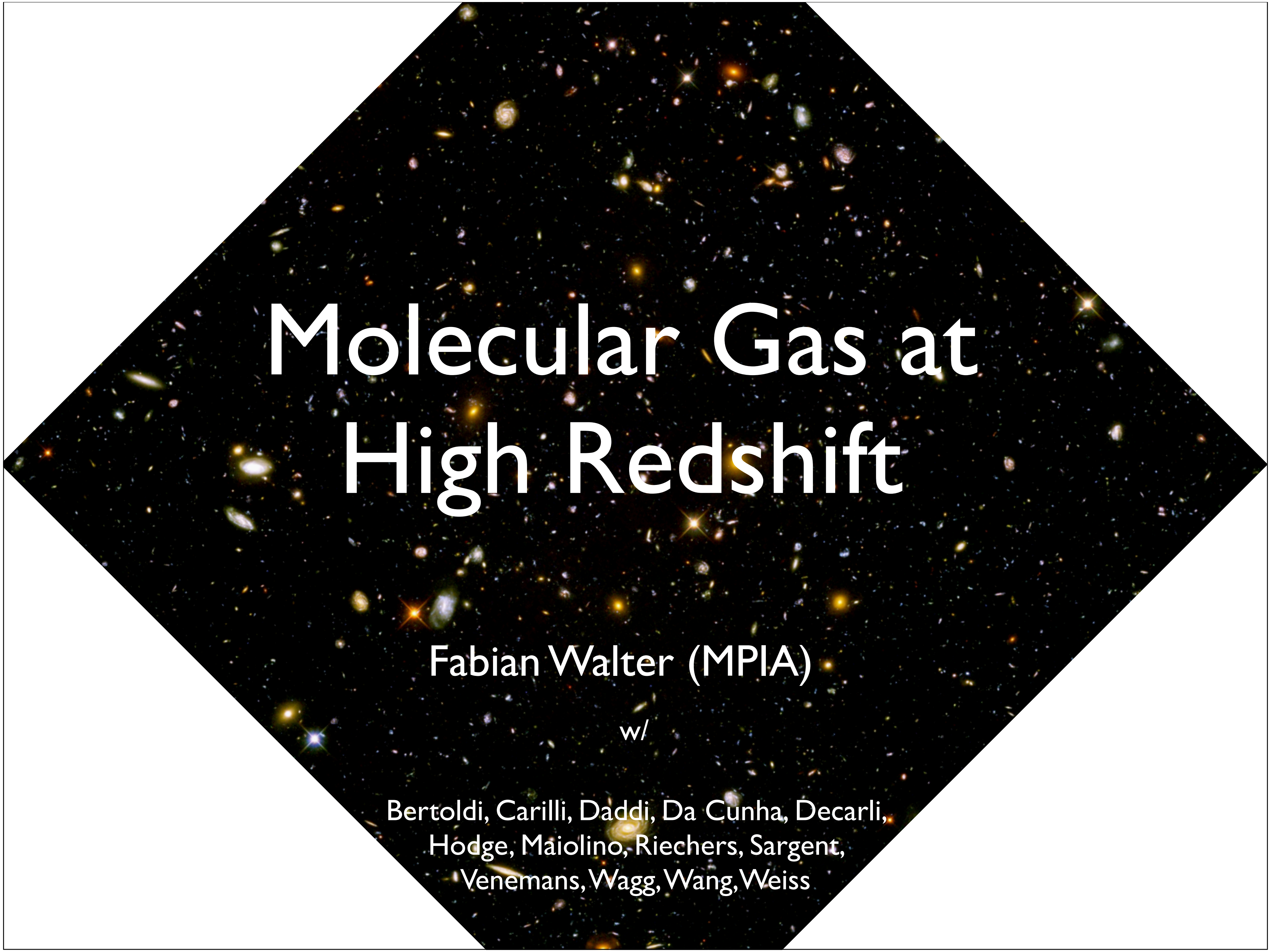


Molecular Gas at High Redshift

Fabian Walter (MPIA)

w/

Bertoldi, Carilli, Daddi, Da Cunha, Decarli, Hodge, Maiolino, Riechers, Sargent, Venemans, Wagg, Wang, Weiss

history of the universe

z~1000
0.0003 Gyr

z~15-1000
0.0003-0.3 Gyr

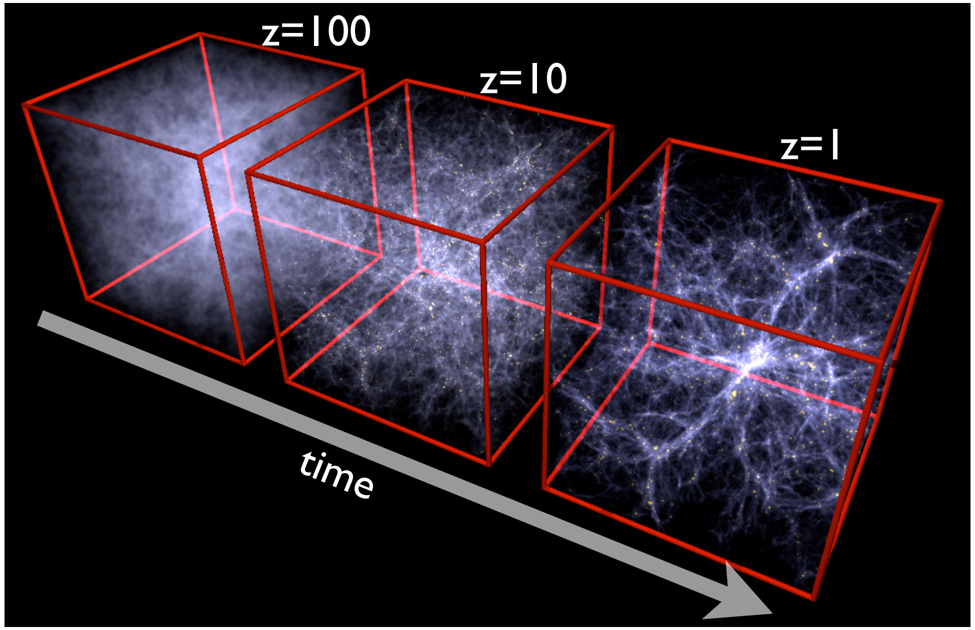
z~8-15
0.3-1 Gyr

z<~8
>1 Gyr

z~0
14.3 Gyr

theoretical framework

Hydrodynamical simulations of cosmological structure formation



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

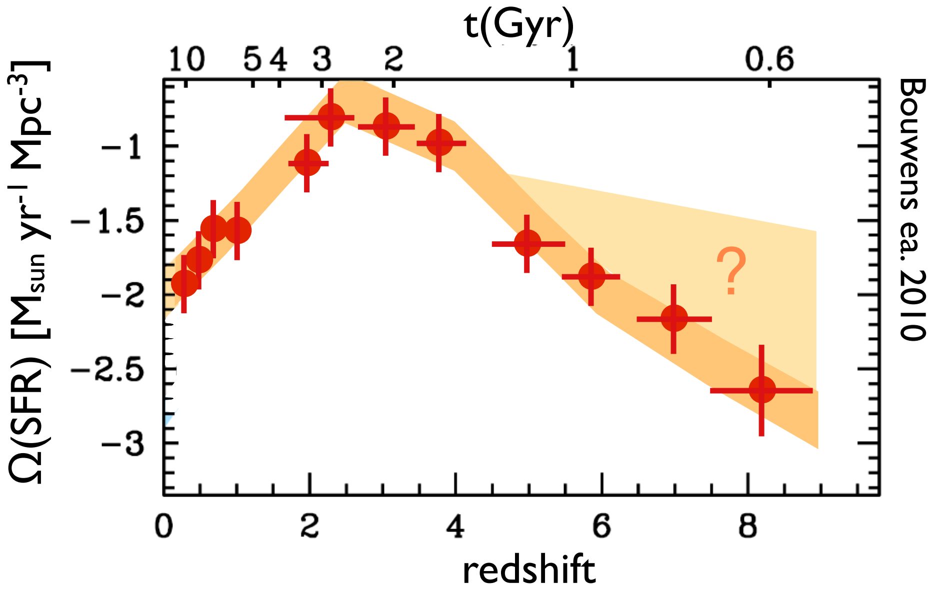
Galaxy growth through gas accretion...

...but this gas supply is currently largely unconstrained observationally

Research in last decade - Cosmic Evolution of the cosmic star formation rate density

Deep fields: 100s hours, <1 sqdeg, mostly done in optical/NIR

→ this plot shows the consequence of gas supply in galaxies



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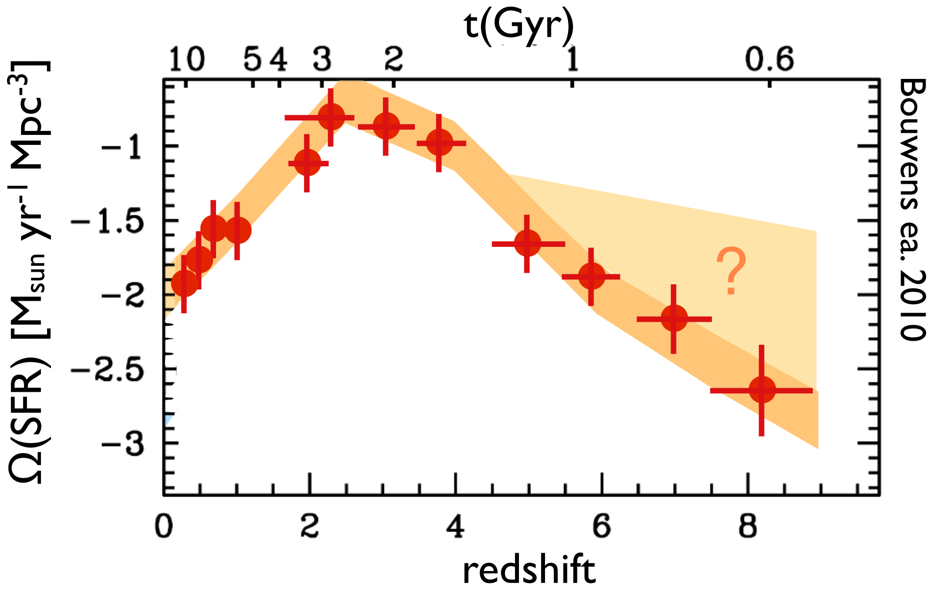
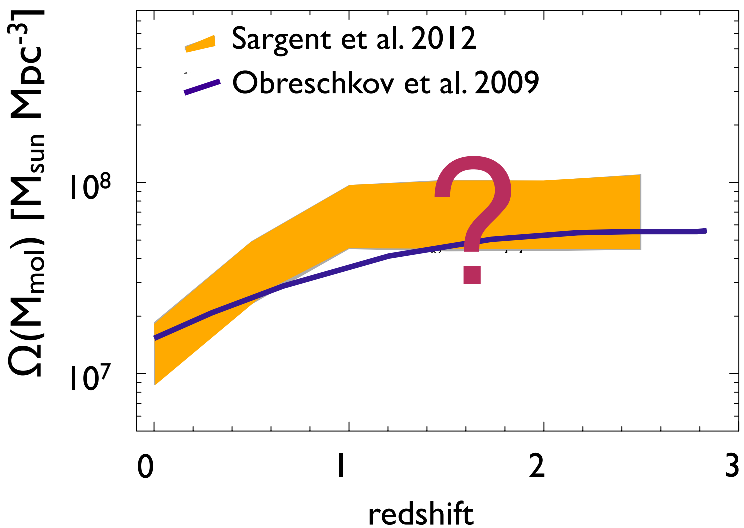
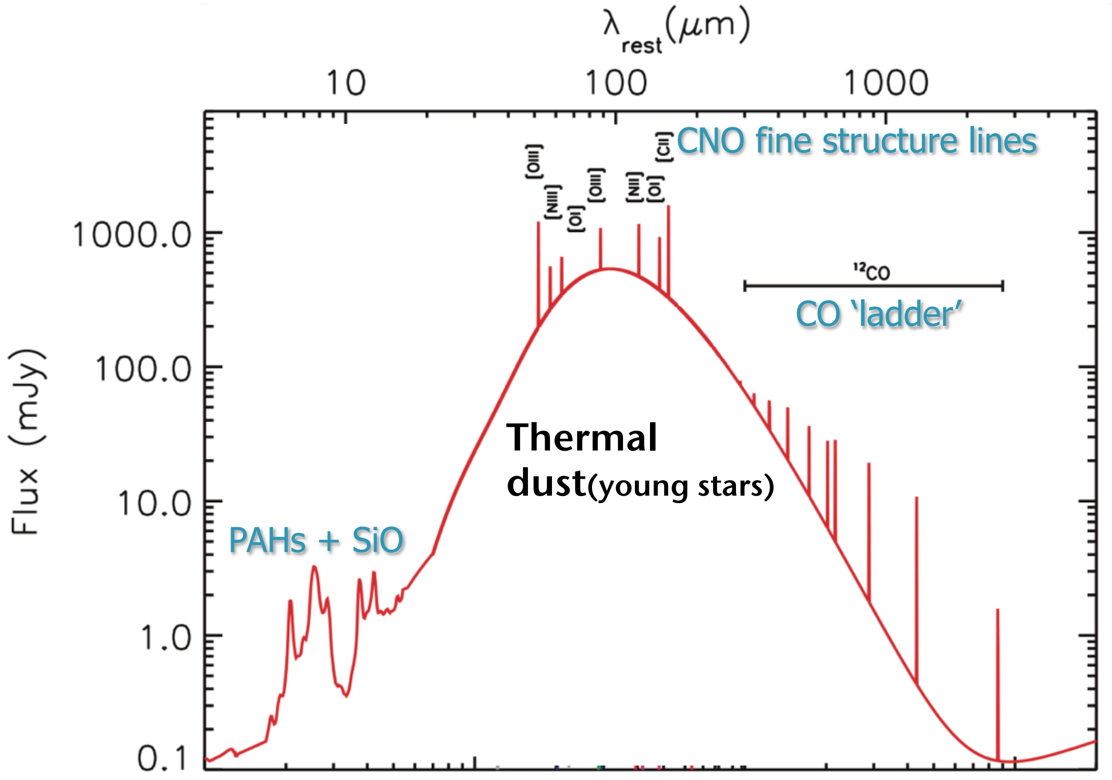


perhaps the more fundamental plot would be:

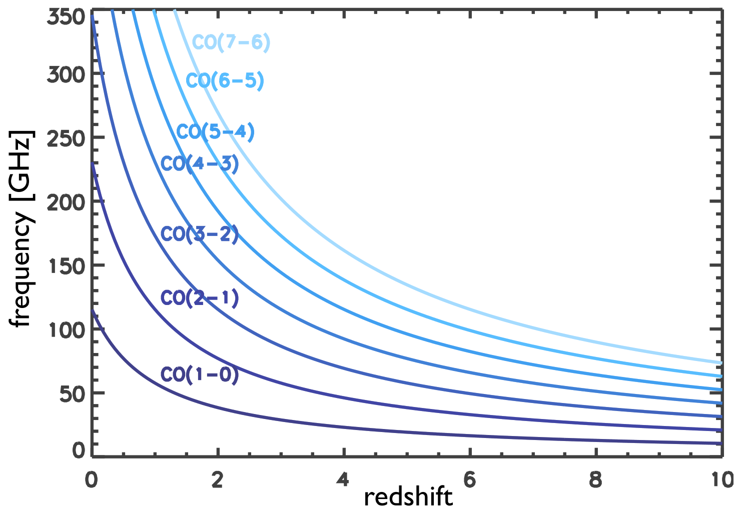


how do we get there?

A typical dusty high-redshift SED

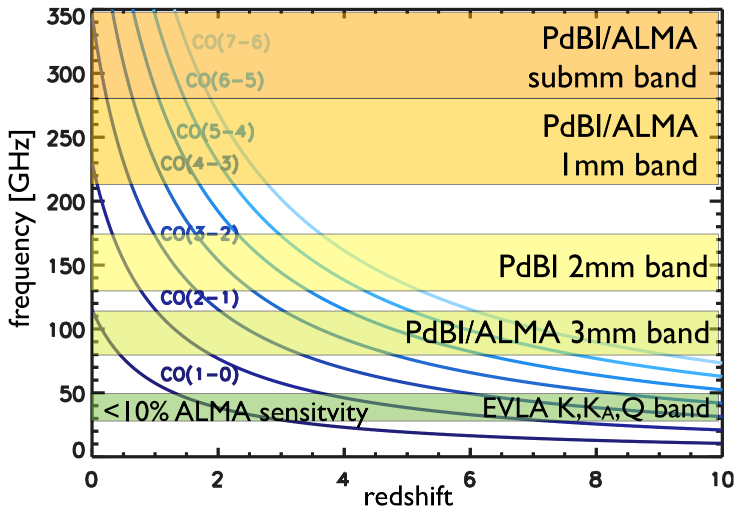


CO transitions as function of redshift, f(T, ρ)

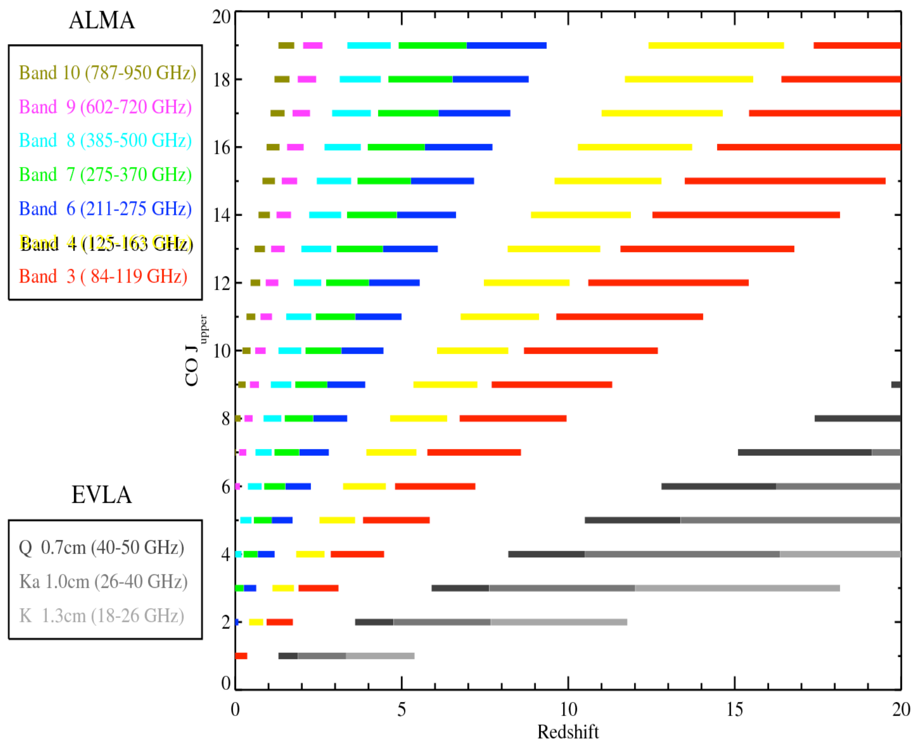


practical issues

CO transitions as function of redshift, f(T, ρ)



significant coverage in frequency space



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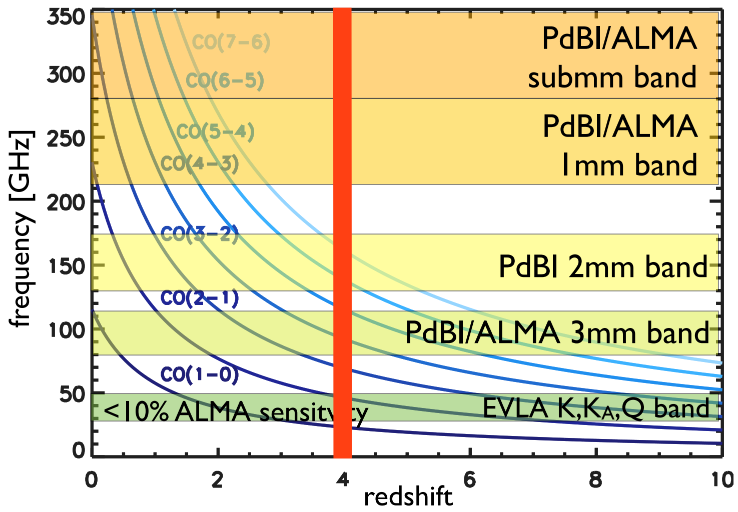

significant coverage in frequency space

at high redshift: can only detect high-J CO transitions

non-trivial to derive molecular gas masses, even if conversion factor $L_{CO(1\text{-}0)} \rightarrow H_2$ mass was known

practical issues

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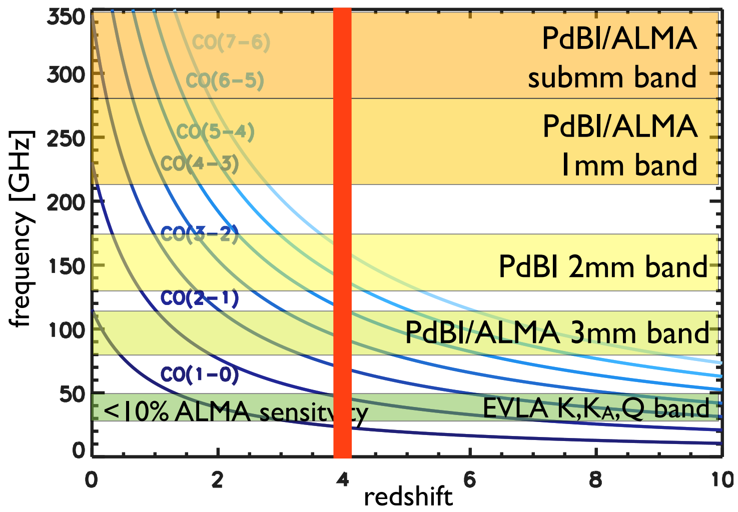

significant coverage in frequency space

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once CO is detected:

Brightness => M_{gas} (fuel for SF, evol. state, t_{dep})

Excitation => n_{gas} , T_{kin} (phys. conditions for SF)

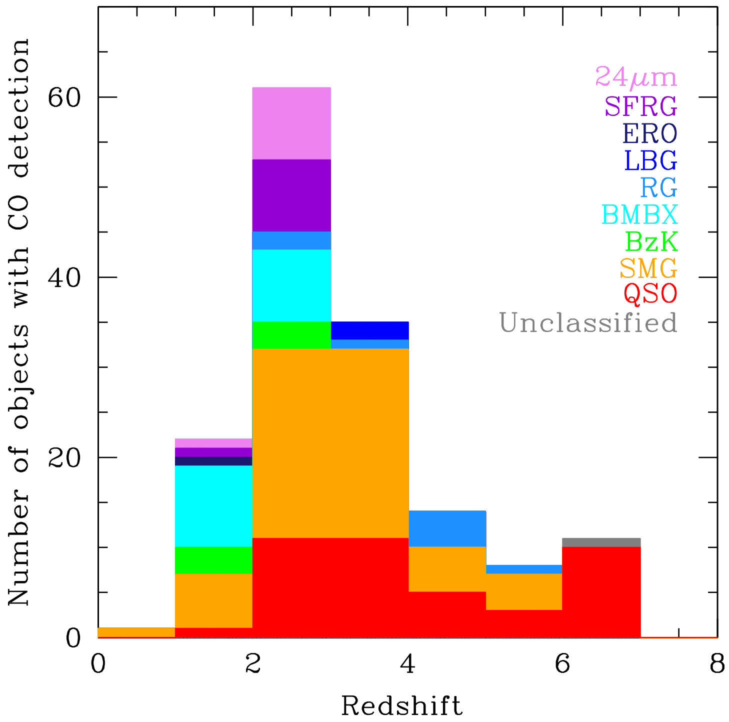
Imaging => Σ_{gas} ,M_{dyn} (sys. potential => M_{tot})

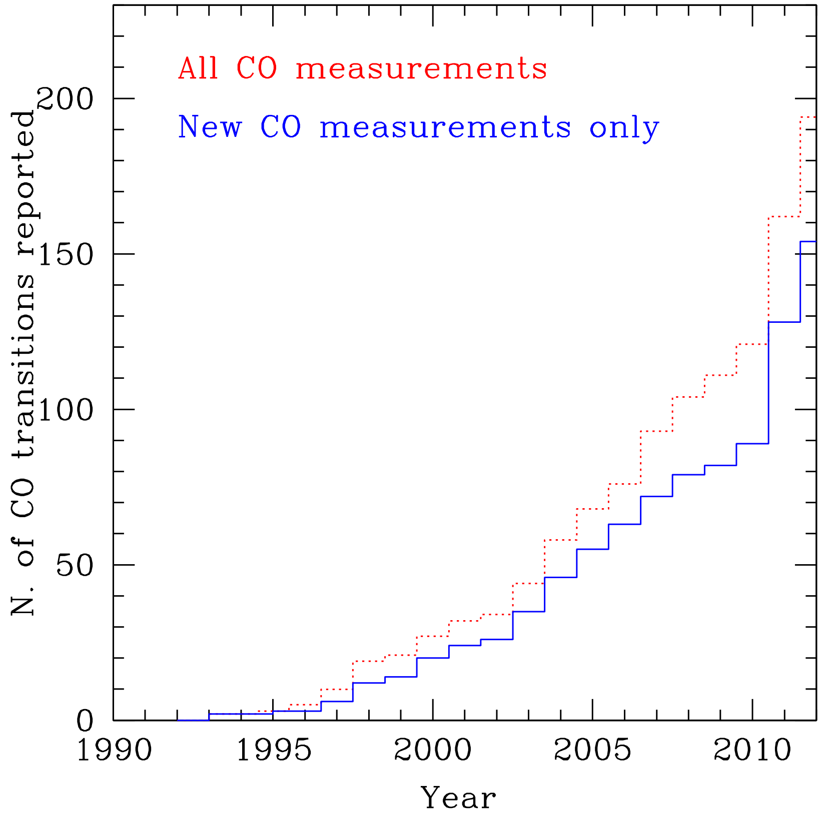
high redshift gas supply

- CO is best (but by no means perfect) tracer for molecular gas, H_2

so far: individual studies, mostly
QSO: host galaxies of accreting Black Holes
SMGs: highly SF galaxies

} SFR $\geq 1000\ M_{sun}\ yr^{-1}$





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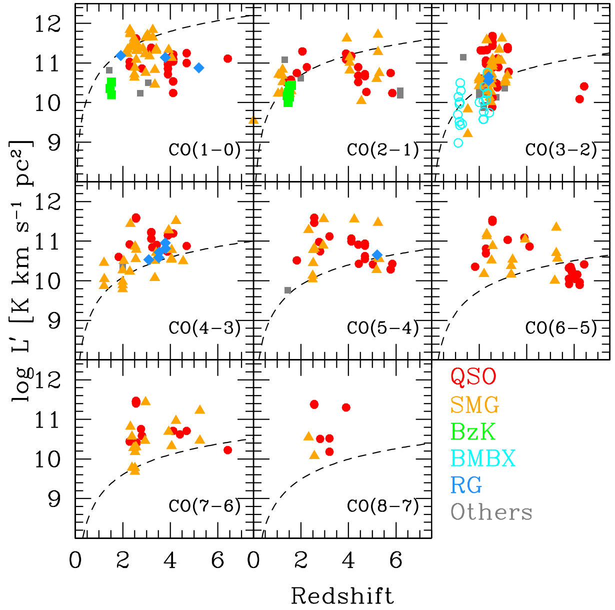
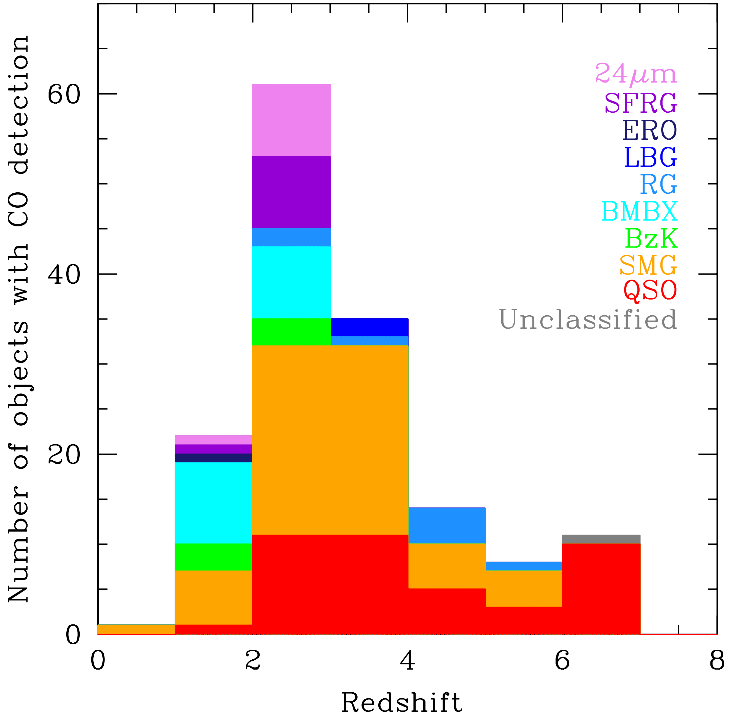
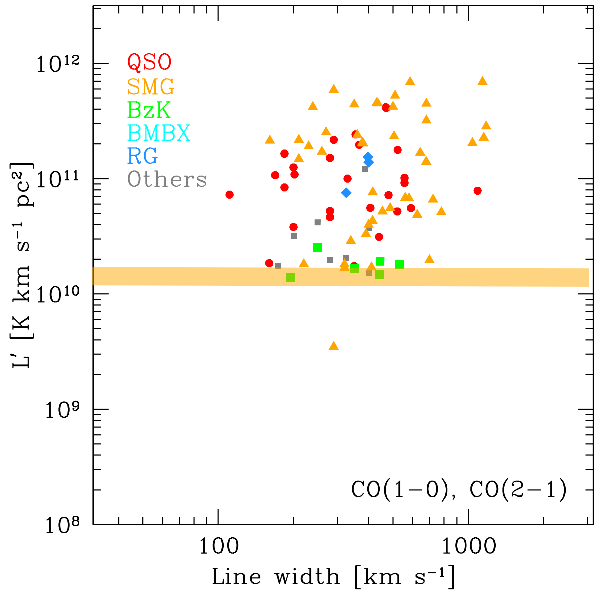


Carilli & Walter, in prep.

