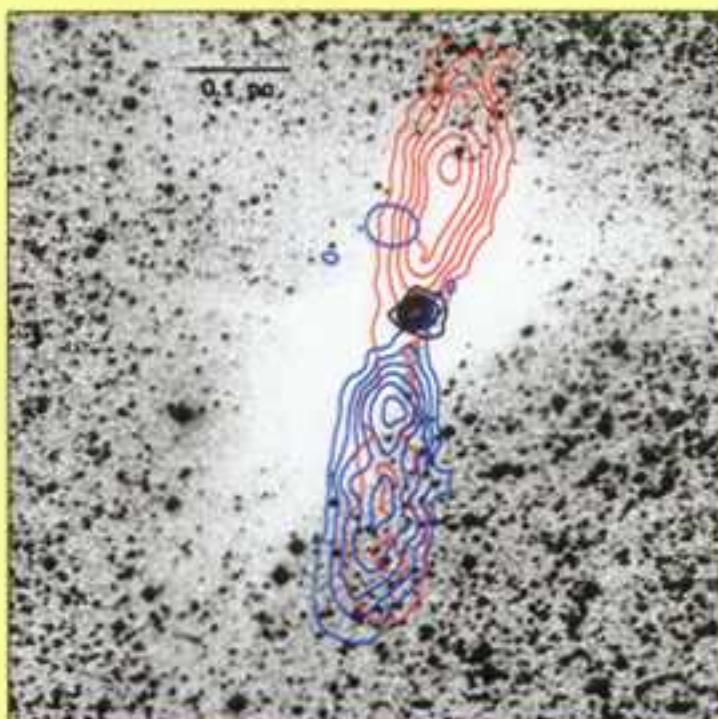


Star Formation Studies with the mm ATCA

Tyler Bourke

Harvard-Smithsonian Center for Astrophysics



Overview of Star Formation

- Molecular Clouds
- Cloud Cores
- Protostars
- Outflows/Infall

Studies with the mm ATCA

- Protostar searches (mm continuum)
- Protostellar Cores (N_2H^+) – Clusters
- Infall (HCO^+ 1-0, CS 2-1)
- Outflows (SiO , ?CO 1-0, NH_3)
- Protoplanetary Disks (^{13}CO , C^{18}O , chemistry)
- Outflows/Disks in High-Mass Protostars

Molecular Clouds

Properties

- diameter 10–100 pc
- mass $10^{4-6} M_{\odot}$
- density $10-300 \text{ cm}^{-3}$
- temperature 10-30 K
- line-width $5-15 \text{ km s}^{-1}$ (30 K only 0.2 km s^{-1})
- magnetic field $\sim 30 \mu\text{G}$
- nearby clouds appear as dark clouds

Examples: Orion Ophiuchus Taurus Coalsack

Consequences

- MC are gravitationally bound $\Delta v^2 \sim GM/R$
- cannot be in free-fall \rightarrow SF rate $250 M_{\odot}/\text{yr}$
- $\Delta v \sim v_A \rightarrow$ global support?

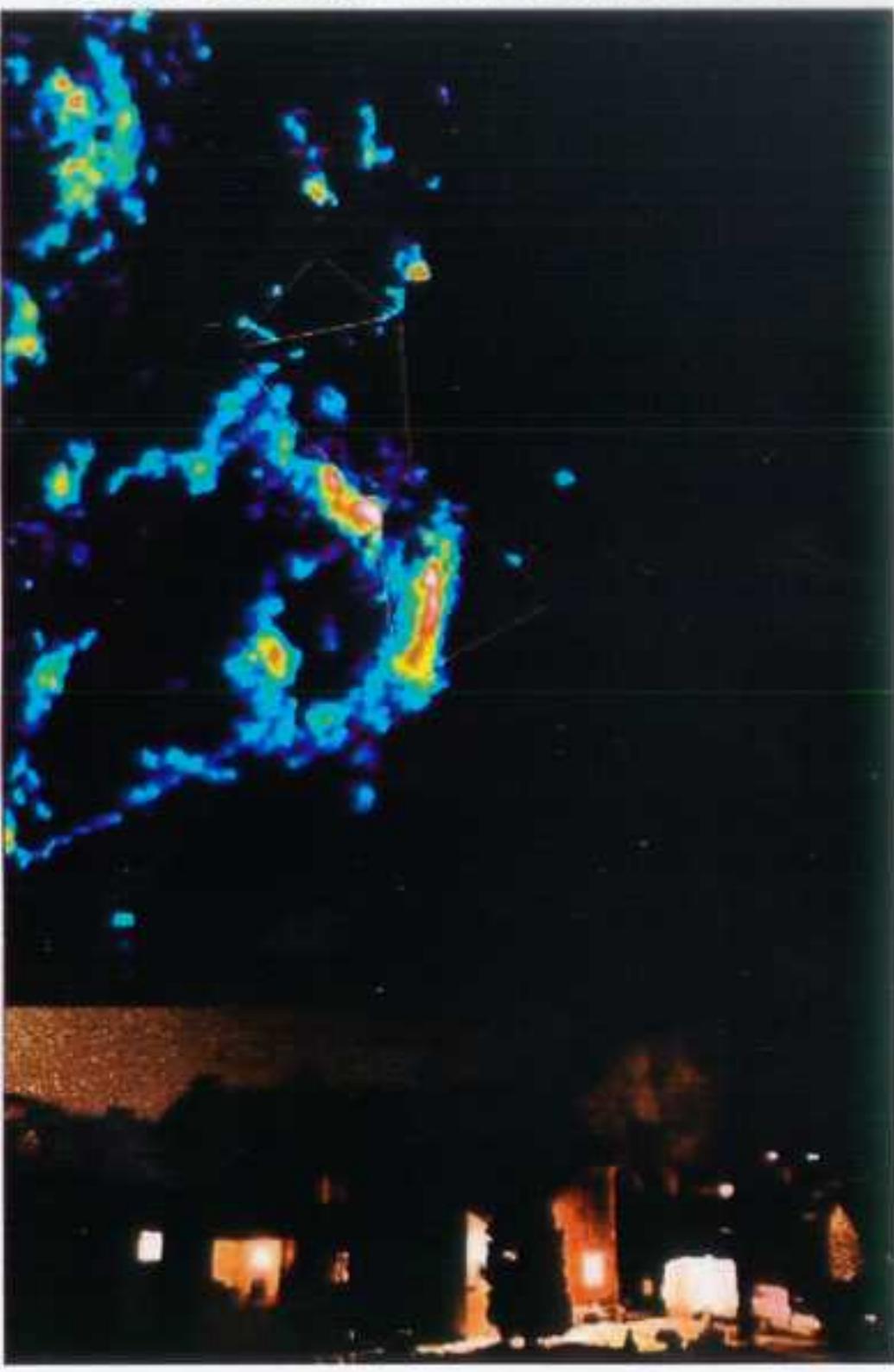
Star Formation in Molecular Clouds

- All stars form in Molecular Clouds
- uneven distribution - “groups/clusters” & isolated
- clumpy - youngest stars found near the densest clumps

Orion Constellation: As you see it

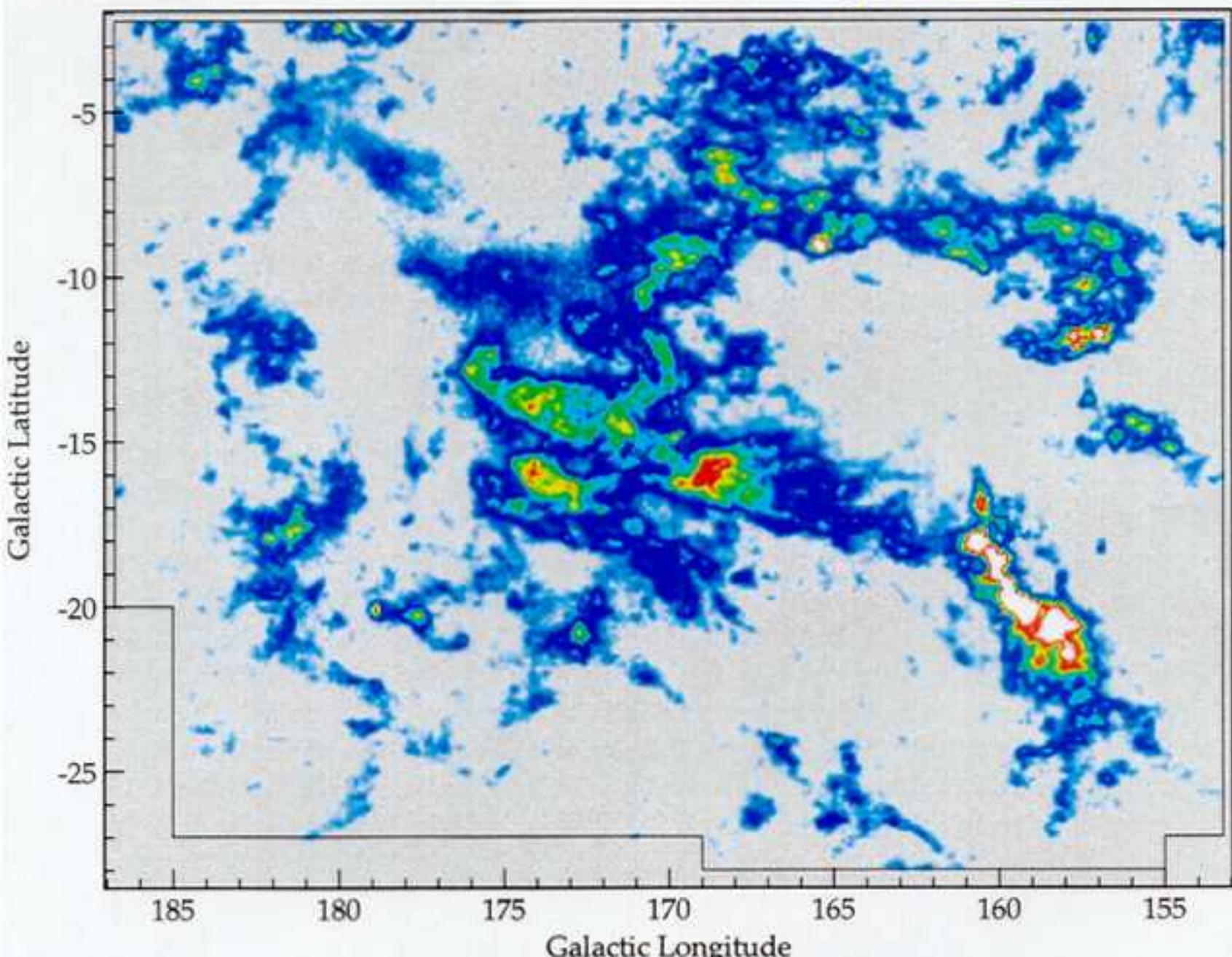


Orion Constellation: As 1.2 m sees it



Moment Map

$\int^{12}\text{CO}$ 1-0

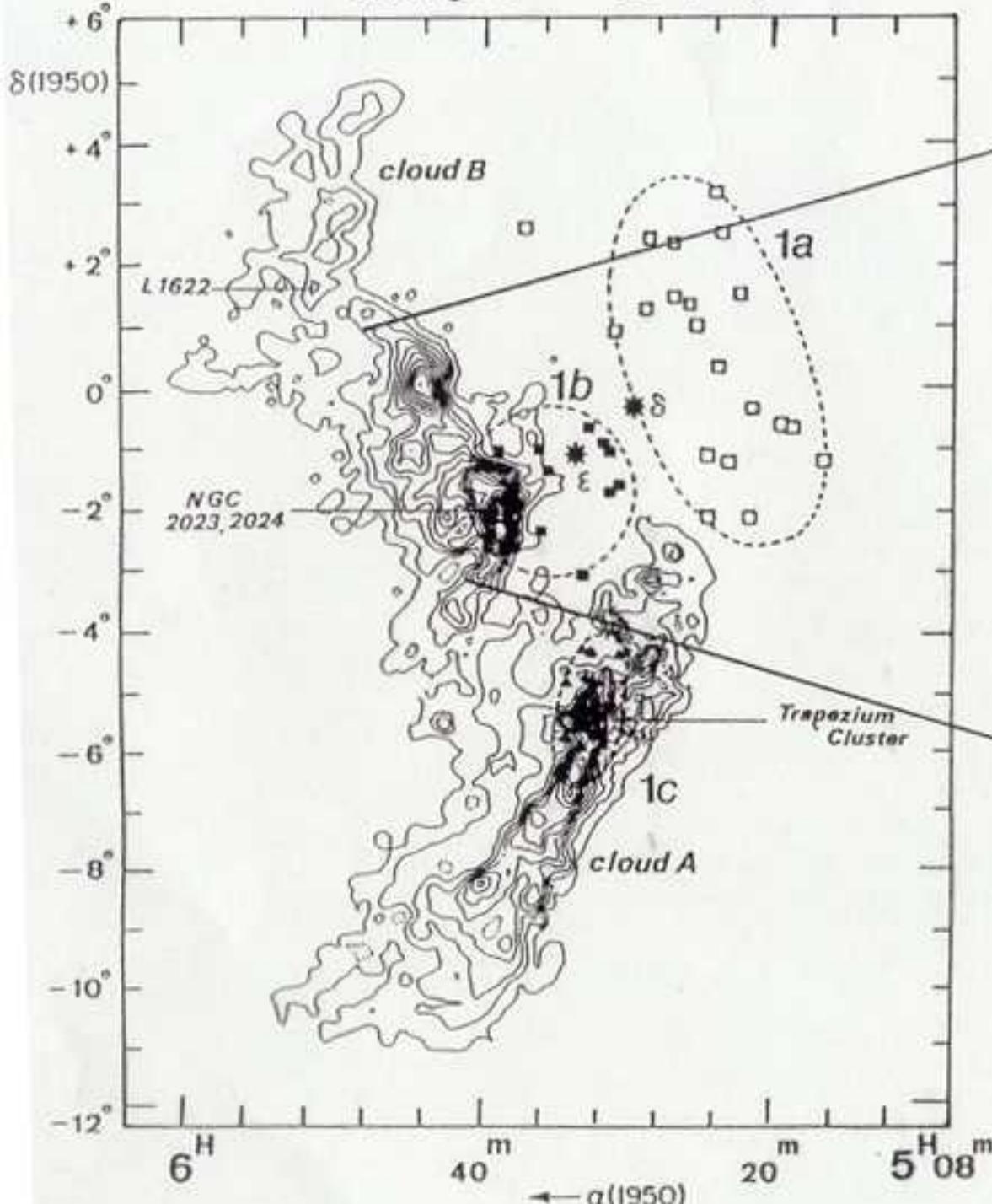


↑
Taurus

↑
Perseus

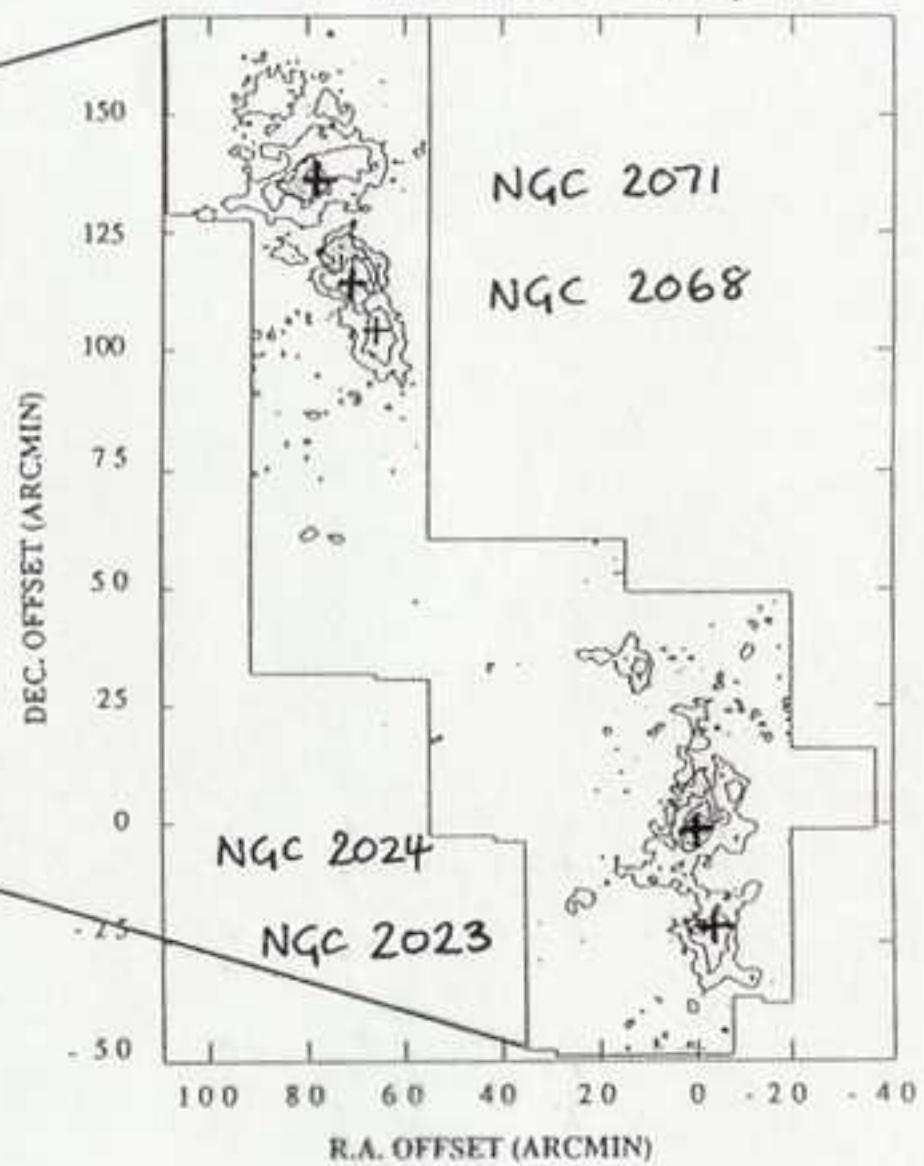
Megeath, Dame & Thaddeus (in prep)

ORION ^{12}CO 1-0



Blaauw (1991)
Crete I

CS 2-1 98GHz



E. Lada (1999)
Crete II

Cloud Cores = “Dense Cores”

Properties

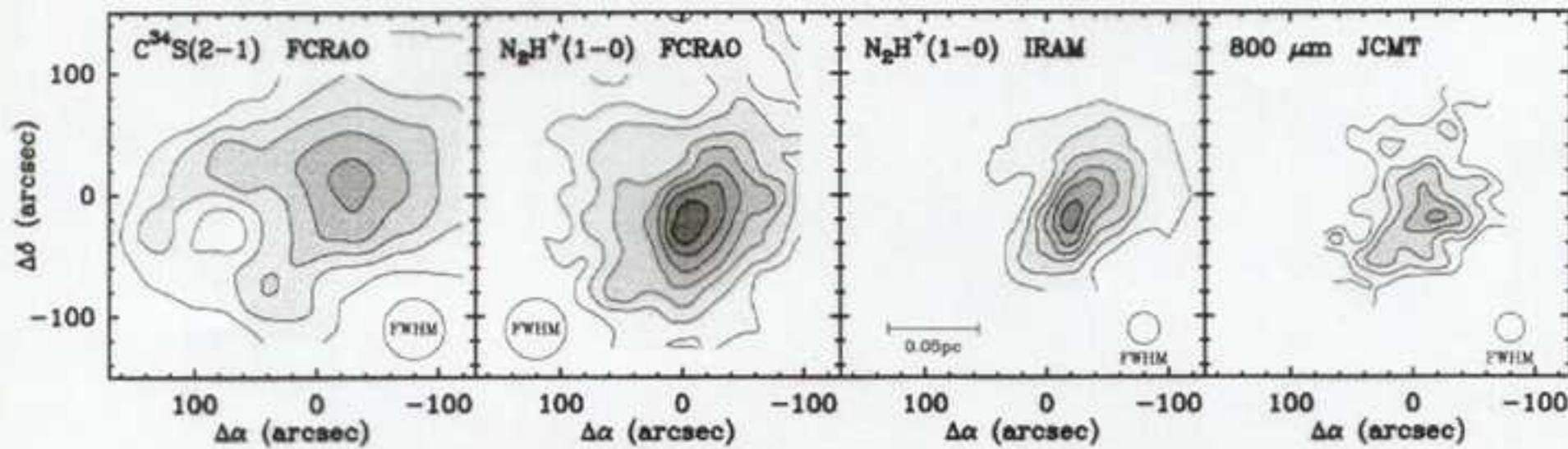
- diameter 0.1-0.5 pc
 - mass $1-10 M_{\odot}$
 - density $> 10^4 \text{ cm}^{-3}$
 - line-width $0.3-1.0 \text{ km s}^{-1}$
- (all the above depend on the tracer used!)
- temperature 10 K (15 K)
 - $x_e \sim 10^{-7}$
 - aspect ratio 1.5-2
 - 30-50% associated with a young star (IRAS)

