A Multi-Wavelength Perspective of the Massive Protostar AFGL 2136 IRS 1

Nick Indriolo (STScI), T. Hirota (NAOJ), L. Maud (ESO), D. A. Neufeld (JHU), A. G. Barr (Leiden), A. C. A. Boogert (IfA), C. N. DeWitt (USRA), A. Karska (Torun), M. J. Richter (U.C. Davis), A. G. G. M. Tielens (Leiden)

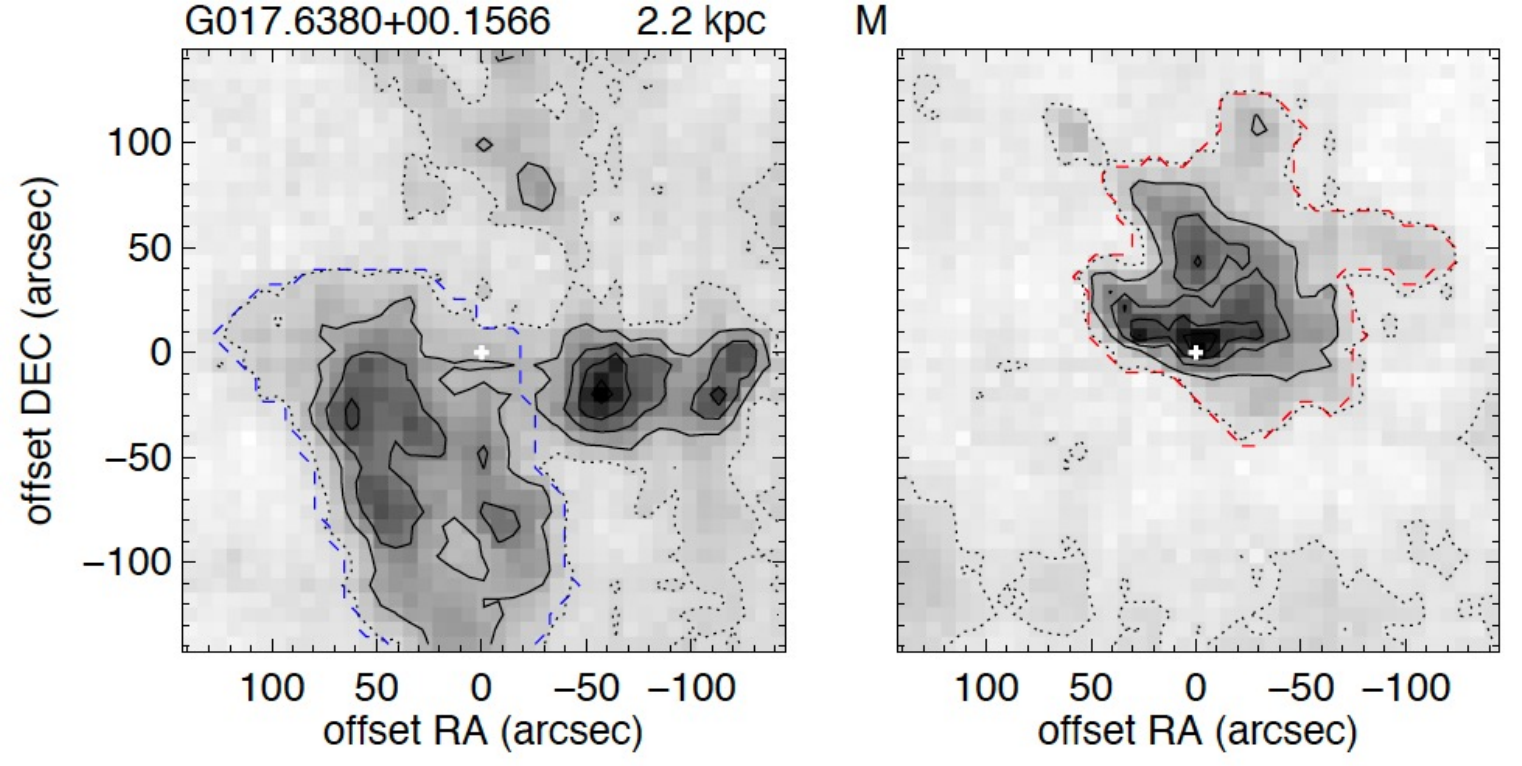
Outline

- Background
  - Previous observations
  - Source characteristics
- IR absorption observations (EXES, TEXES, CRIRES)
- ALMA band 7 (320-340 GHz) observations
- Interpretation of combined data sets
- Summary

Background

Large Scale CO Emission

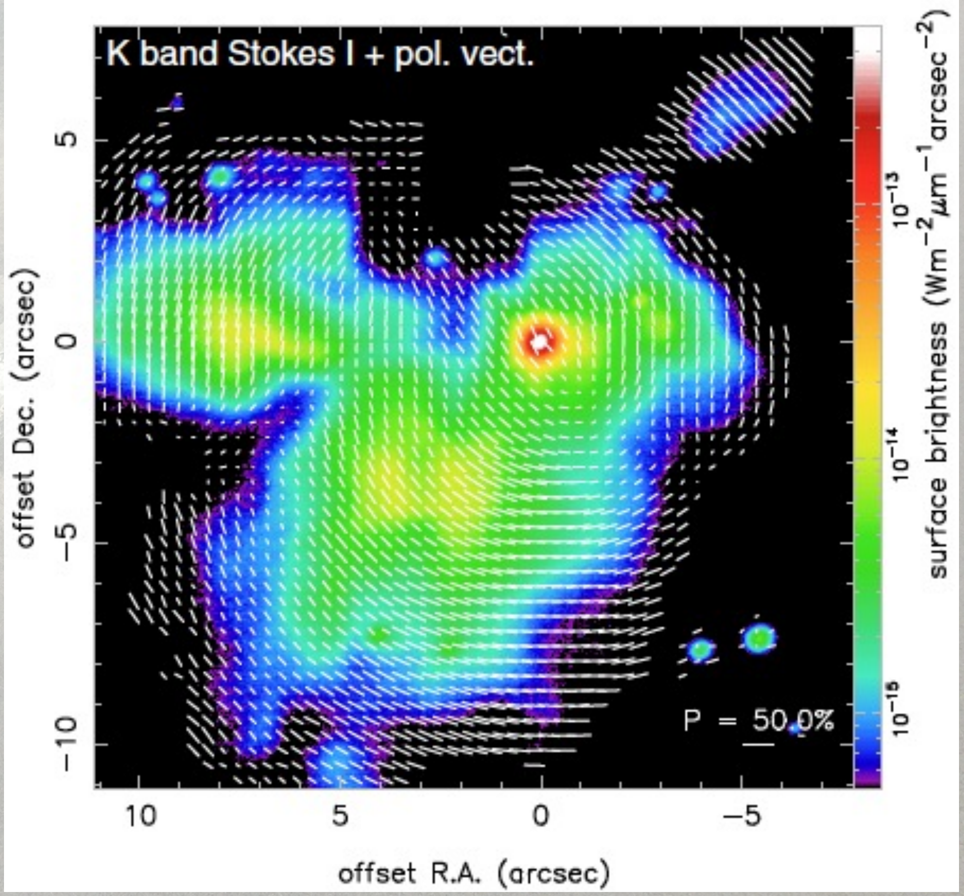
- JCMT CO J=3-2 emission shows bipolar outflows



Maud et al. 2018, A&A 620, A31

Near IR Imaging

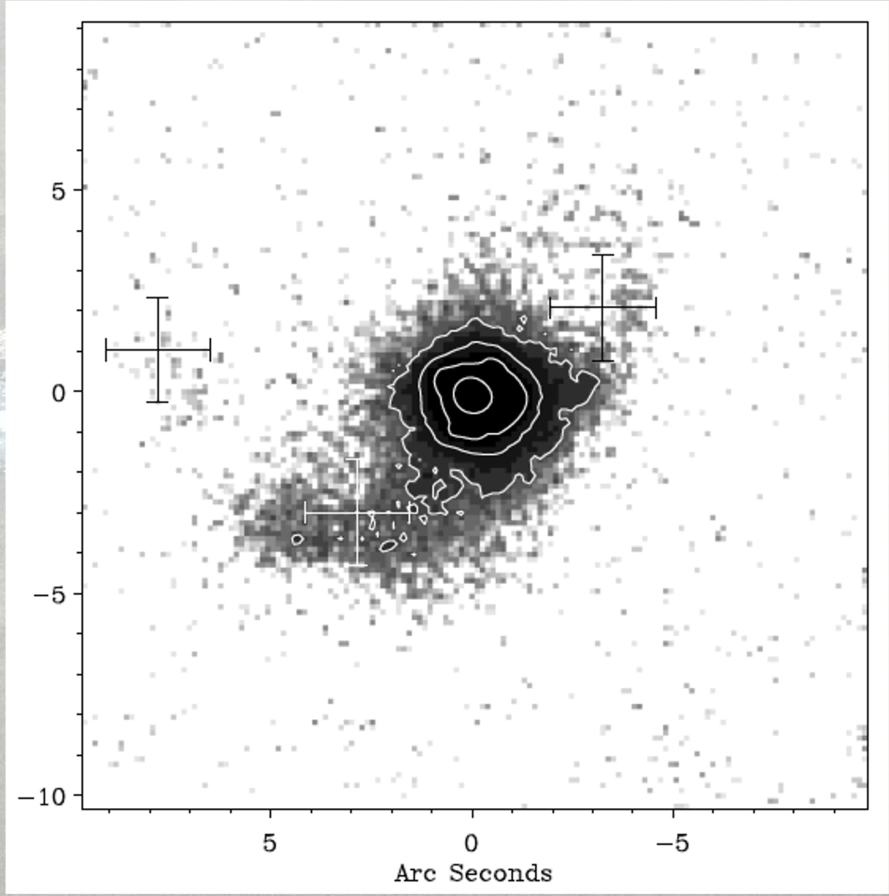
- Observed in *H* and *K* bands with Subaru/CIAO
- Extended diffuse structure is visible, but there is a single bright point source in *K* band
- Polarization vectors are consistent with an optically thick dust disk around the central source



Murakawa et al. 2008 A&A 490, 673

Mid IR Imaging

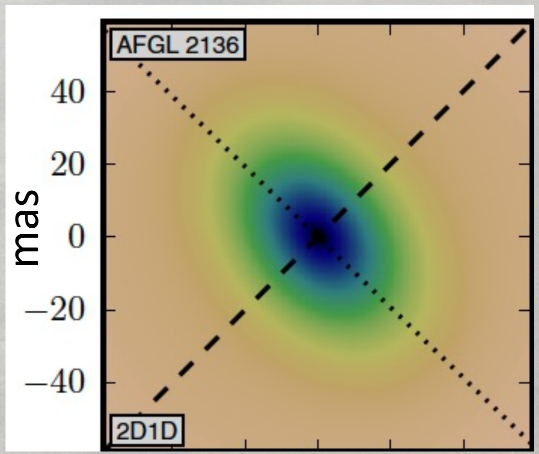
- Observed at 24.5 μm with Subaru/COMICS
- Central source is still the brightest object
- Emission is resolved, so this is the warm dust in the envelope and/or cavity walls



