Probing the initial conditions of star clusters

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Thanks to: A. Belloche (MPIfR Bonn),
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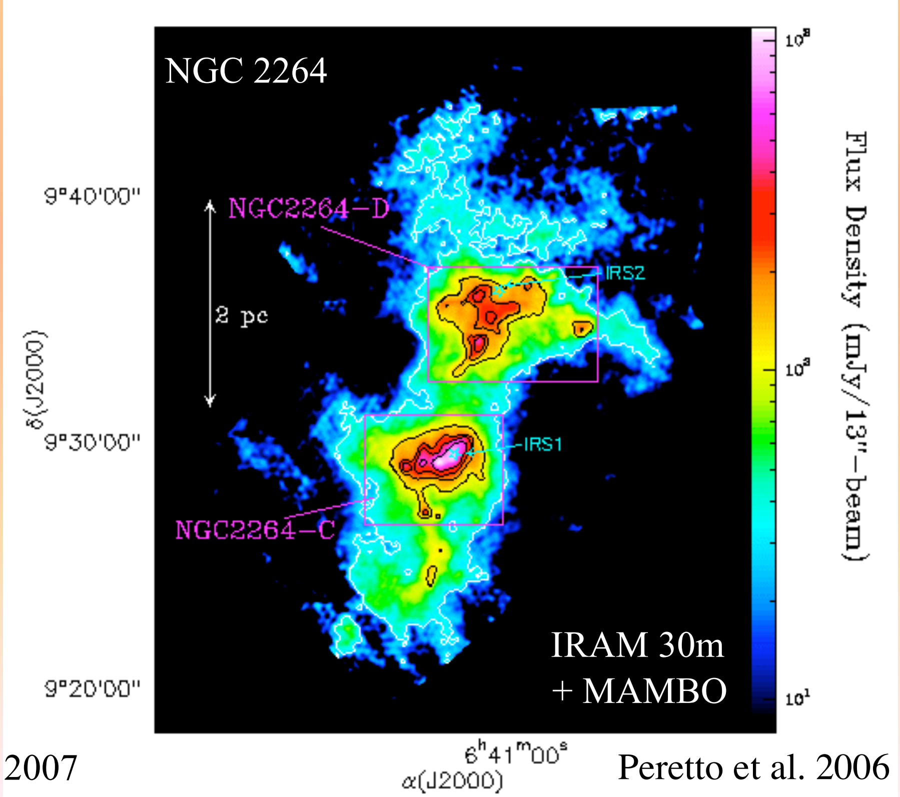
N. Peretto (Manchester),
D. Ward-Thompson (Cardiff)

Outline:

- Core Mass Function in cluster-forming clumps
- Core internal motions
- Relative core-core motions
- Evidence of large-scale collapse
- Conclusions

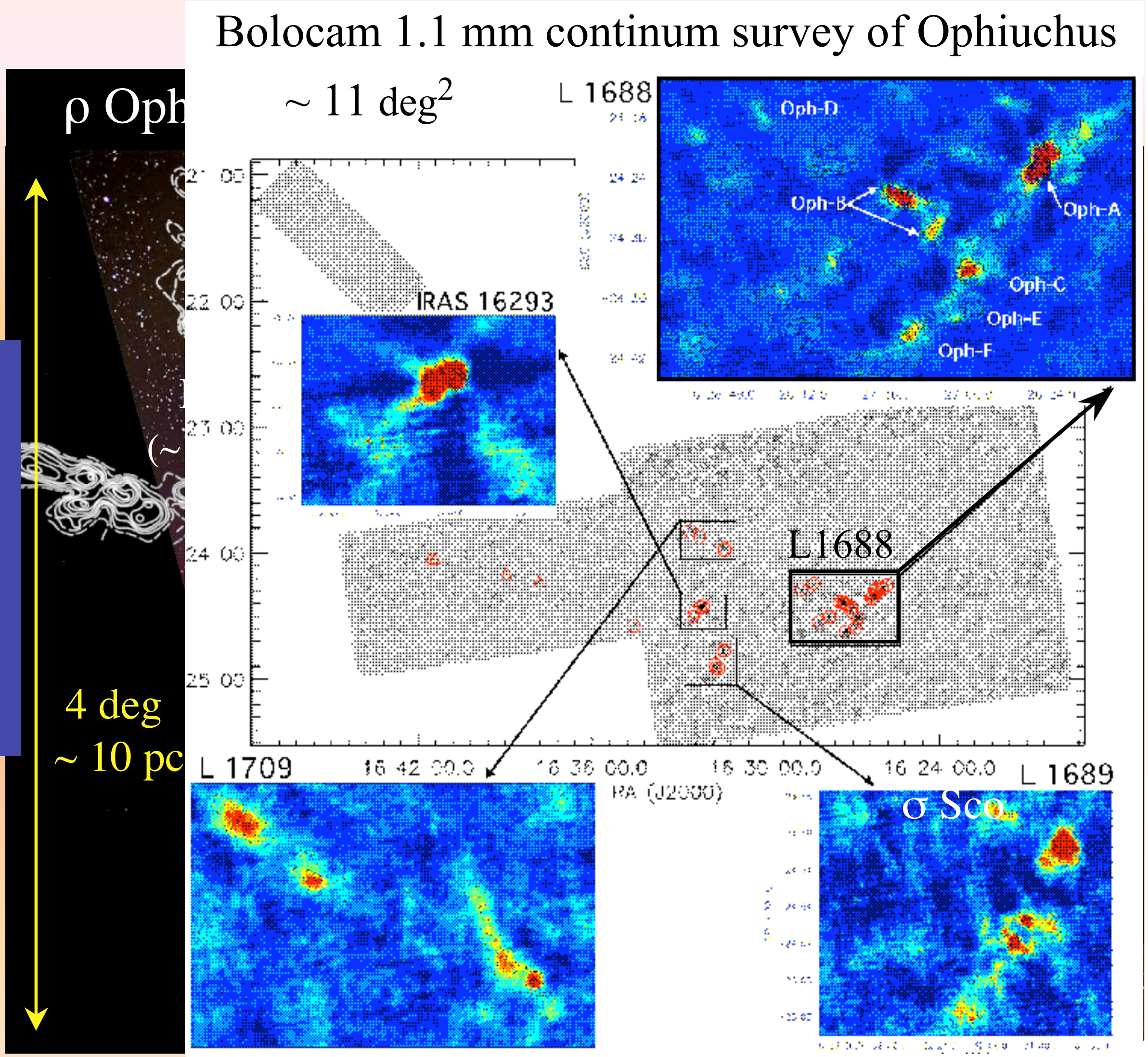


Peretto et al. 2006

« Complete » surveys for cores in nearby clouds

→ Clouds are mostly « empty » of cores

→ Inefficiency of core formation process (M_{cores}/M_{cloud} ~ 1-10% Johnstone et al. 2004; Hatchell et al. 2005; Nutter et al. 2006)

