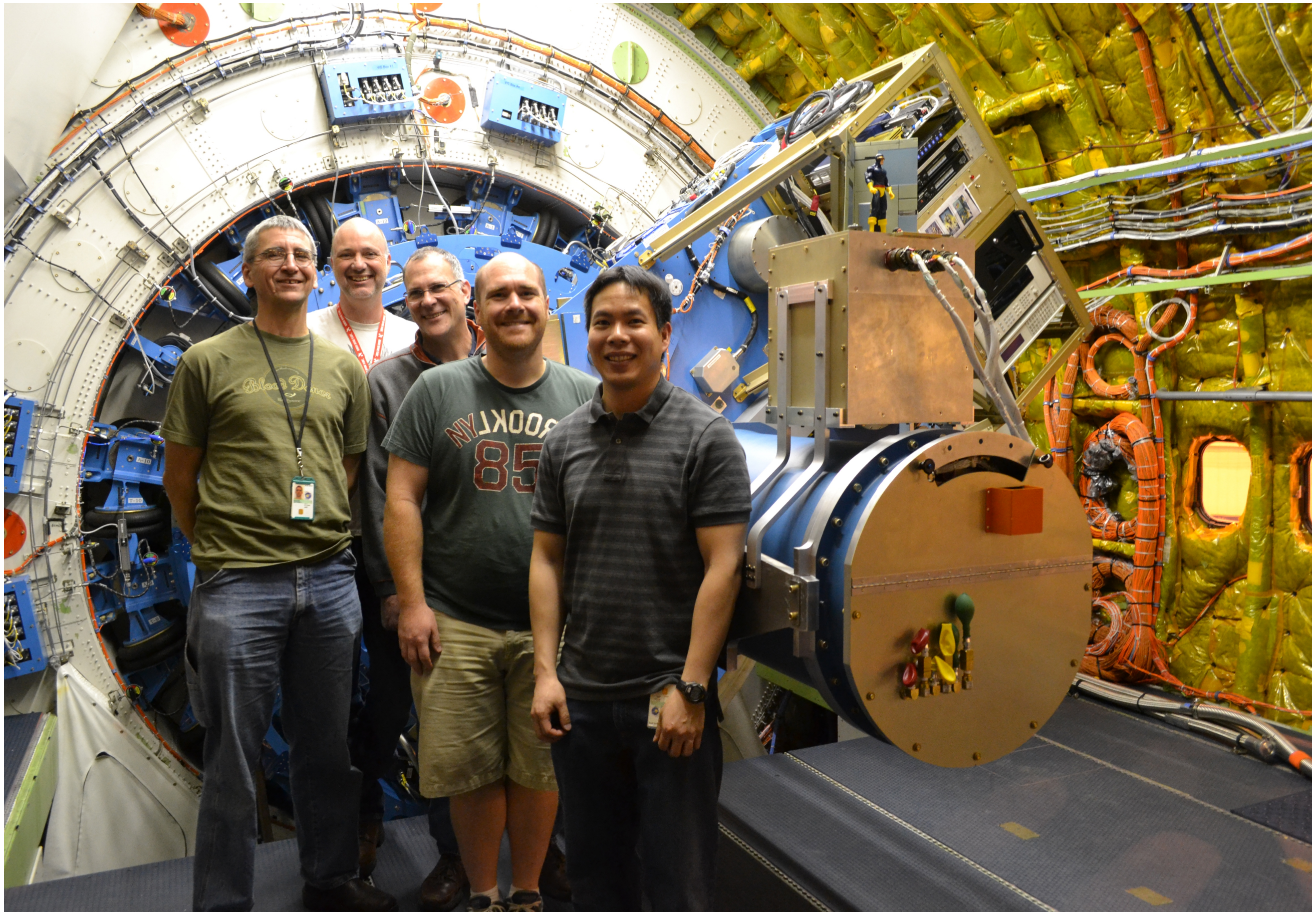
SOFIA/EXES Study of CH_4 and SO_2 toward Massive YSOs



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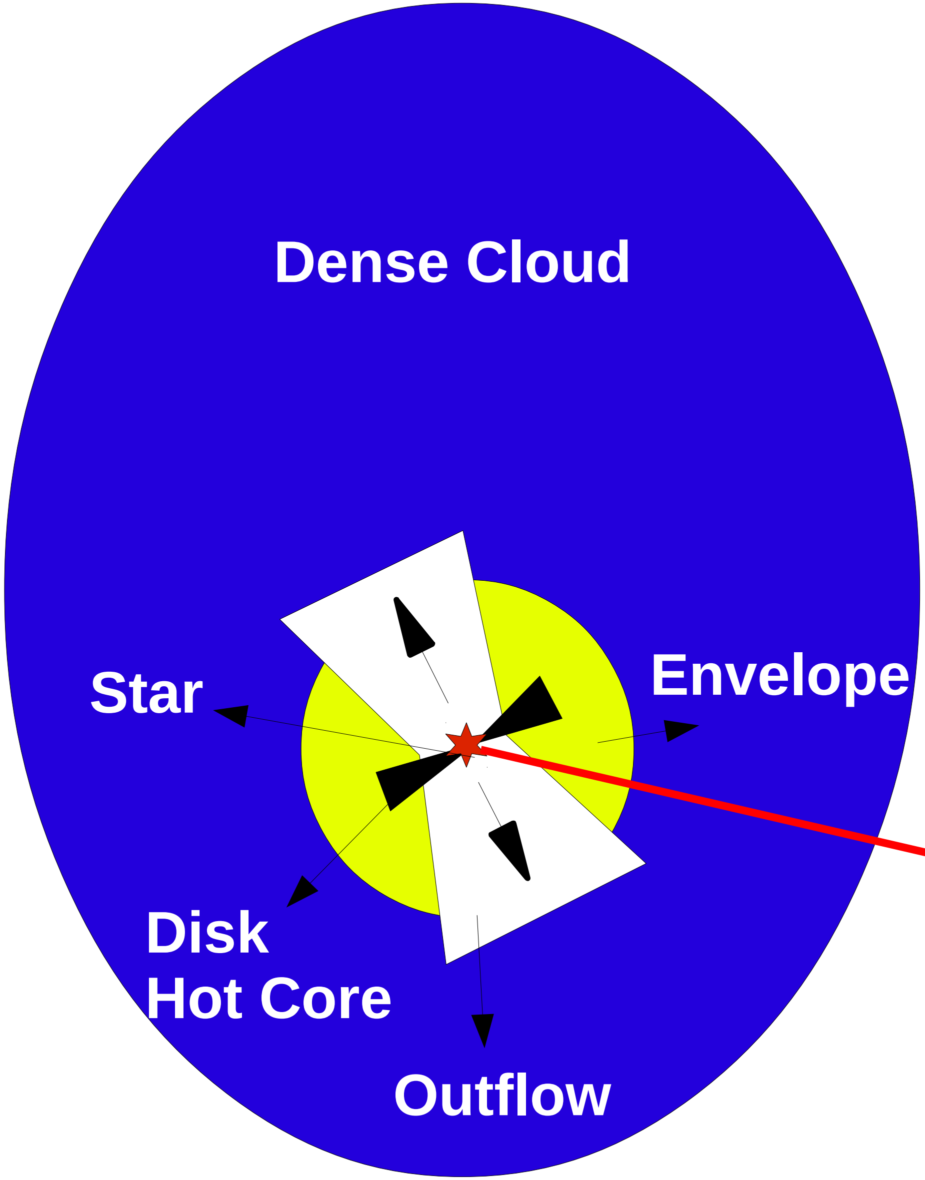
Contents

High Resolution Mid-IR Spectroscopy



1) Absorption of molecular species against strong mid-IR continuum sources: sensitive to material close to YSO

2) Mid-IR traces species with no dipole moments.

3) High resolution spectroscopy: kinematics relates to location.

GO Programs

02_0104: 3.3 hours to observe gaseous CH_4 in two massive YSOs (both NGC 7538 IRS1 and Mon R2 IRS3 observed)

04_0153: 4.0 hours to observe gaseous SO_2 in three massive YSOs (W3 IRS5 observed, GL 2136 and Mon R2 IRS3 not yet)

Different chemistries CH_4 and SO_2 offer different tracers physical conditions in massive YSOs.

Team

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CH_4

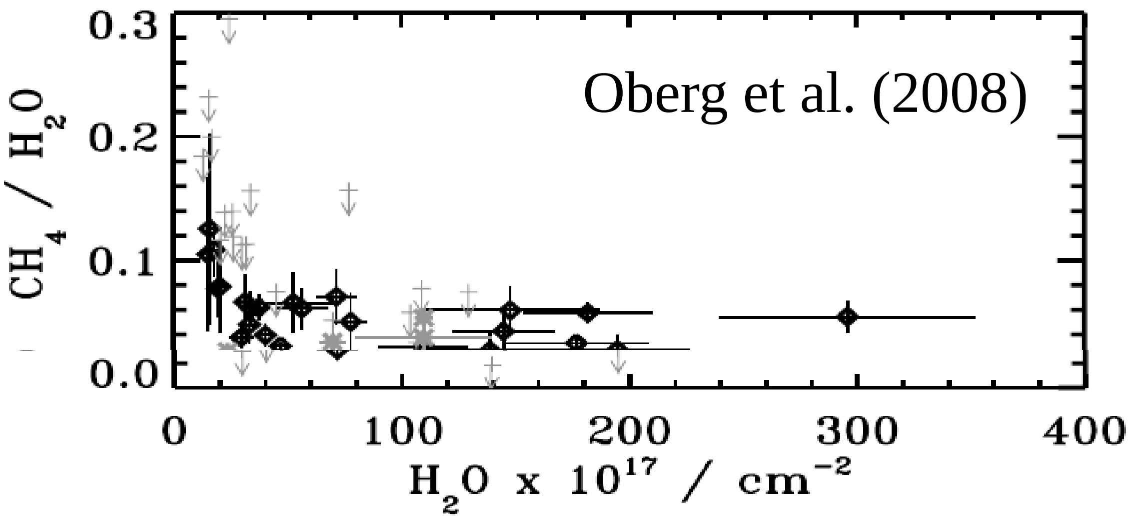
CH_4 Chemistry

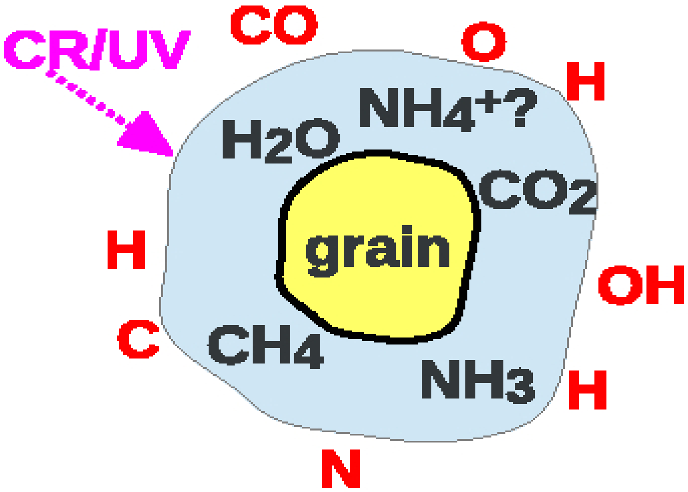
Low extinction (A_V~1 mag):

- Gas phase CH_4 formation slow due to energy barriers
- C preferably in gas phase CO

High extinction (A_V>2 mag):

- CH_4 formed on grain surfaces (C hydrogenation) as is H_2O (O hydrogenation)
- Low CH_4/H_2O ice ratio (few percent)





CH_4 Chemistry

CO destruction enhances CH_4: at high gas phase temperature or on grain surfaces.