Examples: B335, L1544, BHR 71, TMC-1; NGC 1333, Serpens

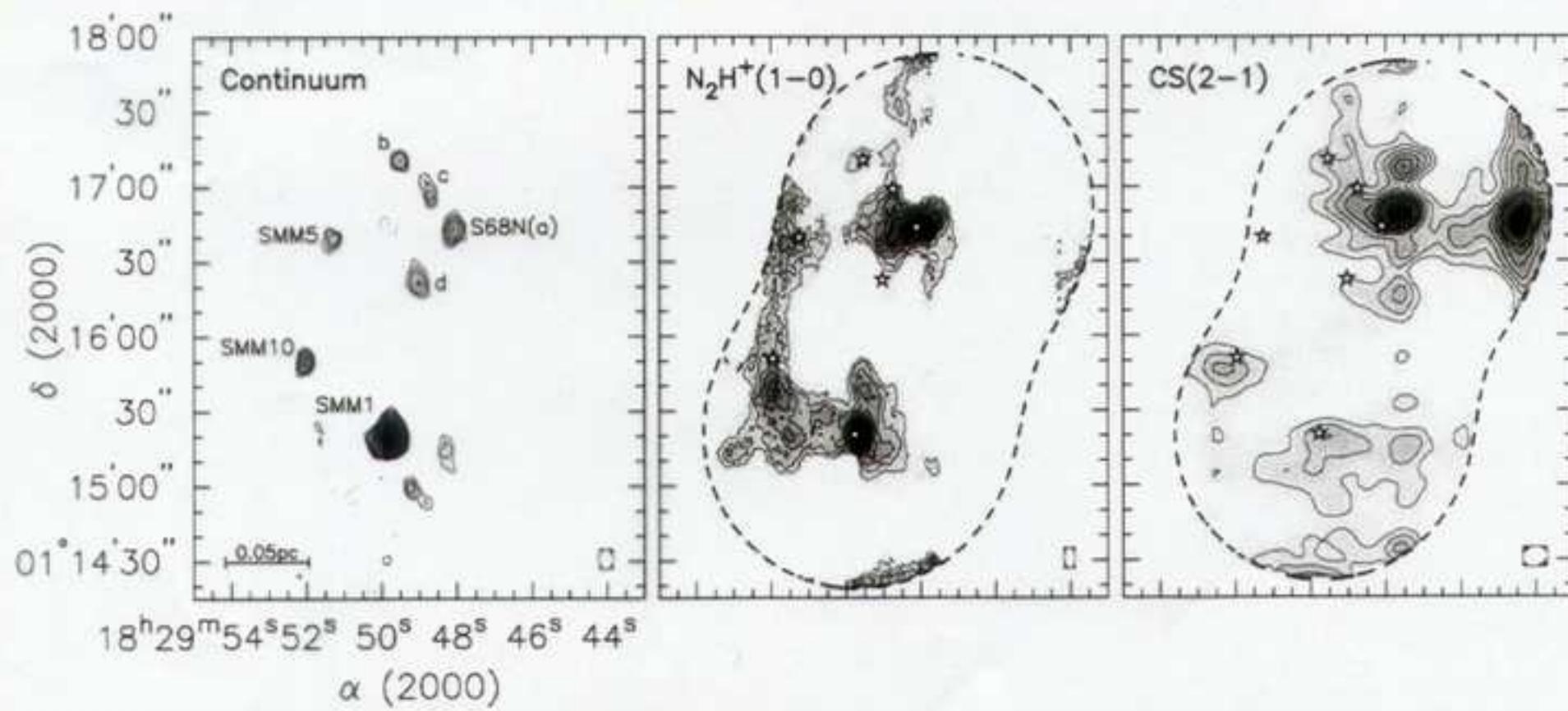
Tracers

- $\text{NH}_3 (1,1) \& (2,2)$ at 23.7 GHz (13mm)
- CS 2-1 at 97.9 GHz (3.1 mm)
- N_2H^+ 1-0 at 93.7 GHz (3.2 mm)
- HCO^+ 1-0 at 89.1 GHz
- dust emission mm/sub-mm

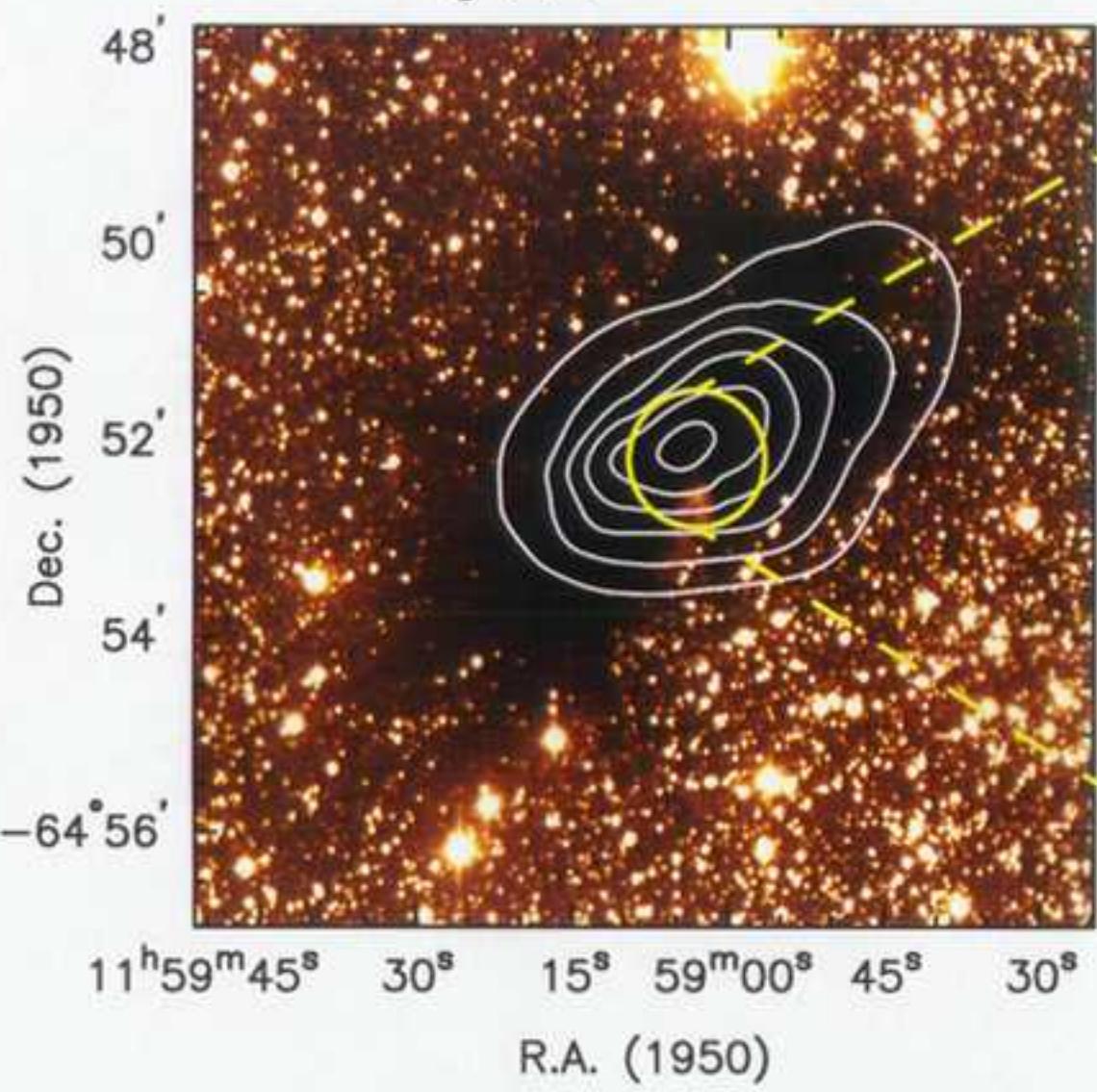
L1544 - Tafalla et al. 1998



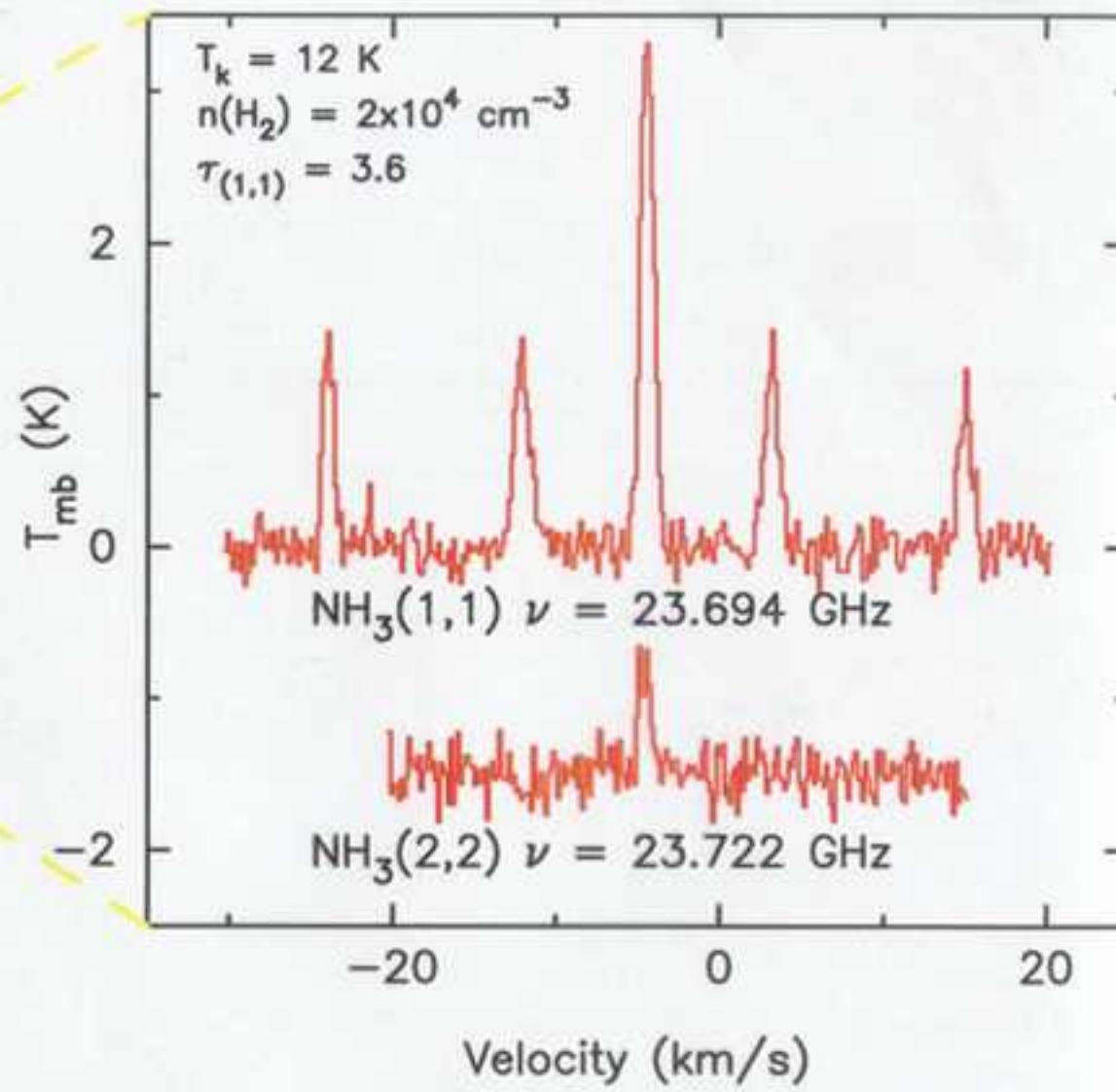
Serpens - Williams & Myers 2000

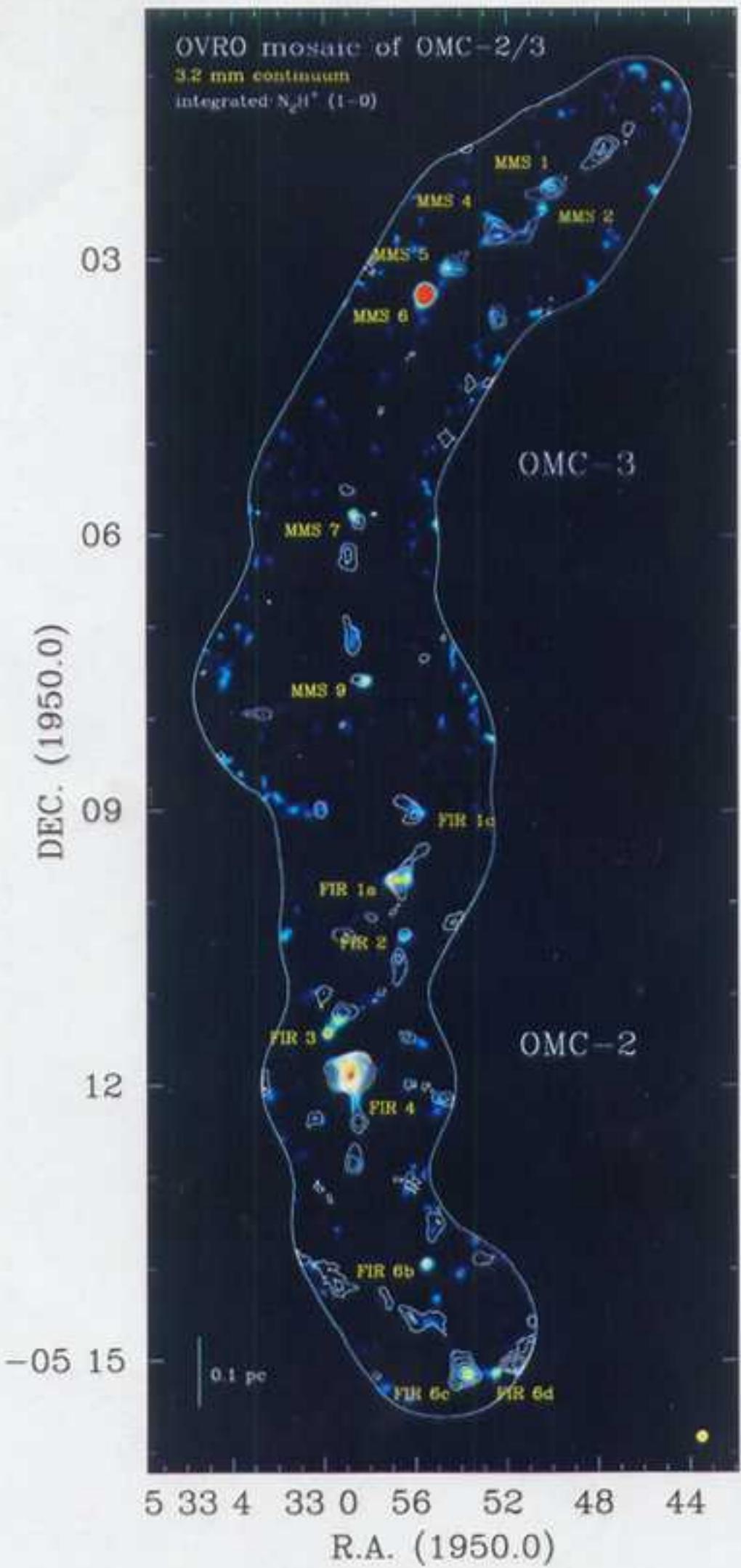


Bok Globule DC 297.7–2.8
 NH_3 (1,1) from Parkes

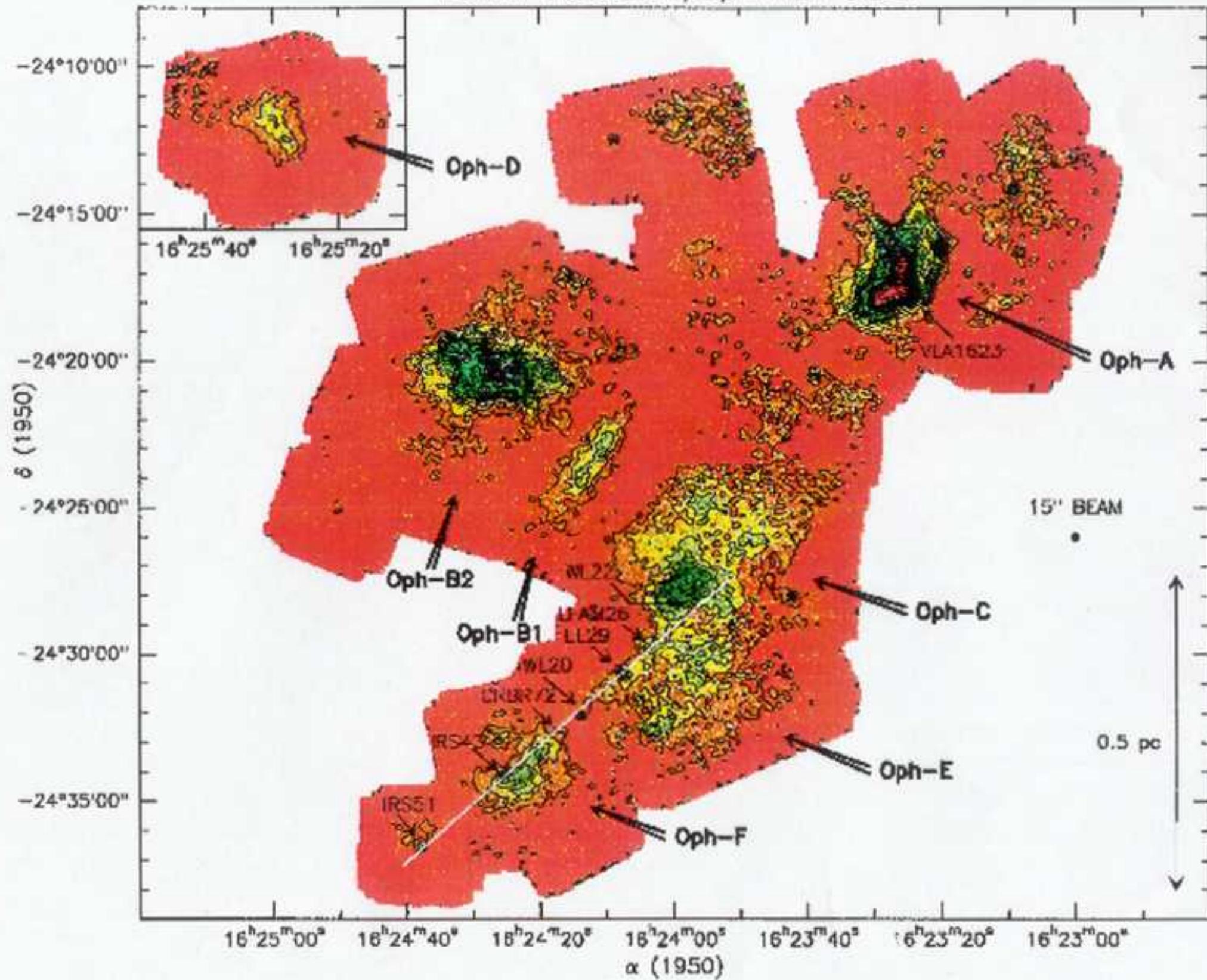


Bok Globule DC 297.7–2.8
 NH_3 (1,1) and (2,2)





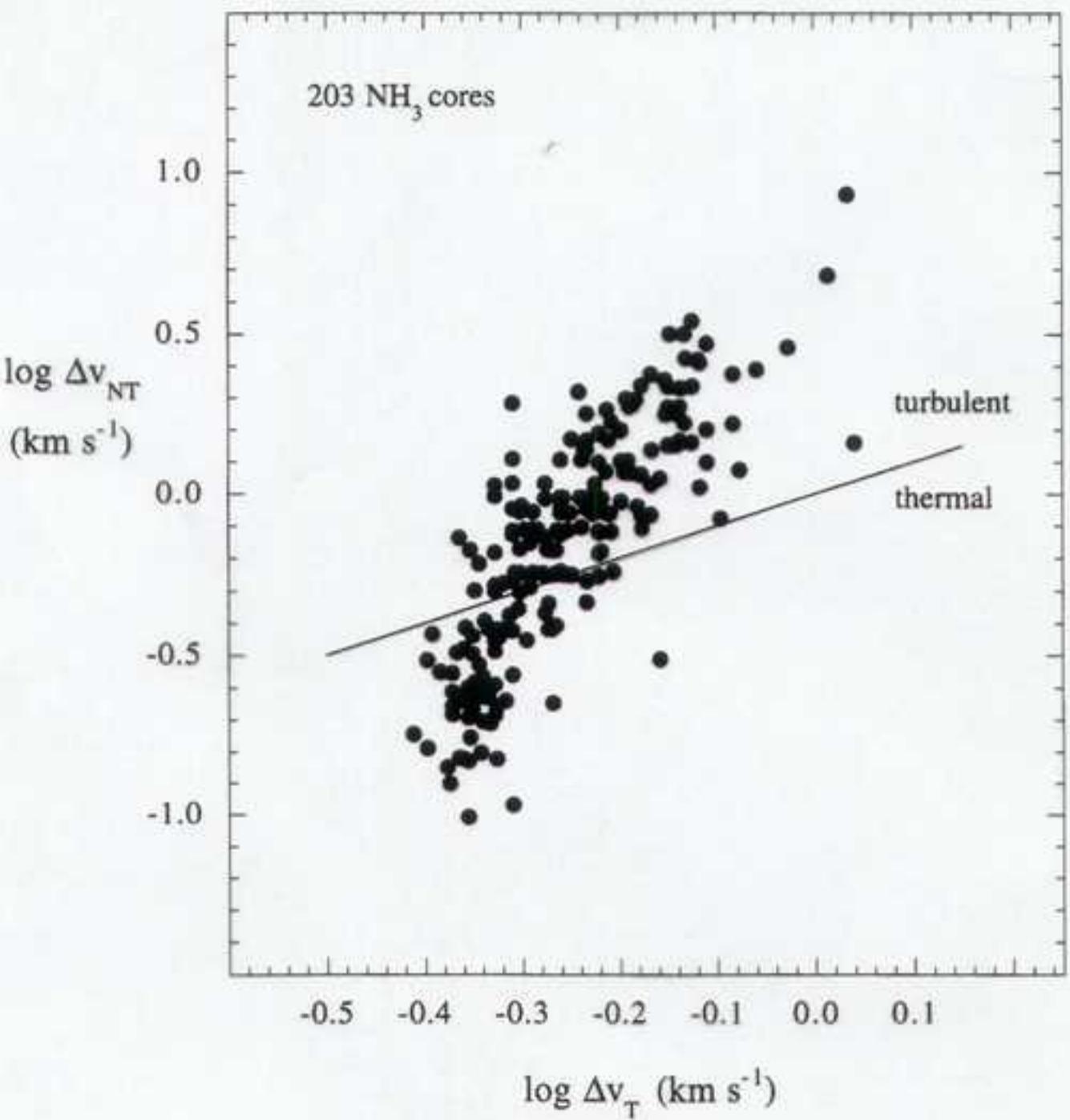
1.3mm mosaic of ρ Oph main cloud



Cloud Cores = “Dense Cores”

