

Alla ricerca delle condizioni iniziali del processo di formazione stellare

Paola Caselli

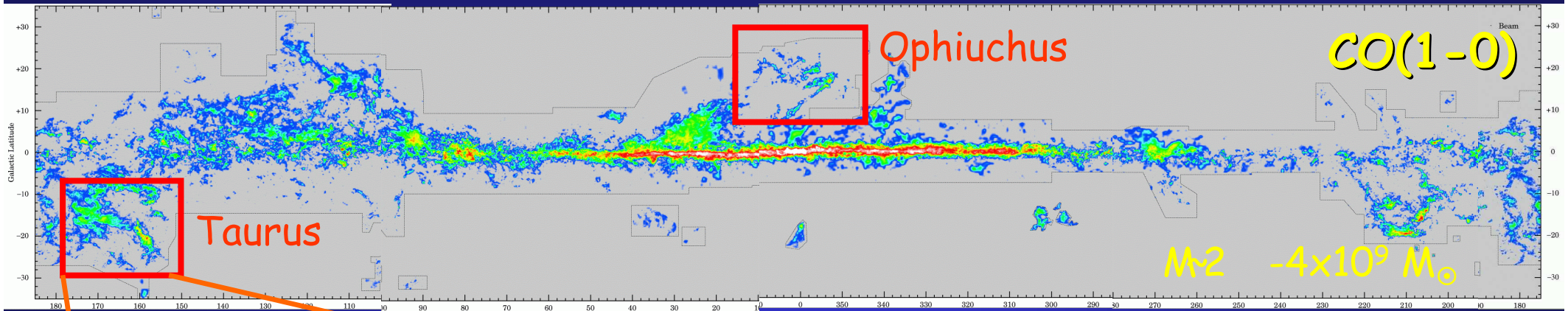
INAF - Osservatorio Astrofisico di Arcetri

- Complessi molecolari, nubi quiescenti e nuclei pre-stellari
- Eterogeneità chimiche e ricerca dei traccianti
- Scoperta di forte emissione di H_2D^+
- Progetti futuri

Collaboratori: M. Walmsley, A. Crapsi, T. Gatti, L. Dore (UdB)

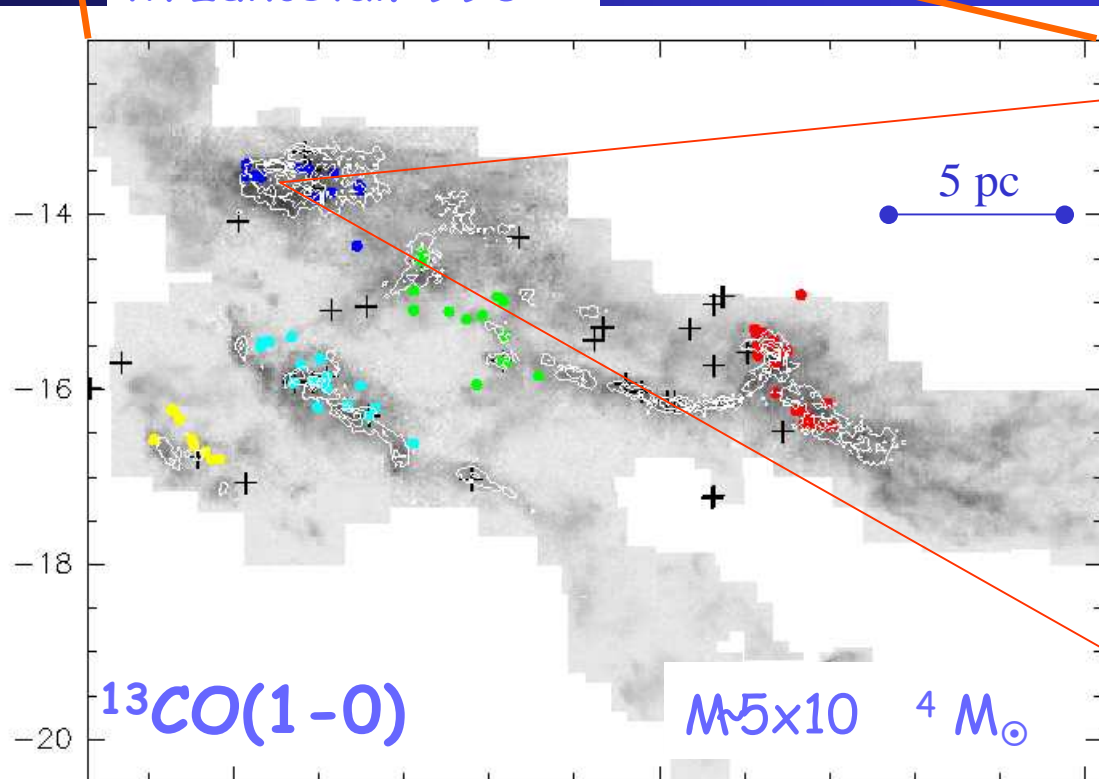
M. Tafalla (OAN), P. Myers (CfA), F. van der Tak (MPI)

Nubi e condensazioni molecolari

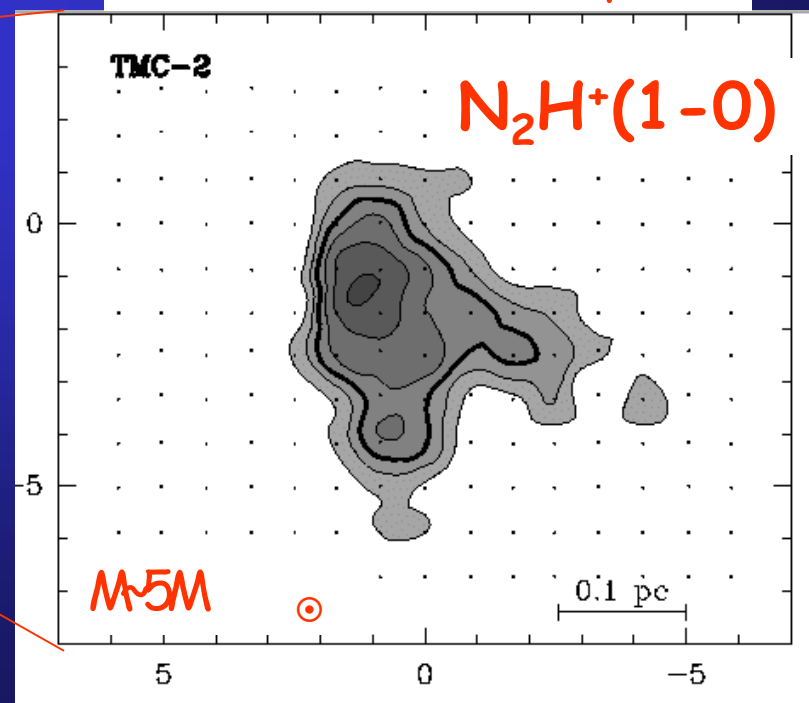


Dame, Hartman and Thaddeus 2001

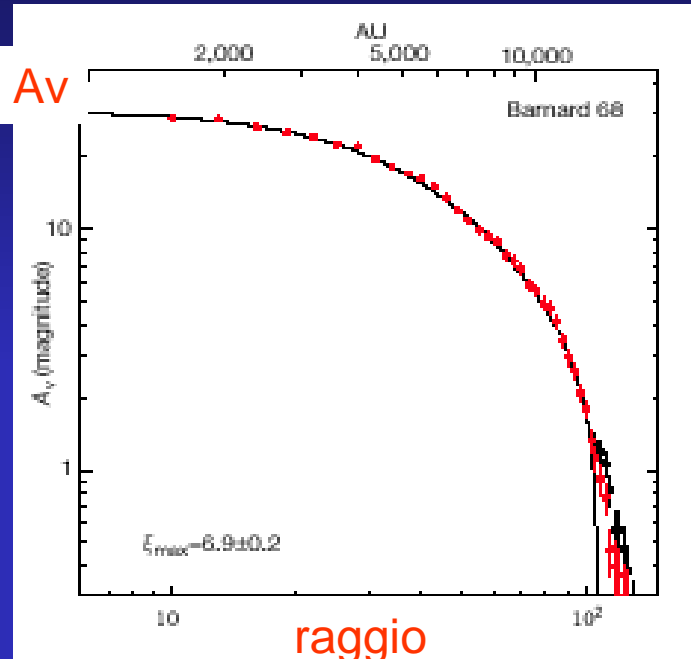
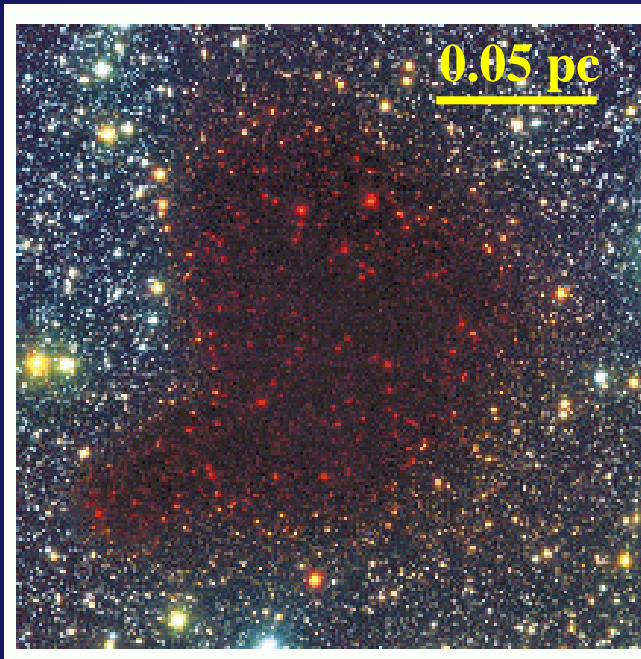
Mizuno et al. 1995



