Next Generation VLA:

Galaxy Assembly through Cosmic Time

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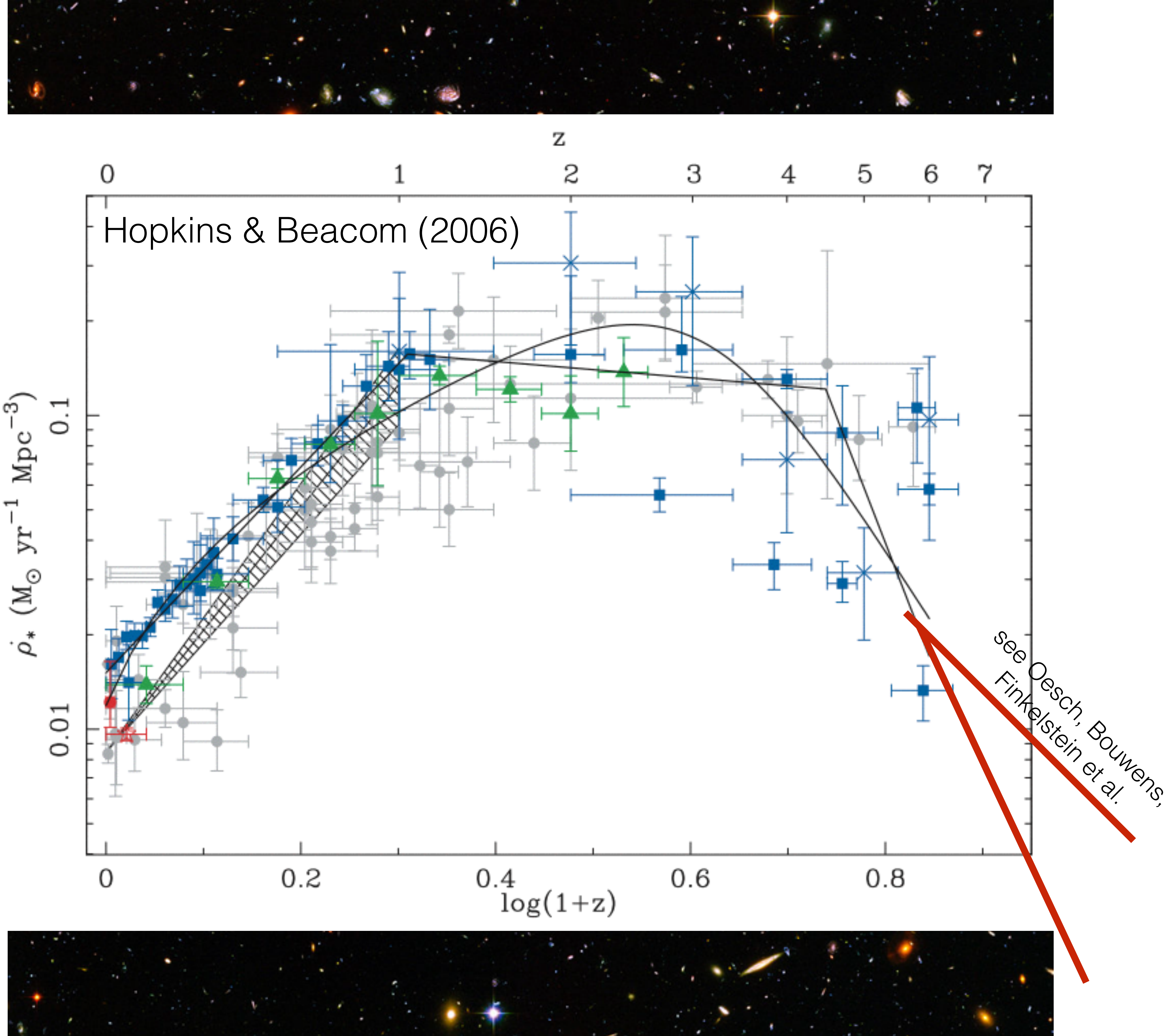
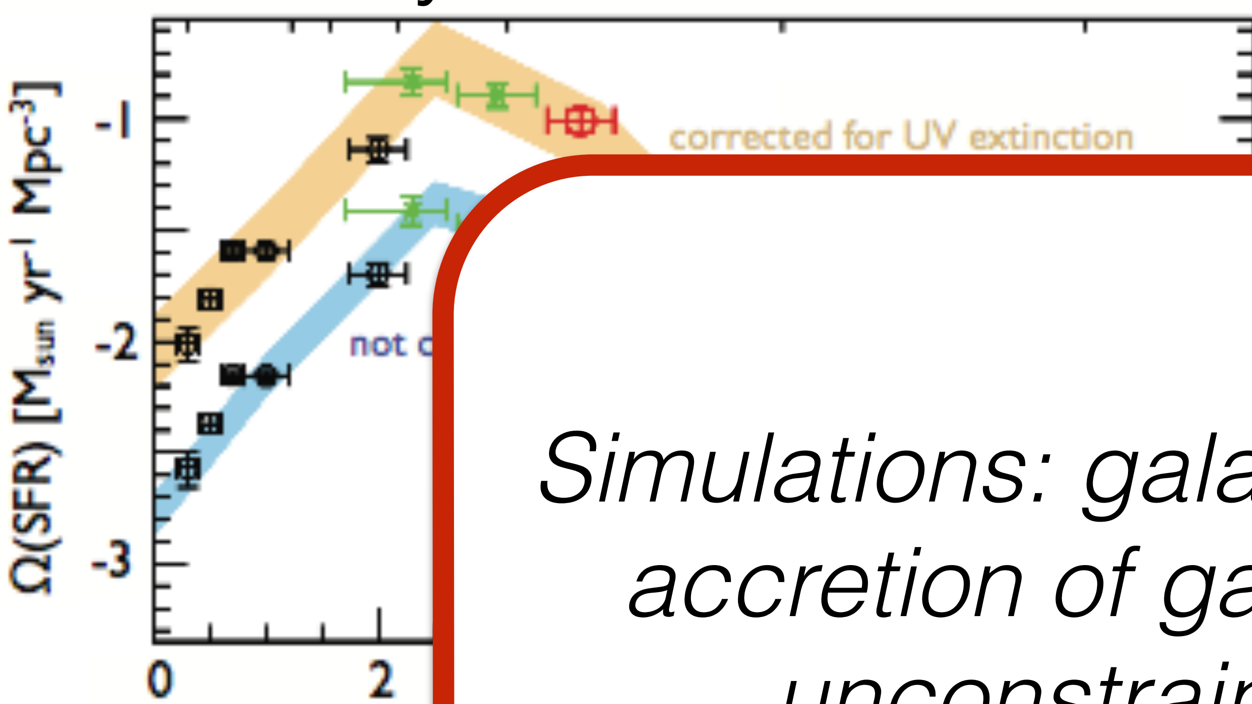
~10000s of galaxies
~100000s of galaxies


z
0
1
2
3
4
5
6
7
Hopkins & Beacom (2006)
$\dot{\rho}_*$ ($M_\odot$ yr^{-1} Mpc^{-3})
0.1
0.01
0
0.2
0.4
0.6
0.8
log(1+z)
see Oesch, Bouwens,
Finkelstein et al.

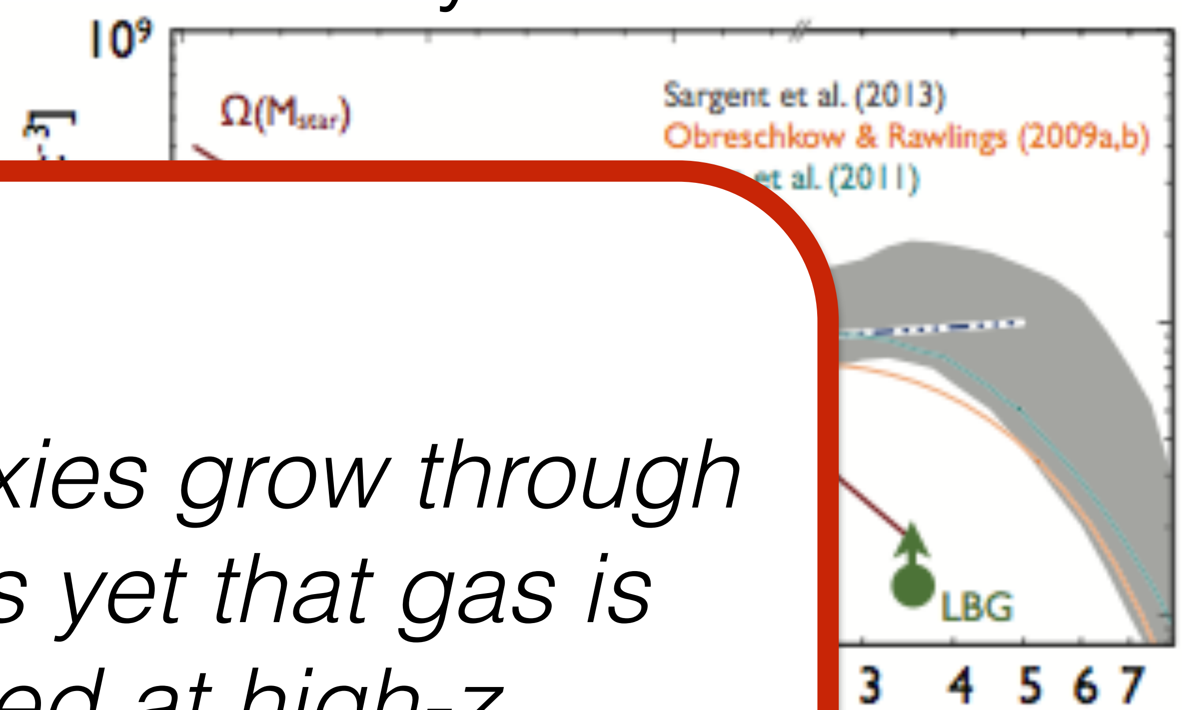

starlight
gas
dust

Cold Gas Fuels Galaxy Evolution

History of Star Formation



History of Gas Content



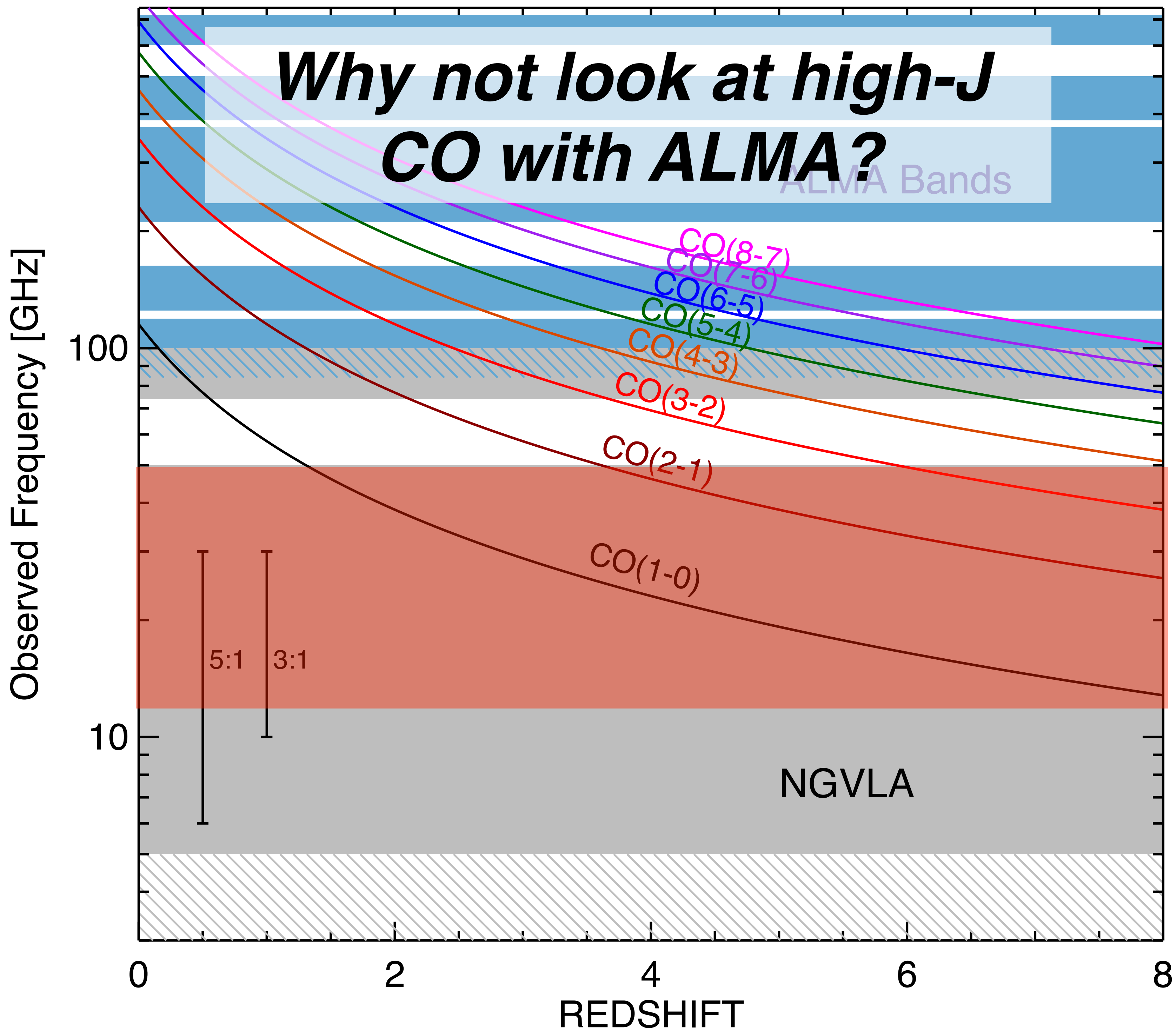
Simulations: galaxies grow through accretion of gas yet that gas is ***unconstrained*** *at high-z observationally.*

ter 2013 ARA&A

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!

