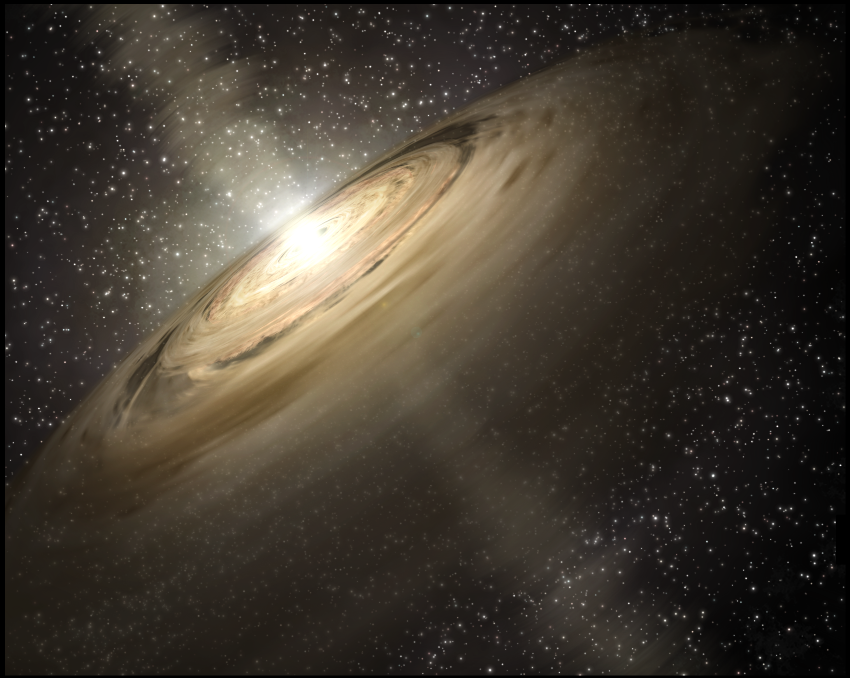
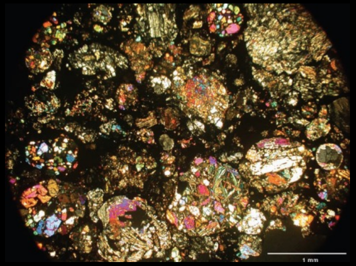
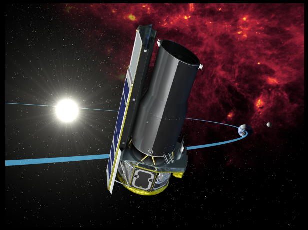
Protoplanetary Disks & Cometary Precursors







Geoffrey A. Blake, Div. of Geological &
Planetary Sciences, Caltech

KISS Short Course, Comets

5 June 2017

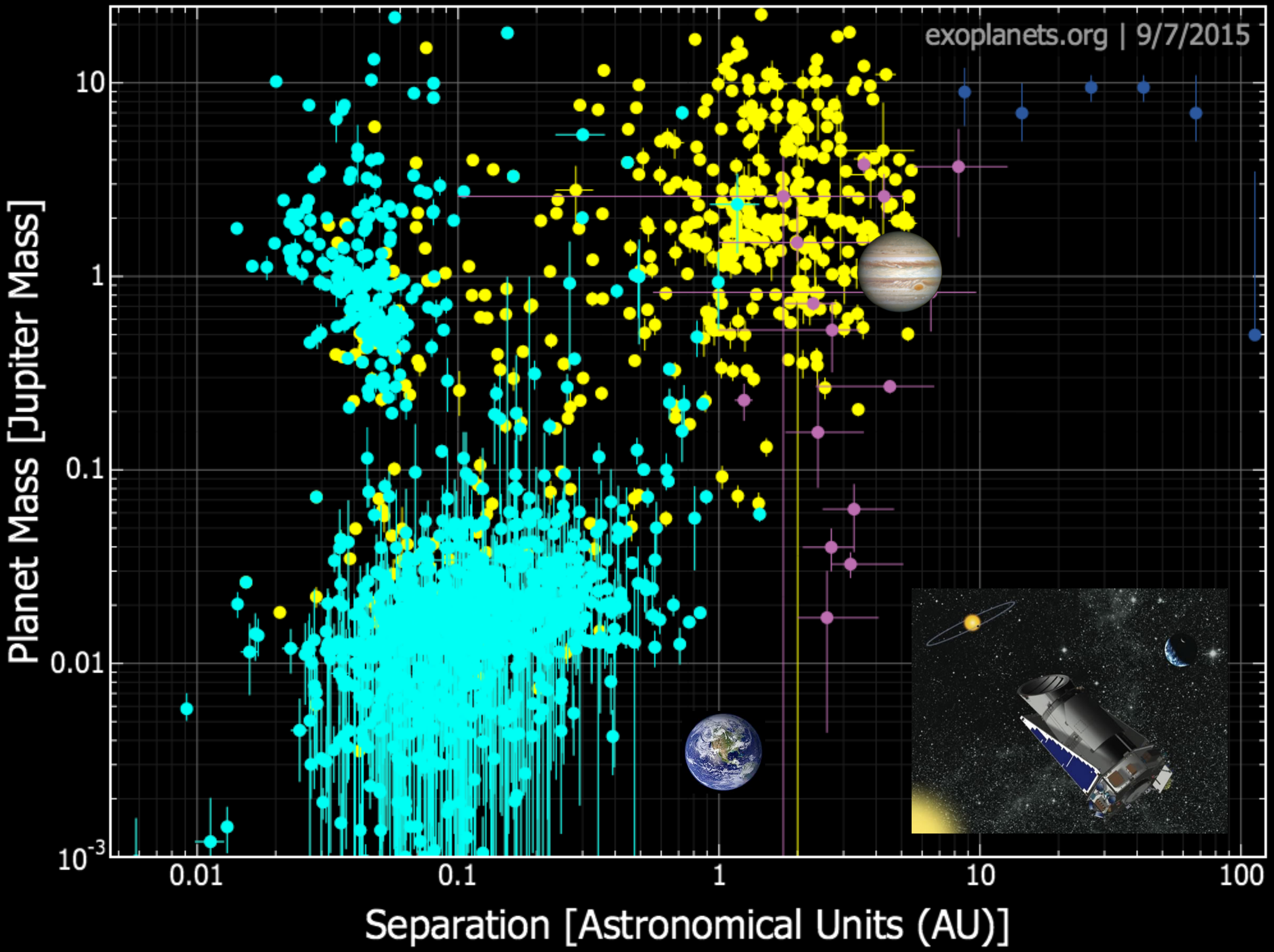
Laplace 1796 – What can the solar system tell us about the formation & evolution of planetary systems?

Key insights:

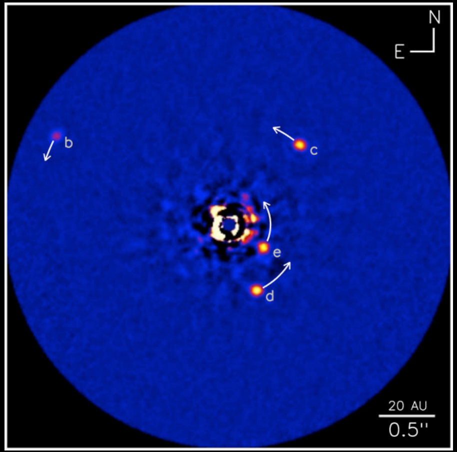
1. Most of the mass is in the sun.
2. The "major planets" all orbit in the same sense.
3. Small bodies, especially comets, are very different (history can be retained, this workshop).

An exoplanet perspective – How many Earths?

Jupiter mass planets from <0.05 to >50 astronomical units!



HR 8799

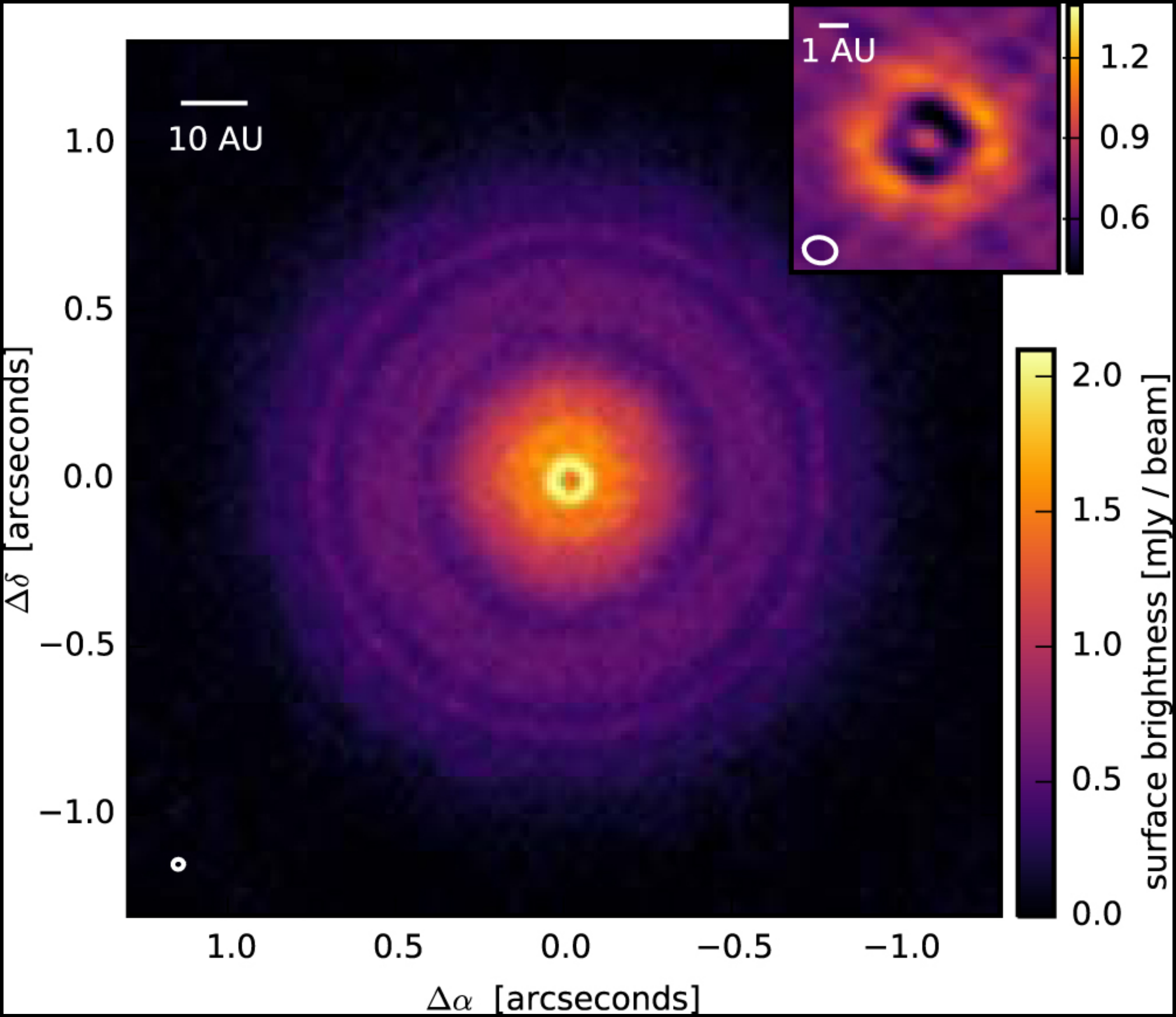


C. Marois (2010)

How many 'Solar system' like outcomes?

$\geq 4 \times 10^6$!!

How can we explain Earth-to-Jupiter-mass planets over such wide distances?



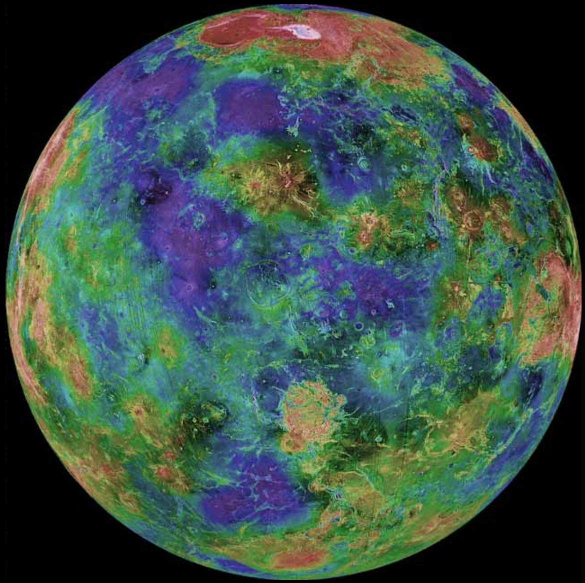
Disk-star-and protoplanet interactions can lead to migration while the gas is present. Disks serve to *move* mass, ang. mom.!

Jupiter (5 AU):
$V_{doppler}$ = 13 m/s
V_{orbit} = 13 km/s

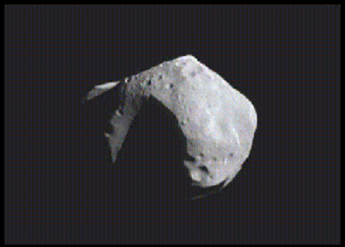
Andrews et al. 2016, ApJ 820, L40.

