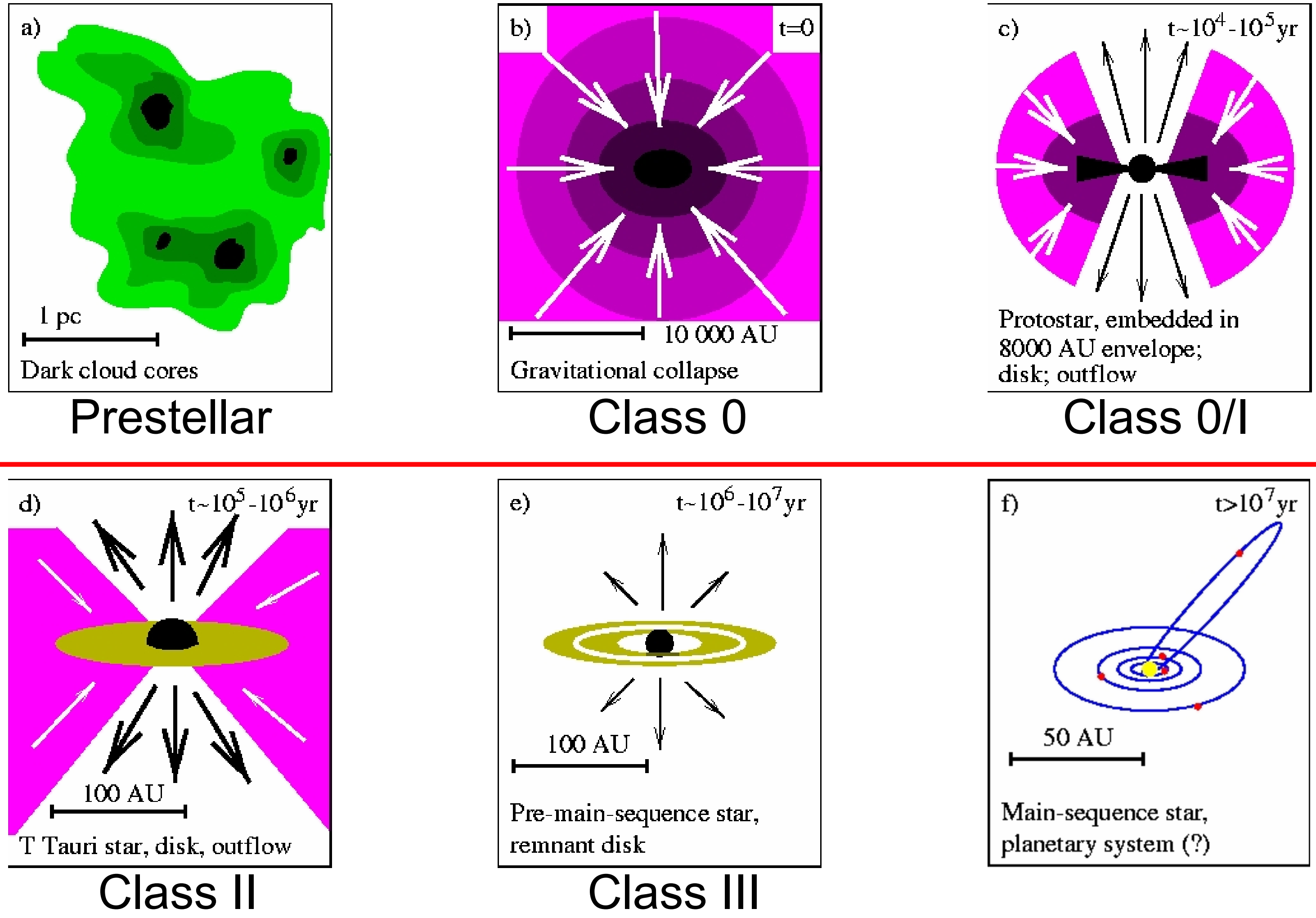
Low Mass Star Formation Studies with the Submillimeter Array

Tyler Bourke
Harvard-Smithsonian Center for Astrophysics

on behalf of everyone doing great
low mass star formation science

Phases of Low Mass Star Formation



(Shu et al. 1987 ARAA; Lada 1987 IAU Symp 115; Hogerheijde 1998)

SMA advantages for Low Mass Star Formation Studies

High spatial resolution in high J lines coupled with high spectral resolution and large bandwidth

- separation of disk from envelopes
- kinematics of inner envelopes and DISKS
  (see also Wilner presentation)
- complex molecules (incl. organics)
- origin of hot corinos (disks, shocks)
- structure of prestellar cores
- clusters – resolve components
- outflows (presentation by Hirano)
- resolved dust polarimetry (presentation by Rao)

Protostellar Submillimeter Array Campaign (PROSAC)

Survey 9 Class 0 protostars in many lines and continuum (230/345 GHz)

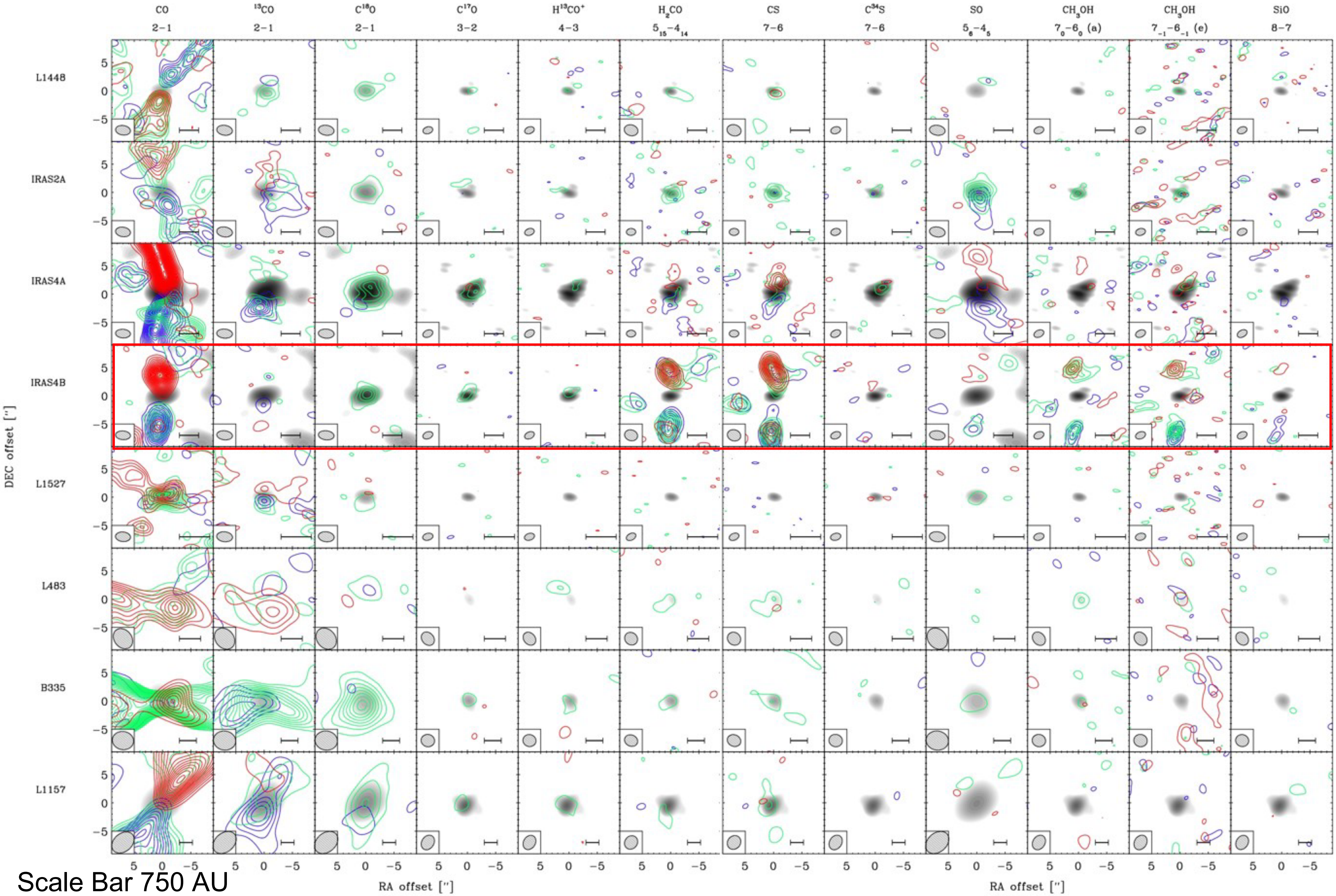
Nearby (< 350 pc), previously surveyed with single-dish telescopes (> 1500-2000 AU scales) and millimeter wavelength interferometers (500-1000 AU scales).

Envelope large scale physical (temperature and density; $T(r)$ and $n(r)$) and chemical structures (abundances; $X_i(r)$) established on basis of detailed dust and line radiative transfer modeling (*Jørgensen et al. 2002, 2004, 2005a*). Important as reference and for addressing missing short-spacings.

