High resolution infrared observations towards late-type stars – Opportunities and Challenges

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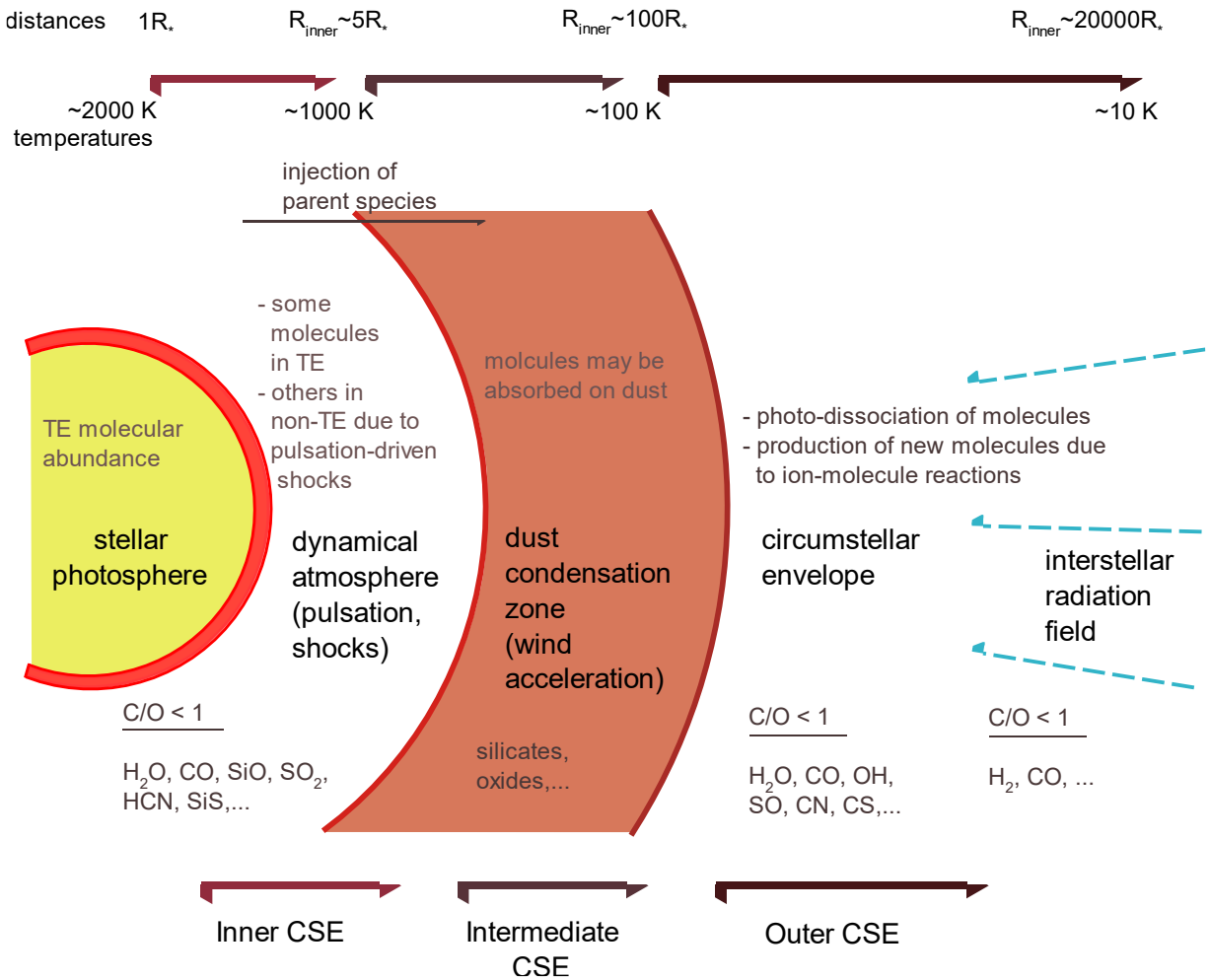
"Future Astronomical Opportunities in Stratosphere and Space"

Thursday afternoon session (17:50 – 18:10)
September 19, 2019; room 47.05

Motivation

- Late-type stars, e.g. M-type: o-ceti (Mira), VY Canis Majoris
- Understand molecular content of envelopes ⟶ first step of chemical evolution & dust formation
- Some molecules only in IR, e.g. CO_2



CO_2 IR emission bands towards AGB stars

- CO_2 studies by K. Justtanont et al. (1998), A&A, 330, L17 using ISO/SWS
- Strong correlation between 13 µm dust feature and emission bands
- Other candidates for emission features:
  - Al_2O_3 (Onaka et al. 1989)
  - Mg silicate (Begemann et al. 1997)
  - Al oxide core coated by silicate (Kozasa & Sogawa 1997)

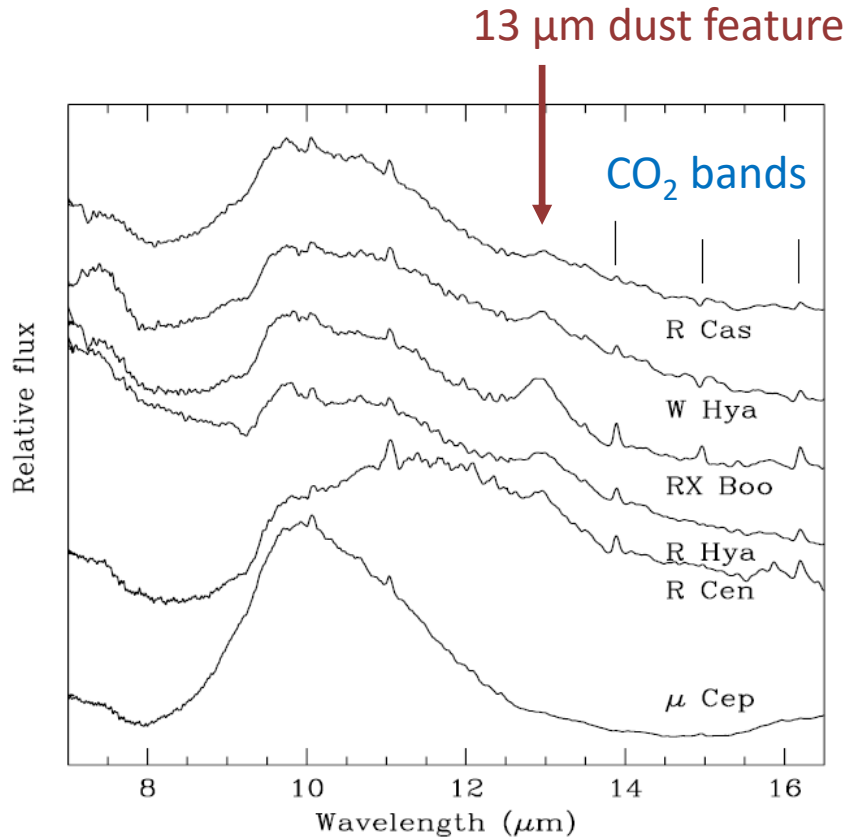


Table 1. Stars observed at full-grating resolution.

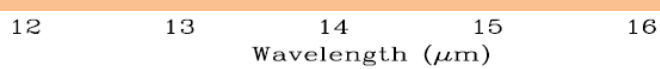
Object	Sp class	P (days)	v_e (km s^{-1})	D (pc)	f
R Hya	M	388	7.5	130	0.50
W Hya	SRa	361	9.7	100	0.43
R Cen	M	546	7.0	376	0.54
RX Boo	SRb	340	11.5	225	0.46
R Cas	M	430	11.0	216	0.48
EP Aqr	SRb	-	11.0	250	-

CO_2 identification: high resolution

Result:

- Stars with low mass loss rates:
  CO_2 bands expected to be in emission.

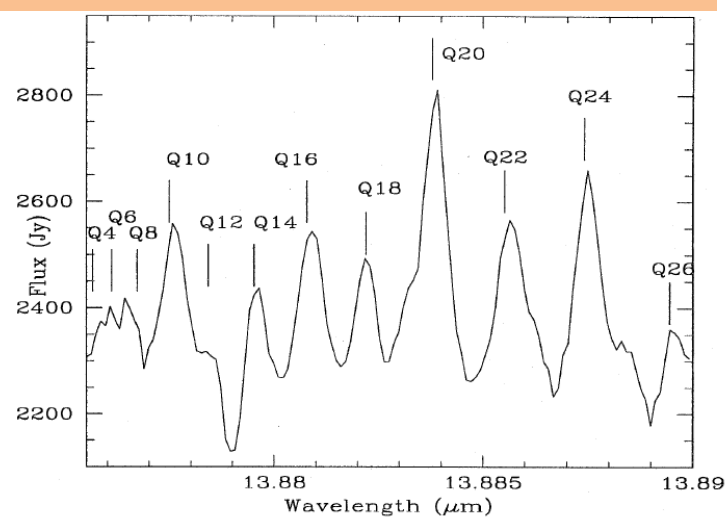
- High mass loss rate ($\gtrsim 10^{-5}\ M_\odot\ yr^{-1}$) ⇒ absorption



[1] Justtanont et al. (1998), A&A, 330, L17

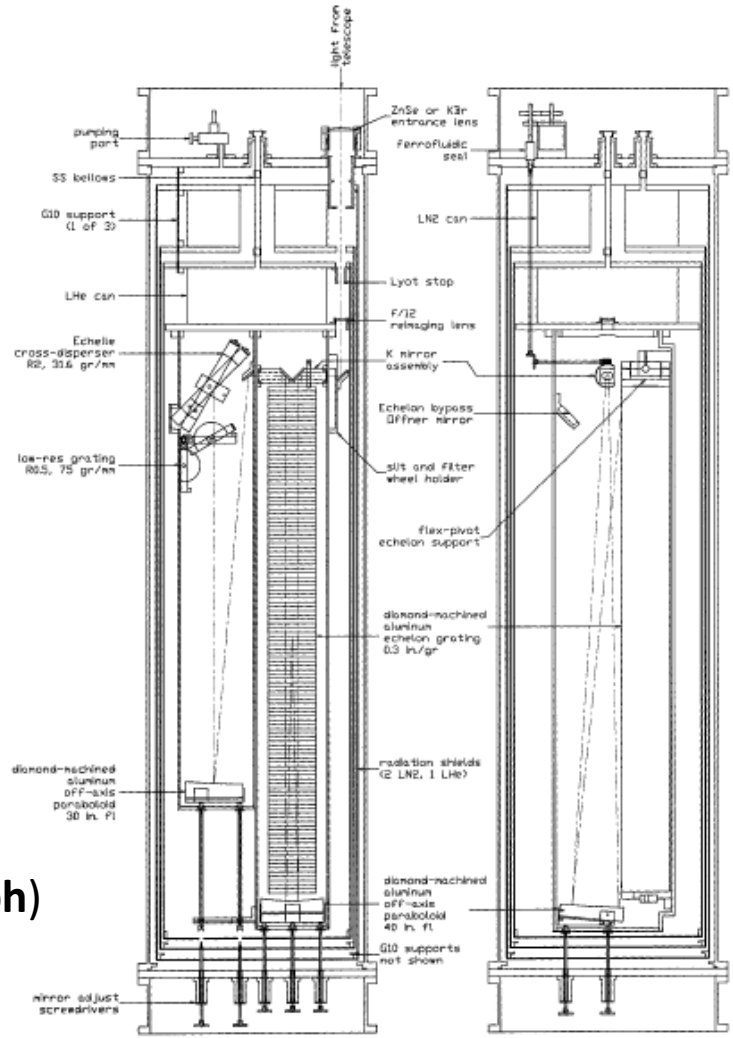
High-resolution (R = 1500) ISO/SWS data on W Hya,
Q-branch transitions of the $10^00\ \Sigma_g^+$ - $01^10\ \Pi_u$ band,

