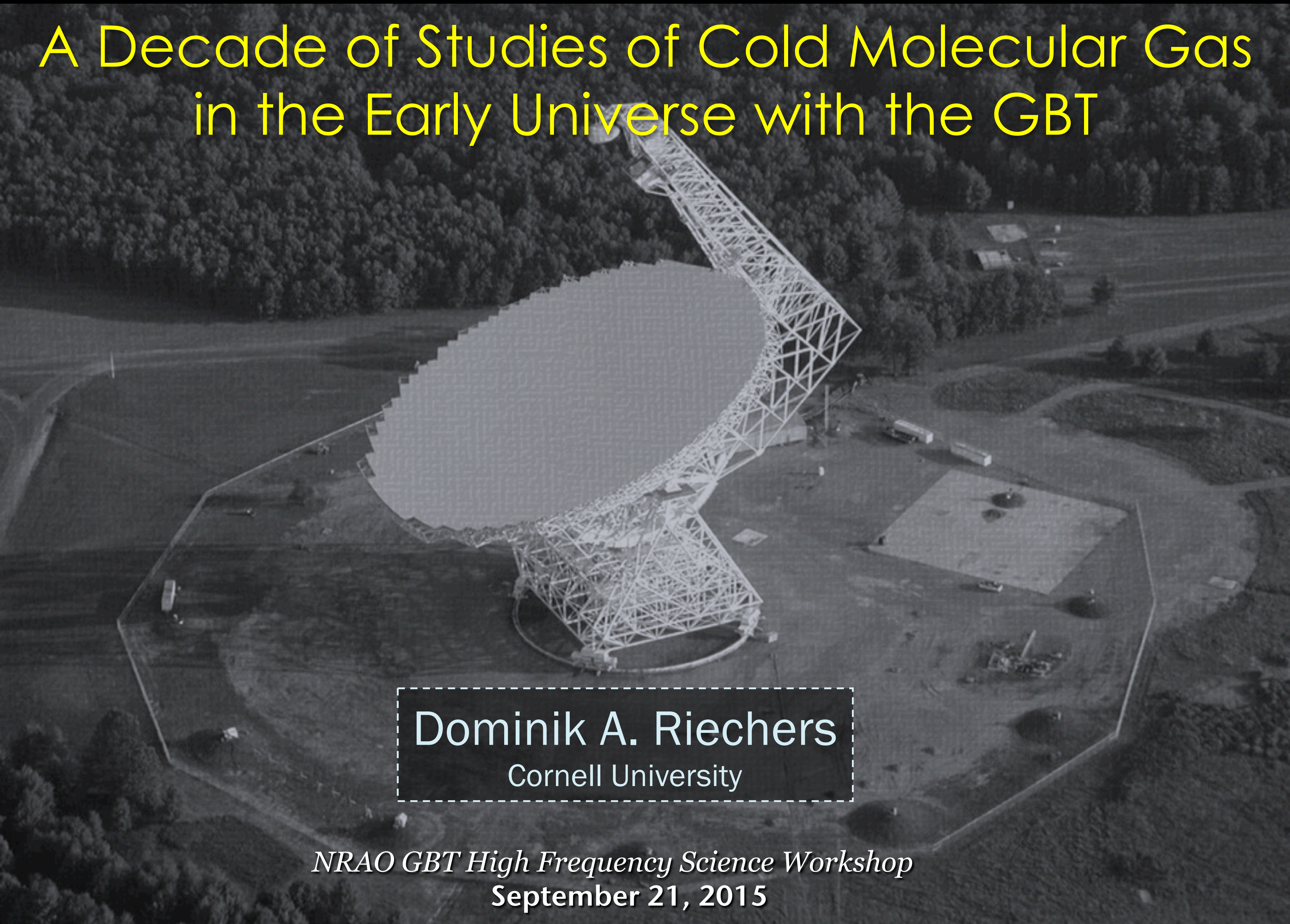
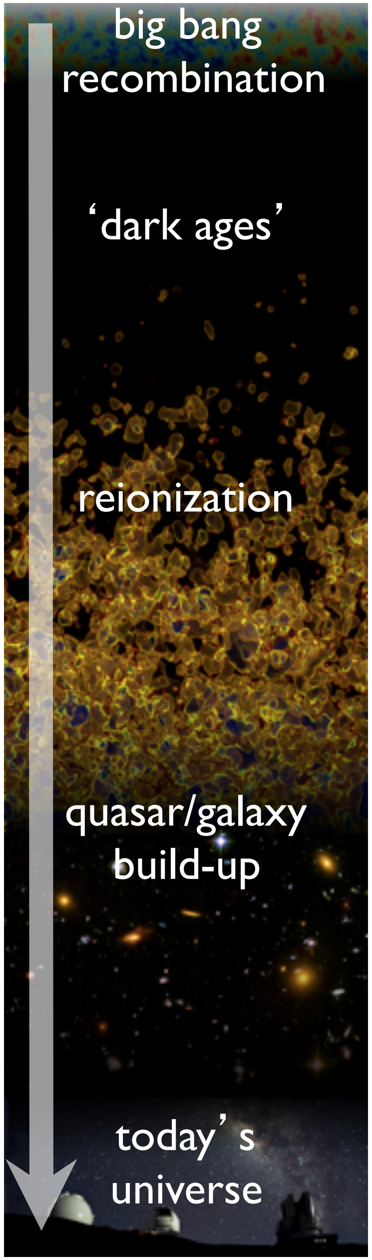