Observation?

Central Question: Building a habitable planet, or

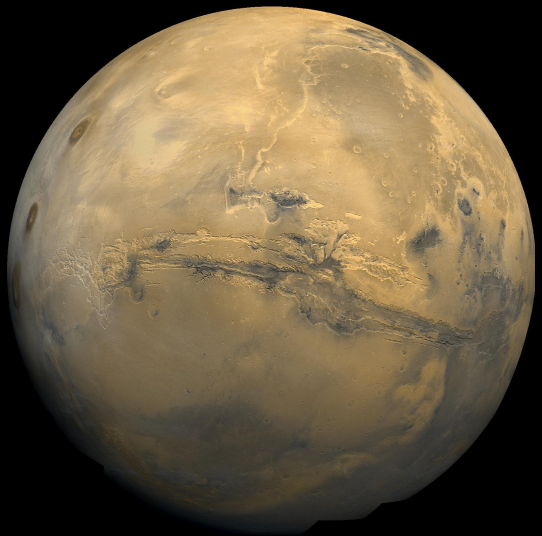


Why is the Earth wet?
And alive?

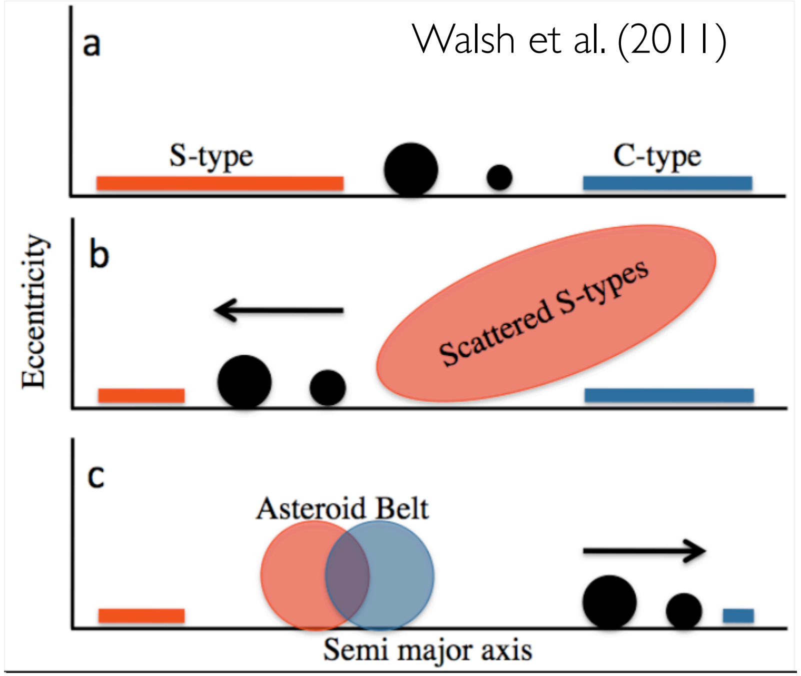


Planetesimal accretion from the outer solar nebula?

Early solar system dynamics?

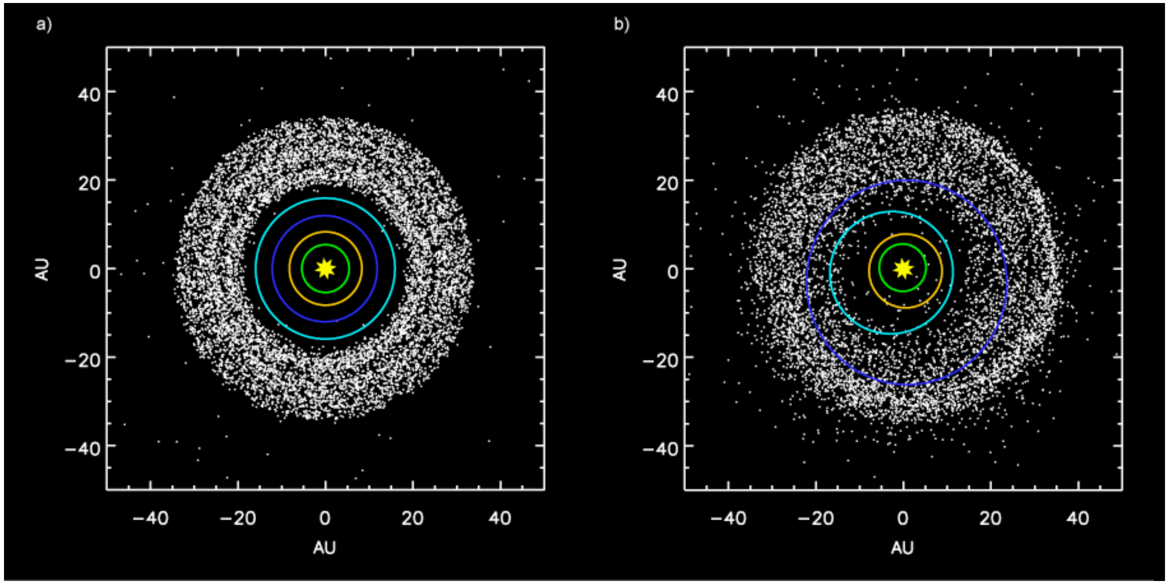


From an initial/well mixed state, how and when might planetesimals be sculpted?



I. Grand Tack – Early, in the presence of gas. Can the snow line location affect the resulting asteroid belt composition & volatile delivery to the Earth?

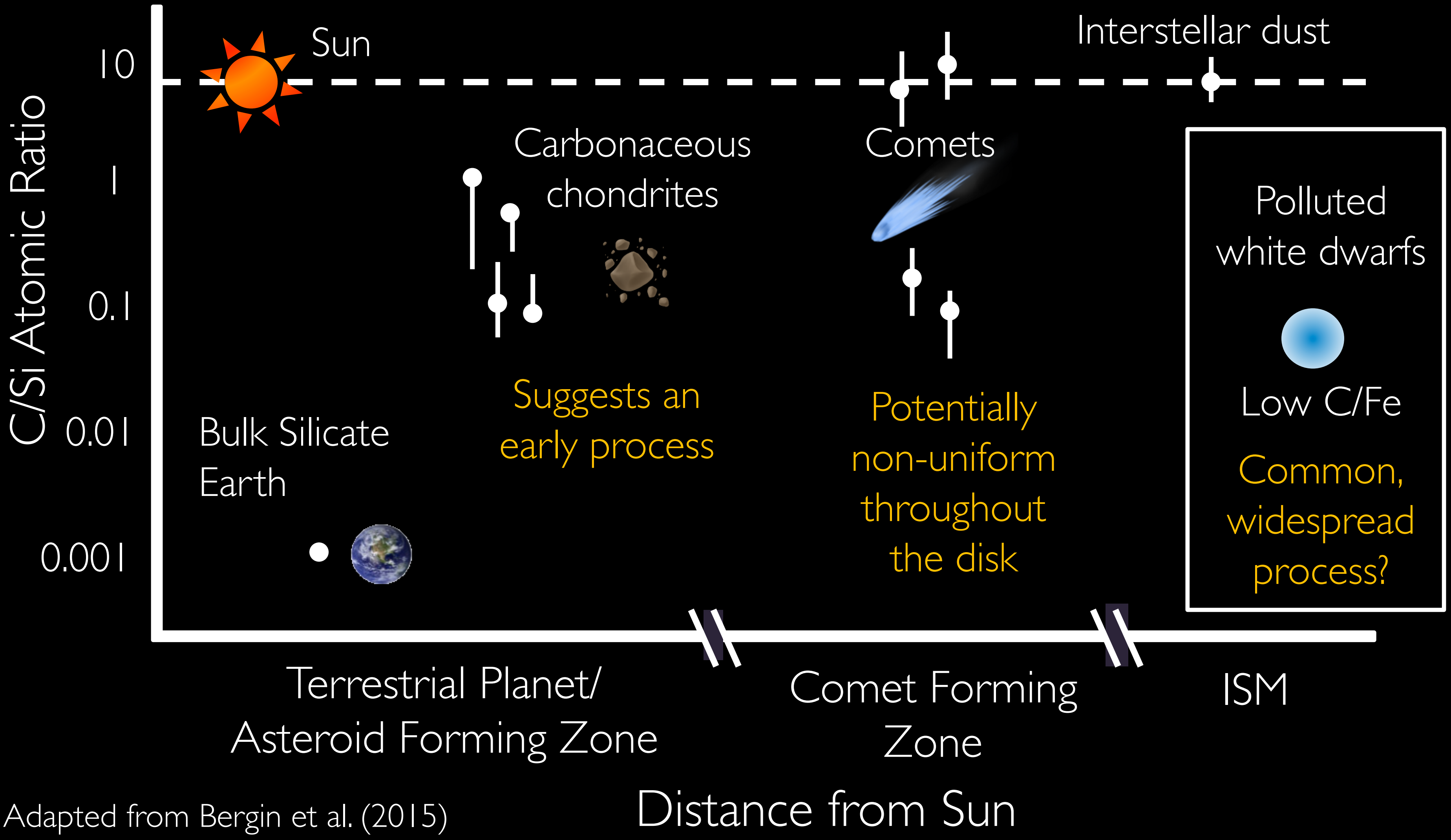
II. Nice Instability – Much later, what mix of asteroids and comets? Timing may be relevant to Earth's C, N budget (atm, core).



Planetary System & Comet Formation: An Astrochemical Cycle

The dense gas and dust that forms stars, and the disks around young stars, are so opaque/cold that only infrared and (much) longer wavelength photons can penetrate them.

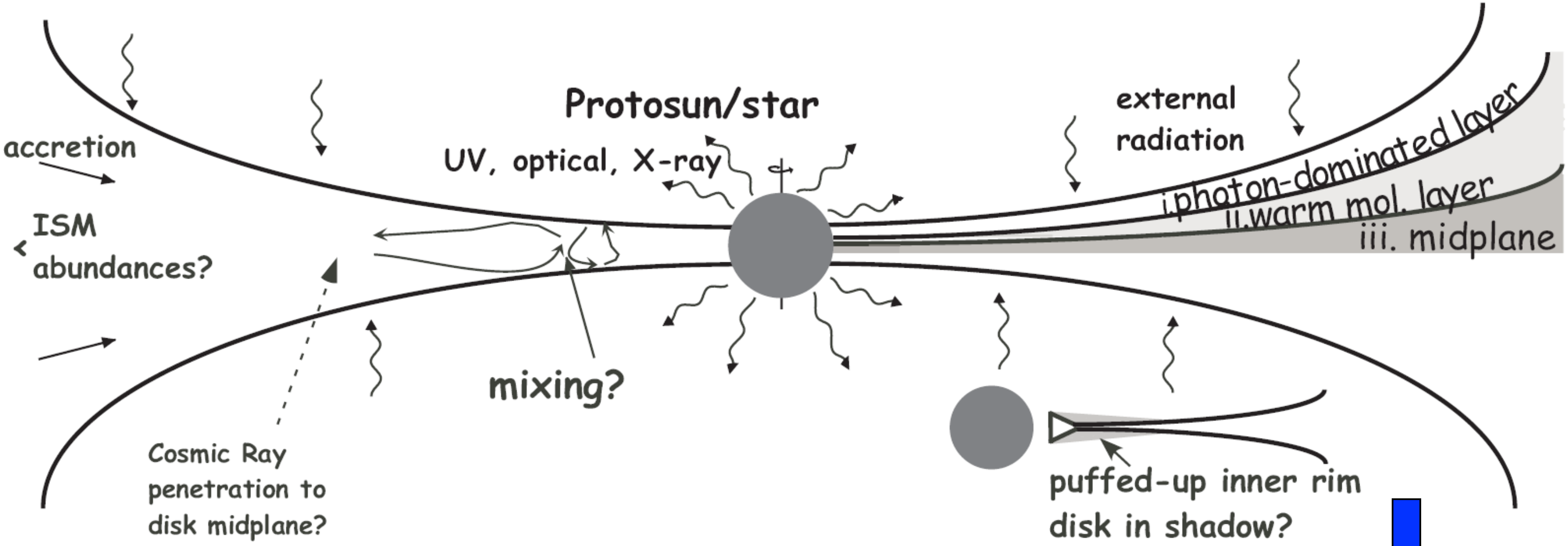
Large rocky bodies in the solar system are carbon-poor:



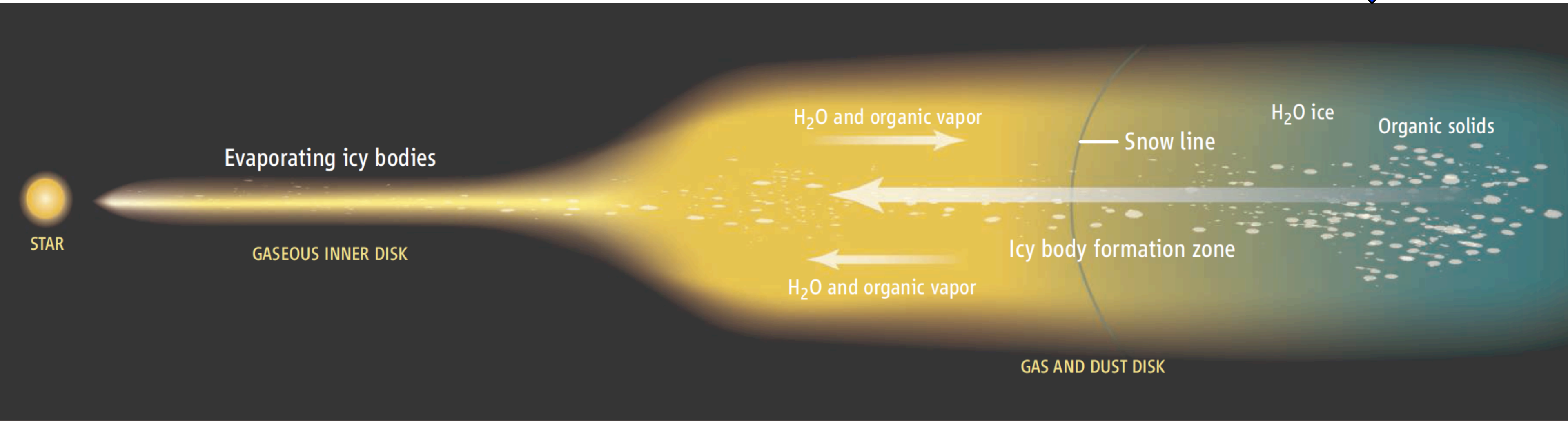
Adapted from Bergin et al. (2015)

Carbon principally enters the disk as CO, C-grains.

