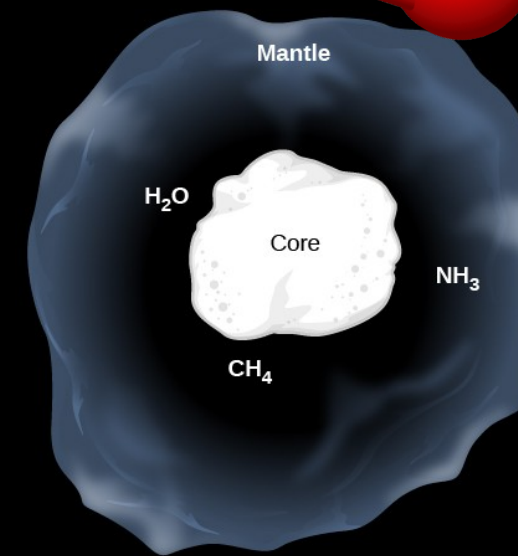
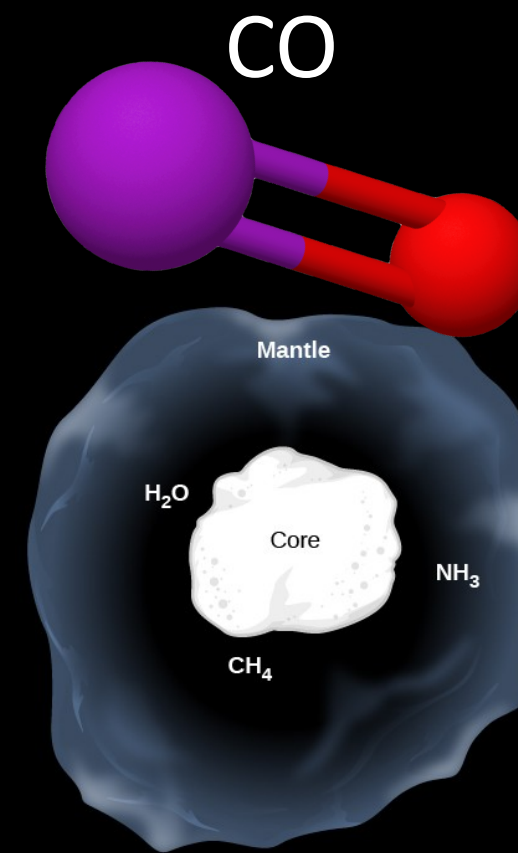
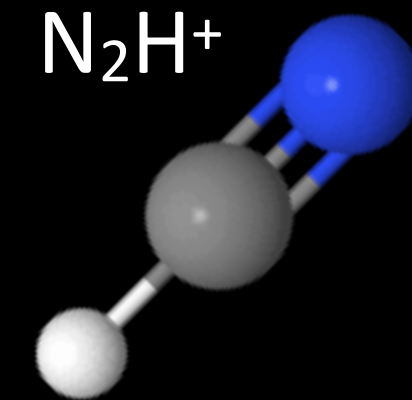


The earliest phases of massive star-formation: pushing Riccardo towards astrochemistry



Francesco Fontani

INAF-OAA, LUX, MPE-CAS, UniPI

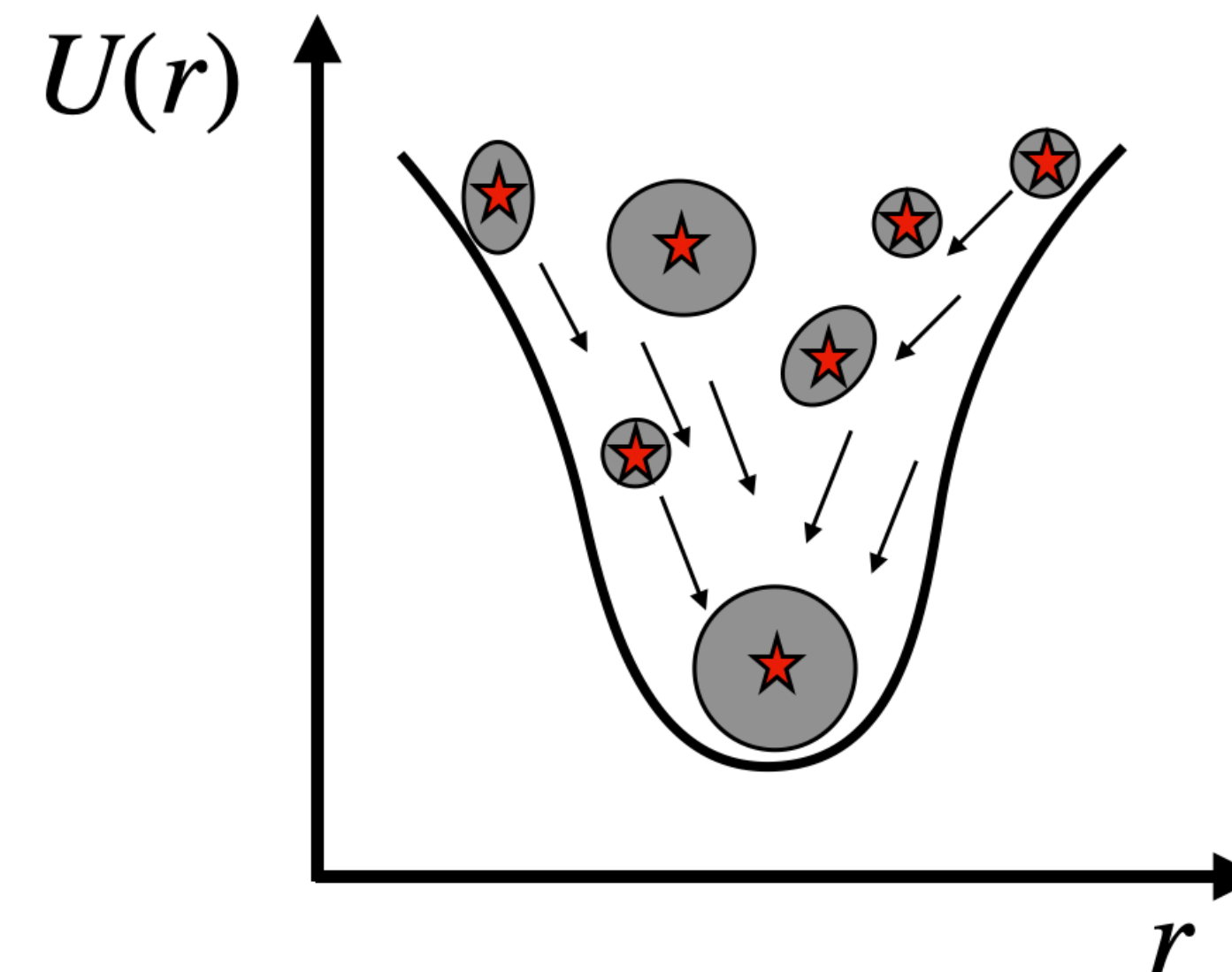
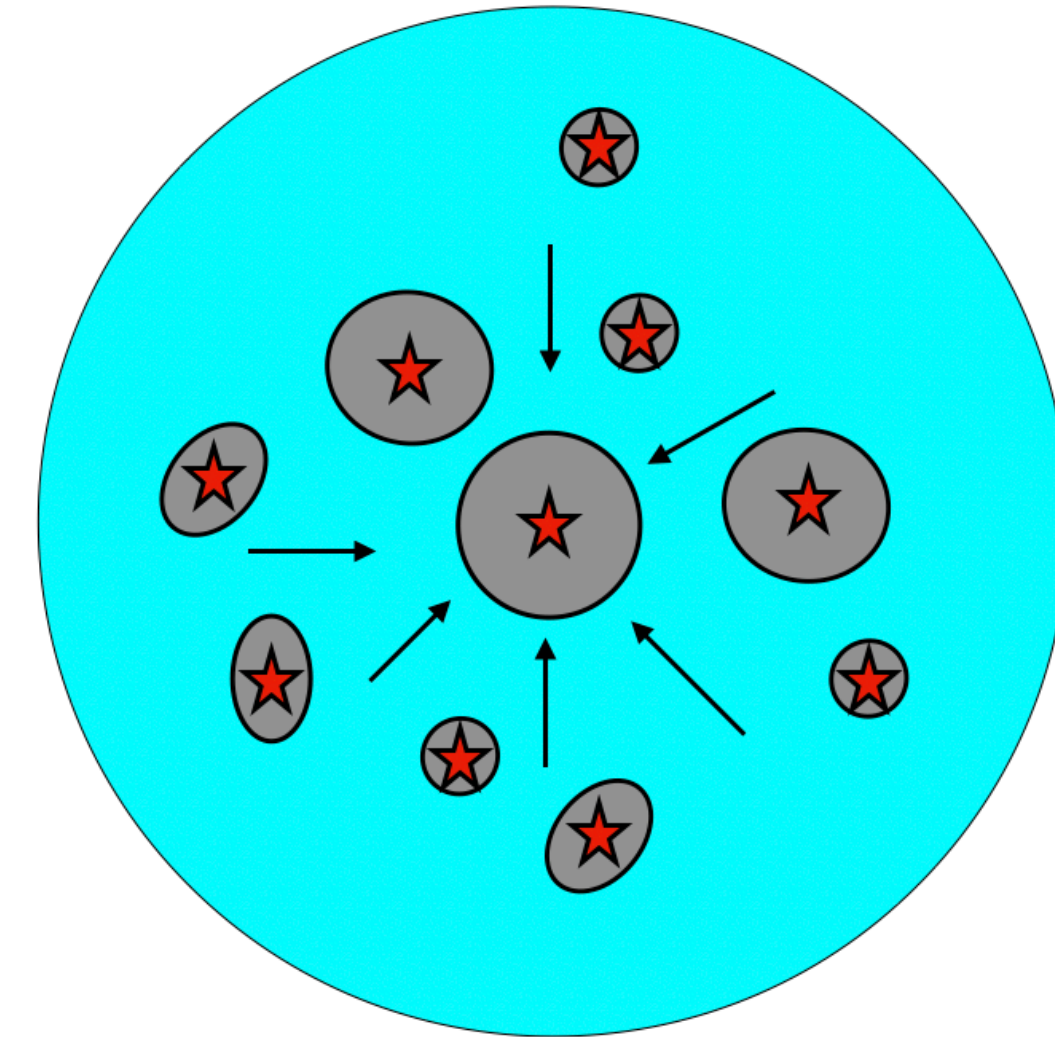


The HIGH-MASS SF PROBLEM: THEORETICAL SOLUTIONS

See e.g. review by Tan et al. 2014, PPVI

1. Coalescence / clump-fed models

- Multiple low-mass protostars form within a dense *(proto-)cluster*.
- They compete for material from a *shared* gas reservoir.
- Protostar(s) at the *minimum of $U(r)$* attract more gas from the unbound shared reservoir, and “win” the competition over the other protostars