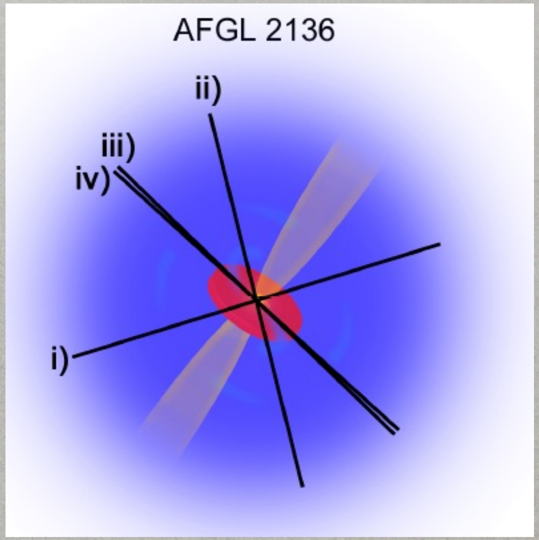
de Wit et al. 2009 A&A 494, 157

Mid IR Interferometry

- Multiple studies have used VLTI/MIDI (8-13 μm) observations to constrain source geometries on the scale of tens of mas
- Results have a dependence on what goes into the models that are used to interpret the visibilities
  - 2D gaussian (top)
  - disk with inner+outer radii, envelope, outflow cavities (bottom)



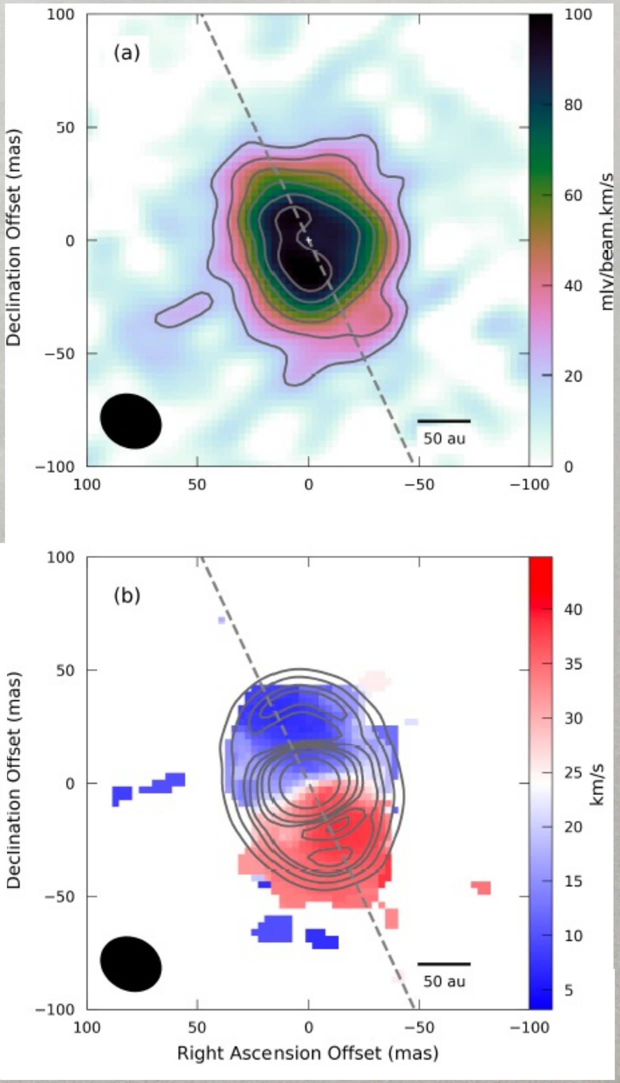
Boley et al. 2013 A&A 558, A24

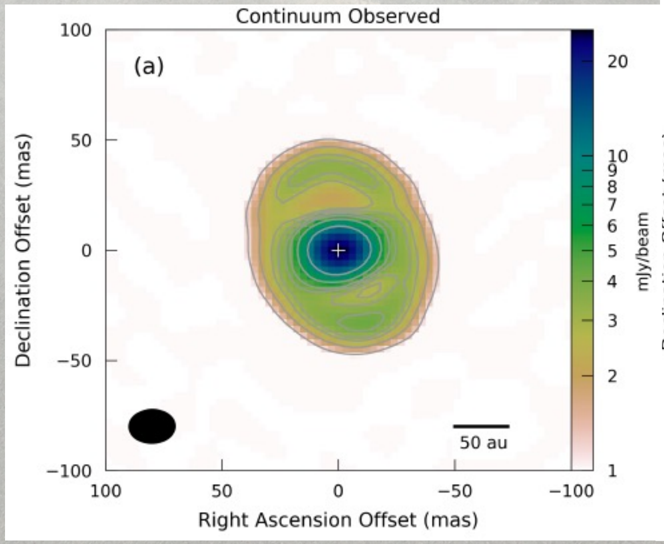


Frost et al. 2021 A&A 648, A62

mm Interferometry

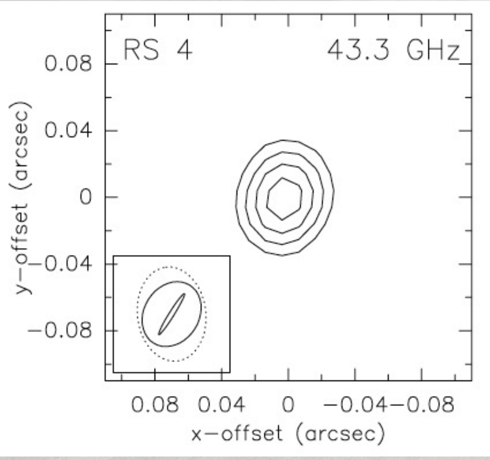
- 1.3 mm continuum shows disk-like or ring-like morphology (consider free-free contribution from central object)
- H_2O $5_{5,0}$-$6_{4,3}$ ν_2=1 (E_u=3461.9 K) emission shows a Keplerian disk
- R=120 AU; M=45 $M_\odot$; Inc.=$40° \pm 5°$



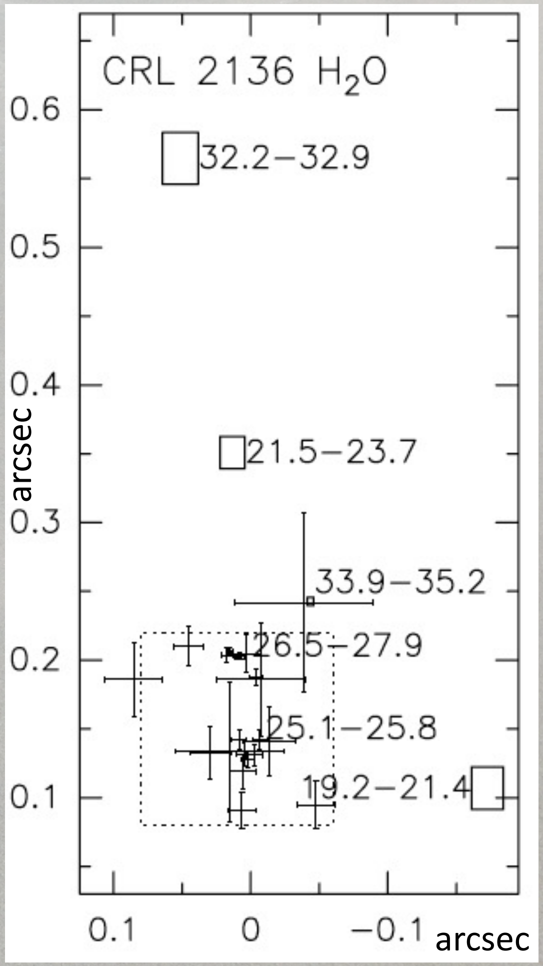


Maud et al. 2019 A&A 627, L6

22 GHz H_2O Masers

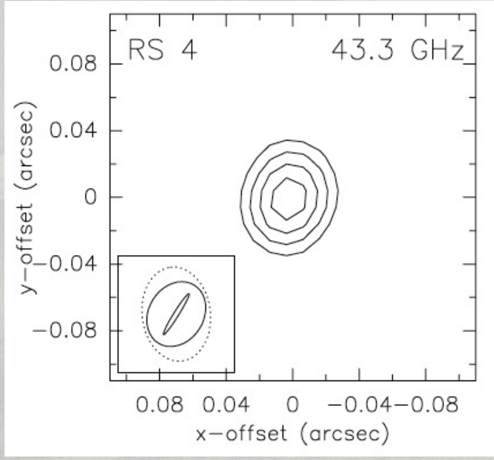


Menten & van der Tak 2004
A&A 414, 289



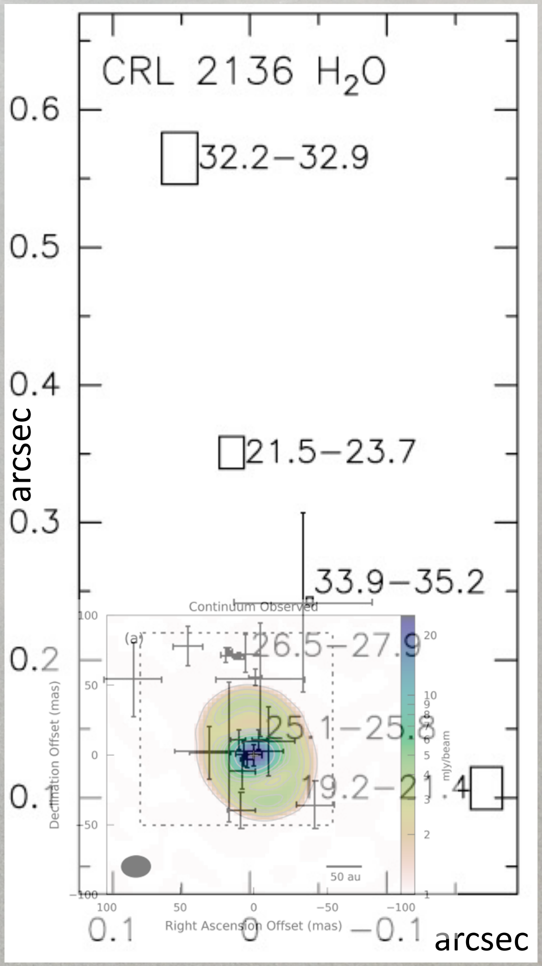
- 43 GHz continuum elongated roughly perpendicular to 1.3 mm disk major axis
- Potentially traces free-free emission from a jet
- Cluster of H_2O masers, but 0.3 arcsec uncertainty in relative registration precludes association with 43 GHz continuum
- Bandwidth only covered LSR velocities 16-36 km/s
- Redshifted from systemic velocity, so not the near-side outflow. Maybe accretion shock?

