Star formation in the Orion Molecular Cloud System and the BN/KL Region

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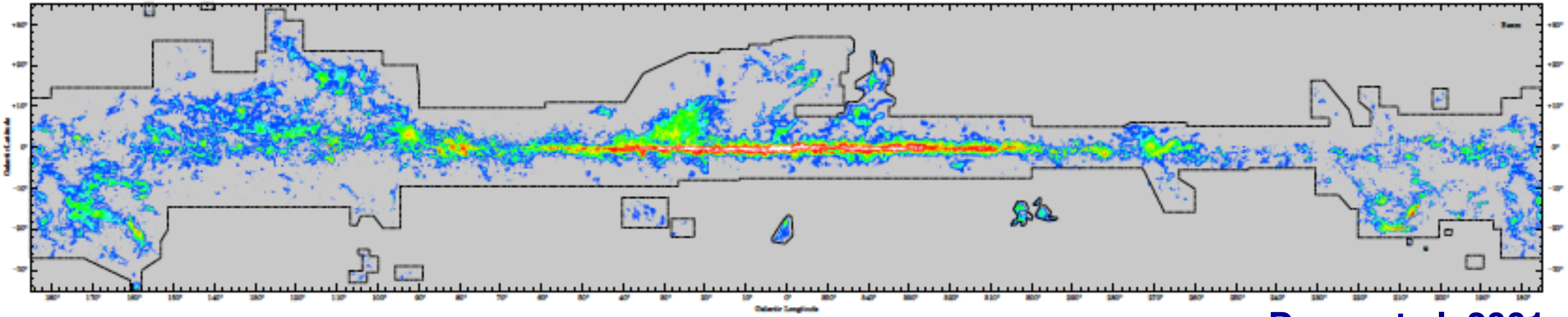
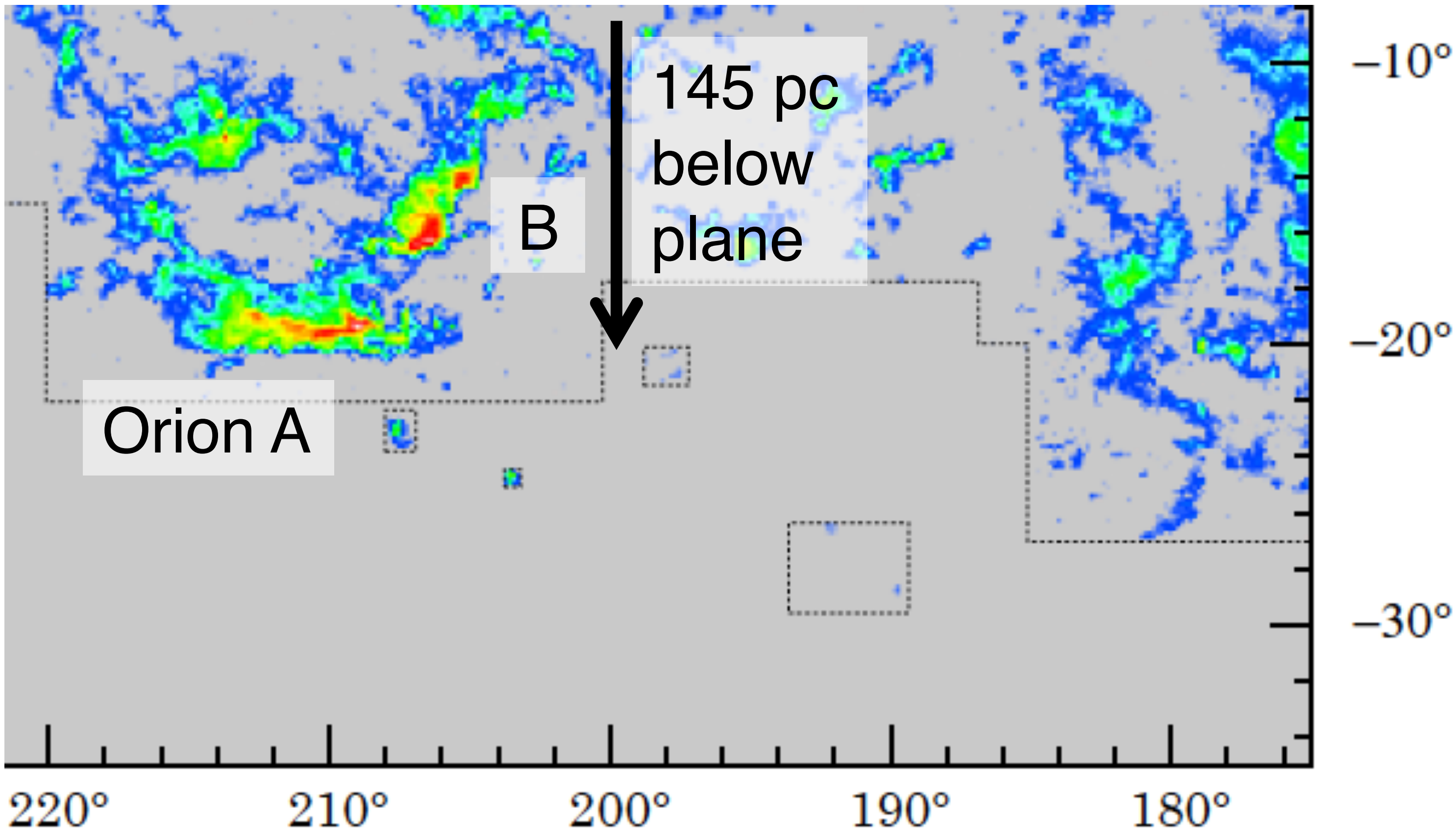
2nd NCAC Symposium – The Orion Nebula

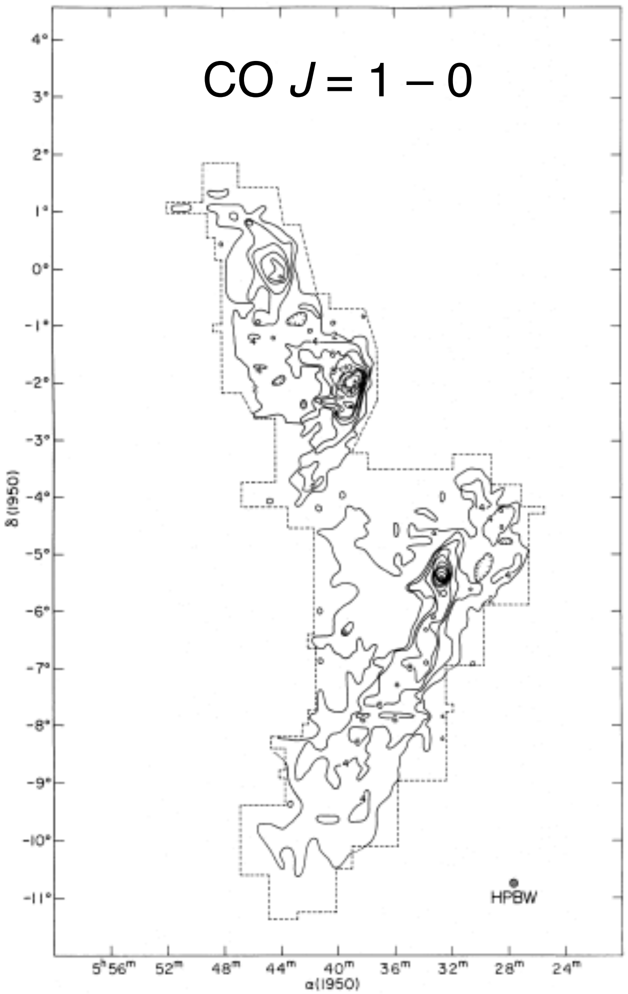
Warszawa, 2012 July 17

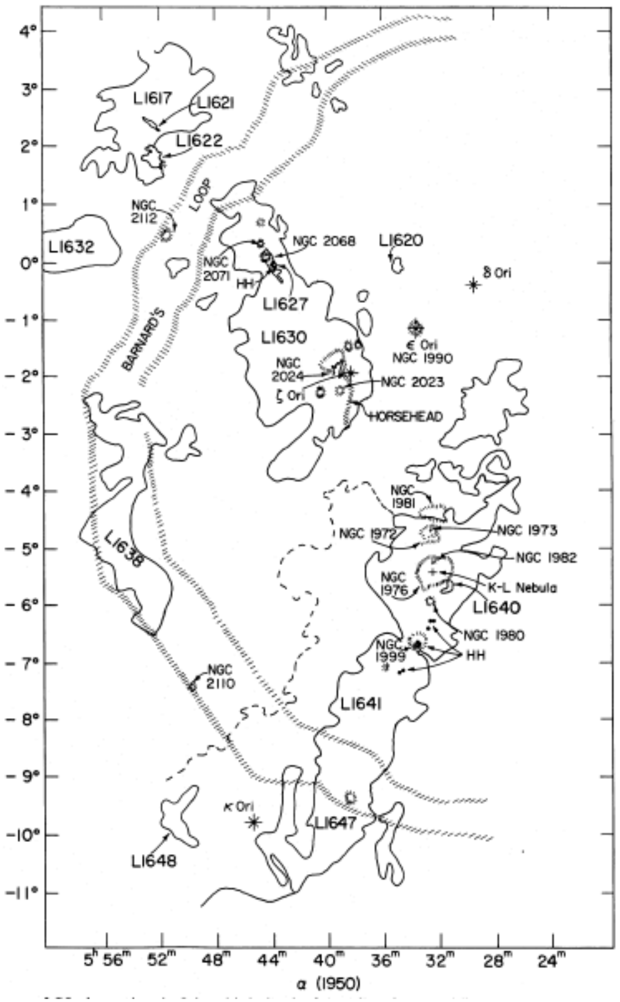
Columbia/CfA CO $J = 1–0$ Survey

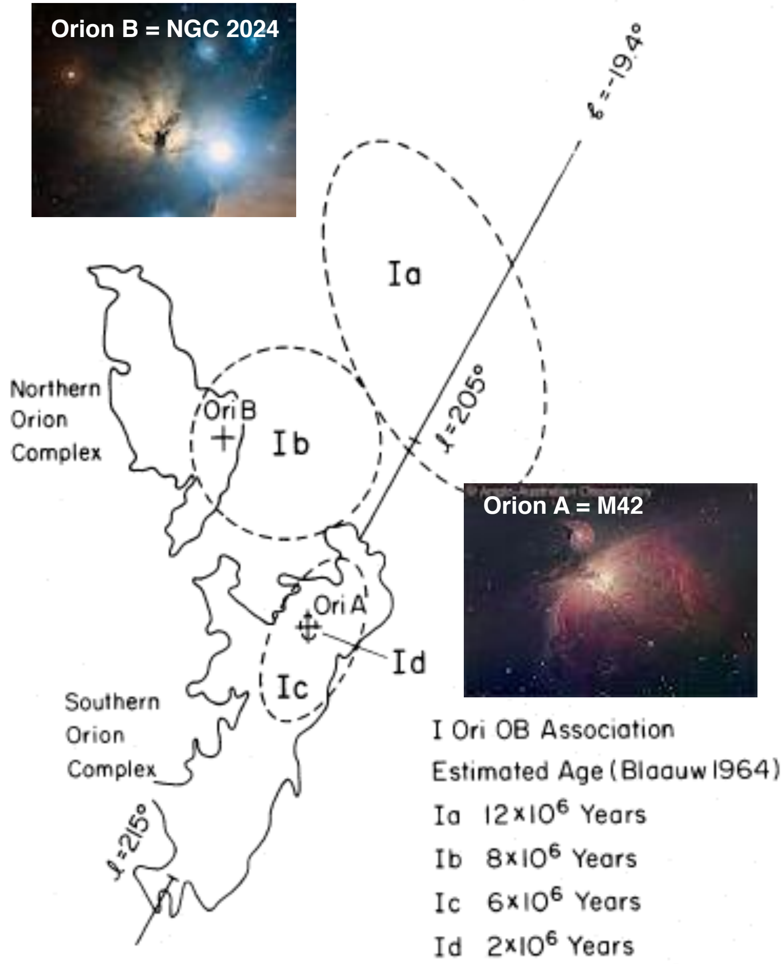


Dame et al. 2001









Kutner et al. 1977

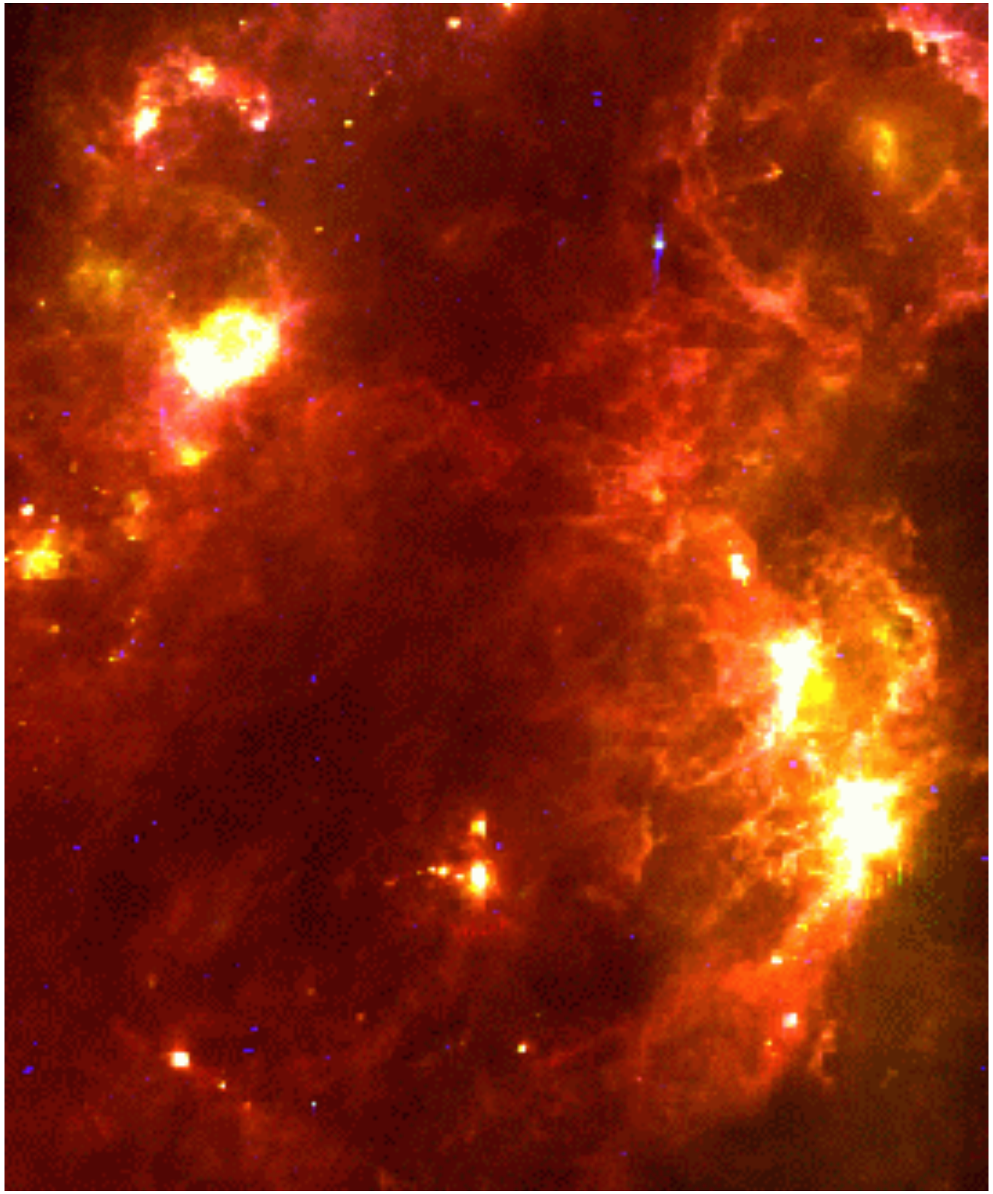
Orion GMCs

From: CfA Harvard, Millimeter Wave Group

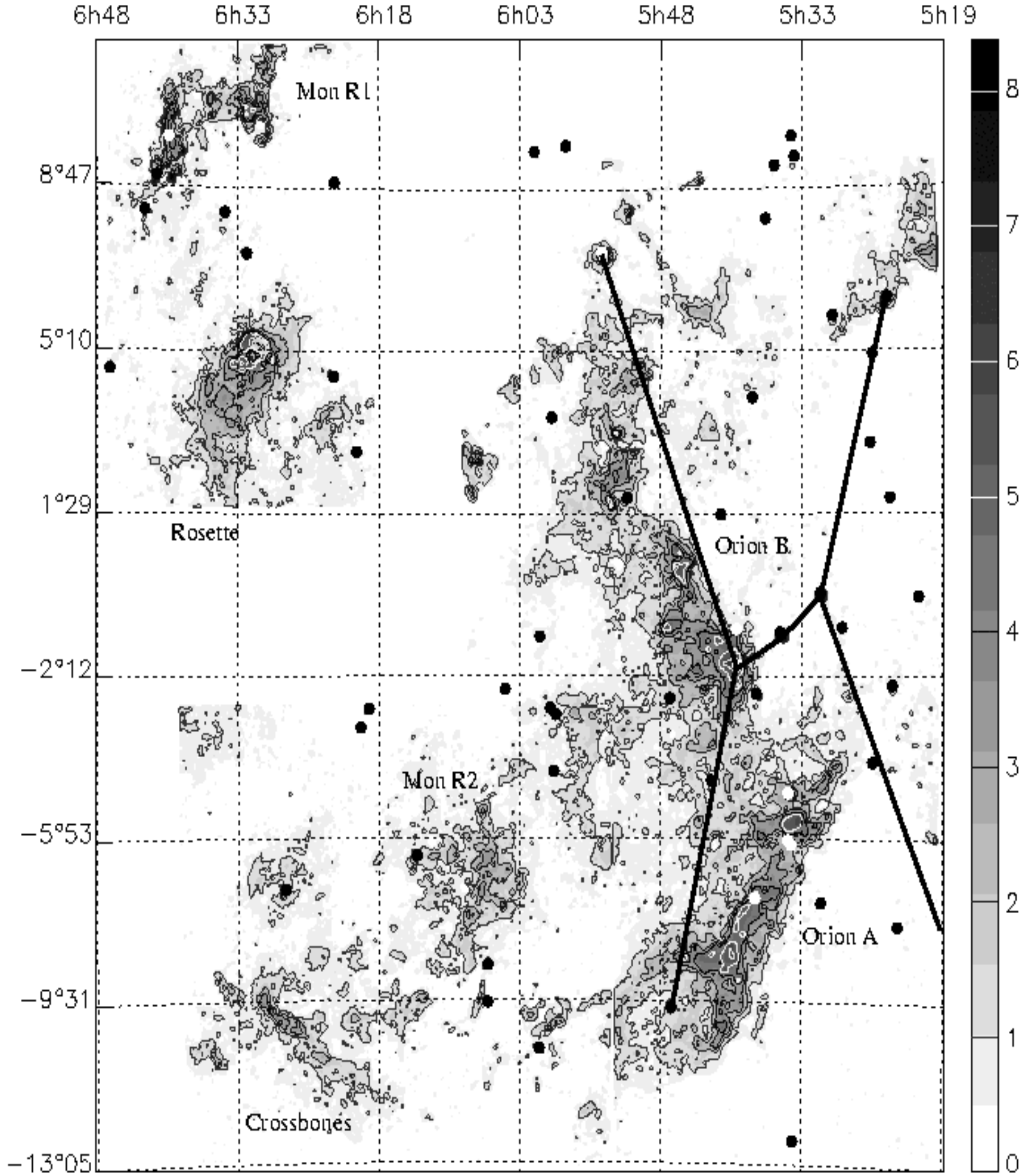
Orion Nebula (M 42 = Orion A)