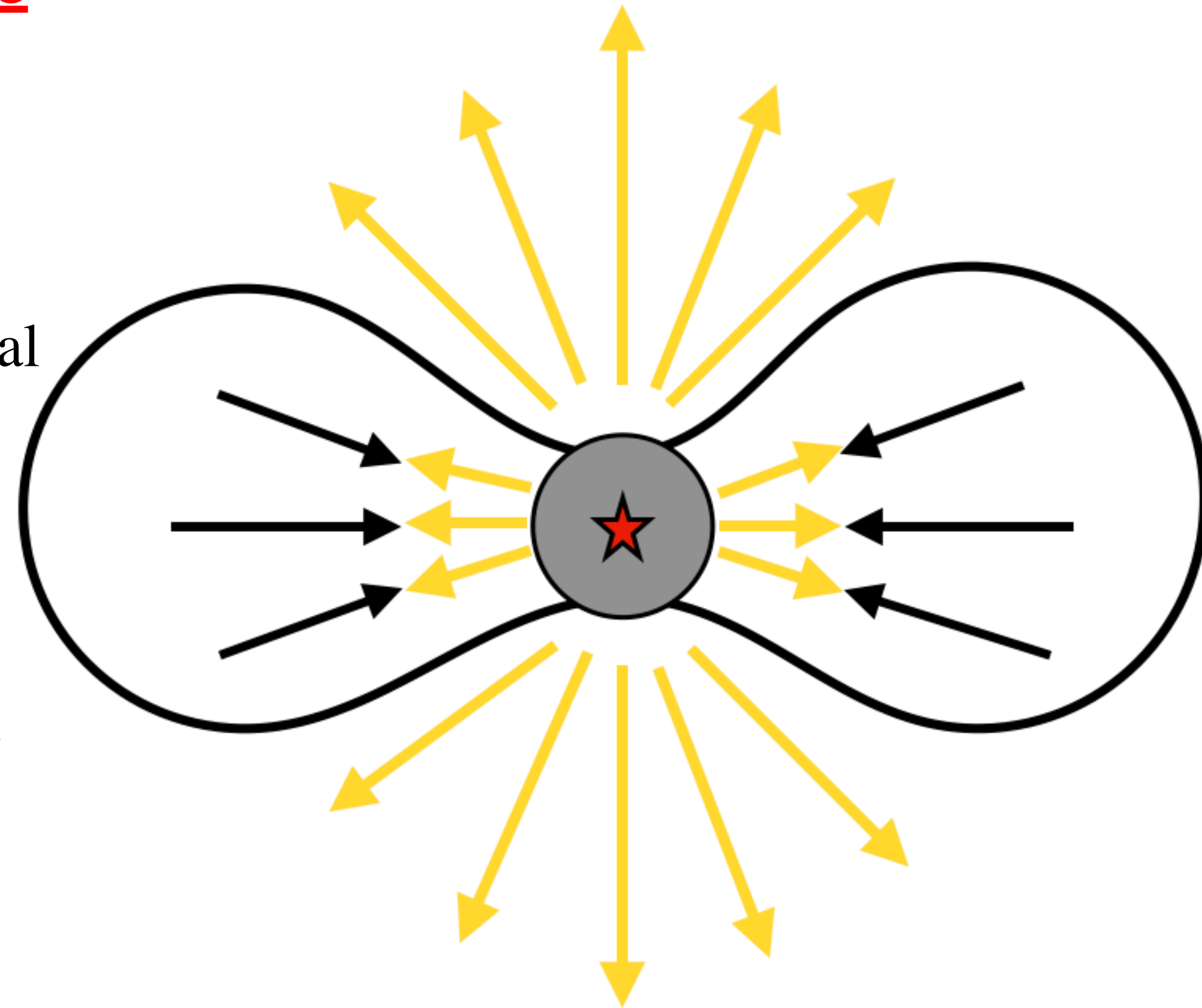


The HIGH-MASS SF PROBLEM: THEORETICAL SOLUTIONS

See e.g. review by Tan et al. 2014, PPVI

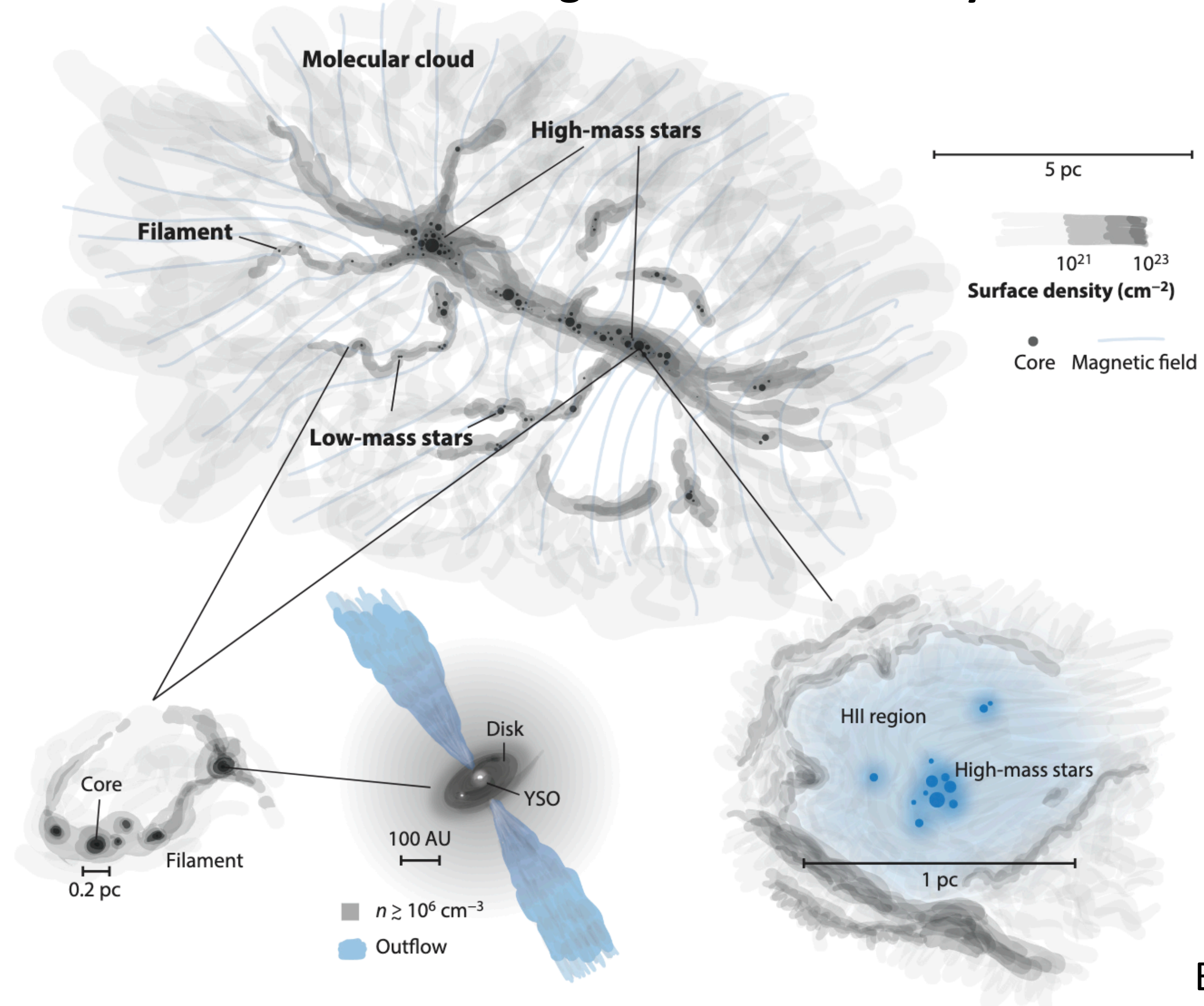
2. Monolithic / core-fed models

- A single massive molecular core collapses under gravity.
- The protostar grows by accreting material from its *own nonspherical* envelope.
- Environment around can be relatively quiet; the process is “*isolated.*”
- The *effective radiation pressure* against the ram pressure of the collapsing material is a small fraction of the total



Massive pre-stellar cores: do they exist?

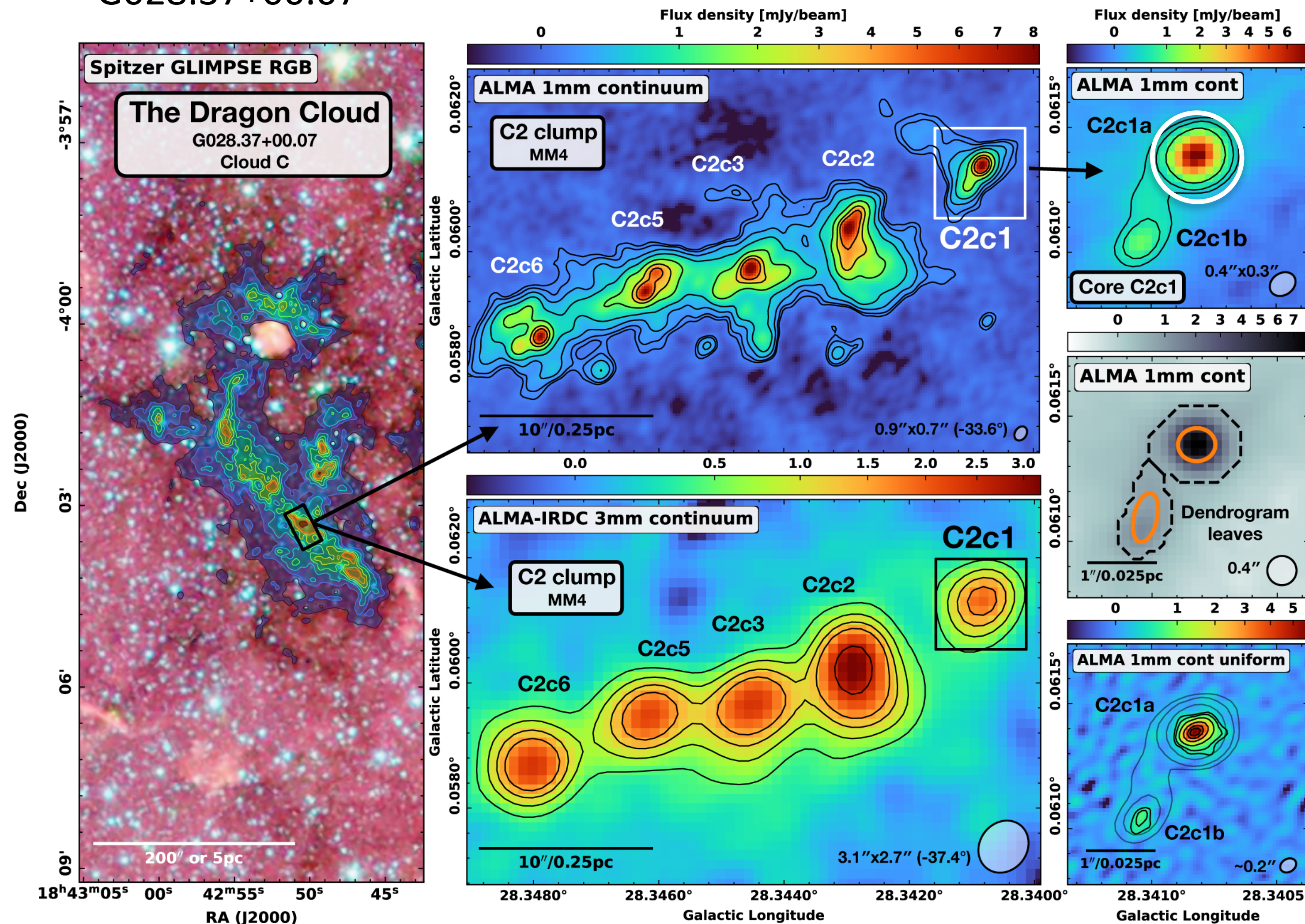
Star formation often detected in **fragmented filamentary** molecular clouds



Massive pre-stellar cores: do they exist?

“Dragon nebula” -
G028.37+00.07

Only a few (4/5) firm cases of starless
cores candidates with $M > 10 - 20M_{\odot}$



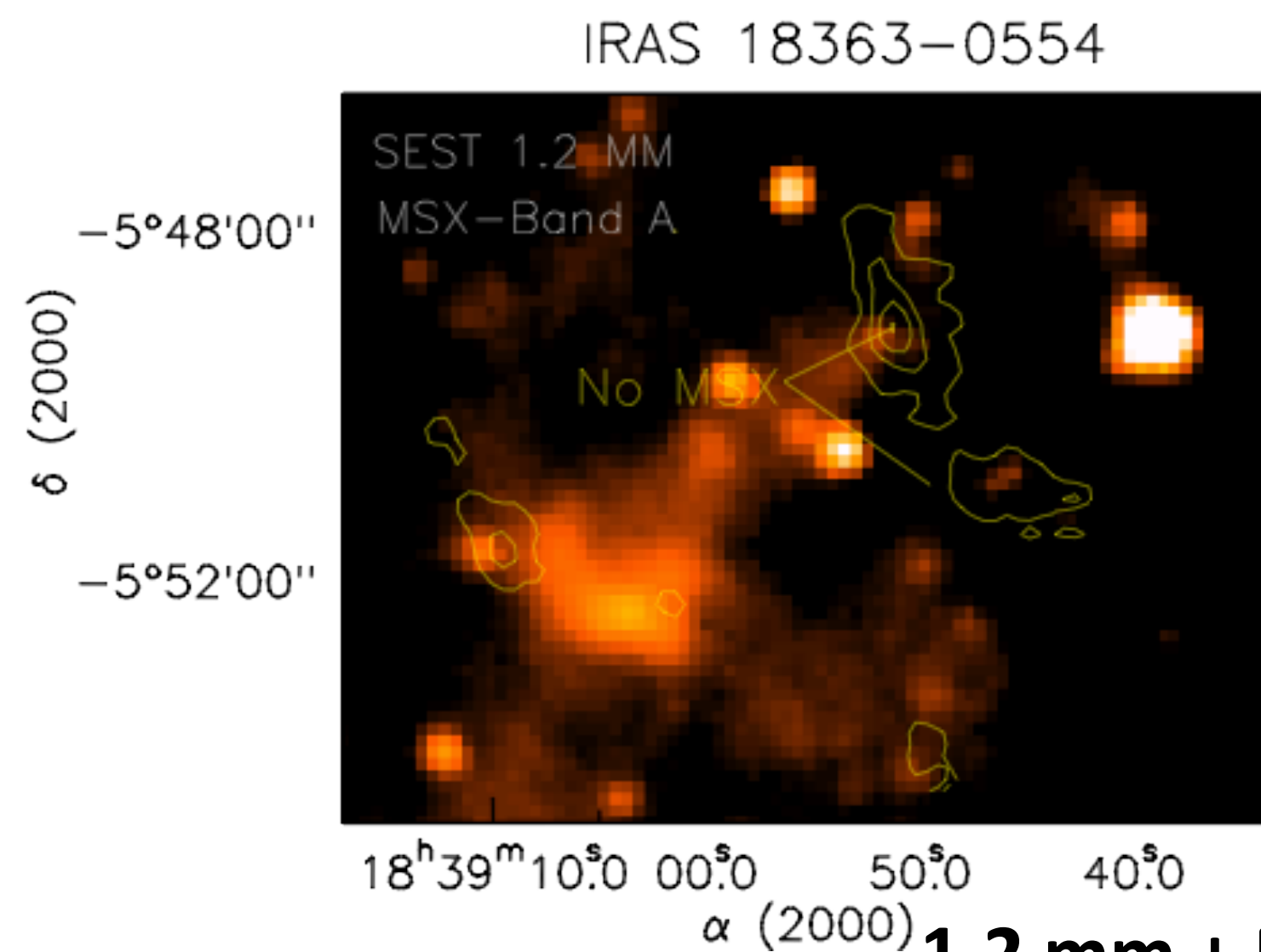
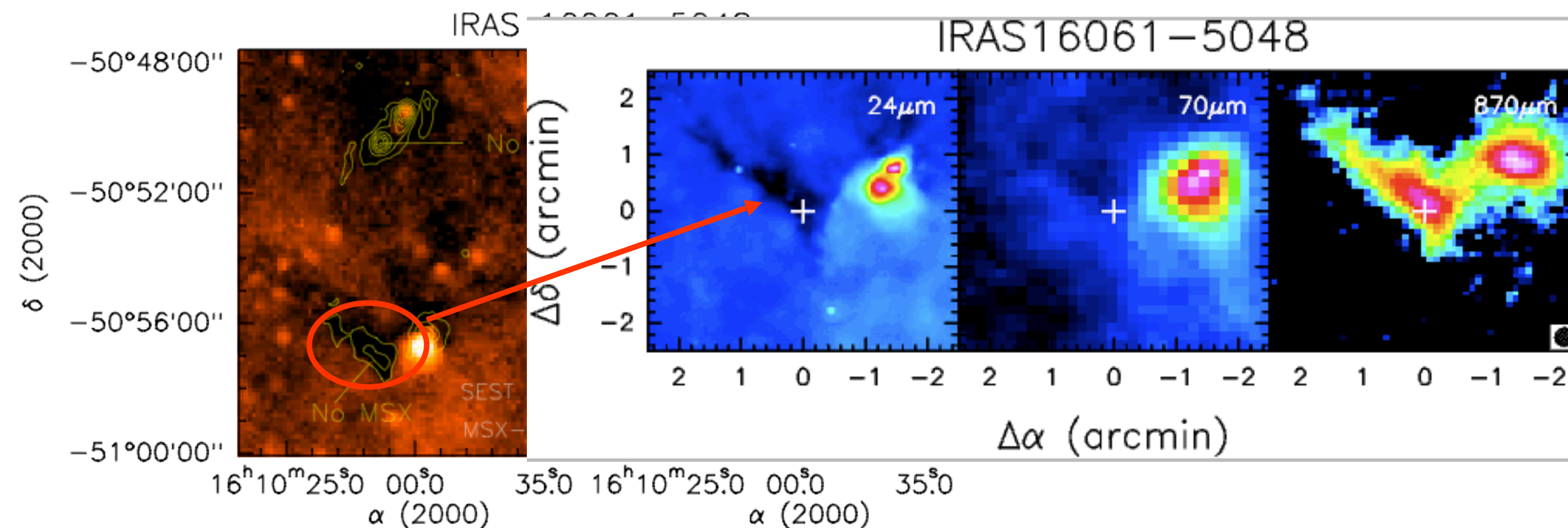
C2C1a is massive
($M \sim 23M_{\odot}$)
and starless