22 GHz H_2O Masers



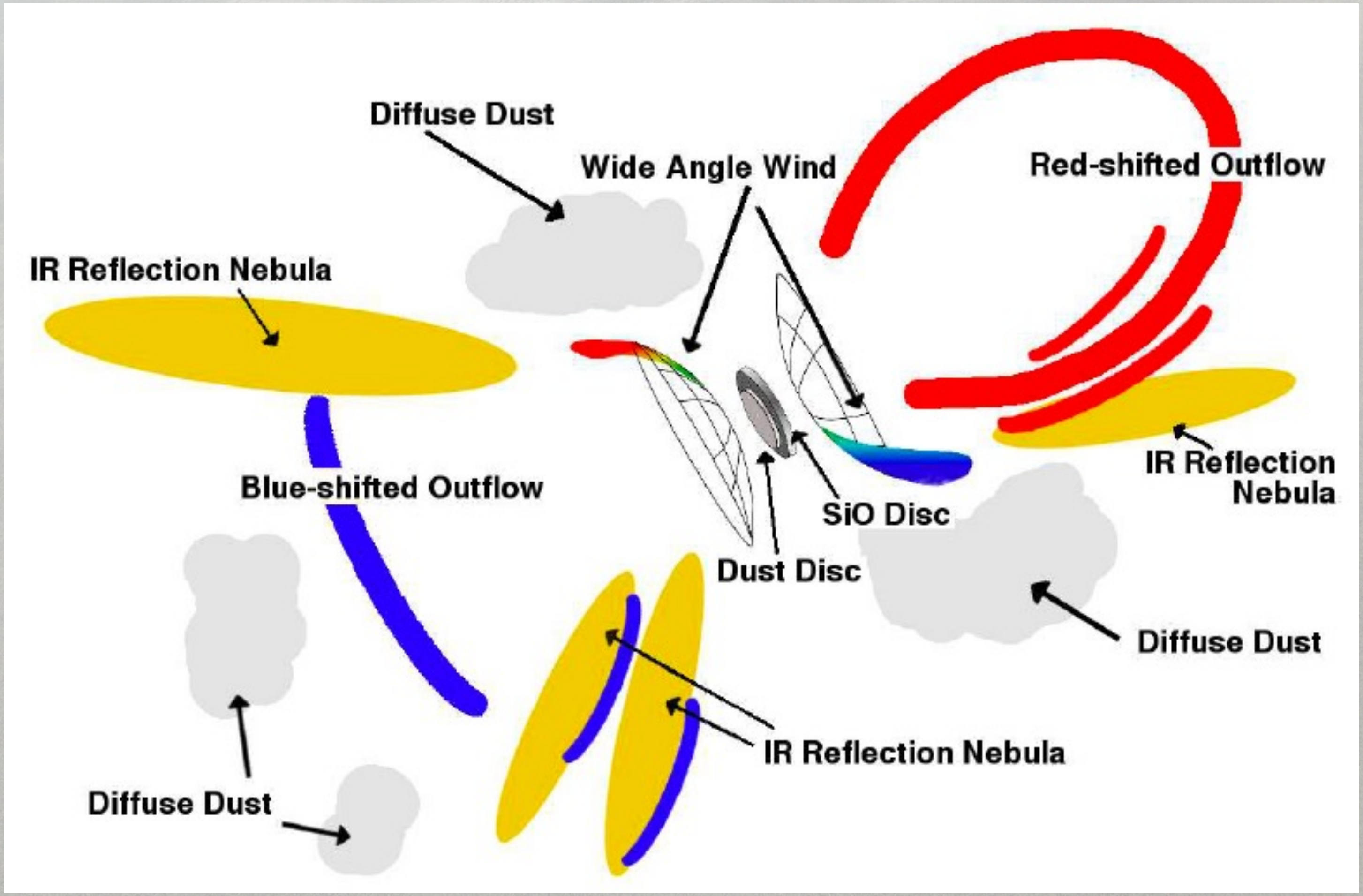
Menten & van der Tak 2004
A&A 414, 289

- 43 GHz continuum elongated roughly perpendicular to 1.3 mm disk major axis
- Potentially traces free-free emission from a jet
- Cluster of H_2O masers, but 0.3 arcsec uncertainty in relative registration precludes association with 43 GHz continuum
- Bandwidth only covered LSR velocities 16-36 km/s
- Redshifted from systemic velocity, so not the near-side outflow. Maybe accretion shock?



Relative position unknown!
Only for size comparison!

AFGL 2136 Overall Picture



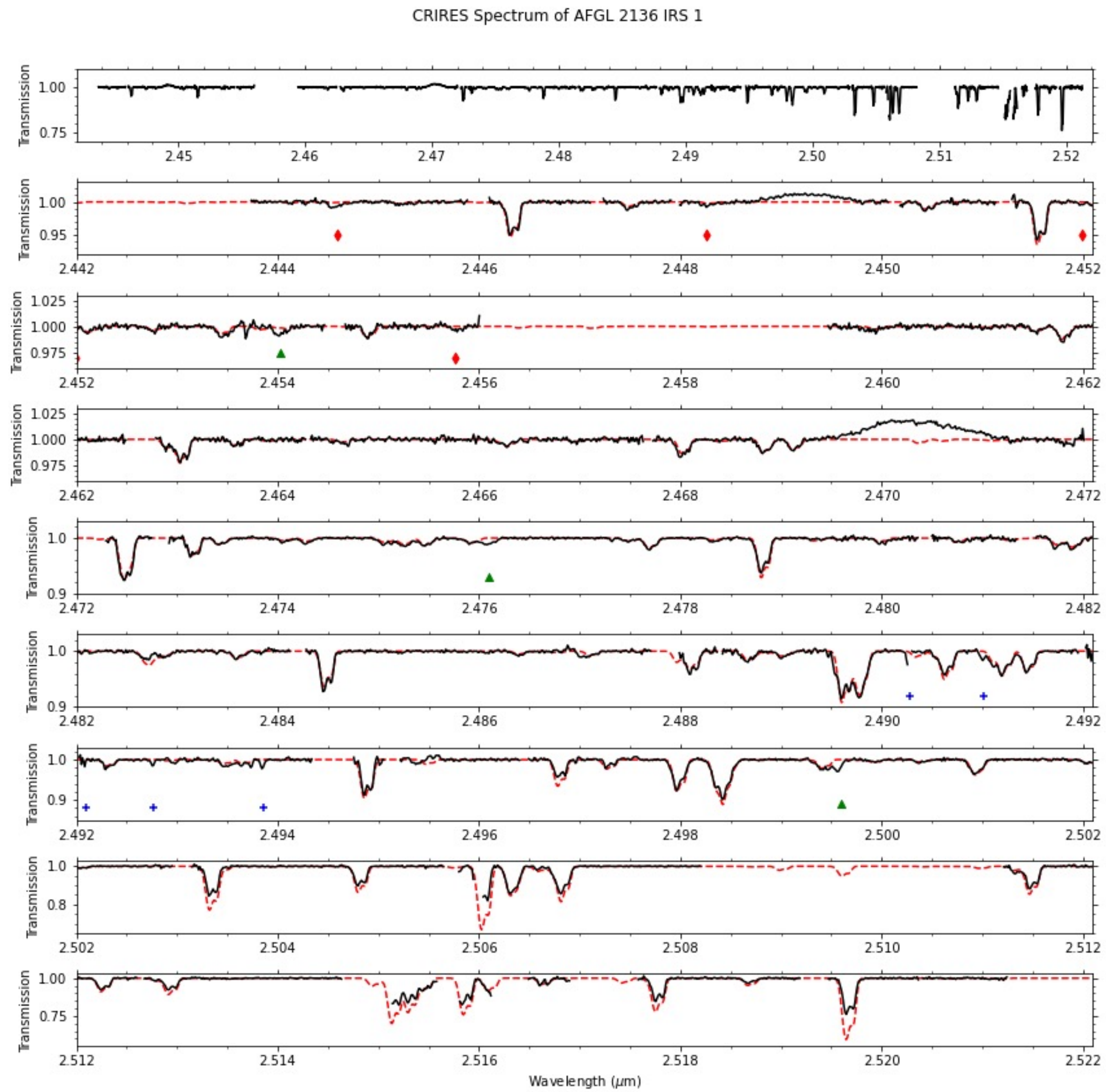
Maud et al. 2018, A&A 620, A31

IR Absorption

Indriolo et al. 2020 ApJ 894, 107

- H_2O ν_1 and ν_3
- CO *v*=2-0 *P*(34)-*P*(37)
- HF *v*=1-0 *R*(0)-*R*(2)
- Unidentified
- H Pfund 19-5, 18-5

