High-Resolution Mid-IR Spectroscopy towards the Massive Young Stellar Binary W3 IRS 5

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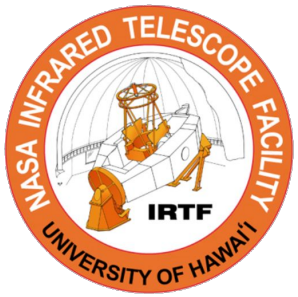
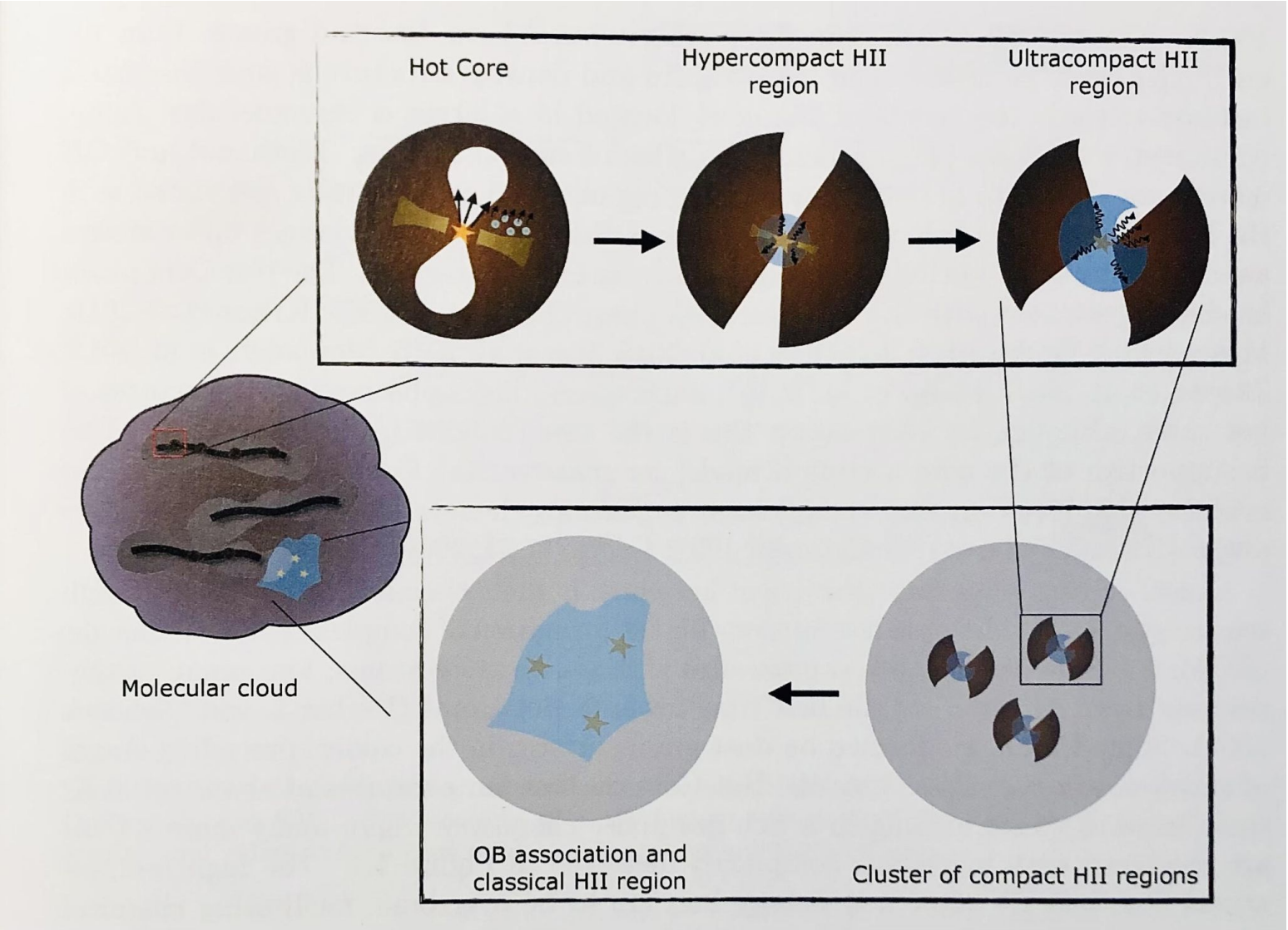
Collaborators: Andrew Barr (Leiden), Adwin Boogert (U. Hawaii), Xander Tielens (Leiden, UMD)



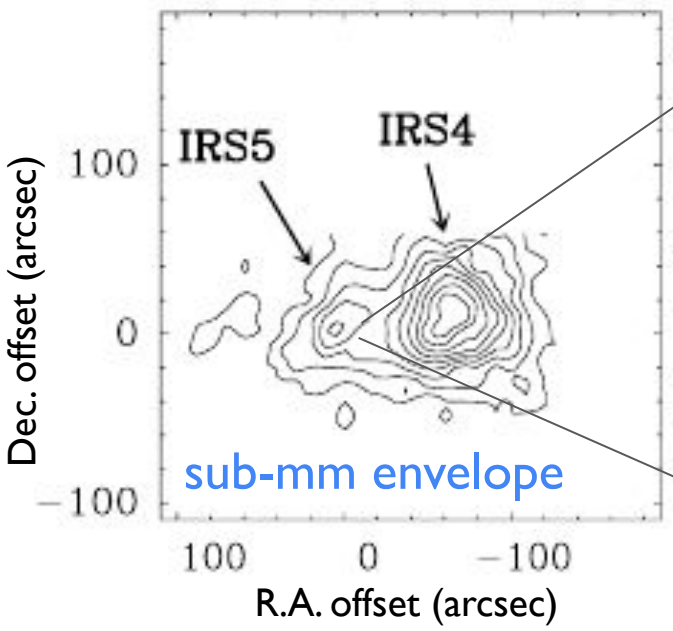
The Evolutionary Sequence for the Formation of Massive Stars



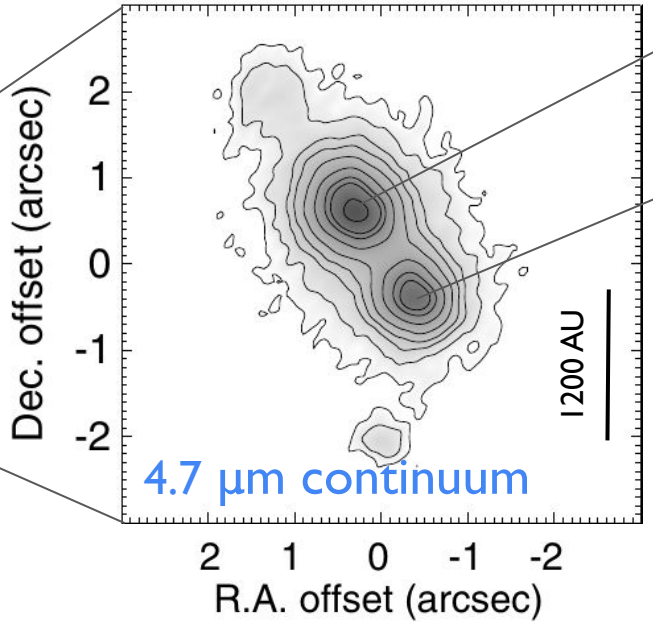
(Beuther 2007; Fig: Barr, PhD thesis, 2022)