Consequences

- virial balance - gravitational potential $E \equiv KE$
- “thermal cores” – line widths thermally dominated
 - ignore turbulence in models
- “turbulent cores” – turbulent motions provide support against gravity (but what is their origin?)
- cosmic ray ionization is sufficient
- ions and neutrals are well coupled
- line-widths similar with or without star - external excitation
- turbulent cores contain more stars, and are more likely to contain a star (Taurus – thermal, 50% stars; Orion – turbulent, 90% stars, many with groups > 5)
- turbulent cores are larger (factor 2) → greater mass
- turbulent cores are warmer (15-20 K v 10 K) even for starless cores



Myers 1999 Crete II
 (Adapted from Tijina, Myers & Adams)
 1999 ApJS 125 161

Young Stellar Objects - YSOs

Classification

- youngest YSOs hidden from view - IRAS
- classification schemes based on SED
 - slope in IR

(Lada 1987; André, Ward-Thompson & Barsony 1993)

→ flux weighted frequency T_{bol}

(Myers & Ladd 1993; Chen et al. 1995)

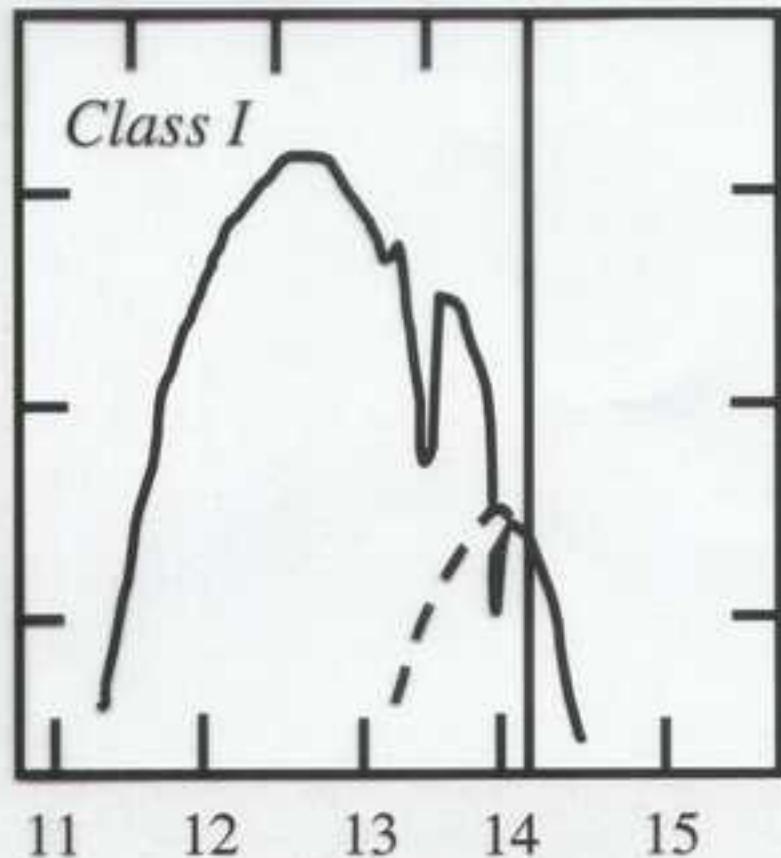
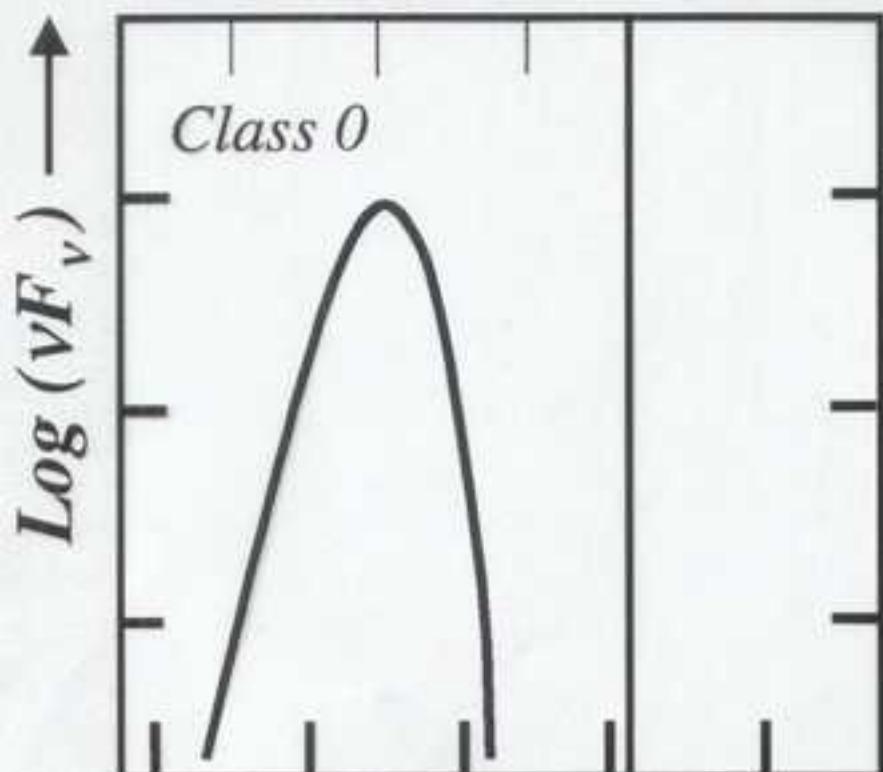
- Protostars - Class 0 and I, $T_{\text{bol}} < 650\text{K}$
 - still accreting bulk of material
- Pre-Main-Sequence (PMS) stars - Class II & III
 - Class II = T Tauri stars still accreting through disk
 - Class III = weak-line TTS, remnant disk

YSO ENERGY DISTRIBUTIONS

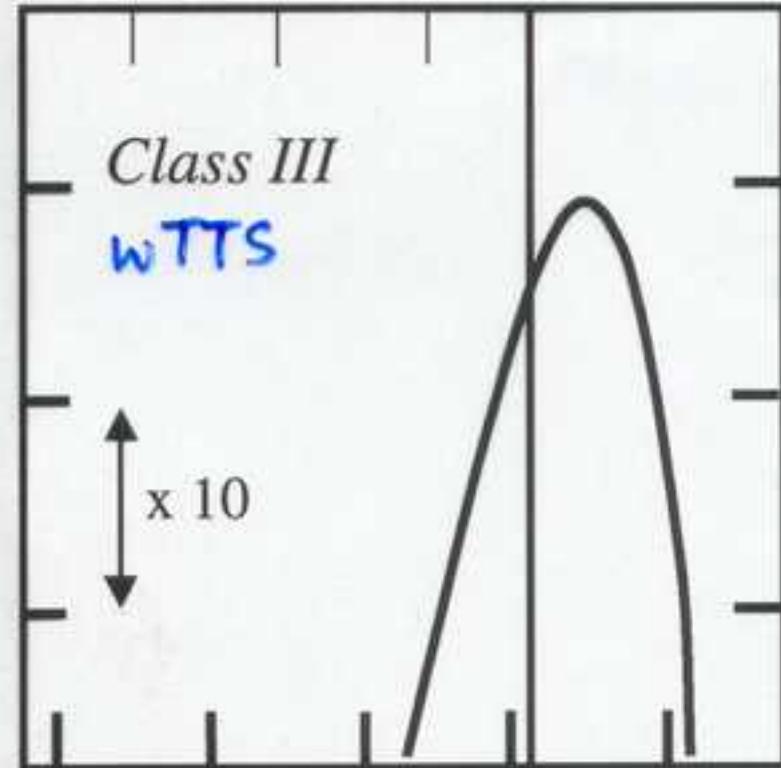
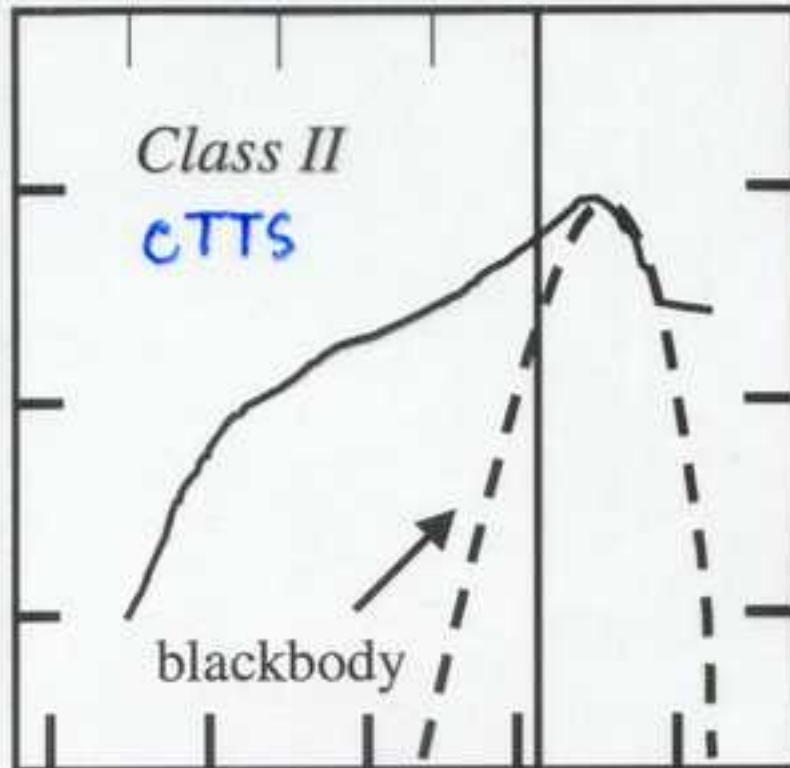
Protostars:

λ (μm)

1000 100 10



Pre-Main Sequence Stars:



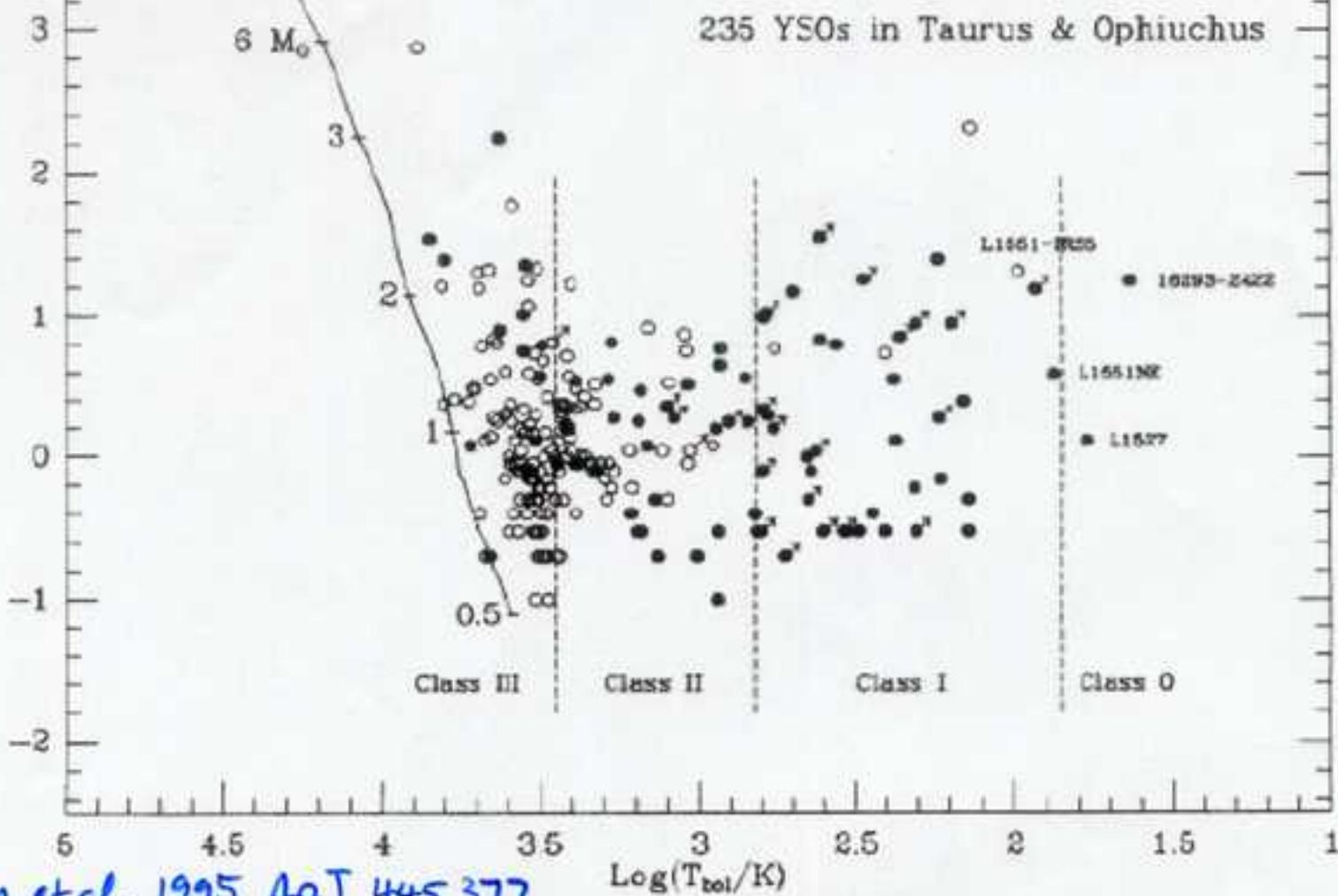
$\log(v)$

Lada 1999 Crete II

Main sequence

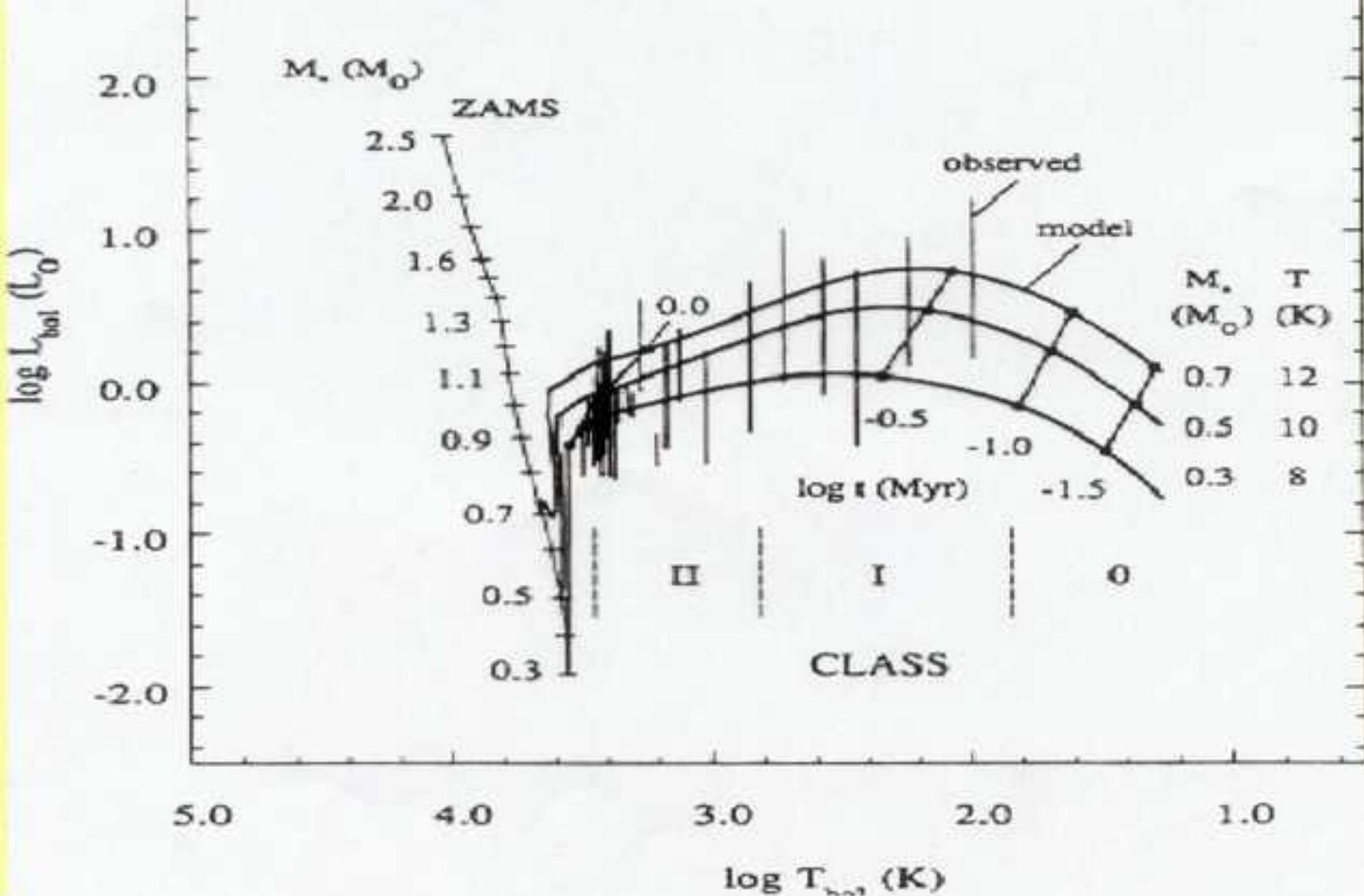
235 YSOs in Taurus & Ophiuchus

$\log(L_{\text{bol}}/L_{\odot})$

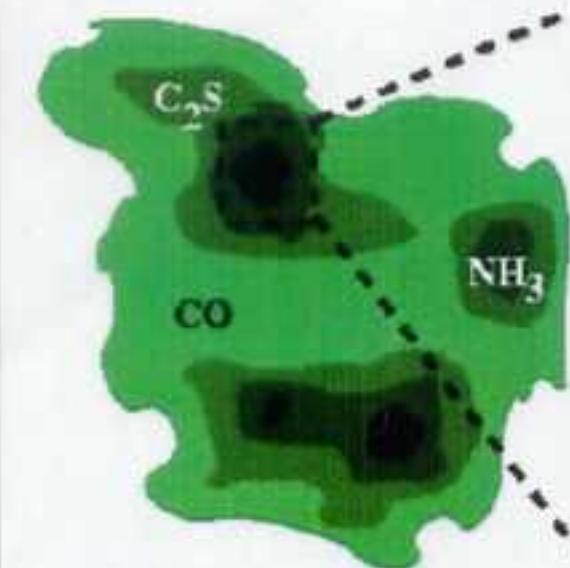


Myers et al. 1998 ApJ 492 703

$$\frac{M_{\text{co}}}{M_{\text{H}_2}} = 6$$
$$t_e/t_c = 3$$

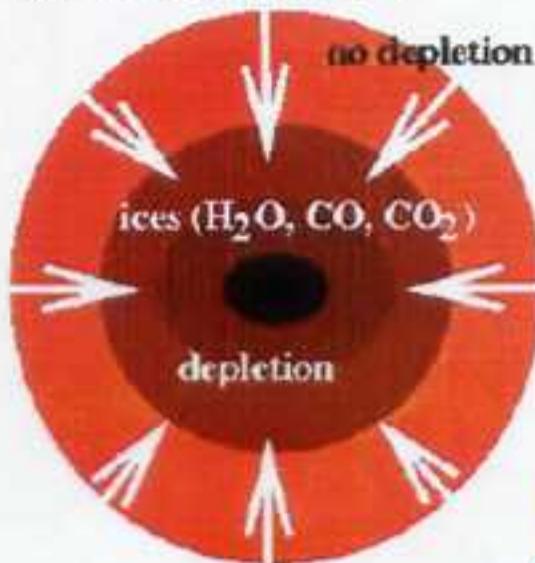


a) dark cloud cores



1 pc

b) gravitational collapse



10 000 AU

$t = 0 \text{ year}$

pre-protostellar
and Class 0

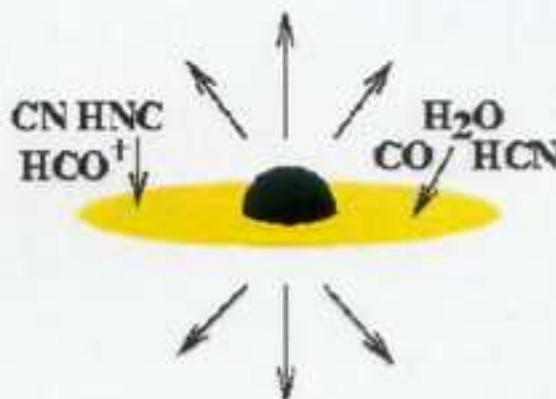
c) embedded YSO



$t = 10^4 - 10^5 \text{ year}$

d) T Tauri star, accretion disk

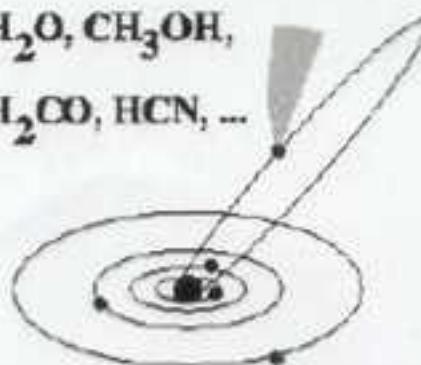
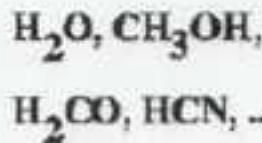
Class II



100 AU

$t = 10^6 - 10^7 \text{ year}$

e) main sequence star; planetary system (?)



