Inward Motions In Star-Forming Clouds

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- Inward motion - kinematic evidence of formation of stars and cores
- Starless cores
- Cluster-forming cores
- Main result - infall asymmetry with v ~ 0.1 km/s, R~0.1 pc is detected in many dense cores
- SOFIA applications to infall studies

Collaborators

Lori Allen*	CfA
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Diego Mardones	U. Chile
Mario Tafalla	OAN (Spain)
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*see poster

Observational Approach

- **infall asymmetry**

surveys	incidence, infall candidates
caveats	outflows, rotation
maps	spatial extent and structure

- **choice of lines**

$n_{cr} > 10^4$ cm^{-3}

optically thick	H_2CO, CS, HCO^+
optically thin	N_2H^+, $C^{34}S$, $H^{13}CO^+$

- **choice of telescopes**

<u>ground-based</u>

filled-aperture	IRAM, NRO, JCMT, CSO, FCRAO, *GBT, LMT*
synthesis arrays	BIMA, OVRO, IRAM, *SMA, ALMA*

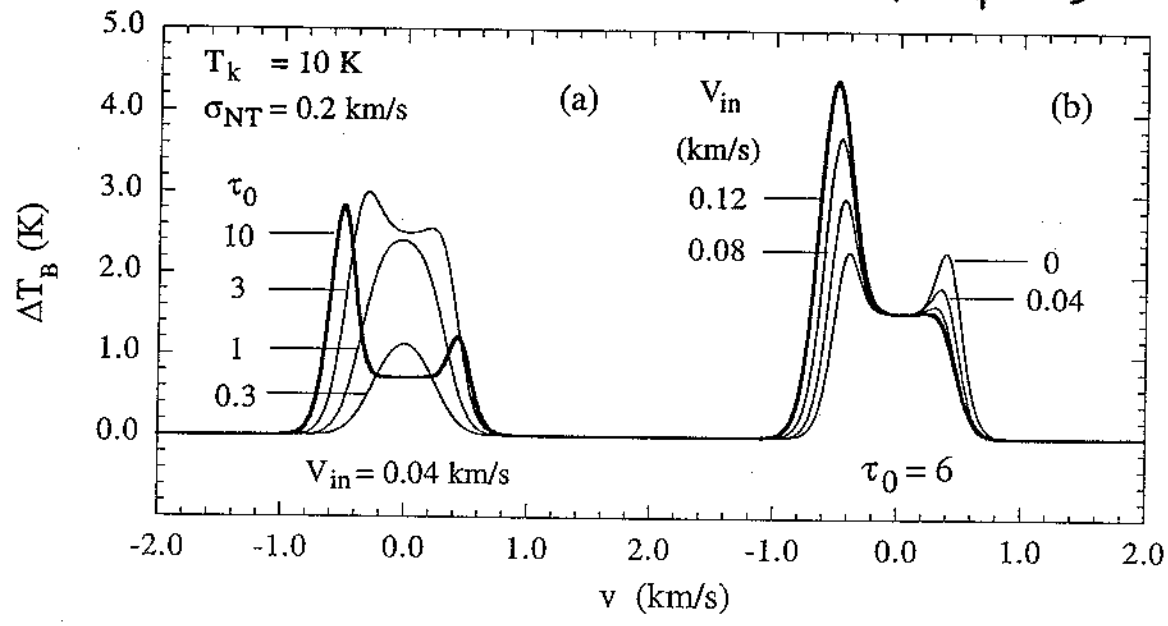
<u>airborne</u> ***SOFIA***

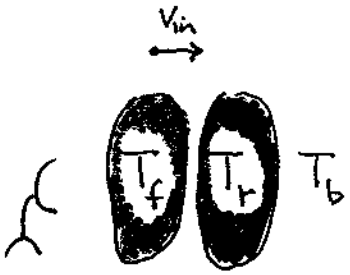
- **targets**

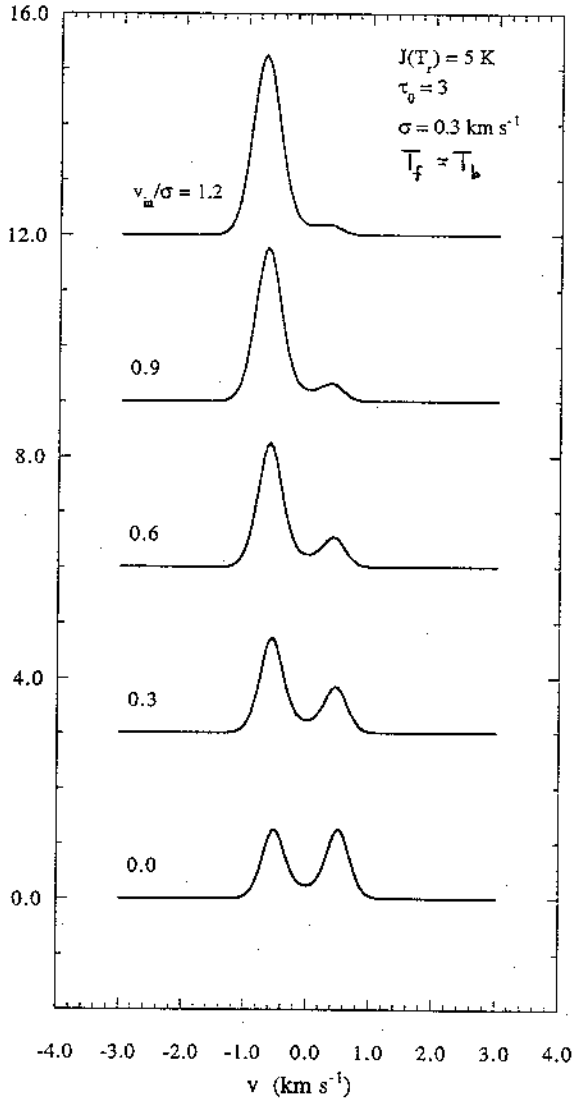
isolated starless cores	L1544 L183
isolated core with star	B335 L1544
cluster-forming core	Serpens NGC 1333

Infall Profiles - 2 Layer Model

$T_r > T_f > T_b$







$T_r > T_f = T_b$

cf. Leung & Brown '79
Lucas '96
Walker et al '94
Zhou '92

Myers et al '96

Isolated Starless Cores

infall asymmetry is "subsonic"

