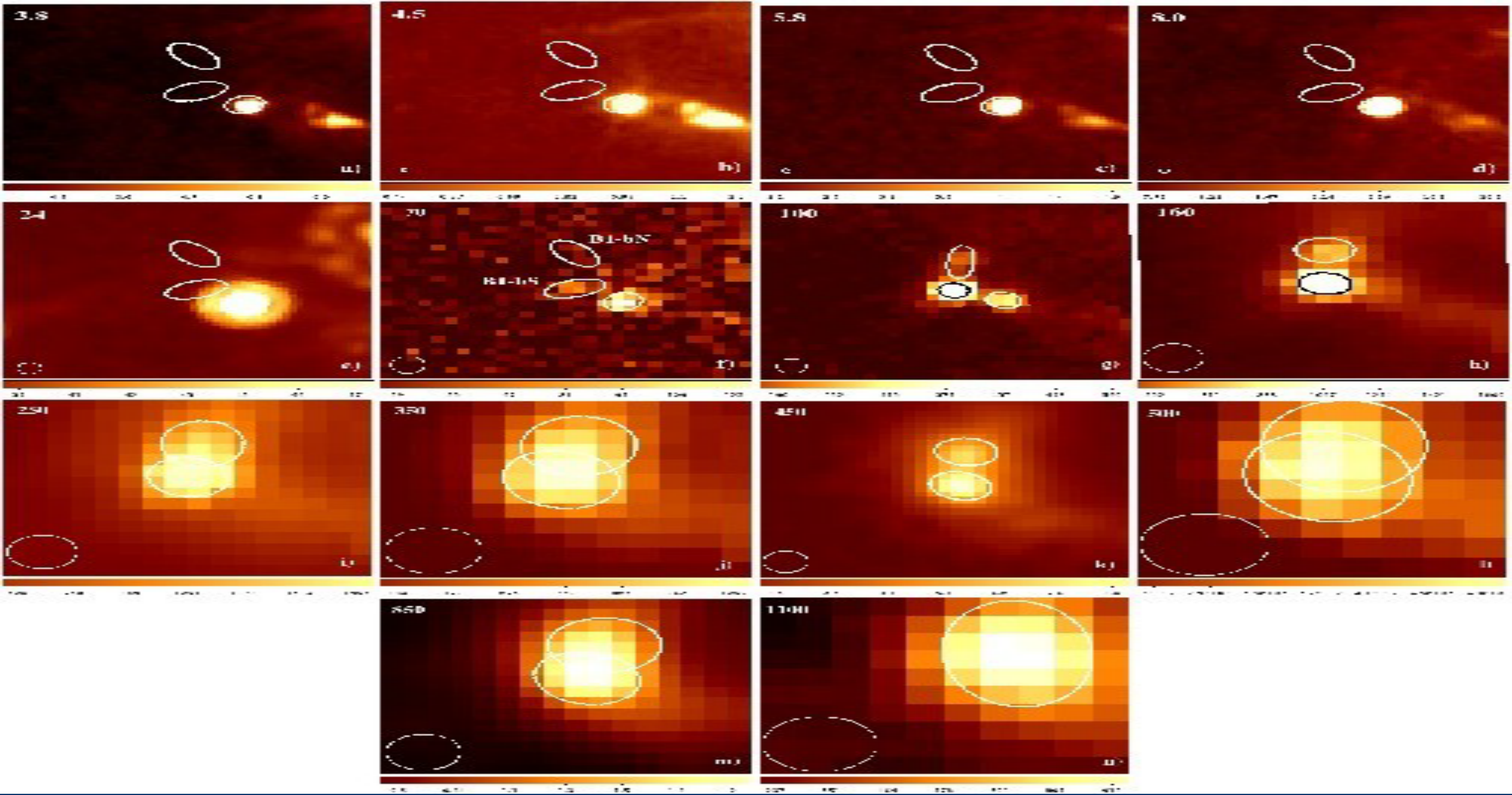


Molecules Tracing Conditions in the Perseus B1 Cores

Al Wootten, NRAO

N. Marcelino, M. Gerin, J. Pety, A. Fuente, J. Cernicharo, B. Commerçon

First Hydrostatic Cores?

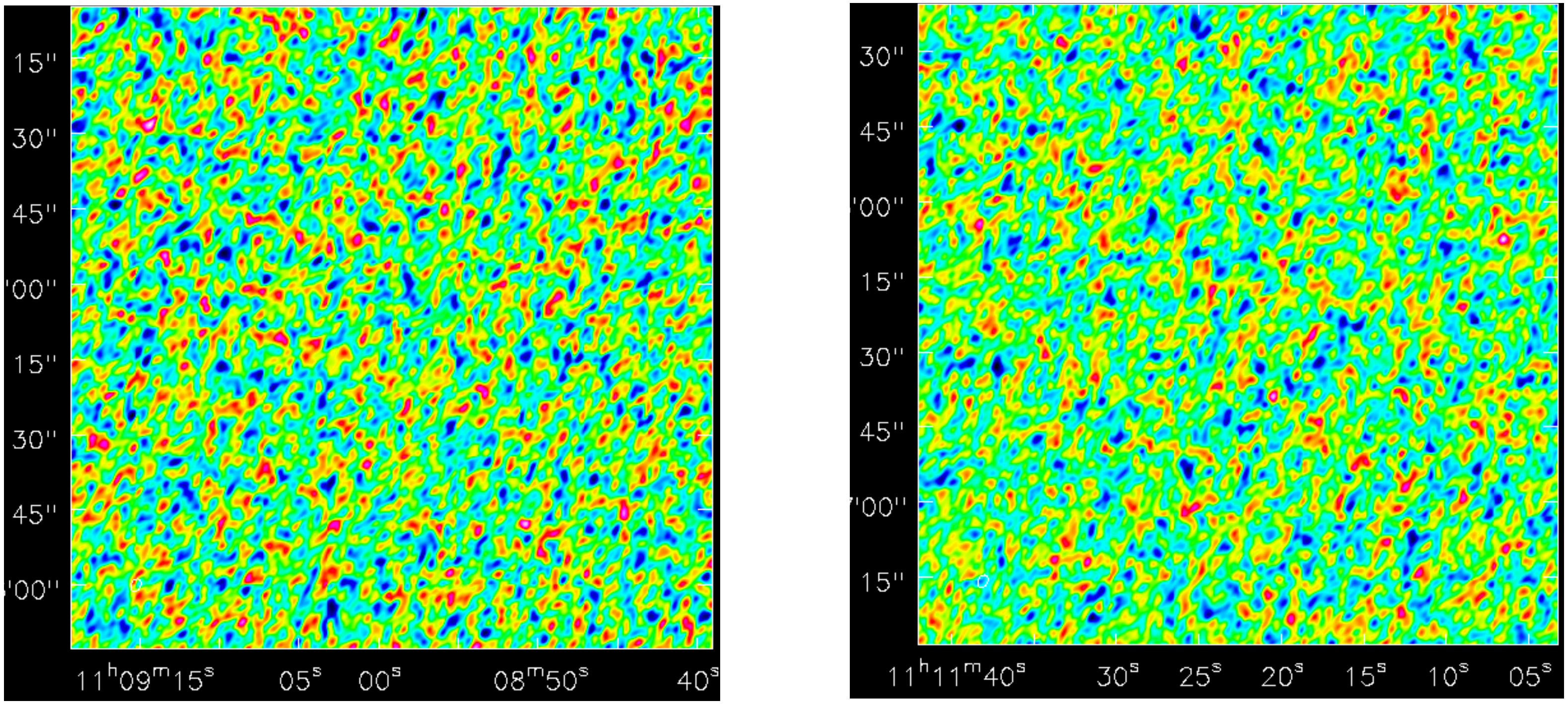
In search of early phases of star formation

- An isothermal sphere approximates a pre-stellar core
  - Cf. Schnee cores—invisible to interferometry
- The first stage of star formation is thought to be the first collapse of that core to the FHSC (t~500-1000 years)
  - Only slow outflows at this stage
  - $n_{central} \sim 10^{10}$ cm^{-3}
- That is followed by the 2nd collapse, accompanied by H_2 dissociation (few days) (T reaches ~2000K)
- As rotation couples with the collapse and embedded magnetic field, jetlike outflows arise and the star is on its way to Class 0
- This is an intrinsically low-contrast stage, invisible or difficult to image with interferometers.

Starless Cores: Weak or No mm Continuum

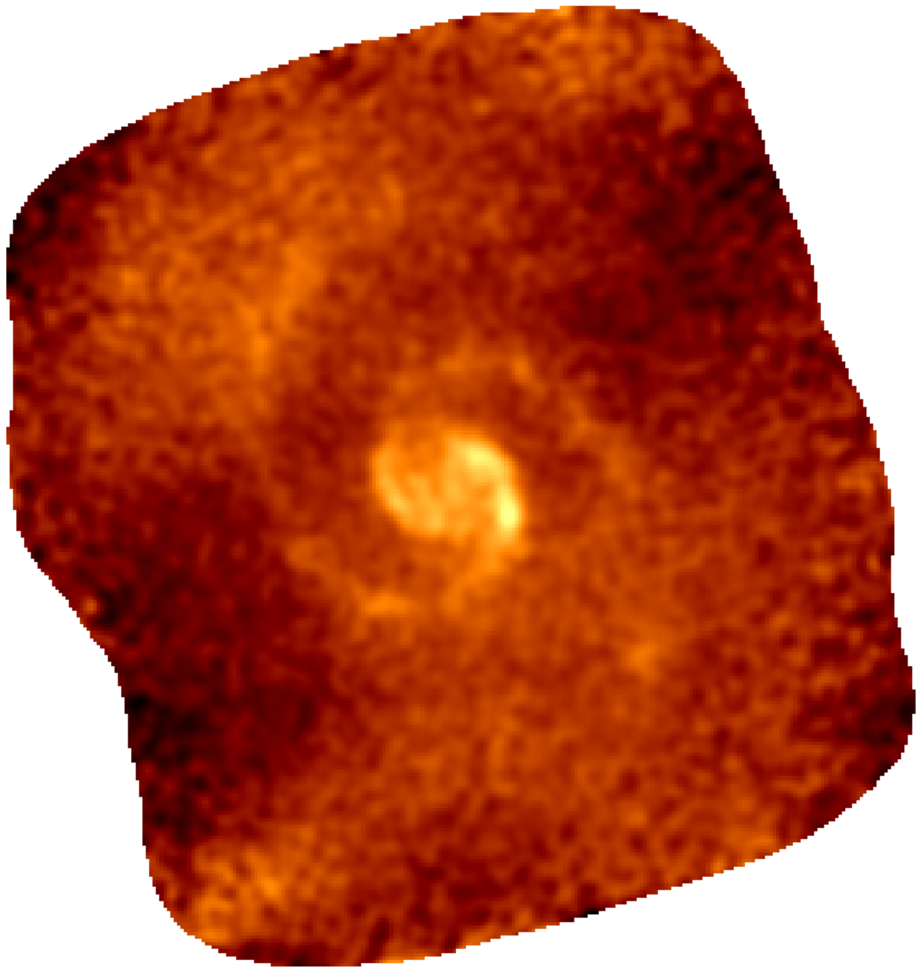
Every Starless Core (ALMA)

(Schnee et al. in prep.)



