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For IRAM use
Registration N°:
Date:

PROPOSAL FOR INTERFEROMETER

Deadline: 11 Sep 2003 Period: 15 Nov 2003 — 15 May 2004

TITLE **High Resolution mm-Interferometry of Submm Galaxies: Testing High-z Mass Assembly**

CATEGORY: 1.3mm: ○ 3mm: ○ dual freq.: ● time filler: ○ special: ○

Scientific type: - *Extragalactic*: continuum ● CO lines ● other ○
- *Galactic*: continuum ○ lines ○ circumstel. env. ○ young stel. obj. ○ cloud struct. ○ chem. ○ other ○
Observing type: mapping ● detection ○ size measure ○ snapshot ○ mosaic ○ other ○

ABSTRACT

We propose high resolution PdBI follow-up observations of three submm galaxies at z∼2.4, 2.5 and 3.4 from our successful ongoing submm-PdBI survey. Our 3mm CO 3-2/4-3 and 1.2mm continuum measurements in AB configuration will spatially resolve the continuum and line emission and allow us to determine dynamical masses. All three sources are part of a complex environment with at least two sources at about the same redshift, but spatially separated on the arcsecond scale and with different physical characteristics. The high resolution observations will probe whether only one or both of these sources contribute to the mm emission and major star formation activity and how the sources are related kinematically. Our observations will test galaxy interactions/mergers at z∼2.5 and provide insights into the assembly of mass at the upper end of the galaxy luminosity function.

Is this a resubmission of a previous proposal ? no ● yes ○ – proposal number(s): ....
Is this a continuation of (a) previous proposal(s) ? no ● yes ○ – proposal number(s): ....

LST range(s) per configuration from: 05h to: 15h number of intervals: 3
from: 11h to: 21h number of intervals: 5

Configurations: **A** ● **B** ● **C** ○ **D** ○ **Any** ○

Frequencies (exact) 3mm: 100.115 102.17 106.001 1.3mm: 240

Confidential information:

List of Objects (give most common names) with equatorial coordinates in J2000 (accurate to 2″) and LSR velocities

Source	α_{J2000}	δ_{J2000}	V_{LSR}
SMMJ09431	09:43:03.74	47:00:15.3	z=3.346
SMMJ16368	16:36:50.43	40:57:34.7	z=2.3853
SMMJ16370	16:36:58.22	41:05:23.4	z=2.43

(continue on next page, if needed)

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who will reduce data: Neri,Tacconi,Greve

join to this form: scientific aims ≤ 2 typed pages and ≤ 2 pages Figs., Tables and list of related publications

IRAM Plateau de Bure Interferometer: Proposal Technical Summary

Please fill one sheet per frequency setup

- **Program Title:**

High Resolution mm-Interferometry of Submm Galaxies: Testing High-z Mass Assembly

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)
SMMJ09431+4700	09:43:03.74	47:00:15.3	3.346

- **Category and Project type:** dual-frequency continuum lines mapping
- **Size of largest structure in (arcseconds)** <2–3 arcsec
- **Expected continuum flux:** 2.3 mJy
- **Expected continuum source size:** <2–3 arcsec
- **For pure continuum projects:**
  - *Preferred observing frequency:* 240 GHz
  - *Expected Line contamination at observing frequency:*
  - *Frequencies to avoid:*
- **For line projects:**
  - *Receiver configuration (fill in empty columns) :*

	line name	*Freq. (GHz)*	*band*	
LINE	CO(4-3)red	106.001	LSB	/RECEIVER 1
LINE	1MM(Cont)	240	LSB	/RECEIVER 2