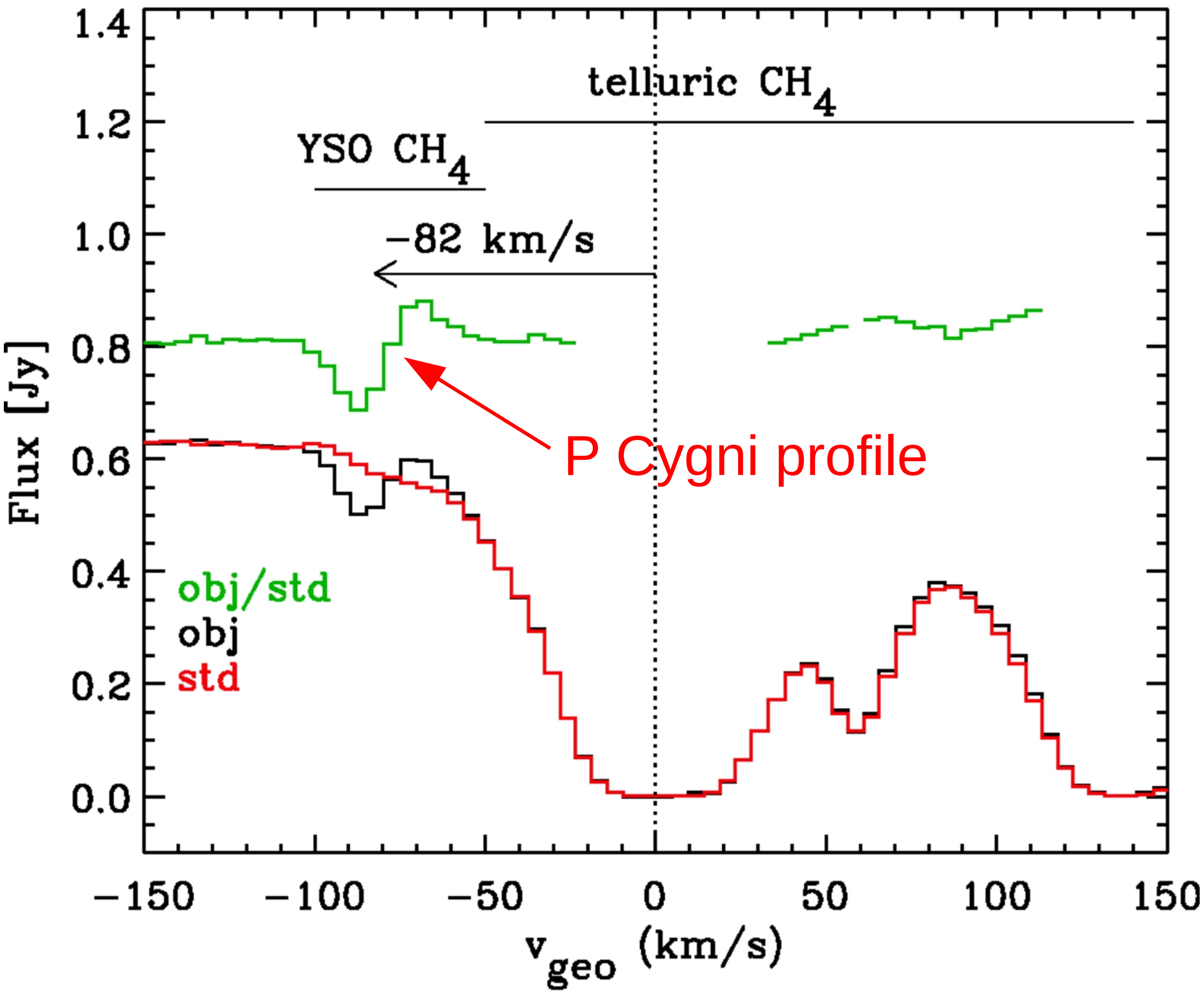
COM (Complex Organic Molecules) formation:

- CH_4 → carbon chains, e.g., “Warm Carbon Chain Chemistry Sources”
- CO → H_2CO, CH_3OH, ...

Measurements CH_4 important:

- Ice not possible with SOFIA... telluric CH_4 Q-branch, insufficient instrumentation.
- Gas phase CH_4 possible with EXES

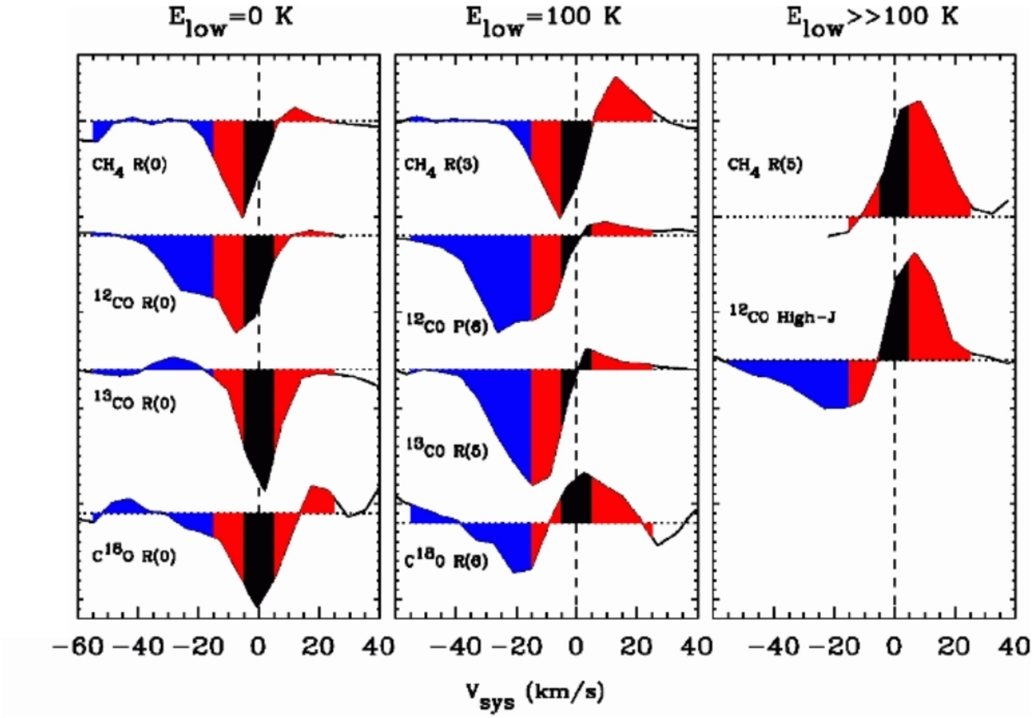
Previous CH_4 Observation



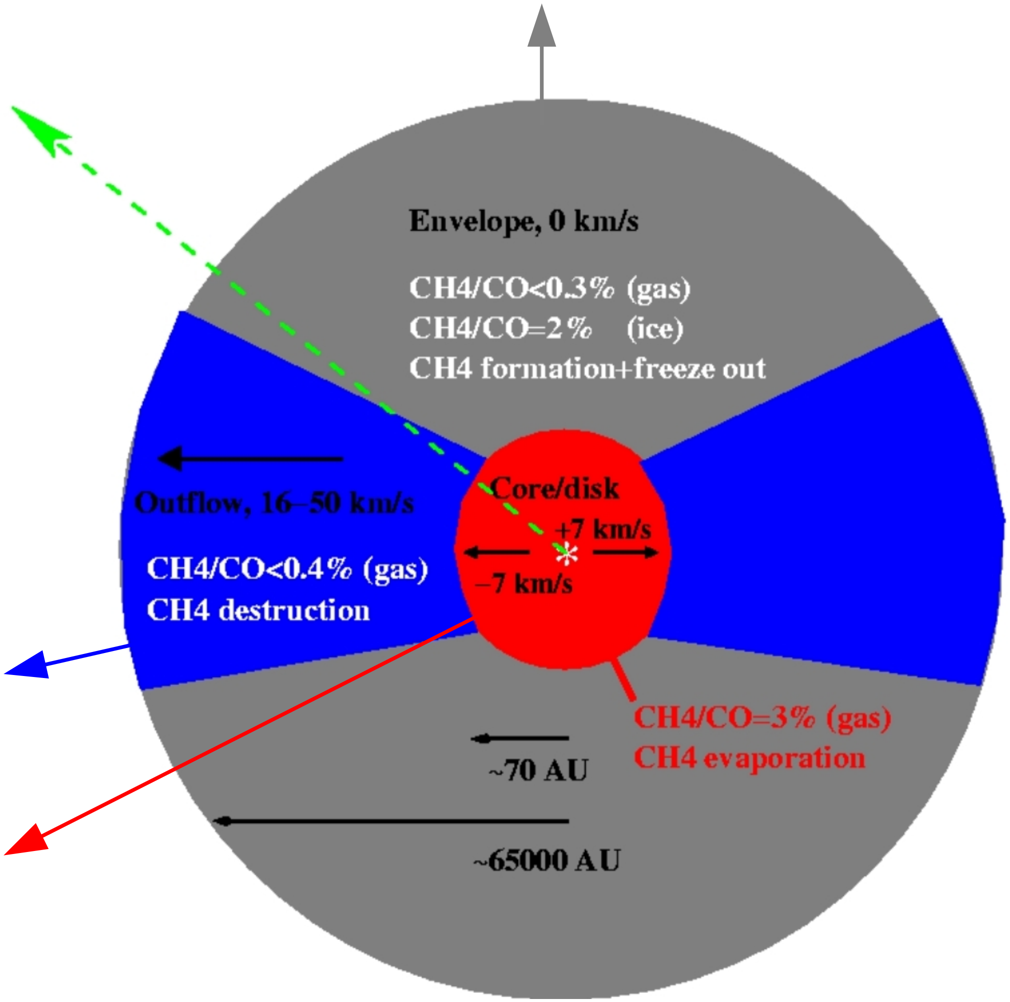
[Boogert et al., ApJ 615, 344, 2004]

- Ground-based telescopes at 3.32 µm (C-H stretch): large Doppler shift needed to detect gas phase CH_4:
  - -82 km/s for NGC7538 IRS9 combination of earth motion and high sourceV_{helio}
- P Cygni line profile indicates warm CH_4 in expanding shell.

