SOFIA/EXES Survey of Gaseous Water in the Binary Hot Core W3 IRS 5

ApJ 953 103

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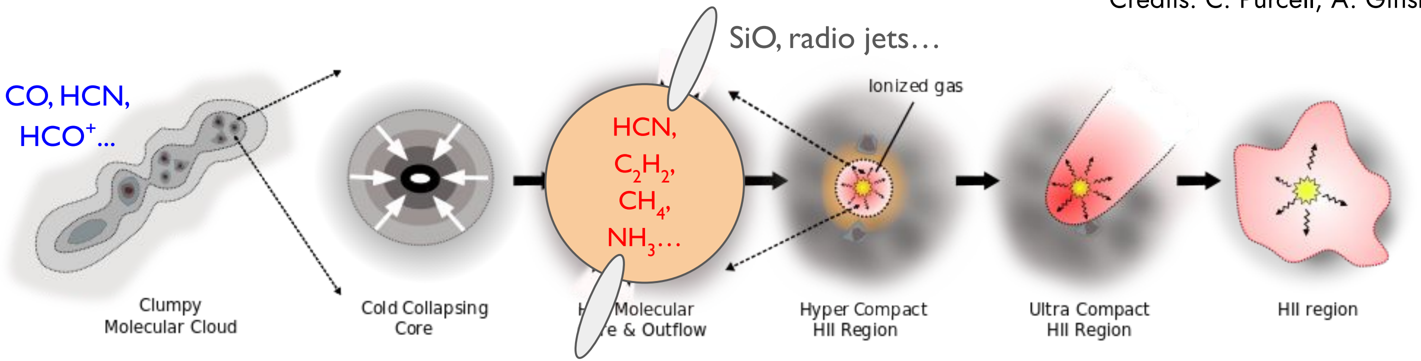
Hot Core Phase in Massive Star-Formation Processes

Credits: C. Purcell, A. Ginsburg



- Formation of massive stars:
  - Not a simply scaled-up version of low-mass star formation
- Early phases, heavily obscured by dust– invisible at optical and NIR
  - Distribution & kinematics of materials within ~1000 AU are poorly known
- Benchmark for studying hot corinos in low-mass protostellar systems

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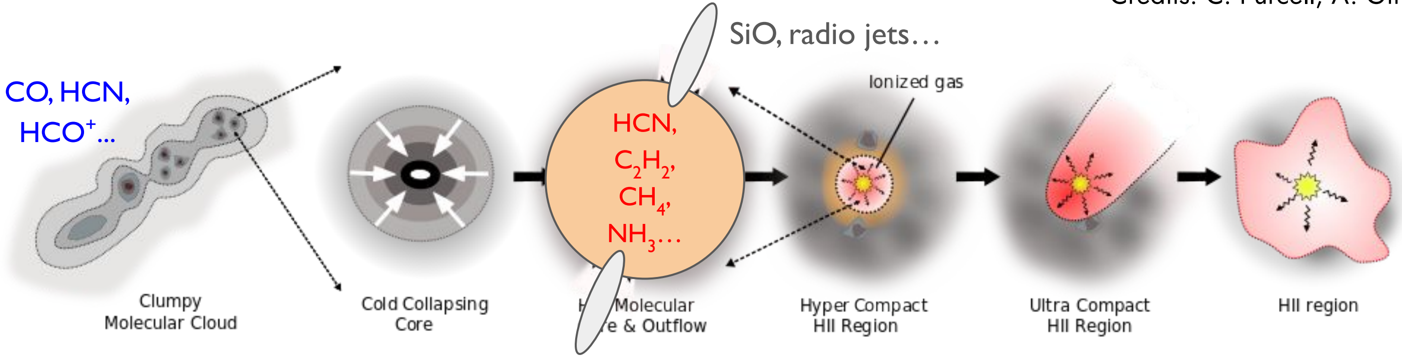
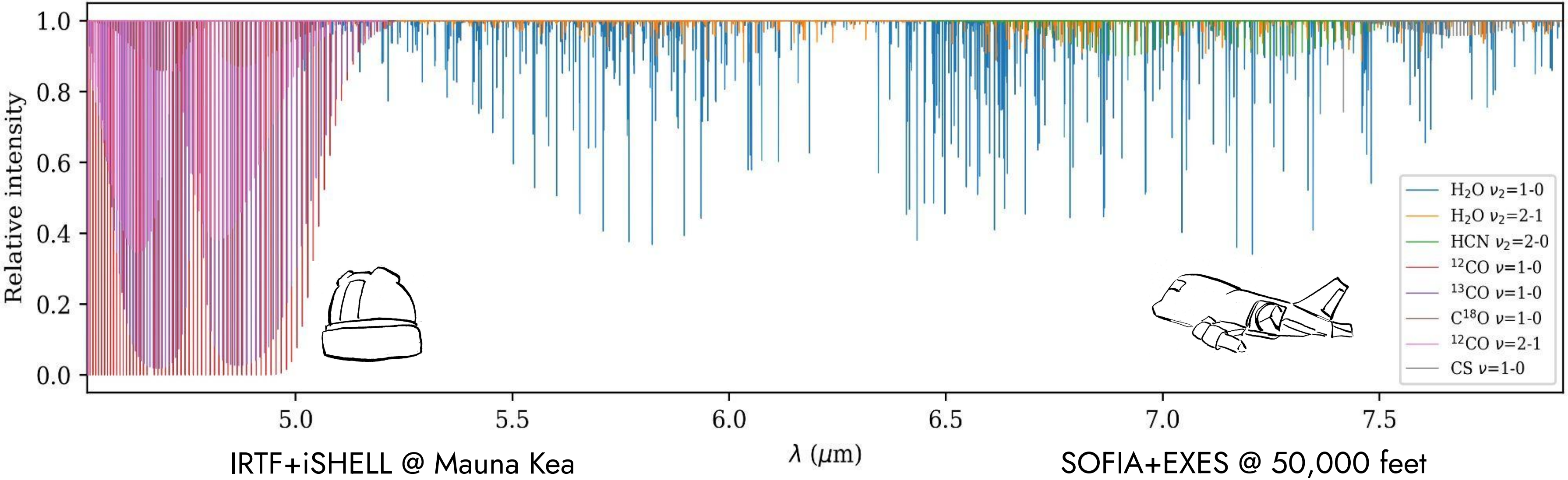


- Hot core phase:
  - Chemically: rich chemistry driven by ice sublimation & gas-phase chemistry
  - Physically: accretion disks, outflows, shocks, disk winds…
- Great to be studied at mid-infrared (MIR):
  - Bright with pencil beam size (a few hundreds of AU)
  - Against which many ro-vib absorption lines are observed

Rich Ro-vibrational Lines at MIR

CO v=1-0, v=1-0 H$_2$O ν_2=1-0, ν_2=2-1 HCN ν_2=2-0 ……



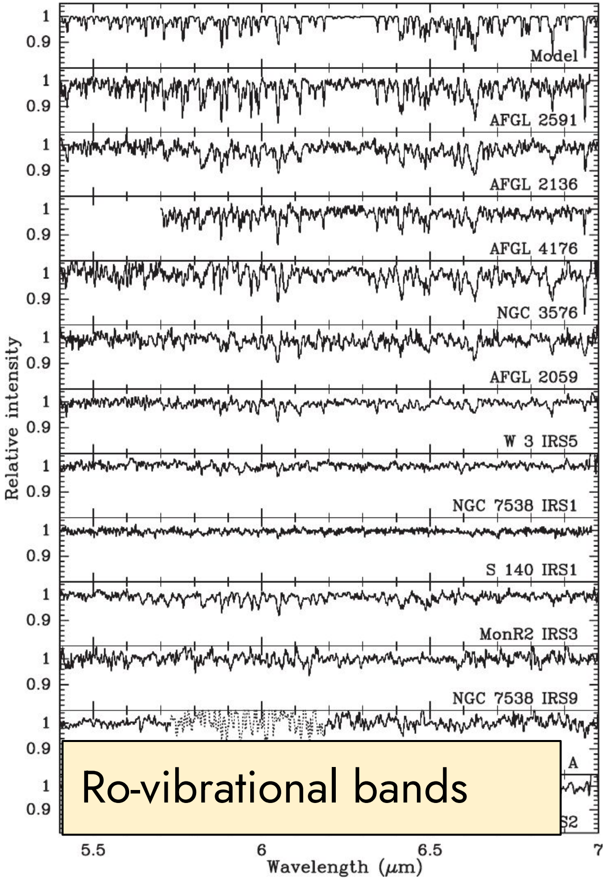
IRTF+iSHELL @ Mauna Kea
R~88,000 Δv ~ 3.4 km/s

SOFIA+EXES @ 50,000 feet
R~50,000 Δv ~ 6 km/s

- Many transitions spanning a large excitation energy range
- Same beam against the same background

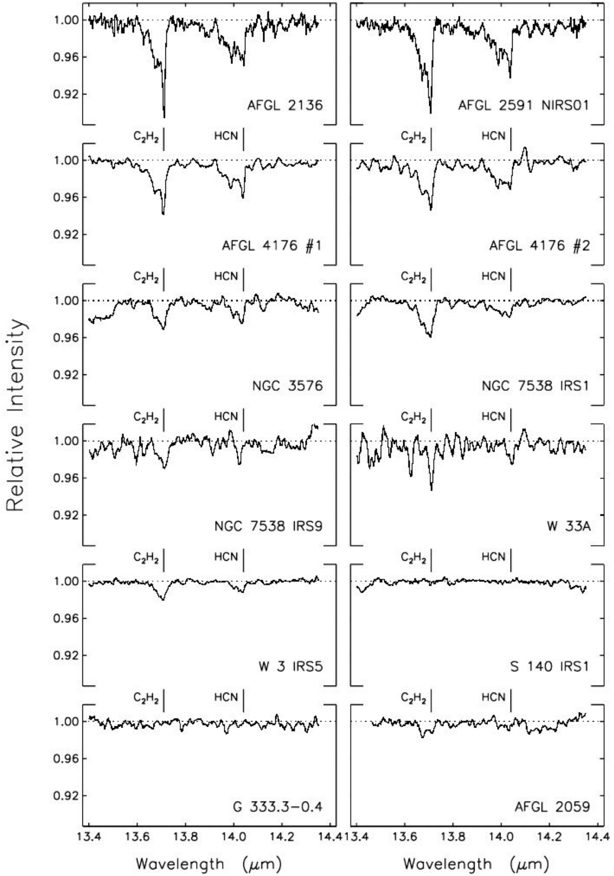
20 Years Ago: MIR Spectroscopy Toward Hot Cores (ISO-SWS)