Sources: NGC1333-IRAS2, -IRAS4A, -IRAS4B
L1448-C, L1527, L483, B335, L1157 IRAS16293-2422 (for comparison)

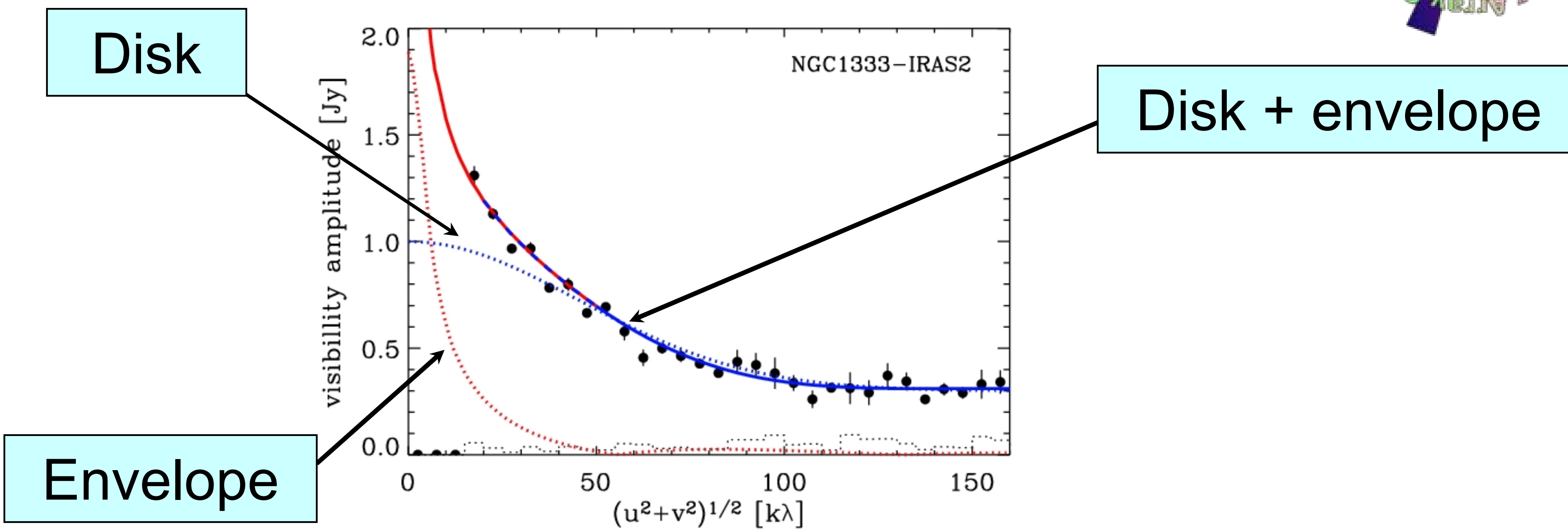
Lines (examples):
CO, ^{13}CO, $C^{18}O$ 2-1, $C^{17}O$ 3-2, $H^{13}CO^+$ 4-3,
CS, $C^{34}S$ 7-6, H_2CO 5_{15}-4_{14}, CH_3OH 7_K-6_K, SiO 8-7
trans. of SO, SO_2, various organic molecules and more

J□ørgensen et al. 2005 ApJ, 632, 973 (IRAS2), 2007 ApJ, 659, 479 (Basic Results)



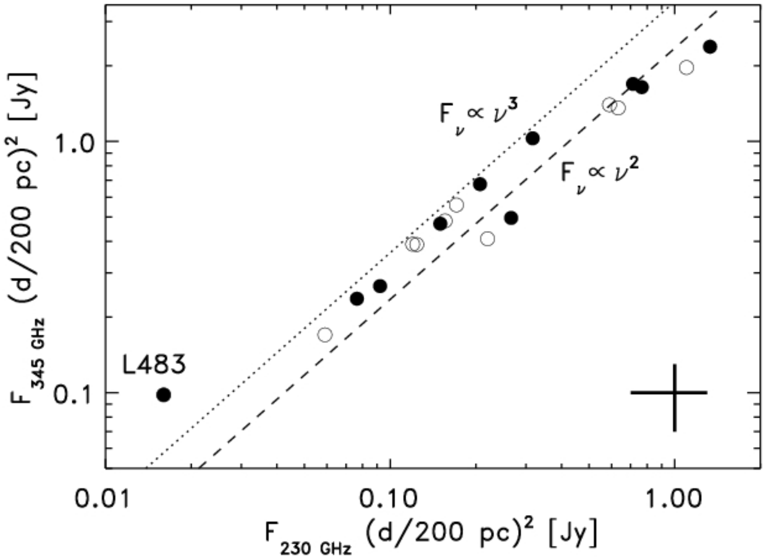
Scale Bar 750 AU

Disk and envelope continuum emission



Continuum emission at 350 GHz toward a Class 0 protostar, NGC1333-IRAS2A, plotted as visibility amplitude as function of projected baseline length. The emission is well-reproduced with a model including the extended envelope and a 300 AU circumstellar disk of mass a few x 0.01 – 0.1 $M_{\odot}$

Disk and envelope continuum emission



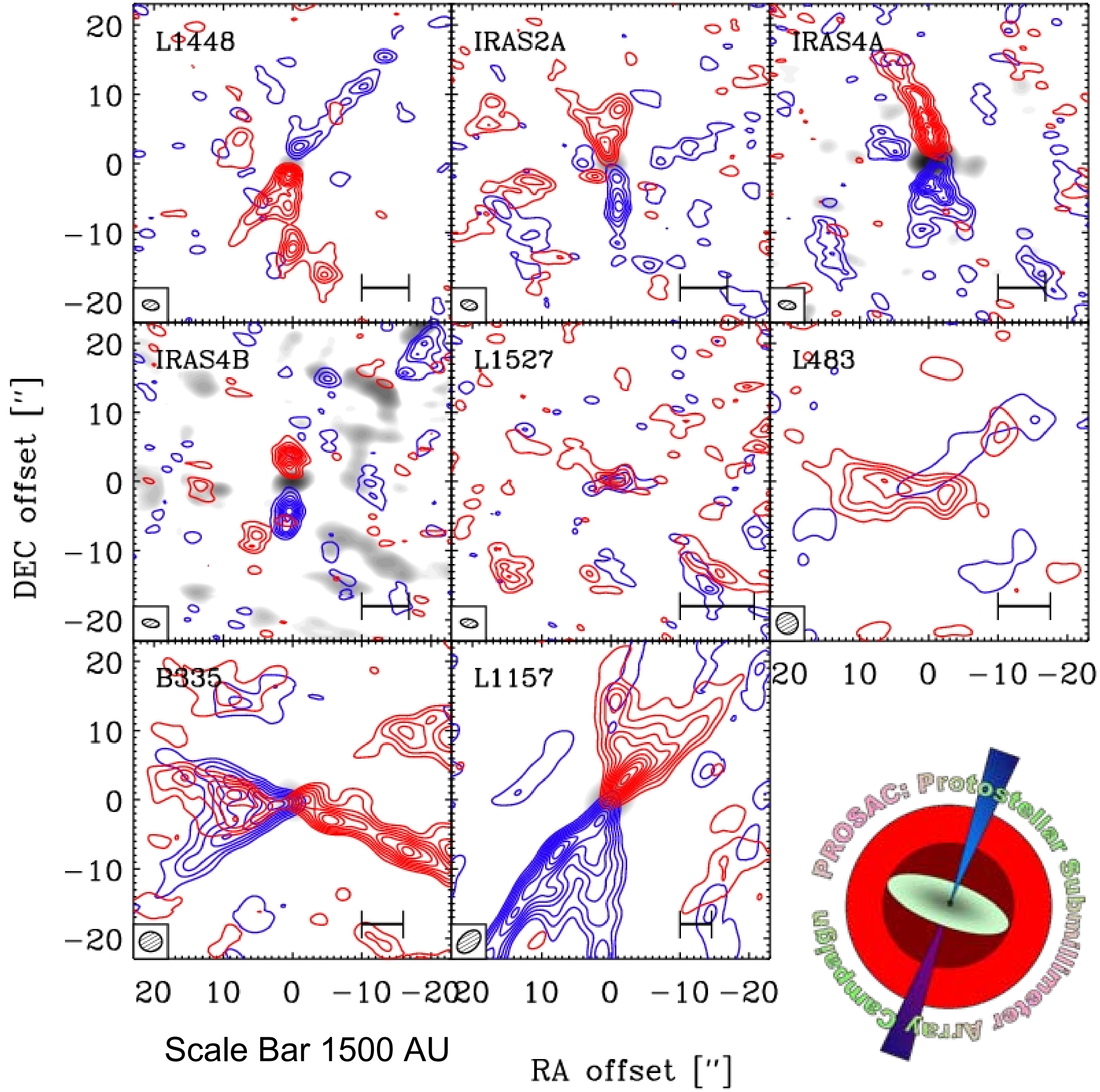
open circles - actual data
solid circles - normalized to 200 pc

Comparison of point source fluxes at 0.8 and 1.3 mm obtained from fits to baselines longer than 40 kλ (30-50 m) corresponding to material on scales smaller than about 5". The spectral indices of the continuum emission between 230 and 345 GHz suggest a dust opacity law, $\kappa_\nu \propto \nu^\beta$, with $\beta \sim 1$ – and supports the interpretation that the continuum emission has its origin in the circumstellar disks rather than the protostellar envelope. The large variations in continuum fluxes likely reflects the variations in the physical properties of the disks.

Outflows

The outflows are found to be very well collimated down to arcsecond scales underscoring the young ages of the driving sources.

The sources with the least collimated outflows are also those with the lowest disk-to-envelope mass ratios - perhaps suggesting that these sources are close to the end of their main accretion phases and the remainder of their envelopes will be dispersed by the outflows (e.g. L1527, L483).



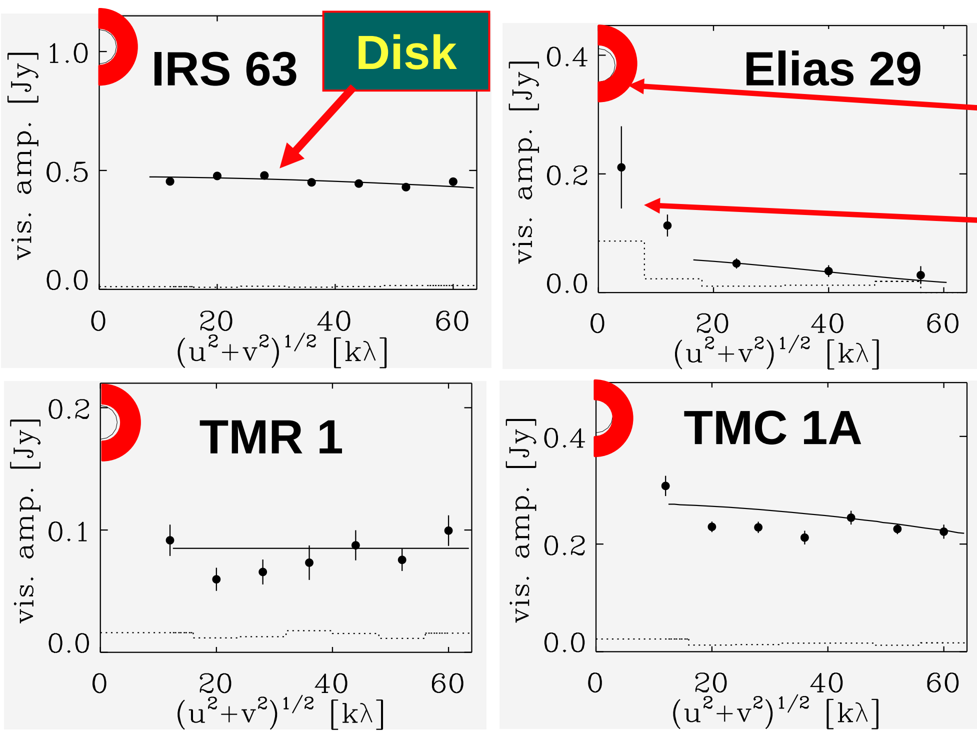
Survey(s) of Class I Protostars

Continuum and HCO^+ 3-2 (267 GHz)