Searching for high-mass starless cores

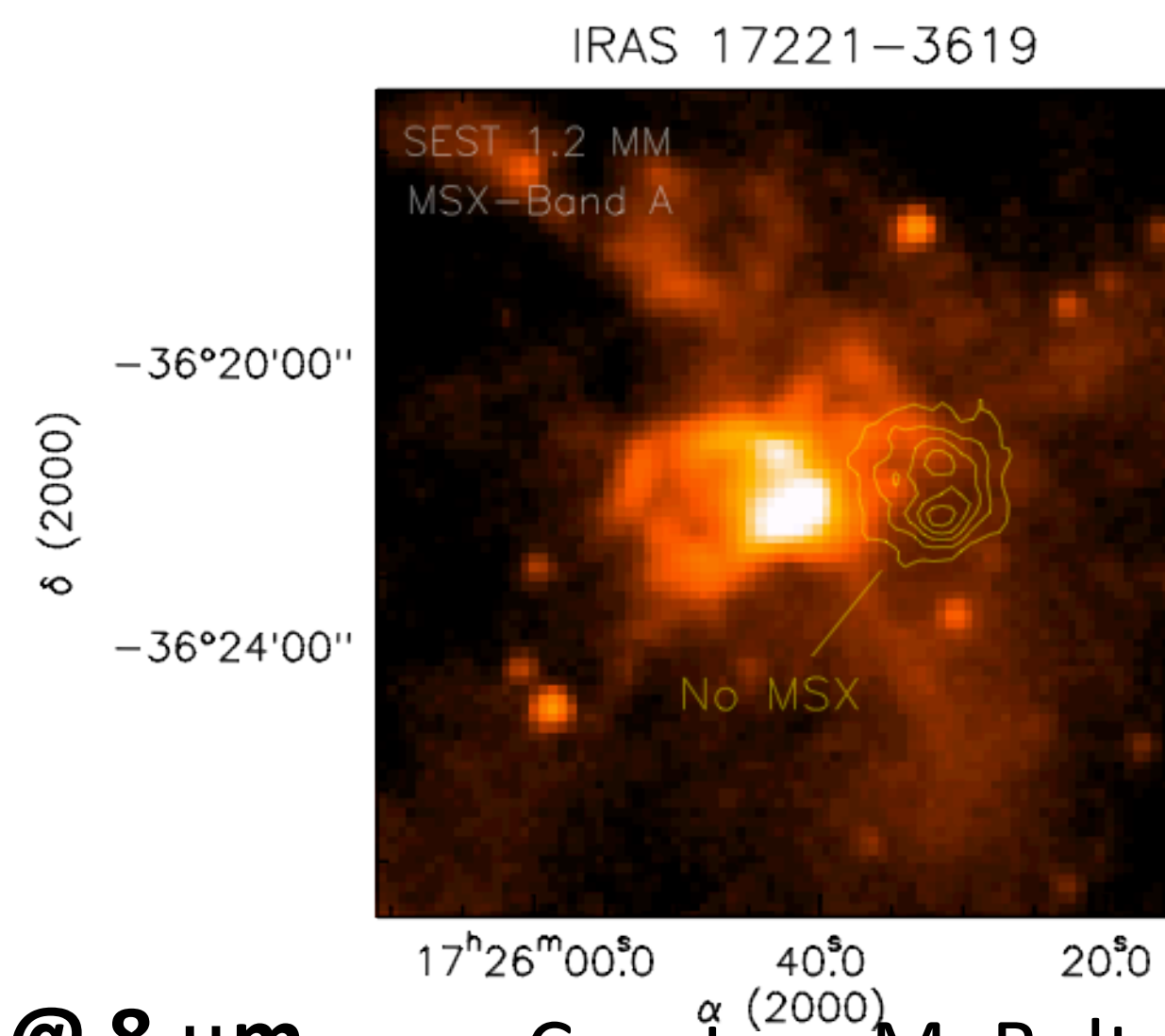
Initial sample: 95 millimeter continuum clumps, MSX-dark

(Fontani+2005; **Beltrán+2006**; Fontani+2012; Sánchez-Monge+2013; Giannetti+2014)

1.2 mm +
MSX @ 8 μm



1.2 mm + MSX @ 8 μm

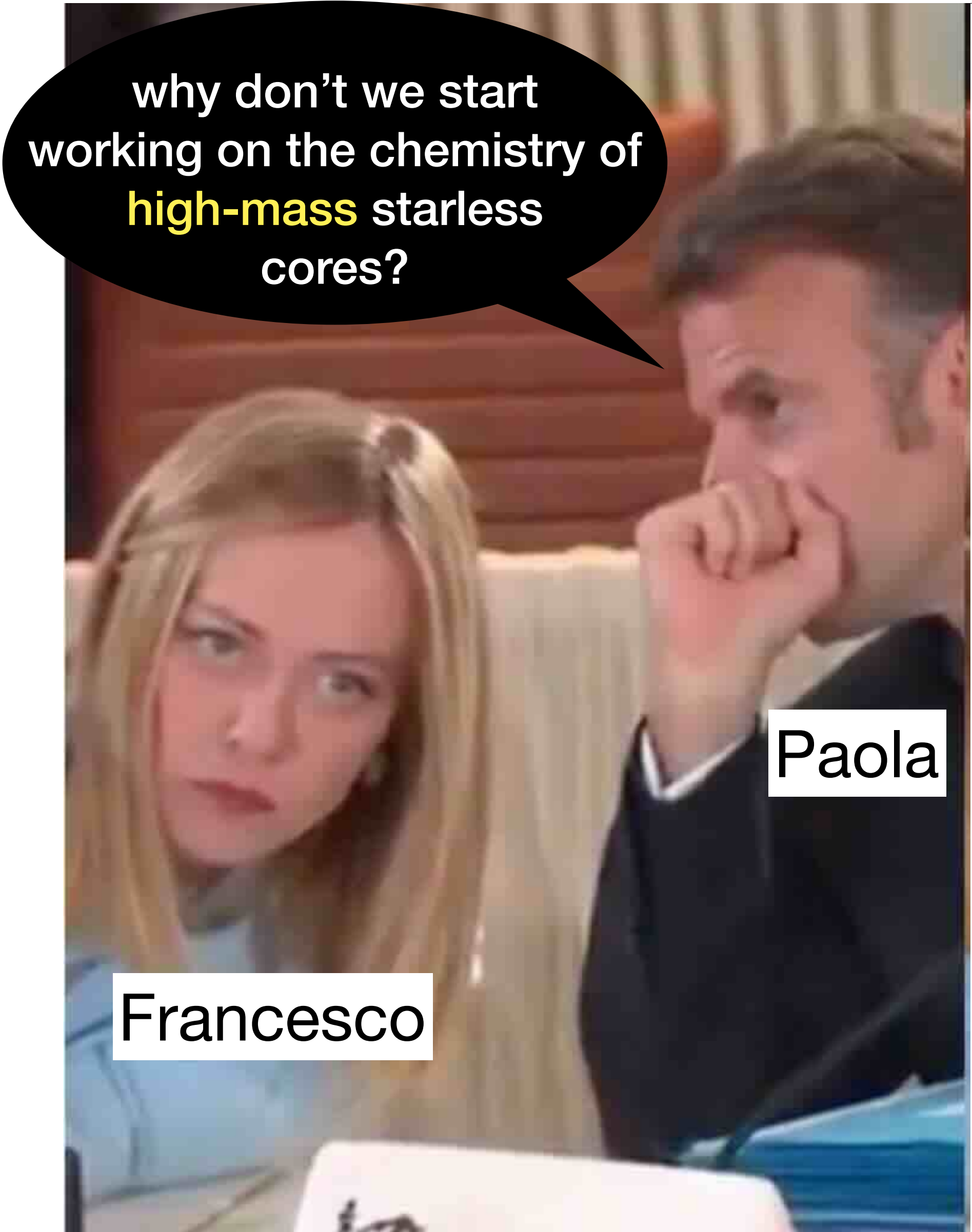


Courtesy M. Beltran



Francesco

Paola



why don't we start working on the chemistry of **high-mass** starless cores?

Paola

Francesco

Chemical properties of massive starless cores

why don't we start working on the chemistry of **high-mass** starless cores?



Paola

Francesco

Chemical properties of starless (pre-stellar) cores

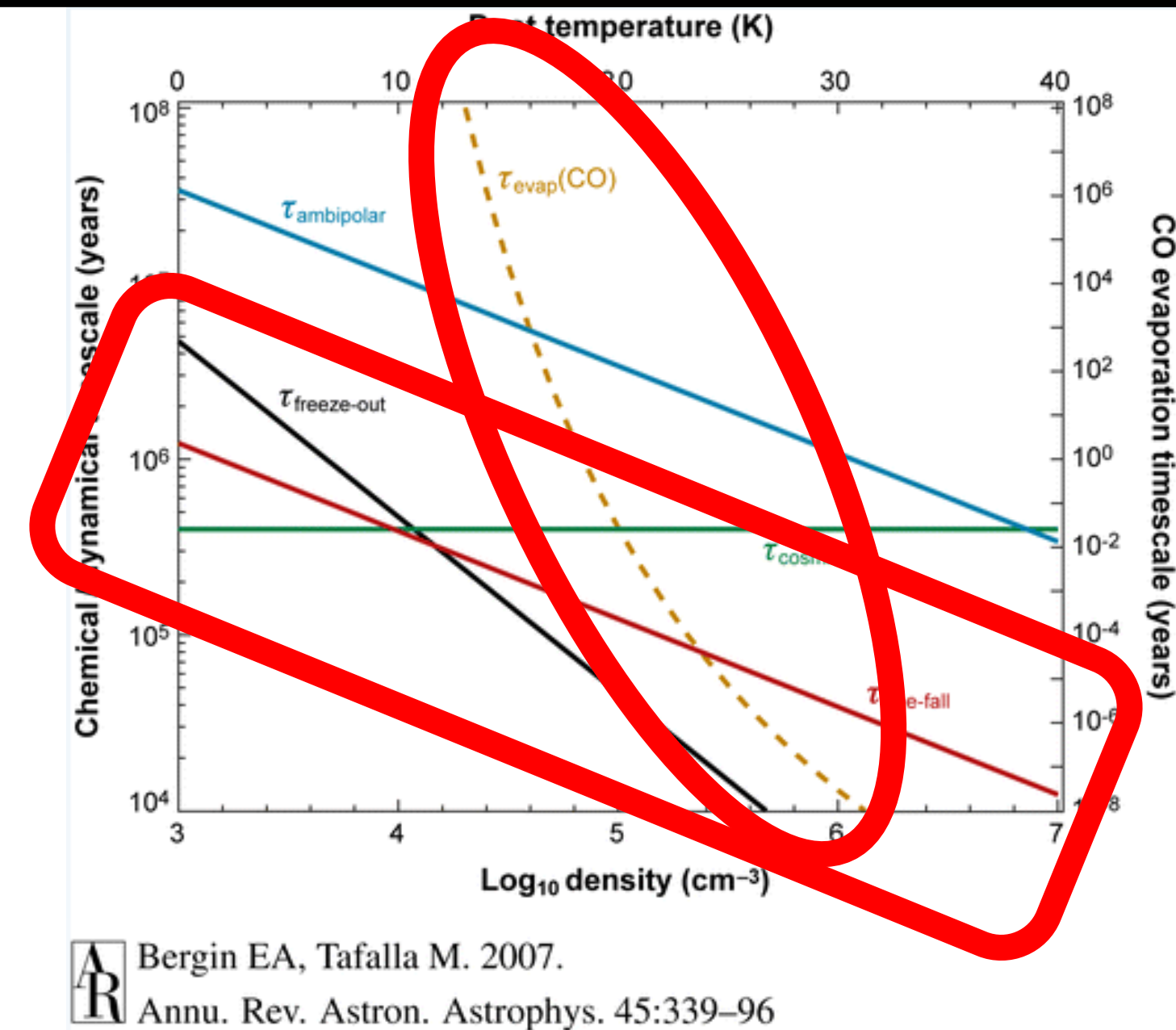
$$T < 20 \text{ K}$$

$$n(\text{H}_2) > 10^5 \text{ cm}^{-3}$$

High CO (and CS) DEPLETION FACTOR

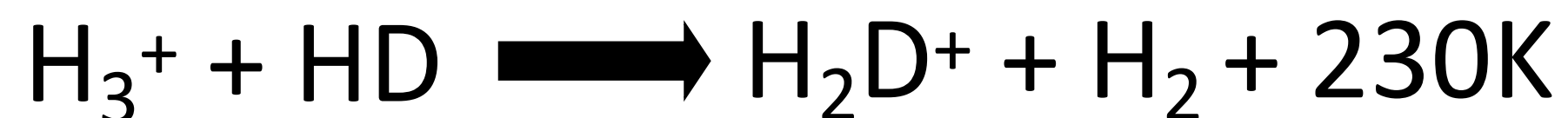
$$f_D = X(\text{CO})^T / X(\text{CO})^0 > 1$$