Massive Young Stellar Binary W3 IRS 5

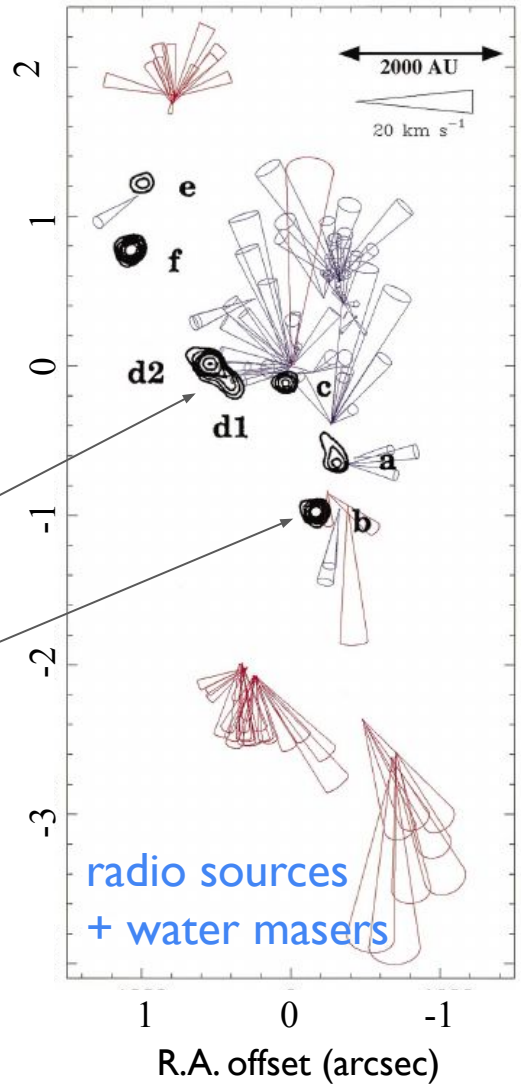
- Proto-stellar binary: each ~ 20 $M_{\odot}$
- submm: shared envelope
- NIR: looking through the cavity
- MIR: two disk-like structures
- Thermal radio sources: HII regions
- Mapping molecules & water masers: outflows



(van der Tak et al. 2000)



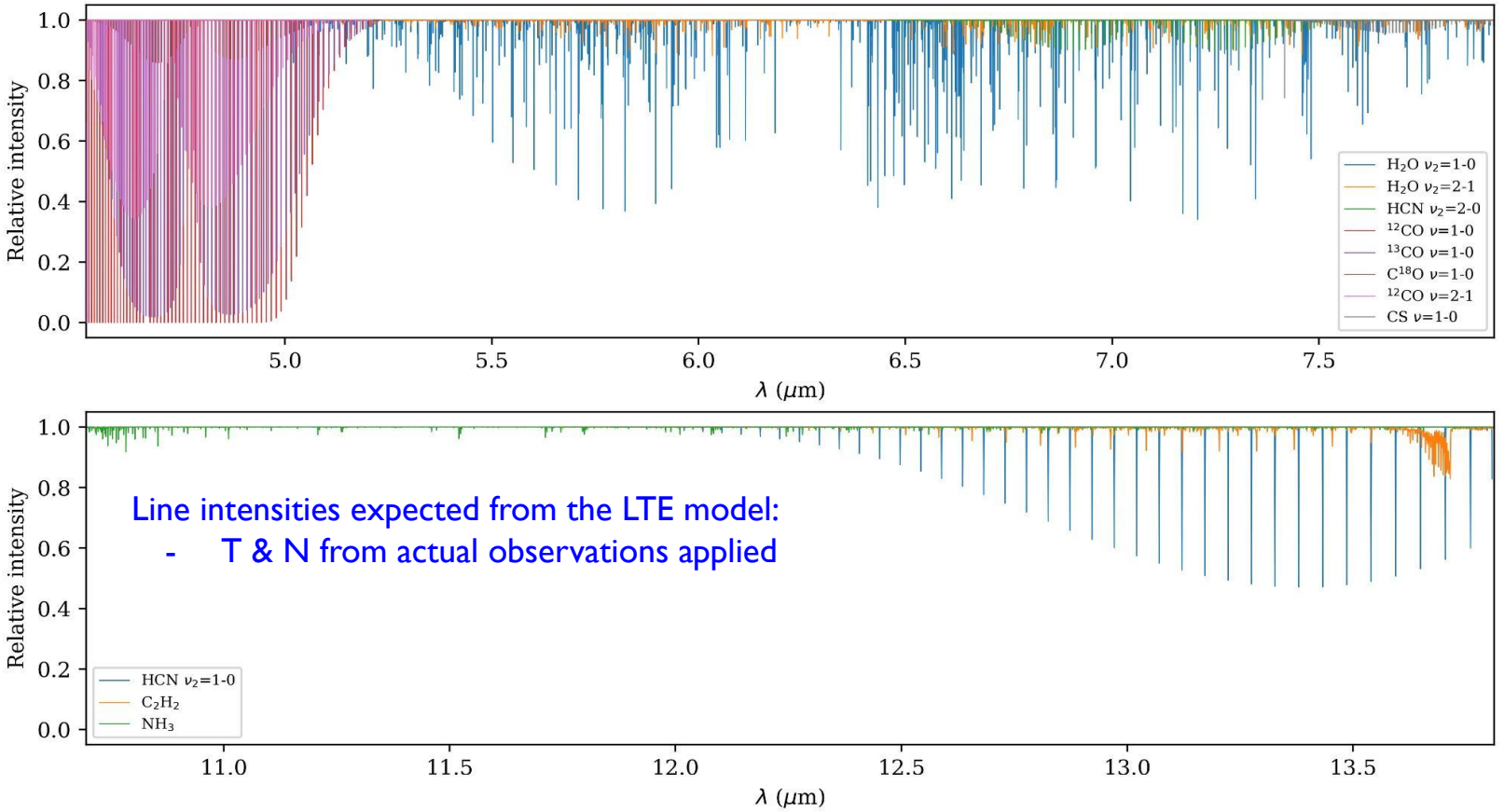
(van der Tak et al. 2005)



(Imai et al. 2000)

Why MIR Absorption Spectroscopy for Massive SF?

