Water in Massive Protostars: a Comparison of 5 Sources

Nick Indriolo (STScI), A. C. A. Boogert (IfA), C. N. DeWitt (SSI), A. Karska (MPIfR), E. J. Montiel (USRA), D. A. Neufeld (JHU), and M. J. Richter (U.C. Davis)

Outline

- Background
- Observations with SOFIA/EXES
- Data Analysis and Results
- Source Comparison
- Multi-wavelength interpretation
- Summary

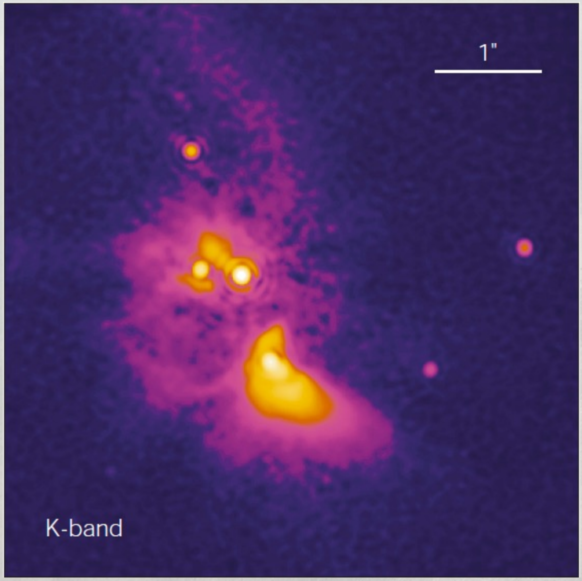
Massive Protostars

- Luminous central objects ($10^4\ L_\odot$)
- Deeply embedded within gaseous envelope
- High temperature chemistry
- Multiple kinematic components (envelope, disk, torus, jet, wind, outflow, infall)
- Drive large scale molecular outflows
- Caveat: sources are simultaneously similar, and yet significantly different. What you learn about one source may not be applicable to others

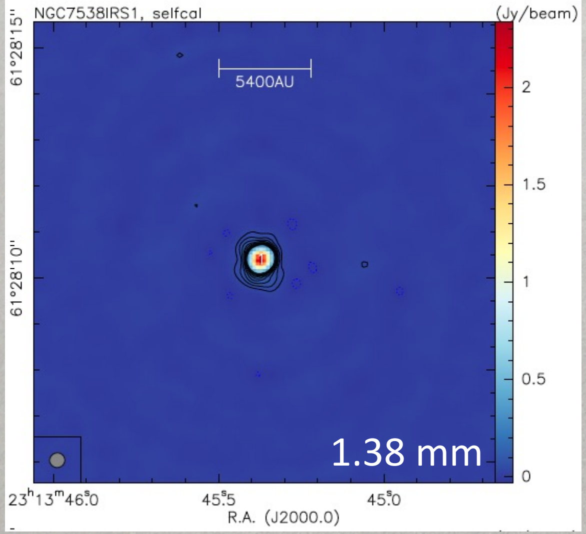
Protostar Properties

Source	**Mass**	**Bol. Luminosity**	**Distance**	**Comments**
	($M_\odot$)	(10^4 $L_\odot$)	(kpc)	
AFGL 2136	45	10	2.2	disk
AFGL 2591	40	20	3.3	
MonR2 IRS 3	5-15 (×3)	1.3	0.78	triple
NGC 7538 IRS 1	30	20	2.7	
W3 IRS 5	20 (×2)	17	2.3	binary

