Spectral Imaging: HARP and Beyond

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Outline

- HARP
- JCMT Surveys
  - JCMT SLS
- Possible future directions with CCAT

Retooling the JCMT

- SCUBA-2
  - 850/450 μm camera
  - Arrived at JCMT April 2008.
  - Installation starting
  - Commissioning starts June
- HARP
  - 345 GHz heterodyne camera
  - First light 11 Dec 2005
- ACSIS
  - autocorrelation spectrometer

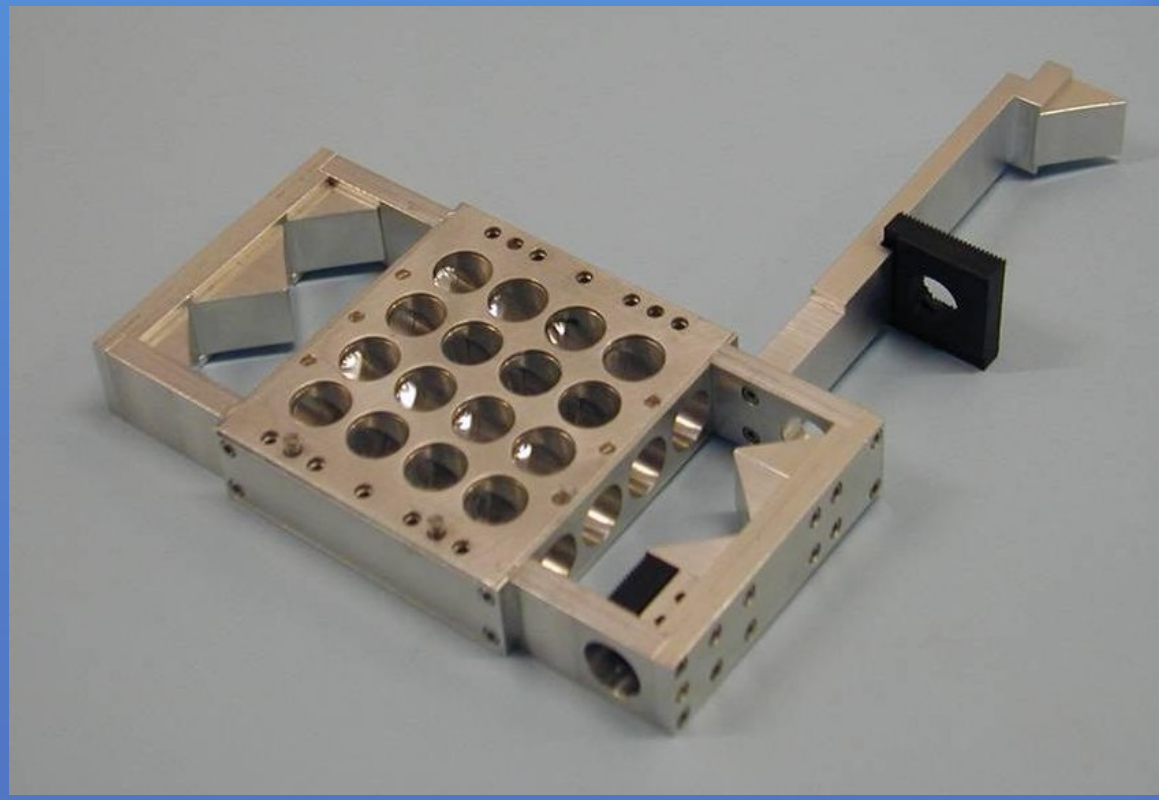
3 April 2008

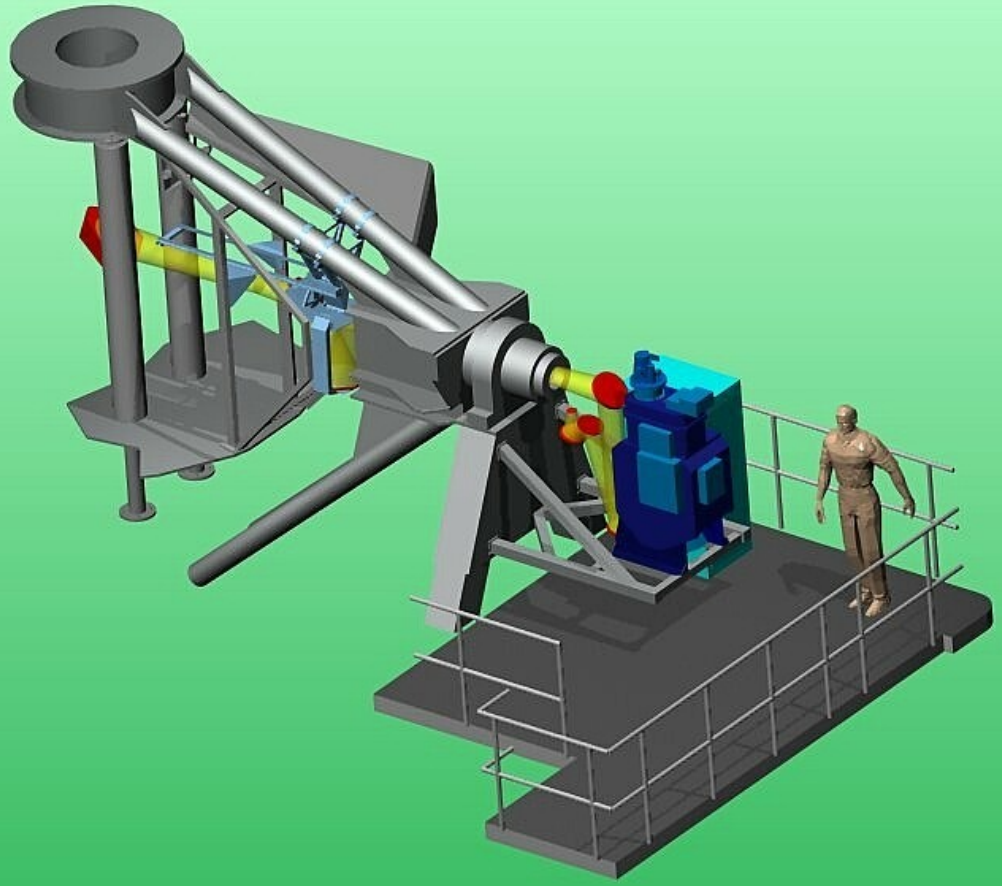
HARP

- 16-pixel (4x4) imaging array: 30 arcsec beam spacing, 15 arcsec beam
- 2 arcmin x 2 arcmin field of view, undersampled by factor of 4 or 5 wrt Nyquist
- 325-375GHz coverage
- Single sideband tuned (via interferometer)
- K-mirror for field rotation
- Tsys:

290	--	340	340
340	330	310	270
282	340	250	260
--	300	290	--

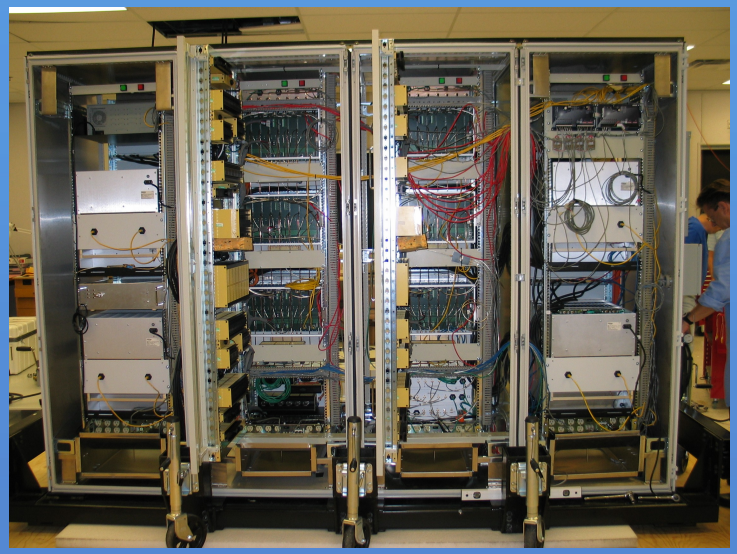
- Mean Tsys 303+/-33 K (345GHz)





ACSIS backend

- 16 IF inputs (actually 32, paired up)
- Nominal bandwidth per channel: 2GHz, in 2x1GHz hybrid configuration
  - Actual BW reduced by 10-20% due to filter roll off: 1.6GHz at least
- Up to 4 spectral windows per IF
  - Highest resol. 0.027 km/s, covering 230 km/s
  - Lowest: 0.87 km/s, 1700 km/s
- Minimum sample time: 50ms
  - Allows fast mapping
- Maximum output map size: 16Gbytes
- Total disc space: 4Tbytes
- Full data reduction and display pipeline
- Programmable data reduction



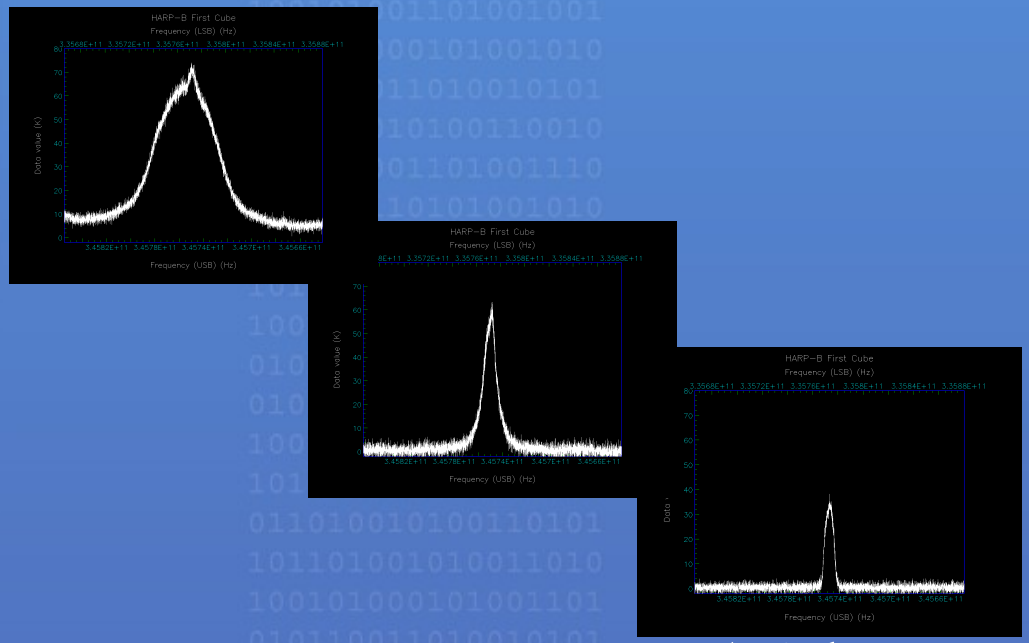
Nominal Bandwidth	Resolution
250MHz	30kHz
500MHz	61kHz
1GHz	500kHz
2GHz	1MHz

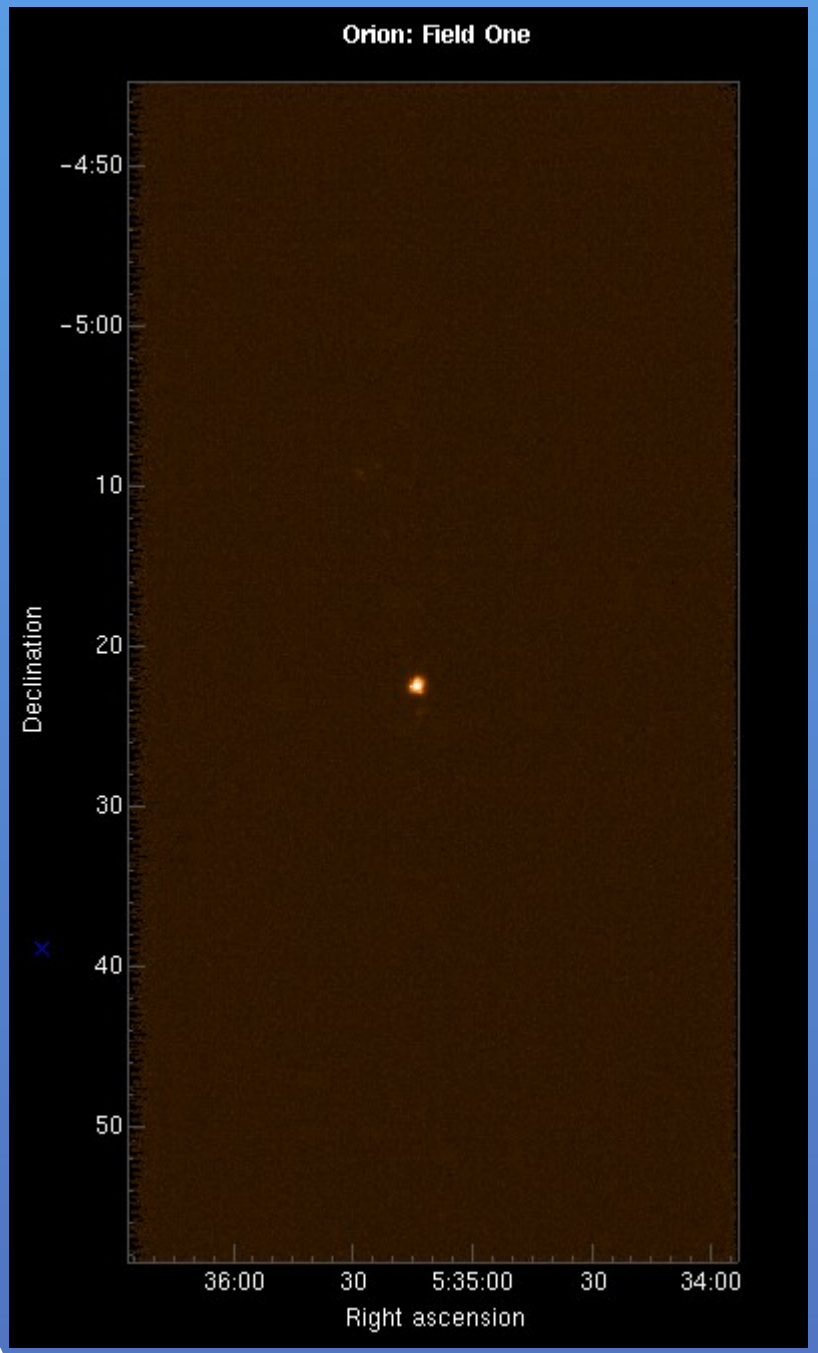
Mapping Modes

- Raster position switch (on the fly PSSW)
  - For large maps, typically of bright objects
  - Telescope is continuously tracked
  - maximum map size: approx 2x2 degrees, Nyquist-sampled
- Jiggle chop (beam-switch)
  - For deep maps of compact objects
  - Secondary mirror fills in missing samples (4x4 pointings, or 5x5)
  - Creates map 120 arcsec square
  - K-mirror for field rotation keeps pixels in fixed grid positions
- Jiggle frequency-switch
  - As above, but uses FSWITCH of >200MHz
  - frequency switching is slower than jiggle rate
- Grid position switch (Grid PSSW)
  - Used for deep observations of small objects

Wide Field Image

- Orion
- CO J=3-2
- ~160,000 spectra
- 30x80 arcmin





(Richer, Buckle)

JCMT Legacy Surveys

- The SCUBA-2 Cosmology Legacy Survey (CLS)
- The SCUBA-2 `All Sky' Survey (SASSy)
- The Debris Disk Survey (DDS)
- The JCMT Galactic Plane Survey (JPS)
- The Nearby Galaxies Survey (NGS)
- The Gould Belt Survey (GBS)
- The Spectral Legacy Survey (SLS)