(e.g. Caselli et al. 1999, 2002, Tafalla et al. 2004)

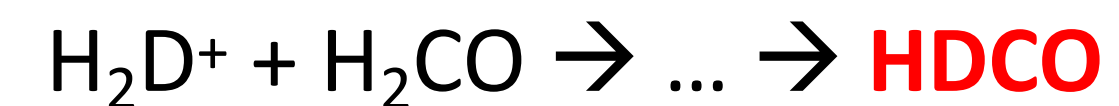
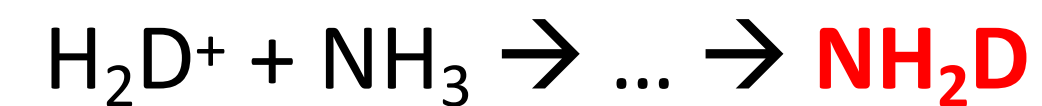
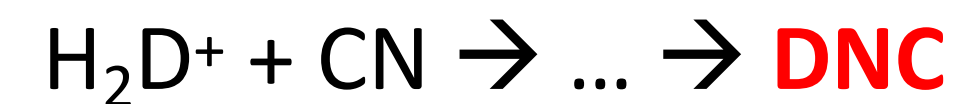
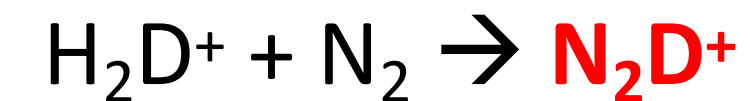


Roberts & Millar 89; Gerlich+02; Asvany+04; Gerlich & Schlemmer 02; Flower+06

If T is low



If $n(\text{H}_2)$ is high

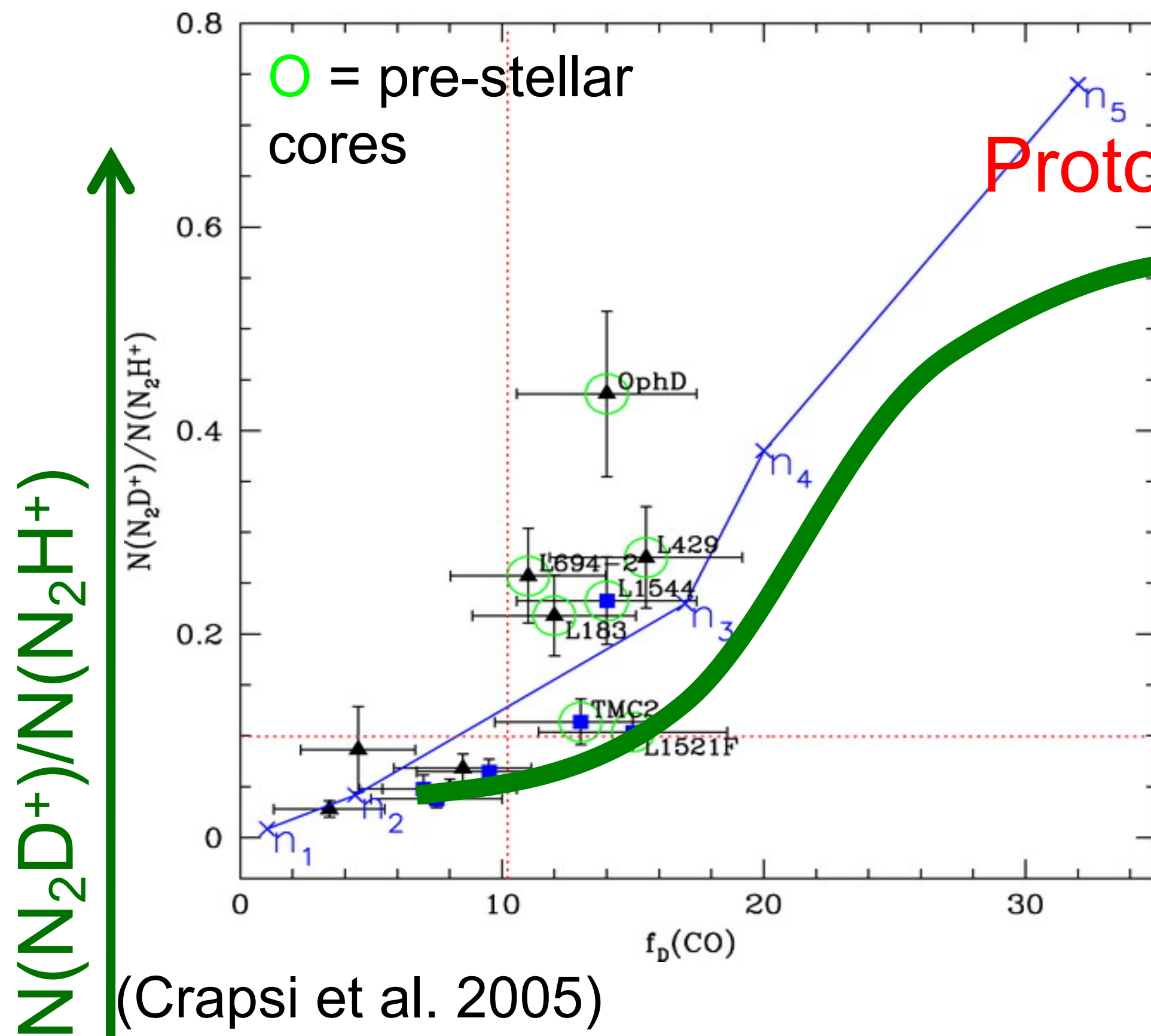


$$D_{\text{frac}} = N(\text{XD}) / N(\text{XH}) \gg 10^{-5}$$

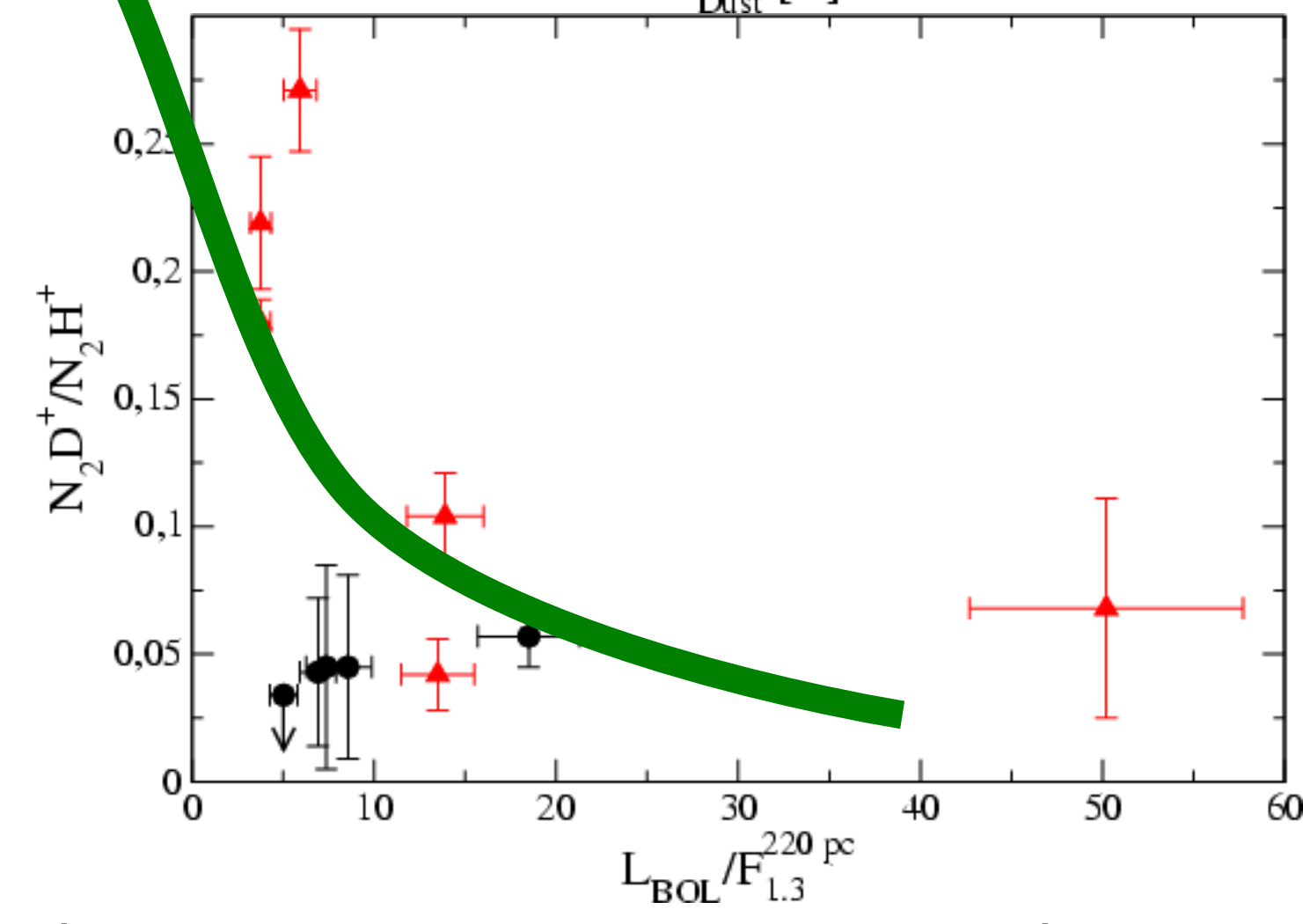
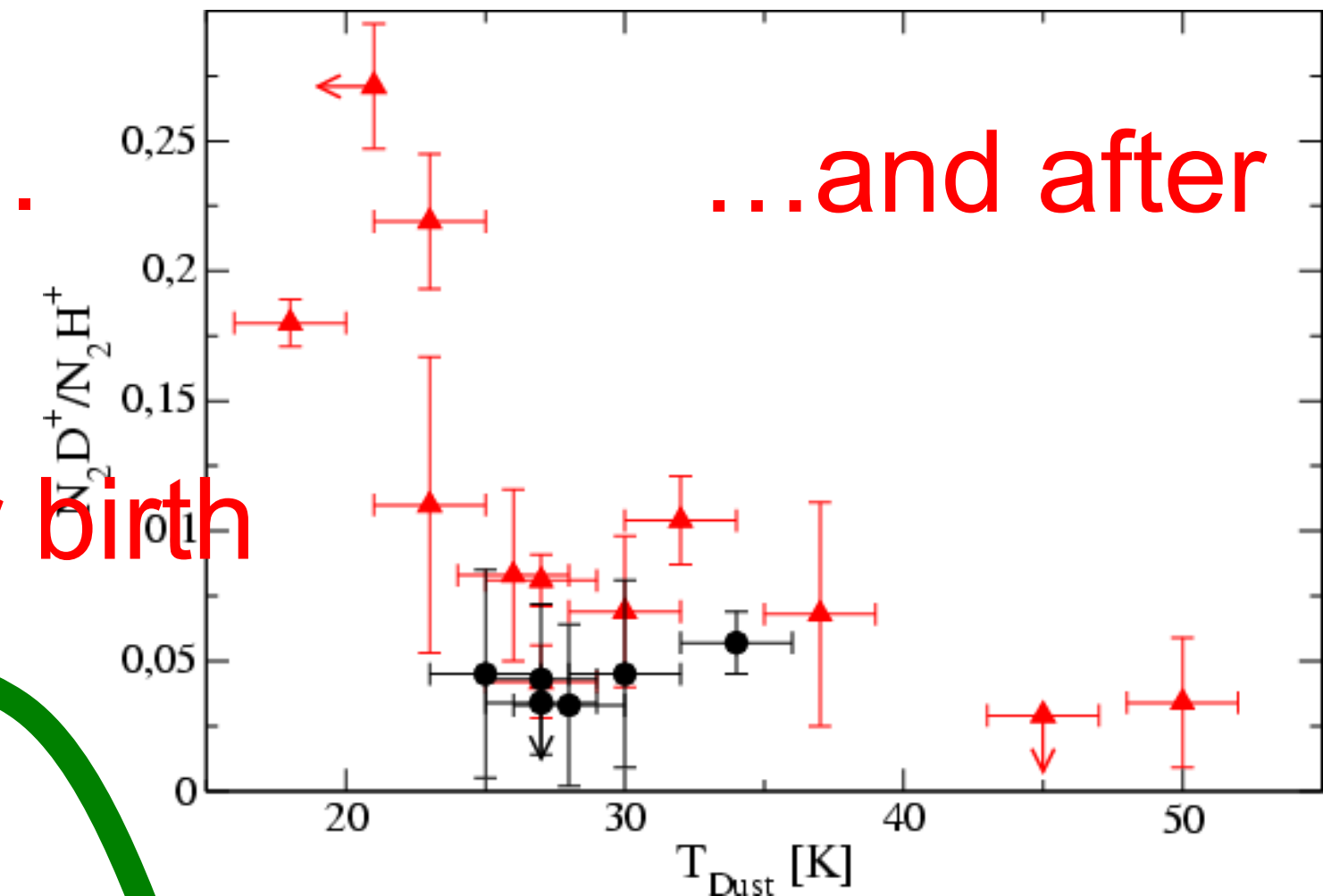
(e.g. Crapsi et al. 2005, Emprechtinger et al. 2009, Gerner et al. 2015)

Chemical properties of starless (pre-stellar) cores

before the formation of the protostar....