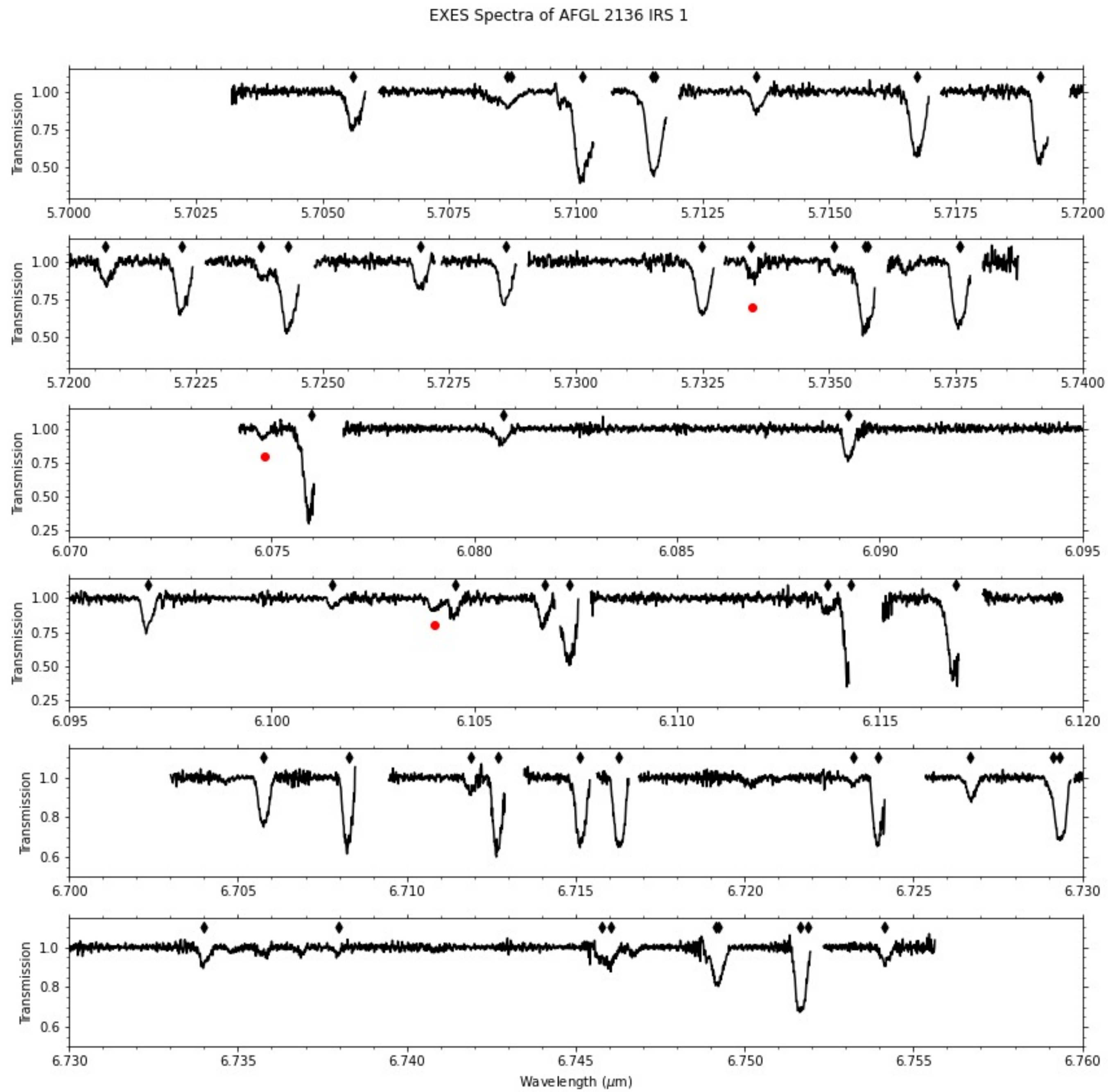
VLT CRIRES



Indriolo et al. 2020 ApJ 894, 107

- H_2O ν_2
- $H_2{}^{18}O$ ν_2

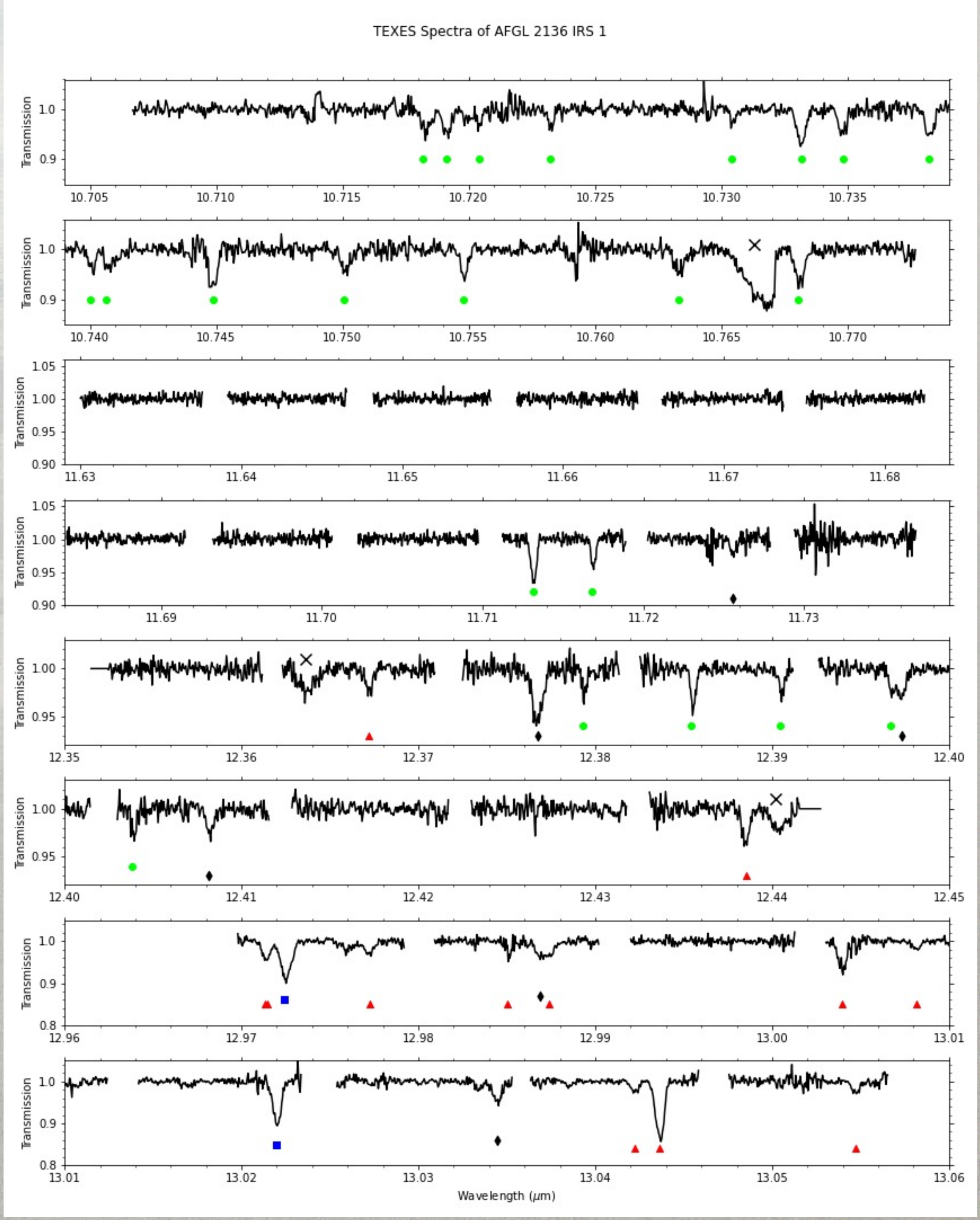
SOFIA EXES



Indriolo et al. 2020 ApJ 894, 107

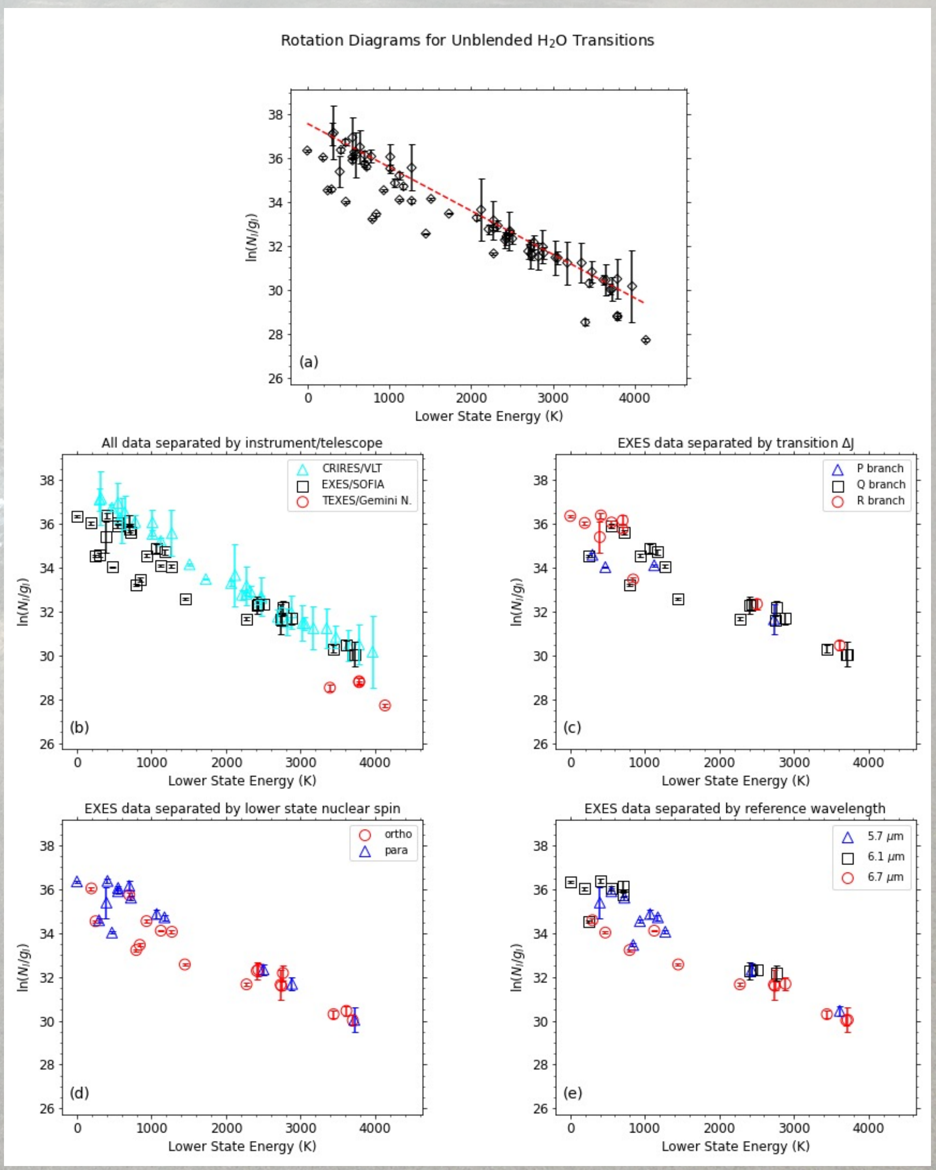
- H_2O rotational
- C_2H_2
- NH_3
- HCN

Gemini N. TEXES



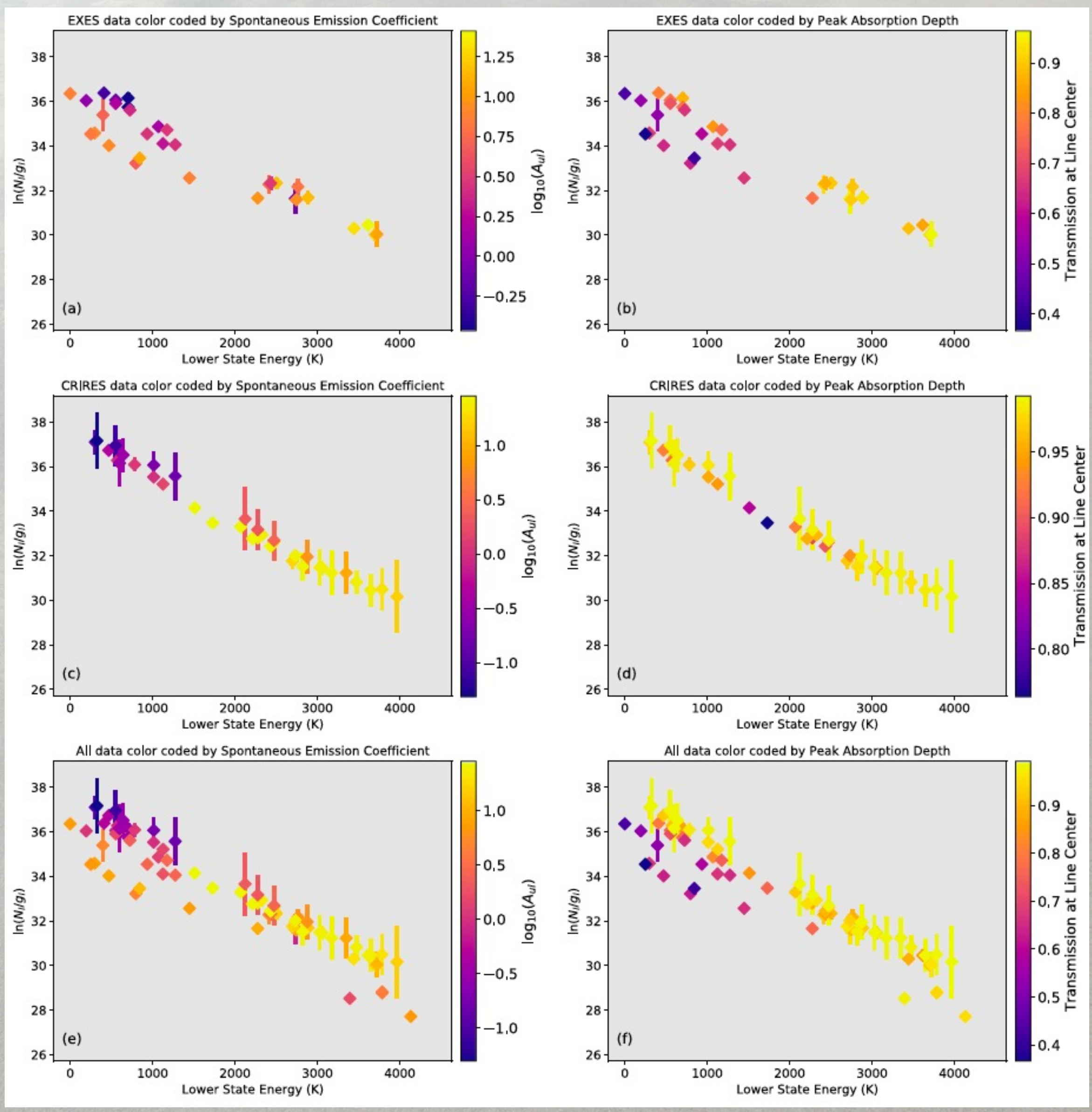
Rotation Diagrams

- Rotational state column densities show a linear relation in ln(*N*/*g*) vs. E_l, but with significant scatter
- Scatter is not related to transition branch (*P*,*Q*,*R*), nuclear spin (ortho, para), or wavelength
- Seems to indicate that many states are underpopulated with respect to the linear relation seen in the upper envelope of points



