# *High Resolution Molecular Spectroscopy of Submillimeter Galaxies*

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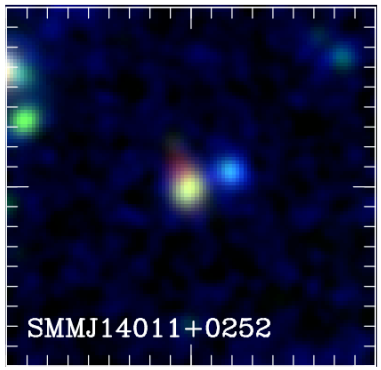
*Obscured AGN Across Cosmic Time, Seeon – June 7, 2007*

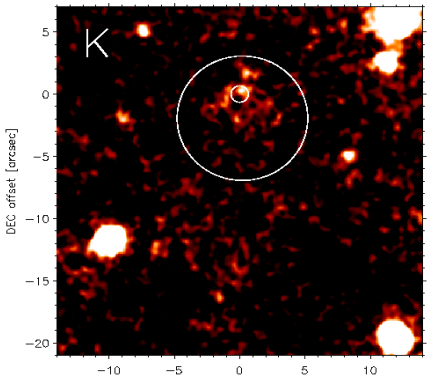
# *Outline*

- *(Sub)arcsecond interferometry of SMGs: compact & massive*
- *SMGs are scaled up versions of local ultraluminous IR galaxies*
- *SMGs as "maximal starbursts"*
- *Evidence for major merging at z~2-3*

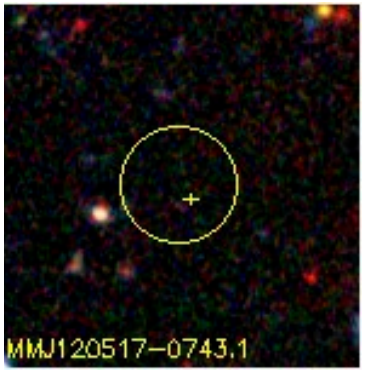
# *Submm Selected Galaxies*




UV detected




ERO

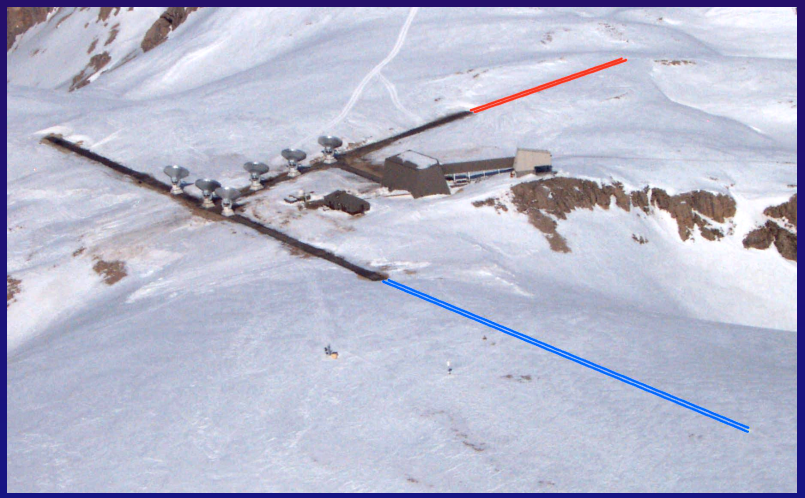



Empty field

- *>few hundred well detected sources > a few mJy (850μm) (positional accuracy 5")*
- *Make up a significant fraction of the submm background and energy release at redshift 1-4*
- *Likely trace the massive tail of galaxy evolution*

*Barger et al. 2001, Smail et al. 2001, Lutz et al. 2001, Dannerbauer et al. 2002, 2004, Ivison et al. 2002, 2005, Blain et al. 2002, Bertoldi et al. 2000,2007*

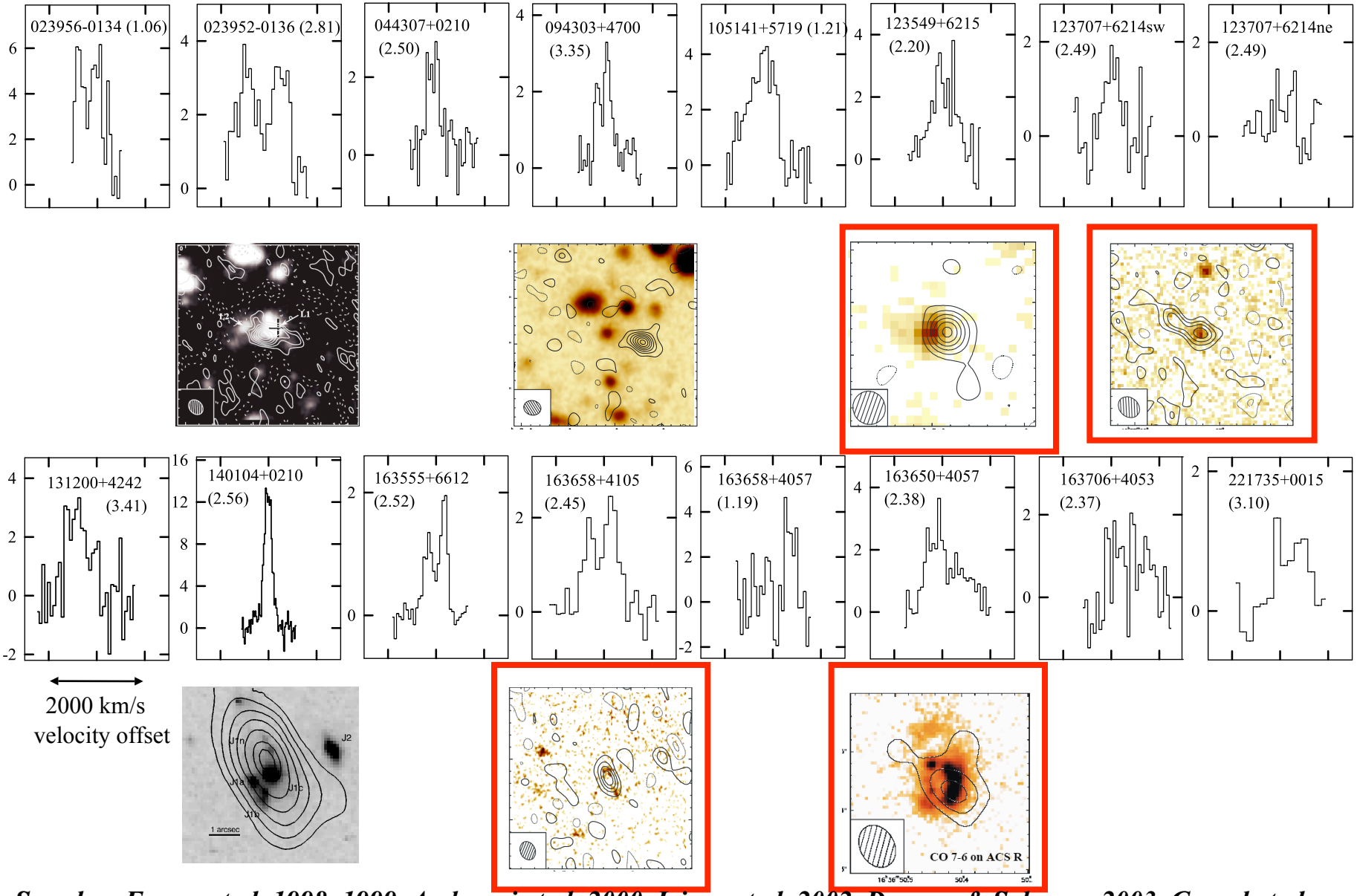
# *PdBI CO Survey of Submillimeter Galaxies (SMGs)*