Previous CH_4 Observation



grain surface chemistry
solid CH_4 formation



shock chemistry

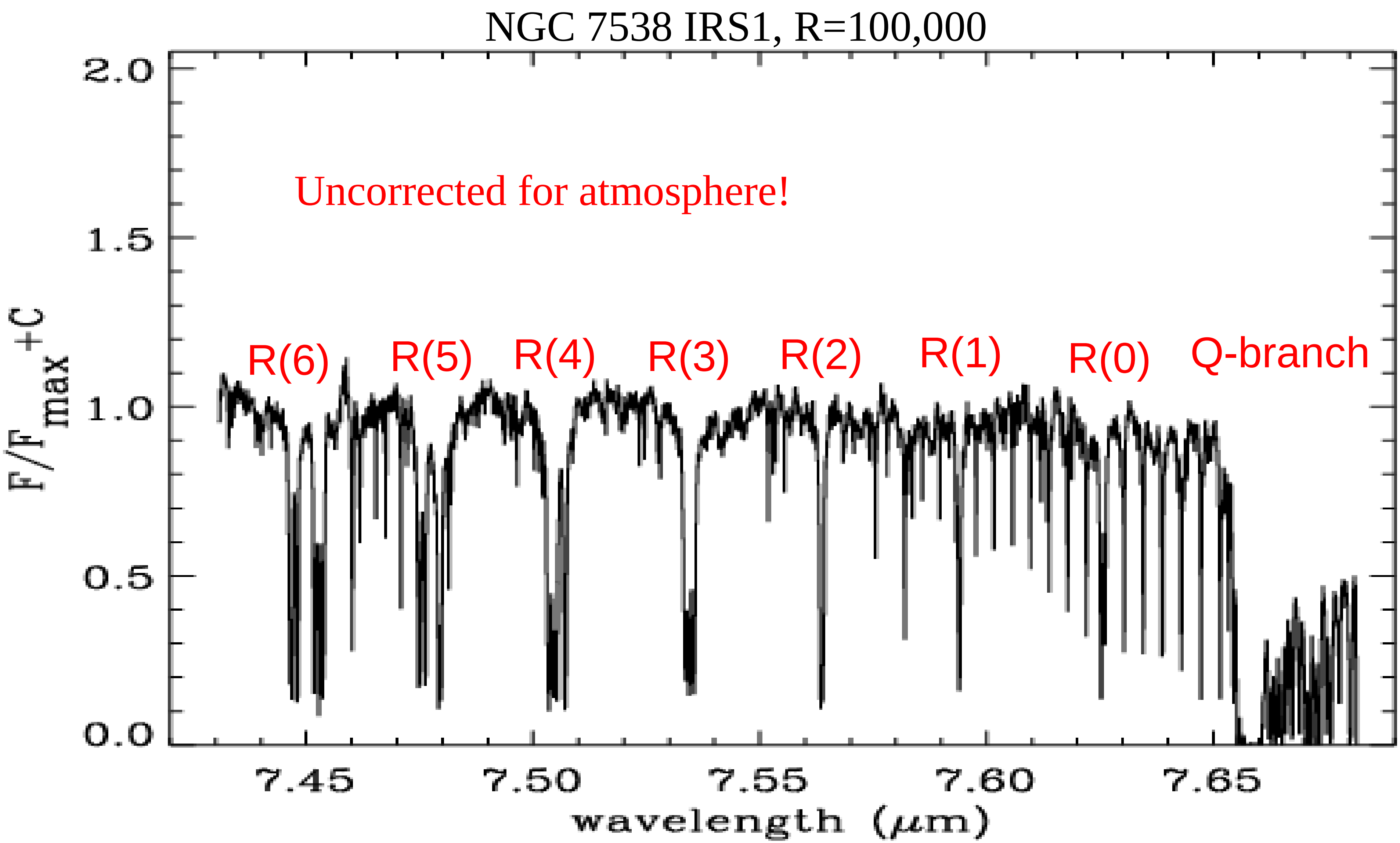
$CH_4 \rightarrow CO$

hot core chemistry
CH_4 sublimation

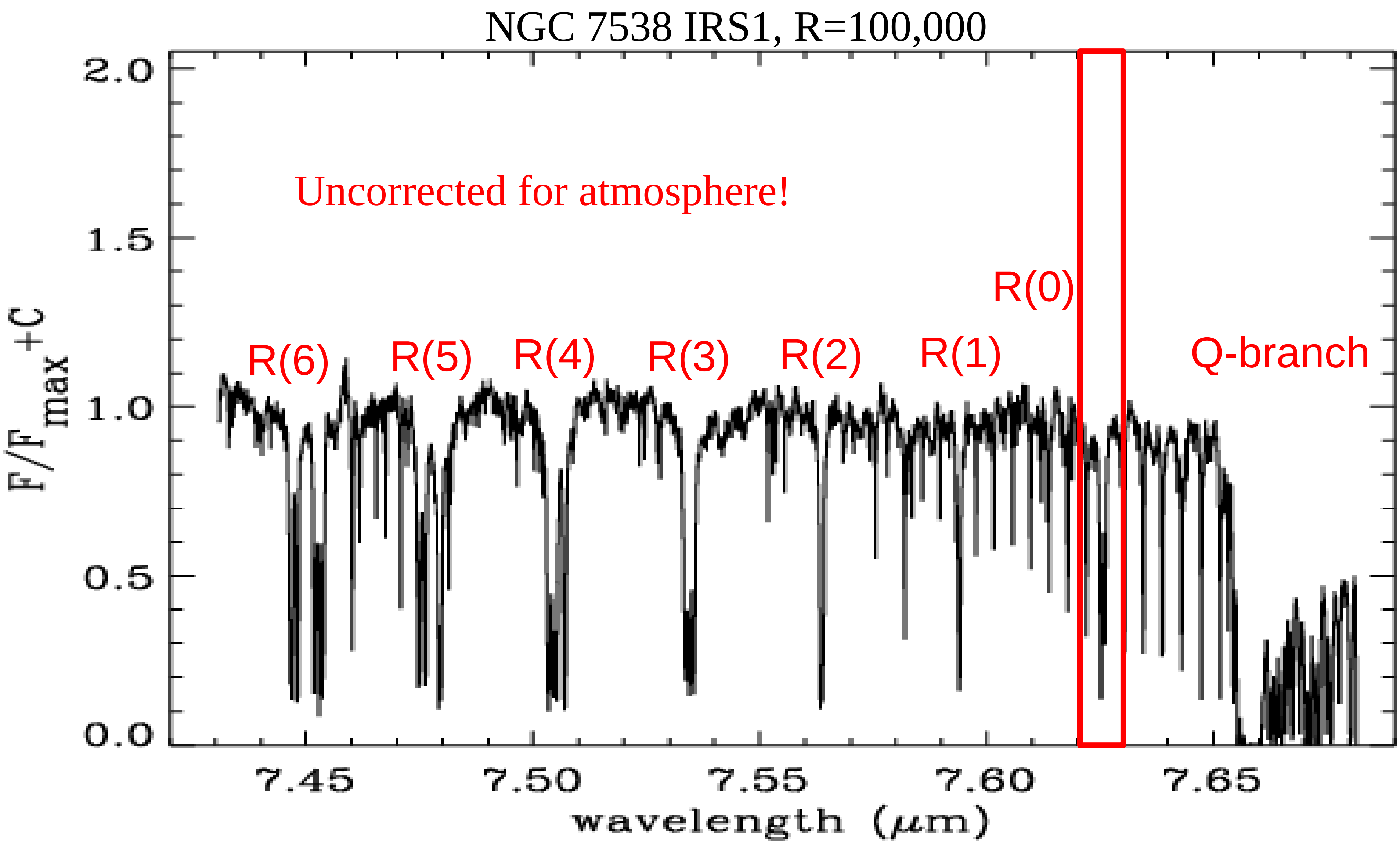
$CH_4 \rightarrow$ complex species

[Boogert et al., ApJ 615, 344, 2004]

