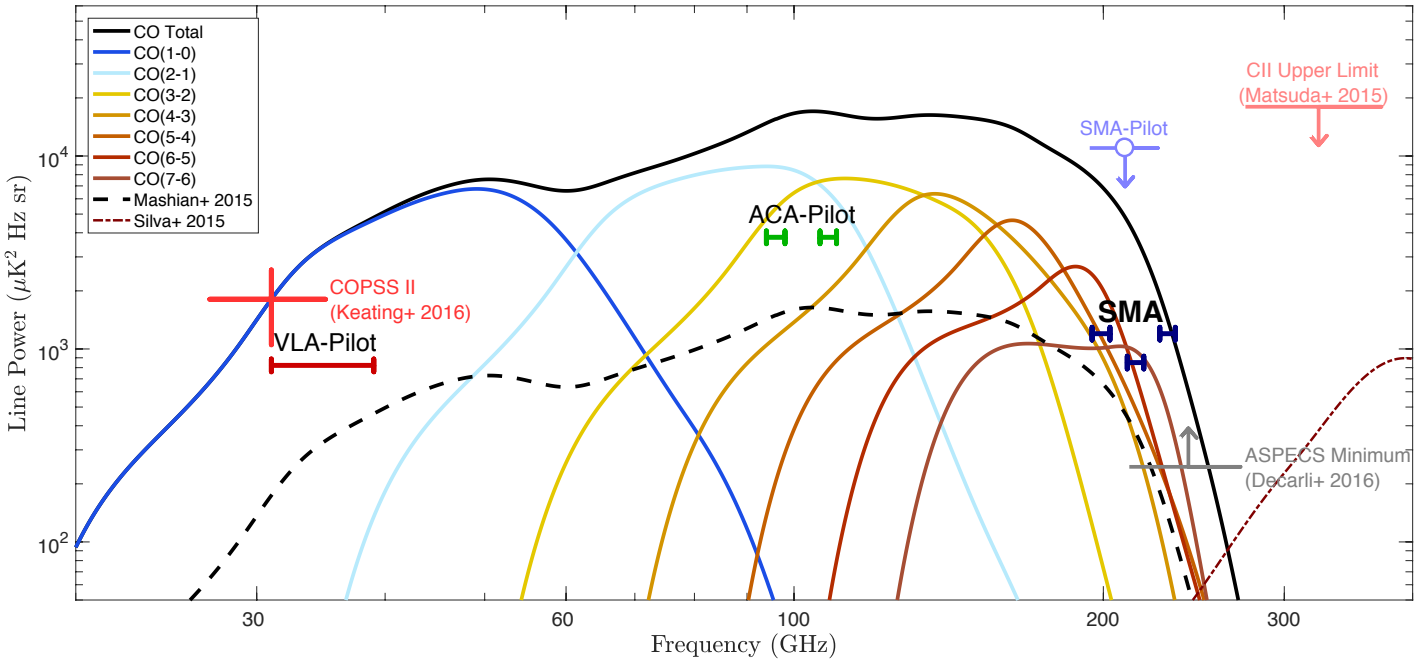




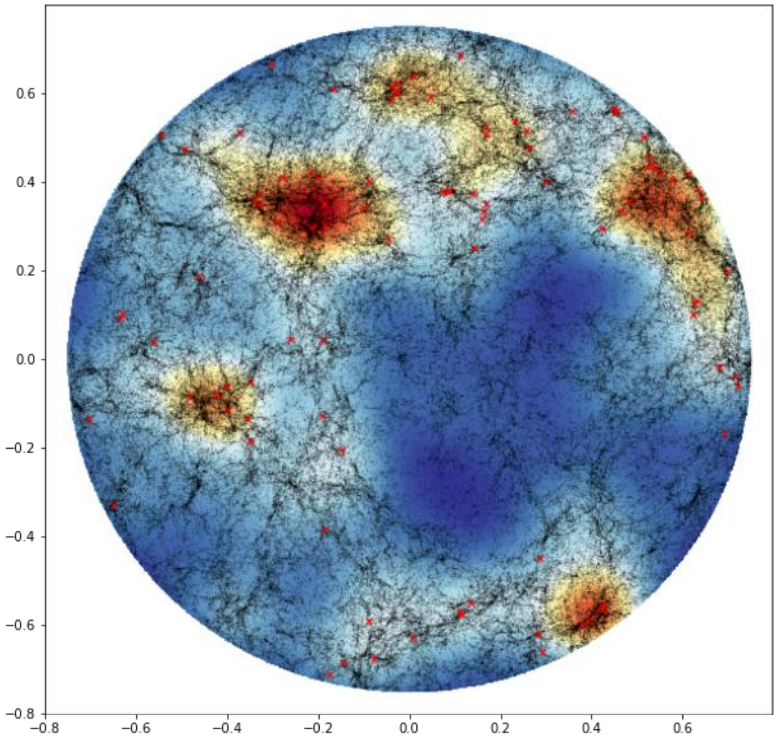
ACA/ALMA (3mm)