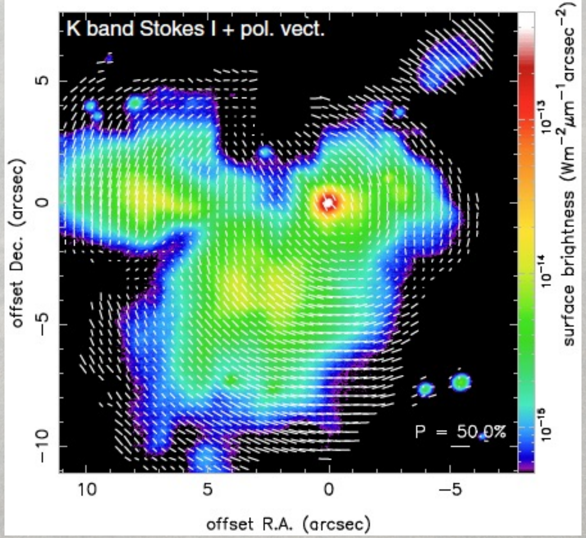
Image Gallery



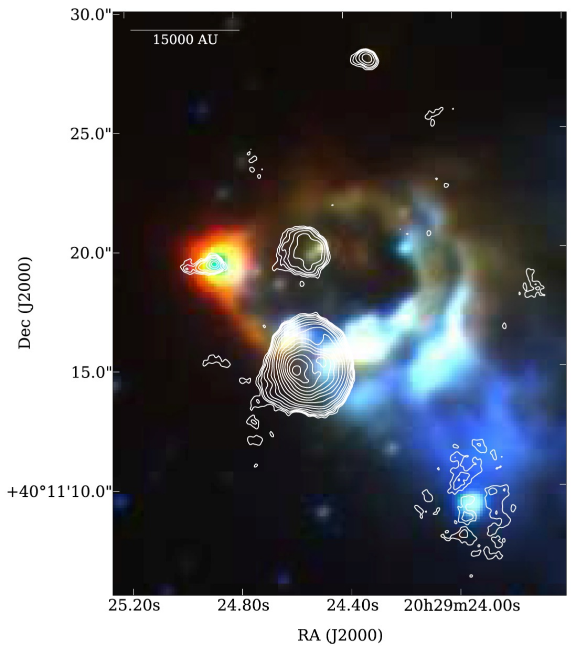
Mon R2 IRS 3; Preibisch et al. 2003



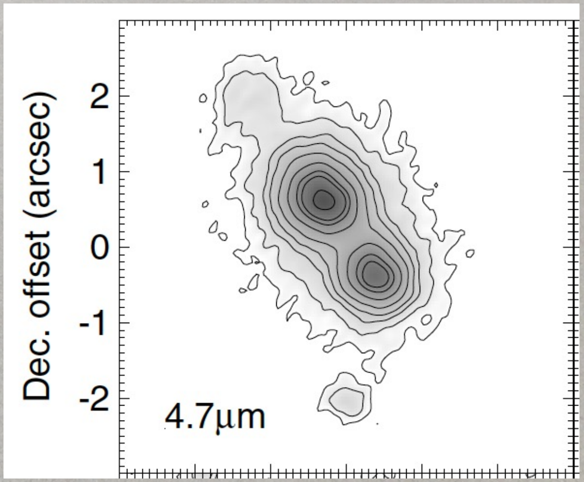
NGC 7538 IRS1; Beuther et al. 2018



AFGL 2136; Murakawa et al. 2008

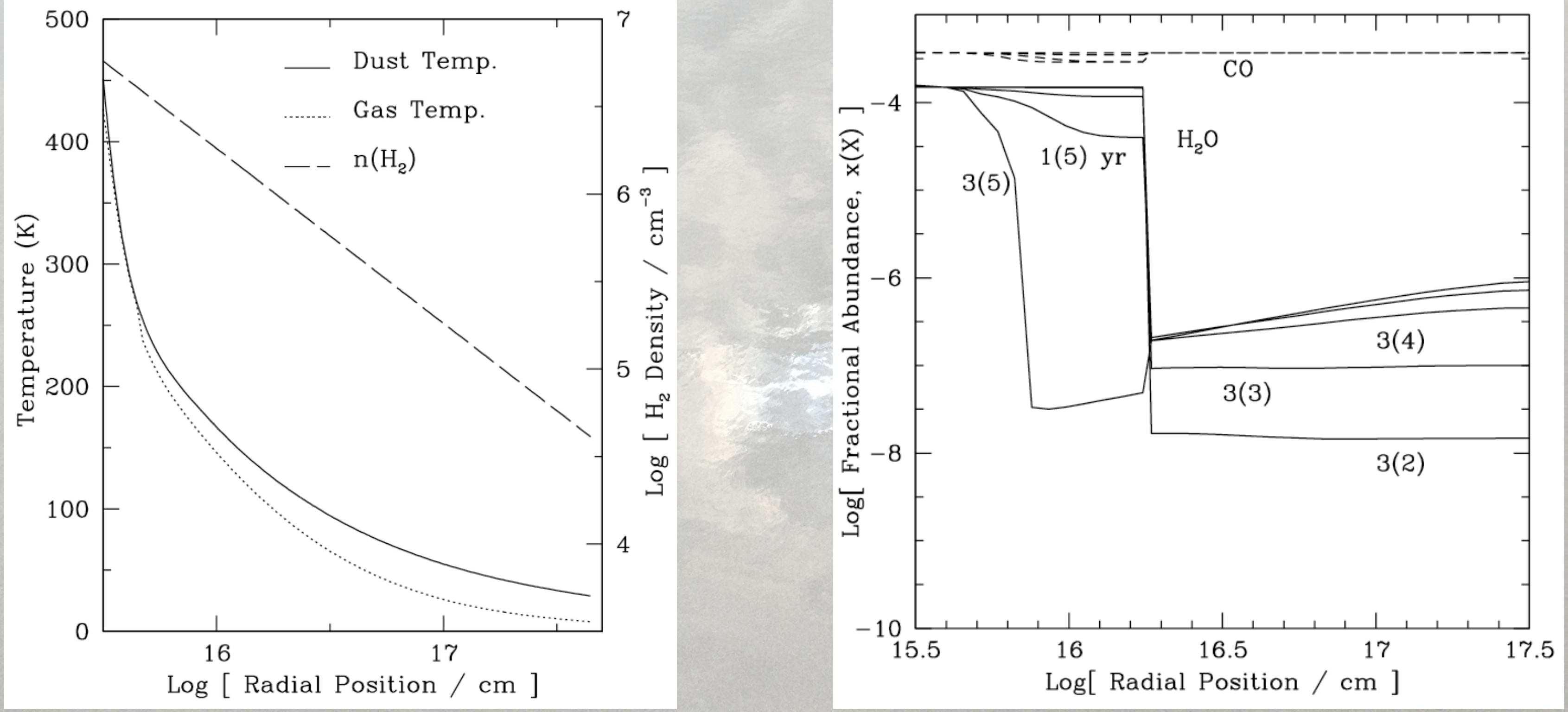


AFGL 2591; Johnston et al. 2013



W3 IRS5; van der Tak et al. 2005

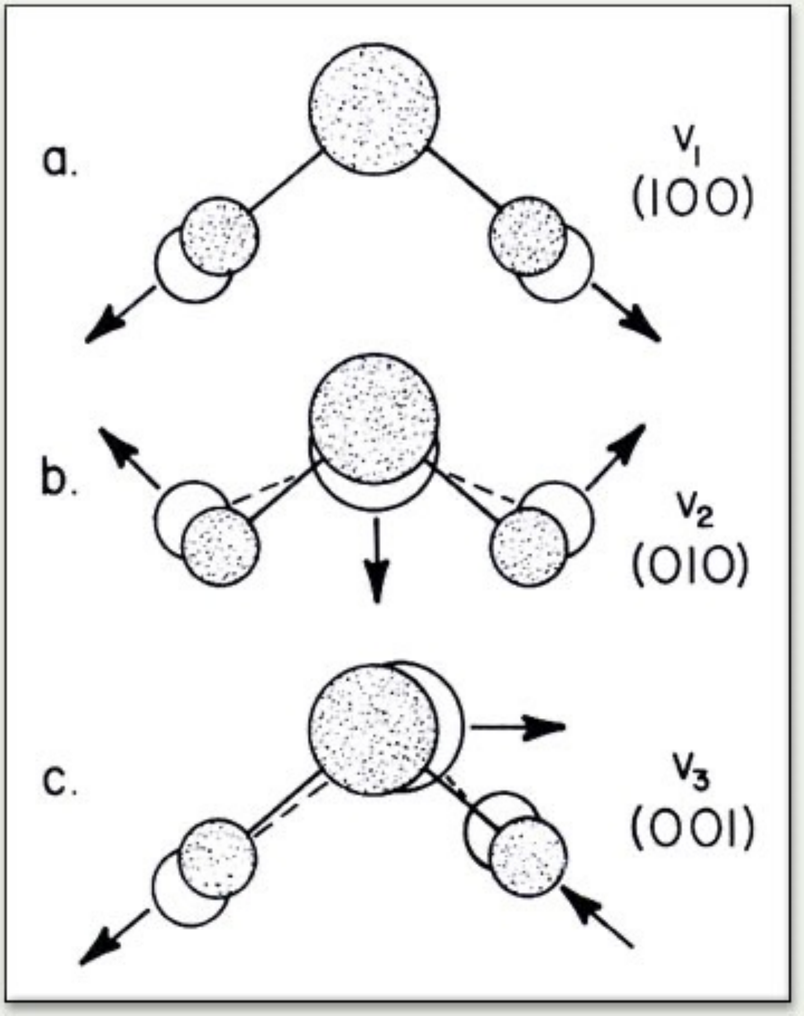
Chemical Models



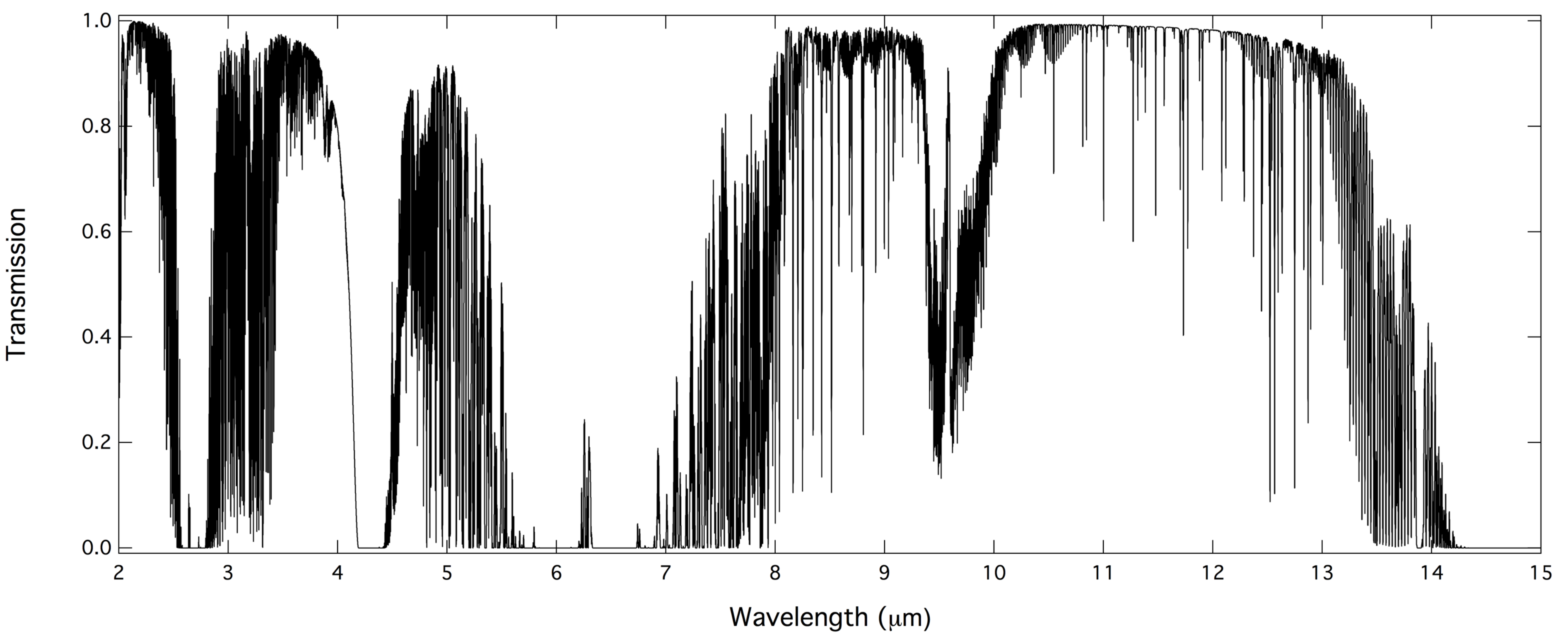
Simple models predict roughly half of the oxygen in CO and half in H_2O in the inner envelope. H_2O transitions to ice in the outer envelope, while CO remains in the gas phase. (Doty et al. 2002)

H_2O Vibrational Modes

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

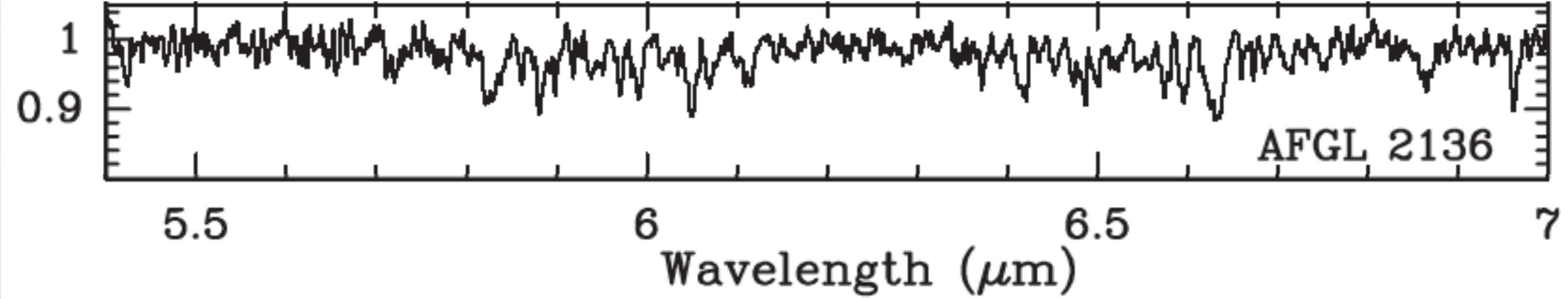


Atmospheric Transmission



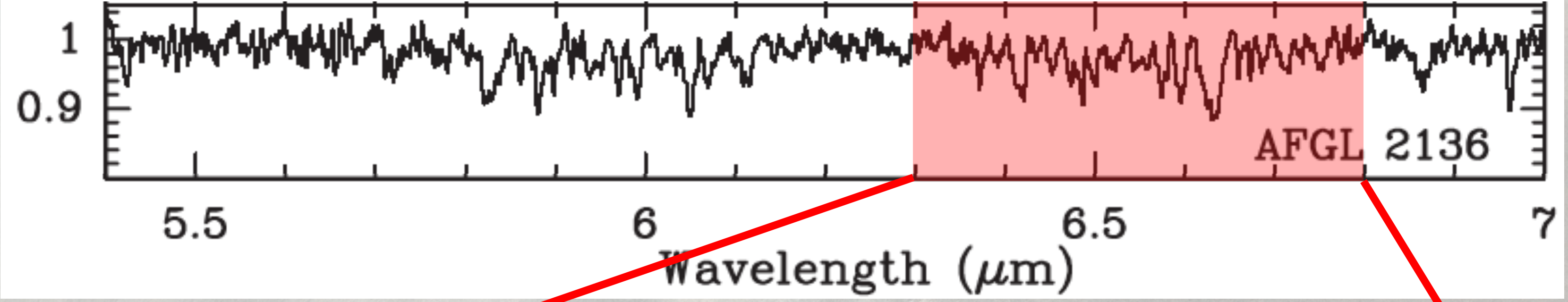
ATRAN (Lord 1992) simulated atmospheric spectrum at 14,000 ft with 2.5 mm PWV