- energy regime: ~600 K at 4.7 μm
- effective spatial resolution: size of the MIR source (disk or hot core)
- molecules without dipole-moments (C_2H_2, CH_4) → observable ro-vib transitions
- full set of lines covered in a short bandwidth
- sufficient velocity offset relative to atmospheric telluric lines



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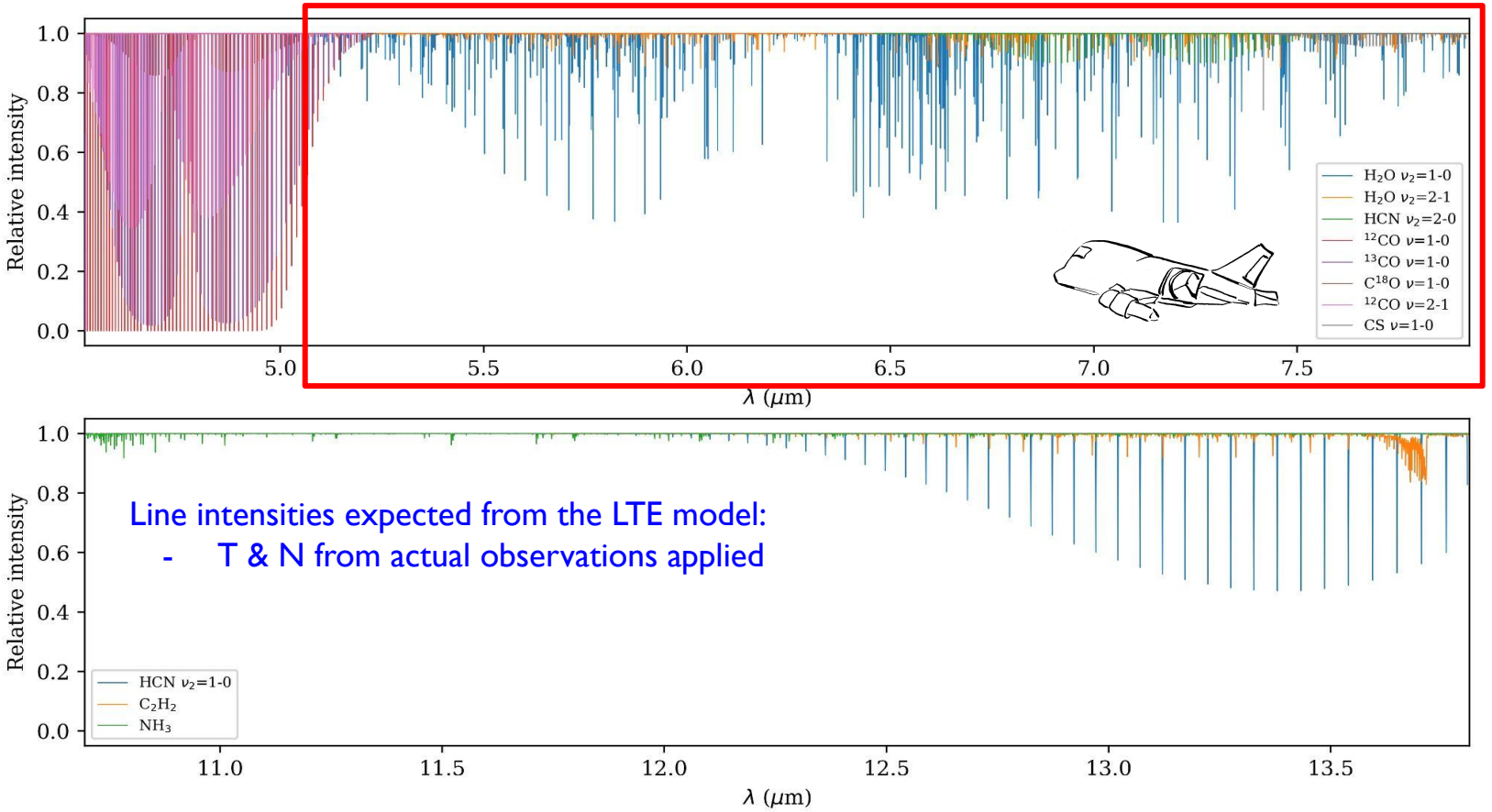
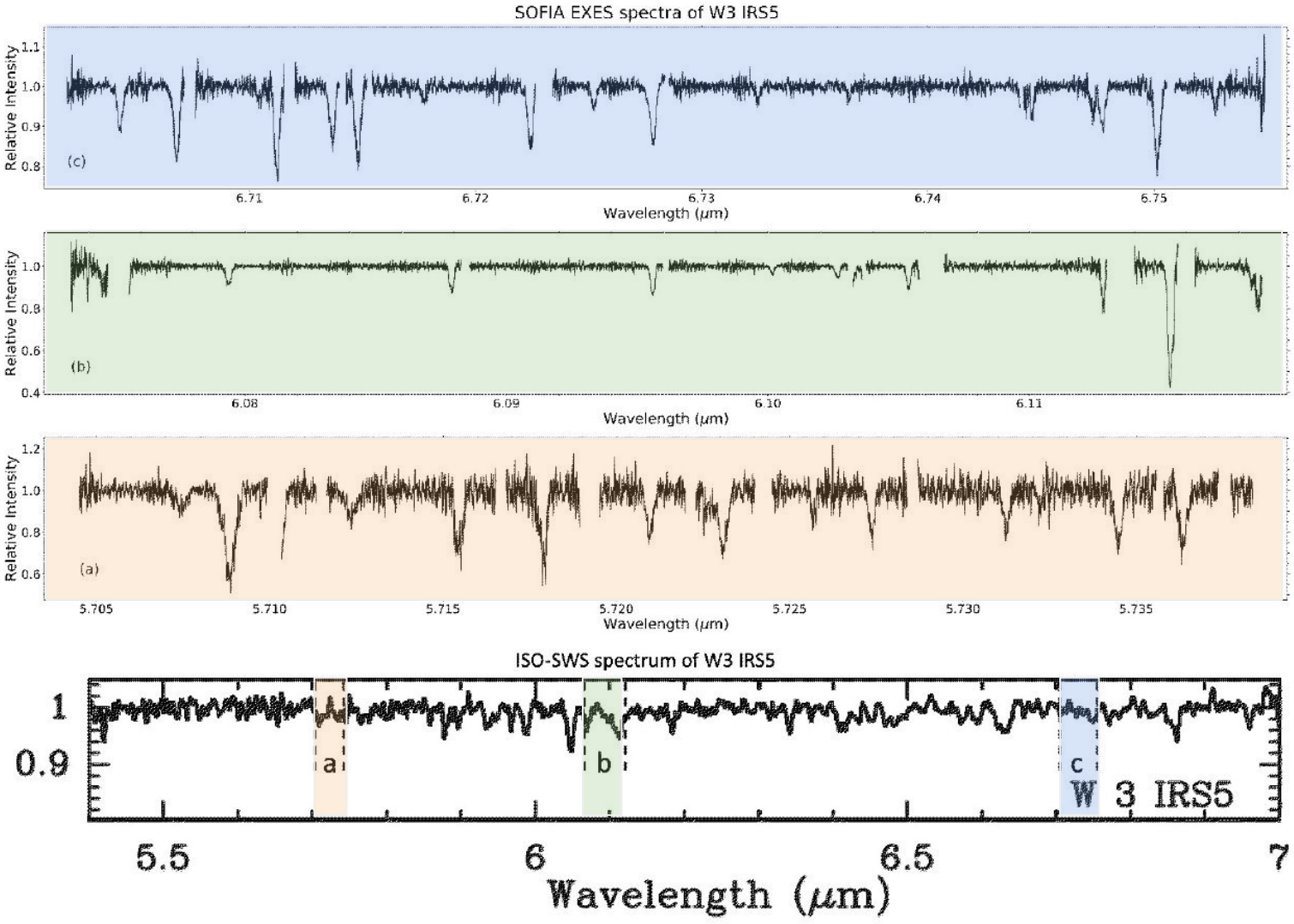


Why High-Resolution MIR Spectroscopy?