- 2-layer infall speed up to 0.1 km s^{-1}
- self-absorption: similar speeds from scales 0.01 (Williams et al 99) to 0.1 pc (Tafalla et al 98)

prevalent

- 7 cores with strong infall asymmetry (Lee, Myers & Tafalla 99a)
- ~ 5 cores with extended infall asymmetry in CS 2-1

spatially extended

- seen in lines of HCO^+, CS, C_3H_2, N_2H^+, ...
- extent increases with τ(line) > 0.1 pc -> $n < 10^4$ cm^{-3}
  > HM contour of N_2H^+
  > HM contour of 850 μm -SCUBA

examples - extended infall asymmetry

- L1544 Tafalla et al 98, Williams et al 99, Ohashi et al 99
- L694-2 Lee, Myers &Tafalla 99b
- MC27 Onishi et al 99

L1544 - The "Rosetta Stone"

infall asymmetry

too extended for inside-out collapse
too fast for subcritical ambipolar diffusion
too concentrated for uniform collapse (Tafalla et al 98)

density structure

~uniform center surrounded by r^{-2} envelope (Ward-Thompson et al 99, dust emission)

molecular abundance

depleted by a factor ~ 10 (Caselli et al 99, $C^{17}O$)

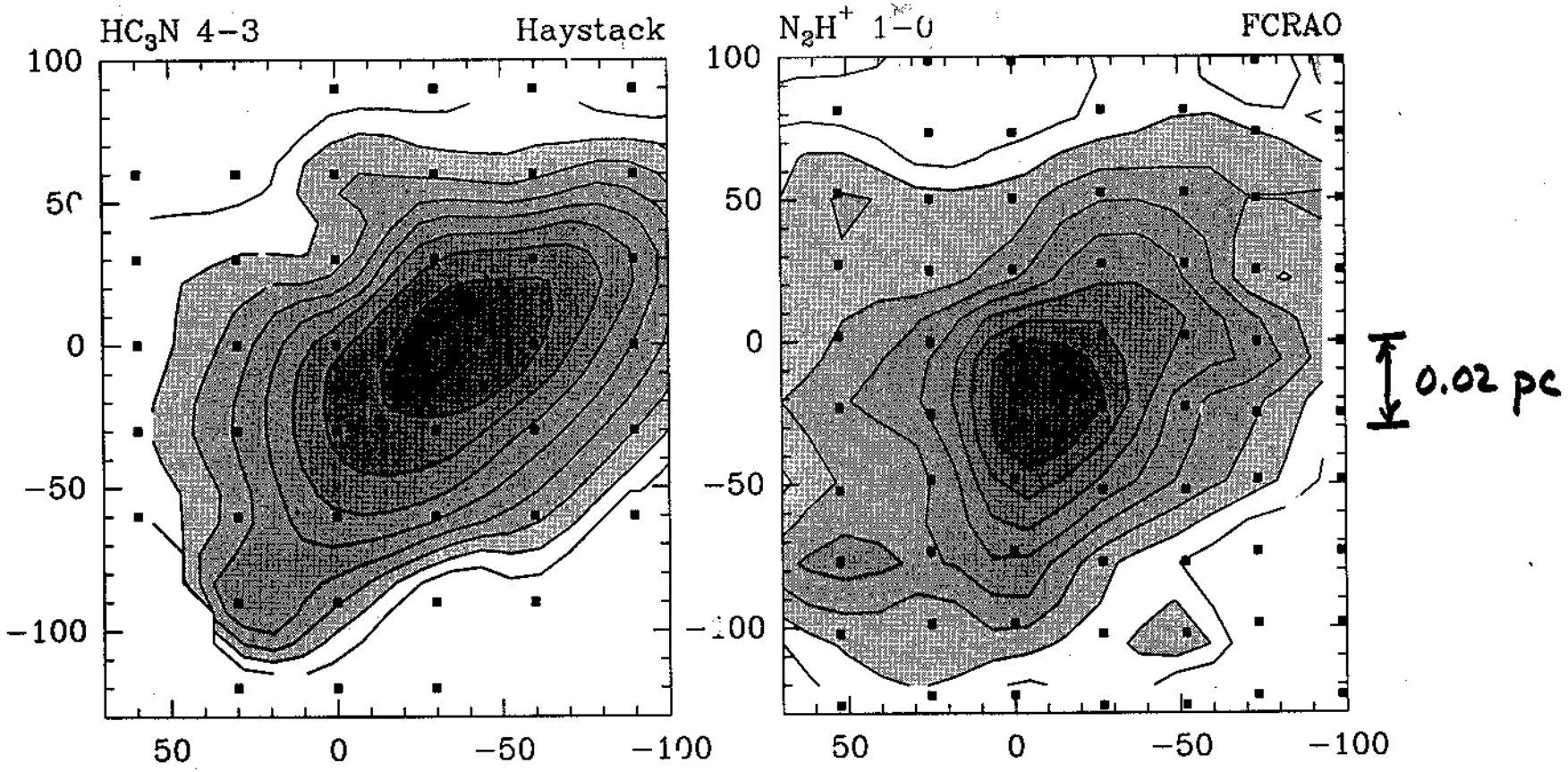
kinematic structure

infall plus rotation (Williams et al 99, N_2H^+)
flattened rotation plus infall (Ohashi et al 99, CCS)

dynamical process

turbulent cooling flow (Myers & Lazarian 98)
magnetically diluted collapse (Ciolek & Basu 99)

