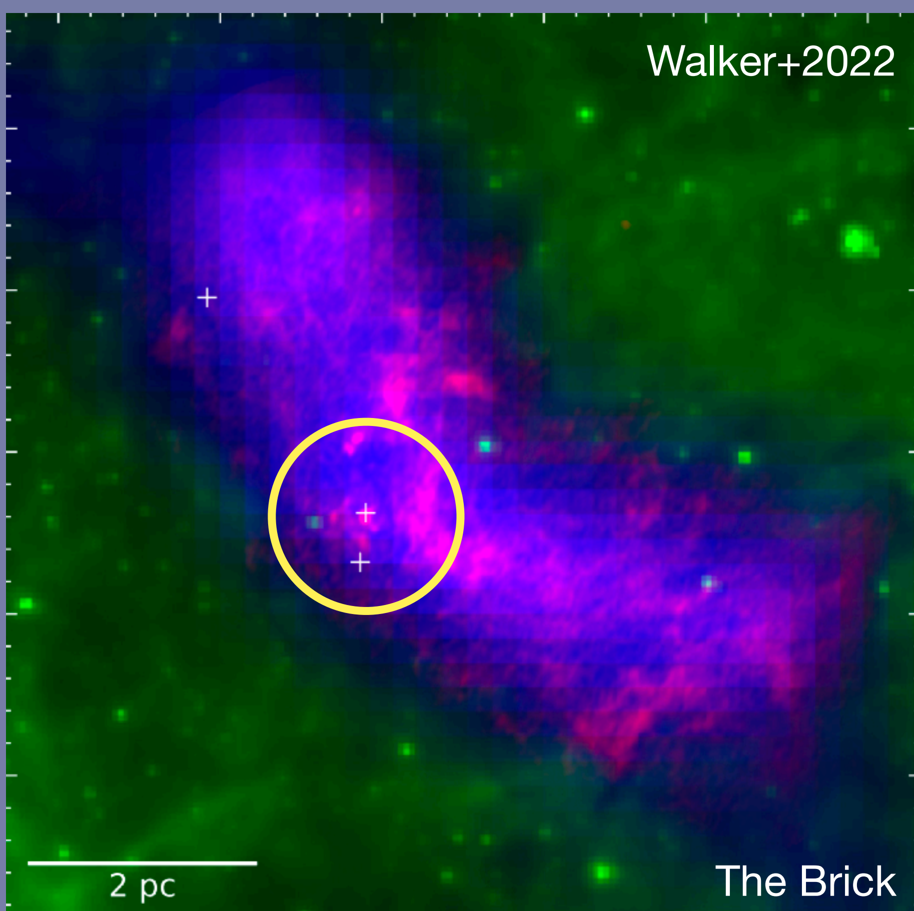
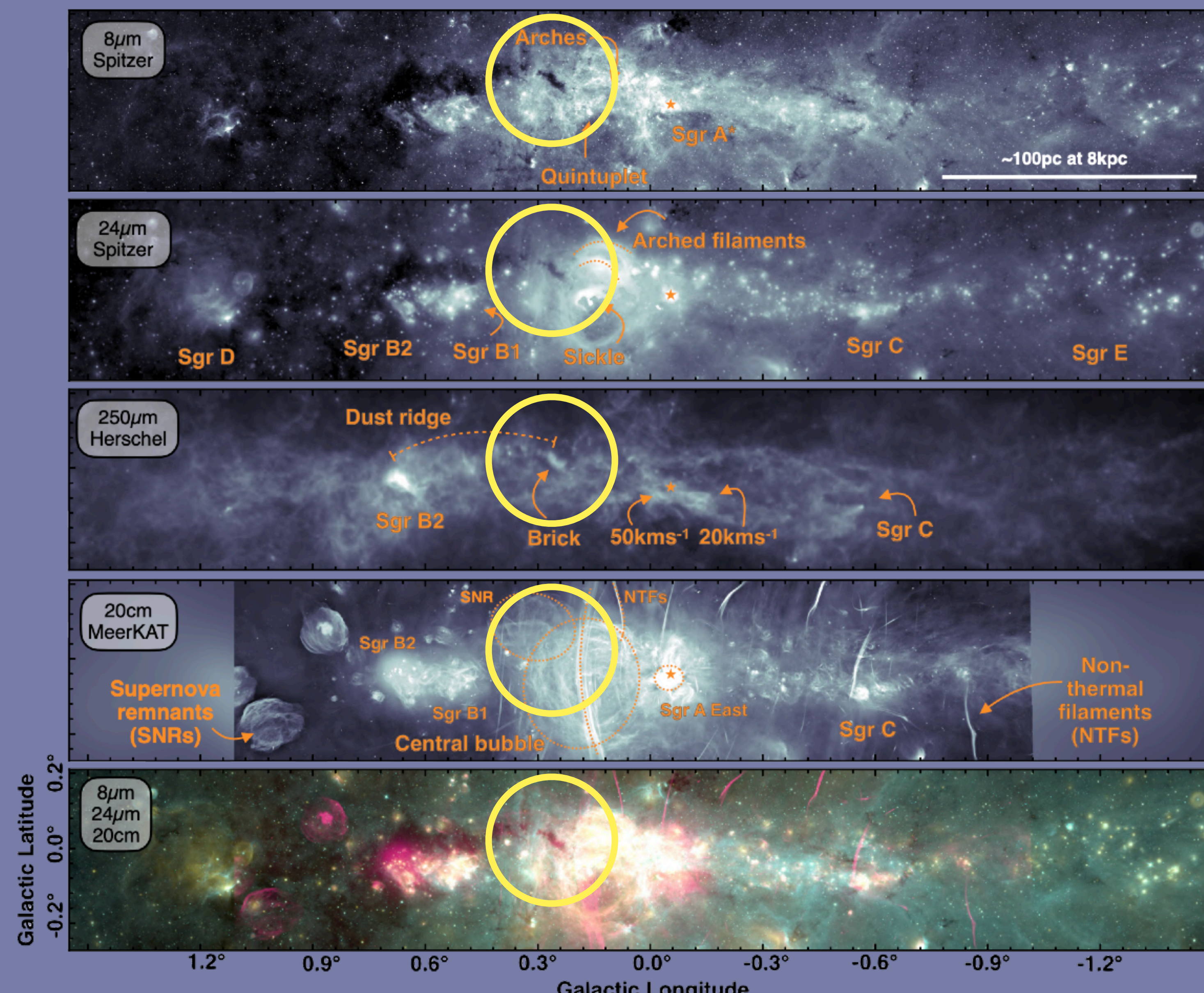
Which spectral lines trace what physical processes in the Galactic Center?

First results: temperature structure and line list

Henshaw+2022





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Masters Presentation

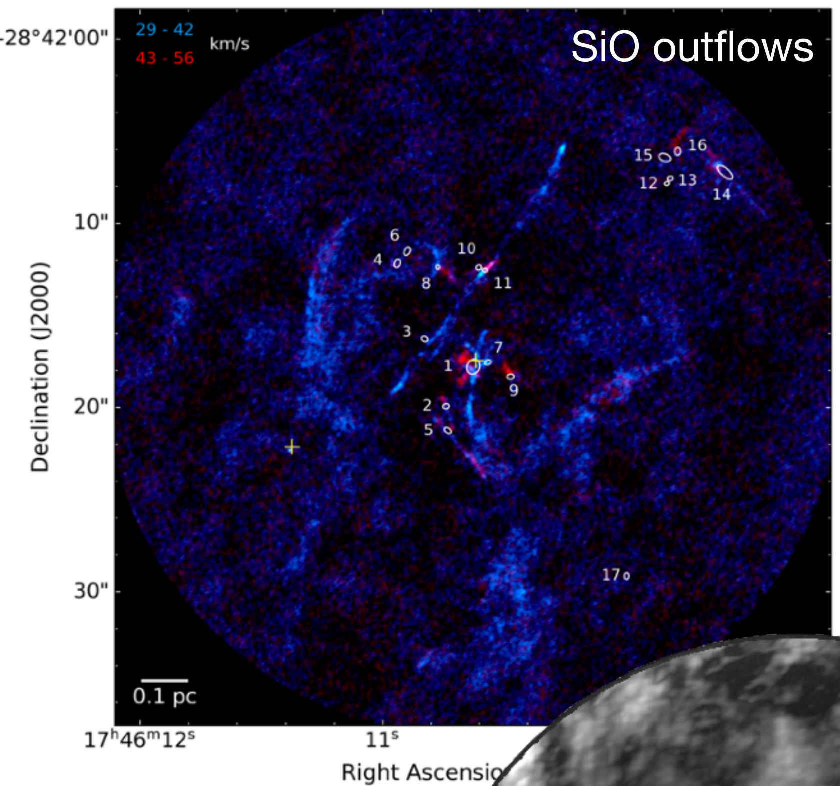
Molecular Fingerprints

Where do our "rules of thumb" fail?

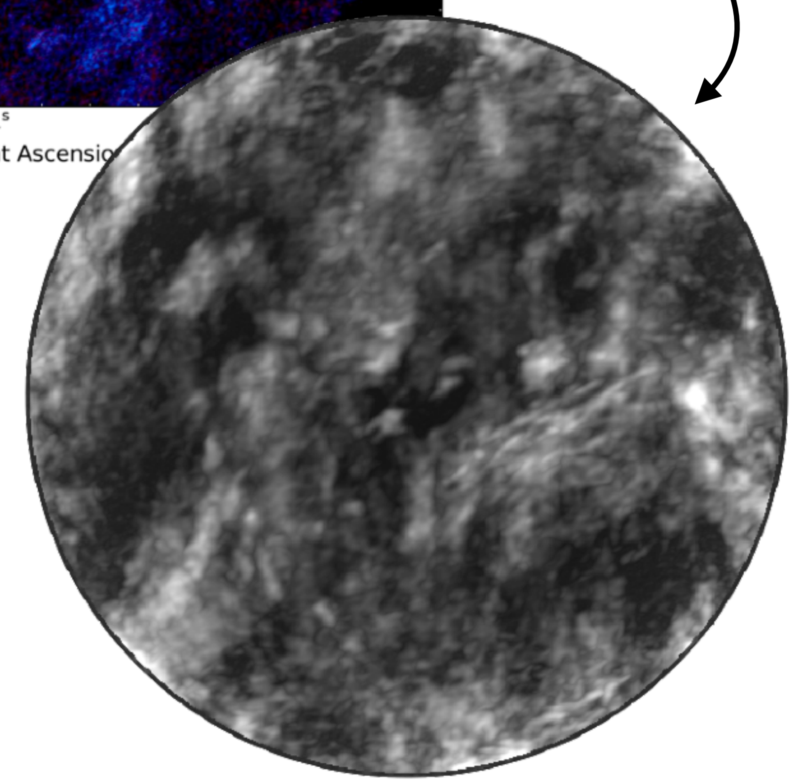
- Several molecules are widely used as heuristic tracers for different processes in the interstellar medium (ISM)
    - Outflows: CO, SiO
    - Hot cores: CH_3OH, CH_3CN
    - Shocks: SiO, HNCO
    - Dense gas: HCN, HCO+

- **Problem: all of these tracers are *widespread* in the Central Molecular Zone (CMZ)**
    - These molecules don't uniquely trace processes... they trace everything!

