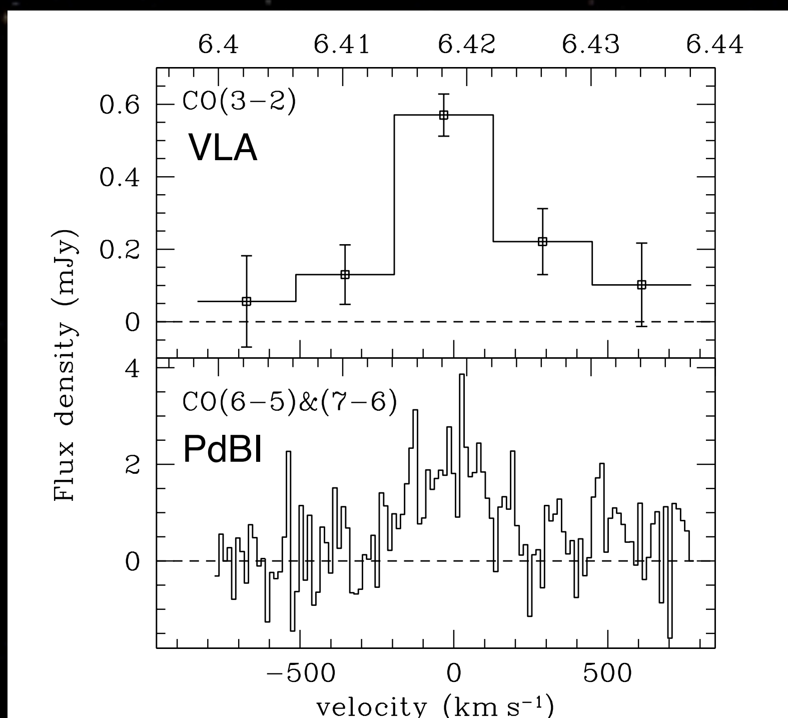
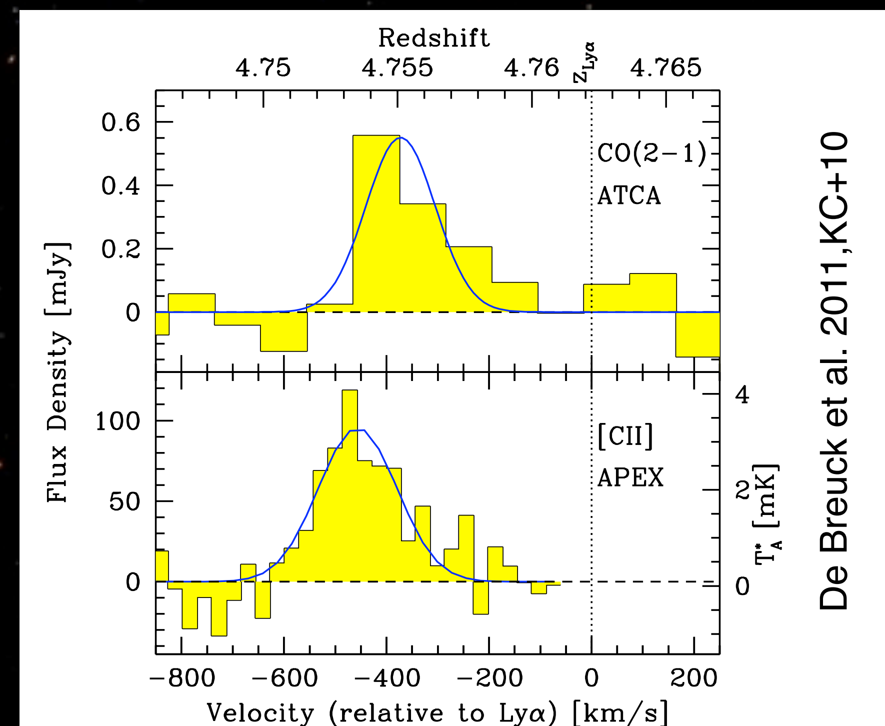
Molecular Gas Properties of AGN and Starburst Galaxies at High-Redshift

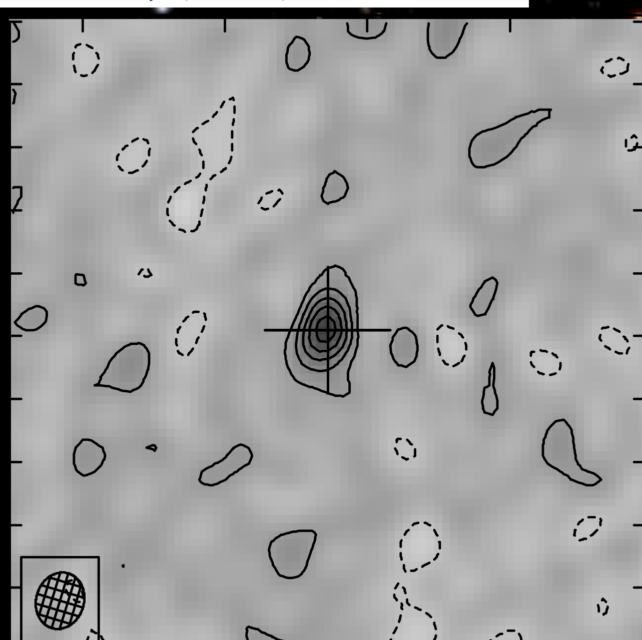




De Breuck et al. 2011,KC+10

CO detection in a QSO at z=6.42 SDSSJ1148+5252

Walter et al. (2003)



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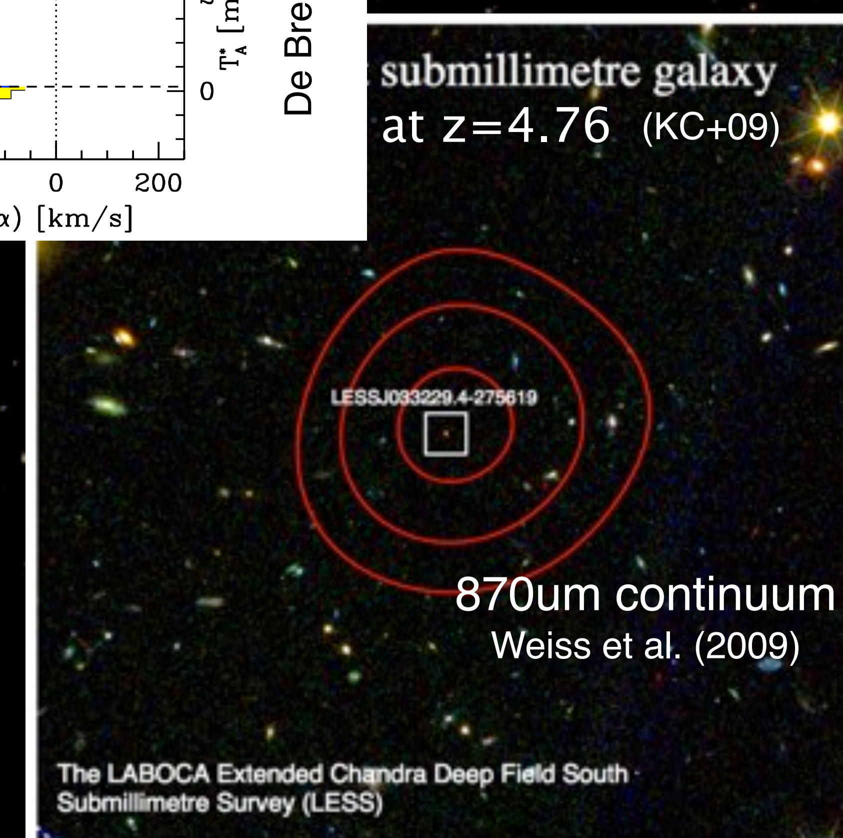


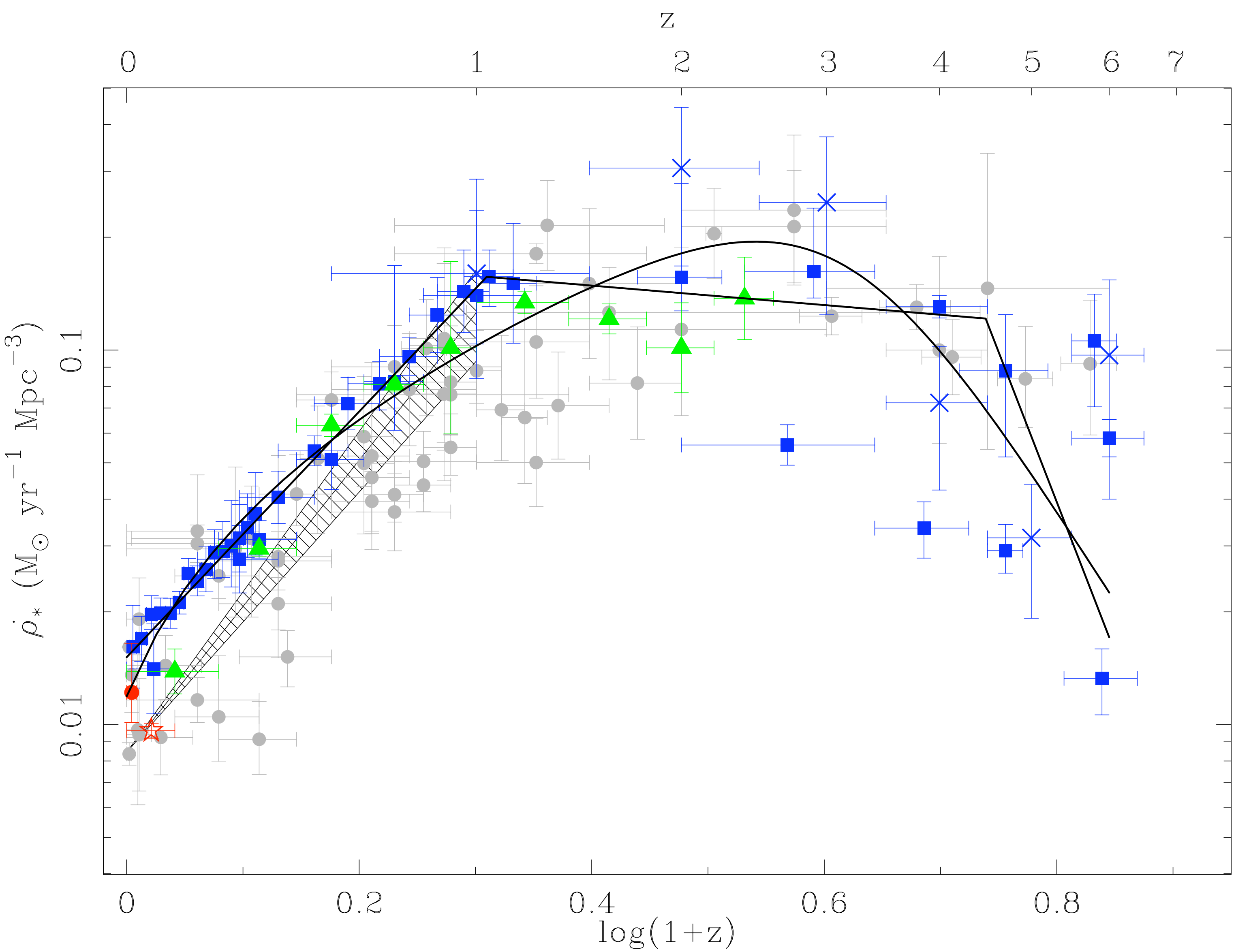
Multiwavelength Views of the ISM in High-Redshift Galaxies, Santiago, June 2011

Talk overview

- The big picture: What can studying the molecular gas in starbursts and AGN at high-z tell us?
- Primer on molecular gas observations
- What have we learned so far about the molecular gas in high-z galaxies?
- What's next?

Epoch of galaxy formation

- Galaxy assembly was much more efficient at high-z
- Can identify populations at these redshifts and probe their properties (e.g. distribution of SF, dynamics, gas and stellar masses, timescales) to constrain models
- H_2 is the raw material for star formation and a critical component in the evolution of galaxies. Does it trace the SFRH of the Universe?

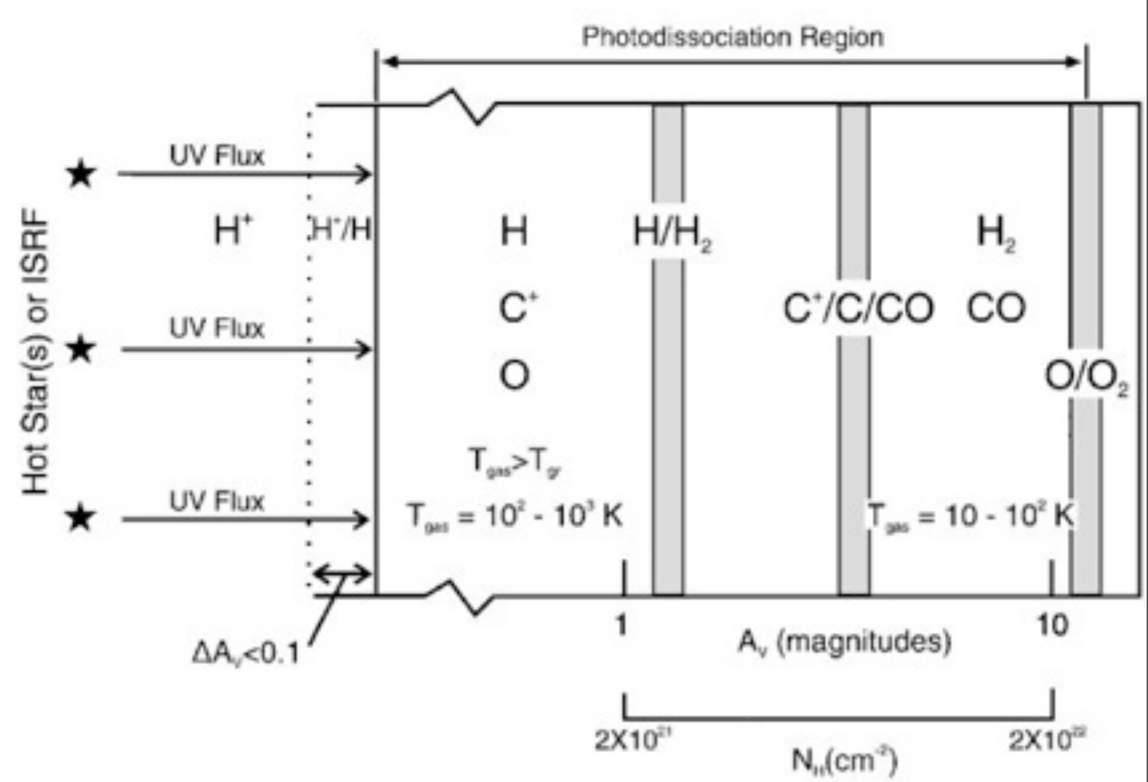


History of energy generation rate in the Universe (Hopkins & Beacom 2006)