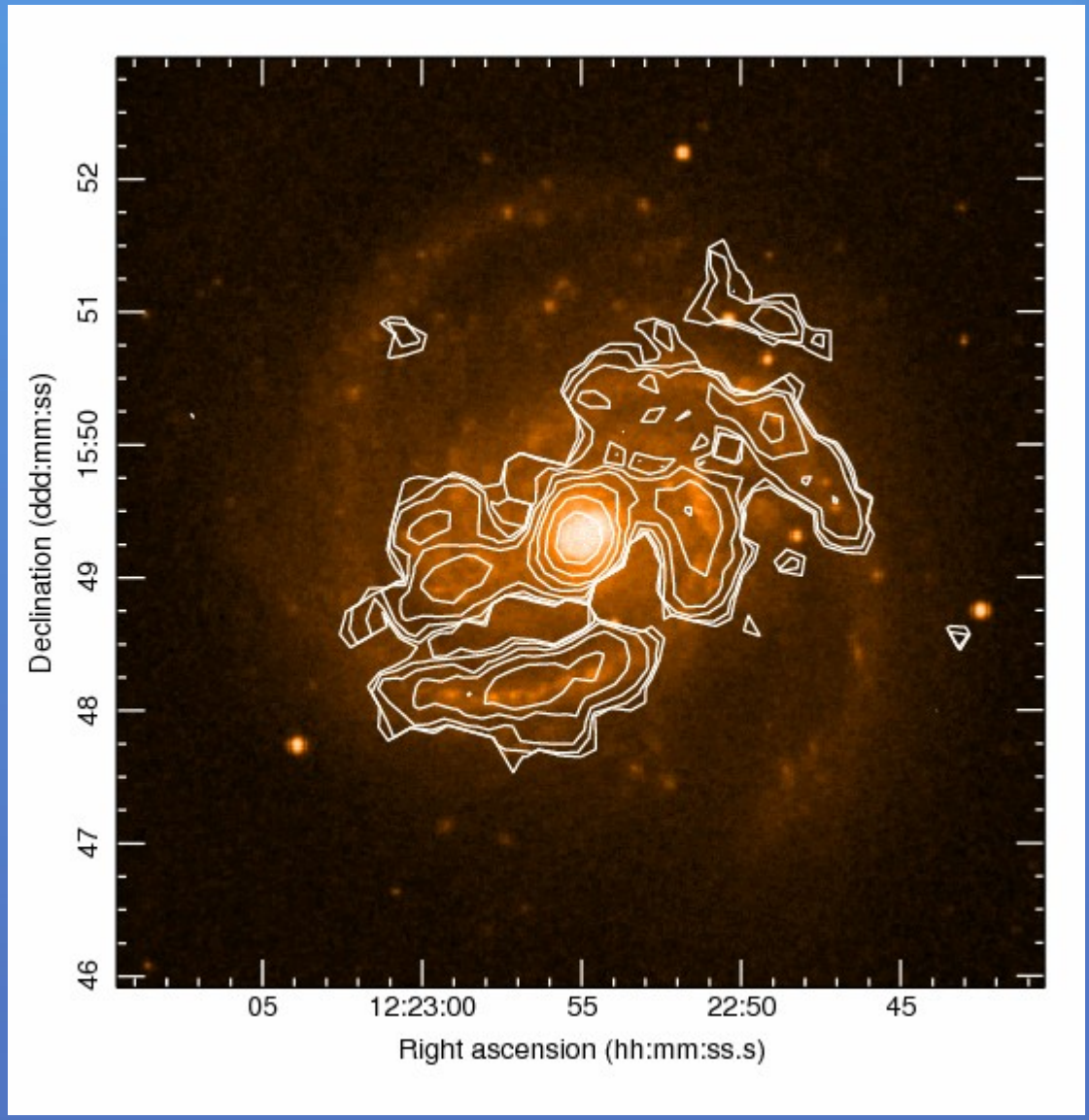
50 % of telescope time to these surveys

The Nearby Galaxies Survey

PI: C. Wilson

- Image 155 galaxies withing 25 Mpc with SCUBA-2 & in CO J=3-2

NGC4321 CO 3-2 + DSS



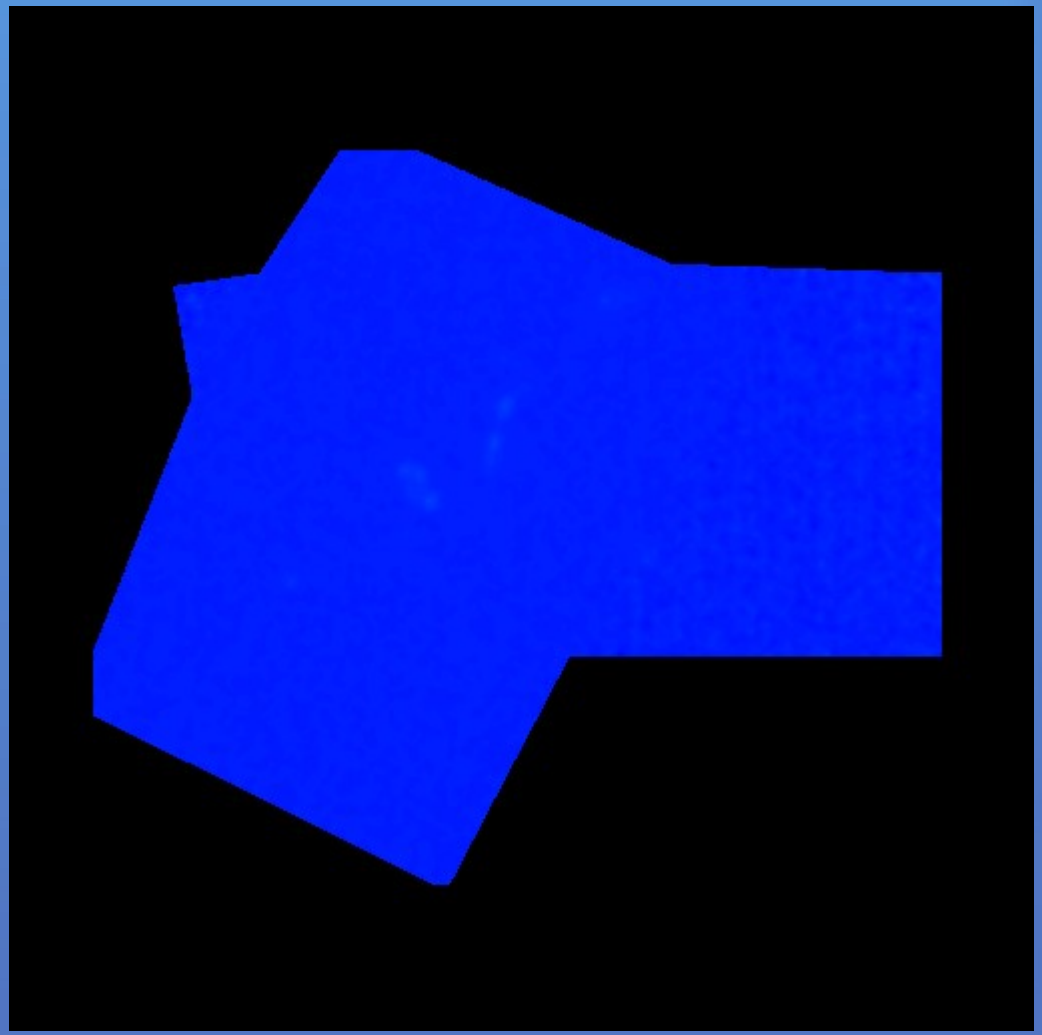
The Gould Belt Survey

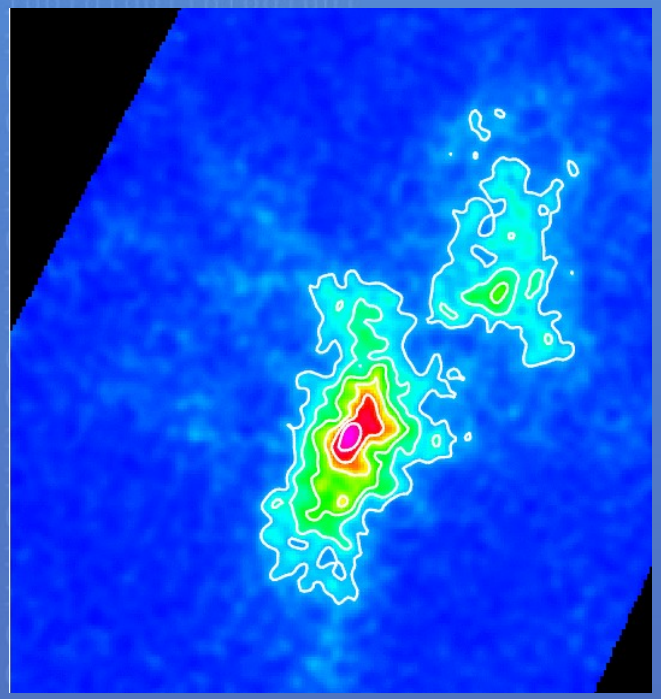
PI: D. Ward-Thompson

- SCUBA-2 & HARP imaging of clouds within 0.5kpc of the Sun
- ~370 sq. deg. in 2yr with SCUBA-2
  - 10mJy/3mJy @ 850um, 0.08M_o 10K
- HARP cloud (5'x5') and core (2'x2') maps in ^{12}CO and ^{13}CO/C^{18}O 3-2
- ~30 clouds maps at each frequency in 2 yr

Ward-Thompson et al. 2007, PASP,119,855

Serpens CO J=3-2



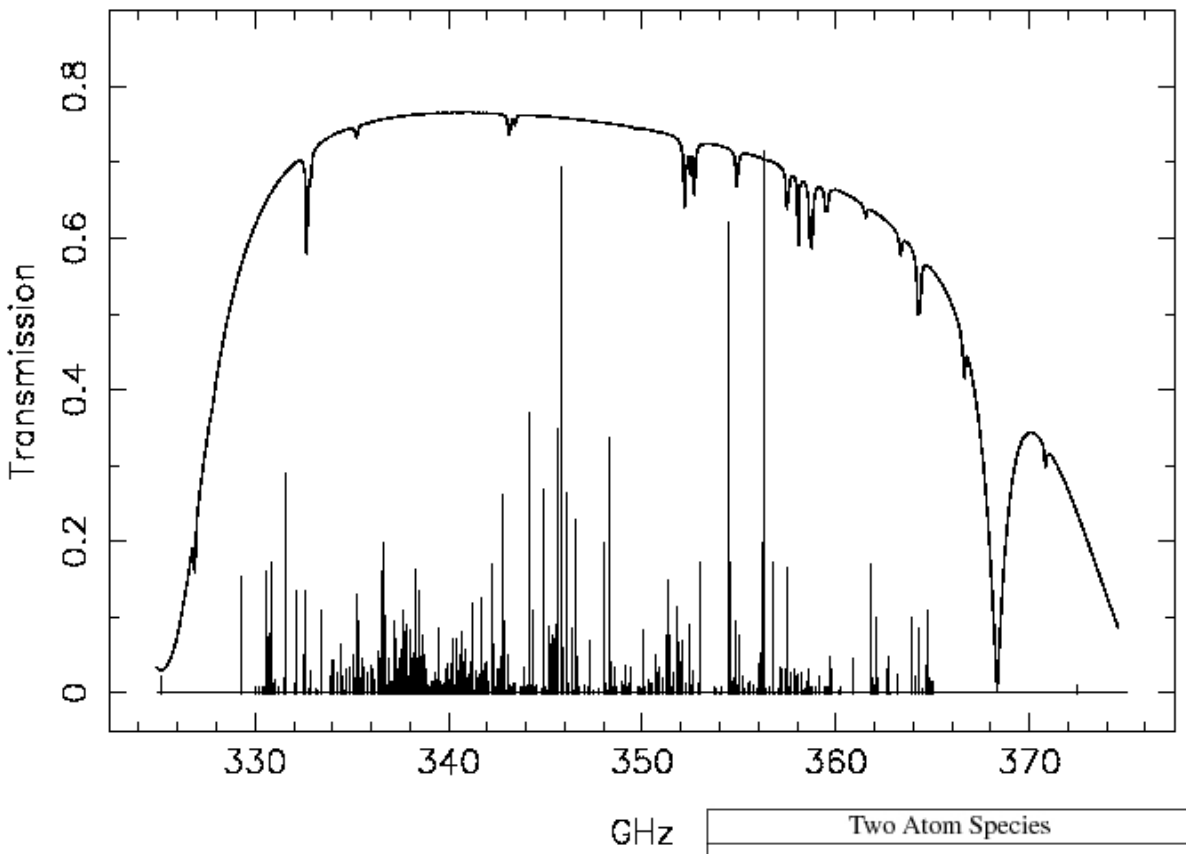


$C^{18}O$ J=3-2

Exploring The Spectral Domain: JCMT Spectral Legacy Survey

- Only spectral lines probe
  - kinematics
  - physics
  - chemistry
  - evolution – hot core clocks, depletion
- Poor understanding of molecular inventory and its evolution
  - Spectral survey
    - Complete census of species
    - Comparison of species
    - Trace range of excitation
    - New/unexpected species
    - Define continuum
  - Typical spectrum of different types of sources ?
  - Typical spectrum of kinds of environments ?

The 345 GHz Window



Lovas (2004)
- 866 transitions
- 82 species

Two Atom Species	Three Atom Species	Four Atom Species
CO ^{13}CO C^{17}O C^{18}O CS C^{34}S C^{33}S CN CO$^+$ NO NS SiO ^{29}SiO ^{30}SiO SiS Si33S Si34S 29SiS 30SiS SO 33SO S18O 34SO SO$^+$ SO2 ^{34}SO2	OCS OC^{34}S O^{13}CS HNC HN^{13}C H^{15}NC HCO+ H^{13}CO+ HC^{18}O+ DCO$^+$ HCN H^{13}CN HC^{15}N DCN H2O HDO HCO$^+$ SiC$_2$ HDS C$_2$H HNO HCS$^+$ HCO H$_2$D$^+$	CCCS H$_2$CS HDCO HNCO H3O+ NH2D NHD2 H$_2$CO H$_2$C^{18}O H$_2^{13}$CO D$_2$CO
Five Atom Species	**Six or More Atom Species**	
HCCCN HCC^{13}CN HC^{13}CCN H^{13}CCCN HCOOH HCOOD CH2CO NH2CN CH2NH c-C3H2	CH2CHCN CH3CCH CH3CH2CN CH3OCHO CH3CN ^{13}CH3CN	CH3OH ^{13}CH3OH NH2CHO t-CH3CH2OH CH3OCH3

Important spectral band:
ALMA DRSP: >30% of observing time in this band

But poorly explored...