H_2O, Boonman et al. 2003



Ro-vibrational bands

C_2H_2, **HCN**, Lahuis & van Dishoeck 2000



- Low R (~1500, 200 km/s)
- In the innermost regions:
  - hot (~500 K),
  - abundant,
  - gas-phase molecules,

  in absorption, exist ubiquitously
- Emission lines are seen in
  - low mass T Tauri stars
  - intermediate mass Herbig AeBe stars
- *Hot absorbing clumps? Or something else?*

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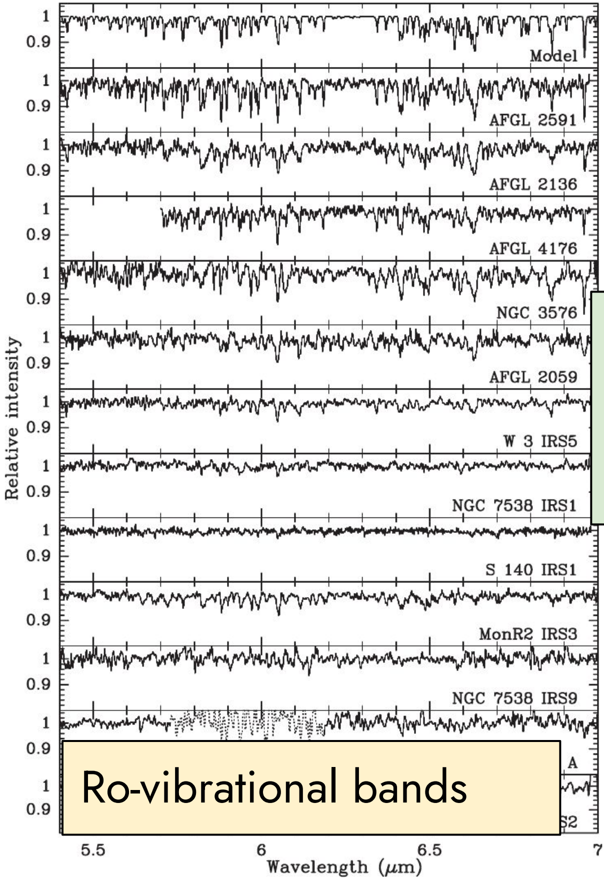

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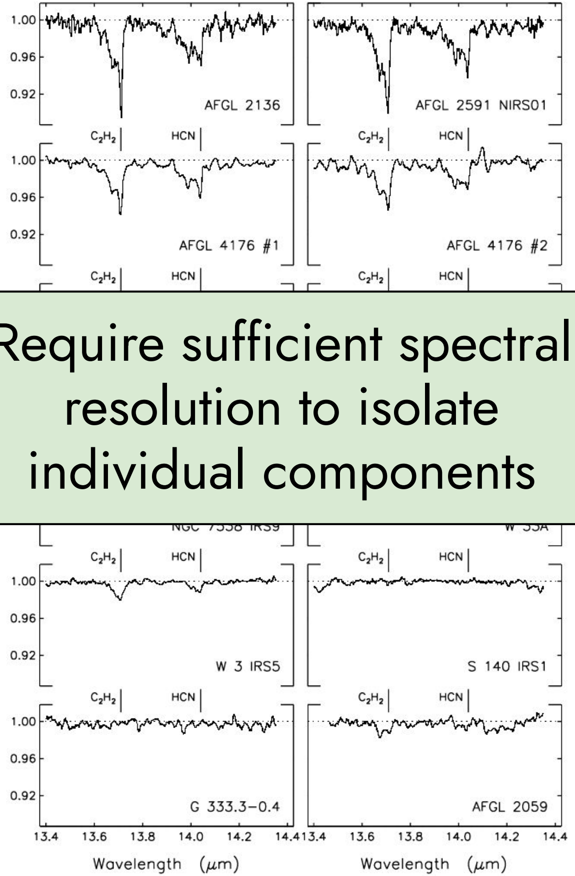

Require sufficient spectral resolution to isolate individual components

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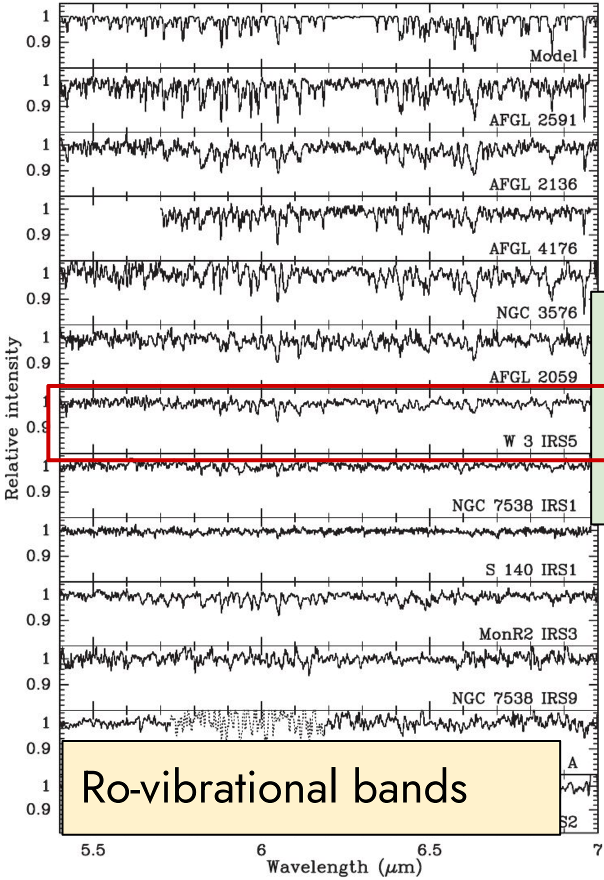

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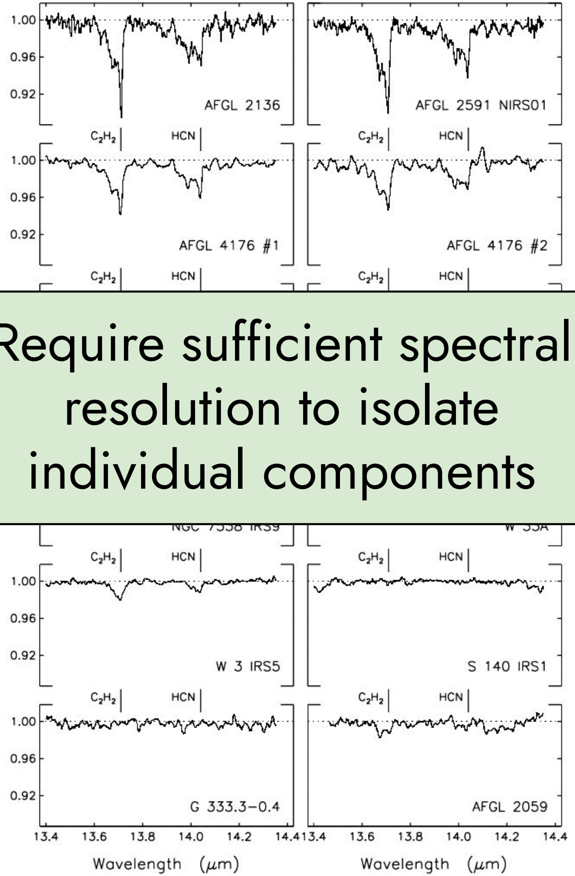

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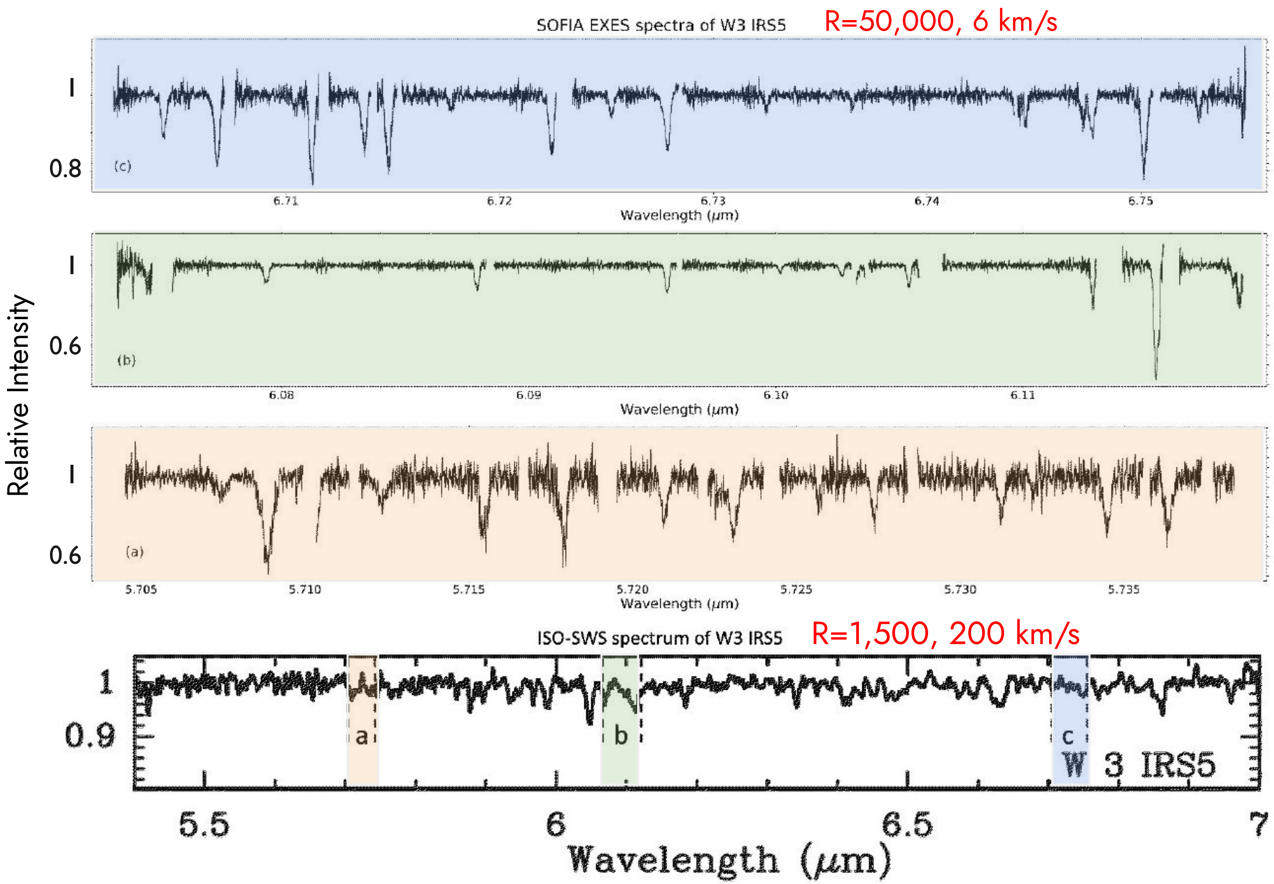
High Resolution of MIR Spectroscopy Is A Must