Separate Disk from Envelope in (u,v) space

Disk masses (continuum) and stellar masses (kinematics)

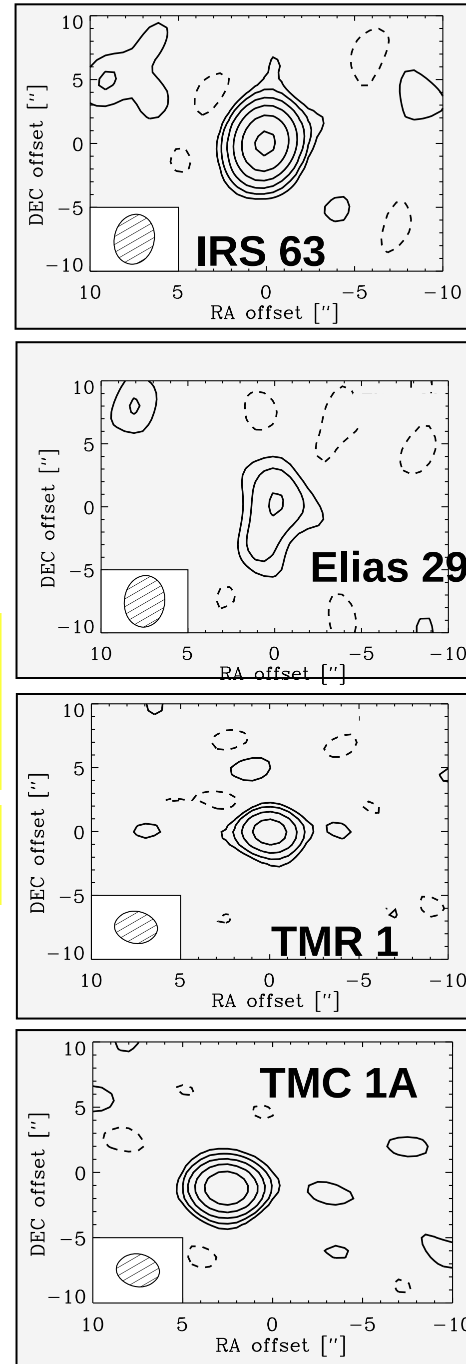
Lommen et al submitted and in prep



Total flux: disk + envelope + environment from SD

Envelope contribution?

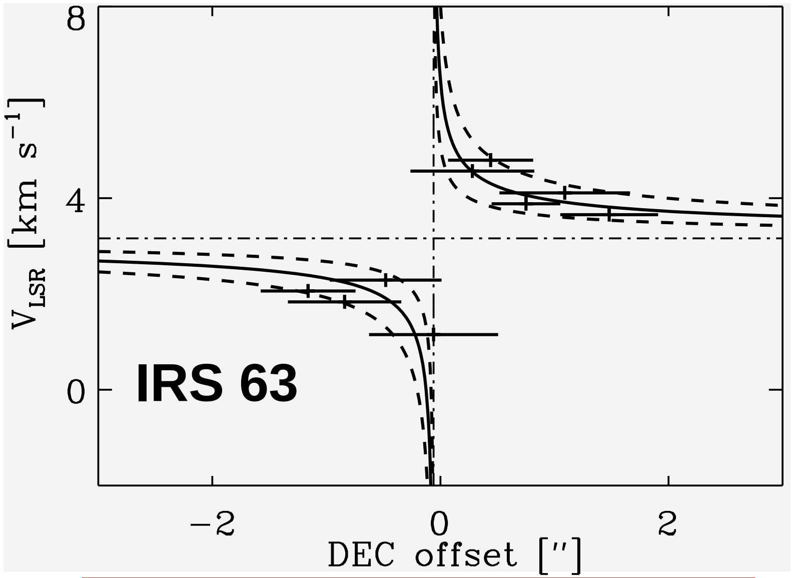
1.1 mm

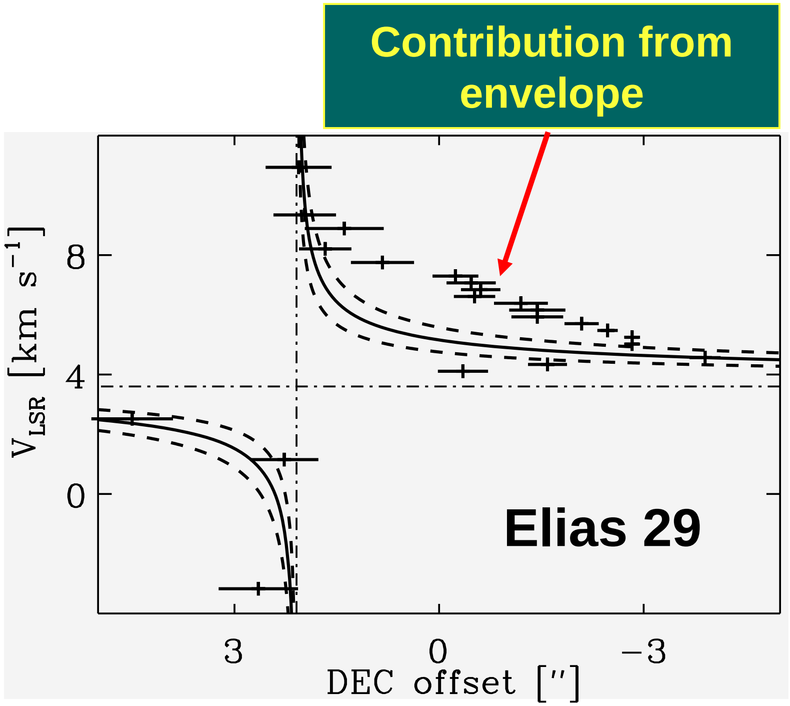


Survey(s) of Class I Protostars

HCO^+ 3-2 seems to be a good disk tracer in many Class I sources (Lommen et al, Covey et al, Launhardt et al) >> HCO^+ 4-3 will be popular

Target southern sources (Lupus, CrA, B59, isolated) – SMA advantage, different environments (Covey et al)





M_{star} = 1.4 $M_\odot$ (i = 15°)

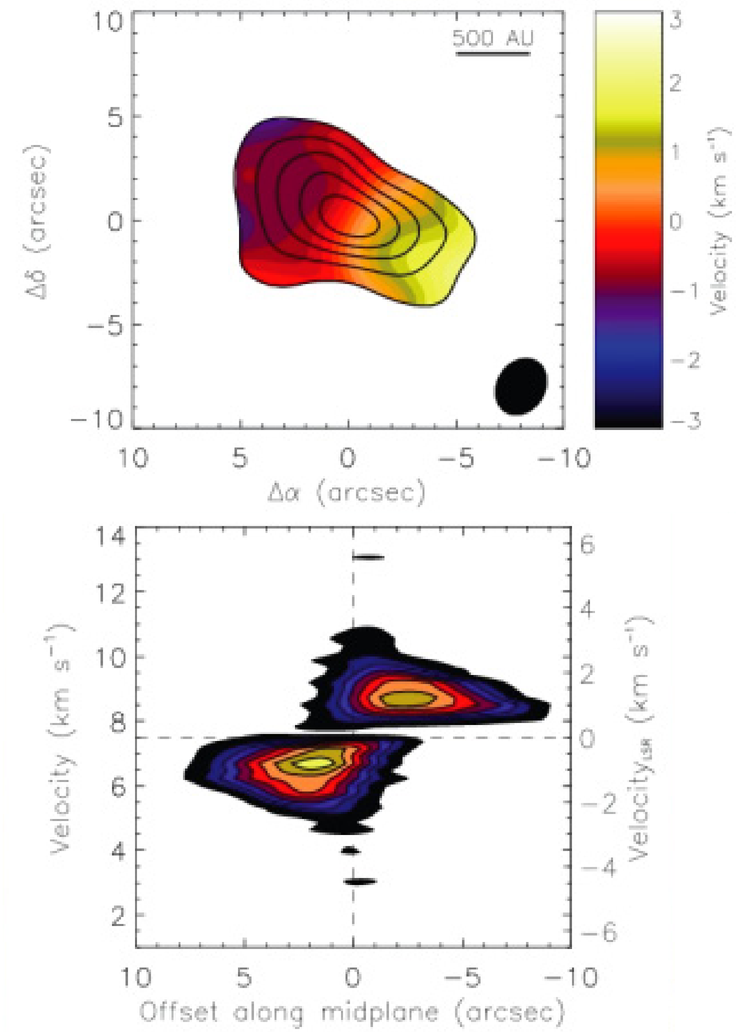
M_{star} = 2.5 $M_\odot$ (i = 30°)

Lommen et al submitted and in prep

Kinematically separating Disk and Envelope Emission in Protostars

L1489-IRS

- Class I YSO (3.7 $L_{\odot}$) in Taurus.
- Large scale infalling and rotating envelope constrained by single-dish observations and 2D radiative transfer *(Brinch et al. 2007).*
- Mapped in HCO^+ J = 3-2 and continuum at arcsecond resolution with the SMA.
- Central disk added to envelope model and modeled self-consistently. Keplerian motions allow mass of star to be measured.



