CH_3OH Masers in Massive Star-forming Regions

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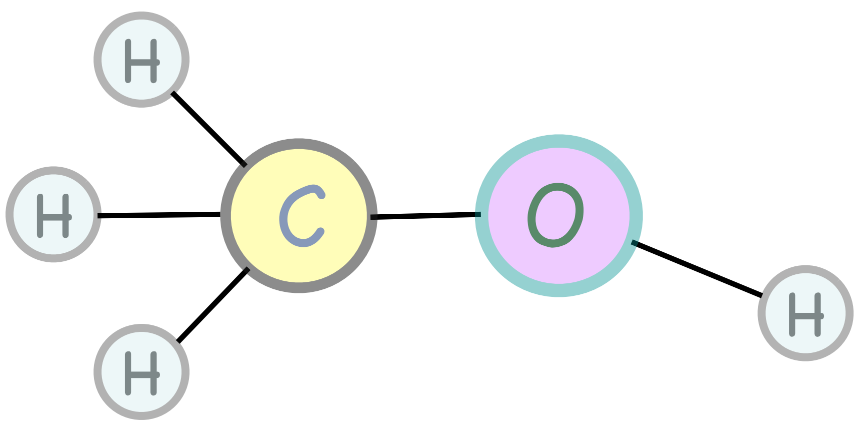


- Methanol is an alcohol, which has nearly the same geometry as water, with one H being replaced by a methyl group ($-CH_3$).
- Since the methyl group has three equivalent H atoms, the combinations of the nuclear spins of these three H atoms create symmetry states called A and E. The A state corresponds to all spins being parallel for a total of I = 3/2, while the E state has I=1/2.
- The internal rotation of the methyl group against the HO-C framework is referred to as torsion.
- A slightly asymmetric rotor with hindered internal rotation and significant a- and b-axis dipole moments (μ_a=0.885D, μ_b=1.44D), methanol has a complex spectrum that is sensitive to IS conditions.

1. Observations of Methanol
2. Methanol Chemistry
3. Thermal Emission in Astronomical Sources
4. SMA Observations
5. Summary

1. Observations of Methanol

Rotational Energy Levels of Methanol

Although methanol is an asymmetric rotator, it is nearly a prolate symmetric top. -> rotational level, K

Many of the rotational lines have been detected. Observable lines cover a wide range of energies and line strengths, allowing for a detailed analysis of excitation conditions and opacities.

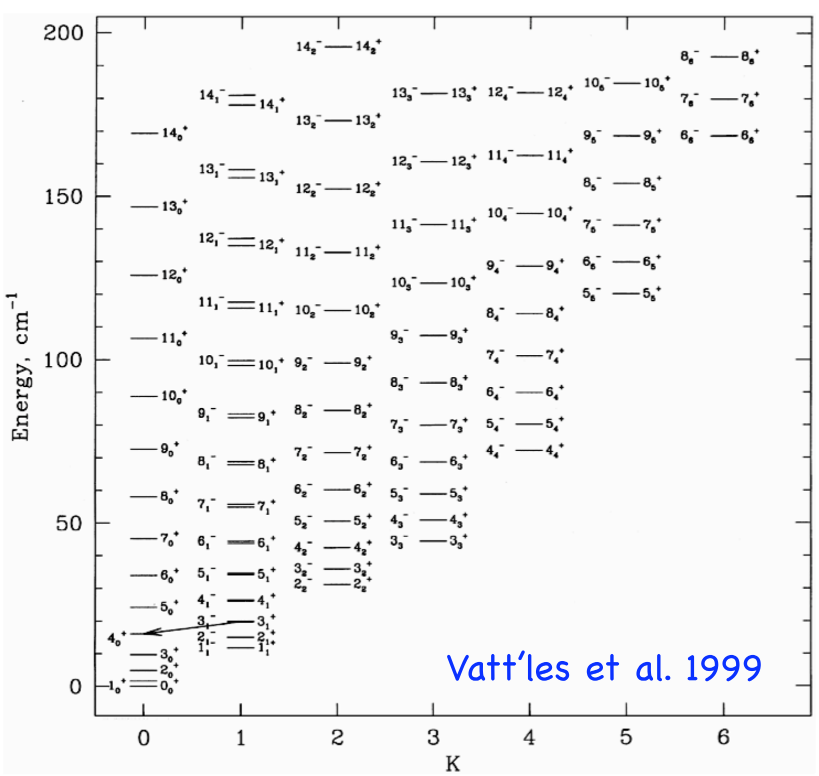


Figure 1. Energy levels for A-methanol species. The arrow represents the 107-GHz transition.

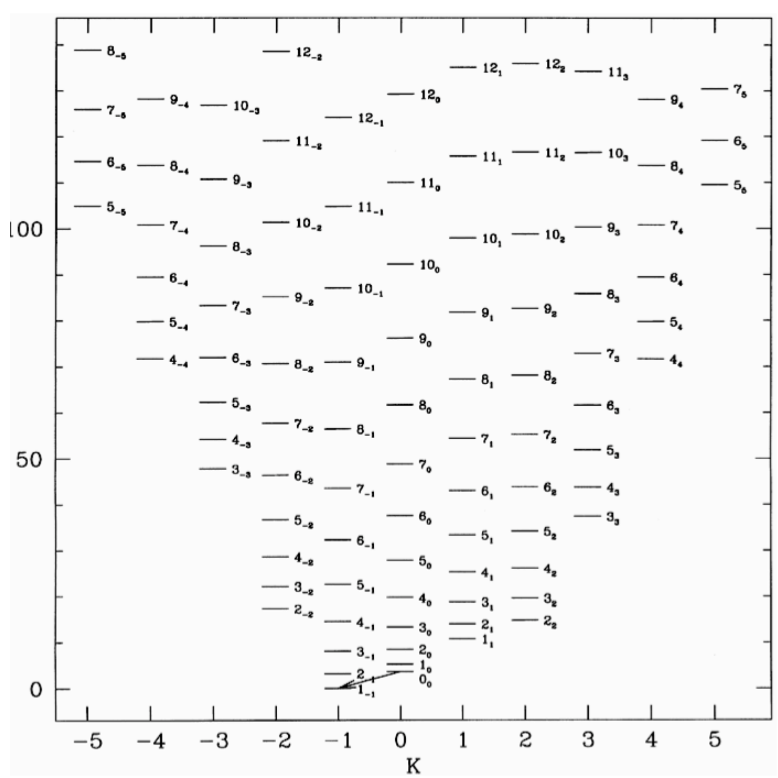
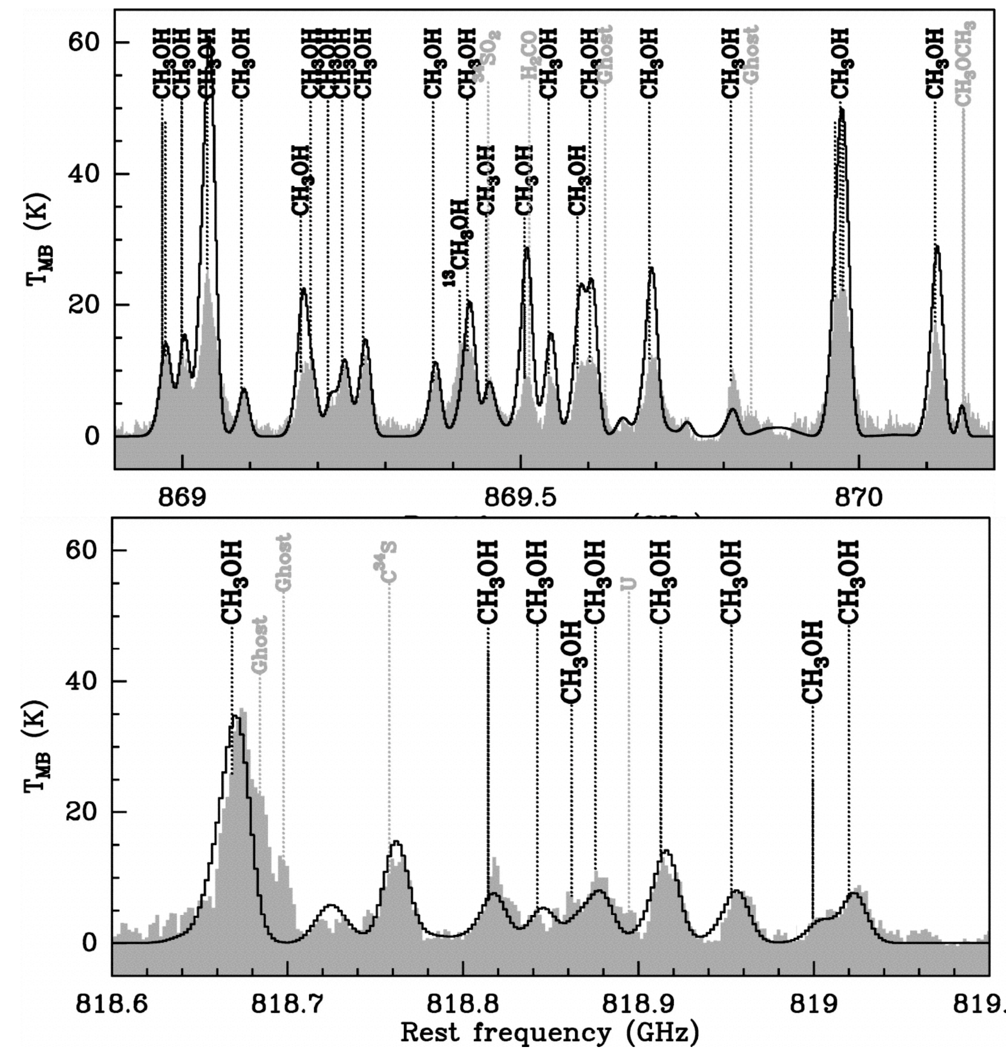


Figure 2. Energy levels for E-methanol species. The arrow represents the 108-GHz transition.

Excitation and radiative transfer modeling efforts: e.g., Leurini et al. 2004, 2007

Thermal Emissions - Gas Phase Observations



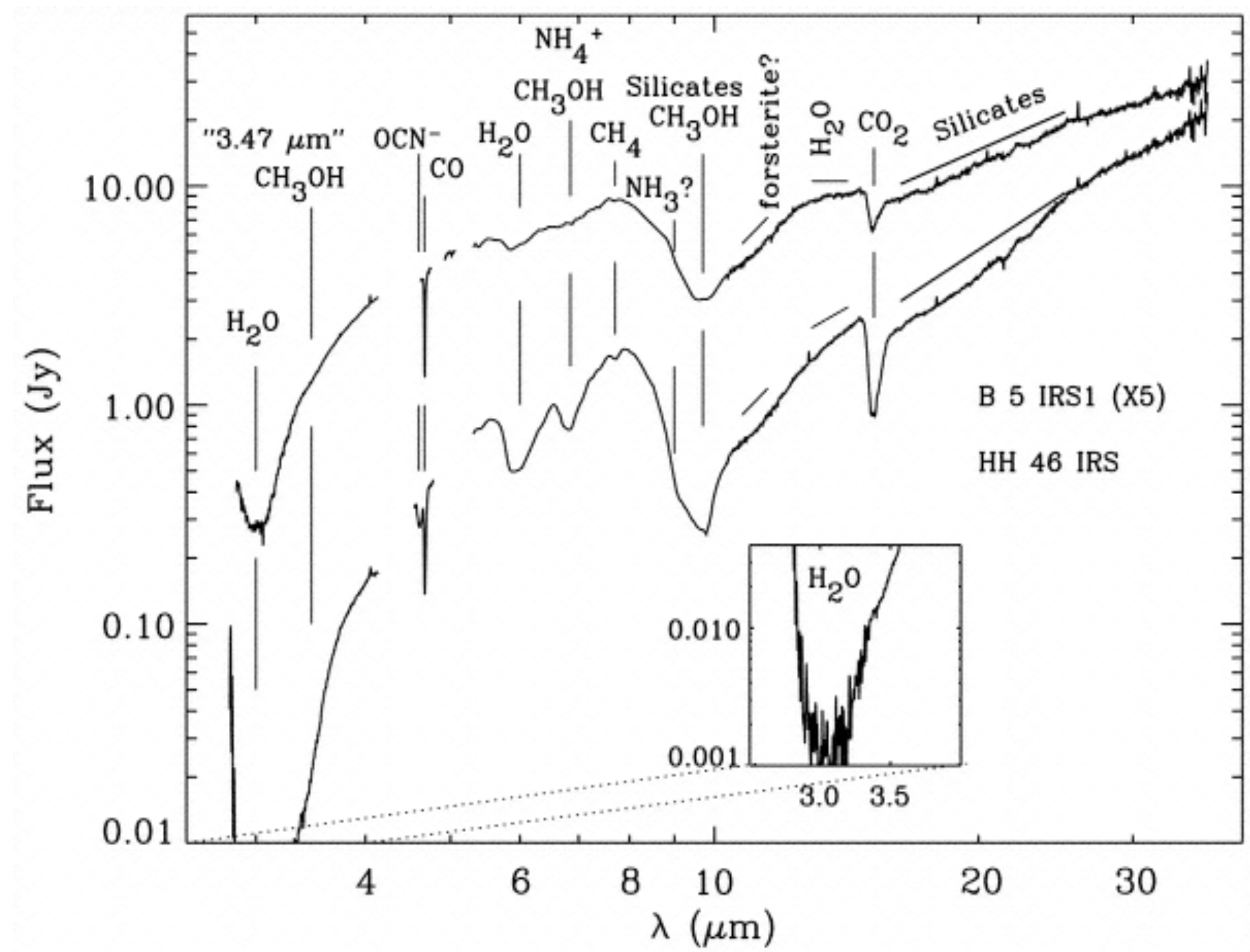
CSO 350 μm Line Survey of Orion KL Comito et al. 2005

Even when not masing, methanol may be expected to distinctly non-LTE excitation, except under the highest density conditions, where collisions could thermalize the level populations.

Solid Methanol Observed

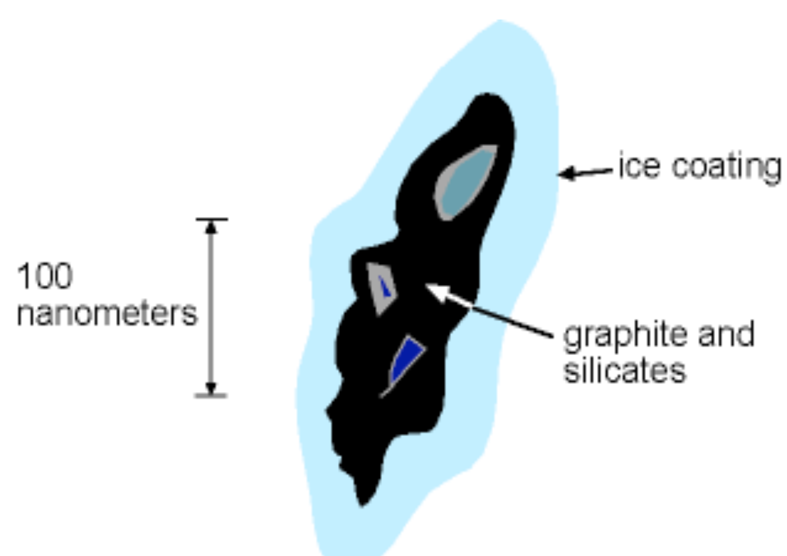
- Methanol has six atoms – 12 vibrational modes:
- They corresponds to O-H stretch (ν_1), C-H stretches (ν_2, ν_3, ν_9), C-O stretch (ν_8), CH_3 rocks (ν_7, ν_{11}), OH bend (ν_6), CH_3 deformations (ν_4, ν_5, ν_{10}), and ν_{12} torsion (ν_1 – ν_{11} : 3 – 10 μm)

- 3.54 μm band (C-H stretch): W3A, NGC7538(IRS1), GL2136
- 8.9 and 9.7 μm band (CH_3 rock and CO stretch): GL2136
- 6.85 μm (C-H bending): W3A, NGC7538(IRS9)



Boogert et al. 2004: (Spitzer satellite)

The main ice constituents: H_2O, CO_2, CO, CH_3OH (3.47, 6.85 μm)



A typical dust grain (note the tiny scale!).

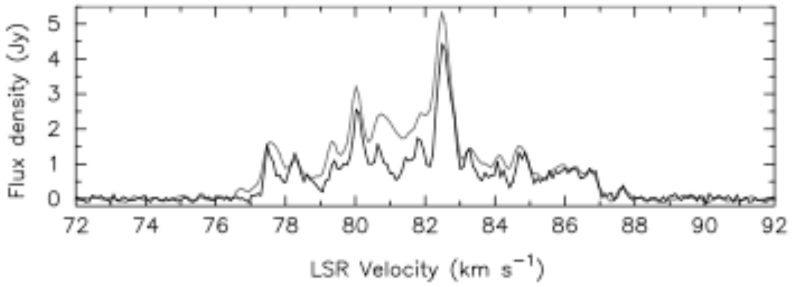
Ice Mantle: H_2O, CH_3OH (1-30 %), NH_3 (a few – 30 %), CO, CO_2, OCS, ..

