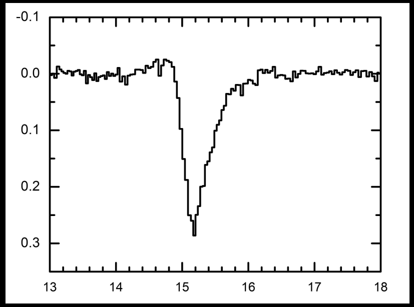
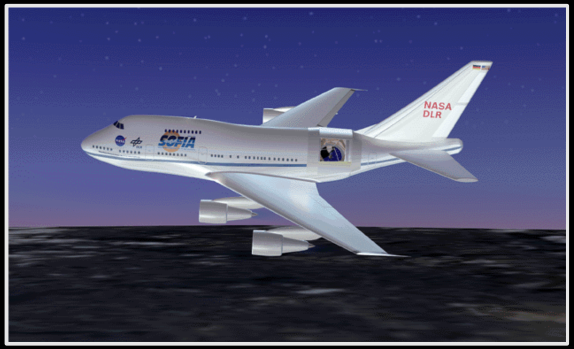
Infrared Studies of Interstellar Dust and Ices with SOFIA





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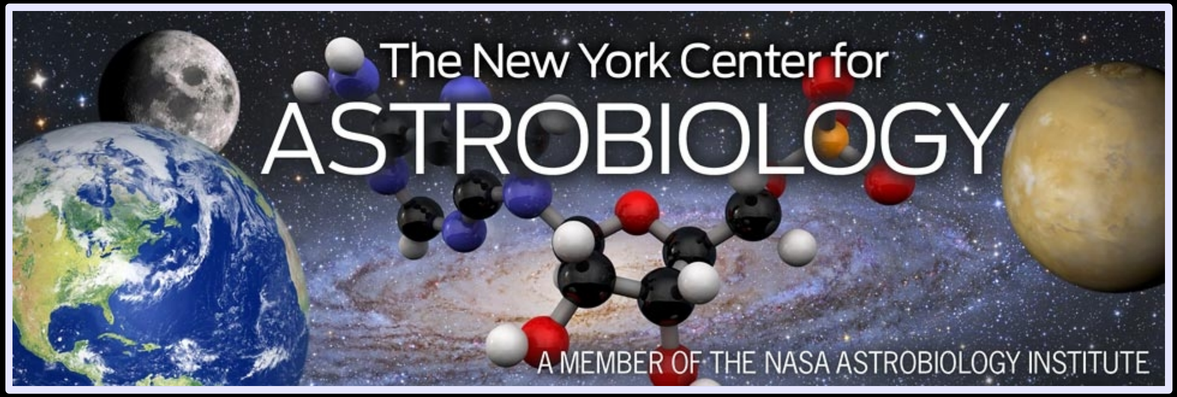
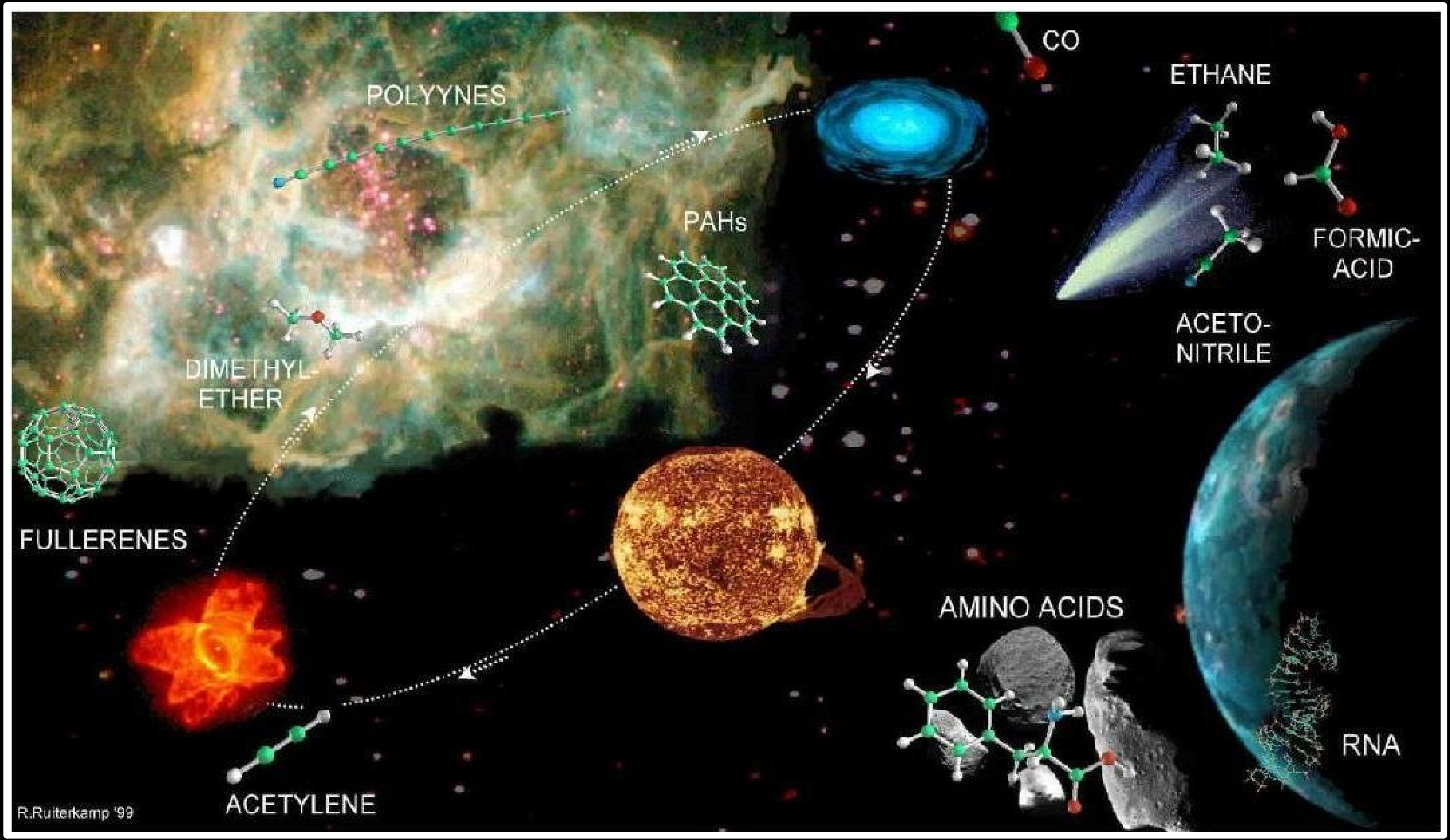