Walker+2022



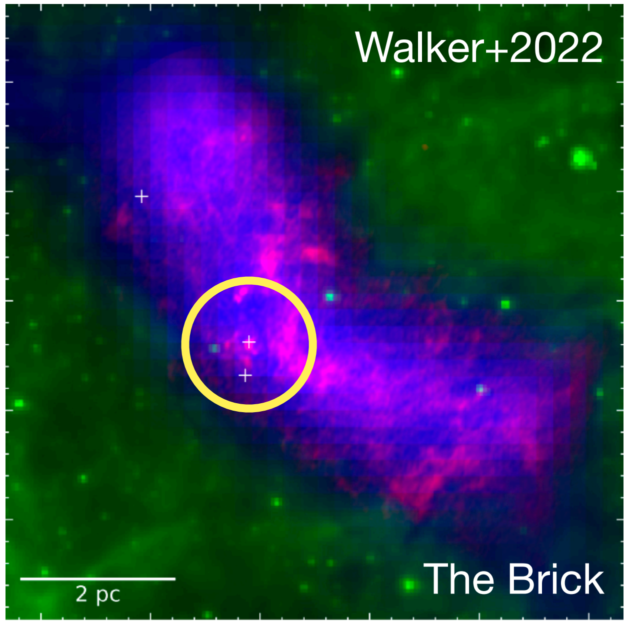
multiple turbulent layers of material

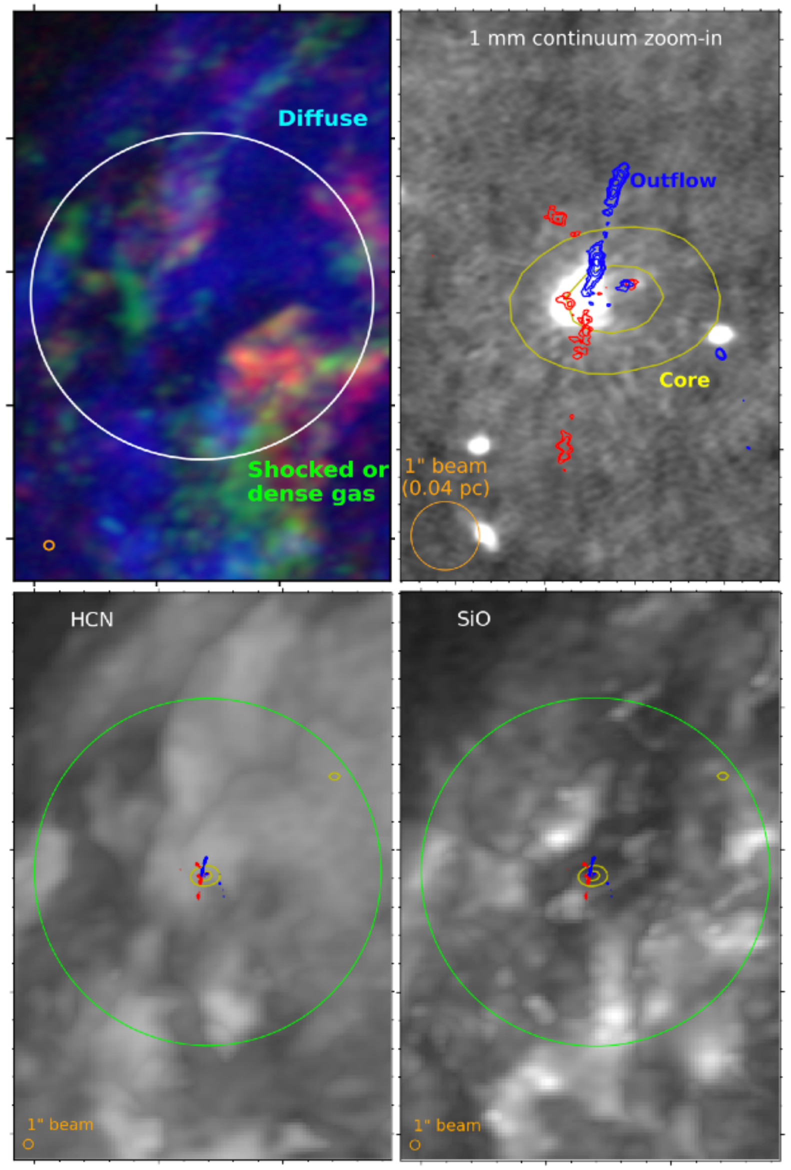


The CMZ and The Brick

The Brick is the prototypical dense but low-SF cloud

- Need unique tracers
- **G0.253+0.015** ("The Brick") contains examples of four ISM processes:
  - Protostellar outflows
  - Pre- and protostellar cores
  - Turbulent shocks
  - Diffuse, quiescent molecular gas
- ALMA proposal: wideband (4:1) spectral line survey
  - **Goal:** build a toolkit of tracers that uniquely identify these processes, for use in the CMZ and intensely star-forming galaxies





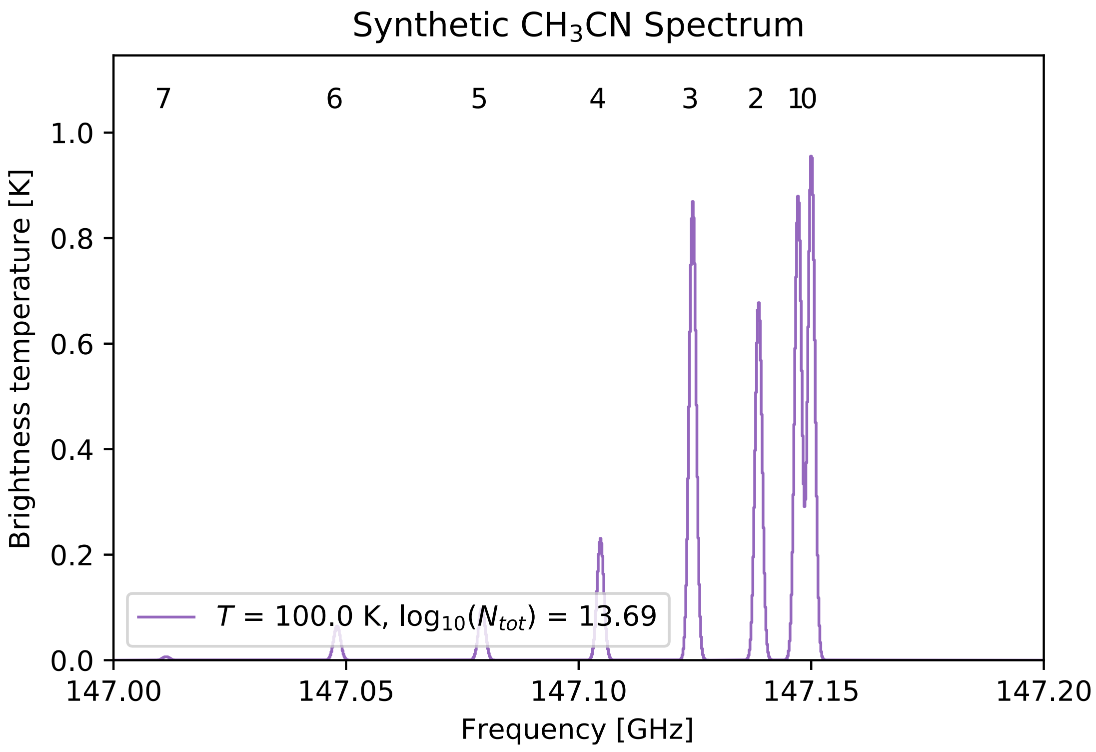
Rathborne+2015 and Walker+2022

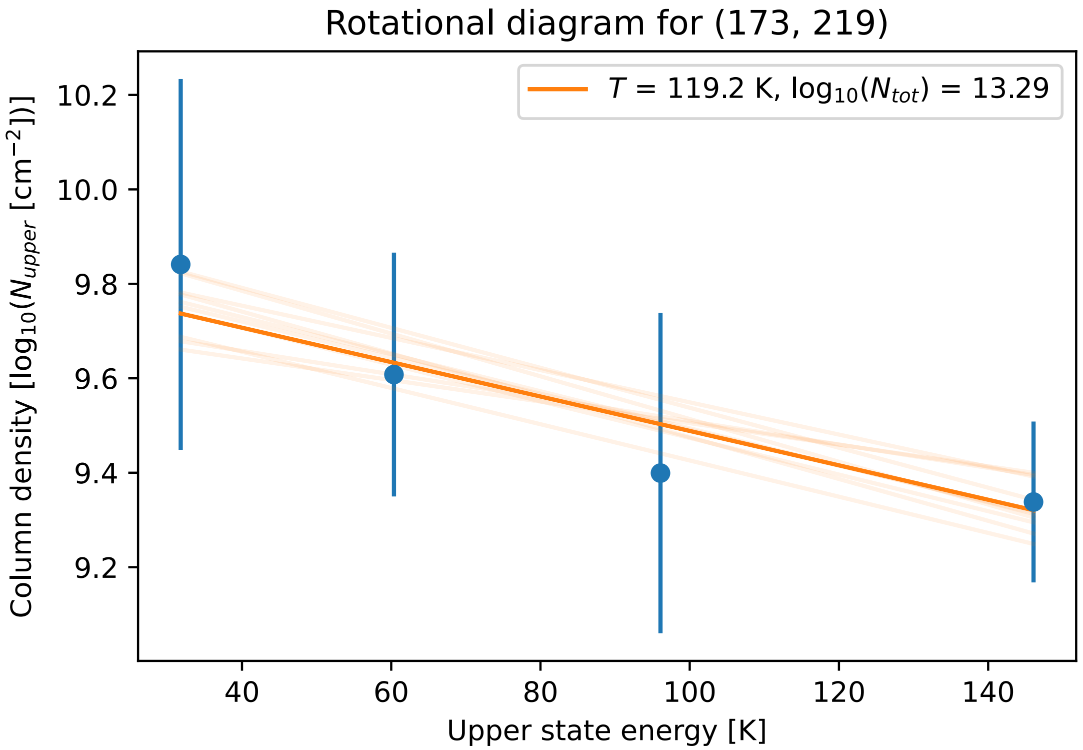
What is the environment like where these molecules are?

