Volatiles in Inner Disks – an observational perspective

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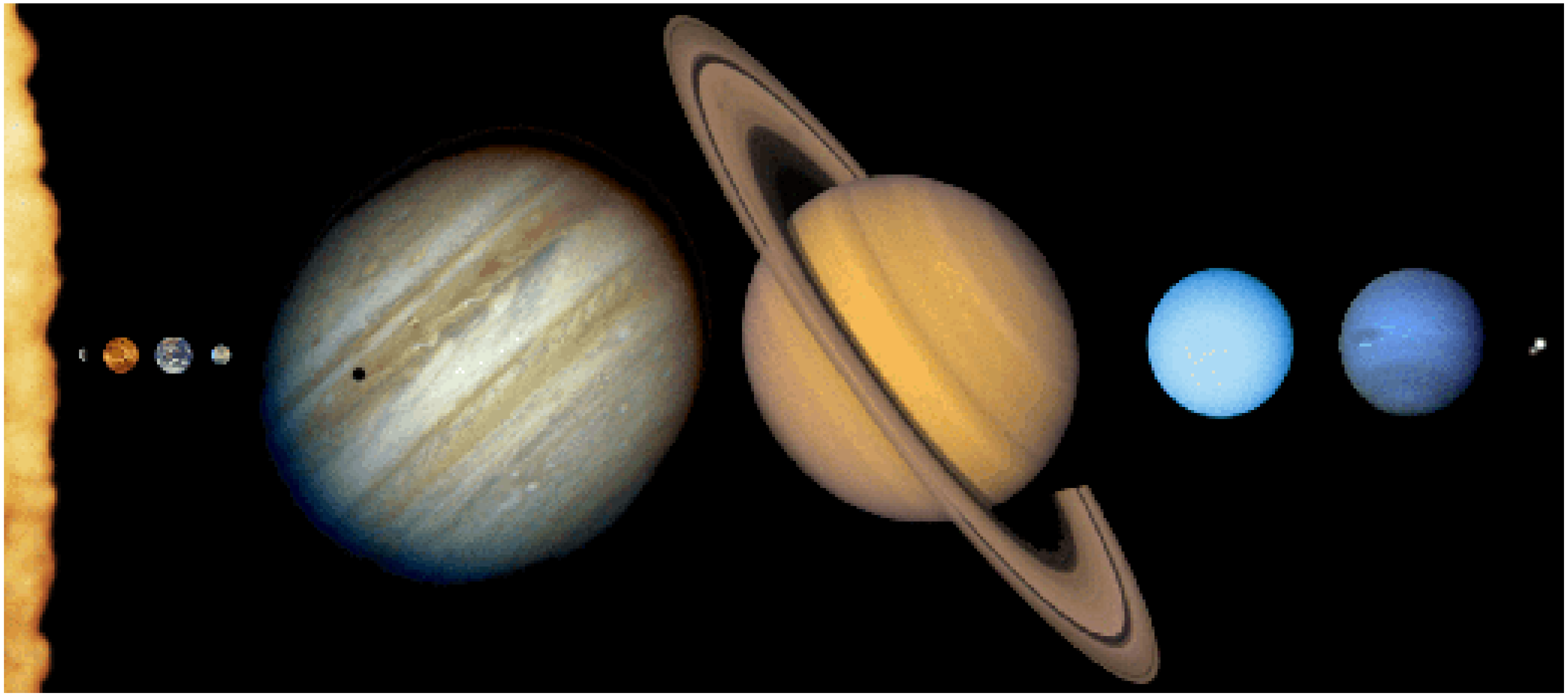
What is the connection between disk volatiles and planetary properties?

Most **refractory** ⟷ Most **volatile**

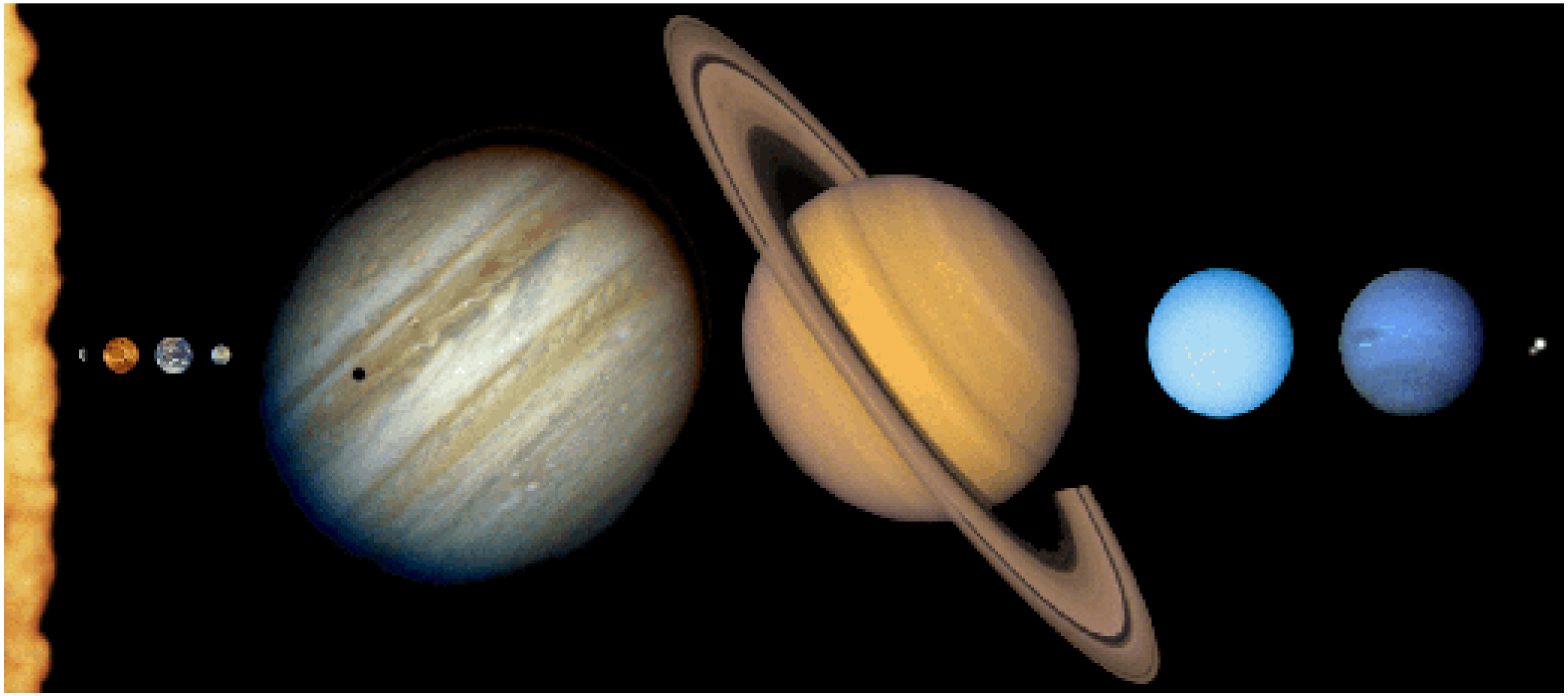


Source: NASA

What is the connection between disk volatiles and planetary properties?

Hot: Volatiles in **gas** phase

Cold: Volatiles in **solid** phase



Source: NASA

The condensation sequence

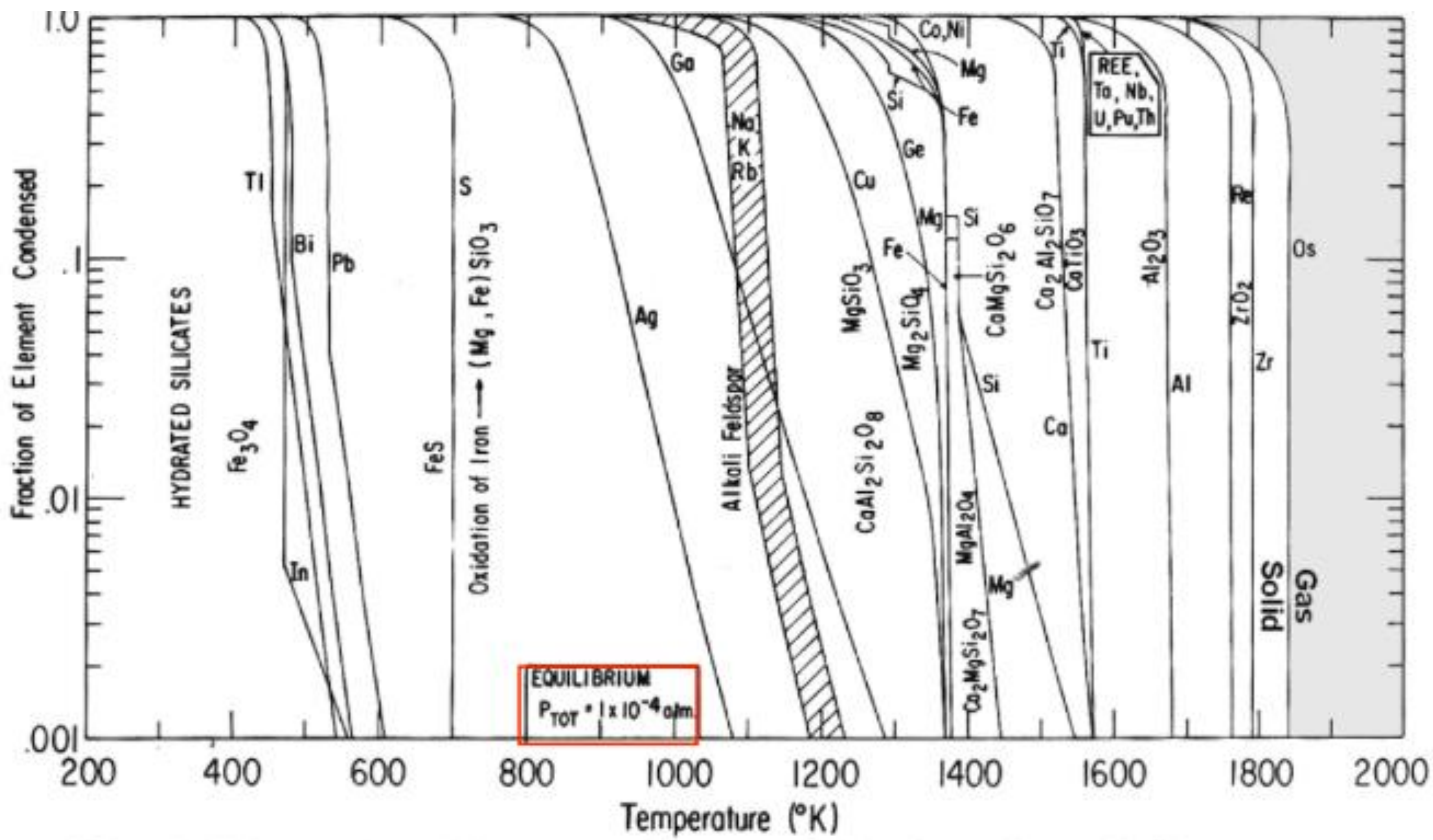


Figure 6.6 Condensation of the elements from a gas of solar composition at 10^{-4} atm.