Studying molecular gas

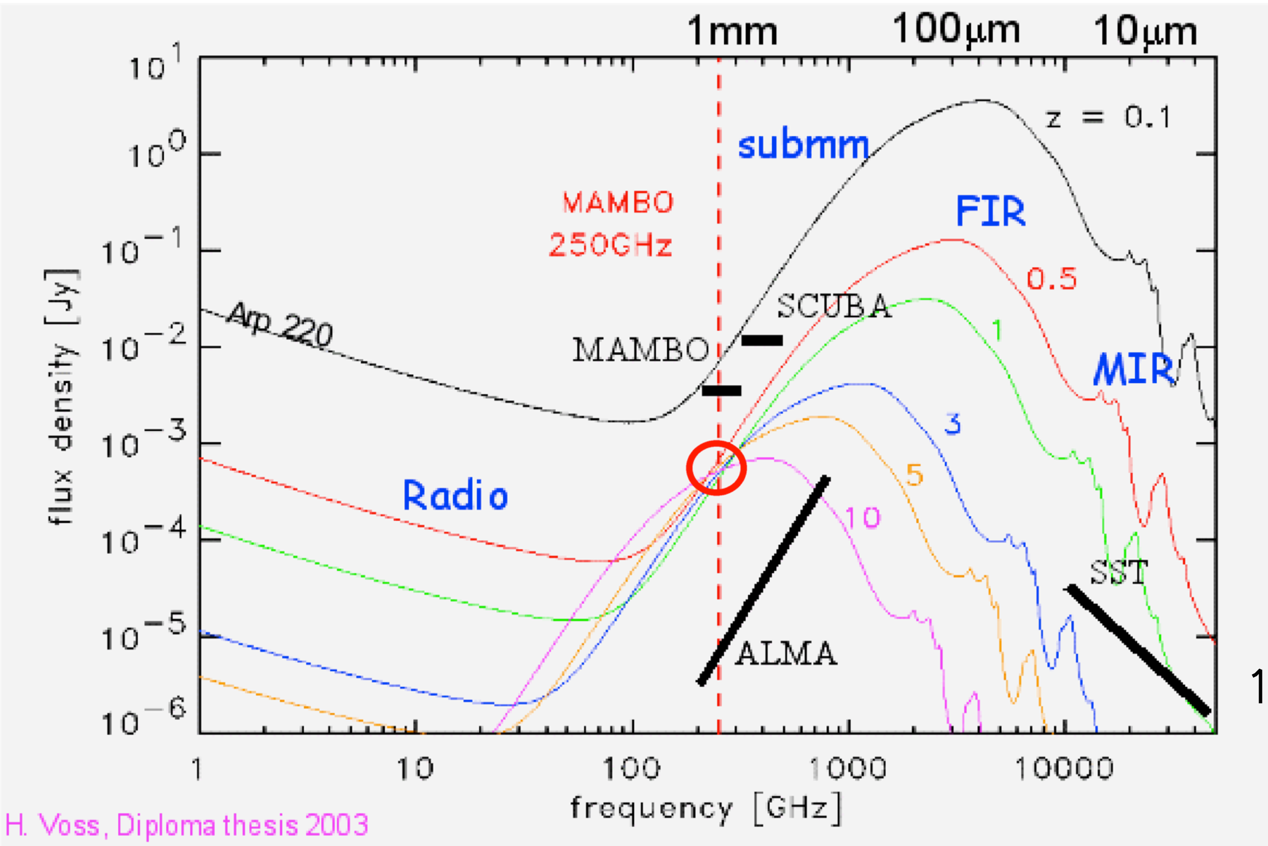
- H_2 dominates interstellar clouds with n>100 cm^{-3} & is made in the presence of dust
- But H_2 has no permanent electric dipole moment - basically invisible!
- CO traces H_2 well (see nice ARA&A by Young & Scoville 1991):
  - Very stable and abundant
  - weak dipole moment --> excited & thermalized by collisions with H_2 at low densities
- There are other (commonly fainter) tracers of molecular gas: CI, CII and HCN, etc...

PDR model

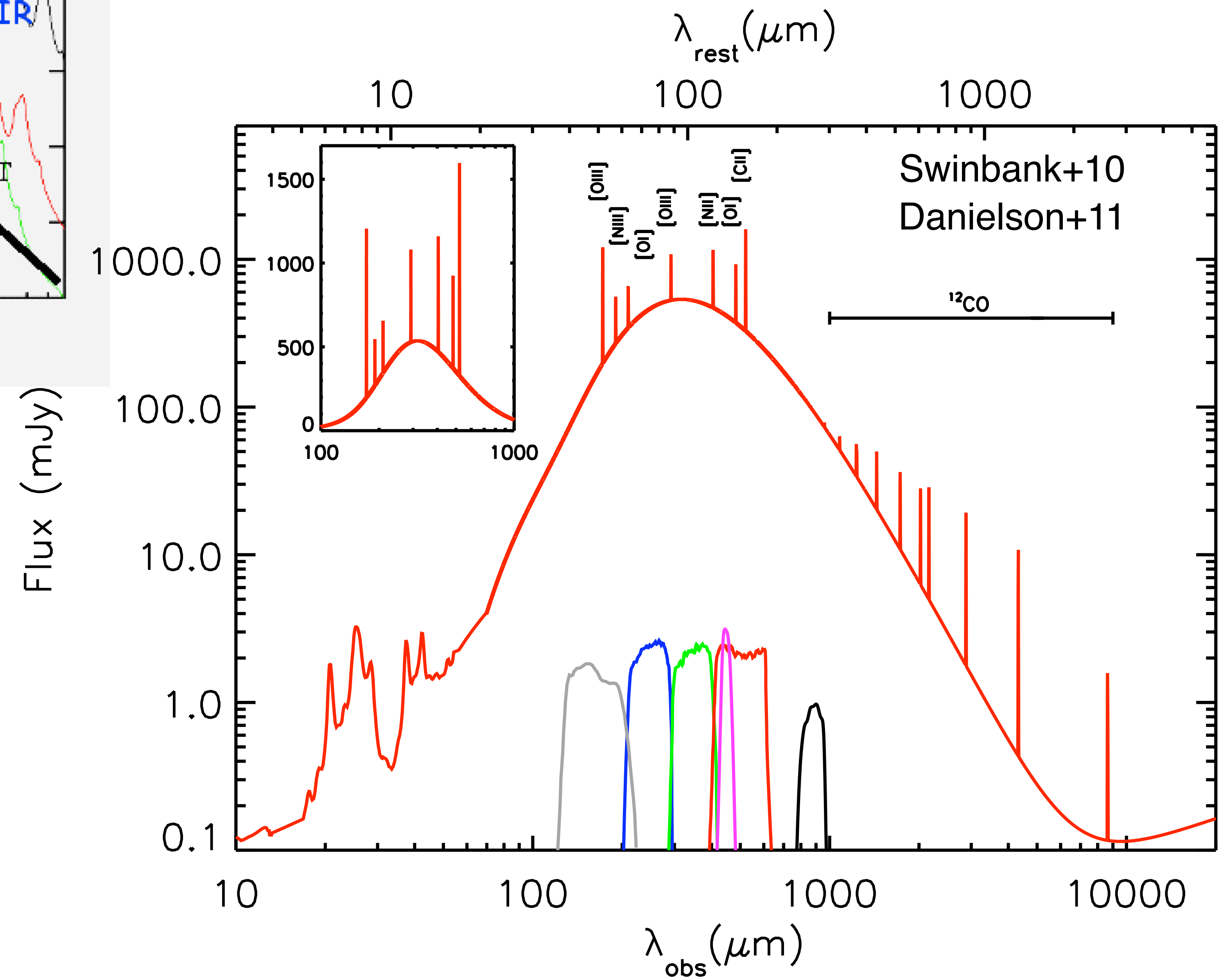


From Hollenbach & Tielens (1997)

Visibility of far-IR continuum & emission lines at high-redshift



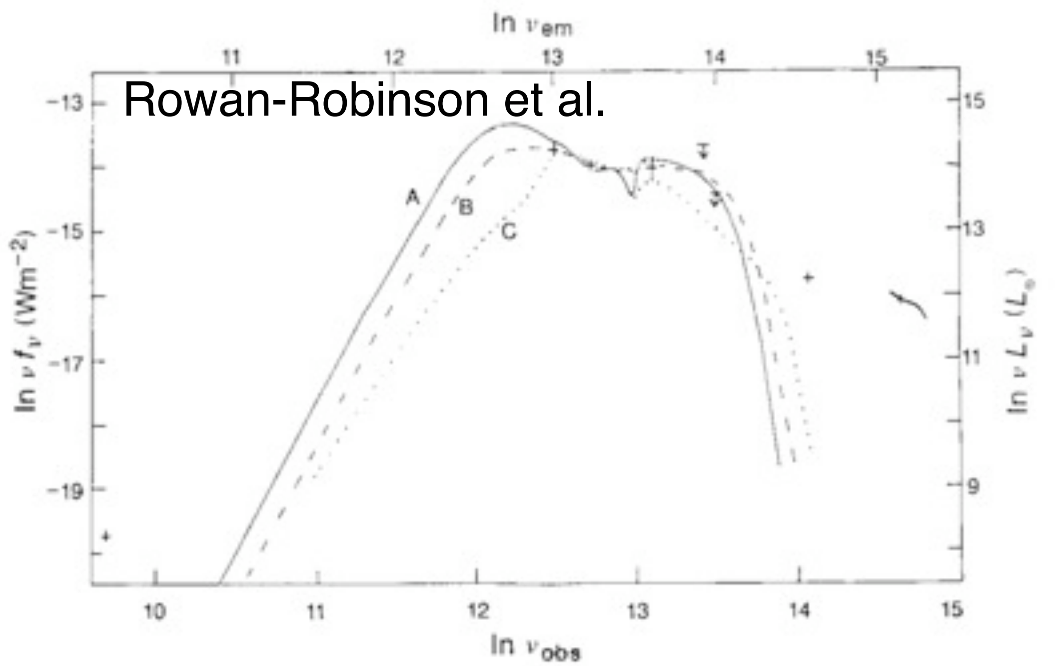
---> submm band samples the Rayleigh-Jeans tail. When SED is shifted to high-z, the **negative k-correction** applies



- Negative K-correction makes finding dusty high-z objects easy in submm/mm
- 99% of L_{FIR} is thermal emission from dust
- ~1% from fine-structure atomic and molecular rotational line emission (CO dominates this)

It all started with IRAS F10214

- First z>>1 galaxy to be detected in CO (z=2.3)
- intrinsic M_{gas}~10^{10} $M_☼$ (lensed by factor of ~10)
- Similar CO properties (mass, excitation) to local ULIRGs
- dust-enshrouded QSO dominates mid-IR
- starburst dominates the far-IR emission



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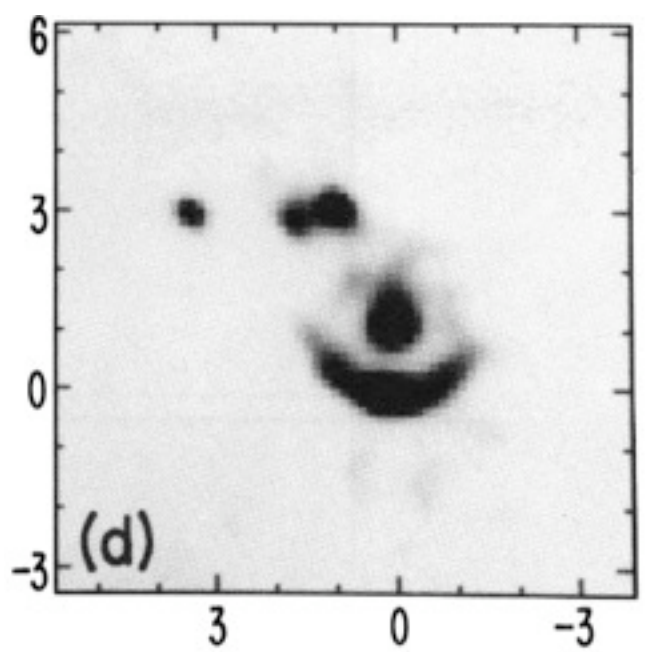
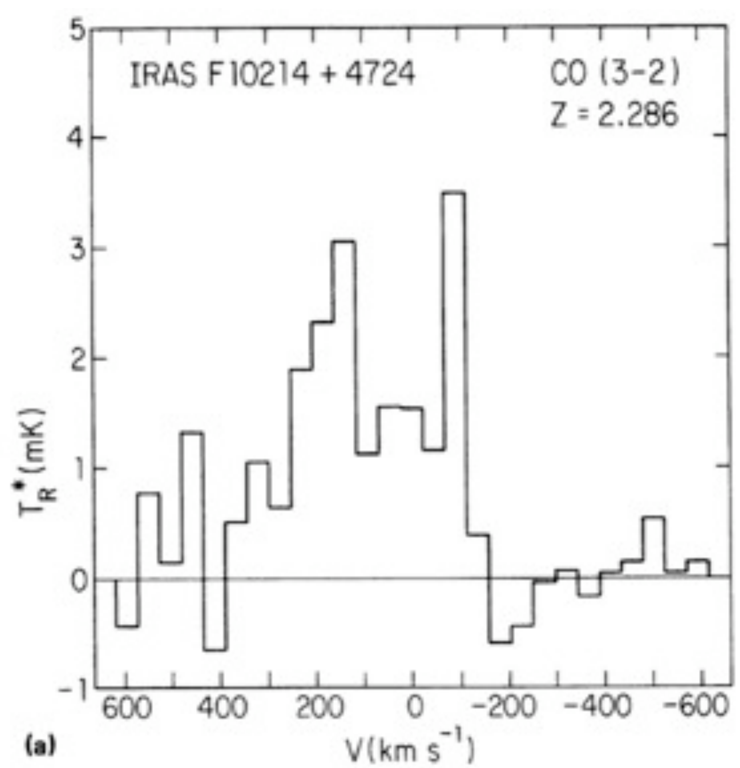


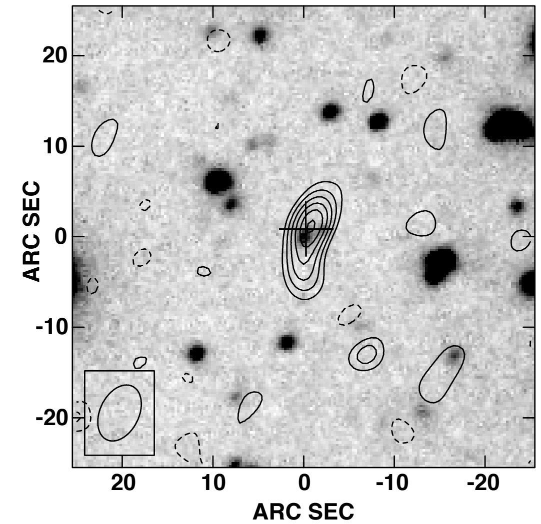
Enhanced Keck K-band image (Matthews et al. 1994)