- For Starless cores, GBT has huge advantages over ALMA
  - SMA, CARMA, ALMA saw nothing (Schnee et al 2010, 2012, in prep)
- ALMA Total Power continuum modes are not on the radar screen
  - ContinuumTP imaging using nutators
  - Continuum TP polarization
- An interferometer can, however, find low mass stars hidden within apparently starless cores

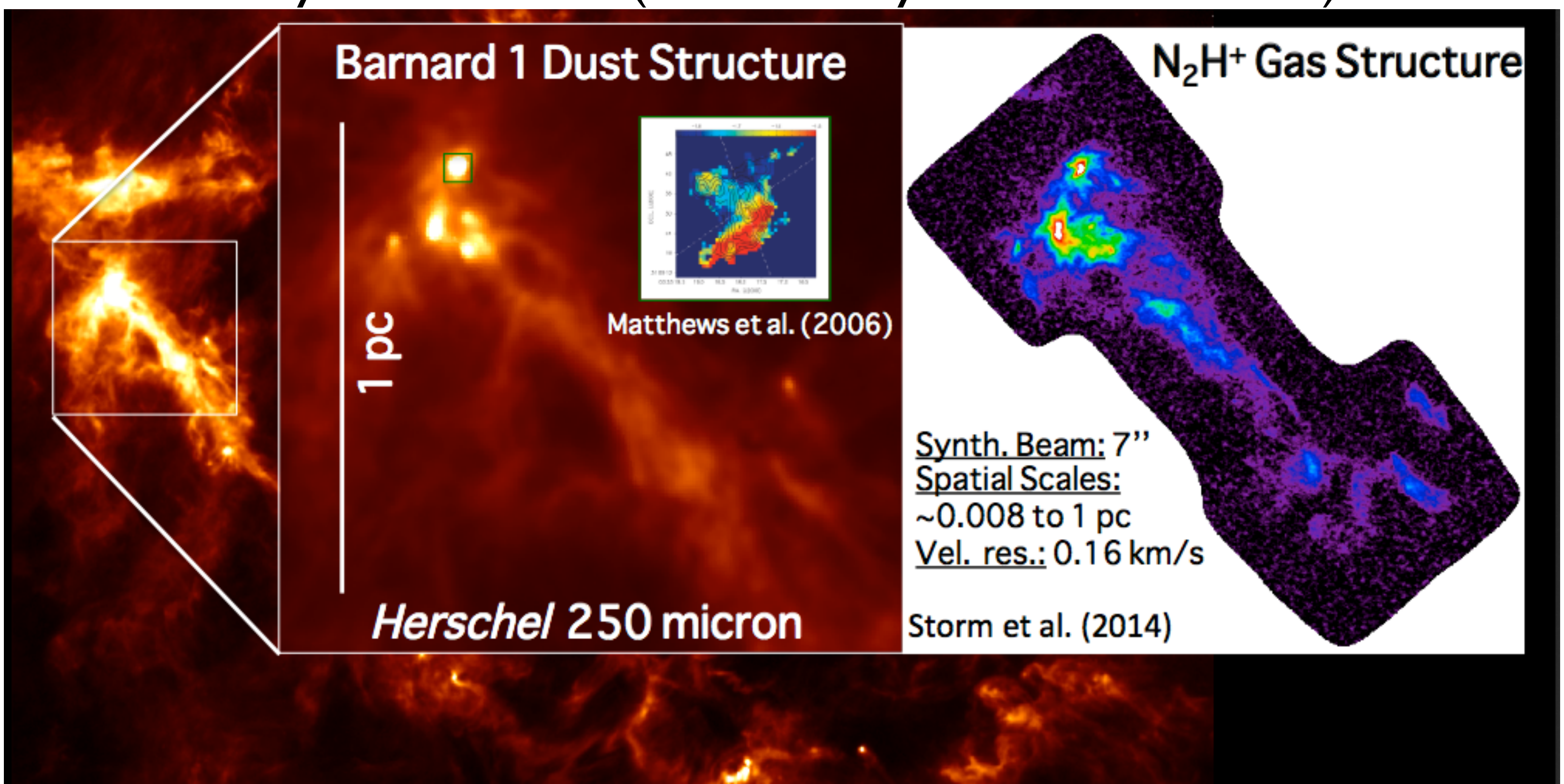
Example: large scale TP is hard…



CSO Image of M51 dust with SHARCII bolometer array, no nutator
Problem: Large scale low-level baseline
ALMA TP array has nutators, not yet commissioned

Early Stages of Star Formation

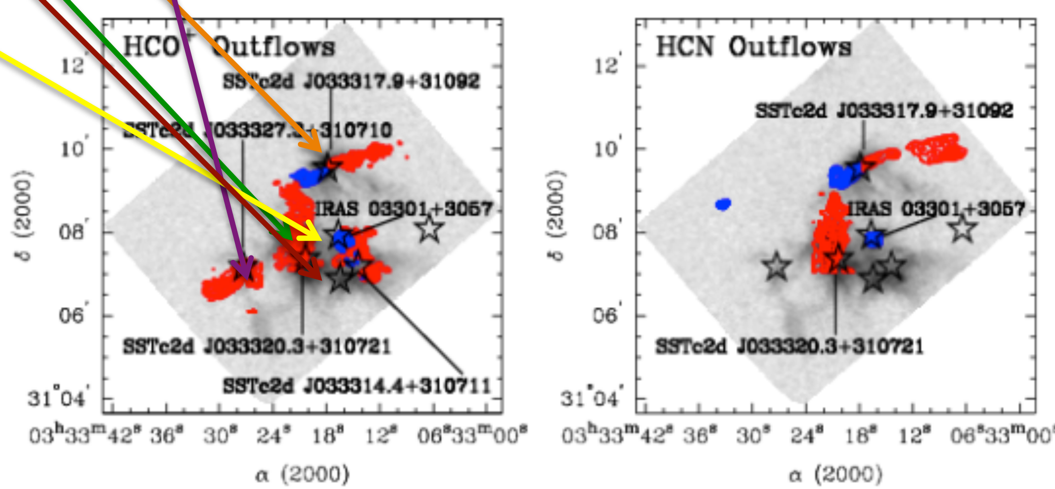
- To detail the physical parameters describing star formation we focus on star formation in the part of the Per B1 core
  - Several cores are present, perhaps nearly coeval, in the nearby core
    - Distance = 230 pc, 1”=230 AU
  - Cores lie in a roughly filamentary region, large column densities
  - Relatively well-studied (see CLASSy Storm et al 2014)



YSOs in B1

7 Spitzer Class 0/I YSOs, 4 $N_{H2}>10^{23}cm^{-2}$ dense cores

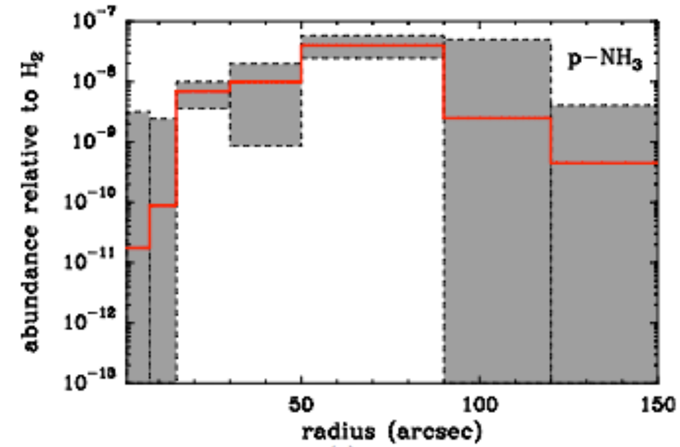
- B1c: A well developed core containing a star and outflow
- B1b:
  - Core contains at least two objects,
    - One is a star with outflow (B1bS);
    - Second also contains an object with an outflow (B1bN)
  - Third object, Per-emb 30, status has a red lobed outflow
- Also B1a and B1d



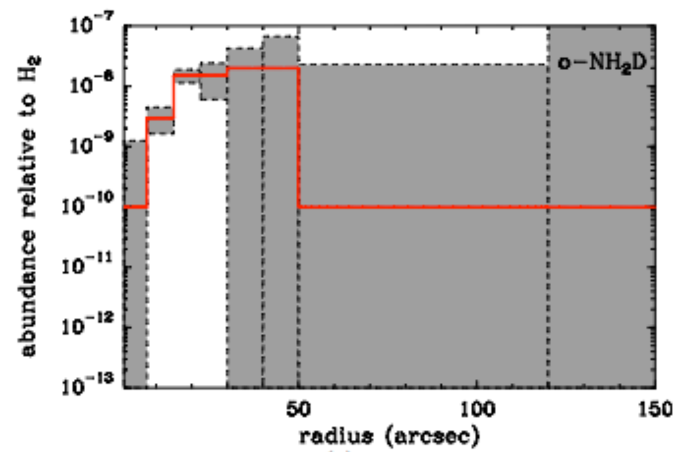
Focus: Densest, Least Evolved Cores B1b S and N

- High column density
- High space density
- Large columns of deuterated species (Roueff et al, Marcelino et al, Gerin et al)
- Densest parts show depletion (Daniel et al) in many molecules, notably NH_3 and NH_2D
  - Marked in inner ~10” (2300AU)

Daniel et al 2013



(a)

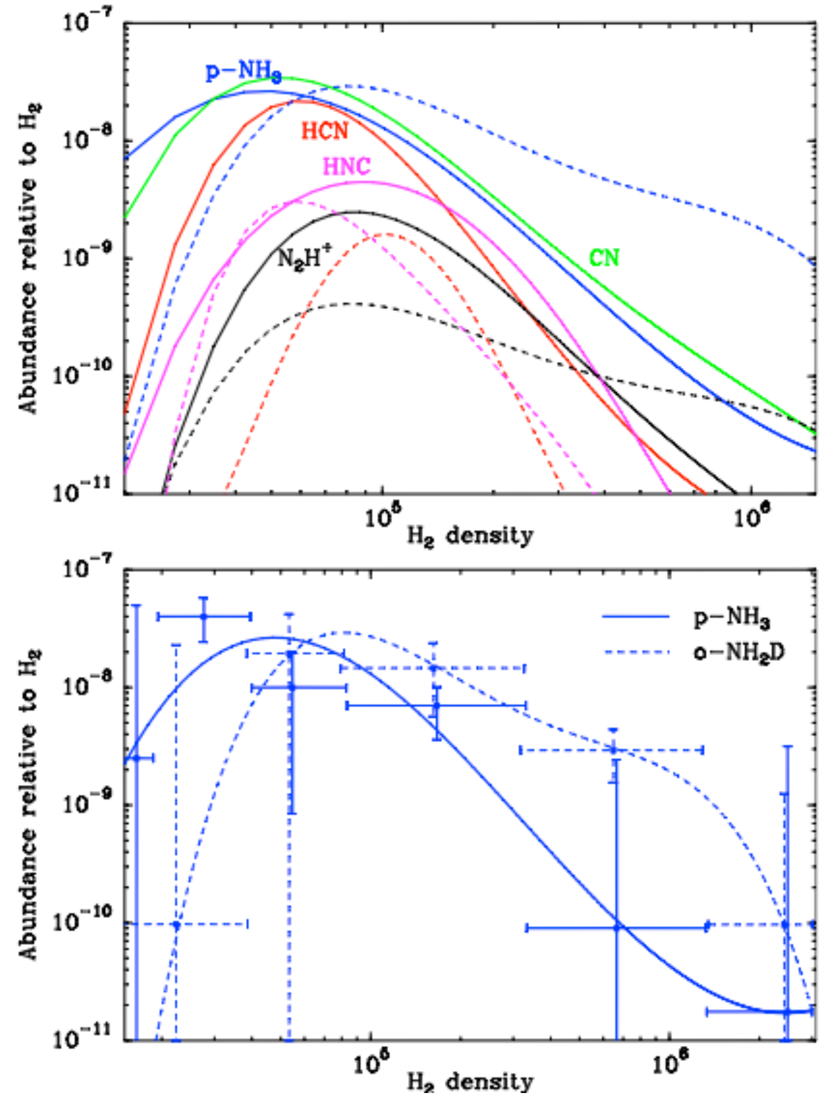


(c)

Densest Core Material Strongly Depleted

- Suggests that probing physical conditions deep within the core hard
  - Very sensitive spectroscopy needed (large A_{eff})
  - High resolution needed to ferret out signal from densest core (here ≤ 10”)
  - A problem for large telescopes (GBT, VLA, ALMA, NOEMA)
  - Even then, NH_3 is too depleted
- For now: what is the molecular content of the deep core?