Orion

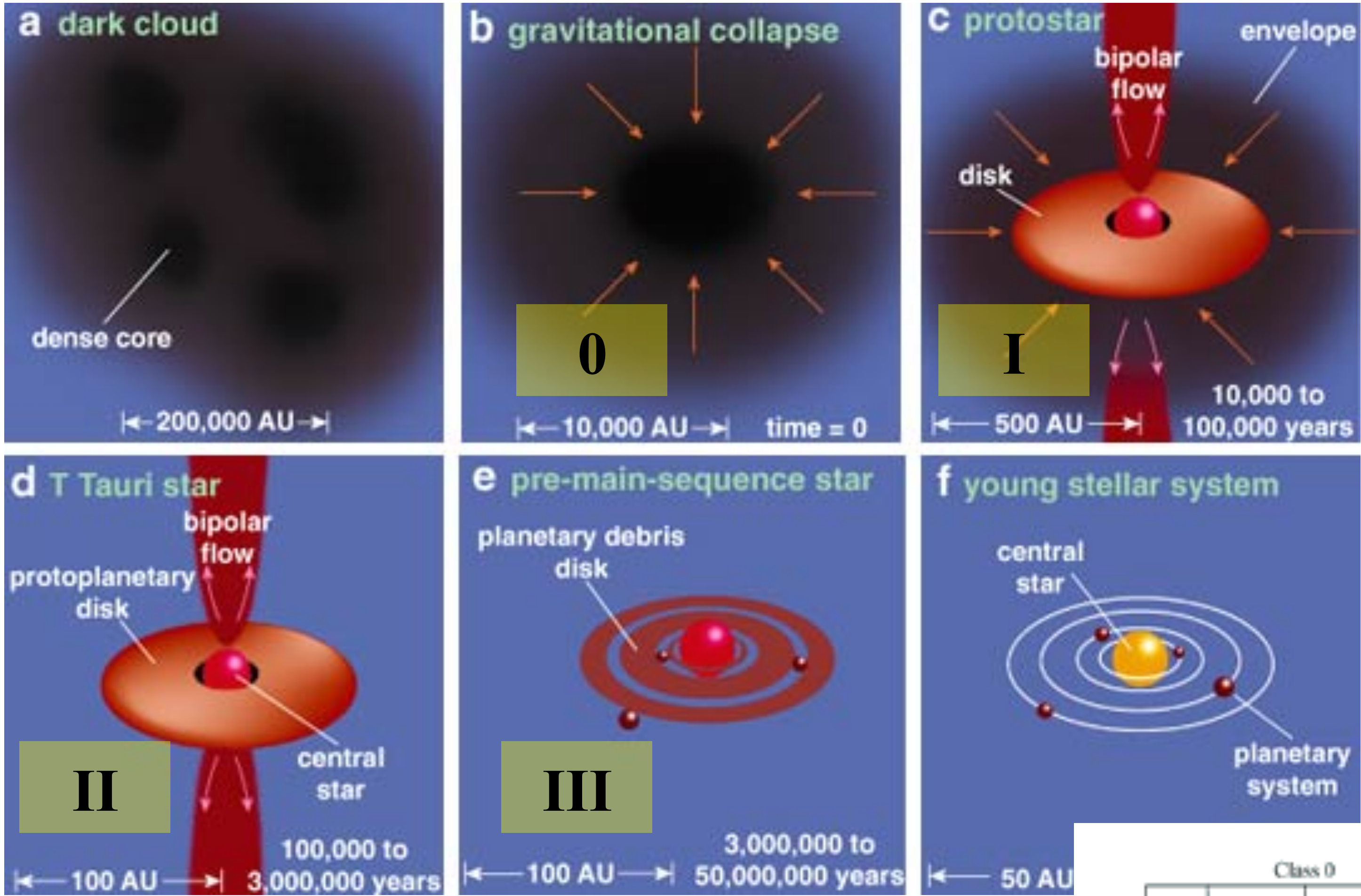
IRAS 100 μm



Star Counts

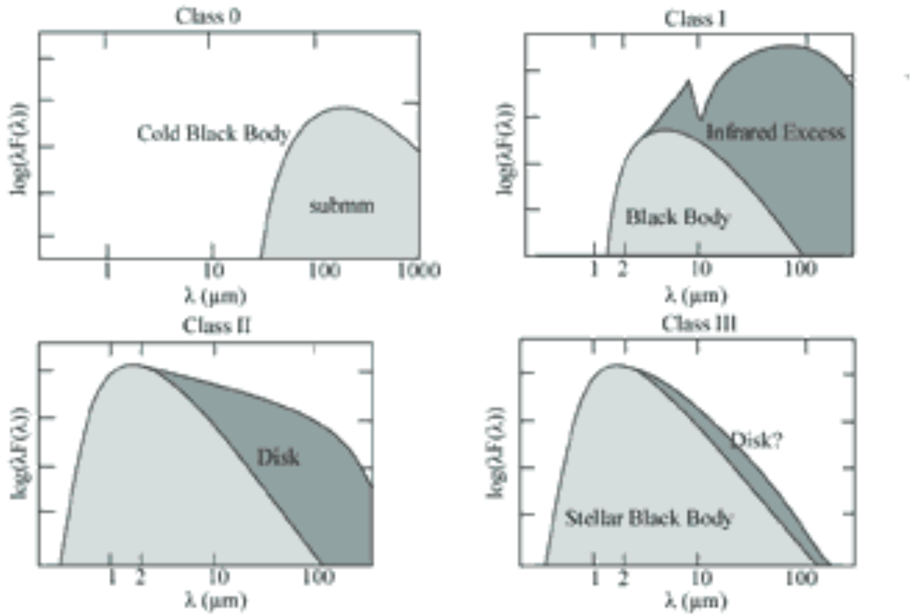


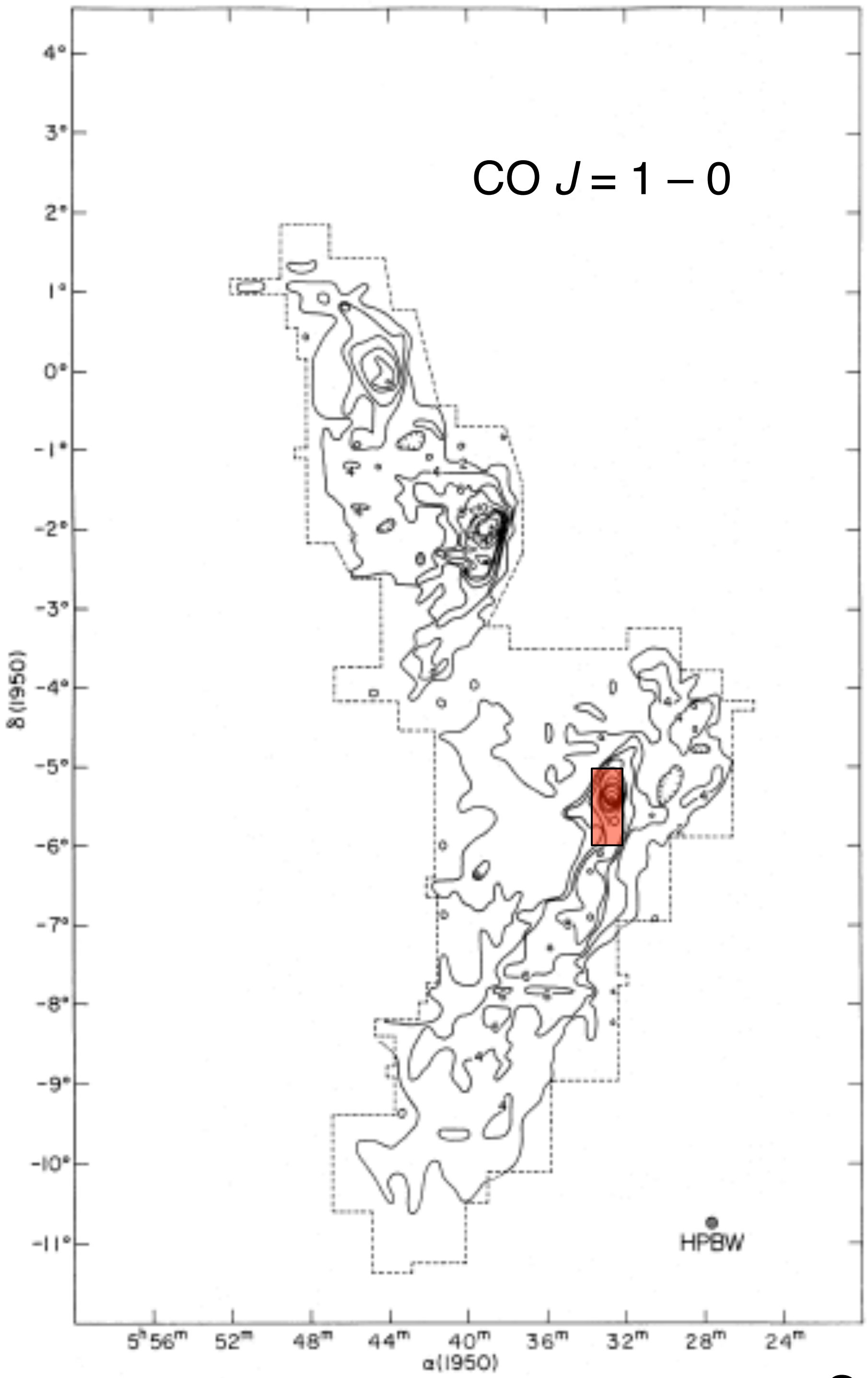
Cambresy 1999

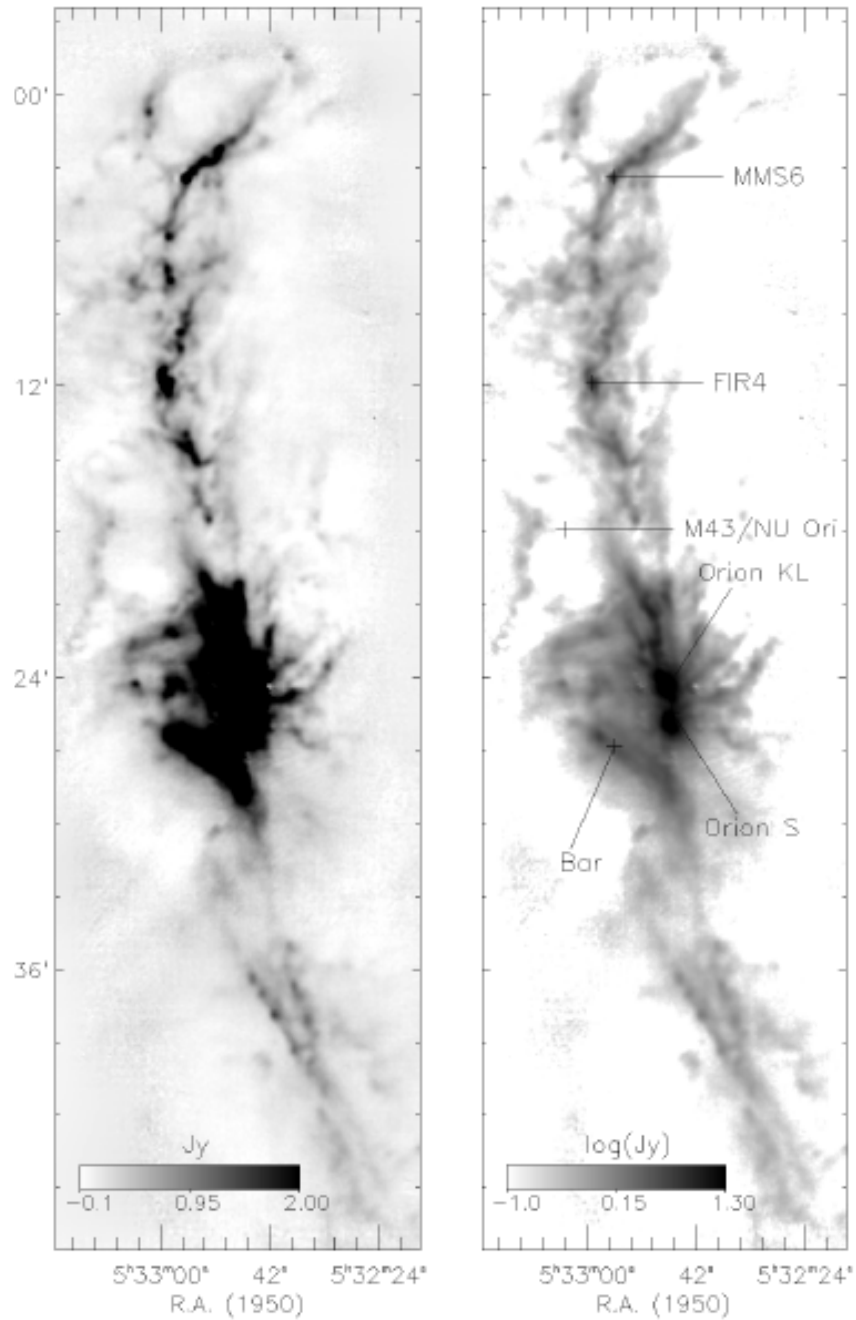


Classes of Protostars

Lada, André, …







SCUBA 870 μm Johnstone & Bally 1999

Submm Continuum Sources: Cold or Warm Dust from Protostellar Condensations (High-Mass SFRs)

Source brightness $$S_\nu = B_\nu(T_D)\left(1 - e^{-\tau_\nu}\right)$$

Continuum emission from interstellar dust is almost always optically thin

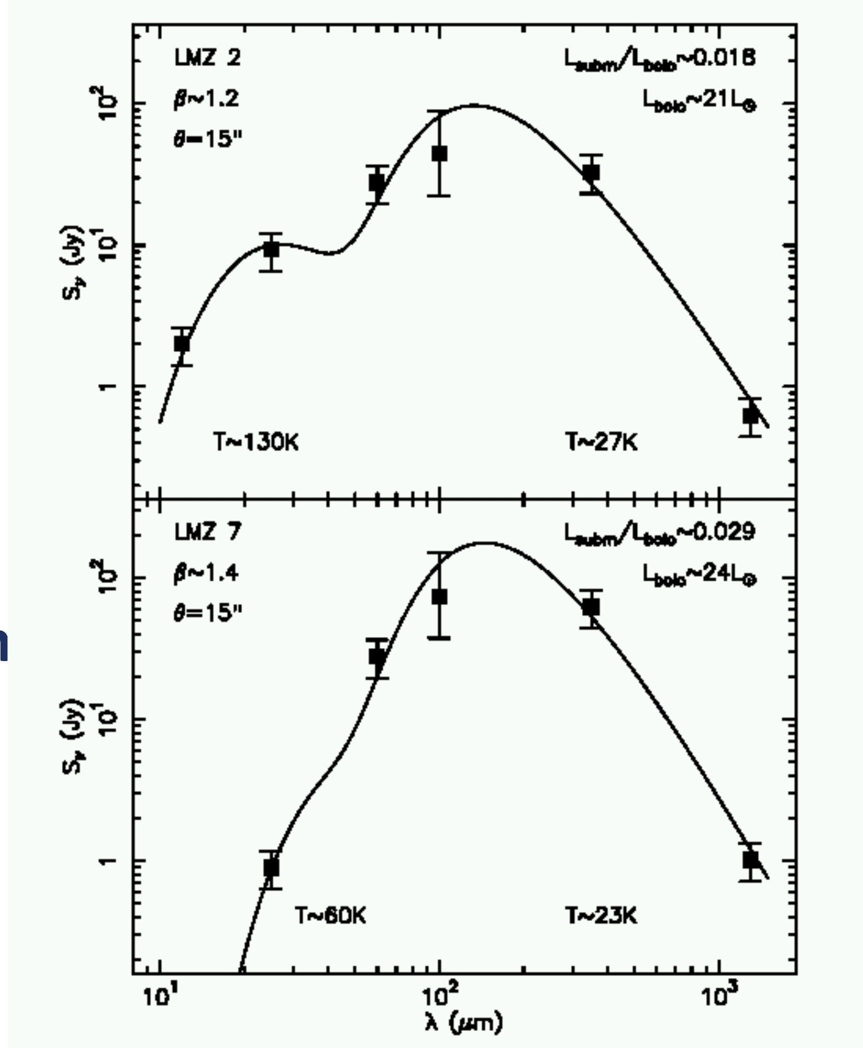
$$S_\nu \approx B_\nu(T_D)\tau_\nu \approx \frac{2k}{c^2} T_D \nu^2 \tau_\nu$$

$$\tau_\nu = \int \kappa dl = N_{\mathrm{H}} \sigma_\nu^{\mathrm{H}} \propto N_H \nu^\beta \; (1 < \beta < 2)$$

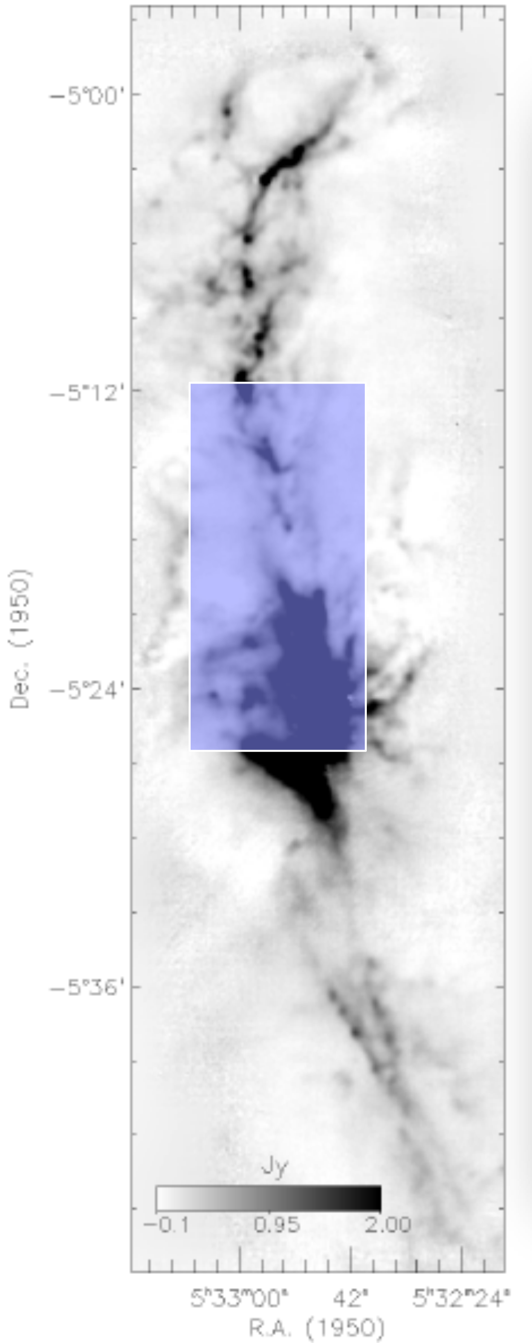
(Sub)mm observations of dust emission yield the total (hydrogen) column density and the gas mass

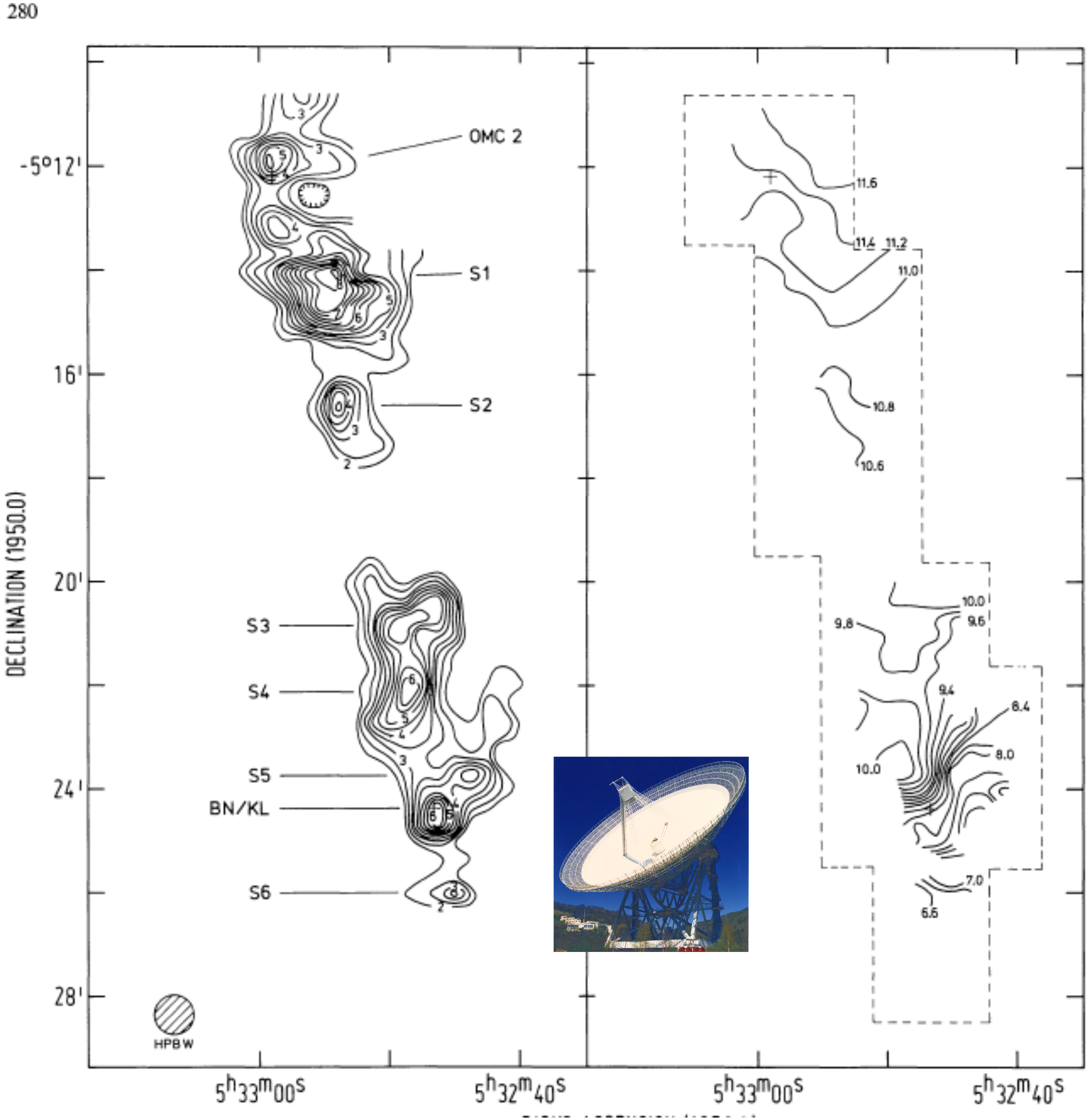
$$N_H \propto \frac{\nu^{-2-\beta}}{T_D} S_\nu$$

$$M \propto \frac{\nu^{-2-\beta}}{T_D} D^2 \int S_\nu d\Omega$$



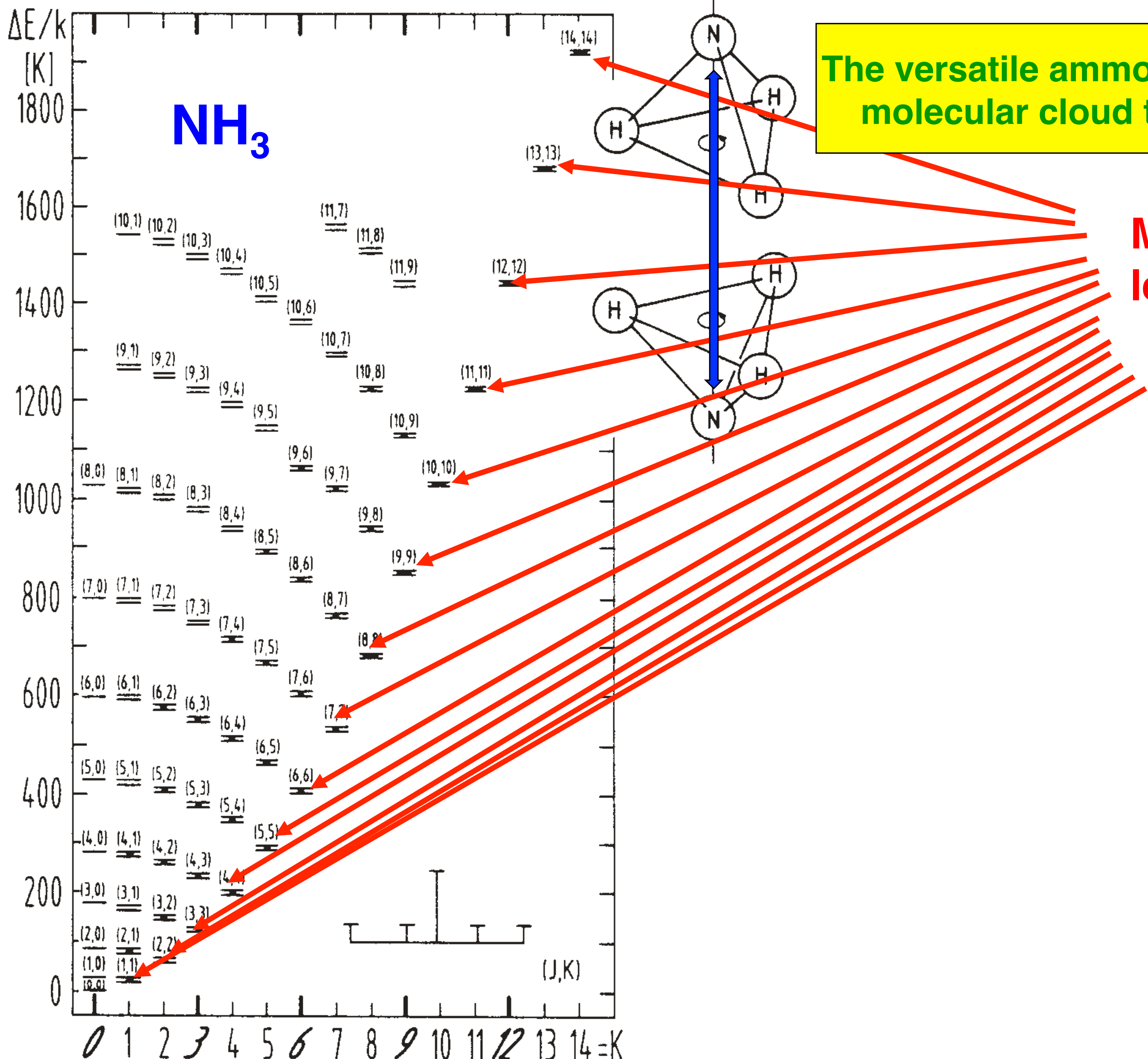
Lis et al. 1999





NH_3 *(J,K)* = (1,1) Batrla et al. 1983

The versatile ammonia molecule – molecular cloud thermometer

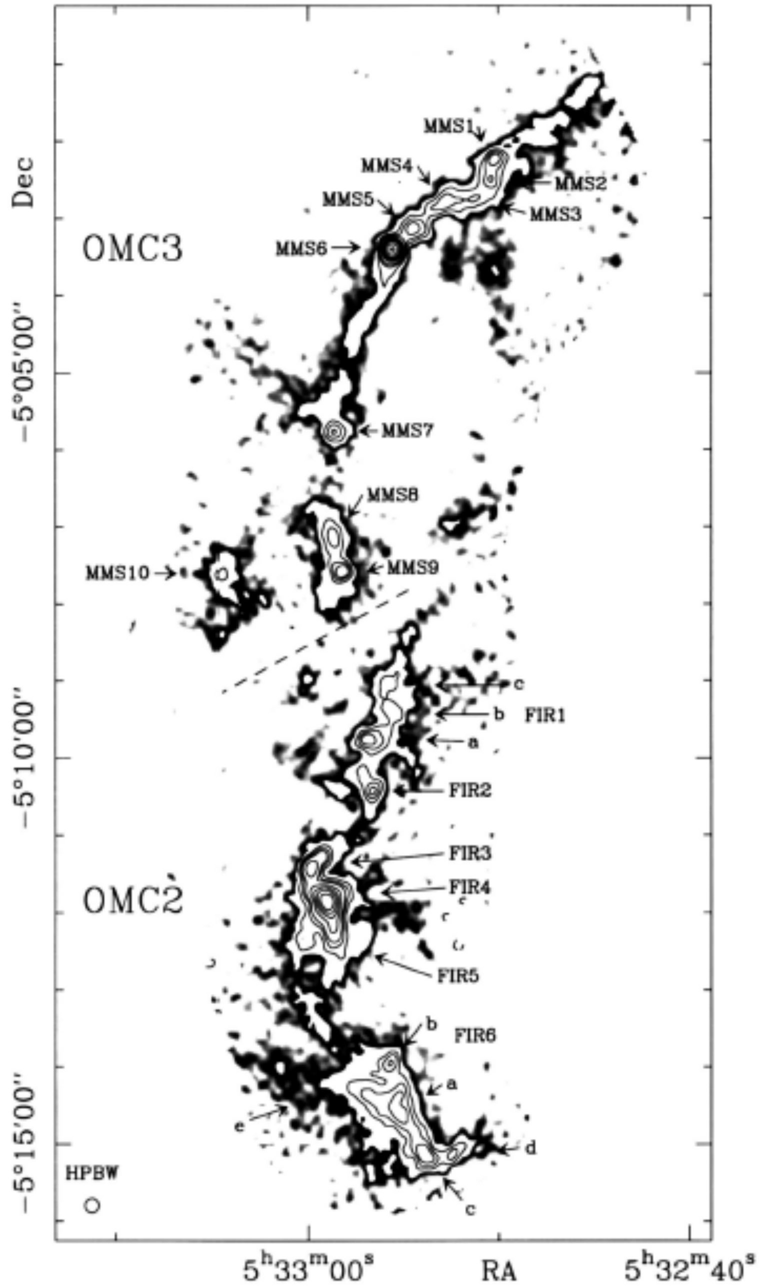


Metastable levels ($J = K$)

Source (1)	Radial velocity V_{LSR} (km s^{-1}) (2)	Kinetic temperature T_K (K) (3)	Source size from NH_3 data[a] (″) (4)	(pc)	Full width to half power $\Delta V_{1/2}$ (5)	Virial estimates[b]: Mass ($M_\odot$) (6)	H_2 density (cm^{-3}) (7)	H_2 column density (cm^{-2}) (8)	Jeans'[c] length (pc) (9)	Jeans'[c] mass ($M_\odot$) (10)
OMC-2	11.2	24	35	$8.6\ 10^{-2}$	1.0	10	$2\ 10^5$	$5\ 10^{22}$	$6\ 10^{-2}$	2
1	11.0	35	33	$8.1\ 10^{-2}$	0.8	~10	$1\ 10^5$	$2\ 10^{22}$	~$1\ 10^{-1}$	~4
2	10.7	24	16	$3.9\ 10^{-2}$	0.8	~ 5	~$5\ 10^5$	$6\ 10^{22}$	~$4\ 10^{-2}$	~1
3	9.7	24	48	$1.2\ 10^{-1}$	1.4	30	$2\ 10^5$	$7\ 10^{22}$	$6\ 10^{-2}$	2
4	9.7	15	86(?)	$2.1\ 10^{-1}$(?)	1.0	30	$3\ 10^4$	$2\ 10^{22}$	$1\ 10^{-1}$	2
5	7.9	25	30	$7.3\ 10^{-2}$	1.0	10	$2\ 10^5$	$4\ 10^{22}$	$6\ 10^{-2}$	2
	9.9	95	20	$4.9\ 10^{-2}$	1.7	20	$2\ 10^6$	$3\ 10^{23}$	$4\ 10^{-2}$	4
BN/KL	8.3	40	20	$4.9\ 10^{-2}$	2.7	50	$4\ 10^6$	$6\ 10^{23}$	$2\ 10^{-2}$	1
	6.0	85	9	$2.2\ 10^{-2}$	8.6	>100[d]	10^6–10^8 [d]	$1.3\ 10^{25}$	$4\ 10^{-3}$	0.3
	5.6	~ 85	~15	~$3.7\ 10^{-2}$	≲30	—	10^6 [e]	—	$5\ 10^{-2}$	4
6	6.5	100	16	$3.9\ 10^{-2}$	2.2	20	$4\ 10^6$	$5\ 10^{23}$	$3\ 10^{-2}$	3
	7.4	75	9	$2.2\ 10^{-2}$	4.9	70(?)	$6\ 10^7$	$4\ 10^{24}$	$6\ 10^{-3}$	0.5

Batrla et al. 1983

Only low mass protostars in OMC-2 and OMC-2



PROPERTIES OF CONDENSATIONS IN OMC-2 AND OMC-3

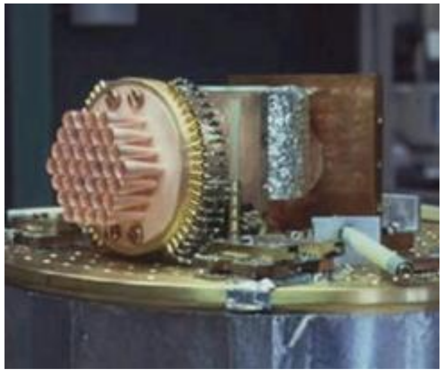
Object	L_{bol} ($L_\odot$)	L_{smm} ($L_\odot$)	L_{bol}/L_{smm}	T_d (K)	M_{gas} ($M_\odot$)
OMC-3:					
MMS 1	<55	0.90	<61	20–25	18
MMS 4	<56	0.78	<72	20–25	11
MMS 6	<60	1.21	<50	15–25	36
MMS 7	76	0.59	129	26	8
MMS 8	<89	0.50	<178	20	9
MMS 9	<94	0.65	<145	20	10
OMC-2:					
FIR 1c......	128	0.36	356	33	5
FIR 1a......	<138	...	...	...	...
FIR 2.......	<157	0.49	<320	20	8