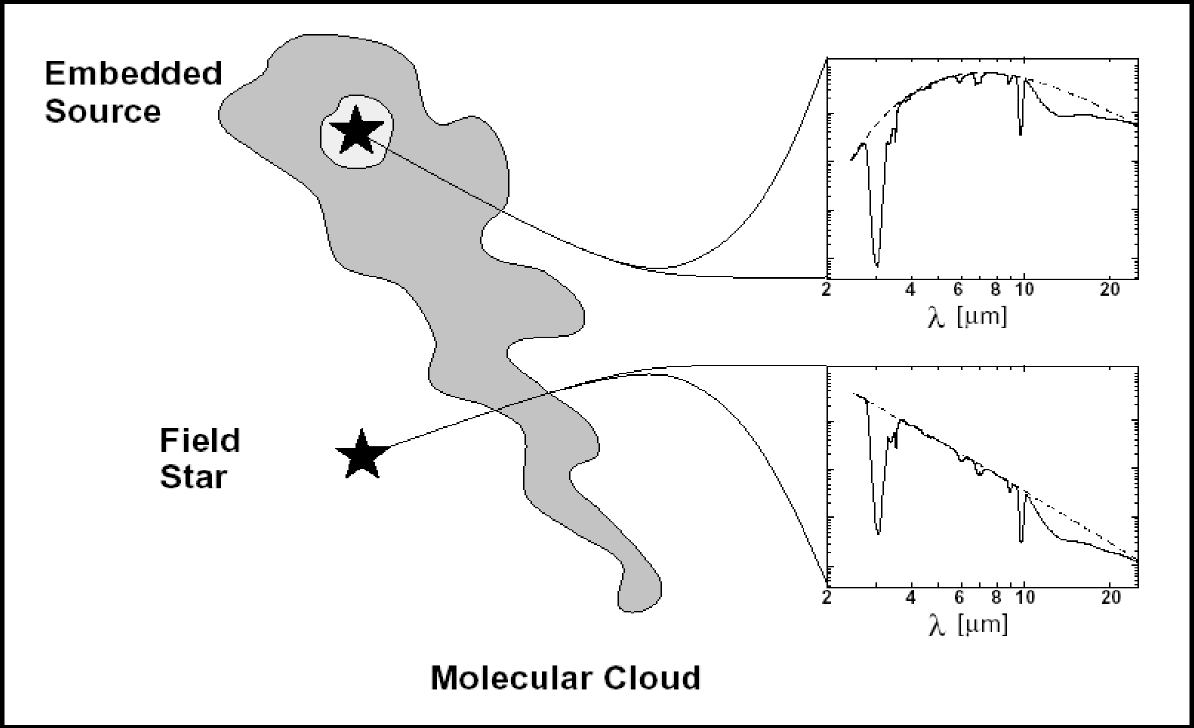
Interstellar dust and astrobiology

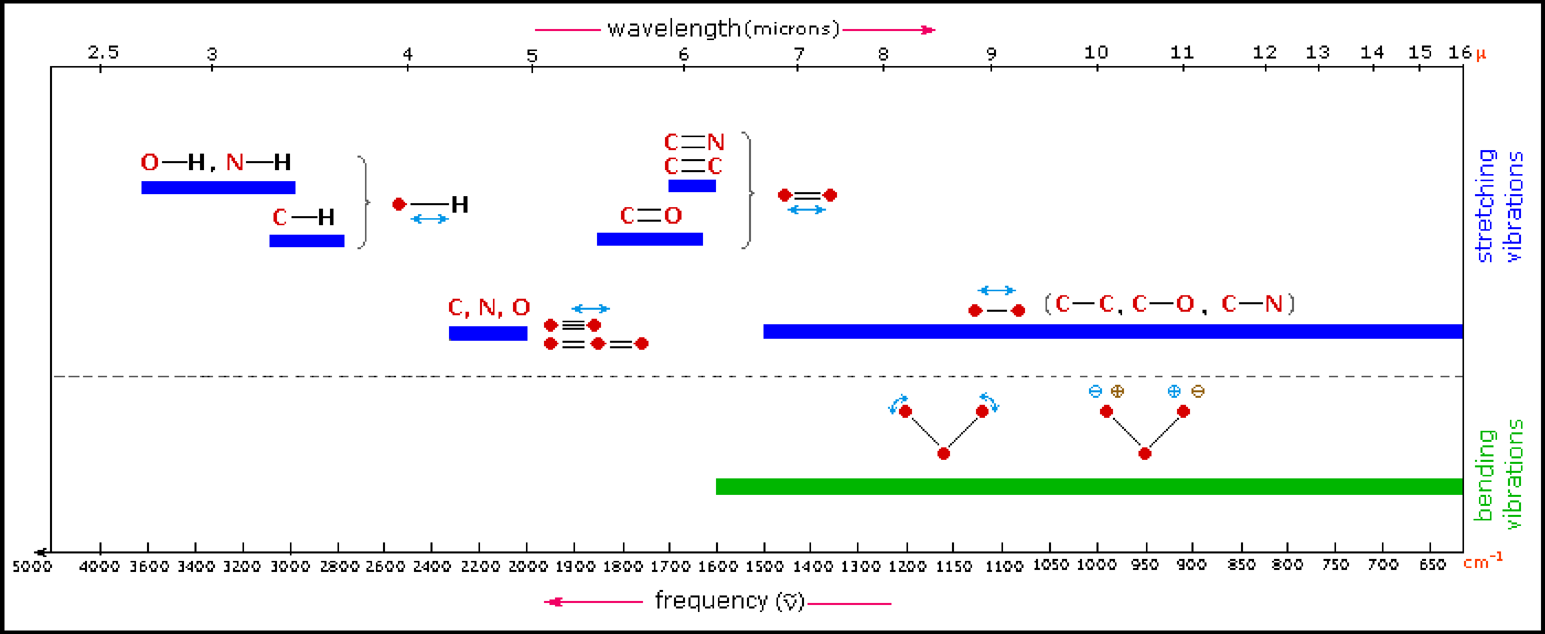


"Processing of simple ices yields complex chemistry that finds its way into planetary systems and eventually into living beings. Understanding the chemistry of interstellar dust and the environments where dust survives will thus provide important clues about the chemistry of life." – Science Vision for SOFIA (2009).

Infrared Spectroscopy

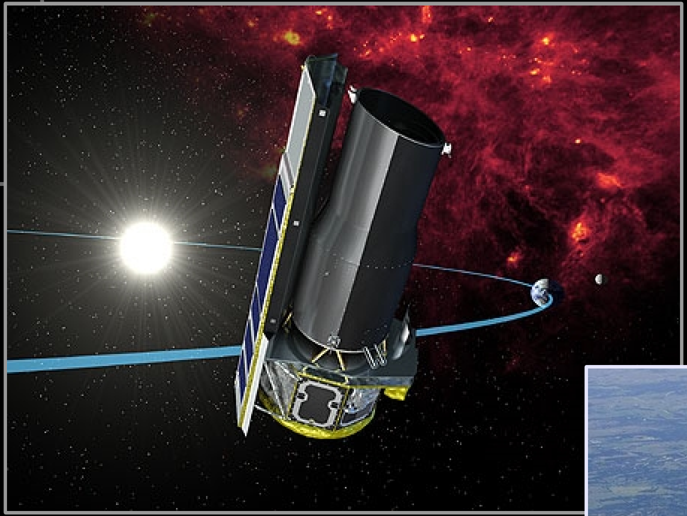
- We observe IR absorption features of dust and ices.
- The 2 – 20 μm spectral range covers almost all of the important vibrational modes of common ices and organics.
- Distinct environments are sampled by observations of background field stars and embedded YSOs.





Space and airborne facilities for IR spectroscopy (1995 – present)

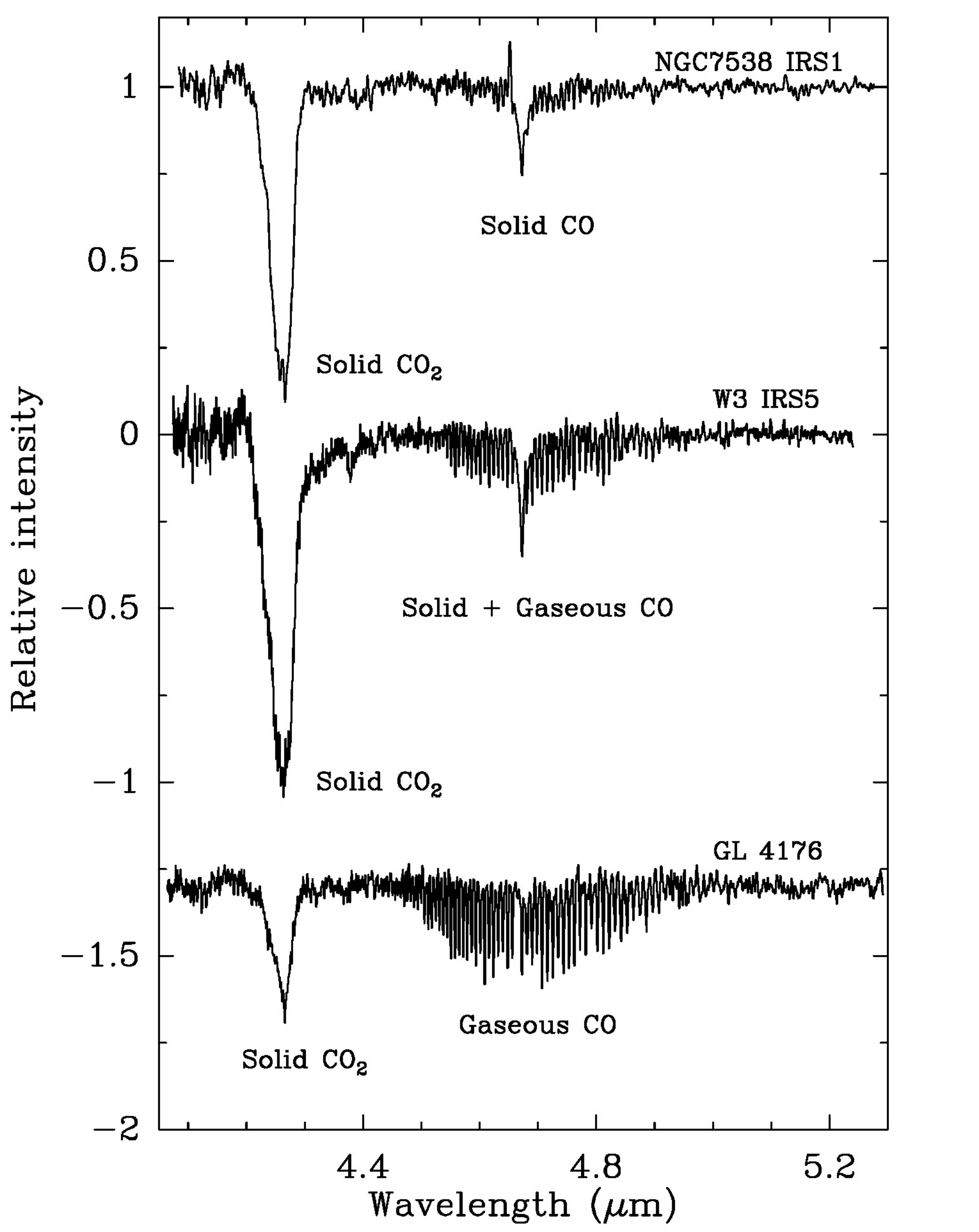
ISO SWS (1995/98)
high resolving power
(modest sensitivity)



Spitzer IRS (2003/09)
Excellent sensitivity
(modest resolving power)