  - *Correlator configuration (fill in empty columns) :*

	width	*freq.*		*Receiver*		*Mode*
SPECTRAL 1	160	180	/RECEIVER	1	/BAND	SSB
SPECTRAL 2	160	320	/RECEIVER	1	/BAND	SSB
SPECTRAL 3	160	460	/RECEIVER	1	/BAND	SSB
SPECTRAL 4	160	600	/RECEIVER	1	/BAND	SSB
SPECTRAL 5	160	180	/RECEIVER	2	/BAND	DSB
SPECTRAL 6	160	320	/RECEIVER	2	/BAND	DSB
SPECTRAL 7	160	460	/RECEIVER	2	/BAND	DSB
SPECTRAL 8	160	600	/RECEIVER	2	/BAND	DSB

  - *Expected width of spectral line (to zero power) and narrowest feature:* 420 km/s
  - *Number of lines observed simultaneously (add sketch of frequency setup):* 1
  - *Line frequencies:* 106.001 GHz
  - *Expected source size in each line:* ∼2 arcsec
  - *Expected line strength:* 2mJy/chan
- **For mapping projects:**
  - *Configuration required (AB, BC, CD, D, other):* AB
- **For detection projects:**
  - *Observing time required:*
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:*
  - *Number of hour angles per baseline:* 3
  - *Observing time per hour angle:* 8 hours
- **Phase Calibrators (2 or more):** 0923+392, 0945+408
- **Amplitude Calibrator:** 3C84 or 3C273
- **Required accuracy of bandpass calibration:** good
- **Special requirements:** no sun avoidance during this semester

IRAM Plateau de Bure Interferometer: Proposal Technical Summary

Please fill one sheet per frequency setup

- **Program Title:**

High Resolution mm-Interferometry of Submm Galaxies: Testing High-z Mass Assembly

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)
SMMJ16368+4057	16:36:50.43	40:57:34.7	z=2.3853

- **Category and Project type:** dual-frequency continuum lines mapping
- **Size of largest structure in (arcseconds)** <1 arcsec
- **Expected continuum flux:** 2.5 mJy
- **Expected continuum source size:** <1 arcsec
- **For pure continuum projects:**
  - *Preferred observing frequency:* 240 GHz
  - *Expected Line contamination at observing frequency:*
  - *Frequencies to avoid:*
- **For line projects:**
  - *Receiver configuration (fill in empty columns) :*

	line name	*Freq. (GHz)*	*band*	
LINE	CO(3-2)red	102.1463	LSB	/RECEIVER 1
LINE	1MM(Cont)	240	LSB	/RECEIVER 2

  - *Correlator configuration (fill in empty columns) :*

	width	*freq.*		*Receiver*		*Mode*
SPECTRAL 1	160	180	/RECEIVER	1	/BAND	SSB
SPECTRAL 2	160	320	/RECEIVER	1	/BAND	SSB
SPECTRAL 3	160	460	/RECEIVER	1	/BAND	SSB
SPECTRAL 4	160	600	/RECEIVER	1	/BAND	SSB
SPECTRAL 5	160	180	/RECEIVER	2	/BAND	DSB
SPECTRAL 6	160	320	/RECEIVER	2	/BAND	DSB
SPECTRAL 7	160	460	/RECEIVER	2	/BAND	DSB
SPECTRAL 8	160	600	/RECEIVER	2	/BAND	DSB

  - *Expected width of spectral line (to zero power) and narrowest feature:* 840 km/s
  - *Number of lines observed simultaneously (add sketch of frequency setup):* 1
  - *Line frequencies:* 102.1463 GHz
  - *Expected source size in each line:* <1 arcsec
  - *Expected line strength:* 2mJy/chan
- **For mapping projects:**
  - *Configuration required (AB, BC, CD, D, other):* A
- **For detection projects:**
  - *Observing time required:*
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:*
  - *Number of hour angles per baseline:* 2
  - *Observing time per hour angle:* 8 hours
- **Phase Calibrators (2 or more):** 3C345, 1633+382, 1638+398
- **Amplitude Calibrator:** 3C345
- **Required accuracy of bandpass calibration:** good
- **Special requirements:** no sun avoidance

