Probing the initial conditions of MSF through observations of N_2D^+

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………..	

Presentation outline

1 The initial conditions in Massive Star Formation: Accretion vs Coalescence

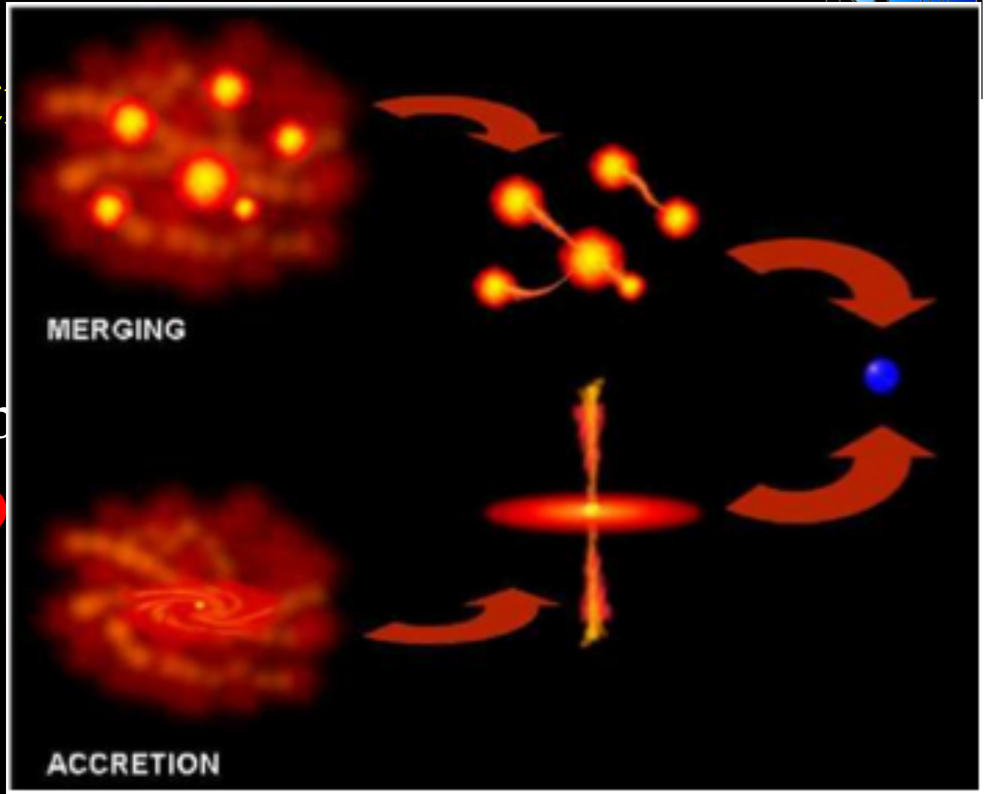
2 Deuterated molecules

3 N_2D^+/N_2H^+ in massive cores (IRAM-30m): identifying the best targets where to study the initial conditions (Fontani et al. 2011, A&A, 529, L7)

4 N_2D^+ at high angular resolution (ALMA cycle-0 !!): Testing theories (Accretion vs Coalescence) through targeted observations (Tan et al., in prep.)

5 Summary, conclusions, outlook

High-mass star format



Courtesy of L. Carbonaro

PROBLEM:

The radiation pressure of the "emb

➡ $M_{*}>8M_{sun}$ CANNO

SOLUTIONS:

1. MERGING / COALESCENCE MODELS:

Fragmentation of a massive starless core into low-mass seeds which keep accreting from unbound gas, and/or merge through collisions

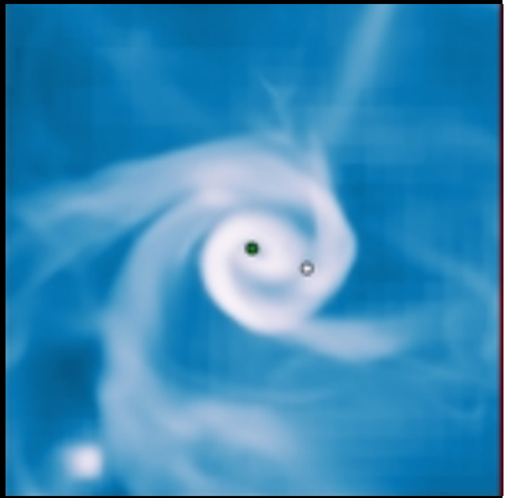
(e.g. Bonnell et al. 1998, 2001, Bonnel & Bate 2005, 2006)

2. ACCRETION MODELS:

Non-spherical collapse (massive disks) of a massive starless core into a single high-mass star or close binary system