CO: probing H_2, star-forming gas



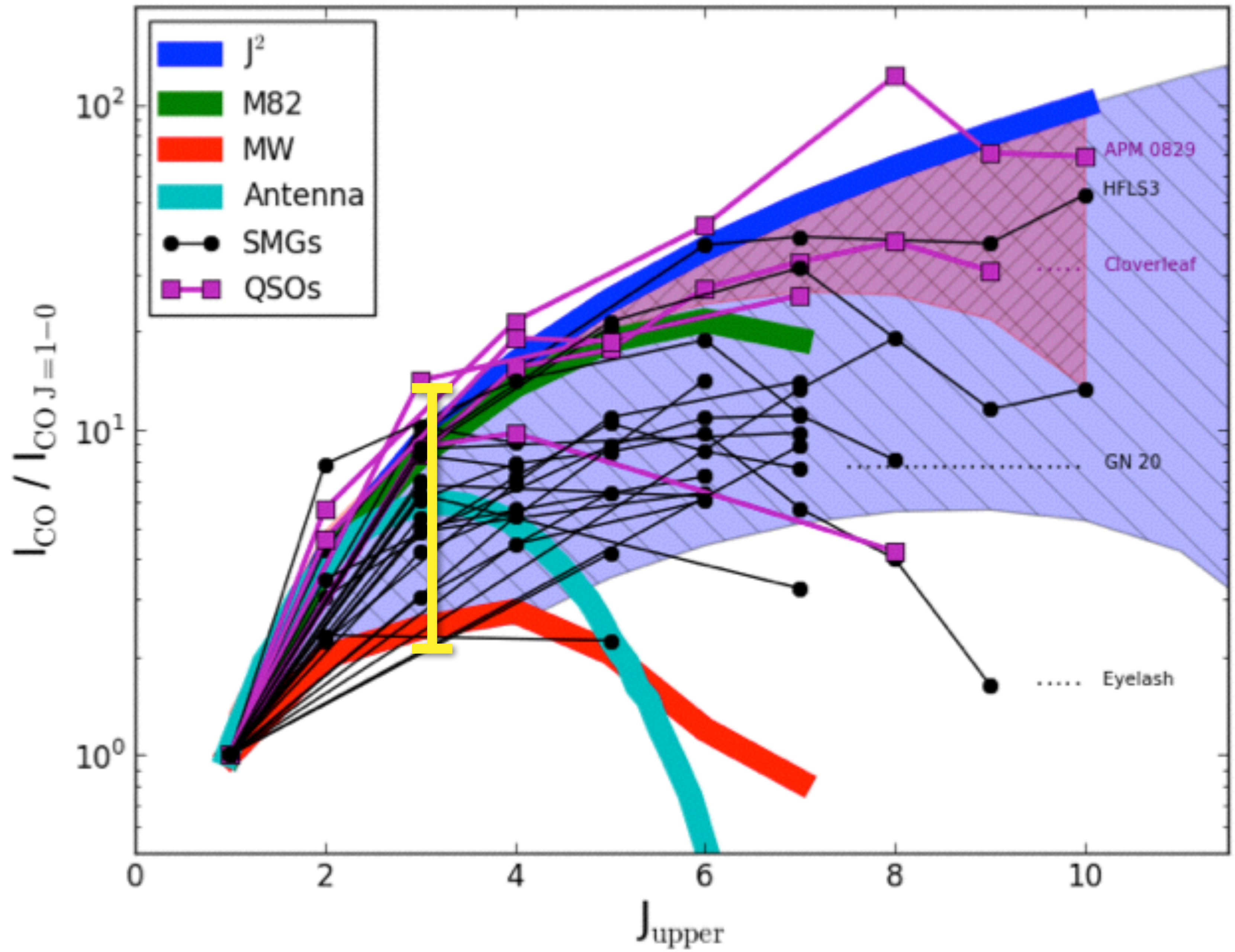
sweet spot

WG3 White Paper

CO: probing H_2, star-forming gas

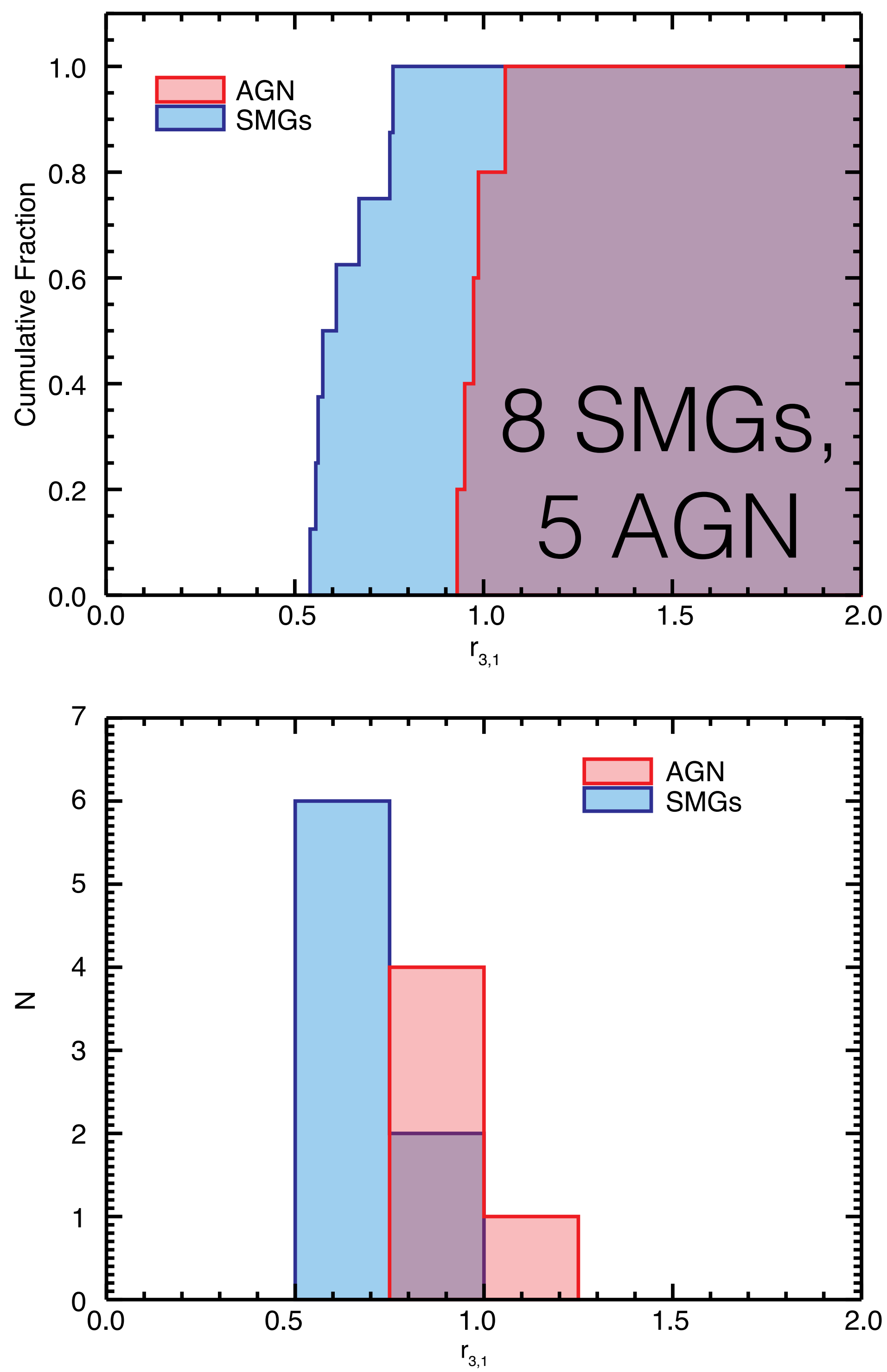
Need low-J CO due to variation in CO excitation ladder: diverse SLEDs at high-z!

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



Casey, Narayanan & Cooray (2014) Phys Rep.

CO: probing H_2, star-forming gas

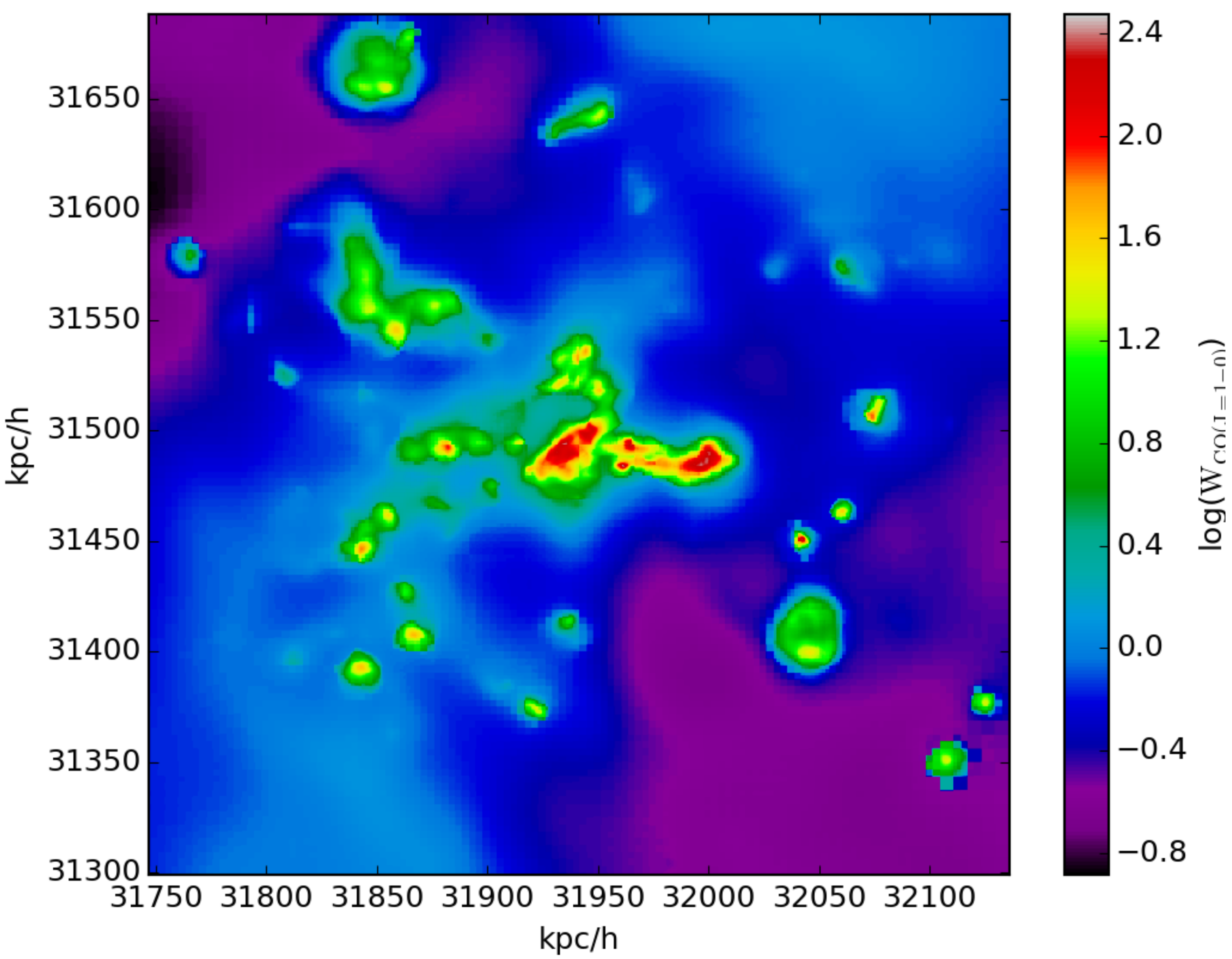


$r_{3,1}$ = CO(3-2) / CO(1-0)

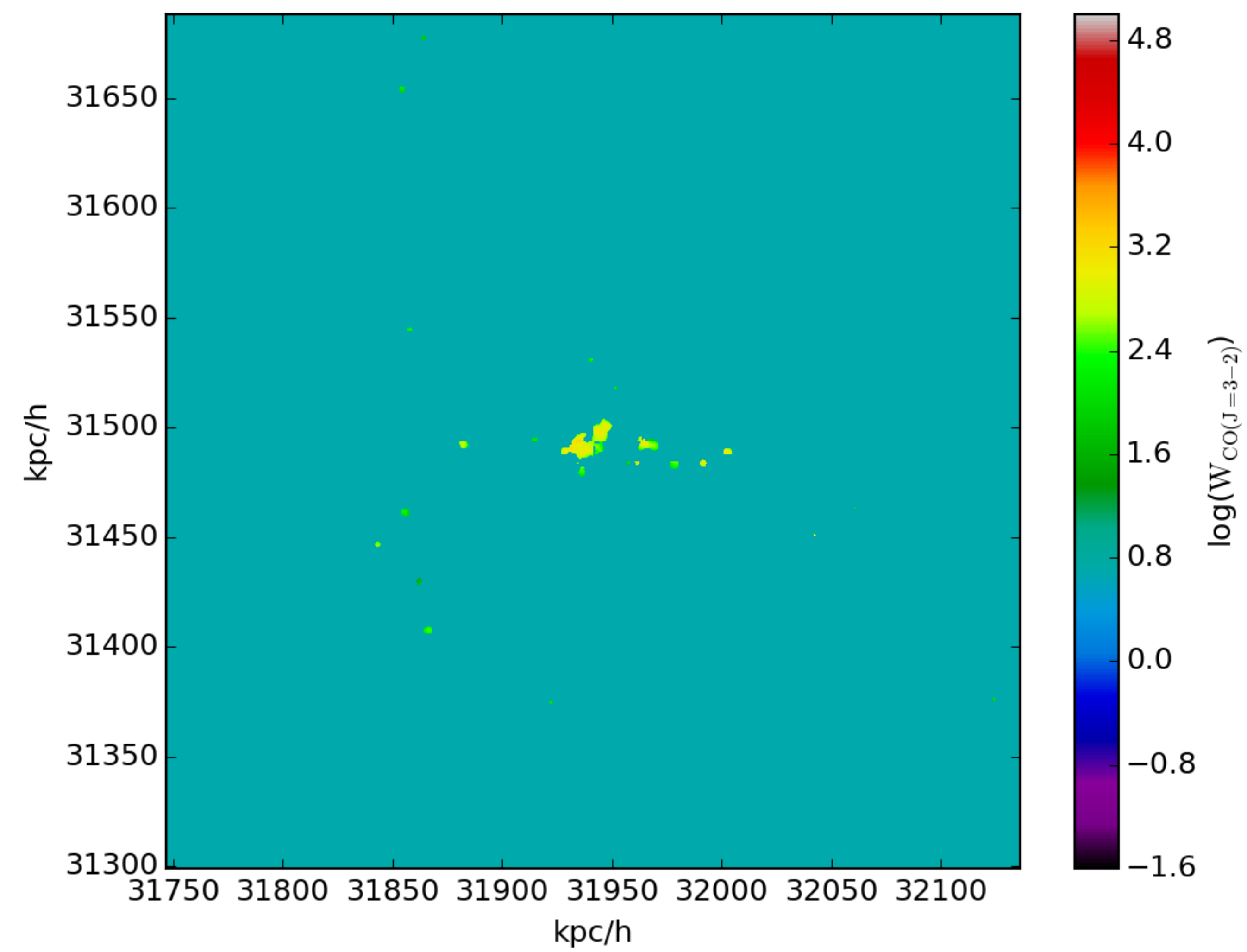
Sharon et al., in prep

CO: probing H_2, star-forming gas

Simulations perspective:
(Narayanan Powderday RT code)



CO(1-0)



CO(3-2)

CO: probing H_2, star-forming gas

We need CO(1-0) because:

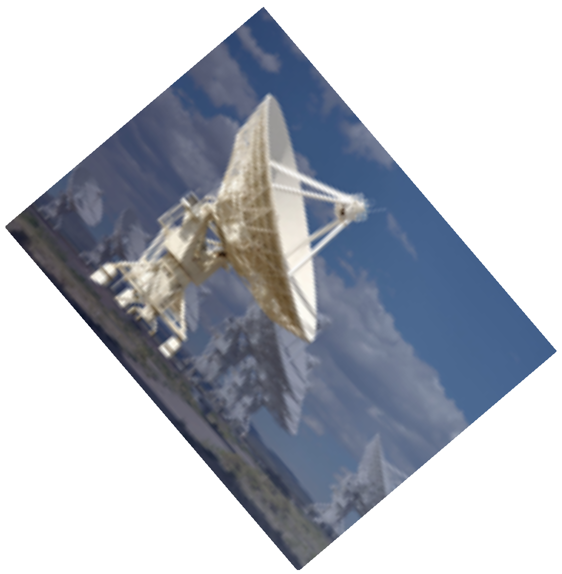
1. CO excitation is highly variable galaxy to galaxy,

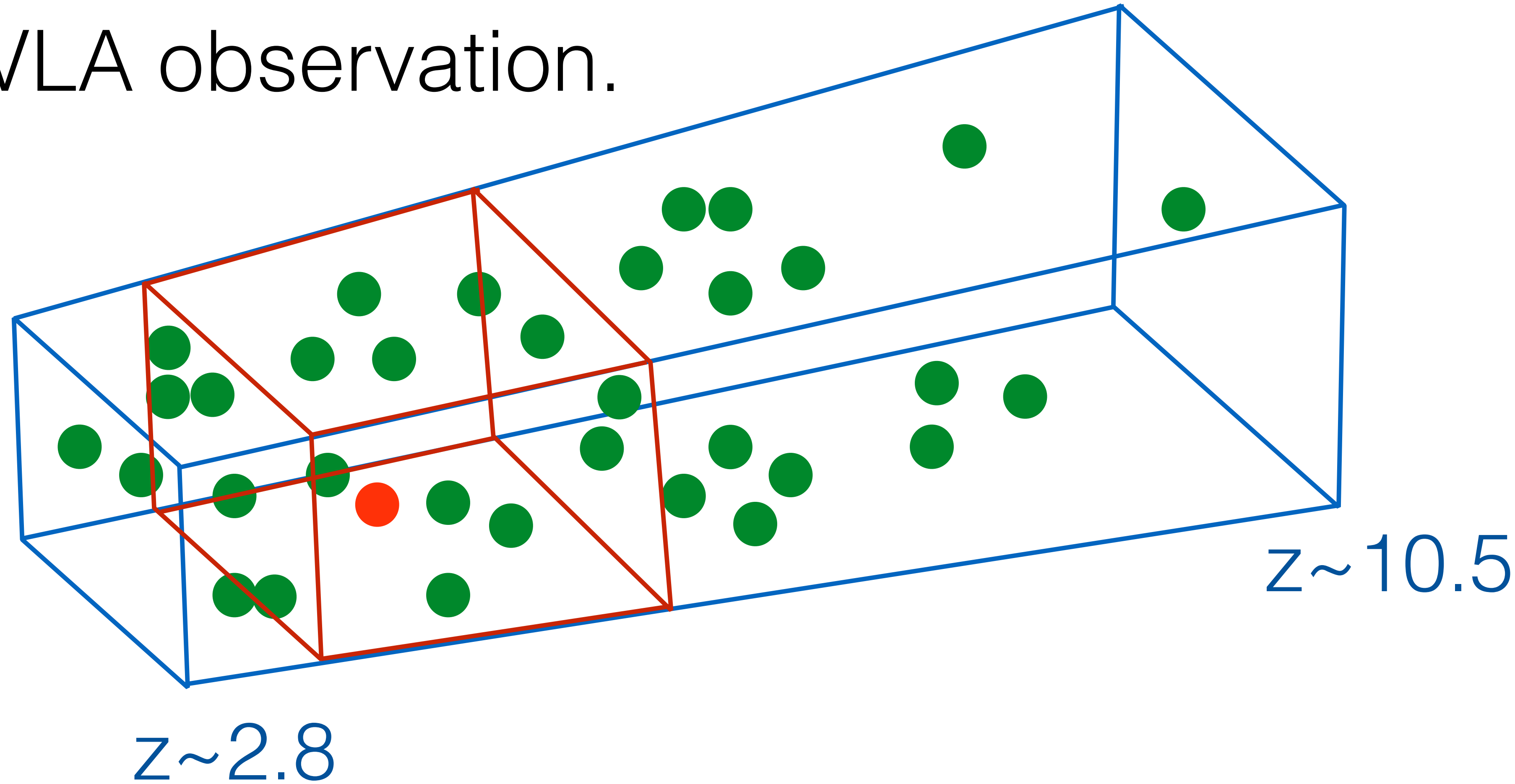
   adds a factor of ~5 uncertainty to gas mass derivations

2. high-J CO transitions do not probe the entire molecular gas potential well, spatially or by mass

   could lead to underestimates in dynamical mass, gas surface density

An example ngVLA observation.





