A Molecular Inventory of the Orion Hot Core in Mid-Infrared with SOFIA/EXES

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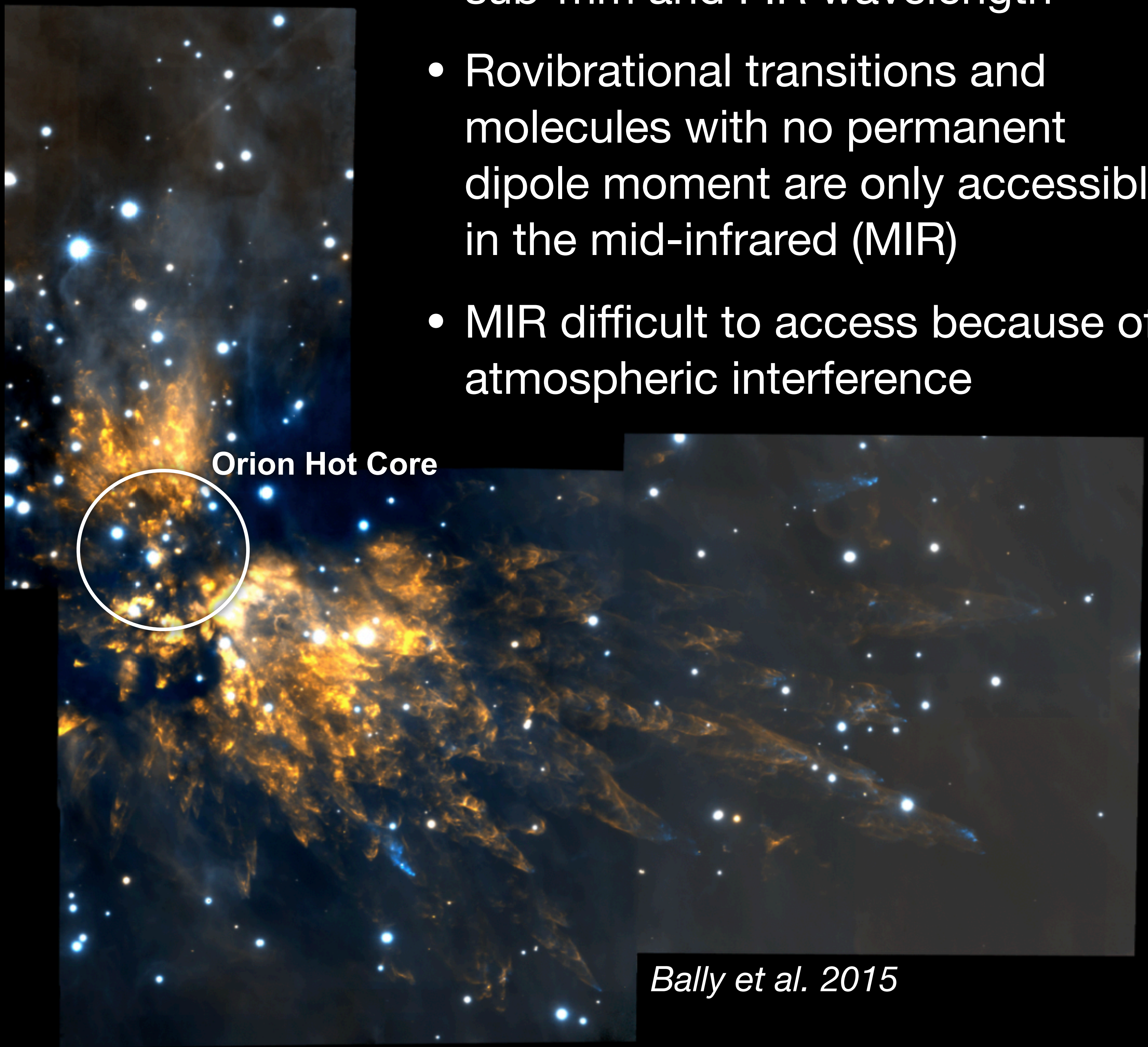
Hot Cores

- Warm, dense regions near young, high mass protostars
- Stellar radiation evaporates ice on dust grains in molecular clouds
- Chemically rich reservoirs of complex and prebiotic molecules
- Become the building blocks of planetary systems, such as our own Solar System