Source	Frequency Range (GHz)	Noise (K)	Reference
High Mass Sources			
Orion KL	325 - 360	0.15	Schilke et al. 1997, Jewell et al. 1996
G34.3+0.15	330 - 365	0.05	Macdonald et al. 1996, Thompson et al. 1999
G5.89-0.39	330 - 360	0.06	Thompson & Macdonald 1999
W3 IRS5, IRS4, OH	334 - 365	0.03	Helmich & van Dishoeck 1997
Sgr B2	330 - 355	0.06	Sutton et al. 1991
IRAS 23385-6053	330 - 360 (incomplete)	0.03	Thompson & Macdonald 2003
Low Mass Sources			
IRAS 16293-2422	330 - 365	0.018	Caux et al. in progress

All current surveys are at single positions
BUT none of the sources are isolated point sources

→ Need imaging to probe structure

Multiple physical environments along lines of sight

JCMT SLS: An imaging spectral survey

PI: G. Fuller

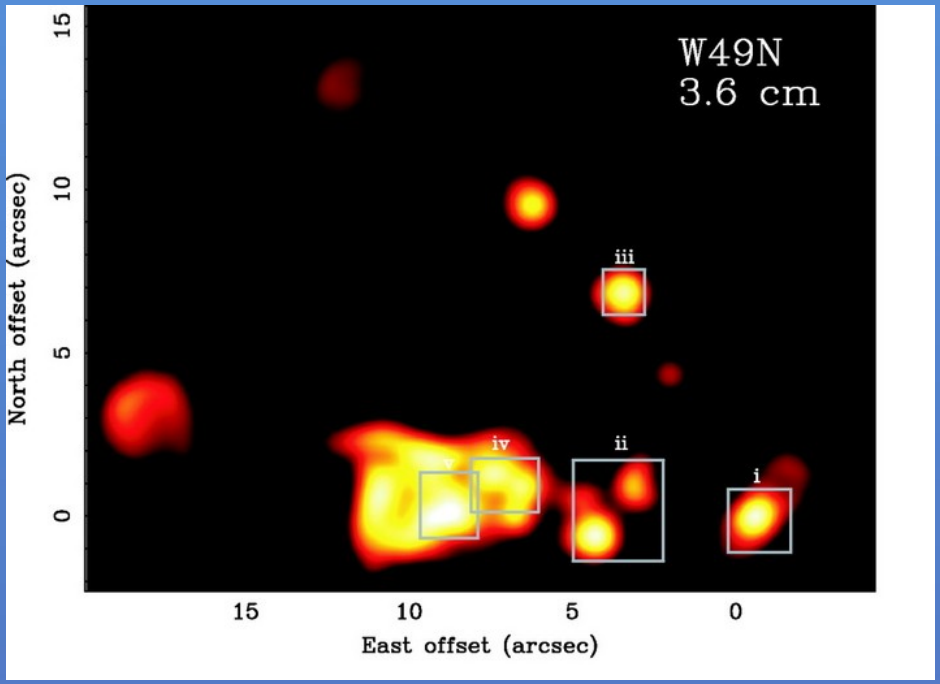
- Goals
  - understand the molecular inventory and its evolution
  - probe a range of environments
- Five target sources
  - Chosen to span range of star forming environments and evolutionary stages

SLS: The parameters

- Five sources
  - W49
  - IRAS20126+4104
  - AFGL2591
  - NGC1333 IRAS4
  - Orion Bar
- Noise levels (in 2.5 km/s channels)
  - 25mK
  - Low mass source: 9mK
- Allocation
  - 187 Hours (in grade 4 weather)
- Coverage
  - 330 GHz 363 GHz*
  - Single fully sampled footprint (2'x2')

A Galactic Starburst: W49

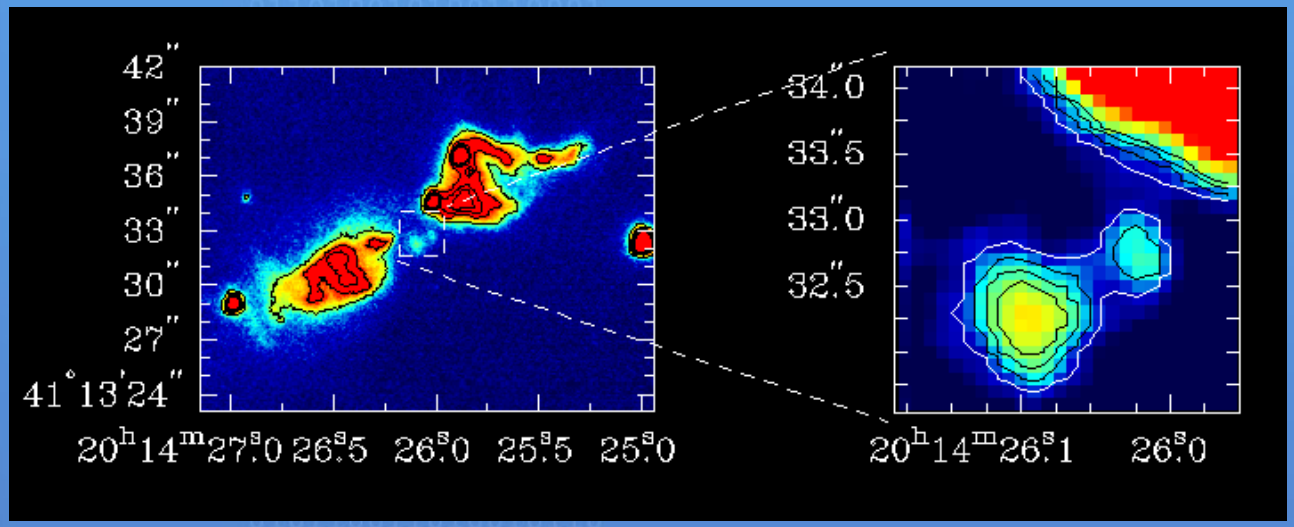
- Distant: 11.4 kpc
- Luminous: 10^7 L_o
- Cluster of UCHII regions embedded in 10^5 M_o cloud



(De Pree et al. 2003)

Stepping stone to extragalactic star formation regions

An Intermediate Mass Protostar: IRAS20126+4104

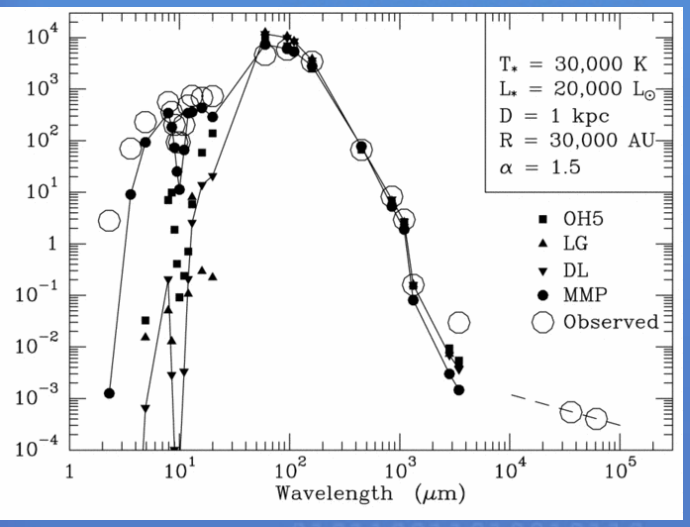


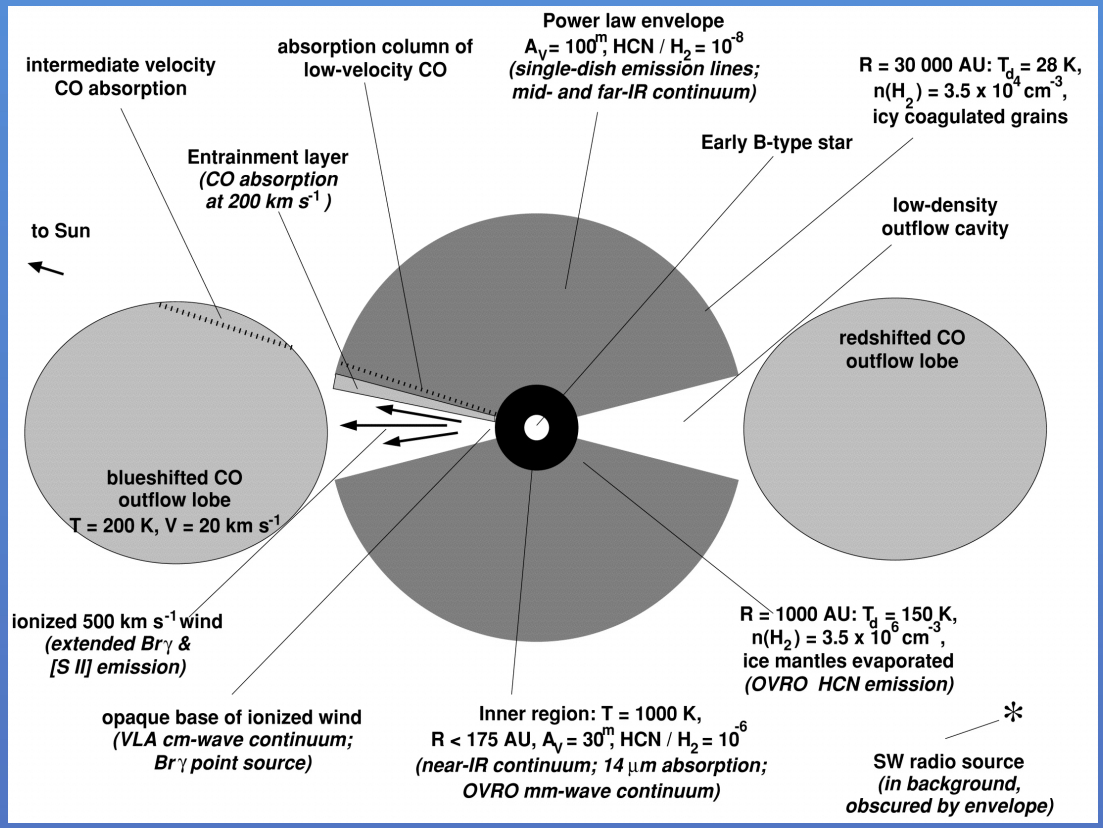
2μm image
(Sridharan, Williams & Fuller 2005)

- Embedded young 10^4 $L_\odot$ source at 1.7 kpc
- 5-7 $M_\odot$ central source in 200$M_\odot$ core
- Keplerian disk, 5000 AU in radius – CH_3CN, OH masers
- Outflow – CH_3OH, SiO, H_2O masers - precessing?
- Target for HIFI on Herschel

A massive protostar: AFGL 2591

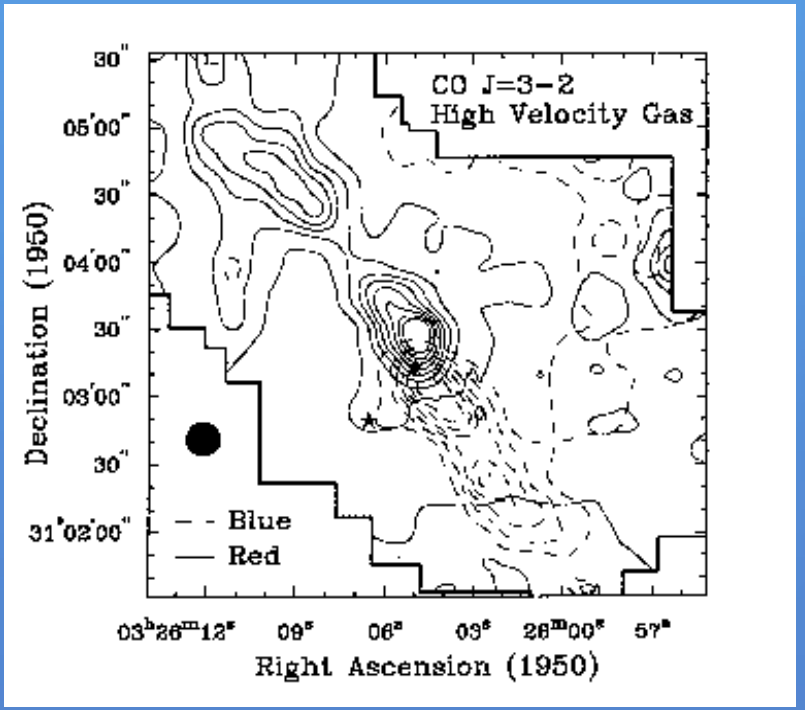
- $2x10^4$ Lo at 1 kpc
- Infrared bright
- Very well studied
- Rich molecular spectrum
- Source structure well characterized (van der Tak et al 1999)

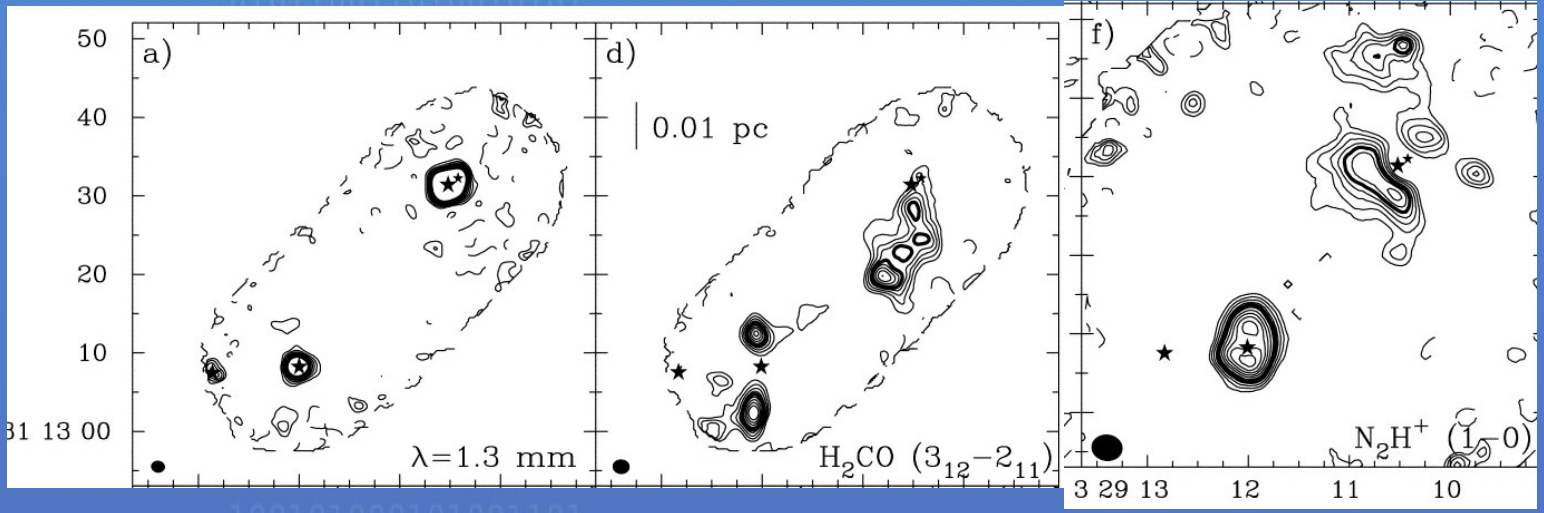




Low Mass Protostar: NGC1333 IRAS4 (Blake et al. 1995)

- 30" binary – resolved and imaged
- Class 0 sources – infall, outflow, rotation
- Differences between components
- Depletion, high deuterium fractionation
- (L1157, L1544)

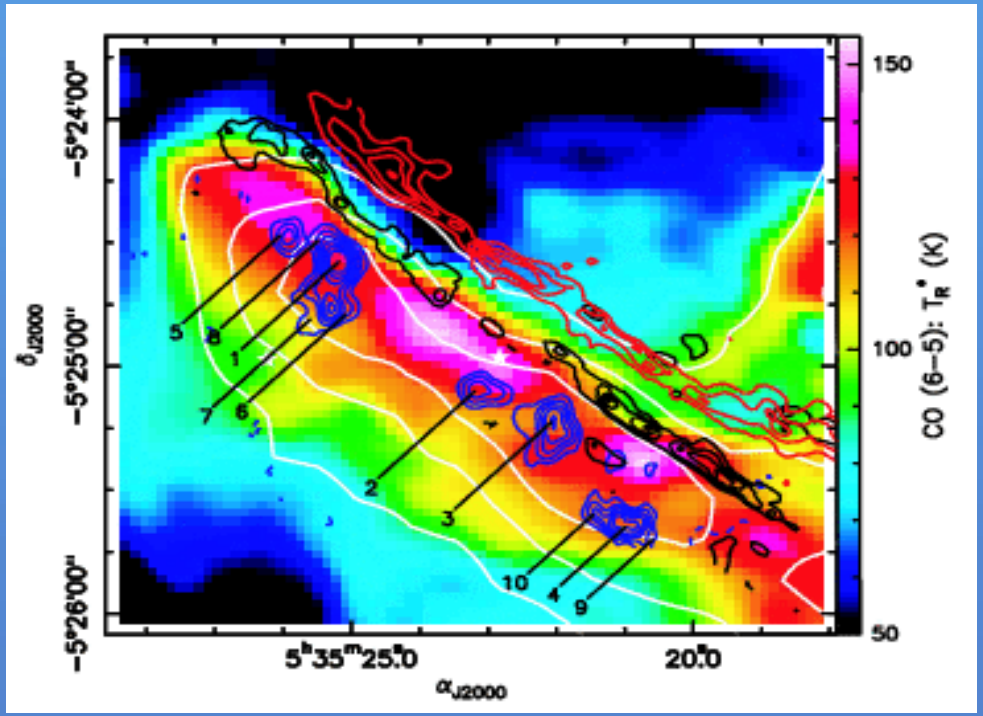




(Di Franesco et al. 2001)

Photon Dominated Region : Orion Bar

- Dense gas exposed to 10^4 G_o
- Dense clumps ~10^6 cm^{-3}
- Inter-clump ~10^4 cm^{-3}
- No (internal) star formation



(Lis & Schilke 2003)