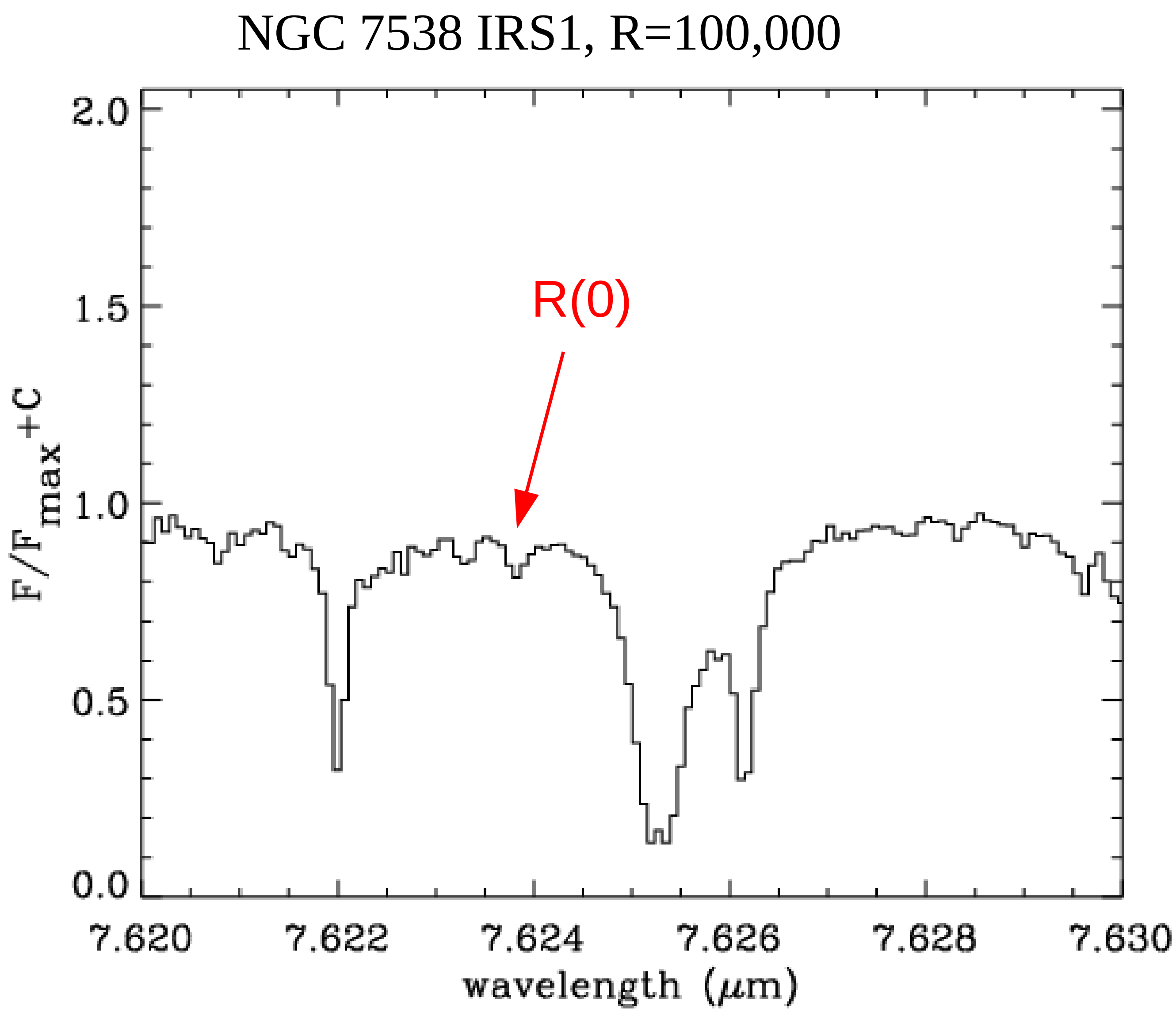
CH_4 with SOFIA/EXES



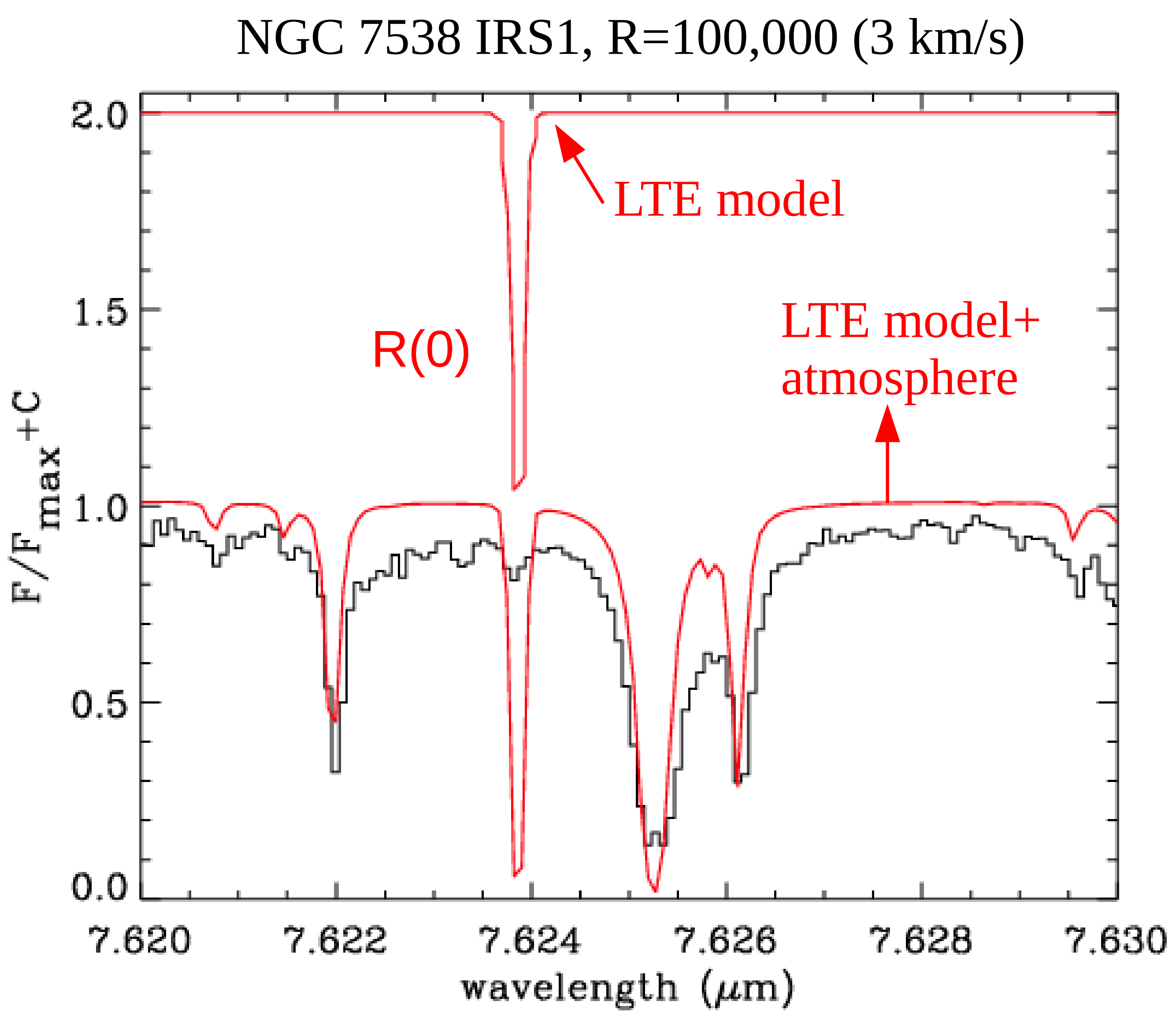
CH_4 with SOFIA/EXES



CH_4 with SOFIA/EXES



CH_4 with SOFIA/EXES



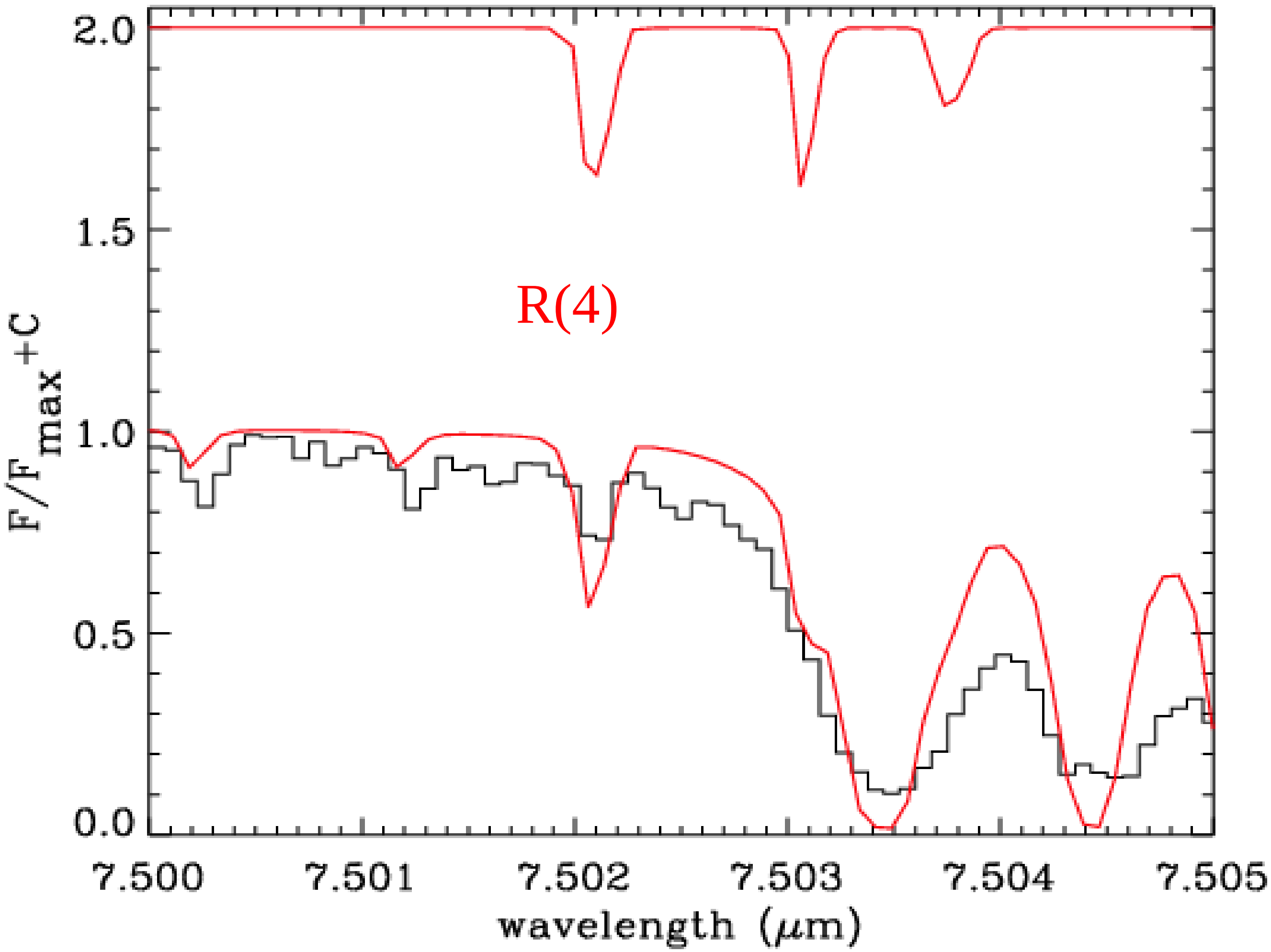
LTE model assumes CO parameters (Mitchell et al. 1990):

- CH_4/CO=1% (1.2e17 cm^{-2})
- T=25 K
- FWHM=3.3 km/s

“Spectacular” non-detection of CH_4 in cold gas phase:
At cold temperatures it is frozen out.

