Exploring the Physical Conditions and Structure of Massive Protostars through Spectroscopic Observations of H_2O in the Infrared

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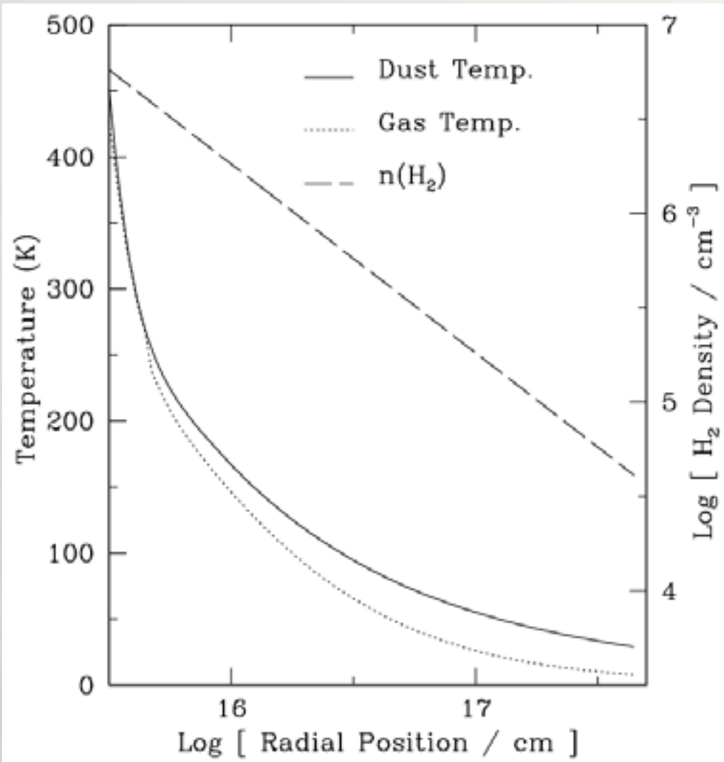
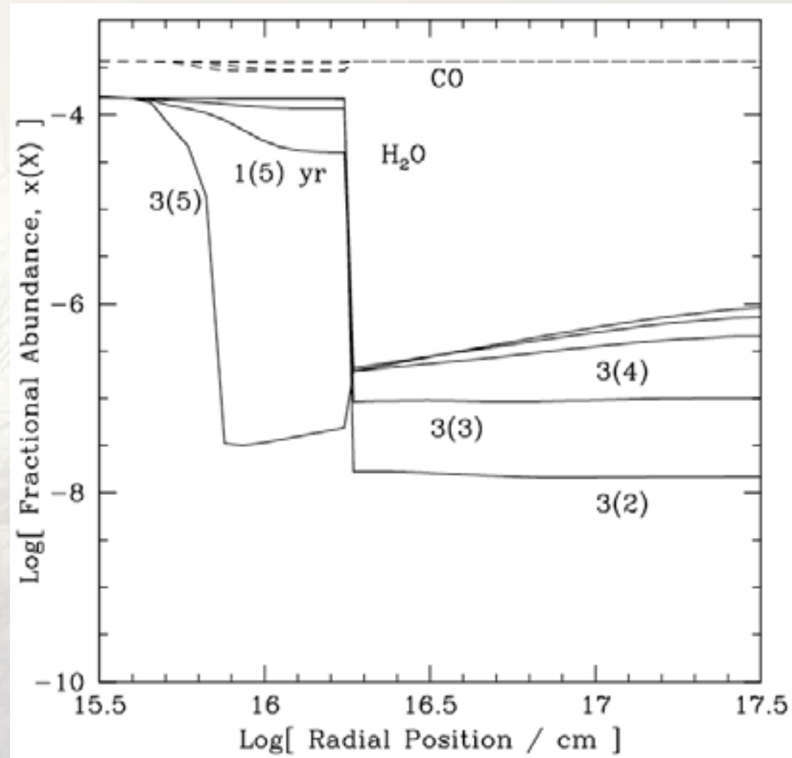
Massive Protostars

- 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

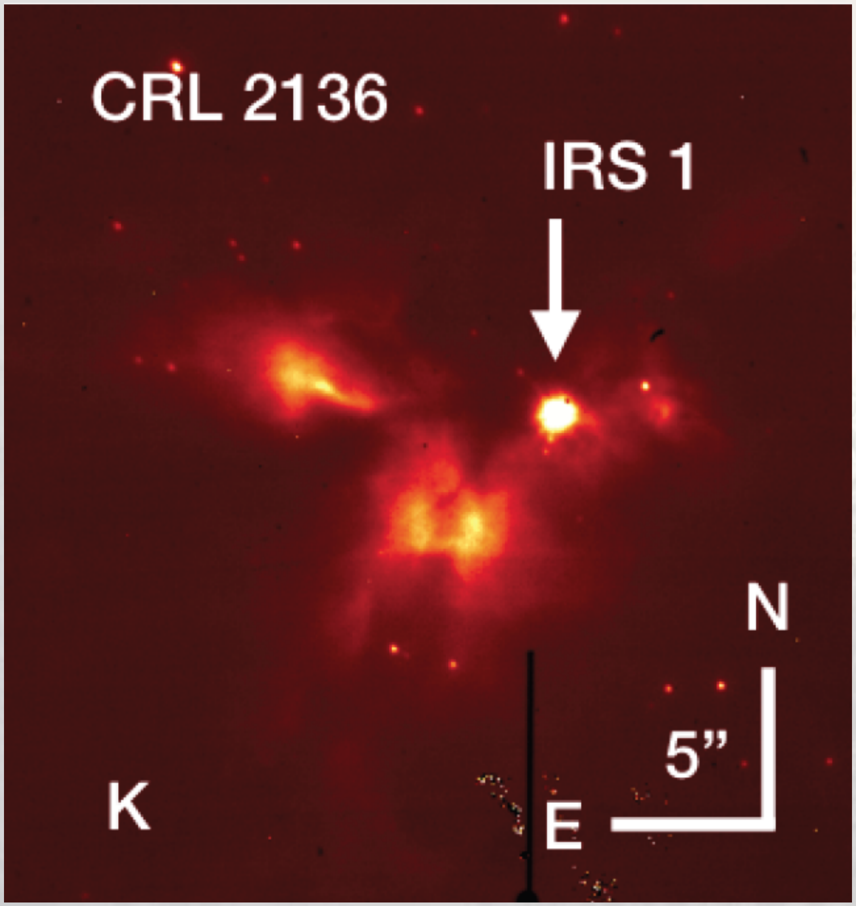




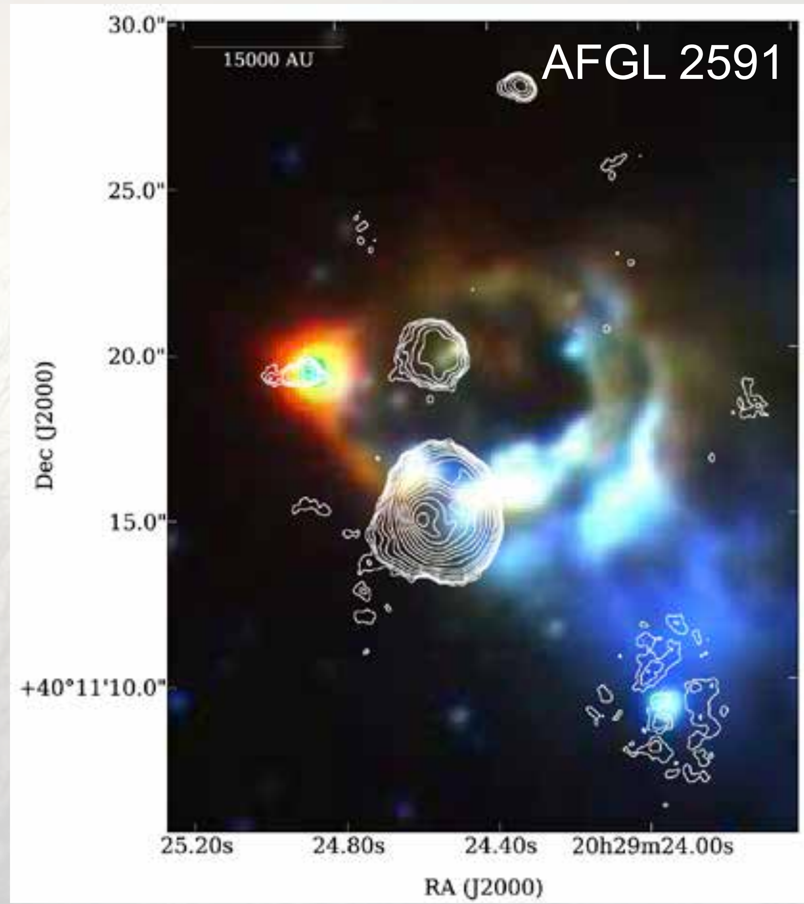
Simple models predict roughly half of the oxygen in CO and half in H_2O in the inner envelope. H_2O ice is abundant in outer envelope.

NIR Images

Not exactly spherically symmetric, eh?



