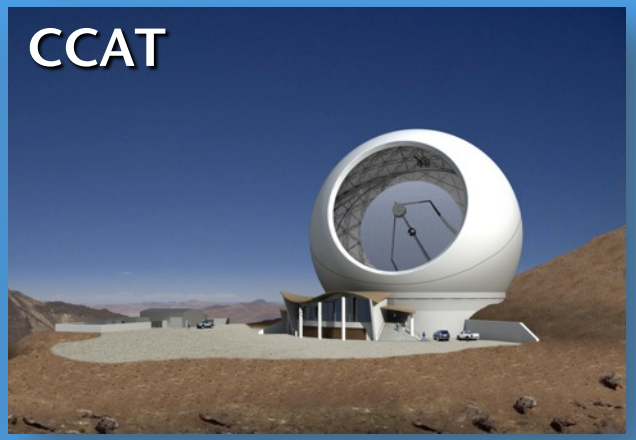
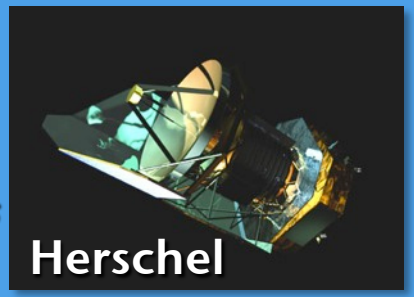


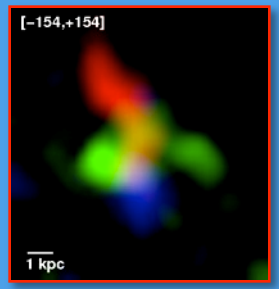
Fueling Cosmic Star Formation: The Molecular Interstellar Medium in High Redshift Starburst Galaxies

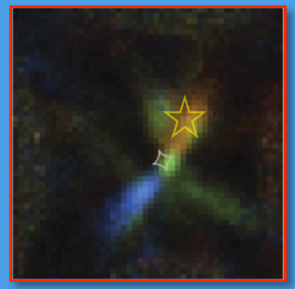
Dominik A. Riechers
California Institute of Technology

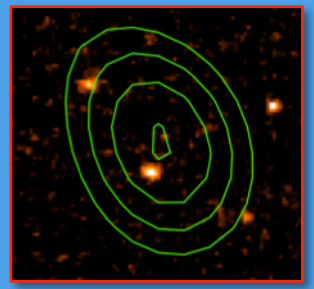


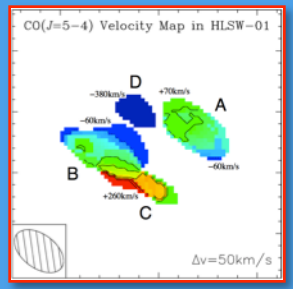
Multiwavelength Views of the ISM in High–z Galaxies
June 28, 2011

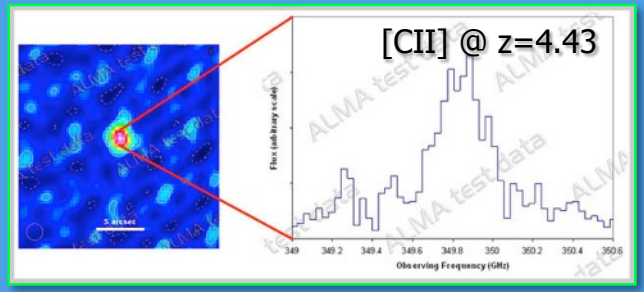
with: C. Carilli (NRAO), F. Walter (MPIA), F. Bertoldi (AIfA), A. Weiss (MPIfR), A. Cooray (UCI), P. Cox (IRAM), P. Capak (SSC), N. Scoville (Caltech), E. Daddi, H. Dannerbauer (CEA), K. Menten (MPIfR), P. Vanden Bout, M. Aravena (NRAO), J. Wagg (ESO), J. Hodge (MPIA)





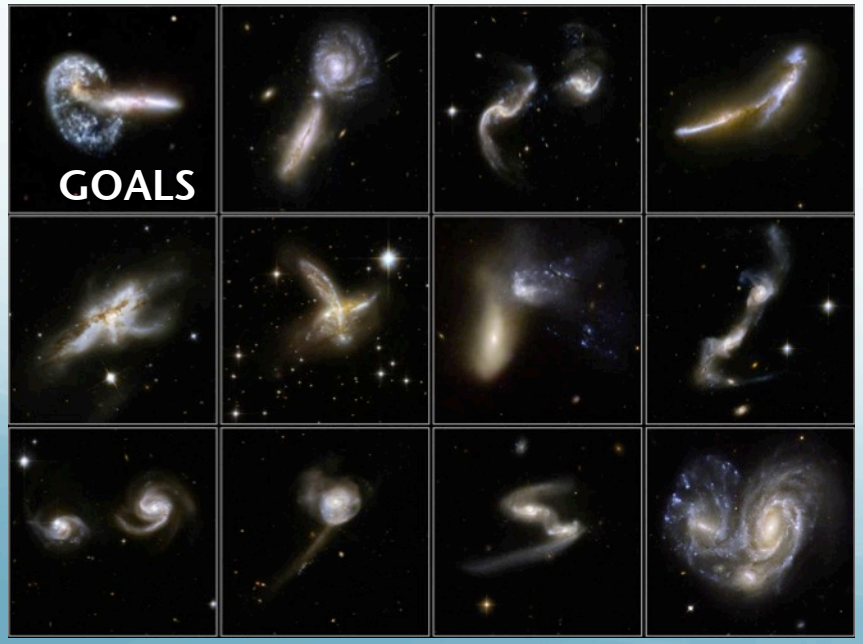


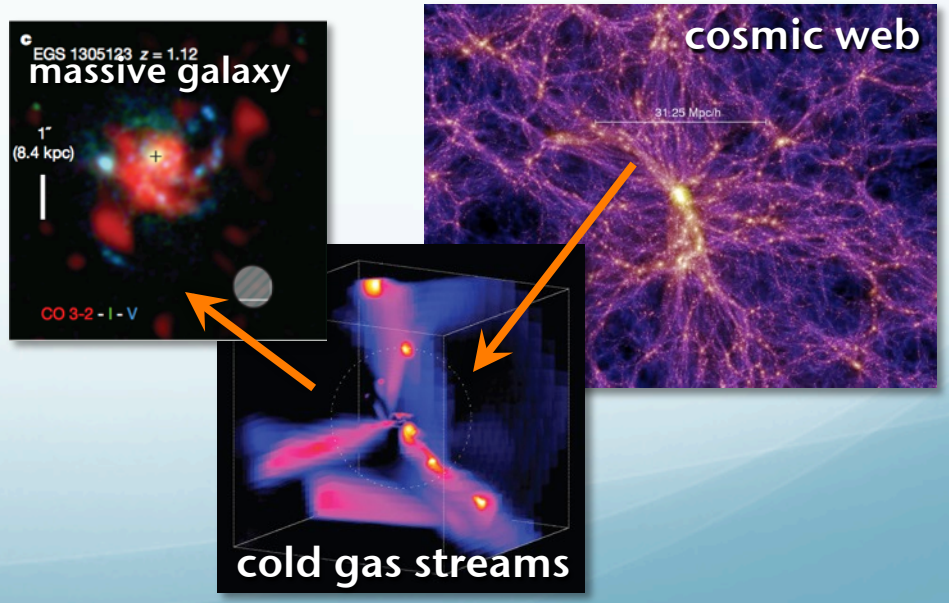




Outstanding Major Issues in Galaxy Evolution

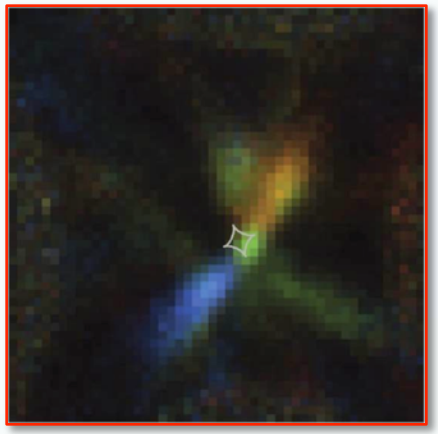
- Does star formation/M_* buildup at early cosmic times occur dominantly through major mergers, minor mergers, steady 'cold mode' accretion?
- How do high-z galaxies get their gas? What are their gas mass fractions?
- What are the physical/chemical properties, distribution, and dynamics of the gas in high-z galaxies that set the initial conditions for star formation?