Space-based Observations

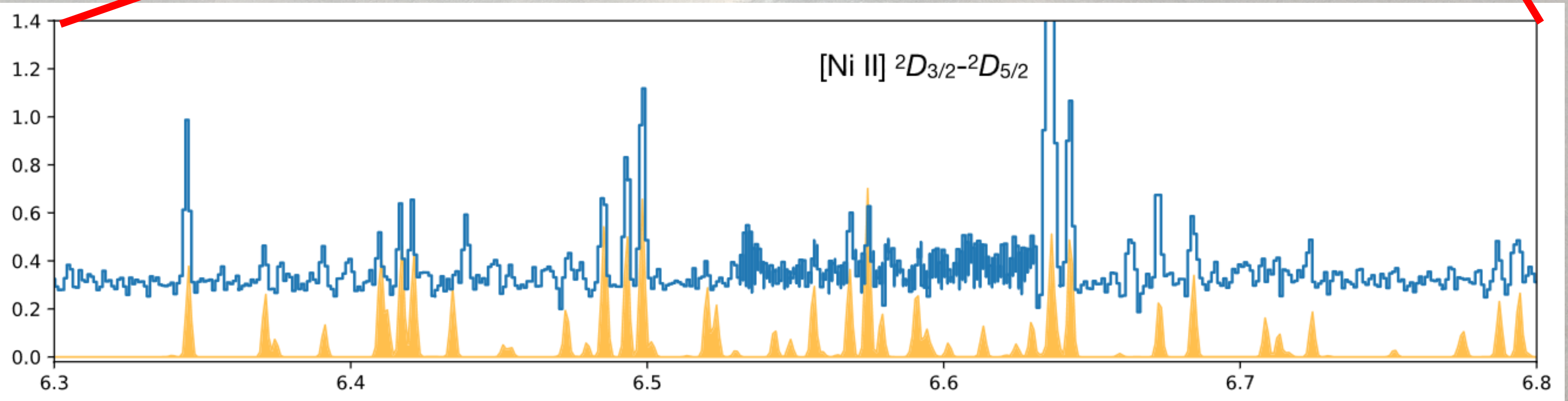


ISO SWS (215 km/s); Boonman & van Dishoeck 2003

Space-based Observations

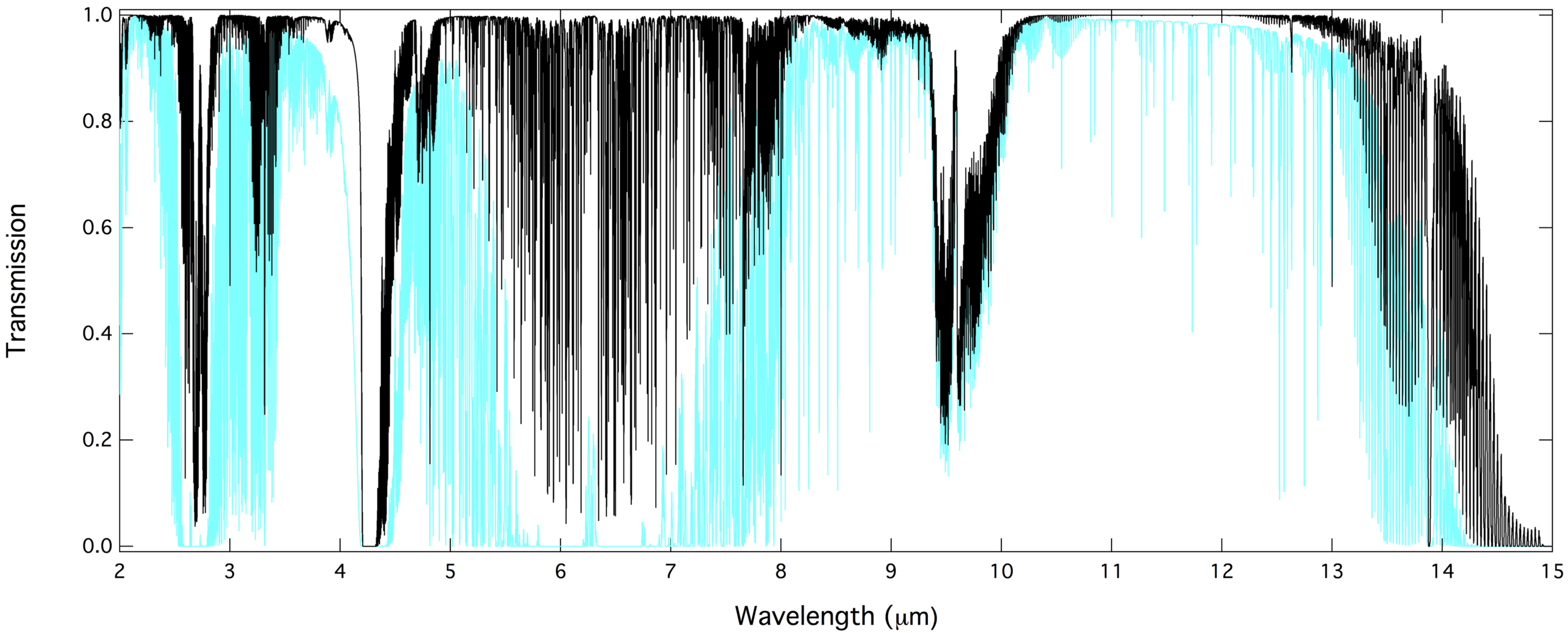


ISO SWS (215 km/s); Boonman & van Dishoeck 2003



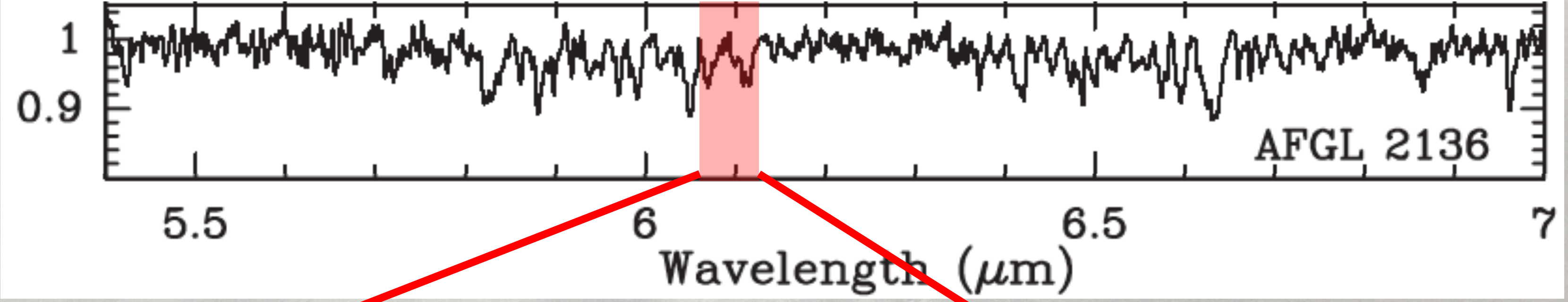
JWST MIRI (100 km/s); Yang et al. 2022 (IRAS 15398-3359)