A Decade of Studies of Cold Molecular Gas in the Early Universe with the GBT

Dominik A. Riechers
Cornell University

NRAO GBT High Frequency Science Workshop
September 21, 2015

history of the universe



z~1000
0.0003 Gyr

z~15-1000
0.0003-0.3 Gyr

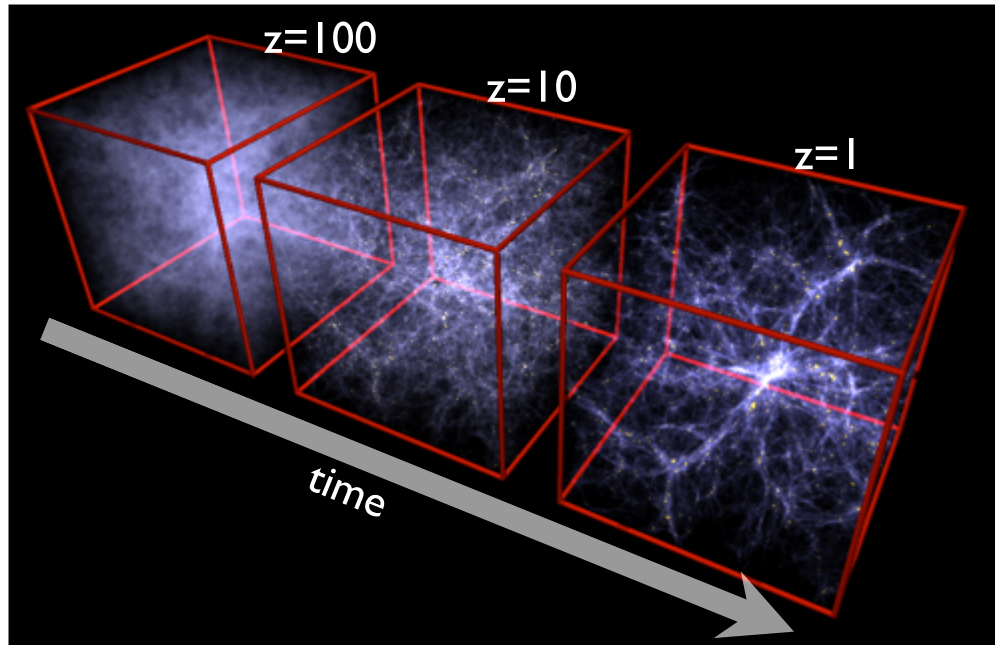
z~6-15
0.3-1 Gyr

z<~6
>1 Gyr

z~0
13.8 Gyr

theoretical framework

Hydrodynamical simulations of cosmic structure formation



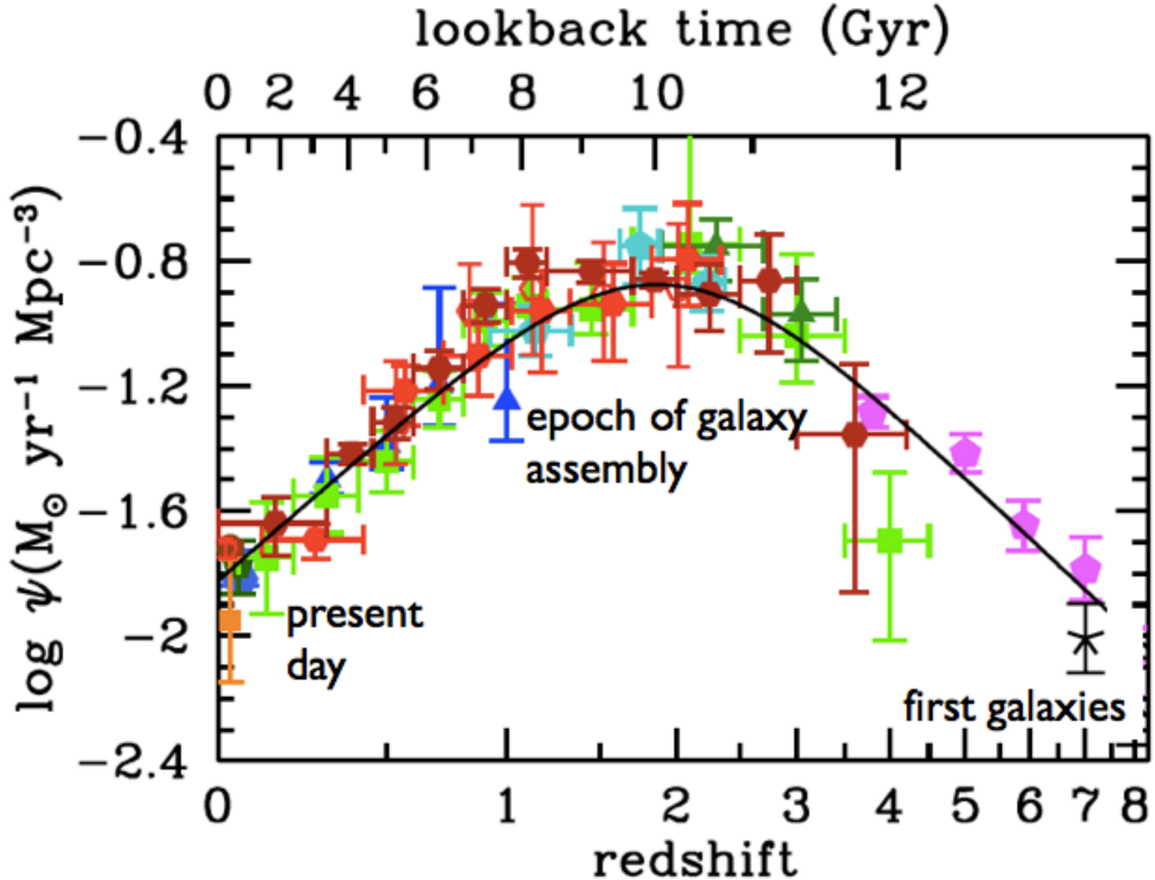
e.g. GADGET, AREPO, Springel et al.

Galaxy growth through gas accretion and mergers...

...but the *gas supply/conversion* is largely unconstrained observationally at high redshift

cosmic star formation

Volume density of star formation in galaxies as f(cosmic time)