IRAM Plateau de Bure Interferometer: Proposal Technical Summary

Please fill one sheet per frequency setup

- **Program Title:**

High Resolution mm-Interferometry of Submm Galaxies: Testing High-z Mass Assembly

- **Source position and velocity:**

Source	RA (J2000.0)	DEC (J2000.0)	LSR Velocity (km/s)
SMMJ16370+4105	16:36:58.22	41:05:23.4	z=2.43

- **Category and Project type:** dual-frequency continuum lines mapping
- **Size of largest structure in (arcseconds)** <2–3 arcsec
- **Expected continuum flux:** ∼2 mJy
- **Expected continuum source size:** <2 arcsec
- **For pure continuum projects:**
  - *Preferred observing frequency:* 240 GHz
  - *Expected Line contamination at observing frequency:*
  - *Frequencies to avoid:*
- **For line projects:**
  - *Receiver configuration (fill in empty columns) :*

	line name	*Freq. (GHz)*	*band*	
LINE	CO(3-2)red	100.115	LSB	/RECEIVER 1
LINE	1MM(Cont)	240	LSB	/RECEIVER 2

  - *Correlator configuration (fill in empty columns) :*

	width	*freq.*		*Receiver*		*Mode*
SPECTRAL 1	160	180	/RECEIVER	1	/BAND	SSB
SPECTRAL 2	160	320	/RECEIVER	1	/BAND	SSB
SPECTRAL 3	160	460	/RECEIVER	1	/BAND	SSB
SPECTRAL 4	160	600	/RECEIVER	1	/BAND	SSB
SPECTRAL 5	160	180	/RECEIVER	2	/BAND	DSB
SPECTRAL 6	160	320	/RECEIVER	2	/BAND	DSB
SPECTRAL 7	160	460	/RECEIVER	2	/BAND	DSB
SPECTRAL 8	160	600	/RECEIVER	2	/BAND	DSB

  - *Expected width of spectral line (to zero power) and narrowest feature:* ∼800 km/s
  - *Number of lines observed simultaneously (add sketch of frequency setup):* 1
  - *Line frequencies:* 100.115 GHz
  - *Expected source size in each line:* <2 arcsec
  - *Expected line strength:* 2mJy/chan
- **For mapping projects:**
  - *Configuration required (AB, BC, CD, D, other):* AB
- **For detection projects:**
  - *Observing time required:*
- **For snapshot or size measurements:**
  - *Baseline range in meters:*
  - *Configuration list:*
  - *Number of hour angles per baseline:* 3
  - *Observing time per hour angle:* 8 hours
- **Phase Calibrators (2 or more):** 3C345, 1633+382, 1638+398
- **Amplitude Calibrator:** 3C345
- **Required accuracy of bandpass calibration:** good
- **Special requirements:** no sun avoidance

High Resolution mm-Interferometry of Submm Galaxies: Testing High-z Mass Assembly

BACKGROUND: At least half of the cosmic extragalactic energy density (not counting the microwave background) emerges at far-infrared wavelengths. During the last years, surveys with SCUBA at 850μm and MAMBO at 1.2mm have resolved a significant fraction of this background into a population of faint (mJy) submm sources that may be luminous and ultra-luminous infrared galaxies at redshifts $1 \leq z \leq 5$ (Smail et al. 1997, Hughes et al. 1998, Bertoldi et al. 2002). One of the key goals of present research is to determine the redshift distribution and physical properties (gas and dynamical mass, star formation rate, environment) of this population. Until recently, however, progress has been very slow because submm galaxies are faint in the optical/near-IR band, submm source positions are often poorly known, and only three galaxies had redshifts confirmed by mm CO-line emission. The evidence available so far from these few examples suggests that the submm galaxies are gas rich, massive ($\sim 10^{11} M_{\odot}$) starburst/AGN systems (SF rates 500–2000 $M_{\odot}$/yr). They may trace the epoch of bulge/elliptical formation and may account for more than half of the high-z star formation activity. The presence of such massive galaxies at z$\sim$ 2–3 is hard to understand in current hierarchical models of galaxy formation (Fig.1, Genzel et al. 2003). As such, the distant submm population is a key tool for studying the high-redshift assembly of mass at the upper end of the galaxy luminosity function, thus providing a critical test of different galaxy formation scenarios.