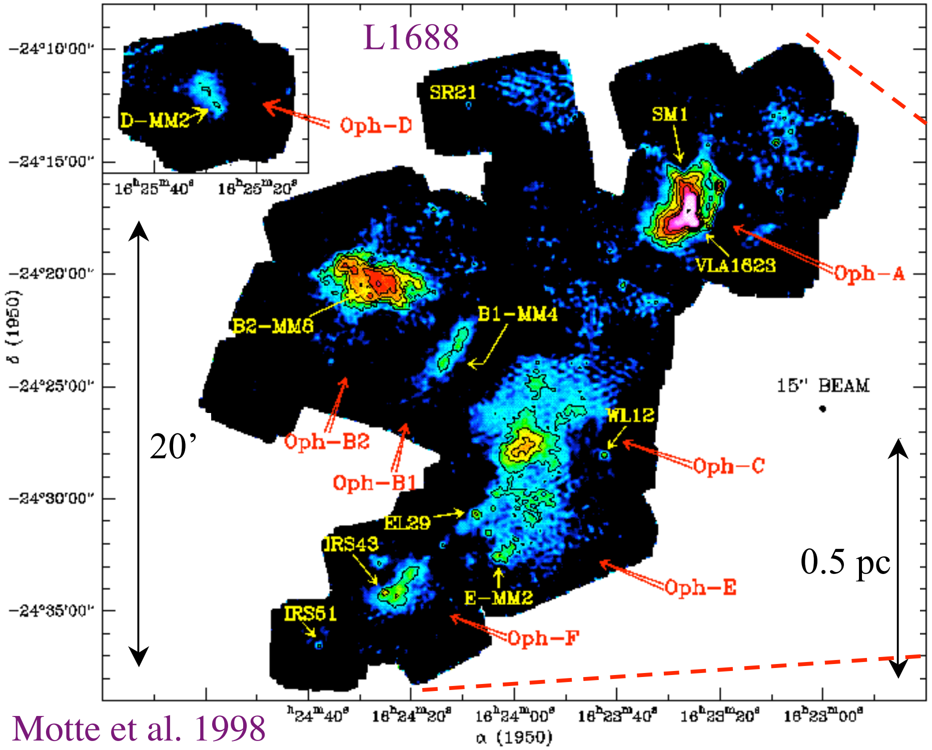


Bolocam 1.1 mm continuum survey of Ophiuchus

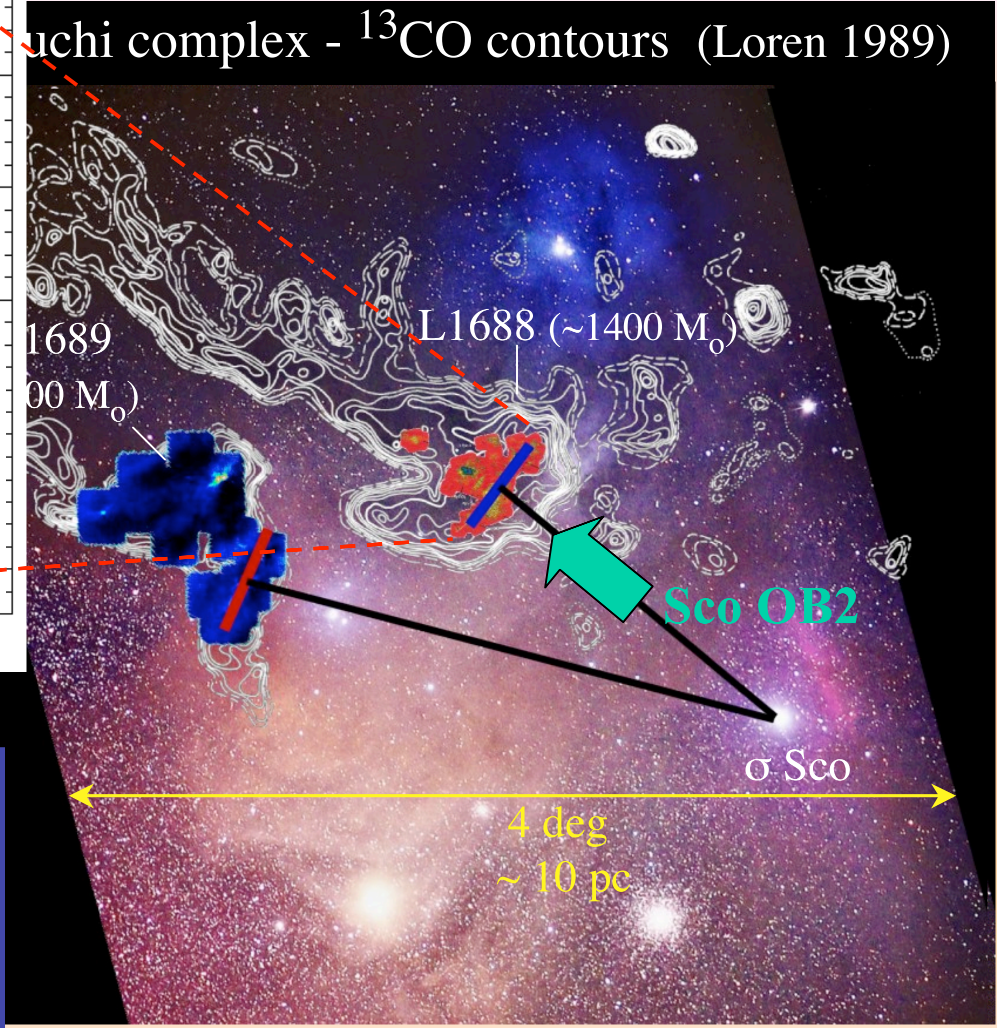
K. Young et al. 2006

« Complete » surveys for cores in nearby clouds

1.2mm mosaic of ρ Oph main cloud (IRAM 30m + MAMBO)



Motte et al. 1998


uchi complex - ^{13}CO contours (Loren 1989)

→ Inefficiency of core formation process (M_{cores}/M_{cloud} ~ 1-10% - Johnstone et al. 2004; Hatchell et al. 2005; Nutter et al. 2006)

→ Active cluster-forming clumps only observed at $A_V > 10$; may be triggered (e.g. Nutter et al. 2006; H. Kirk et al. 2006)

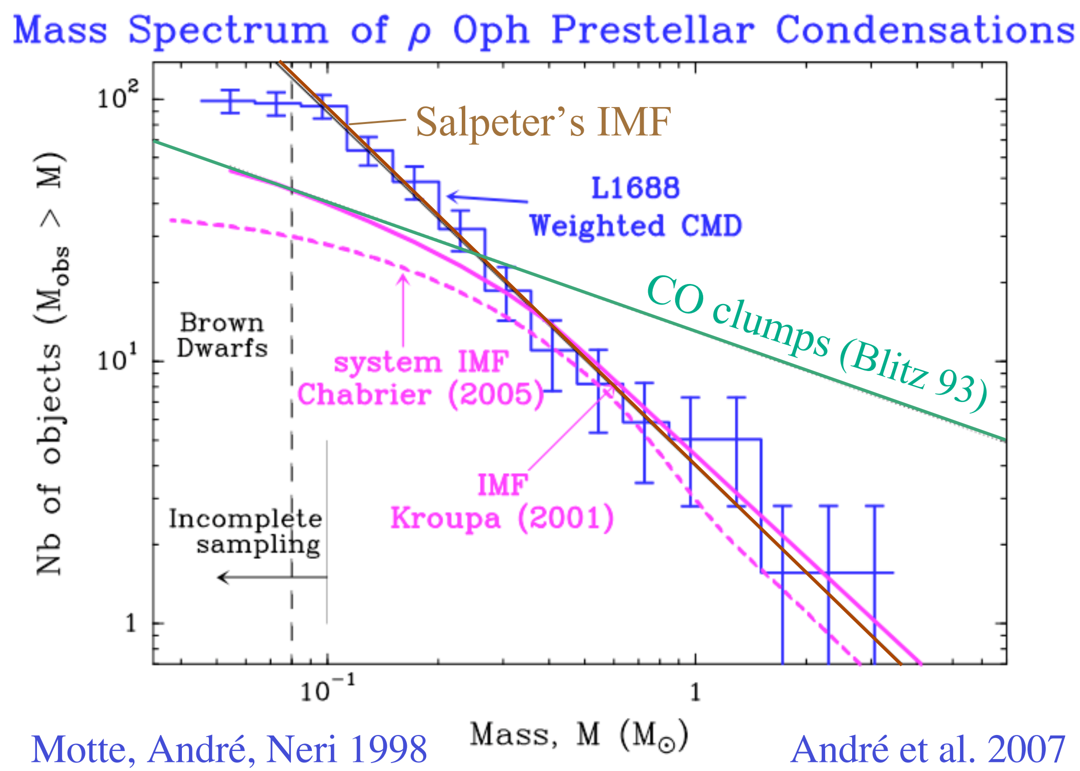
The prestellar Core Mass Function (CMF) observed in cluster-forming clumps resembles the stellar IMF