Warm layer of molcular gas in AgB star:
CO_2 excitation temperature ~ 650K



Own studies: TEXES instrument on IRTF

3-meter telescope



TEXES (**Texas Echelon Cross Echelle Spectrograph**)
4.5 – 25 µm wavelength region
R ≈ 50,000 – 100,000

Lacy et al. (2002), PASP, 114, 153

o-ceti A (Mira)

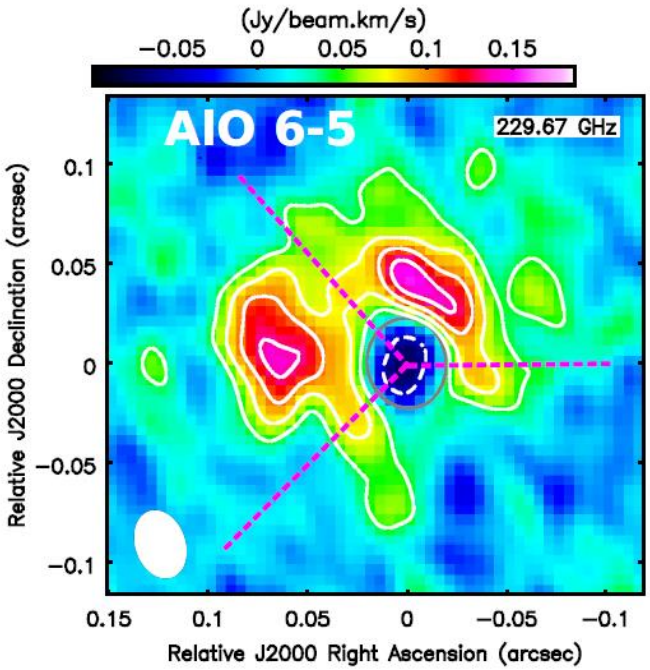
- Pulsating variable star
  (d = 90 – 100 pc)
  T ≈ 332 days ($\Delta m_v \approx 3$)

- Binary stellar system (r. giant + w. dwarf)
  A) M=1.2 $M_\odot$, R ≈ 330 - 400 $R_\odot$,
  L ≈ 8 400 – 9400 $L_\odot$, age ≈ 6 Gyr

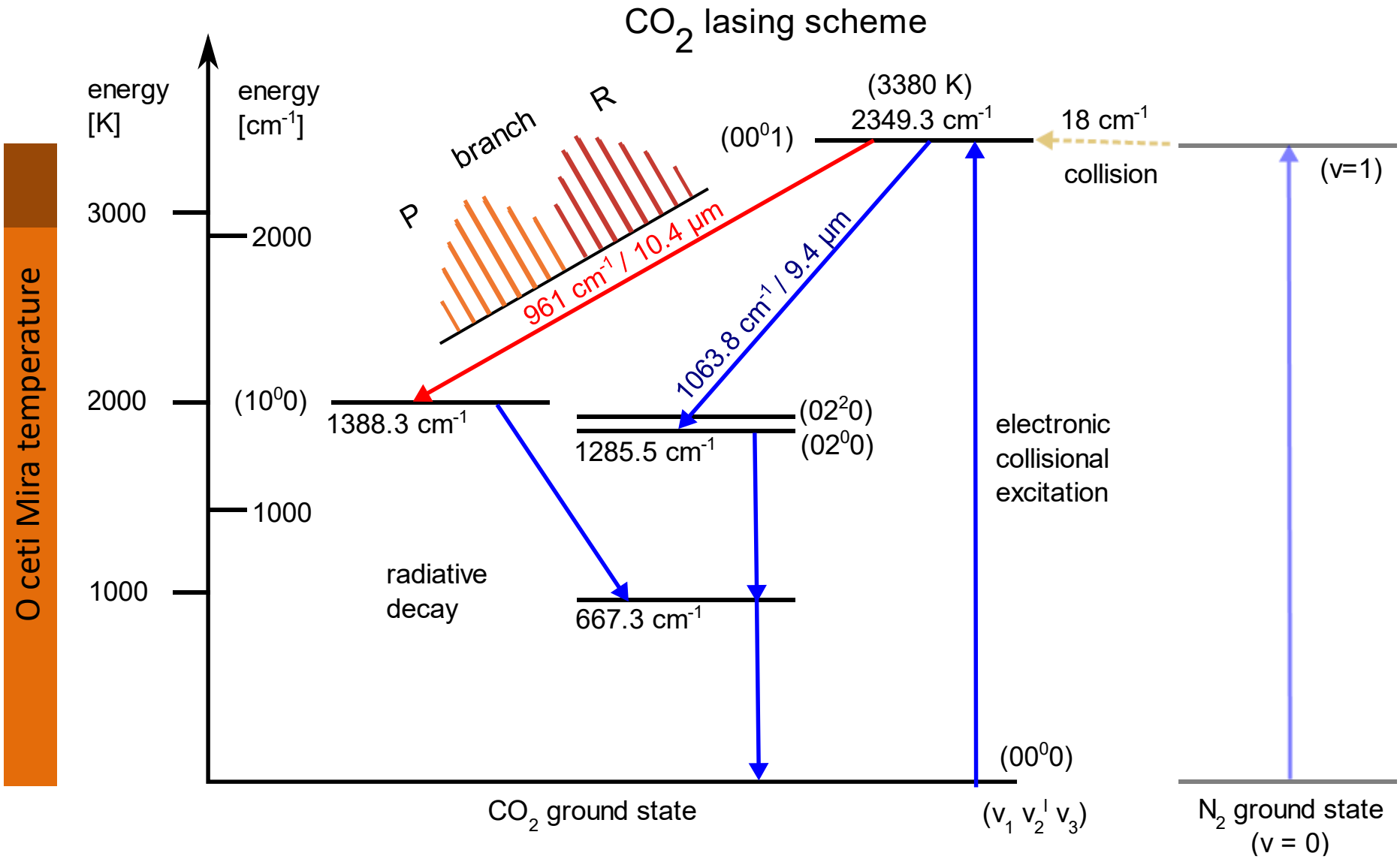
- Spect. type: M5 – M9 (T ≈ 2900-3200 K)

- AlH, AlO, AlOH, CO, ^{13}CO , HCN, H_2O, NH_3, OH, SiO, ^{29}SiO, TiO
  (list not comprehensive)

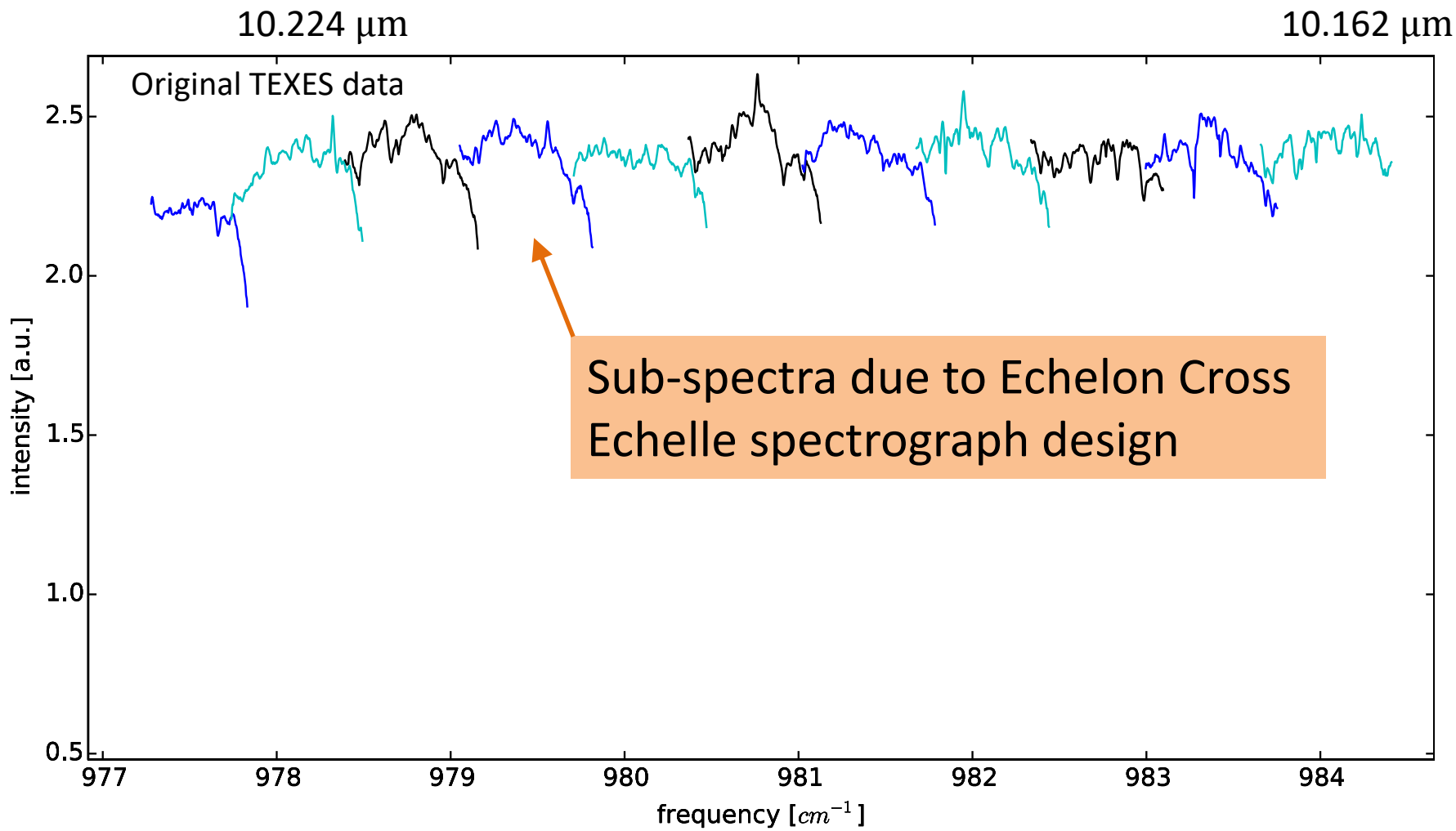
- mass-loss ≈ $2 \cdot 10^{-7}\ M_\odot\ yr^{-1}$ ⇒ CO_2 in emission