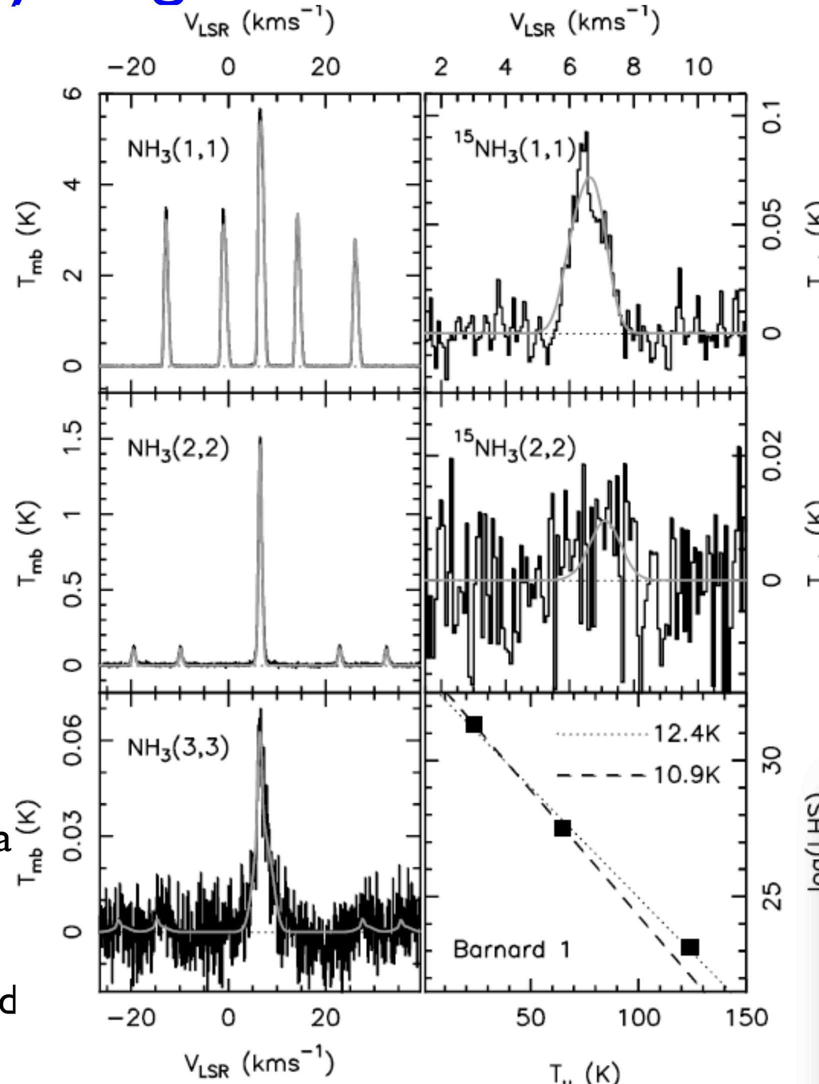
Daniel et al 2013



Previous Observations: Frequency-targeted and Wideband

Narrowband Deep Observations

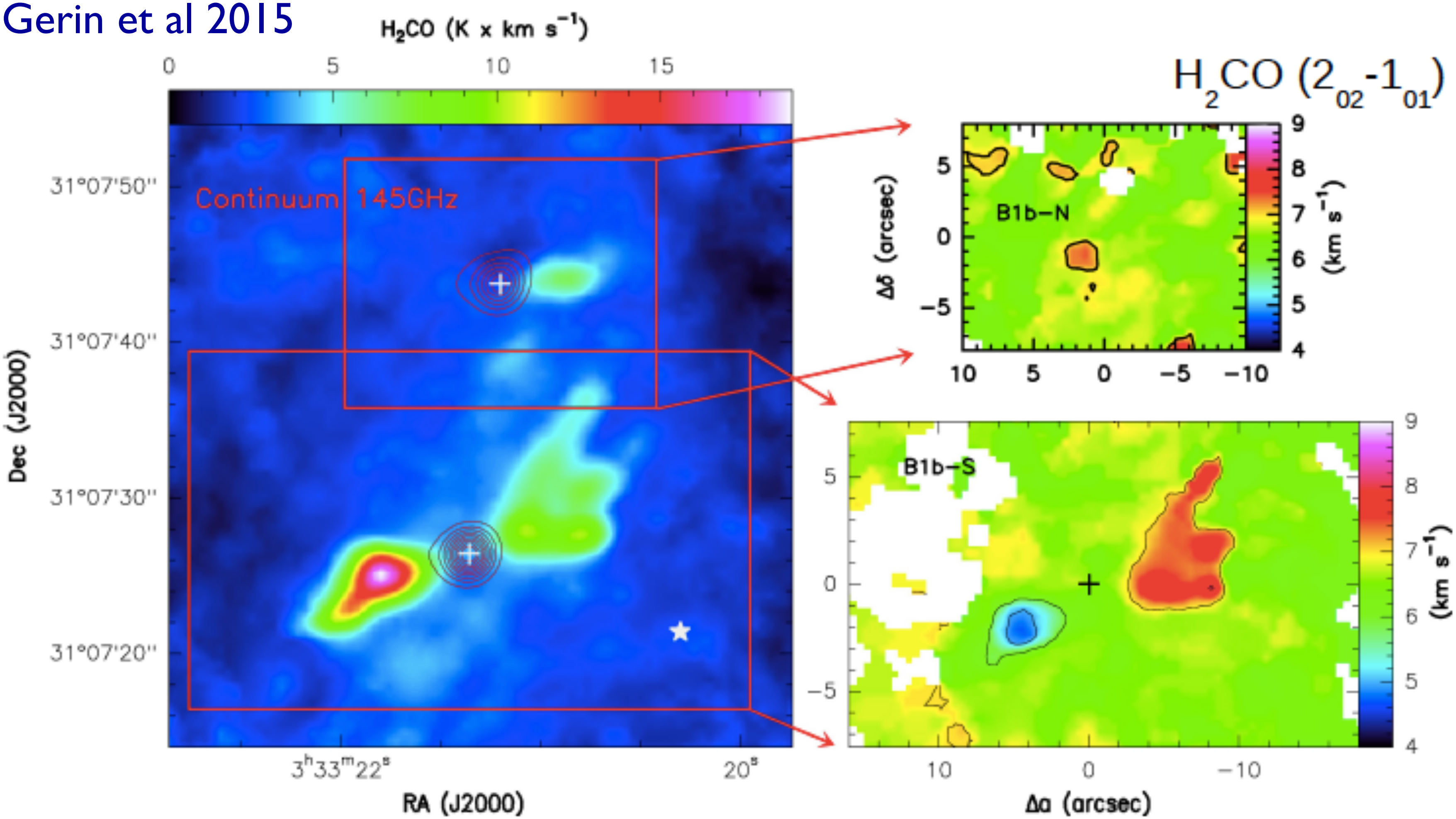
- Seeking weak lines of indicative species
  ^{15}N proposed to fractionate in very cold regions where D also becomes highly fractionated
  - Large column densities of singly and multiply deuterated species : ND3, 15NH2D, D2S, D2CS, …(Roueff et al., Marcelino et al '12., Gerin et al. '15)
- Need ~3 hr to detect $^{15}NH_3$ (1,1) lines observed w/GBT, broad backend
  - NH_3 (1,1) and (2,2) lines are narrow (~0.8 km s^{-1}), but the (3,3) line has broad (~3.5 km s^{-1}) pedestal—outflow? (e.g. $^{15}NH_3$: Lis et al. '10)
  - From the rotation diagram analysis we derive a low temperature, Trot=12.4 K, and $N(NH_3)=(2.1\pm0.3) \times 10^{15}$ cm^{-2}
  - The $^{14}NH_3/^{15}NH_3$ ratio is 304±49, as compared to 470 (+170,-100) in NH_2D
- A buried lurking higher excitation source
  - Detection of organic species CH_3O, HCOOH, CH_3SH, HCCCHO, CH3CHO, ... (Cernicharo et al. 2012)



Warm component: what and where is it and how does one characterize it?

PdBI Observations

Gerin et al 2015



7-field mosaic in C+D configurations at 145GHz + IRAM-30m short spacings

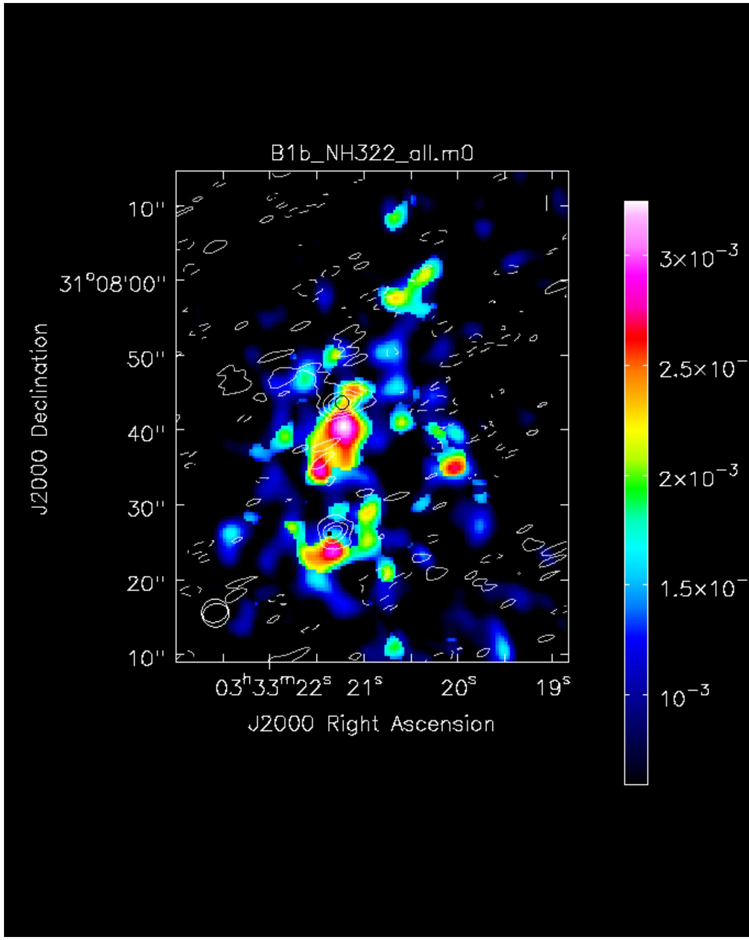
Beam : 2.2 x 2.3" (500 AU) PA = 108°

H_2CO (2_{02}-1_{01}) ; CH_3OH (3_K - 2_K) ; c-C_3H_2 (3_{12} - 2_{21}) ; DCO^+(2 - 1) ; DCN (2 - 1) ; Continuum

VLA Observations of B1b (Marcelino et al in prep)

Two protostars for the price of one!

- B1b-S: A well-developed protostar
- B1b-N: A First Hydrostatic Core??
- Observed:
  - NH_3 (1,1), (2,2), (2,1), (3,3) and (4,4),
  - $^{15}NH_3$ (1,1), (2,2) and (3,3),
  - HC_5N J=9-8
  - HCNO J=1-0
  - Continuum
- Results
  - Detected continuum
  - NH_3 (1,1) and (2,2): does not define core
  - Consistent with depletion at high n
  - Need zero-spacing data from GBT (available in archive)