Measuring Physical Parameters

Temperature and density are initial conditions

- We use CH_3CN (methyl cyanide) to measure temperature
  - Seven CH_3CN "ladders" in delivered data
- **Rotational diagrams** (column density versus upper-state energy) reveal physical conditions of environment (Goldsmith+1999)
  - Slope is $-1/T$
  - Intercept is related to N_{tot}
- Repeat for each pixel in cube to get **maps** of temperature and column density

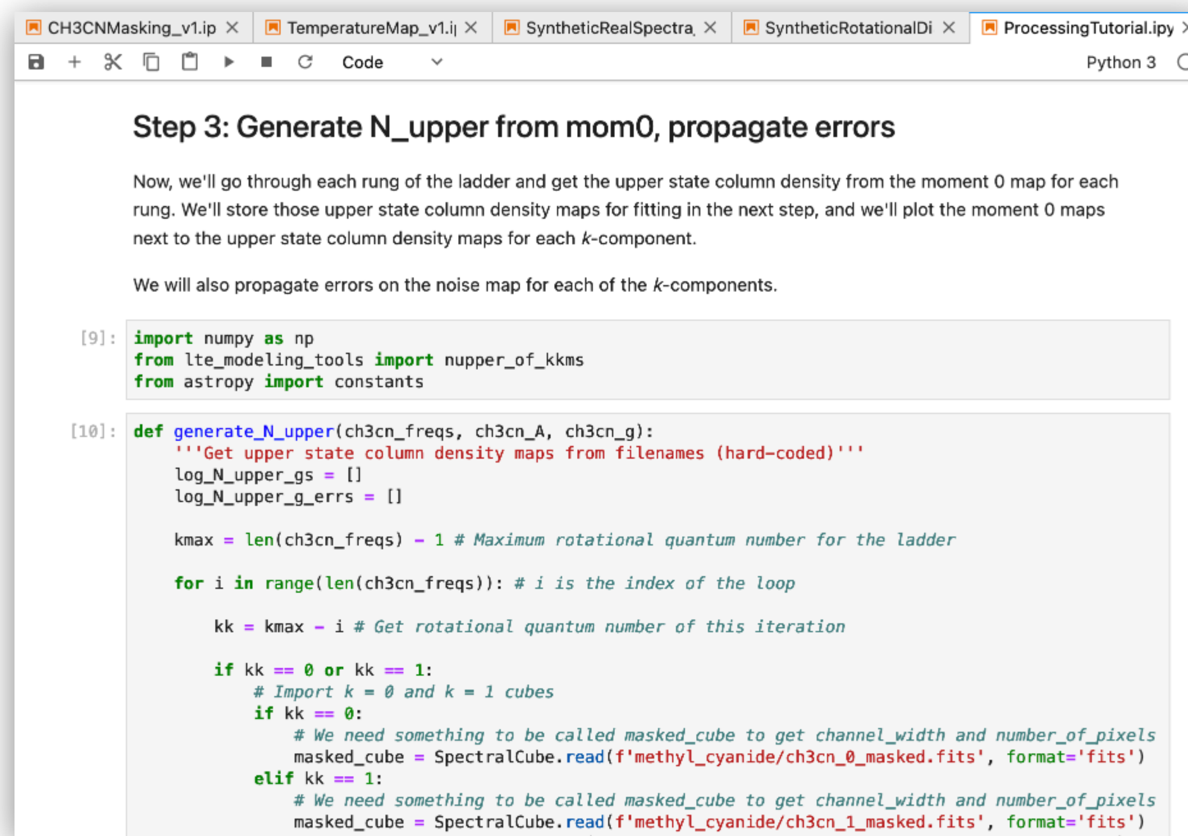




Tutorial Development

Reproducibility for fun ~~and profit~~

- Raw data need a lot of processing
  - Spectral masking (to enable isolation of multiple blended velocity components)
  - Rotational diagram fitting pixel-by-pixel
  - Modeling synthetic spectra to validate rotational diagrams
- Wrote tutorials in Jupyter Notebooks
- Available on GitHub now
  - Hope to publish on learn.astropy after project is complete