[Kaminski et al. 2016, AA, 592, A42]

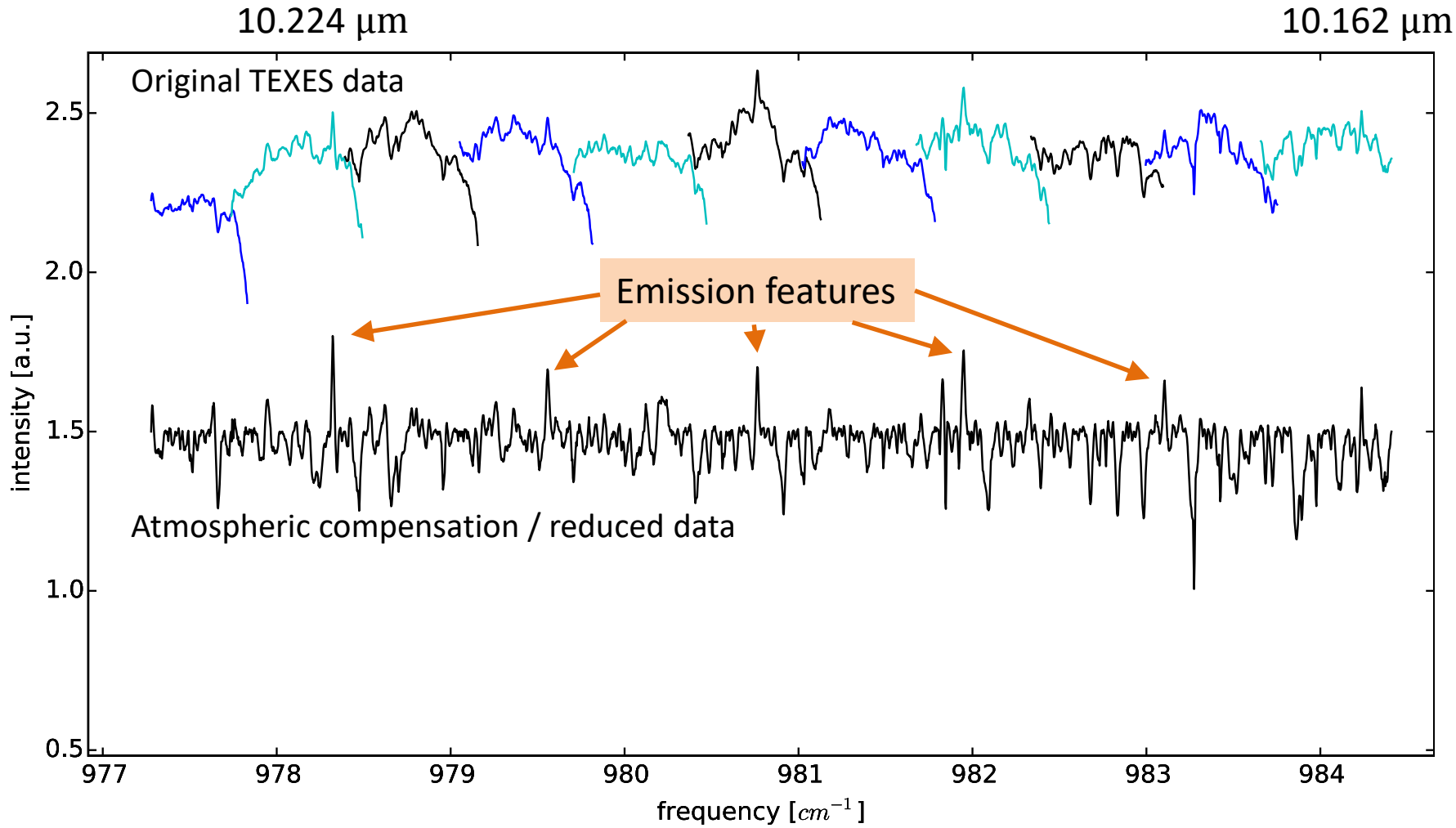

CO2 lasing scheme
energy [K]
energy [cm-1]
3000
2000
2000
1000
1000
O ceti Mira temperature
P
branch
R
961 cm-1 / 10.4 µm
1063.8 cm-1 / 9.4 µm
(00^01)
(3380 K)
2349.3 cm-1
18 cm-1
collision
(v=1)
(10^00)
1388.3 cm-1
(02^20)
(02^00)
1285.5 cm-1
electronic
collisional
excitation
radiative
decay
667.3 cm-1
(00^00)
CO2 ground state
(v1 v2l v3)
N2 ground state
(v = 0)