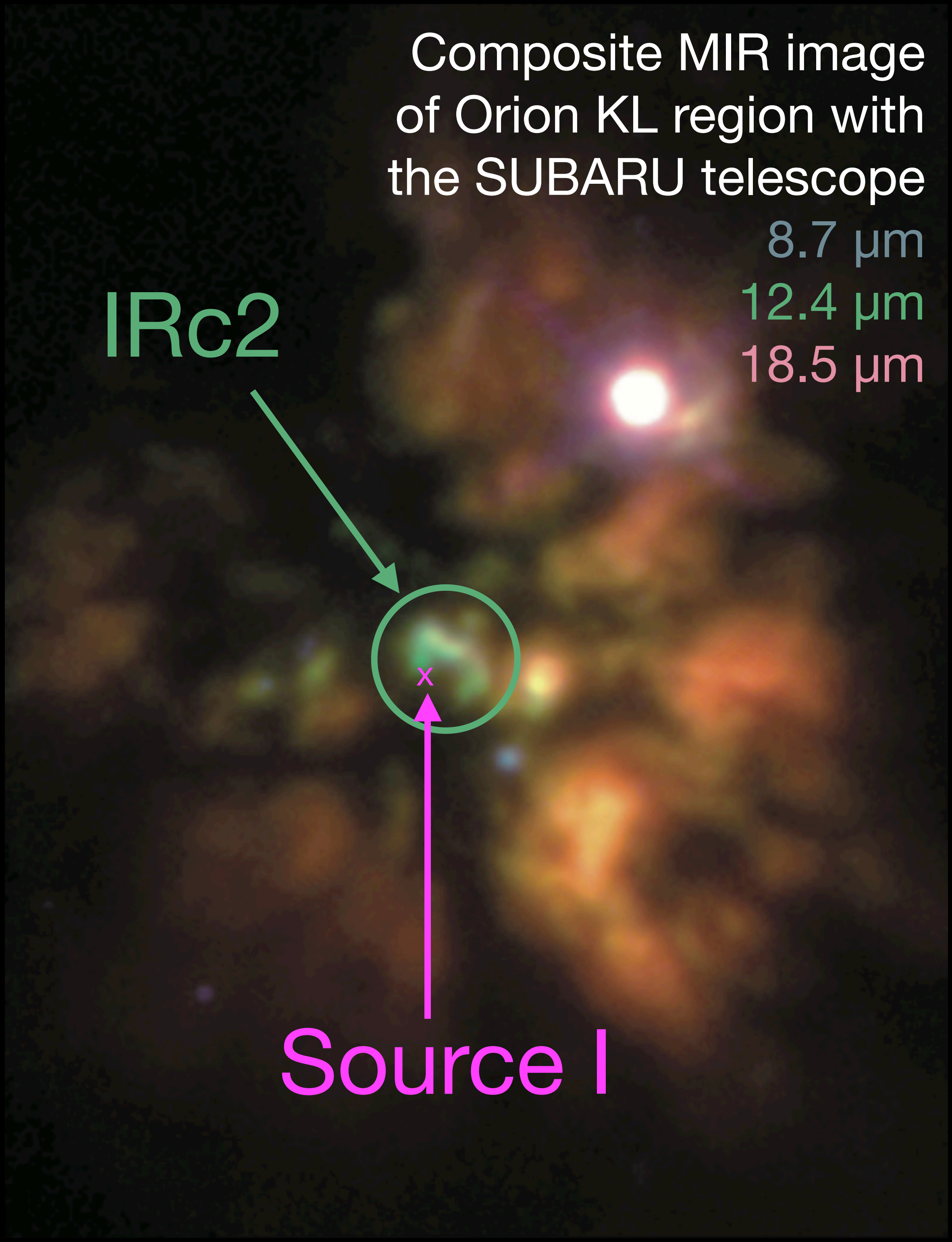


- Previous high spectral resolution surveys have been limited to radio, sub-mm and FIR wavelength
- Rovibrational transitions and molecules with no permanent dipole moment are only accessible in the mid-infrared (MIR)
- MIR difficult to access because of atmospheric interference

Bally et al. 2015

The Orion Hot Core: IRc2

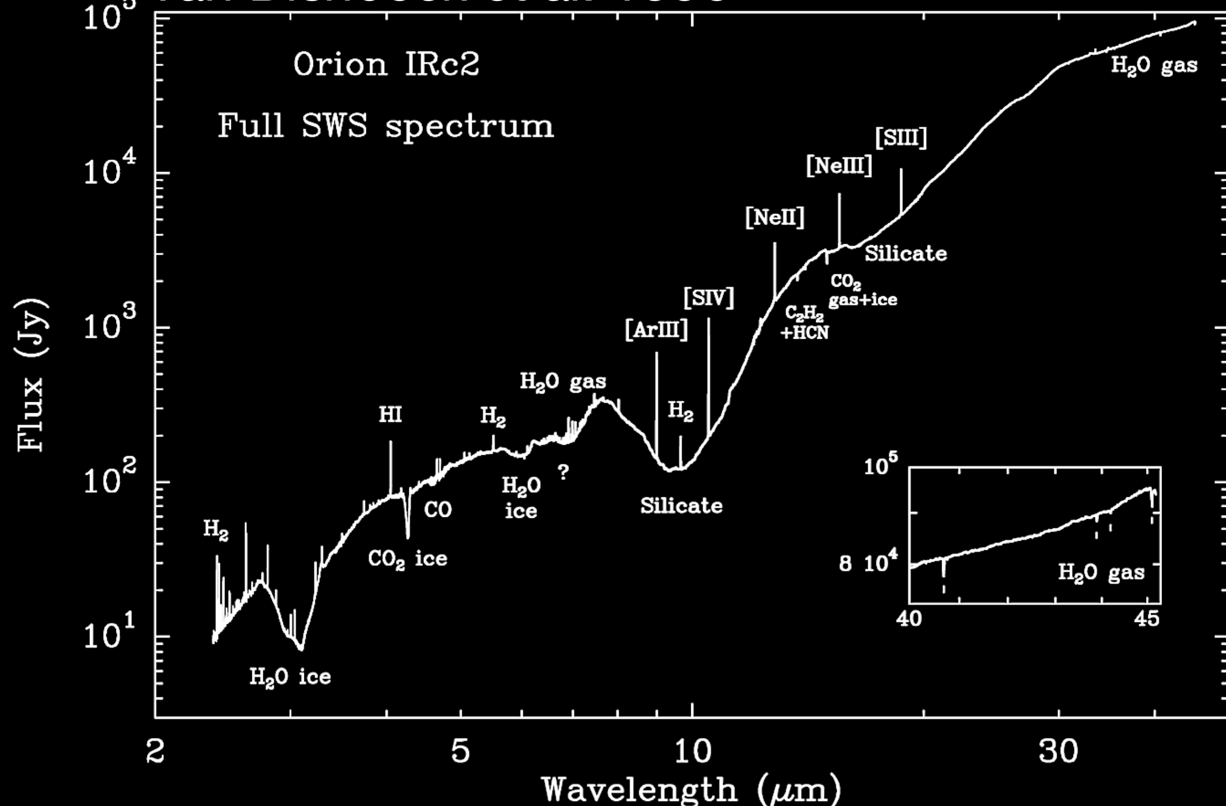
- The Orion Kleinmann-Low Nebula (Orion-KL, Kleinmann & Low 1967) is the best studied massive star formation region
- Also nearest at 388 ± 5 pc (Kounkel et al. 2017)
- This eponymous hot core peaks in infrared at IRc2, discovered via NH_3 emission (Ho et al. 1979)
- Atypical for a hot core, externally heated cavity (e.g. Shuping et al. 2004, Zapata et al. 2011)
- Possibly heated by embedded radio source I which has no IR component