Protostar birth



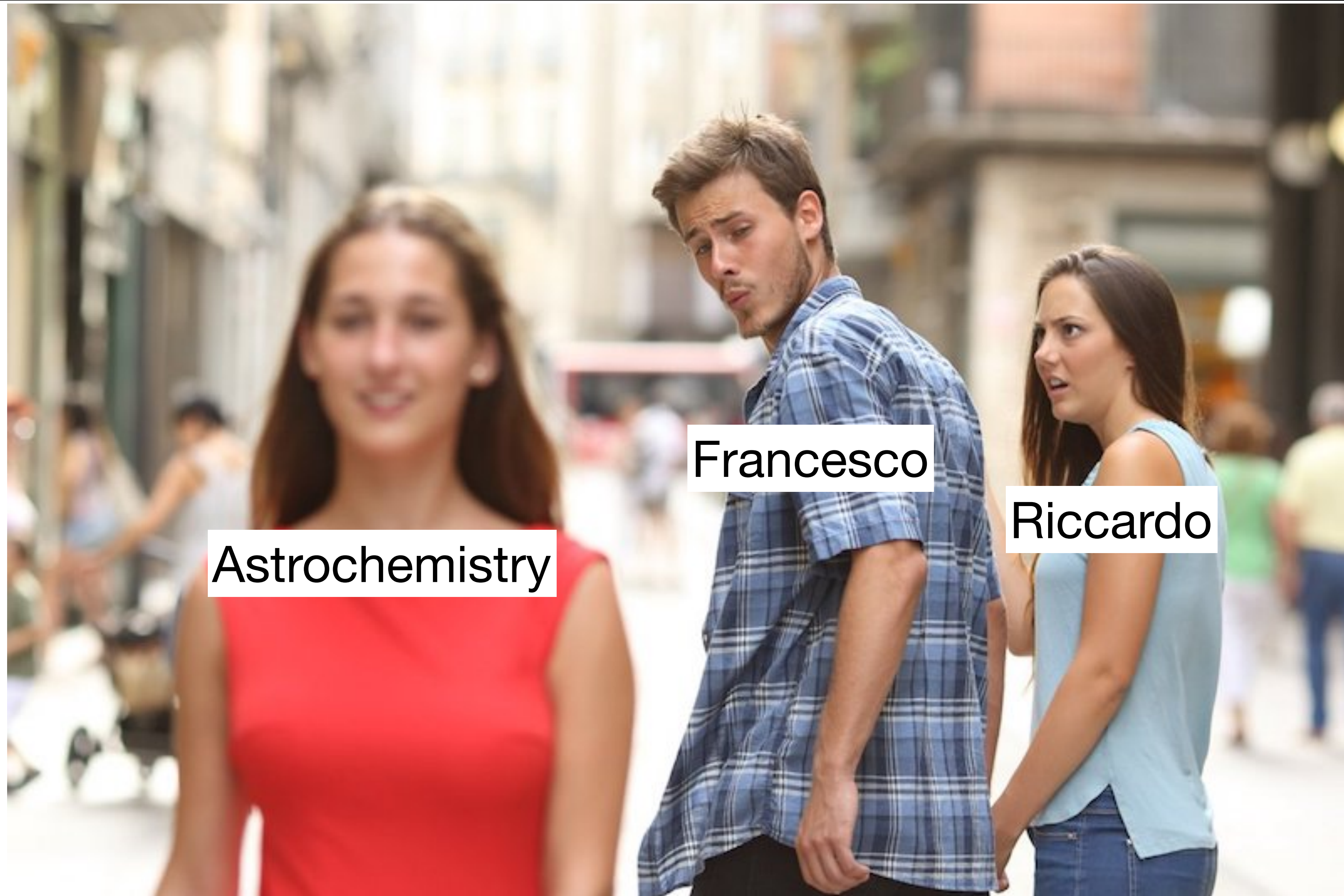
time

$N(N_2D^+)/N(N_2H^+)$ is maximum at the verge of collapse

Chemical properties of massive starless cores



Chemical properties of massive starless cores



Chemical properties of massive starless cores



Astrochemistry



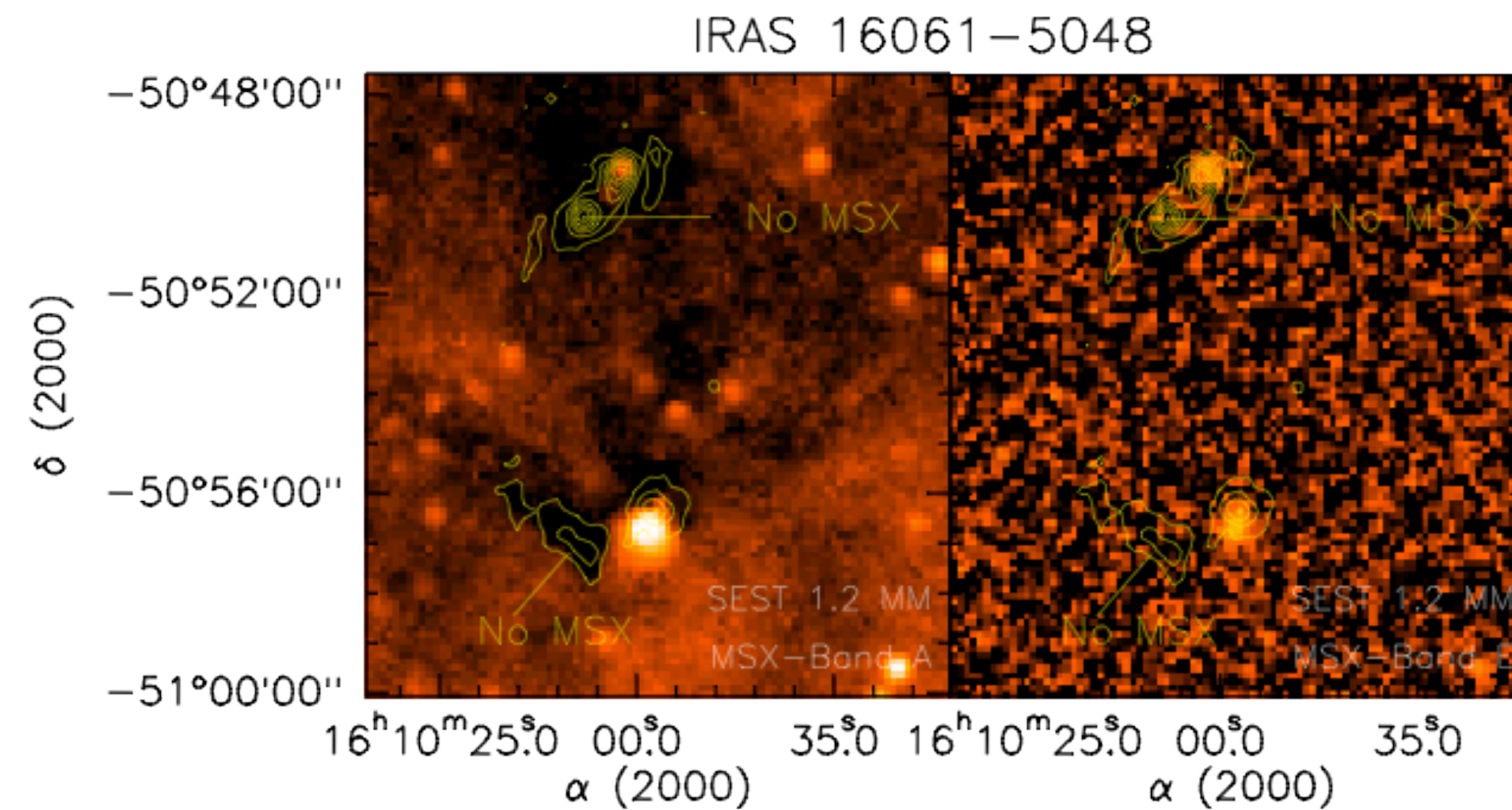
Astrochemistry
to study physics

high-mass starless cores: CO depletion

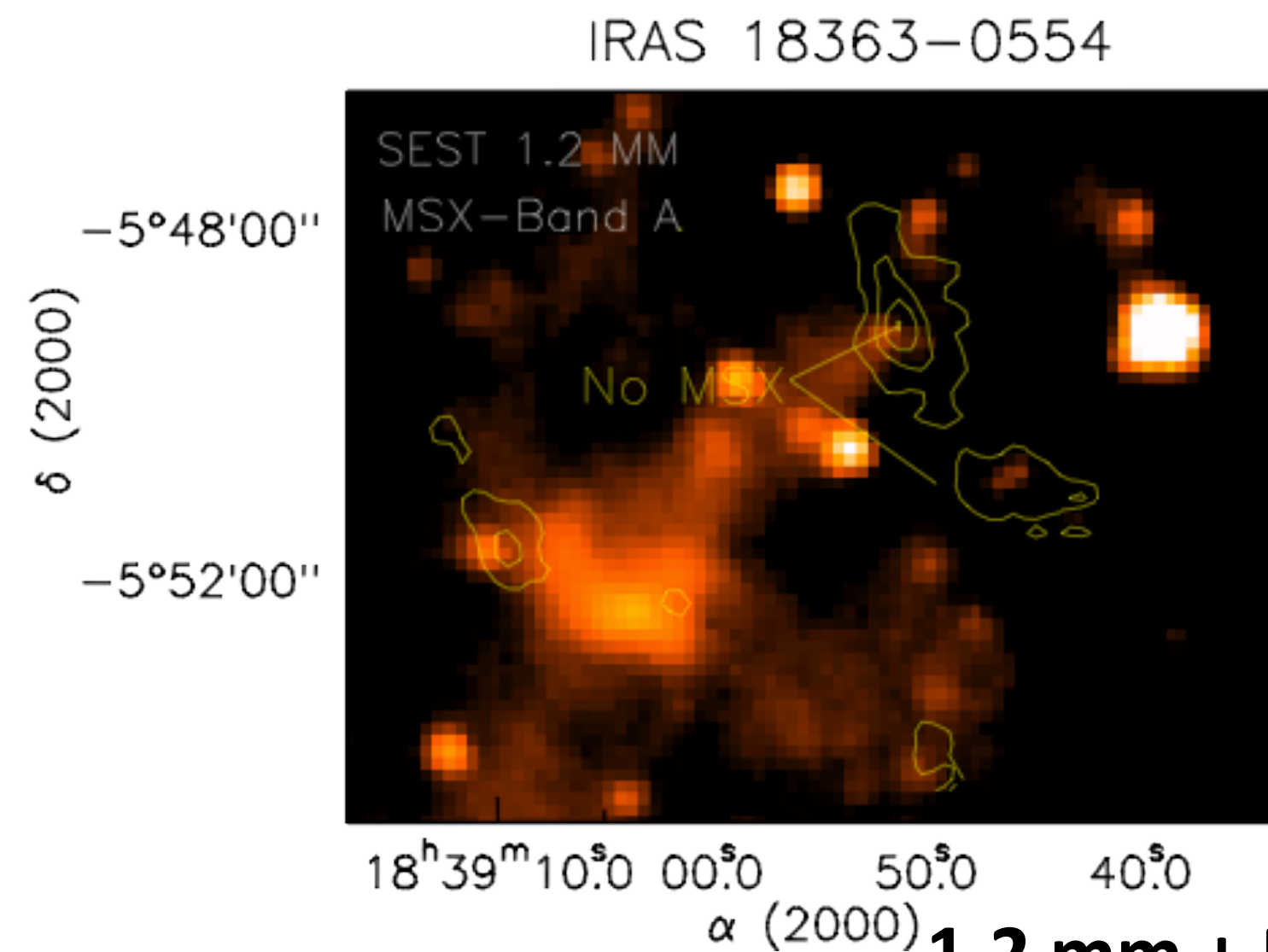
Initial sample: 95 millimeter continuum clumps, MSX-dark

(Fontani+2005; **Beltrán+2006**; Fontani+2012; Sánchez-Monge+2013; Giannetti+2014)