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

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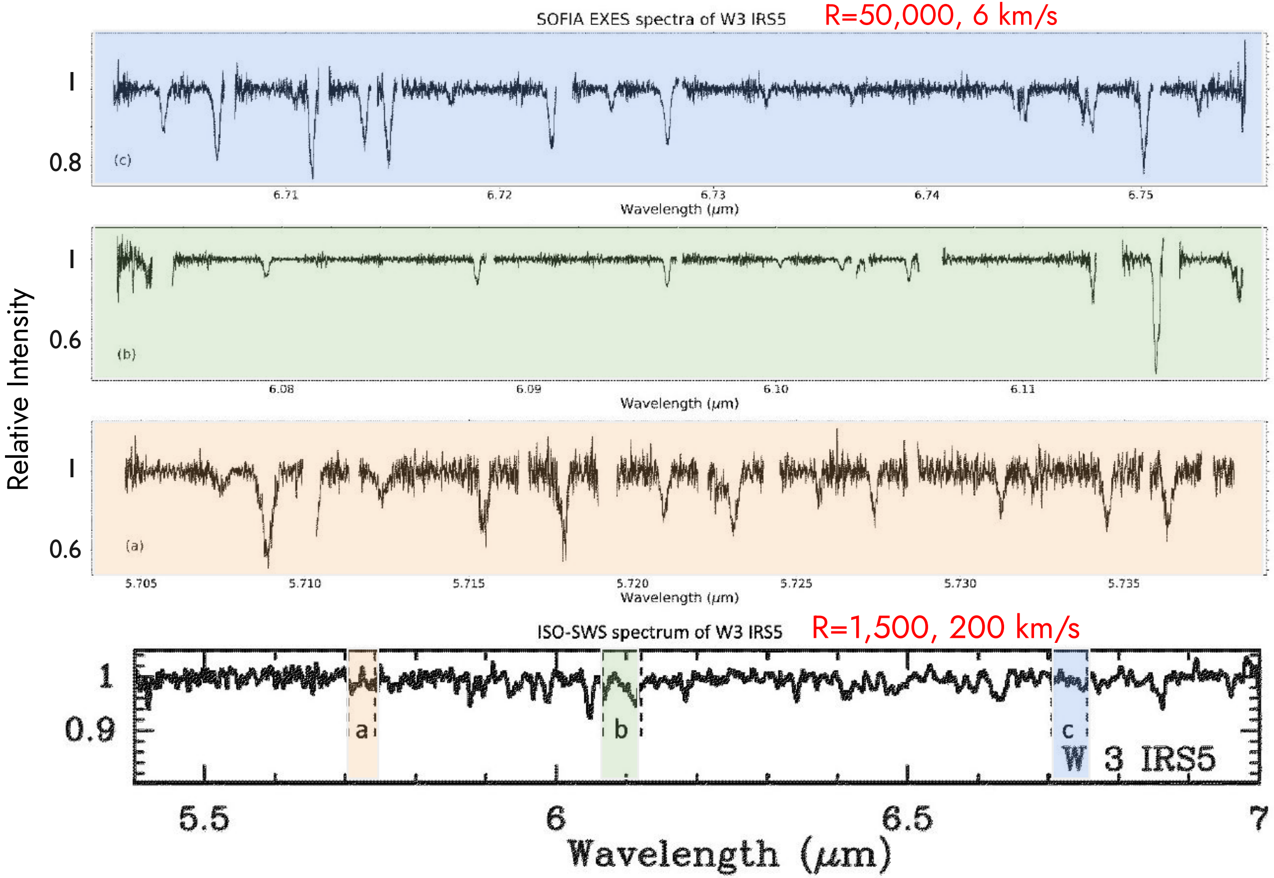

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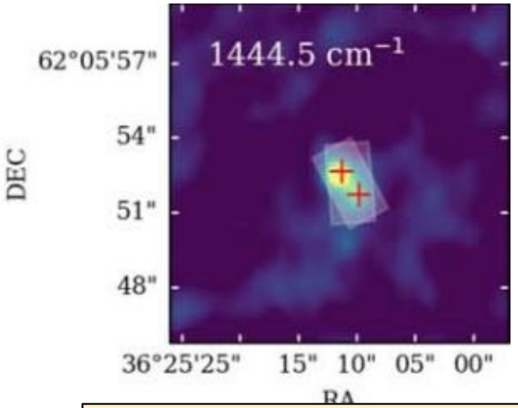
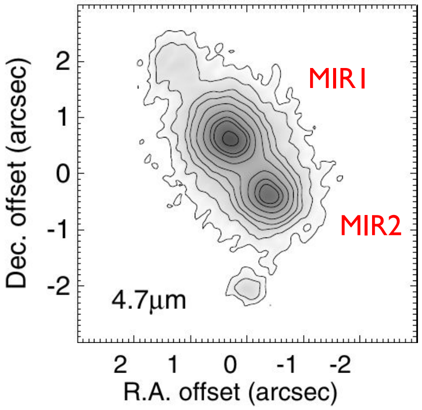
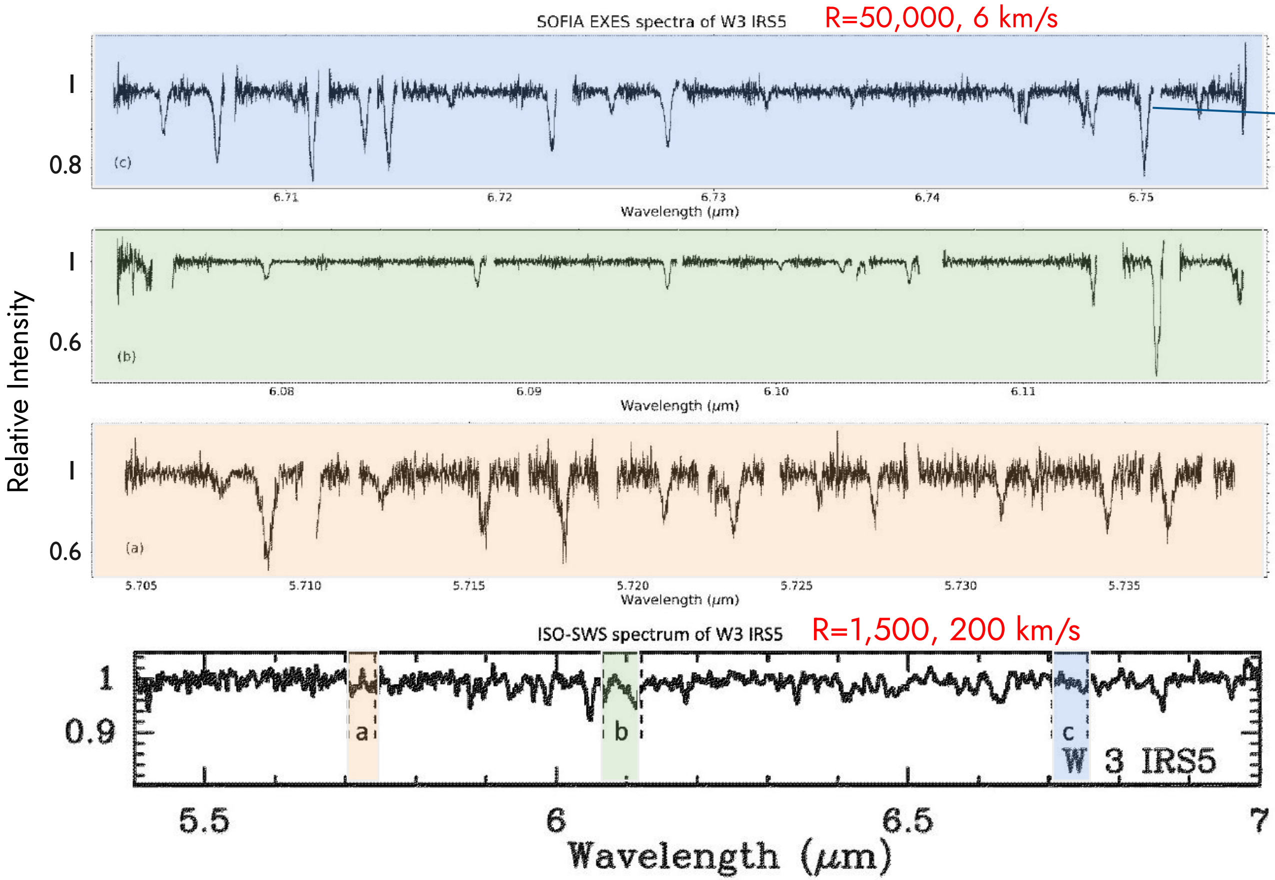
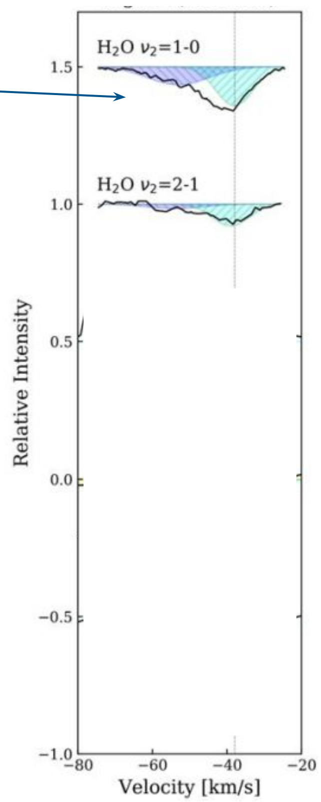