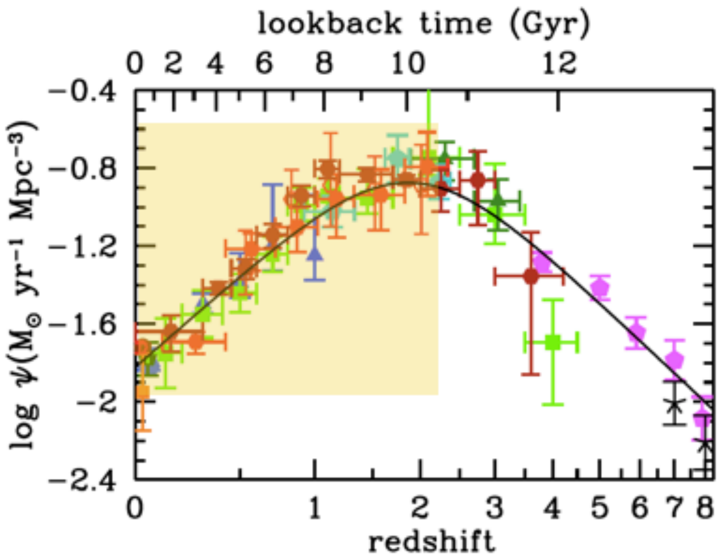


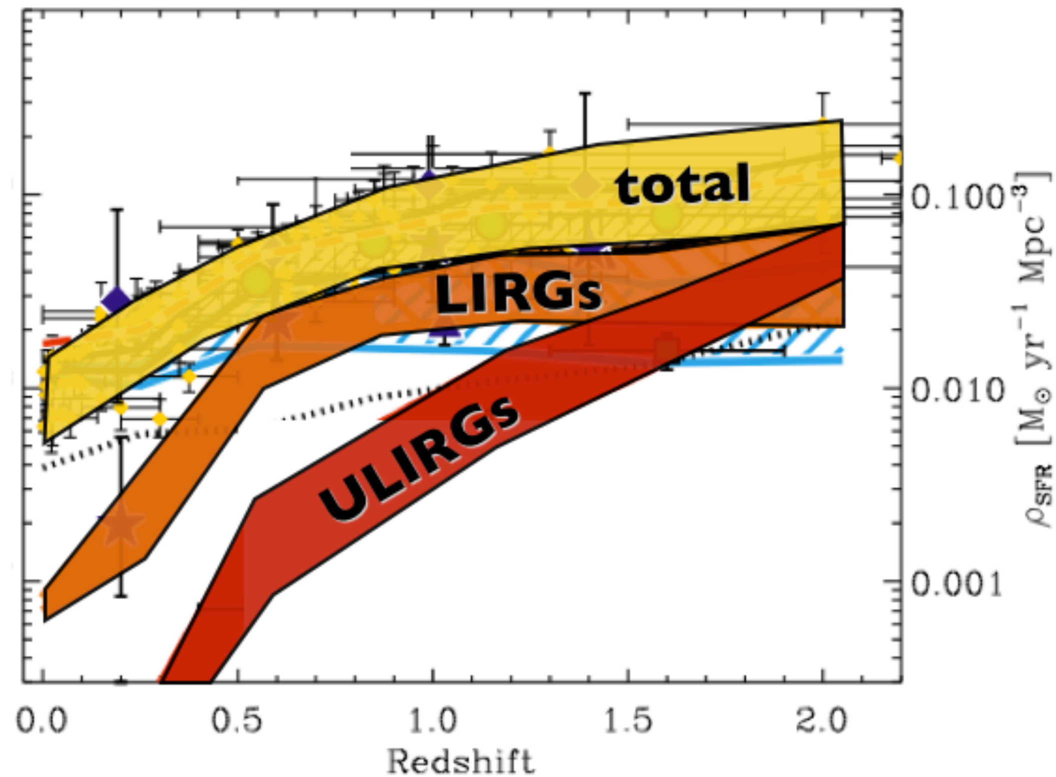
Madau & Dickinson, ARA&A 2014

early work: Madau et al. 1998, Steidel et al. 1999

cosmic star formation

Contributors to cosmic star formation density



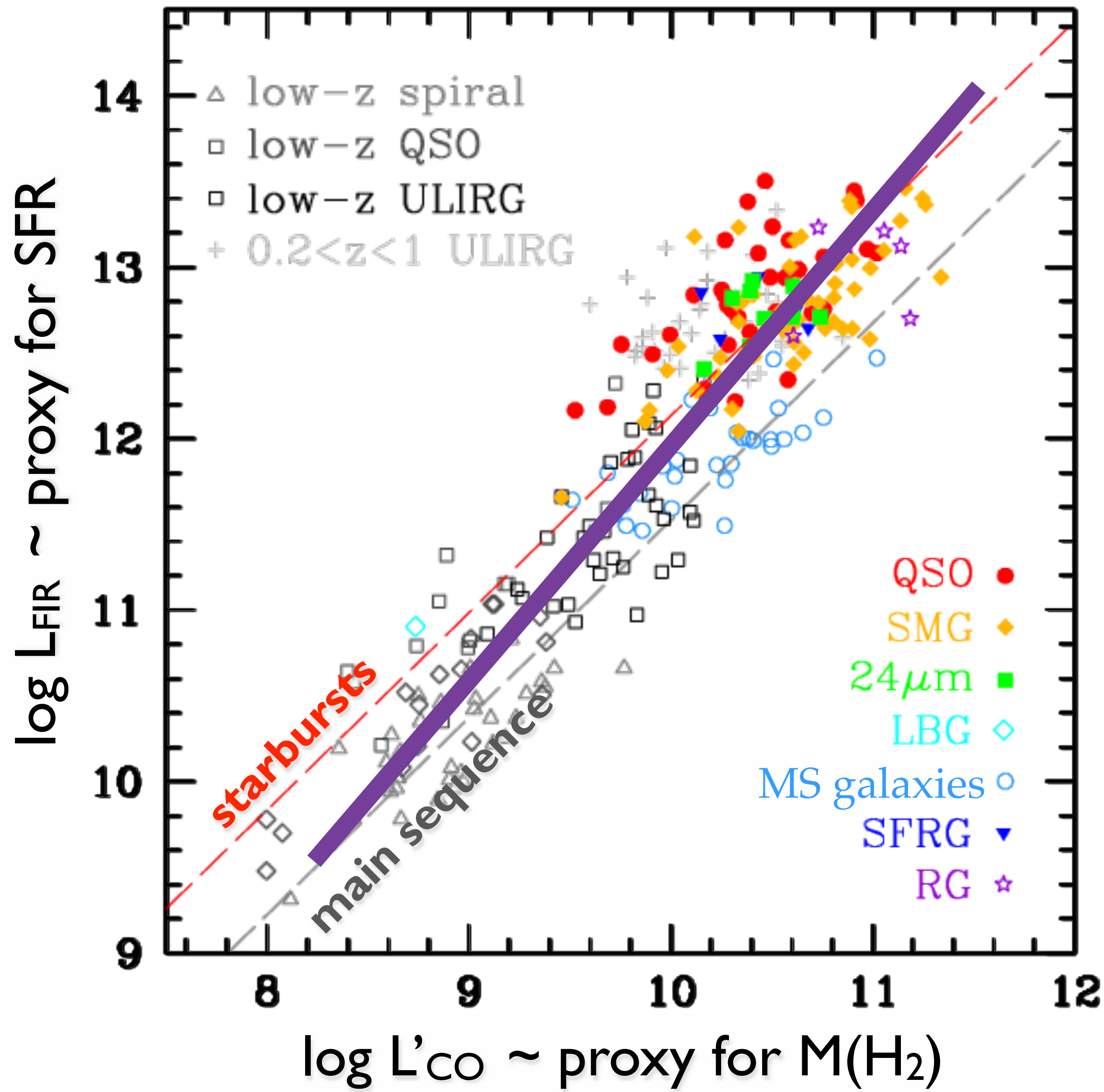


adapted from Magnelli et al. 2013

ULIRGs (L_{IR}>10^{12} L_{sun}, SFR >100 M_{sun} yr^{-1}:) **- negligible contributor at z=0.**

- main contributor at z=2.

Kennicutt-Schmidt Relation: The ISM drives Star Formation



Simplest Version of "Star Formation Law": Spatially Integrated Observables

L'_{CO} vs. L_{FIR}

as a surrogate for

M_{gas} vs. SFR

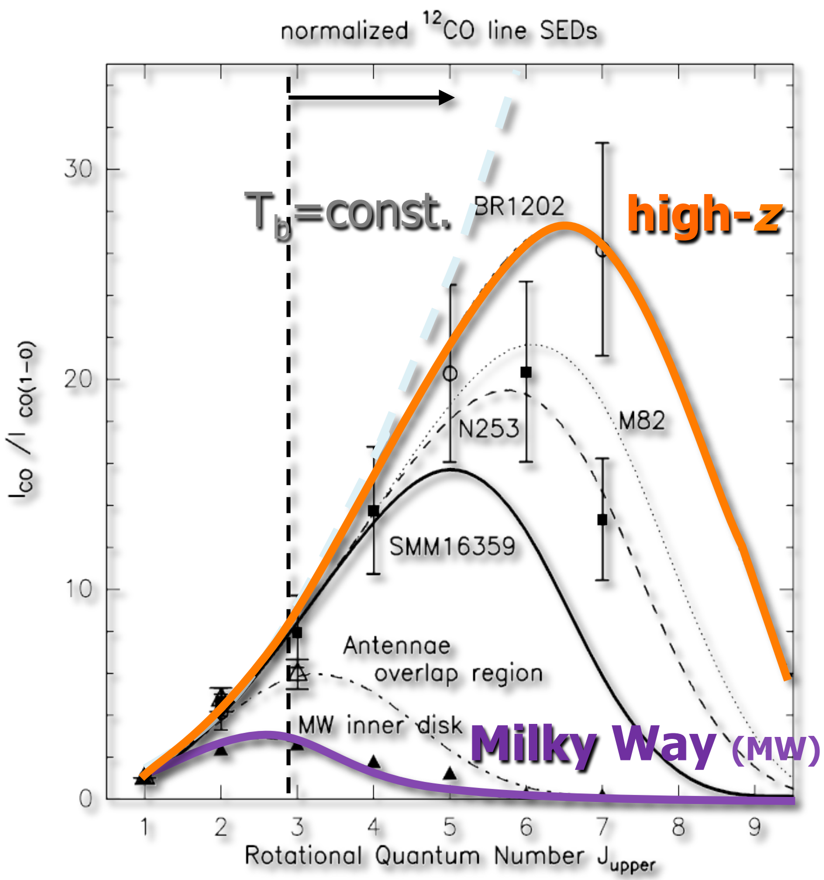
One super-linear relation or
Two sequences (*quiescent/starburst*)
Bimodal or running *conversion factor*

…many subtleties, but:
High-z galaxies higher on *both* axes
Quiescent *and* Starburst Galaxies

→ High-z galaxies have more gas!

Carilli & Walter 2013 ARAA; after Daddi et al. 2010, Genzel et al. 2010

Star Formation Law at High Redshift: Biases (or: Hidden Physics)



- Typically observed at

  - z=0: CO(1-0)

  - high-z: CO(3-2) and higher

    Same observing bands (typ. 3mm)

Caveat:

- CO(3-2) obs may miss Milky Way-like, cold, low-excitation gas component

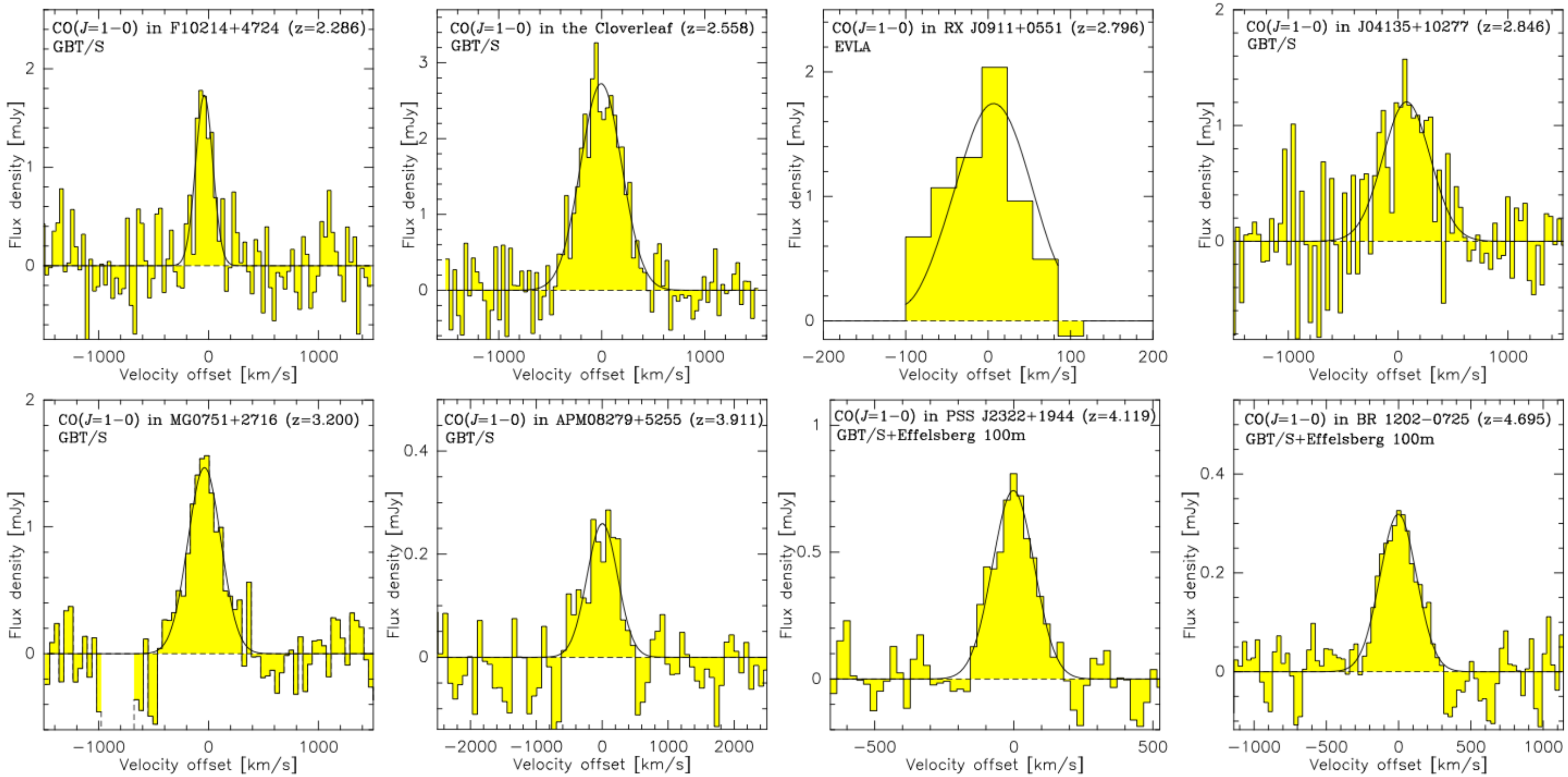
- only CO(1-0) traces full $M(H_2)$

$\Rightarrow$ need to observe CO(1-0) also at high z

<u>but:</u> requires to go to 'classical' radio frequencies

Weiss et al. 2005; Riechers et al. 2006a

Total Molecular Gas Masses: GBT CO(1-0) Spectroscopy in z>2 Quasars



First Detailed CO(1-0) Spectroscopy of z=2-5 Quasar Hosts:

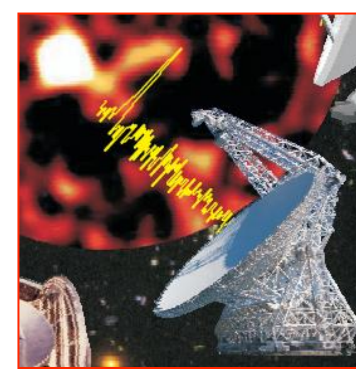
- **Typically few kpc size gas reservoirs**
- **M_{gas} = 4 x 10^{10} M_{sun}**

Brightness temperature ratio:

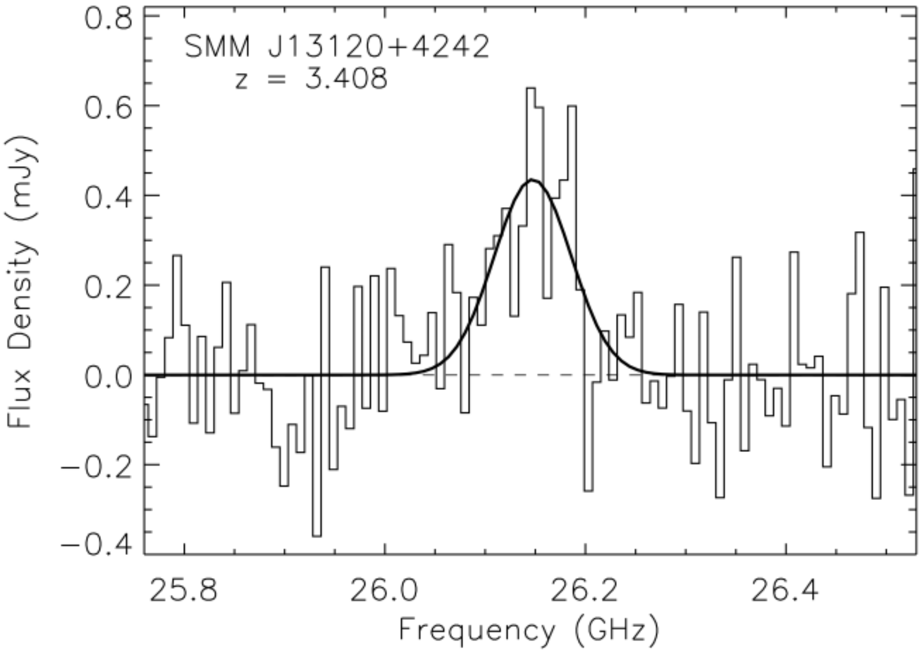
$r_{3-2/1-0}$=1.04±0.03

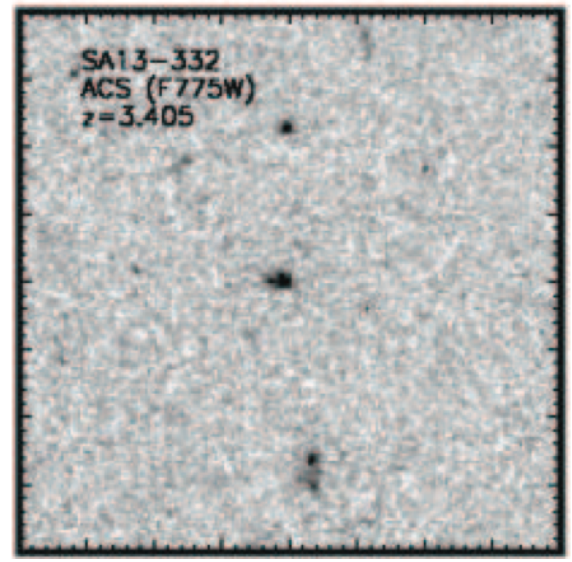
⇒ z>2 Quasars consistently show compact CO(1-0) & high gas excitation

Riechers et al. (2006a, 2011f)



GBT CO(1-0) Spectroscopy of Submillimeter Galaxies





First CO(1-0) Measurement of a Submillimeter Galaxy:

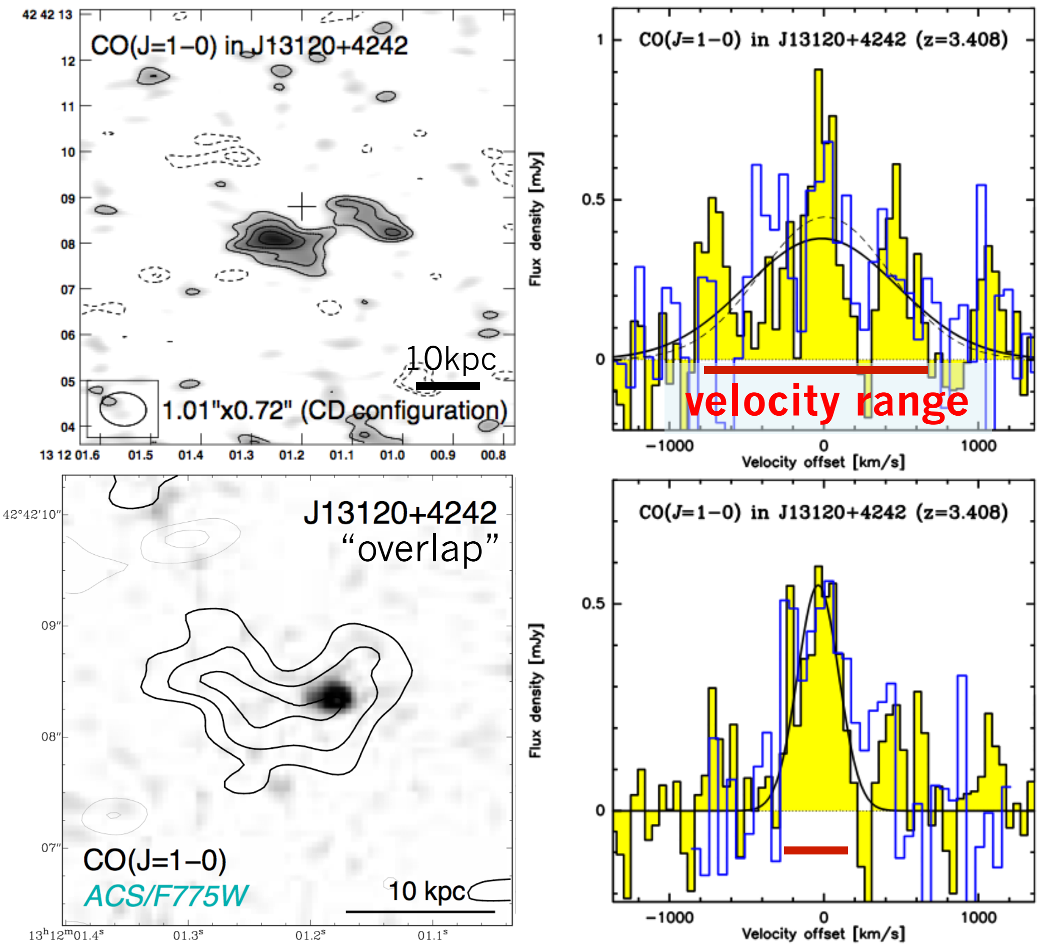
- unusually broad line profile: line FWHM of 1040 km/s
- inferred molecular gas mass: 1.6 x 10^{11} M_{sun}

→ 4x higher than estimated based on CO(4-3)

HST image shows only a single, compact source…but this is a very dusty galaxy.