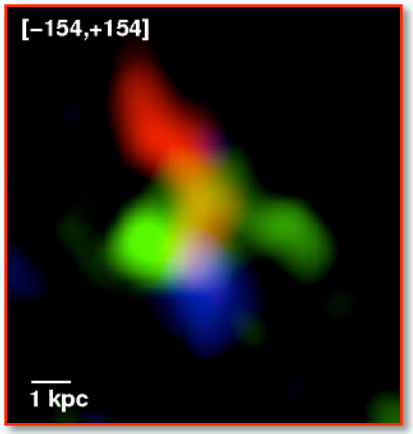


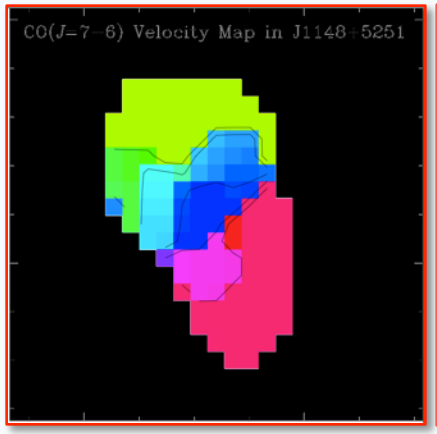


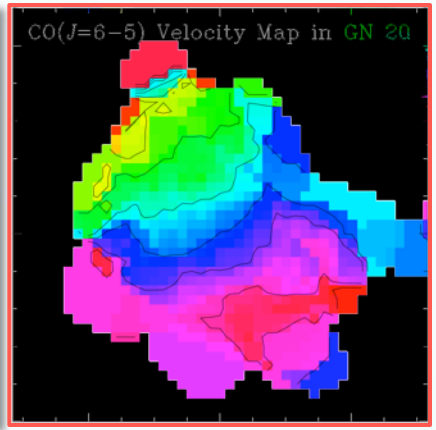
Images: Springel, Dekel, Tacconi

Critical element: molecular gas in galaxies









Requirements:

(1) Detailed studies of molecular gas in individual high-z galaxies

⇒ need to dynamically resolve few 100pc/cloud scales to study mechanism for SF and determine robust rotation curves/3D merger structure

⇒ need to dynamically calibrate gas mass/dispersions for star-forming clumps

⇒ robust gas masses, gas fractions, merger fractions, dynamical drivers of SF

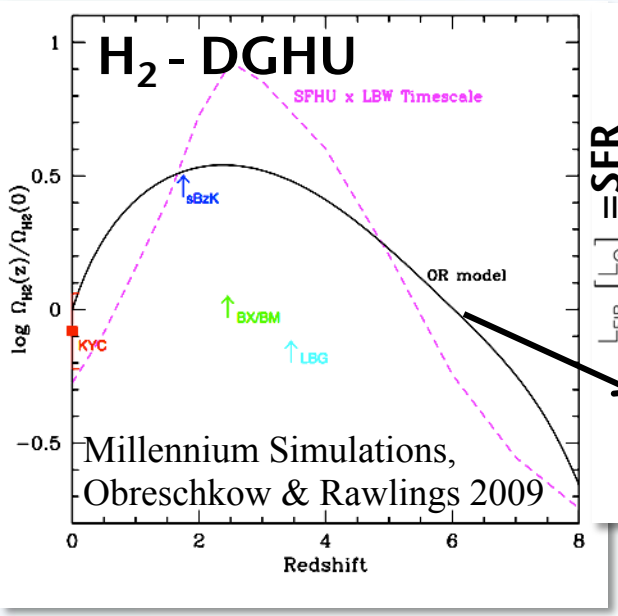
⇒ need to study multiple molecular gas tracers and their excitation properties

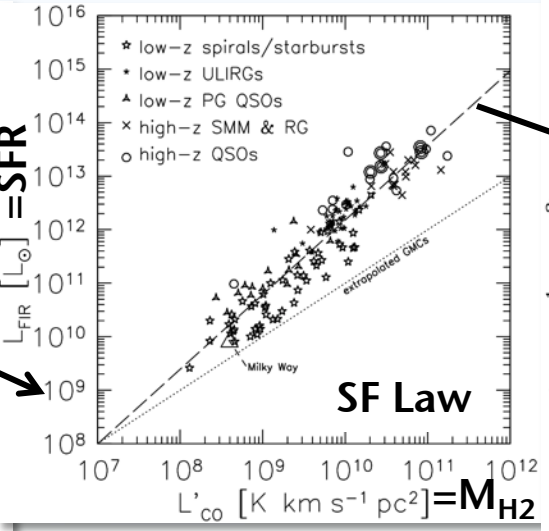
(2) Systematic studies of molecular gas in *all* high-z galaxy populations

⇒ Dense gas history of the universe, "blind" CO Deep Field study

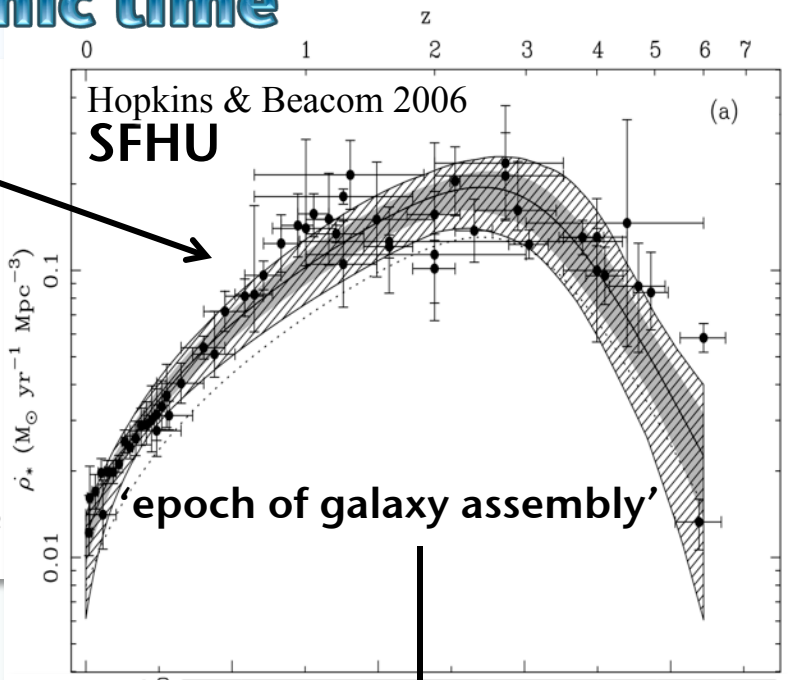
Images: Riechers ea. 2008a, 2008b, 2009; Carilli ea. 2010

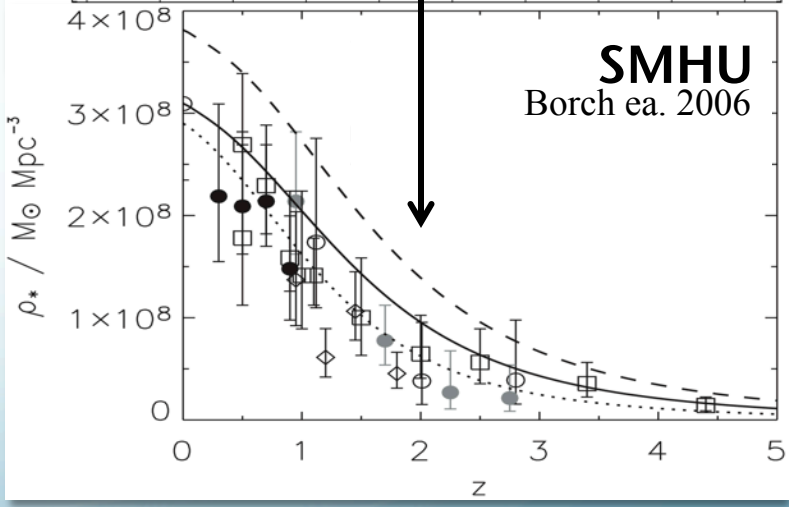
Dense gas history of the Universe → Tracing the fuel for galaxy formation over cosmic time





Riechers ea. 2006





Dense Gas -> SF Law -> Star Formation -> Stars

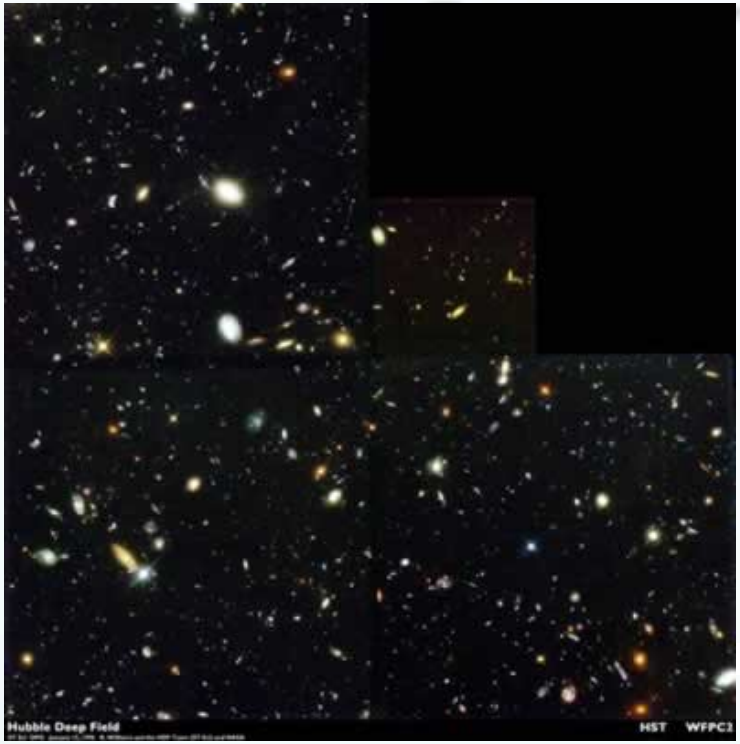
~50% present day M_* produced @z~1-3

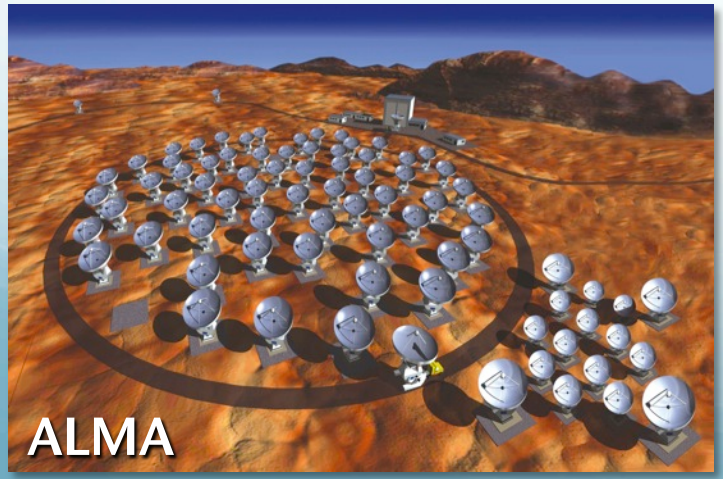
Formation History:

- past: **M_*** ('effect')
- current: **SFR**
- future: **M_{gas}** ('cause')

⇒ DGHU is critical next step for a complete picture of galaxy formation

H_2 Mass Function: CO Deep Field Study





Problem:

CO studies at high z are highly selected
(optical/FIR/radio brightness, spectral features)

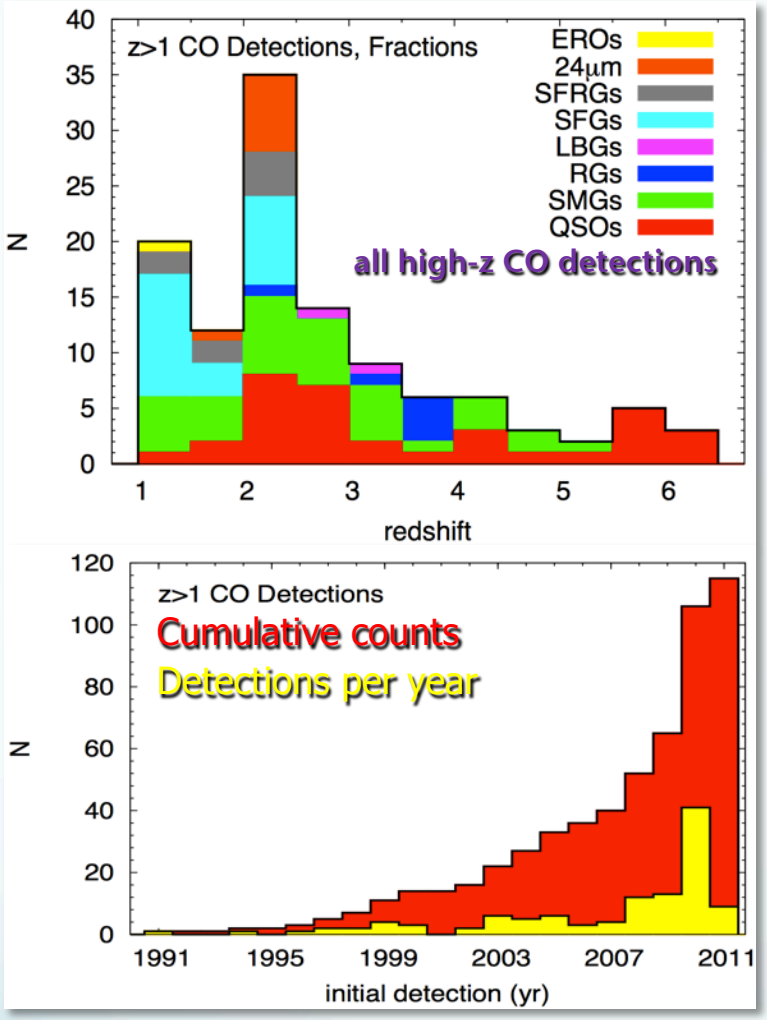
Method to overcome selection bias:

⇒ select *directly* in CO!
⇒ like early SFRD studies: do 'Deep Field'
⇒ ideal: CO data cube contains redshifts

Requirements:

⇒ disentangle galaxy populations based on CO (CO -> H_2)
⇒ direct, 'blind' CO redshift selection
⇒ continuous redshift coverage (=volume)

M_{gas}: Molecular Gas at High z



- molecular gas observations at high-z help to constrain:

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})

kinematic evidence for disks/mergers

(triggering mechanism of AGN activity & SF: cold gas accretion flows vs. major mergers)

Solomon & Vanden Bout 2005,

Riechers 2007, 2011

- >99% H_2 – difficult to observe, use **CO** as tracer
- rotational transitions of **CO** at [n x 115 GHz/(1+z)],

[115GHz = 2.6mm]

More details: K. Coppin's talk

Powerful suite of existing cm/mm interferometers: pushing back to the first galaxies

CARMA-23

High res imaging at 3/1mm:
<0.3" resolution

Very Large Array (1979) -> EVLA (2012)

High res imaging at 12-7mm

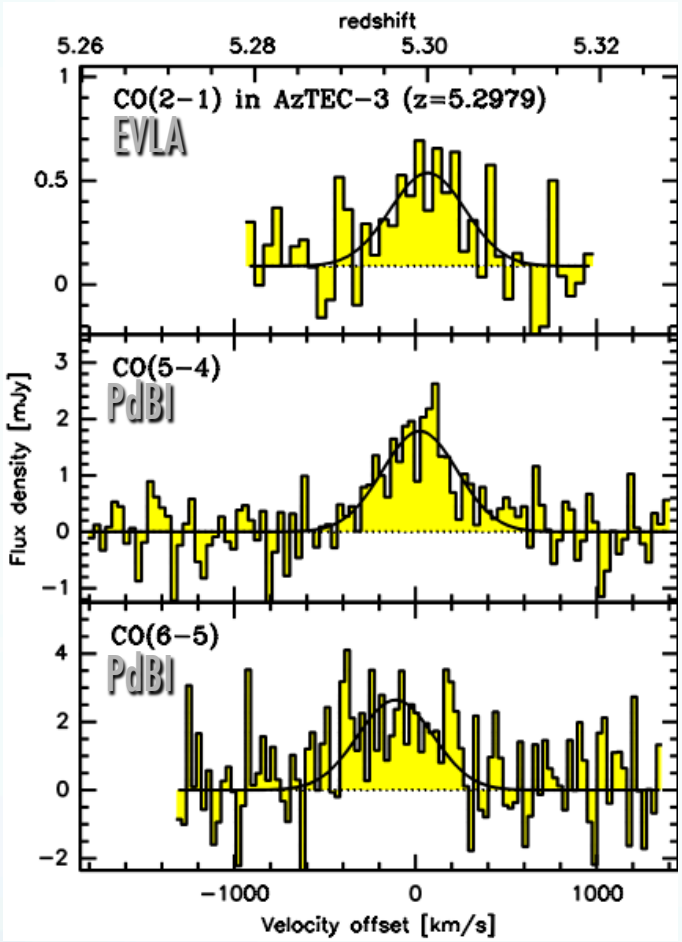
res < 0.15"

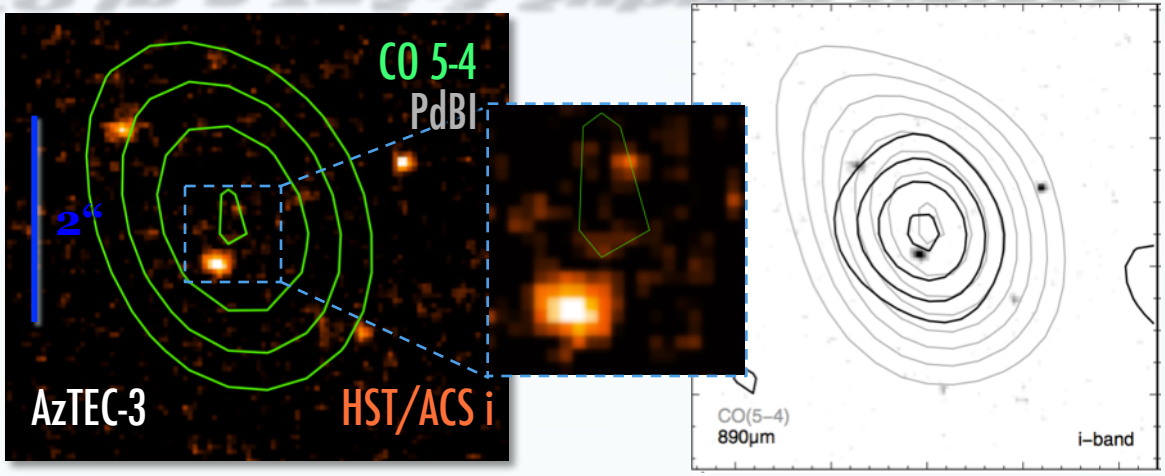
Plateau de Bure Interferometer (PdBI)

High res imaging at 3-0.8mm

res < 0.3"

First EVLA result: CO in a z=5.3 Submm Galaxy





COSMOS/AzTEC

- $M_{H2} = 5.3 \times 10^{10} M_{sun}$
- $f_{gas} > 0.7\text{-}0.8$
- SFR >1800 M_{sun}/yr (Chabrier)
- $t_{dep} \sim 30$ Myr
- $SFR/M_* = 180\ Gyr^{-1}$

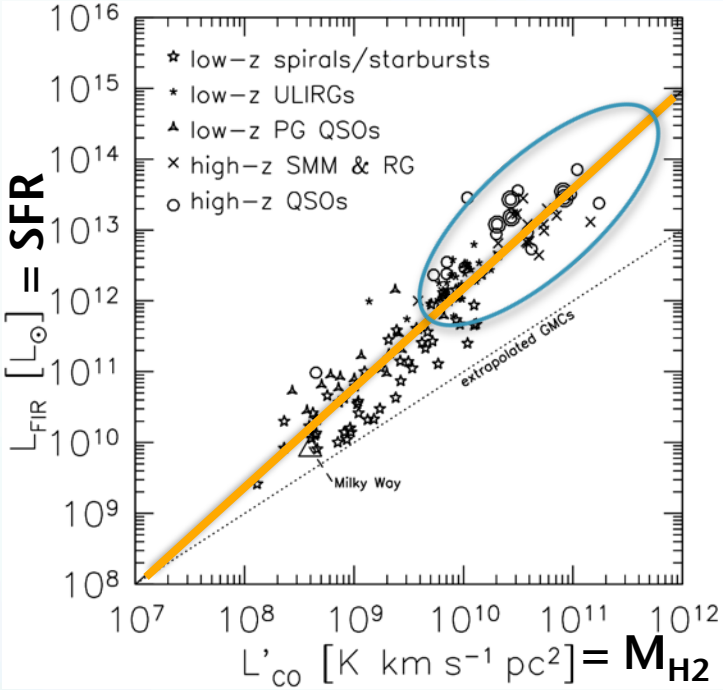
⇒ starting to probe extended high-z tail of SMGs radio-undetected, position from 890μm SMA
(Younger ea. 2007)