SOFIA: Excellent sensitivity;
high resolving powers available

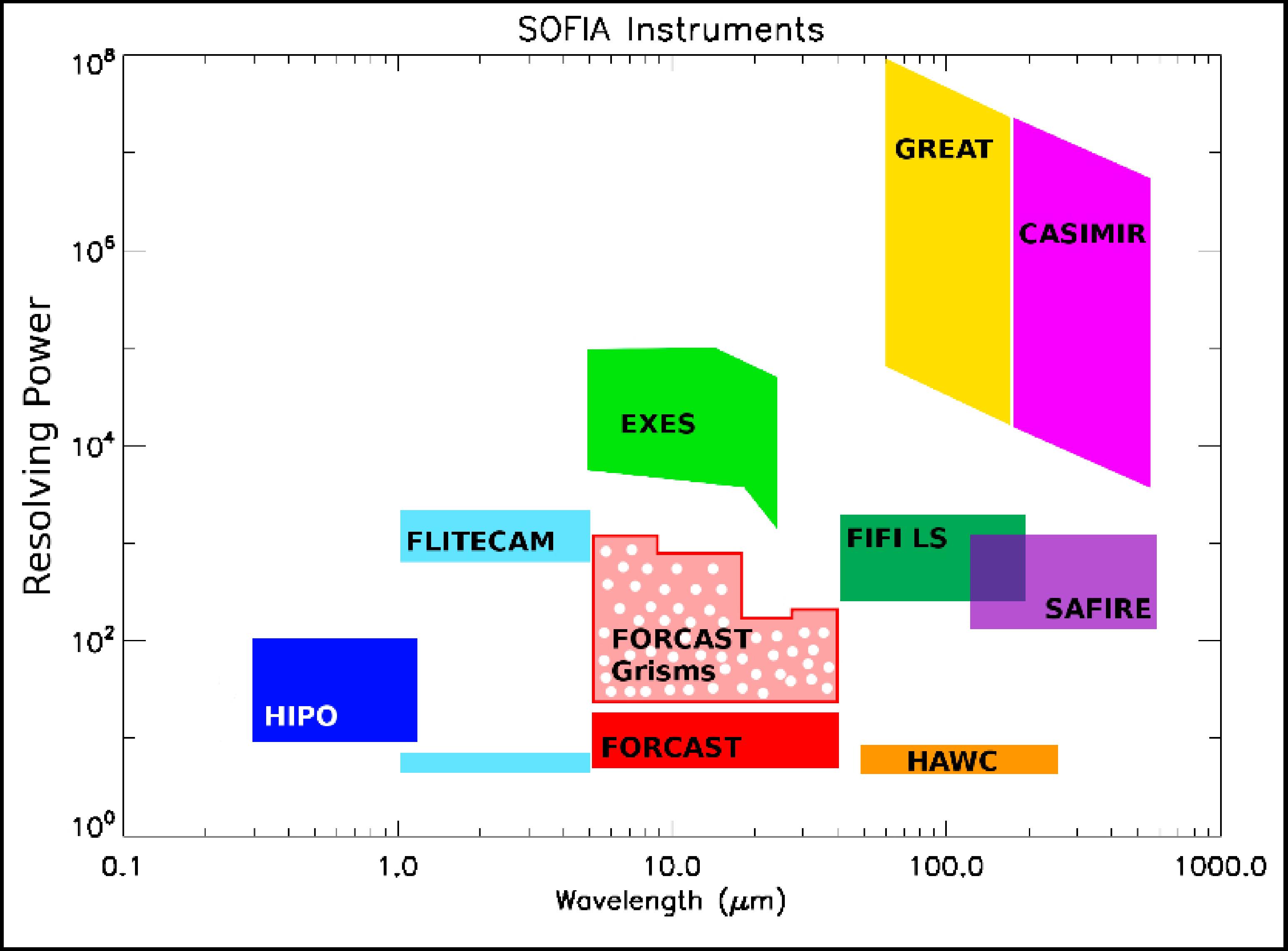
Resolving power: Solid state vs. gas phase



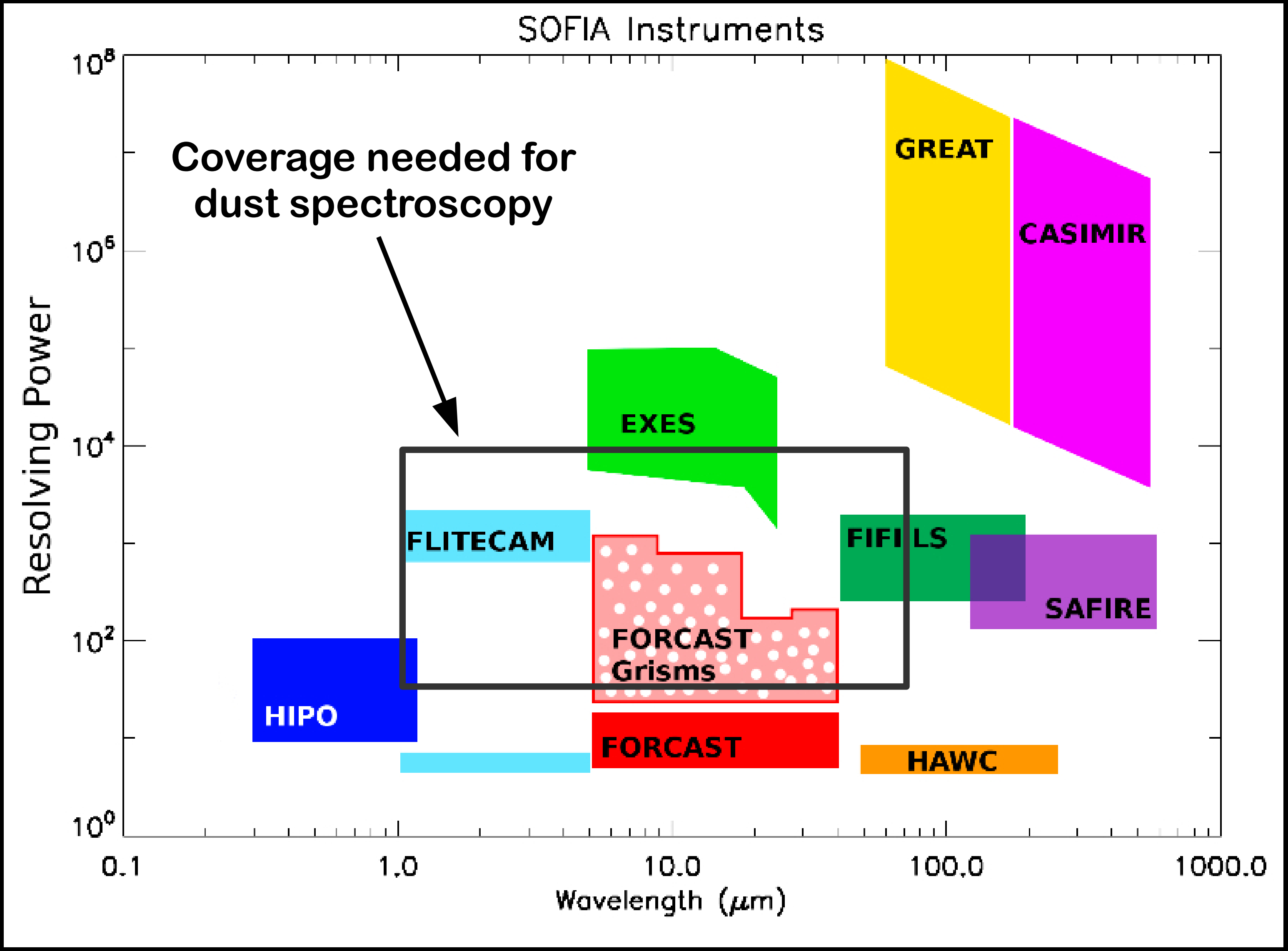
Examples of observed IR features: vibration-rotation bands of gaseous CO and pure vibrational features of solid CO and CO_2. [ISO SWS data; van Dishoeck et al.]

RESOLVING POWERS NEEDED TO EXTRACT ALL INHERENT INFORMATION

Feature	$R = \lambda/\Delta\lambda$
Broad solid features	~ 100 – 500
Narrow solid features + sub-features	~ 500 – 2000
Gaseous vibration-rotation bands	$\geq 10^4$



(From Deen et al. 2008)



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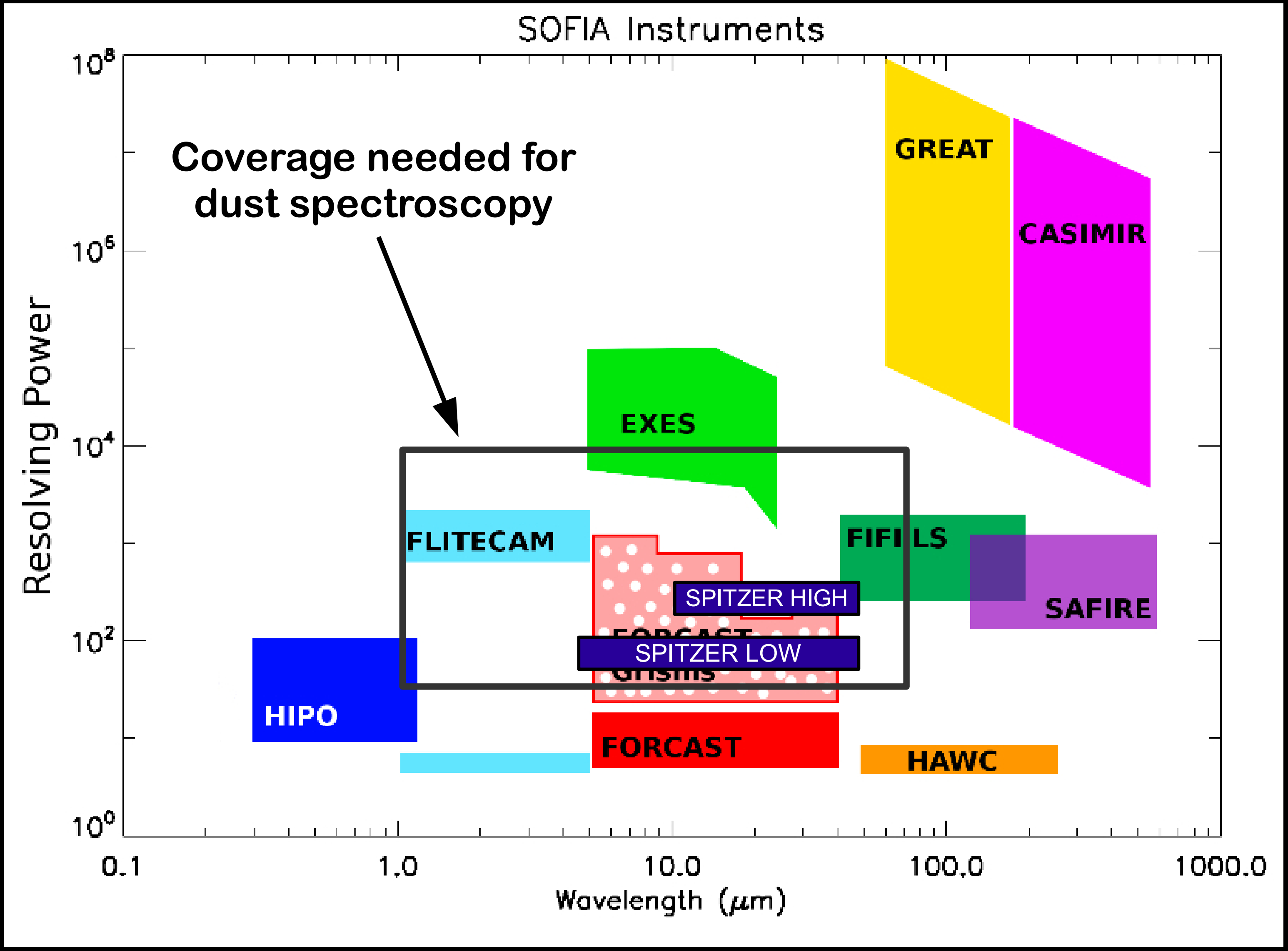