Hainline et al. (2006)

Karl G. Jansky VLA Reveals an Extended, Advanced Stage Merger



Total CO(1-0) Emission

Extended tidal structure
multi-peaked line profile
full single-dish flux (blue)

"Nuclear" CO(1-0) Emission

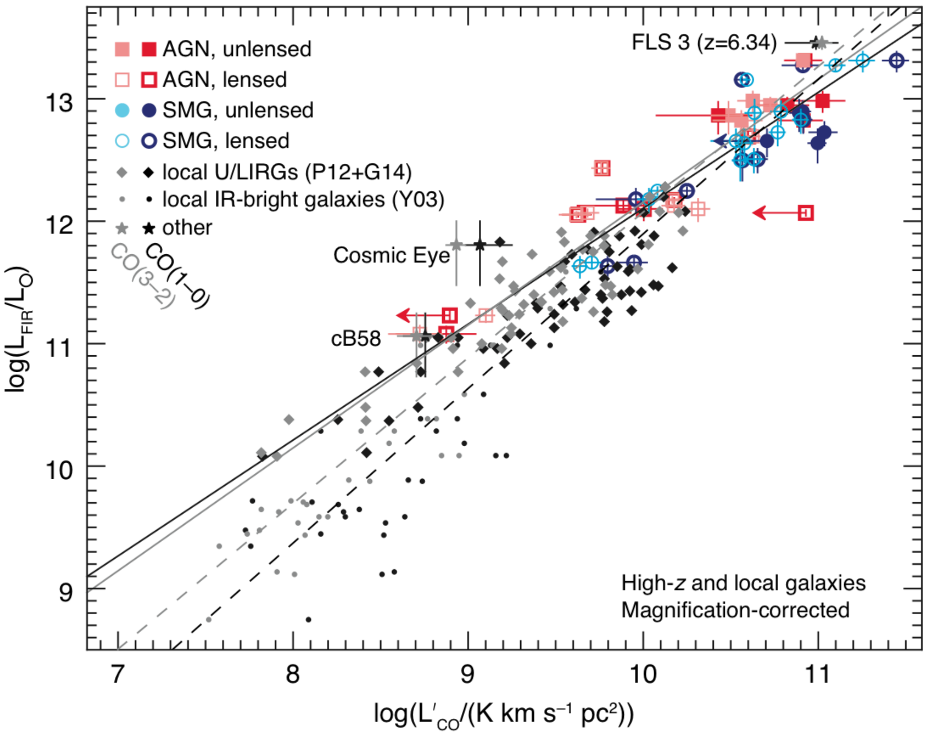
>10kpc structure ("overlap"?)
optical emission peaks off-center
single-peaked line profile,
similar to high-J CO lines (blue)

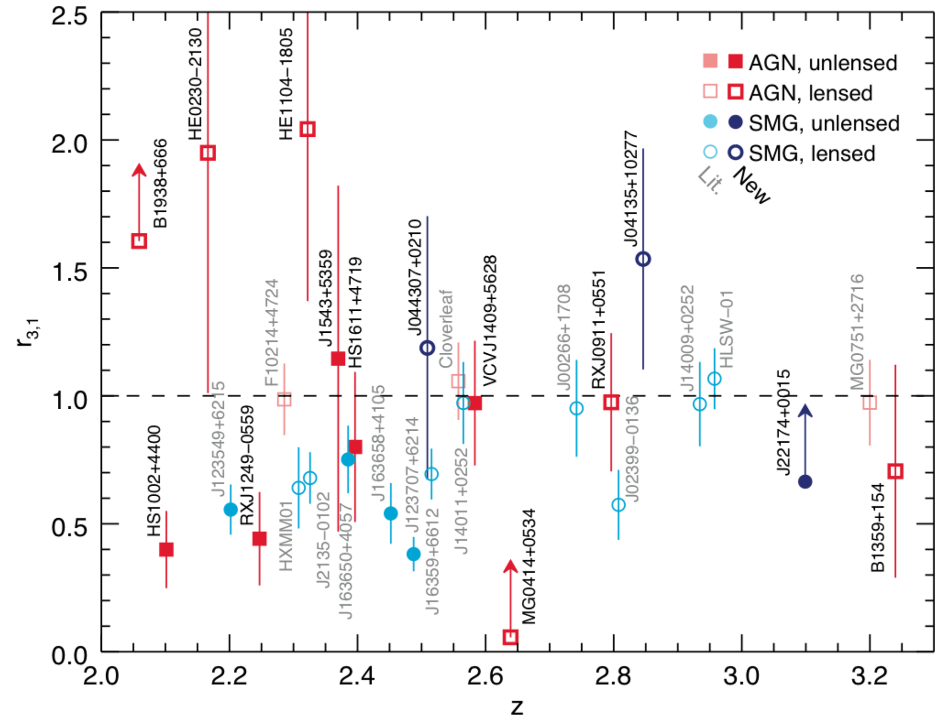
Brightness temperature ratio:
$r_{3-2/1-0}$=0.55±0.05

⇒ z>2-4 SMGs show complex, extended, low-excitation gas reservoirs
(in addition to highly-excited starburst components)

Riechers et al. (2011e)

Gas Excitation & CO Line Ratios vs. Star Formation Law





Given differences in excitation conditions between different populations, gas excitation may alter the slope & normalization of the star formation law.

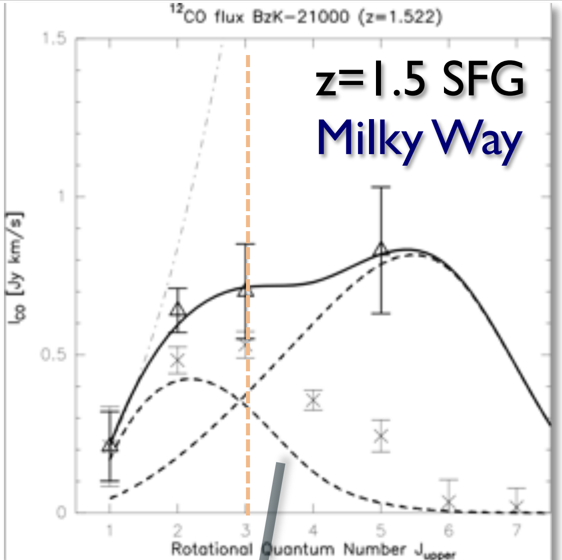
Problem: most past measurements at high-z were carried out in J>3 excited states of CO.

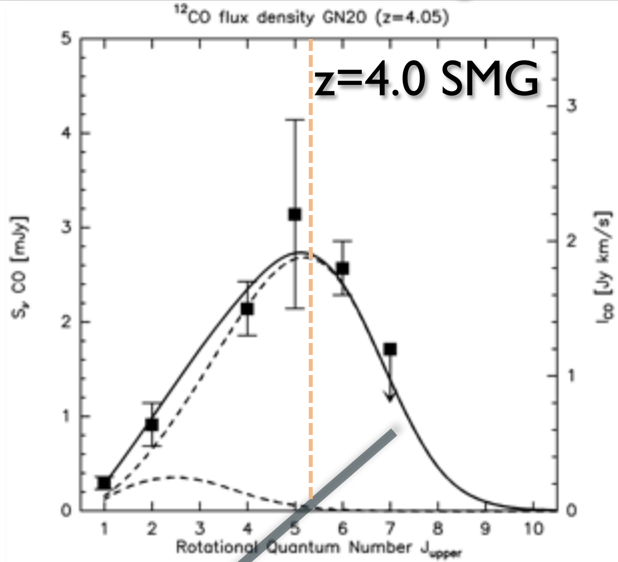
Solution: do it the hard way with GBT+VLA by detecting CO(J=1-0)

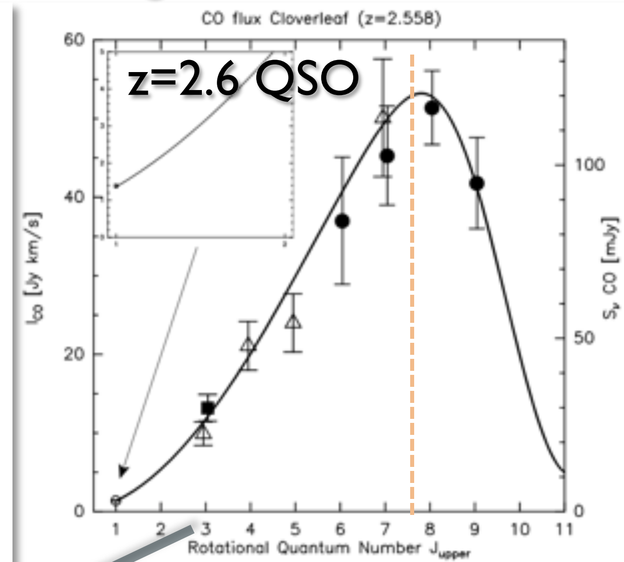
Here: comparison of J=1 vs. J=3 based SF law based on observed r_{31} line ratio

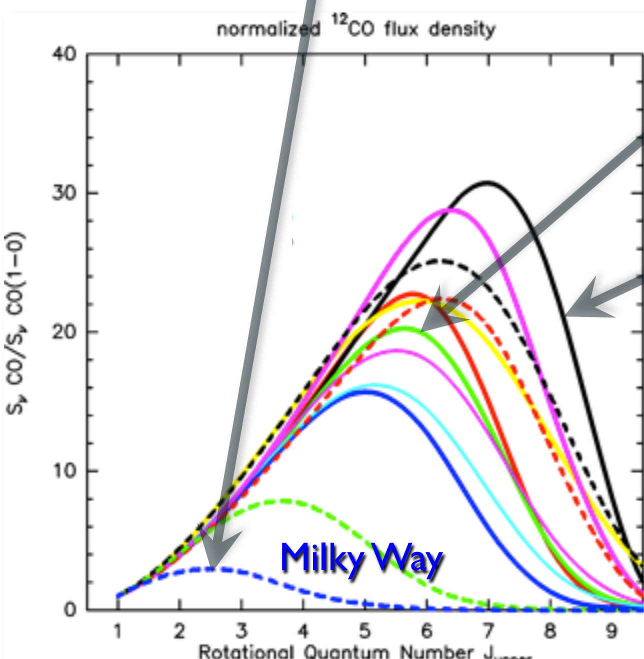
Sharon, Riechers et al. 2015

AGN vs. Starbursts vs. "Normal" Star-Forming Galaxies: High-Excitation Gas









CO Excitation Line Ladders:

(1) low, "Milky-Way-like" CO excitation

T_{kin} ~ 10-20K , n_{gas} ~ 300 cm^{-3} (GMCs)

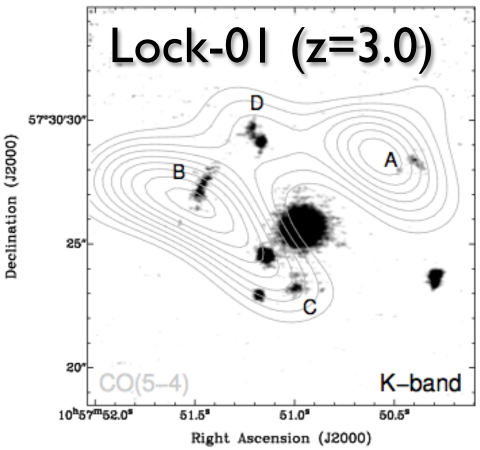
(2) high, "ULIRG-like" CO excitation

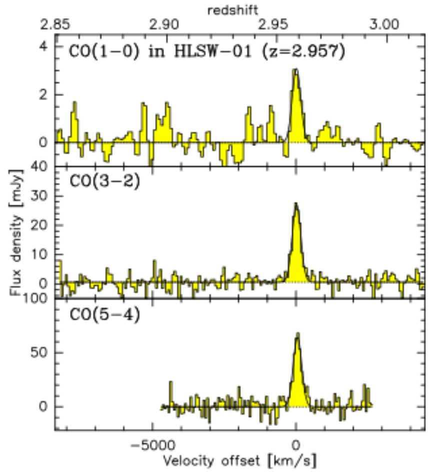
T_{kin} ~ 40-60K , n_{gas} ~ 3x10^4 cm^{-3}

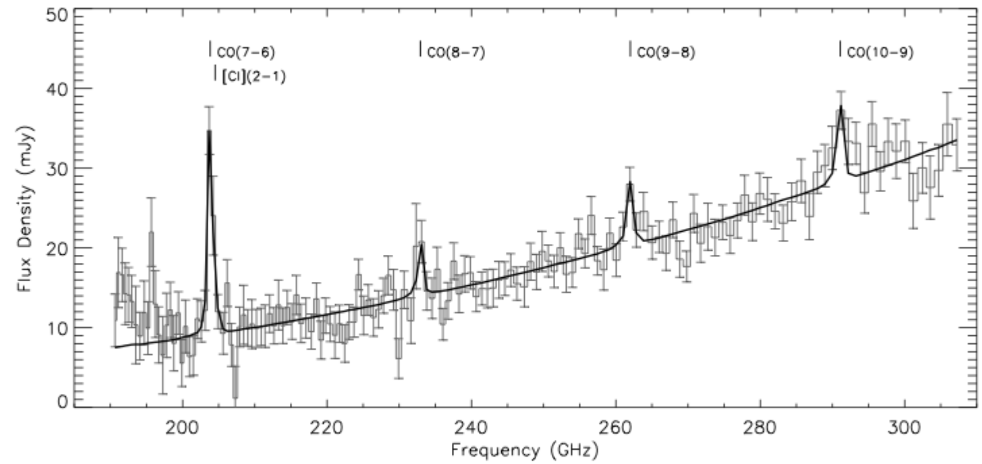
- SFGs: strong MW-like, some ULIRG-like
- SMGs: some MW-like, strong ULIRG-like
- QSOs: ULIRG-like & higher

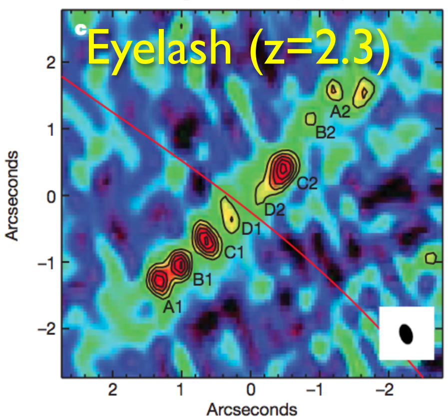
Riechers ea. 2006b, 2009b, 2011a, Weiss ea. 2007
Dannerbauer ea. 2009, Carilli ea. 2010, Daddi et al. 2015

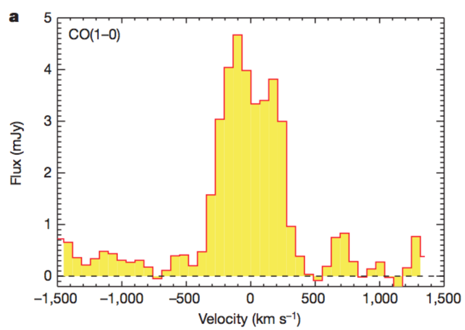
“Blind” CO Spectroscopy of Strongly-Lensed Dusty Starbursts

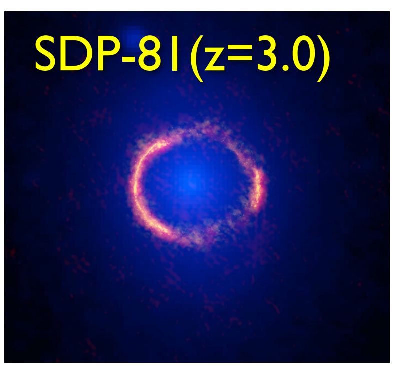


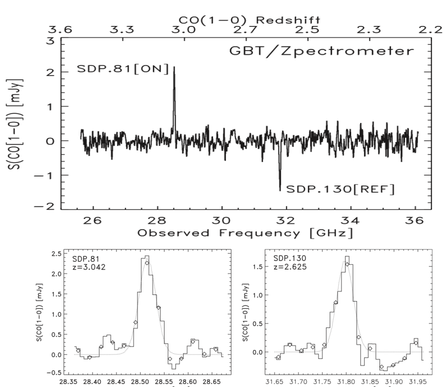












GBT+Zpectrometer CO(J=1-0) observations:

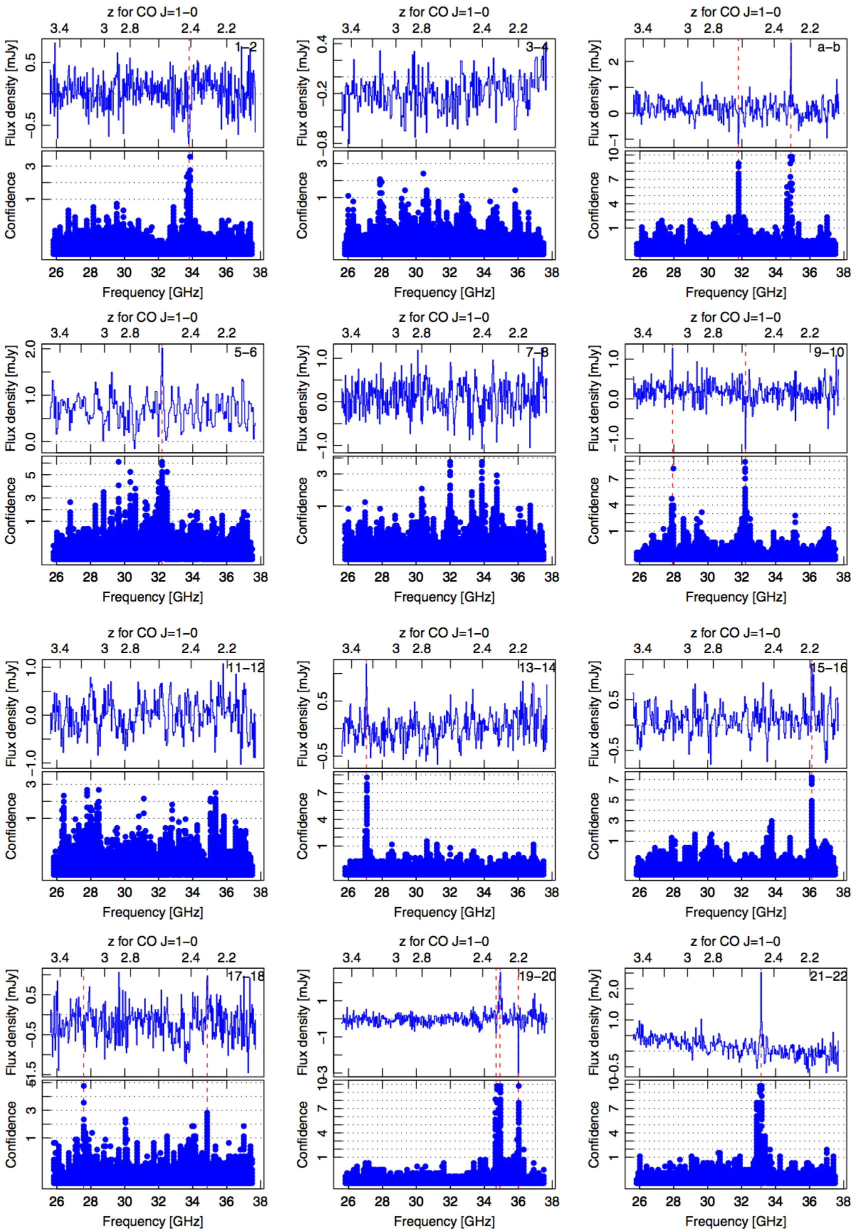
A few now-famous examples of the brightest, strongly-lensed dusty starbursts at z=2-3.

