Molecules in Massive Protostars from the Near to Mid Infrared: Unique Constraints from SOFIA/EXES

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Based largely on results from...

Indriolo et al. 2015, ApJL, 802, L14

SOFIA/EXES Observations of Water Absorption in the Protostar AFGL 2591 at High Spectral Resolution

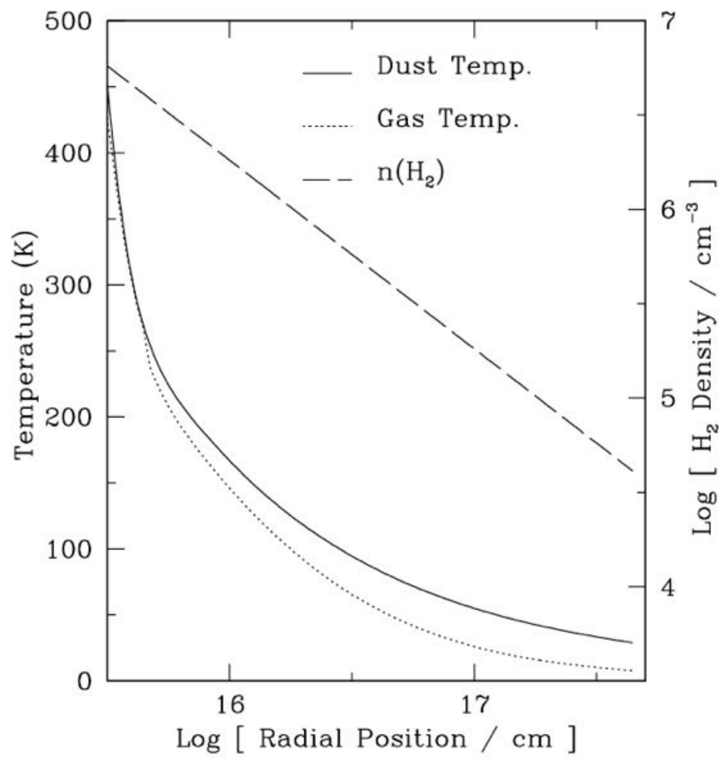
David Neufeld, Curtis DeWitt, Matt Richter, Adwin Boogert, Graham Harper, Dan Jaffe, Kristin Kulas, Mark McKelvey, Nils Ryde, & Bill Vacca

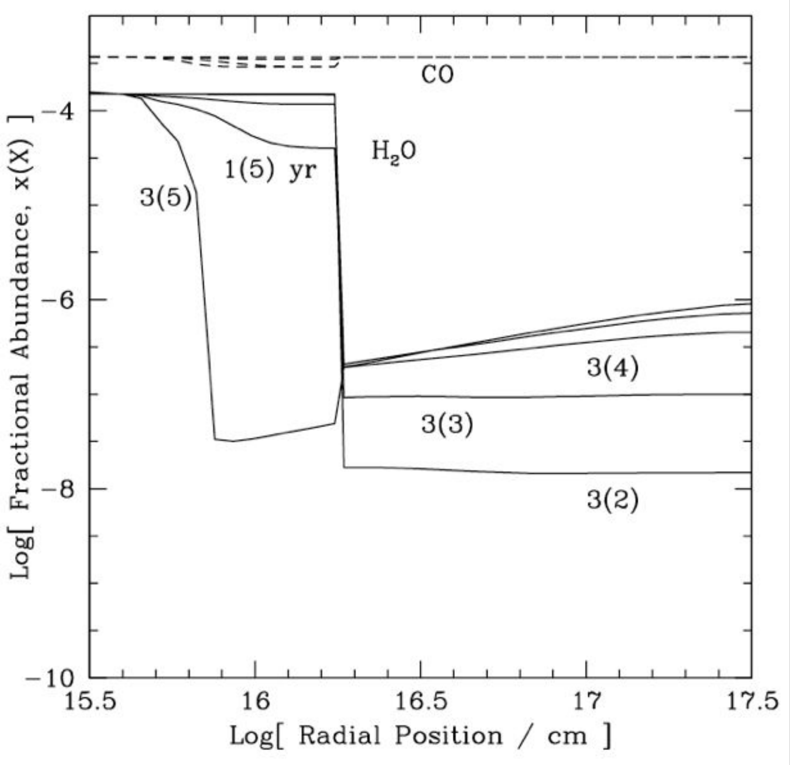
Massive Protostars

- Luminous central objects (10^4 L_{sun})
- Deeply embedded within gaseous envelope
- High temperature chemistry
- Multiple kinematic components (envelope, disk, torus, jet, wind, outflow, infall)
- Large scale molecular outflows

Chemical Models

Doty et al. 2002, A&A, 389, 446

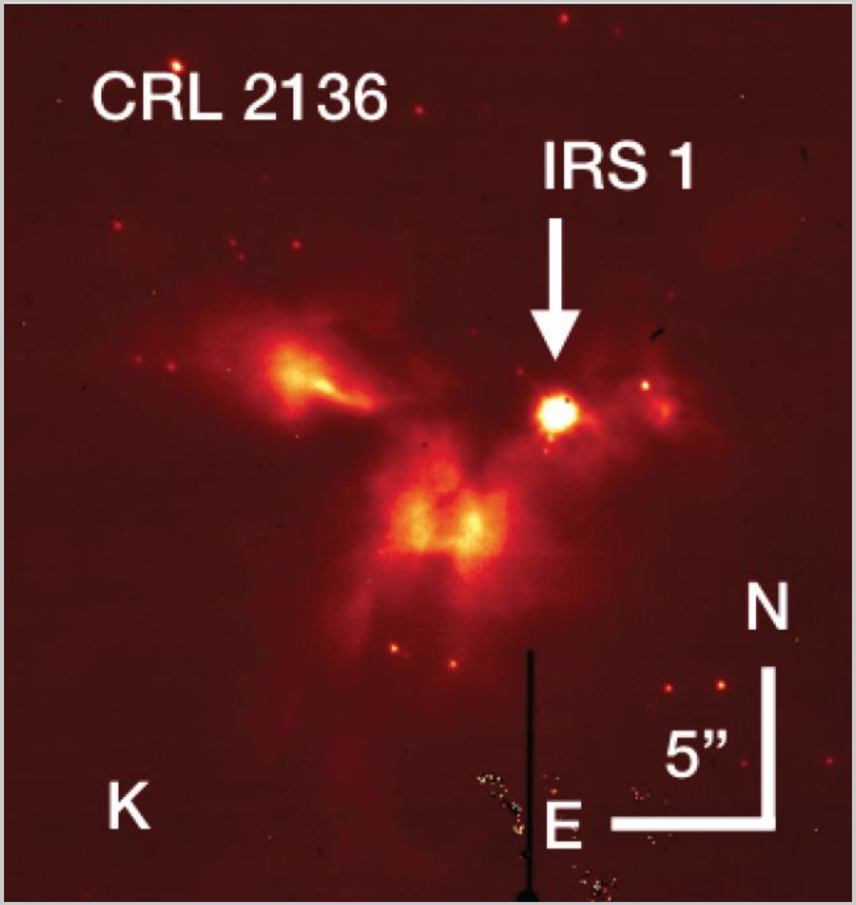




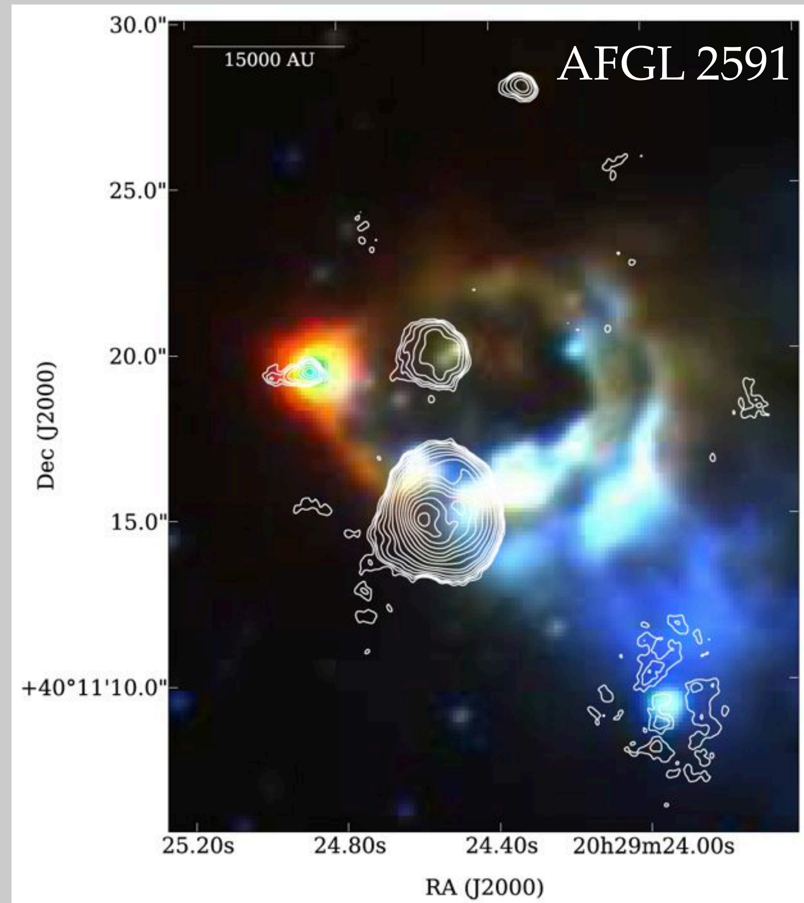
Simple models predict roughly half of the oxygen in CO and half in H_2O in the inner envelope. H_2O ice is abundant in outer envelope.

NIR Images

Not quite spherically symmetric

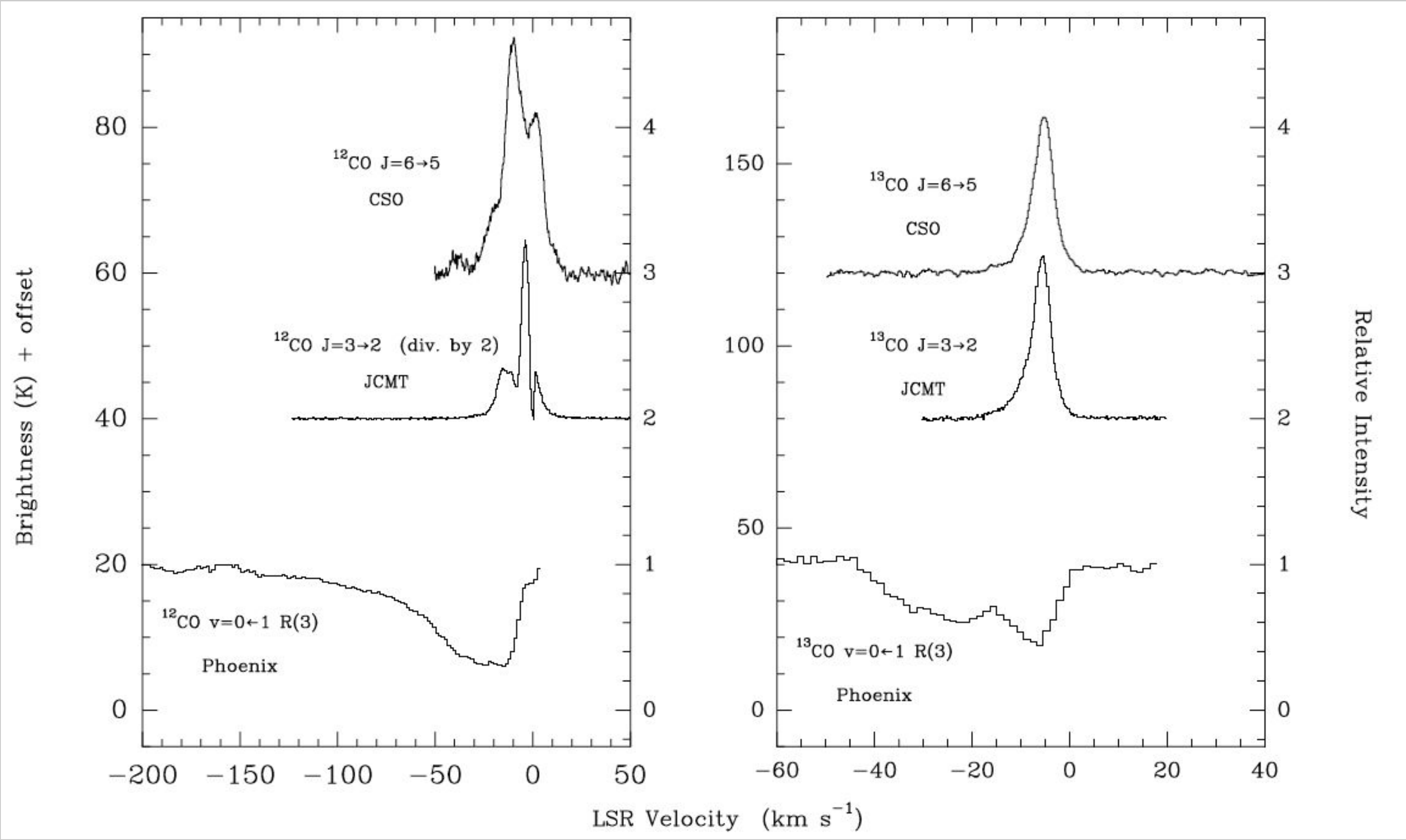


M. Goto 2013, private comm.



Johnston et al. 2013, A&A, 551, A43

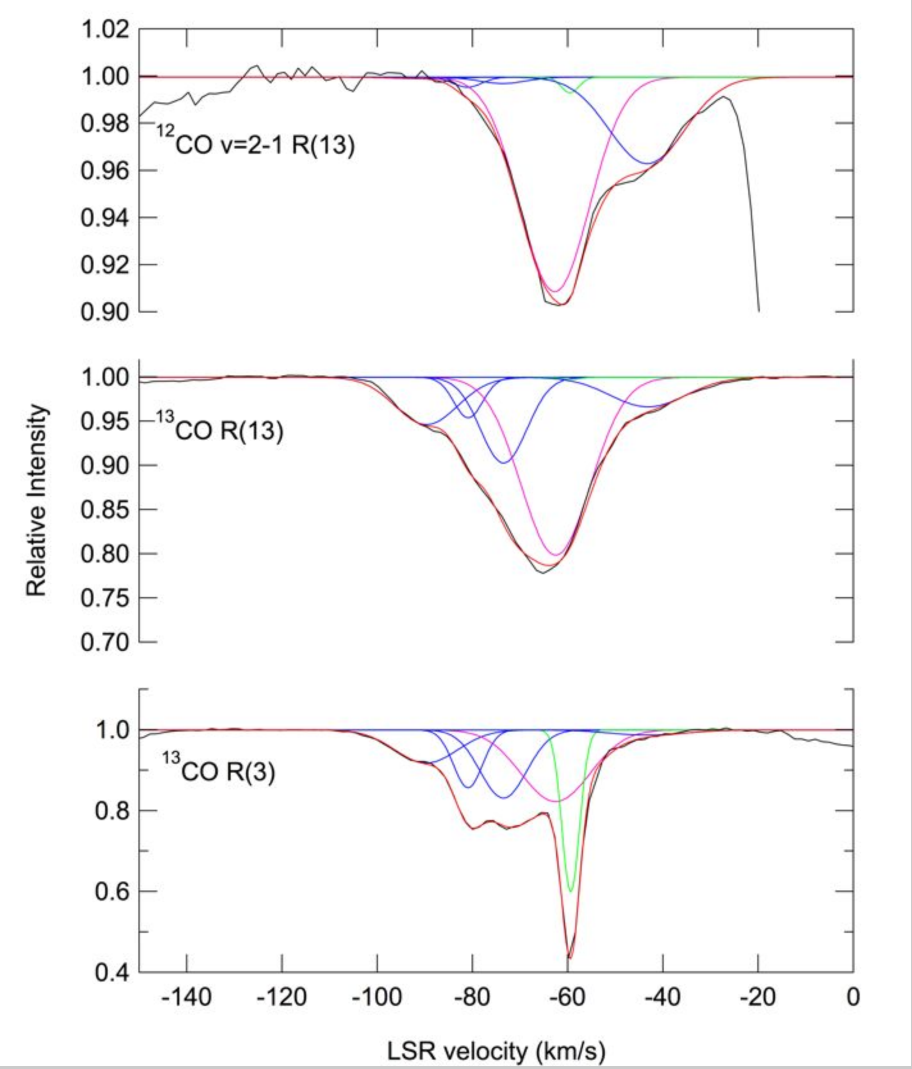
CO Observations of AFGL 2591



van der Tak et al. 1999, ApJ, 522, 991

CO in AFGL 4176

- CRIRES observations of ^{13}CO v=1-0 band
- Detections of ^{12}CO, ^{13}CO, $C^{18}O$, $C^{17}O$, and ^{12}CO v=2-1
- Currently under analysis by Agata Karska