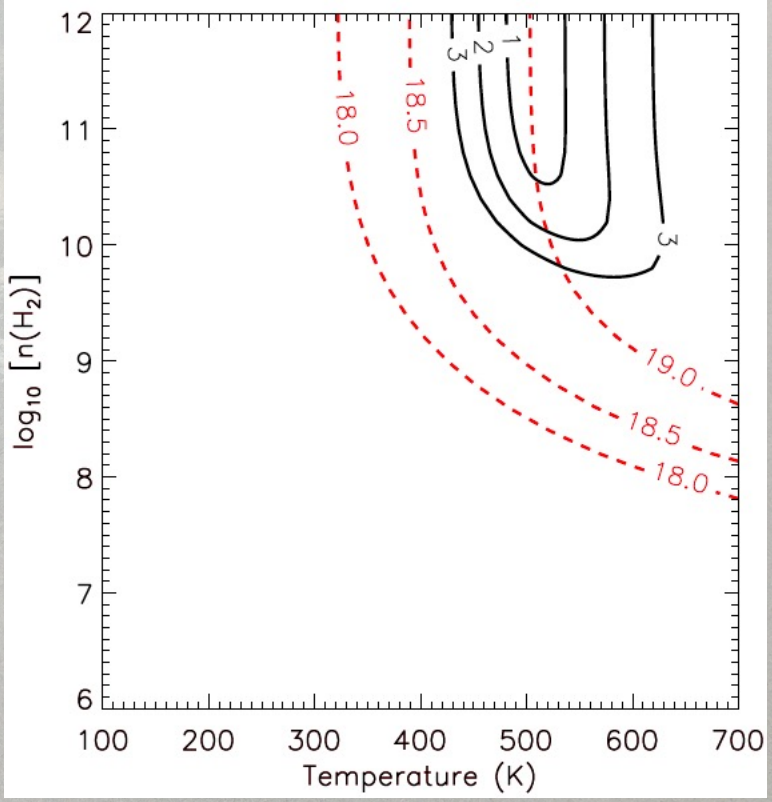
Rotation Diagrams

- There appears to be a correlation between deviation from the linear relation and depth of the absorption feature from which the column density was measured (optically thin limit)
- Suggests that the model of an optically thin absorbing slab is invalid
- Absorbing gas may be mixed with the warm dust that provides continuum emission
- Requires temperature inversion in disk (i.e., warmer midplane)



Statistical Equilibrium Analysis

- Best-fit temperature, gas density, and H_2O column density found by analyzing level populations
- Collision dominated
  - $T = 506 \pm 25$ K
  - $n(H_2) \gtrsim 5{\times}10^9$ cm^{-3}
  - $L \lesssim 1.1$ AU
- Radiative dominated
  - T is unconstrained
  - $n(H_2) \lesssim 10^6$ cm^{-3}
  - 700 K blackbody subtends 2π sr
  - $L \gtrsim 5500$ AU



Indriolo et al. 2013 ApJ 776, 8

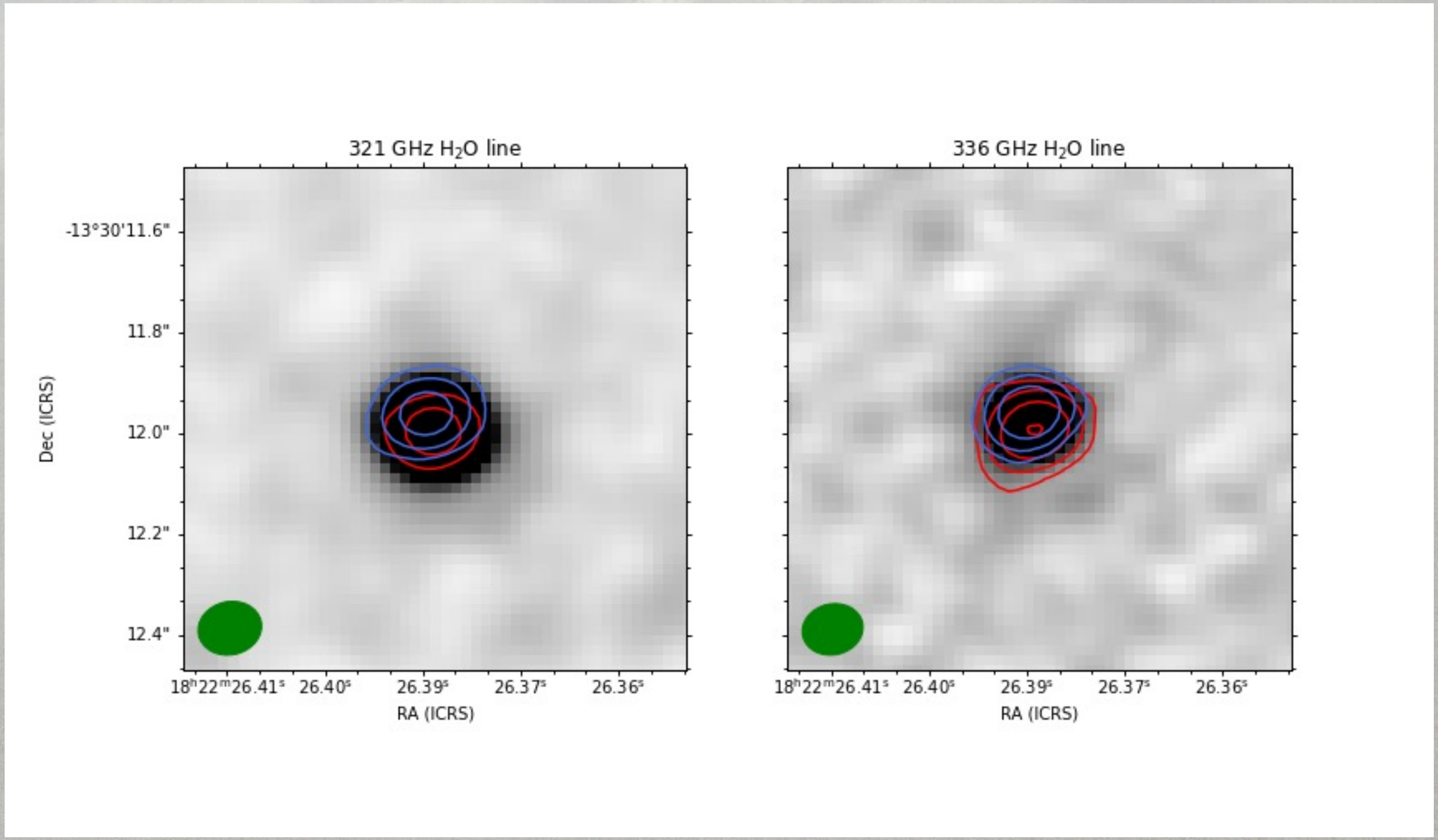
Where is the H_2O Absorbing Gas?

Warning!

- From this point forward, all figures shown are preliminary.
- ALMA data being presented are the standard pipeline products, and have NOT been reprocessed using optimal inputs/constraints/masks/etc.
- Viewer discretion is advised