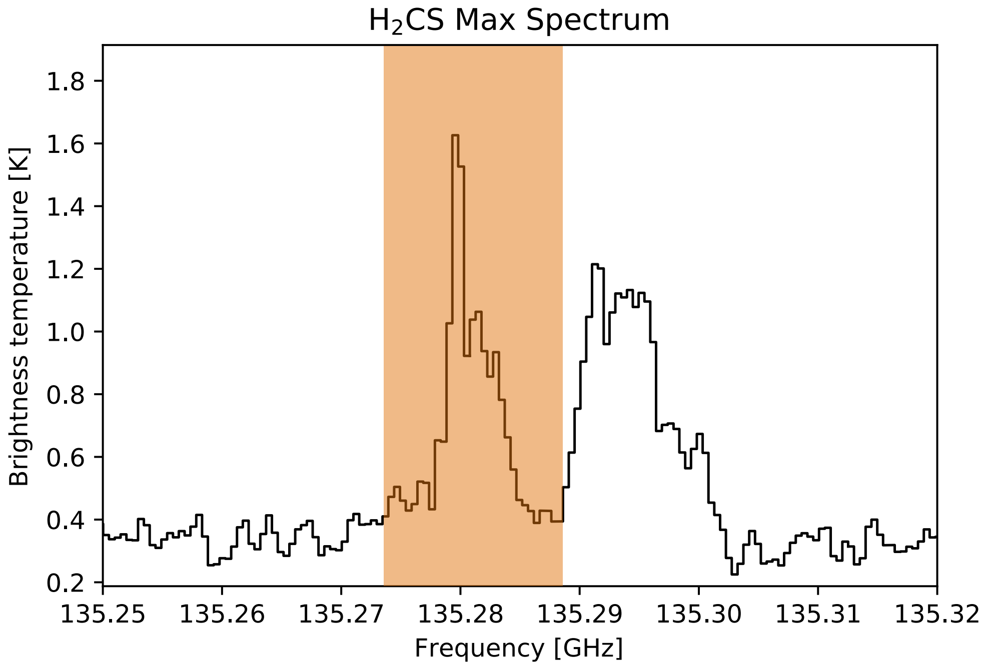


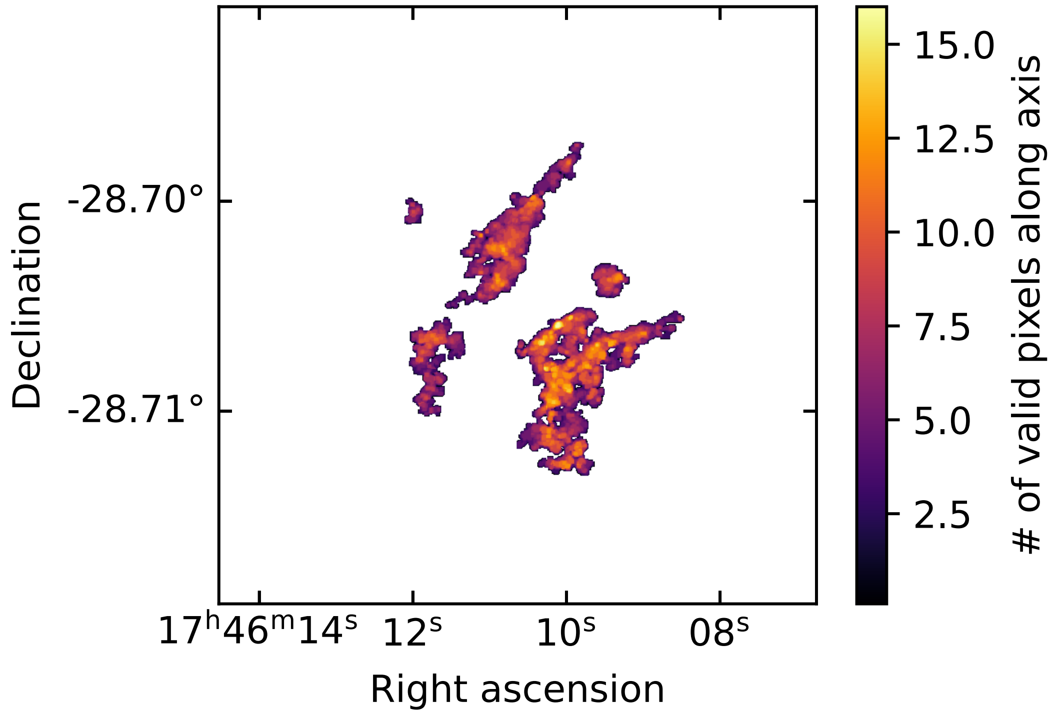
https://github.com/abulatek/brick

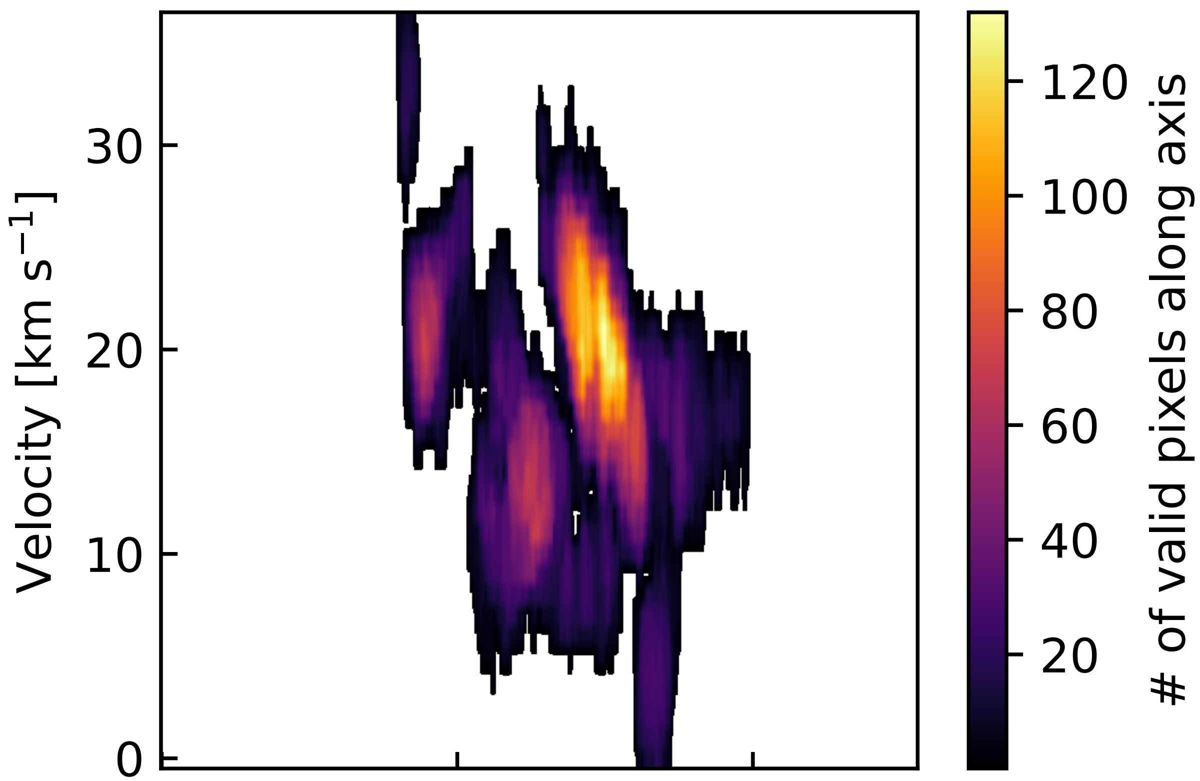
Signal Masking

Signal extraction using a different molecule

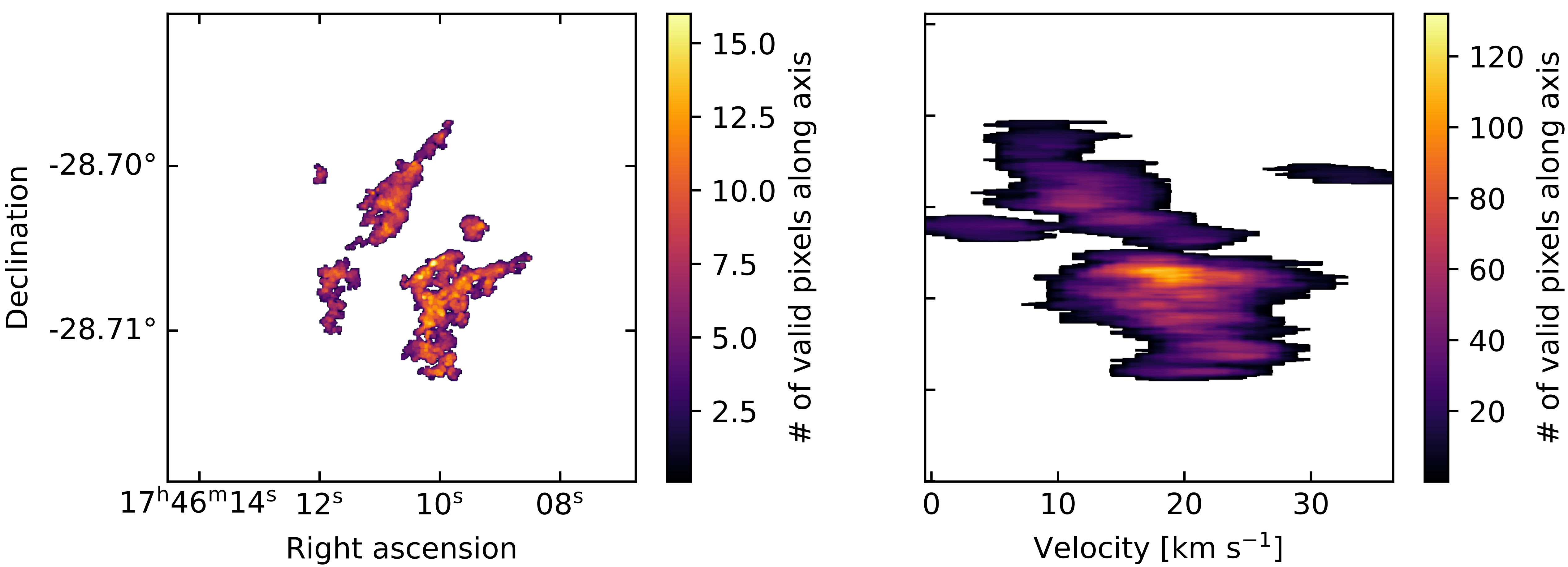
- CH_3CN signal is relatively weak, so we extract it with a molecule we assume will trace it: **H_2CS** (thioformaldehyde)
    - Because these lines are at different frequencies (and we're converting to velocity), need to "re-grid" both **spectrally** and **spatially**
- Output of signal masking: cutout cubes of CH_3CN signal