50 AU

$t > 10^7 \text{ year}$

Young Stellar Objects - YSOs

Outflows (and jets)

- ubiquitous - Class 0 and I
- Class 0 - highly collimated and more energetic
- release of gravitational energy - details unknown
(e.g., X-wind - Shu et al.)

Disk-wind - Konigl & Pudritz 2000)

- observed as wings in molecular line spectra
- energetic enough to disrupt cores
- impact on dynamics of GMCs (multiple sources)
(enough to provide support to clouds?)
- chemical effects - shocks, high-T

Is this the way protostars

- (i) remove angular momentum?
- (ii) stop the main accretion phase?

CO (1-0) and 1.3 mm continuum
overlaid on I band image

Dec. (1950)

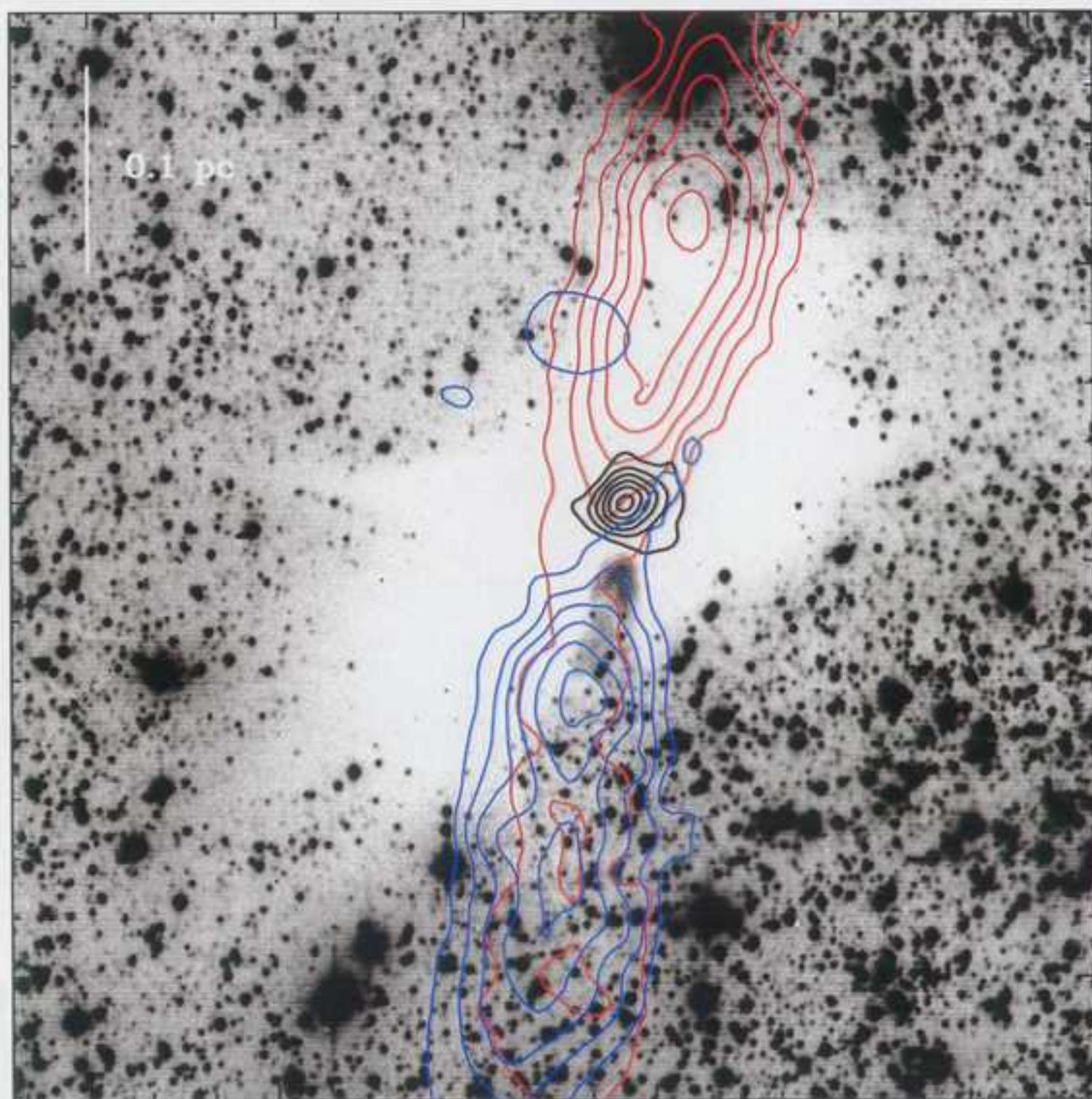
48

50

52

54

-64°56'



11^h59^m45^s

30^s

15^s

59^m00^s

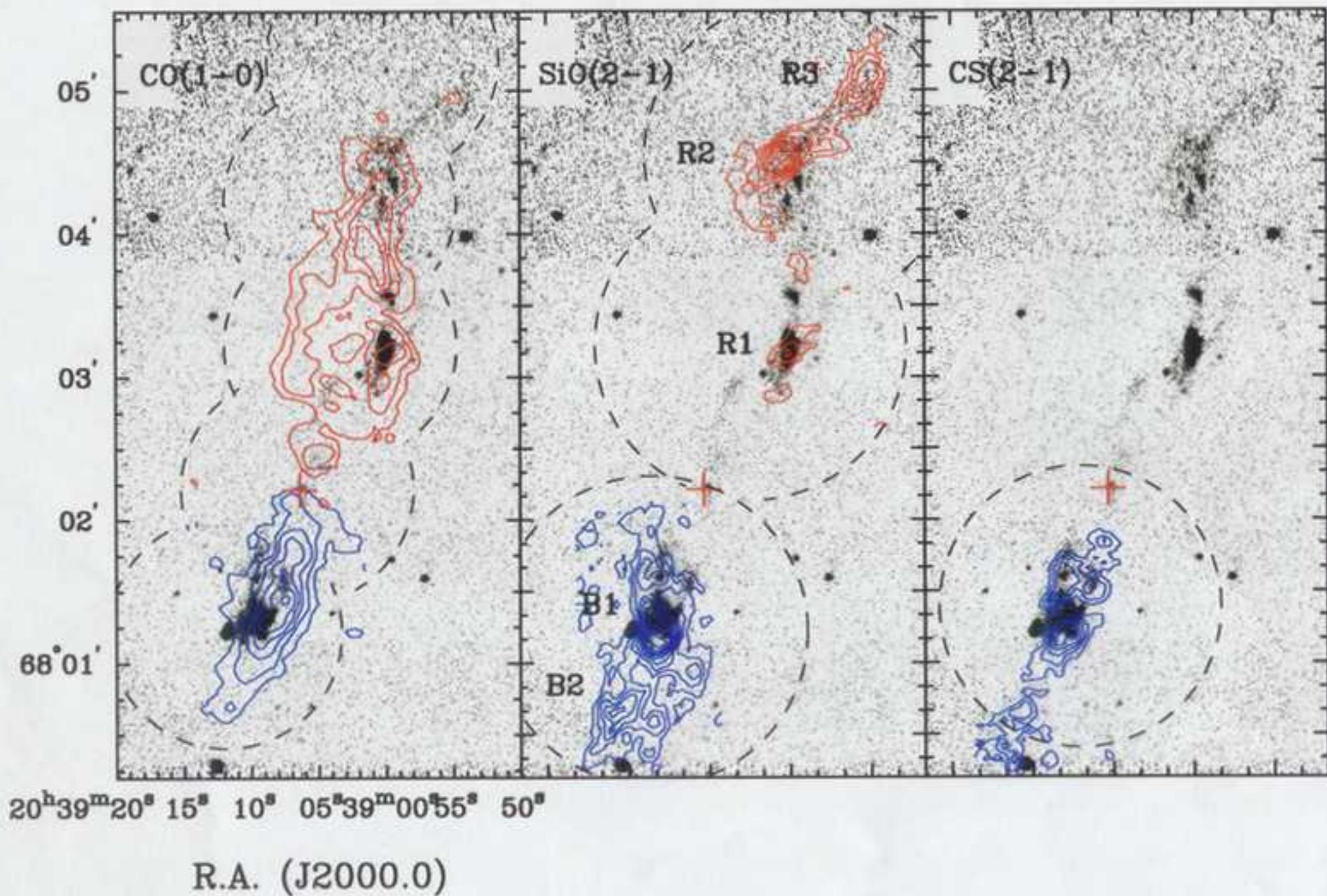
45^s

30^s

R.A. (1950)

L1157

Dec. (J2000.0)



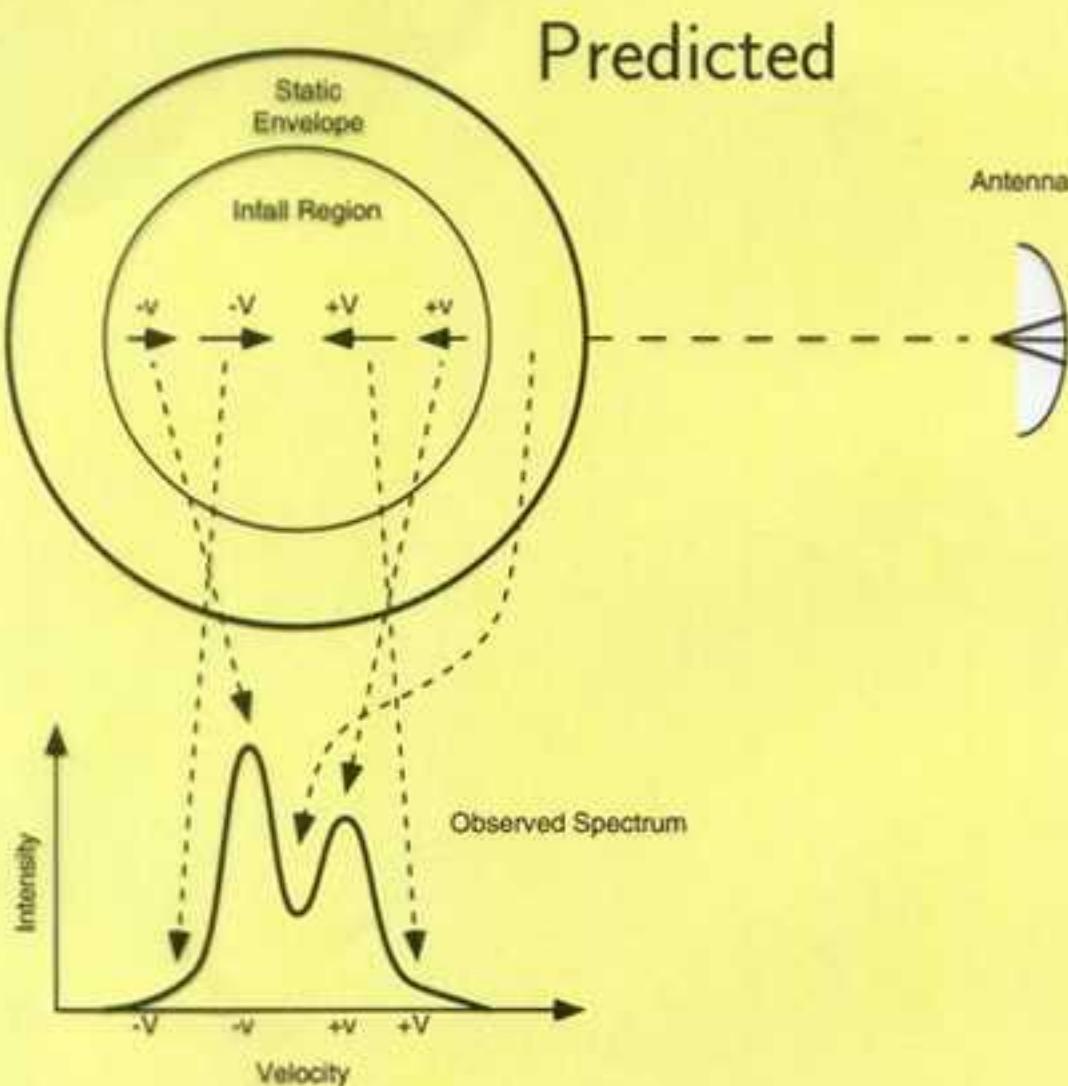
Theory

- cores evolve (contraction/collapse) to form stars

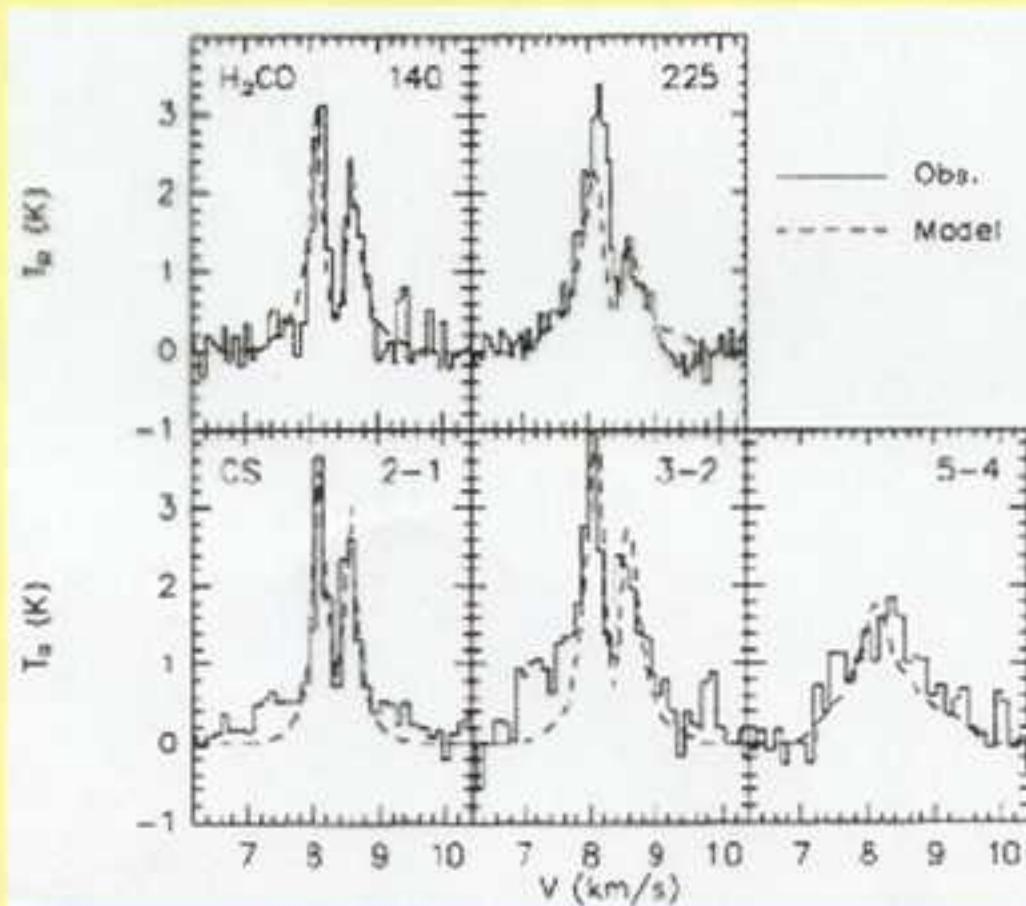
HOW??

- "standard model" (Shu et al. 1987 ARAA)
 - (i) contraction via ambipolar diffusion $n \propto r^{-2}$
 - (ii) gravitational 'inside-out' collapse (SIS)
- other extreme Larson-Penston (1969)
 - fixed outer boundary, uniform density
- intermediate configurations e.g., Bonnor-Ebert Spheres
 - isothermal with density contrast (Foster & Chevalier 1993)
- all solutions go to $v(r) \propto r^{-0.5}$

Evolution - Collapse



Observed in B335 (Choi et al. 1995)



Evolution - Collapse

Observations

- 30% Class 0/I show infall

(Mardones et al. 1997; Gregersen et al. 1997, 2000)

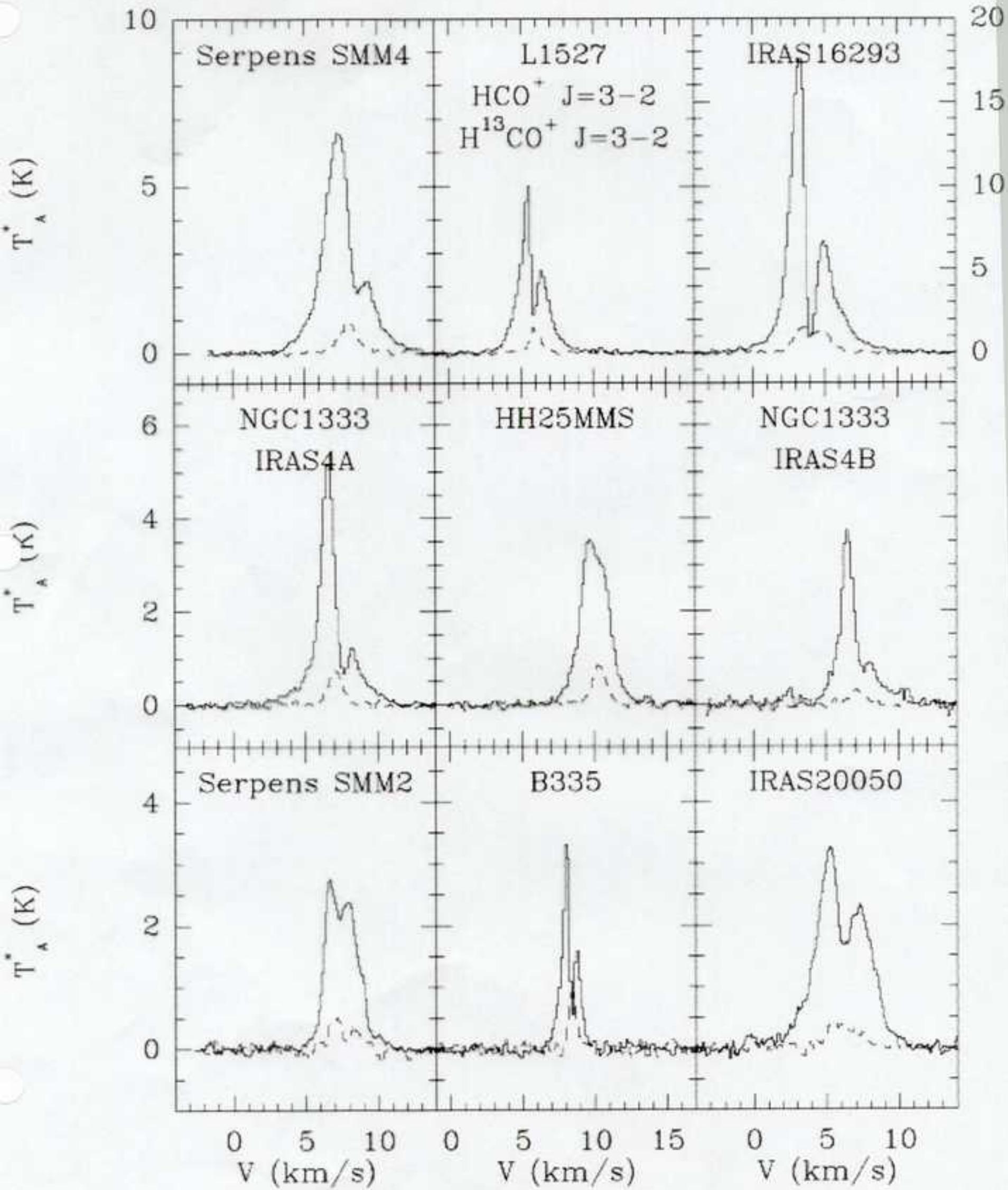
Tracers HCO^+ , CS, H_2CO (N_2H^+ as thin tracer)

- “standard model” reasonable fit to data
- 10% starless cores show extended infall in CS 2-1

(Lee, Myers & Tafalla 1999, 2001)