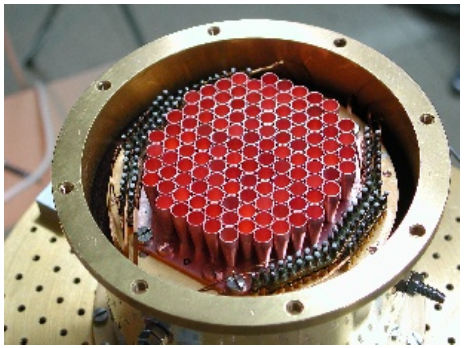
MAMBO 1100 μm / Chini et al. 1997

Max-Planck-Institut
für
Radioastronomie

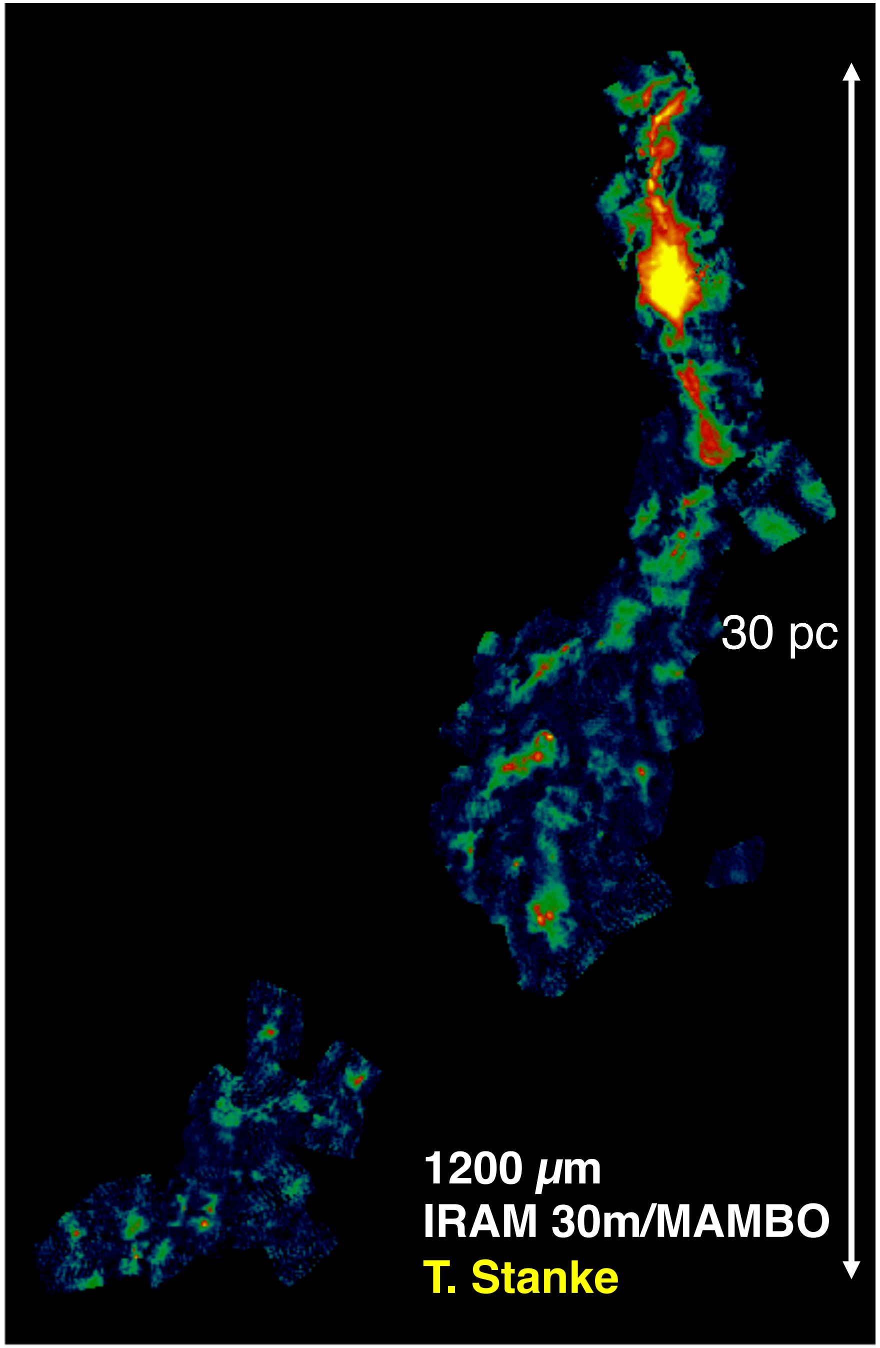
MPIfR Bolometer Array-Cameras

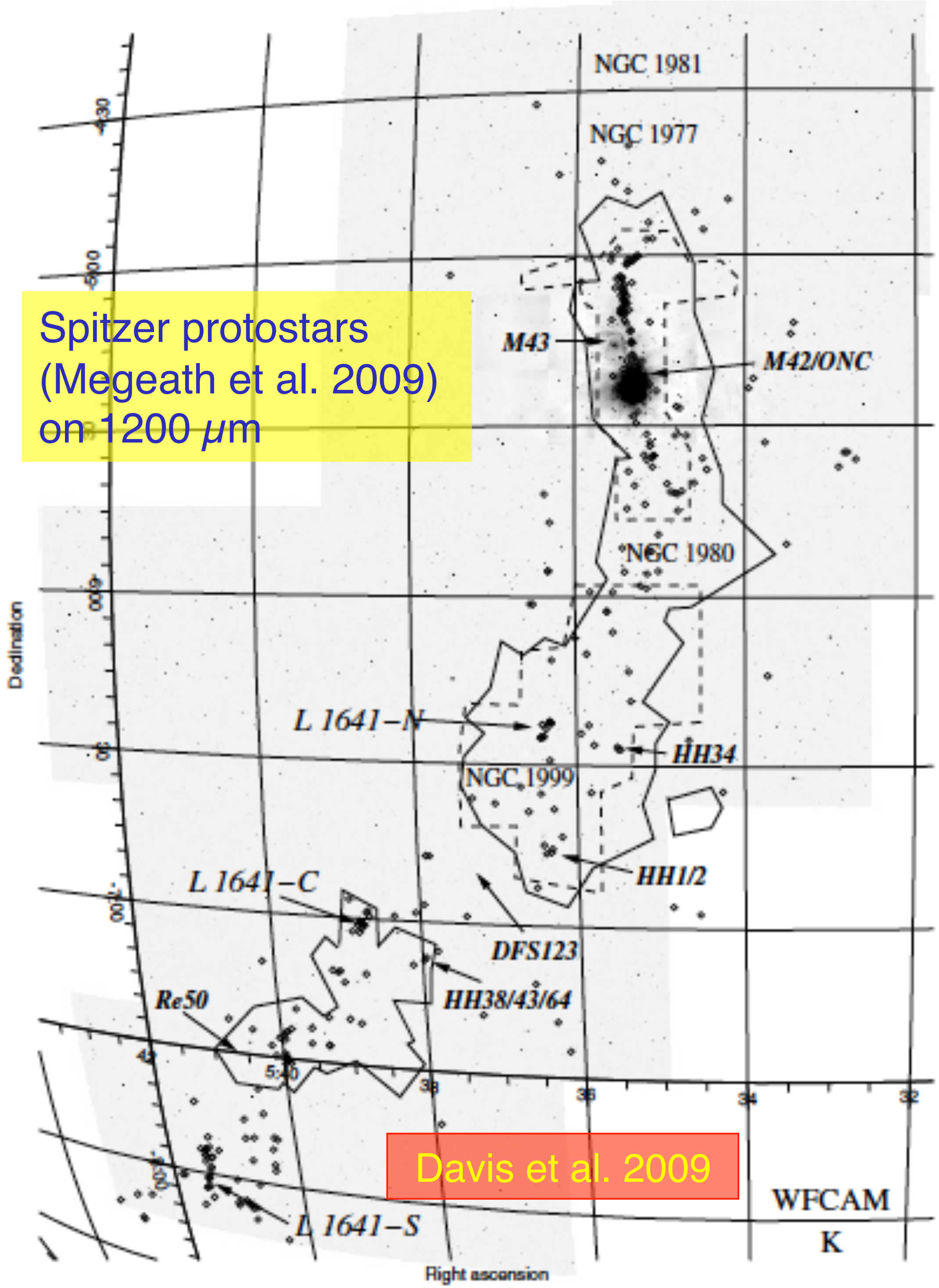
Telescope	Name	Elem.	λ/mm	Debut
IRAM 30m	MAMBO	7-117	1.2	1991
IRAM 30m	HUMBA	19	2	1999
HHT (Arizona)		19	0.87	1999
SEST (Chile)	SIMBA	37	1.2	2000
30m/HHT	Polarimeter	37/19	1.2/0.87	2003
30m/APEX	TES-Test	7	1.2	2003
APEX	LABOCA	295	0.87	2005
APEX	SABOCA	37	0.35	2008

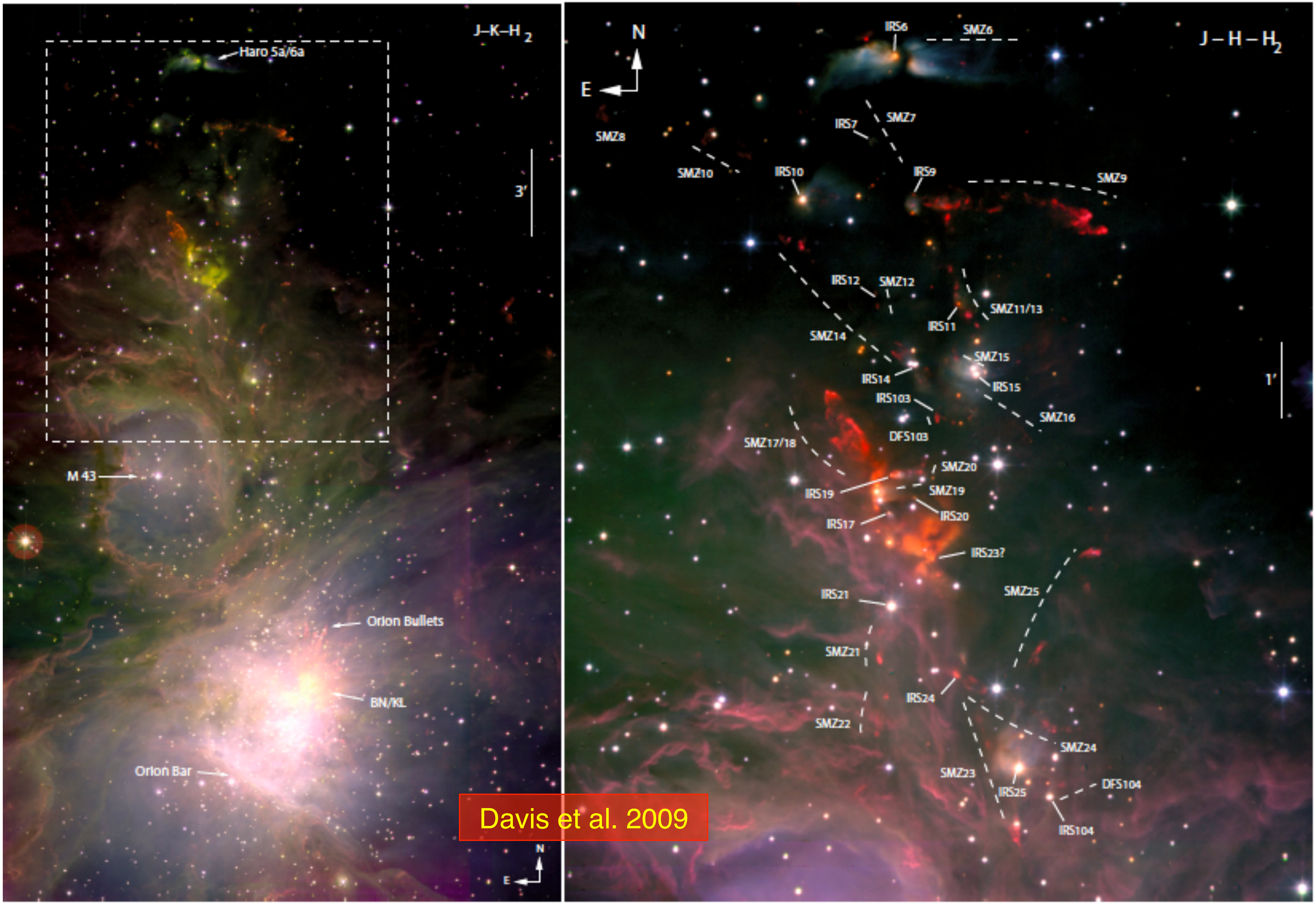

MAMBO-37


MAMBO-117


LABOCA 295


30 pc
1200 μm
IRAM 30m/MAMBO
T. Stanke


Spitzer protostars
(Megeath et al. 2009)
on 1200 μm
NGC 1981
NGC 1977
M43
M42/ONC
NGC 1980
L 1641–N
HH34
NGC 1999
HH1/2
L 1641–C
DFS123
HH38/43/64
Re50
L 1641–S
Declination
Right ascension
WFCAM
K
Davis et al. 2009



Davis et al. 2009

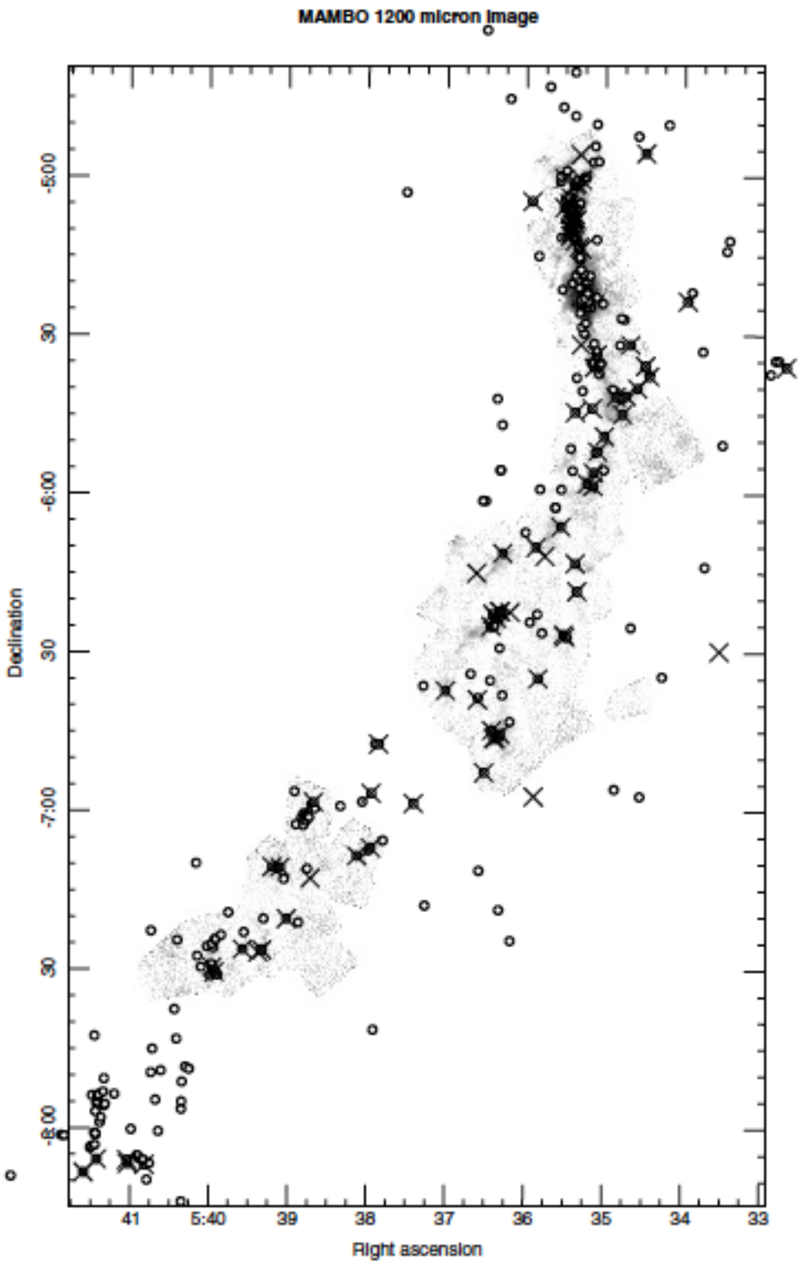
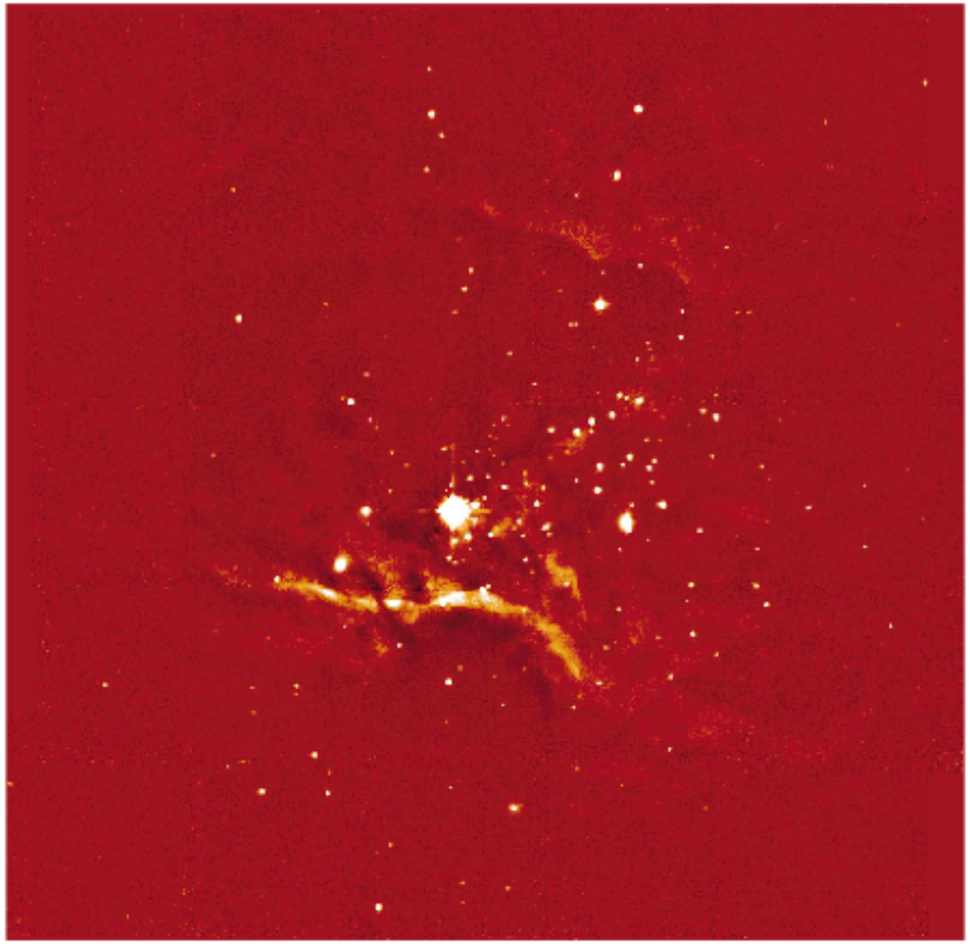


Fig. 18. A logarithmically-scaled image of 1200 μm emission with, superimposed, the locations of all Spitzer-identified protostars (open circles). H_2 outflow sources are marked with crosses (note that a handful of H_2 jet sources are disc-excess sources).

Davis et al. 2009

Orion B: The NGC 2024 Star Cluster

JHK (1.3/1.6/2.2 μm)

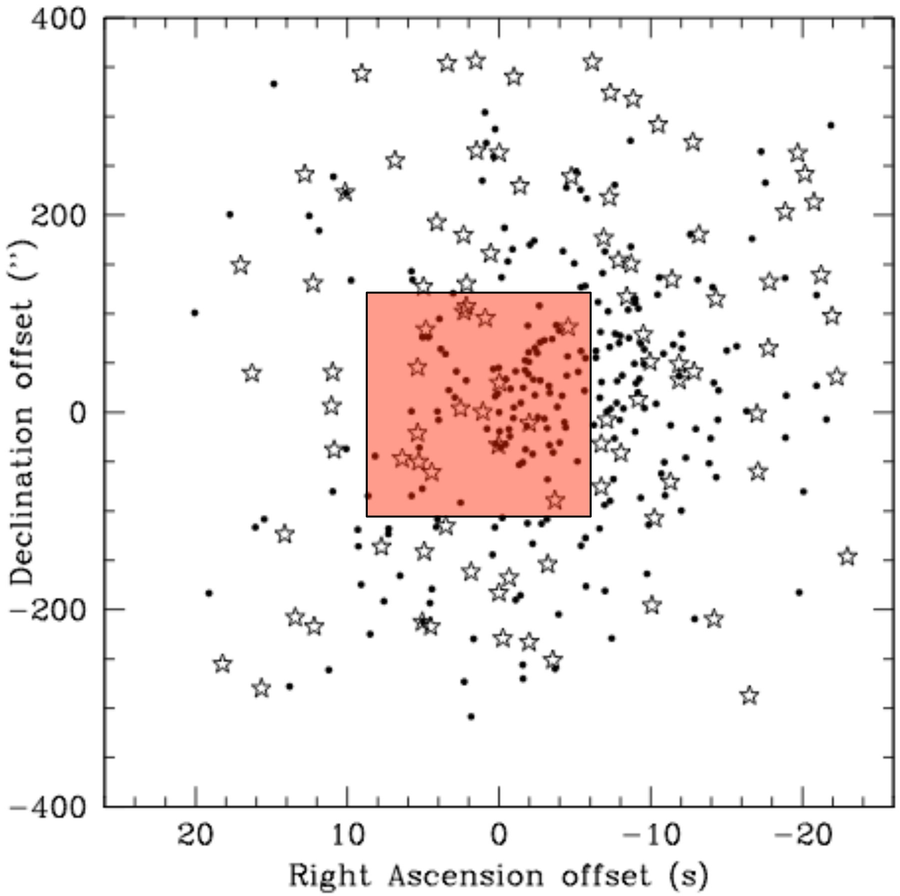


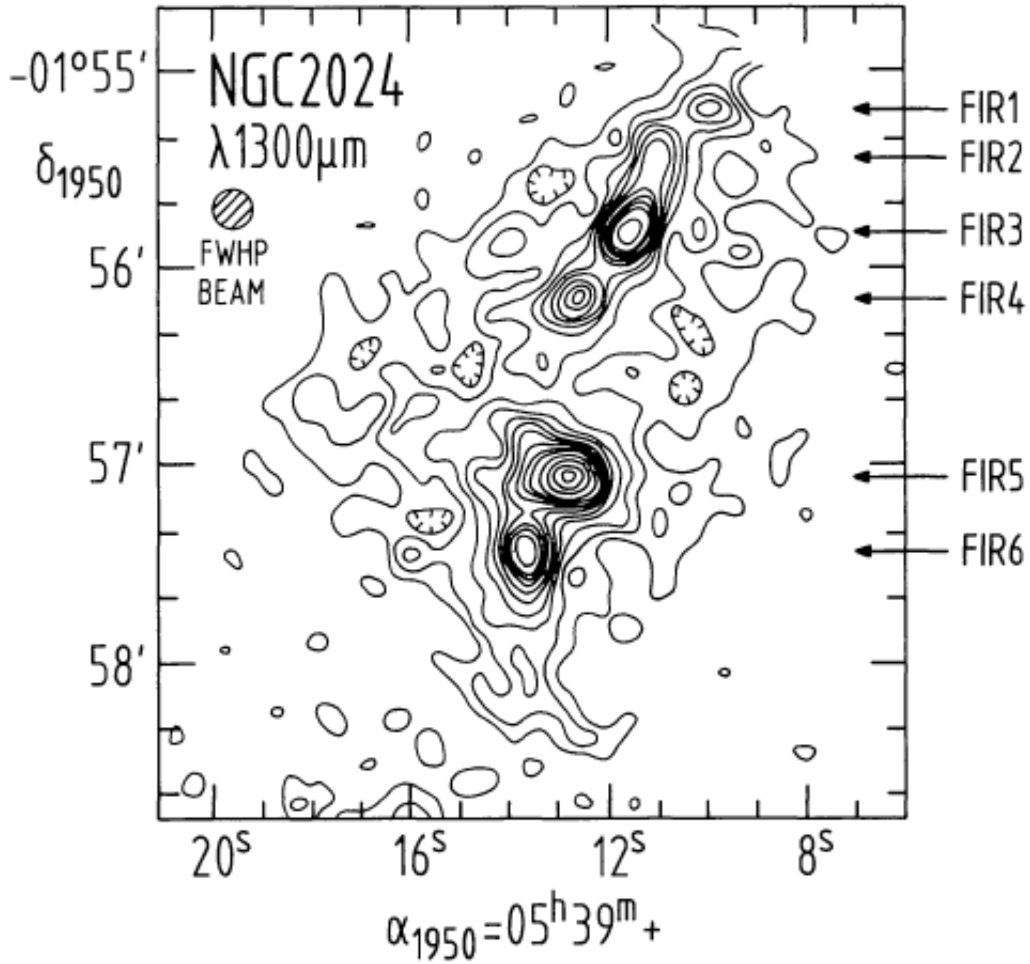
L (3.4 μm)

10.5' = 1.3 pc

- ~200 sources
- very high disk fraction (IR excess in 86%)