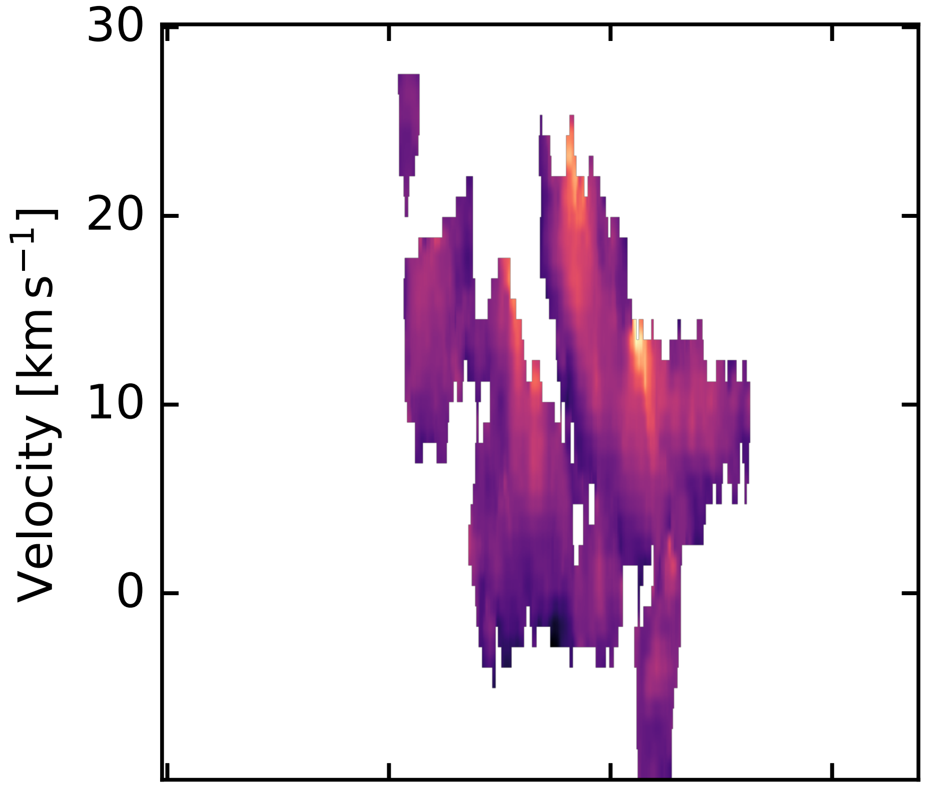




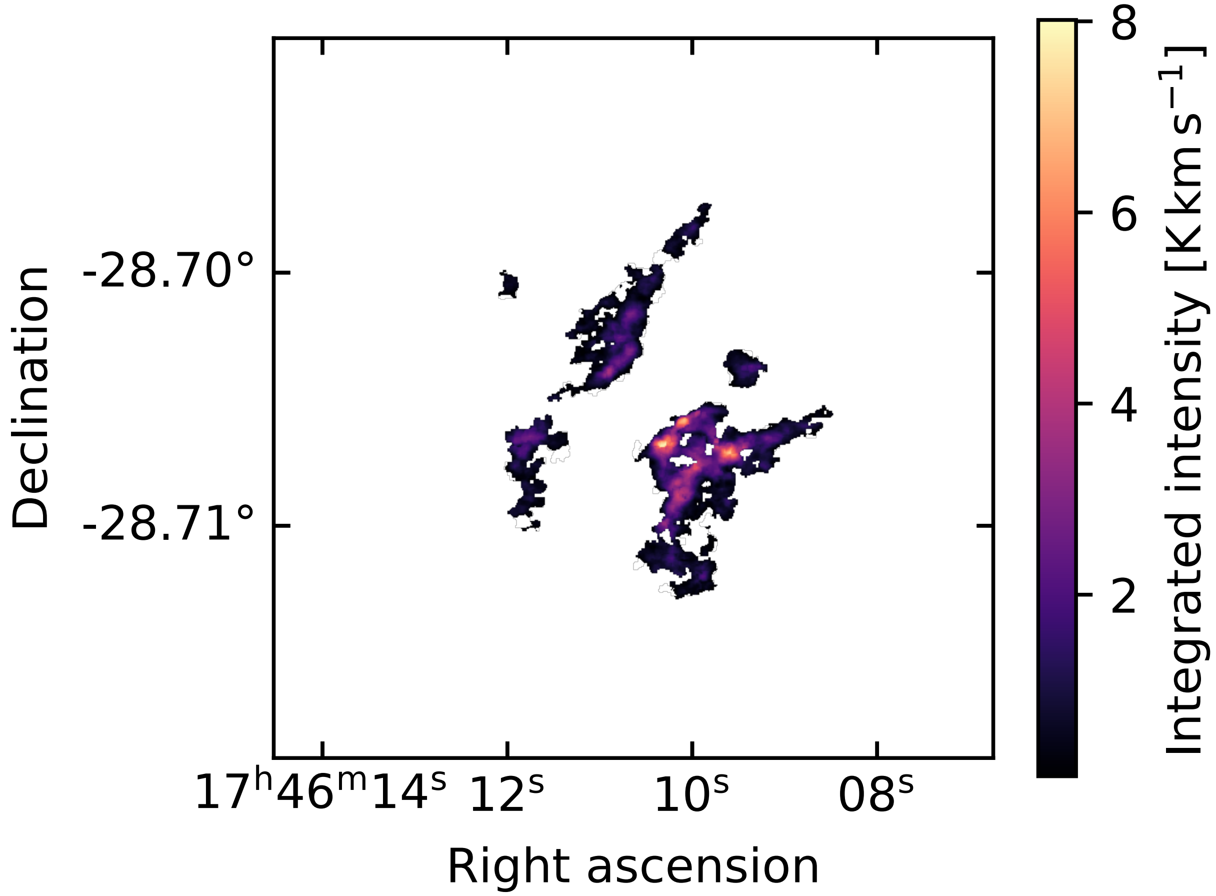


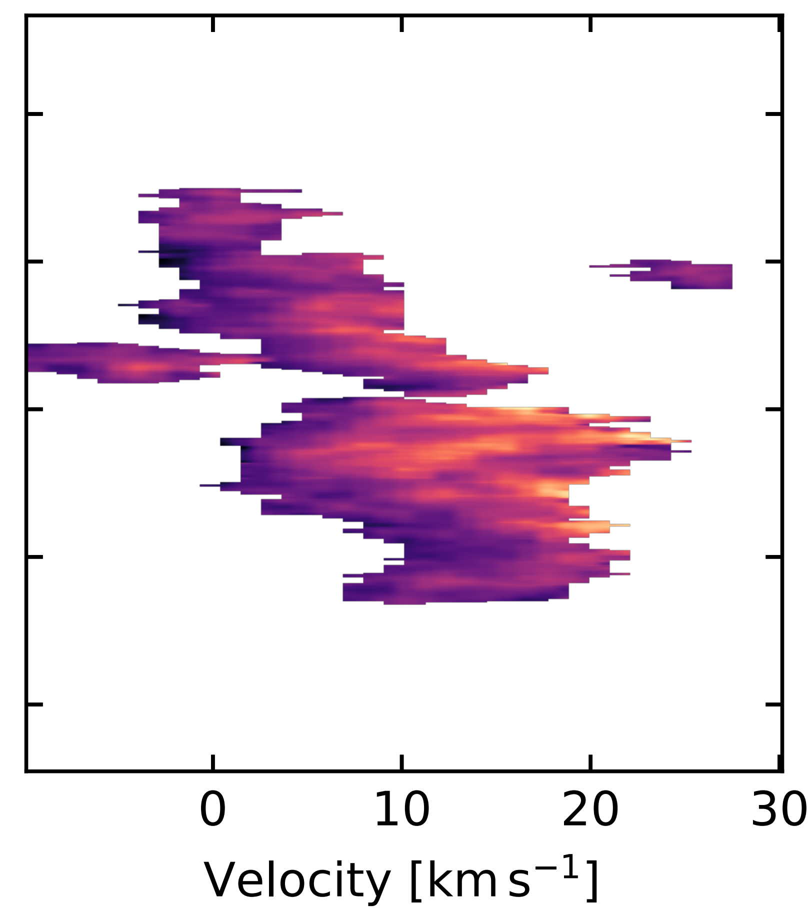
H_2CS-derived signal mask (LL) and projections of mask along spatial axes





CH_3CN moment 0 map (LL) and projections of cube along spatial axes



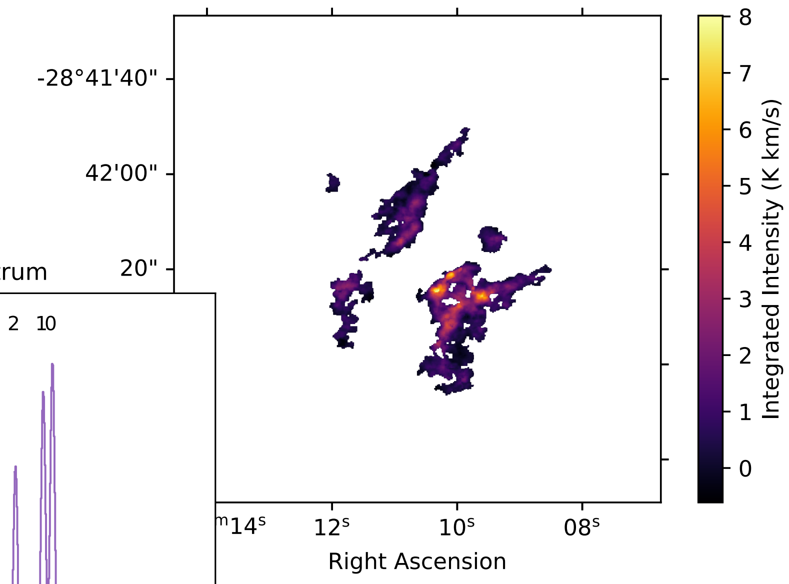


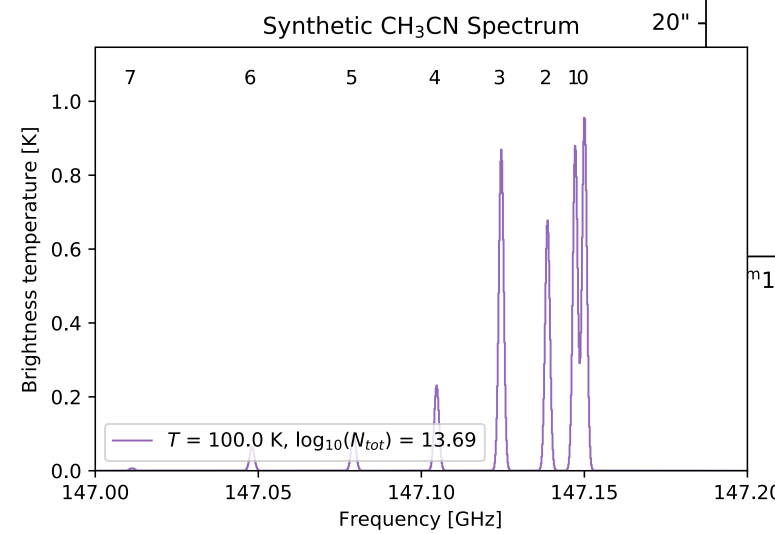
How to we get from the data products to temperatures?

Rotational Diagrams

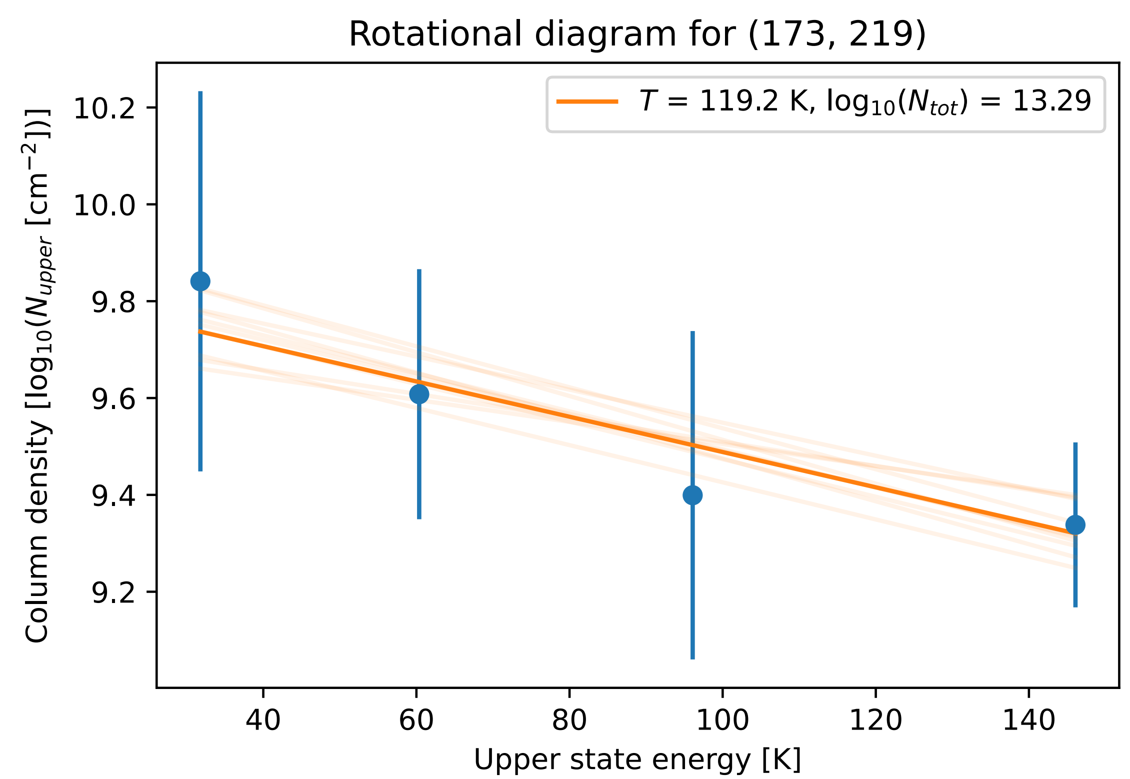
Going from data to temperatures

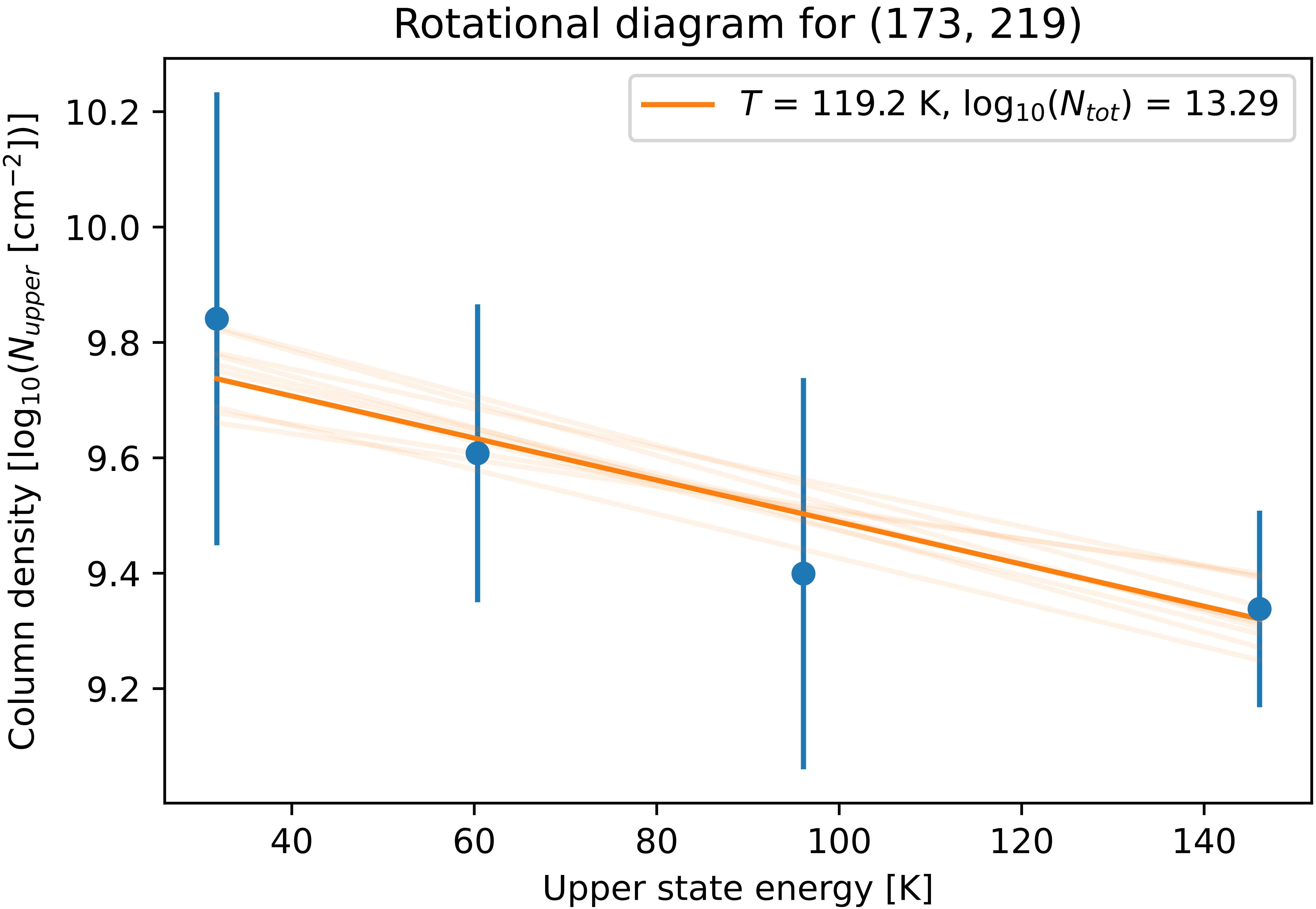
- Make moment map for each *k*-component in CH_3CN ladder
- Convert from integrated intensity [K km s^{-1}] to upper state column density [cm^{-2}] (Mangum+2015)
    - These are the y-axis points on a rotational diagram
- Linear fit to rotational diagram for each pixel
    - Extract temperature from slope
    - Extract total column density from intercept