Atmospheric Transmission

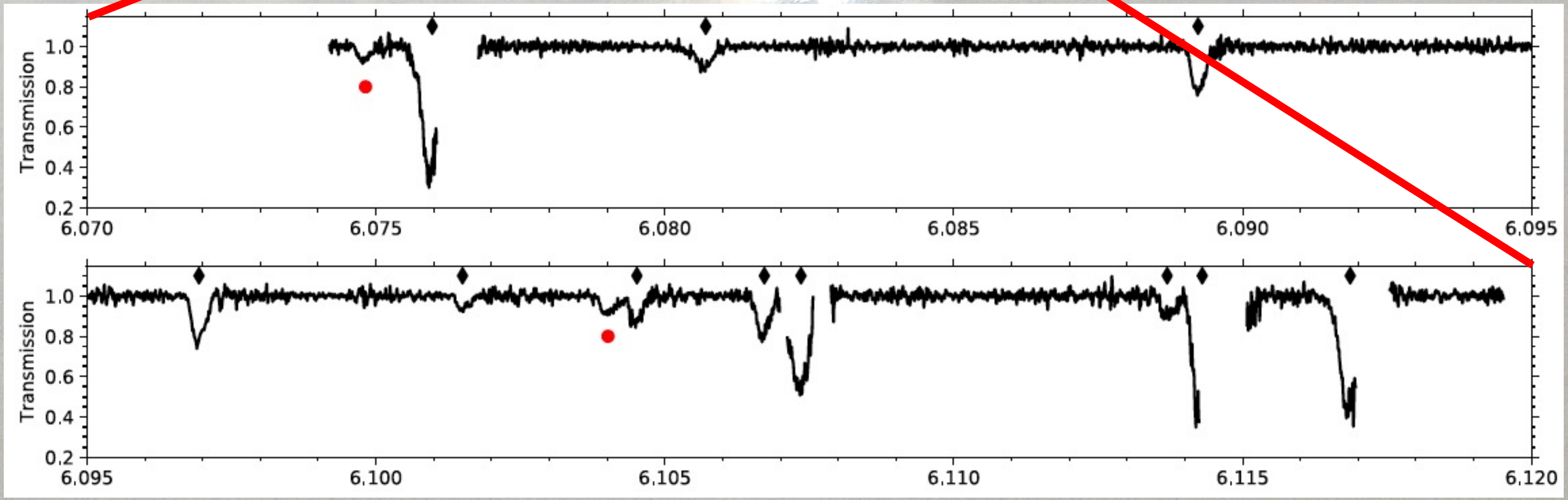


ATRAN (Lord 1992) simulated atmospheric spectrum at 43,000 ft with 0.01 mm PWV

Stratospheric Observations

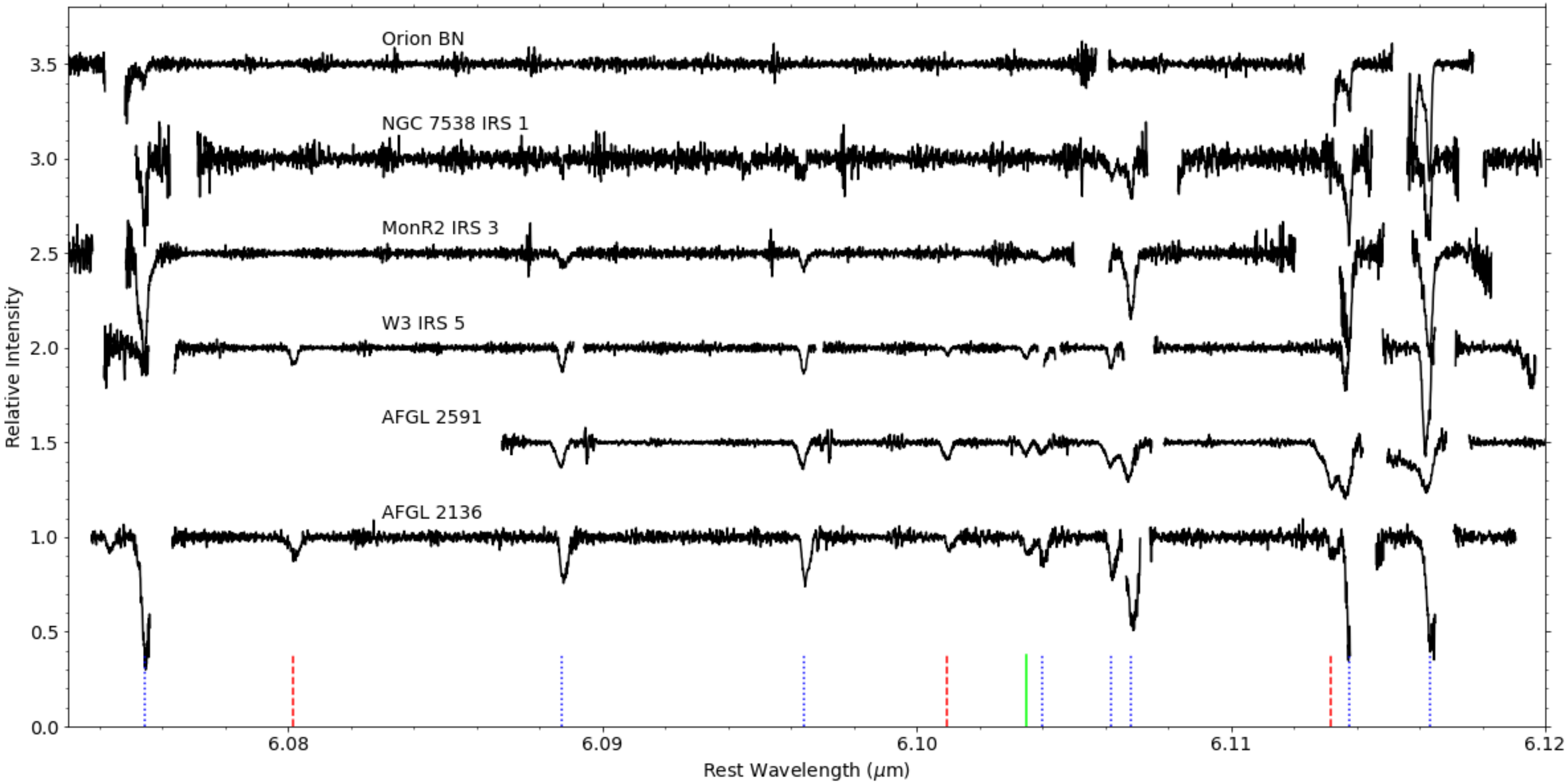


ISO SWS (215 km/s); Boonman & van Dishoeck 2003

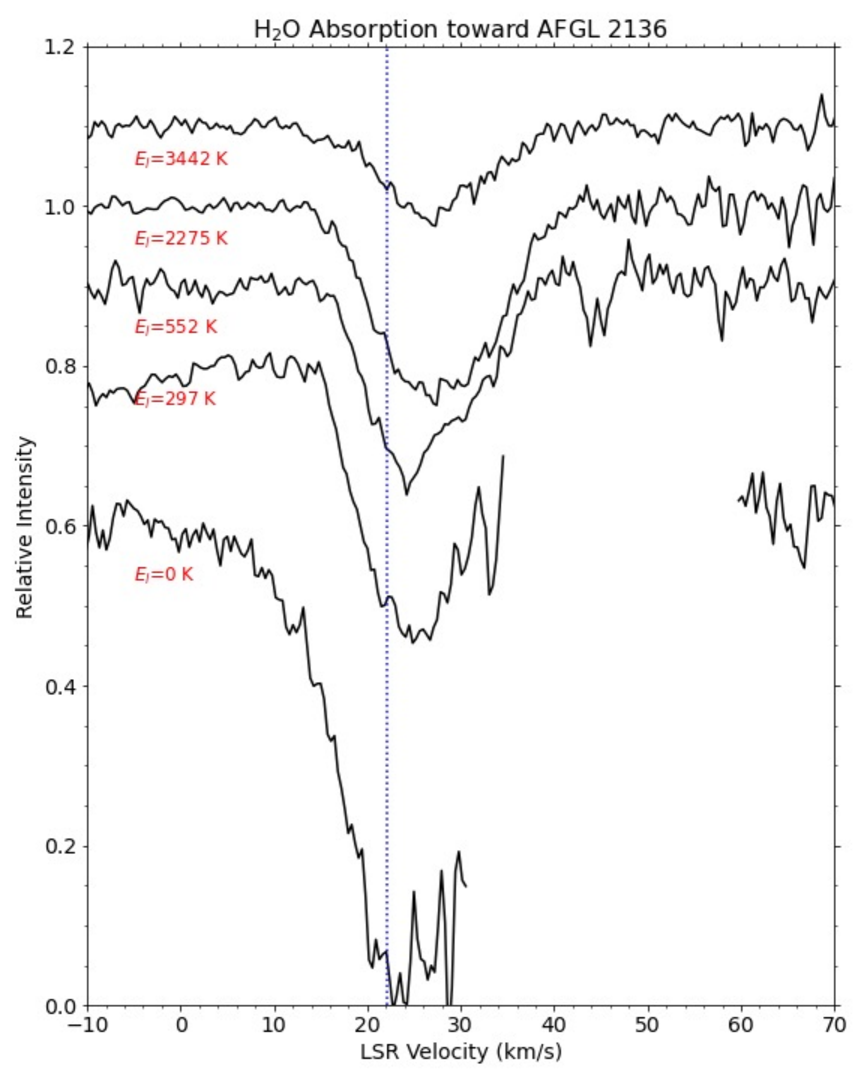


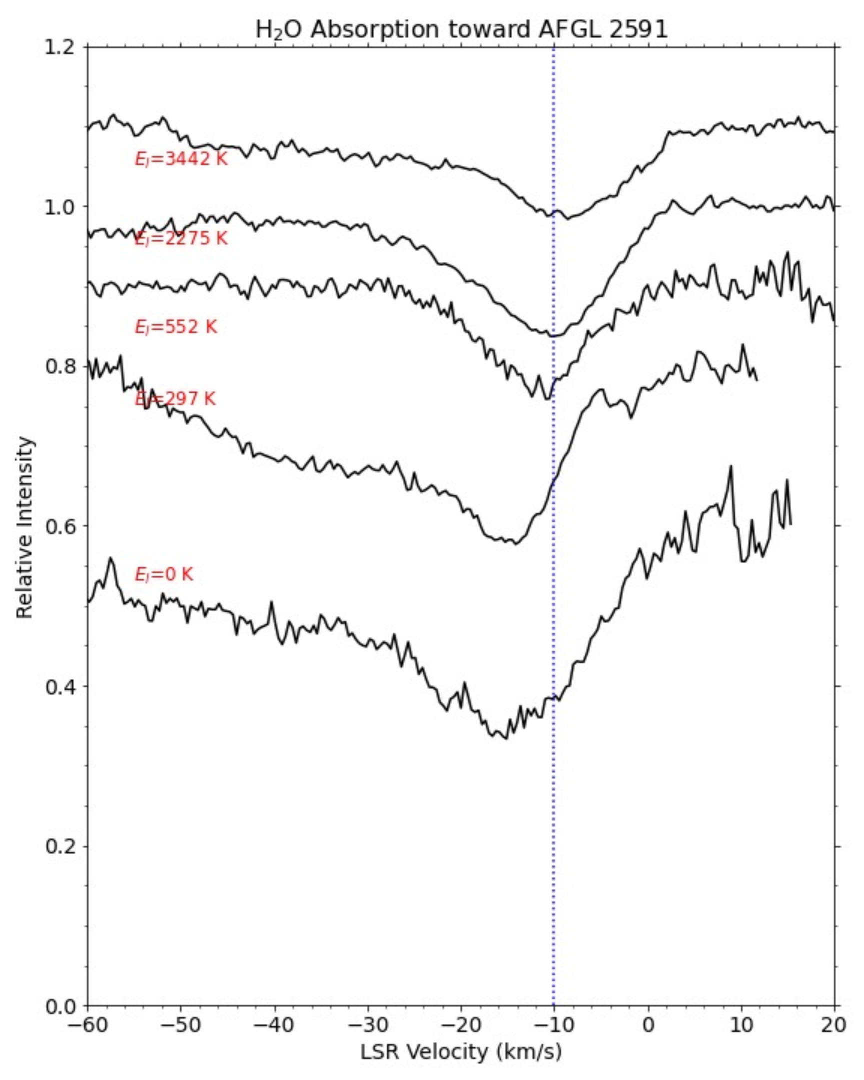
SOFIA/EXES (3.5 km/s); Indriolo et al. 2020

