Astrochemistry with MOPRA

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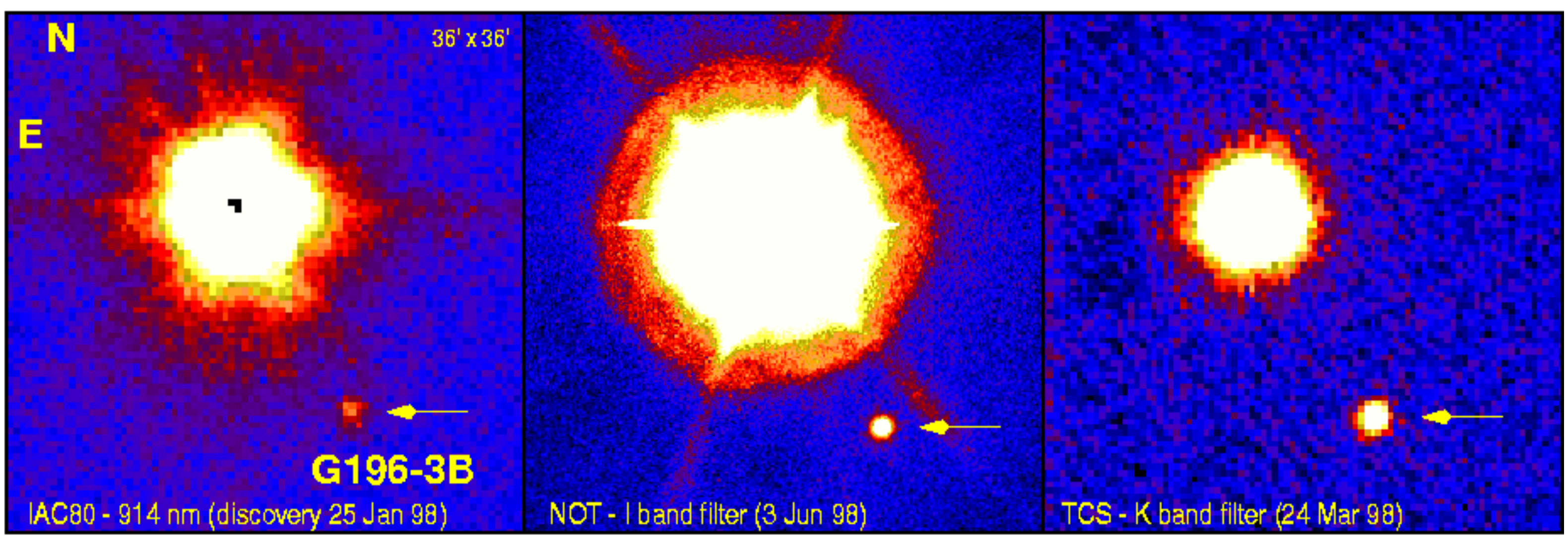
How do Brown Dwarfs (or ‘Failed Stars’) form?

- A brown dwarf is a ‘star’ with < 0.075 solar masses → it does not ignite nuclear fusion

How can objects so small become gravitationally unstable and collapse?

- Several theories: e.g. fragmentation of prestellar disk, photo-erosion of a prestellar core or turbulent fragmentation of a molecular cloud → **can we chemically differentiate among models?**



Rebolo et al., 1998

Turbulent fragmentation of a cloud compared to a standard collapse forming low mass stars: $NH_3(1_{1,0}-1_{1,0})$, CS(3-2), N_2H^+(1-0), CO(2-1), HCO^+(3-2)