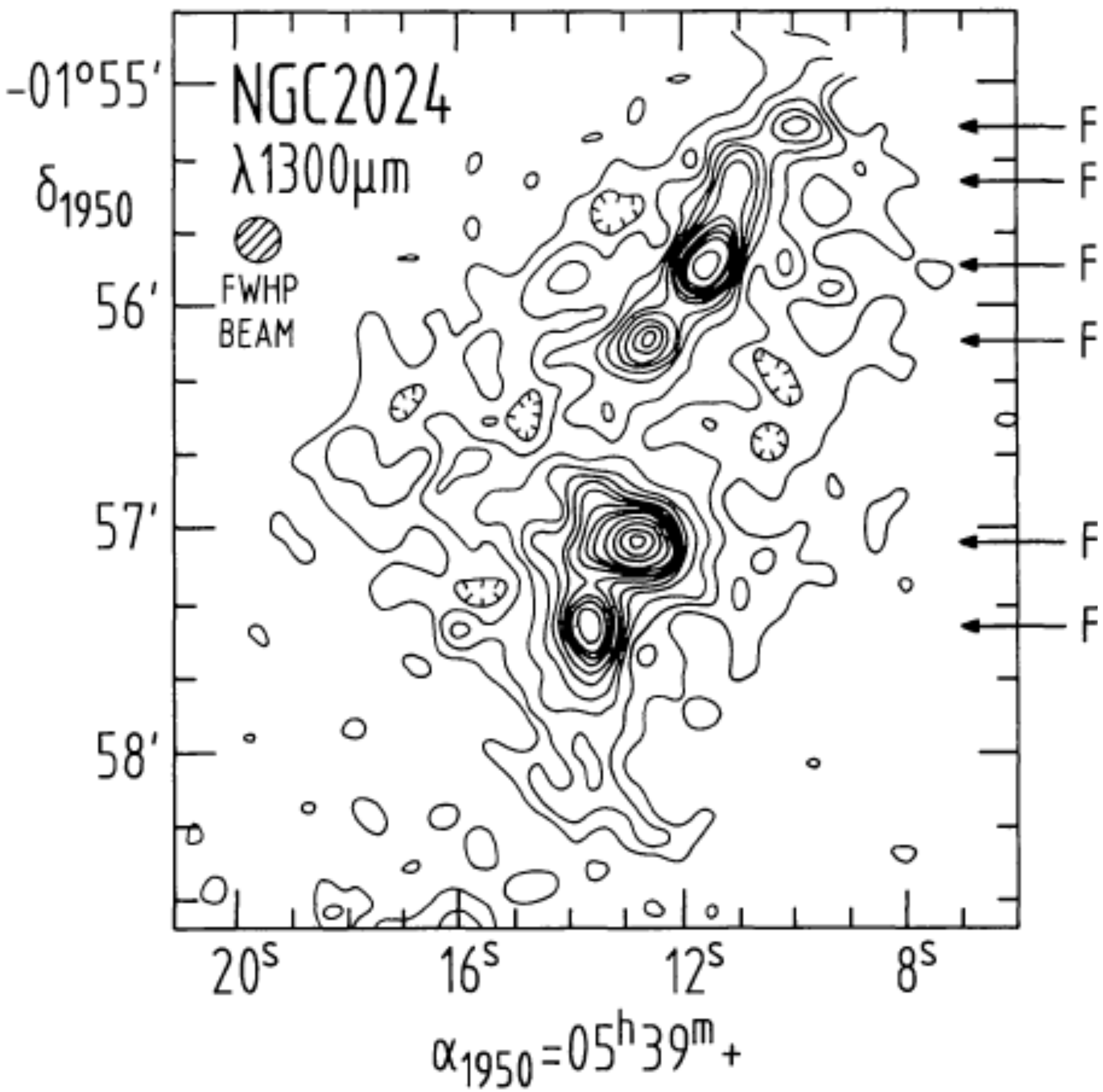
Haisch, Lada[2] 2000

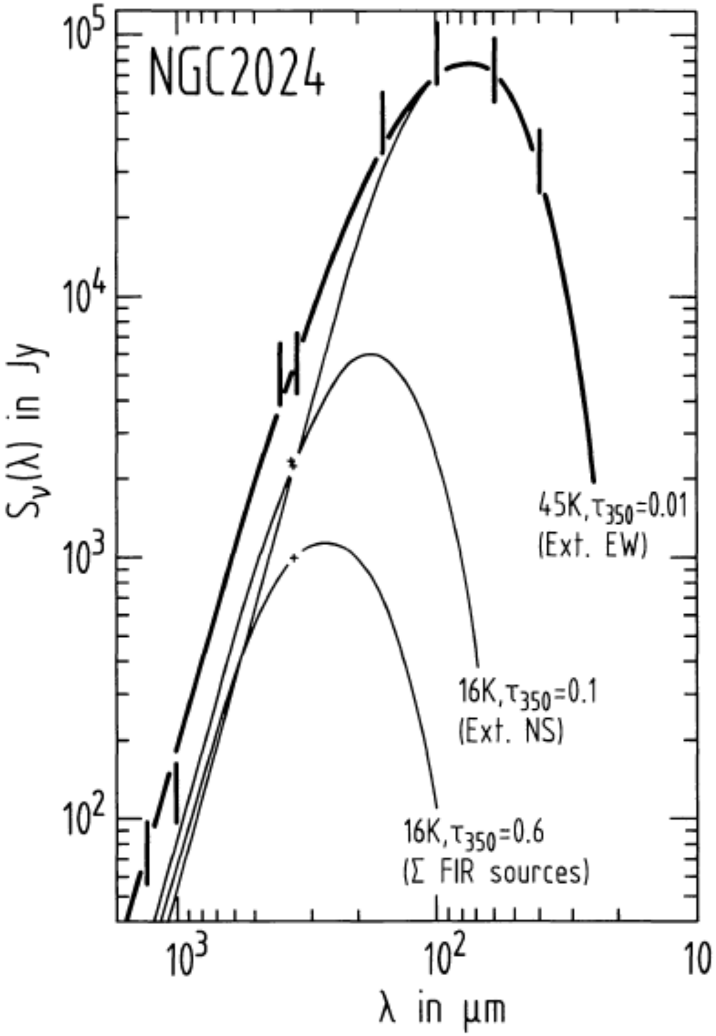




NIR K/L
Haisch, Lada² 2000

1200 μm
Mezger et al. 1988





Six high density condensations

- sizes 10^{16} – 10^{17} cm
- $n_H \sim 10^8 - 10^9$ cm^{-3}
- M ~ 10–60 $M_\odot$
- cold (16 K) with warmer envelope

Mezger et al. 1988

TABLE 1 Catalog of embedded clusters

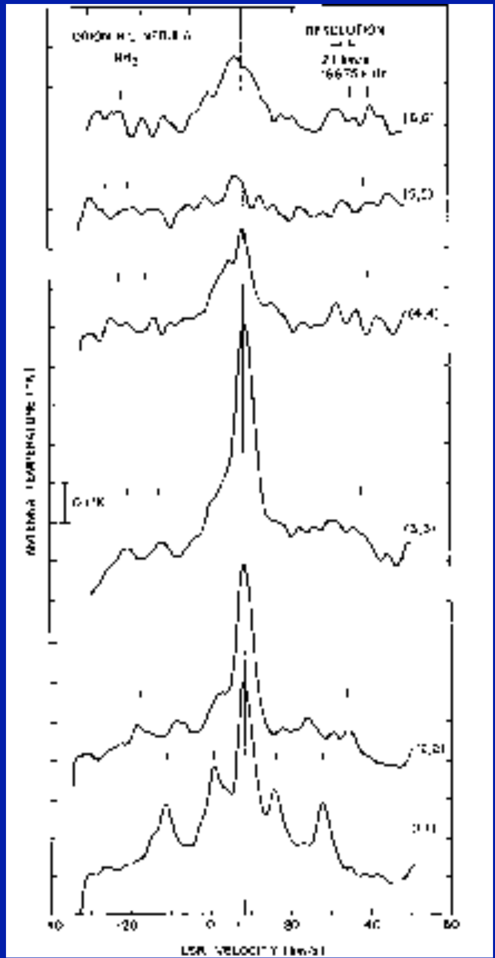
EC	Name	RA (J2000)	Dec (J2000)	Distance (pc)	Size (pc)	N_*	K (limit)	Mass $M_\odot$	References
	OMC 2	05:35:27.3	−05:09:39	500		119	17.5	63	1
	L1641 N	05:36:23.1	−06:23:40	500	0.33	43	14.7	24	1, 10
	ONC/Trapezium	05:37:47.4	−05:21:46	450	3.8	1740	14.0	1100	11, 12
	Trapezium	05:37:47.4	−05:21:46	450	0.24	780	17.5	413	13
	L1641C	05:38:46.9	−07:01:40	500	0.33	47	14.7	27	1, 10
	NGC 2024	05:41:42.6	−00:53:46	400	0.88	309	14.0	180	14
	NGC 2068	05:46:41.8	+00:06:21	400	0.86	192	14.0	110	14
	NGC 2071	05:47:10.0	+00:19:19	400	0.59	105	14.0	60	14

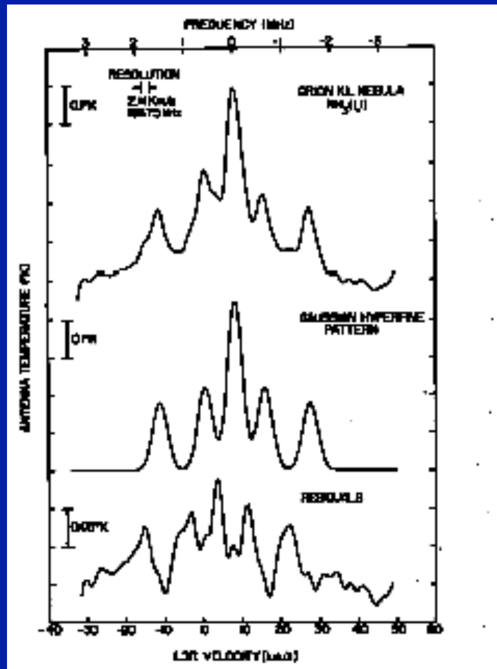
Lada & Lada 2003 (ARA&A)

Orion in NH_3 (late 1970s)

- Al Barrett and collaborators at MIT noticed a blue shifted component in their NH3 line profiles towards Orion-KL

- It was most apparent in the highly excited transitions tracing hot gas





Ho et al. 1979

THE ASTROPHYSICAL JOURNAL, **234**:912–921, 1979 December 15

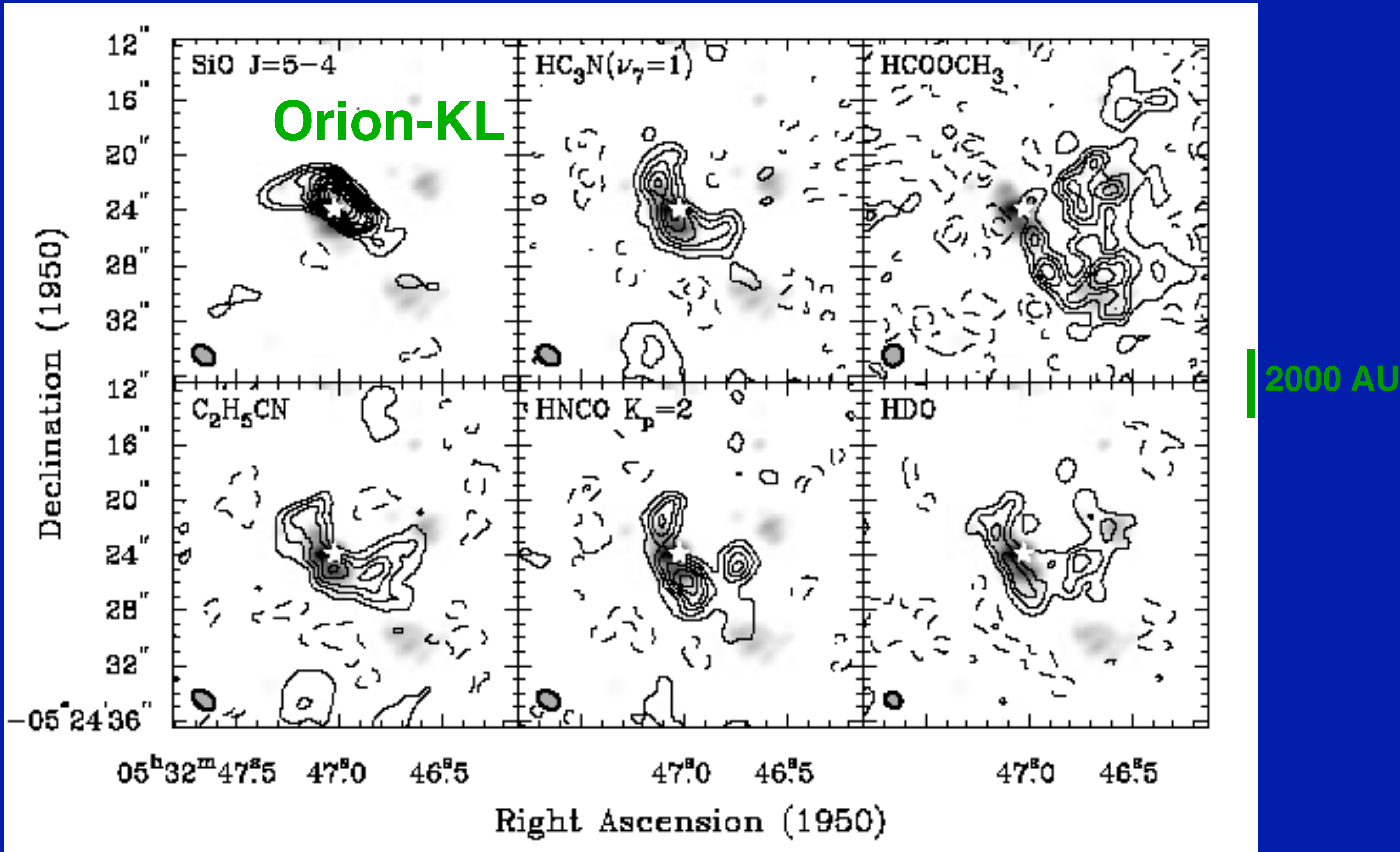
AMMONIA OBSERVATIONS OF THE ORION MOLECULAR CLOUD

P. T. P. HO,[1,2] A. H. BARRETT,[1] P. C. MYERS,[1] D. N. MATSAKIS,[3] A. C. CHEUNG,[4]
M. F. CHUI,[3] C. H. TOWNES,[3] AND K. S. YNGVESSON[5]
Received 1979 April 16; accepted 1979 June 28

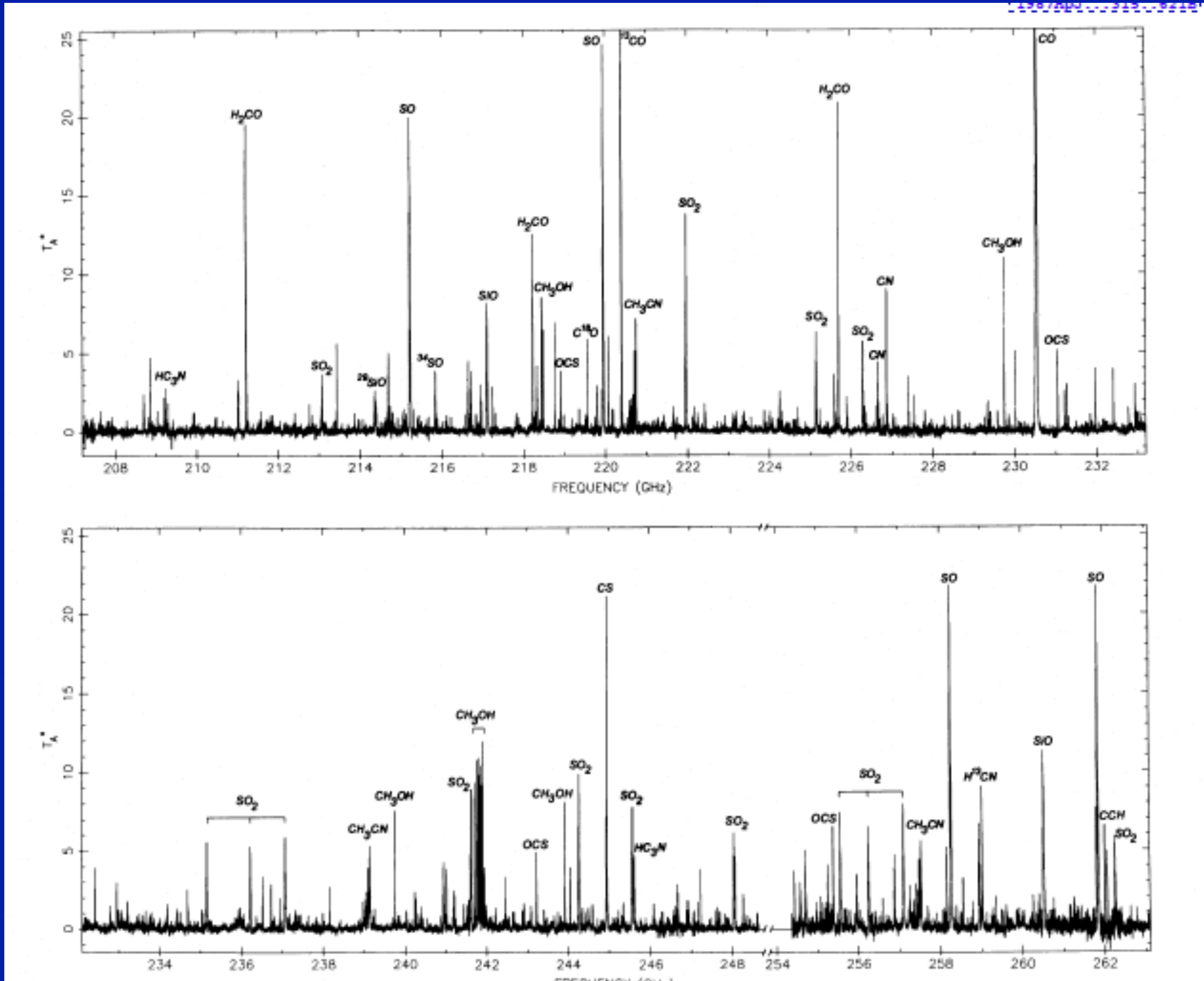
ABSTRACT

Emission from several metastable states of NH_3 is mapped in the OMC-1 and OMC-2 regions. Rotational temperatures are deduced from a comparison of the $(J, K) = (1, 1)$, $(2, 2)$, and $(3, 3)$ lines. A hot core is found at KL, embedded in the cooler OMC-1 ridge. Clumping is found to be extended over the entire OMC-1 region with only about one-tenth of the 1.′4 beam filled by regions which provide most of the emission.

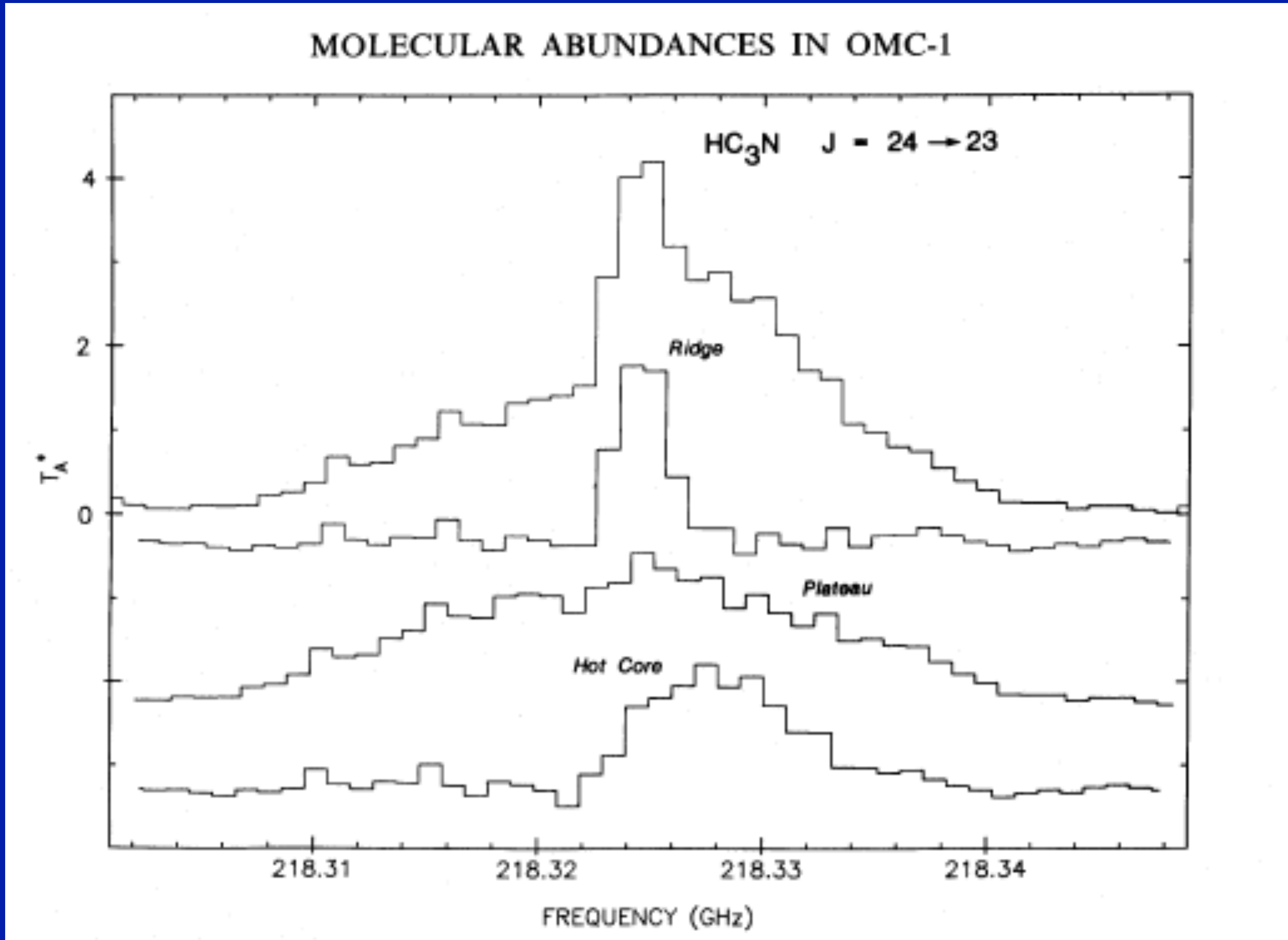
The first Hot Core:



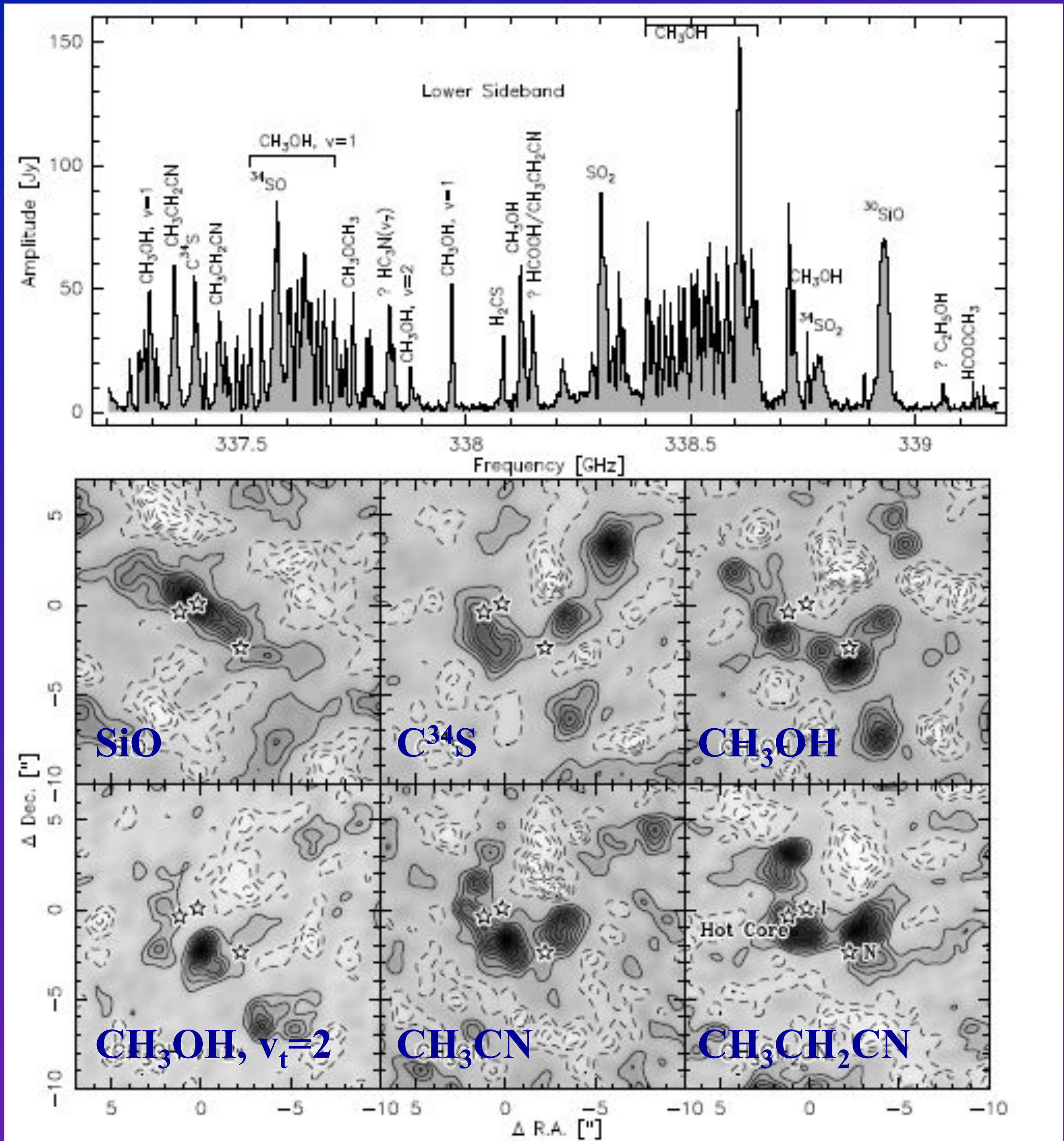
Blake et al. 1996



Blake et al. 1987, Sutton et al. 1984, 1986

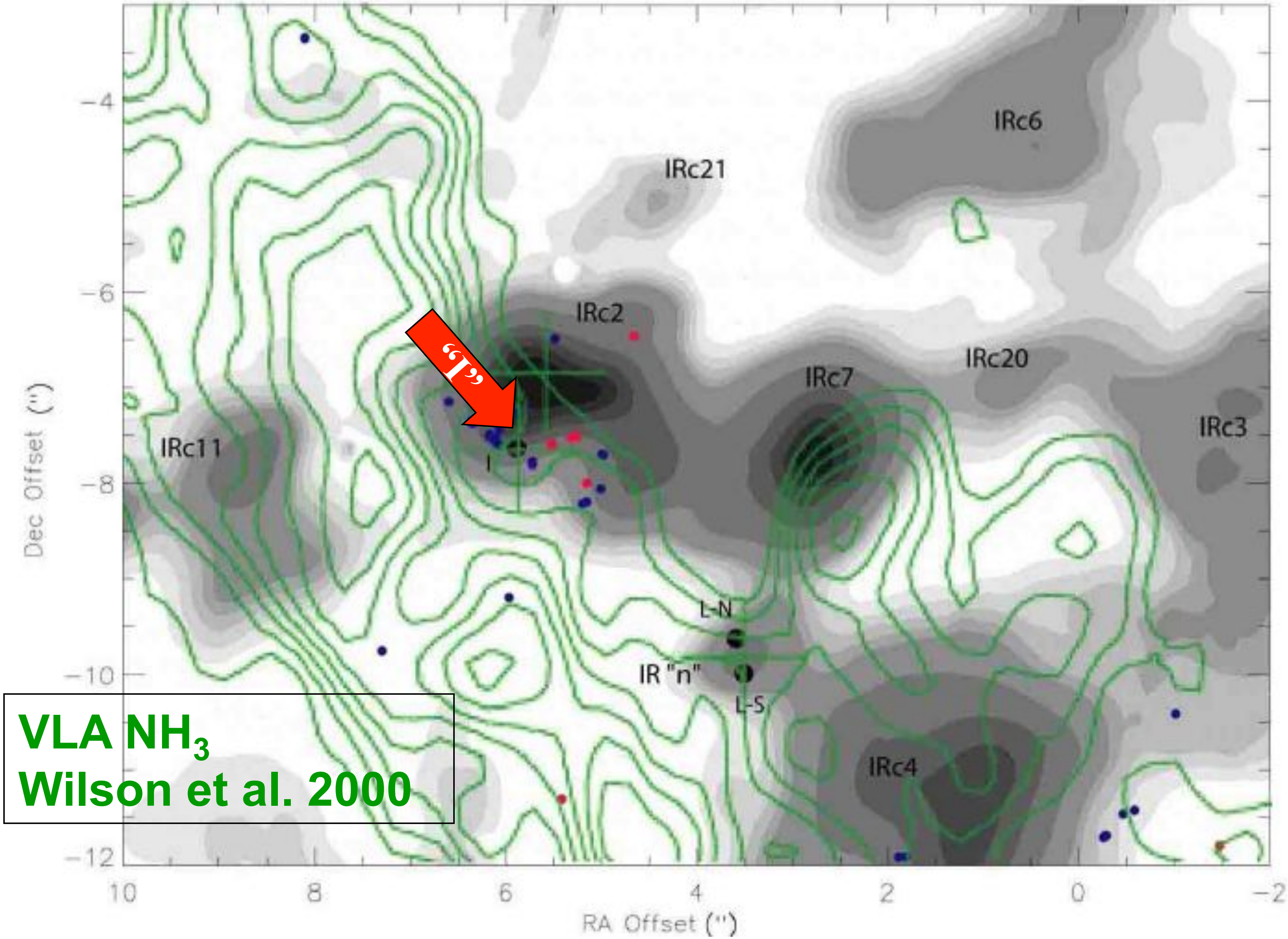


Blake et al. 1987



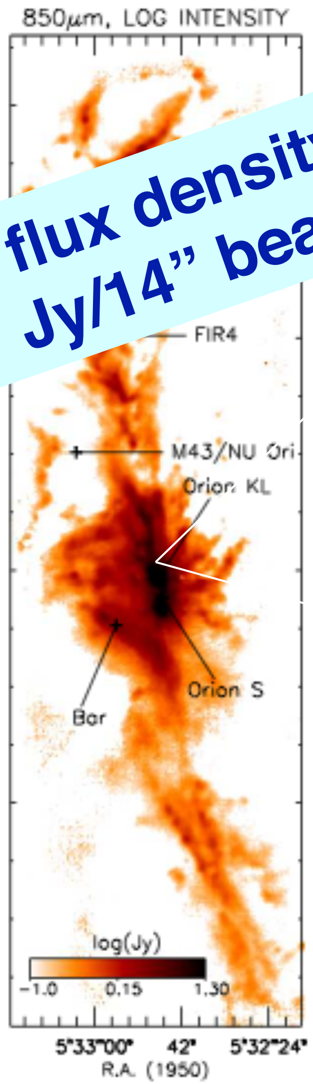
Submillimeter Array

Beuther et al. 2006 (P&PIV)