Okumura et al. 2011

IRc2 in MIR

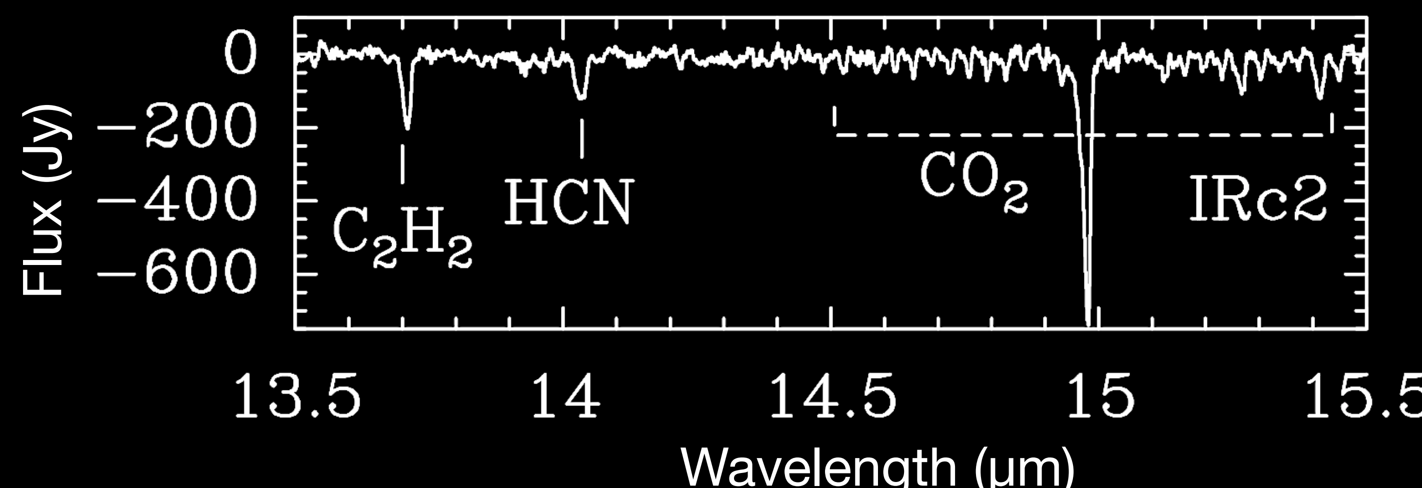
van Dishoeck et al. 1998



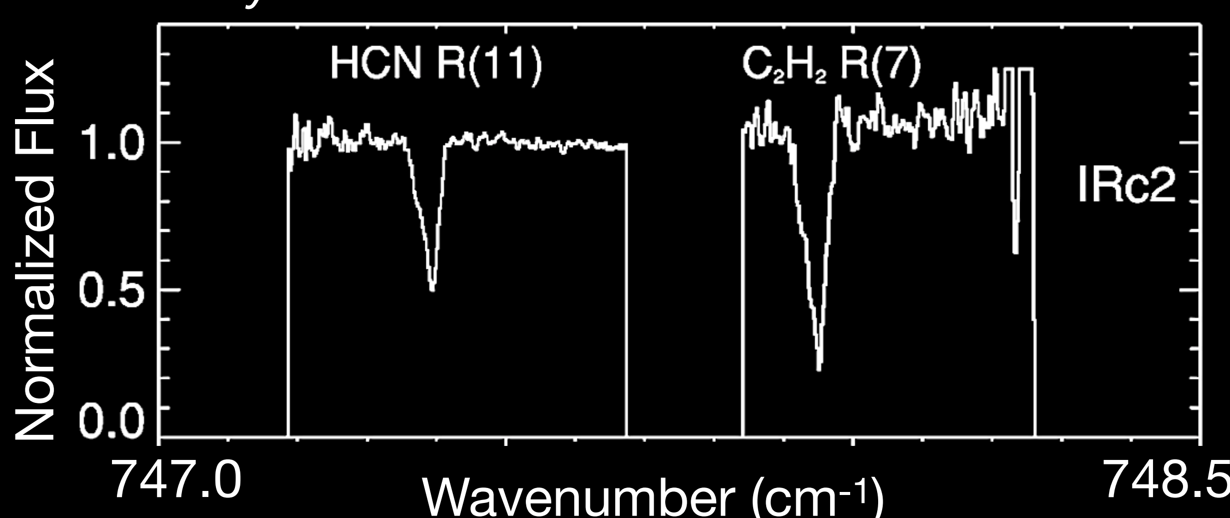
Previous survey in MIR with space-based telescope ISO 2.4 to 45.2 μm reveals rich molecular gas chemistry, species CO, H_2, C_2H_2, HCN, SO_2, and CO_2 (van Dishoeck et al. 1998)

From 13.5 to 15.5 μm ISO only detects strongest absorption features, not individual lines; excitation temperatures of ~175-275 K (Boonman et al. 2003)

Boonman et al. 2003



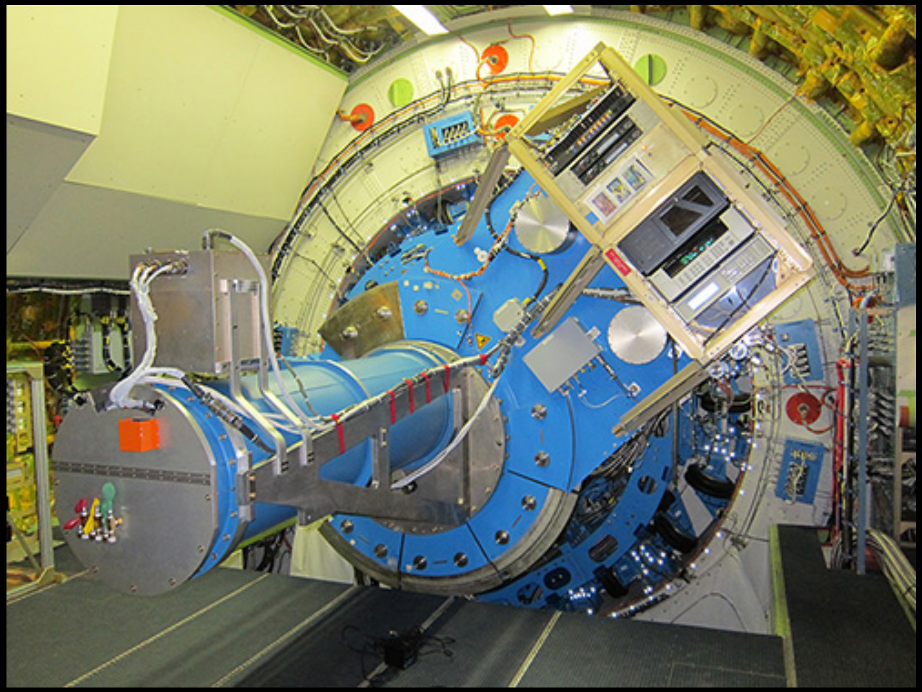
Lacy et al. 2002



Ground-based TEXES can resolve individual lines of HCN and C_2H_2 in absorption, and SiO in emission but much of MIR is obscured by atmosphere; for absorption lines v_{LSR}~-10 km/s (Lacy et al. 2002, 2005)

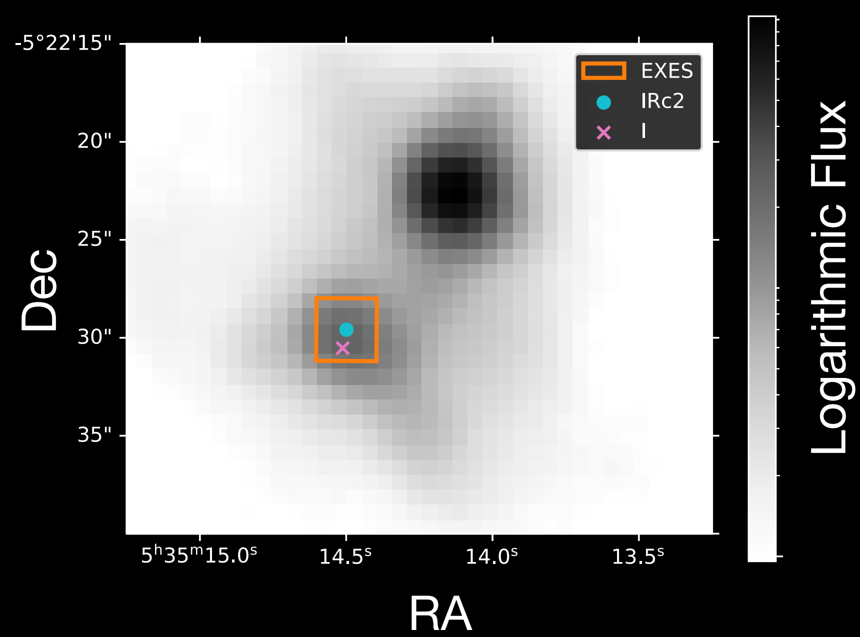
Note: ambient cloud velocity v_{LSR}~9 km/s (Genzel & Stutzki 1989)