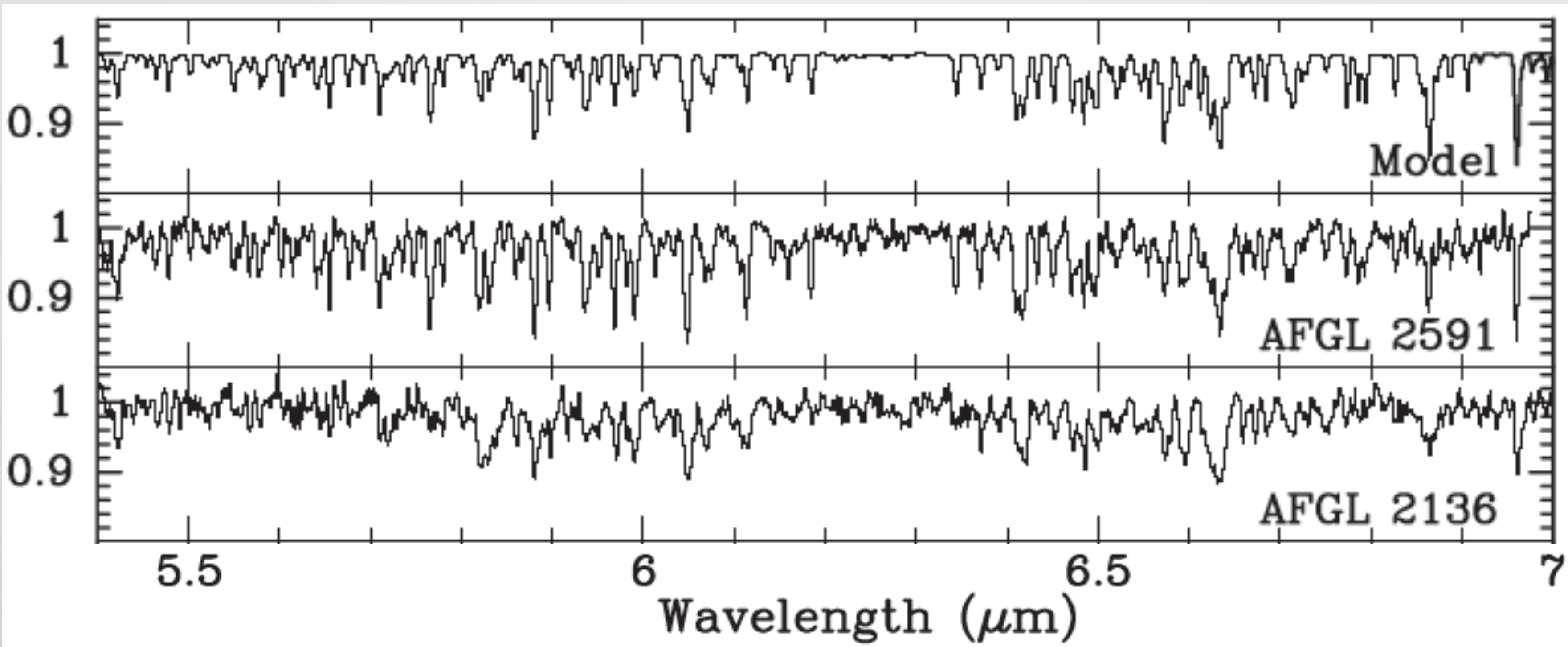
M. Goto 2013, private comm.



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

Water in Massive Protostars: ISO

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



- v_2 bending mode seen in absorption toward about 10 objects
- At R~1400 lines are blended and full band fit simultaneously
- No kinematic information

Water in Massive Protostars: ISO

Table 2. Model parameters for the ν_2 band of gas-phase H_2O[a].

Source	$T_{ex}(H_2O)$ K	$N(H_2O)$ 10^{18} cm^{-2}	$N(H_2^{hot})$[b] 10^{22} cm^{-2}	$x(H_2O)$[c] 10^{-5}
AFGL 2591	450^{+250}_{-150}	3.5 ± 1.5	6.0	5.8
AFGL 2136	500^{+250}_{-150}	1.5 ± 0.6	7.5	2.0
AFGL 4176	400^{+250}_{-250}	1.5 ± 0.7	4.0	3.8
MonR2 IRS3	250^{+200}_{-100}	0.5 ± 0.2	2.2[d]	2.3
NGC 7538 IRS1	500[e]	< 0.5	4.1	< 1.2
NGC 7538 IRS9	300[f]	< 0.6	0.1	< 60
NGC 2024 IRS2	45[g]	< 0.3	–	–
AFGL 2059	500^{+300}_{-300}	0.6 ± 0.3	2	3
NGC 3576	500^{+250}_{-250}	0.9 ± 0.3	4	2.3
S 140 IRS1	390[h]	< 0.3	2.2	< 1.4
W 33 A	120[h]	< 0.8	6.9	< 1.2
W 3 IRS5	400^{+200}_{-150}	0.3 ± 0.1	6.2	0.5

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

Unanswered Questions

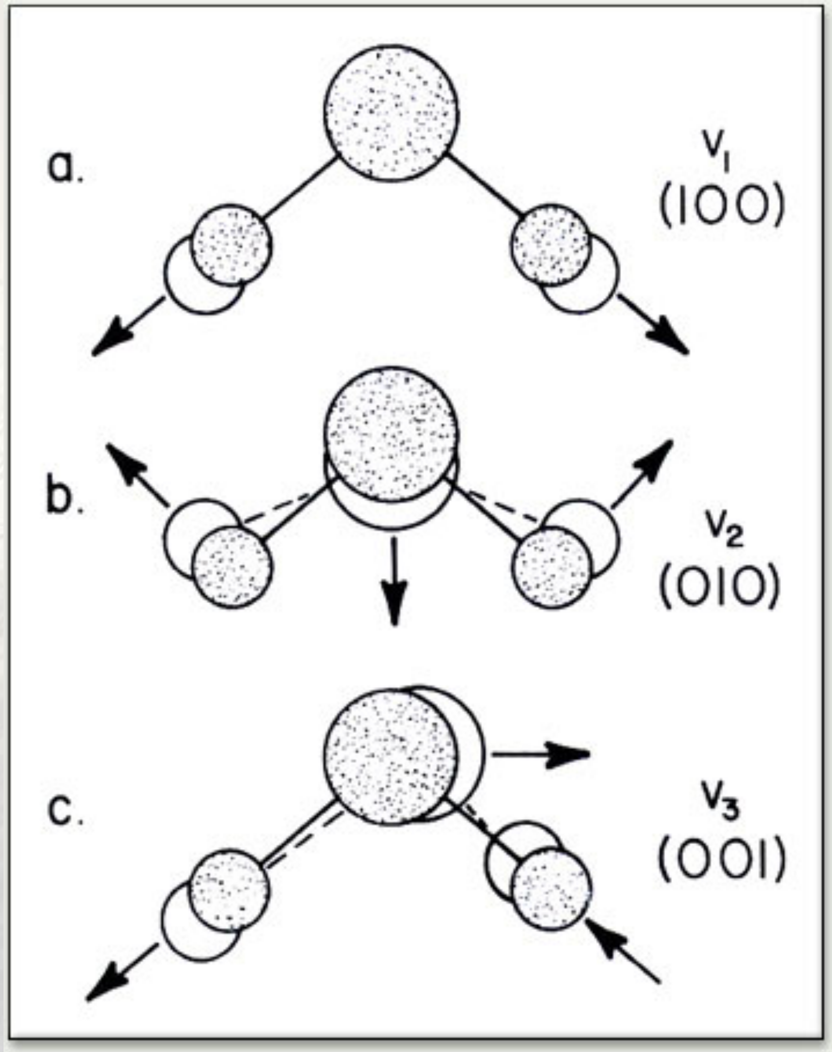
- At what velocity does the absorption arise?
- Are the line profiles complex with multiple absorption/emission components?
- Do line profiles change with energy?

Requires high spectral resolution

- CRIRES/VLT (2-5 μm)
- EXES/SOFIA (6-28 μm)
- TEXES/Gemini (5-25 μm)