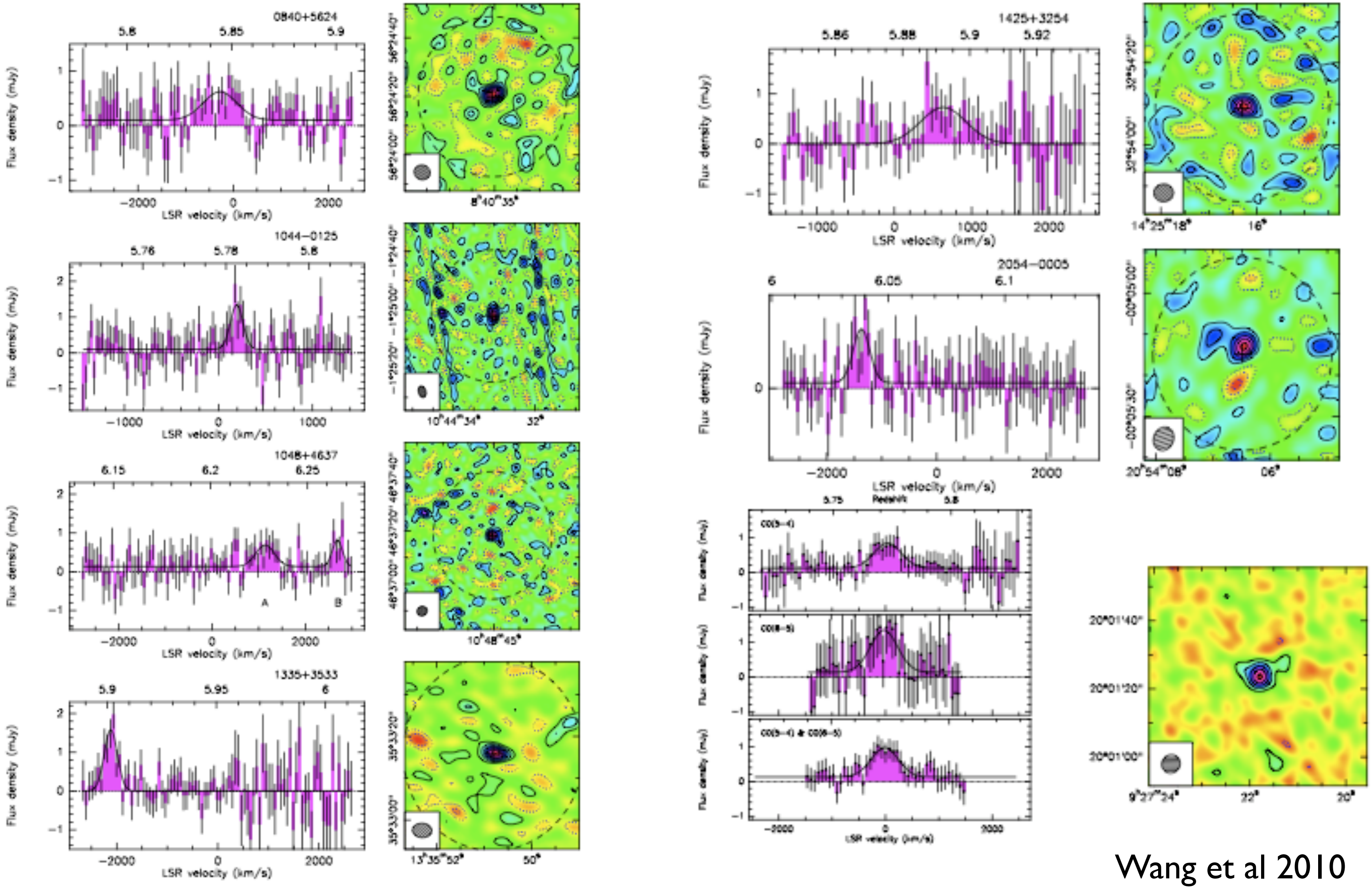




detection limit:
~$10^{10\text{-}11}$ M_{sun}

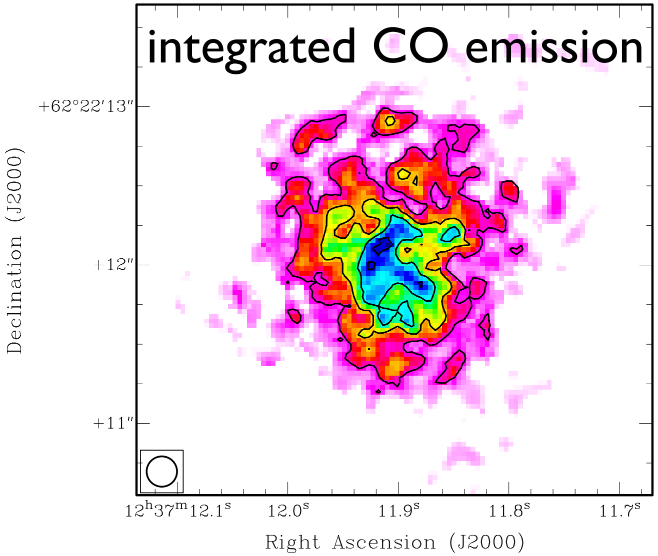
CO now ‘routinely’ detected in z=6 QSOs

z=6: age of universe less than 1 Gyr.
presence of CO(6-5) implies major enrichment in quasar host galaxies



Wang et al 2010

CO emission can be spatially resolved

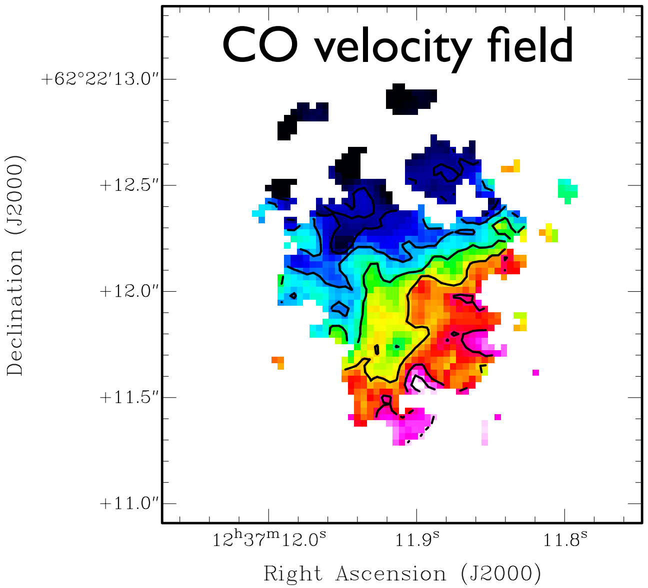


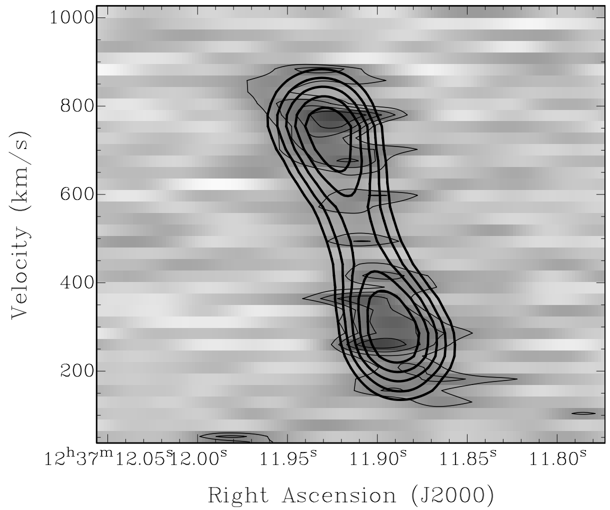
Bright z=4 submillimeter galaxy GN20

1kpc resolution at z=4!

Reveals clumpy rotating molecular gas disk: evidence for cold mode accretion?

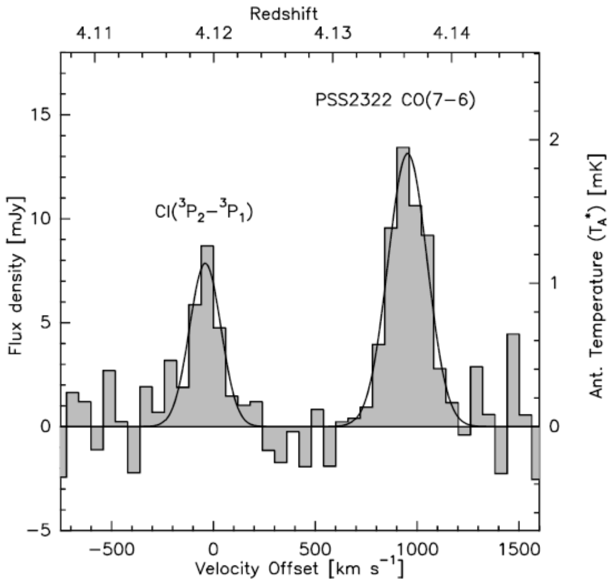
but: expensive.... ~100 hours with JVLA





Hodge et al. 2012

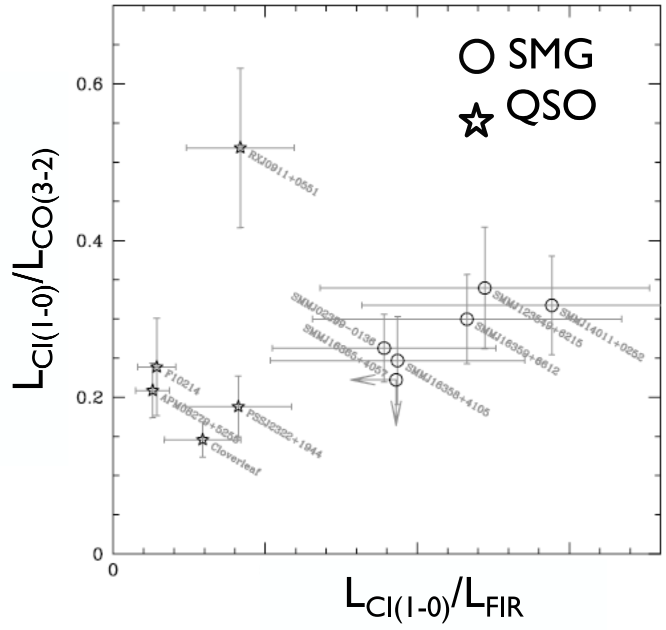
Other tracers: Atomic Carbon (CI)

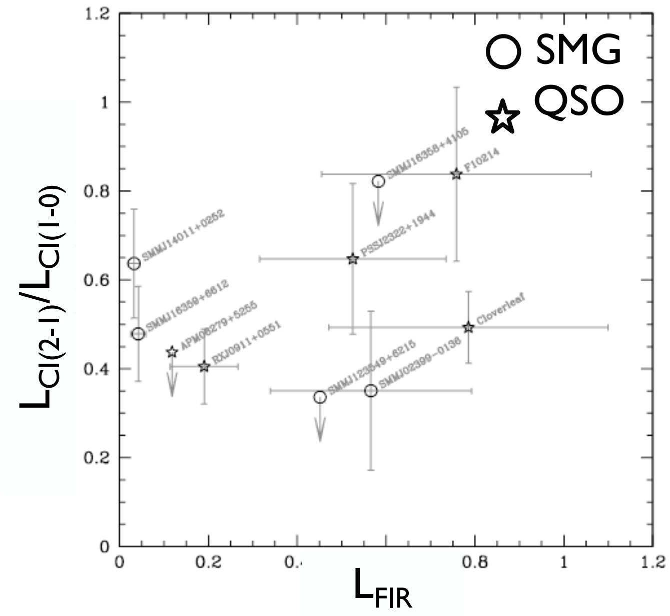


CI(2-1)[809GHz] and CI(1-0)[492GHz]

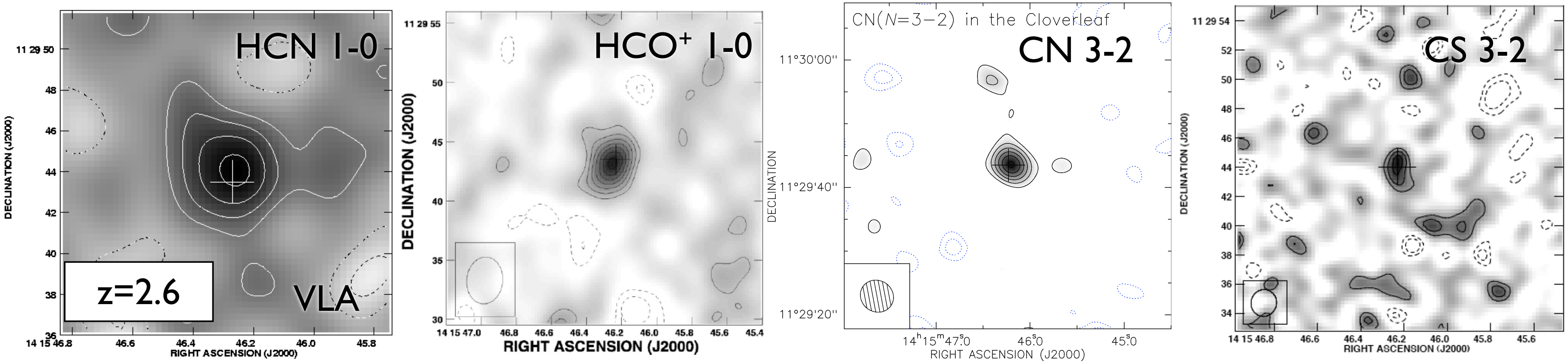
independent constraints on T_{ex} needed for LVG modeling

Walter et al. 2012



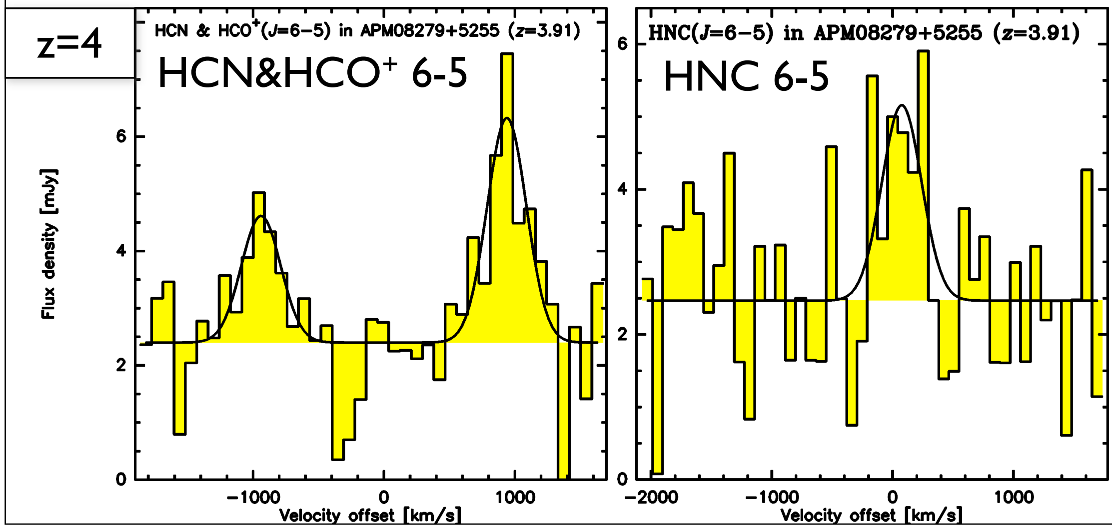


Other tracers at high density



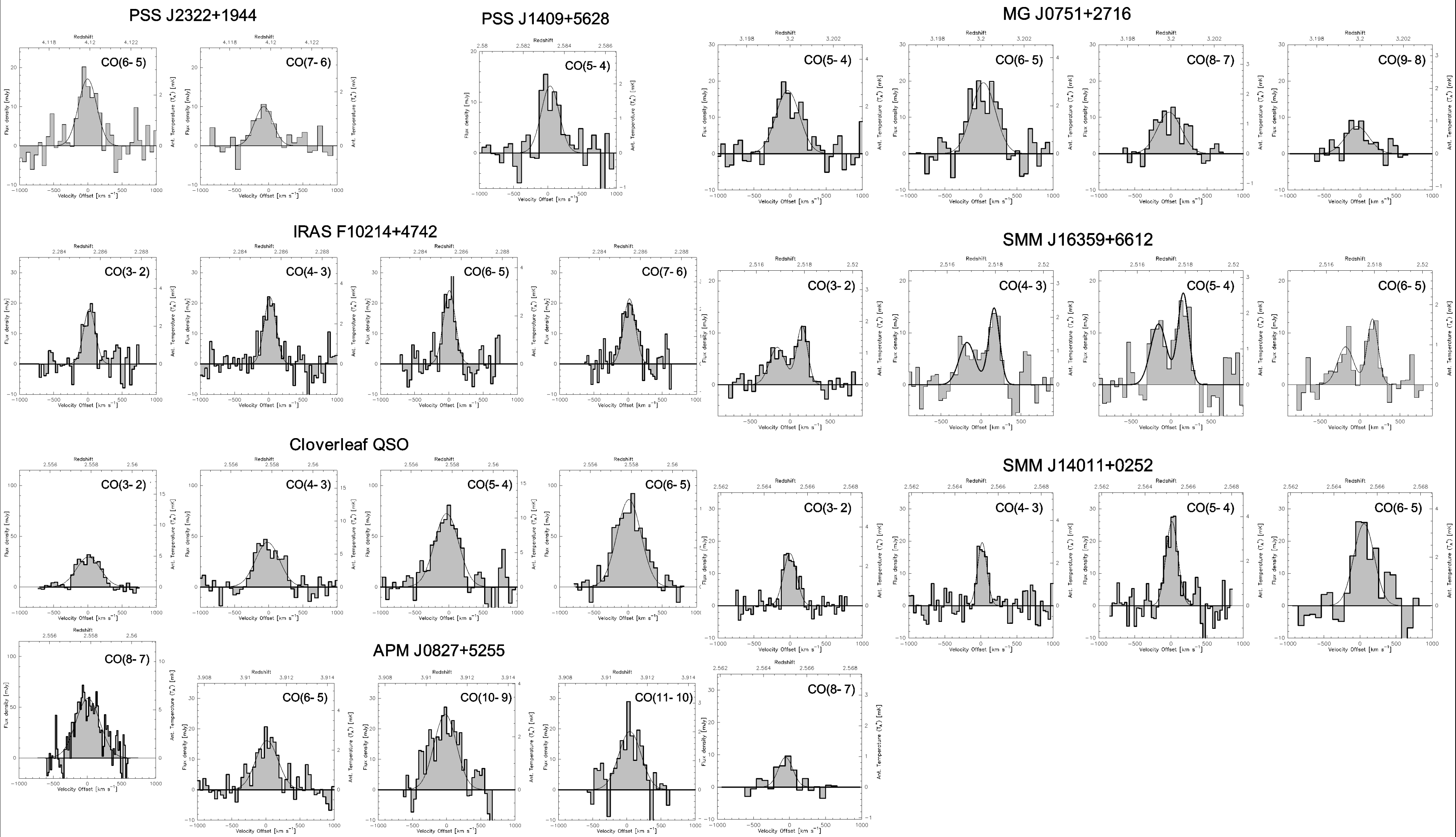
- n_{cr} > 1e5 cm^{-3} - 100x denser than CO, ~ GMC cores
- Dense gas lines 10-30x less luminous than CO
- line ratios similar to local ULIRGs, e.g., Arp 220

⇒ No significant 'chemical evolution' of mol. ISM?



Solomon ea. 2003
Riechers ea., 2007a, 2009
Garcia-Burillo ea 2008

CO ladder -- tedious observations...

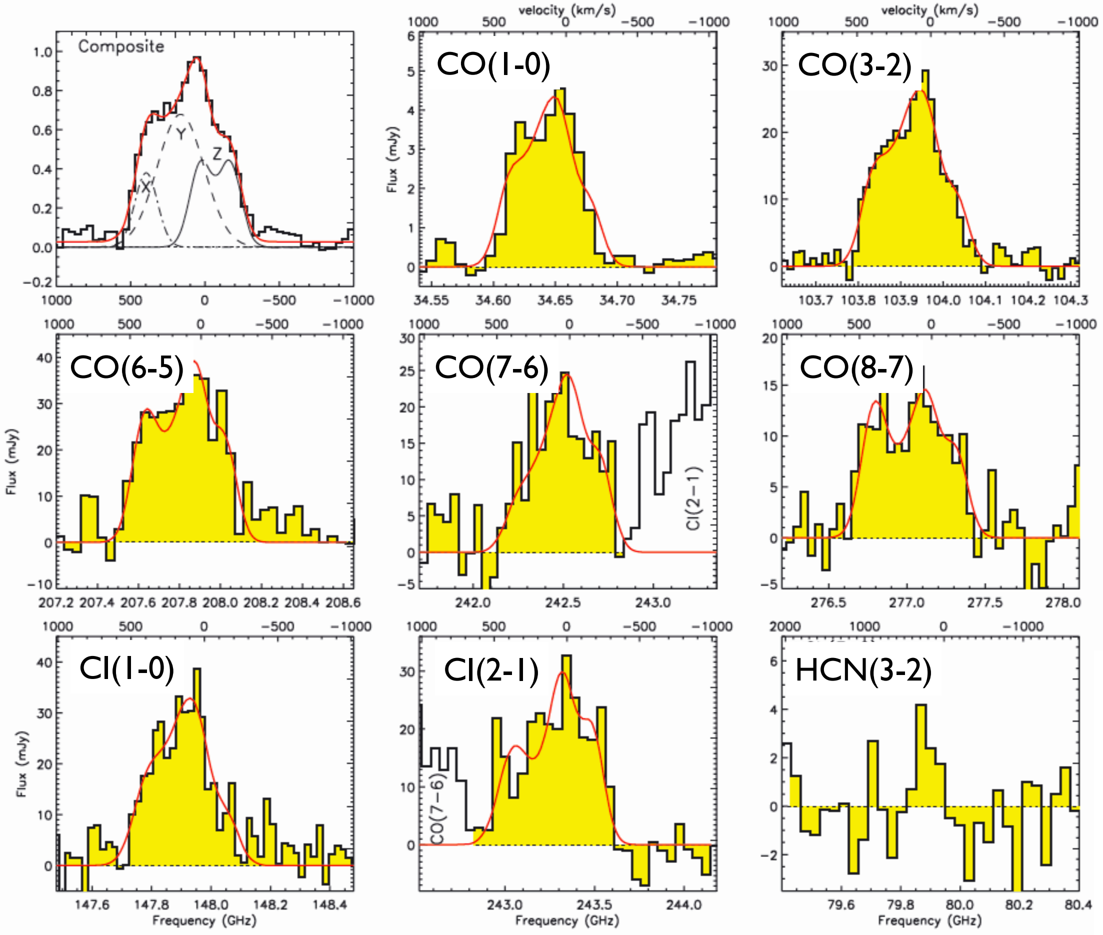


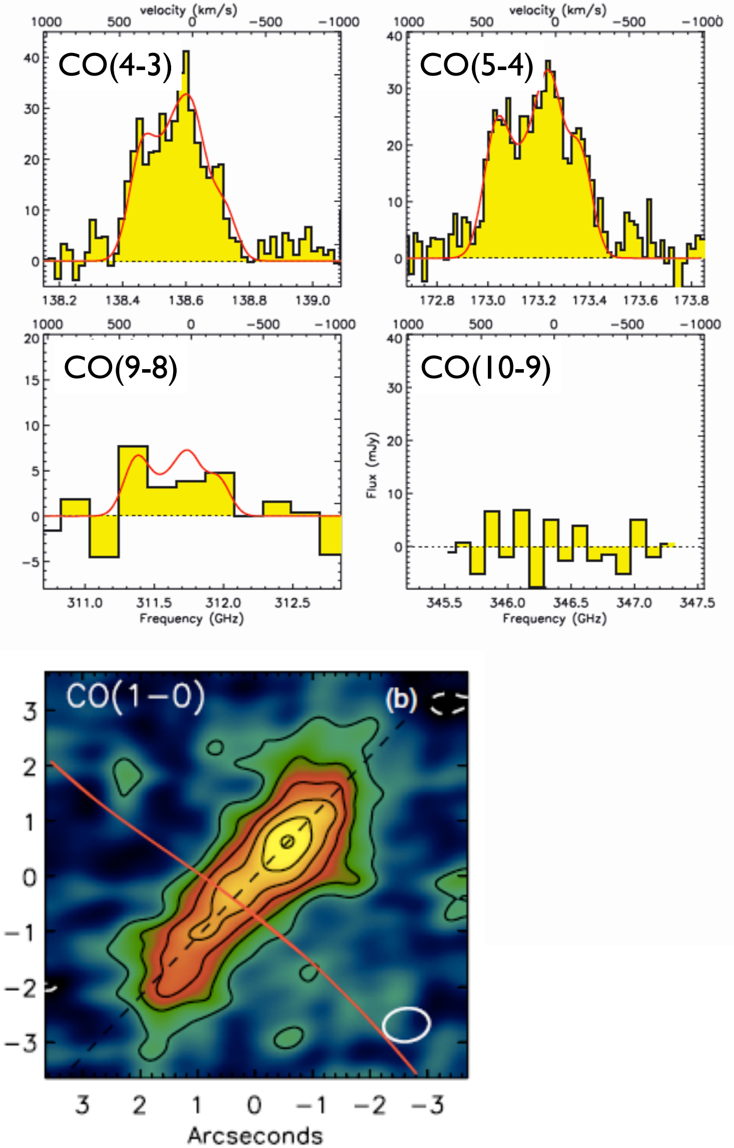
IRAM 30m CO SED survey
(1, 2, 3mm bands)