o-ceti (Mira) observation

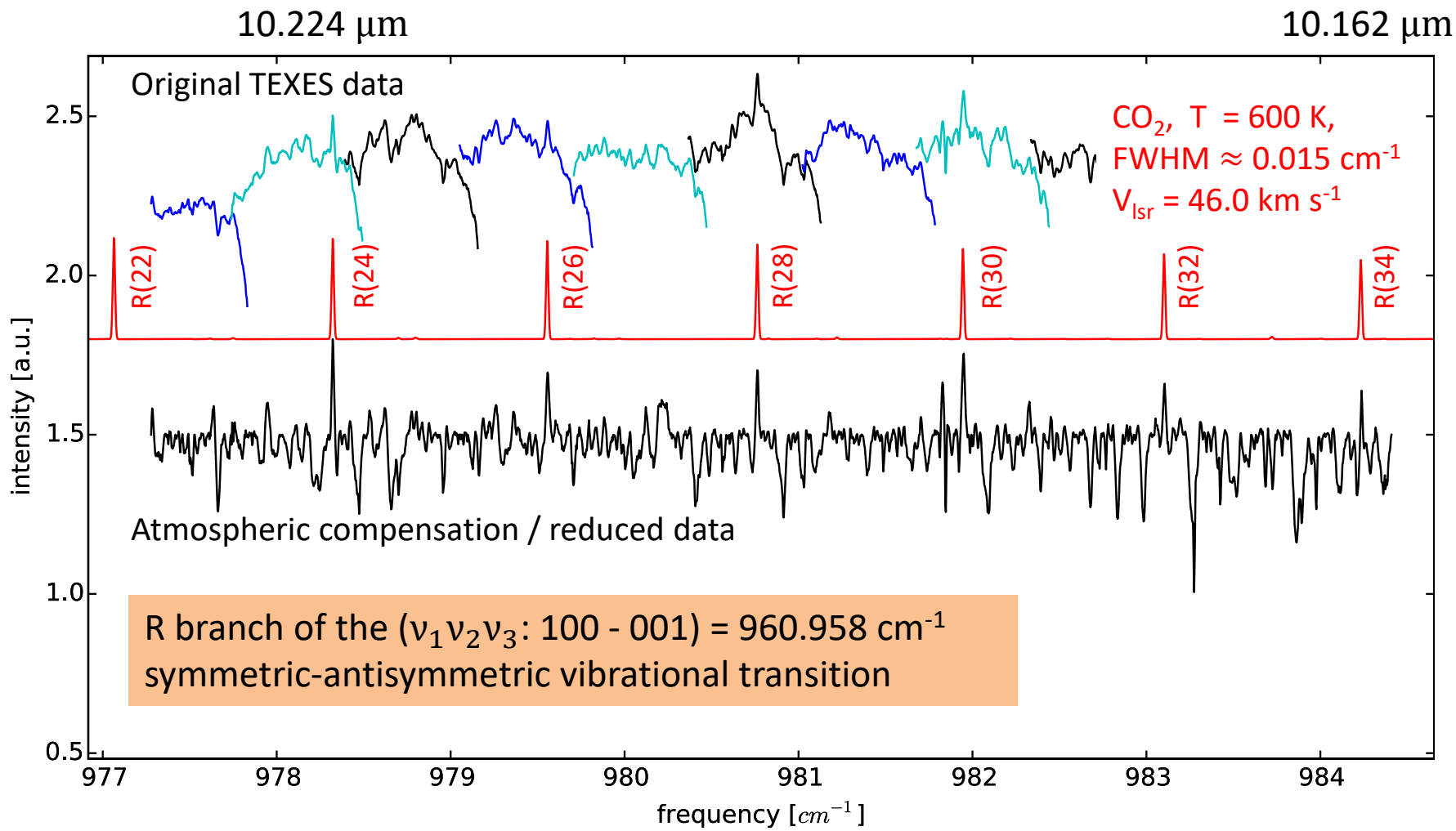


Sub-spectra due to Echelon Cross Echelle spectrograph design

o-ceti (Mira) observation

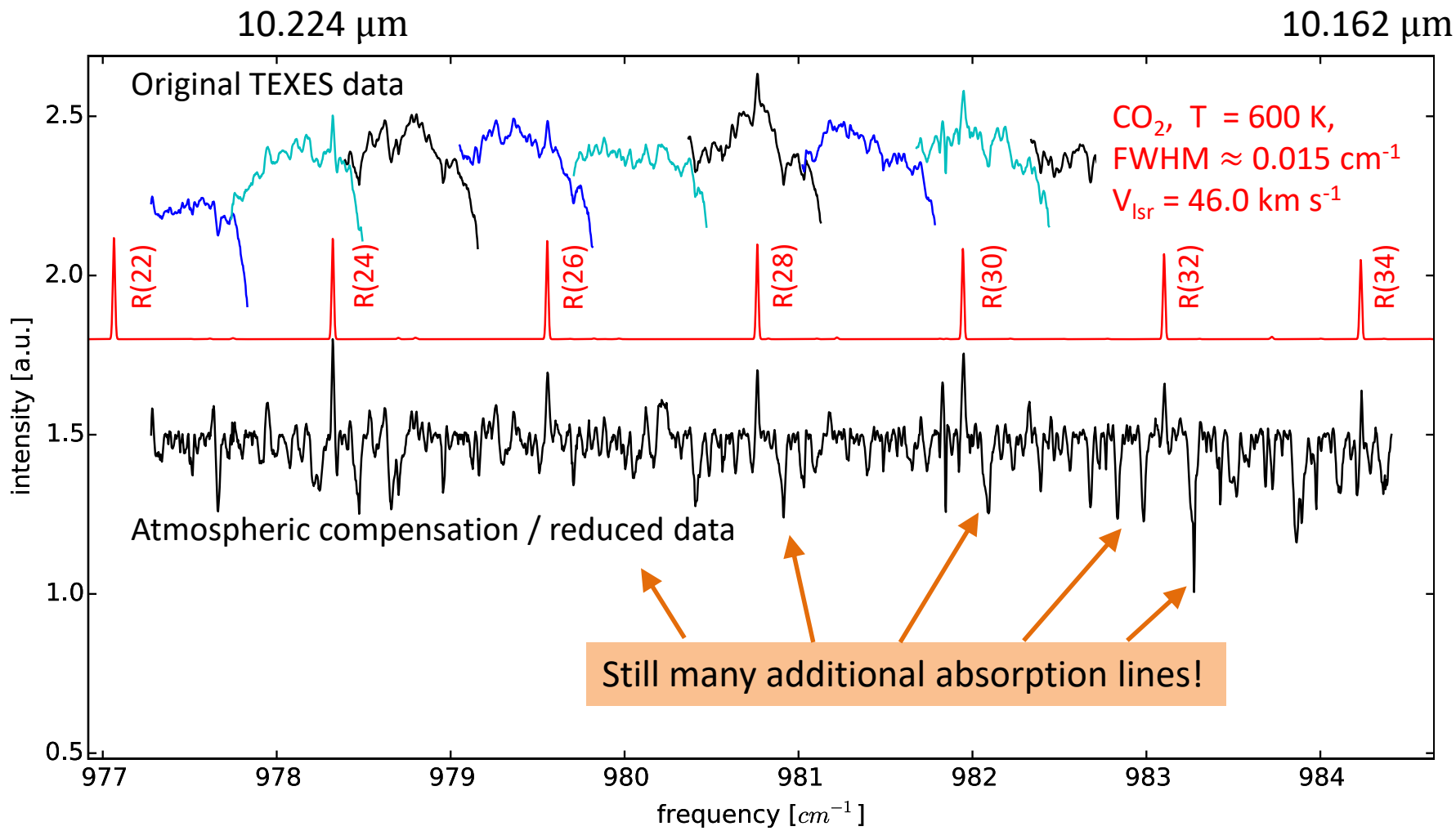


o-ceti (Mira) observation

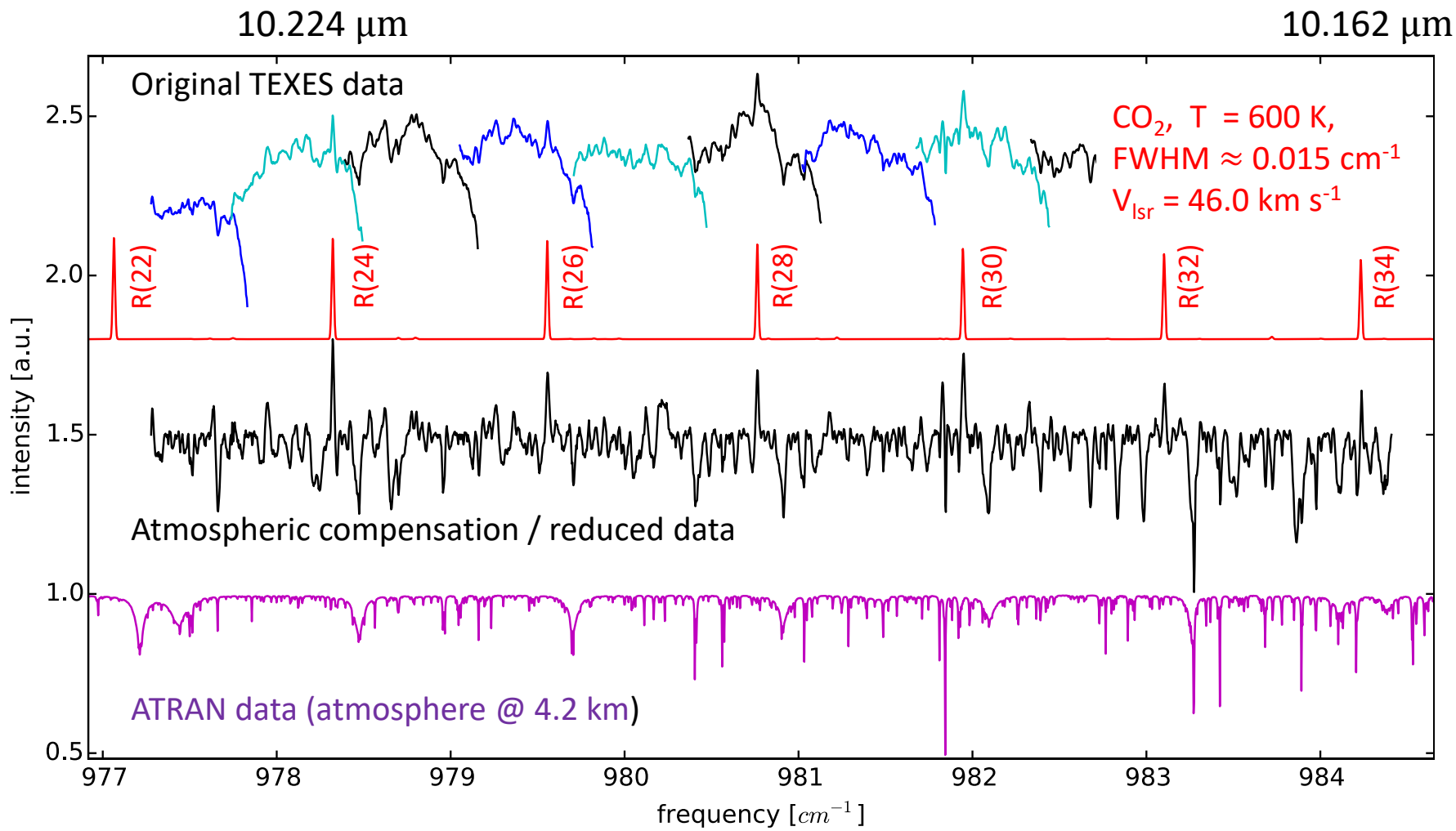


R branch of the ($\nu_1\nu_2\nu_3$: 100 - 001) = 960.958 cm^{-1}
symmetric-antisymmetric vibrational transition