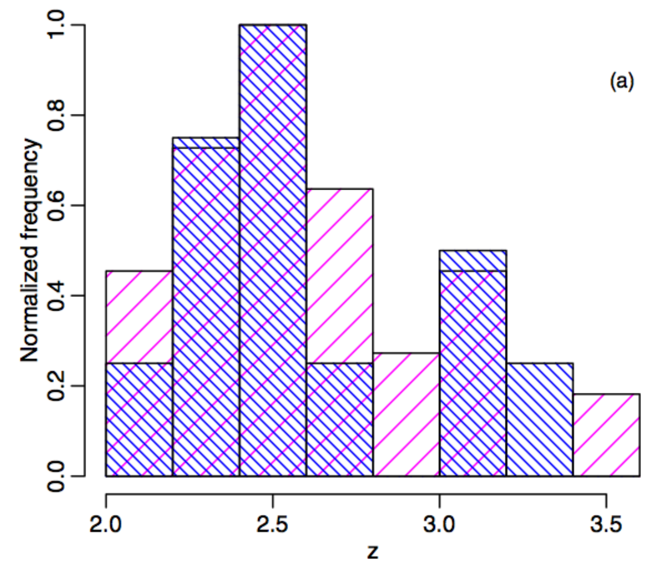
GBT measurements provide redshifts, overall line shapes, and total gas masses.

Follow-up interferometry with the VLA, ALMA, NOEMA, CARMA, SMA reveal detailed lensing structure and intrinsic morphology, dynamics, and excitation of the gas.

Swinbank et al. 2010; Frayer et al. 2011; Riechers et al. 2011; Scott et al. 2011

GBT+Zpectrometer: CO(J=1-0) Redshift Distribution of 350 μm Peakers





GBT+Zpectrometer CO(J=1-0) observations of 24 Herschel/SPIRE 350 μm-selected SMGs:

- 11 detections (all z confirmed in *J*=3/4 lines w/ CARMA; Riechers et al., in prep.)

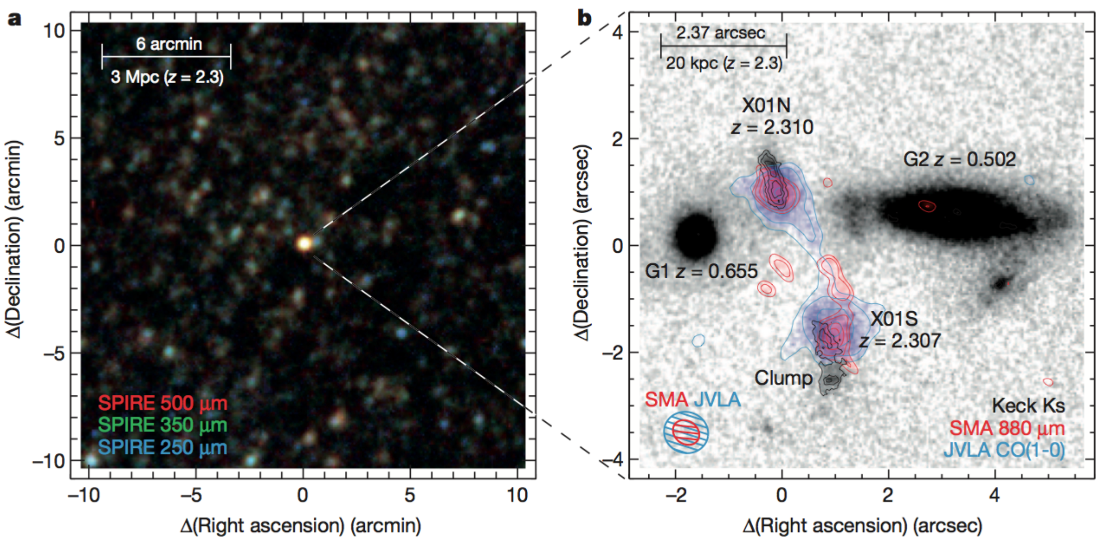
- T_{dust} ~ 34 K
- μ_L ~ 3-20
- Intrinsic M_{gas} ~ 3 x 10^{10} M_{sun}

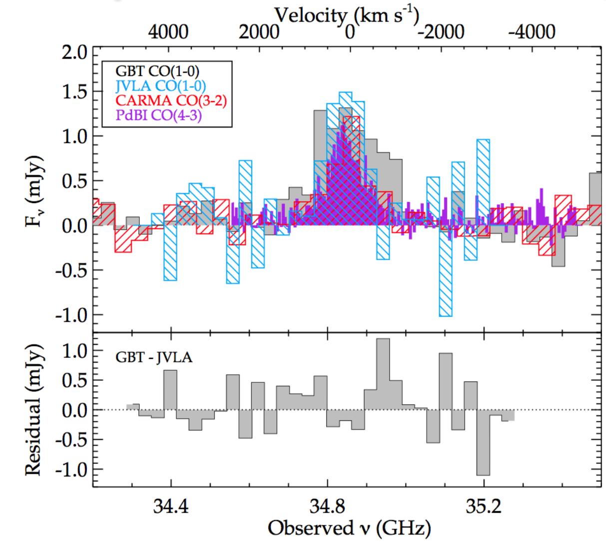
- Redshift distribution peaks a t z~2.5

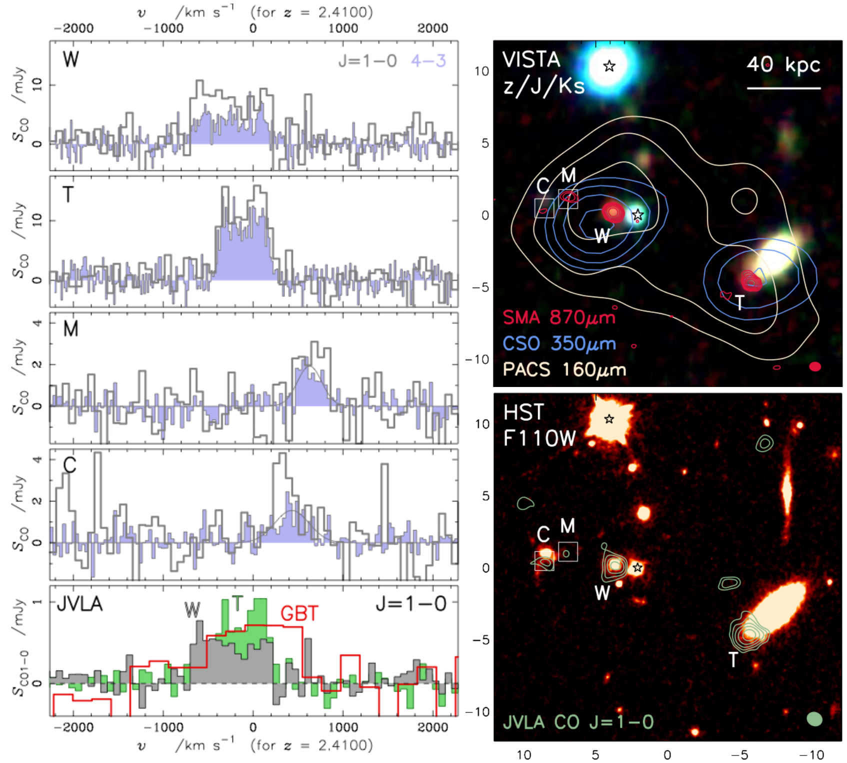
⇒ consistent with 850 μm-selected populations

Harris et al. 2012

Hyper-LIRGs: Total Gas Masses in Complex Group-Scale Gas-Rich Mergers







GBT+Zpectrometer CO(J=1-0) observations of some bright Herschel reveal broad line profiles.