Detectable with current VLA

e.g. z=4.05 CO(1-0)

$L'_{CO} \sim 10^{10}$ Lsun

8GHz bandwidth

3.2<z<5.0

Detectable with ngVLA

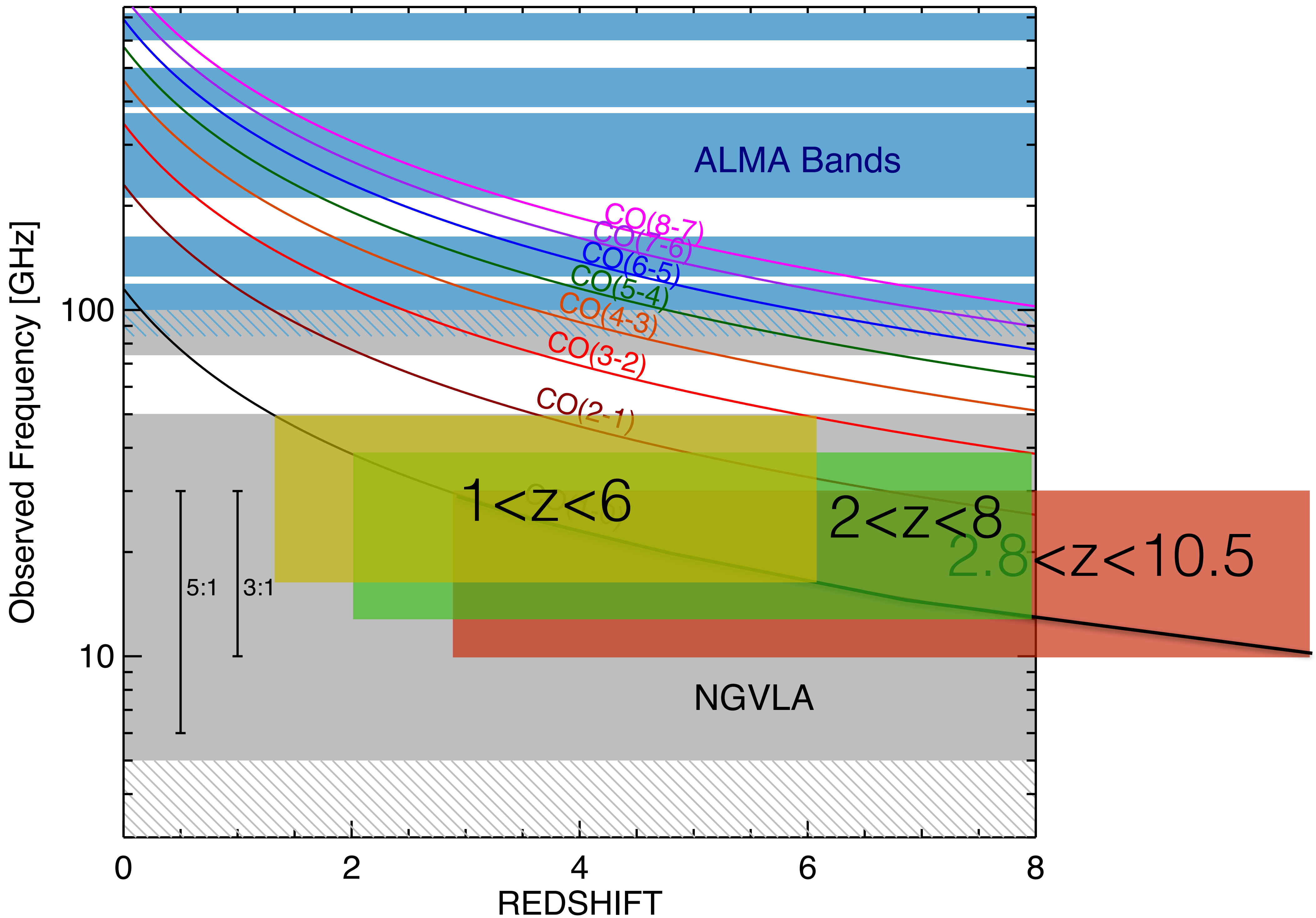
2.8<z<10.5 CO(1-0)

$L'_{CO} \sim 2 \times 10^{9}$ Lsun

3:1 bandwidth ratio

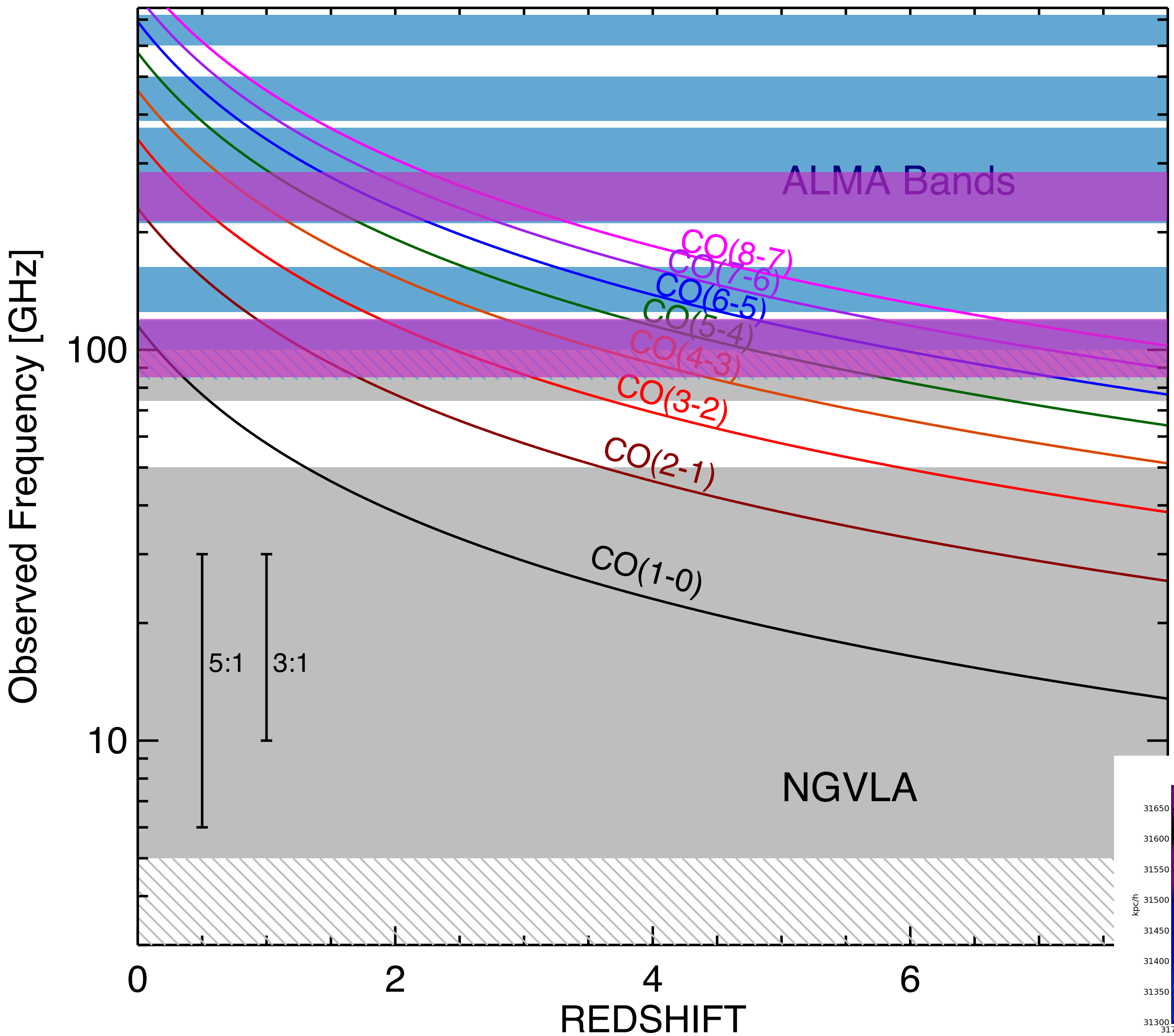
100s of blind

CO(1-0) detections!

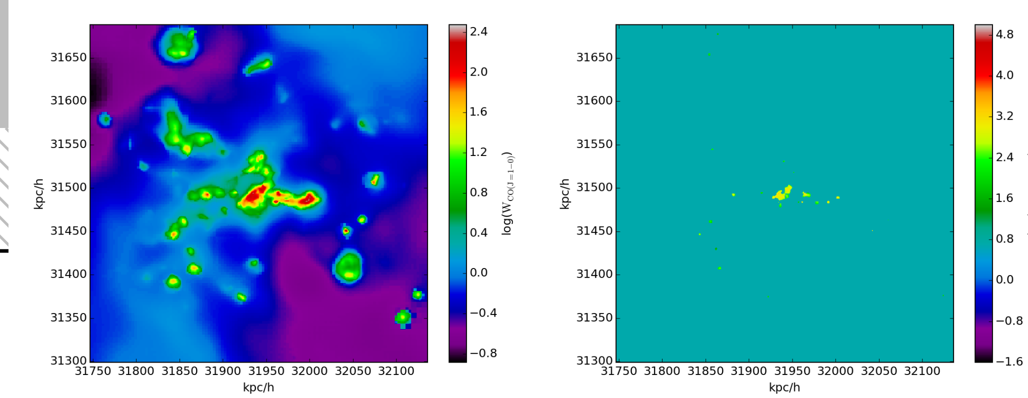

ALMA Bands
CO(8-7)
CO(7-6)
CO(6-5)
CO(5-4)
CO(4-3)
CO(3-2)
CO(2-1)
1<z<6
2<z<8
2.8<z<10.5
5:1
3:1
NGVLA
Observed Frequency [GHz]
100
10
0
2
4
6
8
REDSHIFT

A Molecular ALMA Deep Field in the UDF

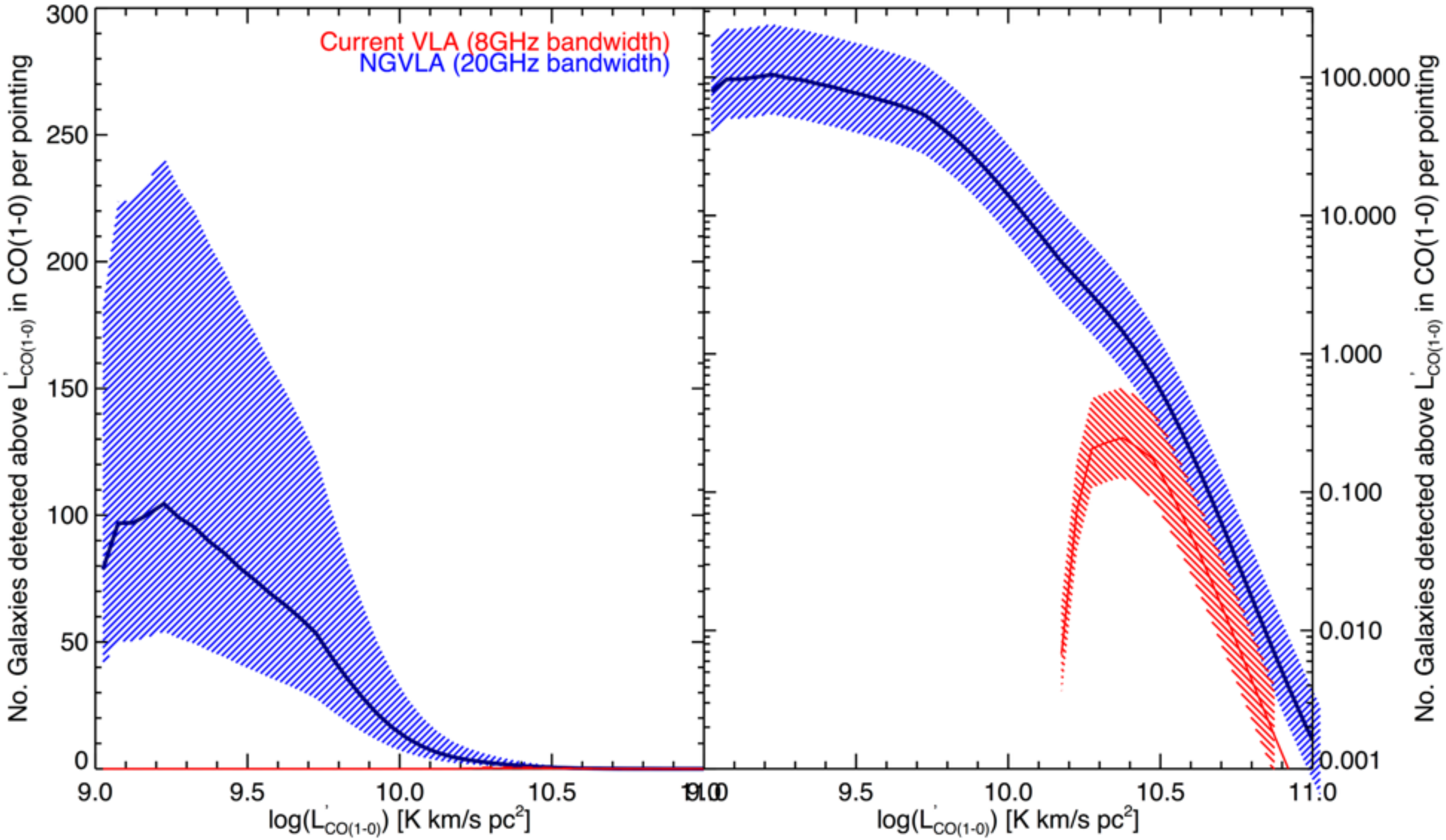
PI Fabian Walter, Cycle 2



A handful of high-J CO detections in the UDF (sensitive to a few 10’s of Msun/yr)



An example ngVLA observation: one hour.