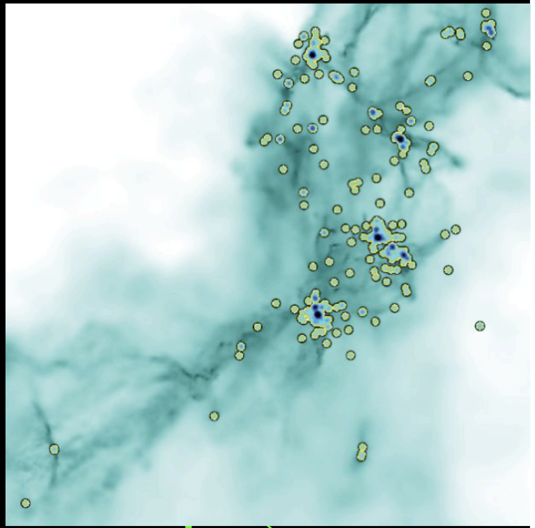
(e.g. Wolfire & Cassinelli 1978, Yorke & Sonnhalter 2002, Tan & McKee 2003)

Initial conditions: predictions



1. Accretion models :

- ✓ Virial-equilibrium conditions: YES
- ✓ Non-thermal support dominant: YES (turbulence, B…)
- ✓ SINGLE high-mass star or close binary ($M \gg M_{J,th}$) ; CMF = IMF



2. Merging / coalescence models :

- ✓ Virial-equilibrium conditions: NO
- ✓ Non-thermal support dominant: NO (thermal fragmentation)
- ✓ MANY low-mass protostellar seeds ($M \sim M_{J,th} \leq M_{\odot}$) ; CMF ≠ IMF

Intro 1: Accretion vs Coalescence

Testing theories with observations of massive starless cores: PROBLEMS

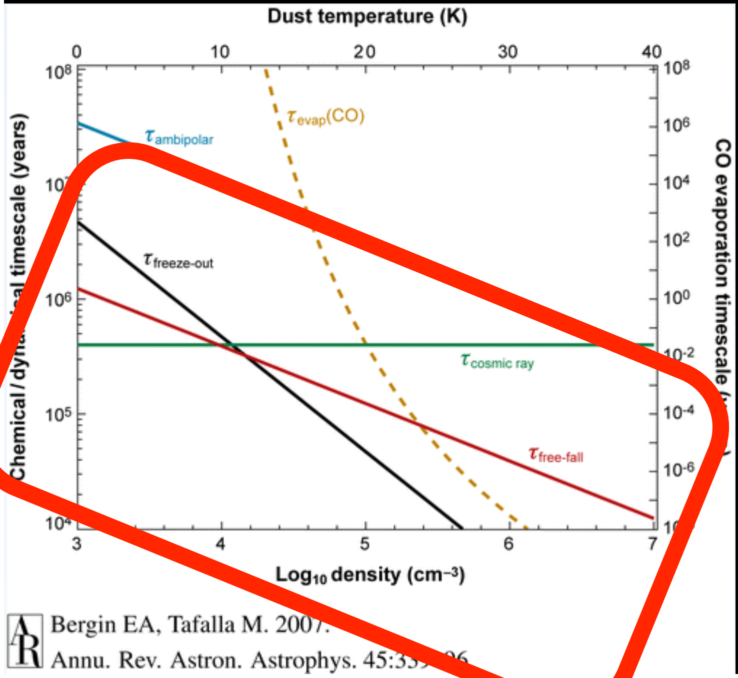
- ✓ Massive starless core are RARE
- ✓ Typical distances greater than 1 kpc: SMALL ANGULAR SIZE
- ✓ Surrounded by large amount of other gas: CONFUSION
- ✓ FREEZE-OUT of species commonly used to derive physics and kinematics

$T < 20$ K
$n(H_2) > 10^5$ cm^{-3}

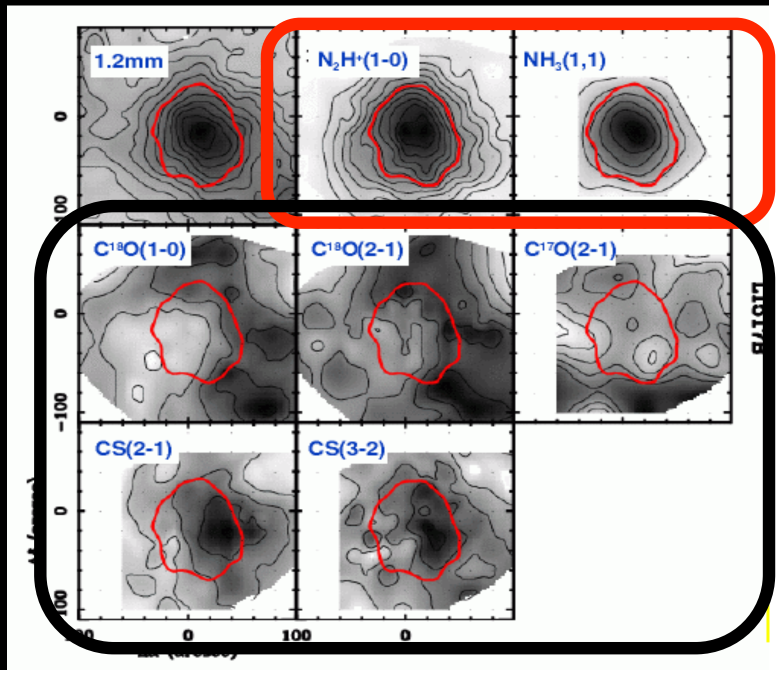
High CO (and CS) DEPLETION FACTOR

$$f_D = X(CO)^T/X(CO)^O > 1$$

(e.g. Caselli et al. 2002, Tafalla et al. 2004, Fontani et al., 2012 accepted)