Grossman 1974

The condensation sequence: The assumptions

Abstract—The distribution of the major elements between vapor and solid has been calculated for a cooling gas of cosmic composition. (is well-mixed)

(was originally hot, Is *in equilibrium*)

“reset” (history lost)

Grossman 1972

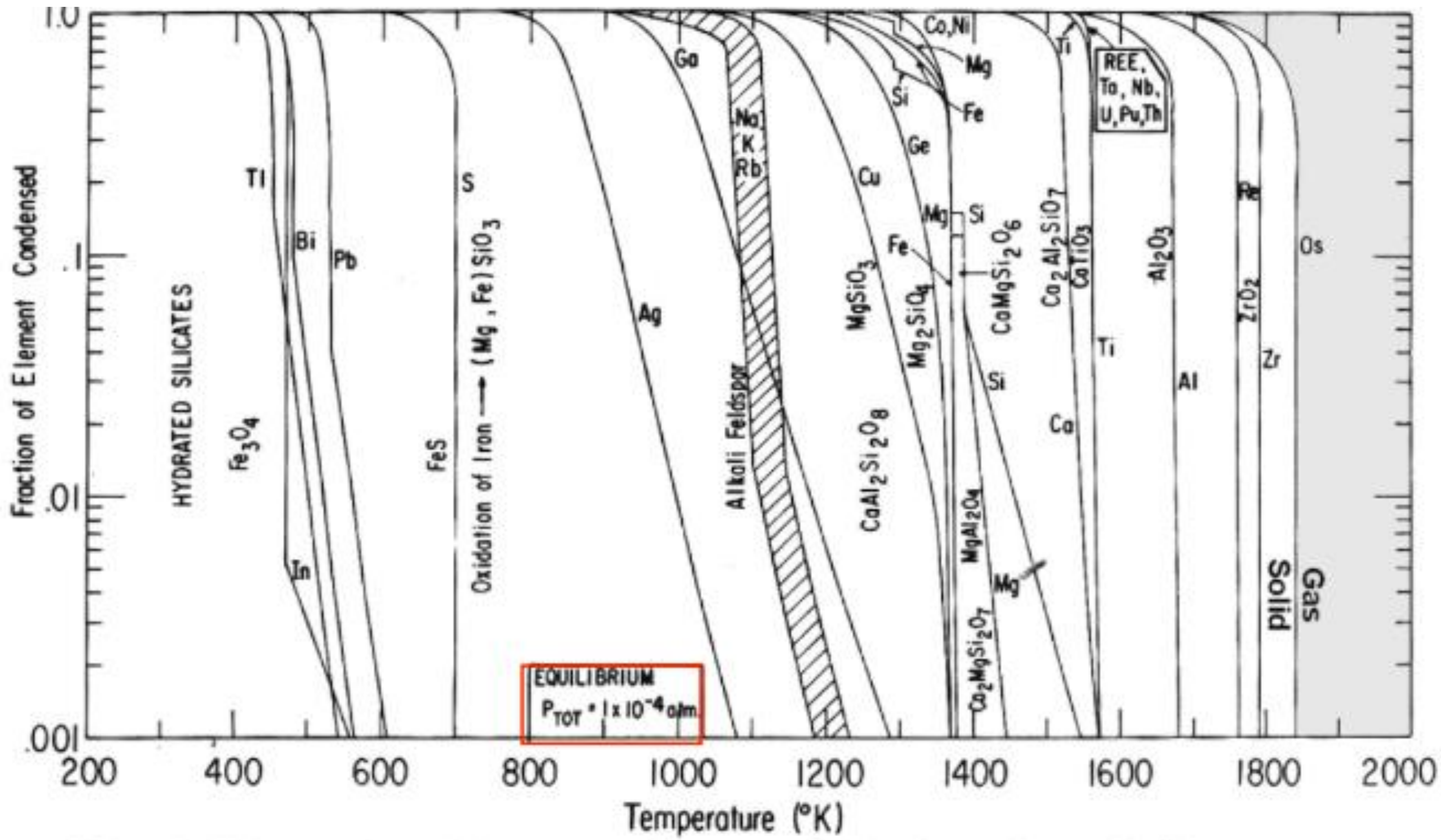


Figure 6.6 Condensation of the elements from a gas of solar composition at 10^{-4} atm.

Grossman 1974

If the solar nebula was NOT hot, or not well mixed… the condensation sequence calculations no longer hold.

A tale of two C carriers:

Becomes planetary building block

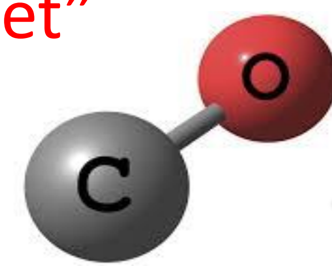
Stays cold, and intact

graphite

“inheritance”

“reset”

Is “blown away” into space



Heats up and vaporizes
Recombines with O in gas phase

Evidence for hot, well-mixed protoplanetary disks: FU Ori objects

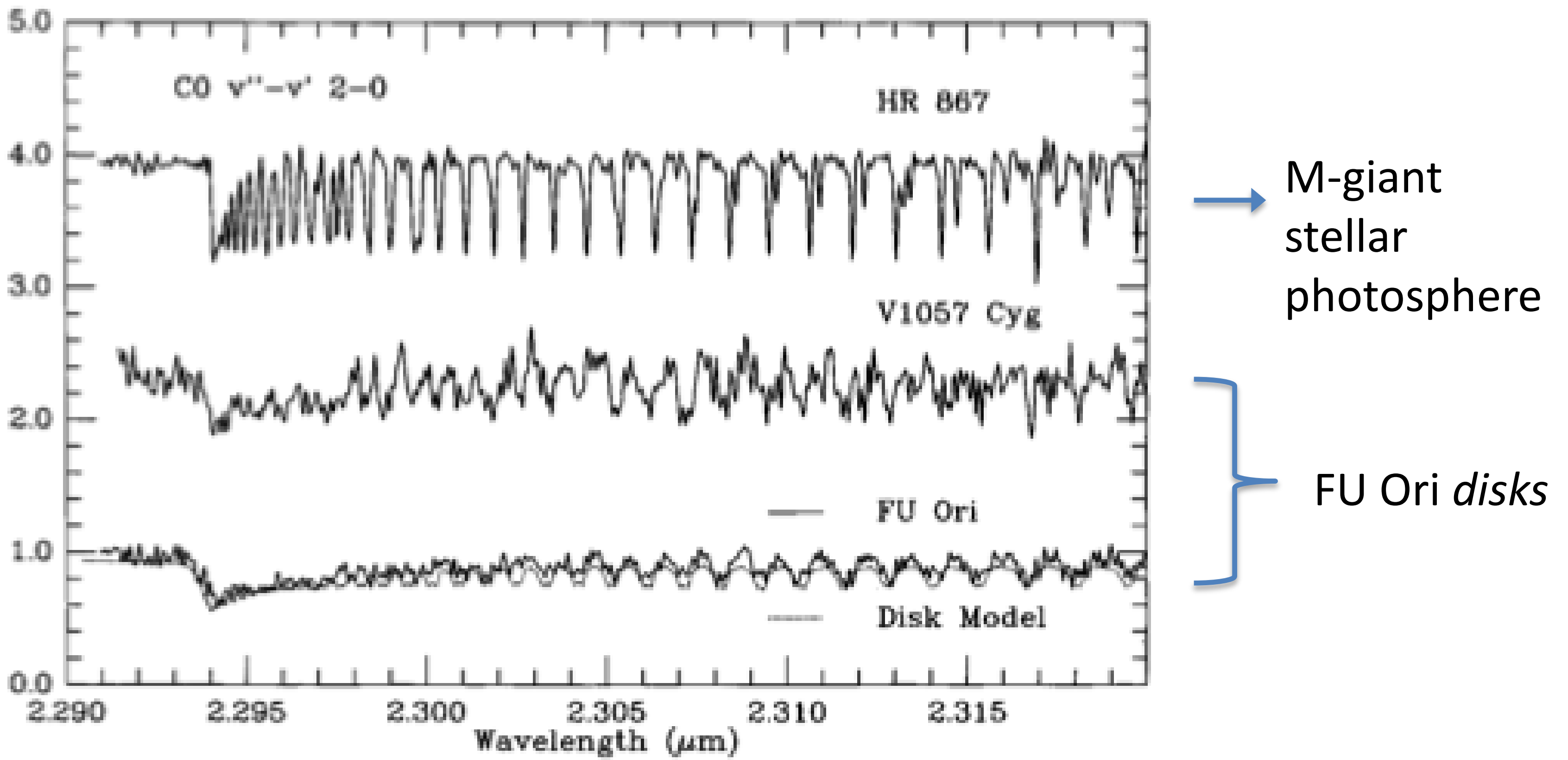


Figure from Hartmann & Kenyon 1996

FU Ori events may be caused by accretion instabilities
But not clear how universal/widespread this phenomenon is

Disk temperatures in a simulated FU Ori disk undergoing outburst

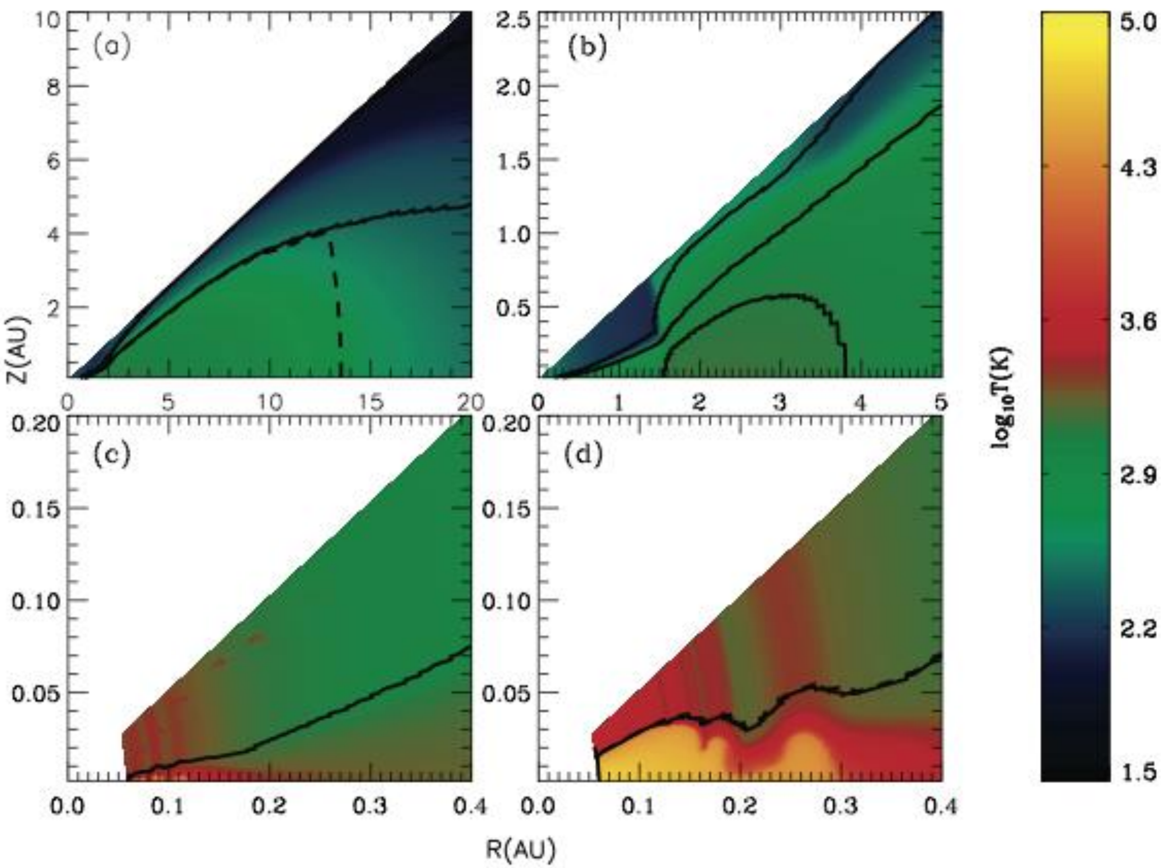
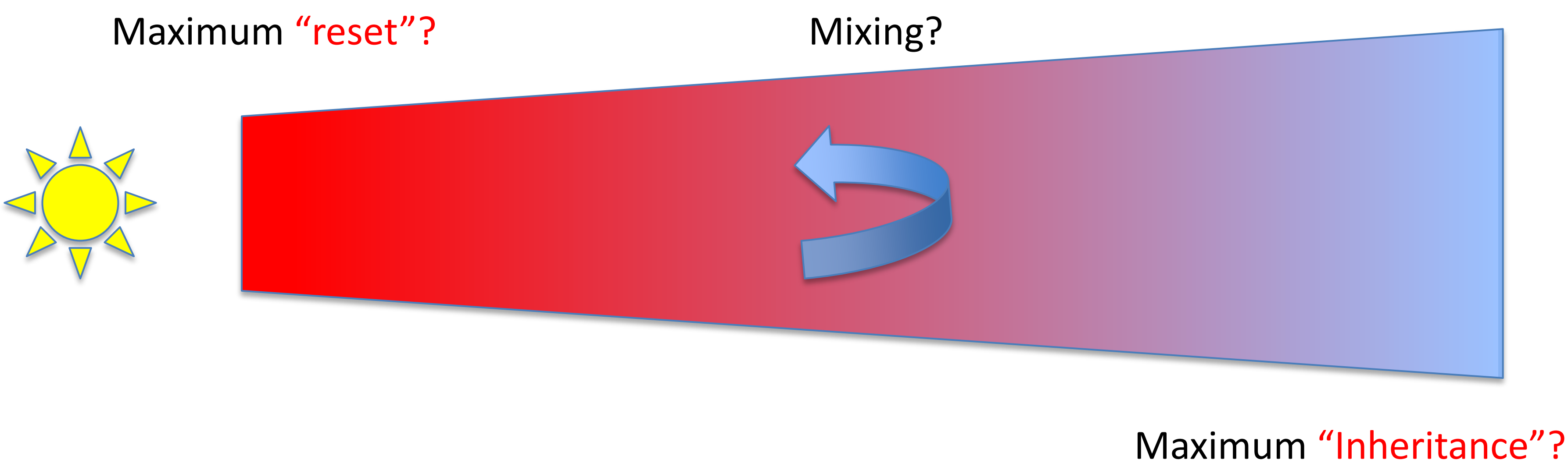


Figure from Zhu+ 2009

What is the path of volatiles? Inheritance or reset?