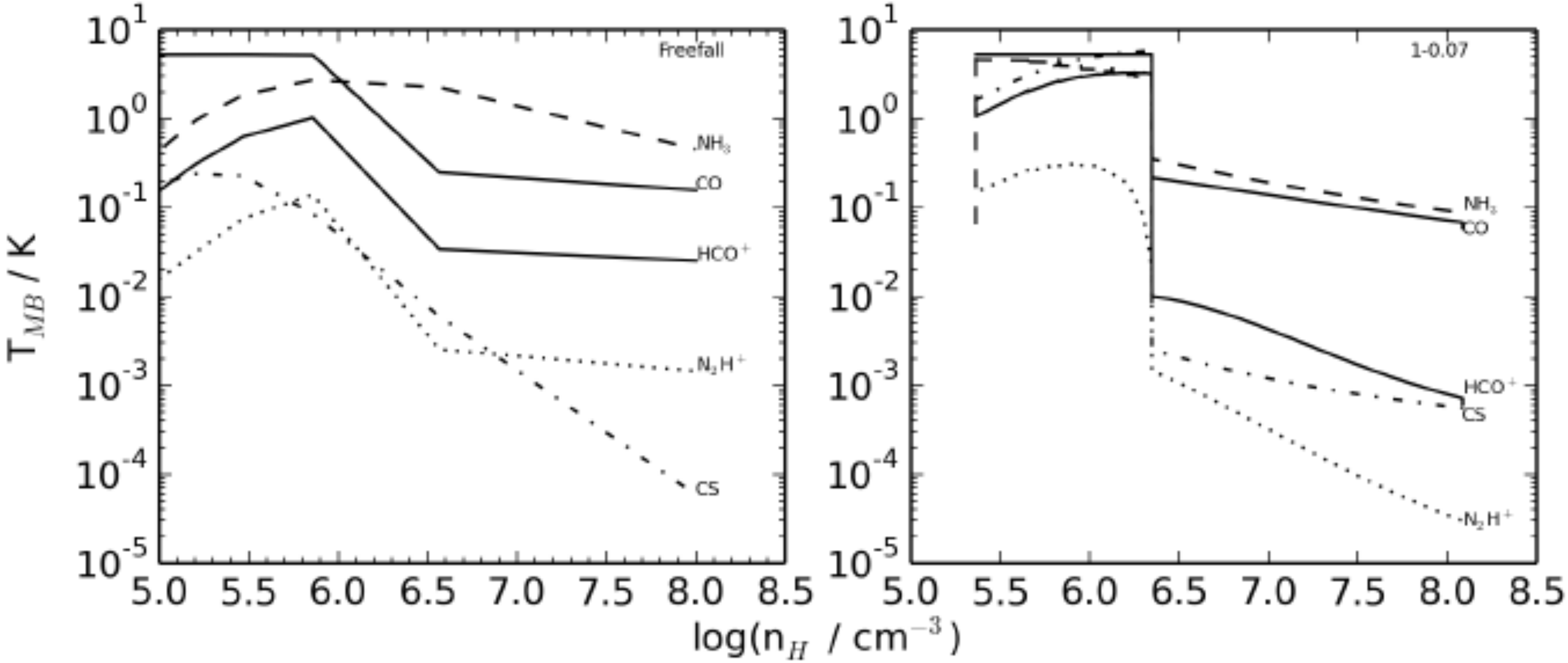


Figure 2. Brightness temperature expected for the five transitions discussed in Section 4.1. On the left, a freefall model is show on the right a turbulent fragmentation model in which a 0.07 M⊙ core is formed from a cloud using the first set of initial conditi clear gap is apparent in the turbulent fragmentation model with CO and NH_3 being much brighter than other molecules.

Holdship & Viti, MNRAS, 2016

Observational tests and comparisons with observations

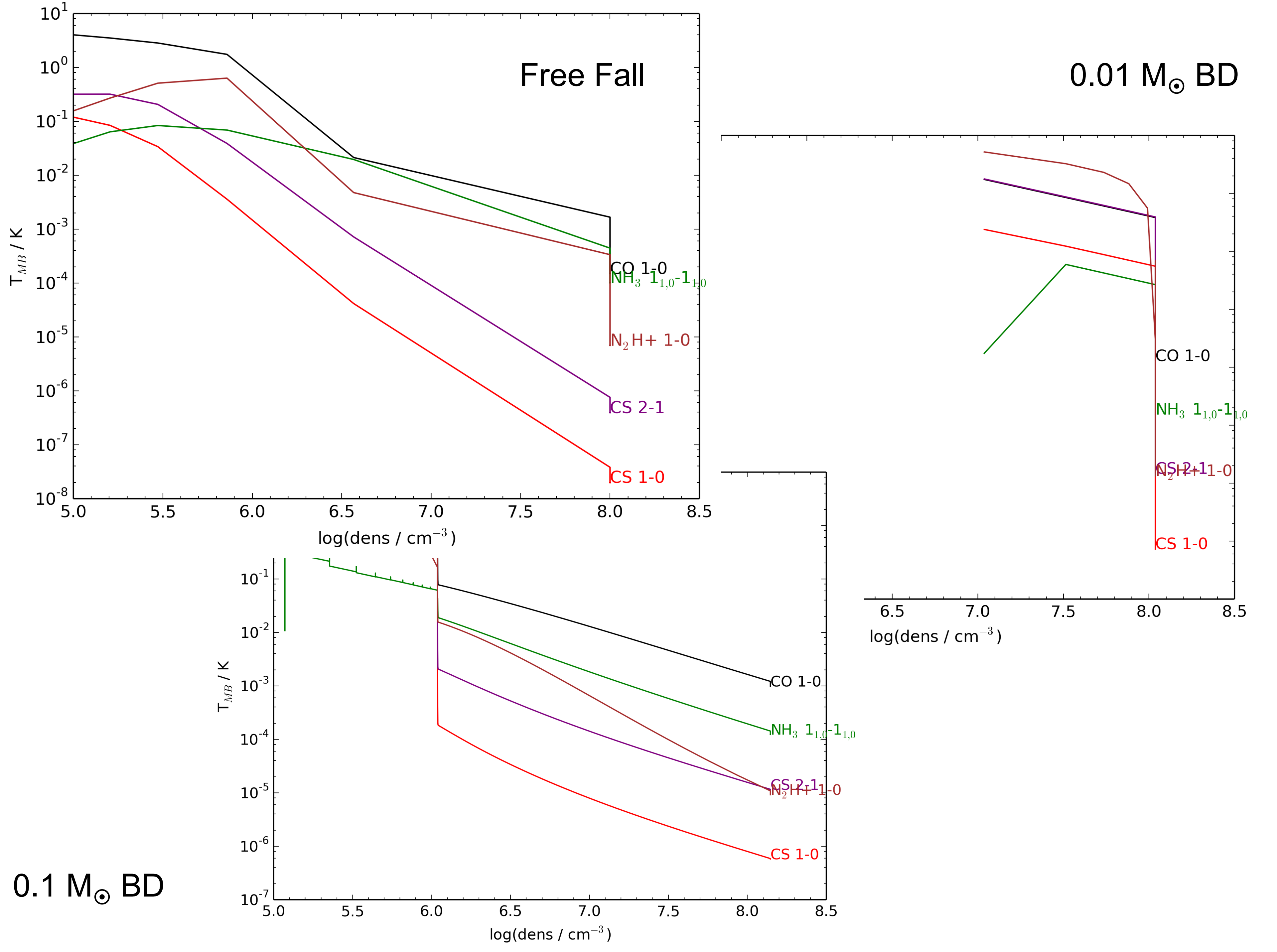
- Models were fitted to data from Benedettini et al. (2012) on Lupus and Seo et al. (2015) on Taurus
- Lupus: Density and Mass unknown but they provide column densities; none of those cores seem to be forming BDs
- Taurus →

Table 2. Observable molecules for different models at $n_H > 10^7 cm^{-3}$. Where an observable molecule is considered to be one that has a transition which would emit with a brightness temperature greater than 100 mK. All models use the first set of initial conditions. A + indicates an observable molecule.