SLS: The Parameters & Status

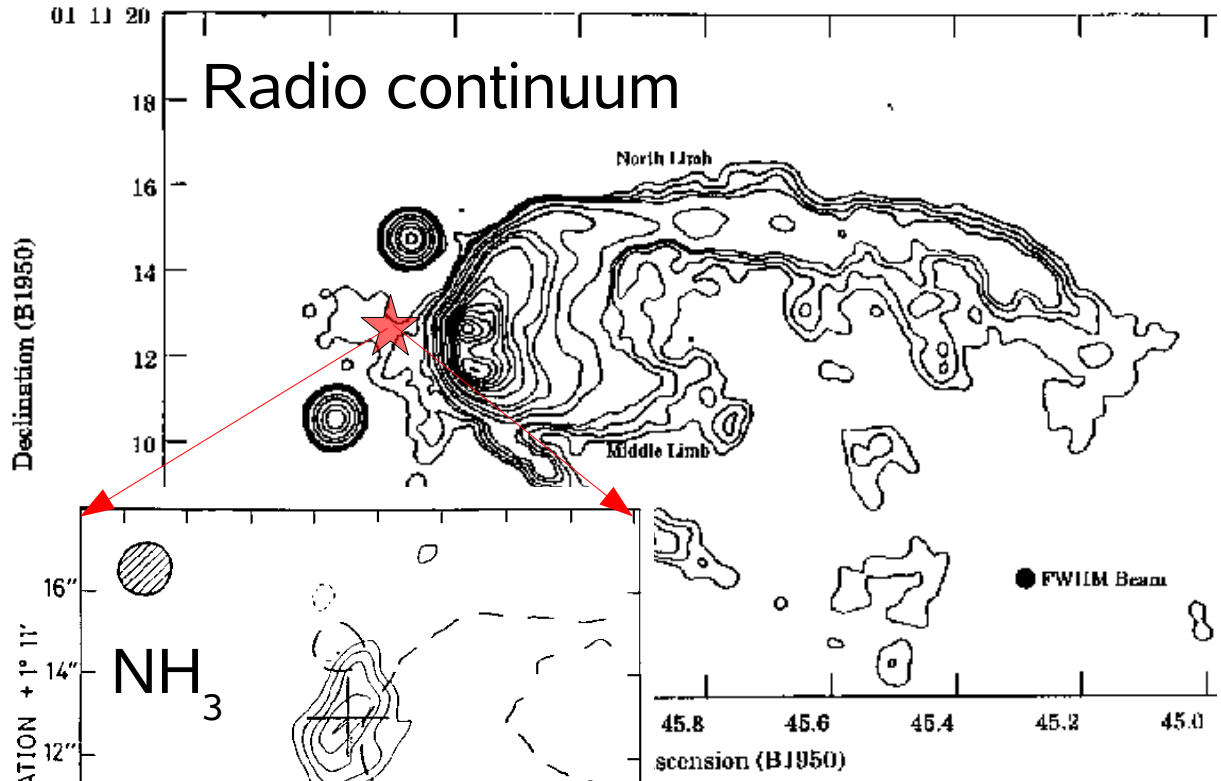
- Five Sources
- Noise levels (binned to 2.5 km/s channels)
  - 25mK
  - Low mass source: 9mK
- Allocation
  - 187 Hours (in grade 4 weather)
- Coverage
  - 330 GHz 363 GHz
  - Single footprint (2'x2')
- 2 GHz spectra (0.87 km/s channels)
- Spatial & spectral redundancy
- Started Nov 2007
- About 30 hours observed so far
- Parallel high frequency extension 363-375 GHz

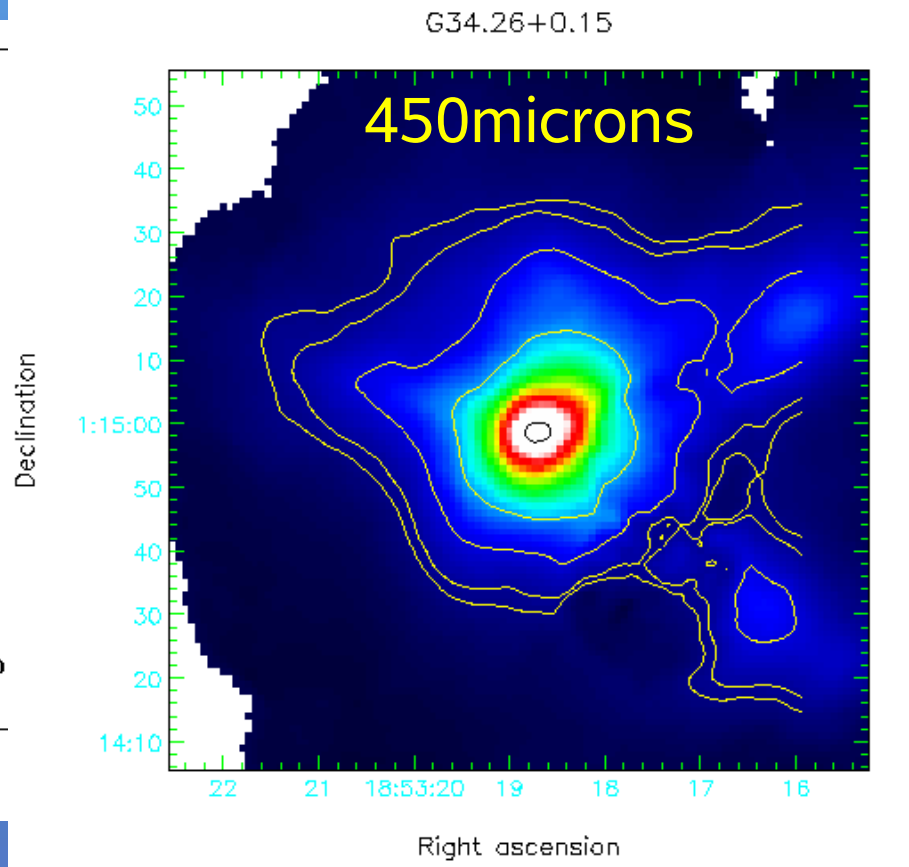
http://www.jb.man.ac.uk/research/sls

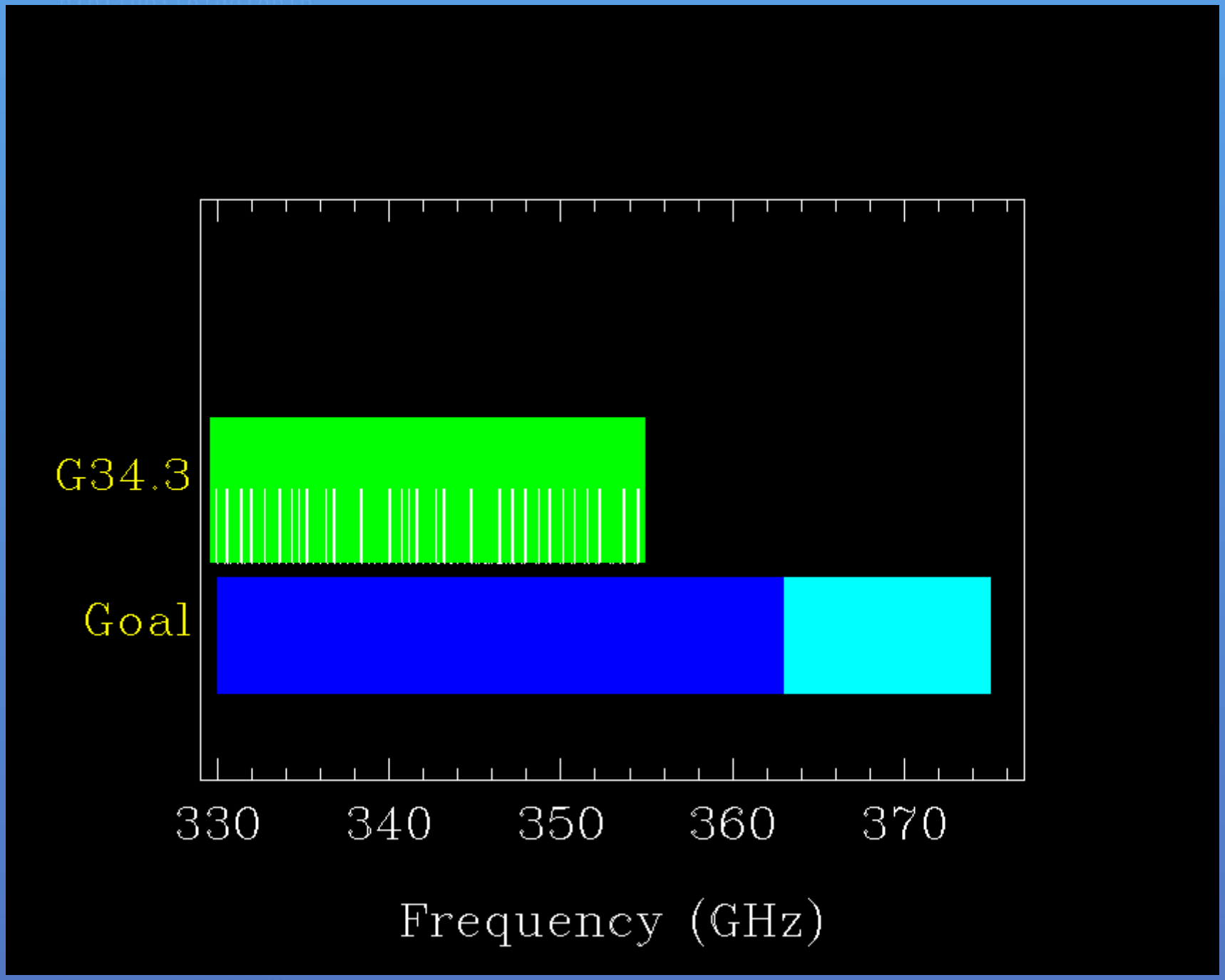
Plume et al. 2007, PASP, 119,10

A Demonstration Case: G34.26+0.15

- Classical hot core: ~0.01pc, 300K, 10^7 cm^{-3}, 10^{24} cm^{-2}
- Single point survey by Macdonald et al. (1996)
  - 35 species, 19 isotopologues, 70 U lines
- Multipoint chemical model by Millar et al. (1997)
- Survey of envelope by Thompson et al. (1999)

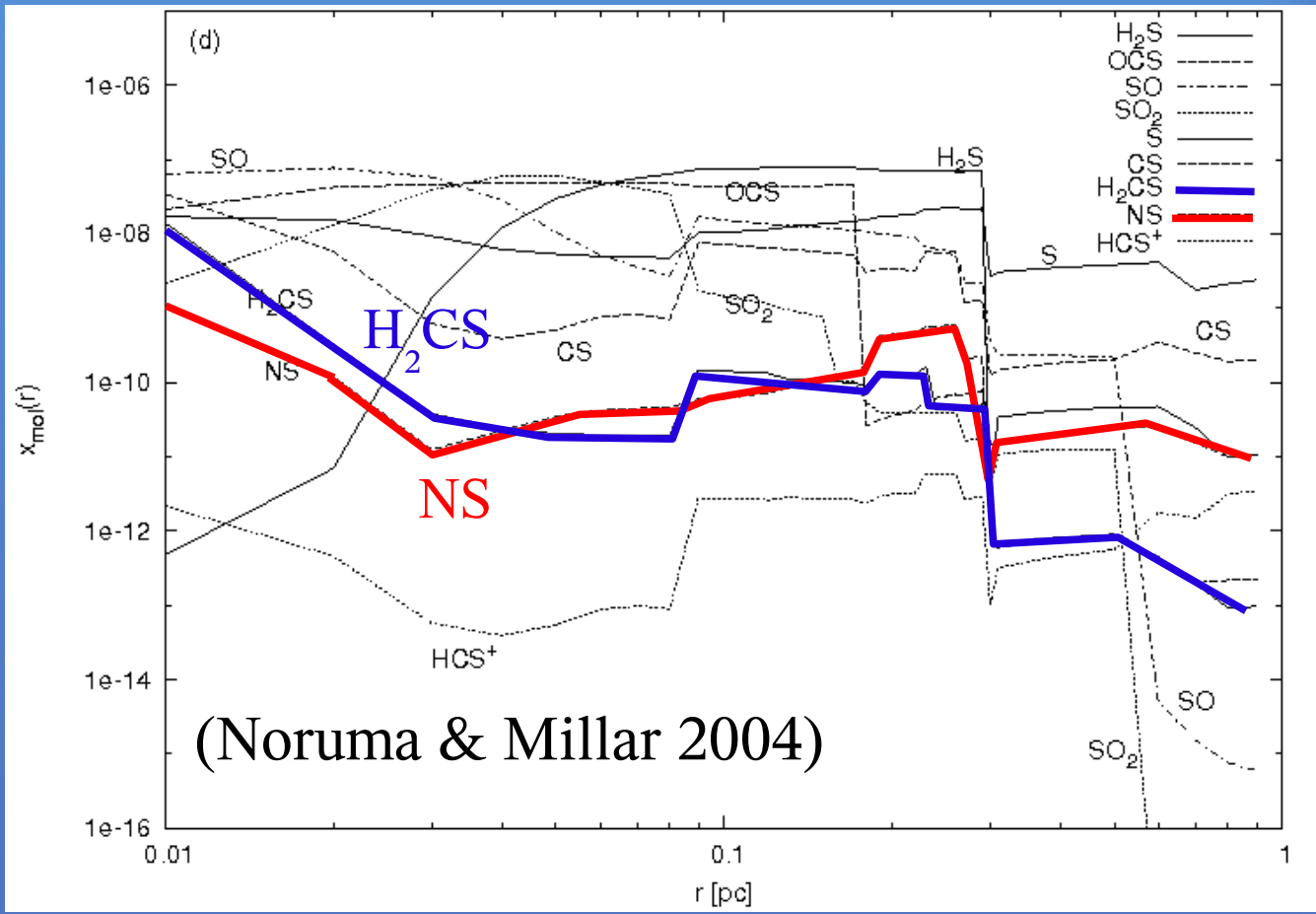




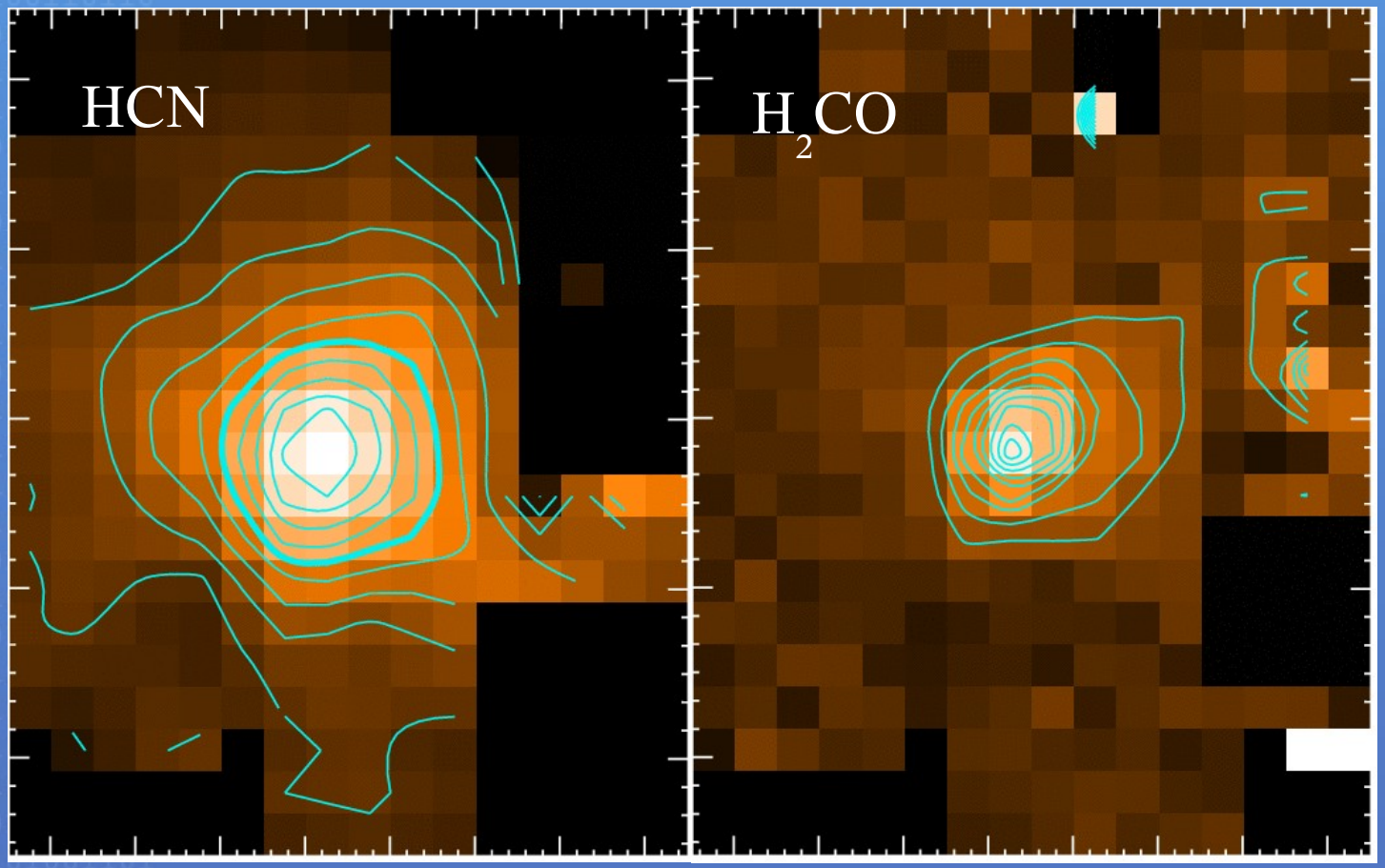

G34.3
Goal
330
340
350
360
370
Frequency (GHz)