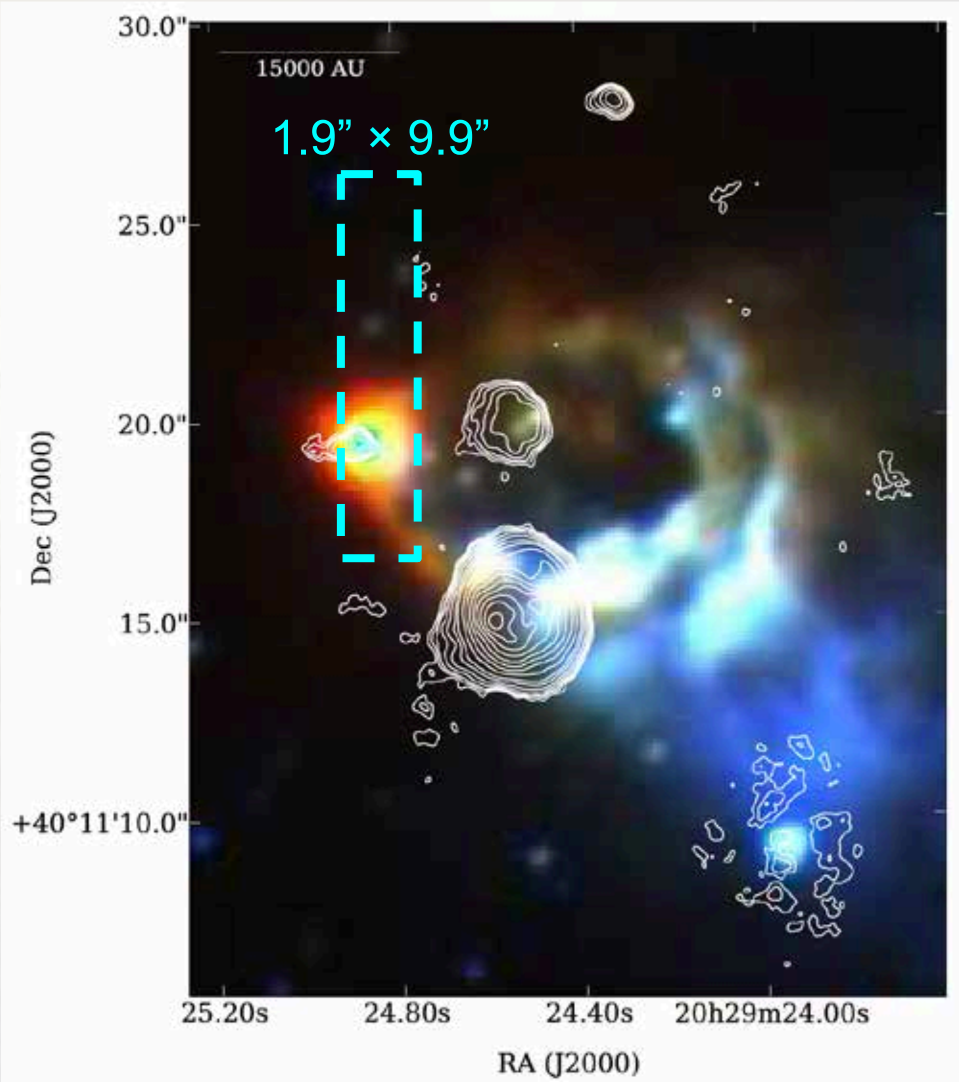
Water Vibrational Bands

- v_1: symmetric stretch
  - 2.7 µm
- v_2: bend
  - 6.1 µm
- v_3: asymmetric stretch
  - 2.7 µm

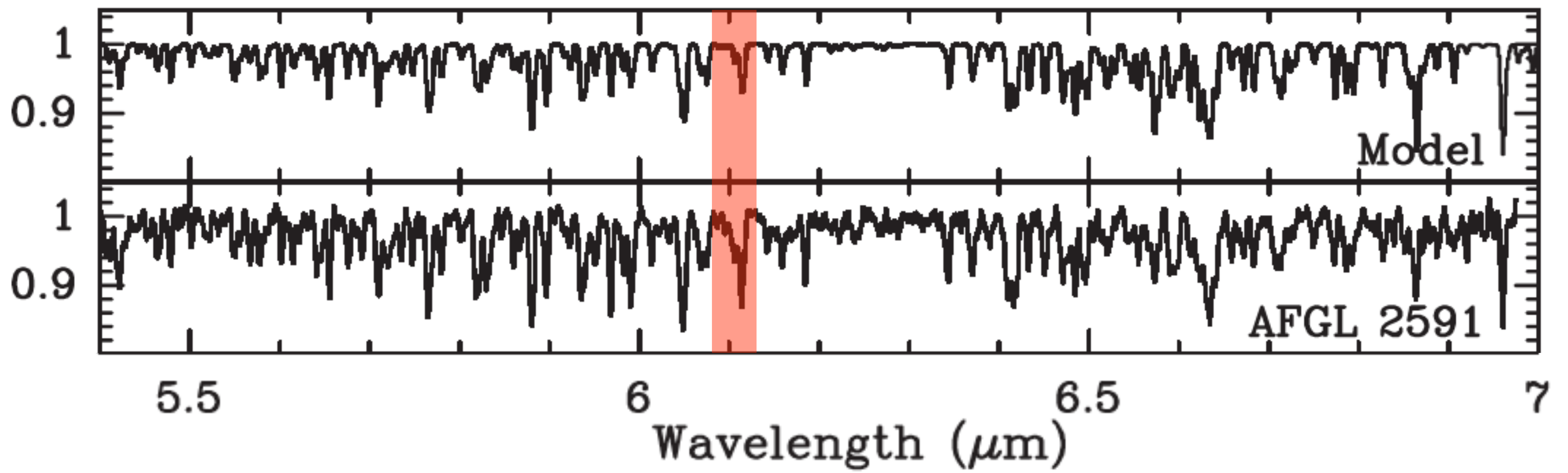


AFGL 2591 with SOFIA/EXES

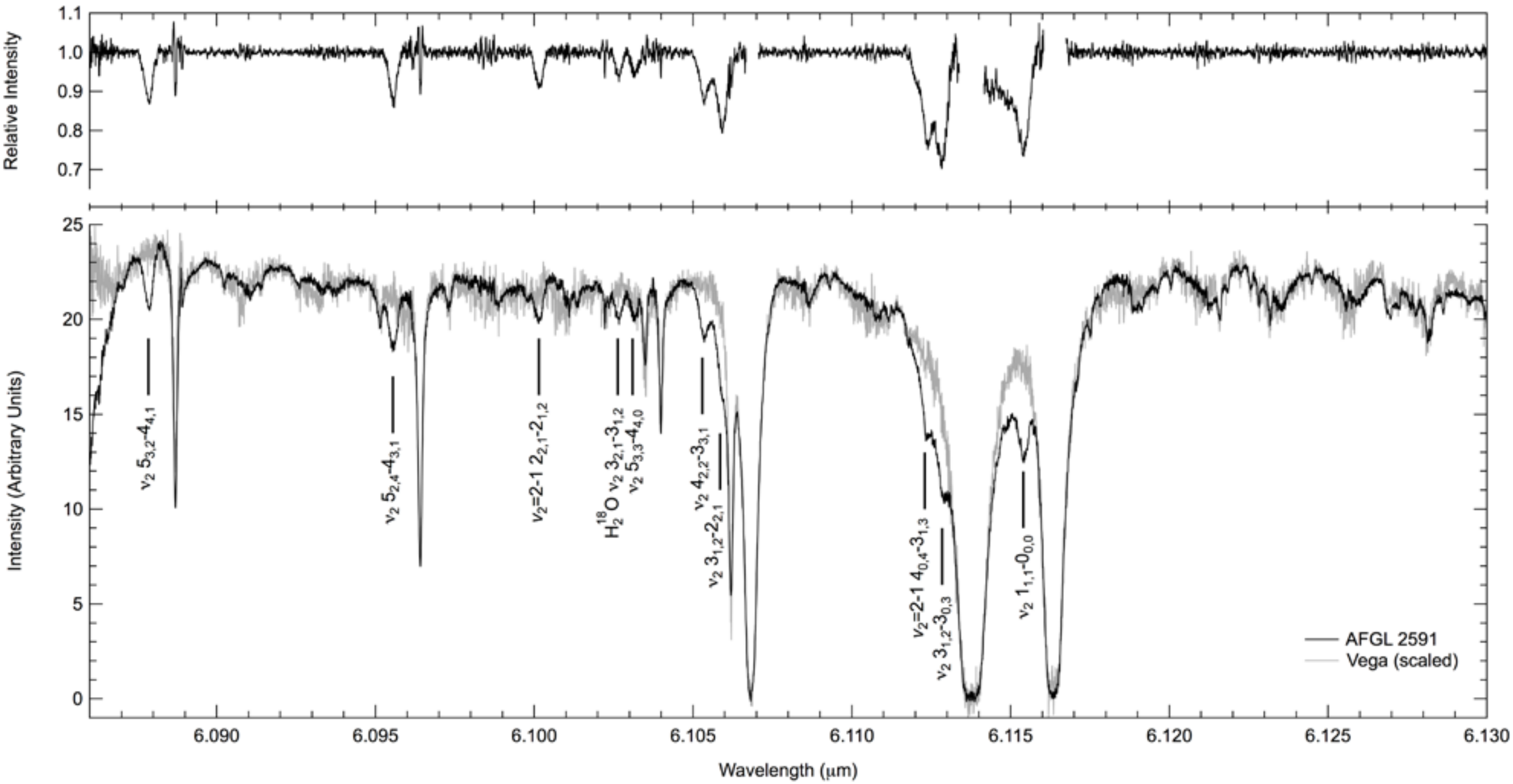
- Narrow slit placed on central object
- Observed for about 20 min
- Vega observed in earlier flight leg for use as telluric standard star