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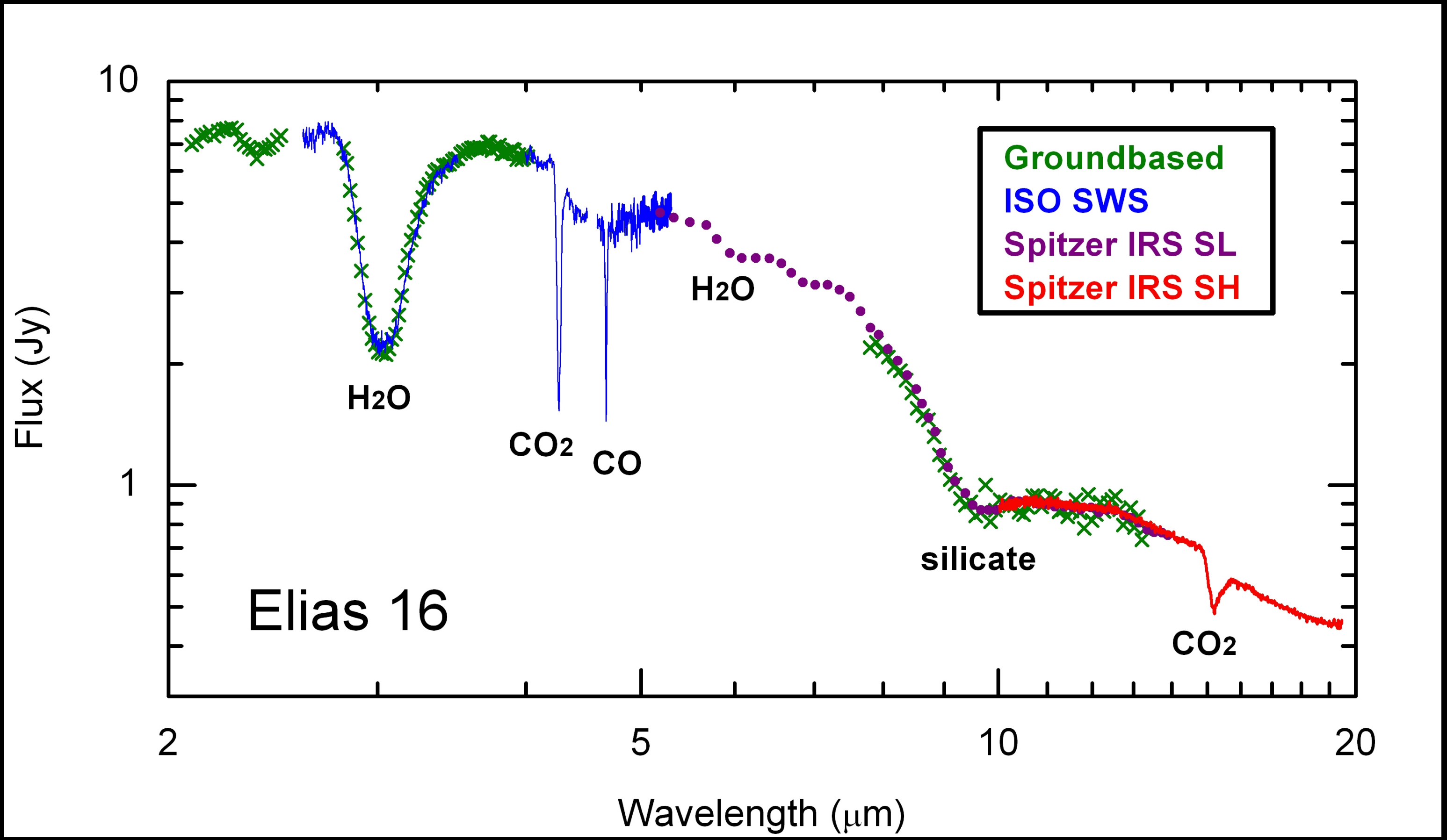
The spectroscopic capability of SOFIA provides opportunities for many important investigations that build upon previous work with ISO and Spitzer.

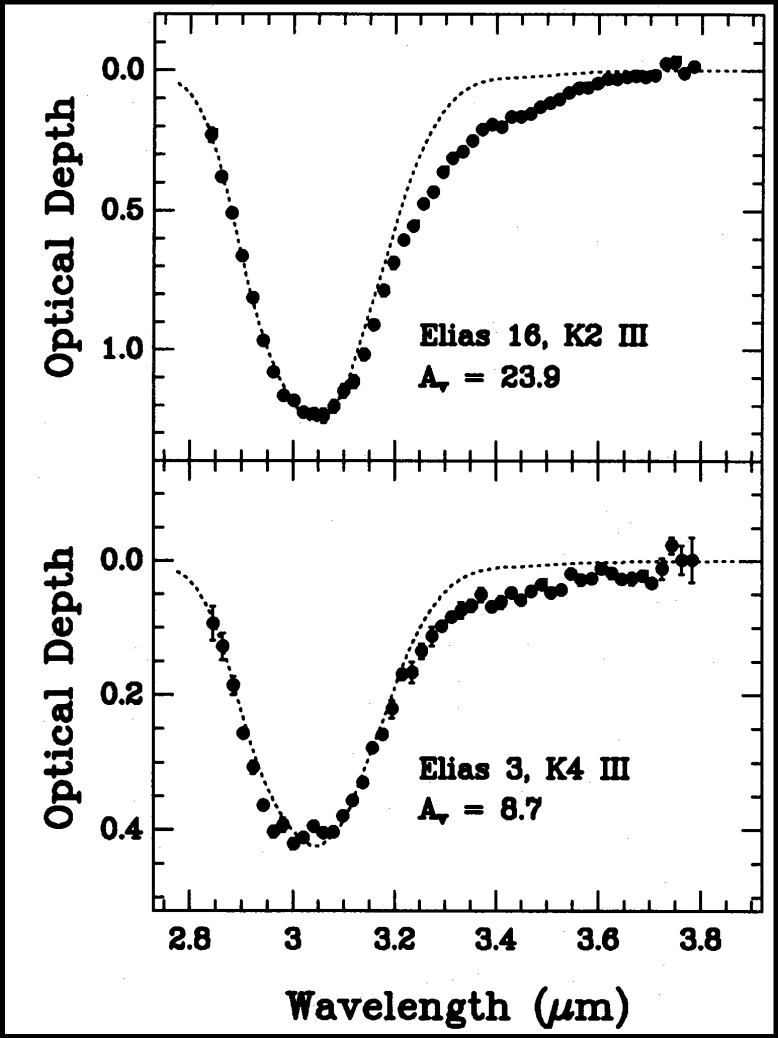
Before describing them in more detail, I discuss two examples of our recent work that underpin planned investigation with SOFIA:

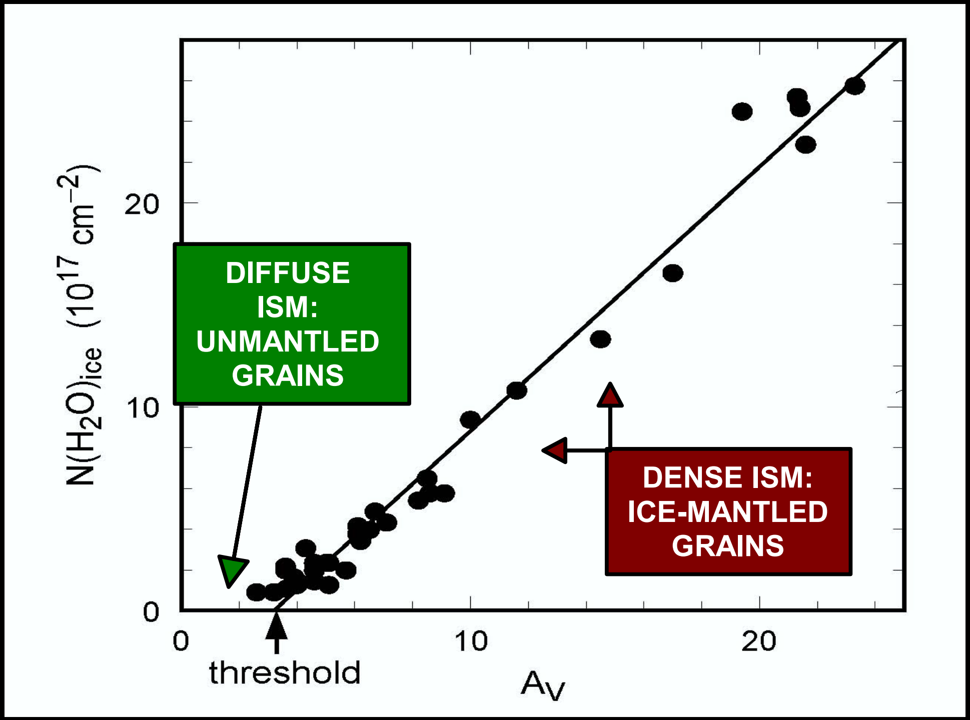
- Evolution of ices from molecular clouds to protostellar envelopes
- The oxygen deficit: O-bearing organics in the ISM?

Ices in molecular clouds



Elias 16 – a well-studied field star behind a dense molecular cloud (Taurus). The Spitzer IRS was particularly well suited to studies of the CO_2 bending-mode feature at 15.3 μm (short-high mode of the IRS).