SOFIA/EXES



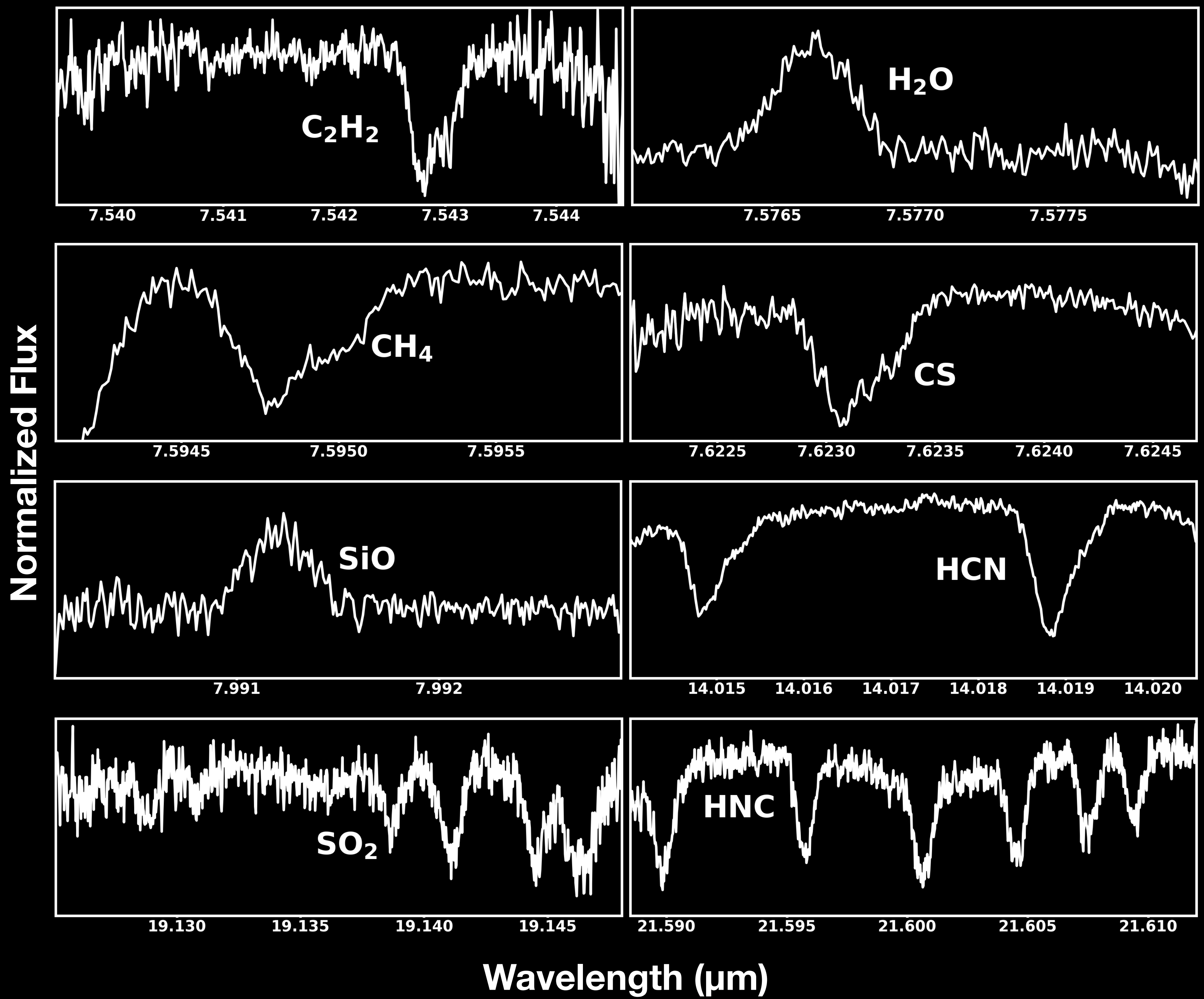
EXES slit at 7.6 μm setting projected onto FORCAST image at 7 μm

FORCAST: De Buizer et al 2012
Source I: Rodríguez et al. 2005



- Stratospheric Observatory for Infrared Astronomy (SOFIA) has high spectral capability in IR
- Flies above most of the water vapour in the Earth's atmosphere ~40,000 ft
- EXES: Echelle spectrometer, 5–28 μm, resolution 10^3-10^5 configuration dependent
- Sister spectrograph to TEXES
- Currently only spectrograph with high enough resolution to identify individual molecules over the whole MIR
- We conduct an unbiased, MIR line survey at high resolution (R ~ 60,000) from 7.2 to 25 μm of Orion IRc2 with SOFIA/EXES

EXES IRc2 Spectra



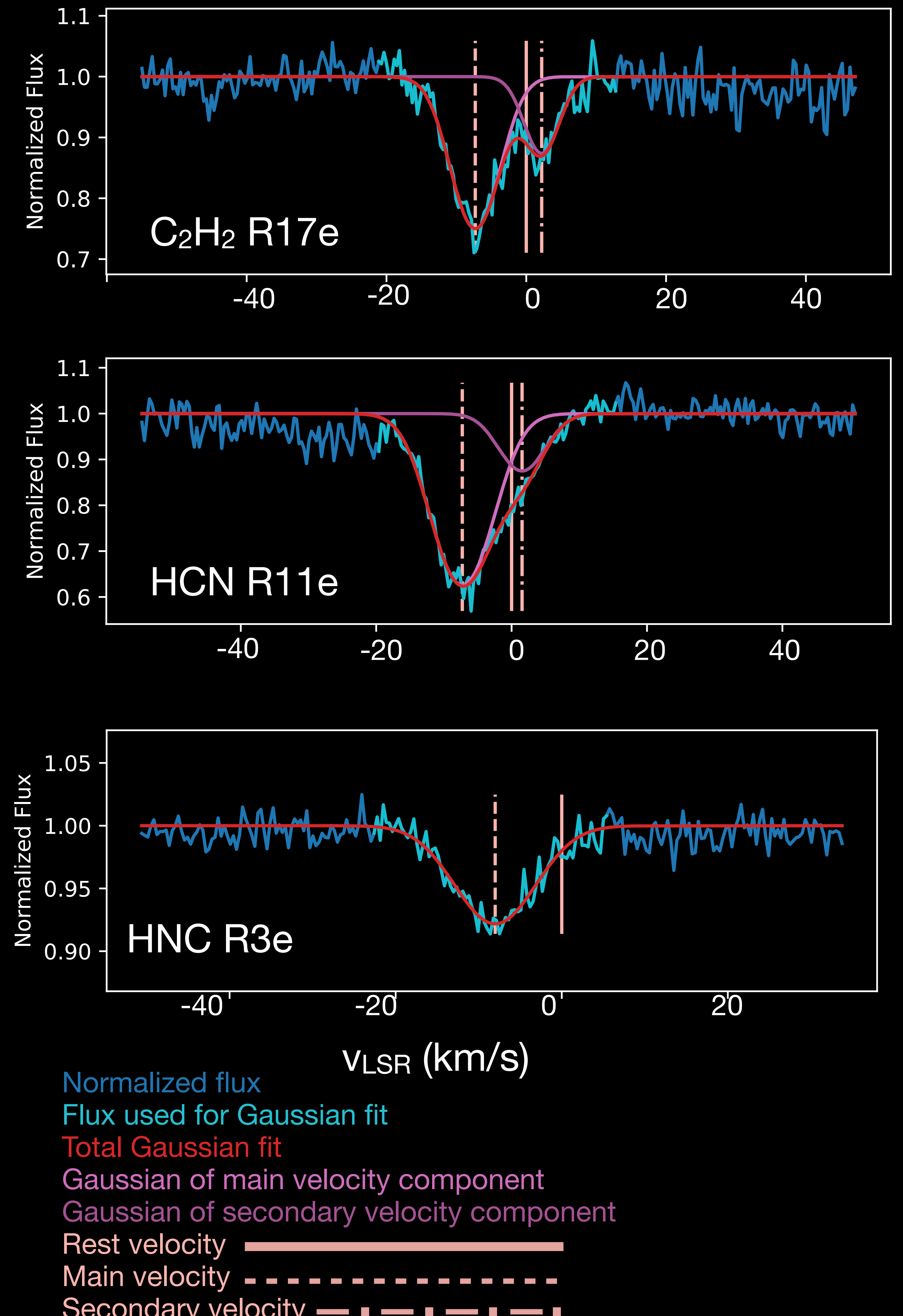
- Over 350 unique lines
- Species identified so far: HCN, HNC, C_2H_2, H_2O, CH_4, SO_2, SiO and CS
- Some species exhibit double Gaussians pointing to two velocity components: C_2H_2, HCN, CH_4, and CS
- Main absorption velocity component ~-7 km/s
- Secondary component not well resolved, requires further analysis

