# Microwave emissions, critical tools for probing massive star formation

## —Function of $NH_3$ molecule

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# Outline

1. Star formation regions and their probing
    - Stars form in molecular clouds (MCDs)
    - Micro-wavelength emissions of rare molecules
    - Observable molecular lines so far found

    useful tools to study MCDs-especially for massive star forming
2. $NH_3$ microwave spectroscopy
    1). Mechanism and advantages
    2). Investigate for early massive cores
    3). Probing kinetic process of high-mass star formation
    4). Other functions
3. Outlook

# 1. Star formation regions and their probing

- Stars form in molecular clouds:
  - Jeans criterion

    $M_J \propto (T^3/p)^{1/2}$

    Diffuse (atom) clouds $T \approx 100$ k too high

    $n \approx 1/cm^3$ too low

    Molecular clouds: $T \approx 10$ times lower usually

    $n \approx 10^3$ times higher

  - All star forming phenomena or activities are in MCDs

    Young stellar sources

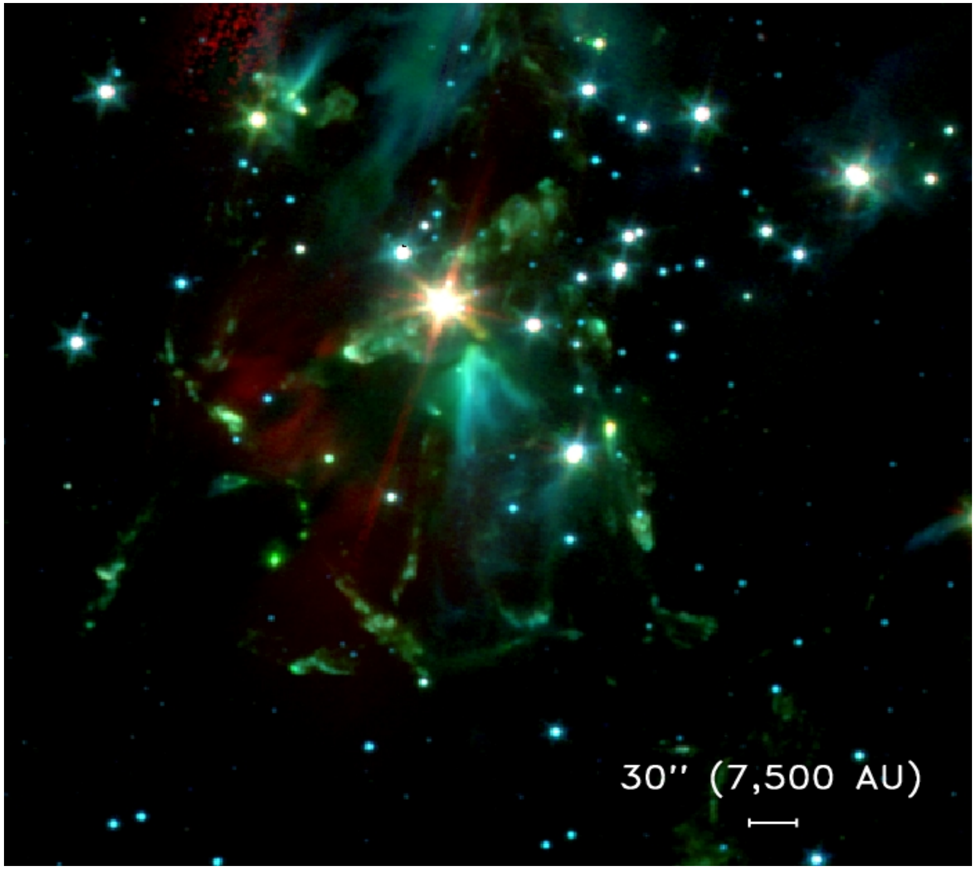
    outflows, HH objects

    Disks

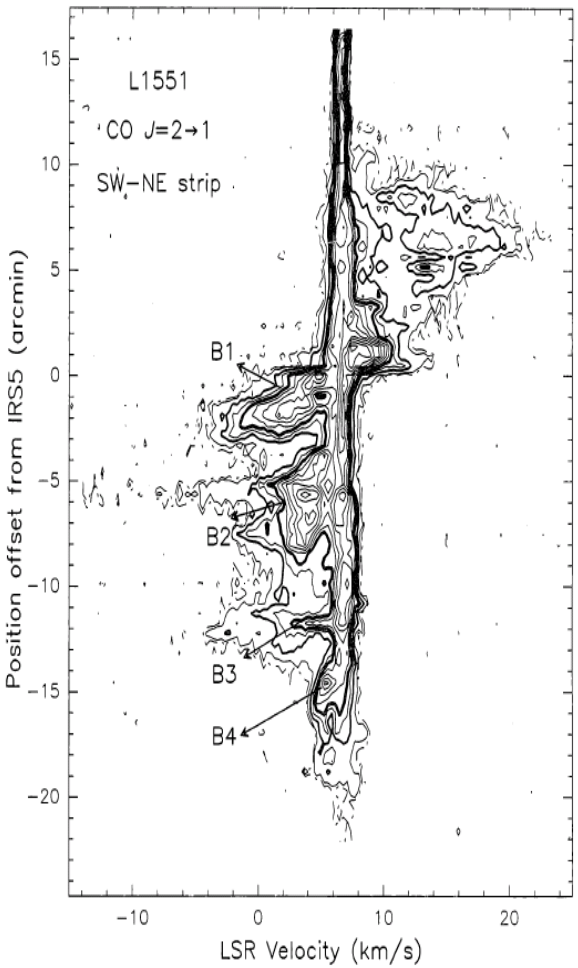
    Infall motions

    ... ...