CO spectra are complicated

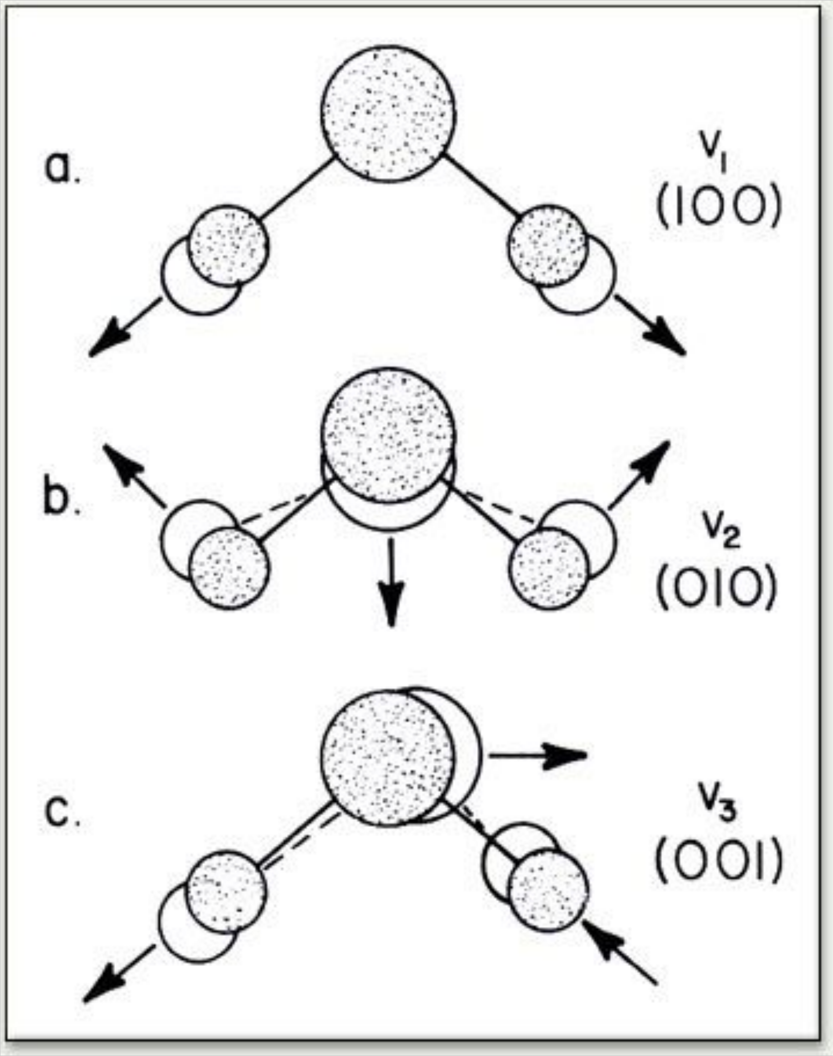
- There are multiple velocity components absorbing in CO, all of which vary in different ways with rotational level
- Difficult to decompose absorption features, especially with blends between isotopologues
- We'd like a simpler tracer of the gas around protostars
- Some possibilities: H_2O, C_2H_2, HCN

Astrophysical Water

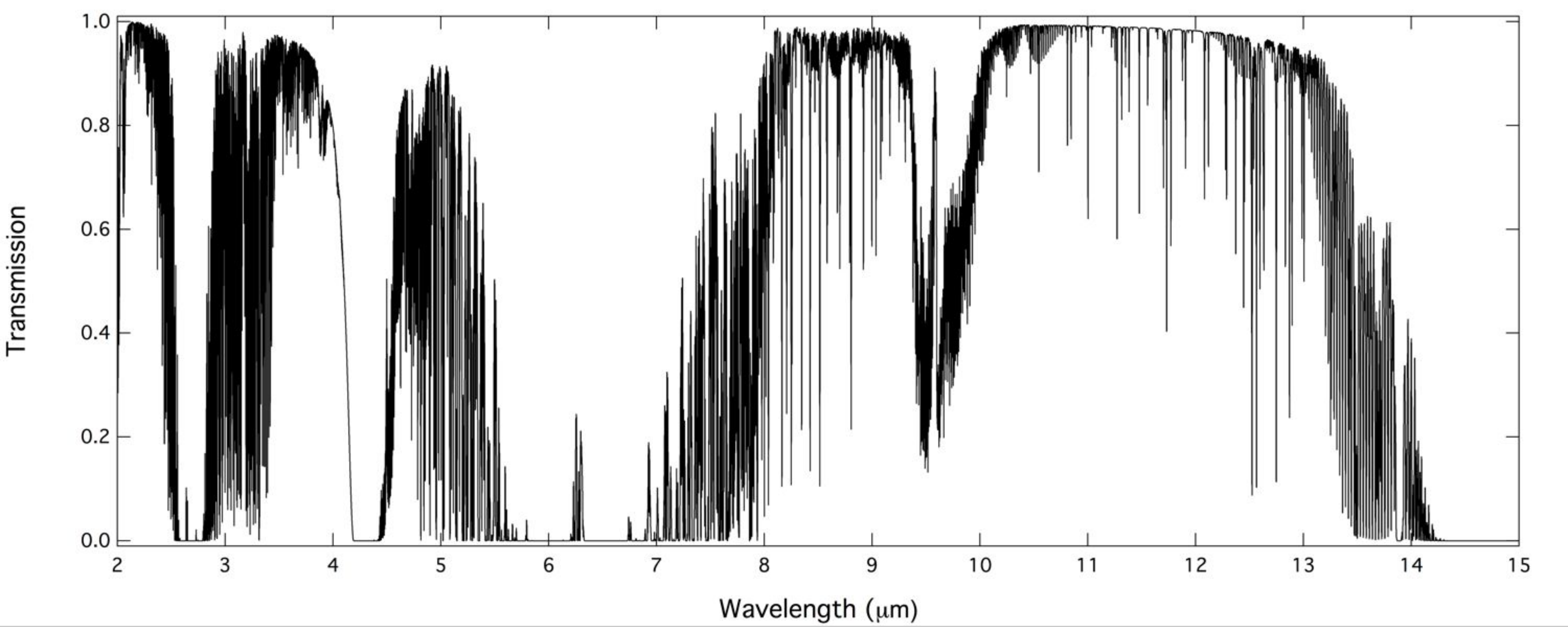
- H_2O is difficult to observe in astrophysical objects due to Earth's atmosphere (with the exception of masers)

Water Vibrational Bands

- ν_1: symmetric stretch
  - 2.7 μm
- ν_2: bend
  - 6.1 μm
- ν_3: asymmetric stretch
  - 2.7 μm



Atmospheric Transmission

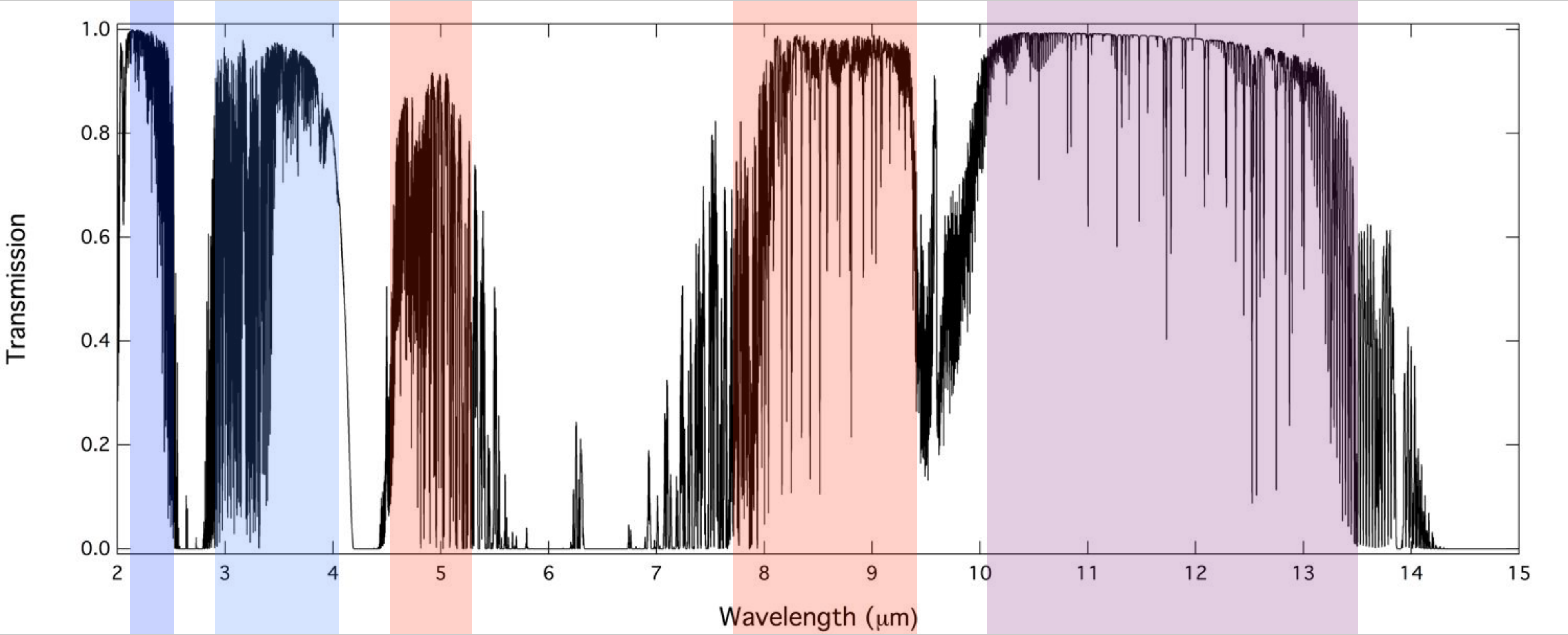


ATRAN (Lord 1992) simulated atmospheric spectrum at 14,000 ft with 2.5 mm PWV

Astrophysical Water

- H_2O is difficult to observe in astrophysical objects due to Earth's atmosphere (with the exception of masers)
- Two options:
  - (1) target transitions not populated in atmosphere
  - (2) go above the atmosphere

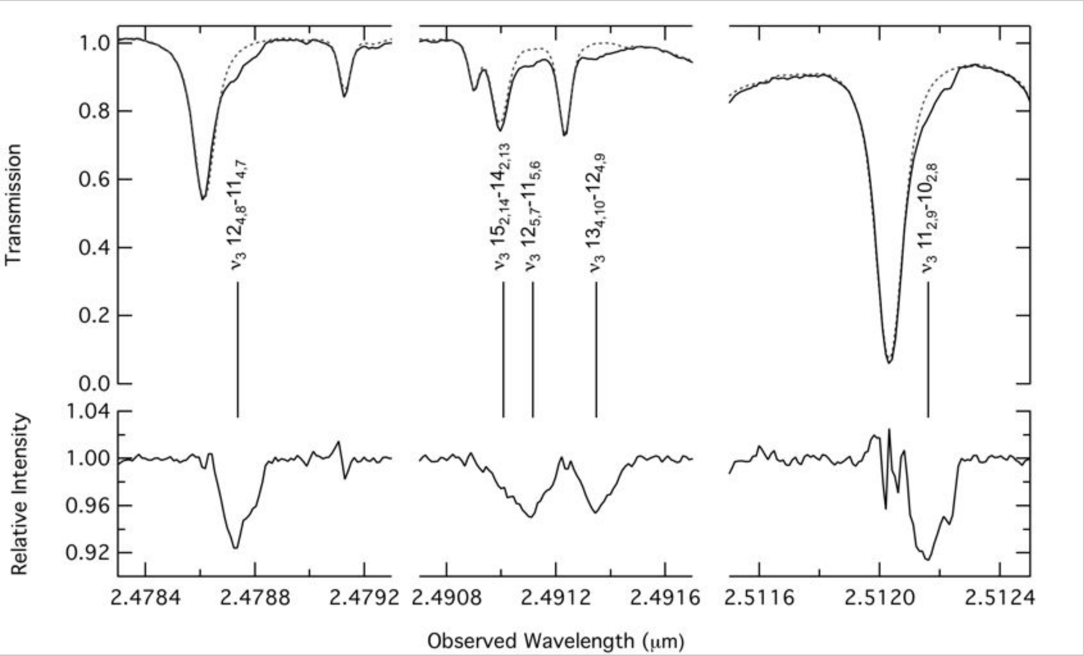
Go Over (in wavelength)



H_2O ν_1 and ν_3 H_2O ν_2 H_2O rotational

Water in AFGL 2136

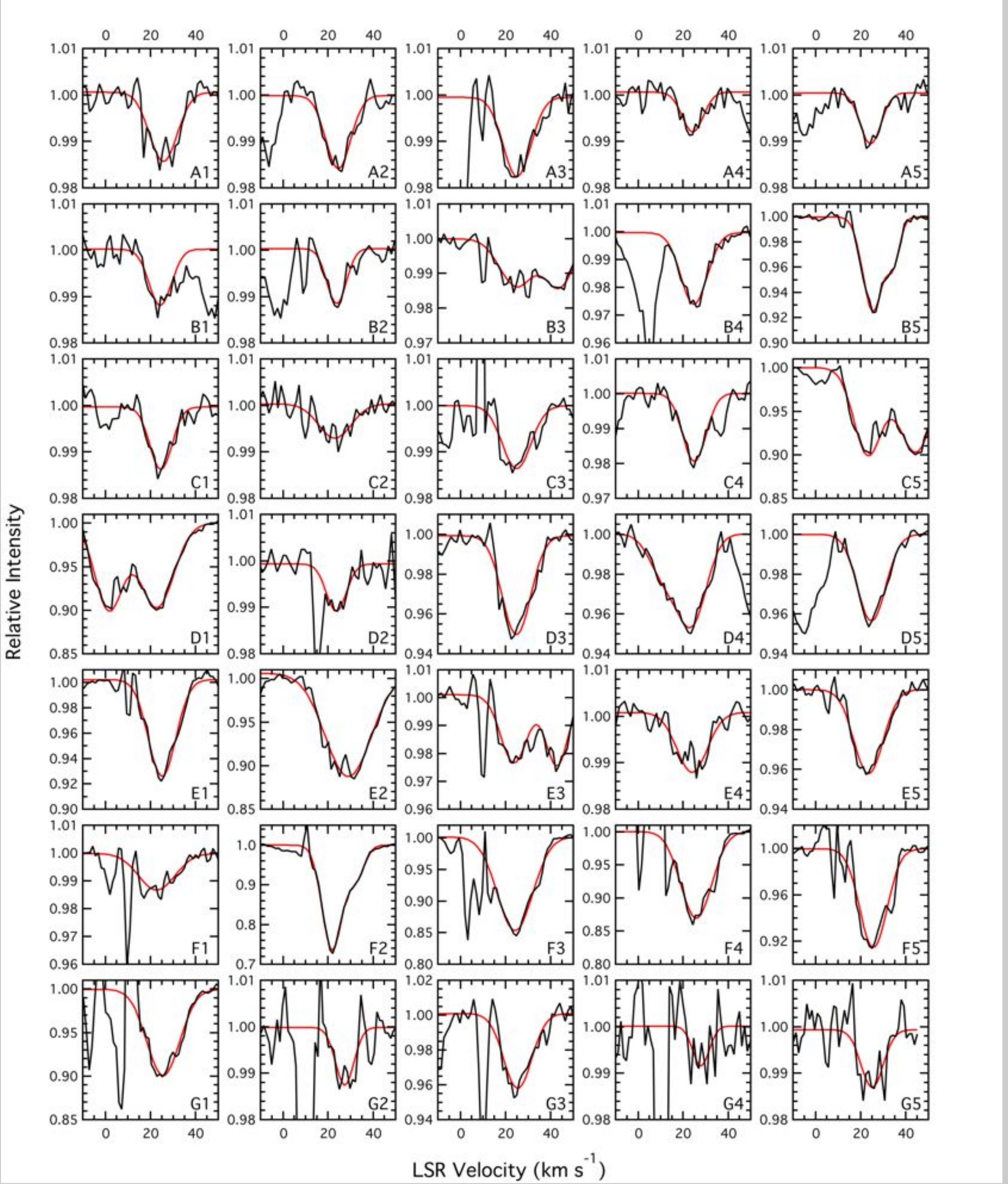
- Massive protostar used as a background source searching for HF $R(0)$ transition
- Atmospheric water lines show absorption wing
- Realized it's coming from the protostar