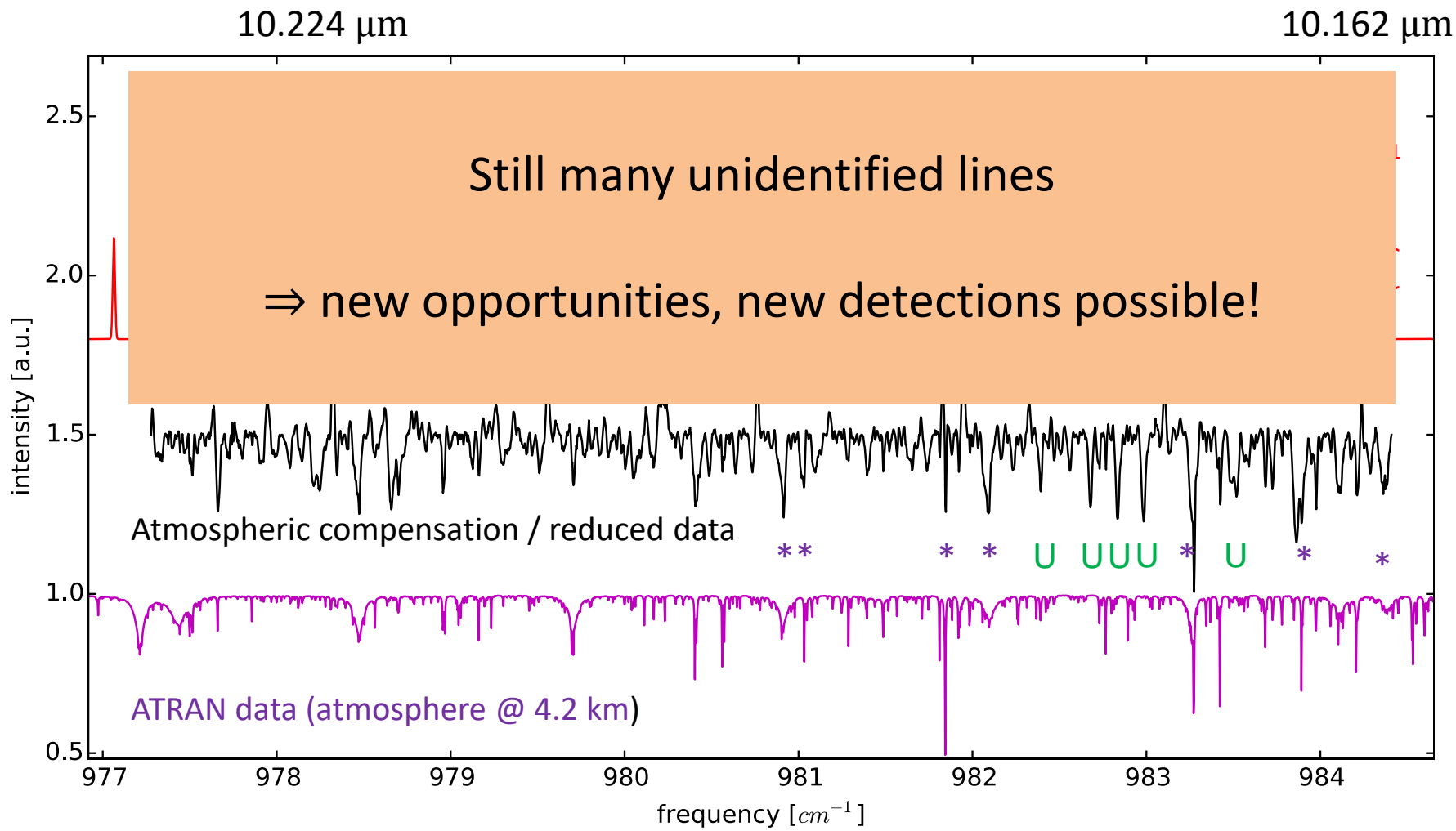
o-ceti (Mira) observation



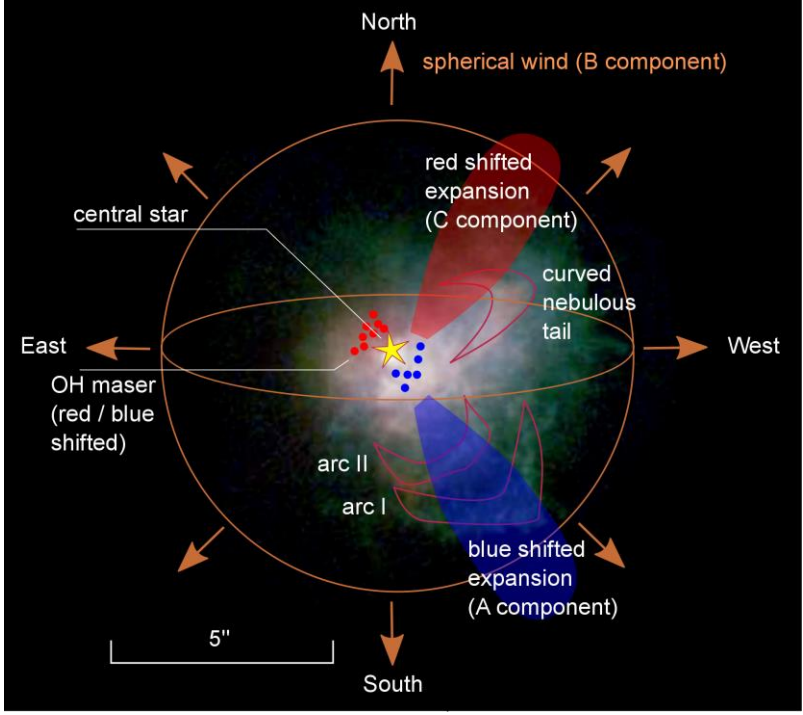
o-ceti (Mira) observation



o-ceti (Mira) observation



VY Canis majoris



- red hypergiant (RHG)
  M=17$M_\odot$, R = 1420 $R_\odot$,
  L = 270 000 $L_\odot$, d = 1200 pc
  age ≈ 8 M yr

- Spect. type: M3 II / M4 II (T≈3500 K)

- Heavy mass-loss 6×10^{-4} $M_\odot$yr^{-1} (⟶ extensive circumstellar envelope)

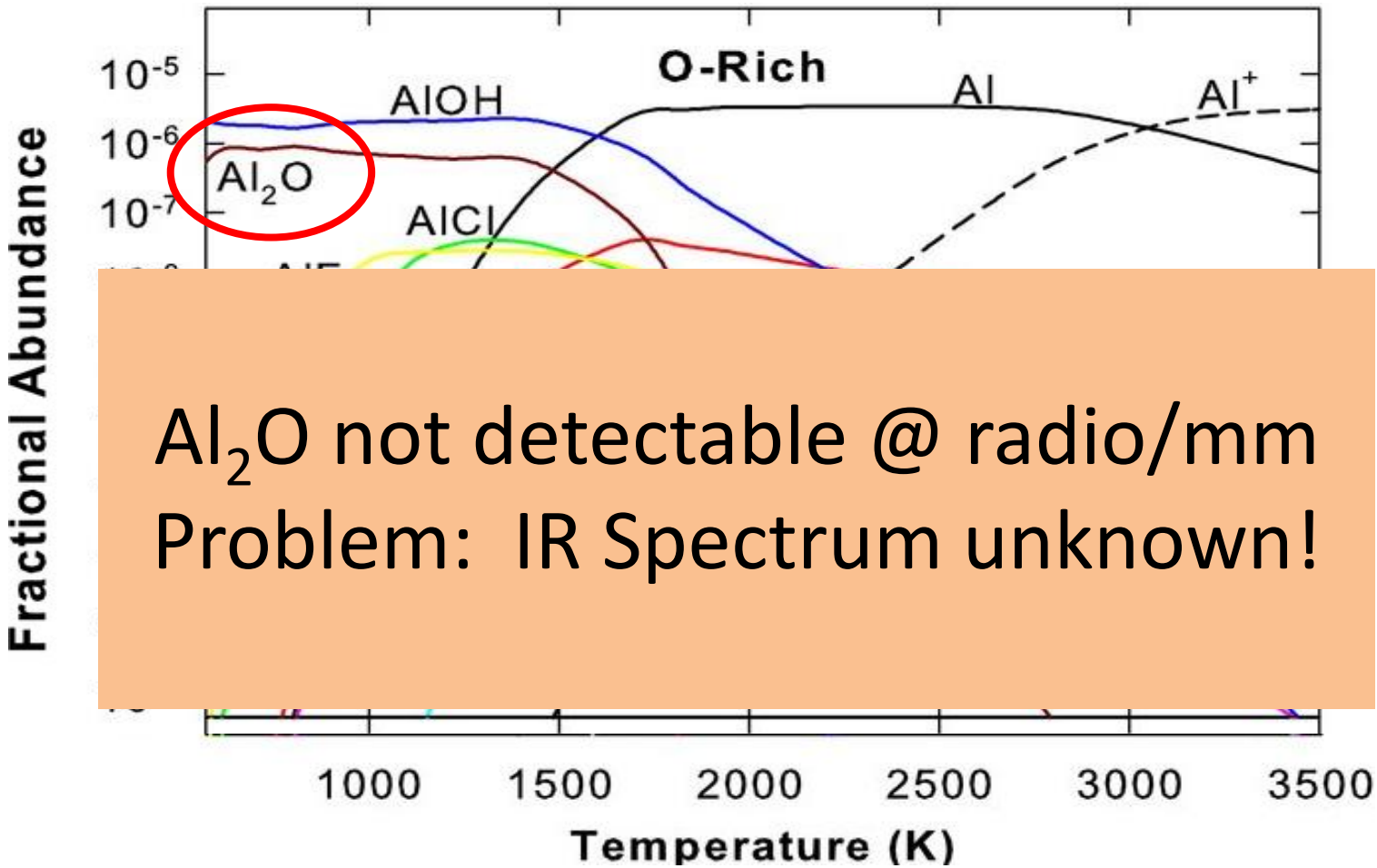
- Molecular content: 23 species + 14 isotopologue:
  AlCl , AlO, AlOH, CN, CO, ^{13}CO , CS, C^{34}S, H_2O, H_2S, HCN, H^{13}CN, HCO^+ ,HNC, HN^{13}C, NaCl, Na^{37}Cl, NH_3, NS, OH, PN, PO, SiO, ^{29}SiO, ^{30}SiO, Si^{18}O, SiS, ^{29}SiS,^{30}SiS, Si^{34}S, SO, ^{34}SO SO_2, $^{34}SO_2$, TiO, TiO_2 , $^{50}TiO_2$

SiO in VY CMa

Is there more?

We also have IR spectra of NH_3 near 960 cm^{-1} in VY Cma…

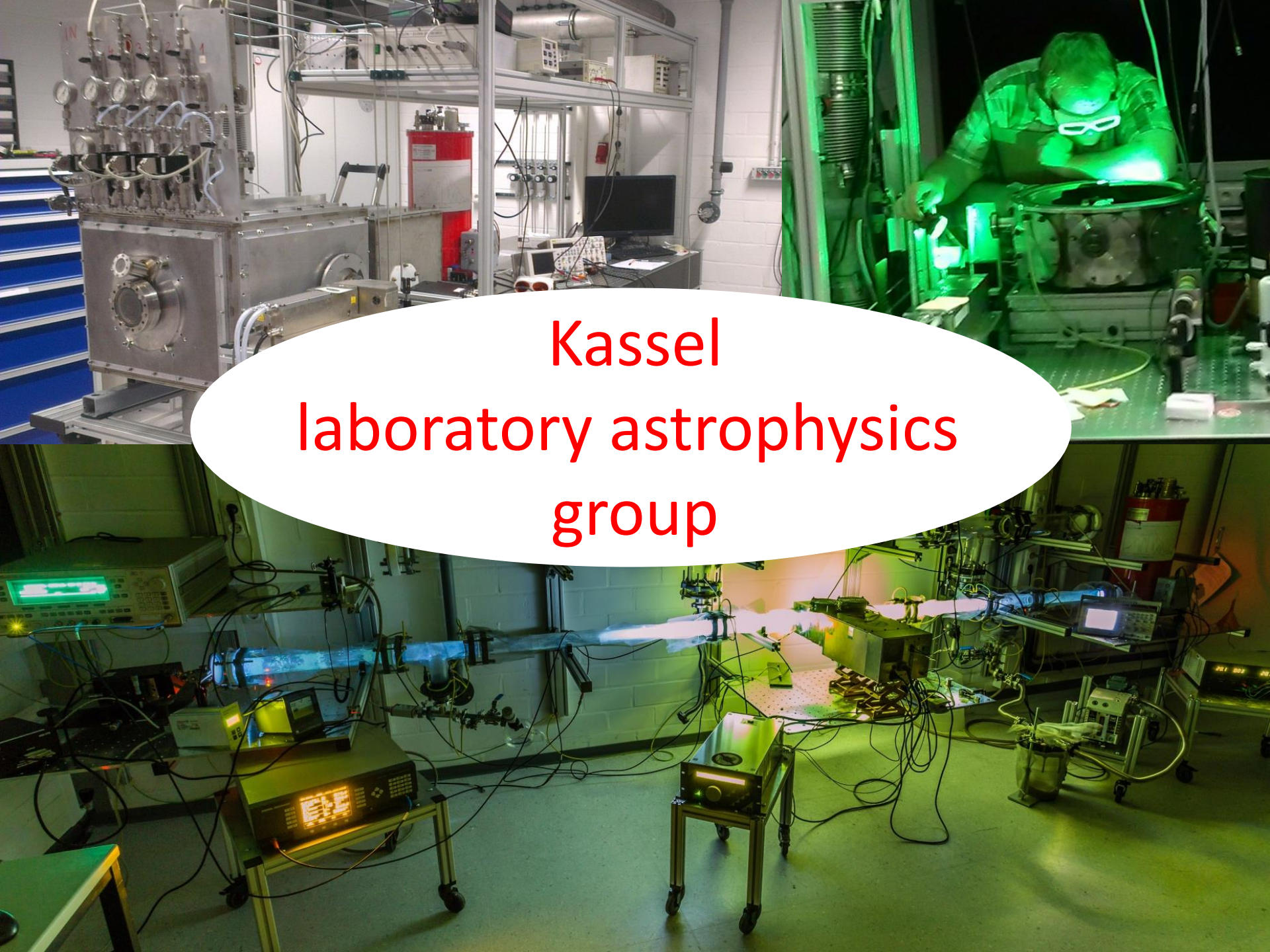
Aluminum bearing molecules in Late type Stars



Al_2O not detectable @ radio/mm
Problem: IR Spectrum unknown!

