Introduction to Millimeter Astronomy

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IRAM Interferometry School 2008

iram
Institut de
Radioastronomie
Millimétrique

Millimeter waves probe cold matter

VISIBLE

Hot matter

Stars between 3000 et 100,000 K

Ionised gas: 10,000 K

MILLIMETER

Cold Matter

Dust & Molecules

3 à 70 K (-270 à -200 deg Celsius)

STARS ARE BORN IN COLD MATTER

Because molecular ISM is cold and opaque to the visible and UV, the sub/millimeter is key to probe molecular clouds through:

- Molecular rotational transitions, where the photon energy is ~ kT_k
- Cold dust (10-20 K) emission
- Observations of high-z galaxies

Atmospheric windows: 3, 2, 1 and 0.8 mm

The 3mm window (72-116 GHz) includes practically one rotation of *most* molecules.

Fortunate situation that the mm windows all include transition of CO, which is the most abundant molecule after H_2

[J=1-0 at 115.271 GHz, J=2-1 at 230.538 GHz and J=3-2 at 345.796 GHz]

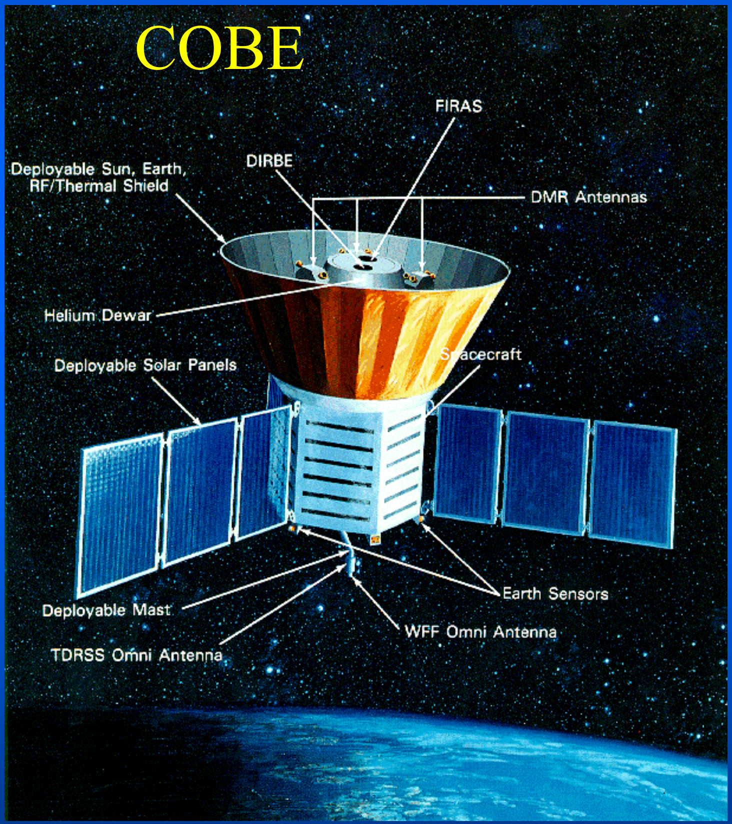
Millimeter studies fully benefit from the advantages of radio astronomy for high velocity resolution with the heterodyne techniques, and the high angular resolution with large dishes or interferometers.

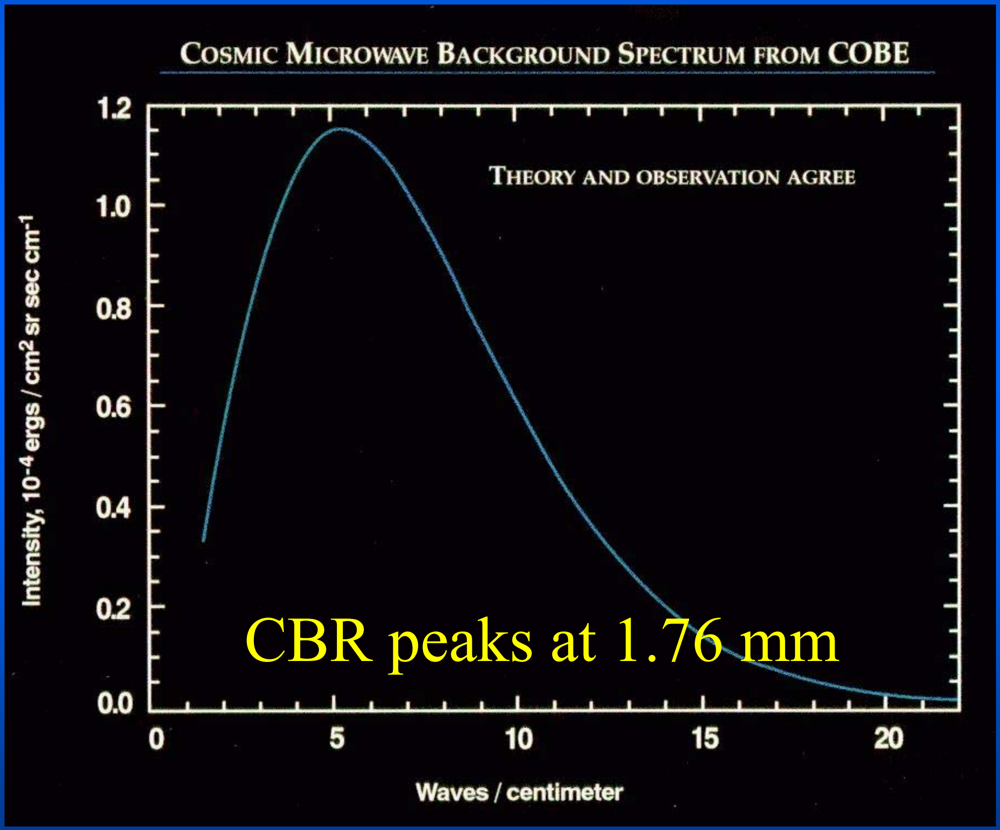
Interest of the mm/submm domain

$h\nu=kT$ **1.44 K ≡ 30 GHz ≡ 1 cm^{-1}**

- Black-body emission peaks at **λ_m=hc/3kT=0.48/T cm**
- Dust emission peaks at **λ_m=hc/(3+β)kT=0.3/T cm**
- Typical energies involved in molecular transitions
- SED of galaxies
- SZ effect, interstellar scintillation (VLBI)
- Atmosphere transparency

Black body emission: Cosmic Background Radiation

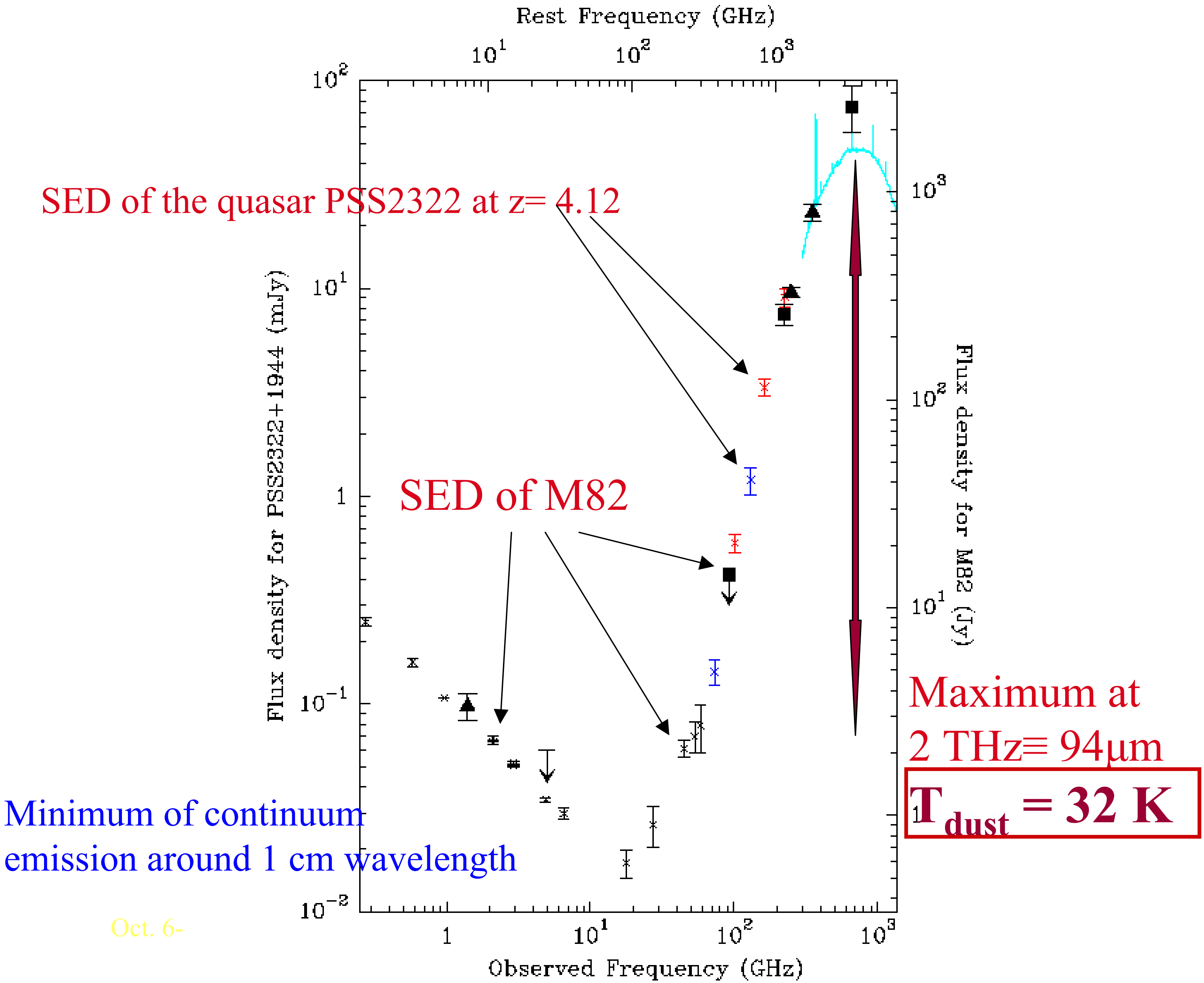




$n=10\text{-}10^{3}$ cm^{-3}
T=20-100 K
$A_v<1$

$n=10^{3}\text{-}10^{6}$ cm^{-3}
T=8-15 K
$A_v>1$

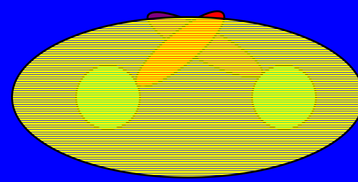
Dust emission peaks at 0.3 mm



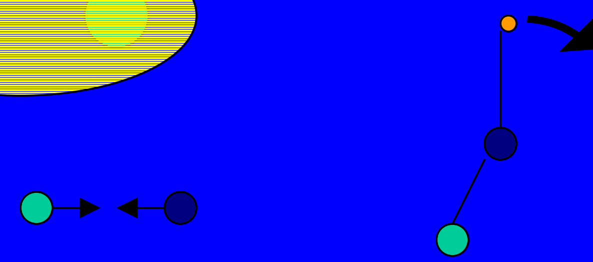
Rest Frequency (GHz)
Observed Frequency (GHz)
Flux density for PSS2322+1944 (mJy)
Flux density for M82 (Jy)
SED of the quasar PSS2322 at z= 4.12
SED of M82
Minimum of continuum
emission around 1 cm wavelength
Maximum at
2 THz≡ 94μm
T dust = 32 K

Typical energies involved in molecular transitions

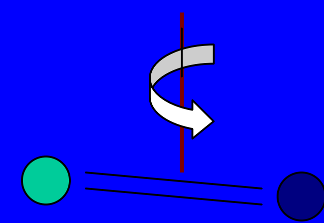
- Electronic transitions



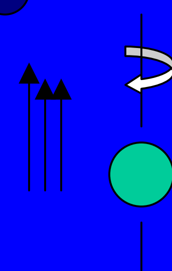
- Vibrational transitions



- Rotational transitions

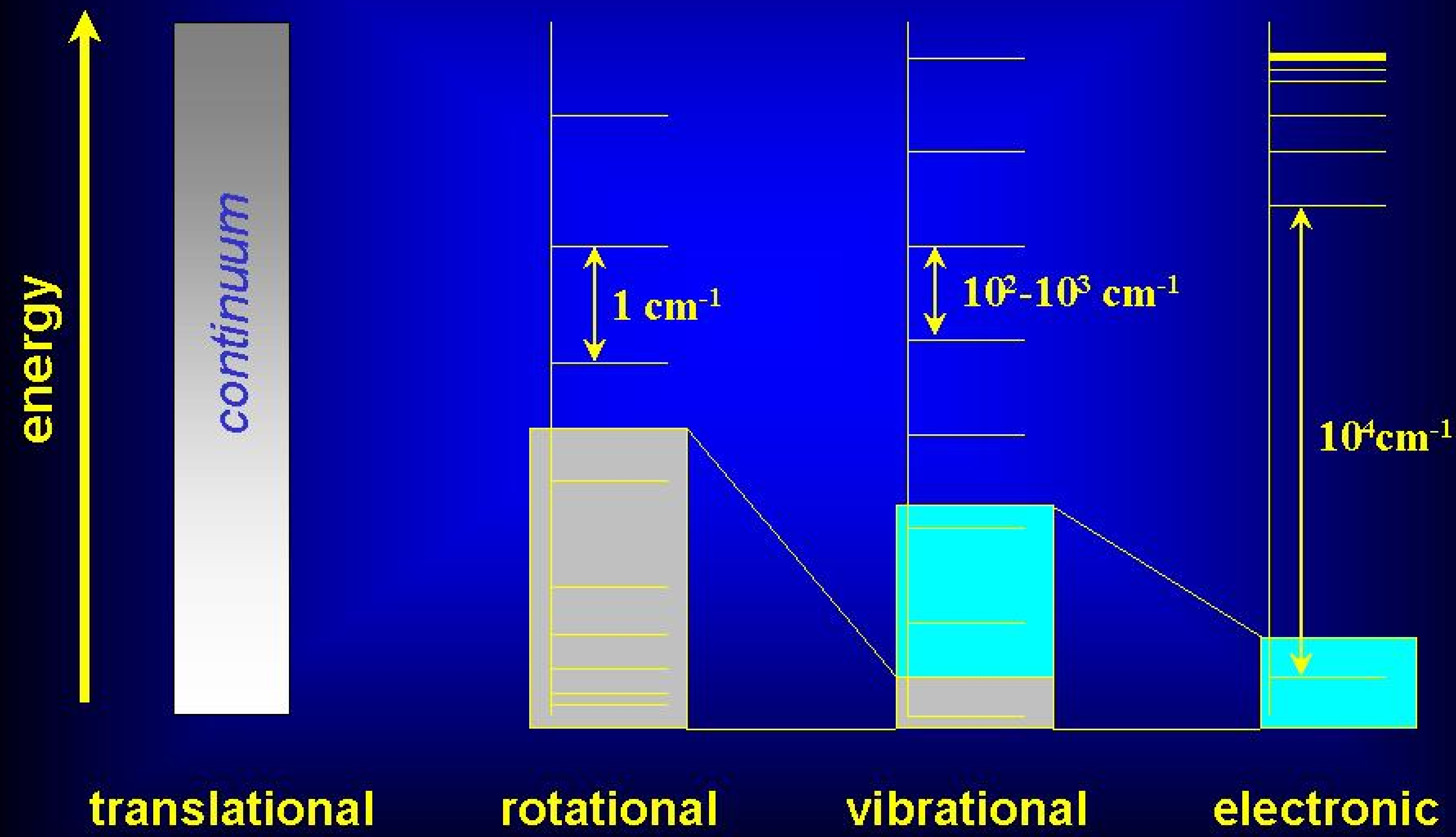


- Electronic/nuclear Spin interactions

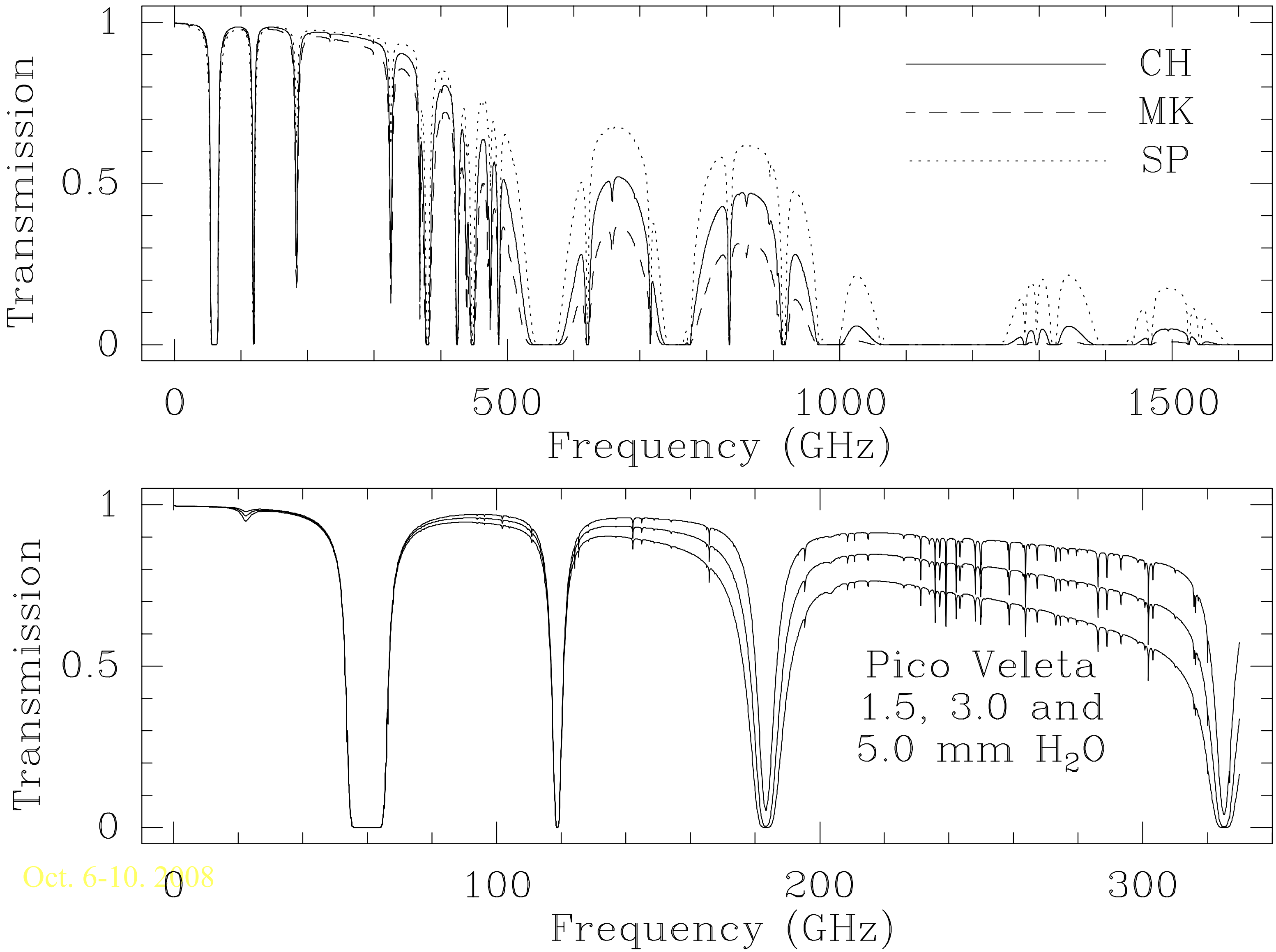


energy level separations

low-energy rotational transitions of small molecules lie at mm wavelength



Atmospheric transmission (calculations by J. Pardo)



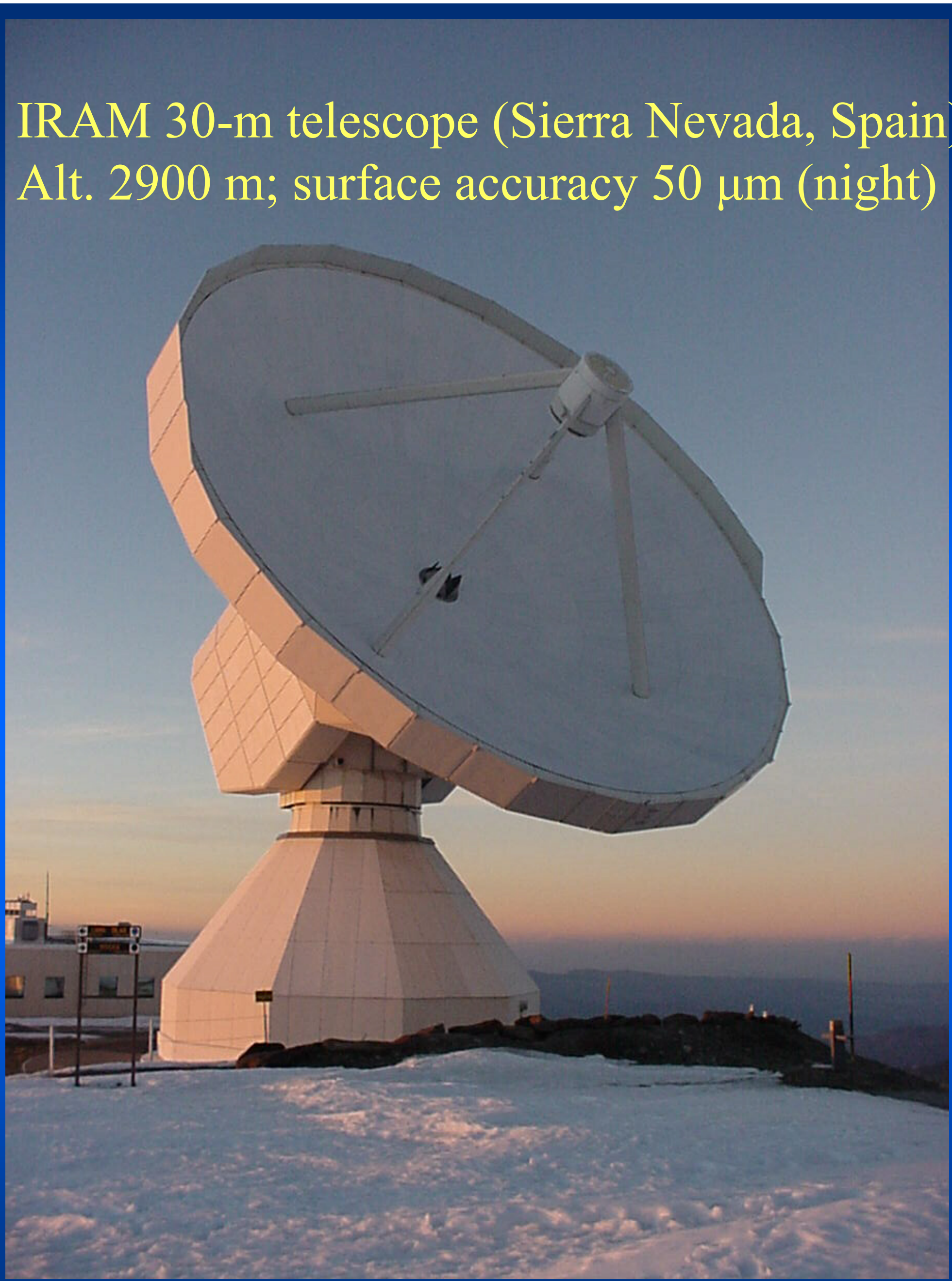
Emission processes at sub/mm wavelengths