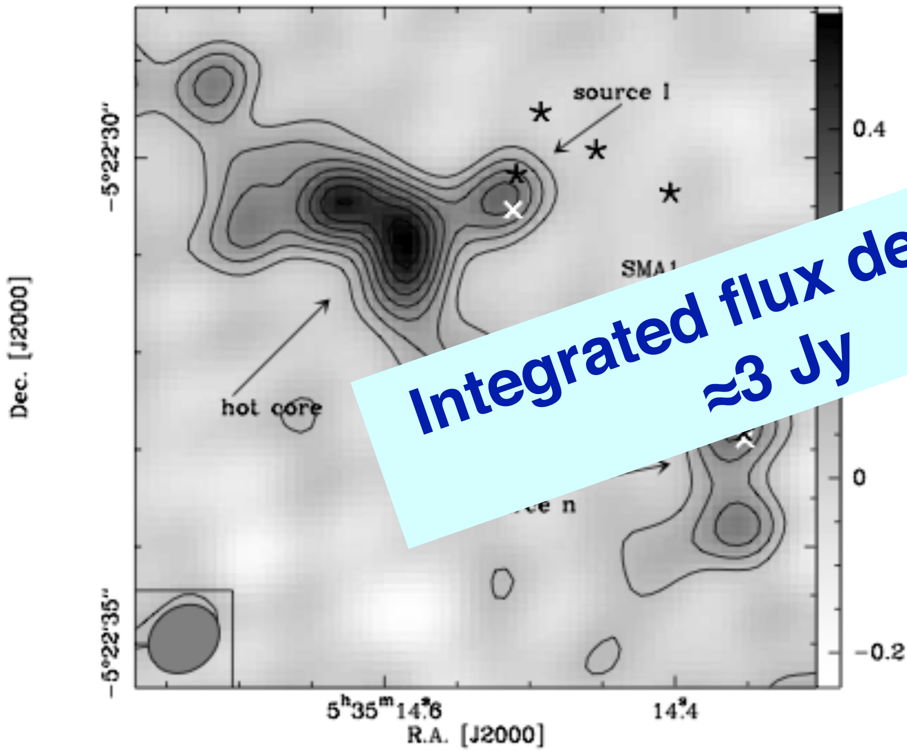


12 μm / Shuping et al. 2004

Two views of Orion at 870 µm (= 345 GHz)



Peak flux density: 167 Jy/14" beam



Integrated flux density: ≈3 Jy

SMA: Beuther et al. 2004/5

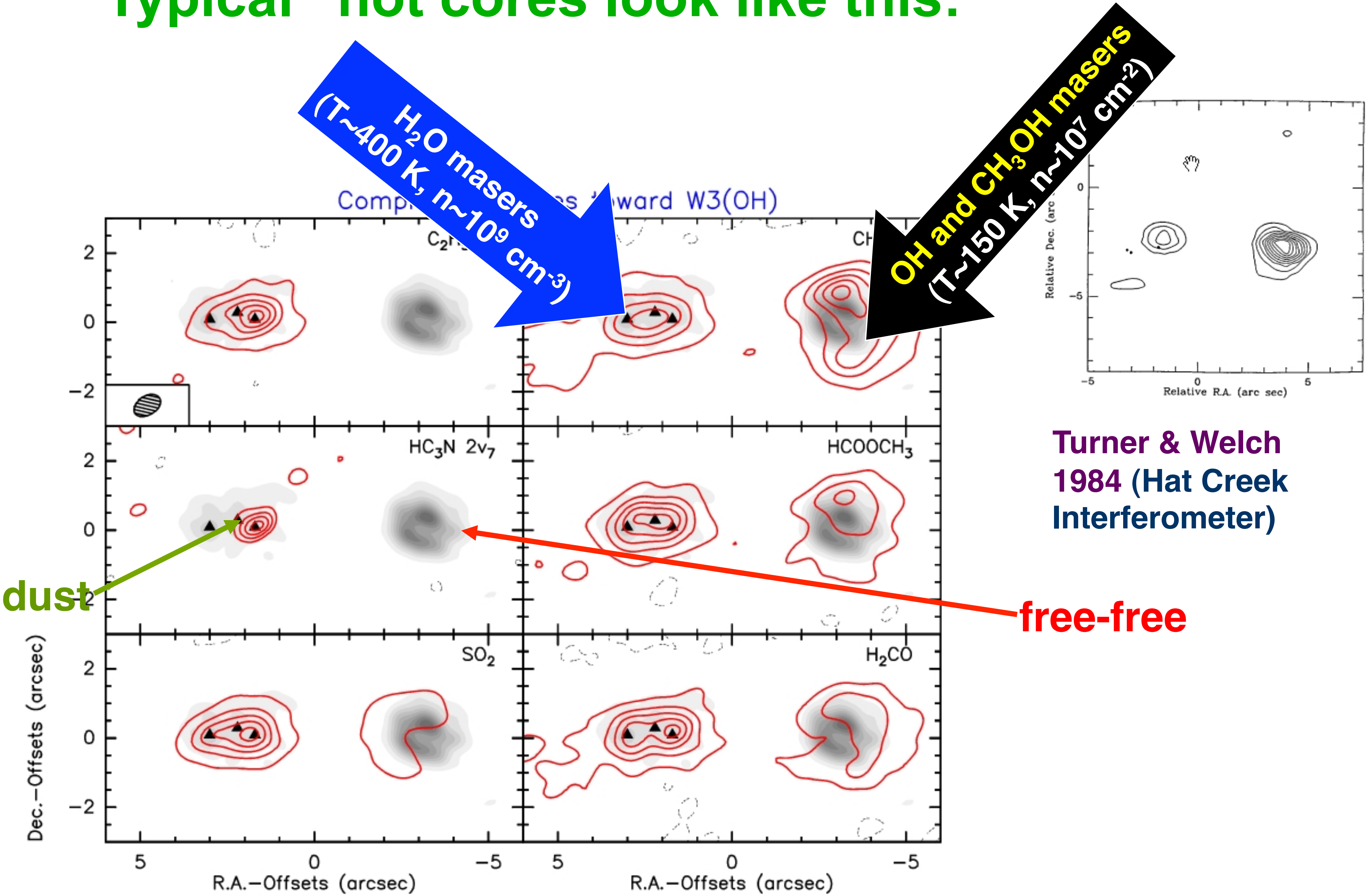
SCUBA@JCMT: Johnstone & Bally 1999

Deeply embedded high-mass proto- and young stellar objects are surrounded by

Hot Cores

- hot (>150 K)
- dense (>10^6 cm^{-3})
- compact (< a few thousand AU)
- rich organic chemistry

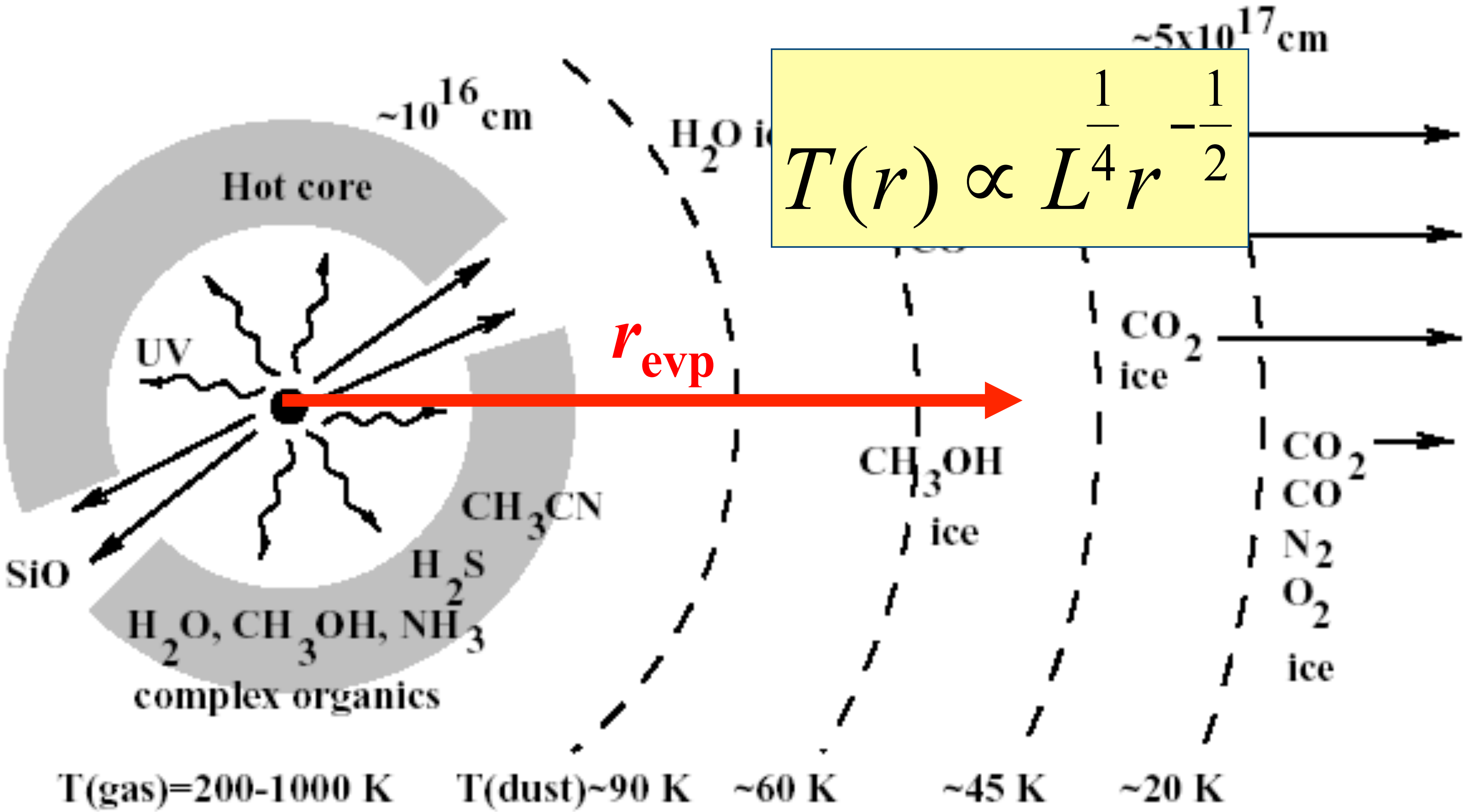
"Typical" hot cores look like this:

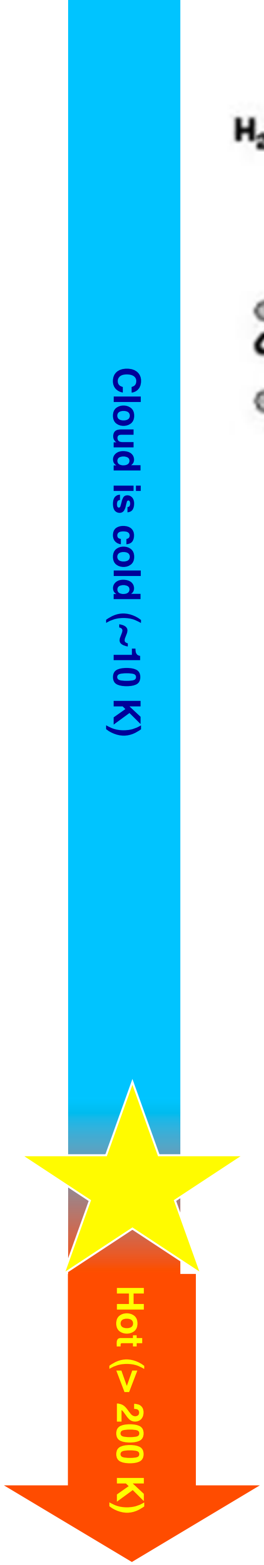


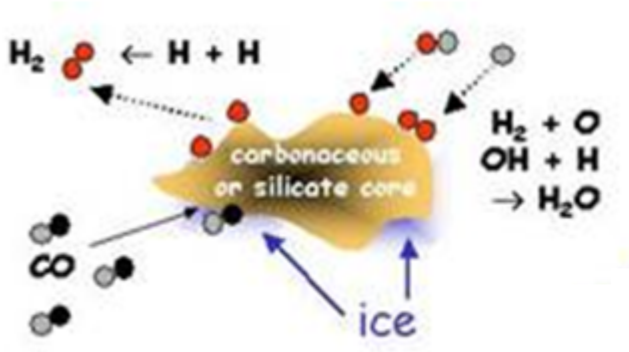
Turner & Welch 1984 (Hat Creek Interferometer)

Wyrowski et al. 1999 (IRAM PdBI)

$$T(r) \propto L^{\frac{1}{4}} r^{-\frac{1}{2}}$$







Forming interstellar ice

An icy grain of interstellar dust.

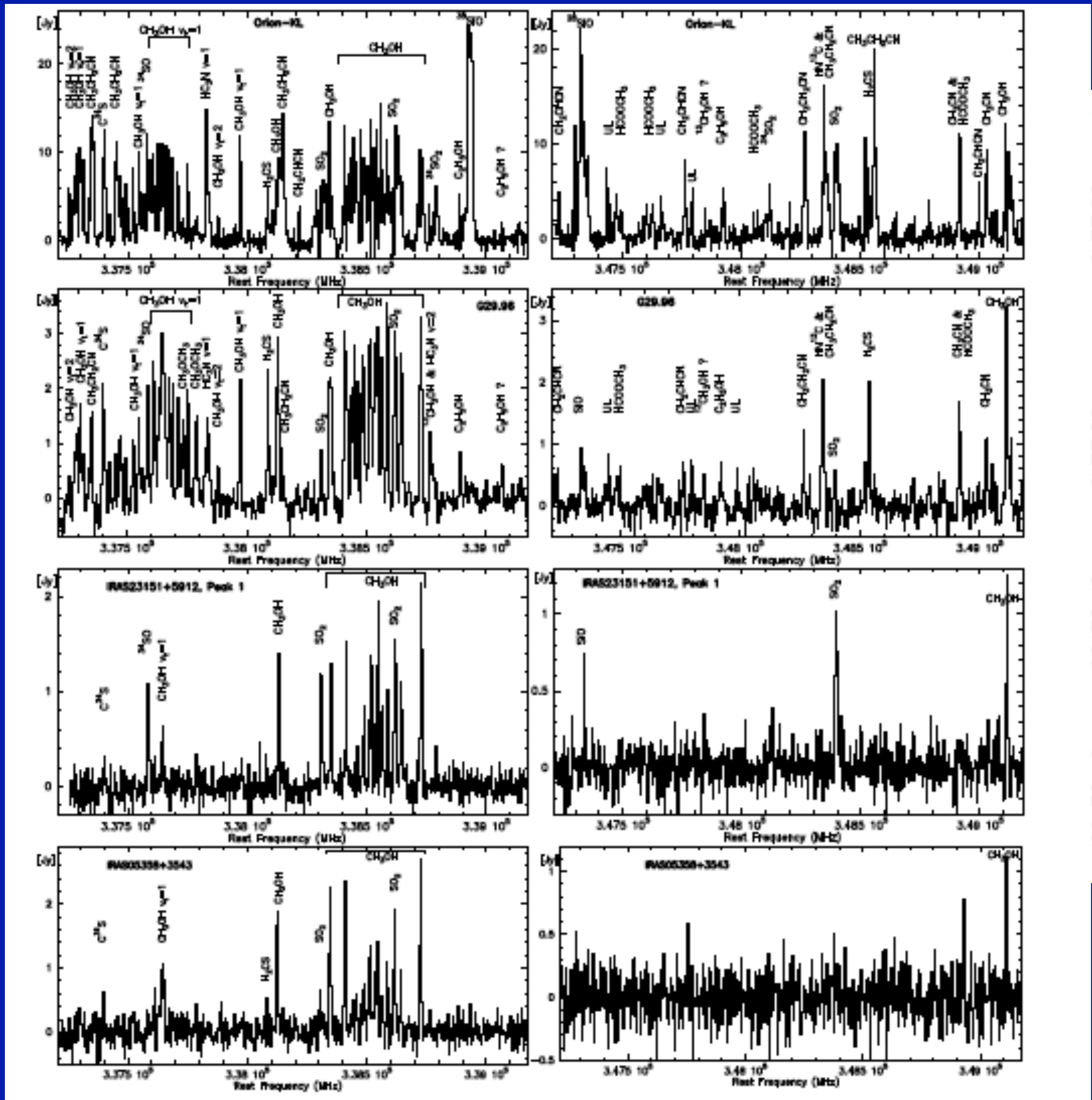
Processing interstellar ice

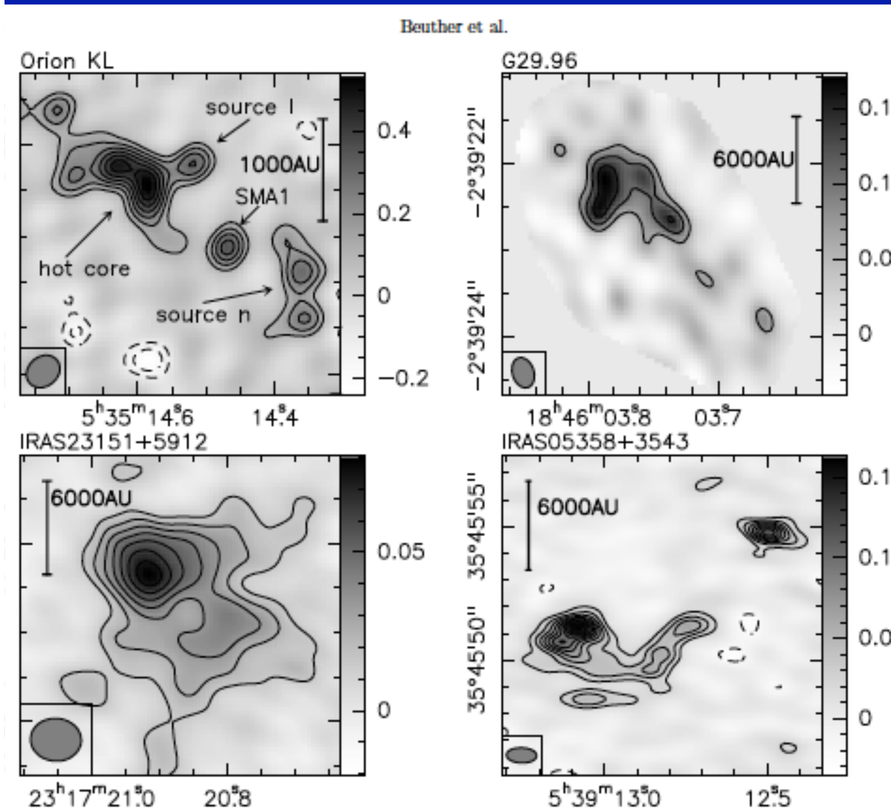
Back to the gas phase

Material from http://bcp.phys.strath.ac.uk/astro/astro.php (after Fraser et al. 2002)

Surveys found lots of Hot Cores

* With astonishing chemical diversity
* small-scale structure





Beuther et al. 2007

The Orion-KI region does not contain your typical hot core

- Energy source(s) unclear
- Physical and evolutionary status of hot molecular clumps unclear
- no class II methanol maser
- Large-scale explosion

→ We're seeing shrapnel!