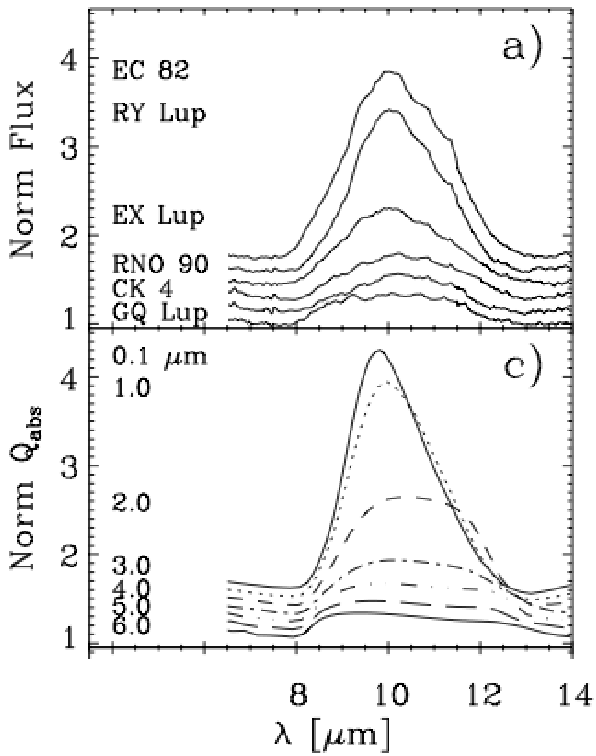


Why chemistry is difficult to determine a priori

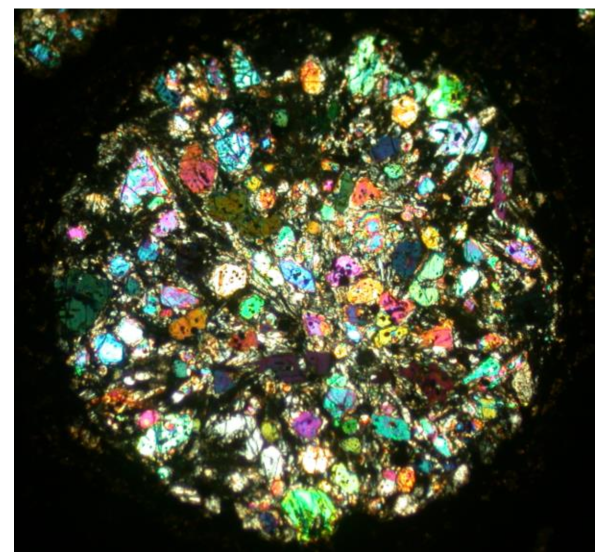
- Many different chemical reactions and corresponding rates
- Many different temperature, density, and radiation field regimes
- Temperatures that depend on details of stellar radiation, whose propagation depends on uncertain dust properties
- Temperatures that depend on details of accretion, whose physics is poorly constrained
- Temperatures and radiation fields that evolve with time as accretion rates change, dust grows
- Things move

All we know about solid state chemistry: Small (but evolved) dust, consistent with olivine composition

Spitzer spectra of Si-O stretch



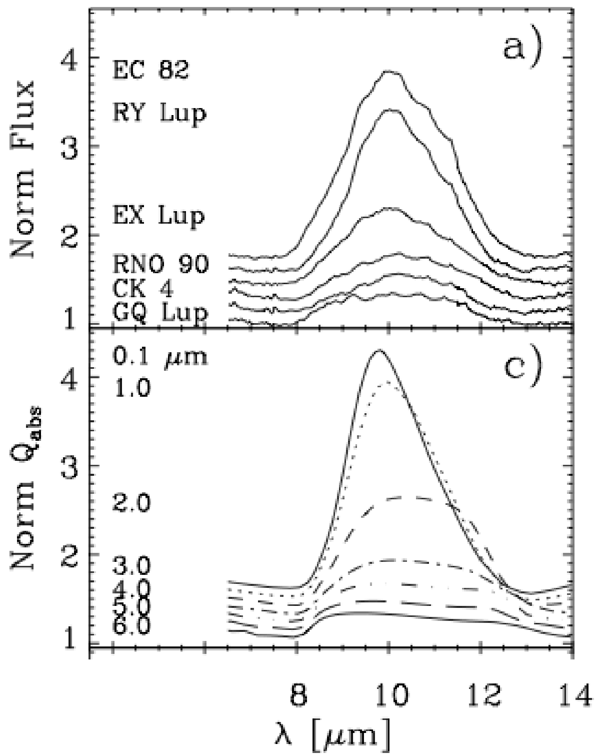
Kessler-Silacci + 2006



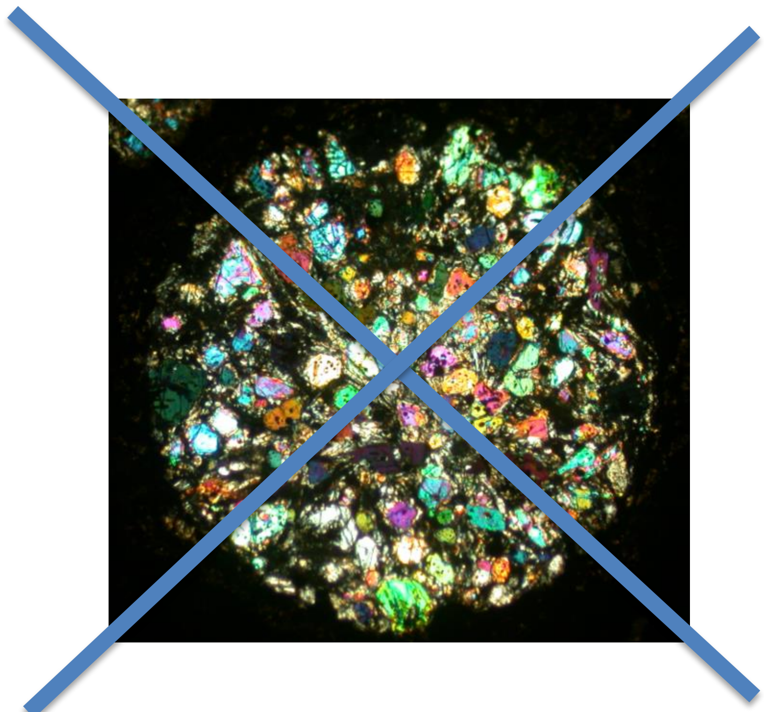
Chondrule from American Museum of Natural History meteorite collection