- Atoms: electronic (**spin**, Rydberg states)
- **Molecules**: electronic, vibrational, **rotational**
- Free electrons:
  - Synchrotron
  - Thermal free-free
- **Dust particles** (grey body radiation)

Millimeter-wave Radio Telescopes

- Large collecting surface for sensitivity
- Large physical dimensions for angular resolution
- High altitude to reduce atmospheric water vapor absorption
- Heterodyne receivers for high spectral resolution (10^{-7} —10^{-8})

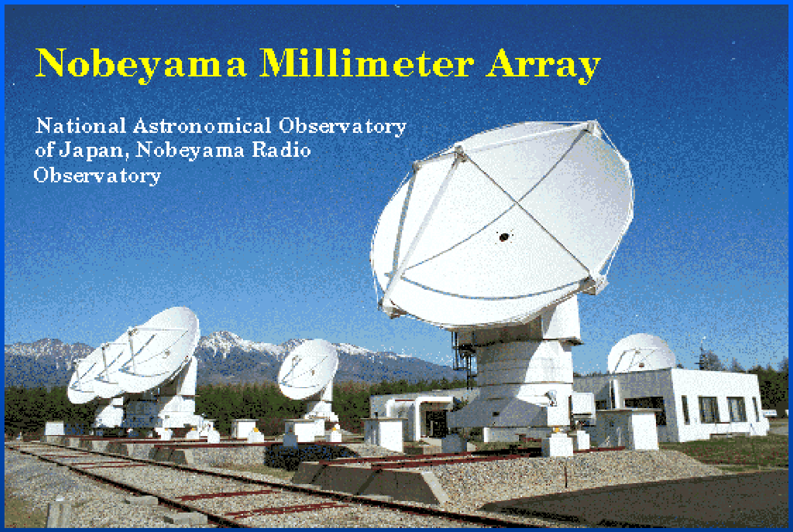
IRAM 30-m telescope (Sierra Nevada, Spain)
Alt. 2900 m; surface accuracy 50 μm (night)

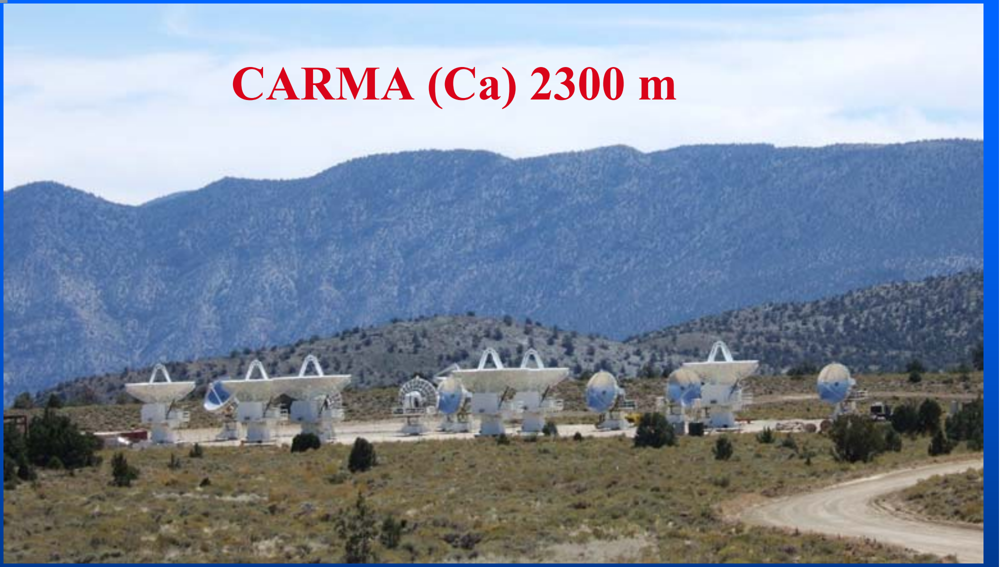


APEX 12-m telescope (Atacama, Chile)
Altitude 5100 m; surface accuracy 17μm

Sub/Millimeter Interferometers

CSO, JCMT & SMA (Hawaii) 4300m





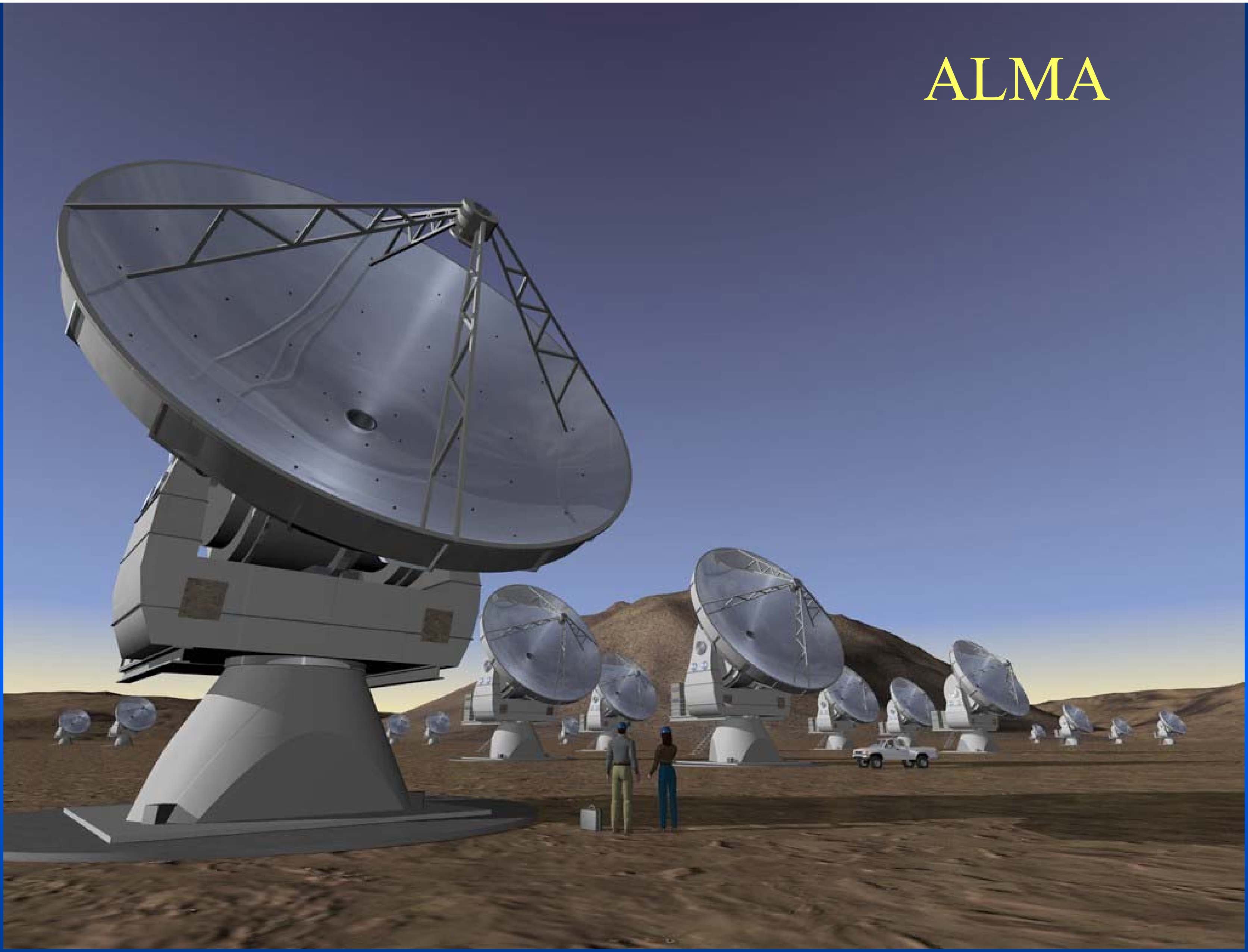
The Green Bank telescope

No aperture blockage

Surface accuracy:300 μm

Very Large Array (up to 7 mm)

ALMA



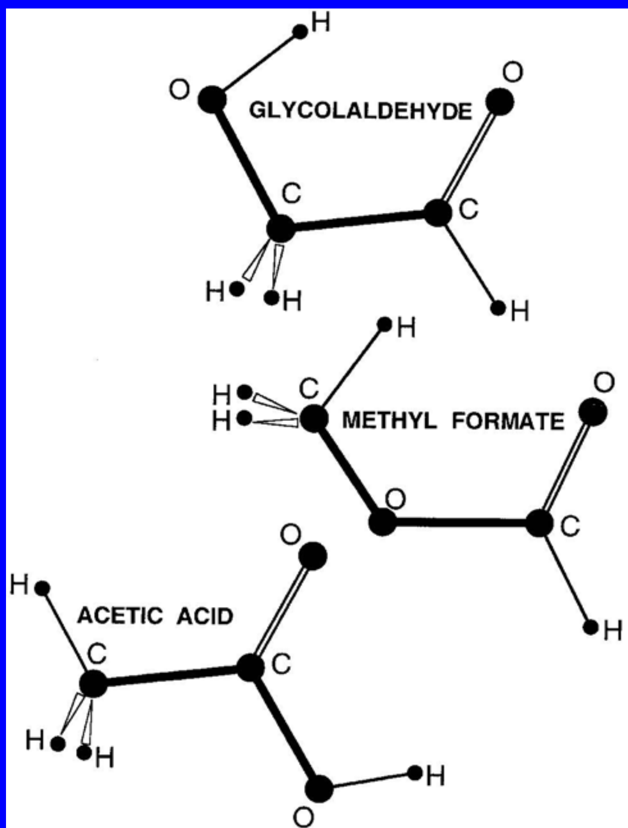
Advantages of Interferometry

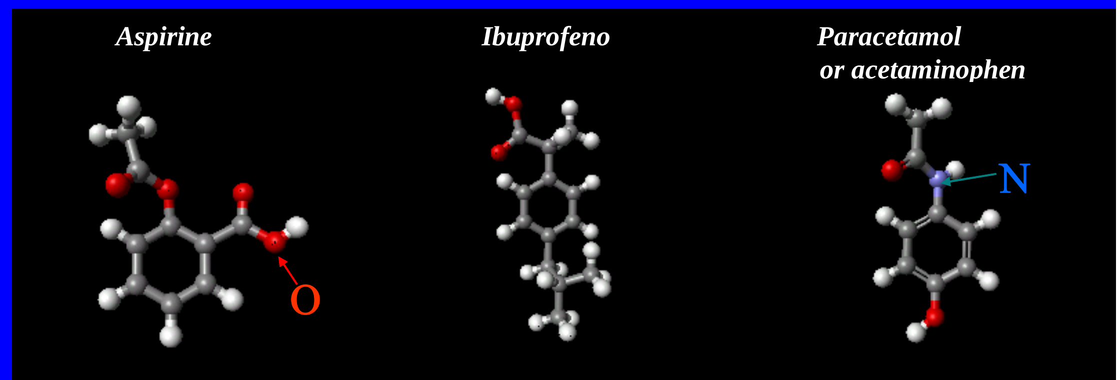
- **High angular resolution** (@ λ=1 mm: 0.25” with PdB; 20 μarcsec with VLBI)
- **Large collective area**
- **No need of reference position** (factor 2 in sensitivity replaced by $N(N-1)/N^2$)
- **Flatter baselines** (depends less on receiver/atmosphere stability). Makes possible composite spectra.
- **Field of view with many independent pixels** →good noise statistics makes possible secure detections down to 4 sigma.
- **Well suited for special observations**: polarimetry, SZ
- **Accurate source positions** (by stable atmosphere: HPBW/SNR)
- **Eliminates extended** (foreground/background) **emission**

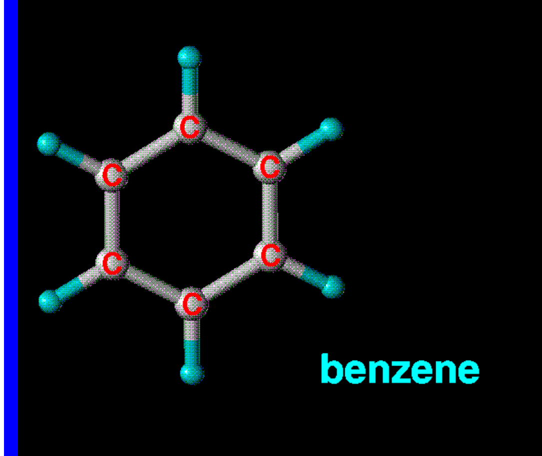
Disadvantages of Interferometry

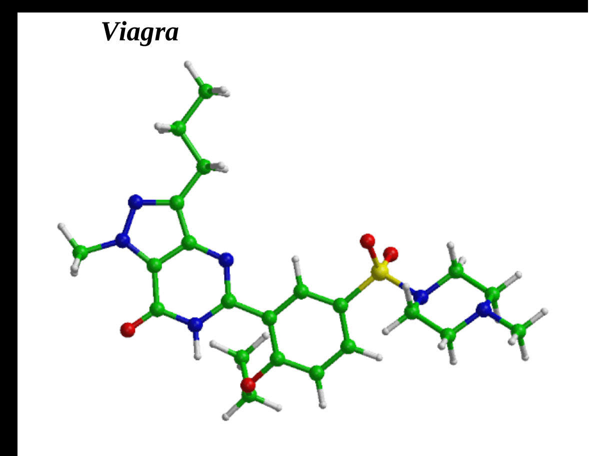
- **Several receivers to build**; more complex correlator, but heterodyne interferometry is easy
- **Short spacings filtered out**: extended source emission lost (partly recovered by mosaicing techniques)
- **Needs a stable atmosphere** (or needs phase corrections or self-calibration)
- Difficult to observe very strong sources, such as planets (unless modelized)

Interstellar molecules









List of Interstellar Molecules (142, January 2006)

Hydrogen Compounds

H_2	*HD*	**H_3^+**	**H_2D^+**		

Hydrogen and Carbon Compounds

CH	***CH^+***	*C_2*	CH_2	**C_2H**	*C_3
CH_3	C_2H_2	**C_3H**(lin)	**c-C_3H**	*CH_4	**C_4**
c-C_3H_2	**H_2CCC**(lin)	**C_4H**	***C_5***	*C_2H_4	**C_5H**
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	**H_2C_6**
C_7H	CH_3C_4H	**C_8H**	*C_6H_6		

Hydrogen, Carbon (possibly) and Oxygen Compounds

OH	*CO*	***CO^+***	H_2O	**HCO**	**HCO^+**
HOC^+	**C_2O**	CO_2	**H_3O^+**	**$HOCO^+$**	H_2CO
C_3O	CH_2CO	HCOOH	**H_2COH^+**	CH_3OH	CH_2CHO
CH_2CHOH	CH_2CHCHO	HC_2CHO	**C_5O**	CH_3CHO	c-C_2H_4O
CH_3OCHO	CH_2OHCHO	CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO
$(CH_3)_2CO$	$HOCH_2CH_2OH$	$C_2H_5OCH_3$	$(CH_2OH)_2CO$	CH_3CONH_2	

Molecular ions are in **red**. Free radicals are in **purple**. Closed-shell highly unstable molecules are in **blue.**

Hydrogen, Carbon (possibly) and Nitrogen Compounds

NH	***CN***	*N_2*	***NH_2***	HCN	**HNC**
N_2H^+	NH_3	**$HCNH^+$**	**H_2CN**	**HCCN**	**C_3N**
CH_2CN	CH_2NH	HC_2CN	**HC_2NC**	NH_2CN	**C_3NH**
CH_3CN	**CH_3NC**	**HC_3NH^+**	*__HC_4N__	**C_5N**	CH_3NH_2
CH_2CHCN	**HC_5N**	CH_3C_3N	CH_3CH_2CN	**HC_7N**	CH_3C_5N?
HC_9N	**$HC_{11}N$**				

Hydrogen, Carbon (possibly), Nitrogen and Oxygen Compounds

NO	HNO	N_2O	HNCO	NH_2CHO	

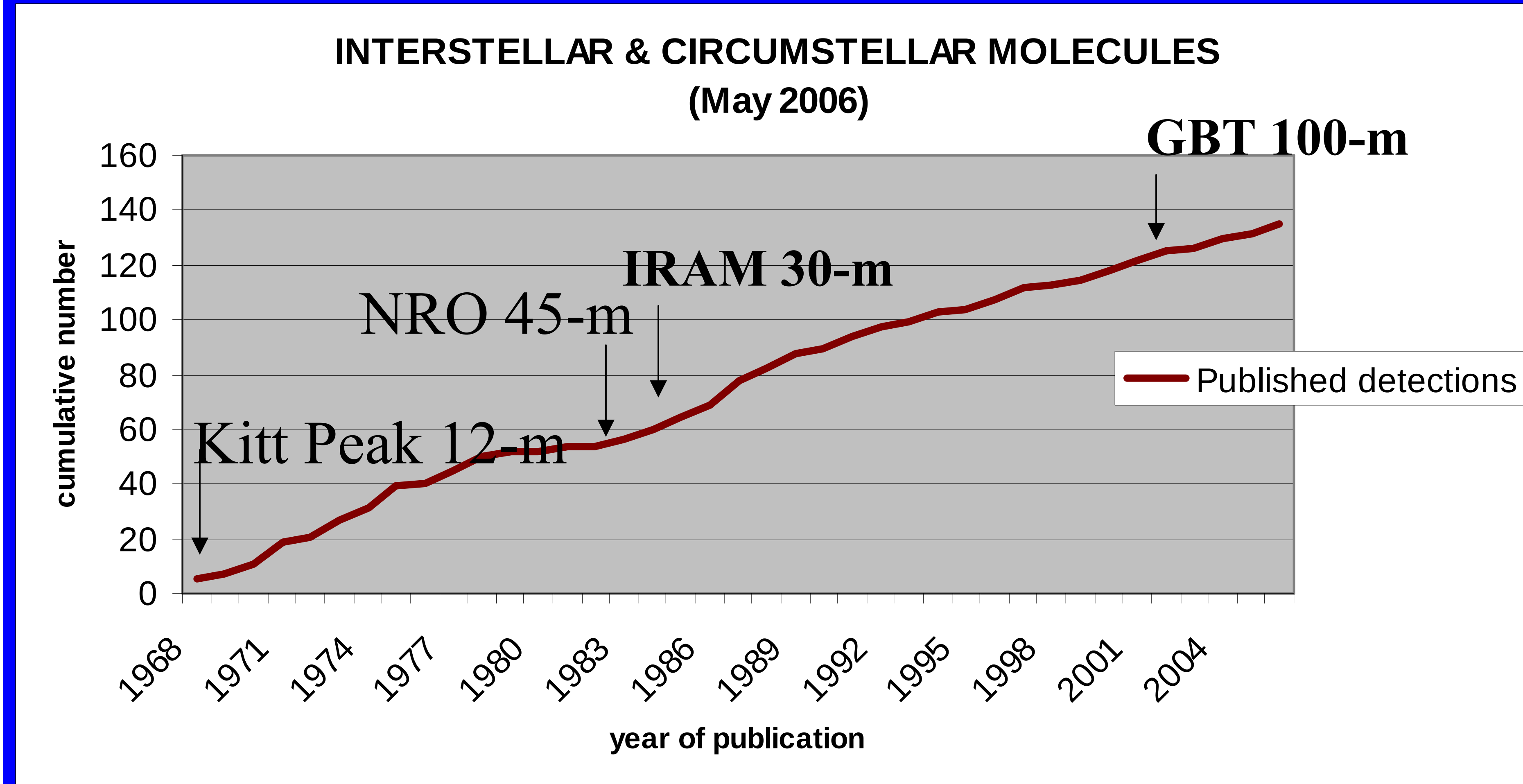
Other Species

SH	CS	**SO**	**SO^+**	**NS**	**SiH**
***SiC**	**SiN**	SiO	SiS	HCl	*NaCl
*AlCl	*KCl	HF	*AlF	*CP	PN
H_2S	**C_2S**	SO_2	OCS	**HCS^+**	c-SiC_2
***SiCN**	***SiNC**	*NaCN	***MgCN**	***MgNC**	*AlNC
H_2CS	HNCS	C_3S	c-SiC_3	*SiH_4	*SiC_4
CH_3SH	**C_5S**	**FeO**	**CF^+**		

Ref. PCMI/CNRS

Inter- & Circumstellar molecules

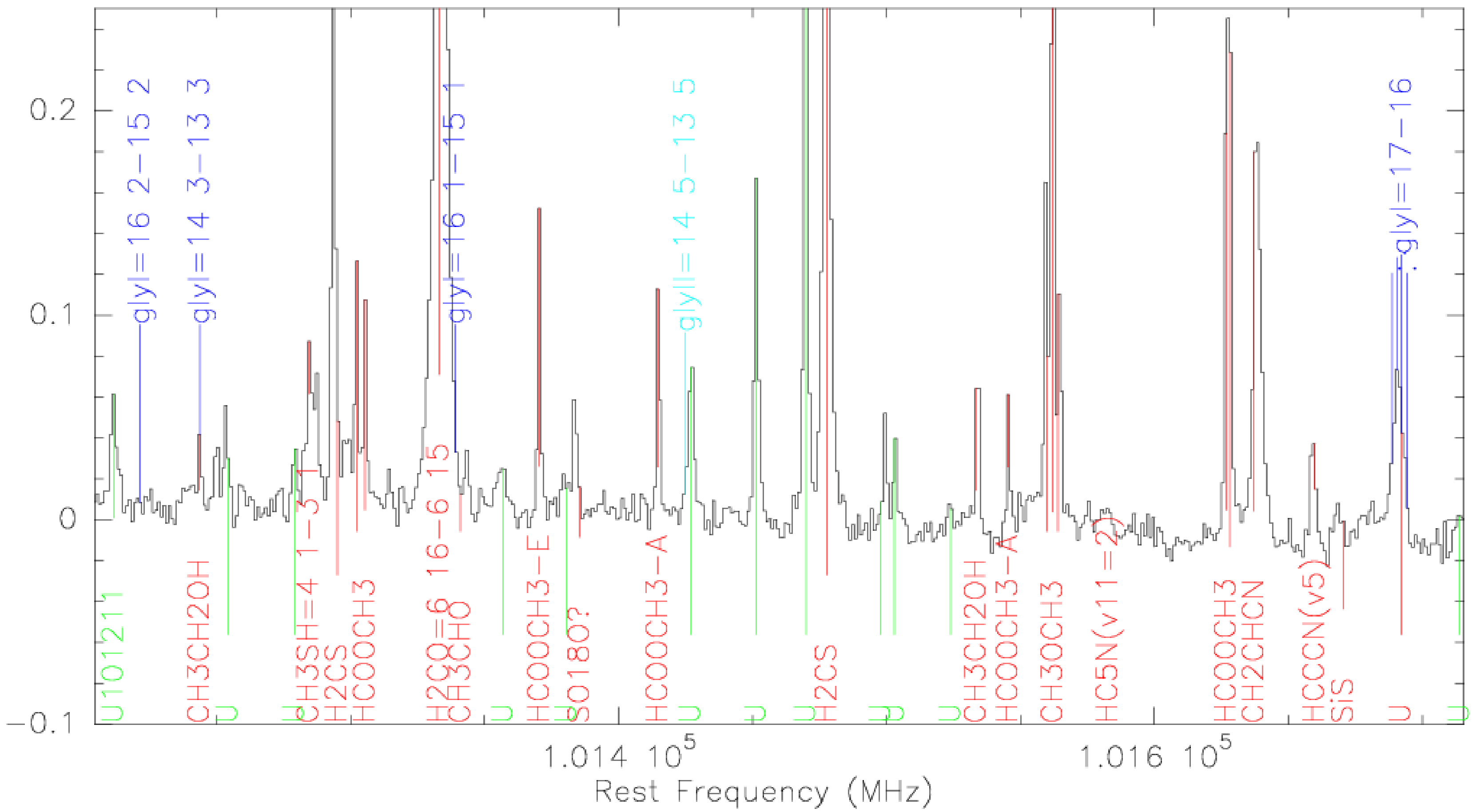
- 135 species (+-5 ?)
- 14 ions (and 2 anions)
- 29 free radicals (part of which identidied in space prior to be studied in the laboratory)
- 19 isomers or highly unstable closed-shell molecules
- 18 molecules with refractory atoms, amidst which 8 silicon compounds
- 5 cycles, among which benzene (1 line!). No other benzenic ring detected, except perhaps PAHs.