Molecule	0.01 $M_\odot$	0.04 $M_\odot$	0.07 $M_\odot$	0.10 $M_\odot$	Freefall
CO	+	+	+	+	+
HCO^+	+				
CS	+				
NH_3	+	+	+	+	+
N_2H^+	+				

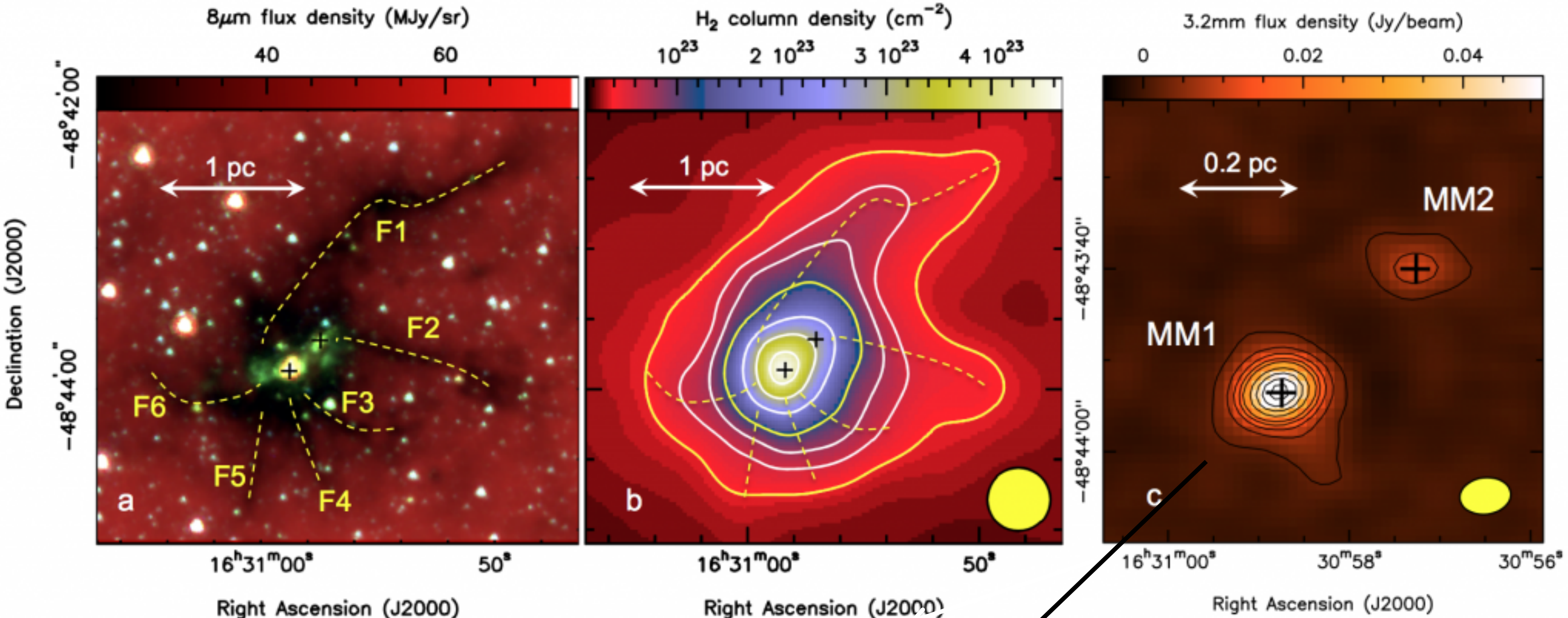
Table 3. List of cores from Seo et al. (2015) with model equivalents. Fractional abundances given in units of 10^{-9}, those from the model are taken to be the average abundance for the post shock core.

Mass/ $M_\odot$	Virial Mass/ $M_\odot$	$X(NH_3)_{observed}$	$X(NH_3)_{model}$
0.04	0.31	1.13	0.07
0.07	0.22	1.07	0.32
0.10	0.58	1.8	0.5
0.88	0.77	3.65	1.5
0.95	0.98	1.35	2.5
0.99	1.09	1.00	1.0



Free Fall
0.01 M$_\odot$ BD
0.1 M$_\odot$ BD
T$_{MB}$ / K
log(dens / cm^{-3})
CO 1-0
NH$_3$ 1$_{1,0}$-1$_{1,0}$
N$_2$H+ 1-0
CS 2-1
CS 1-0