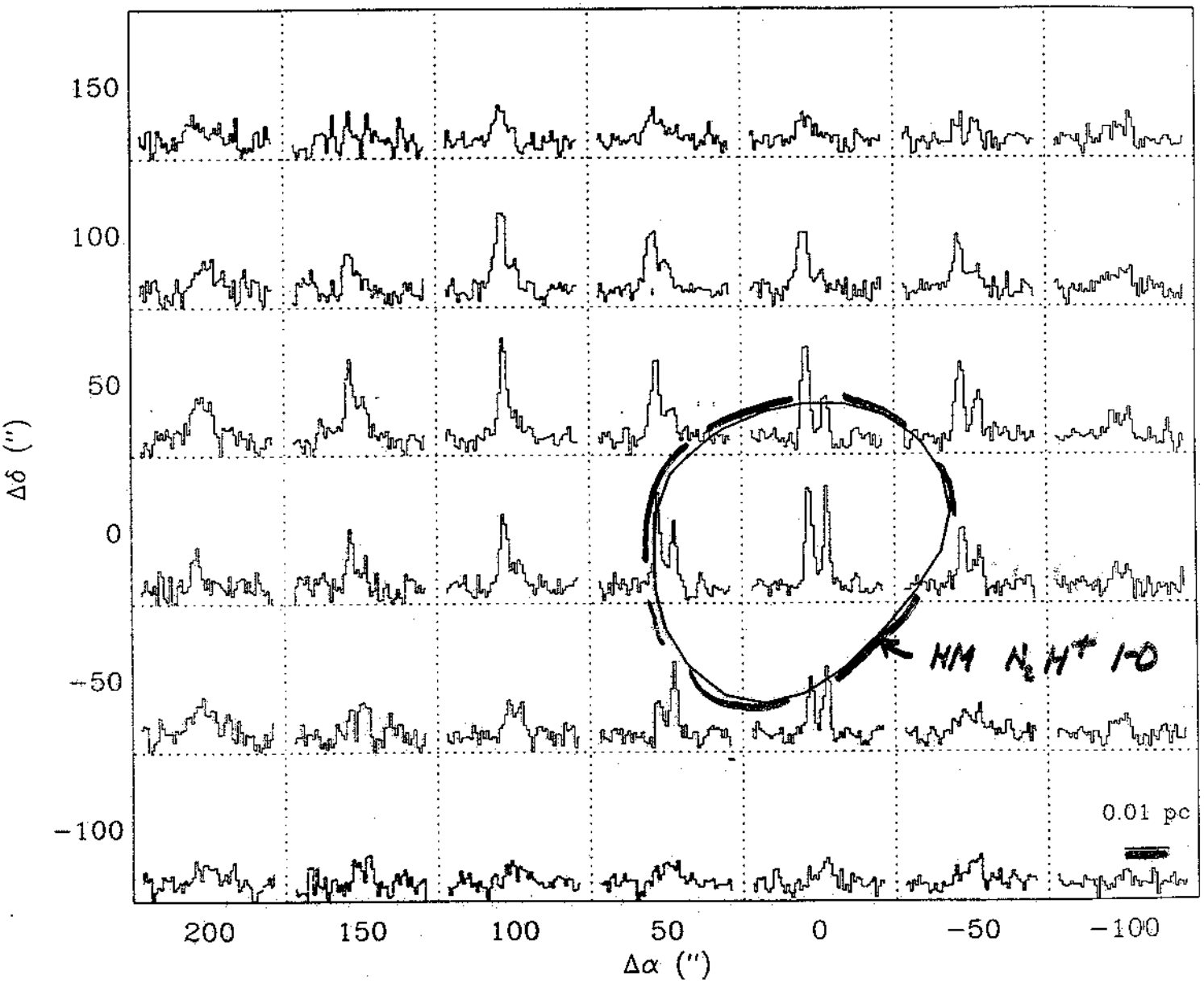
L1544



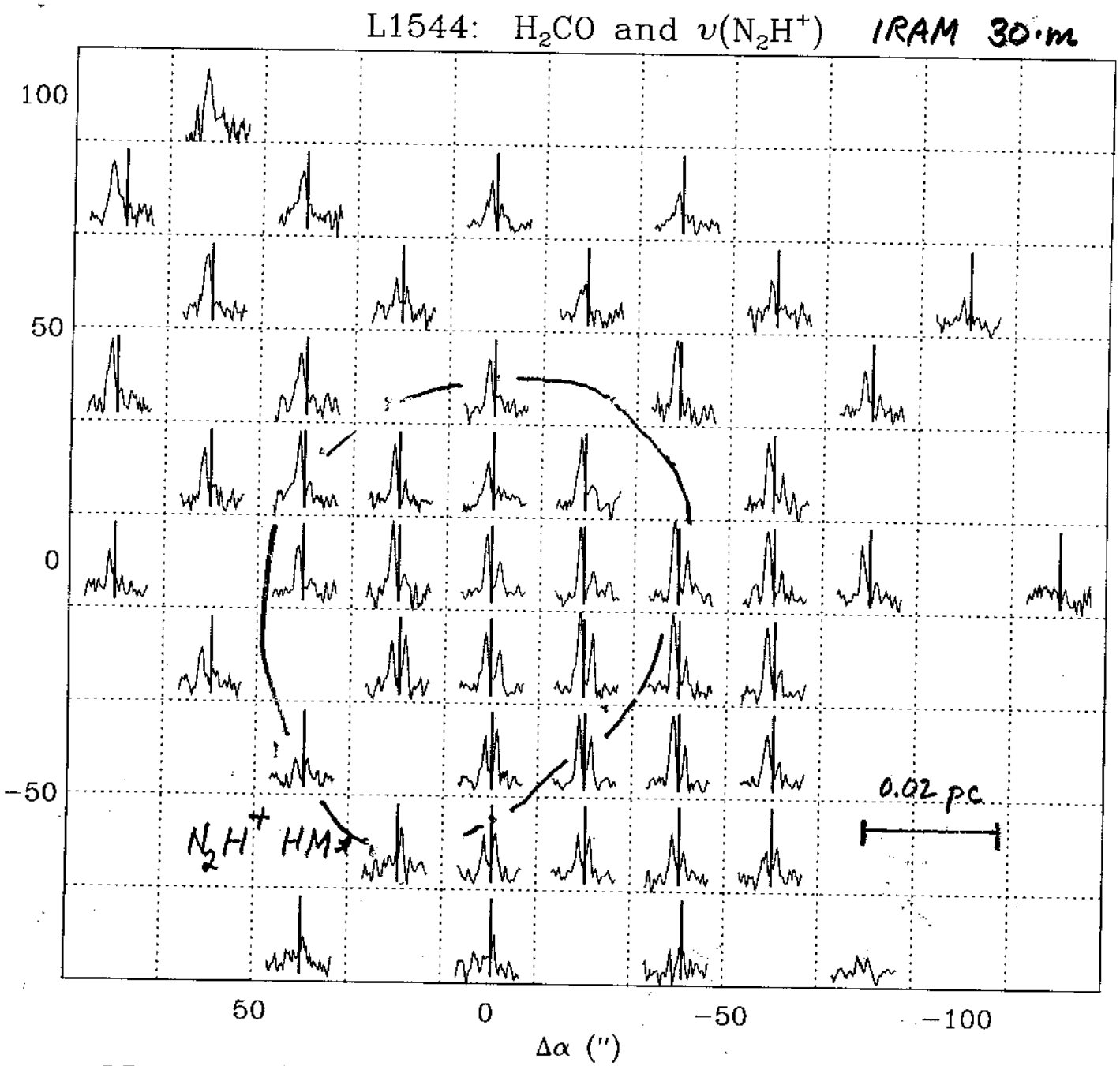
Caselli, Benson & Myers '96

- a 'starless' dense core in eastern Taurus
- dense part has no IRAS point source, no CO outflow
  no T Tauri star
  weak submm emission {André + '96 / Tafalla + '96}

