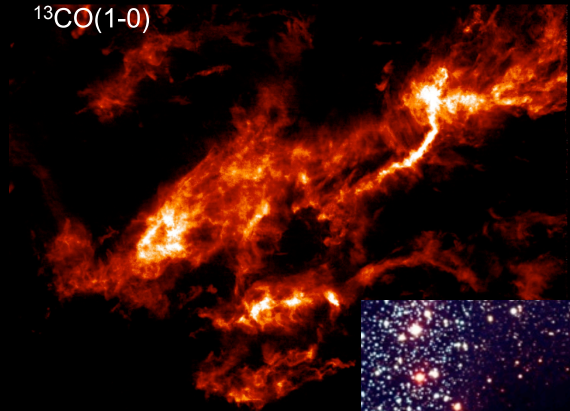
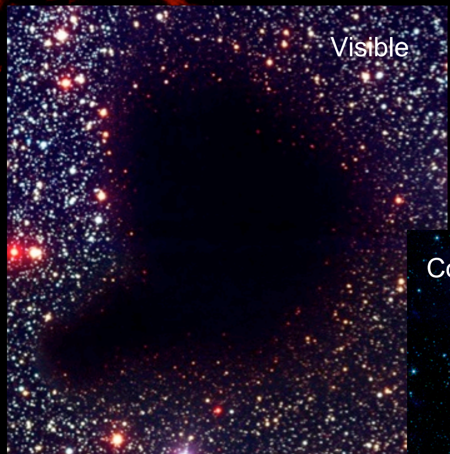
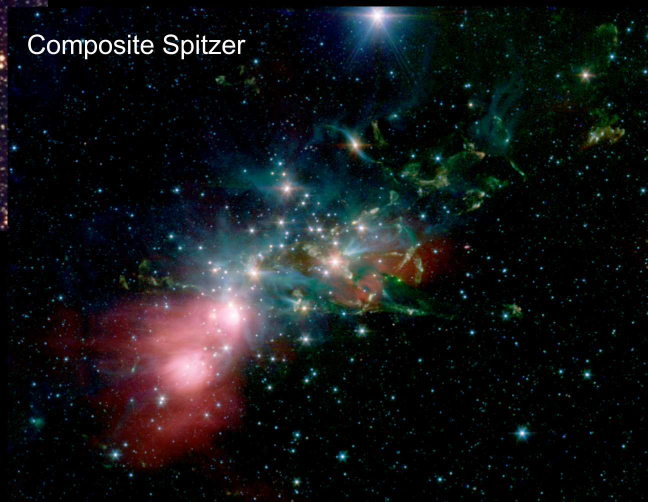
School of Physics and Astronomy
FACULTY OF MATHEMATICS & PHYSICAL SCIENCES

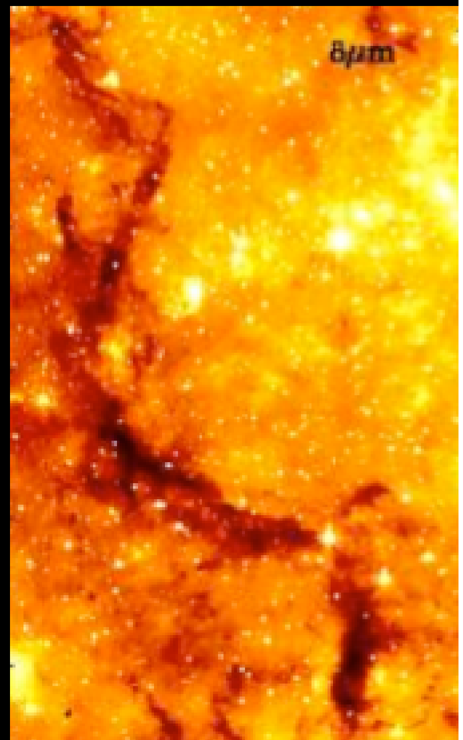
UNIVERSITY OF LEEDS



Pre-stellar cores







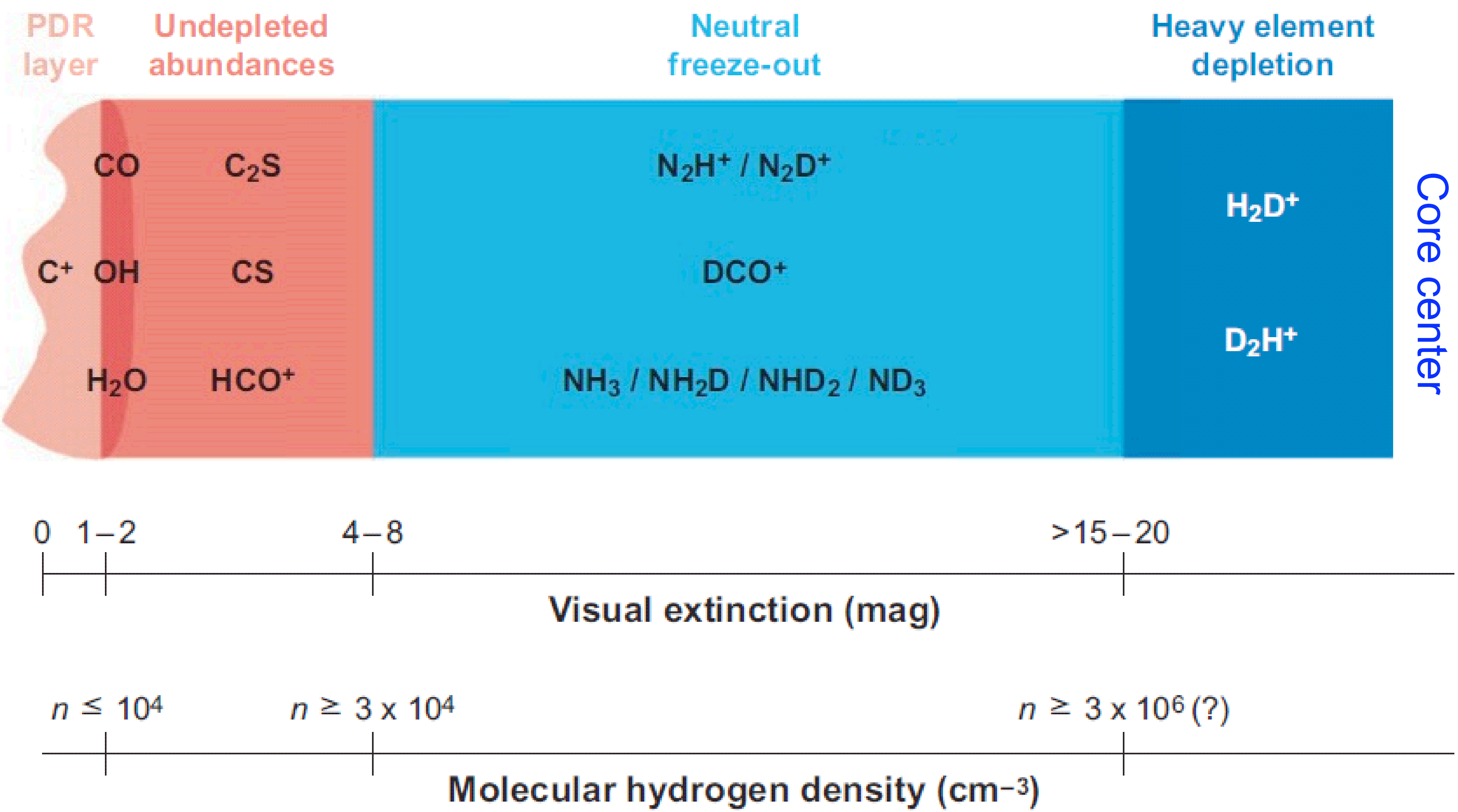
Paola Caselli

Outline

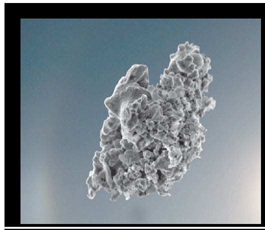
- The pre-stellar core (PSC) chemical structure
- Dust grains: freeze-out and deuteration
- Environmental effects and protostellar feedback
- Isolated vs. clustered low-mass pre-stellar cores
- Low-mass vs. high-mass

The PSC chemical structure

Molecular freeze-out and deuterium fractionation (Bergin & Tafalla 2007)

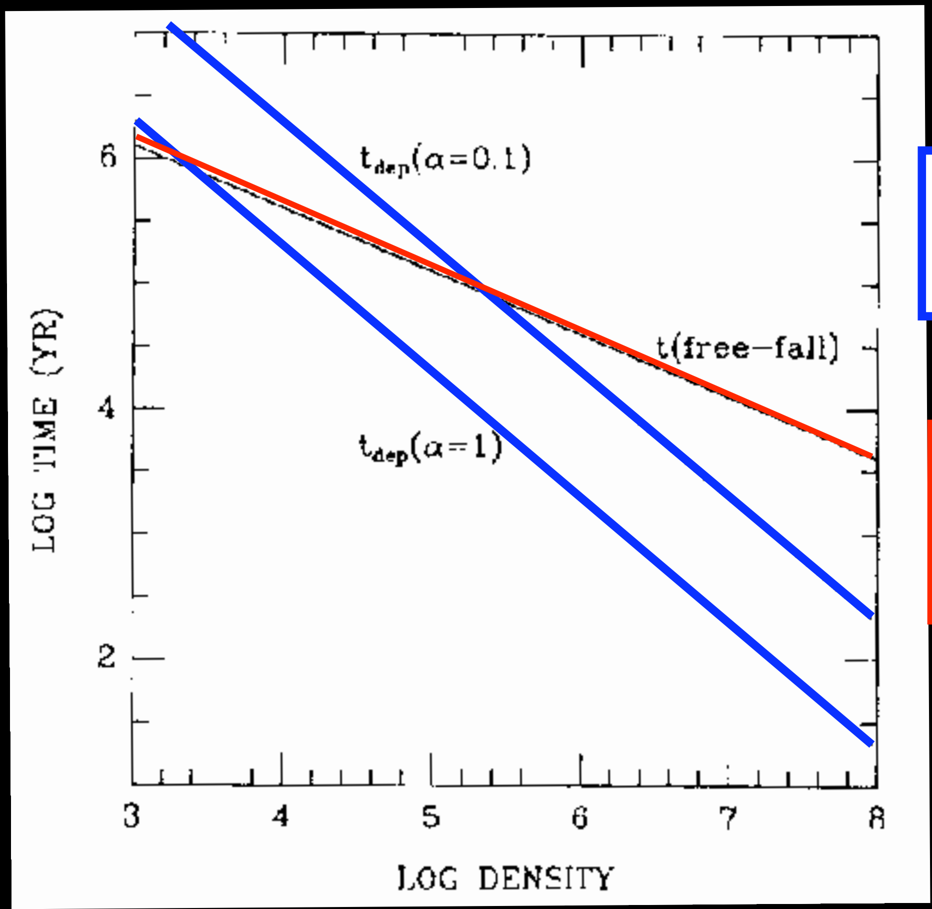


see also Di Francesco et al. 2007



The effects of gas-dust interaction

Freeze-out versus Free-fall



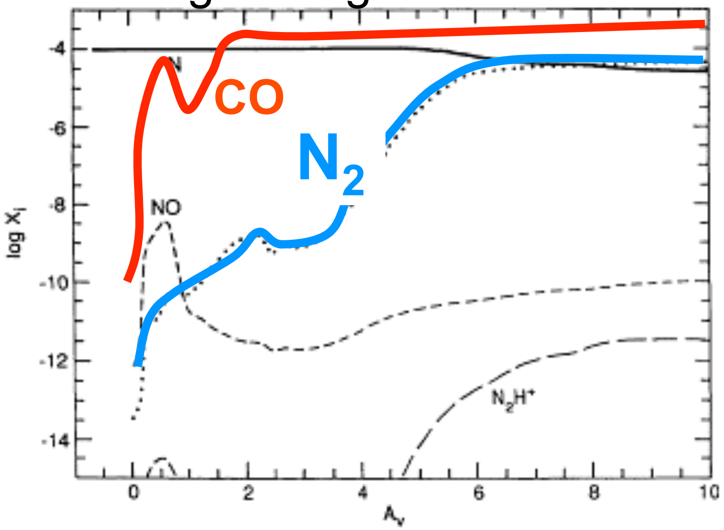
$$t_{dep} = \frac{1}{\alpha n_d \pi a_d^2 \mathrm{v}_t} \approx 10^9 \sqrt{m_X / T}\,(n_H \alpha)^{-1}\ \mathrm{yr}$$

$$t_{ff} = \left(\frac{3\pi}{32 G \rho}\right)^{-1/2} = 4 \times 10^7\ (n_H)^{-1/2}\ \mathrm{yr}$$