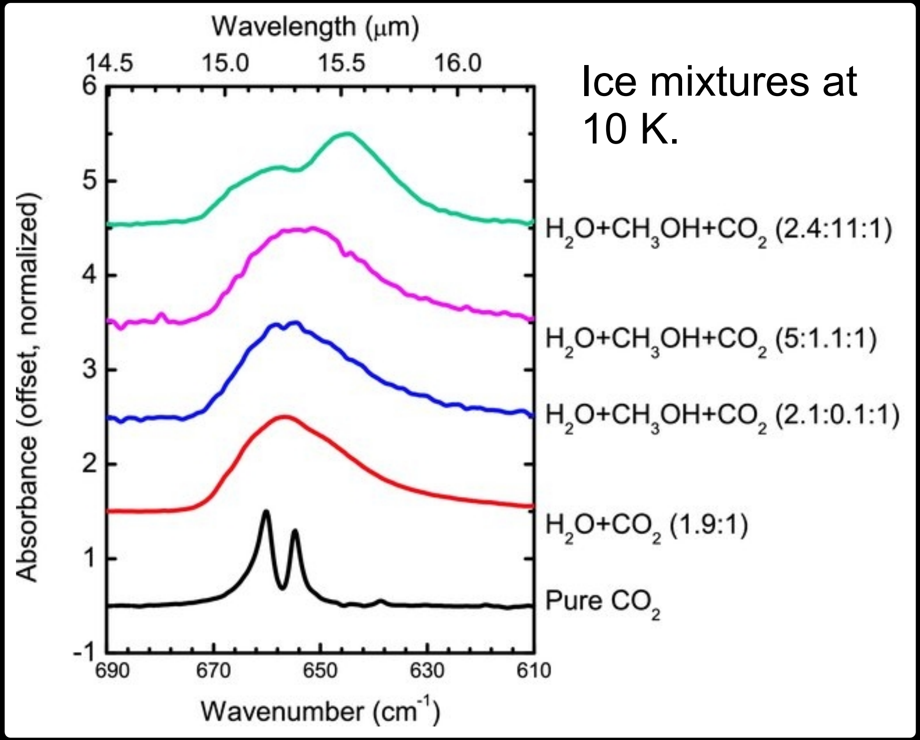


H_2O and CO_2 ice column densities correlate closely with each other and with dust extinction above some threshold value. Abundances relative to total H can thus be estimated.

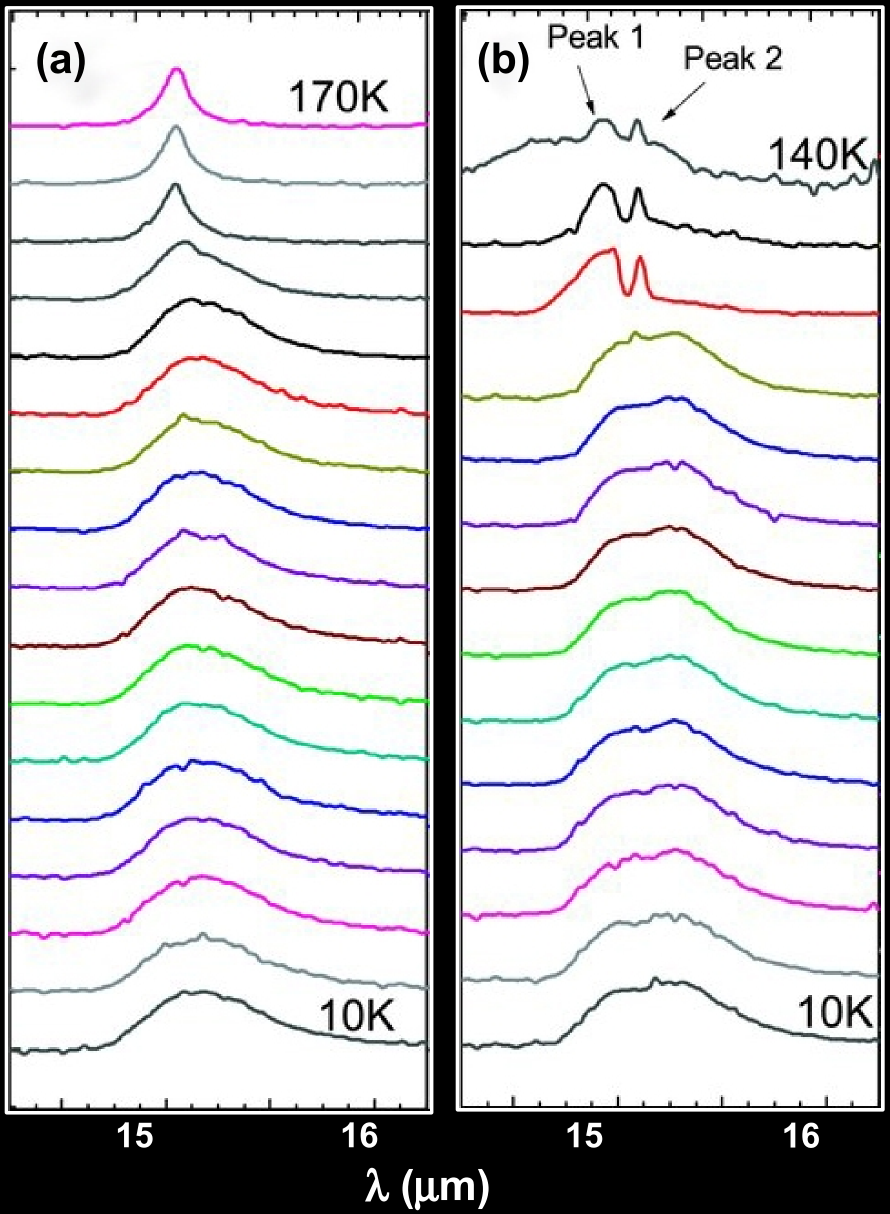
Solid state profiles in cold clouds are consistent with amorphous ice at T ~ 10 K (e.g., Smith, Sellgren & Brooke 1993).

Case study: The CO_2 bending mode and thermal processing

Lab results from White et al. 2009, ApJS, 180, 182.

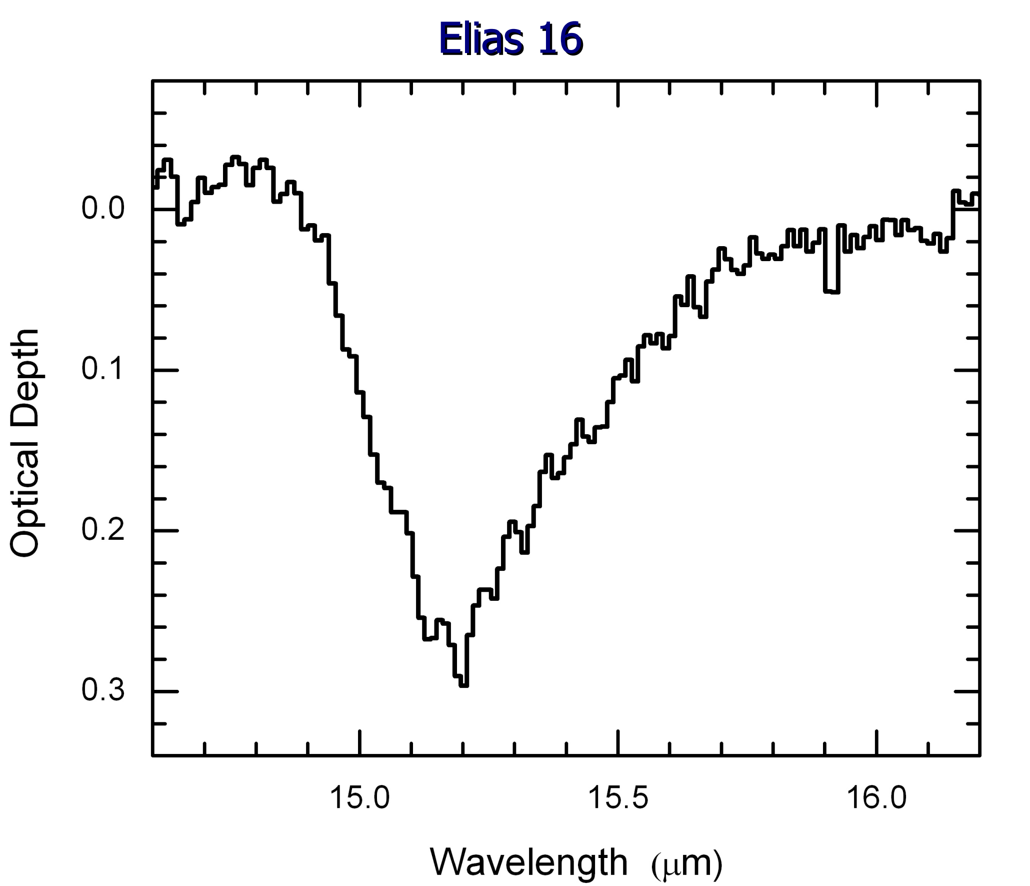


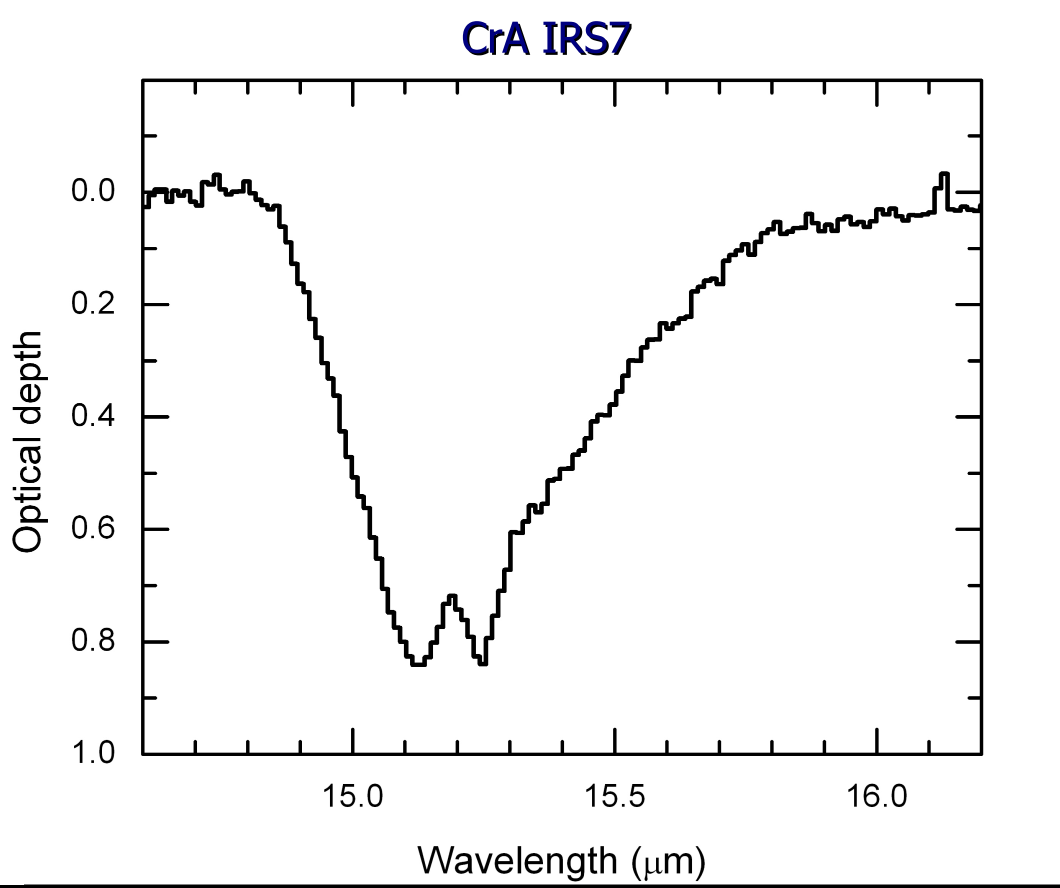
Effect of composition.