Brinch et al. submitted

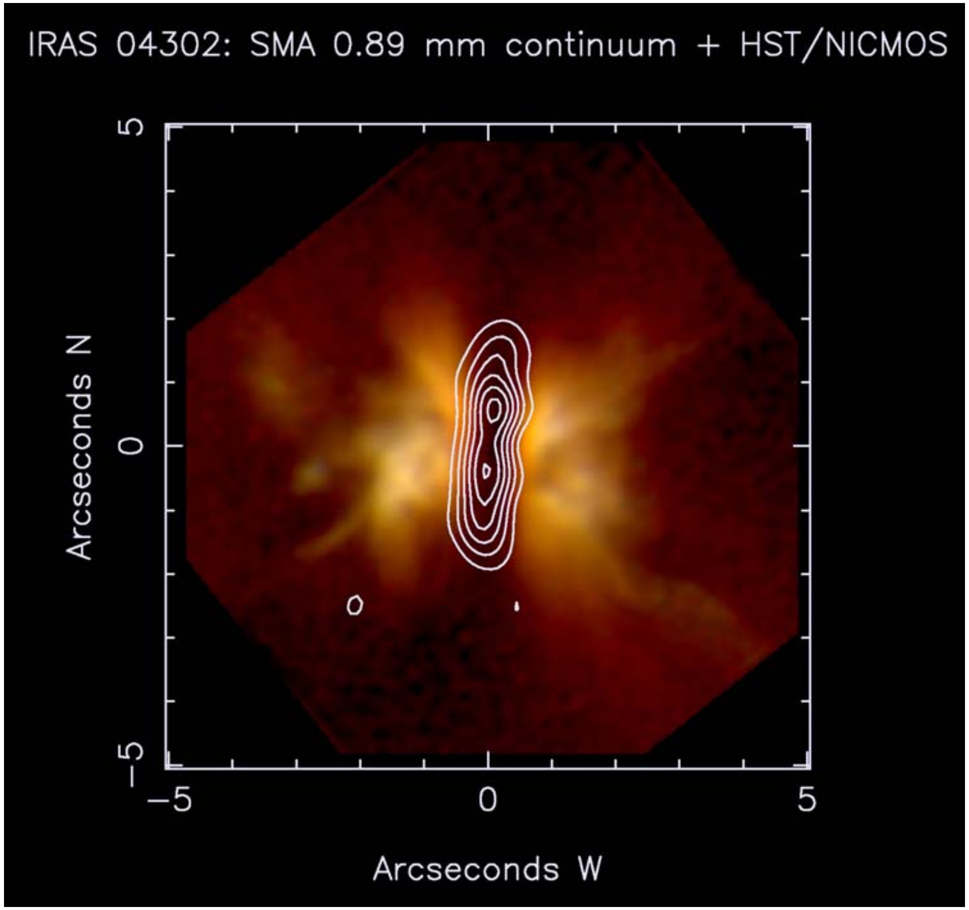
IRAS 04302+2247 aka the Butterfly Star

Class I in Taurus (0.4 $L_\odot$)
Edge on system

Initial model based on low resolution mm imaging (Wolf et al 2003)

SMA provides information on the radial + *vertical* disk structure at 100 AU scale (planet forming region)

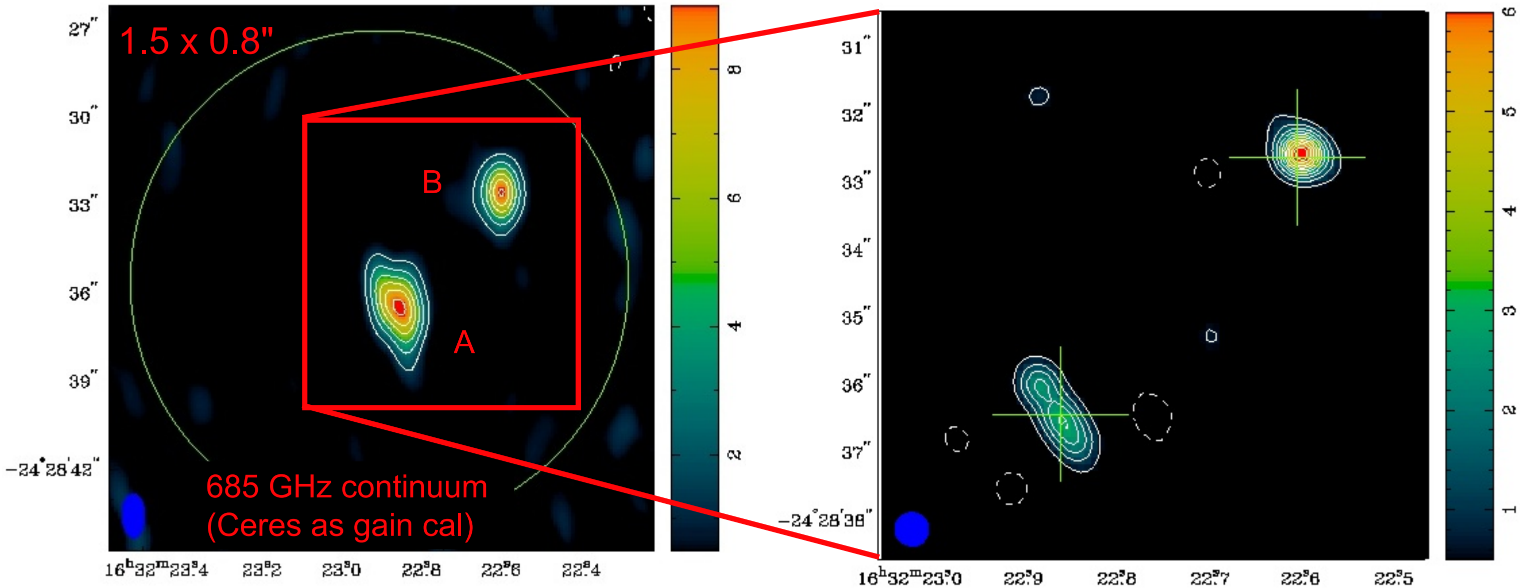
Depression due to optical depth effects (comparison to model)



Wolf et al submitted

IRAS 16293-2422 (125 pc)

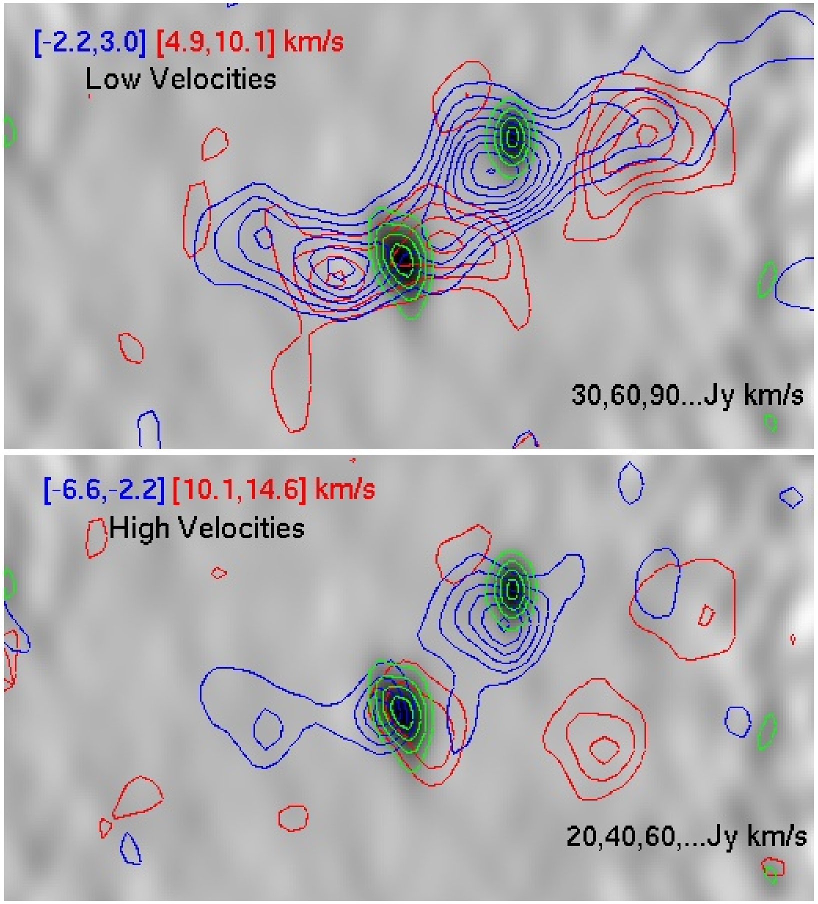
Detailed multitransition study of a well resolved protobinary (separation 625 AU) in the 230, 345 and 690 GHz

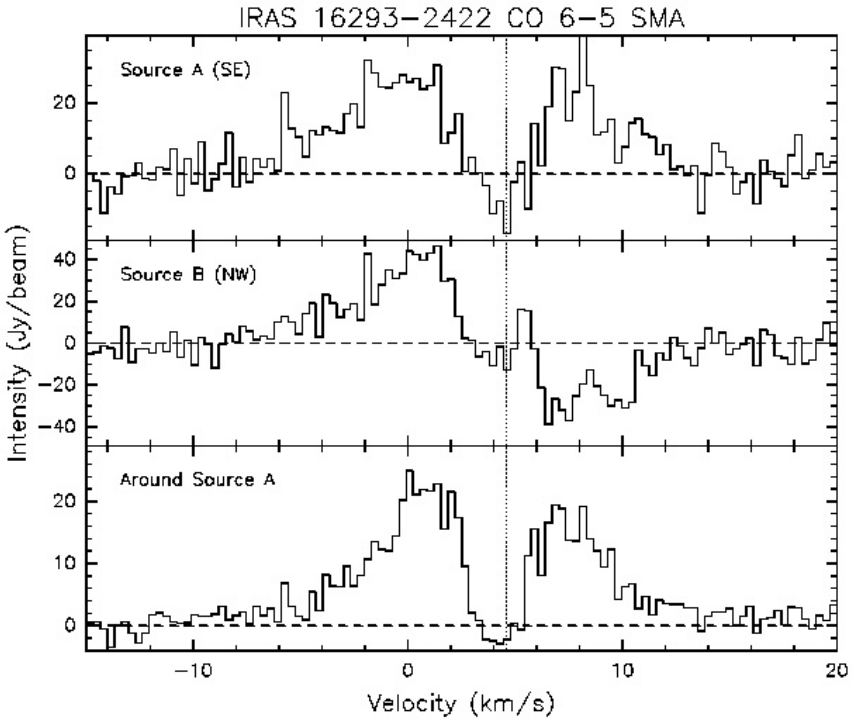


Continuum:
Both sources almost equally bright in all bands (peak).