Caselli et al. 2002a, ApJ



Nubi quiescenti e...



$$T_c \sim 10 \text{ K}$$

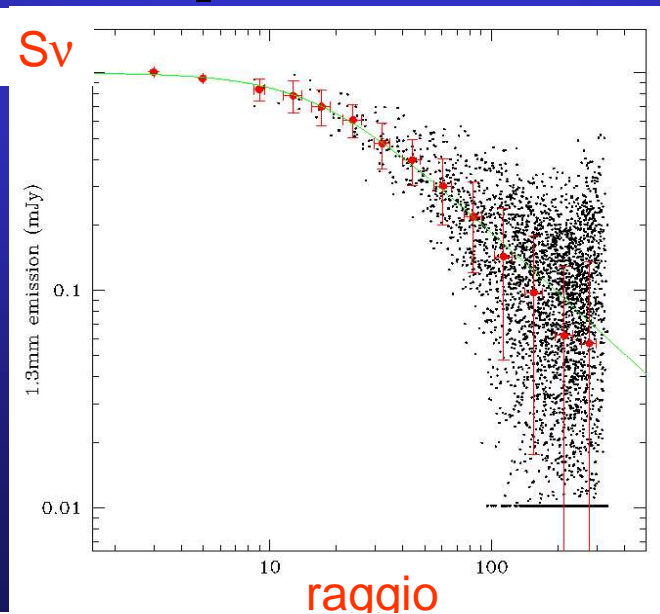
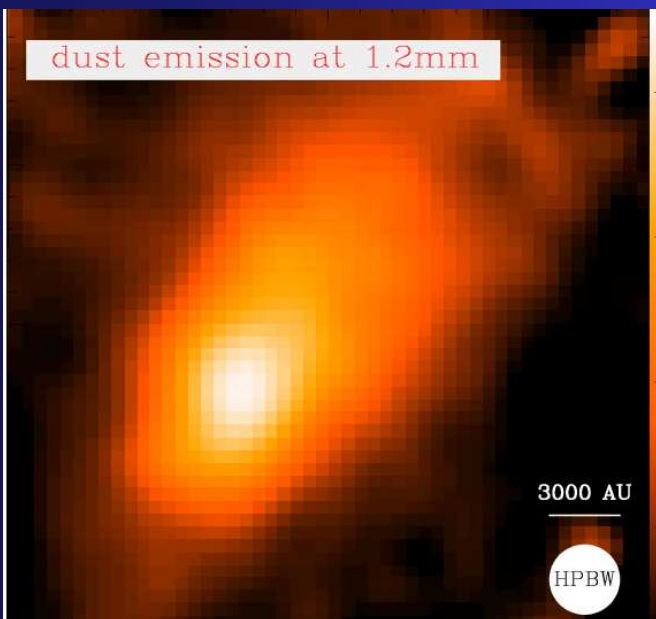
$$n_c(\text{H}_2) \sim 10^5 \text{ cm}^{-3}$$

$$R_f \sim 5000 \text{ AU}$$

(Andre' et al. 2000; Tafalla, Myers, Caselli et al. 2002)

Alves et al. 2001

nubi pre-stellari



$$T_c \sim 7 \text{ K}$$

$$n_c(\text{H}_2) \sim 10^6 \text{ cm}^{-3}$$

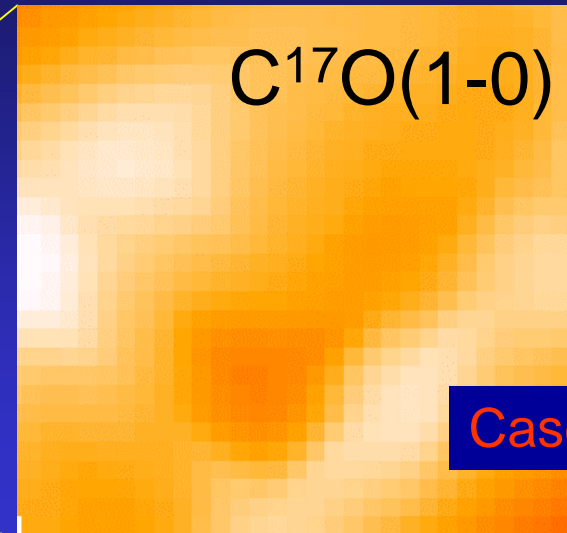
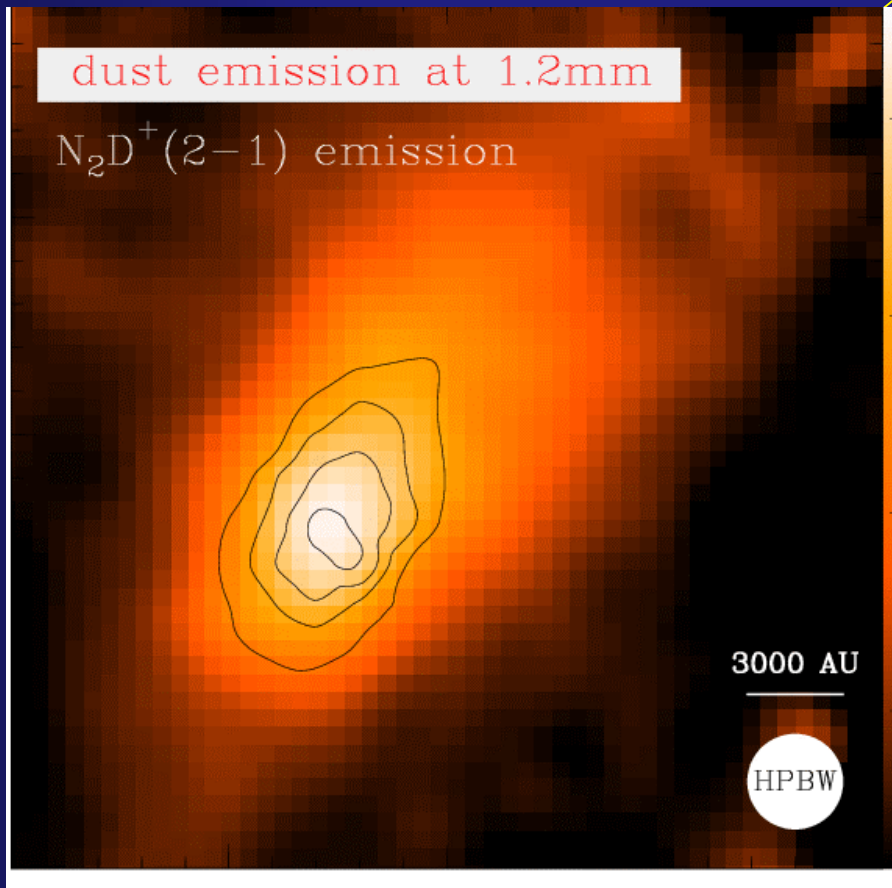
$$R_f \sim 2500 \text{ AU}$$

(Ward-Thompson et al. 1999; Pagani et al. 2003)