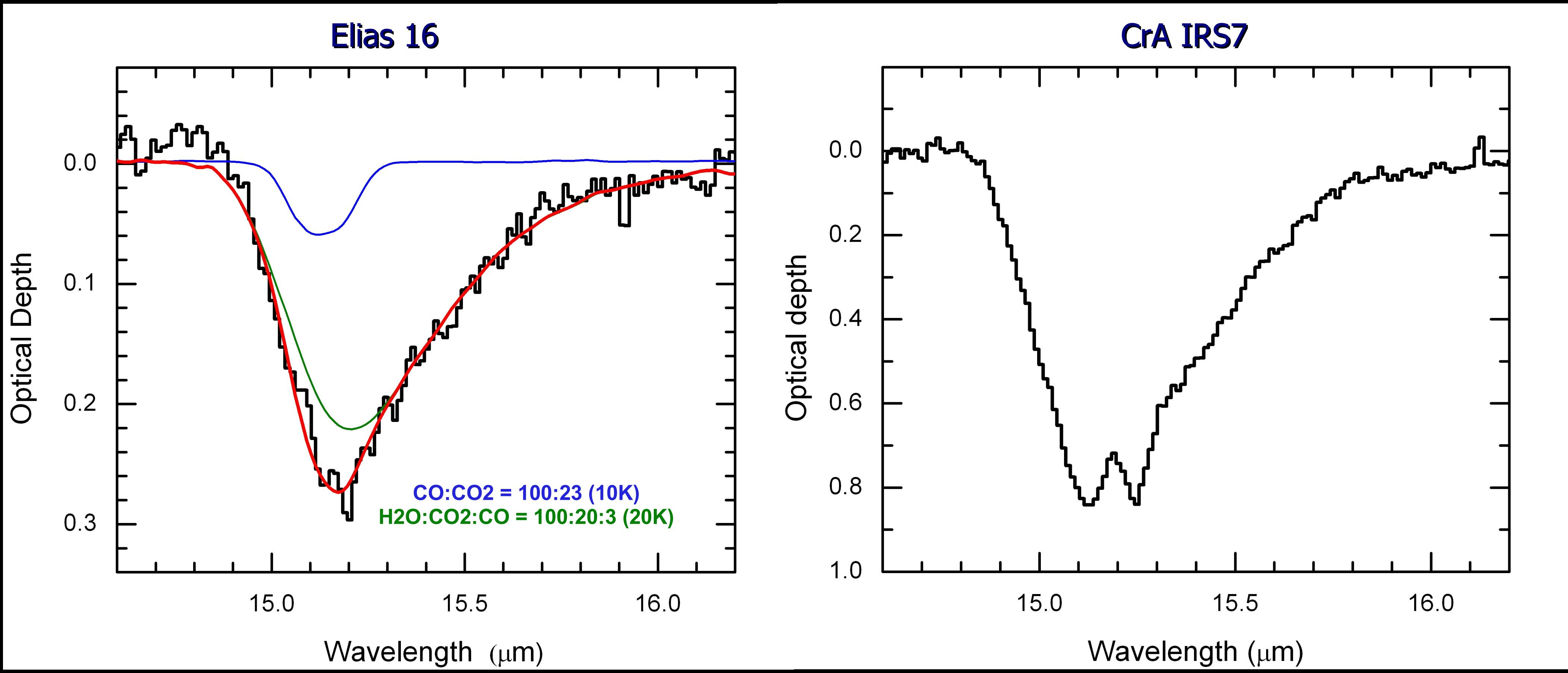
Effect of temperature: (a) Water-rich mixture (H_2O + CH_3OH + CO_2 = 5.3:0.6:1); (b) Methanol-rich mixture (H_2O + CH_3OH + CO_2 = 1.5:2.1:1).

Field star vs. YSO





Field star vs. YSO



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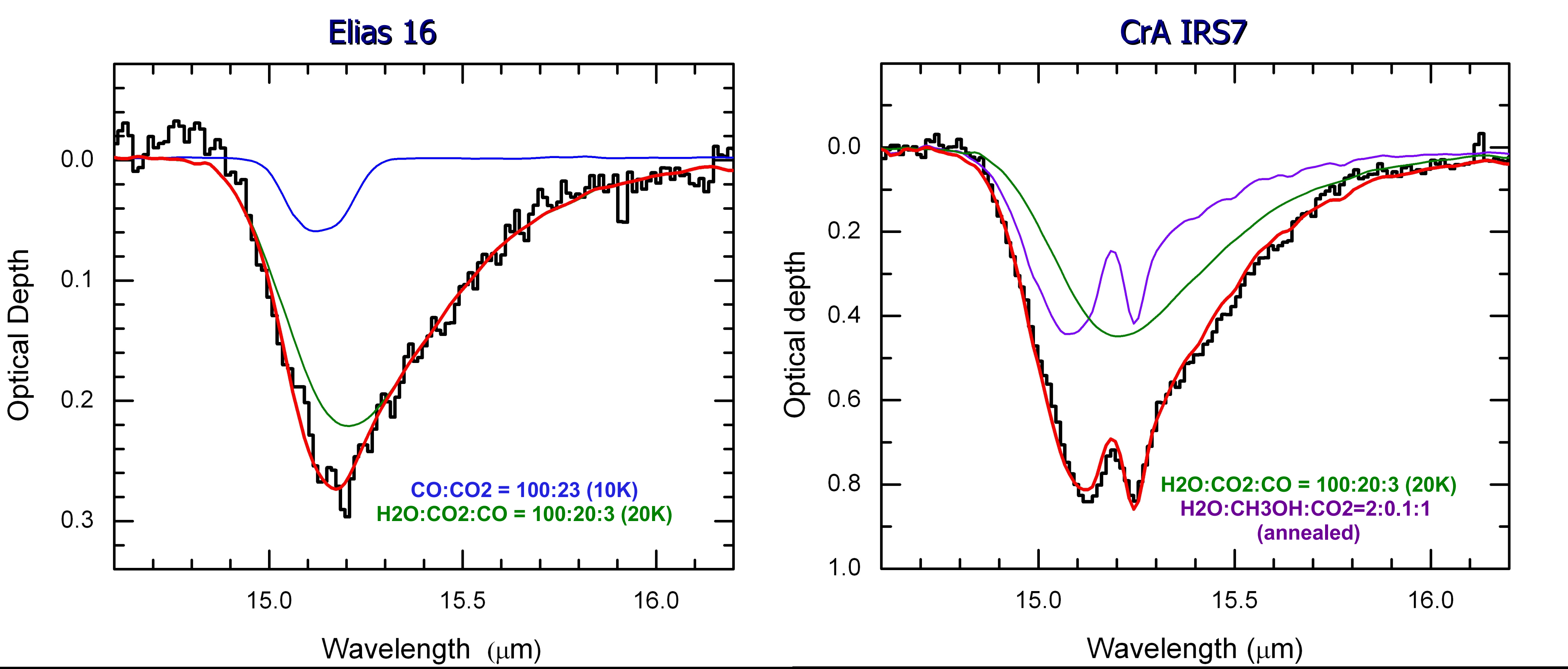