Unresolved binary with SOFIA



Velocity-Resolved Spectroscopy

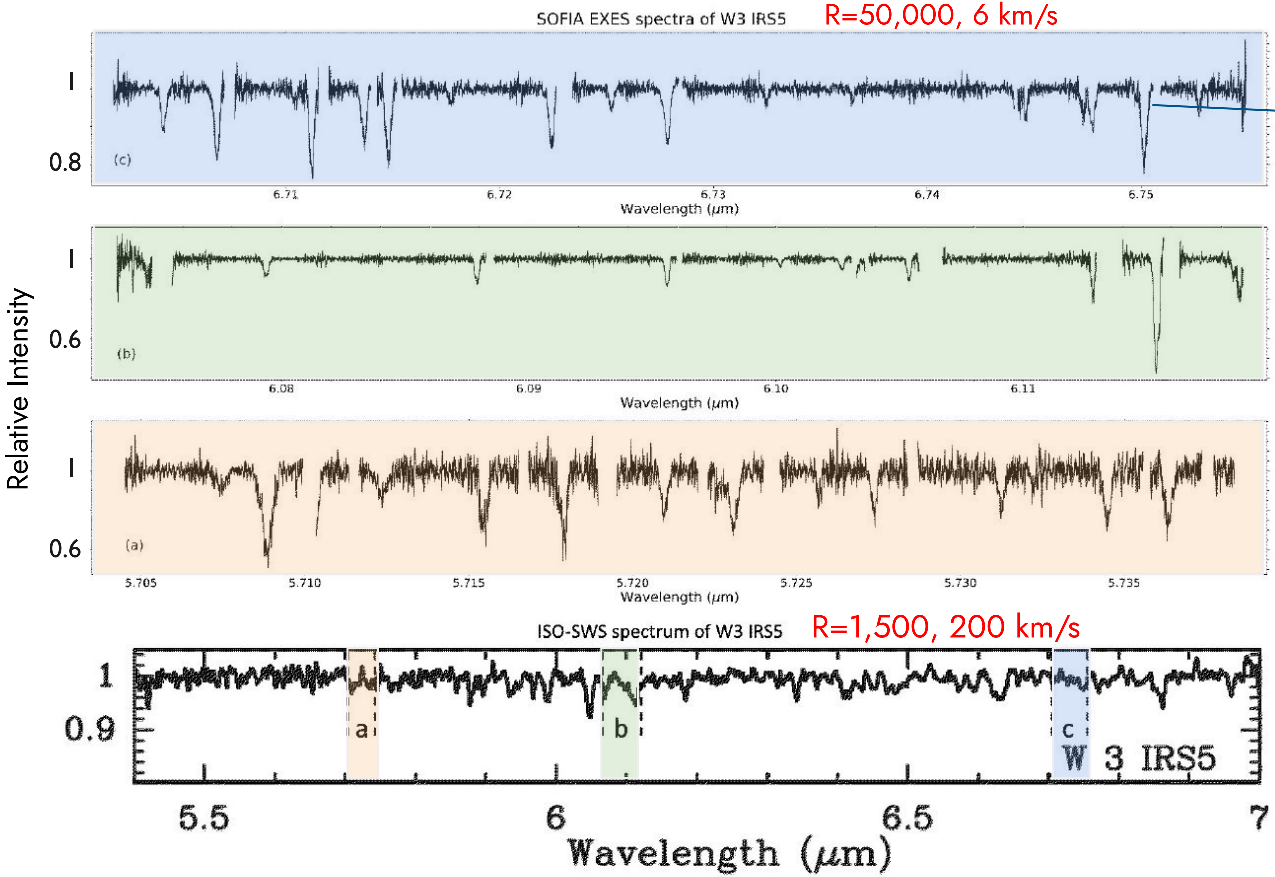




Multiple velocity components characterized by different temperatures and column densities

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

Velocity-Resolved Spectroscopy



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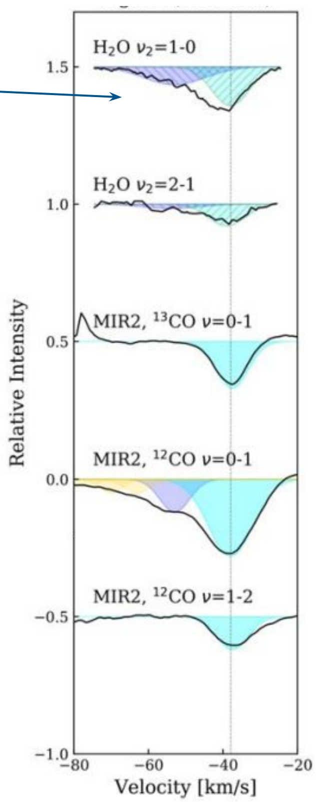


Multiple velocity components characterized by different temperatures and column densities

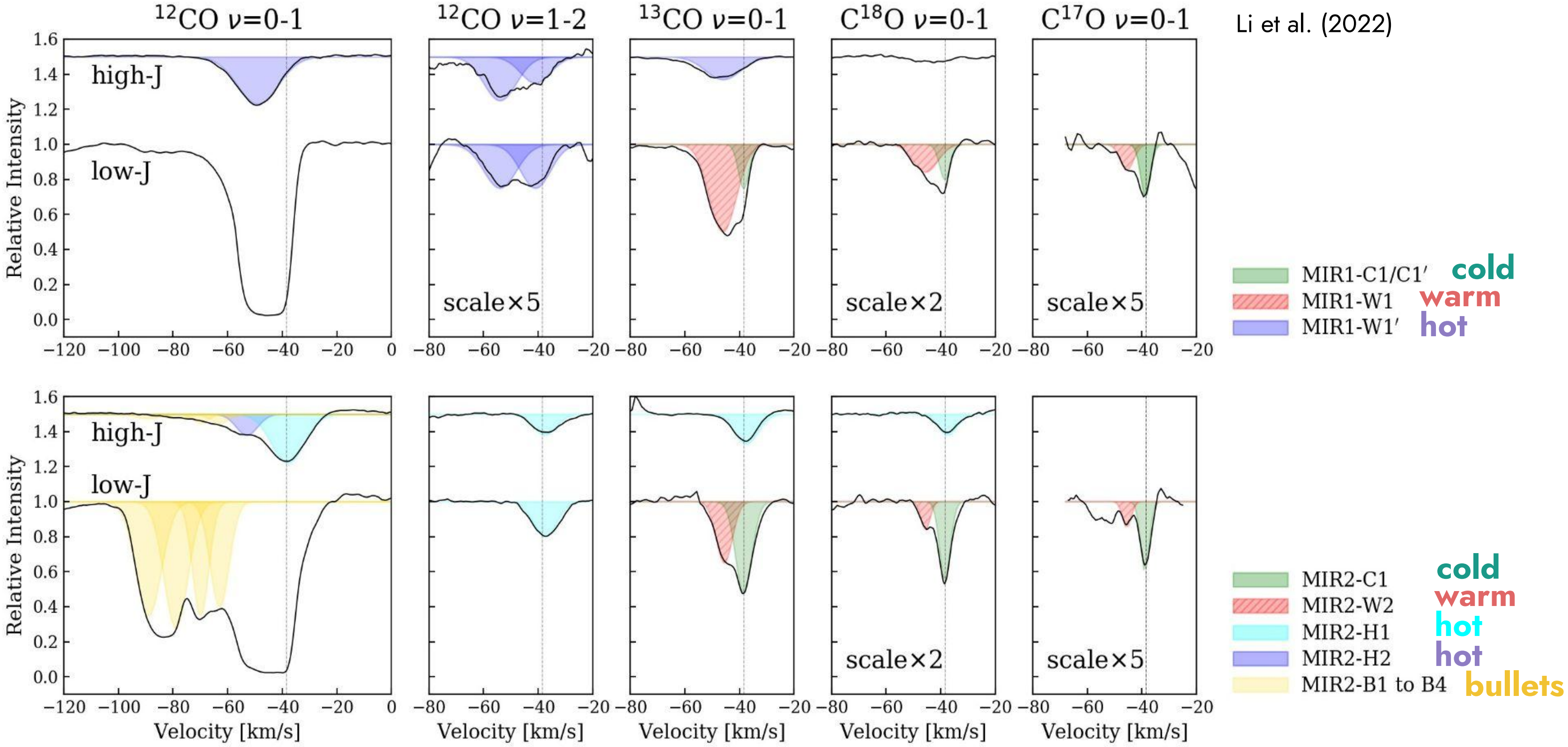
Properties can be linked & compared with other species such as CO.

(Part of) Averaged water & CO lines in W3 IRS5; Li et al. (2023)

CO from iSHELL/IRTF: Components in the Binary

MIR1

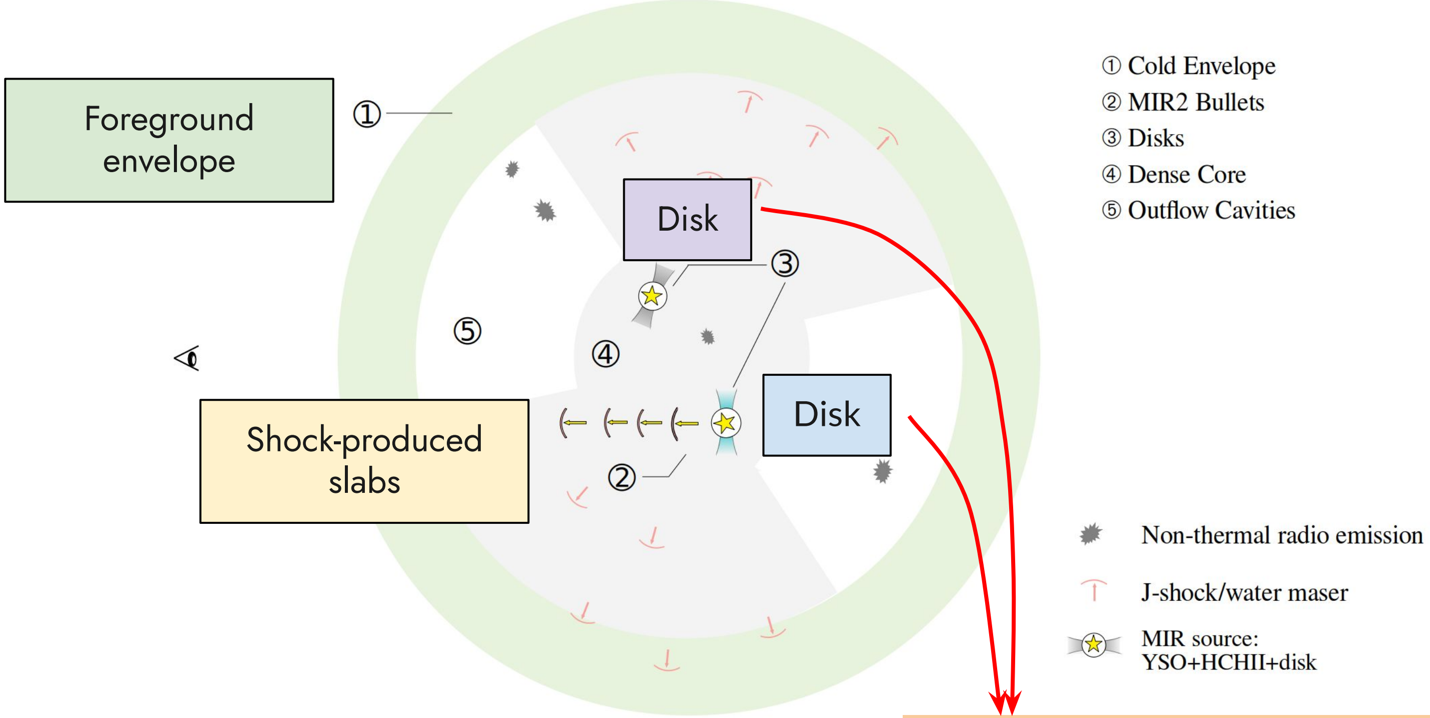
MIR2



Each color indicates a different physical origin: Foreground envelope, shocks, clumps on the disks.