data from CRIRES at VLT

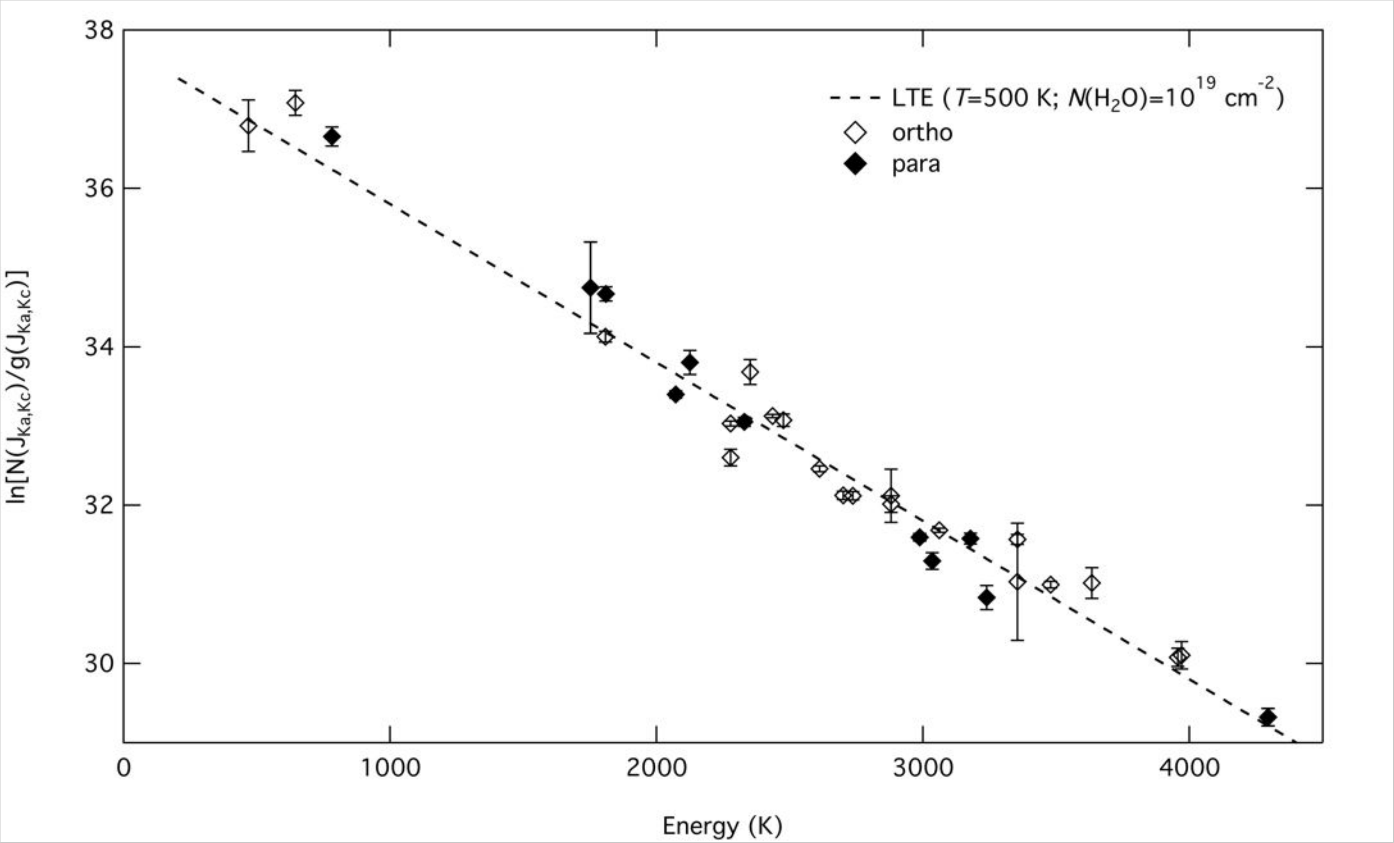
Water in AFGL 2136

- 35 absorption features
- 47 transitions probing 44 unique levels



Indriolo et al. 2013, ApJ, 776, 8

AFGL 2136 Rotation Diagram



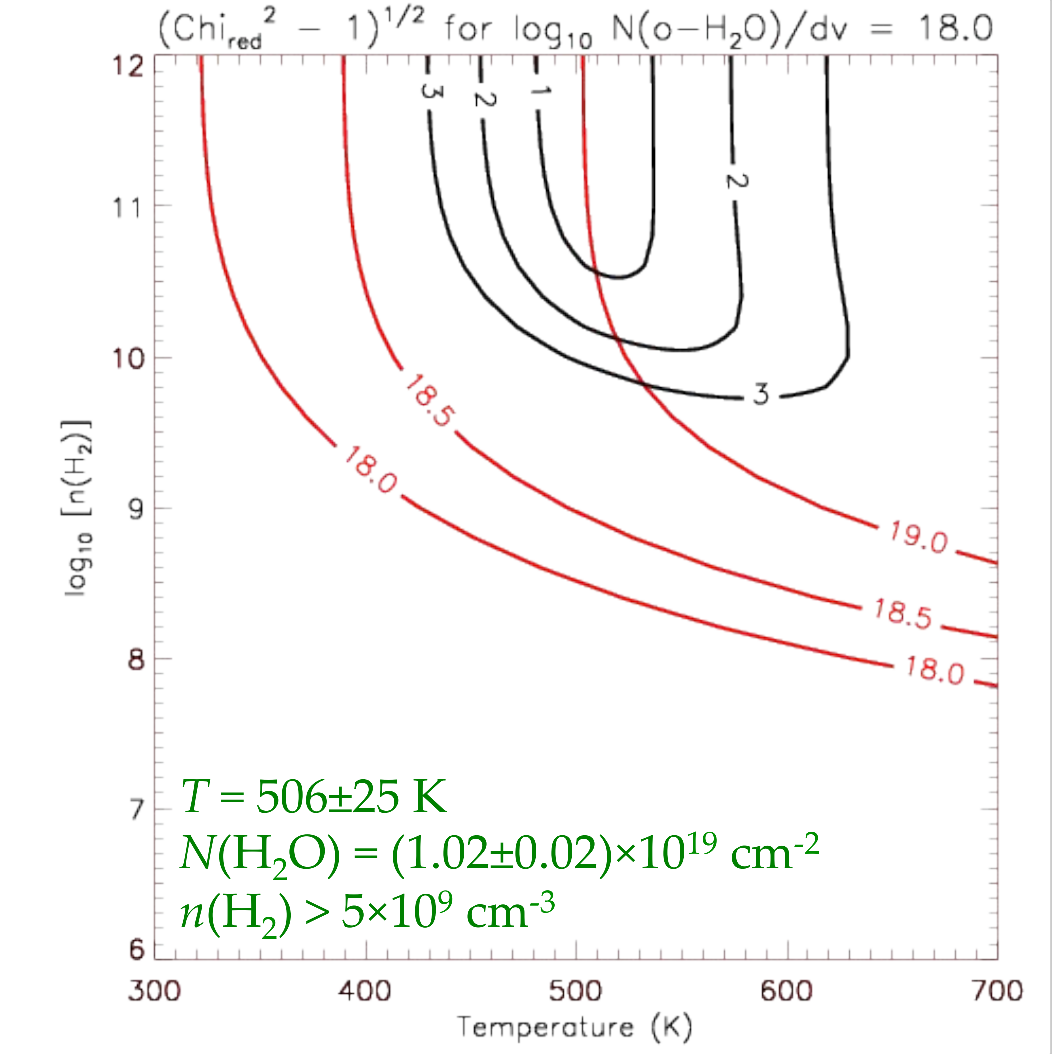
- Well matched by single temperature LTE

Model with Radiative Transfer

- Statistical equilibrium analysis
- Accounts for radiative trapping
- Fair agreement with ISO results

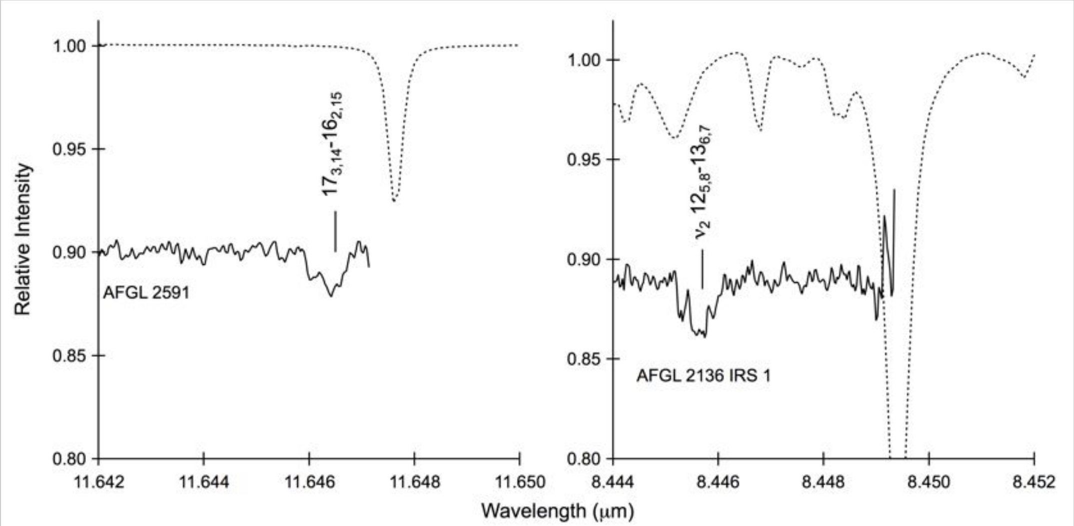
  $T = 500 \pm 200$ K
  $N(H_2O) = (1.5 \pm 0.6) \times 10^{18}$ cm^{-2}

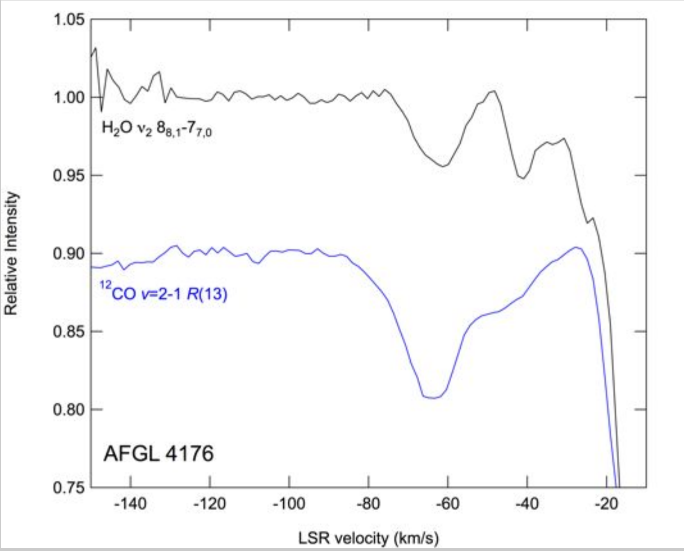
- Improved with data probing levels at low/high energy



Example ν_2 & Rotational Transitions

- Archival TEXES data courtesy of John Lacy and Matt Richter
- H_2O detected in absorption

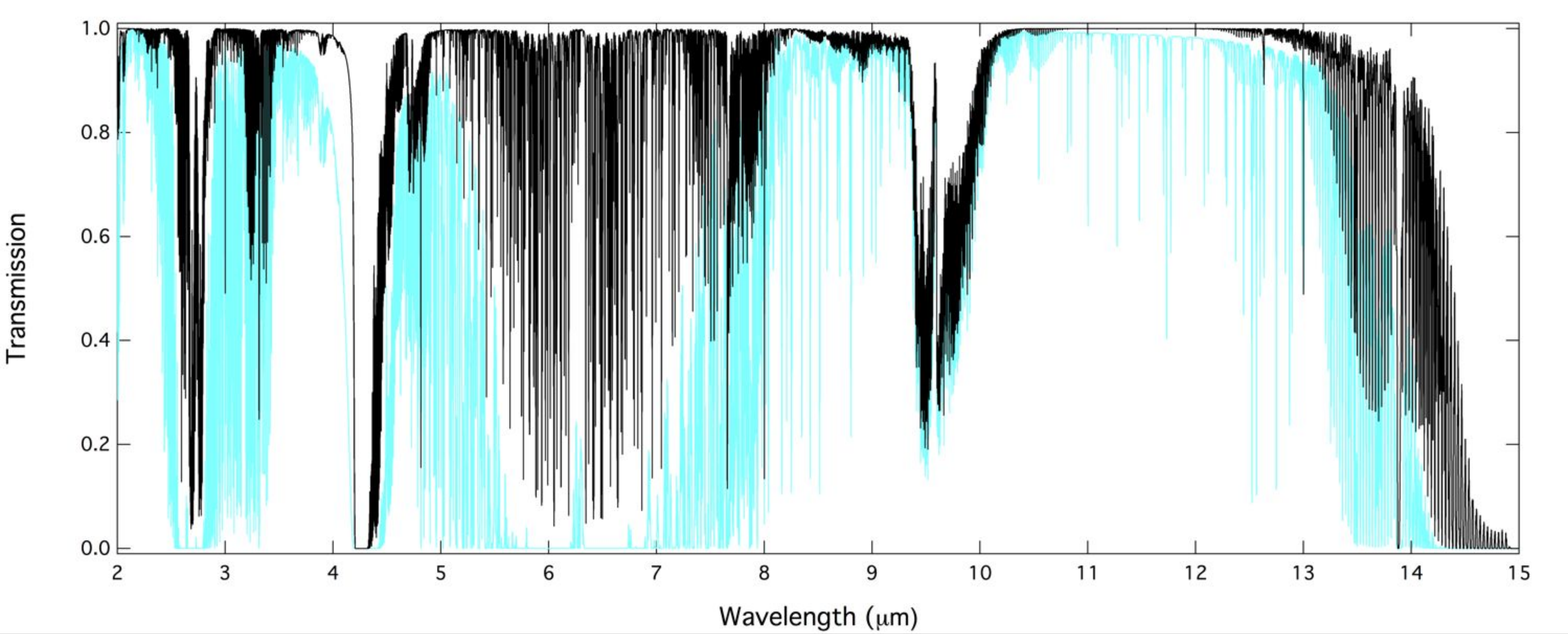




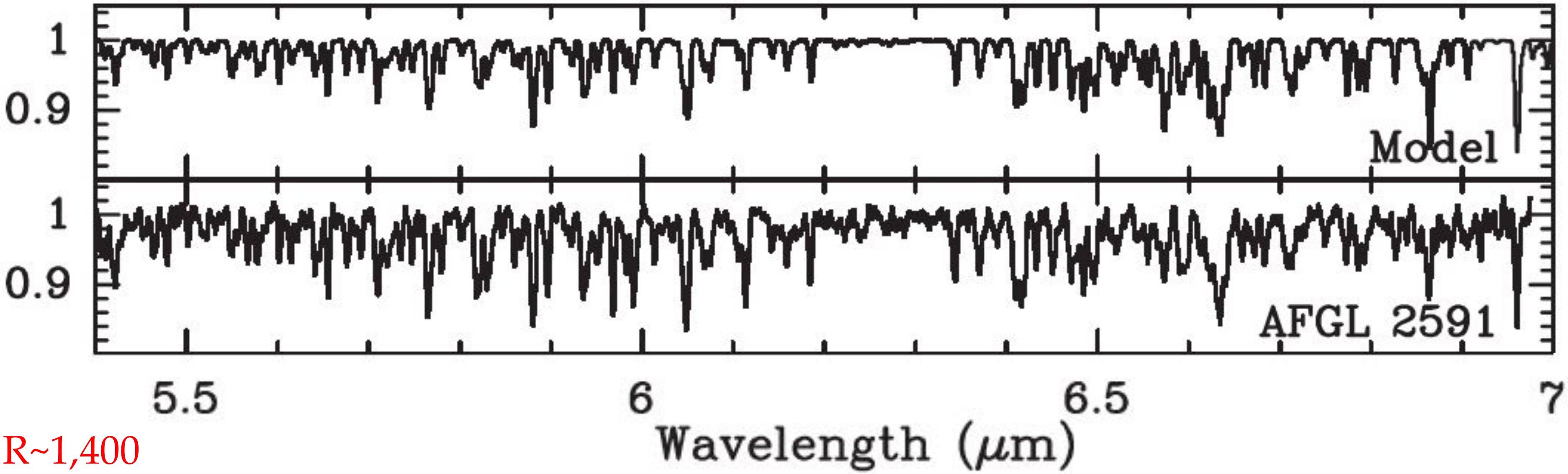
- CRIRES observations targeting CO at 4.7 μm also cover water transitions
- Absorption profile best matches vibrationally excited ^{12}CO