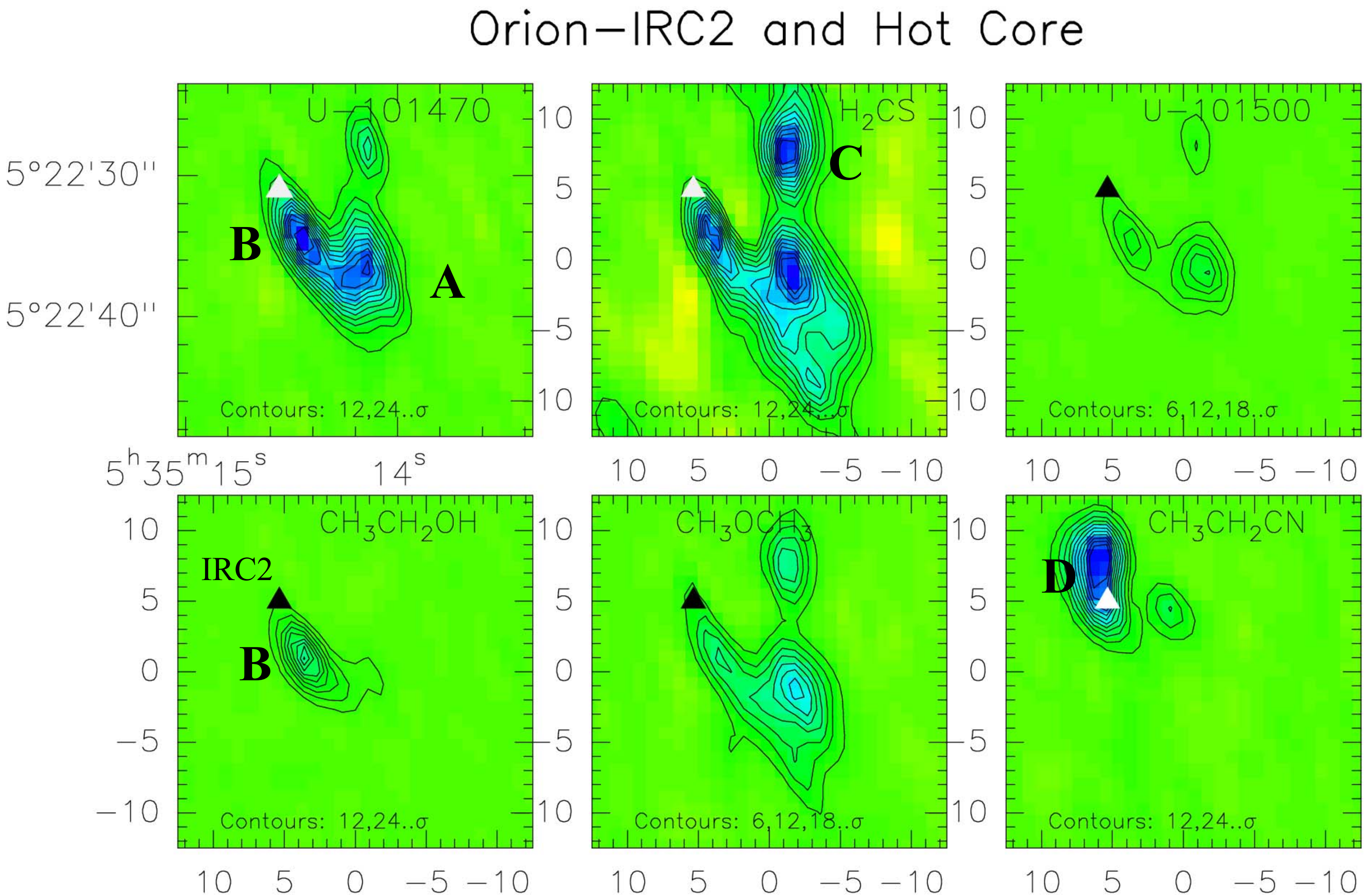

INTERSTELLAR & CIRCUMSTELLAR MOLECULES
(May 2006)
GBT 100-m
IRAM 30-m
NRO 45-m
Kitt Peak 12-m
Published detections
cumulative number
160
140
120
100
80
60
40
20
0
1968
1971
1974
1977
1980
1983
1986
1989
1992
1995
1998
2001
2004
year of publication

Interstellar Molecules: where?

- Diffuse IS clouds
- **Cold dark clouds**
- Protostellar cores
- **Hot cores (star forming regions)**
- **Circumstellar disks**
- **Circumstellar envelopes**
- **Jets and shocked regions**
- **External galaxies: up to z=6.4!**

Same spectrum as previous one, but with line identifications (in red). Unidentified lines in green (noted U)





Maps of Orion-IRC2 in the lines of 6 different molecules:
The molecules arise from different hot cores (or corinos) labelled A,B,C and D.

Guelin et al. (2006)

AGB star envelope IRC+10216

IR emission

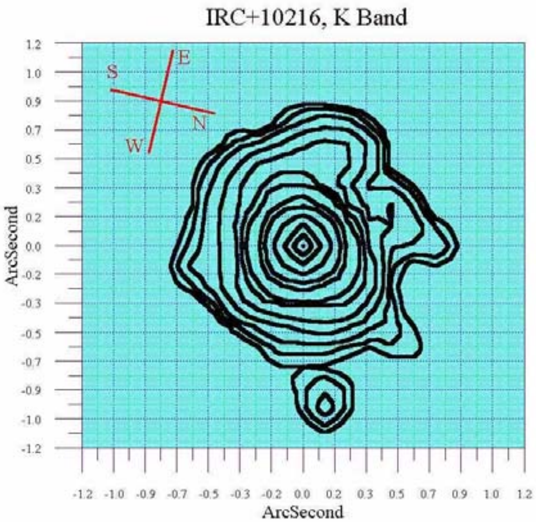
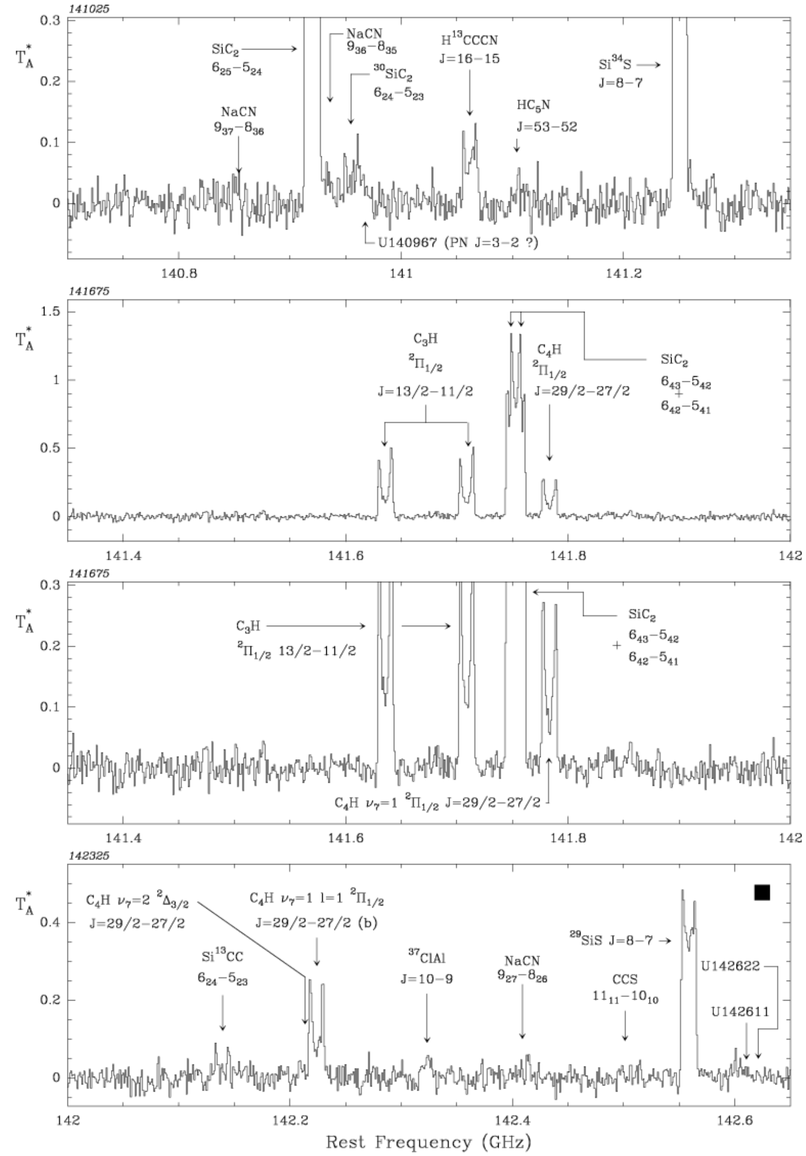
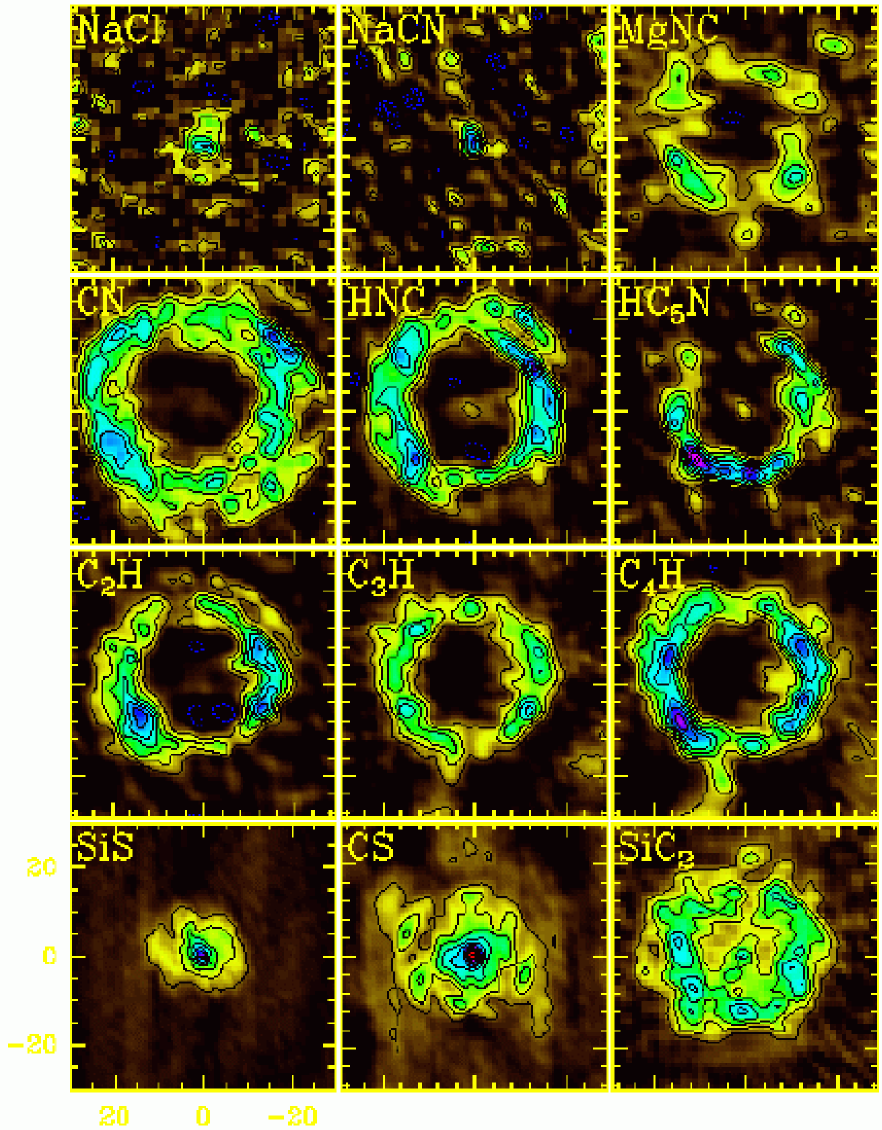


Figure 3: Contour plot of the carbon rich star IRC+10216.

Spectral line survey 80-250 GHz

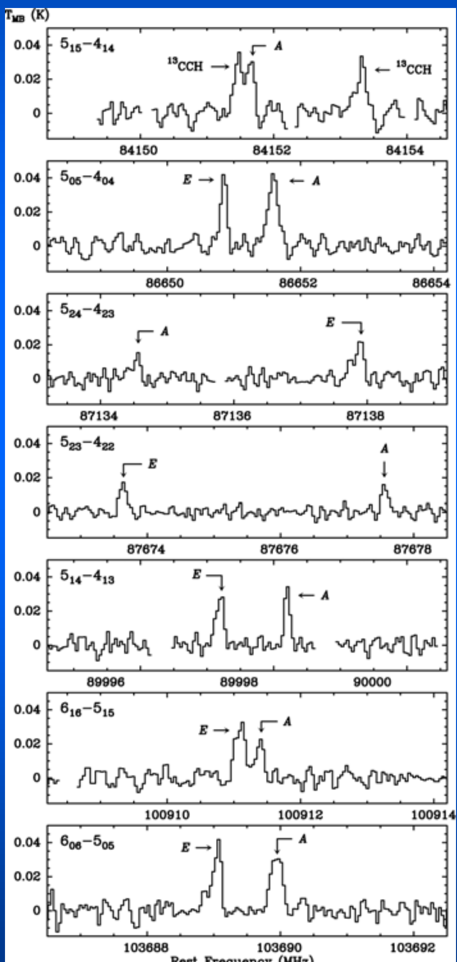
Cernicharo, Guelin, Kahane (2000)





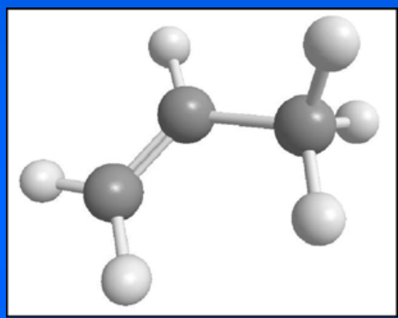
NaCl
NaCN
MgNC
CN
HNC
HC_5N
C_2H
C_3H
C_4H
SiS
CS
SiC_2
20
0
−20
20
0
−20

Recent Detection of new molecules



Interstellar Propylene

CH_2CHCH_3 in TMC-1



Marcelino et al. 2007

Also

Amino Acetonitrile

NH_2CH_2CN in Sgr B2

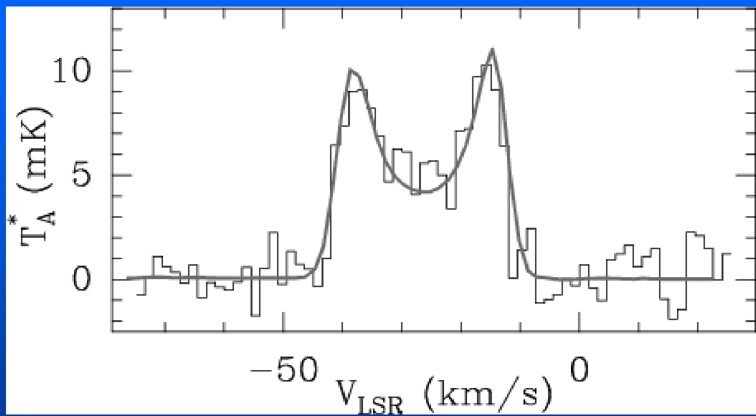
and

Phosphaethyne HCP in IRC+10216

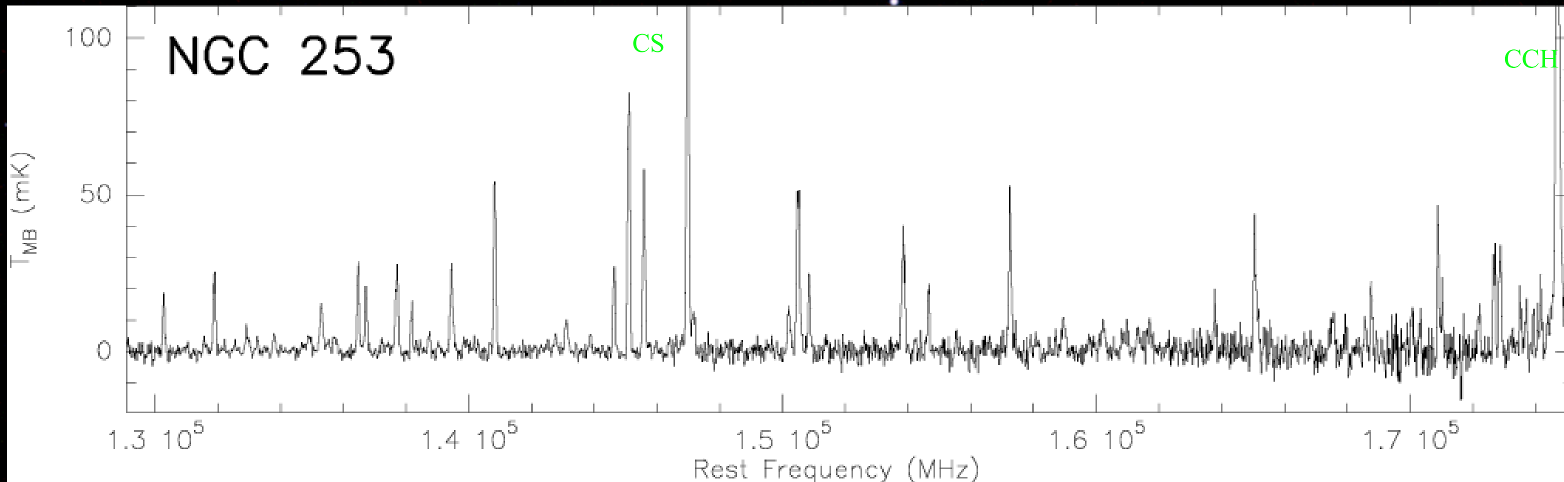
Second interstellar anion

$C\text{-}_4H^-$ in IRC+10216

Average spectrum of the J=9-8, 11-10, 12-11, 14-13, and 15-14 lines of $C\text{-}_4H^-$ (histogram) compared with the average of the same lines of the neutral counterpart C_4H, scaled down by a factor of 100



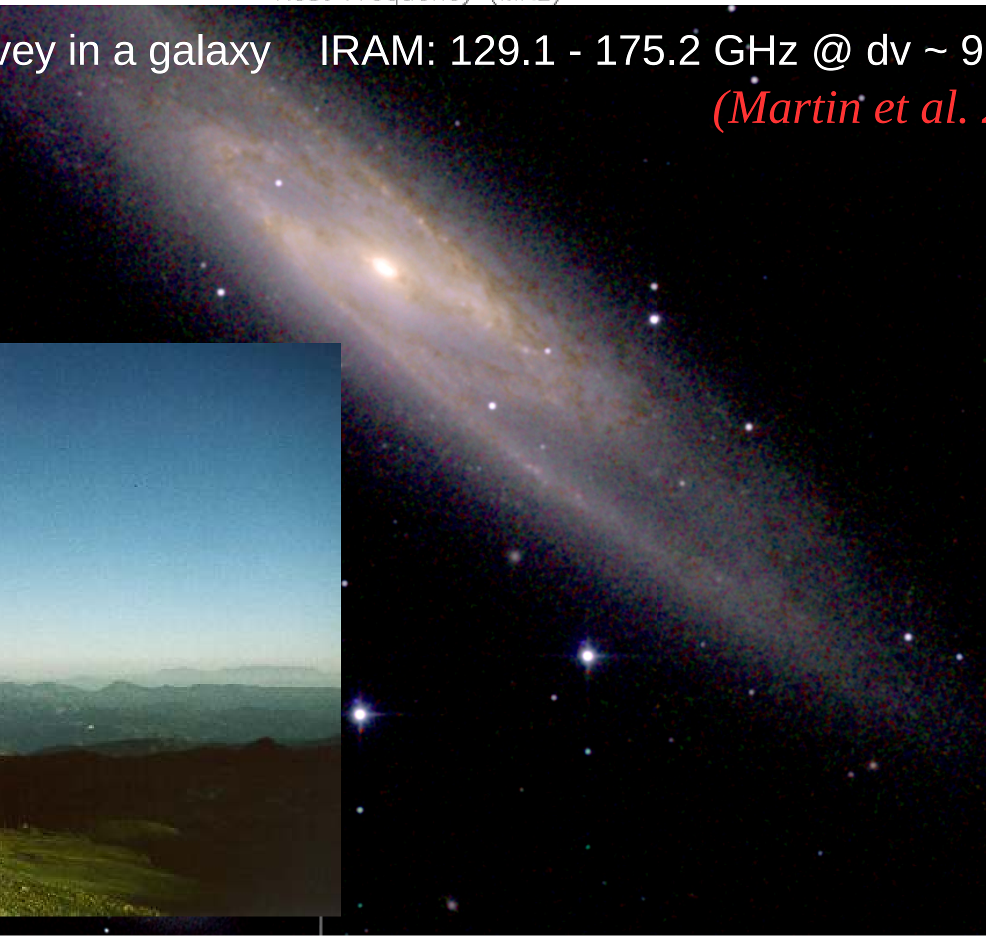
(Cernicharo et al. 2007)



First unbiased line survey in a galaxy   IRAM: 129.1 - 175.2 GHz @ dv ~ 9 km/s

(Martin et al. 2006)

IRAM 30-meter



2MASS - Jarrett

DETECTED EXTRAGALACTIC MOLECULES

Nb. of atoms	2	3	4	5	6	7
Molecules	H_2	H_2O	H_2CO	c-C_3H_2	CH_3OH	CH_3CCH
	OH	HCN	H_2CS	HC_3N	CH_3CN	
	CO	HNC	NH_3	*CH_2NH*		
	CH	HCO	HNCO	NH_2CN		
	CS	HCO^+	*C_3H*			
	CH^+	H2S	*$HOCO^+$*			
	CO^+	SO_2				
	NO	C2H				
	CN	HOC^+				
	NS	C2S				
	SiO	N_2H^+				
	SO	OCS				
	LiH	H_3^+				

* NGC 253's chemistry closely resembles that of Sgr B2(M) (Turner 1989)