Caselli et al. 1999, 2002

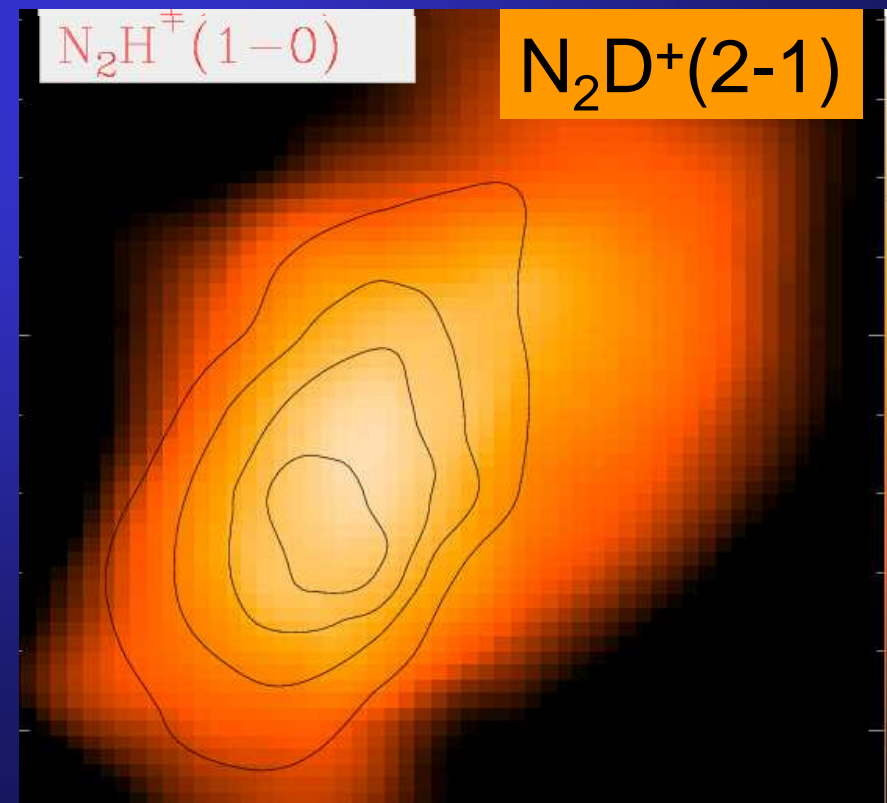
Crapsi, Caselli et al. 2004

Ricerca del tracciante del nucleo



CO scompare
dalla fase gas
a $R < 7000$ AU

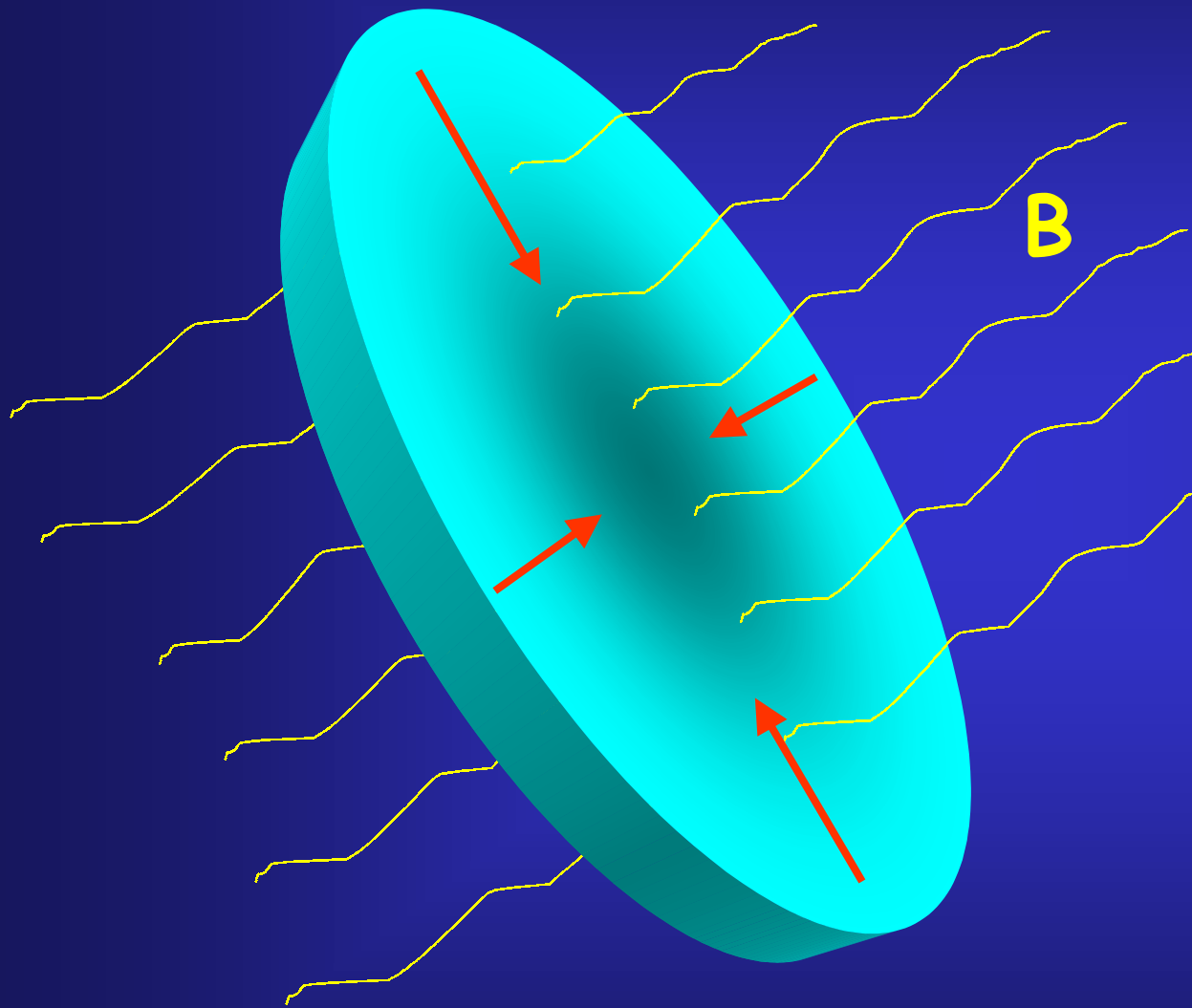
Caselli et al. 1999 (ApJ L)



N_2 è più volatile di CO $\Rightarrow N_2H^+$ e N_2D^+
sono migliori traccianti del nucleo

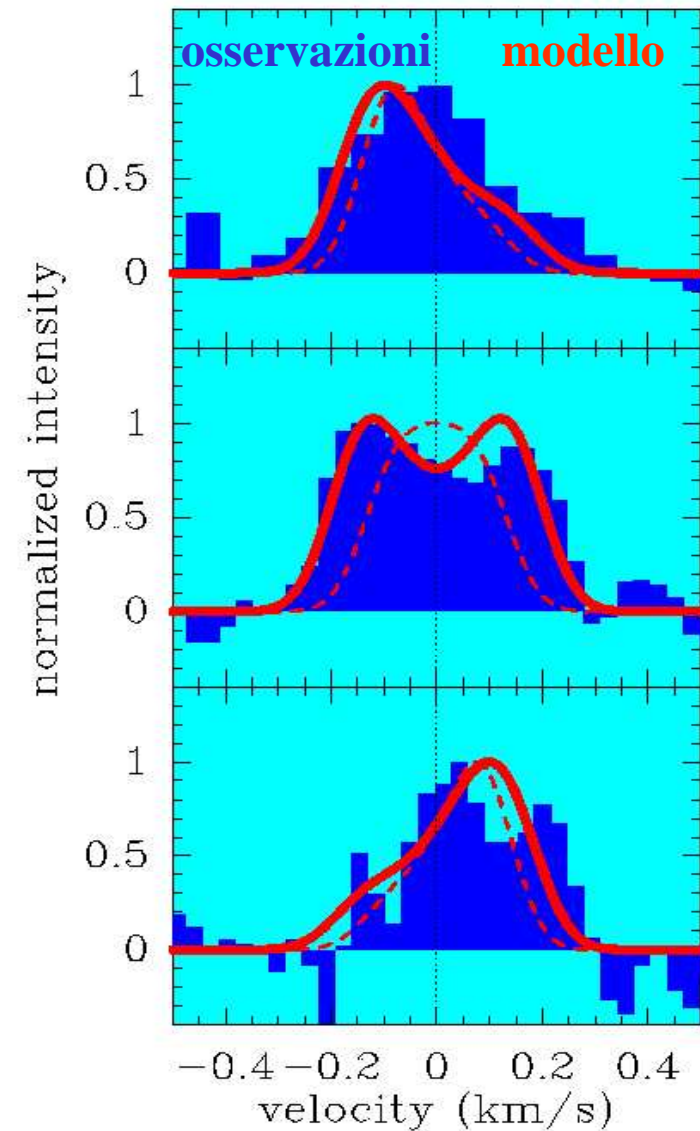
Caselli et al. 2002b,c (ApJ)

La cinematica nel nucleo pre-stellare ($r \leq 5000$ AU) è consistente con modelli di diffusione ambipolare (Caselli et al. 2002b):