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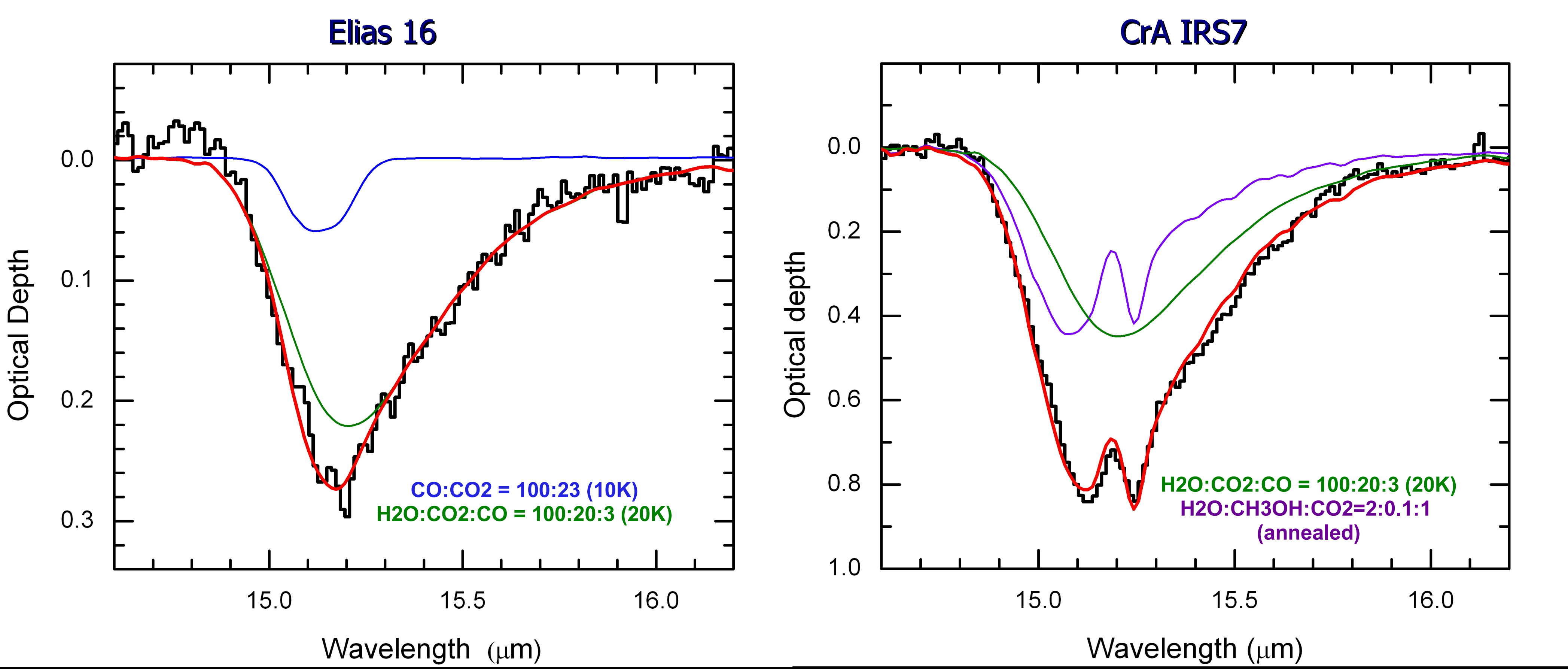


CrA IRS7 is representative of a class of low-mass YSOs that exhibit a crystallized ice component, indicative of heating and annealing of the ices at T ~ 60–100 K in the vicinity of the star (Pontoppidan et al. 2008; Zasowsky et al. 2009; Cook et al. 2009).

Questions

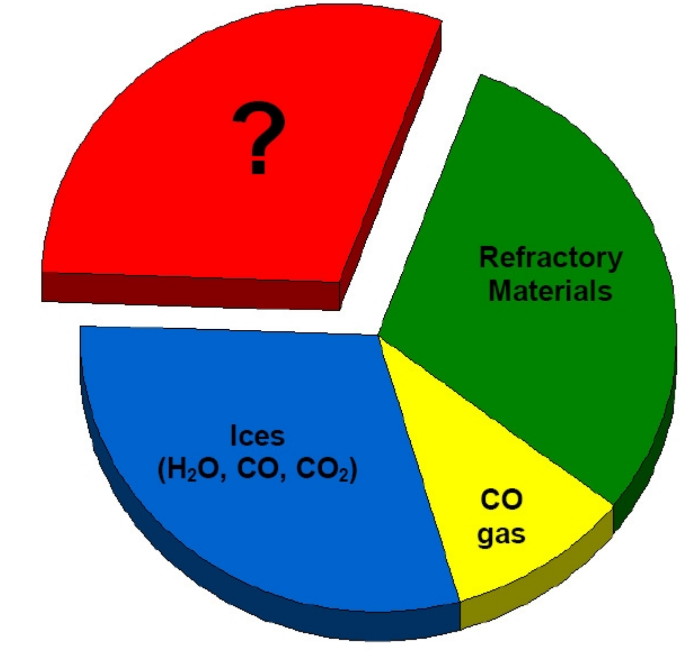
- Does thermal evolution affect the composition as well as the structure of the ices? Is photochemistry also important? *→ Study other species at other wavelengths in sources characterized by observations at 15 μm.*

- What is the distribution of key molecules between solid and gaseous phases? What is the contribution of ice sublimates to gas phase chemistry in hot cores and corinos? *→ Observe solid and gas phase features in the same lines of sight.*

- What are the primary chemical pathways that determine the organic/volatile inventories of protoplanetary disks? *→ Use observations to constrain astrochemical models.*

The oxygen deficit

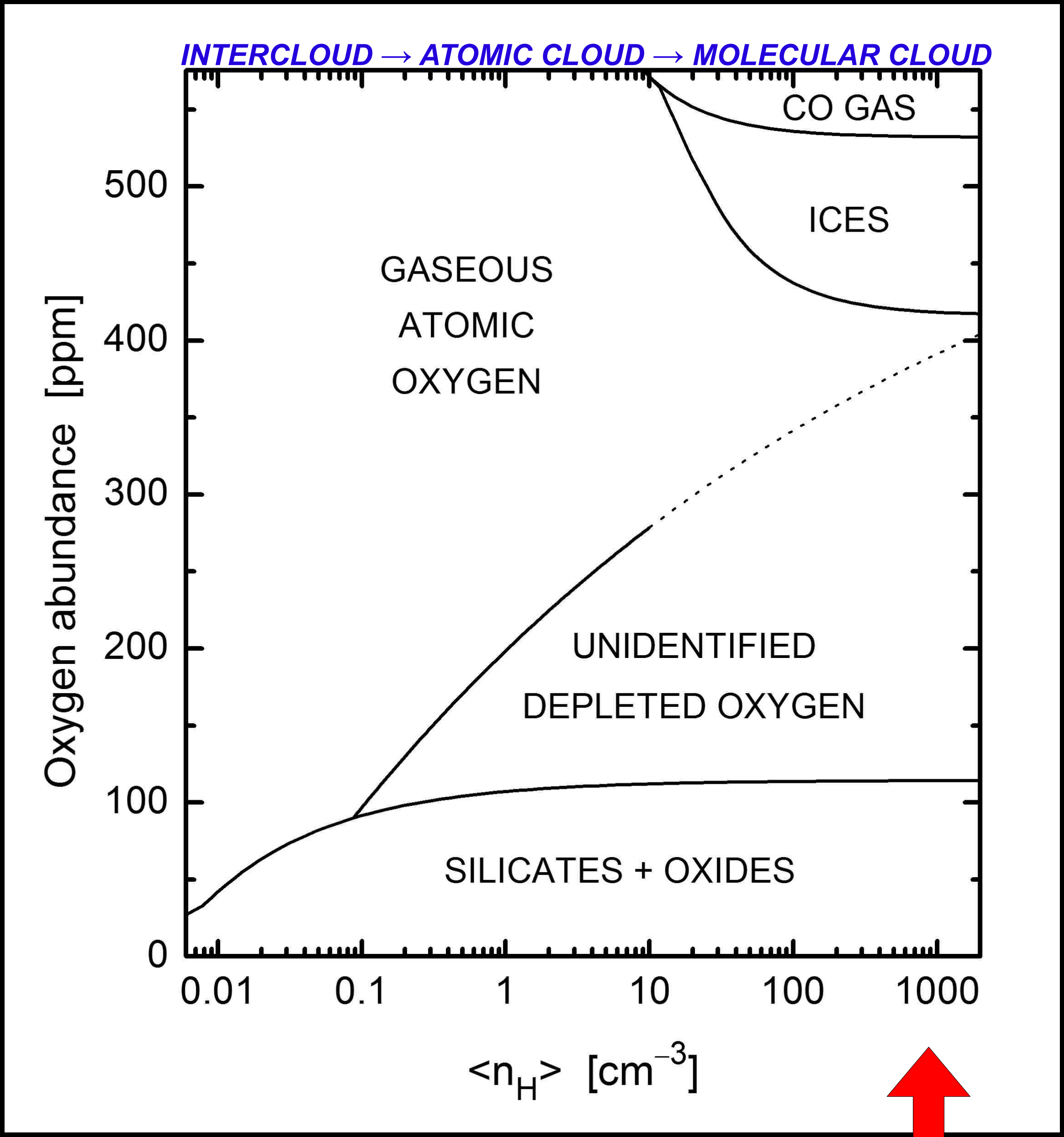
A key question for SOFIA is *"Where is the oxygen in star-forming clouds and disks?"* (Science Vision for SOFIA).



Reservoirs of O in molecular clouds

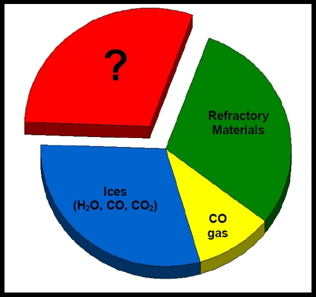
- O is the least well understood of the major chemical elements relevant to life, in terms of its distribution between major reservoirs.
- SOFIA will allow a far more precise inventory of O in the solid phase to be determined, as well as providing access to important gas phase lines of O, OH and H_2O.
- Recent work shows that the "missing O" problem is not limited to molecular clouds but extends to diffuse regions of the ISM as well.

The oxygen deficit (cont.)