Example Spectra

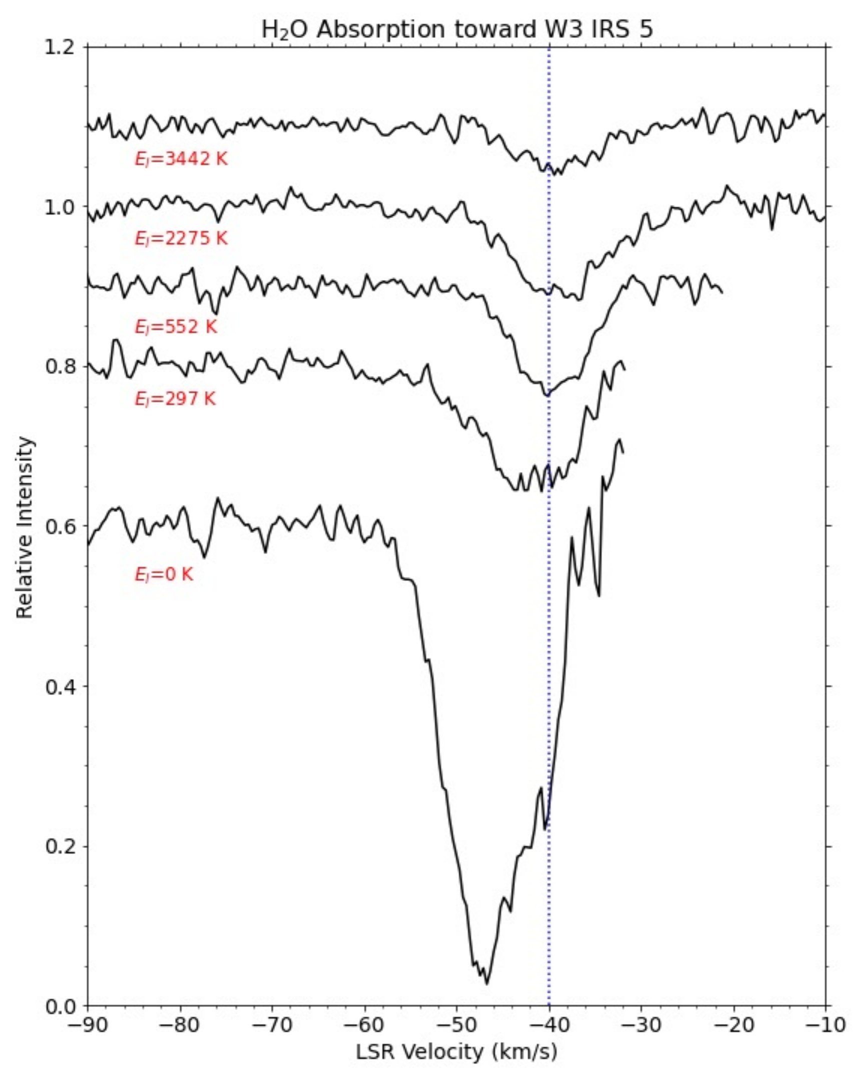


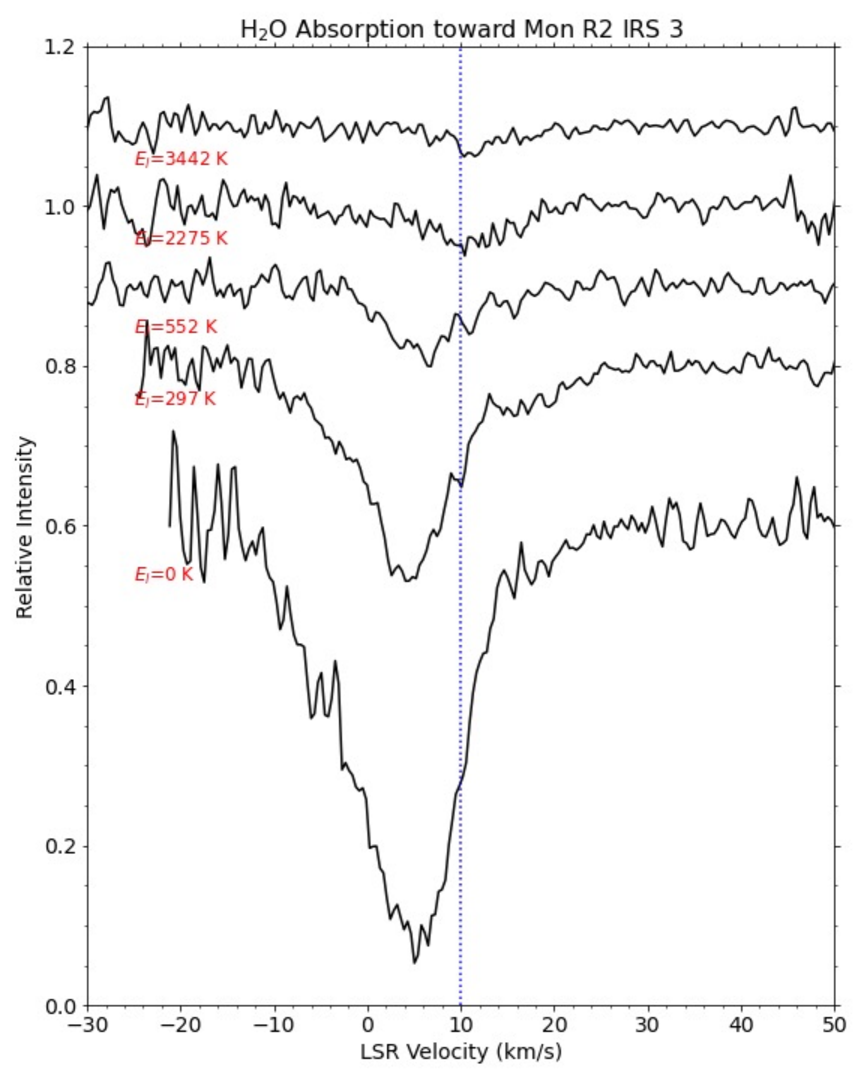
Velocity Profiles



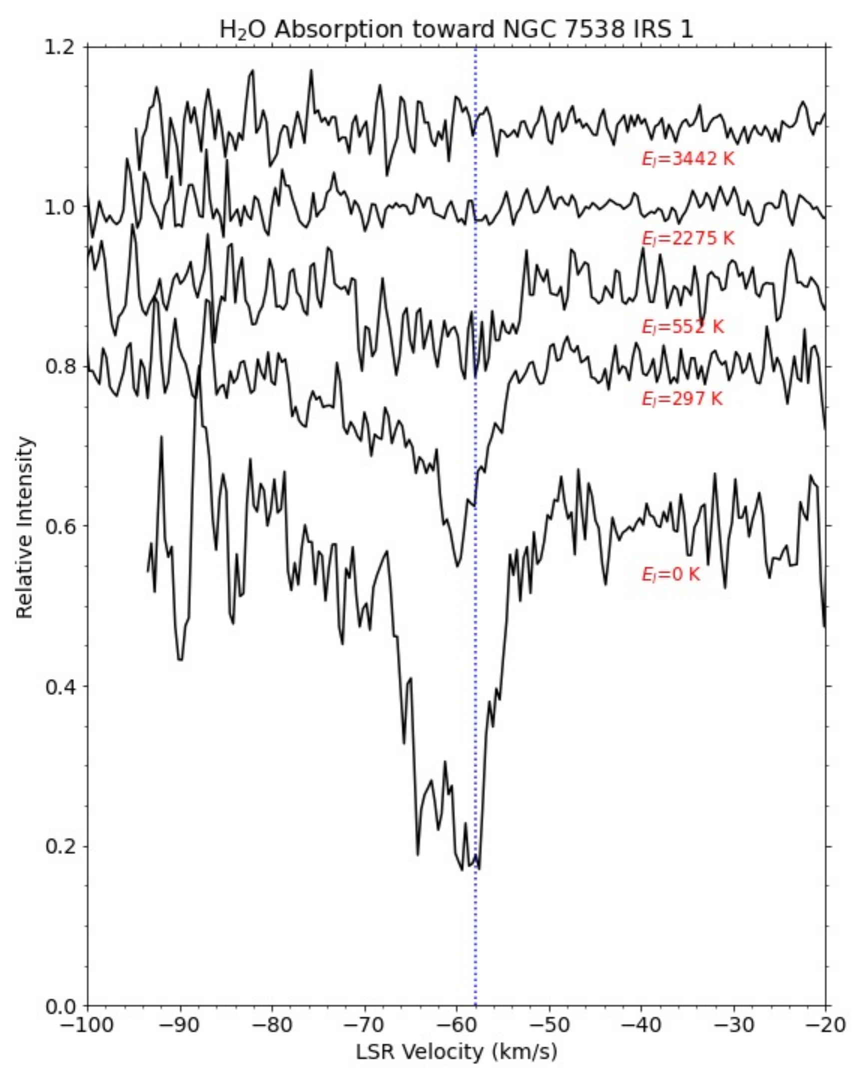


Velocity Profiles



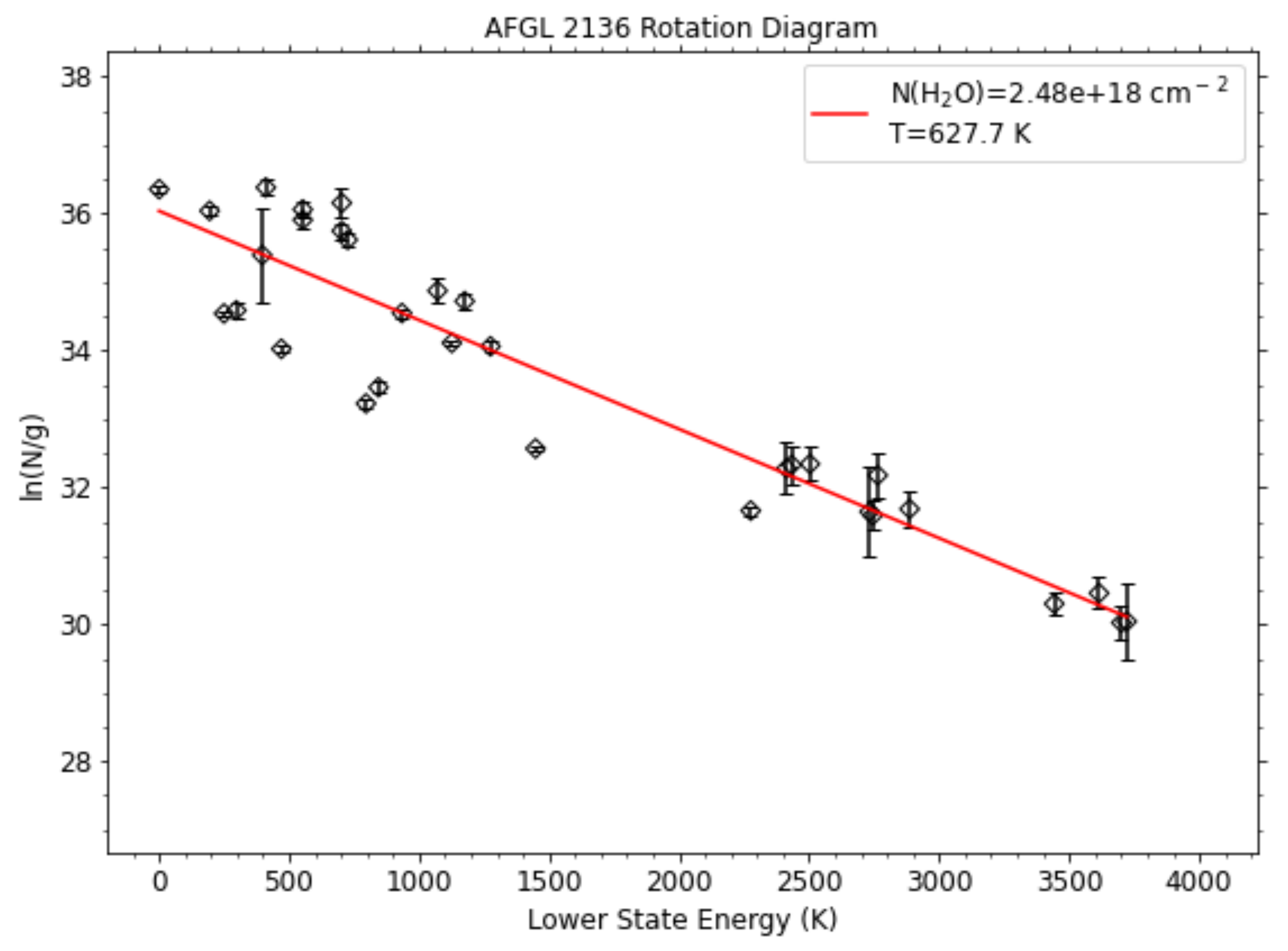


Velocity Profiles

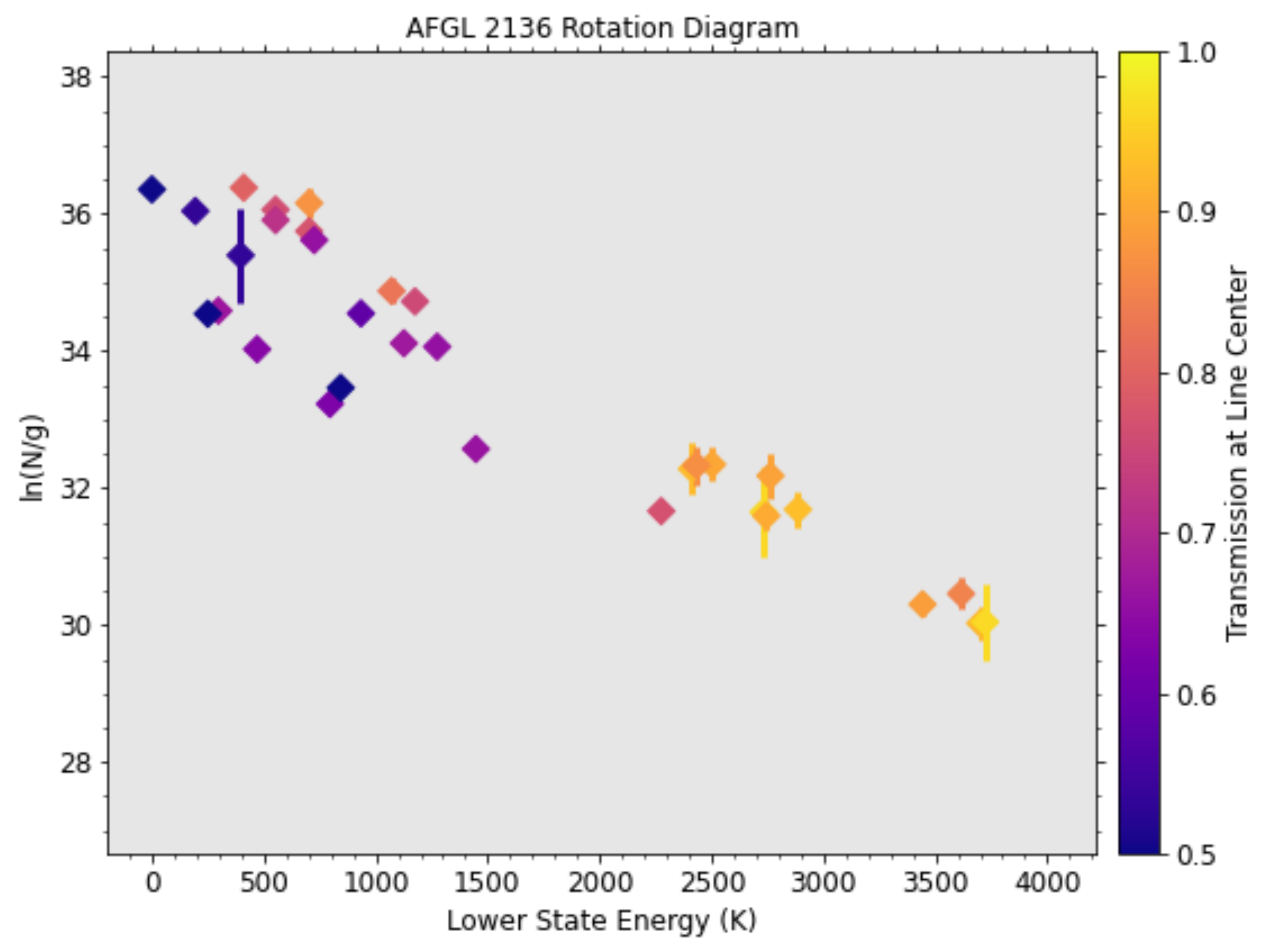


- AFGL 2591, NGC 7538 IRS 1, Mon R2 IRS 3, and W3 IRS 5 all show blue-shifted “outflow” components
- AFGL 2136 absorption is more red-shifted with respect to systemic velocity
- No source shows any water in emission at IR wavelengths