Ciolek&Basu2000

Asse minore



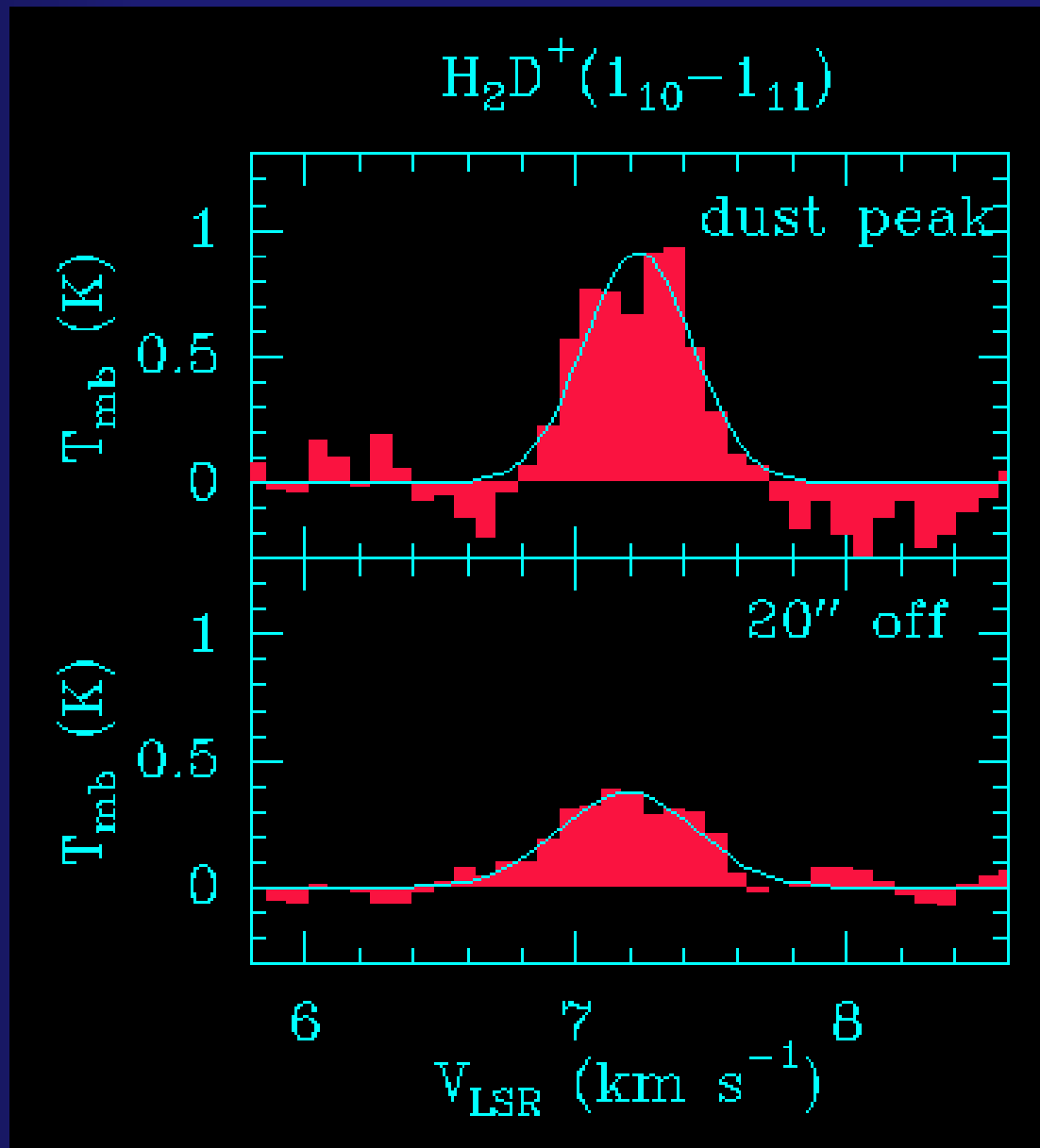
Alti gradi di deuterazione nei nuclei pre-stellari:

$$[\text{N}_2\text{D}^+]/[\text{N}_2\text{H}^+] = 0.24 \pm 0.02 \quad \text{Caselli et al. 2002c (ApJ)}$$



$\text{H}_2\text{D}^+ / \text{H}_3^+$ aumenta con la diminuzione di specie neutre dalla fase gassosa (Dalgarno & Lepp 1984)

Forte riga di *ortho*-H₂D⁺ a 372 GHz:

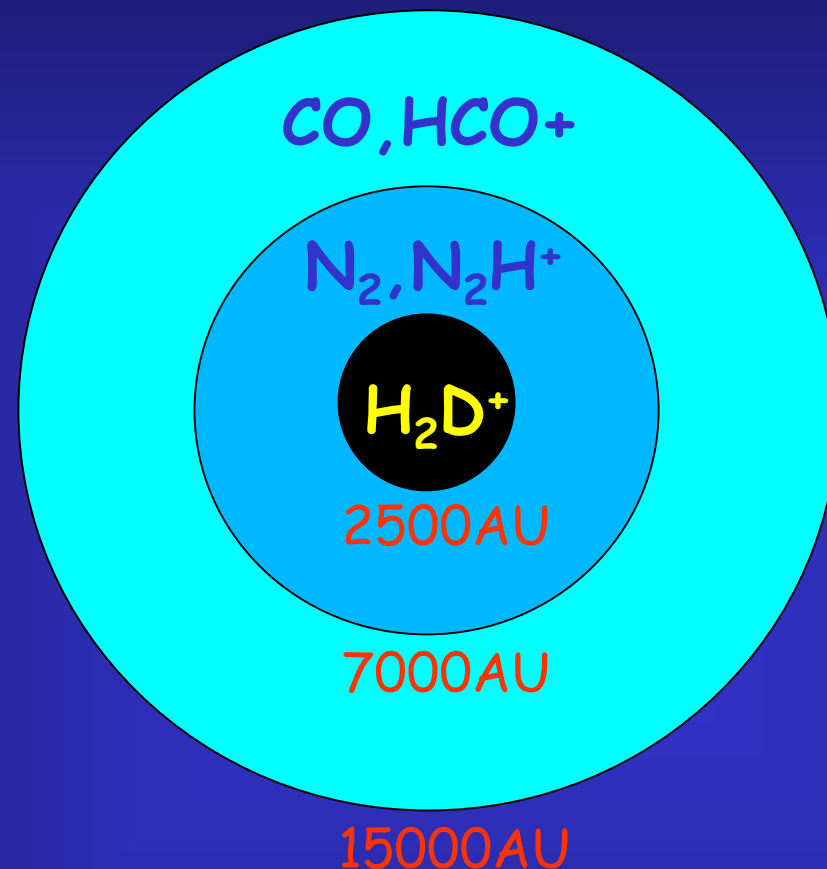


$[\text{H}_2\text{D}^+]/[\text{H}_2] \sim 10^{-9}$
entro $R \sim 2500$ AU



Tutti gli elementi più pesanti di He sono quasi totalmente ($\geq 98\%$) scomparsi dalla fase gassosa.

Sommario



Le nubi pre-stellari hanno “buchi molecolari” con raggi ~ 2500 AU, dove le particelle di polvere sono ricoperte da spessi mantelli di ghiaccio e dove l'unica specie osservabile è H_2D^+ .

Progetti futuri

- Osservazioni ad alta risoluzione angolare di H_2D^+ (D_2H^+ , H_3O^+)

- Studio dettagliato delle proprietà fisiche e chimiche di un campione statisticamente significativo di nubi pre-stellari (+ H_2D^+).

- *Utilizzæ* sviluppo di modelli chimico-dinamici e trasporto radiativo per vincolare le teorie vigenti di formazione stellare.

- Studio di ioni molecolari in laboratorio per determinare con alta precisione le frequenze, per studi cinematici e missioni future.



Utilizzo di IRAM 30m e PdB, CSO, Effelsberg 100m, VLA

...aspettando **APEX, SOFIA, Herschel, ALMA**

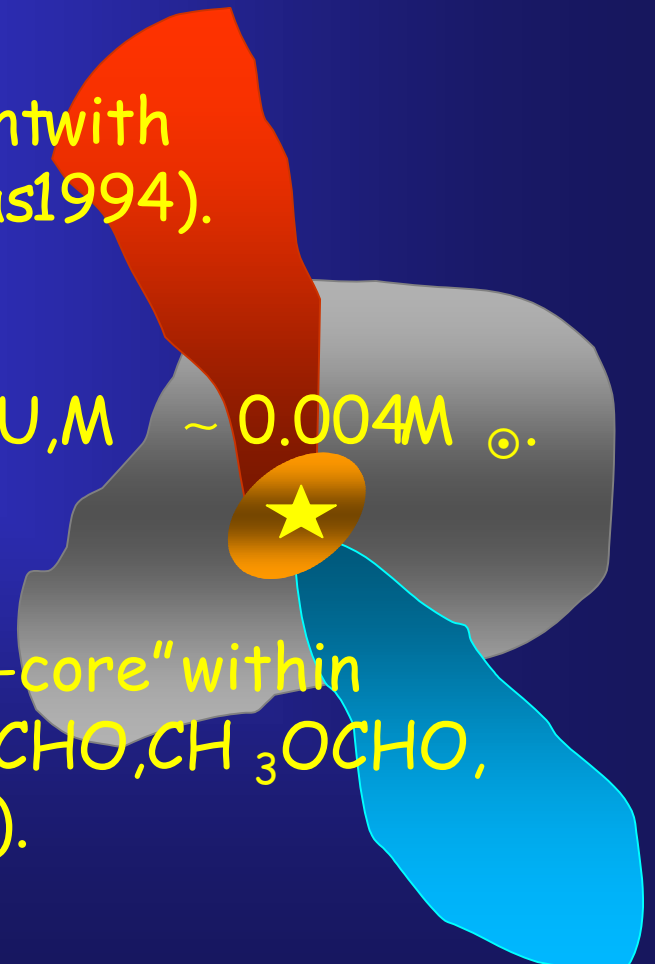
PC's summary 2: physical properties

- Internal structure ($r \leq 5000 \text{ AU}$) consistent with ambipolar diffusion models (Ciolek & Mouschovias 1995). BUT: extended infall velocities too large (Tafall et al. 1998, 2003).
- Outer envelope ($5000 \leq r \leq 15000 \text{ AU}$) kinematics: MHD turbulence (McKee & Zweibel 1995) and pressure-driven motions due to turbulence dissipation (Myers & Lazarian 1998) ? BUT: Δv increases with increasing density (Caselli et al. 2002b).
- Non-magnetic model of turbulent fragmentation of molecular cloud material (Ballesteros-Paredes et al. 2003; Klessen et al. 2003) predicts large velocity gradients in cloud cores.