Multiple Velocity Components in W3 IRS 5

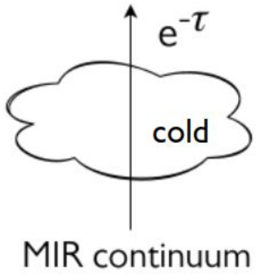
Li et al. (2022)



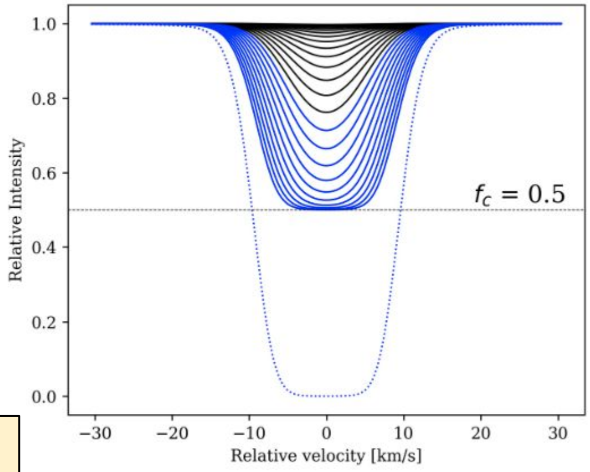
Color refers to different components in the profiles.

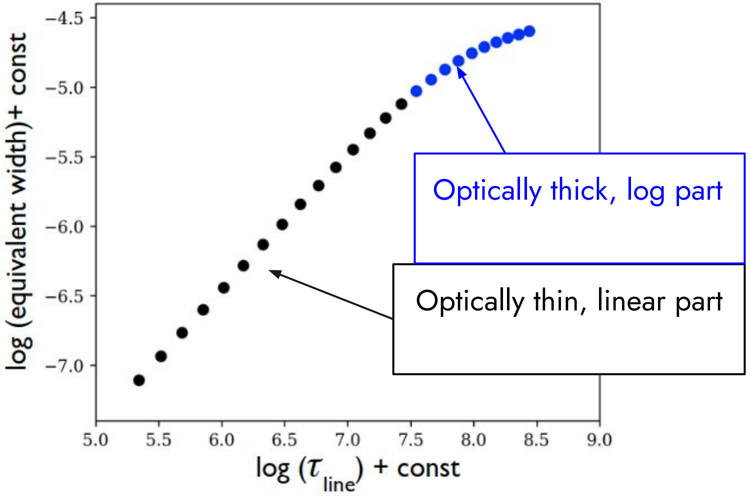
Focus on the abundant hot water in the disk.

Curve of Growth Analysis to Derive T & N (Slab Model)

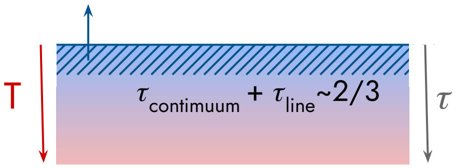


Isothermal foreground absorbing slab

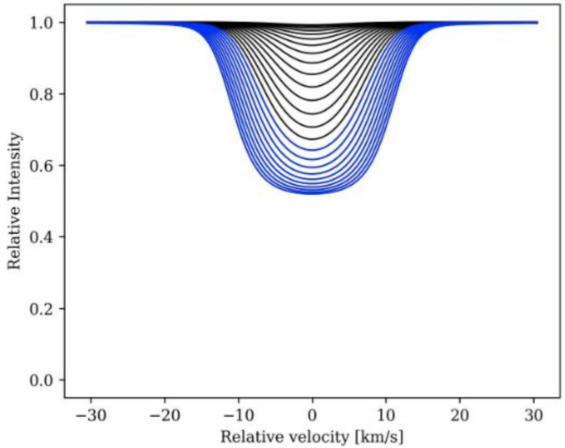


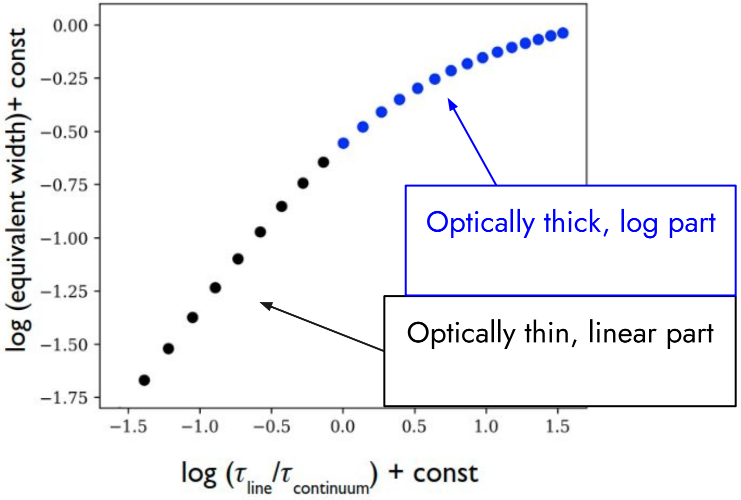


Curve of Growth Analysis to Derive T & N (Disk Model)



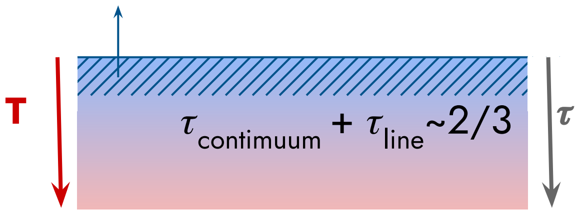
Disk photosphere model

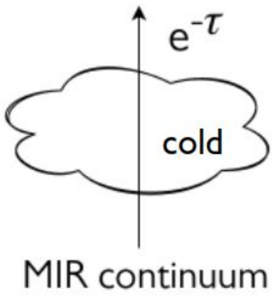




- Treatment is analogous to stellar atmosphere curve of growth analysis
  - Takes care of optically thick lines
- The disk has an outward-decreasing temperature gradient
  - Disks around T Tauri stars show emission lines of H_2O, CO, CO_2, HCN, C_2H_2, OH, …

Locations of Hot Gaseous Water Absorption Lines



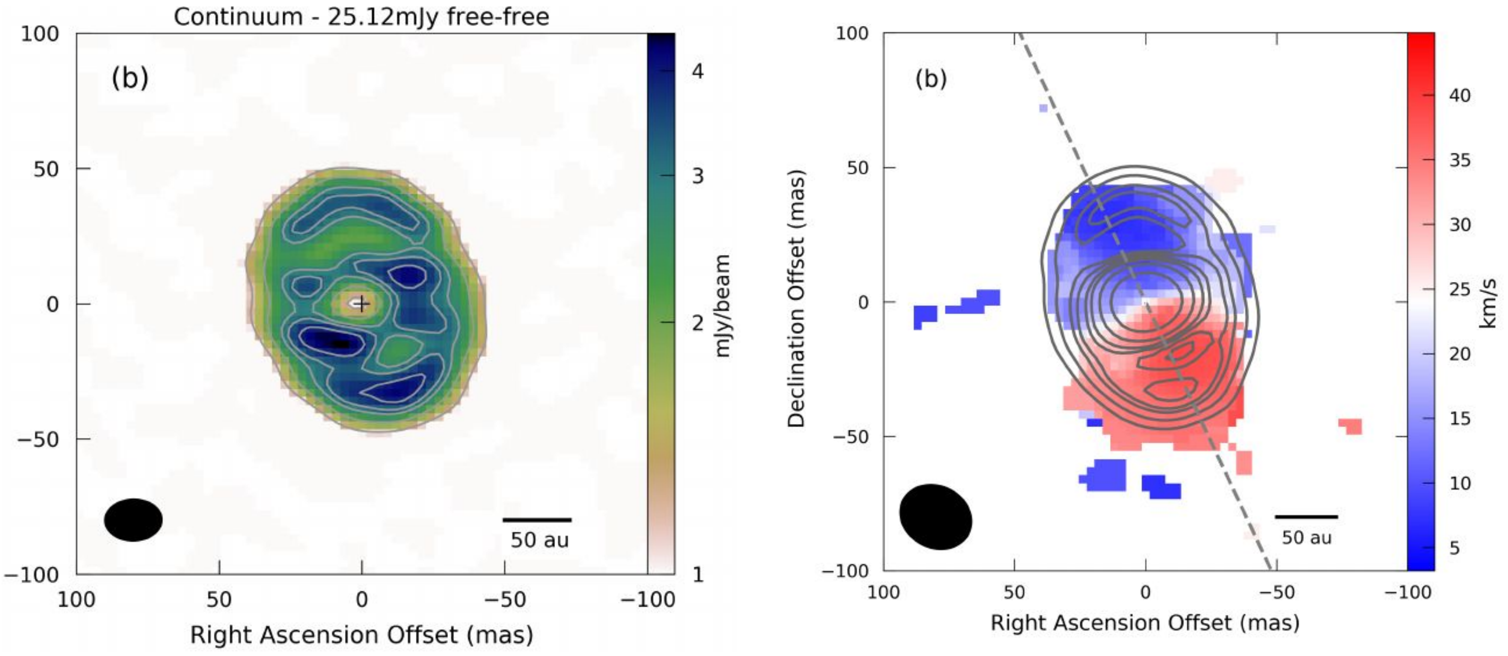


Photosphere of the disk ✓

Foreground slab ✗

1. (Hot) absorption lines are ubiquitously observed in hot cores (ISO studies);
   - Slab model: (1) smaller than the continuum (2) must be aligned along the l.o.s.
2. T_{gas} temperature is always comparable with, but slightly less than than $T_{continuum}$
3. For transitions of HCN (and C_2H_2), the derived abundance at 7 μm is 10x higher than those at 13 μm (Barr et al. 2020).
   - Problem: originating from the same ground level
   - Possibility: a dilution effect at 13 μm

Hot Absorbing Gas: Blob(s) on the Disk?