* 35 (+ 4 tentatively) detected species

* 13 (+ 2 tentatively) detected rare isotopic substitutions

Italics = tentative

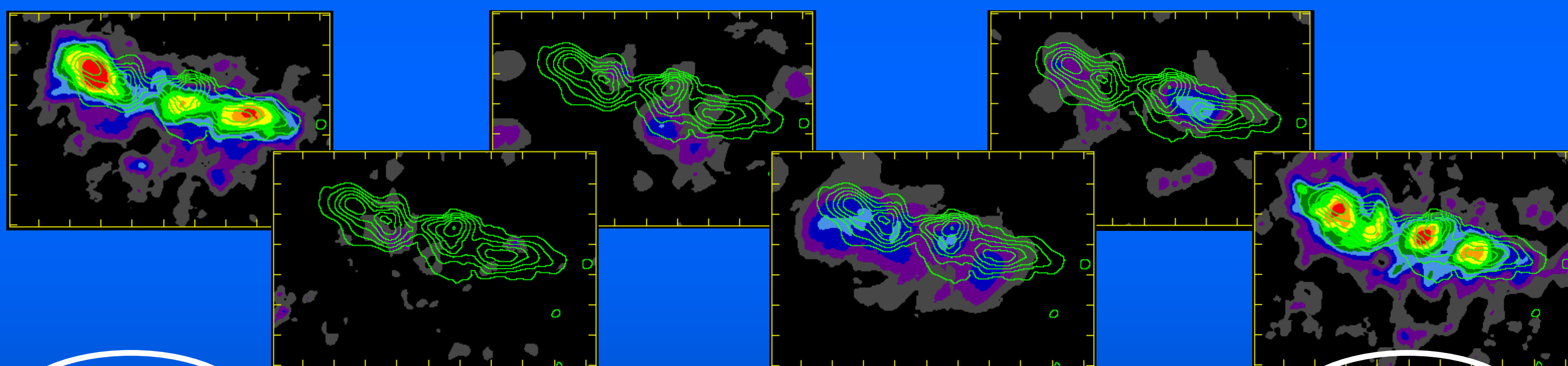
(Compiled: Martin et al 2006; updated by Turner 2007)

M82: a different kind of chemistry

CH_3OH and HNCO undetected in these maps

CN, C_2H and HNC bright & more extended than CO ➔ *effect of strong radiation field*

BIMA observations (Meier & Turner, in prep)

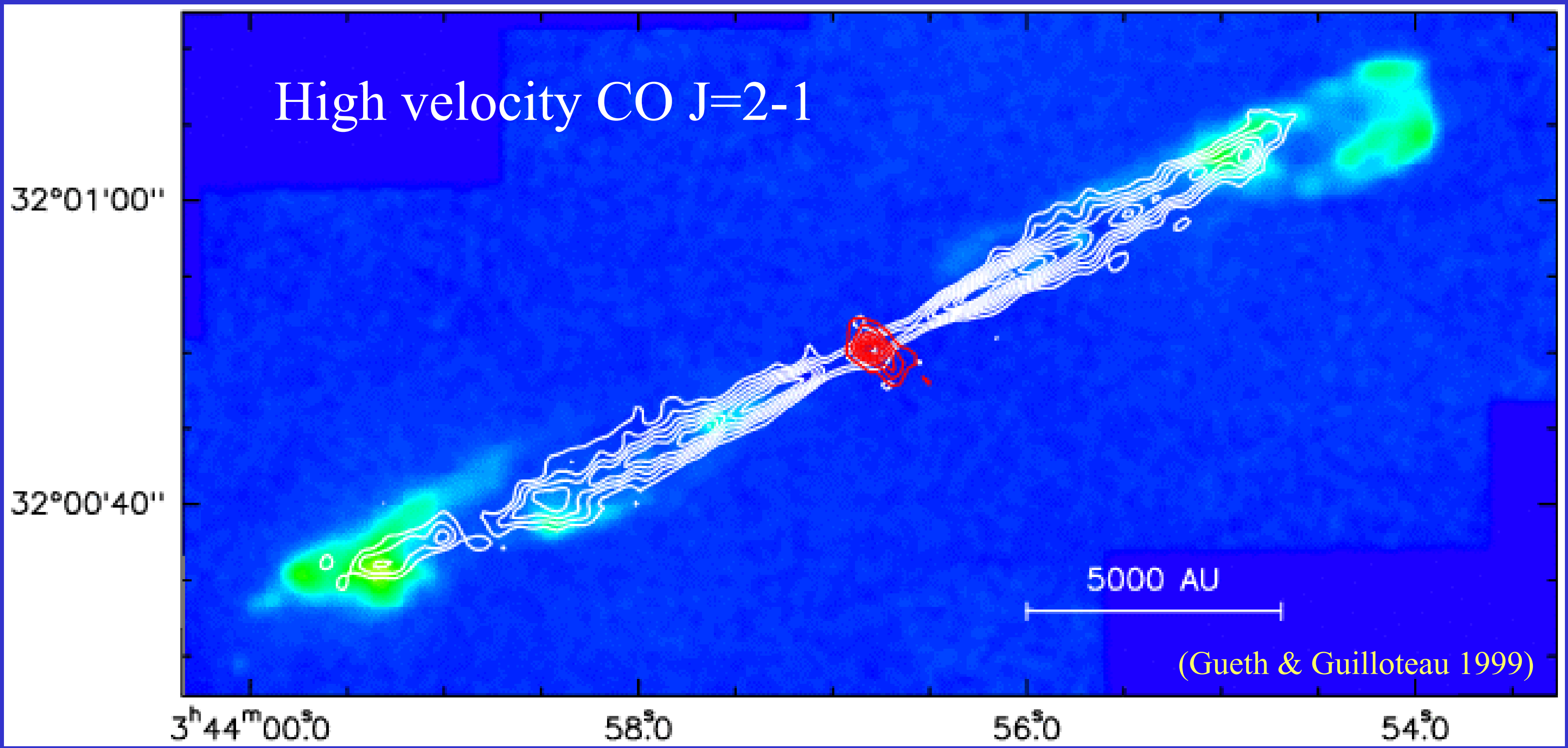


CCH HNCO $C^{34}S$ N_2H^+ HC_3N HNC

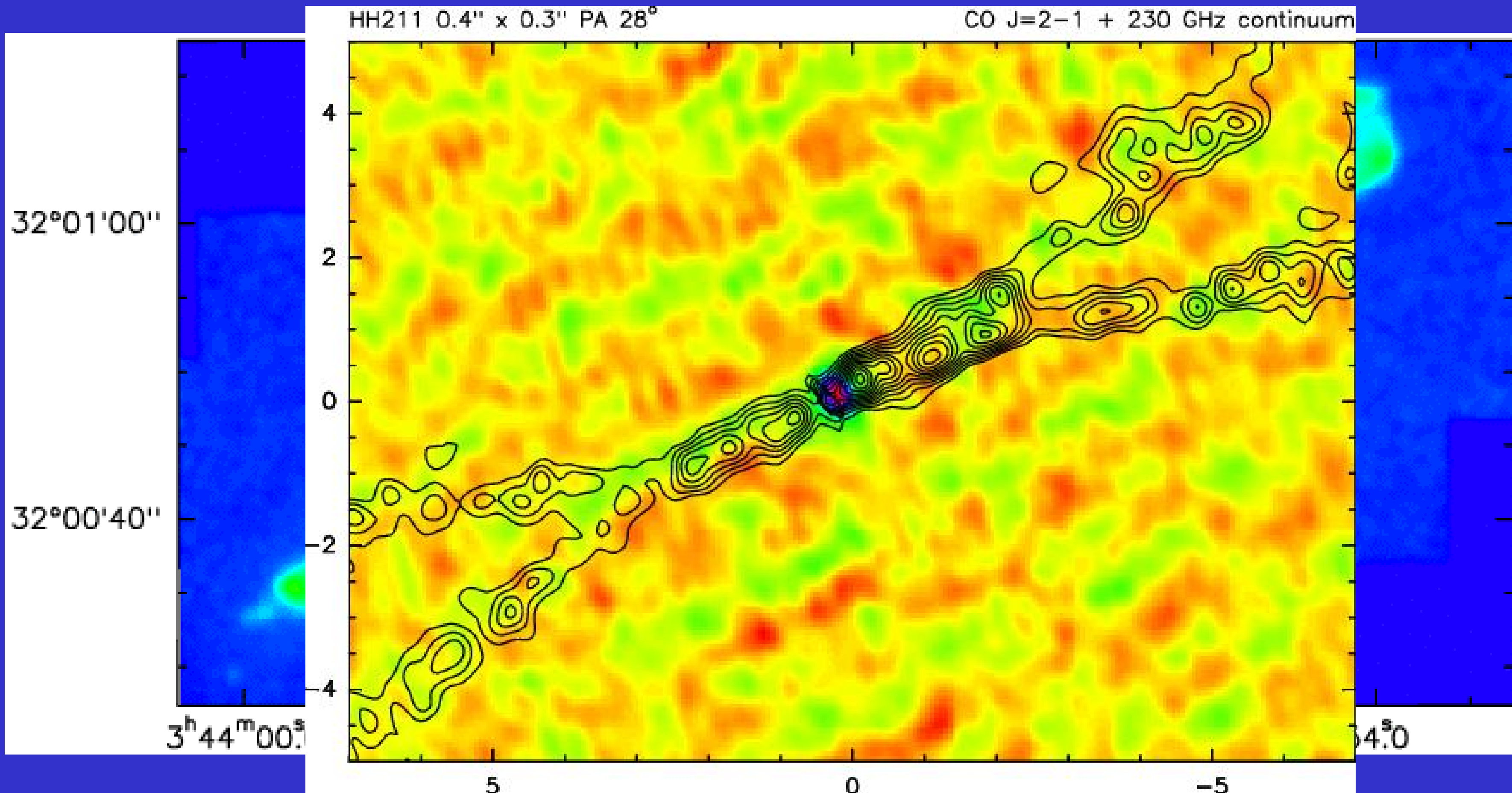
M82 "giant PDR": Garcia-Burillo et al. 2002 (HCO) Mauersberger & Henkel 1991, Henkel et al. 1991

HH211 at 1.5" resolution

Molecular outflow driven by a **Class 0 low-mass protostar**
(dynamical age~1000 yr, distance of 300pc)

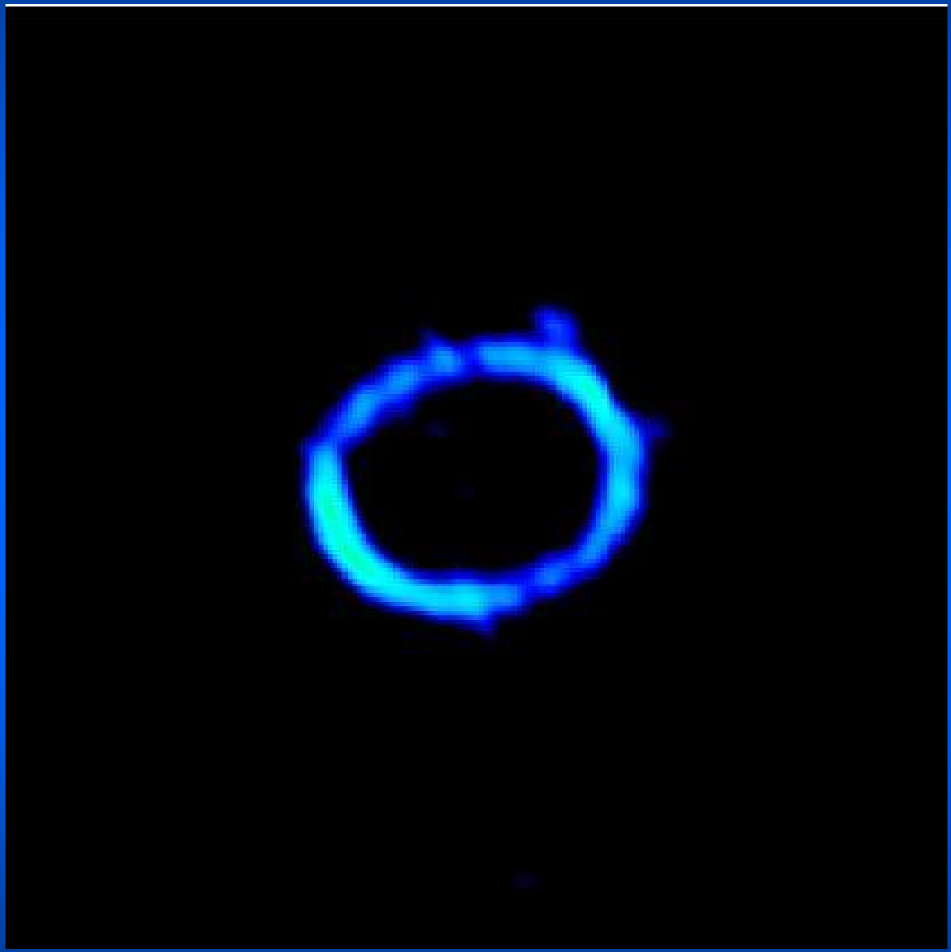


1.5” → 0.3” resolution



 Gueth et al. (2008)

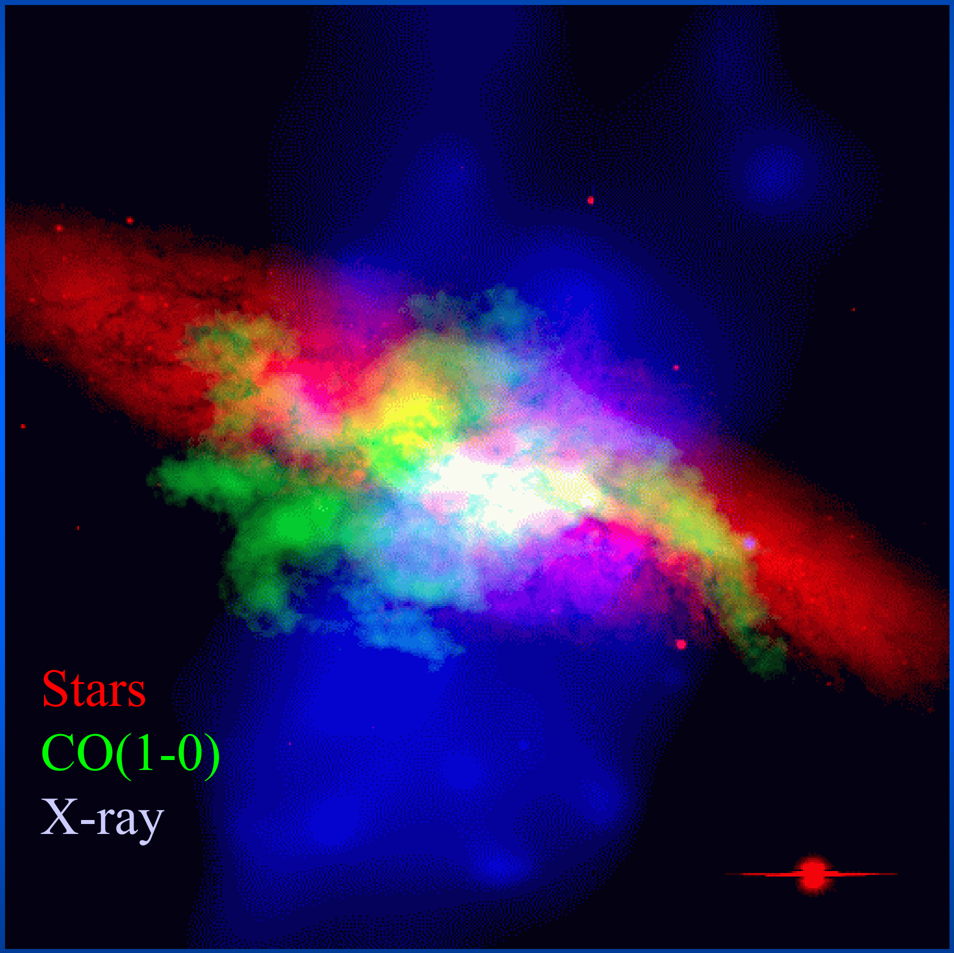
GGTau in the continuum at 267 GHz



Beam 0.45”x0.25”

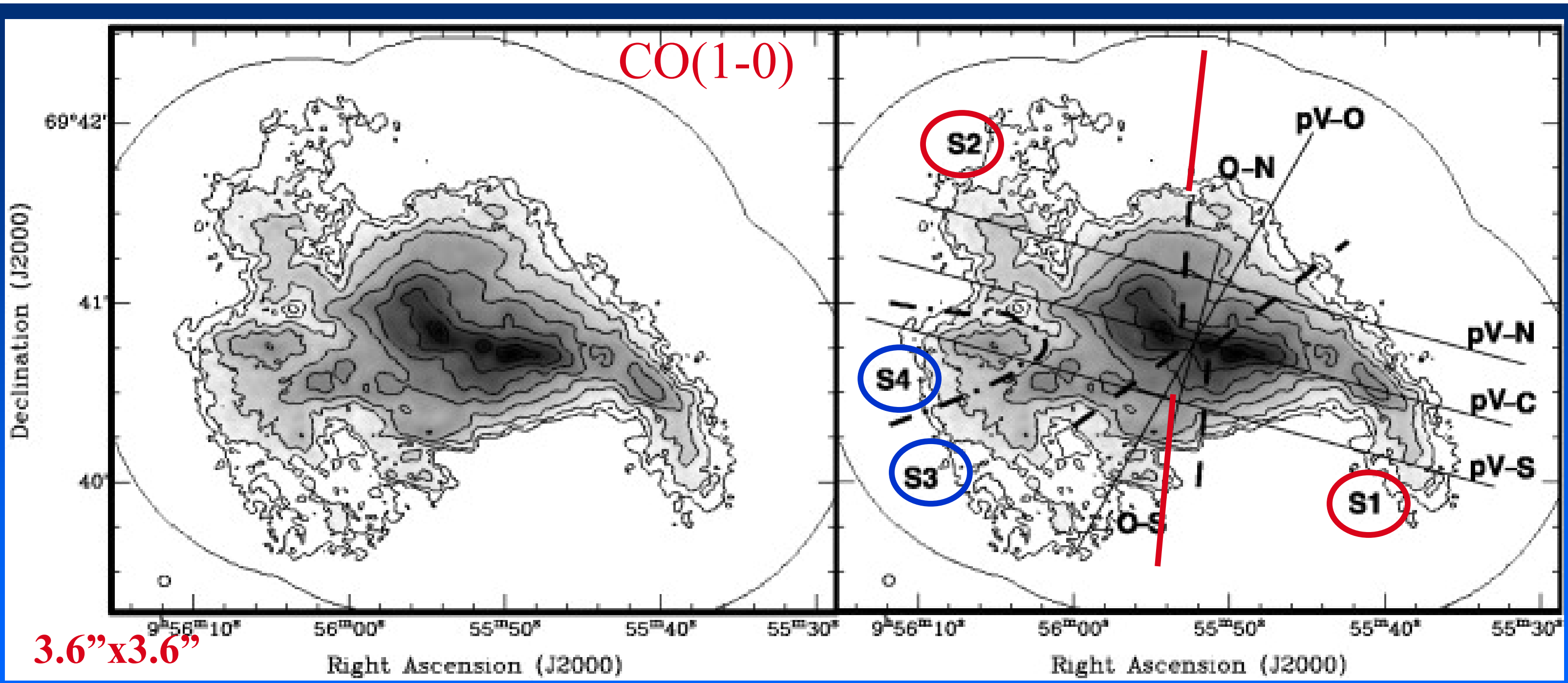
Pietu et al. 2008

Example of a starburst: M82



Prominent starburst at 3.9 Mpc
(1' ~ 1.1 kpc)
Central regions are site of tremendous star-forming activity: Halpha, FIR, X-rays outflows, SNRs
M_{tot}~2.3 x 10^8 M_{sun} in center, dense and warm gas

In interaction with M81:
M81-M82 tidal tail – (Yun et al. 1993)
➔Triggered star formation



(~70 pc)

Labels of the molecular streamers (S1–S4) and the outflow gas (O-N and O-S);

- Detection of molecular streamers – S1 (and S2) similar orientation and velocities as the HI streamer that point toward M81
- The molecular gas in the inner region is severely affected by the interaction with M81 and its redistribution is the likely trigger of the starburst activity
- The distribution is extended, almost in a halo comparable to ionized gas

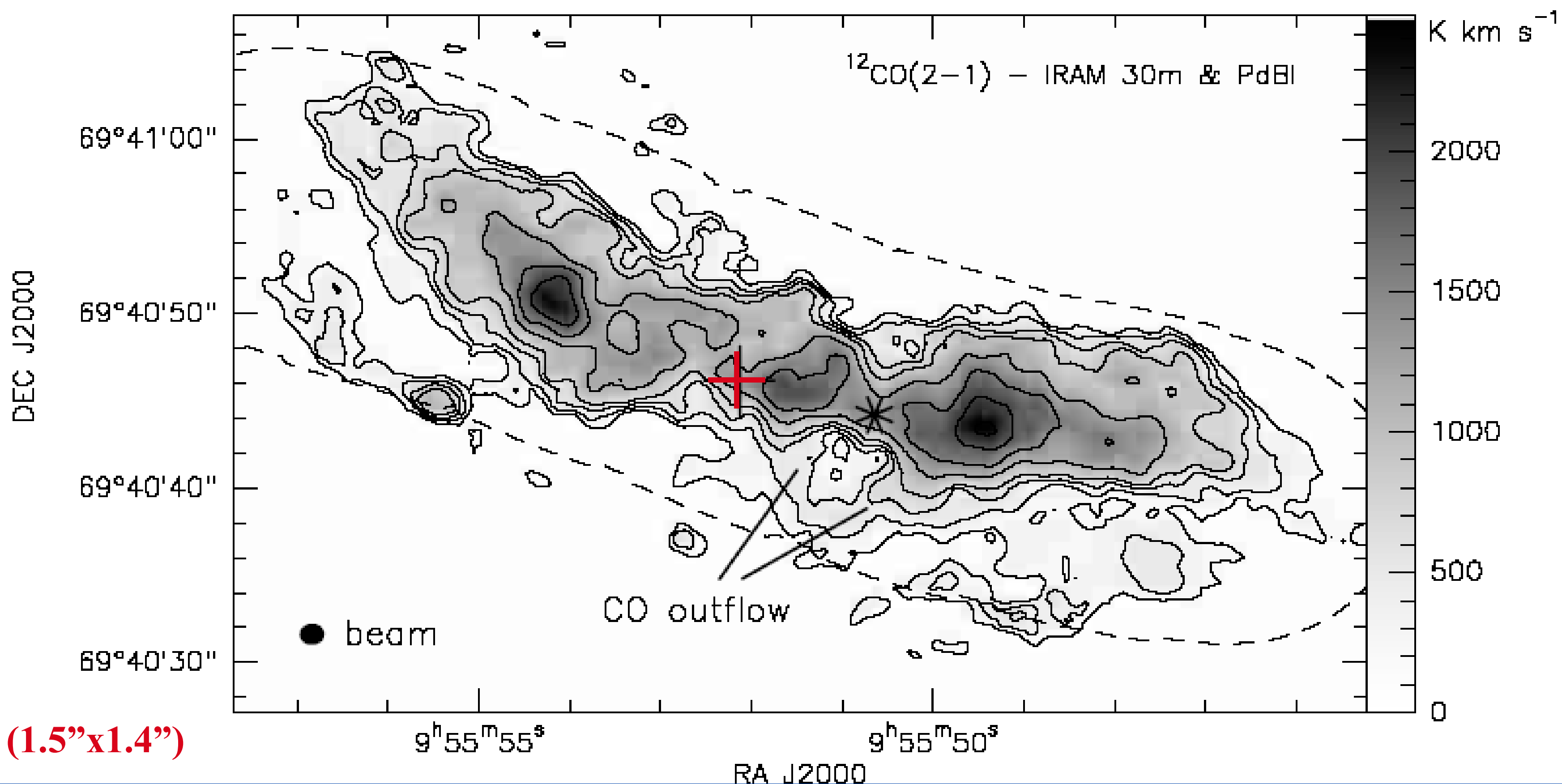
➔ From velocities, the gas is out flowing through cone into the halo