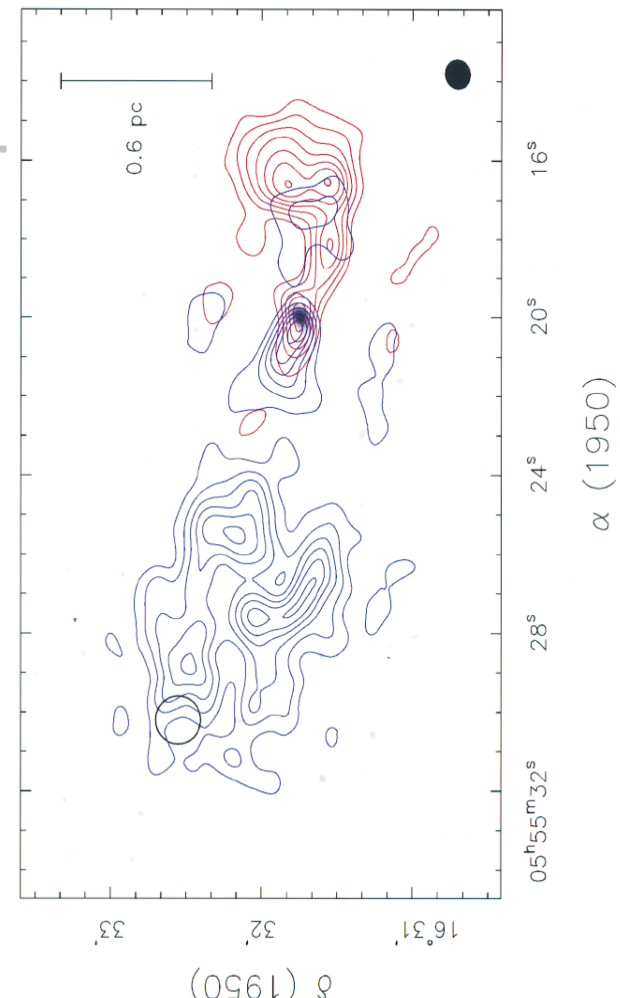

Orion



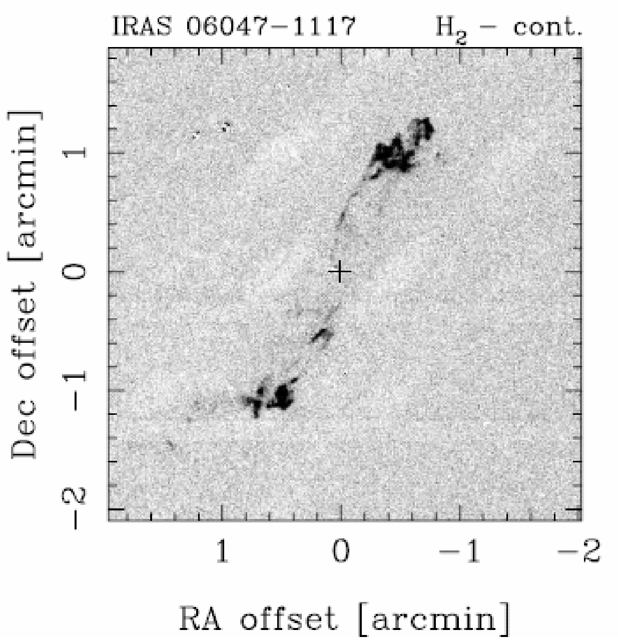

NGC 1333




L1551
Bachiller et al. 2004

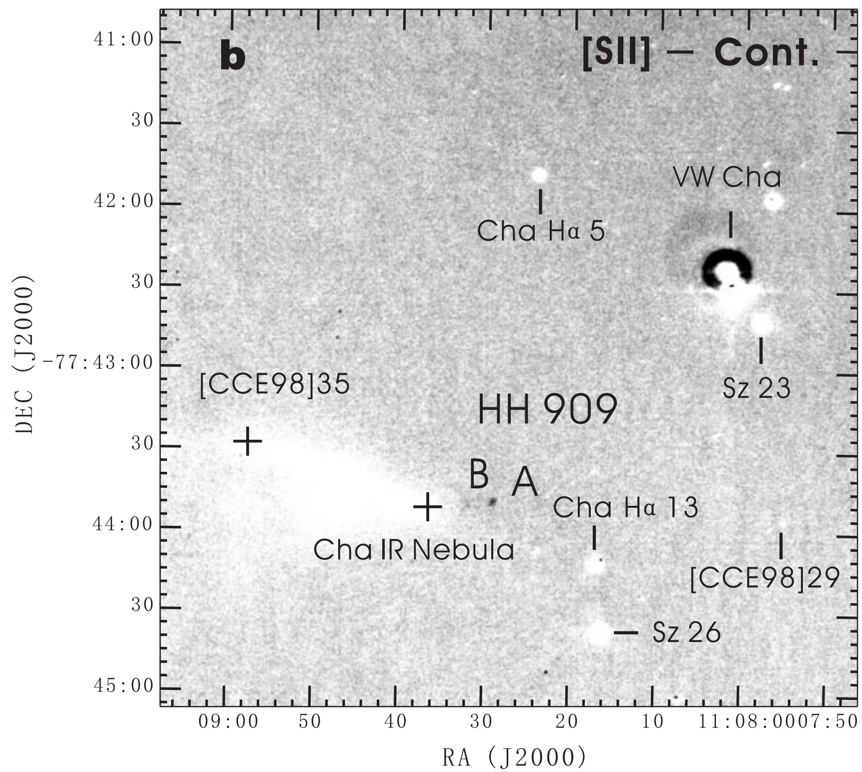


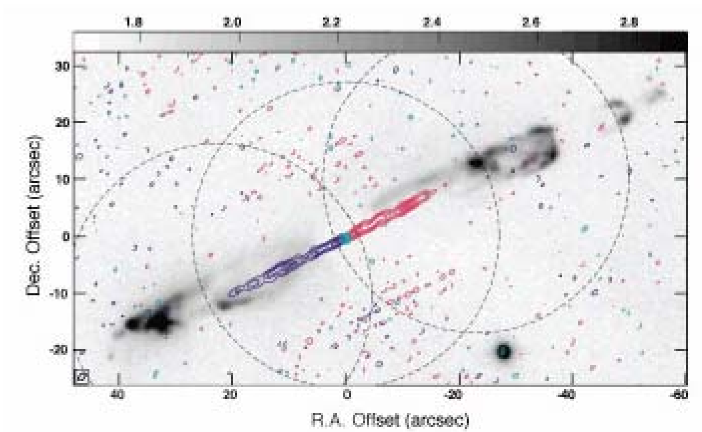

G 192.16
Shepherd et al. 1998



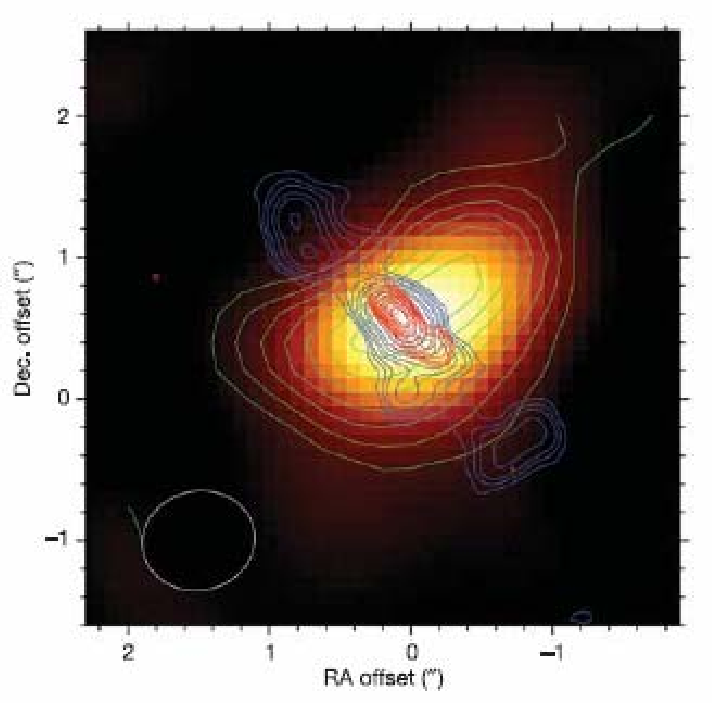

Yun et al. 2001

Wang et al. 2005

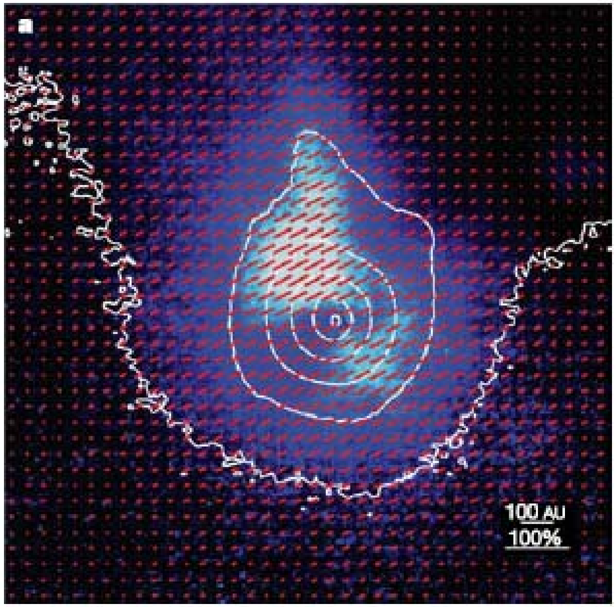


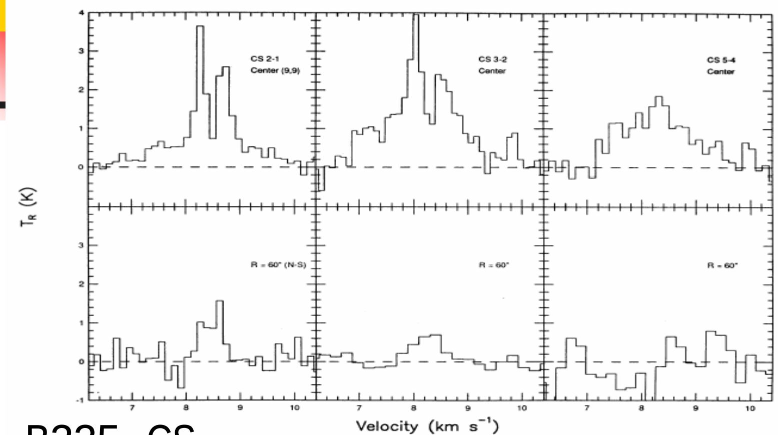

Hirano et al. 2005



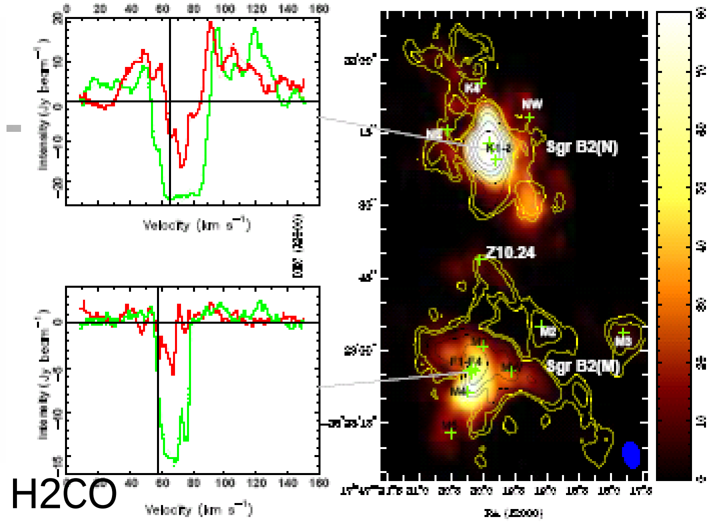

Cep A
Patel et a. 2005




NB in Orion
Jiang et al. 2005

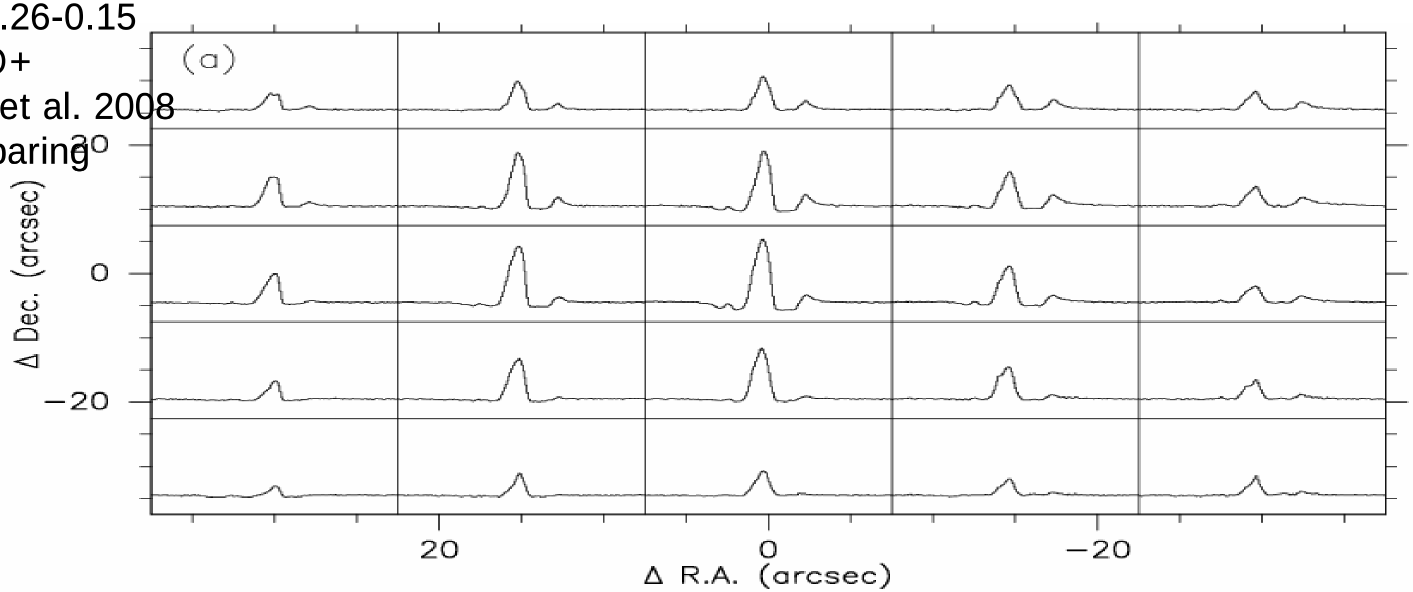



B335, CS
Zhou et al. 1993



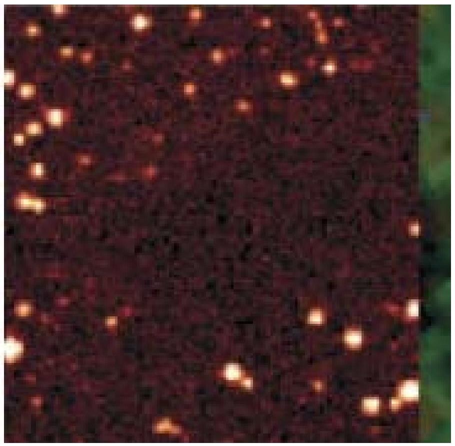

Sgr B2, H2CO
Qin et al. 2008

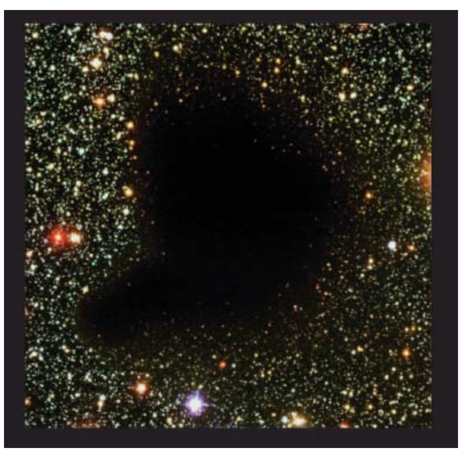
G34.26-0.15
HCO+
Wu et al. 2008
preparing



# Stars do form in dense parts of MCDs:

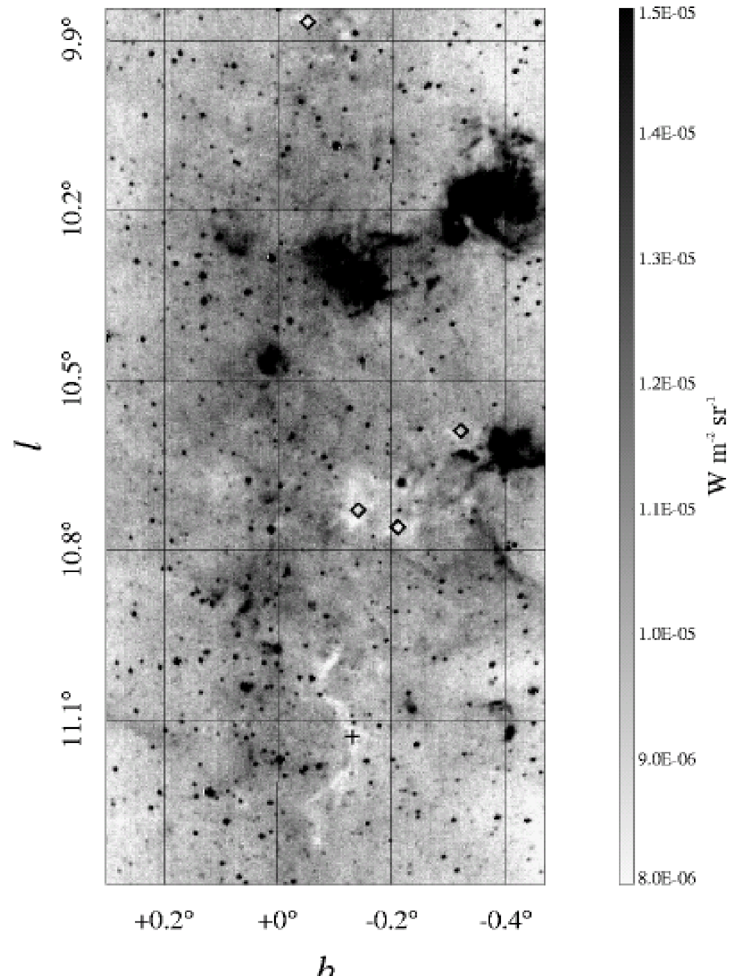
L1014, Young et al. 2004





La da et al. 2003

Part of Gal. plane Egan et al. 1998



- Micro-wavelength emissions—tools to study MCDs

Major component—$H_2$
—ultraviolet spectral lines do little (Kutner 1984)
Middle infrared emission: difficulty to excite
—without microwave length emission

Rare molecular species
Abundance: $[X]/[H_2]$: CO $\approx 4\times10^{-5}$ ; $^{13}$CO $\approx 10^{-6}$ NH3 $\approx 10^{-7}$
$CH_3CN \approx 10^{-8}$ -$10^{-9}$… …
With microwave spectral lines: observable
provide their environment information

Interstellar molecules: more than 140,
uncountable transitions
various excitation conditions

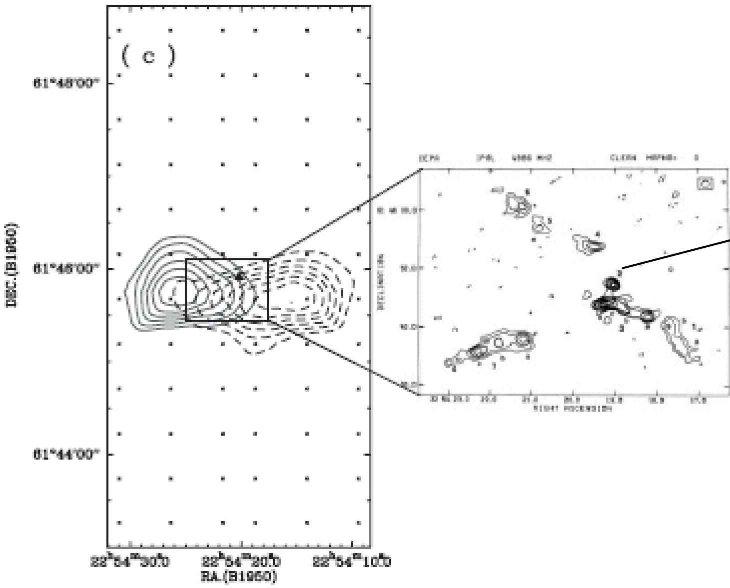
general molecular probes CO, 13CO, C18O… …
dense molecular probes CS, HCN, HCO+ … …
hot molecular probes, CH3CN, CH3OH, CH3OCH3… …

Emission, absorption, masers

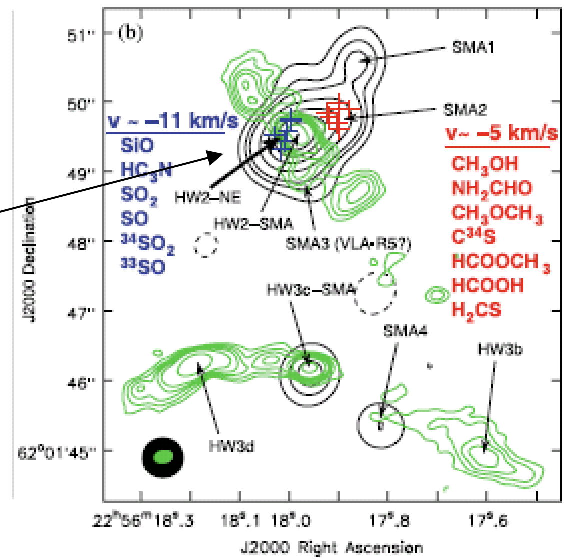
Critical for massive star formation —hot topic:
But difficulty: complex region, Rapid evolution

Huge system of microwave lines — rulers for wide range of physical conditions and fine structure

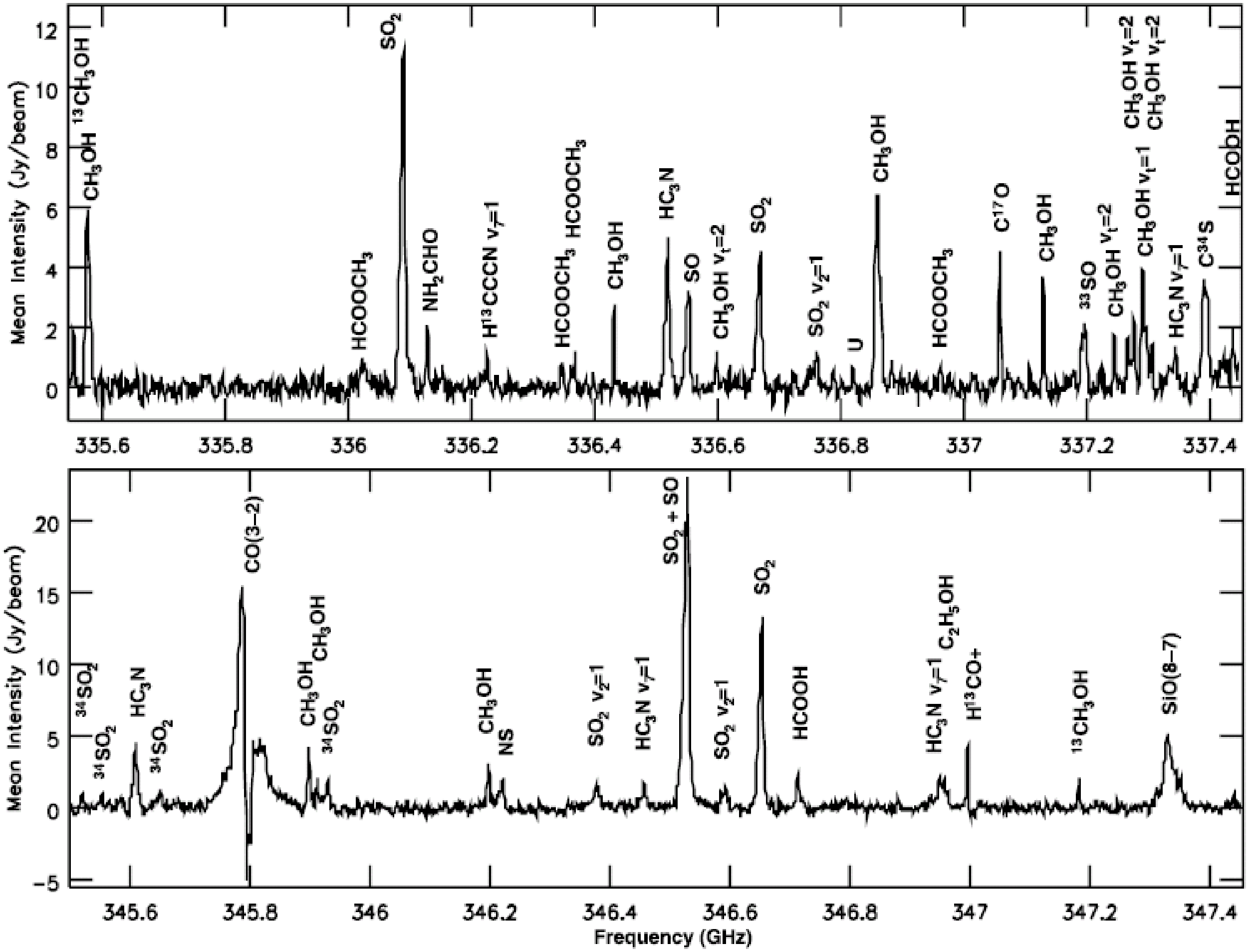
# Cep A



Wu et al. 2005a
NRAO 12 m




Brogan et al. 2008
SMA




Brogan et al. 2008

# 2. $NH_3$ microwave spectroscopy

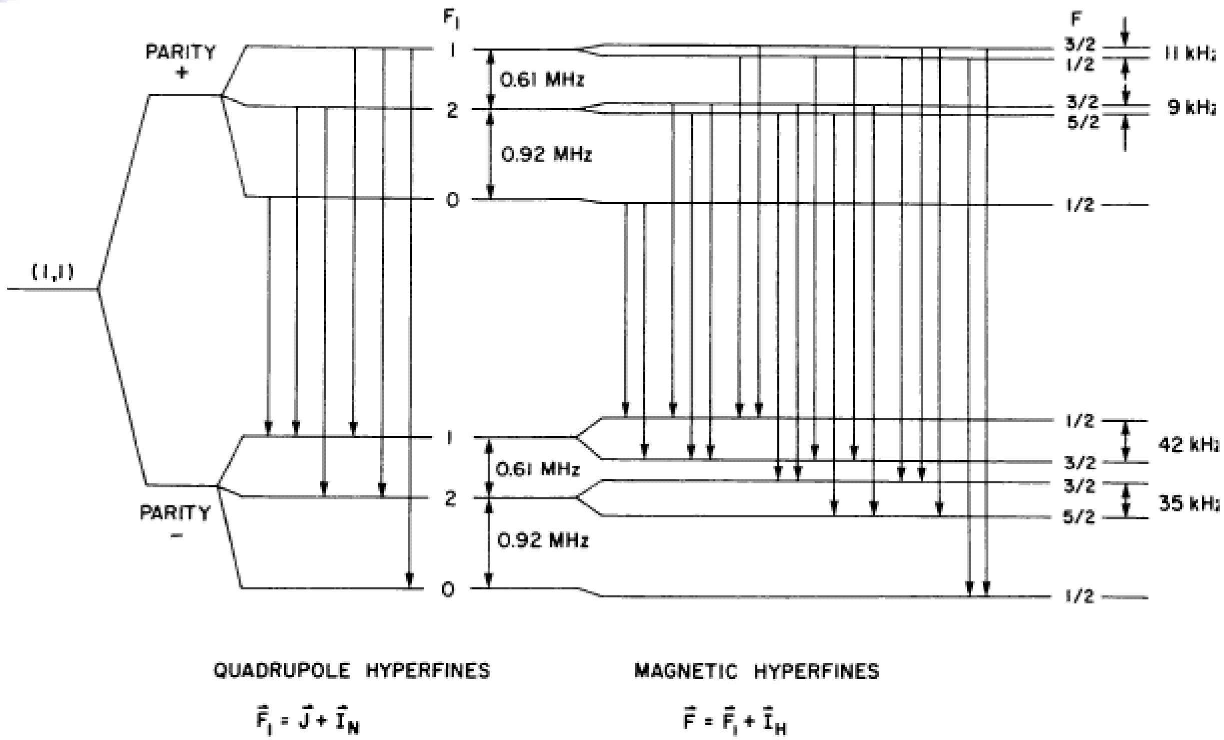
1). Mechanism and advantages

Inverse doublets-split of rotation energy level (J,K)

effect of N nucleus spin— hyperfine structure

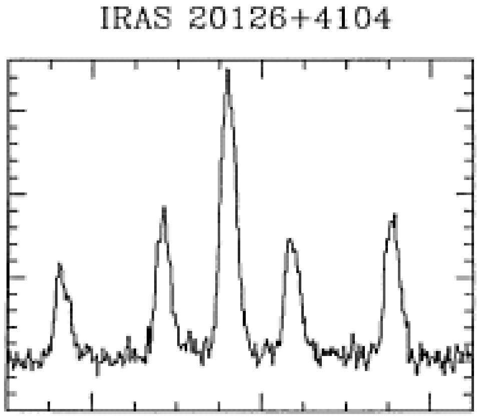
effect od H nucleus spin— magnetic hyperfine structure

(Ho & Towanes 1983)



F1
F
PARITY +
PARITY −
(1,1)
1
2
0
0.61 MHz
0.92 MHz
3/2
1/2
5/2
11 kHz
9 kHz
42 kHz
35 kHz
QUADRUPOLE HYPERFINES
$\vec{F}_1 = \vec{J} + \vec{I}_N$
MAGNETIC HYPERFINES
$\vec{F} = \vec{F}_1 + \vec{I}_H$

(1,1)--18 components
2, 3, 8, 3, 2
-- 1 main
4 satellite




Estalella
et al.1993

Advantages: lower inverse doublets
easily excited by collision
frequency difference small (1,1)-- (4,4)  23.69—24.13 GHz
convenient for detection
with satellite lines convenient for obtaining cloud parameters

# 2). Investigate for early massive cores

Physical properties of massive core —star forming

Natal cloud is easily altered by the onset of HII region
difficult to catch
$H_2O$ masers: thought as early characteristics
Plume et al. 1992, 1997; Shirley et al. 2003,
Muller et al. 2002