Spatial Information

Species	Peak	Size (")
H_2CS	(0,+7.5")	7.8
CH_3OH	(0,+7.5")	7.3
$H^{13}CN$	(0,+7.5")	8.6
$H^{13}CO^+$	(0,0)	11
NS	(0,0)	8.3
U346.2186	(0,0)	5.7
H_2CO	(0,0)	10.4



Extended Emission



High Frequency Extension

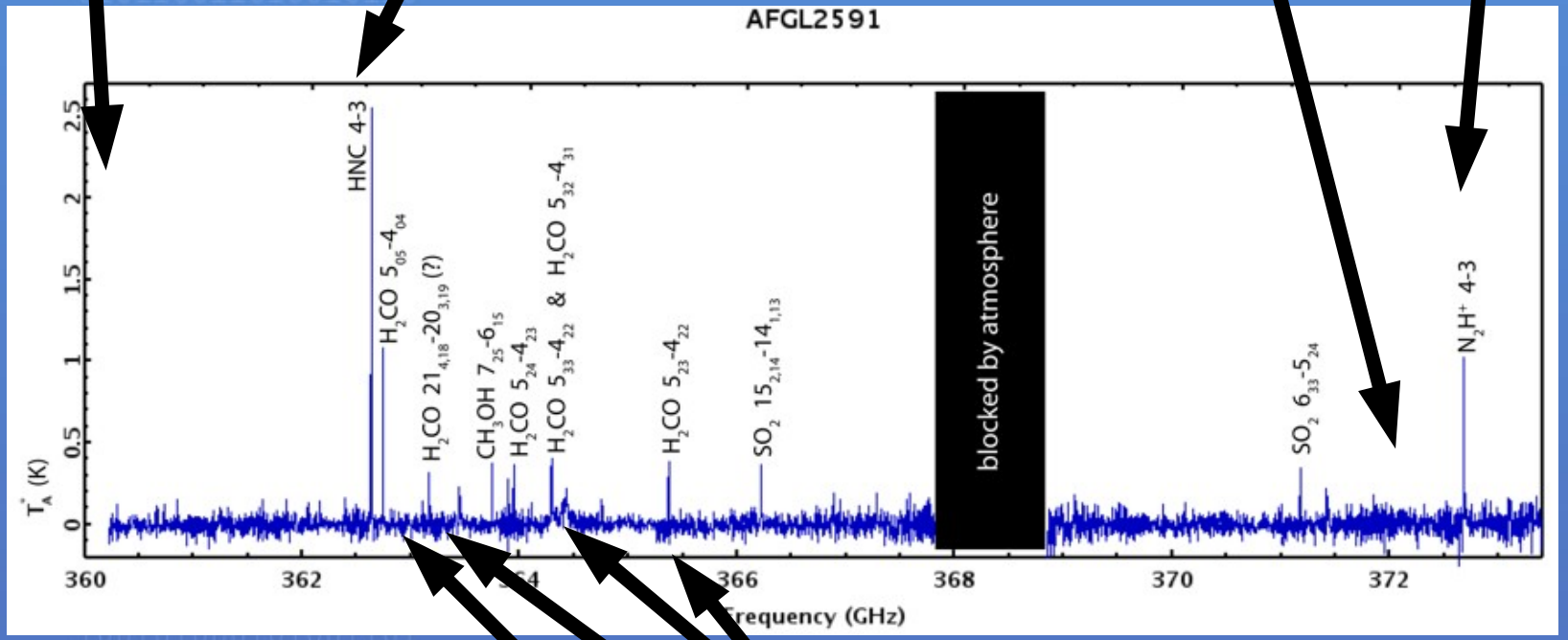
AFGL2591

D containing species

Isomer HCN favoured in hot gas

No H_2D^+

Cold, dense, depleted



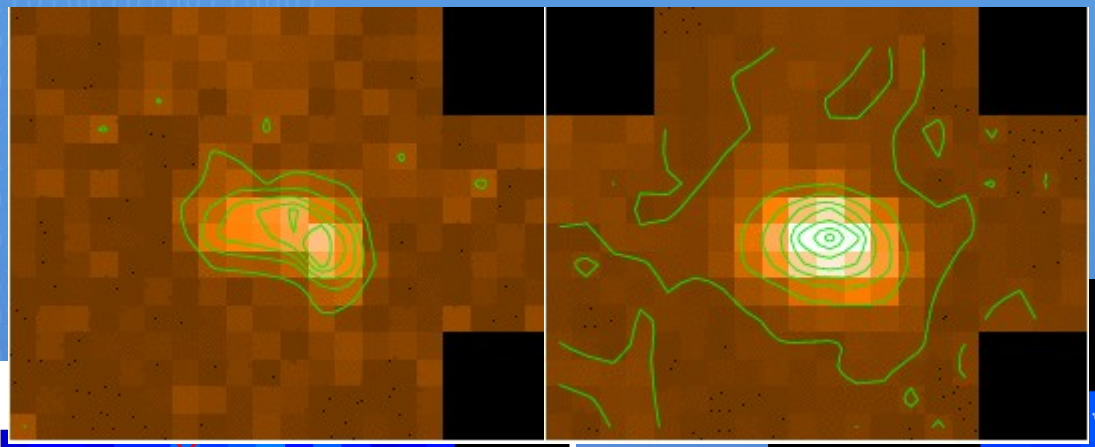
Constrain T, n

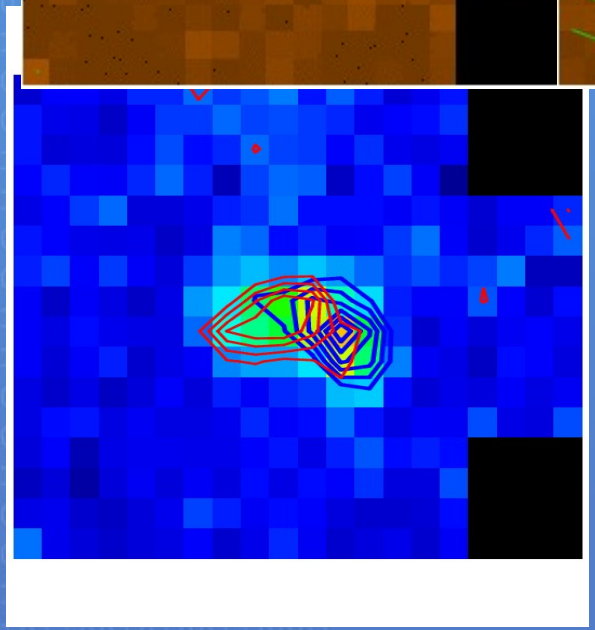
AFGL2591

N_2H^+ J=4-3

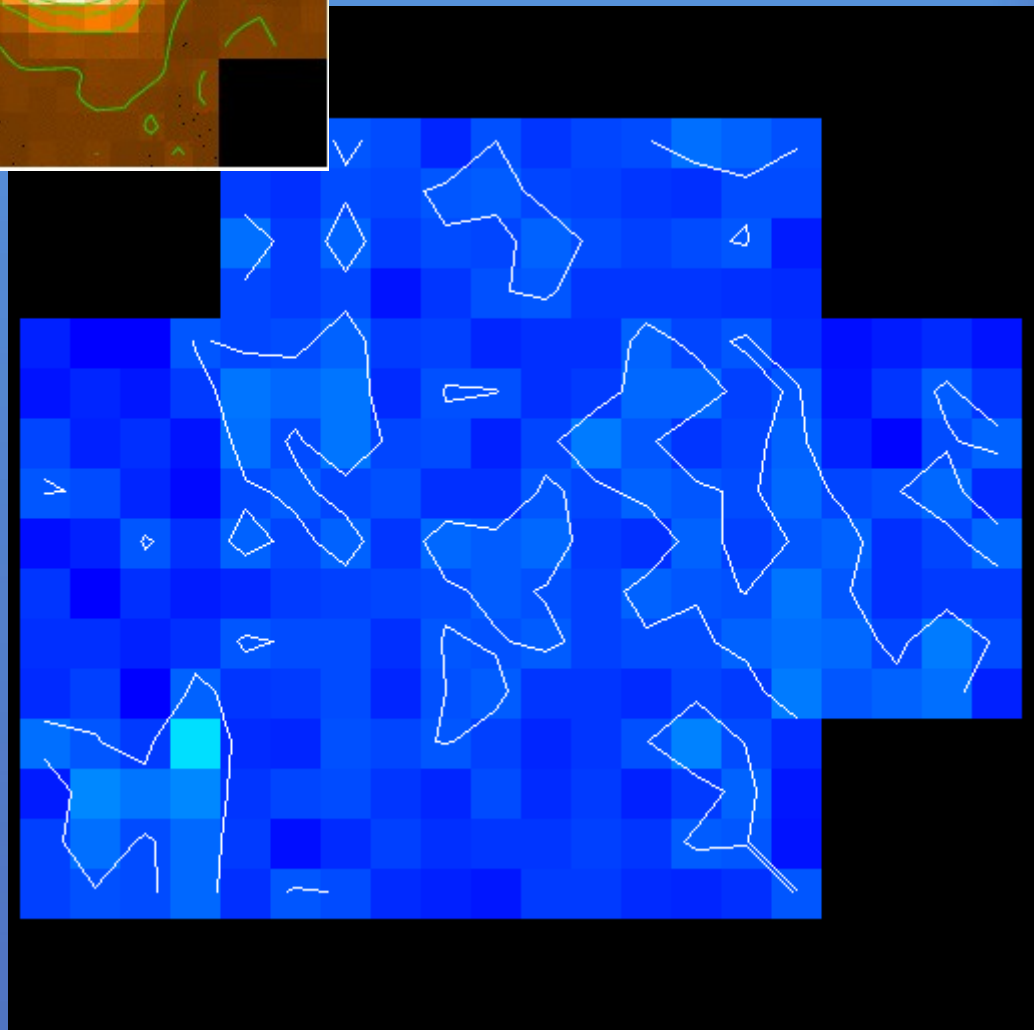
HNC J=4-3

Integrated





Red & Blue wings



Science with the SLS

- Gas-star interaction
  - Thermal & Chemical
- Tracers of the outflow
- Hot core chemistry
- Evolution of envelope material infall and dispersion
- Intercomparison of sources

Wide Field* Imaging Science Beyond HARP

- Distributed Sources
  - Clusters
- Extended sources
  - Clouds
  - Outflows
  - Nearby Galaxies
- (Large samples)

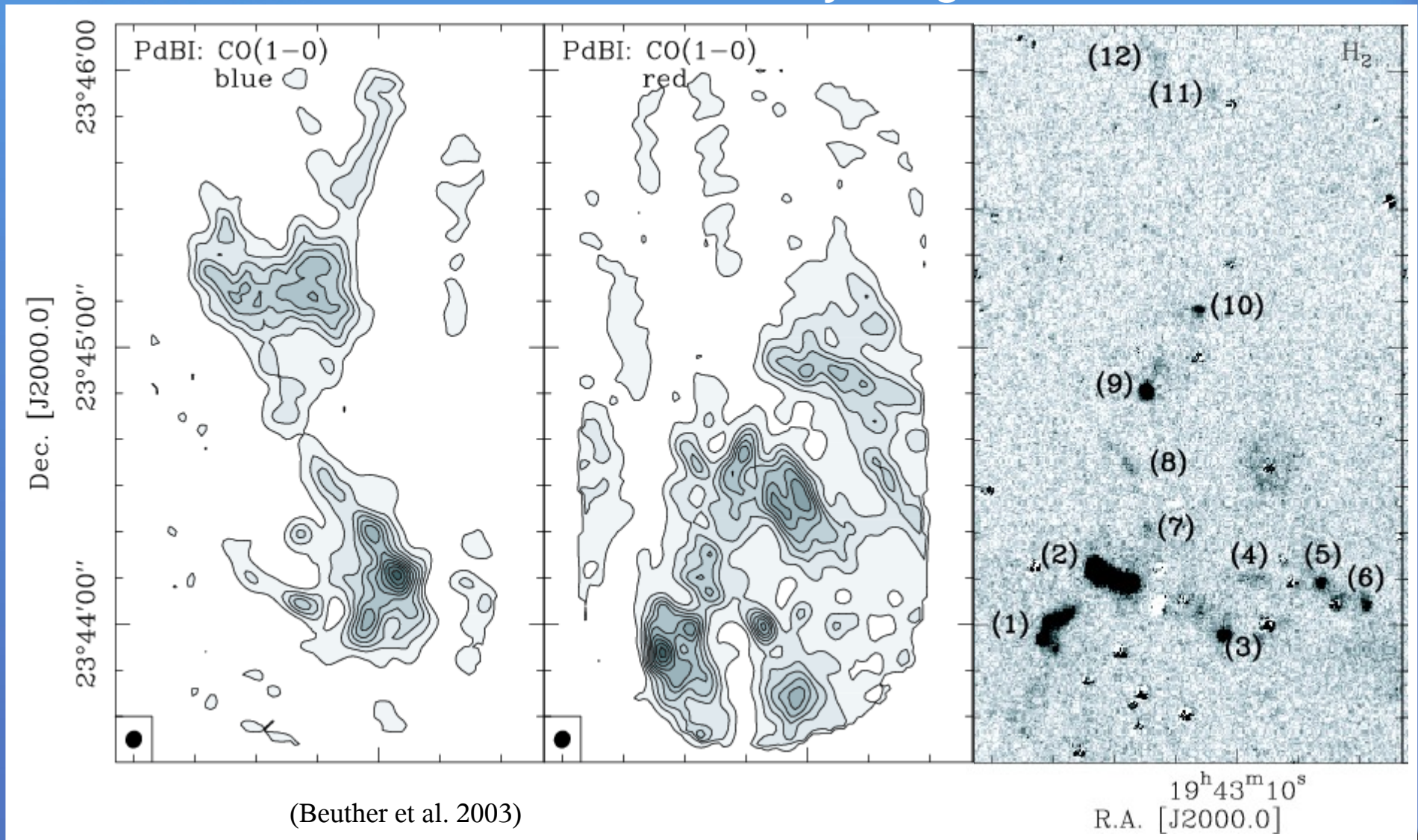
* - compared with ALMA

Freq. (GHz)	Primary Beam FWMH	Pointings for 1'x1'
115	52.5	4
230	26.25	16
345	17.5	36
460	13.13	81
690	8.75	169
850	7.1	289