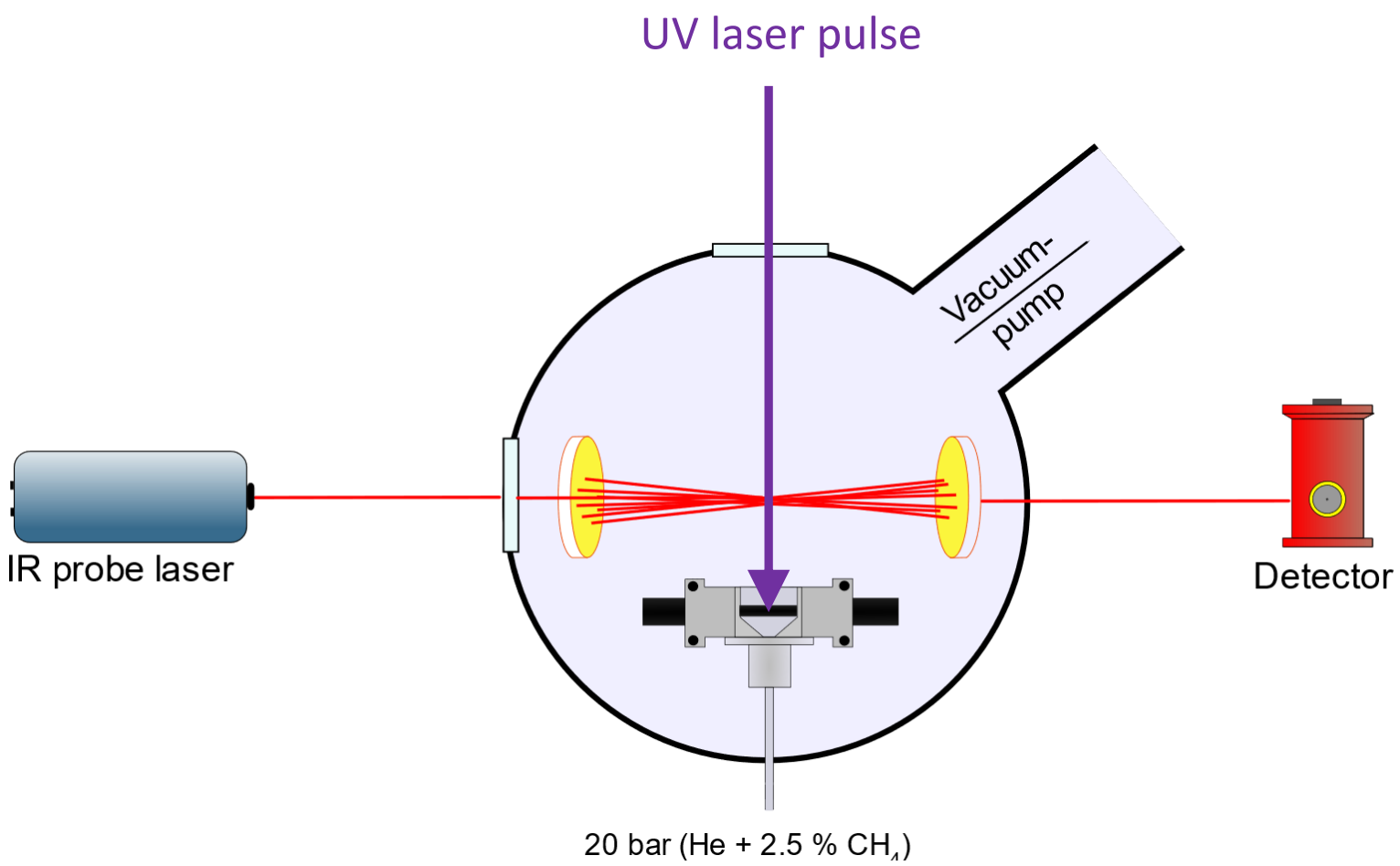
LTE- Model: The Formation of Small Aluminum Molecules

[1] E. D. Tenenbaum and L. M. Ziurys, APJ, 694, L63 (2009)



Kassel laboratory astrophysics group

CCC (Cassel Carbon Cluster) Experiment



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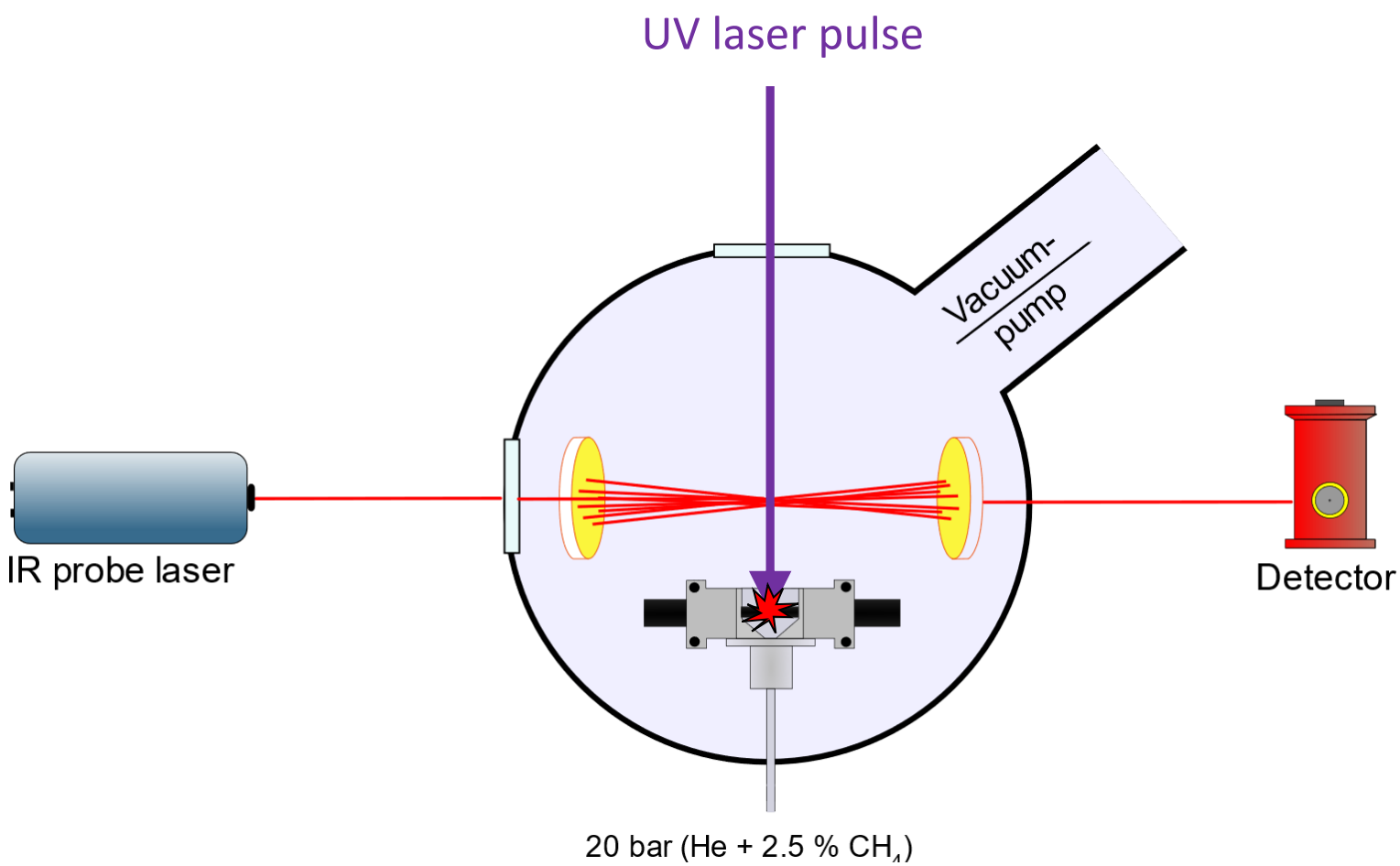