Bergin EA, Tafalla M. 2007.
Annu. Rev. Astron. Astrophys. 45:339–96



Production of deuterated species

Millar et al. 1989, Roberts & Millar 2000

1. If $T \leq 20$ K $\quad H_3^+ + HD \Rightarrow H_2D^+ + H_2 + 230K$ $\quad H_2D^+/H_3^+$ increases

2. If CO depletes (i.e. if $n \geq 10^5$ cm^{-3})

~~$H_3^+ + CO \longleftrightarrow HCO^+ + H_2$~~

~~$H_2D^+ + CO \longleftrightarrow DCO^+ + H_2$~~

H_3^+ and H_2D^+ remain abundant

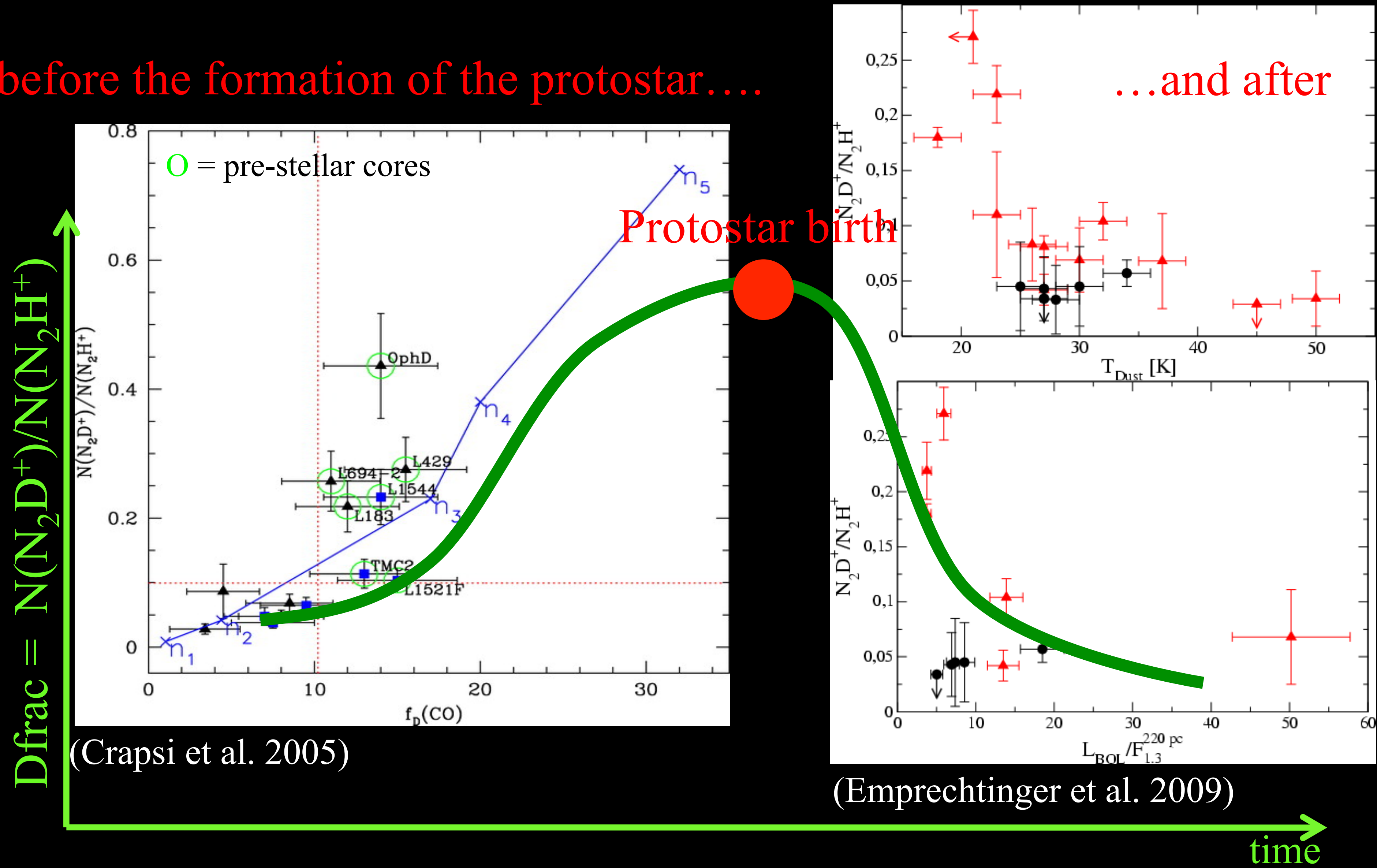
$H_3^+ + X \longleftrightarrow XH^+ + H_2$

$H_2D^+ + X \longleftrightarrow XD^+ + H_2$

XD^+ and XH^+ abundant and XD^+/XH^+ increases

Conditions 1 and 2 are typical in dense pre-stellar cores:
XD^+/XH^+ orders of magnitude larger than the [D/H] IS value (10^{-5})

$N(N_2D^+)/N(N_2H^+)$ in low-mass SF



$N(N_2D^+)/N(N_2H^+)$ perfect to trace the initial conditions

Intro 2: Deuteration

PROBLEM: is Dfrac = $N(N_2D^+)/N(N_2H^+)$ good to trace the earliest phases of MSF too?

