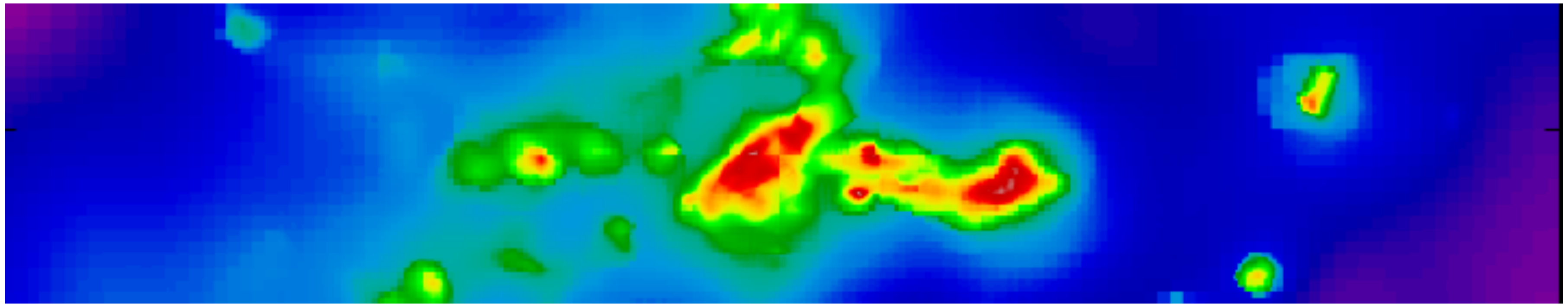
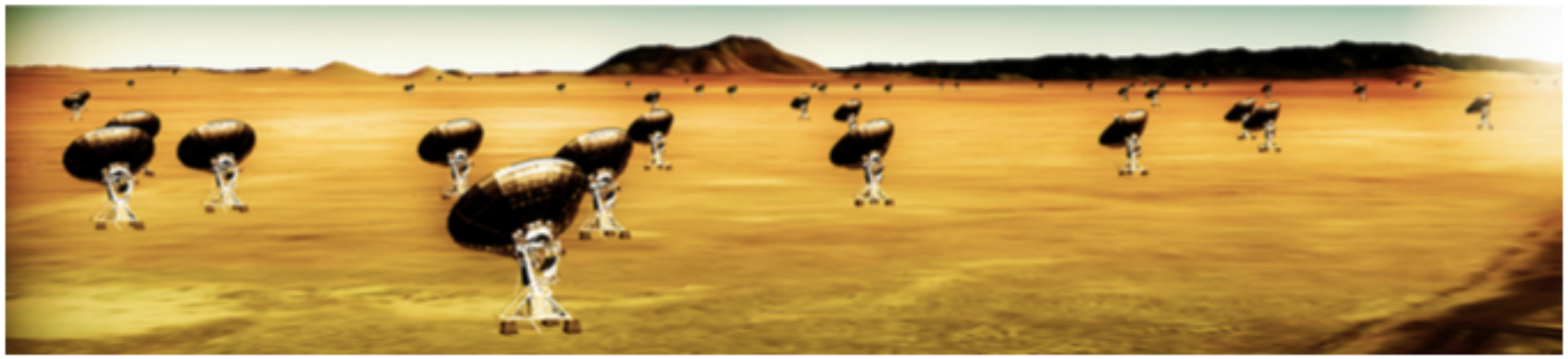


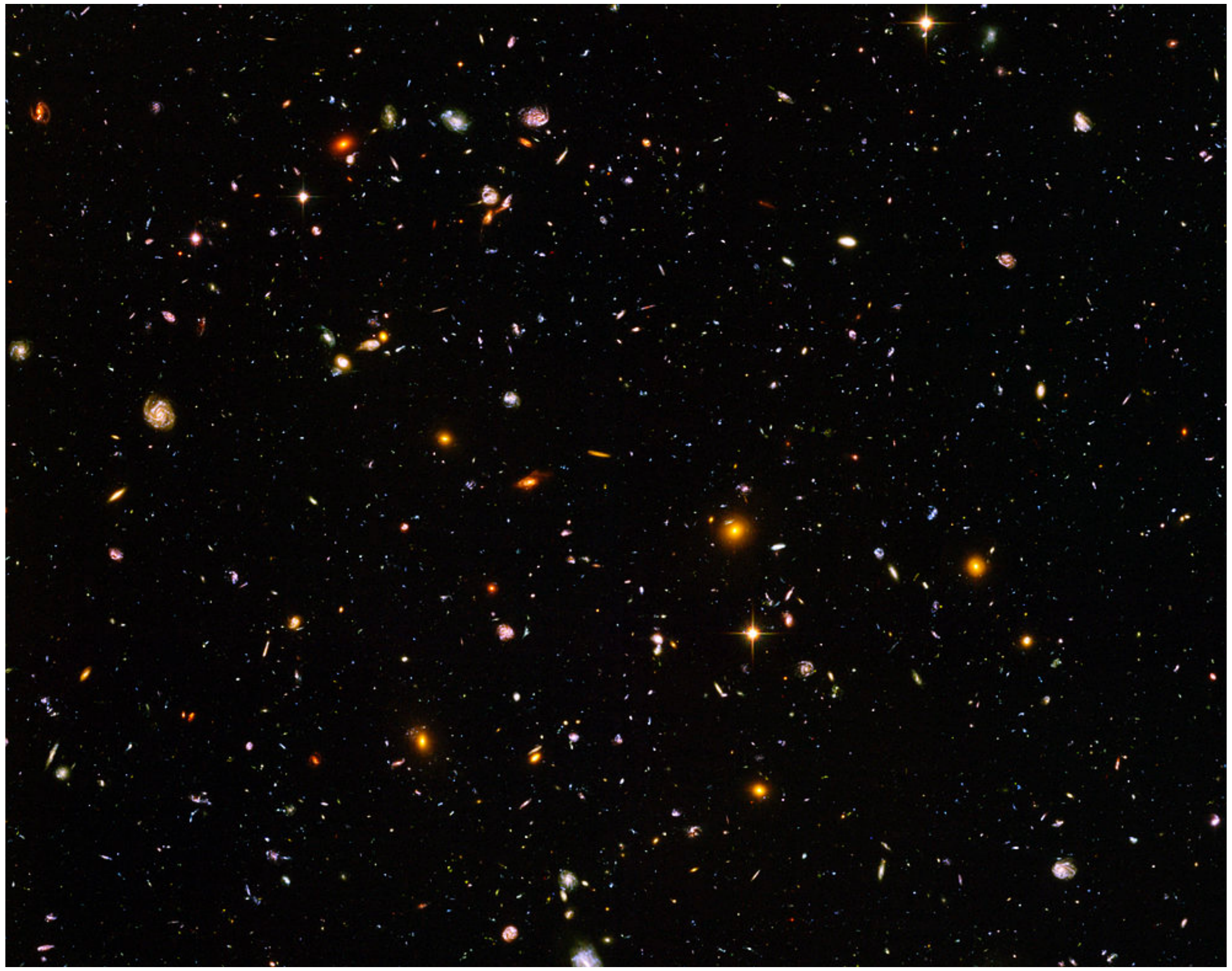


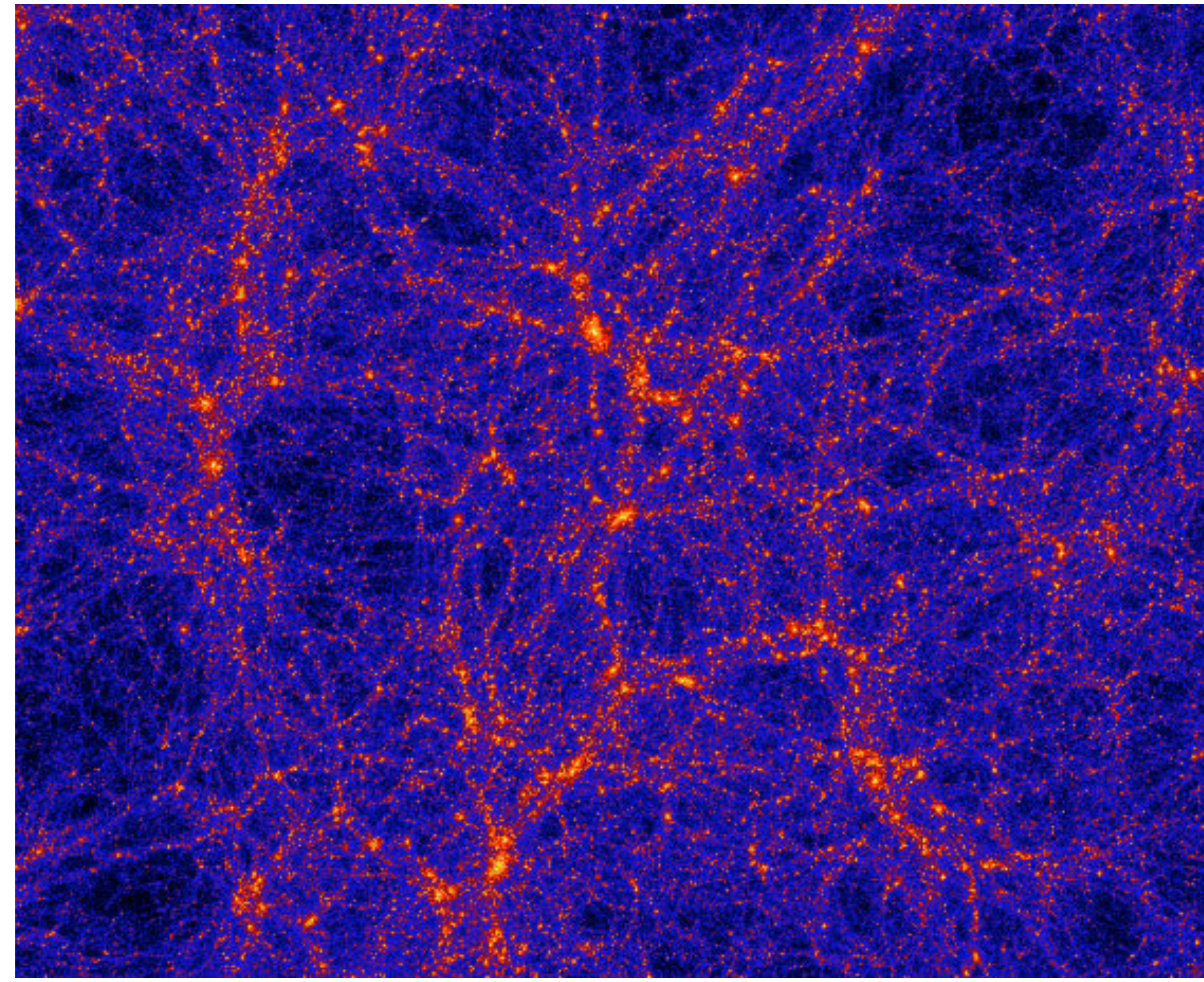
Next Generation Very Large Array Memo No. 8
Science Working Group 3
Galaxy Assembly through Cosmic Time

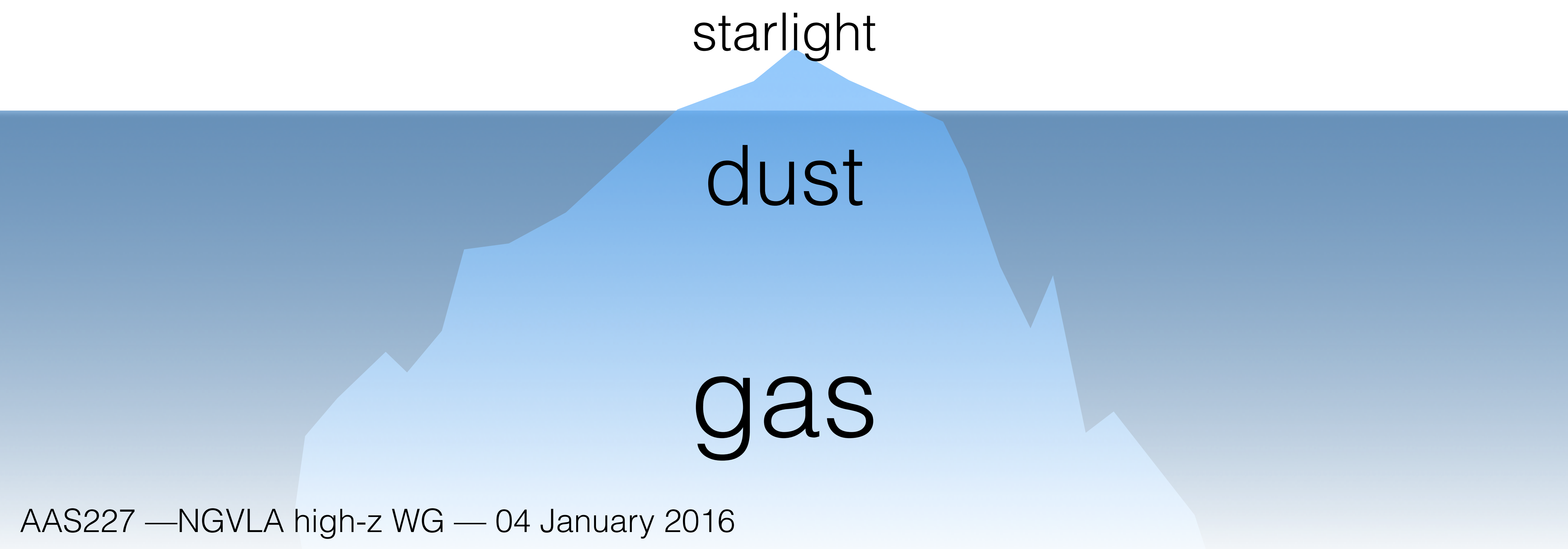
Caitlin M. Casey[1], Jacqueline A. Hodge[2,3], Mark Lacy[2], Christopher A. Hales[4], Amy Barger[5], Desika Narayanan[6], Chris Carilli[4,18], Katherine Alatalo[7], Elisabete da Cunha[8], Bjorn Emonts[9], Rob Ivison[10,11] Amy Kimball[12], Kotaro Kohno[13], Eric Murphy[14], Dominik Riechers[15], Mark Sargent[16], Fabian Walter[17]

Caitlin Casey
Assistant Professor
UT Austin

next generation VLA workshop AAS 227
Kissimmee, FL
4 January 2016






starlight
dust
gas

Our link to the Cosmic Web.

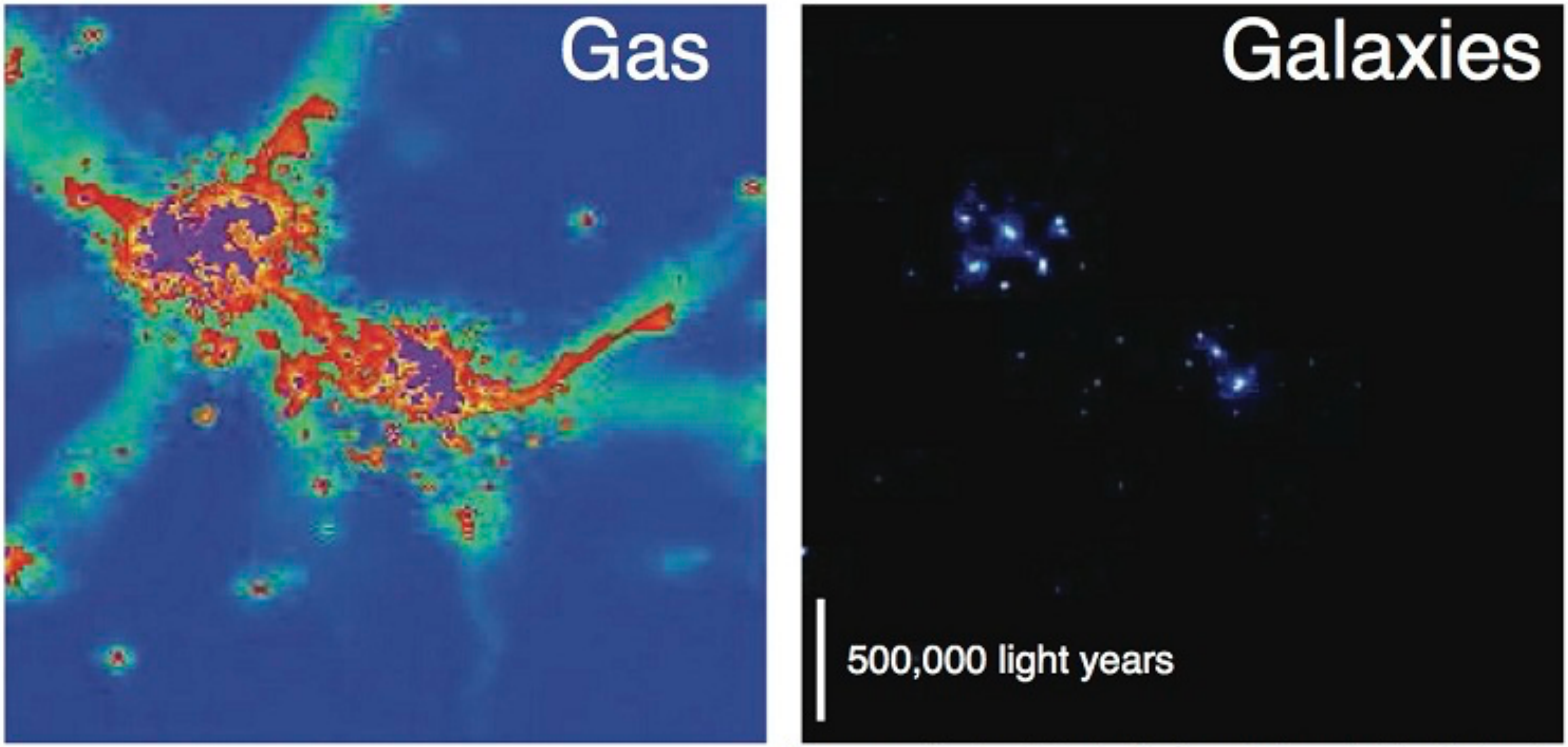
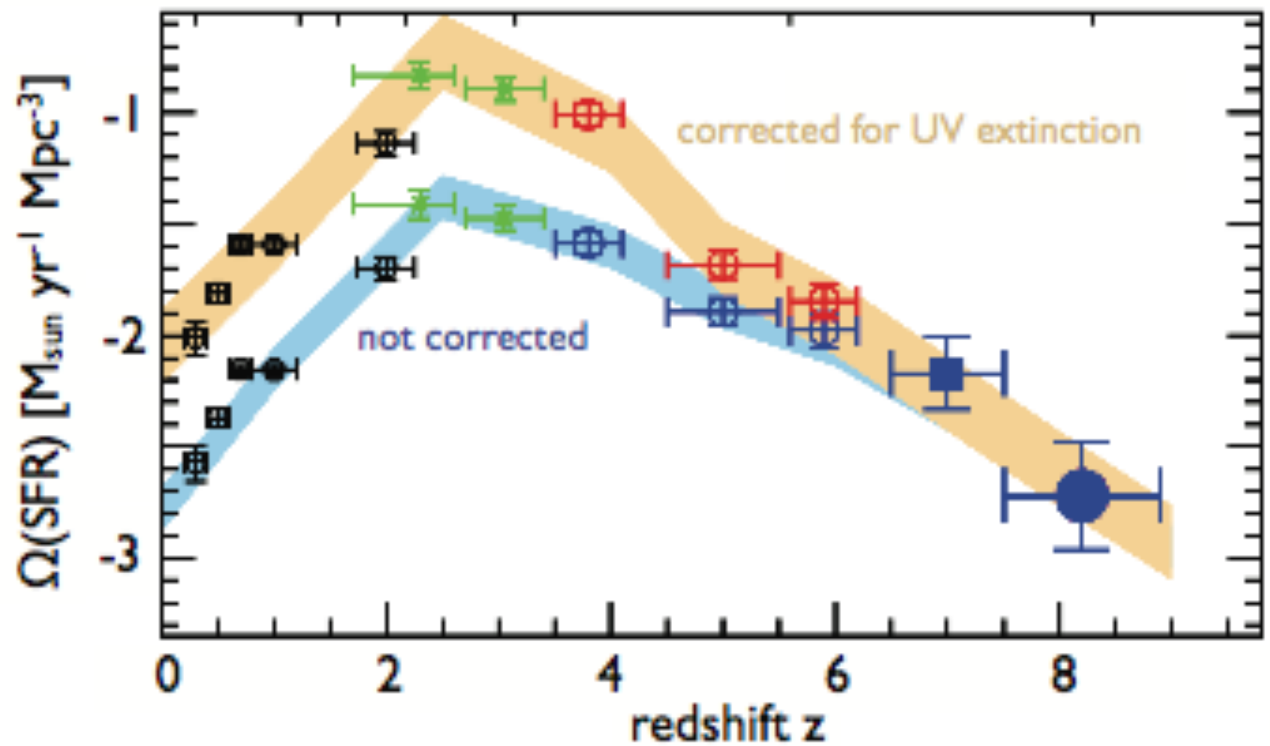