Go Over (the Atmosphere)

ATRAN (Lord 1992) simulated atmospheric spectrum at 43,000 ft with 0.01 mm PWV



ISO Observations (AFGL 2591)



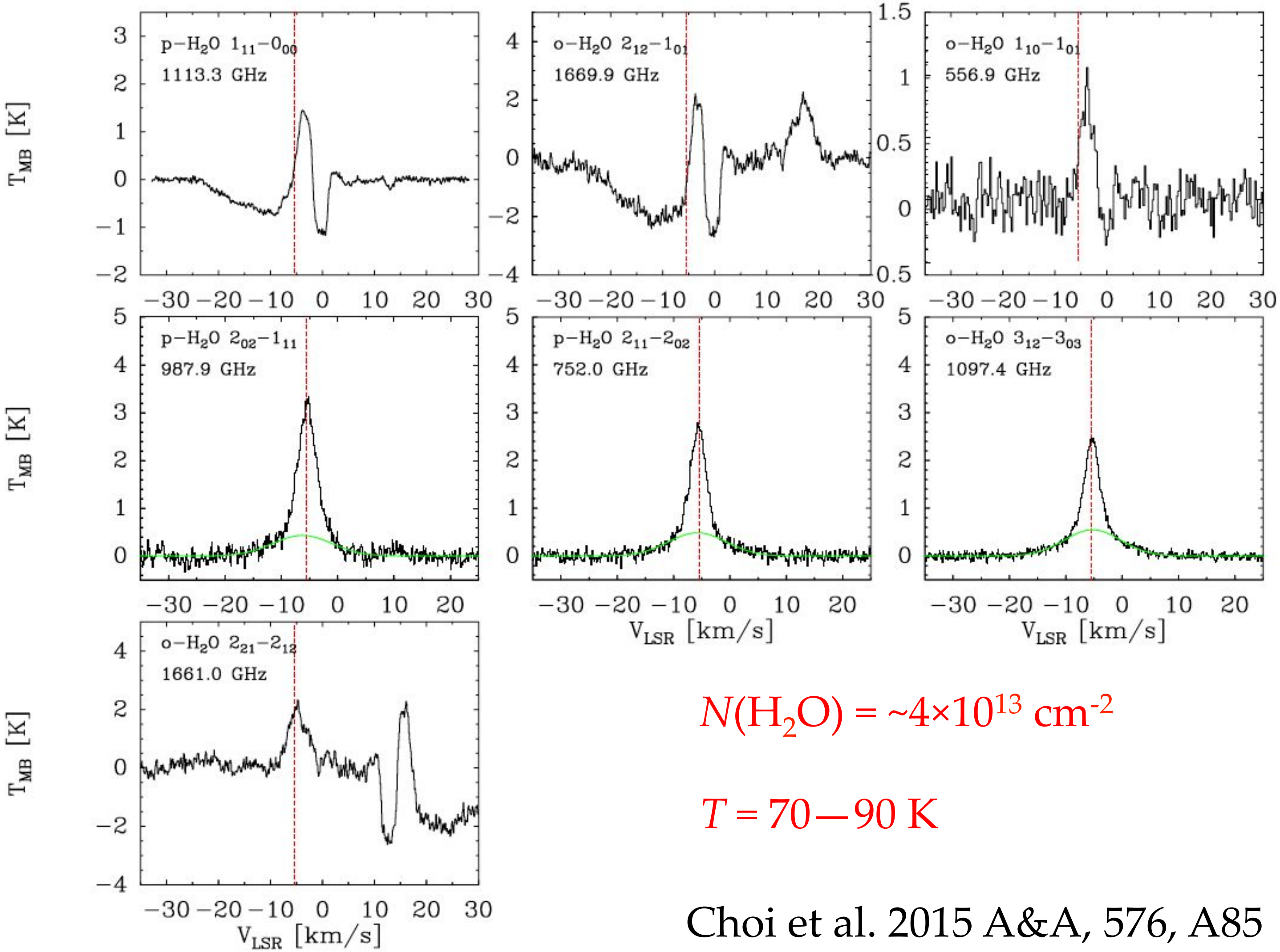
R~1,400

Boonman & van Dishoeck 2003, A&A, 403, 1003

$N(H_2O) = (3.5 \pm 1.5) \times 10^{18}$ cm^{-2} $\quad T = 450 \pm 200$ K

- Analysis relies on model fit assuming some Doppler parameter

HIFI Observations (AFGL 2591)



$N(H_2O) = \sim 4\times10^{13}\ cm^{-2}$

$T = 70$—90 K

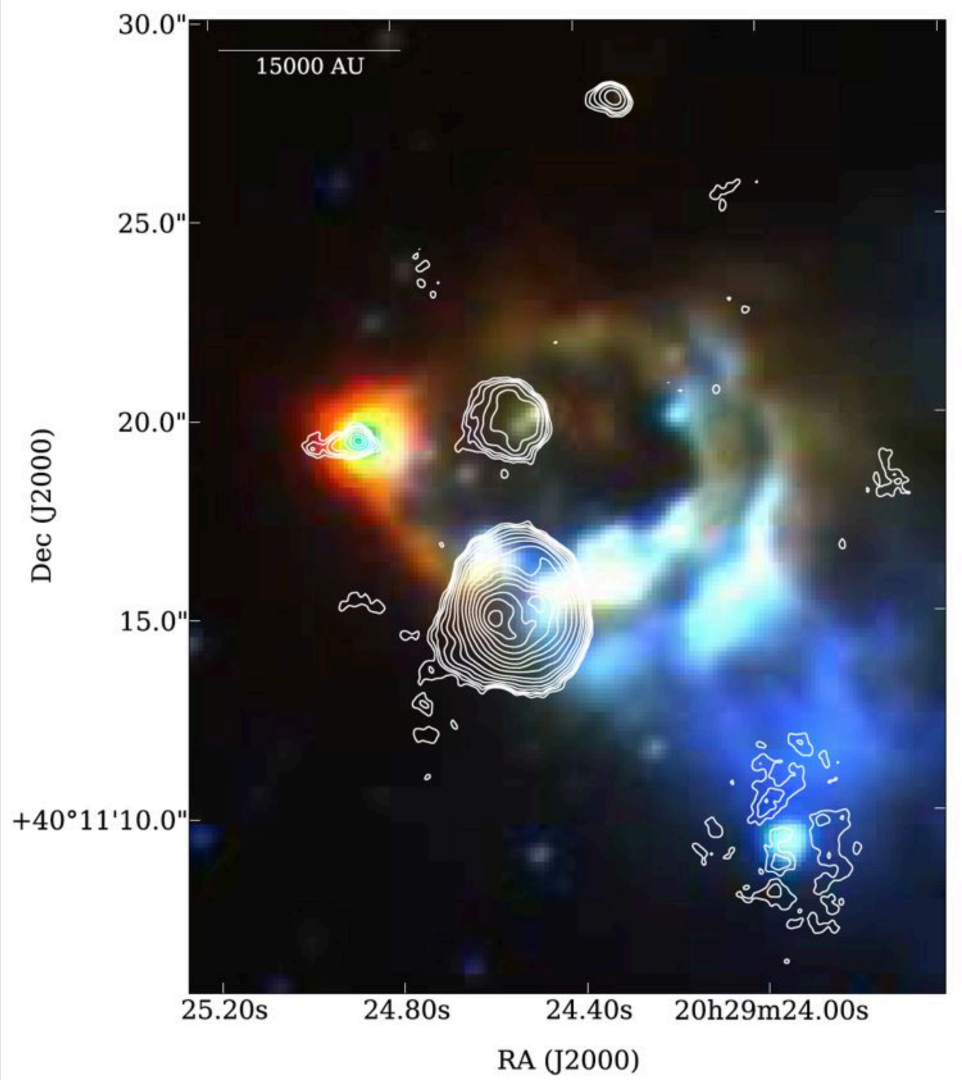
Choi et al. 2015 A&A, 576, A85

Targeting AFGL 2591

- ISO observations show that source has 6 μm water absorption
- Know that it shows absorption from the $J_{KaKc} = 0_{0,0}$ and $1_{0,1}$ levels (ground para & ortho)
- Flux at 6 μm is 520 Jy
- Good target for EXES commissioning flight (Apr. 10, 2014), both with respect to location and Doppler shift

AFGL 2591 Region

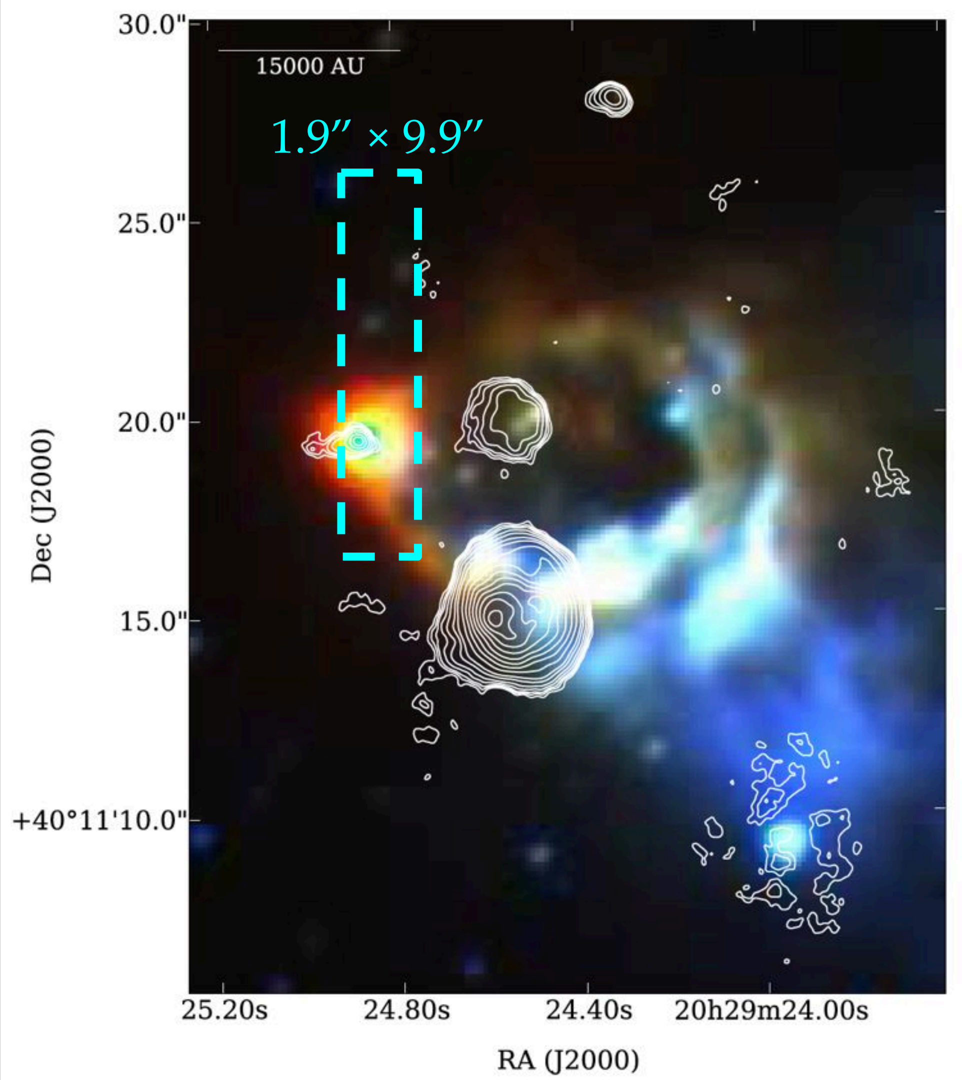
- *JHK′* image GemN
- 3.6 cm contours VLA
- Massive protostar is associated with source VLA 3



Johnston et al. 2013, A&A, 551, A43

AFGL 2591 Region

- *JHK′* image GemN
- 3.6 cm contours VLA
- Massive protostar is associated with source VLA 3
- Central source nodded along slit
- Subtract image pairs