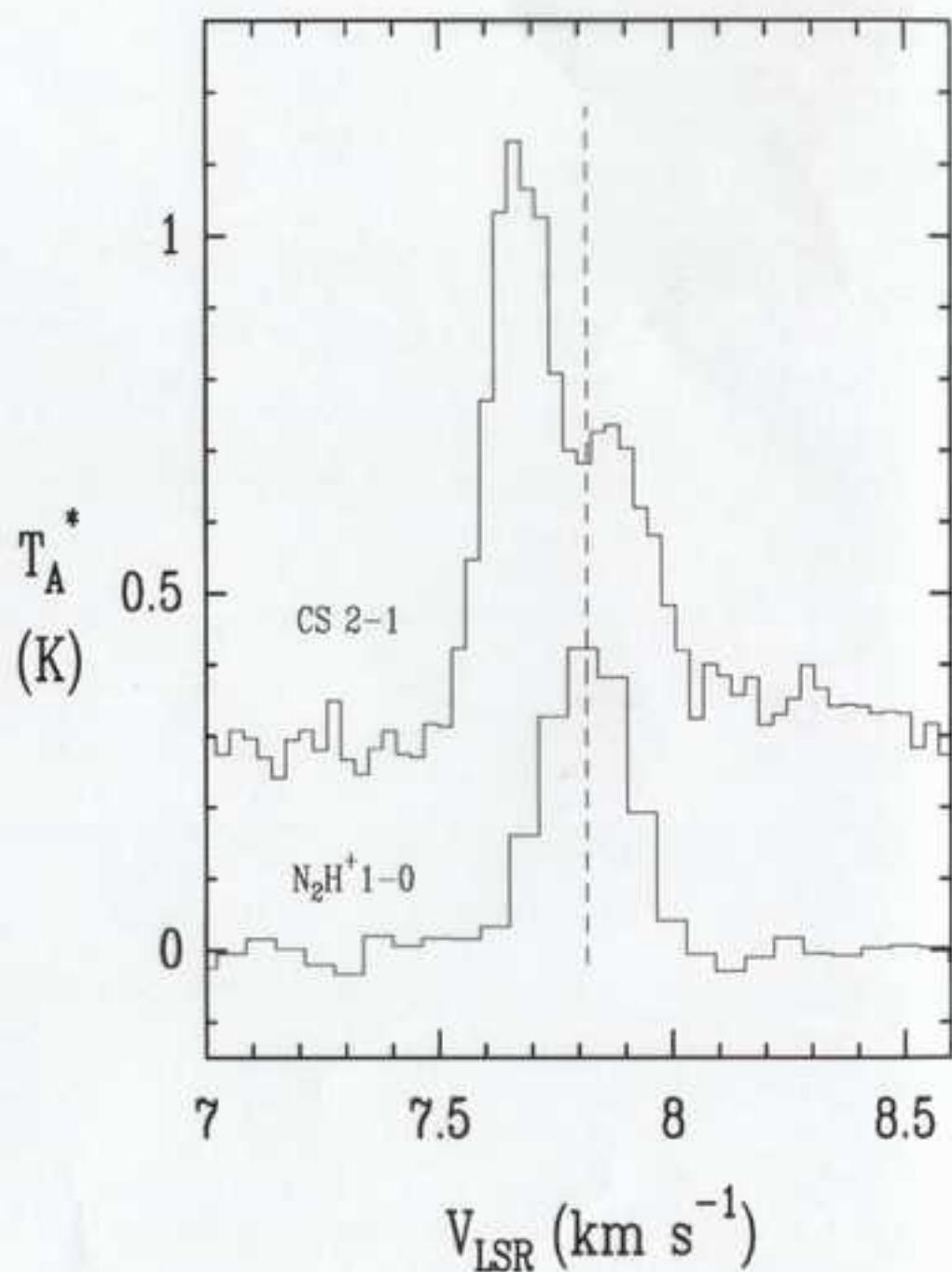
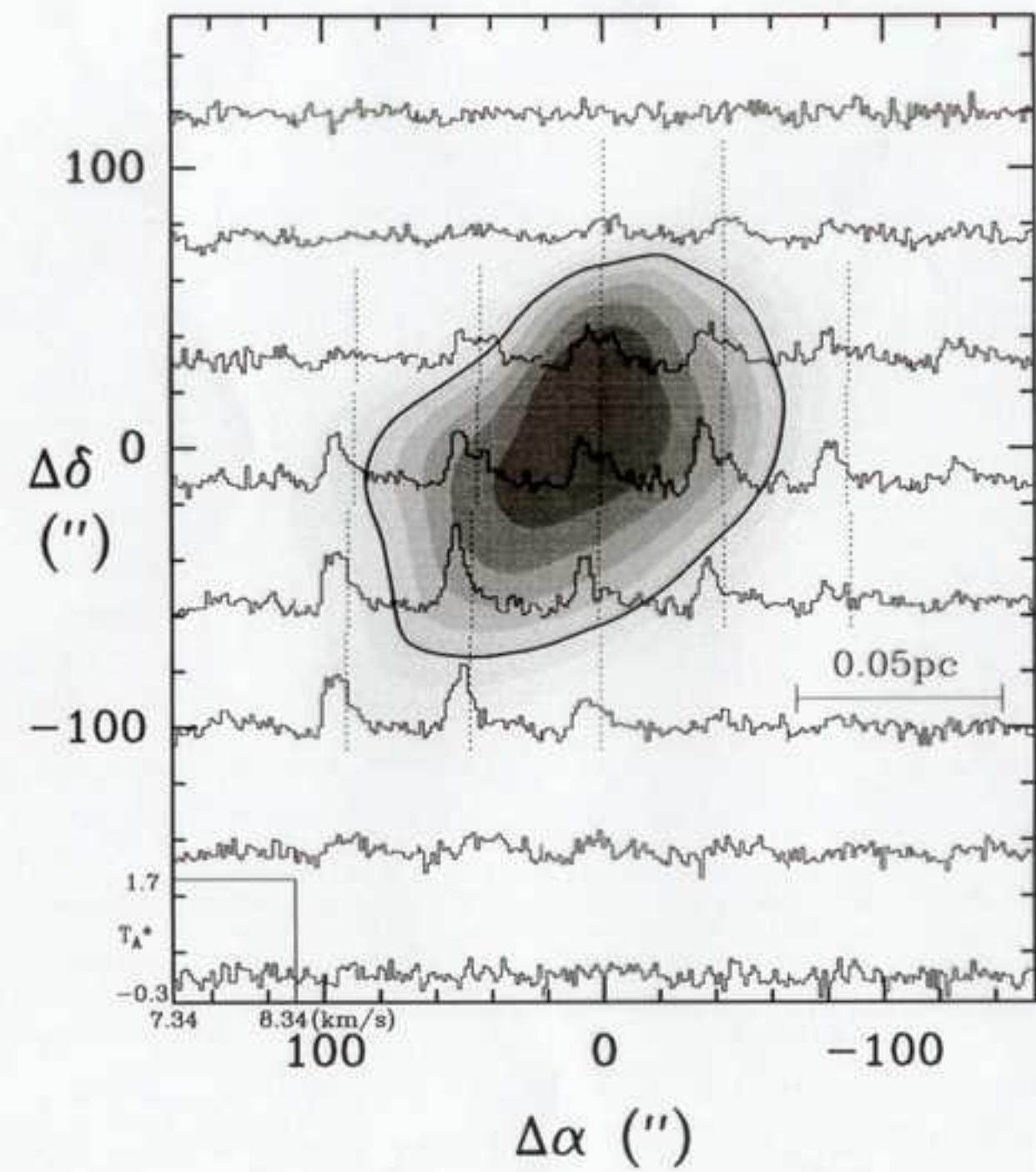
HUH?

- too extended for standard model - no central source
- too fast for ambipolar diffusion
- depletion a problem (CS) - not tracing high v ?
- loss of turbulence?? Nakano 1998



L1498

CS 2-1

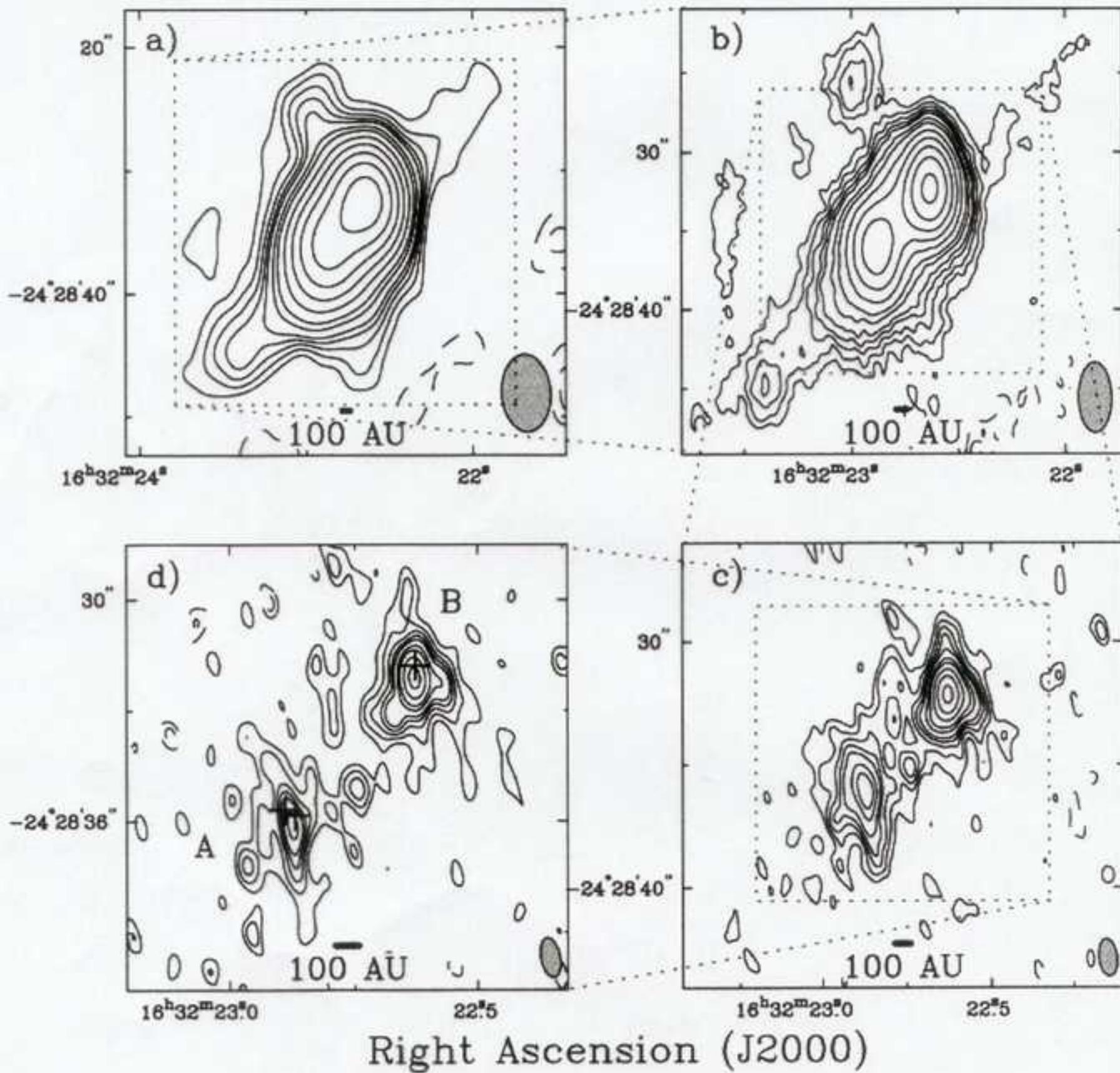


Protostars - Envelopes, Disks and Multiplicity

- SIMBA (1.3mm) will discover lots of protostars
- resolution only $23''$ (IRAS only $1'$)
- ATCA at 3mm continuum will be able to
 - resolve close systems
 - find compact structures (disks)
 - resolve large disks (e.g., circumbinary disks)
- classify multiple systems as (Looney et al. 1998 529 477)
 - (i) independent envelopes (>6000 AU)
 - (ii) common envelopes (150-3000 AU)
 - (ii) common disks ($\frac{<150}{150-3000}$ AU) circumbinary

3-mm BIMA

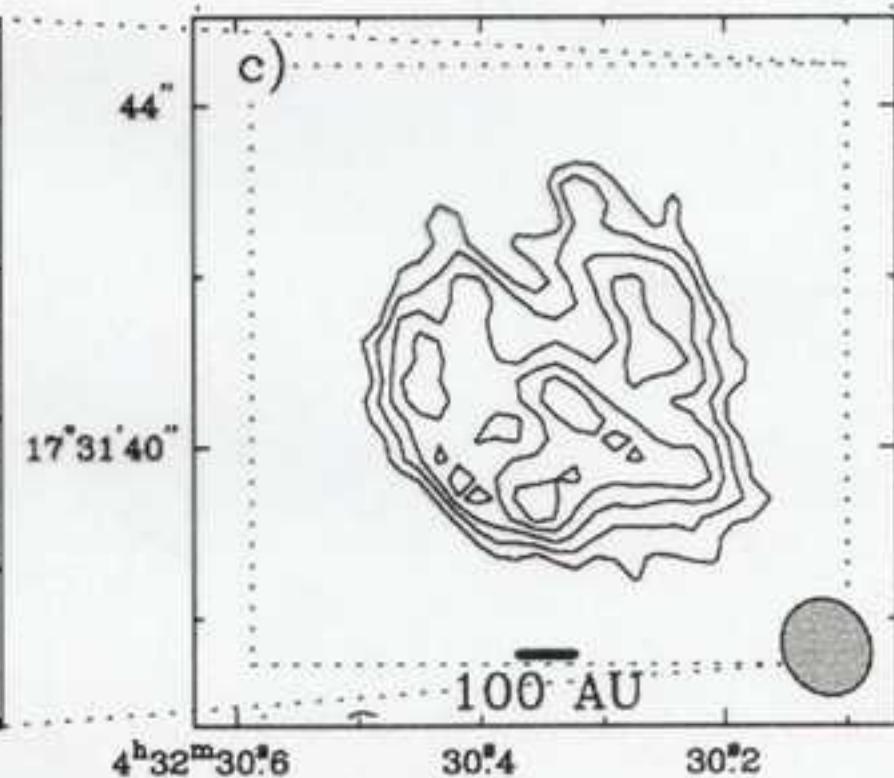
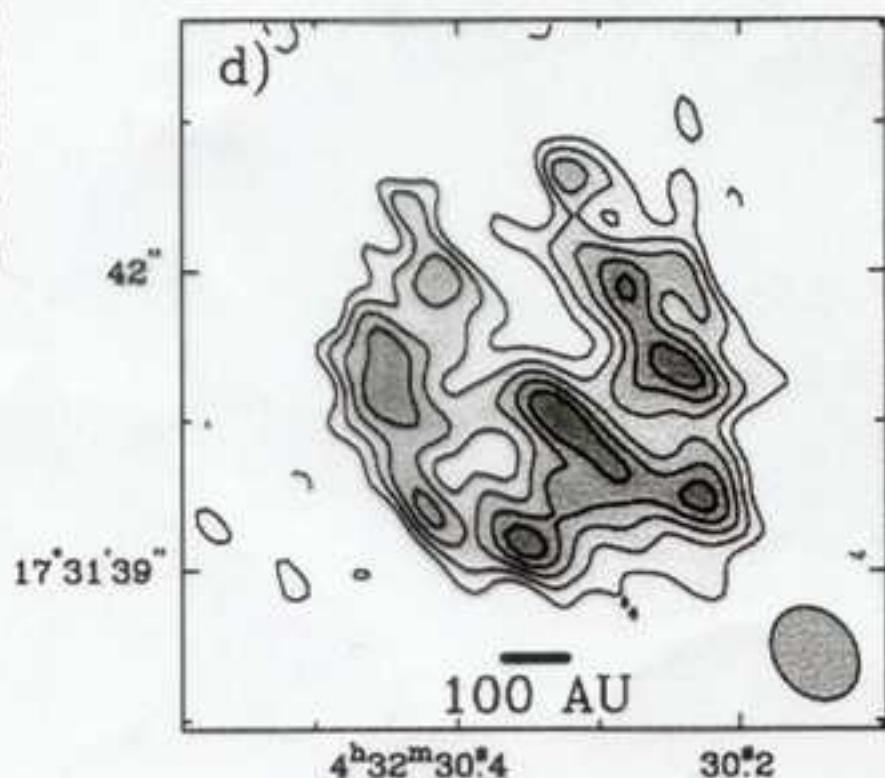
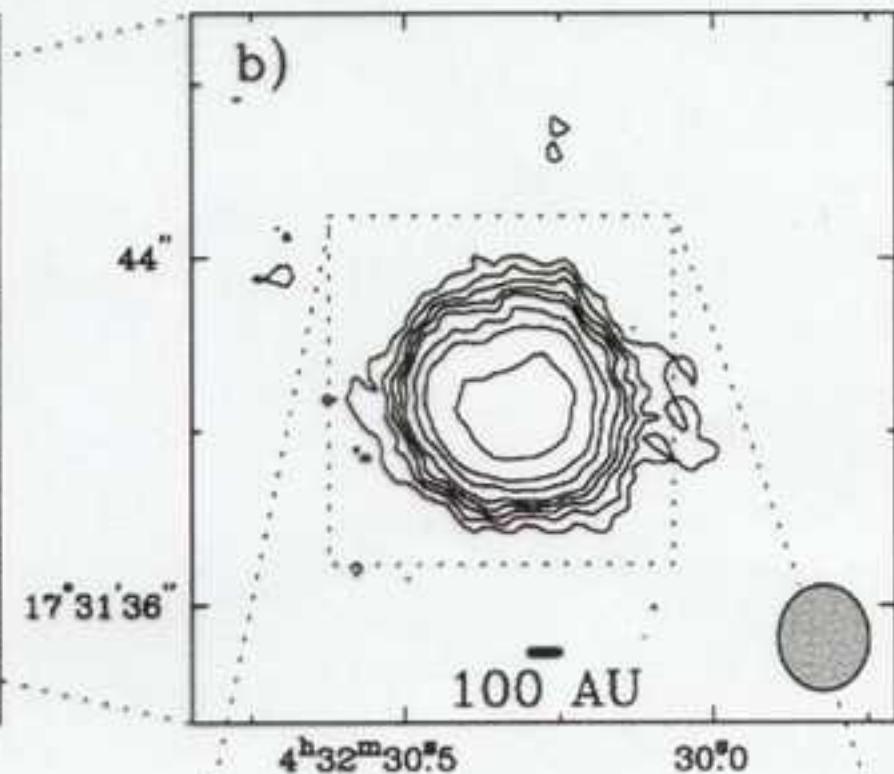
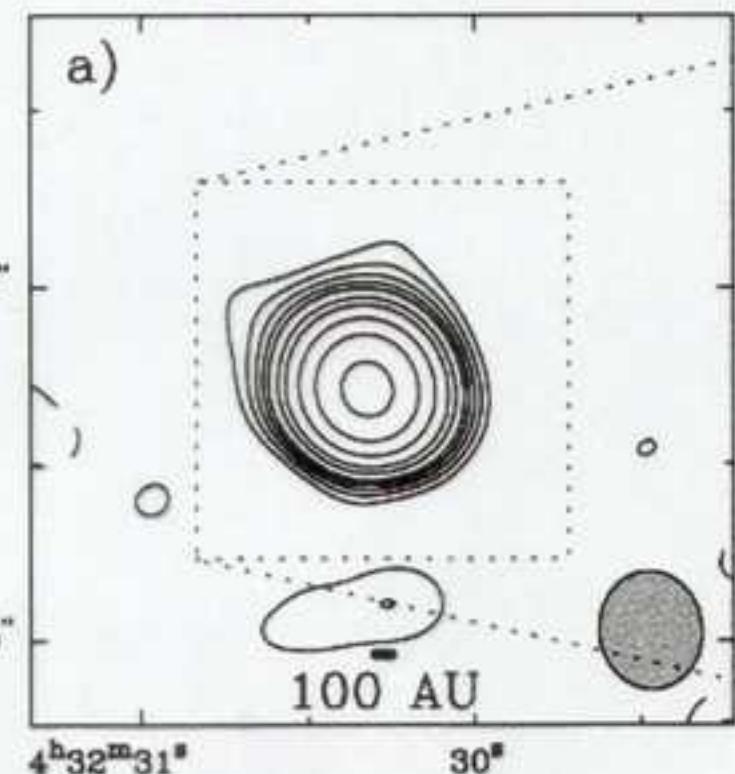
Declination (δ , J2000)