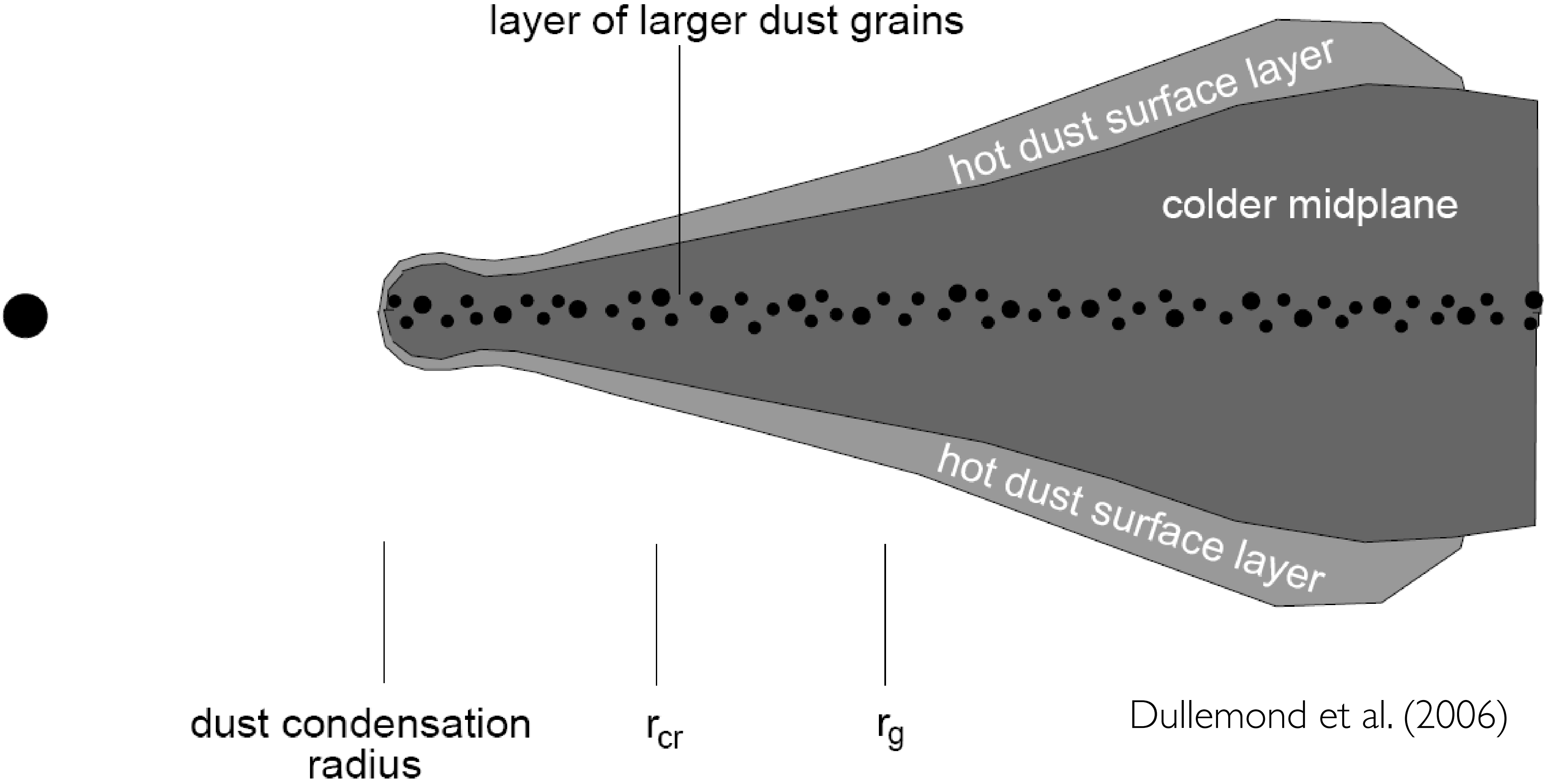
For comets we need to understand the evolution of volatile reservoirs.



The "snow line":



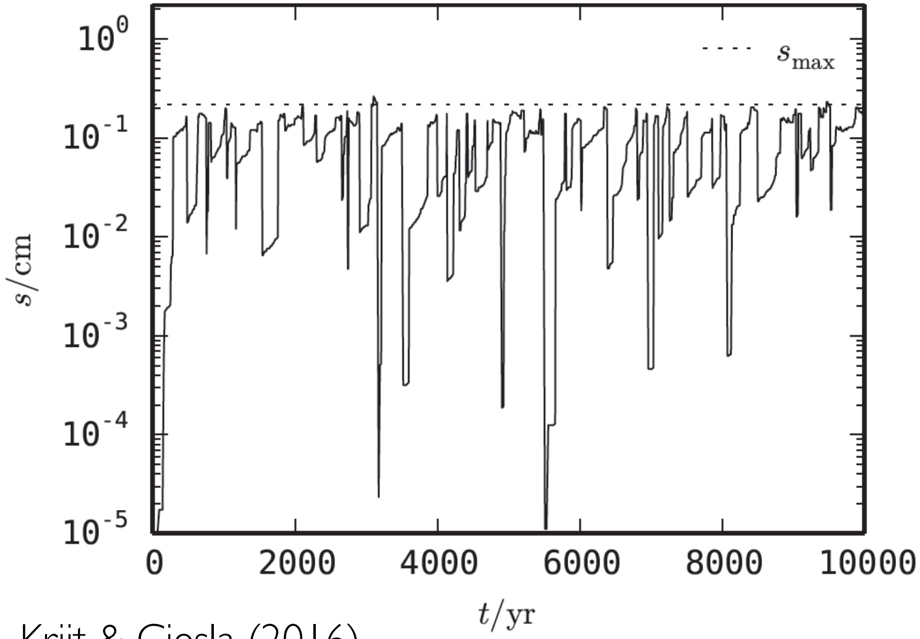
In particular, do volatiles aid grain growth? That is, do small grains remain lofted, ~mm/cm bodies settle quickly?



Dullemond et al. (2006)

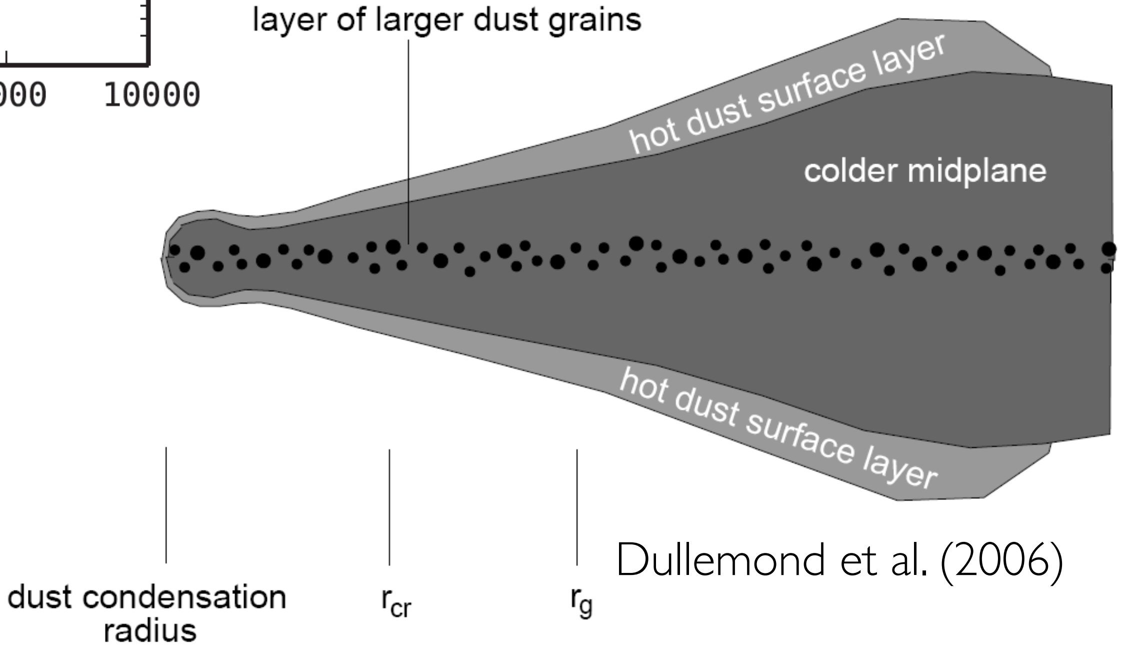
If so, the radial location of snow lines may be critical!

Key point: A situation such as that shown here is dynamic!



Krijt & Ciesla (2016)

Small dust and ice particles are exchanged between dust aggregates on short time scales.



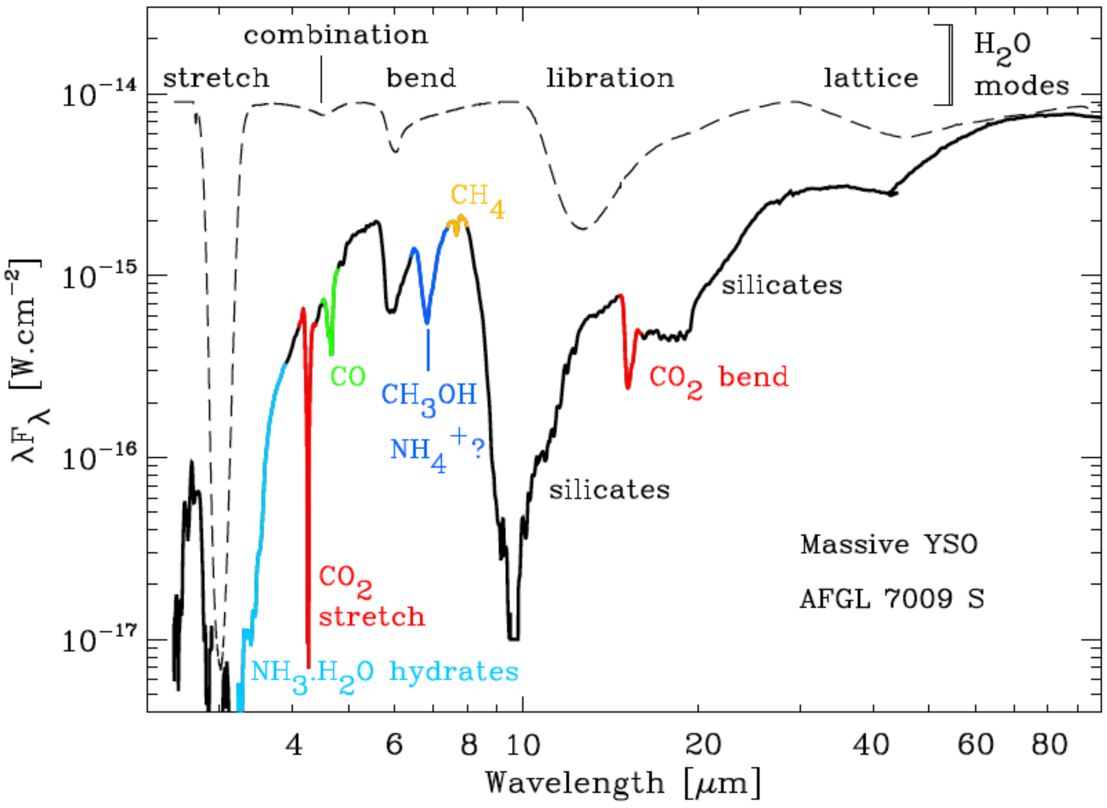
Dullemond et al. (2006)

Does such a dynamic equilibrium in dust/ice growth have chemical consequences for comets?