→ One-to-one correspondence between core mass and star/system mass with high (> 50%) local star formation efficiency in each core

→ IMF partly determined by cloud fragmentation at prestellar stage

- **Potential timescale problem** (Clark, Klessen, Bonnell 2007):
  - Observed CMF is only a snapshot
  - May not reflect intrinsic CMF if core lifetime varies with mass (e.g. $t_{ff} \propto M_J$)

→ Not a serious problem: **high-mass end of ρ Oph CMF is robust**



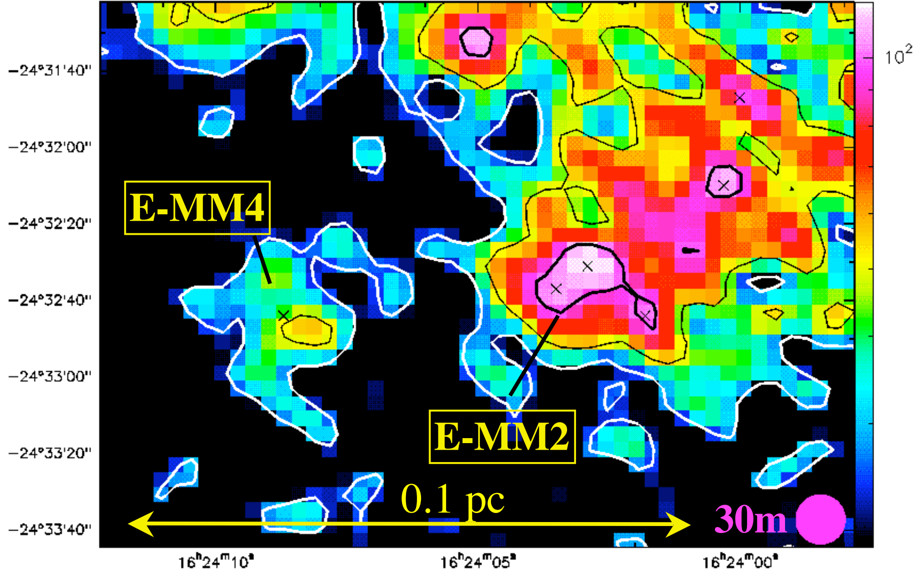
Motte, André, Neri 1998

André et al. 2007

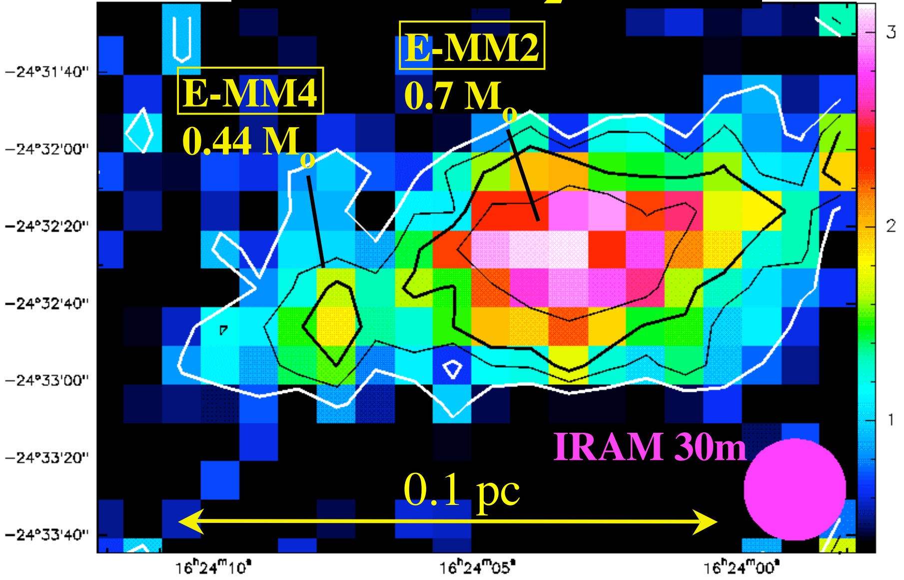
See also: Testi & Sargent 1998; Johnstone et al. 2000; Stanke et al. 2006; Alves et al. 2007; and for massive cores: Beuther & Schilke 2004; Reid & Wilson 2005

Evidence that the ρ Oph condensations are gravitationally bound

ρ Oph-E in 1.2 mm continuum

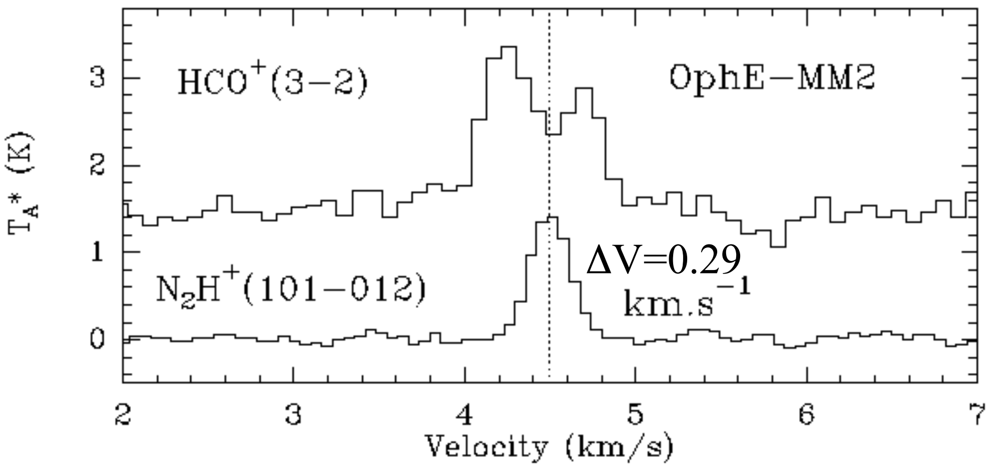


ρ Oph-E in N_2H^+(1-0)



- Narrow N_2H^+(101-012) linewidths ($\Delta V < 0.5$ km/s) => subsonic levels of internal turbulence ($\sigma_{turb} < c_s \sim 0.2$ km/s)
- $\alpha_{vir} = M_{vir} / M_{mm} \sim 0.5\text{-}2$
- Infall signatures in, e.g., HCO^+(3-2) in some cases