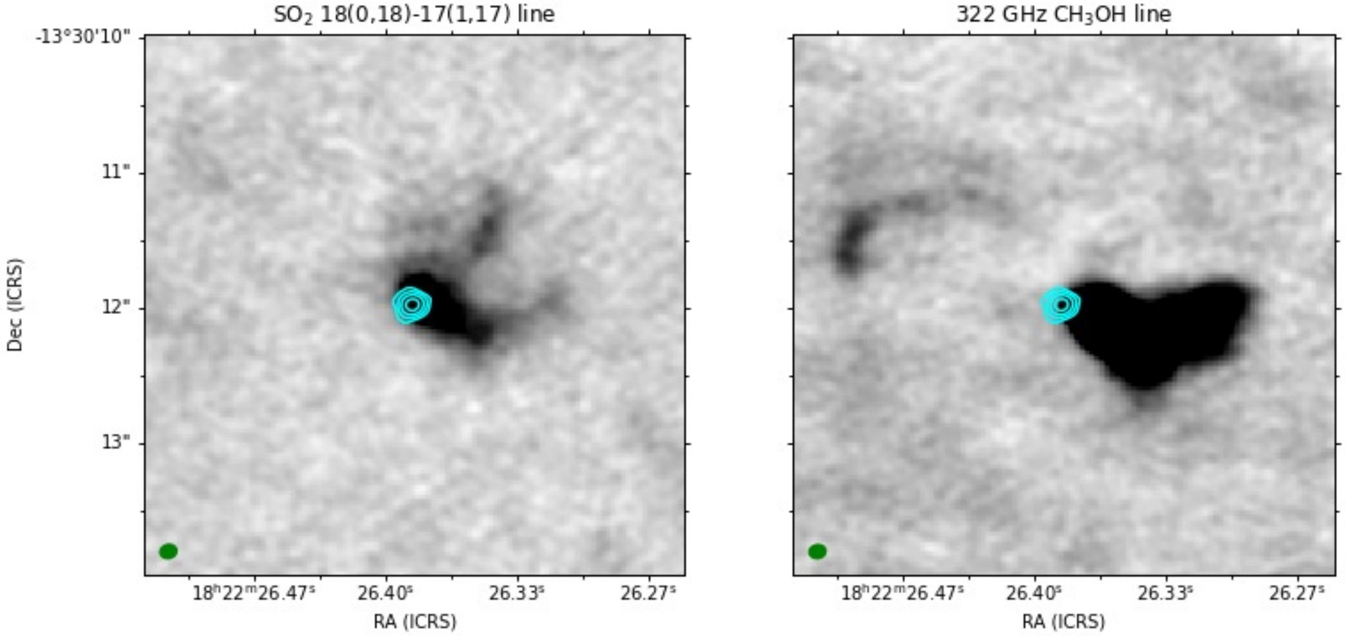
Cycle 7 ALMA Observations

Integrated intensity maps of H_2O emission lines

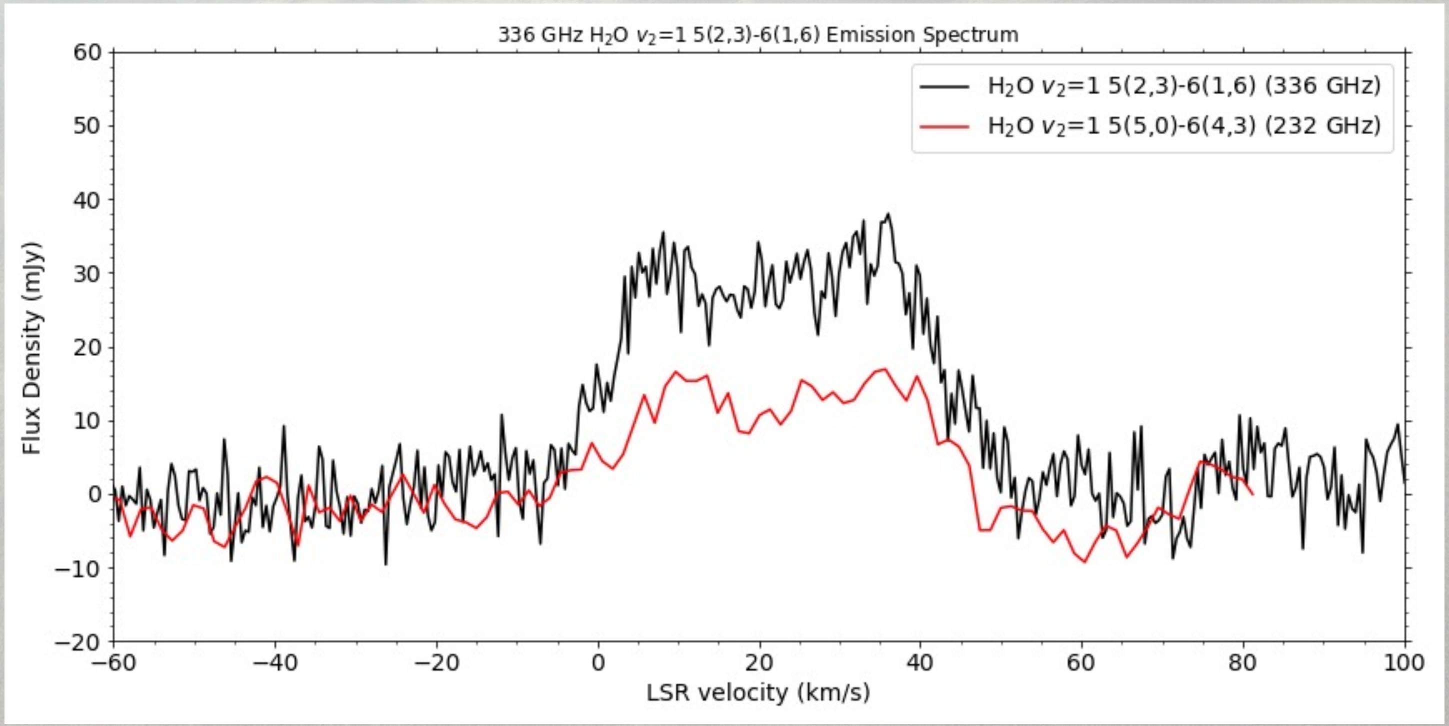


Cycle 7 ALMA Observations

Integrated intensity maps of SO_2 and CH_3OH

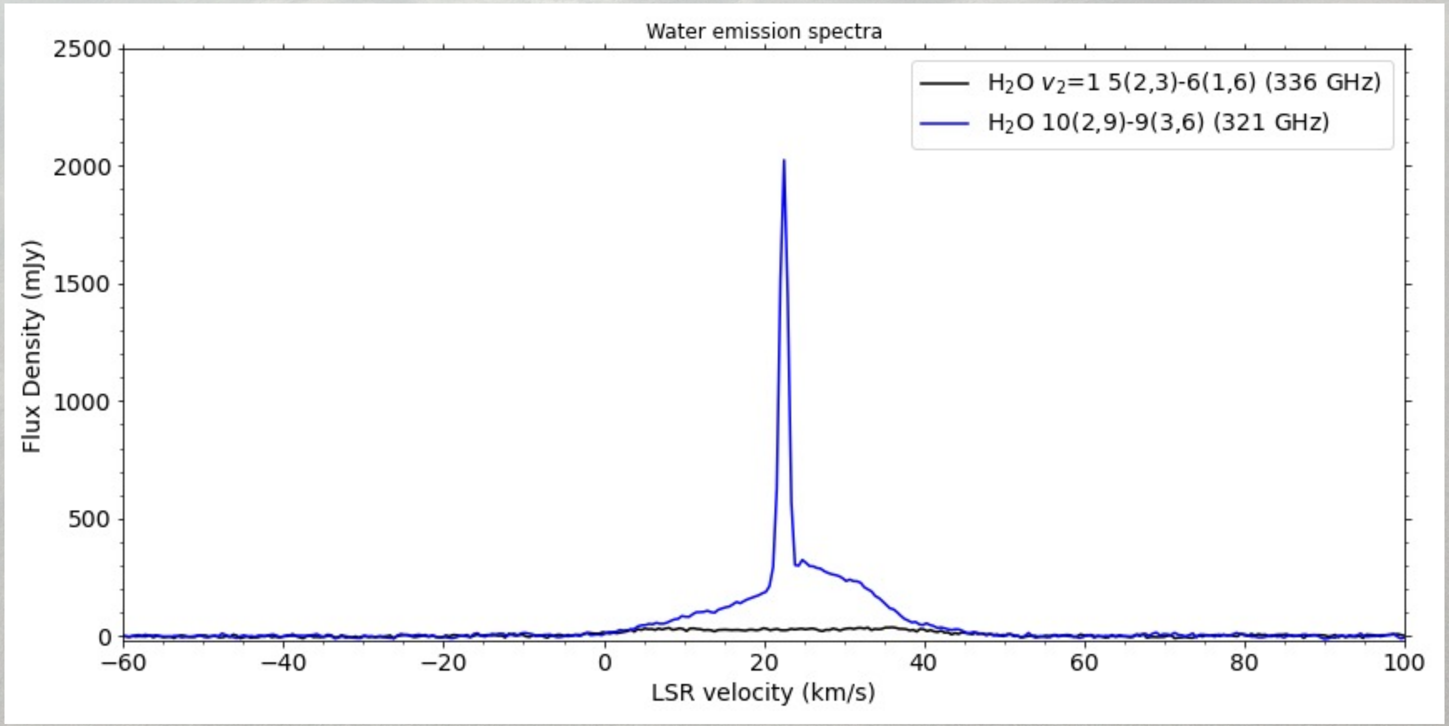


H_2O Spectra



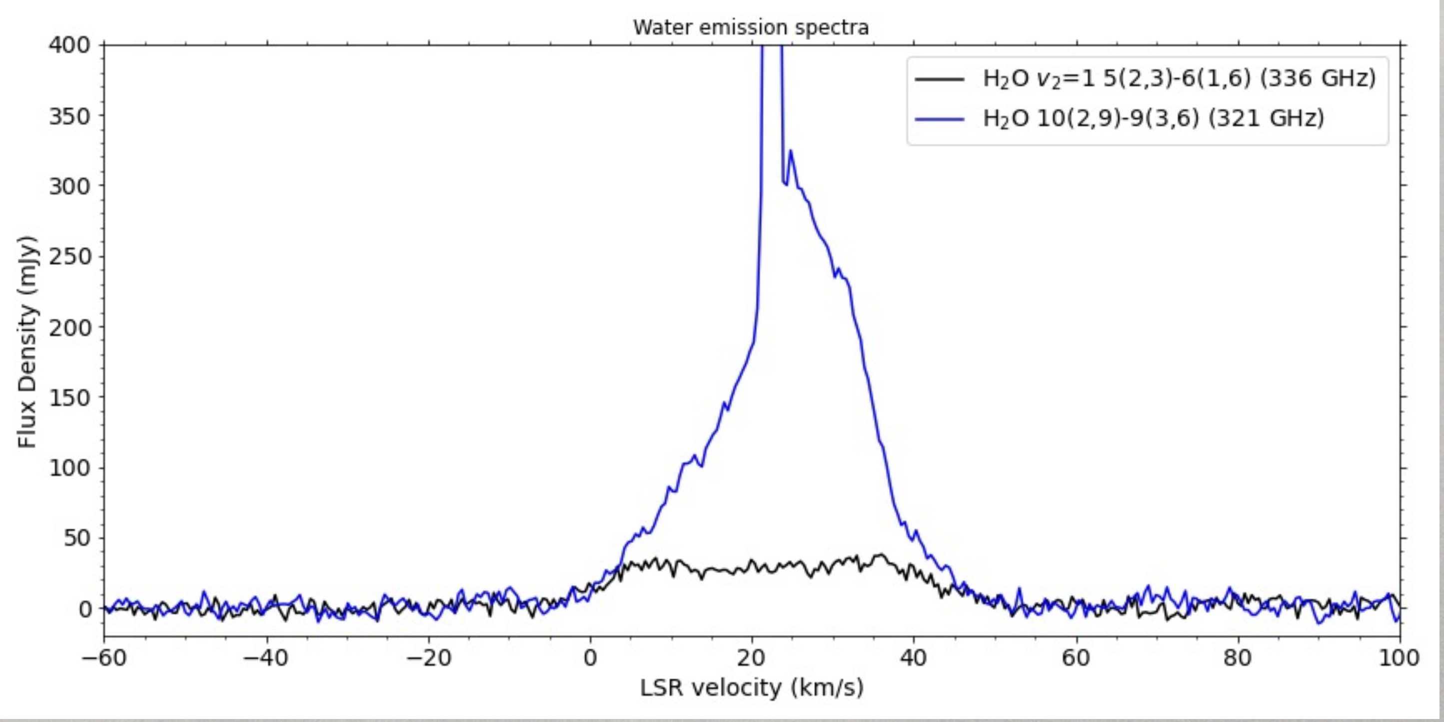
336 GHz H_2O emission profile is consistent with that of the 232 GHz H_2O line extracted from the data cube presented in Maud et al. 2019

H_2O Spectra



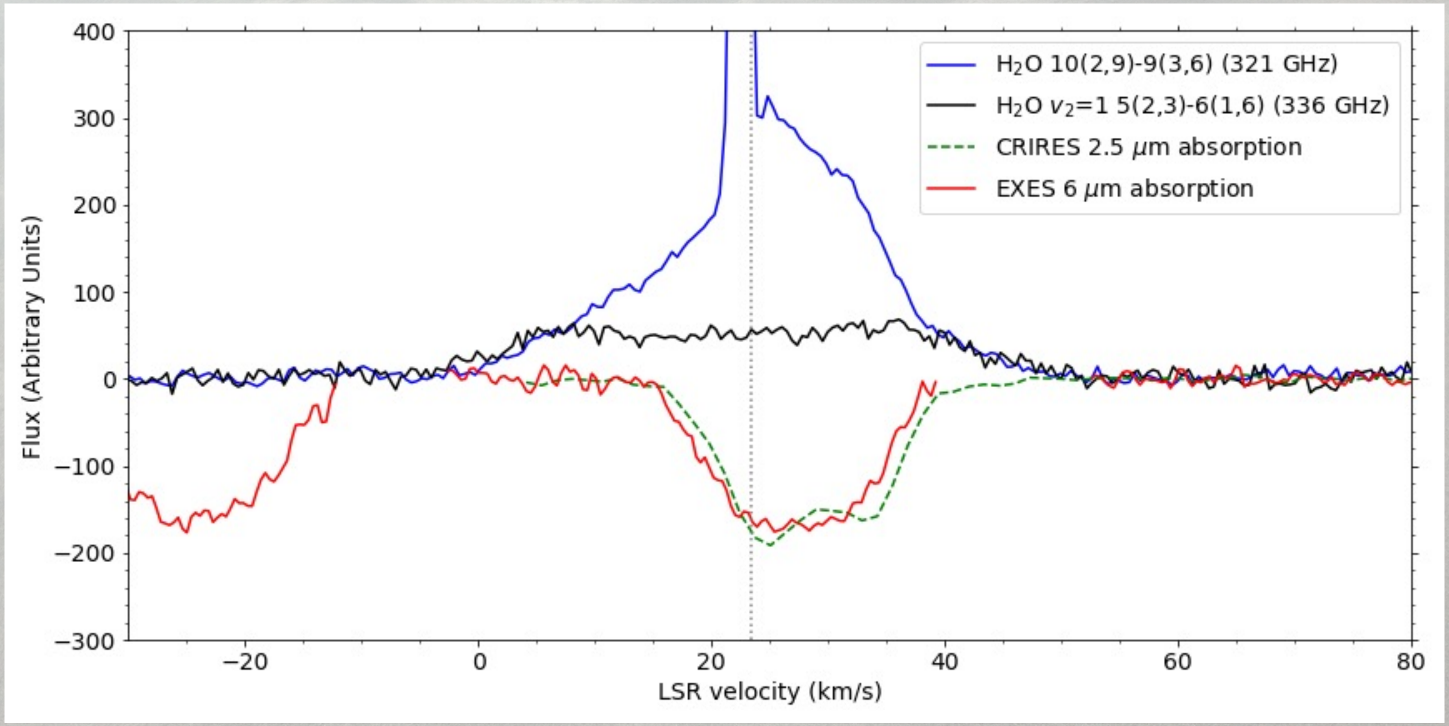
321 GHz H_2O line shows strong maser component