3.6μm/890μm/CO offset from optical peak
⇒ heavily obscured star formation

Riechers ea. 2010a
ID: Capak, Riechers ea. 2011, Nature

More on z>4 SMGs: V. Smolcic's talk

Gas Properties of Distant Galaxies: EVLA CO(1-0) Survey



Investigate Differences between Populations:

- **best studied in CO(1-0):**
  - **no excitation bias**
  - **total gas masses**
  - **full size of the gas reservoirs**

⇒ study CO(1-0) in ~30 z>2-6 QSOs, SMGs, LBGs
(bulk of known CO sources at the time)

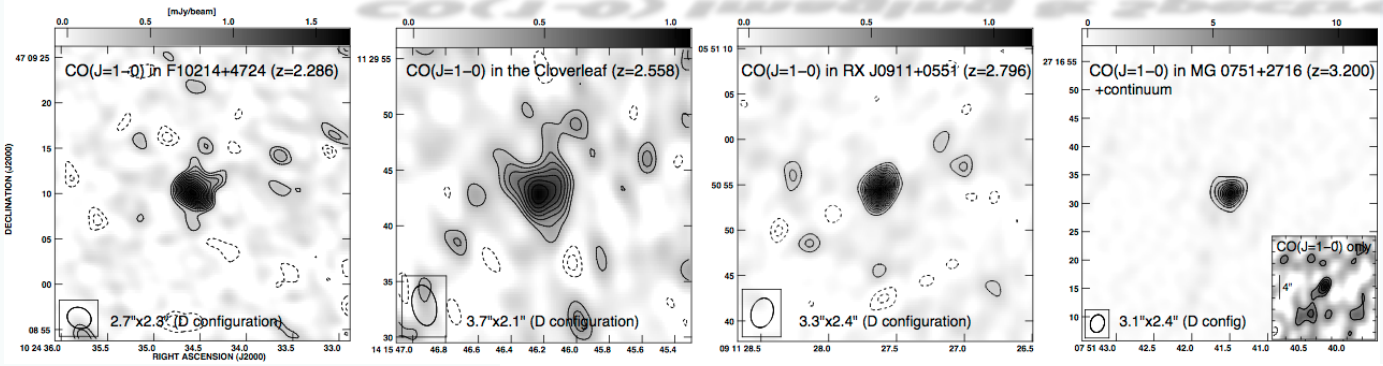
⇒ sample has complementing higher-J CO data

⇒ complementing sample of optical/IR-selected z~2 massive gas-rich star-forming galaxies (SFGs)
drawn from Daddi ea. 2008, 2010, Tacconi ea. 2010
H. Dannerbauer's & M. Aravena's talks

⇒ covering main known populations, corresponding to source densities of several per arcmin^2 down to 'knee' of CO luminosity function

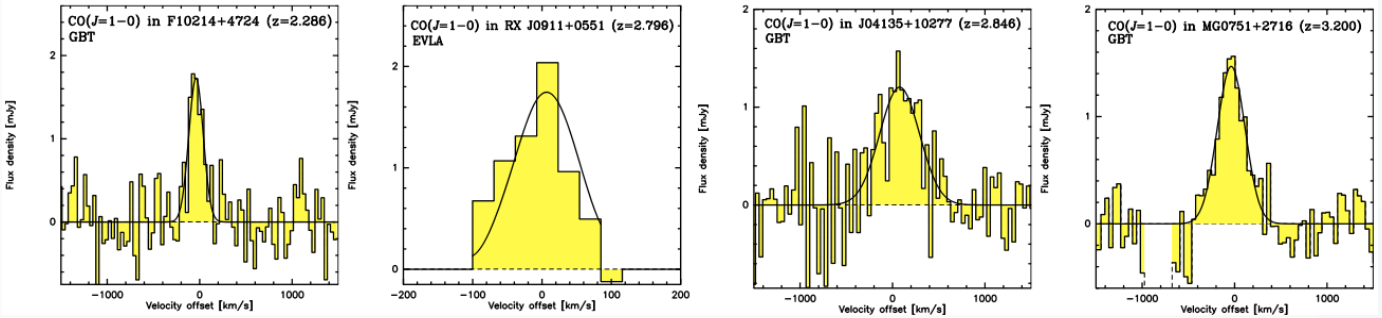
CO(1-0) Imaging & Spectroscopy @z>2

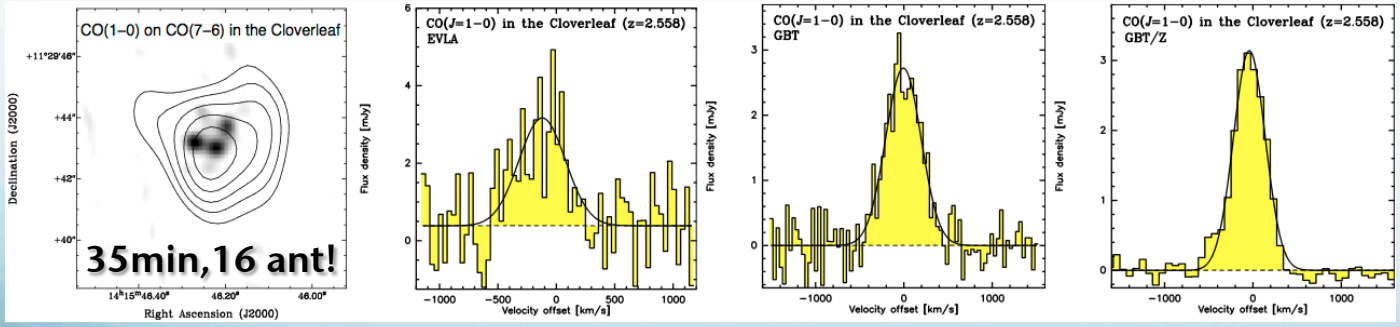
Quasars



EVLA Images

GBT+EVLA Spectra





Cloverleaf (z=2.6):

- EVLA+WIDAR
- GBT+Spectrometer
- GBT+Zpectrometer

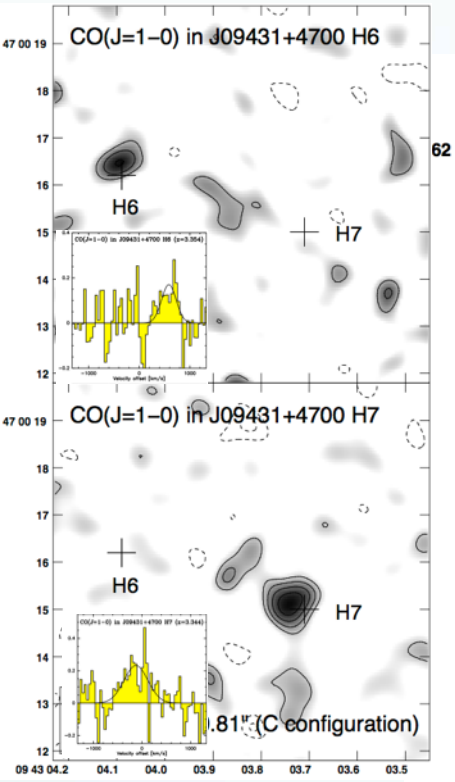
⇒ 35σ detection
⇒ consistent calib

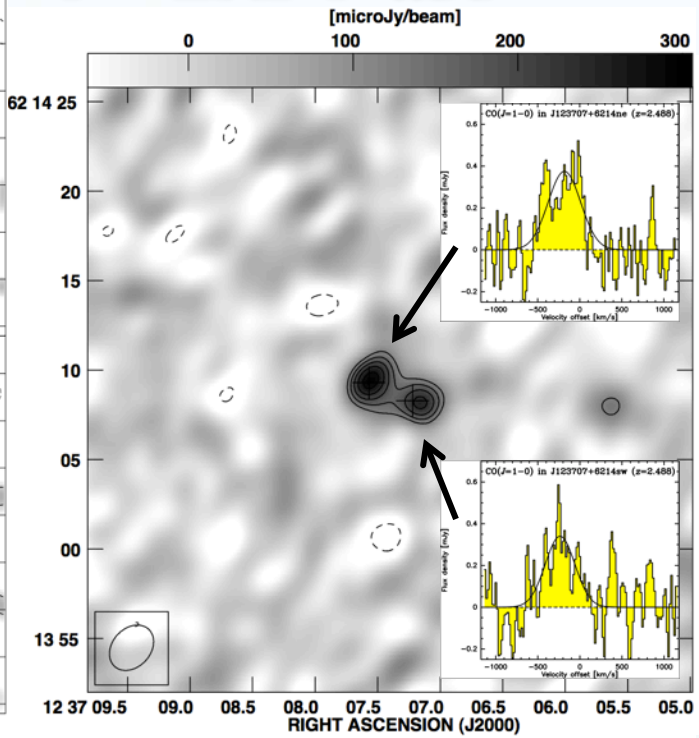
⇒ z>2 Quasars consistently show compact CO(1-0) & high gas excitation

Riechers et al. (2011e)