STRATEGY: to measure Dfrac in MASSIVE CORES in different evolutionary stages

10 High-Mass Starless Cores (HMSCs)

10 High-Mass Protostellar Objects (HMPOs)

7 Ultracompact HII regions (UC HIIs)

time

OBSERVATIONS: Rotational transitions of N_2H^+ & N_2D^+; IRAM-30m Telescope

METHOD: $N(N_2H^+)$, $N(N_2D^+)$ from fits to the hf structure of N_2H^+(3-2) and N_2D^+(2-1)

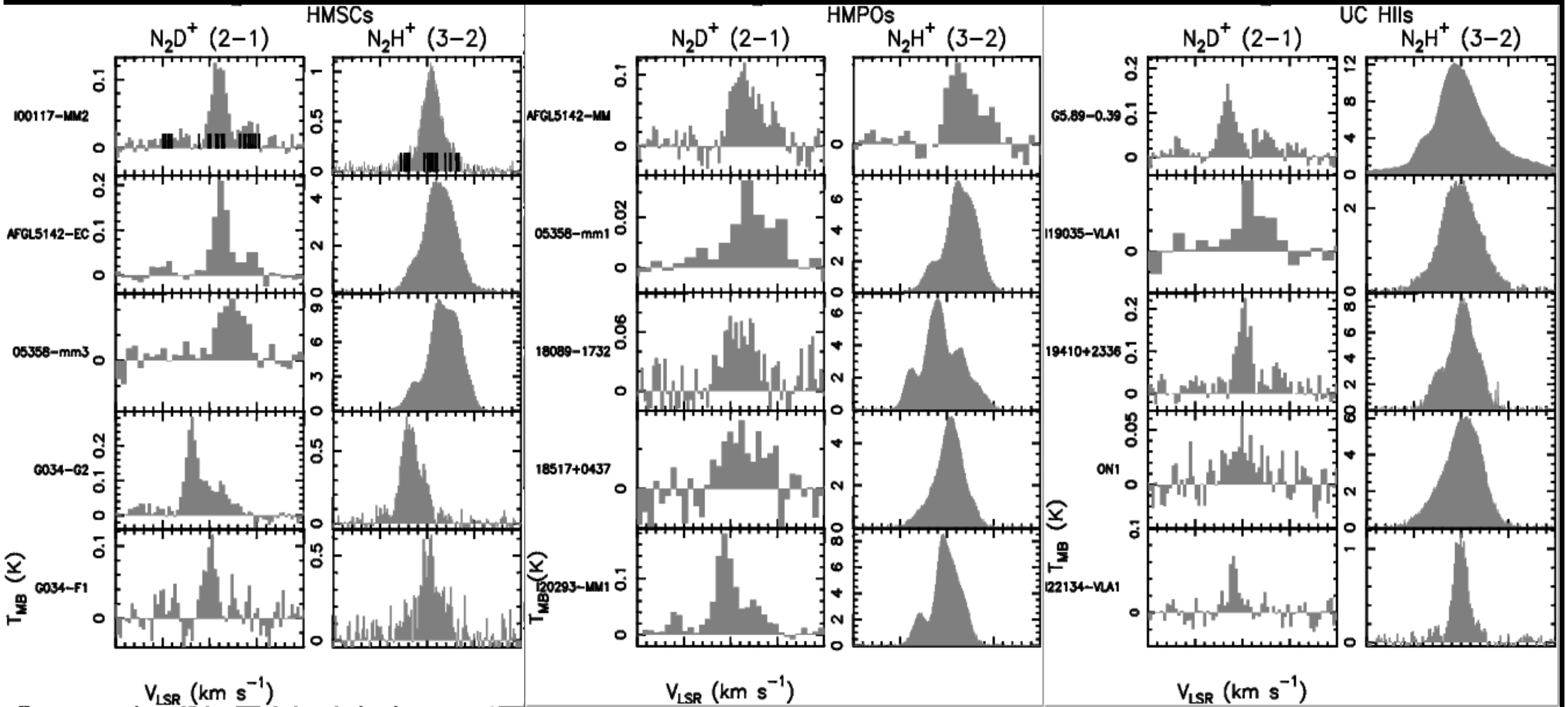
$$N_{\rm tot} = \frac{8\pi^{3/2}\Delta v}{2\sqrt{\ln 2}\lambda^3 A}\frac{g_l}{g_u}\frac{\tau}{1-\exp\left(-h\nu/kT_{\rm ex}\right)}\frac{Q_{\rm rot}}{g_l\exp\left(-E_l/kT_{\rm ex}\right)},$$