Walmsley 1991
van Dishoeck et al. 1993

Nitrogen chemistry

Sternberg & Dalgarno 1995



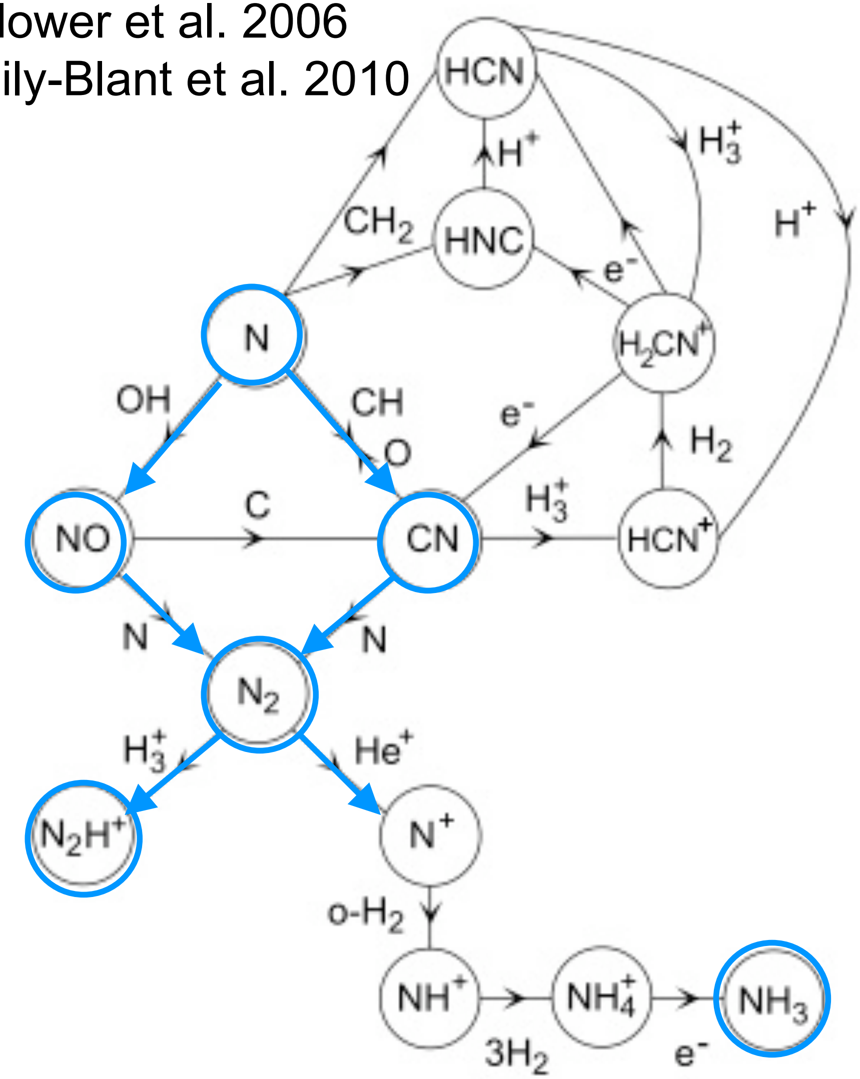
$N + H_3^+ \not\rightarrow NH^+ + H_2$

$N + OH \rightarrow NO + H$

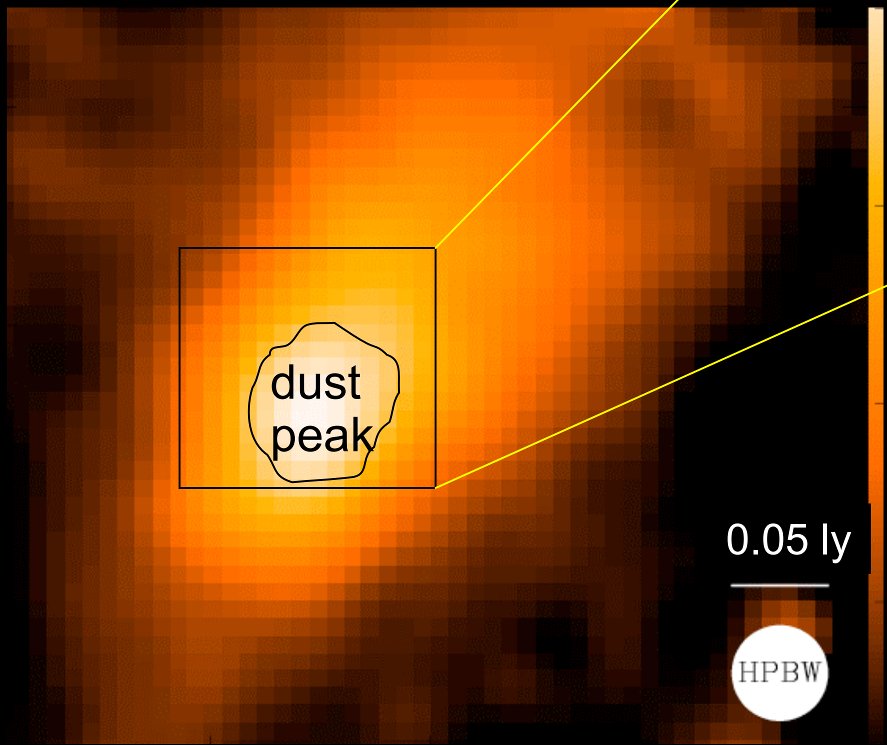
$N + CH \rightarrow CN + H$

Flower et al. 2006

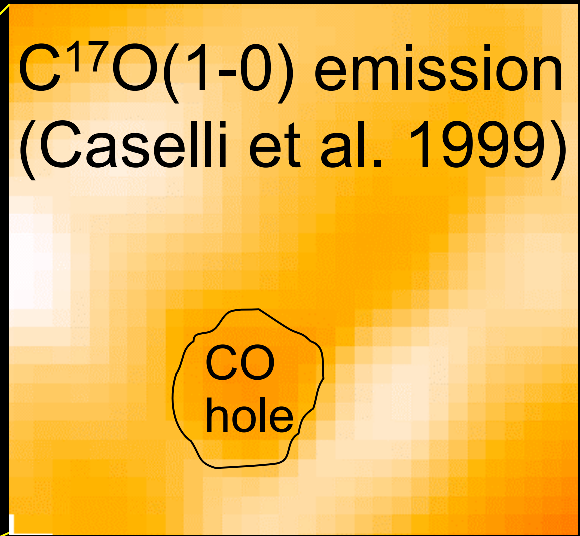
Hily-Blant et al. 2010



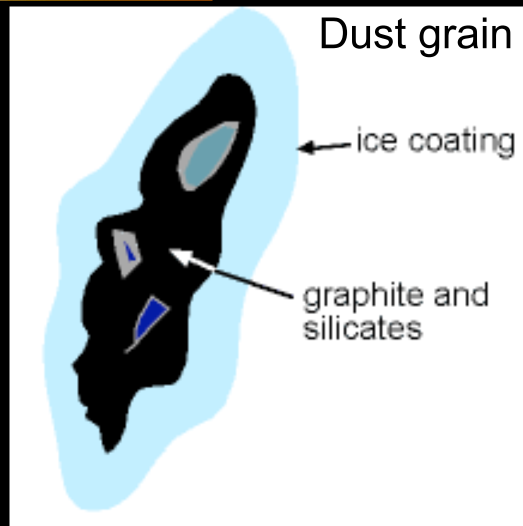
Evidence of freeze-out: the "missing" CO



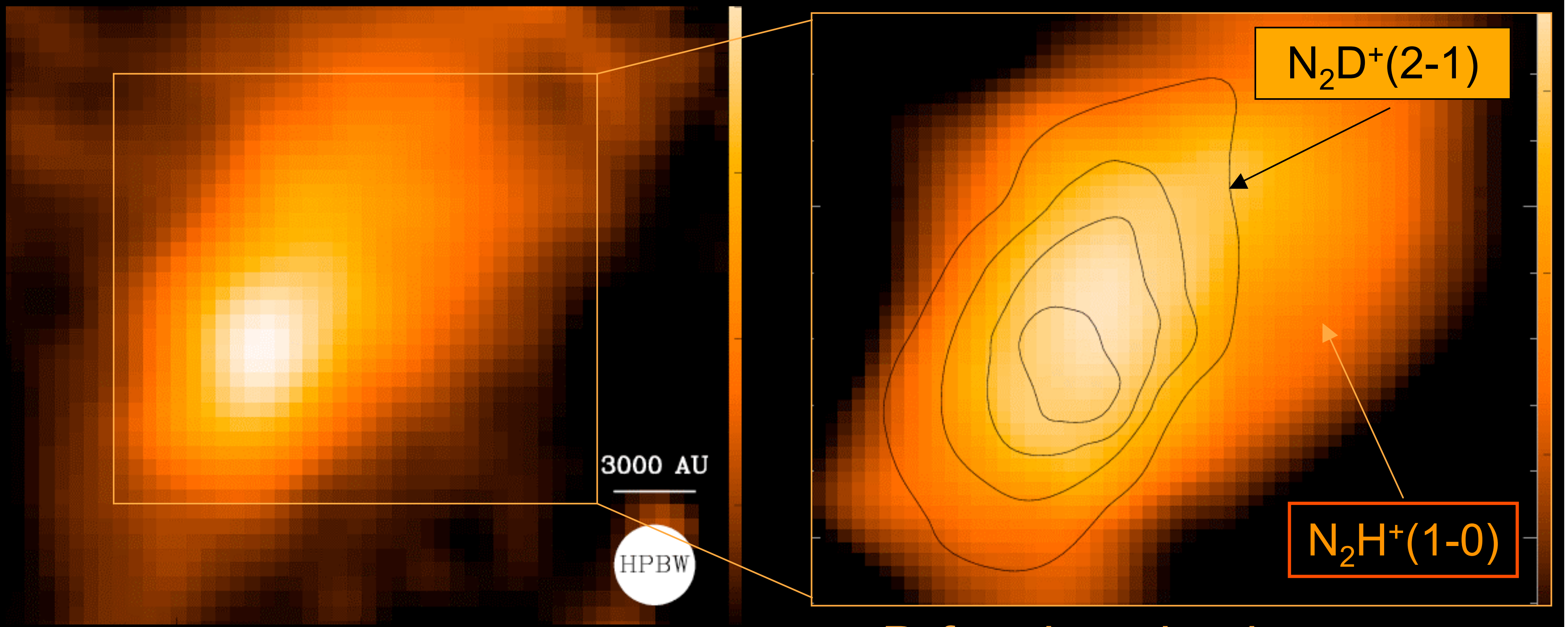
Dust emission in a pre-stellar core (Ward-Thompson et al. 1999)



Molecules freeze out onto dust grains in the center of pre-stellar cores ➔



Evidence of freeze-out: deuterium fractionation



Dust emission in the pre-stellar core L1544 (Ward-Thompson et al. 1999)

D-fractionation increases towards the core center (~0.2; Caselli et al. 2002; Crapsi et al. 2004, 2005)

See also Bacmann et al. 2002; 2003

Deuterium Fractionation at T < 20 K

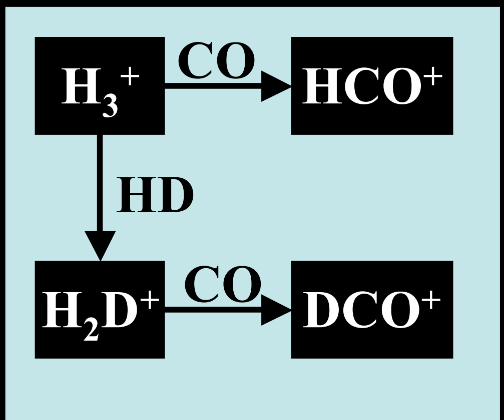
$$H_3^+ + HD \Rightarrow H_2D^+ + H_2 + 230\ K$$

Watson 1974
Millar et al. 1989

$$H_2D^+ + N_2 \rightarrow N_2D^+ + H_2$$

$$H_2D^+ + CO \rightarrow DCO^+ + H_2$$

H_2D^+ / H_3^+ increases if the abundance of gas phase neutral species decreases (Dalgarno & Lepp 1984; Roberts & Millar 2000)