➔ Enrichment of the IGM

Walter et al. (2002)

M82

CO (2-1) PdB+ 30-m



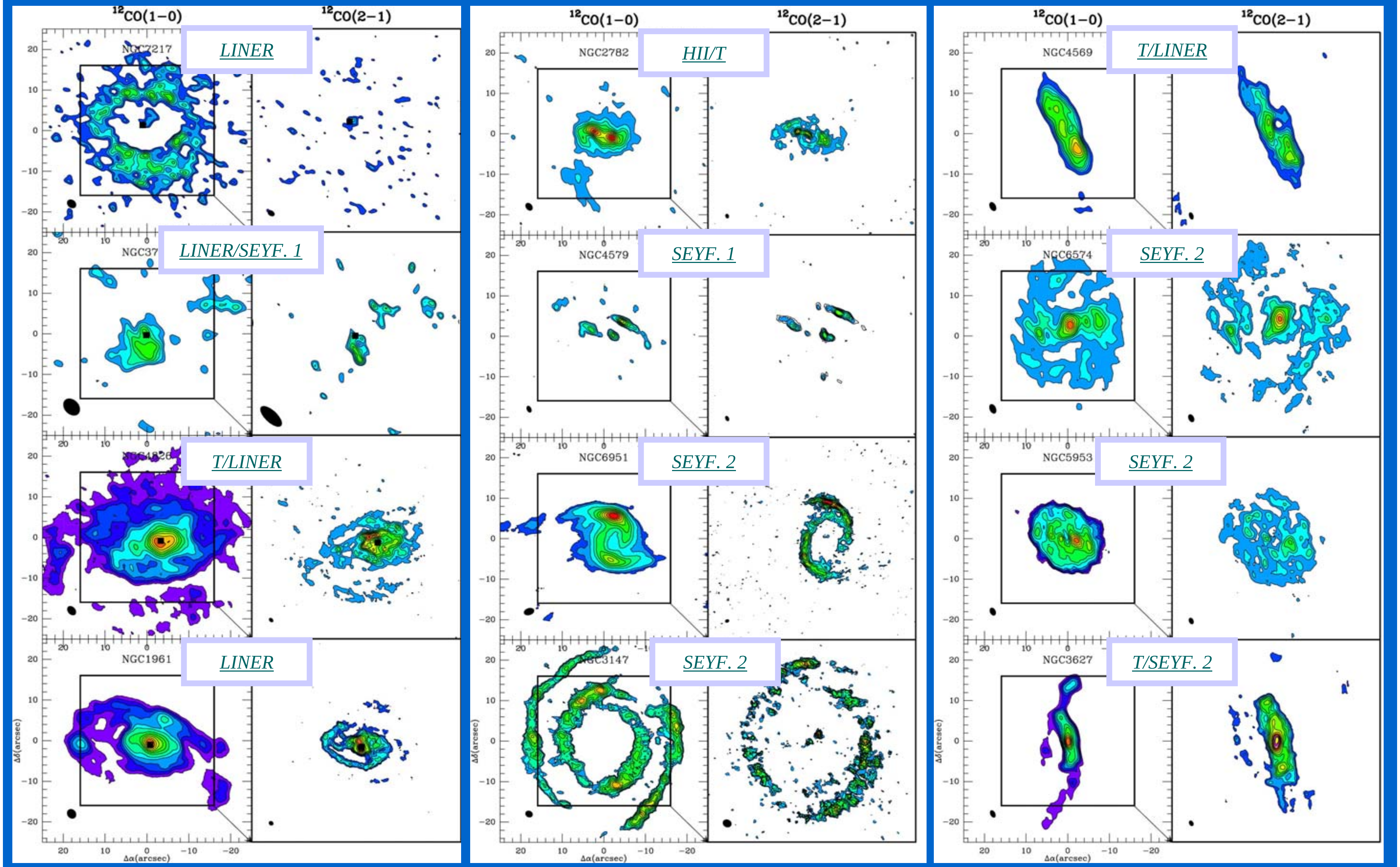
(1.5"x1.4")

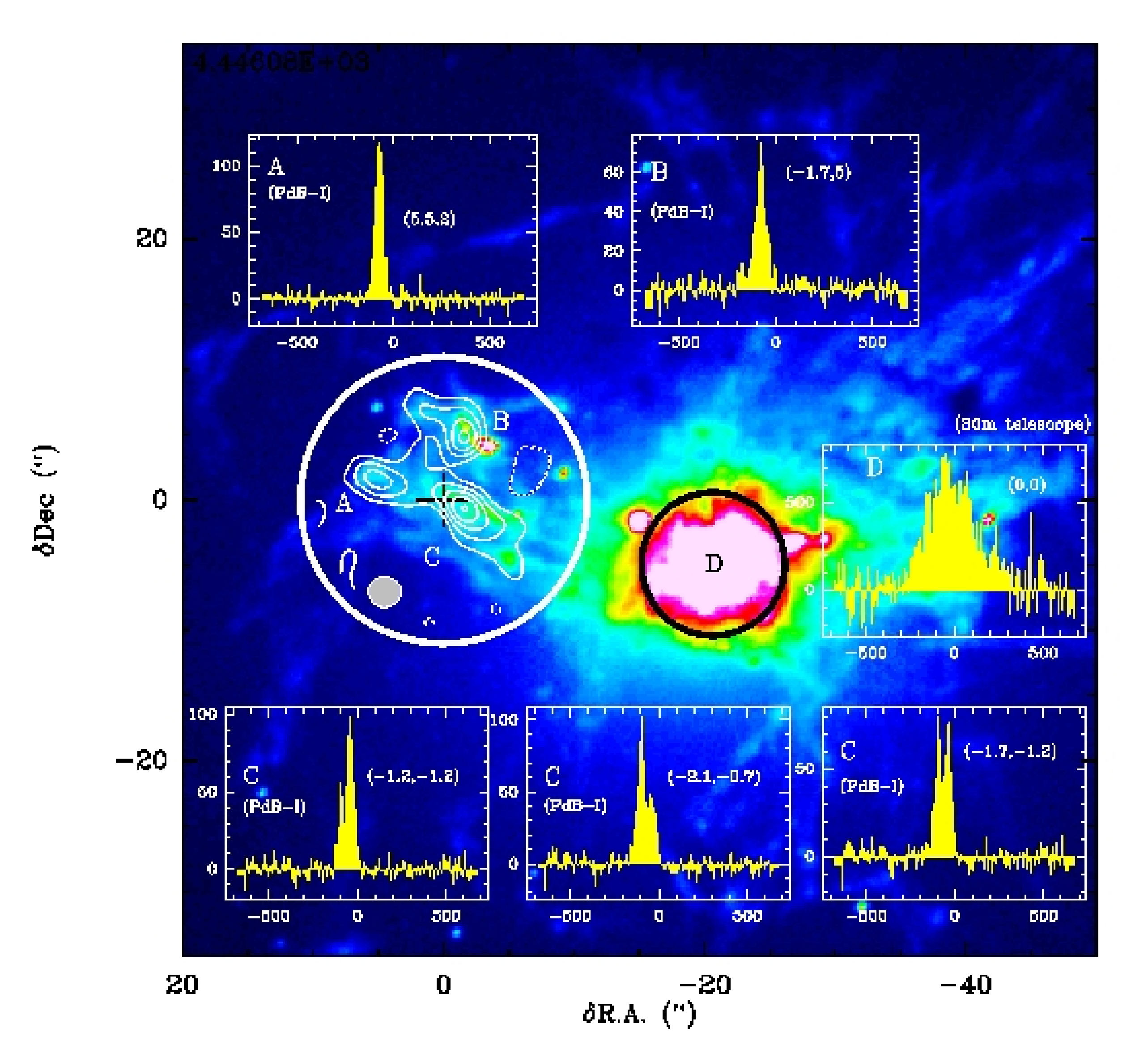
The dynamical center of the molecular gas coincides wuth the 2.2 microns nucleus

Weiss et al. (2001)

Nuclear Gas Dynamics

The NuGa View





Detection of CO(2-1) emission in the Halpha filaments surrounding the galaxy NGC1275

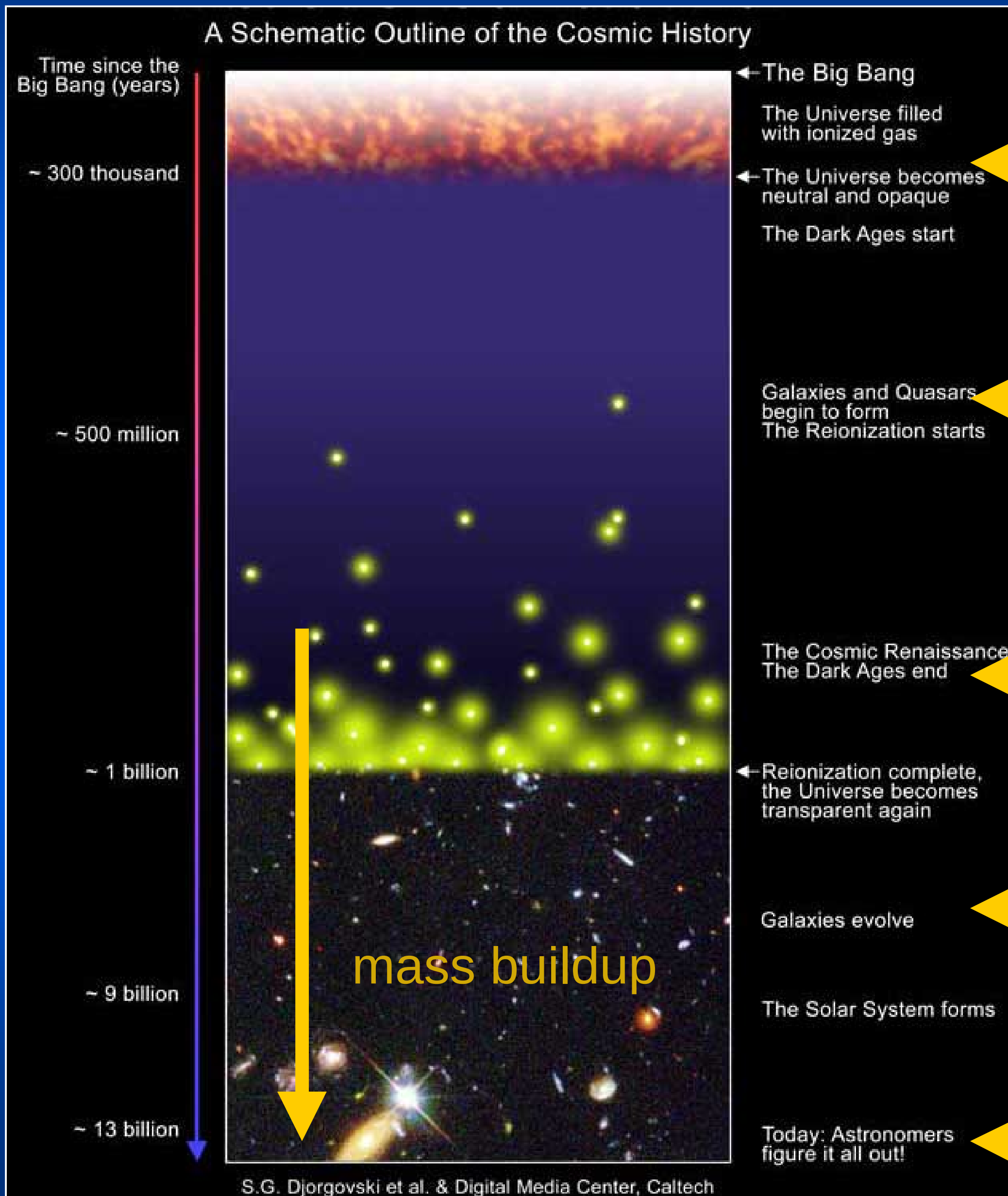
➔Cold molecular clouds that may fall back in the gravitational potential well of the galaxy

➔Positive feedback scenario

➔Recent detection of CO as far as 50 kpc from the galactic center

Salome et al. 2008

History of the Universe



Recombination (z~1000)

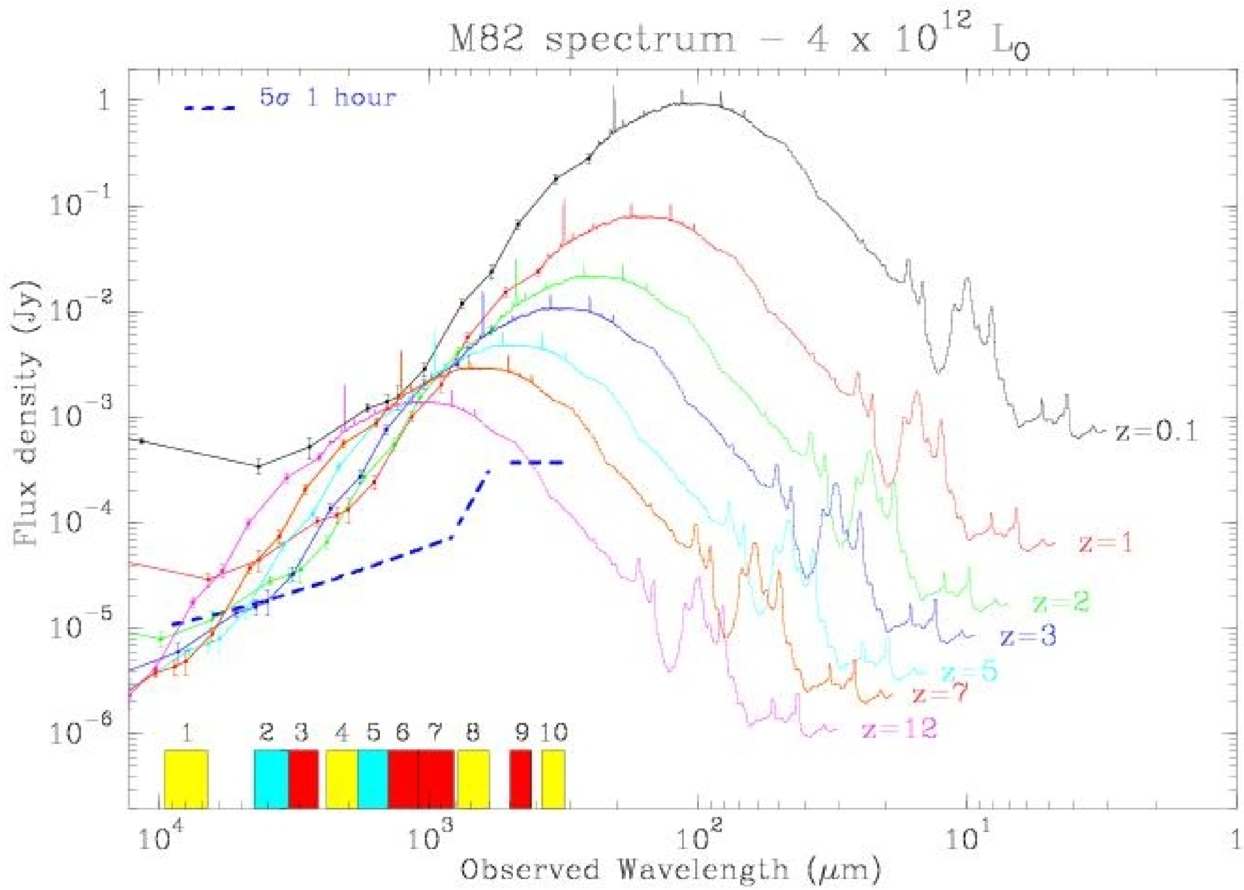
Cosmic ‘Dark Ages’ - no stars/quasars

Epoch of re-ionization (6<z<20)

Peak of activity QSOs & submm galaxies (z~2.5)

Galaxies today

Inverse K-correction



The Galaxy Cluster A 1835

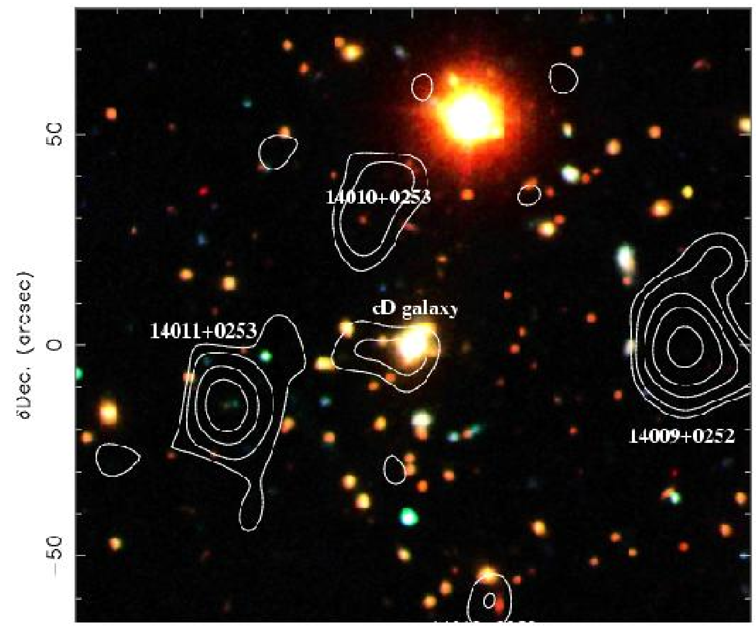
SCUBA image at 850 microns superimposed on an optical image.

Complementary information on the cluster:
The submm sources are weak in the optical and vice versa.

- ~300 Deep submm field sources known

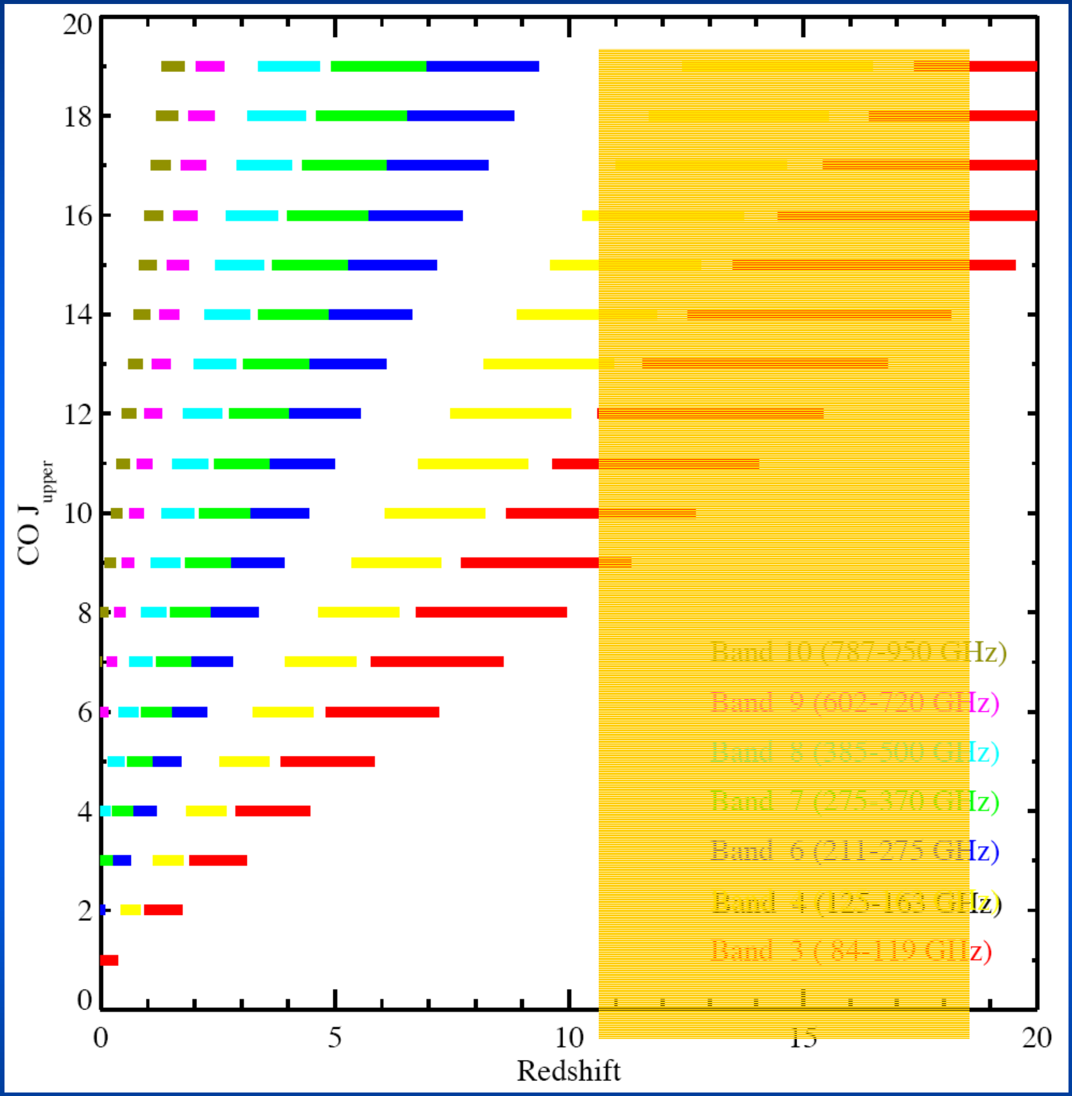
- Difficult redshift determinations

Amplification



Ivison et al. (2000)

CO discovery space

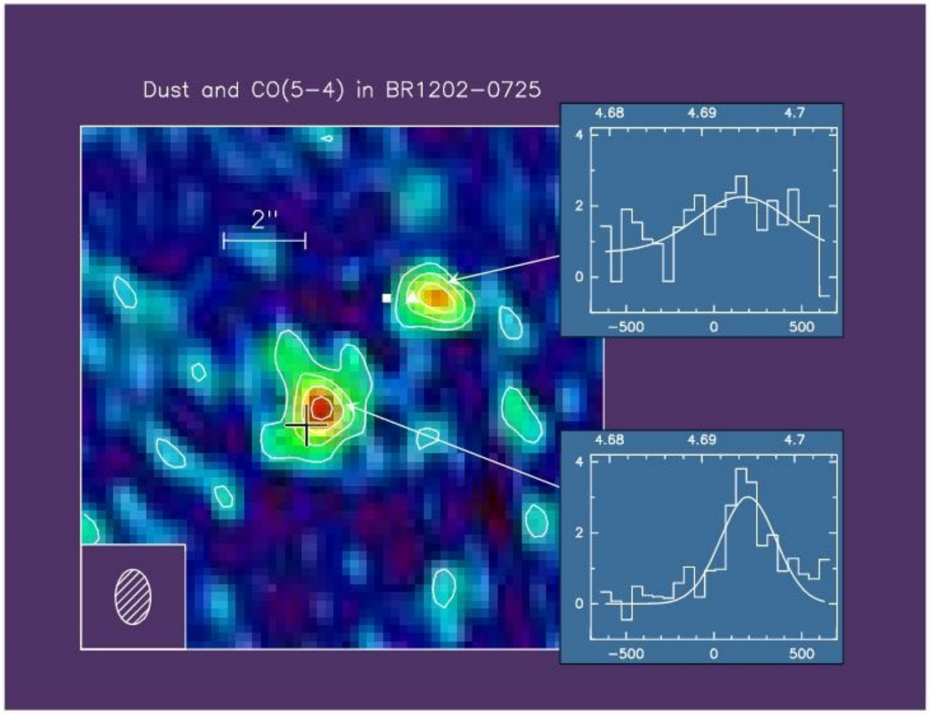


For *z*~10, need to observe CO transitions J>8

Is gas actually excited?