Major reservoirs in ISM, comets?

Comet Dust/Ice~1.

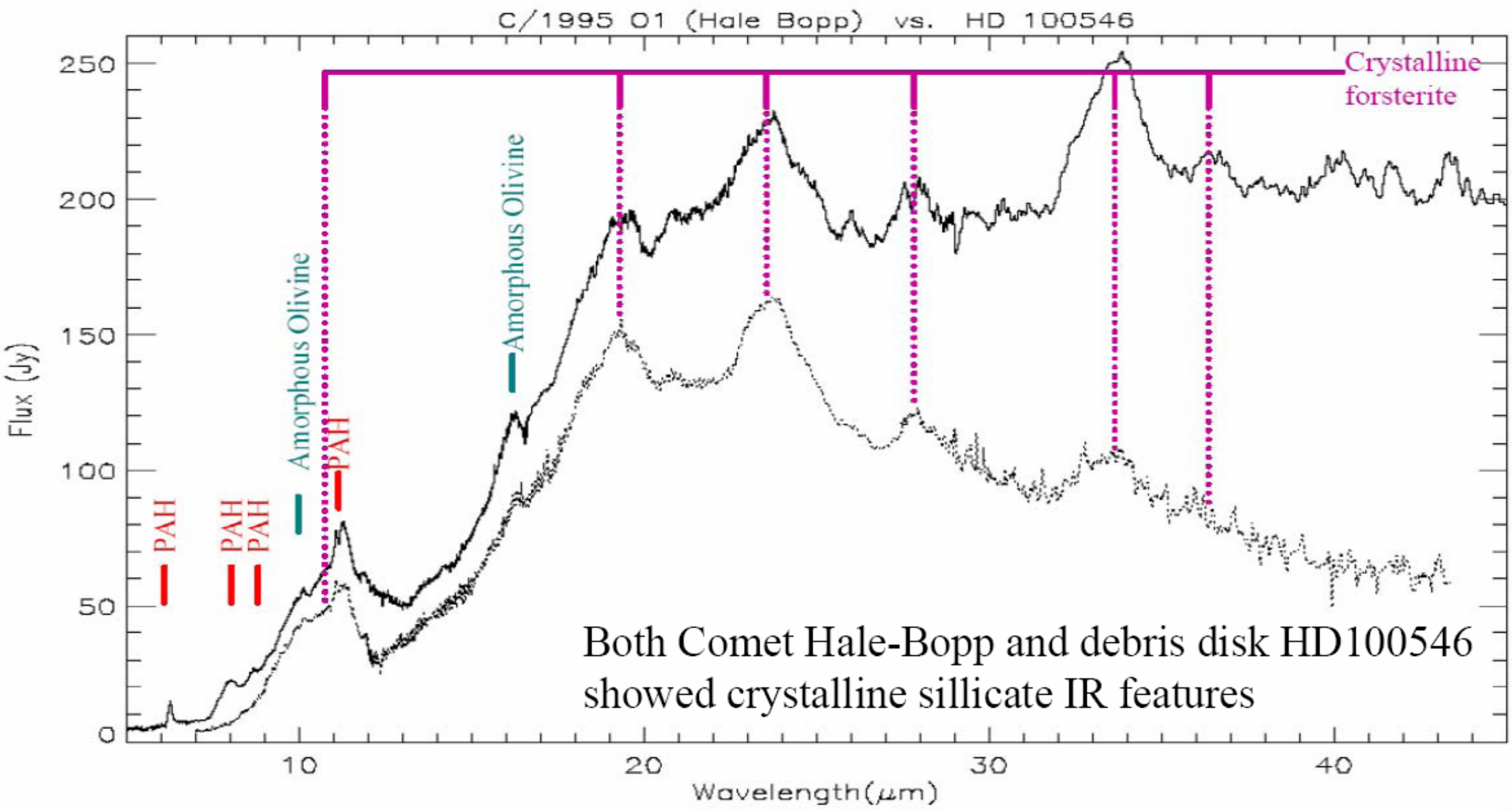
Observations of the Icy Universe; ARAA 53 (2015; accepted), v. 05/05/2015 5



How are these ice and dust components determined, remotely?

What do we know variability? What to do about carbonaceous dust?

Cometary Dust

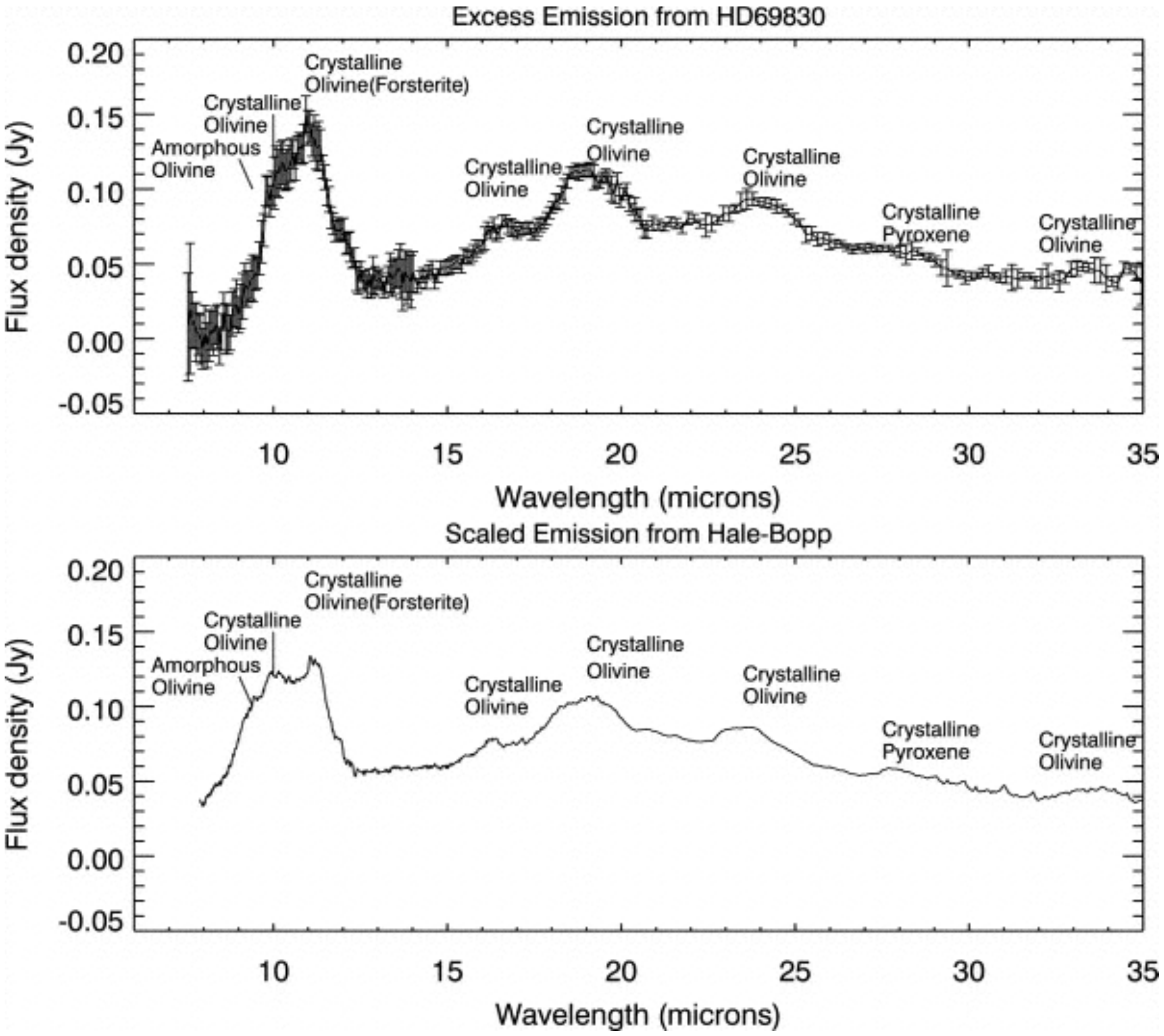


Both Comet Hale-Bopp and debris disk HD100546 showed crystalline sillicate IR features

- Formation of crystalline silicates requires high temperatures
- Small dust particles are required to exhibit strong spectral features

- Zodiacal cloud has weaker silicate features, in part because small particles are quickly removed from system.
- Expectation that comets and debris disks have relatively untouched dust, however explaining crystallization is difficult!

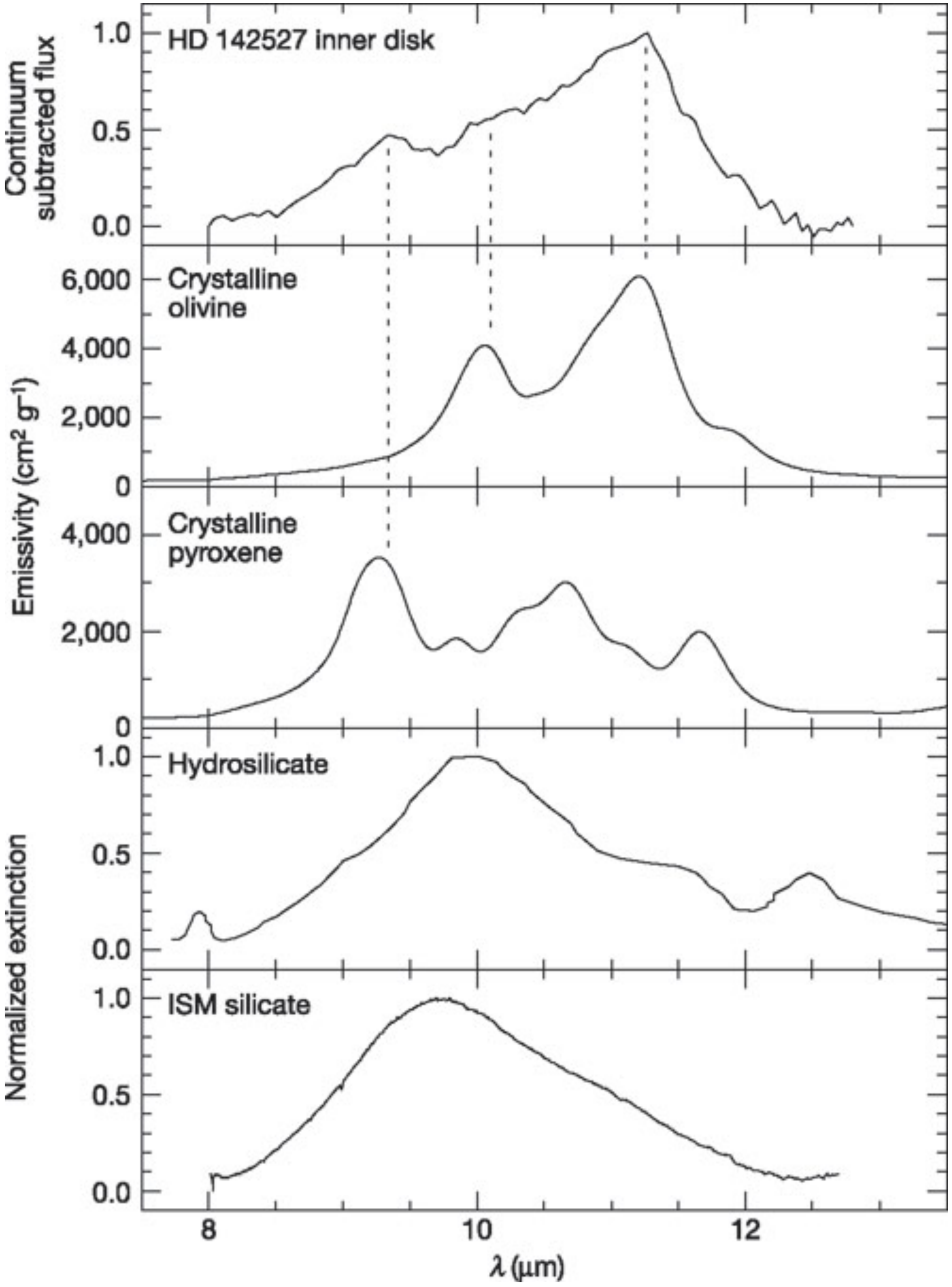
What about “exo-zodii’ s? That is, dust in ~1 AU range?



Beichman et al., ApJ, 626, 1061

Rare!

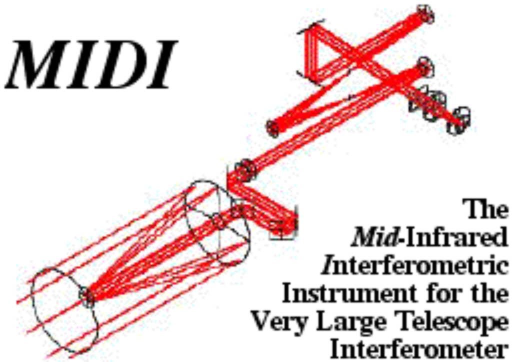
Only a few convincing case so far, in large aperture searches. Need to get closer to the star….