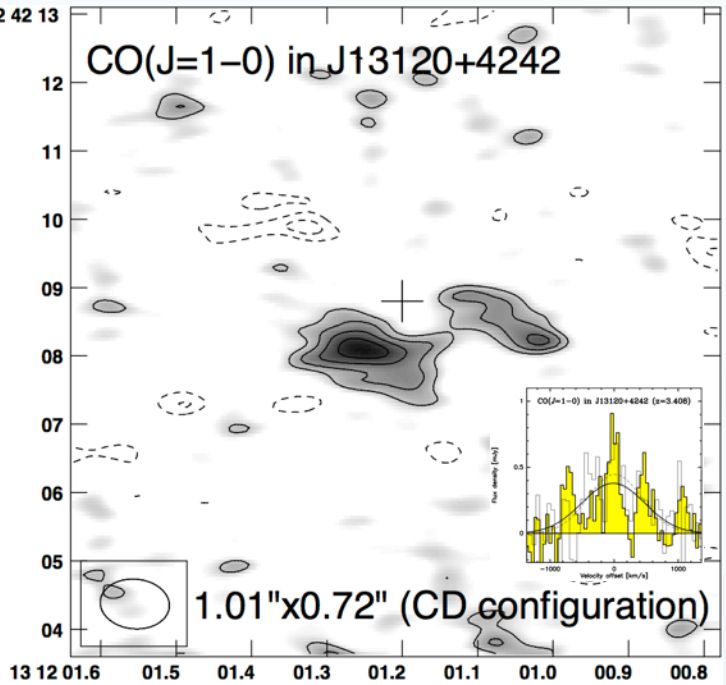
DRAFT VERSION MAY 24, 2011, ACCEPTED FOR PUBLICATION IN THE ASTROPHYSICAL JOURNAL LETTERS (EVLA SPECIAL ISSUE)

An EVLA "Merger Sequence" at z>2?





Submillimeter Galaxies



Early stage → **Intermediate stage** → **Late stage**

~30kpc & 750km/s separation

~20kpc & <100km/s separation

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

Riechers et al. (2011d, 2011f)

Modeling: D. Narayanan's talk

see also: Ivison et al. (2011)

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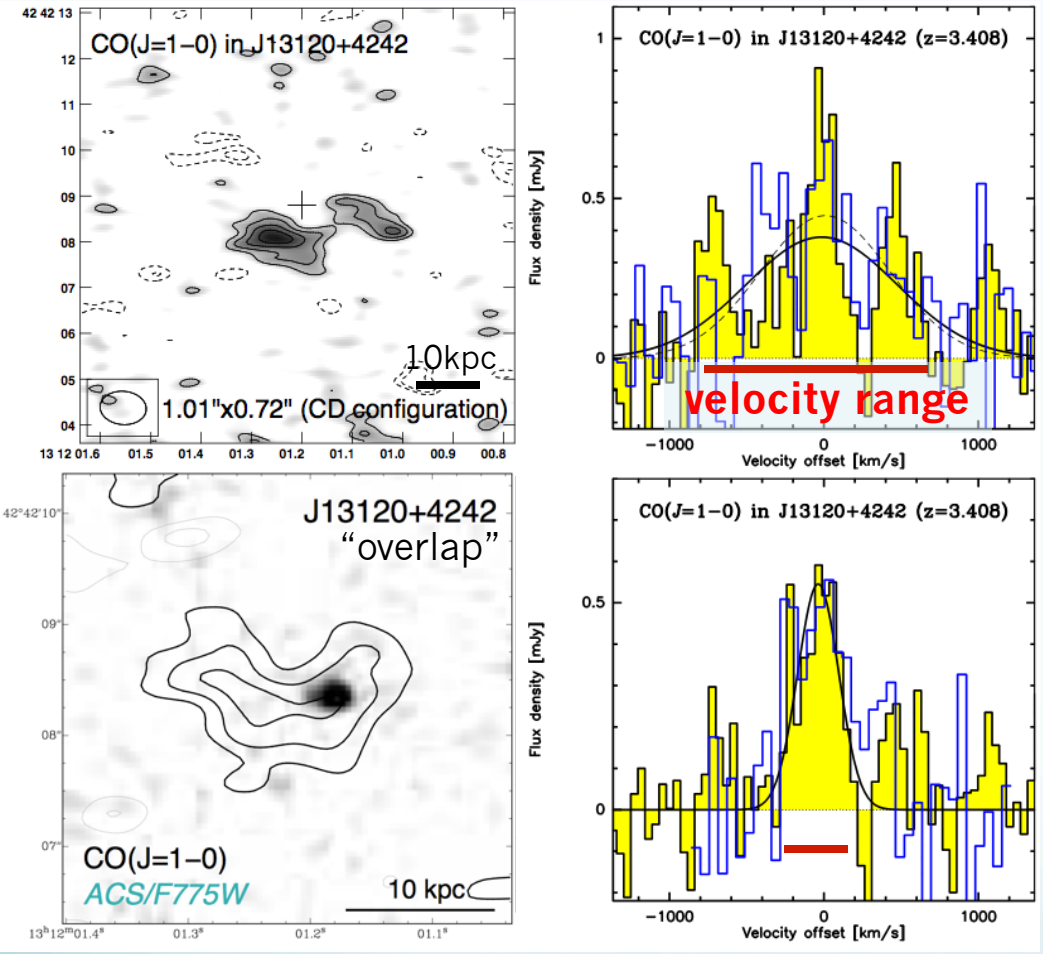
An Extended, Advanced Stage Merger

Submillimeter Galaxies



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)

⇒ z>2-4 SMGs show complex, extended, low-excitation gas reservoirs

Riechers et al. (2011f)

More on SMG CO Imaging: J. Hodge's talk

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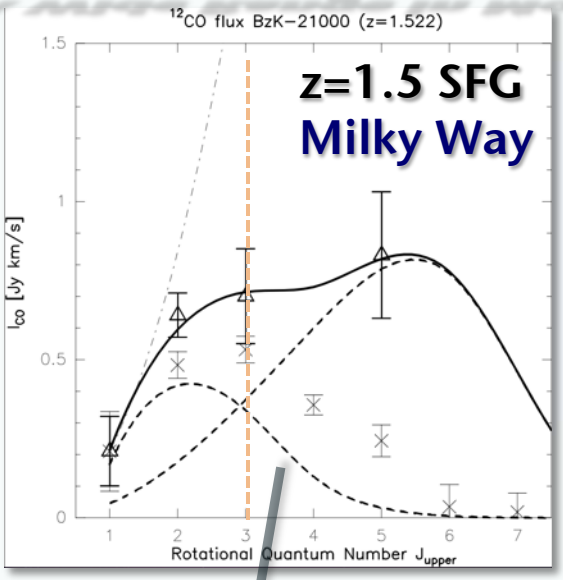
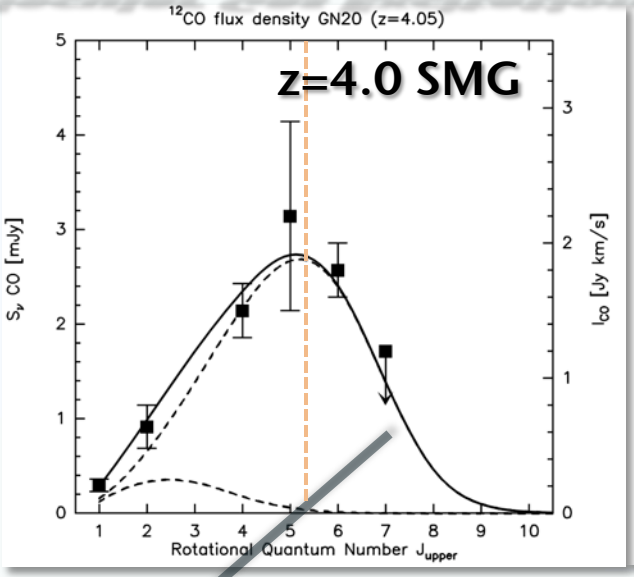
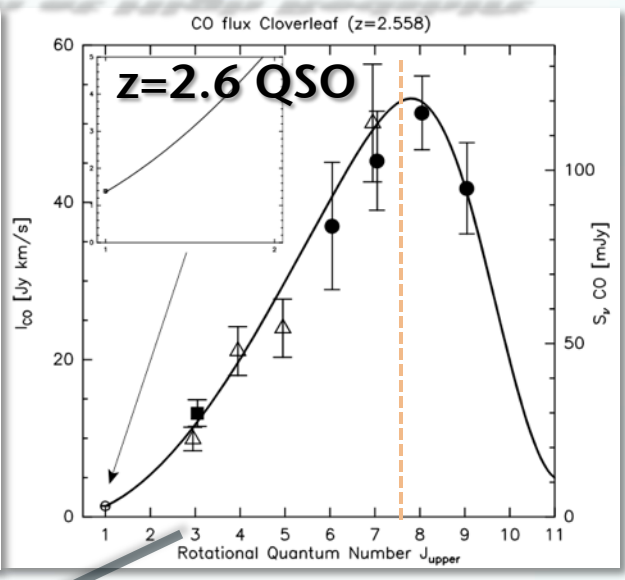
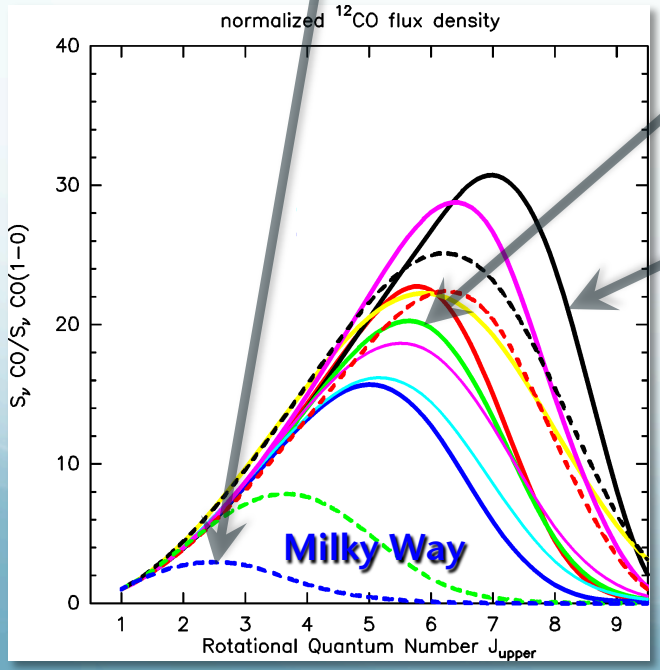
A Wide Range in Molecular Gas Excitation at High Redshift