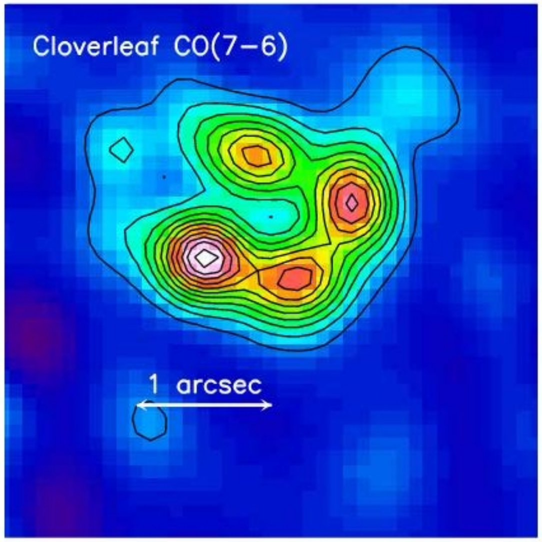
The two next detections of CO at high redshift

BR1202-0725 at z=4.69



Omont et al. (1996)

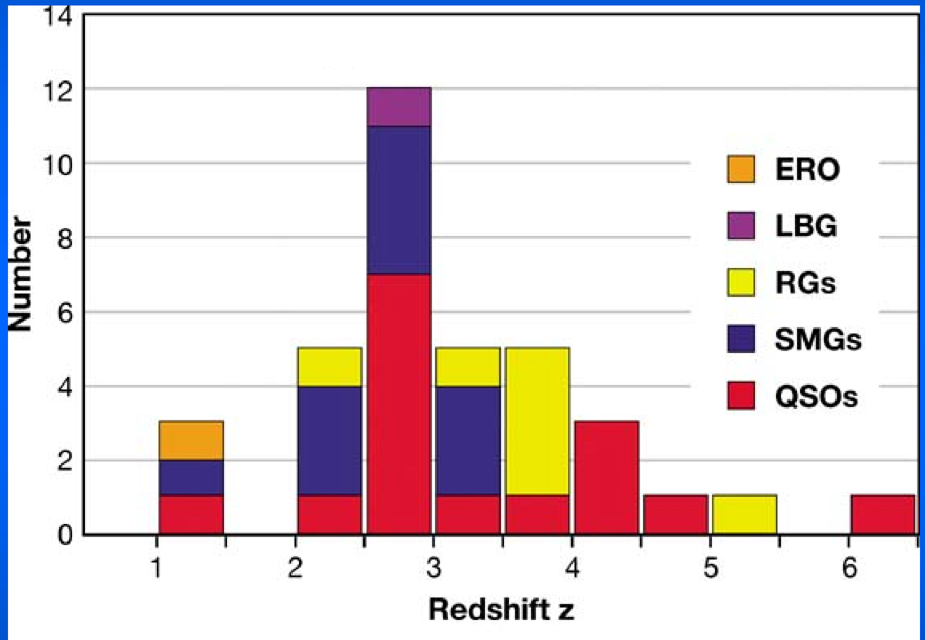
Cloverleaf at z=2.6



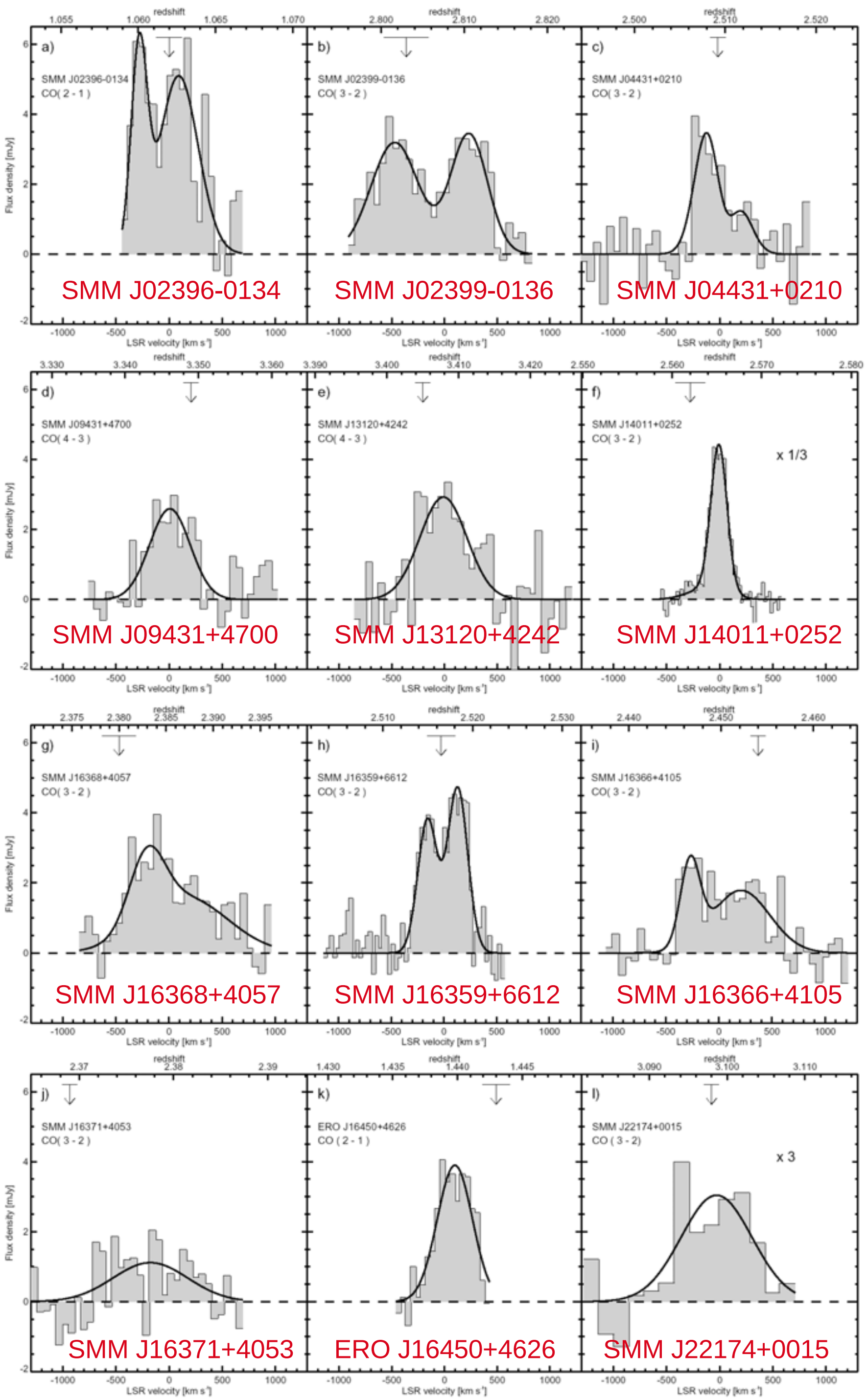
Alloin et al. (1997)

Distribution in redshift of high-z sources

Despite the large selection effects of the flux-limited sample, the distribution Reflects the current understanding of the star formation history in the Universe



Solomon, PM and Vanden Bout, PA . 2005
Annu. Rev. Astron. Astrophys. 43: 677–725



CO Survey of sub/mm Galaxies (SMG)

- **18** radio-detected submm galaxies with known optical/near-IR redshift detected in CO (sep. 2007)
- 1<z<3.5
- Variety of profiles: 780+-230 km/s
- Mergers/Rotating Disks
- Star Formation Rate: 720 $\mathbf{M}_{\mathbf{sun/yr}}$
- $M_{H2} \sim 3 \times 10^{10}\ M_{sun}$
- $M_{dyn} \sim 10^{11}\ M_{sun}$
- *The submm-population consists of gas rich and massive, composite starbursts/AGN systems, which are going a major burst of star formation (i.e. 10^8 yr) and evolving in m*-galaxies*

(Greve et al. 2005; Neri et al. 2004)

Resolving z>4 CO Emission

Paving the Road for ALMA

Ultimate goal:resolve CO emission spatially/kinematically

⇒ Dynamical masses, host galaxy sizes, disk galaxies vs. mergers

⇒ compare to optical/NIR: evolution (?) of M_{BH}-σ relation

critical scale: 1 kpc = 0.15" @z=4-6

M_{BH}	black hole
M_{bulge}	stars
M_{gas}	gas
M_{dyn}	dynamical mass

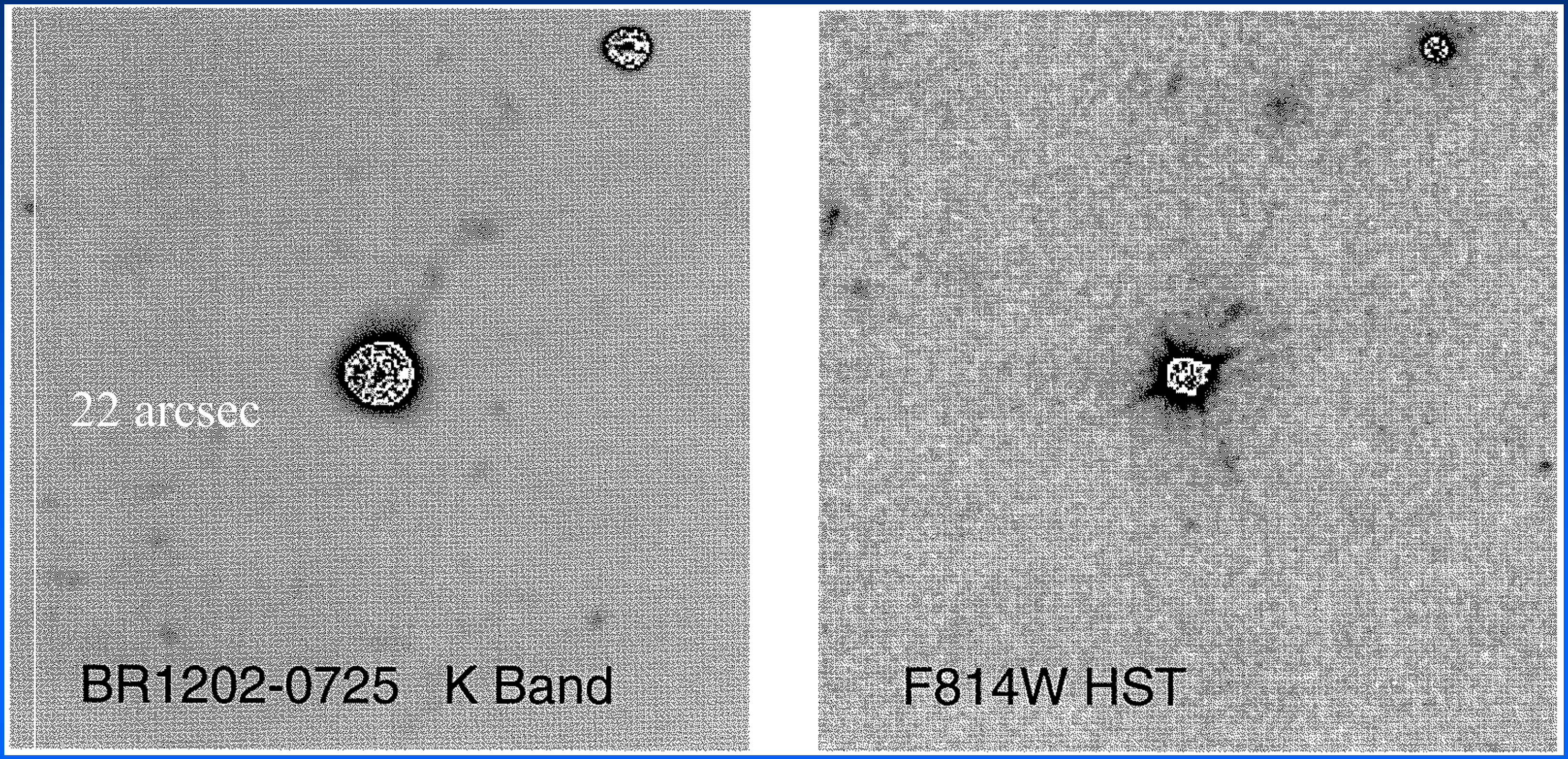
Only VLA / IRAM can observe CO in z>4 QSOs at 0.15"-0.3"/1-2 kpc resolution (B array, 10 km; A array, 800 m)

⇒We don't need ALMA for (all of) this!

Caveat: needs 50-80 hours per source (VLA) – only one/two track at PdBI

& the best weather conditions

BR1202-0725 at z=4.69



Comparison of K-band image (left panel) of the region near the quasar BR 1202−0725 with the HST F814W ("wide I," right panel) image, showing the extension in continuum light to the northwest in both images.

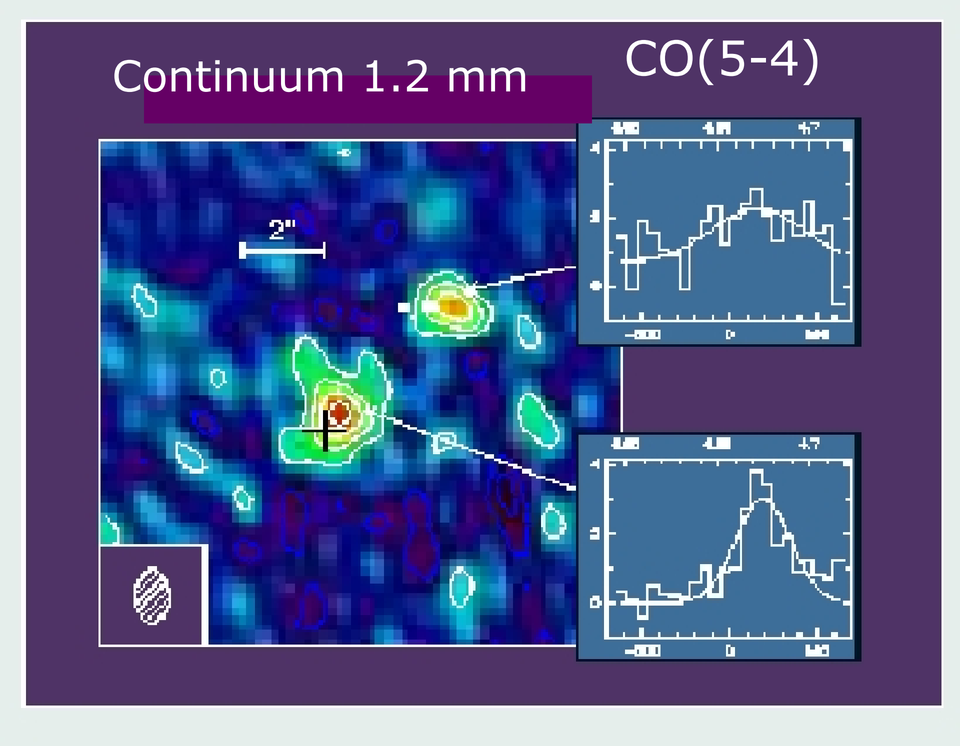
Evidence for star-forming activity from Ly_{alpha} line emission (~1100 km/s)

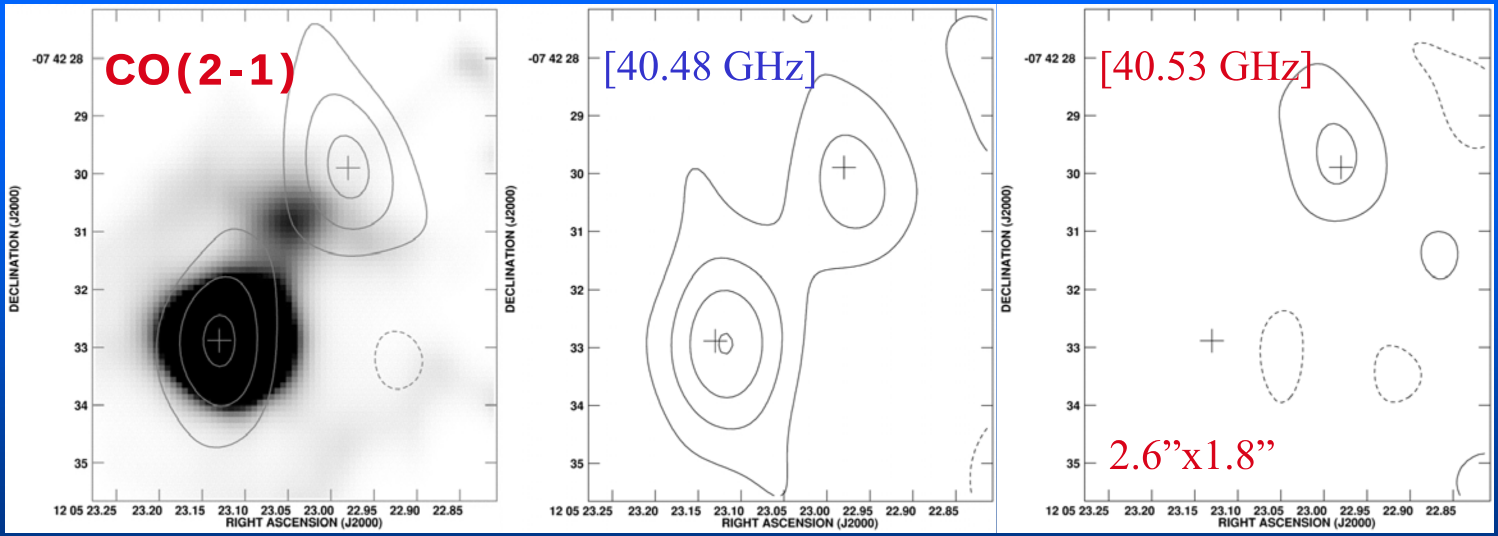
Super-wind activity expelling material in the halo region

Hu et al.1996

Two sources in CO & dust emission
Southern source - 65% of total

Amplification or Merger?