Recently some of the proposers have been able to substantially increase the number of accurate source positions from ultra-deep VLA maps (Ivison et al. 2002). Rest-frame UV follow-up spectroscopy at Keck for these radio-detected submm sources was surprisingly successful, resulting in a reliable sample of now $\sim$50 sources with precise redshifts, indicating that the mean redshift of the radio selected submm population is about 2.5 (Chapman et al. 2003). Based on these results and as part of a several semester program initiated by the proposers in 2002, about a dozen of these sources were observed with the IRAM Plateau de Bure interferometer in 2002/2003 in the CO (3-2/4-3) transitions. The PdBI program has been remarkably successful. We were able to obtain seven clearcut and two tentative detections of z$\sim$2.4–3.4 CO lines, in effect quadrupling the number of mm-confirmed redshifts (Neri et al. 2003, Greve et al. 2003). This constitutes a major breakthrough and opens the avenue for follow-up studies. As the CO submm-survey project continues (proposal by Ivison/Genzel et al), we would like to embark now on the second phase of our program, which is a key element: **observing a selected number of the newly detected sources at the highest possible spatial resolution ($\leq$1") in CO and 1.2mm continuum to determine their spatial structure and dynamical masses.**

SCIENTIFIC GOALS: Spatially resolved mm measurements deliver several key parameters characterizing the submm galaxies: a luminosity weighted size and/or spatial distribution (from the 1.2mm continuum), a mass (from the size and rotation velocity of the 1.3/3 mm molecular emission) and accurate absolute position information (from both). Cold molecular gas kinematics is an ideal tracer of gravity on galactic scales, quite in contrast to optical (Lyα, Hα etc.) line emission, which is often dominated by outflows and galactic winds. As mentioned above a reliable determination of the average mass of submm galaxies (from a suitably culled sample) provides a crucial constraint on high-z mass assembly and galaxy formation models at the upper end of the mass function (Fig.1). Together with the CO-derived gas mass and the near-IR inferred stellar mass, the dynamical mass and far-IR/submm luminosity allow constraining the star formation history and evolutionary state of the system (Tecza et al. 2003). Together with the near-IR/optical morphologies and ionized gas dynamics (which we are also presently investigating with the HST, UKIRT and the SPIFFI integral field spectrometer on the VLT), the positional and structural information of the mm continuum gives important information on the environment and physical extent of the high-z star formation: whether it occurs in a spatially concentrated circum-nuclear starburst characteristic of local ultra-luminous galaxies (and presumably of bulge formation, Downes & Solomon 2003), or whether it comes from a major galaxy merger, or from a more extended, 'protogalactic' region (Ivison et al. 2001). Five of the six best studied submm galaxies appear to be composite starburst/AGNs in a complex environment (Neri et al. 2003, Greve et al. 2003). The submillimeter population thus may trace the epoch of major galaxy merging at z$\sim$2.5. Comparison of the mm and optical data also elucidate the role of extinction in the rest frame UV/optical morphology and the importance of outflows/superwinds in the ionized gas dynamics.