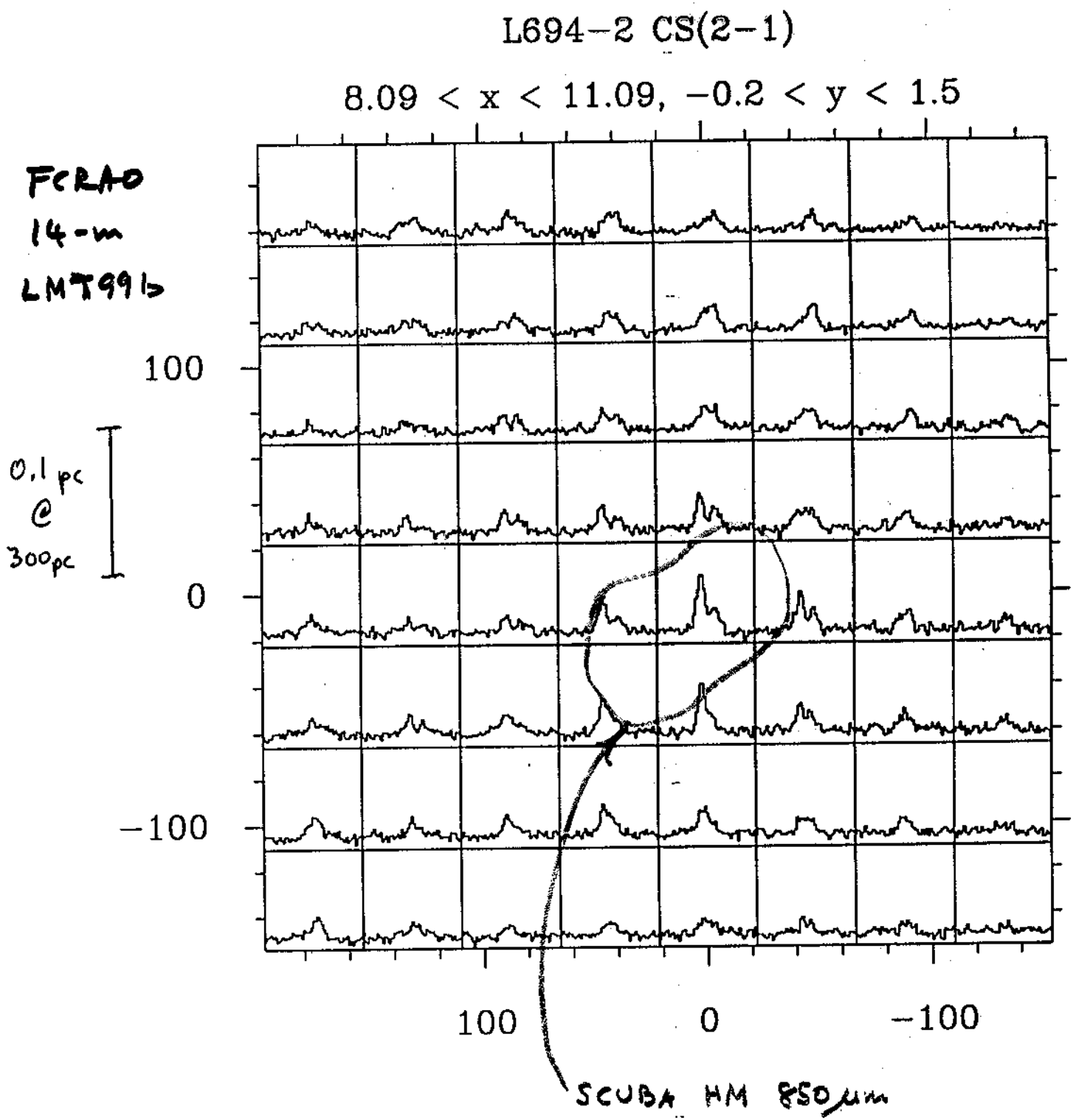
L1544 CS 2-1 FCRAO 14m



Tafalla et al '98



Tafalla et al '98


L694−2 CS(2−1)
8.09 < x < 11.09, −0.2 < y < 1.5
FCRAO
14-m
LMT99
100
0
−100
0.1 pc
@
300pc
100
0
−100
SCUBA HM 850μm

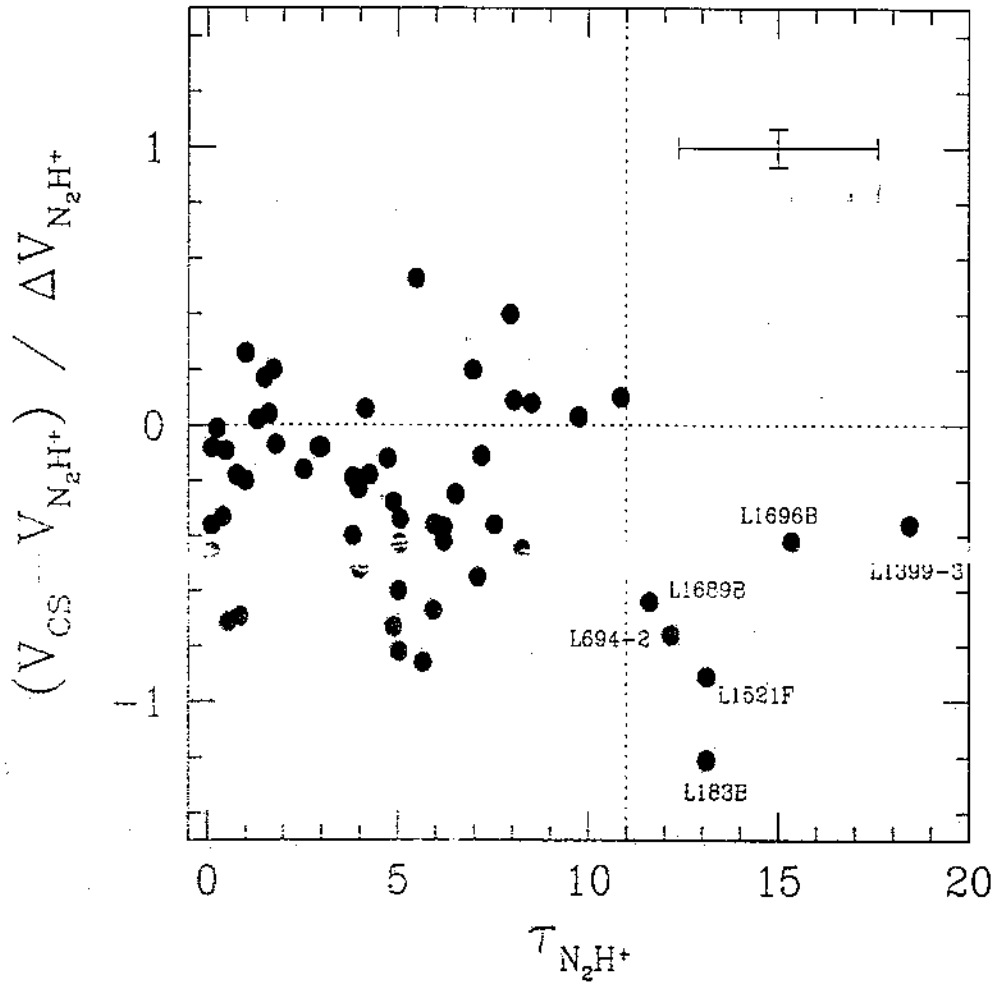


Fig. 7. — Dependence of δV_{CS} on the total optical depth ($\tau_{N_2H^+}$) of N_2H^+ (1–0) line. The 1σ error bars drawn in the Figure are the means of errors of $\tau_{N_2H^+}$ and δV_{CS}, respectively.