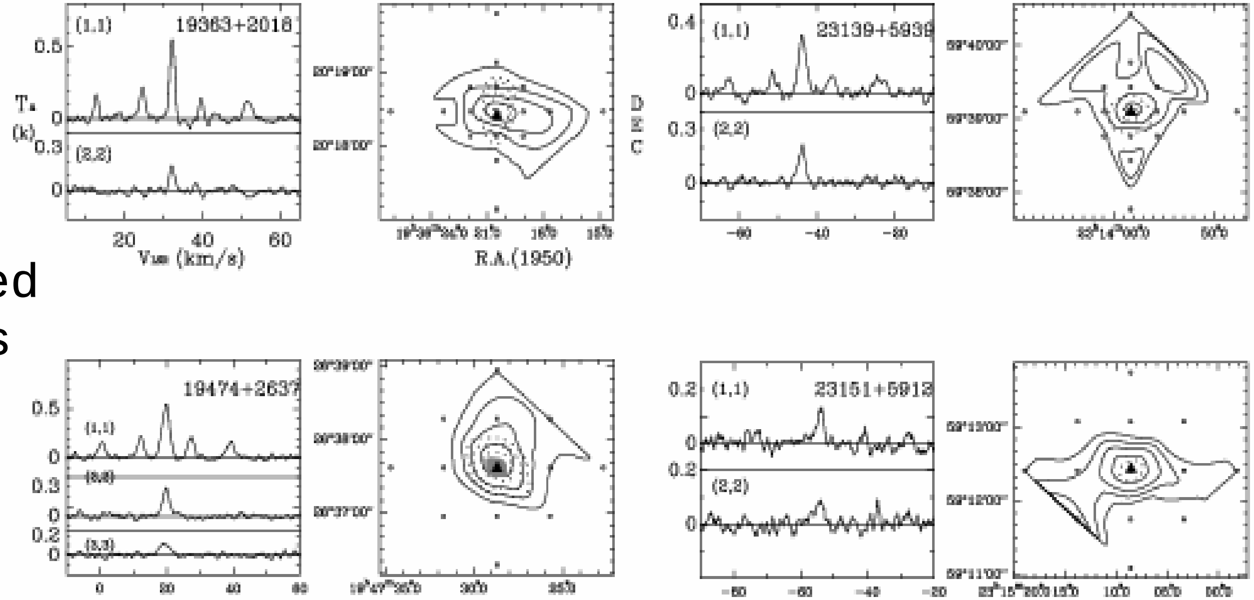
An $NH_3$ survey:

- Purpose: to search precursors of UC HII regions (PUCHIIs) or high-mass protostellar objects (HMPOs)
- Sample –Key criteria: With IRAS Lb = $10^3 \sim 10^6 L_\odot$ --Massive
  without 6 cm emission—young
  Same as Molinari et al. 1996 and Sridharan et al. 2002
  35 water masers , 100m Effelsberg, MPIfR
  (Wu et al. 2006)
- (1,1), (2,2), (3,3), (4,4); Mapping
- Results: 17 were obtained

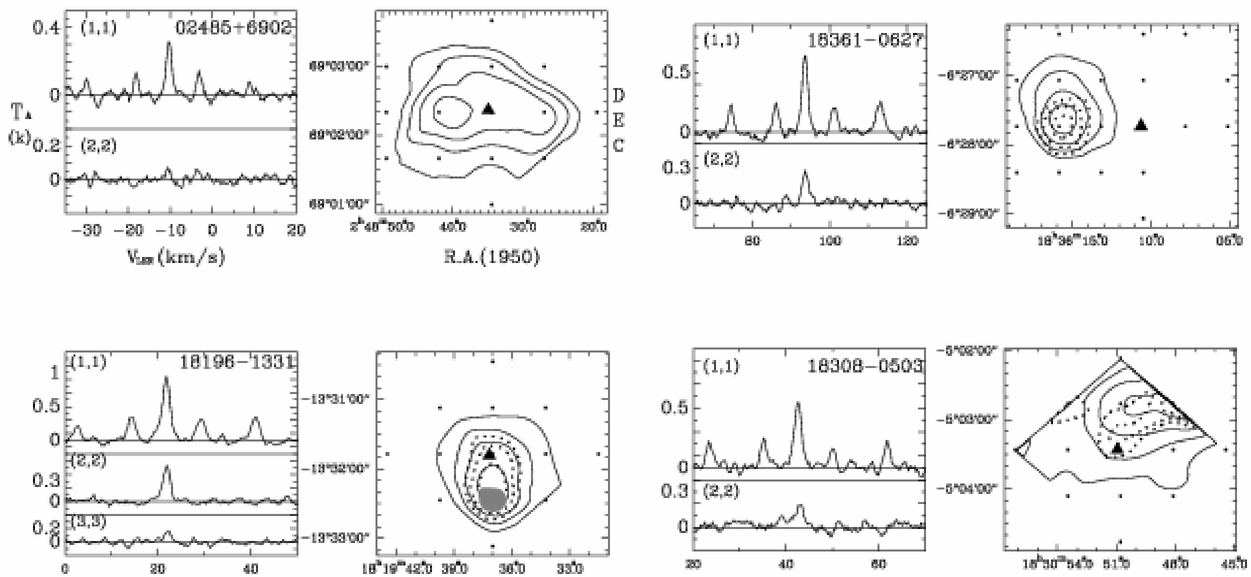
11 coincide with IRAS sources, may be candidates of PUCHIIs (group I)

6: the emission peak is deviated from the IRAS sources (Group II)

Cores with peaks overlapped by IRAS sources




Cores with peaks offsetting from IRAS sources



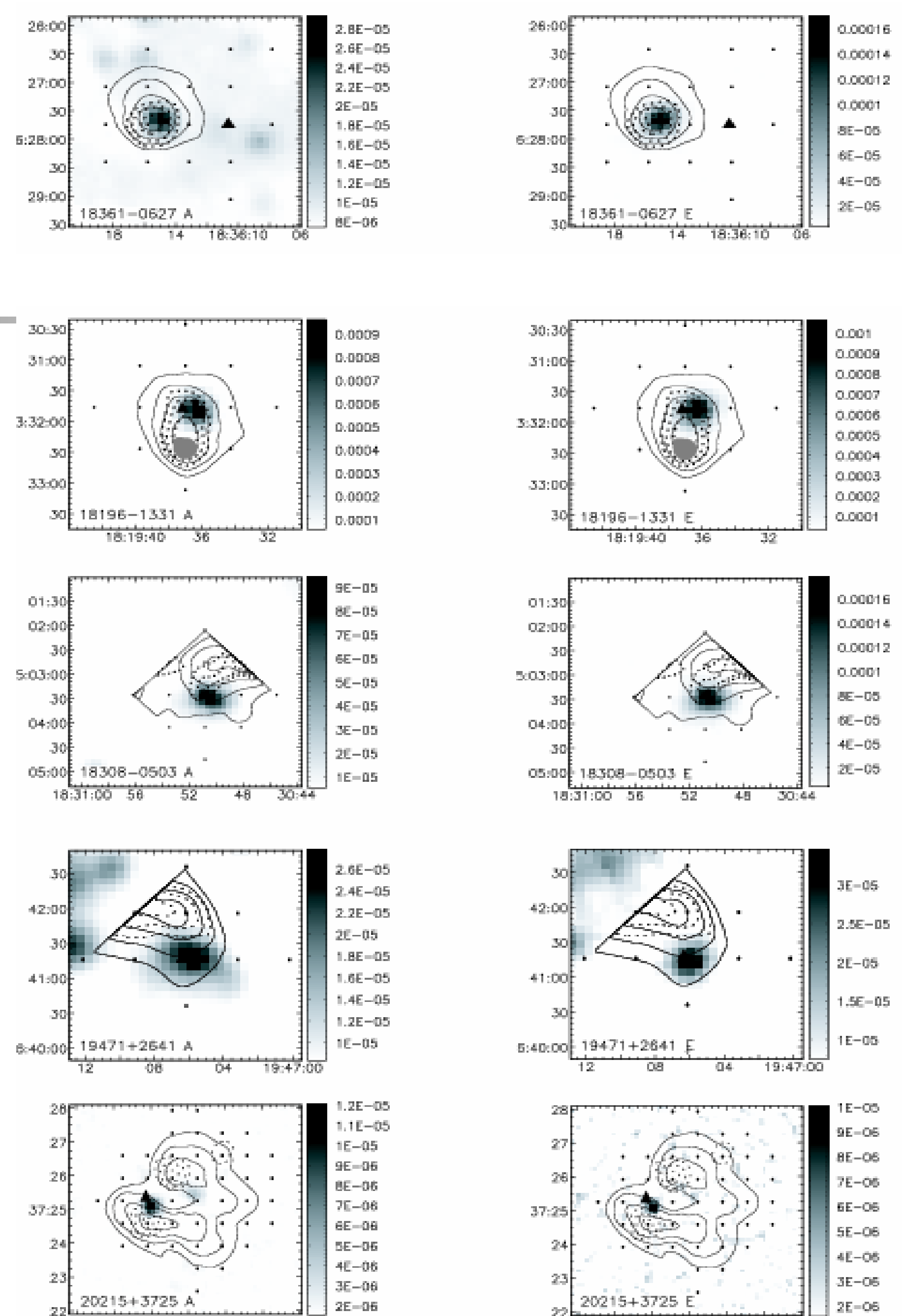
Sources in group II may have MSX (Midcourse Space Experiment) or Spitzer sources

**One with MSX source**

**five without detectable infrared sources**

**— younger**

**massive, $7.8\times10^{2}\,M_{\odot}$**



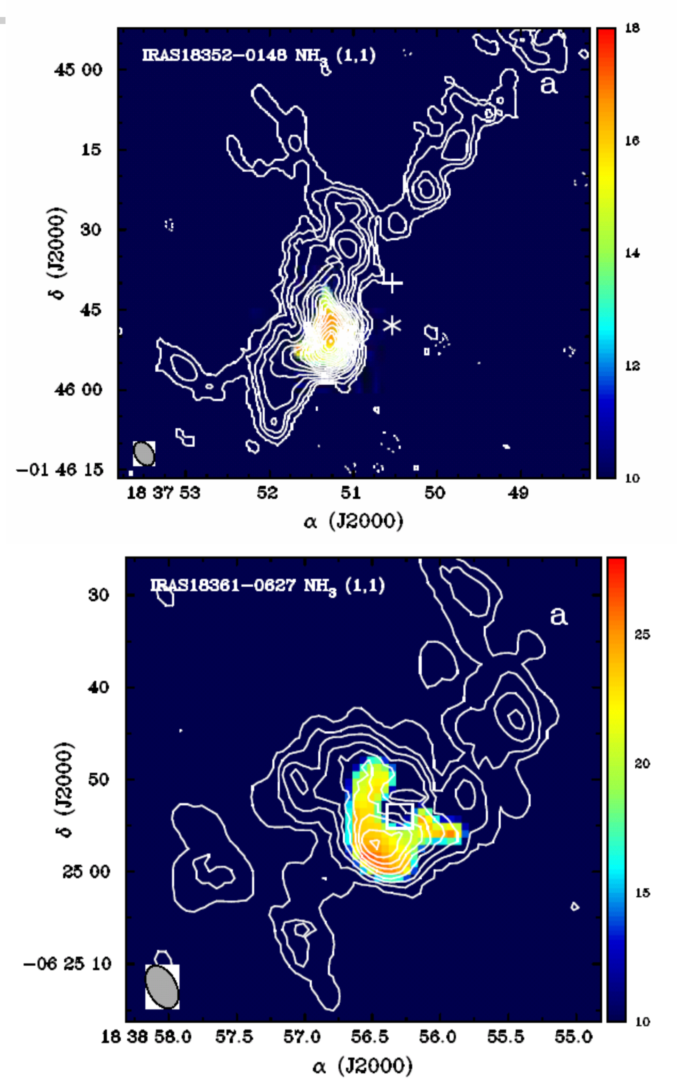
Followed up observation:

VLA for 5 $NH_3$ cores of group I

(Wang et al. 2007)

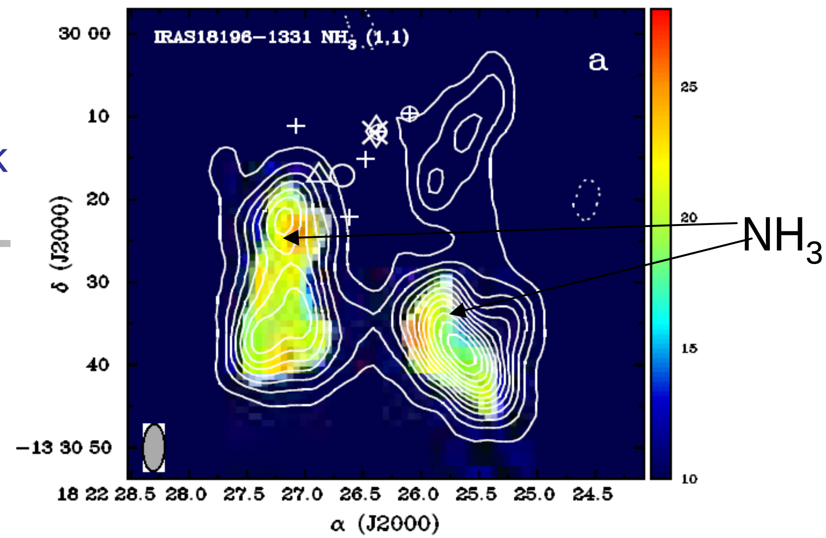
2 of them with the core also deviated from the infrared sources

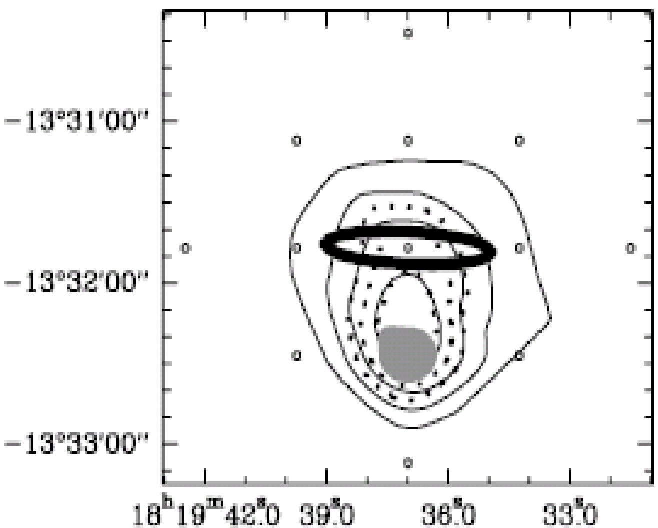
→ 47% ((6+2)/17) are deviated



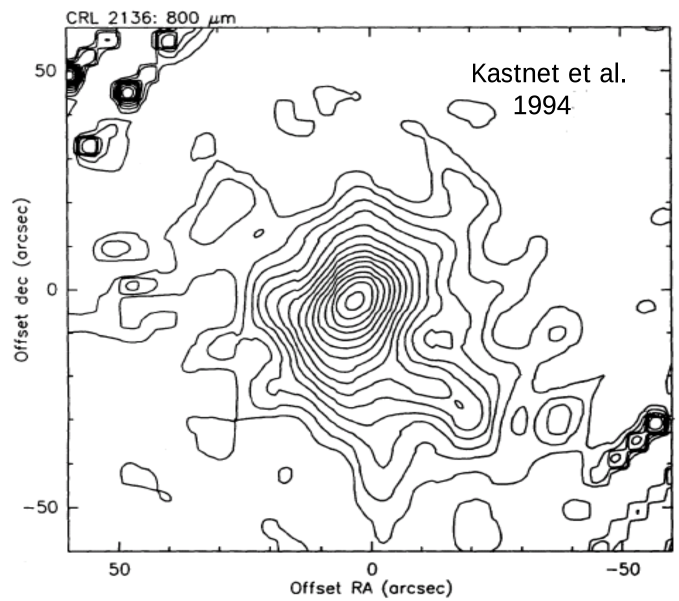
# IRAS18196-1331:

2MASS H$_2$O maser
7mm peak 3.4mm peak
800 μ m peak
370 μ m peak
(Wang et al. 2006)




NH$_3$ core: (Wu et al. 2006)
Emission regions



A new survey toward 100 IRAS sources with 6 cm or $CH_3OH$ masers is ongoing (Wu et al. 2008)