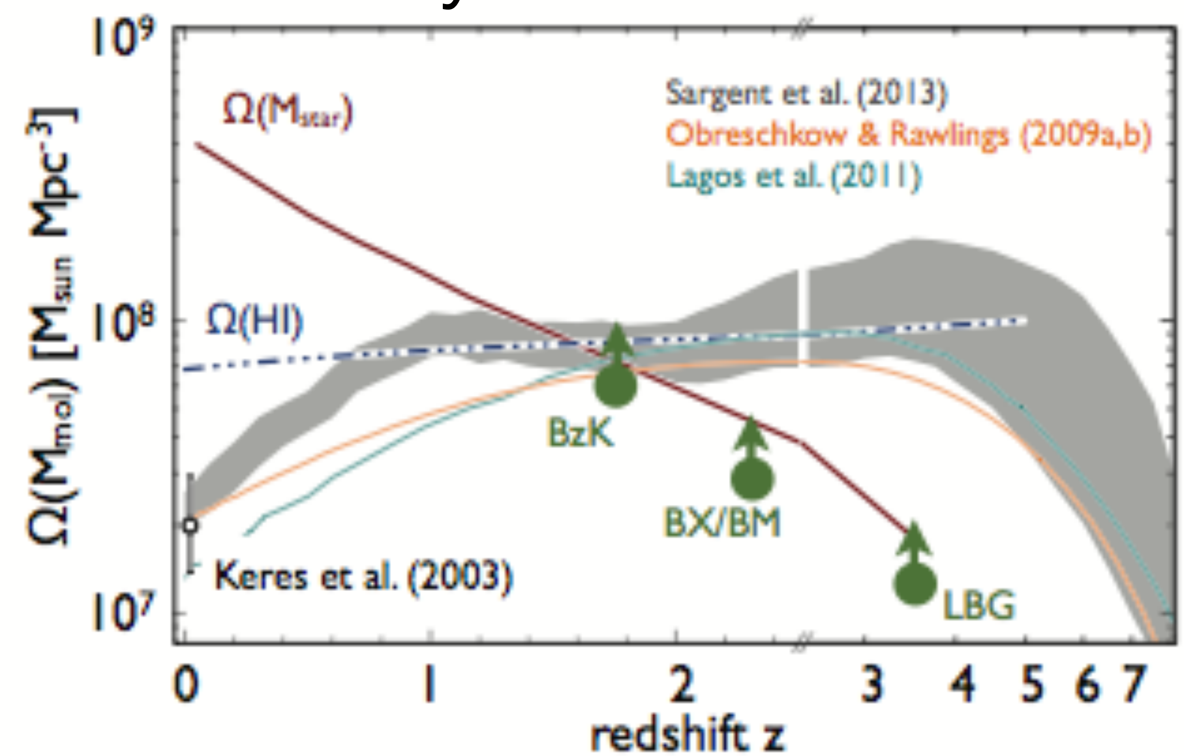
Image credit: simulation by B. Oppenheimer, Leiden University

IGM ⟷ CGM ⟷ HI Gas ⟷ H_2 Gas ⟷ Star-Forming Clouds

History of Star Formation



History of Gas Content

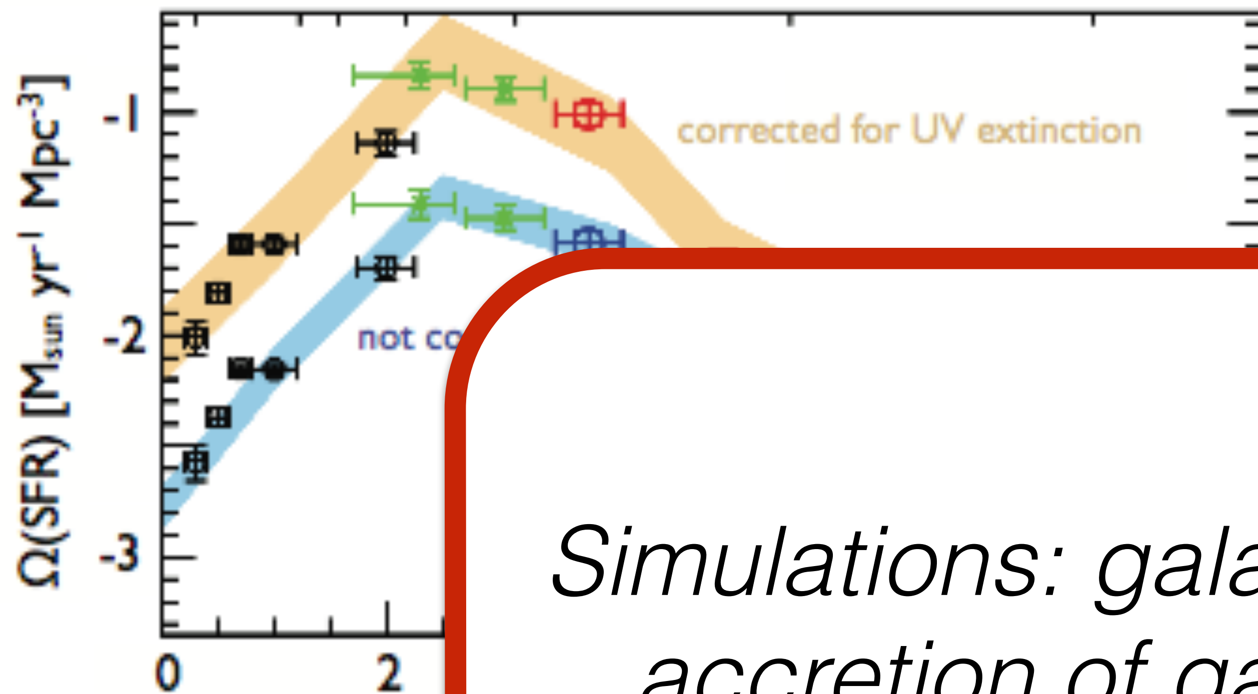


Carilli & Walter 2013 ARA&A

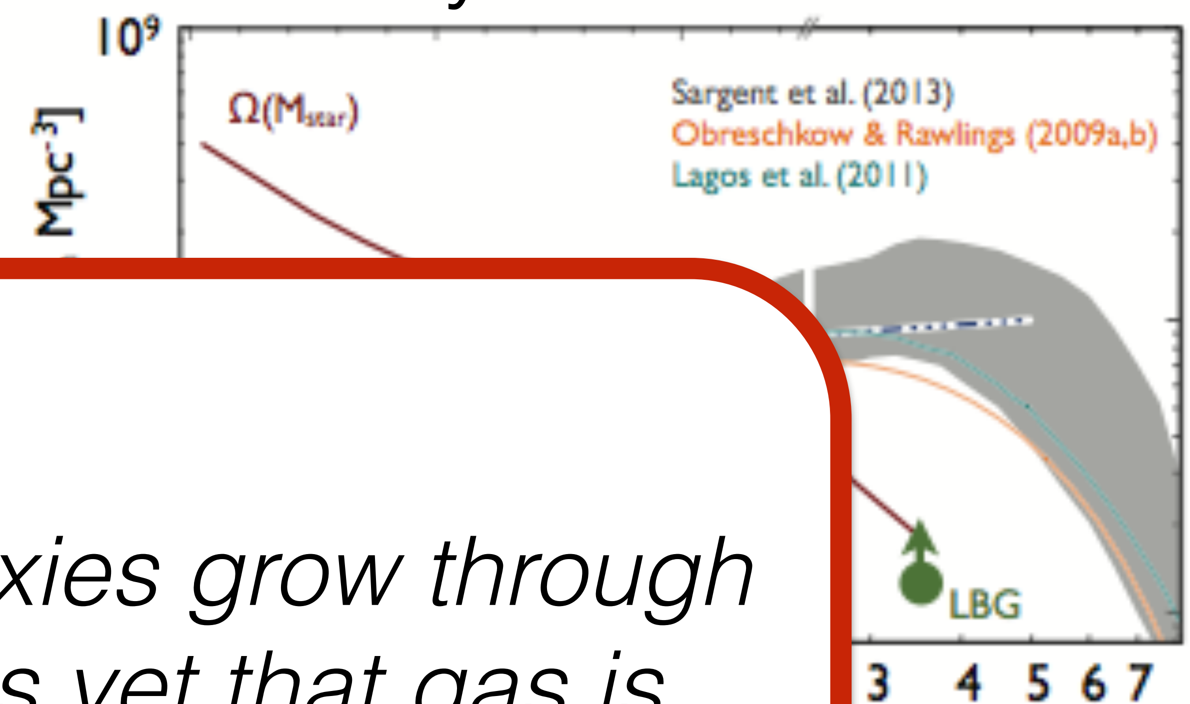
Cold gas fuels star formation, but cold gas content in high-z galaxies much less understood than star-formation.

Yet cold gas is essential to constraining physical mechanisms of early Universe star formation!

History of Star Formation



History of Gas Content

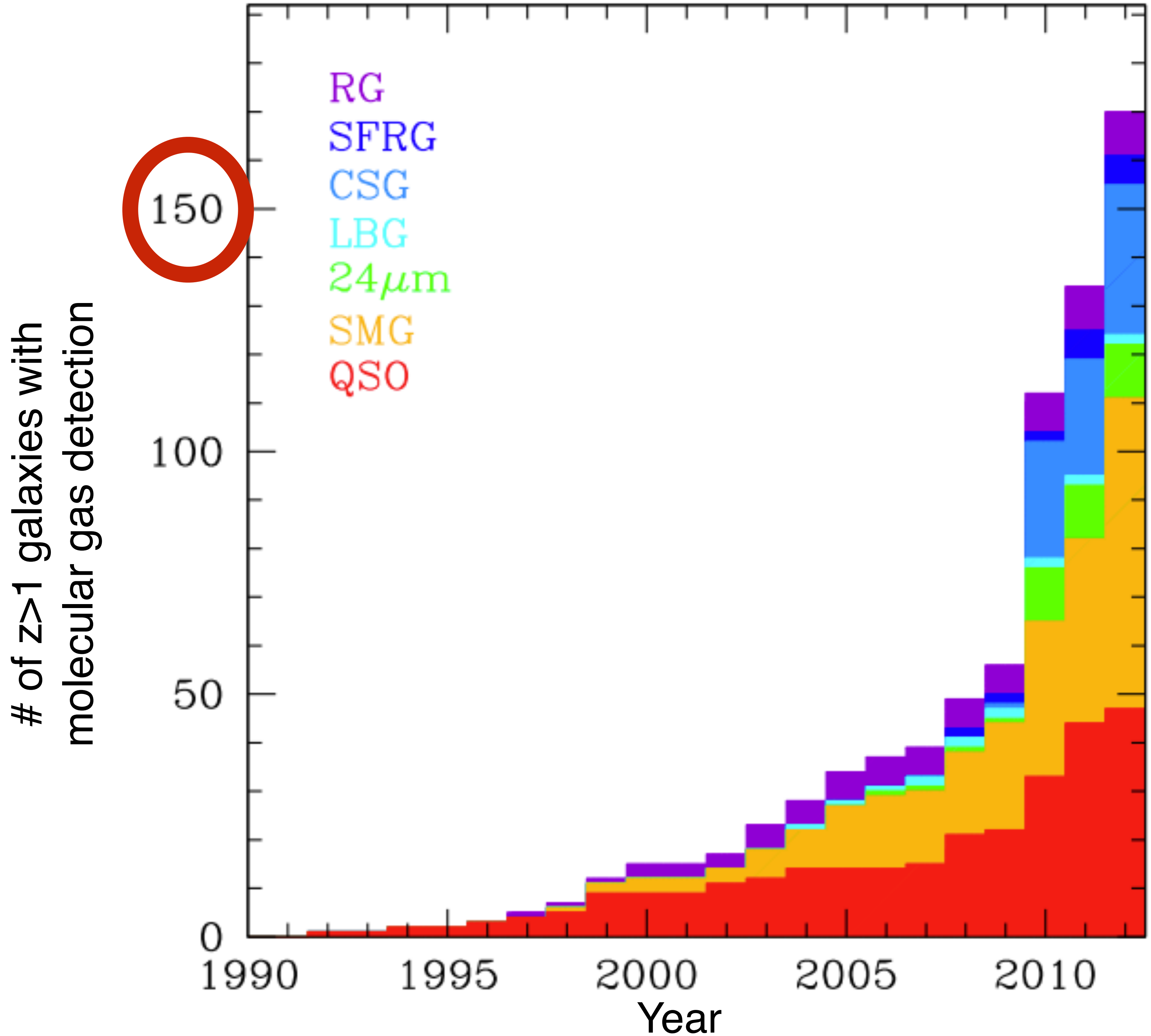


2013 ARA&A

Simulations: galaxies grow through accretion of gas yet that gas is *__unconstrained__* *at high-z observationally.*

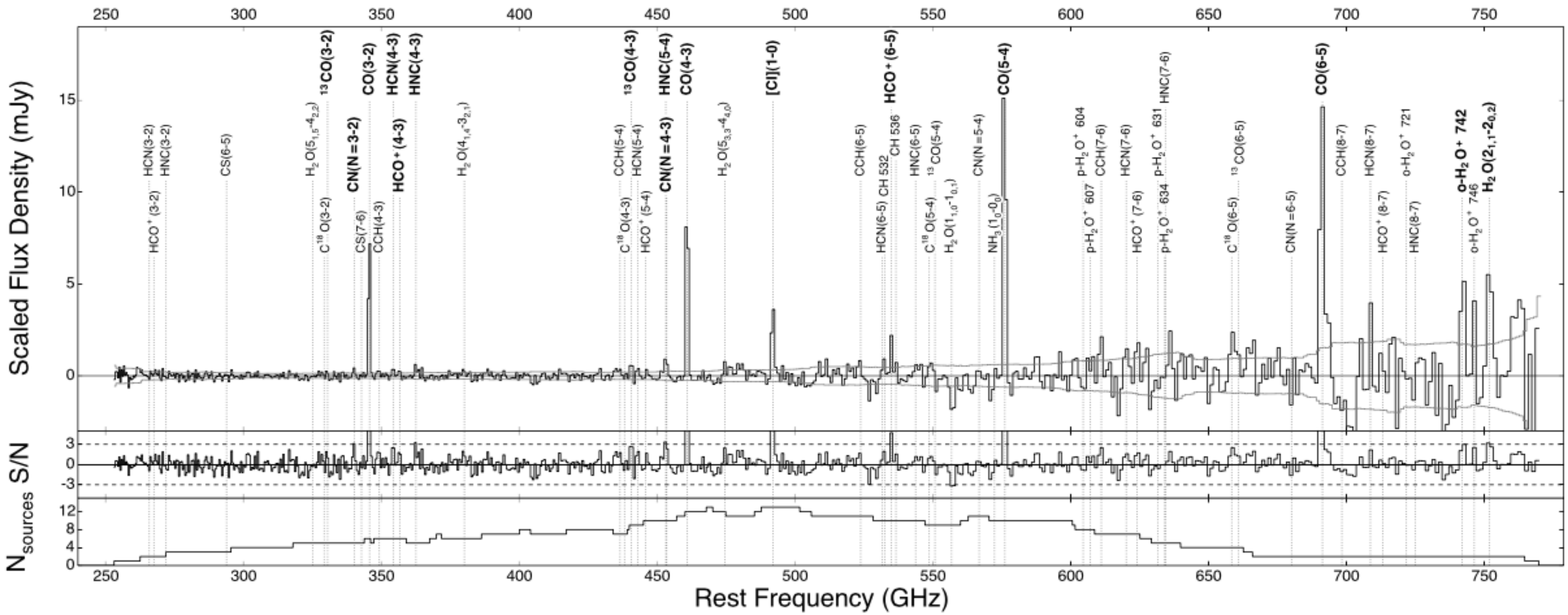
Cold ga ntent in high-z galaxies much less understood than star-formation.

Yet cold gas is essential to constraining physical mechanisms of early Universe star formation!



Carilli & Walter (2013)

CO: probing H_2, star-forming gas



(continuum subtracted composite DSFG spectrum from ALMA, 22 galaxies; Spilker et al. 2014)

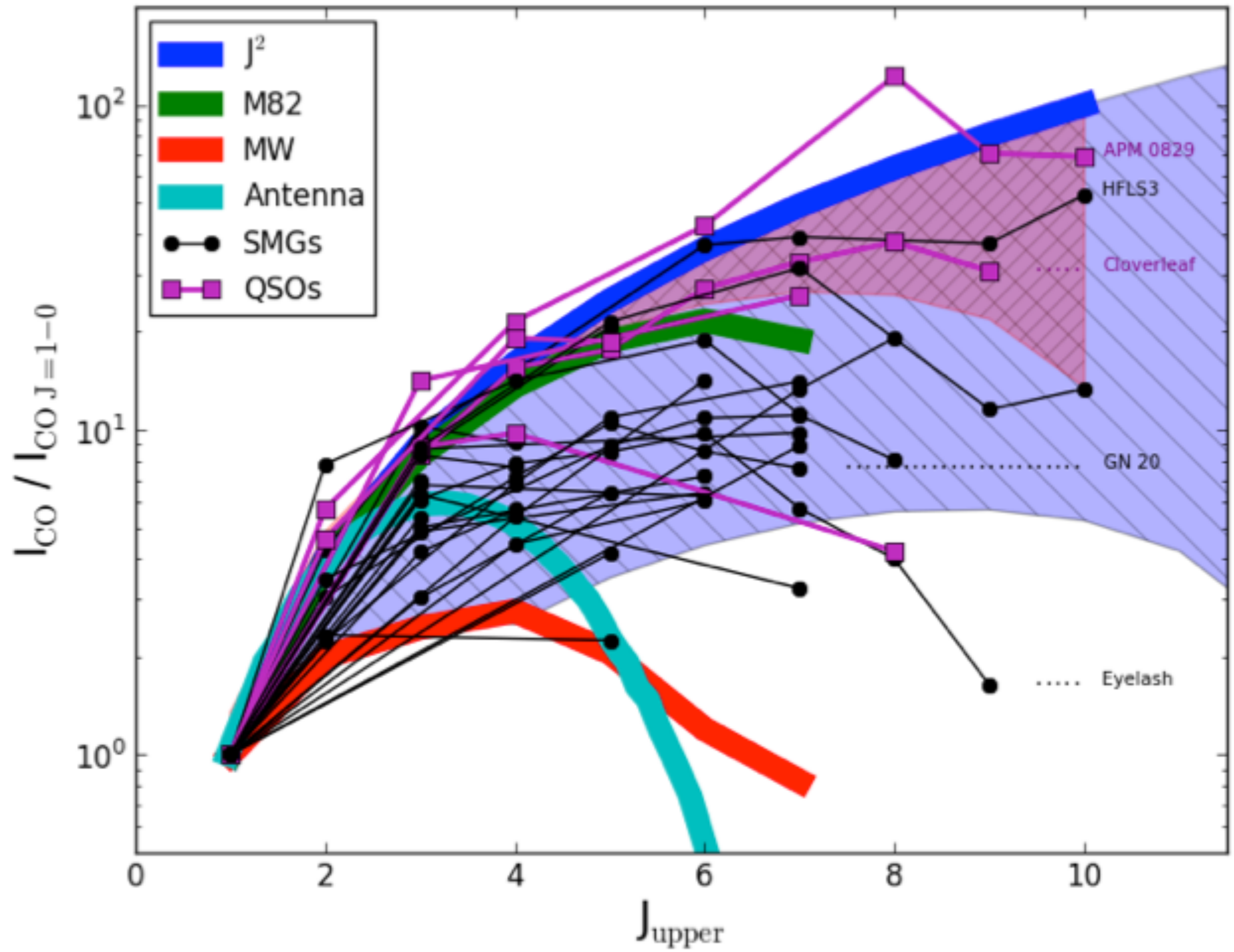
high-J CO ⟶ CO(1-0) ⟶ H_2 gas mass

CO excitation

$\alpha_{CO}(X_{CO})$

CO: probing H_2, star-forming gas

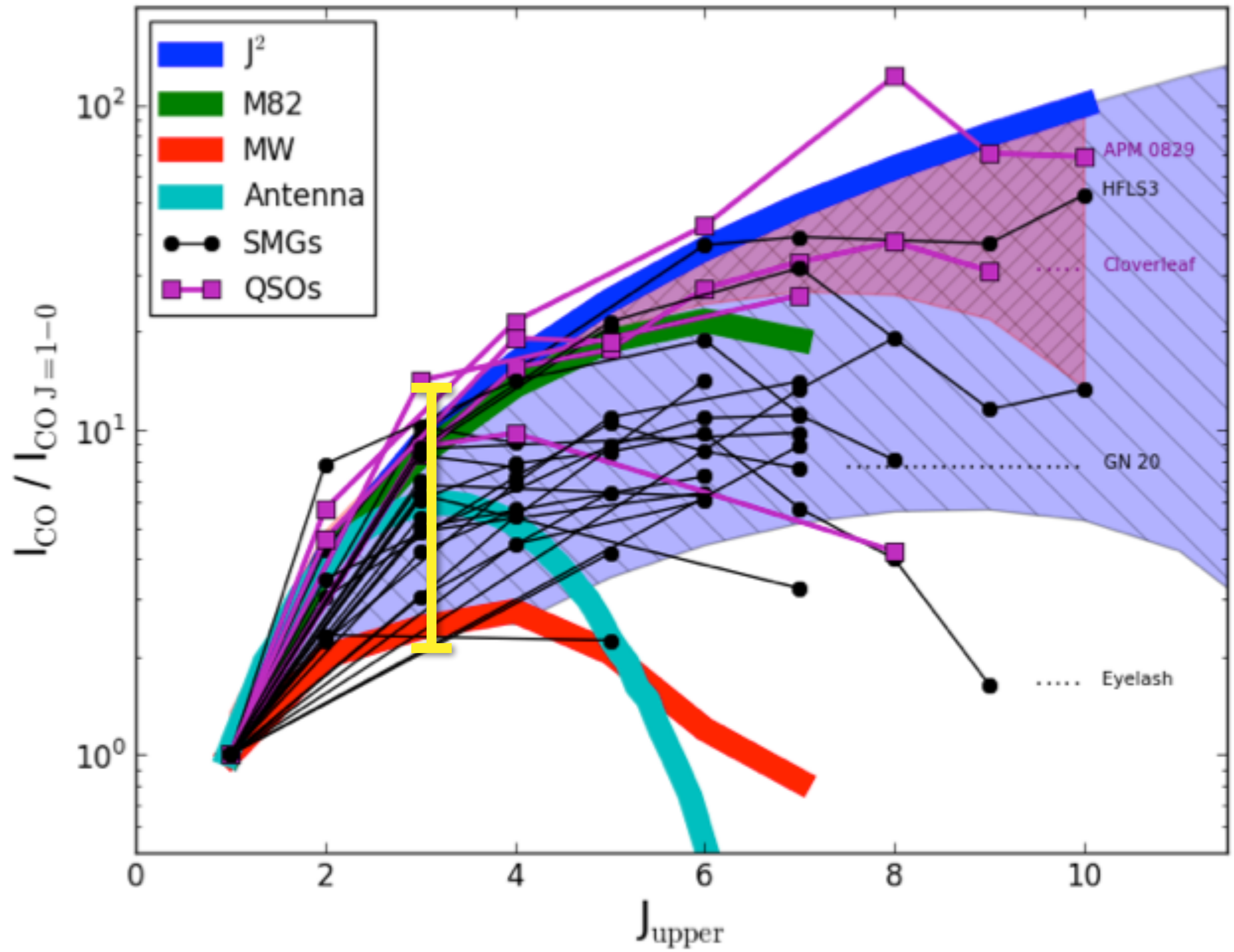
Need low-J CO due to variation in CO excitation ladder: diverse SLEDs at high-z!