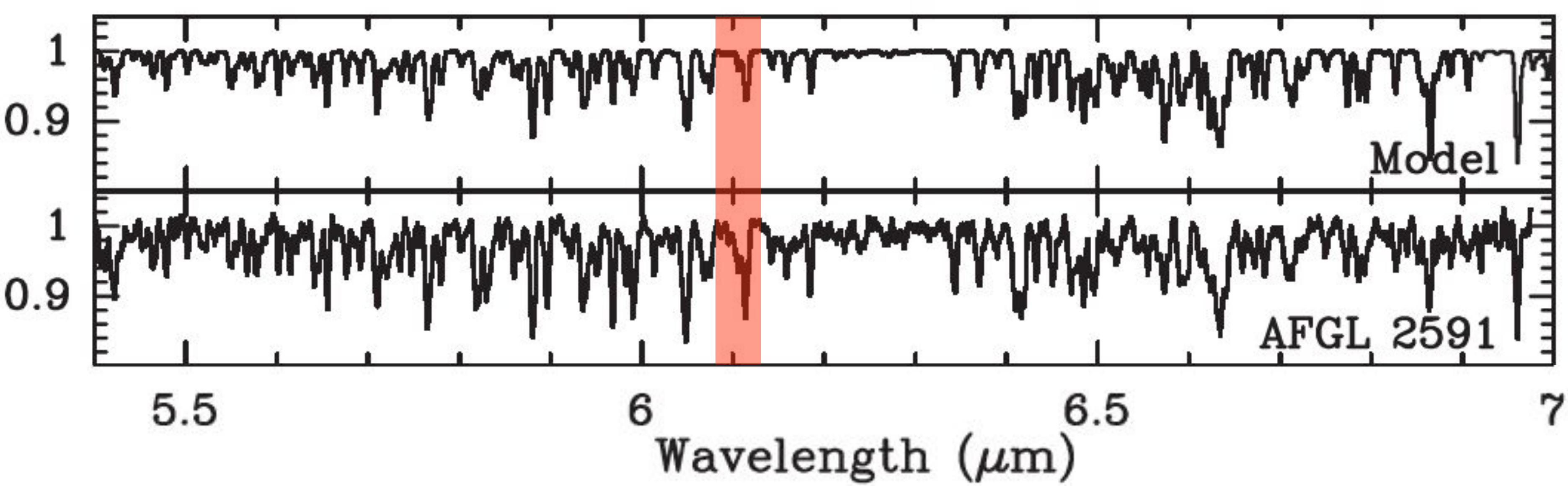


Johnston et al. 2013, A&A, 551, A43

Observing Setup

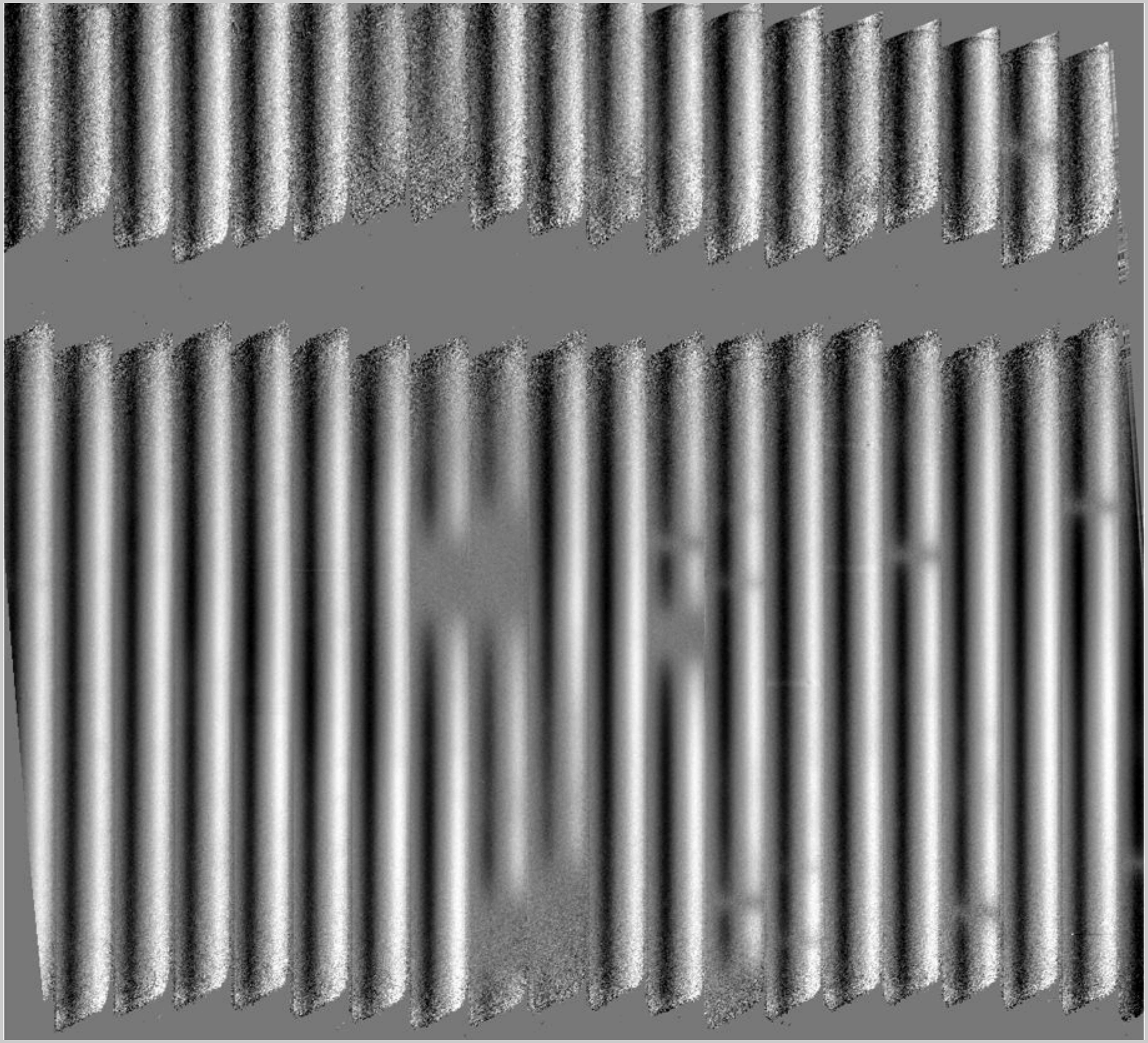
- Altitude: 43,000 ft
- Reference Wavelength: 6.1125 μm
- Slit: 1.9″× 9.9″ (R~86,000; res~3.5 km/s)
- Exposure Time: 1134 s (42 at 27 s each)
- Standard Star: Vega (100 Jy @ 6μm)
  - Observed during flight leg 2 hr prior to science target, at comparable altitude and air mass