ISO-SWS vs EXES Coverage



EXES Spectrum of AFGL 2591

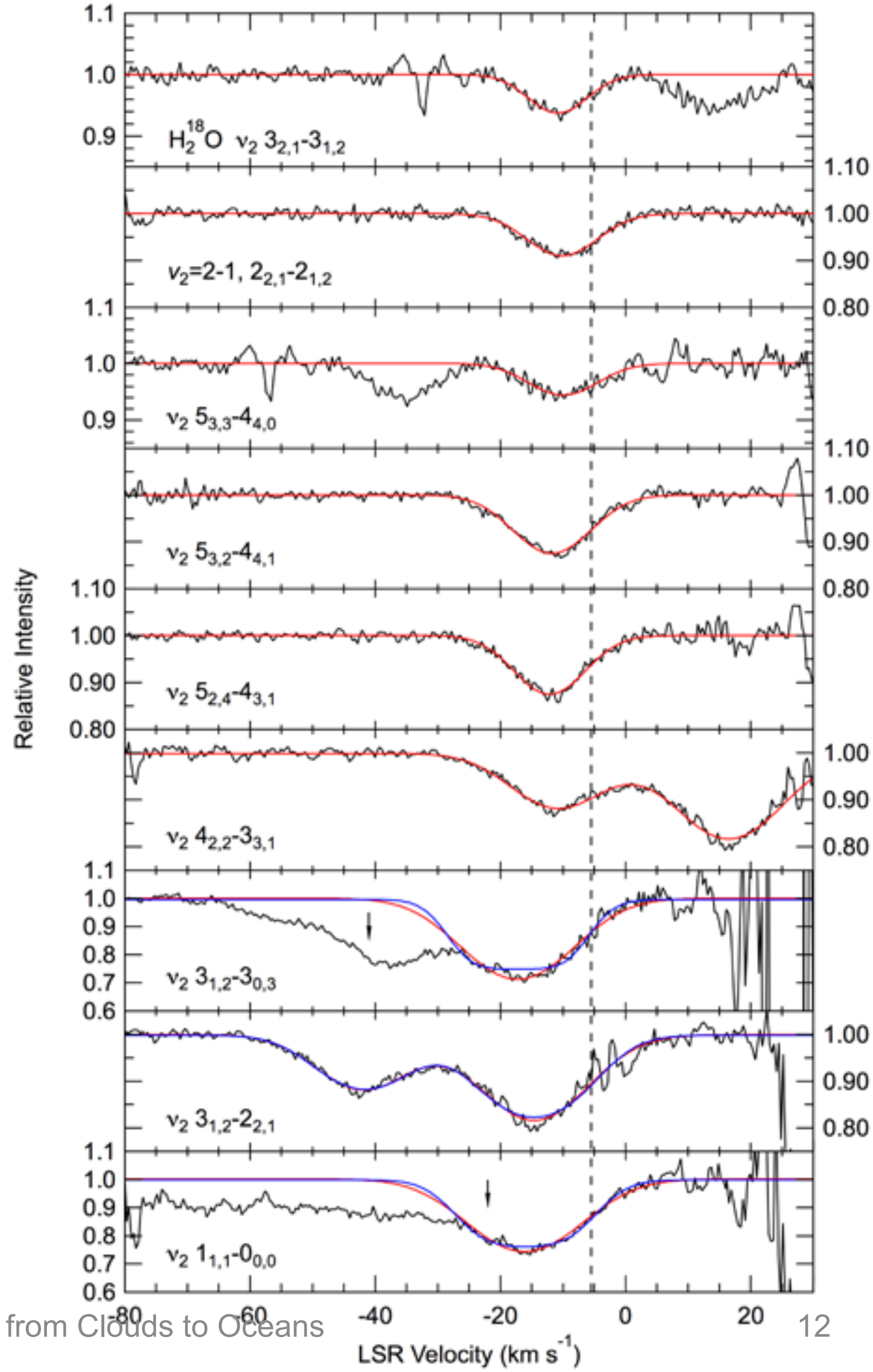


Indriolo et al. 2015, ApJL, 802, L14

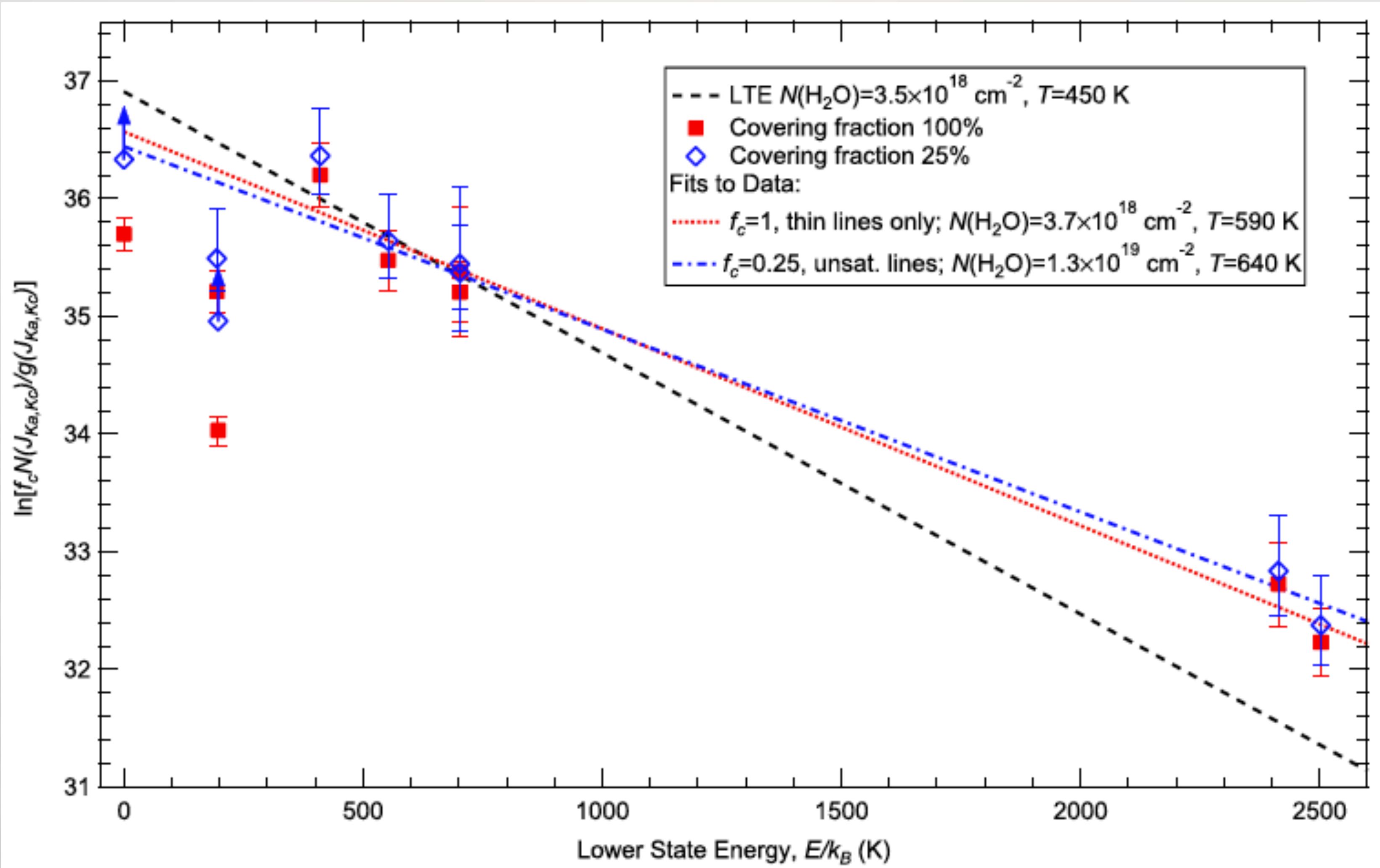
Absorption Line Fitting

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

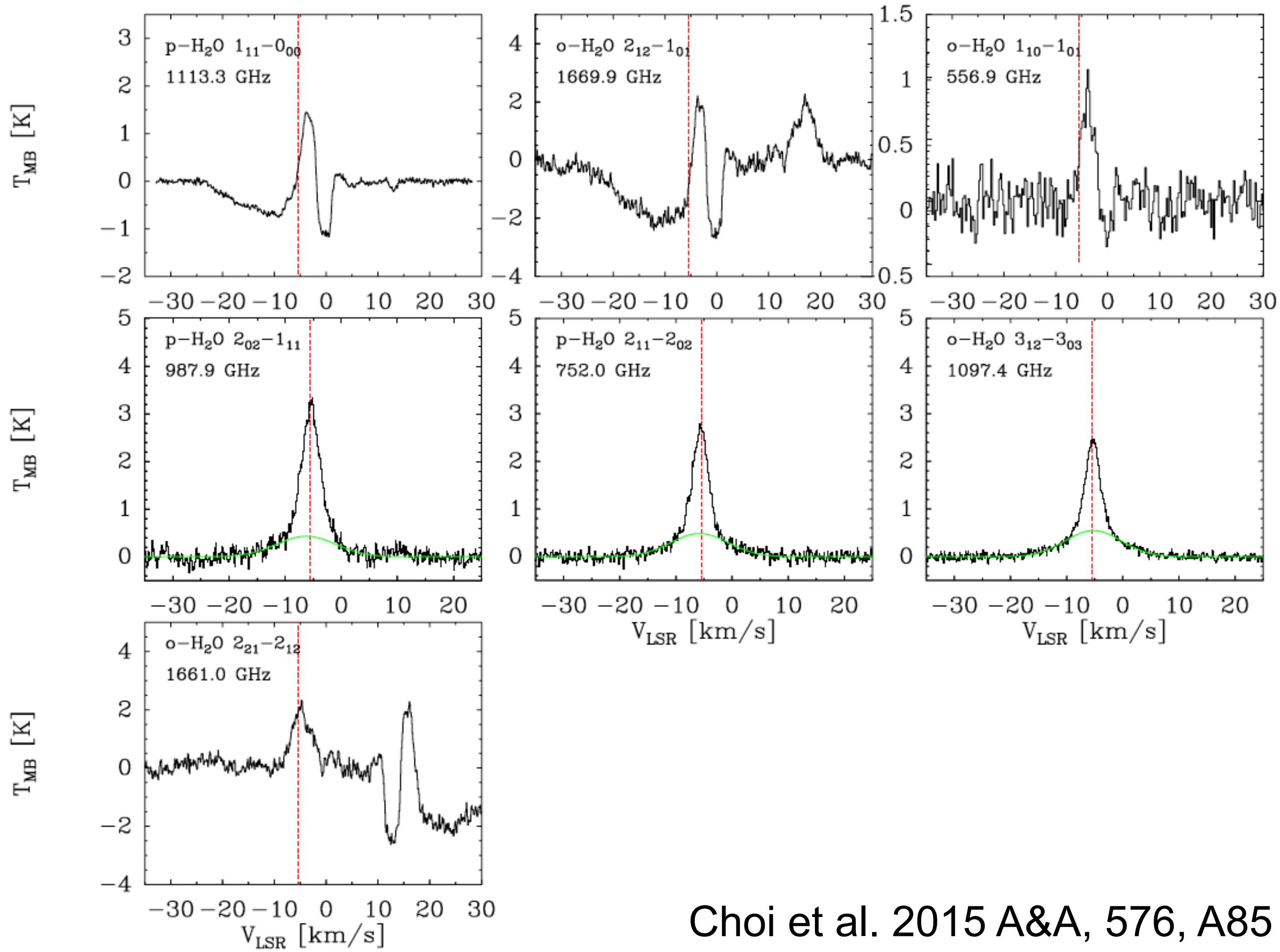
- Gaussian in optical depth
- Allows for fractional coverage of source by absorbing gas, f_c