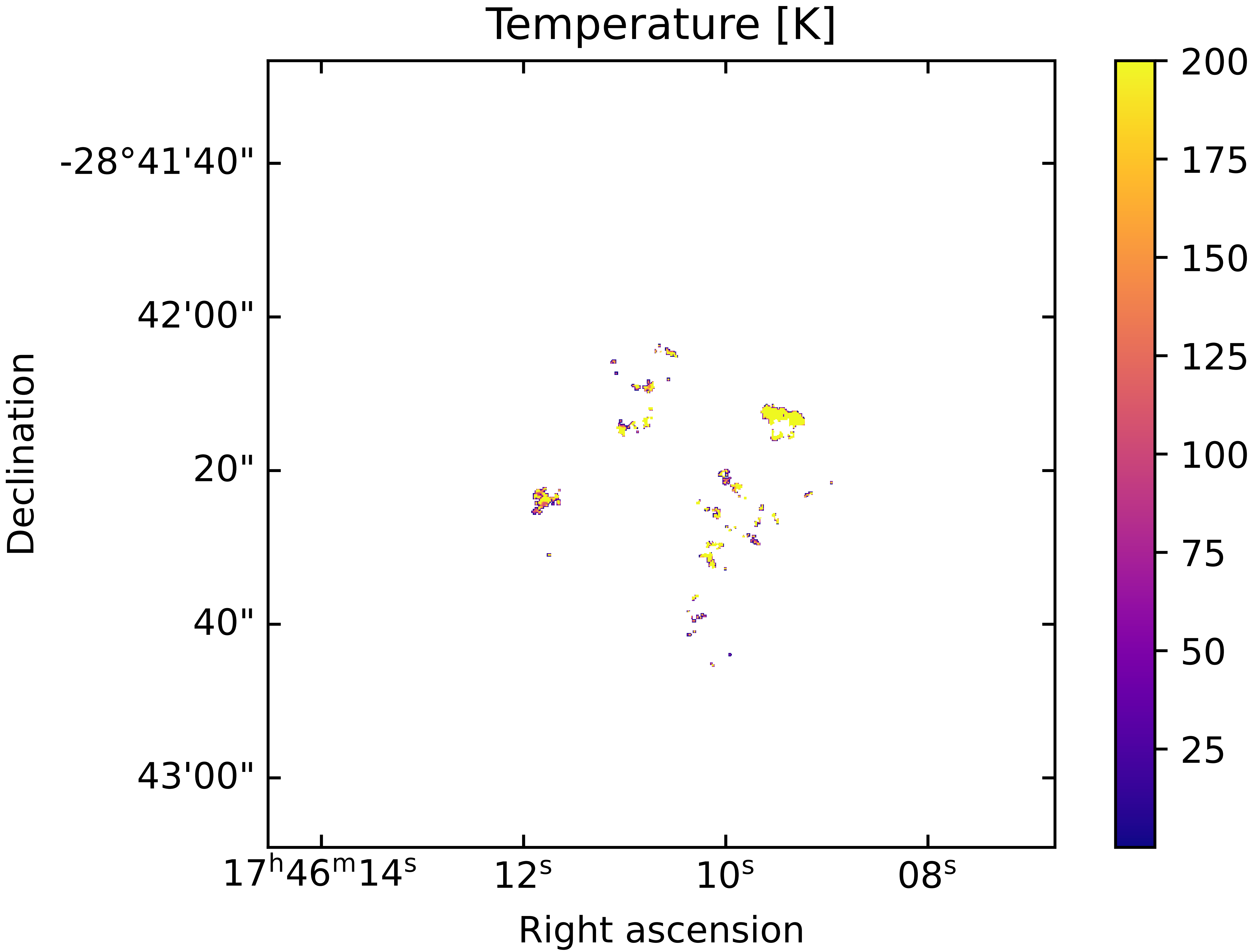


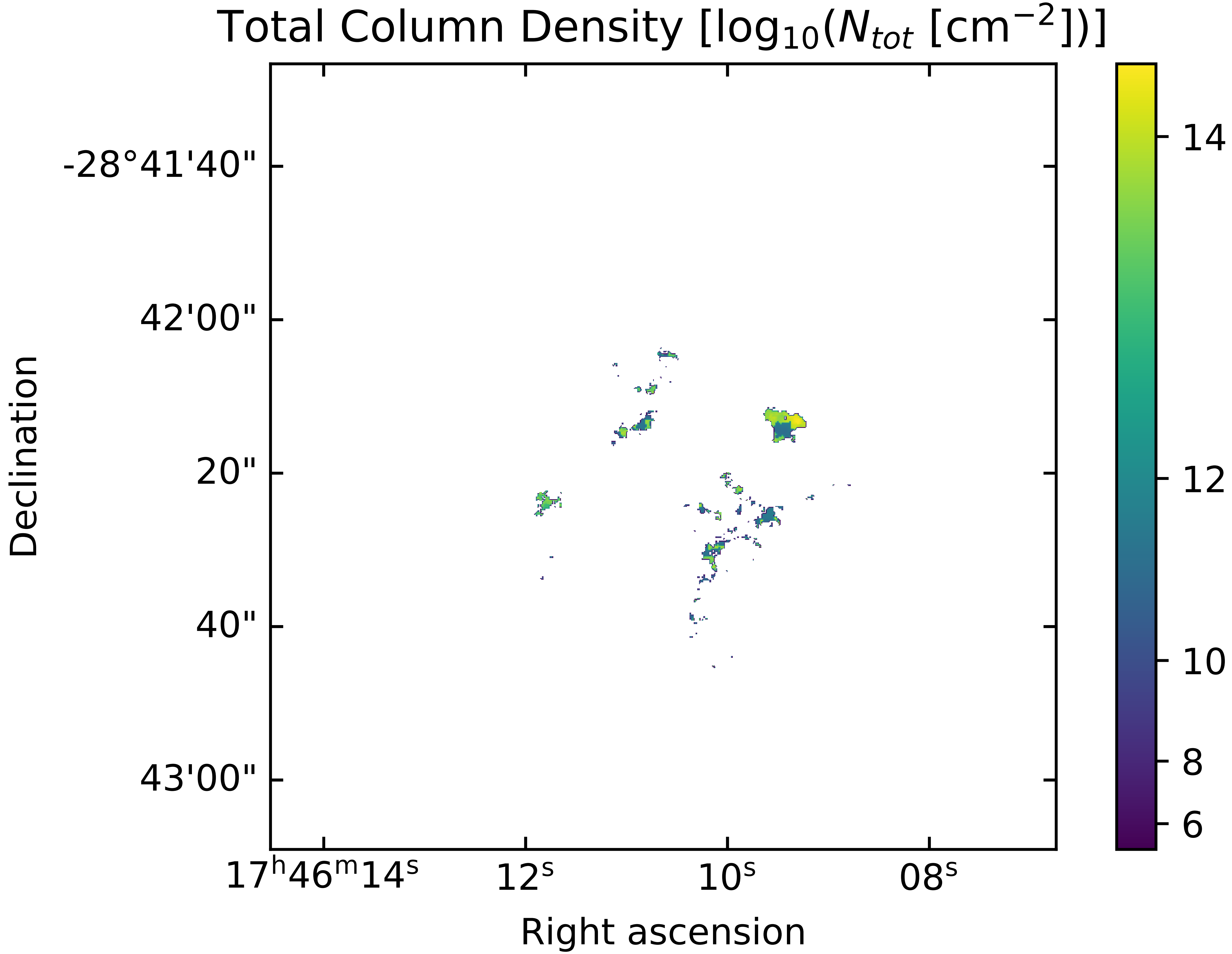


$$N_{upper} = \frac{8\pi\nu k_B}{hA_{ul}c^2} \cdot I$$




Rotational diagram for (173, 219)
T = 119.2 K, $\log_{10}(N_{tot})$ = 13.29
Column density [$\log_{10}(N_{upper}$ [cm^{-2}])]
10.2
10.0
9.8
9.6
9.4
9.2
40
60
80
100
120
140
Upper state energy [K]