Solid state chemistry difficult to study; gas phase studied instead

Spitzer spectra of Si-O stretch



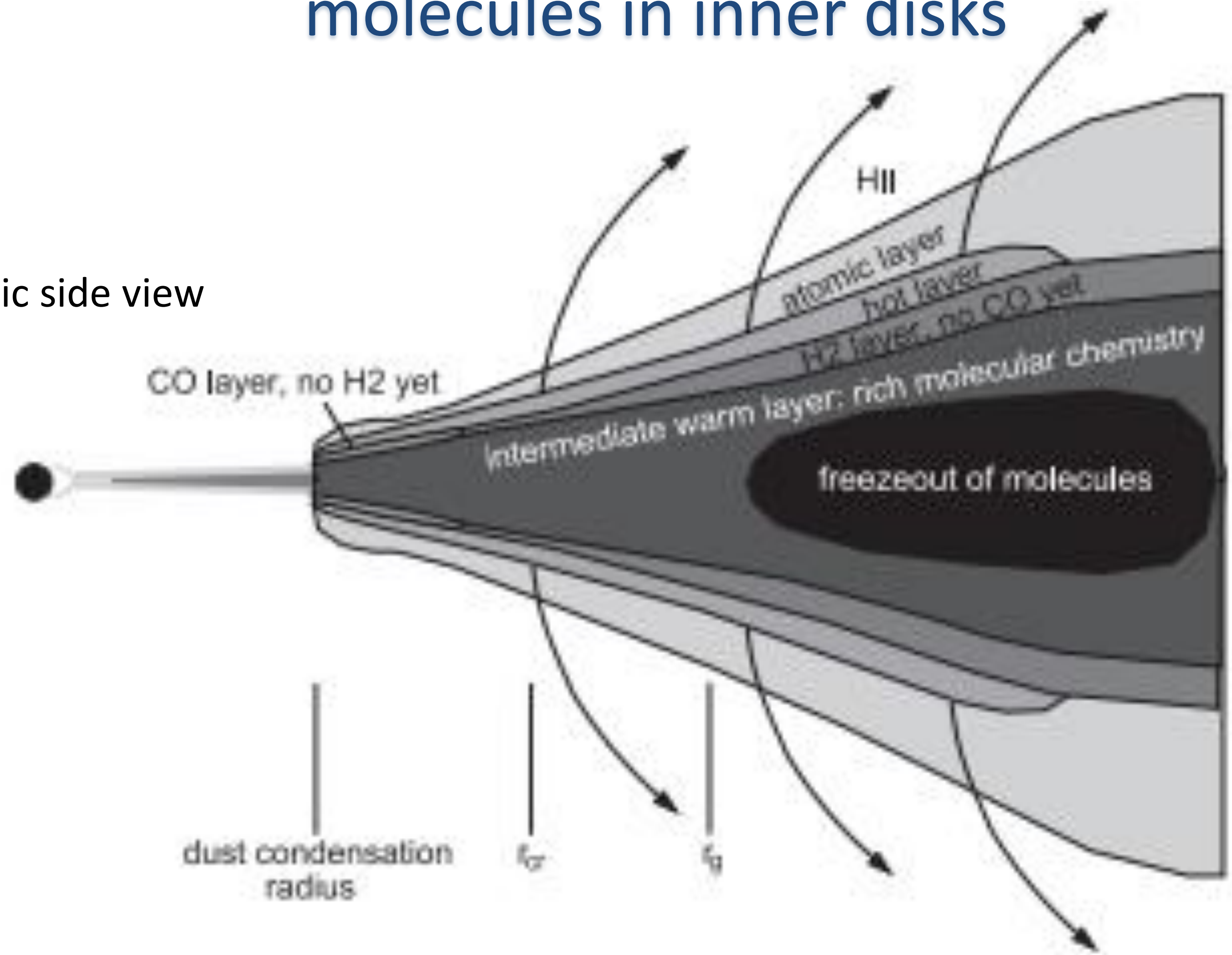
Kessler-Silacci + 2006



Chondrule from American Museum of Natural History meteorite collection

Disk structure did not *guarantee* detectability of molecules in inner disks

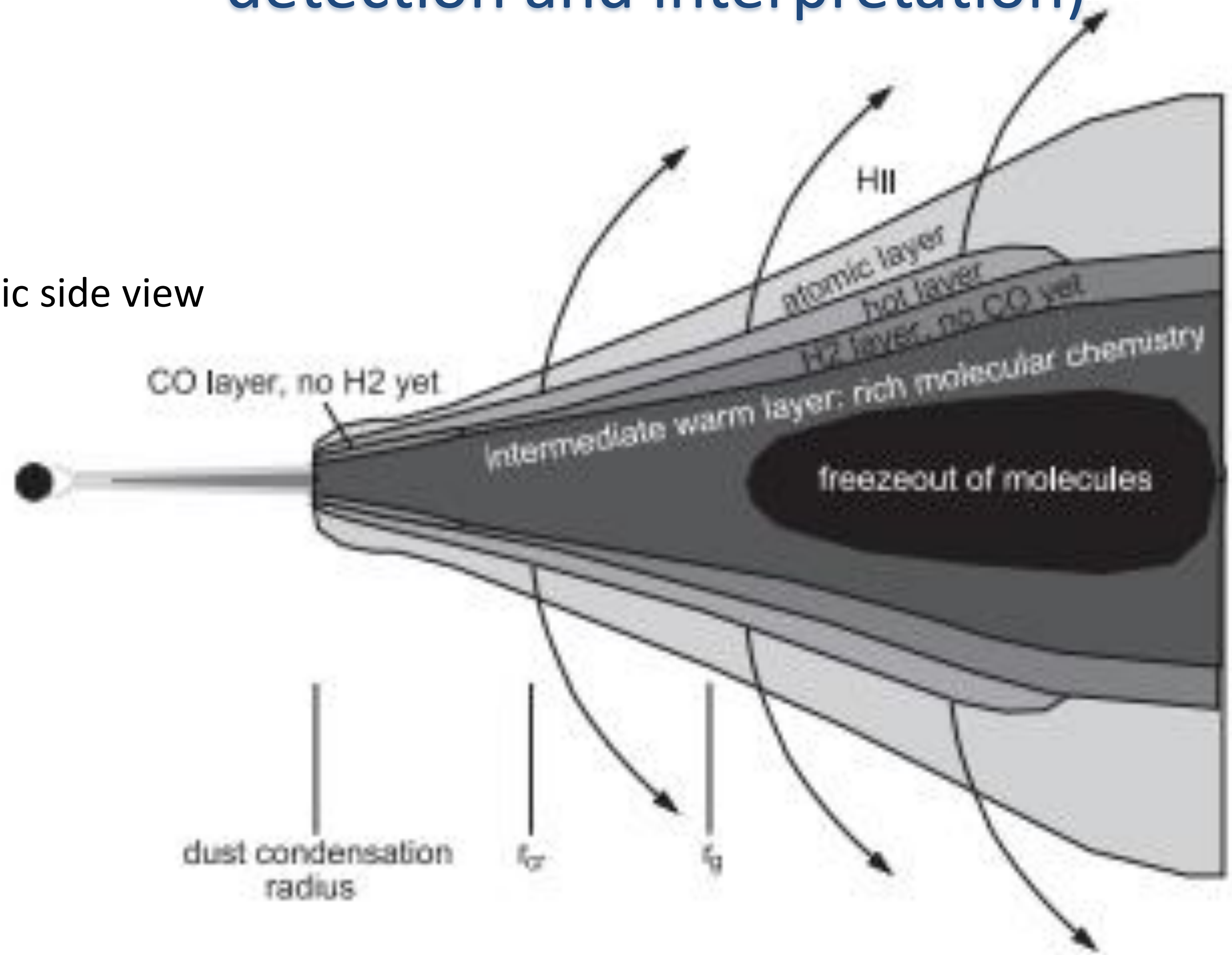
Schematic side view



Dullemond+ 2014

(And dust opacities still cause challenges to detection and interpretation)

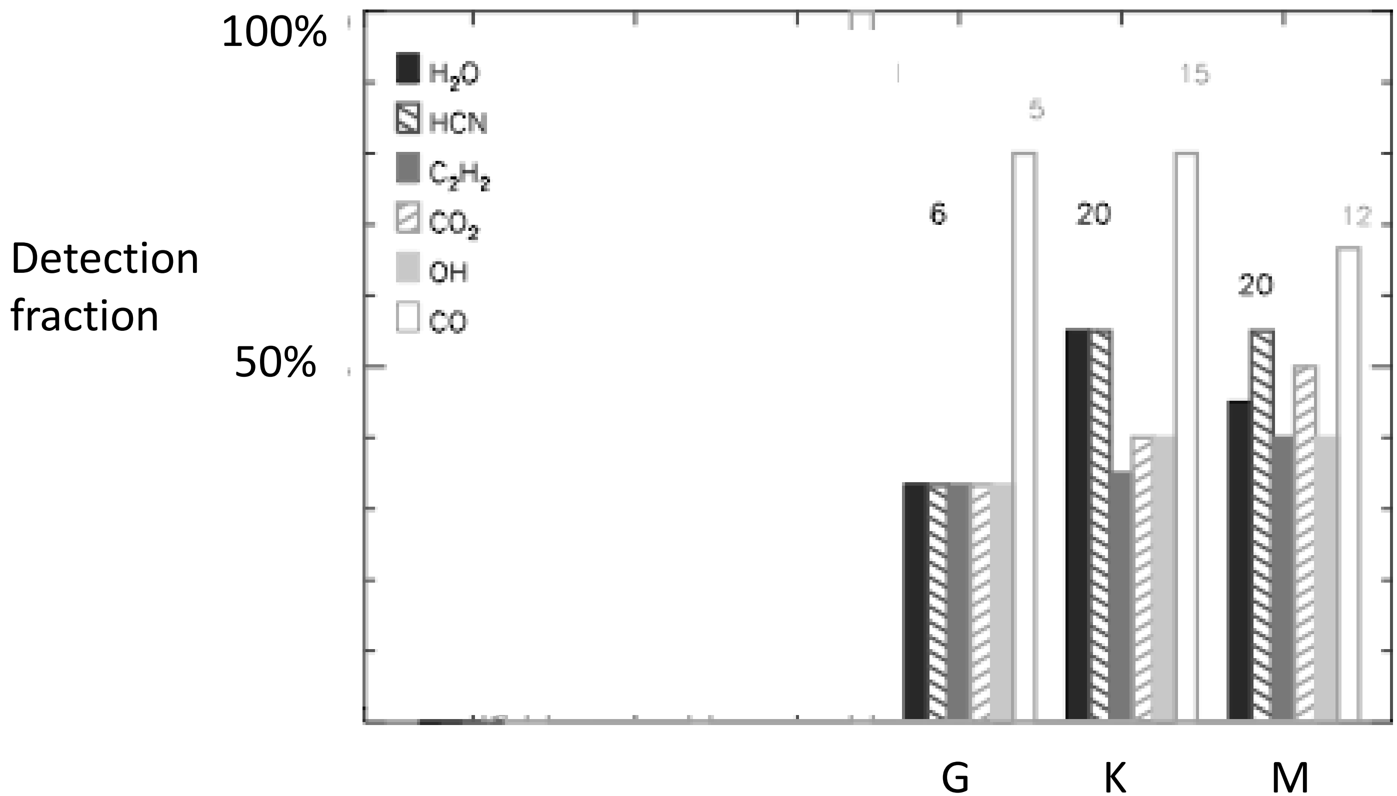
Schematic side view



Dullemond+ 2014

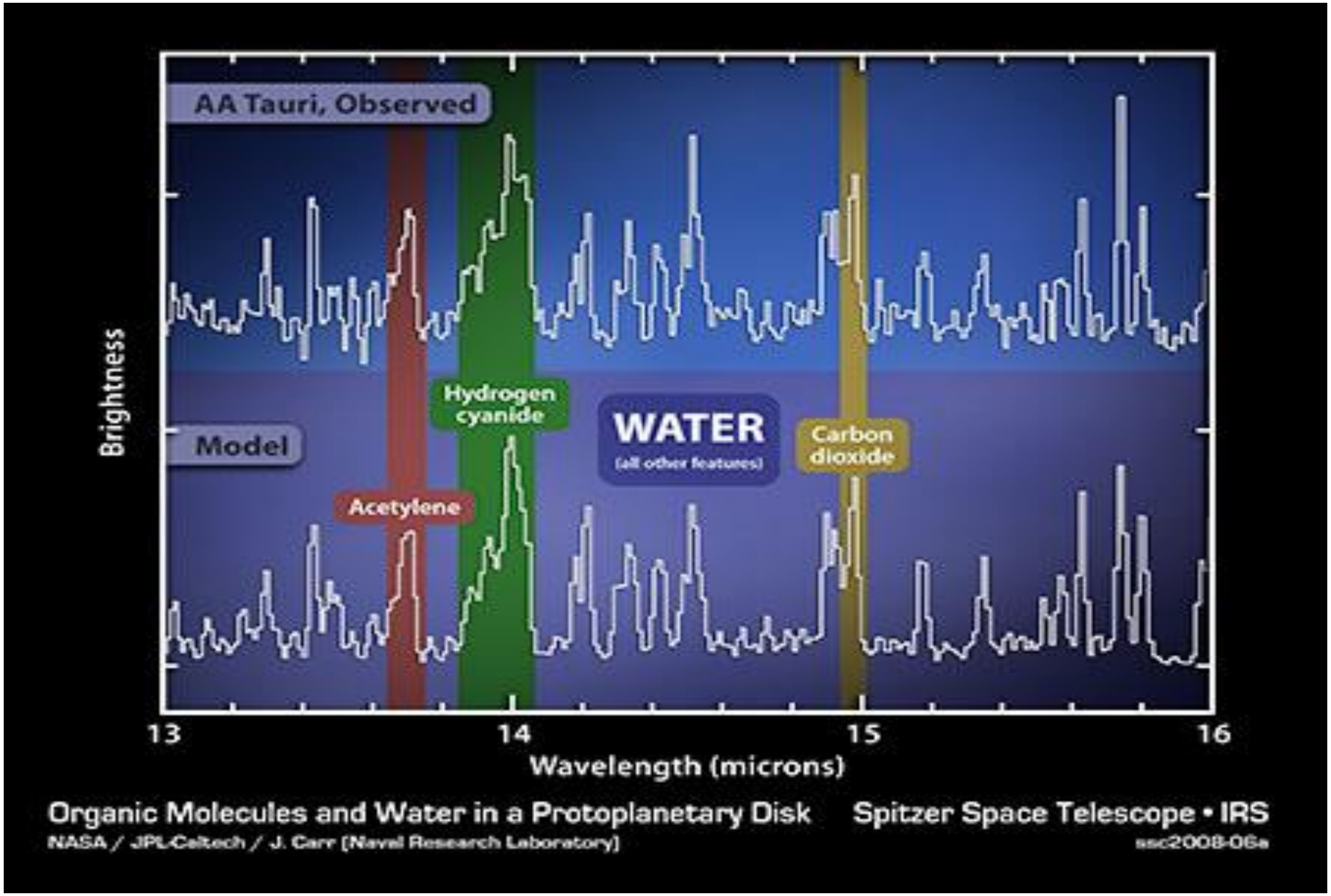
The study of volatiles in inner disks was enabled by the Spitzer InfraRed Spectrograph (IRS)

Molecular emission is *commonly* seen



Pontoppidan, Salyk+ 2010

Detection of molecules – gas phase chemistry, temperatures, densities



Carr & Najita 2008

Once we find the molecules, we can also map them

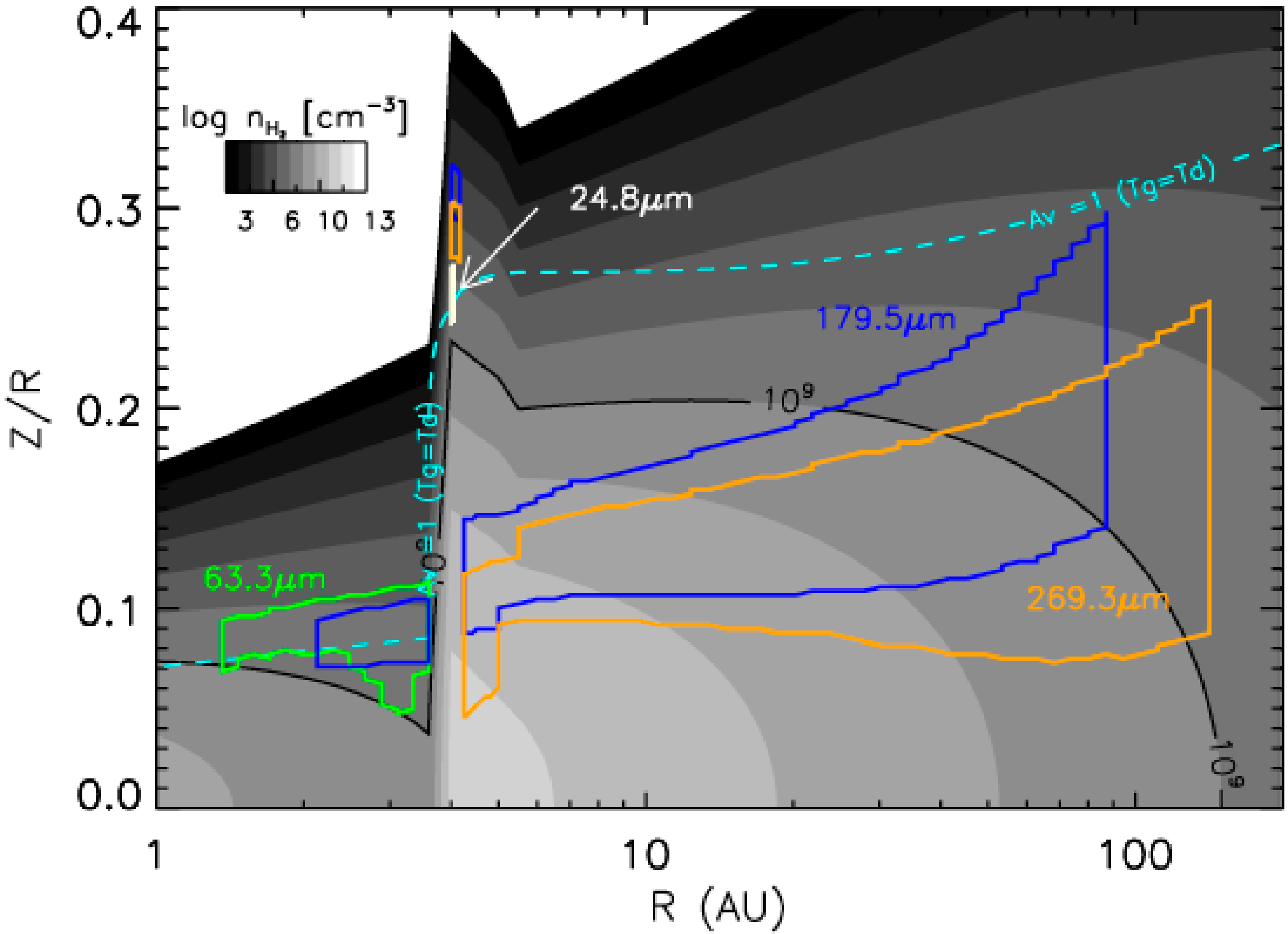
Three approaches:

1: Study with very high *spatial* resolution, and try to directly figure out where the molecules are. (but… diffraction limit for 10m telescope at 3μm, d=140 pc ~ 10 AU)

2: Use excitation models

3: Use Keplerian motion to locate molecules

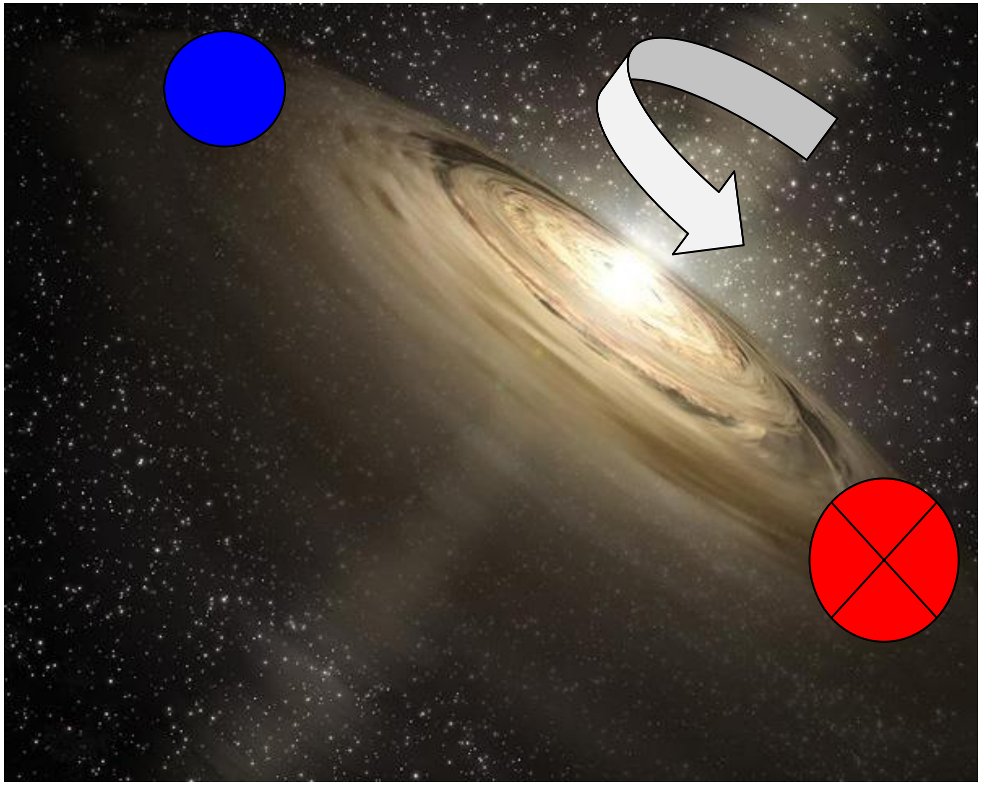
Spatial locating of molecules: Excitation models + multiple line observations



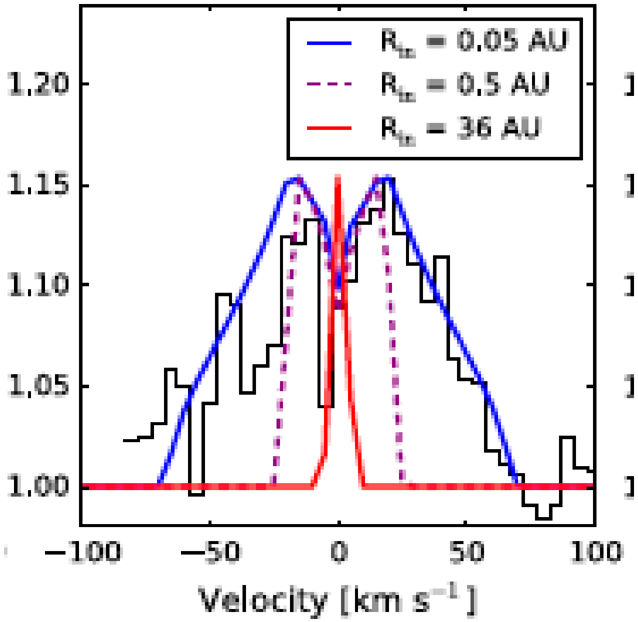
Main contributions to 24, 63, 179 and 269 micron water lines in TW Hya

Zhang+ 2013

Spatial locating of molecules: Line shapes (Doppler shift + Kepler's 3rd law)*



Credit:NASA, T. Pyle



Salyk+ 2015

measured **λ** ➔ **v** ➔ **R** inferred

*requires spectrally resolved observations, currently only possible from the ground

And now… some results!

How to turn Spitzer spectra into a bulk molecular inventory

-*Assume all molecular emission from same region*

-Determine column density of each species

-Use solar abundance of Si to determine silicate abundance

-Assume all O accounted for

-Use solar abundances to determine % of C,N accounted for

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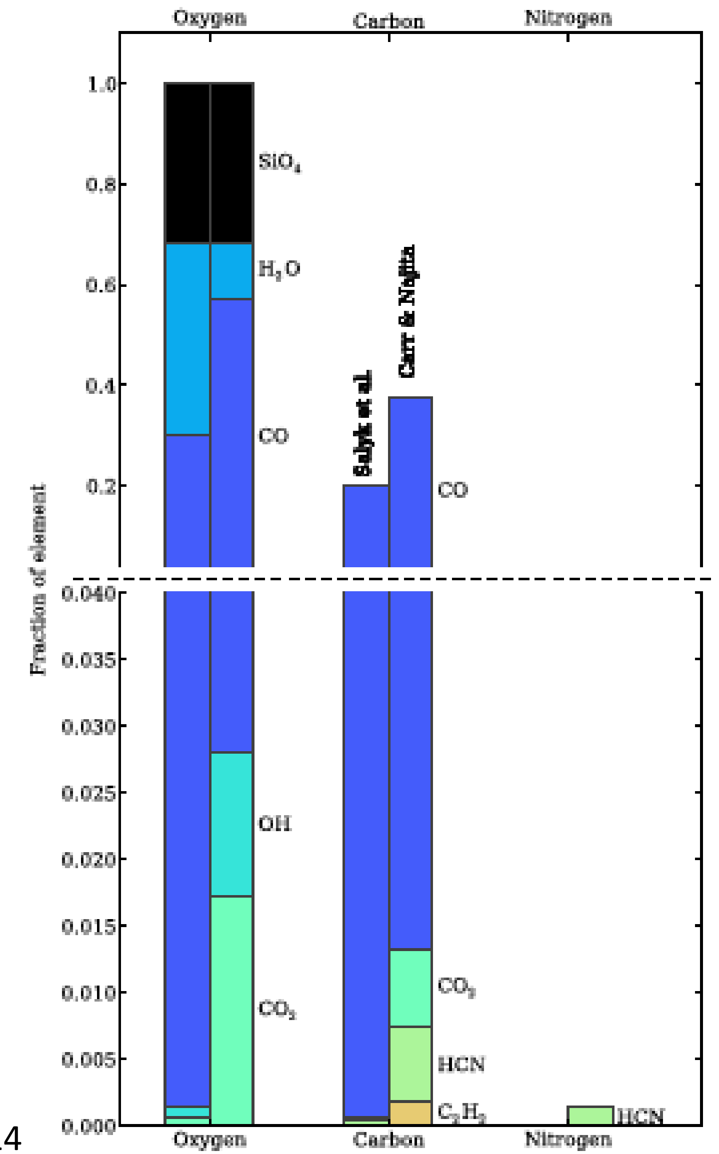
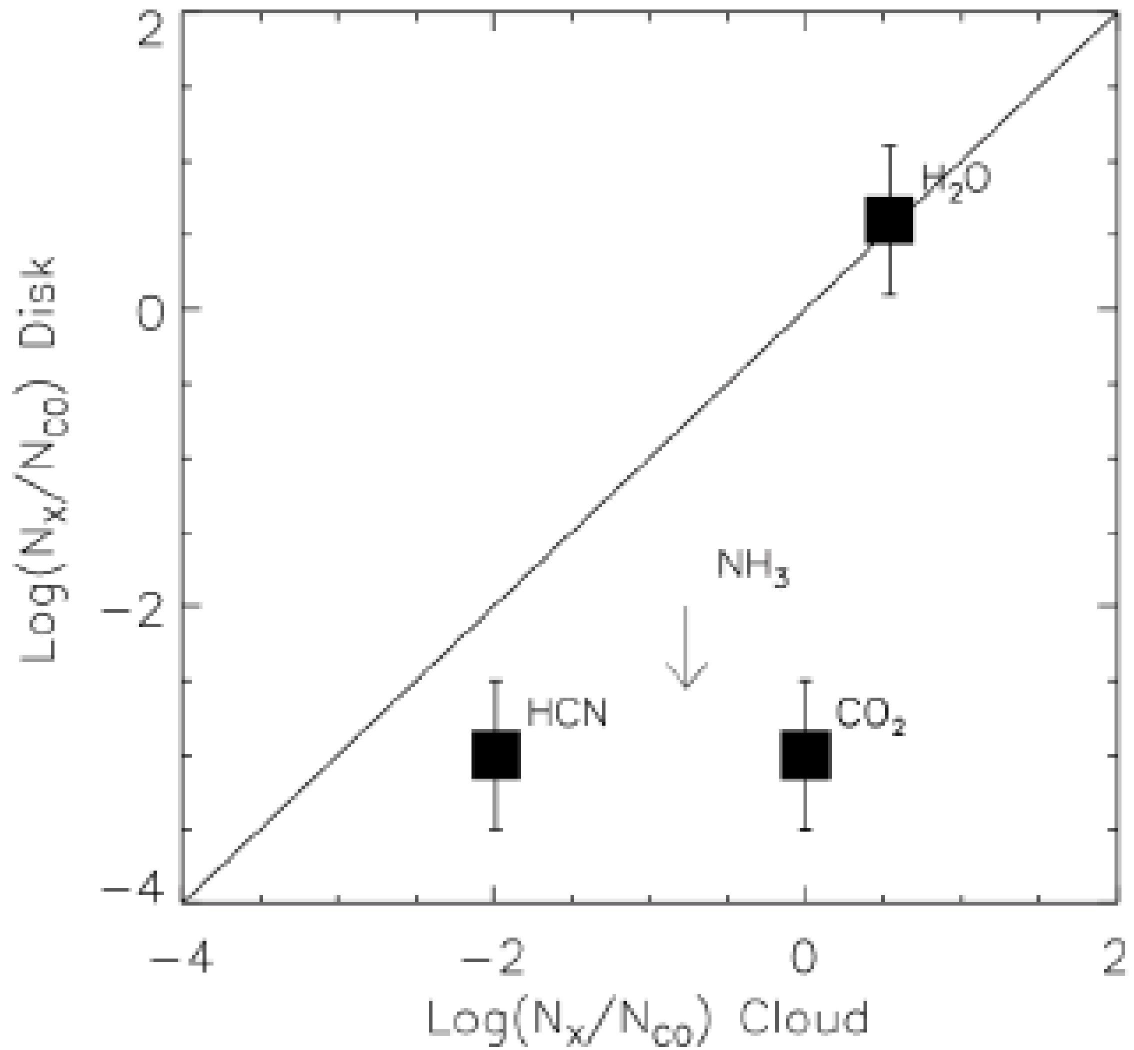