LMT 99a

10

Infall Asymmetry in Cluster-Forming Regions

how do cluster-forming regions form so many stars?

- much richer than Taurus and similar complexes
- spacing < 0.05 pc
- turbulent on scale > 0.1 pc
- quiescent condensations with "thermal" line widths, <0.02 pc

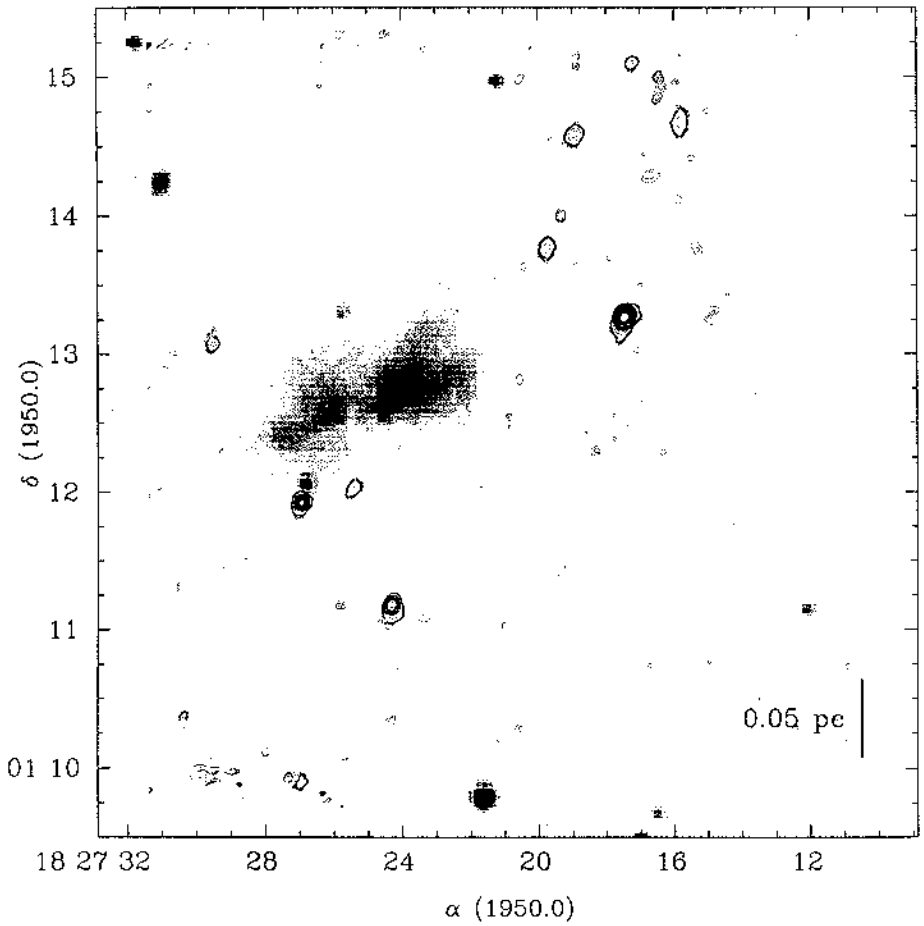
infall asymmetry

- extended over 0.2 pc in Serpens, NGC1333, L1251B (Mardones et al 99)
- complex pattern - smooth on large scale, patchy on small scale
- small-scale motions most pronounced onto starless cores (?)

example

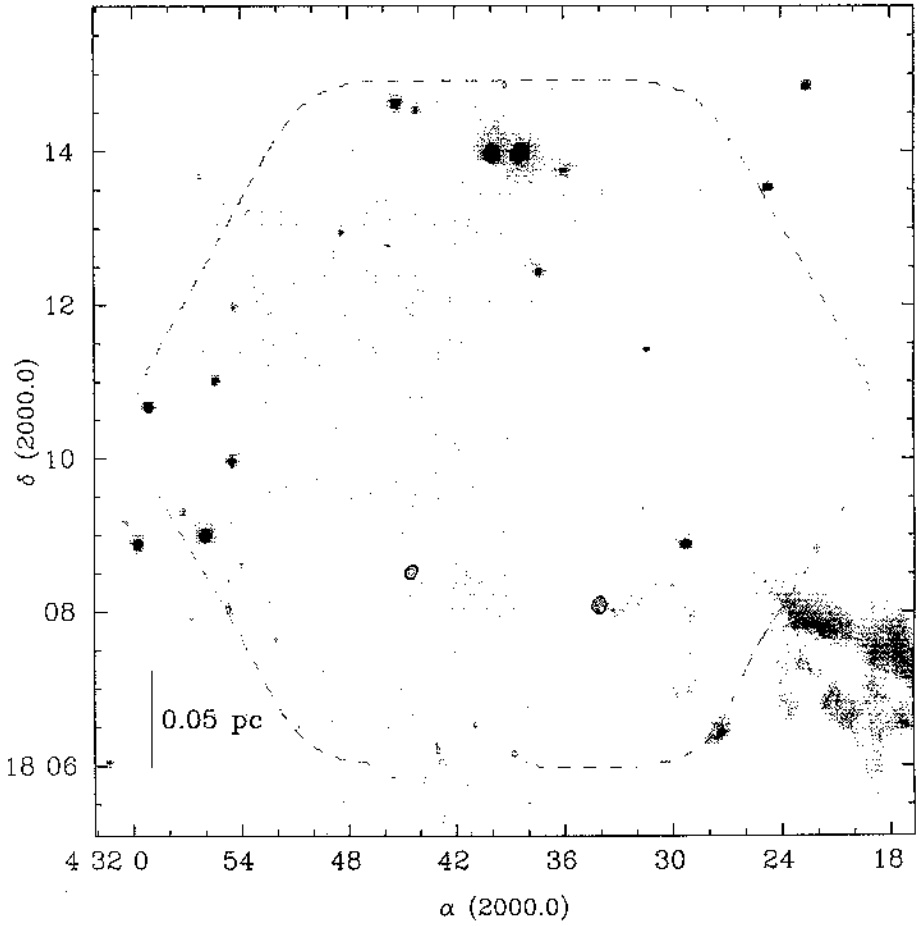
- Serpens FCRAO & BIMA data

Serpens region (50 OVRO pointings)