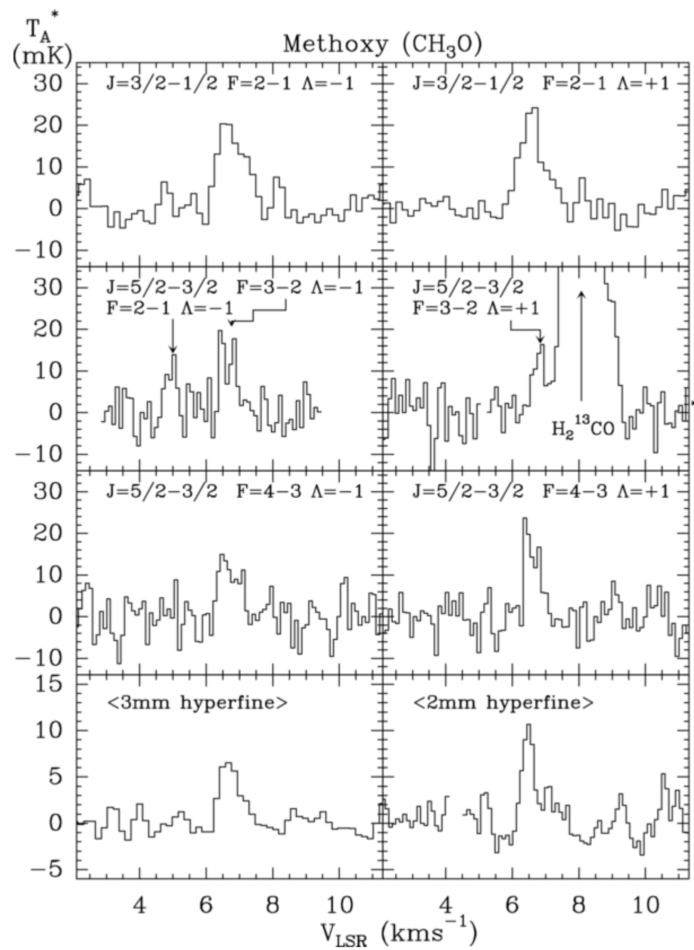


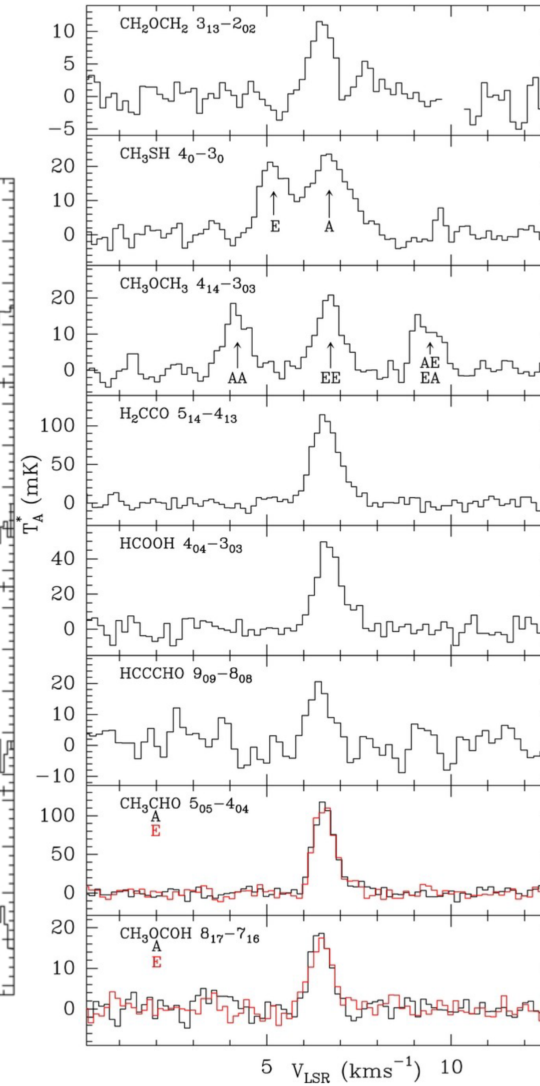
Wideband spectral surveys of B1b

Starting with Cernicharo et al (2012) using venerable IRAM 30m

- EMIR receivers (83-.-117GHz, 2x4 GHzBW, DSB)
- 24 FFT spectrometers provide 50kHz resolution over 7.2 GHz
- Rms~4-6mK in 2 hrs per setting, or 15 hrs per source
- Beam 21-30” does not resolve sources

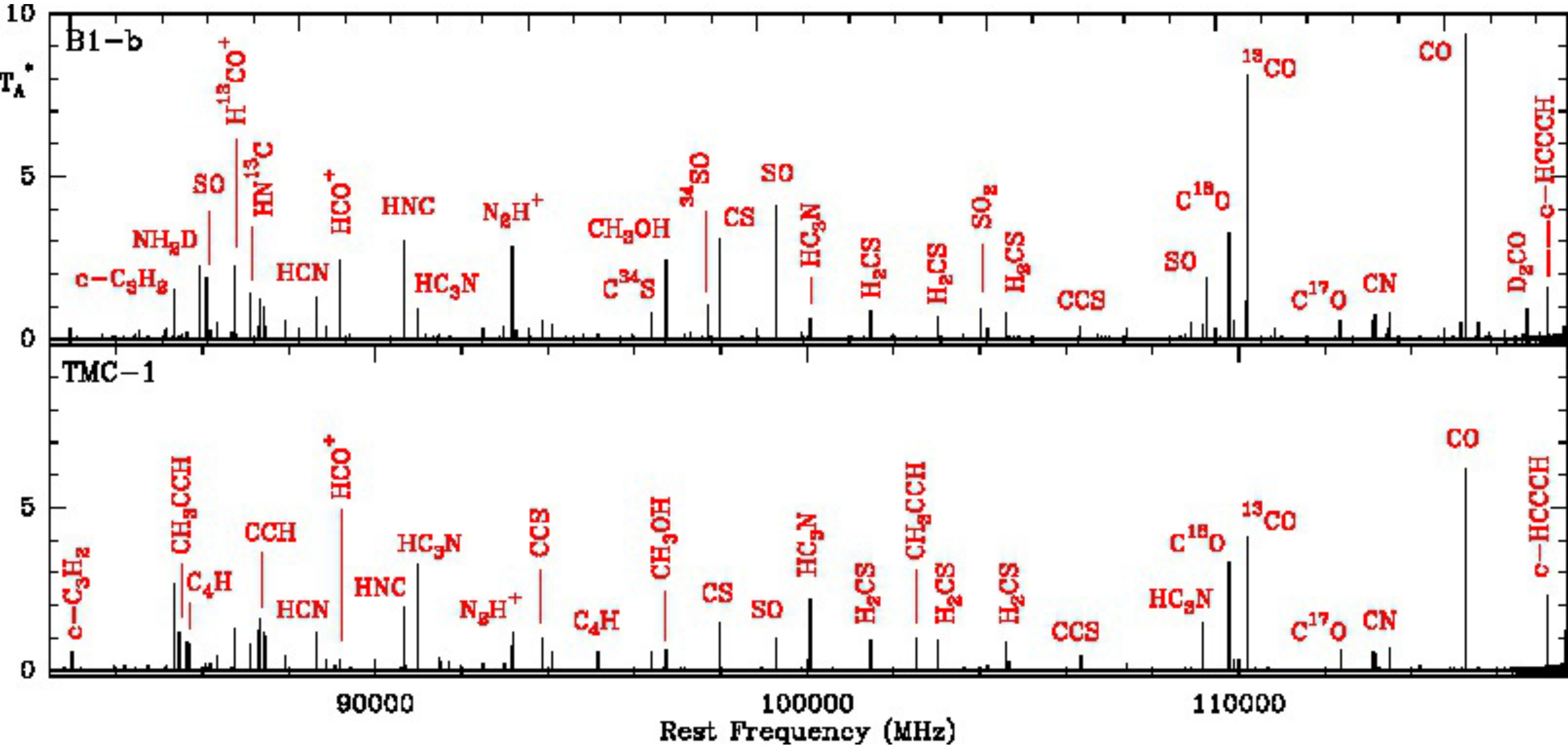
Discovery of Methoxy, rich spectrum





IRAM scan

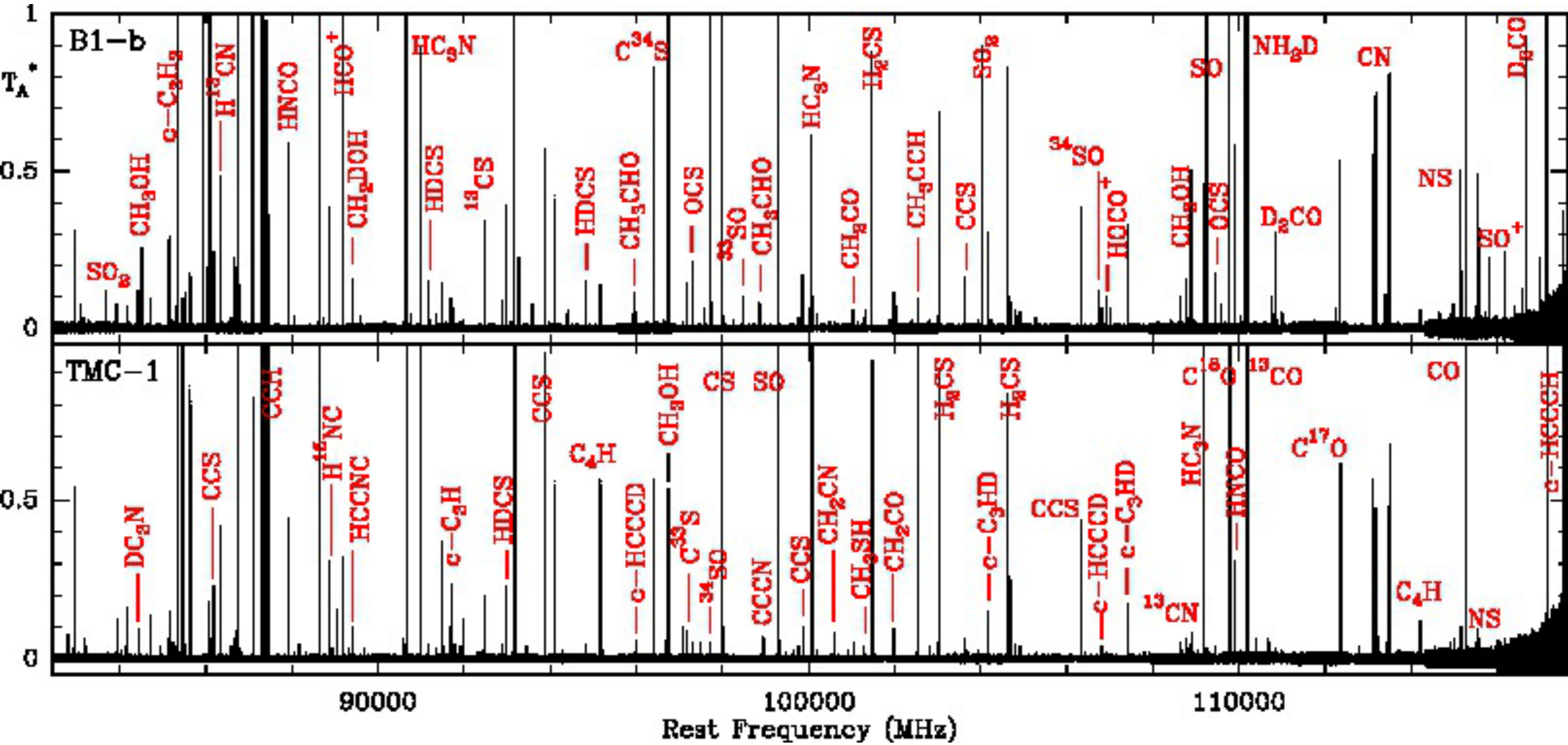
Marcelino et al (in preparation)



- Note the striking differences—owing to the protostar?
- 325 lines 110 species.