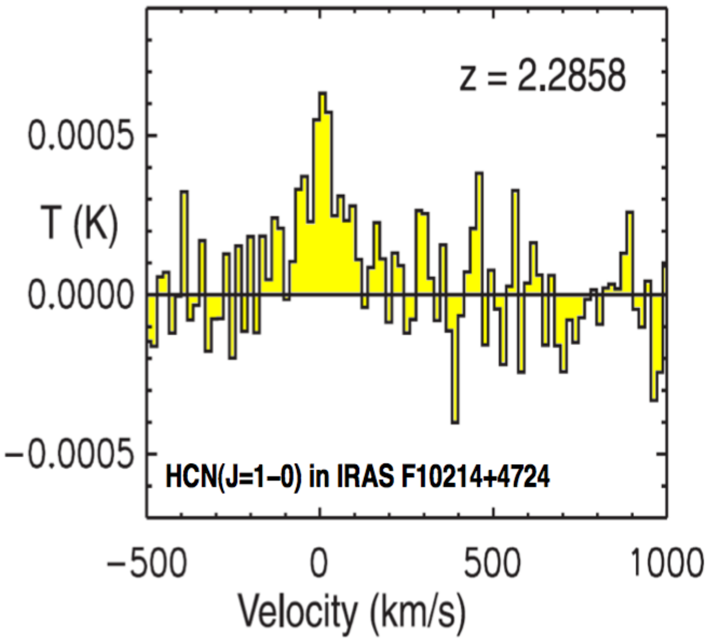
VLA follow-up: not strong lenses, but groups of very massive, gas-rich, high star formation rate (>5000 M_{sun}/yr total) galaxies at z=2-3.

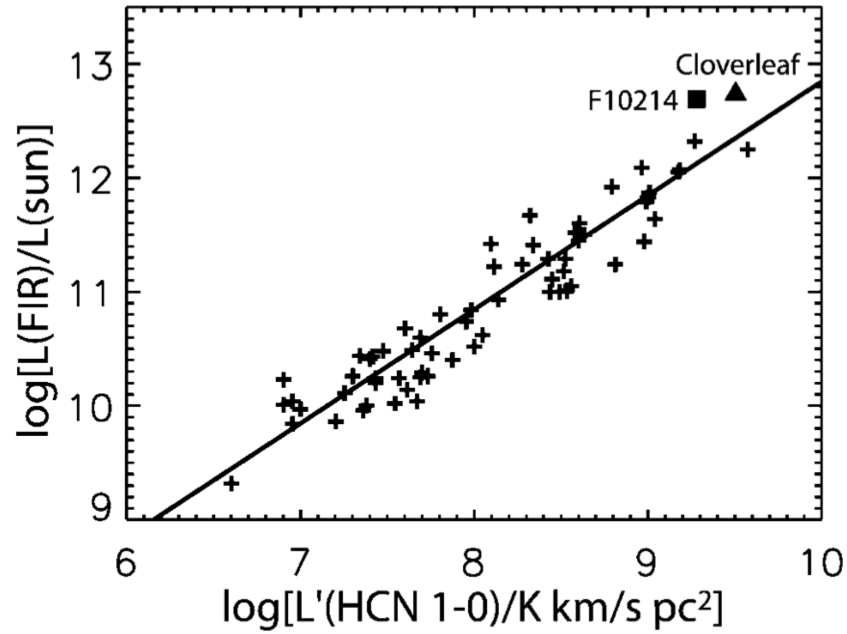
Total VLA CO emission detected sometimes less than GBT single-dish flux → need GBT zero spacings to recover the full amount of gas.

⇒ critical combination of GBT+VLA capabilities

Fu et al. 2013; Ivison et al. 2013

Dense, Actively Star-forming Gas at High Redshift





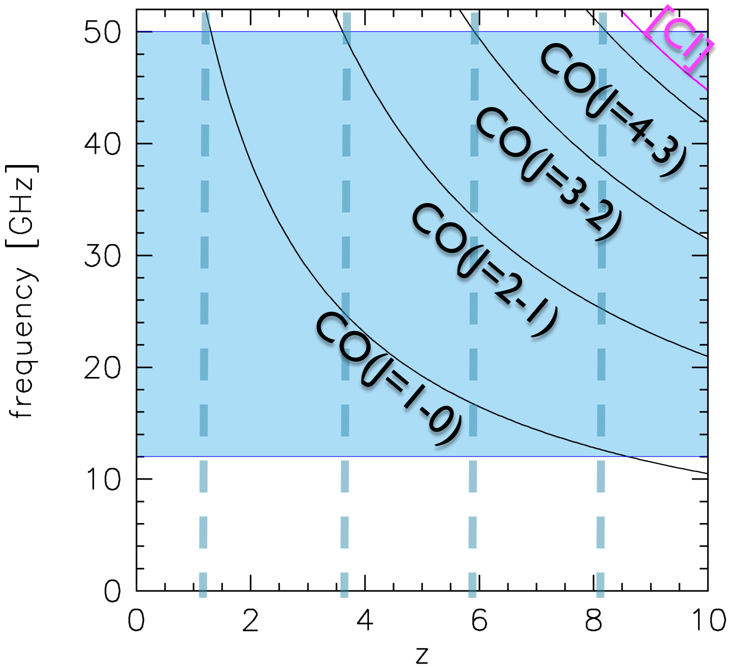
CO is a good tracer of the total amount of molecular gas in galaxies, but not a specific tracer of cold, dense star-forming cores → use high (>10^{4-5} cm^{-3}) critical density tracers

Most common tracer of dense gas in the nearby universe: HCN

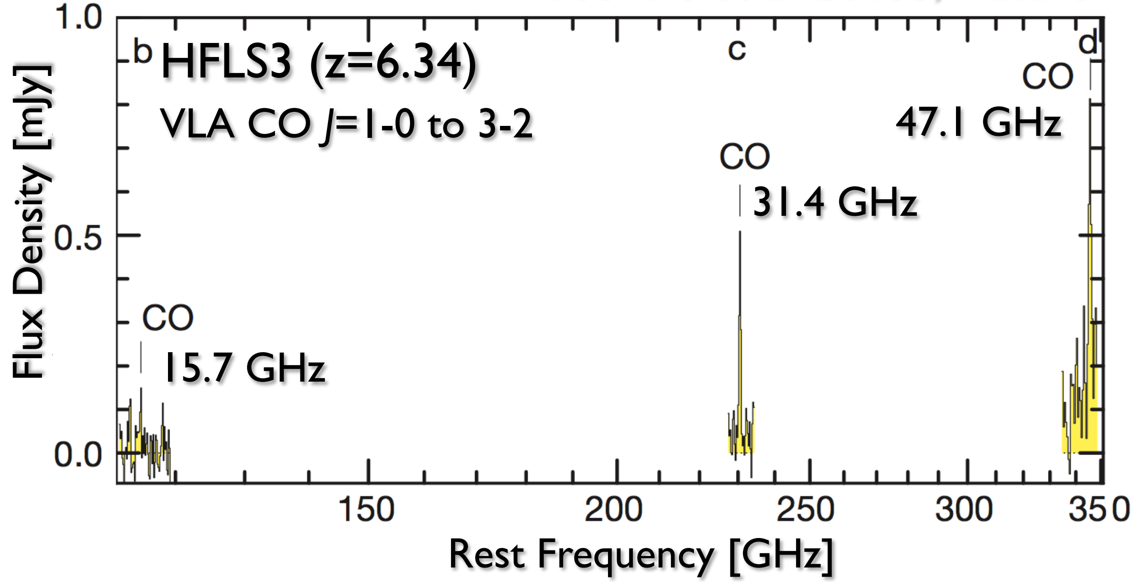
→ Detected in >100 galaxies in the nearby universe, but only 3 solid (+3 tentative) detections at z>1
→ Second detection: HCN(1-0) in IRAS F10214 at z=2.3
→ To first order, high-z galaxies follow linear HCN-FIR "dense gas-star formation" relation (but there may be an excess in L_{FIR} at the highest luminosities)

Vanden Bout et al. 2004

Future Instrumentation?



Riechers et al. 2013b, Nature



GBT has large collecting area (~65% VLA); with stable spectrometer, can stay competitive in the age of the fully upgraded Karl G. Jansky VLA. Where to go next?

- Multiple (>5-10) beams on the sky? Utility perhaps limited by FoV/target density.
- Array receivers? Tomographic mapping of CO, but perhaps more suitable for smaller dish (2'-5' resolution instead of ~20"; scale of proto-groups/proto-clusters at z>1.5)
- Ultra-large bandwidth receivers? Synergy with NGVLA development, perhaps ideal.
- 12-50 GHz instantaneous covers:

  CO(1-0) at z=1.3-8.6 *[+HCN, HCO^+, HNC, H_2O, CN, CS,…]*

  CO(2-1) at z=3.6-18.2

  CO(3-2) at z=5.9-27.8

⇒ great "redshift machine", multiple lines at z>3.6; would be competitive until full NGVLA

Summary

- cold molecular gas:
  - fundamental driver of star formation through cosmic times
  - galaxies at z=1-3 have 10x – 30x higher SFR than today
  - underlying reason: an order of magnitude higher gas fractions
- GBT played a crucial role in measuring cold gas properties at high z:
  - first CO(J=1-0) spectroscopy at z=2-5

  → total molecular gas masses, gas excitation, high-z star formation law
  - GBT+Zpectrometer: "redshift machine" for luminous dusty galaxies
  - in concert with VLA, measure full gas distribution of groups/clusters
- a future role for the GBT in cold gas studies in the early universe
  - "zero spacings" for VLA in crowded environments w/ diffuse gas
  - ultra-wide bandwidth CO spectroscopy: synergy w/ NGVLA
  - measure suite of dense gas tracers at same time in deep spectra