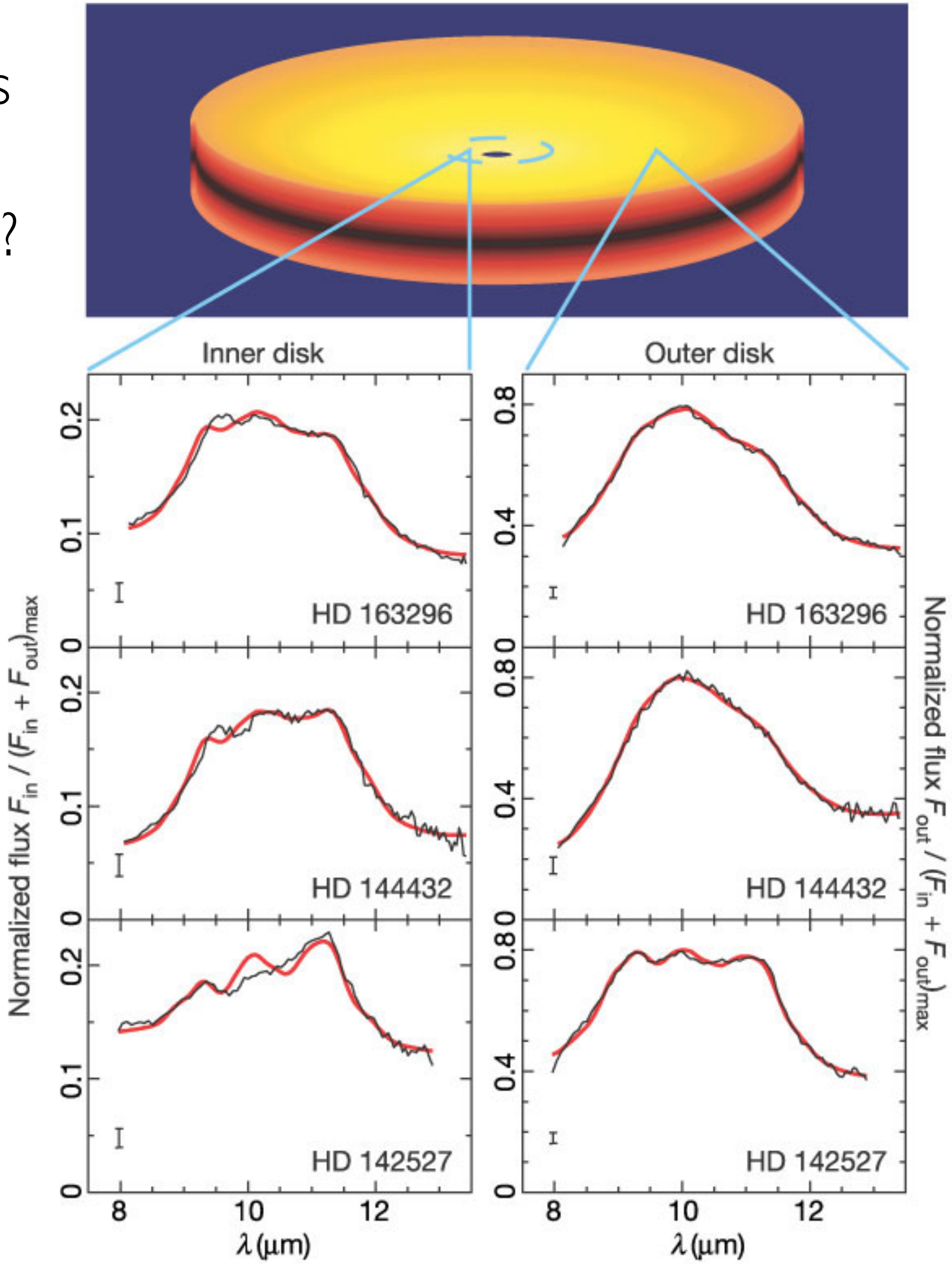
Astronomically,
we only have
spectroscopy to
probe the dust.

Crystalline silicates do seem to be formed in the inner parts of disks. How to transport to comet-forming zone (>10 AU)?

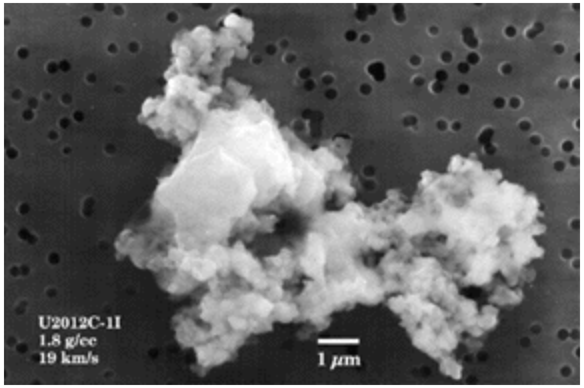
MIDI

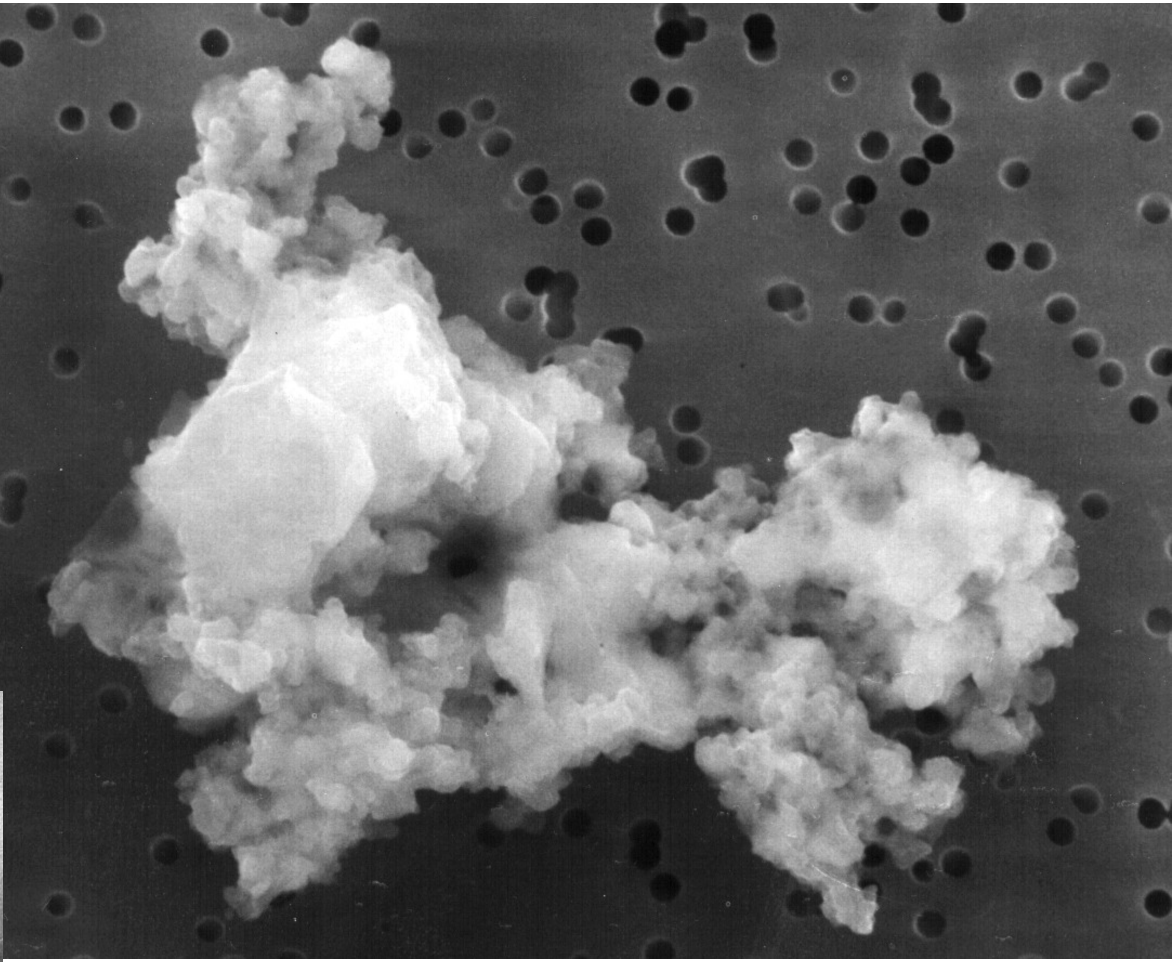


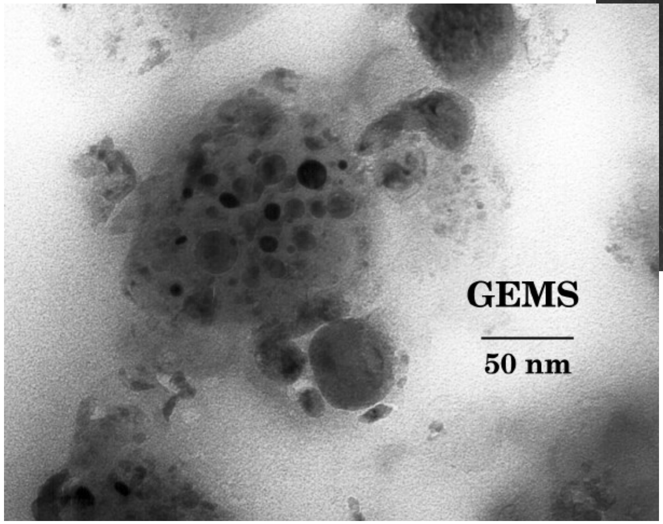
The *Mid*-Infrared *Interferometric* Instrument for the Very Large Telescope Interferometer



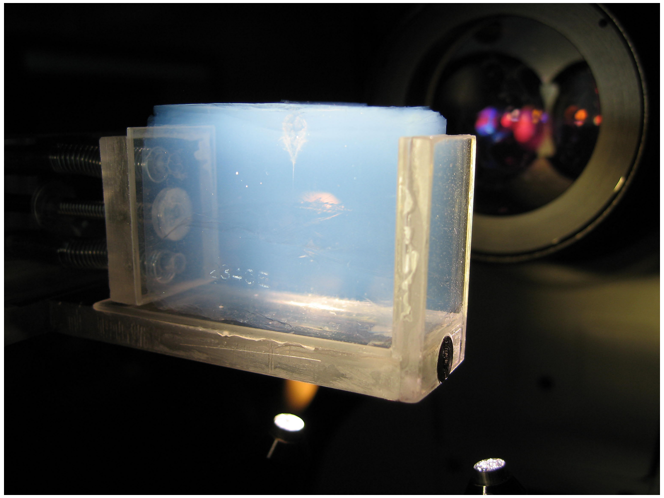
IDPs can be analyzed in the lab!

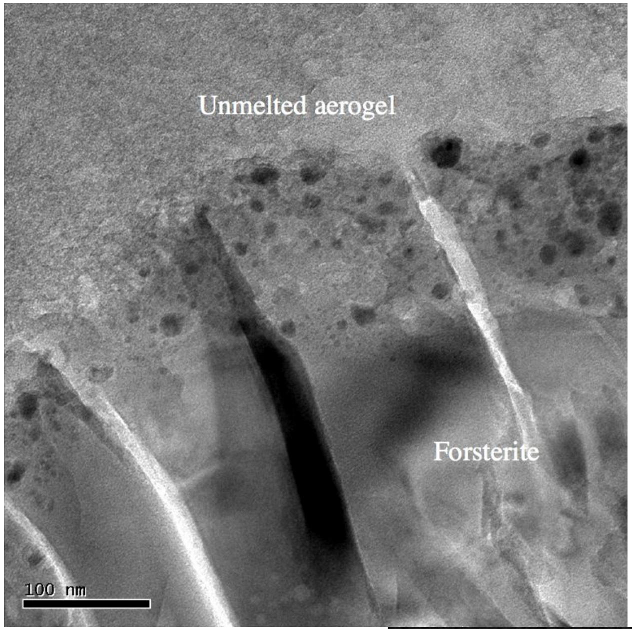




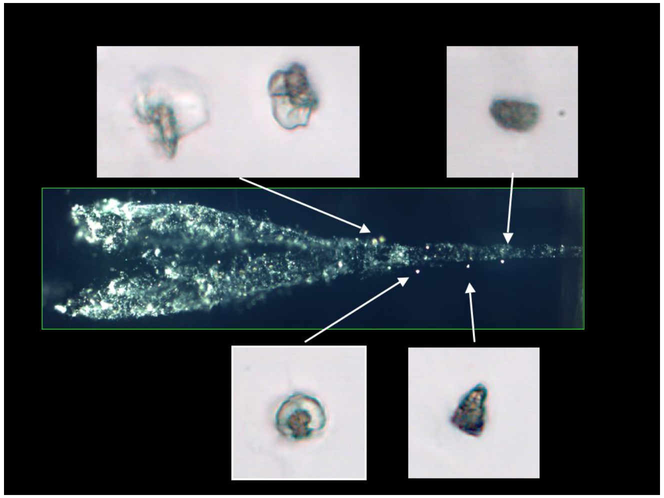


Comet dust assembled from sub-micron sized components.