59 sources were searched with a five point mapping in a cross pattern

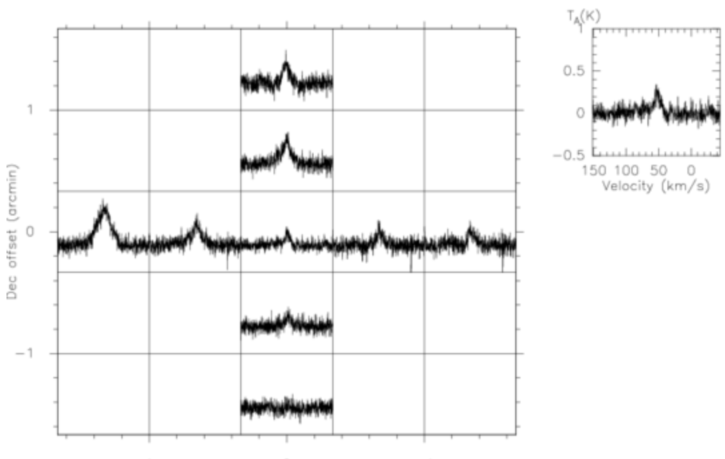
33 sources were detected

15 are deviated from the infrared source

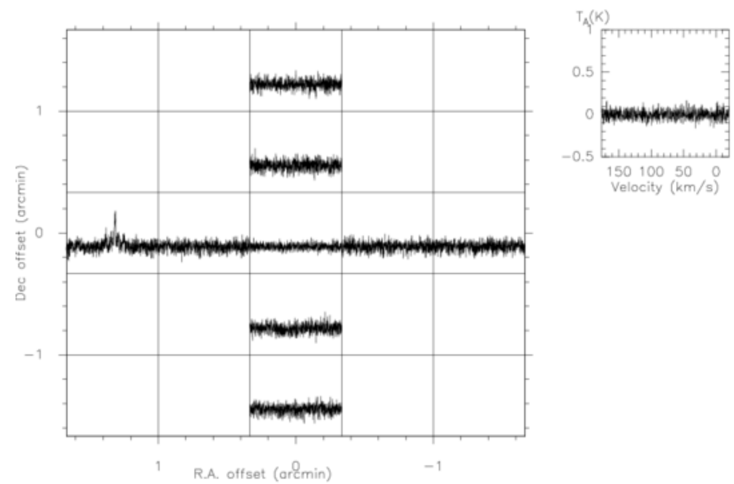
not observed with VLA

→ 45% (15/33) of the $NH_3$ cores were not coincident with the IRAS sources

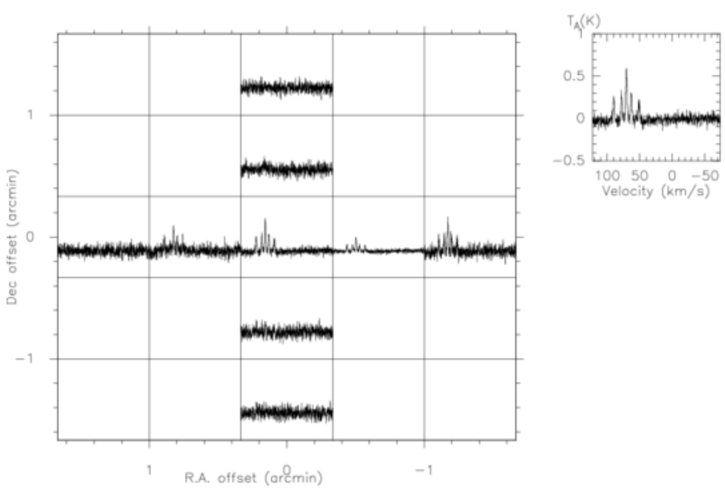
17440−2825, NH3(1,1), Δv=−0.245km/s, σrms=0K km/s

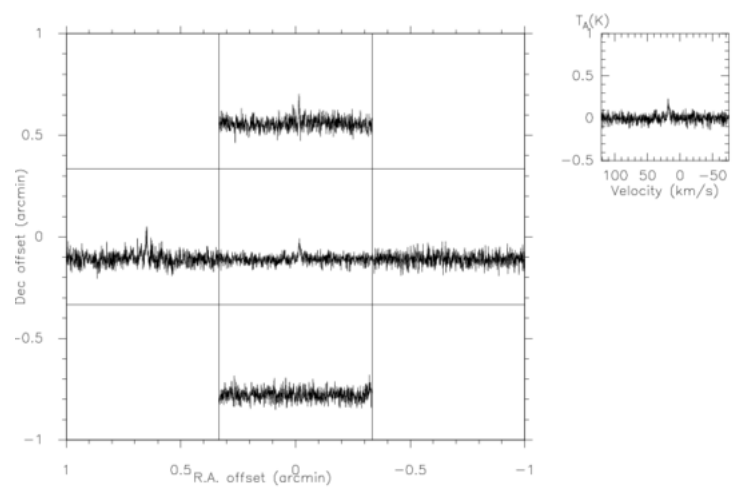



19031+0621, NH3(1,1), Δv=−0.245km/s, σrms=0K km/s




18249−1116, NH3(1,1), Δv=−0.245km/s, σrms=0K km/s

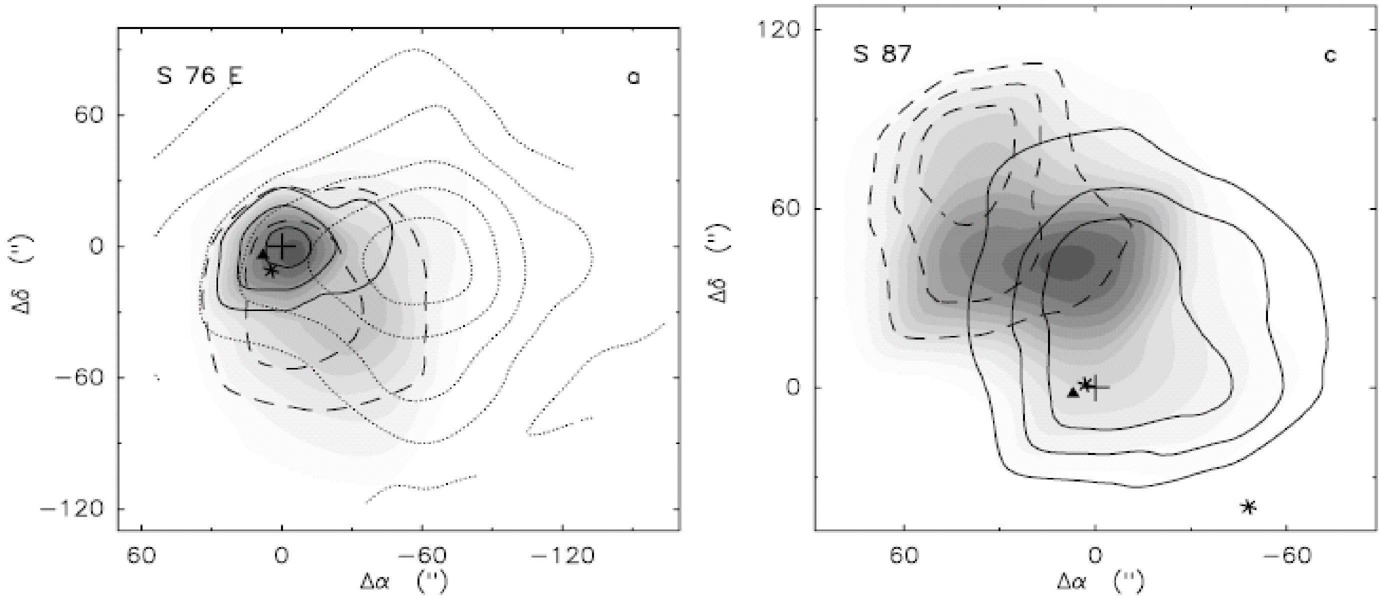


- **Such kind of cores exist in previous $NH_3$ surveys:**

( Harju et al 1993; Zinchenko et al. 1997)

Zinchenko et al. (1997) found $NH_3$ underabundance in the vicinity of the central source: for example, S87



## Explanation:

- Stars move away from the cores

  It seems to be difficult for the situation with several infrared sources around the core (Clark 1987; Harju et al. 1993)

- The core peak and the IRAS position correspond to different gas clumps.

  --The IRAS source might be more evolved and has dispersed the parental clump (Wu et al. 2006)

- The $NH_3$ core is destroyed by a reaction with carbon ion (Turner 1995)
- $NH_3$ core may be triggered by the vicinity stellar sources

  (Churchwell 1999; Deharveng et al. 2004)

  Ice mantles on dust grains evaporated by UV radiation generated in shocks

→ $NH_3$ core could exist before infrared source appears

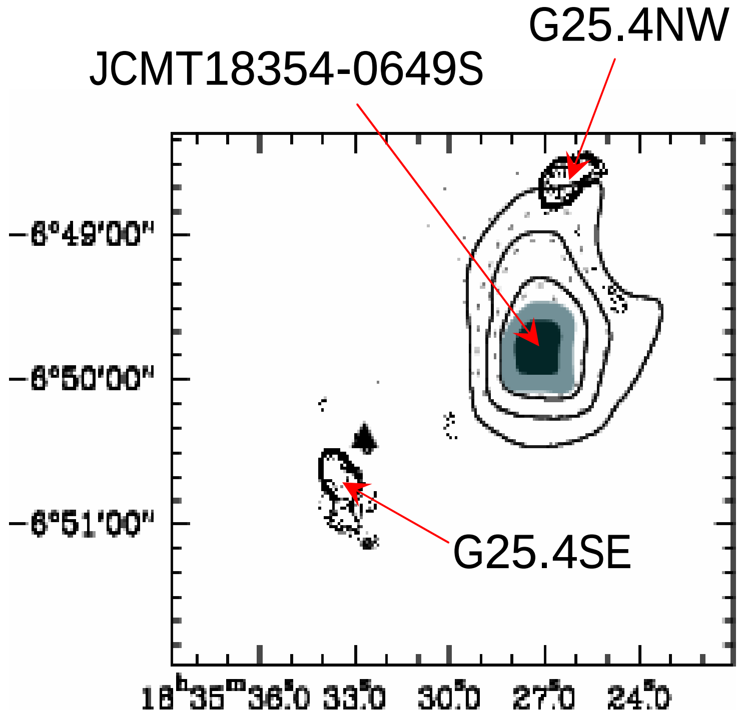
# $NH_3$ cores and star forming activities

G25.4-0.2 region:

Three sources:

- CoreJCMT18354-0649S
- G25.4NW
- G25.4SE

(Wu et al. 2005b)

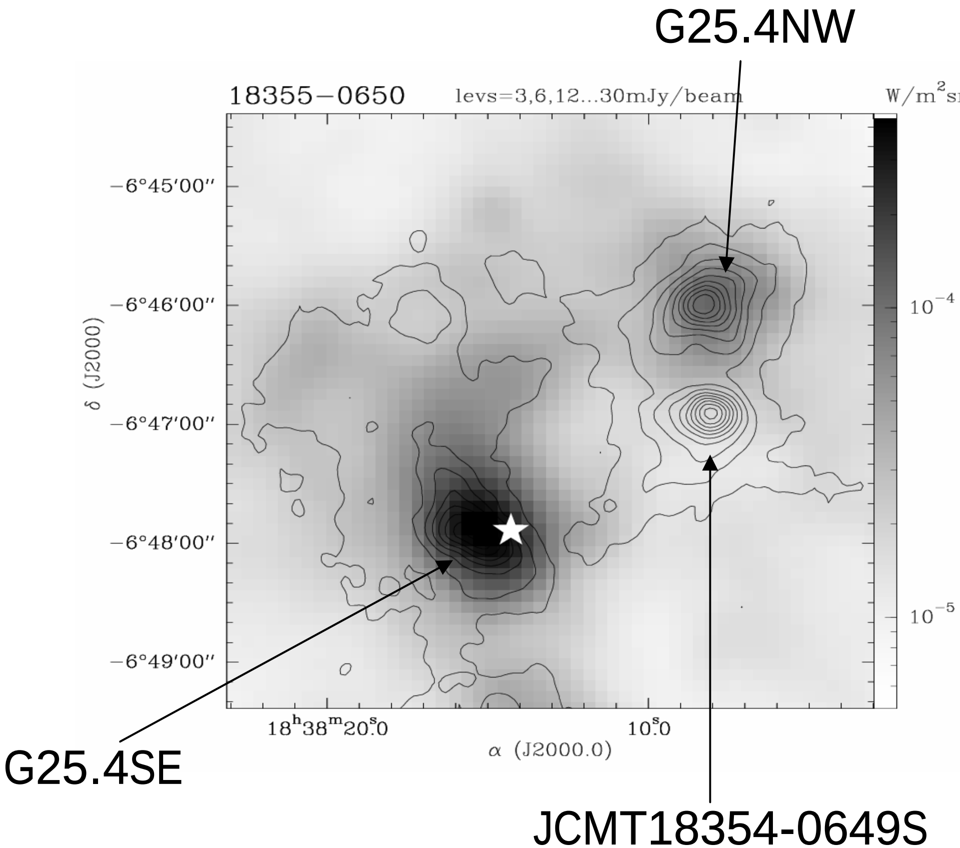


**850μm +MSX A band:**
**Sub mm data from JCMT archive:**

- **JCMT18354-0649S**
  **Sub mm, 450, 850μm**
  **no MSX**

- **G25.4NW**
  **Sub mm, 450, 850μm**
  **MSX source**

- **G25.4SE**
  **Sub mm,450，850μm**
  **IRAS source**



# Core JCMT18354-0649S

M: 820 Msun

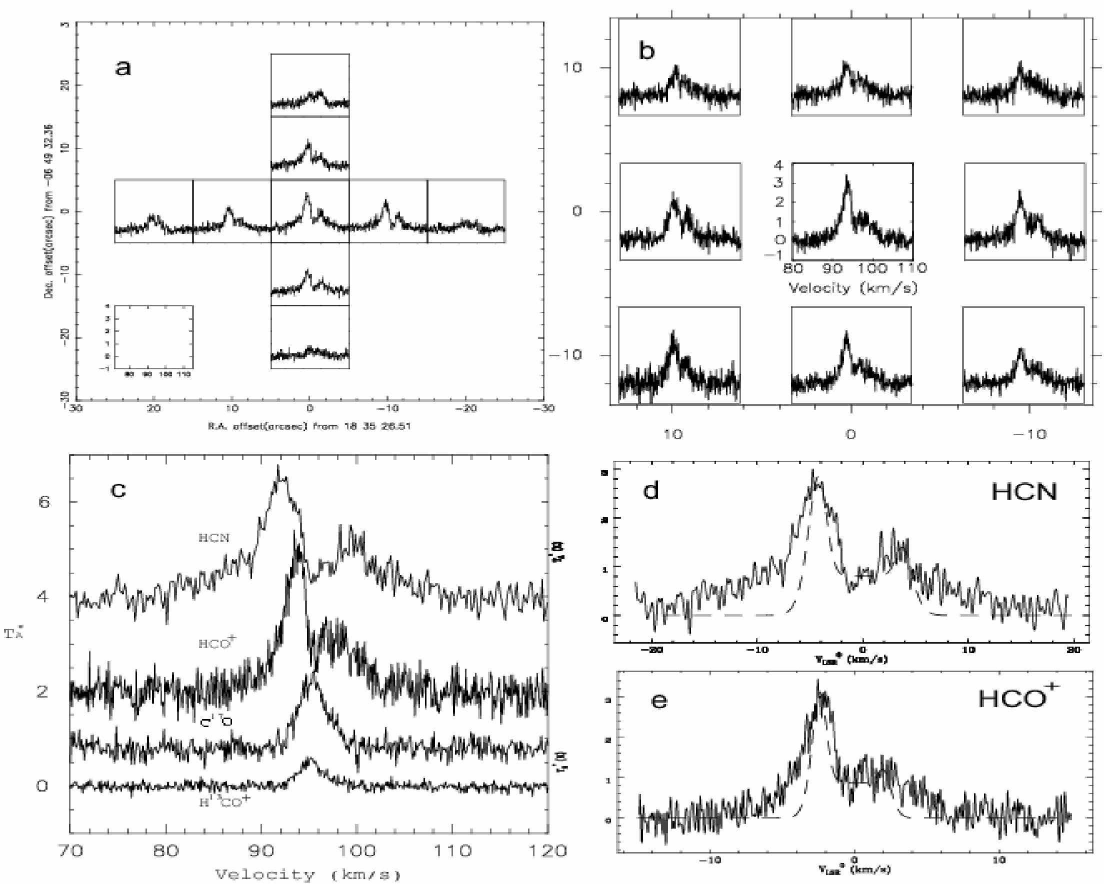
Td: < 29 K

Optical Thick:
- HCN (3-2),
- $HCO^+$(3-2)

Optical thin:
- $H^{13}CO^+$(3-2)
- $C^{17}O$ (2-1)

→ multiple evidence was obtained

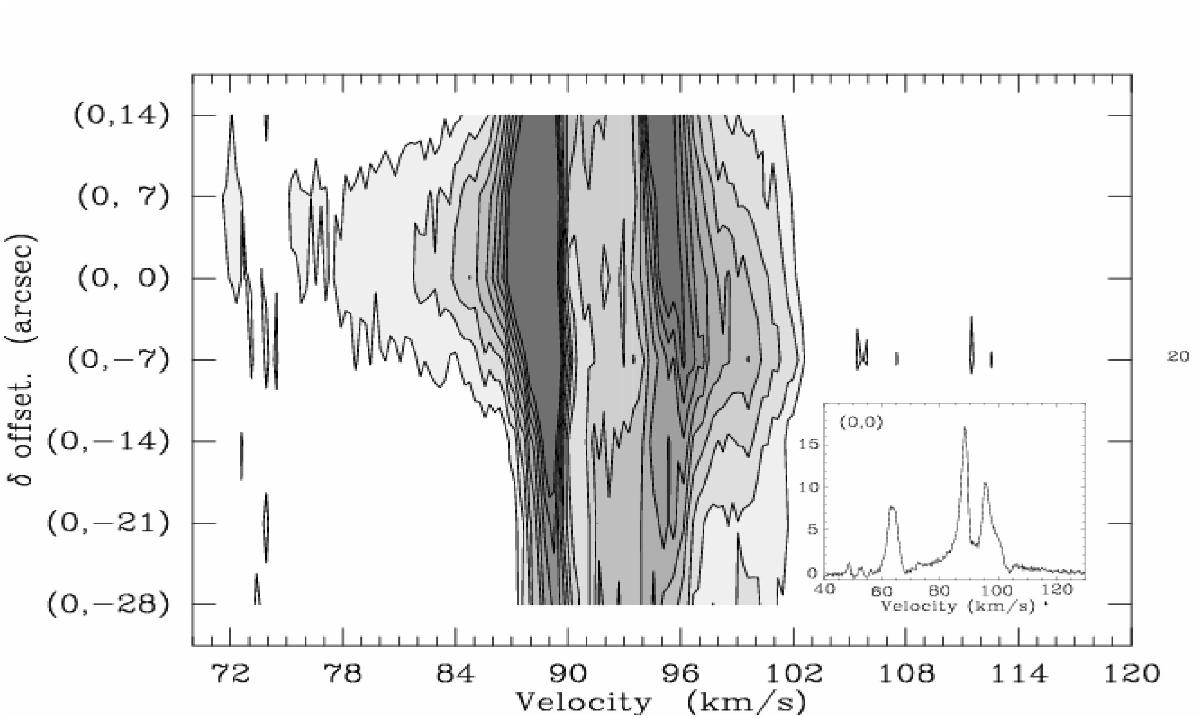
Model fitting



Molecular outflow: CO(3-2), JCMT, an obvious outflow

$\Delta V \sim 38$ km/s,

t ~ estimated 6600 yr.