CO freeze-out ⇒

LOWER H_2D^+ **and** H_3^+ destruction rates

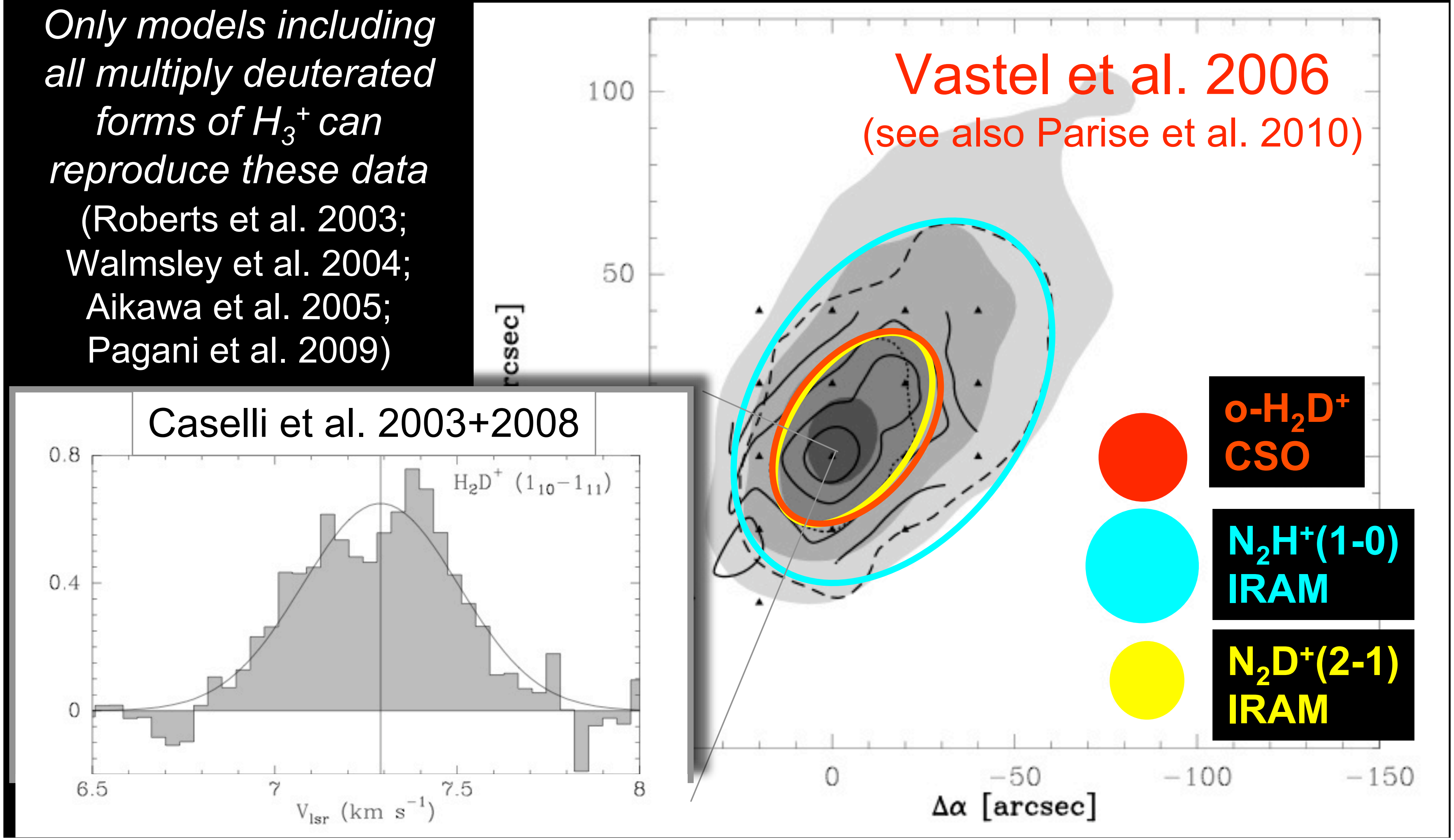
HIGHER H_2D^+ formation rate

LARGER H_2D^+/H_3^+ abundance ratio and deuterium fractionation

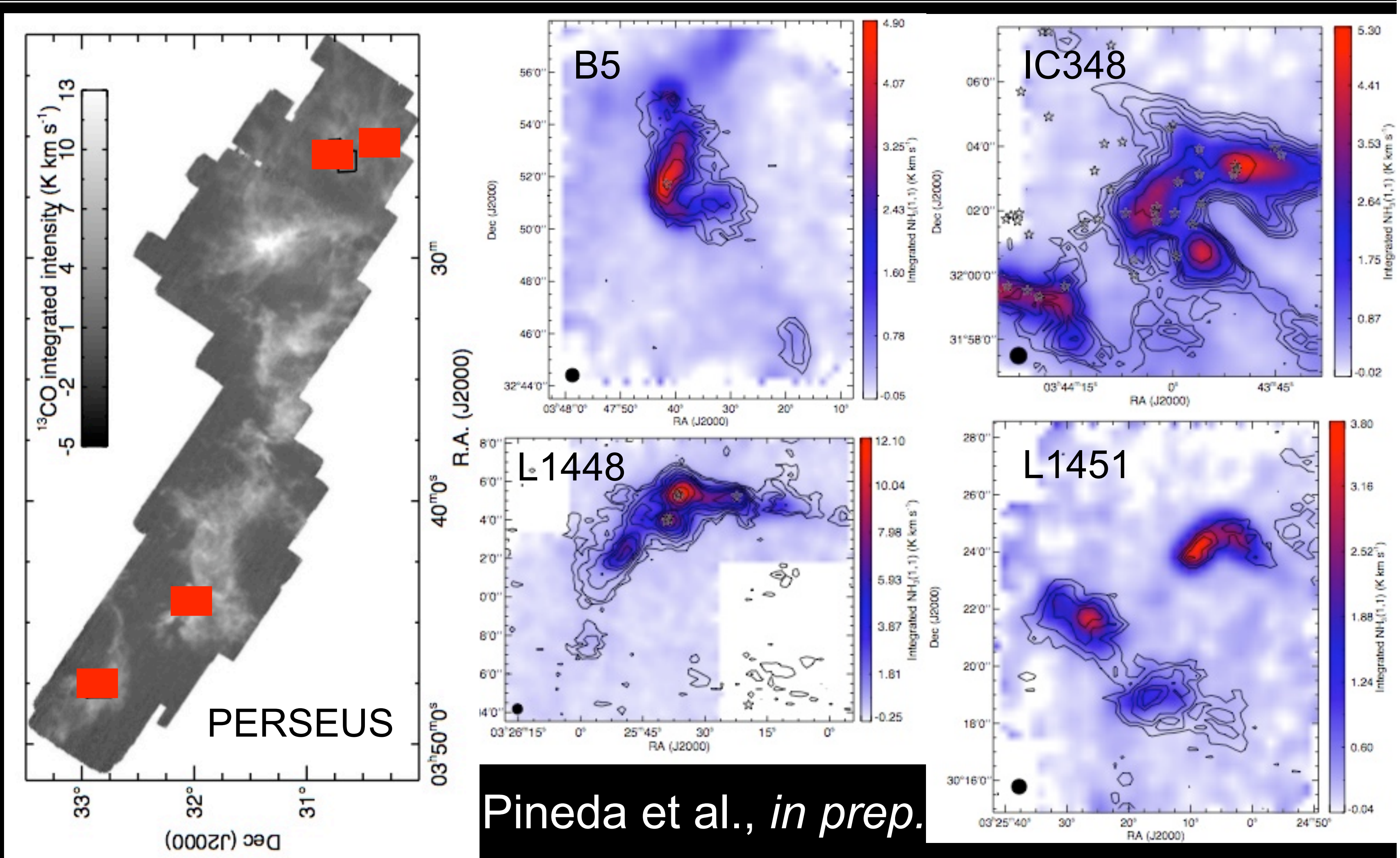
D-fractionation: o-H_2D^+

ortho-H_2D^+ and N_2D^+ trace the same region (size ~ 5000 AU) ➔

Only models including all multiply deuterated forms of H_3^+ can reproduce these data
(Roberts et al. 2003; Walmsley et al. 2004; Aikawa et al. 2005; Pagani et al. 2009)



Environmental effects



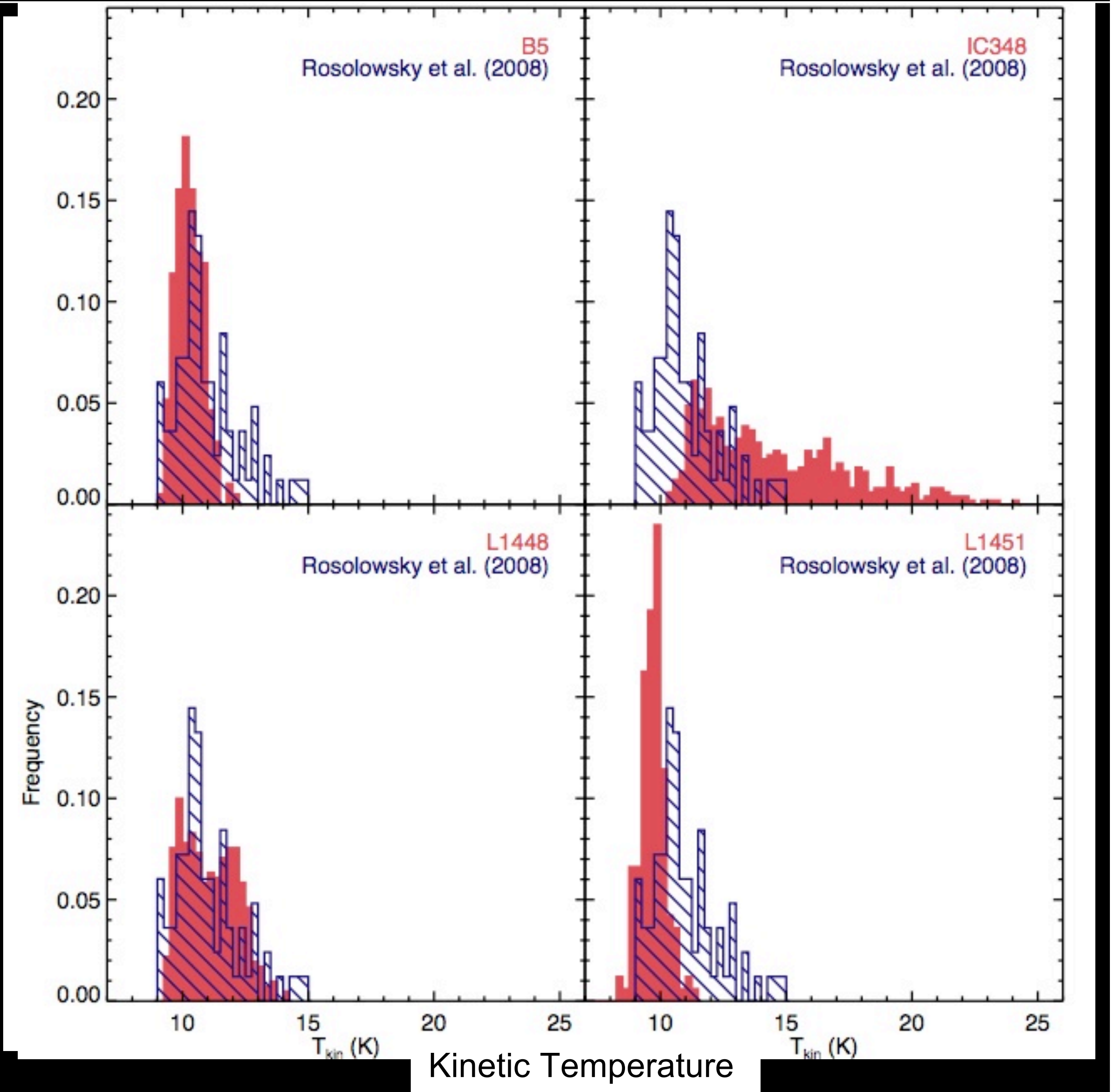
Pineda et al., *in prep.*

Protostellar feedback

Protostellar feedback affects the physical conditions of the surrounding cloud (especially in cluster forming regions).

Quiscence is soon lost…

Pineda et al., *in prep.*



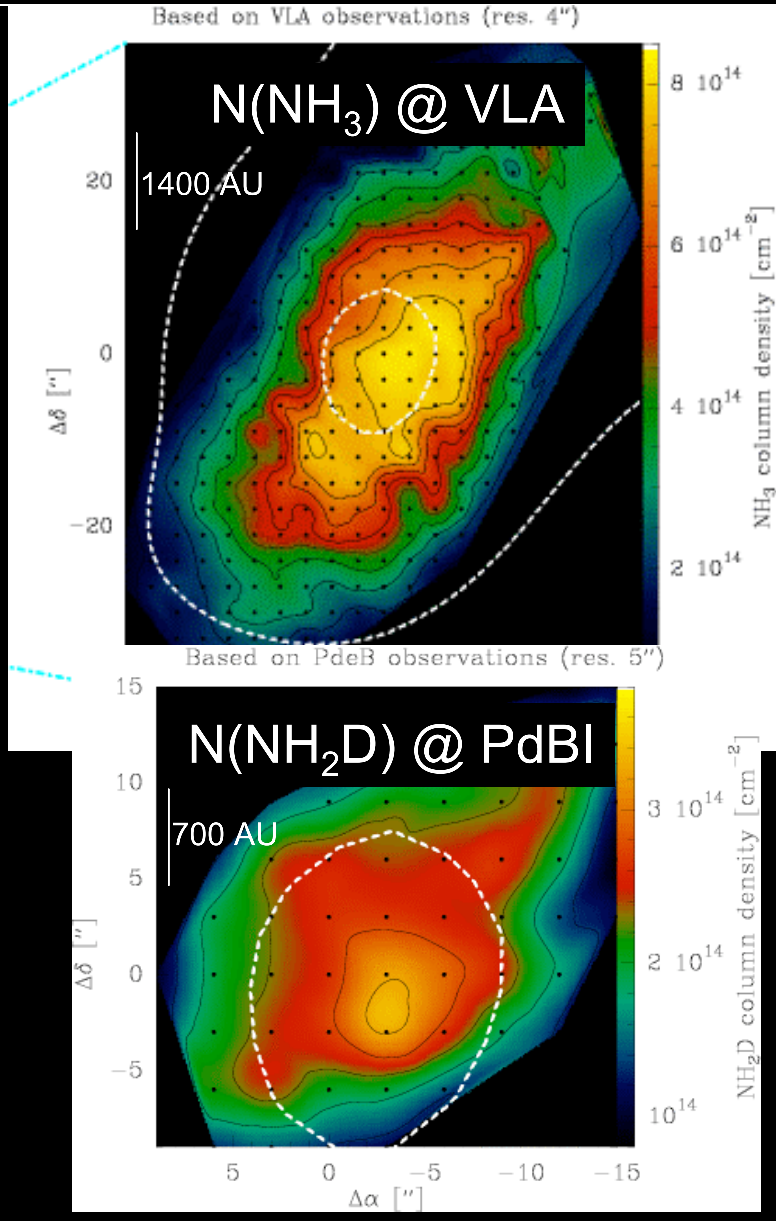
NH_3, NH_2D and the physical structure

- On size scale of ~800 AU:
No NH_3 freeze-out (X_{NH3} ~ 10^{-8}) at n_H ~ 10^6 cm^{-3} (inner 1000 AU) !