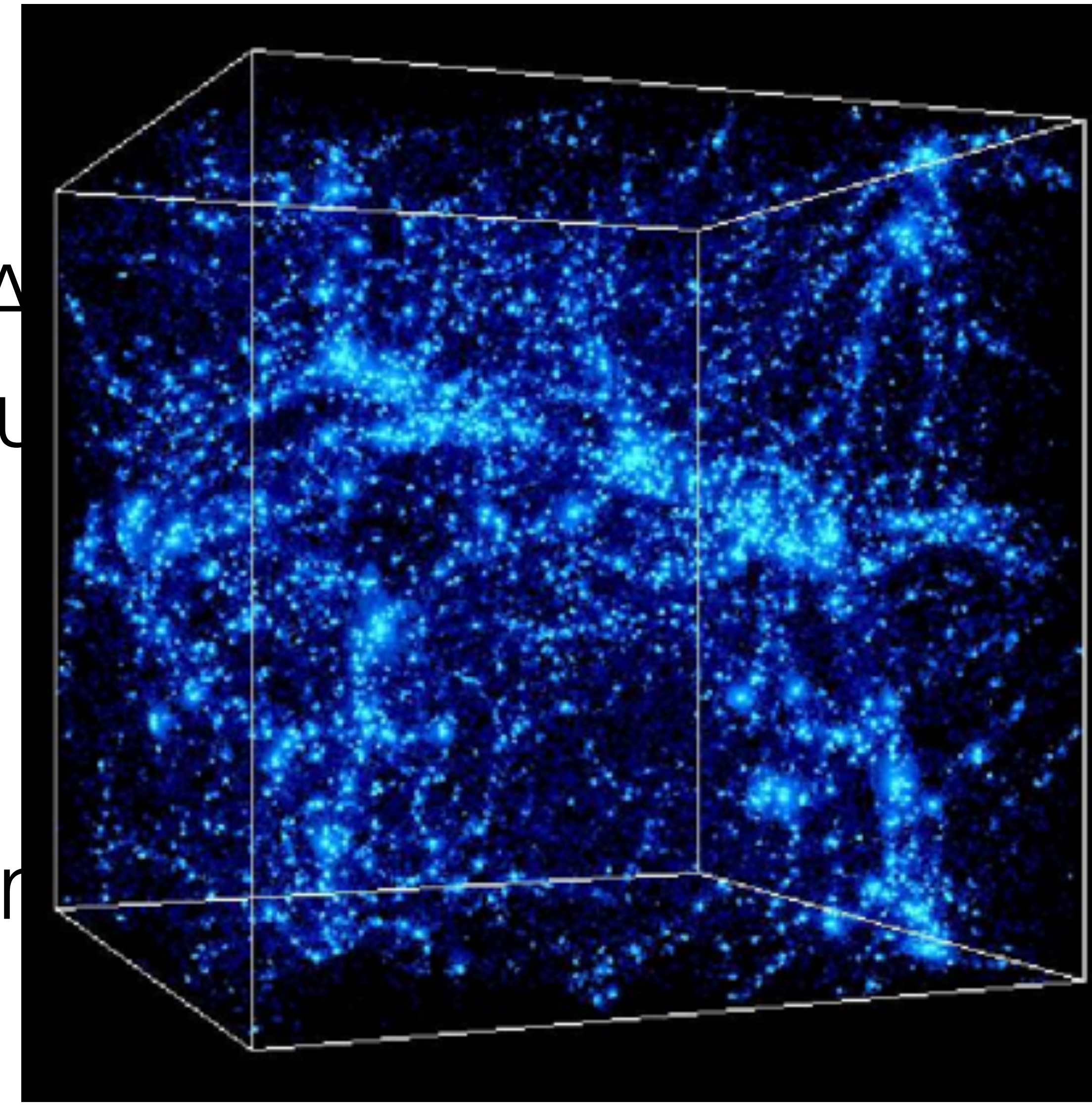


Single Source Science → Population Science

A

/Gas Fu

sq arc



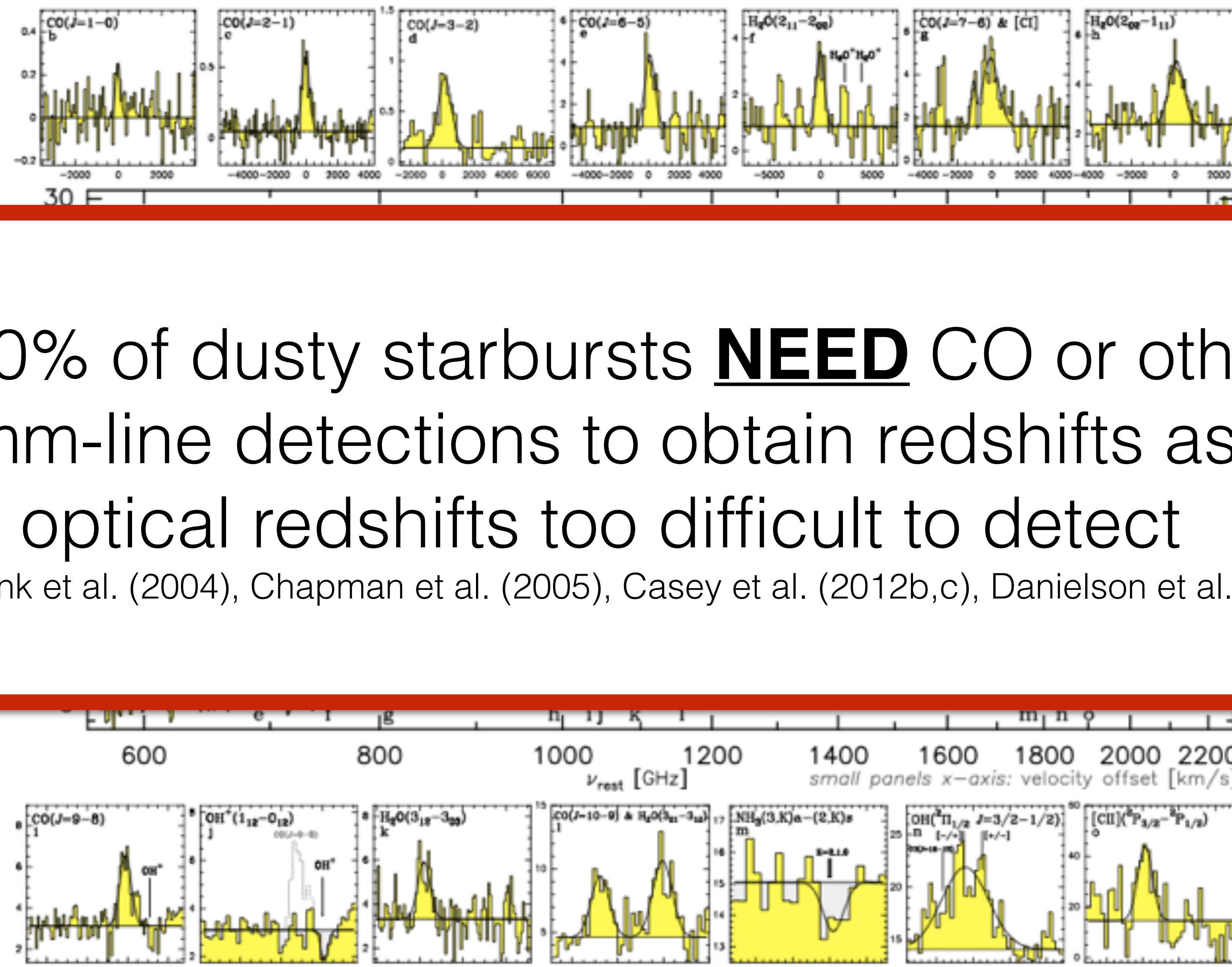
1000 hours: cover ~1sq deg down to ~10Msun/yr

~200,000 galaxies

ALL WITH SPECTROSCOPIC REDSHIFTS.

CO as a redshift beacon

Example source: HFLS3 at z=6.34, a massive starburst… how common are these? Completely absent from optical/NIR surveys.



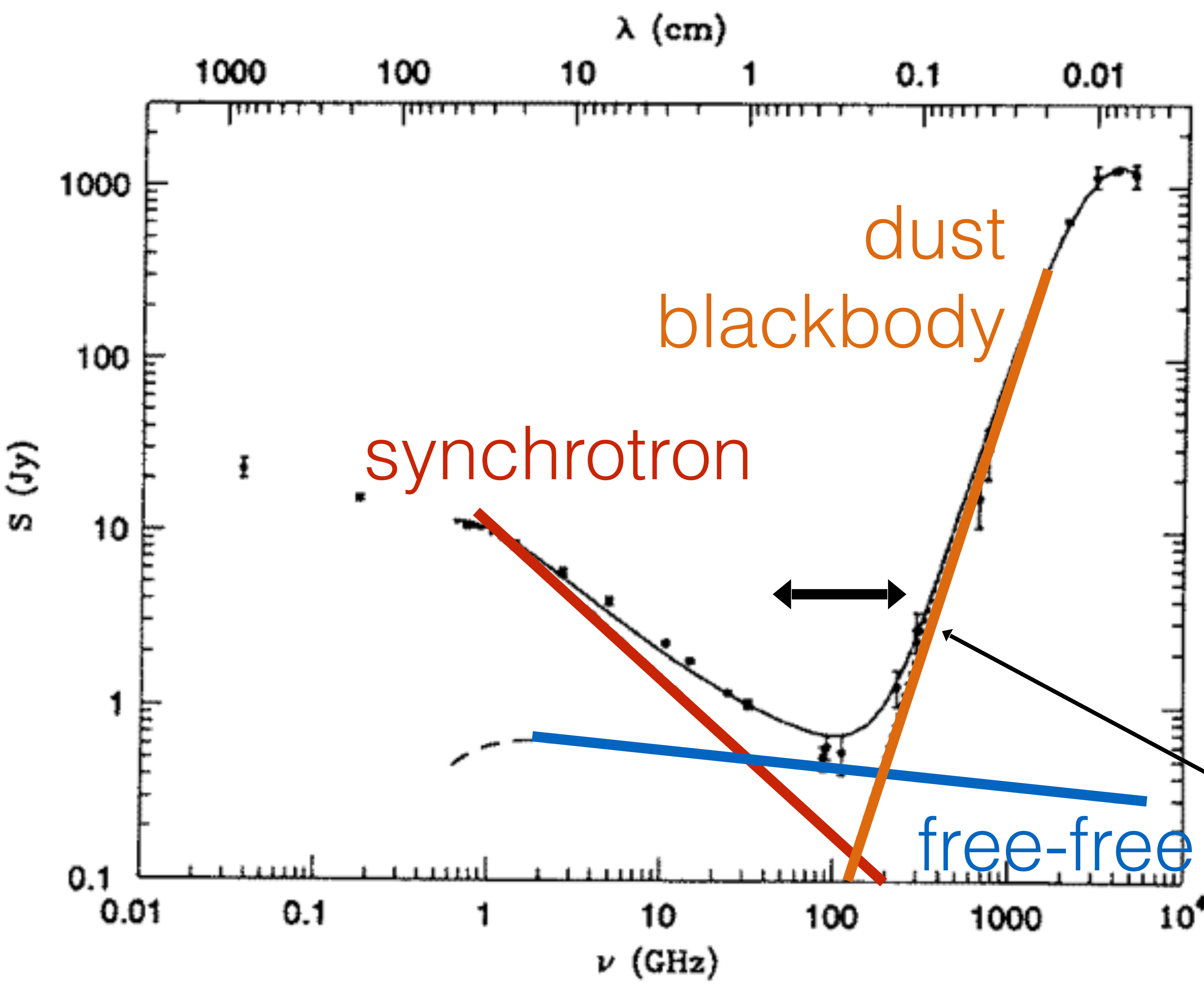
~50% of dusty starbursts **NEED** CO or other mm-line detections to obtain redshifts as optical redshifts too difficult to detect

Swinbank et al. (2004), Chapman et al. (2005), Casey et al. (2012b,c), Danielson et al. 2015

Riechers et al. 2013, Nature

Continuum

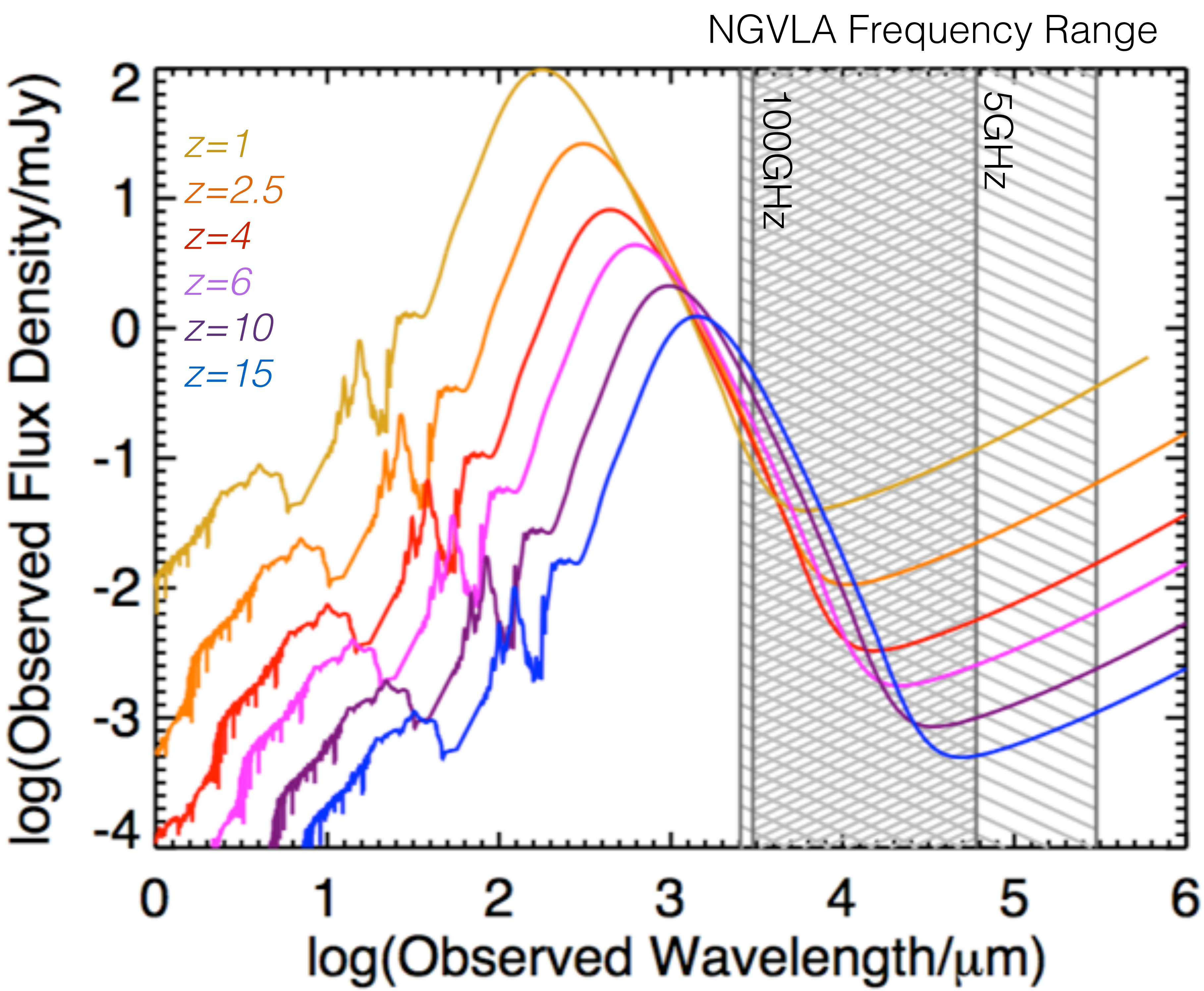
Continuum



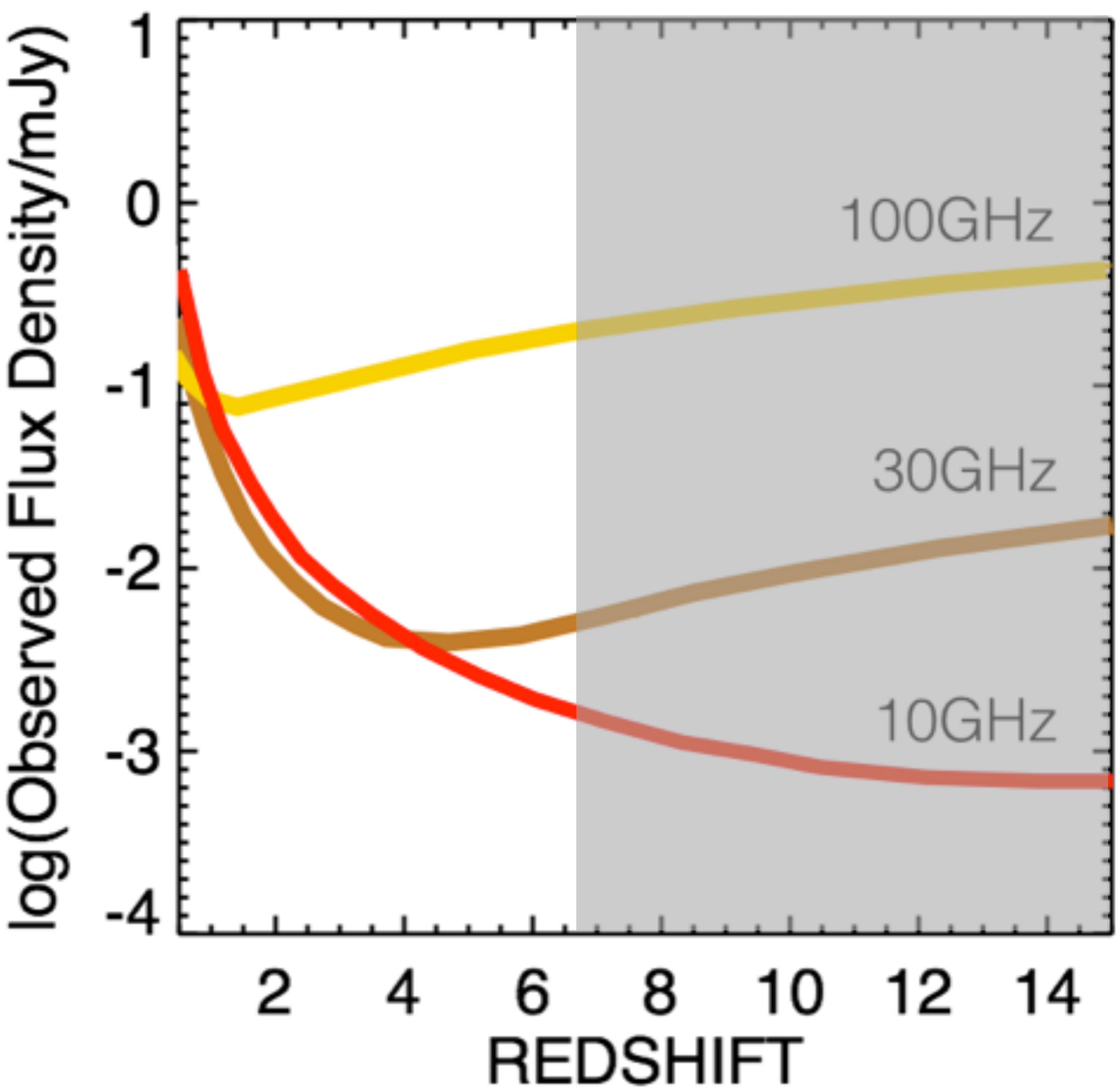
<u>Continuum emission from 5-100GHz:</u> synchrotron emission, free-free, and cold dust emission. Wide-bandwidth observations will be critical to disentangling the spectrum.