- ALMA observations of AFGL 2136 (Maud et al. 2019)
- Dust disk resolved in submm
- The Keplerian kinematics are seen in the vibrationally excited water line (E_l > 3000 K)

Efforts In Submm/mm Observations To Reveal Keplerian Disks

Table 5.1: Detection of Keplerian Disks in MYSOs

(Li 2023, thesis)

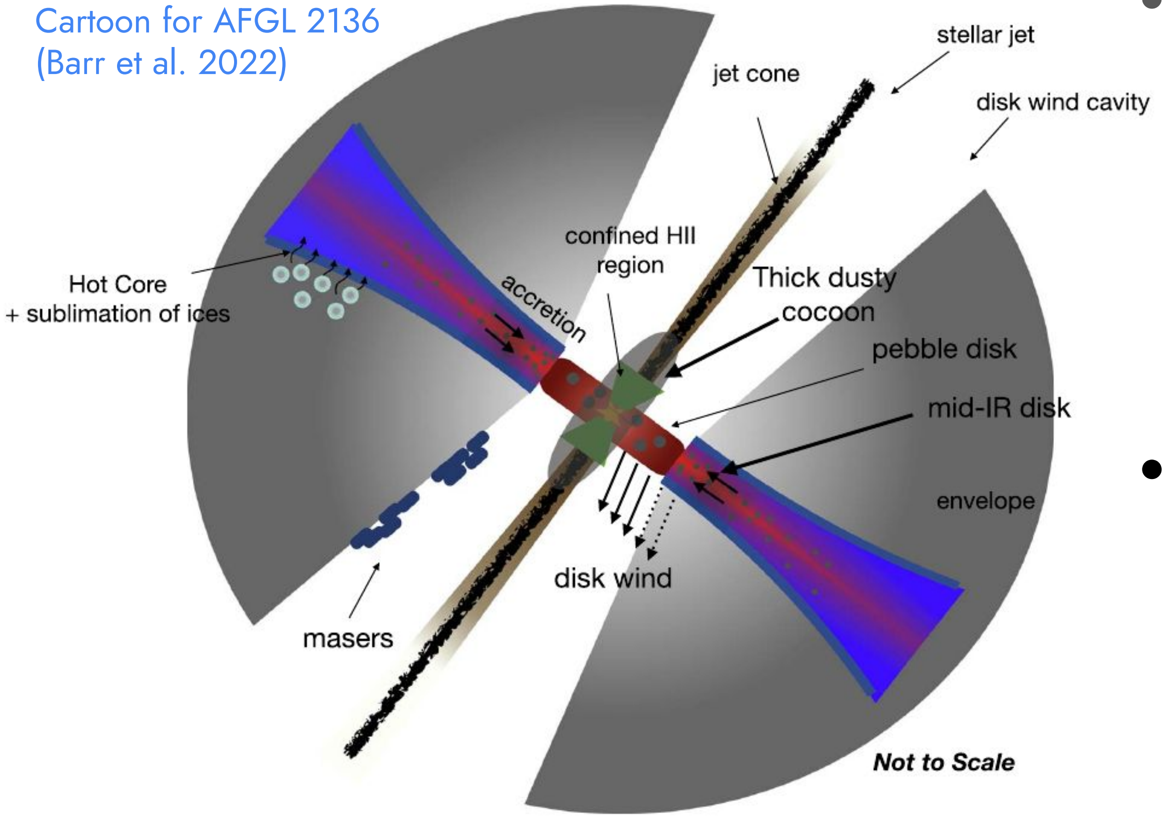
MYSO	d (kpc)	Disk	Tracers	E_u (K)	Disk Scale (AU)	Beam Size (AU×AU)	Ref
AFGL 2136	2.2	Y	H_2O $5_{5,0} - 6_{4,3}$ $\nu_2 = 1$	3462	<50	44×33	(1)
AFGL 2591	3.3	Y	HCN J = 4–3 ν_2 = 1	1067	<1000	627×561	(2)
AFGL 4176	4.2	Y	CH_3CN	80–900	4000	1176×1008	(3)(4)
NGC 7538 IRS1	2.7	Y	CH_3OH masers	...	500	27×14	(5)
W3 IRS5	1.8	?	HCN J = 4–3 ν_2 = 1	1067		500–1000?	(SMA in prep.)

Notes: (1): Maud et al. 2019; (2): Suri et al. 2021; (3–4): Johnston et al. 2015, 2020; (5) Moscadelli & Goddi 2014.

- Surrounding massive protostars from sub-100 to sub-1000 AU
- Thorough case studies of different hot cores are still needed
- *Direct MIR interferometer imaging??*

Disk Model For Hot Absorbing Gas

Cartoon for AFGL 2136
(Barr et al. 2022)



- Absorption lines require an internally heated disk:
  - T Tauri or Herbig stars, emission lines: radiation heated disks
  - The "flashlight effect" may allow the disk to be not externally heated
- Accretion rate needed for 40 $M_\odot$ star to heat disk to 600 K at 125 AU is ~1$M_\odot$/yr (gravitational dissipation).
  - Orders of magnitude more than reasonable (~10^{-3} $M_\odot$/yr)
  - Heating sources other than viscosity?

W3 IRS 5: A High Water Abundance in the Hot Gas

Table 5
Comparison of H_2O Characteristics Derived from ISO-SWS and SOFIA-EXES Observations

Properties	ISO-SWS[a]	SOFIA-EXES	
		H1 (Slab)	H1 (Disk)
$T_{ex}(H_2O)$ (K)	400^{+200}_{-150}	471^{+14}_{-15}	491^{+13}_{-14}
$N(H_2O)$ (cm^{-2})	$3^{+1}_{-1} \times 10^{17}$	$2.5^{+0.3}_{-0.2} \times 10^{19}$	$3.6 \pm 1.2 \times 10^{19}$
$X[H_2O]/X[CO]$	0.05	$1.1^{+0.4}_{-0.4}$	1.5 ± 0.5

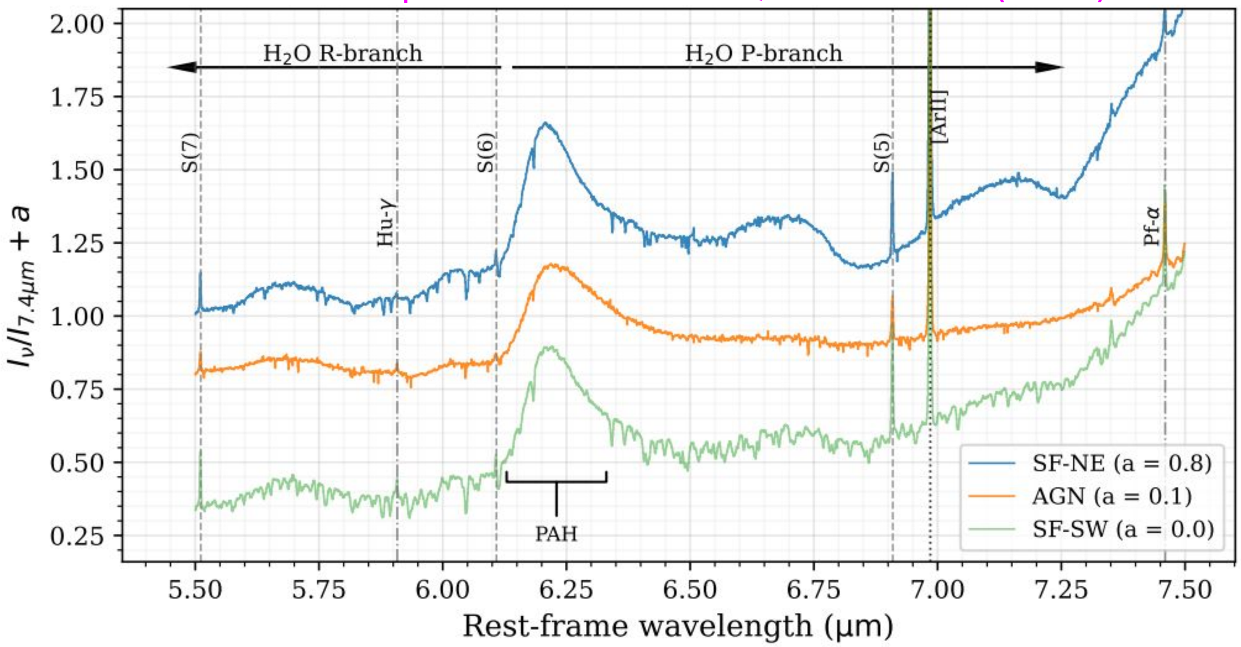
<< or

Note.
[a] Boonman & van Dishoeck (2003).

Low spectral resolution ISO-SWS spectrum (*R*~1500):
- Good estimate for T (~500 K)
- Underestimated N by a factor of ~100 (from $10^{17} \rightarrow 10^{19}$ cm^{-2})

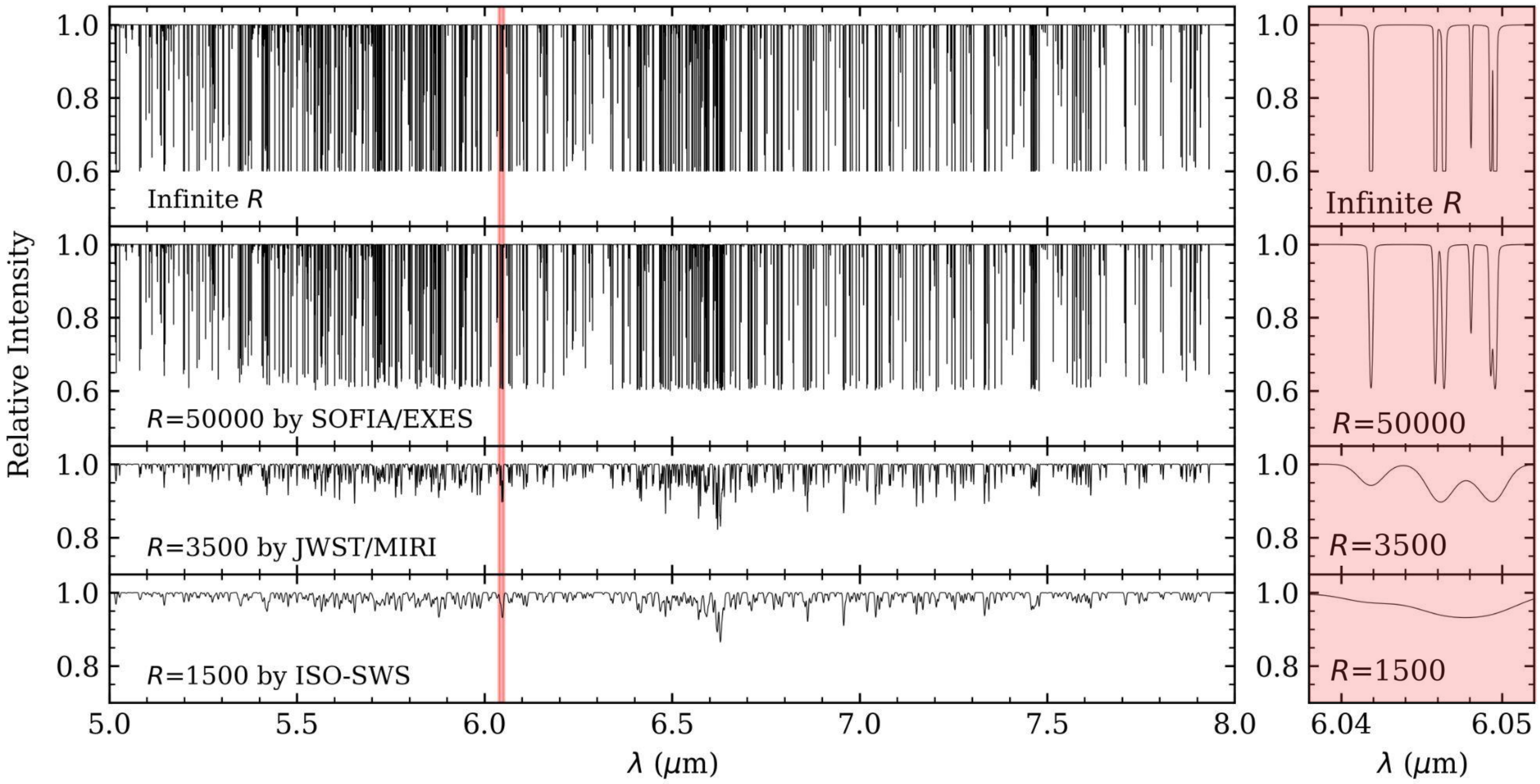
Procedure to Analyze Low Resolution Data

Water absorption lines in VV 114, Buiten et al. (2023)



- JWST will do moderate spectral resolution spectroscopy with *R*~3500
- What is the best way to analyze that?