CH_4 with SOFIA/EXES

NGC 7538 IRS1, R=100,000 (3 km/s)



LTE model (red) assumes CO parameters (Mitchell et al. 1990):

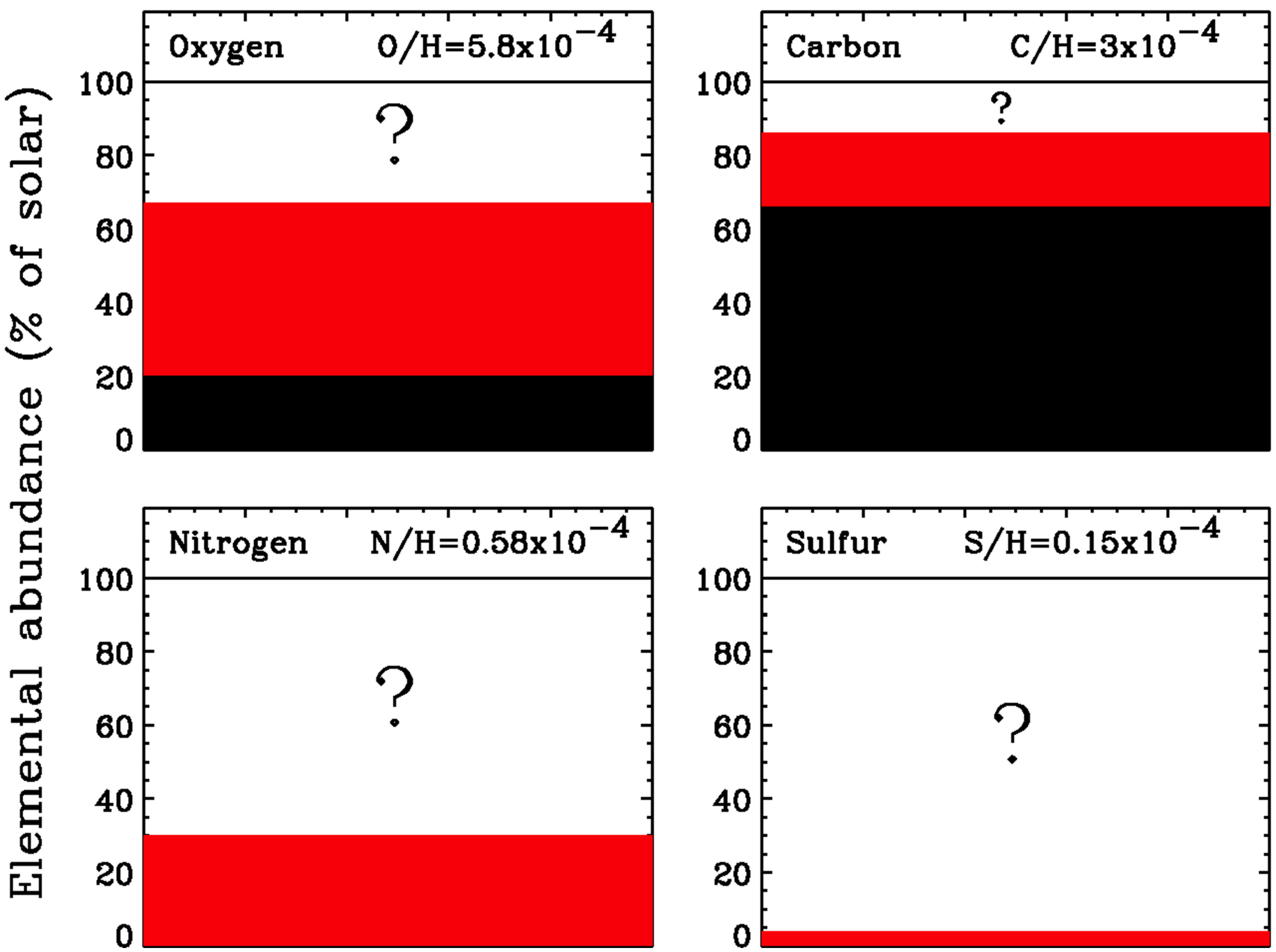
- CH_4/CO=1% (1.1e17 cm^{-2})
- T=176 K
- FWHM=3.3 km/s

CH_4 in warm gas phase: consistent with sublimation off icy grains

Notice simple, narrow line profile...hot core gas, not outflow.

SO_2

Why Study SO_2?



Red: elements in ice

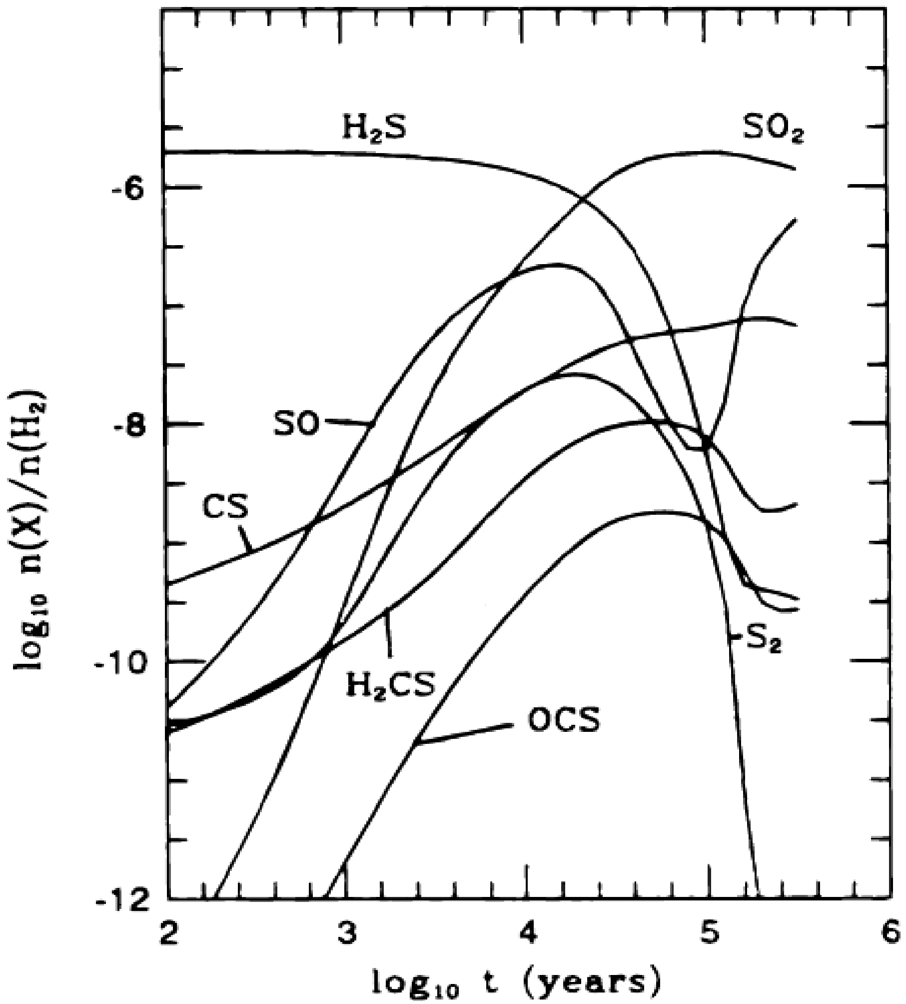
Black: element in refractory material

Location of S in dense clouds is mystery.

Why Study SO_2?