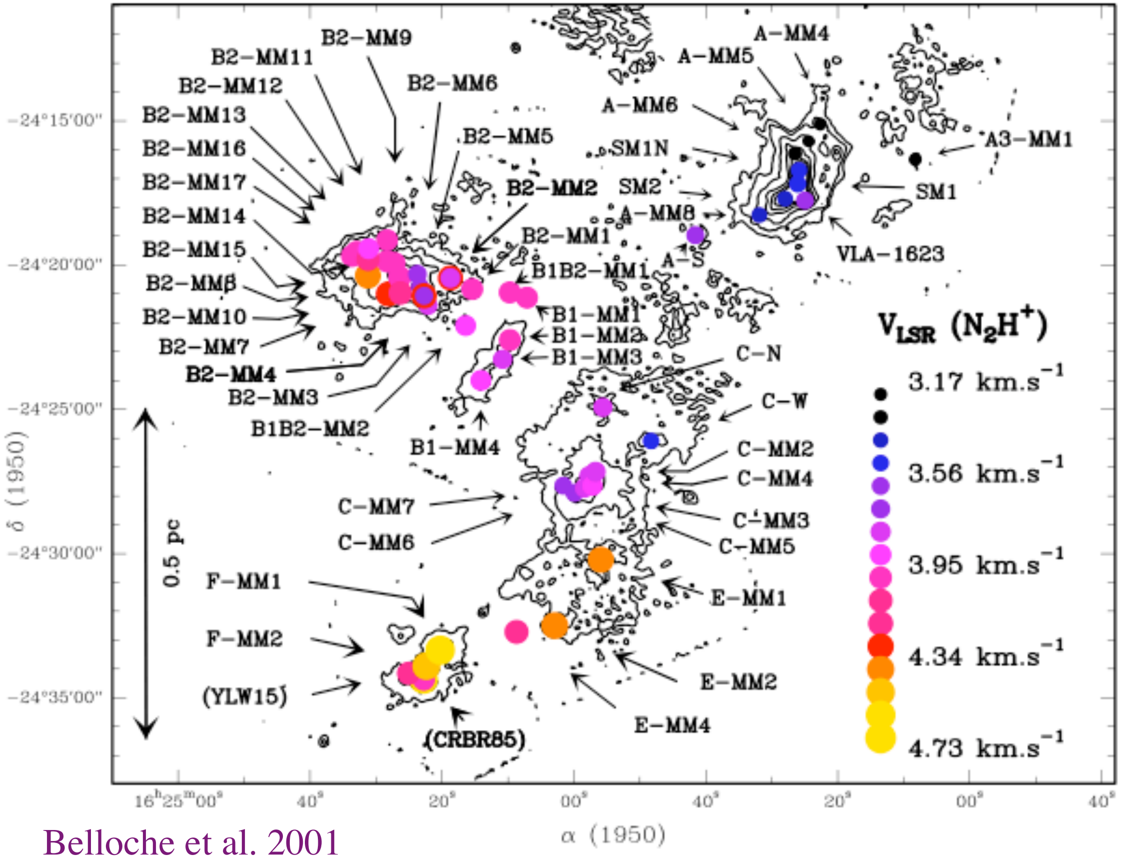
➜ ρ Oph mm continuum condensations are self-gravitating for $M_{mm} \gtrsim 0.1\ M_o$



Belloche et al. 2001; André et al. 2007

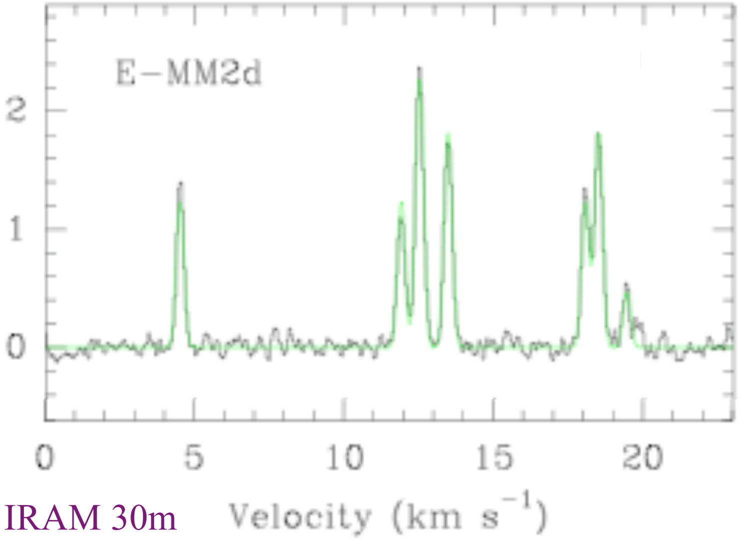
Relative motions of prestellar condensations within protoclusters: The case of the ρ Oph main cloud (L1688)

Line-of-sight velocities of the ρ Oph protocluster condensations



Belloche et al. 2001

Example of N_2H^+(1-0) spectrum



IRAM 30m

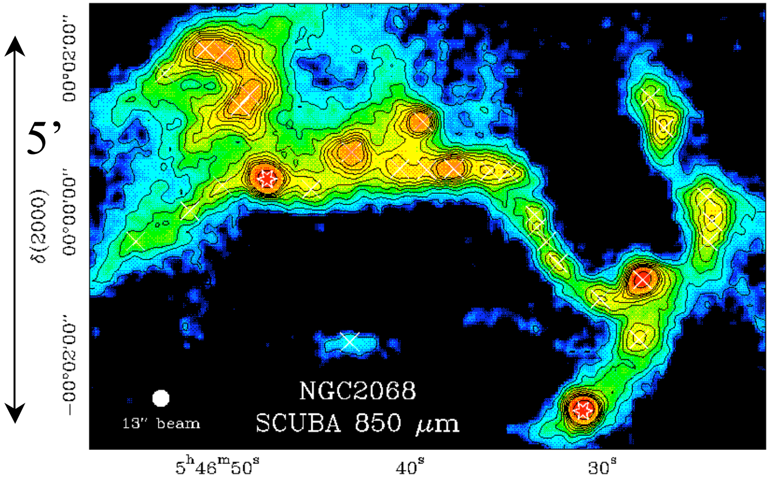
➜ Global core-core velocity dispersion in ρ Oph protocluster:

σ_{1D} ~ 0.36 km/s <=> σ_{3D} ~ 0.6 km/s < σ_{VIR} ~ 2.1 km/s (André et al. 2007)

Similar results in NGC 2264 (Peretto et al. 2006) & NGC 1333 (Walsh et al. 2007)

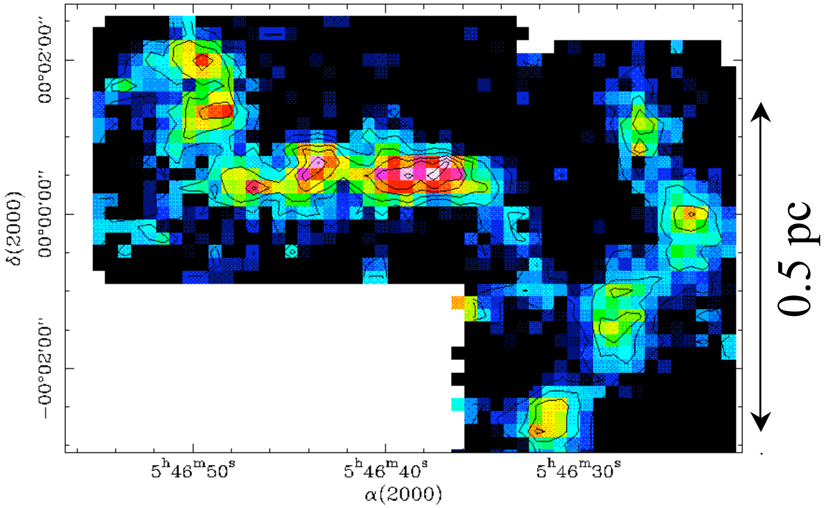
Likelihood of interactions between protocluster condensations