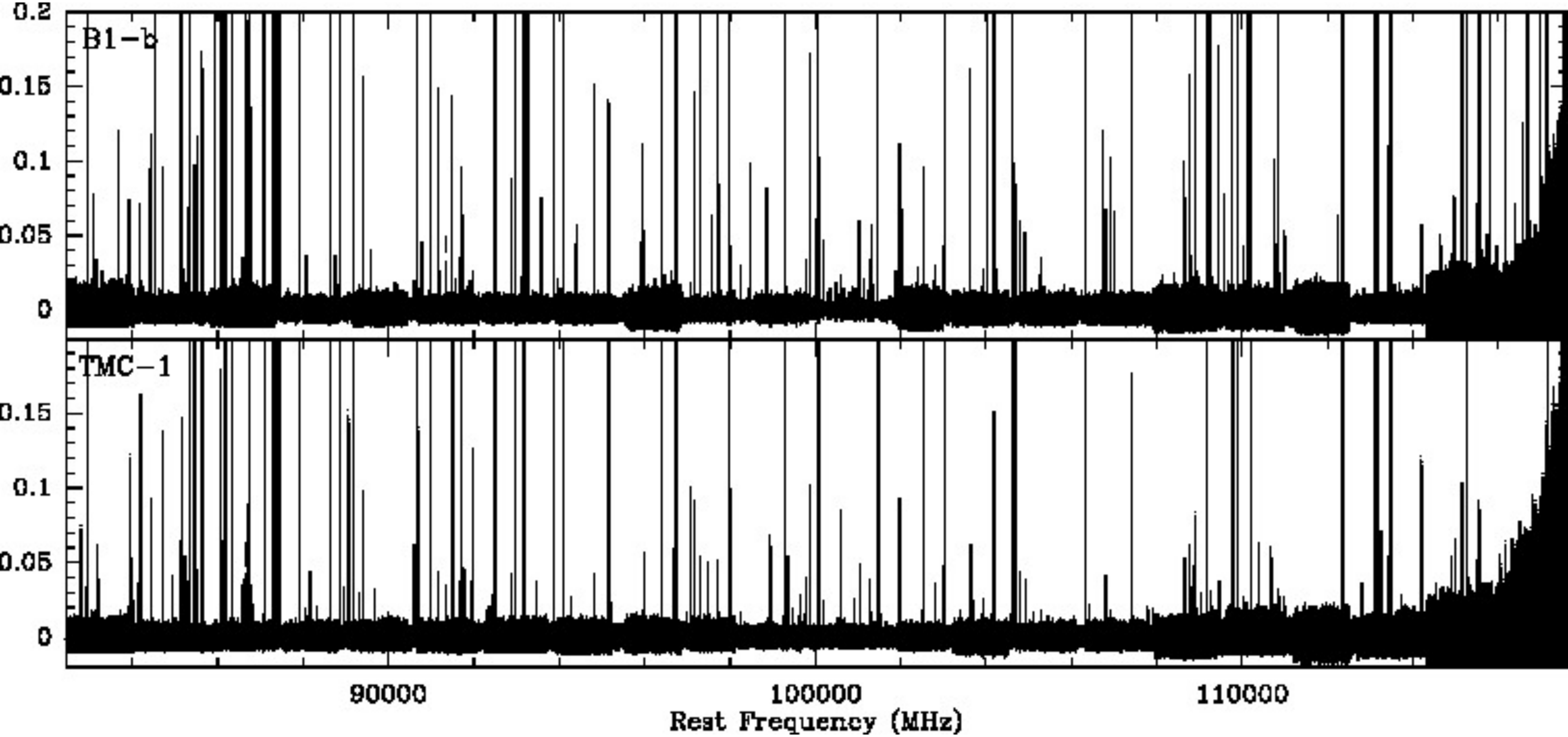
Same scan higher sensitivity

Marcelino et al (in preparation)



Even higher sensitivity

Marcelino et al (in prep)



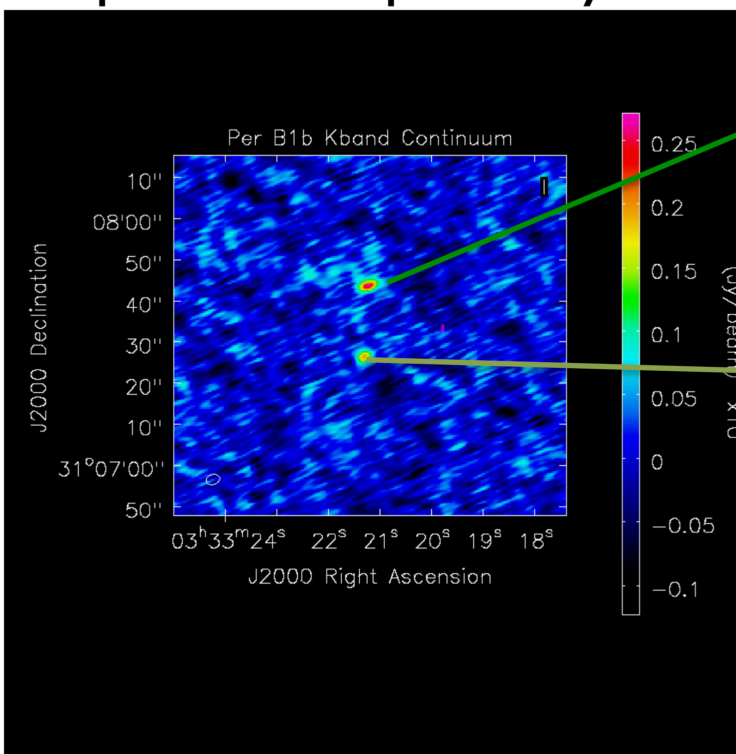
- Note atmospheric noise rise on right.

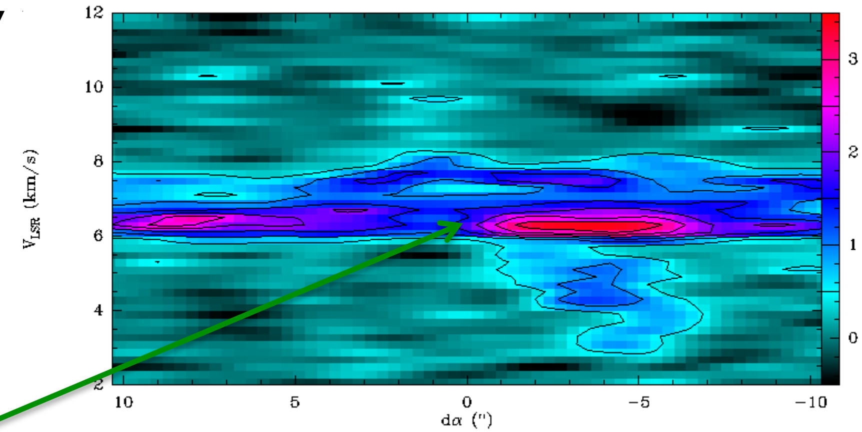
Complex Organic Molecules (COMs)

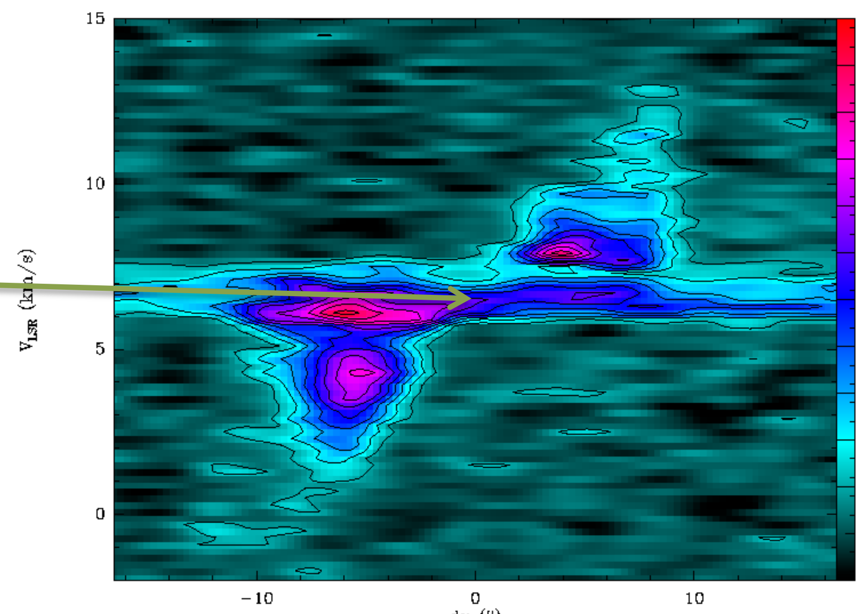
- Note that the complex organics were only detected in B1b
- CH_3O, discovered here, is a precursor to COMs
- Clearly gas-phase chemistry is active in both sources
  - Strong fractionation of D-containing molecules
  - Possibly indicated by abundance of $^{15}NH_3$
    - Value is solar, ~446, in TMC1C.
- Gas-grain chemistry: COMs form on grain mantles during warmup phase (>30K) followed by evaporation
  - But diffusion of radicals ineffective for T<25K.
  - Subsequent gas phase chemistry may occur

High Angular Resolution Constrains Emitting Region

- B1-b, as noted, harbors two very protostellar objects with wimpy outflows (Gerin et al 2015)
- VLA Kband image locates the protostars precisely



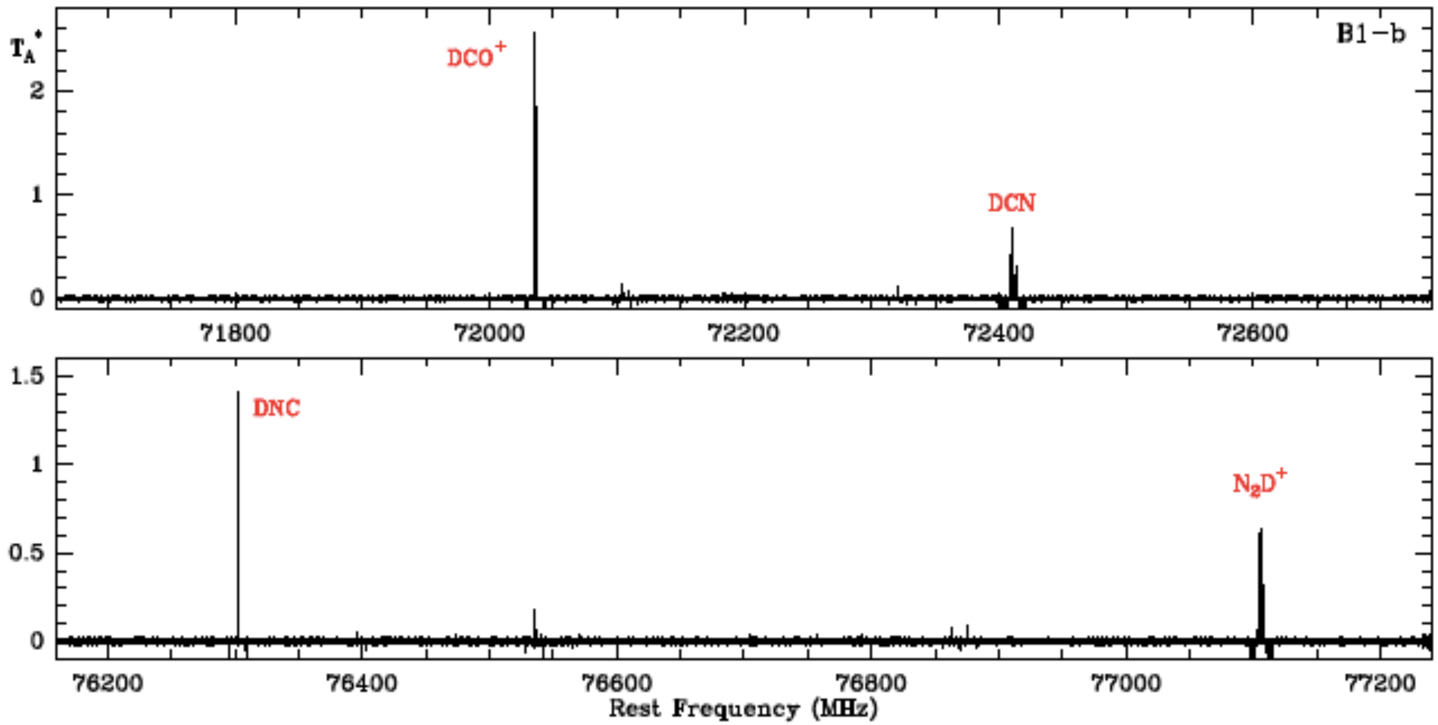




GBT Survey of B1b 67-80 GHz

Marcelino et al: follow up of IRAM survey

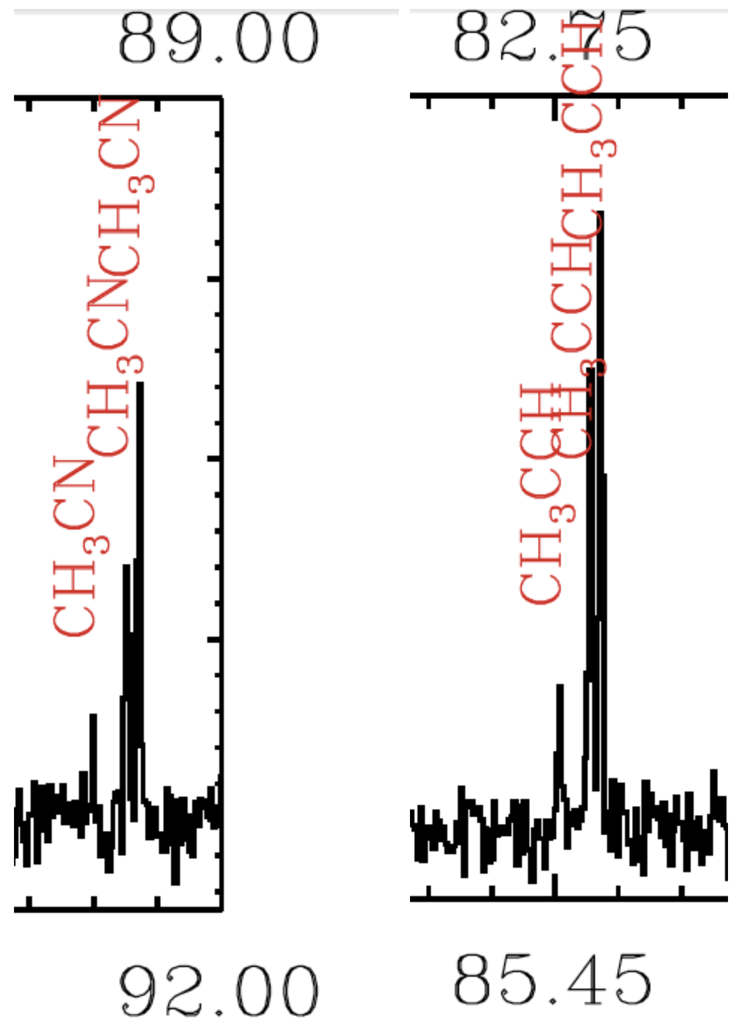
- N.B. IRAM beam ~30" encompasses whole core; GBT beam ~9" pointed between B1b-S and B1b-N samples envelope of both.