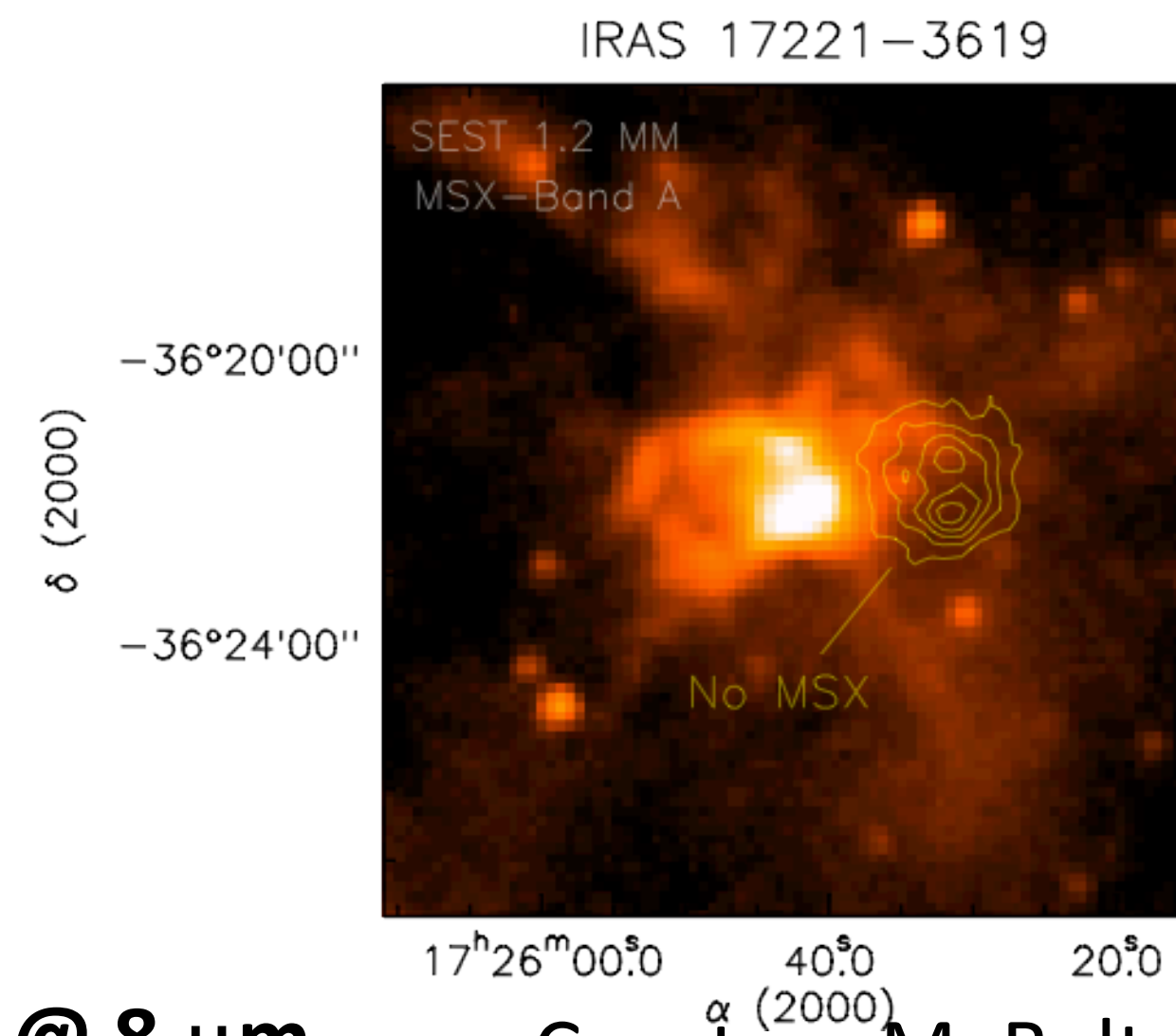
1.2 mm +
MSX @ 8 μm



1.2 mm +
MSX @ 21
 μm



1.2 mm + MSX @ 8 μm



Courtesy M. Beltran

high-mass starless cores: CO depletion

progressive selection of
dense col cores:
11 targets with $f_{\text{CO}} > 5$

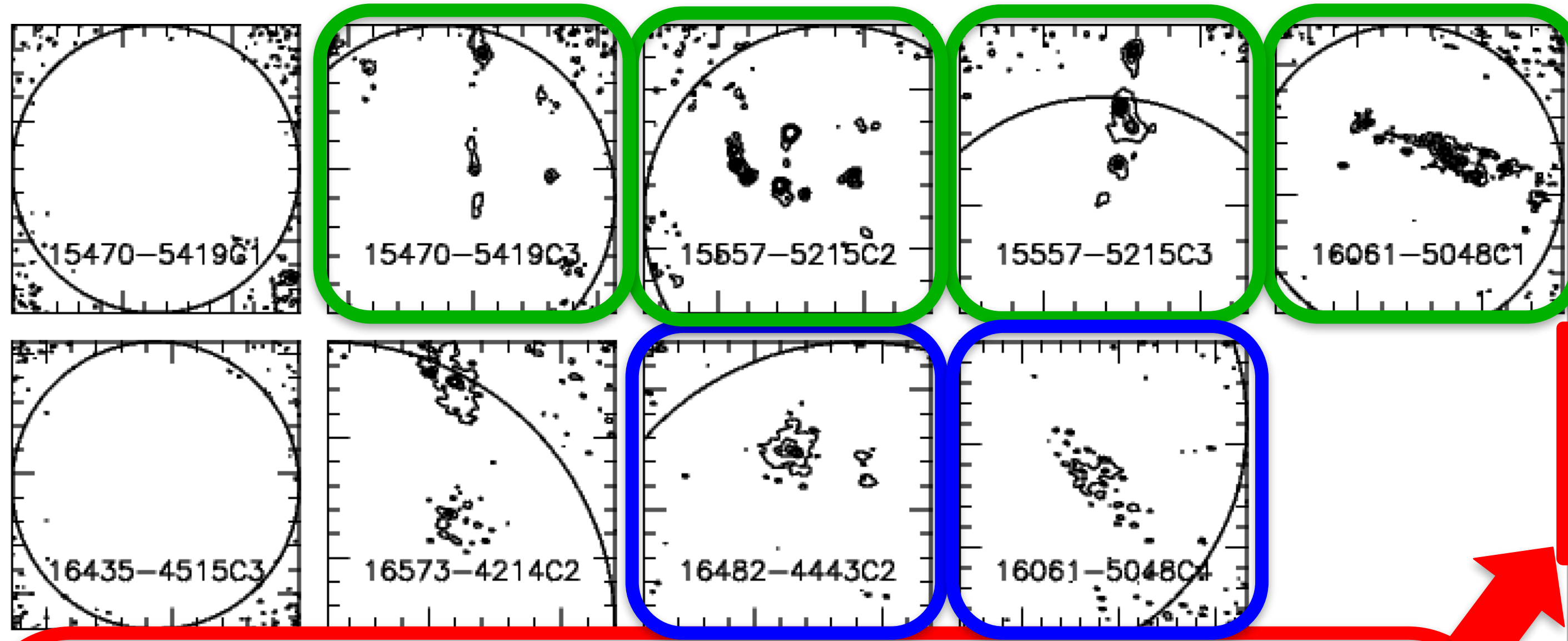
1. Potential sites of massive star formation
2. Cold and chemically young

Table 1: *Sample of massive dense clumps and general properties: coordinates, distance, deconvolved angular diameter, gas mass, gas temperature, H₂ column density, mass surface density and CO depletion factor.*

Source	R.A.(J2000) h m s	Dec.(J2000) ° ' "	d kpc	θ_s "	M M_{\odot}	T_k K	$N(\text{H}_2)$ $\times 10^{23} \text{ cm}^{-2}$	$\Sigma(\text{H}_2)$ g cm^{-2}	f_{CO}
08477–4359c1	08:49:35.13	–44:11:59	1.8	35.6	86.73	19	1.42	0.24	7
13039–6108c6	13:07:14.80	–61:22:55	2.4	40.3	101.5	17	0.68	0.12	22
15470–5419c1	15:51:28.24	–54:31:42	4.1	24.2	310.2	18	1.37	0.36	35
15470–5419c3	15:51:01.62	–54:26:46	4.1	54.1	743.4	19	1.11	0.17	36
15557–5215c2	15:59:36.20	–52:22:58	4.4	41.3	633.4	23	1.55	0.22	32
15557–5215c3	15:59:39.70	–52:25:14	4.4	35.8	194.3	15	0.49	0.09	24
16061–5048c1	16:10:06.61	–50:50:29	3.6	28.1	284.3	25	1.66	0.31	12
16061–5048c4	16:10:06.61	–50:57:09	3.6	62.8	504.2	13	1.22	0.11	34
16435–4515c3	16:47:33.13	–45:22:51	3.1	17.7	147	12	1.20	0.55	73
16482–4443c2	16:51:44.59	–44:46:50	3.7	$\ll 24^a$	59.08	16	$\gg 4.63^a$	0.66	9
16573–4214c2	17:00:33.38	–42:25:18	2.6	7.29	108.3	17	1.89	3.4	25

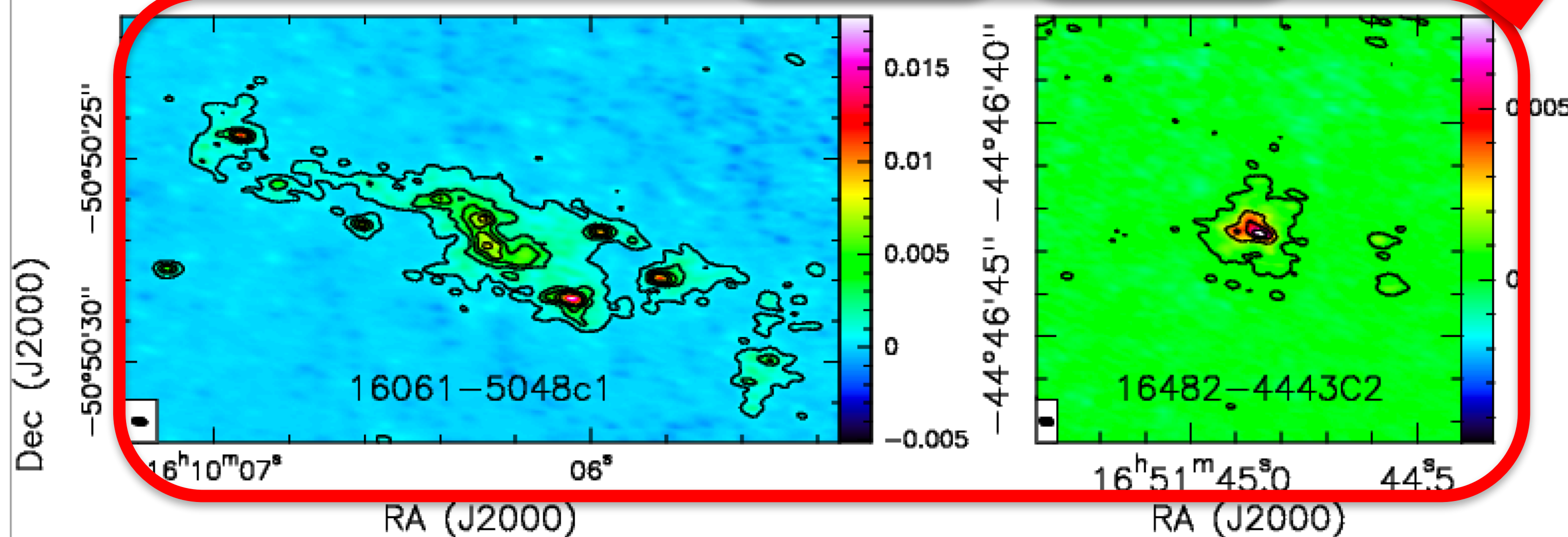
follow-up: ALMA study of fragmentation

9 objects: different fragmentation levels!