Weiss et al. 2013

Lensing helps

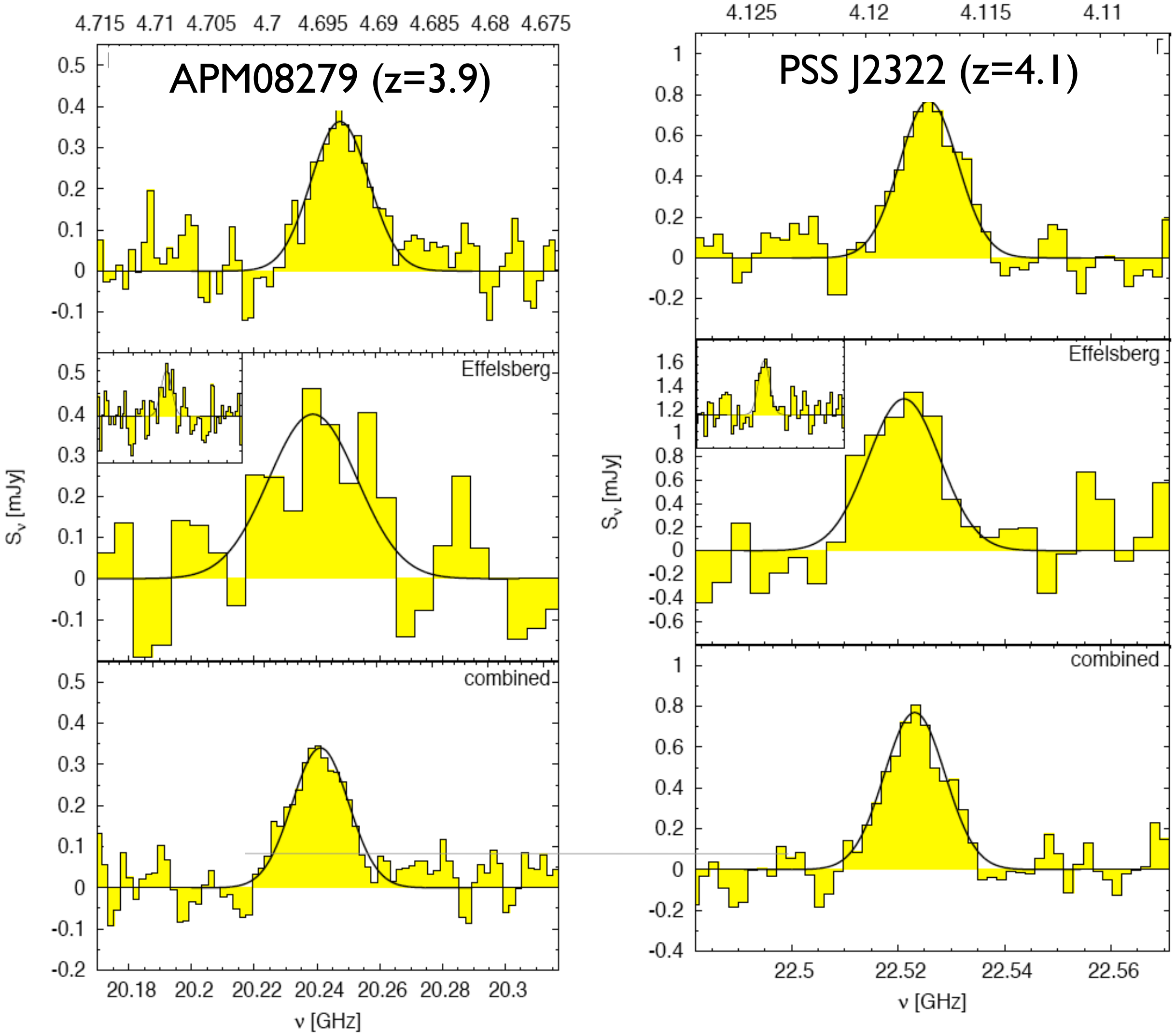
The Eyelash

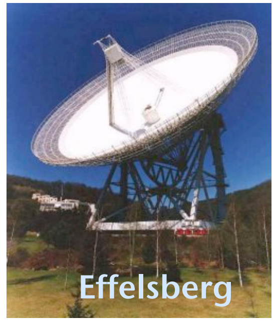




Swinbank et al. 2011, Danielson et al. 2011

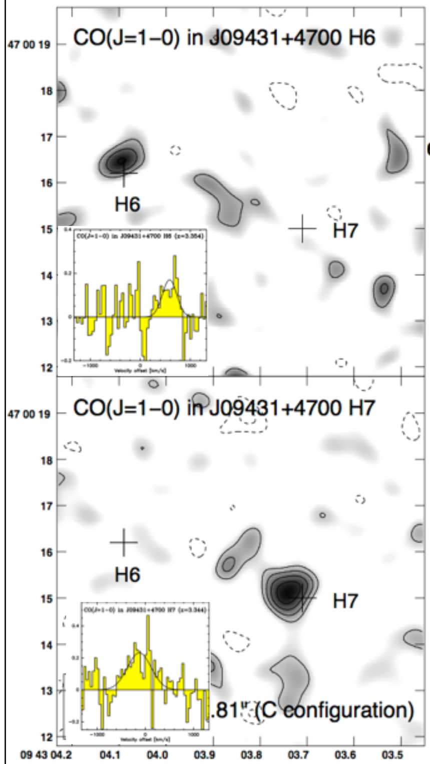
Low-J observations in the cm regime: need large collecting are



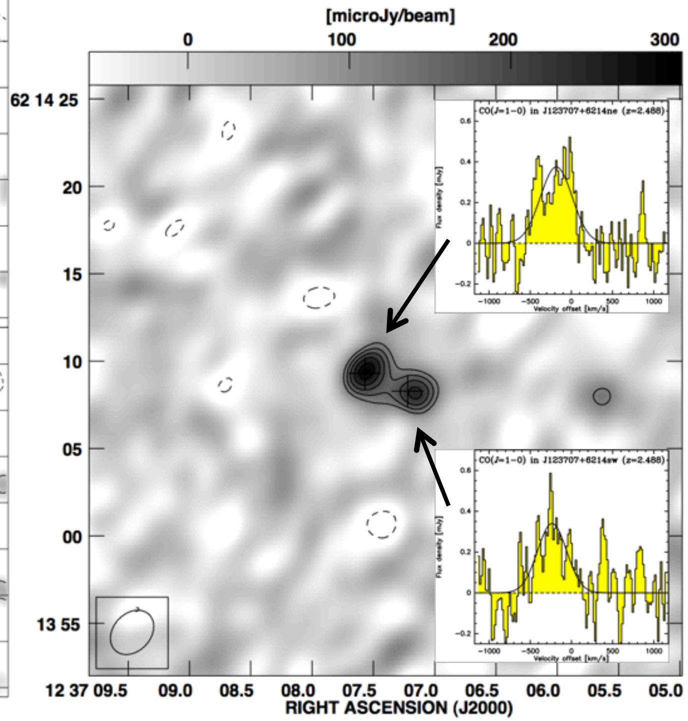


Riechers et al. 2006

Low-J observations: JVLA -- merger sequence in SMGs?

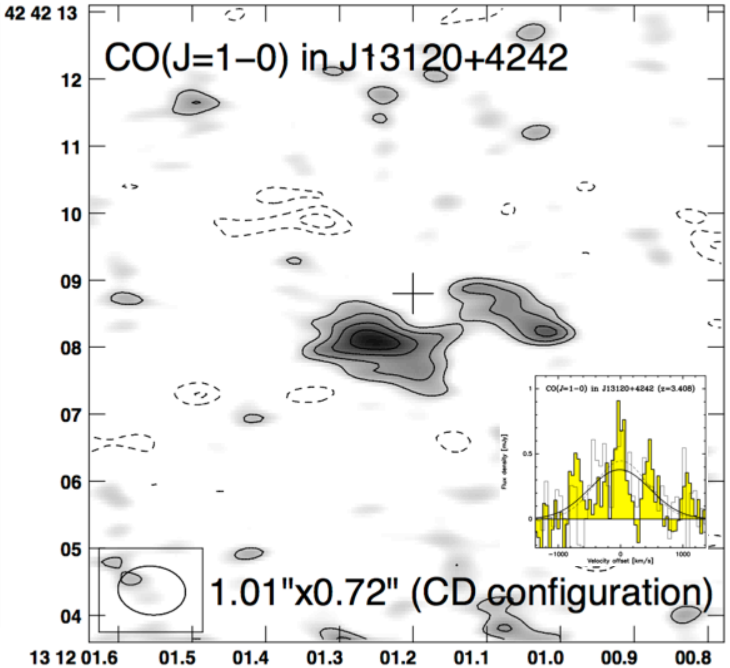


Early stage
~30kpc & 750km/s separation



Intermediate stage
~20kpc & <100km/s separation

Submillimeter Galaxies



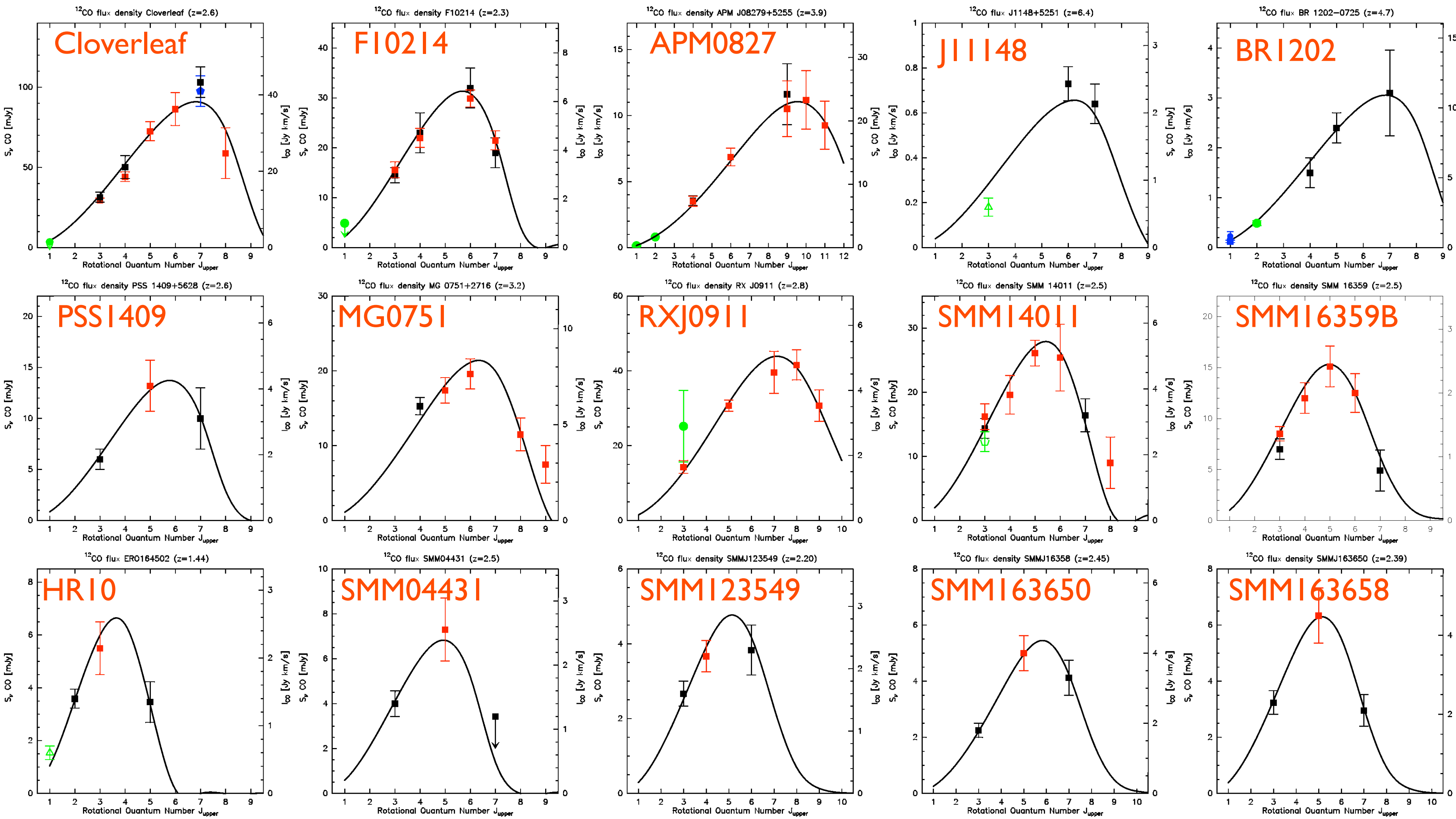
Late stage
7-15kpc nucleus & tidal structure
single broad, multi-peaked line
abundant low-excitation gas

z>2-4 SMGs show complex, extended, low-excitation gas reservoirs
typically 10kpc, with FIR continuum sizes of 2-4kpc (starburst regions)

THE ASTROPHYSICAL JOURNAL LETTERS (EVLA SPECIAL ISSUE)

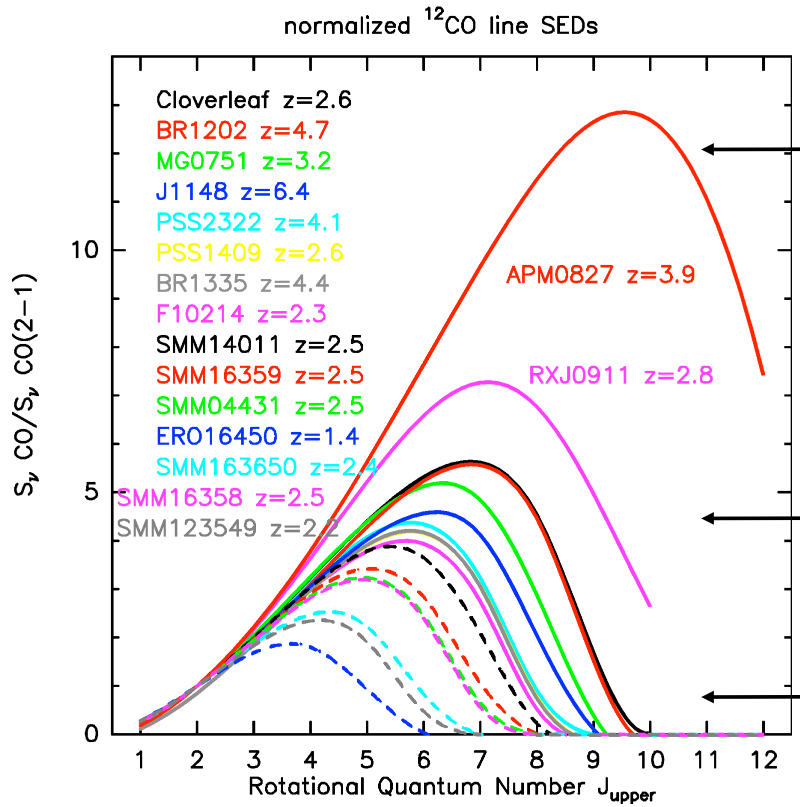
Riechers et al. 2011, Ivison et al. 2011

CO excitation: putting it all together:



Weiss et al. 2013

CO excitation: High Redshift



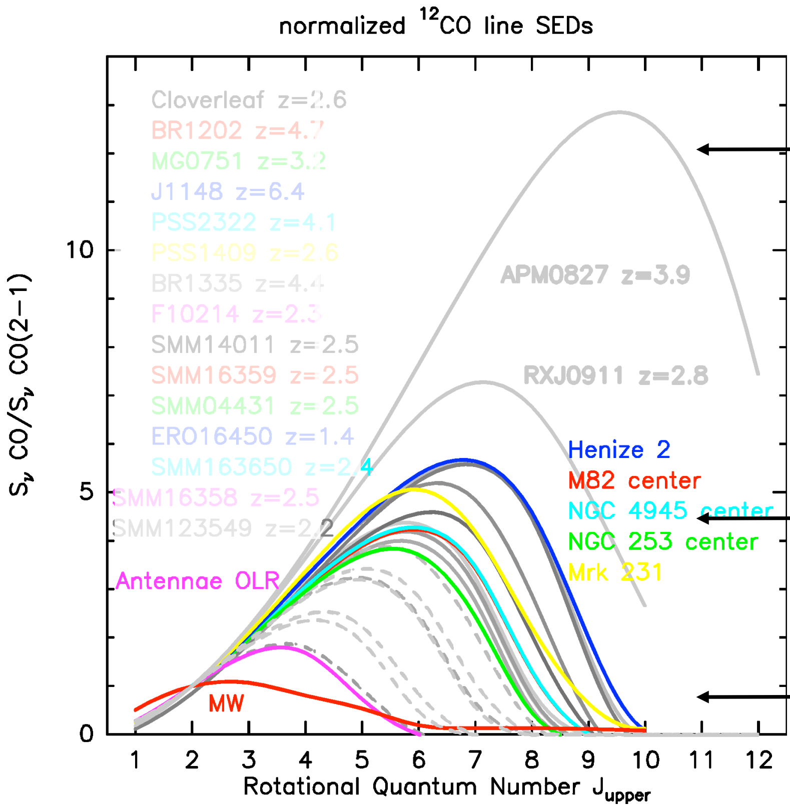
T_{kin} ~ 200 K (T_{dust} ~ 200 K)
$n(H_2)$ ~ $10^{4.2}$ cm^{-3}
Strongly lensed (m=80-100) central ~200pc surrounding the QSO. AGN heating!

T_{kin} ~40 – 60 K (T_{dust} ~ 50 K)
$n(H_2)$ ~ $10^{3.6-4.3}$ cm^{-3}

T_{kin} ~ 30-50 K (T_{dust} ~ 30-50 K)
$n(H_2)$ ~ $10^{2.7-3.5}$ cm^{-3}

Weiss et al. 2013

CO excitation: Low Redshift



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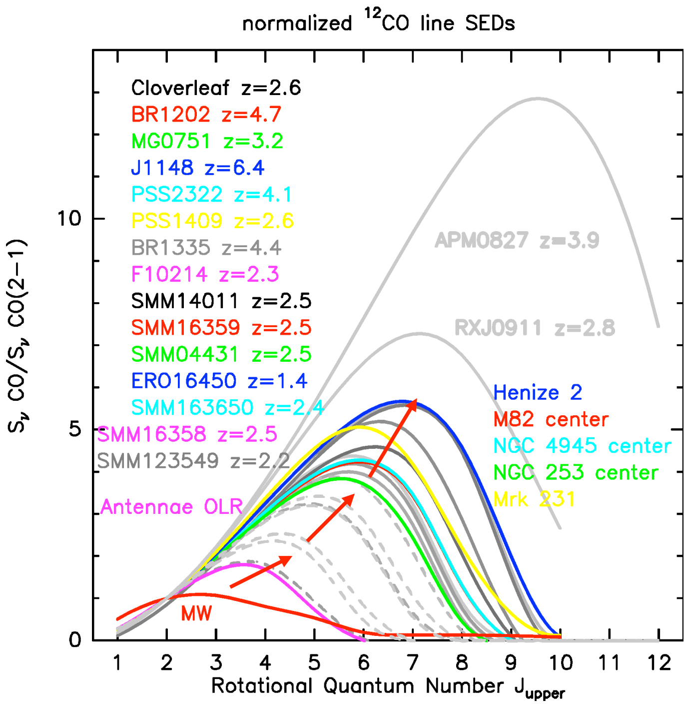
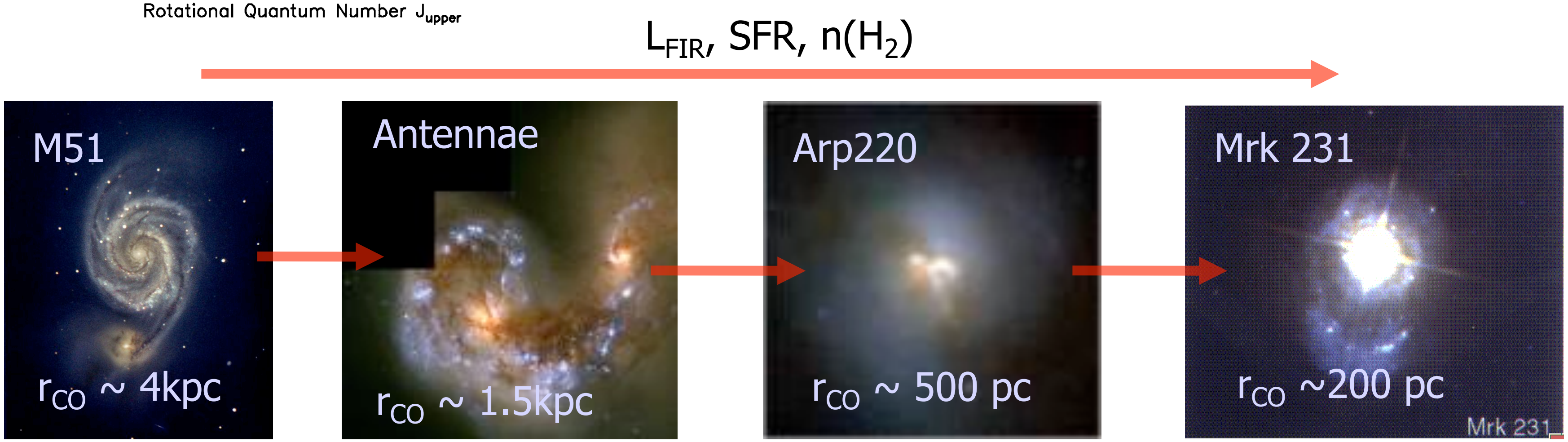
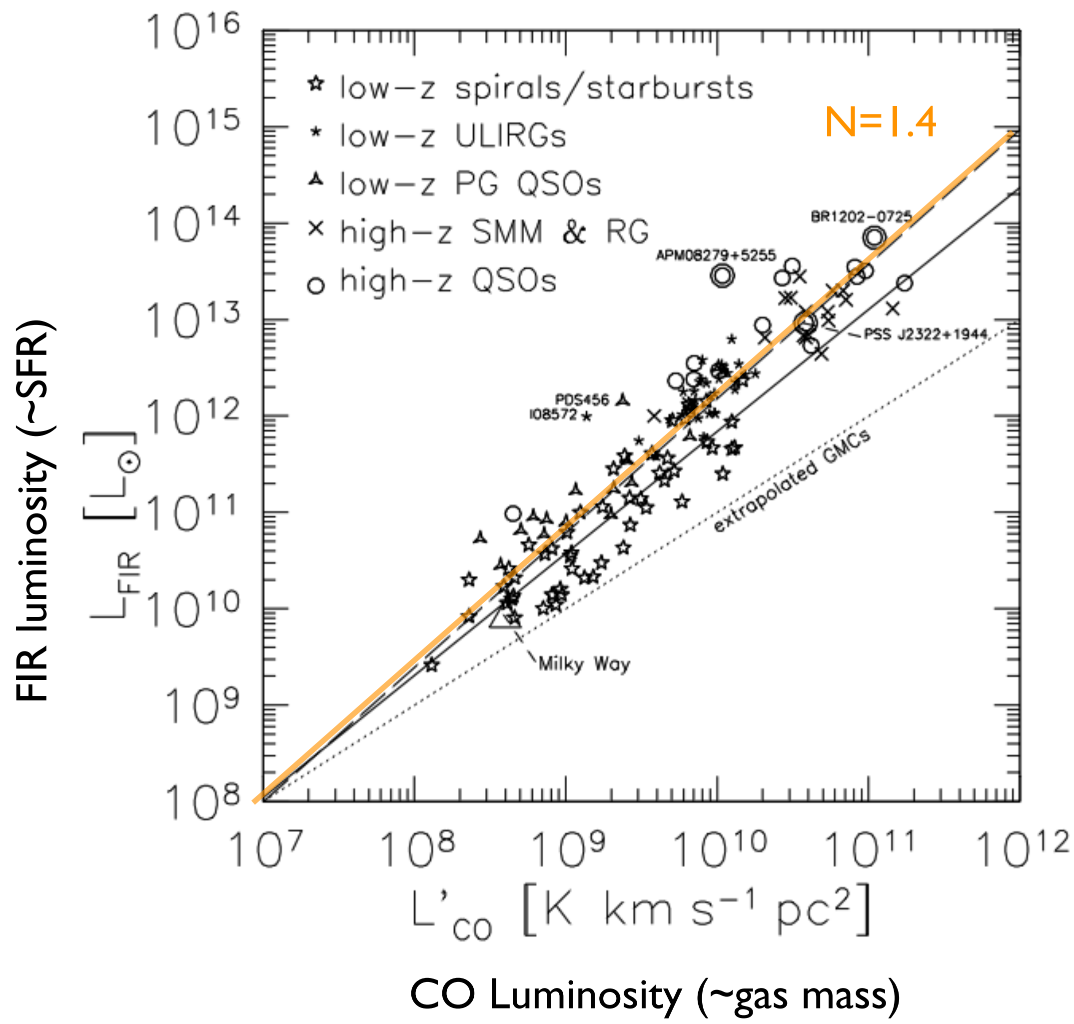
Weiss et al. 2013

Evolutionary Sequence?