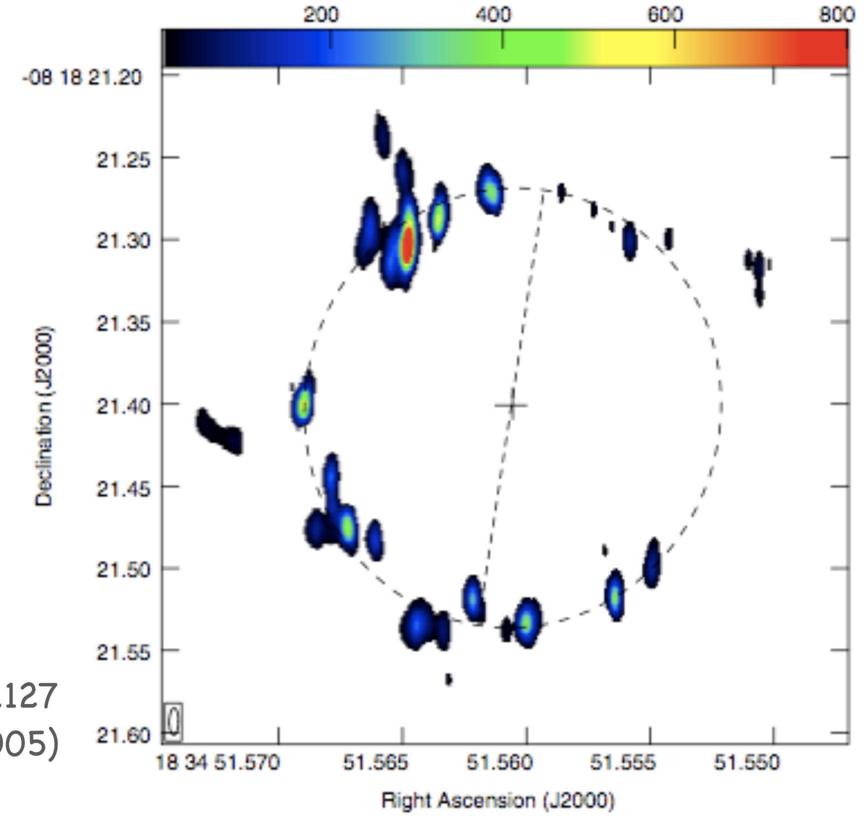
- Daughter molecules: CH_3CN, $HCOOCH_3$, HCN, CH_3CH_2CN, CH_3CH_2OH,...

Methanol Masers

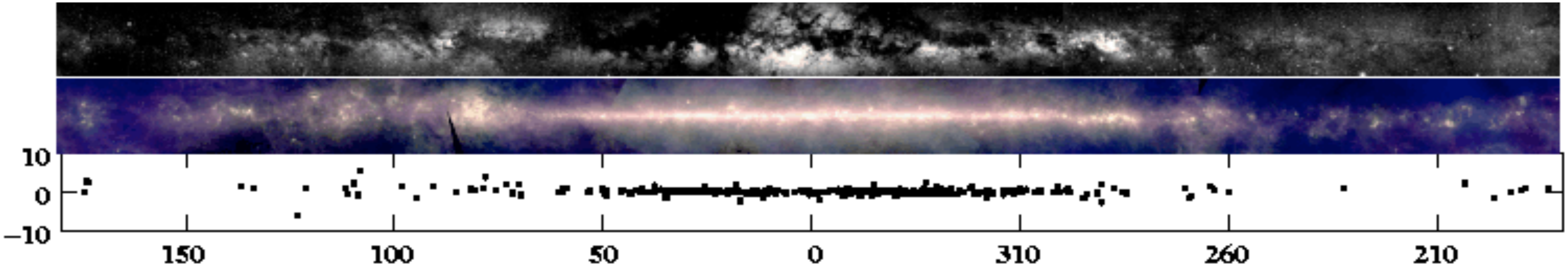
- First methanol masers in 1971 toward Orion nebula (Barrett et al. 1971)
- Over 20 methanol rotational transitions have been found to be masers: in star-forming regions, associated with IR sources, molecular outflows and compact HII regions.
- Probably a sign for star-birth of massive YSOs.

- They are divided into two classes, I and II.
- Class I: probably produced by collisional pumping (generally well separated from the center of activity)
- Class II: probably by radiative excitation at IR (spatially well correlated with YSOs OH masers





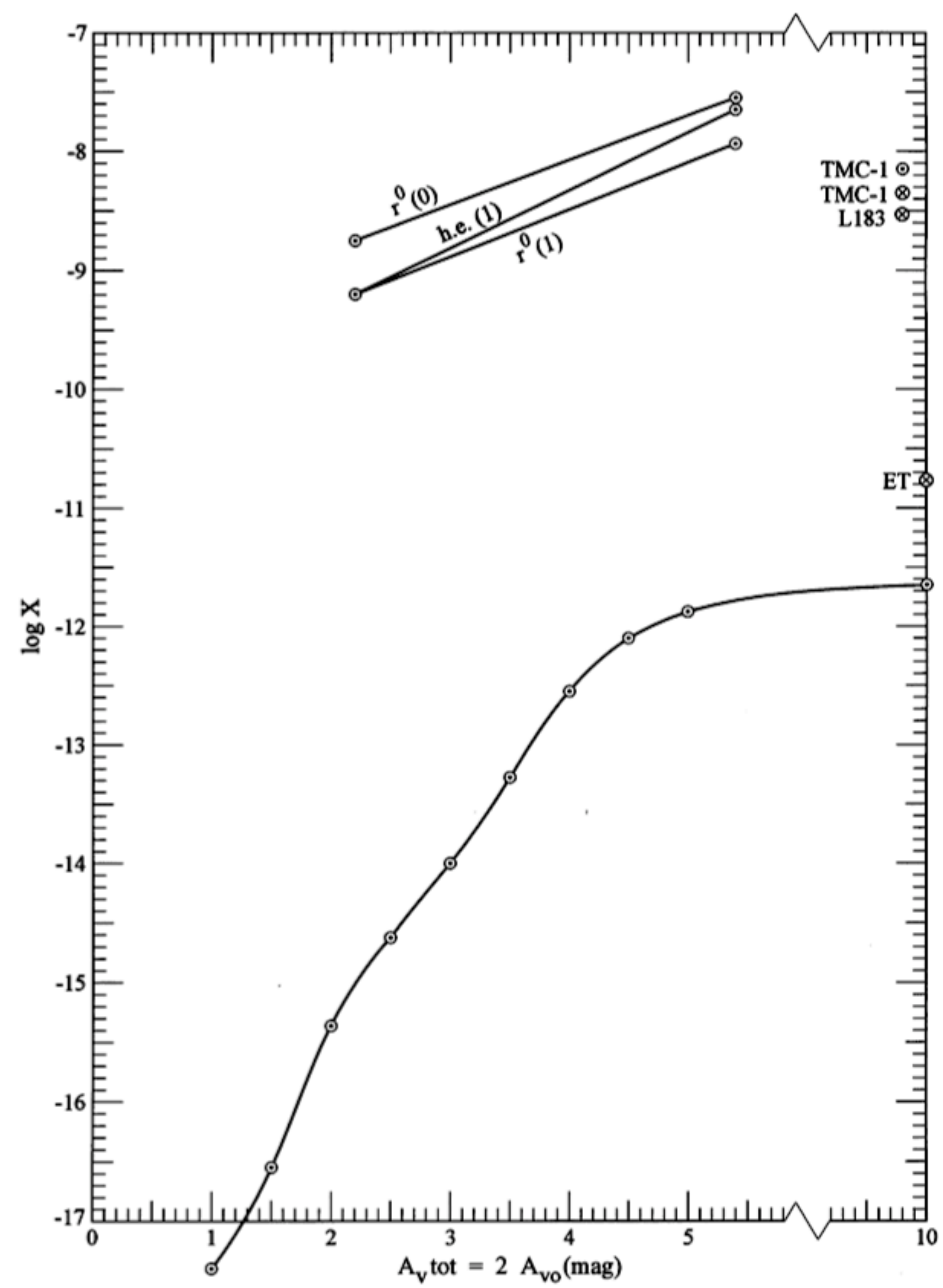
6.7 GHz methanol maser in G23.657-0.127 (Bartkiewicz et al. 2005)



2. Methanol Chemistry

Gas Phase Formation

- **Methanol Abundance**: 0.4-1 x 10^{-8} in cold dark clouds
  $> 10^{-5}$ in hot cores
- **Formation** in the gas phase,
  via the radiative association reaction:
  $CH_3^+ + H_2O \rightarrow CH_3OH_2^+ + h\nu$
  followed by the electron recombination to CH_3OH (50%) and H_2CO (50%)
  Miller et al. 1991, Lee et al. 1996, Turner 1998
- **Destruction** is dominated by reactions with C^+ (most important for $2.5 < A_{vo} < 5.0$ mag) , He^+, H_3^+, and UV dissociation (most important for $A_{vo} < 2.5$ mag)
- Many uncertainties in methanol related reactions
  - Model expectations are less by 3-4 orders of magnitudes than the observed values
  - Whether surface CH_3OH can be desorbed to produce the observed gas-phase CH_3OH is controversial in dark clouds.



Turner 1998

Solid Methanol - Grain Chemistry

- CH_3OH is a "primary" ice that forms other products after nearby stars turn on.
  - Laboratory work (Bernstein et al. 1995): the mixtures of $H_2O/CH_3OH/CO/NH_3$ ices irradiated by UV → complex organic species ← at the expense of CH_3OH as the primary carbon source
- Solid CH_3OH: hydrogenation of CO (or H_2CO) (Charnley et al. 1992, Caselli et al. 1994, Gibb et al. 2000).
  - may be inefficient in quiescent sources: high CO/H_2O ratio source show no solid CH_3OH feature (Elias 16)
  - laboratory works (Hiraoka et al. 1994)
- CH_3OH formation may need energetic processing (Chiar et al. 1996)

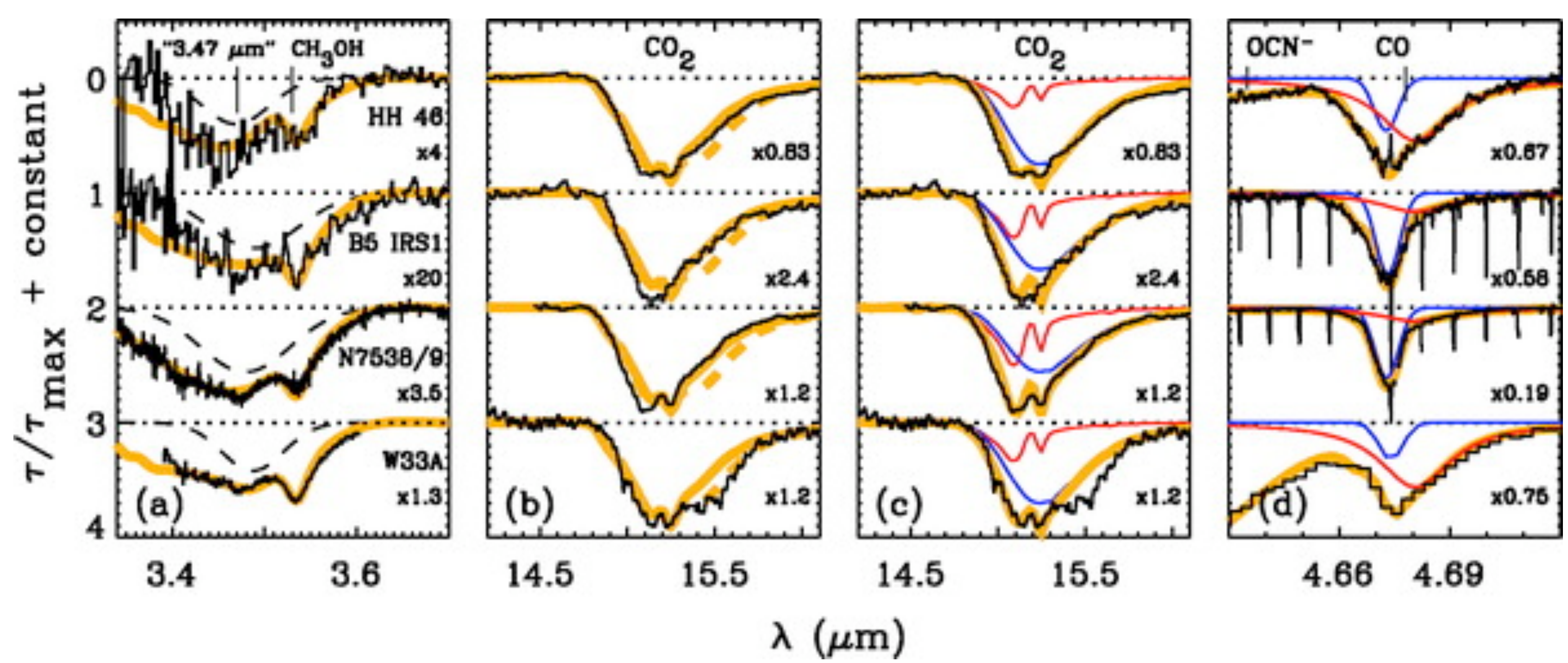
  -> Mainly we detect CH_3OH toward massive star-forming region

Low-mass SF Cores

Massive Proto-stars

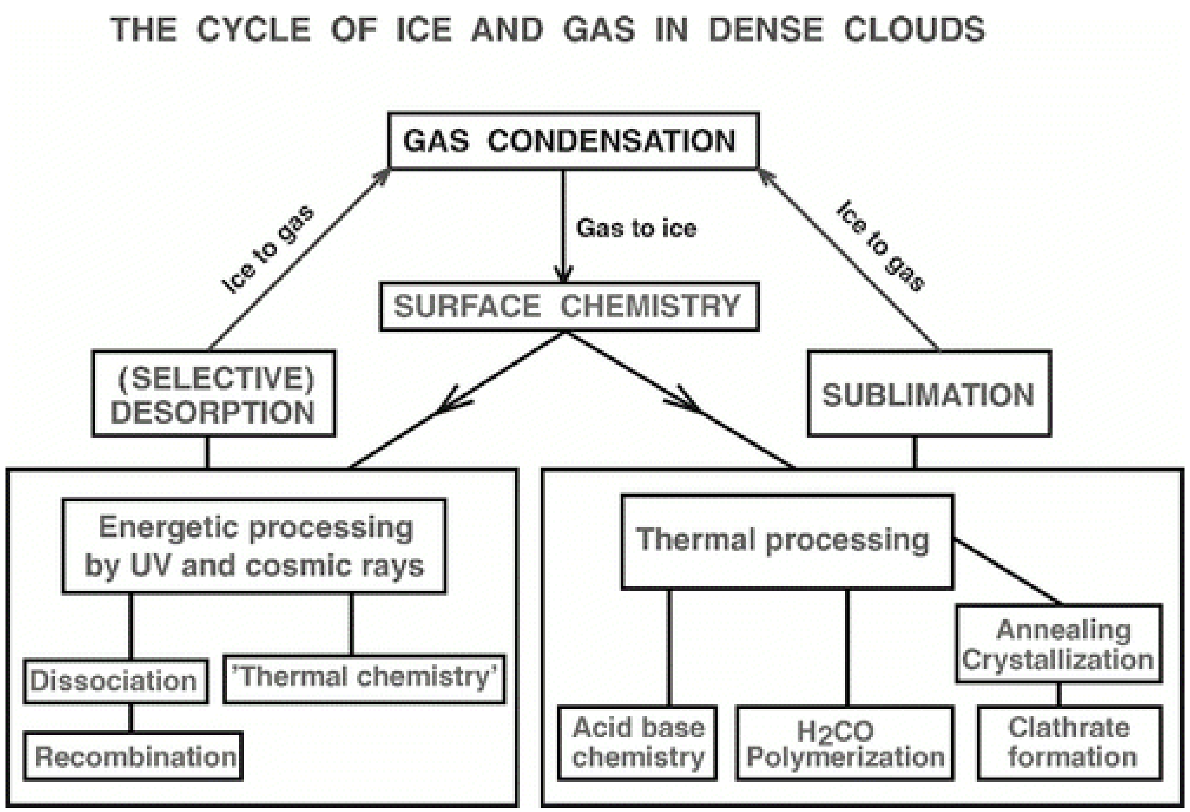
Yellow: Lab experiments

CO: apolar, polar



Desorption and Sublimation

- Heating by CRs or UV followed by thermal evaporation of the surface molecules
- UV photodesorption: direct interaction with surface molecules