ice sublimation

gas phase chemistry

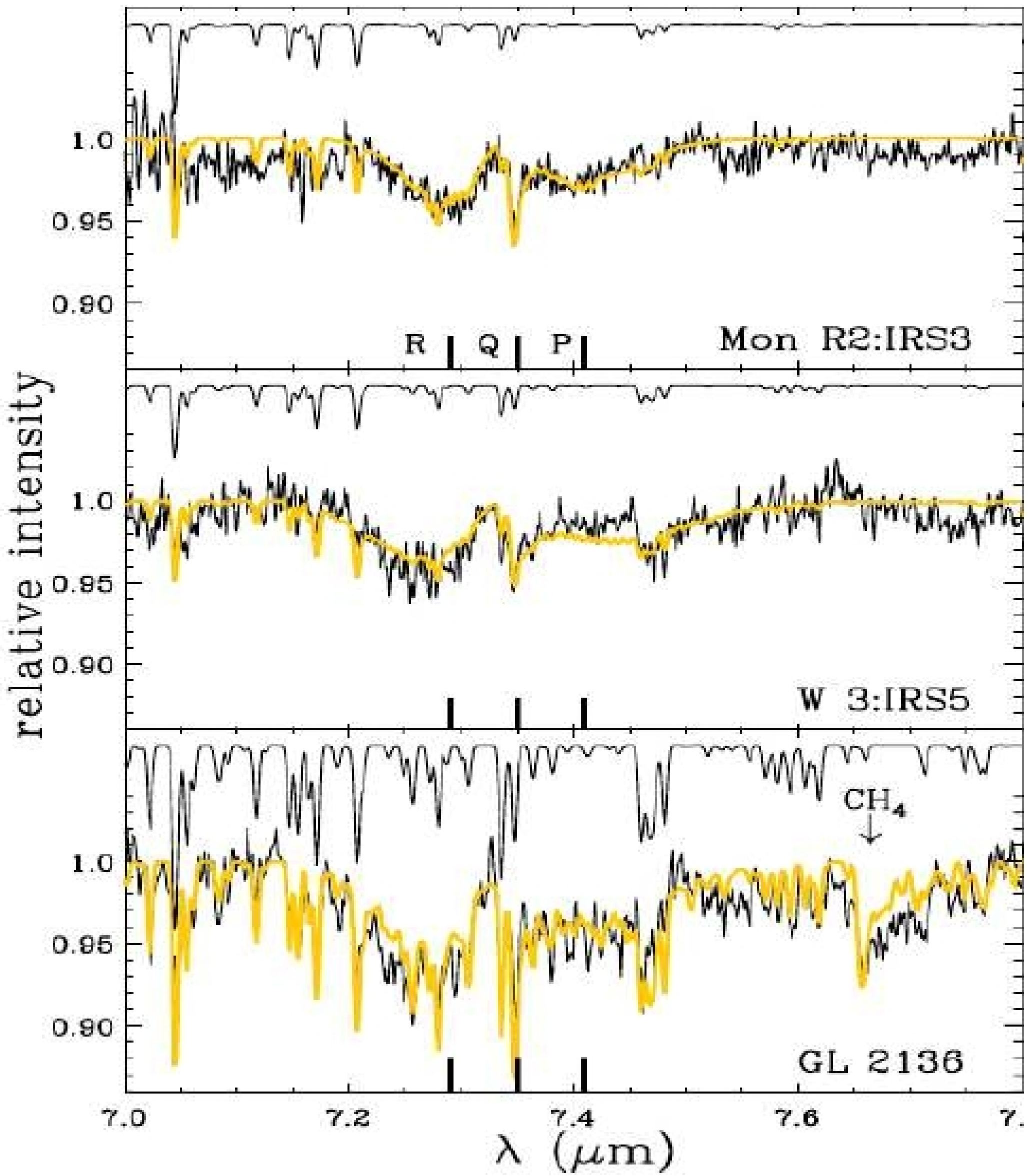


SO_2 Abundance relative to SO or H_2S is hot core age indicator.

Problem: little H_2S in ice. What is source of S?

Charnley et al. (1997)

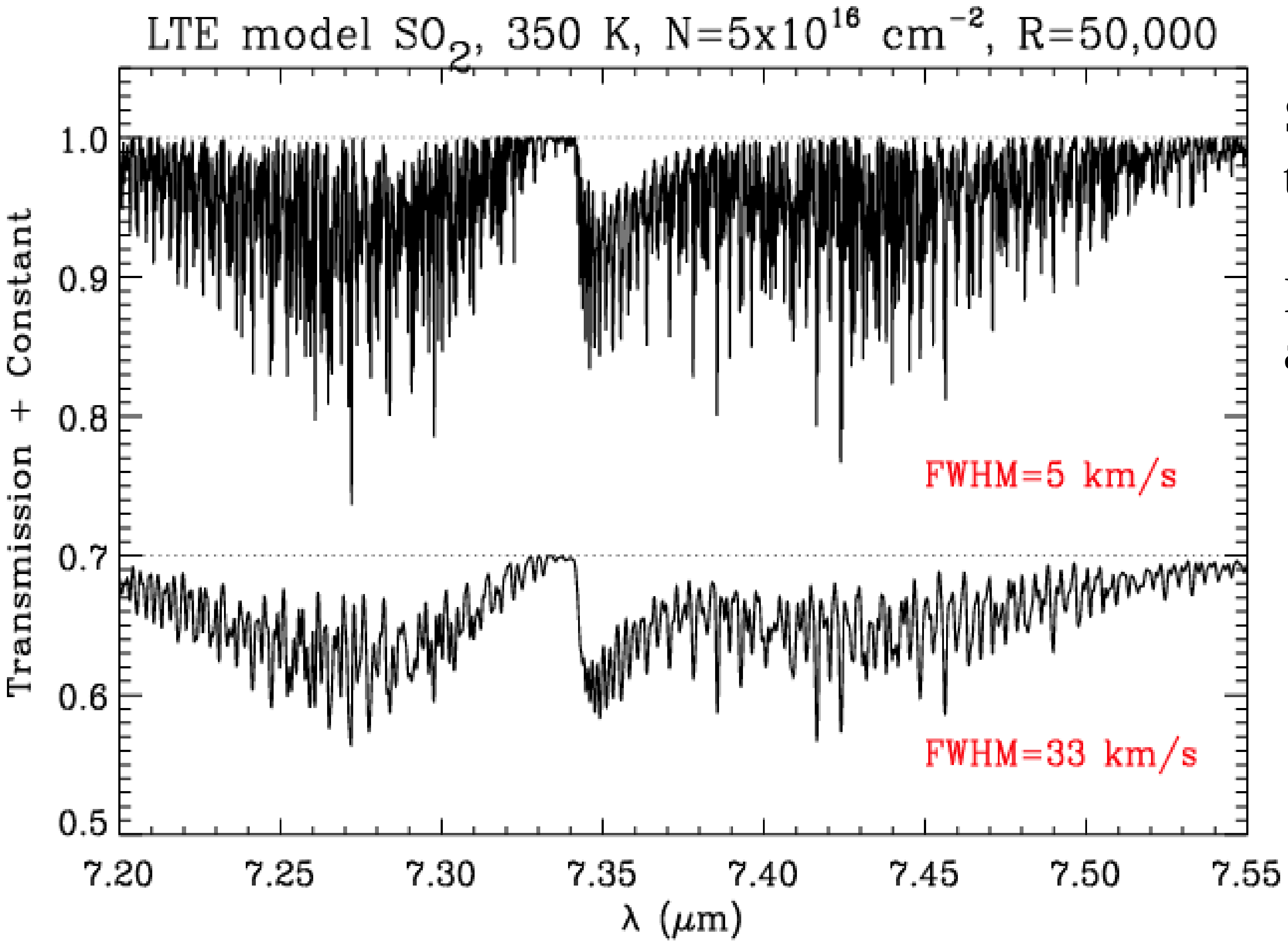
SO_2: Previous IR Observations



- ISO/SWS detected warm gas phase SO_2 toward massive YSOs
- Factor ~10 more abundant than in sub-millimeter studies of pure rotational lines
- What is location of this SO_2? Need line profile information.

Keane et al. A&A, 371, 5, 2001

SO_2: Complex IR Spectrum

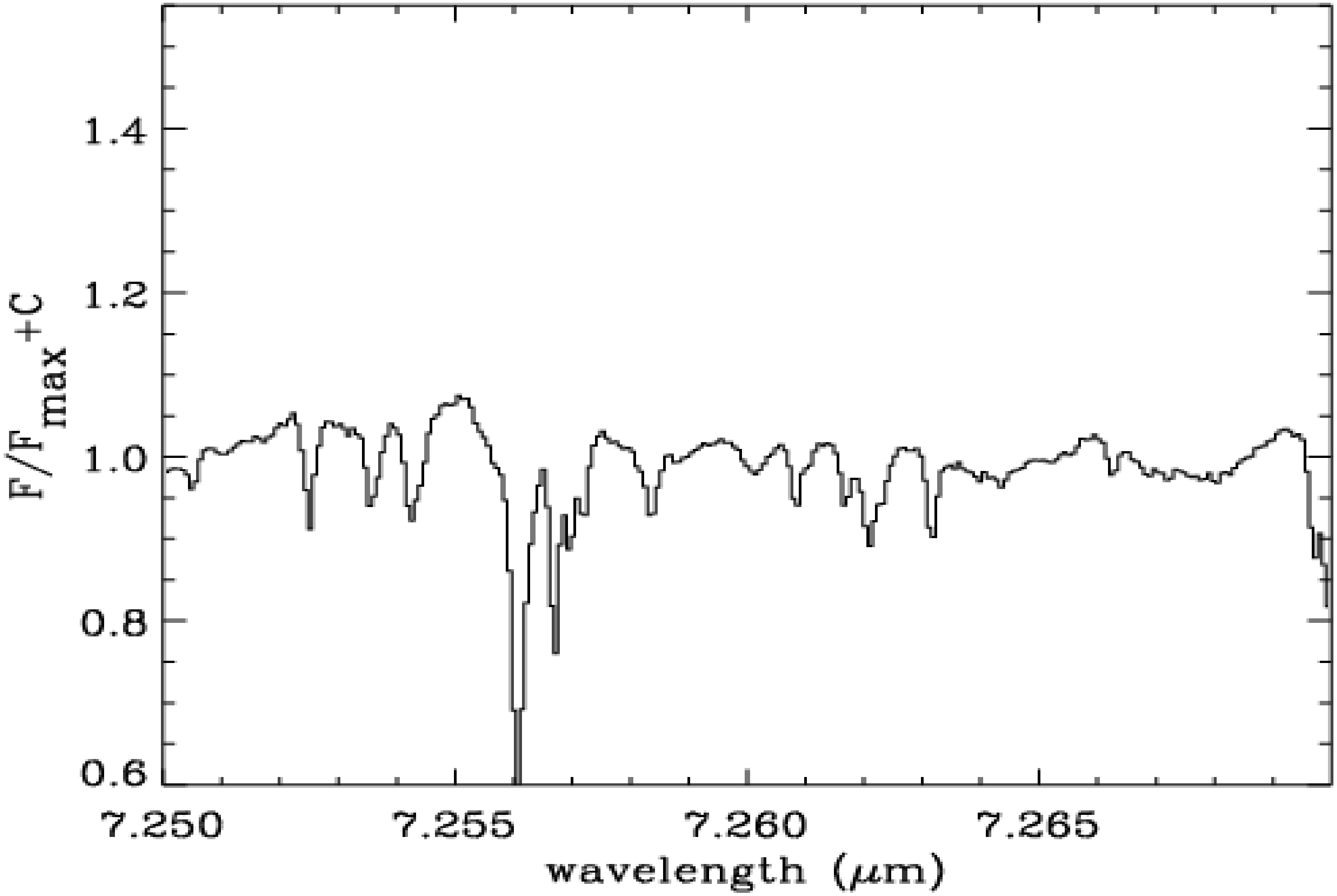


SO_2 is "asymmetric top", just like H_2O.

Its spectrum is complex and lines overlap.