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

Continuum


NGVLA Frequency Range
100GHz
5GHz
z=1
z=2.5
z=4
z=6
z=10
z=15
log(Observed Flux Density/mJy)
log(Observed Wavelength/μm)
2
1
0
-1
-2
-3
-4
0
1
2
3
4
5
6

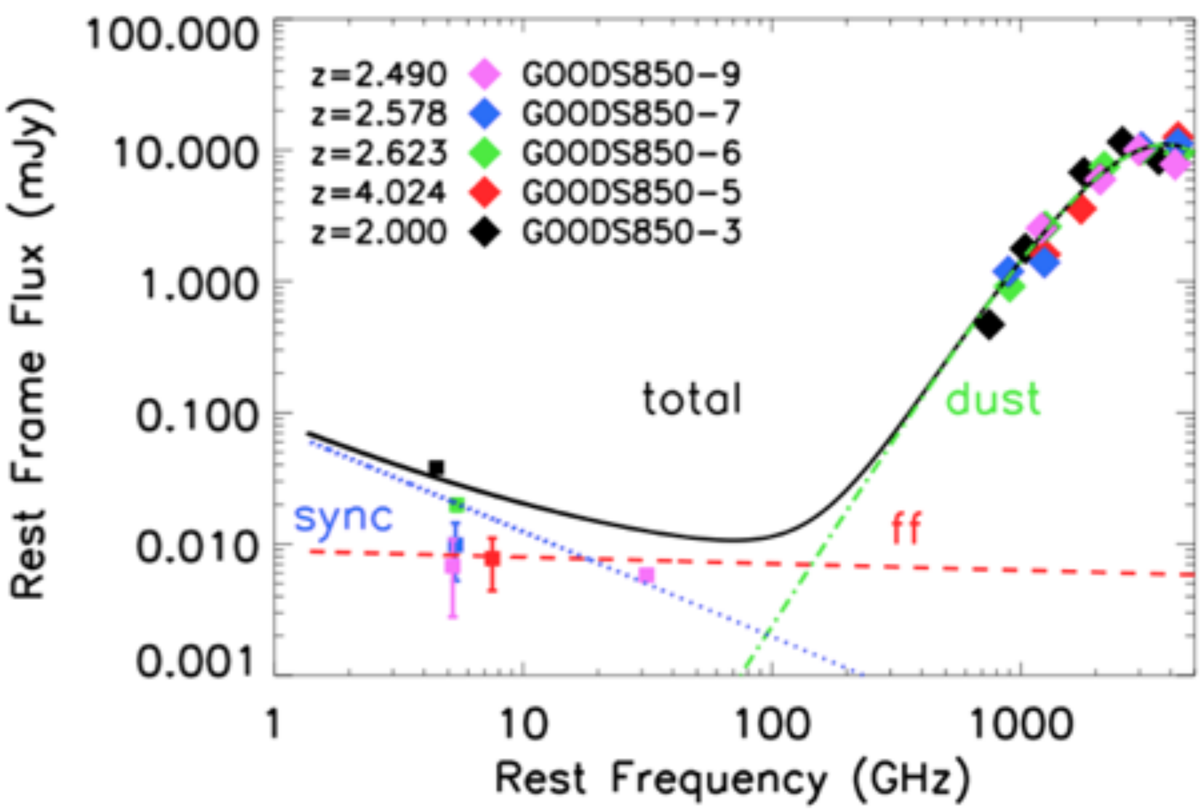
Continuum

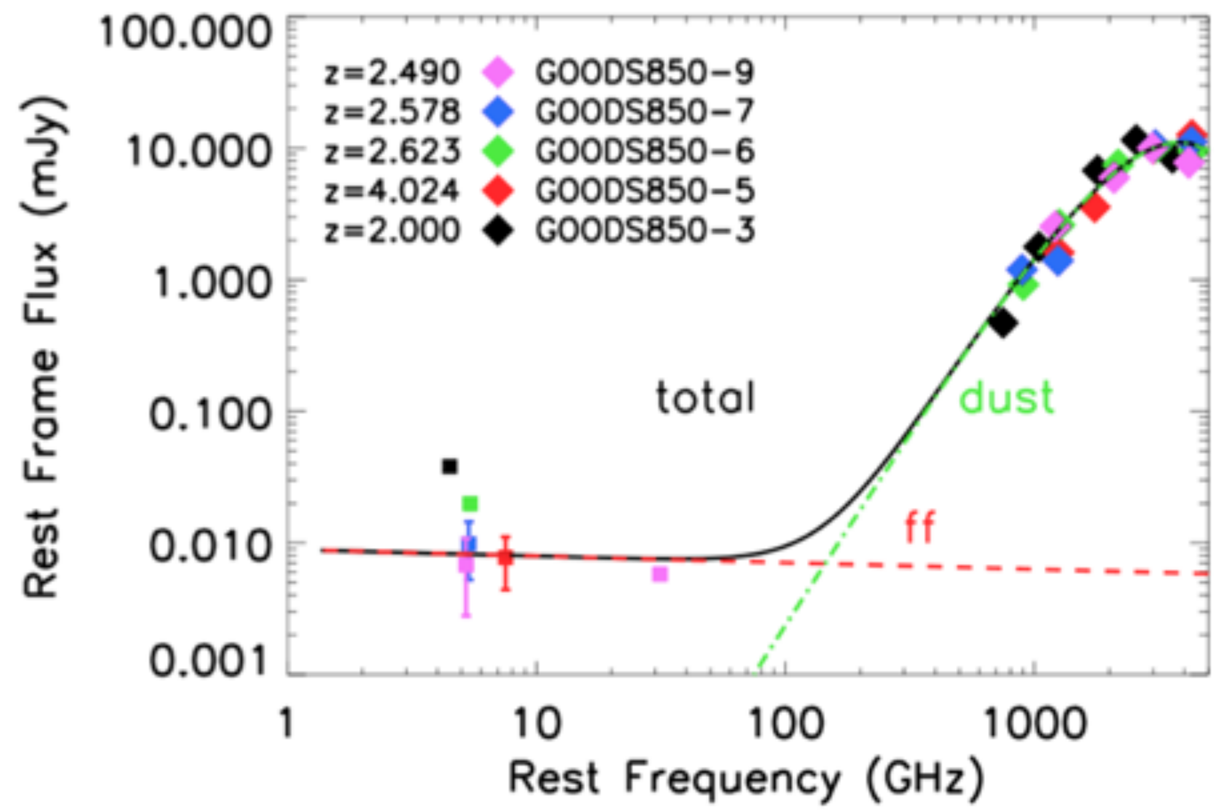


At sufficiently high-redshift, the NG VLA bands benefit from the very-negative K-correction on the cold dust Raleigh-Jeans tail (not just the higher-frequency submm bands!).

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

Continuum





CMB suppression of synchrotron in normal high-z galaxies: free-free directly proportional to # ionizing photons from massive stars: very accurate SFR indicator.

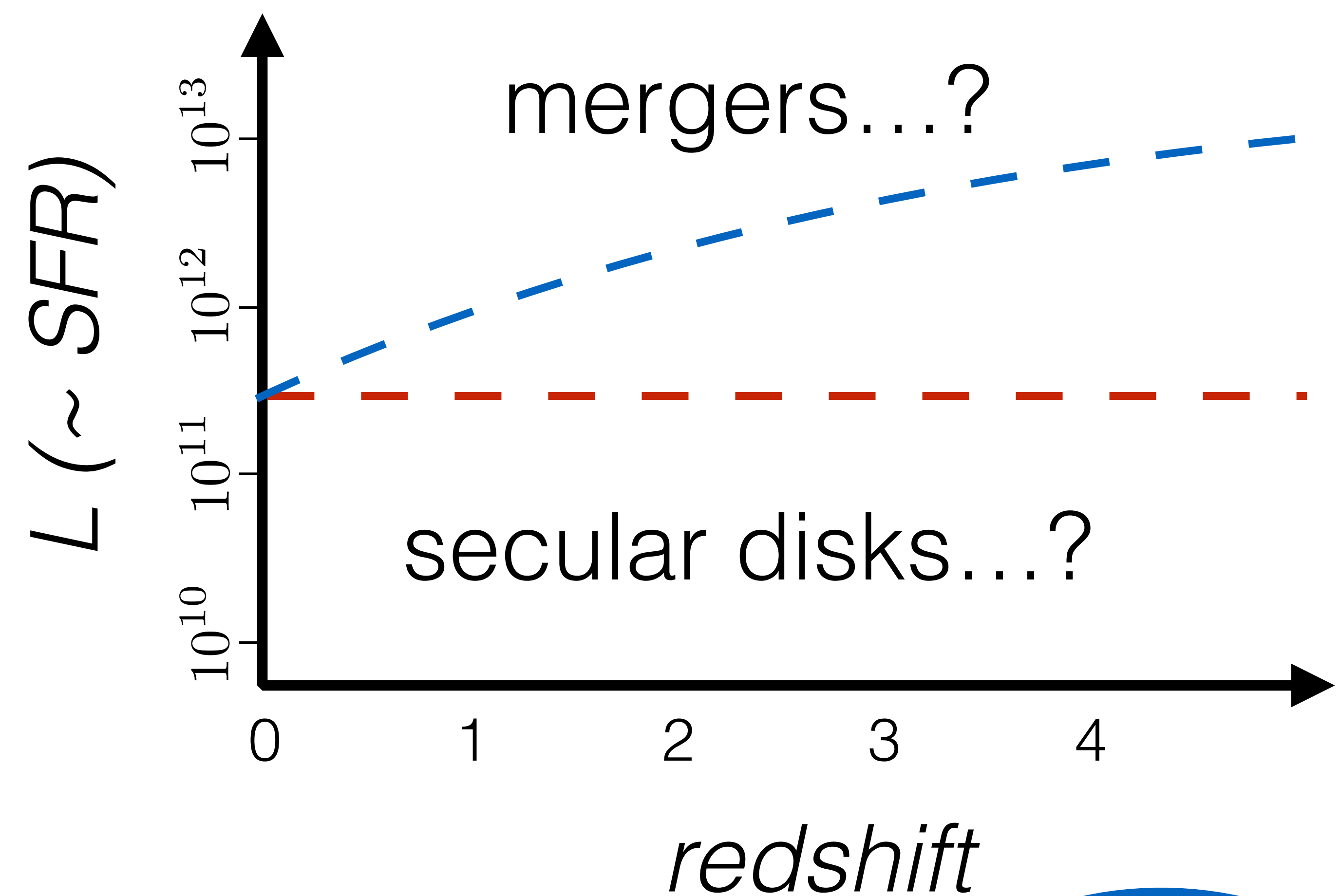
Dynamics

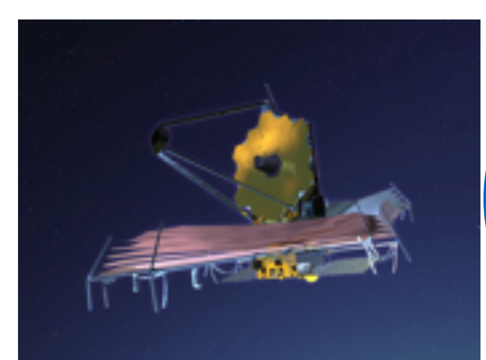
Mergers or secular disks?

What role do **mergers** have in early Universe galaxy formation?

Locally, all with $L_{\rm IR} > 10^{11.5} L_\odot$ are mergers, but very rare.
At high-z, are mergers more prominent?

Important to probe moderate SFR regime at z>2: impossible with Hubble Space Telescope morphologies because:
(a) Optical light redshifted out of range (wait for JWST), and
(b) DUST (80-95% of luminosity emitted by gas/dust, not direct starlight)
(c) Kinematics!



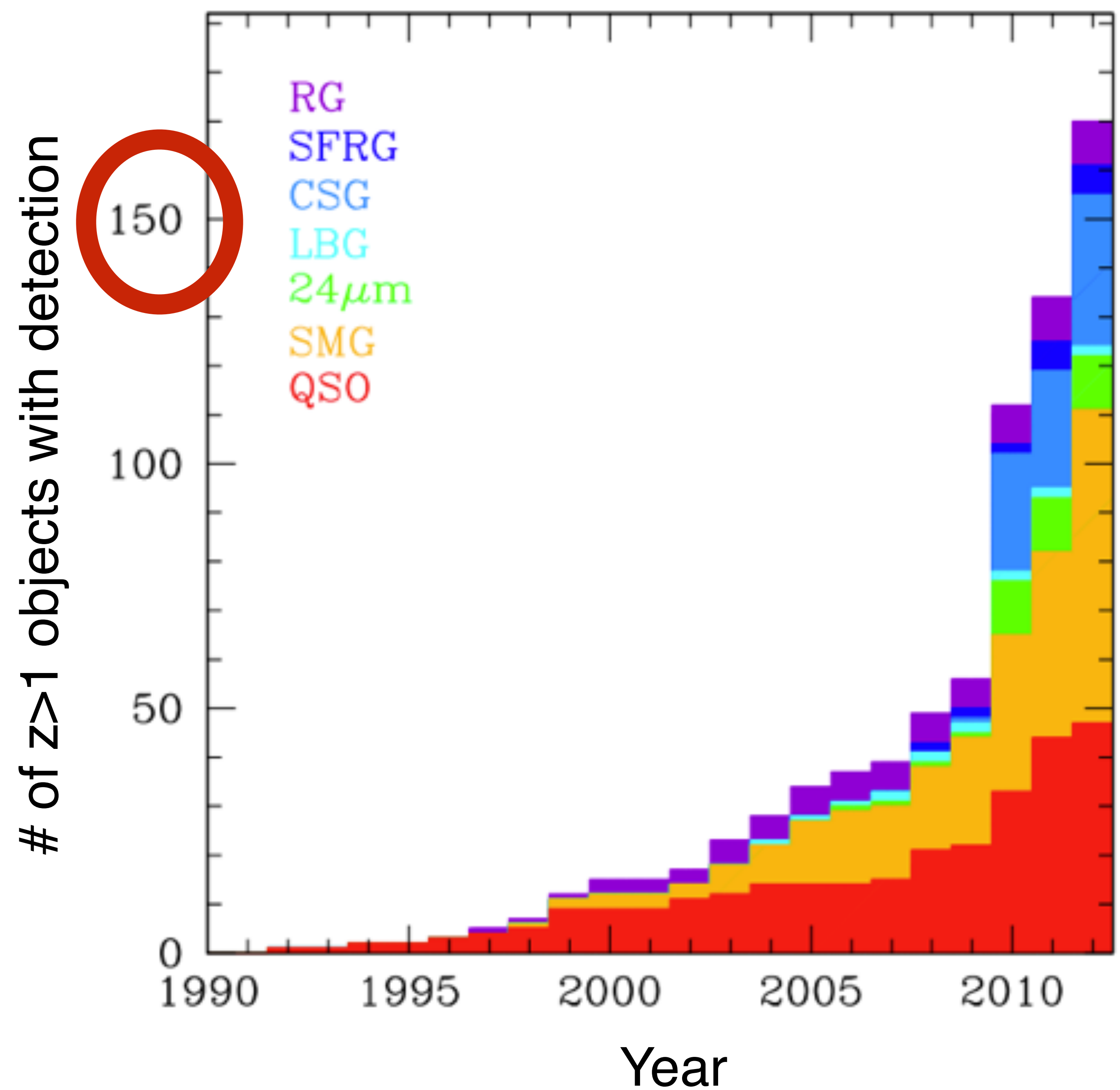


Dynamics

The majority of high-z gas detections are unresolved or marginally resolved

< 200 high-z galaxies with CO detections, total!