AFGL 2591 Rotation Diagram



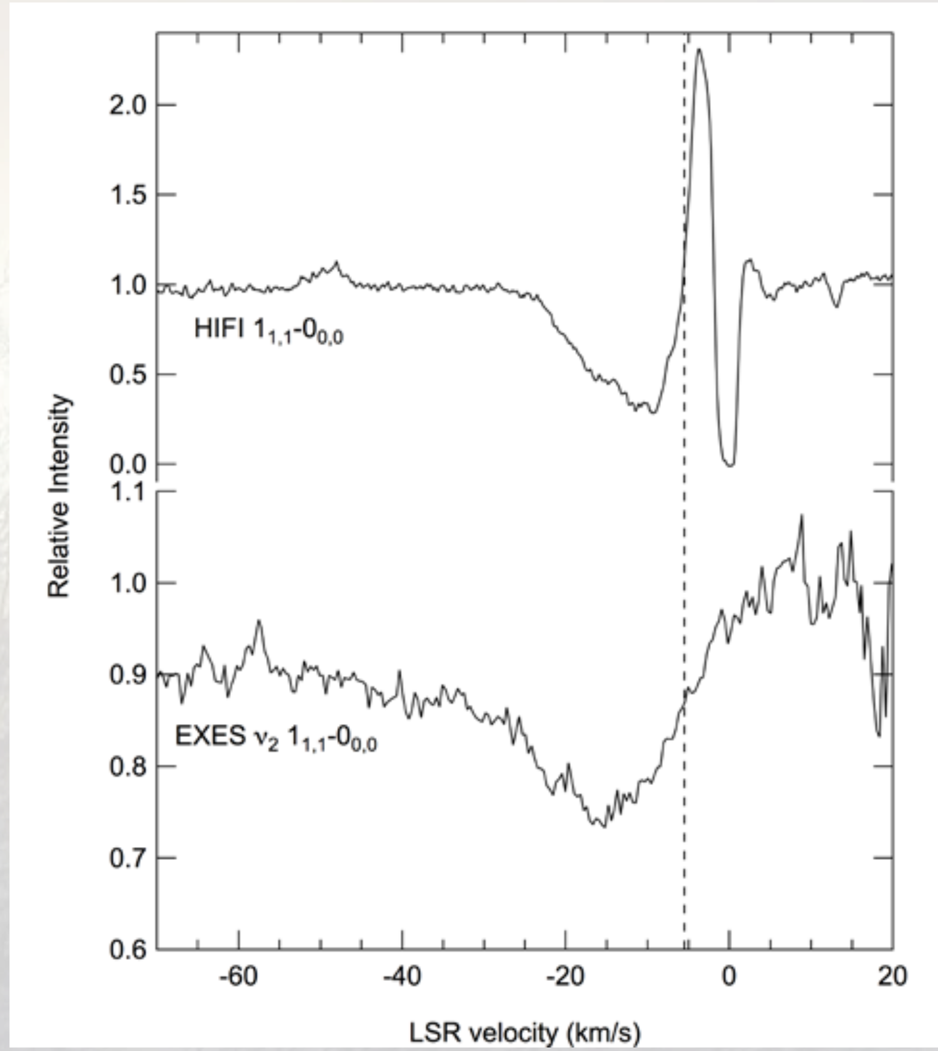
HIFI Observations



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

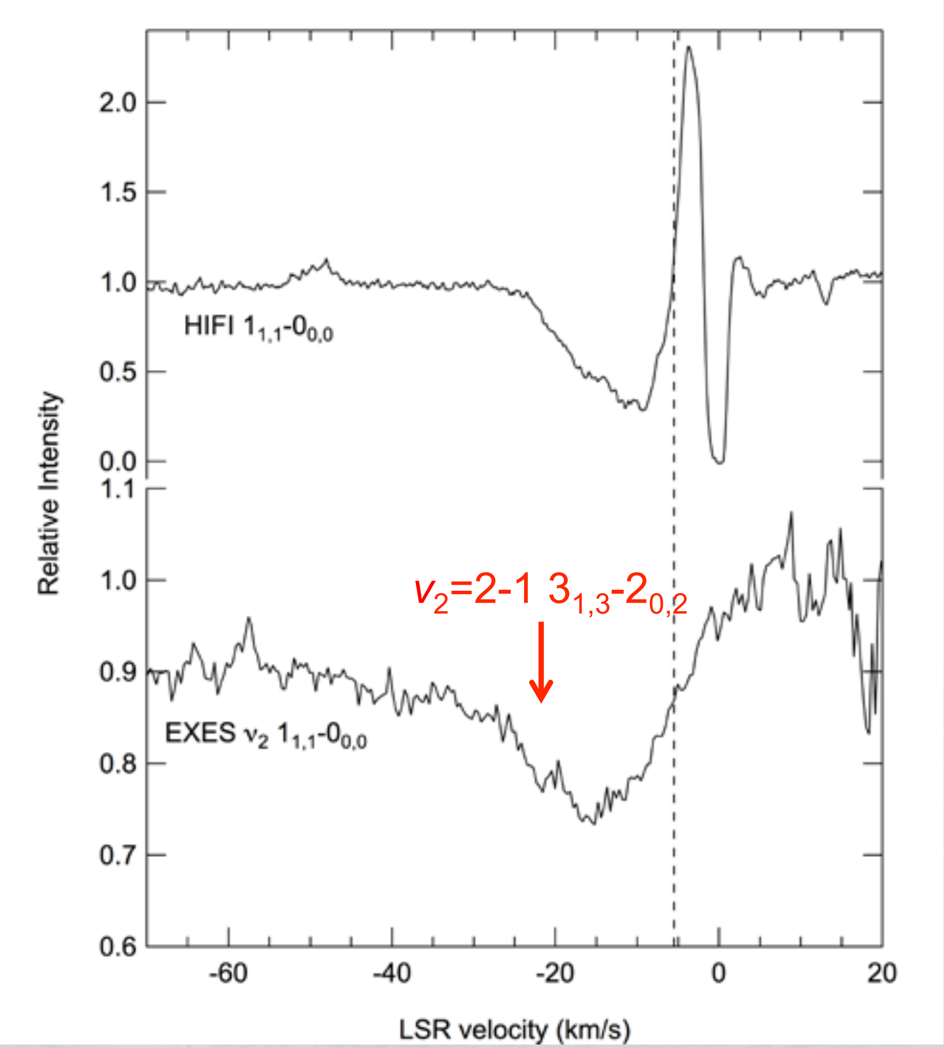
Ground state with HIFI and EXES

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



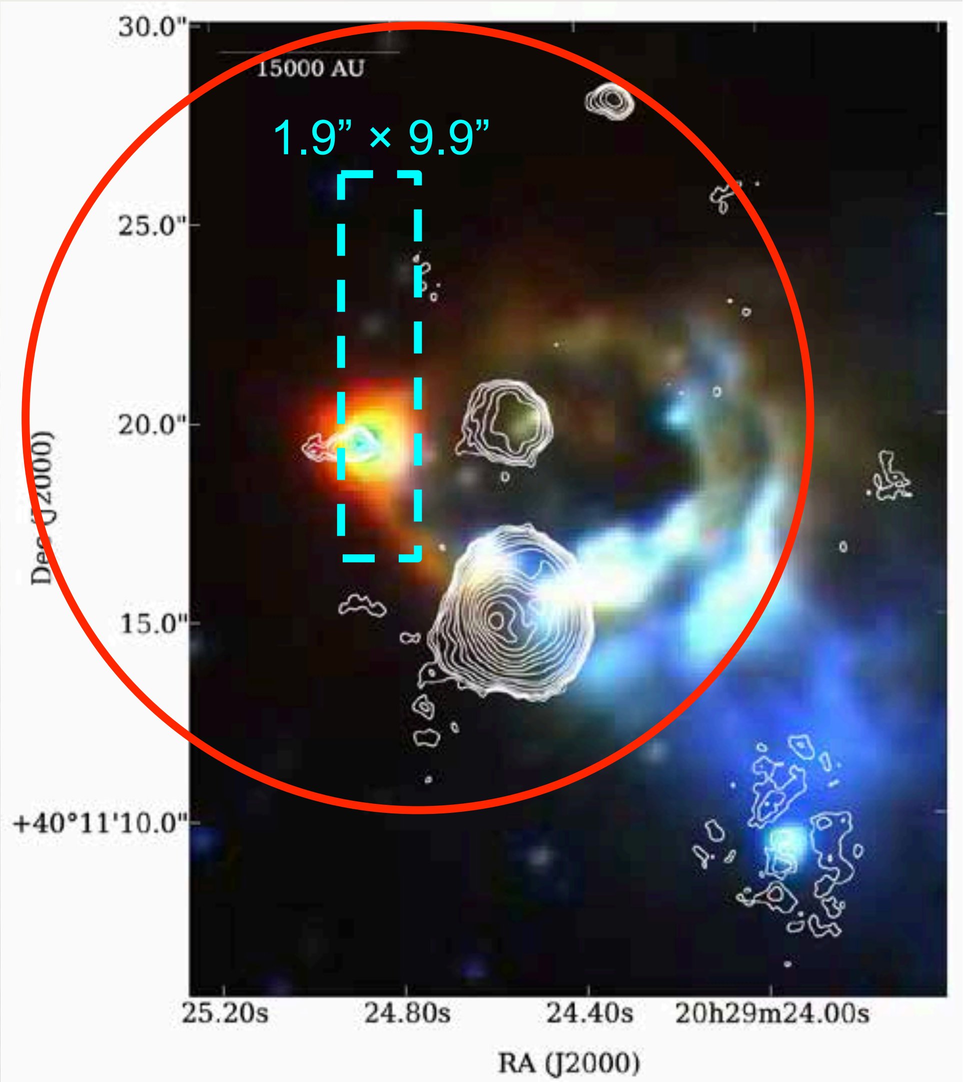
Ground state with HIFI and EXES

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



Apertures on AFGL 2591