SO_2 with SOFIA/EXES

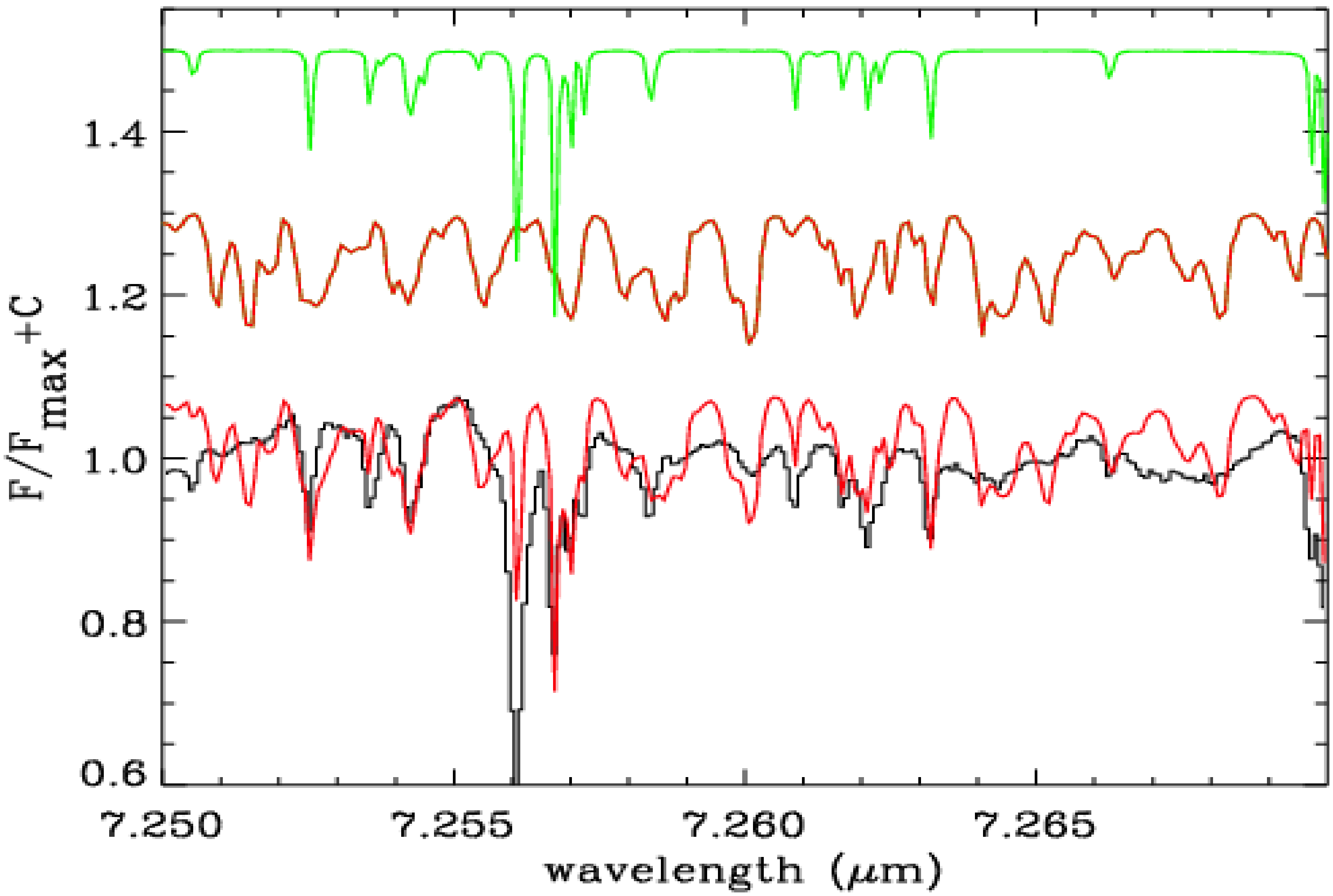
portion of the observation (includes atmosphere!)



W3 IRS5, R=50,000

SO_2 with SOFIA/EXES

lines must be much broader than 5 km/s!



Atmosphere

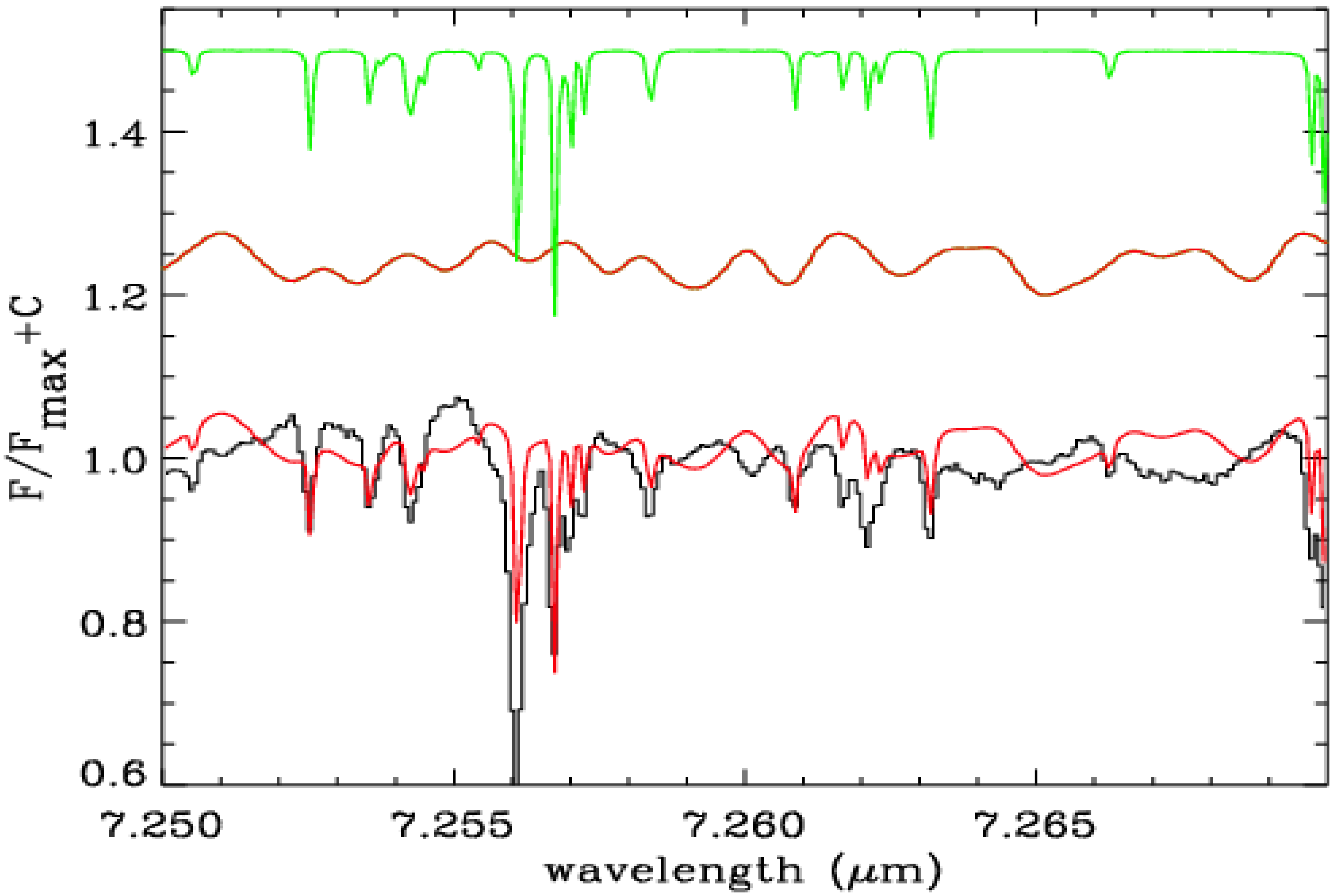
SO_2, LTE: 450 K, 5e16 cm^{-2}, FWHM=5 km/s

atmosphere+LTE model

W3 IRS5, R=50,000

SO_2 with SOFIA/EXES

lines must be ~30 km/s wide!



Atmosphere

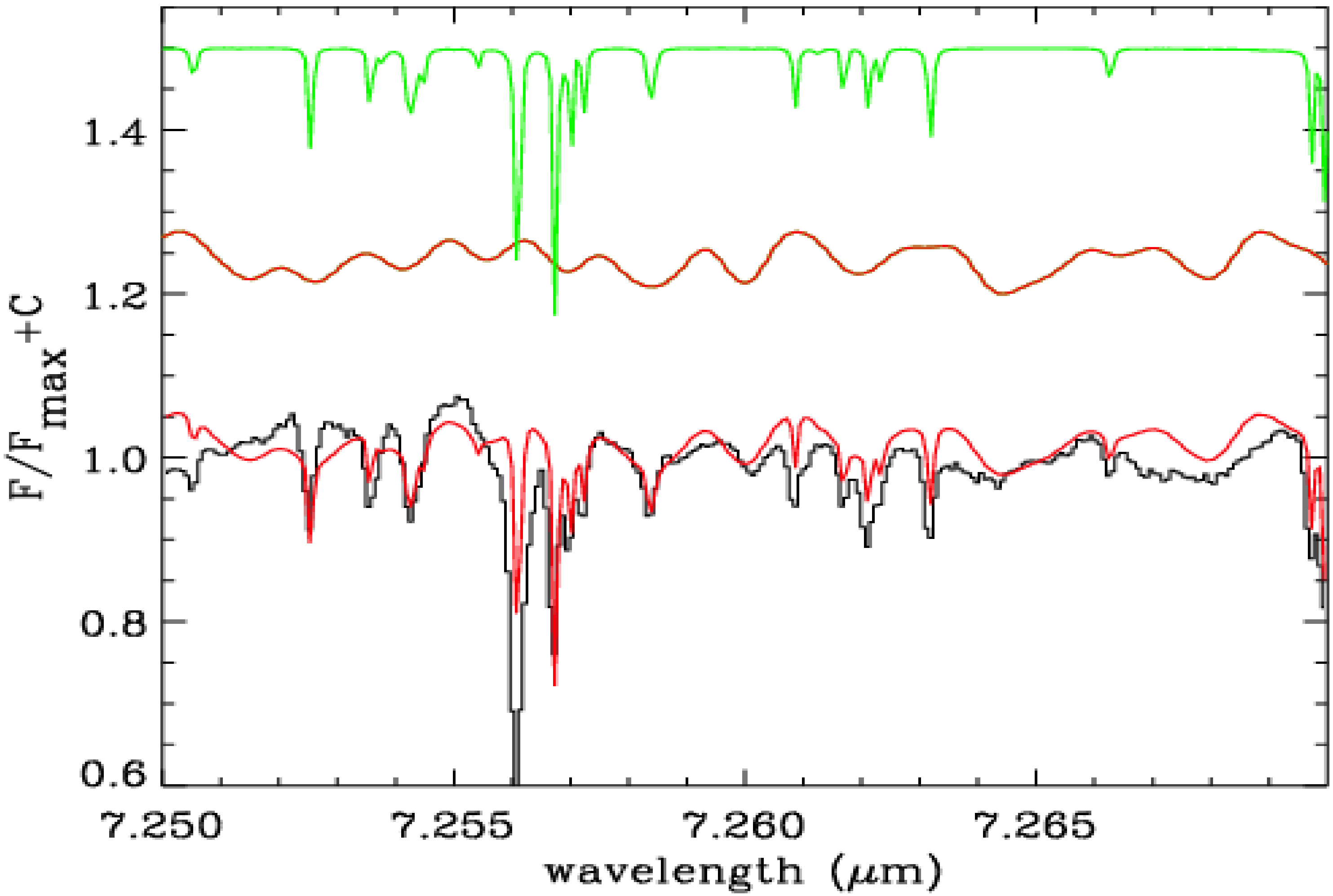
SO_2, LTE: 450 K, 5e16 cm^{-2} FWHM=33 km/s