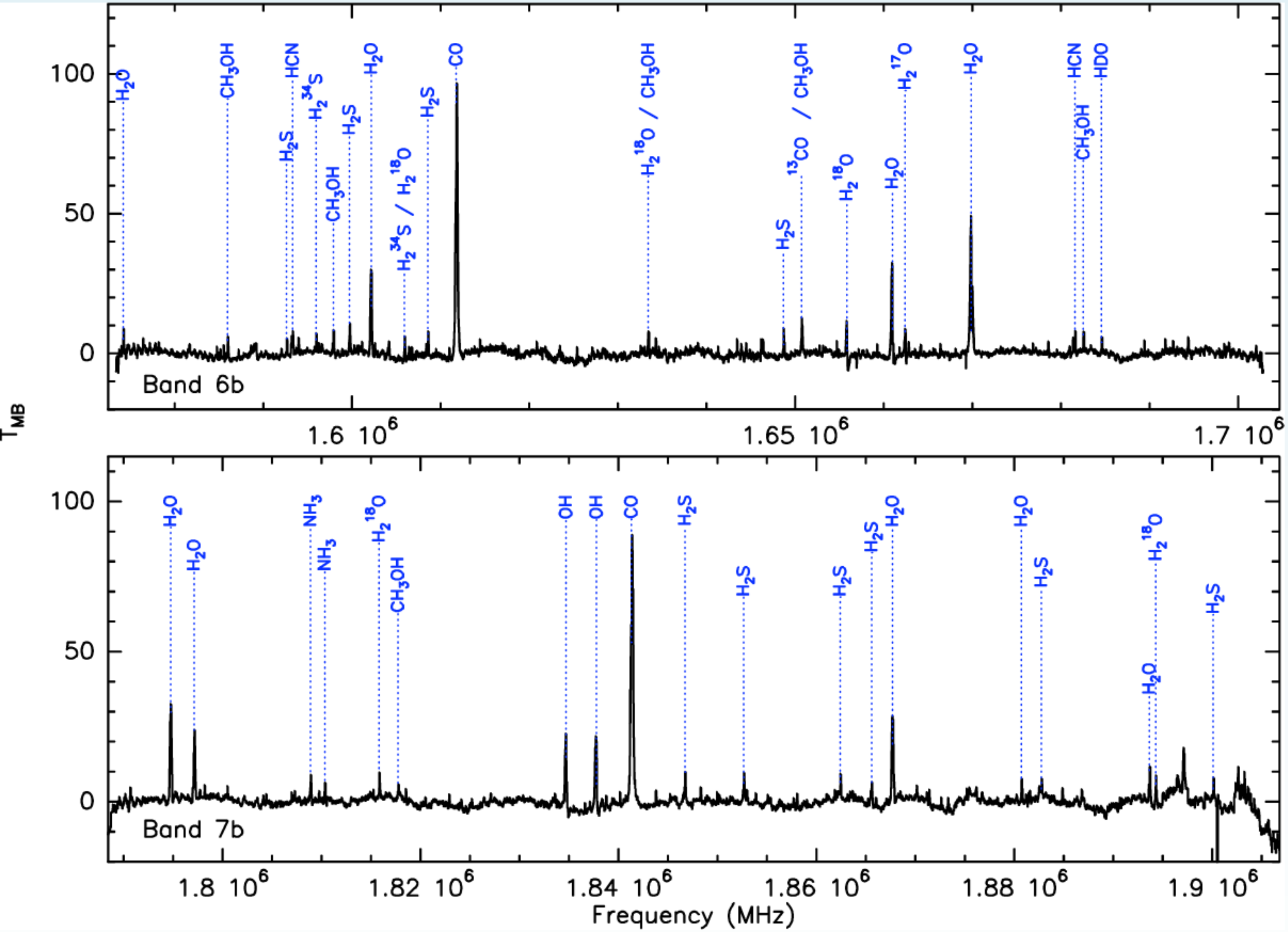
Massive star formation: tracing the very early stages



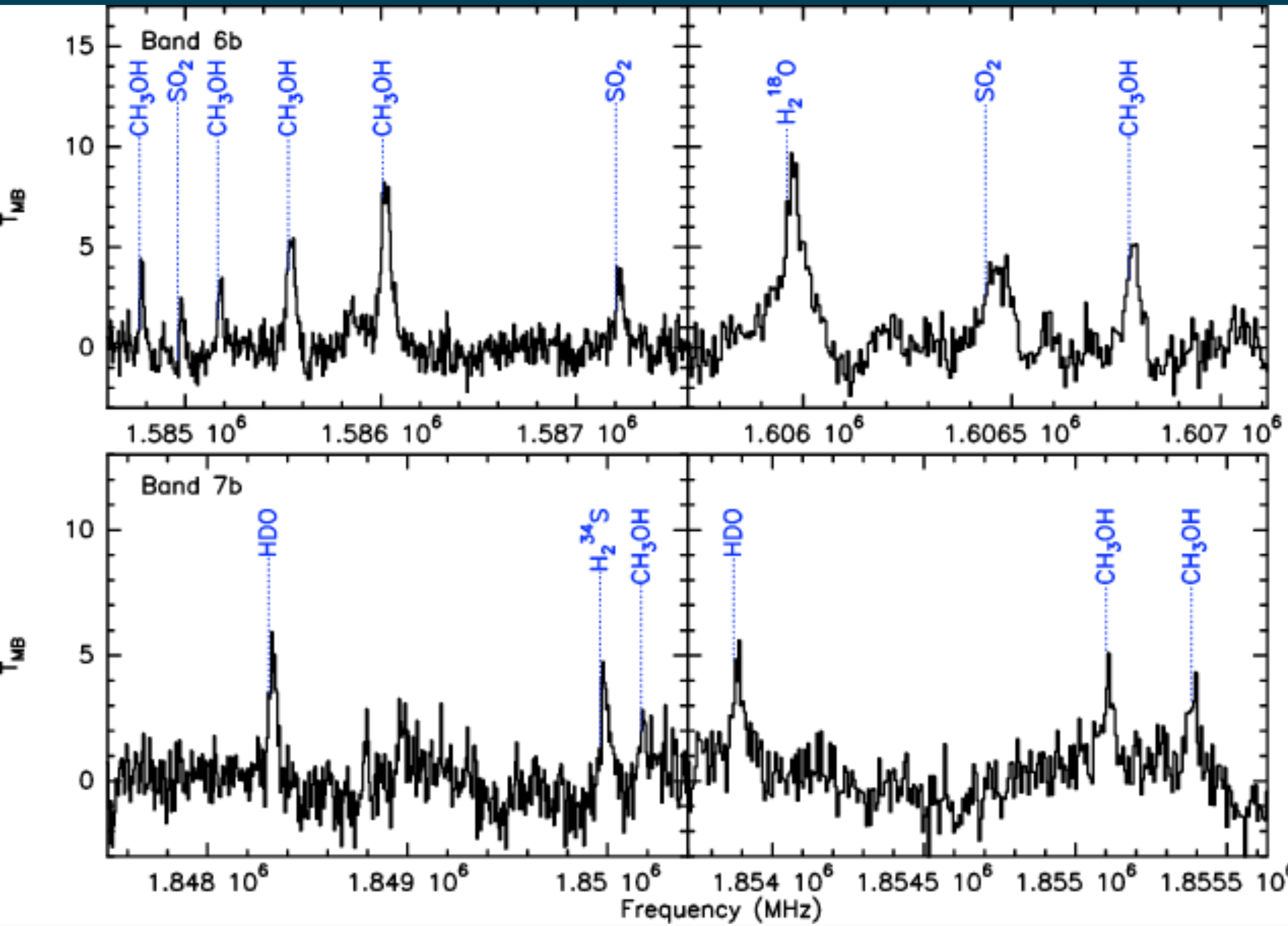
Perretto et al. (2013)