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}

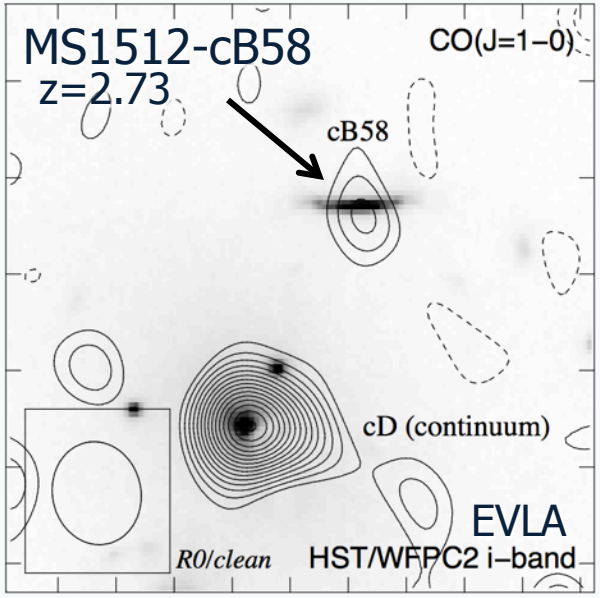
- SFGs: strong MW-like, some ULIRG-like
- SMGs: some MW-like, strong ULIRG-like
- QSOs: ULIRG-like & higher

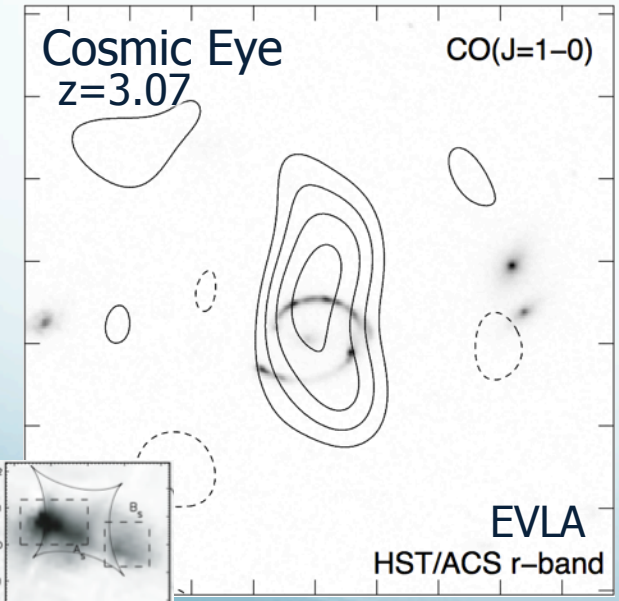
A. Weiss' talk

Riechers ea. 2006b, 2009b, 2011a, Weiss ea. 2007
Dannerbauer ea. 2009, Carilli ea. 2010

Molecular Gas in Lensed LBGs

Studying FIR-faint high-z galaxy populations





Riechers ea. 2010b

Lensed Lyman-break Galaxies (LBGs):

- *not* most extreme high-z starbursts
- 30x lens-magnified
- probing down to L*-ish LIRGs at z~3

⇒ properties mostly similar to nearby LIRGs
- SFRs: 30-60 M_0/yr
- M_{gas}: 5-10 x 10^8 M_0 (CO 1-0: 30-50% higher M_{gas})

⇒ 30x less M_{gas} & SFRs than SMGs/QSOs

- UV light distributed over 1-2 kpc
- CO (at least) over the same area

⇒ ALMA will probe CO in L* galaxies at z>3

⇒ can differentiate high-z galaxy populations based on molecular gas properties

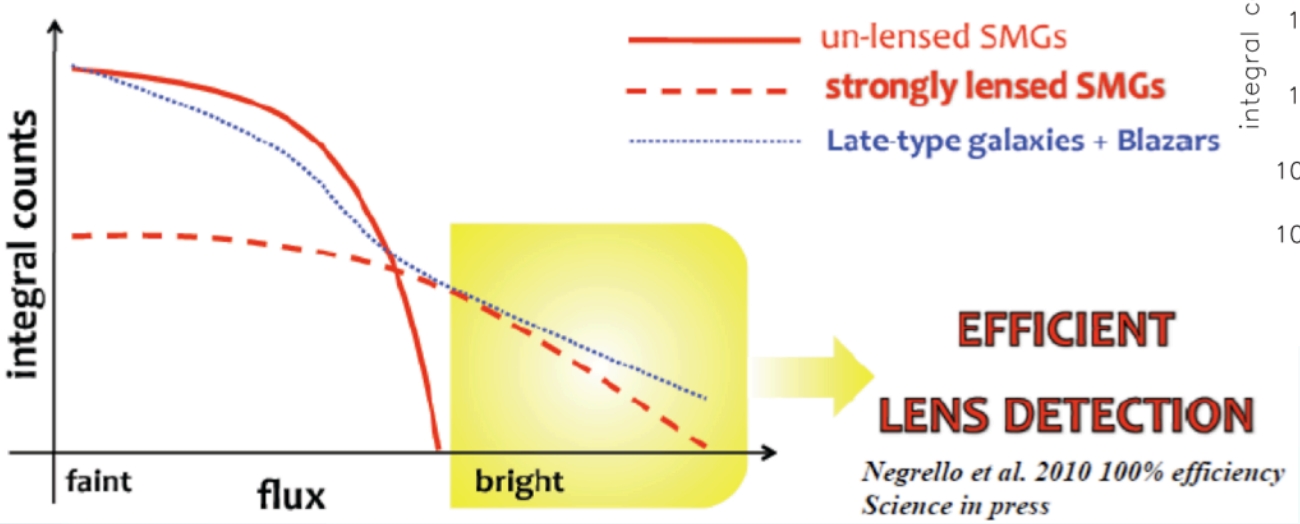
Local analogs: T. Goncalves' talk

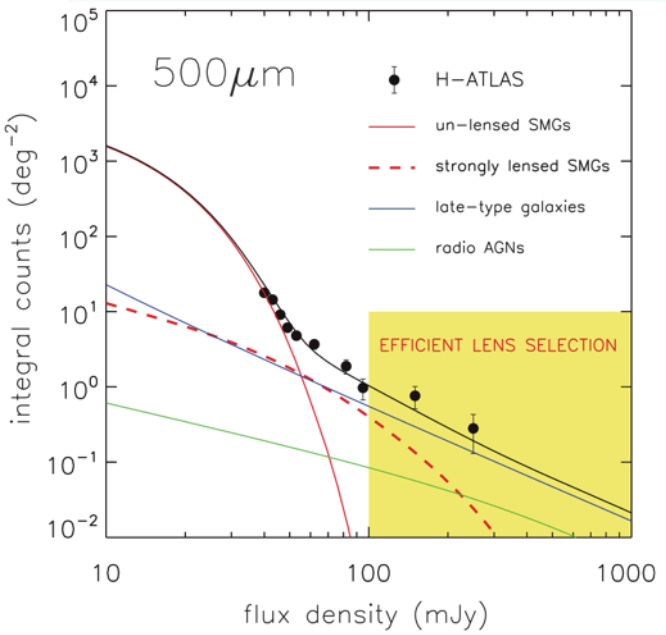
Submillimeter Galaxies: The Herschel View

Sub-mm surveys are ideal for finding lenses

Blain (1996), Perrotta et al. (2003), Negrello et al. (2007)

- high redshift → high efficiency for lensing
  Chapman et al. (2005)
- steep counts → strong *magnification bias*
  Coppin et al. (2006)





Observed Counts
Negrello et al. 2010

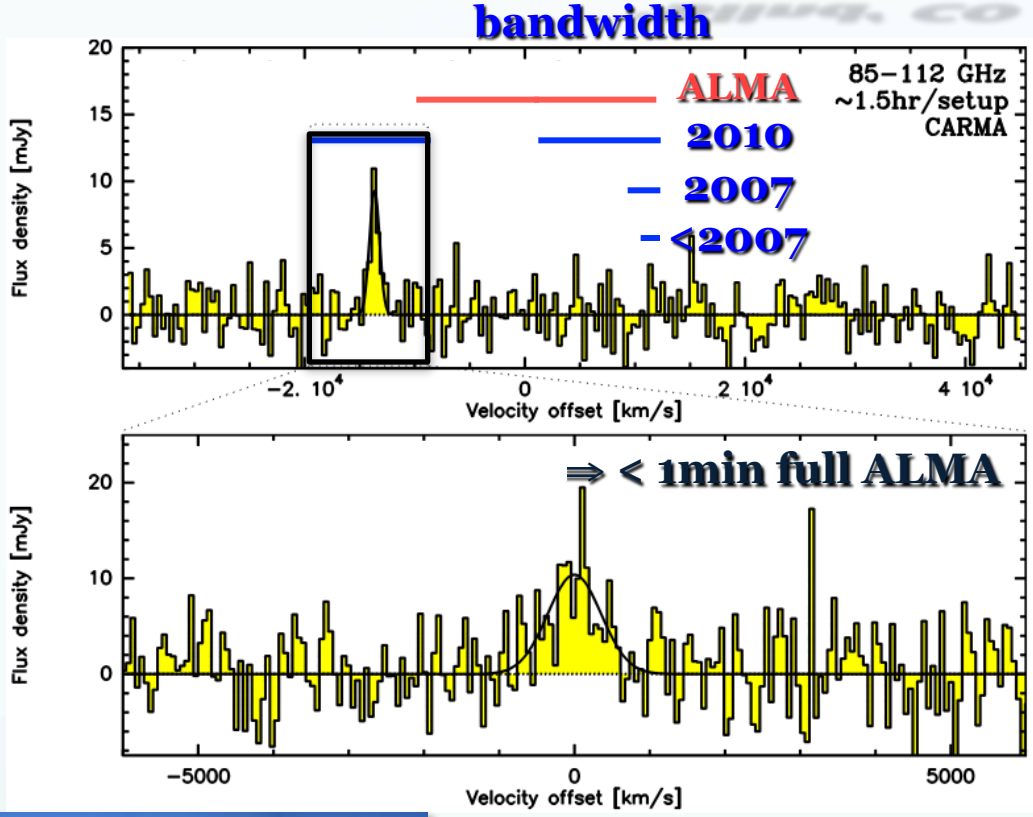
Herschel/SPIRE 250/350/500 μm surveys ideal to find <u>rare, lensed SMGs</u>