# G25.4 NW

The north-west core:

HII region VLA 4.8GHz, 3.5 Jy

Infrared $T_d$ : 59 K

Lb:5.6x$10^5$ $l_\odot$ (5.7 kpc)

(Lester et al. 1985)

SCUBA core: more extended than the south one, M:1000 $M_\odot$

JCMT:

Optical Thick:

HCN (3-2),
$HCO^+$ (3-2)

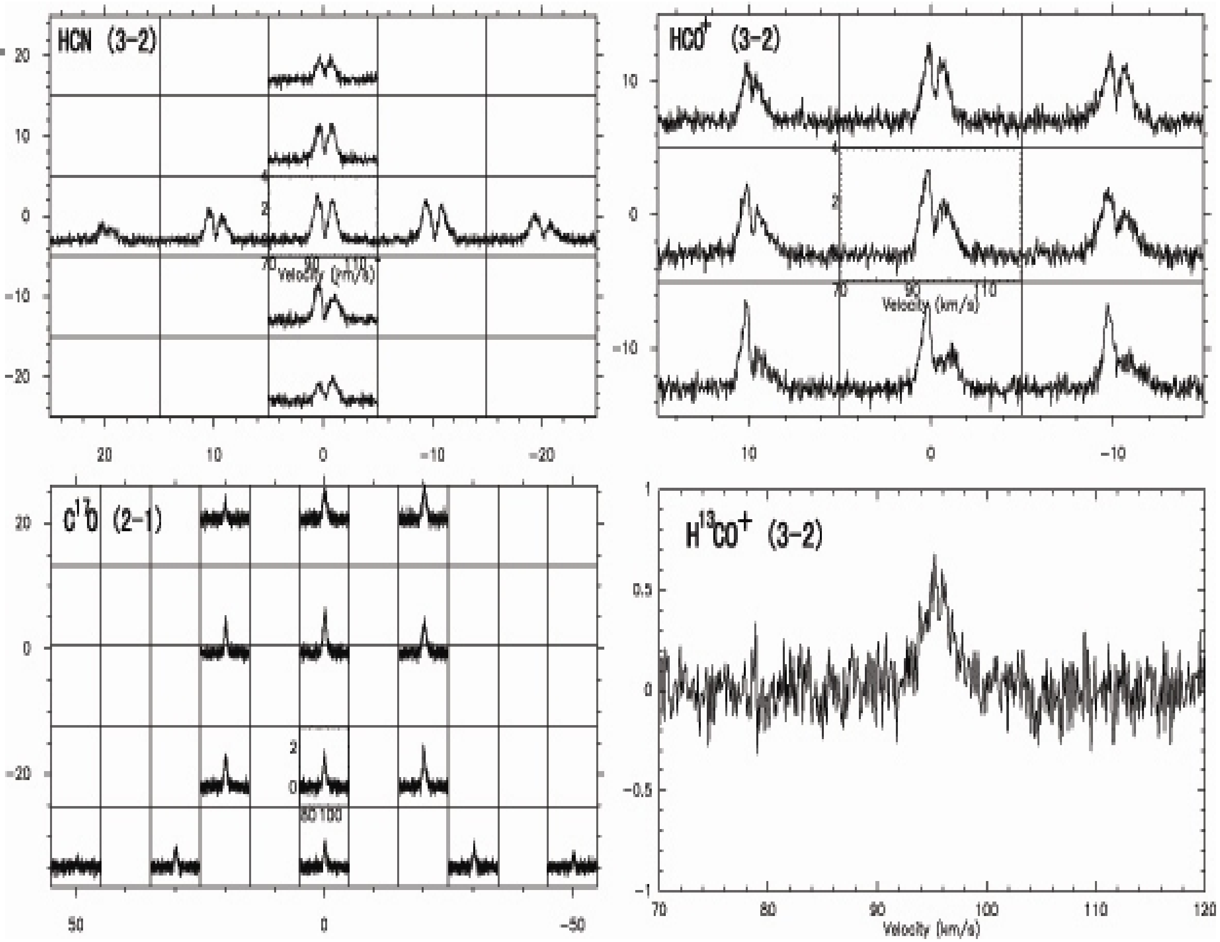
Optical thin:

$H^{13}CO^+$ (3-2)

$C^{17}O$ (2-1)

Model fitting

→ infall



# G25.4SE

The south-east core of G25.4-0.2 region: IRAS 18355-0650

Sub mm

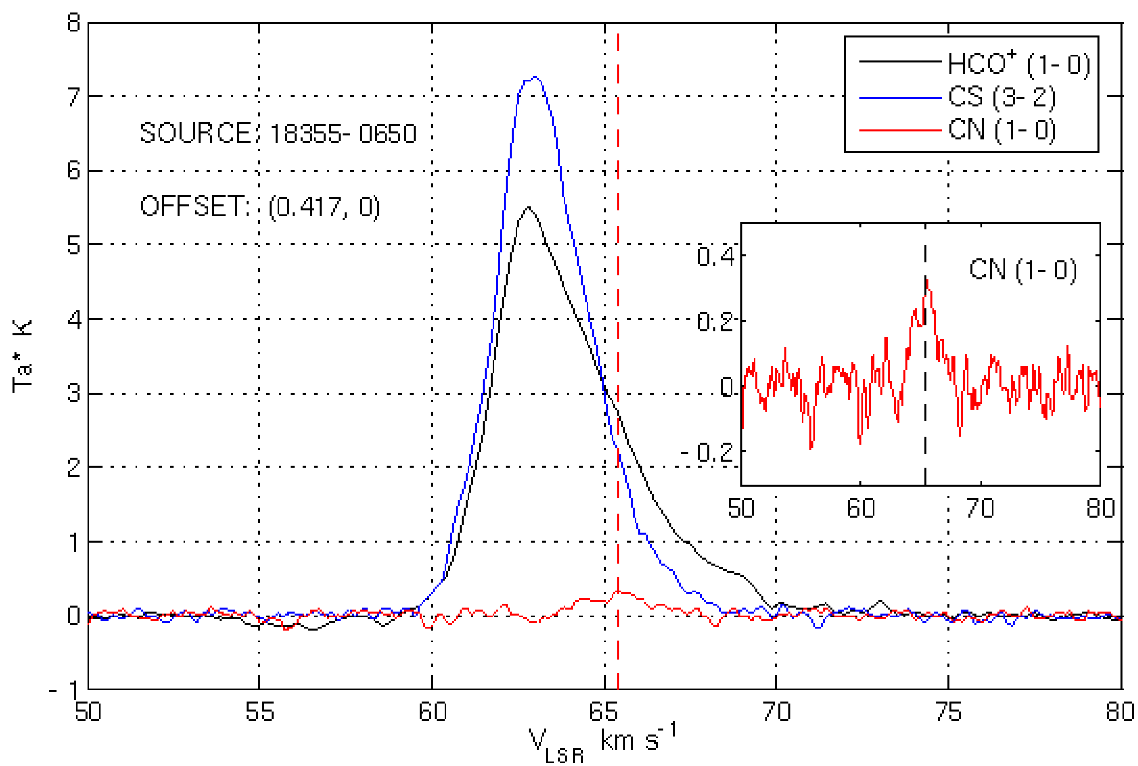
Inflow: (Wu et al. 2008)

Optical thick: IRAM

CS (3-2), $HCO^+$(1-(

Optical thin: PMO (13.7m)

CN N=1-0



| | CoreJCMT | G25.4NW | G25.4SE |
|---|---|---|---|
| $NH_3$ | Y | no core | N |
| HII | N | Y | Y |
| Sub mm | Y | Y | Y |
| Dense lines | Y | Y | Y |
| Infall | Y | Y | Y |
| H2O maser | N | N | Y |

the NH3 core can be with Sub mm, dense gas, inflow, outflow. not associate with HII region and H2O maser