- *submm sources with VLA 1.4 GHz counterparts (tens of μJy)*
- *Keck follow up spectroscopy with LRIS-B: 85 redshifts: <z>~2.3 (Chapman et al. 2003,2005)*
- *PdBI CO to confirm redshift (10-20 hours on source)*
- *high resolution PdBI follow-up for spatially resolved CO emission (~20-30 hours on source)*
- *>16 CO detections of SMGs between z~1 and 3.5 (out of ~30 sources)*

*This Survey: Neri et al. 2003, Greve et al. 2005, Tacconi et al. 2006, SMG team in prep*
*Other CO work: Frayer et al. 1998, 1999, Andreani et al. 2000, Ivison et al. 2002, Downes & Solomon 2003, Genzel et al. 2003, Sheth et al. 2004, Kneib et al. 2005, Weiss et al. 2005, 2007, Solomon & Vanden Bout 2005, Hainline et al. 2006*

# *IRAM PdBI Survey of CO in Luminous Galaxies at High Redshift*




*See also: Frayer et al. 1998, 1999, Andreani et al. 2000, Ivison et al. 2002, Downes & Solomon 2003, Genzel et al. 2003, Neri et al. 2003, Sheth et al. 2004, Greve et al. 2005, Kneib et al. 2005, Solomon & Vanden Bout 2005, Weiss et al. 2005, 2007, Tacconi et al. 2006, Hainline et al. 2006*