- EXES slit in blue
- HIFI beam in red

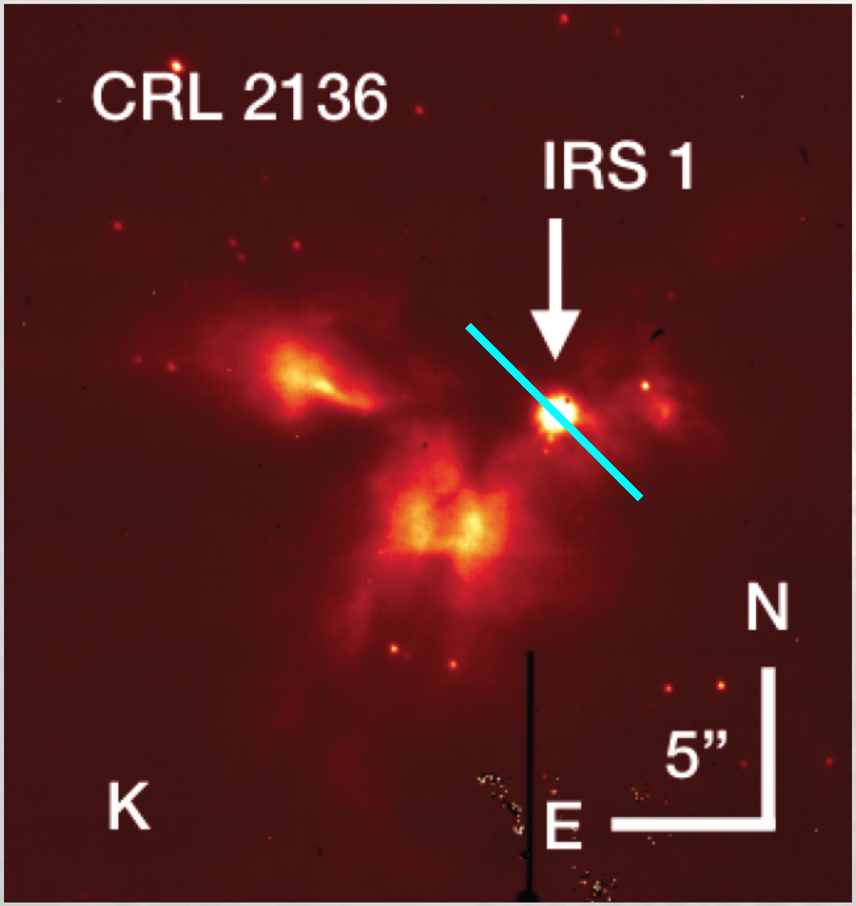


Comparison of Analyses

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

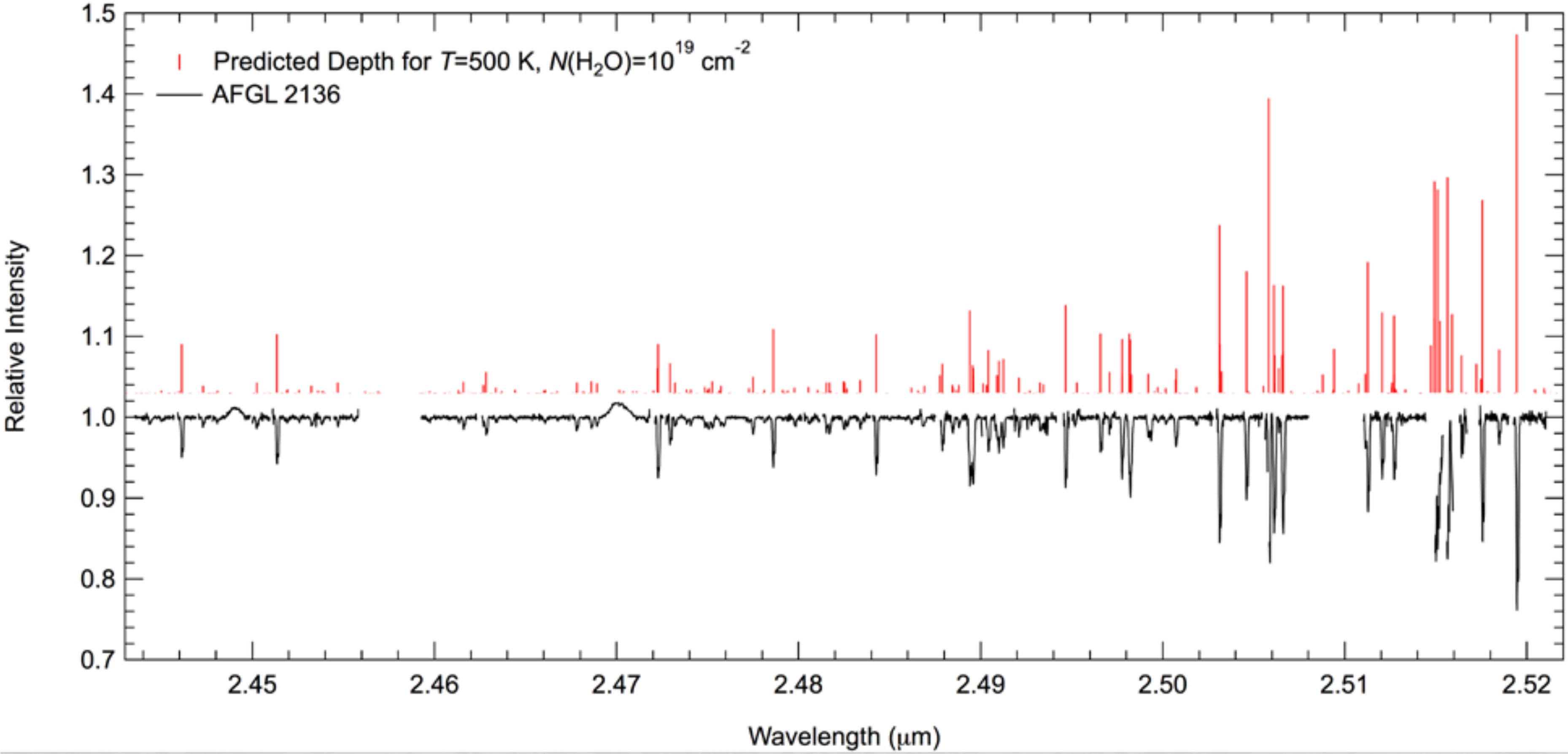
- IR observations give both larger column densities and temperatures
- *Herschel* observations primarily probe transitions out of relatively low-energy states
- $N(CO)=7\times10^{18}$ cm^{-2} (Mitchell et al. 1989, ApJ, 341, 1020)