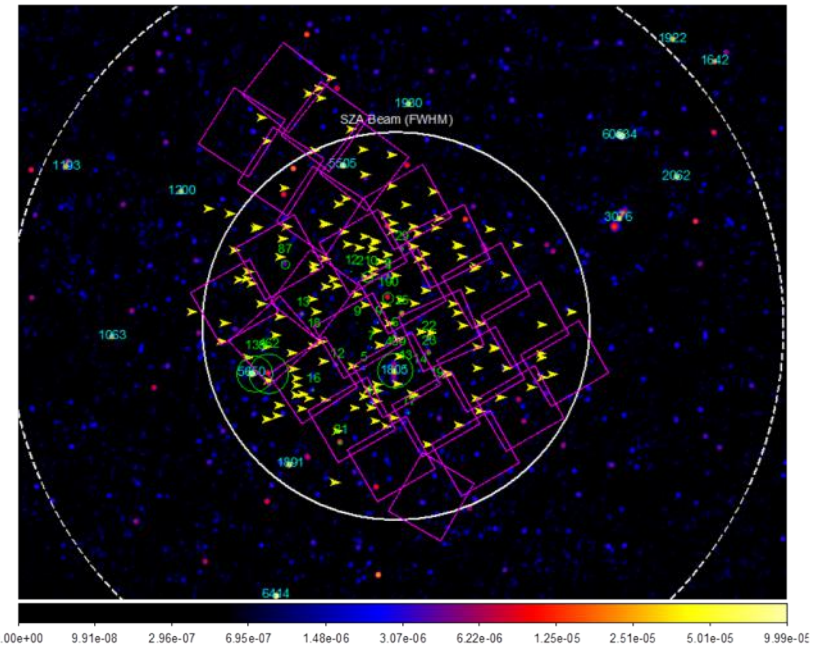
Recent Progress with mmIME

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



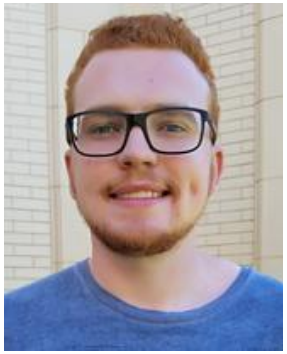
Cross-Correlation Studies





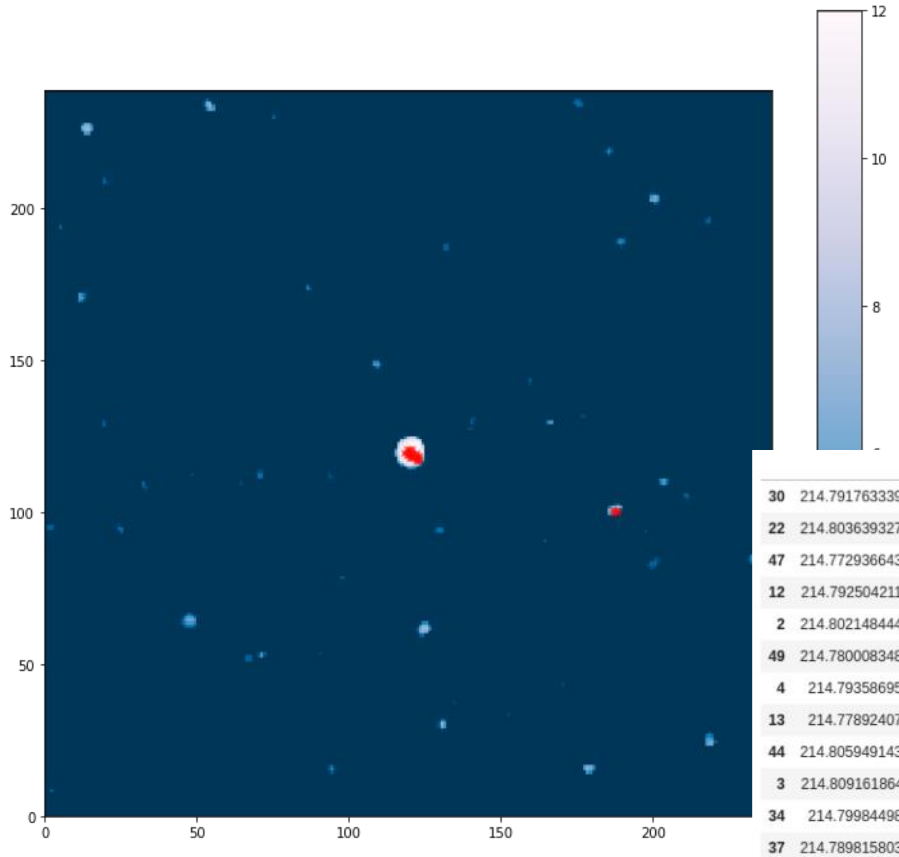
Steidel z~2 -3 galaxies

ACS Observations



Keenan, Marrone, and Keating., 2019 (in prep)

Making use of the SMA Archive



Yin and Keating (in prep)

	RA	DEC	XPIX	YPIX	CHAN	SRC	SIZE	DIS	SIG
30	214.79176333959958	52.812389740393314	119.8	119.1	[126, 483]	([114, 114, 115, 115, 115, 114, 115, 115, 116,...	[2.77, 2.52]	0.507816	12
22	214.80363932720763	52.810380233485844	186.9	100.3	[560, 853]	([99, 99, 100, 100, 99, 100, 101, 101, 101, 99...	[0.98, 1.3]	70.114025	8
47	214.77293664322434	52.82378705822913	13.5	225.7	[515]	([224, 224, 225, 225, 225, 225, 226, 226, 226,...	[1.03, 1.05]	150.058237	7
12	214.79250421163056	52.80617398777872	124.0	61.0	[147]	([59, 59, 60, 60, 60, 60, 61, 61, 61, 61, 61, ...	[1.19, 1.19]	58.672822	7
2	214.80214844403392	52.80127641446763	178.5	15.2	[478]	([14, 14, 15, 15, 15, 15, 16, 16, 16, 16], [17...	[0.75, 1.02]	119.831089	7
49	214.78000834828052	52.824587932150905	53.5	233.2	[727]	([232, 232, 233, 233, 233, 232, 233, 234, 234,...	[0.94, 0.99]	131.474552	7
4	214.7935869508954	52.80282272723328	130.1	29.7	[241]	([28, 29, 29, 29, 30, 30, 30, 31, 31], [130, 1...	[0.94, 0.74]	90.457855	7
13	214.7789240708599	52.80646507213511	47.2	63.8	[136]	([62, 62, 63, 63, 63, 62, 63, 64, 64, 64, 64, ...	[1.26, 1.26]	91.258561	6