We have selected three galaxies from our ongoing PdBI CO survey to carry out detailed 3mm CO (3-2/4-3) and 1.2mm continuum/CO (7-6) interferometry with 1" or better resolution, in A and B configurations (Fig.2). As discussed above, our primary goals are

1) to spatially resolve the line and continuum emission and determine dynamical masses. In all three cases the CO emission is strong ($\sim$1-2 Jy km/s) and spatially compact. High resolution AB configuration data are both required and sufficient to resolve source structures. In SMMJ16358 we already have BC configuration data that indicate that the 1.2mm continuum and CO 3-2 emission is marginally resolved at the $\leq$1" level, and the

two other sources studied with high resolution with the PdBI (SMMJ02399: Genzel et al. 2003, SMMJ14011: Downes & Solomon 2003) are also just resolved at 1-2" resolution.

2) to study the source environment. In all three selected cases there is strong evidence that the submm galaxies are part of a complex environment, with at least two sources present at the same redshift, but spatially separated by 1-4" and of different physical characteristics (Fig.2). The high resolution observations will probe whether only one or both of these sources contributes to the mm emission and major star formation activity, and elucidate how the sources are related kinematically. In SMMJ09431 the submm source (=radio source H7) is located about 4" away from a UV bright Seyfert galaxy (=radio source H6), and undoubtably physically associated, since they are separated in redshift by only 115 km/s. In SMMJ16358 both optical data (Smail et al. 2003) and the available PdBI data indicate the presence of at least two source components (i.e. an AGN and a starburst component) on a scale of 0.7-1". In SMMJ16370 the CO/radio source is about 0.9" north of an extremely red object (ERO) that gives rise to most of the rest-frame optical emission.

In all three cases we wish to carry out both 1.2mm continuum and 3mm line observations, as they provide complementary information. The 1.2mm continuum traces the star formation activity sites and - in AB configuration - will provide the desired subarcsecond resolution in all three sources. The 3mm emission traces the gas dynamics, albeit at somewhat lower spatial resolution (of around 1.5" for the planned observations). Note that in a rotating system the large velocity gradient couples with the high velocity resolution afforded by the PdBI to effectively enhance spatial resolution, as the location of the blue- and redshifted emission peaks can be determined to a fraction of the beam size. By combining the line and continuum spatial data with line shape information we will be able to determine whether the gas kinematics is well fit by a rotating disk, or requires a more complex dynamical system (e.g. a merger, Genzel et al. 2003). Foreground lensing may play an important and sometimes hard to quantify role in the interpretation of high-z data (e.g. Downes & Solomon 2003). SMMJ099431 is known to be located behind the z=0.4 cluster Abell 851 but detailed lensing models indicate a modest amplification factor of only $\sim$1.2. There is no indication for the presence of significant lensing in the other two cases. For the application of the fundamental mass assembly test, it is necessary to correct for inclination if the molecular emission comes from a rotating disk-like system. There are two approaches for eliminating the inclination parameter. One is to select the widest CO emission spectra and assume that they originate from almost edge-on systems with $sin(i) \sim 1$. The second approach is to observe a large enough sample of galaxies (≥ 10) so that the inclination dependence can be statistically eliminated in the sample mean. We will be following both approaches.

OBSERVING STRATEGY: For these 3 already well-detected sources we propose to map the 3-mm CO line and 1-mm continuum emission at the highest resolution possible, and to combine the high resolution tracks with our existing data to maximize the sensitivity. The optimum configuration for this is the AB configuration. We realize that high resolution observations of weak sources are very tricky given atmospheric decorrelation, but already Bure has succesfully completed B configuration maps of four SMM galaxies, two from the present CO survey. To ensure success, we will reduce the B-configuration tracks as they are taken, before deciding whether to proceed with A-configuration or continue integrating in B. Our continuum (CO) maps would, therefore either have spatial resolutions of $\sim$0.6 ($\sim$1.5) arcsec (AB combined with D/CD data) or $\sim$0.9 ($\sim$ 1.7) arcsec (B only combined with D/CD data).