Caselli et al. 2002

N_2D^+/N_2H^+ in massive cores

N_2D^+ (2-1), N_2H^+ (3-2) spectra

HMSCs HMPOs UCHIIs

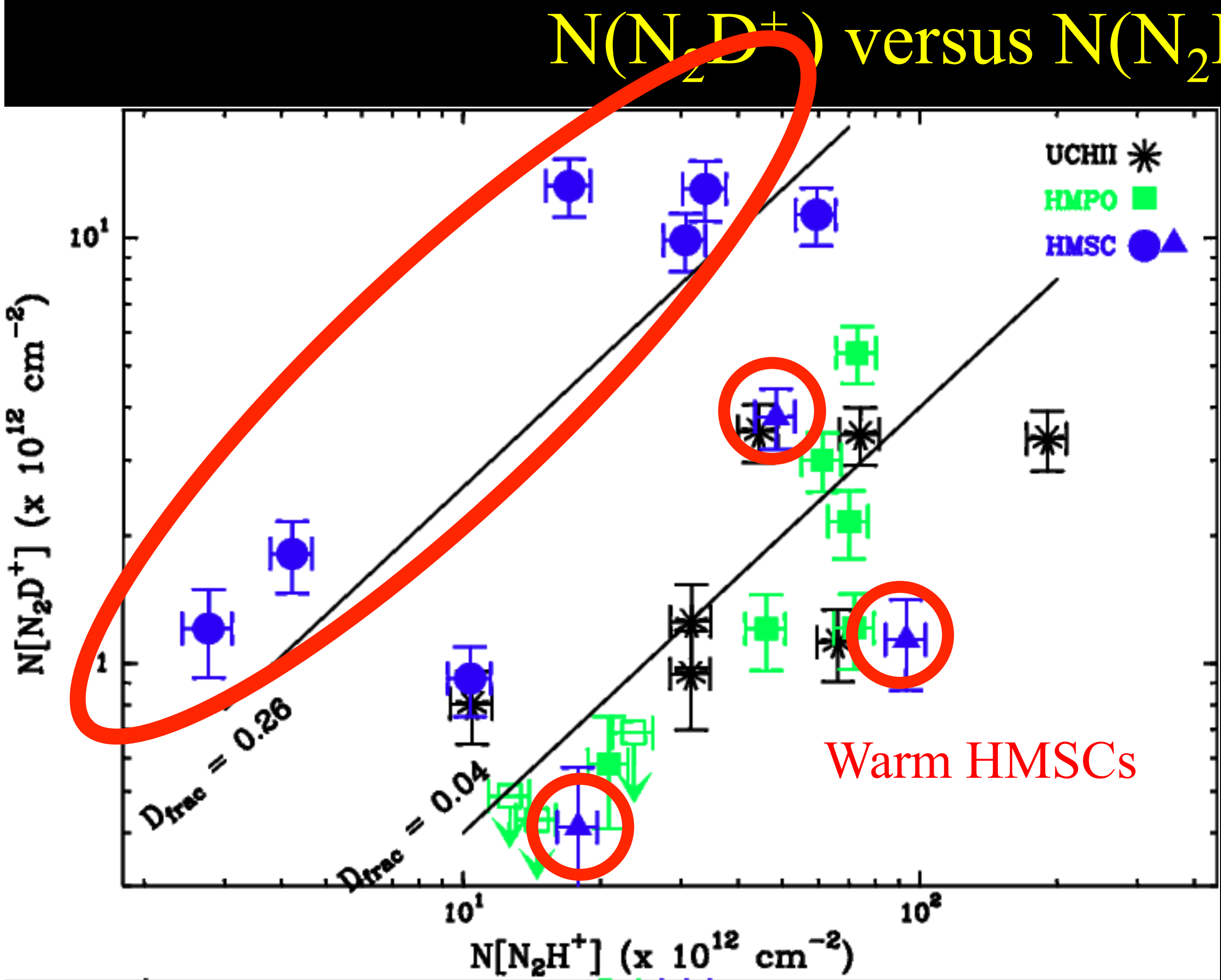


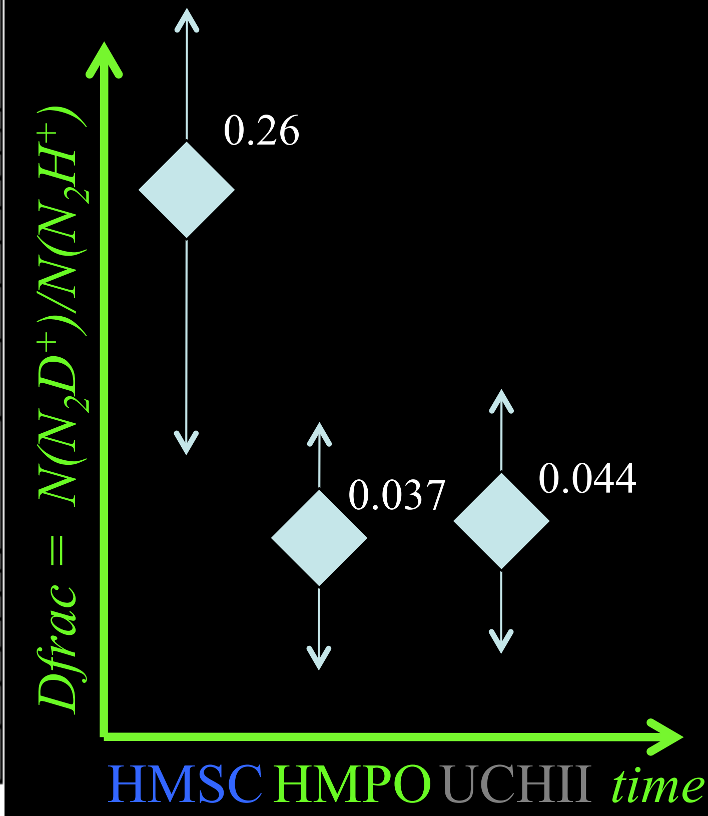
Detection of deuterated gas: 85% total

100% HMSCs - 64% HMPOs - 100% UCHIIs

N_2D^+/N_2H^+ in massive cores

$N(N_2D^+)$ versus $N(N_2H^+)$



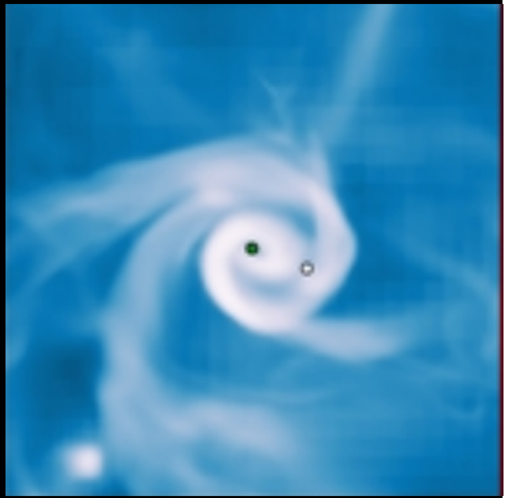


Statistical separation between HMSCs and HMPOs/UCHIIs:

Kolmogorov-Smirnov test: P ~ 0.004

The best targets to study the initial conditions of MSF!!

Initial conditions: predictions



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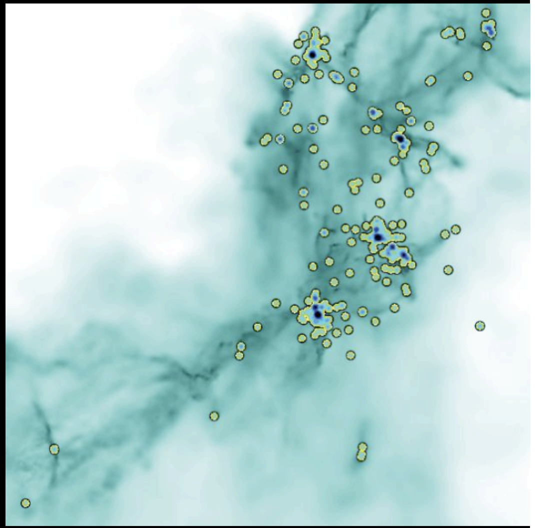

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Dynamics of massive starless cores

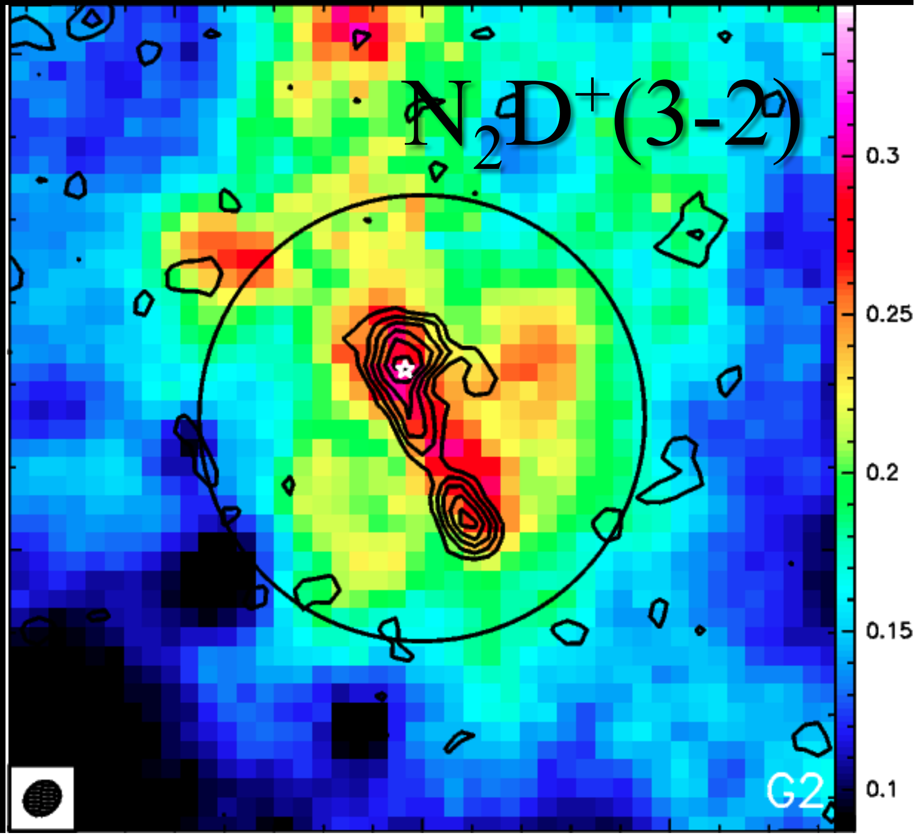
Target: 4 HMSCs with: Dfrac>0.2, Σ>0.2 g cm^{-2}, 70µm-dark (MIPS & Herschel)