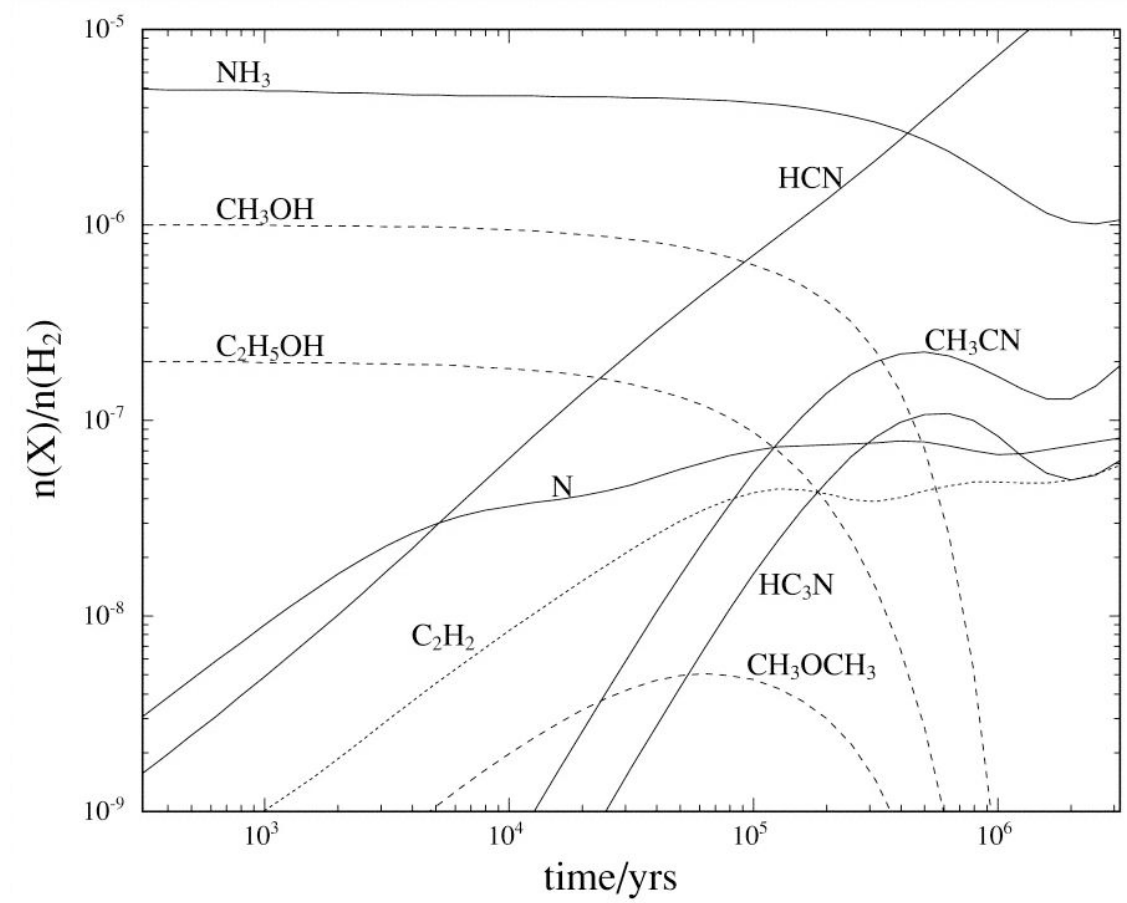


Eherenfreund 2000

Sublimation Temperature

CO ~ 20K, H_2S ~ 40K, NH_3 ~ 65K,

H_2O, CH_3OH ~ 100K

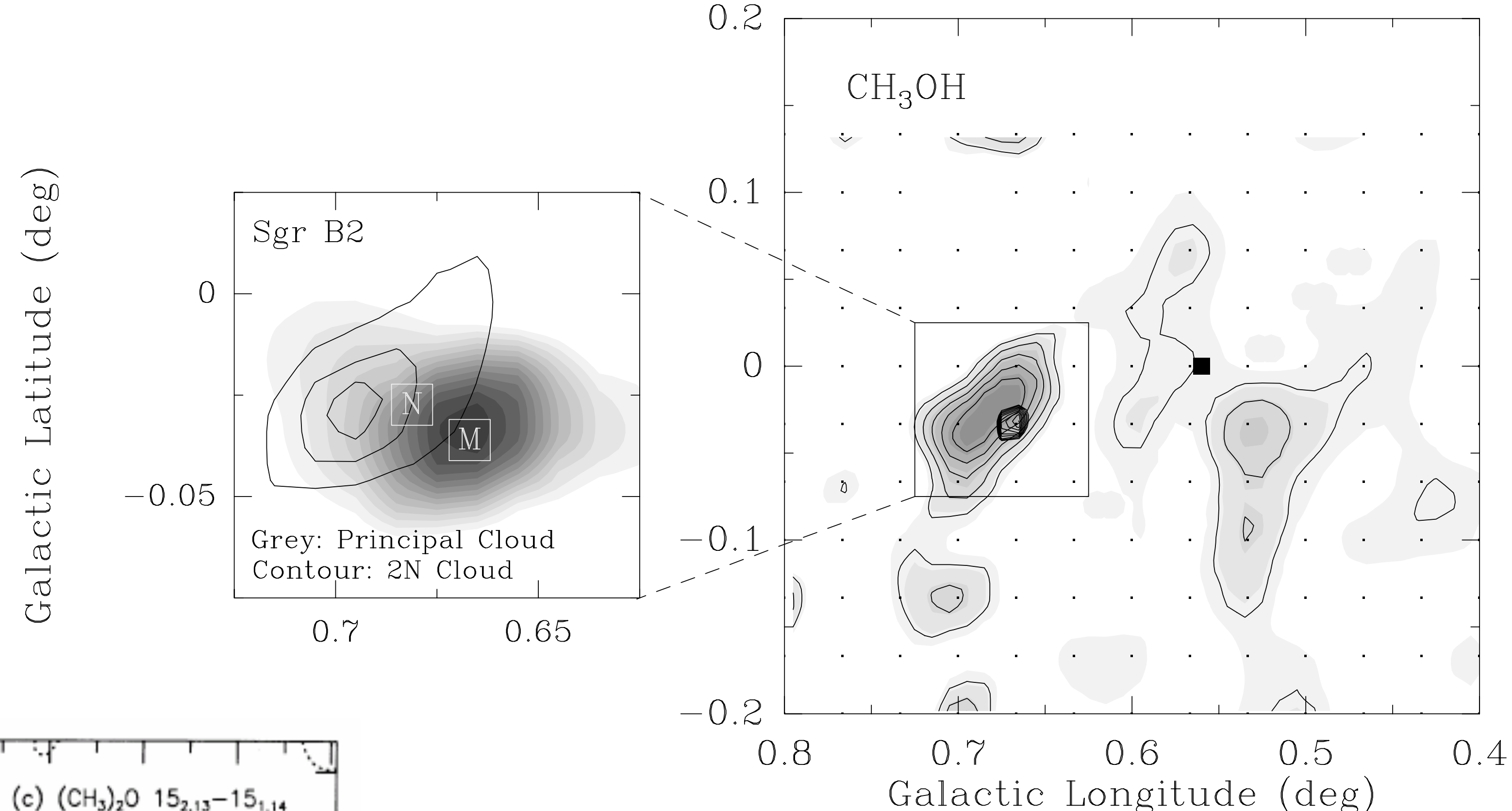


Abundances vs. time of large O-bearing (dotted lines) and simple N-bearing (solid lines) organic molecules in hot cores following the evaporation of representative interstellar ices, T=300K (Rodgers & Charnley 2001)

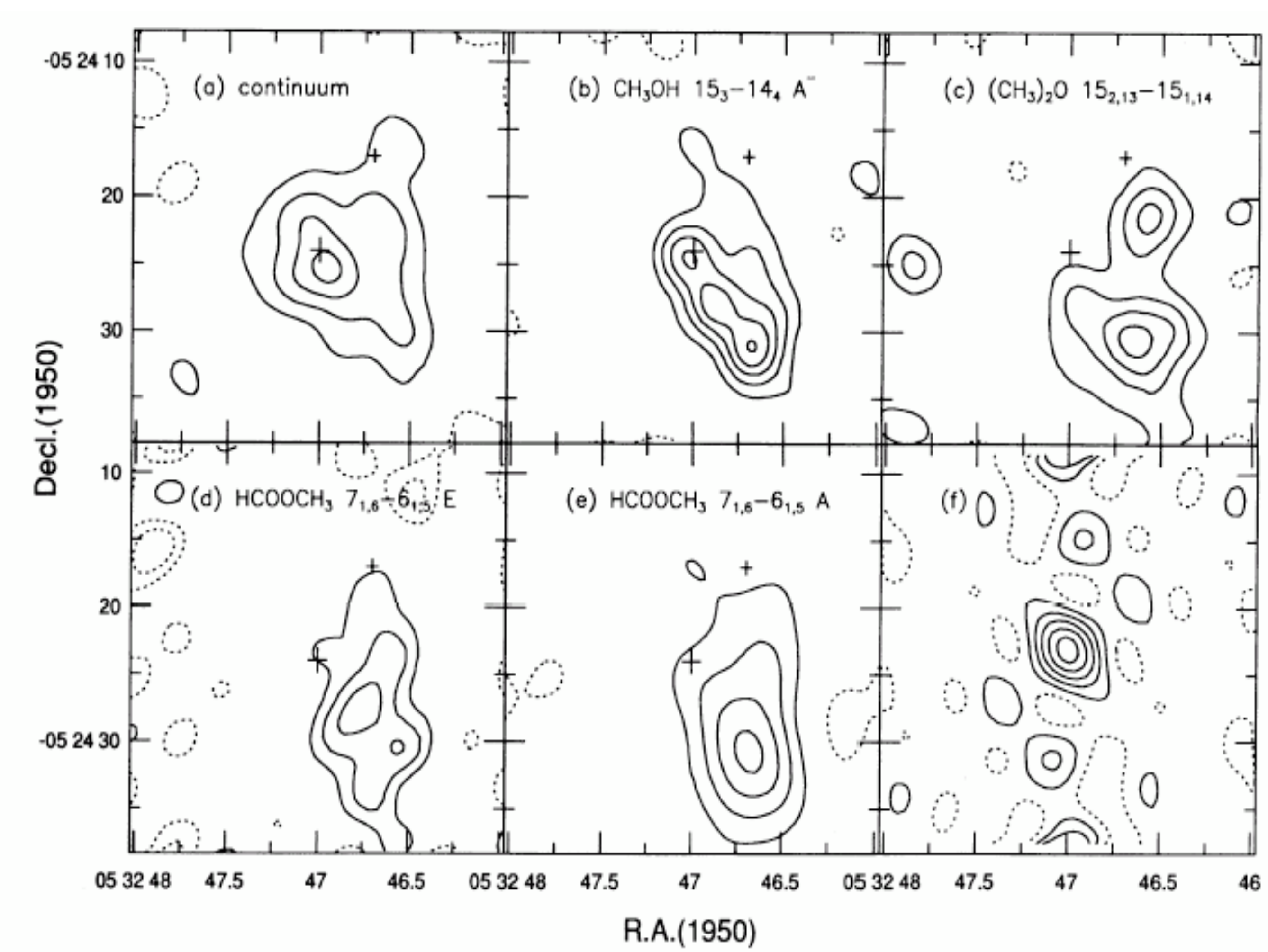
- More volatile species are evaporated before more tightly bound species.
- Small-scale spatial differentiation is observed in the chemical composition of many hot cores.
- N/O differences: Orion KL(Hot Core, Compact Ridge), W3(OH) (Wyrowski et al. 1999), G29.96-0.02 (Pratap et al. 1999), G5.89-0.39 (Thompson & Macdonald 1999), and Sgr B2 (Nummelin et al. 2000).

3. Thermal Emission in Astronomical Sources

Methanol: traces outflows or shocks

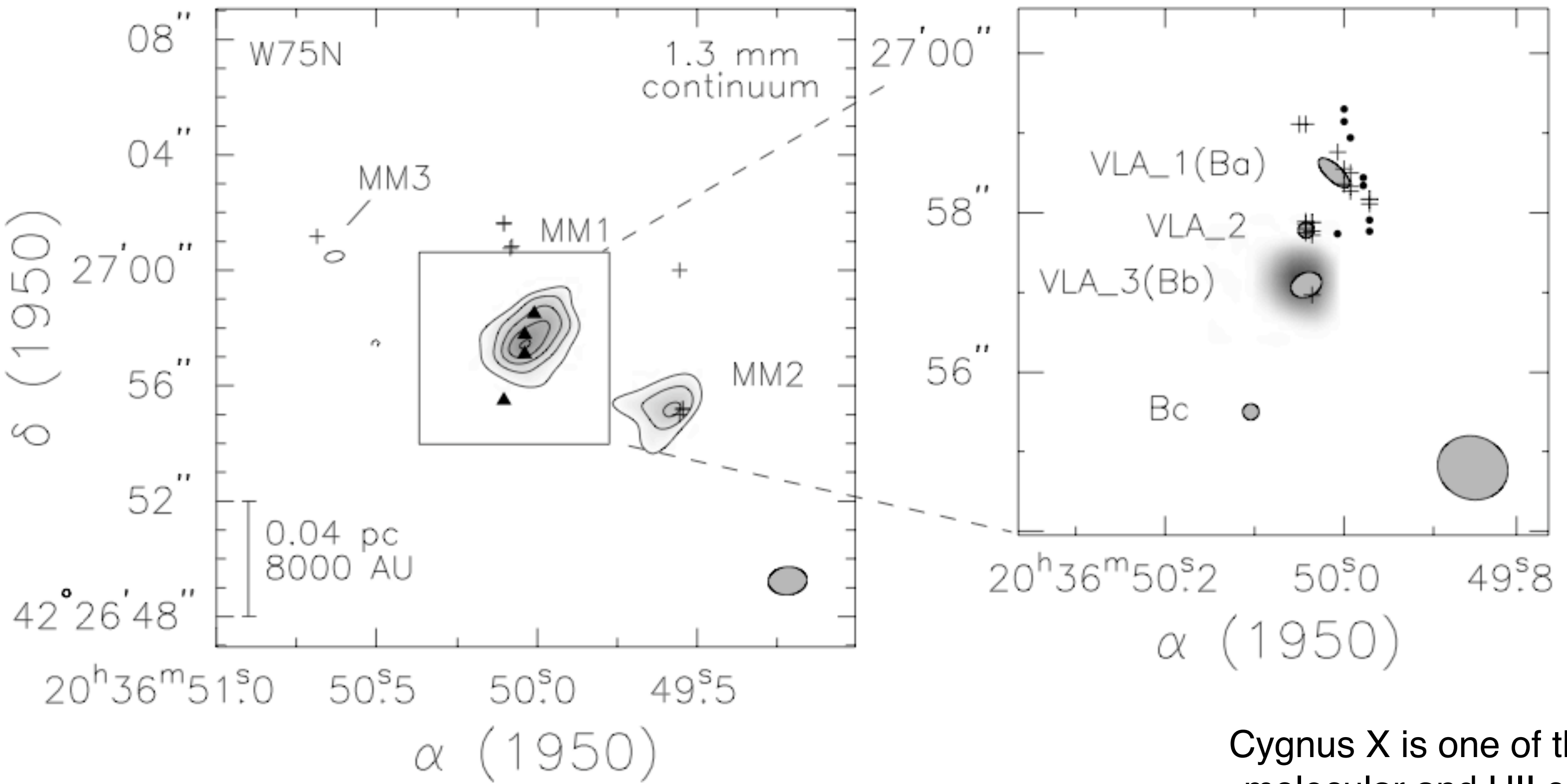


Minh et al. in preparation



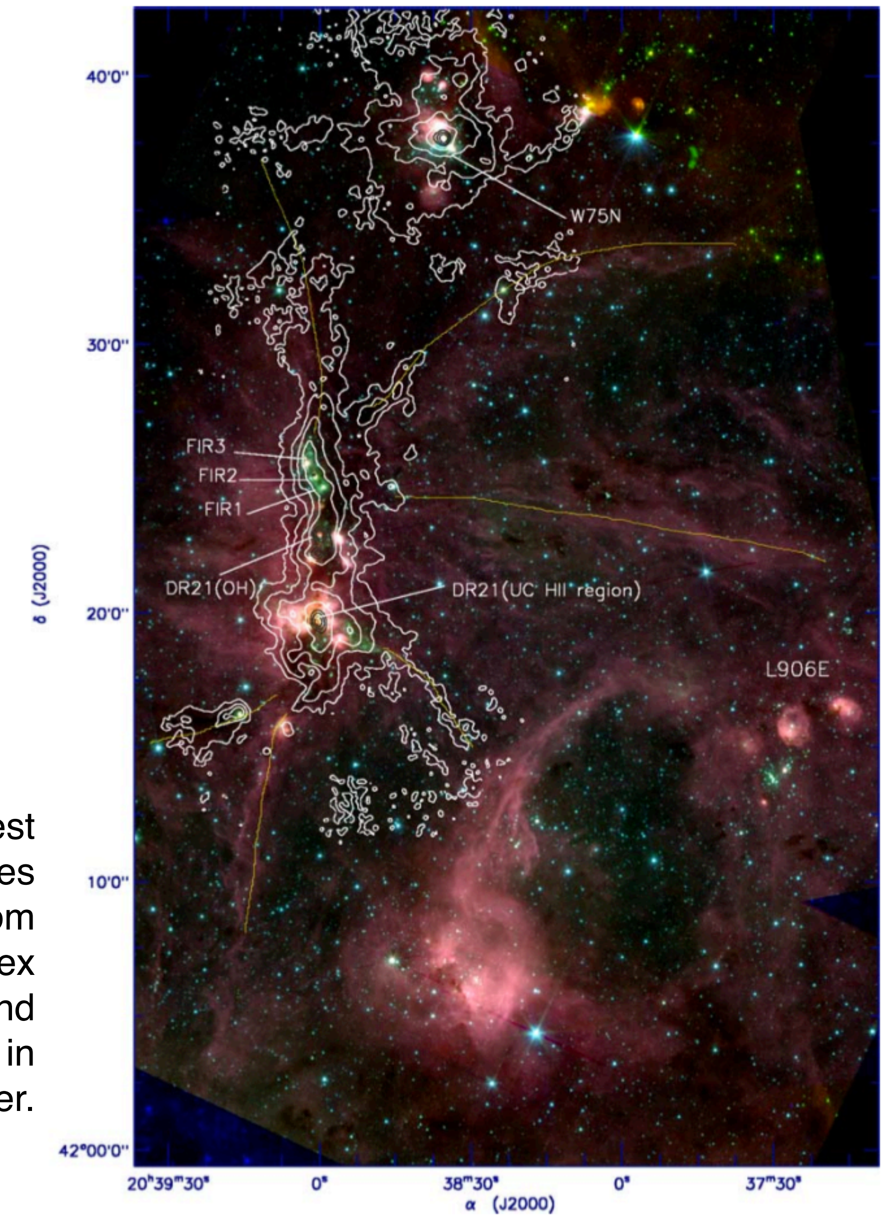
Methanol in Orion-KL: NMA, CH$_3$OH 15_3-14_4 A$^-$ (Minh et al. 1993)

4. SMA Observations towards W75N and DR21(OH)



(contour) 1.3 mm continuum, (triangles) UC HII, (+) H_2O masers, (dot) OH masers [Shepherd et al. 2001]

Cygnus X is one of the richest molecular and HII complexes located at less than 3 kpc from the Sun. The molecular complex is massive (4x10^6 $M_\odot$) and extends over ~100 pc in diameter.