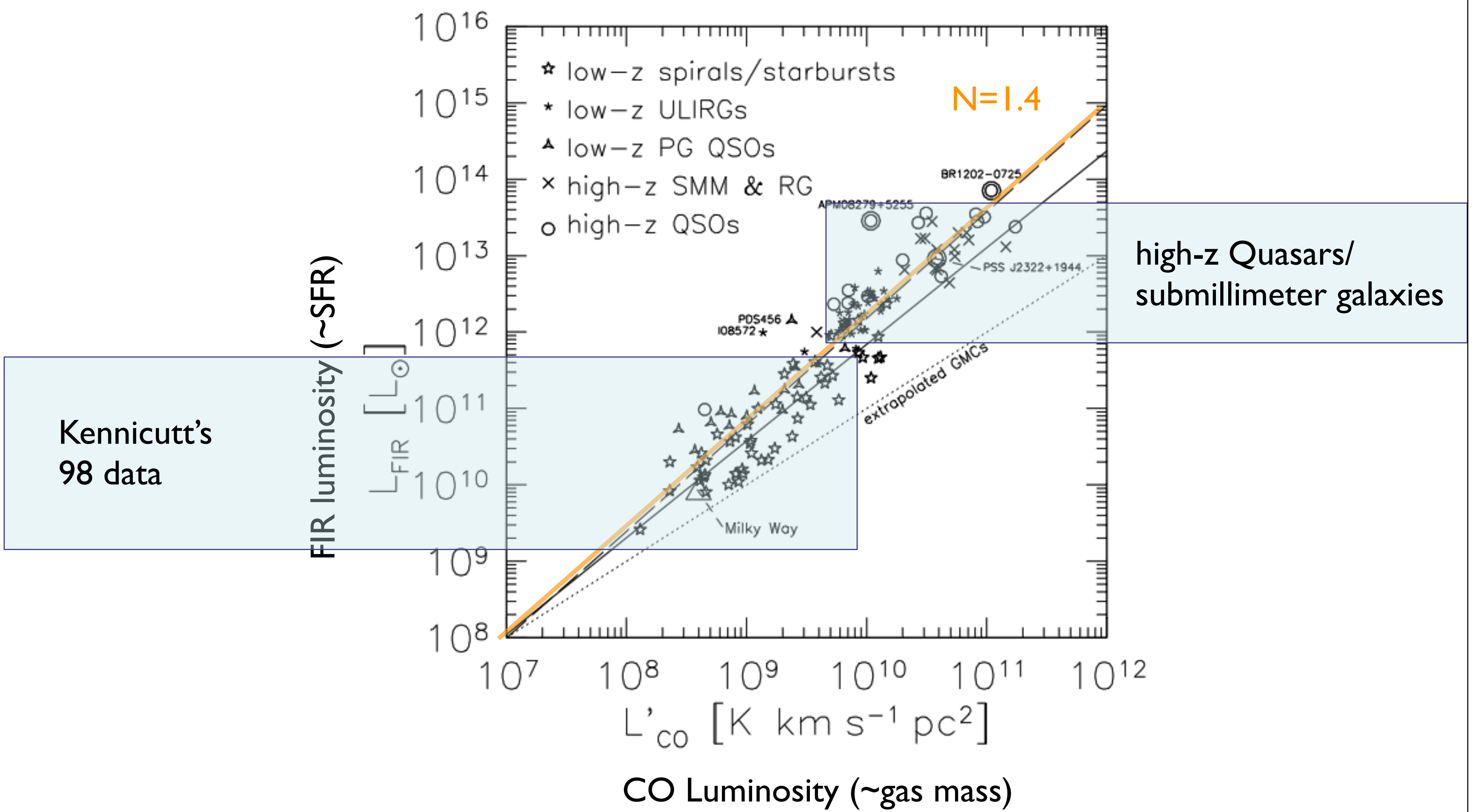


FIR vs. CO luminosity



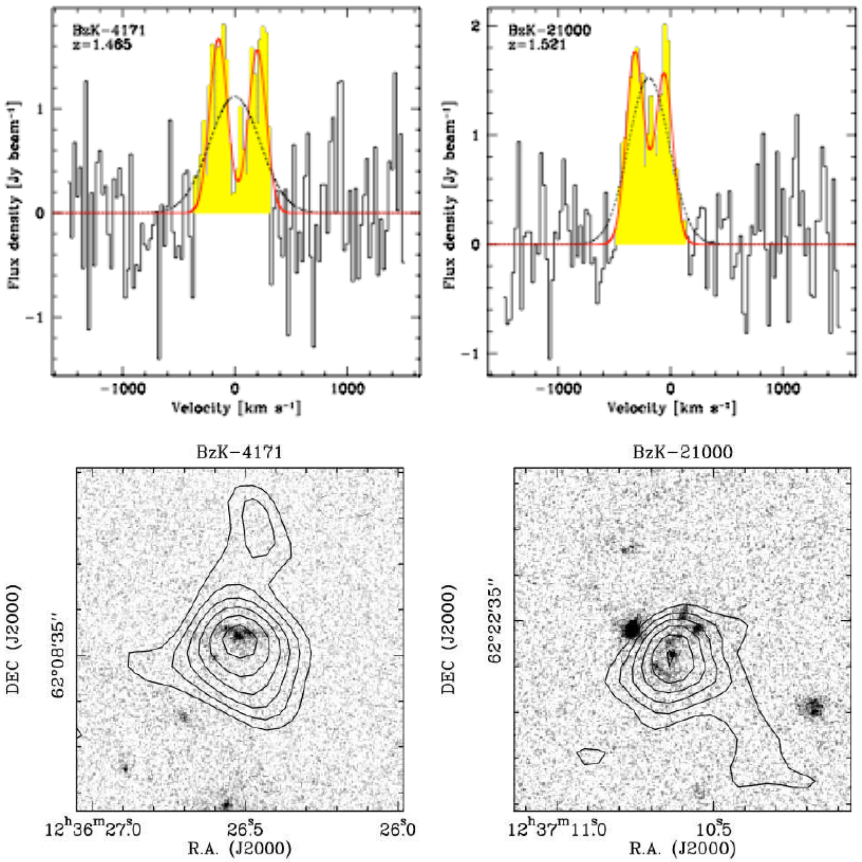
Riechers et al.

FIR vs. CO luminosity



Riechers et al.

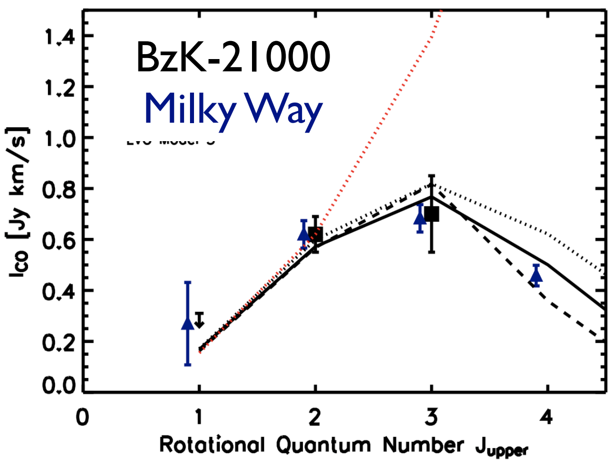
2008-2010: Detection of 'normal' star forming galaxies



optical/NIR selected galaxies (BzK), SFR few 100 M_{sun} yr^{-1} are very rich in molecular gas

Molecular conversion factor: Galactic

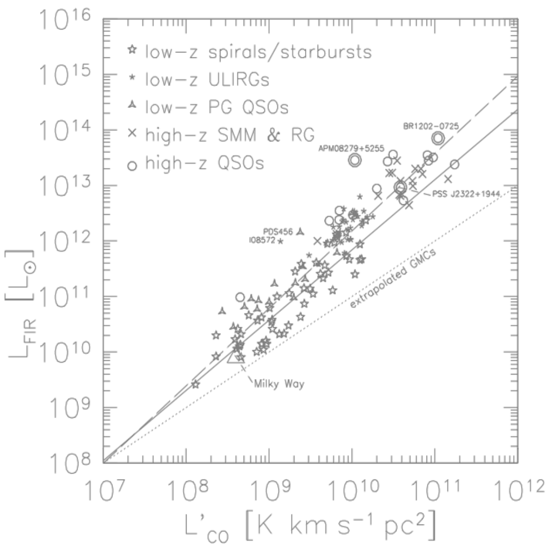
gas fractions: f_{gas}=0.5-0.7

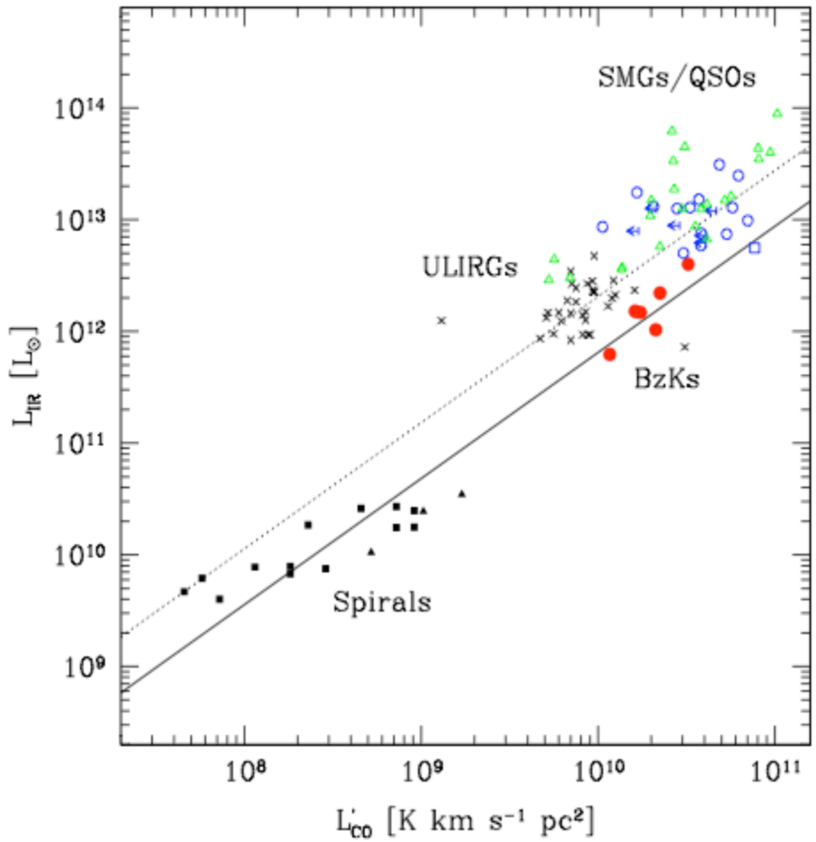


Daddi et al 2008/2010, Tacconi 2010

Dannerbauer et al. 2009

Location of BzK galxies in 'SF law' plot





note: this plot: observables only

- BzKs have significantly less L_{IR} for given L_{CO}

Daddi et al. 2010

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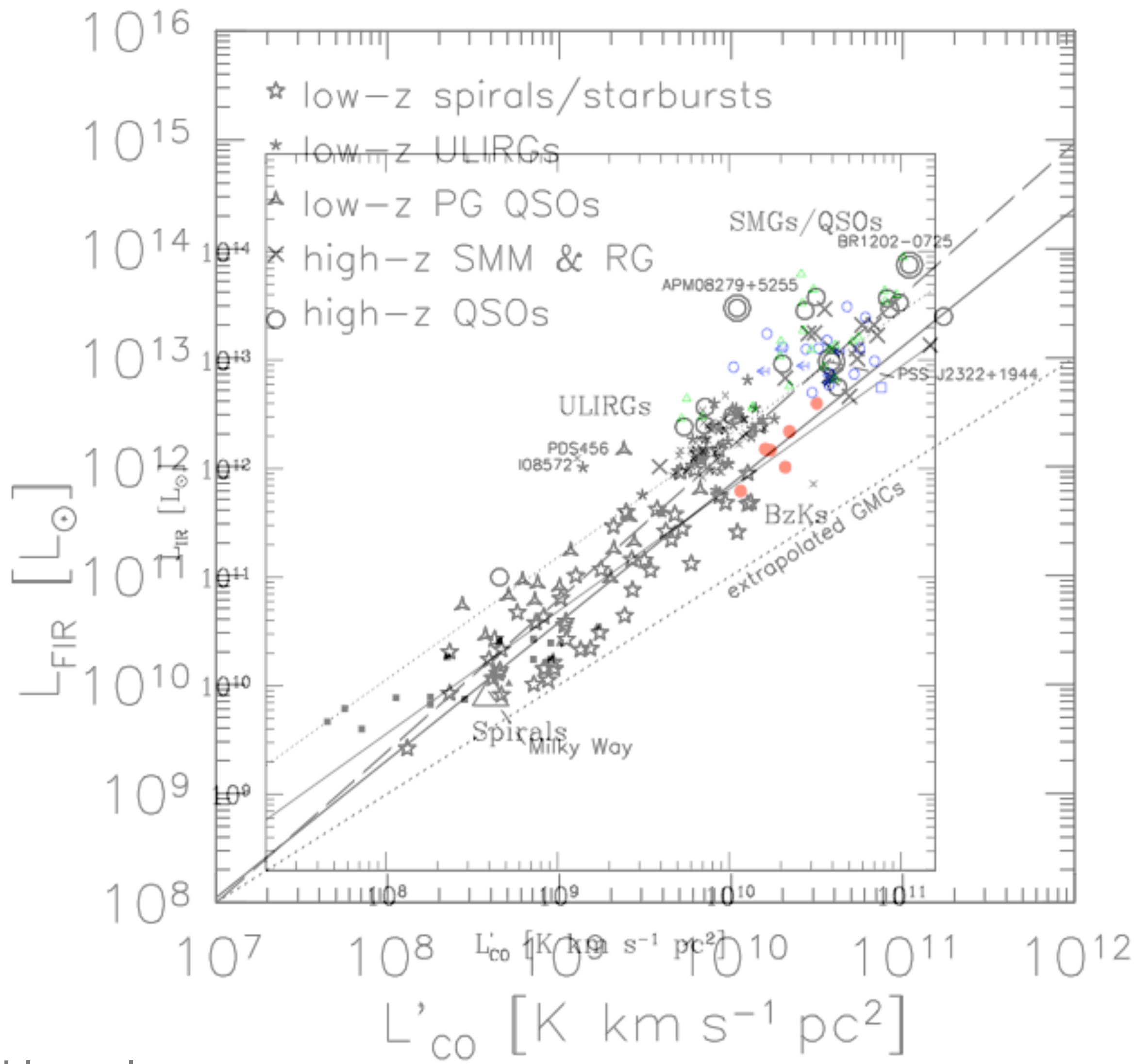

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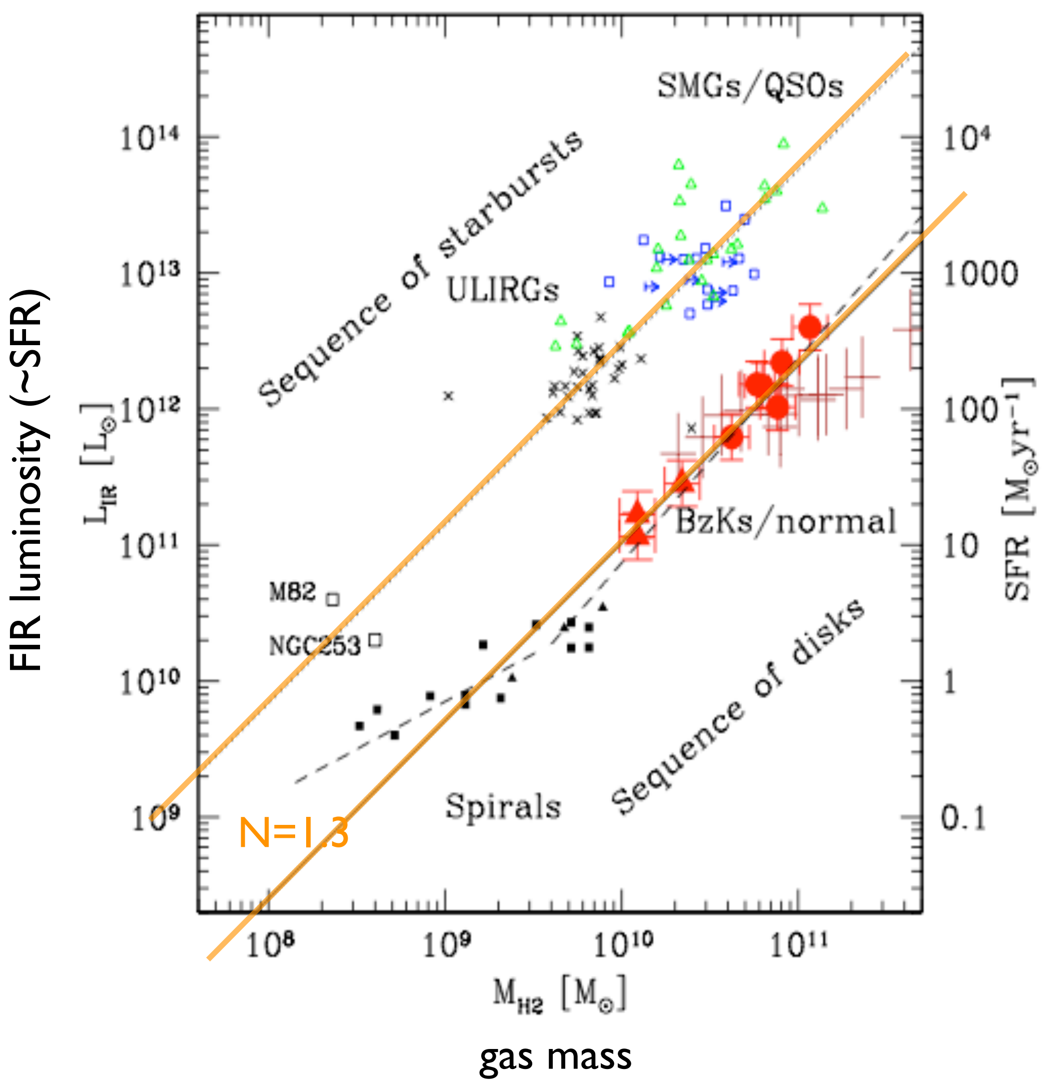
Daddi et al. 2010

Going from luminosities to masses



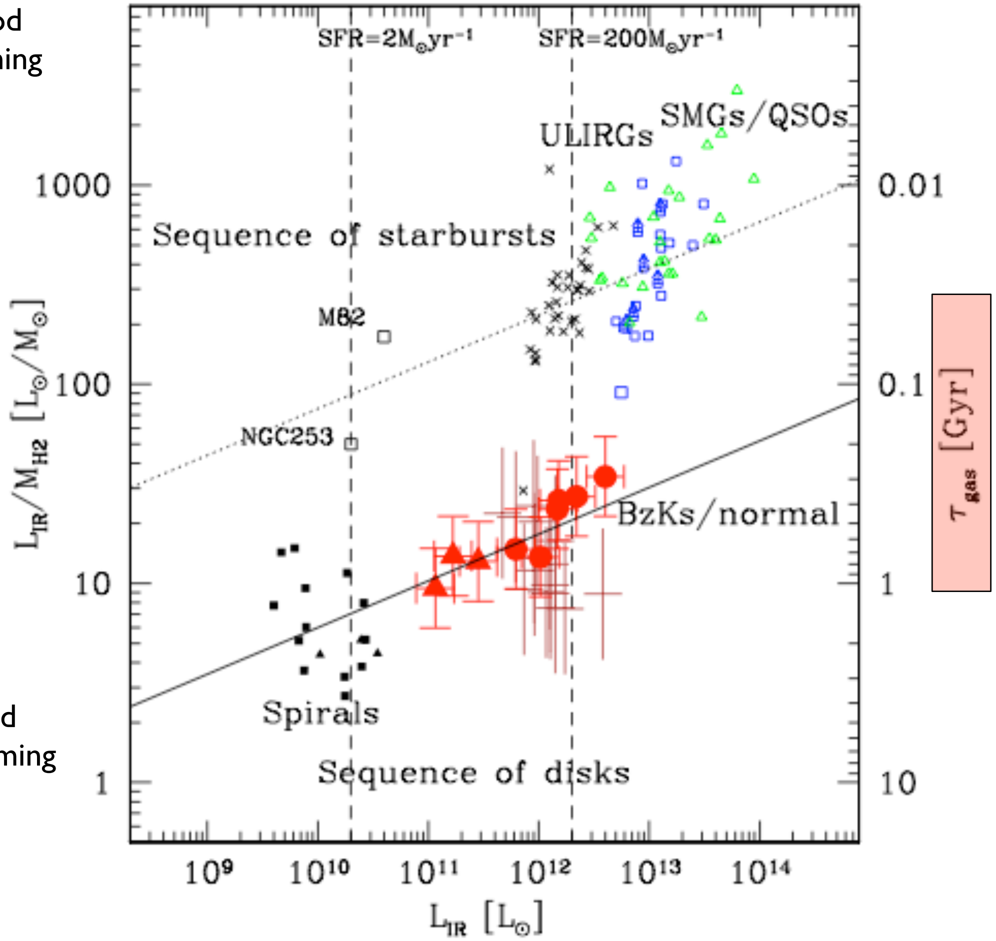
two sequences:

disks & starbursts

Daddi et al. 2010
Genzel et al. 2010

Star Formation Efficiencies a.k.a. Depletion Times

gas good
at forming
stars



gas bad
at forming
stars

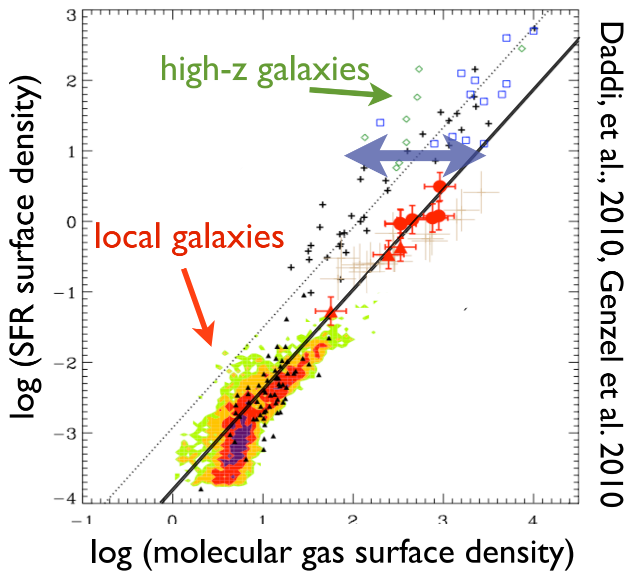
immediate
implication:

gas depletion times
long for BzKs
(sim. to spirals)

Daddi et al. 2010

high redshift gas supply

relation between gas and star formation is complex



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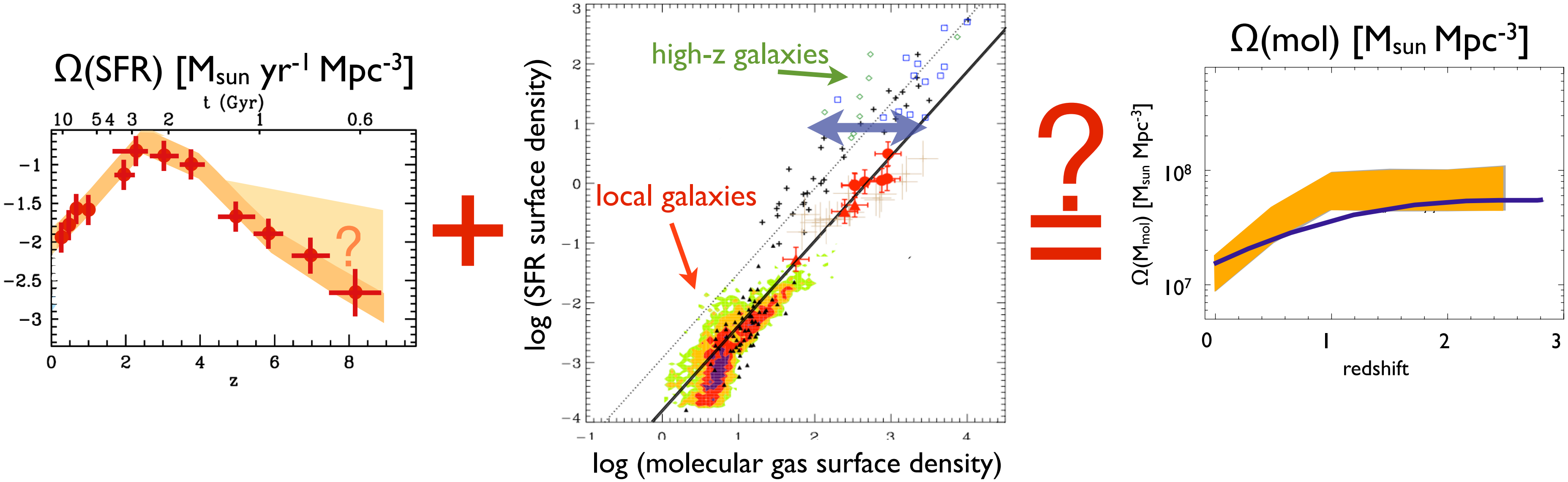
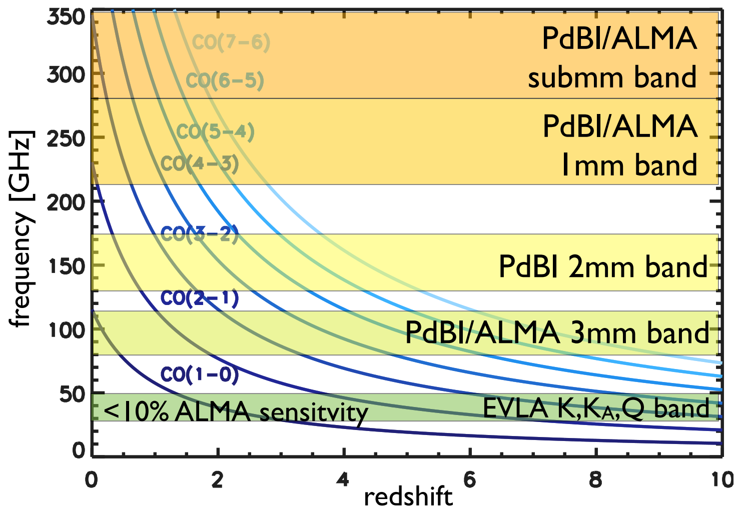


→ not trivial to predict $\Omega(M_{mol})$ from Ω(SFR)
[talk by Mark Sargent]

solution: unbiased census of molecular gas, the fuel for star formation
i.e. a molecular deep field (at the same time: continuum deep field)

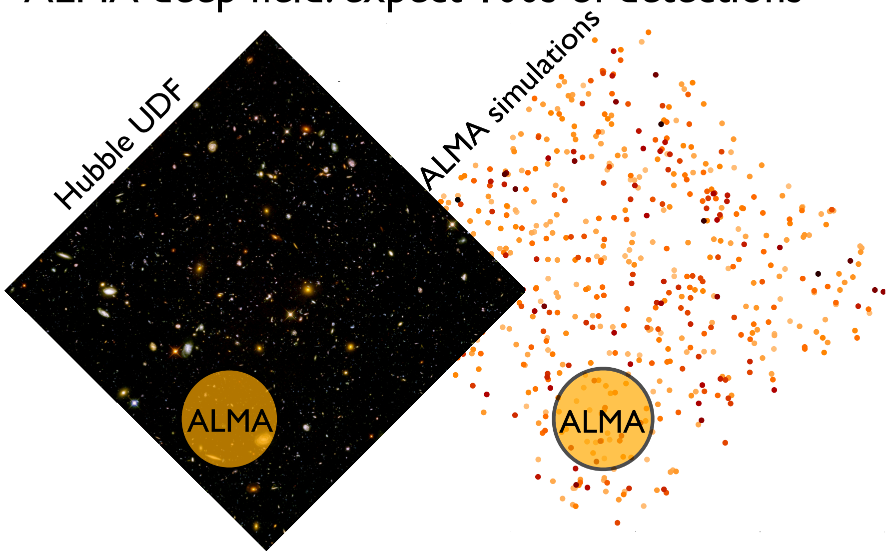
molecular deep field: approach

CO transitions as function of redshift, f(T, ρ)



this is now possible given wide bandwidths of current and upcoming facilities

ALMA deep field: expect 100s of detections

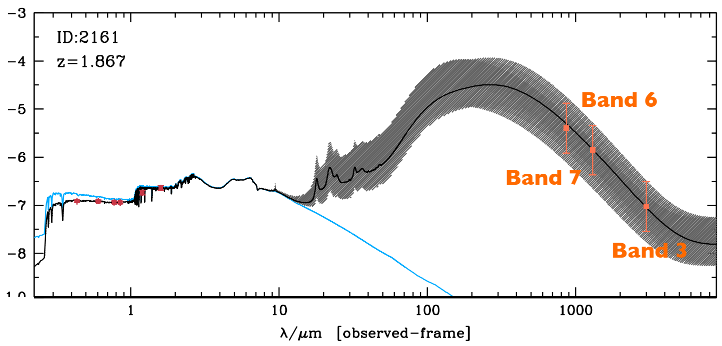


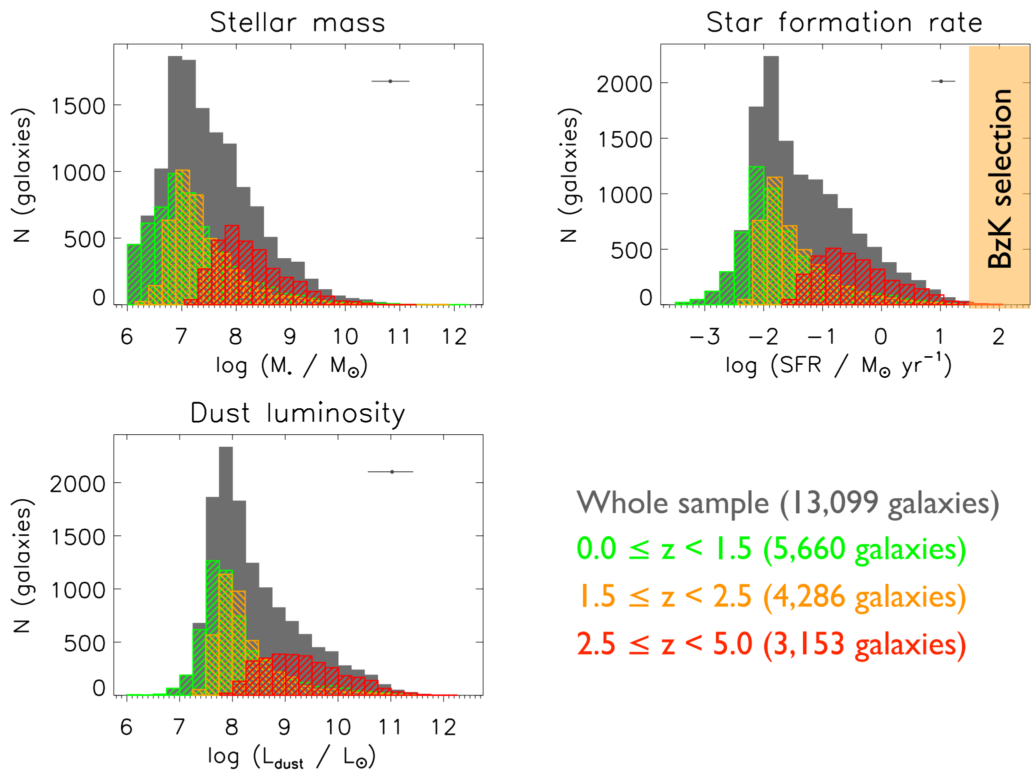
da Cunha et al. submitted

ALMA deep field: predicted properties of UDF galaxies

continuum: observed UV/optical SEDs → SED models (Da Cunha) → dust luminosity (from attenuation in UV) → FIR luminosity → ALMA flux densities

lines: L_{FIR} → L_{CO} (Daddi et al., Genzel et al.), assuming range of CO excitations MW↔M82)

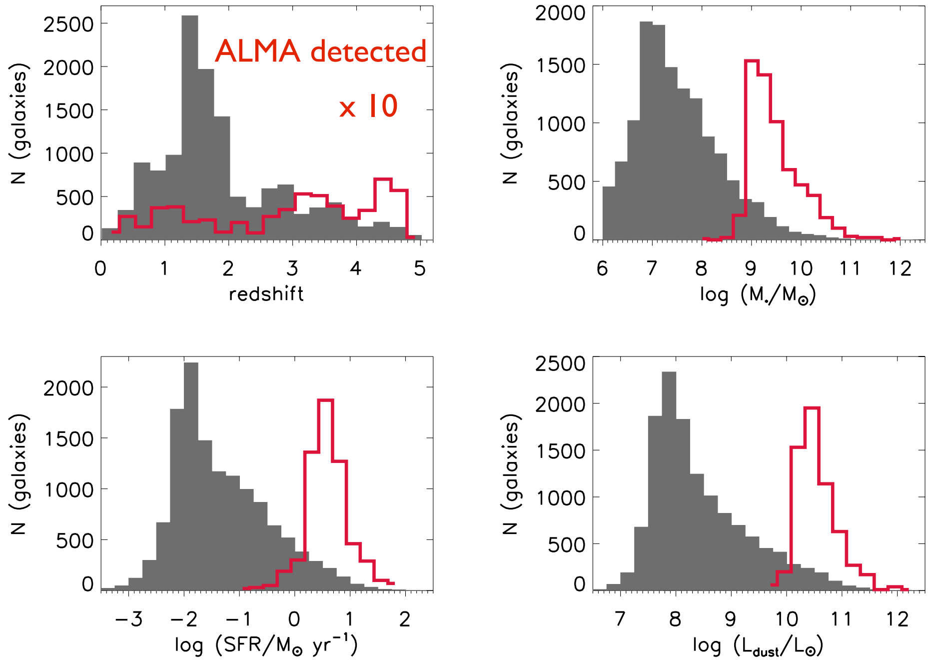




predicted properties of UDF galaxies: example: band 6 continuum

- Full ALMA
- total ~300 hours
- FOV = 26 arcsec
- 6.2 hours/pointing
- rms = 5.1 microJy
- >600 detections

    actual observations can be immediately compared to these expectations!