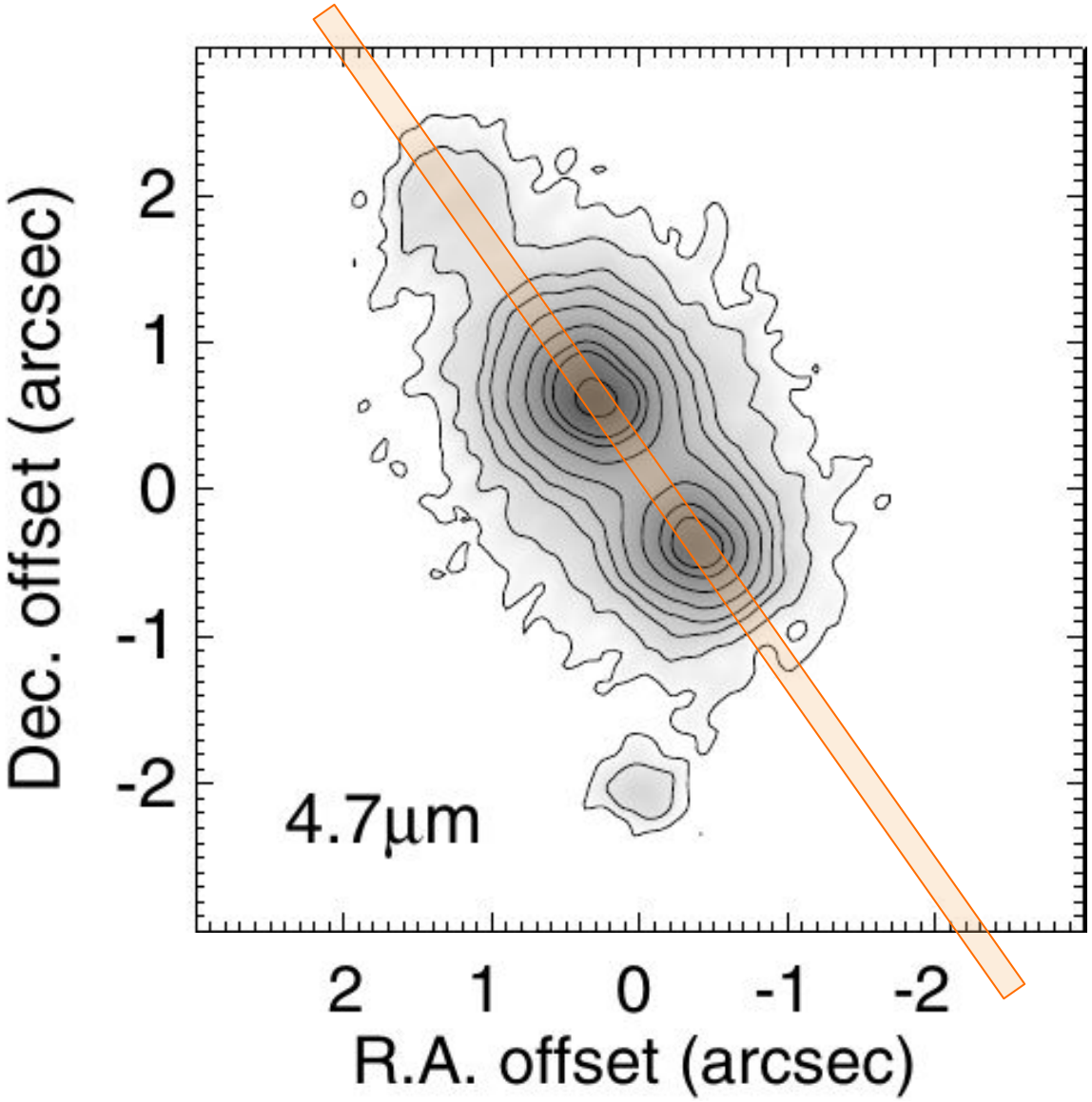


R=50,000
6 km/s

R=1500
200 km/s

(Tielens 2021, Fig 4.10; SOFIA/EXES spectra: Indriolo 2020, private comm; ISO/SWS: Boonman 2003)

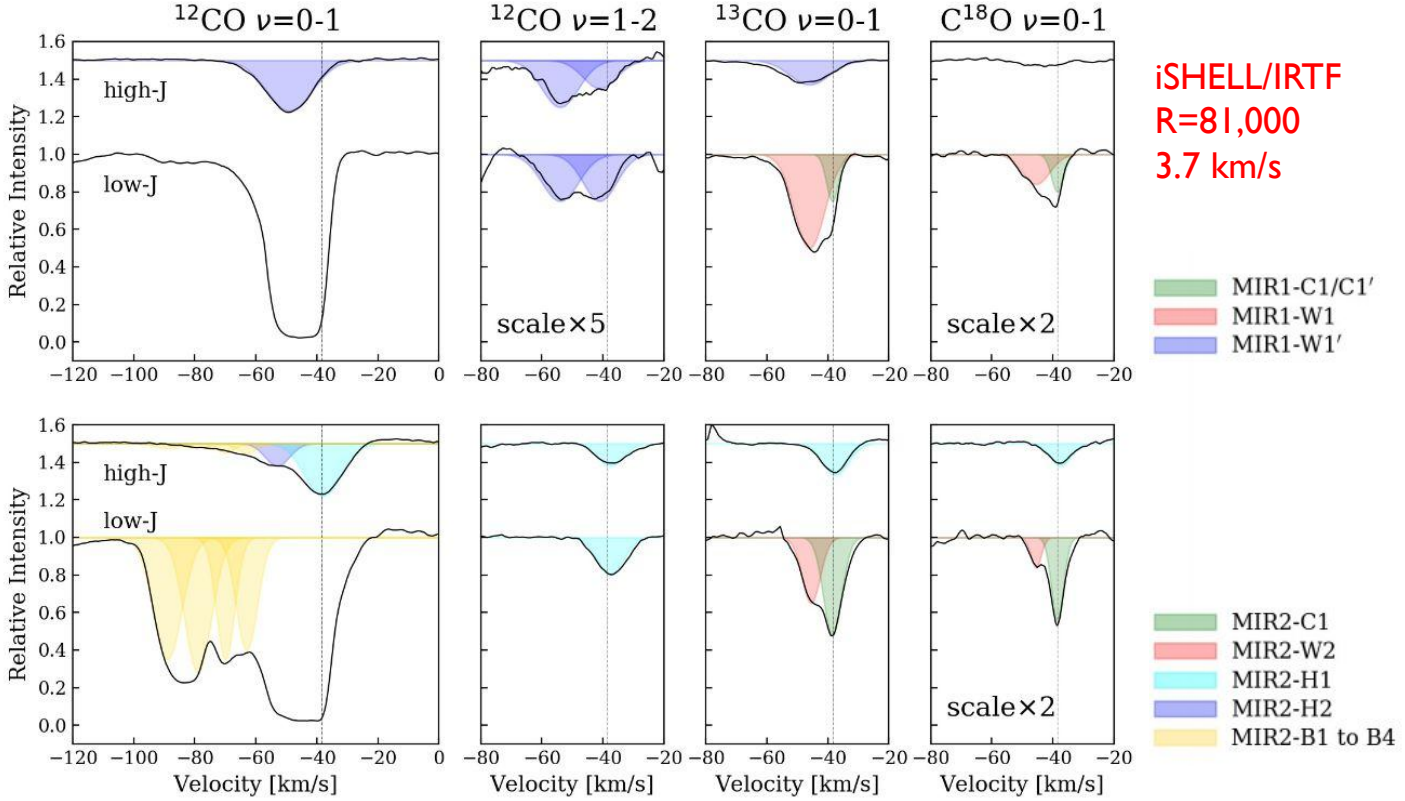
CO Ro-Vibrational Absorption Lines at 4.7 μm