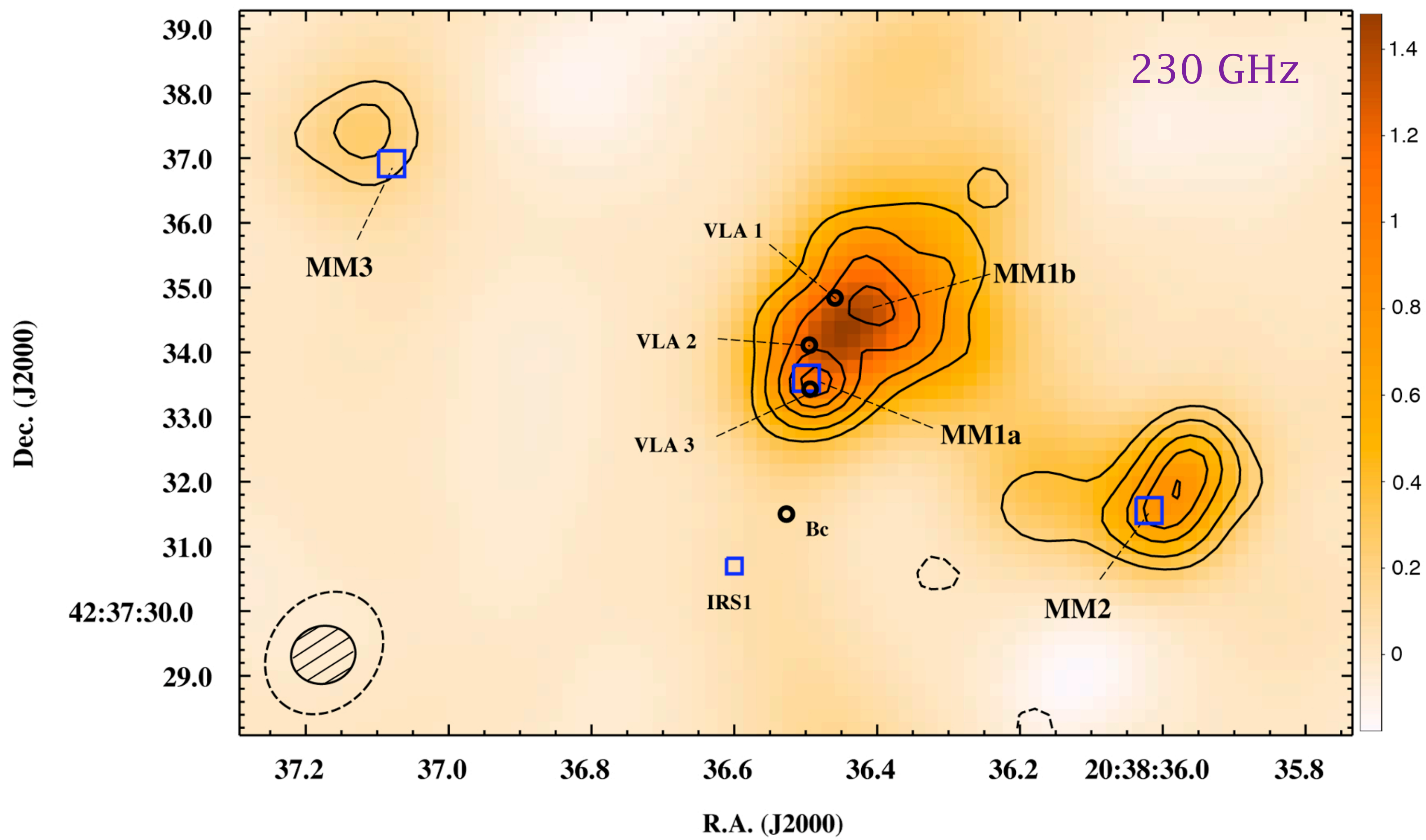


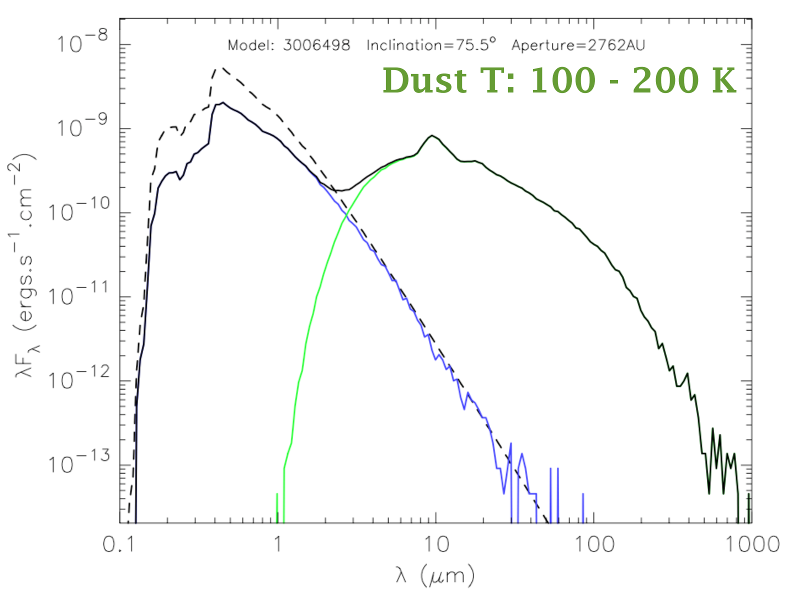
Sub-Millimeter Array (SMA, 8x 6m, 0.5 km, Hawaii)
2006, W75N (230 GHz; 345 GHz), Θ = 1" (230 GHz), 2" (345 GHz)

Detected Molecular Lines: ≥ 100 transitions

- $C^{17}O$, $H^{13}CO^+$, H_2CO, CH_3OH (~ 50 lines), $^{13}CH_3OH$
- HCOOH, $HCOOCH_3$, CH_3OCH_3, CH_3CHO, CH_3CH_2OH
- $C^{34}S$, H_2CS, H_2S, SO, ^{33}SO, ^{34}SO, SO_2, $^{34}SO_2$
- SiO
- HC_3N, DCN, $HN^{13}C$
- CH_2CHCN, CH_3CH_2CN, NH_2CHO, ...

Continuum Emission





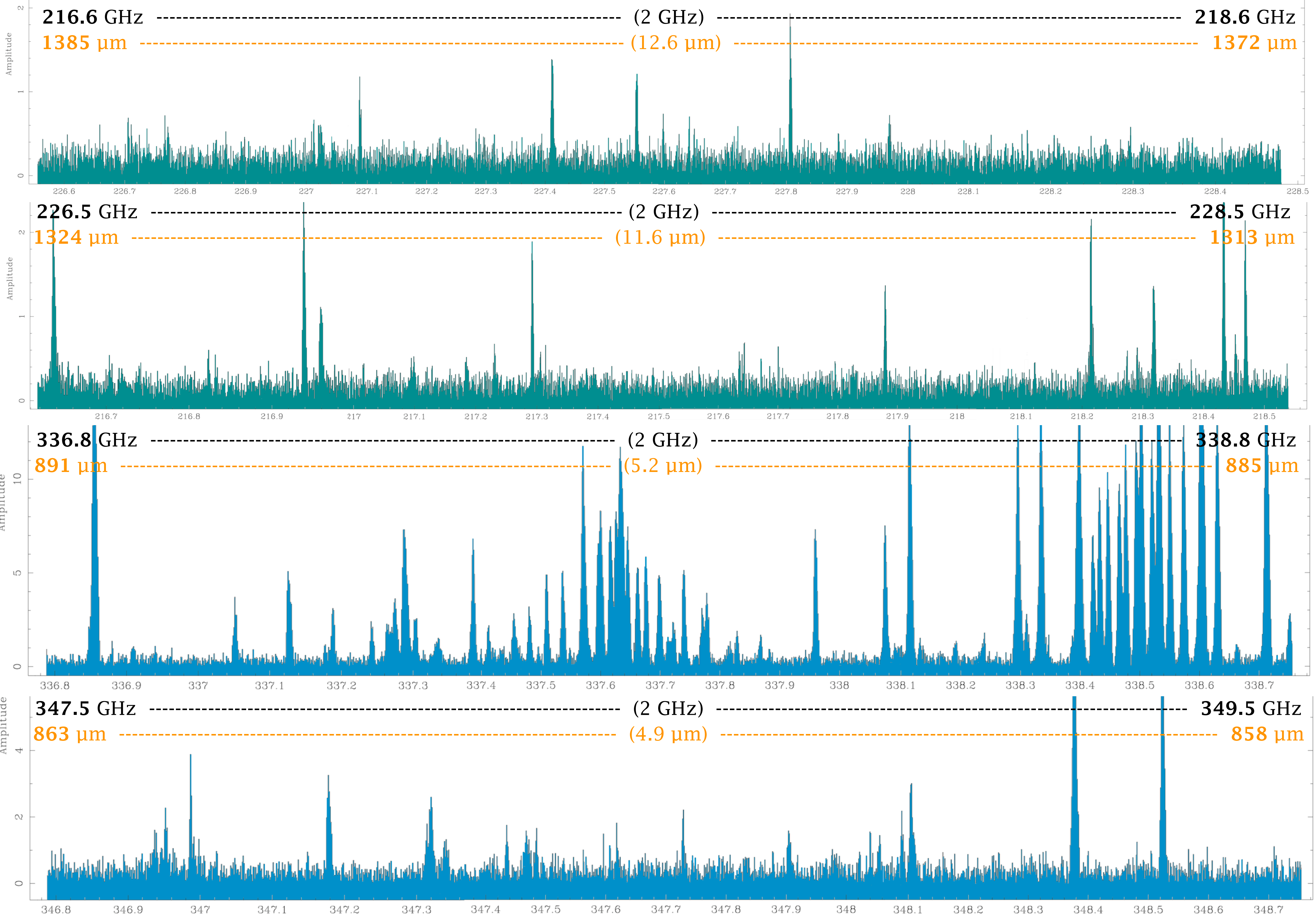
$$M_{dust} = \frac{F_\nu \cdot D^2}{B_\nu(T_d)} \frac{\frac{4}{3}\, a_d \cdot \rho_d}{Q_\nu}\,, \qquad Q_\nu = 6.5 \cdot 10^{-5} \left(\frac{\nu[\mathrm{GHz}]}{200}\right)^\beta$$

$$\frac{M_{core}}{[\mathrm{M}_\odot]} = 1.2 \cdot 10^4 \, \frac{F_\nu}{[\mathrm{Jy}]} \left(\frac{D}{[\mathrm{kpc}]}\right)^2 \frac{a_d}{[0.1\ \mu\mathrm{m}]} \, Q_\nu^{-1} \frac{\rho_d}{[2.8\ \mathrm{g\ cm^{-3}}]} \left(\frac{\nu}{[\mathrm{GHz}]}\right)^{-3} J_\nu(T_d)^{-1} \, \frac{R}{[100]}$$

Table 1: Parameters of the identified continuum cores.[a]

Source	Position[b] ($''$, $''$)	Peak[c] (Jy/beam)	Total Flux (Jy)	Size ($'' \times ''$)	P.A.[d] (°)	$T_{\rm dust}$ (K)	$M_{\rm core}$ ($\mathrm{M}_\odot$)	$N_{\rm H_2}$ ($\mathrm{cm^{-2}}$)	$n_{\rm H_2}$ ($\mathrm{cm^{-3}}$)
MM1a	(0, 0)	0.184 ±0.009	0.195	0.97 × 0.97	55.7	200 ∓ 100	$0.59\ ^{+0.61}_{-0.20}$	$6.2\ ^{+6.5}_{-2.1} \times 10^{23}$	$2.2\ ^{+2.3}_{-0.7} \times 10^{7}$
MM1b	(−0.93, 1.16)	0.128 ±0.004	0.462	1.84 × 1.74	−63.1	200 ∓ 100	$1.39\ ^{+1.47}_{-0.47}$	$1.3\ ^{+1.3}_{-0.5} \times 10^{23}$	$1.3\ ^{+1.4}_{-0.4} \times 10^{6}$

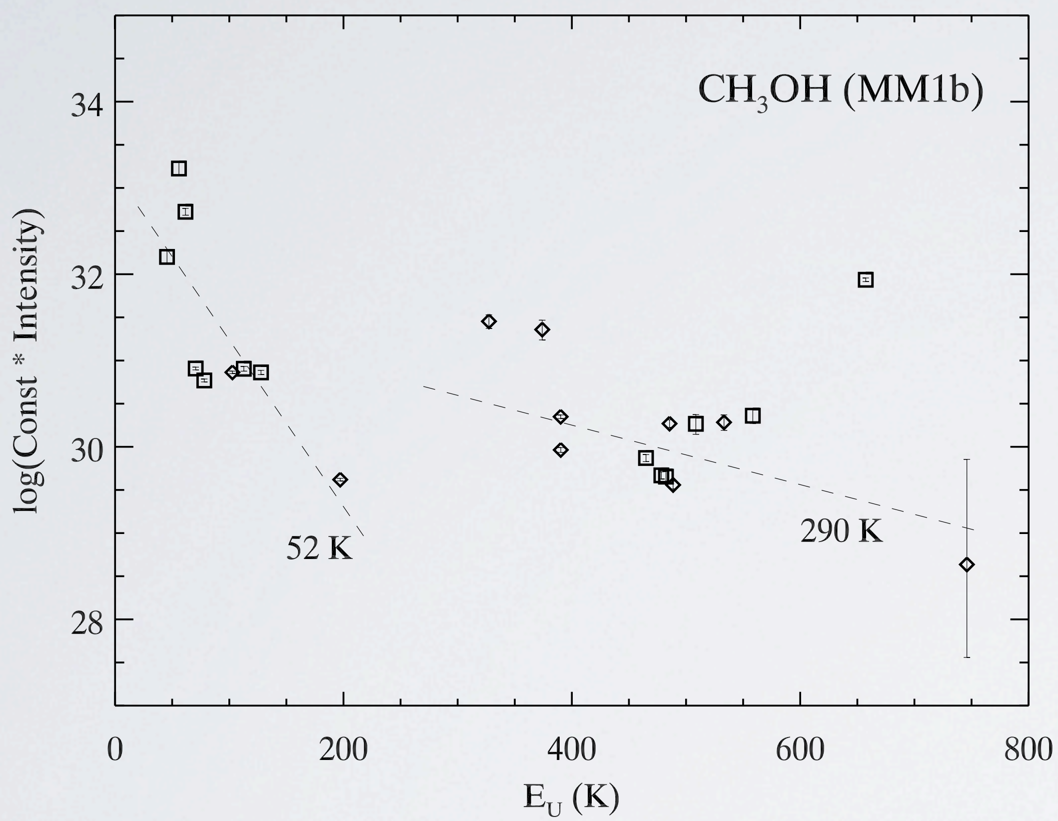
W75N



216.6 GHz (2 GHz) 218.6 GHz
1385 µm (12.6 µm) 1372 µm
226.5 GHz (2 GHz) 228.5 GHz
1324 µm (11.6 µm) 1313 µm
336.8 GHz (2 GHz) 338.8 GHz
891 µm (5.2 µm) 885 µm
347.5 GHz (2 GHz) 349.5 GHz
863 µm (4.9 µm) 858 µm
Amplitude