B is point-like, and A is resolved into 2, separation ~ 0.5"
(Rodriguez et al '05, Chandler et al '05 – SMA)

^{12}CO 6-5





Red-shifted absorption at Source B

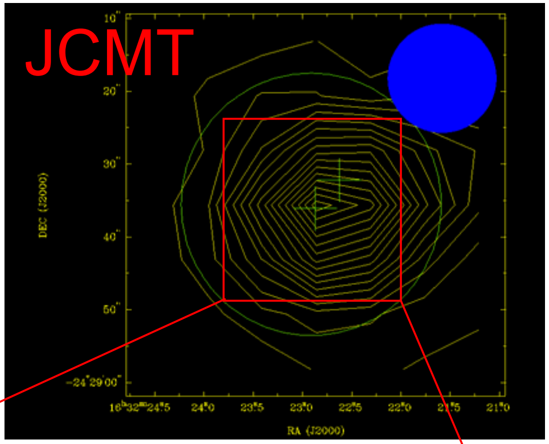
High velocity gas at Source A, in agreement with CO 2-1 and 3-2 (SMA – Yeh et al 2007)

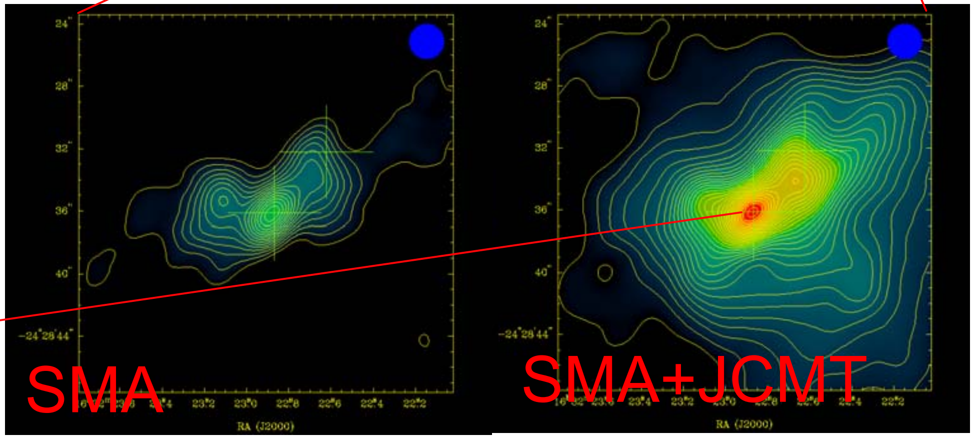
Kinematics

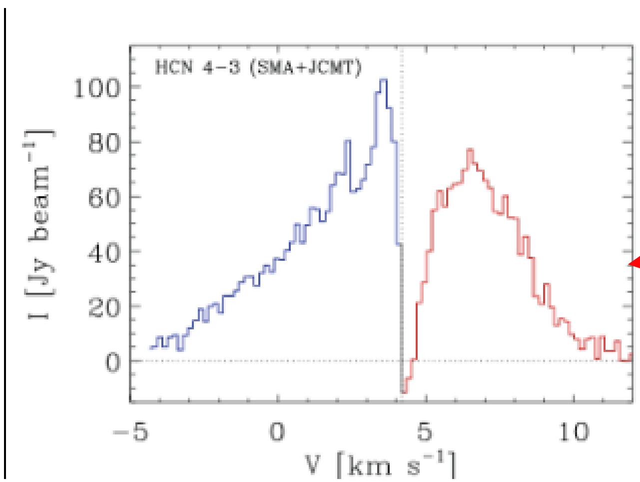
HCN 4-3, JCMT+SMA
(Takakuwa et al 2007)

Mix of outflow and infall motions from A. Compact component (500 AU) shows infall+rotation (HCN + $HC^{15}N$)