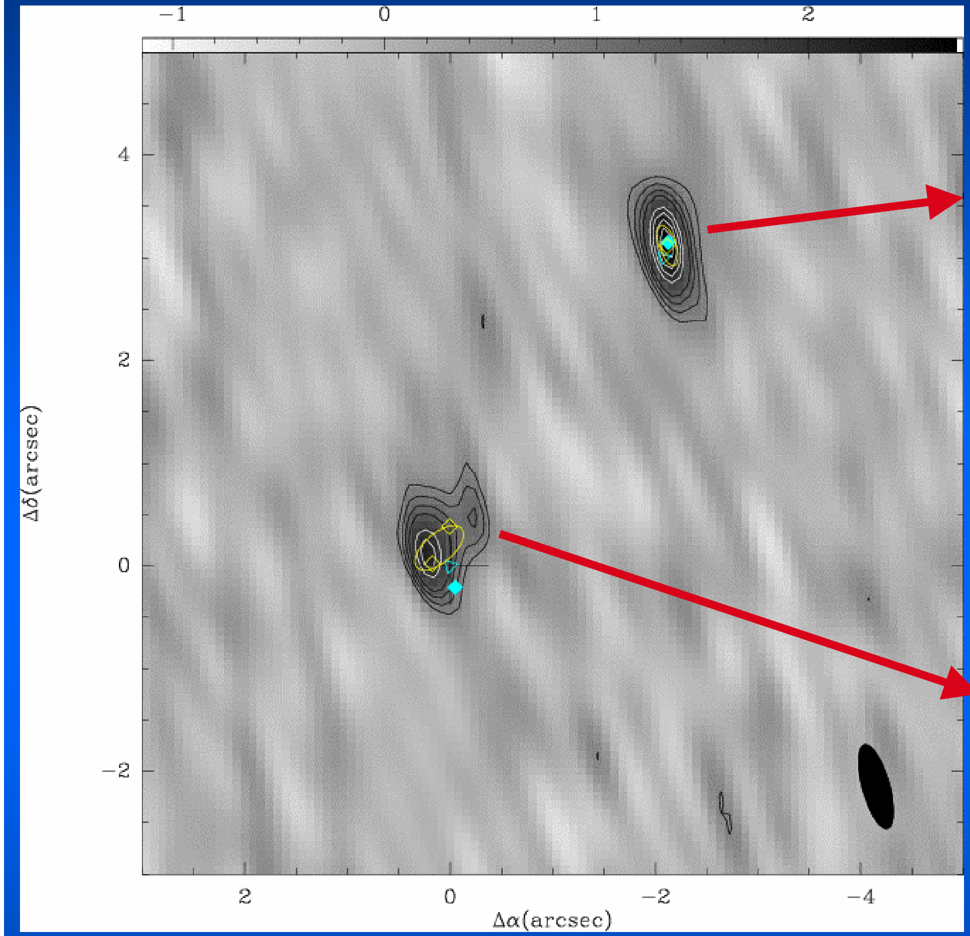


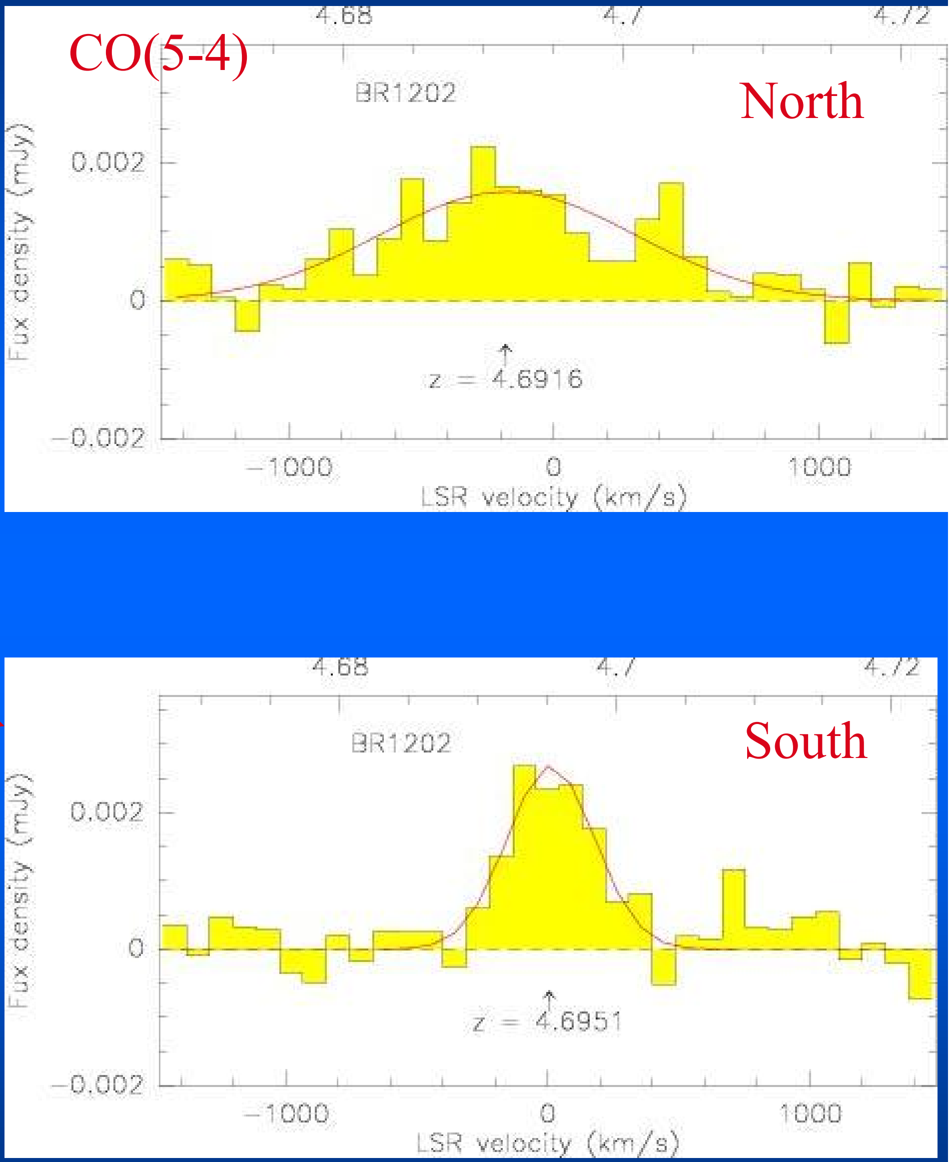


Omont et al. 1996

Carilli et al. 2002

BR1202-0725 at z=4.69 - *First Mergers*

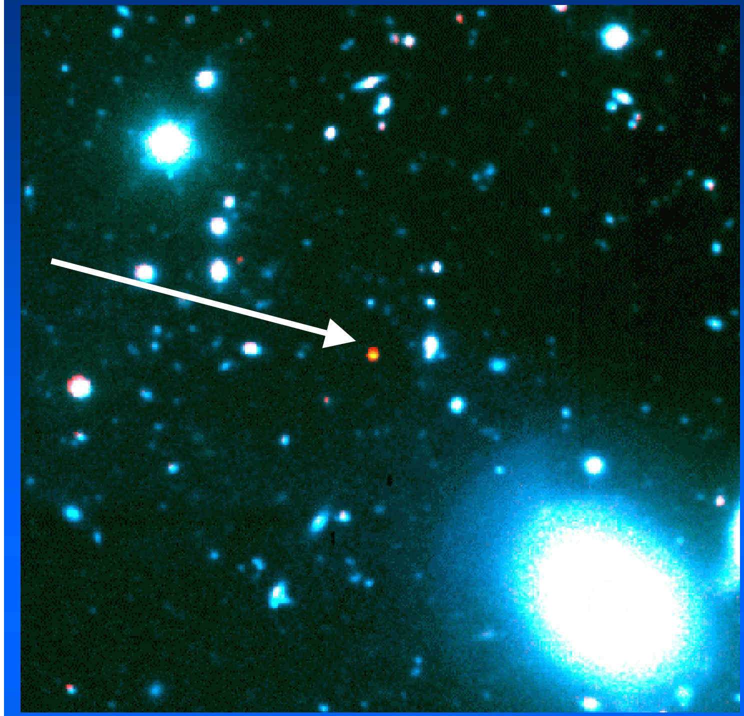




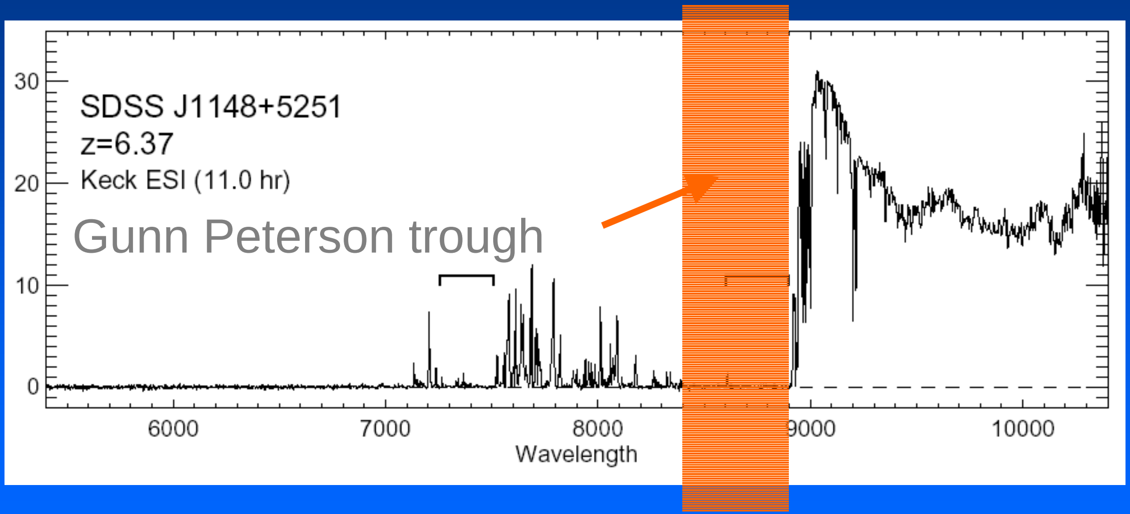
r.m.s 0.3 mJy/beam

Beam 1.7" x 0.6 "

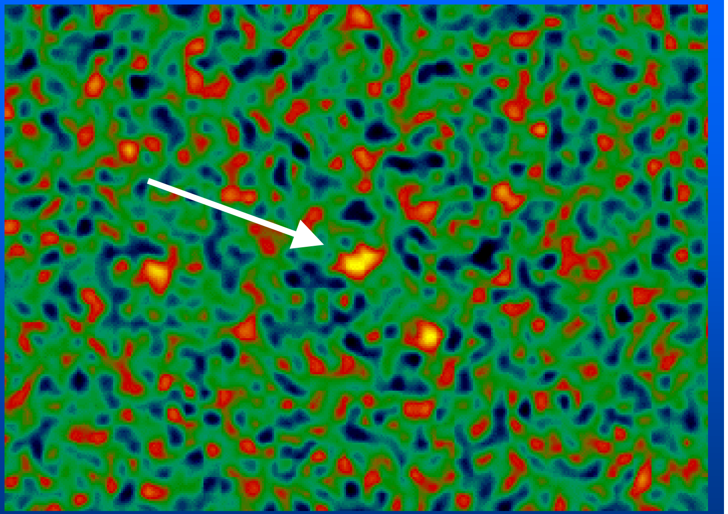
J1148+5251 - The Most Distant QSO at z=6.42



z-band (Keck – Djorgovski et al.)

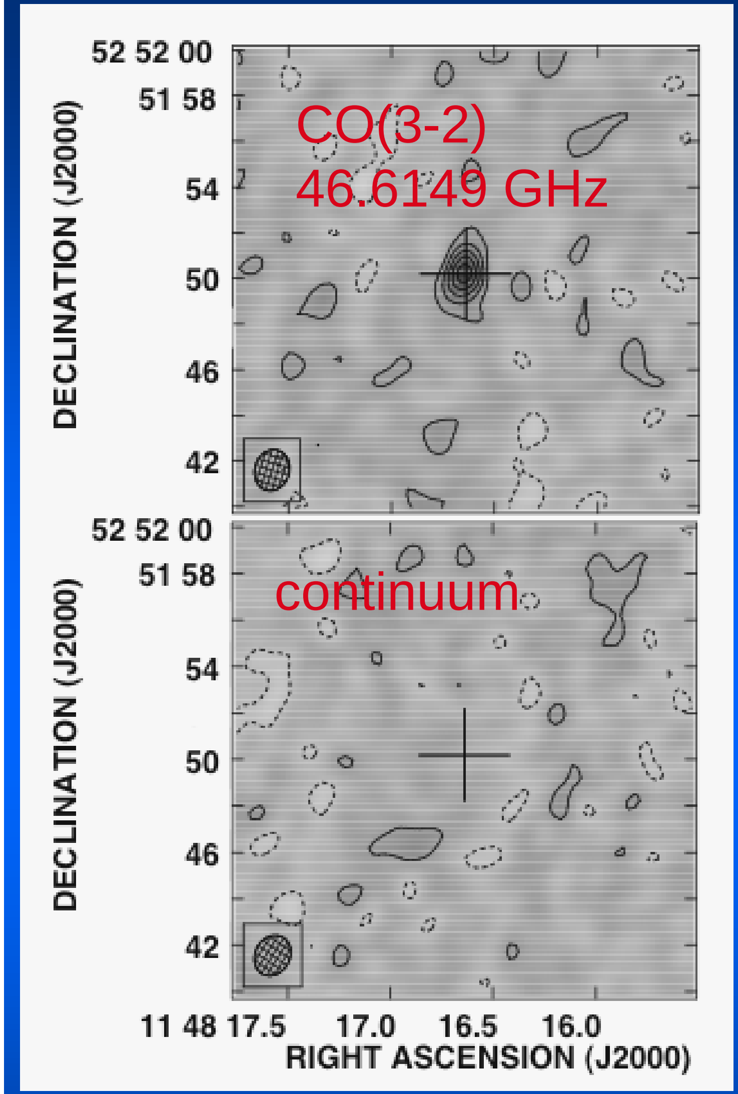


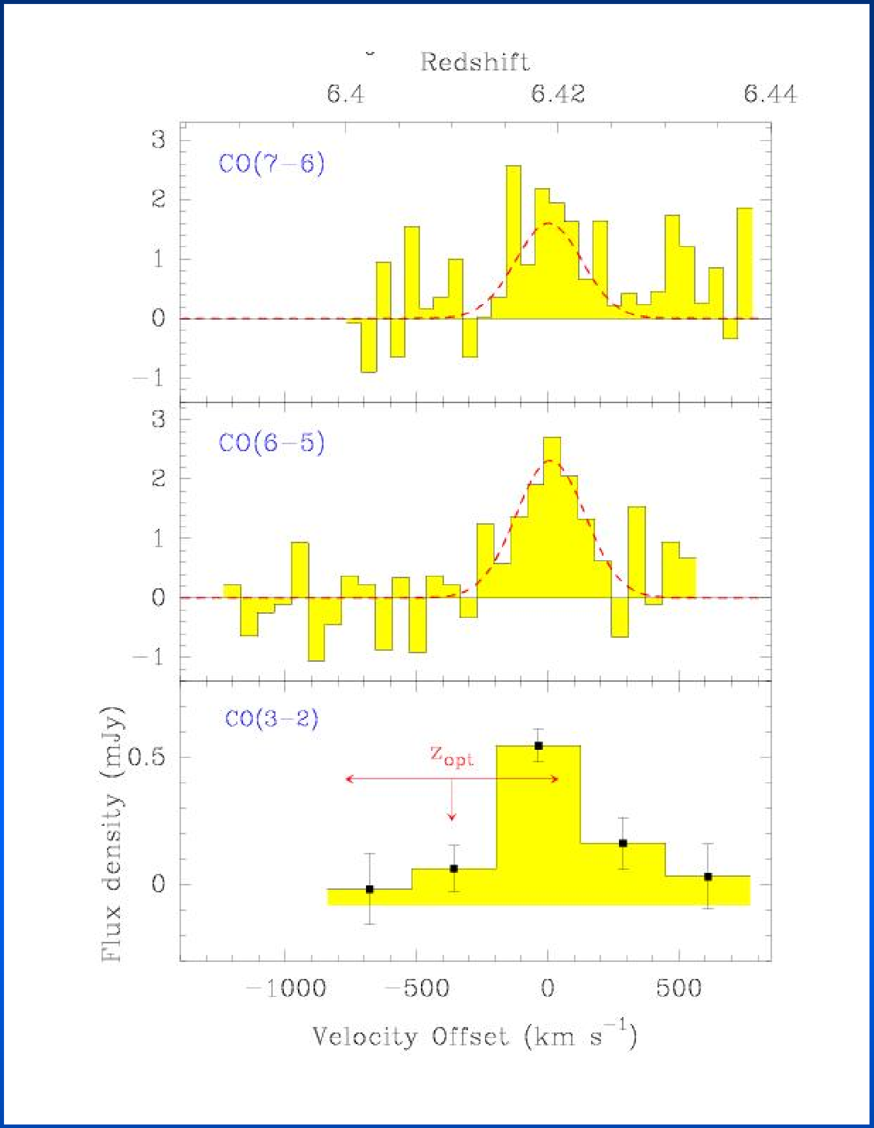
Fan et al. 2003; White et al. 2003



Dust continuum at 1.2 mm

- **z=6.42; age~870 Myr**
- **one of the first luminous sources**
- **M_{BH} ~ 1-5 x 10^9 M_{sun} (Willot et al. 2003)**
- **M_{dust} ~ 10^8 M_{sun} (Bertoldi et al. 2003)**





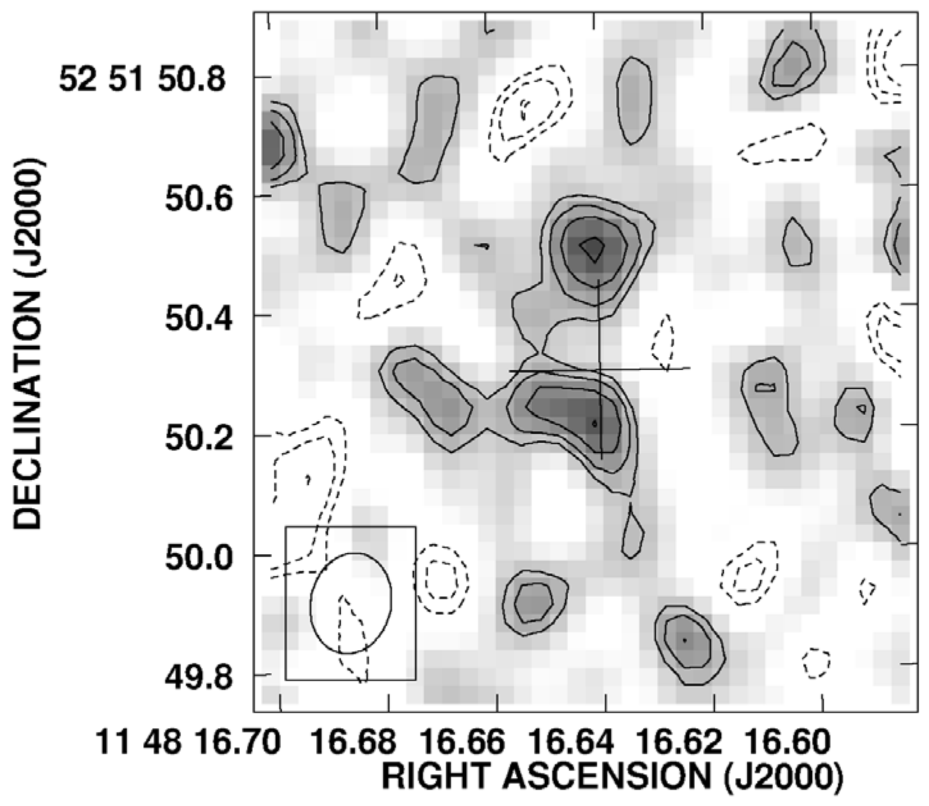
PdBI

VLA

Walter et al. 2003
Bertoldi et al. 2003

Resolving the CO emission in J1148+5251

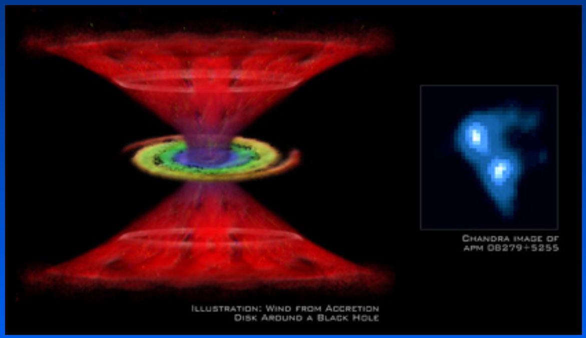
VLA A+B + C array; res.: 0.15” (~1 kpc)

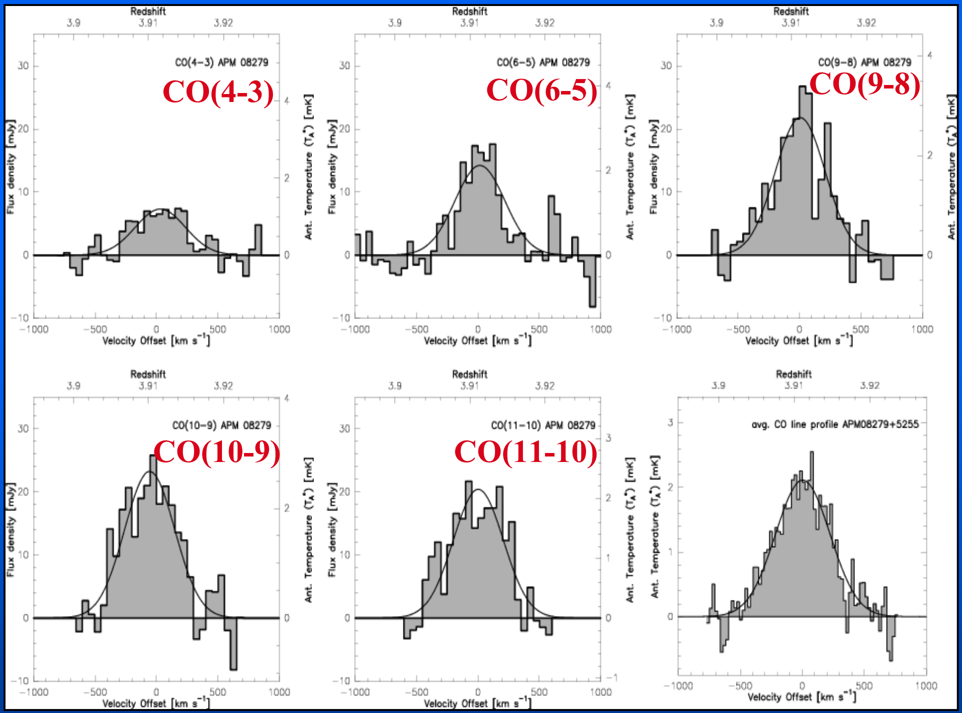


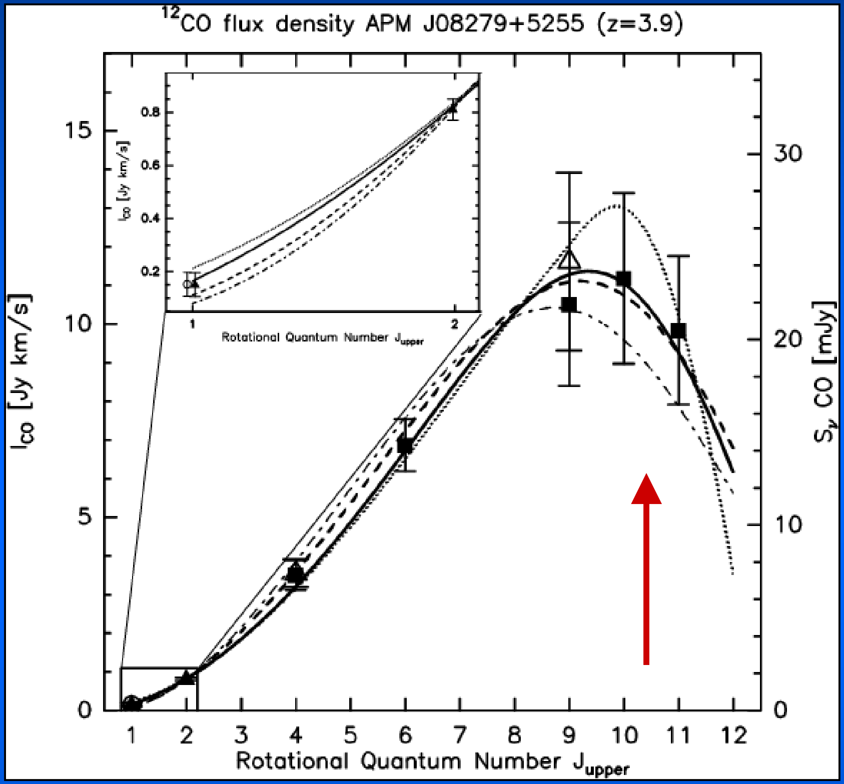
Walter et al. (2004)

- Two sources separated by 0.3” (1.7 kpc at z=6.4) containing each 5 x 10^9 M_{sun}
- Not likely to be amplified
- If gravitationally bound,
  M_{Dyn}=4.5x10^{10} M_{sun}

APM 08279+5255 (z=3.9)







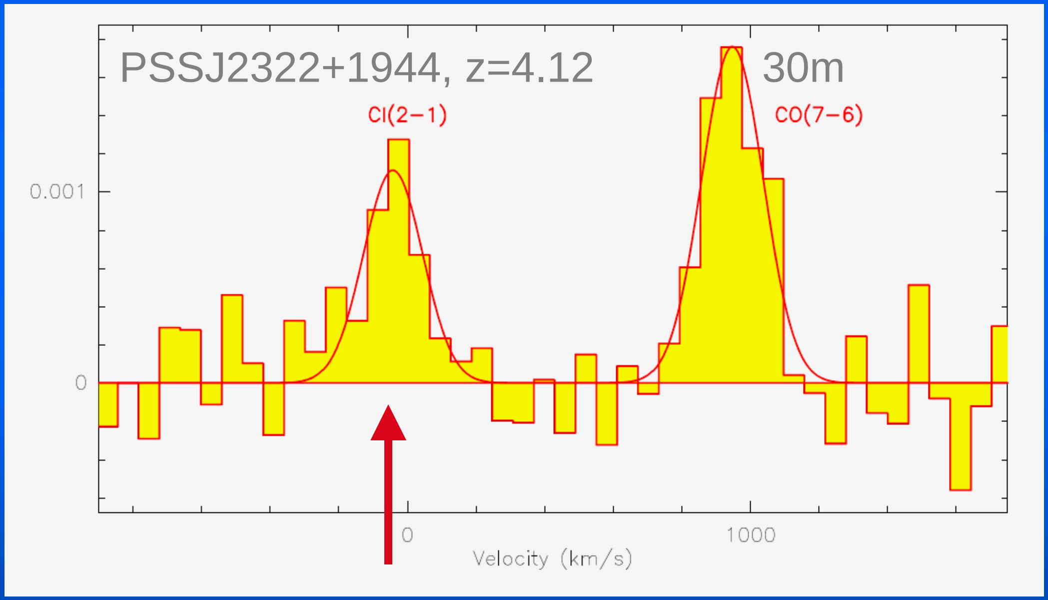
Very warm gas - peaks at CO(10-9)
220 K inner (65-100 pc) disk
65 K outer (150-300 pc) disk
$\sim 10^4 - 10^5$ cm^{-3}

Weiss et al. 2007

Other lines: Atomic Carbon (CI)

CI lines detected in Cloverleaf, F10214, SMM14011, PSS2322

- typically fainter than CO by a factor of few *[e.g., Weiss 2003, 2004, Pety 2004]*



1GHz BW @ 2mm

➔ **Imporant for follow-up, but not line of choice for search**

[CII] detected at z=6.4

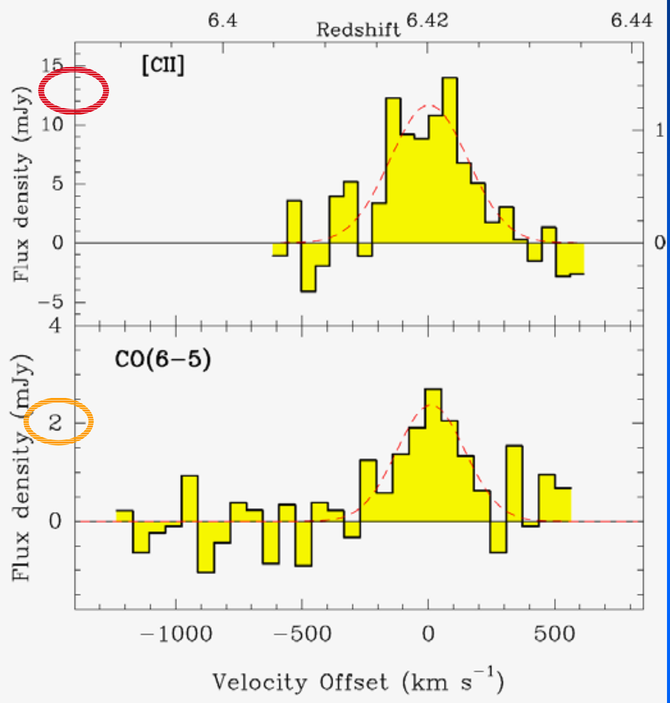
J1148+5251 (z=6.42)

Maiolino, Cox et al. 2005

$L_{[CII]} = 4.4x10^{9} L_{sun}$

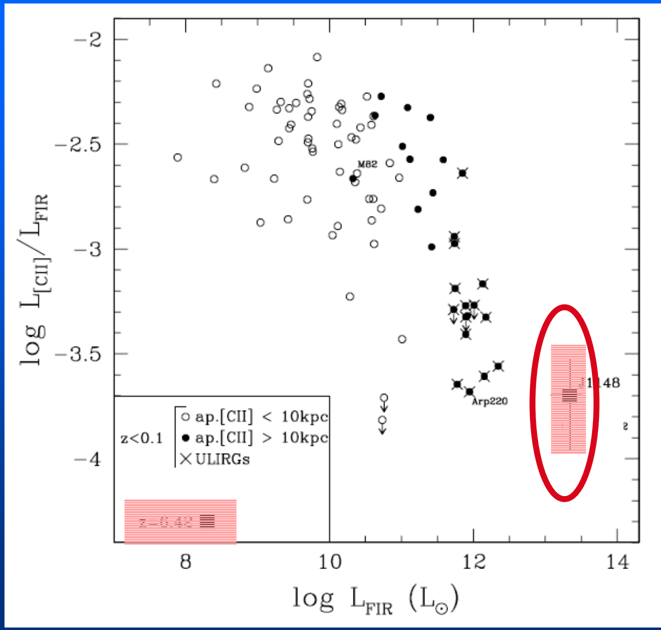
$L_{FIR} = 2x10^{13} L_{sun}$

$L_{[CII]}/L_{FIR} = 2x10^{-4}$



30-meter
36 hours integr.