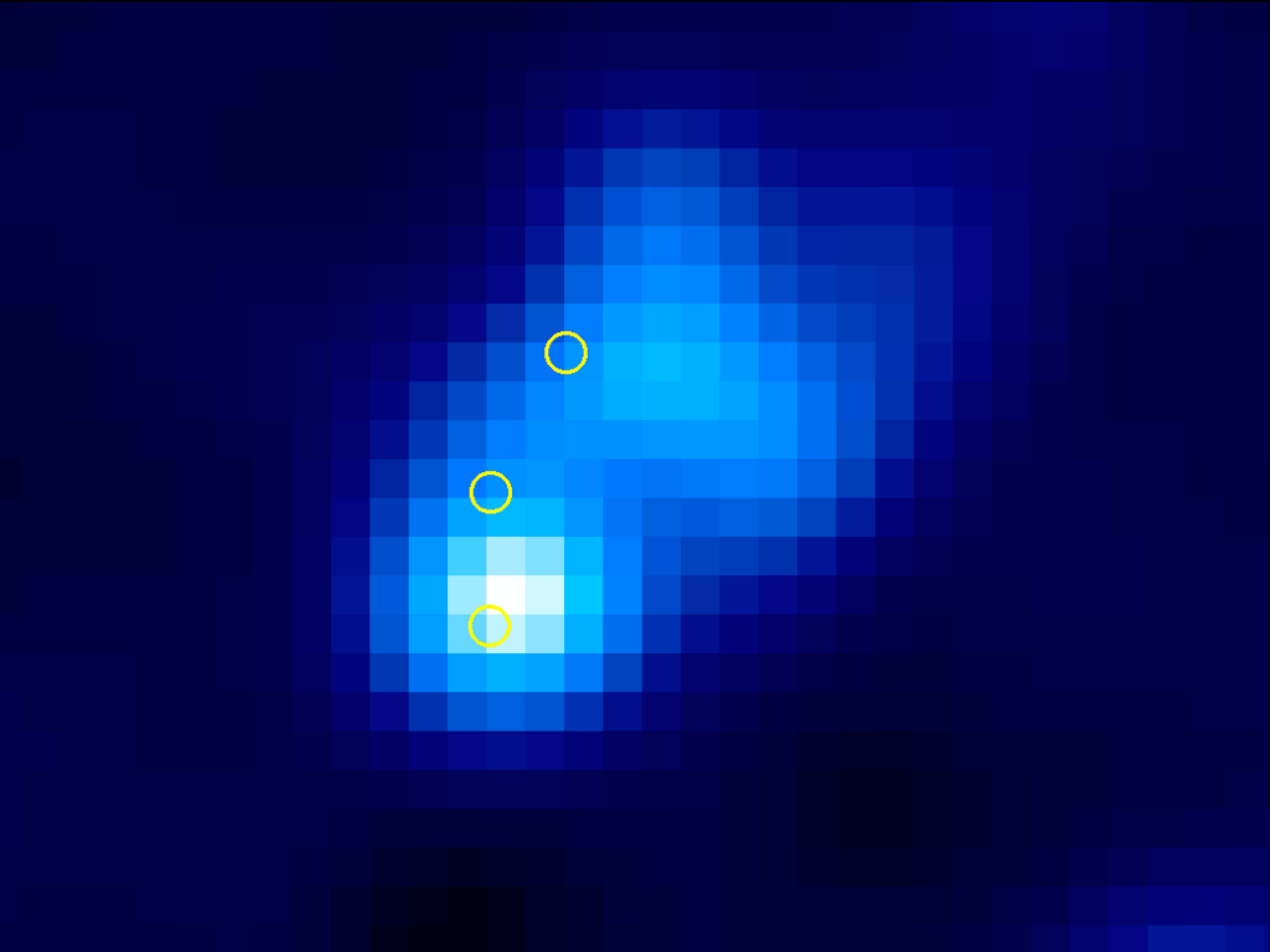
Methanol Lines Observed

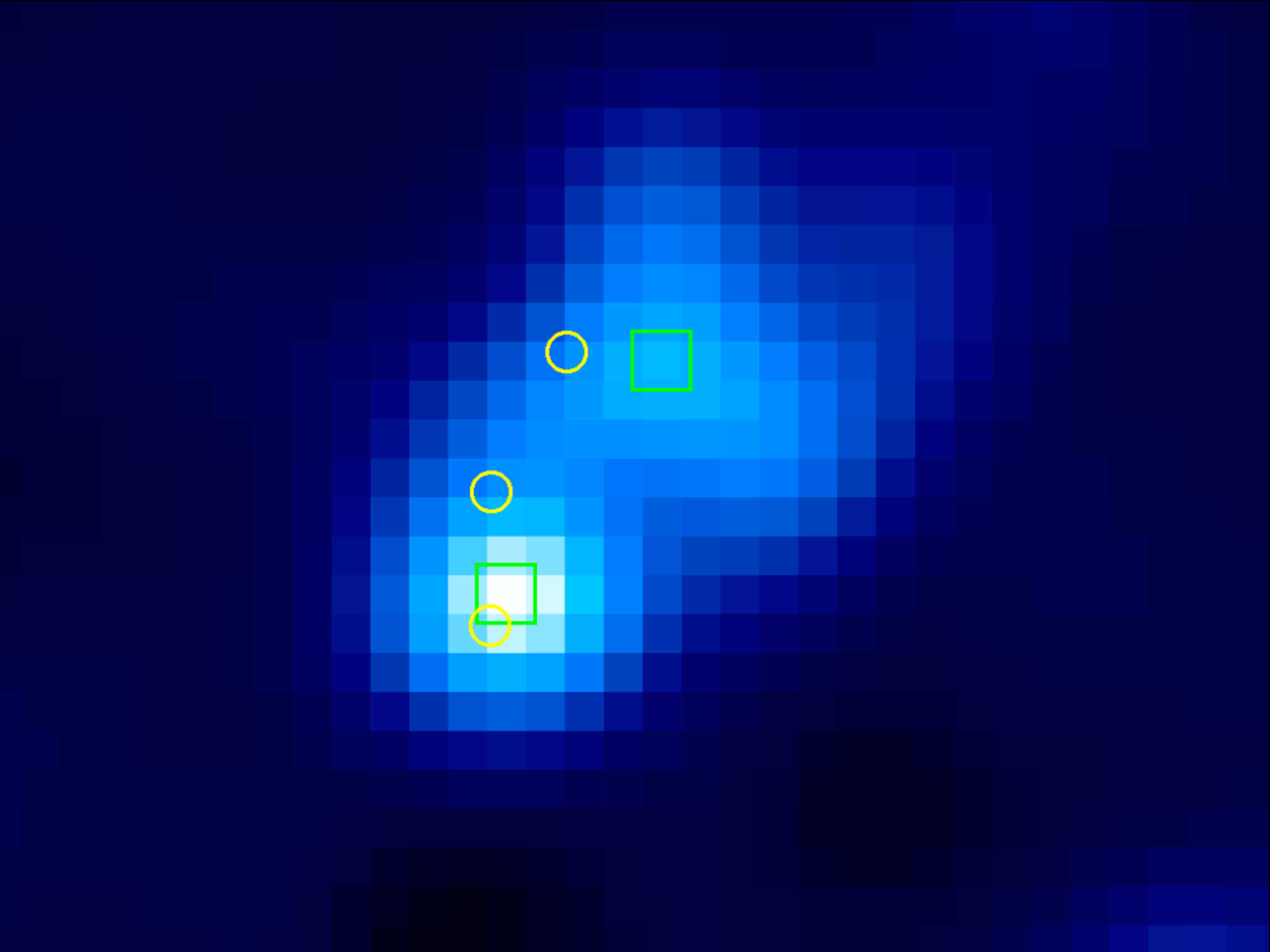
W75N and DR21(OH)

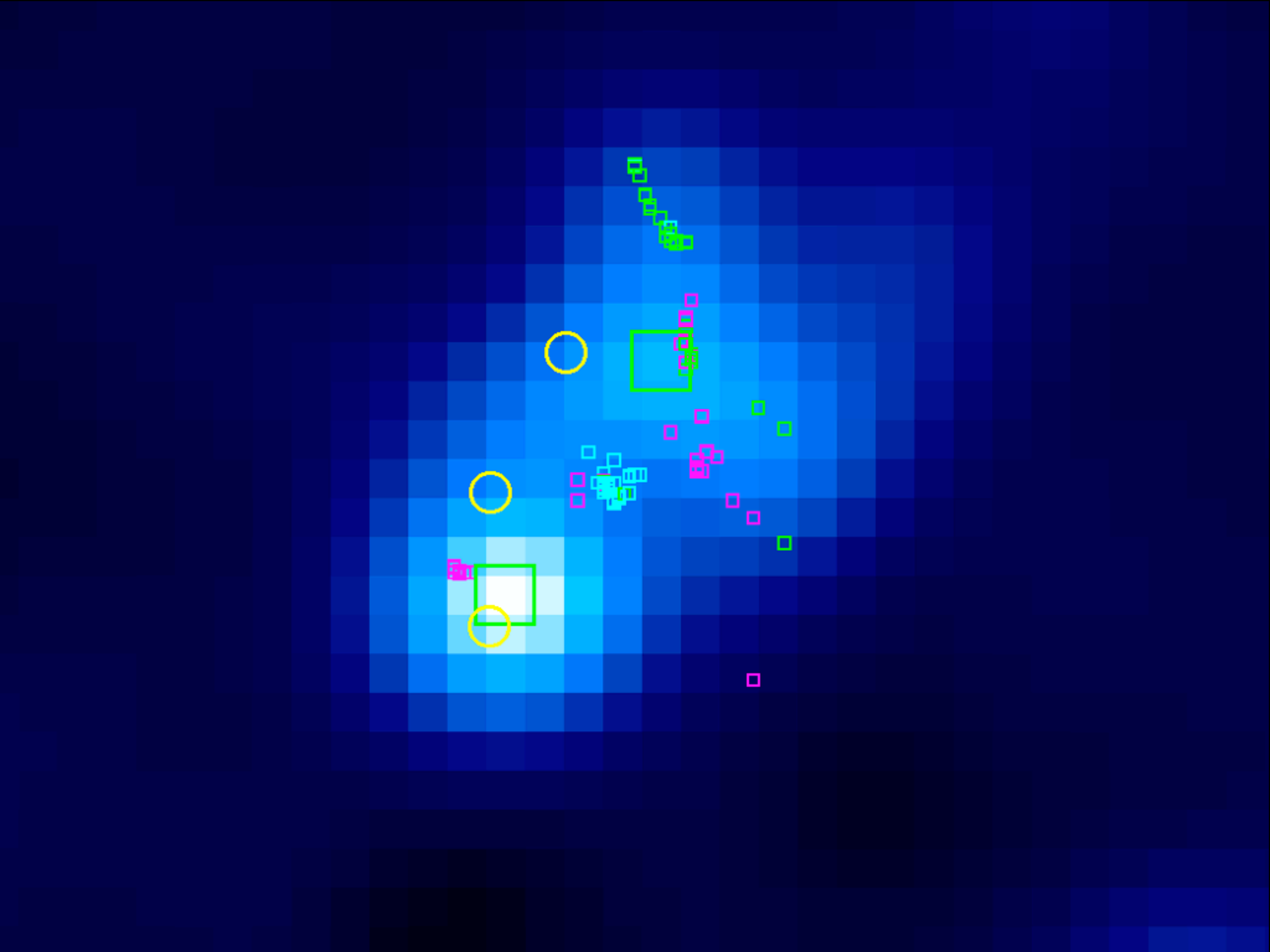


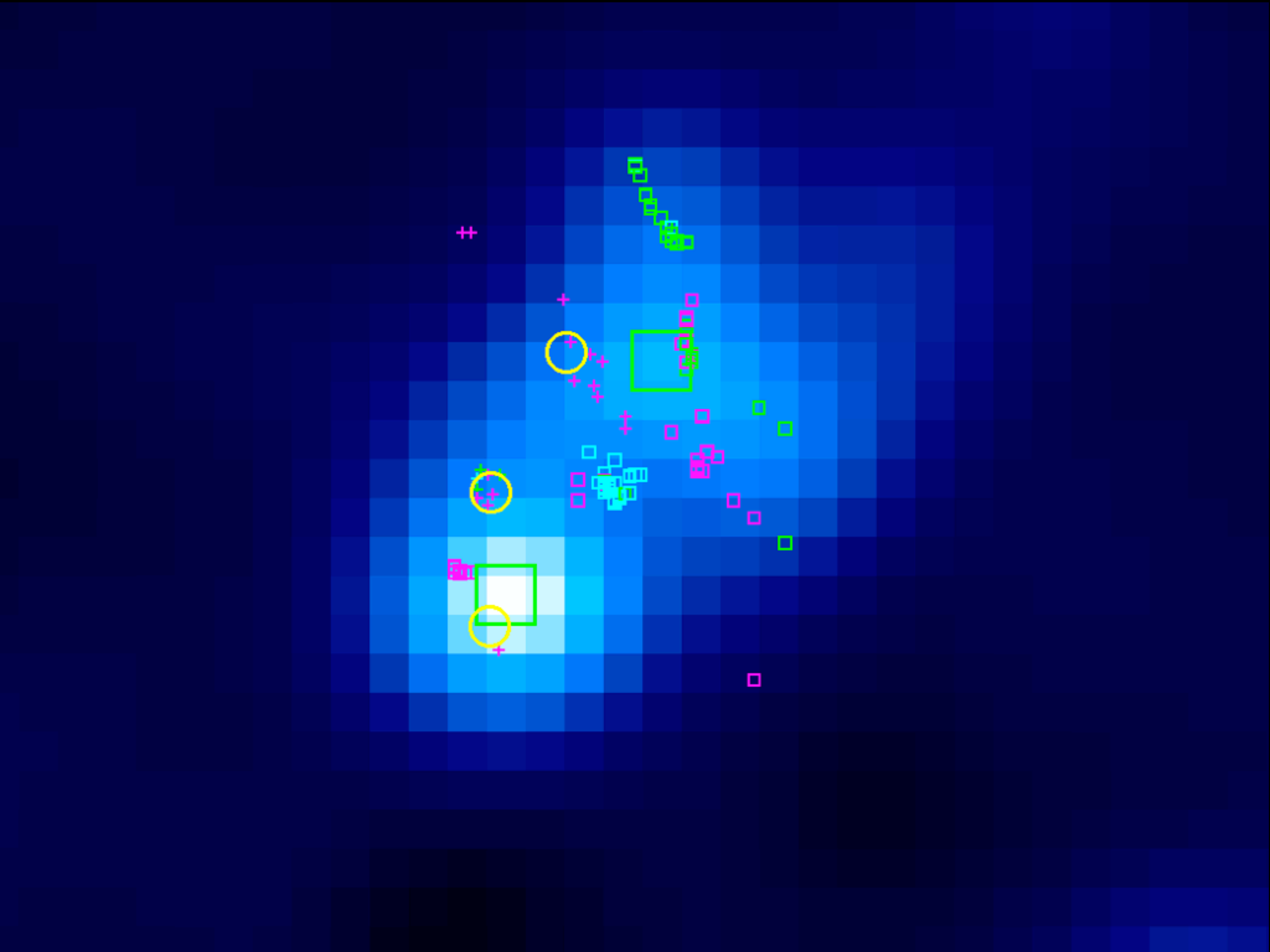
CH3OH -A(v_t=1)	7(5,3)-6(5,2) A++ v_t=1	337545.987	326.086	485.5704
CH3OH -E	7(-2,6)-6(-2,5) E	338722.914	51.889	90.94773
CH3OH -A(v_t=1)	7(4,4)-6(4,3) A-- v_t=1	337685.594	368.154	546.1298
CH3OH -A	7(6,2)-6(6,1) A-- v_t=1	337463.624	359.210	533.2451
CH3OH -A	7(3,4)-6(3,3) A--	338543.149	68.493	114.8389
CH3OH -A (s)	7(4,3)-6(4,2) A++	338512.627	89.720	145.3916
CH3OH -A (s)	7(4,4)-6(4,3) A--	338512.627	89.720	145.3916
CH3OH -A(v_t=1)	7(4,3)-6(4,2) A++ v_t=1	337685.594	368.154	546.1298
CH3OH -E	7(6,2)-6(6,1) E	338404.593	158.155	243.8917
CH3OH -A	7(6,2)-6(6,1) A--	338442.367	168.514	258.8043
CH3OH -A	7 5 3 – 6 5 2 A++	338486.322	129.721	202.9678