B is not a peak. $HC^{15}N$ is narrow and compact



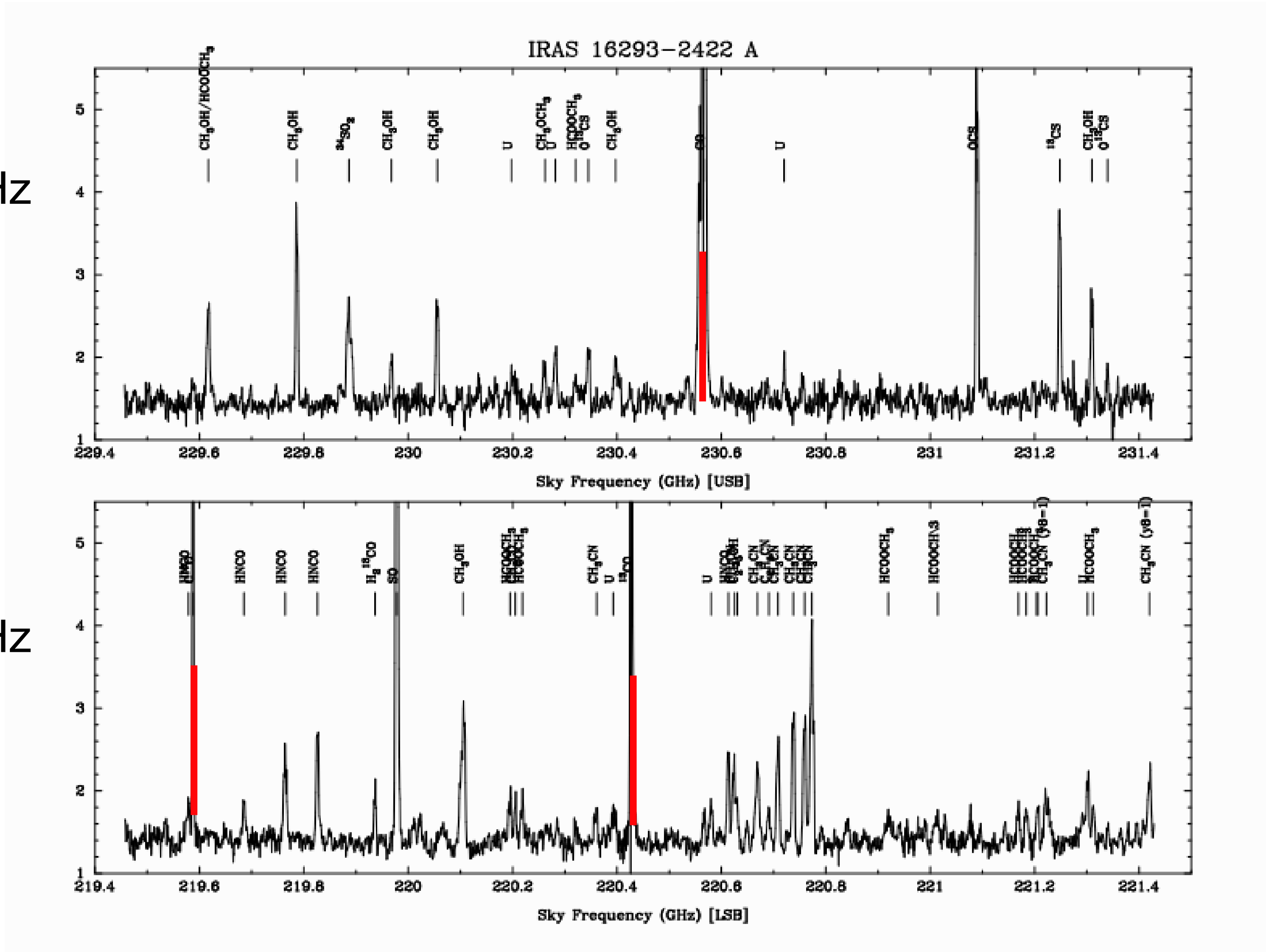




Many lines in all bands – lots of work ahead

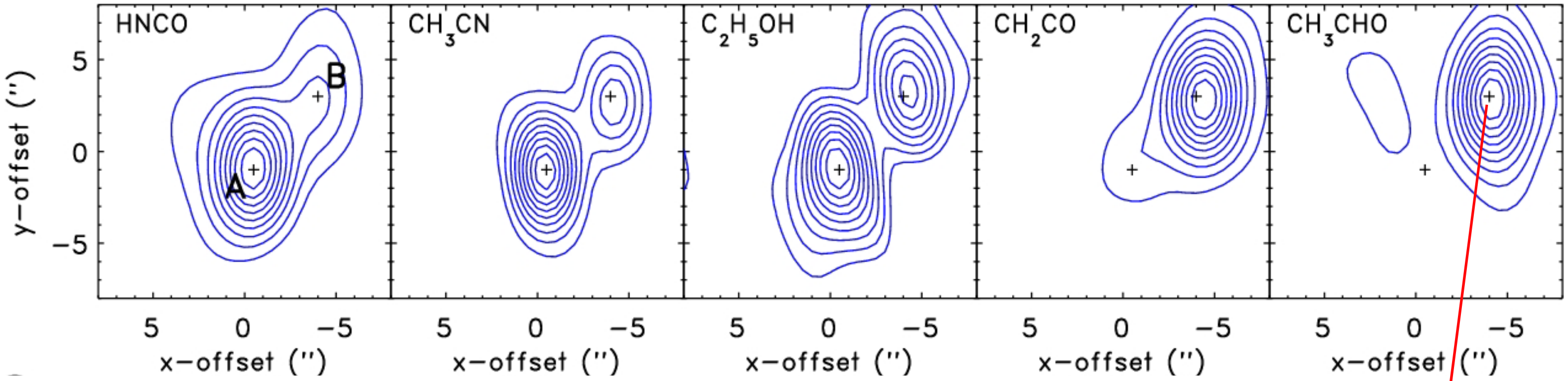
229-231 GHz

219-221 GHz

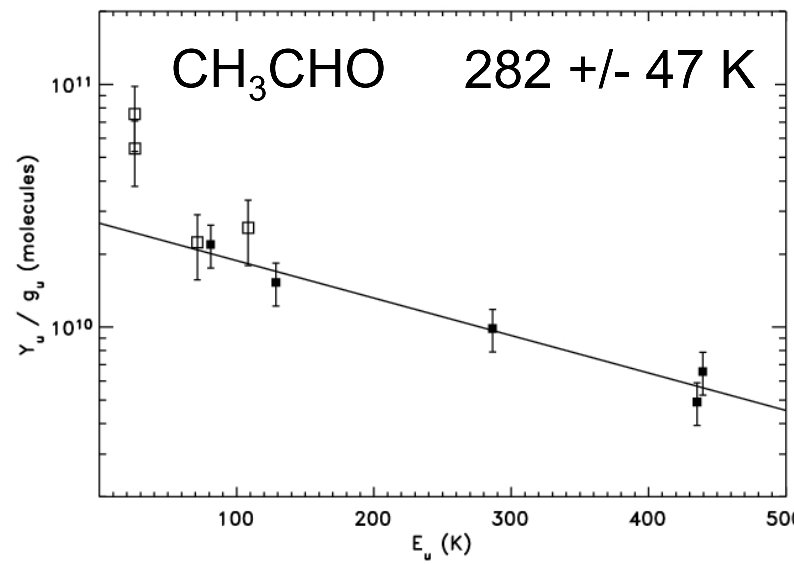


Complex organic molecules

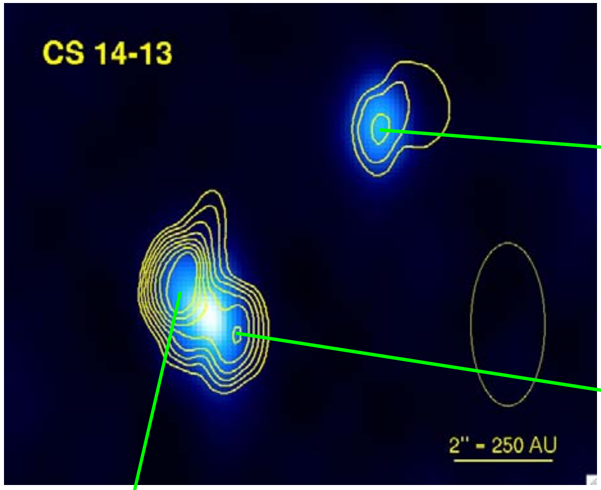
Bisschop et al. Ph.D. and in prep.

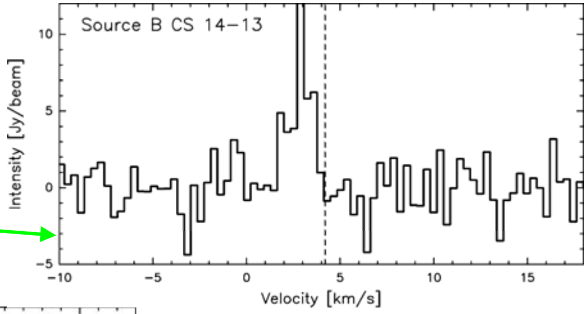


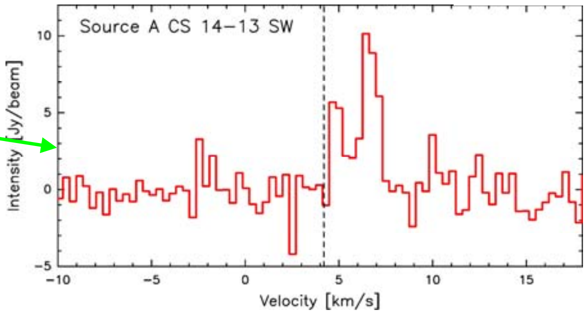
- Compact emission and strong chemical differentiation (see also Kuan et al. 2004). Source independent rotation temperatures - indicate similar excitation conditions in these very different sources.
- Spatial behavior for CH_2CO, CH_3CHO and C_2H_5OH argue against standard scenario for their formation (successive hydrogenation).
- Most likely solid-state formation followed by evaporation

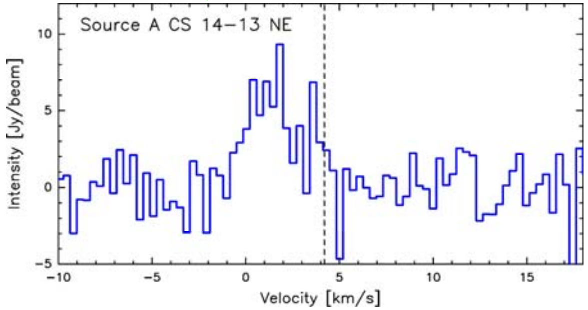


High excitation lines in the 690 GHz window (Many methanol lines…)

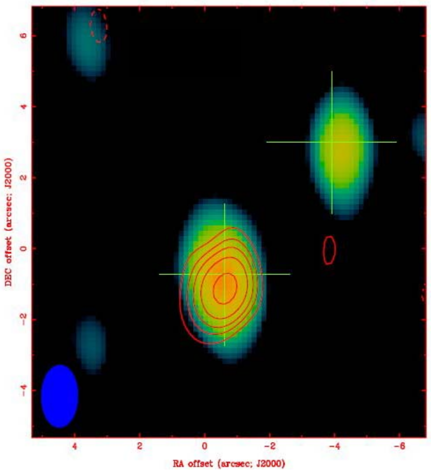




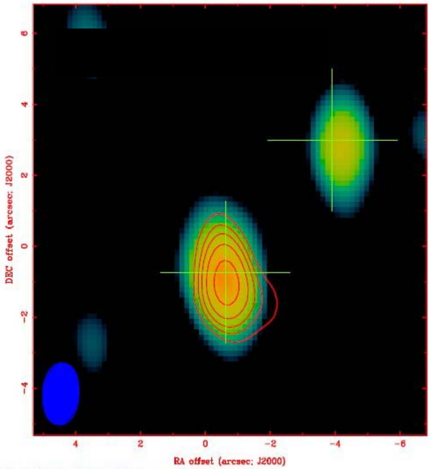




$H^{13}CN$ 8-7 690552 MHz



CH_3OH v=1 $3_{-2,1}$-$4_{-3,1}$
681789 MHz



Very Low Luminosity Objects (VeLLOs)

$L \leq 0.1\ L_\odot$
Embedded

Very young protstars?
Proto-brown dwarfs?
Embedded, or background (AGN..)

Lack of continuum argues against edge on systems (L1014, L1521F)

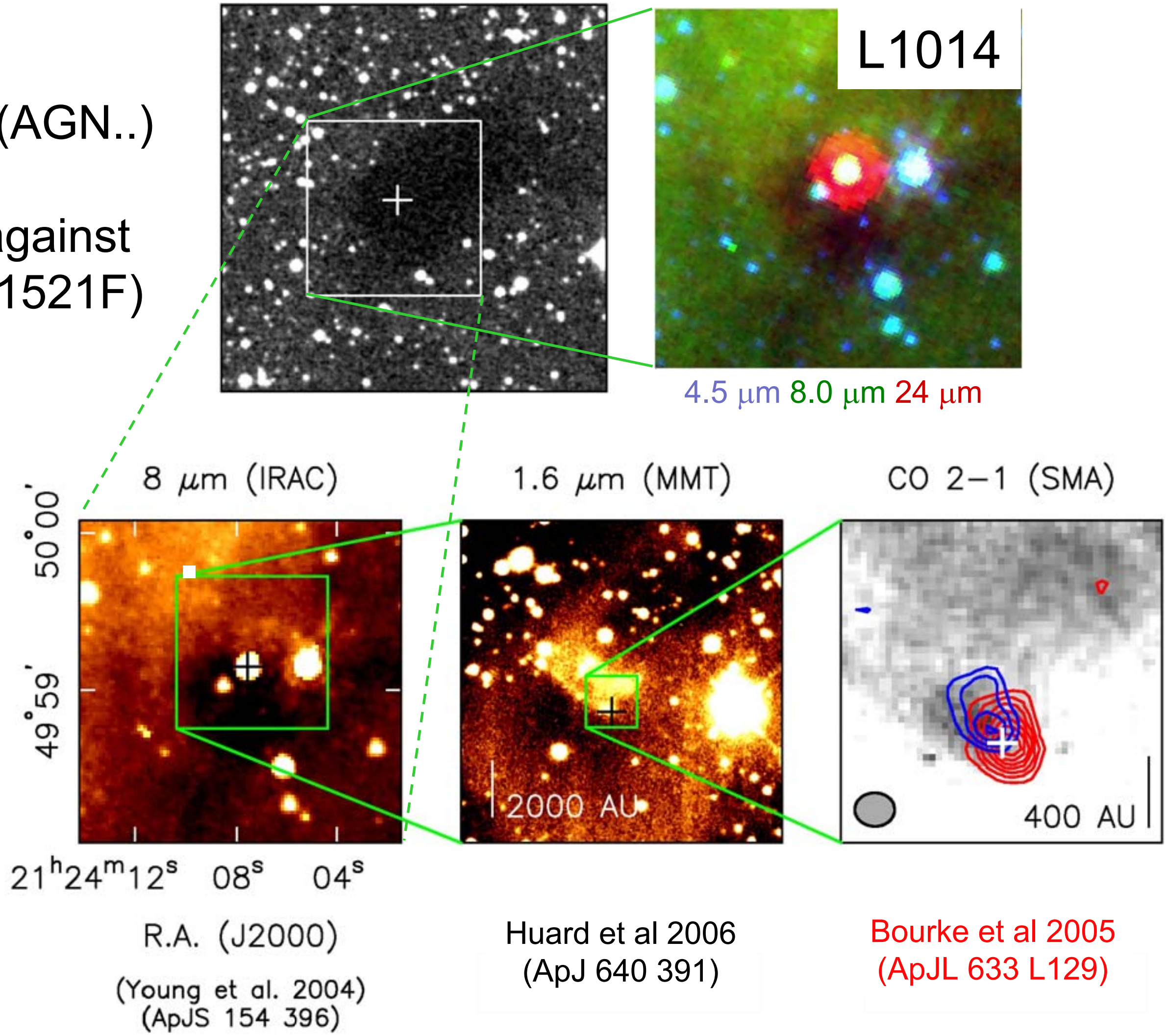
momentum conservation:

$(dM/dt)_{acc} = F/(f \times V_w)$ with $[f=0.1,\ V_w=200$ km/s$]$

$(dM/dt)_{acc} \sim 2\text{-}35 \times 10^{-9}\ M_\odot/yr$

Accretion rate very low, but larger than young BDs (10^{-10} –$10^{-12}\ M_\odot/yr$; Muzerolle et al 2005)

Episodic accretion?