Analysis Recipe

1. Identify line of interest with databases HITRAN (Gordon et al. 2017) and GEISA (Jacquinet-Husson et al. 2015)
2. Normalize the baseline around line and atmospheric flux to 1
3. Divide out atmospheric flux
4. Fit line to a Gaussian, or two if second velocity component
5. Integrate under Gaussian for column density
6. Assuming local thermodynamic equilibrium, can fit to Boltzmann's equation to obtain overall column density and excitation temperature of species:

$$\ln \frac{N_j}{g_j} = \ln \frac{N}{Q_R(T_{ex})} - \frac{E_l}{kT_{ex}}$$

N_j: transition column density
g_j: transition lower statistical weight
N: total column density
T_{ex}: excitation temperature
$Q_R(T_{ex})$: partition function
E_l: energy of transition
k: Boltzmann constant



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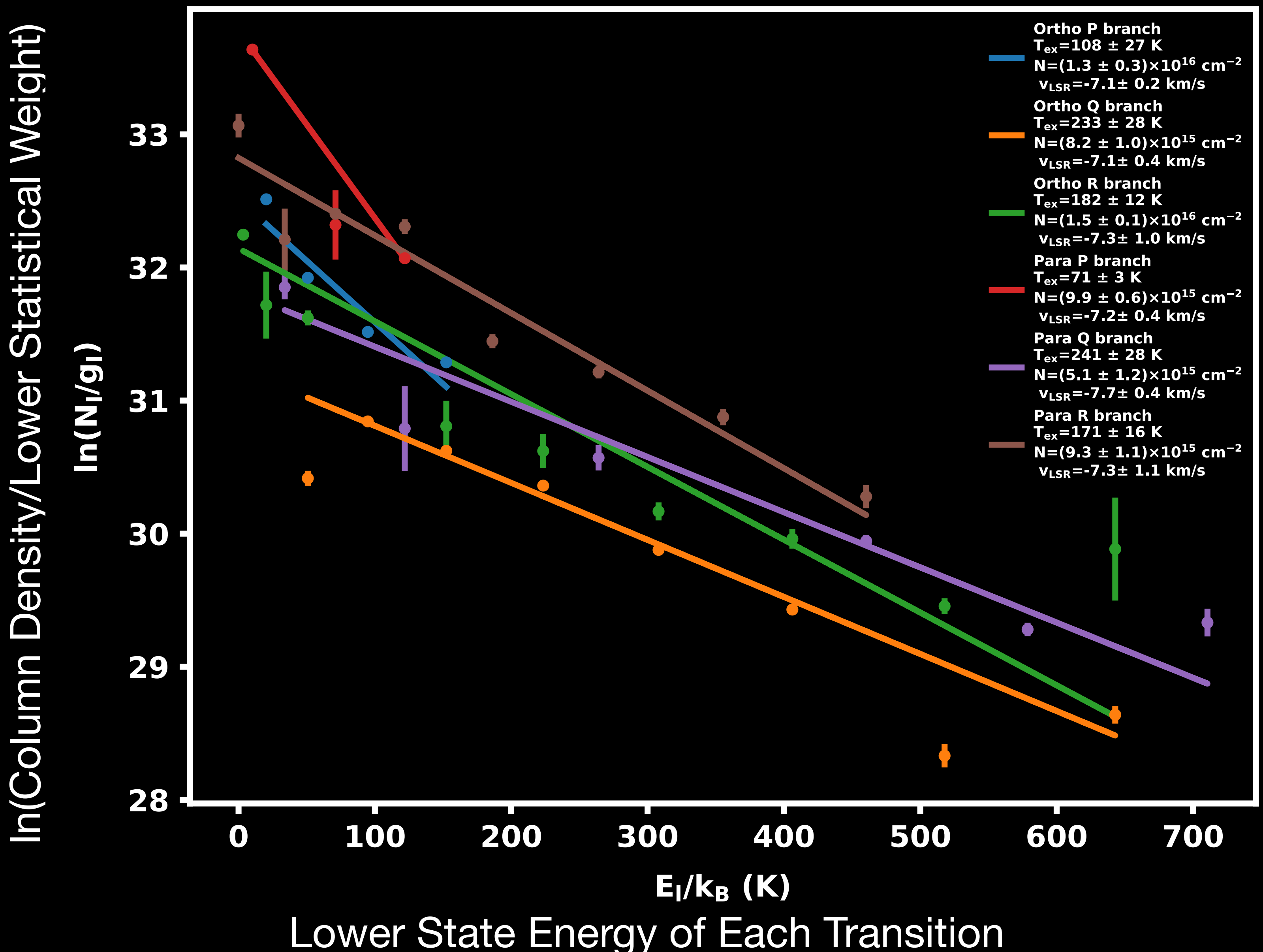
C_2H_2: Ground state to ν_5