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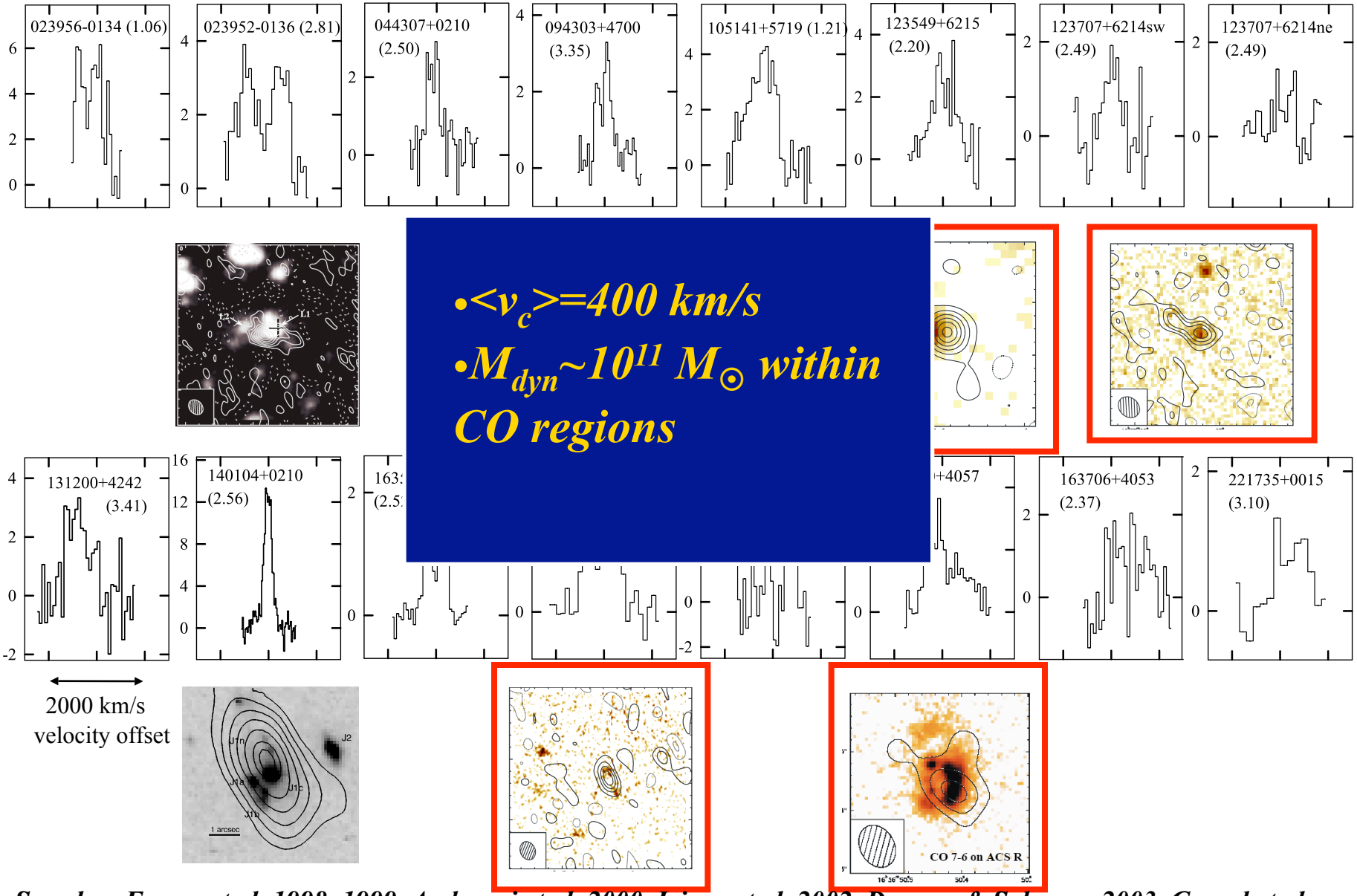
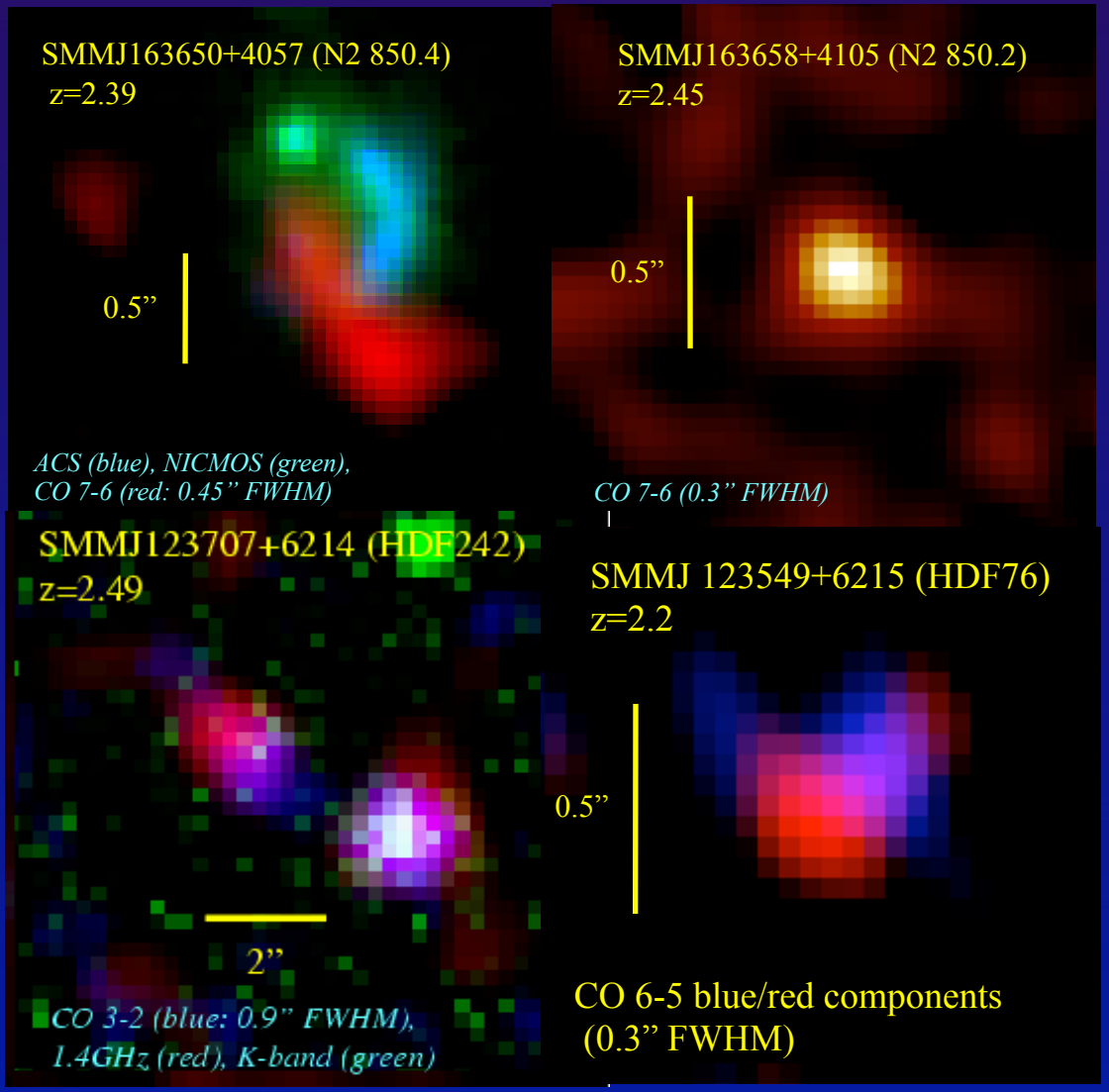



- $\langle v_c \rangle = 400$ km/s
- $M_{dyn} \sim 10^{11}\ M_\odot$ within CO regions

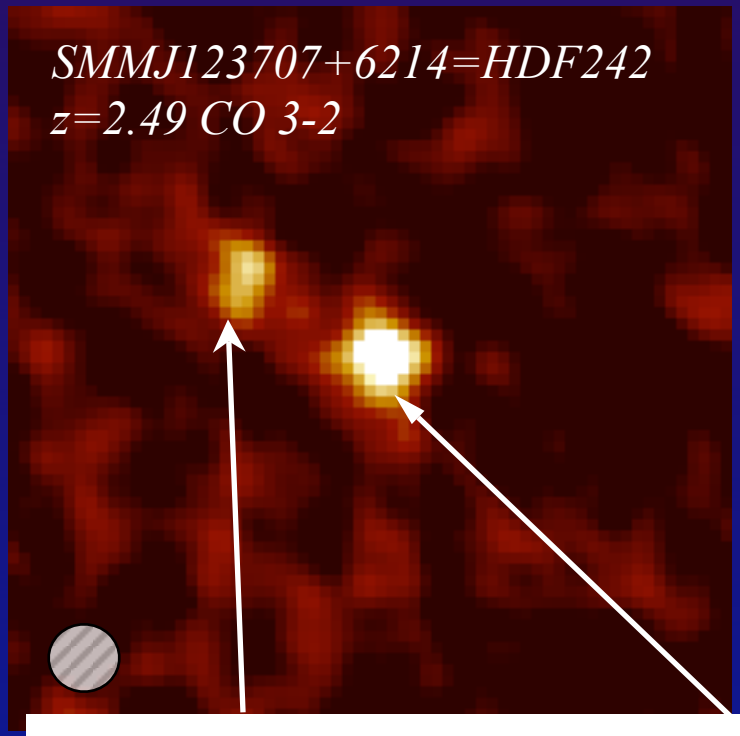
*See also: Frayer et al. 1998, 1999, Andreani et al. 2000, Ivison et al. 2002, Downes & Solomon 2003, Genzel et al. 2003, Neri et al. 2003, Sheth et al. 2004, Greve et al. 2005, Kneib et al. 2005, Solomon & Vanden Bout 2005, Weiss et al. 2005, 2007, Tacconi et al. 2006, Hainline et al. 2006*