H_2O Rotation Diagram

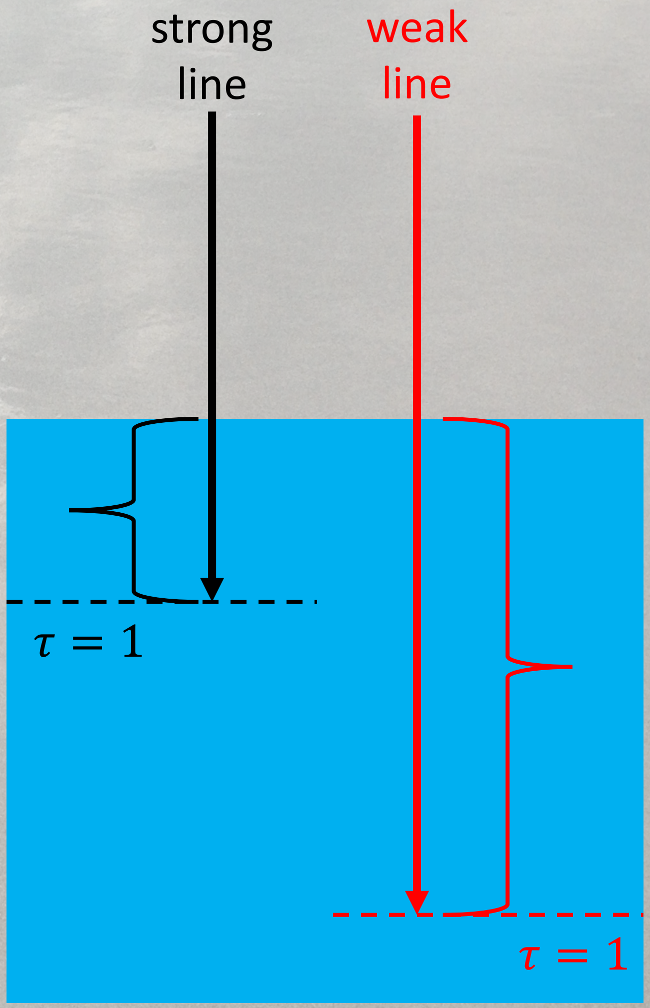


H_2O Rotation Diagram

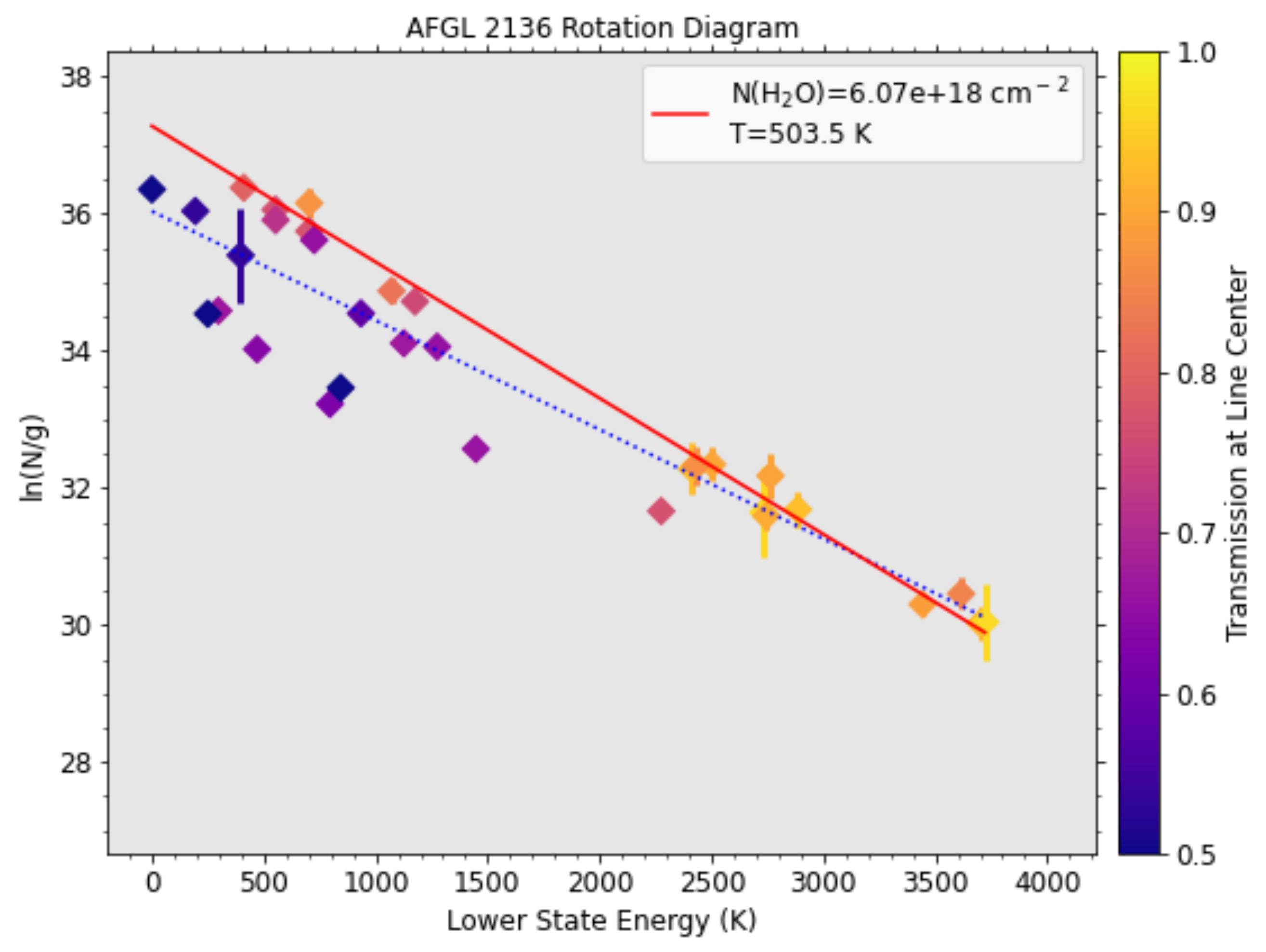


Optical Depth Effects

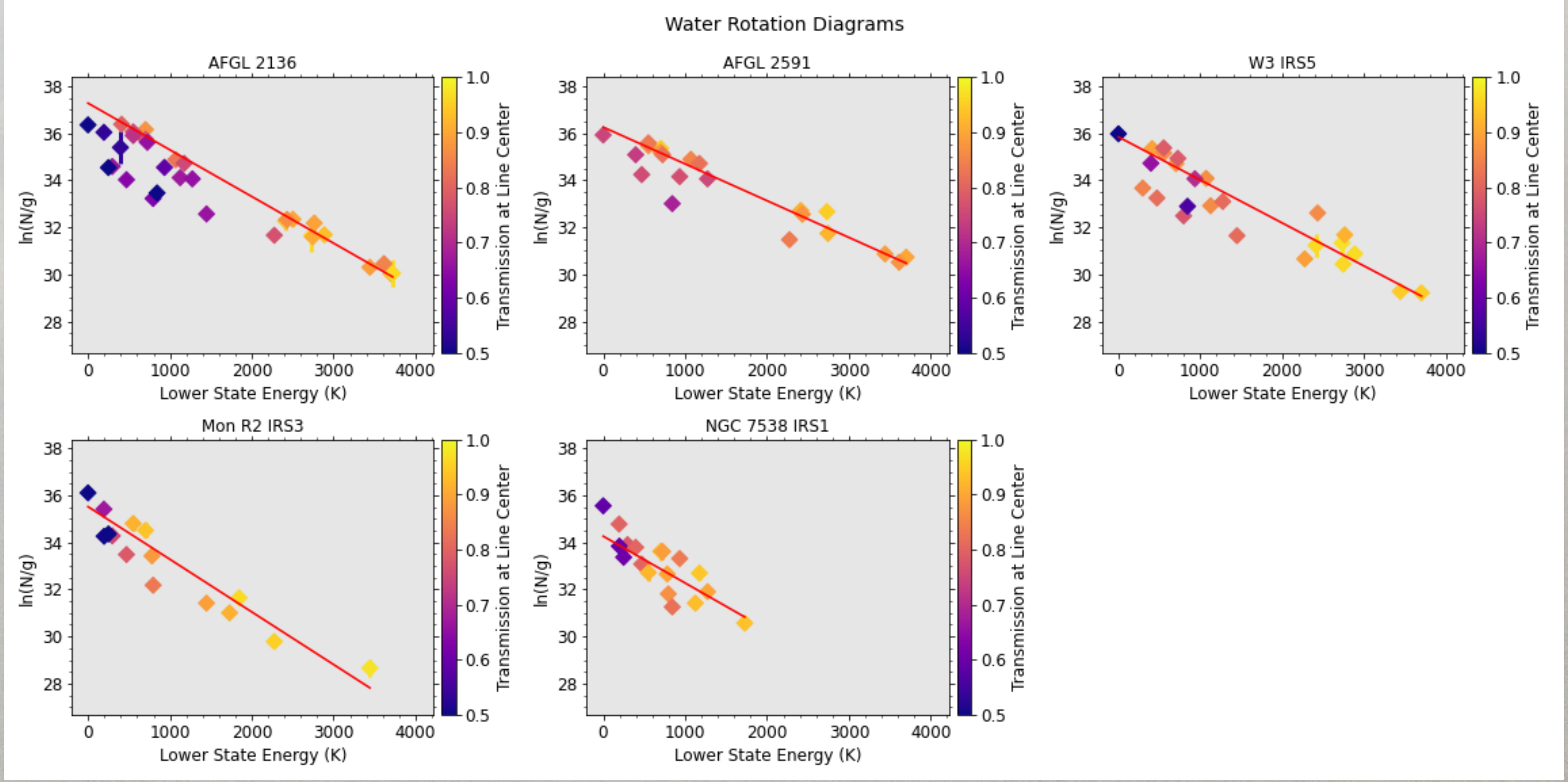
- If absorbing gas is mixed with the emitting photosphere, then different transitions reach an optical depth of 1 at different physical depths
- The result is that weaker lines probe more material, making the stronger lines appear to be underpopulated
- By fitting only the data points derived from weak lines in the rotation diagram, we can better estimate the total H_2O column