- The gas temperature drops to ~6 K in the central 1000 AU

- The deuterium fractionation is ~0.4 in the central 3000 AU

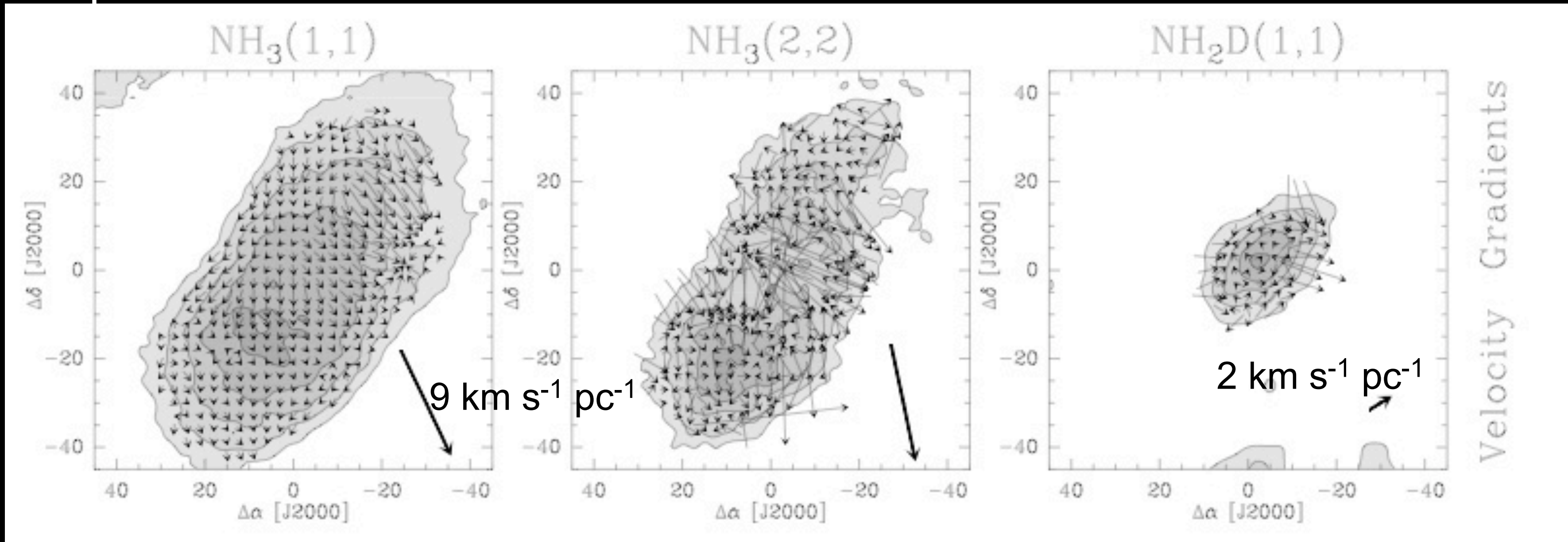
- Loss of specific angular momentum towards the small scales



Crapsi, Caselli, Walmsley & Tafalla 2007

Velocity gradients and the specific angular momentum

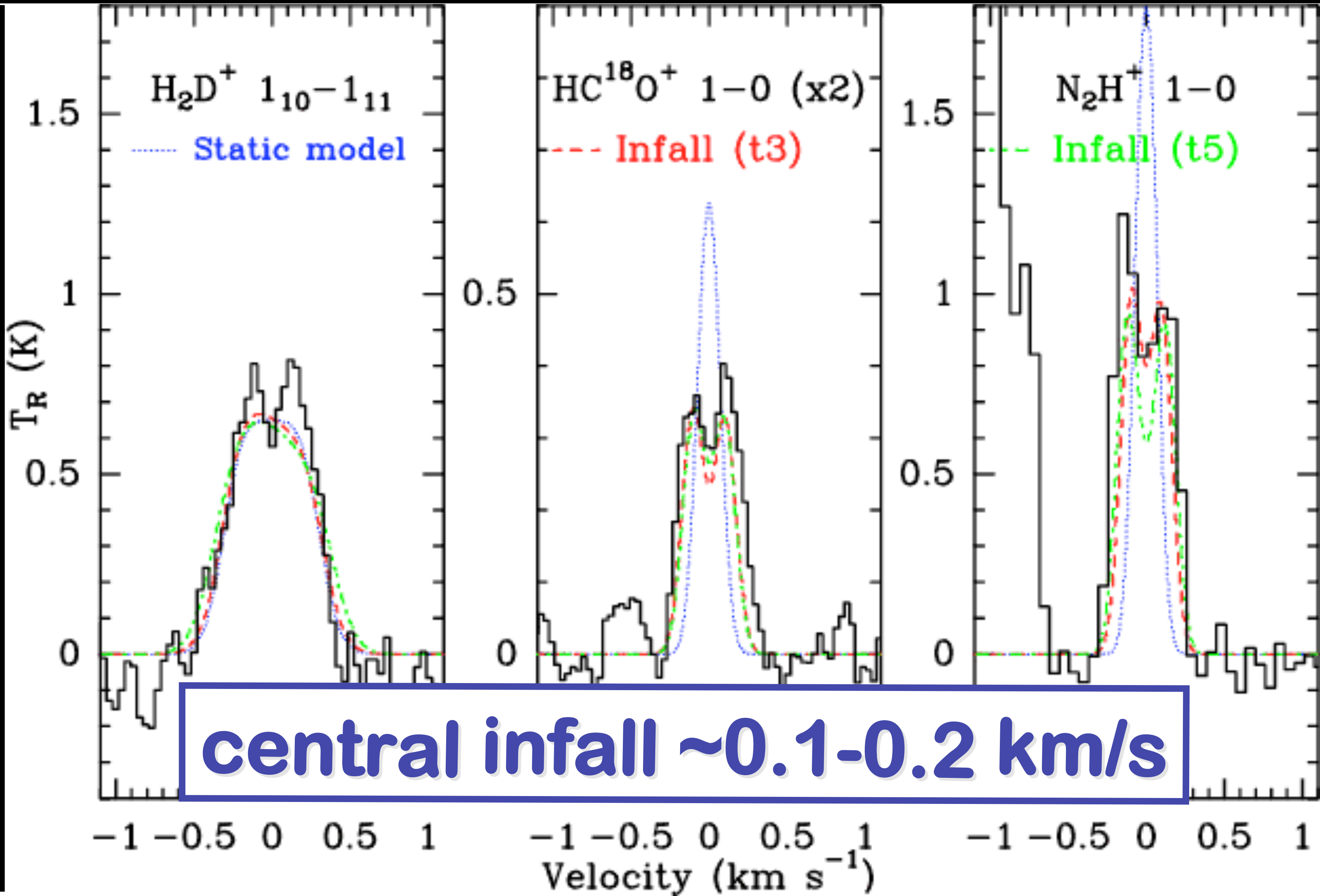
Crapsi et al. 2007



$L(NH_3) \sim 5x10^{21}\ cm^2\ s^{-1}$ $L(NH_2D) \sim 3x10^{20}\ cm^2\ s^{-1}$

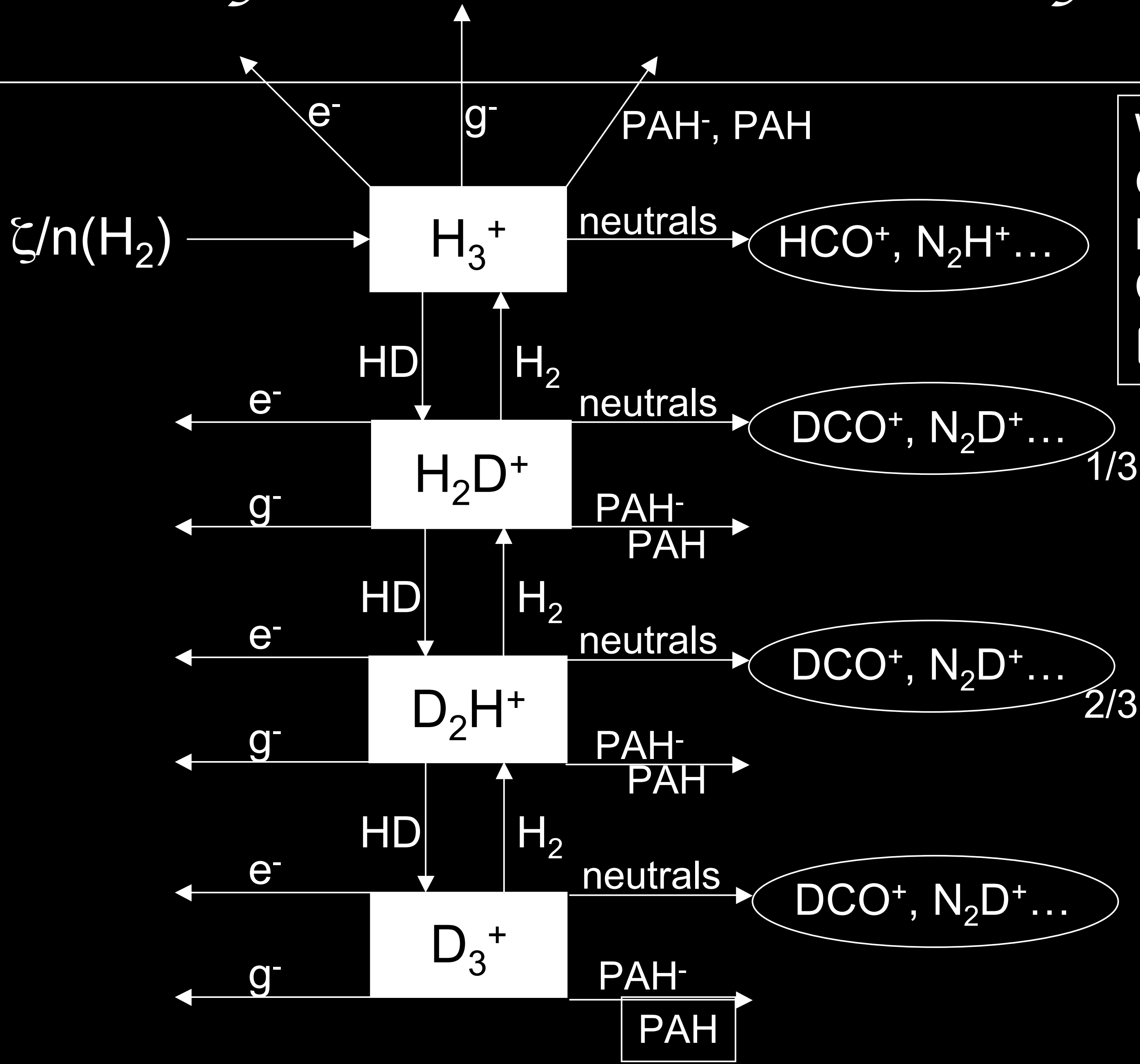
The loss of L towards the small scales is consistent with observations in more evolved sources (Belloche et al. 2002).

Kinematics



van der Tak, Caselli, Ceccarelli 2005 (see also Williams, Lee & Myers 2006)

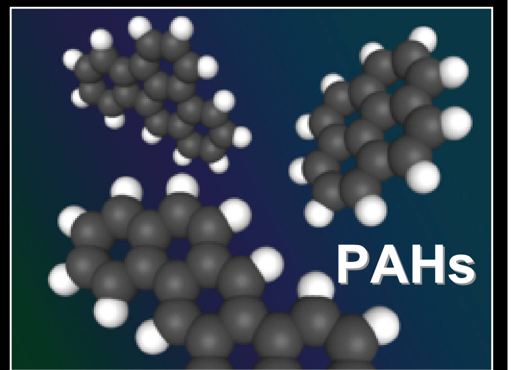
D-fractionation and ion fraction



Wootten et al. 1979
Guelin et al. 1982
Bergin et al. 1998
Caselli et al. 1998
Dalgarno 2006

Uncertainties:
- **PAHs, PAH$^-$s**
- **neutrals (O)**
- **ortho:para H_2**

(Flower et al. 2006)