NGC2068 - 850 μm continuum (JCMT)



Motte et al. 2001

NGC2068 in N_2H^+(1-0) (IRAM 30m)



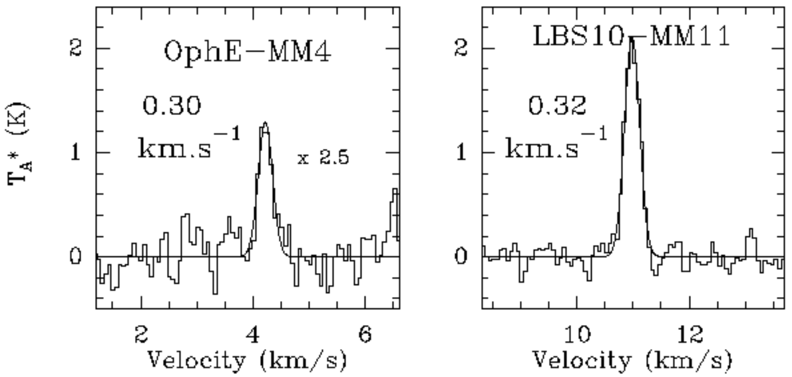
Global core-core velocity dispersion:

$\sigma_{1D} \sim 0.37$ km/s <=> $\sigma_{3D} \sim 0.65$ km/s
for both NGC 2068 and ρ Oph (25+41 objects)

→ **Collision time ~ Crossing time**:
$D/\sigma_{3D} \sim 1\text{-}2 \times 10^6$ yr
>> condensation lifetime ~ $1\text{-}5 \times 10^5$ yr

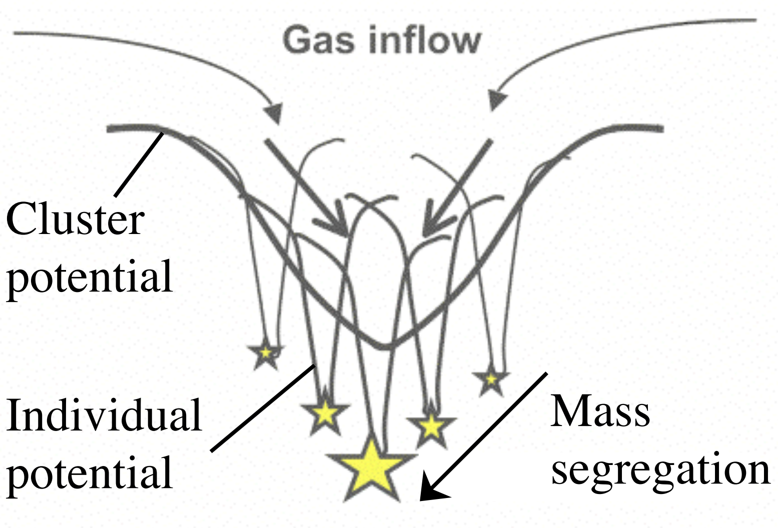
→ In general, not enough time for dynamical interactions prior to PMS stage

Narrow N_2H^+(101-012) lines ($\Delta V < 0.5$ km/s)
→ Good determination of the l.o.s. velocities



André, Belloche, Motte, Peretto 2007, A&A
(astro-ph/0706.1535)

Comparison with the competitive accretion picture



- **Protostellar seeds move around in the cluster potential and compete for accretion of background mass reservoir**
- **Varying mass accretion rates and accretion times --> full IMF from competitive accretion and dynamical ejections (Bonnell et al. 2001, Bate et al. 2003)**

$$\dot{M}_{acc} \sim \pi \, \rho_{back} v_{rel} R_{acc}^{2}$$

(cf. Bonnell et al. 2001)

$$\rightarrow \dot{M}_{acc} \lesssim 10^{-6}\, M_o/yr < a_{eff}^{3}/G \text{ in } \rho \text{ Oph cluster}$$

(André et al. 2007)

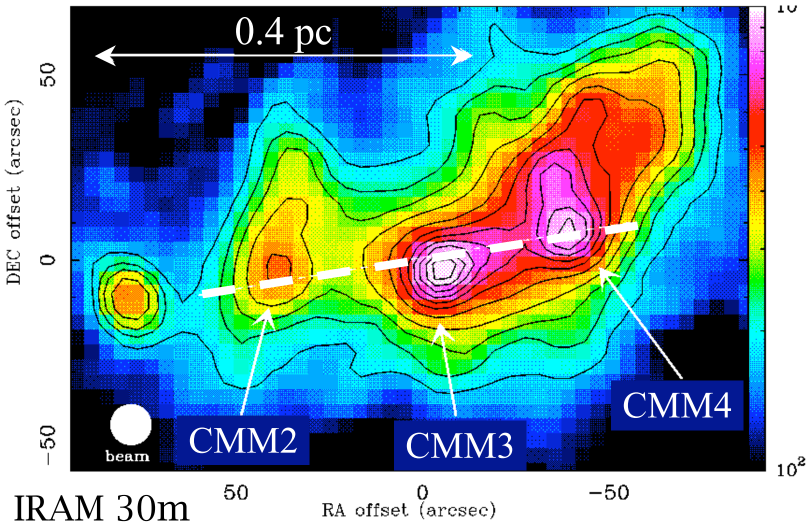
$$\begin{cases} n_{back} \sim 10^{5}\ \text{cm}^{-3} \\ v_{rel} \sim 0.3\ \text{km/s} \\ R_{acc} \sim 3000\ \text{AU} \end{cases}$$

- **Unlikely to be dominant at protostellar stage (Class 0/I): $\dot{M}_{acc}$ too low compared to $\dot{M}_{inf}$ from collapse (see also Krumholz et al. 2005)**
- **May possibly govern the growth of starless condensations produced by gravoturbulent fragmentation toward an IMF-like mass spectrum**

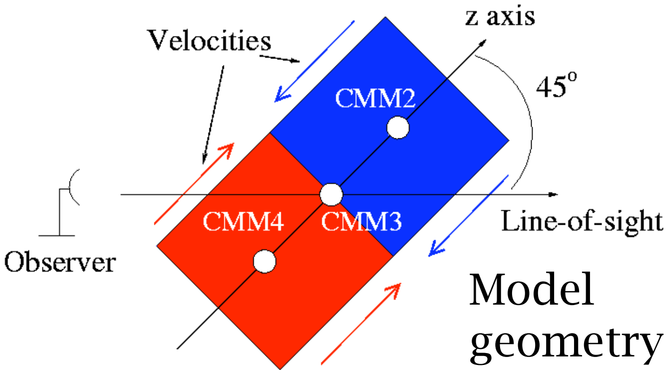
Evidence of large-scale collapse and central dynamical interactions in protoclusters: The example of NGC2264-C

(Peretto, André, Belloche 2006, A&A, 445, 979)