Jastrow protostellar birth: Class 0 phase

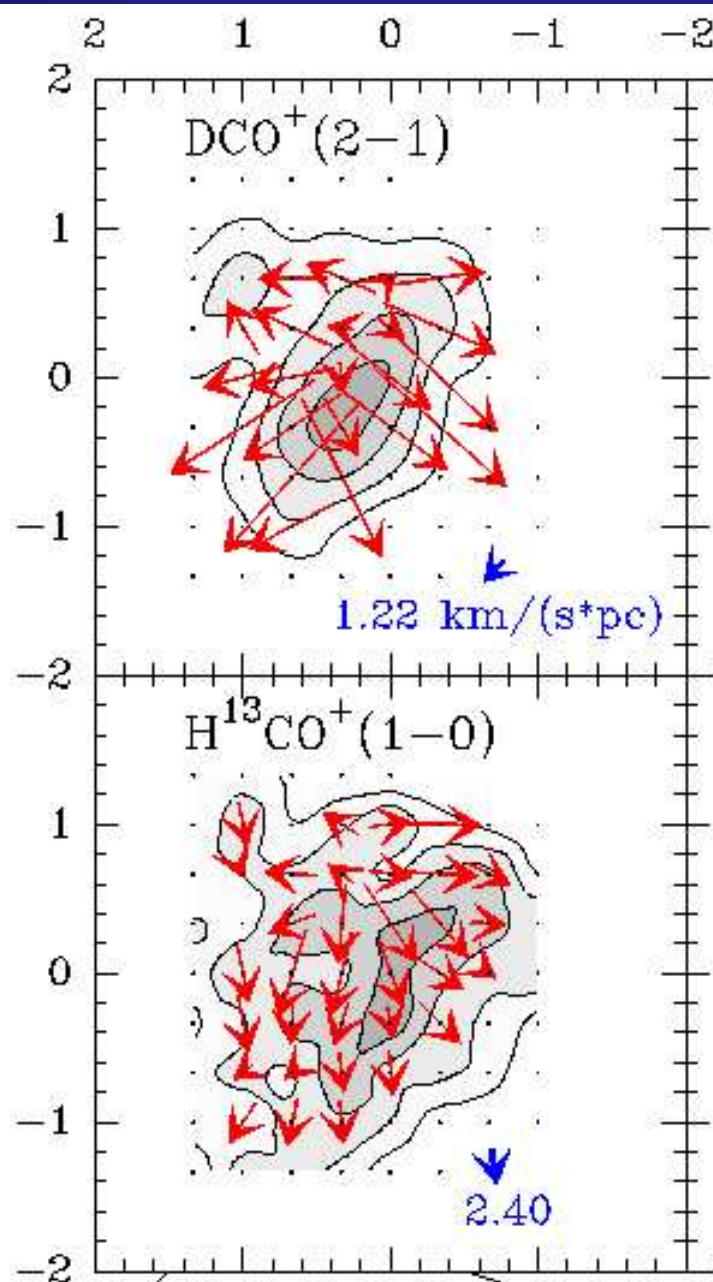
(Andr  et al. 1993, 2000)

- IRAM 04191 (*Belloche et al. 2002*): envelope of ~ 14000 AU, extended in fall, differential rotation, molecular freeze out. Inner part (~ 3500 AU) is in the process of decoupling from the ambient cloud ($\Omega \sim 12$ km/s/pc). (Partial) agreement with ambipolar diffusion models (e.g. Ciolek & Mouschovias 1994).
- B35 (*Harvey et al. 2003*): disk with $r \leq 100$ AU, $M \sim 0.004 M_{\odot}$.
- IRAS 16293 - 242 (*Cazaux et al. 2003*): "Hot-core" within central 150 AU. Rich chemistry (HCOOH , CH_3CHO , CH_3OCHO , CH_3OCH_3 , CH_3COOH , CH_3CN , $\text{C}_2\text{H}_5\text{CN}$, CH_3CCH).

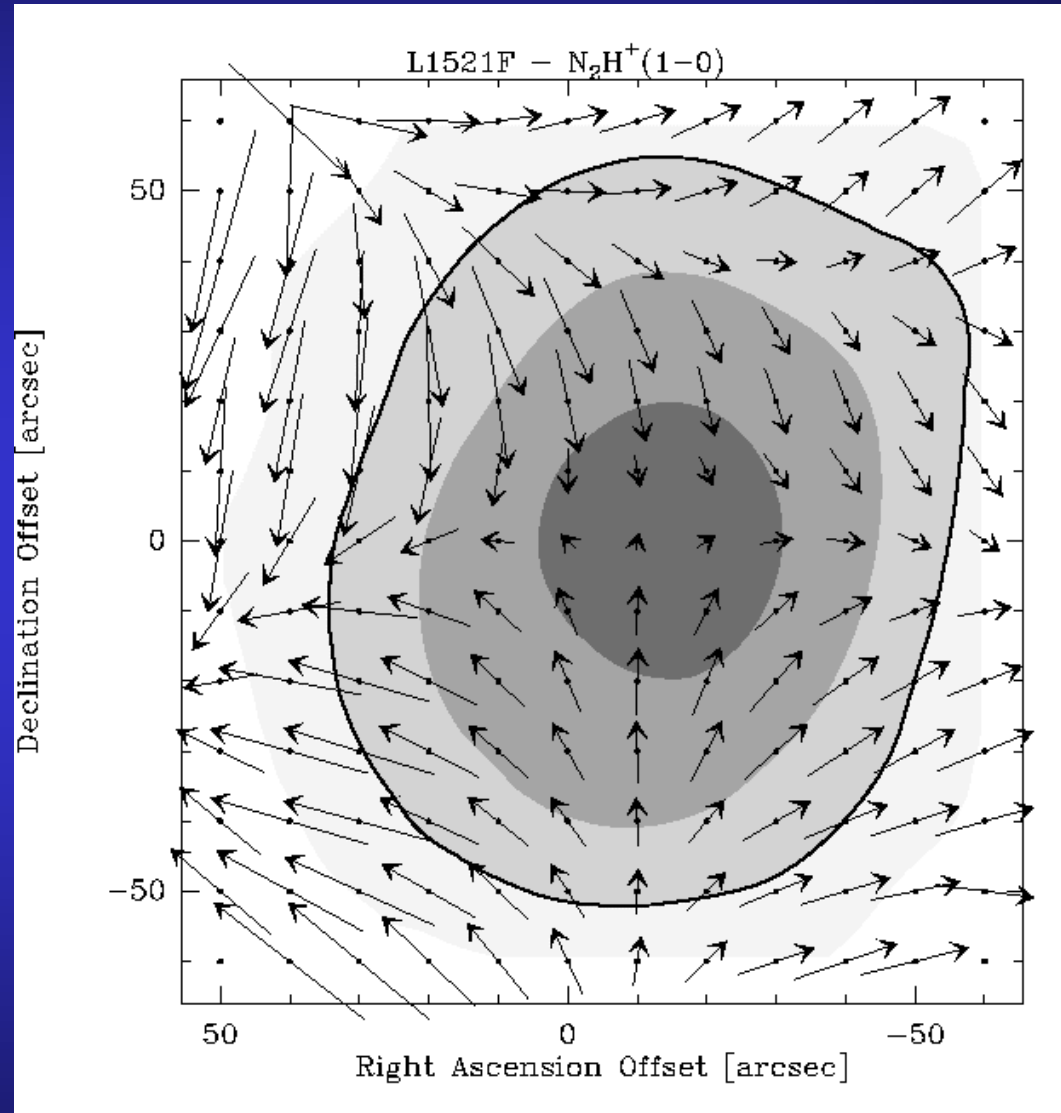


5) Complex kinematics in core envelope ($r > 5000 \text{ AU}$):

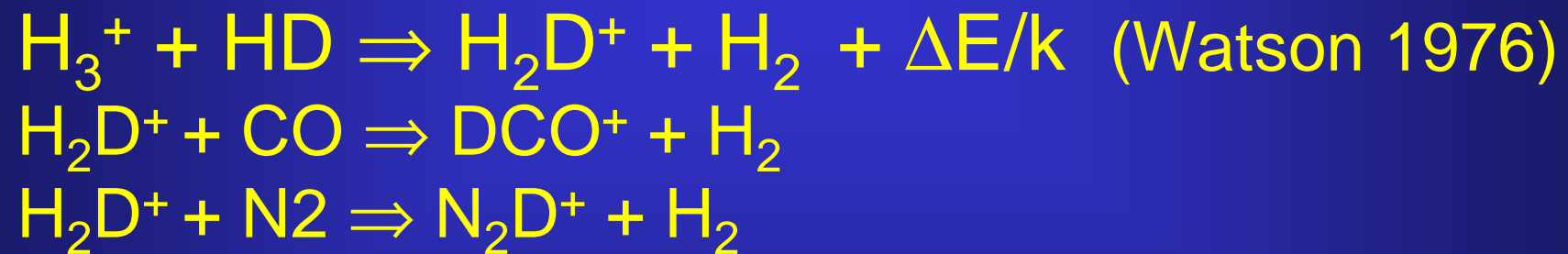
L1544



L1521F



(Crapsi et al., in prep.)