144 pointings to cover HARP fov

Clusters

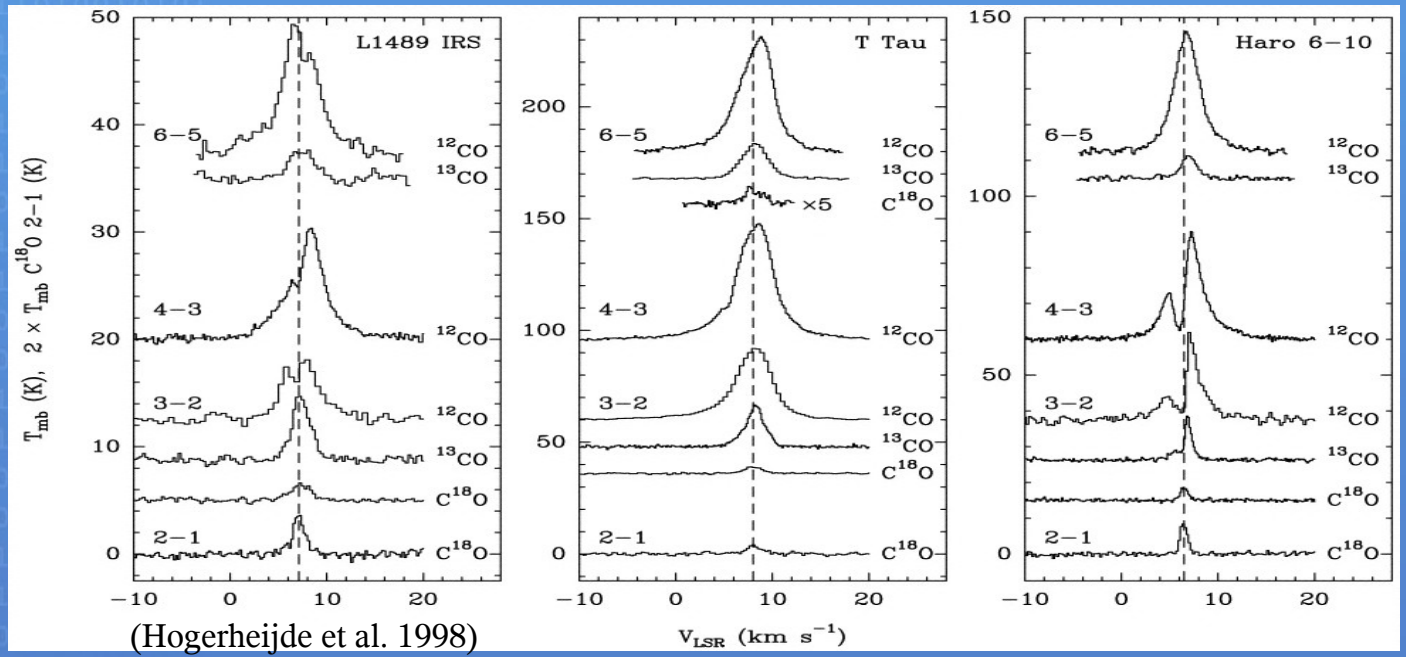
- Outflows, PDRs CO, CN lines
  - Energetics, Census
- Central sources High density tracers
  - Census, evolutionary stage



(Beuther et al. 2003)

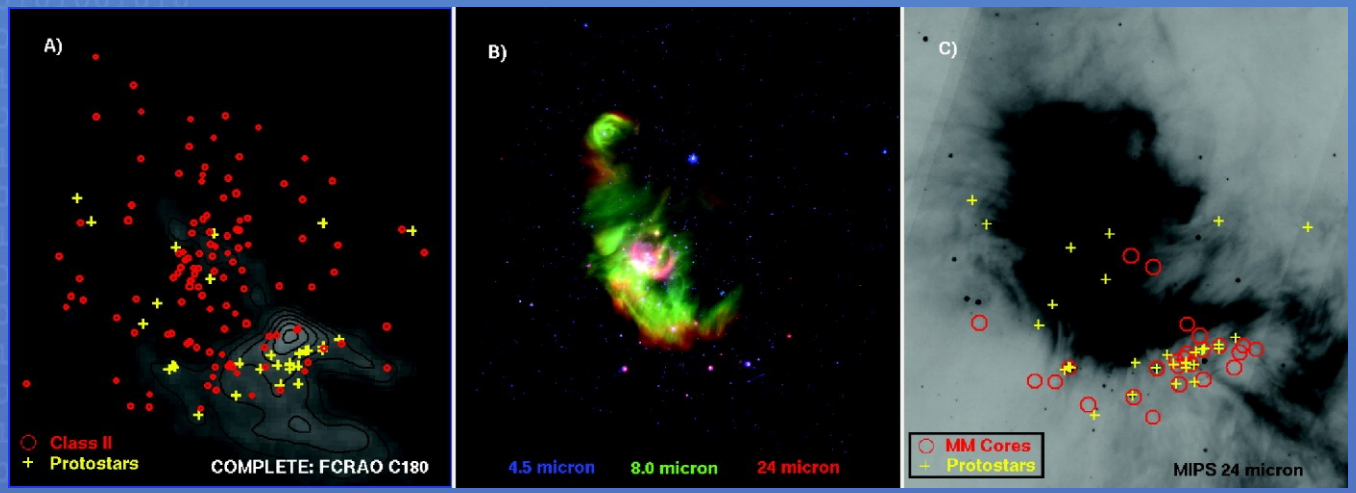
Clusters

- Not just high mass protostars
  - Class I solar mass objects



(Hogerheijde et al. 1998)

IC348
(Munech et al. 2007)



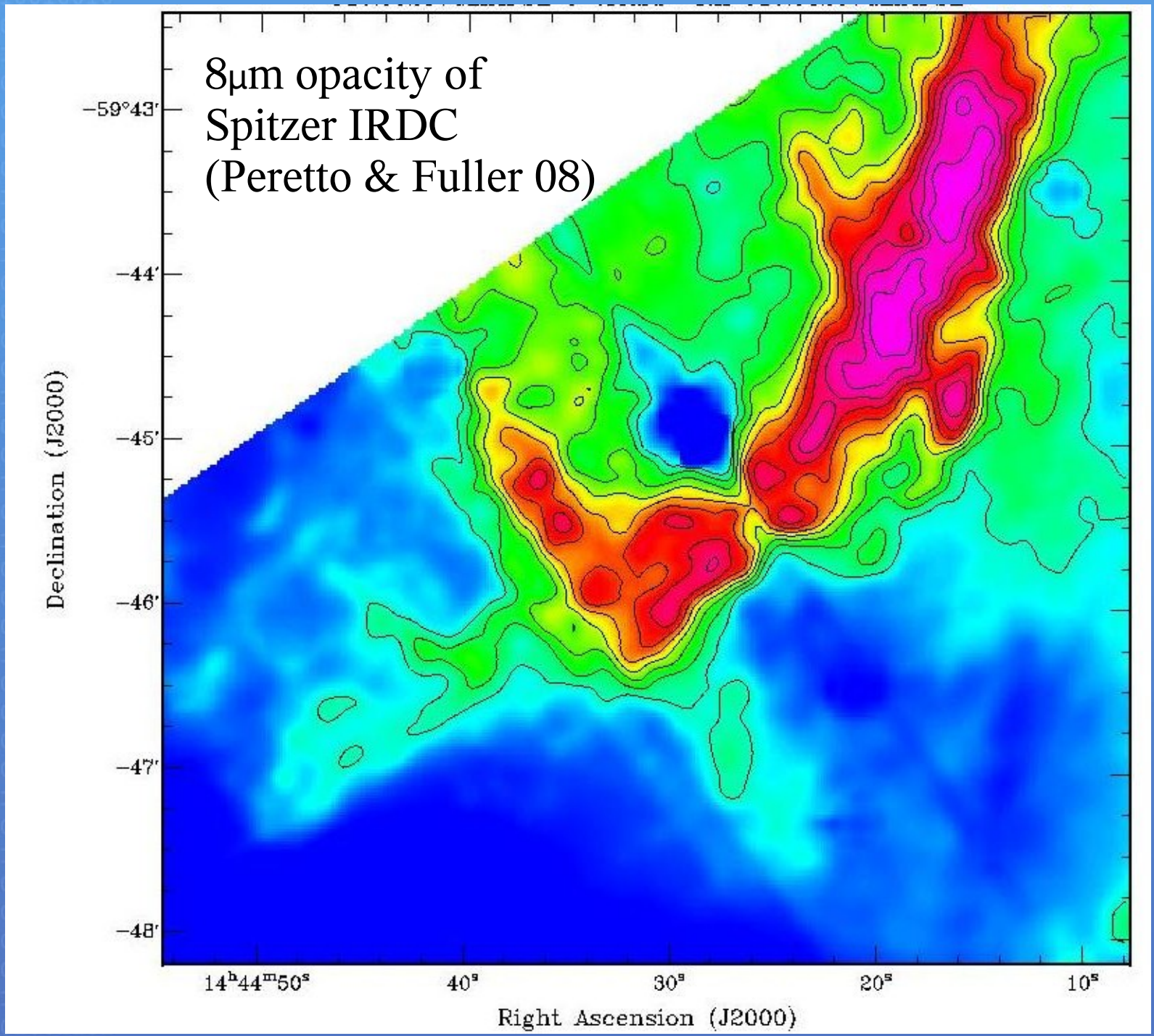
Clouds

Origin and dispersal of dense gas

Small cores but extended structure maybe key to their origin.

Kinematics vital

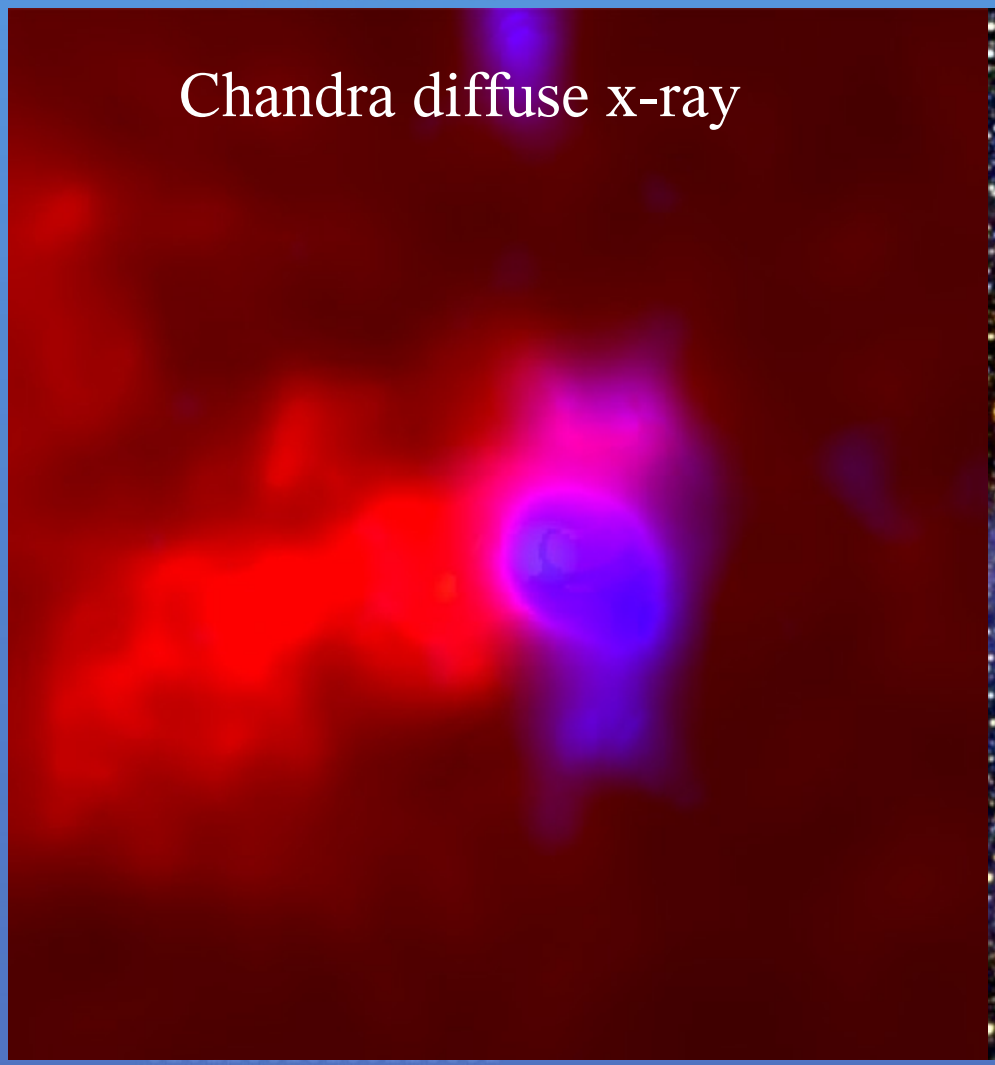
Densest gas cold, but outer edges may be much warmer - extended PDRs