atmosphere+LTE model

W3 IRS5, R=50,000

SO_2 with SOFIA/EXES

SO_2 line detection after Doppler shift



Atmosphere

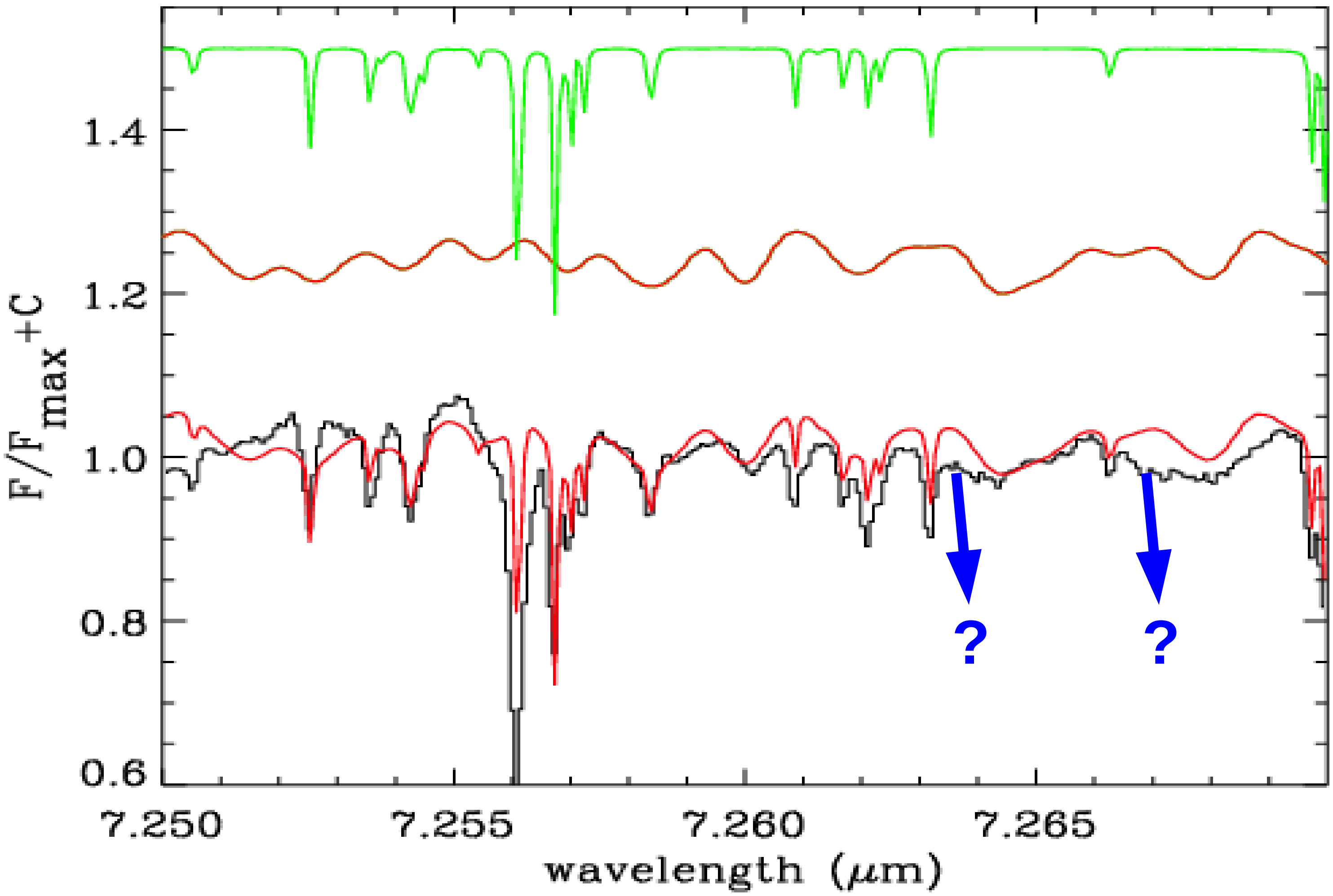
SO_2, LTE: 450 K, 5e16 cm^{-2} FWHM=33 km/s+Doppler shift

atmosphere+LTE model

W3 IRS5, R=50,000

SO_2 with SOFIA/EXES

SO_2 line detection after Doppler shift, but there are residuals!



Atmosphere

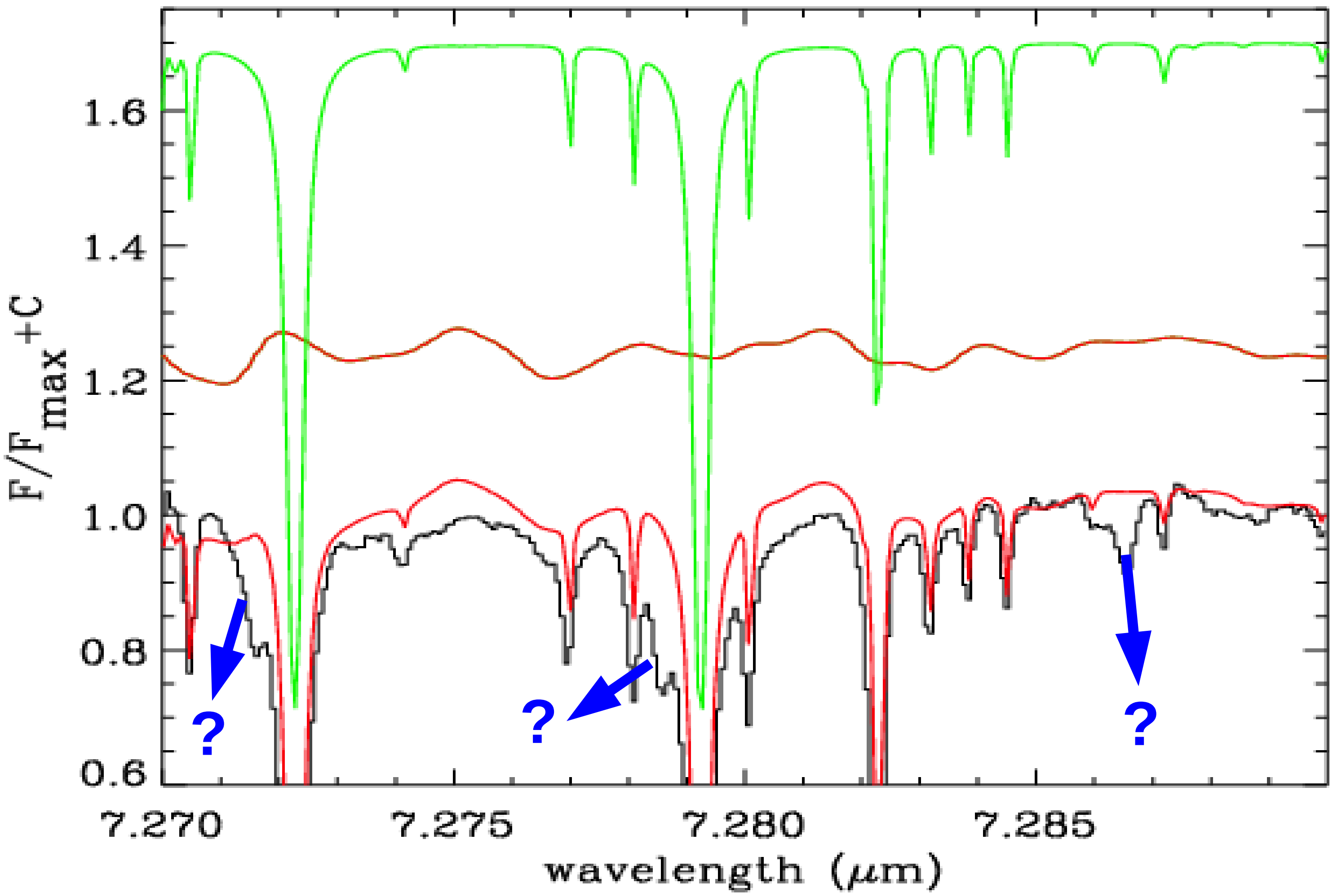
SO_2, LTE: 450 K, 5e16 cm^{-2} FWHM=33 km/s+Doppler shift

atmosphere+LTE model

W3 IRS5, R=50,000

SO_2 with SOFIA/EXES

Not all detected lines are due to SO_2



Atmosphere

SO_2, LTE: T=450 K, N=5e16 cm^{-2} FWHM=33 km/s

atmosphere+LTE model

W3 IRS5, R=50,000

(Preliminary) Conclusions

- SO_2 associated with strong shocks
- SO_2 abundance enhanced w.r.t. large scale cloud suggests shock formation:
  - What is source of Sulfur?
    - unlikely sublimated H_2S.
    - S_2 from ice?
    - S sputtered from refractory grains?
- CH_4 gas **only** present in warm gas phase, but with relatively narrow lines: sublimation from icy grains in hot core.
- Further CH_4 and SO_2 observations needed in larger variety of sources.

EXES Posters

Montiel et al.: Science with EXES
(including line survey of oxygen-rich hypergiant VY Canis Majoris)

Rangwala et al.: SOFIA/EXES 13 μm High Spectral Resolution Observations of Orion IRc2 (ortho and para C_2H_2 temperatures and ratios, formation path C_2H_2)