H_2O Rotation Diagrams



H_2O Rotation Diagrams



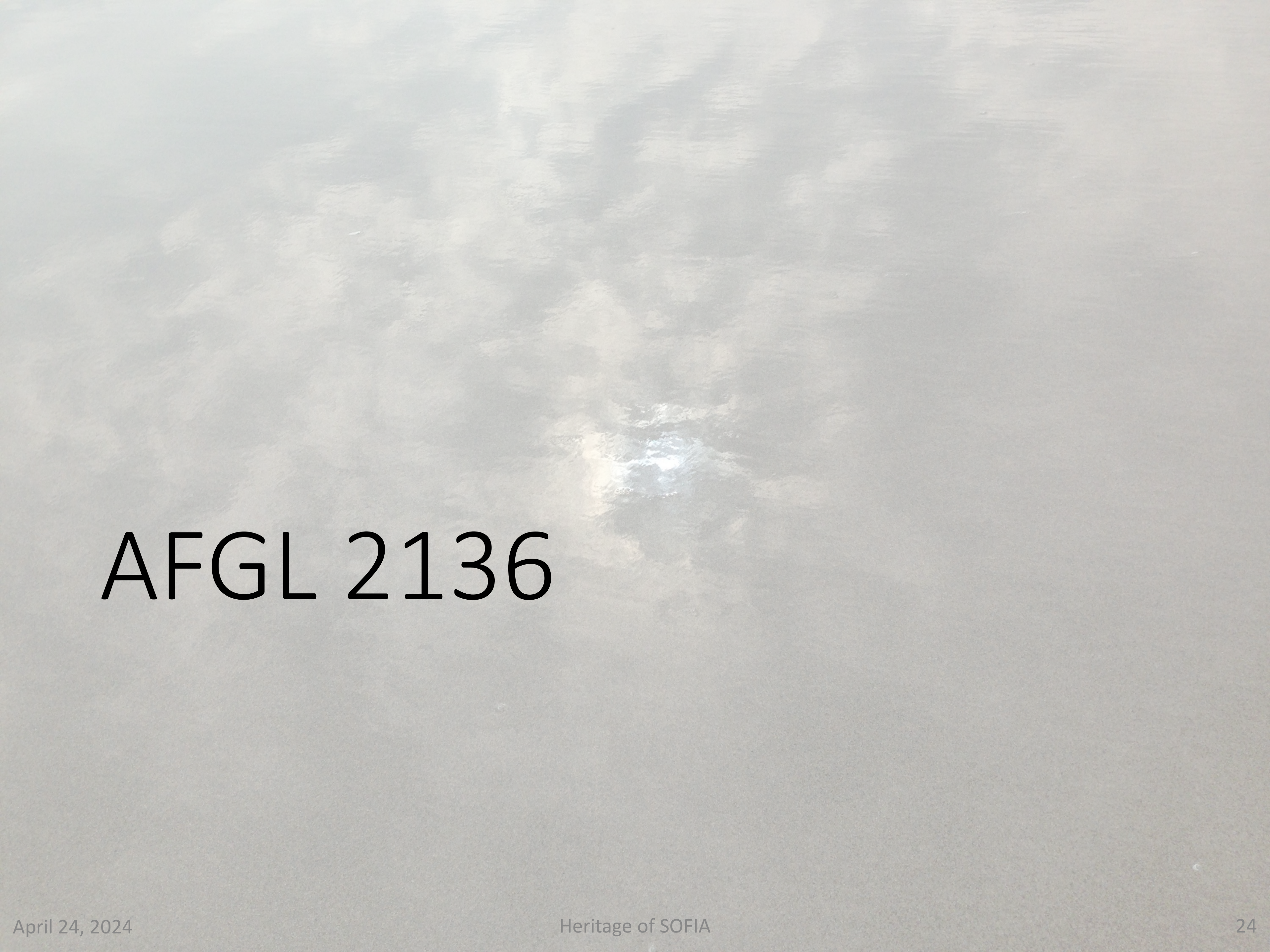
Temperature and H_2O Columns

	$N(H_2O)$ (10^{18} cm^{-2})	**T_{ex} (K)**
AFGL 2136	6.07 ± 1.15	504 ± 17
AFGL 2591	3.19 ± 1.18	640 ± 55
MonR2 IRS 3	0.87 ± 0.53	447 ± 47
NGC 7538 IRS 1	0.30 ± 0.21	503 ± 140
W3 IRS 5	1.64 ± 0.58	546 ± 42

Temperature and H_2O Columns

	$N(H_2O)$ (10^{18} cm^{-2})	T_{ex} (K)	$N(H_2O)$ (10^{18} cm^{-2})	T_{ex} (K)	Ref.
AFGL 2136	6.07 ± 1.15	504 ± 17	8.25 ± 0.95	502 ± 12	I-20
AFGL 2591	3.19 ± 1.18	640 ± 55		$540 - 630$	B-22
MonR2 IRS 3	0.87 ± 0.53	447 ± 47			
NGC 7538 IRS 1	0.30 ± 0.21	503 ± 140			
W3 IRS 5	1.64 ± 0.58	546 ± 42	$5 - 36$	$500 - 600$	L-23

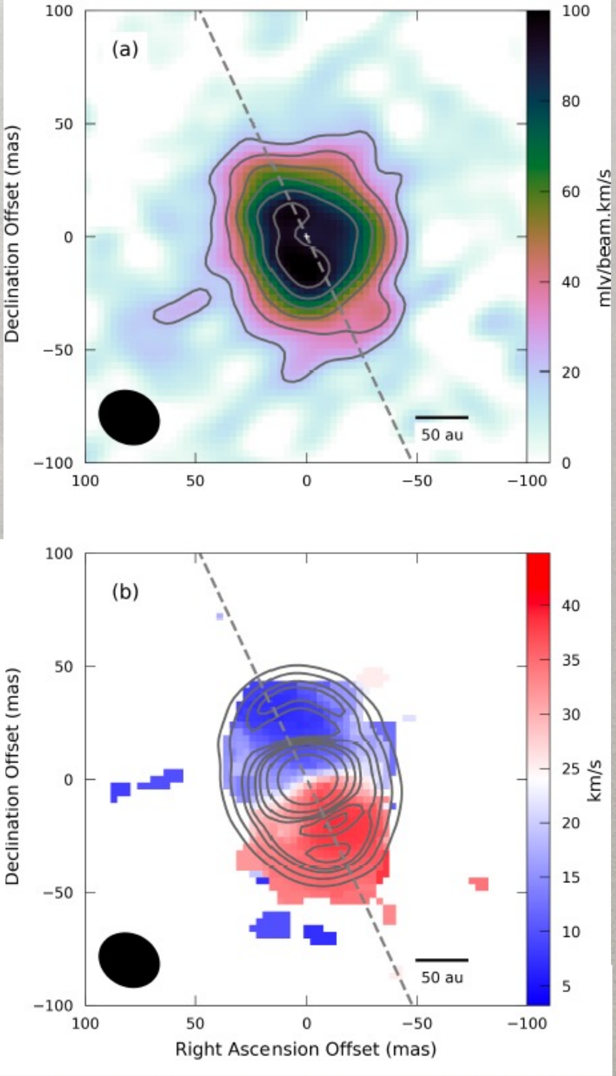
I-20: Indriolo et al. 2020
B-22: Barr et al. 2022
L-23: Li et al. 2023

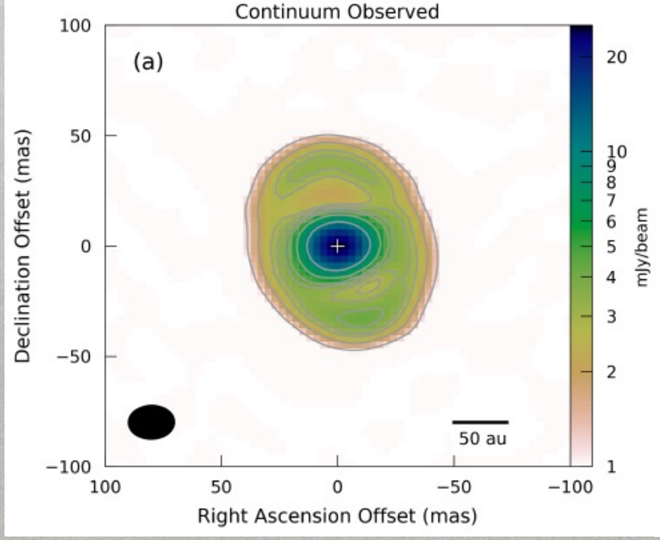


AFGL 2136

ALMA Observations

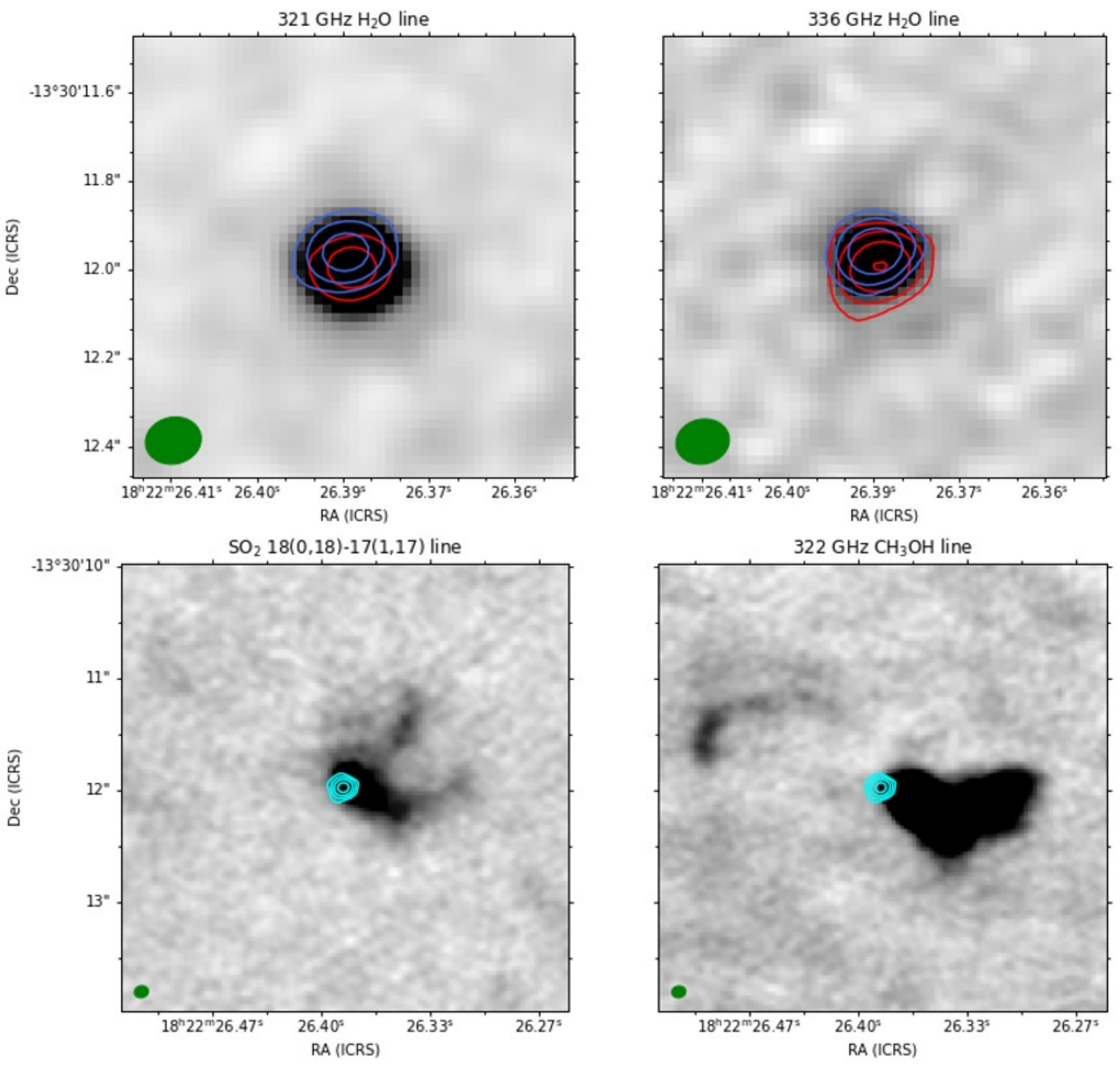
- 1.3 mm continuum shows disk-like or ring-like morphology (consider free-free contribution from central object)
- H_2O $5_{5,0}$-$6_{4,3}$ ν_2=1 (E_u=3461.9 K) emission shows a Keplerian disk
- R=120 AU; M=45 $M_\odot$; Inc.=$40° \pm 5°$