Casey, Narayanan & Cooray (2014)

CO: probing H_2, star-forming gas

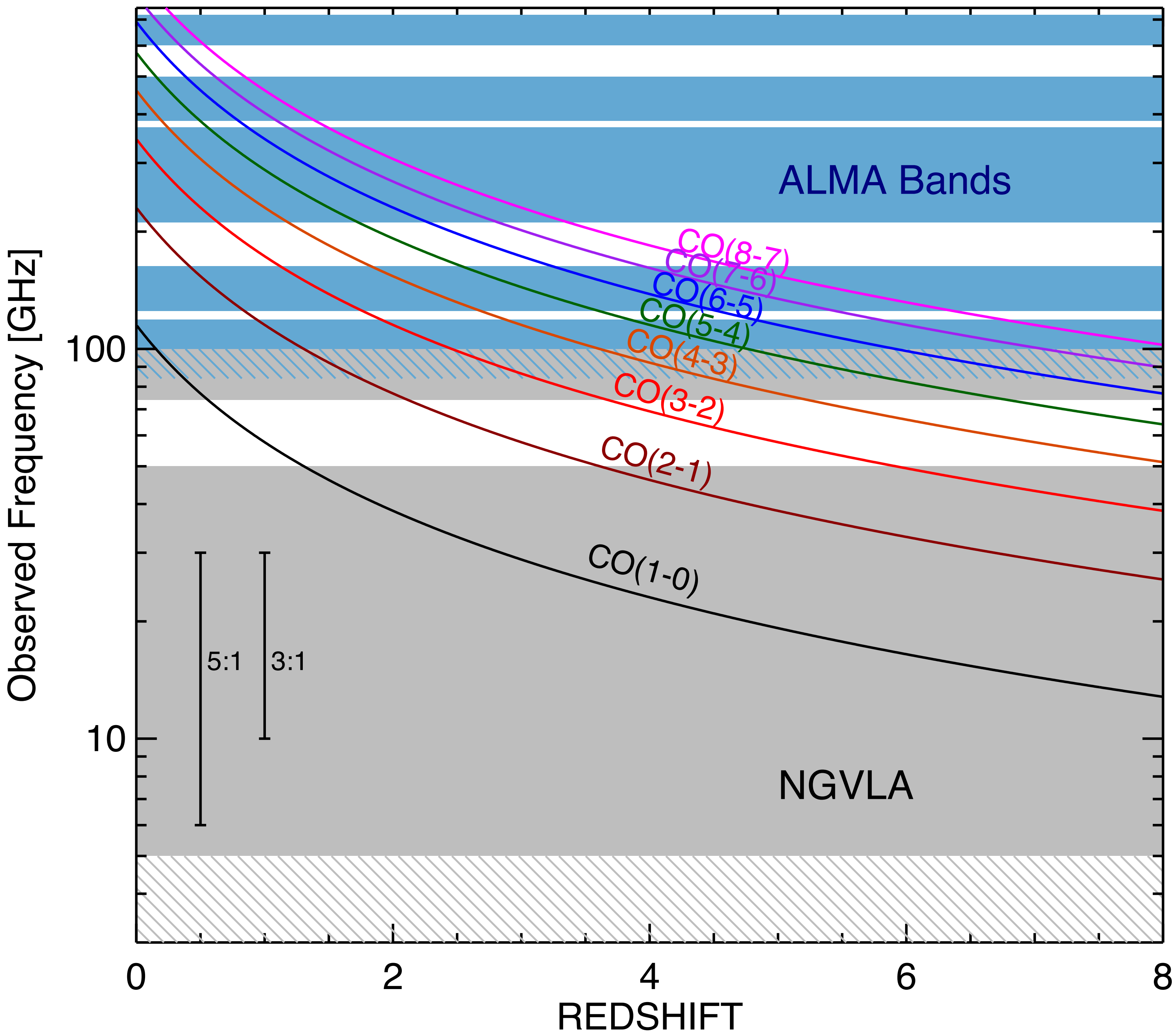
Need low-J CO due to variation in CO excitation ladder: diverse SLEDs at high-z!



Casey, Narayanan & Cooray (2014)

Factor of ~3-8 variation in $I_{CO(3-2)}/I_{CO(1-0)}$ translates to same uncertainty in M_{H_2} (even without ~5x uncertainty in α_{CO})

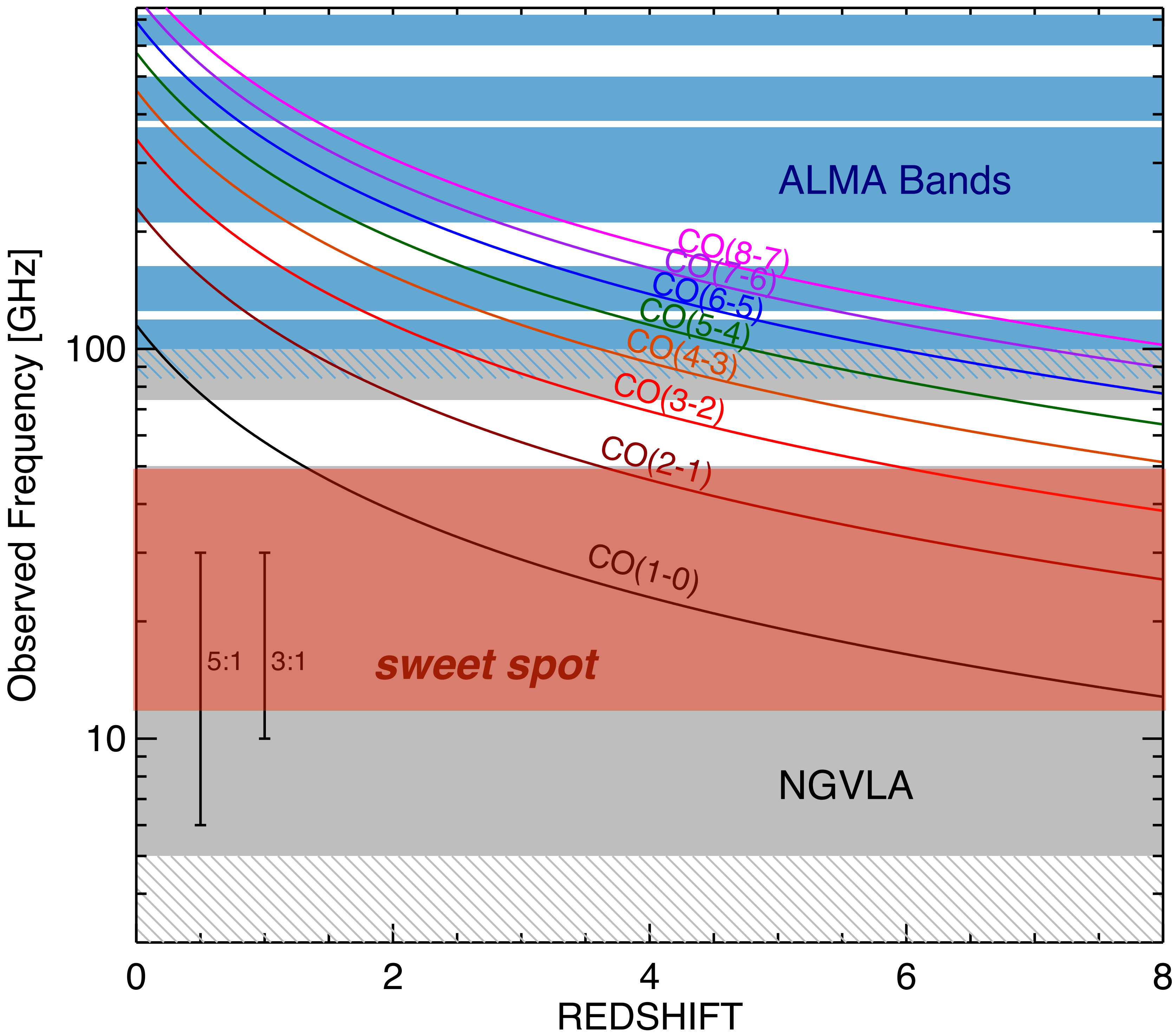
CO: probing H_2, star-forming gas



(WG3 White Paper: Casey et al. 2015b)

ALMA Bands miss low-J CO at high-z.

CO: probing H_2, star-forming gas

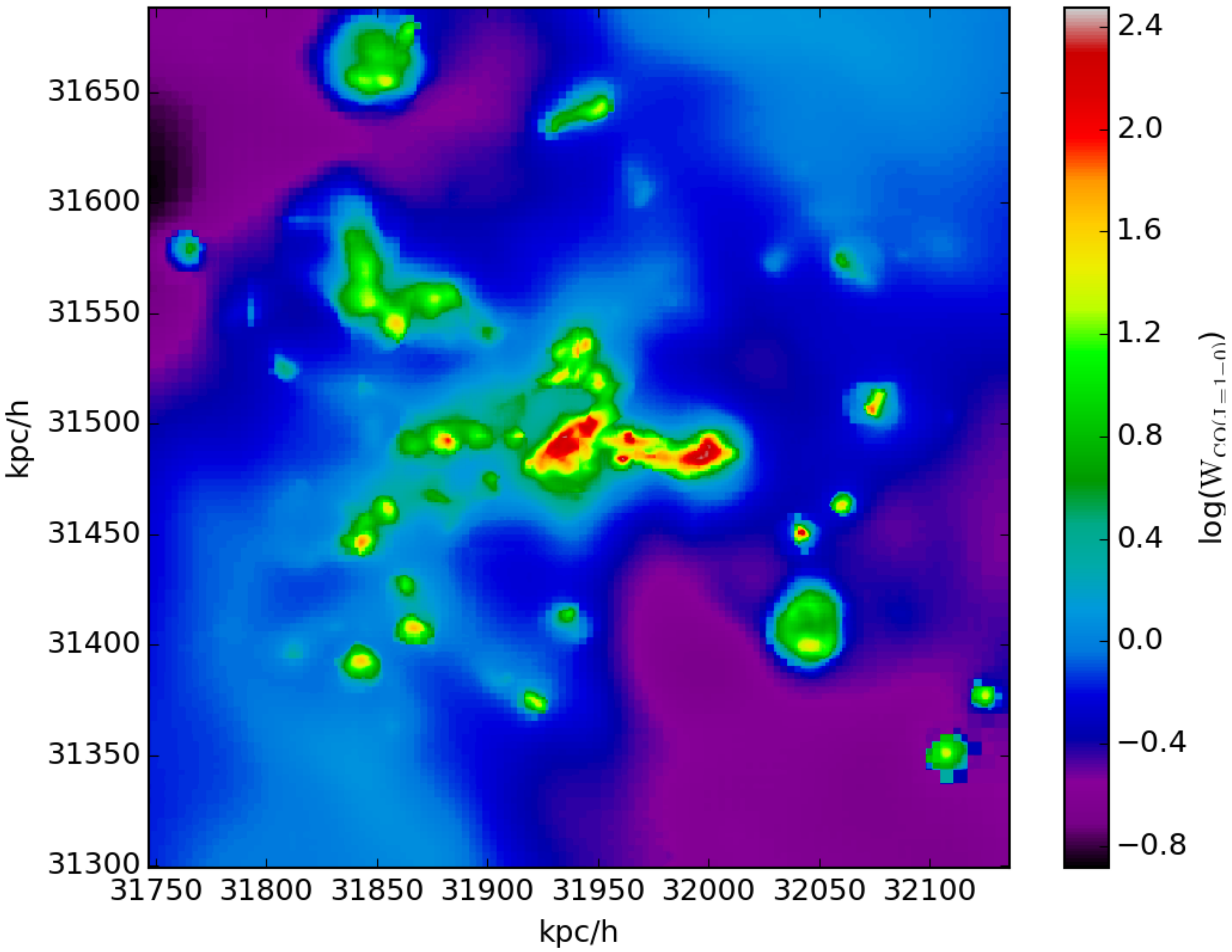


ALMA Bands miss low-J CO at high-z.

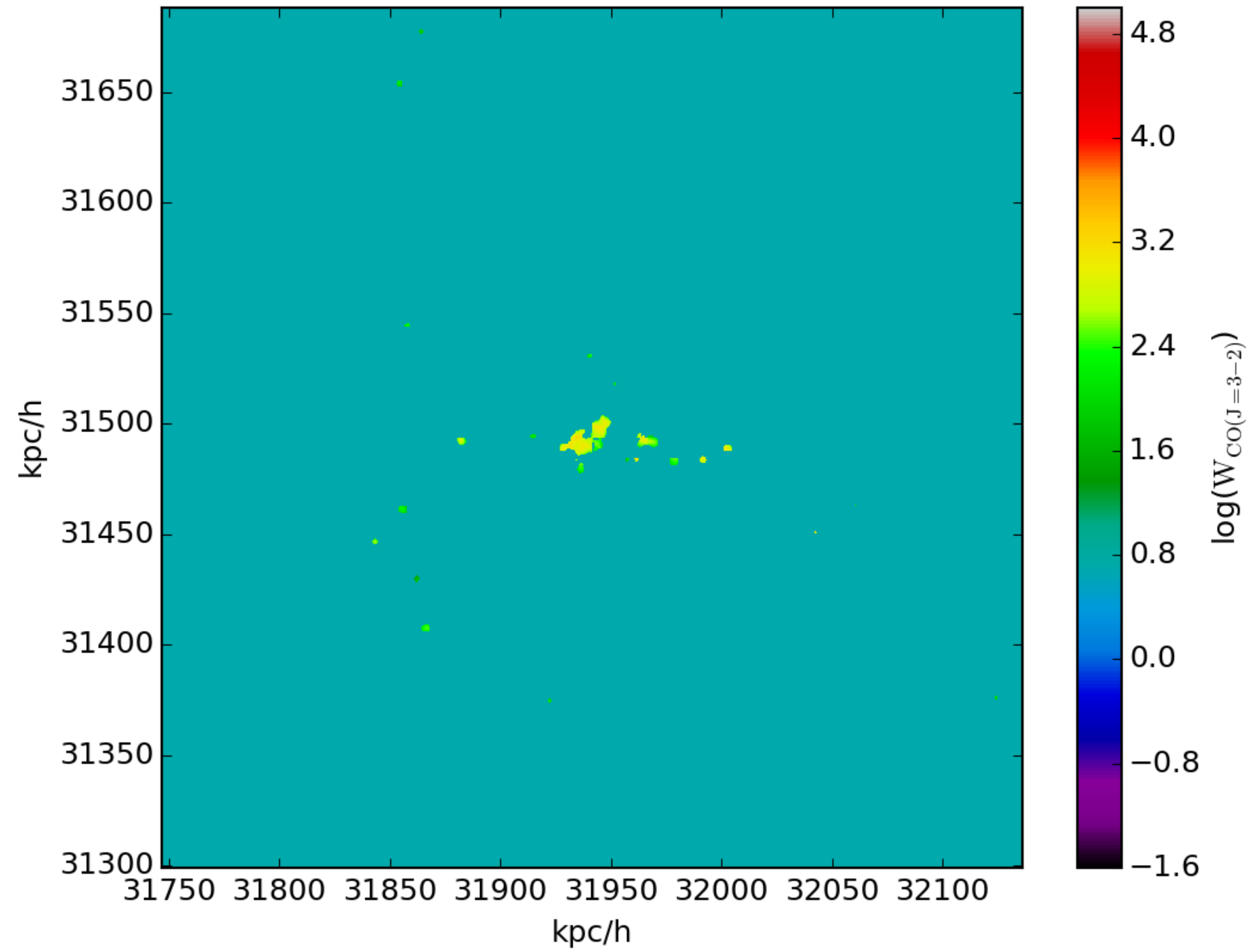
(WG3 White Paper: Casey et al. 2015b)

CO: probing H_2, star-forming gas

Simulations perspective:
(Narayanan Powderday RT code; Narayanan et al. 2015)



CO(1-0)



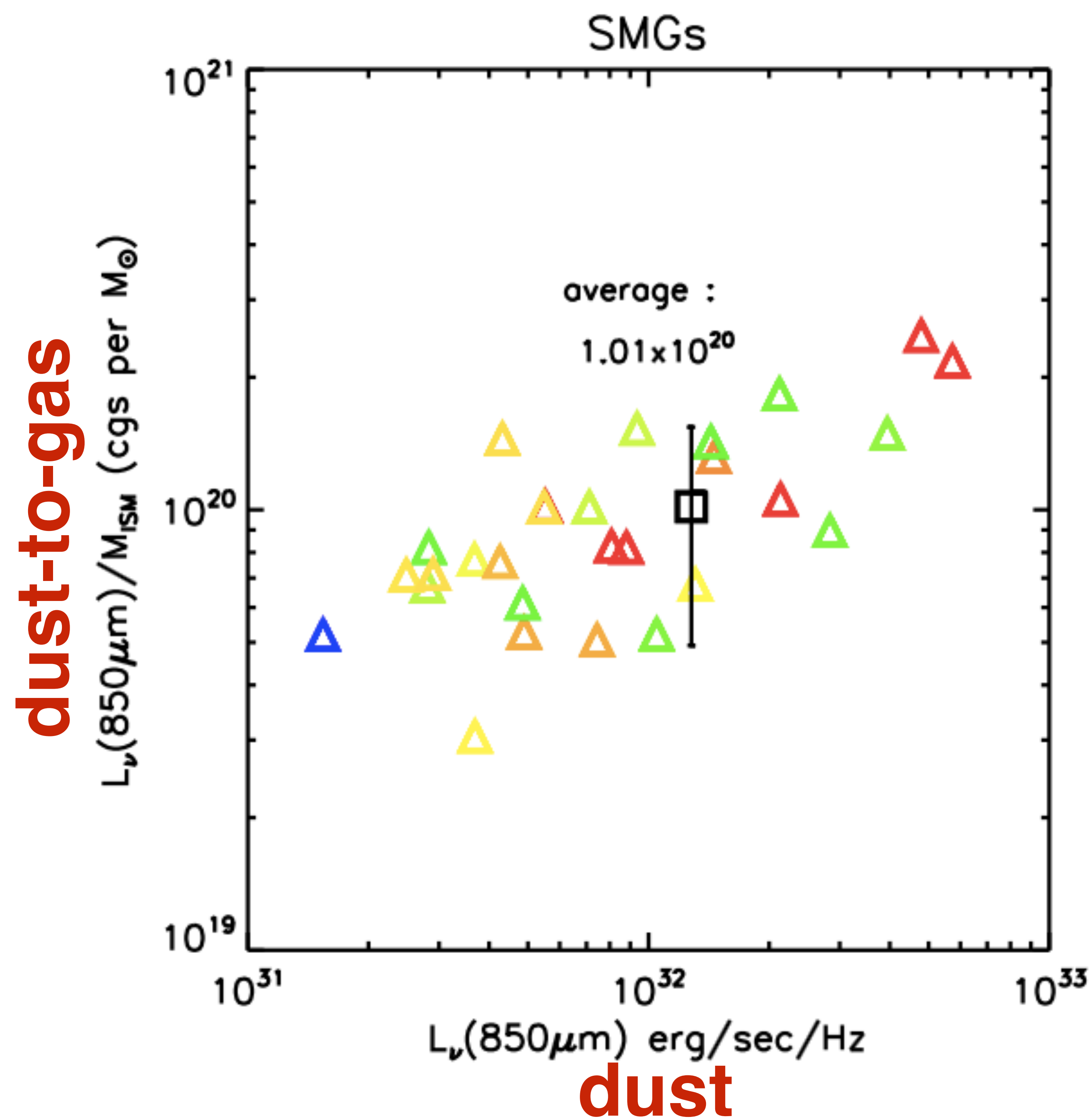
CO(3-2)

Dust continuum proxy for gas?