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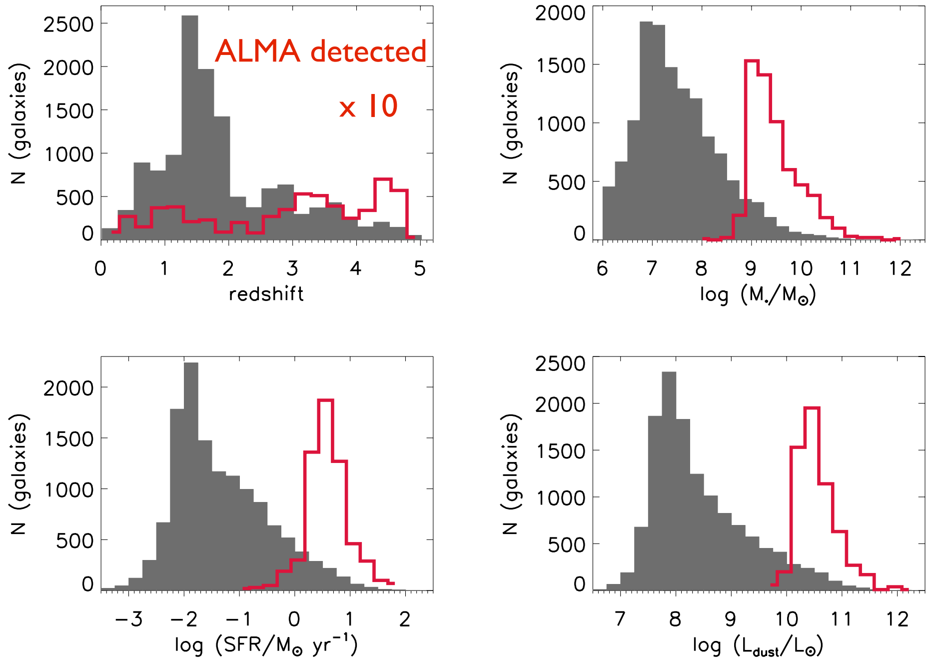
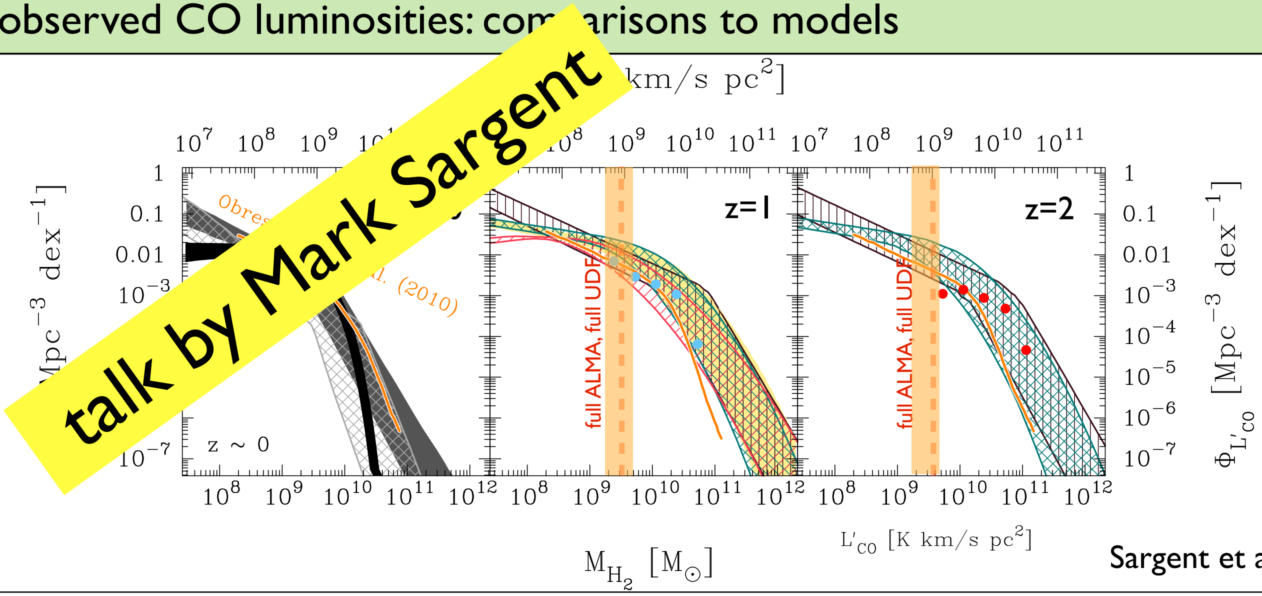


observed CO luminosities: comparisons to models

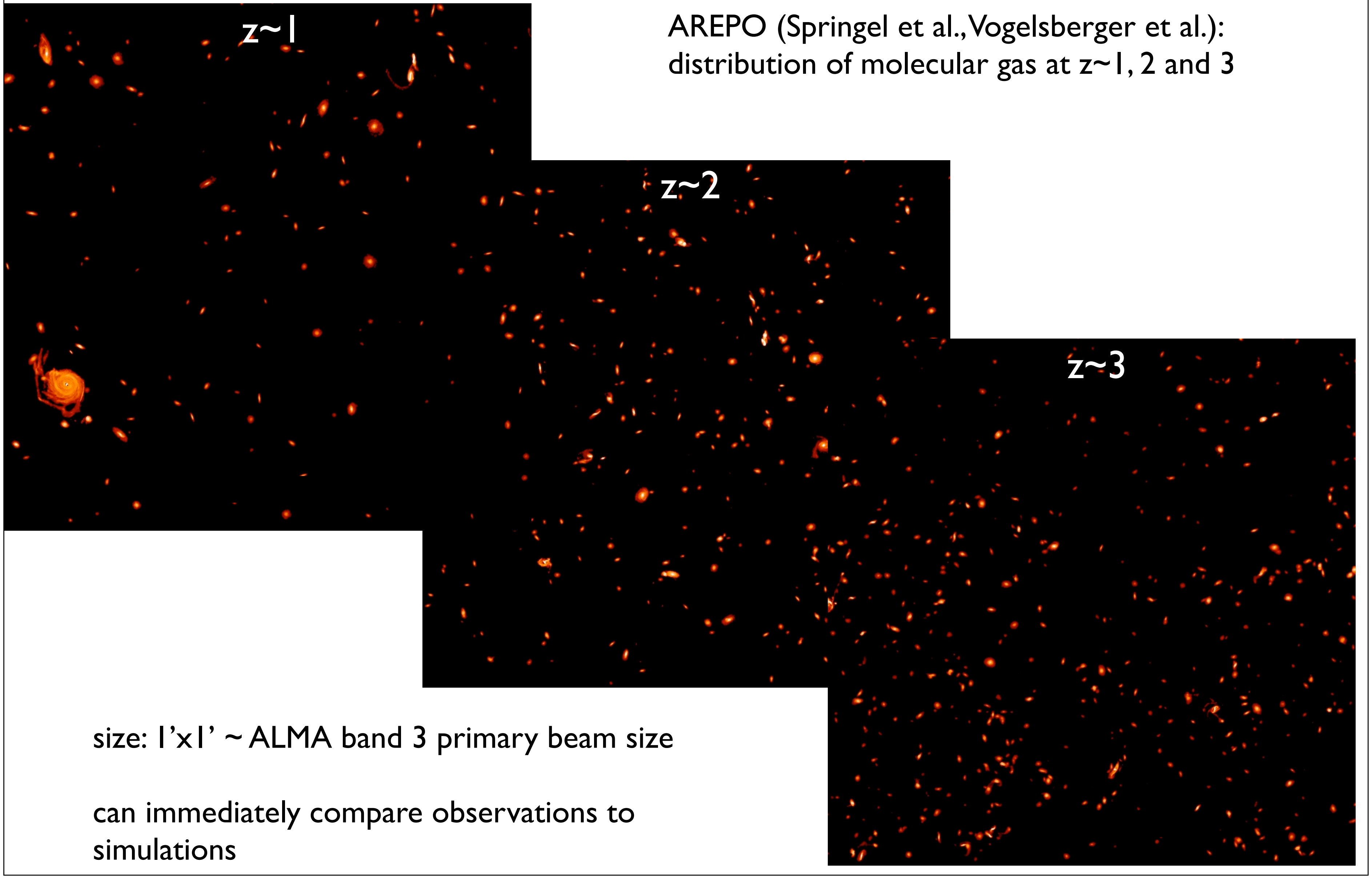
e.g. comparison to Obreschkow et al. Lagos et al., Sargent et al.



Sargent et al. 2012

predictions by numerical simulations

AREPO (Springel et al., Vogelsberger et al.): distribution of molecular gas at z~1, 2 and 3



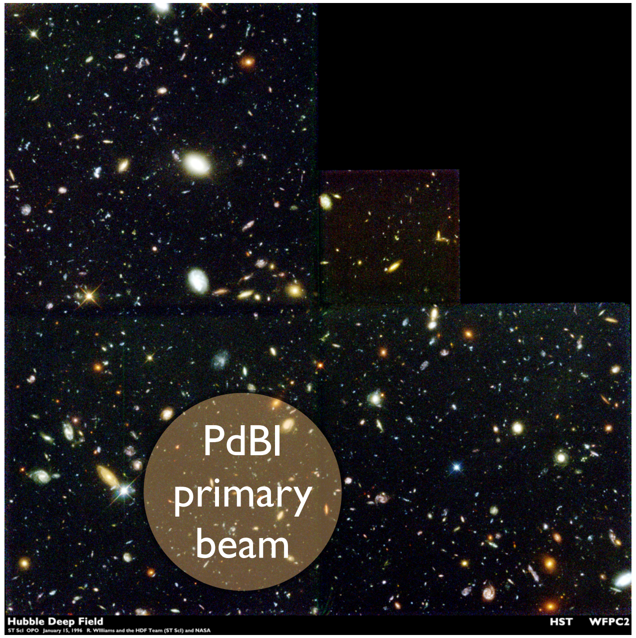
size: 1'x1' ~ ALMA band 3 primary beam size

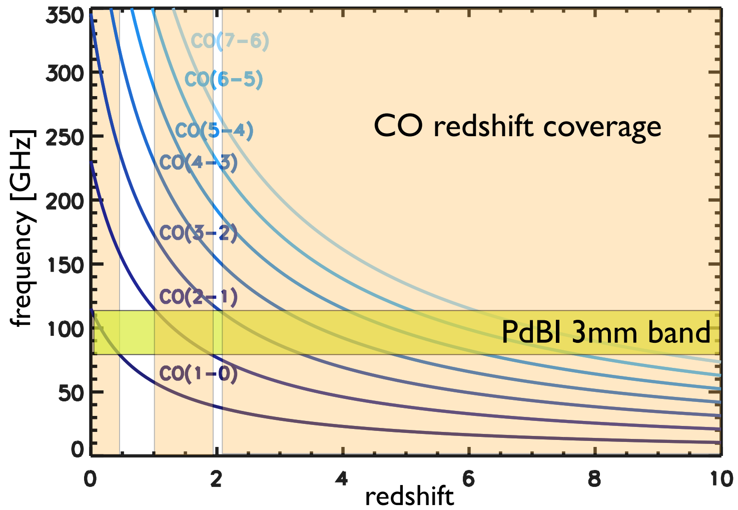
can immediately compare observations to simulations

first molecular deep field with PdBI: HDF

covered full 3mm band in 10 frequency settings (2011-2012)

3mm band: low-J coverage, highest fractional BW, largest PB





almost complete redshift coverage

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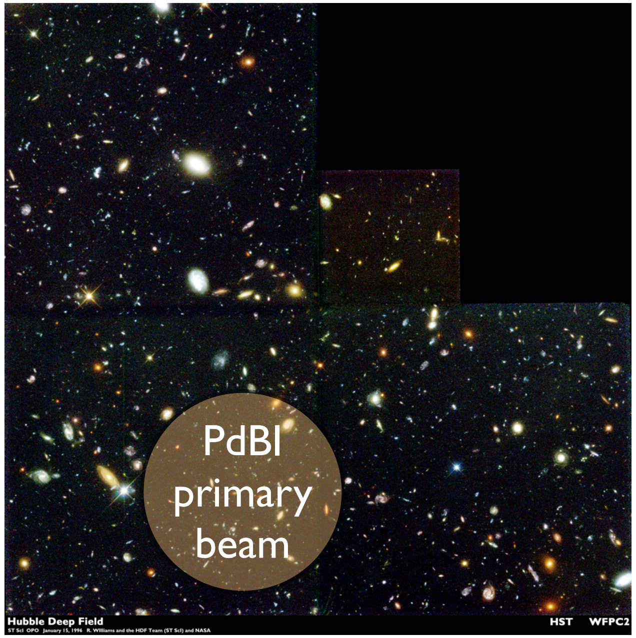
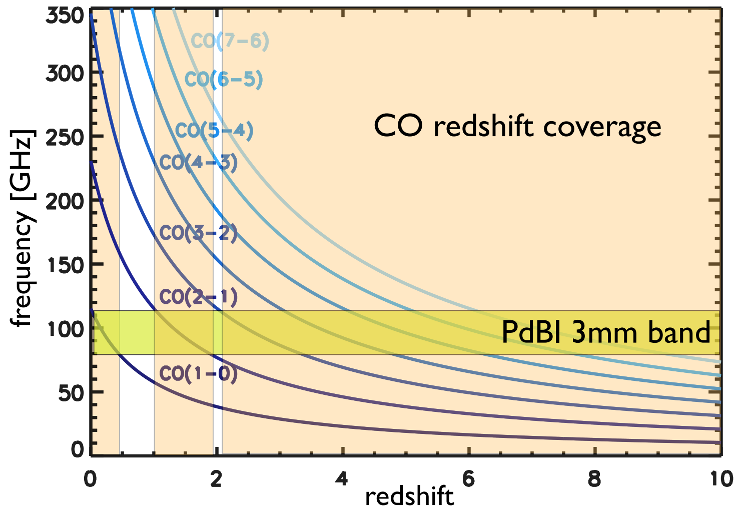
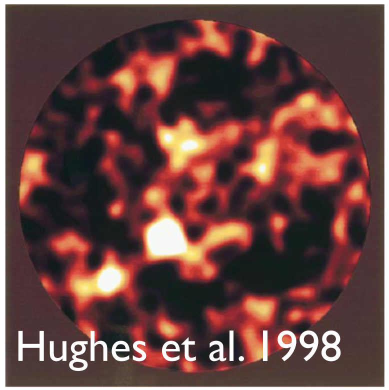




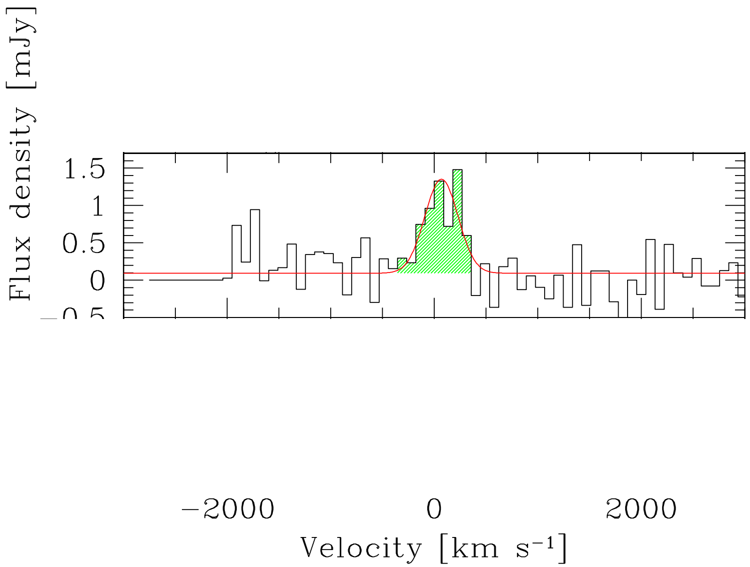
almost complete redshift coverage

this field included HDF850.1



The Case of HDF850.1

spectrum at position of HDF850.1



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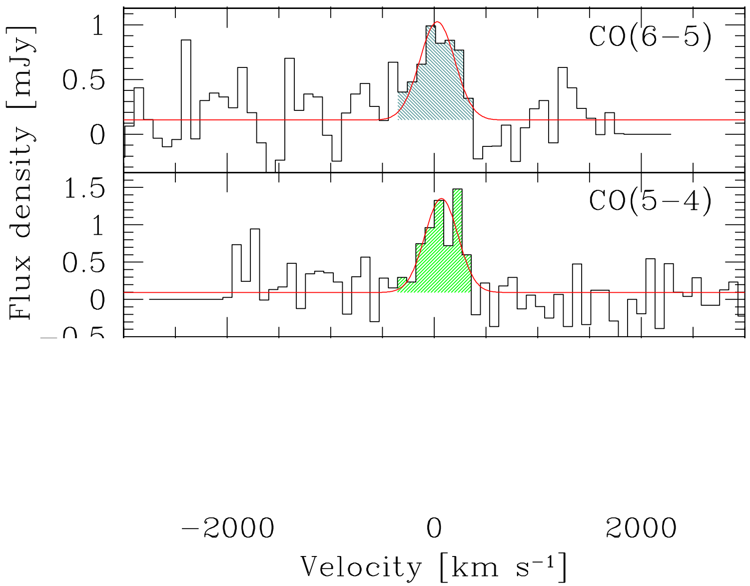

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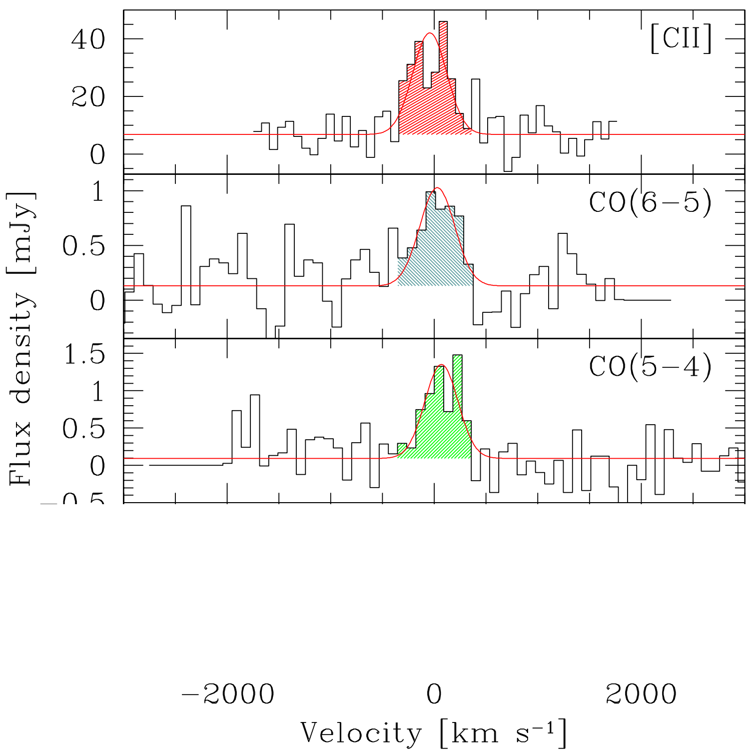
spectrum at position of HDF850.1

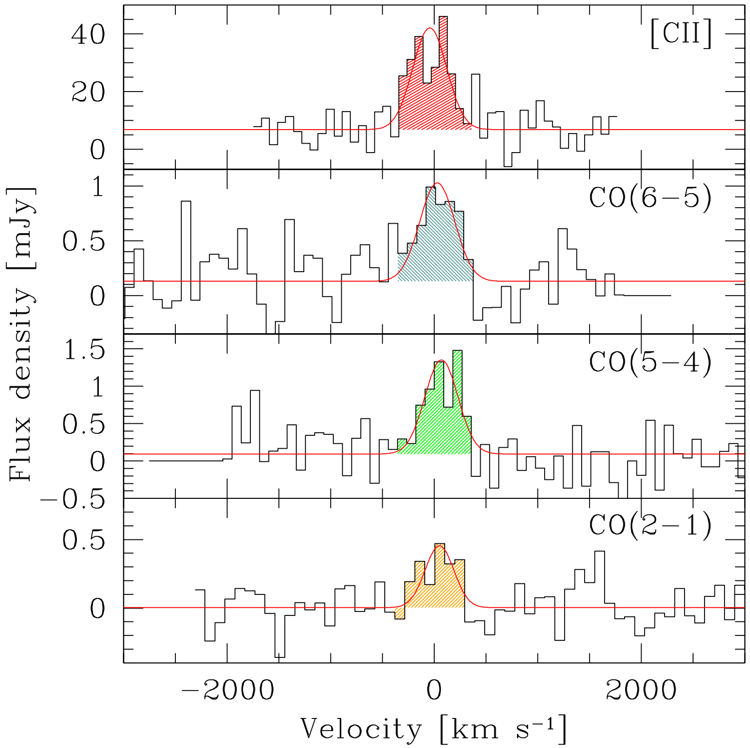


This nails the redshift to z=5.183!