- Small: 10^{-1} - 10^{-2} pc
- Dense: ~ 10^7 H_2 cm^{-3}
- Warm: ≥ 10^2 K
- Opaque: A_V >10^2 mag
- Transient: ≤ 10^5 yrs
- Location: < 0.1 pc from star
- Chemically very rich because they retain the chemical **history of the natal cloud**

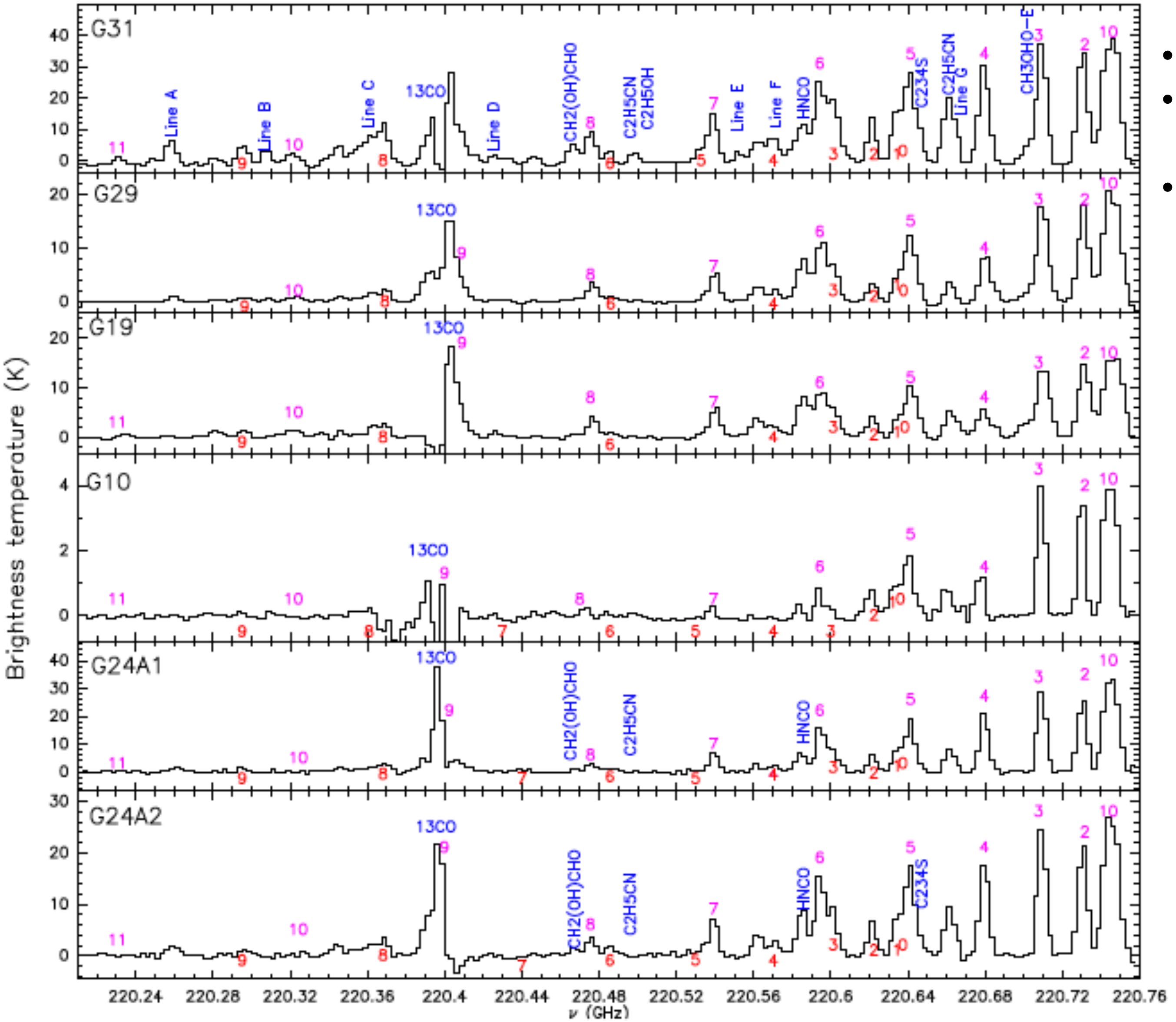
Massive star forming regions: the big problem of line confusion in the submm/far IR



Crockett et al. (2010)



If one zooms in…..



Line confusion due to:

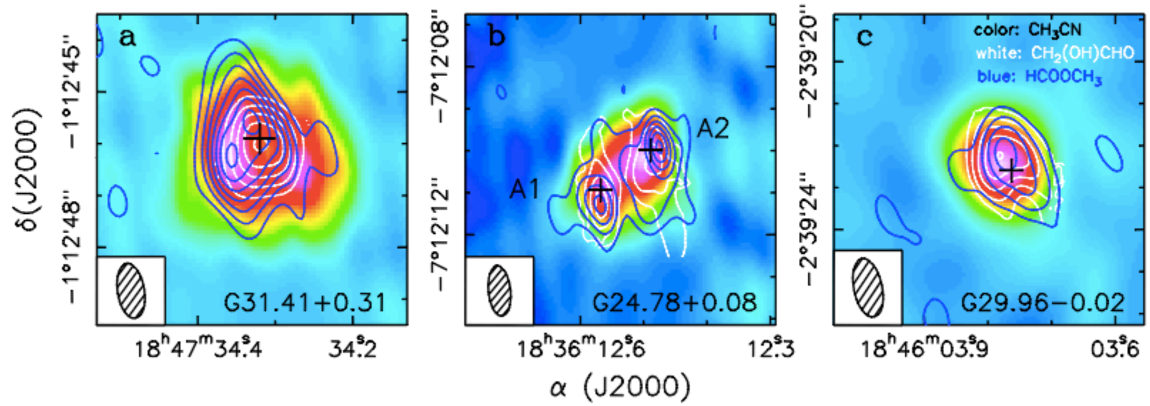
- Richness of the spectrum
- Blending (due to large linewidths)
- Uncertainties in the lab rest frequencies as well as in the observations

This leads to only tentative detections in most cases (e.g. glycolaldehyde @ 220.4 GHz may be acetone instead!)