# W 3 region

W3 main

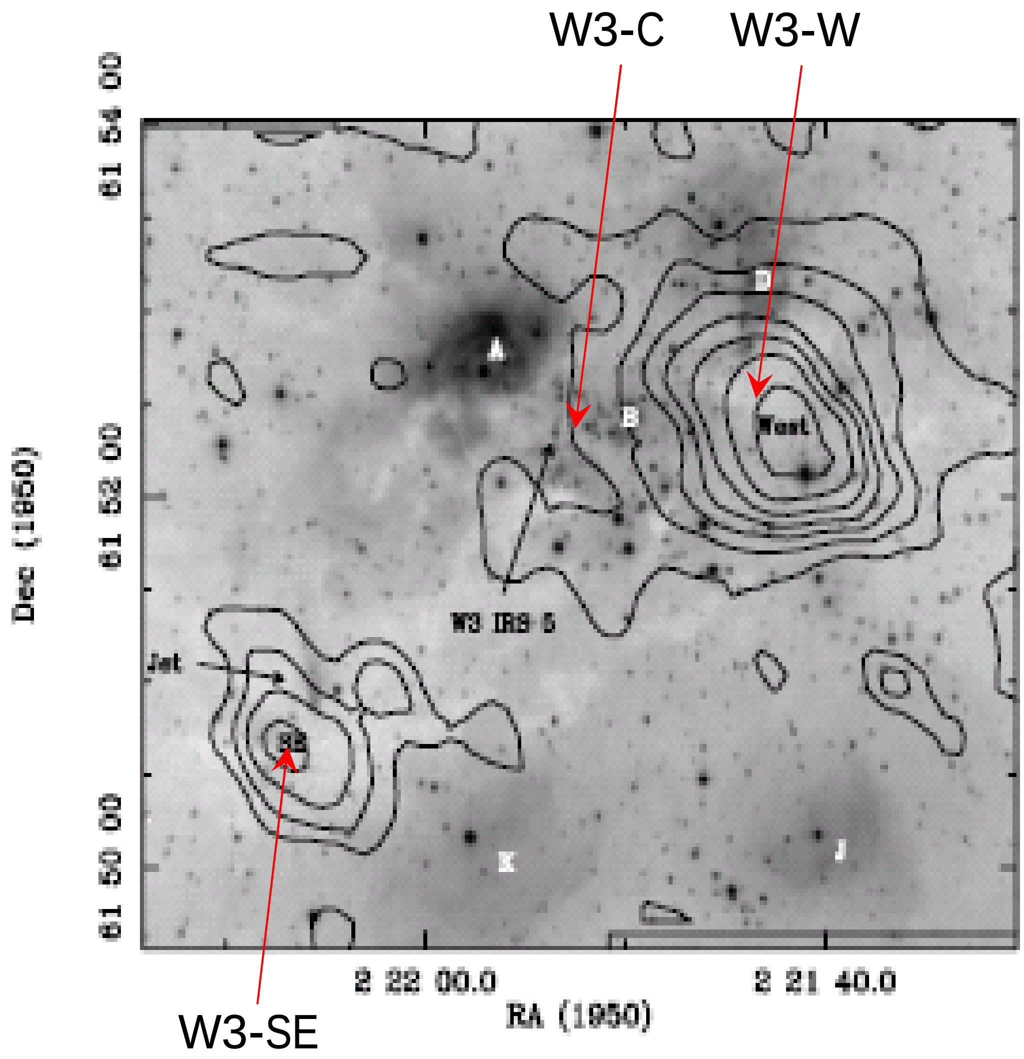
NH3 core at

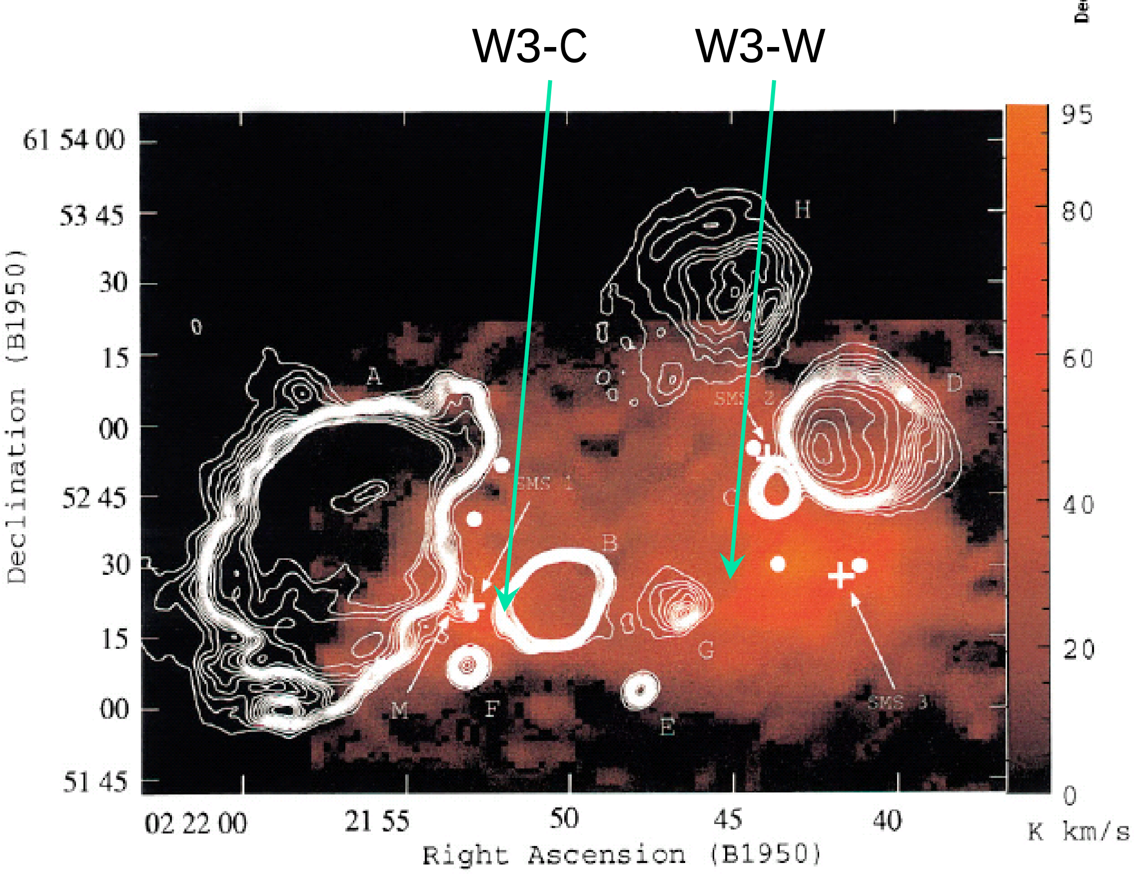
- W3-W
- W3-SE

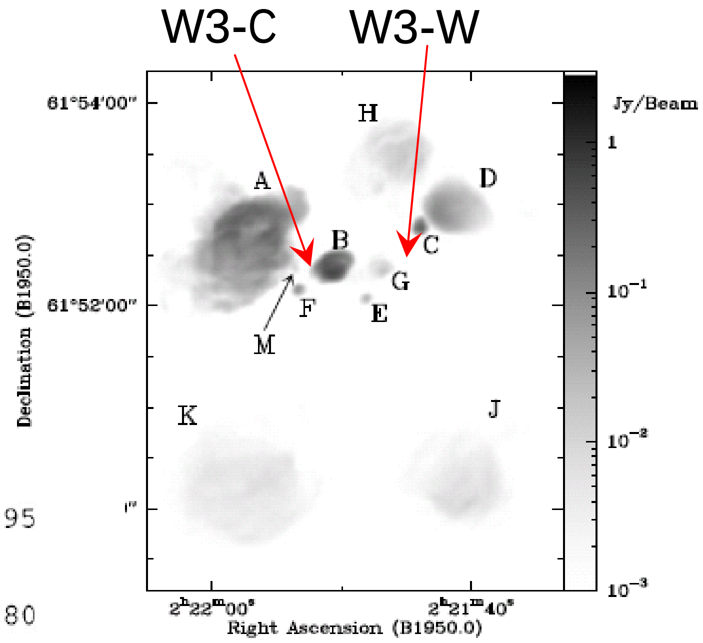
Not at

W3-C

Tieftrunk et al. 1998





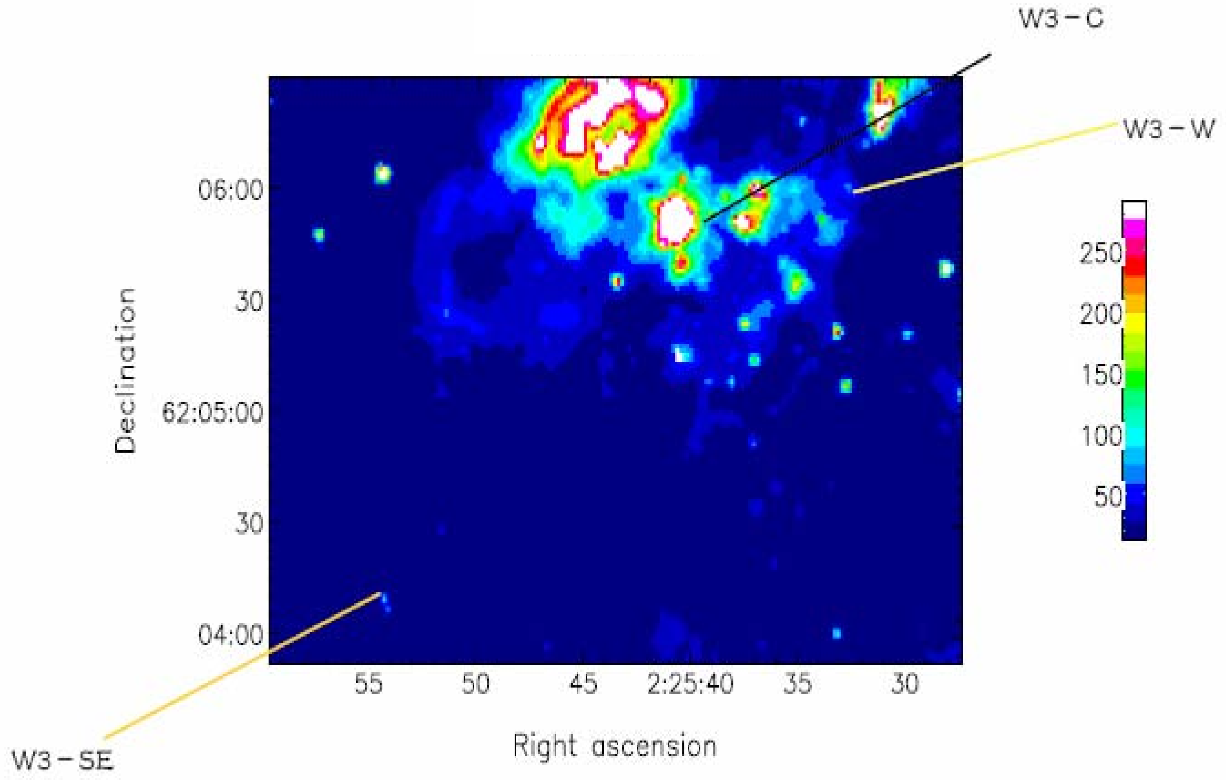




Tieftrunk et al. 1997

IRAC

3.6 μ m

image



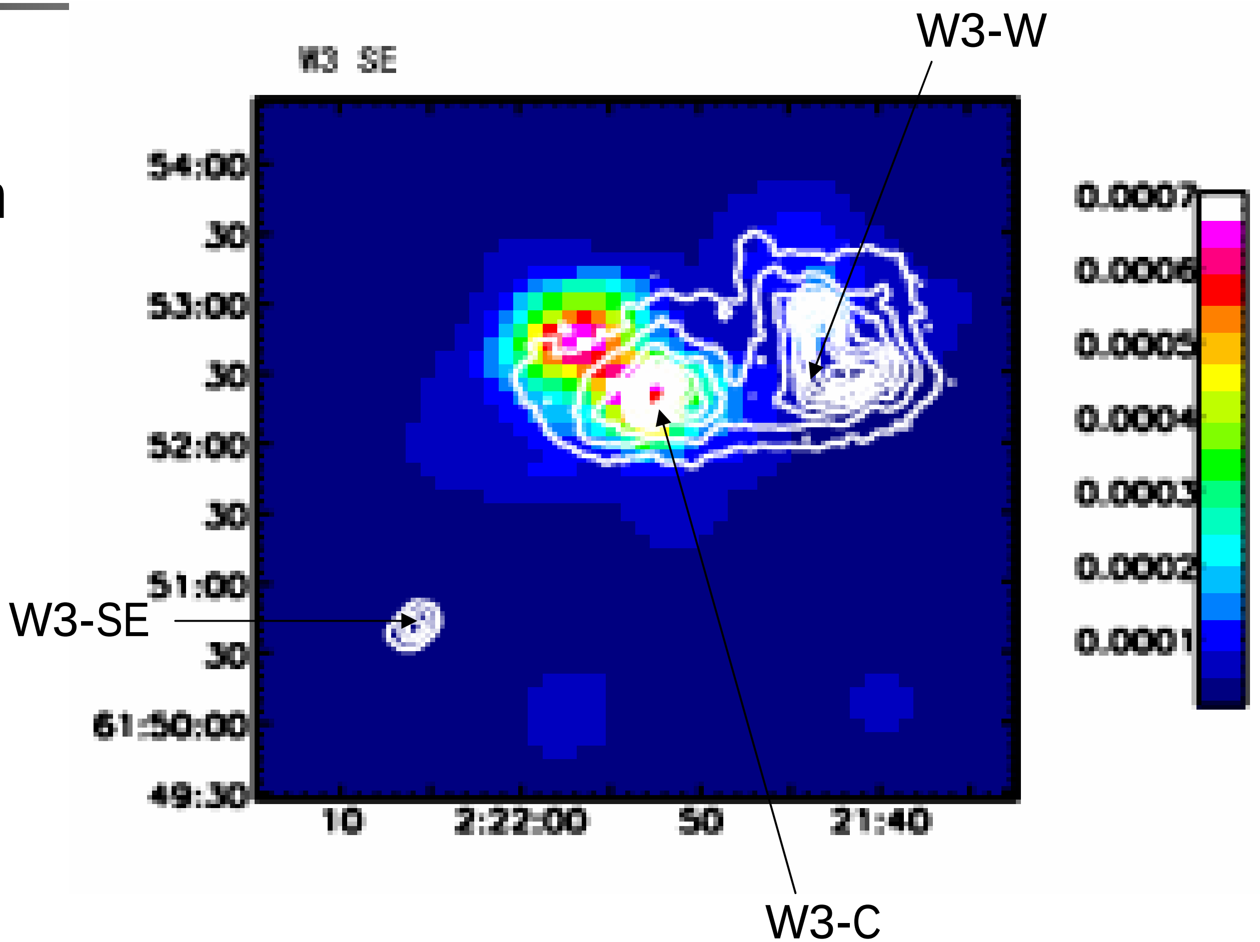
SCUBA

850 μ m

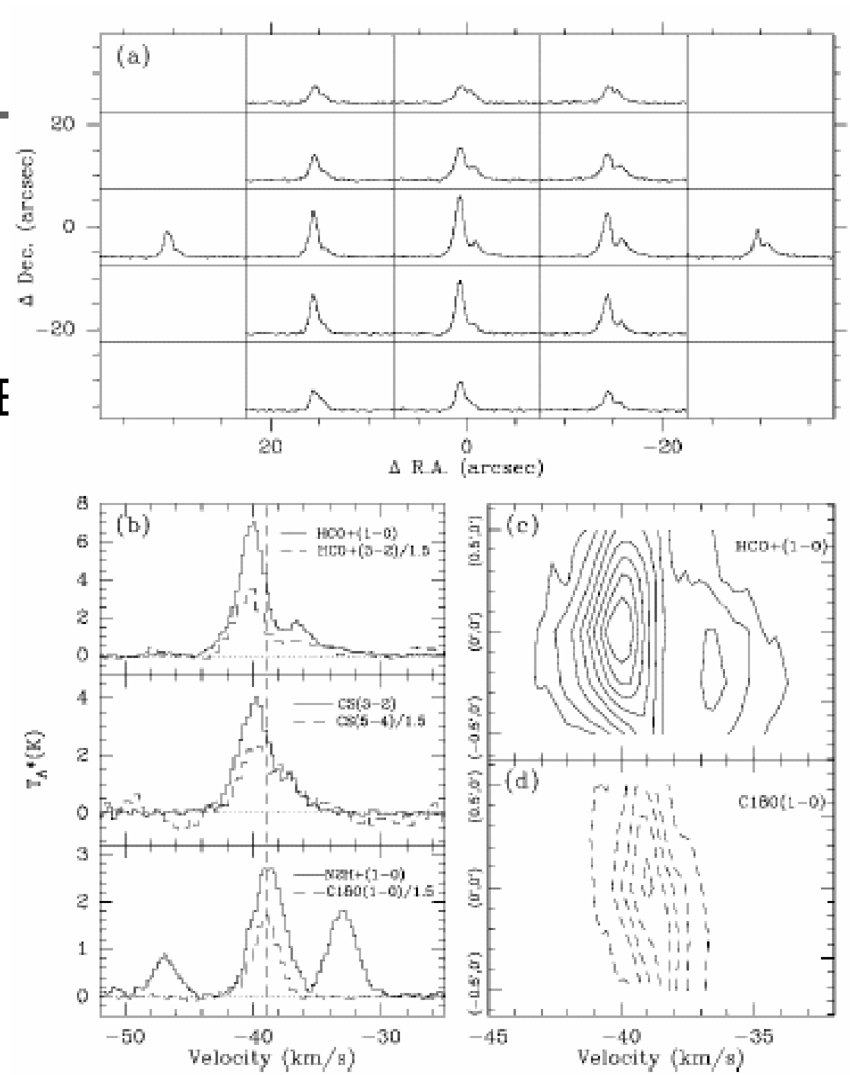
All have

Sub mm

emission

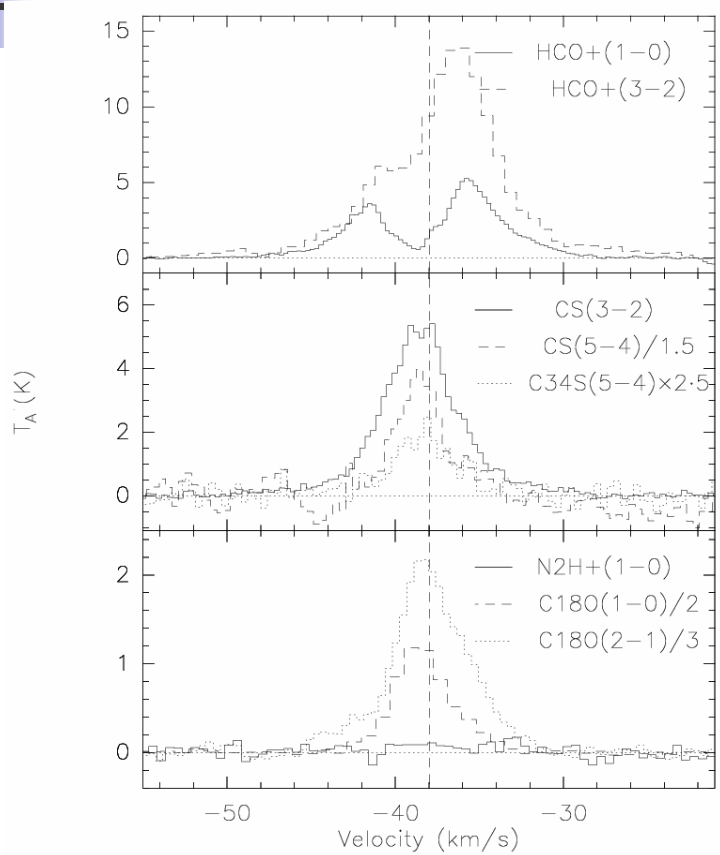


W 3-SE



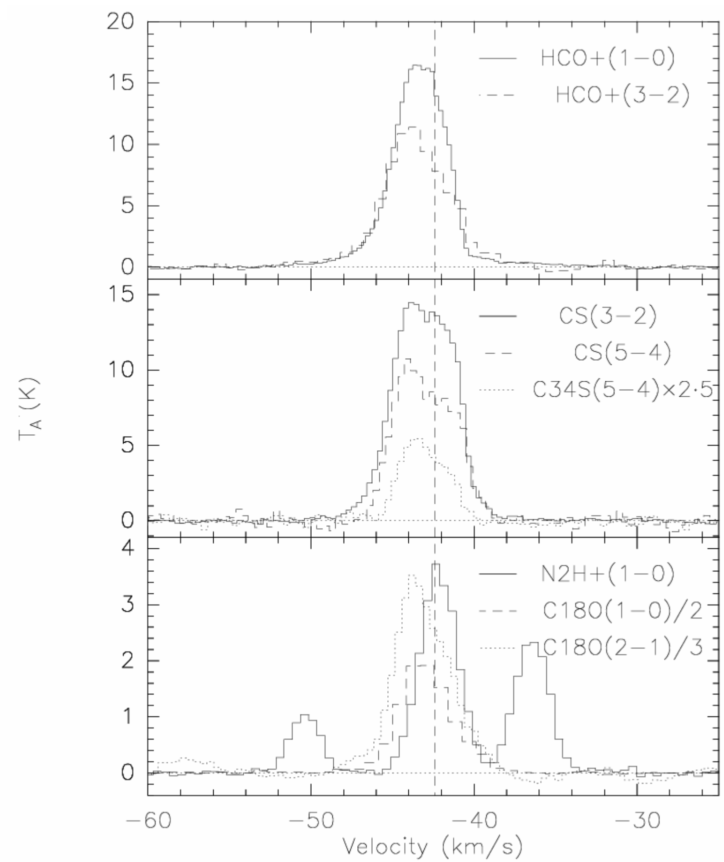

Wu et al. 2007

W 3-C



HCO+(1−0)
HCO+(3−2)
CS(3−2)
CS(5−4)/1.5
C34S(5−4)×2.5
N2H+(1−0)
C18O(1−0)/2
C18O(2−1)/3
T_A (K)
Velocity (km/s)


W 3-W



HCO+(1−0)
HCO+(3−2)
CS(3−2)
CS(5−4)
C34S(5−4)×2.5
N2H+(1−0)
C18O(1−0)/2
C18O(2−1)/3
T_A (K)
Velocity (km/s)

| | W3-W | W3-SE | W3-CL |
|---|---|---|---|
| $NH_3$ | Y | Y | no core |
| HII | N | N | Y |
| Sub mm | Y | Y | Y |
| Dense lines | Y | Y | Y |
| Infall | Y | Y | N |
| H2O maser | N | Y | Y |

→Similar to the situation of G25.4-0.2

# More information for H2O masers:

A survey for water masers toward IRDCs

140 dense clumps from 1.2 mm images

Mass 20-2000 $M_{\odot}$

VLA C-configuration (Wang et al. 2006)

17 were detected

12%

43% HMPOs (Sridharam et al 2002)

67% UCHII (Churchwell et al. 1990)

NH3 studies: IRDCs, HMPOs, UCHII

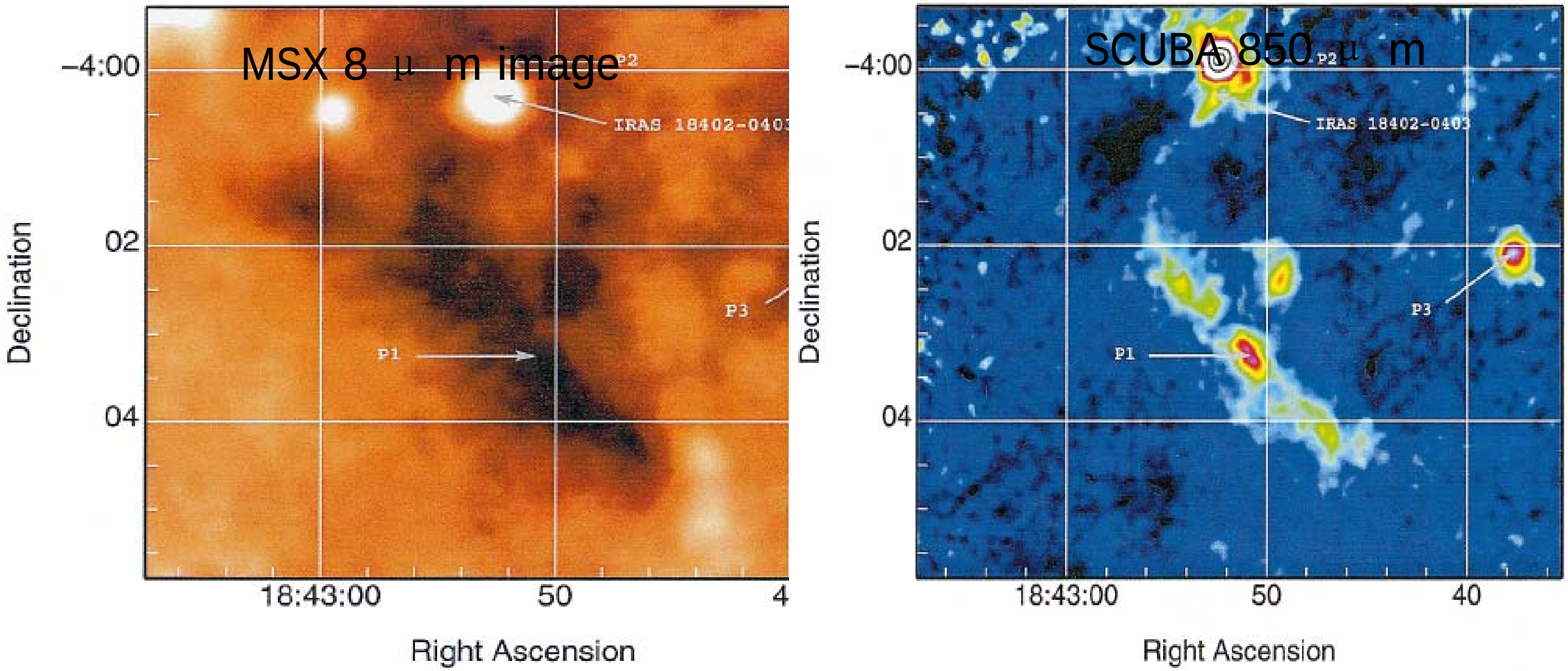
with similar mass

but lower maser detection sources with lower Tk and smaller $\Delta V$

→ $NH_3$ may be in favor to probe early conditions of high mass star formation

# Trace early conditions of massive star formation

An example: **star forming in G28.34+0.26** (Wang et al. 2008)




Carey et al. 2000

Counters of NH3(1,1) integrated intensity with VLA overlapped on IRAM 1.2 mm image (Wang et al. 2008)