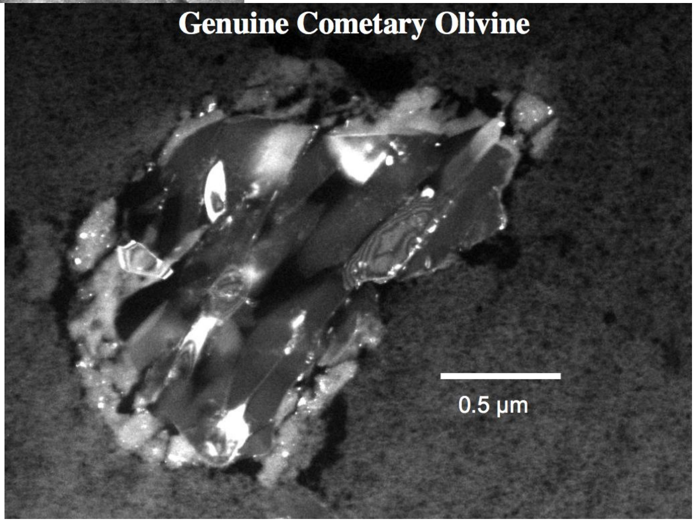




Samples of known provenance!



But unknown petrographic context…



Major reservoirs in comets? Dust/ice~1. Ices?

	HH46	W33A	Hale-Bopp
Water	100	100	100
CO	20	1	23
CO_2	30	3	6
CH_4	4	0.7	0.6
H_2CO	…	2	1
CH_3OH	7	10	2
HCOOH	2	0.5	0.1
NH_3	9	4	0.7
OCS	…	0.05	0.4

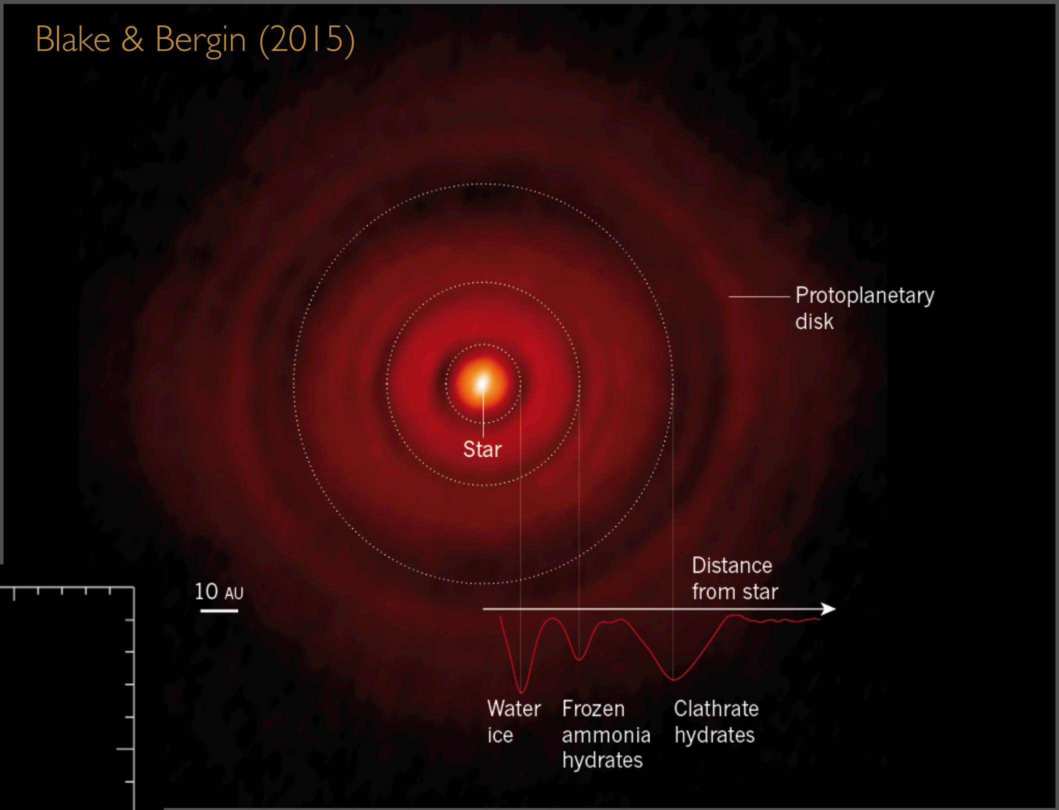
How are these ice components determined?

What do we know variability?

Coagulation vs. disk gaps? The cautionary tale of HL Tau:

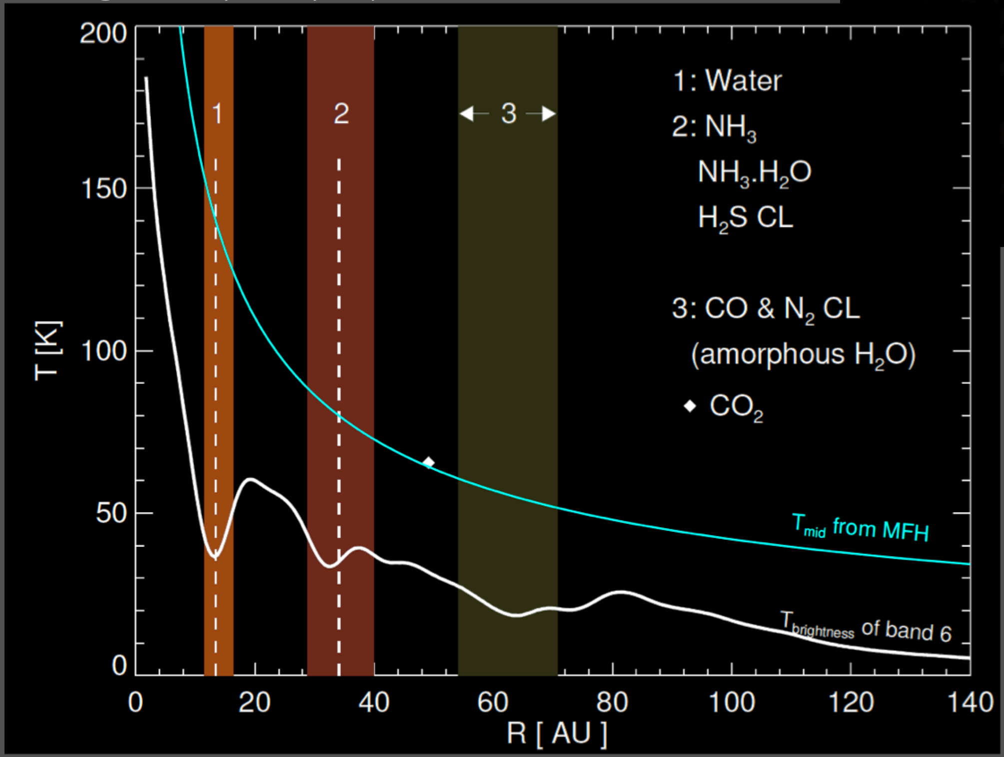
Beautiful ring structures in the dust continuum of this young disk:

HL Tau Band 7 (SV Data)



Partnership/Brogan et al. (2015), ApJL 808, L3.

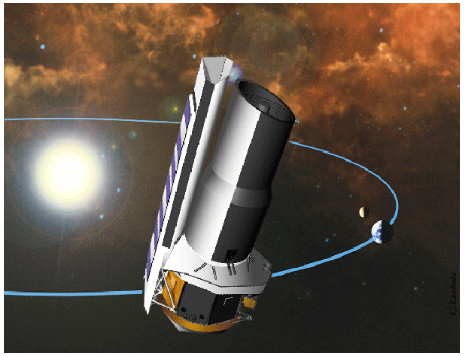
Zhang et al. (2015), ApJL 806, L7.



Interesting correlation:

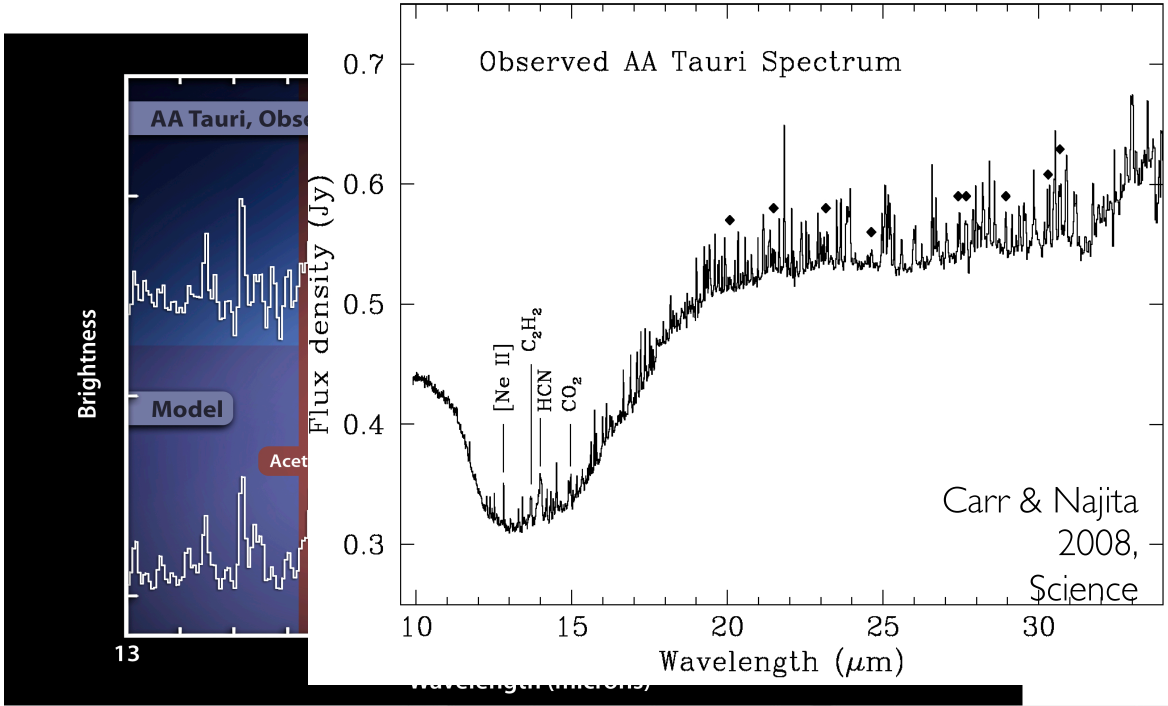
- The drops in emission well matched w/frost lines.
- The changes in mm spectral slope only require growth to decimeter scales.

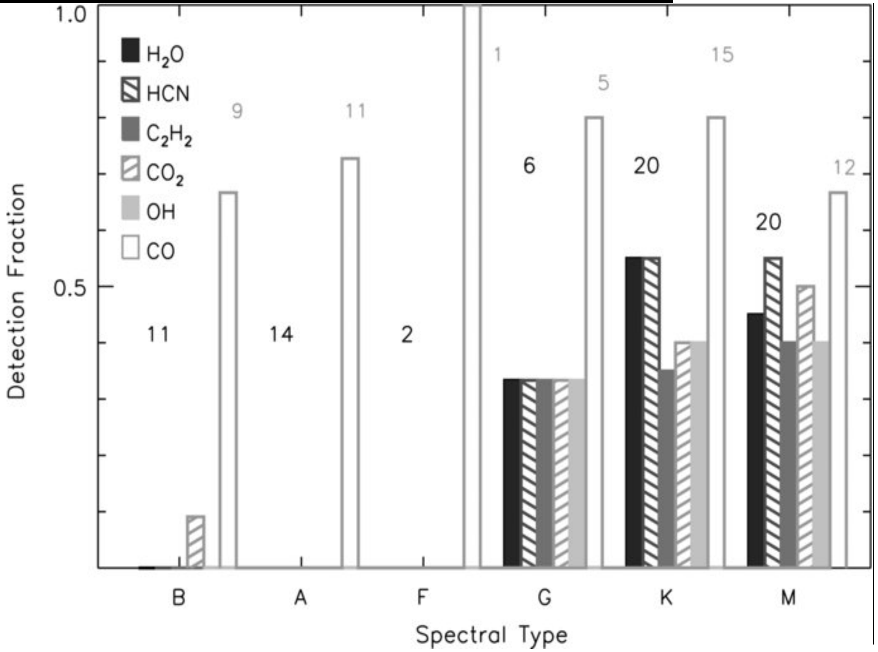
Disk species?