- Sensitive spectral surveys with large telescopes reveal astounding chemical complexity, can elucidate evolutionary status of protostars

The lines are seen in cold cores

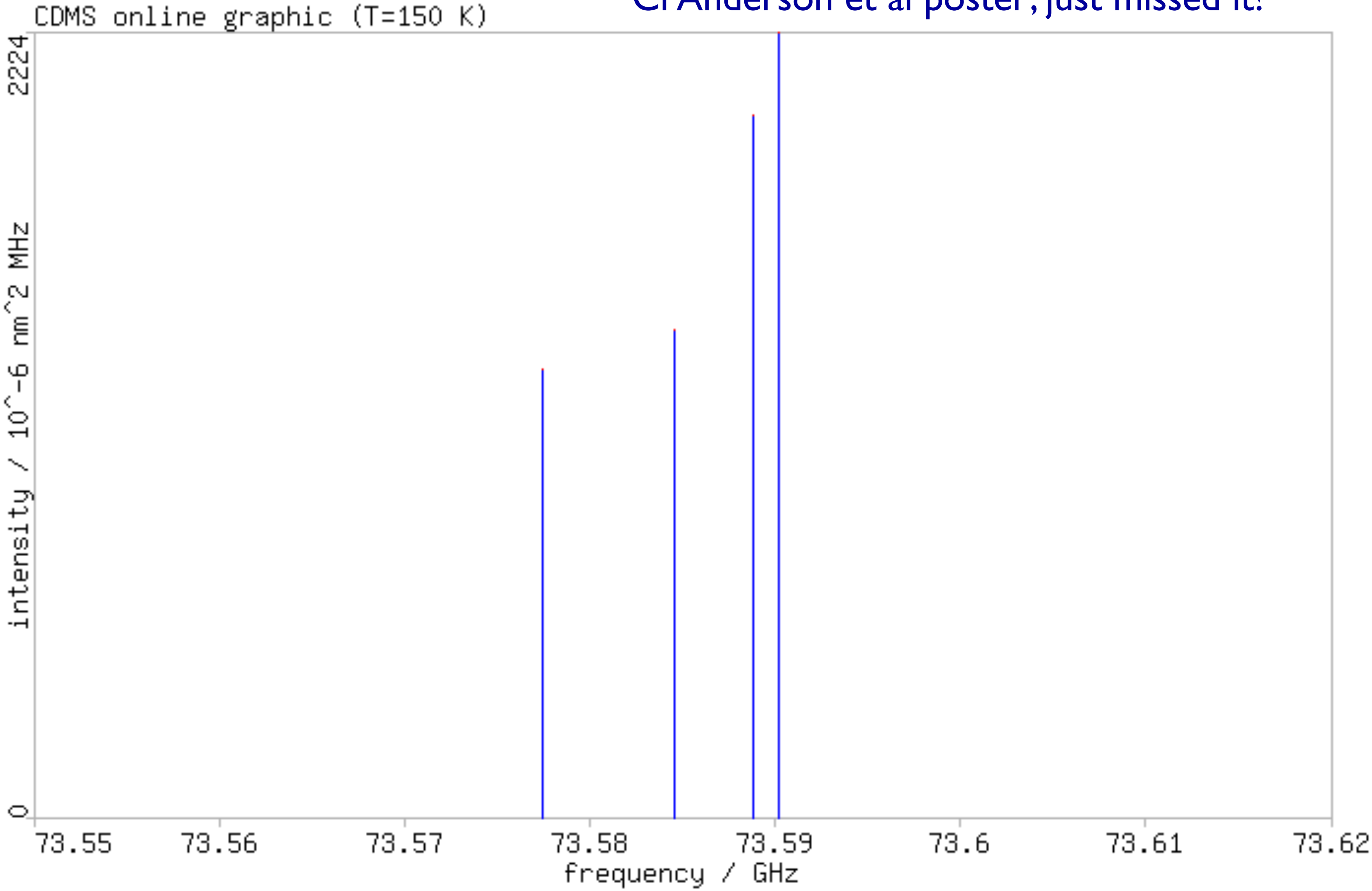
- Marcelino et al Survey of the B1b core shows emission from both 80 GHz lines at tenth K level. Temperature fit suggests ~15K, agrees with NH_3
- J=5-4 and J=4-3 can be observed simultaneously with other lines with broadband receivers (e.g. GBT, ALMA Band2).
- Relative intensities of different J lines provide a measure of density over a range 10^4 to 10^6 cm^{-3}; they lie near excitation peak



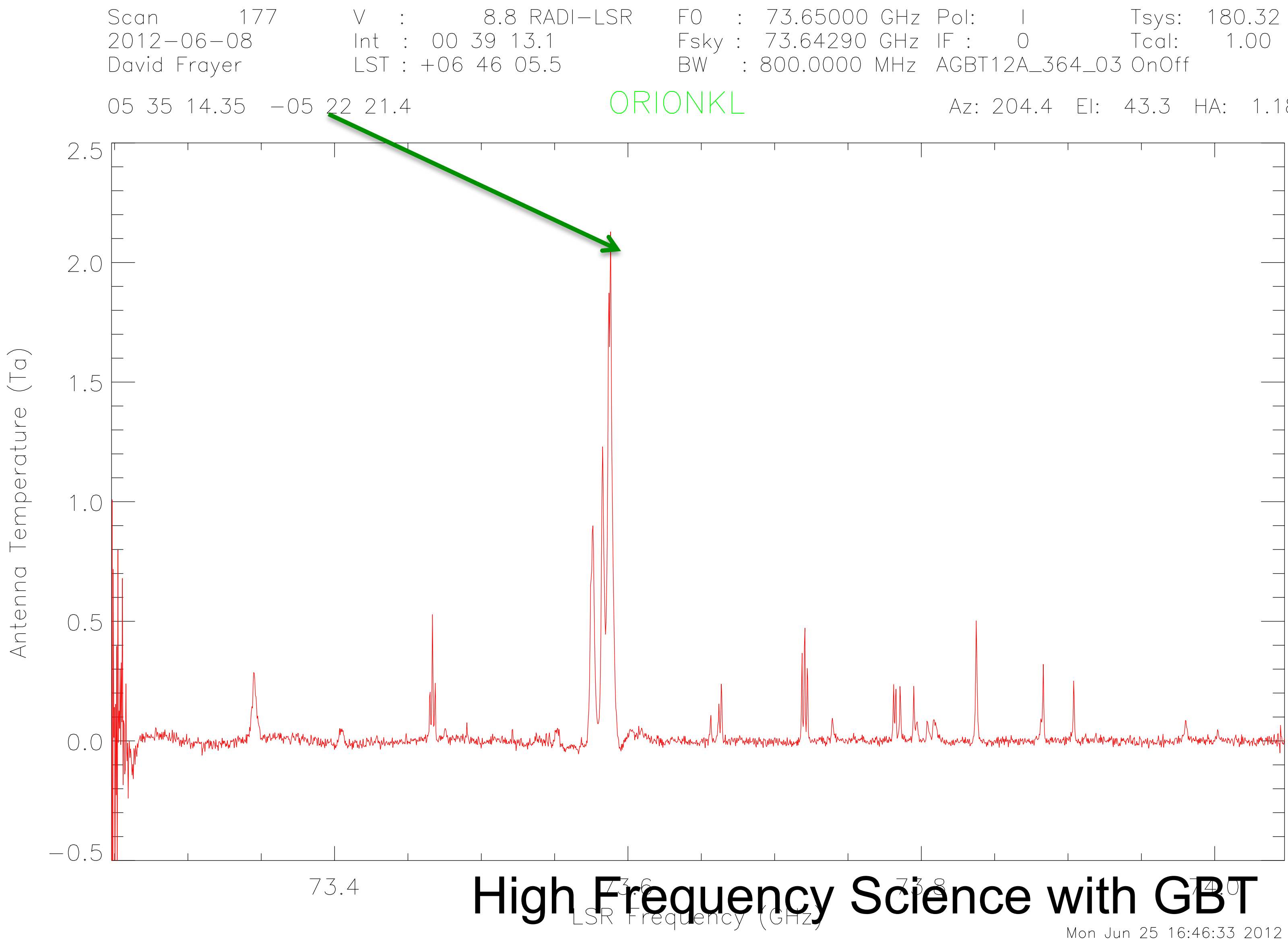
High Frequency Science with GBT

CH3CN J=4-3

Cf Anderson et al poster; just missed it!