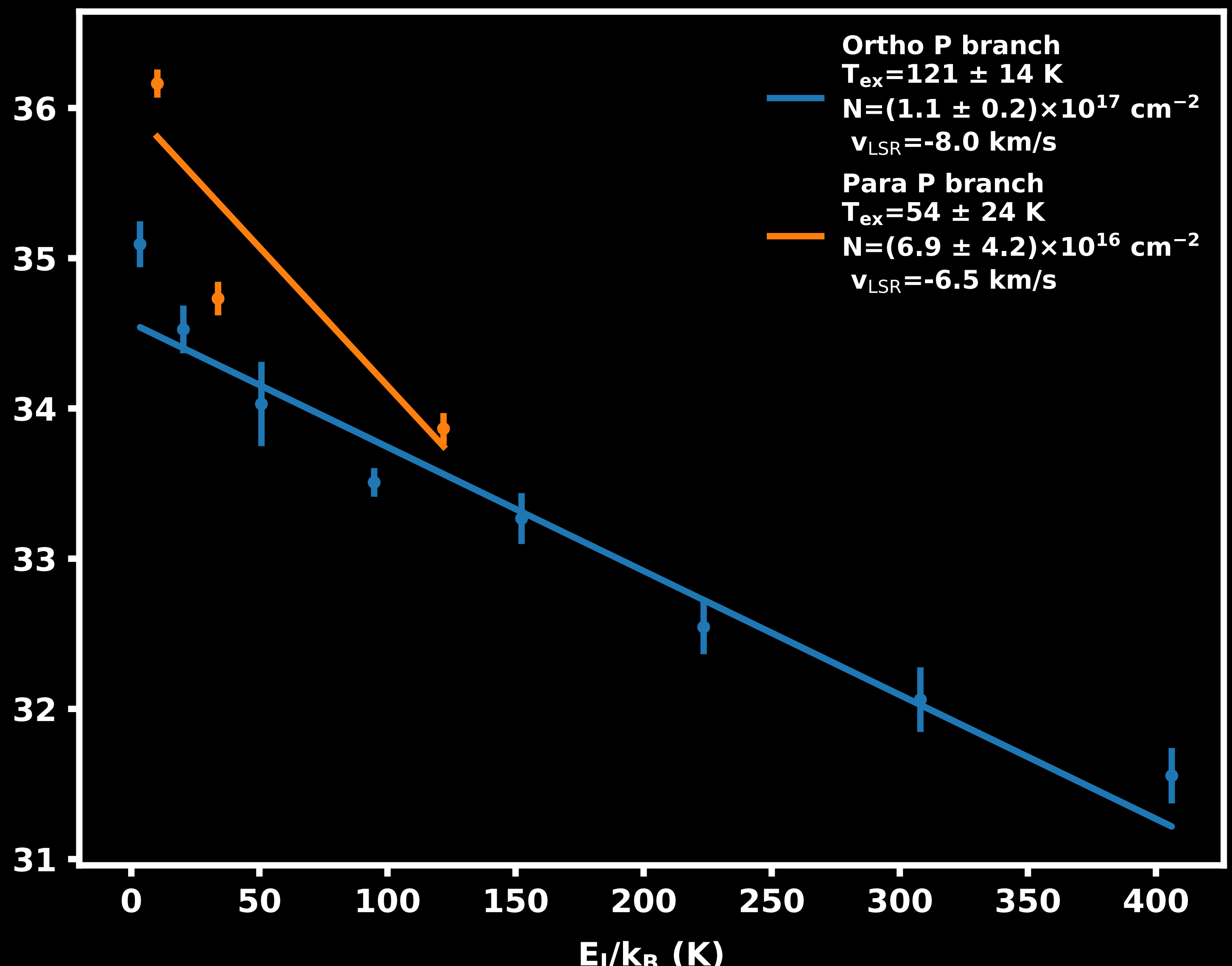
Observed in the wavenumber range 705 to 776 cm^{-1}



- Analyzing main velocity component only
- Find ortho and para transitions for P, Q, and R branches (J→J-1, J→J, and J→J+1 respectively)
- Not so many P branch lines
- P branch ~ 89.5 K, 1.2×10^{16} cm^{-2}
- R branch ~ 176 K, 1.2×10^{16} cm^{-2}
- Q branch ~ 237 K, 6.7×10^{15} cm^{-2}
- Different branches tracing different temperatures of gas
- Average v_{LSR} -7.3 km/s

C_2H_2: Ground state to $\nu_4+\nu_5$

Observed in the wavenumber range 1293 to 1326 cm^{-1}



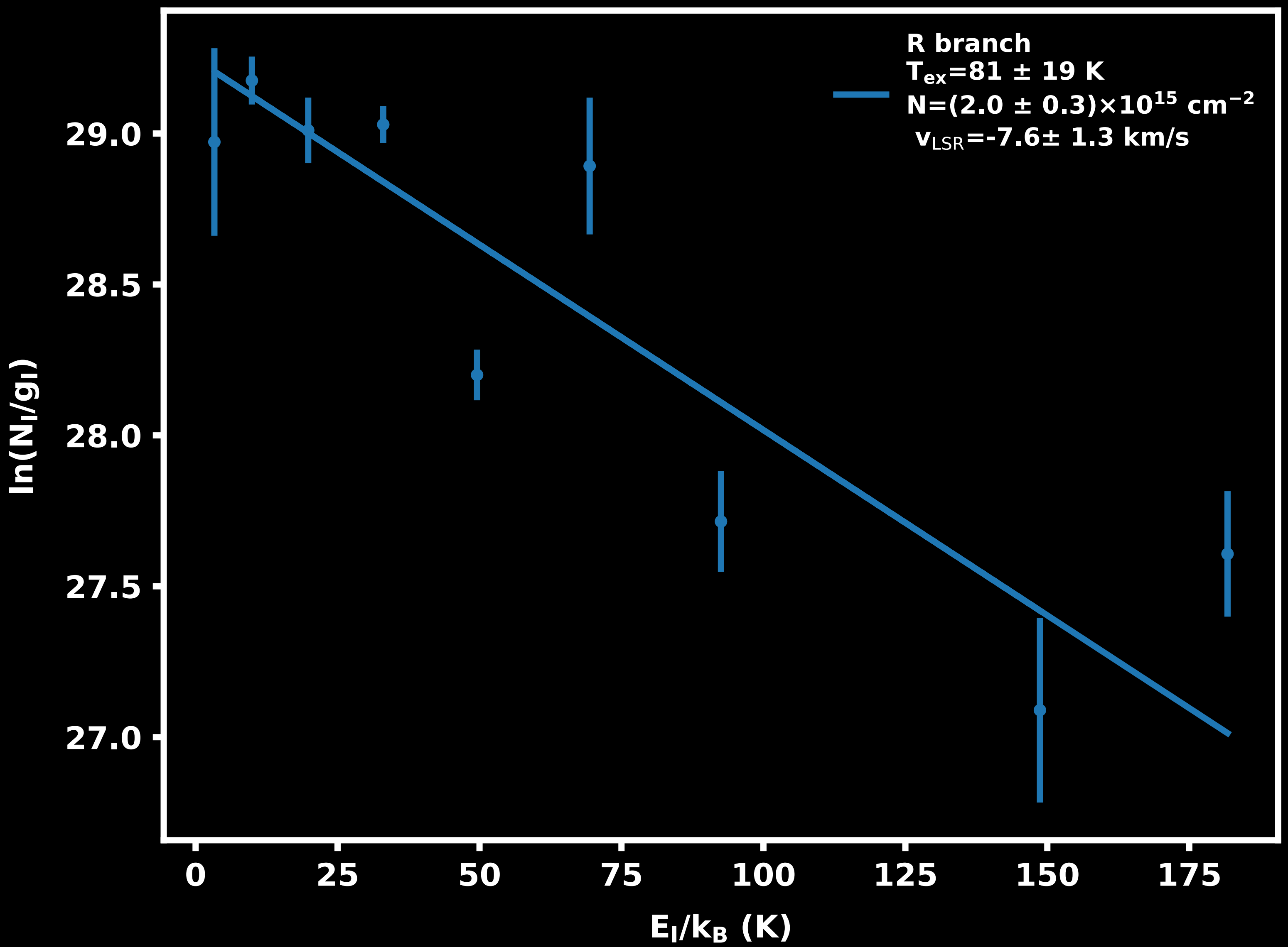
ln(Column Density/Lower Statistical Weight)