CO Ro-Vibrational Absorption Lines at 4.7 μm

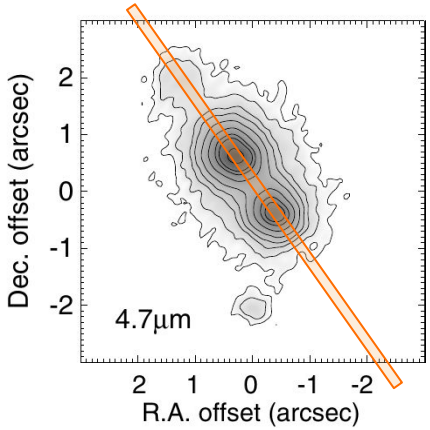
MIR 1

MIR 2

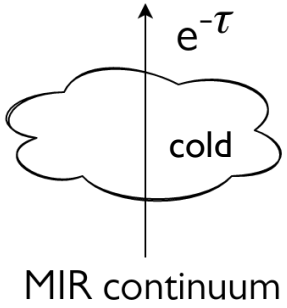


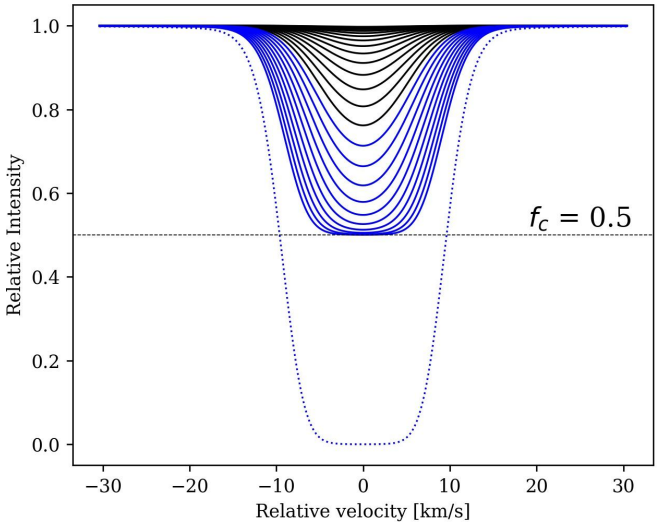
iSHELL/IRTF
R=81,000
3.7 km/s

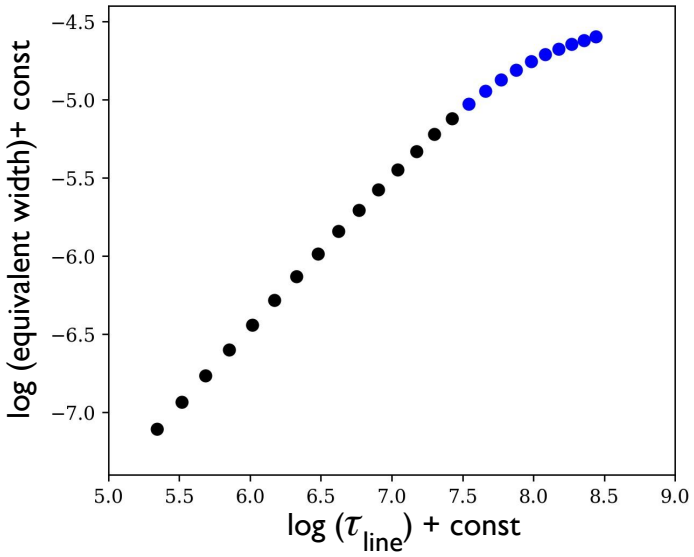
- Multiple velocity components resolved in both sources
- Various line profiles at different energy levels
- Decomposing with information from the rotation diagrams
  - C-components: cool (< 100 K)
  - W-components: warm (100 ~ 400 K)
  - H-components: hot (> 400 K)
  - B-components: "bullets", high velocity (Δv > 30 km/s; 200–300 K)



Curve of Growth Analysis







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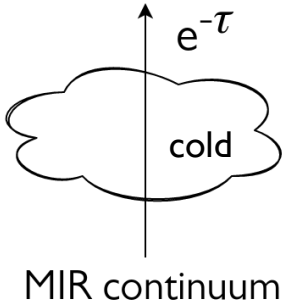
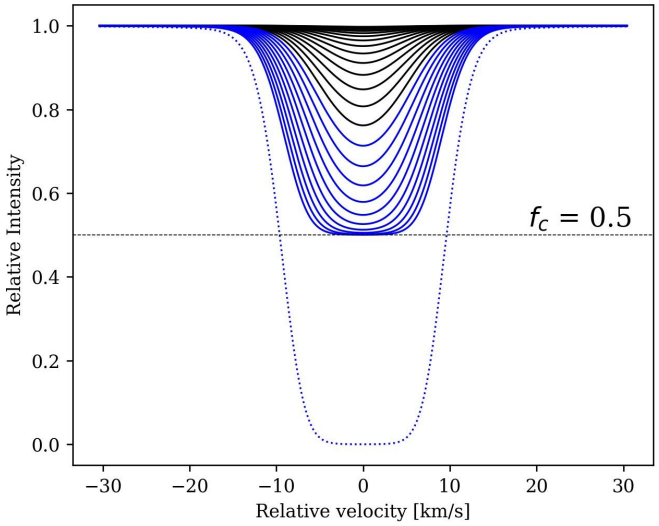
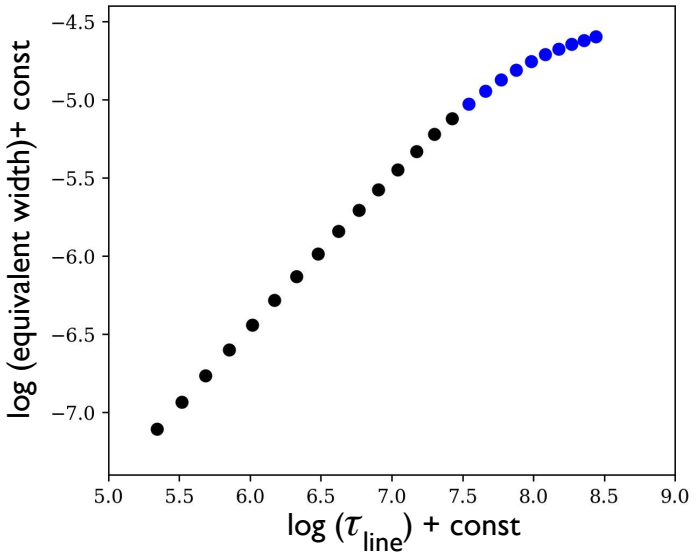
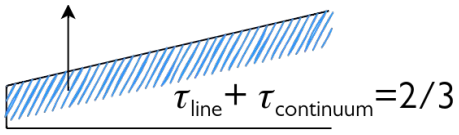
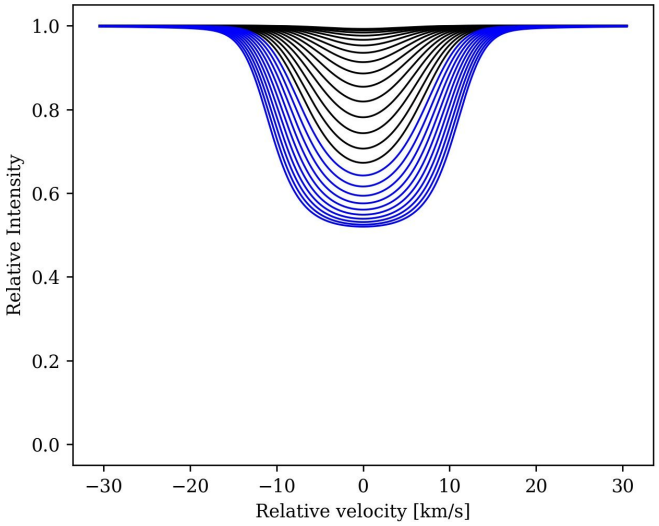
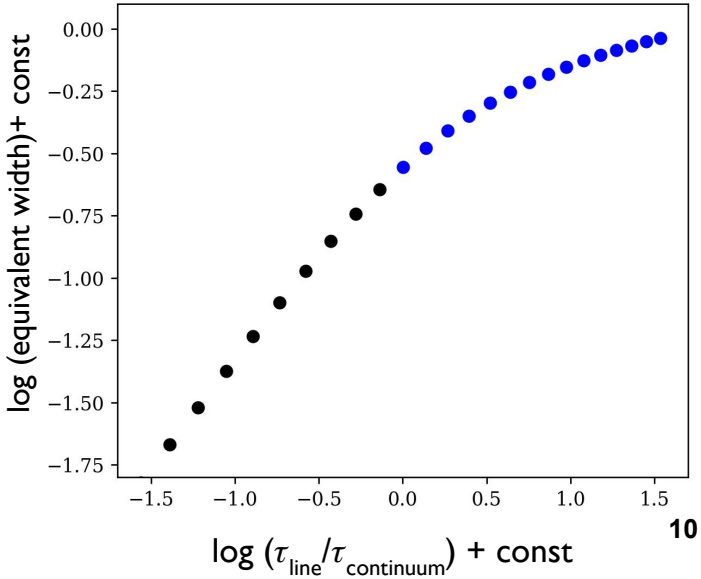