Goal: Virial analysis of the DENSE GAS at high-angular resolution

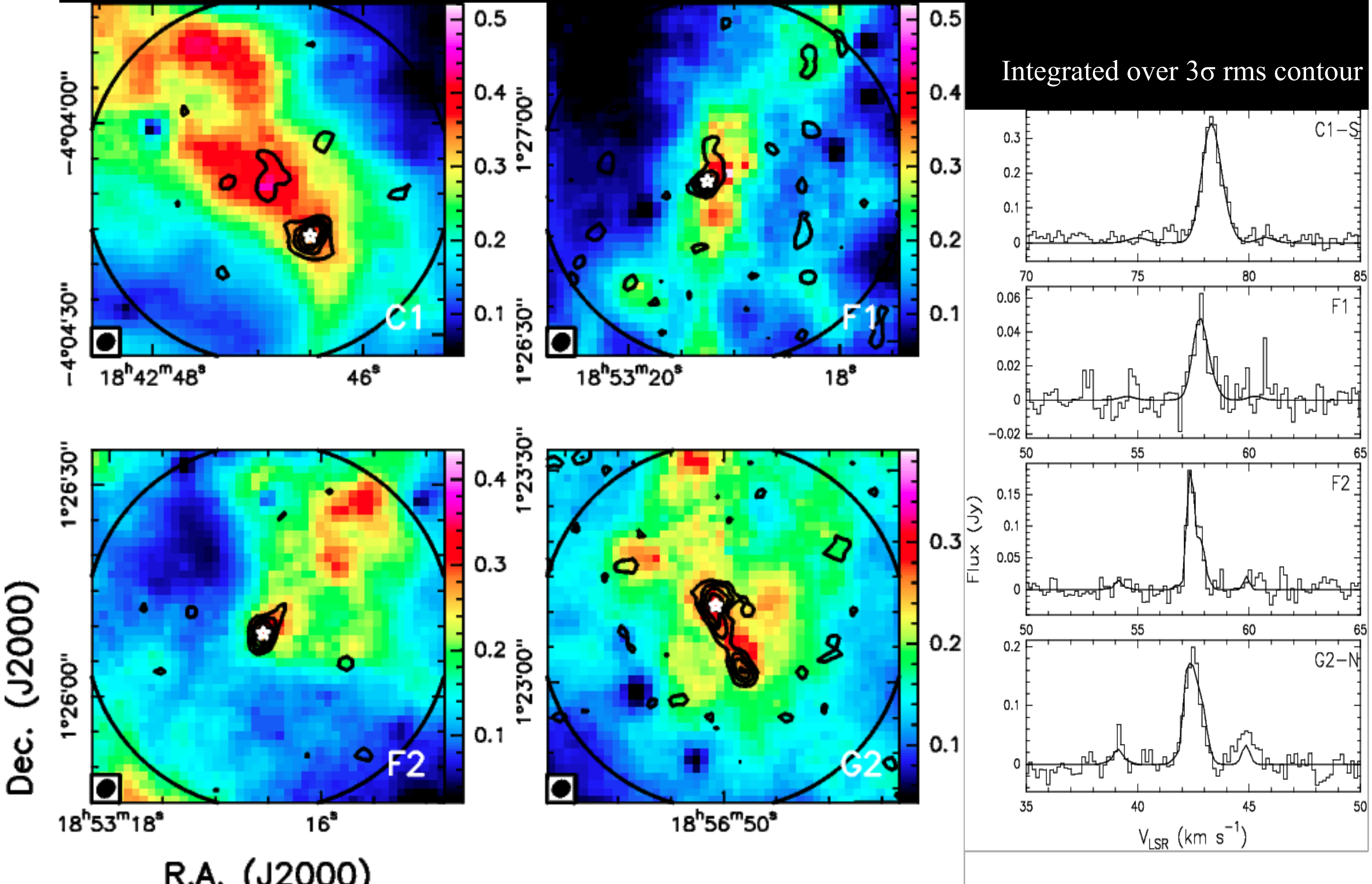
Σ

Tool: N_2D^+ (3-2) , $n_{crit} \sim 3\times10^6$ cm^{-3}

Instrument: ALMA (cycle-0) compact configuration



Dynamics of massive starless cores from N_2D^+ observations



Integrated over 3σ rms contour

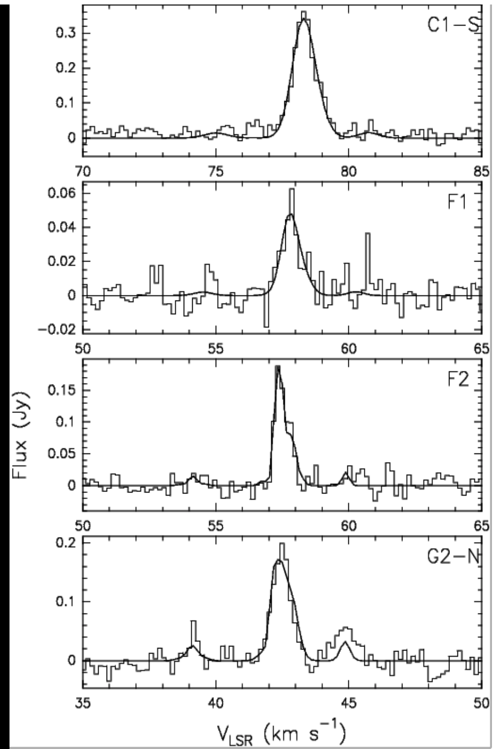
Dynamics of massive starless cores from N_2D^+ observations

Virial equilibrium?

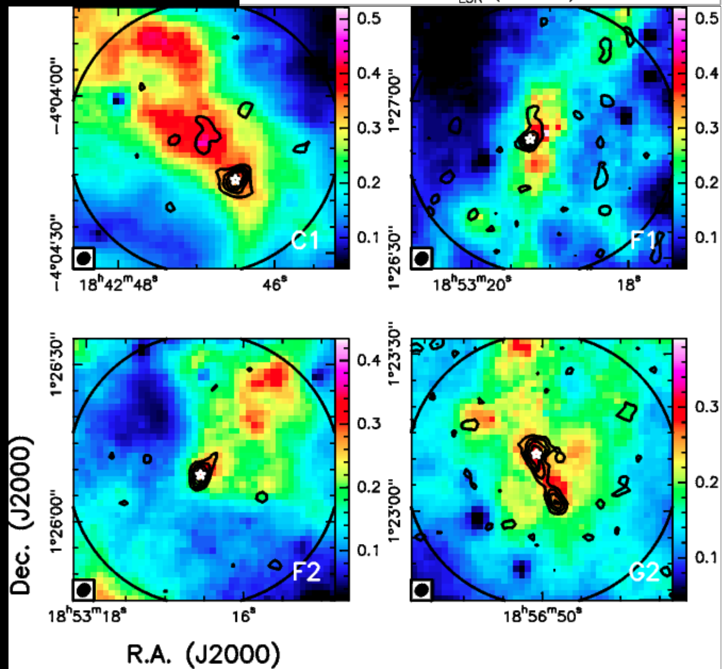
$$\sigma_{vir} = 1.089\,(M_{core}/60\,M_\odot)^{1/4}\,(\Sigma_{clump}/0.2\ \mathrm{g/cm^2})^{1/4}\ \mathrm{km/s}$$

$$R_{core} = 0.127\,(M_{core}/60\,M_\odot)^{1/2}\,(\Sigma_{clump}/0.2\ \mathrm{g/cm^2})^{-1/2}\ \mathrm{pc}$$

8-90 $M_\odot$ 0.2-0.3 g/cm^2 McKee & Tan 2003



	Predictions		Observations:	
	σ_{vir}(km/s)	R(pc)	σ_{obs}(km/s)	R(pc)
C1-N	0.47	0.11	0.29	0.11
C1-S	0.61	0.14	0.44	0.14
F1	0.34	0.076	0.36	0.063
F2	0.36	0.081	0.25	0.083
G2-N	0.30	0.071	0.27	0.069
G2-S	0.24	0.049	0.34	0.049



Virial equilibrium: ~YES ➔ ACCRETION MODELS

Summary - Conclusion

(1) the N_2D^+/N_2H^+ is higher at the pre-stellar stage, then drops of one order of magnitude (on average) during the HMPO and UC HII stages ➔ perfect to identify cores where to study the initial conditions even in massive cores

Fontani et al. 2011, A&A, 529, L7

(2) The most promising HMSCs observed with ALMA in N_2D^+(3-2) harbour single or double dense cores.
Most of them in close-to-virial conditions ➔ consistent with Accretion models (but more work to do…)

Tan et al. in prep.

outlook

Tomorrow

GOALS:

a. To increase the ANGULAR RESOLUTION;
b. To increase the CHEMICAL/PHYSICAL DIAGNOSTICS;
c. To run MODELS

TOOLS:

a. INTERFEROMETERS ~ 1 ", 3000 - 4000 A.U. @ 3-4 kpc
b. NH_3, NH_2D, H_2CO, HDCO, H_2O, HDO, (sub-)mm and cm continuum
c. Caselli, Tan, Hennebelle, van Loo et al… ☺