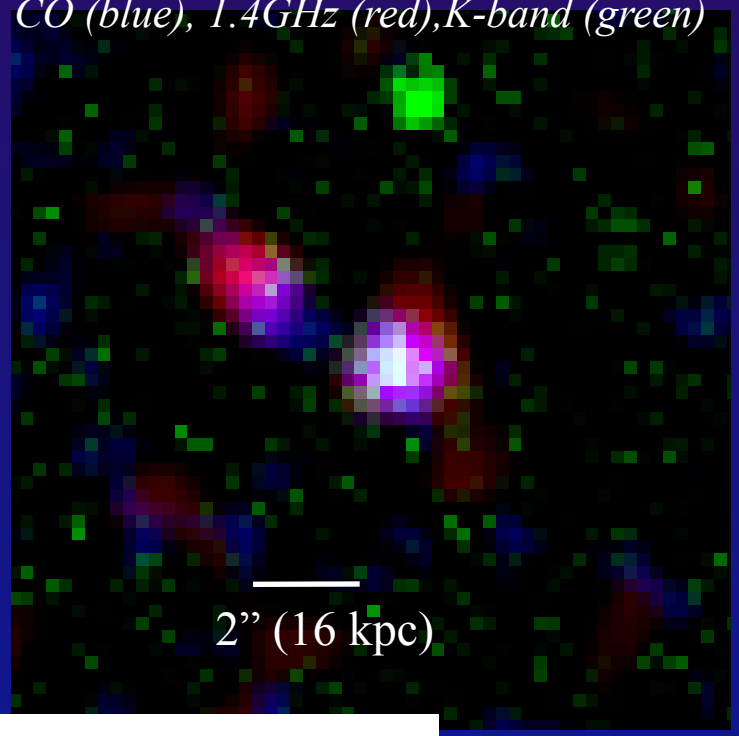
# *Sub-arcsec Interferometry of SMGs*

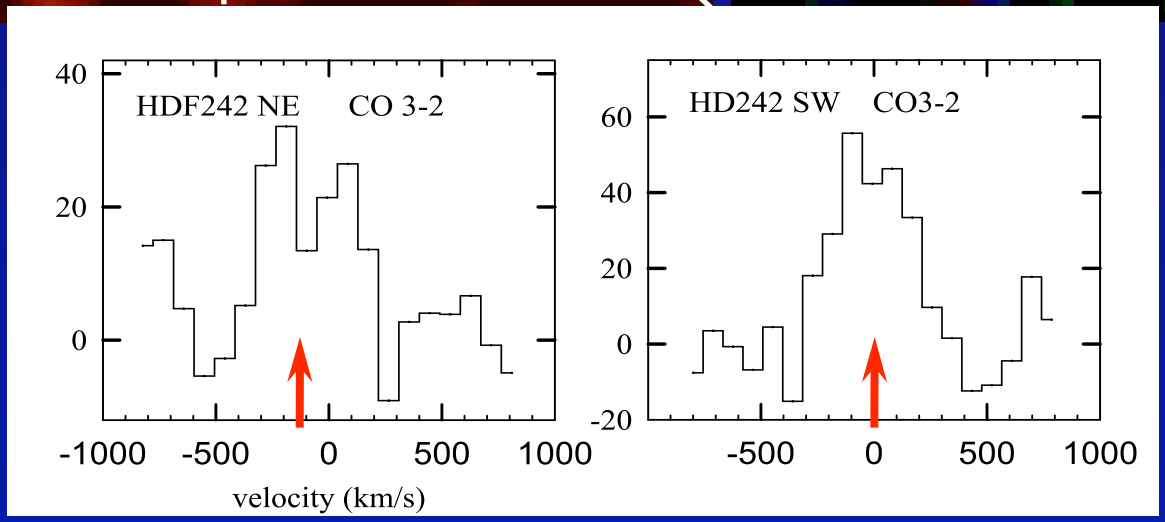



- ***IRAM Plateau de Bure Interferometer***
- ***800 meter baselines***
- ***~0.3-0.5” resolution at 1mm***