(compare to >>thousands of galaxies characterized in optical)

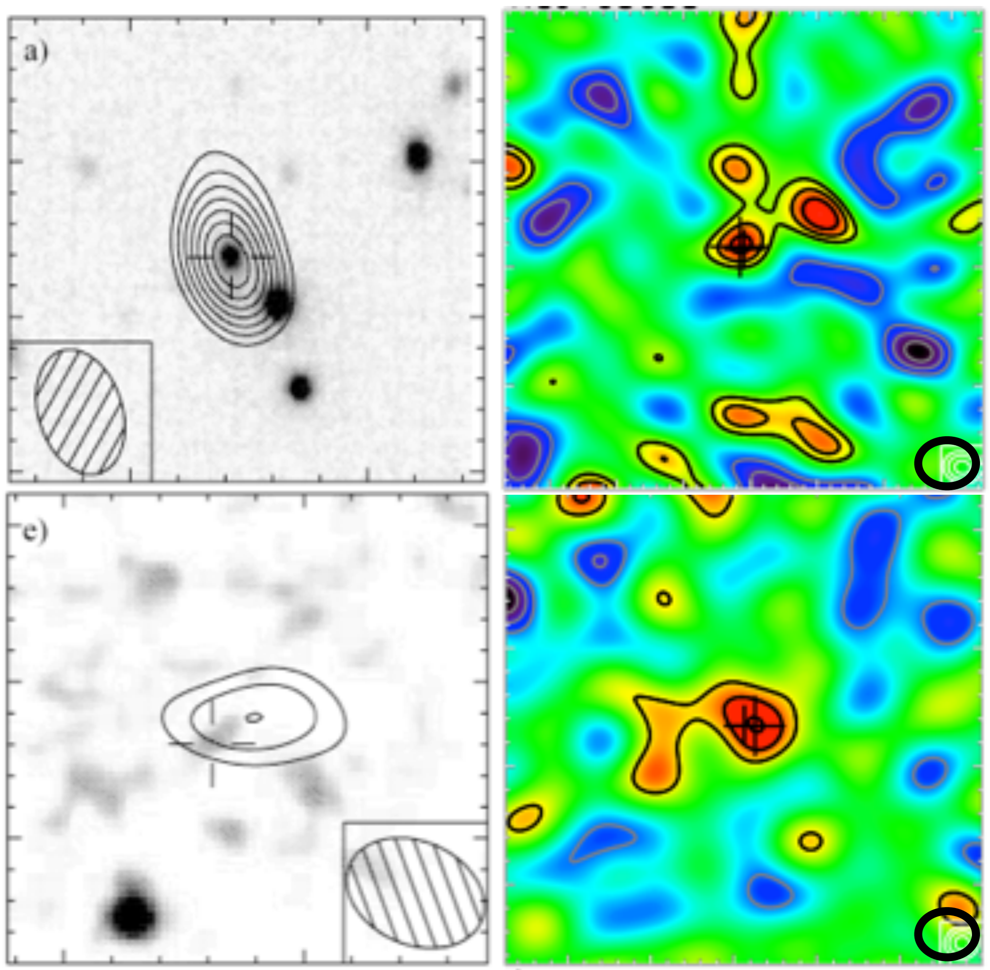


Carilli & Walter 2013 ARA&A

Dynamics

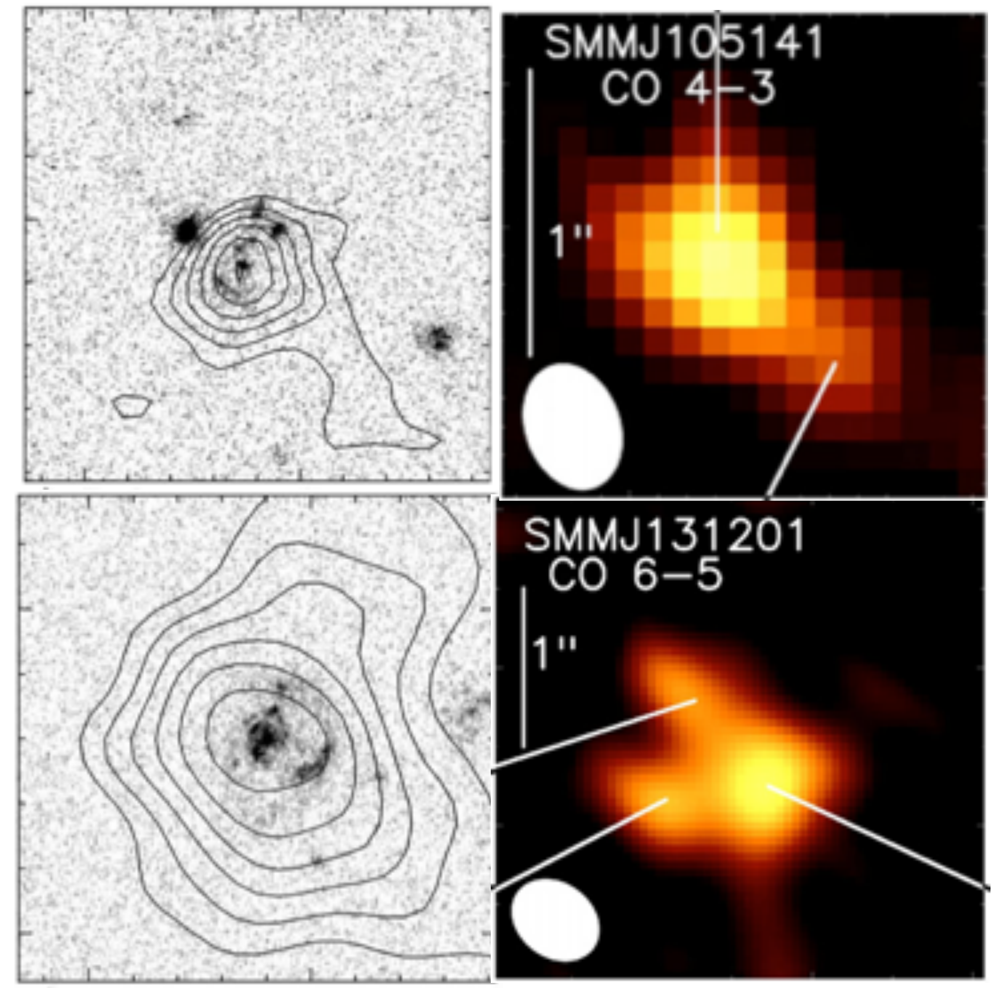
EXAMPLES

UNRESOLVED



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

MARGINALLY RESOLVED

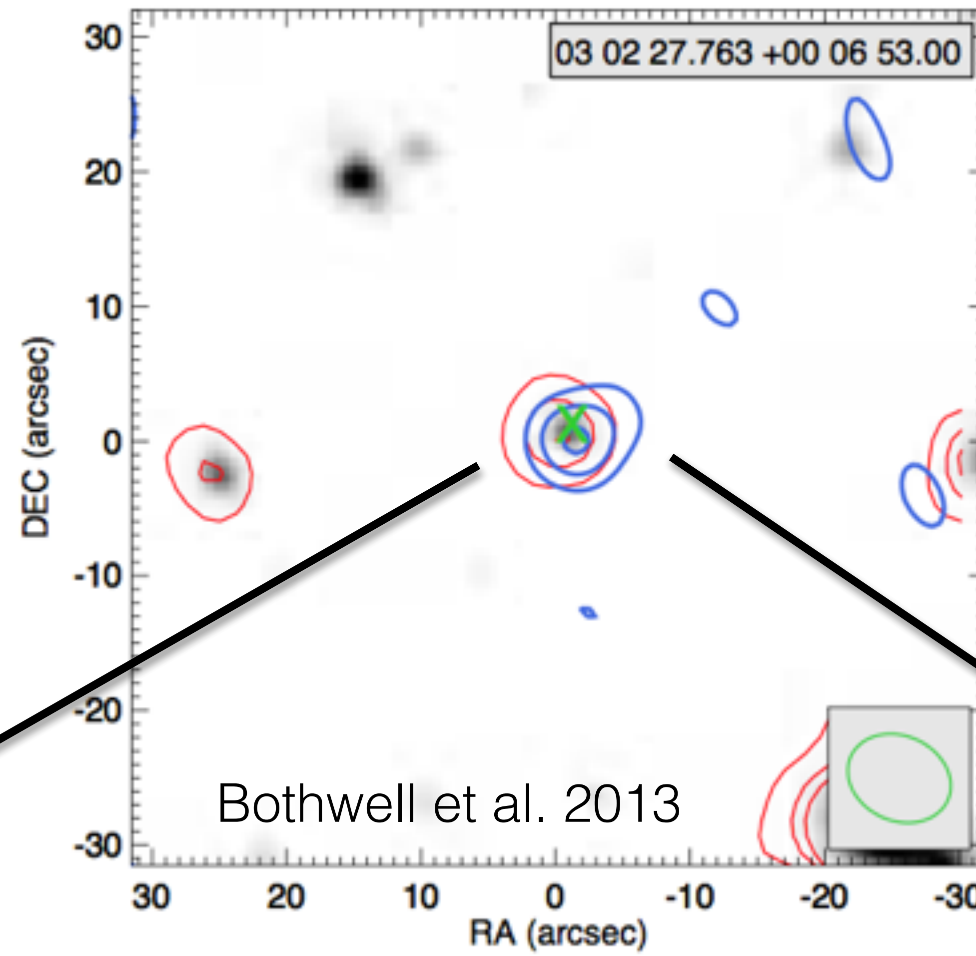


Tacconi et al. (2008), Daddi et al. (2010), Tacconi et al. (2010), Bothwell et al. (2010), Engel et al. (2010)

KINEMATICS + MORPHOLOGY

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

Dynamics



Bothwell et al. 2013

Merger?

Image credit: NOAO/AURA/NSF

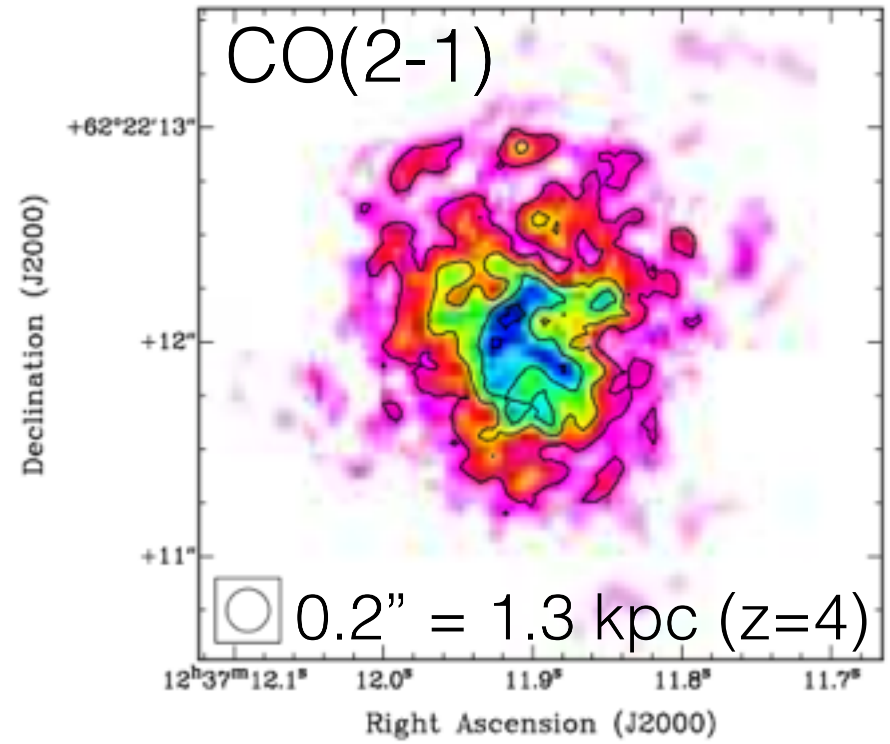
Disk?

Image credit: NASA/STScI/ACS ScienceTeam

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

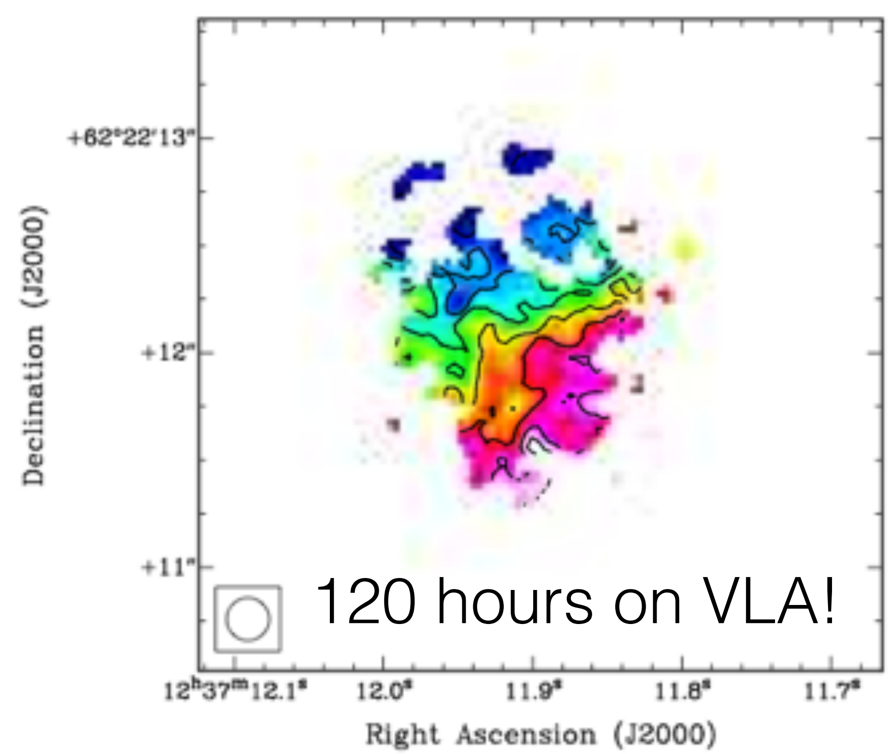
Dynamics

Hodge et al. (2012)



Why not use the VLA?

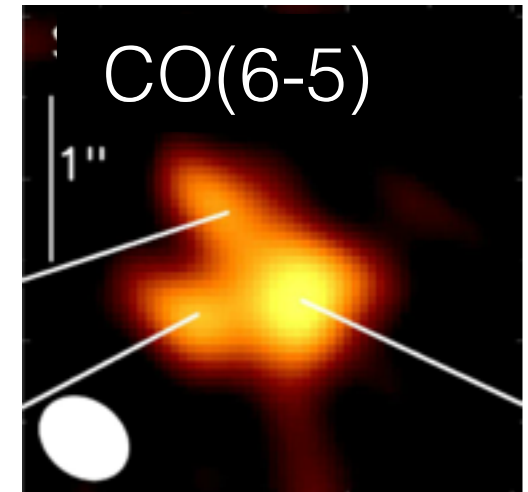
It takes too long!



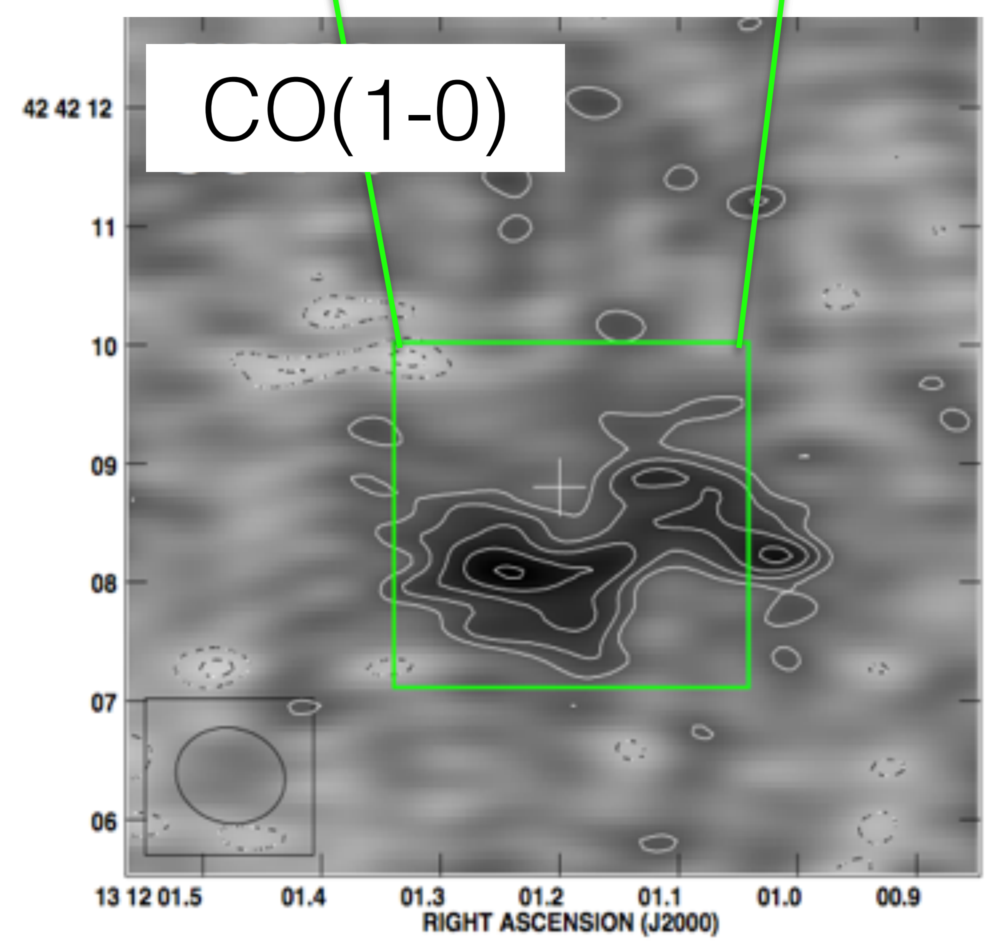
Significantly increased sensitivity is crucial if we are to do this on more than a handful of the very brightest objects