Walter et al. 2012

The Case of HDF850.1

spectrum at position of HDF850.1



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Walter et al. 2012

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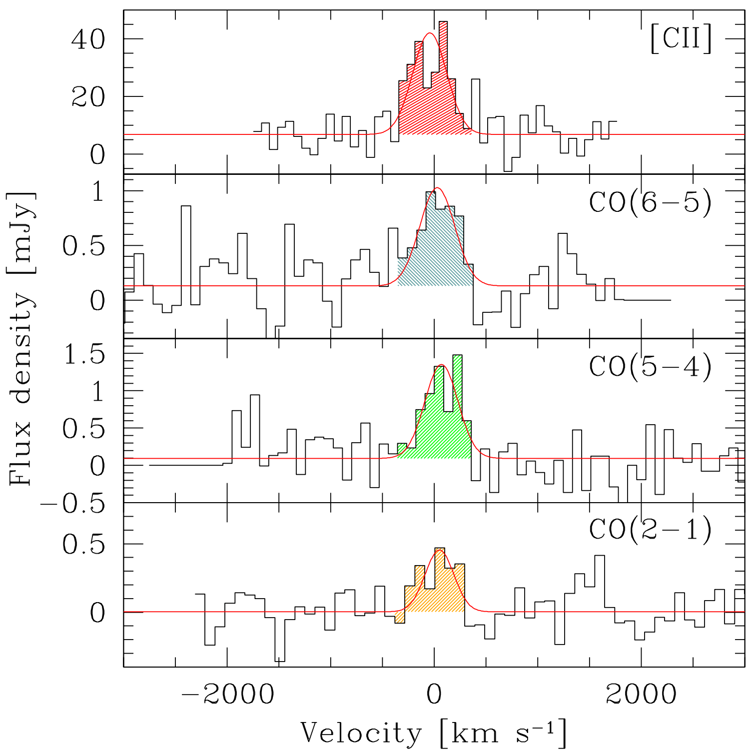
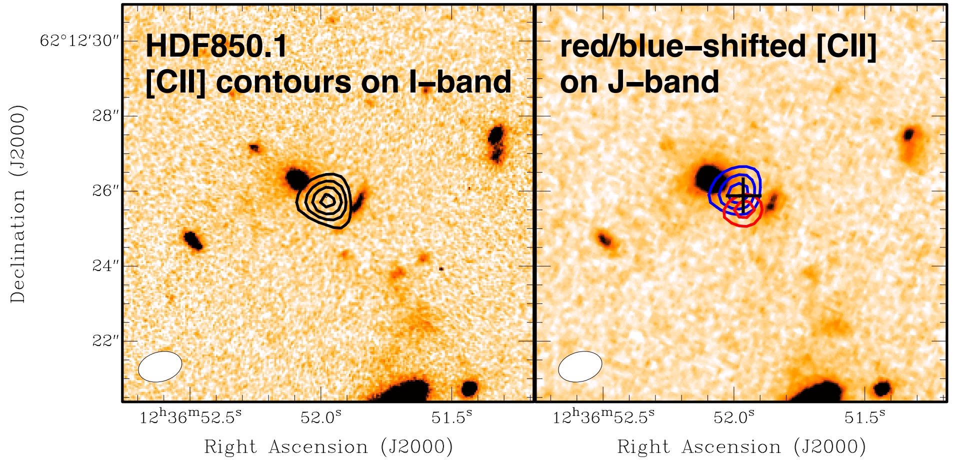


precise location and redshift: ***no counterpart*** identifiable in deepest HST observations



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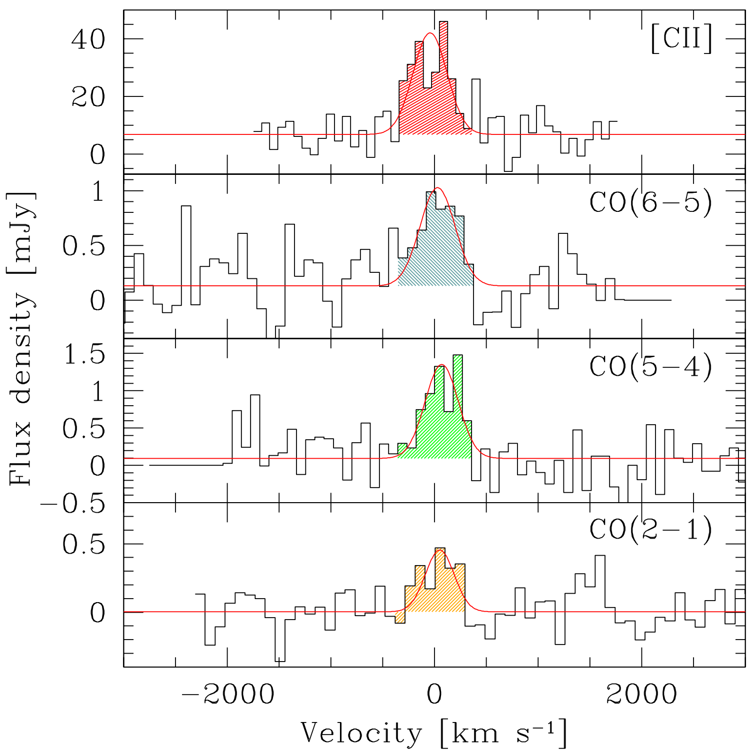
Walter et al. 2012

The Case of HDF850.1

spectrum at position of HDF850.1



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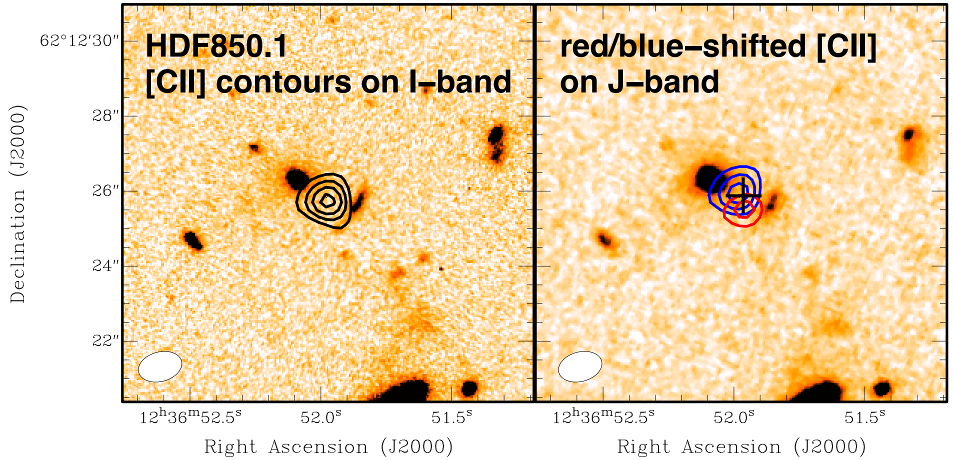
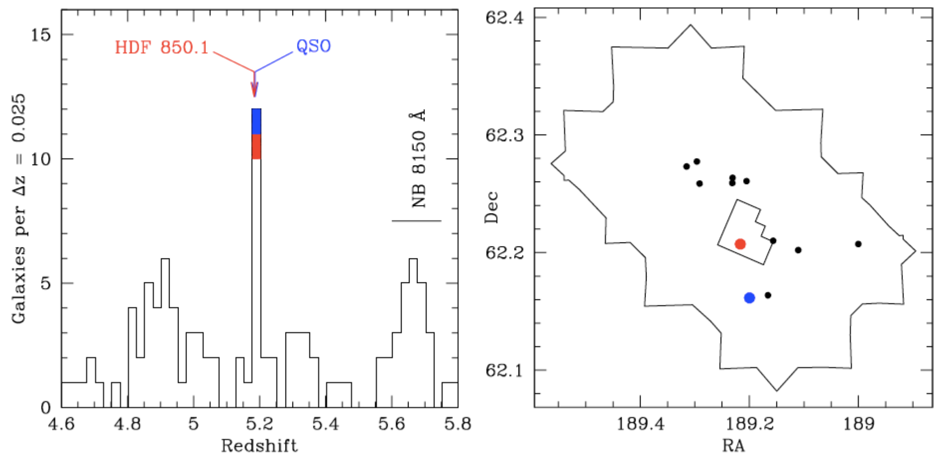


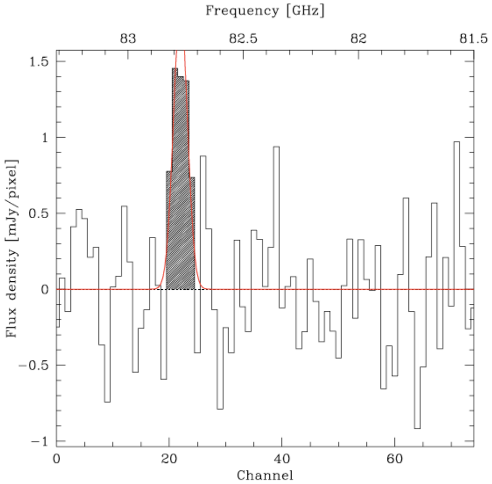
however source is located in galaxy ***overdensity*** at z=5.2, including one quasar!

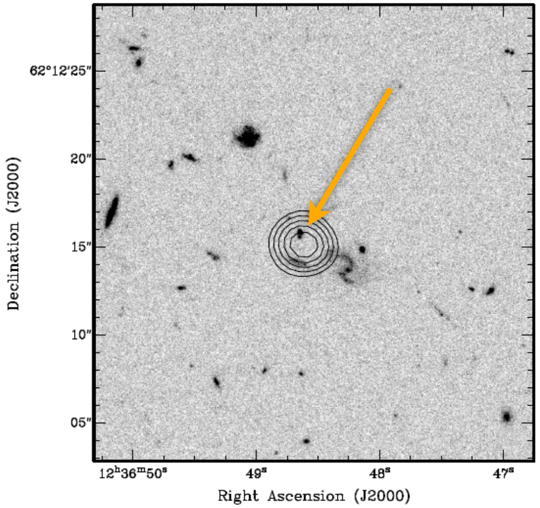


Walter et al. 2012

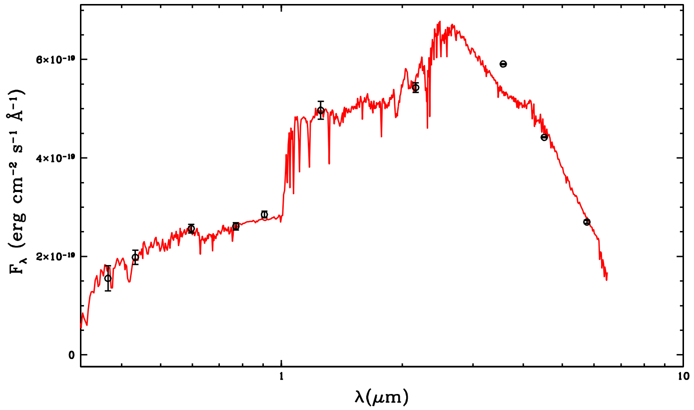
blind detection of other sources:

example:



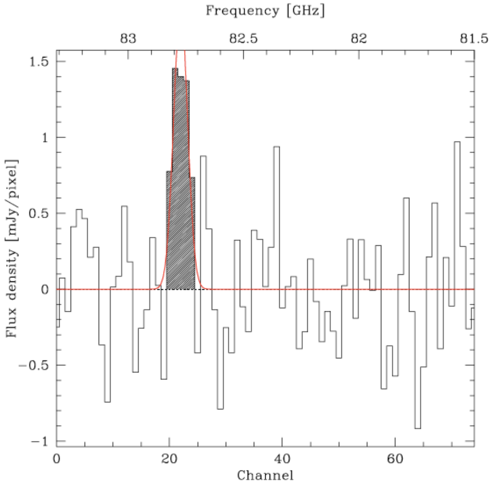


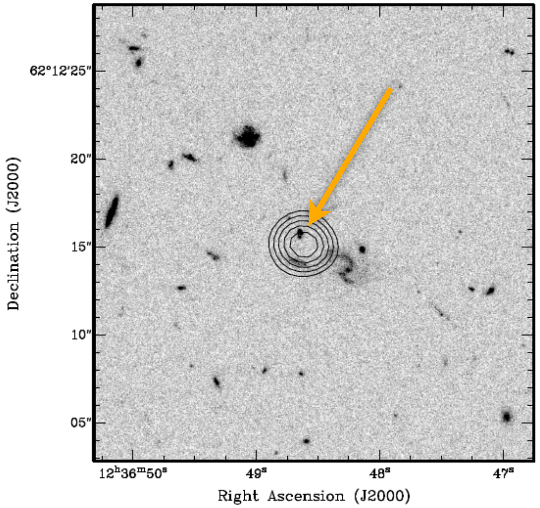
2nd CO line confirms z=1.76



blind detection of other sources:

example:





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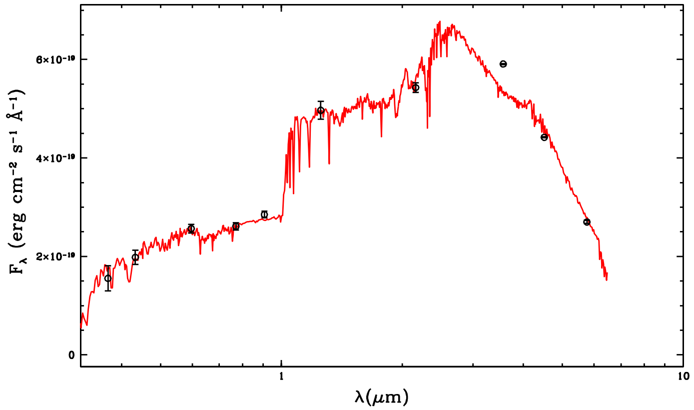
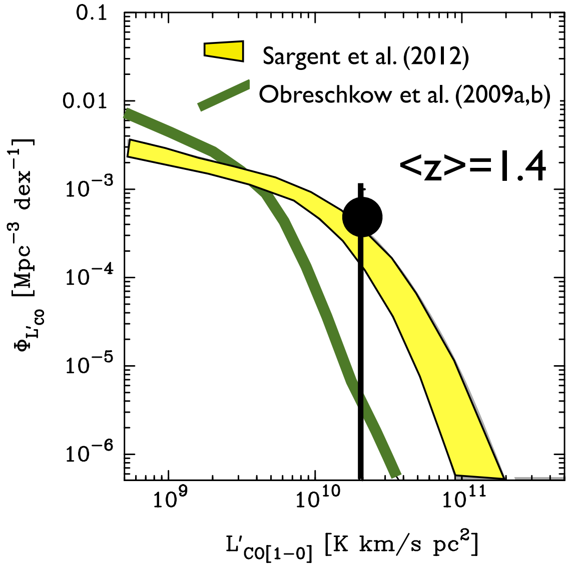
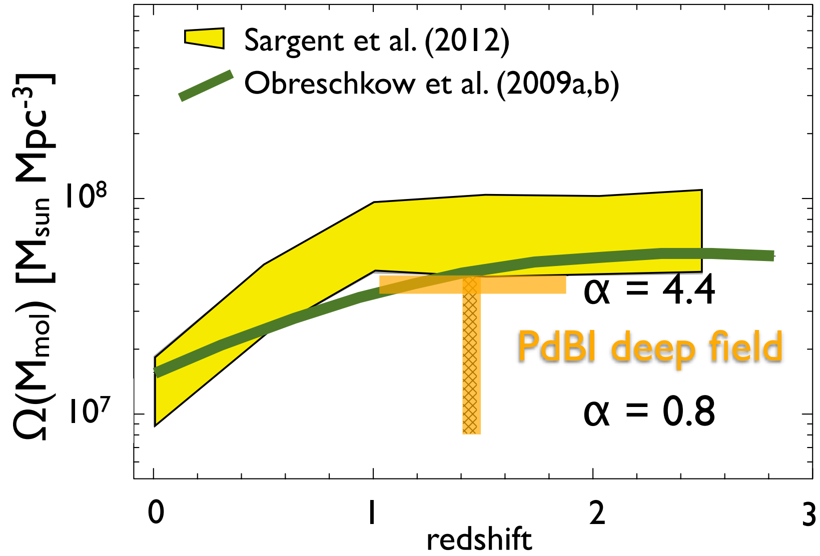


volume probed for CO(2-1)
line from z=1.0-1.8 (<z>=1.4)



first blind constraints on $\Omega(M_{mol})$

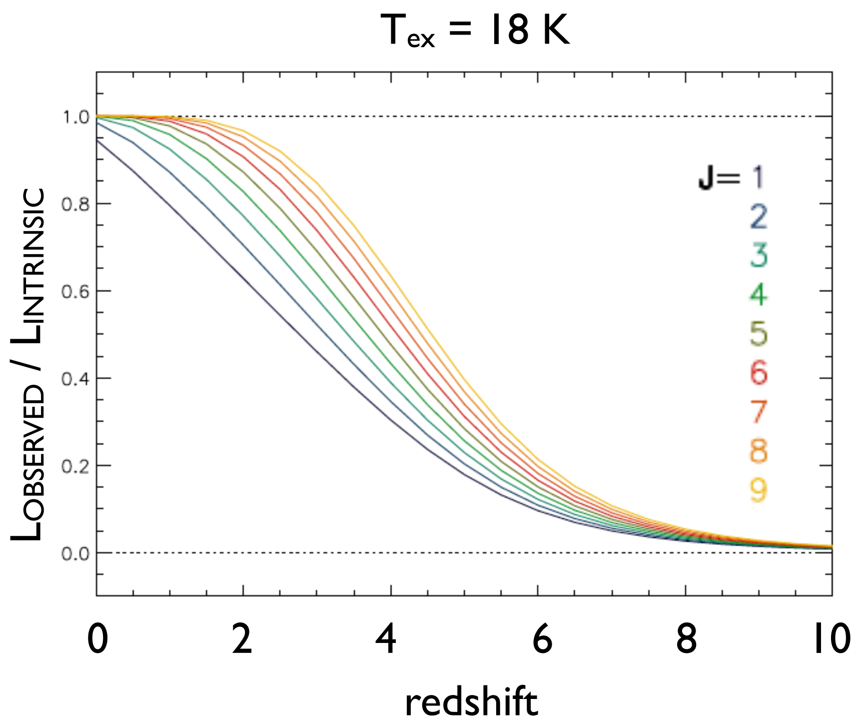


going to the highest redshifts, z>>5

will we loose CO as our main tracer?

problem I: conversion factor at low metallicities?

problem II: the CMB is not our friend



da Cunha et al. 2012

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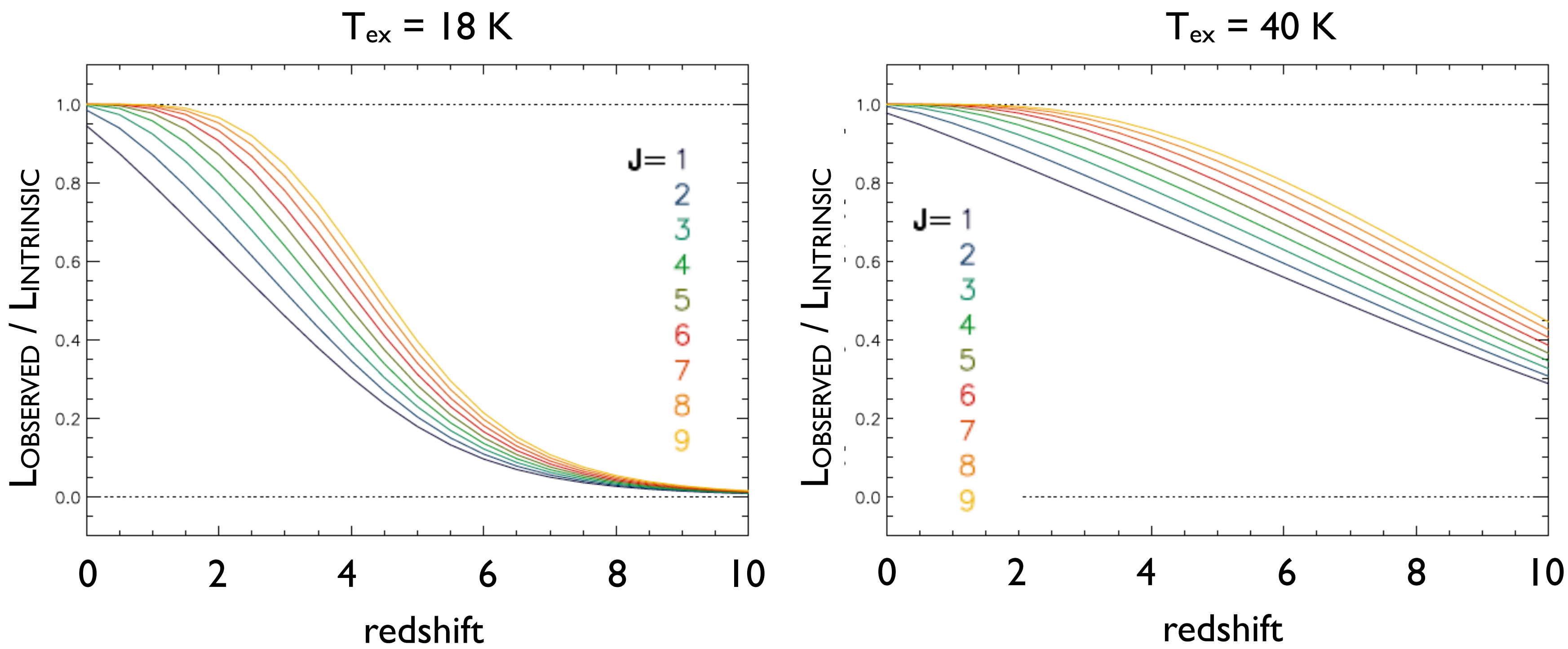
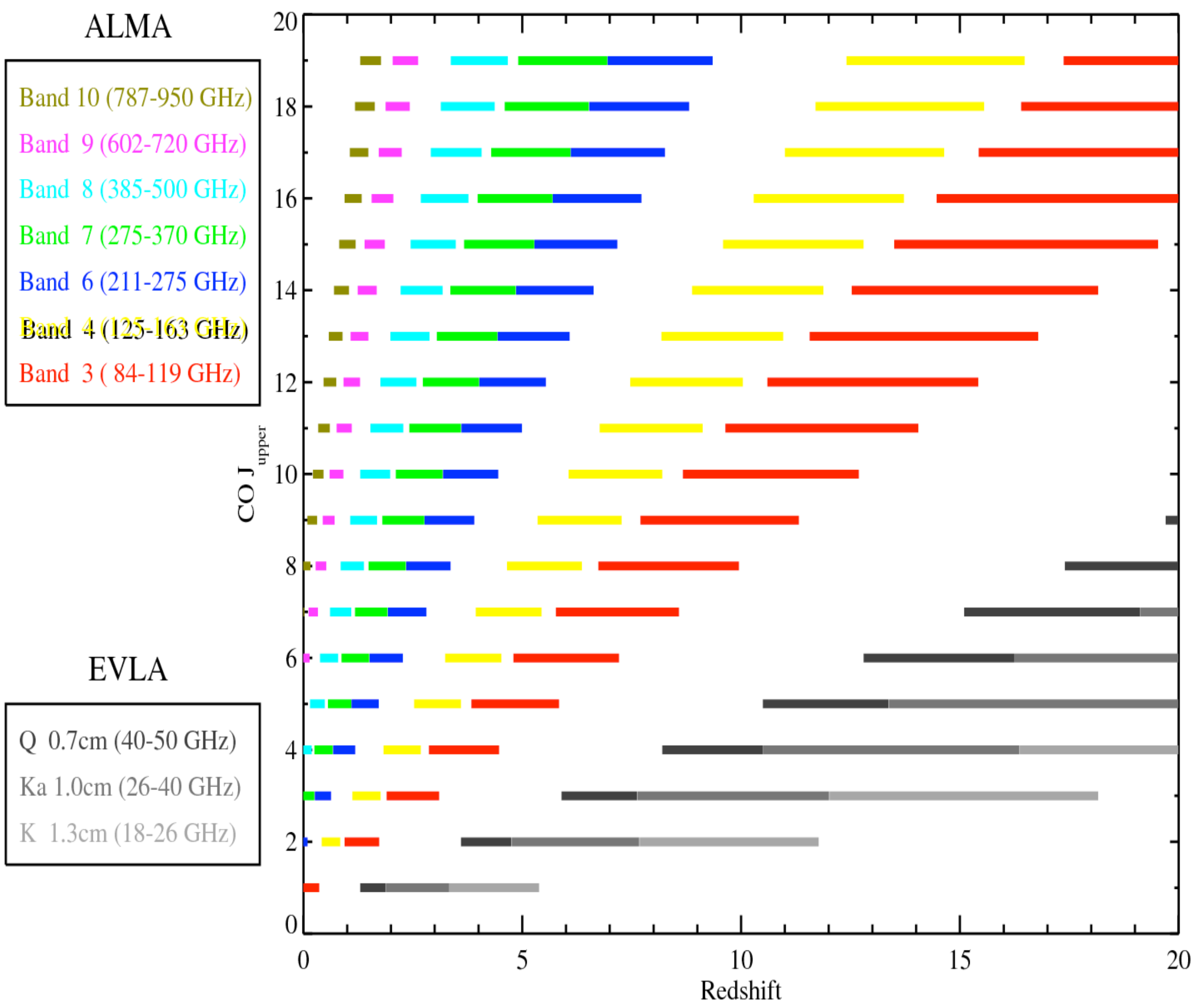
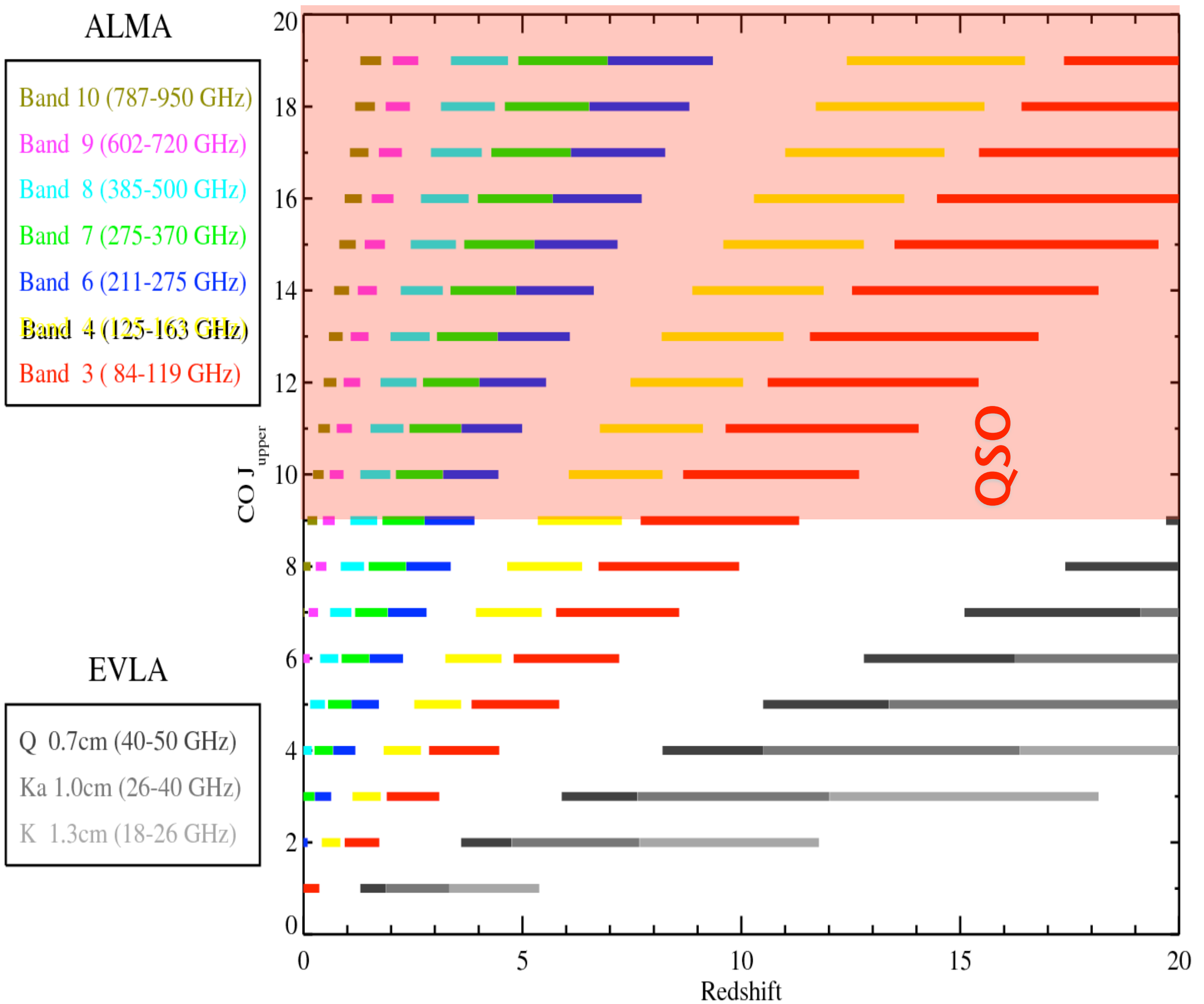


da Cunha et al. 2012

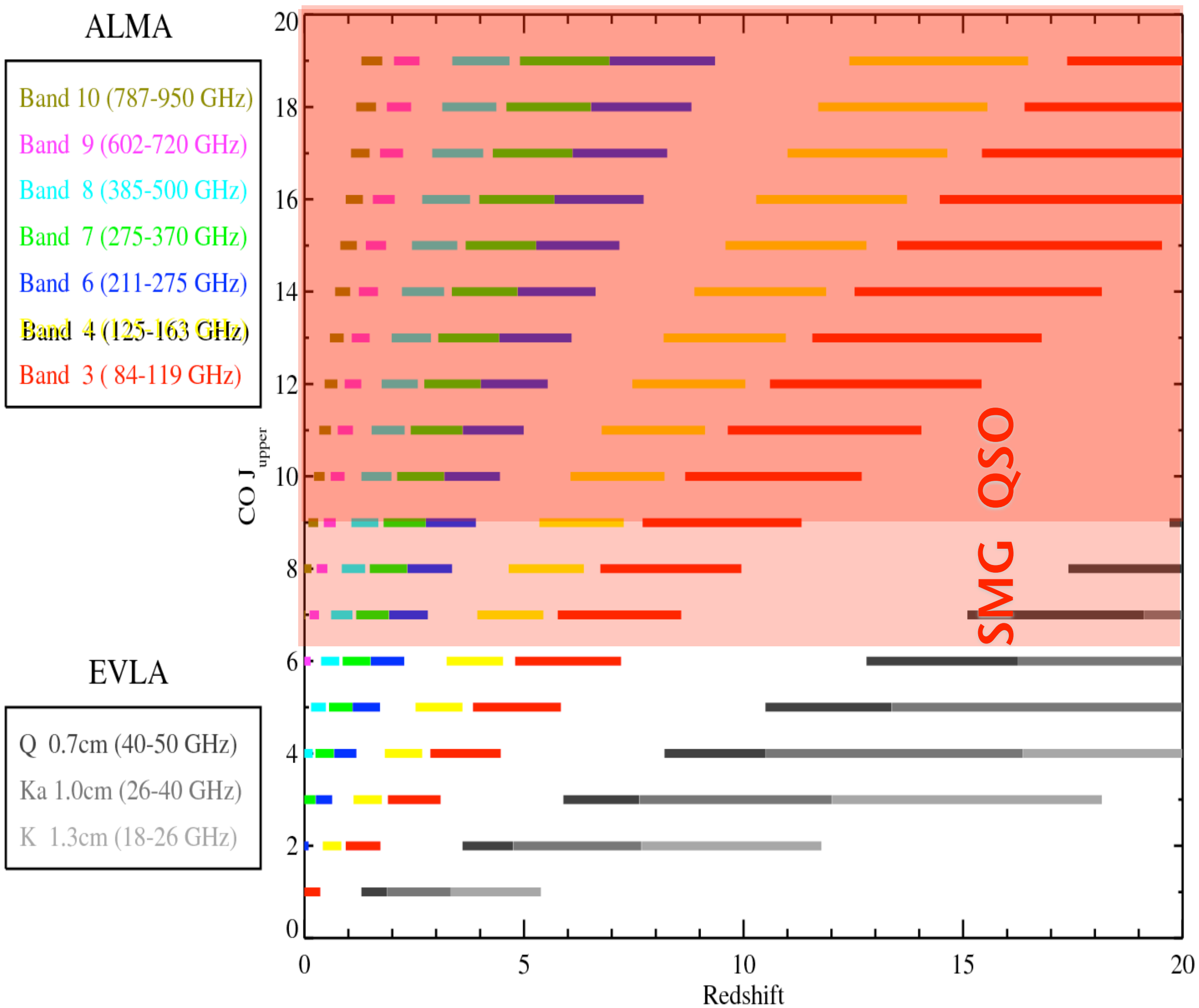
CO line redshift coverage for ALMA and JVLA