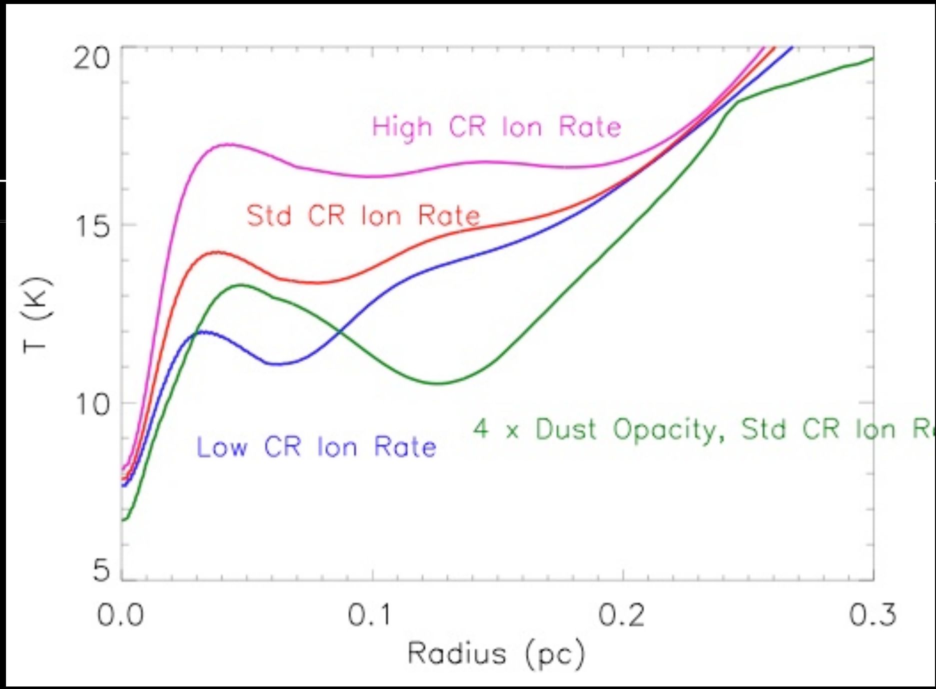


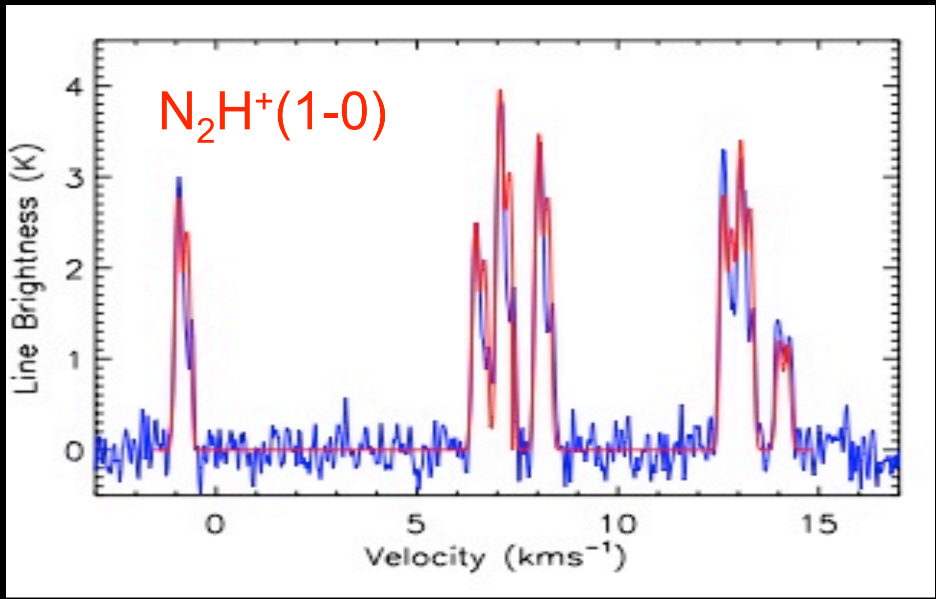
Radiative transfer Analysis

- Contracting Bonnor-Ebert sphere
- Simple CO chemistry (freeze-out + photodissociation)
- Radiative energy balance (+photoelectric heating)
- Radiative transfer

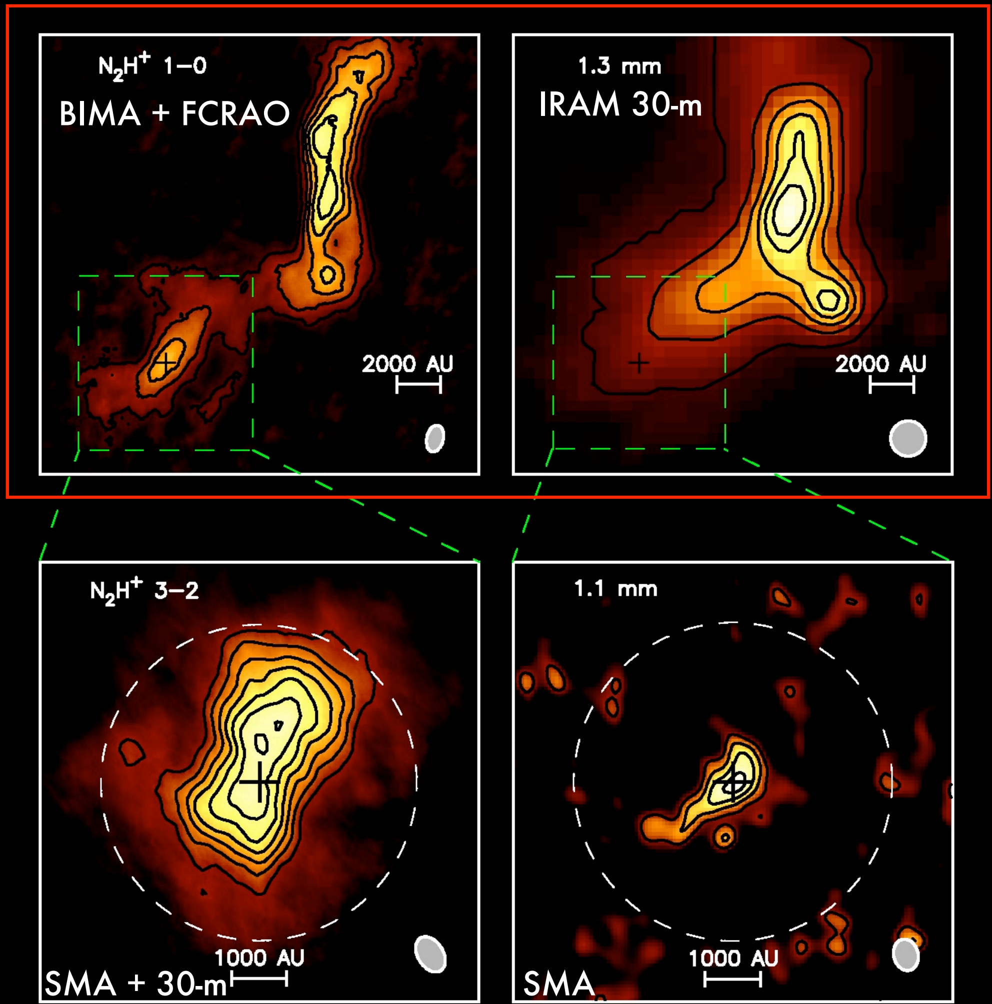
$\zeta \sim 1\times10^{-17}$ s^{-1}, fluffy grains,
$n_c \sim 2\times10^7$ cm^{-3} within 500 AU
$v_{inf} \sim 0.1$ km s^{-1} at 1000 AU

Keto & Caselli 2008, 2010





N6: starless core in the nearest cluster-forming region



BOURKE et al., submitted

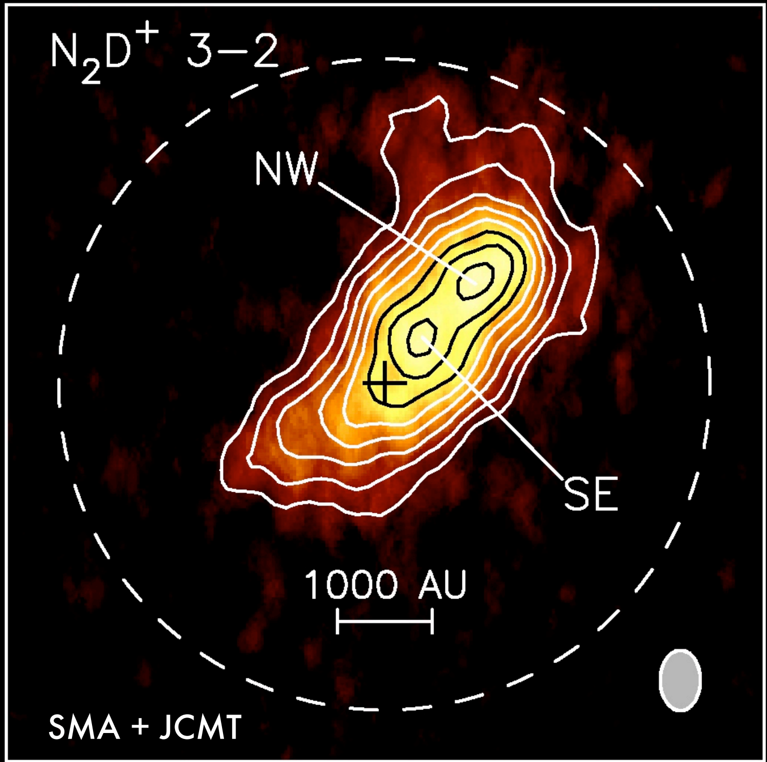
– densest gas condensation in Ophiuchus, the nearest cluster-forming region (125 pc)

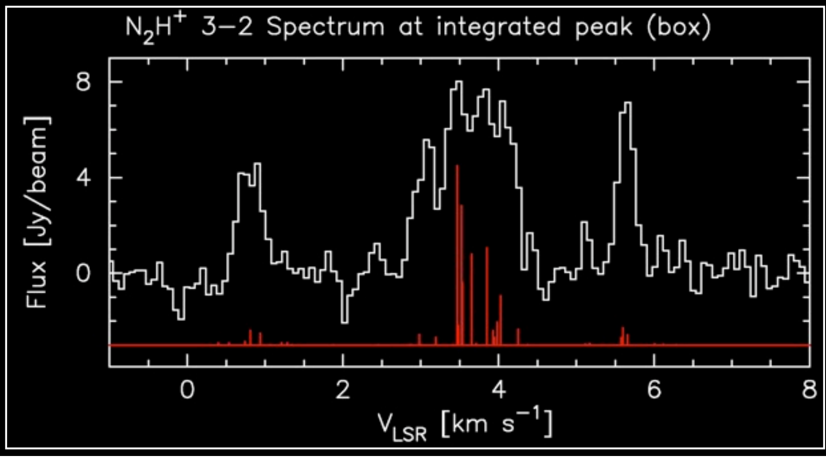
– half a dozen local maxima of emission (dust and line; 10" resolution; N_2H^+ 1-0 Di Francesco et al 2004; 1.3 mm Motte et al. 1998)

– starless dense core N6 is an N_2H^+ peak but not a dust continuum peak (10 mJy; 1000 AU and mass 0.01 $M_\odot$)

– warm at 20 K (NH_3 observations with the GBT; Pon et al. 2009)

N6: starless core in the nearest cluster-forming region

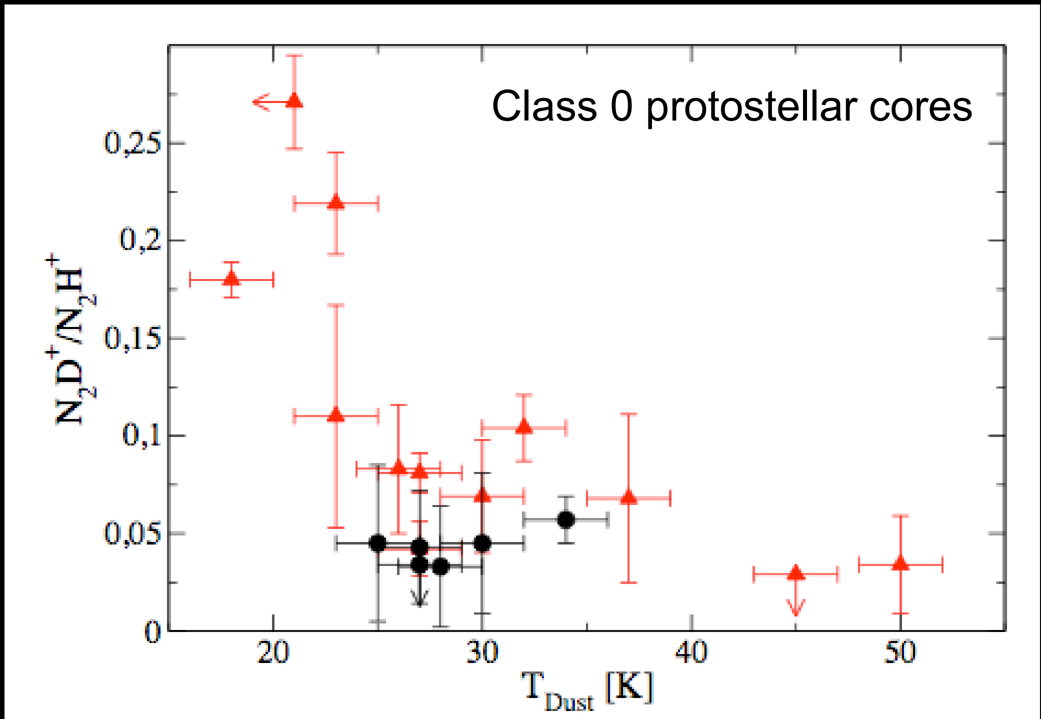


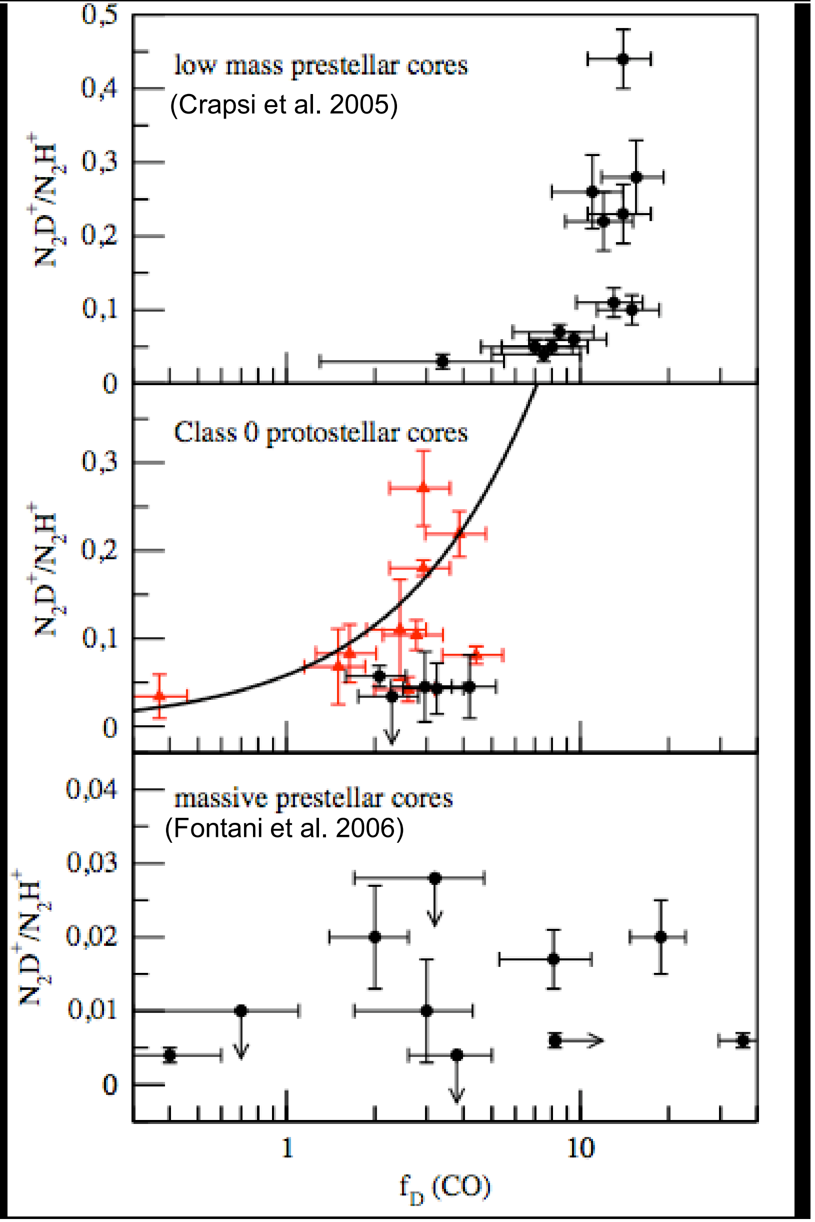


BOURKE et al., in prep.