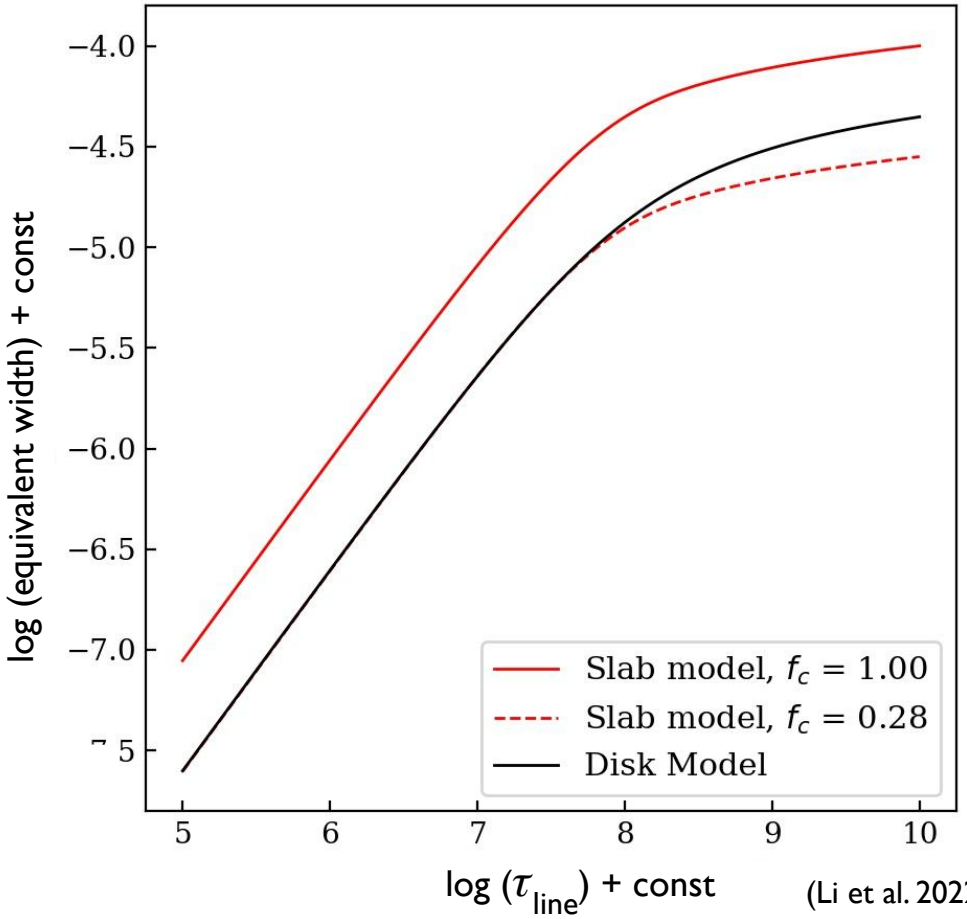






Curve of Growth Analysis

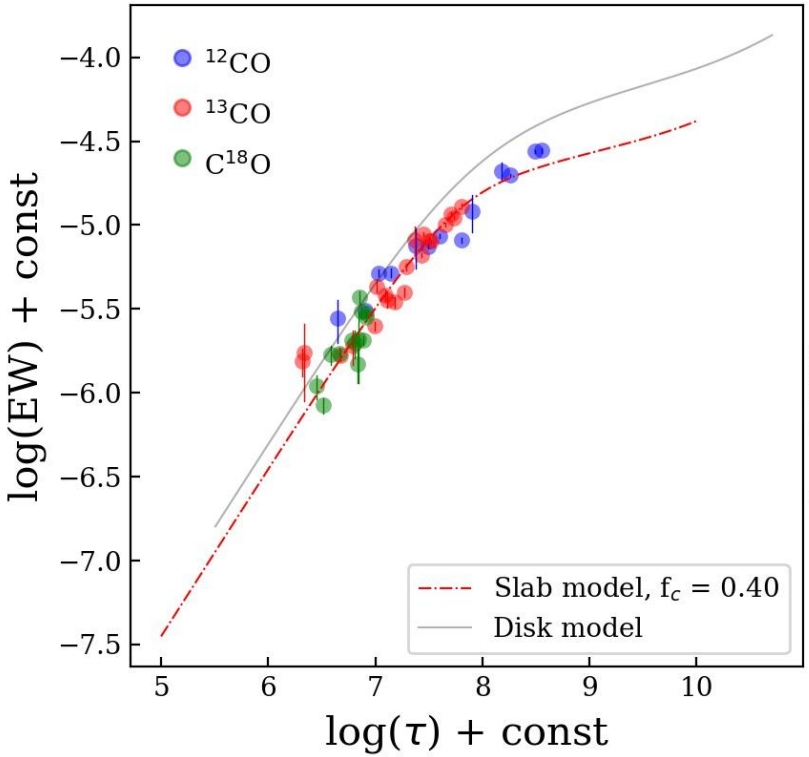
- Degeneracy between the two curve of growth analyses
  - slab model with/without a partial coverage
  - disk photosphere model