Lower State Energy of Each Transition

- Also see two velocity components v_{LSR} ~-7.3 km/s
- Find ortho and para transitions for P branch
- Only see three transitions for para P branch because of atmosphere, unsure of how sensible the analysis is
- Ortho P ~121 K and 1.1x10^{17} cm^{-2}
- Similar temperature to otho P from ν_5 transition, but 10x denser

$^{13}C_2H_2$

ln(Column Density/Lower Statistical Weight)



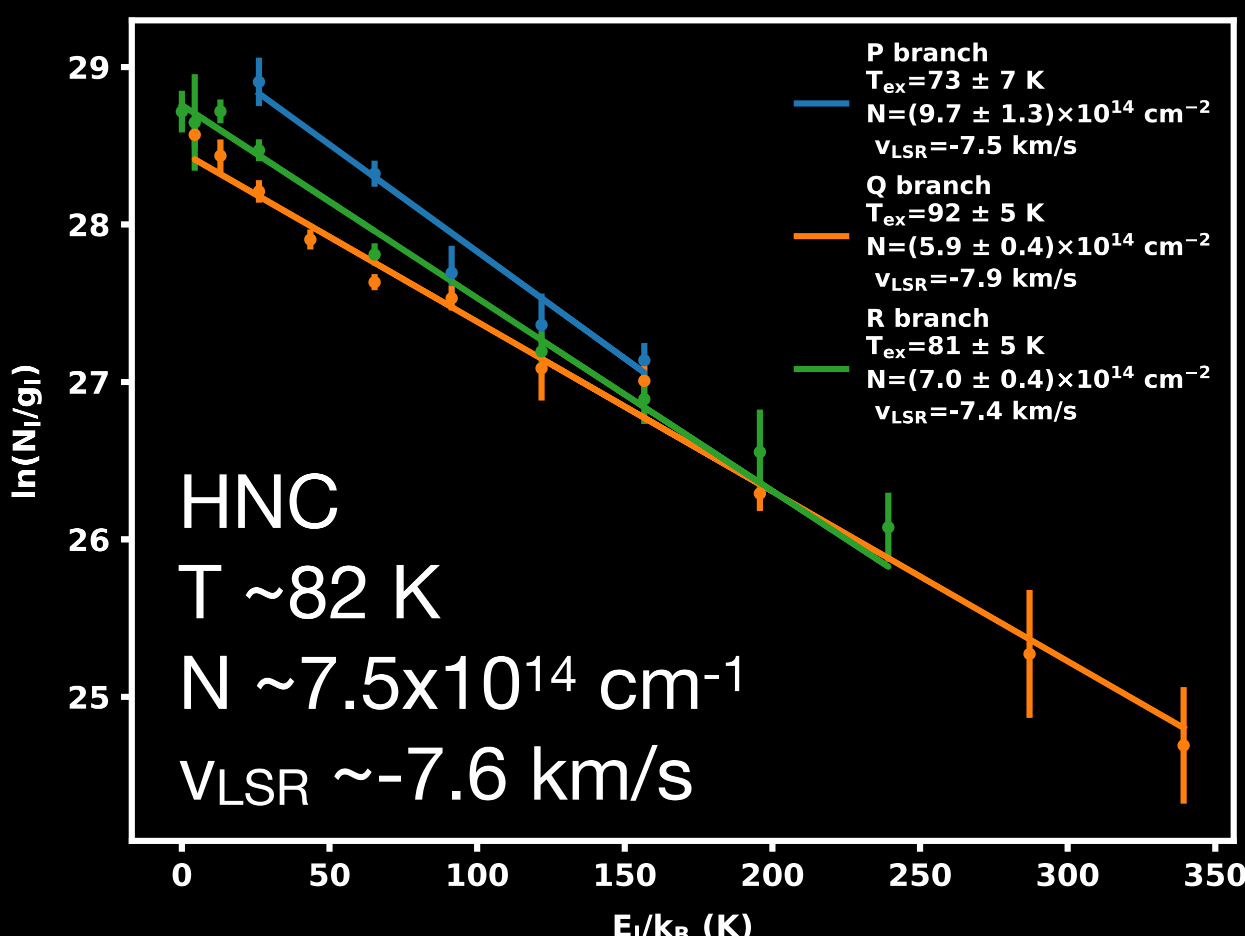
Lower State Energy of Each Transition

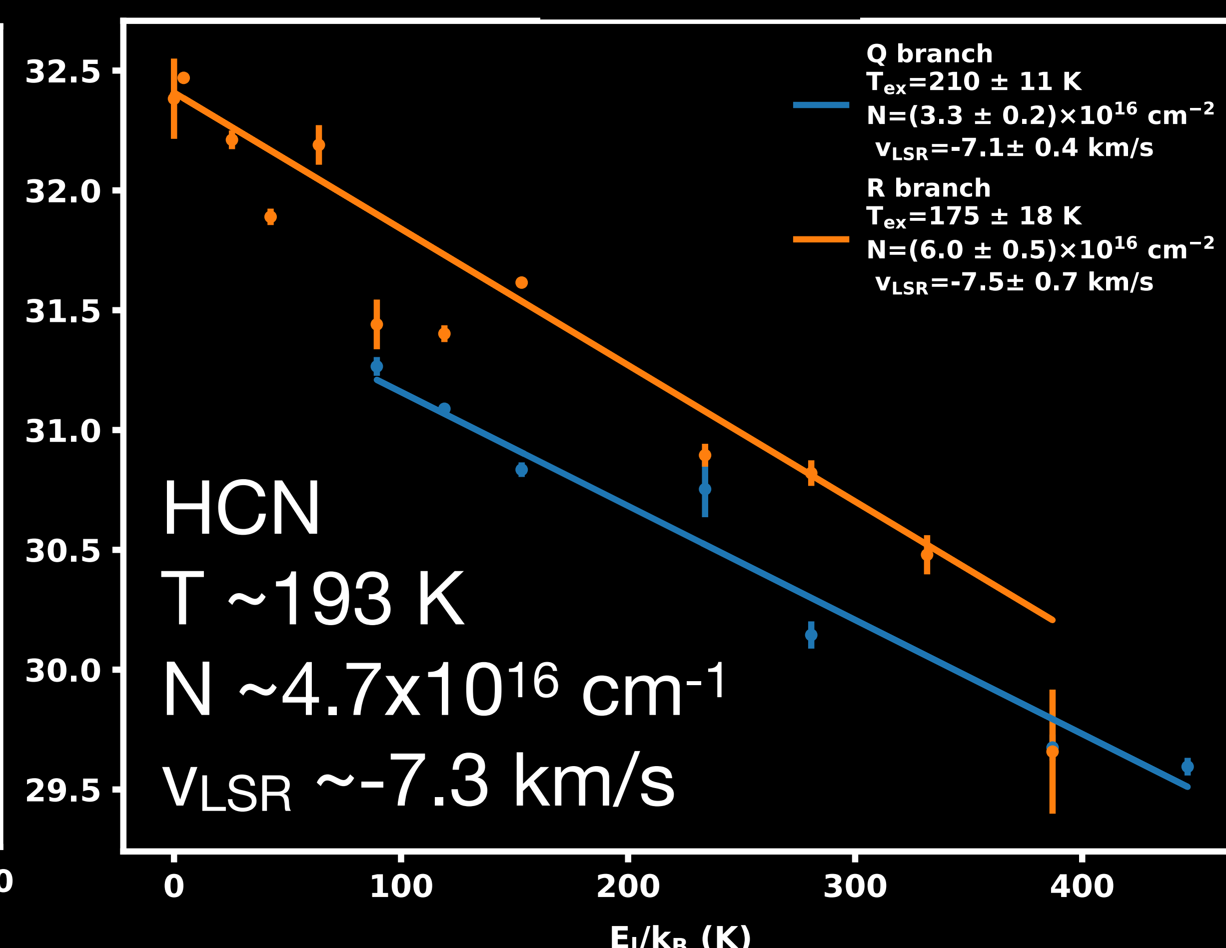
- Similarly to C_2H_2, see two velocity components for cleanest lines; only analyze main one here
- Lines have lower signal to noise than C_2H_2, so more inconsistent line on the Boltzmann diagram
- Only see R branch~81 K, 2x10^{15} cm^{-2}
- Gives isotope ratio: $^{13}CCH_2$/ C_2H_2=0.17