H_2O Spectra



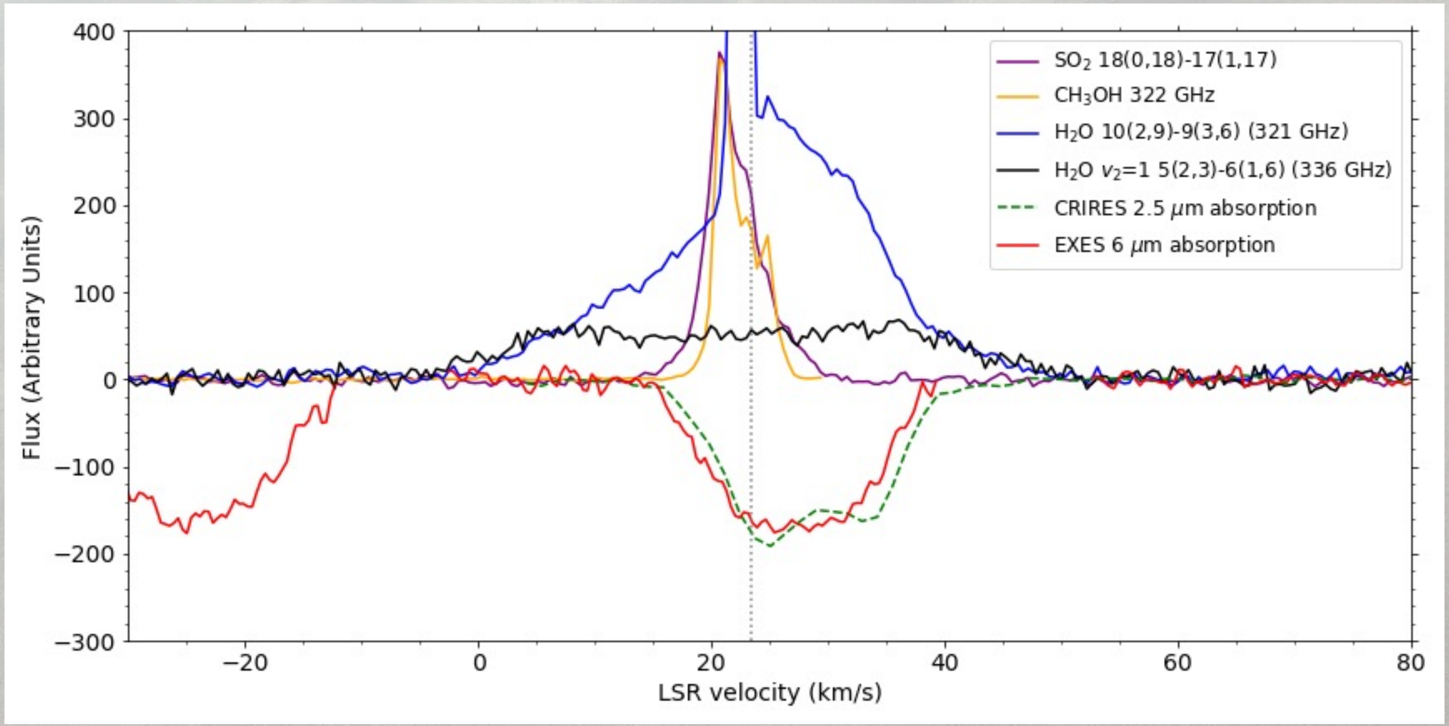
- 321 GHz H_2O line profile is not consistent with a Keplerian disk, suggesting non-thermal excitation
- Similar to observations in Ori source I (Hirota et al. 2012-2018)

H_2O Spectra



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

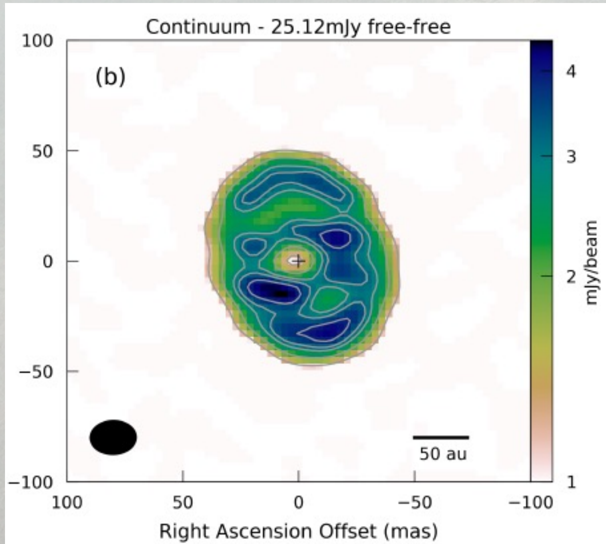
H_2O Spectra

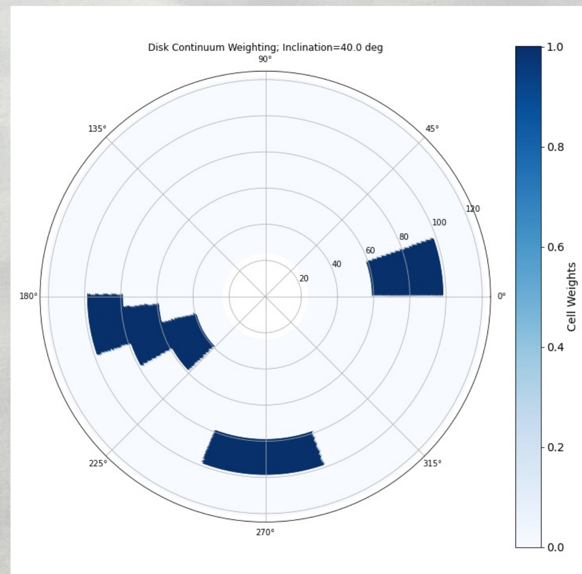


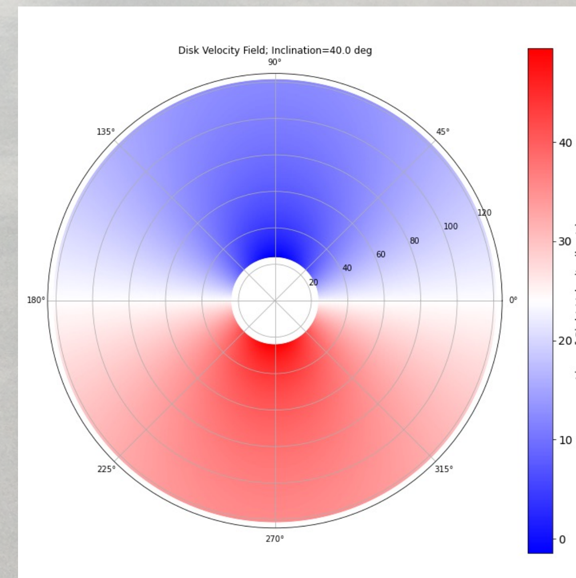
- Velocity profiles of SO_2 and CH_3OH emission are not consistent with H_2O absorption
- H_2O absorption is not caused by a more spatially extended component that happens to pass in front of the central object