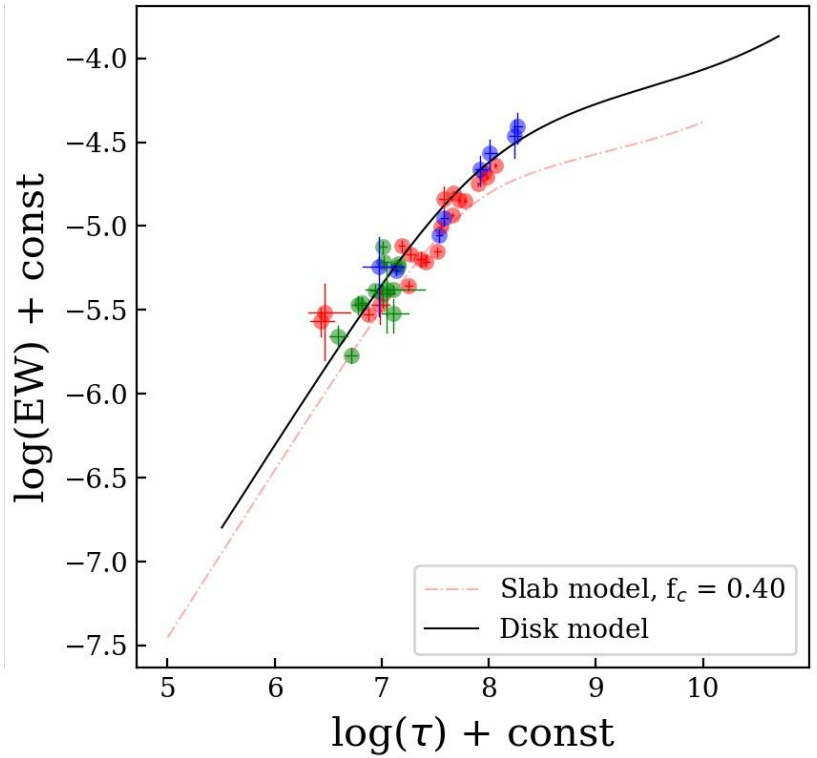


(Li et al. 2022 in prep)

Curve of Growth Analysis

- Degeneracy between the two curve of growth analyses
- Comparing with real data:
  - one of the hot (~600 K) component
  - each dataset fitted with the best (T, N) fitting results
  - (T, N) are consistent within constraints from error bars





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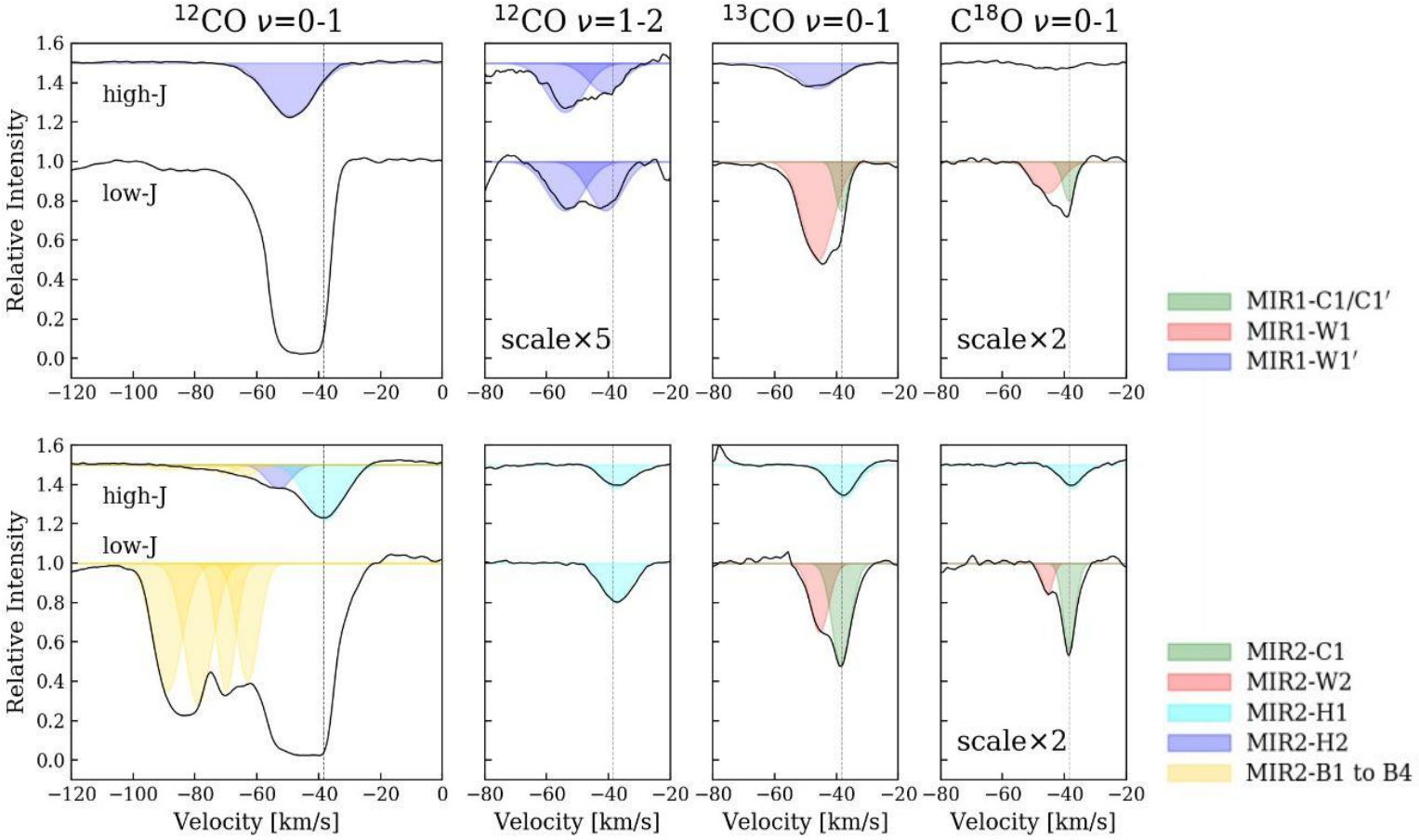
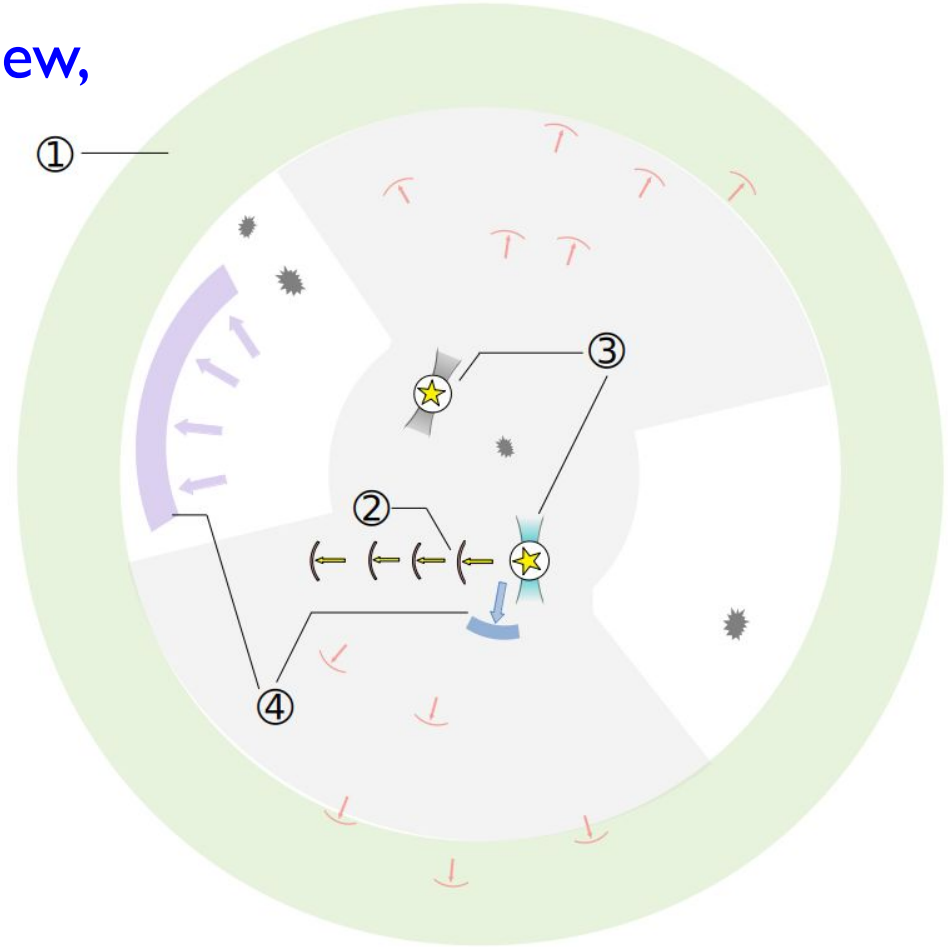
MIR 1