AFGL 2136 with VLT/CRIRES

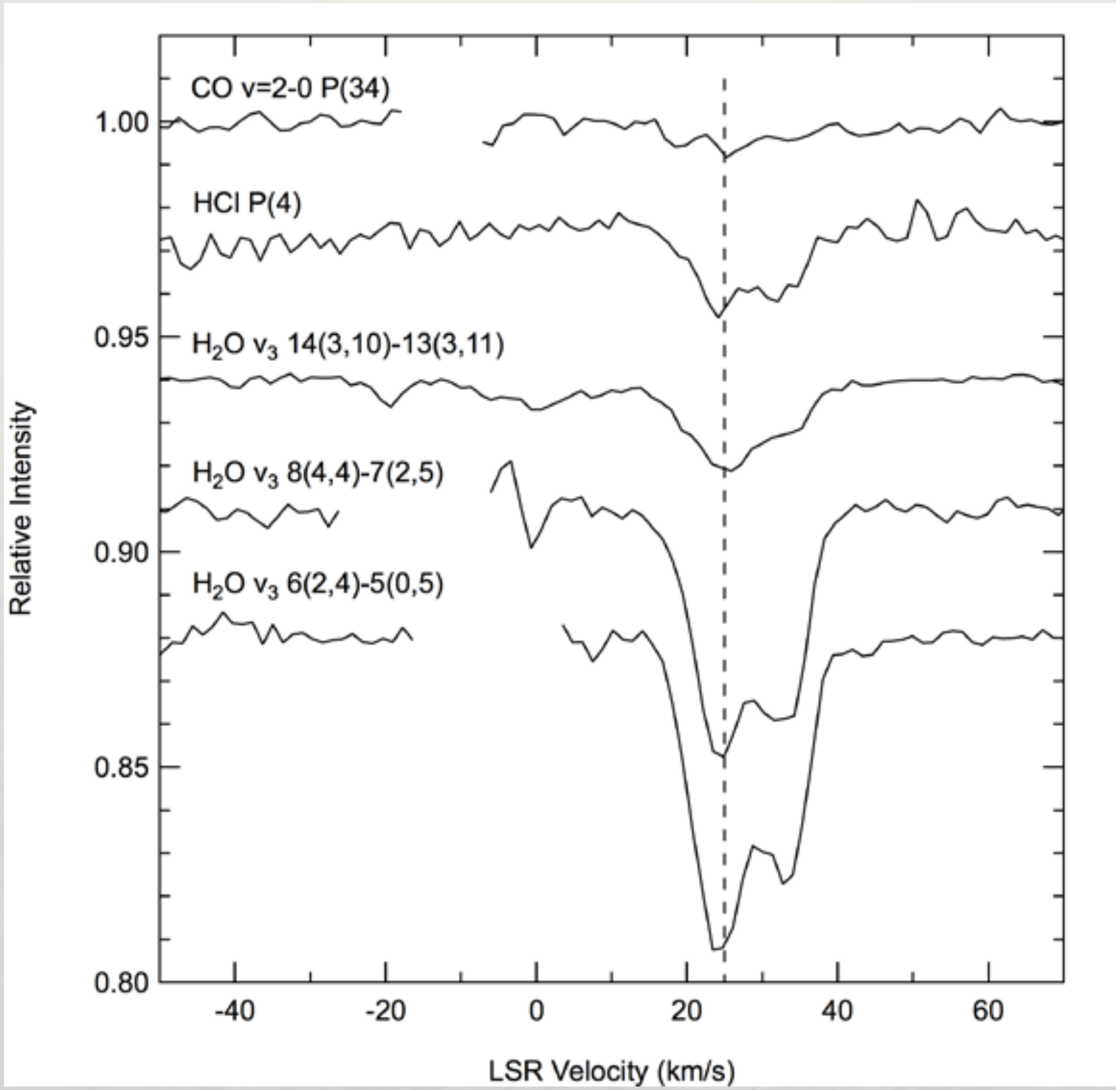


- Ground based observations focus on transitions out of higher energy levels
- Narrow 0.2 arcsec slit oriented to avoid diffuse *K* emission

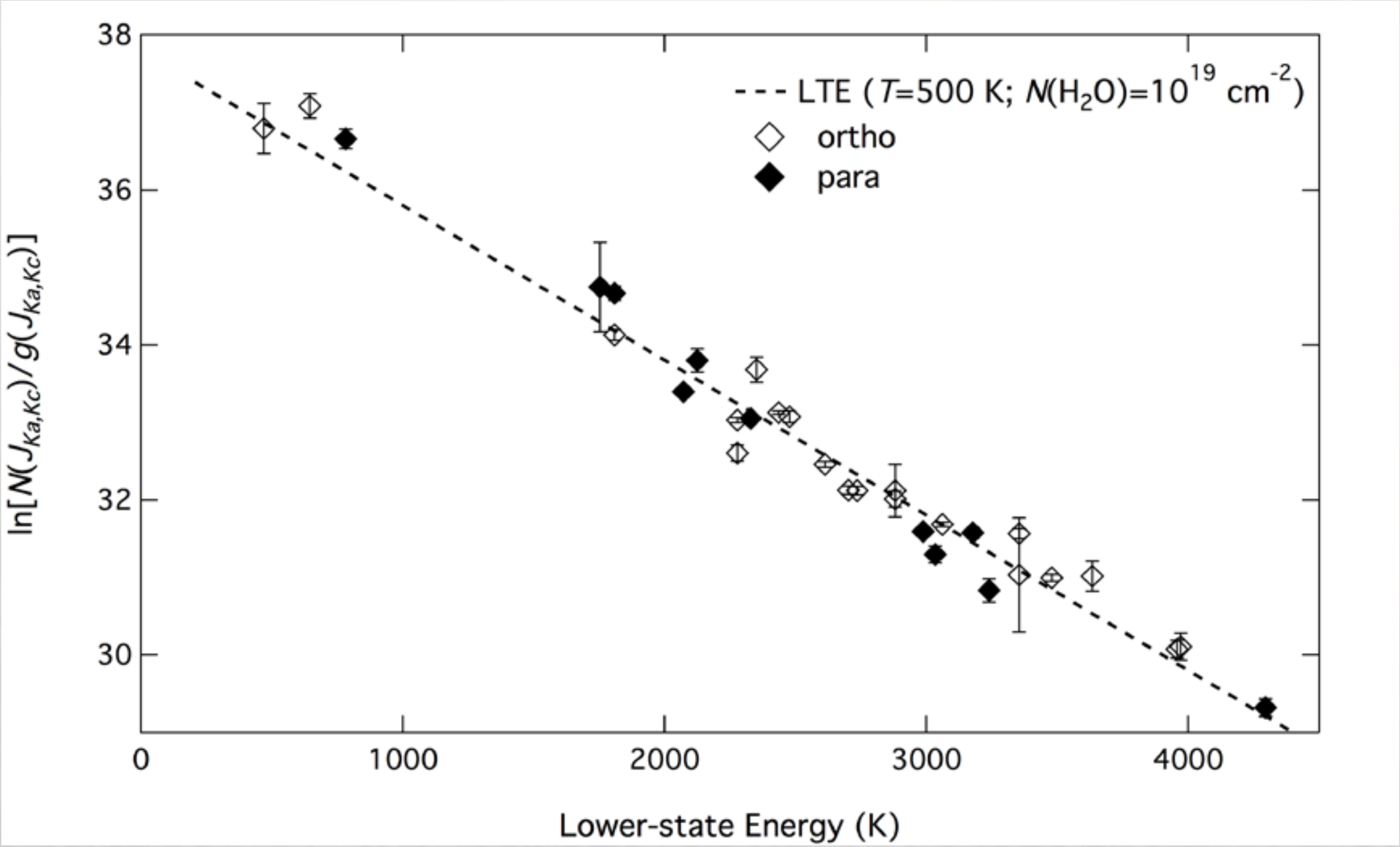
Water in AFGL 2136



AFGL 2136 Line Profiles



AFGL 2136 Rotation Diagram



Indriolo et al. 2013, ApJ, 776, 8

Comparison of Analyses

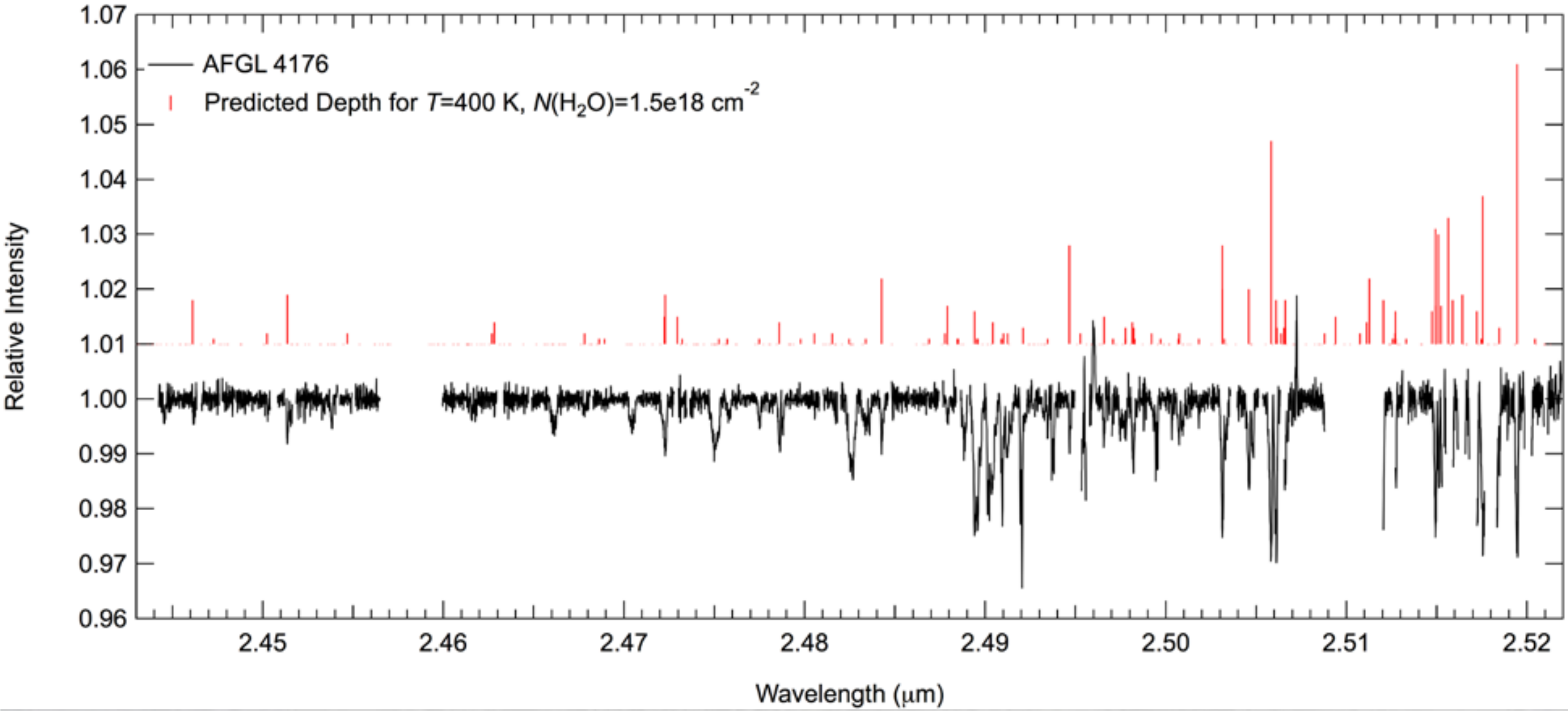
Instrument	H_2O Column Density (cm^{-2})	Temperature (K)	Reference
ISO-SWS	$(1.5\pm0.6)\times10^{18}$	500±200	Boonman & van Dishoeck 2003
VLT CRIRES	$(1.0\pm0.1)\times10^{19}$	506±25	Indriolo et al. 2013