Based on fixed dust-to-gas ratio; less uncertainty than CO excitation and conversion factor.

Is there any underlying bias?

Lacks dynamical constraints.



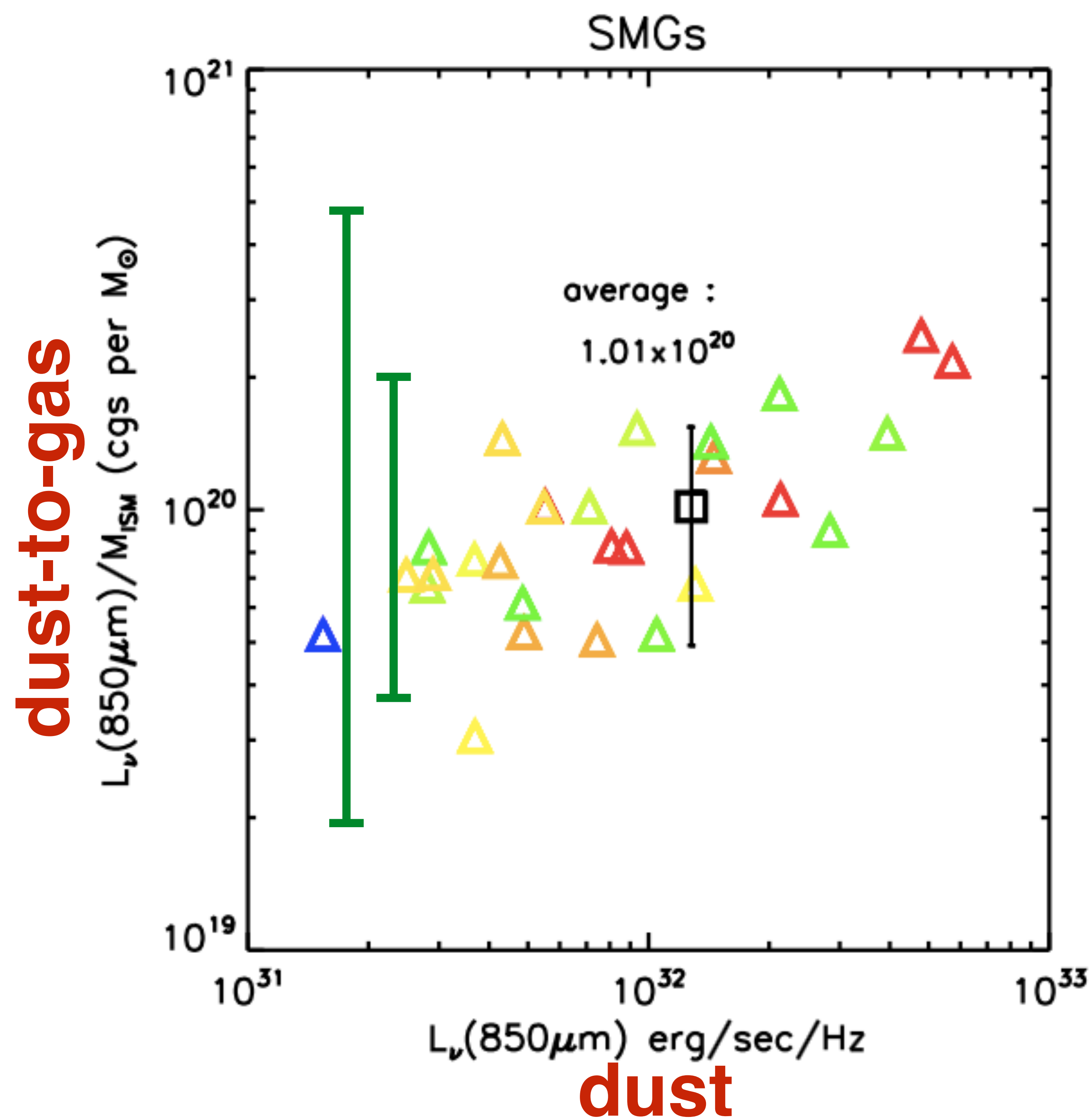
Scoville et al. (2014)

Dust continuum proxy for gas?

Based on fixed dust-to-gas ratio; less uncertainty than CO excitation and conversion factor.

Is there any underlying bias?

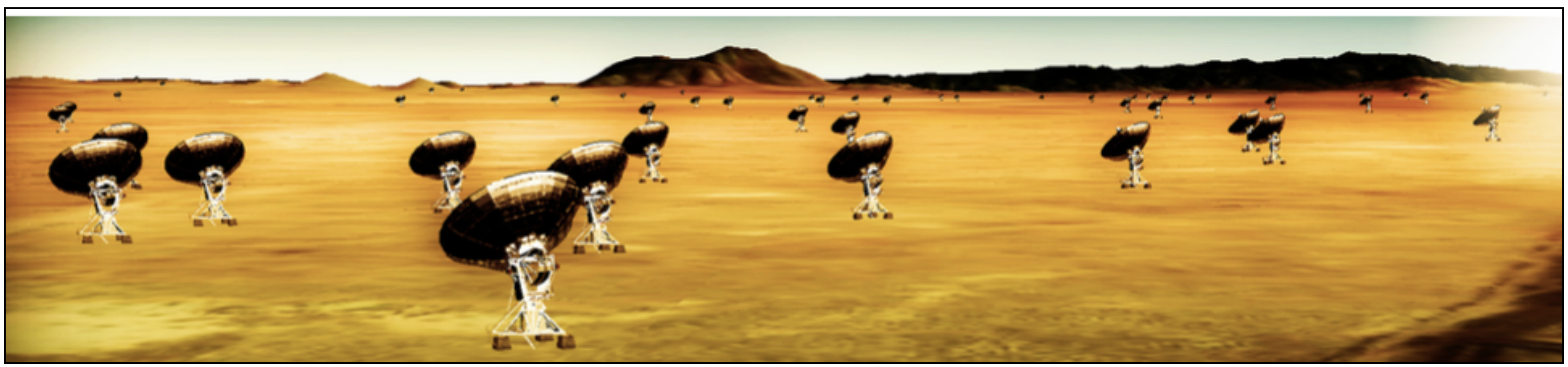
Lacks dynamical constraints.



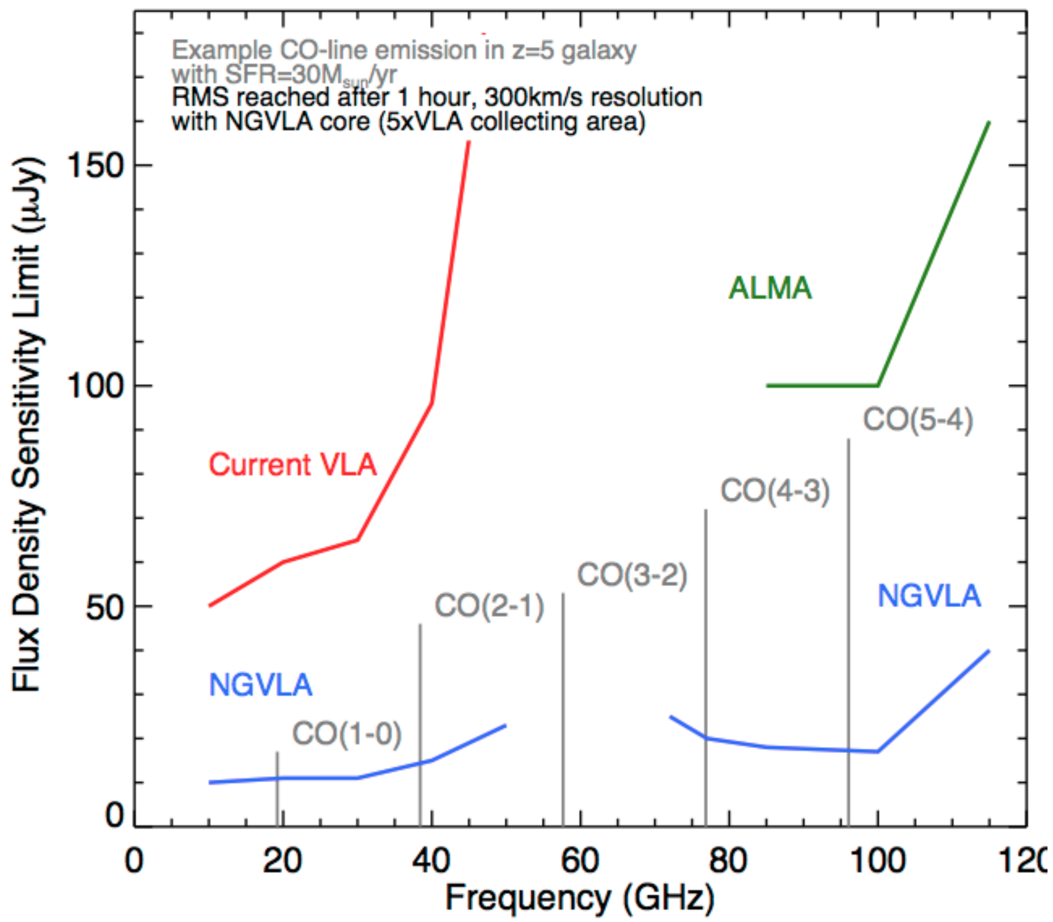
Scoville et al. (2014)

Surveying gas in the early-Universe:

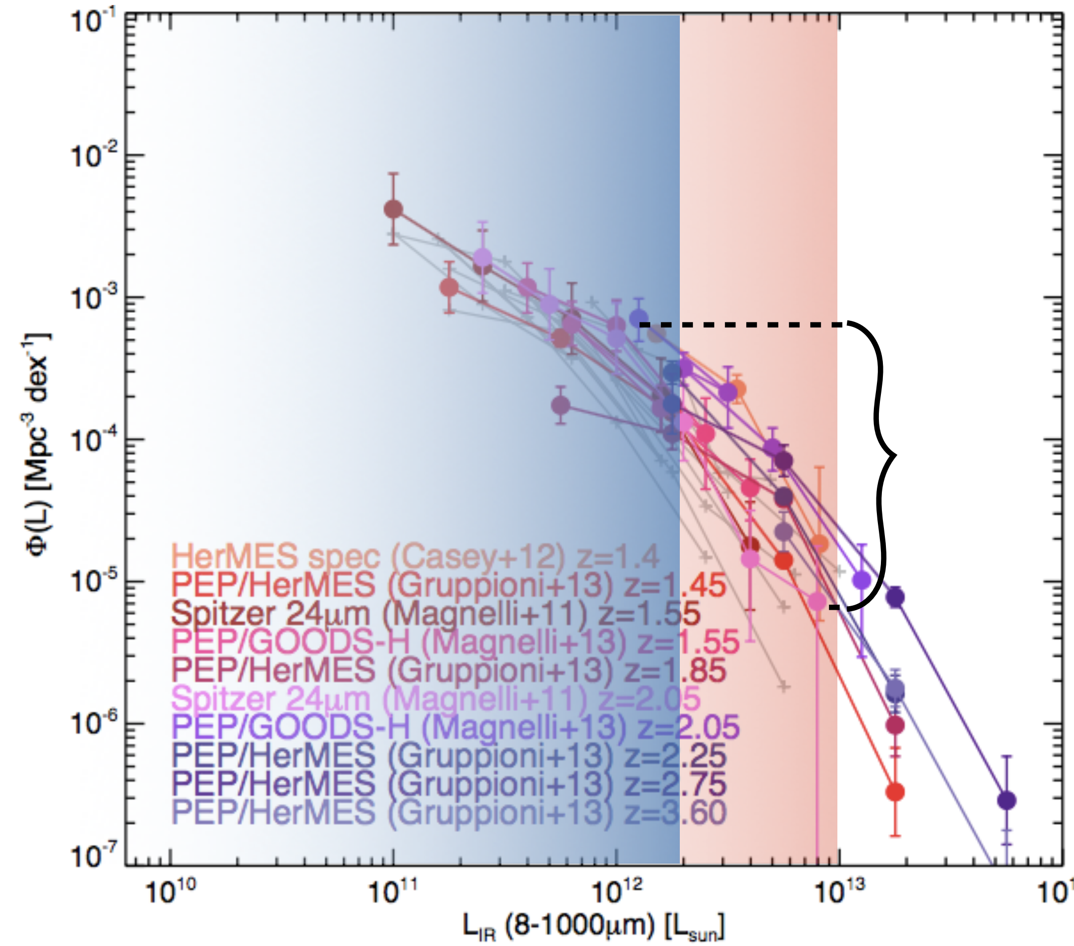
The need for a next generation VLA



Single source follow-up to population work



Carilli et al. (2015)

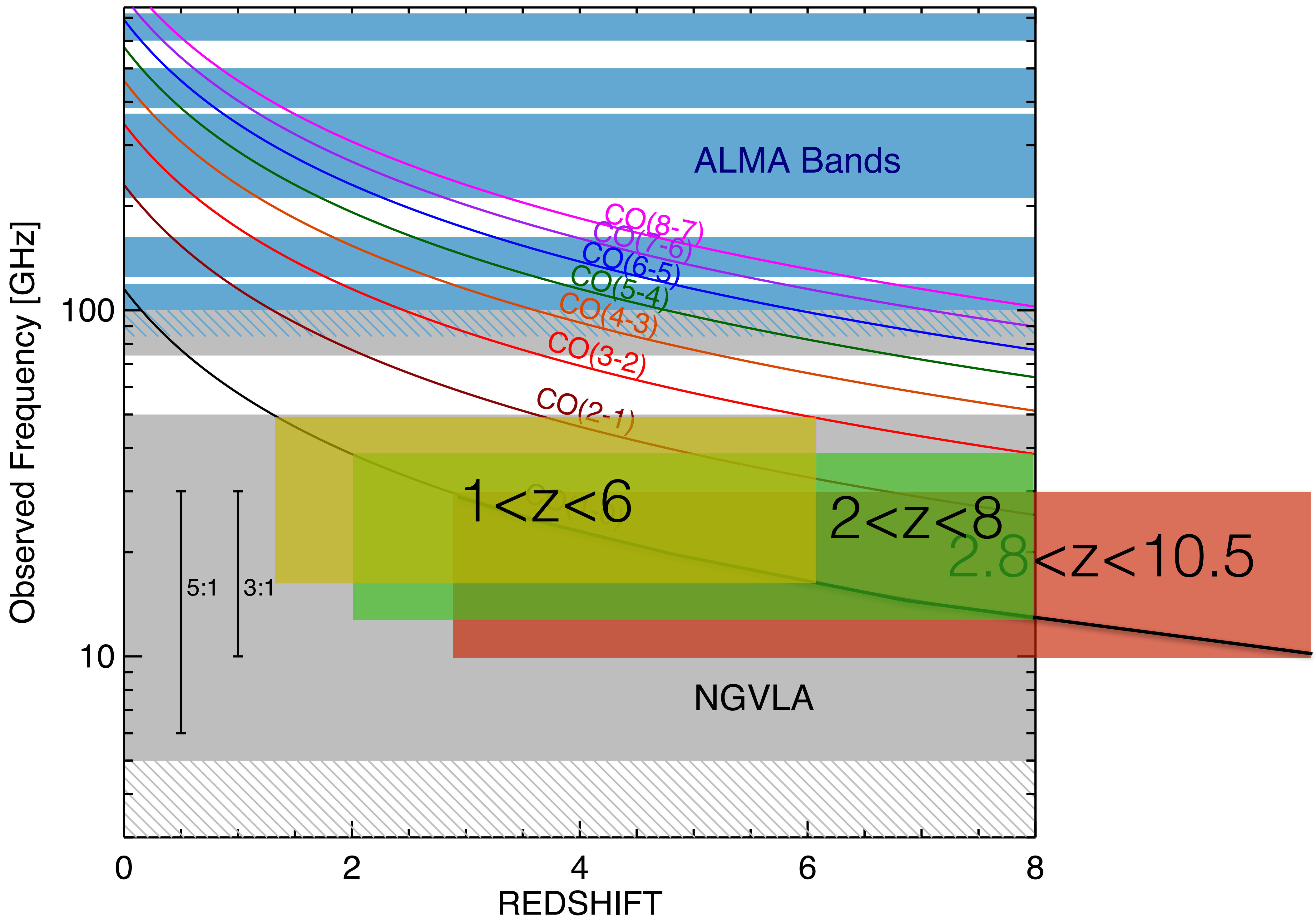


Casey, Narayanan & Cooray (2014)