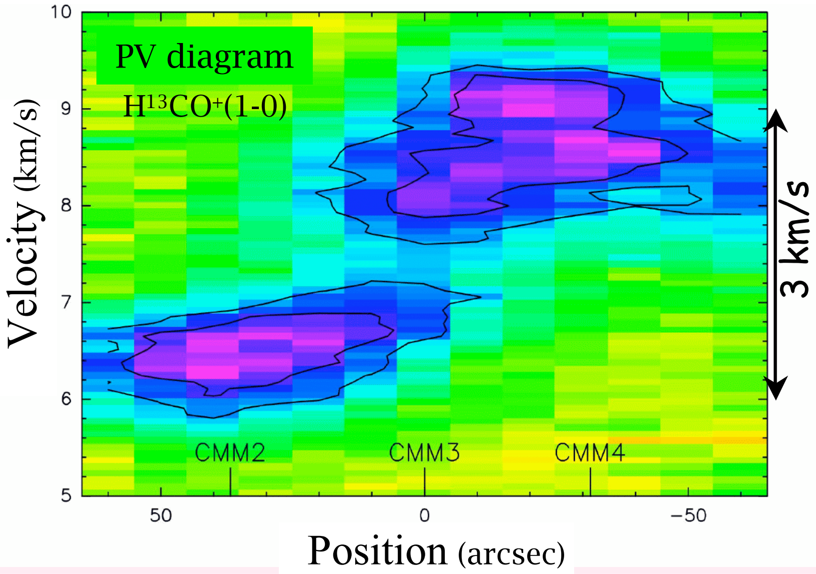
NGC2264C: 1.2mm continuum map



A ~ 1600 M_o cluster-forming clump with several Class 0 objects and widespread infall motions



Sharp central discontinuity in velocity



$M = 15 + 40 + 35 = 90\ M_o$

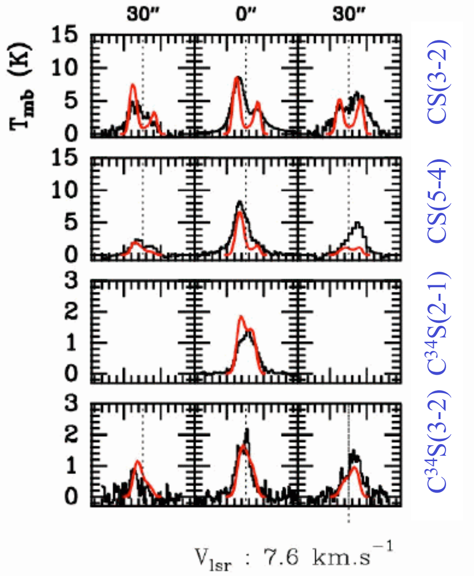
$V_{inf} = 1.5$ km/s

↓

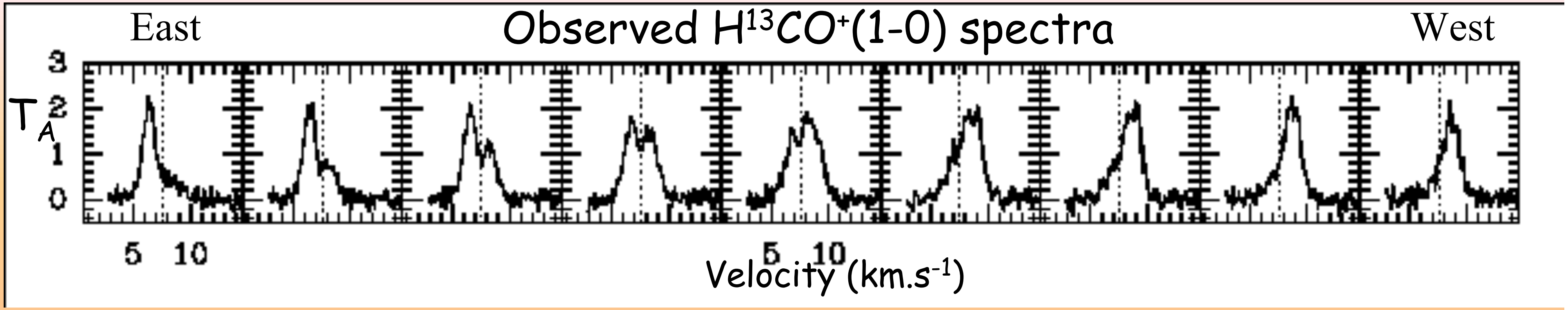
Potential formation of massive core by merging of 3 Class 0 objects ?

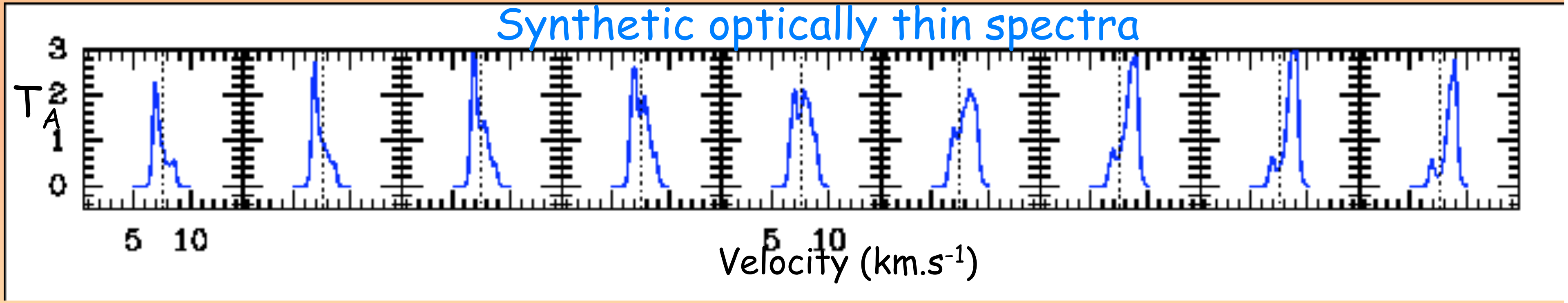
(cf. Bonnell et al. 1998)

CS line profiles with radiative transfer



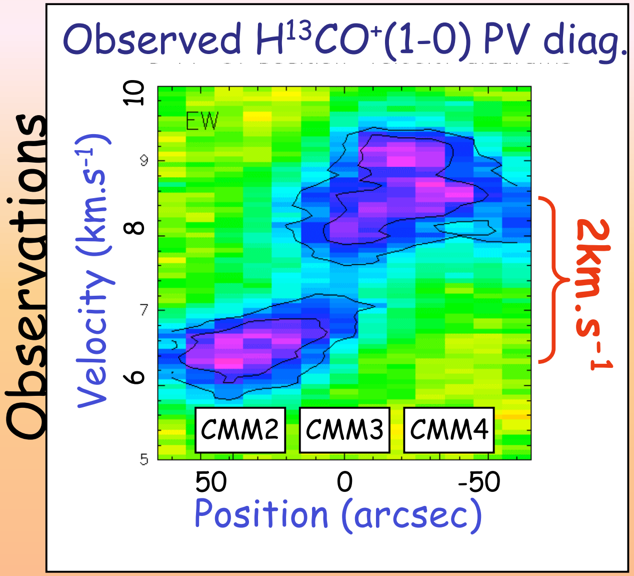
Observed vs. model spectra along the long axis of NGC2264-C