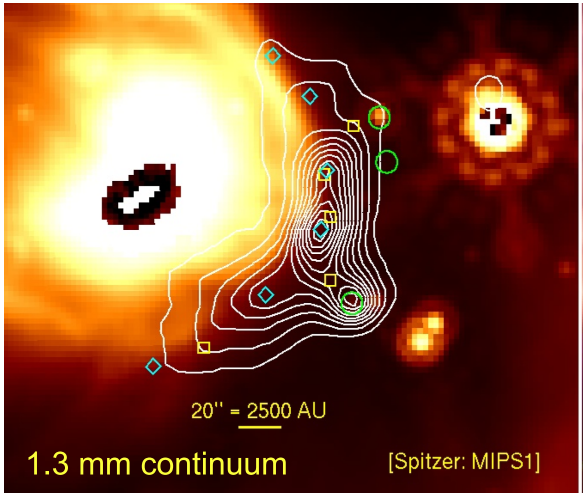


Huard et al 2006 (ApJ 640 391)

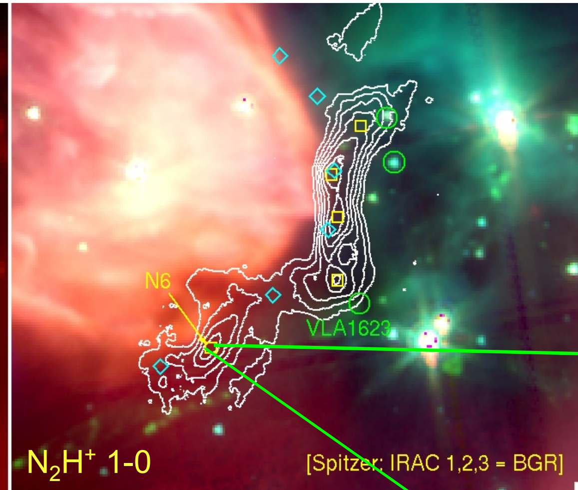
Bourke et al 2005 (ApJL 633 L129)

Outflow confirmed with recent SMA CO 3-2 observations

Oph A N6 - starless (prestellar) core in Oph A ridge

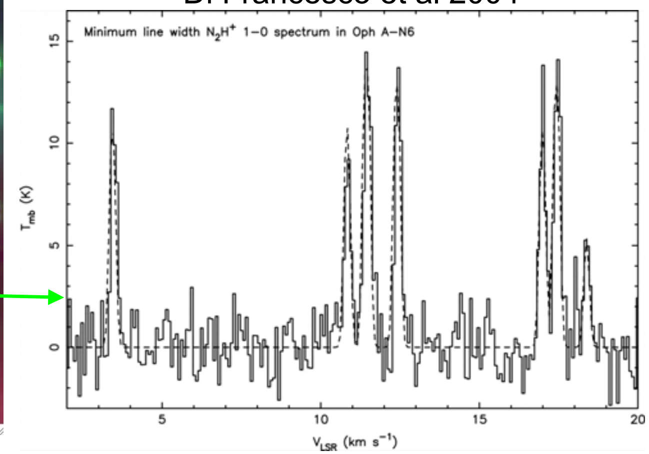


Motte et al 1998



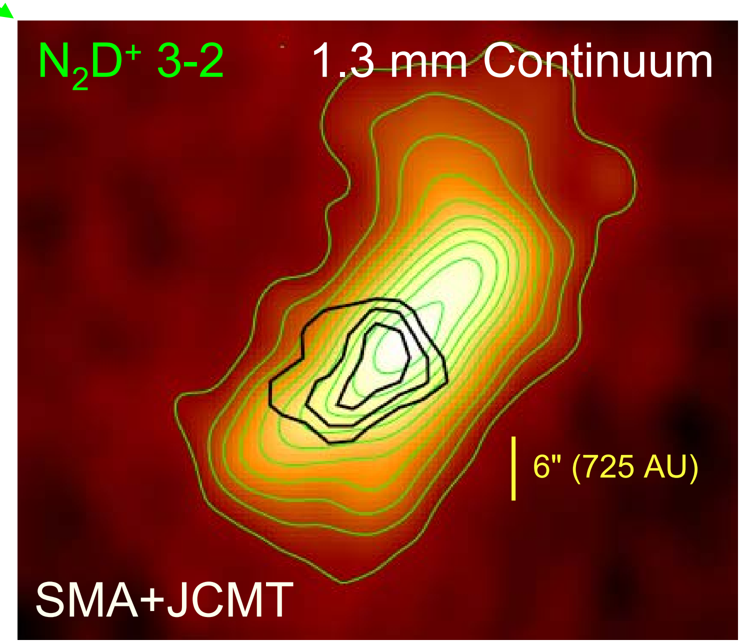
Di Francesco et al 2004

Di Francesco et al 2004

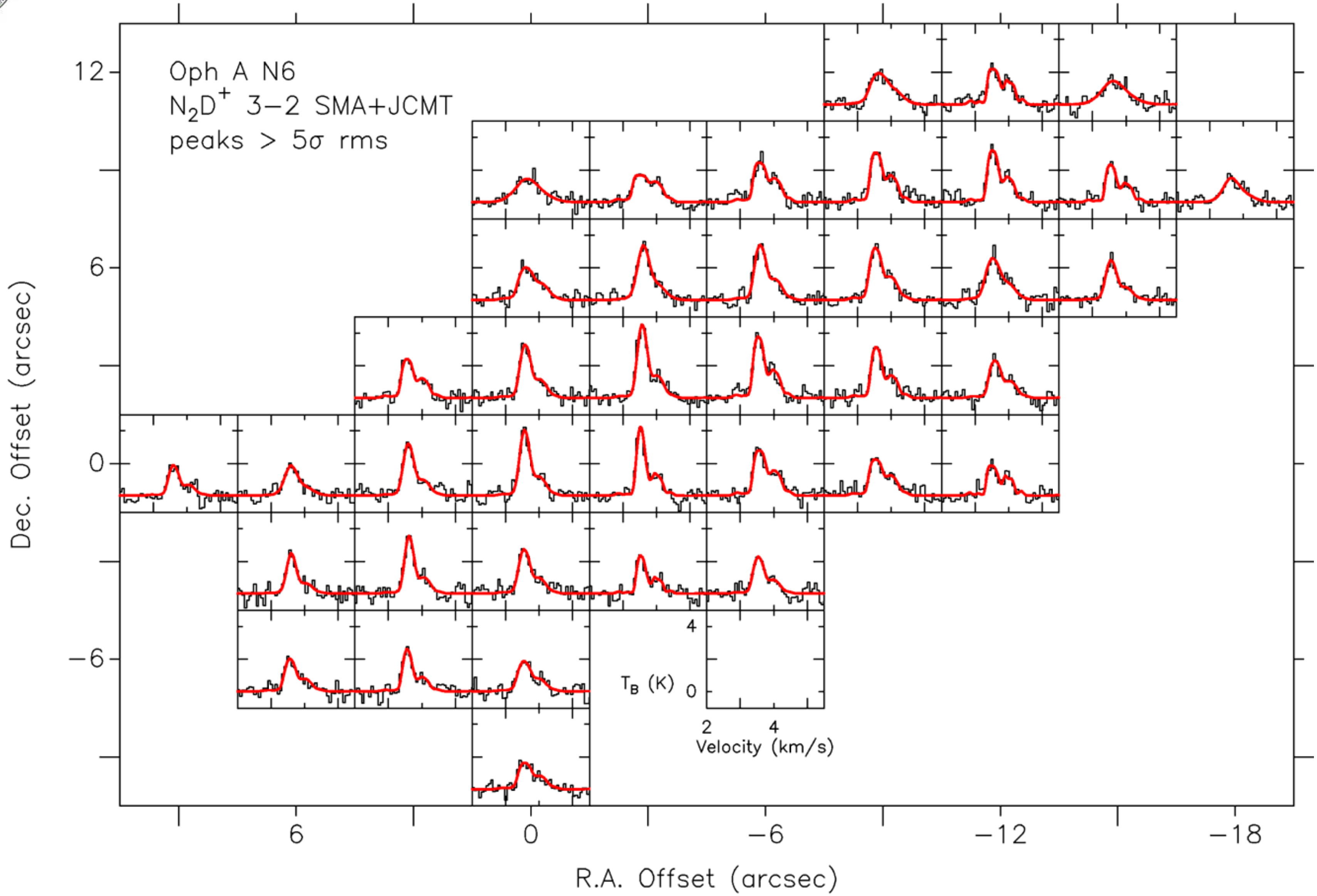


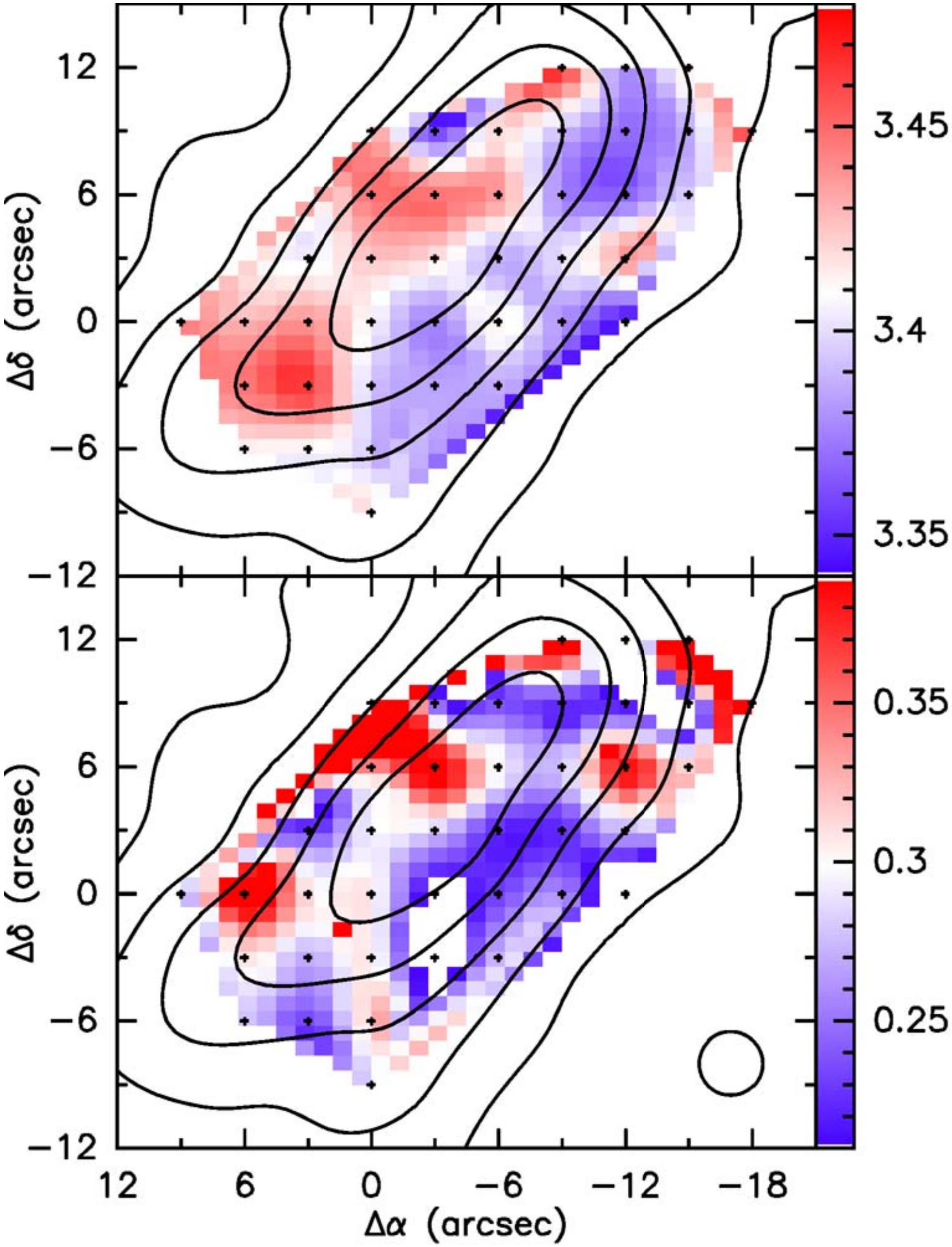
Observed N_2H^+ and N_2D^+ 3-2 with high spectral resolution – SMA correlator with 2048 channels (0.065 km/s spacing)