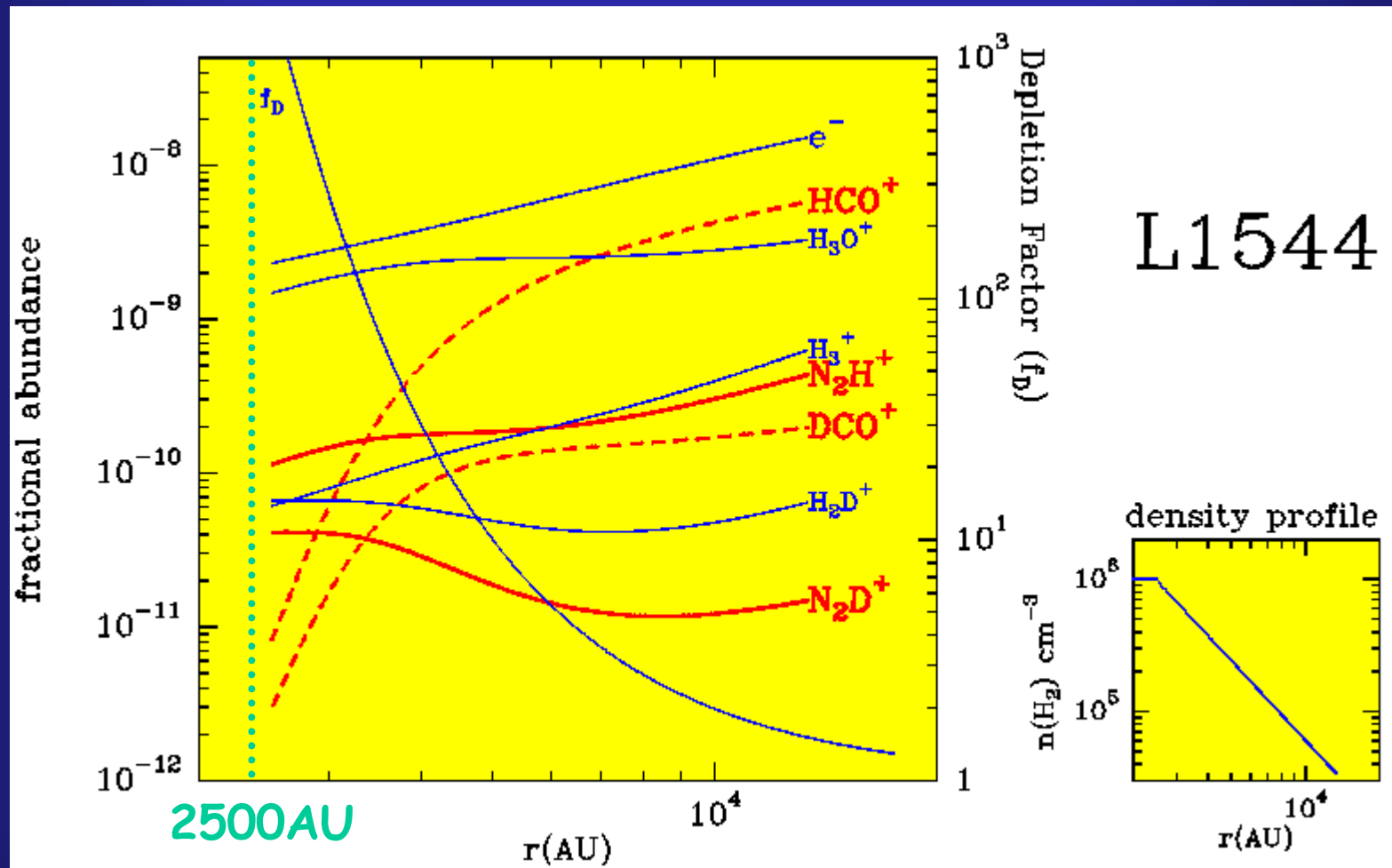


$\text{H}_2\text{D}^+ / \text{H}_3^+$ aumenta con la diminuzione di CO
(Dalgarno & Lepp 1984)

2)selectivemoleculardepletion(Casellietal.2002c)

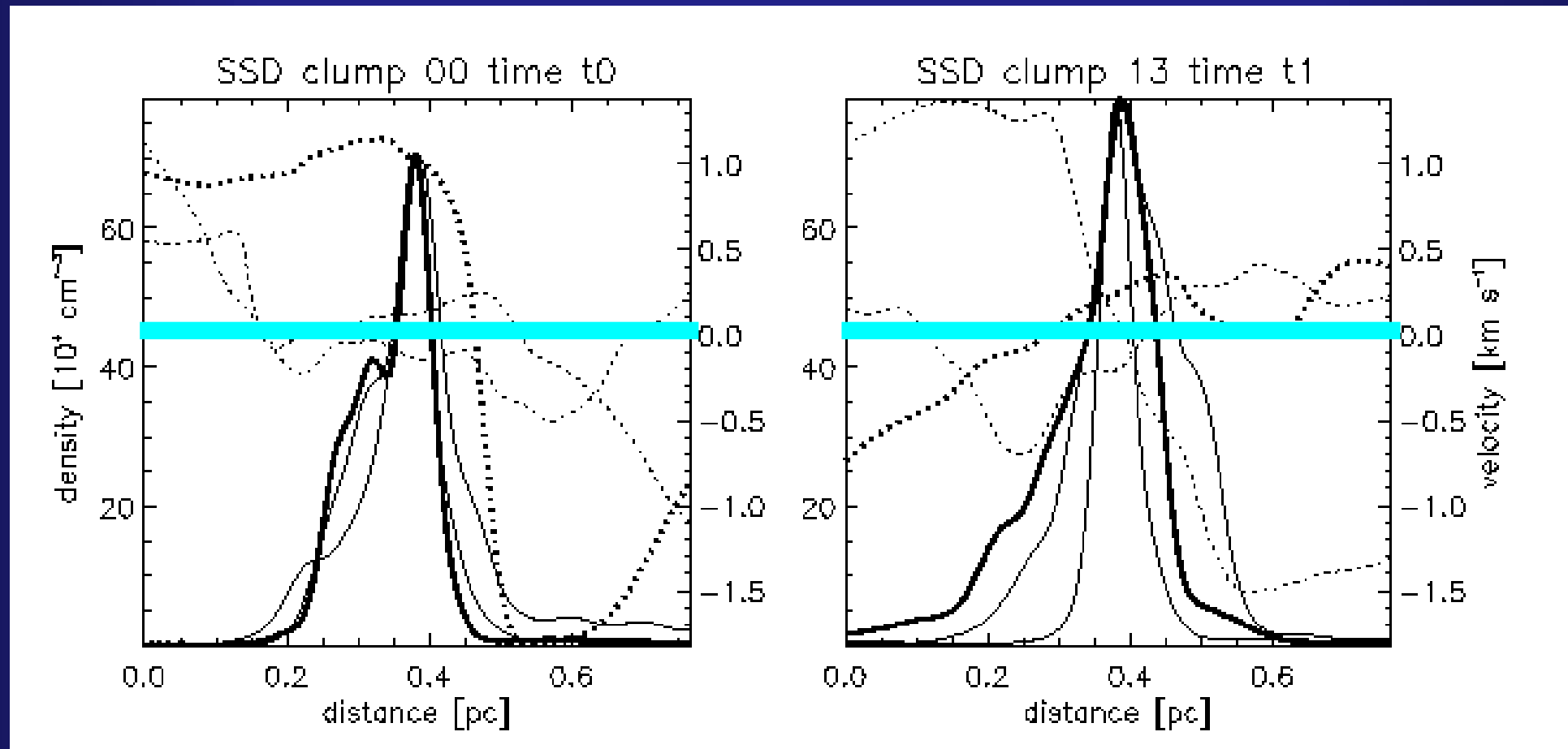
$$[\text{DCO}^+]/[\text{HCO}^+] = 0.04$$