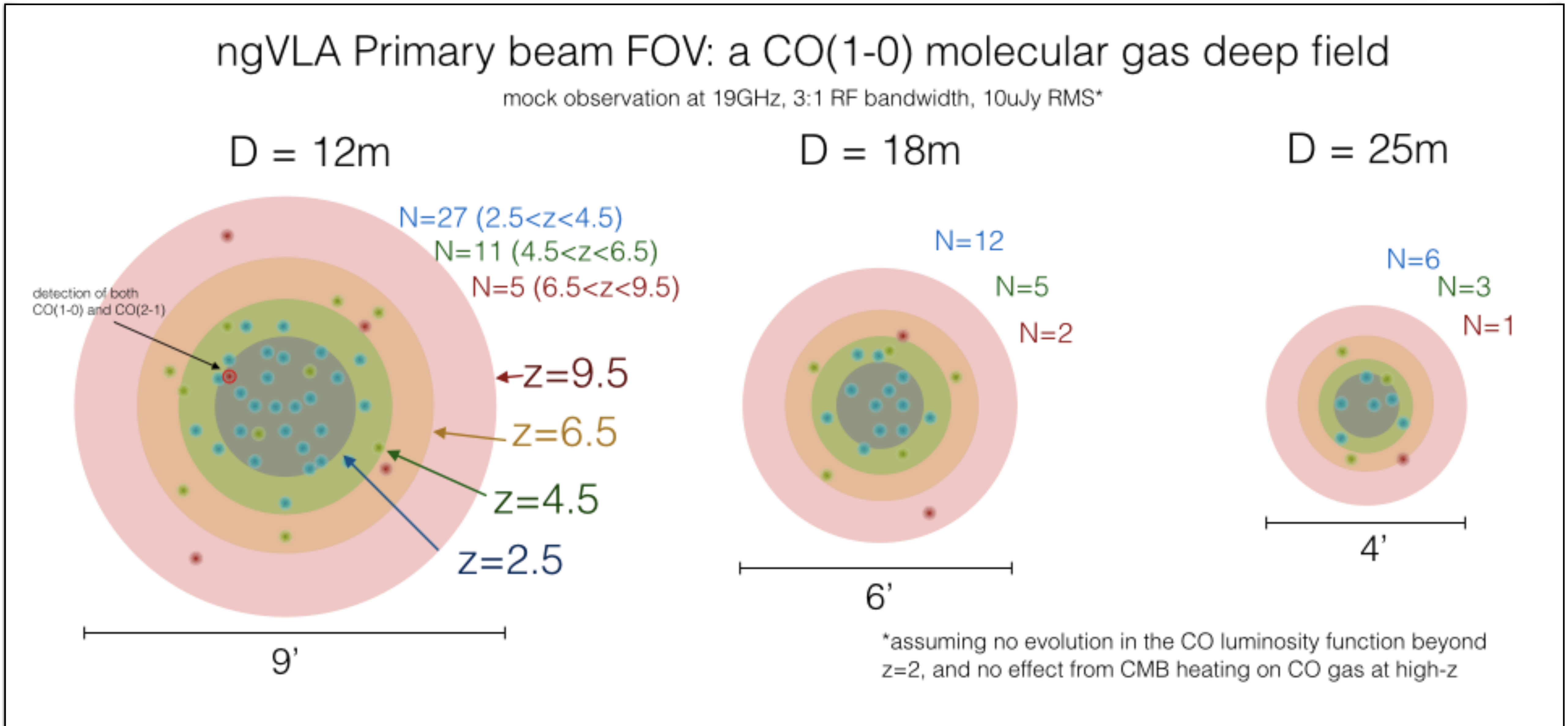
10s of galaxies → 1000s of galaxies

Sensitivity Improvements

Ultra-wide Bandwidth

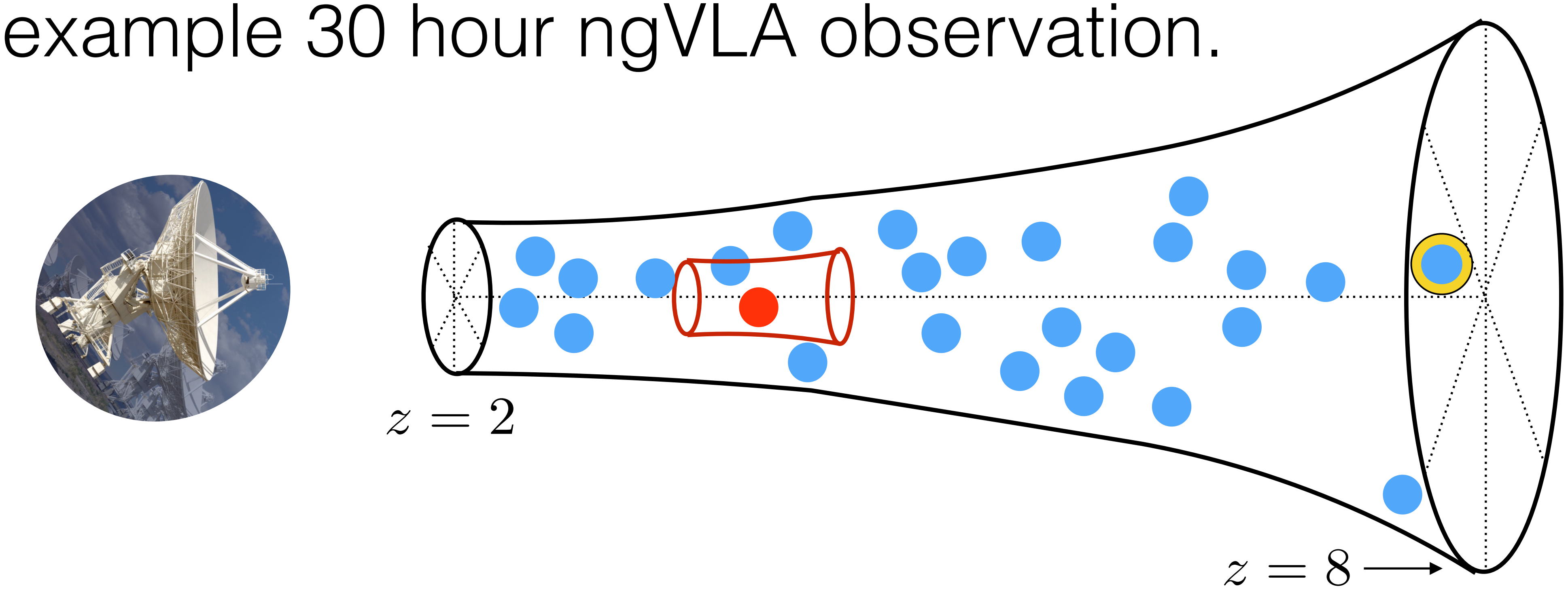


AAS227 —NGVLA high-z WG — 04 January 2016



Casey et al. (2015b)

An example 30 hour ngVLA observation.



Detectable with current JVLA

e.g. GN20, a single source at $z = 4.05$ in CO(1-0) to depth of $L'_{\rm CO} \approx 10^{10}\, L_\odot$, with 8GHz bandwidth gives

$$3.2 < z < 5.0$$

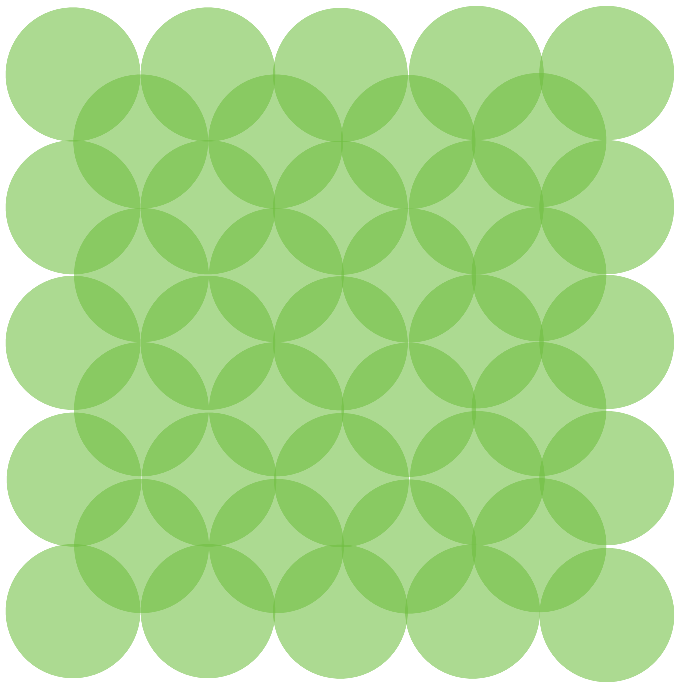
Detectable with ngVLA

~50-100 sources per pointing from $2 < z < 8$ in CO(1-0) to depth of $L'_{\rm CO} \approx 10^{9}\, L_\odot$, with 3:1 bandwidth ratio. In addition, ~1 z>6 source in CO(2-1) & CO(1-0)

ngVLA mosaic: a CO(1-0) molecular gas deep field

mock 10-30GHz observation, 3:1 RF bandwidth, 10uJy RMS per pointing

Coverage map at 33GHz (z=2.5)



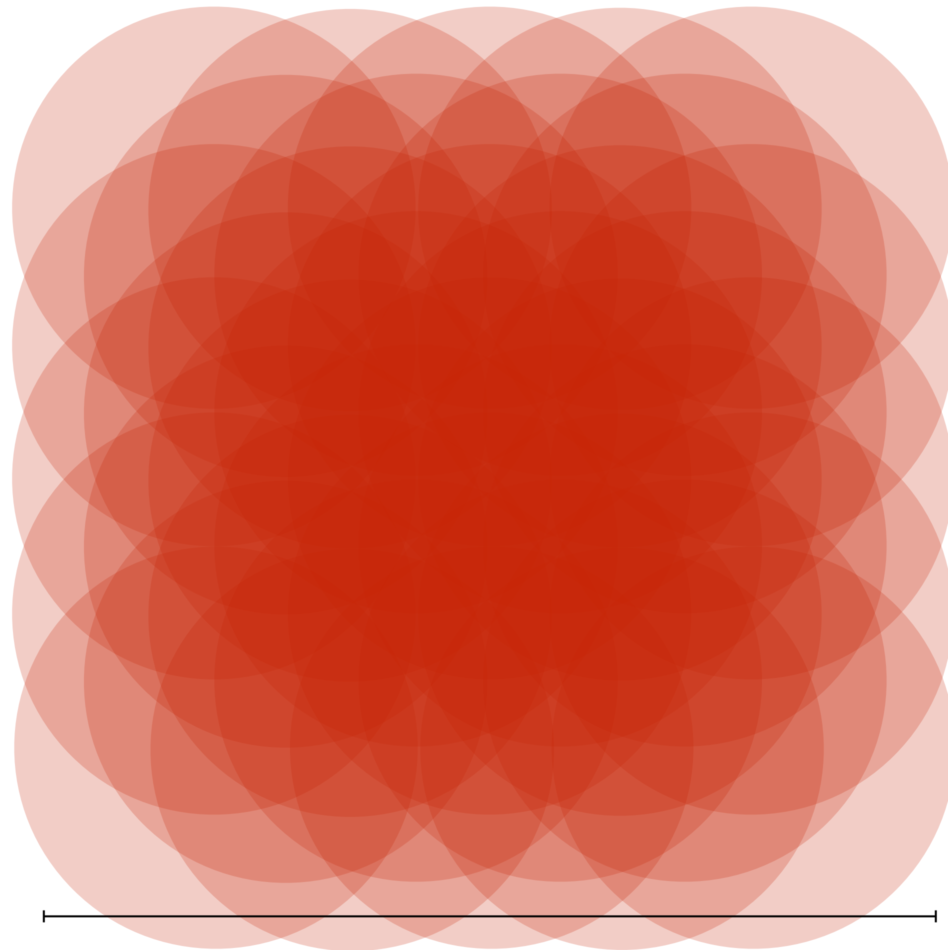
N=240 (2.5<z<4.5) $\langle\sigma_{26\mathrm{GHz}}\rangle = 7\mu\mathrm{Jy}$

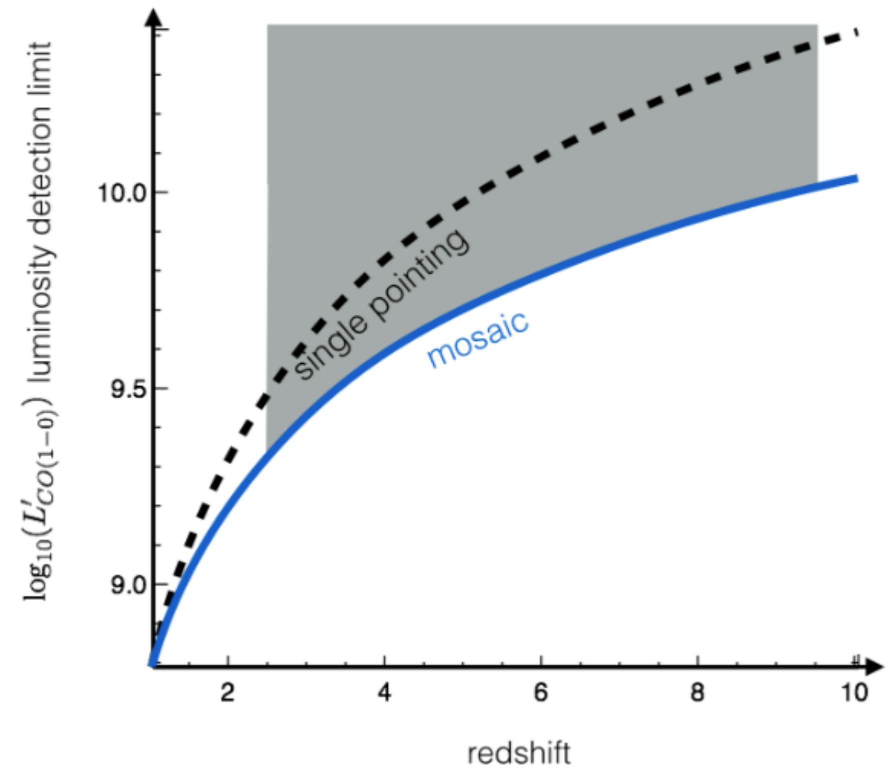
N=390 (4.5<z<6.5) $\langle\sigma_{17\mathrm{GHz}}\rangle = 6\mu\mathrm{Jy}$

N=800 (6.5<z<9.5) $\langle\sigma_{13\mathrm{GHz}}\rangle = 4\mu\mathrm{Jy}$

*assuming no evolution in the CO luminosity function beyond z=2, and no effect from CMB heating on CO gas at high-z

Coverage map at 10GHz (z=9.5)





Assumes 12m antennae.

What about ALMA deep fields?

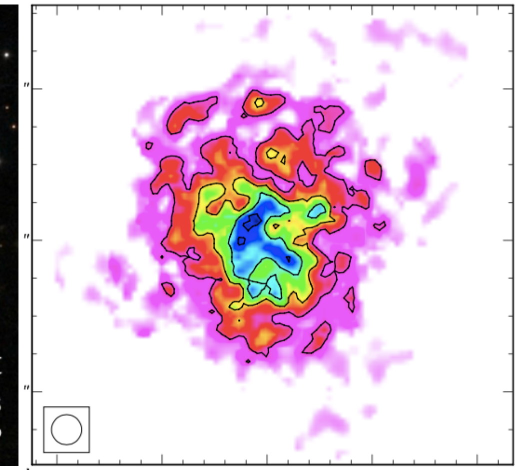
Molecular gas deep fields pursued by PdBI, ALMA (F. Walter, R. Decarli, et al), only producing a **handful** of sources in high-J transitions. Over narrow FOV, normal galaxies need **low-J CO, direct tracer to H_2 gas**.

Importance of Probing dynamics of galaxies

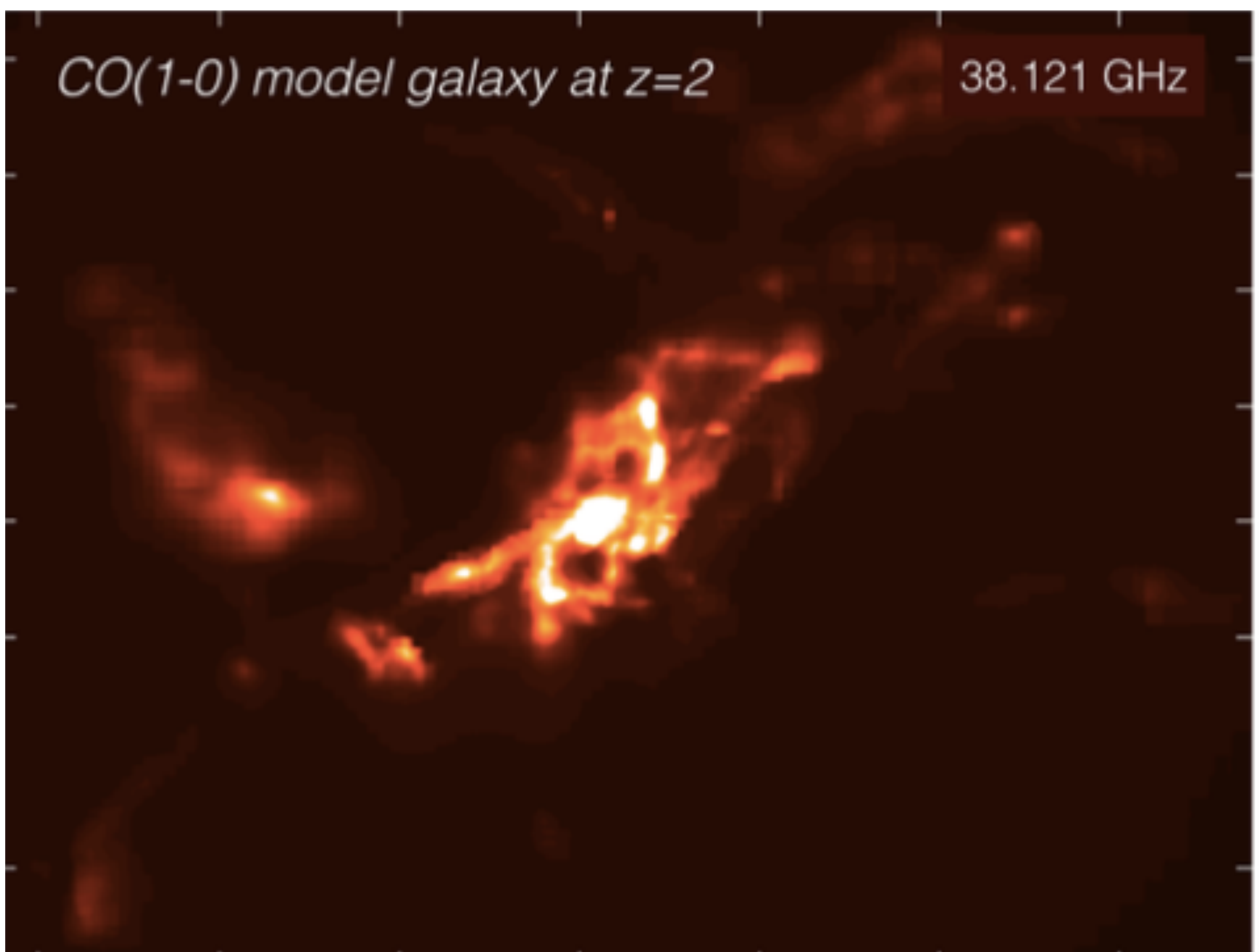
role of merging & stochasticity?
measurements of molecular outflow rates?
constrain CO-to-H2 conversion via direct detection of 40-100pc clouds at z~4?

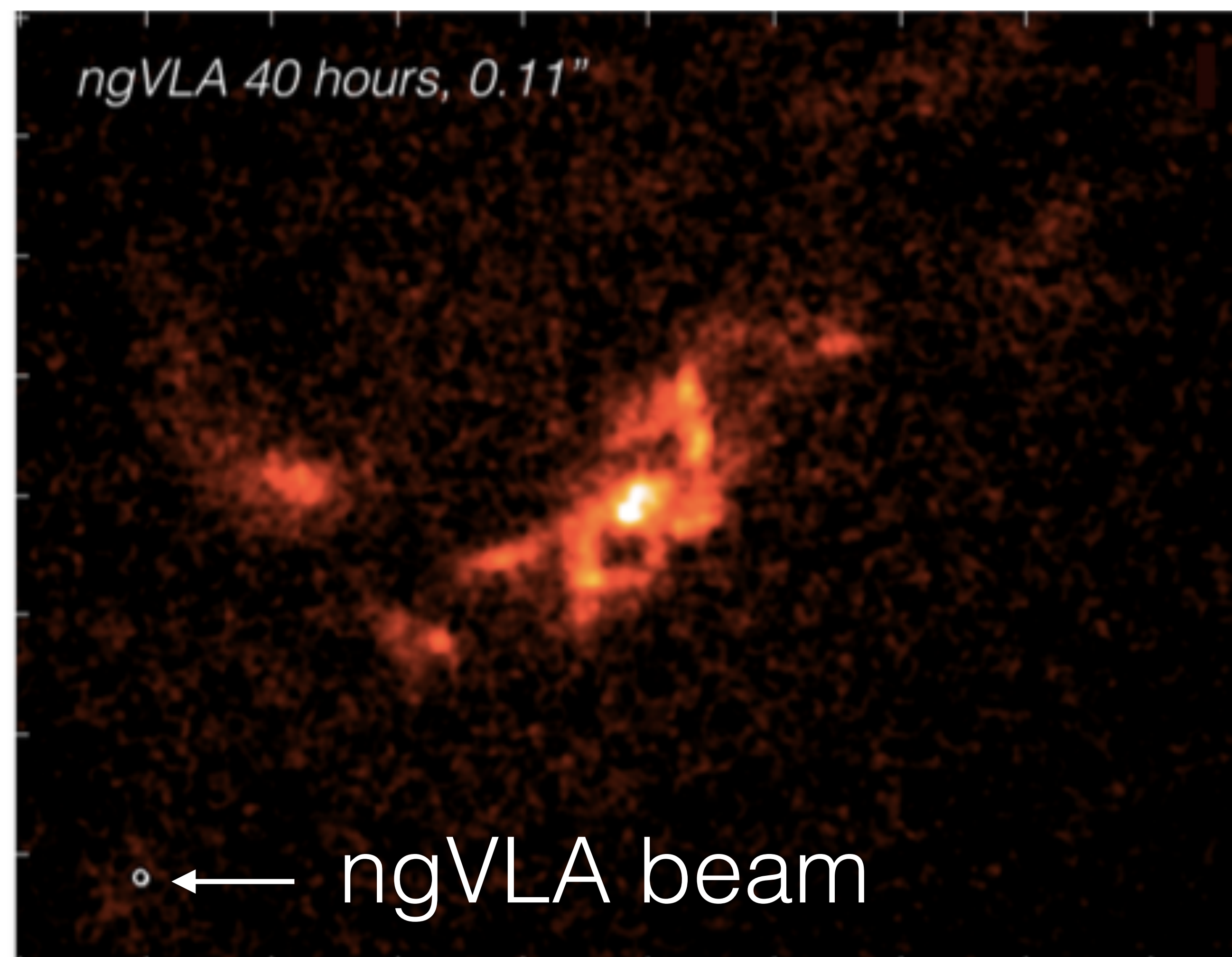
Surface Brightness Sensitivity

current VLA CO(1-0) at z~4, 120 hours



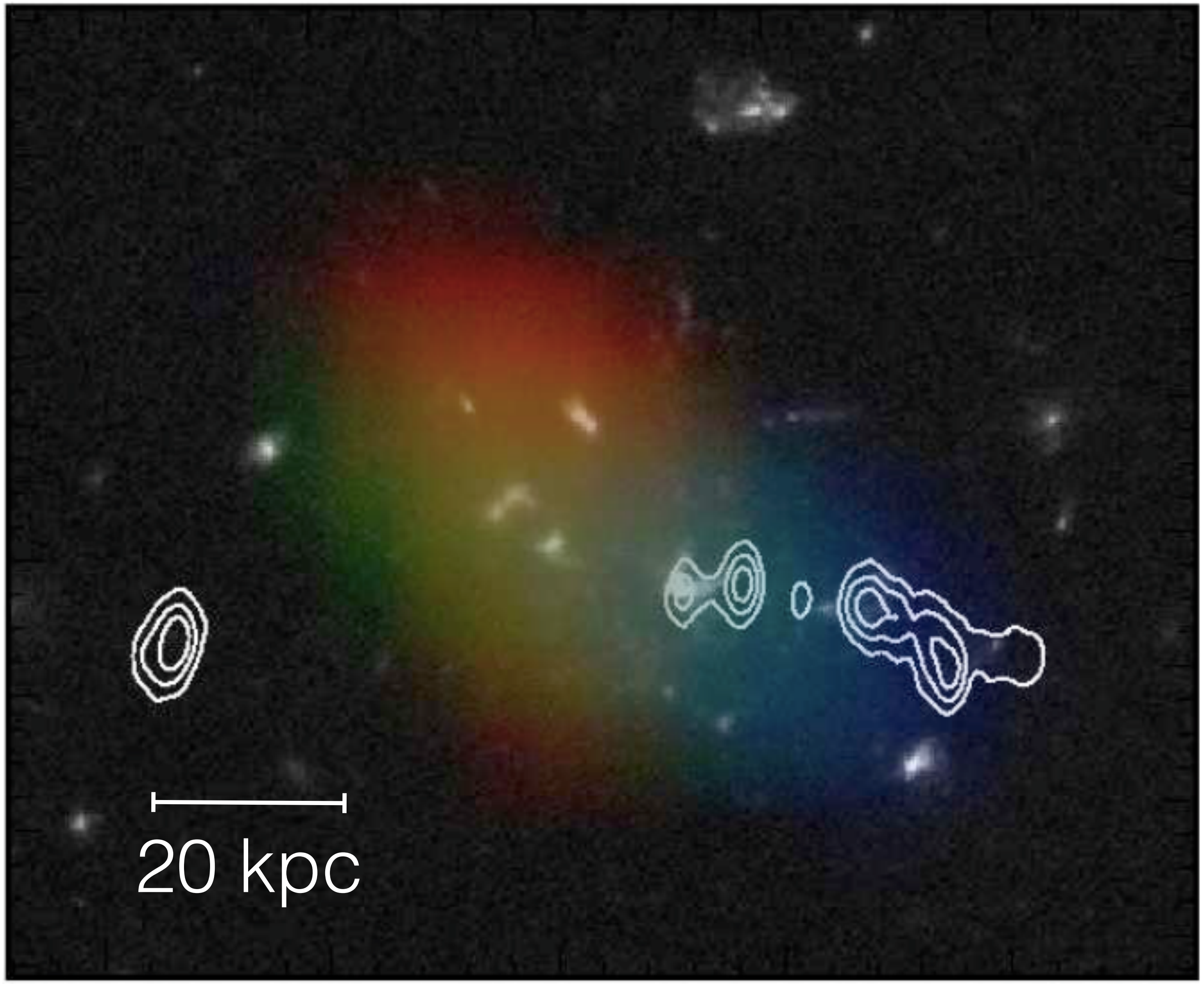
Hodge et al. (2012)





Tracing gas to the outskirts

Beginning to make very crude measurements of molecular gas potentials extending well beyond boundary of z~2 galaxies: can be routine for ngVLA if there is dense core of <u>compact, short-baseline elements</u> *and* 12m antennae.