Goals: measure line widths and gradients in a quiescent core within a cluster forming region
(Are cores in clusters like isolated cores?)



Bourke et al in prep


Oph A N6
N_2D^+ 3−2 SMA+JCMT
peaks > 5σ rms
12
6
0
−6
Dec. Offset (arcsec)
6
0
−6
−12
−18
R.A. Offset (arcsec)
4
0
T_B (K)
2
4
Velocity (km/s)



Possible small gradient across minor axis

N_2D^+ 3−2 Velocity Field

Channel separation is 0.07 km/s

Fit uncert. typically < 0.025 km/s

Map resolution is 3"

Linewidths not much greater than thermal at 10 K

N_2D^+ 3−2 Linewidth

Channel separation is 0.07 km/s

Fit uncert. typically < 0.025 km/s

Map resolution is 3"

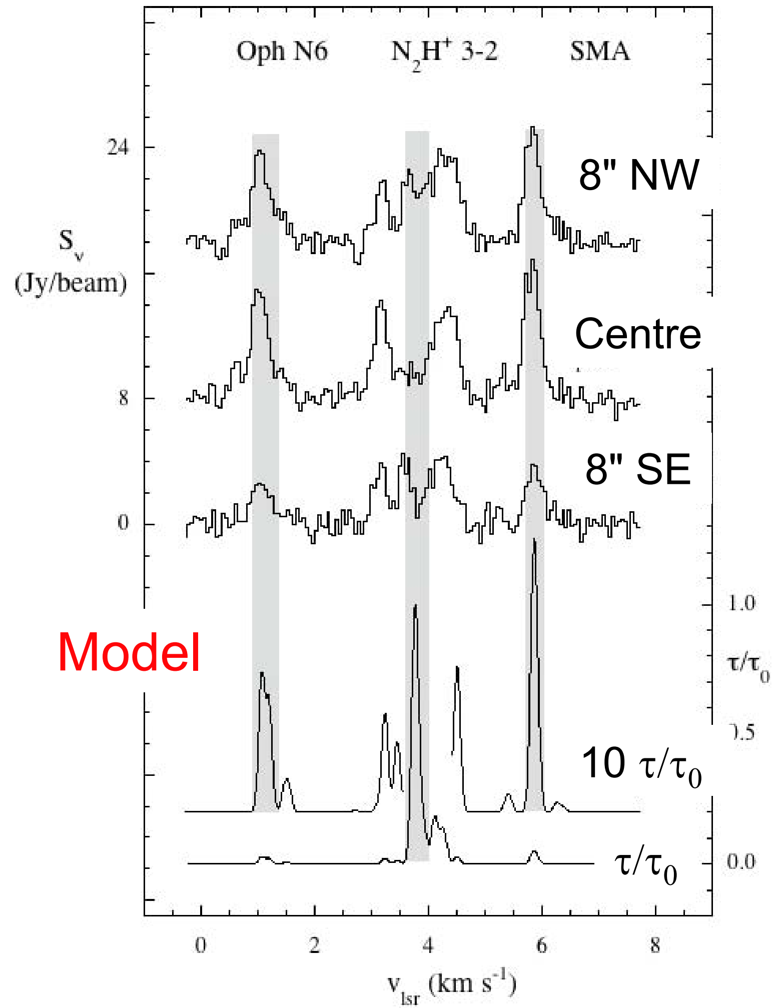
Oph A N6 – preliminary N_2H^+ 3-2

- compact + subcompact
- 2048 channels, 0.06 km/s resolution

Spectra along long axis compared to a model of its hyperfine structure, assuming optically thin emission and T=10 K. The four strong observed features match hyperfine components having relative intensity ~0.01, but no emission features match the two central hyperfine features having relative intensity of 0.1-0.2.

This is contrary to that seen in the isolated starless core L1544 with the IRAM 30-m telescope, where the central hyperfine features are dominant (Caselli et al 2002).

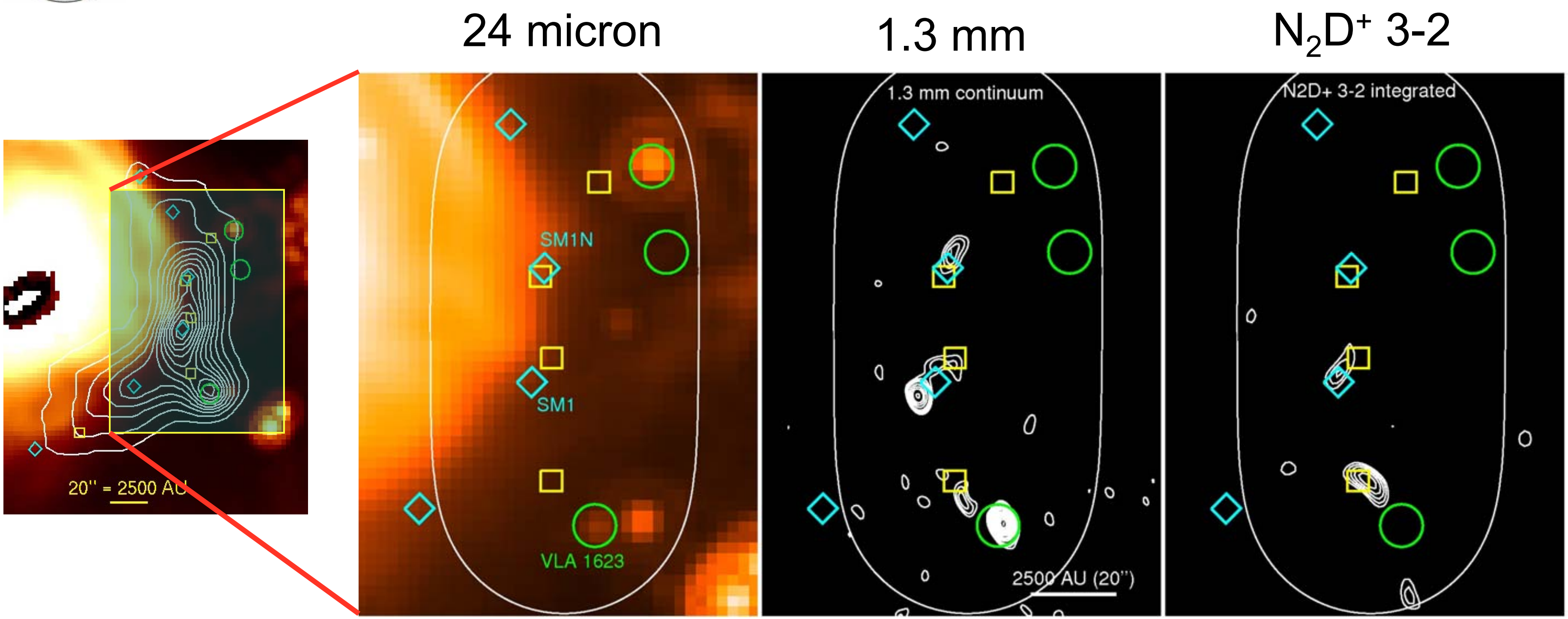
Need to compare to 30-m to access missing flux vs self-absorption



Good target for N_2H^+ 4-3

Oph A ridge

4 point N-S mosaic



– compact cont. ass. with N_2H^+ peaks (not always true for single-dish cont, ie N6, N3)

– 2 of 4 N_2H^+ 1-0 peaks in N_2D^+ 3-2

– N5 single dish continuum and N_2H^+ not in N_2D^+

– N3,N4 compact continuum and N_2D^+

– SM1 is protostellar

see also J.E. Lee et al 2006 and 2007 for L1251B

N3,N4 cold and starless, N5 warm (protostellar?)

No time to discuss….

- IRS 7 in CrA by Groppi et al 2007 astro-ph/0707.2979
- Orion proplyds by Williams et al 2005 ApJ 634 495
- Small group L1251B by J.E. Lee et al 2006 ApJ 648 491 and 2007 (astro-ph)
- Full results from Chandler et al 2005 ApJ 632 371 on IRAS 16293-2422
- any others I inadvertently overlooked….

Apologies

SMA advantages for Low Mass Star Formation Studies

High spatial resolution in high J lines coupled with high spectral resolution and large bandwidth

- separation of disk from envelopes
- kinematics of inner envelopes and DISKS
  (see also Wilner presentation)
- complex molecules (incl. organics)
- origin of hot corinos (disks, shocks)
- structure of prestellar cores
- clusters – resolve components
- outflows (presentation by Hirano)
- resolved dust polarimetry (presentation by Rao)