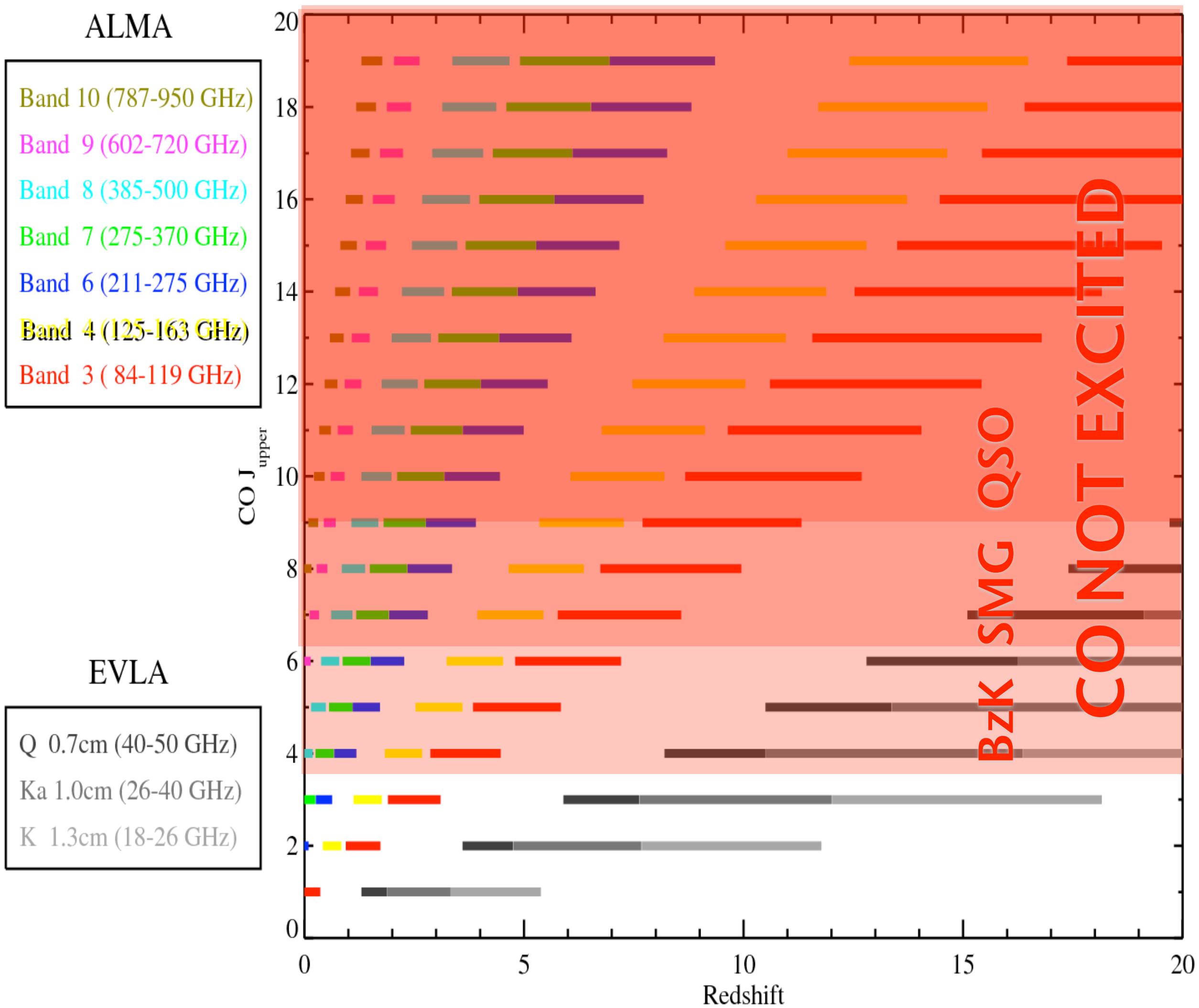
CO line redshift coverage for ALMA and JVLA



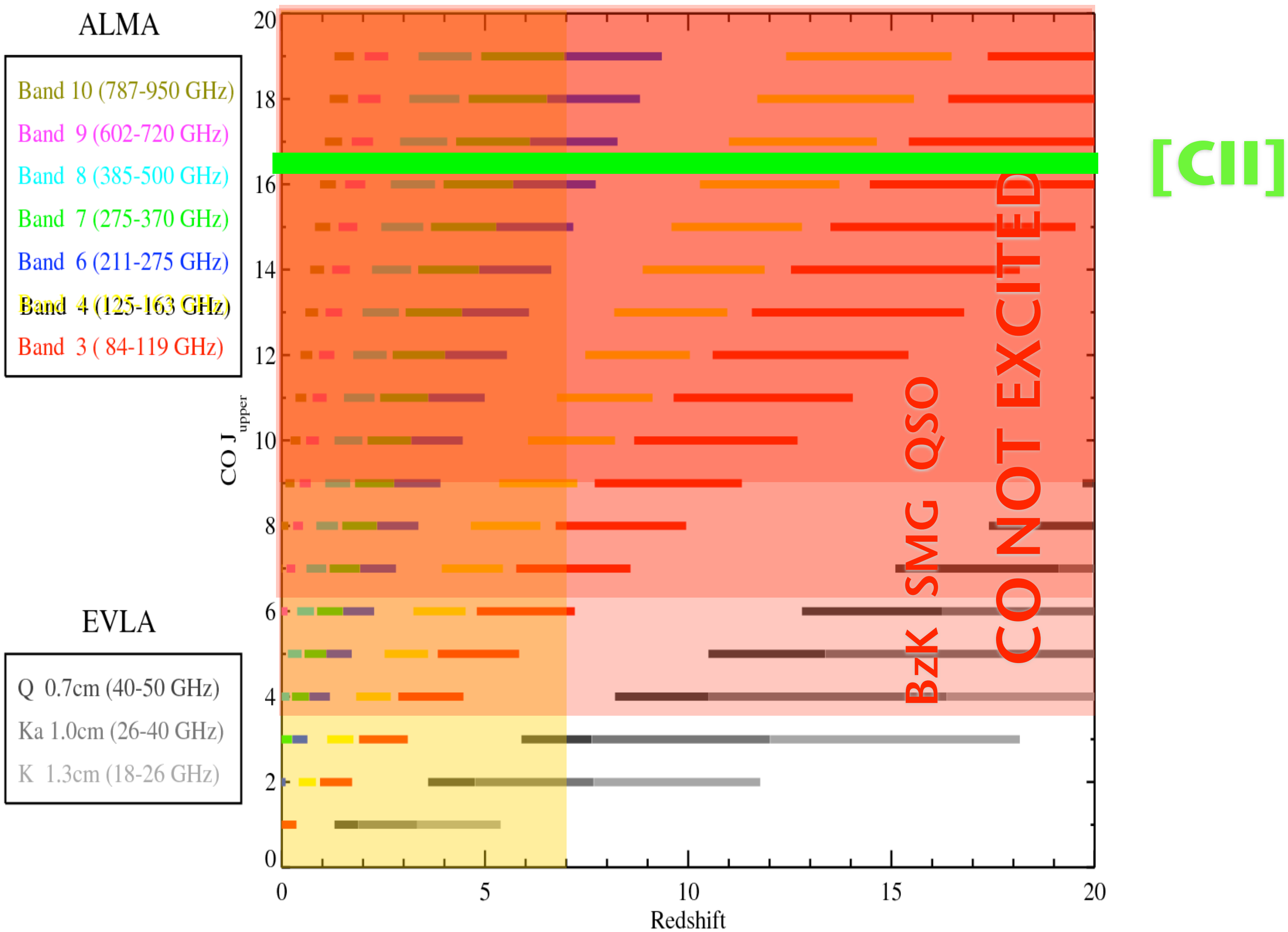
CO line redshift coverage for ALMA and JVLA



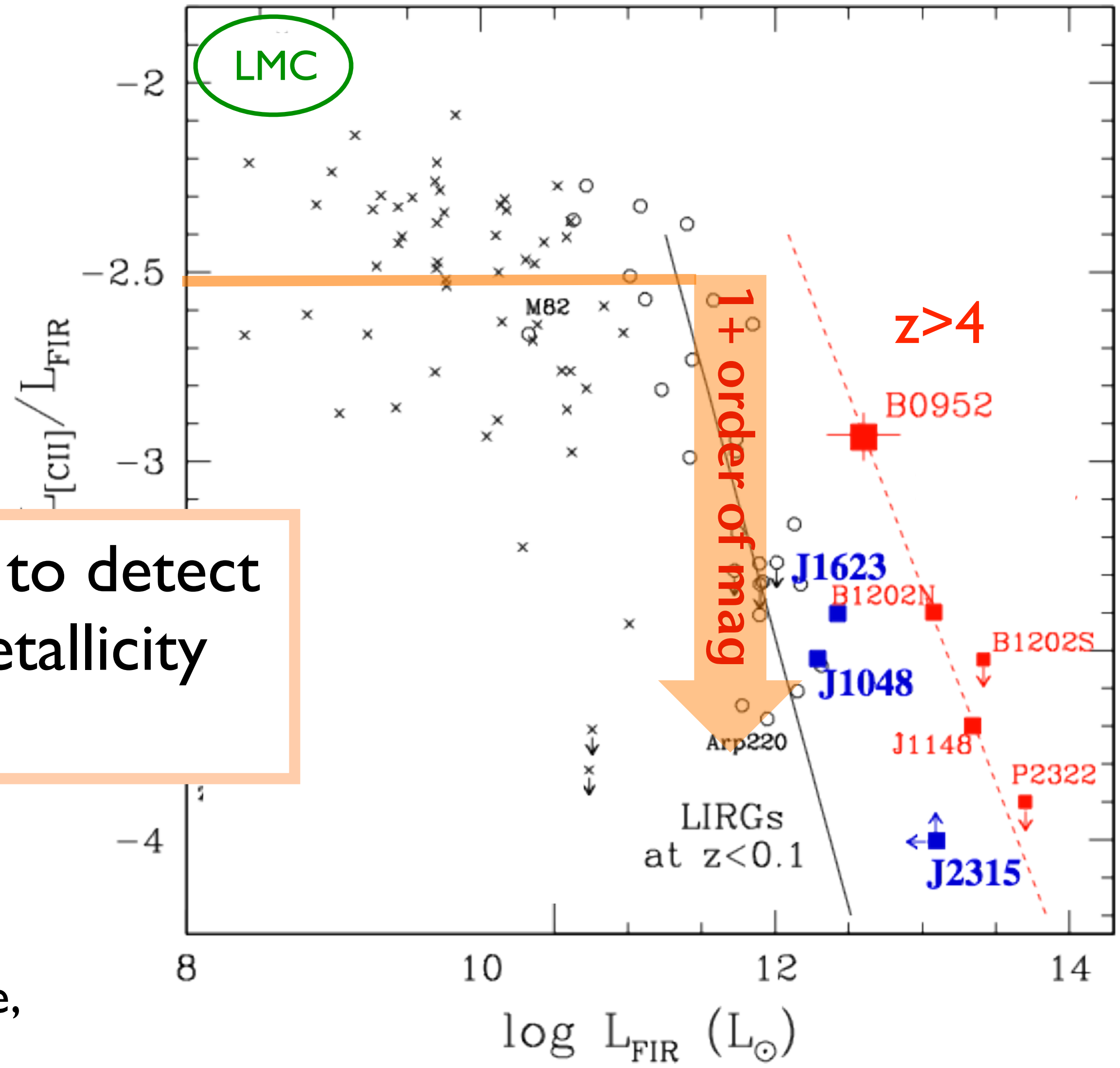
CO line redshift coverage for ALMA and JVLA



going to the highest redshifts



[CII] to the rescue?

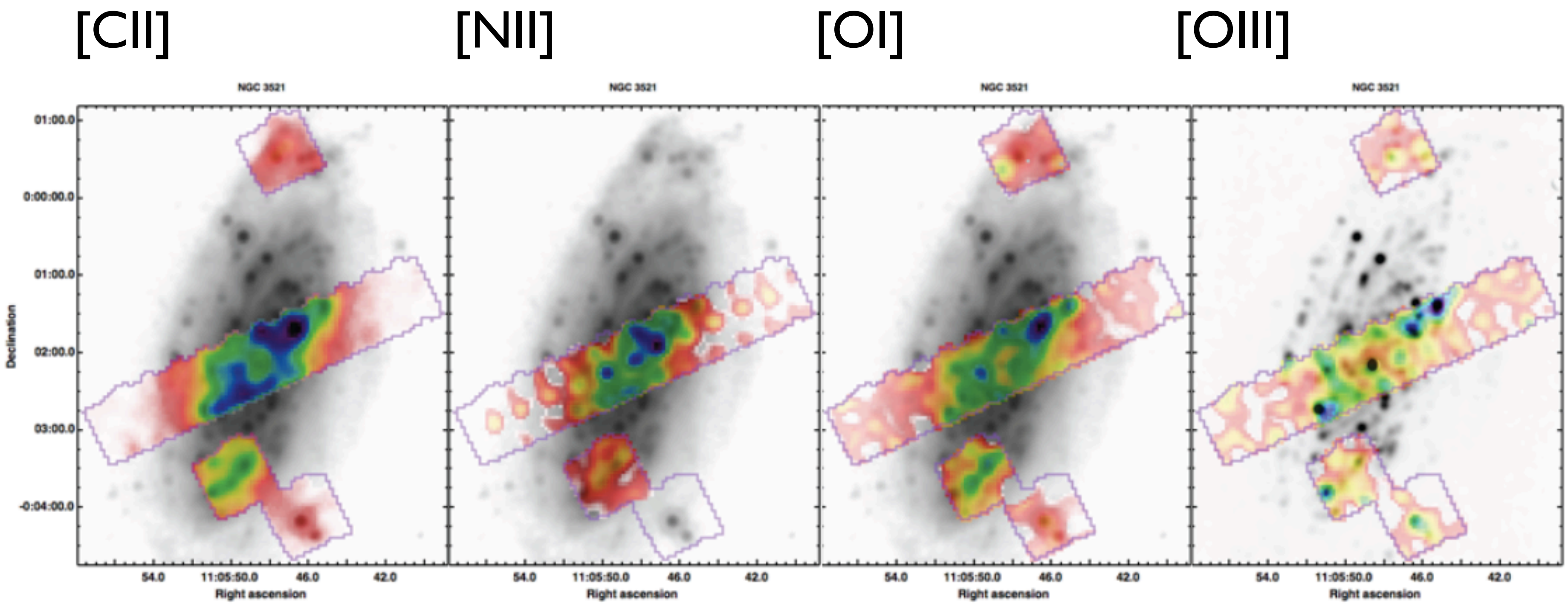


may be easier to detect fainter, low metallicity sources?

- [CII] is bright
- [CII] is not easily interpretable, traces ionized and neutral gas

Maiolino et al. 2009 [updated]

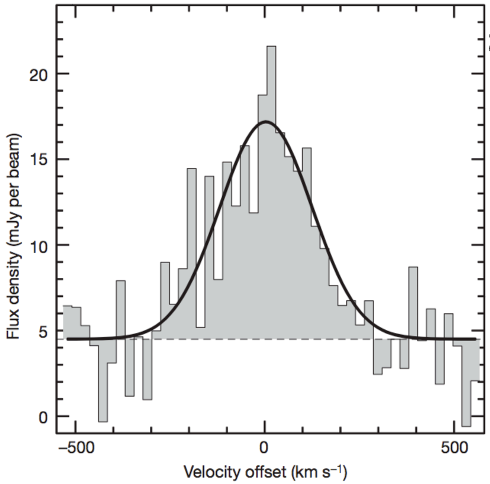
Local [CII] calibrations ongoing...

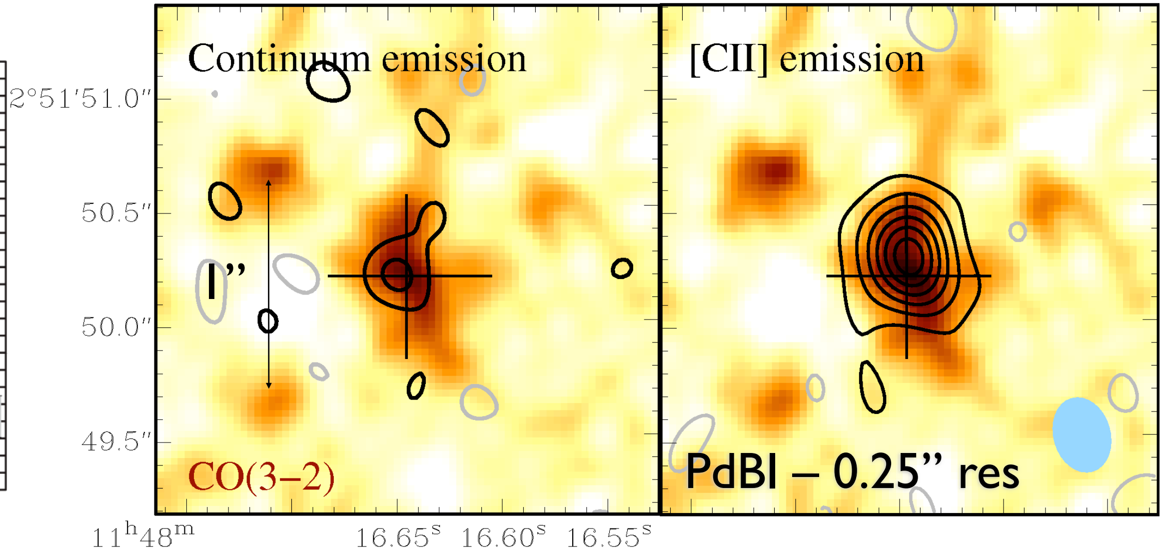


e.g., KINGFISH project
(Smith et al., Bolatto et al.)

Maximum Starburst at z=6.4 - resolved [CII] emission

Walter ea. 2009





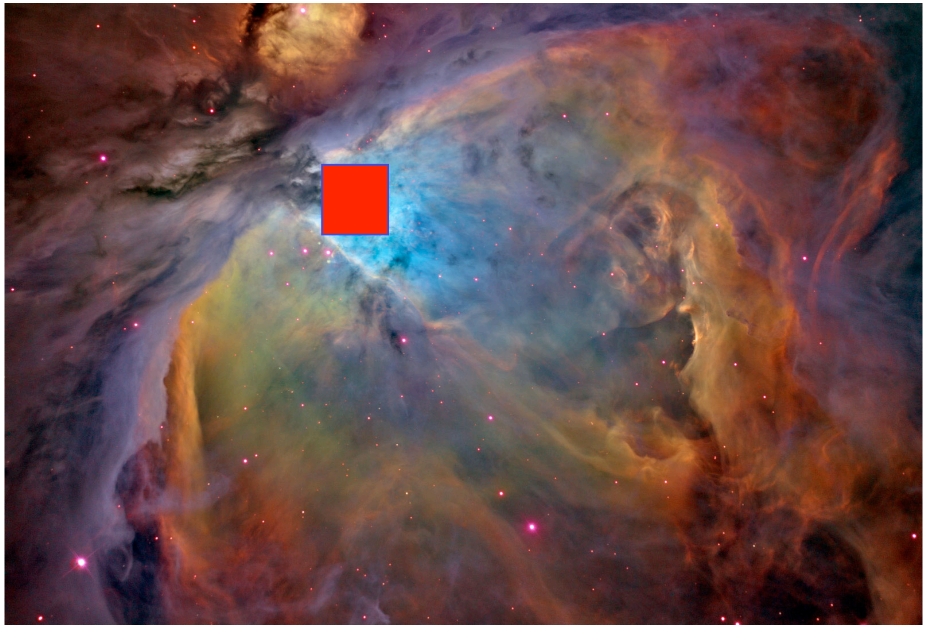
FIR continuum

[CII]

- [CII] size ~ 1.5 kpc => SFR/area ~ 1000 $M_{\odot}$ yr^{-1} kpc^{-2}
- Maximal starburst: (Thompson et al. 2005)
    - ➢ Self-gravitating gas disk, Vertical support: radiation pressure

quick poll!

SFRSD=1000 M_{sun} yr^{-1} kpc^{-2} !!??



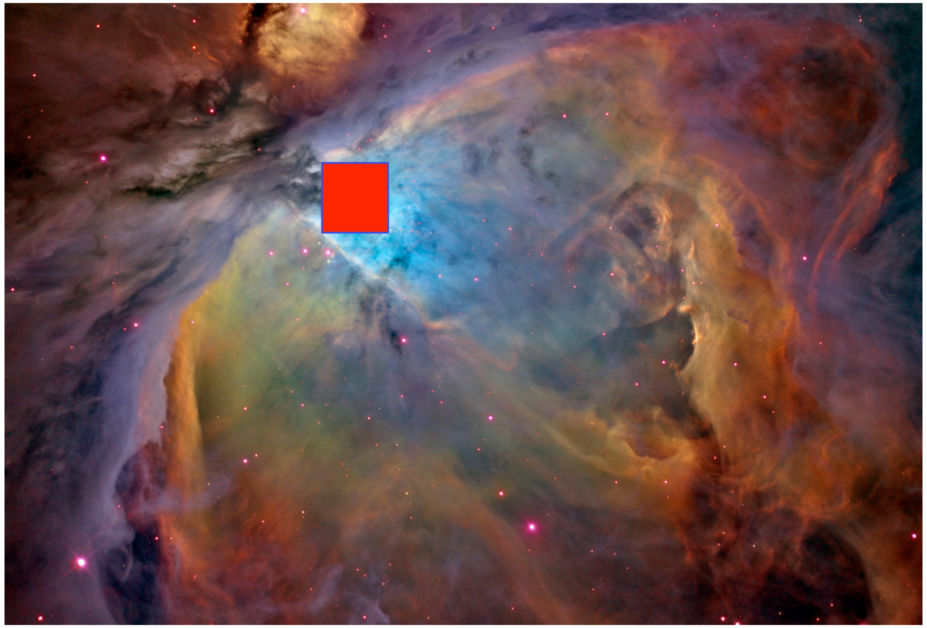
Comparison to star formation rate surface density in Orion?!

$SFRSD_{J1148}$=1000 M_{sun} yr^{-1} kpc^{-2}

A) $SFRSD_{Orion}$ = $\mathbf{10^{-6}}$ x $SFRSD_{J1148}$
B) = $\mathbf{10^{-3}}$ x $SFRSD_{J1148}$
C) = **1** x $SFRSD_{J1148}$

quick poll!

$SFRSD=1000\ M_{sun}\ yr^{-1}\ kpc^{-2}$!!??



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- ✖ B) $= \mathbf{10^{-3}} \times SFRSD_{J1148}$
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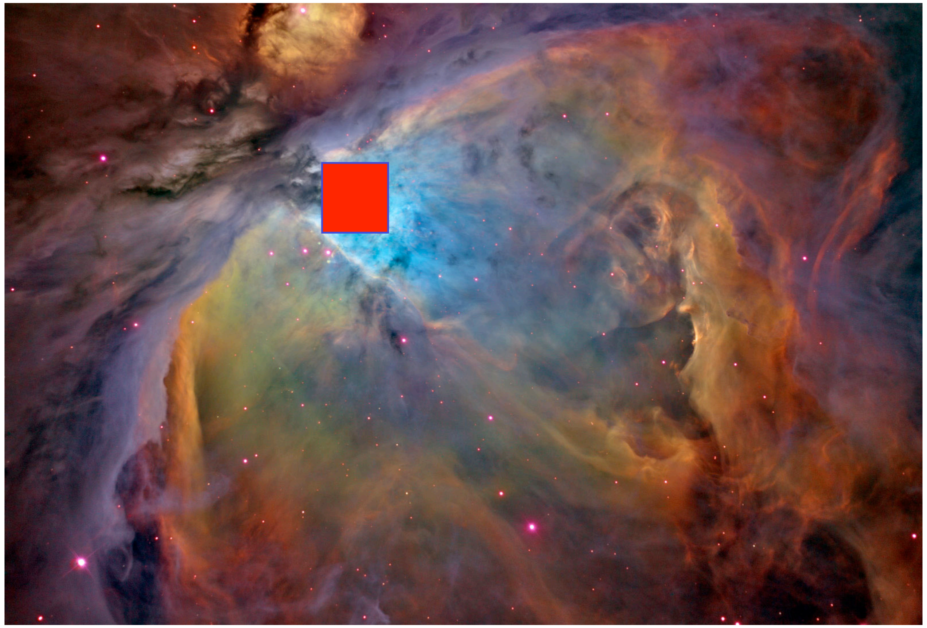
quick poll!

SFRSD=1000 M_{sun} yr^{-1} kpc^{-2} !!??