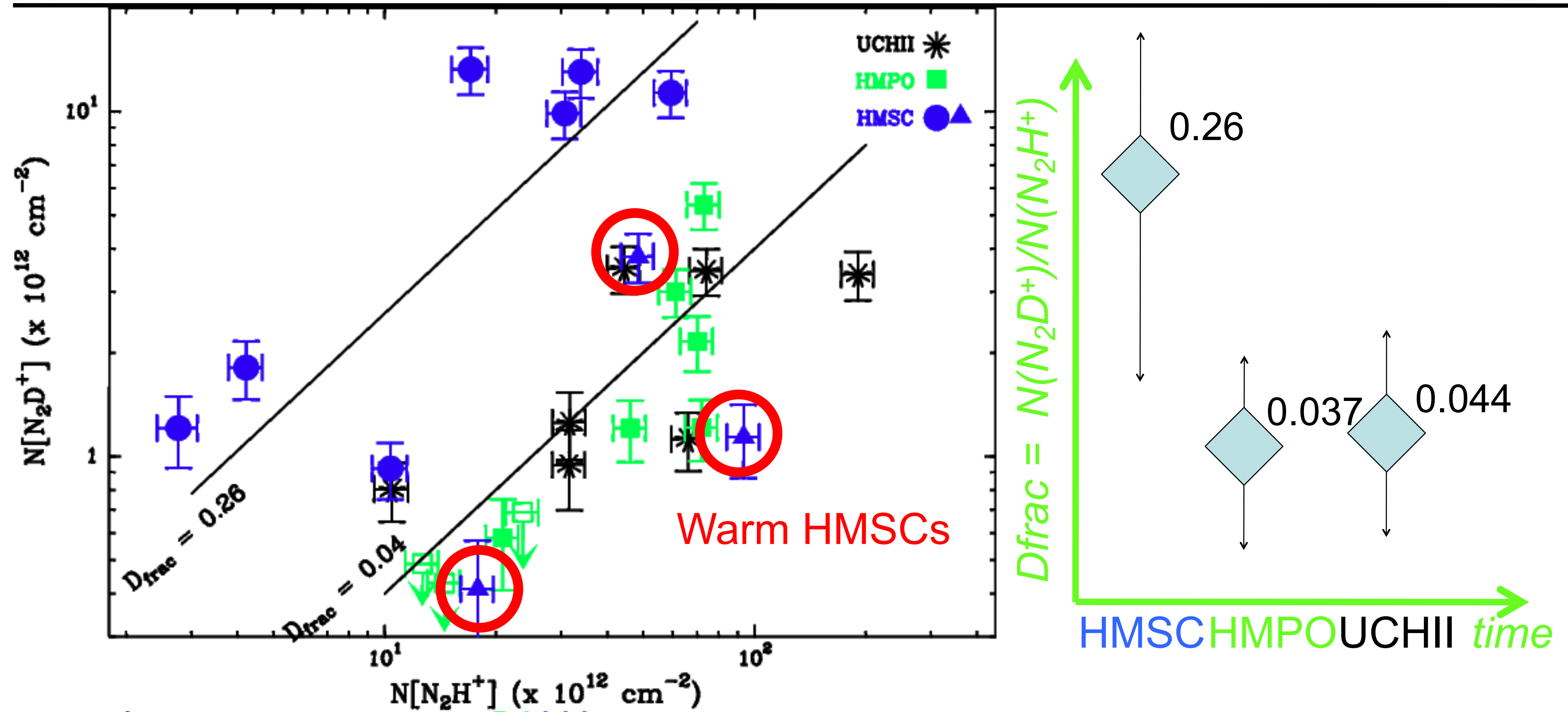


Resolution: $\theta \sim 0.25''$
Sensitivity: $\sim 0.07 M_{\odot}$

Two "extreme" cases:
- 12 fragments
- 1 fragment

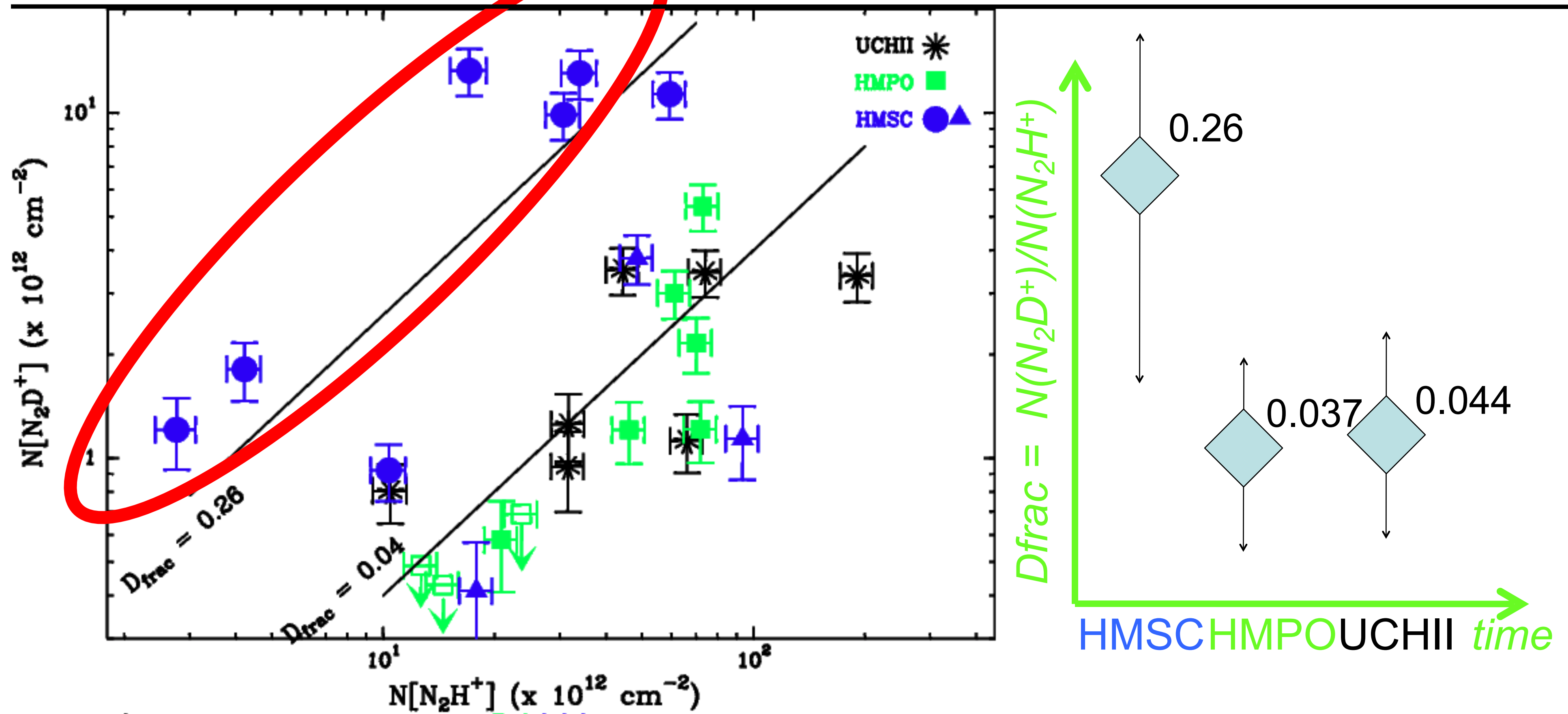


high-mass starless cores: Deuterium frac.



Statistical separation between **HMSCs** and **HMPOs**/UCHIIs:
Kolmogorov-Smirnov test: $P \sim 0.004$

high-mass starless cores: Deuterium frac.



Statistical separation between HMSCs and HMPOs/UCHIIs:
Kolmogorov-Smirnov test: $P \sim 0.004$

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

Follow-up: the CHEMICO project

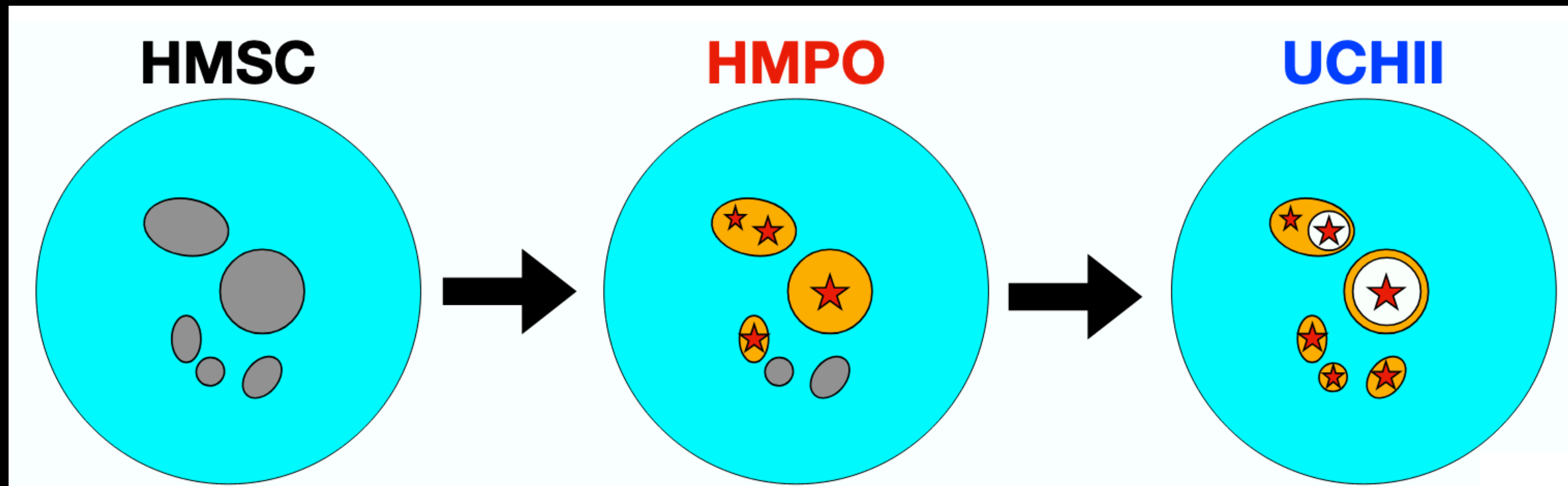
CHEMical evolution in Massive star-forming COres

V. Rivilla (CAB), H. Martín-Caballero (CAB), A. López-Gallifa (CAB), L. Colzi (CAB)

M.T. Beltrán (INAF), A. Sánchez-Monge (ICE), L. Bizzocchi (UniBO), C. Mininni (INAF)

E. Roueff (LUX), P. Caselli (MPE), A. Vasyunin (Ural University)

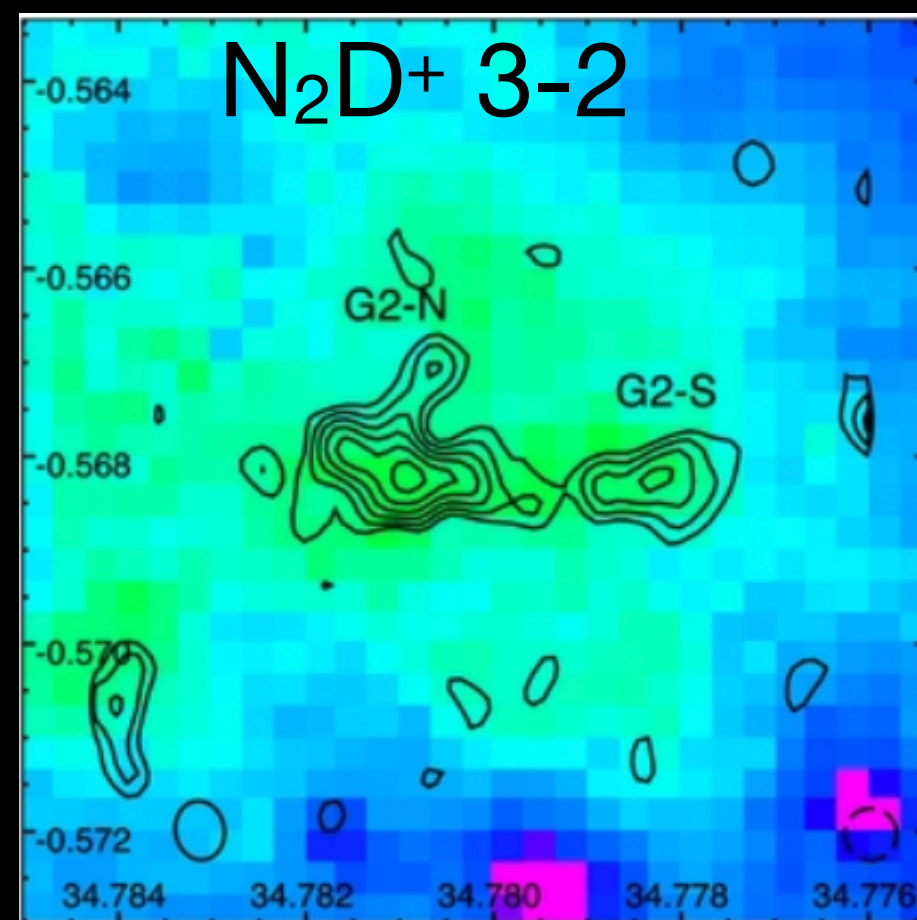
✓ **Main goal:** study how chemical complexity changes with time



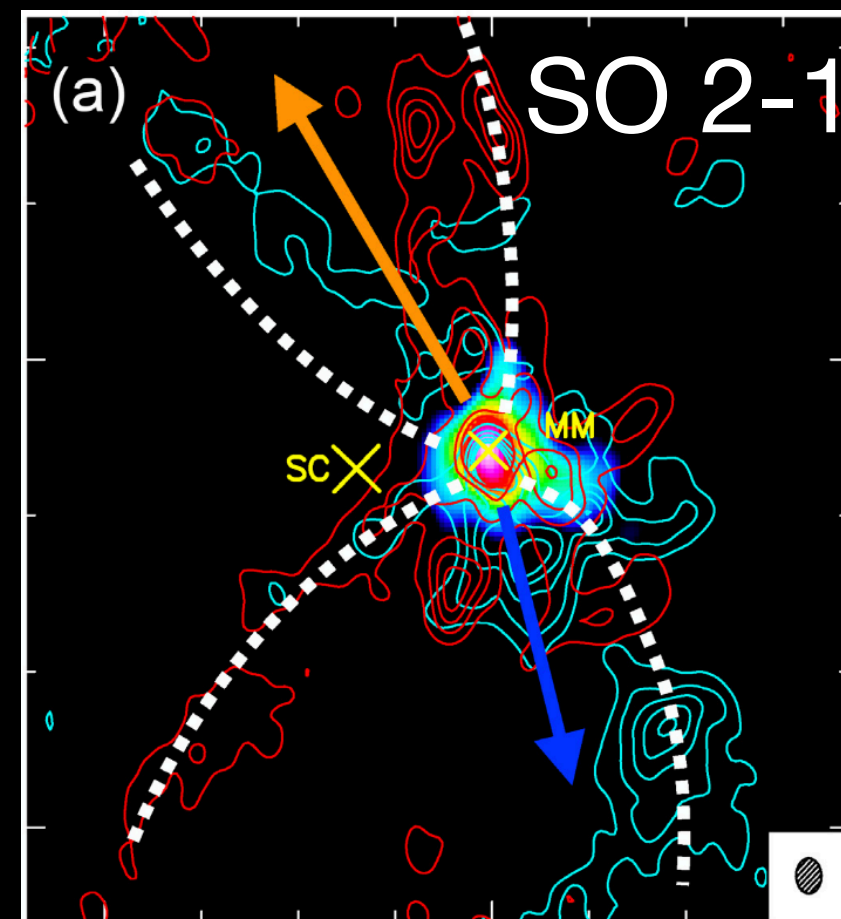
Fontani+2025, FrASS: "Chemical evolution in high-mass star forming regions"

CHEMical evolution in Massive star-forming COres

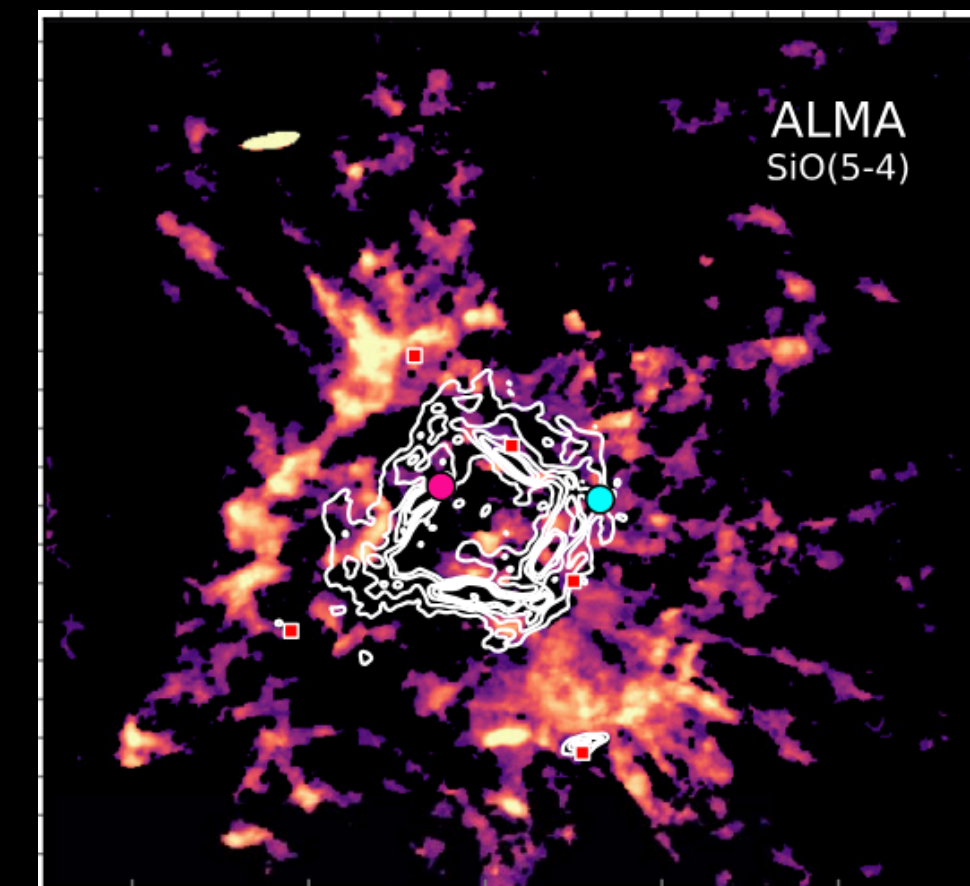
- ✓ **Main goal:** study how chemical complexity changes with time
- ✓ **Method:** unbiased spectral survey of rotational molecular lines
- ✓ **Target sources:** 3 cores representatives of the 3 evolutionary stages: G034G2(MM2)= HMSCs; AFGL5142-MM = HMPOs; G5.89-0.39 = UCHII