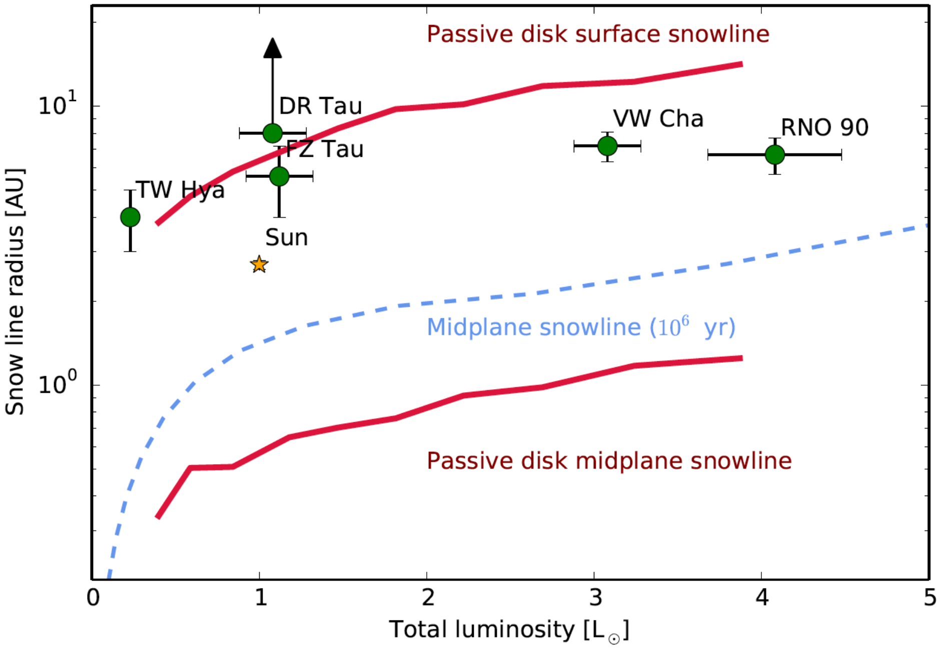
The next key step combined the beautiful emission lines & bands seen with Spitzer (R=600) toward AA Tau (right, Carr & Najita 2008, Science, 319, 1504), and AS 205/DR Tau (Salyk et al. 2008) with Keck/NIRSPEC data.

Now >200 objects.

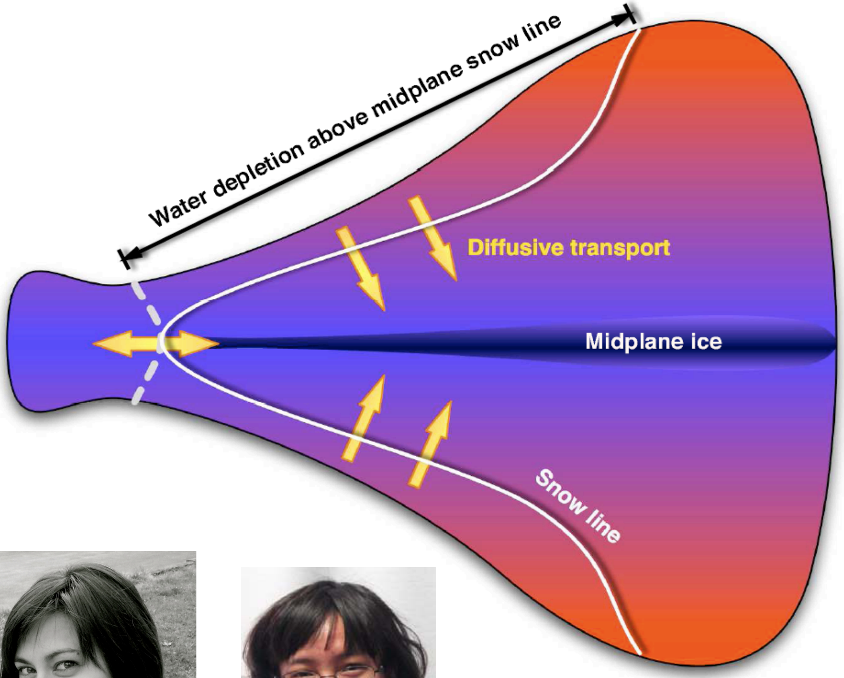




Can measure surface snow lines:



Blevins et al. (2016), ApJ 818, 22.



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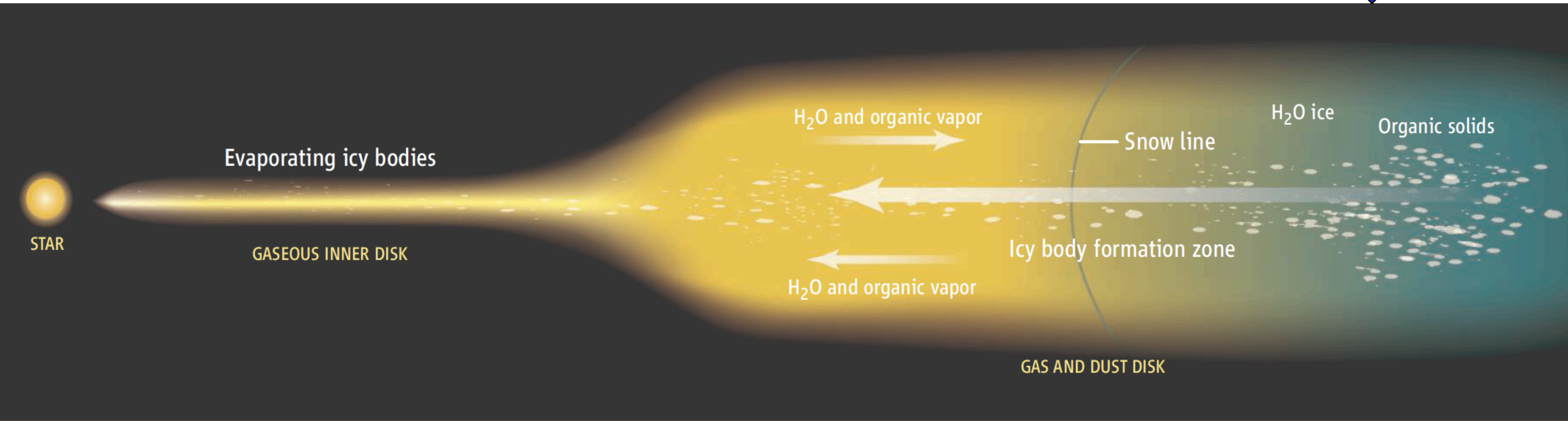
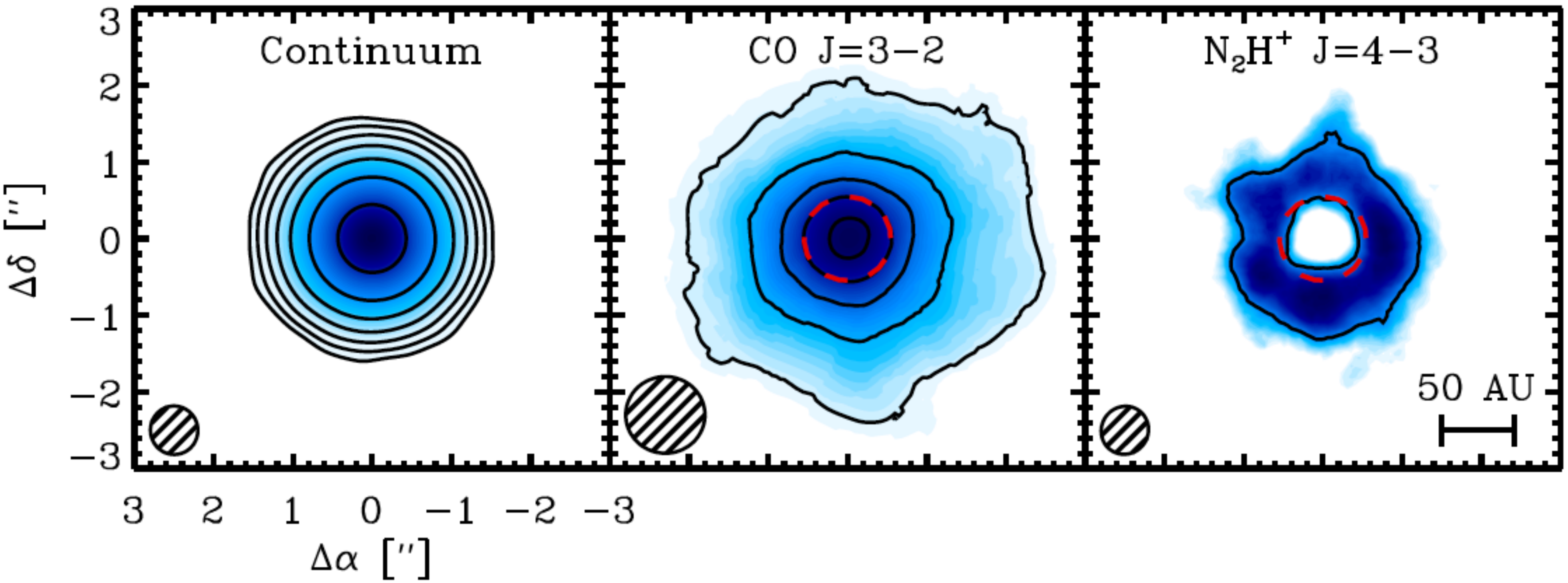


What about the midplane and volatiles? Enter ALMA. Let's start w/the CO snow line via chemistry:



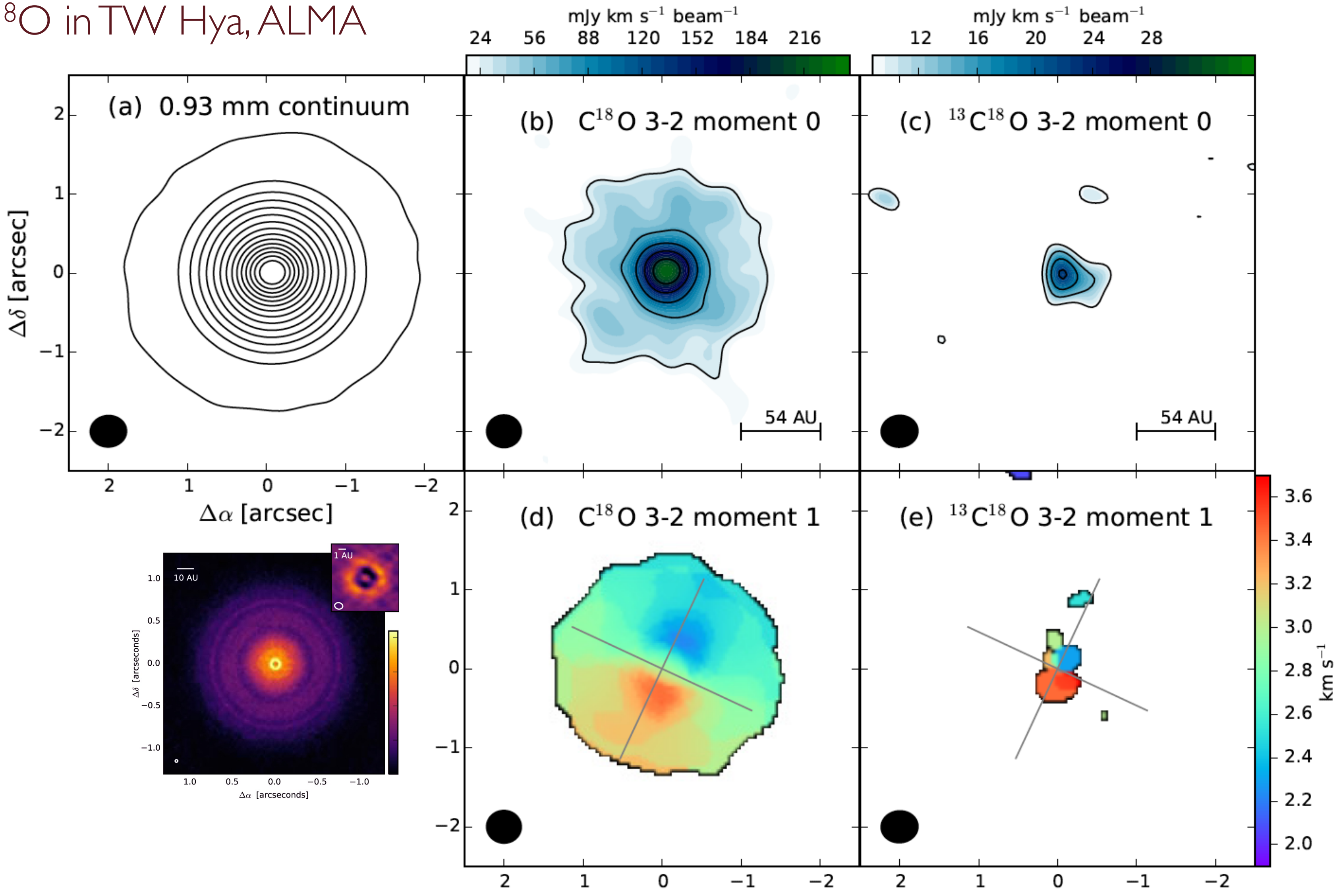
Cycle 0 ALMA data, Qi/Öberg et al. Science (2013)

$$\mathrm{NNH^+ + CO \longrightarrow NN + HCO^+}$$

and so NNH^+ jumps in abundance just where CO depletes onto grains (N_2 has a slightly lower frost temperature).

Can we directly image CO snowlines/C-grain oxidation?