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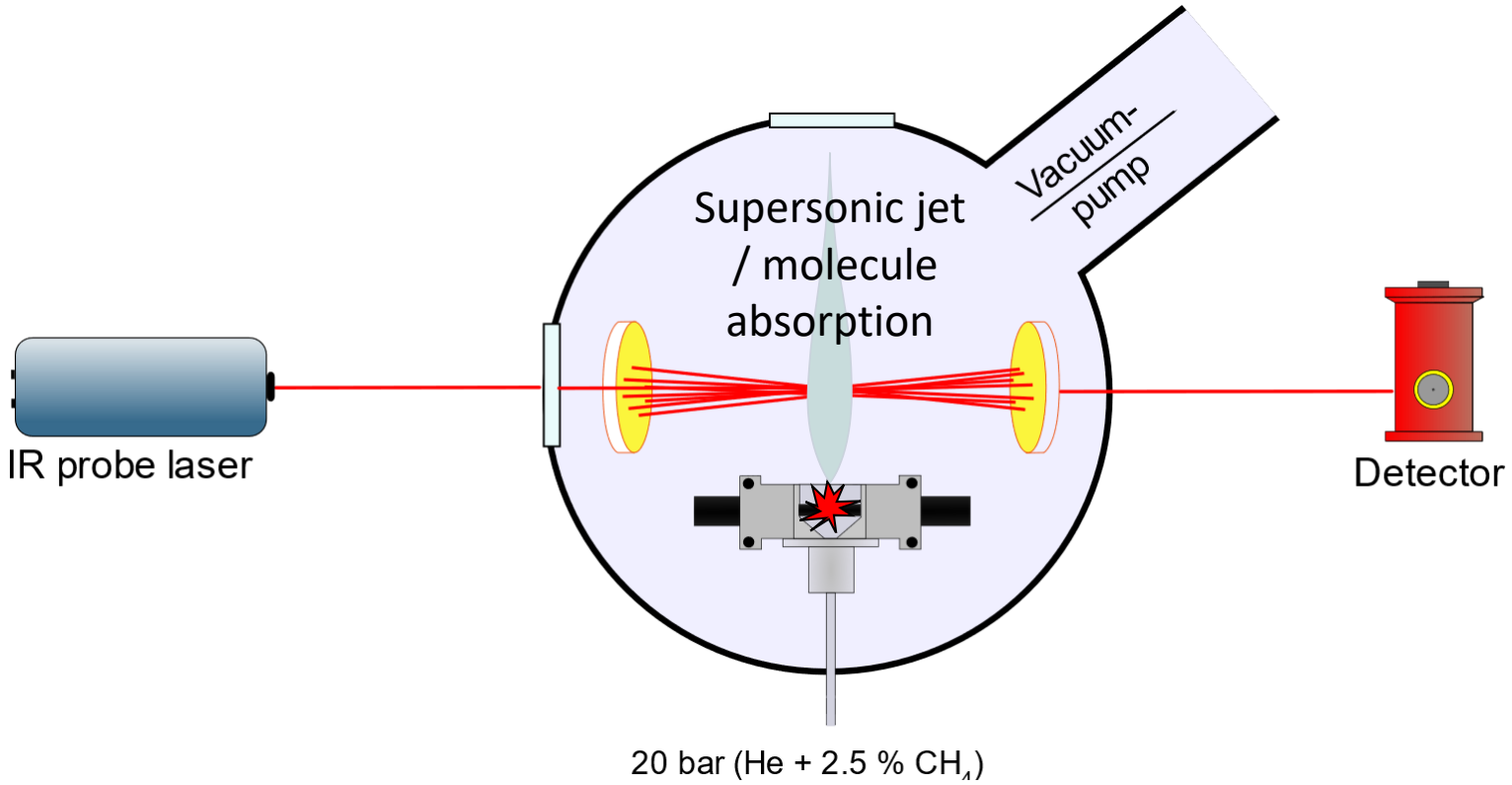
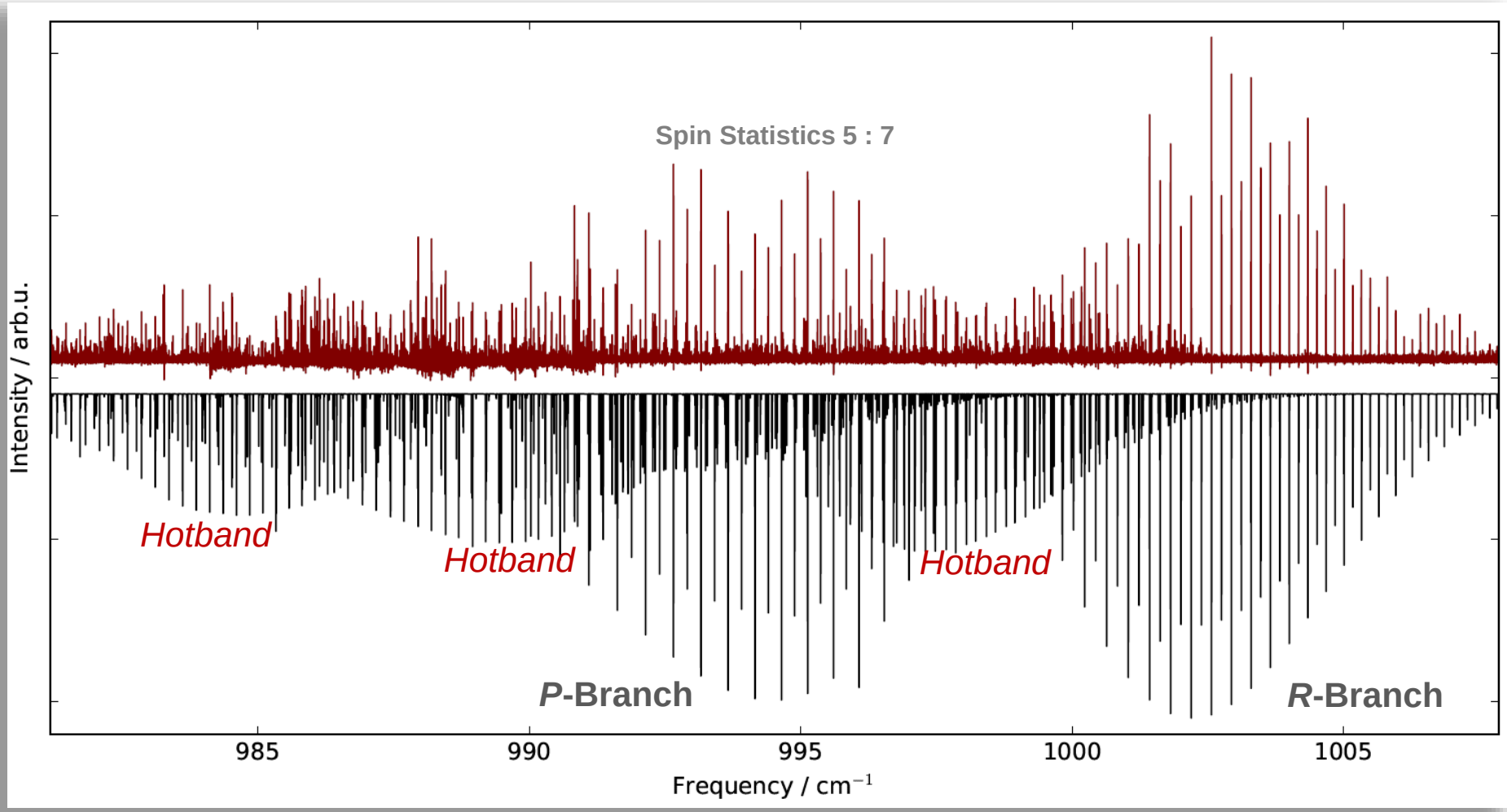


EXAMPLE: Al_2O, (linear form) Asymmetric Stretching Mode



$$I_{Al} = \frac{5}{2}$$

Fermi – Statistics

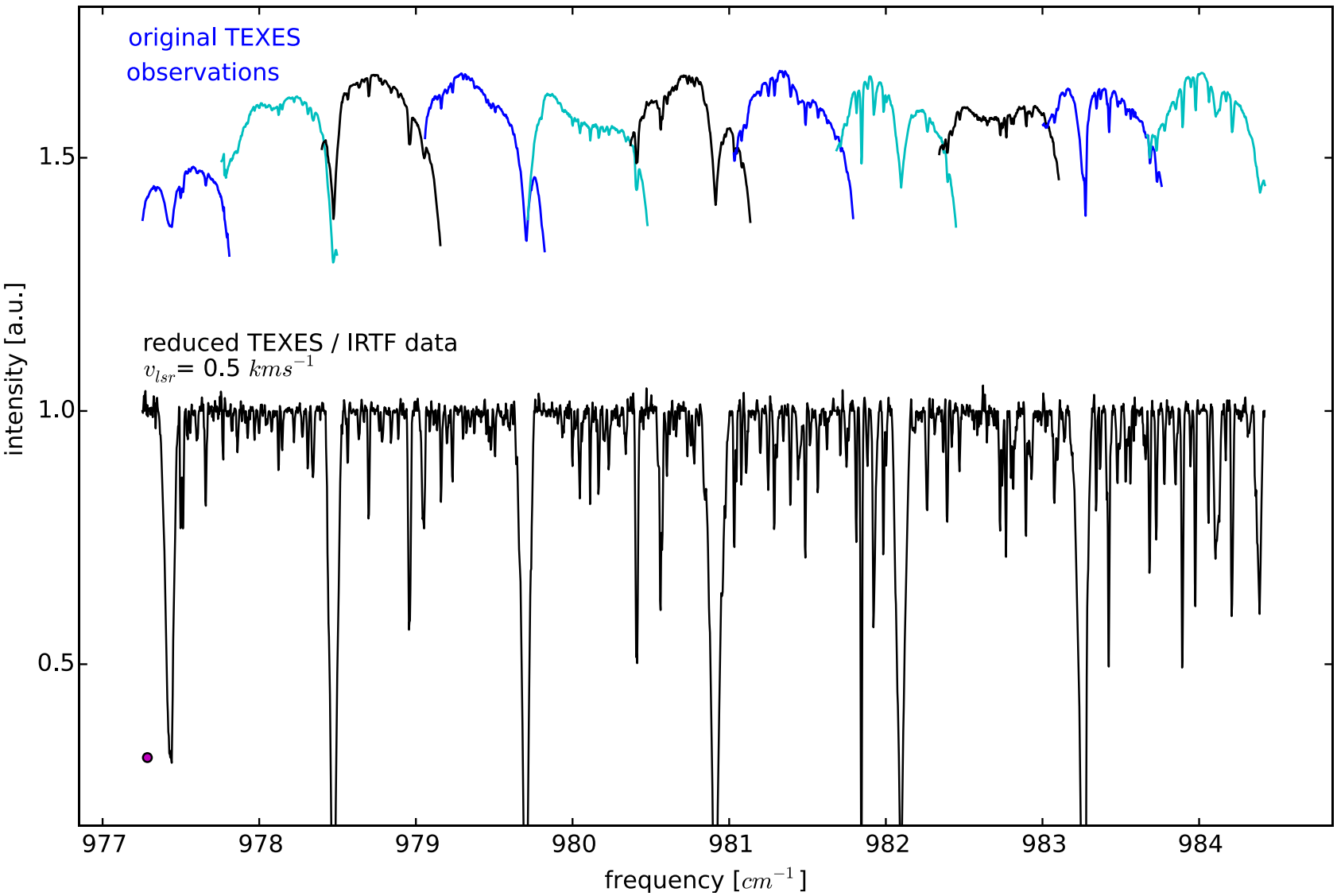
$$\boxed{\frac{g_s}{g_a} = \frac{I+1}{I} = \frac{7}{5}}$$

Nuclear Spin Statistical Weight

Generally, here is what we do:

- Measure spectra (Al_2O, TiO, Si_2C, FeO,…)
- Determine molecular constants & parameters
- Make line lists and highly accurate frequency predictions
- Publish results to enable molecule assignements of astronomically observed spectra
- And make own observations…