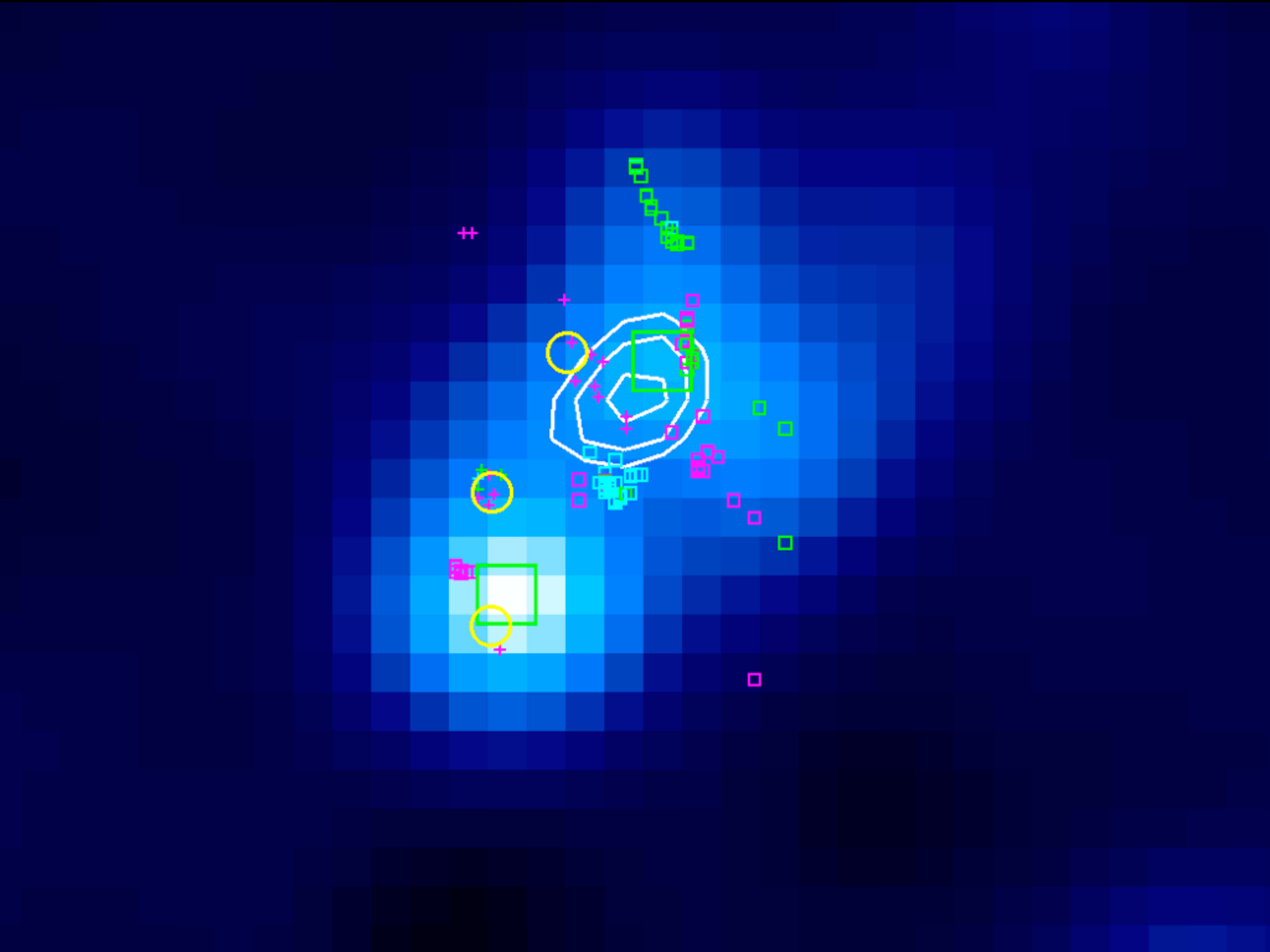
	Transition	NIST (MHz)	E_L (cm^{-1})	Eu (K)
CH3OH -E	5(1,4)-4(2,2) E	216945.559	31.596	55.89267
CH3OH -A(vt=1)	6(1,5)-7(2,6) A- v_t=1	217299.162	252.644	374.0861
CH3OH -E	20(1,19)-20(0,20) E	217886.39	346.073	508.596
CH3OH -E	4(2,2)-3(1,2) E	218440.05	24.31	45.47694
CH_3OH -A	16(1,16)-15(2,13) A+	227814.651	219.844	327.3786
CH3OH -A	12(1,11)-12(0,12) A-+	336865.153	125.737	197.1554
CH3OH -E	3 3 - 4 2 E	337135.858	31.595	61.66036
CH3OH -A(vt=1)	7(1,7)-6(1,6) A++ $_t$=1	337297.483	259.825	390.1824
CH3OH -A	7(6,1)-6(6,0) A++ v_t=1	337463.624	359.210	533.2451
CH3OH -E	7(-6,2)-6(-6,1) E vt=1	337490.378	376.743	558.4834
CH3OH -E(vt=1)	7(3,5)-6(3,4) E v_t=1	337519.117	323.907	482.4327
CH3OH -A(vt=1)	7(5,2)-6(5,1) A-- v_t=1	337545.987	326.086	485.5704
CH3OH -E(vt=1)	7(-2,5)-6(-2,4) E vt=1	337605.272	287.209	429.6137
CH3OH -A(vt=1)	7(2,5)-6(2,4) A++ v_t=1	337625.745	241.381	363.6498
CH3OH -A(vt=1)	7(2,6)-6(2,5) A-- v_t=1	337635.75	241.381	363.6503
CH3OH -E(vt=1)	7 1 7 – 6 1 6 vt=1 E	337642.484	236.378	356.4493
CH3OH -A(vt=1)	7(3,5)-6(3,4) A++ v_t=1	337655.174	309.104	461.1317
CH3OH -E(vt=1)	7(5,2)-6(5,1) E vt=1	337685.218	332.049	494.1602
CH3OH -E(vt=1)	7(-1,6)-6(-1,5) E v_t=1	337707.52	321.108	478.4128
CH3OH -A(vt=1)	7(0,7)-6(0,6) A++ v_t=1	337748.771	328.252	488.6979
CH3OH -A(vt=1)	7(1,6)-6(1,5) A-- v_t=1	337969.434	259.892	390.3111
CH3OH -E	7(0,7)-6(0,6) E	338124.498	42.988	78.1069
CH3OH -E	7(-1,7)-6(-1,6) E	338344.605	37.749	70.57645
CH3OH -A	7(0,7)-6(0,6) A++	338408.718	33.876	65.00473
CH3OH -E	7(-6,1)-6(-6,0) E	338430.981	165.213	254.0523
CH3OH -A	7(6,1)-6(6,0) A++	338442.367	168.514	258.8043
CH3OH -E	7 -5 2 – 6 -5 1 E	338456.521	120.071	189.0761
CH3OH -E	7 5 -3 – 6 5 2 E	338475.217	128.453	201.1421
CH3OH -A	7 5 2 – 6 5 1 A--	338486.322	129.721	202.9678
CH3OH -A	7(2,6)-6(2,5) A--	338512.856	60.090	102.7422
CH3OH -A	7(3,5)-6(3,4) A+	338540.824	68.493	114.8388
CH3OH -E	7 -3 5 – 6 -3 4 E	338559.963	77.468	127.7583
CH3OH -E	7(3,4)-6(3,3) E	338583.223	67.043	112.7537
CH3OH -E	7(1,6)-6(1,5) E	338614.953	48.514	86.08457
CH3OH -A	7(2,5)-6(2,4) A+	338639.807	60.096	102.7569
CH3OH -E	7(2,5)-6(2,4) E	338721.694	49.349	87.29159