HNC and HCN Comparison

- Isomers HNC and HCN trace the densest, coldest gas
- HCN/HNC nearly equal at low temperatures (Schilke et al., 1992) but HNC depletion increases with temperature (Hirota et al., 1998)

- We find HCN has two velocity components while HNC has one; compare main HCN component to HCN
- ~60 times more HCN than HNC
- HCN is ~100 K hotter than HNC





Further Thoughts

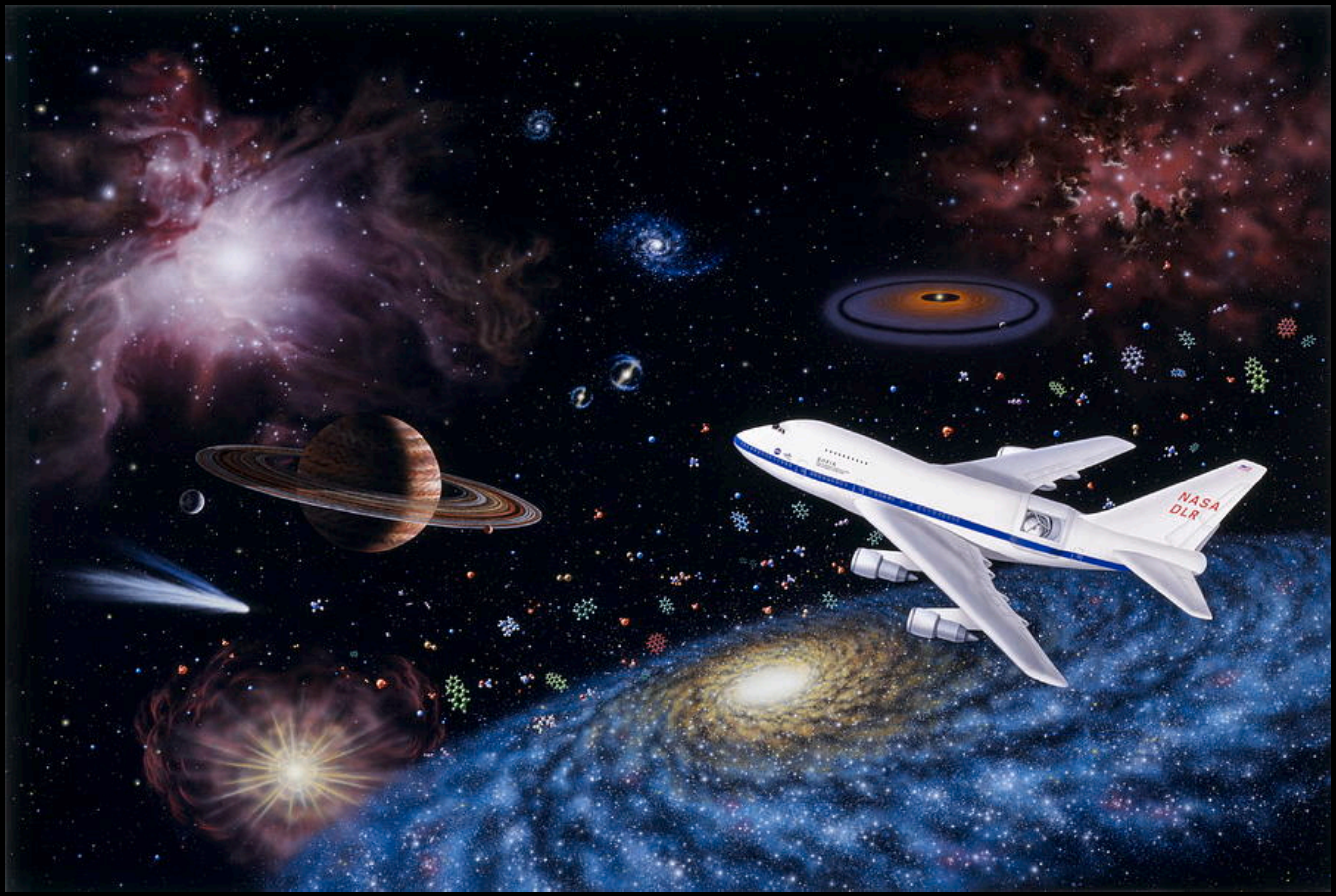
- We also see second isotope $H^{13}CN$ (the latter only has 3 three high signal to noise lines that are difficult to fit)
- HCN/HNC a chemical clock to age IRc2 with modelling of the evolution of the hot core chemistry (e.g. methods of Acharyya et al. 2018, Garrod et. al. 2008)
- HCN an important probe for inflows in star forming regions as seen in radio (Wu and Evans 2003, Sohn et al. 2007)
- Maps of HCN/HNC in Orion-KL region find that it peaks in IRc2 (~80), similar to our ratio, and then decreases to less dense regions (Schilke et al. 1992)
- Morphology of the region, such as the fingers (Bally et al. 2015), suggest shocks, as well as the presence of SO_2 and SiO
- Radio source I has strong OH, H_2O, and SiO maser emission (Johnston et al. 1989 and Genzel et al. 1981)

In future, will connect these puzzle pieces and more to our ongoing chemical survey to figure out what is going on

Conclusions

- With SOFIA/EXES, we are building a molecular inventory for the Orion Hot Core in MIR (7.6 to 25 μm)
- Have identified over 350 features and at least 8 species: HCN, HNC, C2H2, H2O, CH4, SO2, SiO and CS
- Quantities similar to other researchers' findings
- Work is ongoing to calculate the temperatures and physical conditions of the molecular gas
- In future, study how our results fit with models and theoretical interpretations of the hot core
- Will compare our data to other hot cores in the SOFIA archives; how does environment affect chemistry?

Watch this space: more results to come!



Artwork by Lynette Cook