# *HDF 242: A Early Stage Merger?*



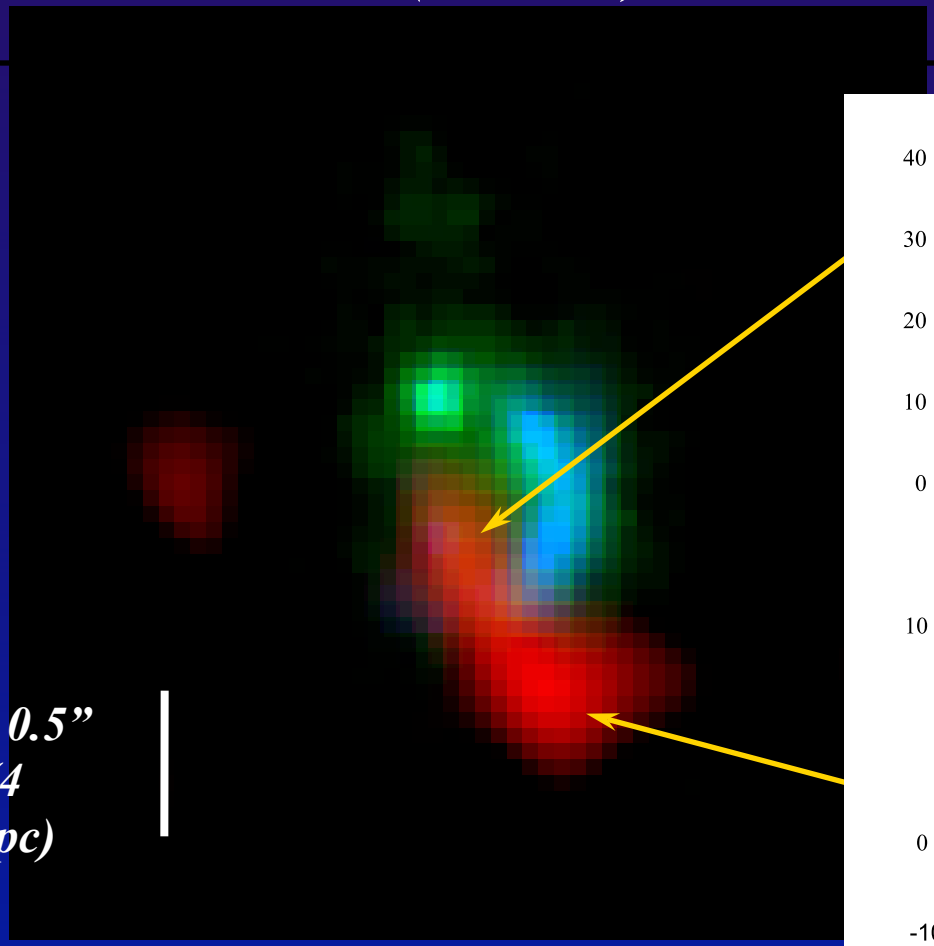



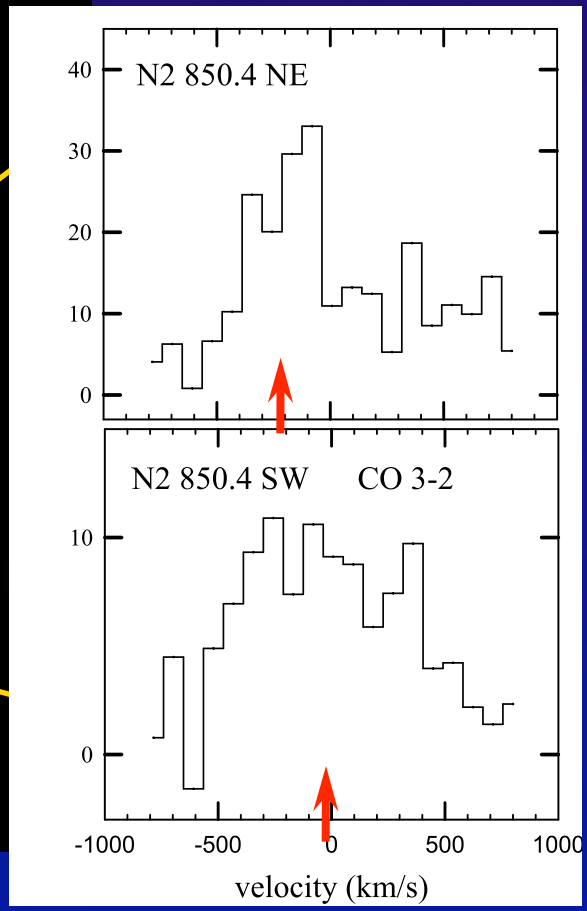

***CO components:***

- *projected separation ~16 kpc*
- *velocity difference 100-150 km/s*

# A Major Merger in Elais N2 850.4

***SMMJ 163650+4057 (N2 850.4)  z=2.39***




***ACS (blue), NICMOS (green), CO 7-6 (red: 0.45” FWHM, IRAM PdBI)***

*Smail et al. 2005, 2007 Swinbank et al. 2005, Tacconi et al. 2006, in prep*

# *Detection of a CO Velocity Gradient in HDF76*

***SMM J123549+6215=HDF 76 , z=2.20***
***CO 6-5***

***IRAM Plateau de Bure***
***resolution = 0.4”x0.3”FWHM***

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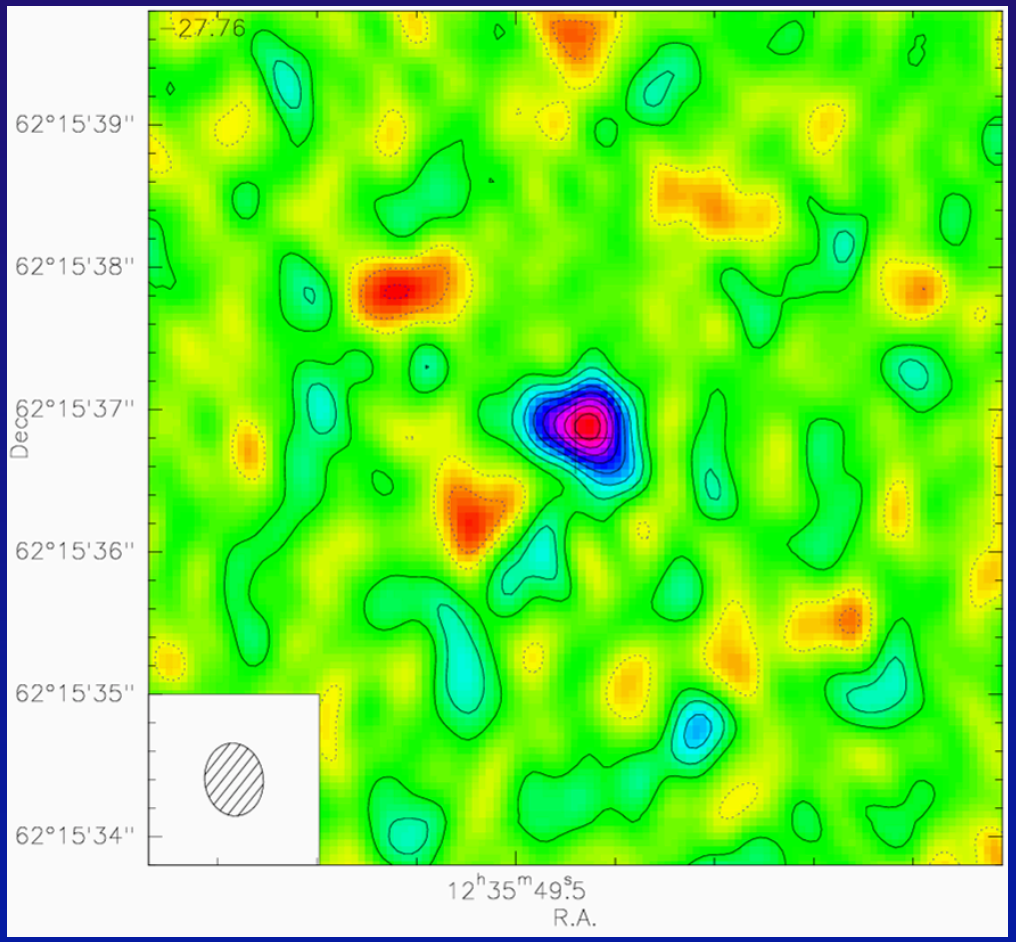