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THE ASTROPHYSICAL JOURNAL, 630:167–185, 2005 September 1

RADIATION PRESSURE–SUPPORTED STARBURST DISKS AND ACTIVE GALACTIC NUCLEUS FUELING

TODD A. THOMPSON,[1,2] ELIOT QUATAERT,[2] AND NORMAN MURRAY[3,4,5]
Received 2005 March 1; accepted 2005 May 14

ABSTRACT

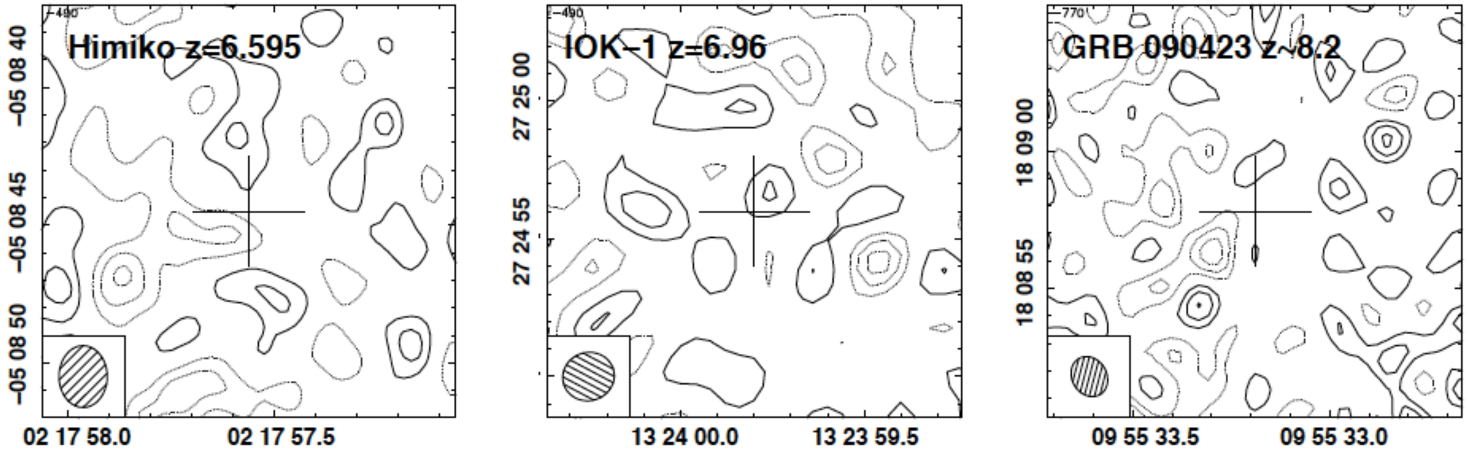
We consider the structure of marginally Toomre-stable starburst disks under the assumption that radiation pressure on dust grains provides the dominant vertical support against gravity. This assumption is particularly appropriate when the disk is optically thick to its own infrared radiation, as in the central regions of ULIRGs. We argue that because the disk radiates at its Eddington limit (for dust), the "Schmidt law" for star formation changes in the optically thick limit, with the star formation rate per unit area scaling as $\dot{\Sigma}_\star \propto \Sigma_g/\kappa$, where Σ_g is the gas surface density and κ is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of $F \sim 10^{13}\ L_\odot\ \mathrm{kpc}^{-2}$, $\dot{\Sigma}_\star \sim 10^3\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$, and $T_{\rm eff} \sim 90$ K, respectively. We compare our model predictions with observations of ULIRGs and find good agreement. We extend our model of starburst disks from many hundred parsec scales to subparsec

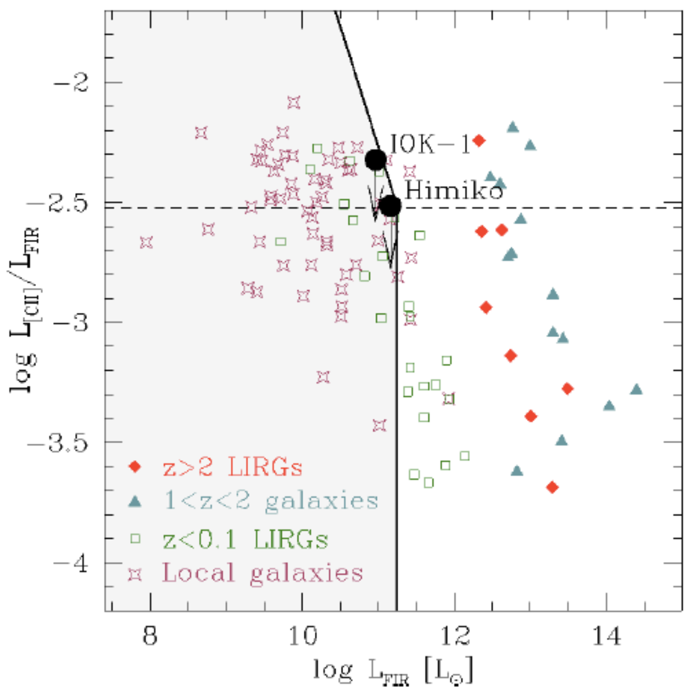
... the starburst disk on parsec scales can approach $h \sim r$, perhaps accounting for the nuclear obscuration in some type 2 AGNs. We also argue that the disk of young stars in the Galactic center may be the remnant of such a compact nuclear starburst.

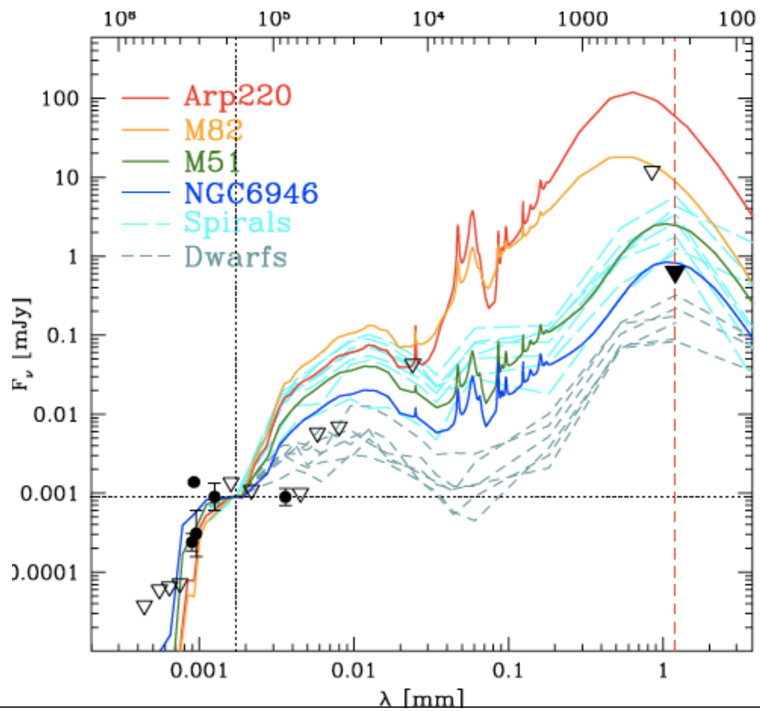
density and κ is the mean opacity of the disk. Our calculations further show that optically thick starburst disks have a characteristic flux, star formation rate per unit area, and dust effective temperature of $F \sim 10^{13}\ L_\odot\ \mathrm{kpc}^{-2}$, $\dot{\Sigma}_\star \sim$ $10^3\ M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$, and $T_{\rm eff} \sim 90$ K, respectively. We compare our model predictions with observations of ULIRGs

Search for [CII] in z>6.5 Lyman Alpha Emitters (and one z~8 GRB host)

Small survey at PdBI to detect [CII] at z>6.5: unsuccessful

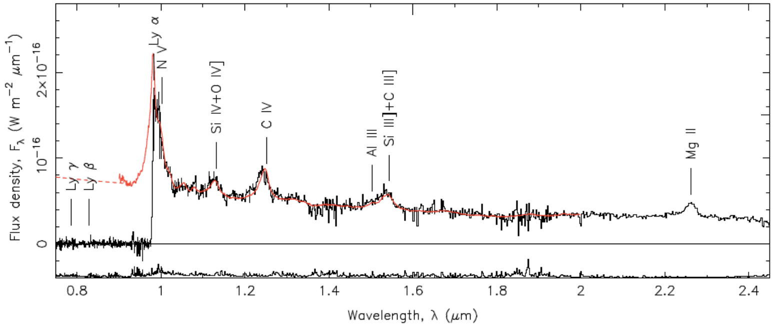






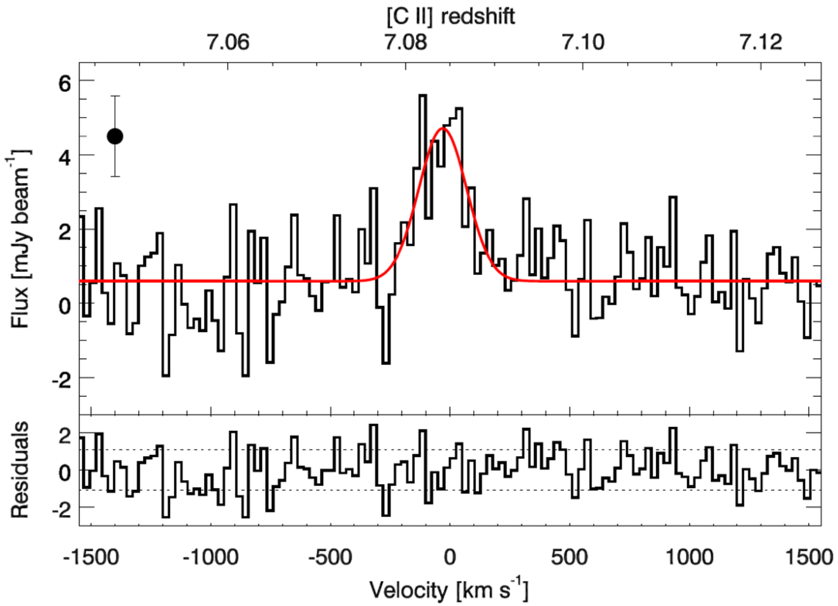
Walter et al. 2012

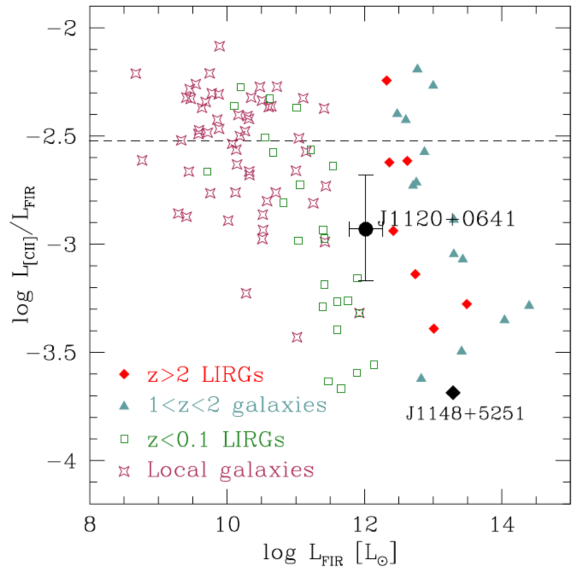
[CII] now detected out to z=7.1(!)



Only one quasar known at z>7 (Mortlock et al. 2011)

Bright detection in [CII] -- source visible from ALMA

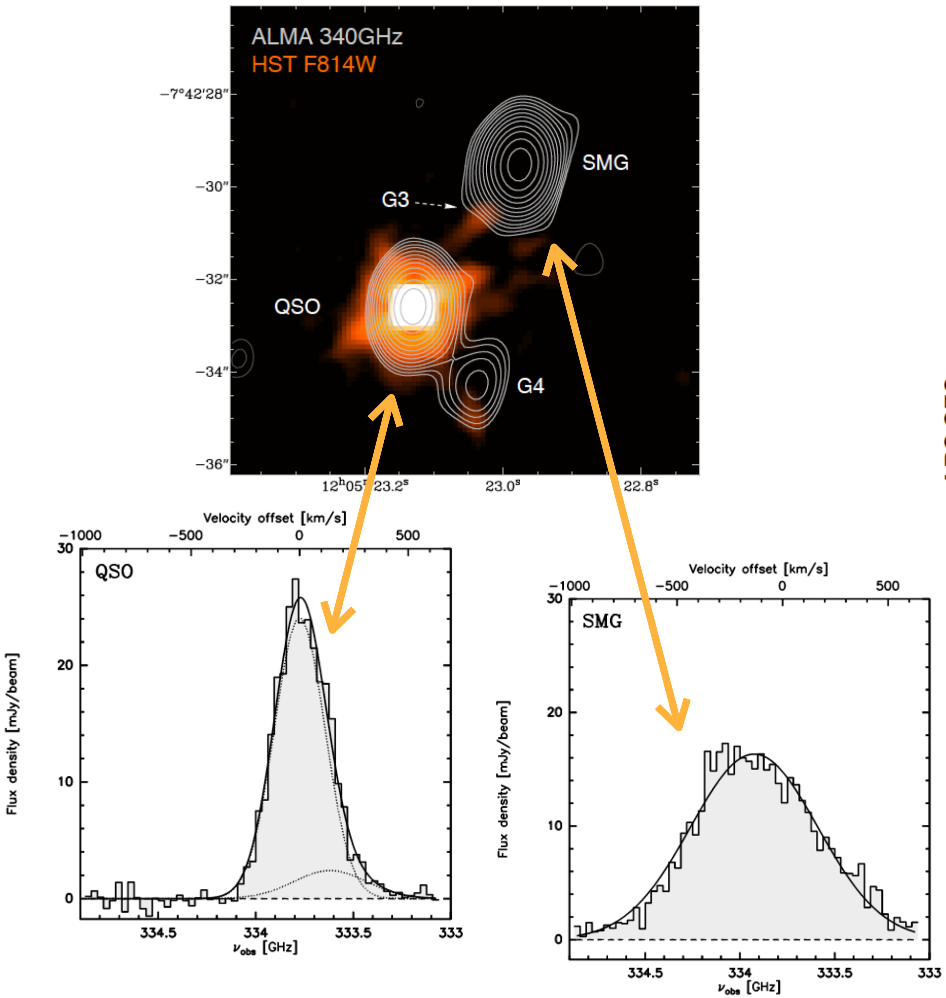


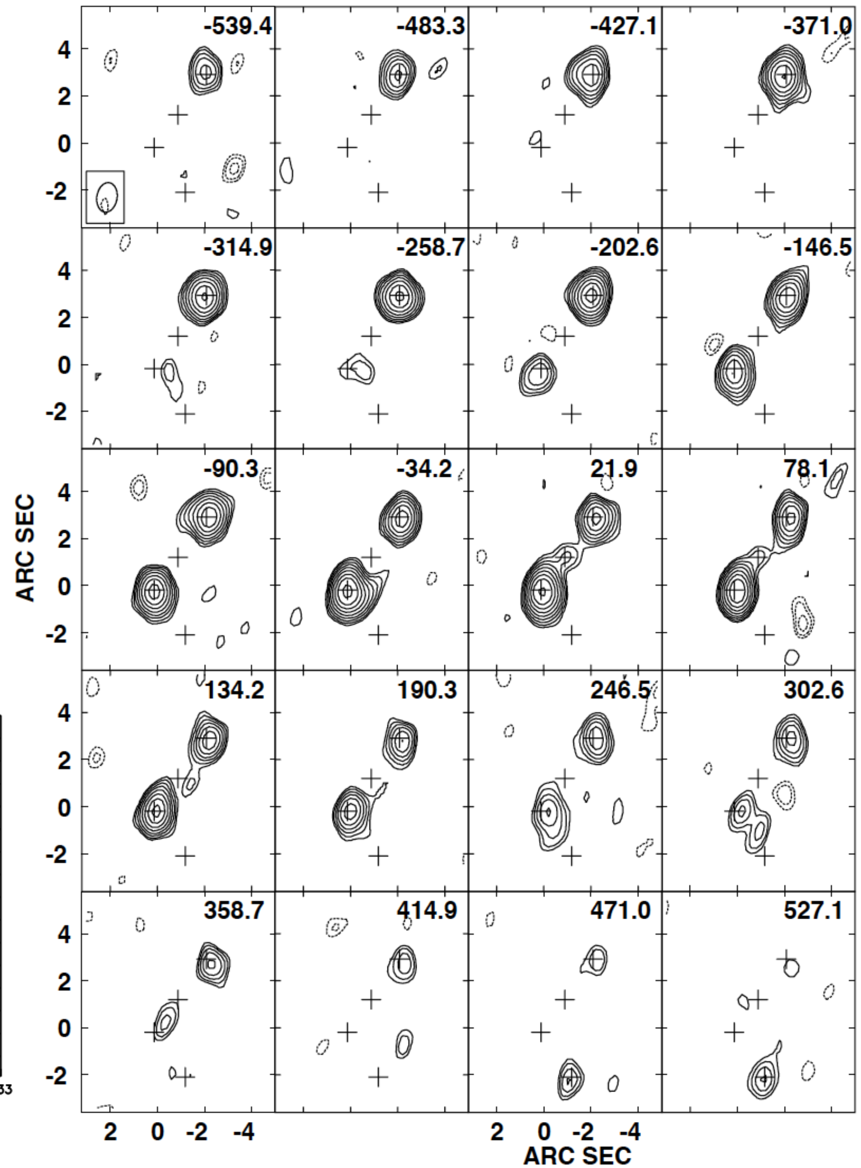


Venemans et al. 2012

ALMA: An SMG-Quasar pair at z=4.7

BRI 1202: [CII]



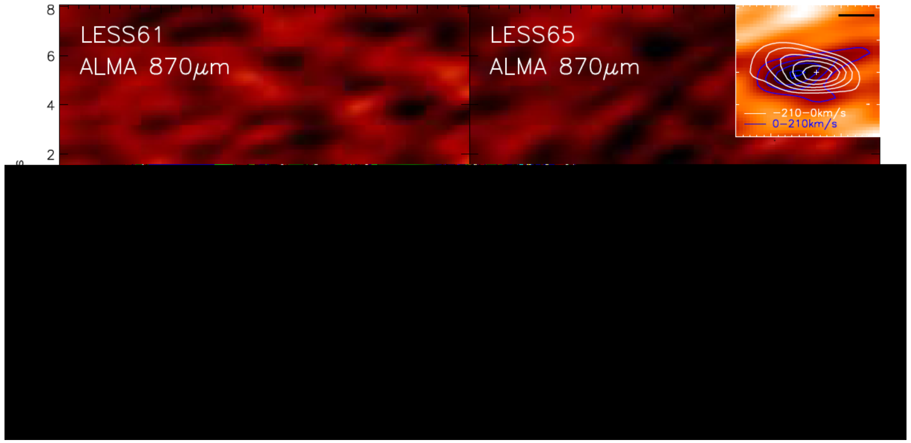


dramatic S/N in 0.5 hours w/ 16 antennae

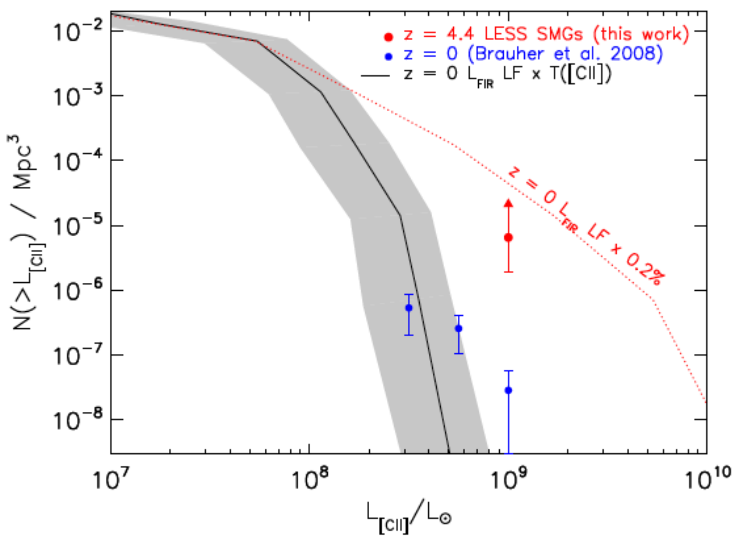
Wagg et al. 2012
Carilli et al. 2012

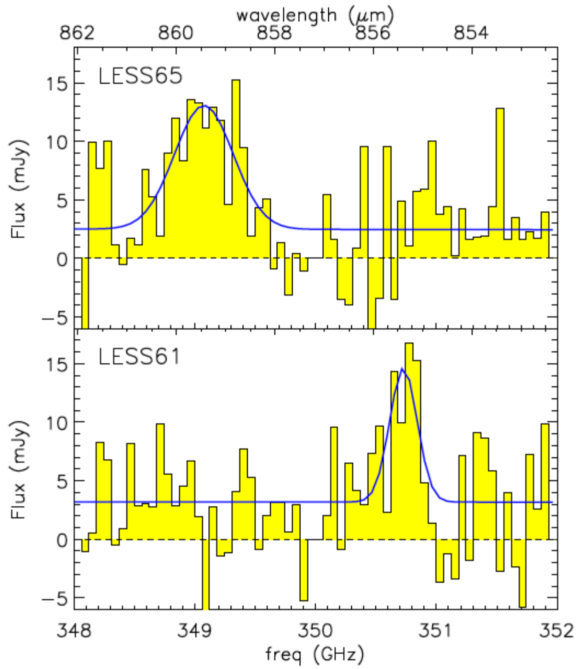
First serendipitous ALMA [CII] detections

ALMA always covers 8GHz of bandwidth -- we looked at ~100 SMGs in ECDFS



Two show evidence for line emission - most likely [CII] at z~4.4

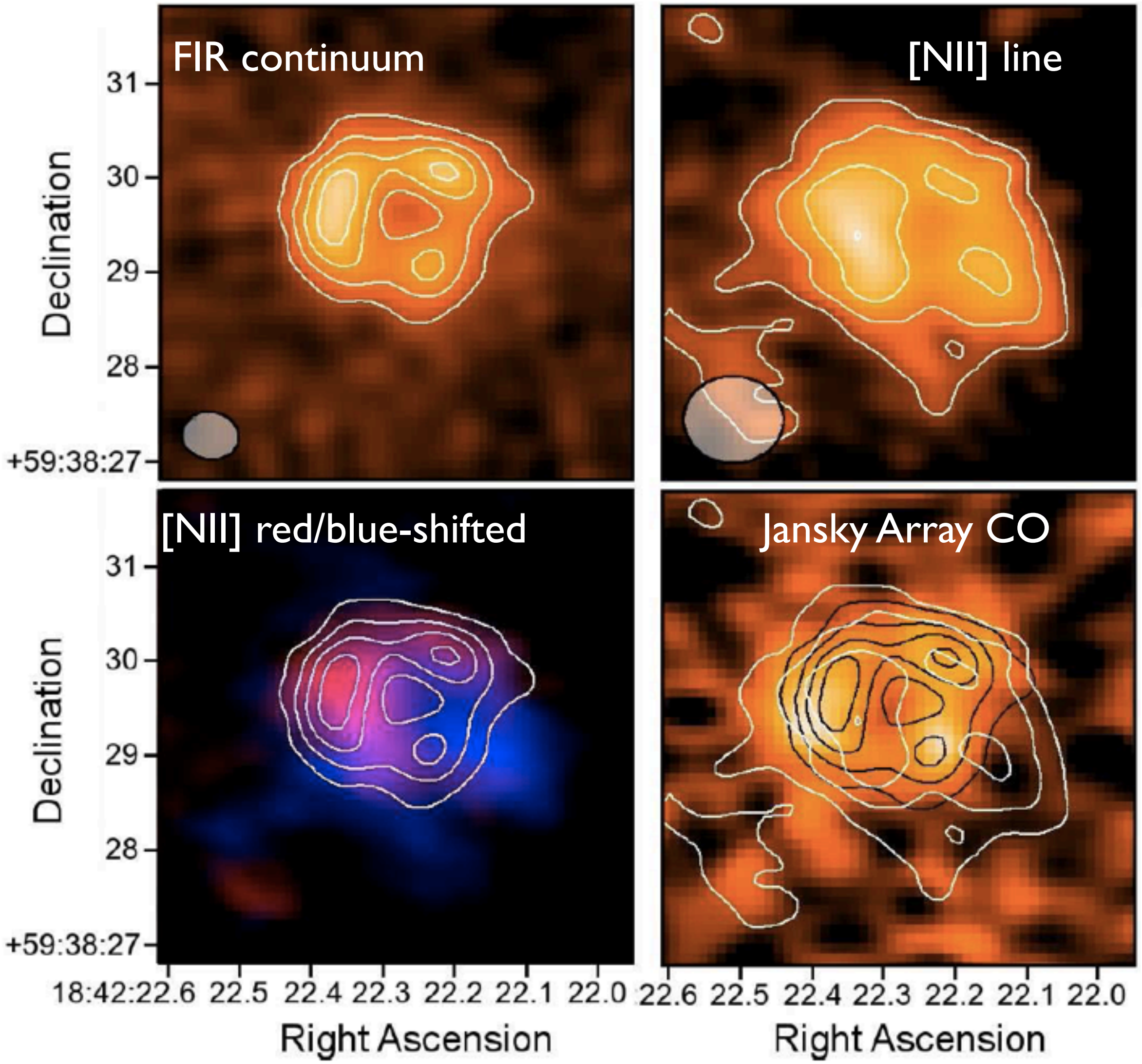




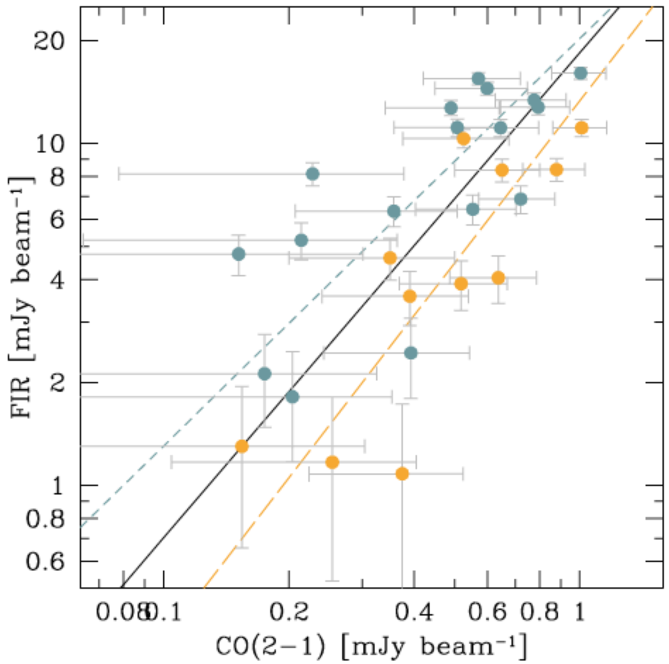
Swinbank et al. 2013

[NII] as a tracer of ionized medium at high redshift

[NII] in strongly lensed source at z=4 (MM18423) (Lestrade et al. 2010)

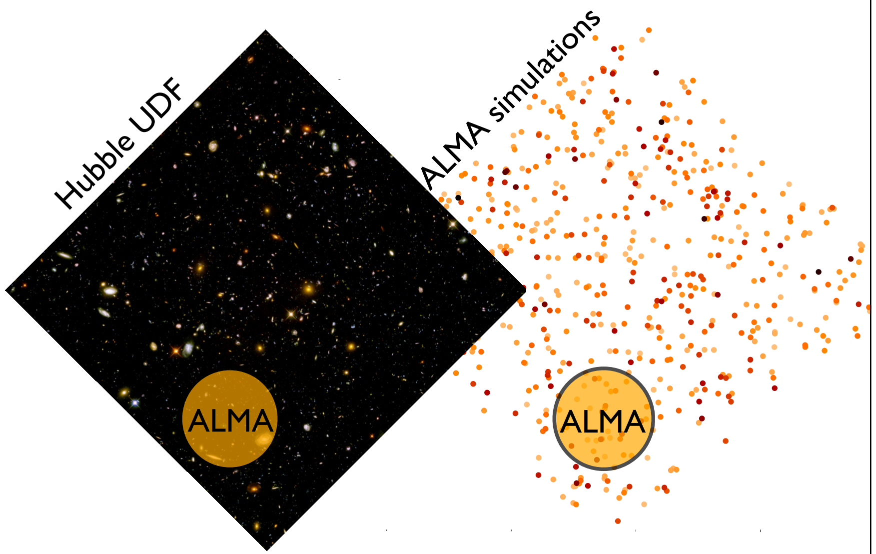


resolved star formation law at high redshift!



Decarli, FW et al. 2012

Summary / Conclusions



- **the future is now**

- CO remains best direct tracer of molecular gas mass at intermediate z

- excitation critical to derive masses etc.

- may loose CO at highest redshifts (CMB)...
  → fine structure lines

- so far: all detections in systems w/ SFR > 100 M_{sun} yr^{-1}

- soon: unbiased blind deep fields with ALMA

- ultimate goal: constraints on $\Omega_{CO}(z)$ and thus $\sim\Omega_{mol}(z)$

THE END