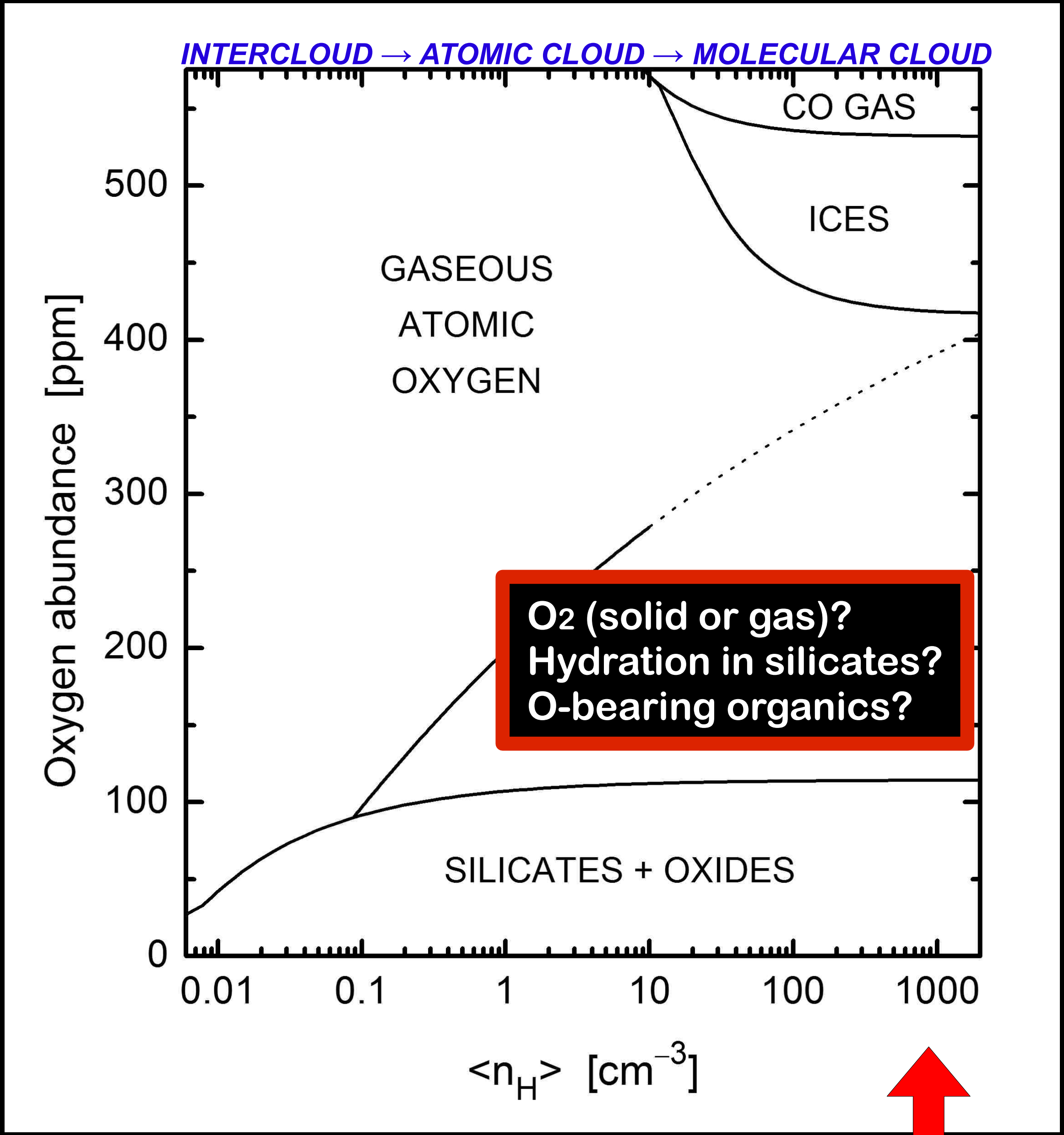


(Adapted from Whittet, 2009, ApJ, in press)

Recent work on abundances in the diffuse H I phase of the ISM (Jenkins 2009) has caused a crisis in our understanding of the nature of interstellar dust. A reservoir of O-bearing dust must exist (additional to the well-documented silicates and ices) to explain the rate at which O atoms are being attached to grains.



The oxygen deficit (cont.)



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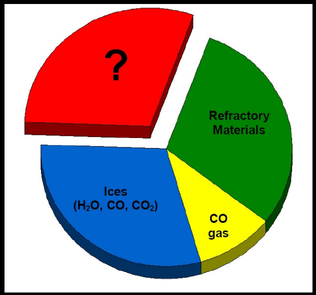
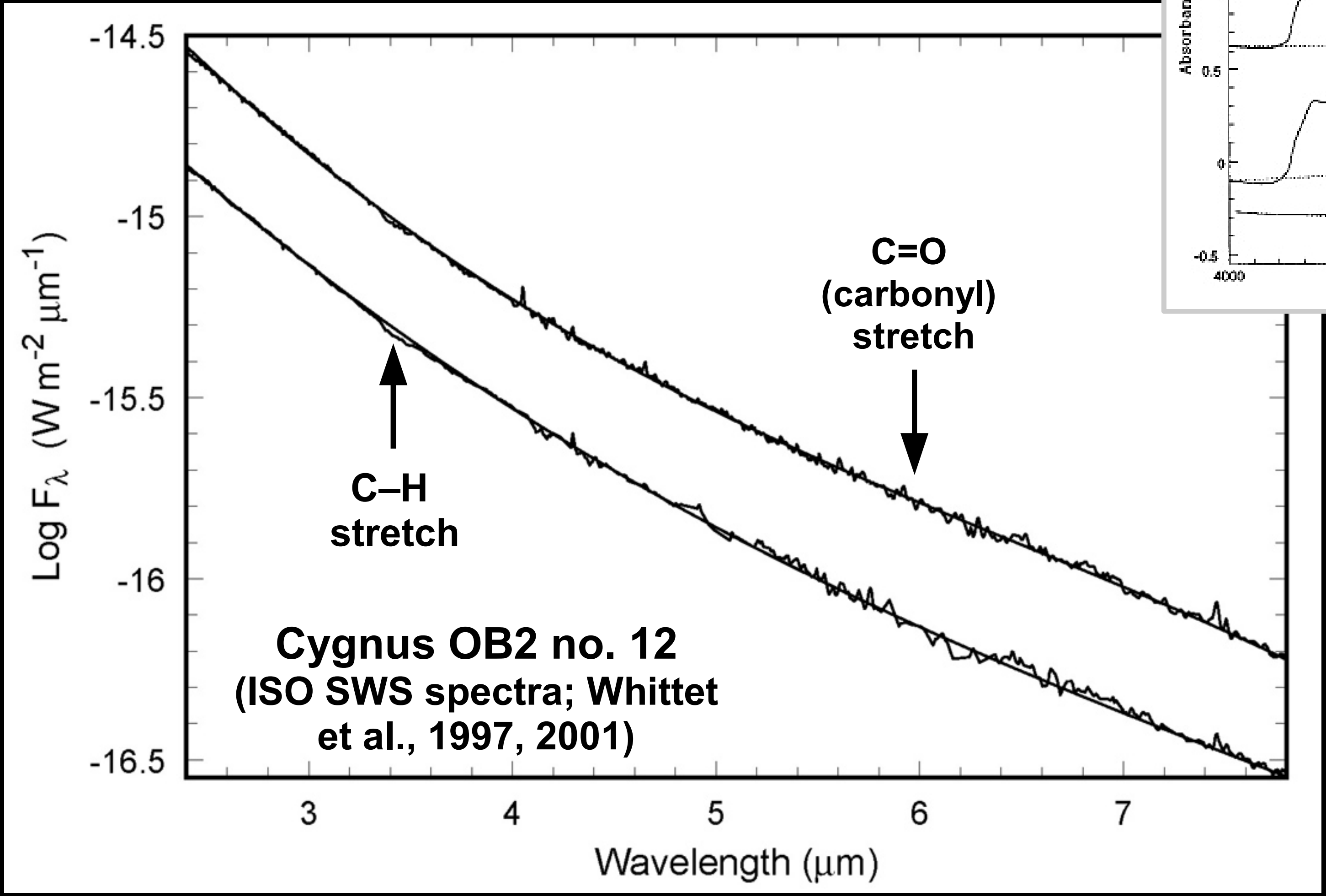
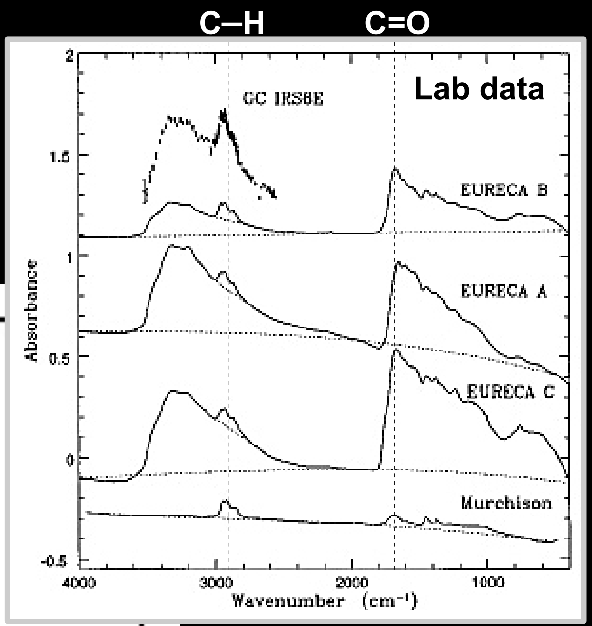


The search for organic refractory matter in interstellar dust (Greenberg's model revisited)





Greenberg et al. (1995)

Previous work by (e.g.) Pendleton & Allamandola (2002) suggests that ORM is no more than a minor constituent of the dust. BUT relevant data are available to date for only a tiny sample of targets observed with ISO SWS. SOFIA will do a much more thorough job.

Key science goals for SOFIA

Quantify reservoirs of key chemical elements in the ISM (especially oxygen)
Identify key pathways for chemical evolution from the ISM to protoplanetary disks; roles of gas phase and surface chemistry
Clarify links between chemistry and physical conditions (crystallization, photochemistry, shocks; role of ice sublimates in hot-core chemistry)
Quantify distribution of key molecules (e.g. CO) between solid and gaseous phases in different environments
Predict organic/volatile inventories of early solar systems as functions of mass; role of star-formation environment (OB vs. T associations)
Clarify origins of primitive matter in our Solar System

Target features by instrument

SOFIA Instrument	Useful λ range	R = λ/Δλ	Target features
FLITECAM grism mode	2 – 5 μm	2000	*N-bearing ices (ammonia, nitriles, cyanates)* *C–H stretch region (ices, organics)* *CO-bearing ices; $^{13}CO/CO$ ratio*
FORECAST grism mode	5 – 40 μm	200	*Water-ice bending mode* *Carbonyl features in kerogens and ices* *Other key ice features (CH_3OH, NH_3, etc.)* *Silicate dust*
FIFI-LS	40 – 80 μm	3000	*Water-ice*
EXES	5 – 28 μm	$10^3 – 10^5$	*Fine structure in solid state features* *Gas phase abundances; gaseous CO survey of targets with solid CO detections*