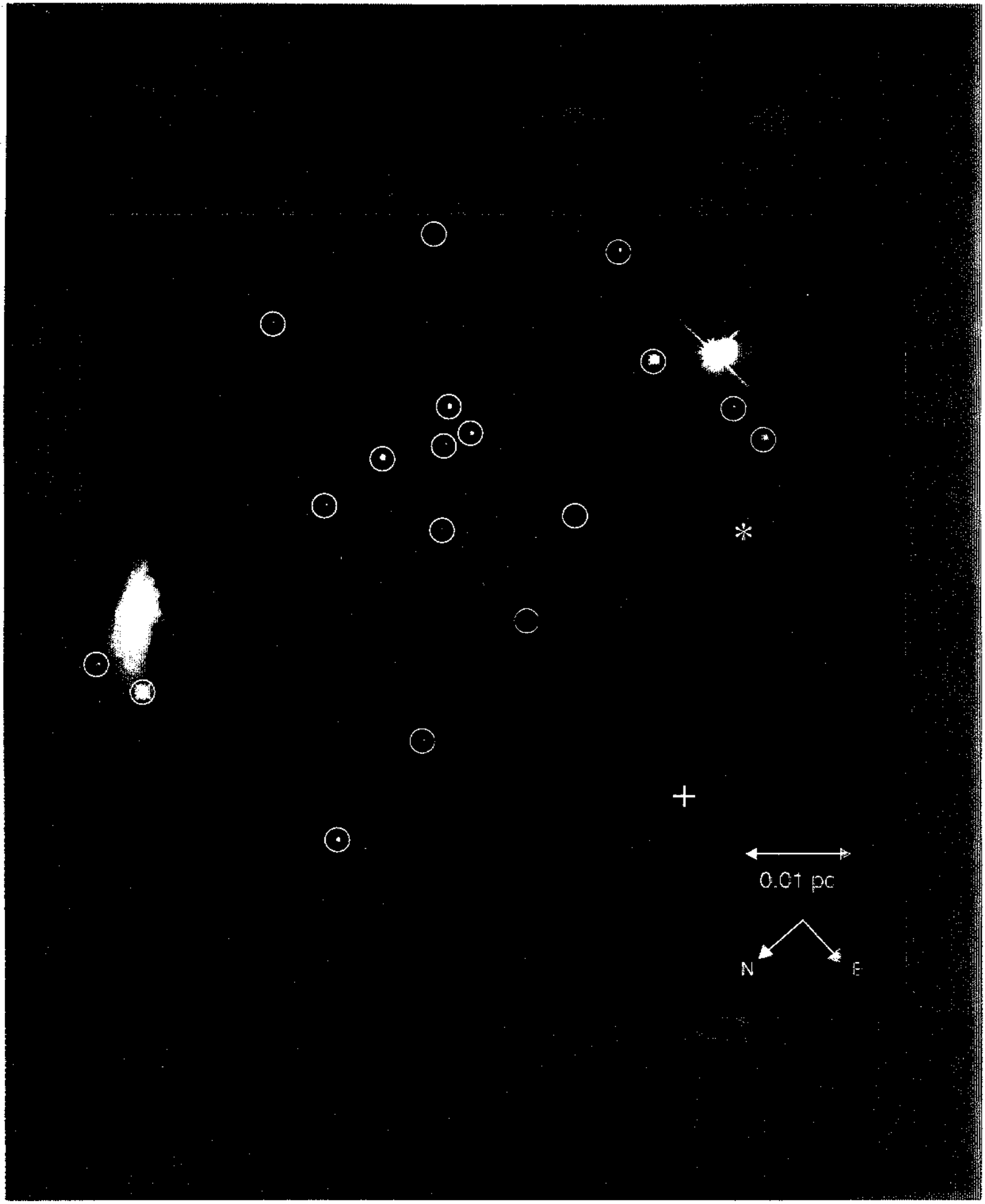


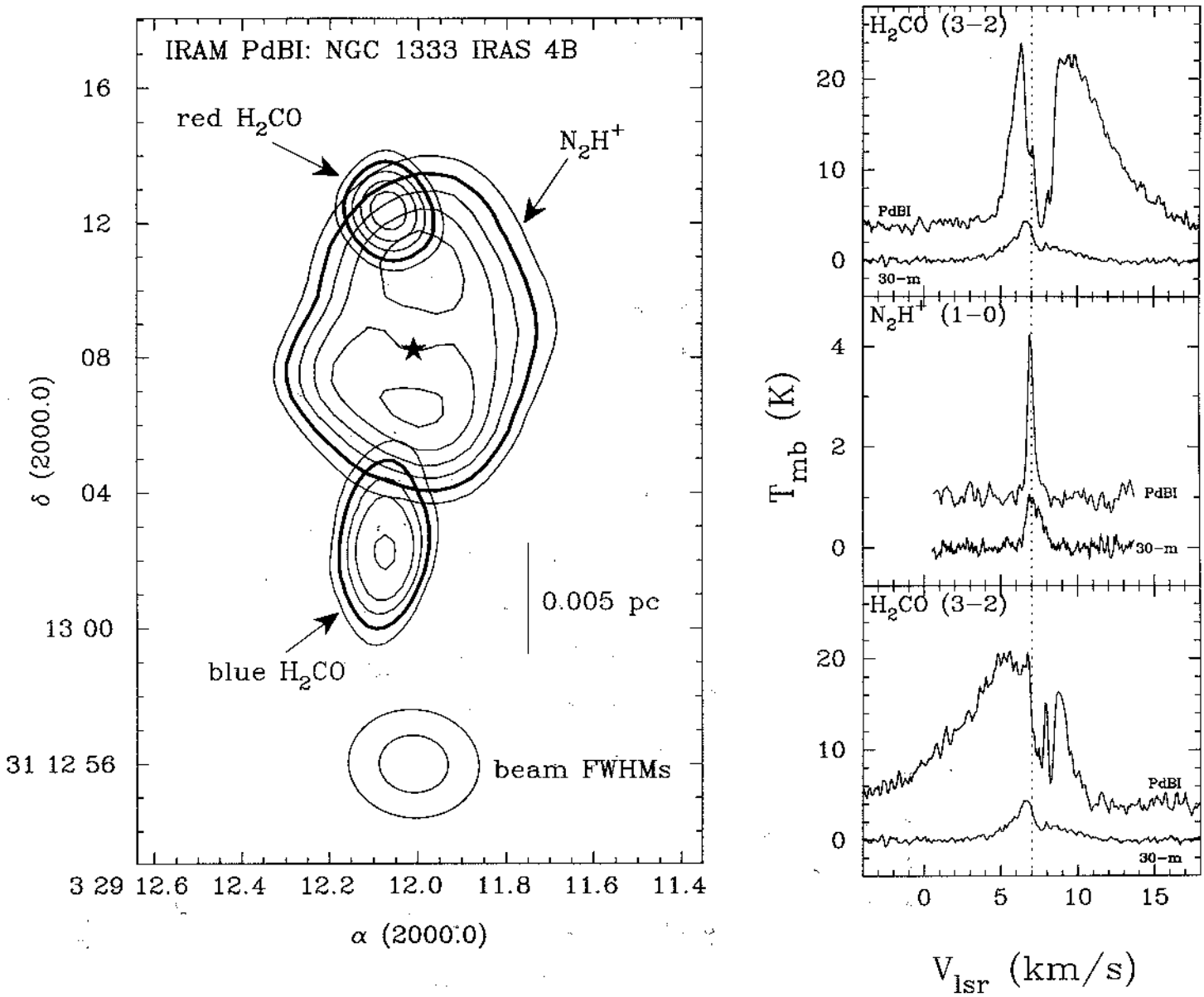
Testi & Sargent 98

L1551 region (61 BIMA pointings)