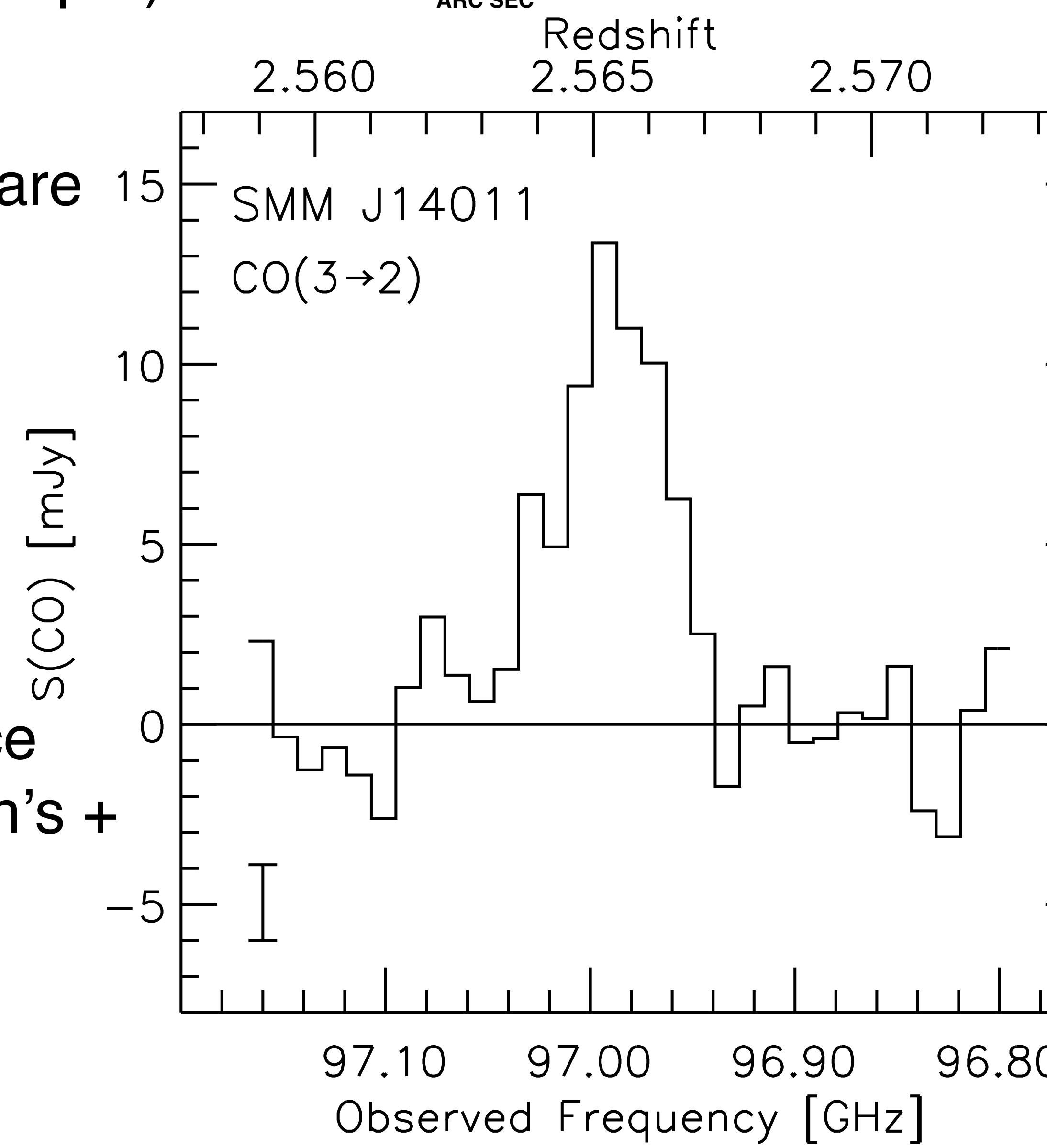
(Brown & Vanden Bout 1991)

Determining M_{gas} from CO line emission

- CO line intensity gives you a measure of L'_{CO} -> M_{gas}
  - Fit a Gaussian & integrate under it --> $S_{CO}\,\Delta v$ (Jy km/s)
  - $L_{CO}=1.04\times10^{-3}\, S_{CO}\,\Delta v\, \nu_{rest}^{-2}\, D_L^2\, (1+z)^{-1}$ ($L_☼$) or $L'_{CO}=3.25\times10^{7}\, S_{CO}\,\Delta v\, \nu_{obs}^{-2}\, D_L^2\, (1+z)^{-3}$ (K km/s pc^2)
- note: thermalized optically thick CO emission, the intrinsic brightness temperature & line luminosity are independent of J and rest frequency, e.g. $L'_{CO}(J=1\text{-}0)=L'_{CO}(J=5\text{-}4)$
- Then apply $M_{gas}=M(H_2+He)= \alpha_{CO}\, L'_{CO(1-0)}$
  - units of α_{CO} are $M_☼$(K km/s pc^2)$^{-1}$
  - But how do we know what α_{CO} should be?(nice discussion in Adam Leroy + Desika Narayanan's + Thiago Goncalves' talks)



One of the first SMGs detected in CO (Frayer +99)



CO-to-H_2 “X” factor:

- Physical basis for deriving M_{gas} from L'_{CO} :

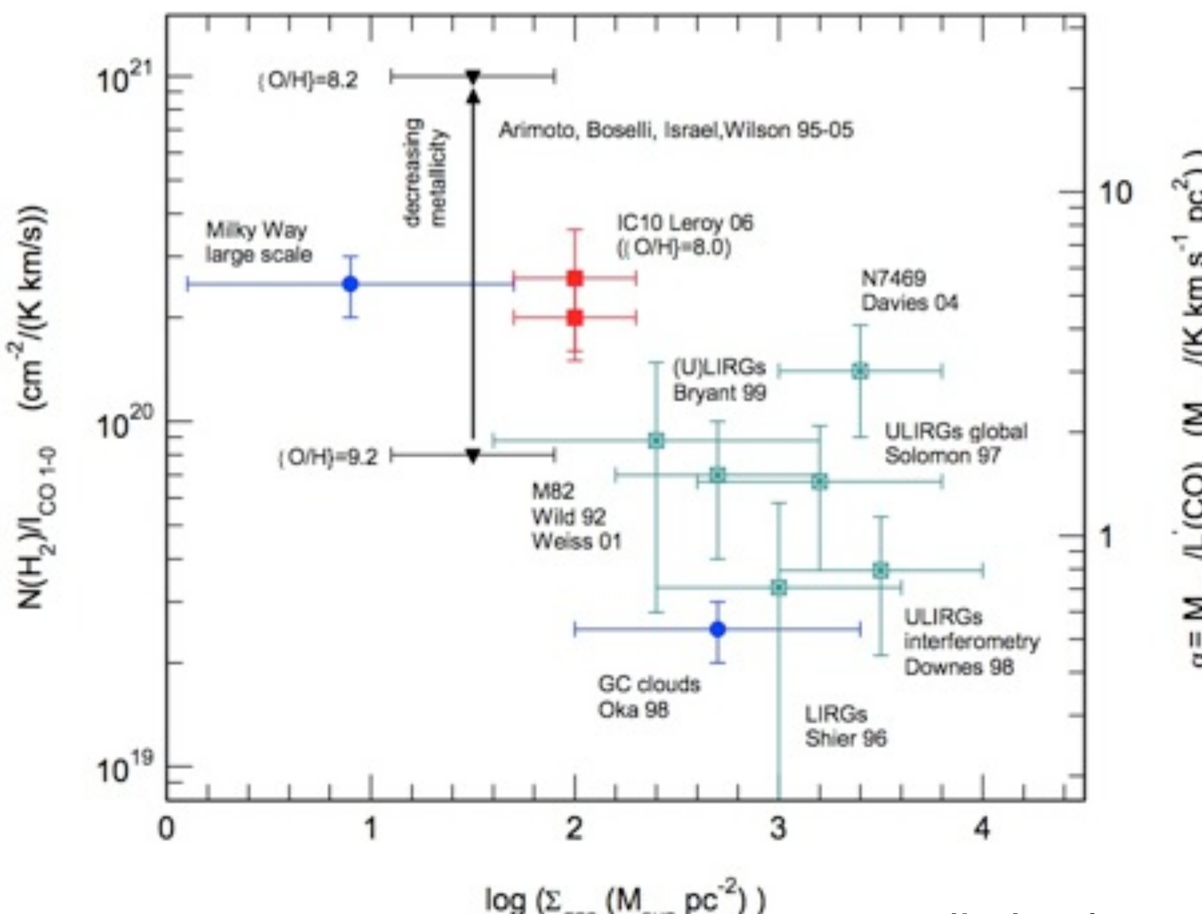
mass H_2 molecule

Average H_2 number density in clouds (cm^{-3})

- $M_{gas}/L'_{CO}=\alpha_{CO}=(4\ m_{mol} \times 1.36)^{0.5}\ (3\ \pi\ G)^{-0.5}\ n^{0.5}/T_b$
  $= 2.6\ n^{0.5}/T_b$ (ref. D. Narayanan’s talk)

Rest-frame brightness temperature of CO line (K)

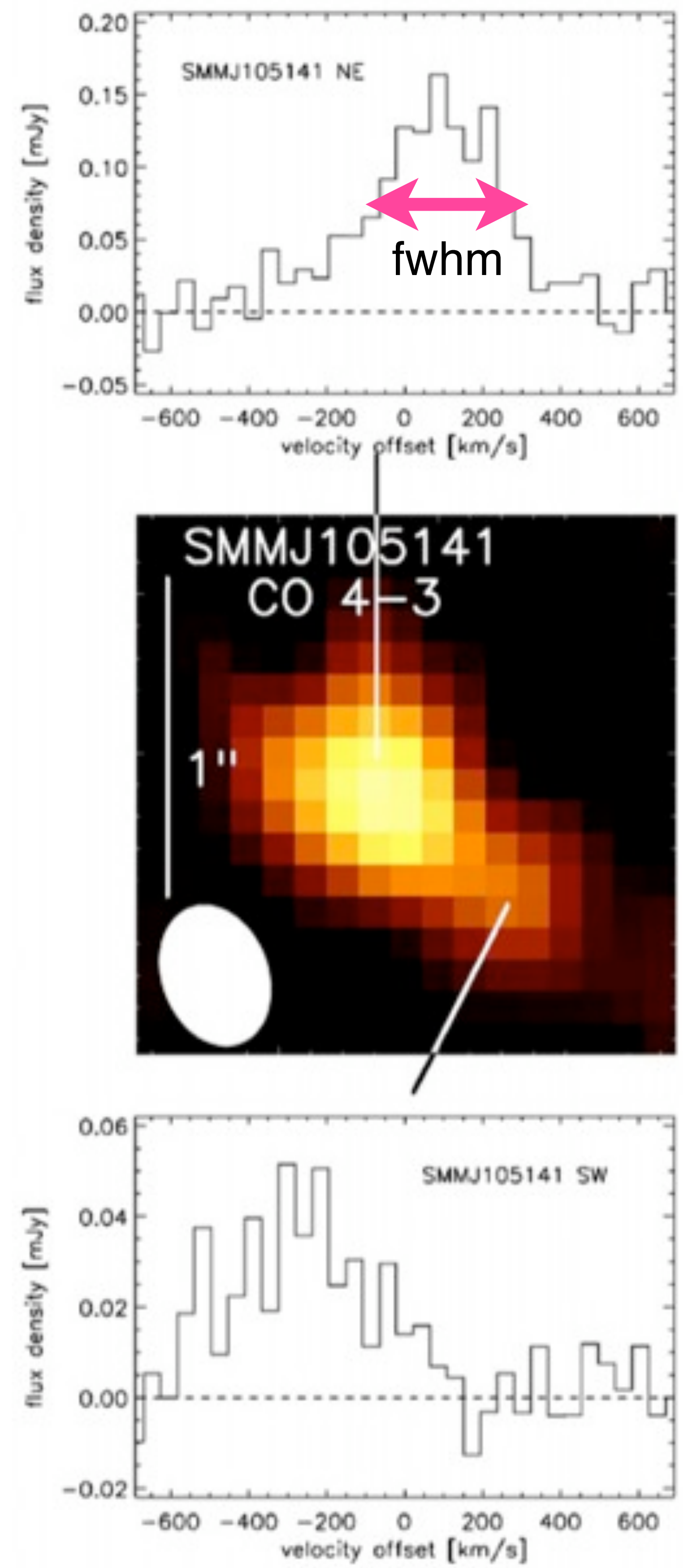
- Can put limit on α_{CO}: i.e. $M_{dyn}>M_{gas}$
  - Milky-Way (+local spiral) galaxies: α_{CO}=4.5 (appropriate for virialized clouds)
  - ULIRGs: α_{CO}=0.8 (Downes & Solomon `98, new model of “filled intercloud medium”) --> adopted for high-z “merger-like” SBs (QSOs SMGs, 24um-galaxies)
  - SF-disk galaxies: α_{CO}~3.4 (Daddi+10)
- additional complications, e.g. α_{CO} is metallicity-dependent (e.g. Genzel+11)



compilation by Tacconi et al. (2008)

Determining M_{dyn} from CO line emission

- For a cloud of mass M in virial equilibrium, $\Delta V=\sqrt{(GM/R)}$
- $M_{dyn} \sin^2(i) = 233.5\ R\ \Delta V^2$
  - ΔV=CO line FWHM or half the separation in velocity of the component CO lines in a merger model (km/s)
  - R=radius of gas disk OR 1/2 the separation between components in a merger model (pc)
- Really need resolved observations to get a good handle on the size of the CO emitting region, otherwise can assume a reasonable size or limit from the beam size used

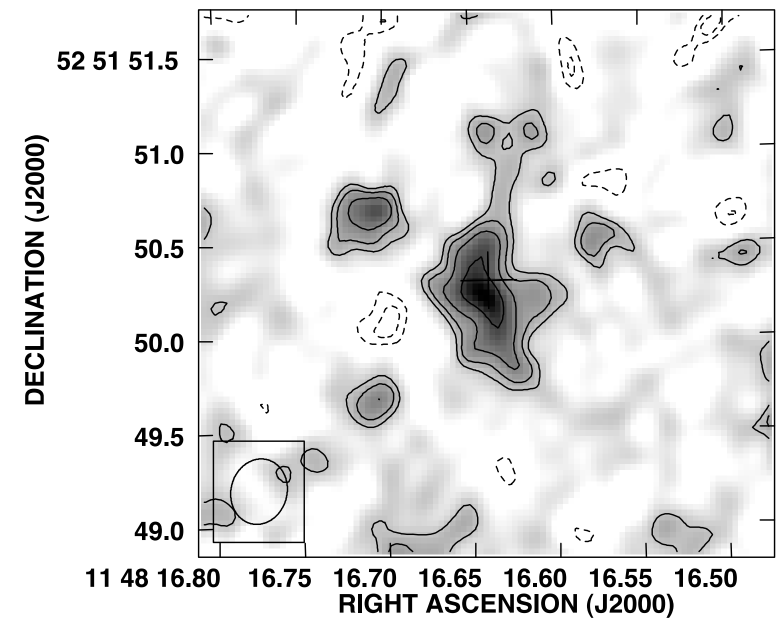


Engel et al. (2010)