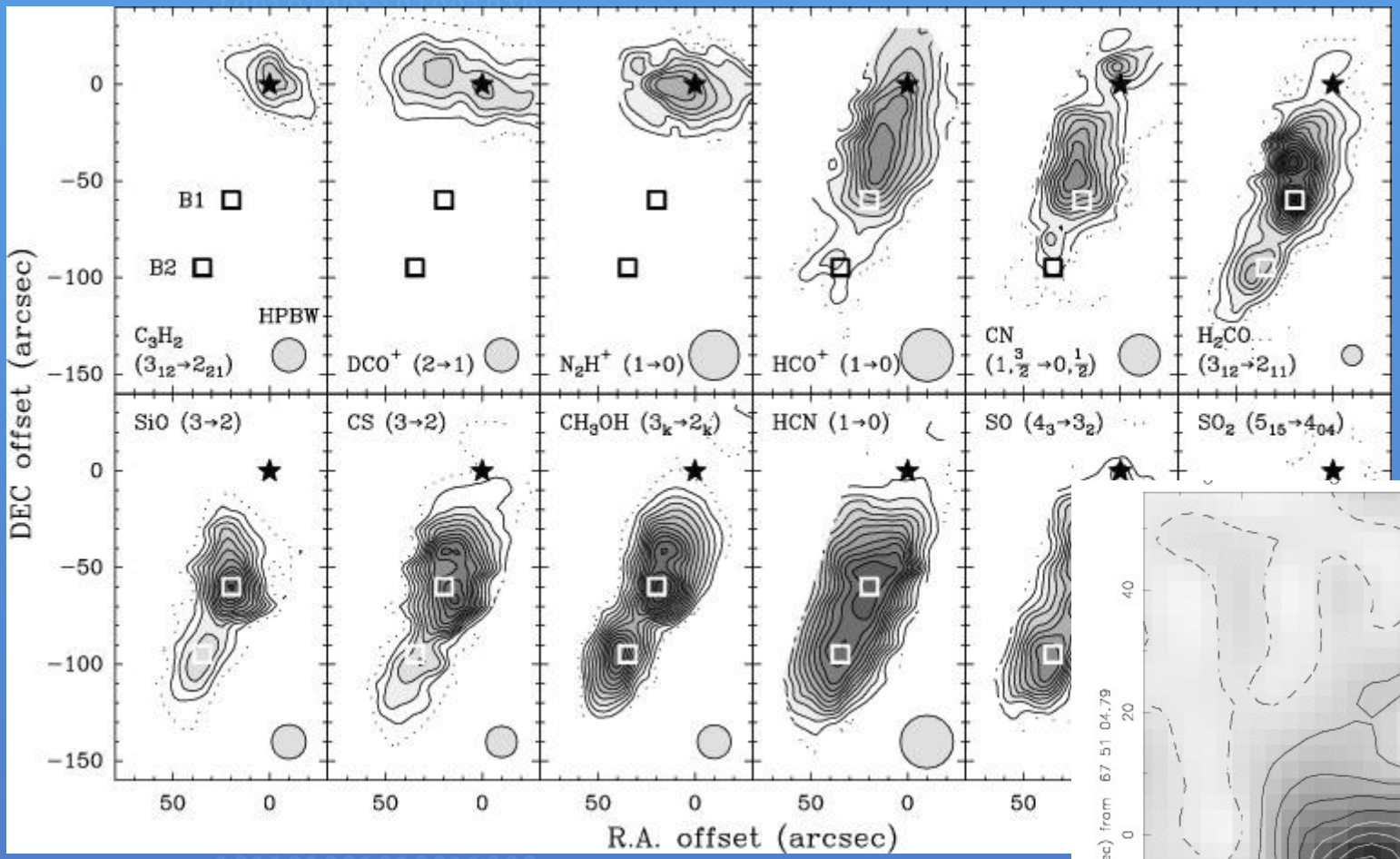
Clouds

- Interfaces between hot and cold gas

M17

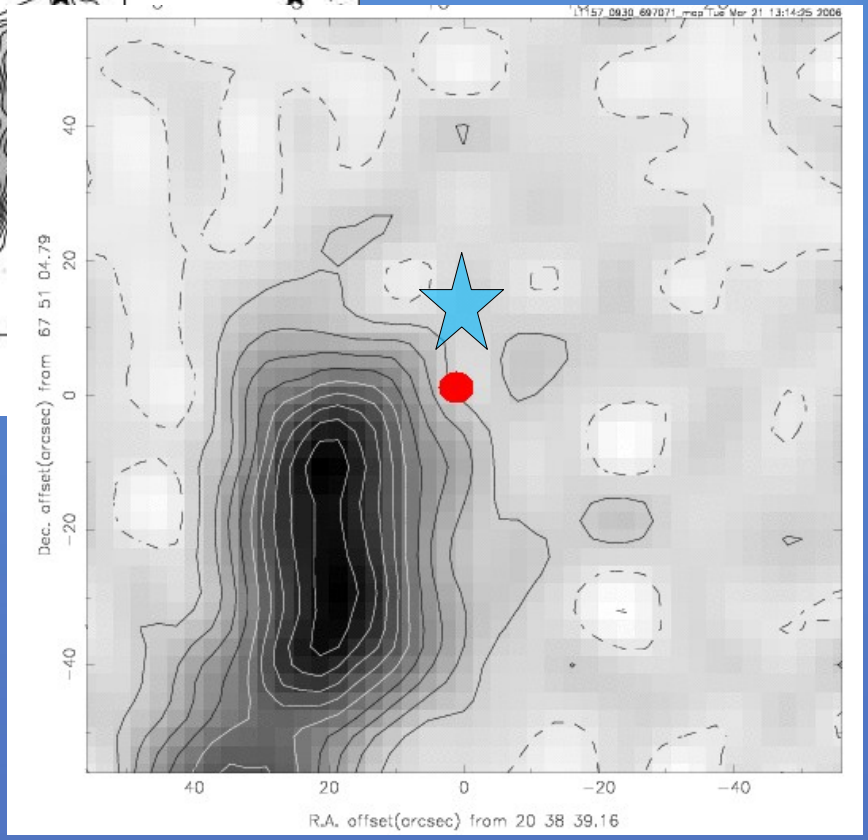


Outflows



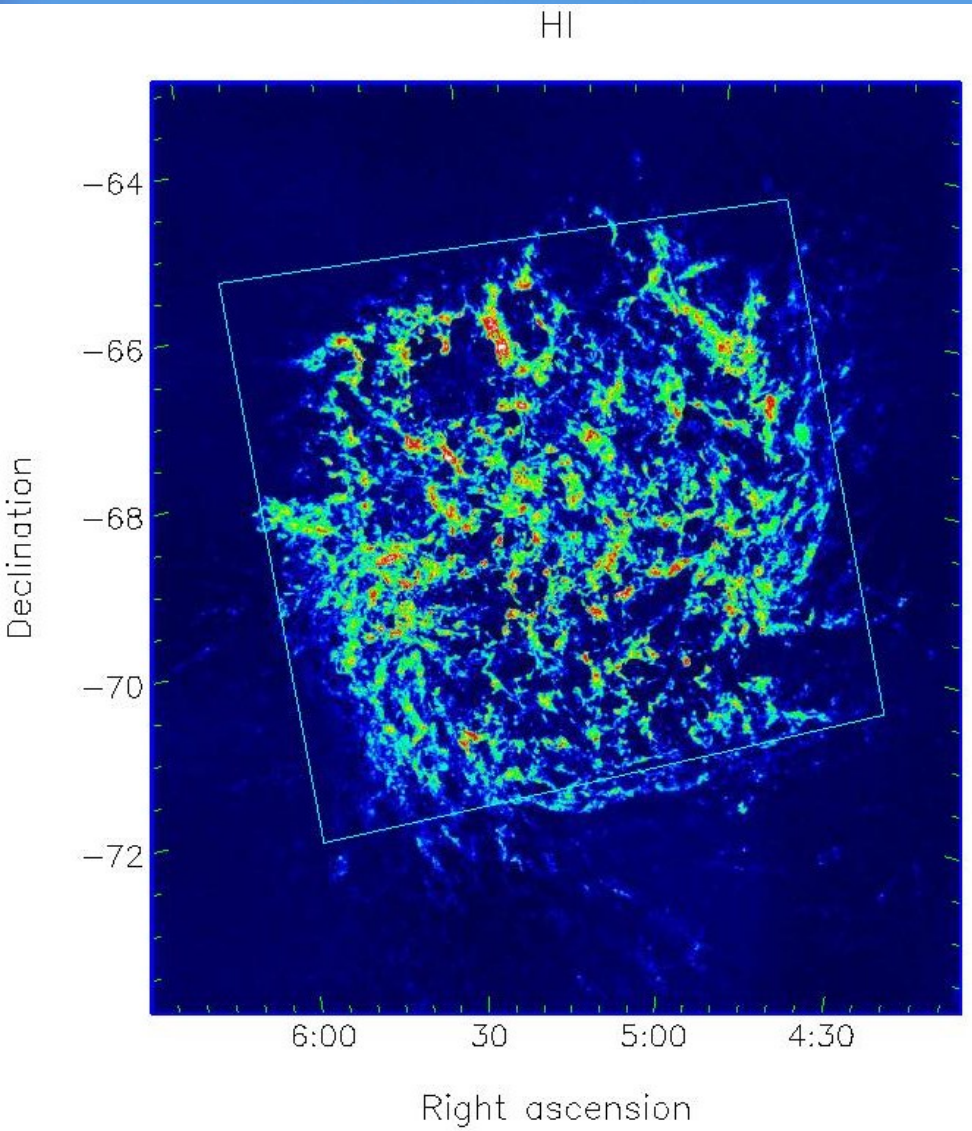
(Bachiller et al 2001)

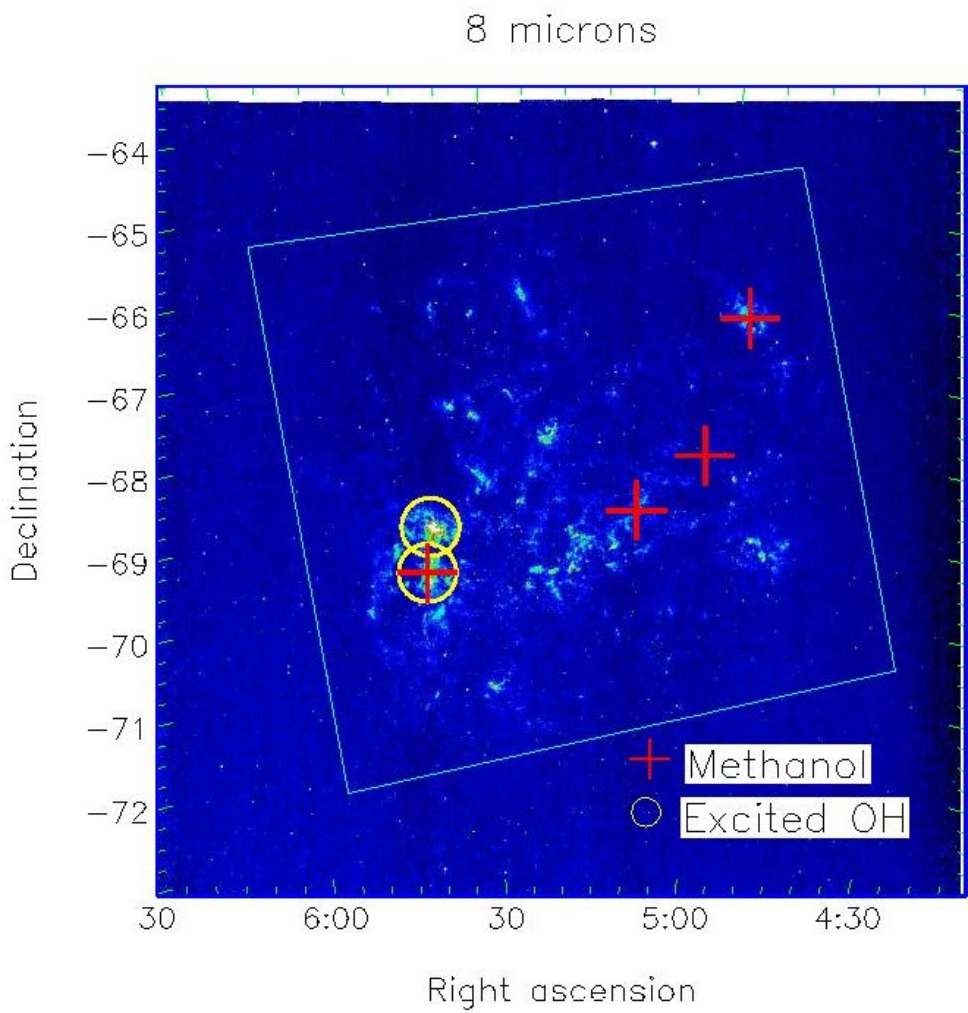
HCN J=3-2



- Large objects
- Role in disrupting/supporting clouds
- Chemical effects
- Probe low mass population

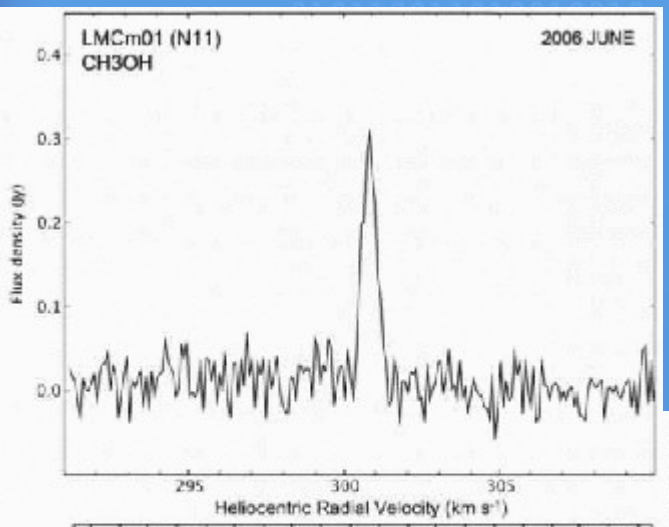
MMB LMC Survey

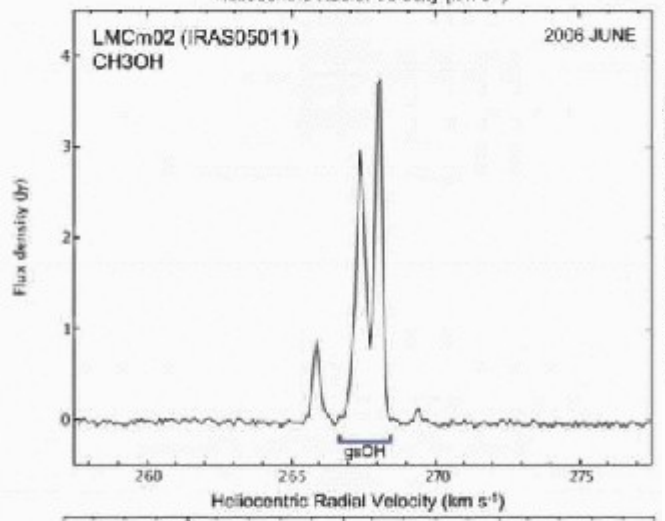


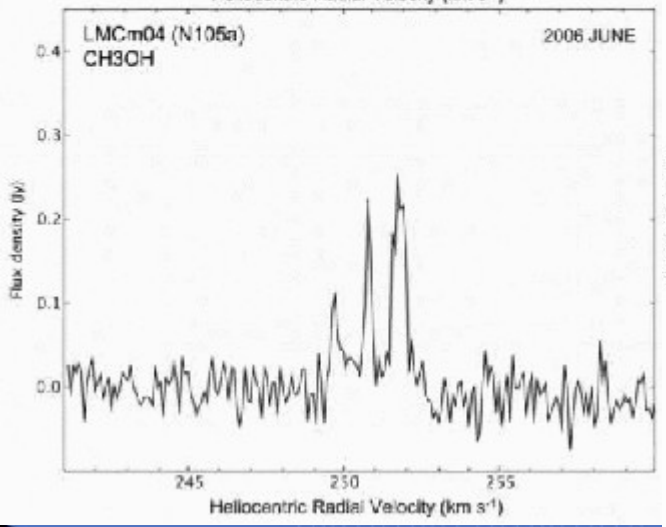


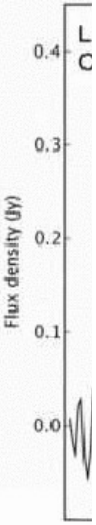
Surveyed area: 56 deg^2

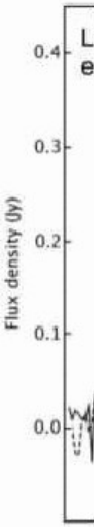
(Green et al 2008, MNRAS)

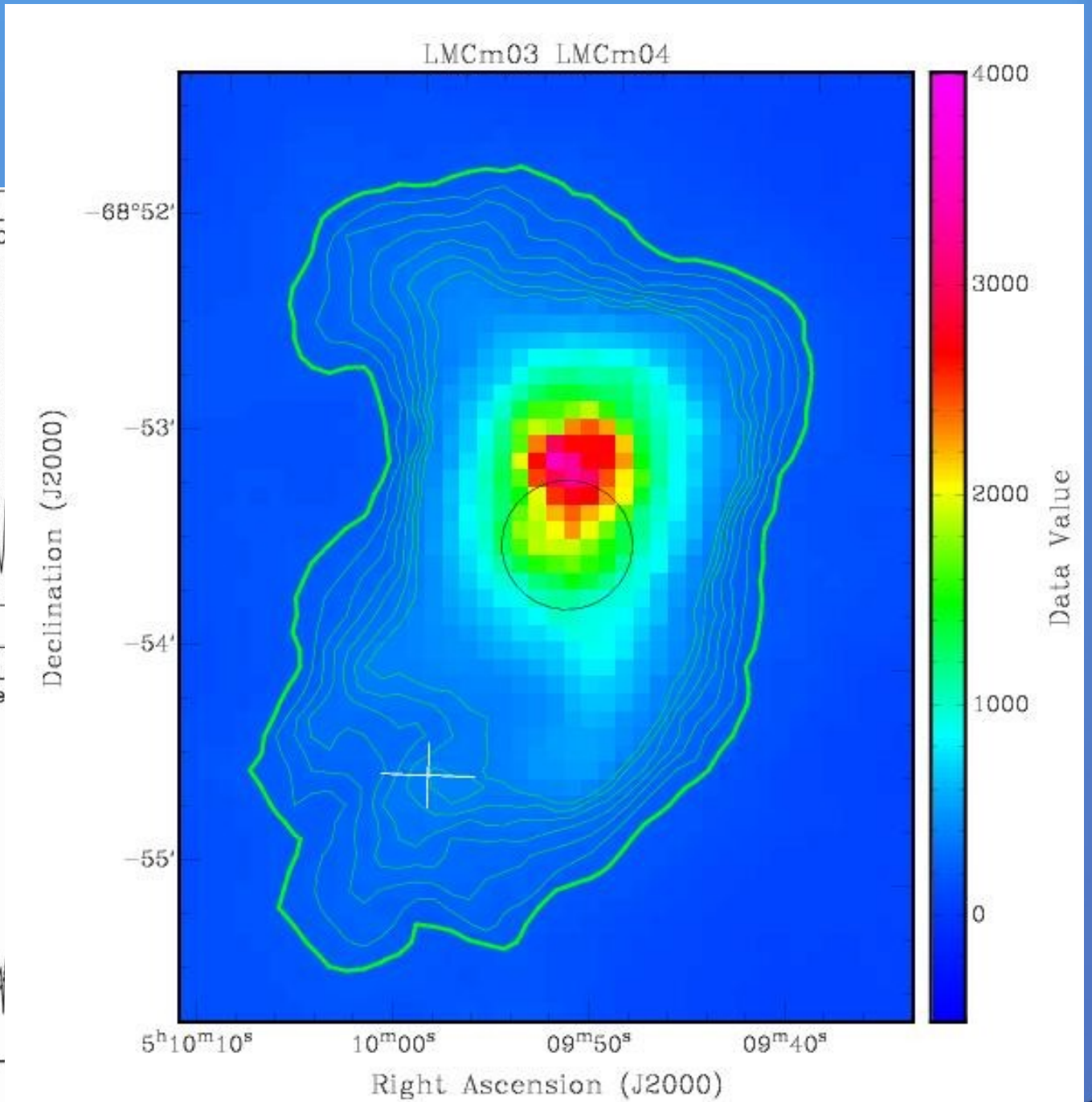

LMCm01 (N11)
CH3OH
2006 JUNE
Flux density (Jy)
Heliocentric Radial Velocity (km s⁻¹)