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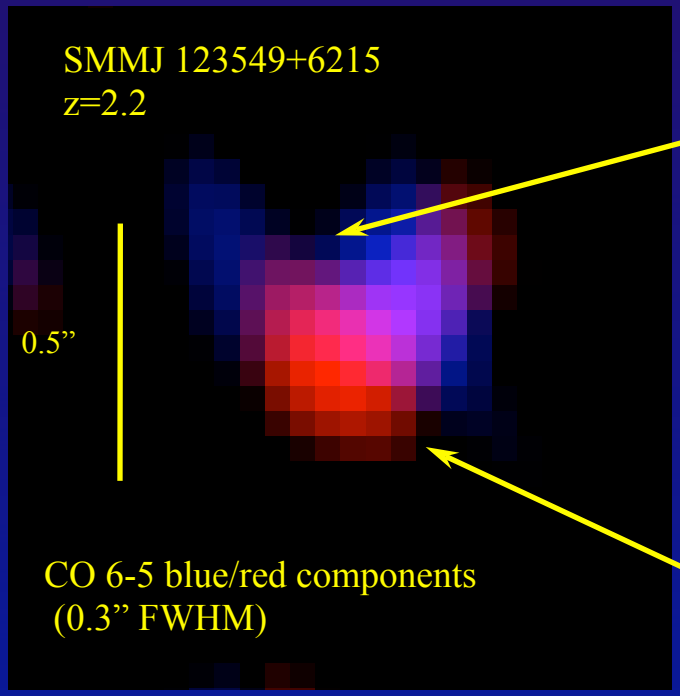
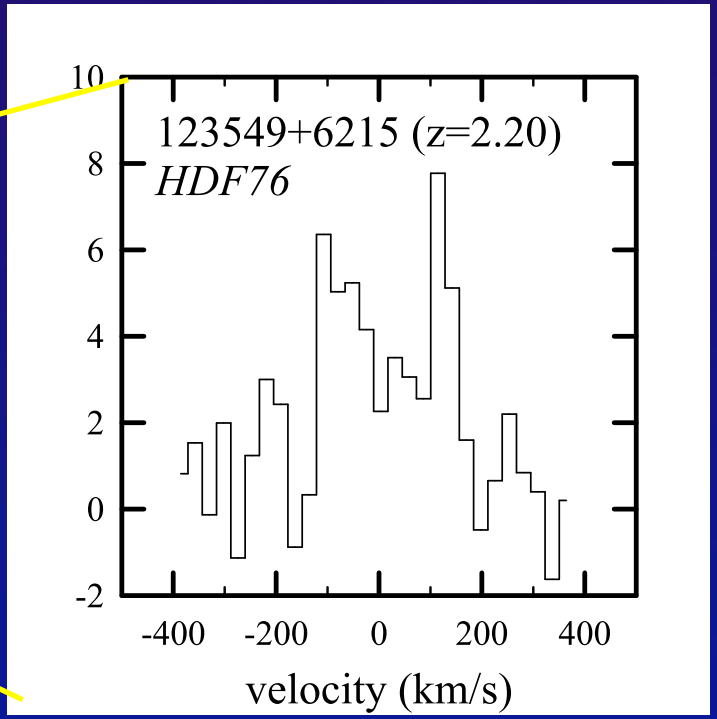
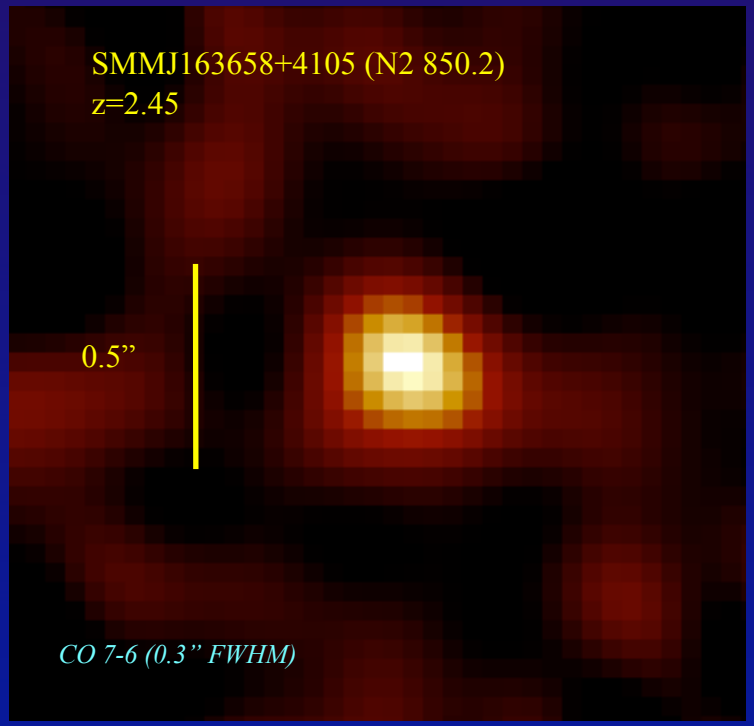
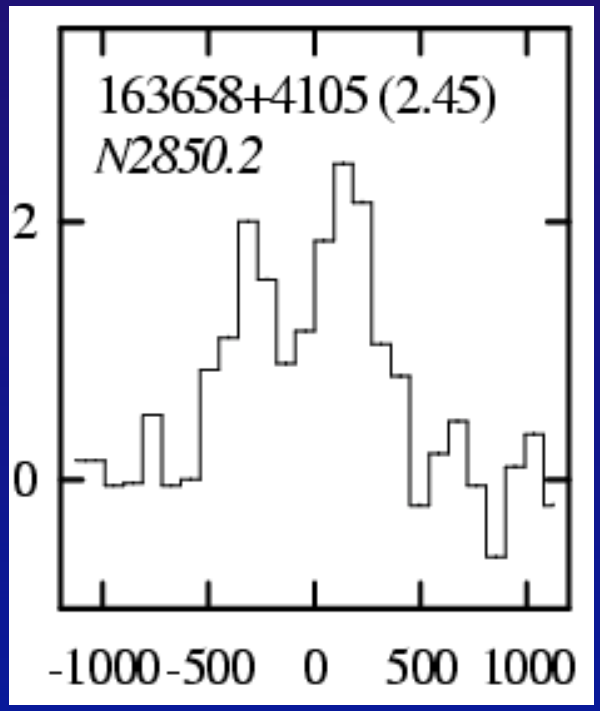