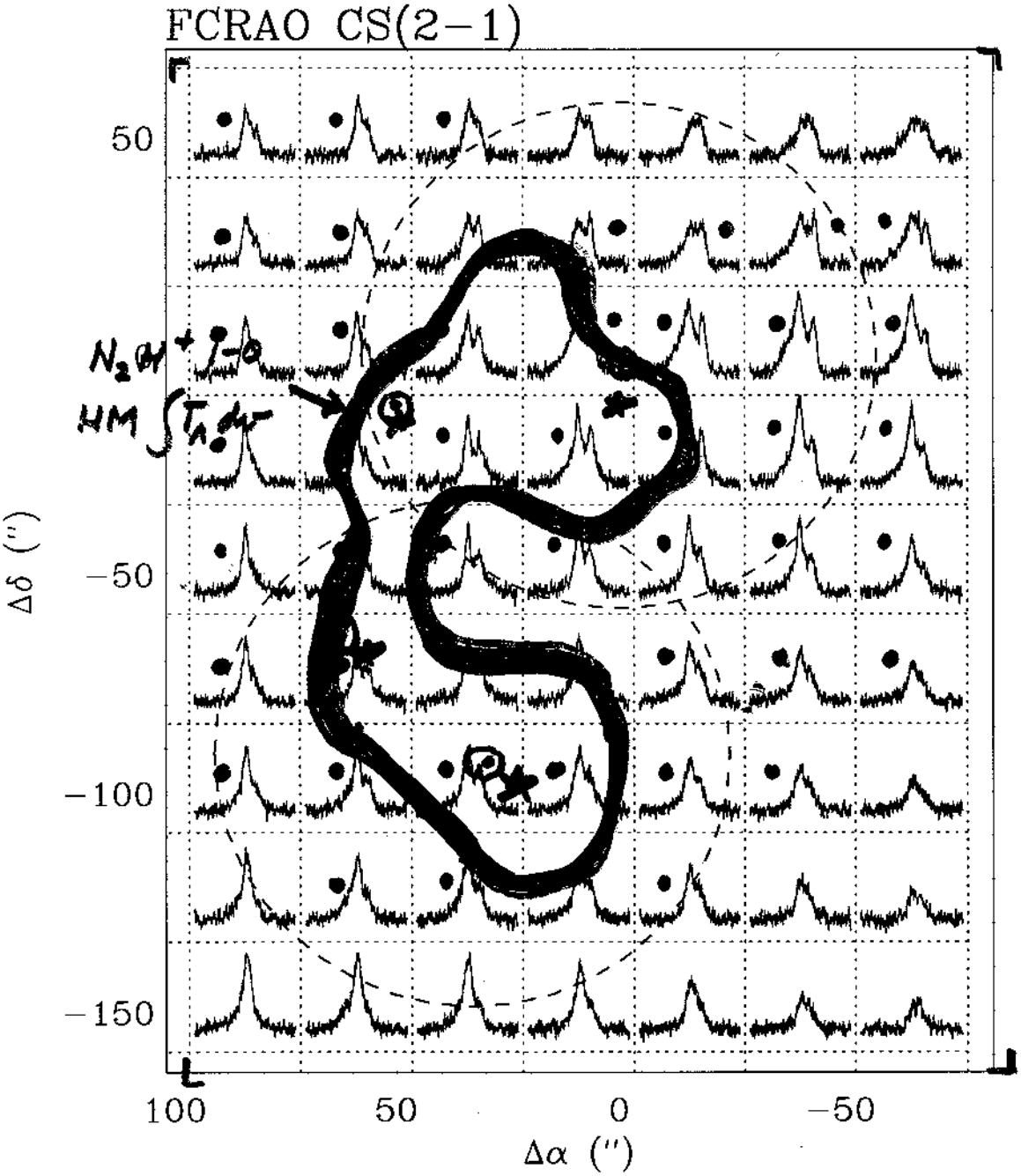


DiFrancesco, Hogerheidje, Myers, Williams & Wilner 99

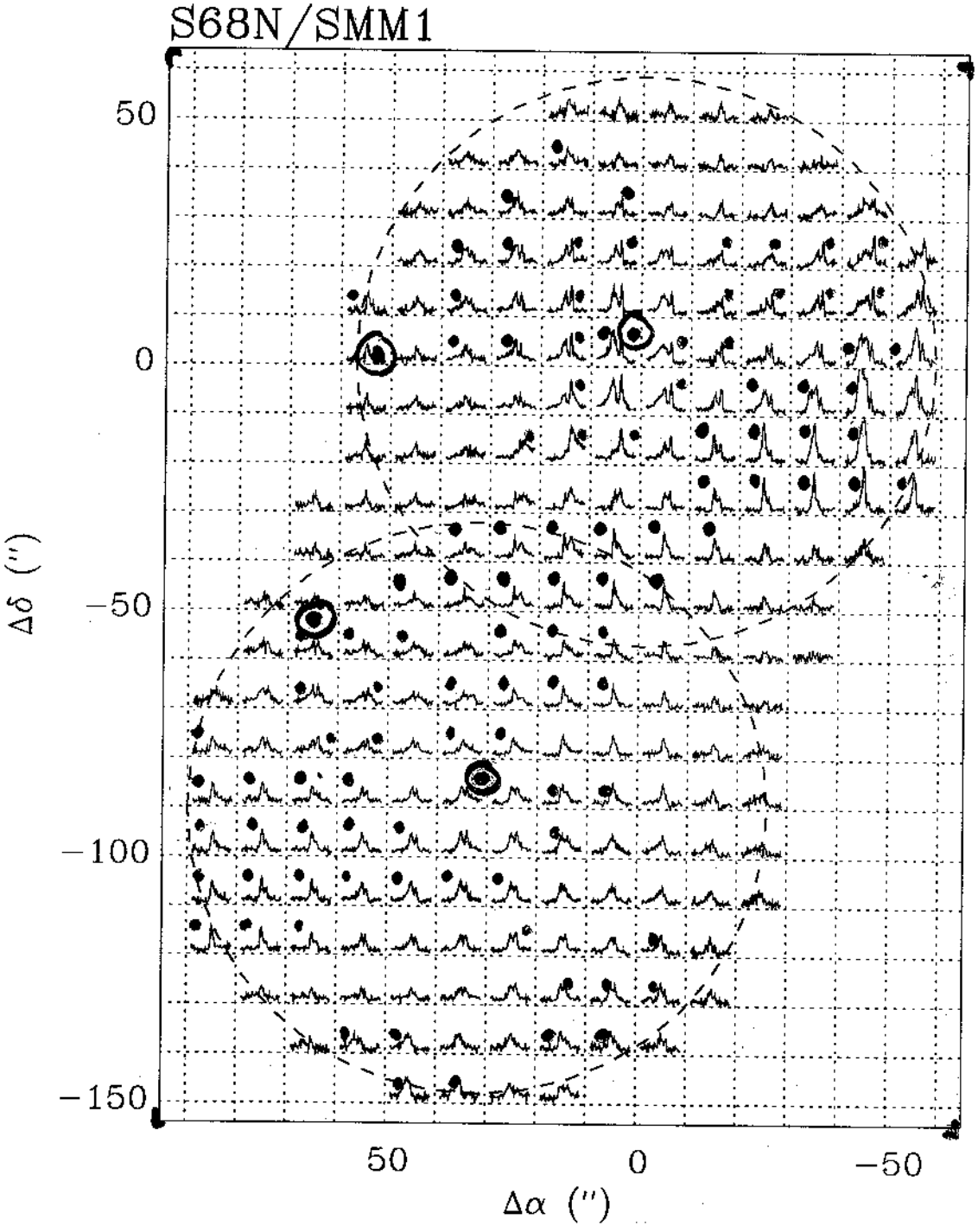

0.01 pc
N
E



Di Francesco, Myers, Wilner & Ohashi '99



infall asymmetry..
mainly blue
extends over >0.2 pc
extends beyond dense gas and young stars



BIMA+FCRAO CS(2−1)

V:−1.2 to 16.8 km/s
T:−1.0 to 7.5 K

infall asymmetry...
remains blue and extended
does not 'concentrate' on dense gas & young stars
is strongest in 2 cores strong in CS, weak in N_2H^+
- new cores?

Turbulent Cooling Flows

concept

- driven by pressure difference, not gravity
- like thermal instability (Elmegreen 89, Meerson et al 96) or flows in galaxy clusters (Cowie & Binney 77)
- molecular clouds are MHD - turbulent (Arons & Max 75)
- MHD turbulence dissipates due to shocks, ion-neutral friction (Nakano 98)
- local dissipation of turbulence->pressure difference -> inward flow (Myers & Khersonsky 95)

model

- inner and outer region with common T and v_A
- MHD waves incident from outside, no internal sources (starless proto-core)
- ion-neutral friction damps waves, allowing inward pressure along field

$$\rho_{in}(\sigma_T^2 + \sigma_{NT,in}^2) < \rho_{out}(\sigma_T^2 + \sigma_{NT,out}^2)$$