A ~50kpc extended diffuse CO(1-0) halo: Emonts et al. (2014), also see Ivison et al. (2011)

Summary: High-z Gas Detection with the ngVLA

Objectives:

1. Detect 1000's of z~2 to z~10 in CO(1-0), inferring evolution of star-forming **gas content in the Universe**.

2. Probe internal dynamics of high-redshift galaxies efficiently: resolve ~40-100pc molecular clouds, outflows, and constrain stochasticity. How important are mergers for building galaxies?

Technical Goals:

- **Sensitivity** improvements crucial: from 'extreme' to 'normal' galaxies
- **Surface brightness sensitivity** for resolving diffuse gas, linking galaxies to their cosmic web
- **Wide bandwidth** enabling very large-volume CO surveys in the early Universe, blind CO confirmation
- **Smaller antennae** (12m) enabling very short baselines and large FOV.

Caitlin Casey: cmcasey@astro.as.utexas.edu

Supplemental Material

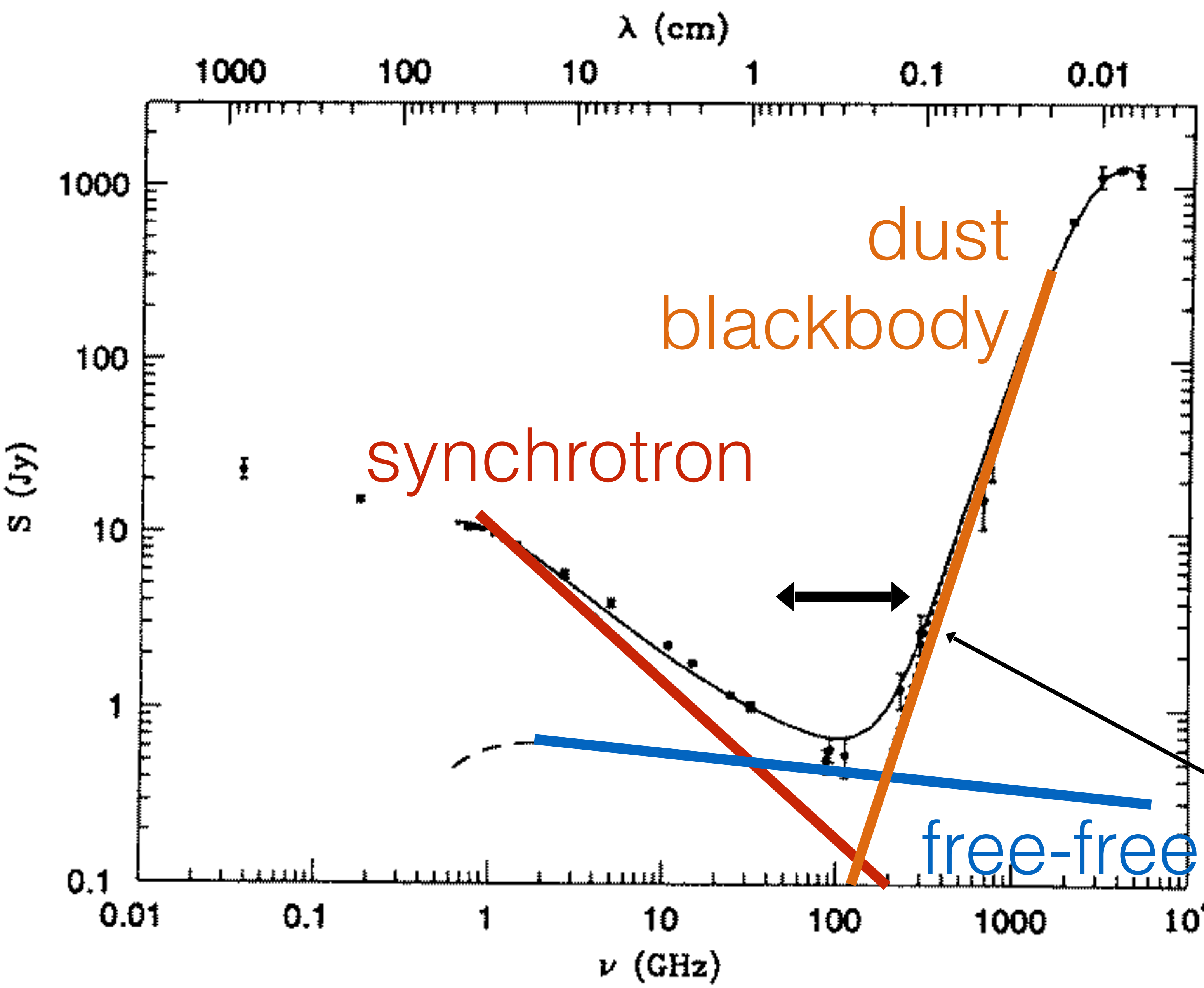
Table 2
SMGs with CO(1-0) data

SMG	Ref.	z	$S_\nu(850\,\mu)$ mJy	$SNR_{850\mu m}$[a]	$\frac{\Gamma_0}{\Gamma_{RJ}}$	I_{CO} Jy km s^{-1}	SNR_{CO}[a]	M_{ISM}[b] 10^{11} $M_\odot$	L_{850} 10^{31}cgs	L_{850} / M_{ISM}[b] 10^{20} cgs/$M_\odot$
HXMM01...	1	2.31	27.0	9.0	2.6	1.73	5.6	20.1± 3.6	10.5	0.5± 0.2
SPT-S053816-...	2	2.79	125.0	17.9	3.2	1.20	6.0	19.3± 3.2	47.9	2.5± 0.6
HATLASJ08493...	3	2.41	19.0	9.5	2.7	0.56	8.0	7.0± 0.9	7.1	1.0± 0.2
H-ATLASJ0903...	4	2.31	54.7	17.6	2.6	1.00	7.7	11.6± 1.5	21.2	1.8± 0.3
H-ATLASJ0913...	4	2.63	36.7	9.4	3.0	0.76	6.3	11.1± 1.7	14.6	1.3± 0.3
H-ATLASJ0918...	4	2.58	18.8	11.8	2.9	1.04	4.0	14.7± 3.7	7.4	0.5± 0.2
HLSW-01...	5	2.96	52.8	105.6	3.5	1.14	10.4	20.2± 2.0	21.4	1.1± 0.1
H-ATLASJ1132...	4	2.58	106.0	5.9	2.9	0.66	3.5	9.3± 2.7	4.9	0.5± 0.2
H-ATLASJ1158...	4	2.19	107.0	5.9	2.5	0.74	6.2	7.9± 1.3	4.9	0.6± 0.2
H-ATLASJ1336...	4	2.20	36.8	12.7	2.5	0.93	7.8	10.0± 1.3	14.3	1.4± 0.3
H-ATLASJ1344...	4	2.30	73.1	30.5	2.6	2.74	7.0	31.7± 4.5	28.4	0.9± 0.2
H-ATLASJ1413...	4	2.48	33.3	12.8	2.8	1.47	8.6	19.4± 2.2	13.1	0.7± 0.1
SMMJ2135-010...	6	2.33	106.0	8.8	2.6	2.25	9.8	26.5± 2.7	39.4	1.5± 0.3
SPT-S233227-...	2	2.73	150.0	13.6	3.1	1.70	6.8	26.4± 3.9	57.3	2.2± 0.5
SMMJ123549.4...	7	2.20	8.3	3.3	2.5	0.32	8.0	3.4± 0.4	2.8	0.8± 0.3
SMMJ123707.2...	7	2.49	10.7	4.0	2.8	0.91	7.0	12.1± 1.7	3.7	0.3± 0.1
SMMJ163650.4...	7	2.38	8.2	4.8	2.7	0.34	8.5	4.2± 0.5	2.8	0.7± 0.2
SMMJ163658.1...	7	2.45	10.7	5.3	2.8	0.37	5.3	4.8± 0.9	3.7	0.8± 0.3
EROJ164502+4...	9	1.44	4.9	6.6	1.8	0.60	6.0	3.0± 0.5	1.5	0.5± 0.2
SMMJ02399-01...	10	2.81	23.0	12.1	3.3	0.60	5.0	9.8± 2.0	8.1	0.8± 0.2
SMMJ04135+10...	10	2.85	25.0	8.9	3.3	0.64	7.9	10.7± 1.4	8.8	0.8± 0.2
SMMJ04431+02...	11	2.51	7.2	4.8	2.8	0.26	4.3	3.5± 0.8	2.5	0.7± 0.3
SMMJ14009+02...	10	2.93	15.6	8.2	3.5	0.31	15.5	5.4± 0.3	5.5	1.0± 0.2
SMMJ14011+02...	10	2.57	12.3	7.2	2.9	0.40	8.0	5.6± 0.7	4.3	0.8± 0.2
SMMJ163555.2...	10	2.52	12.5	15.6	2.9	0.22	5.5	3.0± 0.5	4.3	1.4± 0.4
SMMJ163554.2...	12	2.52	15.9	22.7	2.9	0.40	10.0	5.4± 0.5	5.5	1.0± 0.1
SMMJ163550.9...	12	2.52	8.4	10.5	2.9	0.30	3.3	4.1± 1.2	2.9	0.7± 0.3
HATLASJ08493...	12	2.41	25.0	12.5	2.7	0.49	8.2	6.1± 0.8	9.4	1.5± 0.3
								average[c]	**:**	**1.01 ± 0.52**

Note. — Submm fluxes and CO(1-0) measurements from references given in the second column: 1:(Fu et al. 2013), 2:(Aravena et al. 2013), 3:(Ivison et al. 2013), 4:(Harris et al. 2012), 5:(Riechers et al. 2011a), 6:(Lestrade et al. 2011), 7:(Ivison et al. 2011), 8:(Riechers et al. 2011b), 9:(Greve et al. 2003), 10:(Thomson et al. 2012), 11:(Harris et al. 2010), 12:(Ivison et al. 2013),(Bussmann et al. 2013)

Scoville et al. (2014)

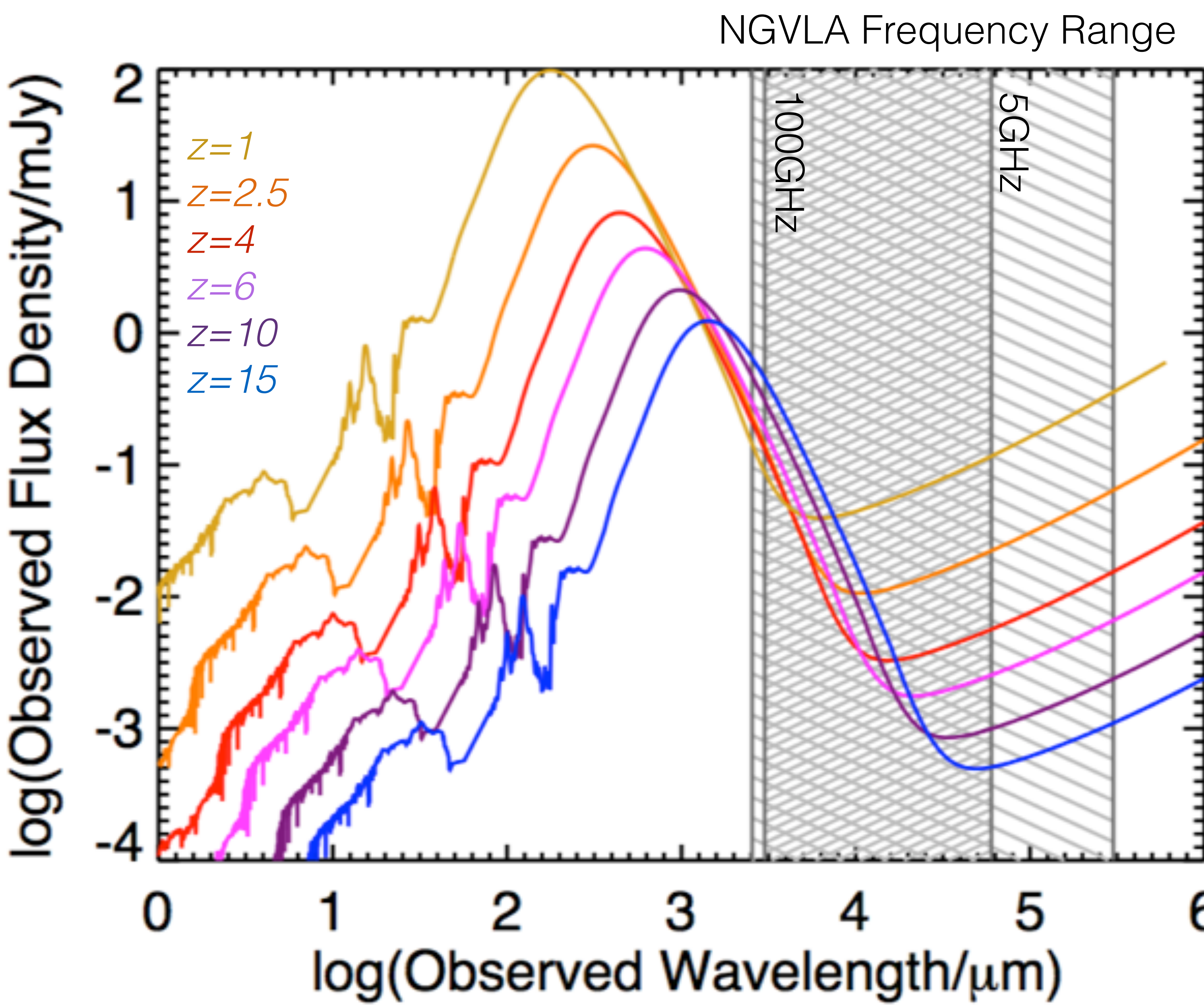
High-z Science Goals: Continuum



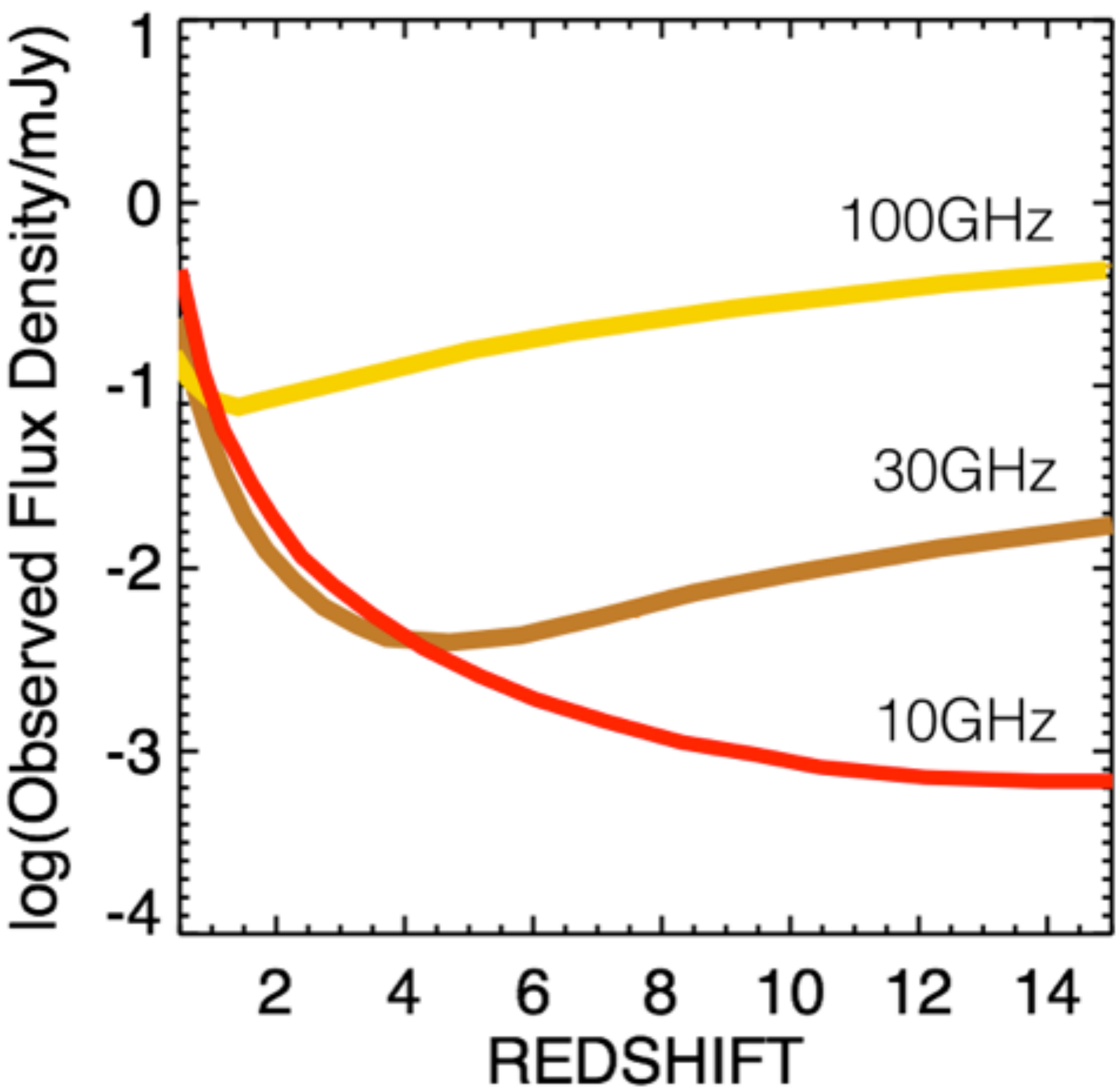
example 5:1 bandwidth for z=2-3 galaxy
(observed frequency 10-50GHz)

<u>Continuum emission from 5-100GHz:</u> synchrotron emission, free-free, and cold dust emission. Wide-bandwidth observations will be critical to disentangling the spectrum.