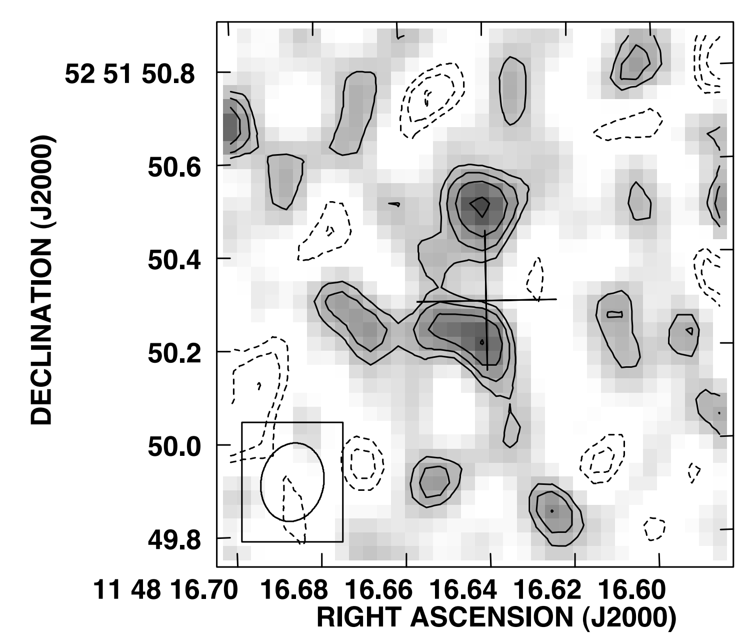
The power of high-resolution CO observations

- Most studies of high-z objects are unresolved. Some could be spatially resolved 0.15-0.3” resolution (1”=8-4kpc at z=2-10)
- Provides info on gas supply mechanism; allows to measure:
  - M_{dyn} (=M_{stars}+M_{BH}+M_{gas}+M_{dust}+M_{DM})
  - gas morphology & surface density
  - compare to optical/IR/H-alpha morphology (Erica Nelson, Karin Menendez-Delmestre’s talks)
  - independent calibration for α_{CO} (e.g. Daddi 2010)
- Process driving SF: major merger vs. gas dynamics driven by ordered rotation? good resolution and no extinction!

Walter et al. (2004)

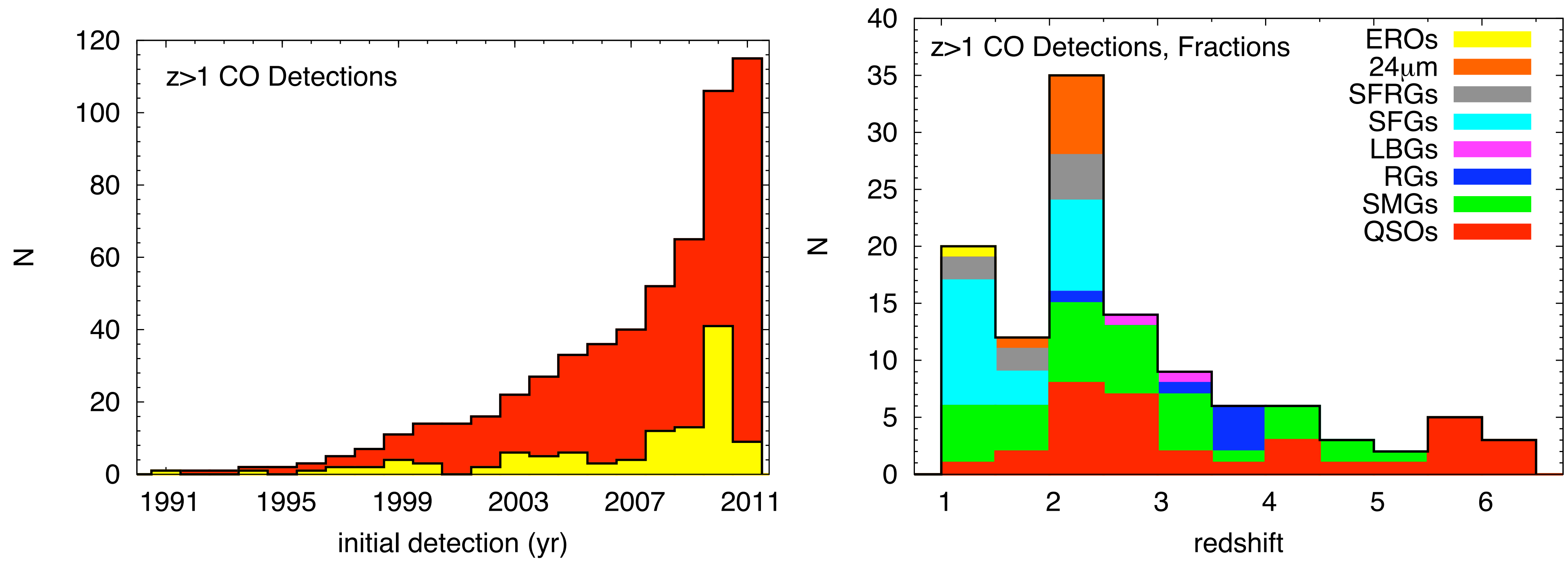


VLA map of CO(3-2) in QSO J1148+5251
0.35” resolution (~2kpc at z=6.4)



at 0.15” resolution (~1kpc at z=6.4)

Summary of CO detections in high-z galaxies

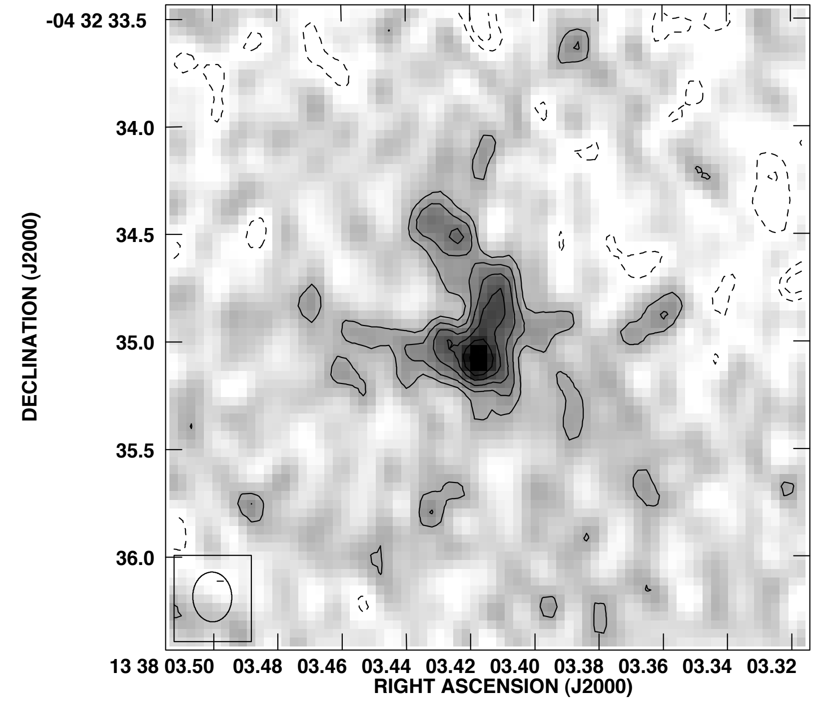


compilation from Riechers+11

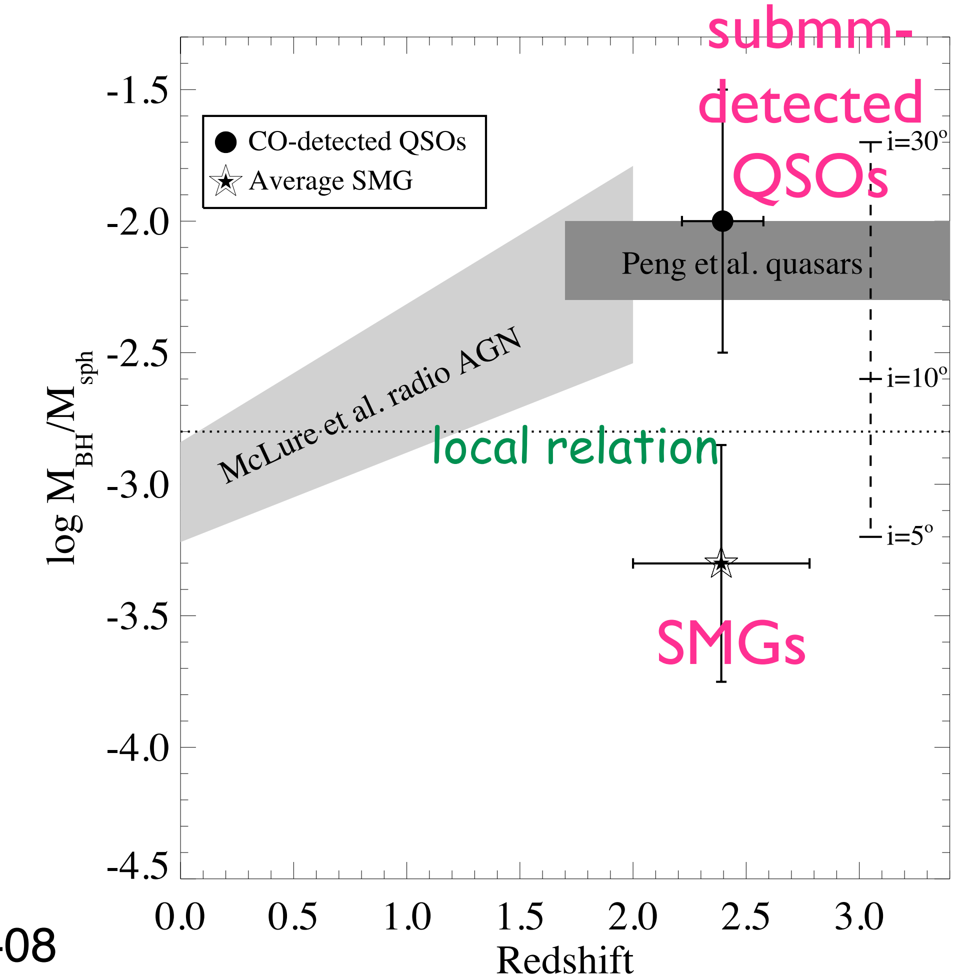
- CO detected in >100 z>1 galaxies (see review Solomon & Vanden Bout 2005)
- Highest redshift detection z=6.42 (QSO; Walter+03; Bertoldi+03; Carilli+04; Riechers+07, 2009)
- Most have $M_{gas}>10^{10}\,M_\odot$ (except for a few lensed galaxies where able to probe to fainter M_{gas})
- some of these have spatially resolved CO emission (but majority are unresolved)
- Most of these had known opt/near-IR redshifts & were submm-bright (far-IR luminous)

High-z QSOs

- Easier to do at high-res, so bright - stunning e.g. Riechers et al. 2008 z=4.4 QSO BRI1335-0417, showing complex structure in gas emission
- 35 z>1, ~1/2 are lensed, 1/2 at 4>4
- M_{gas}~0.1-20x10^{10} M☼ (least massive ones are grav. lensed)
- spatially & kinematically resolved molecular gas distributions --> constrain M_{dyn} of QSO host galaxy
- CO detections of submm-bright QSOs at z~2 suggest evolutionary link (e.g. Coppin+08)

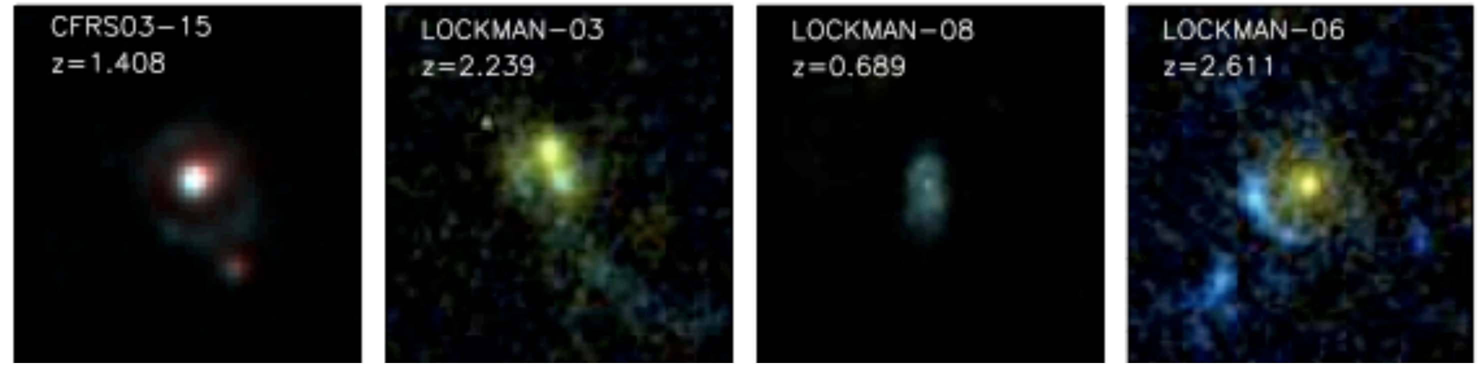


e.g. 0.15"~1kpc at z=4.4, resolved CO emission in a QSO (Riechers+08)