Information Lost in Moderate Spectral Resolution



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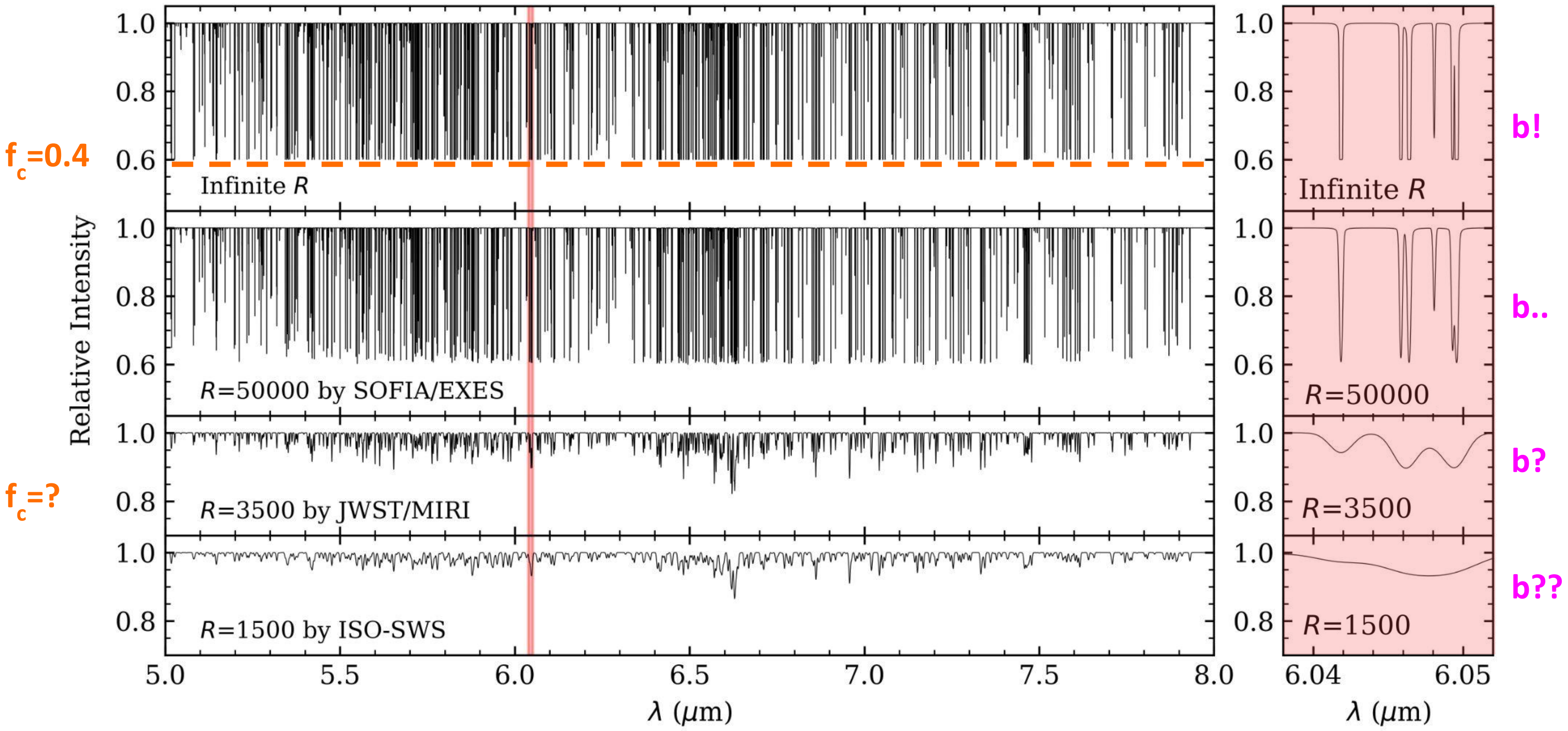

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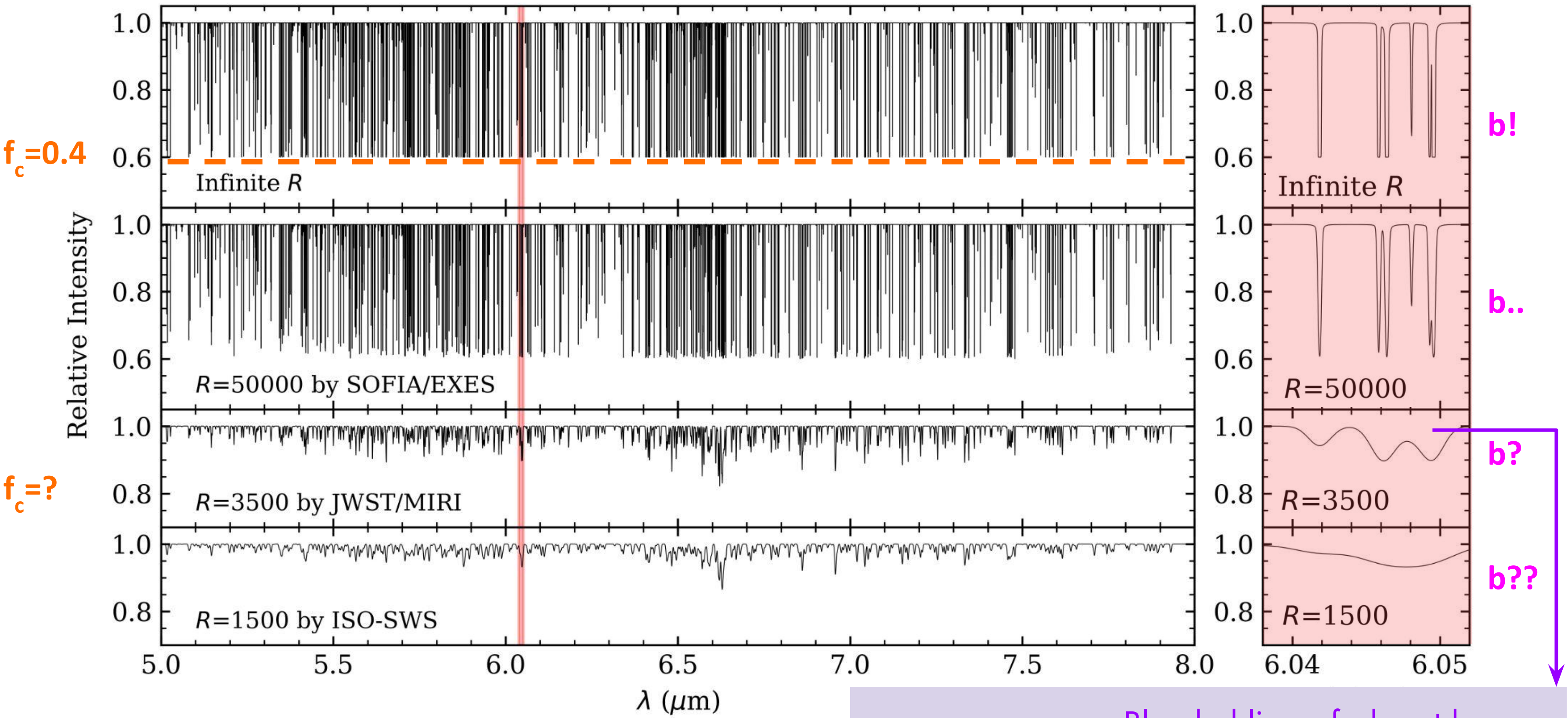
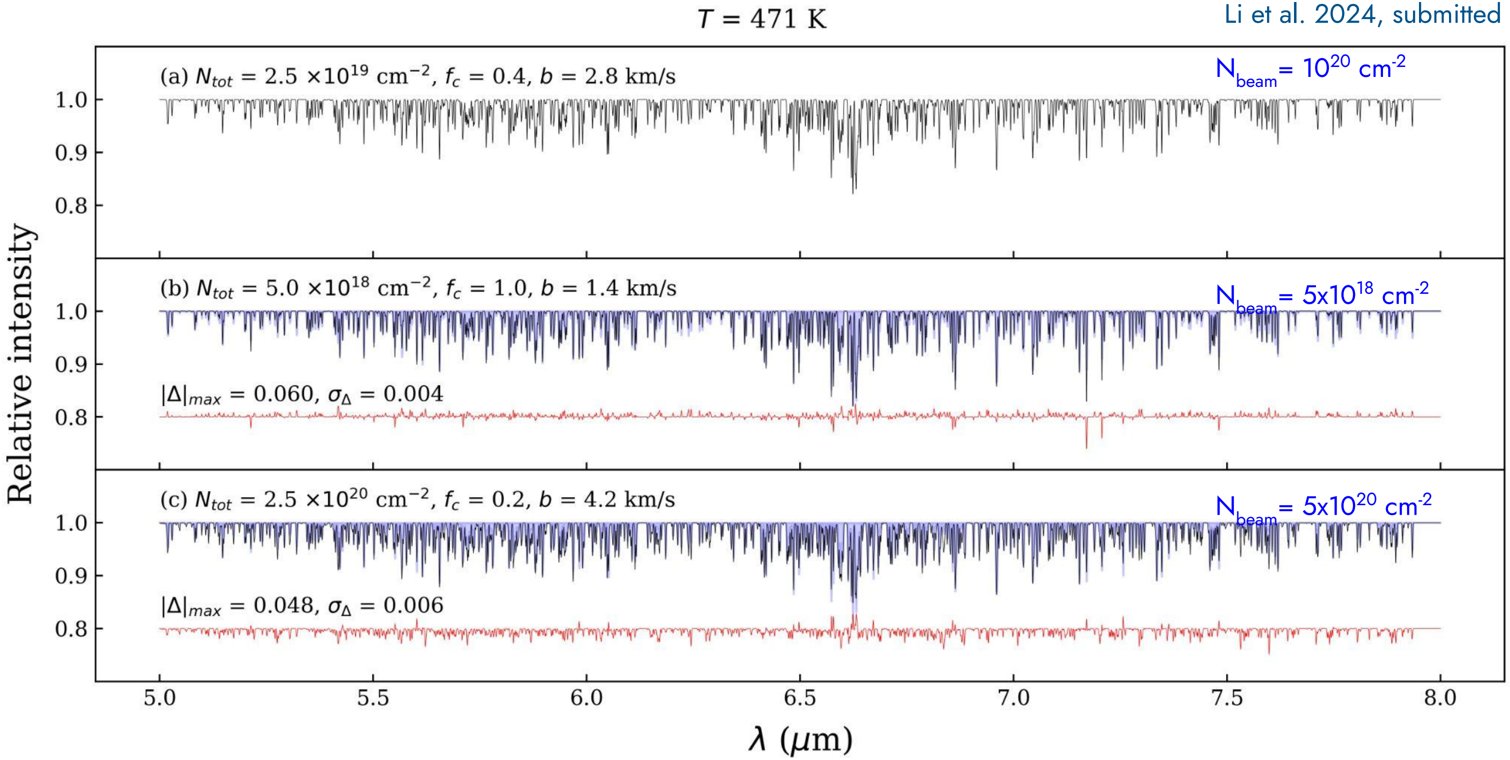