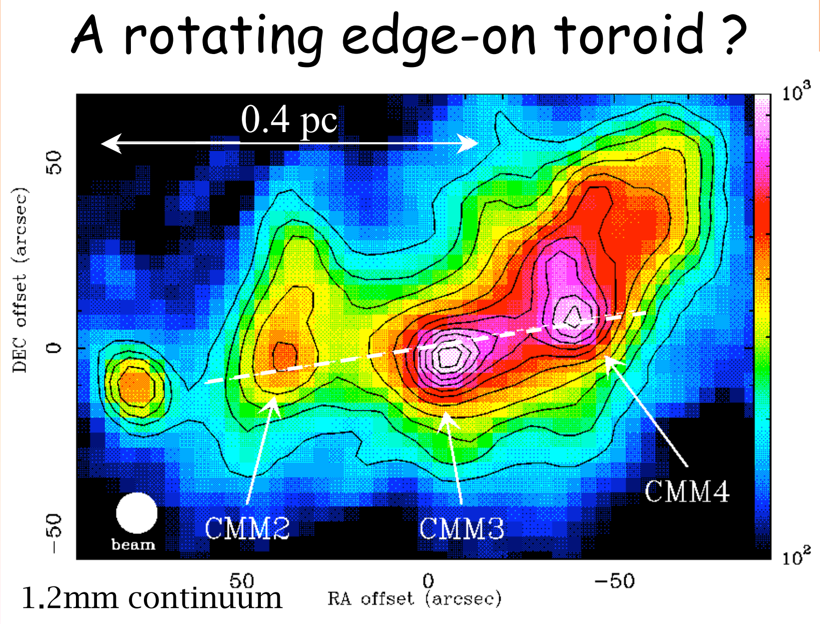

Observed $H^{13}CO^{+}(1-0)$ spectra


Synthetic optically thin spectra

Collapse rather than rotation

Observations

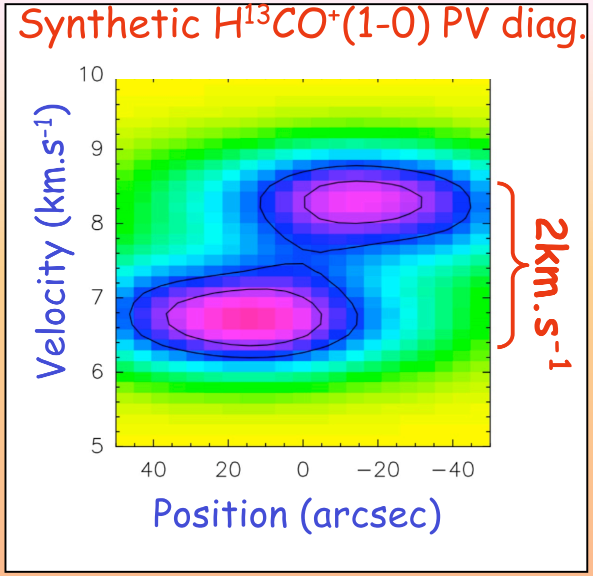

Observed $H^{13}CO^+$(1-0) PV diag.


A rotating edge-on toroid ?

1.2mm continuum

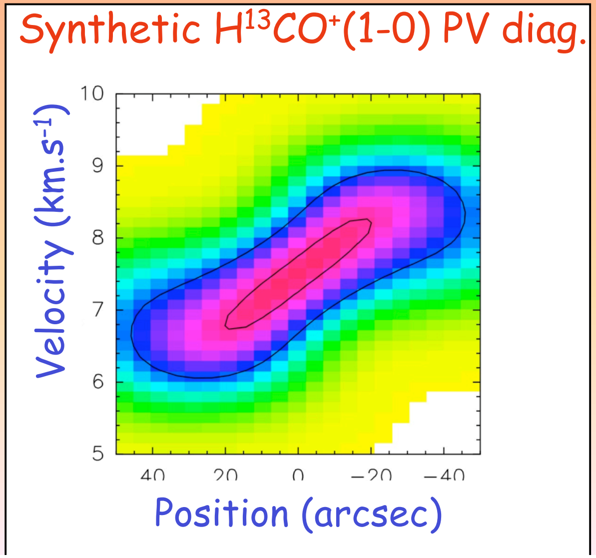
Collapse

Radiative Transfer


Synthetic $H^{13}CO^+$(1-0) PV diag.

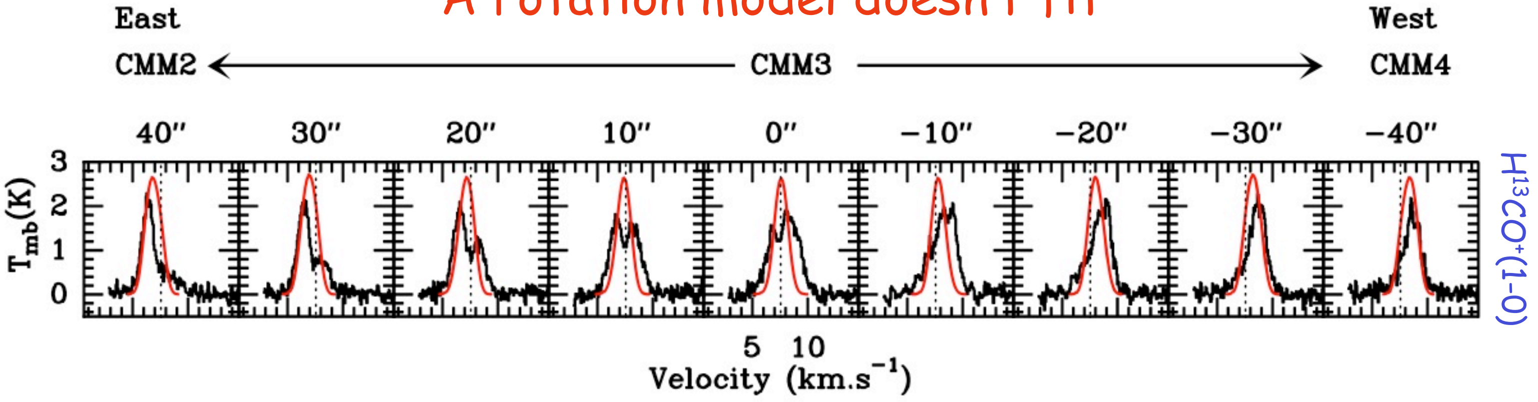
Rotation

Radiative Transfer

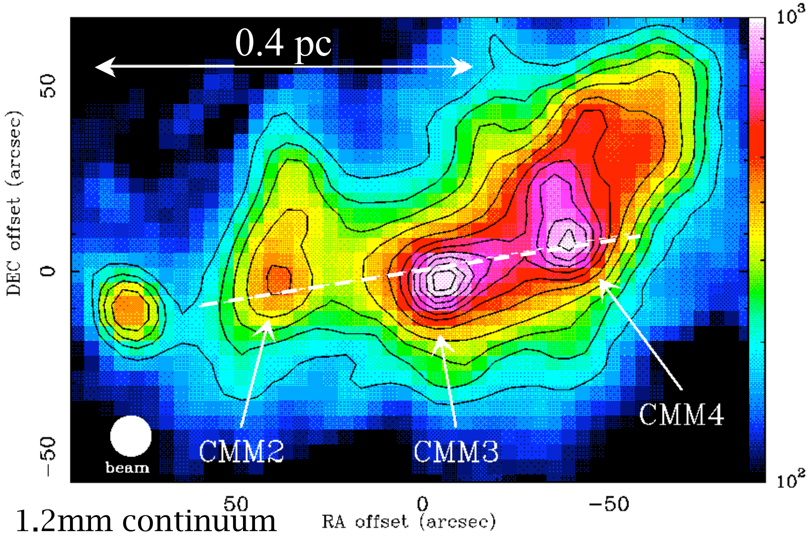

Synthetic $H^{13}CO^+$(1-0) PV diag.