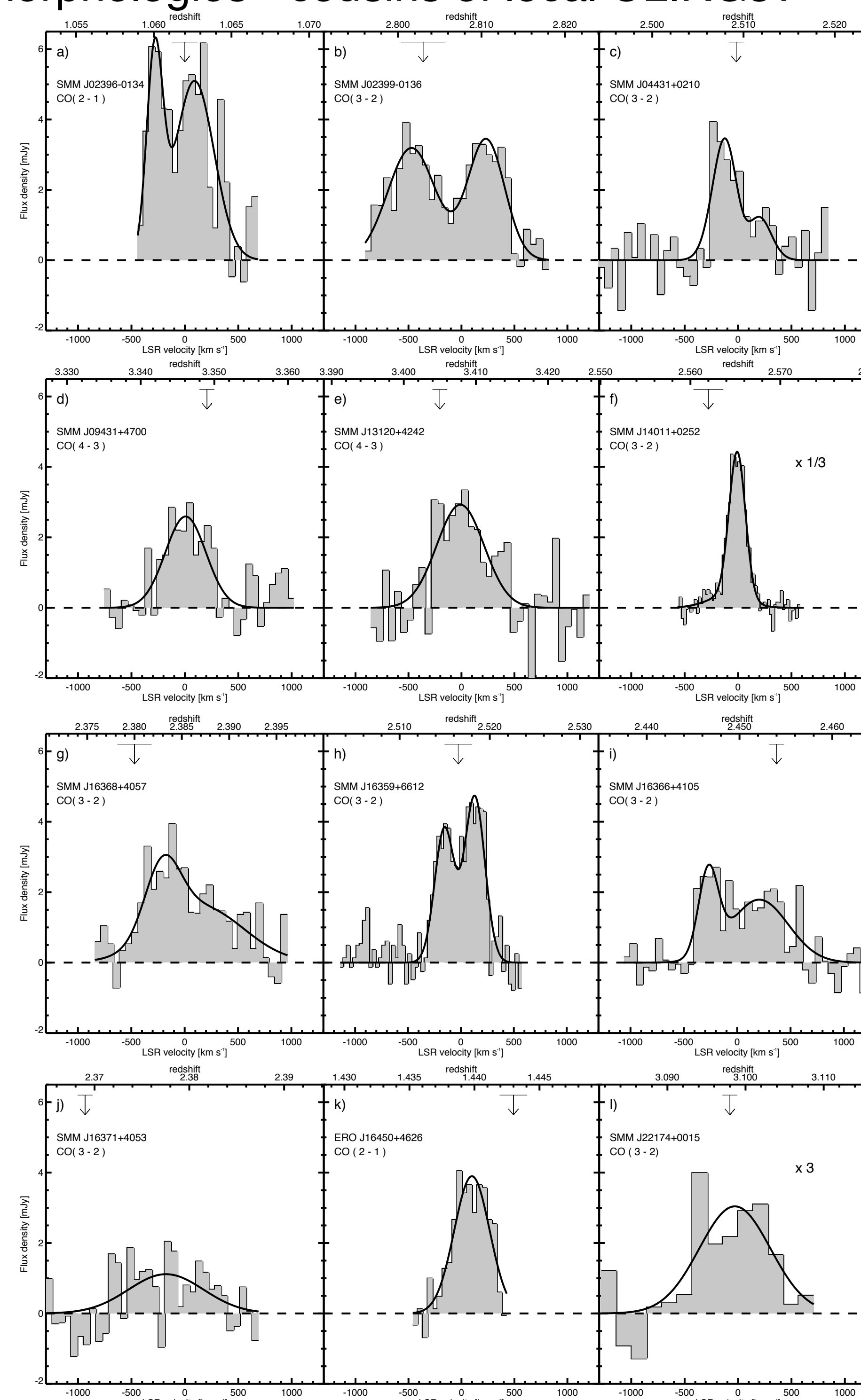


Alexander+08 Coppin+08

SMGs



HST IH-band images of SMGs (Swinbank et al. 2010) show a mix of morphologies - cousins of local ULIRGs?

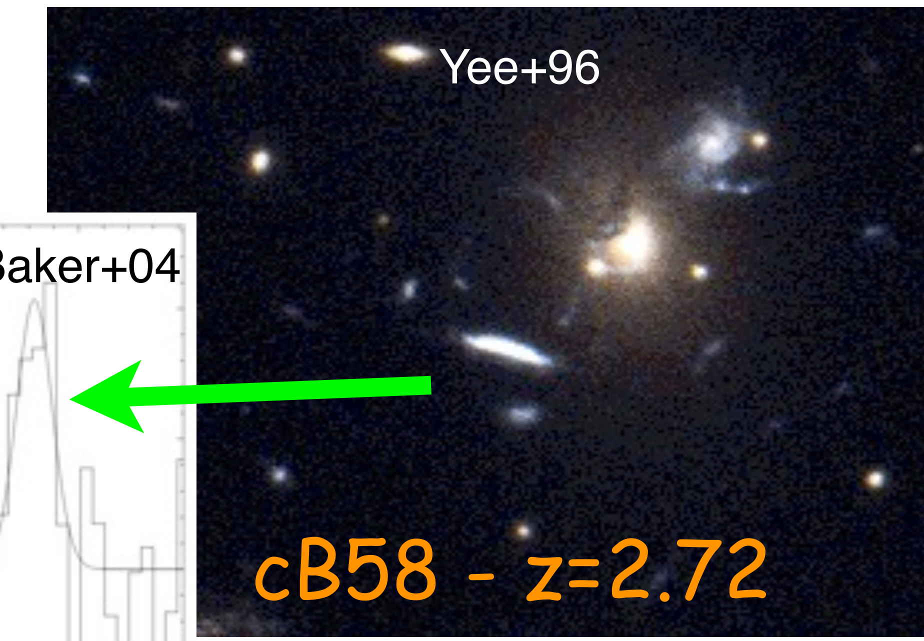


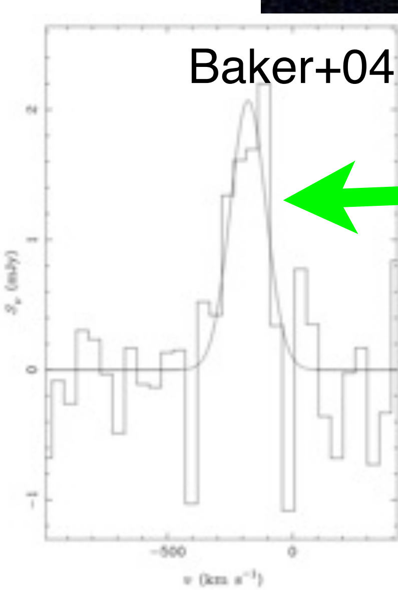
- Blank-field 850um SCUBA-detected galaxies at $1<z<3$ with $L_{FIR}>5\times10^{12}\ M_\odot$, SFRs~1000 $M_\odot$/yr
- Key results from major PdBI campaigns to probe their gas properties (Genzel+03, Neri+03, Greve +05, Tacconi+06+08)
  - SMGs are major SF episodes
  - M_{gas}~0.3-15x$10^{10}\ M_\odot$ (on average M_{gas}~3x$10^{10}\ M_\odot$); 10x more than MW, comparable to QSOs at similar z)
  - Broad CO lines: FWHM~100's-1000's km/s (average 500km/s), often double horned -->merging systems or disks
  - $M_{dyn(<2kpc)}$~1.2x$10^{11}\ M_\odot$ --> implies high gas mass fraction~20-50%

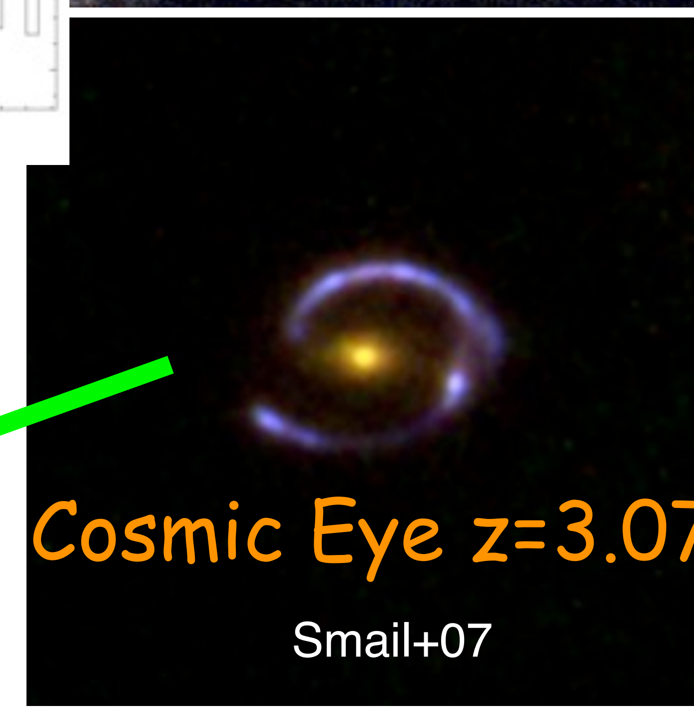
Lyman-break galaxies

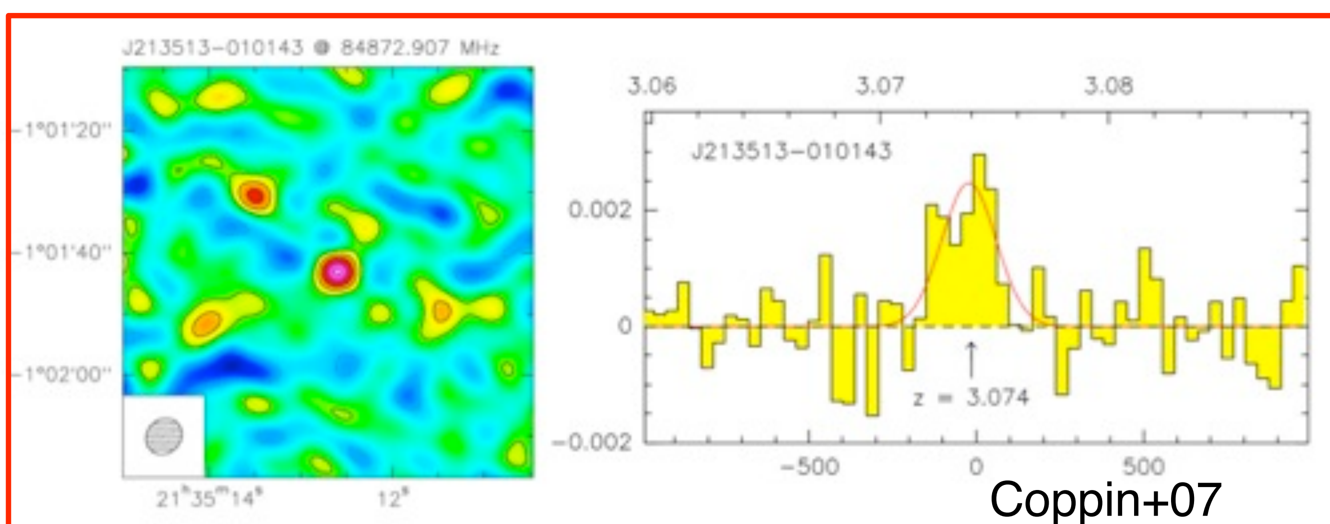
These observations were made possible by generous magnification via gravitational lensing

- LBGs comprise a significant population of “normal galaxies” at z~3
- Currently it is only possible to detect CO in gravitationally lensed LBGs: cB58 & Cosmic Eye (Baker+04, Coppin+07), z~3
- Intrinsic SFRs~25-100 M☼/yr, ~L☼
- Have lowest M_{gas}~5-9x10^8 M☼ (Riechers+10)
- CO line FWHM~200km/s, M_{dyn}~10^{10} M☼





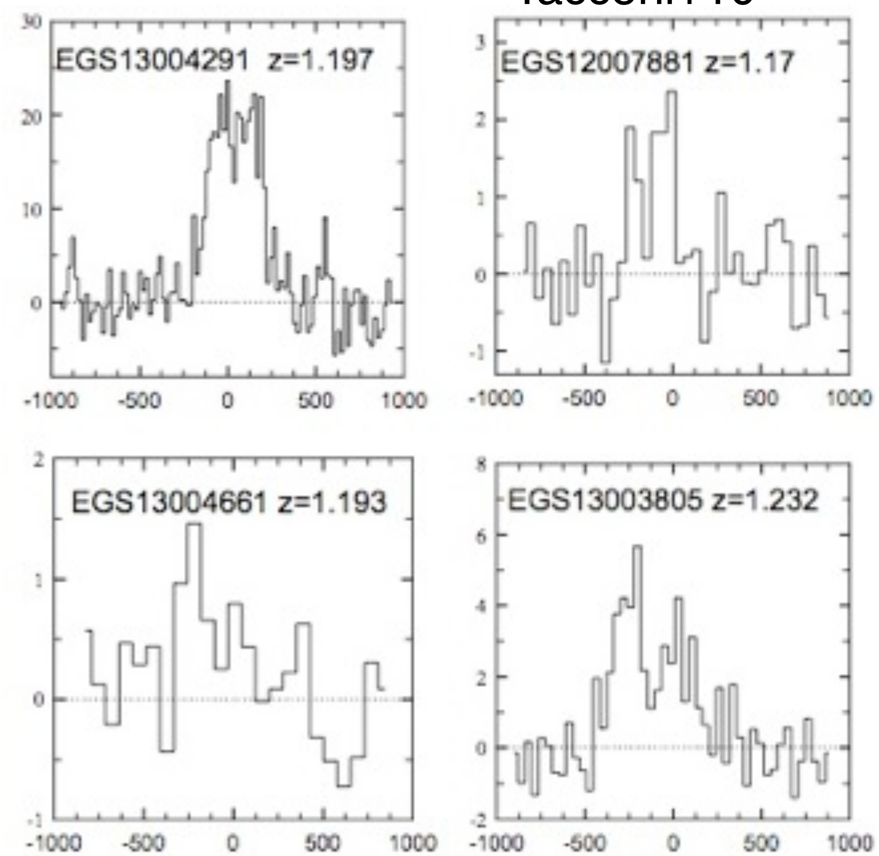


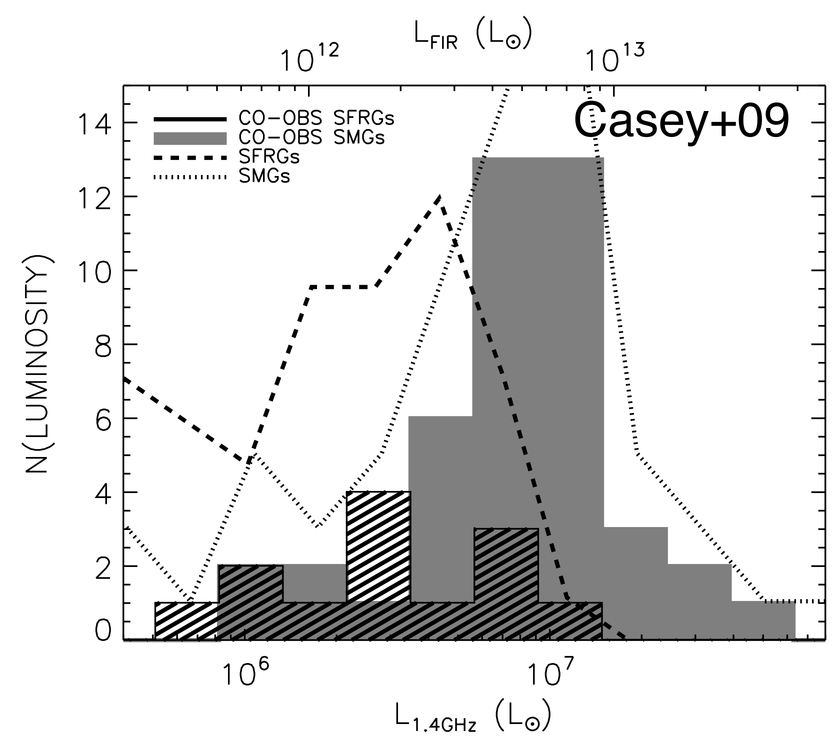


CO in other submm-faint high-z populations

- High-z Massive Gas-Rich Star-Forming Galaxies (SFGs; BzK selection), 22/25 detected in CO(2-1) or CO(3-2) at z=1.1-2.4 (stay tuned for Aravena & Pannella & Dannerbauer talks for more details!)
  - M_{gas}~2-50x10^{10} $M_{\odot}$ (Daddi+08+10, Tacconi+10)
- Star-Forming Radio Galaxies 8/14 detected in CO at z=1.3-2.2 (Chapman+08, Casey+09)
  - M_{gas}~8x10^{9} $M_{\odot}$
  - FWHM~320 km/s (~2x lower on avg. than for SMGs) - intermediate stage major mergers, observed near the peak of SF?
- 24um (MIPS) galaxies (Yan+10, Iono+06) 9/10 detected in CO (24um fluxes=1.1-1.5mJy, z=1.6-2.5) --> ULIRGs with mid-IR dominated by dusty AGN
  - M_{gas}~2x10^{10} $M_{\odot}$