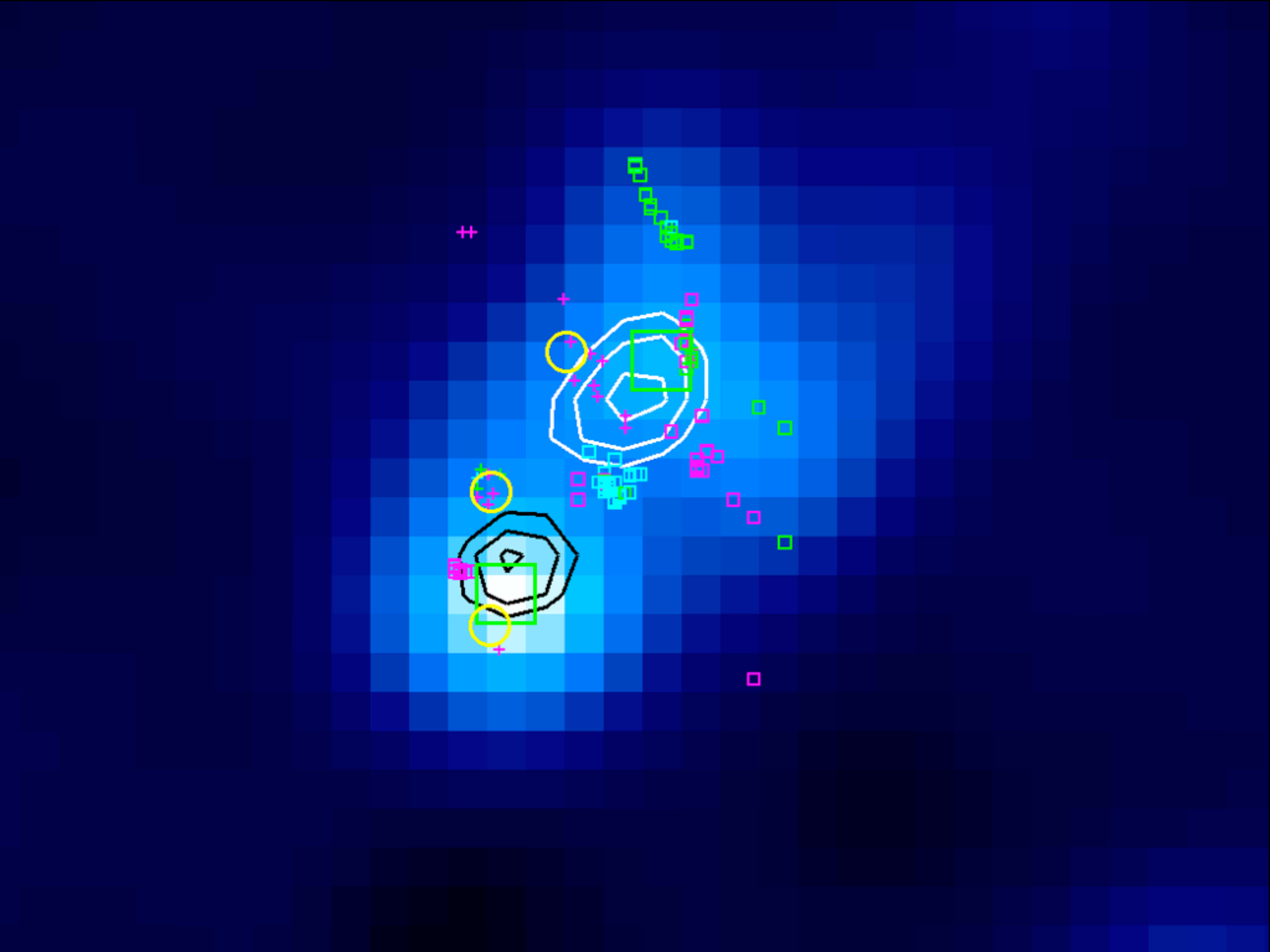


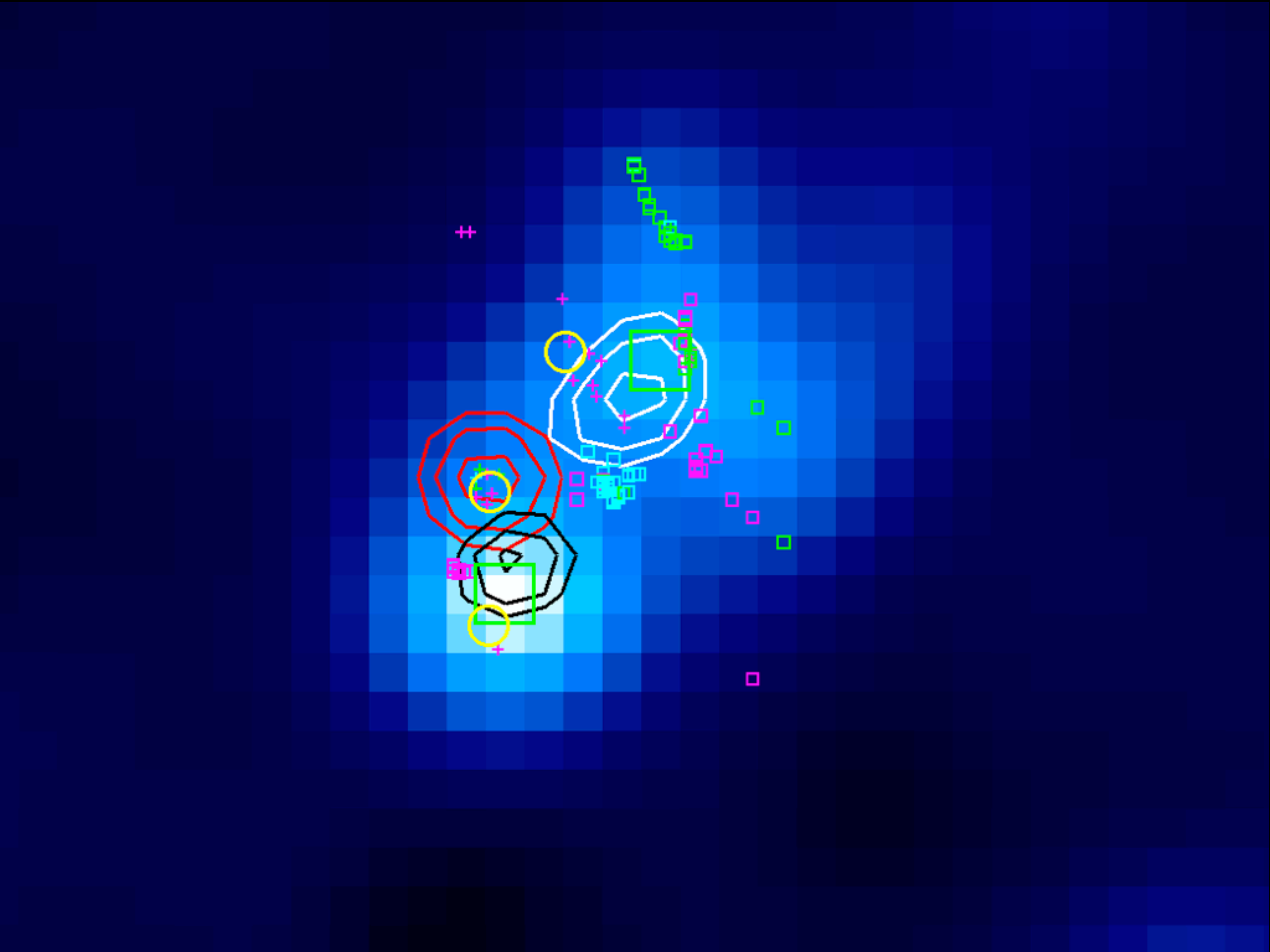




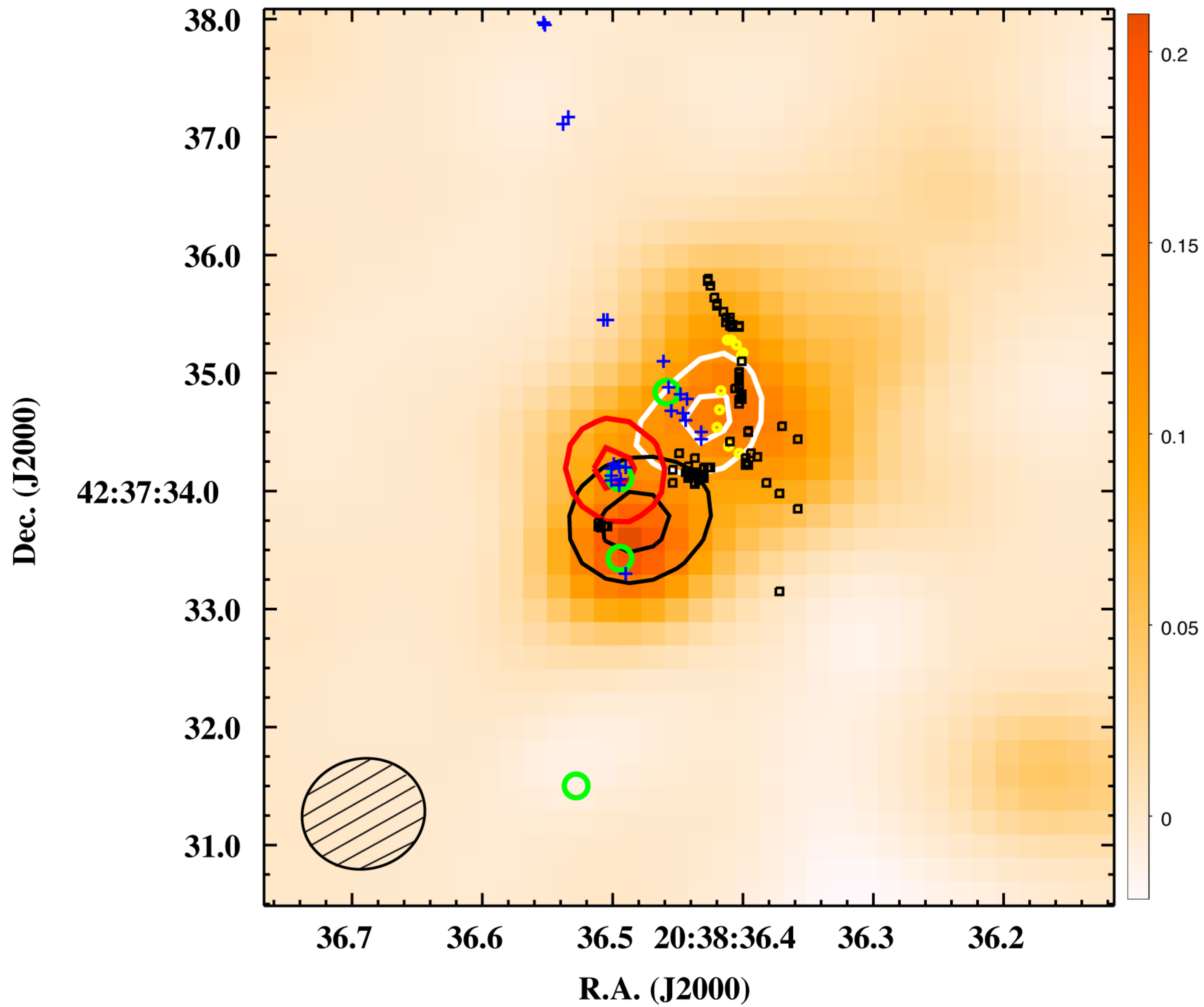




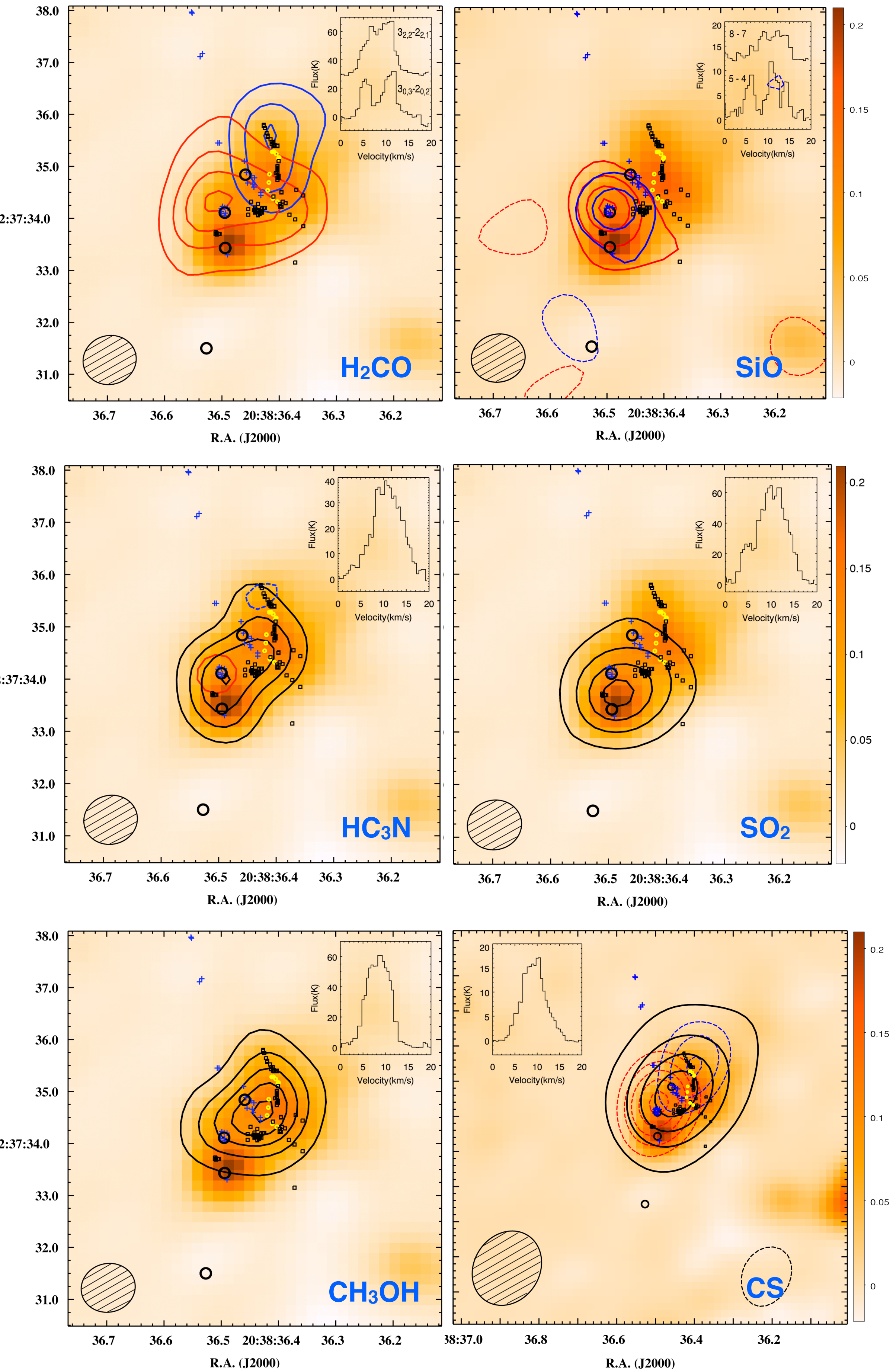


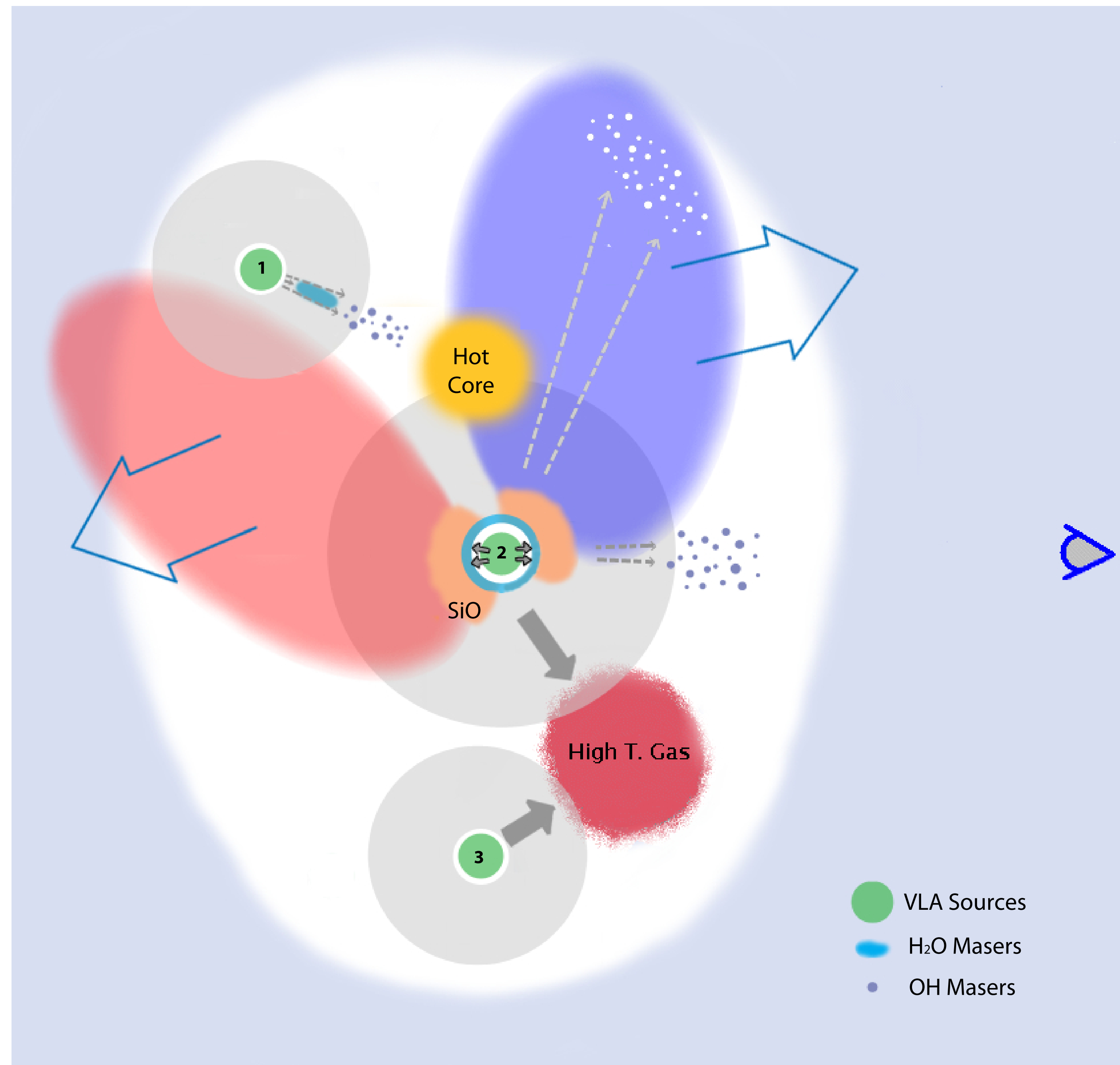


W75N



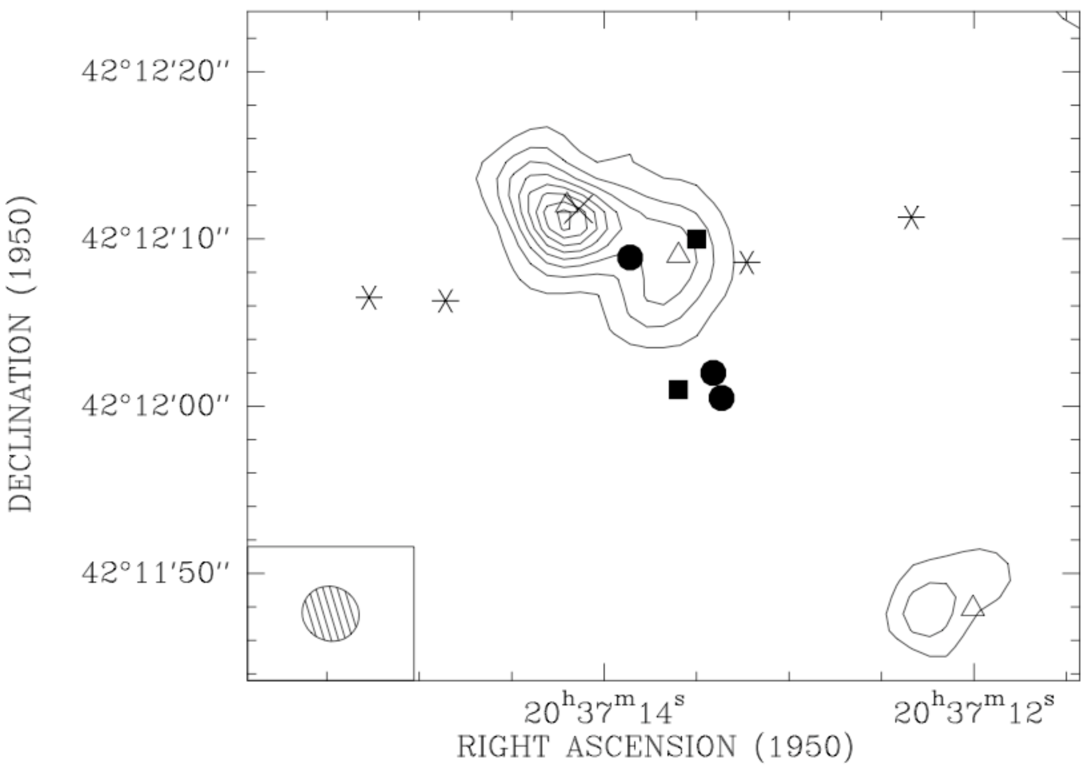
Minh et al. 2010, ApJ, in press



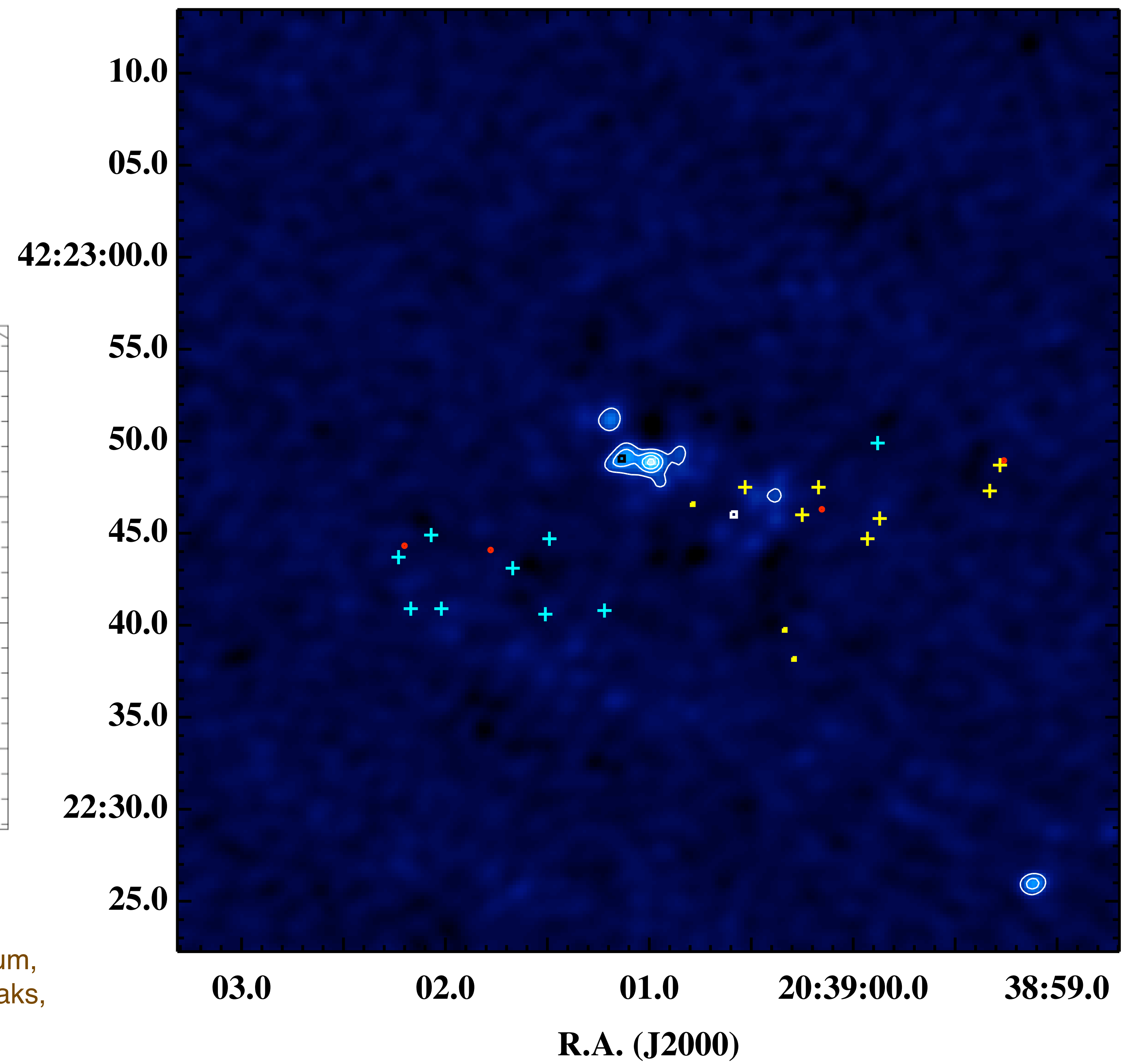


Minh et al. 2010, ApJ, in press

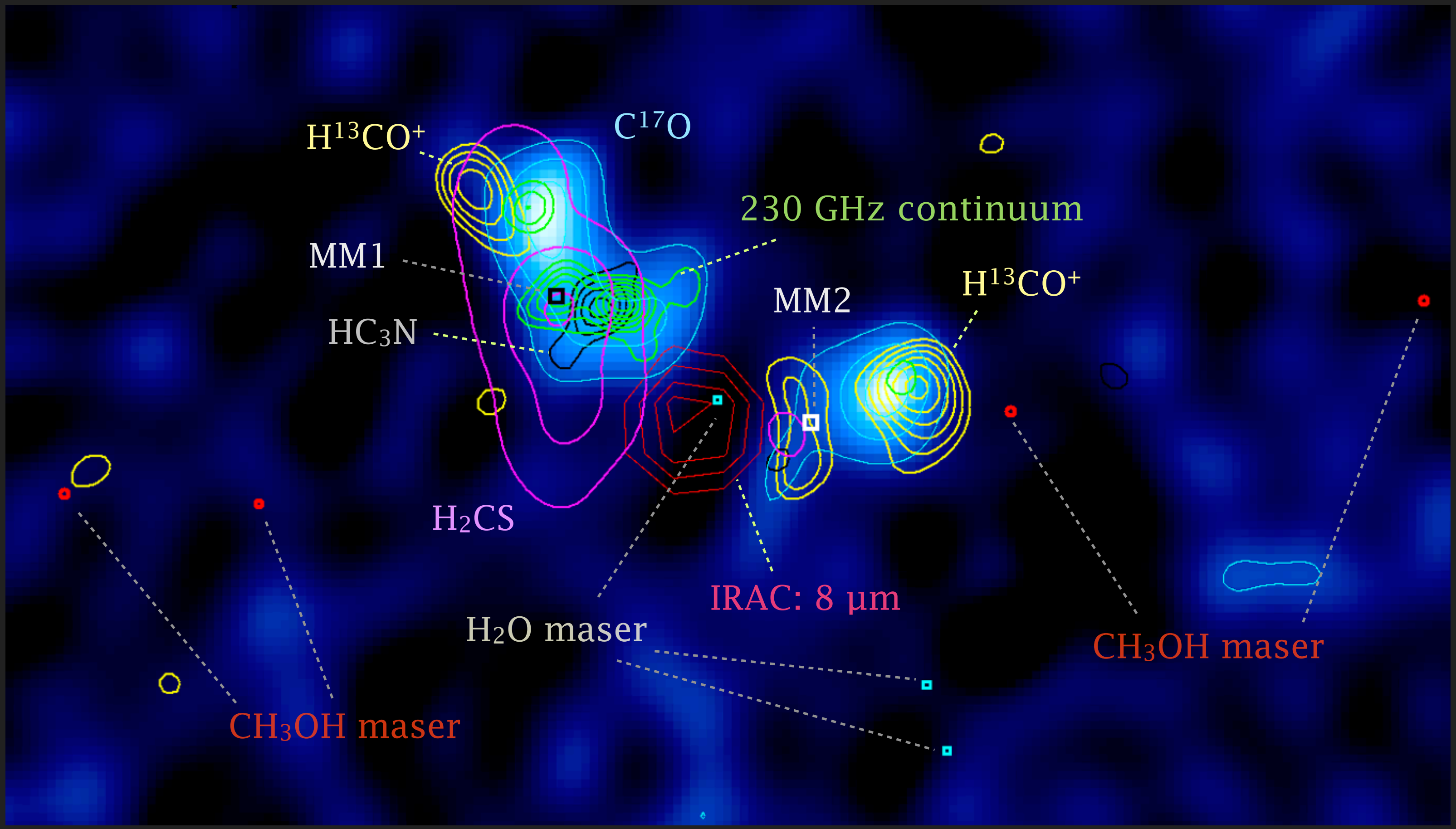
DR21(OH)