Dynamics

Engel et al. 2010



Riechers et al. 2011

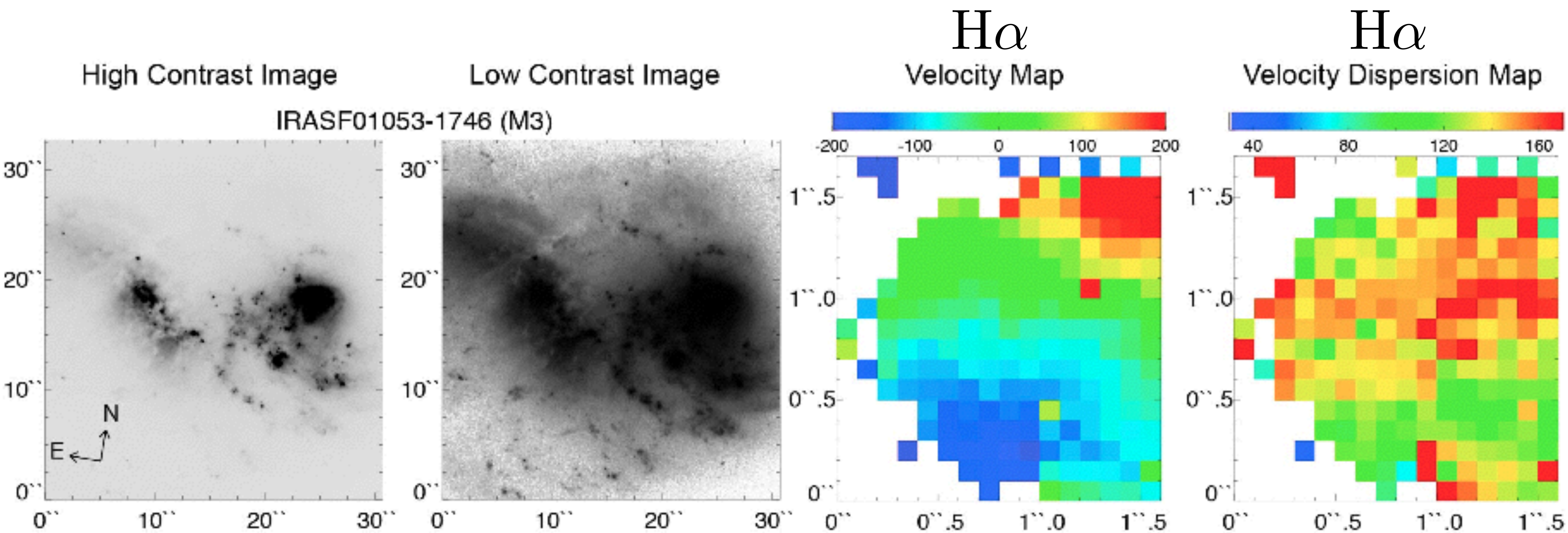


Why not use ALMA?

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

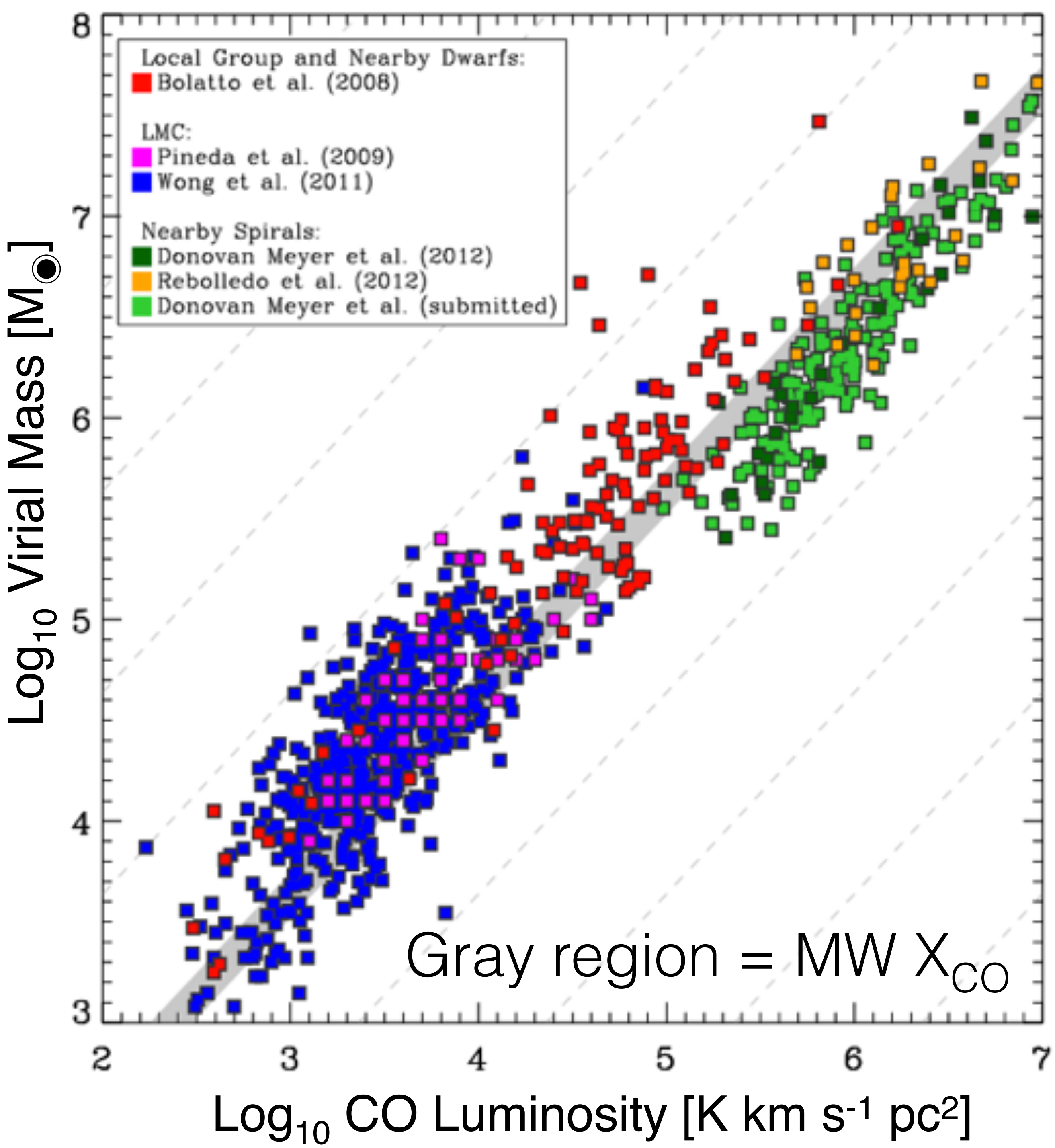
Resolution needed for dynamics!



Hung et al. 2015

artificially redshifted mergers look like disks at z>1.5

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.

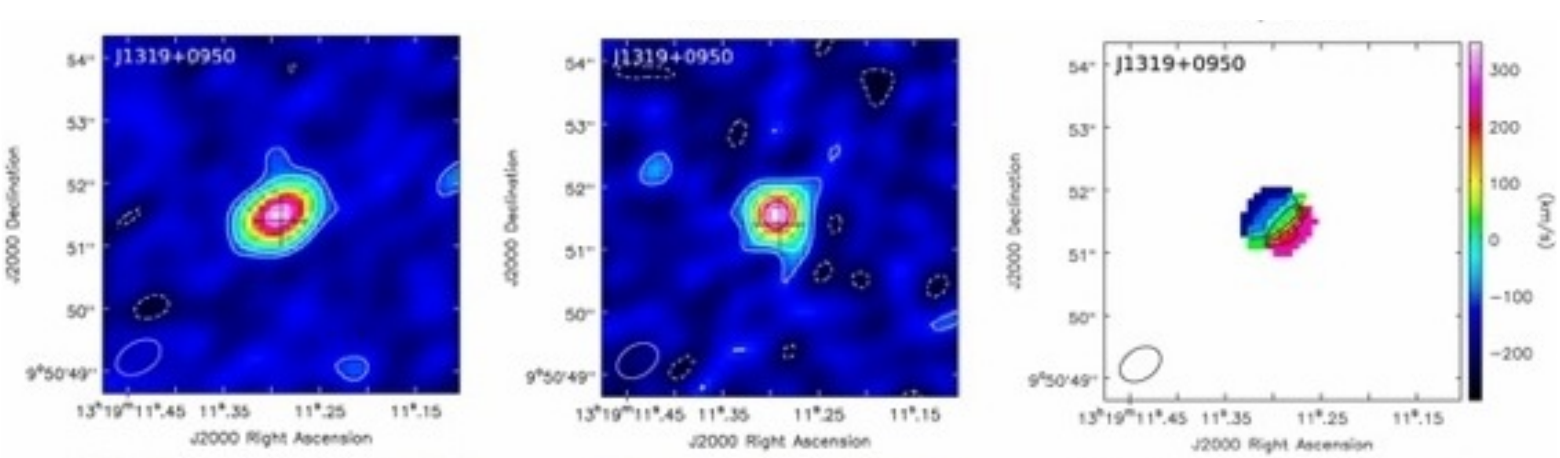
What drives co-evolution of BHs and their host galaxies?

BH masses and M-σ

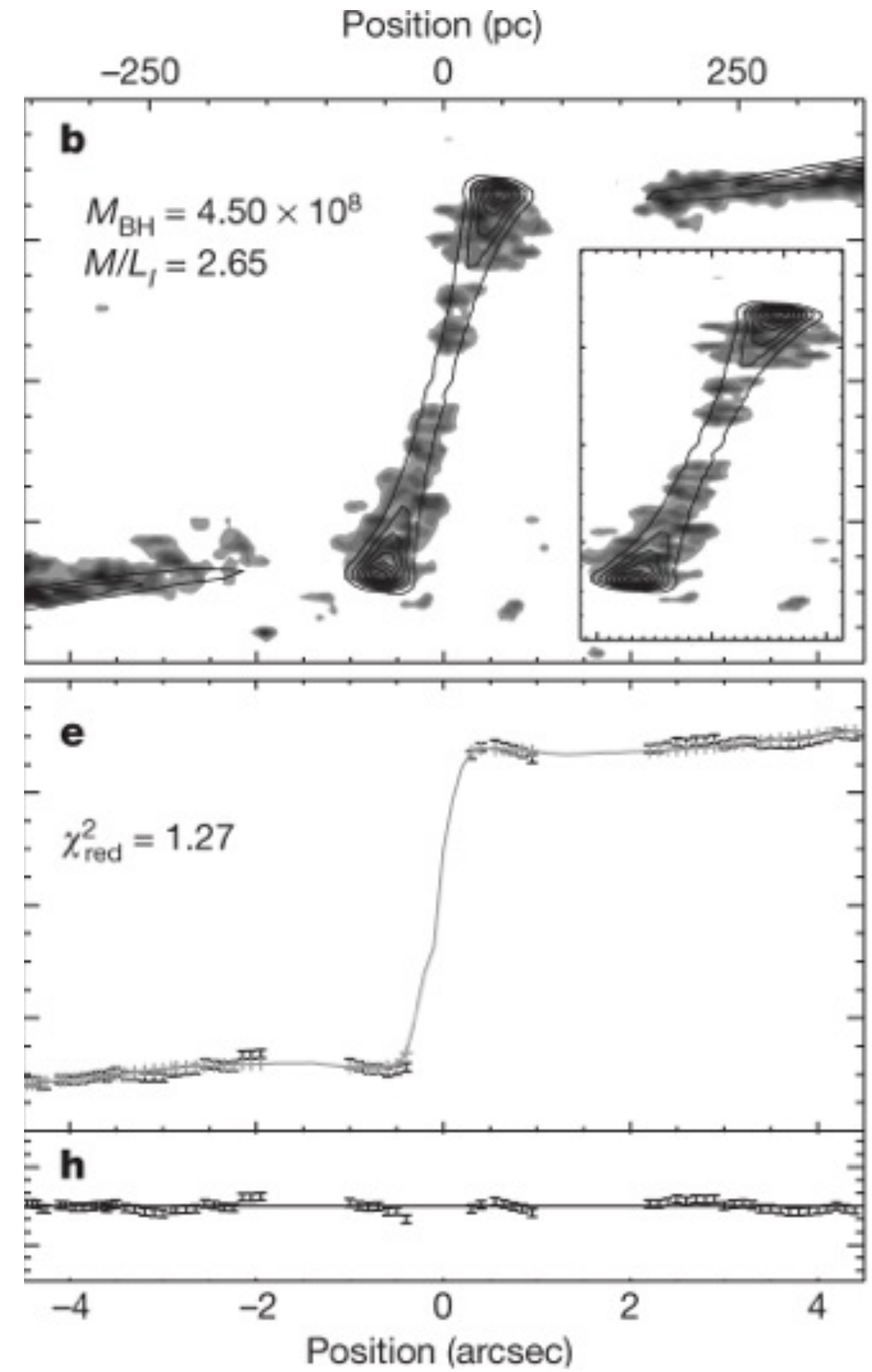
Radius of influence for $10^9\ M_\odot$ BH ~30mas at z~1, resolvable with NG-VLA
(SB sensitivity may limit NG-VLA measurements to z~0.1 in practice)

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)

High-z WG3 Summary

CO(1-0) needed to probe high-z gas mass & full kinematics

Frequency & Bandwidth:

5:1 bandwidth key high-z goal, gives redshift confirmation, CO excitation, continuum emission

20-50GHz range CRITICAL for CO(1-0) at 2<z<6

Do we need the 3mm band?

Sensitivity:

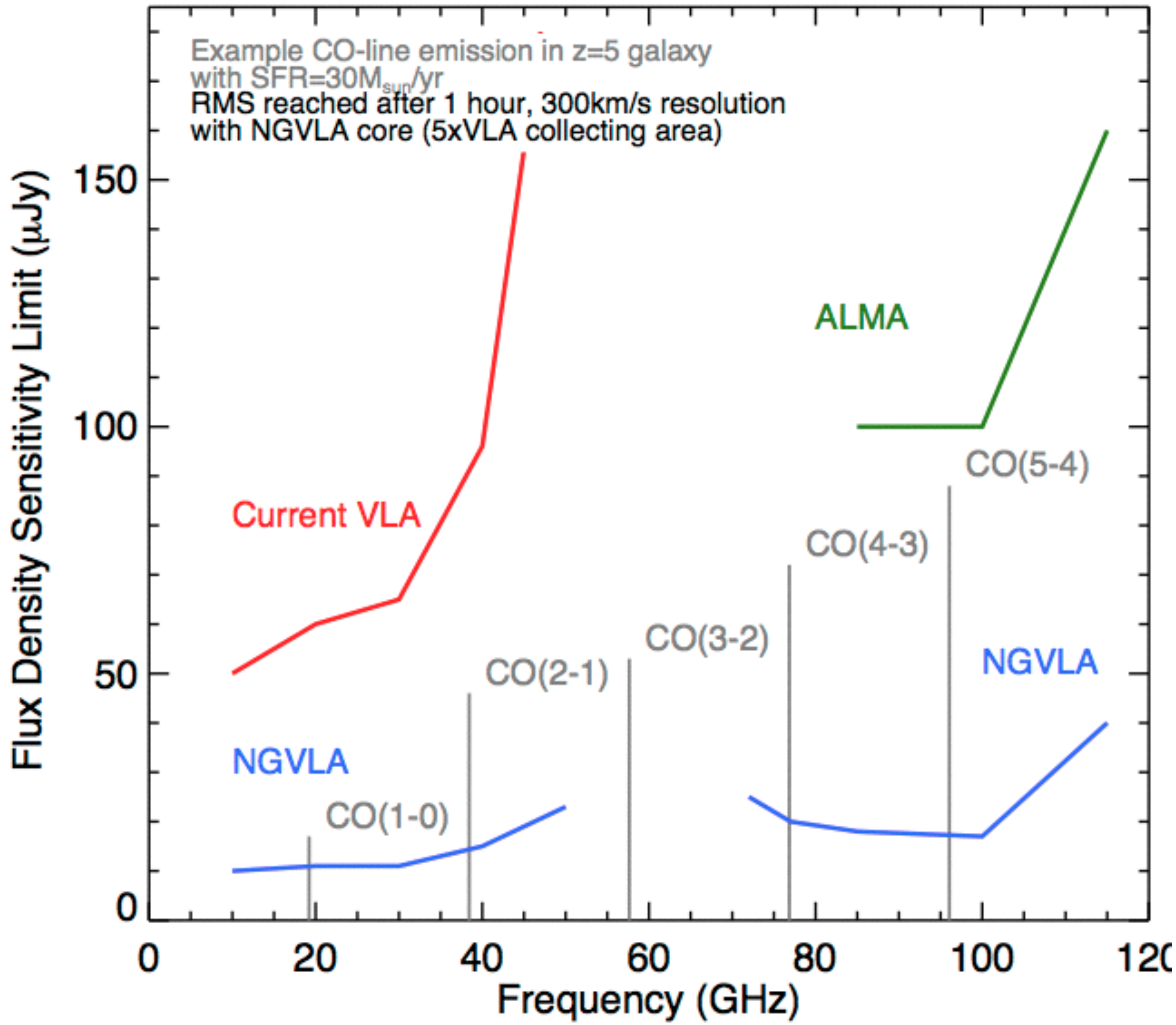
10 times improvement allows us to probe normal high-z galaxies in CO(1-0): not just submm galaxies!