44	214.80594914369252	52.82131043635742	200.0	202.5	[173]	([201, 201, 202, 202, 202, 203, 203, 203, 204,...	[1.02, 0.77]	115.625473	6
3	214.80916186468116	52.802286833274266	218.1	24.6	[529]	([23, 23, 24, 24, 23, 24, 25, 25, 25, 24, 26, ...	[1.23, 0.91]	136.851346	6
34	214.7998449802913	52.81344832747449	165.5	129.0	[555]	([129, 129], [165, 166])	[0.0, 0.5]	46.970736	5
37	214.78981580319984	52.81549691955763	108.8	148.2	[740]	([147, 148, 148, 148, 149, 149], [109, 108, 10...	[0.69, 0.69]	30.586853	5
10	214.7831271653854	52.8052628754255	71.0	52.5	[113]	([52, 52, 53, 53, 52, 53], [70, 71, 70, 71, 72...	[0.5, 0.82]	82.711849	5
26	214.80648151668447	52.81136311323589	203.0	109.5	[507]	([109, 109, 110, 110, 109, 110], [202, 203, 20...	[0.5, 0.82]	84.096671	5
38	214.7726544559421	52.81784109066974	11.9	170.1	[363]	([169, 169, 170, 170, 170, 171, 171, 171], [11...	[0.78, 0.78]	118.937089	5
41	214.80400245610565	52.81978994241771	189.0	188.3	[712]	([187, 188, 188, 188, 189, 189, 189], [189, 18...	[0.7, 0.76]	97.784071	4
1	214.78716946810647	52.8012706024656	93.8	15.2	[259]	([14, 15, 15, 15, 16, 16], [94, 93, 94, 95, 93...	[0.69, 0.69]	107.444042	4
46	214.80332331037962	52.822985981523665	185.2	218.2	[128]	([217, 218, 218, 218, 219, 219], [185, 184, 18...	[0.69, 0.69]	118.520978	4
16	214.81166391386498	52.80863576287154	232.3	84.0	[0]	([83, 83, 84, 84, 84, 85, 85], [232, 233, 231,...	[0.76, 0.7]	118.240718	4
39	214.78583221559467	52.8181879395333	86.3	173.3	[259]	([173, 173, 174], [86, 87, 86])	[0.47, 0.47]	63.230179	4