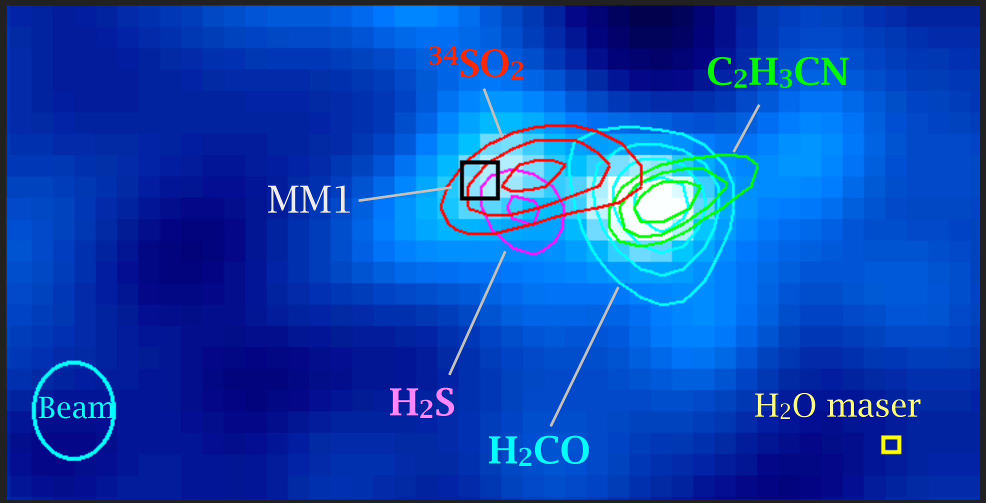


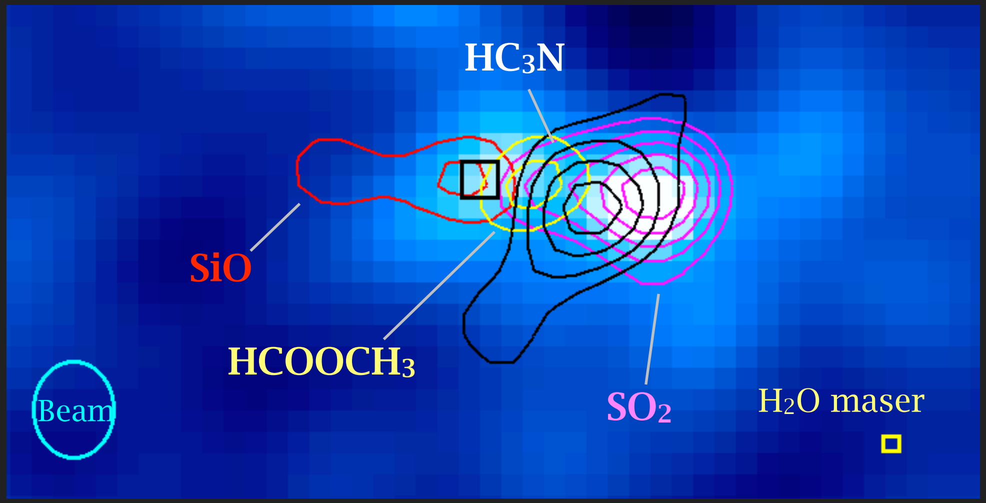
(contour) 3.1mm continuum, (triangle) 2.7mm continuum, (x) OH maser, (circle) H_2O masers, (square) H_2CO peaks, (star) CH_3OH 2_k-1_k (96 GHz) [Liechti et al. 1997]



Minh et al., in preparation



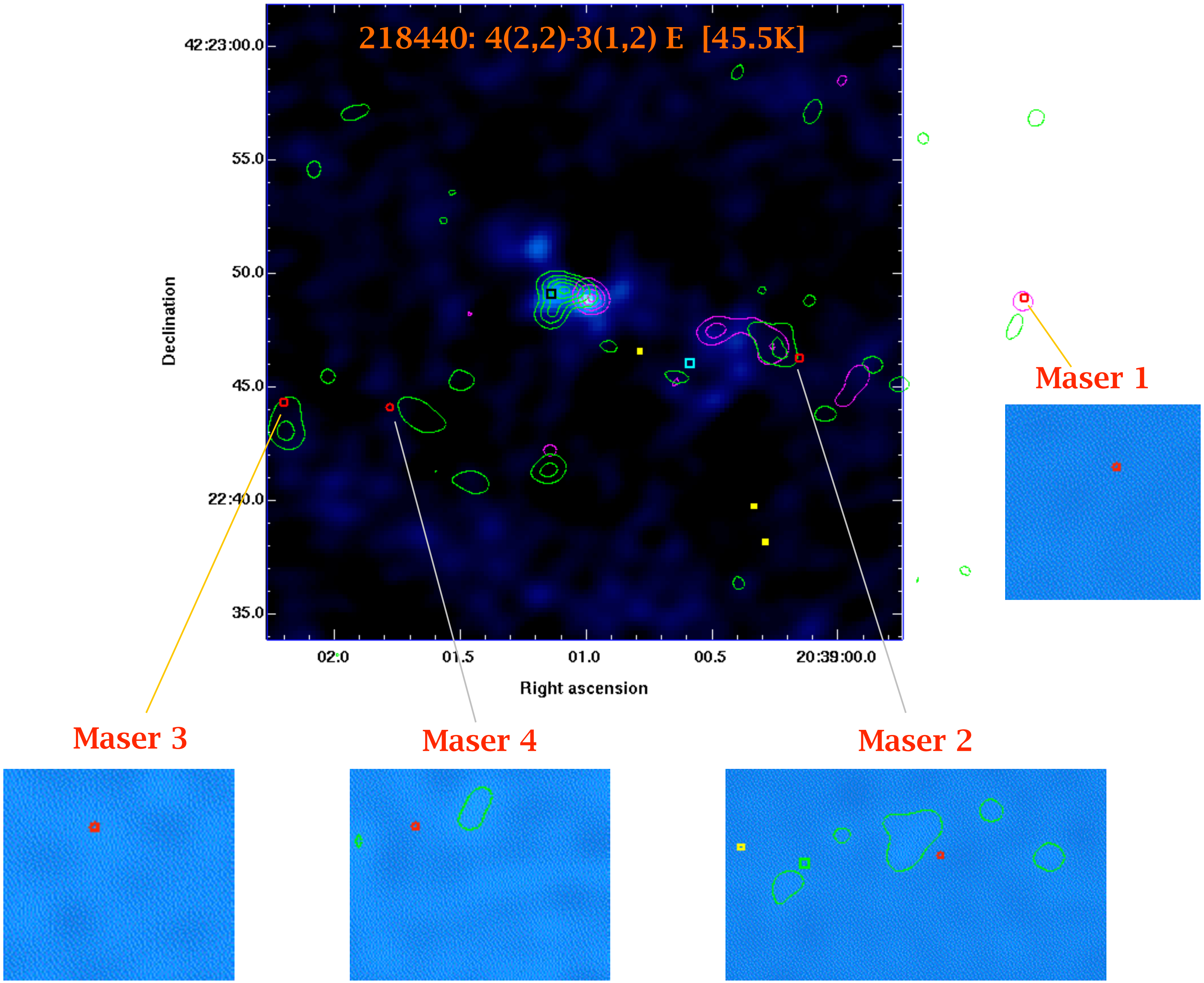




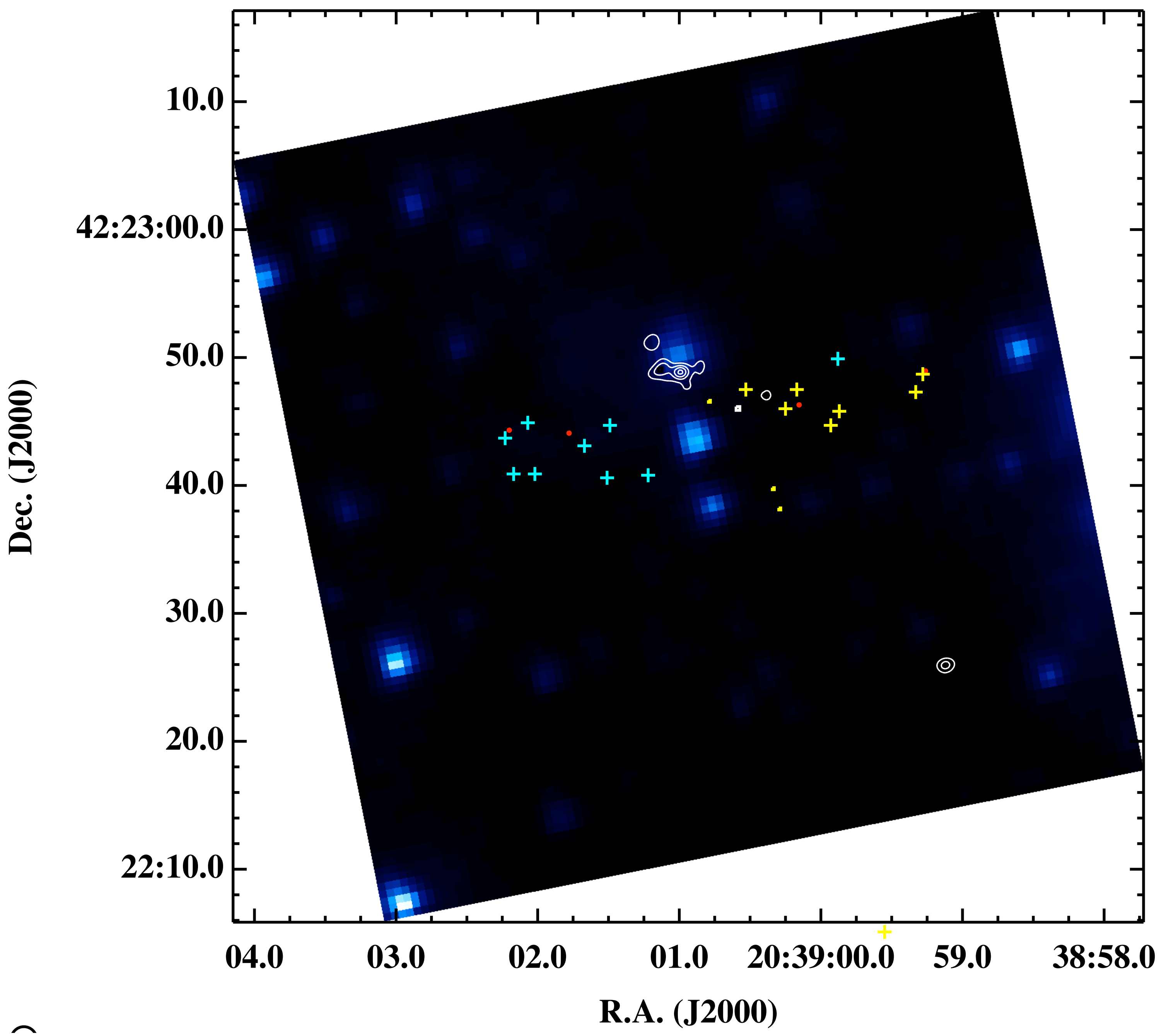
1” = 0.015 pc at 3 kpc

0.015 pc = 3000 AU

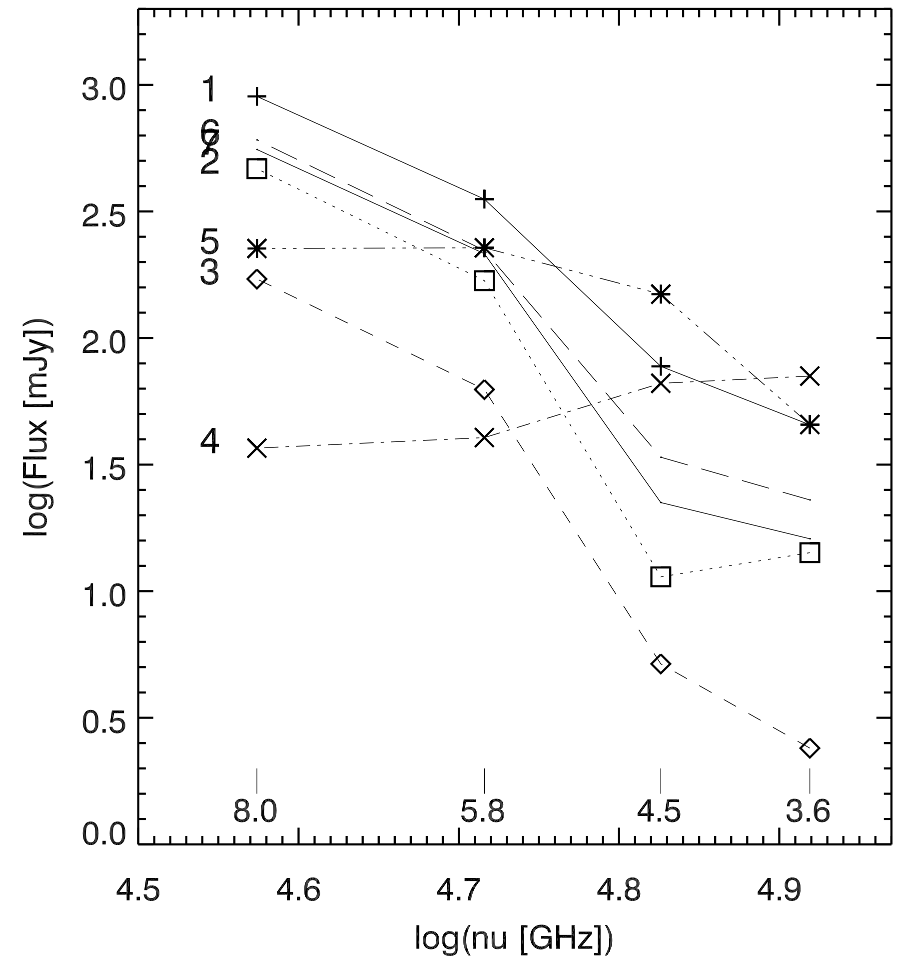
Methanol Masers and Thermal Emission

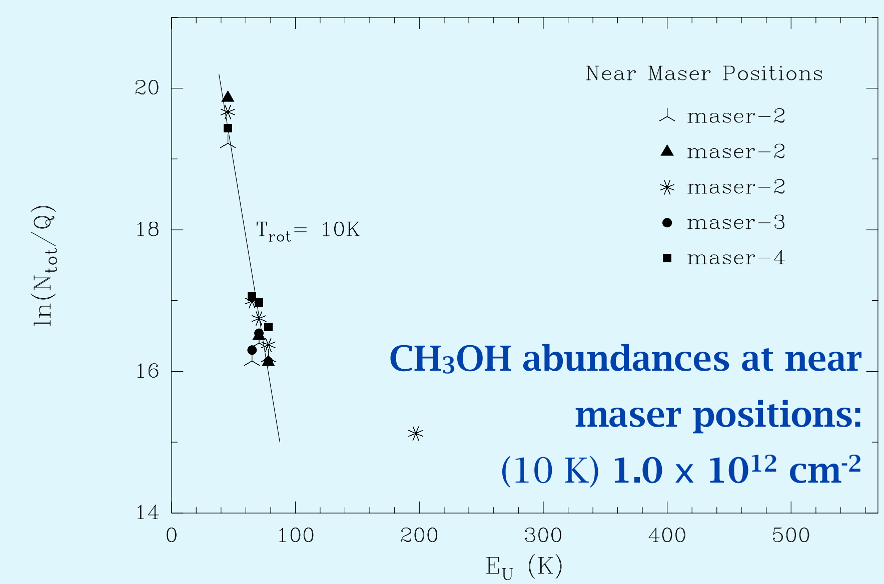


Spitzer IRAC 1



SEDs



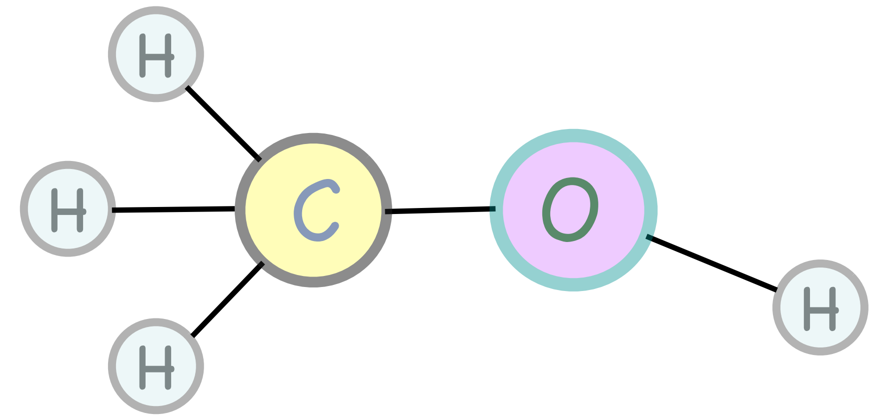


CH_3OH abundances at near maser positions:

(10 K) **1.0×10^{12} cm^{-2}**

Summary

- **Methanol**
  - Oxygen chemistry
  - Many transitions in radio and IR, and masers
  - Traces massive star-forming activities



- **More observations**
  - **thermal emission:** toward various objects, including our solar system objects

    chemical variations, ..
  - **methanol masers:** relation with other masers, kinematics, association with other features like outflows, or other SF features, ...

    probable correlation with regional chemical gradients

- **More studies of its chemistry** - especially surface chemistry on the icy dust grains
  - ice mixture, evaporation, dissociation,..