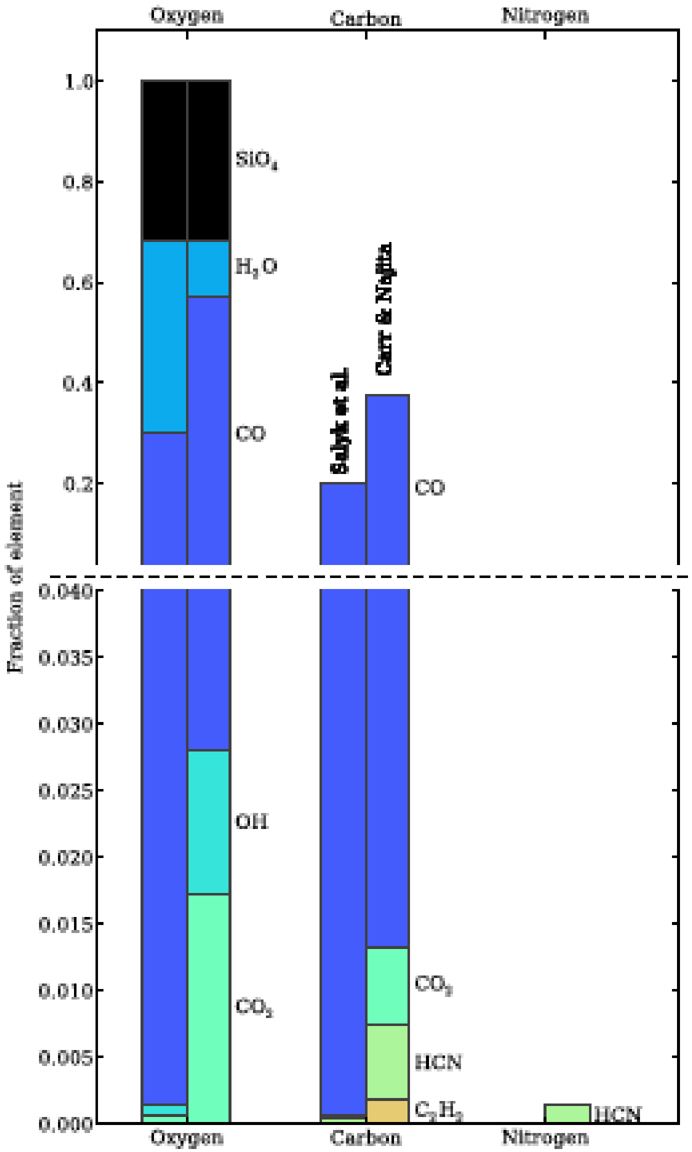
Pontoppidan, Salyk+ 2014

ISM chemistry ≠ inner disk chemistry
Some reset has occurred



Pontoppidan, Salyk+ 2014

Most N unaccounted for; likely in N_2

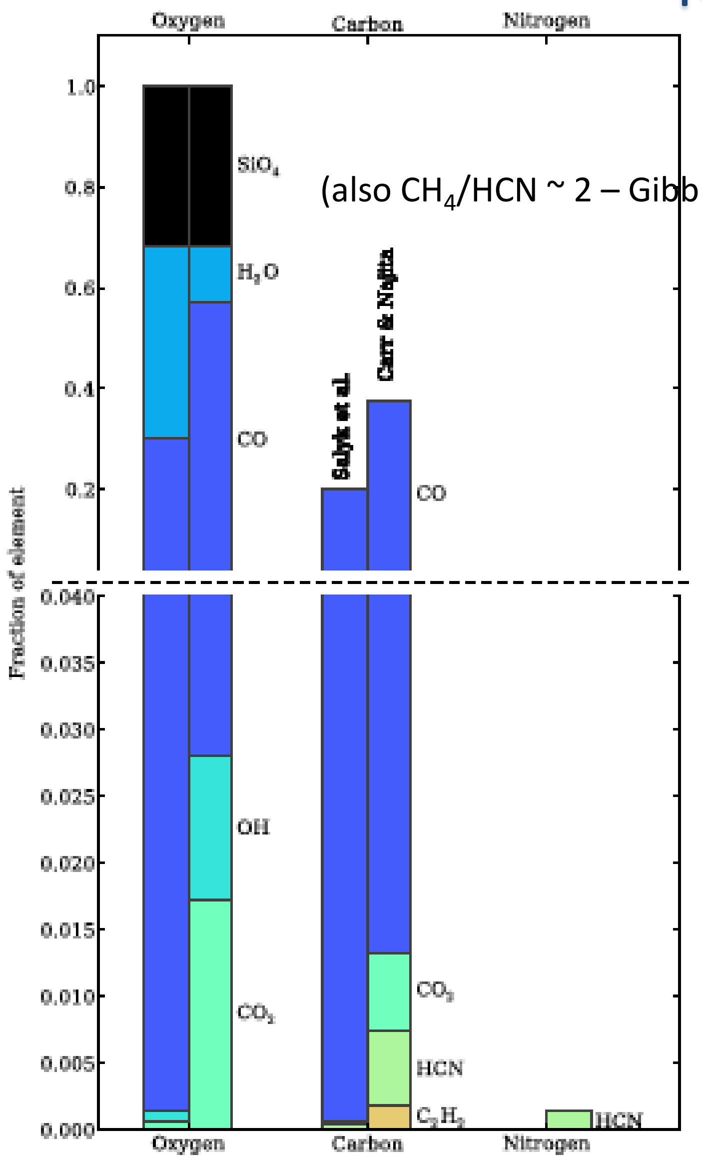


(Only HCN, upper limits on NH_3)

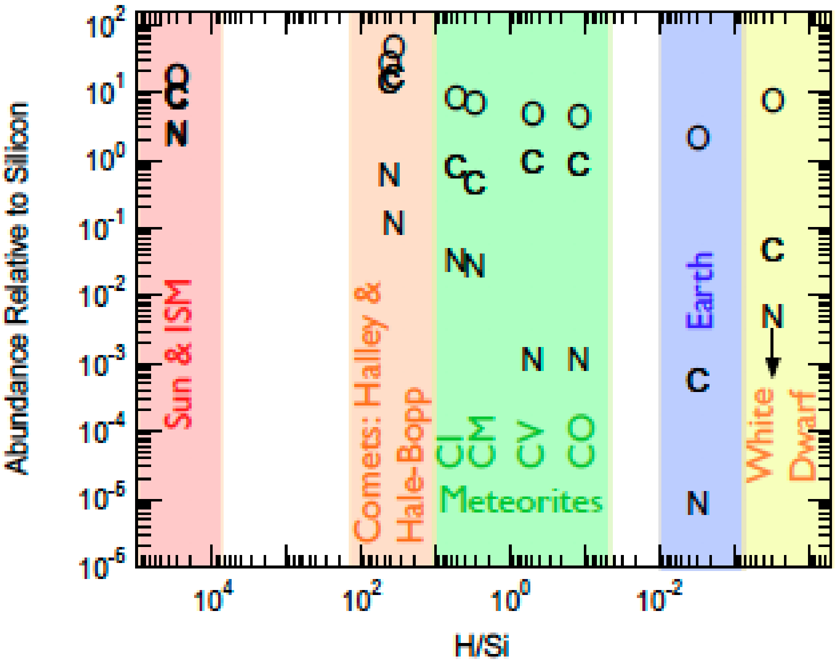
~60-80% of C unaccounted for in gas phase, likely in solids

Not consistent with orders of magnitude depletion of C on Earth

(also CH_4/HCN ~ 2 – Gibb & Horne 2013)

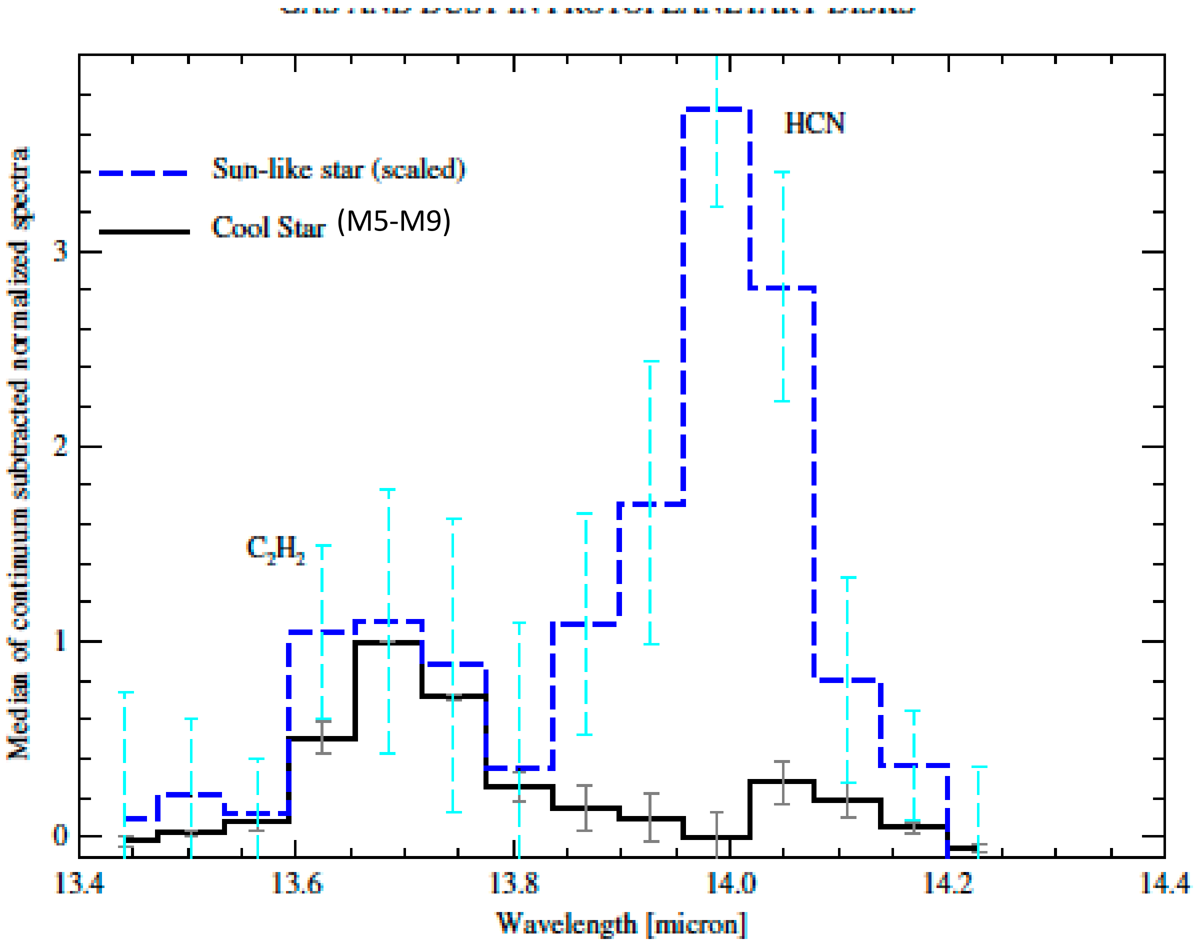


Pontoppidan, Salyk+ 2014



Pontoppidan, Salyk+ 2014, Adapted from Lee+ 2010

Chemistry depends on radiation environment: Different stars have different radiation fields



Pascucci+ 2009

Chemistry depends on radiation environment: Radiation fields change during outbursts