IRAS 16293

ApJ
Looney et al. 1998
529 477

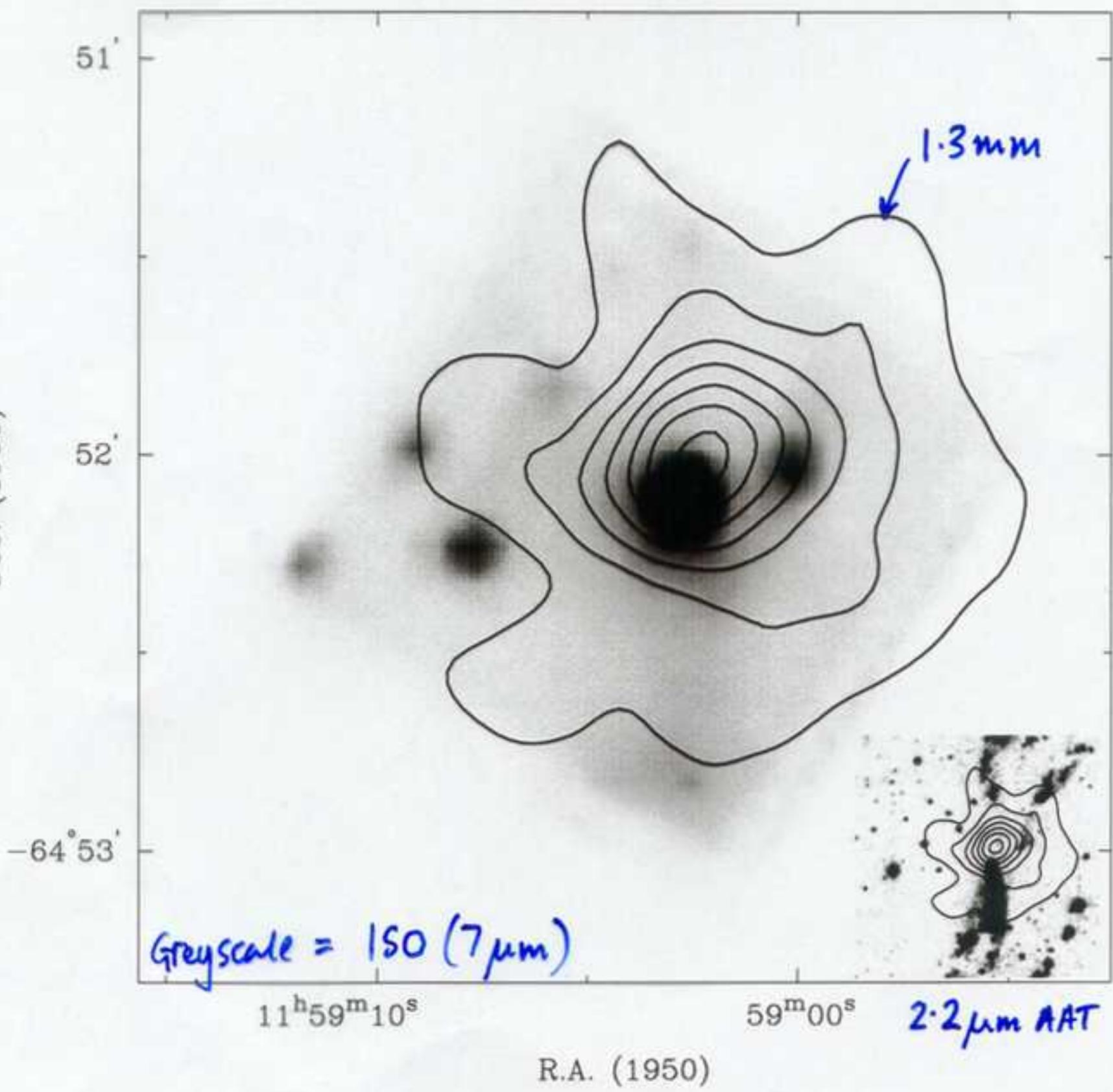
Declination (J2000)



Right Ascension (J2000)

GG Tau

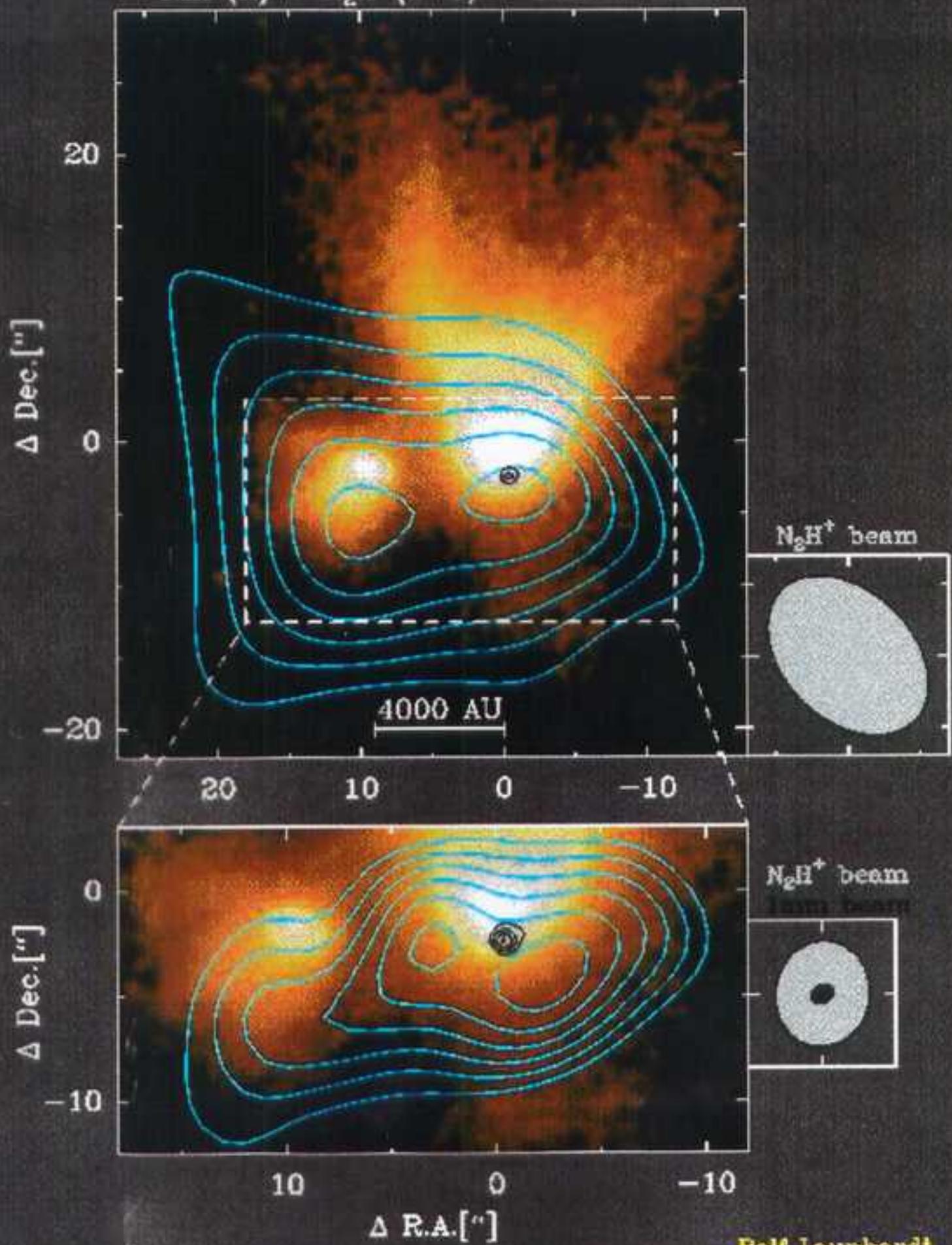
Dec. (1950)



BHR 71

The double core in CB230

NIR (K) + $\text{N}_2\text{H}^+(1-0)$ + 1.2mm cont.



ATCA-mm – Cores

Protostellar Cores – Clusters and Isolated

- SIMBA (1.3mm) will observe many cores
- resolution only $23''$ (IRAS only $1'$)
- mm ATCA will be able to
 - ★ → resolve cluster members (cont.)
 - find starless dense cores (line – NH_3 , N_2H^+)
 - kinematic information
 - ★ → outflow identification (CO?)
(★ filters out large scale muck)

DiFrancesco (Orion)

e.g. Serpens (Williams & Myers)

A Southern Survey for Dense Cores.....

ATCA at 1.3 cm (NH_3) + Parkes FPA at 1.3 cm

(22-m + 44-m perfect for uv plane combining)

- Map with unprecedent resolution and sensitivity
- Obtain both density and temperature information with NH_3 (1,1) & (2,2)
 - (water masers)

(Zermatt 1998)

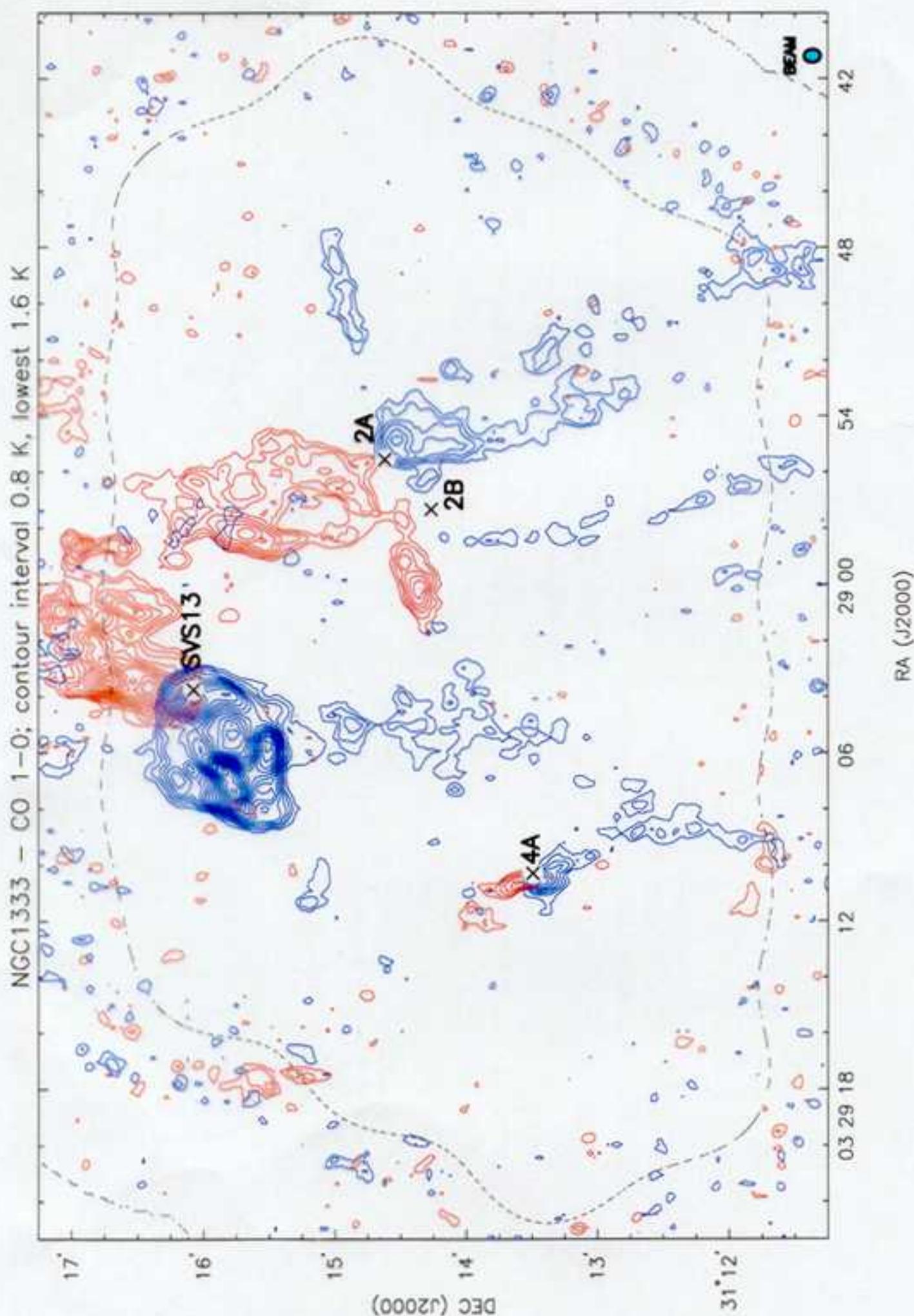
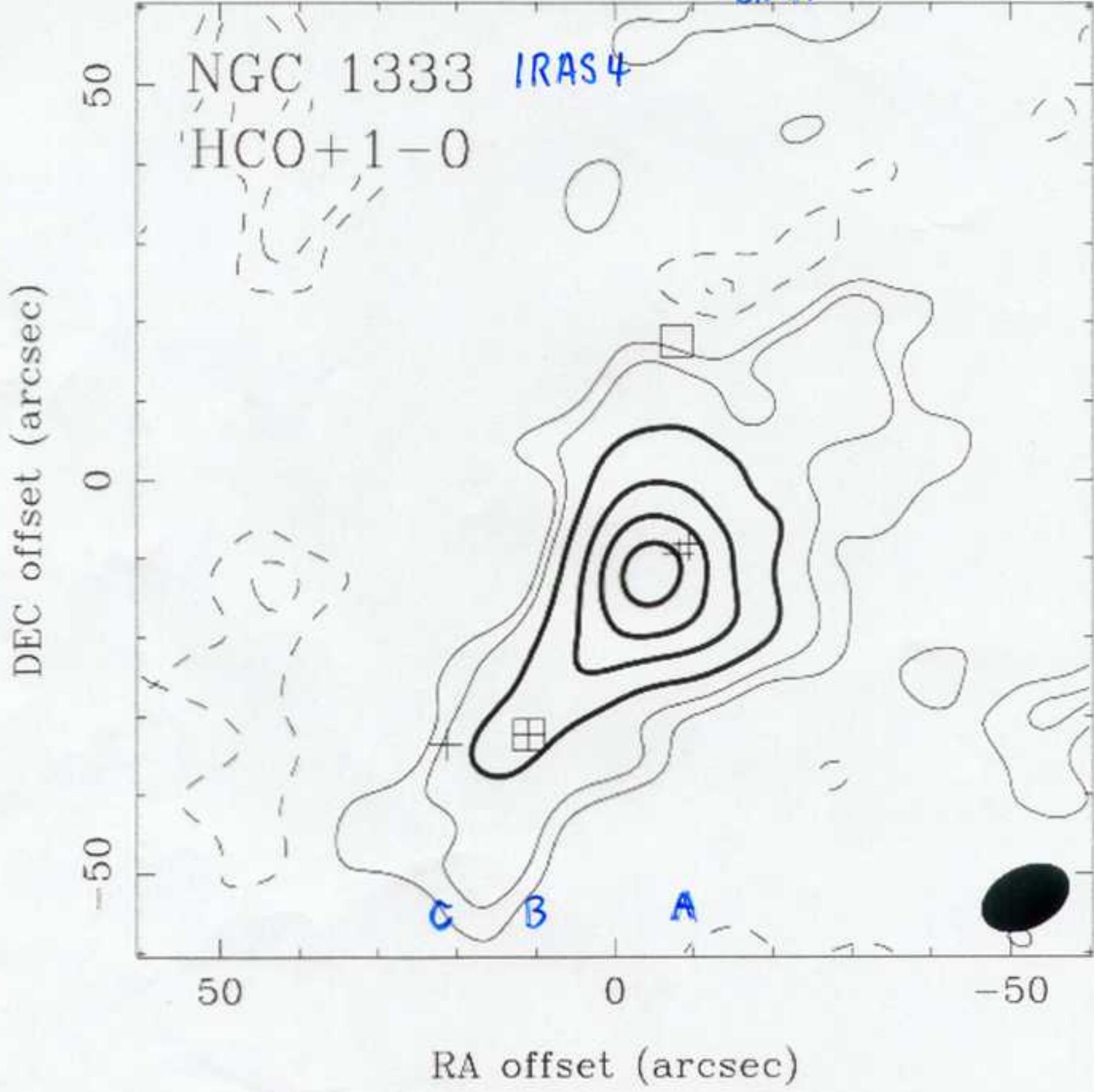


Fig. 4: Redshifted ($11 \leq V_{\text{LSR}} \leq 19 \text{ km/sec}$) and blueshifted ($-3 \leq V_{\text{LSR}} \leq 5 \text{ km/sec}$) CO 1-0 line wings toward NGC1333, the result of a BIMA 44-field mosaic. The outer box is $6' \times 9'$. The synthesized beam is $7'' \times 6''$. The contour level is 1.6 K. The rms noise level is approximately 0.4 K within the dashed contour.

Infall on Small Scales

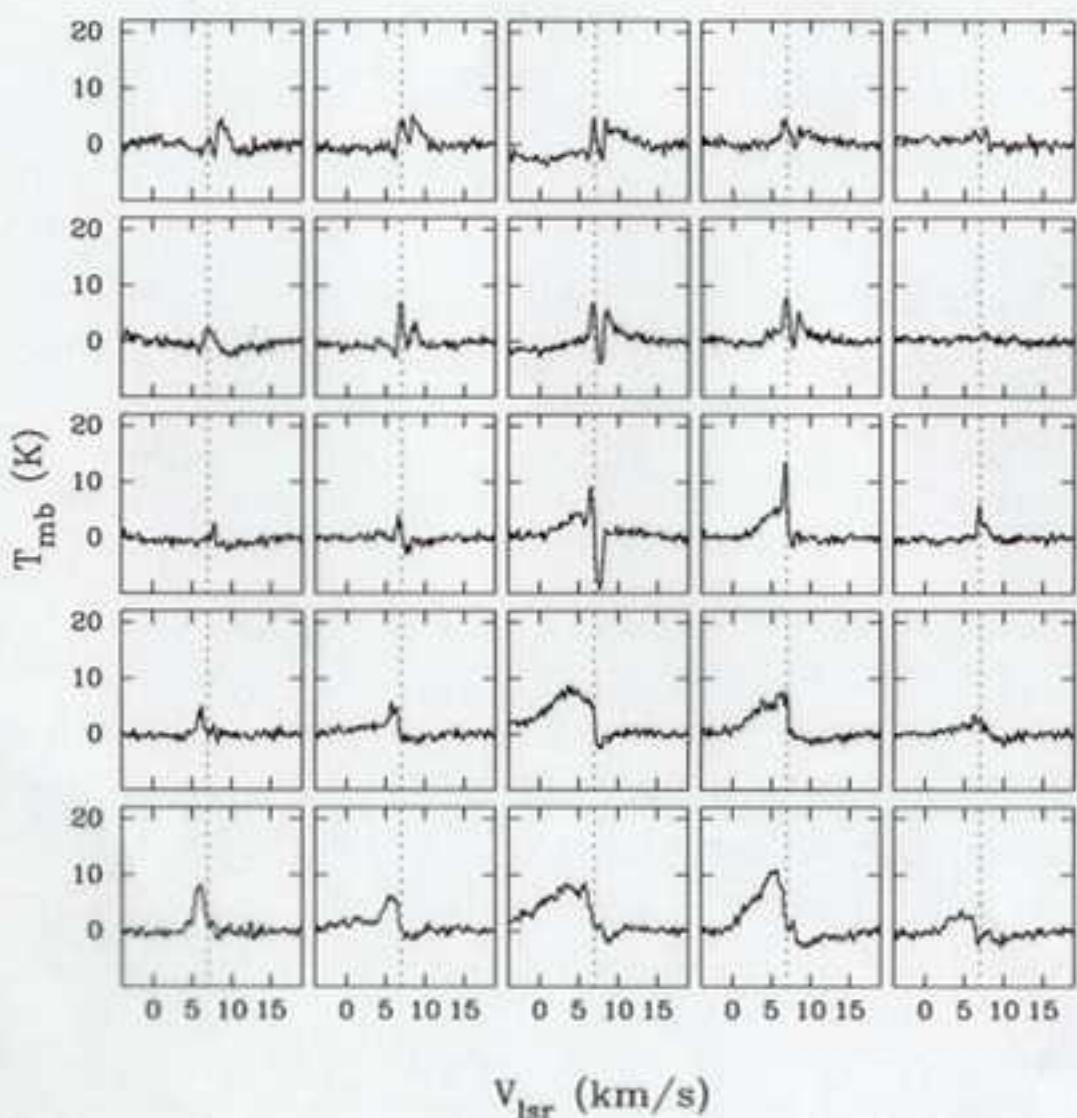
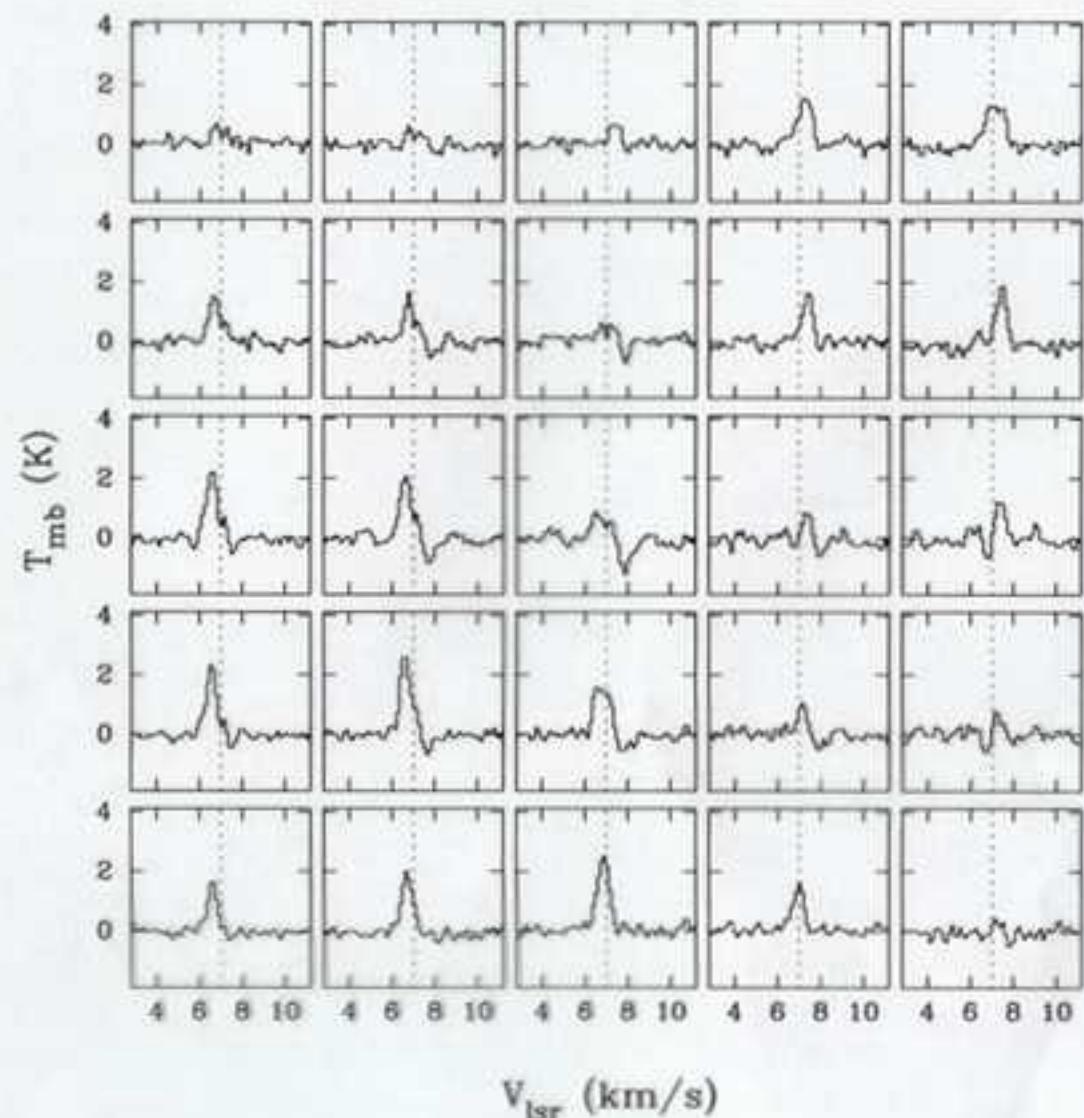
- problem with infall prototype B335 (CS 5-4)
- probes the smallest scales
- inverse P-Cygni profiles - a winner (but rare)
- HCO⁺ 1-0 excellent - sensitive
- real test of theories - models differ in their details
 - non-LTE radiative transfer codes
- infall wings - high velocities - not yet seen...
 - need a non-outflow sensitive tracer - N₂H⁺