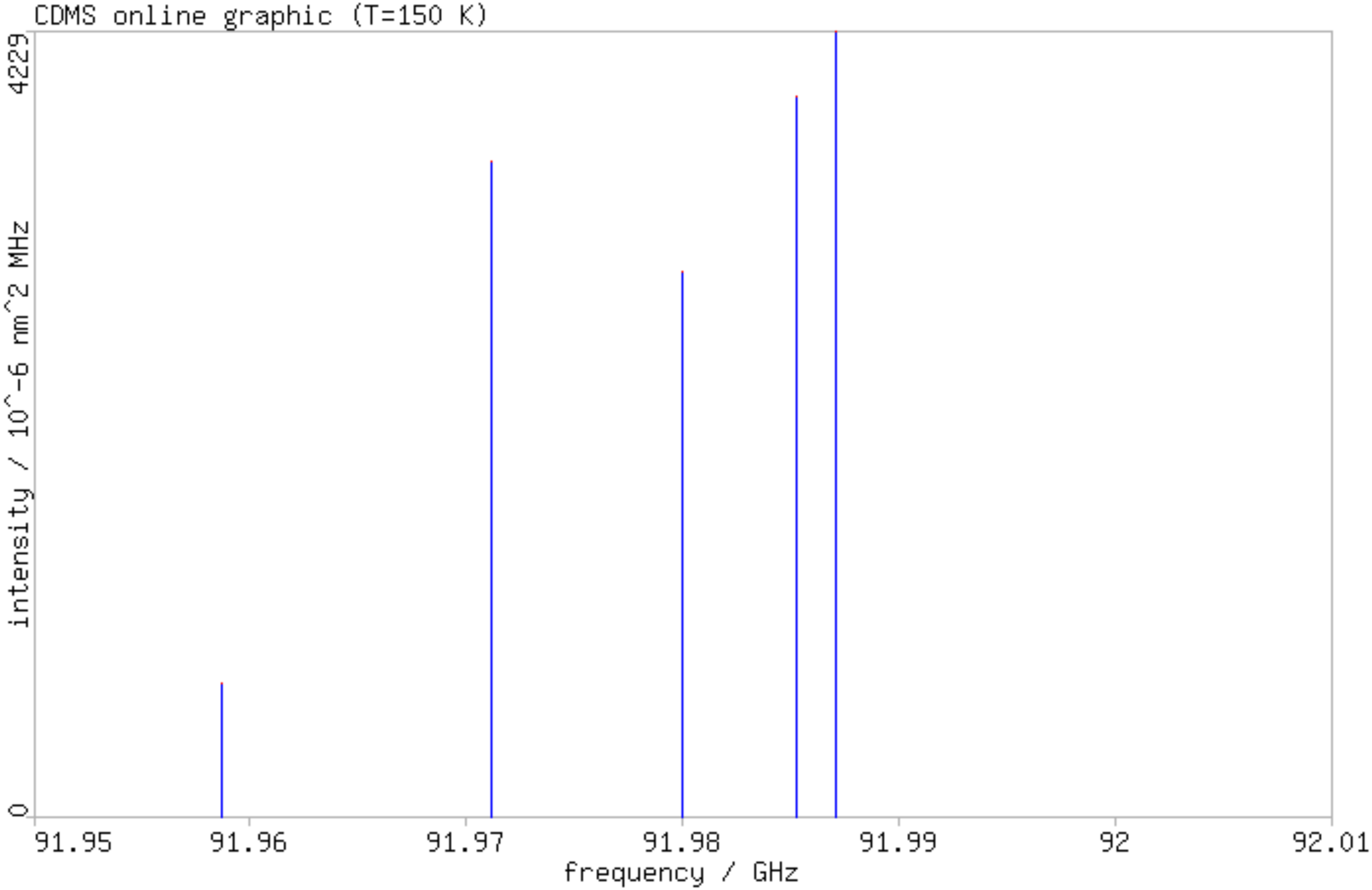


Orion Spectrum

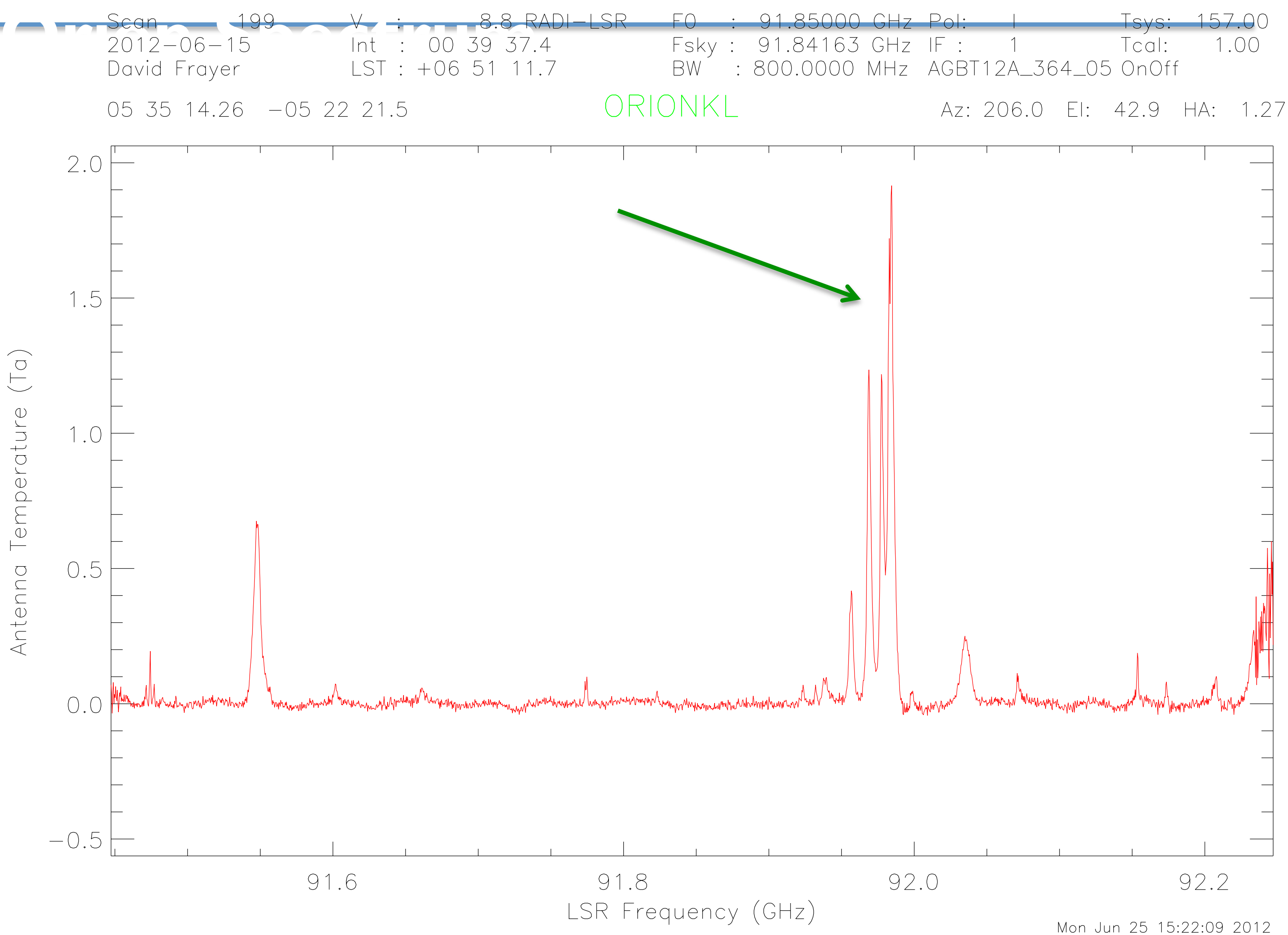


High Frequency Science with GBT

CH3CN J=5-4

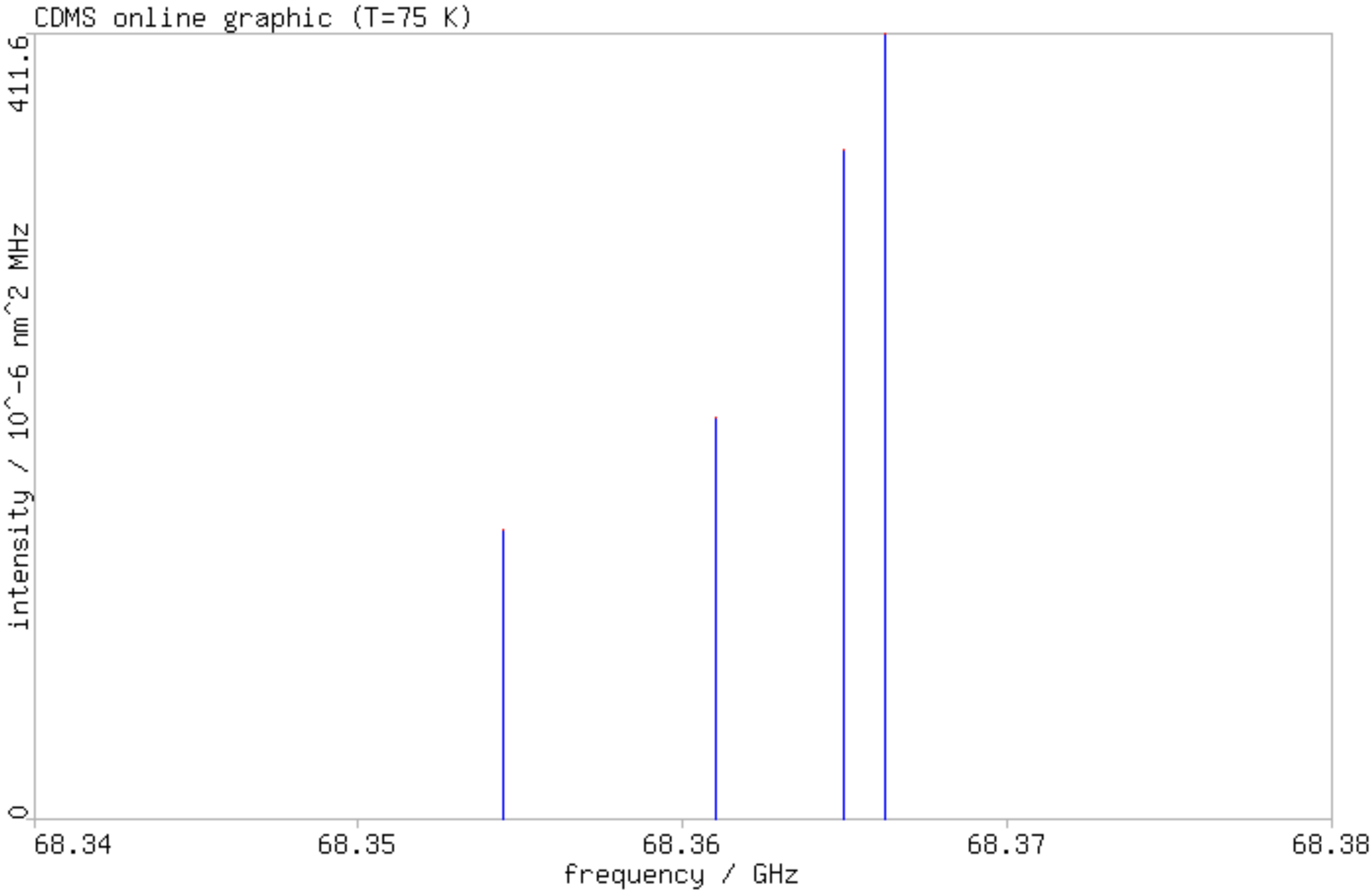


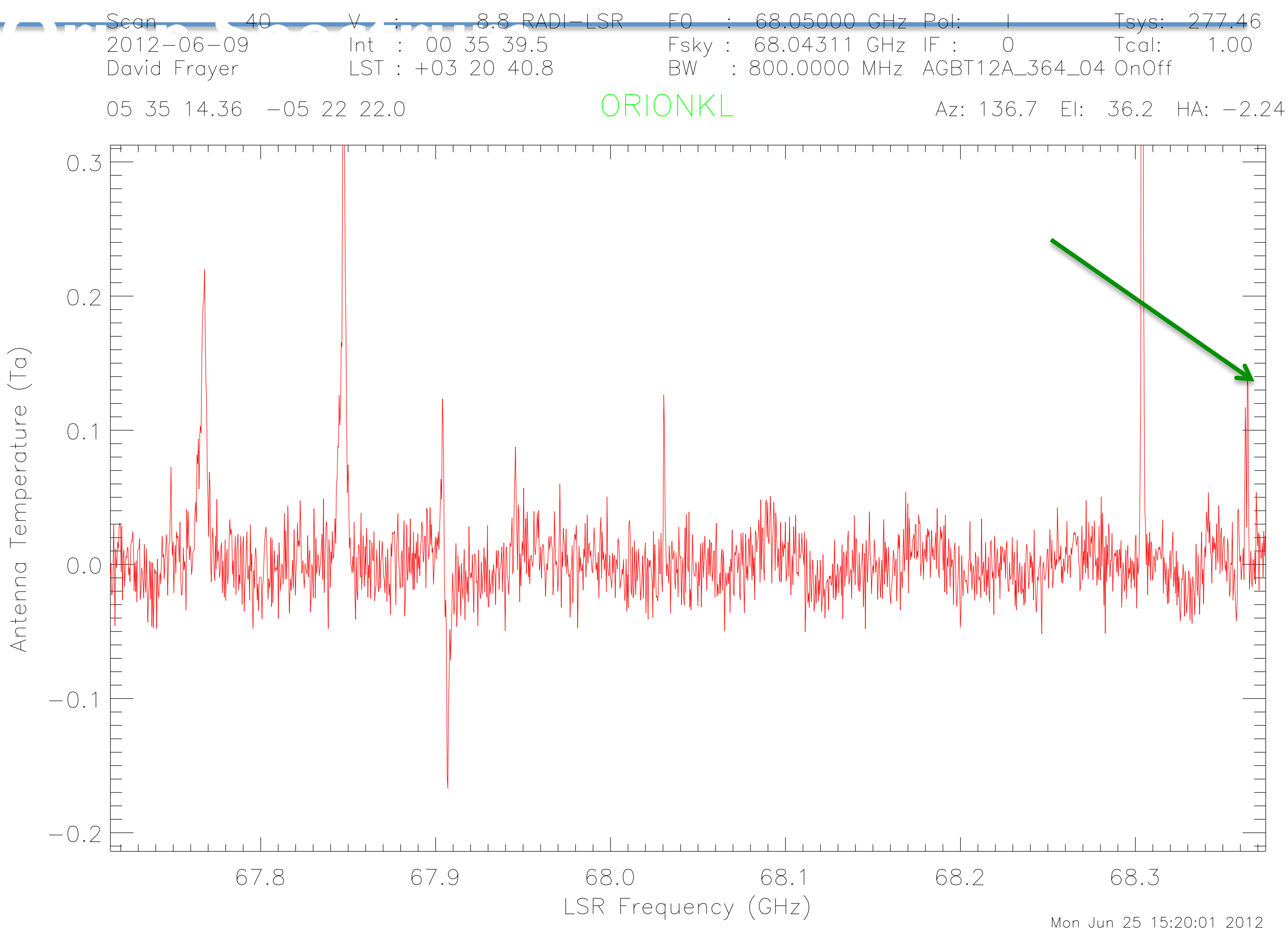
CDMS online graphic (T=150 K)
4229
0
intensity / 10^-6 nm^2 MHz
91.95
91.96
91.97
91.98
91.99
92
92.01
frequency / GHz