Tan et al. 2013



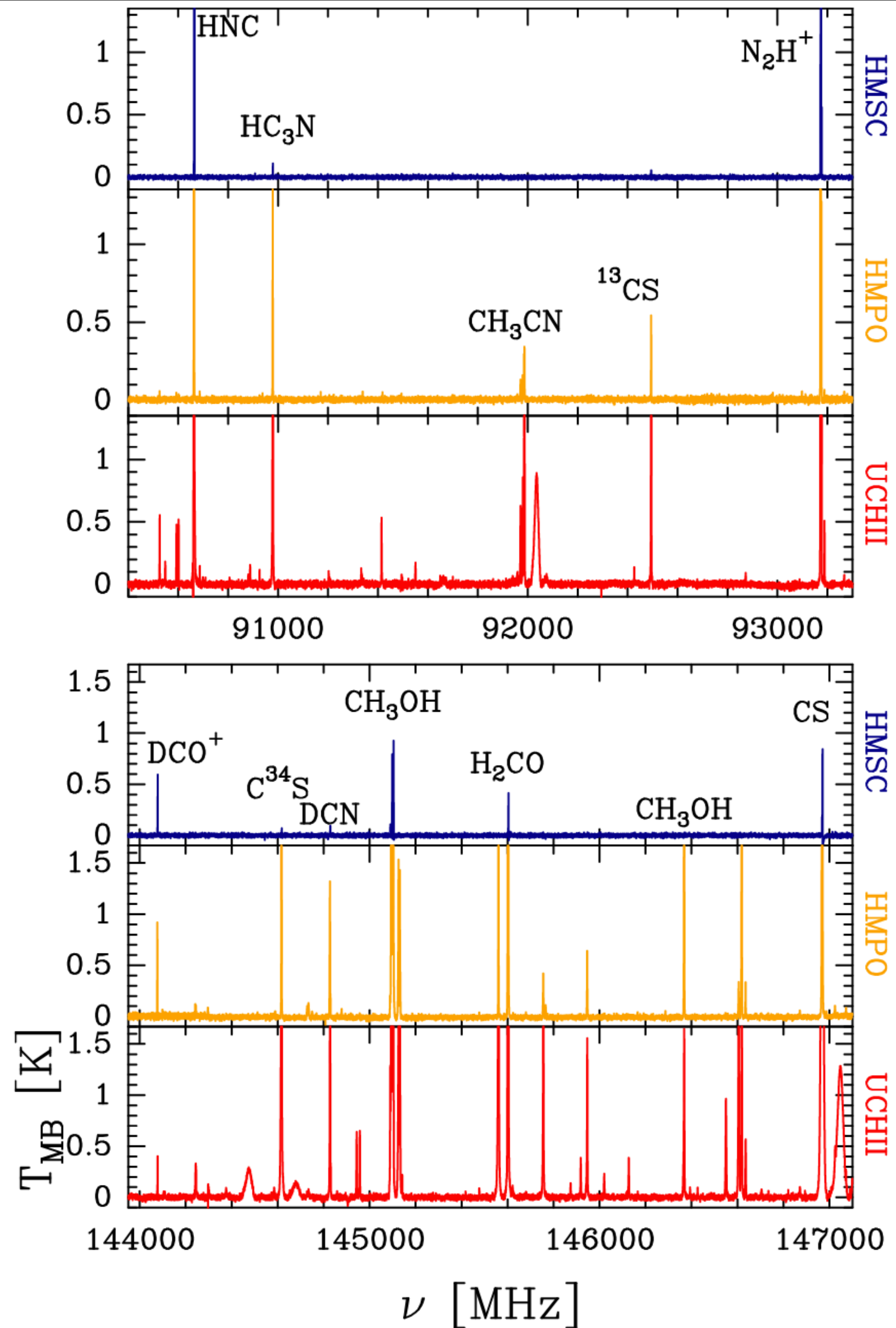
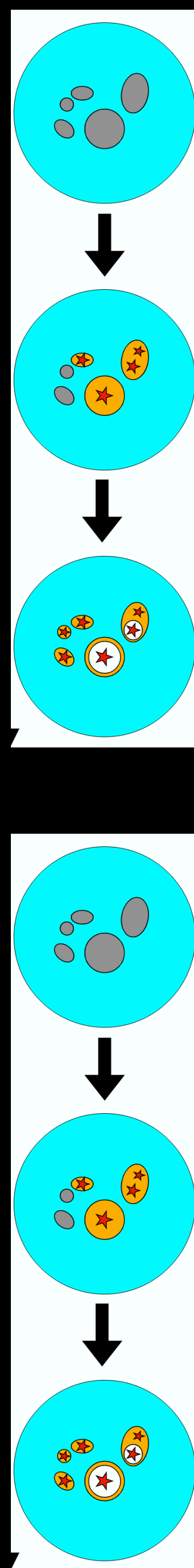
Rivilla et al. 2020

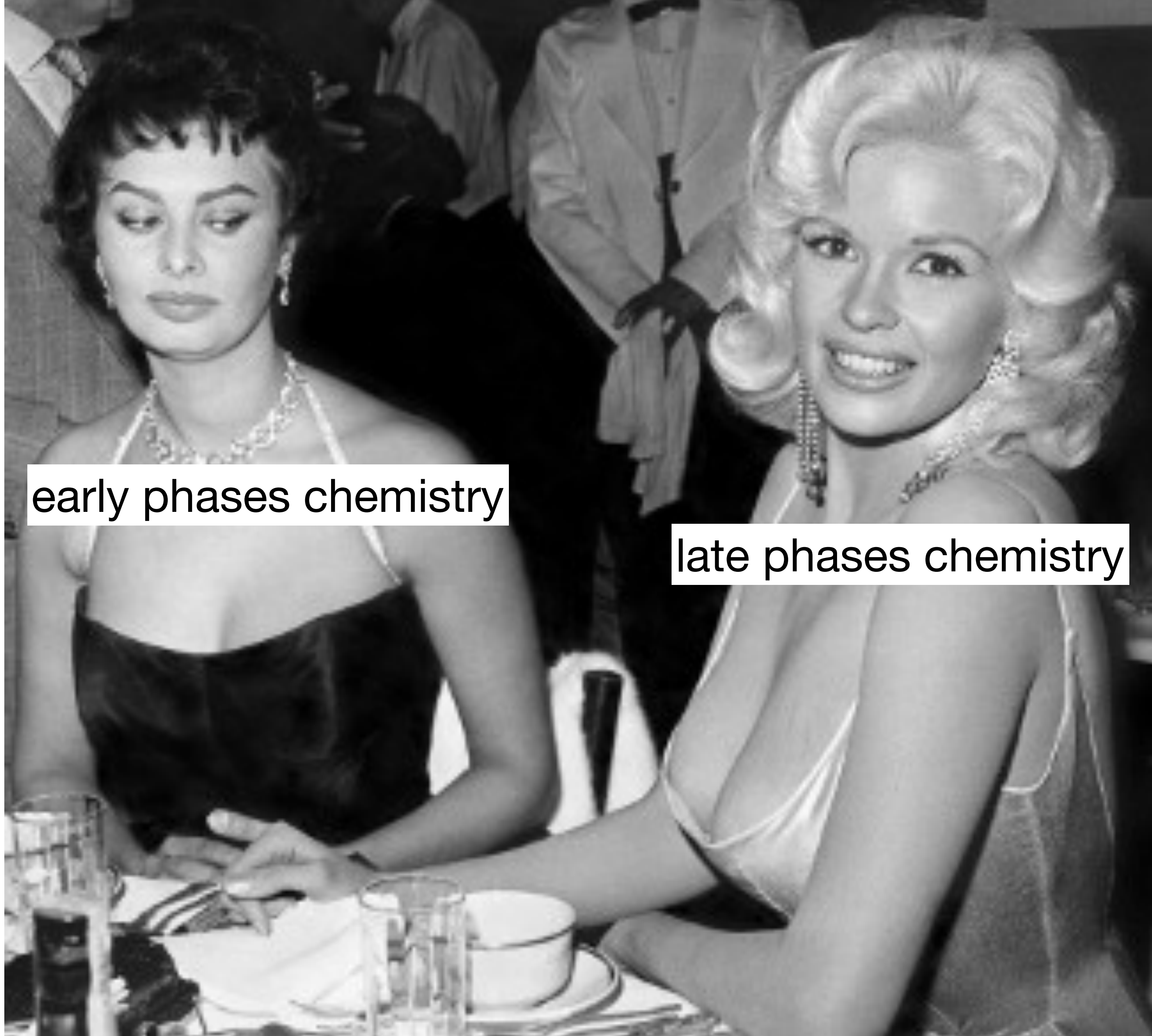


Zapata et al. 2020

- ✓ **Telescopes:** IRAM-30m (72-345 GHz), Yebes (35-50 GHz, Y-CHEMICO)

Chemical richness
increases with time

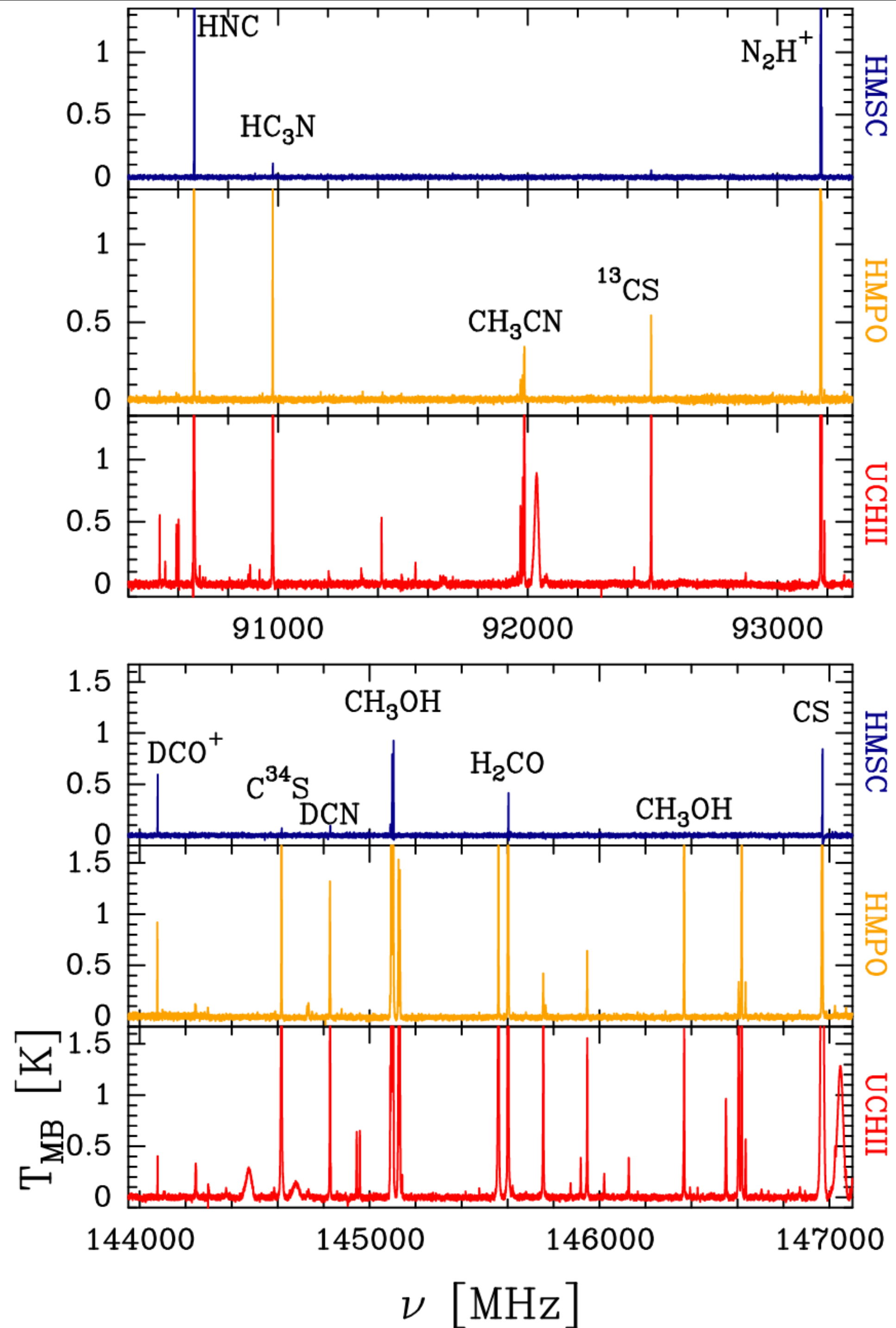
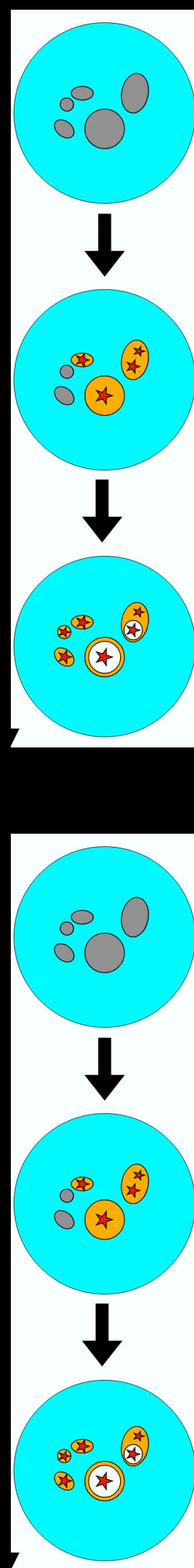




early phases chemistry

late phases chemistry

Chemical richness
increases with time





low-mass chemical complexity



high-mass chemical complexity