	N6	L1544
Size (AU) N_2H^+(3-2)	3000x1500	~8000
$N(N_2D^+)$/ $N(N_2H^+)$	0.06	0.20
T_c (K)	14	7
Δv (km/s) N_2H^+(3-2)	0.25	0.18
$\Delta v_{NT}/\Delta v$ N_2H^+(3-2)	0.25	0.23
M ($M_\odot$) Within N_2H^+(3-2)	0.2	0.05

Deuterium fractionation in star forming regions





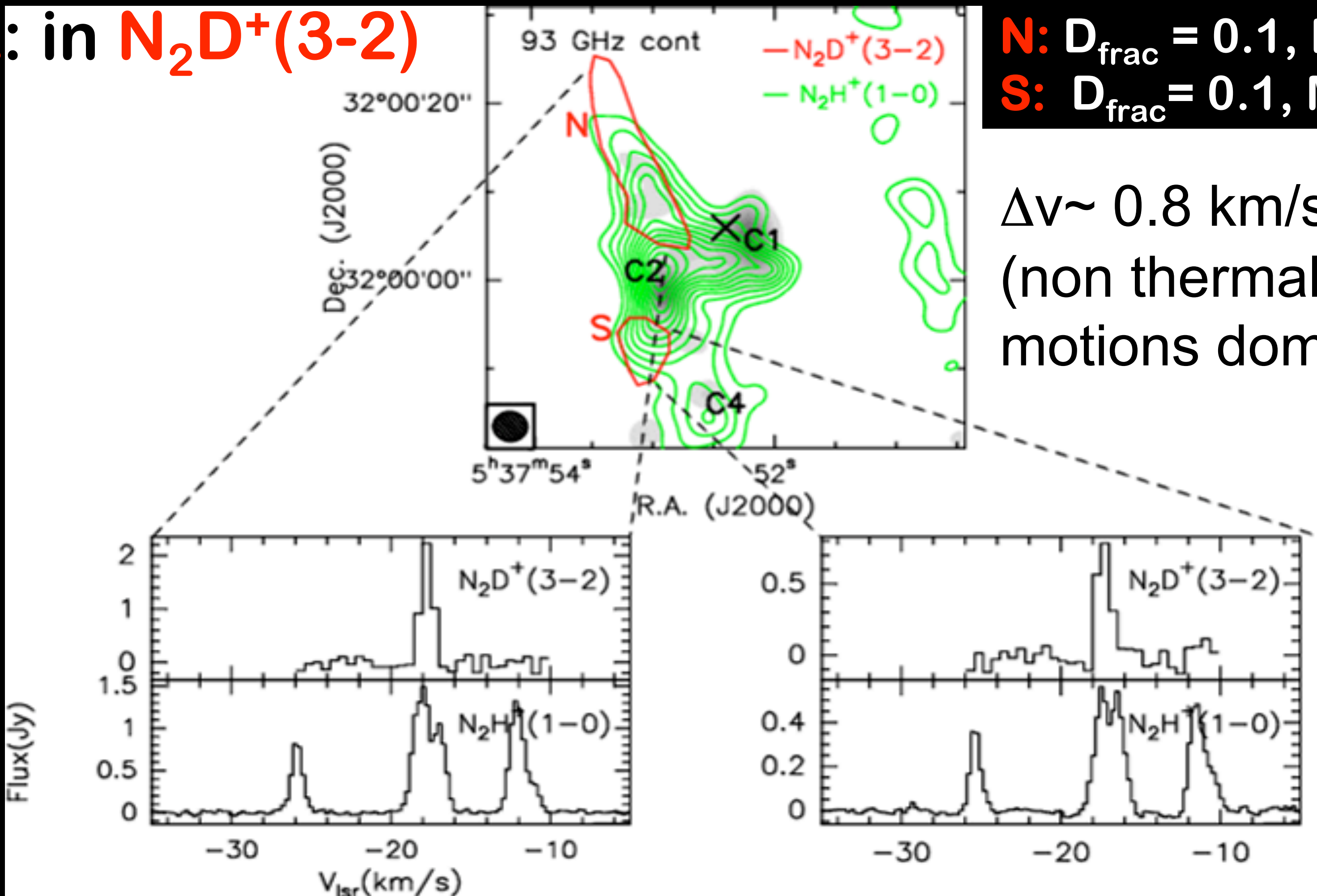
N_2D^+/N_2H^+ can be used to trace core evolution even after star formation.

Emprechtinger, Caselli, Volgenau + 2009

IRAS05345+3157: a young massive star forming region

PdBI: in $N_2H^+(1\text{-}0)$ and 93 GHz continuum

SMA: in $N_2D^+(3\text{-}2)$



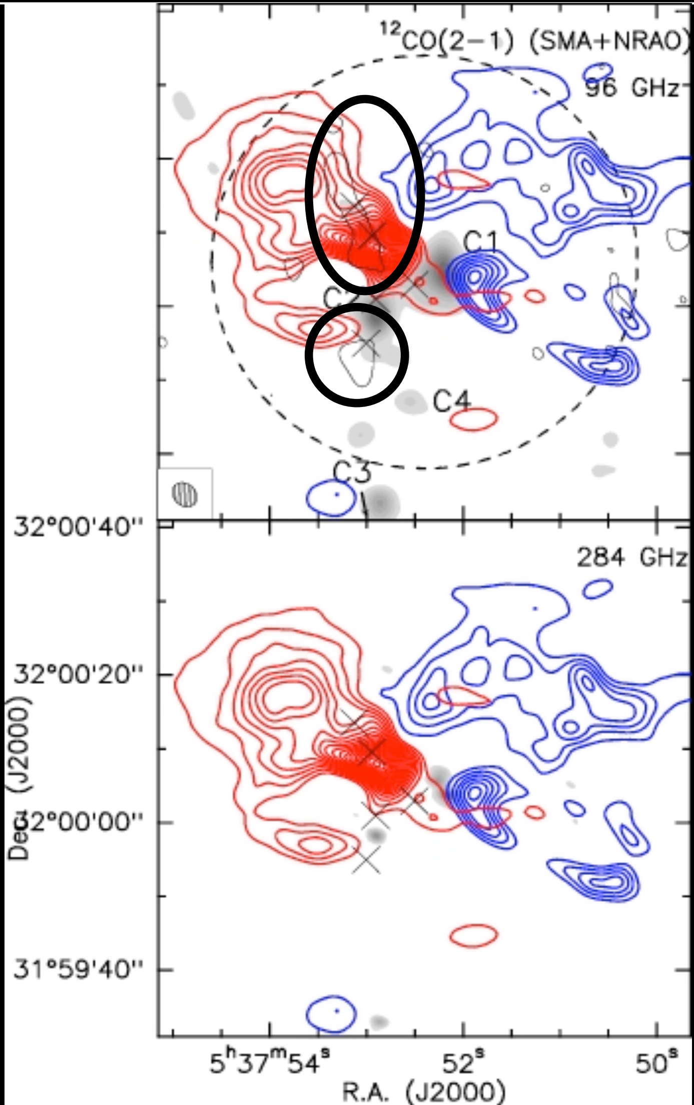
N: $D_{frac} = 0.1$, $M \sim 9\ M_\odot$

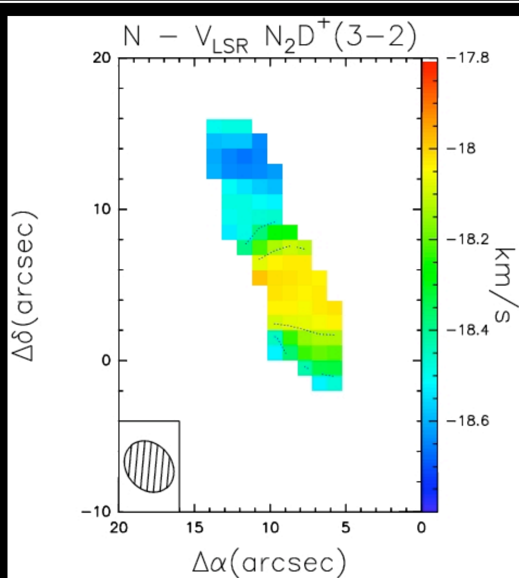
S: $D_{frac} = 0.1$, $M \sim 3\ M_\odot$

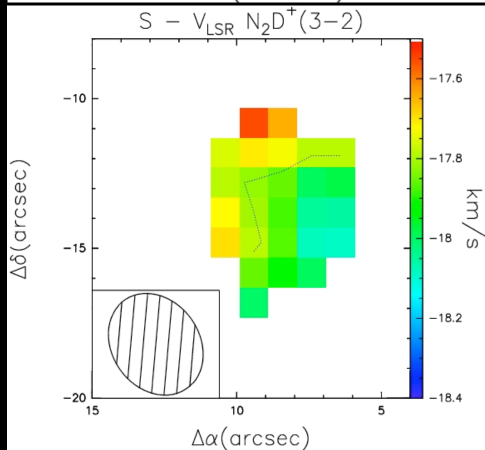
$\Delta v \sim 0.8$ km/s (non thermal motions dominate!)

Fontani, Caselli, Bourke et al., 2008 (+ Fontani et al. 2006)

IRAS05345+3157: a young massive star forming region





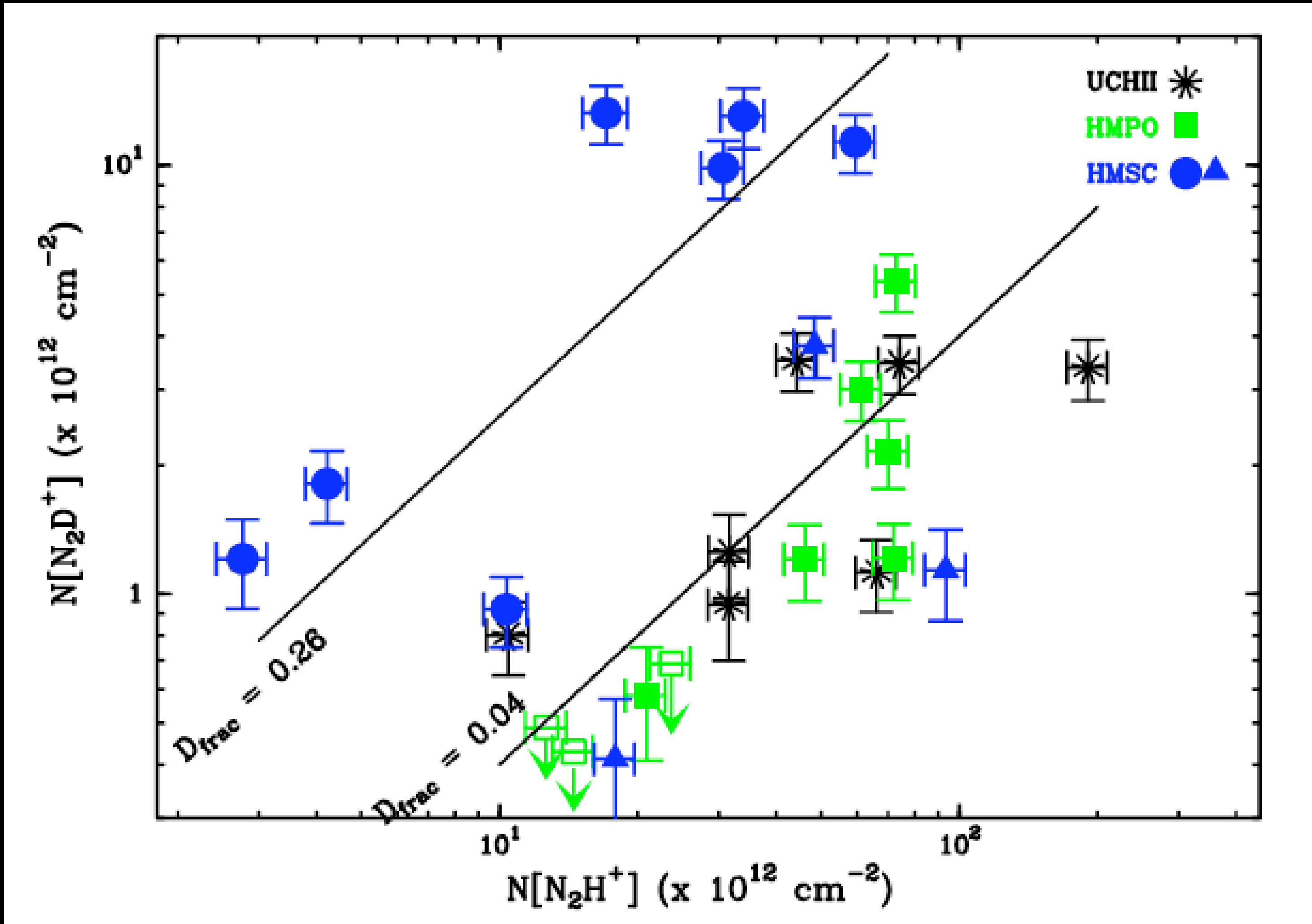


SMA + NRAO map of the CO(2-1) outflow

The kinematics of the deuterated condensations is influenced by the nearby protostars.