High-z Science Goals: Continuum



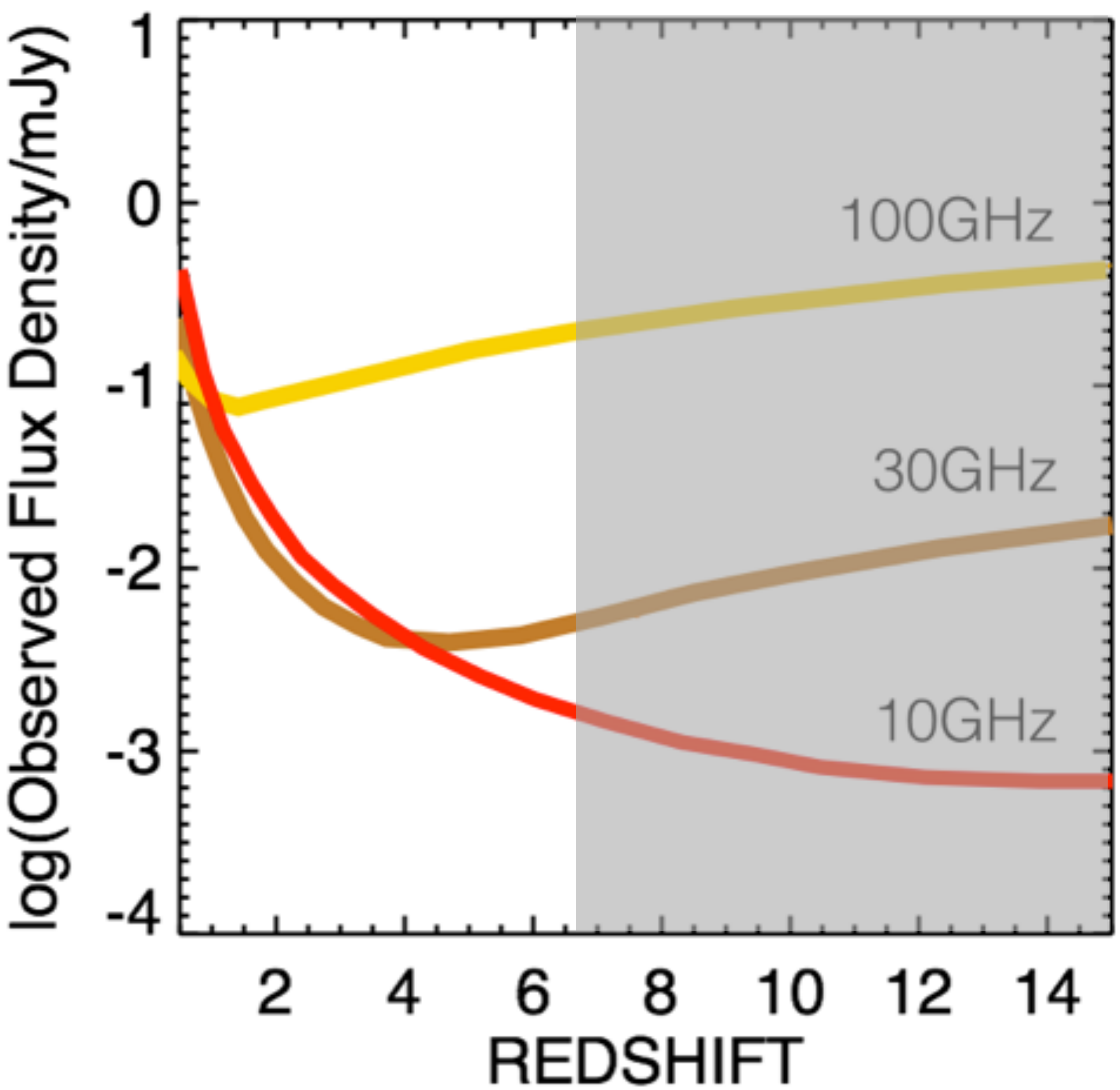
High-z Science Goals: Continuum



At sufficiently high-redshift, the NG VLA bands benefit from the very-negative K-correction on the cold dust Raleigh-Jeans tail (not just the higher-frequency submm bands!).

As a consequence, NG VLA will provide important constraints on high-z dust continuum as well as cold gas.

High-z Science Goals: Continuum



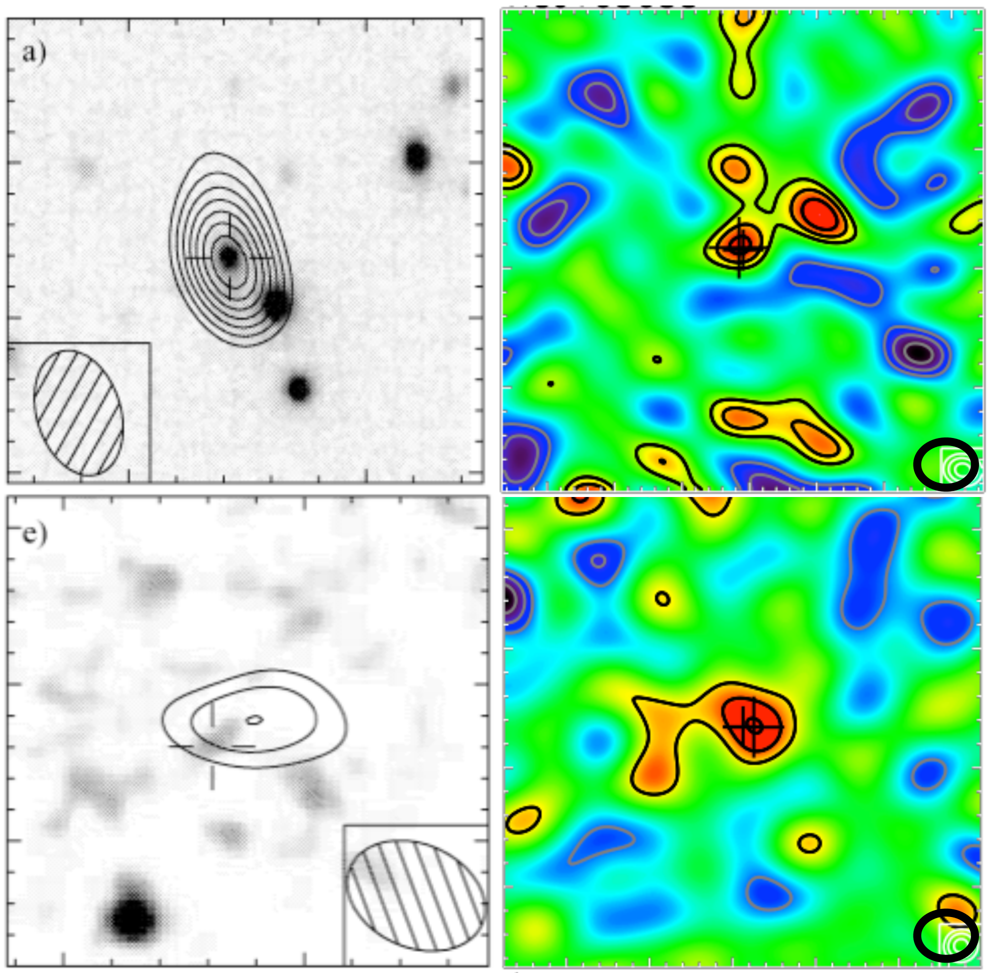
At sufficiently high-redshift, the NG VLA bands benefit from the very-negative K-correction on the cold dust Raleigh-Jeans tail (not just the higher-frequency submm bands!).

As a consequence, NG VLA will provide important constraints on high-z dust continuum as well as cold gas.

High-z Science Goals: Dynamics

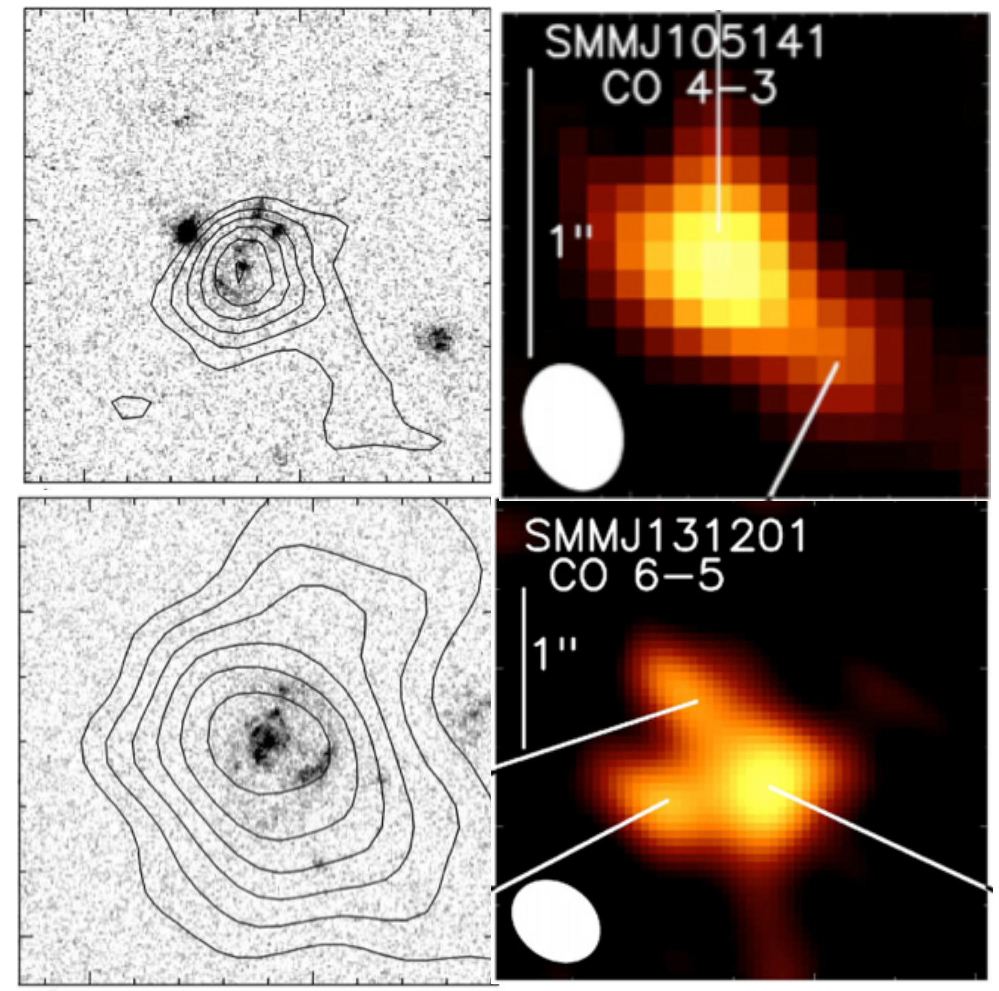
EXAMPLES

UNRESOLVED



Neri et al. (2003), Greve et al. (2005), Tacconi et al. (2006), Casey et al. (2011), Bothwell et al. (2012)

MARGINALLY RESOLVED

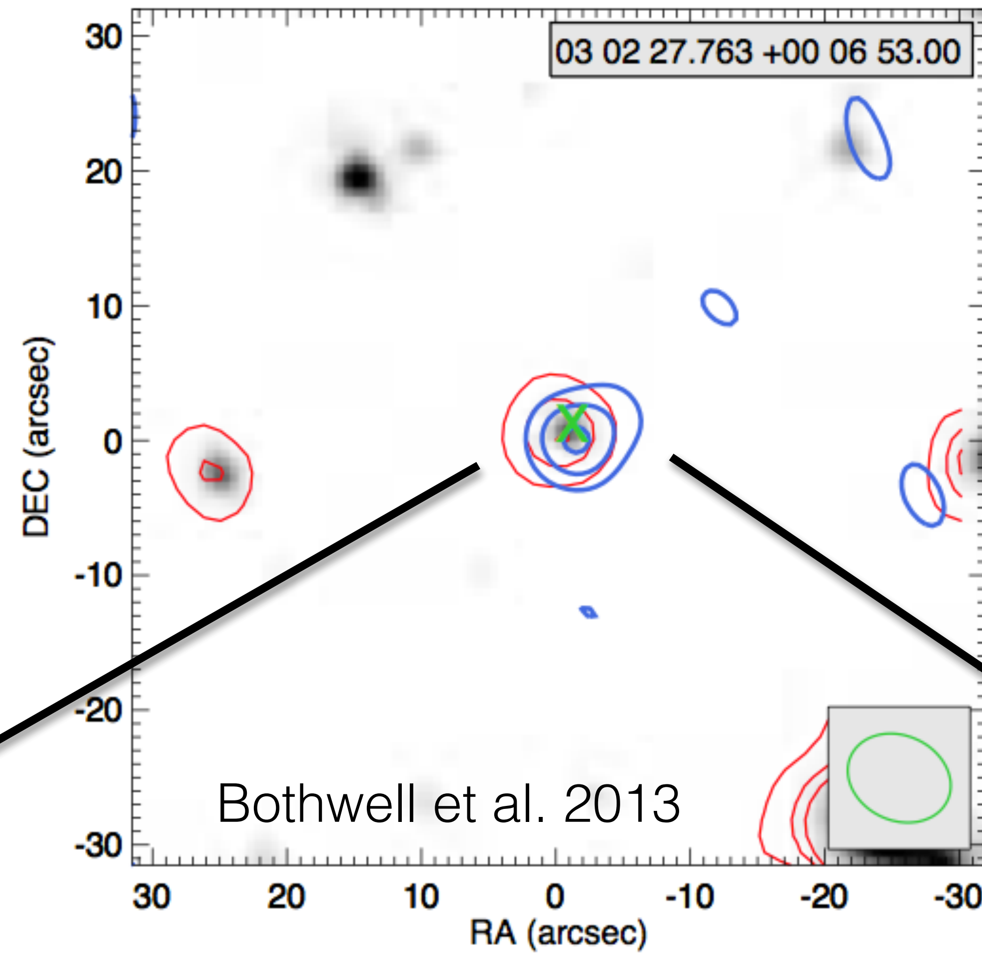


Tacconi et al. (2008), Daddi et al. (2010), Tacconi et al. (2010), Bothwell et al. (2010), Engel et al. (2010)

KINEMATICS + MORPHOLOGY

needed to constrain M_{dyn} (do they sit at center of DM halo?)

High-z Science Goals: Dynamics



Merger?

Image credit: NOAO/AURA/NSF

A Next Generation VLA is needed to reveal the morphology and dynamics of high-z galaxies

Disk?

Image credit: NASA/STScI/ACS ScienceTeam

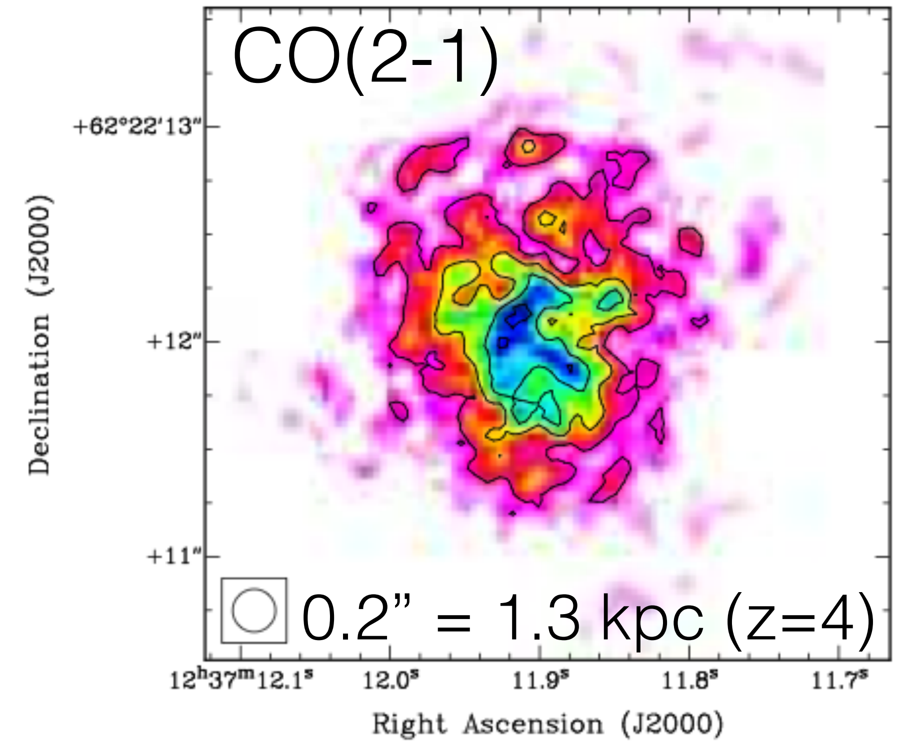
High-z Science Goals: Dynamics

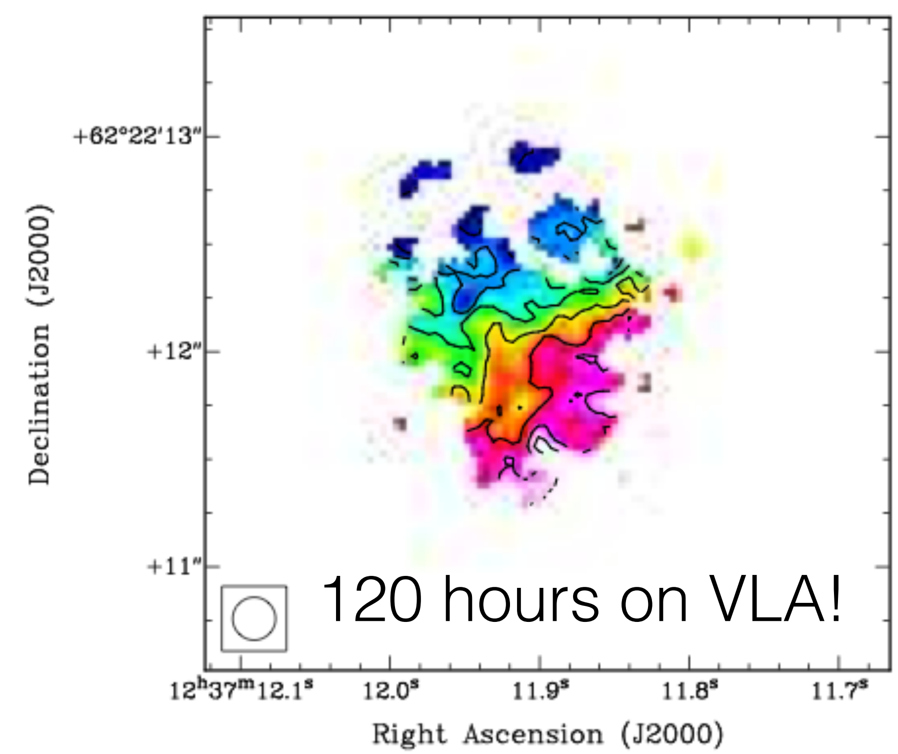
Why not use the VLA?

It takes too long!

Significantly increased sensitivity is crucial if we are to do this on more than a handful of the very brightest objects

Hodge et al. (2012)





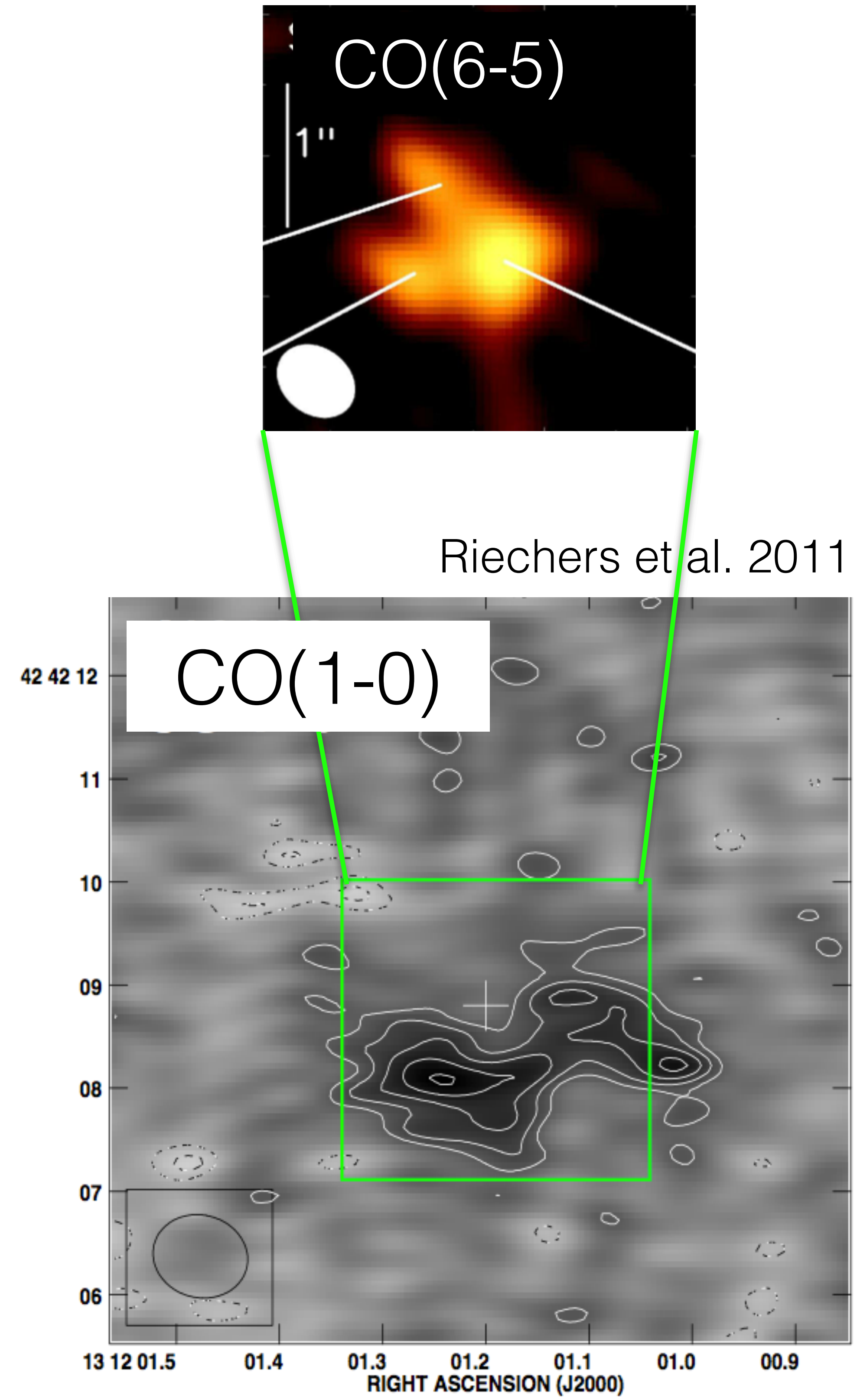
High-z Science Goals: Dynamics

Why not use ALMA?