Talk by L. Zapata

THE ASTROPHYSICAL JOURNAL
LETTERS TO THE EDITOR

VOLUME 149 JULY 1967 NUMBER 1, PART 2

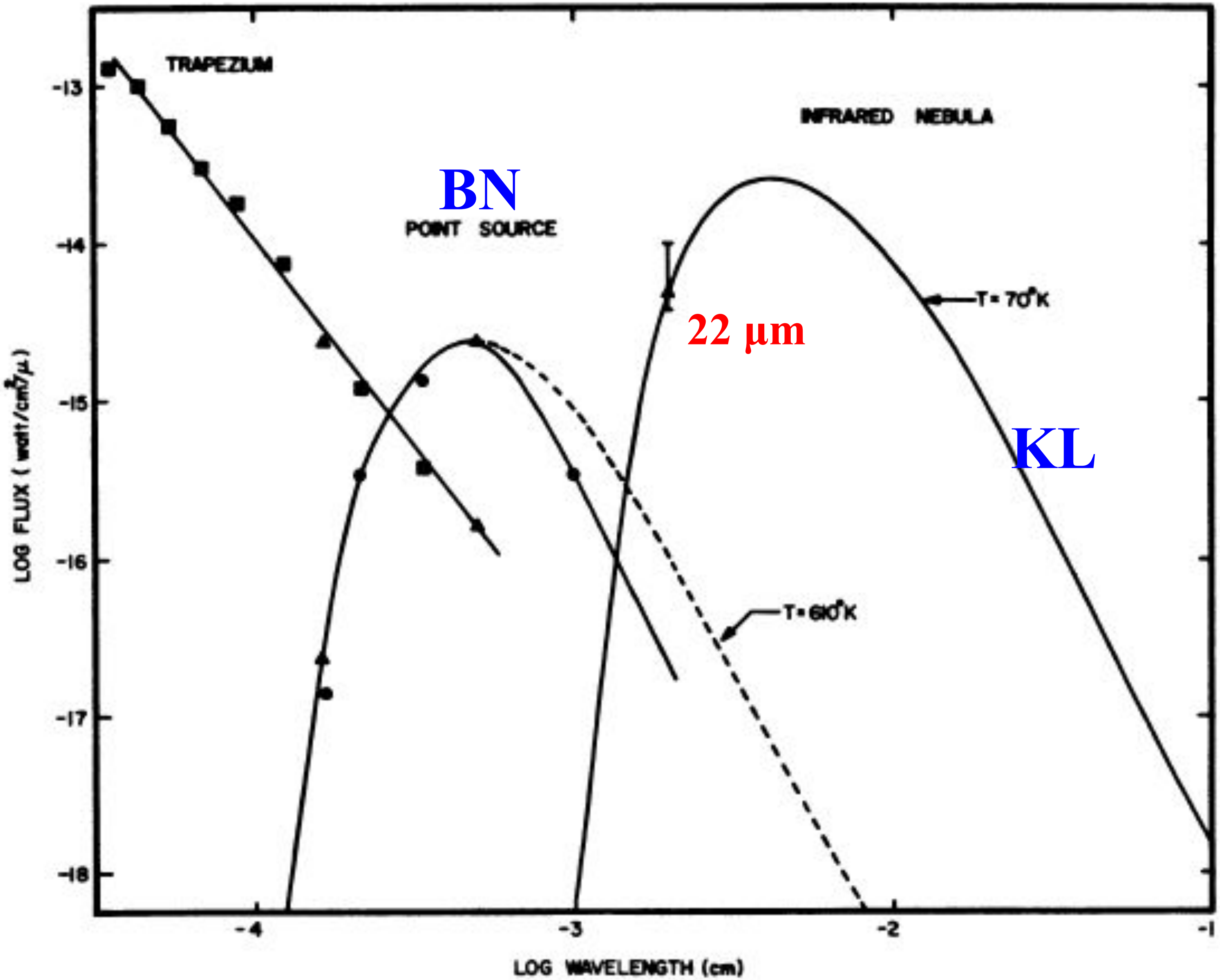
DISCOVERY OF AN INFRARED NEBULA IN ORION

D. E. Kleinmann
Department of Space Science, Rice University

and

F. J. Low
Lunar and Planetary Laboratory, University of Arizona, and
Department of Space Science, Rice University

Received June 1, 1967



Kleinmann & Low 1967

PHYSICAL PARAMETERS

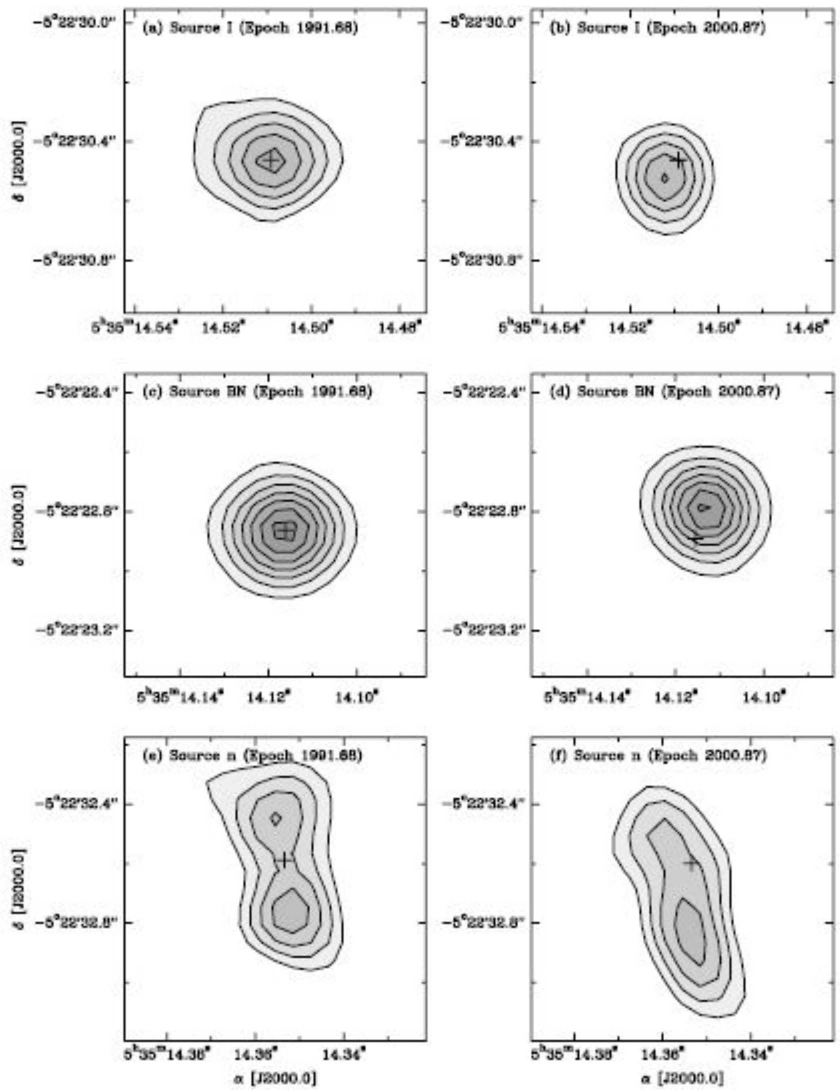
	Infrared Nebula	Point Source
α(1900)	$5^h30^m19^s.4$ ($\pm0^s.1$)	$5^h30^m19^s.7$ ($\pm0^s.2$)
δ(1900)	$-5°26'38''$ ($\pm3''$)	$-5°26'19''$ ($\pm6''$)
Angular diameter	$>30''$	$0''.06$
Magnitude	$Q=-7.0$ ($30''$ beam)	$M=-0.08$ ($13''$ beam)
22-μ flux	$>5\times10^{-15}$ watt cm^{-2} μ^{-1}	$<1\times10^{-16}$ watt cm^{-2} μ^{-1}
Distance	500 pc	500 pc
Linear diameter	2.3×10^{17} cm	4.8×10^{14} cm
Observed luminosity	3×10^{3} $L_\odot$	1.4×10^{3} $L_\odot$
Total luminosity	$>1\times10^{5}$ $L_\odot$	1.4×10^{3} $L_\odot$
Effective temperature	$\sim70°$ K	$\sim610°$ K
Mass	10^2–10^3 $M_\odot$	?
Lifetime	$\geq2\times10^{3}$ years	?

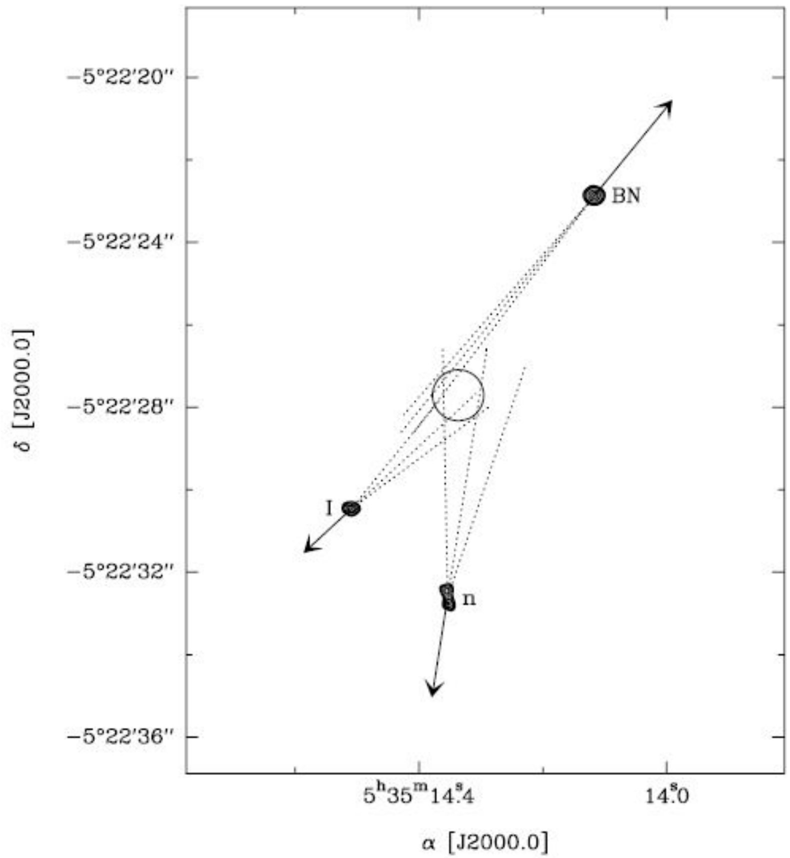
It follows from the above that the effective temperature is 70° K and the luminosity is

$$L = 4\pi\sigma T_e^4 R^2 \approx 1 \times 10^5 L_\odot ,$$

Bally & Zinnecker 2004: **"It is proposed that the outflow emerging from the OMC-1 core in the Orion molecular cloud was produced by a protostellar merger that released between 10^{48} and 10^{49} ergs less than a thousand years ago."**

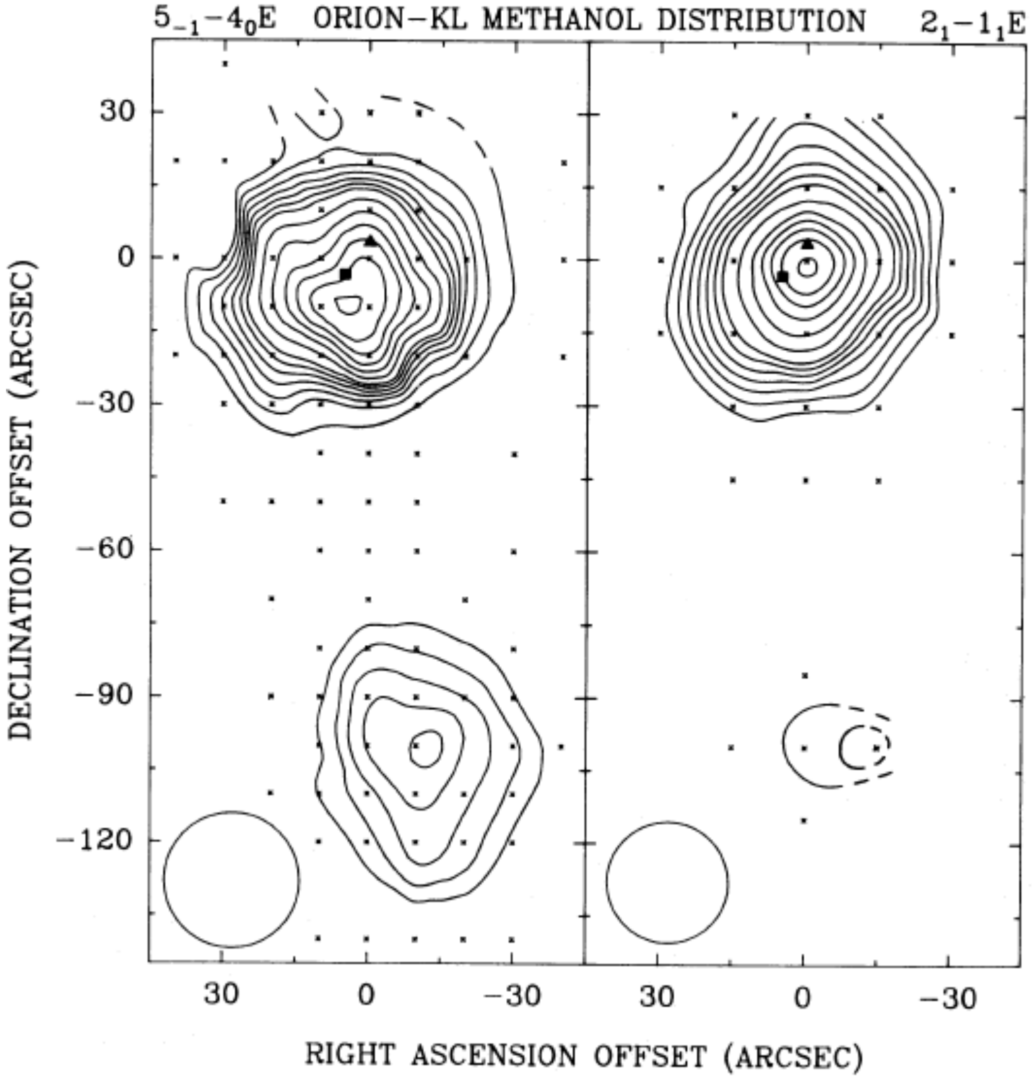
Gomez et al. (2006) measured proper motions and found that BN, I, and n all move away from each other





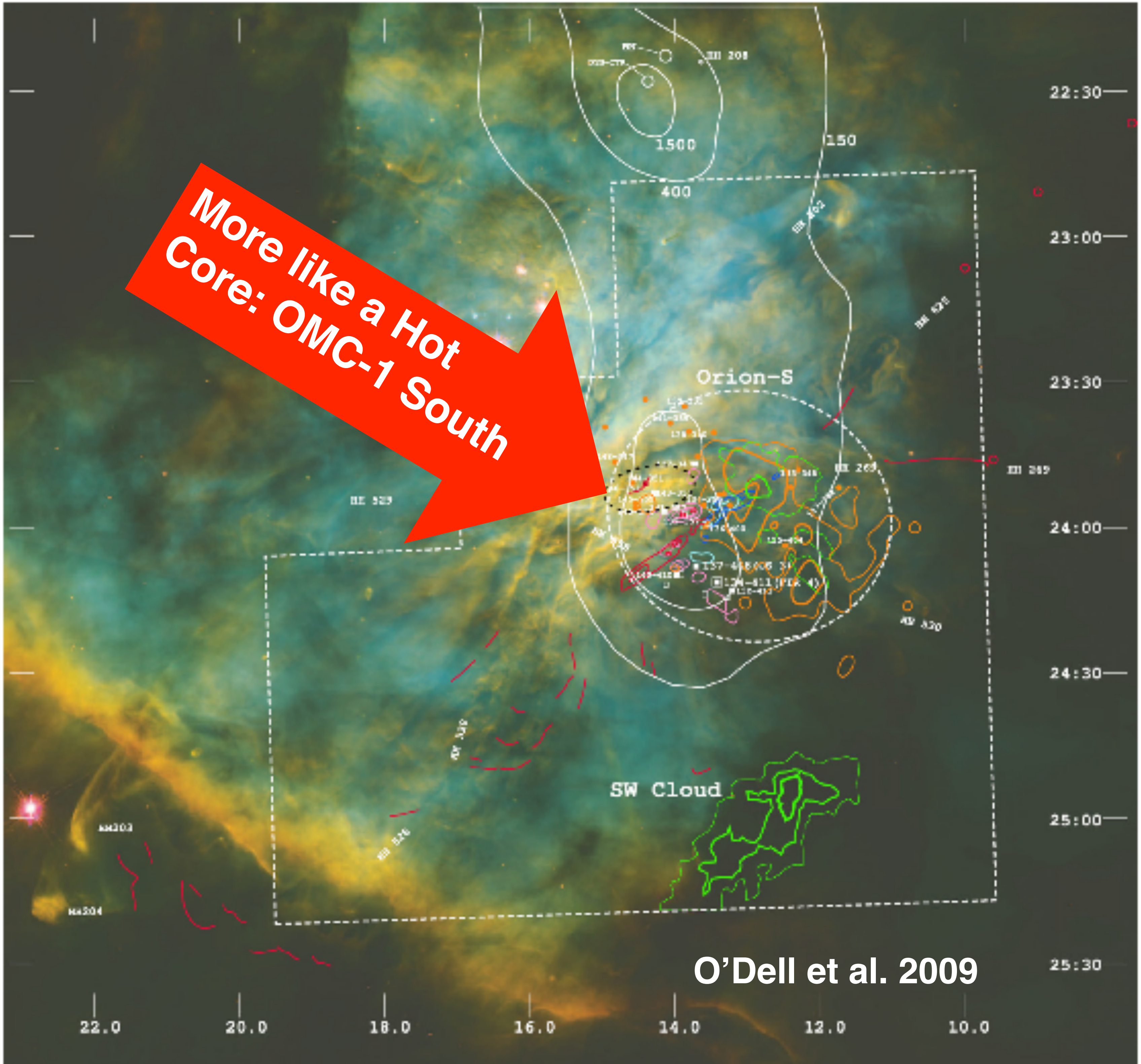
Time of event: about 500 y ago

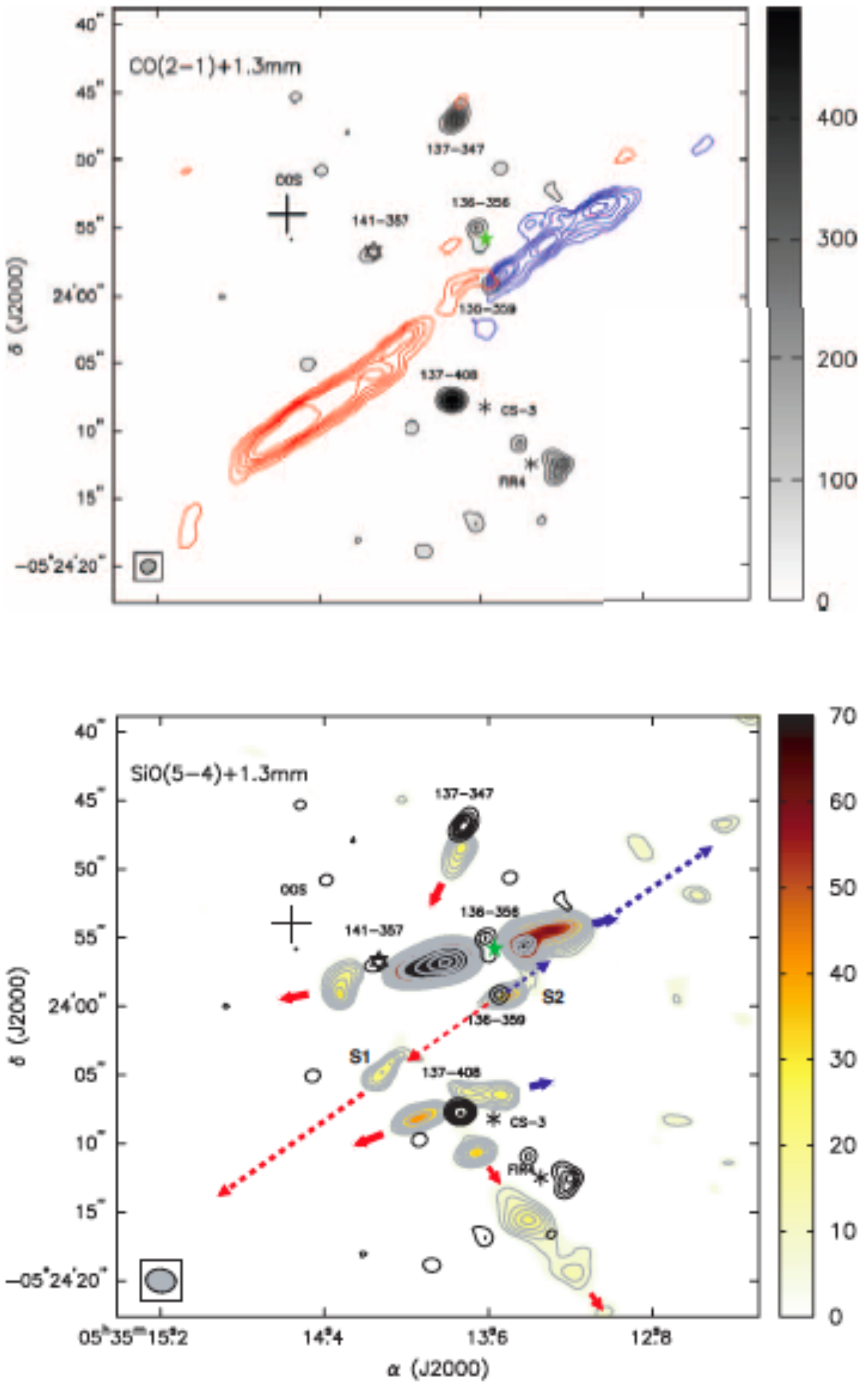
Methanol in OMC-1



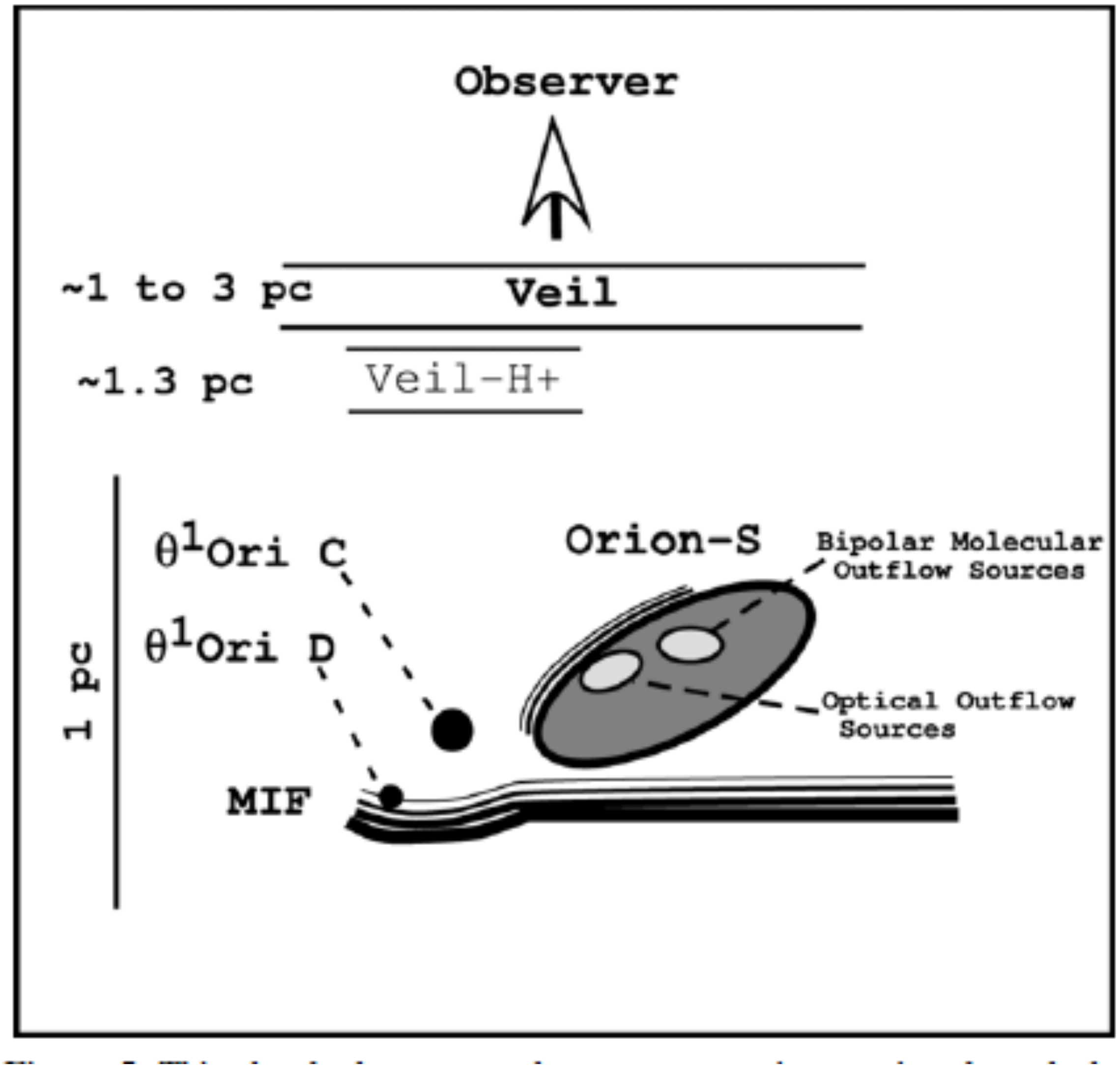
$[CH_3OH/H_2] \sim 10^{-7} – 10^{-6}$!

Menten et al. 1988


More like a Hot Core: OMC-1 South
Orion-S
SW Cloud
1500
400
150
22:30
23:00
23:30
24:00
24:30
25:00
25:30
22.0
20.0
18.0
16.0
14.0
12.0
10.0
O'Dell et al. 2009



Zapata et al. 2005/6



O'Dell et al. 2009

H_2CO in Orion-KL

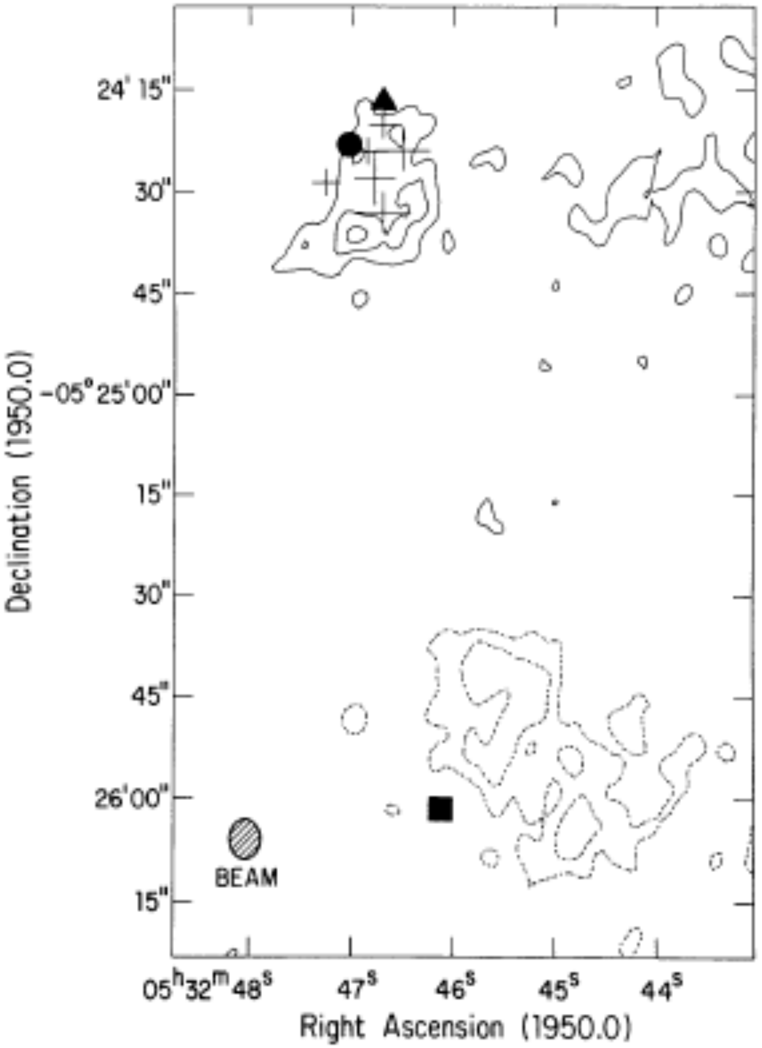
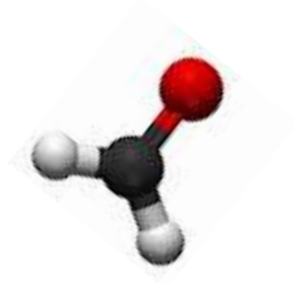
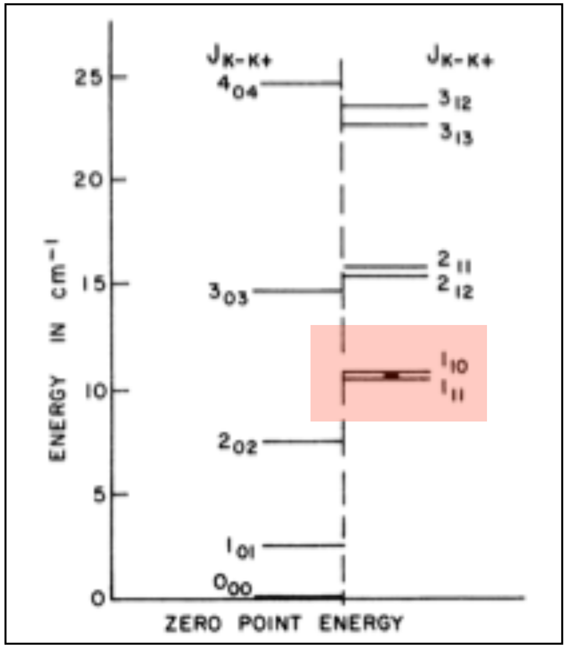


FIG. 2.—Total integrated $1_{10} \rightarrow 1_{11}$ H_2CO emission and absorption from Orion-KL. The contours are −40, −25, 25, 40, and 55 mJy beam^{-1} km s^{-1} (−80, −50, 50, 80, and 110 K km s^{-1}). The positions of the infrared and millimeter continuum sources and the synthesized beam are shown as in Fig. 1.