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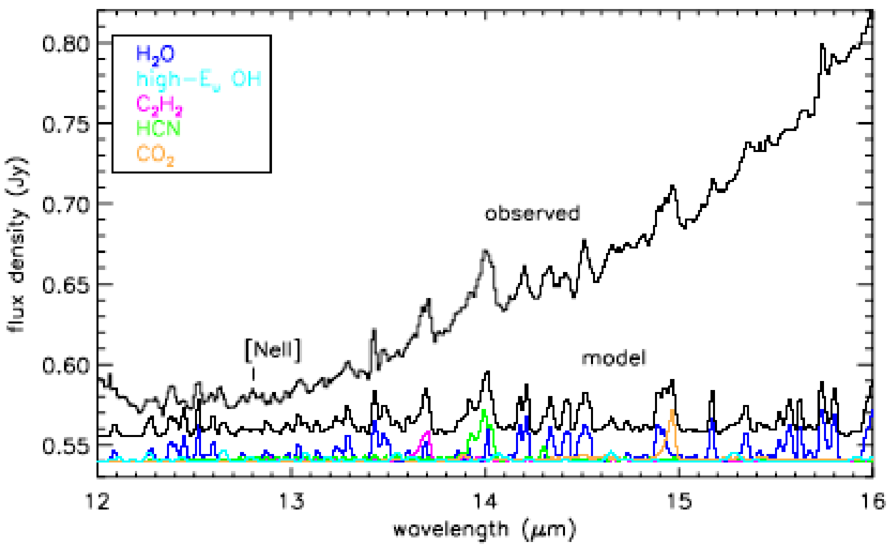
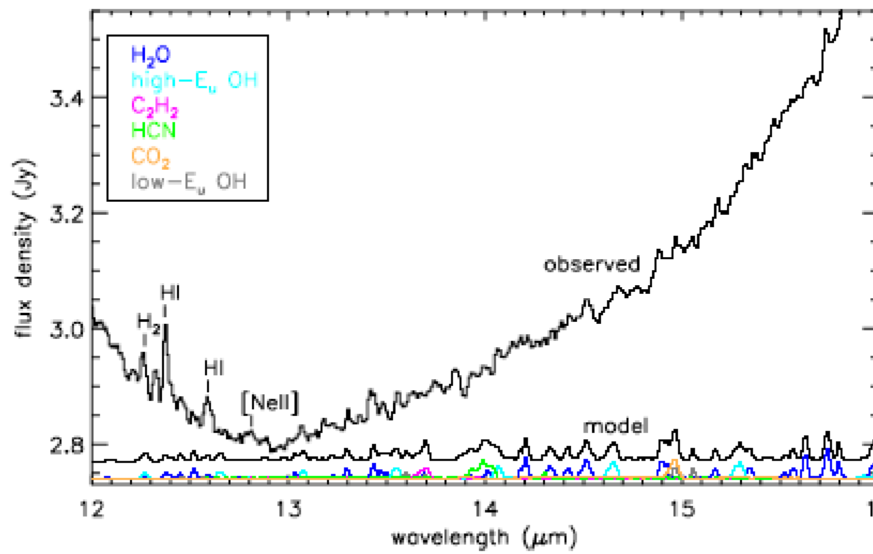




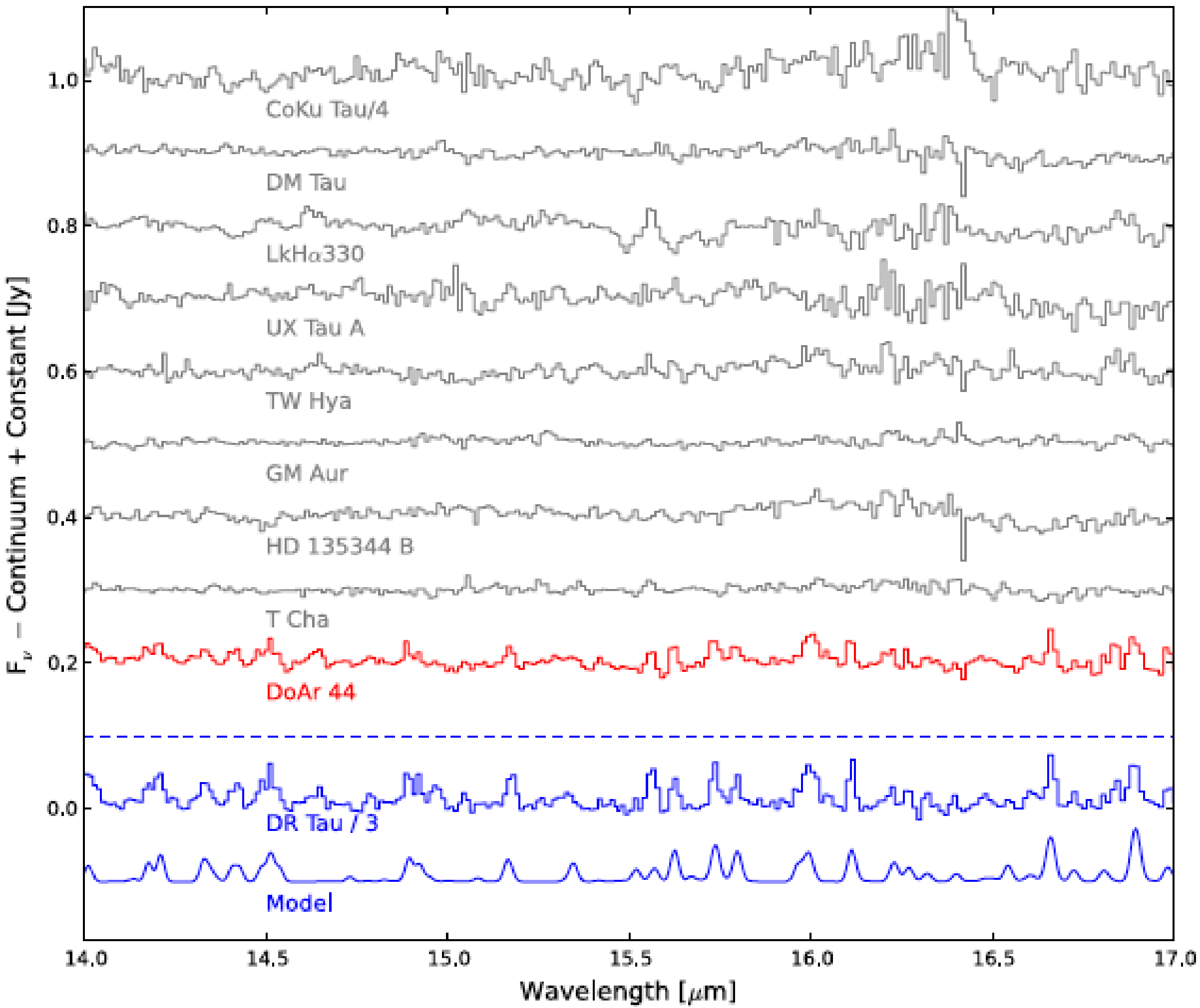
EX Lupi in Quiescence

EX Lupi in Outburst

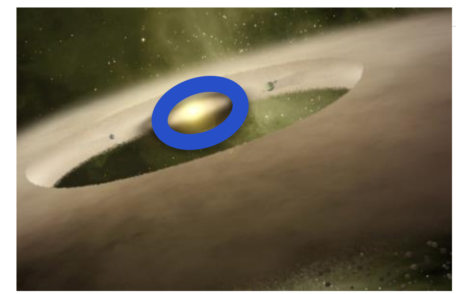
H_2O emission reduced; OH lines appear

Banzatti+ 2011

Chemistry depends on radiation environment: Radiation fields depend on disk structure



"Dry" transitional disks

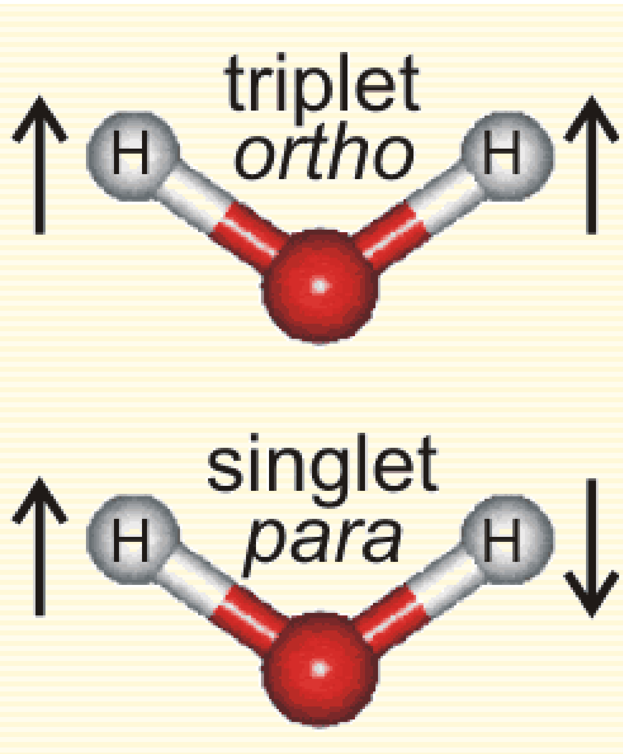


"Wet" pre-transitional disk

"Wet" full disks

Salyk+ 2015

Evidence for transport in disks? Water ortho/para ratios



Ortho:para=3 warm at formation
in-situ formation

Ortho:para<3 cold at formation
desorption from colder ice

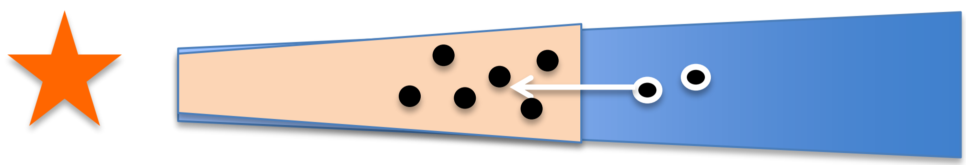


Figure from
http://www.lsbu.ac.uk/water/molecule.html

So far, water vapor detections consistent with ortho:para=3 (in situ formation)

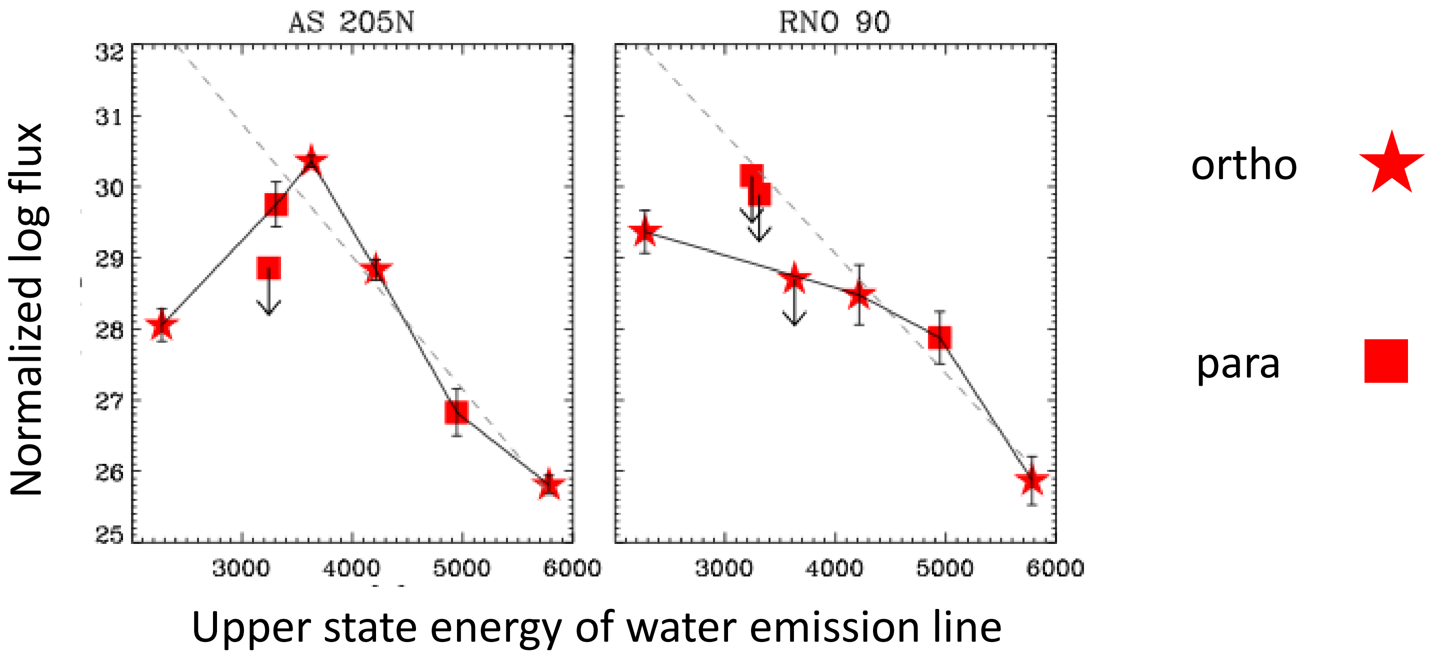
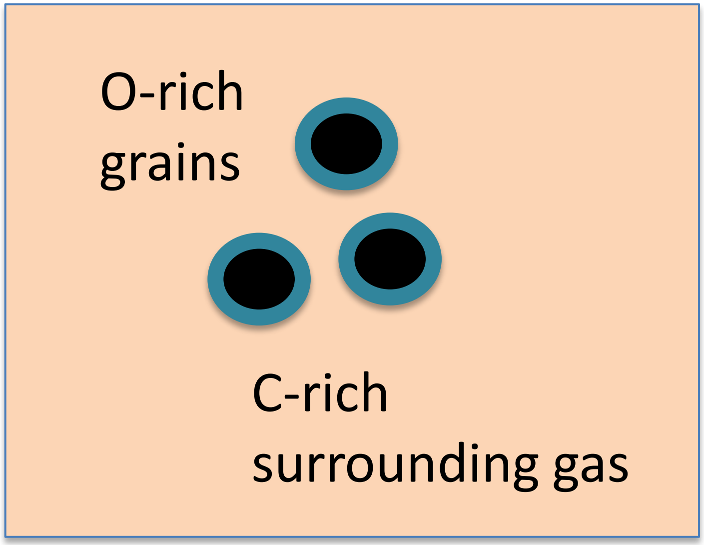