P1: young core

T ≈ 16 k

ΔV≈ 1.8 km/s

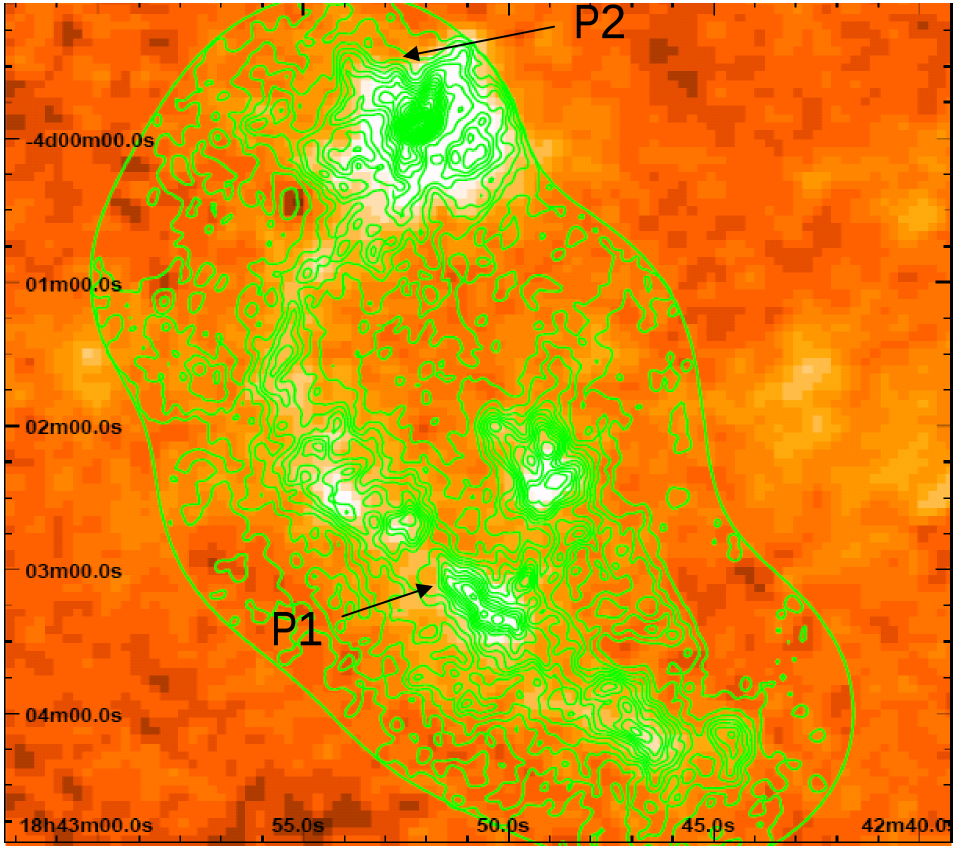
P2: IRAS

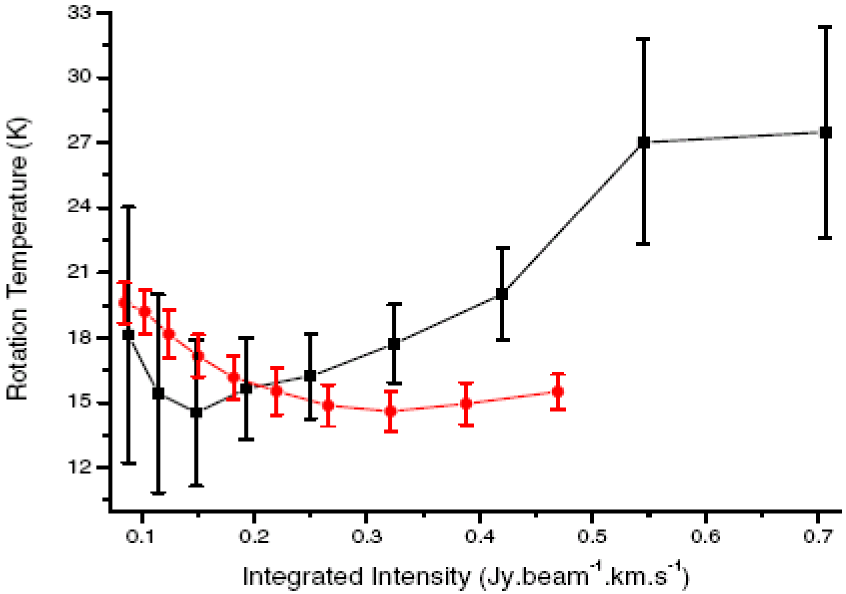
water maser

T≈30 K

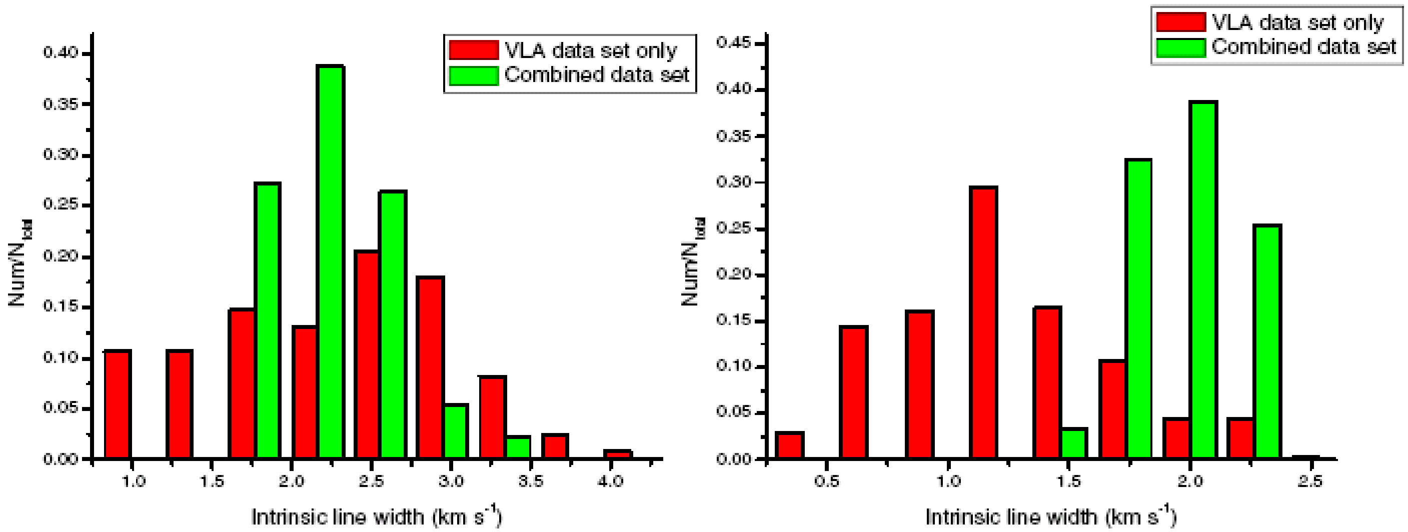
ΔV> 3.0 km/s

more evolved






TR vs. Integration intensity




- A strong evidence
  for a dissipation of turbulence in the dense part of the cloud
  P1 is at a much earlier evolutionary stage than P2

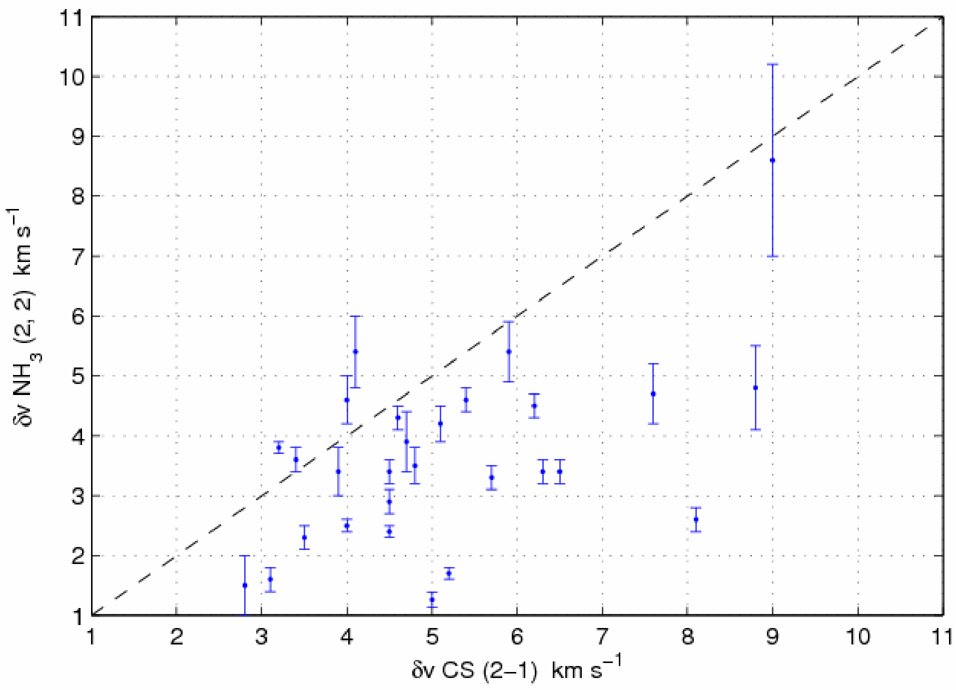
# 3). Probing kinetic process

- Two statistics: a line width comparison between NH3 and CS

Massive cores
ΔV of NH3 (2,2)
VS.
ΔV of line CS (2-1)

Average value:
3.6:5.2 km/s

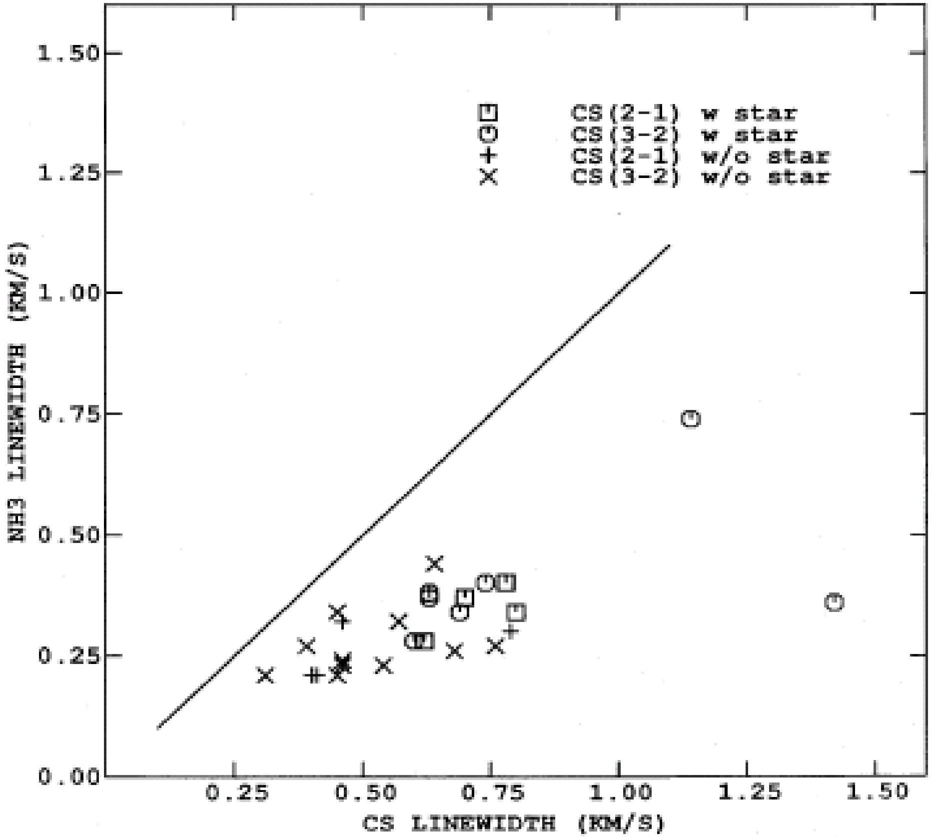
Data from
Churchwell et al. (1990);
Bronfman et al. (1996



low-mass cores:

Zhou et al. 1989

$NH_3$ lines are narrower not dominated by thermal motions



There must be systematic motions

Rotation, outflow, Infall

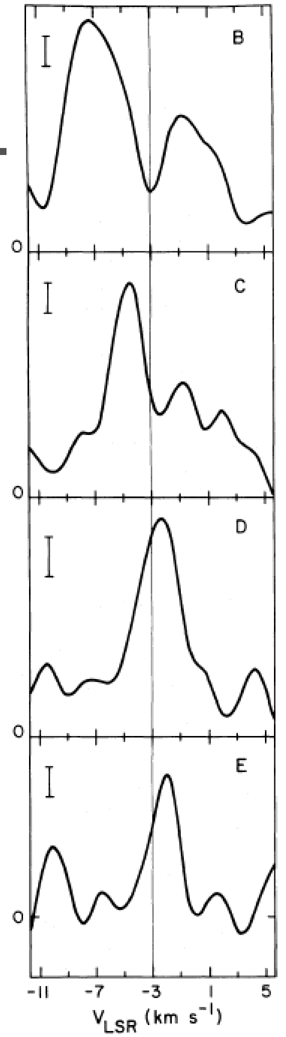
Infall:

later developed than outflow

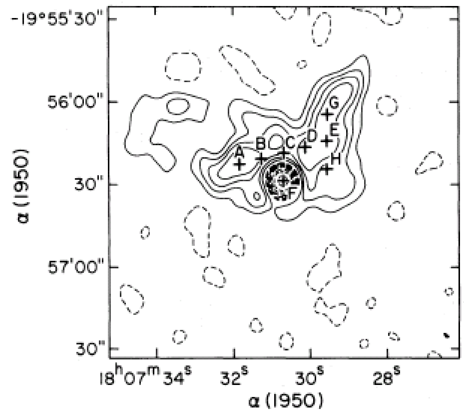
Signatures:

Blue profiles were established towards low-mass cores in the last 90'

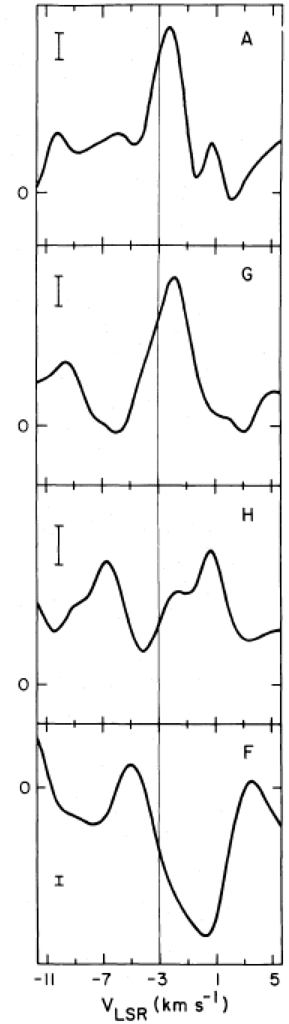
Inverse P Cygni or red shifted absorption of molecular gas were found earlier towards to high-mass star formation regions