$$[\text{N}_2\text{D}^+]/[\text{N}_2\text{H}^+] = 0.24$$



Bergin&Langer1997;Aikawaetal.2001,2003; Lietal.2001

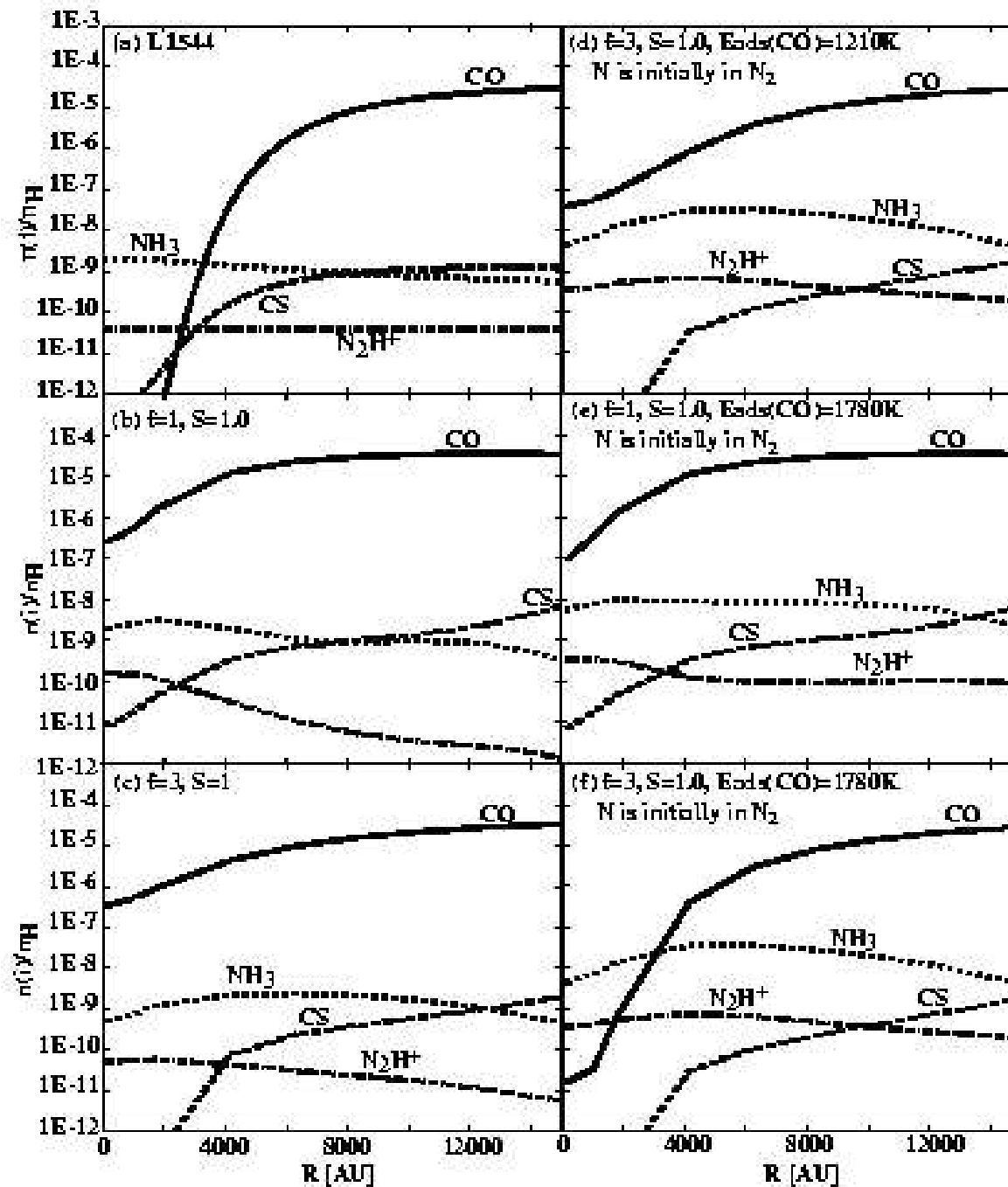
- Hydrodynamic turbulence BU velocity gradient scale:



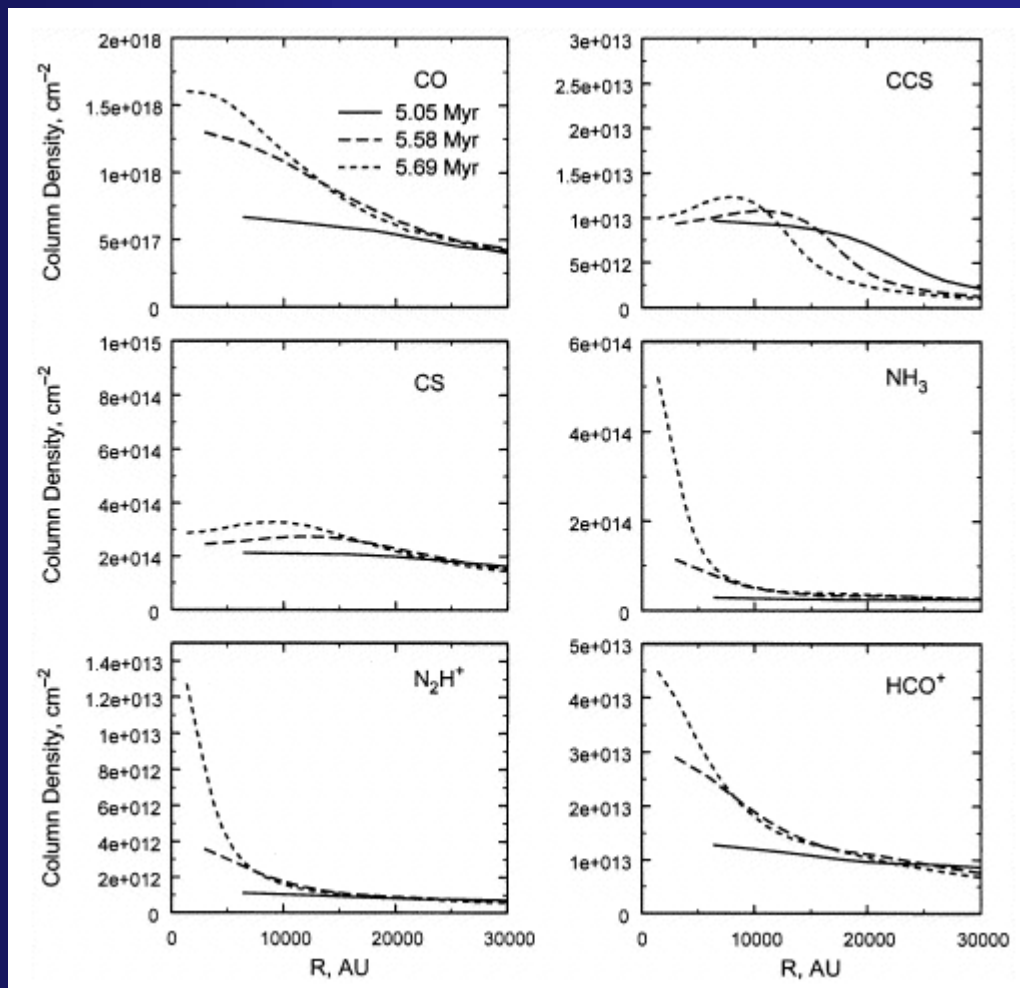
Ballesteros-Paredes, Klessen & Vazquez - Semadeni, 2003, ApJ, inpress

Conclusions

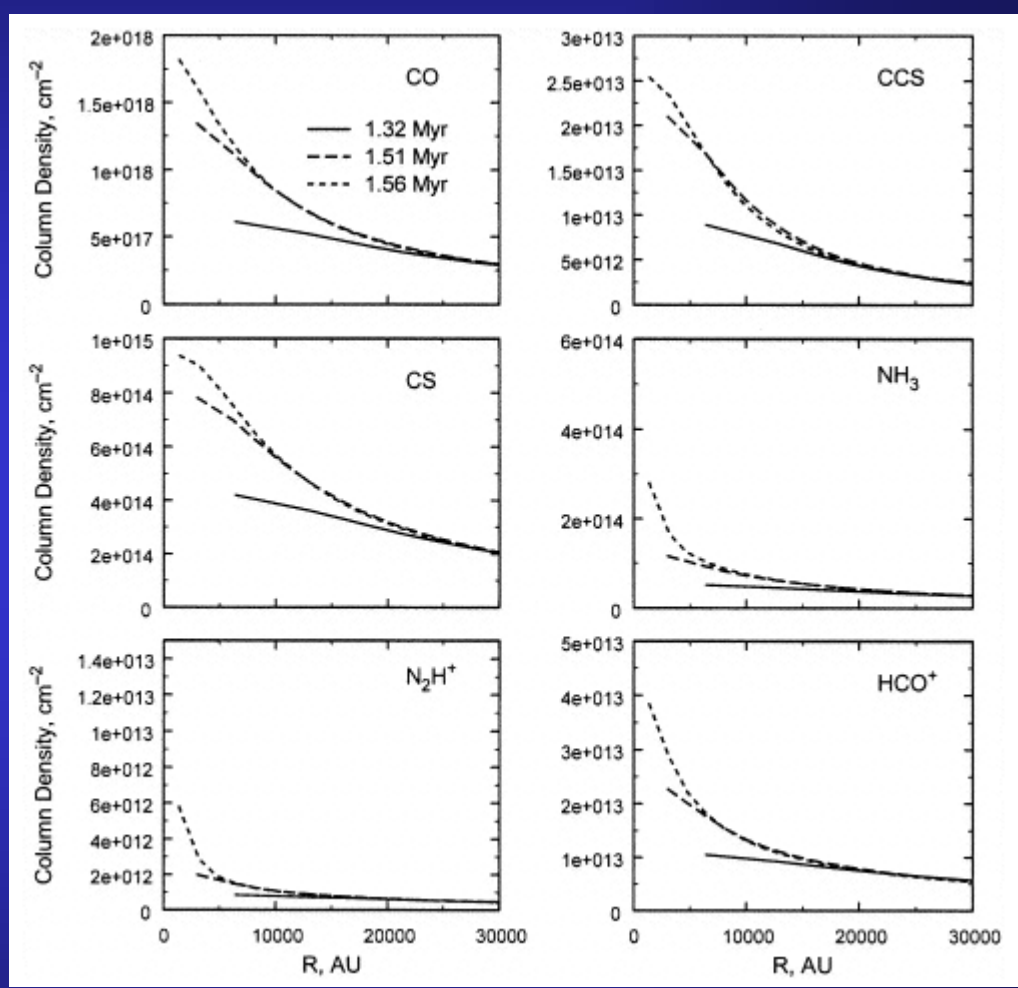
- Density profiles are probably the result of ambipolar diffusion in environments with reduced electron fractions (CS, HCO⁺)
- *Evolved* pre-stellar cores are supercritical objects undergoing infall, and with a quiescent central nucleus ($R \leq 3000 \text{ AU}$).
- CO and CS freeze out onto dust grains at densities $\geq 10^5 \text{ cm}^{-3}$, or within about 5000 AU in L1544.
- N₂D⁺/N₂H⁺: good tracer of core evolution. N₂D⁺ and N₂H⁺ offer a guide for the dynamical behaviour ($r \geq 2500 \text{ AU}$).
- Within 2500 AU (0.01 pc), all elements heavier than helium are totally depleted, leaving H₂D⁺ (and D₂H⁺) as the main ion.
- The phase of "evolved" pre-stellar cores probably lasts about 5% of the core lifetime. In L1544, a protostar will form in $\approx 2000 \text{ yr}$.