Figure from Pontoppidan+ 2010

However, transport processes possibly probed by HCN/H_2O ratio
Inner disk C/O ratio reflects transport

Beyond the ice line…



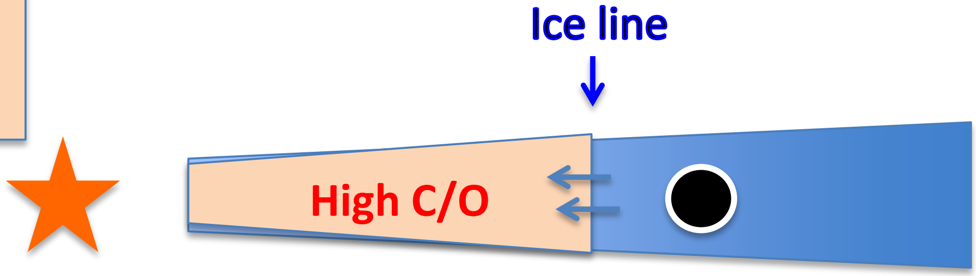
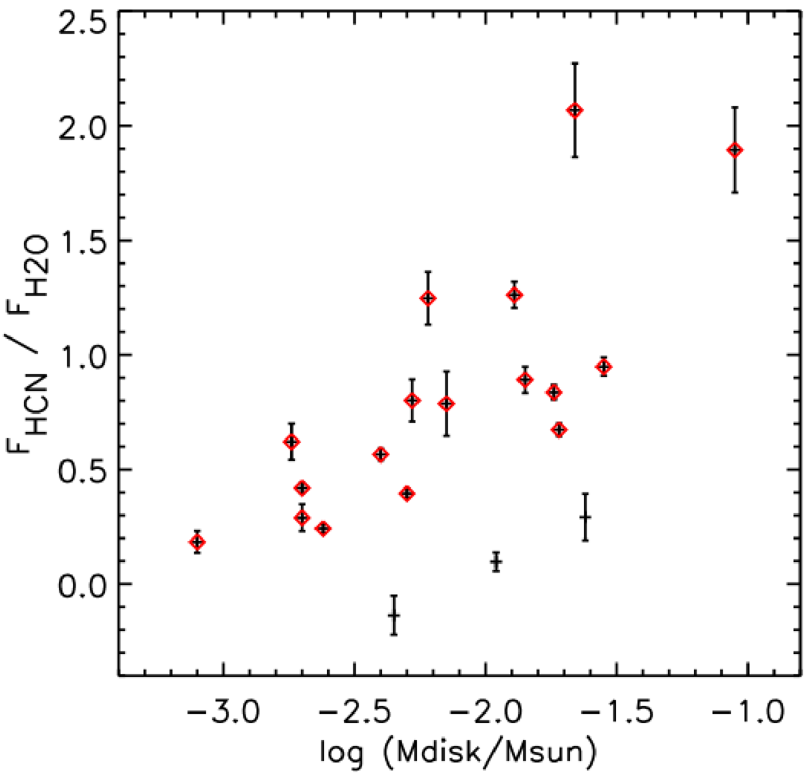
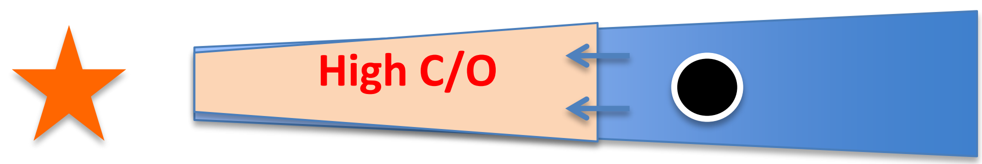


Figure courtesy of Ke (Coco) Zhang

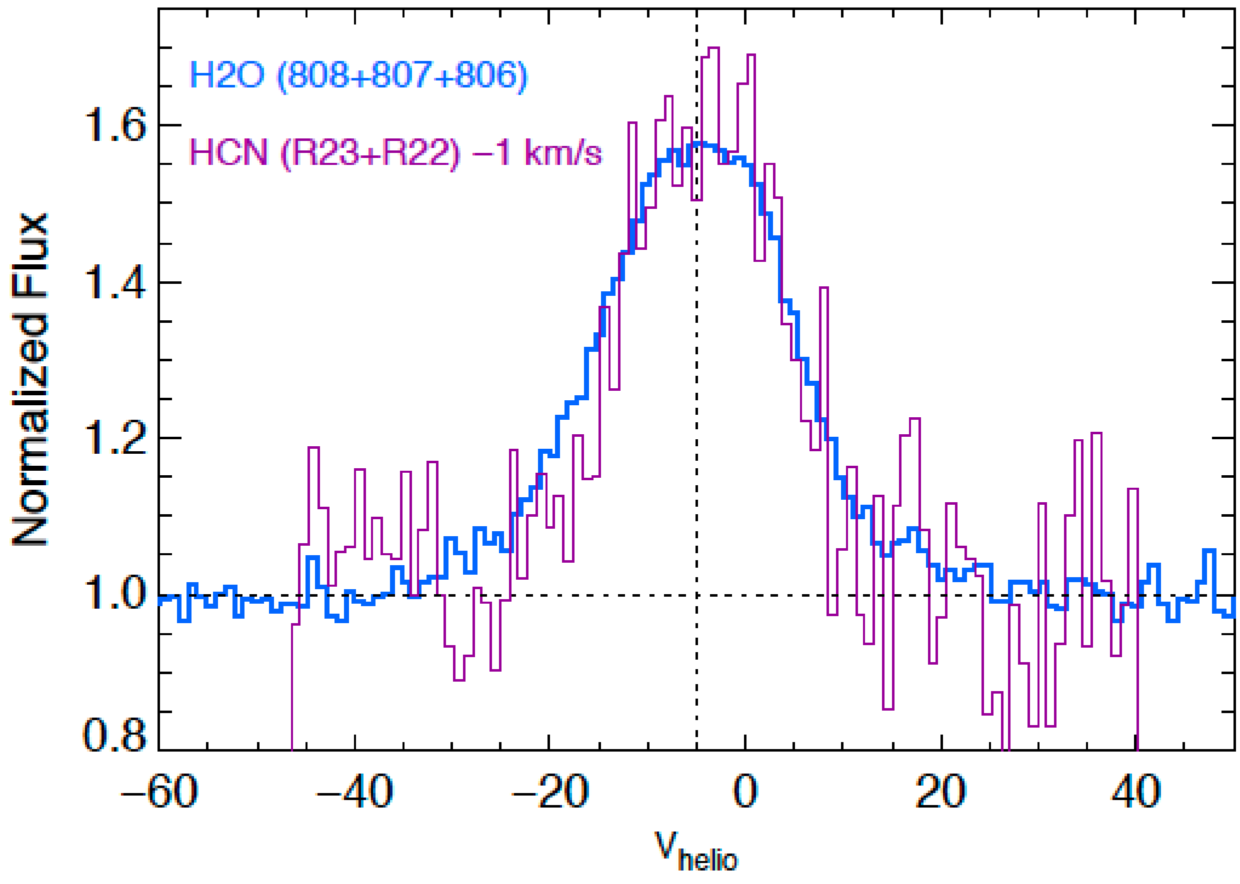
HCN/H_2O ratio correlates with disk mass
If larger mass disks form planets more quickly, they may be more likely to have high C/O in the inner disk



Najita+ 2013

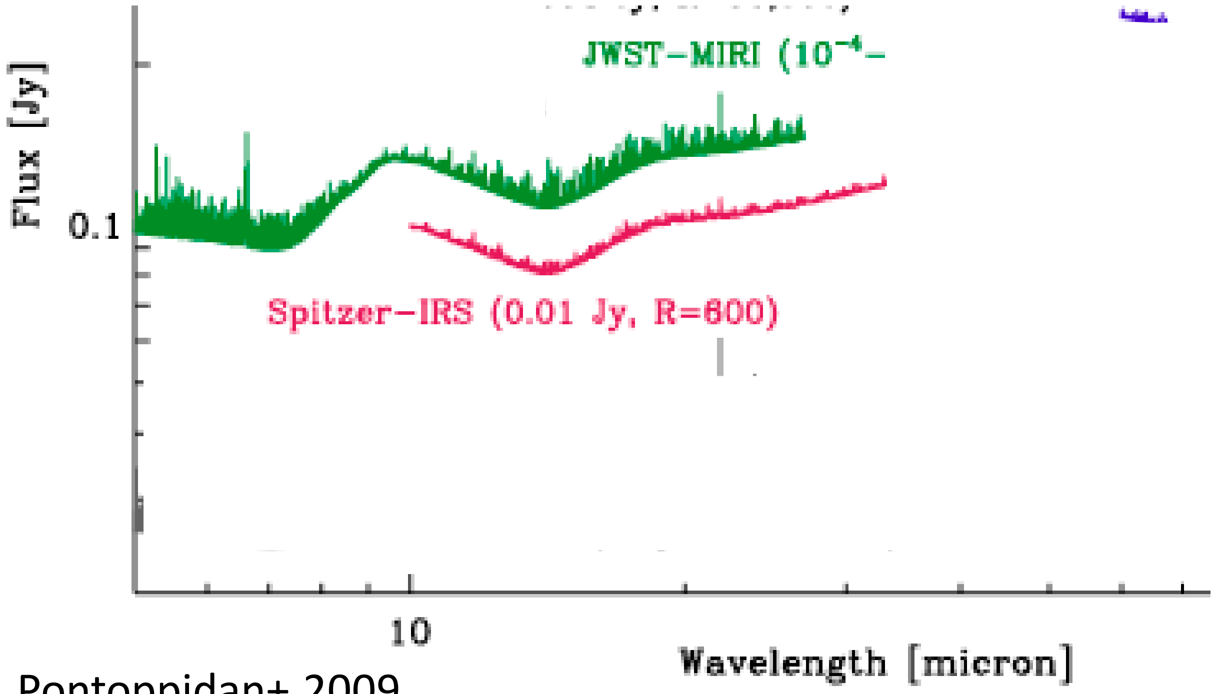


Work in progress: Ground-based "mapping" of molecules: Ongoing work with VISIR, TEXES, NIRSPEC, CRIRES, ALMA



Najita et al., in prep

The near future: JWST's increased sensitivity allow us to probe different star-forming regions, less massive stars/disks, less abundant molecules

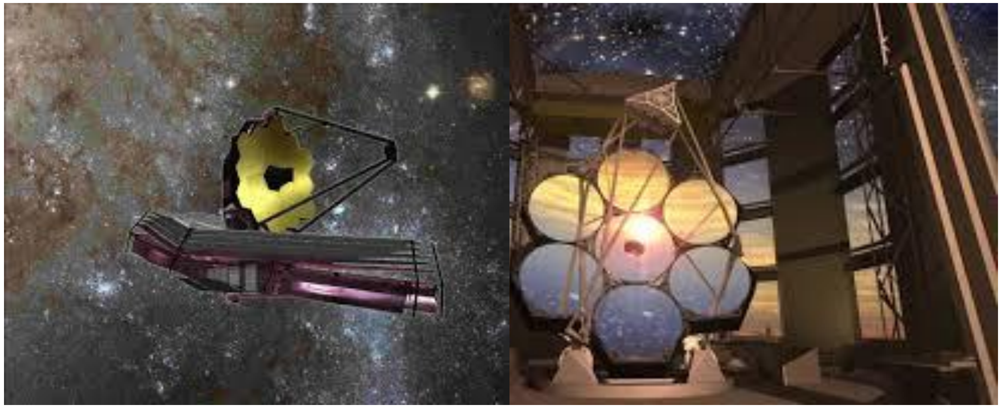


Pontoppidan+ 2009

The future: Extremely Large Telescopes

Detect a rich set of molecules from the *great majority* of protoplanetary disks in nearby clusters

Sufficient spatial resolution to make *chemical maps* on 0.1-0.4 AU scales in the nearest clusters



Thanks

I look forward to two days of great discussions