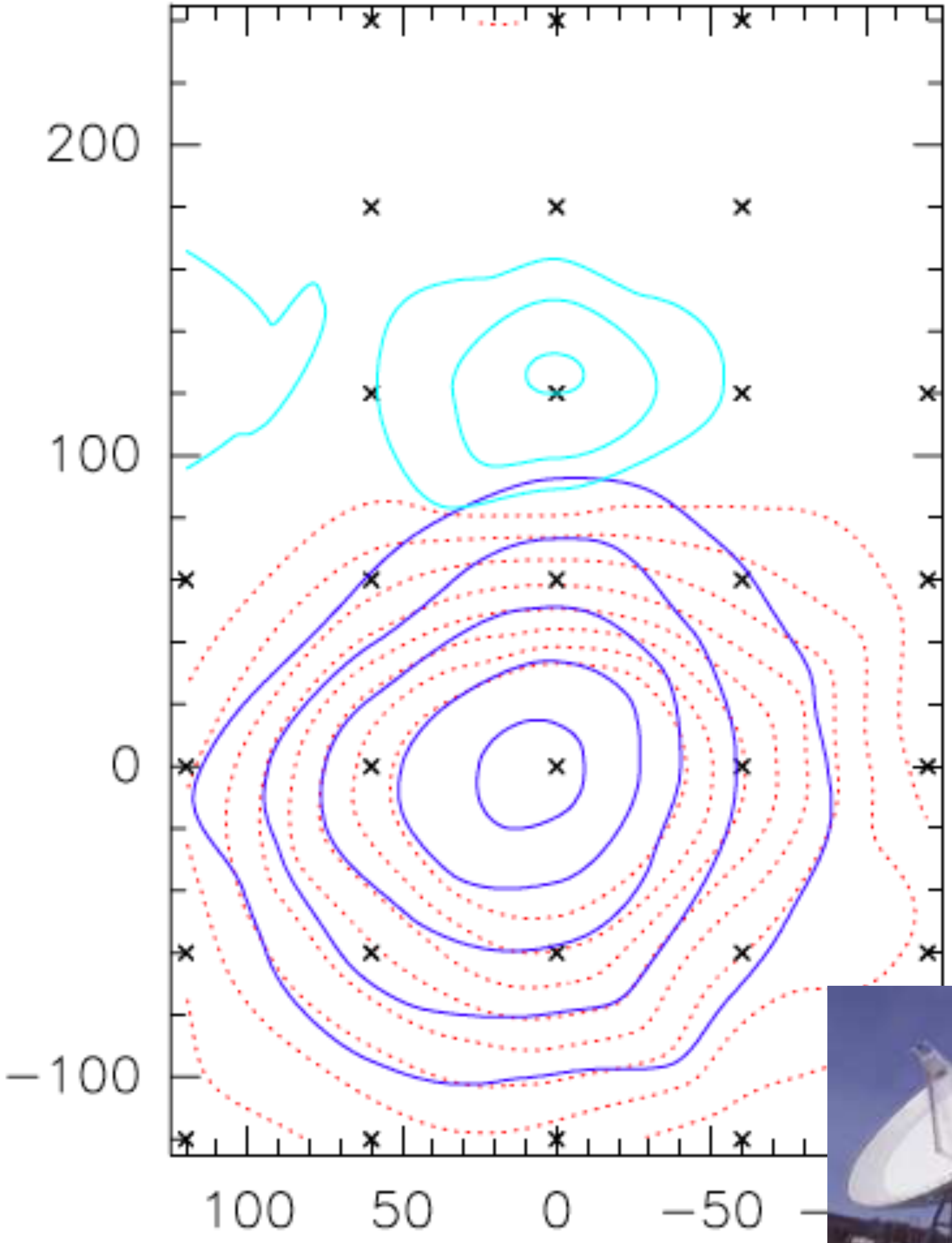
Mangum et al. 1993

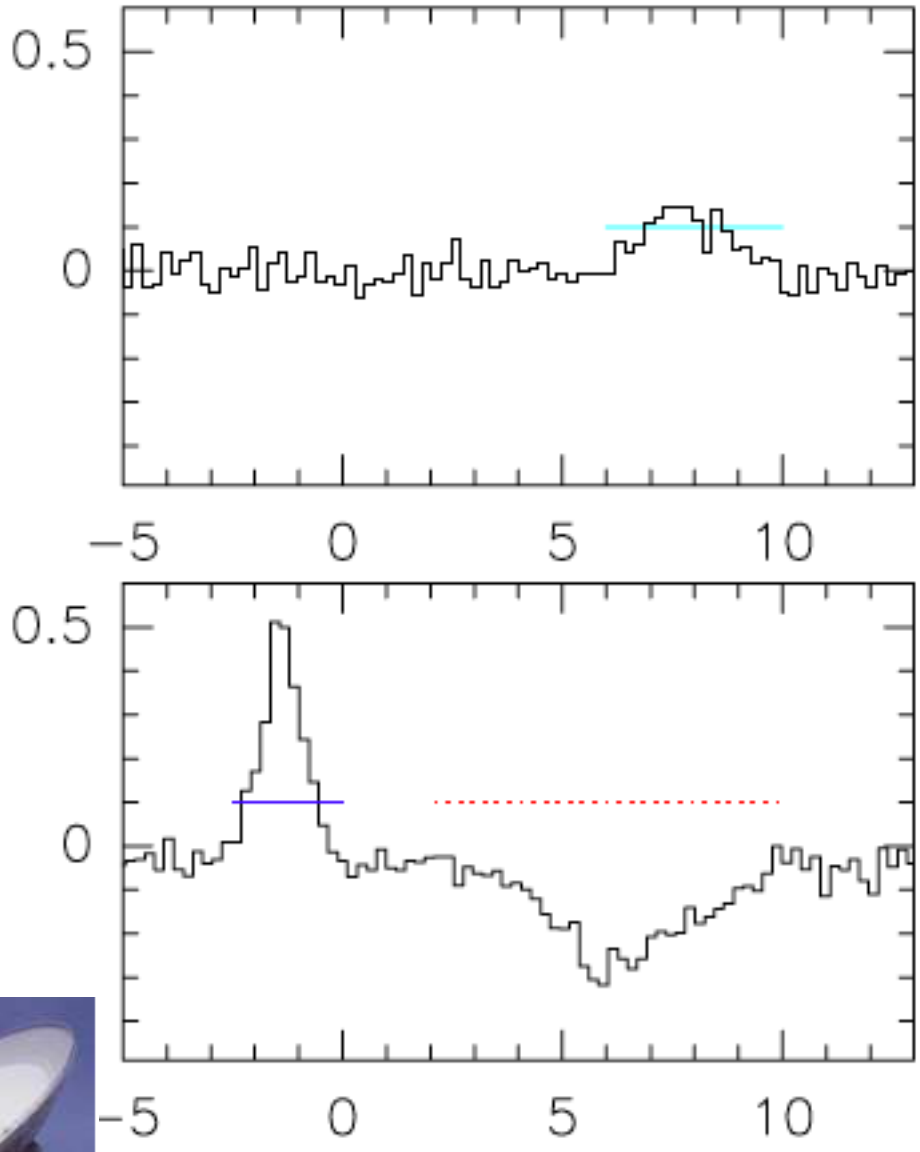
$1_{10} \rightarrow 1_{11}$ H_2CO COMPONENT PROPERTIES

Component	α(1950)	δ(1950)	$\theta_{max} \times \theta_{min}$	Position Angle	Peak T_B (K)	FWZI (km s^{-1})	$\int T_B dV$ (K km s^{-1})
Hot core	05h32m46.9s	−05°24'24"	10.9" × 7.0"	16°	<9.0[a]	9.2	84.8[b]
Compact ridge	05 32 46.8	−05 24 33	34.7 × 20.4	135	40.5	3.8	86.9
Northern cloud	05 32 47.5	−05 24 08	~15 × 10	~45	10.2	3.1	28.1
Orion-S	05 32 45.4	−05 25 48	35.5 × 22.2	29	−30.9	6.1	−107.6

[a] Upper limit given as twice the rms noise in a channel map.

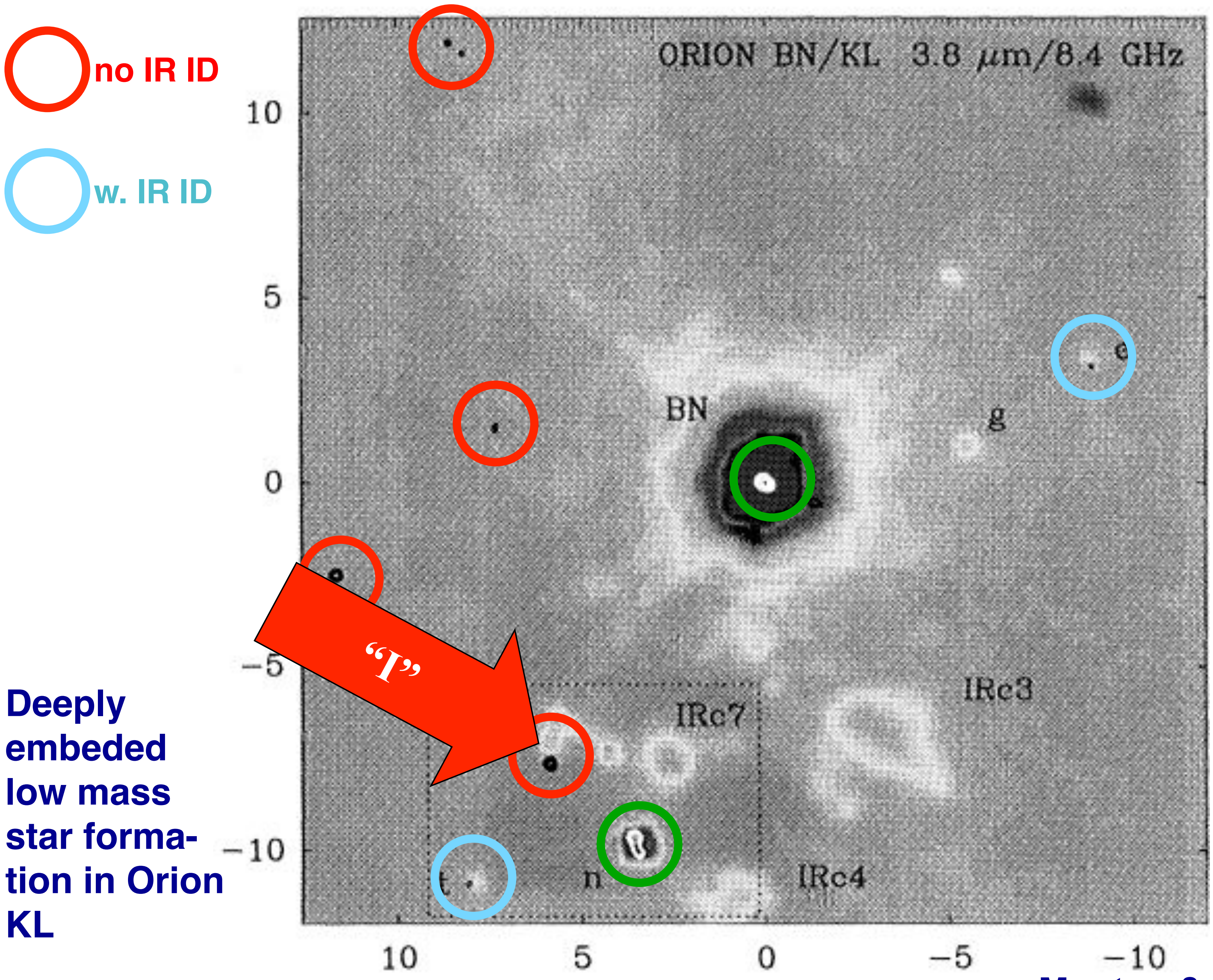
$5_0 - 6_1 A^+$ (6.7 GHz) in OMC 1 and OMC 1-S





See also Voronkov et al. 2005

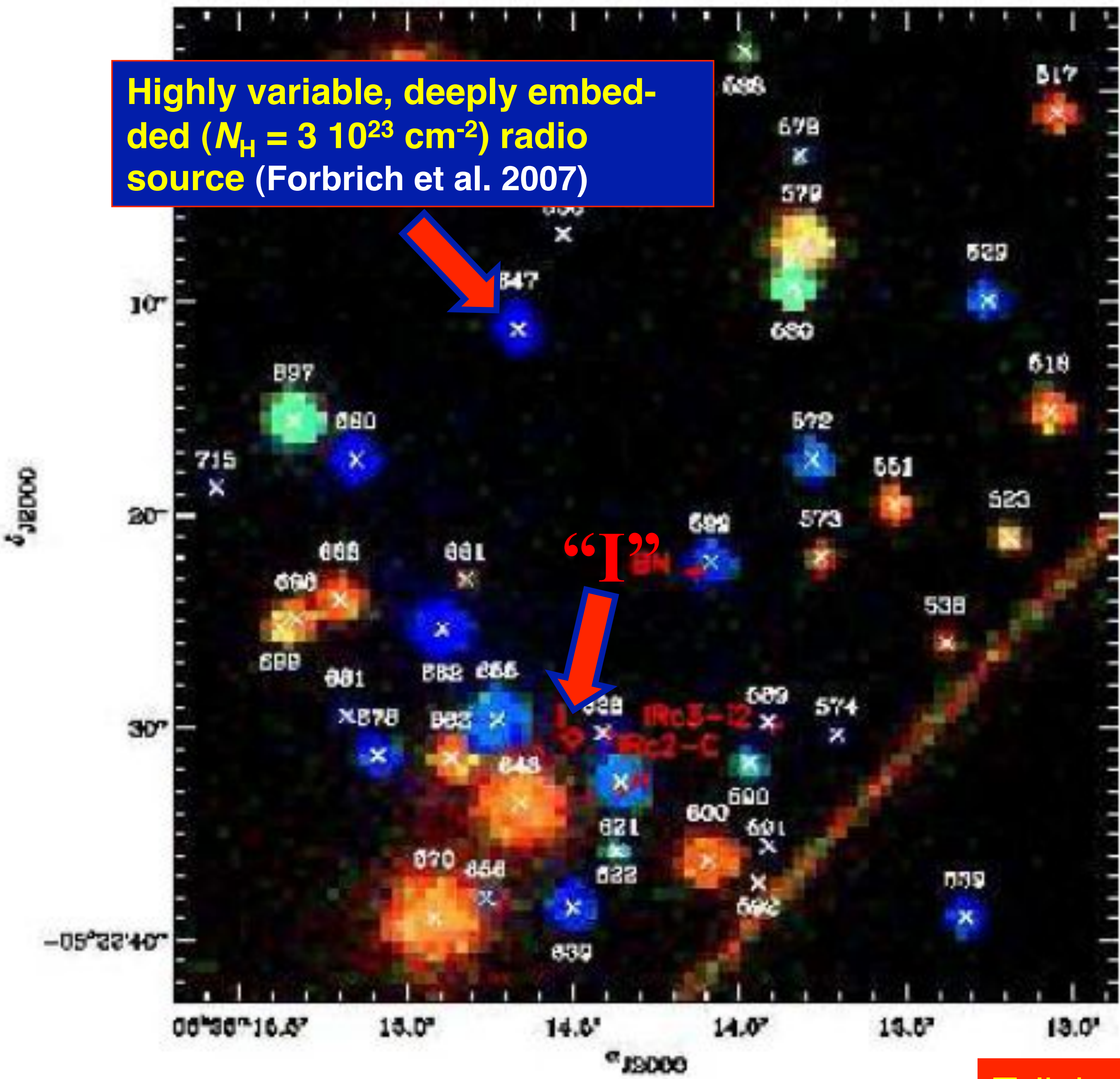
Talk by A. Sobolev



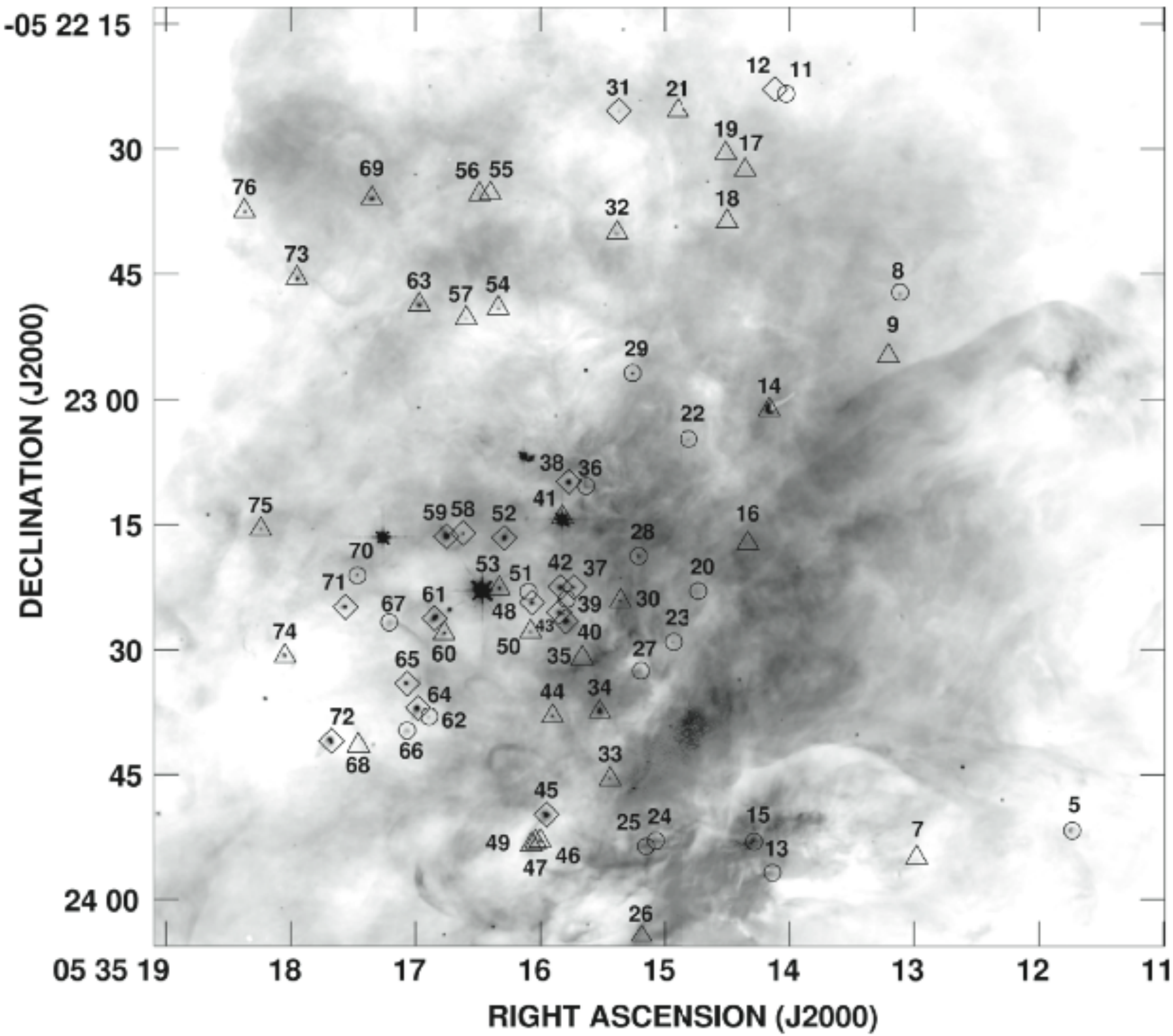
Deeply embeded low mass star formation in Orion KL

Menten & Reid 1995

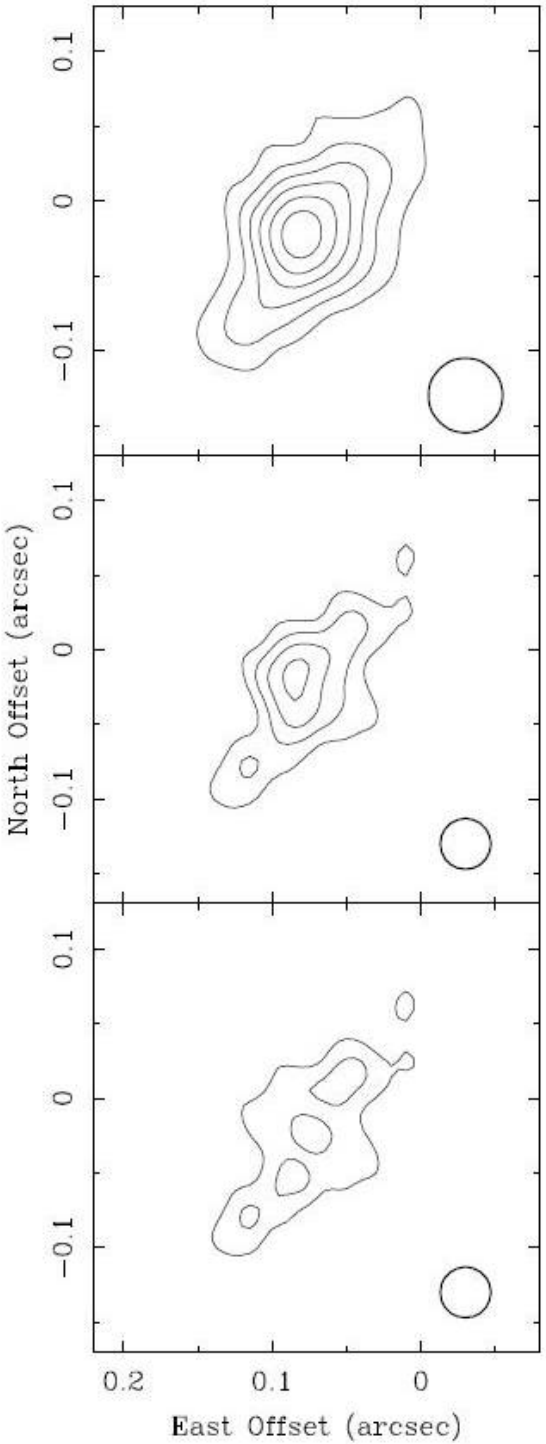
Highly variable, deeply embedded (N_H = 3 10^{23} cm^{-2}) radio source (Forbrich et al. 2007)



Talk by J. Forbrich



Zapata et al. 2004

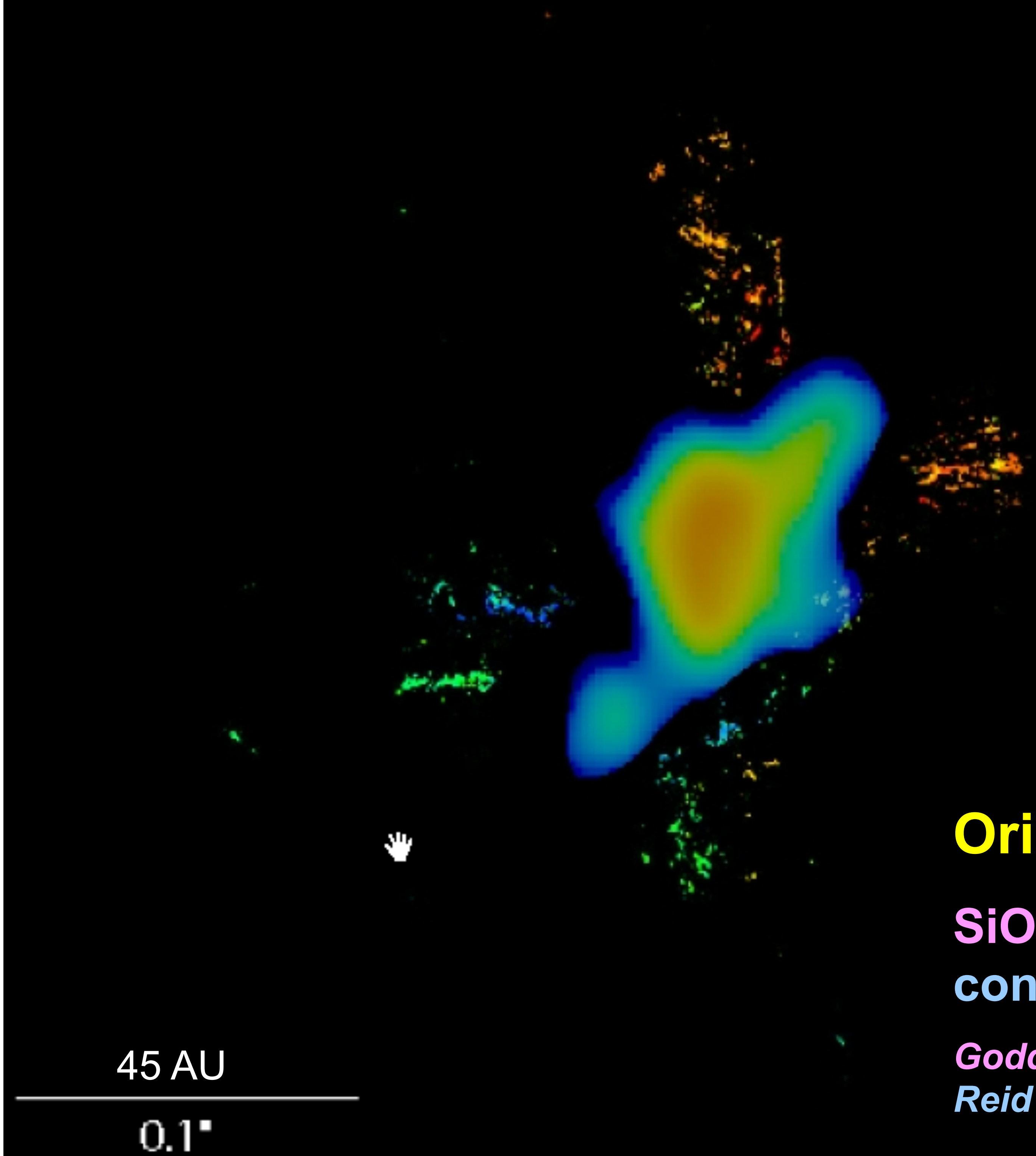


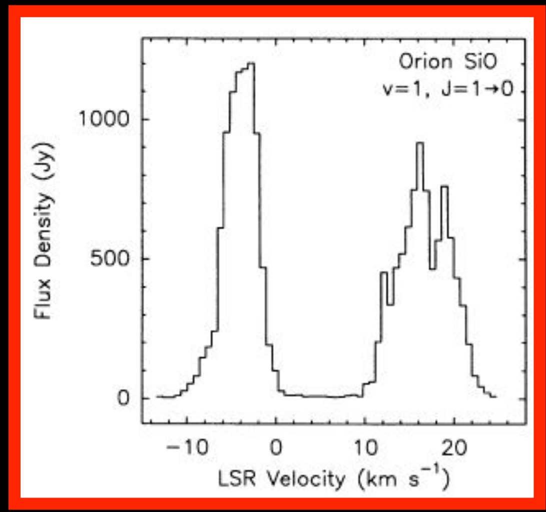
Source "I"