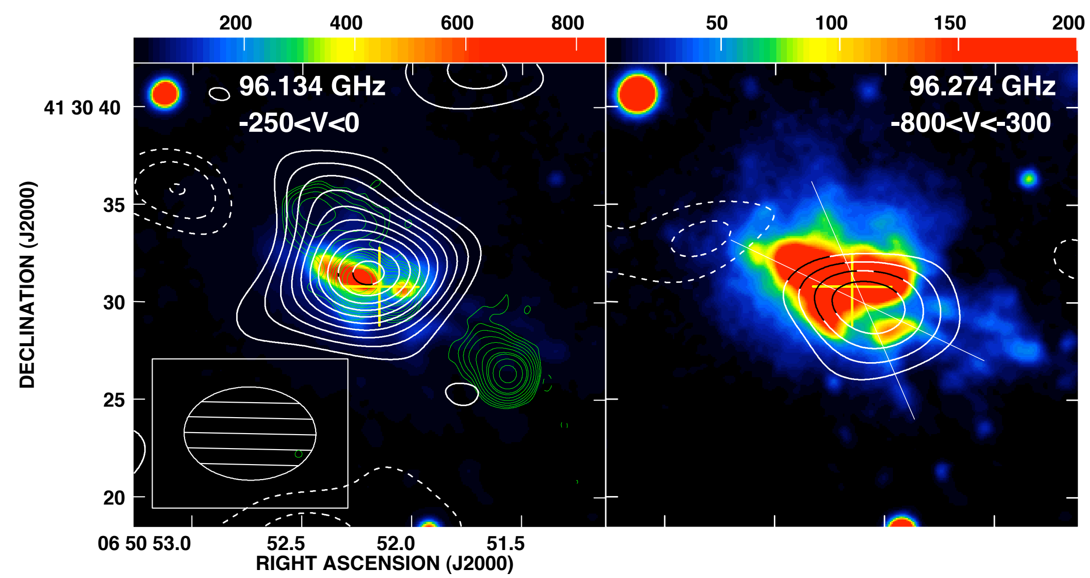
Tacconi+10





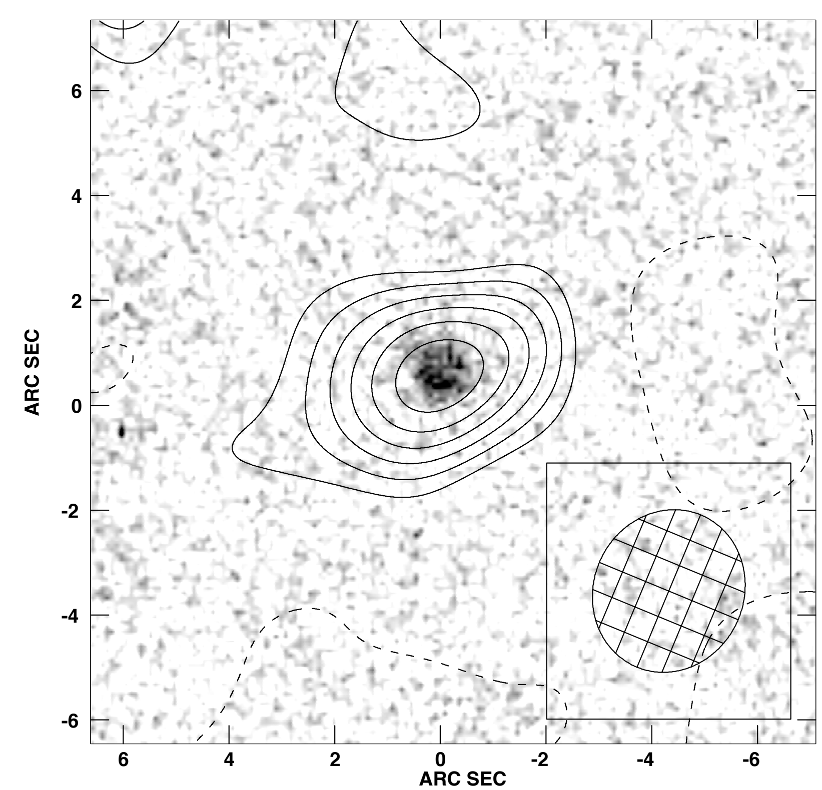
CO in other submm-bright high-z populations

- Radio Galaxies: ~10 z=2-5.2 powerful radio AGN (Scoville+97, Papadopoulos+00, De Breuck +03+05, Greve+04, Klamer+05, Ivison+08, Nesvadba+09, **Emonts**+11)
  - $M_{gas} \sim 5\text{-}10 \times 10^{10}\ M_\odot$



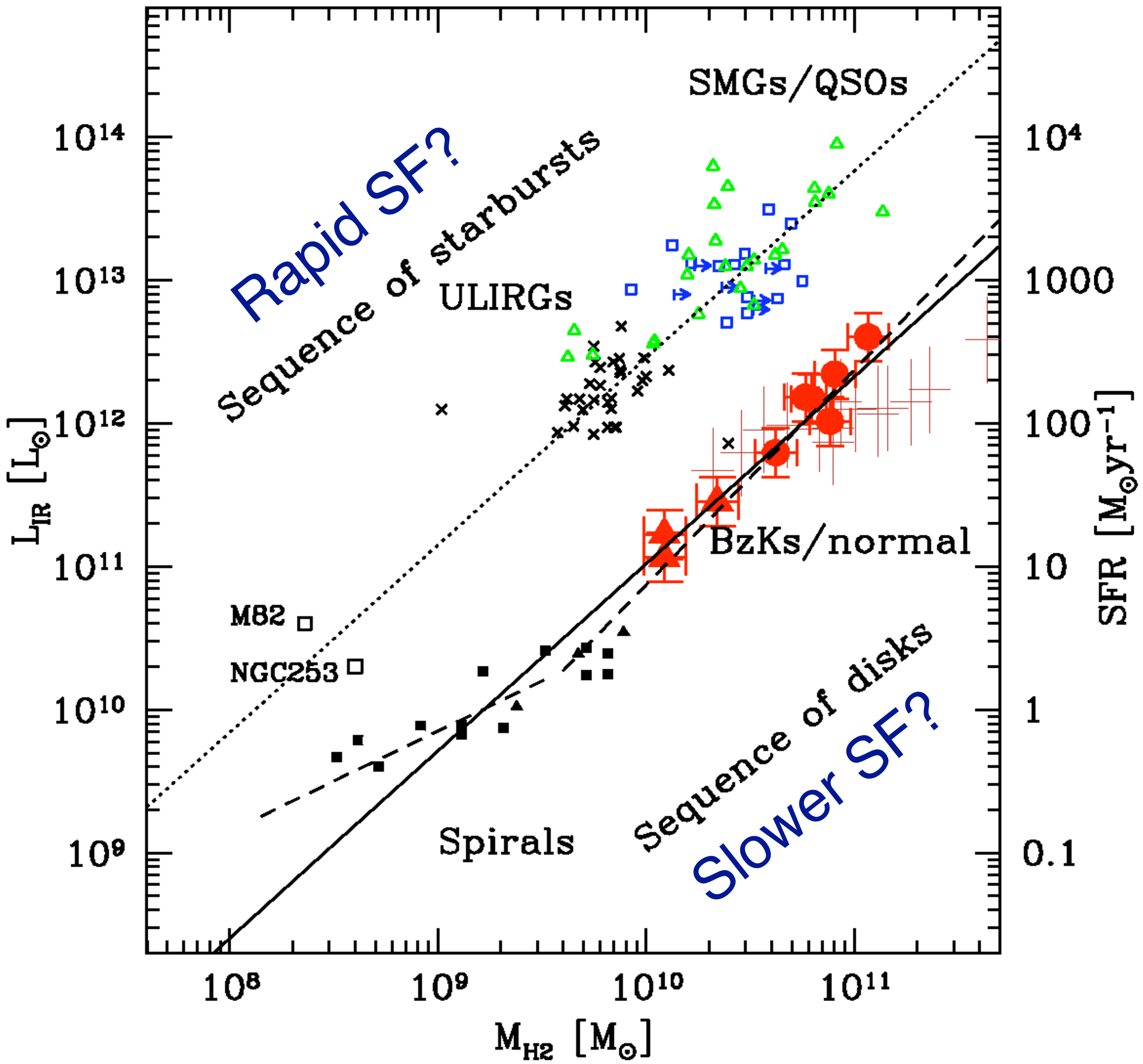
CO in Radio AGN (De Breuck et al. 2005)

- Extremely Red Object (EROs): HR10 - very red opt/nearIR colours(R-K>6) z=1.4
  - $M_{gas} \sim 6 \times 10^{10}\ M_\odot$ (Andreani+00, Greve+03)

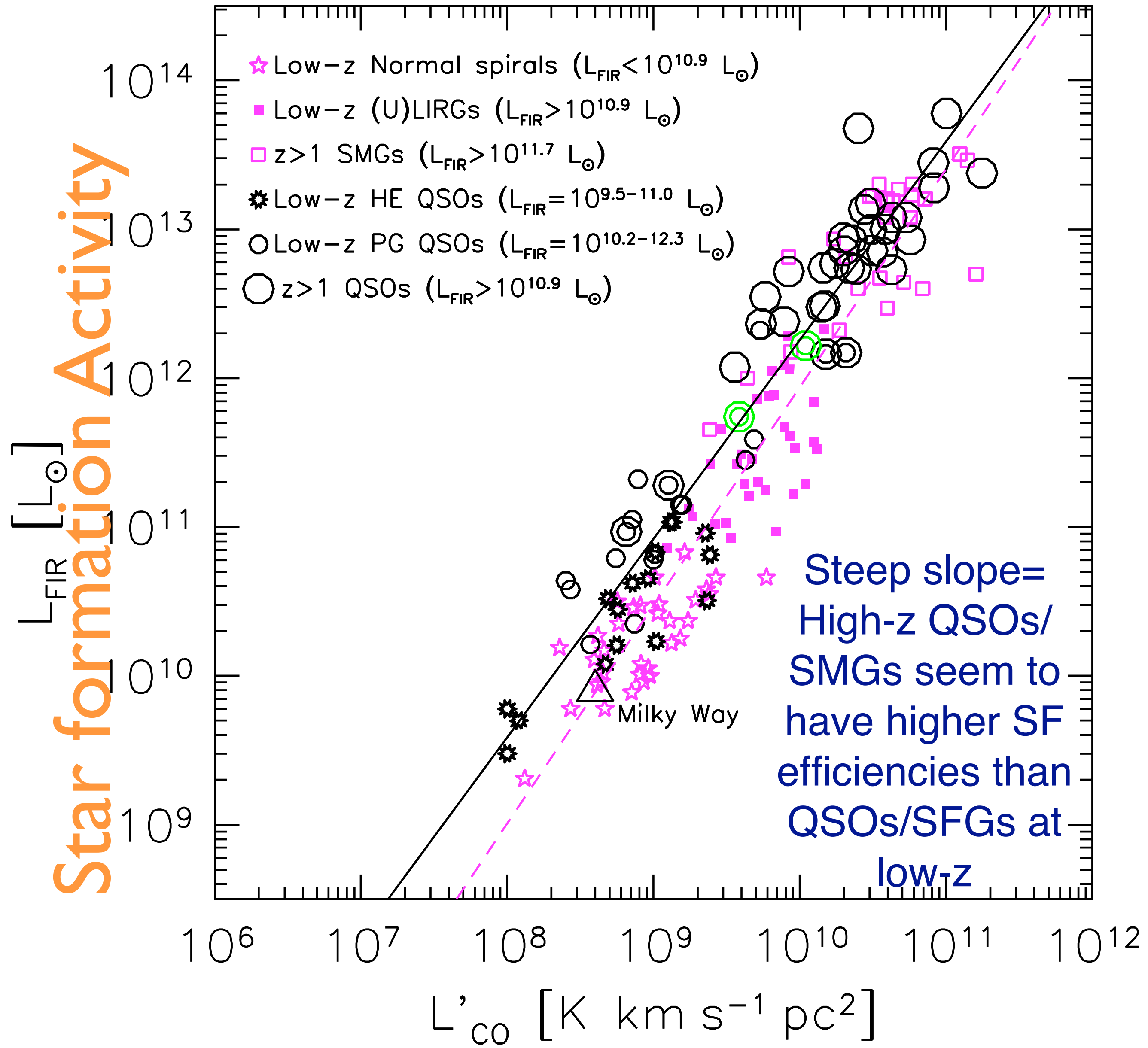


CO(1-0) in an ERO, overlaid on a K-band image (Greve et al. 2003)