We try to find Al_2O,



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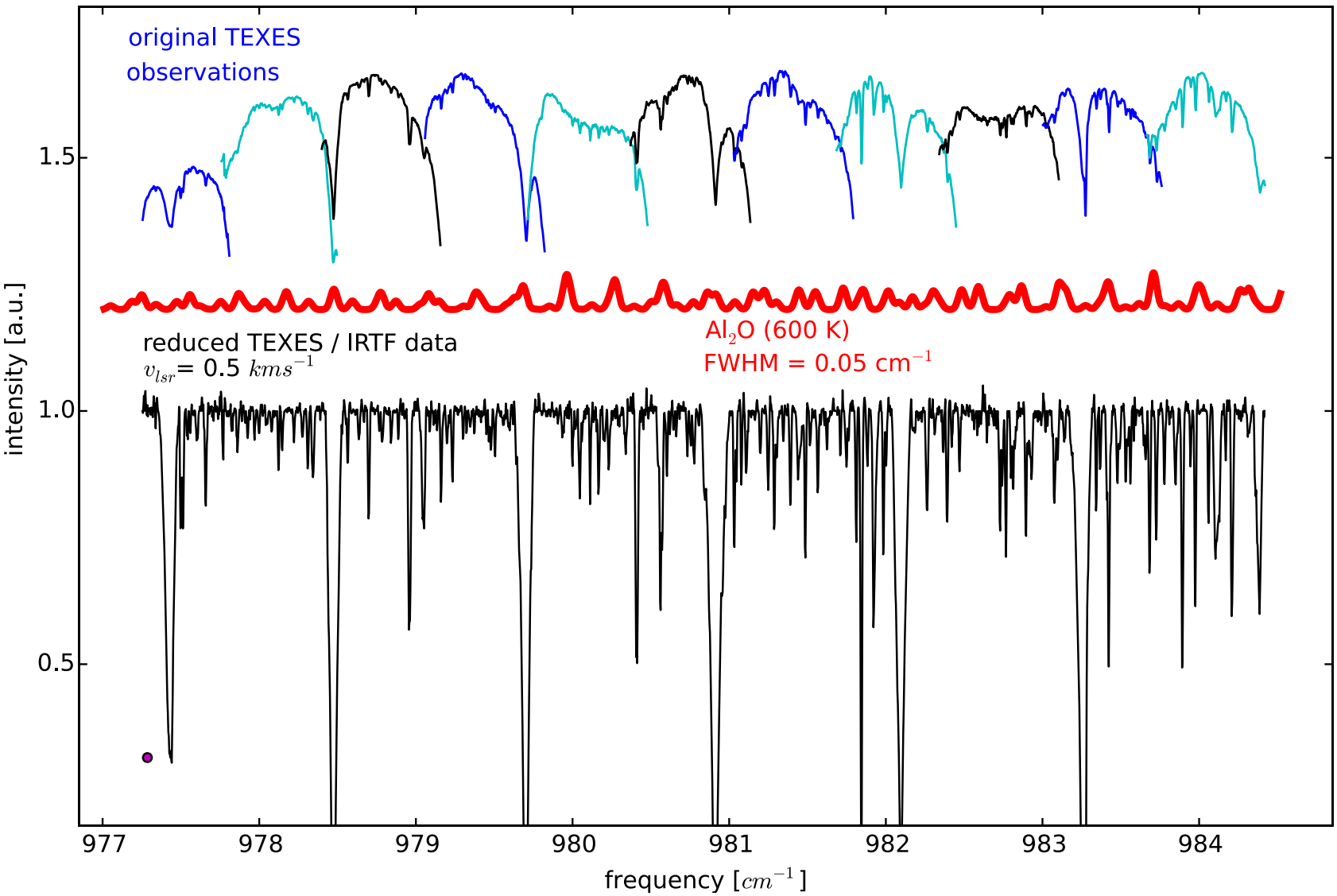
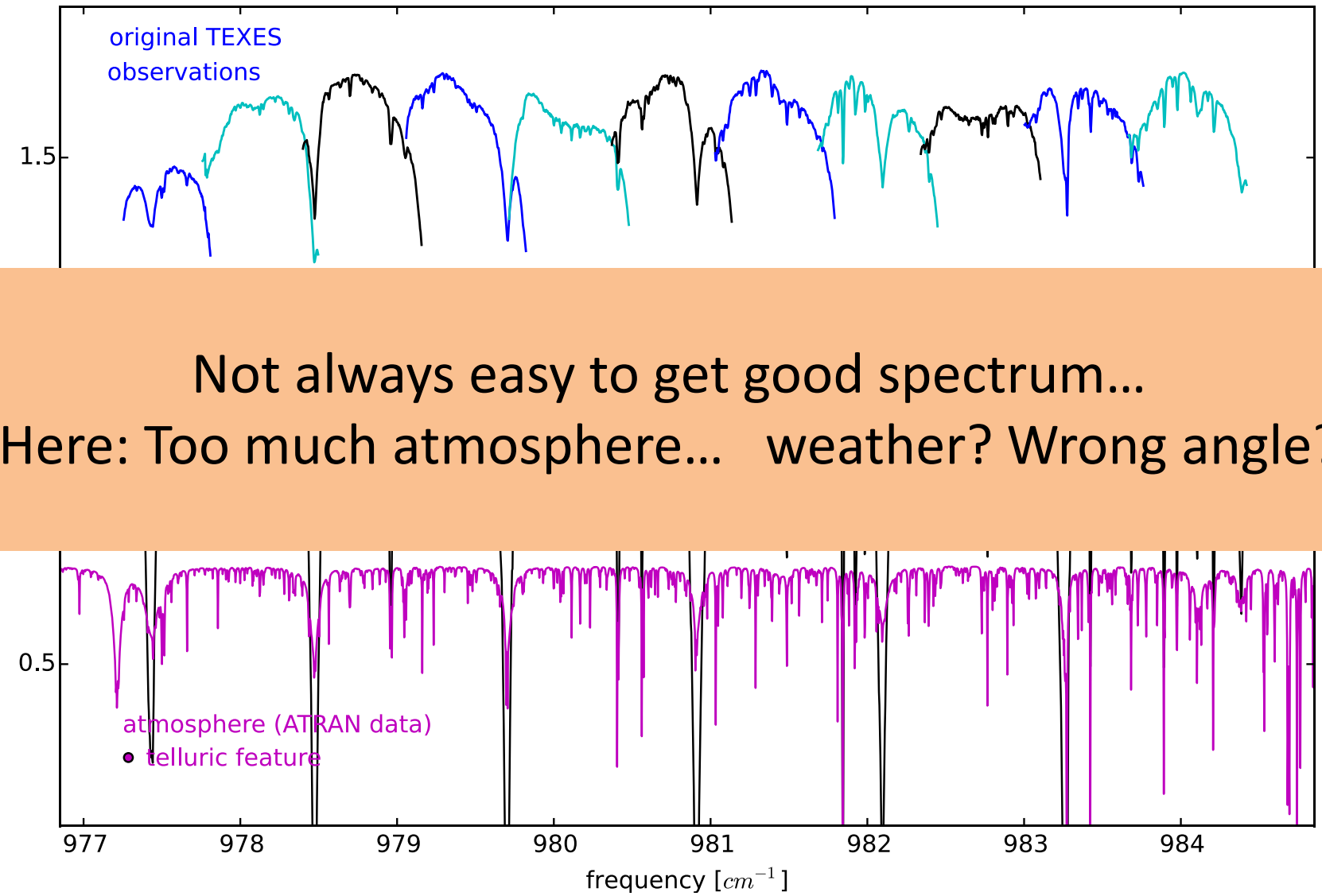


We try to find Al_2O, but…



Not always easy to get good spectrum…
Here: Too much atmosphere… weather? Wrong angle?

Some restrictions apply…

- Only a few high-resolution instruments available (TEXES/IRTF or Gemini N, EXES/SOFIA, CRIRES/VLT, HIPWAC,…)
- TEXES is operated by a small team which has its focus on planetary sciences
  ⇒ only available for a few weeks per semester on IRTF / Gemini N & observing times according to planet visibility, i.e. other targets may not be observable (like VY CMa,…)
- EXES/SOFIA does usually not fly in the southern hemisphere
  (e.g. where VY CMa can best be seen)

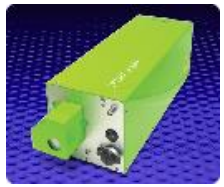
We will not give up…

TEXES / EXES projects in mid-IR

Problem: Dish size (2.5 – 3 m), Gemini North (8.1 m) only available for very limited time

Instrumental freq. coverage

Laboratory equipment



TDLs

DFB-QCLs

OPO | OPO 2 | OPO 2 | OPO

ec-QCLs

1 2 3 4 5 6 7 8 9 10 20 30

λ [µm]

telescopes

VLT / CRIRES 0.95 - 5.2 µm

R = 50.000-100.000

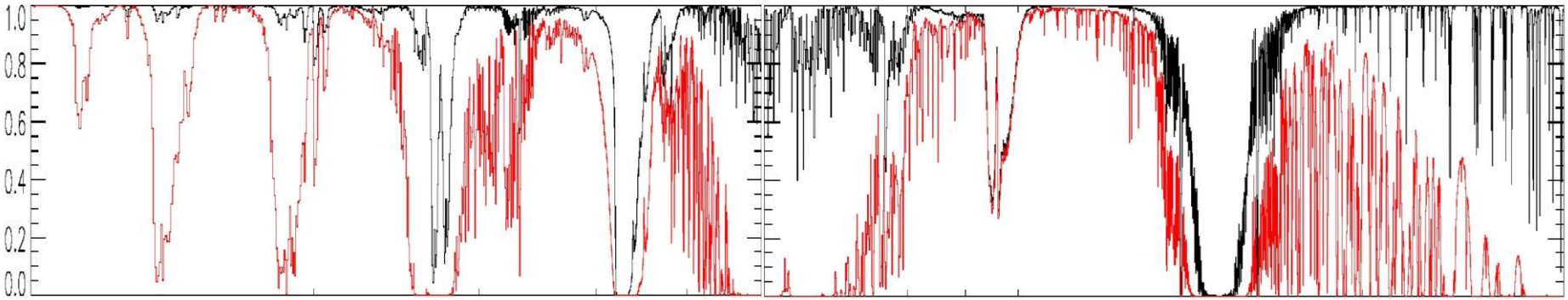
TEXES / EXES 4.5 – 28.3 µm

EXES

EXES

Atmospheric transmission

transmission



1 2 3 4 5 6 7 8 9 10 20 30

λ [µm]

SOFIA (black) @ 12.5 km, 7.3 µm precipitable water vapor
Mauna Kea (red) @ 4.2 km, 3.4 mm water vapor,
SOFIA cycle5 handbook

G.W.Fuchs (Uni Kassel)

Take home message

- New opportunities in mid-IR due to high-res instrum. (SiO, NH_3, CO_2) & many U-lines
- More laboratory high-resolution IR data are needed
- IR databases needed (like CDMS/JPL @ radio wavelengths)
- Weak lines require high altitude observations (EXES/SOFIA) & instrument availability (TEXES)
- Some bands still blocked by stratosphere (ozone) ⇒ space + high resolution (but: JWST no high-res spectrograph!)

Acknowledgment

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Thomas K. Greathouse (San Antonio, TX, USA)
EXES Team, Edward Montiel (SOFIA/USRA),
Matthew Richter (UC Davis)

Thank you for your attention!

End