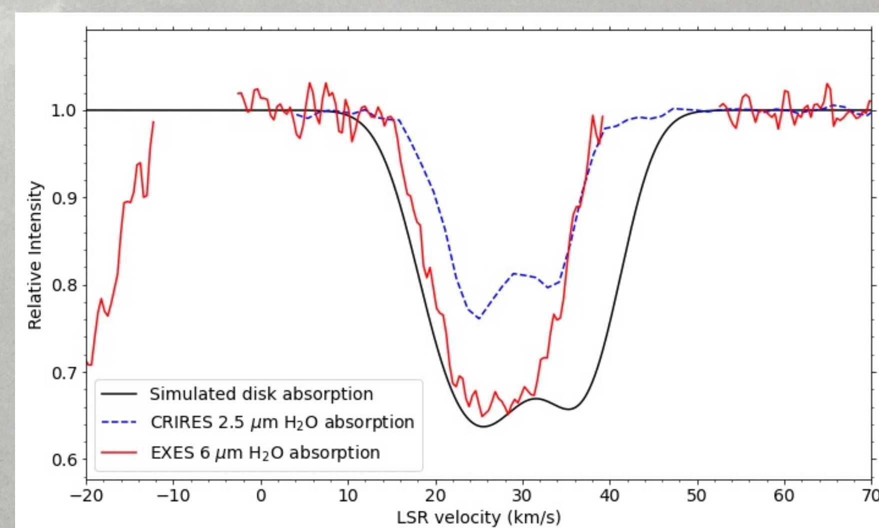
Toy Model of Disk Absorption

Maud et al. 2019 A&A 627, L6

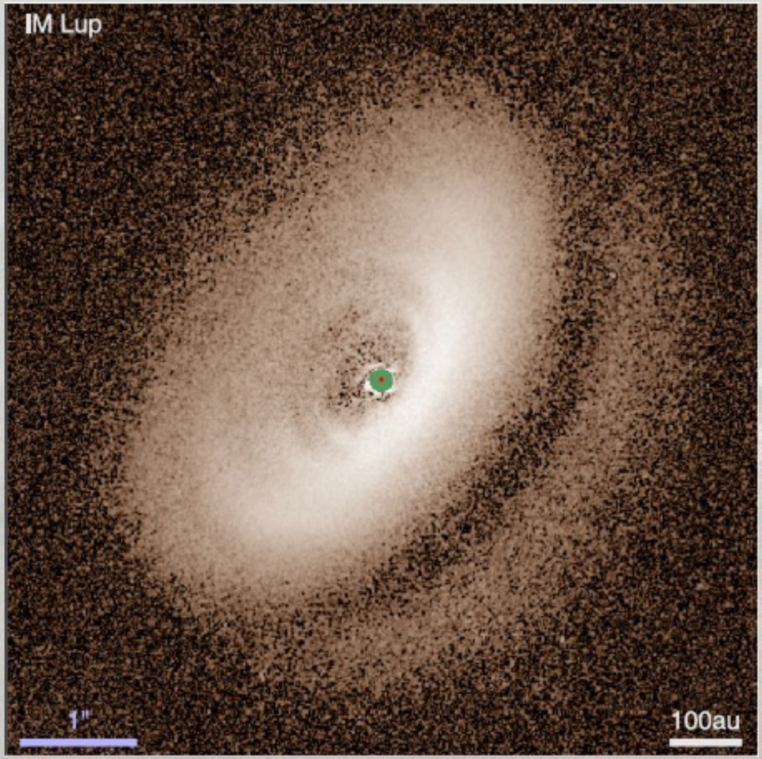




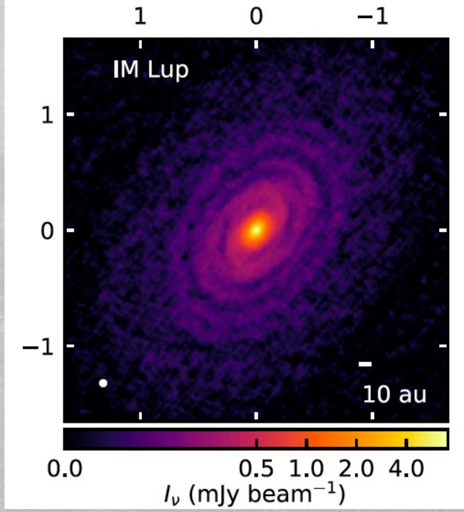




IR vs mm Continuum



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

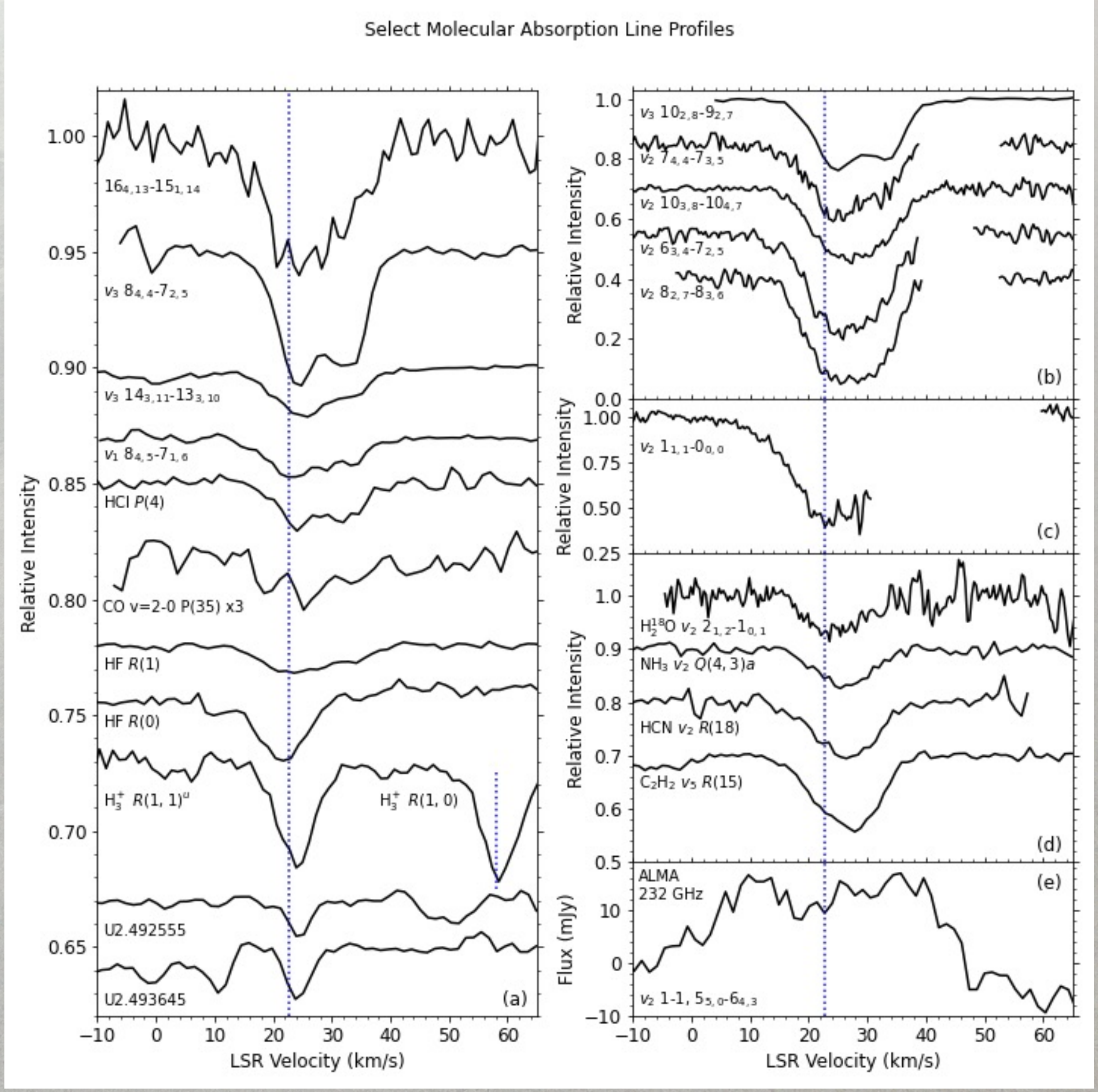
Summary

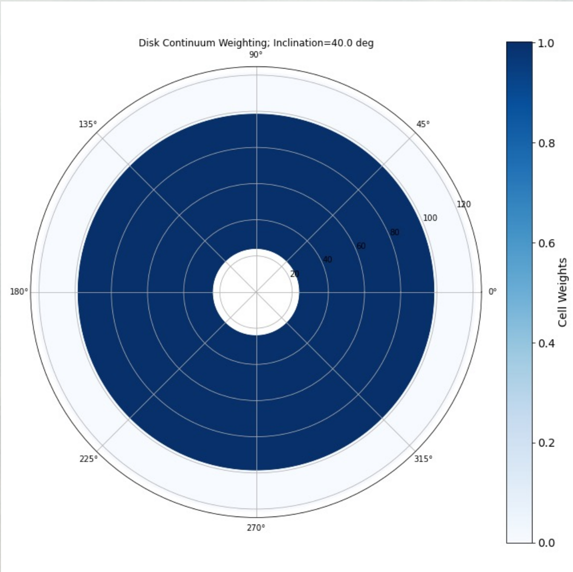
- AFGL 2136 has been observed across a wide range of wavelengths at various spectral and angular resolutions.
- IR absorption lines show relative depths that are not consistent with an optically thin absorbing slab model.
- If the absorbing gas and emitting dust are mixed, then the depth of the τ=1 surface where blackbody emission arises depends on wavelength due to dust opacity and line absorption. As a result, the weakest absorption lines probe the deepest into the region.
- ALMA observations show that hot water emission is spatially constrained to the circumstellar disk.
- Non-thermal emission in the 321 GHz H_2O line has a velocity profile that roughly matches IR H_2O absorption.
- H_2O absorption in AFGL 2136 is either coming from a portion of disk itself, or from a compact region that is spatially coincident with the disk, in the foreground, and redshifted with respect to systemic

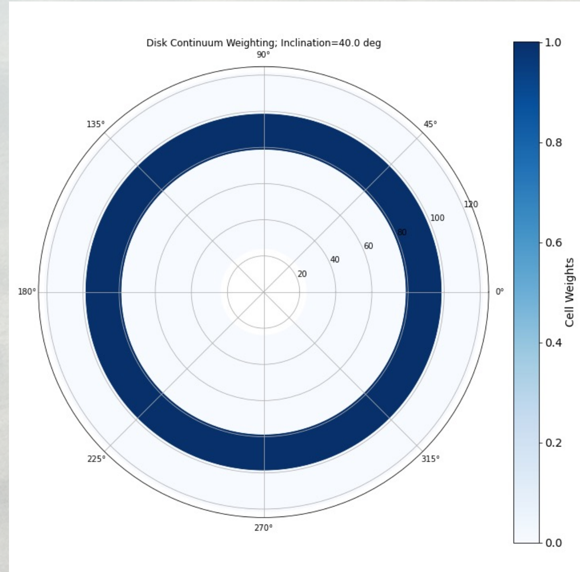
Ancillary Slides

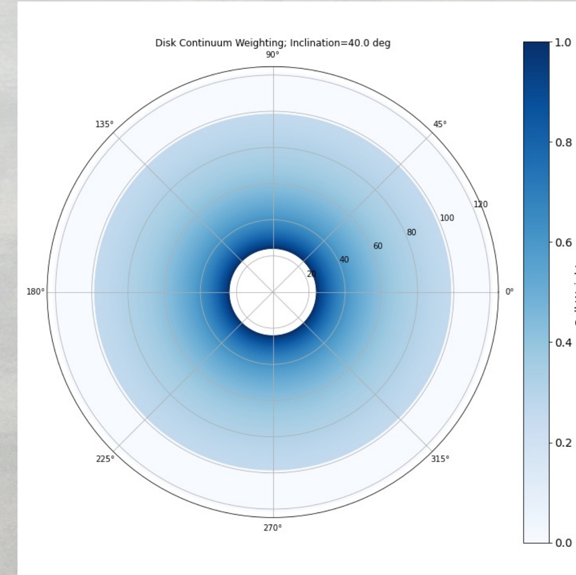
Absorption Line Profiles

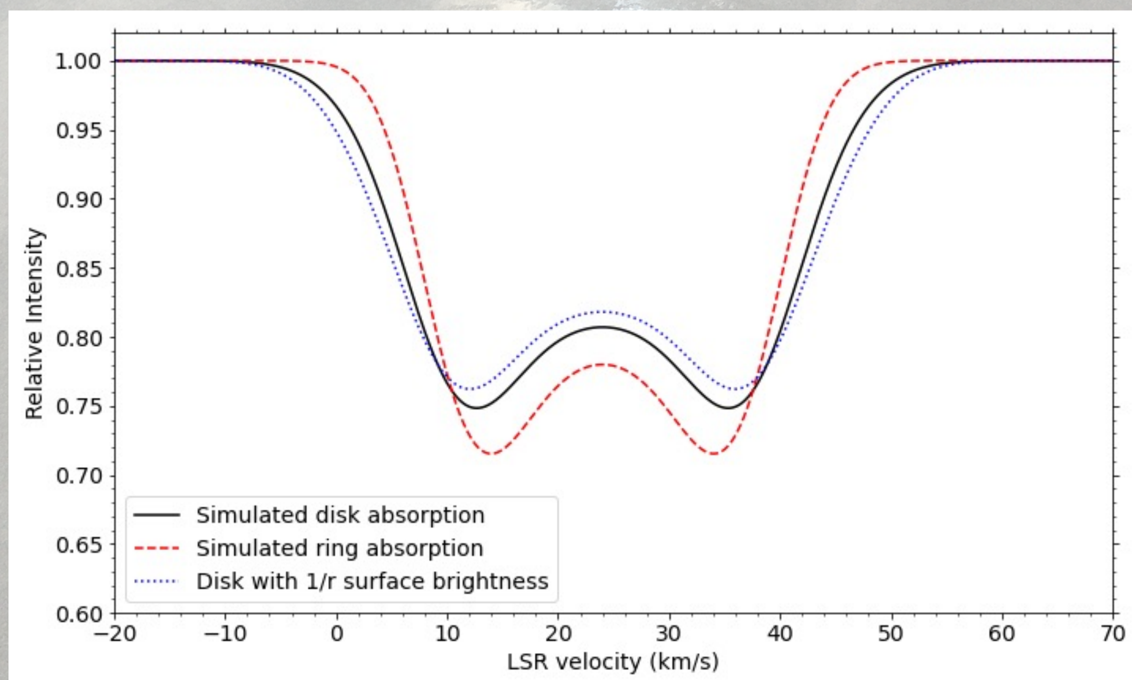
- Primarily 2 different types of line profiles
  - Broad & redshifted
  - Narrow & systemic
- Neither matches the H_2O emission profile of the disk from ALMA




Disk Continuum Weighting; Inclination=40.0 deg
Cell Weights


Disk Continuum Weighting; Inclination=40.0 deg
Cell Weights


Disk Continuum Weighting; Inclination=40.0 deg
Cell Weights


Relative Intensity
LSR velocity (km/s)
Simulated disk absorption
Simulated ring absorption
Disk with 1/r surface brightness