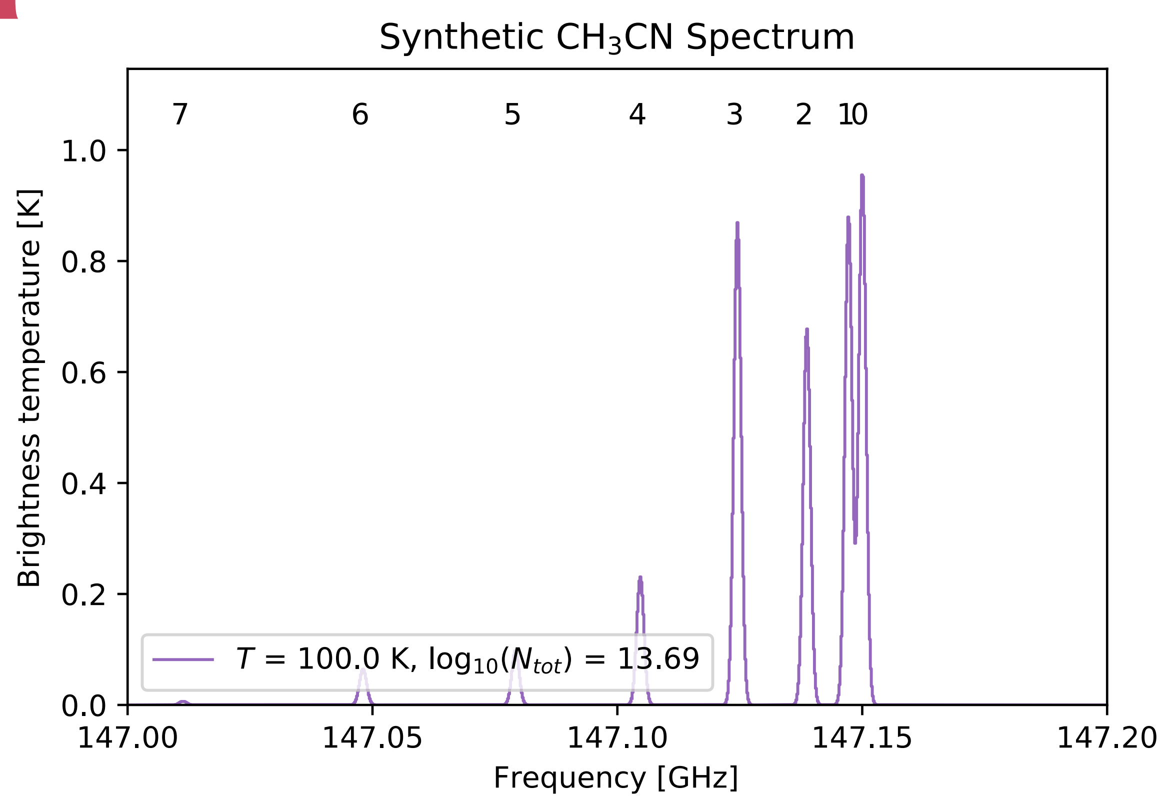

Temperature [K]
-28°41'40"
42'00"
20"
40"
43'00"
Declination
17h46m14s
12s
10s
08s
Right ascension
200
175
150
125
100
75
50
25

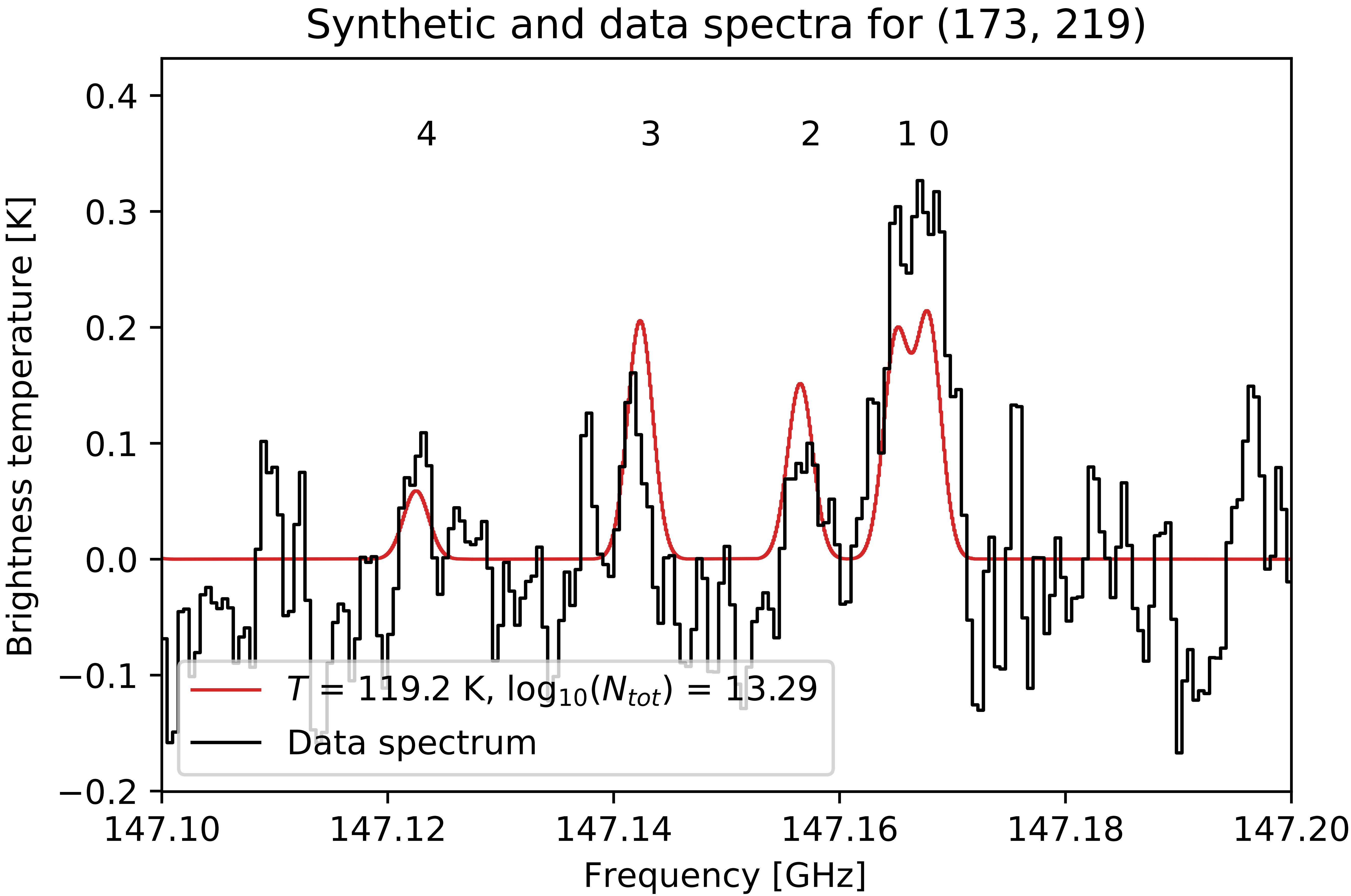

Total Column Density [log$_{10}$(N_{tot} [cm^{-2}])]
-28°41'40"
42'00"
20"
40"
43'00"
Declination
17^{h}46^{m}14^s
12^s
10^s
08^s
Right ascension
14
12
10
8
6

Synthetic Spectra

Checking our math

- If our fitted values for temperature and column density (derived from the data) are correct, a synthetic spectrum created using those parameters should match our data spectrum
  - First step to full LTE model of this region
- Created spectra with Pyspeckit's spectrum.models.lte_molecule



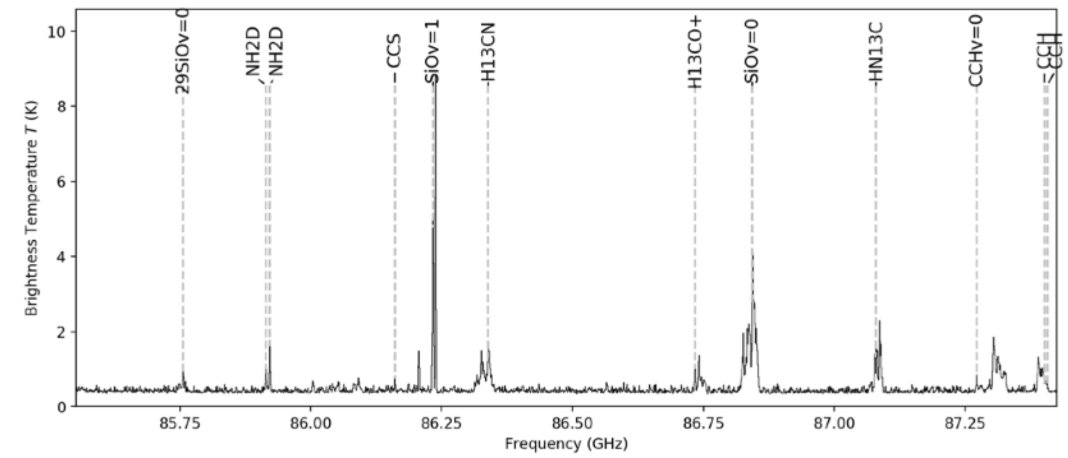

Synthetic and data spectra for (173, 219)
4
3
2
1 0
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
Brightness temperature [K]
147.10
147.12
147.14
147.16
147.18
147.20
Frequency [GHz]
T = 119.2 K, $\log_{10}(N_{tot})$ = 13.29
Data spectrum

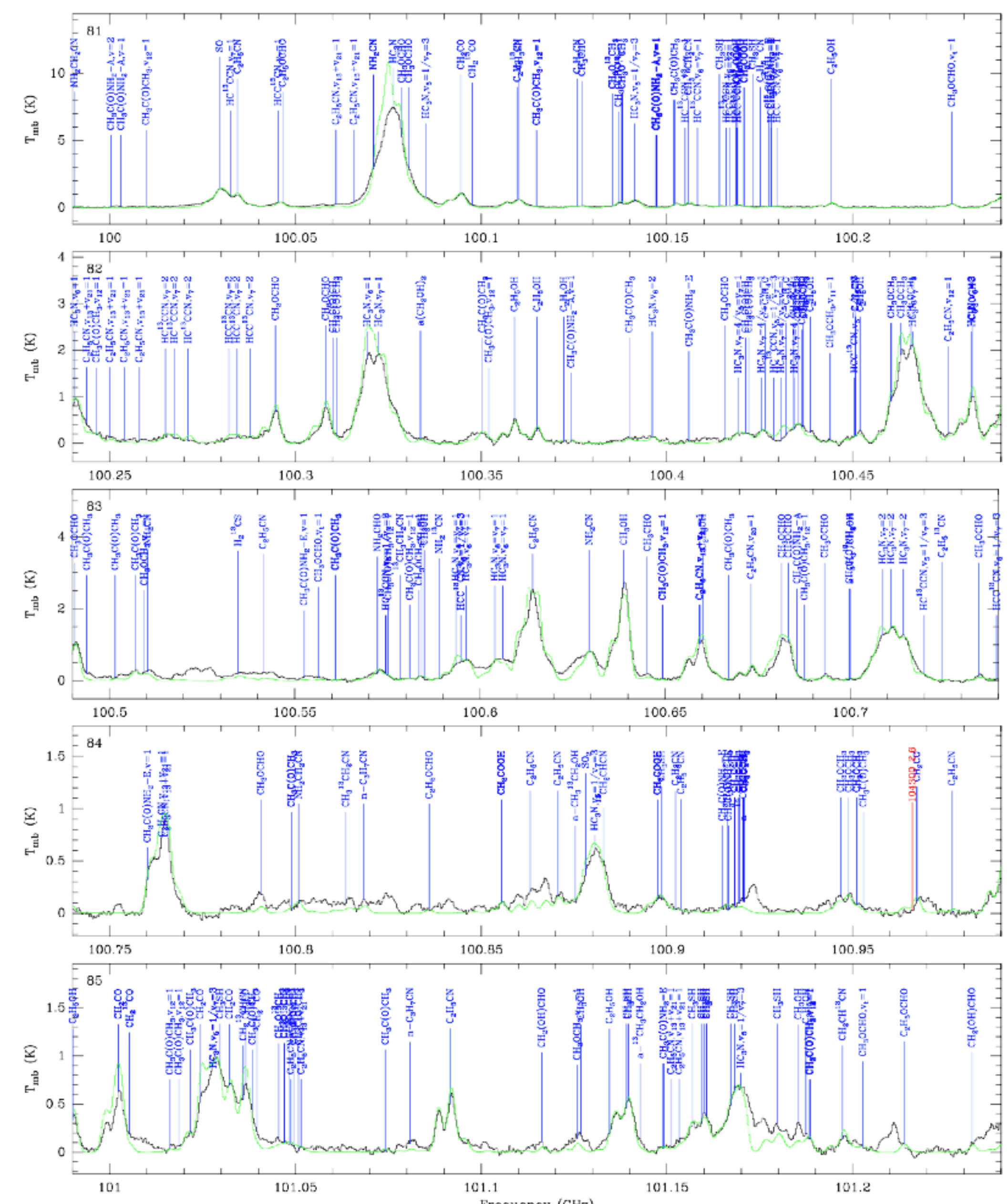
What molecules are in this region of The Brick?