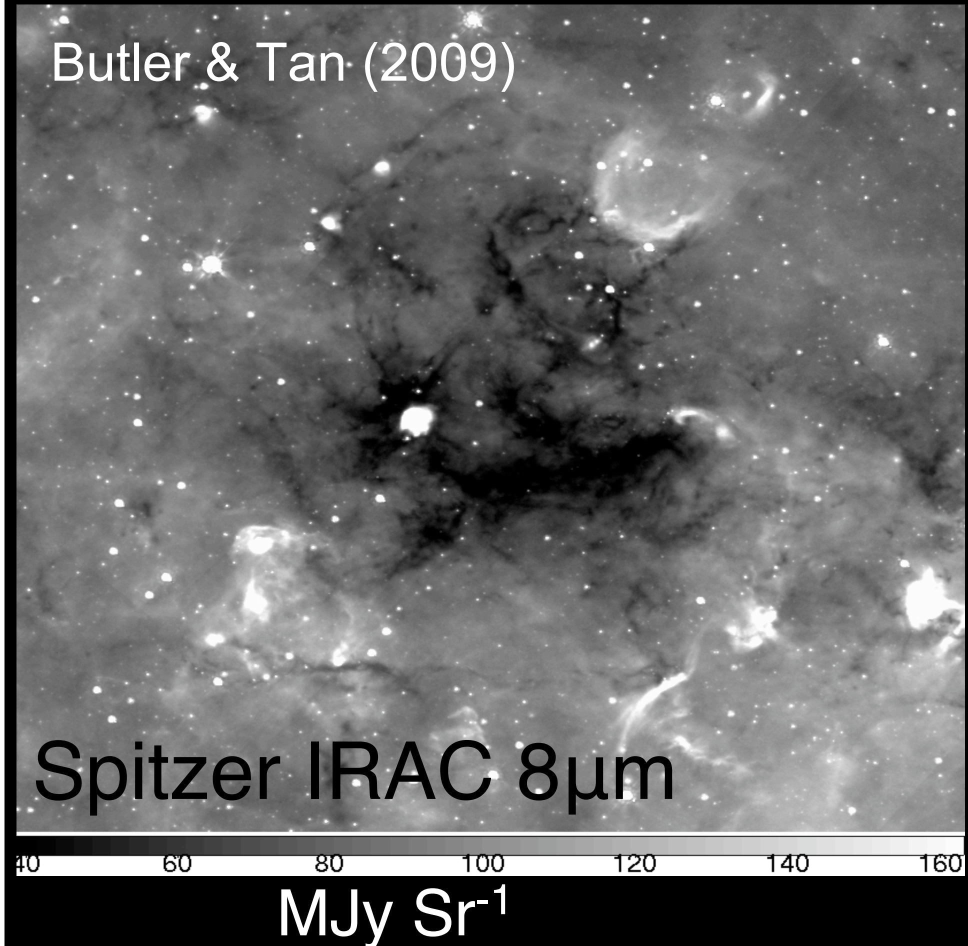
Fontani, Zhang, Caselli and Bourke 2009

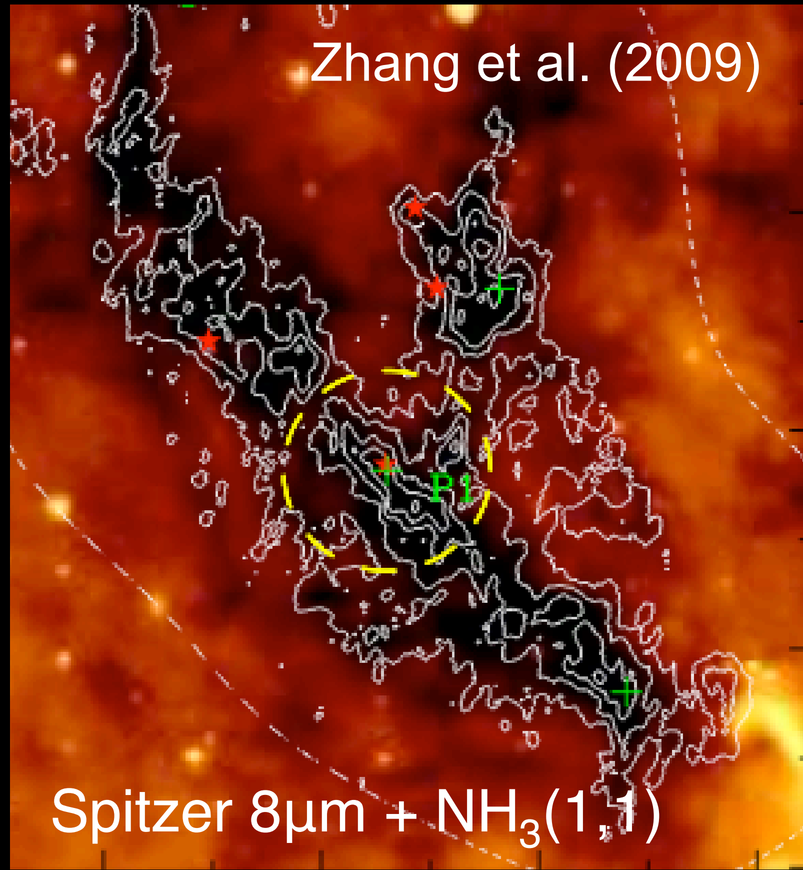
Deuteration in massive star forming regions



Fontani, Palau, Caselli, Butler, Tan + 2011

PSCs in quiescent high-mass IR-dark clouds

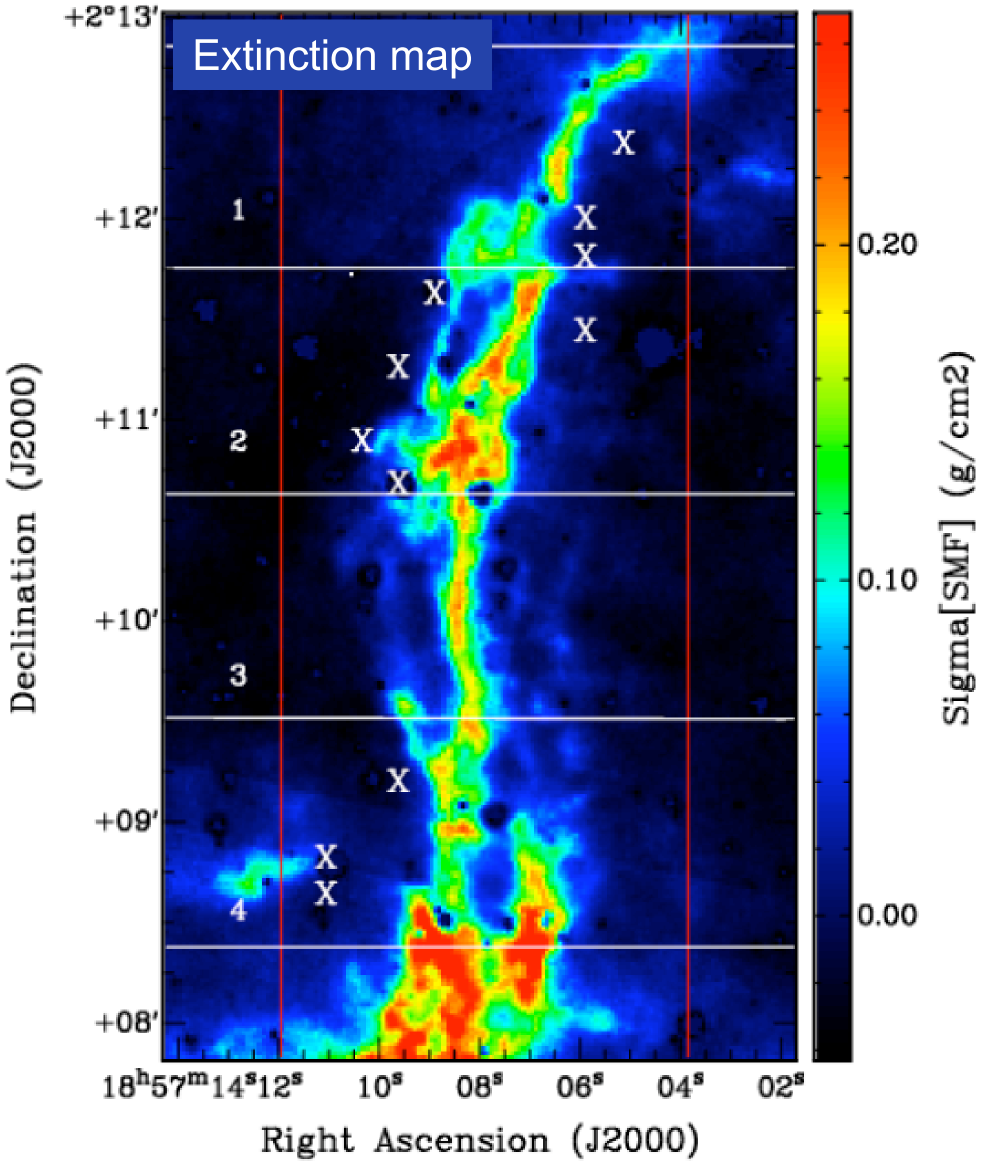


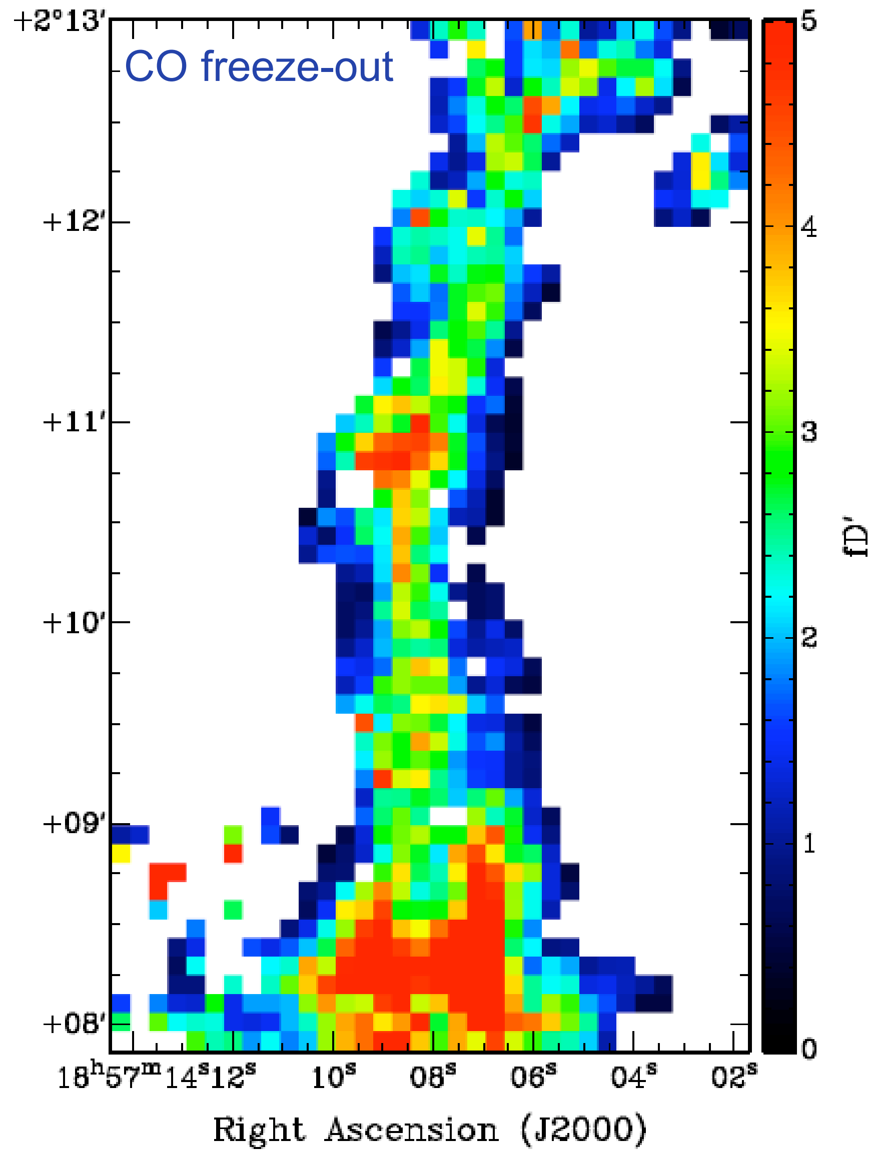


(see also Peretto & Fuller 2009, 2010; Ragan et al. 2009, 2011; Henning et al. 2010; Peretto et al. 2010; Rathborne et al. 2010; Stamatellos et al. 2010)