High Frequency Science with GBT

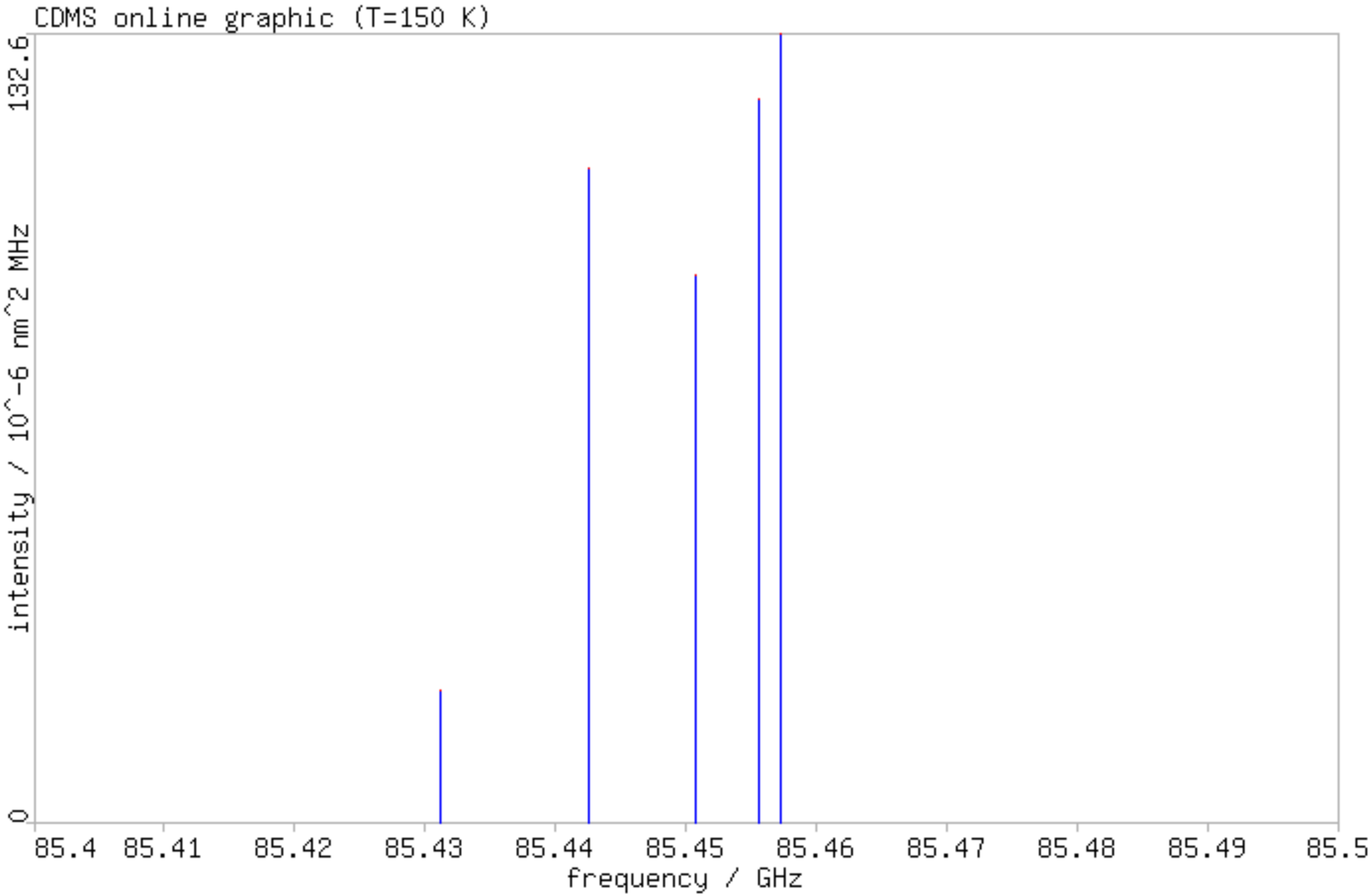
CH3CCH J=4-3


CDMS online graphic (T=75 K)
411.6
0
intensity / 10^-6 nm^2 MHz
68.34
68.35
68.36
68.37
68.38
frequency / GHz

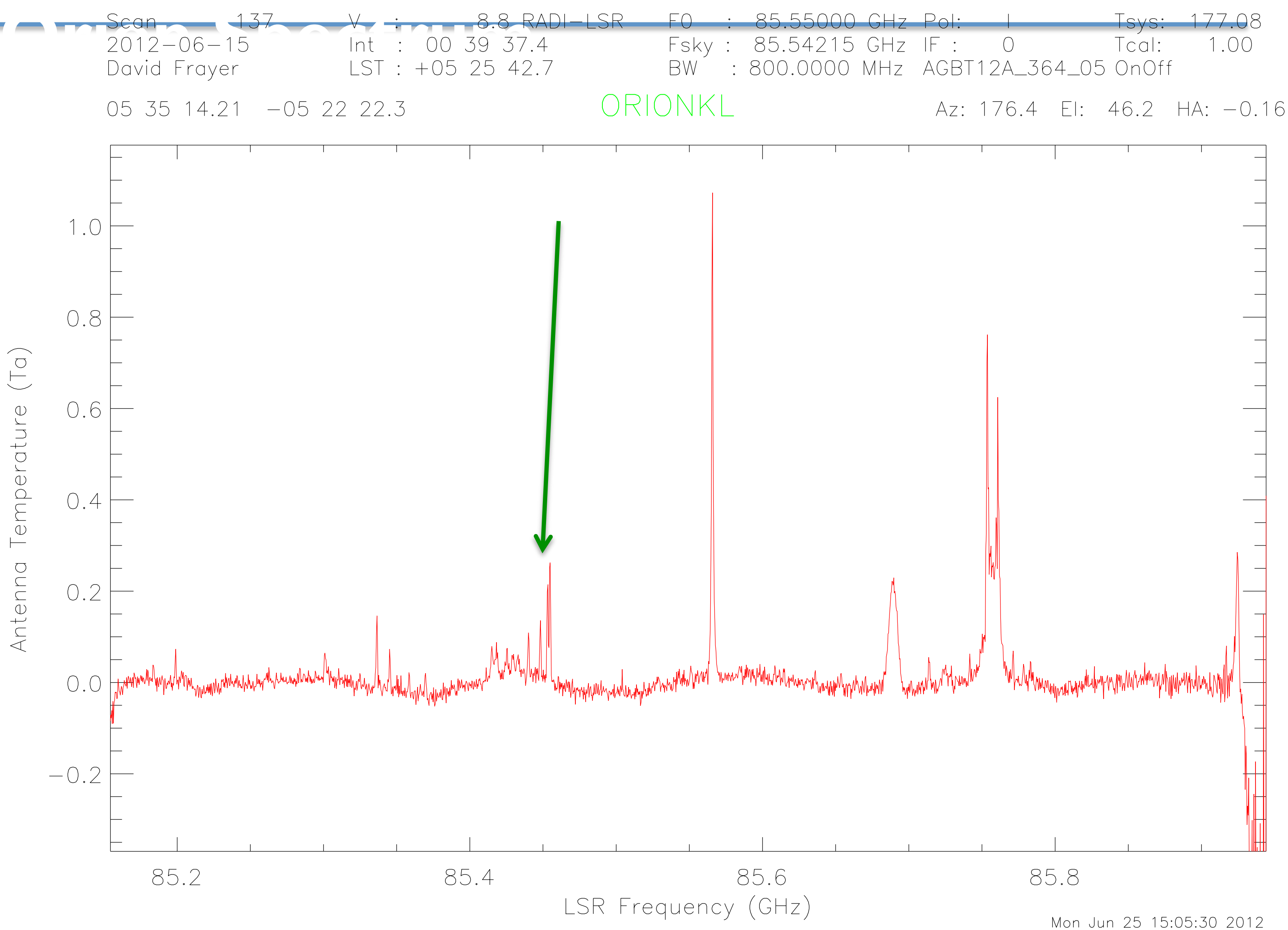


High Frequency Science with GBT

CH3CCH J=5-4



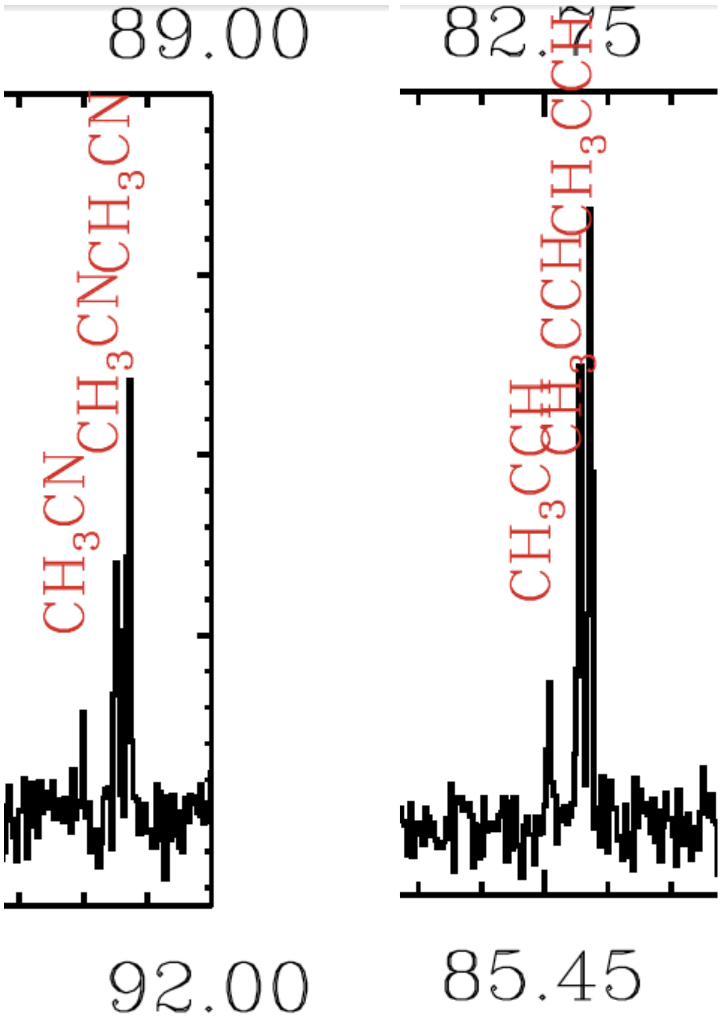
High Frequency Science with GBT



High Frequency Science with GBT

The lines are seen in cold cores

- Marcelino et al Survey of the B1b core shows emission from both 80 GHz lines at tenth K level. Temperature fit suggests ~15K, agrees with NH_3
- J=5-4 and J=4-3 can be observed simultaneously with other lines with broadband receivers (e.g. ALMA Band2).
- Relative intensities of different J lines provide a measure of density over a range 10^4 to 10^6 cm^{-3}
- GBT data being processed…



Summary

- Studies of B1 clouds approaching star formation
  - Starless cores are most effectively studied with large telescopes, not interferometers
  - Onset of star formation occurs in a dense chemically depleted environment, poorly probed by some molecules (NH_3)
  - GBT beam well suited to explore depletion regions at 3mm nearby
- Rich molecular structure in the B1 cores probes the evolution of the cores
  - One core has only weak outflow, may locate a FHSC
  - Second core shows stronger outflow, early star formation
  - Rich spectrum of complex organics compared to cold core TMC1
  - The COM signature may signify the onset of star formation
  - Where present, COMs may be used to probe deep core physics, to which GBT beam is well-suited