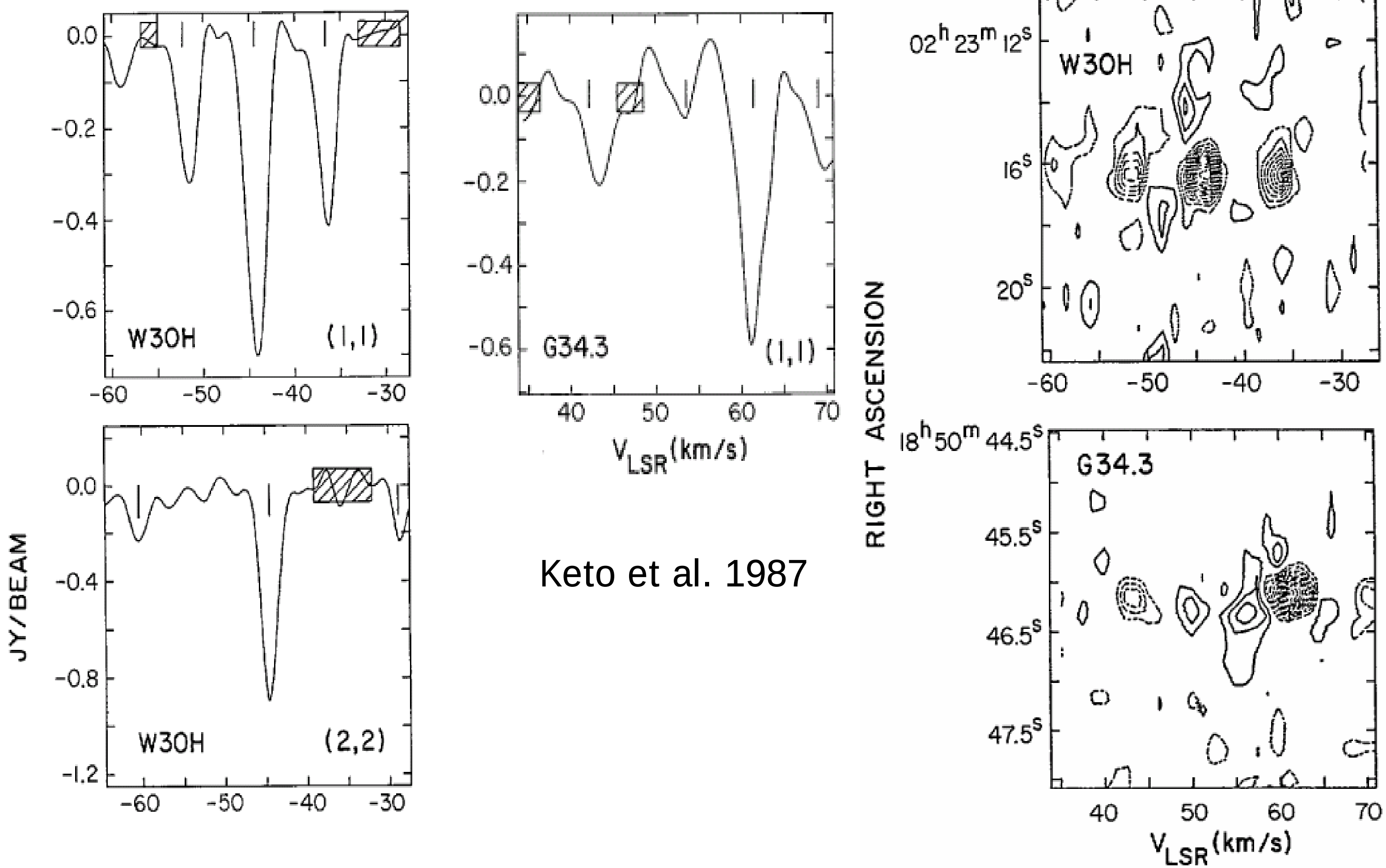



G 10.6-0.4
NH3 (1,1)
VLA-D

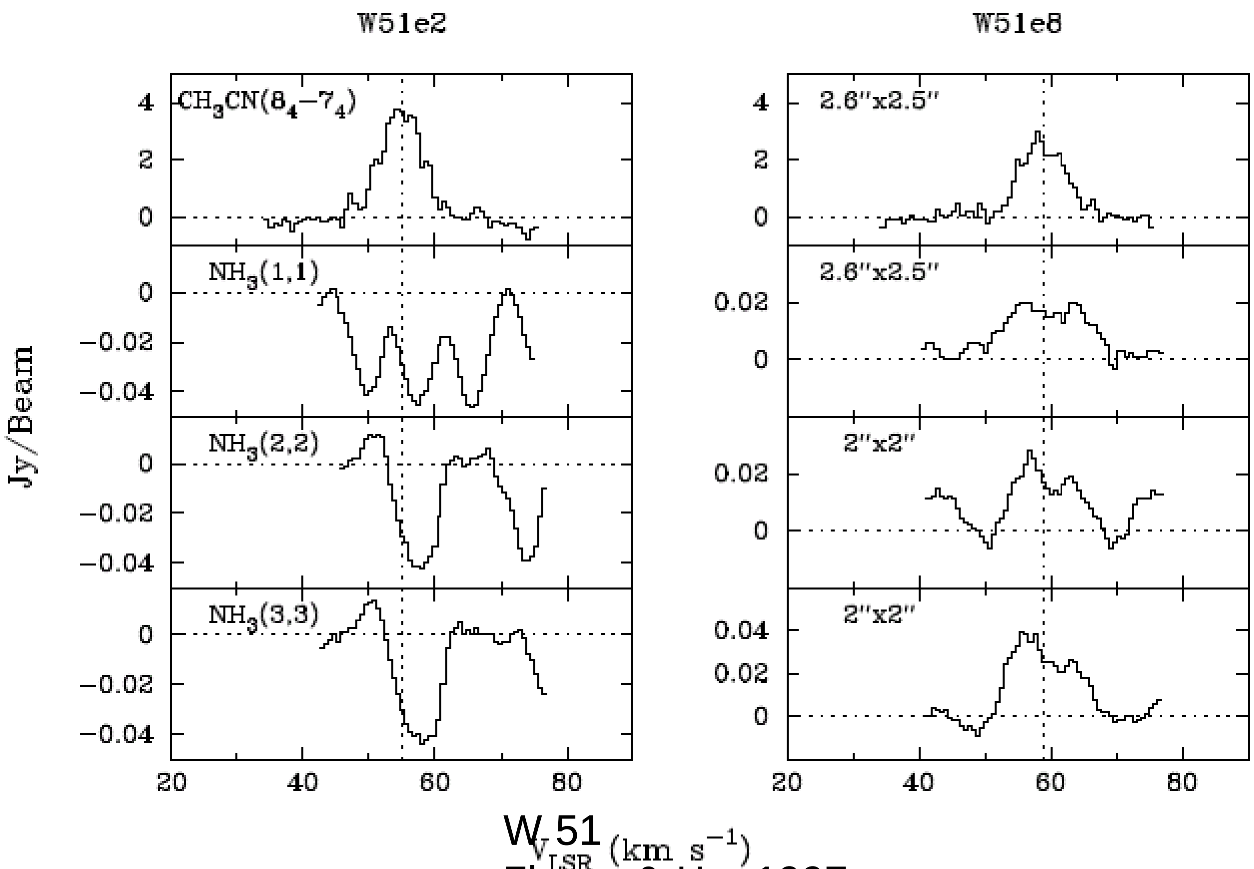



Ho & Haschick
1986






Keto et al. 1987




W 51
Zhang & Ho, 1997

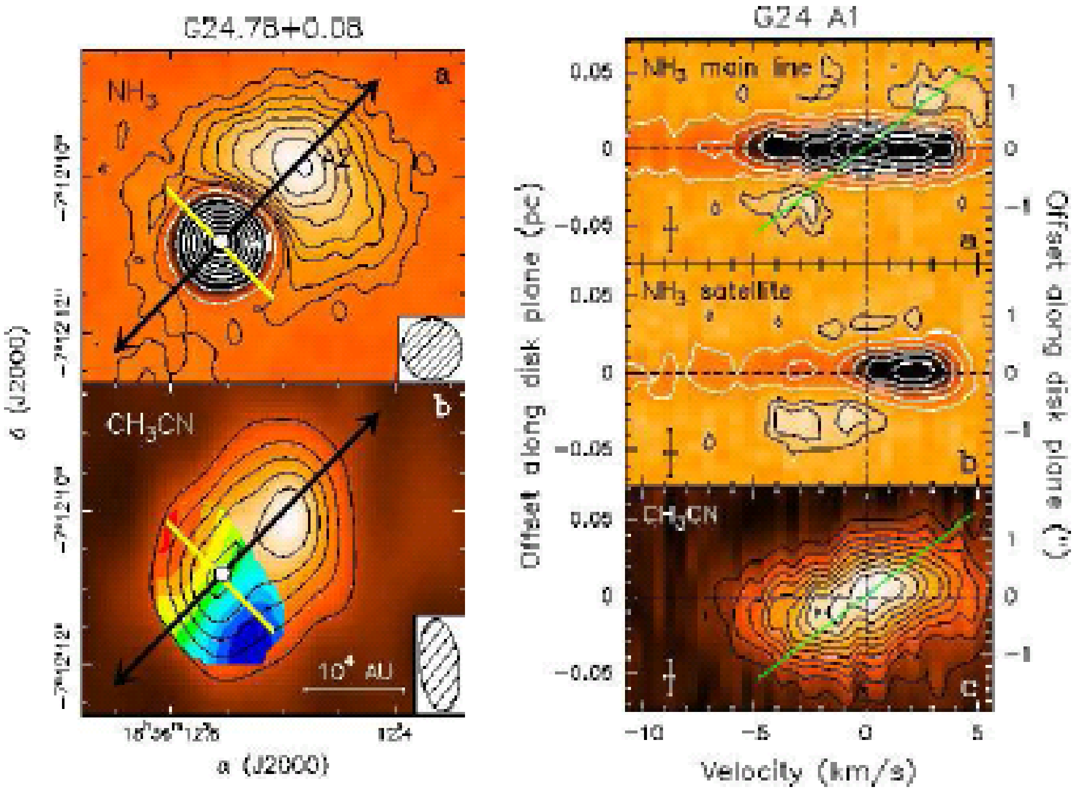



Figure 1:

Figure 2:

NH3 (2,2)
1.3 cm
VLA-B

Beltran et al.
2006

Among 11 massive star formation regions
W3(OH) , G10.6, G34.3+0.2, W49, W51e2, G45.47, G24.78+0.08,G28.20-0.05
W51N, Sgr B2(N), Sgr B2(M)

$NH_3$ detected 7
Other lines, $HCO^+$, CS, $H_2CO$, CN

$NH_3$ also detect rotation

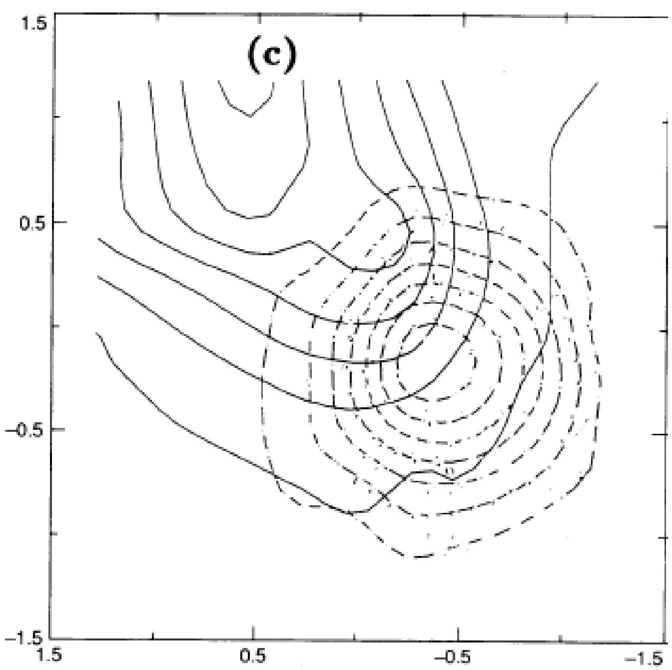
outflow G24.78+0.08 (Beltran et al. 2006), G45.12+0.13 (Hofner et al. 1999)

# 4). Other functions:

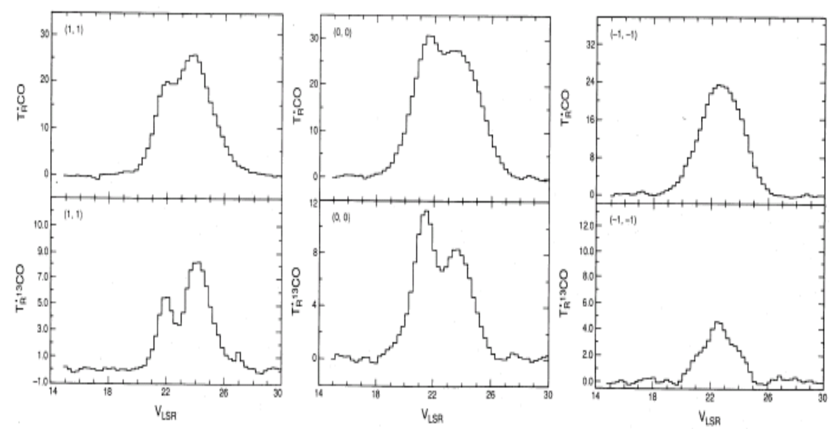
To identify multiple components: narrow line width

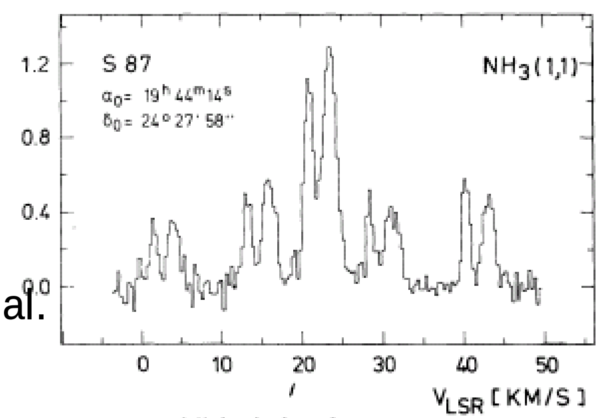
One of the previous detected 391 bipolar molecular outflows (Wu et al. 2004)

S 87

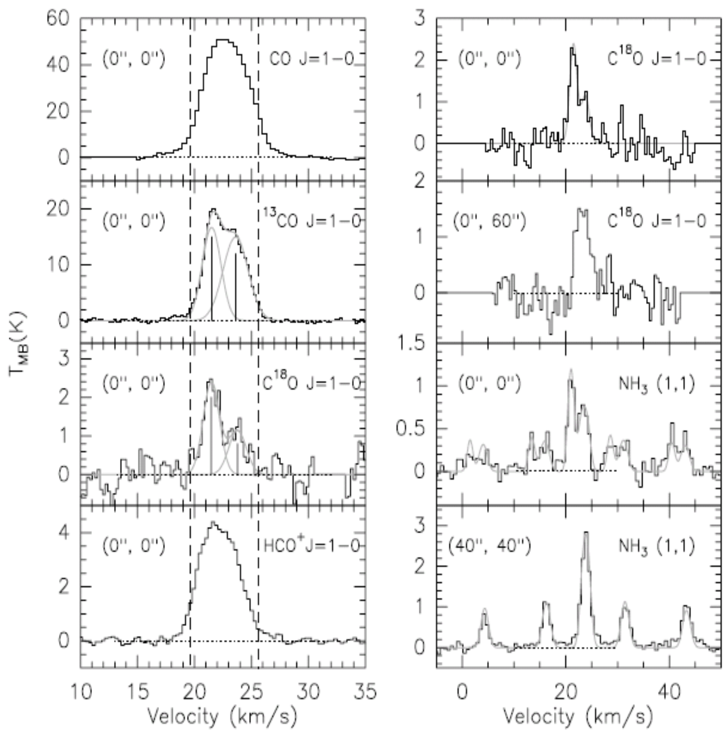


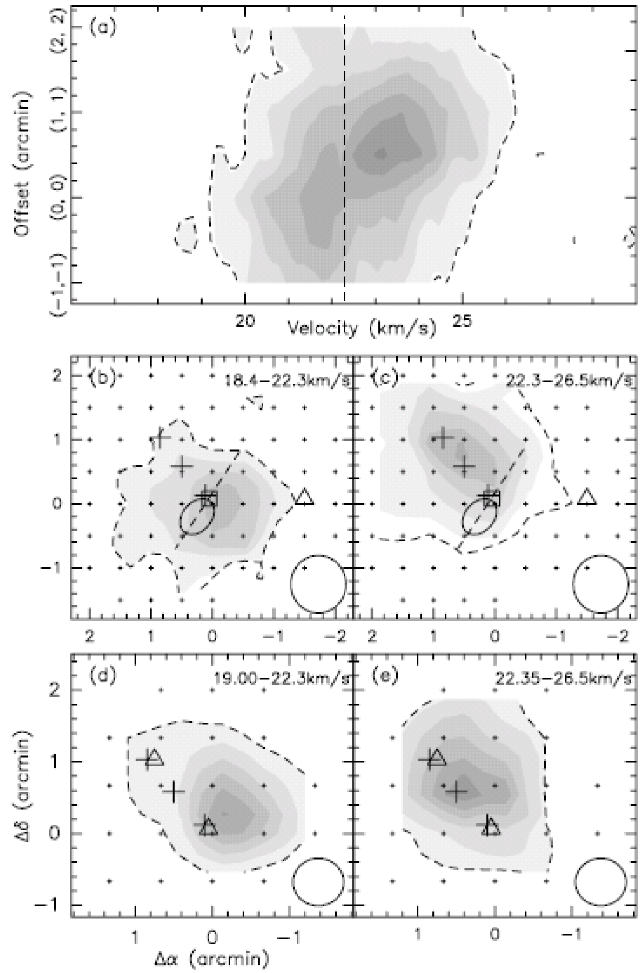

Barsony 1989




Stutzki et al. 1984




CO, 13CO, C18O, HCO+ J=1-0
PMO, 13.7 m
Xue & Wu (2008, ApJ, accepted)

Two clouds
Bipolar outflow identification is difficult

# $NH_3$ microwave spectroscopy:

- Could offset from UC HII regions IR sources, $H_2O$ masers, even gas core without sub mm continuum emission

  Could be with inflow and outflow

  Good to search early massive cores and trace their properties
- Sensitive probe for collapse
- Distinguish different components

# 3. Outlook

- New equipments and microwave spectroscopy exploiting
  With ALMA, FAST, CARMA, SPT, .. …
  expand detection range
  more refine components
  explore new molecules and transitions
  widen applications

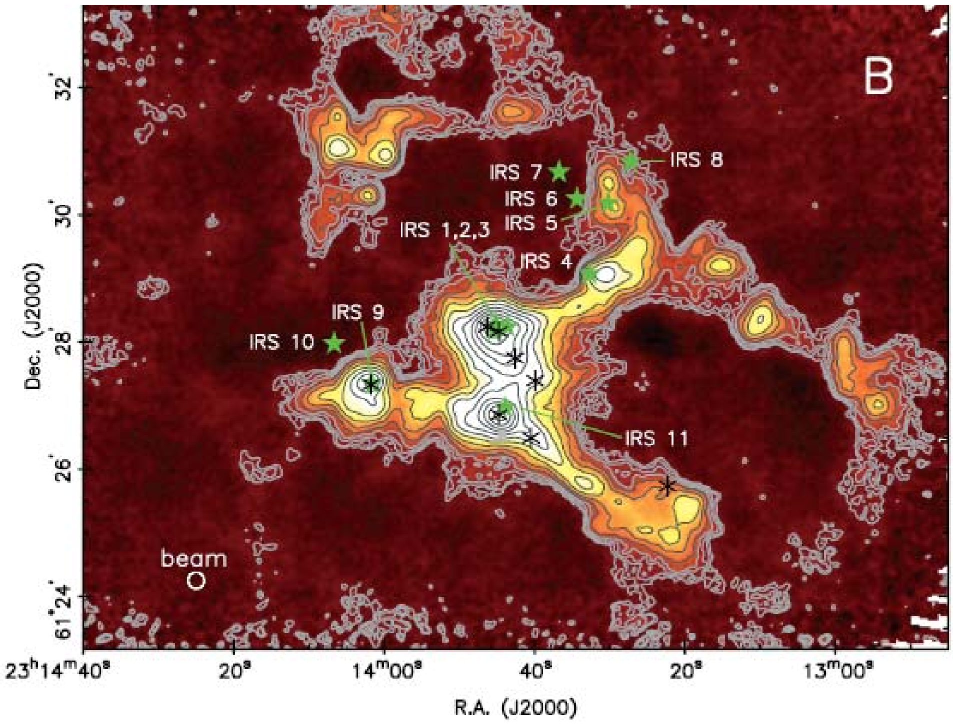
.

- VLA is still playing a significant role
  VLA has made lasting contributions to observations
  to combine the data from SMA and VLA
  —more advanced projects can be realized.

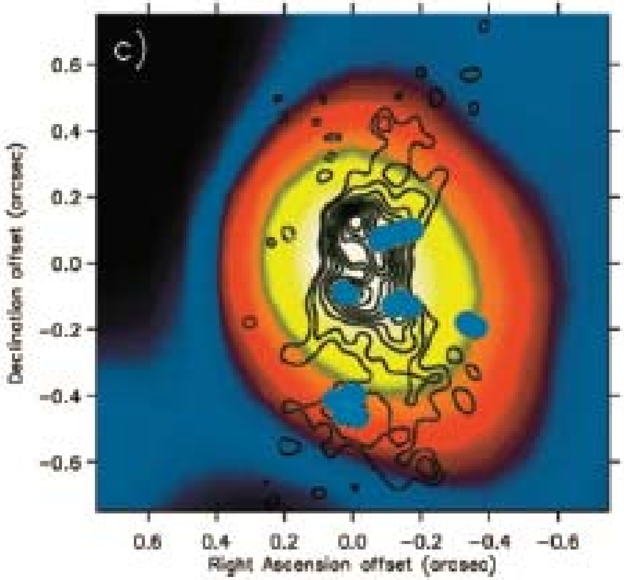
- The equipment for ammonia observation has increased too
  GBT 100m can be employed for ammonia observation.
  A new system will be installed in Urumqi
  to acquire more information on ammonia

Thank you !

Reid & Wilson 2005



- 18.3 μm image



c)
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Declination offset (arcsec)
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
Right Ascension offset (arcsec)

- PUCHs are with the following characteristics:
- Color indices, very young stellar objects or UC HII regions
- Infrared flux: f60 > 100 Jy, or 90 Jy.
- Dense gas cores: $NH_3$, CO, $H_2O$, $CH_3OH$
- Sub-millimeter, mm continuum
- => compact dust core with flat power law.
- High detection rate of outflow (90%(35/39); 84%(58/69)
- With infrared sources:
- => Key criteria: Lb = 103~106 L☉ --Massive
- without 6 cm emission—young