LMCm02 (IRAS05011)
CH3OH
2006 JUNE
Flux density (Jy)
Heliocentric Radial Velocity (km s⁻¹)


LMCm04 (N105a)
CH3OH
2006 JUNE
Flux density (Jy)
Heliocentric Radial Velocity (km s⁻¹)

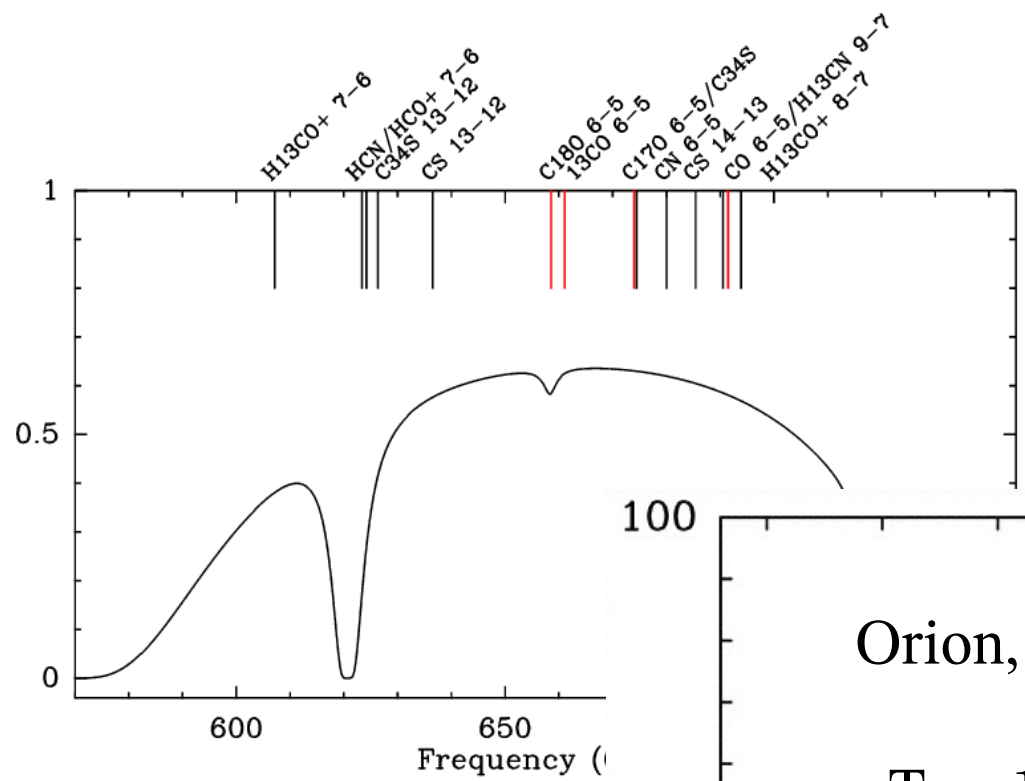

Flux density (Jy)

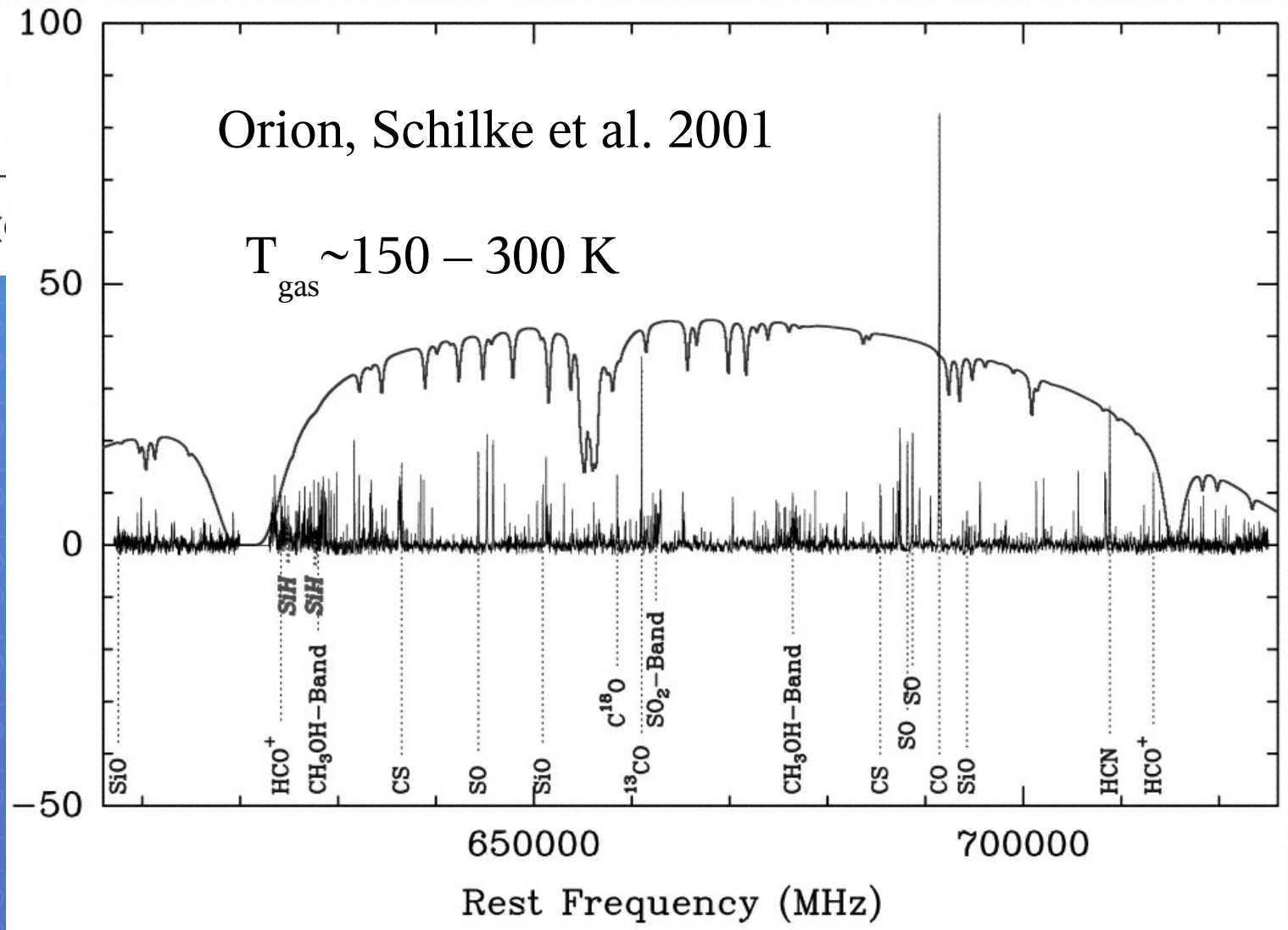

Flux density (Jy)


LMCm03 LMCm04
Declination (J2000)
Right Ascension (J2000)
Data Value

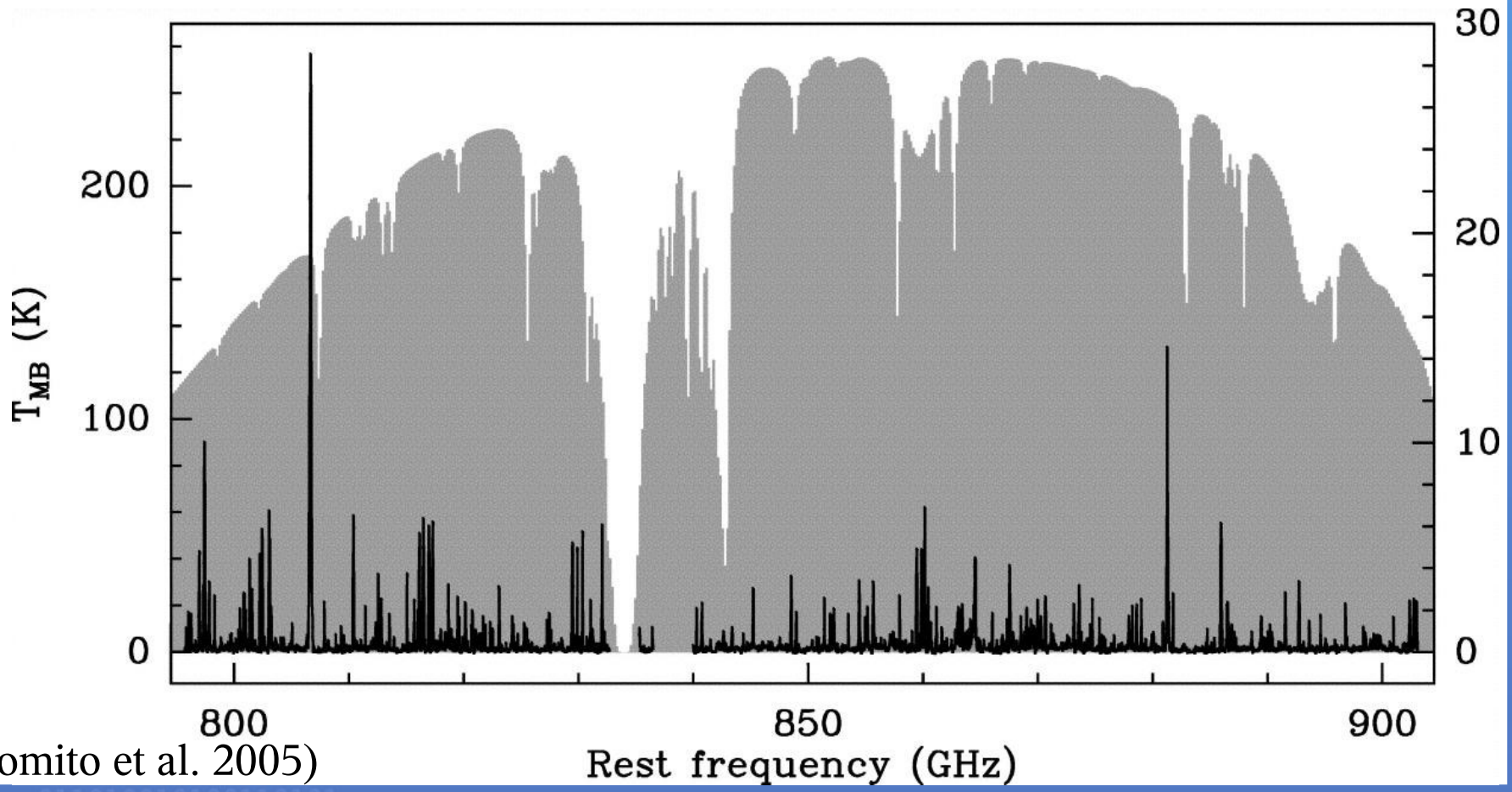
CCAT Opportunities

- Fast mapping for >few tens of pixels
  - Goal >100 pixels - 10x10 array
- IF bandwidth > 8 GHz
  - 2 GHz ^{13}CO & C^{18}O; 11 GHz CO & CN 6-5
  - Spectral resolution 0.1 km/s few km/s
- Choice of bands
  - 345 GHz
    - Peak CO emission for 20 K clouds
  - 490 GHz
    - CI line; strongest CO line in GC.
  - 650 GHz
    - All CO isotopologues
  - 850 GHz


H13CO+ 7–6
HCN/HCO+ 7–6
C34S 13–12
CS 13–12
C18O 6–5
13CO 6–5
C17O 6–5/C34S
CN 6–5
CS 14–13
CO 6–5/H13CN 9–7
H13CO+ 8–7
1
0.5
0
600
650
Frequency (

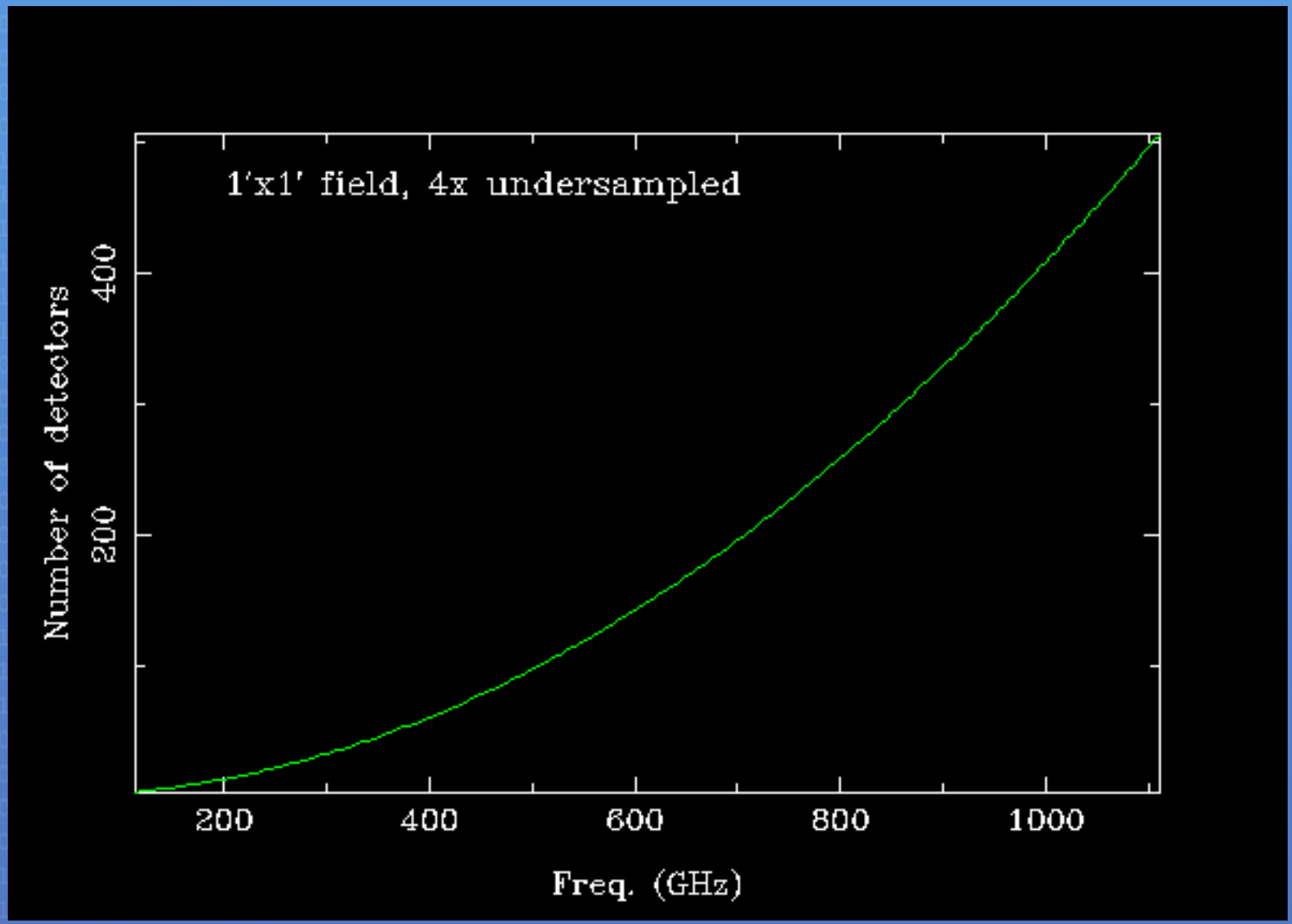

Orion, Schilke et al. 2001
T_{gas} ~150 – 300 K
100
50
0
−50
SiO
HCO+
SiH
SiH
CH3OH−Band
CS
SO
SiO
C18O
13CO
SO2−Band
CH3OH−Band
CS
SO
SO
CO
SiO
HCN
HCO+
650000
700000
Rest Frequency (MHz)

541 features, 929 transitions, 29 species



(Comito et al. 2005)

CCAT Field of View



CCAT Opportunity

- >100 pixels
- IF bandwidth > 8 GHz
- Spectral resolution 0.1 few km/s
- Choice of bands
  - 230 GHz
  - 345 GHz
  - 490 GHz
  - 650 GHz
  - 850 GHz

Hotter, denser gas

Larger field of view
Physically larger

Wide Field Imaging Science

'Big' picture (spatial, spectral & statistical) view of the formation and evolution of cores & clouds