Collapse rather than rotation

A rotation model doesn't fit



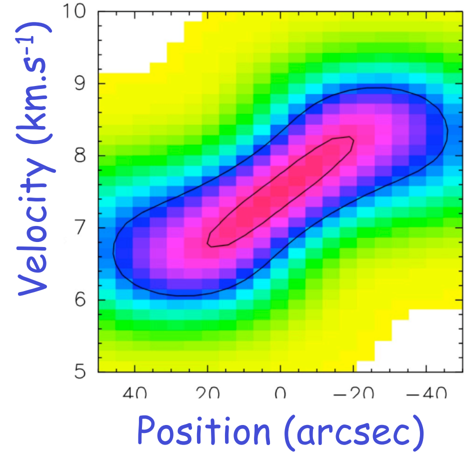
A rotating edge-on toroid ?



Radiative Transfer

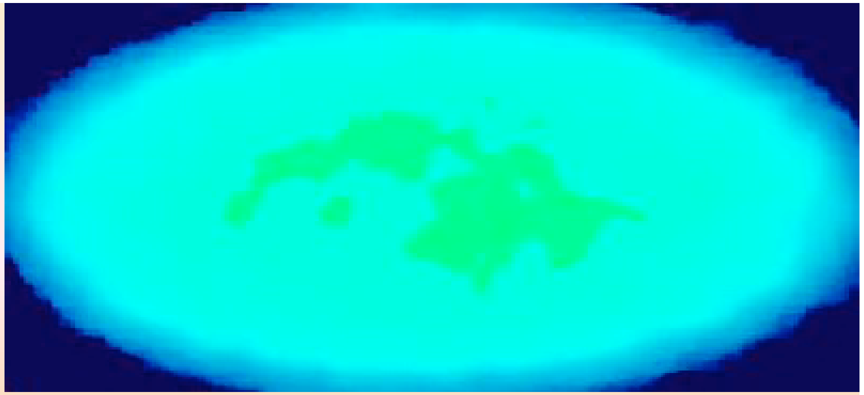
Rotation

Synthetic $H^{13}CO^+$(1-0) PV diag.



Comparison with SPH collapse simulations of a Jeans-unstable ellipsoidal clump

Peretto, Hennebelle, André 2007, A&A, 464, 983



Initial conditions:

Isothermal, highly unstable clump:

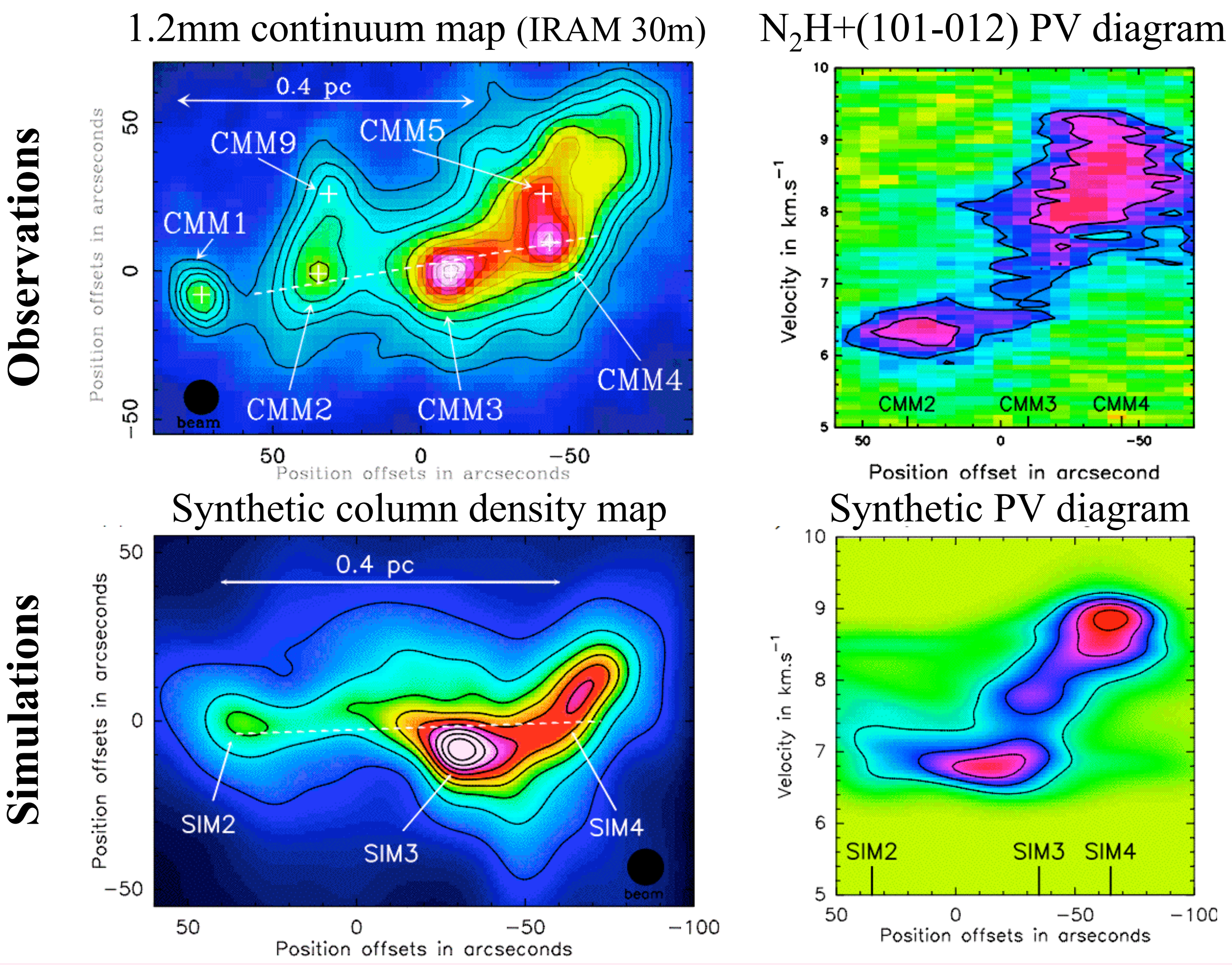
$M_{tot} = 1000\ M_o$

$E_{therm}/E_{grav} = 4\%$

$E_{turb}/E_{grav} = 5\%$

→ Produced by an external trigger ?

→ Mainly gravitational fragmentation


1.2mm continuum map (IRAM 30m)

$N_2H+(101\text{-}012)$ PV diagram

Synthetic column density map

Synthetic PV diagram

Summary and Conclusions

- The formation of a protocluster requires a threshold column density (Av ~ 10) in the parent cloud.
- The stellar IMF in protoclusters is at least partly established at the prestellar stage.
- The observed core-core velocity dispersion is small (sub-virial) and not consistent with strong dynamical interactions in general.
- Evidence that some young protoclusters are in a state of large-scale, global contraction induced by external triggers.
- Competitive accretion cannot be the dominant mechanism once individual protostellar collapse sets in.
- A mixed scenario may be the solution:
  Gravitational fragmentation in a magnetically supercritical clump generates cores which grow until they collapse