Maud et al. 2019

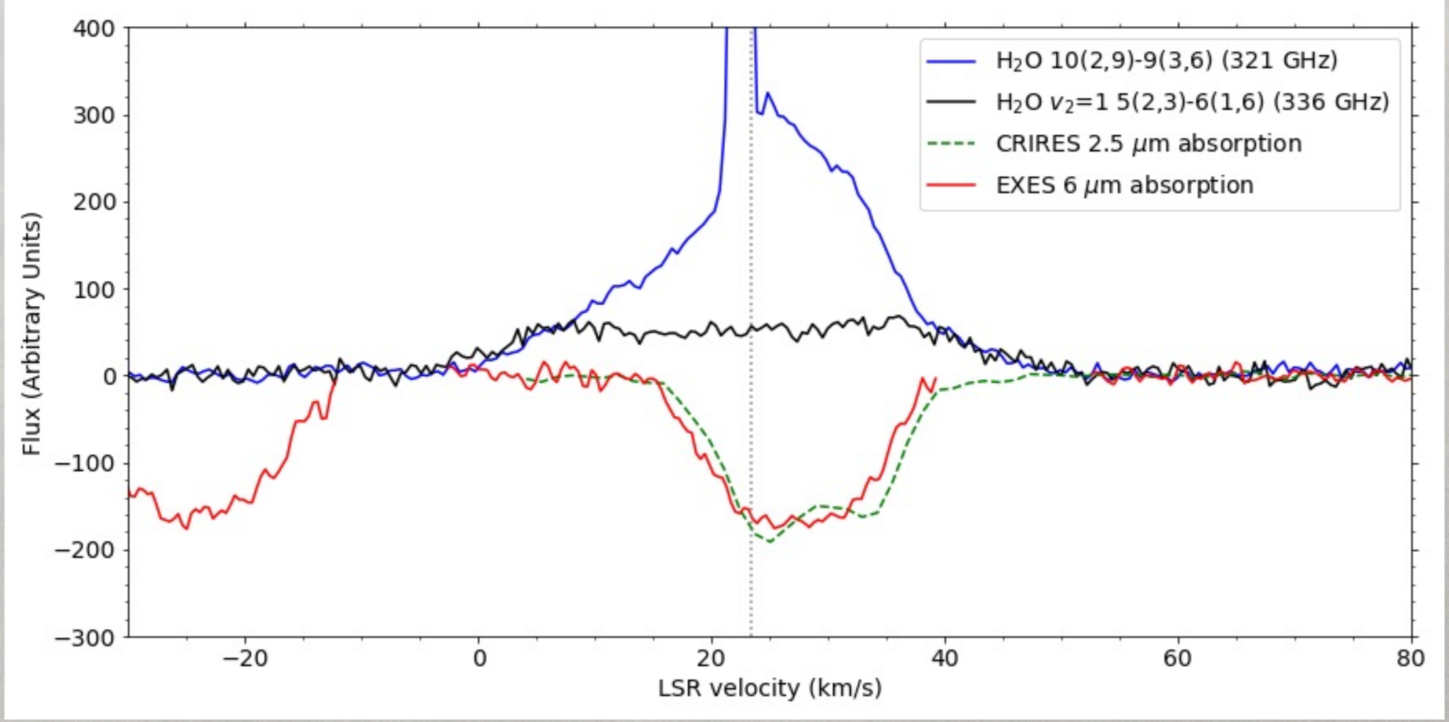
ALMA Observations



Integrated intensity maps of H_2O emission lines

Integrated intensity maps of SO_2 and CH_3OH emission lines

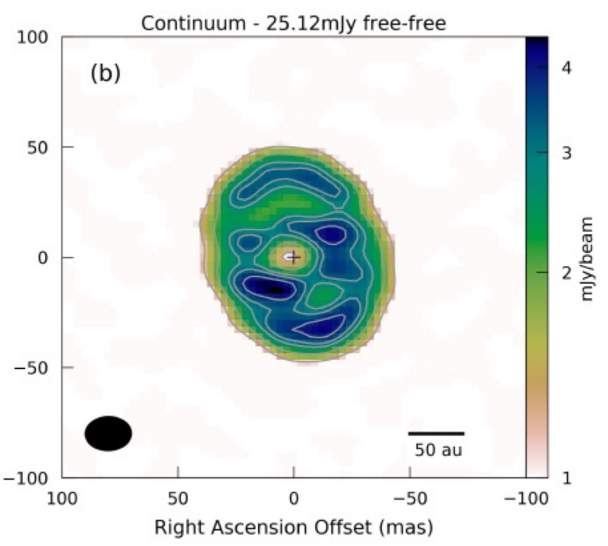
H_2O Spectra

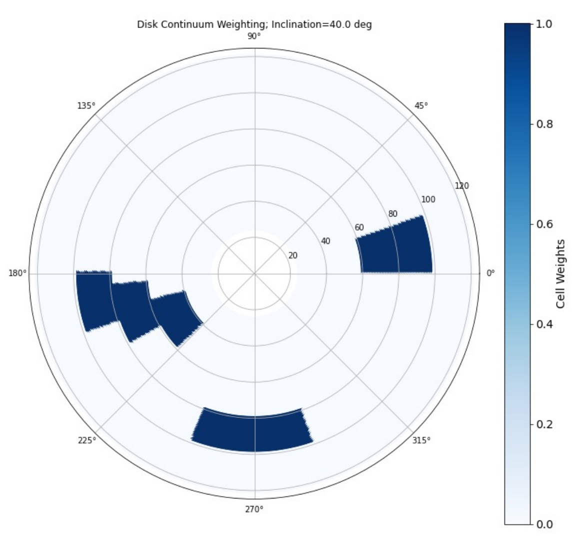


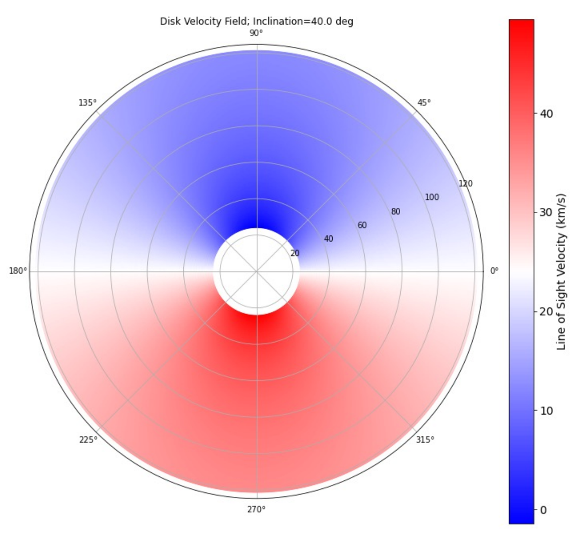
- IR H_2O absorption is reasonably well-matched to the 321 GHz emission profile

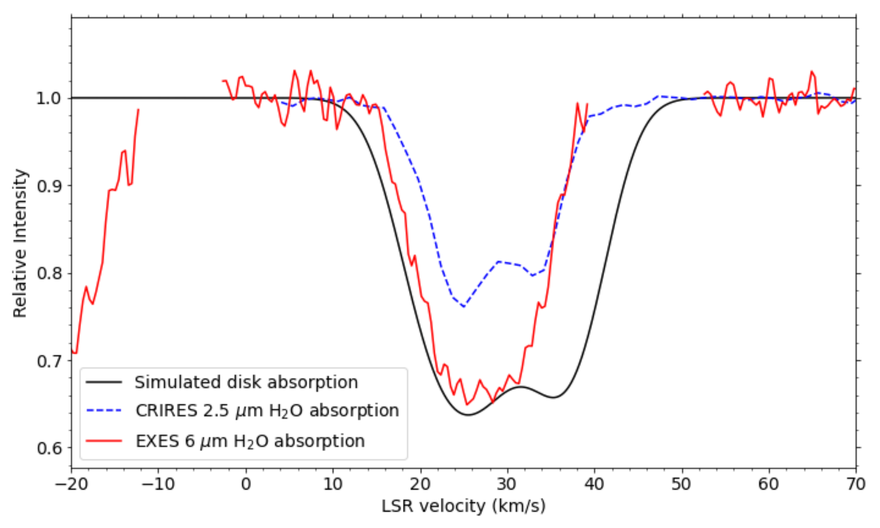
Toy Model of Disk Absorption

Maud et al. 2019 A&A 627, L6







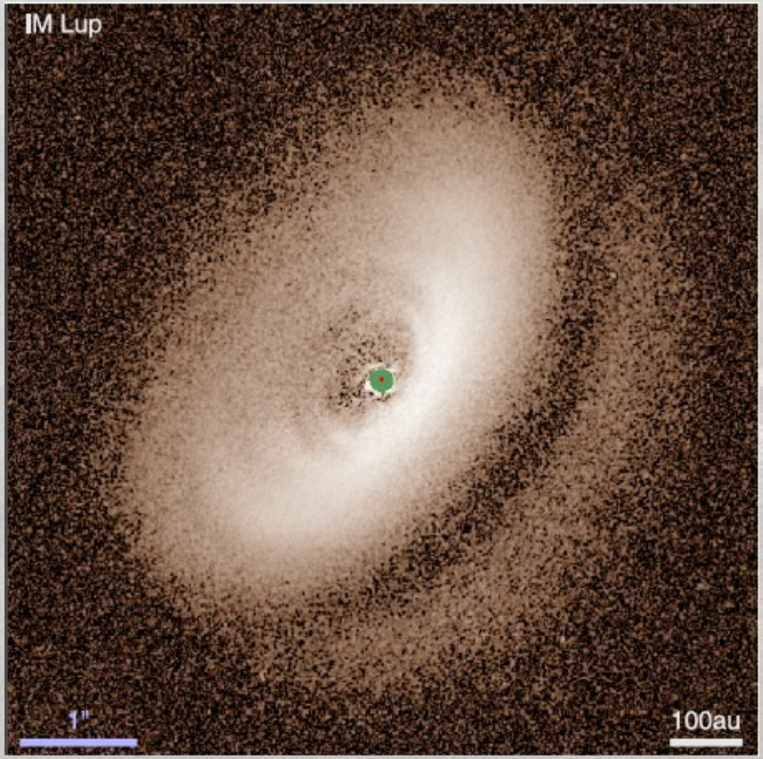


Summary

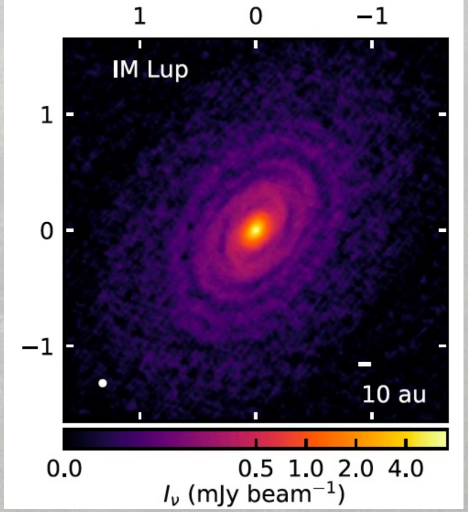
- H_2O absorption (but not emission) at 6 μm is clearly detected in our sample of massive protostars
- Optical depth effects complicate the analysis and interpretation of H_2O spectra
- Inferred rotation temperatures of 400-600 K indicate an origin close to the central source
- Profiles of the resolved absorption lines suggest contributions from disk and wind/outflow components
- Future ALMA observations may reveal the exact location where this hot water resides

Ancillary Slides

IR vs mm Continuum



Avenhaus et al. 2018 ApJ 863, 44
VLT/SPHERE H band (~1.6 μm) scattered light



Huang et al. 2018 ApJL 869, L43
ALMA 1.25 mm continuum

- Evidence for different structures seen in disks around low mass stars