Star-formation Law



Daddi+10

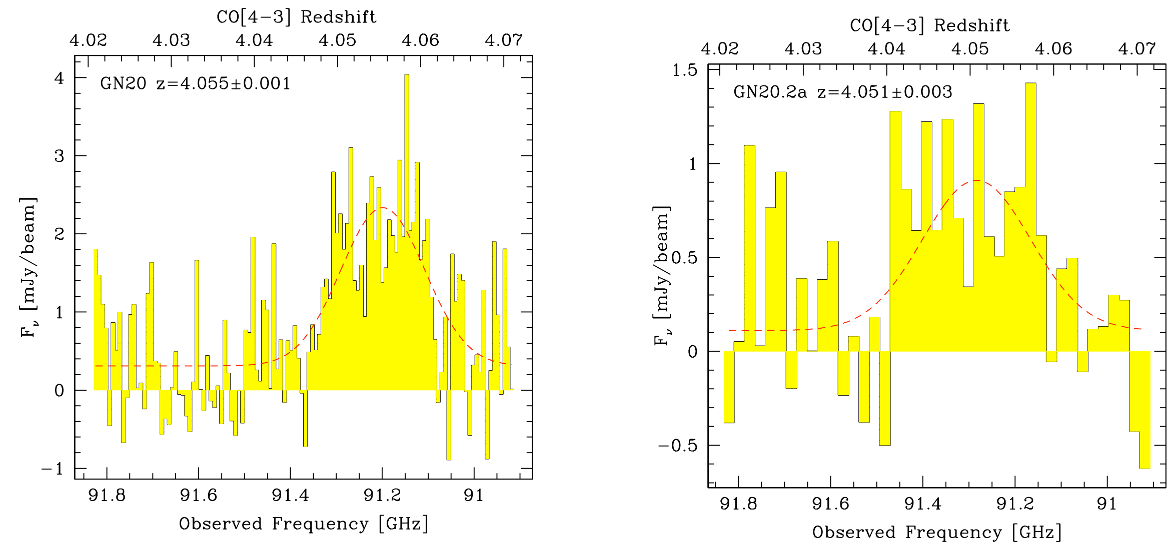


Fuel available for star formation

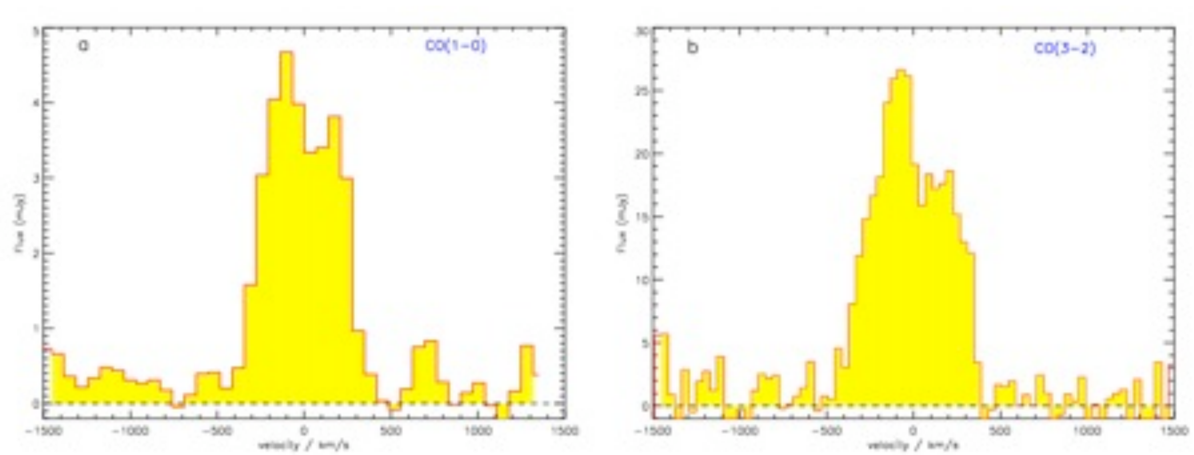
compilation from Riechers+11

Using CO to pinpoint a galaxy’s counterpart (+ redshift!)

- Also, until fairly recently, these CO detections were done only on objects with precise spectroscopic redshifts from opt/IR diagnostics
- Because these galaxies are so dusty, sometimes it is hard to get an optical spectrum, but it pops out in CO
- Require wide enough bandwidth to make it efficient (e.g. EMIR, Z-spec & Zpectrometer)
- we will hear more from Dominik Riechers & Axel Weiss’ talks..



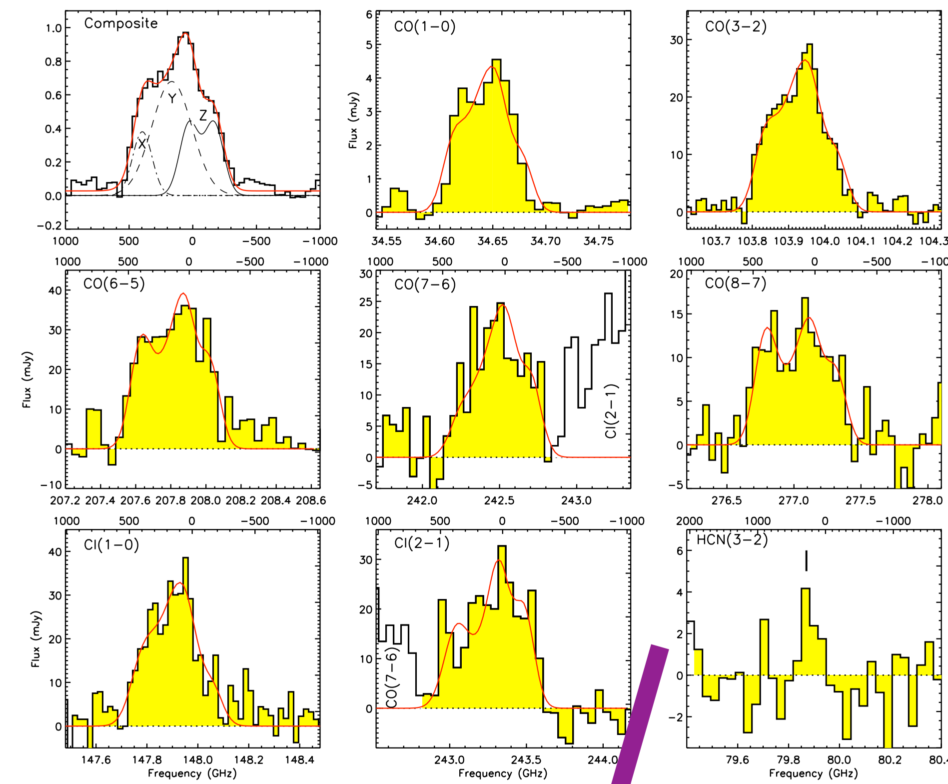
First optically faint high-z galaxy to be directly ID’d through CO emission: GN20 & GN20.2 (Daddi+09)



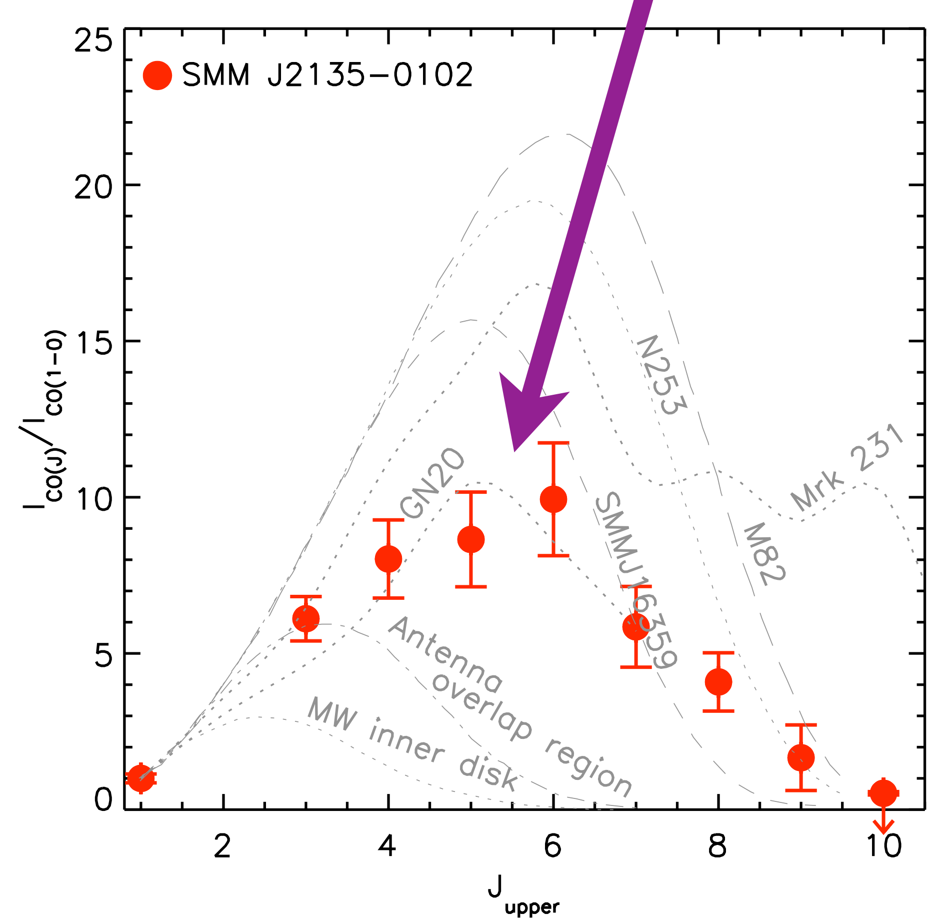
CO redshift search in the “Cosmic Eyelash” using GBT’s ZSpectrometer (Swinbank+09)

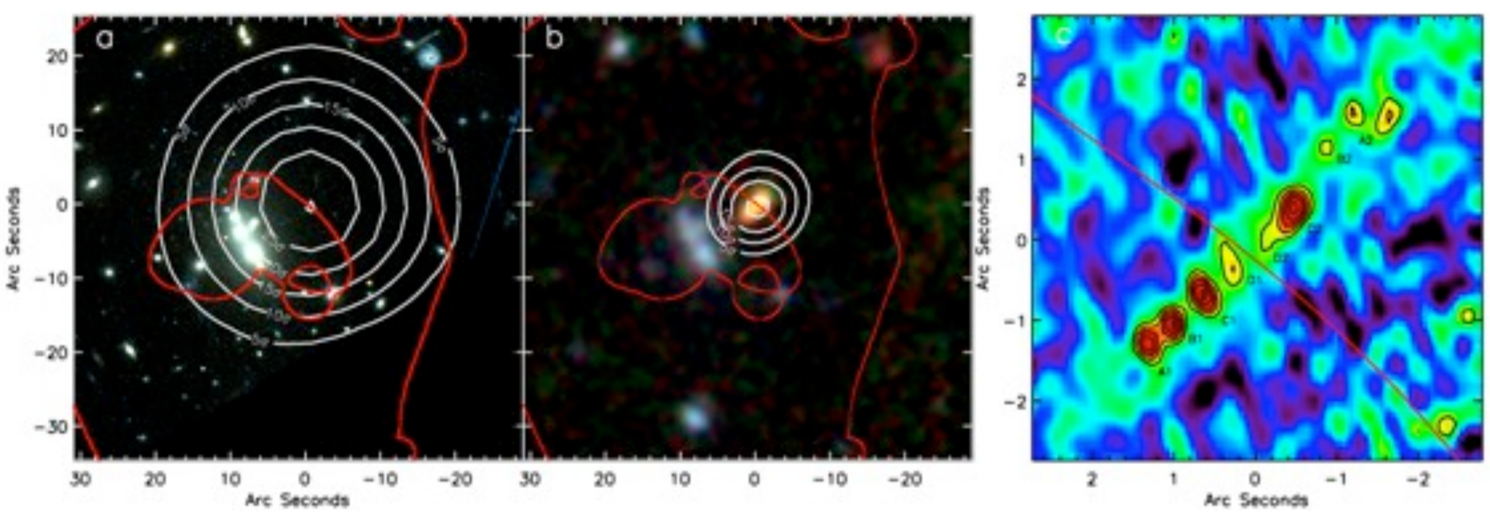
Studies of multiple CO lines

- Different J rotational transitions from collisional excitation/de-excitation
- CO ladders constrain gas density and temperature (Claudia Mastropietro & Axel Weiss' talks)
  - QSOs --> ULIRGs
  - SFGs-->spirals/MW
  - SMGs --> mix of dense + low excitation gas



CO ladder of the Cosmic Eyelash (Danielson+11)

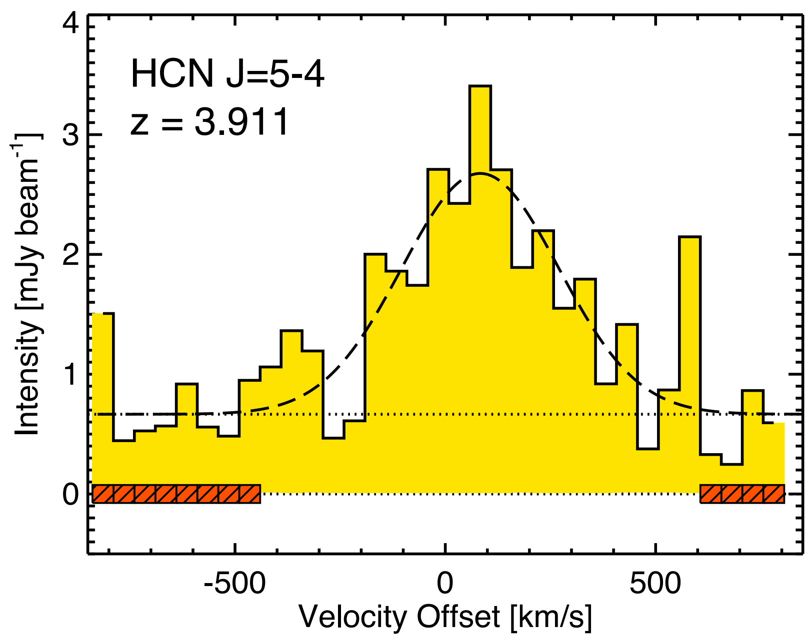




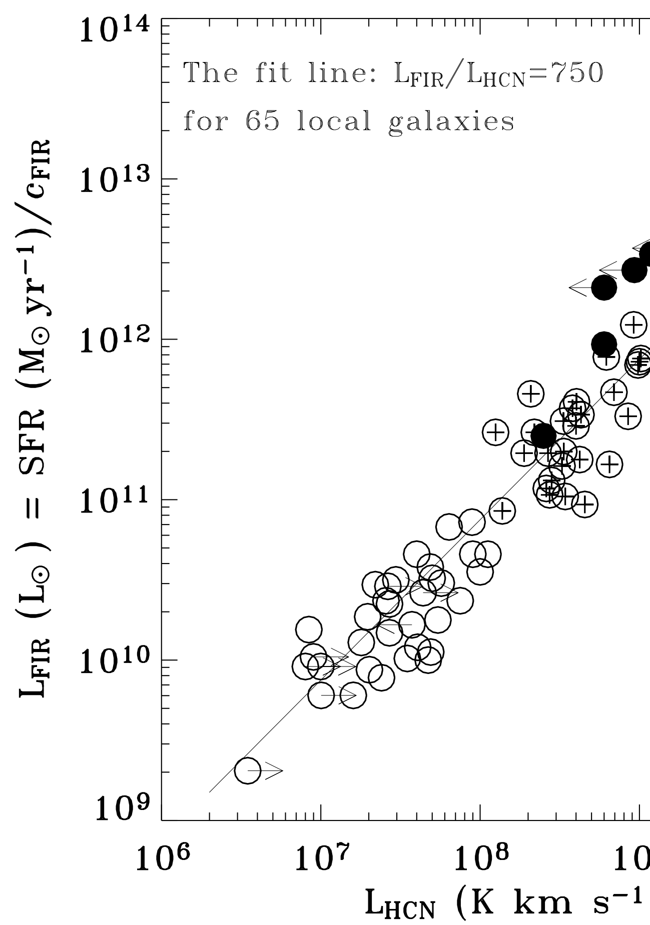
Multiwavelength views of the Cosmic Eyelash, a "normal star forming galaxy" at z=2.3 (Swinbank+10)

Dense Gas Tracers

- CO(1-0) is not the best tracer of dense gas ($n>10^4 cm^{-3}$ -> where SF *actually* occurs!)
- Studies of HCN, HNC, HCO+, CN are better tracers of dense SF cores (density~10^4 cm^{-3})
- These lines are at least 10-30x fainter than CO(1-0), so not much has been done at high-z
- Only a few galaxies have been detected in >1 dense gas tracer line (needed to study chemical composition & excitation of the dense active SF component in molecular ISM)
- This will change with ALMA!