Note: six times brighter than brightest CO line!



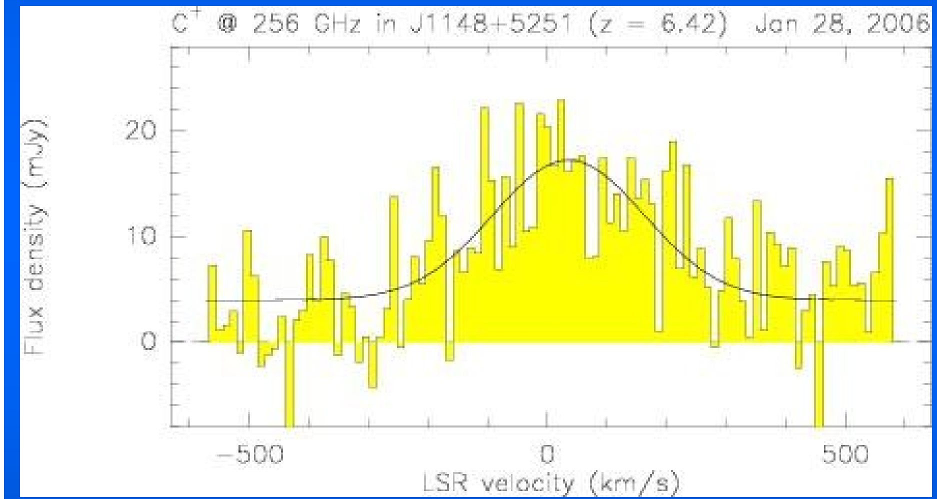
Though 'worst case' still detectable in [CII]

Follow-up to resolve line: PdBI (0.3")

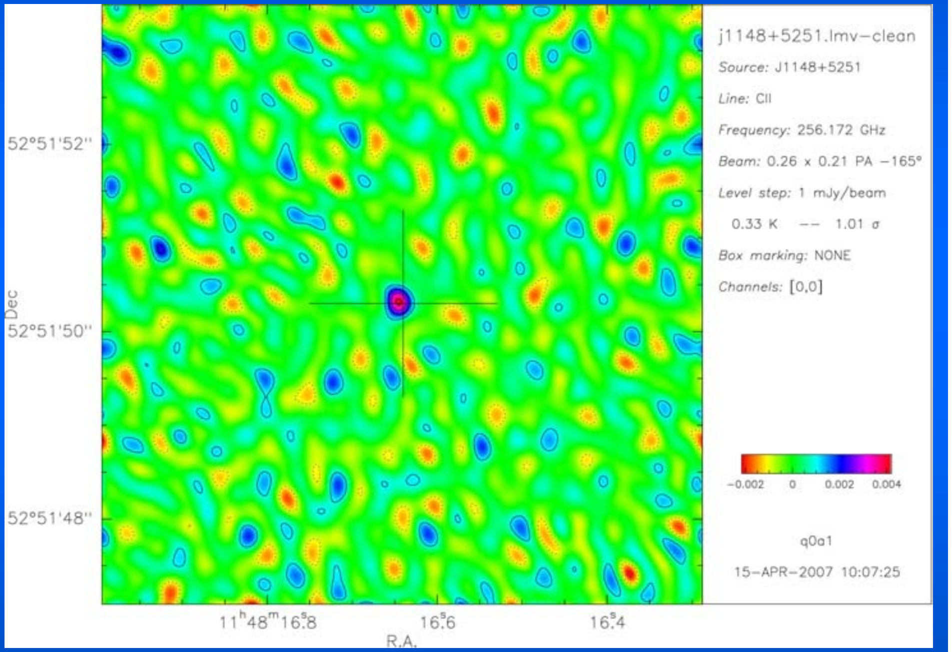
[CII] also detected in B1202 [Iono et al. 06]

Earlier limits on high-z sources: Bolatto et al. 04, Marsden et al. 05, van der Werf 98, …

C^+ at 256.17 GHz in J1148+5251 at z = 6.42 using the Plateau de Bure interferometer



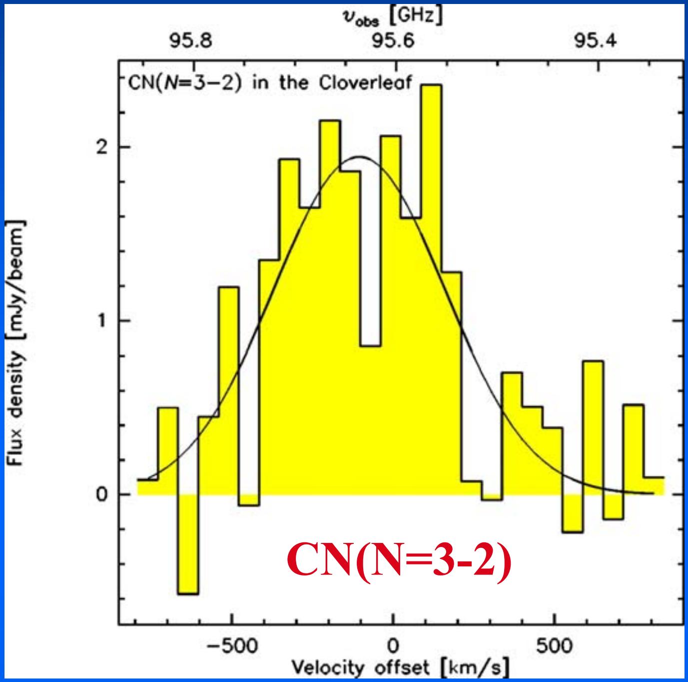
Spectrum: 3.5hrs in D-config



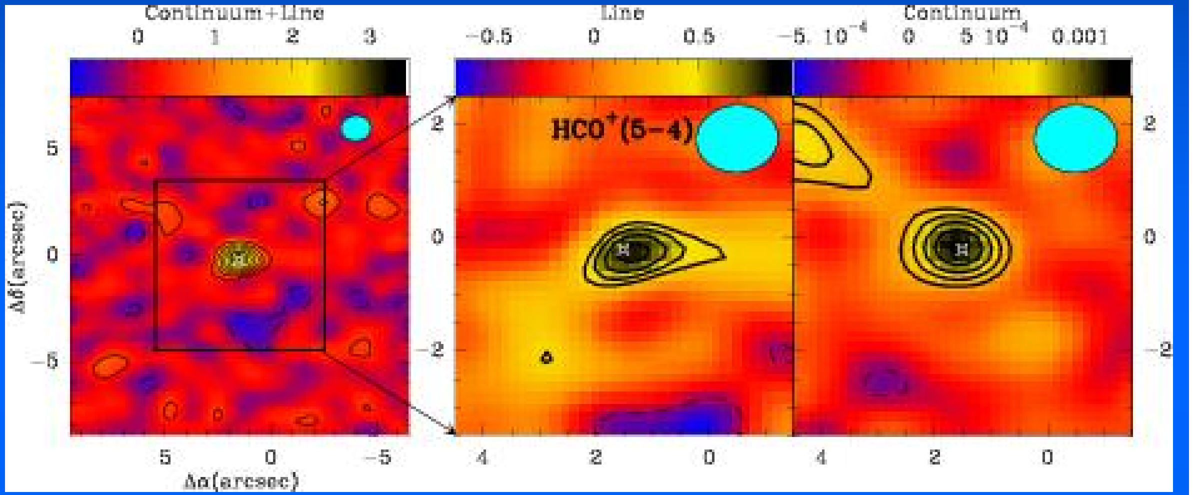
A+ Configuration: beam 0.26" x 0.21"

Walter et al. 2007

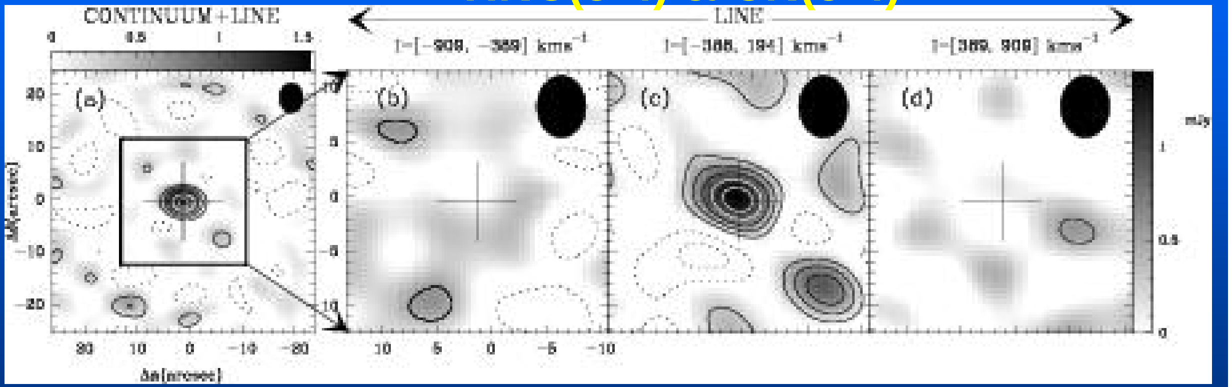
Other High Density Tracers: HNC, CN and HCO^+



HCO^+ (5-4)

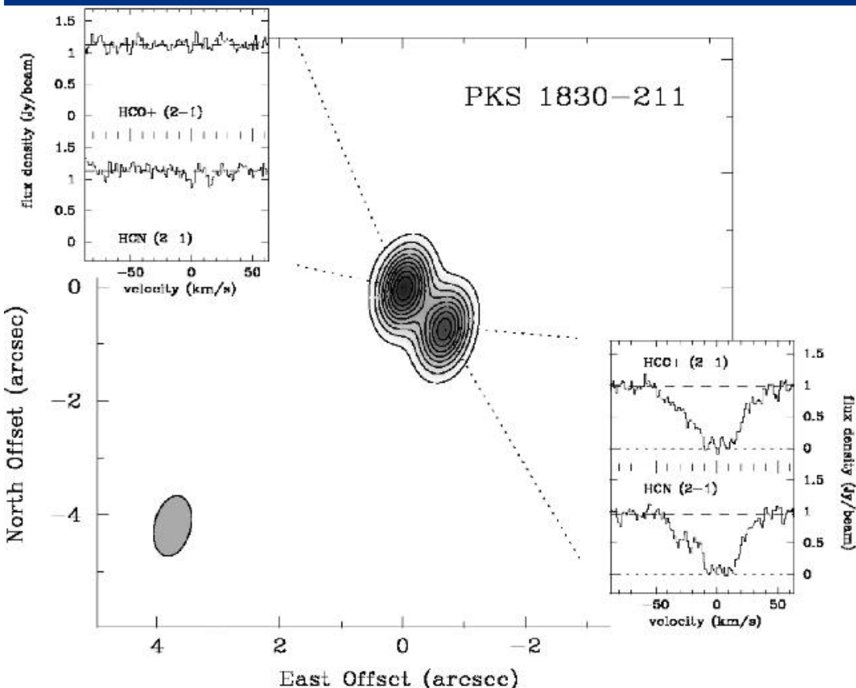


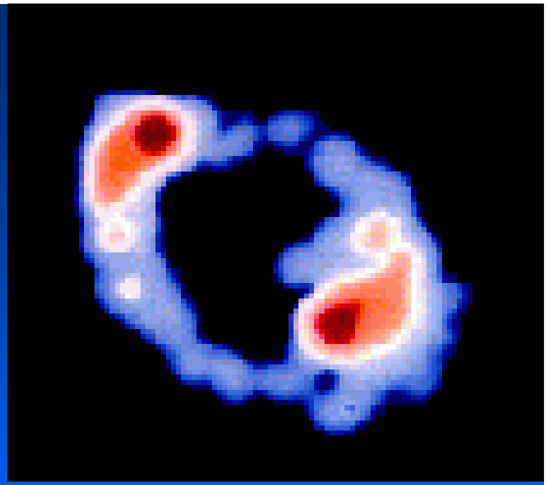
HNC(5-4) & CN(5-4)



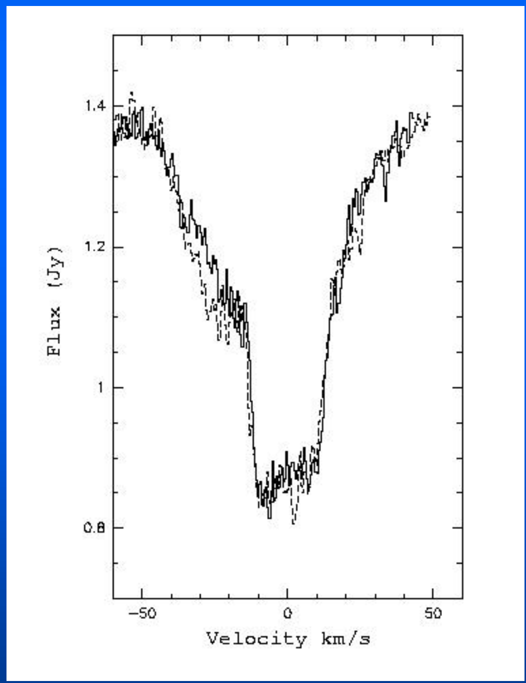
Burillo et al. (2006)
Guelin,Salome et al. (2006)
Riechers et al. (2007)

PKS1830-211 at z=0.88582





Frye et al 97



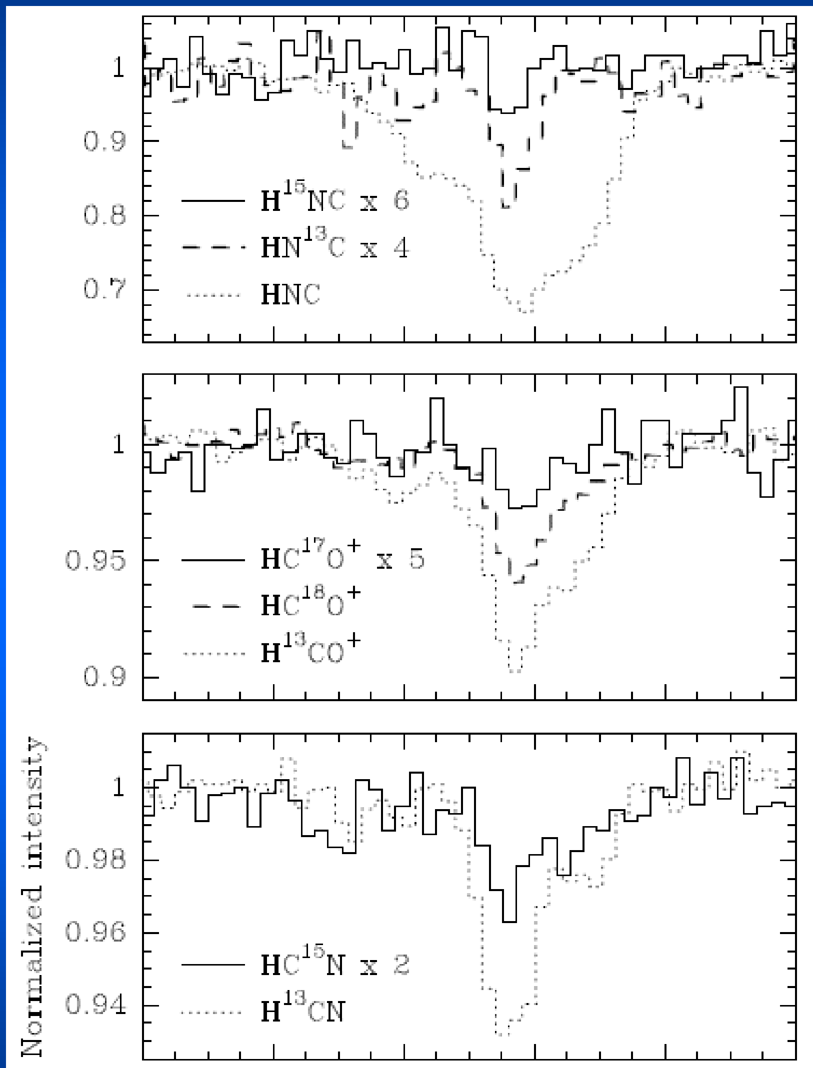
2 components, covering each A or B

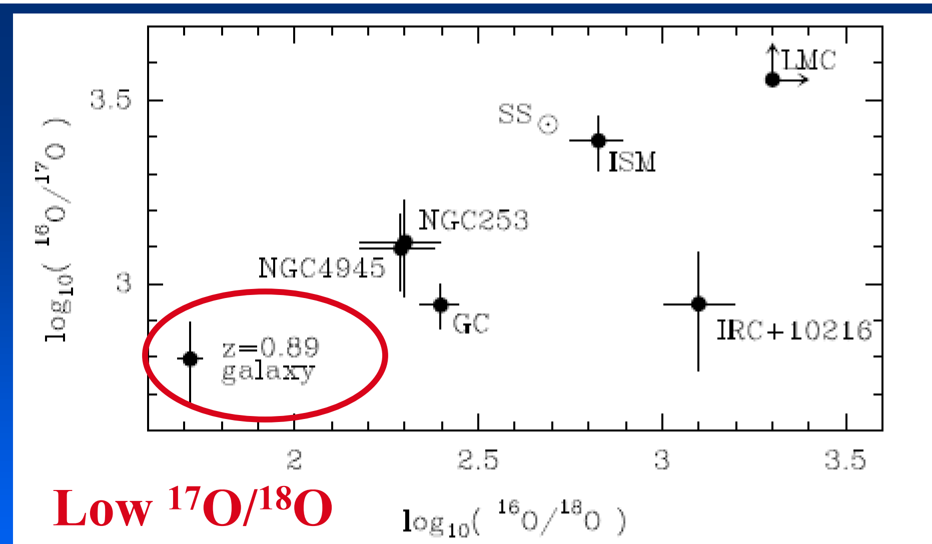
Wiklind & Combes (1998)

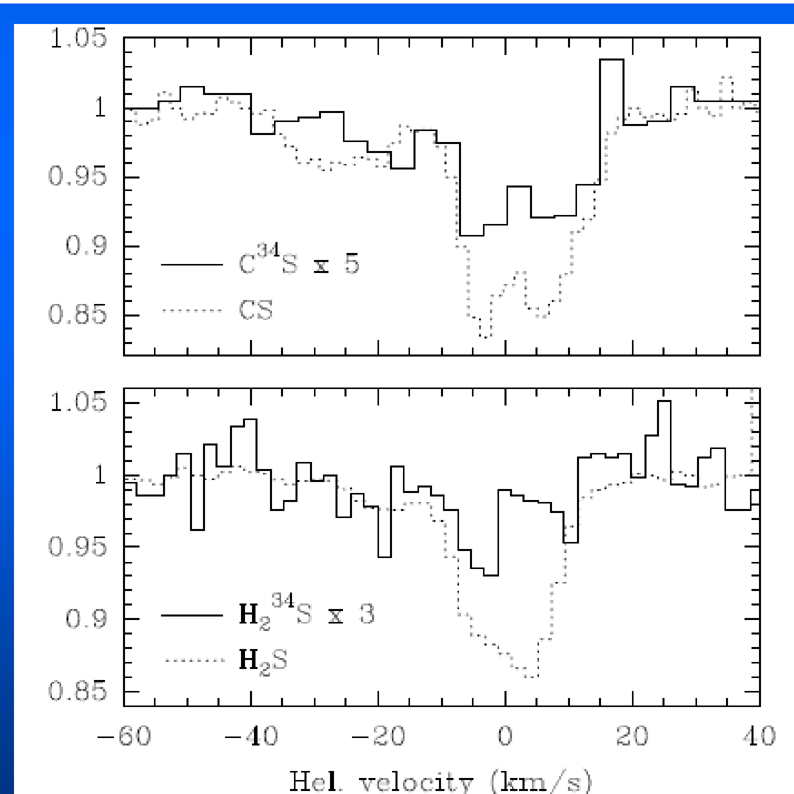
Slight temporal variability

PKS1830-211 - PdB survey

Low $^{14}N/^{15}N$, young stars







Spitzer Space Telescope

Herschel/Planck

APEX

ALMA Early

LMT

CARMA

ALMA

JCMT CSO *SMA*

Plateau de Bure Interferometer

30-meter

2004 2006 2008 2010 2012 2014