Line Identification

Start with some guesses

- Some "brute-force" line identification has been done using two types of summary spectra
  - Max spectra
  - Mean spectra
- Search for "detections" (>5σ), then use Splatalogue to find lines near center frequency of detection given a velocity range (~75 km/s)
- Checked these IDs against line lists in Sgr B2 (Jones et al. 2012, Belloche et al. 2013)





Belloche+2013

Candidate Species

There are a lot (these are not all of them)

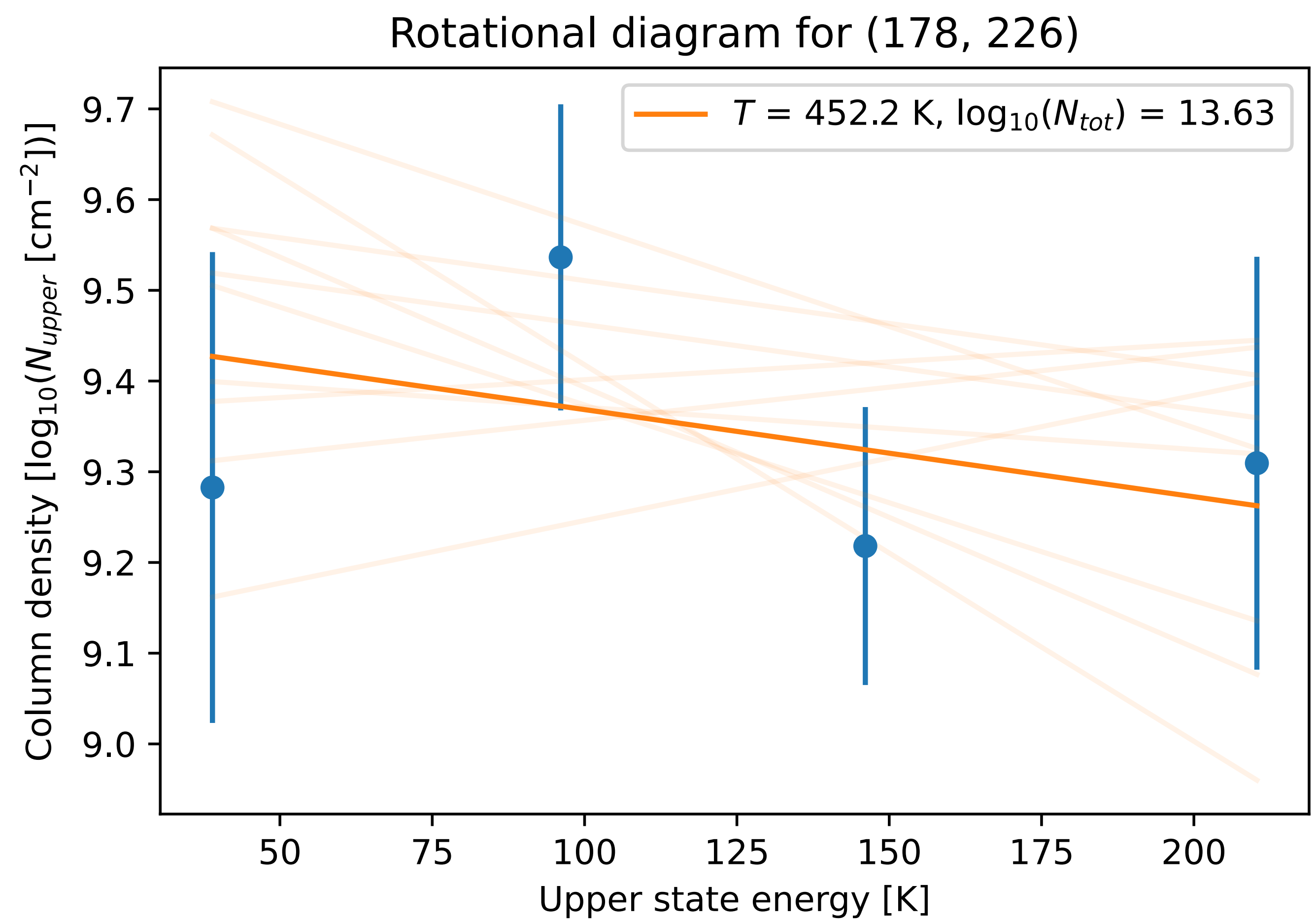
2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms
CO	OCS	H2CS	C4H	CH3CN	CH3CHO	CH3OCHO	CH3OCH3	(CH3)2CO
C17O	CCH	HNCO	HC3N	CH3OH	CH3CCH		CH313CH2CN	
CS	CCS	HDCO	H13CCCN	CH3OD	CH2CHCN		CH3CH213CN	
13CS	HCN	HOCO+	HC13CCN	CH2DOH			g-CH3CH2OH	
CN	H13CN	SO3	HCC13CN	13CH3OH				
13CN	HC15N		CH2NH	NH2CHO				
SiO	HNC		c-HCCCH					
NO	HN13C							
NS	NaCN							
AlF	NaNC							
Al37Cl	SO2							
NaCl	34SO2							
SO+	Si13CC							
	SiC2							
	30SiC2							
	HCO+							
	H13CO+							
	N2H+							

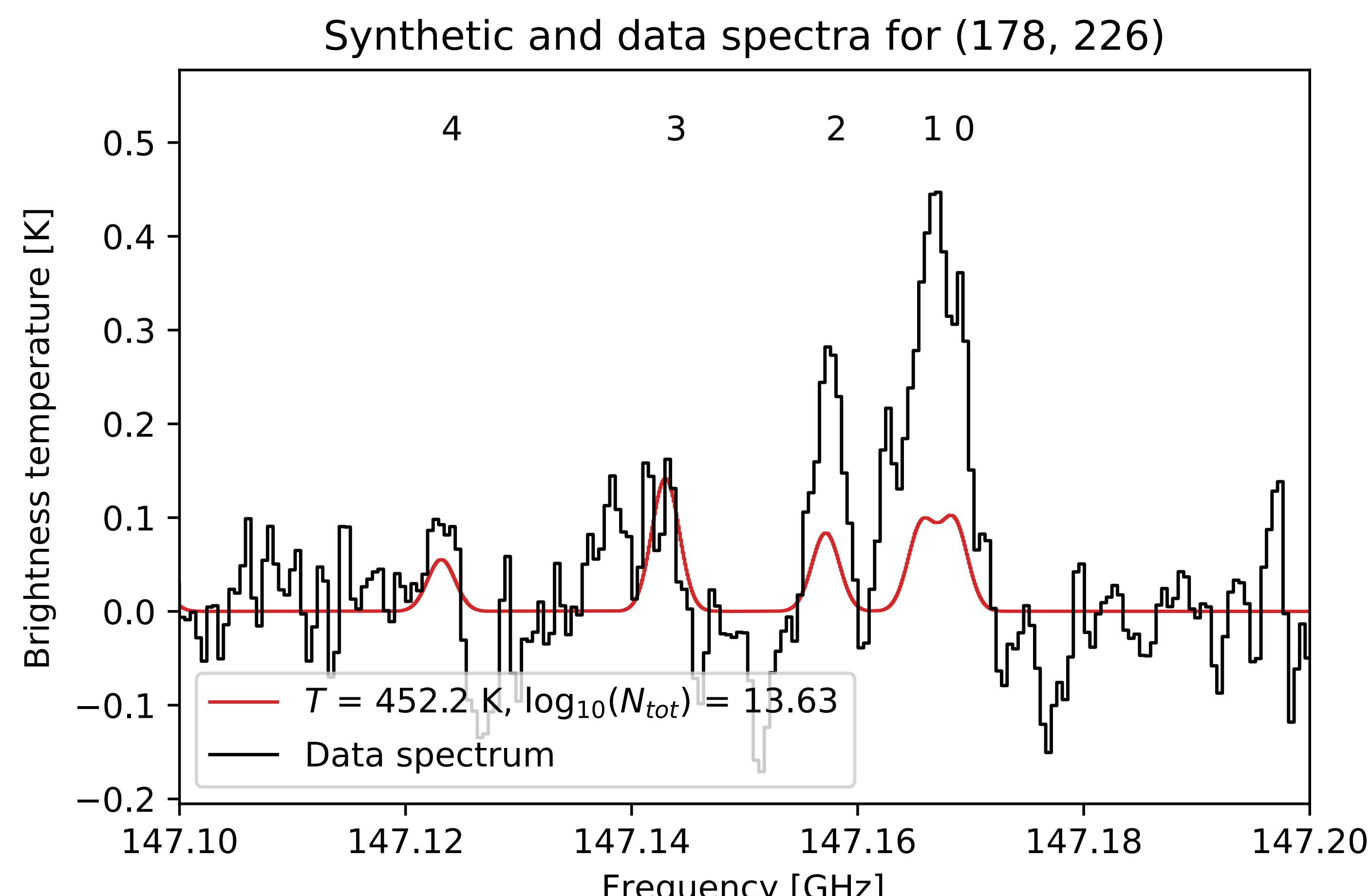
What's next?

Future Work

More pixels, please

- Want more pixels in maps!
  - Incorporate other 6 ladders into parameter maps
  - Measure upper limits for "non-detected" pixels
  - Model multiple velocity components using scousepy
- Still a lot of unknowns in the line identification process
  - Can use temperature to identify lines using synthetic spectra
- The final goal of the project: associate new tracers with ISM processes
  - Morphologically, or with e.g. PCA





Thank you!