- Requires high density $n > 10^9$ cm^{-3}
- $N(CO) = 2\times10^{19}$ cm^{-2} (Mitchell et al. 1990, ApJ, 363, 554)

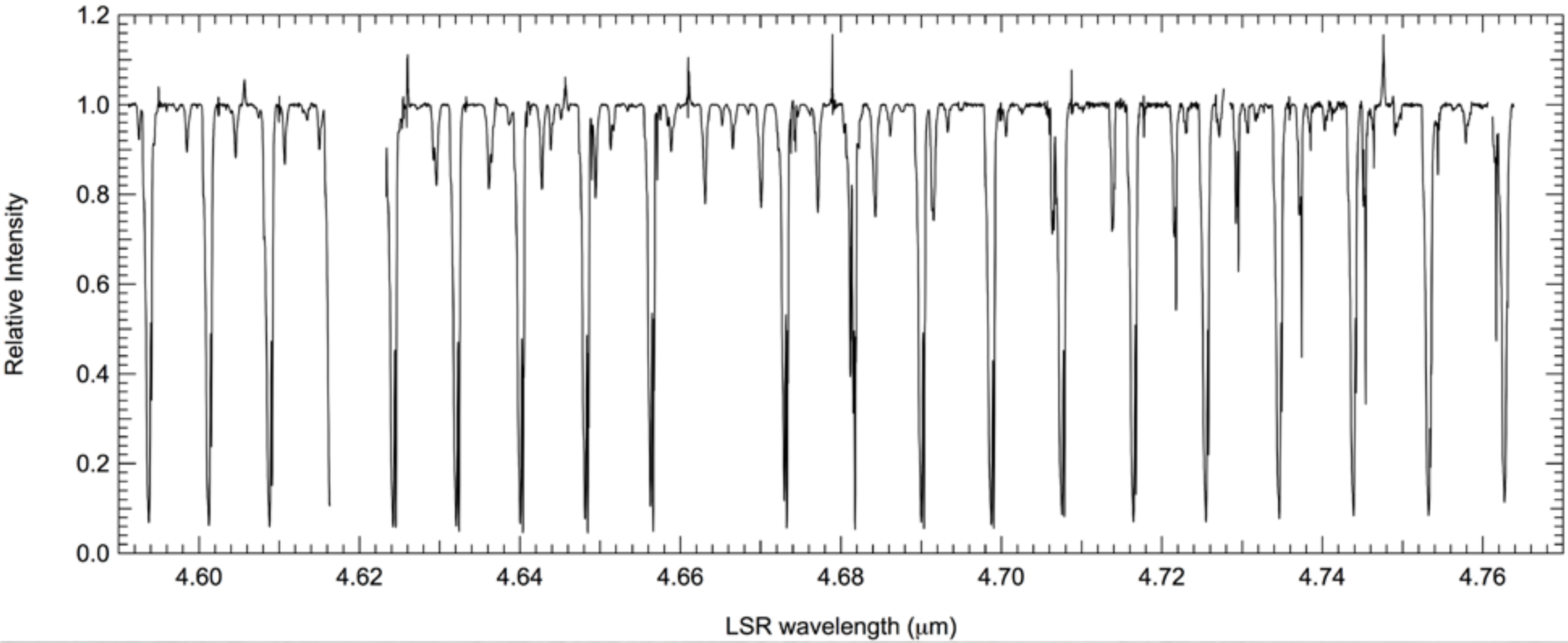
Summary

- H_2O IR absorption in massive protostars arises in hot, dense gas close to the central object
- H_2O/CO is close to 1, supporting model where oxygen is driven into water
- IR absorption and THz emission studies of H_2O are providing complementary data

AFGL 4176: Analysis in Progress

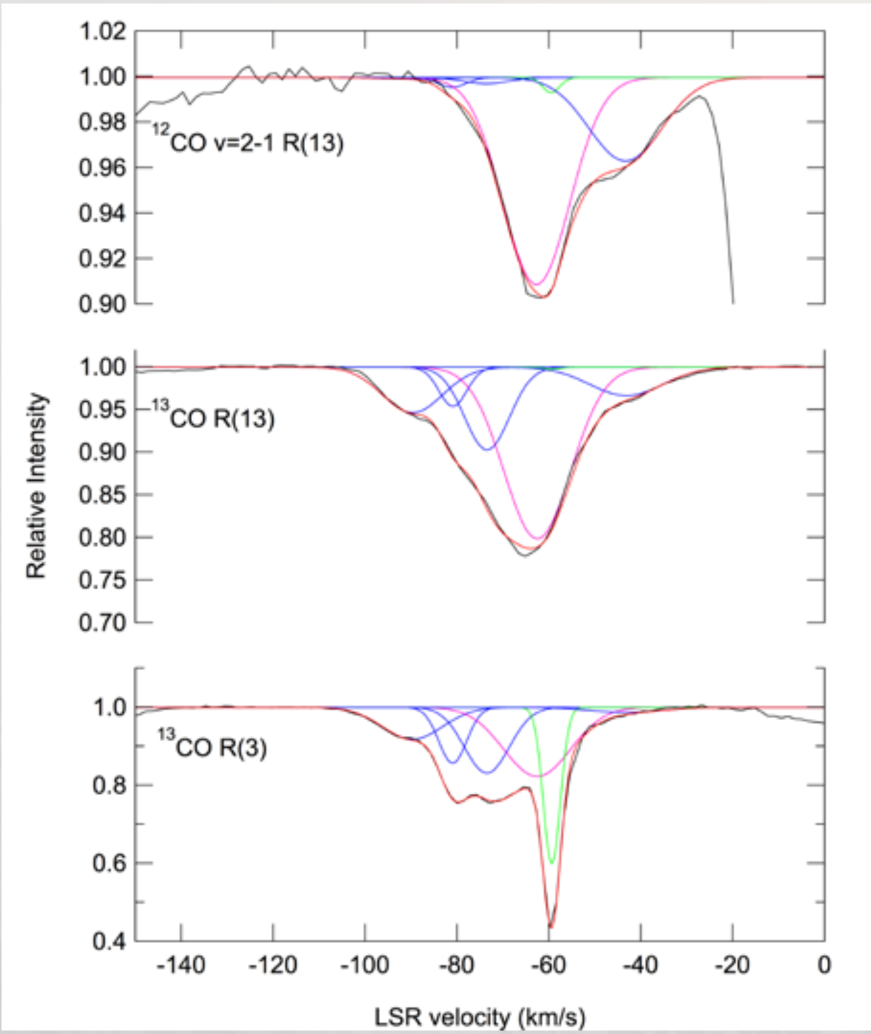


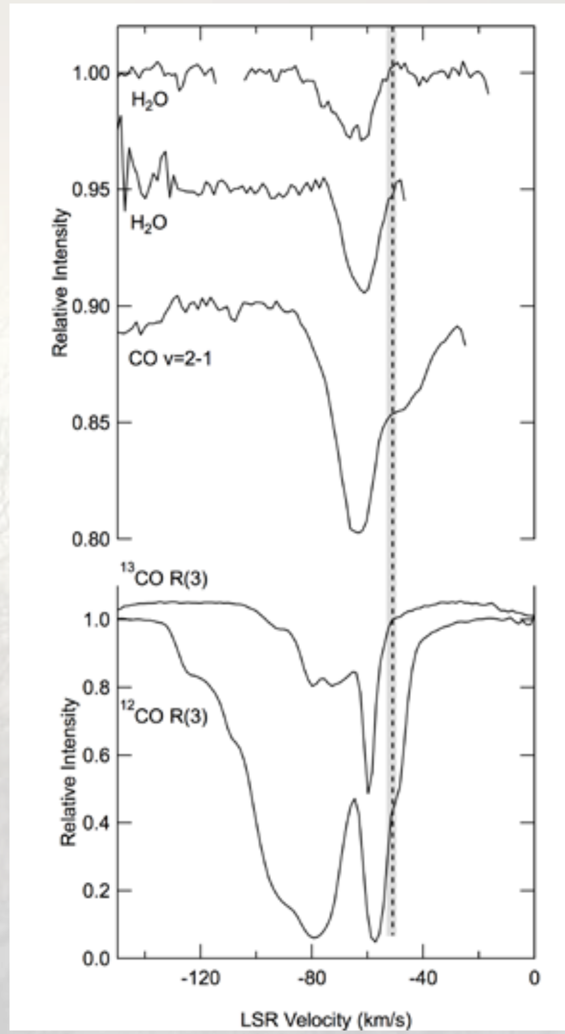
AFGL 4176: Analysis in Progress



^{12}CO v=1-0, ^{12}CO v=2-1, ^{13}CO v=1-0, $C^{18}O$ v=1-0, $C^{17}O$ v=1-0

AFGL 4176: Analysis in Progress





H_2O
v_3 10(2,8)-9(3,7)
v_3 8(8,1)-7(7,0)

^{12}CO v=2-1
R(13)

^{13}CO *R*(3)

^{12}CO *R*(3)

CO absorption

Future Work

- In March 2016 SOFIA/EXES observations of AFGL 2136, W3 IRS5, NGC 7538 IRS 1, Mon R2 IRS 3, and AFGL 2591 at three spectral settings near 6 μm were made
- Compare sources at 2.5 μm, 6 μm, and 10-13 μm to check for consistency in derived results