Calcutt et al. 2014

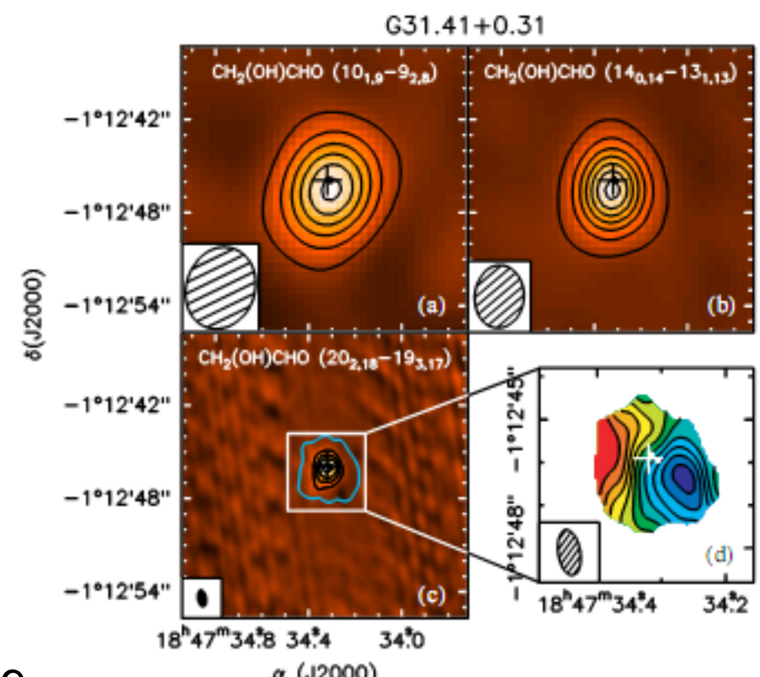
Importance of COMs in hot cores

Calcutt et al. 2014



(i) their detection is a confirmation of the high density warm cores, as most COMs are not easily produced in the gas phase chemistry of dark clouds

(ii) their emission has been observed to be compact in extent in star forming regions outside the Galactic Center → trace the most central region close to the YSO



Beltran et al. 2009

Figure 2. Map of the intensity integrated under the CH_2OHCHO ($10_{1,9}$–$9_{2,8}$) line at 103.67 GHz (a), the CH_2OHCHO ($14_{0,14}$–$13_{1,13}$) line at 143.64 GHz

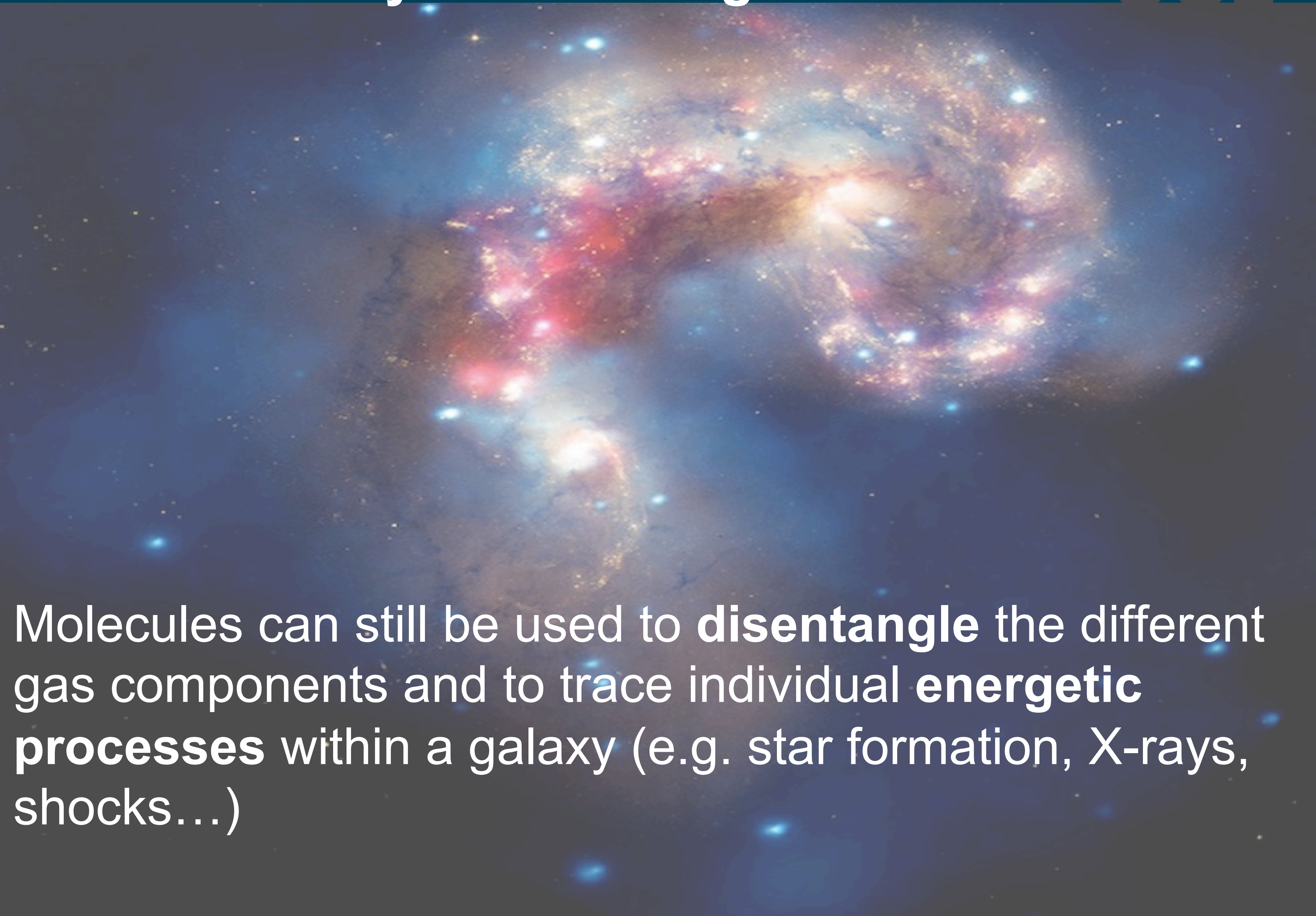
Complex Organics in Hot cores: why low frequencies?