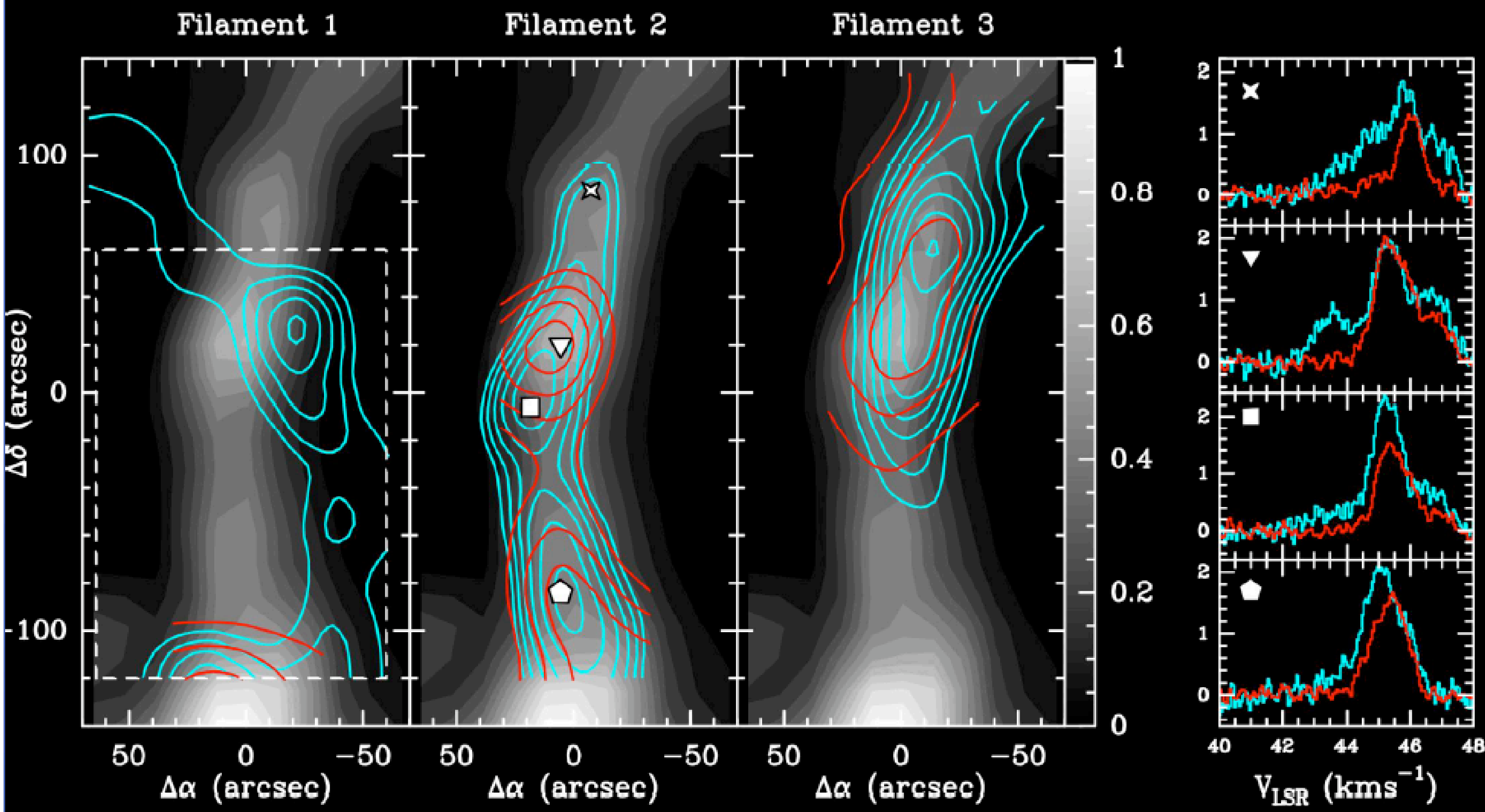
IRDC: extended CO freeze-out

(Hernandez, Tan, Caselli + 2011)



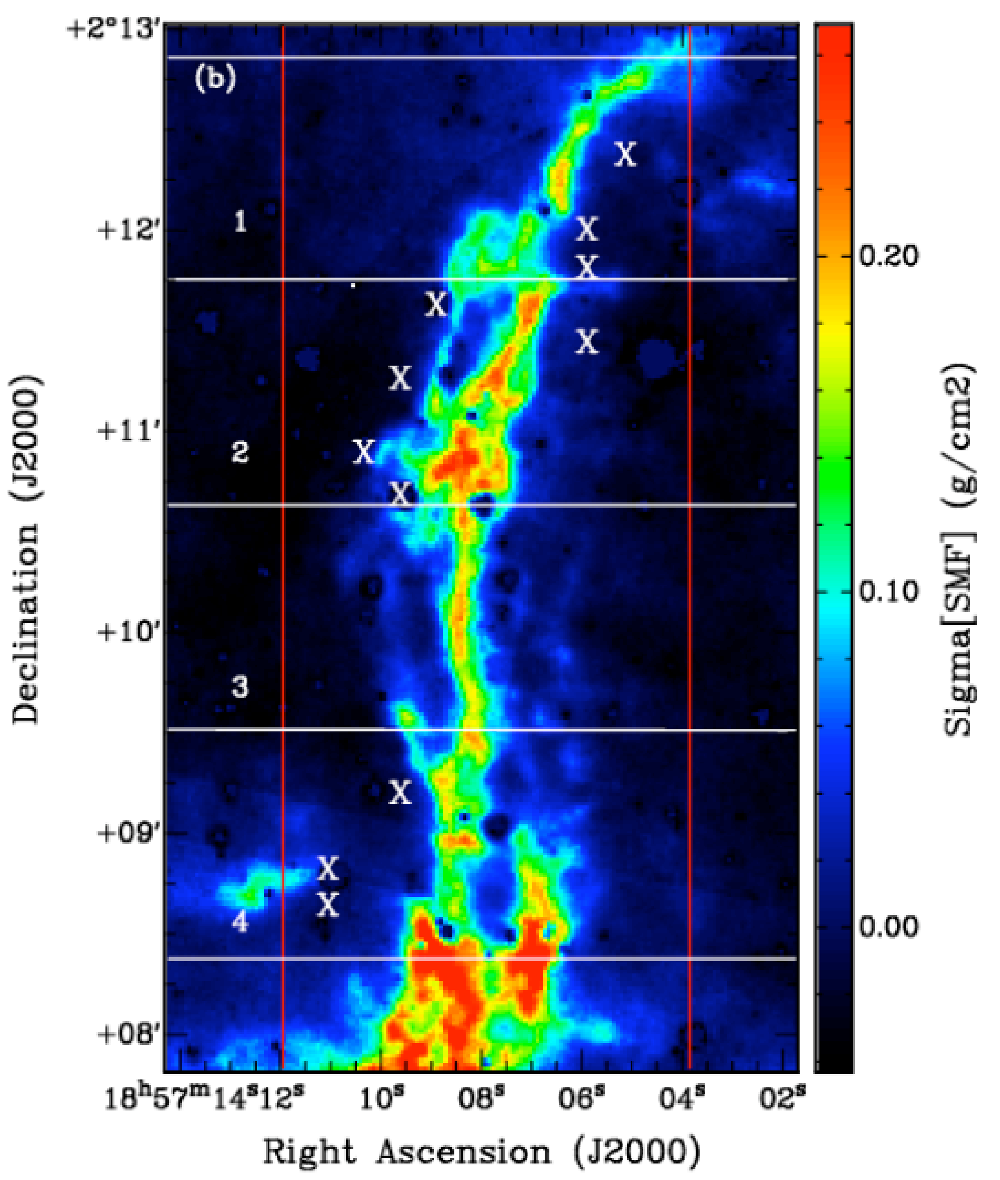


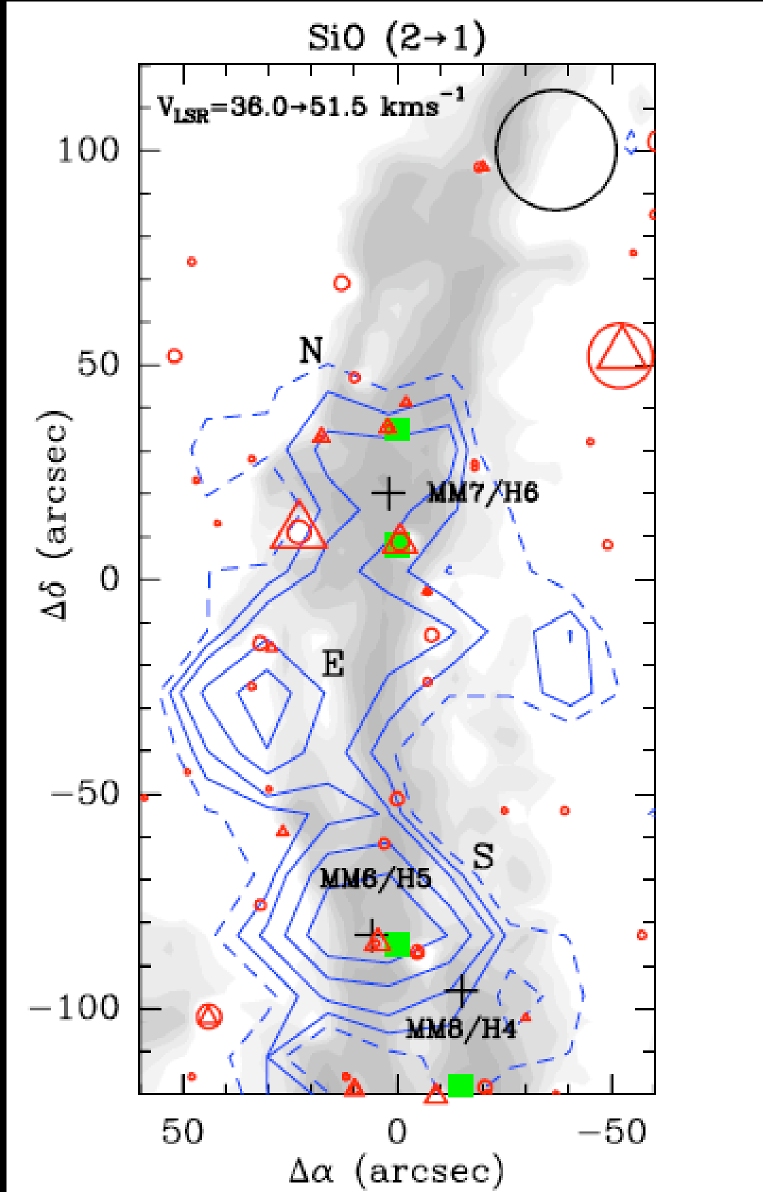
IRDC: multiple filaments and evidence of filament merging
(Henshaw et al., in prep.)

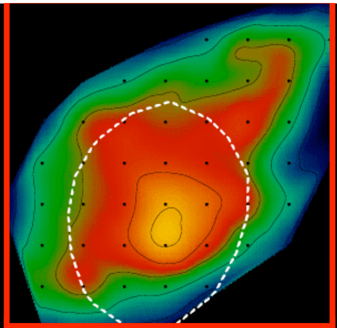


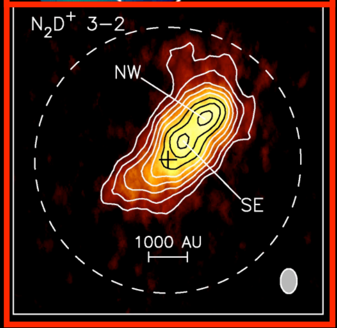
IRDC: extended SiO emission

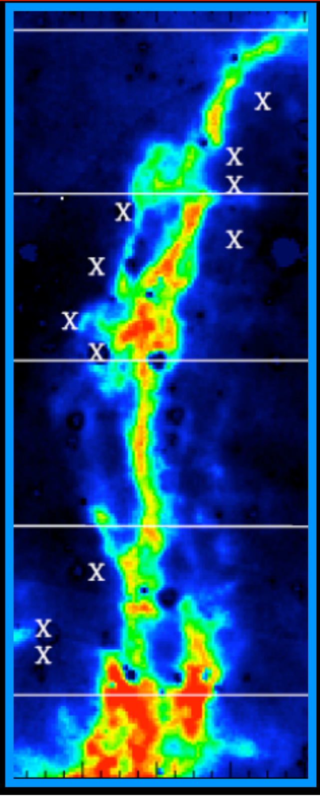
Jiménez-Serra, Caselli, Tan et al. (2010)











Summary

- Astrochemistry(+ observations!) needed to study the initial conditions of star formation.

- Inter-core environment, protostellar feedback, and gas-dust interactions affect chemical/physical evolution (ages?).

- **Low-mass**: (i) isolated: quiescent, T_c~6K, f_D(CO) > 10, D_{frac} > 0.2 ; (ii) in cluster-forming regions: more compact, warmer. D_{frac} decreases with YSO evolution.

- **High-mass**:
  - –highly deuterated (cold) cores nearby HMPOs are affected by outflows.
  - –IRDCs are the best candidates where to find pre-star-cluster clumps (CO freeze-out + D-fractionation similar to low-mass)