We will utilize the full 580 MHz bandwidth of both receivers by overlapping four 180 MHz correlator subbands for each receiver. The 500–800 km/sec linewidths fits comfortably inside the bandpass at 3mm. To improve the sensitivity we will smooth to spectral resolutions of 40 MHz in the CO 3-2/4-3 lines. From our lower resolution maps we will have line line fluxes of 2–3 mJy per smoothed channel (Fig.2). The 1.2mm continuum strength is about 2.5 mJy in all three sources. We request a total of 8 tracks in AB configuration (8 hours on-source integration per track) to make the proposed high resolution maps in the three targets: 2xA configuration for SMM 16368; 3 A/B configuration each for SMM09431 and SMM16370. These observations will result in an effective integration time of 5x8 hours of on-source integration per galaxy, when they are combined with the 2002/2003 lower resolution data. Assuming parameters from the August 2003 Call for Proposals and our previous experience with these galaxies the combined observations will yield sensitivities of 0.29 mJy per 40 MHz channel in the CO 3-2/4-3 lines, and 0.28 mJy across the entire 1mm continuum bandpass (averaging both sidebands), resulting in a signal-to-noise ratio of 10 per line channel and in the continuum map.

References

Bertoldi, F., Menten, K.M., Kreysa, E., Carilli, C.L. & Owen, F. 2002, in Highlights of Astronomy 12, ed. H.Rickman, PASP (San Francisco), 473

Chapman, S.C., Blain, A.W., Ivison, R.J., & Smail, I.R. 2003, Nature, 422, 695

Downes, D. & Solomon, P.M. 2003, ApJ, 582, 37

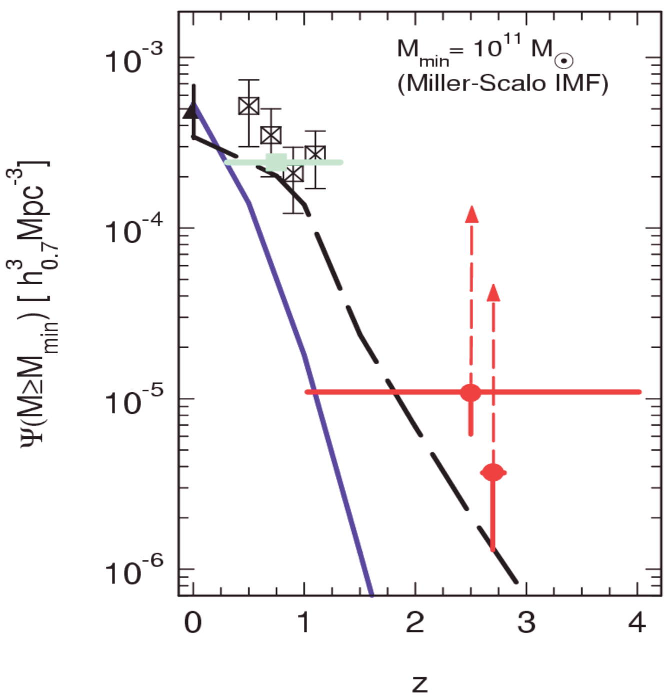

Figure 1: Mass assembly test from CO kinematics of submm galaxies (adapted from Genzel et al. 2003). Cosmic density of galaxies of (baryonic/stellar) mass $\geq M_{\rm min} = 1 - 2x10^{11} M_\odot$, for a flat $\Omega_\Lambda = 0.7$, H=70 $h_{0.7}$km/s/Mpc cosmology. The filled dark circles (and 1σ error bars) are estimated from the SCUBA Cluster Lens Survey galaxies J02399 and J14011 (lower) and from the six SCUBA cluster galaxies with intrinsic $S_{850} \geq$ 4 mJy which may lie at $z \geq 1$ (upper). Mass estimates are from CO rotation curves in J02399 and J14011. The dashed upward arrows indicate correction factors for the finite starburst lifetimes, as discussed in Genzel et al. (2003). The light filled square denotes the density of $S_{15} \geq 300\mu$Jy ISOCAM galaxies in the range z=0.2-1.3. The open rectangles with crosses are source densities for massive early-type galaxies from the MUNICS K-band survey, where stellar masses are estimated from stellar synthesis models. The filled triangle and bar denote the best estimate and range of densities at z=0, as obtained from stellar synthesis modeling for 2dF/2MASS data. For comparison, we show two theoretical curves (solid, long-dashes) from semi-analyic models in CDM cosmogonies. In all cases the stellar masses refer to a Miller-Scalo IMF.