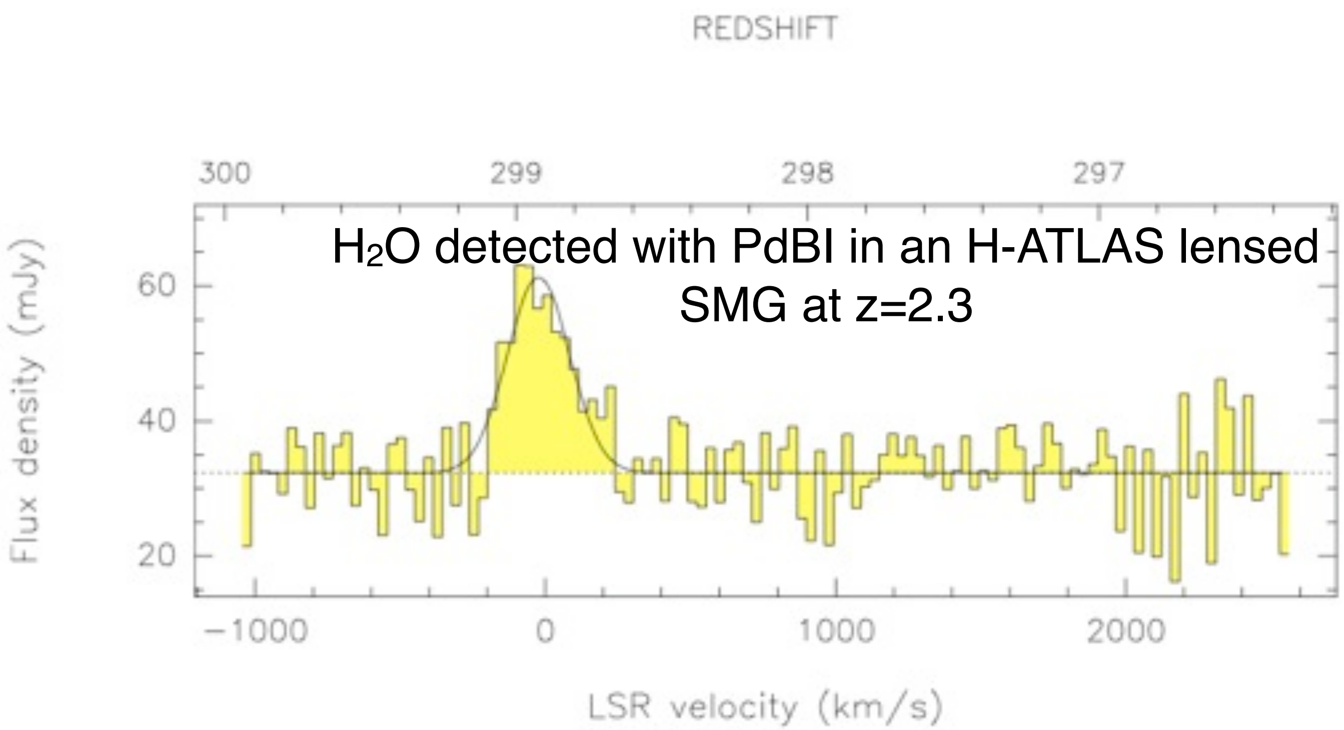
QSO APM08279+5255 (Wagg+05)



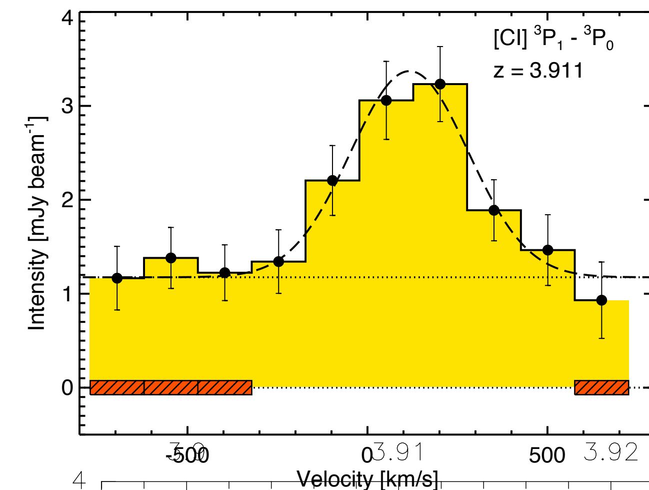
HCN more closely traces star-formation than CO (Gao+07)

Other tracers of molecular gas

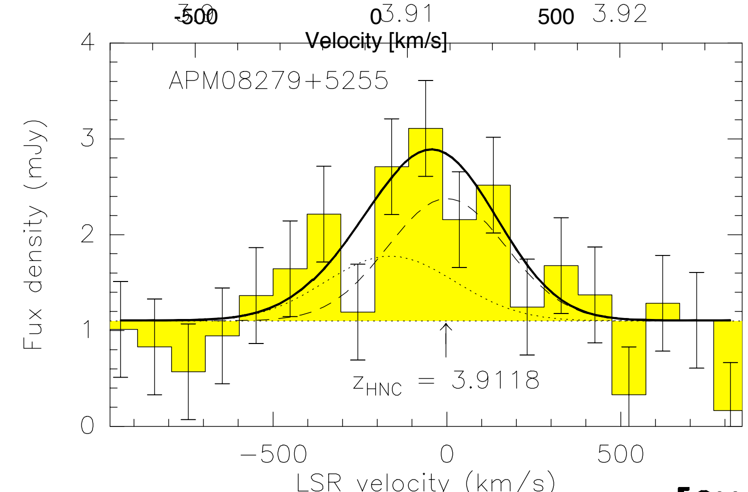
(You will hear more about some of these in the coming days...stay tuned!)



Omont+11



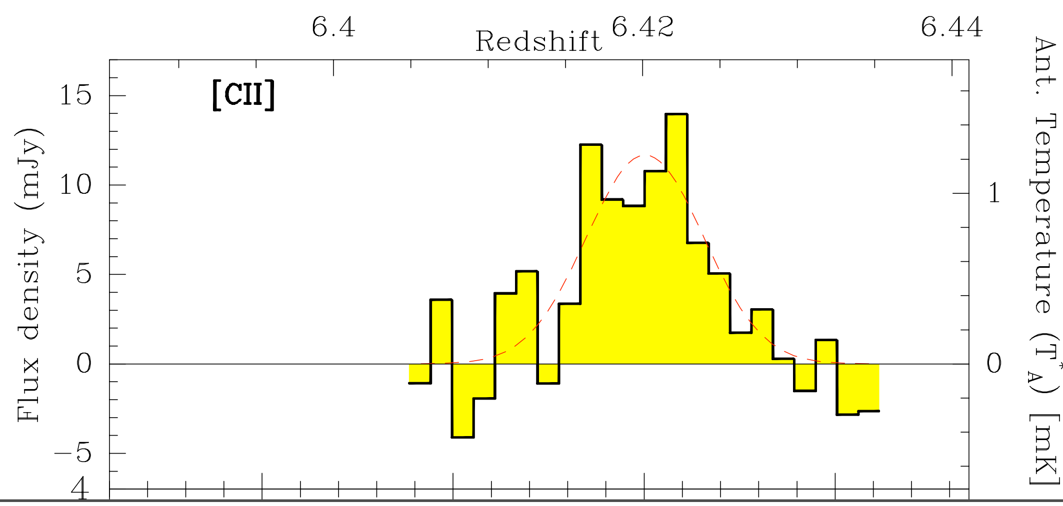
Wagg+06



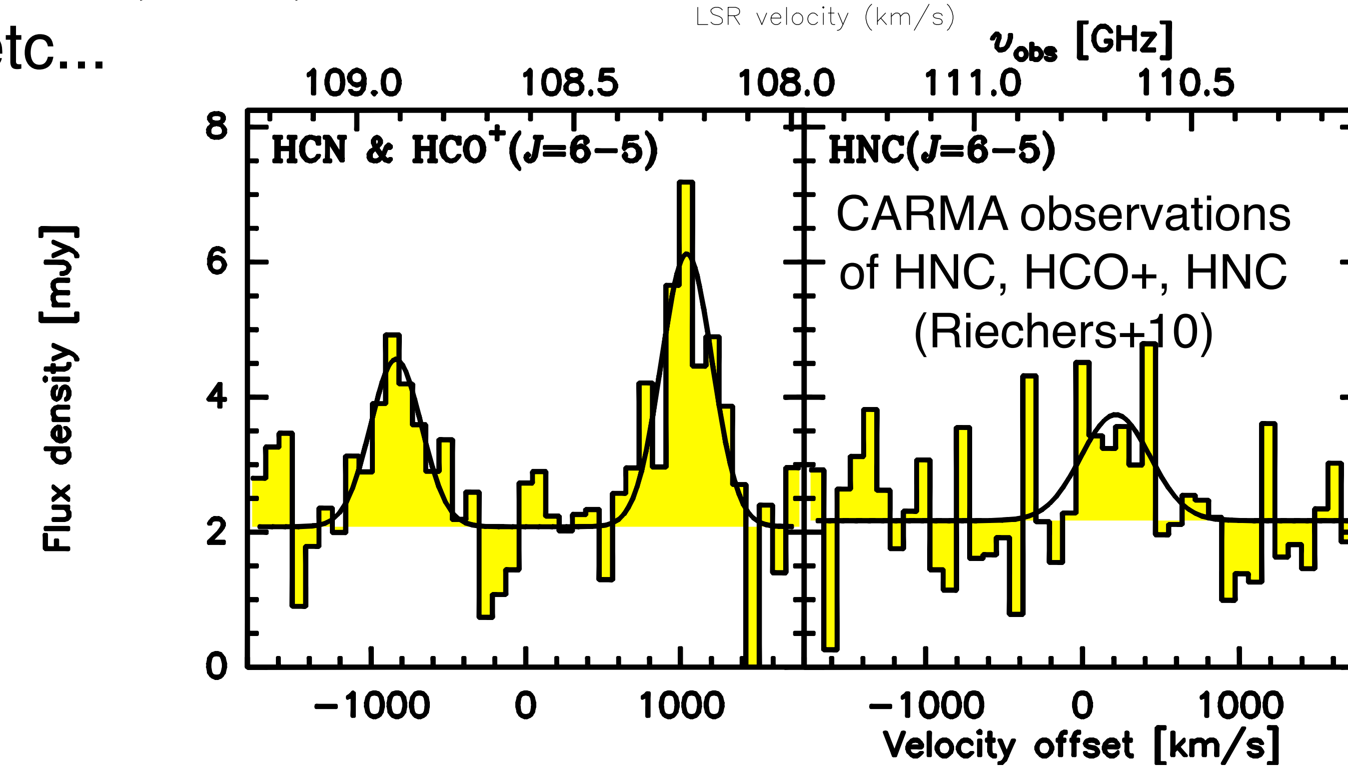
HNC & CN (Guelin+07)

- Species other than CO can provide additional info on molecular gas: fine-structure lines of CI and CII, H_2O, CN, ground states of HCN, HNC, HCO+, etc...

First detection of [CII] at high-z: QSO at z=6.42

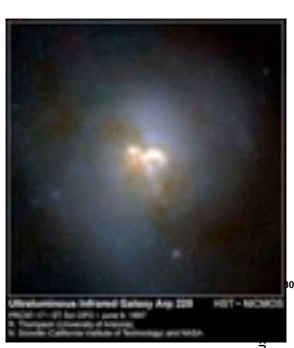


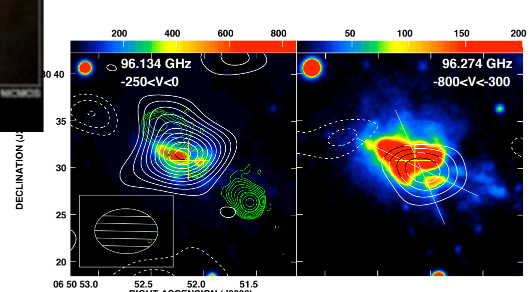
Maiolino+05

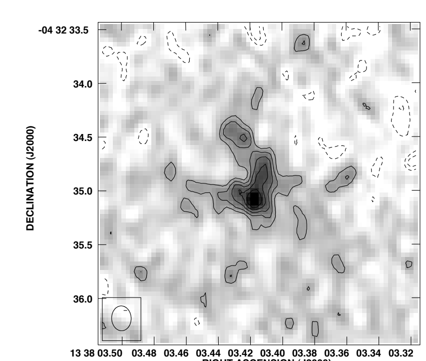


Some Warnings

- Many caveats and assumptions with CO used as a gas & dynamics tracer
  - Looking at multiple independent tracers will provide a more holistic picture
- CO might not be the best tracer of gas in galaxies at the highest-redshifts (z>4)... --> Rachel Somerville & Carlos DeBreuck's talks
- We are probably mostly looking at the "freaks" - how typical are these?
  - Bigger samples with larger dynamical range of properties (L_{IR}, $M_{\odot}$, SFR, environment, etc..) required







Final Remarks

- CO has been used to constrain the physical characteristics (morphology, masses, kinematics, densities, temperatures) of the massive reservoirs of H_2 from which stars are formed (out to z=6.4 so far!)
- Up until now, we have been really probing the TIP of the iceberg at high-z (most luminous/active systems)!
- ALMA will be able to provide a more unified picture of galaxy evolution out to the EoR(see Fabian Walter's talk):
    - spanning a wider range in luminosity from Milky Way types to the most massive systems out to the highest redshifts (Sergio Martin's talk yesterday)
    - resolve many of gas reservoirs to constrain their dynamical masses
    - probe a range of molecular/atomic transitions (other than CO!) more routinely

ALMA (ESO/NRAO/NAOJ)