Blended lines: f_c, b not known;
but the same f_c×b →overlapping curve of growth

“Indistinguishable” Spectra with Different Parameter Sets

Li et al. 2024, submitted

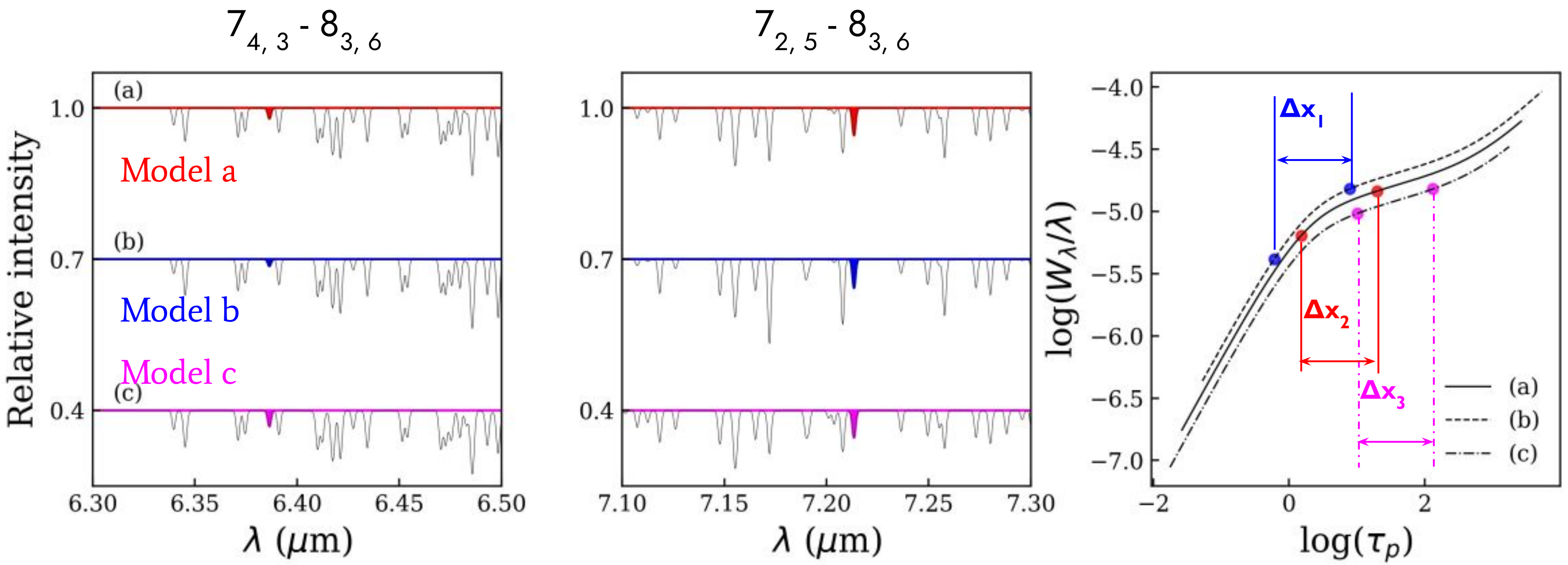


Thin lines reflects N, but thin lines are ignored

→wrong estimation!

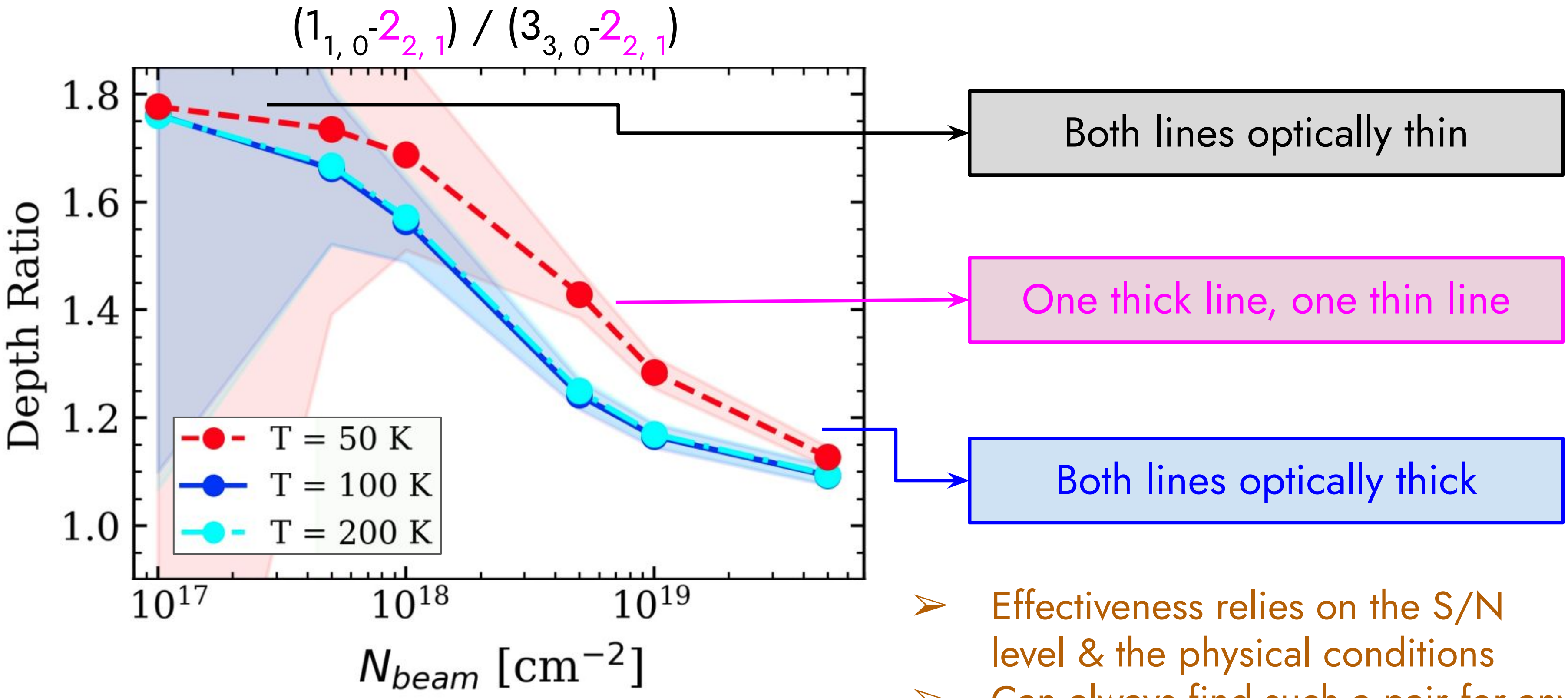
Be careful when applying a χ^2 fitting (which prefers thick lines)!

Further Constraints From Specific & Isolated Line Pairs



- Lines that share <u>the same lower energy level</u> have the same $N_{\text{lower level}}$:
  - $\tau_{peak} \propto N_{\text{lower level}}$, so $\Delta\log(\tau_{peak})$ is a constant
  - EW of thick lines ~ constant; EW of thin lines varies
- Such line pairs can therefore be used to measure the opacity of lines

Ratio of Line Pairs As An Indicator of Physical Conditions



- ➢ Effectiveness relies on the S/N level & the physical conditions
- ➢ Can always find such a pair for any physical conditions

Online Absorption Spectrum Generator

Mid-infrared Ro-vibrational Absorption Spectrum Generator

Slab Model | Photosphere Model

This program generates absorption spectra under a slab model, which assumes that:

- the absorbing gas is located in front of, and may partially cover the background mid-infrared (MIR) continuum;
- the absorbing gas is isothermal and dust-free.

You may generate such an absorption spectrum under your desired physical parameters listed below. Three spectral resolutions are provided according to that of JWST/MIRI (3,500), SOFIA/EXES (50,000), and IRTF/iSHELL (88,000). At this moment, only the ν_2 band of water from 5 to 8 μm is available. More bands will be incorporated into this program in the future.

Please refer to Li et al. (2024) (Section 2) for details of this spectrum generator.

Molecule: H_2O Band: ν_2

Spectral resolution, R ⓘ : 3500

Excitation temperature, T_{ex} ⓘ : 500 K

Column density, N_{tot}: 1e+19 cm^{-2}

Fractional coverage, f_c ⓘ : 0.5

Line width, b ⓘ : 2.0 $km\ s^{-1}$

Velocity shift, Δv ⓘ : 0.0 $km\ s^{-1}$

Generate Spectrum

mirasg.astro.umd.edu

Generate your own spectrum for comparison!

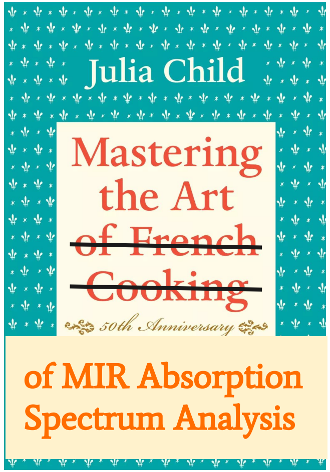
Summary

- High spectral resolution spectroscopy at MIR is an unique tool to probe gas-phase molecules in the innermost region of the embedded massive protostars;

- The hundreds of individually resolved spectral lines can provide precise constraints on the temperature and the column density under appropriate analysis:
  - Different velocity components are linked to different physical origins
  - The property of the same component can be linked from different molecular lines

- The absorption lines seen in MIR trace internally heated circumstellar disks;
  - This could be a common characteristic for hot cores around massive stars
  - Perhaps, this is also true for the earliest phases of hot corinos.

- Moderate spectral resolution spectroscopy have issues:
  - Degeneracy among parameters exists
  - This issue can be solved by pairs of isolated lines that share the same lower energy state



(Li et al. submitted)