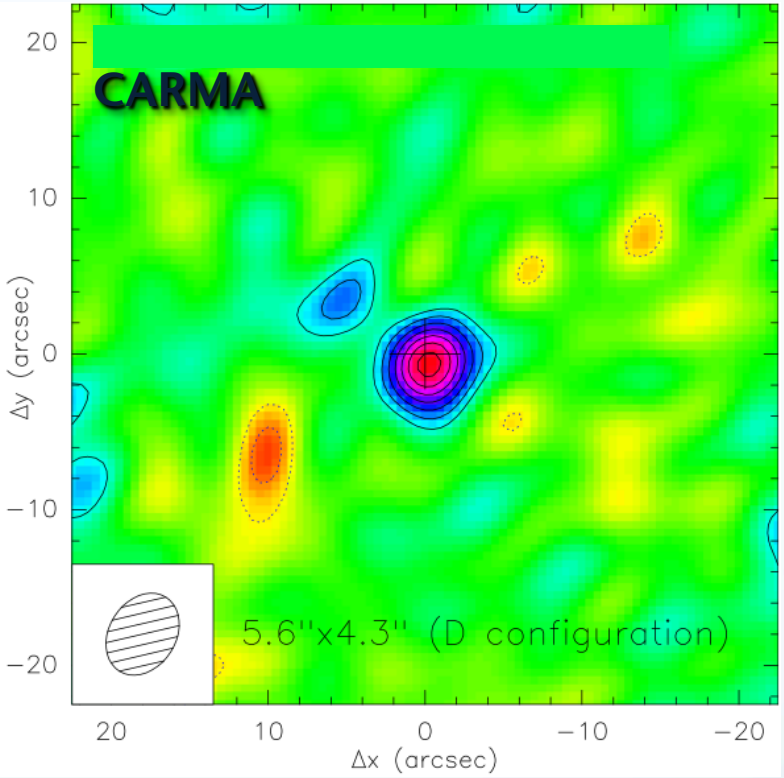
- only 1-2 deg^{-2} on the sky -> <<1 per 'traditional' SCUBA/MAMBO survey

⇒ very submm-bright, but never studied in detail before

- opportunity to establish 'blind' CO redshift technique w/ interferometers
- important for 'Deep Field' CO surveys w/ ALMA: Direct CO selection feasible?

‘Blind‘ CO Redshift Detections





‘Blind’ CO redshifts with Interferometers:
- rotational transitions of CO at [n x 115 GHz/(1+*z*)] (2.6mm)
⇒3mm band covers virtually *any* z<0.5 & z>1.0 in CO

- enabled by vast bandwidth increase in 2010 (to 50% ALMA)
- test study on bright ($S_{250\mu m}$>100mJy) HerMES SMGs
⇒ ALMA will do even better in *faintest* Herschel sources

Riechers ea. in prep.

CO in Herschel/SPIRE-selected SMGs: Status Update

1998-2009: ~20 SMGs detected in CO emission (all selected w/ optical spec-z)

Since 9/2010: 35 new Herschel-selected SMGs obs. w/ CARMA (all 'blind' CO z)

(z~1-4)

(some redshifts by CSO/APEX+Z-spec & GBT+Zpectrometer)

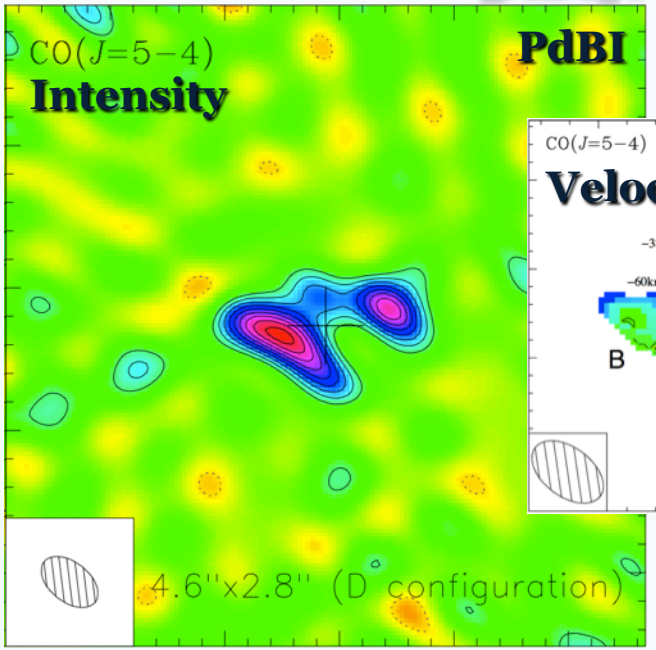
⇒ Already more than doubled no. CO-detected SMGs (mostly since mid-January)!

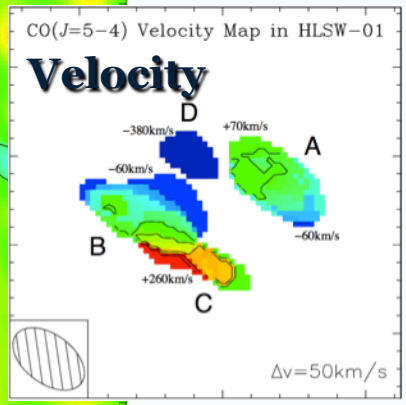
⇒ Mostly galaxy-galaxy lenses

⇒ Synergies: Two sources detected by *Planck*!

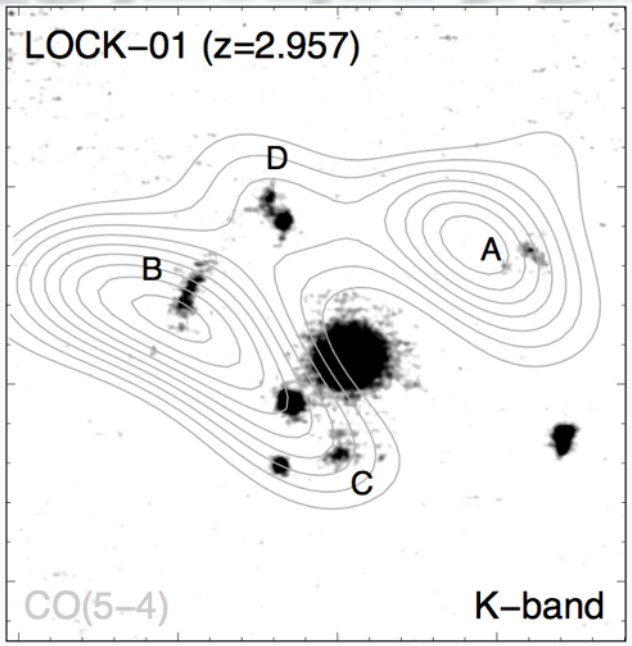
Riechers et al. in prep.