Radio emission is consistent with ionization from a B0-1-type ZAMS star

- $L \sim 10^4\ L_{sun}$
- $M \sim 10\ M_{sun}$

Menten & Reid 1995
Reid et al. 2007

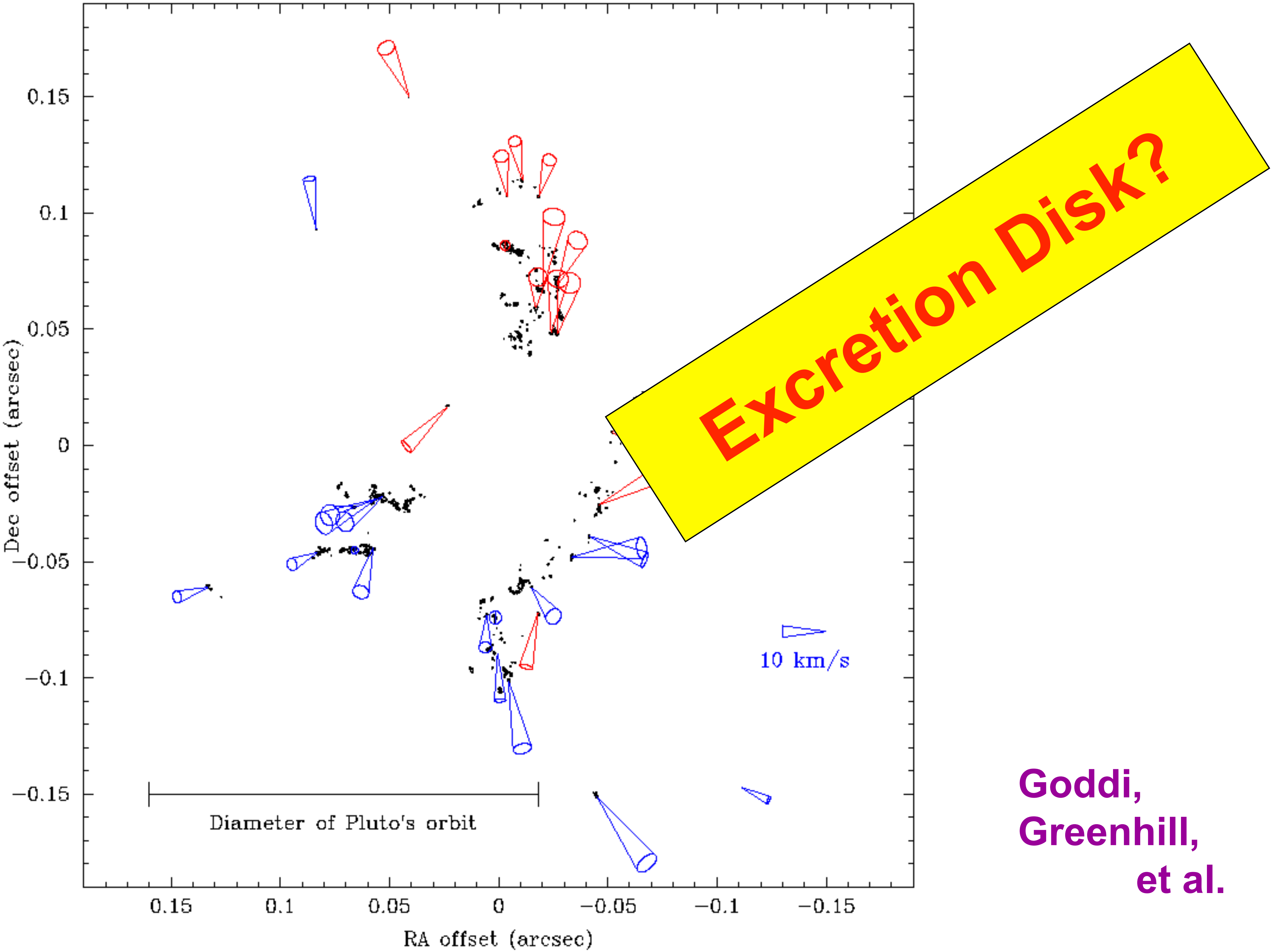




Orion - I

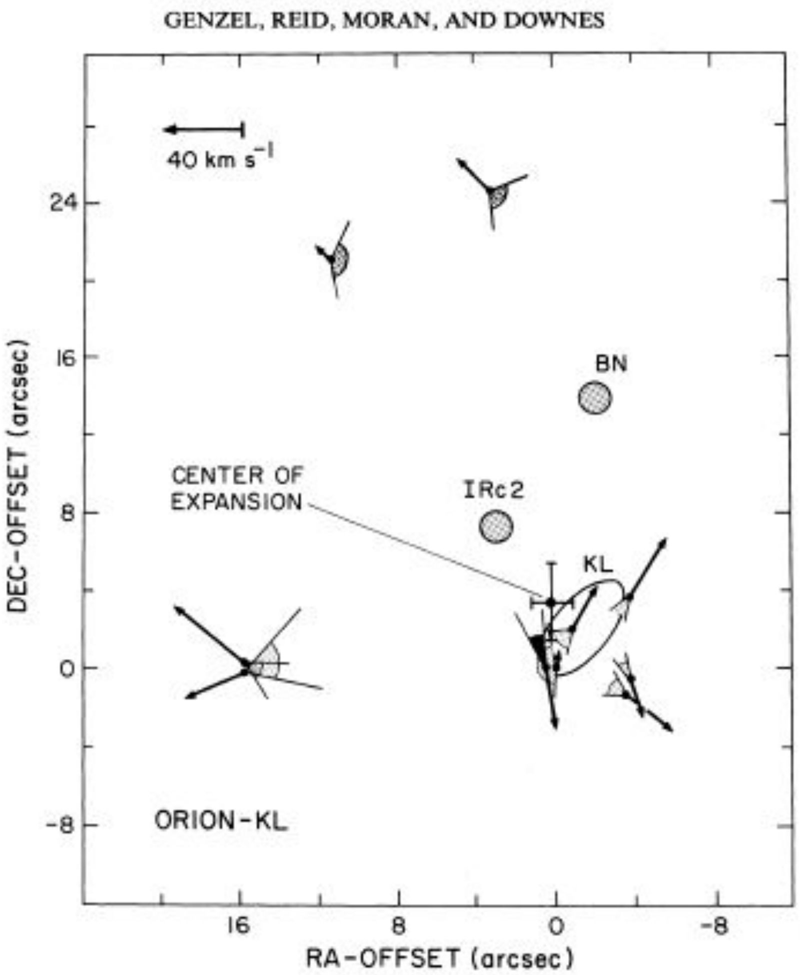
SiO masers + 43.2 GHz continuum

Goddi, Greenhill, Matthews et al.
Reid et al. 2007



Goddi,
Greenhill,
et al.

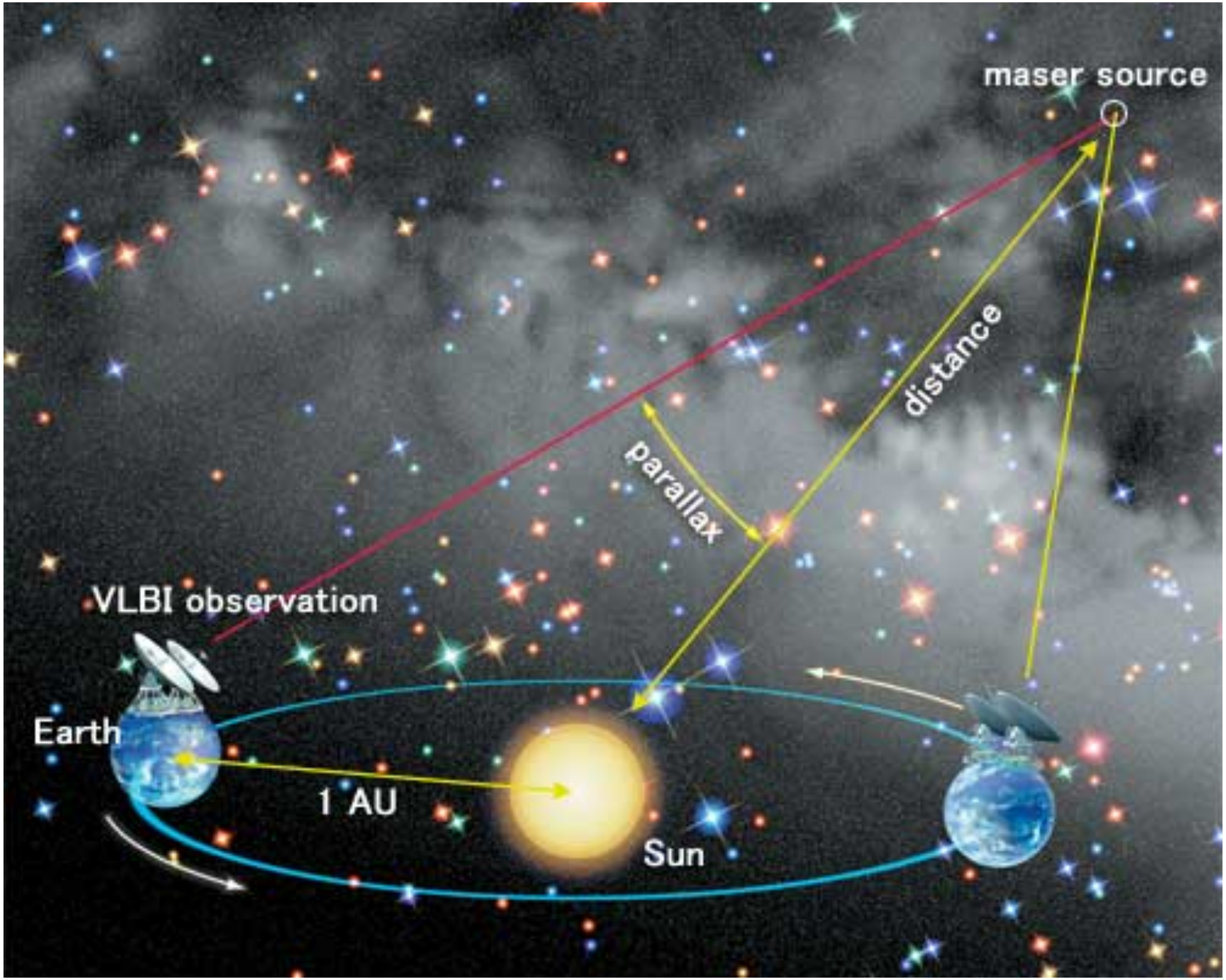
The Distance to the Orion-KL Region



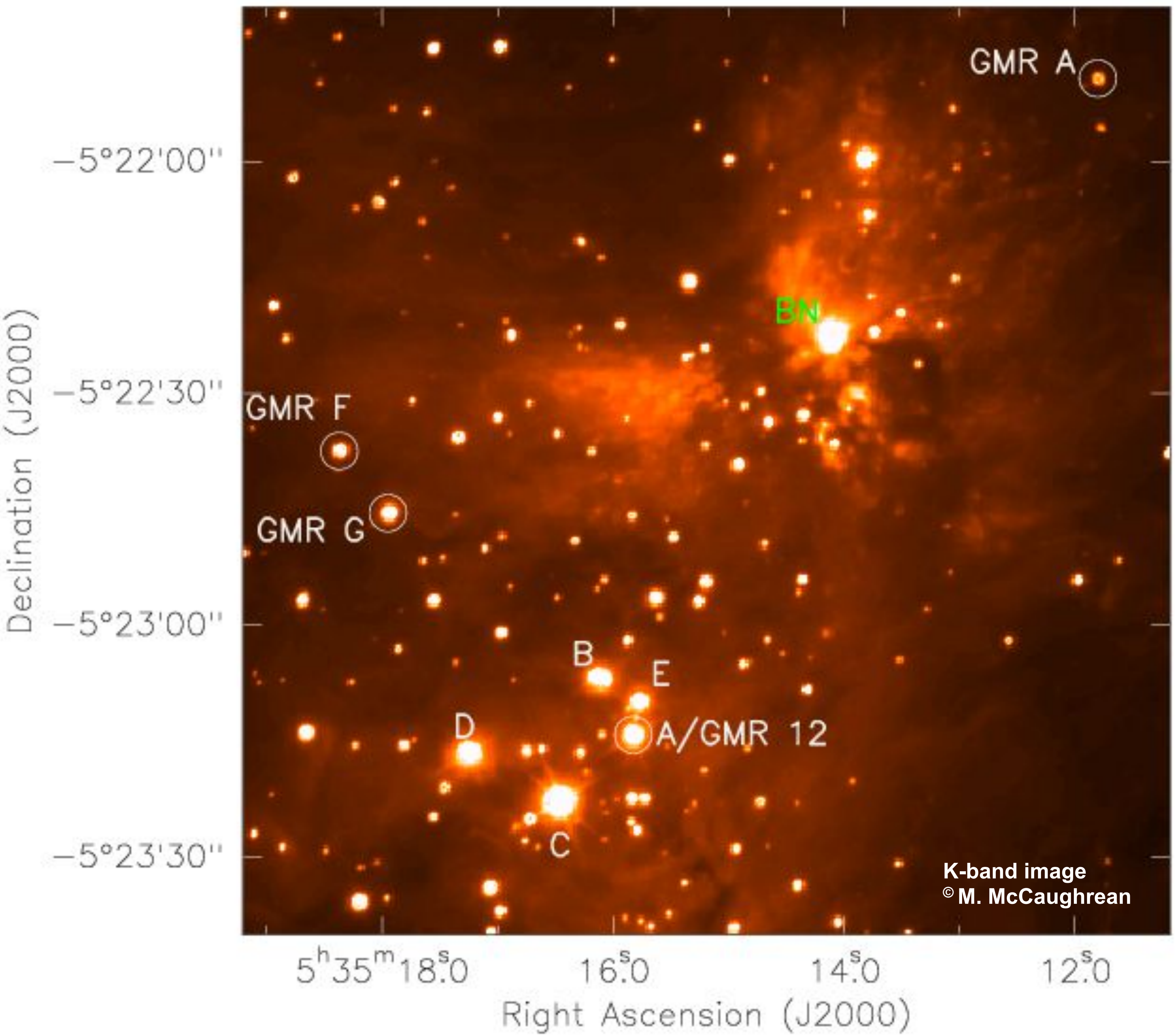
Genzel et al. 1981:

Statistical parallax from H_2O maser proper motions: 480 +/- 80 pc

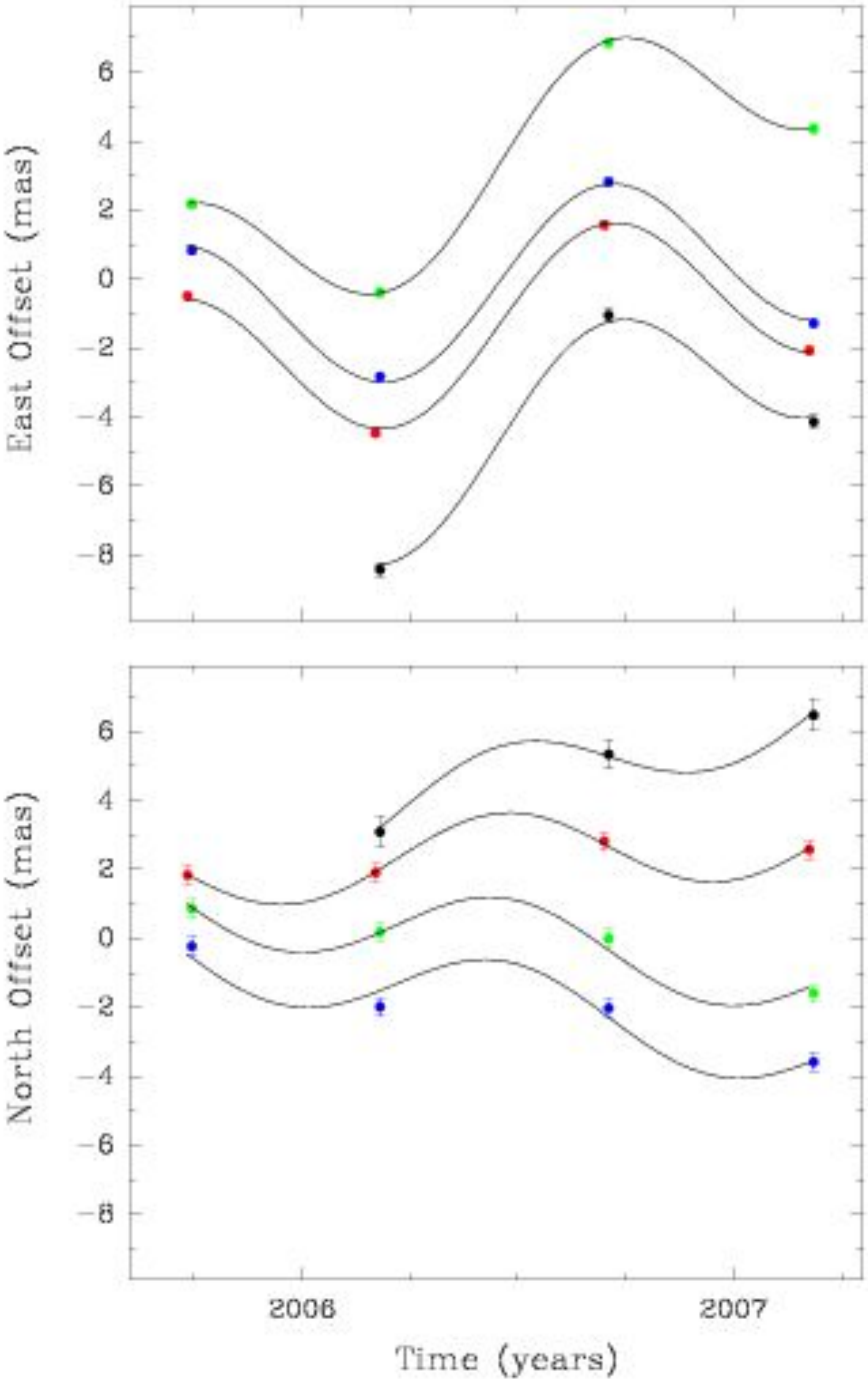
Trigonometric Parallaxes

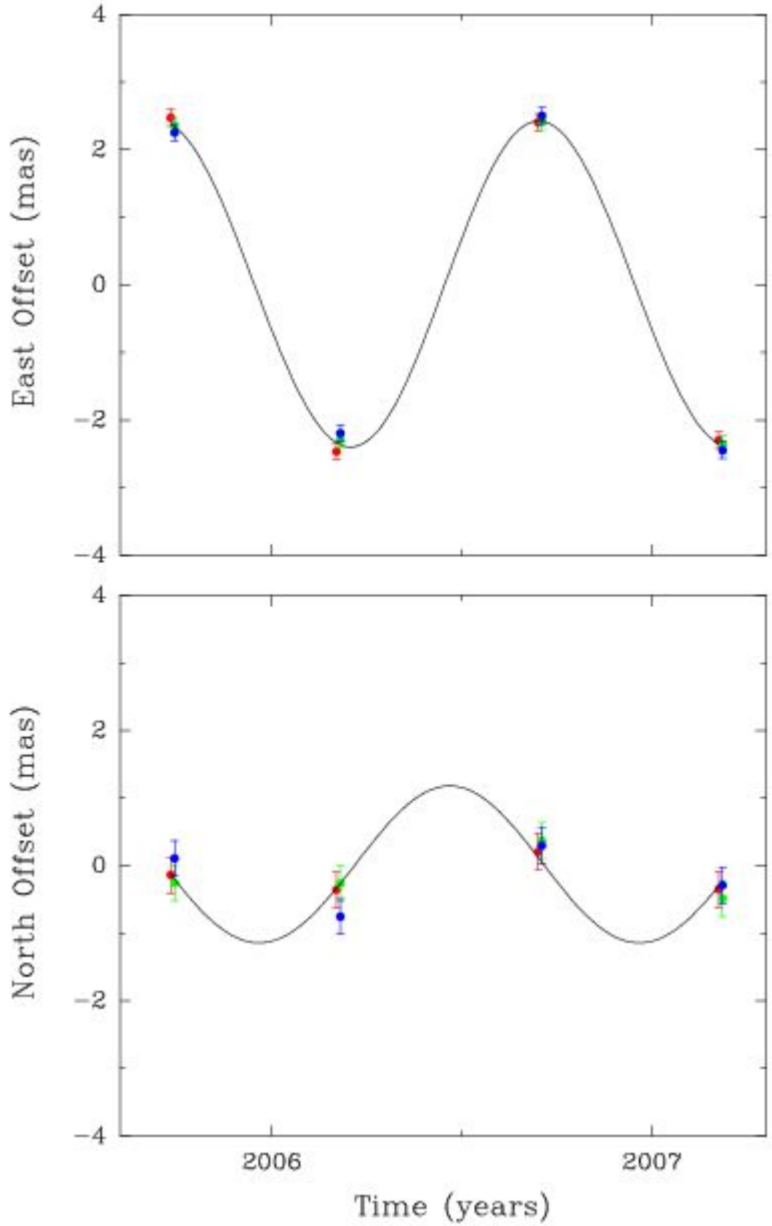


The NRAO Very Long Baseline Array



GMR A
BN
GMR F
GMR G
B
E
D
A/GMR 12
C
−5°22'00"
−5°22'30"
−5°23'00"
−5°23'30"
Declination (J2000)
5h35m18.0s
16.0s
14.0s
12.0s
Right Ascension (J2000)
K-band image
© M. McCaughrean





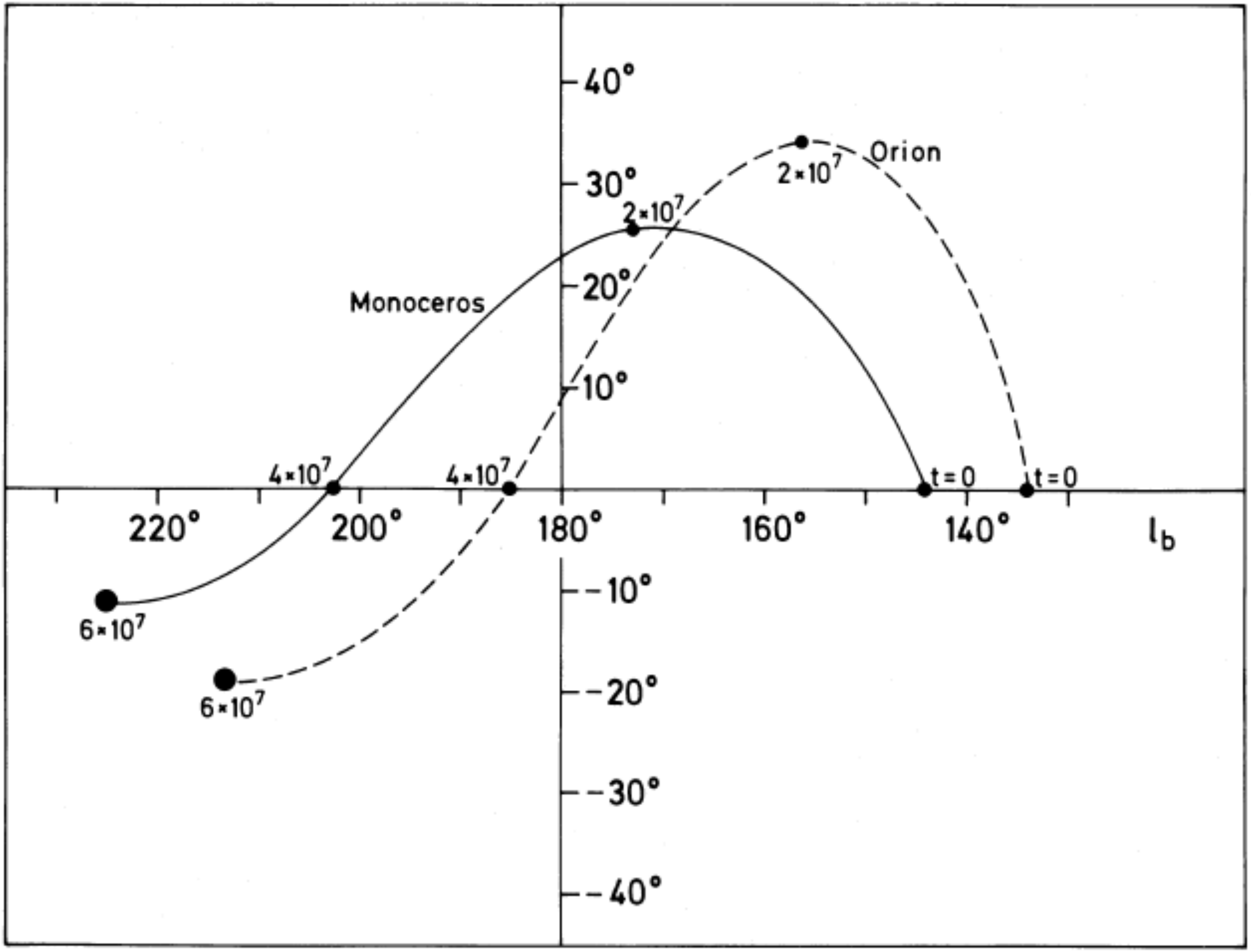
Menten et al. 2007

The Distance to the Orion-KL Region:

Trigonometric Parallaxes

Hipparcos:	**$361^{+168}/_{-81}$ pc**	**(Bertout et al. 1999)**
H_2O masers:	**437 +/-19 pc**	**(Hirota et al. 2007)**
ONC star:	**$389^{+24}/_{-21}$ pc**	**(Sandstrom et al. 2007)**
4 ONC stars:	**414+/-7 pc**	**(Menten, Reid, Forbrich, & Brunthaler 2007)**

(Transverse) velocity dispersion ~ 4 km/s
- > than optical stars (~1 km/s)
- need radial velocities for 3 D motions



Franco et al. 1988

Star formation in the Orion Molecular Clouds

Summary

- SF takes place practically everywhere you look in
  - GMC dense cores (Orion A: OMC-1, 2, 3),
    Orion B: NGC 2024
  - dark clouds (e.g. NGC 2068/71)
- Mostly low and intermediate star formation
  - in a few (relatively) rich clusters
  - All < 10% of ONC
  - in isolated cloud cores (e.g. traced by HHOs/H_2
    outflows
- Presently, there seems no new Trapezium to be forming
  in the Orion region