***IRAM Plateau de Bure***
***resolution = 0.4”x0.3”FWHM***

# *Elais N2 850.2: Compact CO Emission With a Very Broad Line*

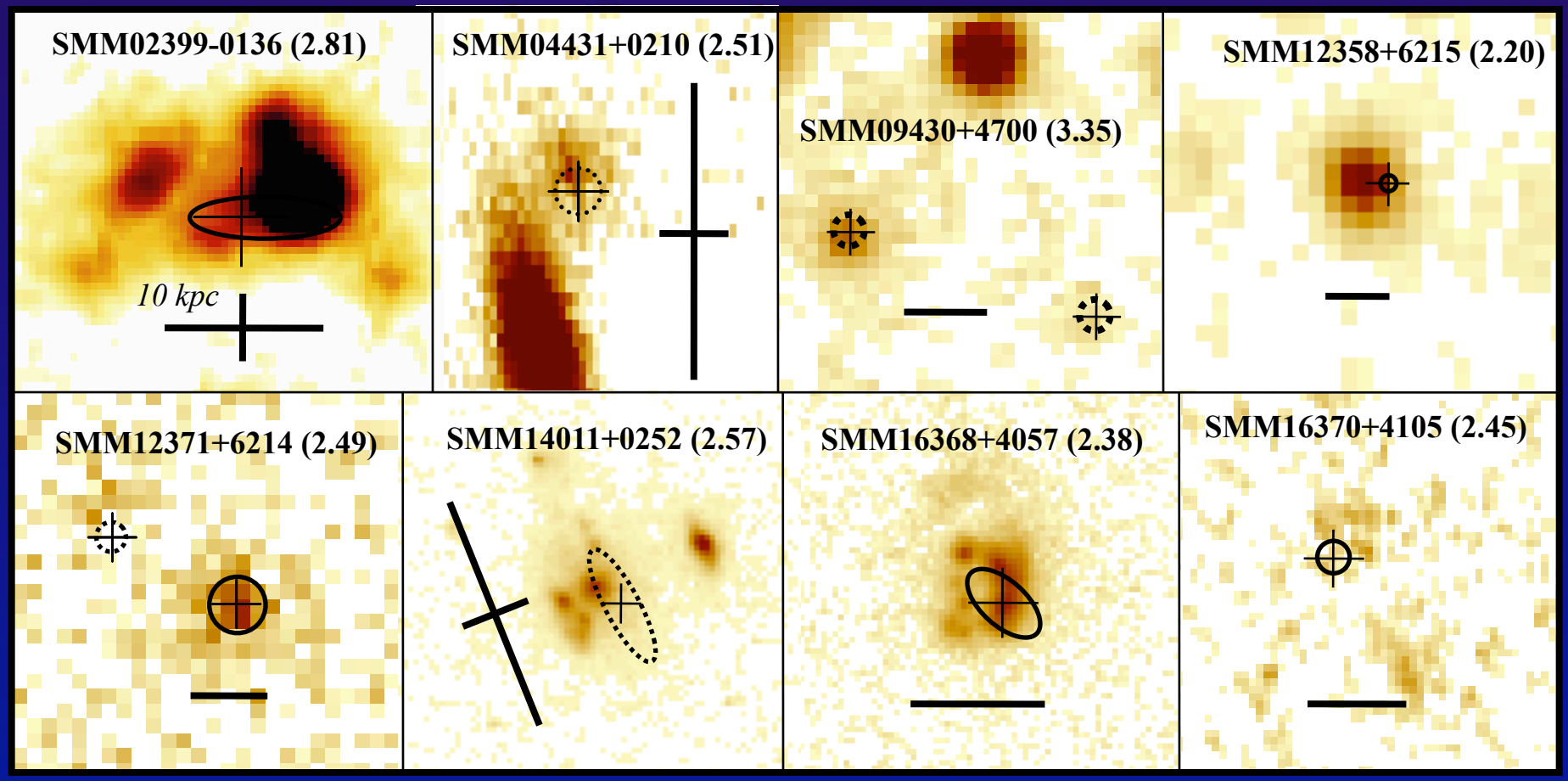



***IRAM Plateau de Bure resolution = 0.3”FWHM***

***CO Size ~0.25” FWHM (1.6 kpc)***

# *Size Measurements: SMGs Are Compact*




*Tacconi et al. 2006, and in prep*

**FWHM Diameters ≤0.5" or <R1/2> =2±0.7 kpc**
**$<\Sigma_{dyn}> \sim 10^{3.7}\ M_{\odot} pc^{-2} \sim \Sigma_{\text{bulges/Es}}$**

# *Submillimeter Galaxies Are Gas Rich Starbursts*

- $\langle M(H_2) \rangle = 3.0 \pm 1.6 \times 10^{10}\ M_\odot$
- $f_{gas} \sim 0.4$
- $SFR \sim 500\text{-}1000\ M_\odot/yr \sim \varepsilon\ M_{gas}/t_{dyn}$
- *global* $SFR/M_{gas}$ *comparable to Galactic star formation regions W49 or W51*

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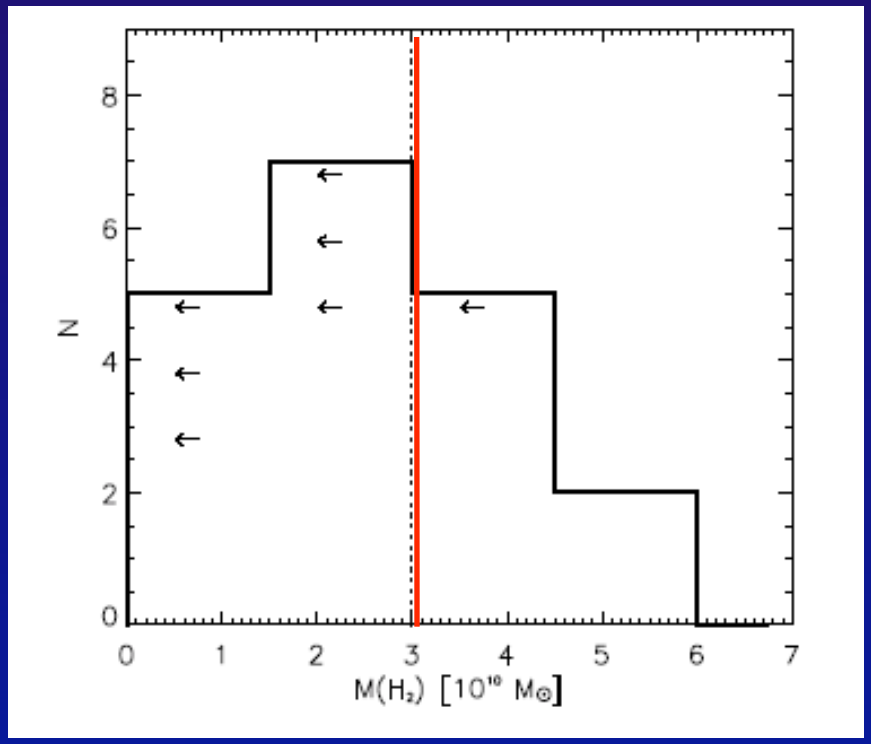
***Molecular gas mass distribution***