And: 'Free' CO Imaging & Dynamics

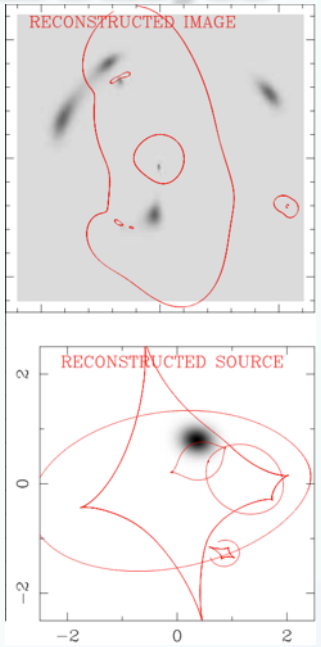




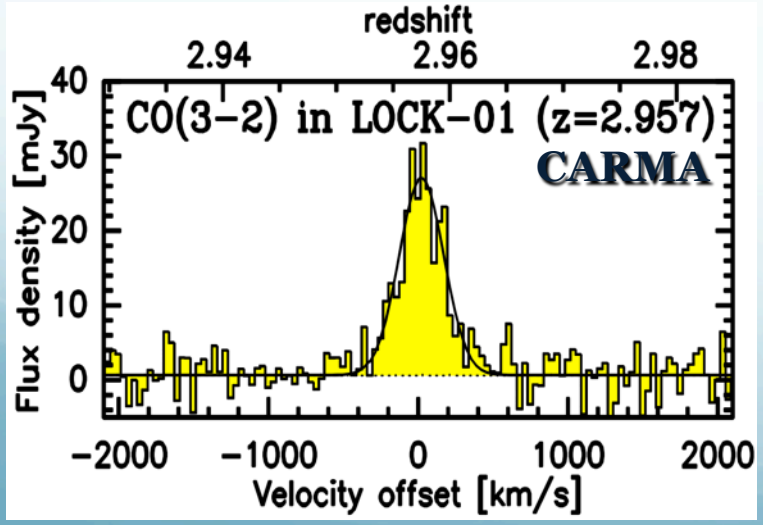
CO(5-4) Riechers ea. 2011c



CO (5-4) on 2.2 μm



Lens Model



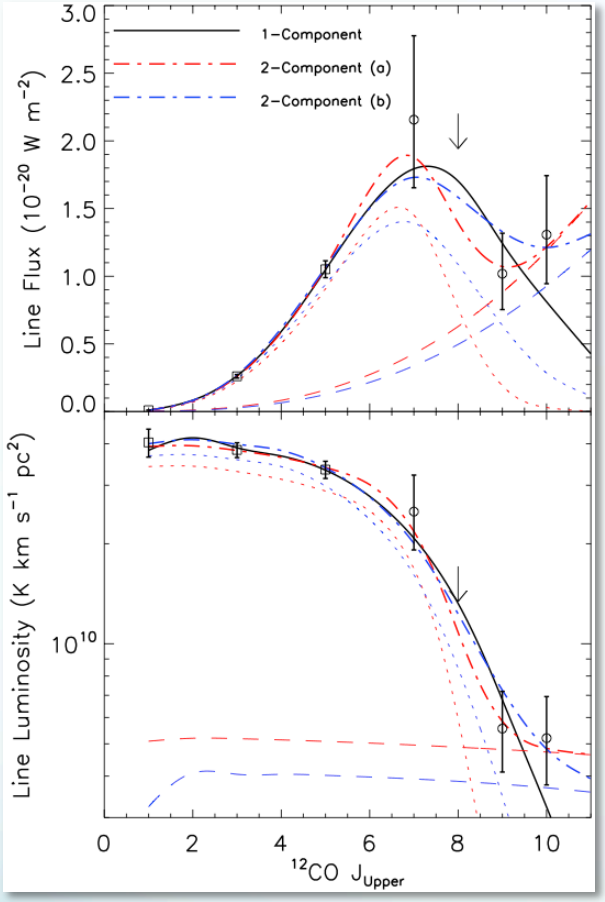
CO confirmation of brightest HerMES SMG
$S_{250\mu m}$=425mJy! (15% brighter than Eyelash)

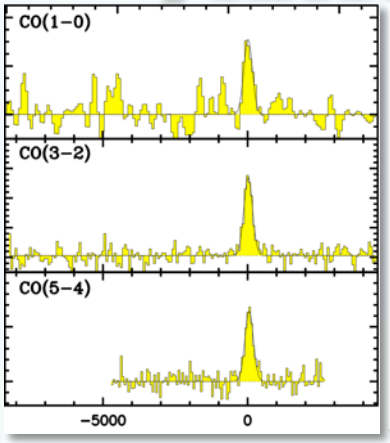
- optically faint quad lens (~5 lenses, group @z~0.6)
- 11x magnified -> M_{gas} ~ 3.3×10^{10} M_{sun}
- CO already resolved in detection experiment
- also dynamically resolved -> multi-component

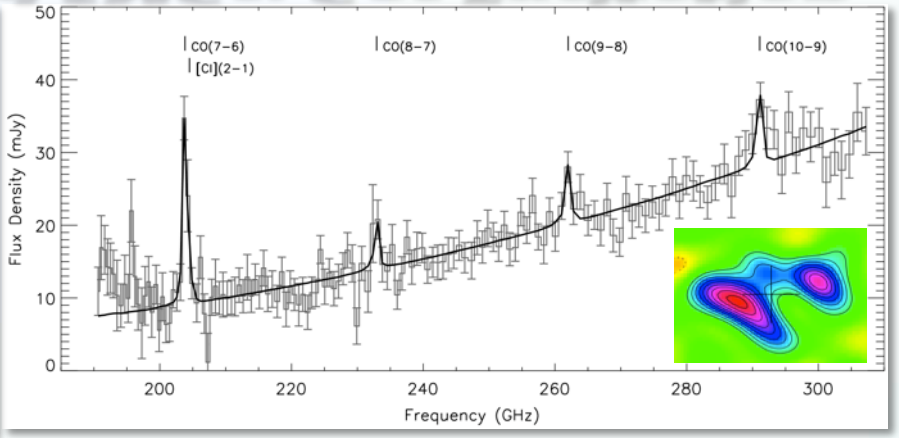
See also Conley ea. 2011, Scott ea. 2011, Gavazzi et al. 2011

Herschel/SPIRE ID: CSO/Zspec Lens Modeling

Lensed SMGs: Gas Excitation







GBT/Zpectrometer + CARMA + PdBI + CSO/Z-Spec

Detected almost entire CO ladder up to CO(J=10-9):

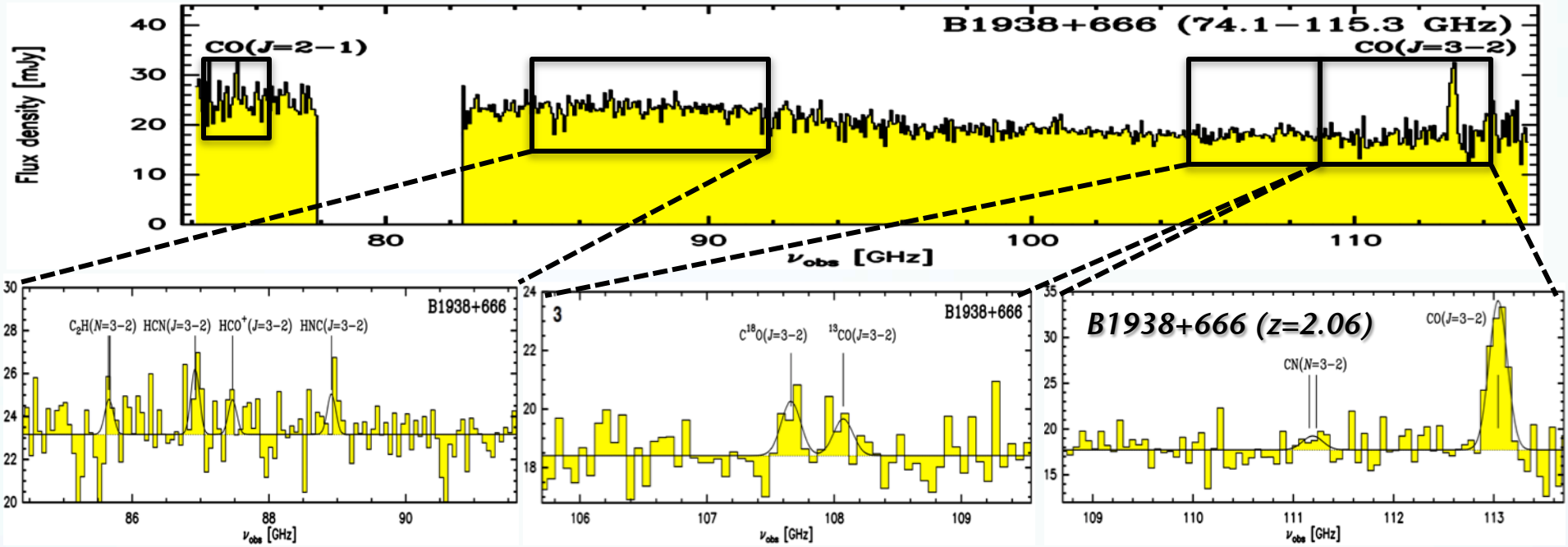
- **High CO excitation, peaking at approx. J=7 line**
- **Tentative 2nd component peaking up in J>9 lines**

⇒ Very dense gas or XDR associated with an AGN?
⇒ Warm dust may also hint at AGN contribution
⇒ Heavily obscured AGN-Starburst System

Scott ea. 2011
Riechers ea. 2011c

More on CO excitation: A. Weiss' talk

Bandwidth => Multiple Spectral Line Diagnostics

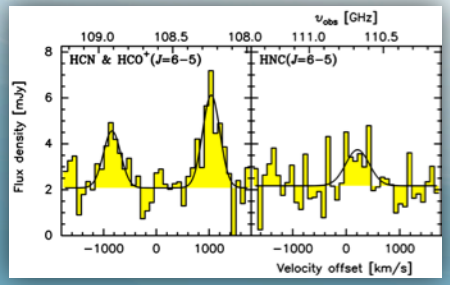


'Blind' CO searches do cover lines other than CO

⇒ start to (almost) pick up tracers of 'dense', star-forming gas (HCN,HCO^+,...)

⇒ HCN only detected in 5 z>1 galaxies to date, HCO^+, HNC, CN in 2 galaxies

⇒ ALMA's broad bandwidth will enable studies of molecular ISM <u>composition</u>



HCN, HCO^+, and HNC in APM08279+5255 (z=3.91)

More on chemistry: S. Martin's talk

Riechers ea. 2010c
Riechers 2011b

Summary

- molecular gas is key probe of conditions for star formation at high z
  - CO brightest tracer of H_2, well calibrated
  - observable out to z>5 in starbursts today
  - wide range of diagnostics for galaxy evolution:
    M_{gas}, M_{dyn}, size, morphology, dynamics, excitation

- milestones reached for "cosmic volume" surveys with ALMA/EVLA
  - sufficient detection rates expected to be affordable
  - CO properties can be used to disentangle galaxy populations
  - 'blind' CO redshift searches with interferometers are feasible

⇒ ALMA will be able to constrain cosmic H_2 mass density

- Herschel surveys play a key role in recent advancements
  - uncovering rare, bright, strongly lensed (& clustered) SMGs
  - providing targets to test observing strategies for ALMA
  - providing critical insight on priorities for CCAT & SPICA