1. mm/Submm so full that it's too difficult to identify COMs
2. Low frequency range is relatively clear (low E of smaller molecules fall at higher frequencies)
3. *J*s across large range of frequencies: population over many energy states because of large partition functions
4. Best range: bright lines ($S\mu^2 \geq 1$ D^2) at low excitation ($E_u \leq 20$ K)

Between 76-117 GHz with log(Aij) > -5

- **Methyl formate (~40 transitions)**
- **Glycolaldehyde (~60 transitions)**
- **Acetic acid (~30 transitions)**
- **Ethyline glycol (>50 transitions)**

Astrochemistry in external galaxies



Molecules can still be used to **disentangle** the different gas components and to trace individual **energetic processes** within a galaxy (e.g. star formation, X-rays, shocks…)

Most observed molecules

- The two most commonly observed molecules are: CO and HCN
- But **CO** traces the amount and distribution of molecular gas *at large scale* → great for identification of GMC structures
- **HCN** is a good tracer of high density gas but not a unique tracer of star formation (e.g. enhanced in AGN environments).
- **CS** (especially $J < 4$) on the other hand is found to be an ideal tracer of gas densities $\geq 10^5$ cm^{-3}

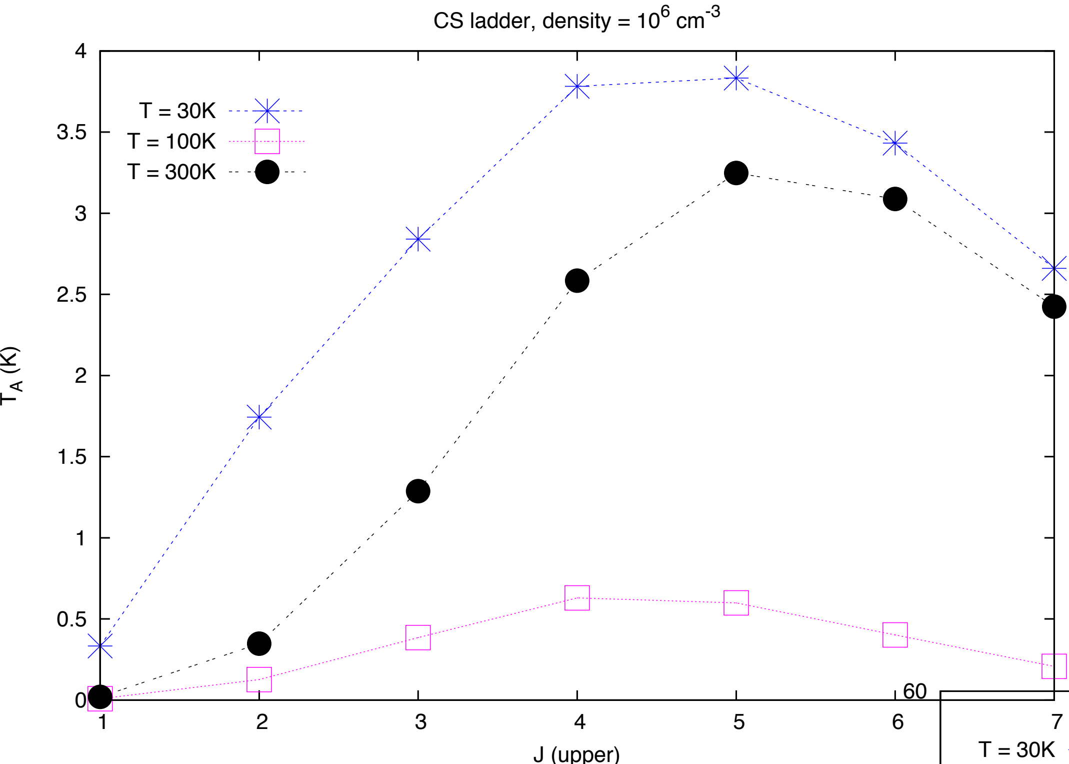
CS as a dense gas tracer

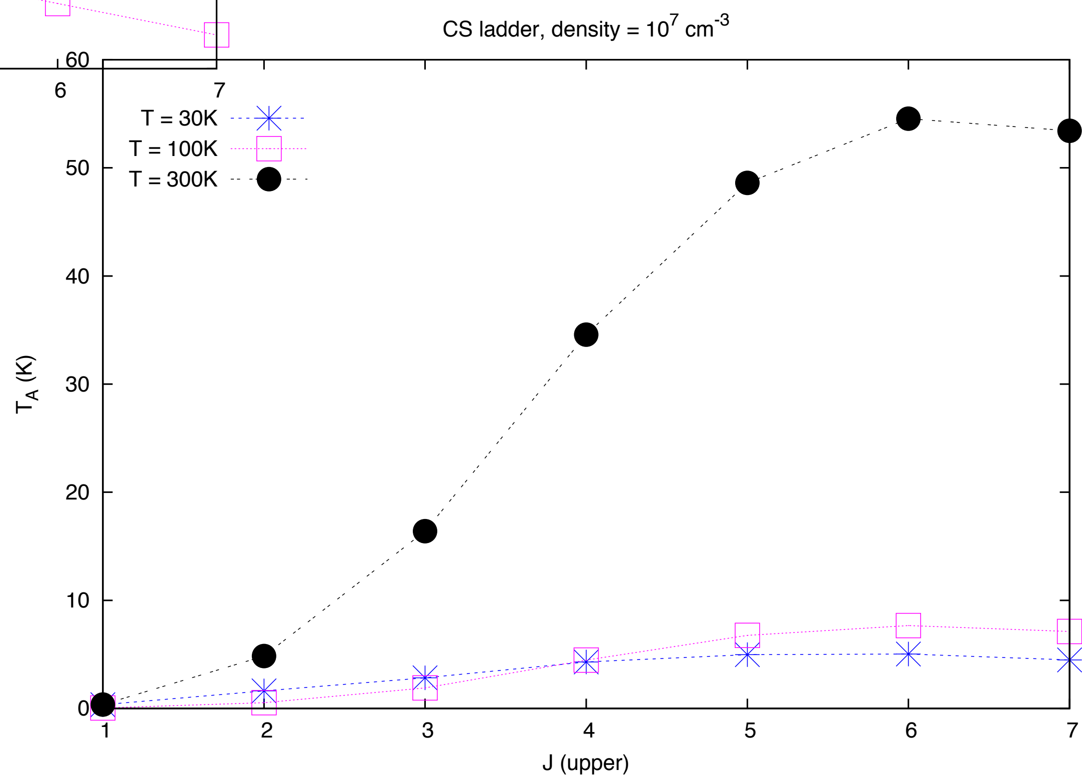
- CS emits quite strongly, not only in hot cores in our own Galaxy but also in external galaxies
- It is also recognized as one of the best tracers of very dense and warm gas with line critical densities of about $10^6 – 10^7$ cm^{-3}

What does mapping CS across a galaxy yield?

↓

1. It potentially reveals the density and temperature structure
2. It ‘isolates’ the dense gas from the ISM
3. It reveals the presence of shocks



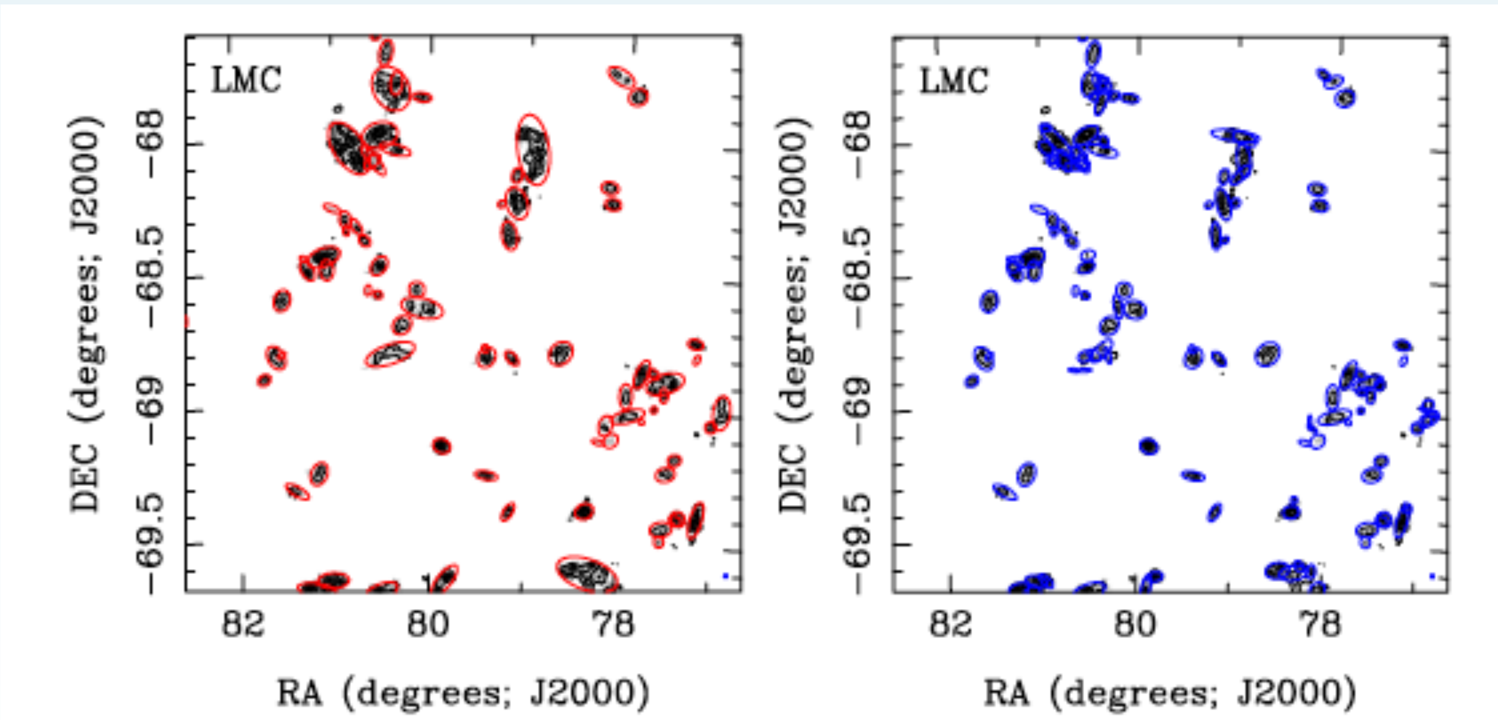


Theoretical CS ladders calculated by coupling chemical and line radiative transfer models

Kelly, PhD thesis

Mapping the LMC in CS(2-1) and CS(1-0):

LMC and SMC with MOPRA: ~ 10 pc resolution (~ GMC sizes)



As it has been done in CO: Hughes et al. 2013

[Also in HCO+ and HCN if not done already]