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*using* $H_2/CO$ *conversion from Downes & Solomon (1998) for z~0.1 ULIRGs (0.8* $M_\odot/(K\ km/s\ pc^2$*, ~1/4 Galaxy)*

*Greve et al. 2005, Tacconi et al. 2006*

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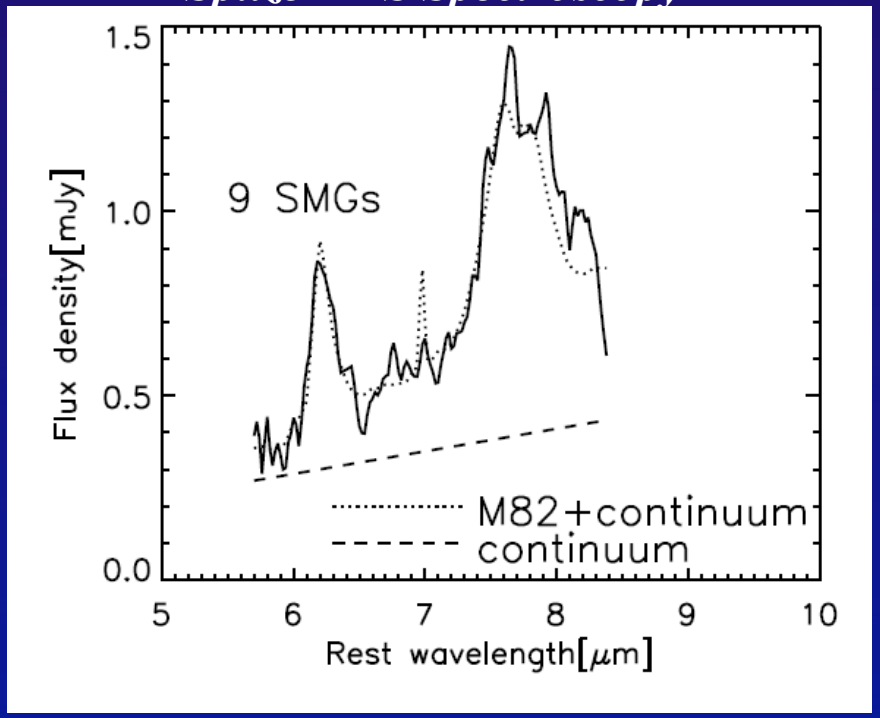
***Spitzer IRS Spectroscopy***




*Valiante et al 2007, Menedez-Delmestre 2007; Lutz et al 2005*

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  - *MIR spectra dominated by PAH emission - consistent with star formation as dominant power source*

  - *Deep x-ray observations (Alexander et al 2005) – evidence for obscured AGN in most cases, but these do not dominate the bolometric luminosity*

# *SMGs are 'Maximum' Starbursts*

***Star formation rate of maximum starburst***

$$SFR_{\max} = \frac{\varepsilon f_g M_t}{t_{dyn}} = 630 \varepsilon_{0.1} f_{0.4} v_{400}^3 \qquad [M_e\, yr^{-1}]$$

***SMGs: SFR~500-1000 $M_\odot$/yr***

***Criterion for global gravitational instability***

$$\Sigma_{gas,crit} \geq 2.3x10^3 \frac{\sigma_{100} v_{400}}{R_2} \qquad [M_e\, pc^{-2}]$$

***SMGs: $\Sigma$~5000***

***Criterion for starburst to continue in the presence of negative feedback (SN, rad. pressure, winds)***

$$SFR_{\max,feedback} \leq 9.6x10^3 f_{0.4} v_{400}^4 \qquad [M_e\, yr^{-1}]$$

*Meurer et al. 1997, Kennicutt 1998, Elmegreen 1999, Scoville 2003, Murray, Quataert & Thompson 2004 , Thompson, Quataert & Murray 2005*

# *Comparison of SMGs and Local ULIRGs*

| | *SMGs* | *ULIRGs* |
|---|---|---|
| $\langle v_c \rangle$ | *400 km/s* | *250 km/s* |
| $\langle M_{dyn,1/2} \rangle$ | $7 \times 10^{10}\ M_\odot$ | $5 \times 10^{9}\ M_\odot$ |
| $\langle R_{1/2} \rangle$ | *2.0 kpc* | *0.6 kpc* |
| $\langle L_{bol} \rangle$ | $10^{13.1}\ L_\odot$ | $10^{12}\ L_\odot$ |
| $M_{gas}/M_{dyn}$ | *0.3-0.4* | *0.16* |
| $\Sigma_{dyn}$ | $5000\ M_\odot/pc^2$ | $4900\ M_\odot/pc^2$ |

*Downes & Solomon 1998; Bryant & Scoville 1999, Sakamoto et al. 1999, Frayer et al. 1998, 1999, Neri et al. 2003, Chapman et al. 2004, Greve et al. 2005, Tacconi et al. 2006*

# *From CO Interferometry of SMGs:*

- ***SMGs are compact & massive***
- ***Evidence for merging in 2 cases so far when observe with sub-arcsec resolution***
- ***SMGs are scaled up versions of local ultraluminous IR galaxies***
- ***Matter densities of SMGs comparable to ellipticals and massive bulges: $\Sigma_{dyn} \sim 5000\ M_{\odot}/pc^2$***
- ***SMGs are very gas rich, 'maximum' starbursts that can convert a large fraction of their original gas mass to stars in a few hundred Myrs***