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Smail, I.R., Ivison, R.J. & Blain, A.W. 1997, ApJ, 490, L5

Smail, I.R., Chapman, S.C., Ivison, R.J., Blain, A.W., Takata, T., Heckman, T.M., Dunlop, J.S. & Sekiguchi, K. 2003, MNRAS, in press (astso-ph 0303128)

Tecza, M. et al. 2003, in press

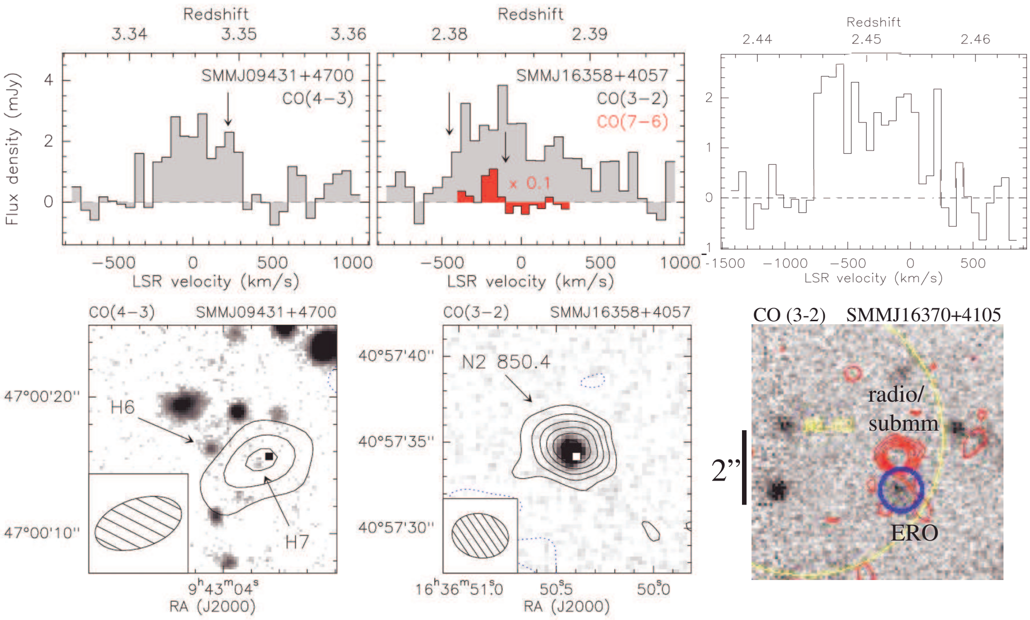

Figure 2: CO spectra (top) and moderate resolution CO maps (bottom left and middle) in our candidate submm galaxies. Plateau de Bure mm-interferometry of CO 3-2/4-3 emission obtained in 2003/2003 for SMMJ09431, SMMJ16358 and SMMJ16370 (left to right, Neri et al. 2003, Greve et al. 2003). Observations were in D-array for the left and right sources, and in D plus BC configurations for the middle source, resulting in FWHM beams of 6",3" and 7". Integration times varied between 13 and 24 hours. Superposed on the mm-contours in left and middle maps are grey-scale optical images to indicate the complex environment. In the right image we plotted the radio VLA contours instead of the mm-contours. In all three sources, there appear to be two or more separate sources at the same redshift, but spatially separated (H6/H7 in left image, within 1" in middle image and radio/ERO in right image) and of different physical characteristics.