MIR 2



Shared Envelope	MIR1-C1	MIR2-C1		<100 K, shared velocity @ v_{LSR} of the molecular cloud, N_{CO}~10^{18} cm^{-2}
Disk/C-shocks	MIR1-W1/W1'	MIR2-H1	MIR2-H2	400-600 K, small Δv (<15 km/s), N_{CO}~$10^{18\text{-}19}$ cm^{-2}, n>10^{10} cm^{-3}
J-shocks	MIR2-B1-B4			200-300 K, high Δv (>30 km/s), constant T ~ 30 yrs, N_{CO}~$10^{17\text{-}18}$ cm^{-2}, n>10^{7} cm^{-3}

Schematic View, W3 IRS 5



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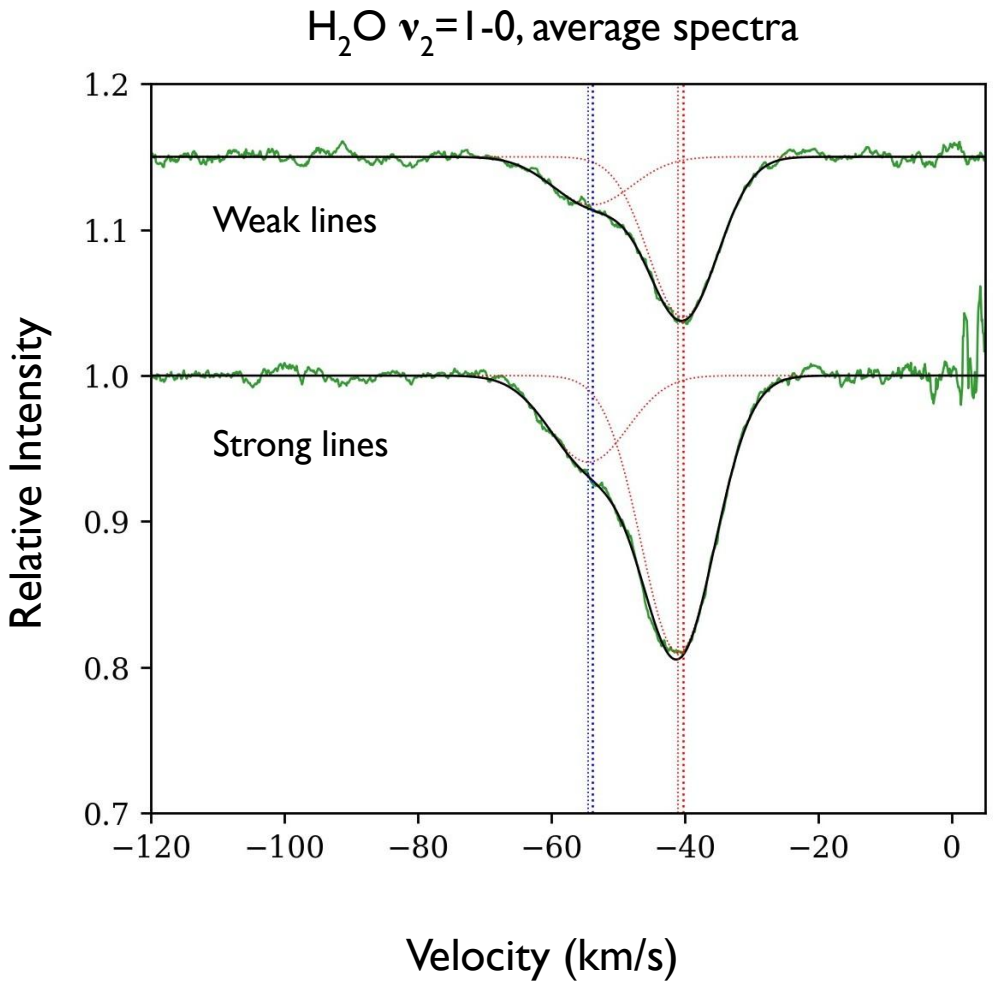
Water lines by SOFIA/EXES at 5-8 μm



- ~250 v_2=1-0 and ~ 70 v_2=2-1 lines detected (2021 June & Dec)
  - more data arrived (yesterday!)
- SOFIA beam doesn't spatially resolve the binary
- rotation diagram analysis:
  - 700 – 1000 K
  - optical depth effects on lines with large Einstein A or high column densities
- require curve of growth analysis for better constraints

Summary and Future Expectations

- CO ro-vibrational spectra observed by iSHELL/IRTF at 4.7 μm:
  - binary spatially resolved
  - high spectral resolution suffient to resolve distinctive velocity components
  - disks, J-/C-shocks, shared envelope in the nearby environment
- Existence of the disk(s)?
  - further observations from SOFIA observations may resolve the degeneracy between the models
    - ⋆ Disk? C-shocks? Both?
  - further evidence: transitions from the same molecule @ different wavelengths
    - ⋆ e.g. AFGL 2136 and AFGL 2591
- What to learn from water spectra?
  - distinguishing MIR1 and MIR2?
  - origin of water lines in the identified CO components
  - potential water lines originated from water masers?
- More species?
  - $HCN/C_2H_2/CH_4$/CS lines → **Boogert's talk for Barr's work!**