EXES vs ISO coverage

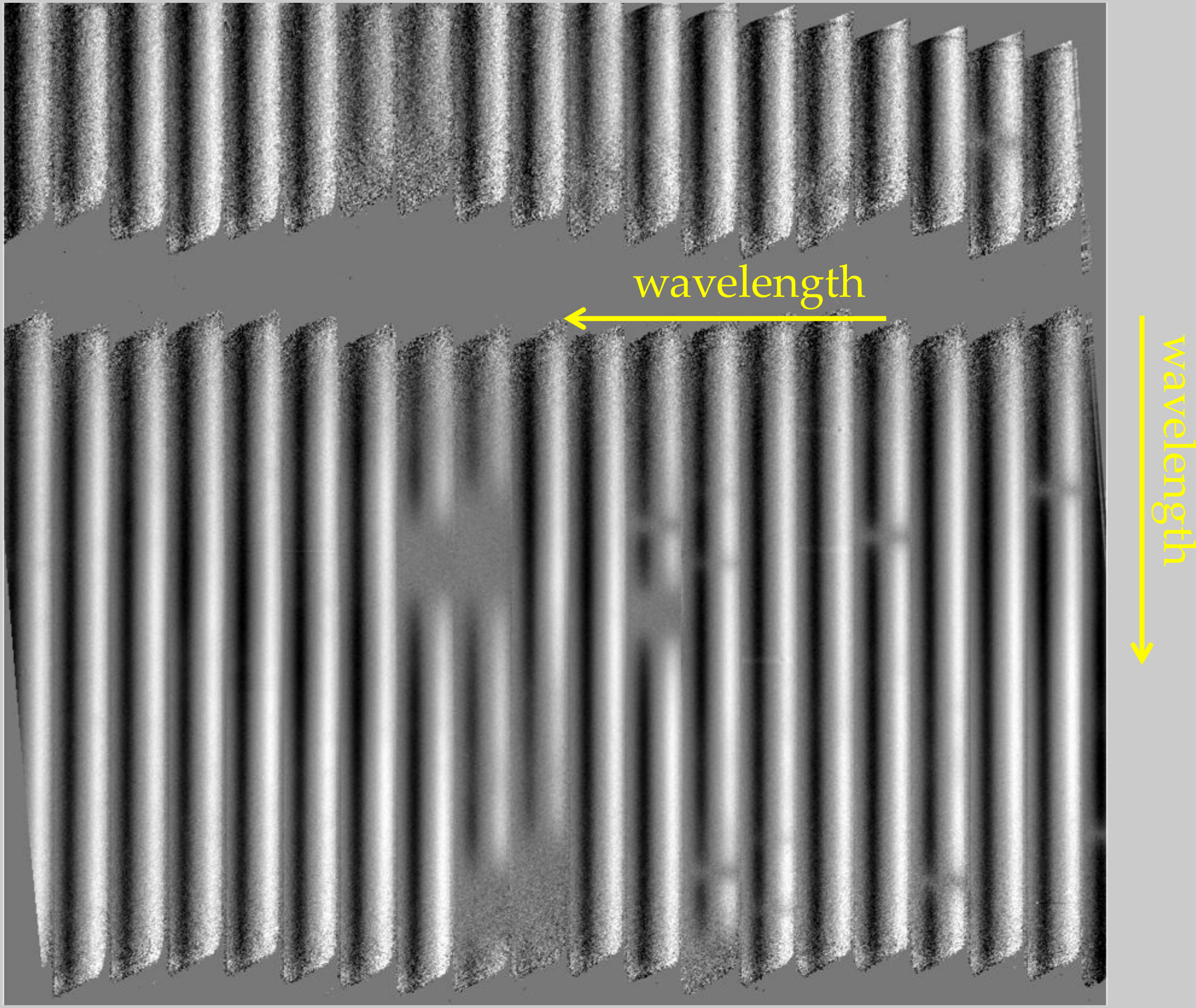


Boonman & van Dishoeck 2003, A&A, 403, 1003

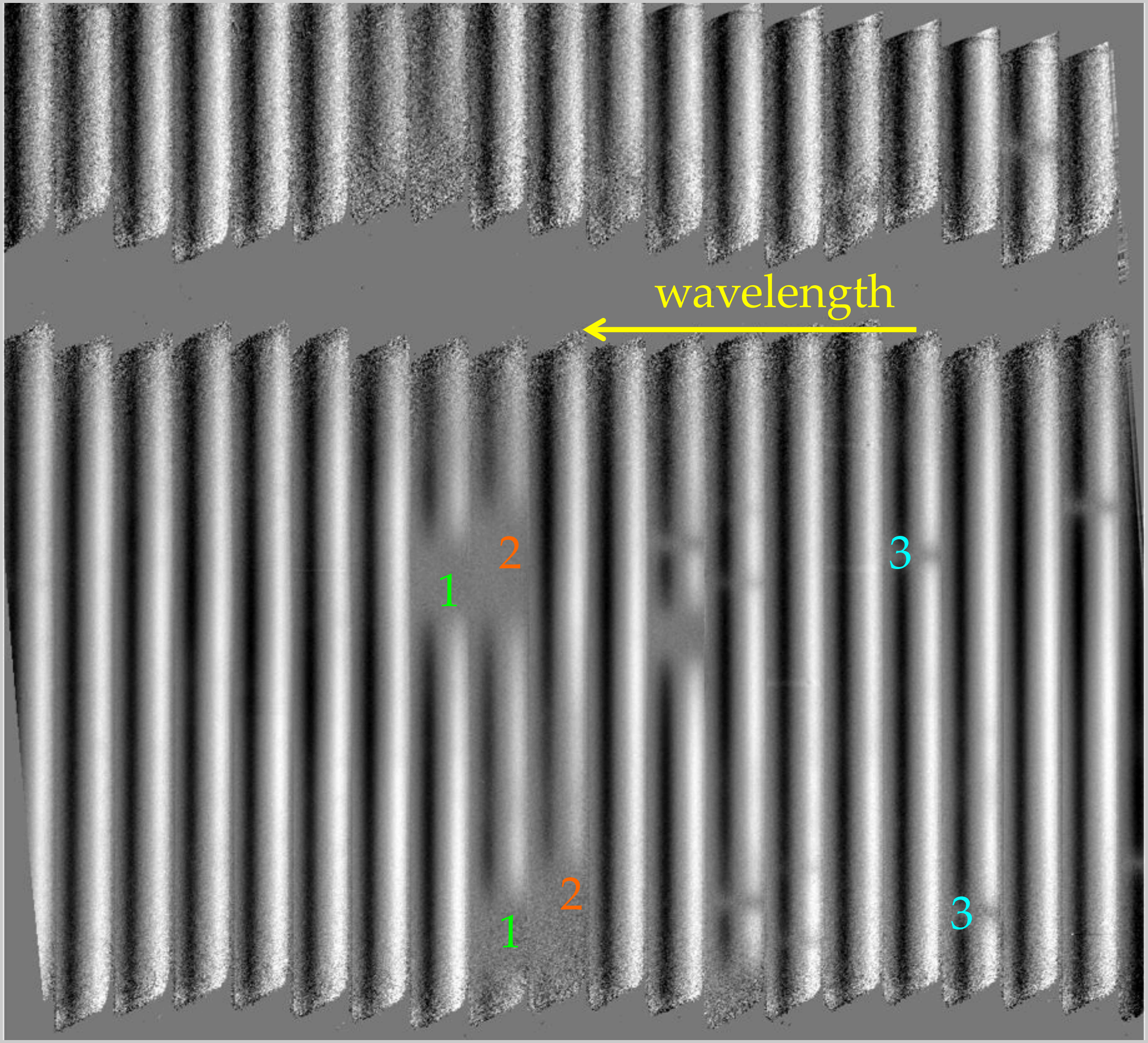
EXES Echellogram



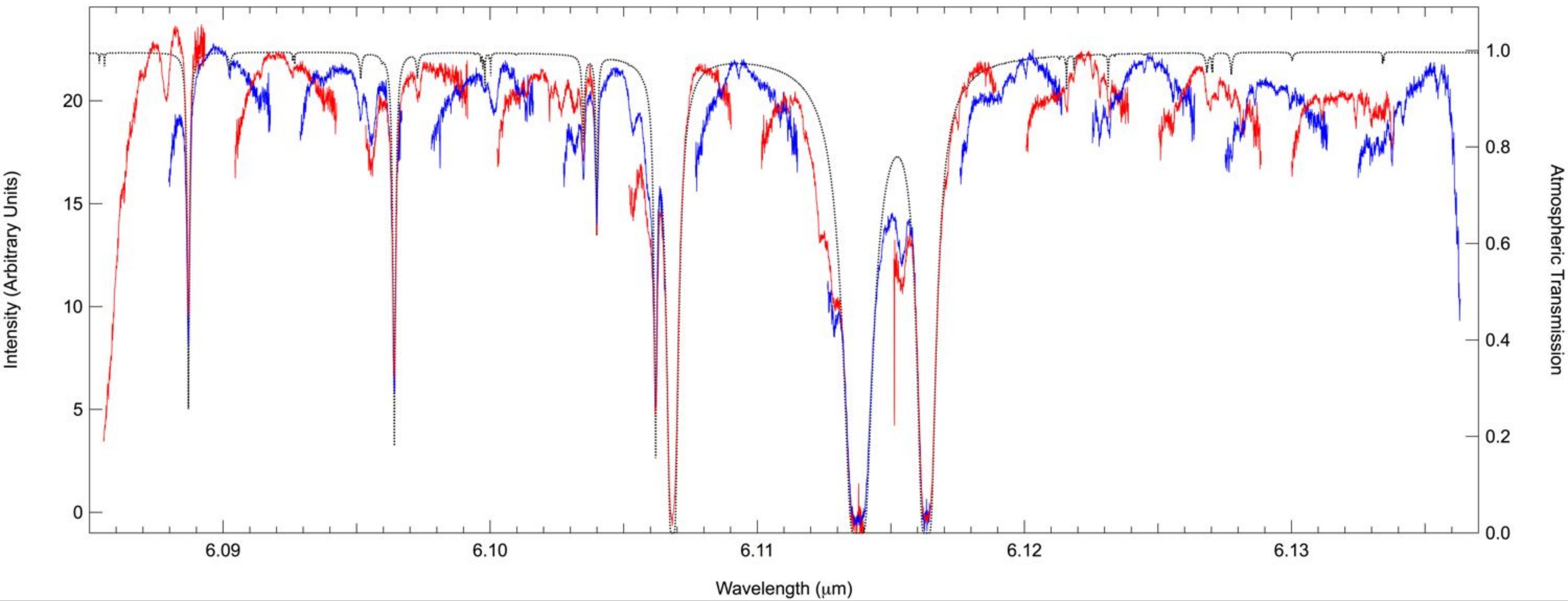
EXES Echellogram



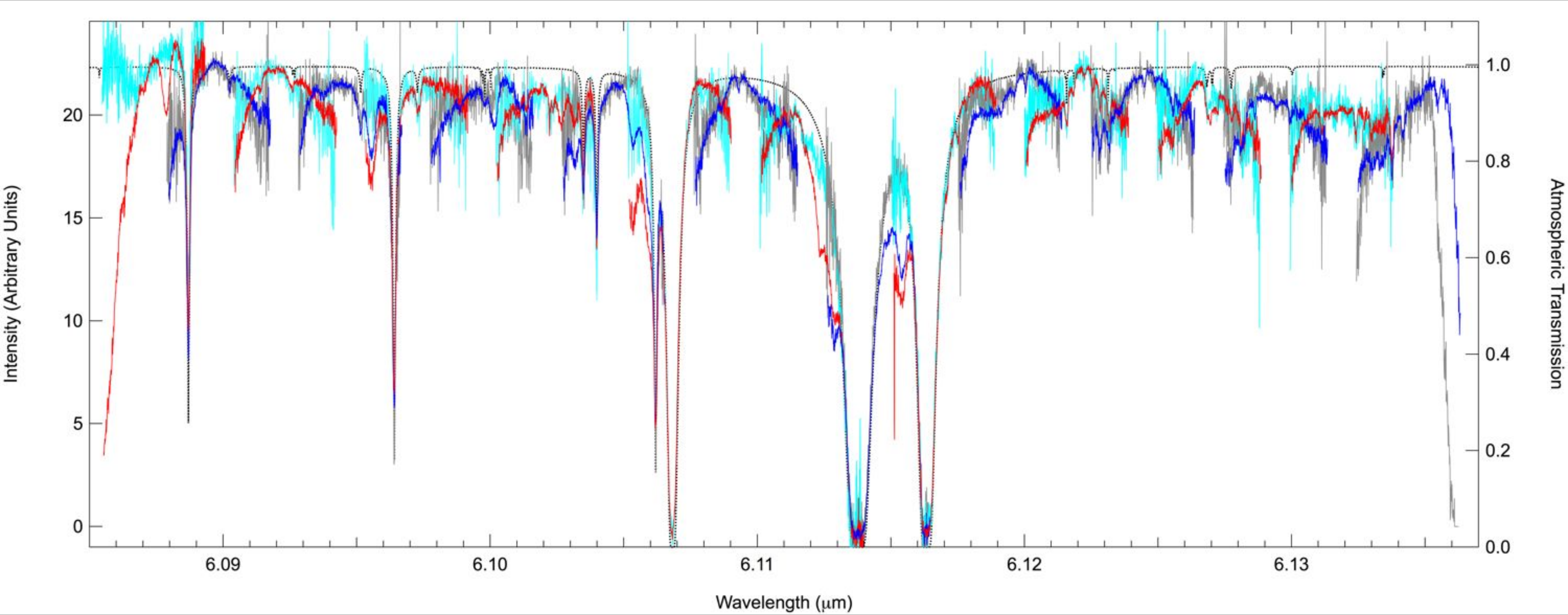
EXES Echellogram



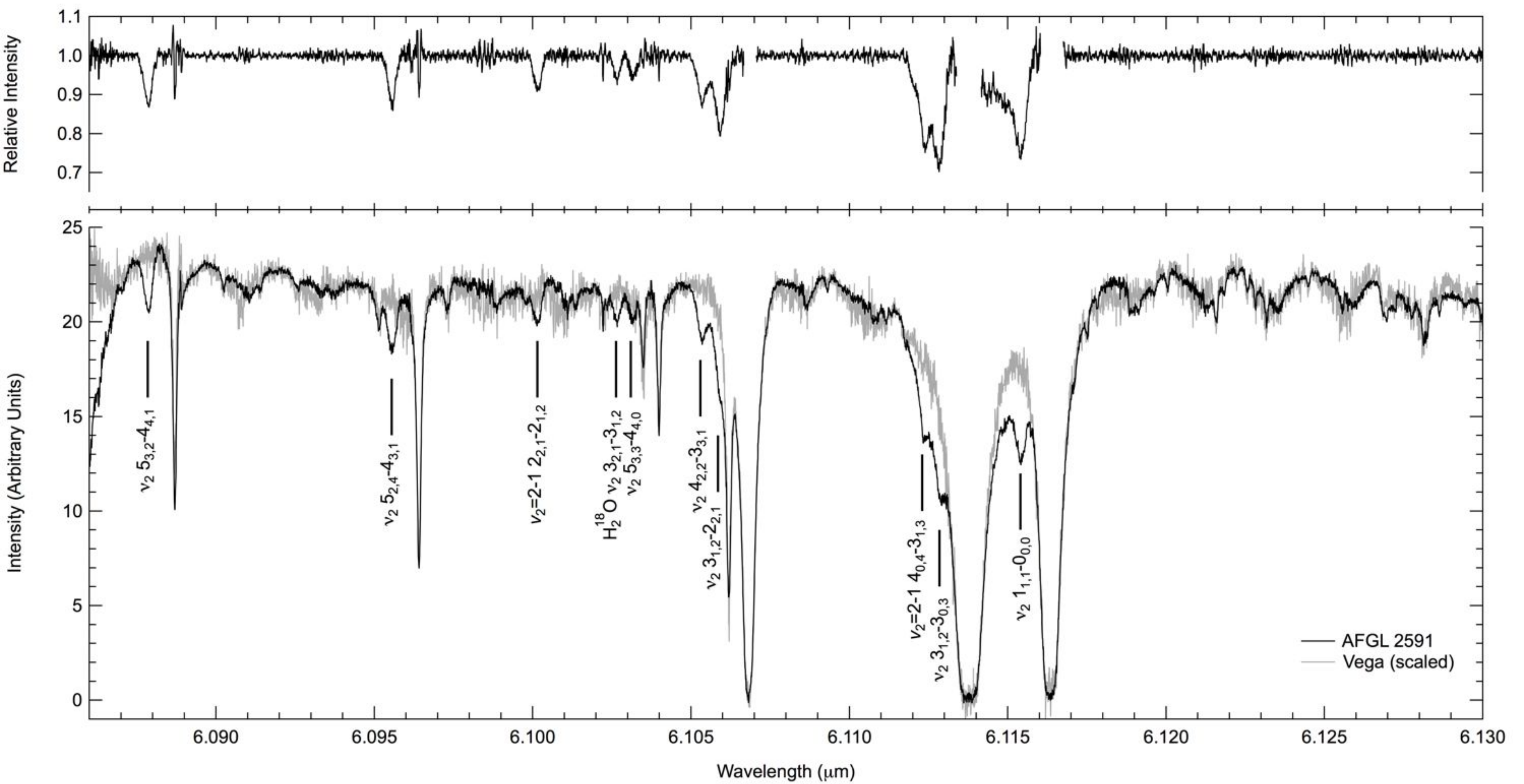
Extracted Spectrum (AFGL 2591)



Spectrum (AFGL 2591 & Vega)



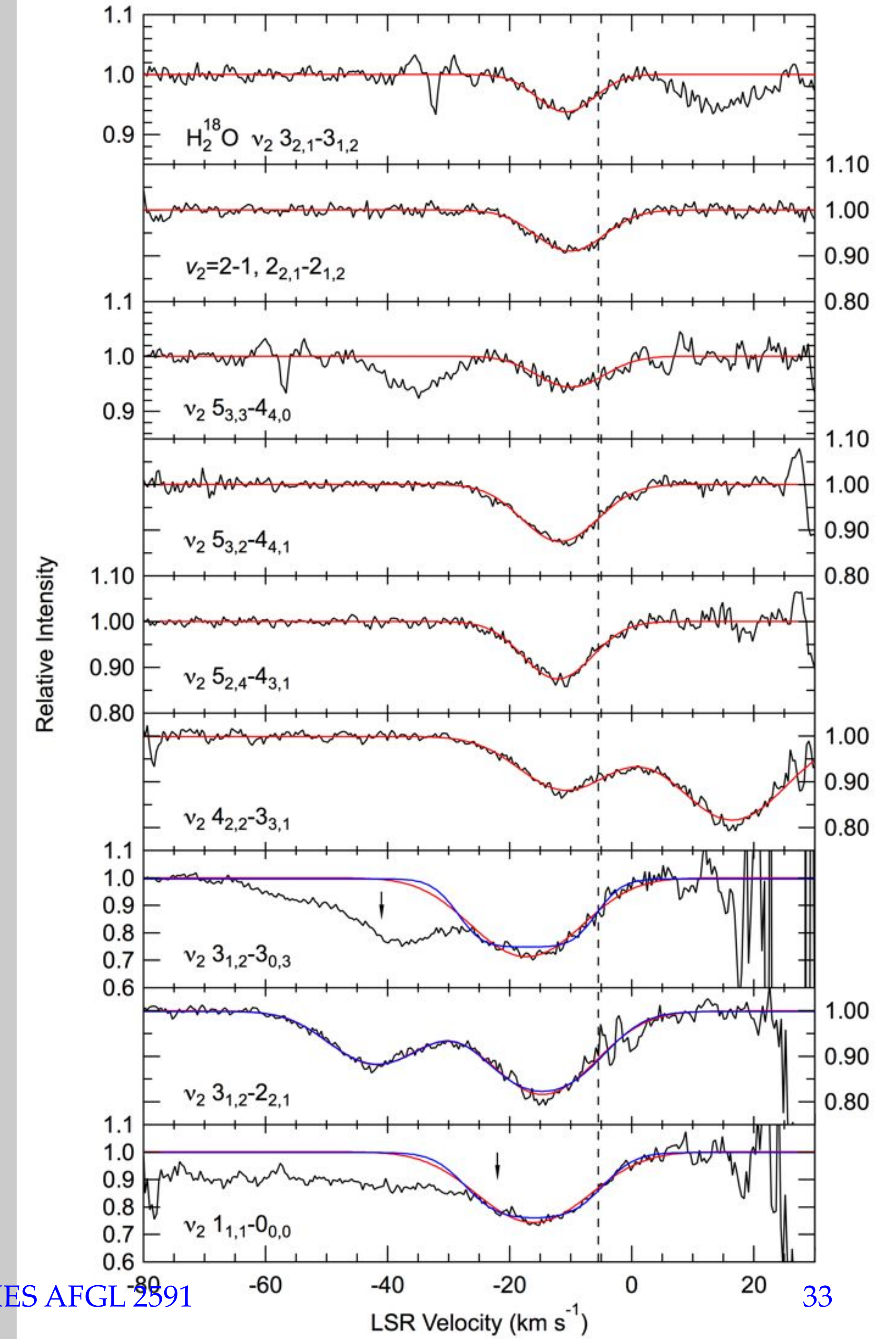
Processed Spectrum



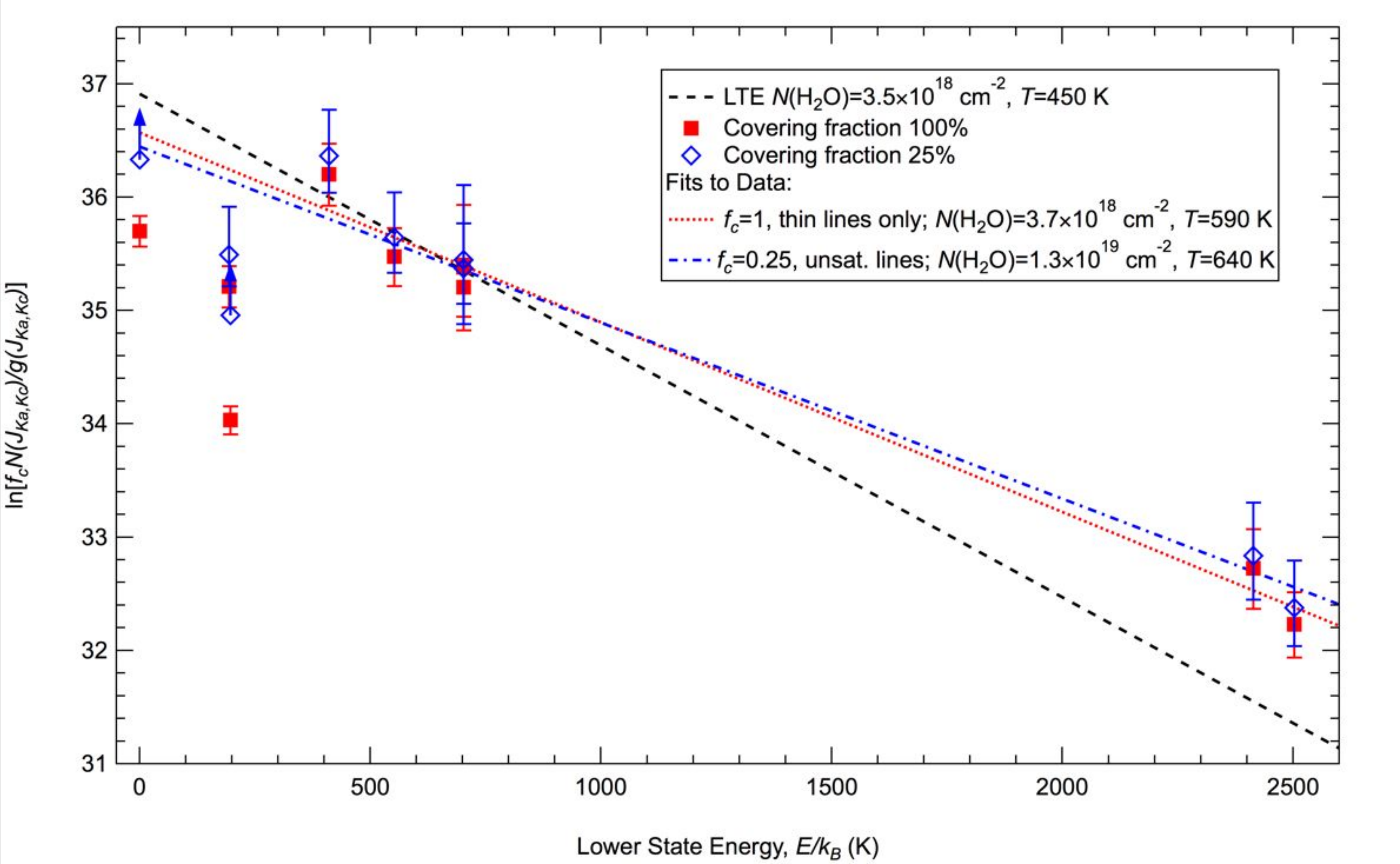
Absorption Line Fitting

$$I = I_0\left[1 - f_c\left[1 - \exp\left(-\tau_0 \exp\left(-\frac{(v - v_{\mathrm{LSR}})^2}{2\sigma_v^2}\right)\right)\right]\right]$$

- Gaussian in optical depth
- Allows for fractional coverage of source by absorbing gas, f_c



Rotation Diagram (AFGL 2591)