BIMA



NGC 1333 - IRAS 4

PdBI

a) 4A (+ 4A'): H_2CO $3_{12}-2_{11}$ (1mm)b) 4A (+ 4A'): N_2H^+ 101-012 (3mm)

HCO+1-0

NGC 1333

HCN1-0

T_b (K)

10

5

0

-5

-10

-15

F = 0-1

2-1

1-1

IRAS4B

IRAS4C

4 6 8 10

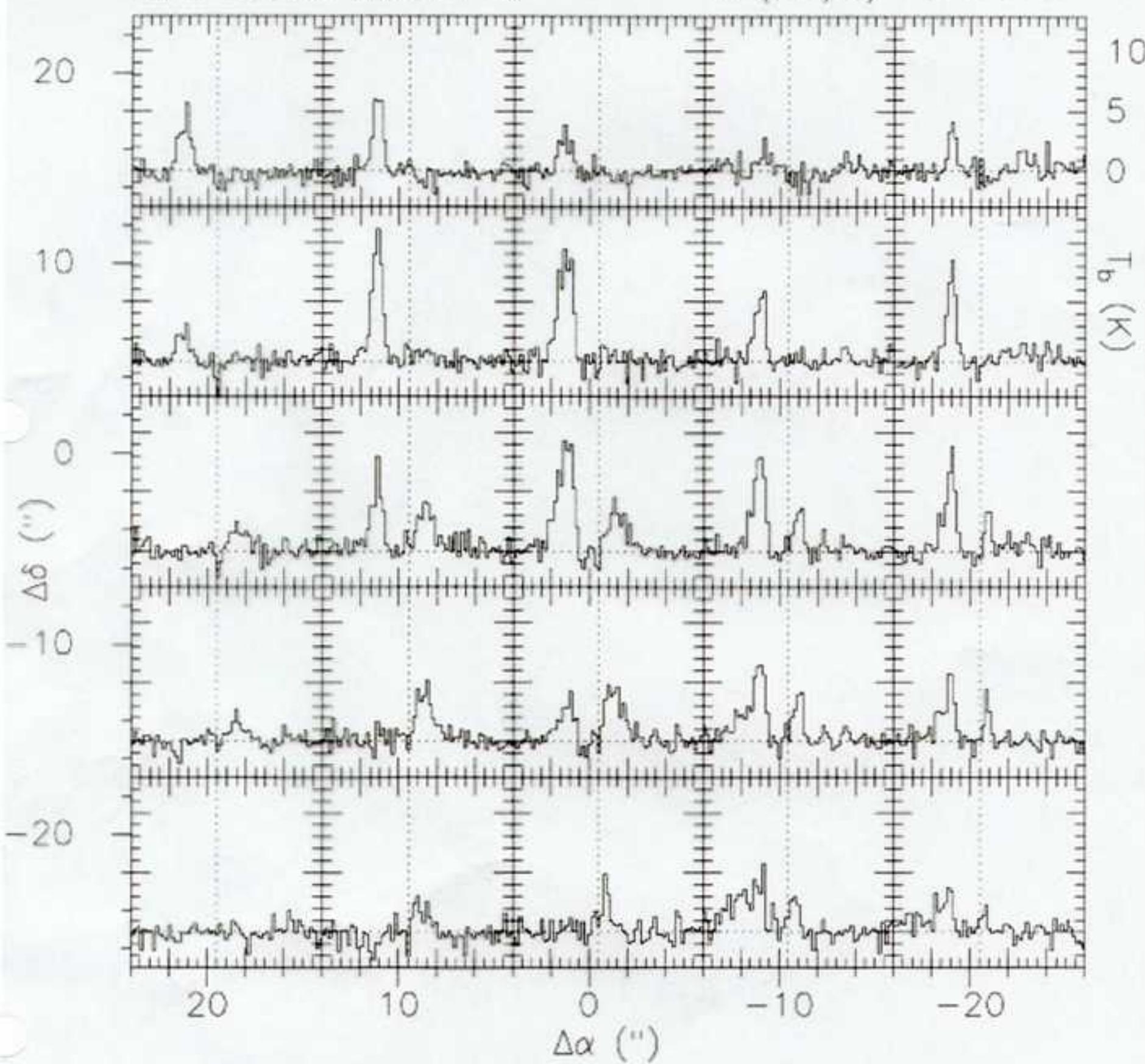
0 5

10 15

V (km/s)

Choi et al.

IRAS 16293 HCO+1-0

 v (km/s) 2 4 6 8

ATCA-mm – Outflows

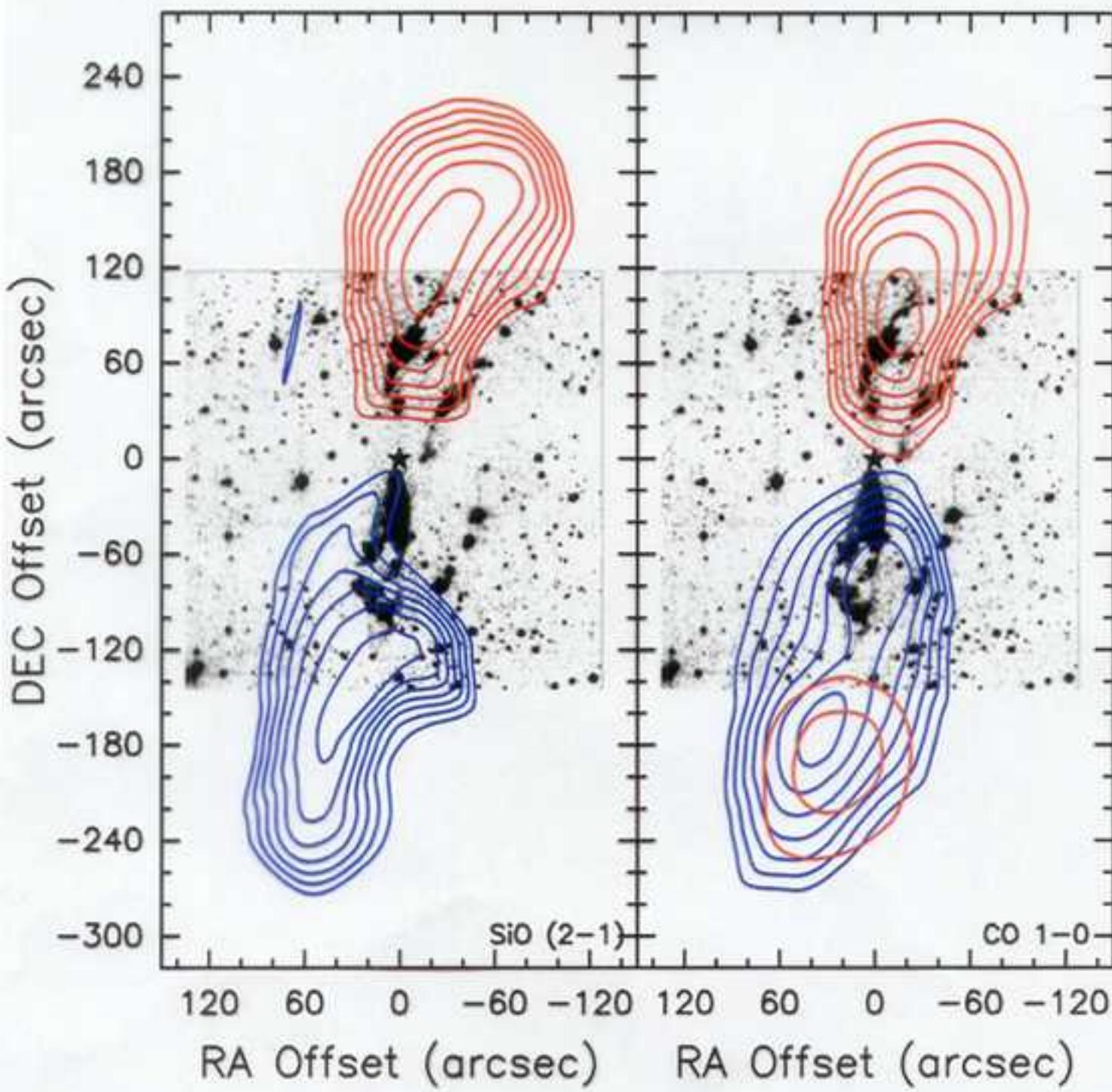
3 and 13mm

- CO 1-0 very important - will ATCA-mm do it?
- others – SiO $v=0$ 2-1, CS 2-1, CH₃OH at 3mm
 - shock tracers - chemistry
- NH₃ (3,3) at 13mm also a good probe (L1157)
- combine AAT 2.122 μm imaging - shocks, jets
- regions - ρ Oph, RCrA, Circinus
 - AAT IRIS-2 mosaic + ATCA mosaic (CO)
 - Mopra CO 1-0 (SEST CO 1-0/2-1)
 - Can outflows support clouds?

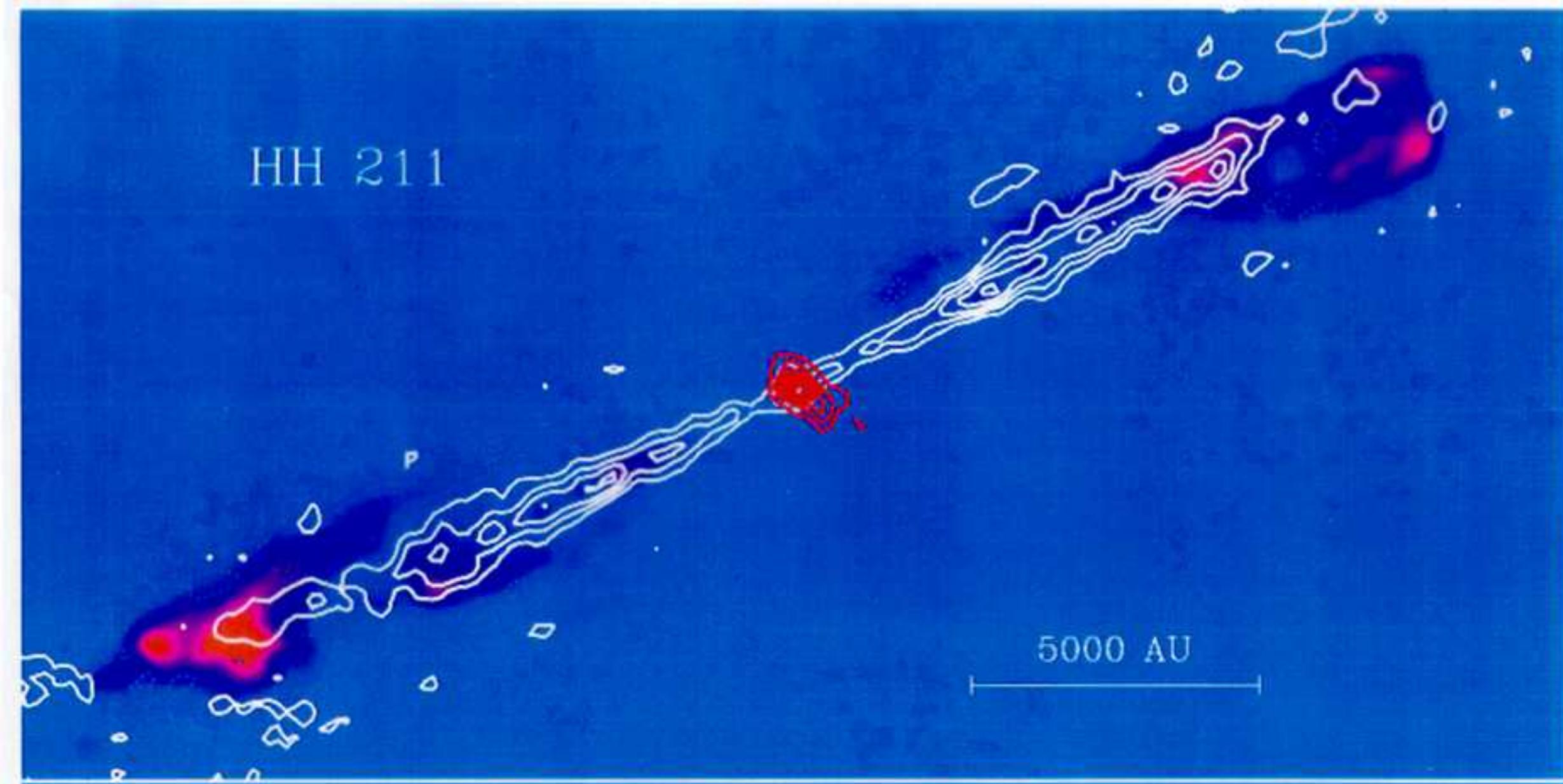
Replenish turbulence?