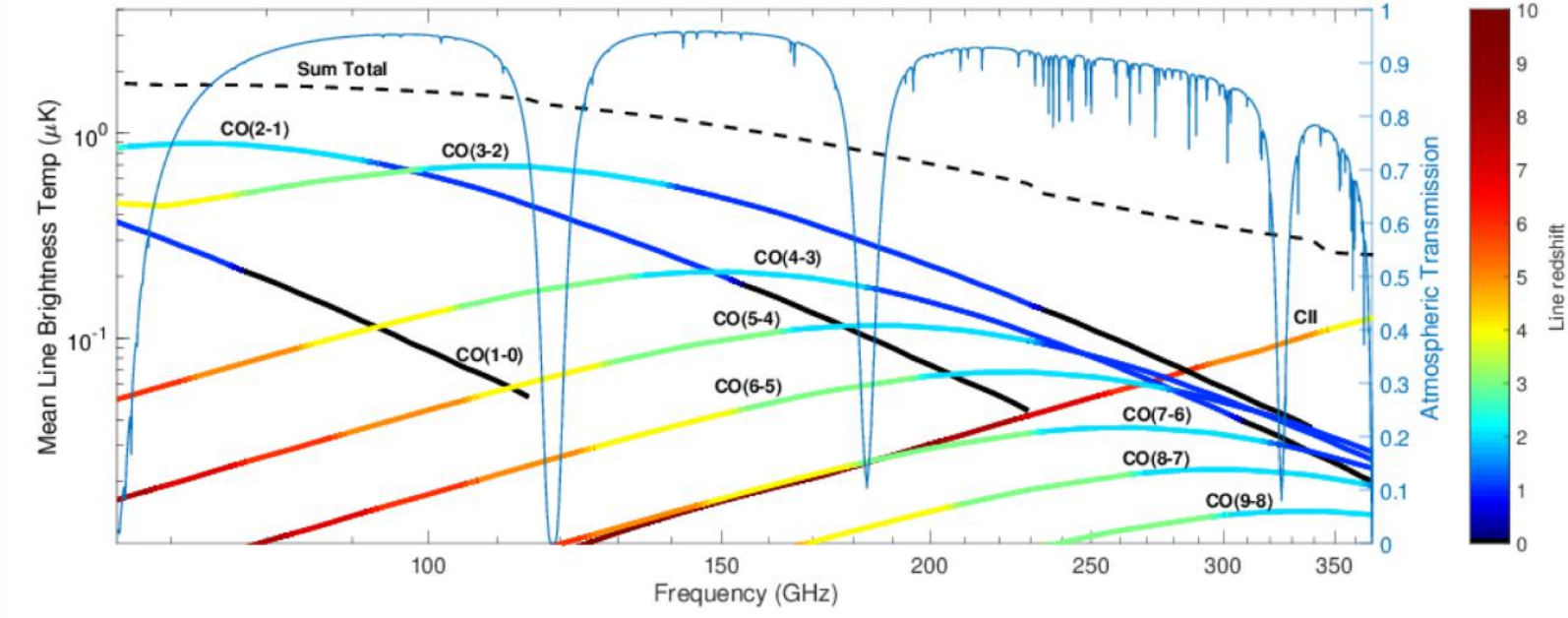
Looking towards the future…

Better frequency coverage means:

- Better continuum sensitivity (wideband + dual band)
- More instantaneous spectral lines

Lots of applicability with potential expansions

- Widefield mapping capabilities (multi-pixel + OTF)
- “Filling the IF hole” -> better redshift coverage
- Lots to be done w/ either lower or higher freq guest instrument



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**
- **1st generation of experiments and instruments are coming online now, next decade will be a boom time for IM-related science**