Indriolo et al. 2015, ApJL, 802, L14

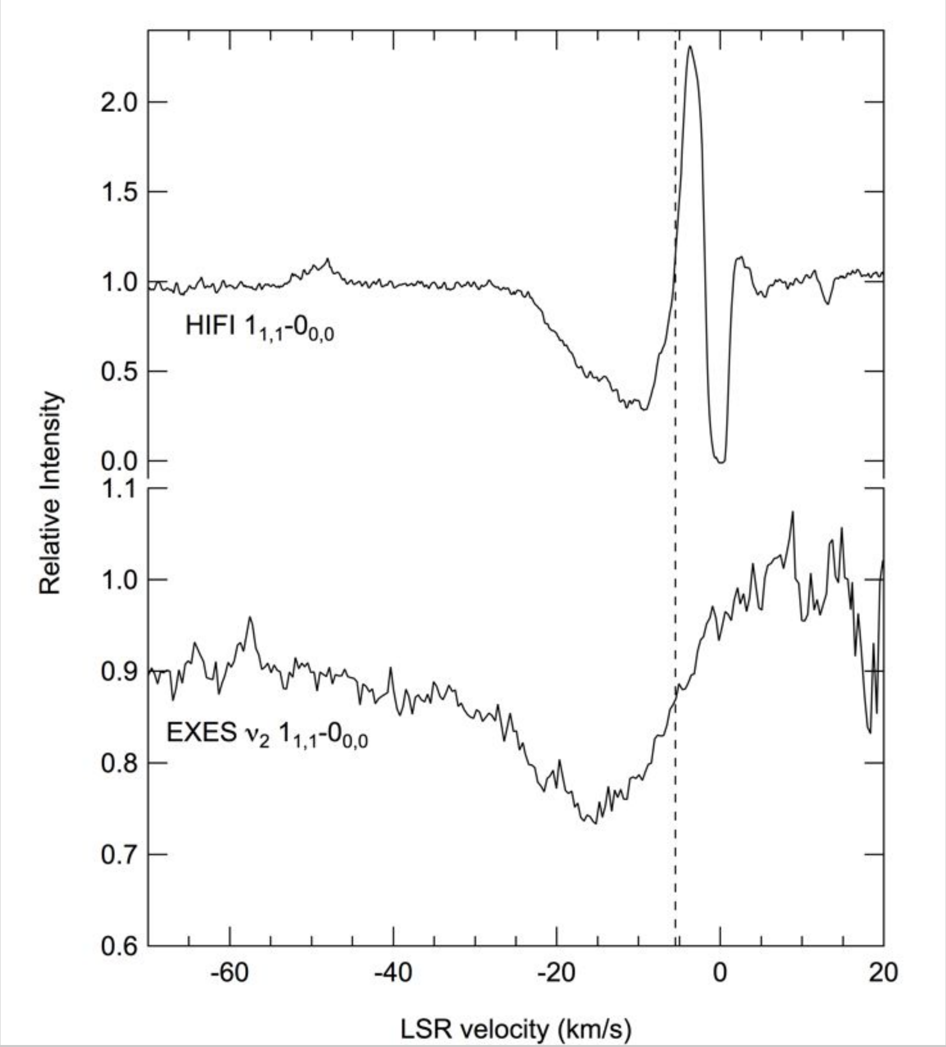
Comparison of Analyses

Instrument	H_2O Column Density (cm^{-2})	Temperature (K)	Reference
ISO-SWS	$(3.5\pm1.5)\times10^{18}$	450±200	Boonman & van Dishoeck 2003
Herschel PACS	$\sim6\times10^{14}$	160±130	Karska et al. 2014
Herschel HIFI	$\sim4\times10^{13}$	70—90	Choi et al. 2015
SOFIA EXES	$(1.3\pm0.3)\times10^{19}$	640±80	Indriolo et al. 2015

- IR observations give both larger column densities and temperatures
- *Herschel* observations primarily probe transitions out of relatively low-energy states

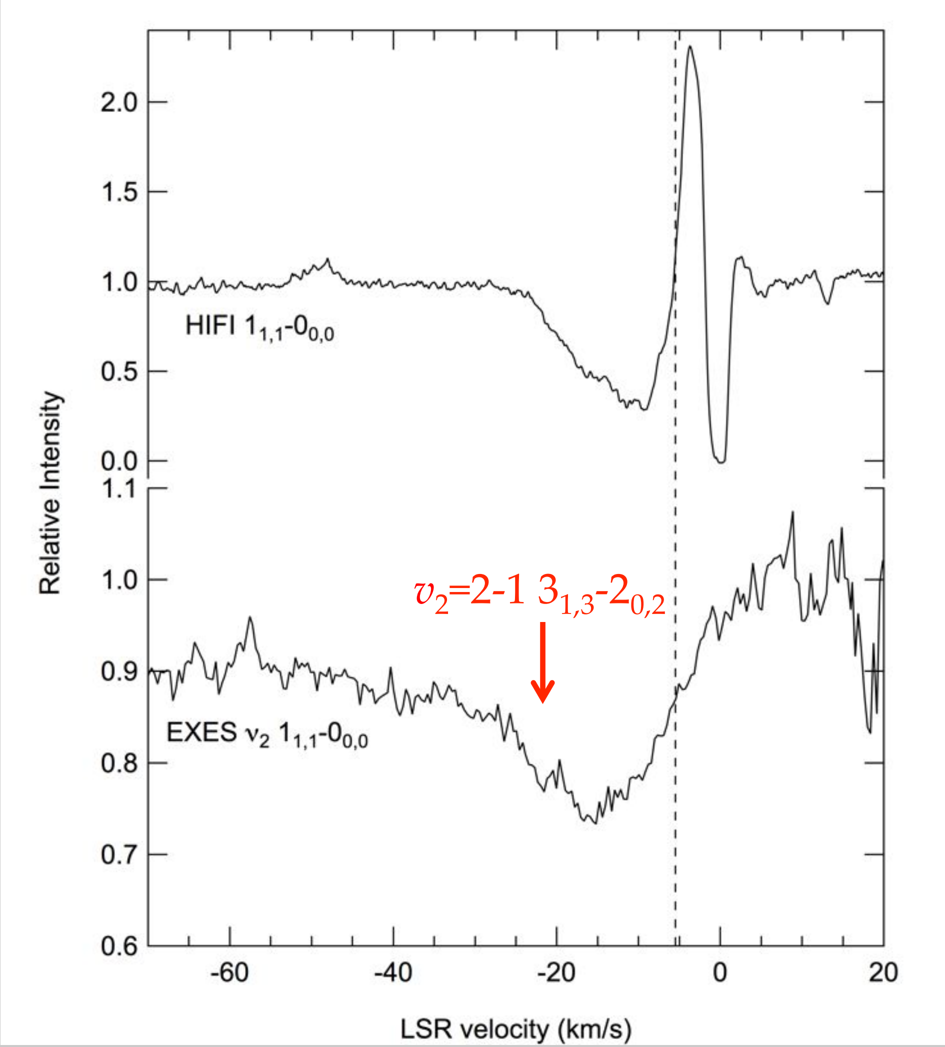
Ground state with HIFI and EXES

- Rotational transition at 1113 GHz observed with HIFI (19" beam)
- Ro-vibrational transition at 6.1 μm observed with EXES



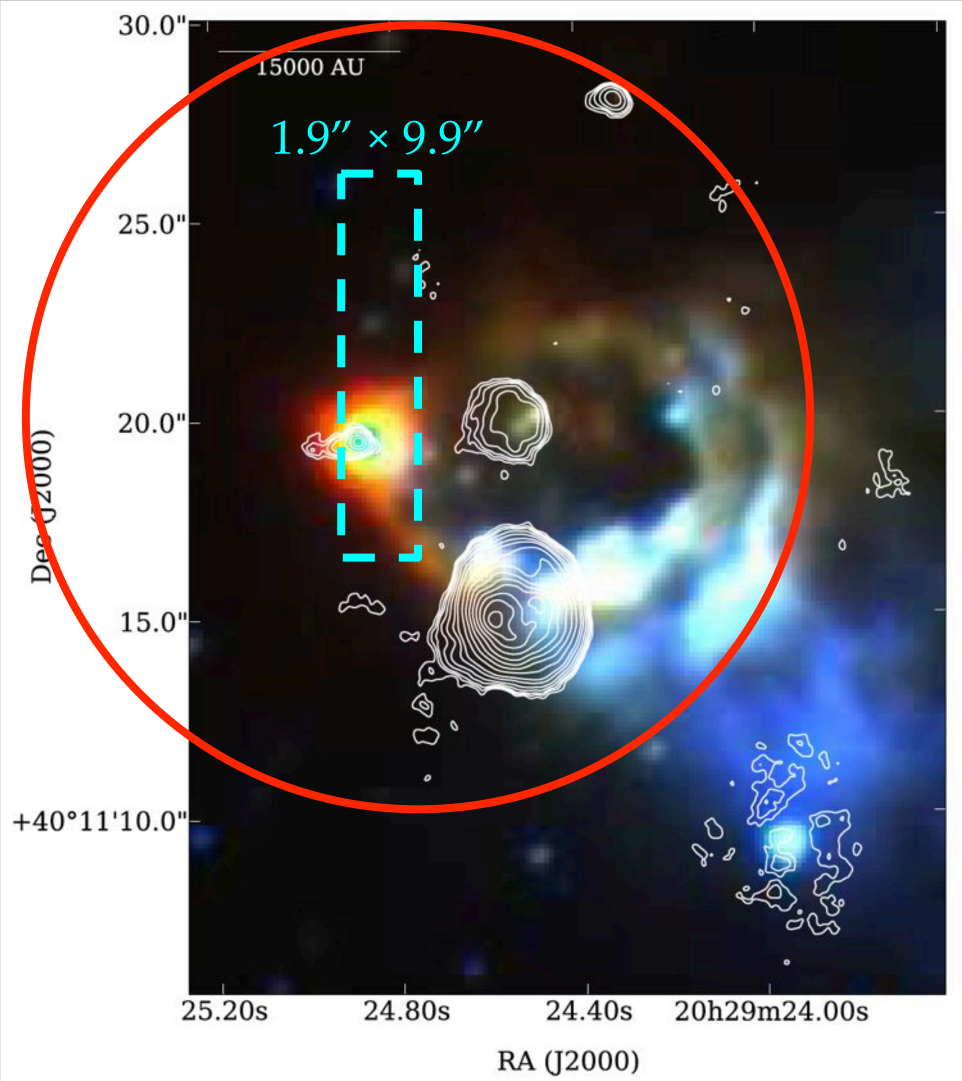
Ground state with HIFI and EXES

- Rotational transition at 1113 GHz observed with HIFI (19″ beam)
- Ro-vibrational transition at 6.1 μm observed with EXES
- Vibrationally excited transition blend with ground state line



AFGL 2591 Region

- EXES slit in blue
- HIFI beam in red



Johnston et al. 2013, A&A, 551, A43

EXES Advantages

- v_2=1-0, $1_{1,1}$-$0_{0,0}$ transition does not suffer significant interference from emission
- Multiple transitions may be observed simultaneously
- Narrow slit provides high resolution, and limits flux from surrounding region

What to do next?

- Target more massive protostars where water absorption is detected (SOFIA/EXES)
- Target massive protostars in NIR and MIR atmospheric windows from the ground to find other molecules (TEXES on Gemini N.; CRIRES+ on VLT, when refurbished)
- Utilize models more complex than simple absorbing slab

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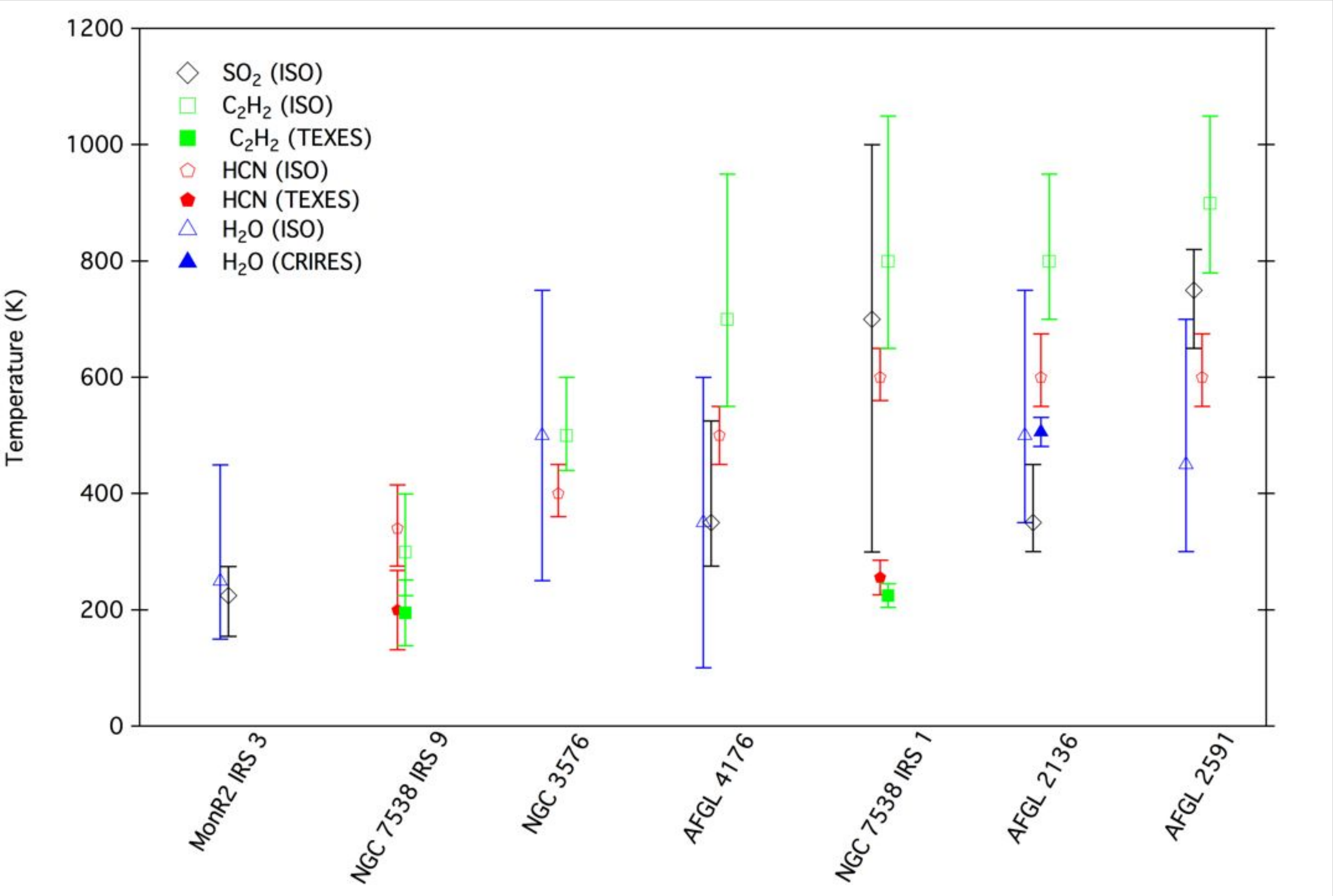
Other Molecules in Protostars

- While CO and H_2O are certainly two of the most abundant species in protostars, many more molecules have been detected
- HCN, C_2H_2, NH_3, HNCO, CH_4, HF, HCl
- All of these can provide important constraints on physical conditions

Temperature Comparison

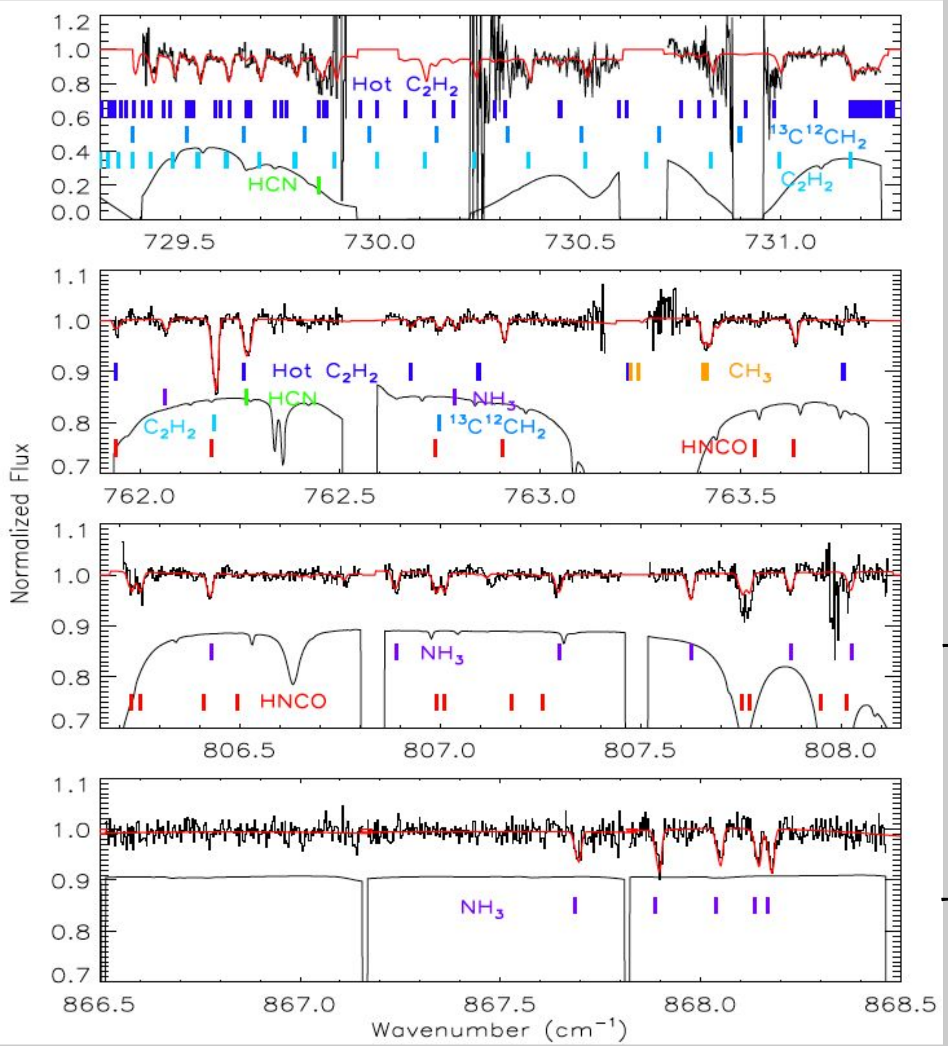


Inferred temperature changes with different molecules, and even with different observations of the same molecule (high vs. low resolution)