Could be a good PhD project

BHR 71 – SiO (*I*) & CO (*r*) over H₂

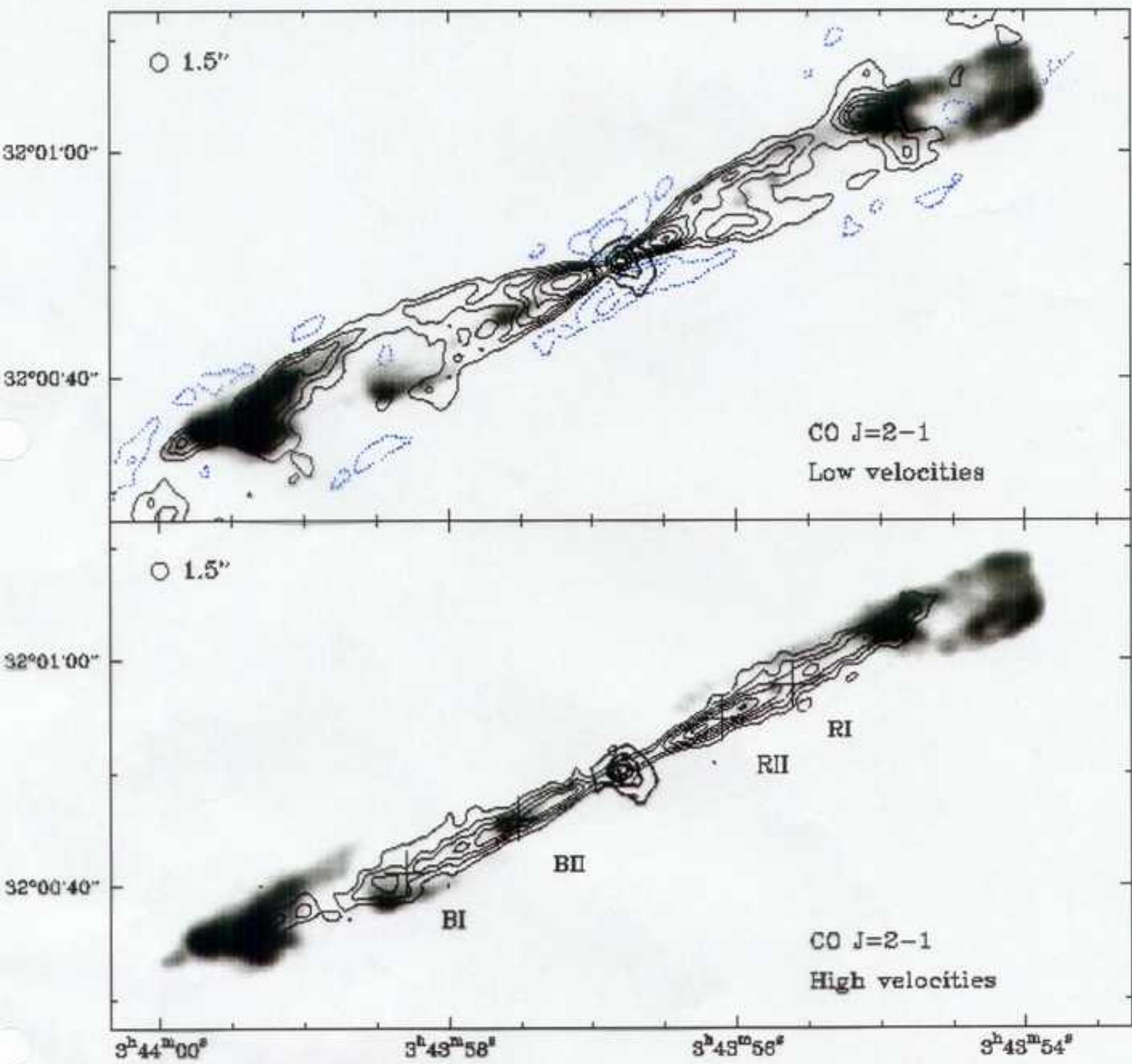


HH 211



Outflow CO 2-1
1mm continuum
H₂ emission

Gueth & Guilloteau (1999)
A&A 343 571

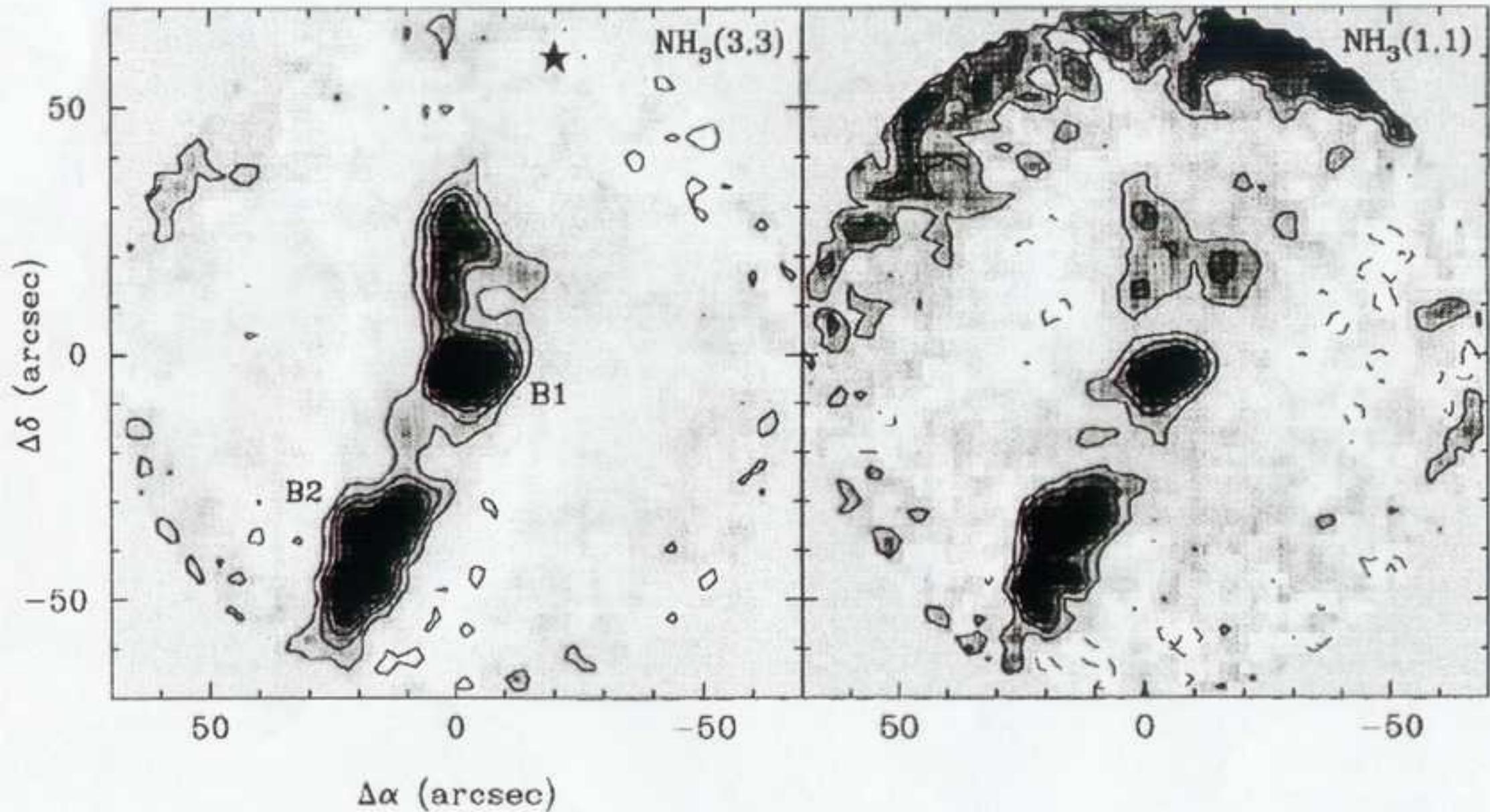


Gueth & Guilloteau

L1157

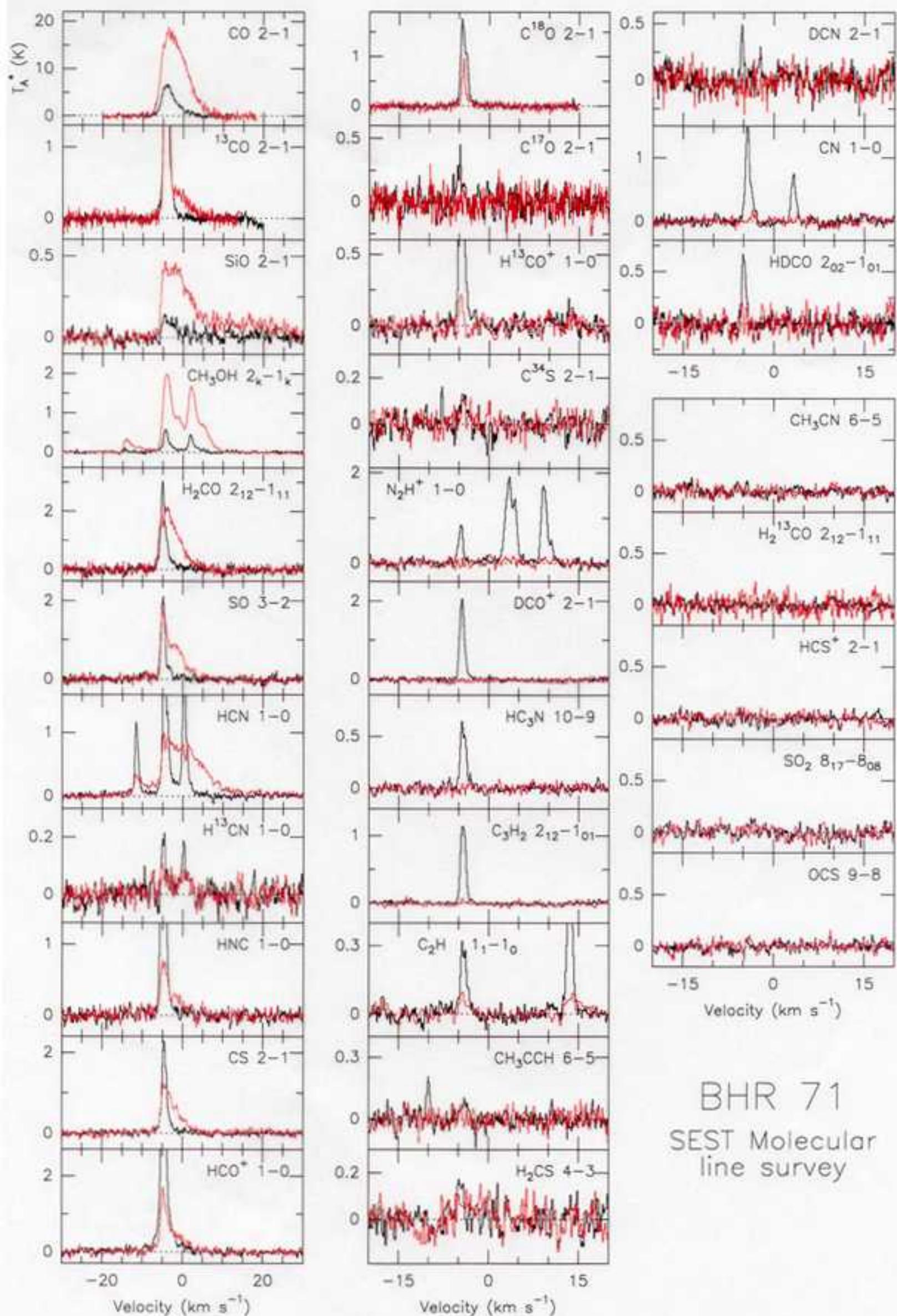
$T_{\text{K}} \sim 60-80 \text{ K}$

VLA



Ammonia abundance
enhanced

Tafalla & Bachiller (1995)
ApJ 443 L37



BHR 71
SEST Molecular
line survey

ATCA-mm – Disks

3 and 13mm

- CO 1-0 very important - will ATCA-mm do it?
- ^{13}CO 1-0, C^{18}O 1-0
- others – HCN 1-0, CS 2-1, HCO^+ 1-0 N_2H^+ 1-0
at 3mm

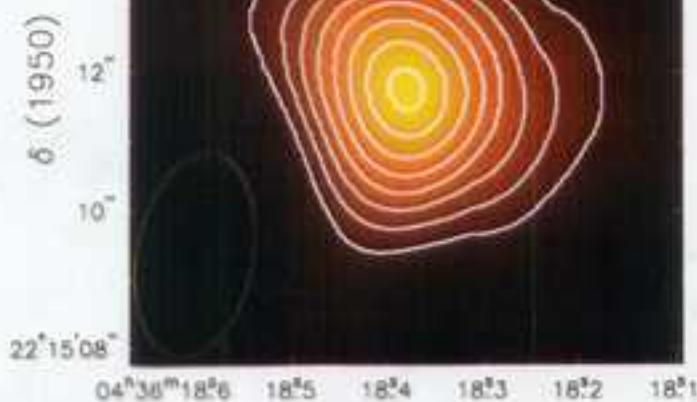
→ Blake, Wright, Maddison

- chemistry - probe different regions of the disk
- kinematics - rotationally support or not (pseudo disk)
- filter out the extended envelopes - only see disk
→ Chamaeleon, Lupus, TW Hyd, η Cham

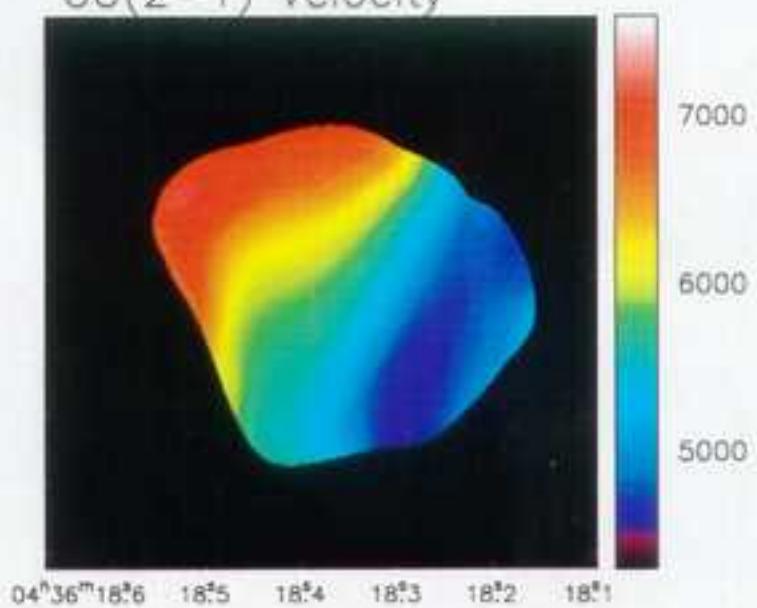
Disks mean Planets

LkCa 15 Disk

CO(2-1)



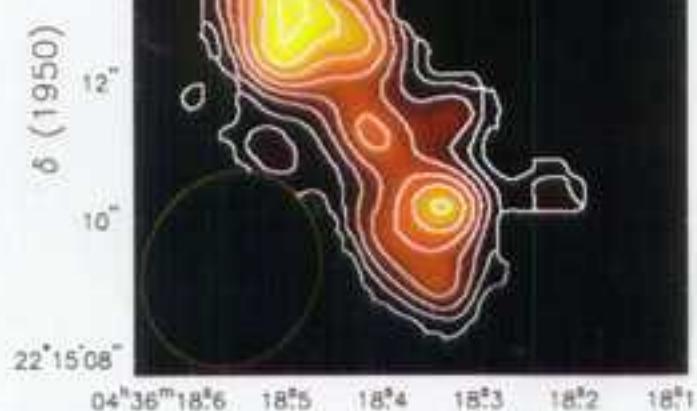
CO(2-1) Velocity



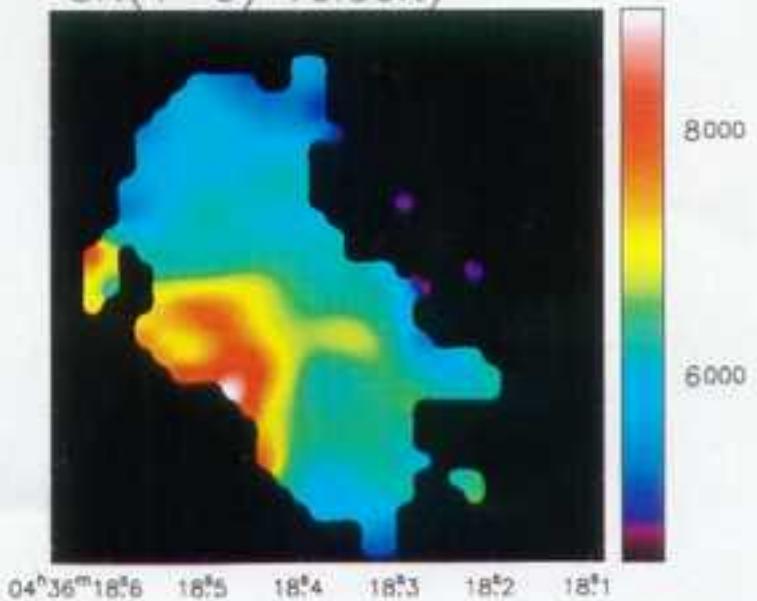
α (1950)

α (1950)

CN(1-0)



CN(1-0) Velocity



α (1950)

α (1950)

Charlie Qi

PhD 2000

OVRO

ATCA-mm – High-Mass Protostars

Does the low-mass paradigm hold for high-mass stars?

- satisfy Wood & Churchwell 1989 (UCHII via IRAS)
- bright at FIR wavelengths
- *not* detected in PMN survey (5 GHz)
- are detected in CS 2-1 survey (Bronfman et al. 1986)

Isolated and Pre-UCHII High Mass Protostellar Objects

→ ATCA cm - continuum and methanol masers

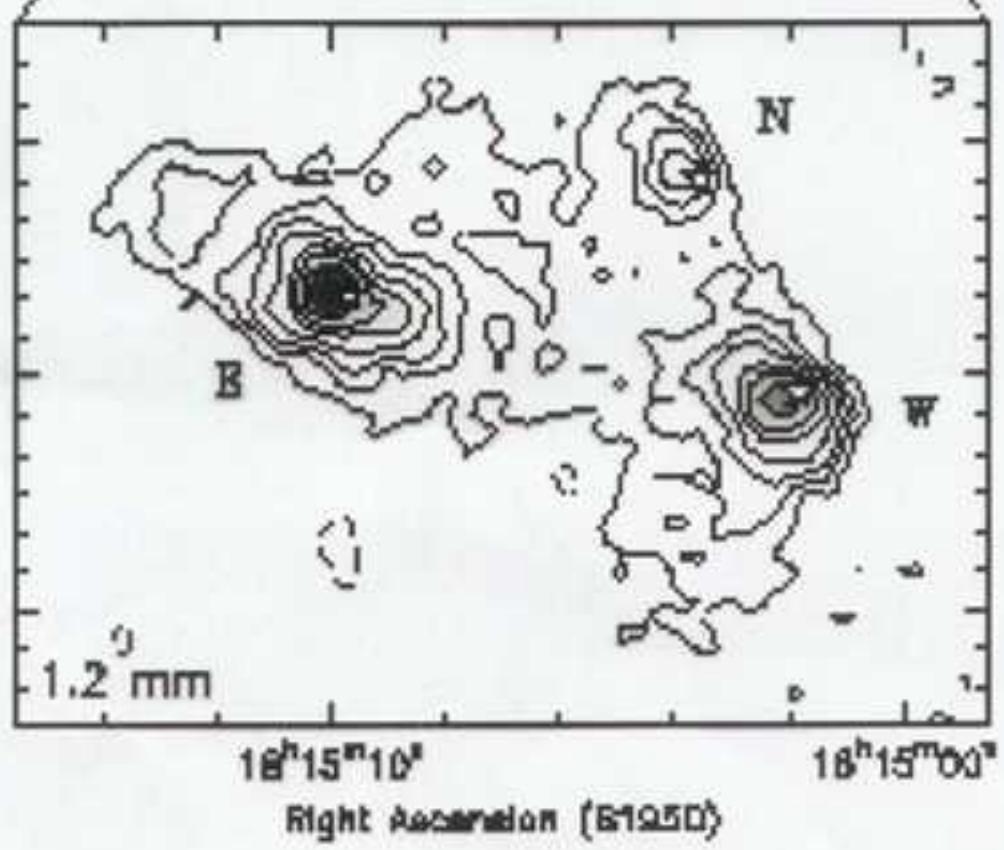
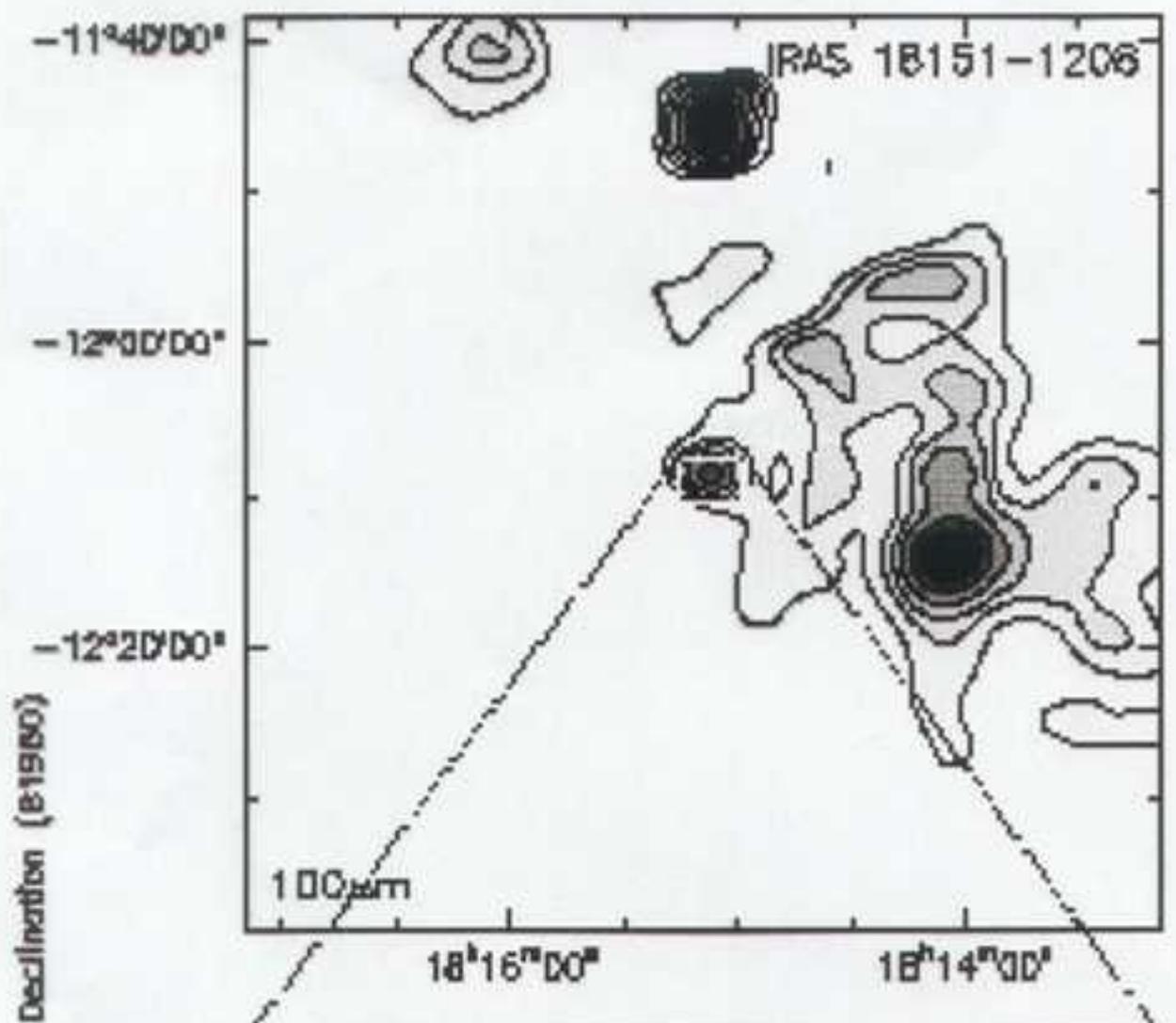
→ ATCA mm - outflows, disks (line)

13mm system very important - hot cores, disks/jets

→ ATCA mm - multiplicity (continuum)

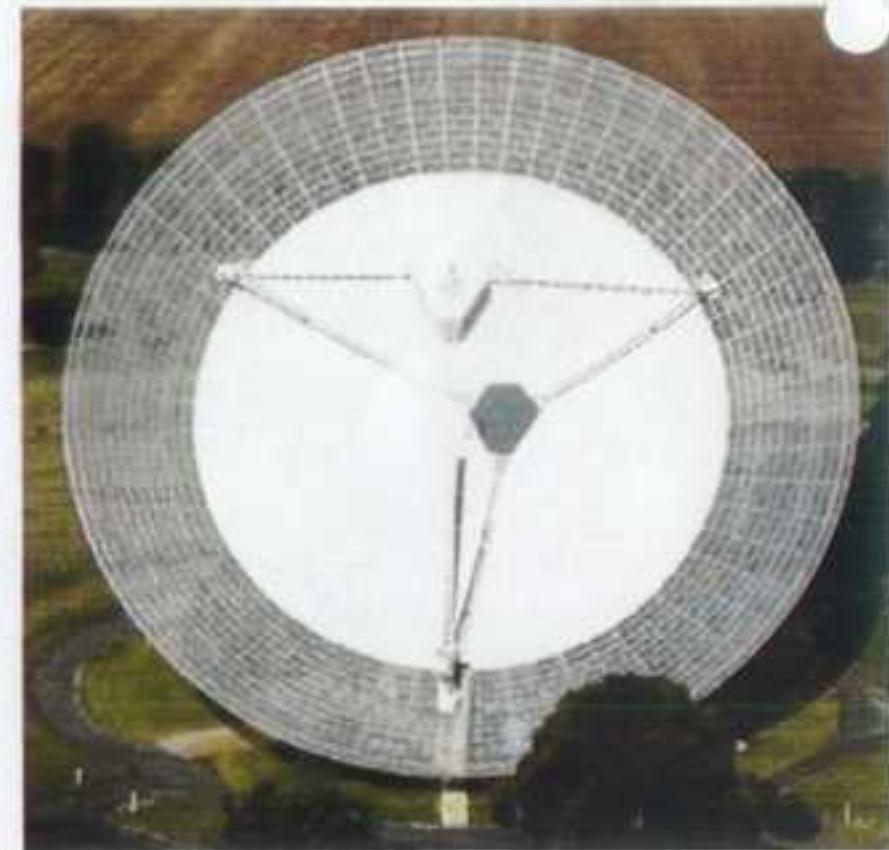
→ AAT infrared - low-mass clusters?

Looking for a student (CfA Predocs...)



Design Concept A

- 19 beam, 2 polarisation
 - Traditional total power, under-sampled array
 - Spectral capability using existing multibeam correlator
- Cost ~\$1.5M + \$0.6M
(manpower)



Design Concept

- 10 x 10 diagonal horn array, 1 polarisation
- Nyquist-sampled ($x=f/2$) at focal plane
- Hardware beam formation + expanded correlator
- Multi-telescope capable (Pks, Mopra, Ceduna, GBT, Bonn)
- Cost ~\$1.9M + \$0.6M

High Angular Resolution in Star Formation

With support from IAU Division VI/Commission 34

Star Formation Working Group

(<http://www.oan.es/sfwg/>)

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Bring your great results from the mm ATCA!

- Evans 1999 ARAA
- Protostars & Planets IV 2000
(Univ. Arizona)
also PP III 1993
- Crete conference (NATO series) 1999
Lada & Kylafis
- 3rd Zermatt - Cologne conference 1999
- IAU Symp. "Astrochemistry" IAU 197?
- IAU Symp Herbig-Haro Flows 1997