magnetic

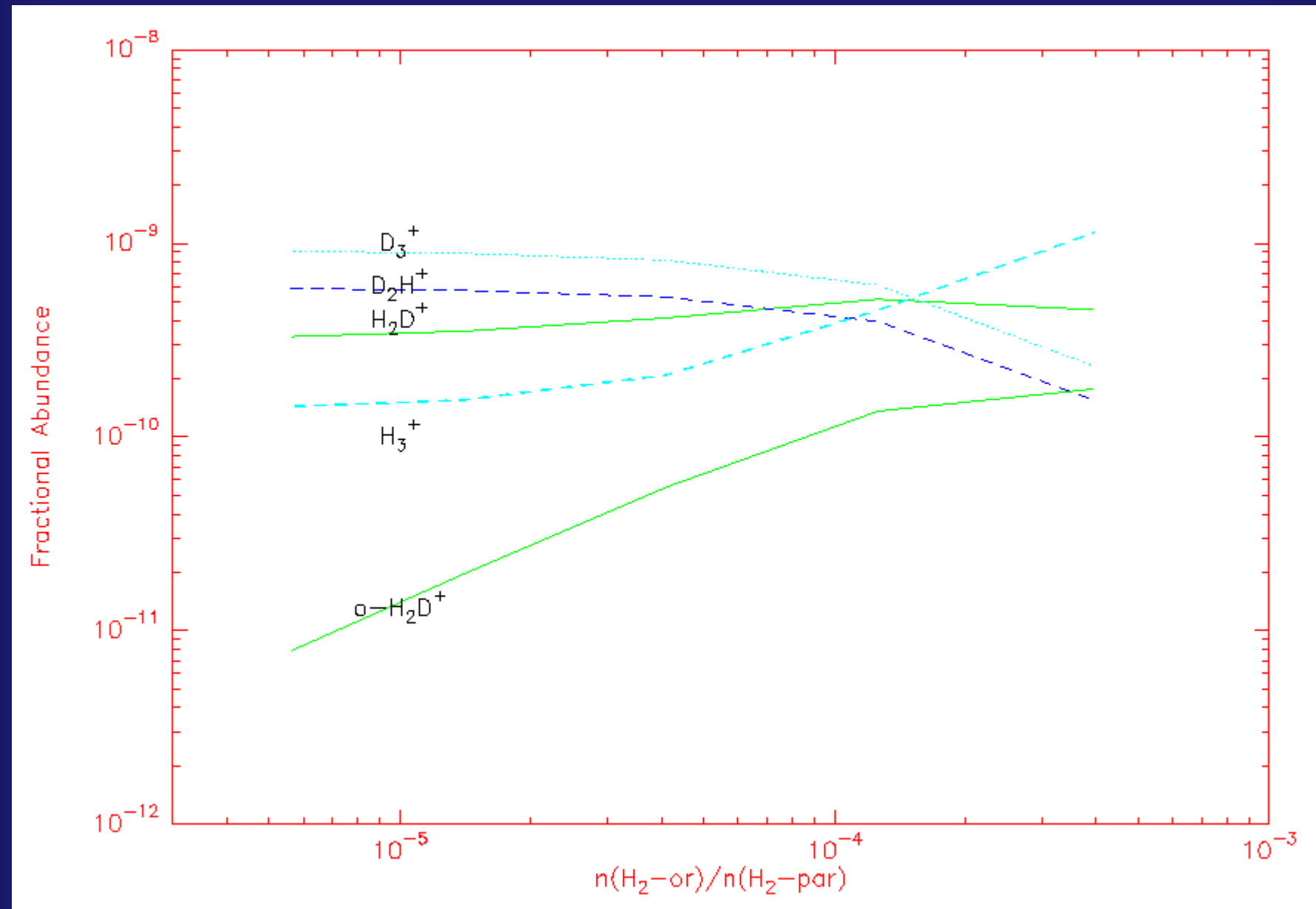


non-magnetic



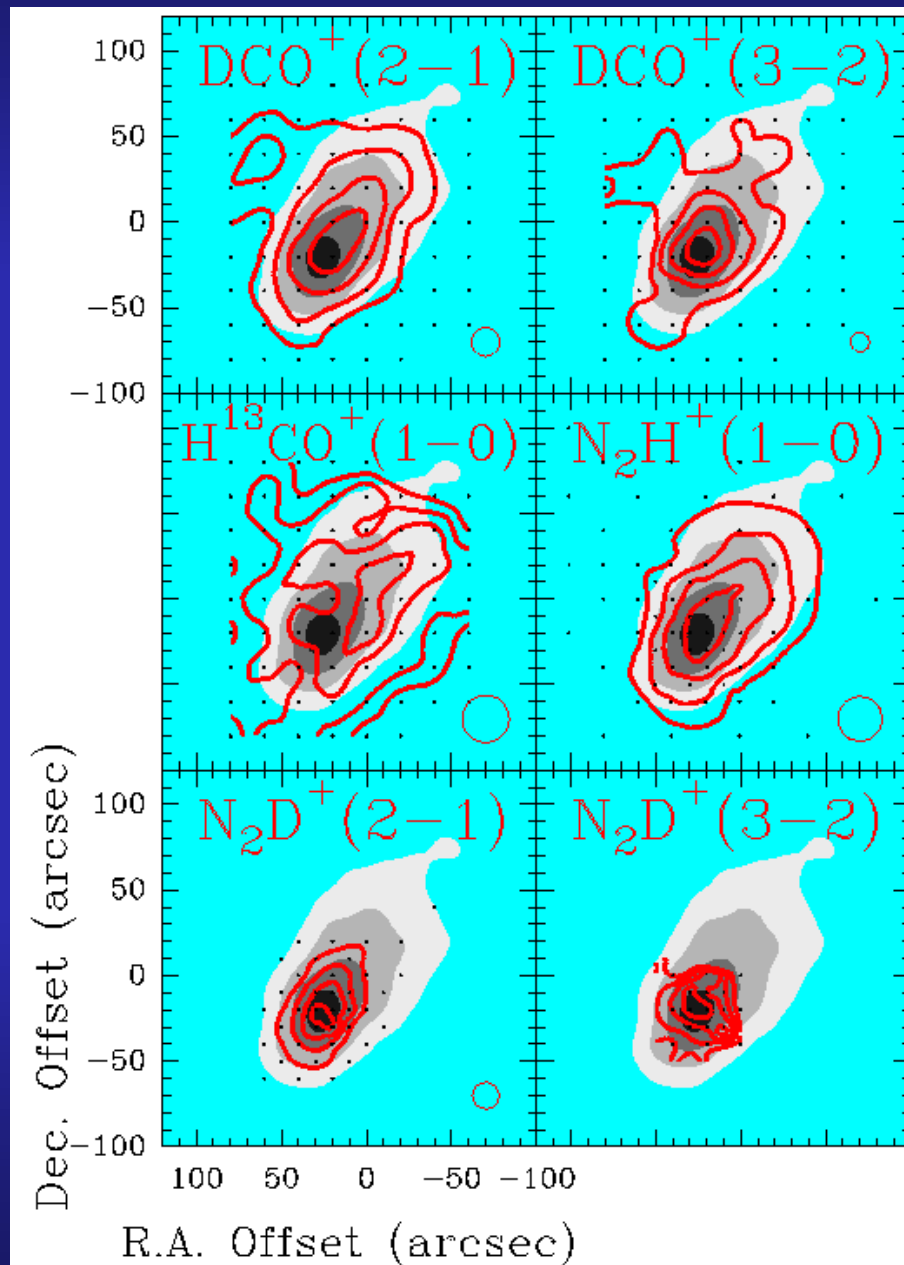
Li et al. 2002, ApJ, 569, 792

Chemistry in a totally depleted core



Walmsley et al., in prep.

The pre-stellar core L1544



Low-mass cloud cores

- in dark and diffuse clouds within a few 100 pc from the Sun.
- about 1/2 associated with low-luminosity ($\leq 10 L_{\odot}$) IRAS sources
Beichman et al. (1986)
- considered as initial conditions for model of low-mass star formation (e.g. Shu, Adams & Lizano 1987, ARA&A)

PROPERTIES BASED ON NH ₃ (1,1) AND N ₂ H ⁺ (1-0)				
	Cores with stars		Starless cores	
Parameter	Mean	Standard deviation	Mean	Standard deviation
Δv (km s ⁻¹)	0.4	0.3	0.26	0.09
T_k (K)	11	2	10	1
n (10 ⁶ cm ⁻³)	2	2	1.1	0.7
R (pc)	0.07	0.03	0.05	0.02
M (M _⊙)	8	14	3	2
Aspect ratio	1.9	0.7	2	1

Benson & Myers 1989

Caselli, Benson, Myers & Tafalla 2002

2) Extended infall (Tafalla et al. 1998; Lee et al. 2001), not consistent with "inside-out" collapse model (Shu 1977):