MIR Survey of NGC 7538 IRS 1

- TEXES/Gemini N. observations
- Detected species varies between protostars
- AFGL 2591 shows only HCN & C_2H_2

Knez 2006 (thesis)



13.7 μm

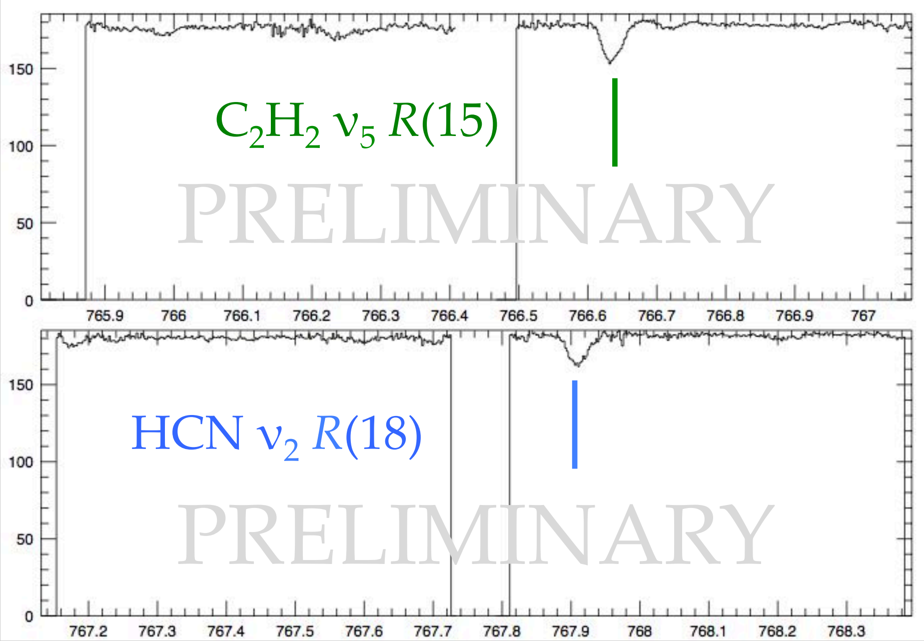
13.1 μm

12.4 μm

11.5 μm

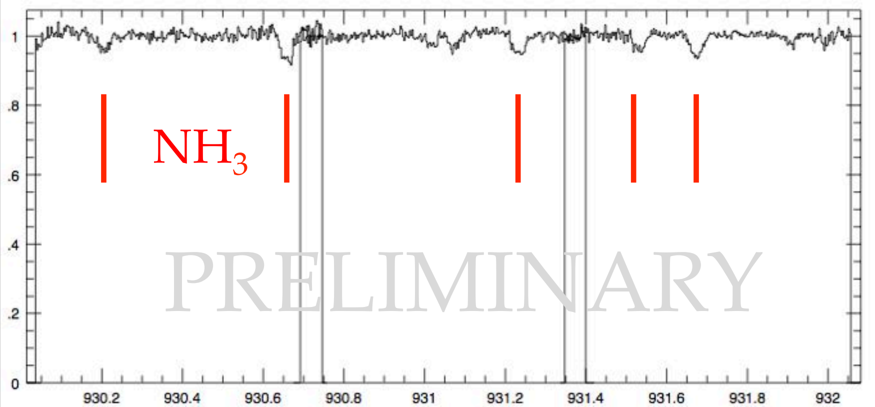
Knez et al. 2009 ApJ, 696, 471

GemN/TEXES Observations



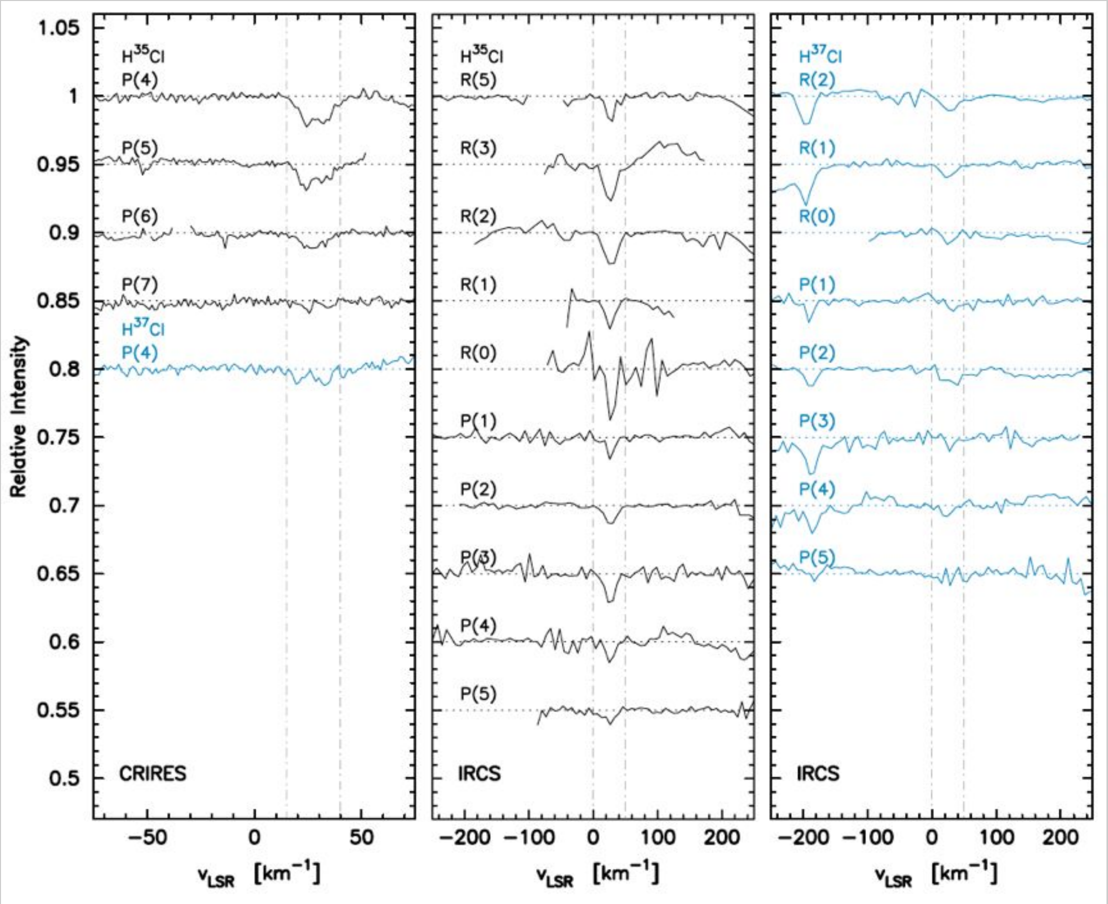
- AFGL 2136 at 13 μm
- C_2H_2 and HCN ro-vibrational bands in absorption

- AFGL 2136 at 10.7 μm
- Several transitions of NH_3



AFGL 2136: HCl

- Trace species HCl seen in absorption (3.5 μm)
- Both ^{35}Cl and ^{37}Cl isotopologues
- Inferred gas properties:
  - T=254±10 K
  - n>10^9 cm^{-3}



Goto et al. 2013 A&A, 558, L5

Molecules Molecules Everywhere...

- Different molecules are indicating different physical conditions
- Possibly probing different locations
- Possibly saying something about radiative versus collisional excitation

Absorption in the Near-Mid IR

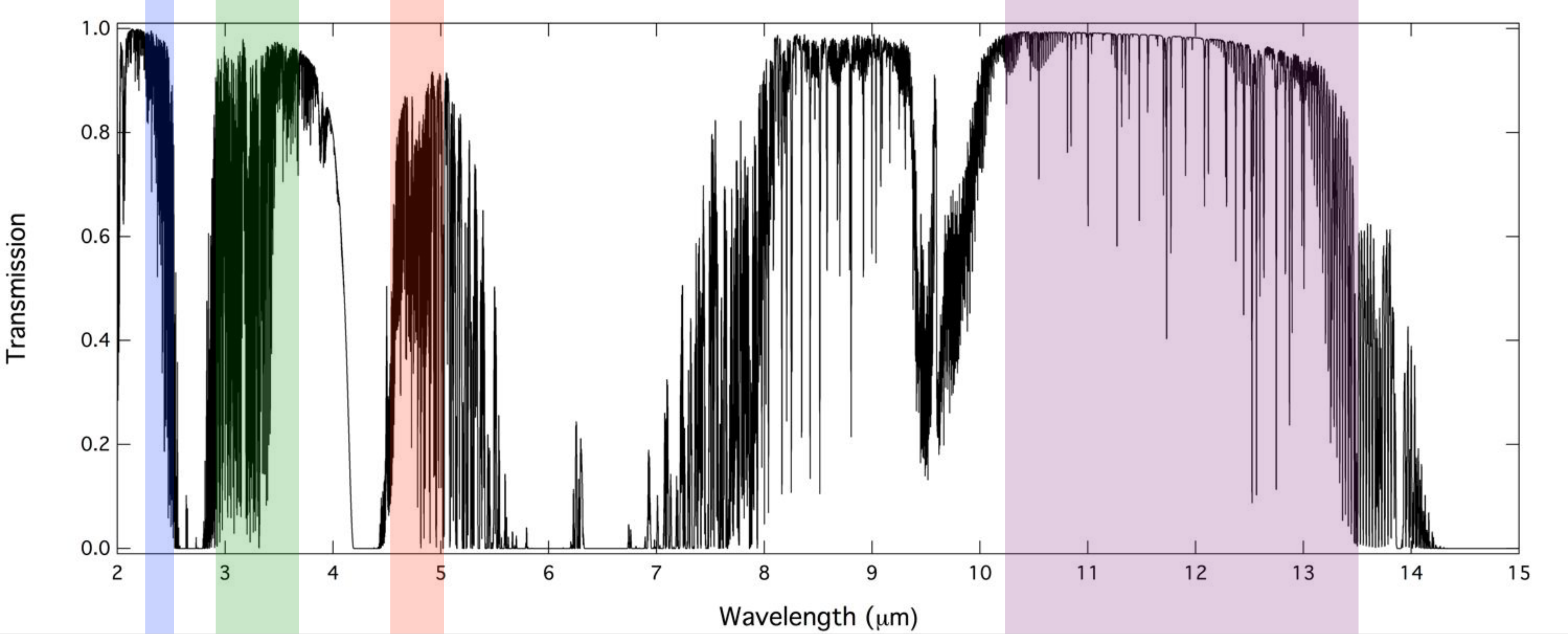
- In objects as complex as massive protostars, the emitting region must change significantly from 2 μm to 14 μm
- Unclear how exactly this effects observed molecular absorption across the near-mid infrared
- Certainly worth targeting the same species across this wavelength range

Current Status

- A wide variety of molecules have been detected in absorption in massive protostars
- Objects have generally been targeted in narrow spectral windows around lines of interest to observer
- There exists neither a uniform sample of spectra across many protostars, nor a "full" spectrum of a single protostar at high resolution

From the Ground

ATRAN (Lord 1992) simulated atmospheric spectrum at 14,000 ft with 2.5 mm PWV



H_2O
HF

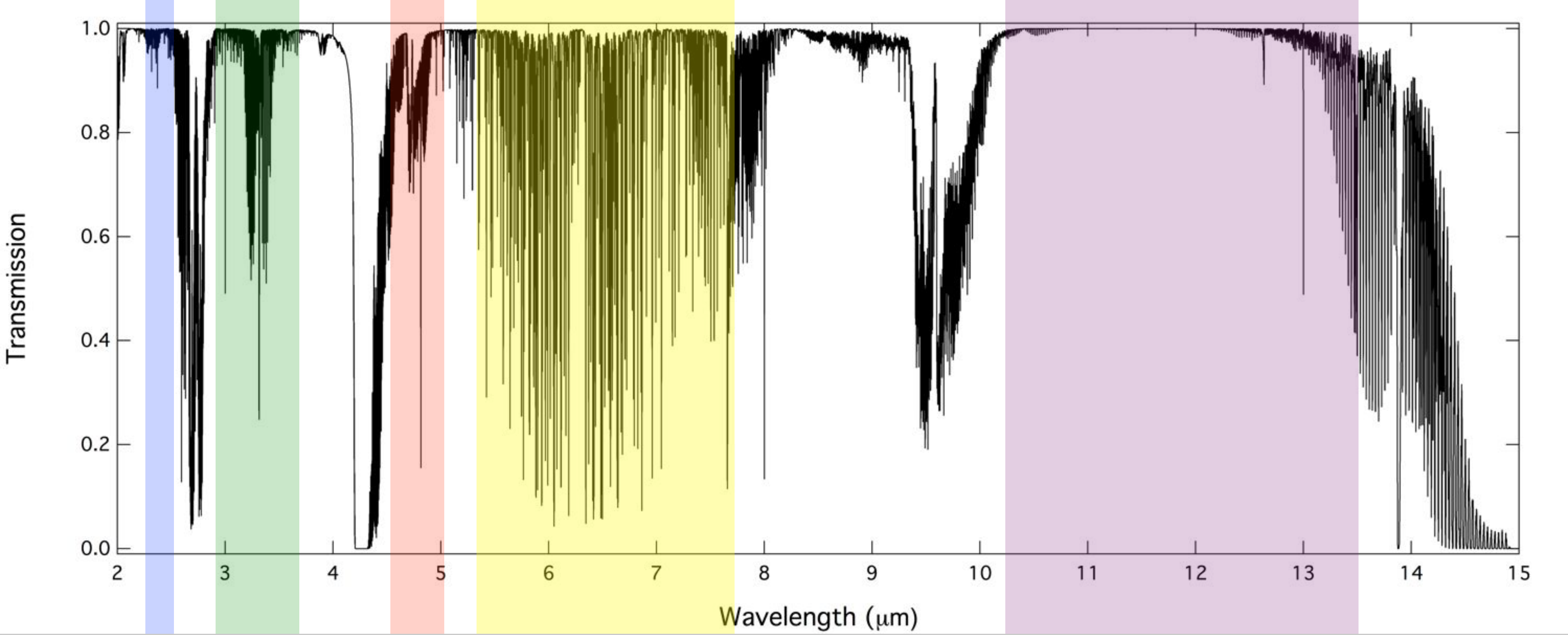
HCN
C_2H_2
H_2CO

CO

HCN, C_2H_2, H_2CO,
H_2O, NH_3

From the Stratosphere

ATRAN (Lord 1992) simulated atmospheric spectrum at 43,000 ft with 0.01 mm PWV



H_2O
HF

HCN
C_2H_2
H_2CO

CO

H_2O

HCN, C_2H_2, H_2CO, H_2O, NH_3

Future Work

- Design observations to target the same spectral window in a sample of protostars
- Select one or two objects for the purpose of performing full spectral scans
- SOFIA/EXES uniquely capable of doing this work at 6-8 μm