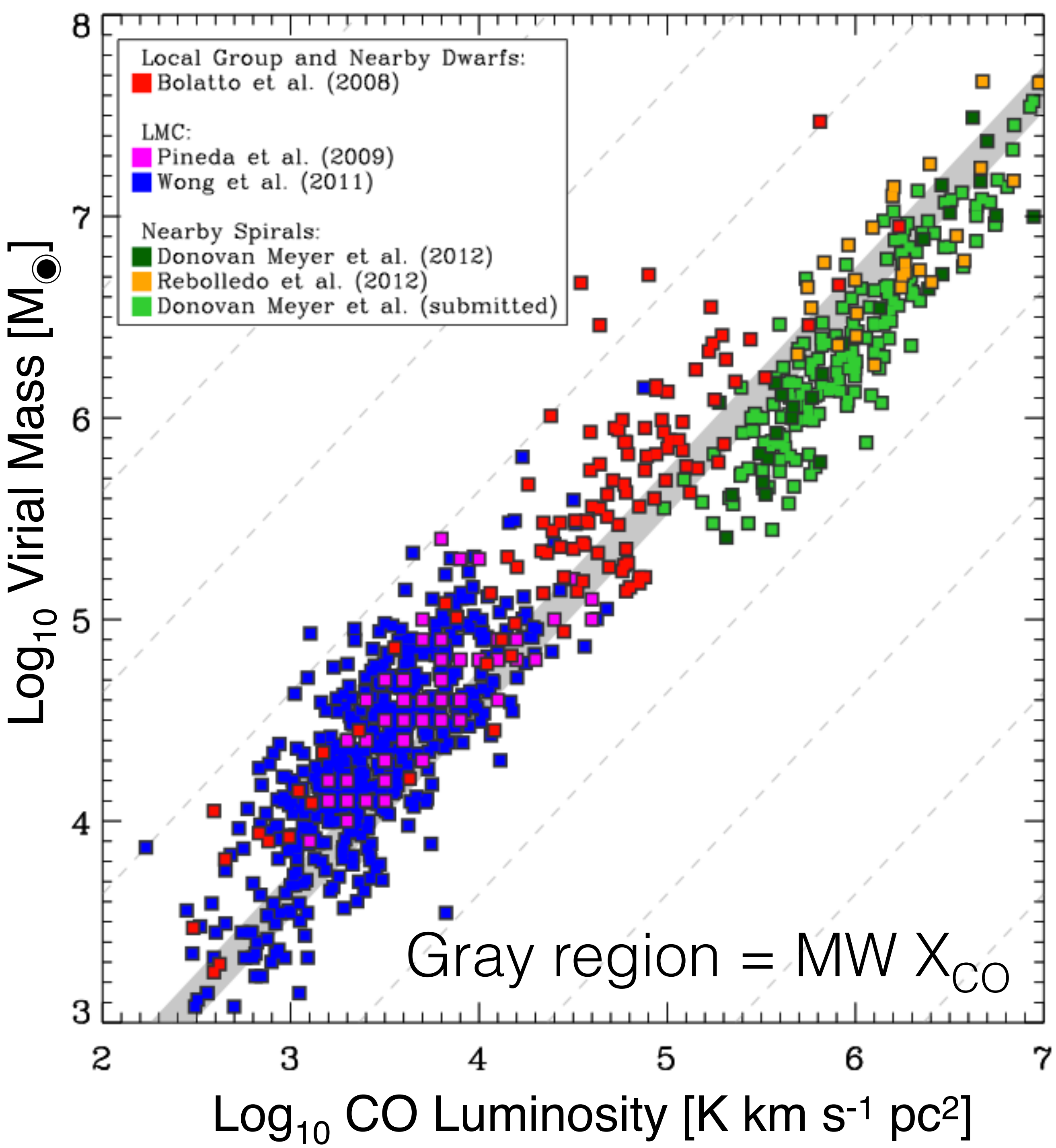
ALMA doesn't probe the crucial low-J transitions at high-z, which can have a completely different structure

A Next Generation VLA is necessary to directly probe the dynamics of the bulk of the gas in high-z galaxies

Engel et al. 2010



High-z Science Goals: Dynamics



Bolatto, Wolfire & Leroy 2013 ARA&A

Total molecular gas masses and the CO-to-H2 conversion factor (X_{CO}):

We currently have to extrapolate from what we know about local galaxies.

A Next Generation VLA is required to directly measure the conversion factor, and thus total gas masses, at high-z

AGN and supermassive black holes

- Two key AGN questions addressed by NG-VLA:
  - Measure BH masses from gas disk dynamics and evolution of the M-sigma relation.
  - Molecular outflows, feedback, and the origin of radio emission from radio-quiet AGN.

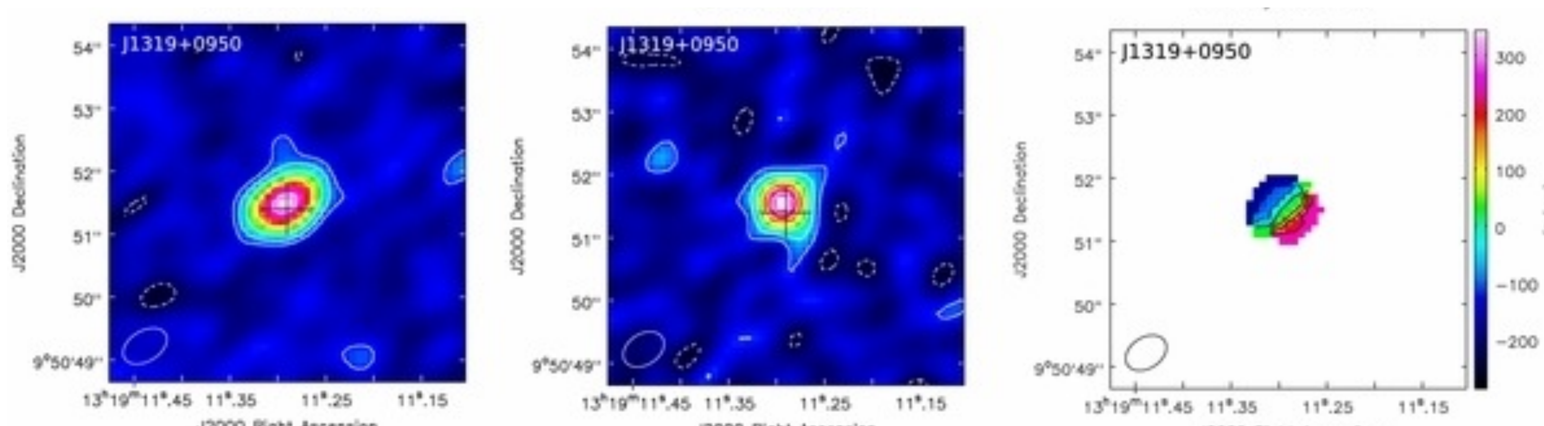
What drives co-evolution of BHs and their host galaxies?

BH masses and M-σ

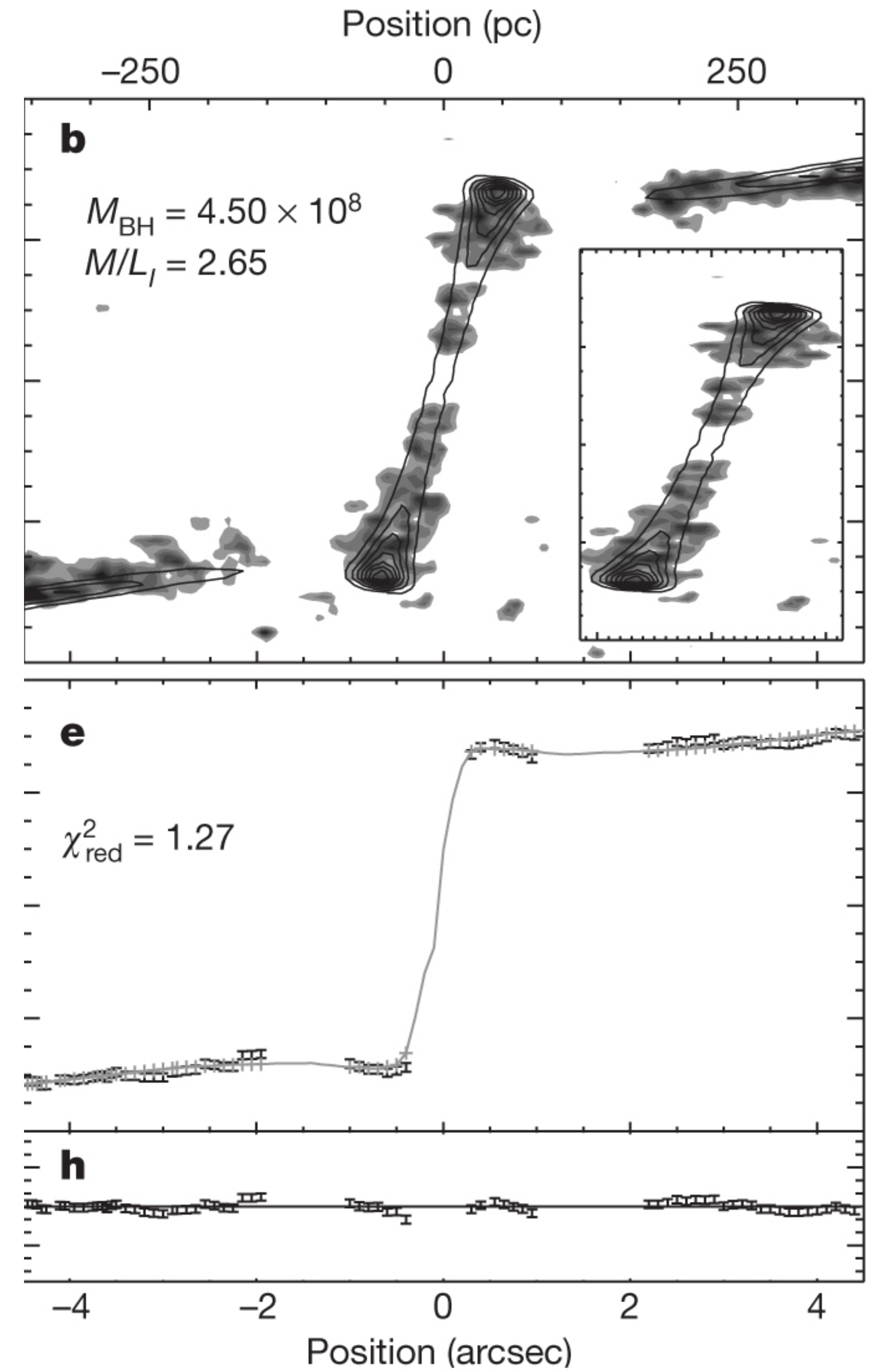
Radius of influence for 10^9 $M_\odot$ BH ~30mas at z~1, resolvable with NG-VLA
(SB sensitivity may limit NG-VLA measurements to z~0.1 in practice)

At high-z, M-σ applied to quasars with C +, but detailed dynamics needed to separate sigma from rotation, outflows and merger activity (sub kpc scales).

ALMA: high-J CO or C+ only.



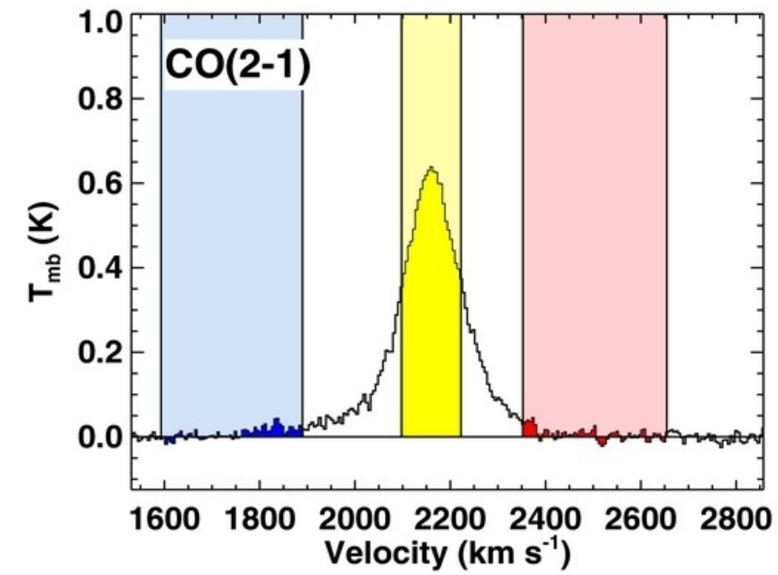
Wang et al. 2013, ApJ, 773, 44 (ALMA)



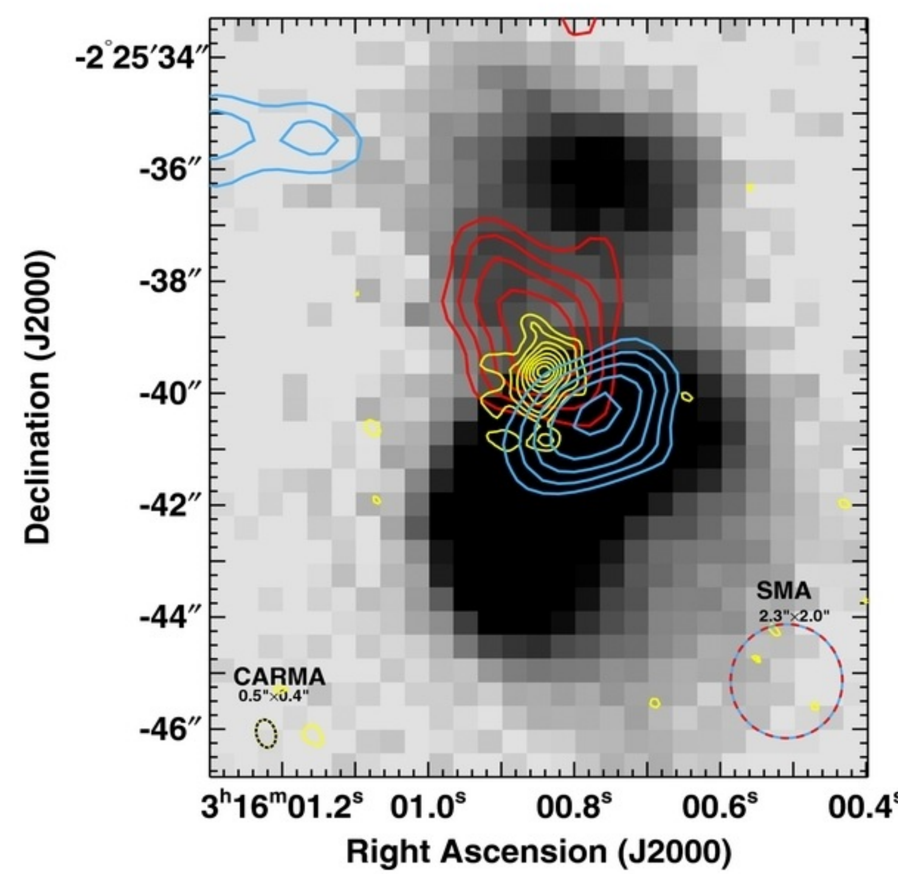
Davis et al. 2013, Nat, 494, 328 (CARMA)

Outflows, feedback and radio emission from radio-quiet AGN

Dynamics of molecular outflows – measure effect of AGN on ISM.



NG-VLA at ~100GHz - detailed studies of molecular gas (low-J CO, high density tracers, XDR vs PDR chemistry). Accurate measurements of molecular outflows.

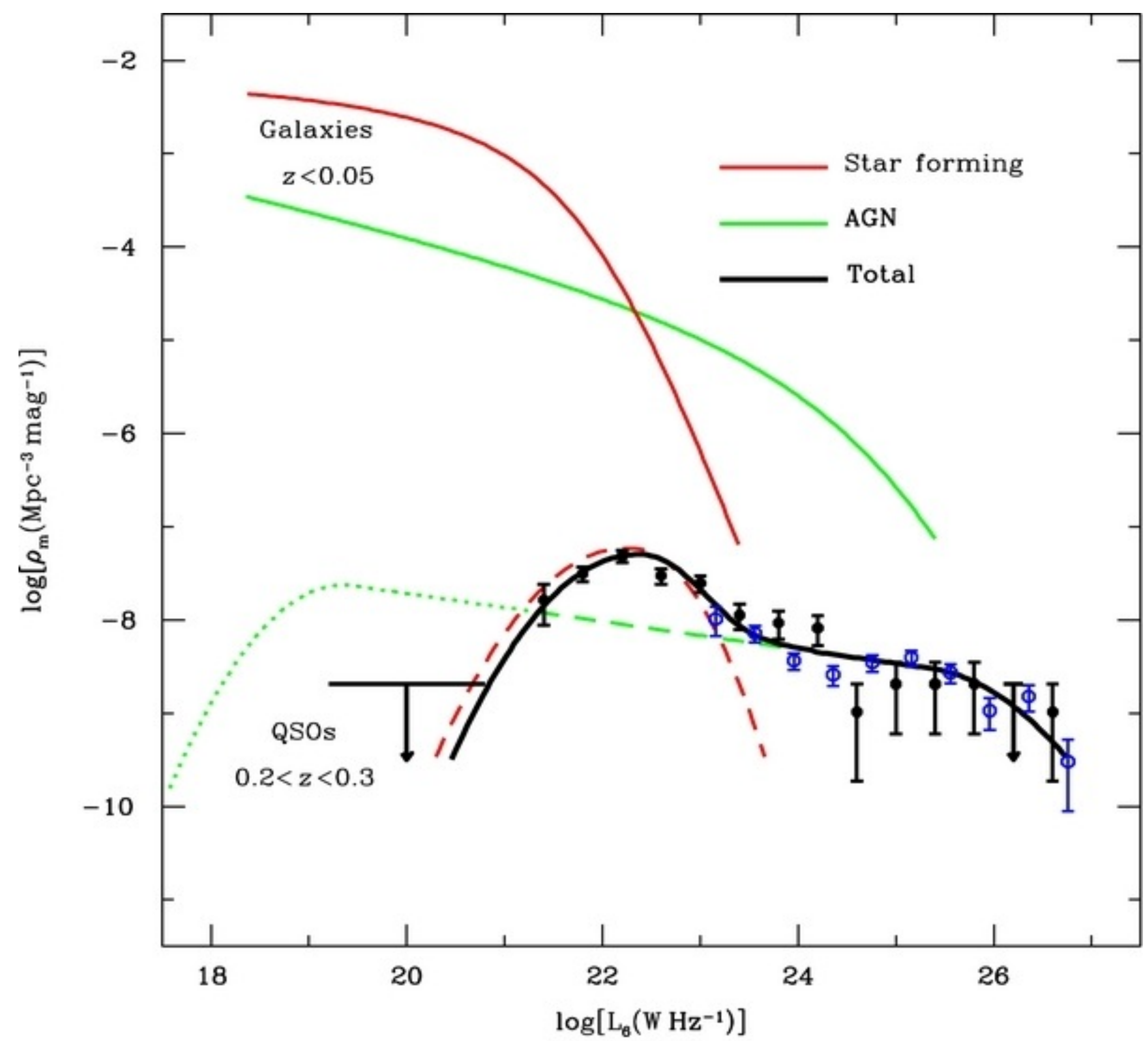


NGC1266: Alatalo et al. 2011, 2014 (CARMA/ALMA)

Outflows, feedback and radio emission from radio-quiet AGN

Wide-bandwidth Continuum:

NG-VLA at GHz frequencies – spectral index, surface brightness and morphology of synchrotron components.



Kimball et al. 2011 (VLA); but see also Greene & Zakamska 2014