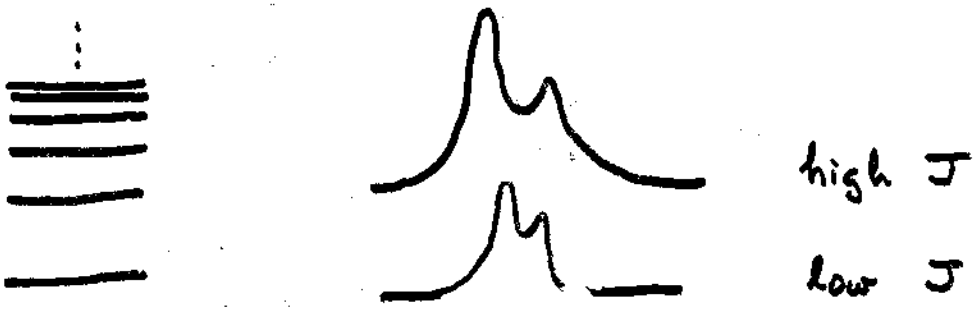
- flow continues until pressures equalize (or gravity takes over)
- likely site - transition from UV to CR ionization
- flow speed ~ 0.1 km s^{-1} as observed, faster than ambipolar diffusion

(Myers & Lazarian 98)

SOFIA Applications

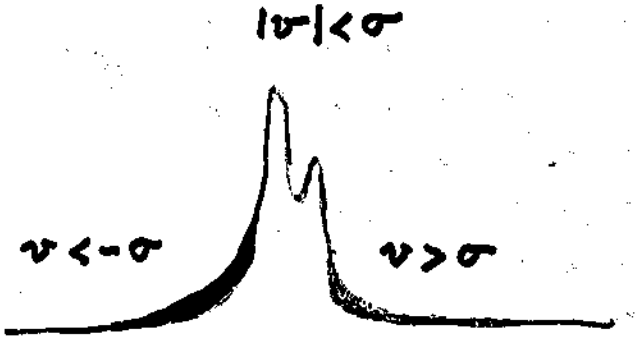
higher-excitation lines

higher rotational lines of CO, CS, HCO^+,...
to probe densities $n \approx 10^{5\text{-}7}$ cm^{-3} with GREAT, CASIMIR



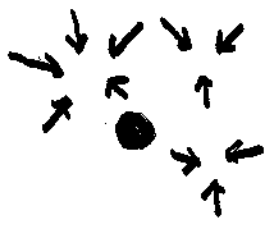
infall wings

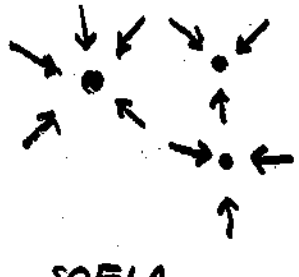
infall velocities $v > \sigma$ in starless cores (no confusing outflow)



resolving groups of FIR protostars

identifying centers of infall in groups and clusters





Extended Infall Asymmetry

properties

- $v \gtrsim 0.1$ km s^{-1}, $R \gtrsim 0.1$ pc, no simple "acceleration"
- no dominant "center," some reversals
- extends into gas with $n < 10^4$ cm^{-3} and with no protostars

questions

- core formation or star formation ?
- motion onto a point or a sheet?
- driving by gravity or pressure?
- are we missing higher-velocity motions?
- does higher-density gas have different infall asymmetry?
  (less extended, more organized, more concentrated onto center(s))