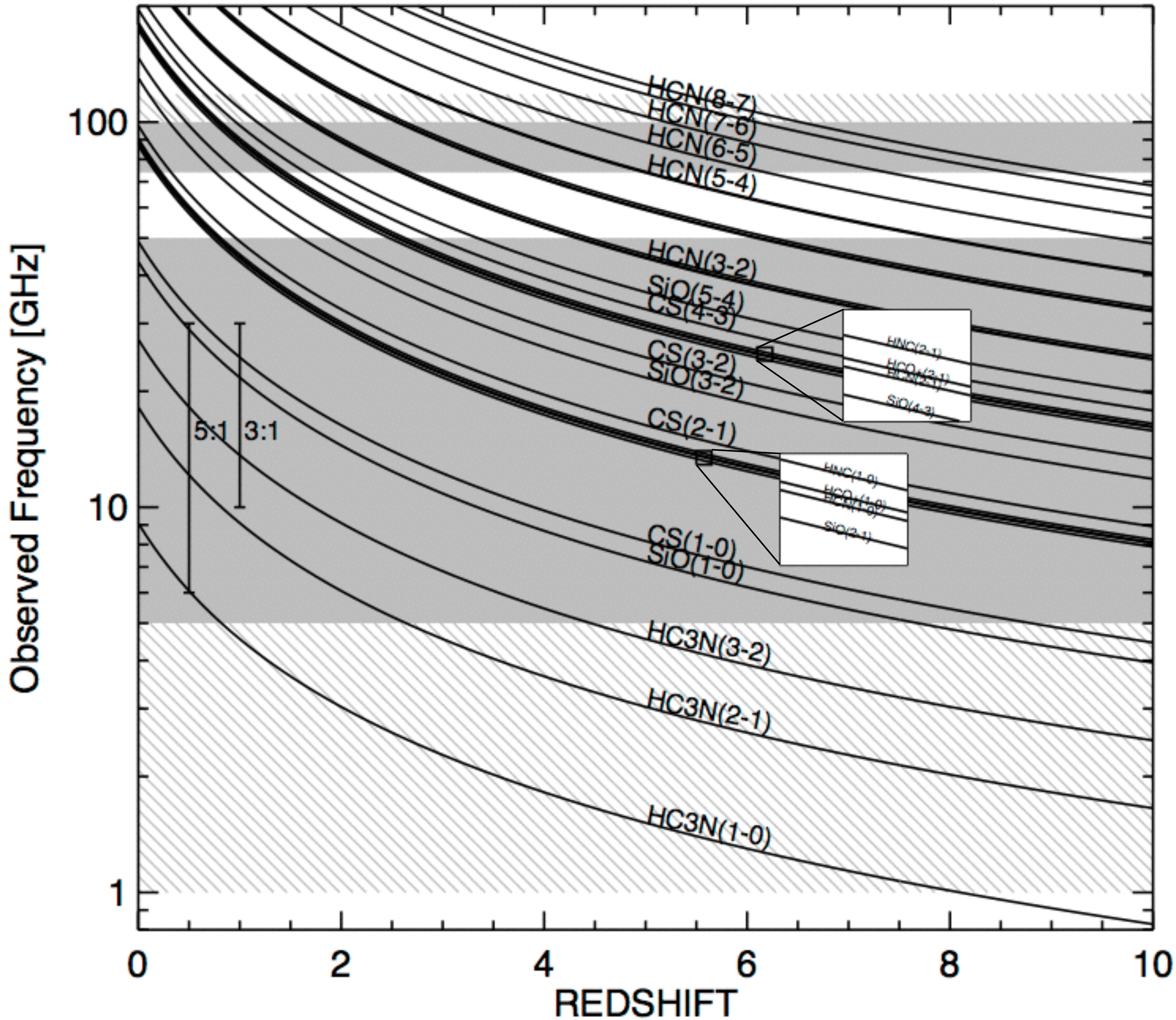
Is it critical to have 10xVLA?

Resolution:

Need sub-kpc (<100mas) resolution to study gas dynamics and nuclear gas disks at <30GHz

Do we need <10mas?


Example CO-line emission in z=5 galaxy
with SFR=30M_sun/yr
RMS reached after 1 hour, 300km/s resolution
with NGVLA core (5xVLA collecting area)
Current VLA
ALMA
NGVLA
NGVLA
CO(1-0)
CO(2-1)
CO(3-2)
CO(4-3)
CO(5-4)
Flux Density Sensitivity Limit (μJy)
Frequency (GHz)
0
50
100
150
0
20
40
60
80
100
120

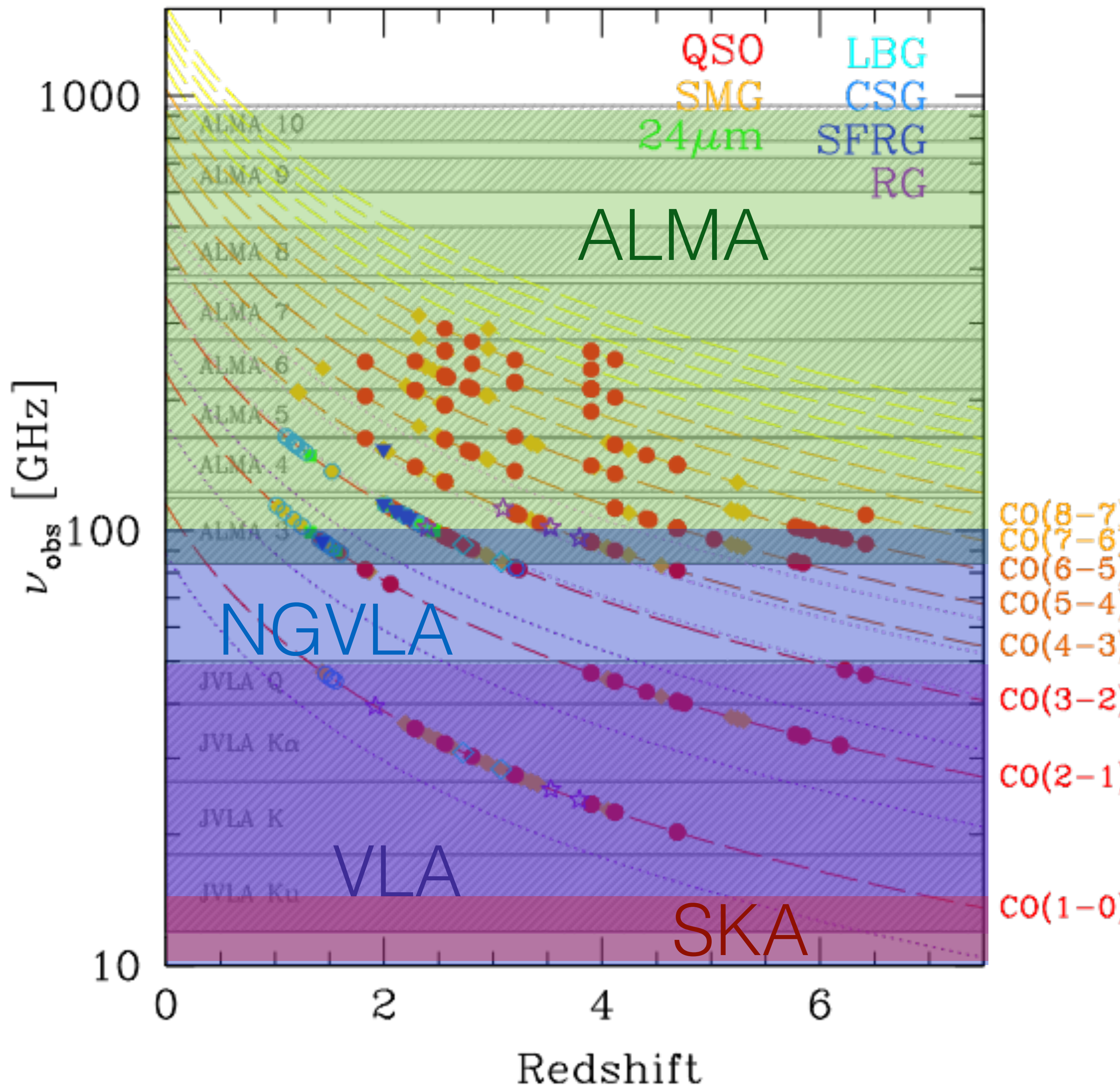


HCN(8-7)
HCN(7-6)
HCN(6-5)
HCN(5-4)
HCN(3-2)
SiO(5-4)
CS(4-3)
CS(3-2)
SiO(3-2)
CS(2-1)
CS(1-0)
SiO(1-0)
HC3N(3-2)
HC3N(2-1)
HC3N(1-0)
HNC(2-1)
HCO+(2-1)
SiO(4-3)
HNC(1-0)
HCO+(1-0)
SiO(2-1)
5:1
3:1
100
10
1
0
2
4
6
8
10
Observed Frequency [GHz]
REDSHIFT


GAS
GALAXY
STARS
dust
metals

Cold gas at high-z probed via CO. CO(1-0) used as proxy for H2: high-J only probes excited gas, not total gas mass in SF reservoir.

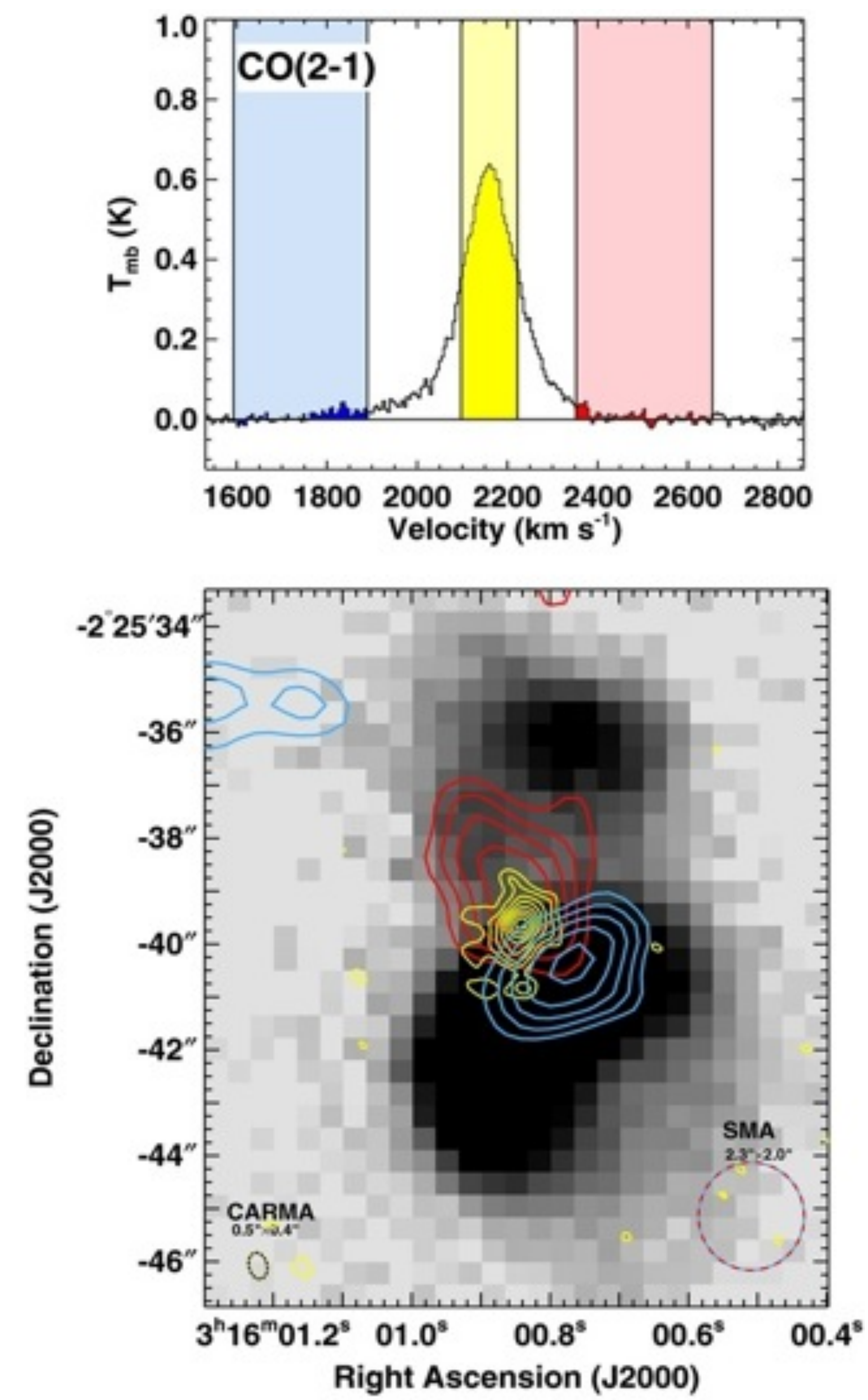
ALMA only probes high-J CO lines at high redshift! Incapable of measuring CO(1-0), even CO(2-1), CO(3-2).



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.

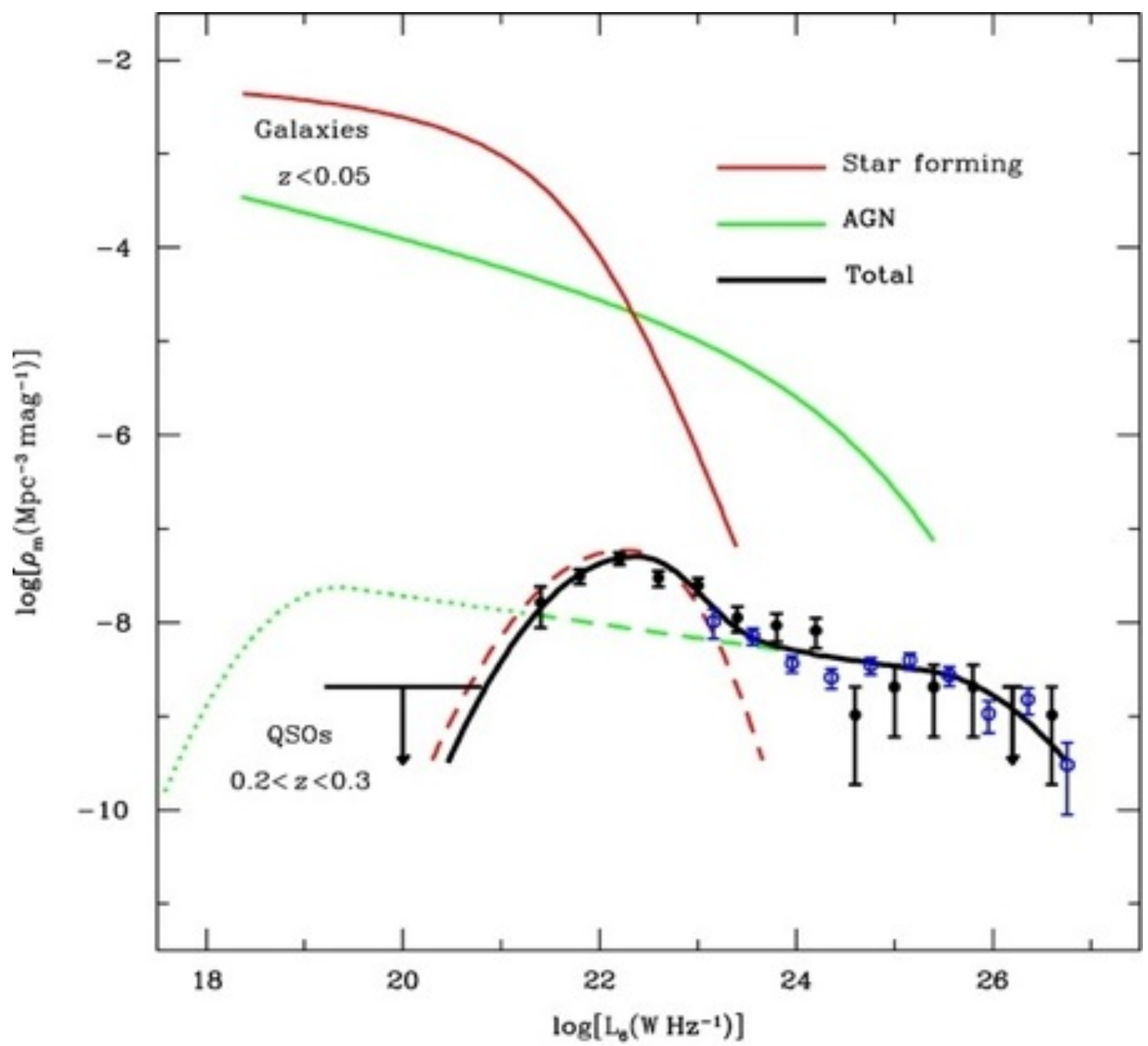


NGC1266: Alatalo et al. 2011, 2014 (CARMA/ALMA)

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