$^{13}C^{18}O$ in TW Hya, ALMA

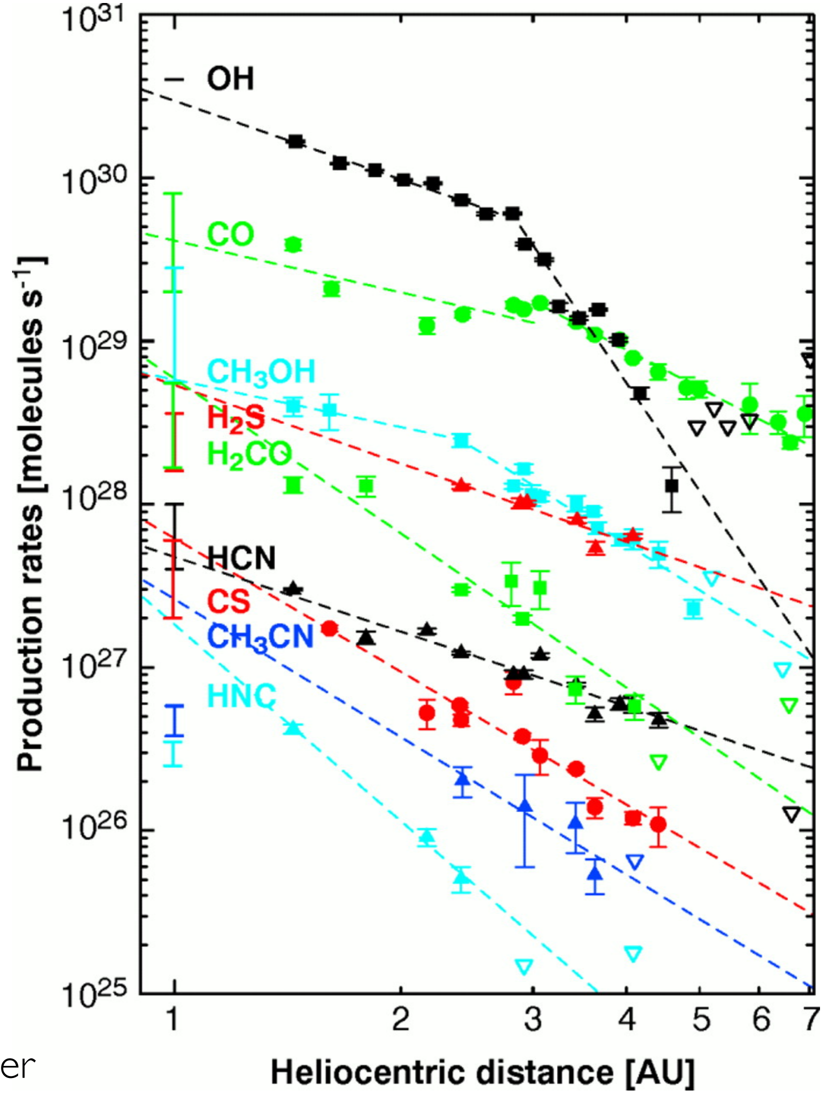


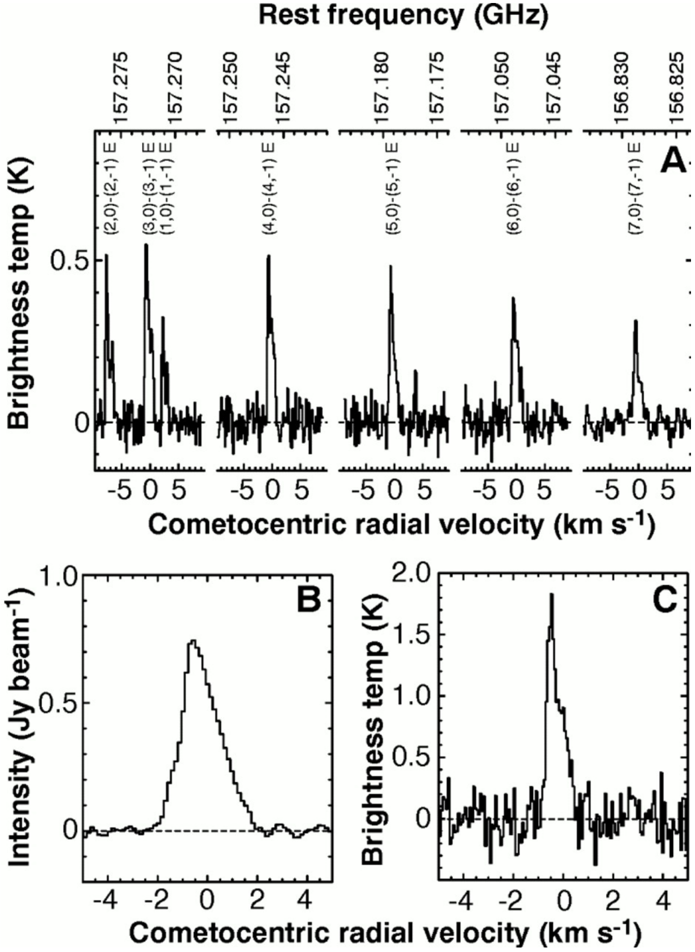
Hard work, even in the closest disk!

In a bit: Can we find other approaches?

Zhang et al. (2017), Nature Astron., in press

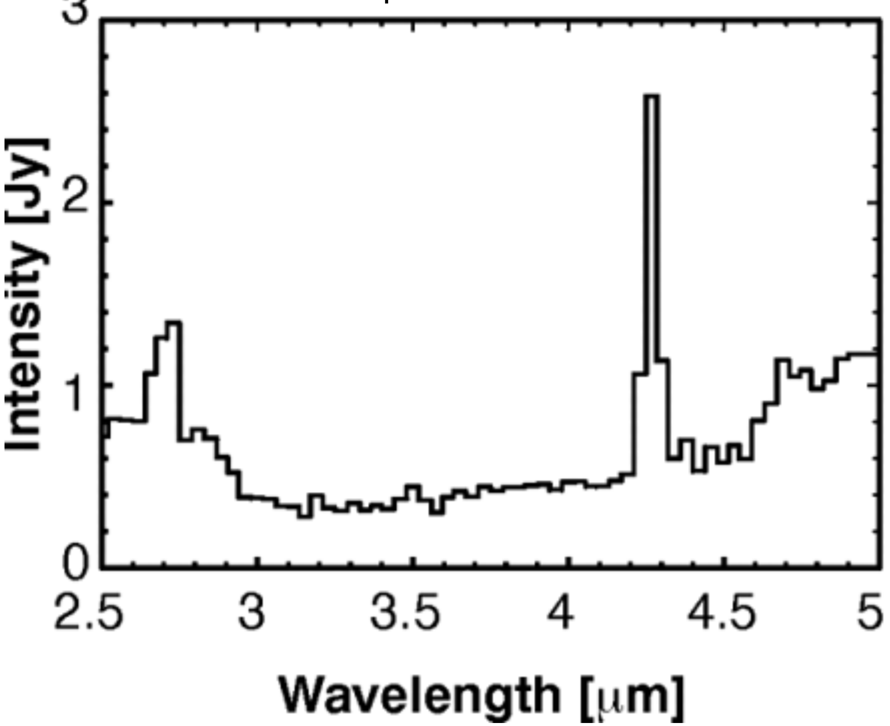
For species with dipole moments, use rotational spectra to study cometary comae:





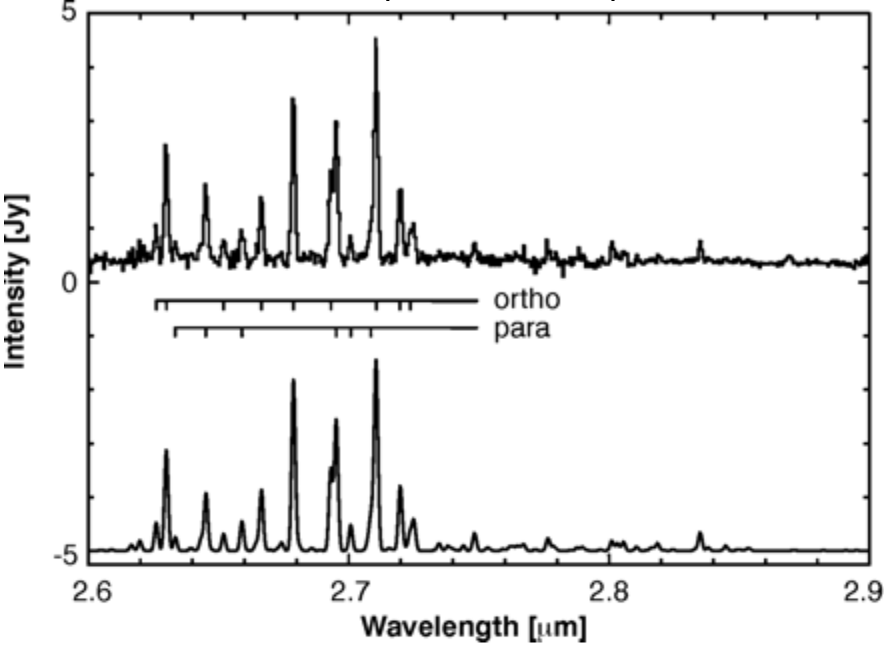
Biver

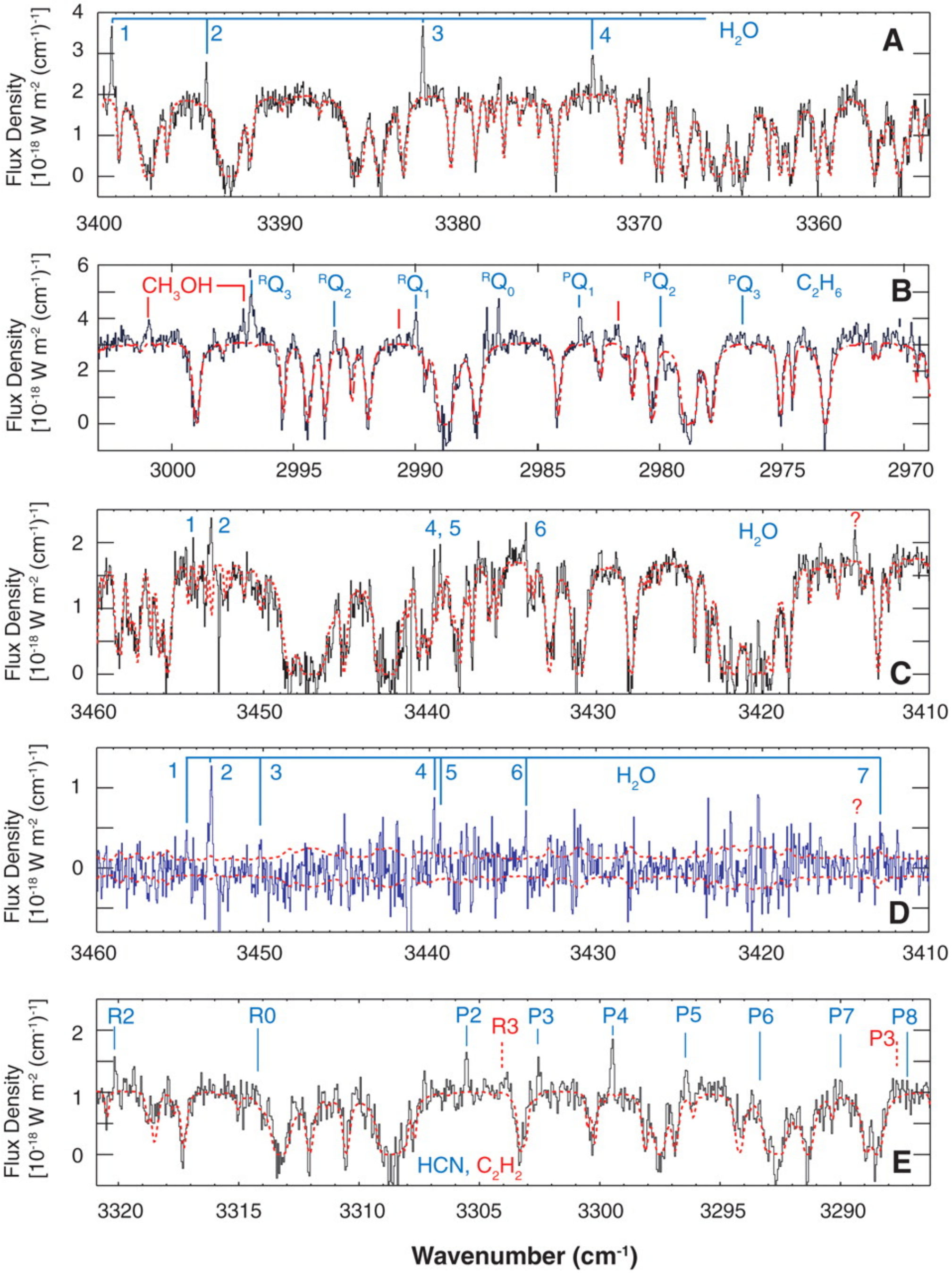
ISO spectra:



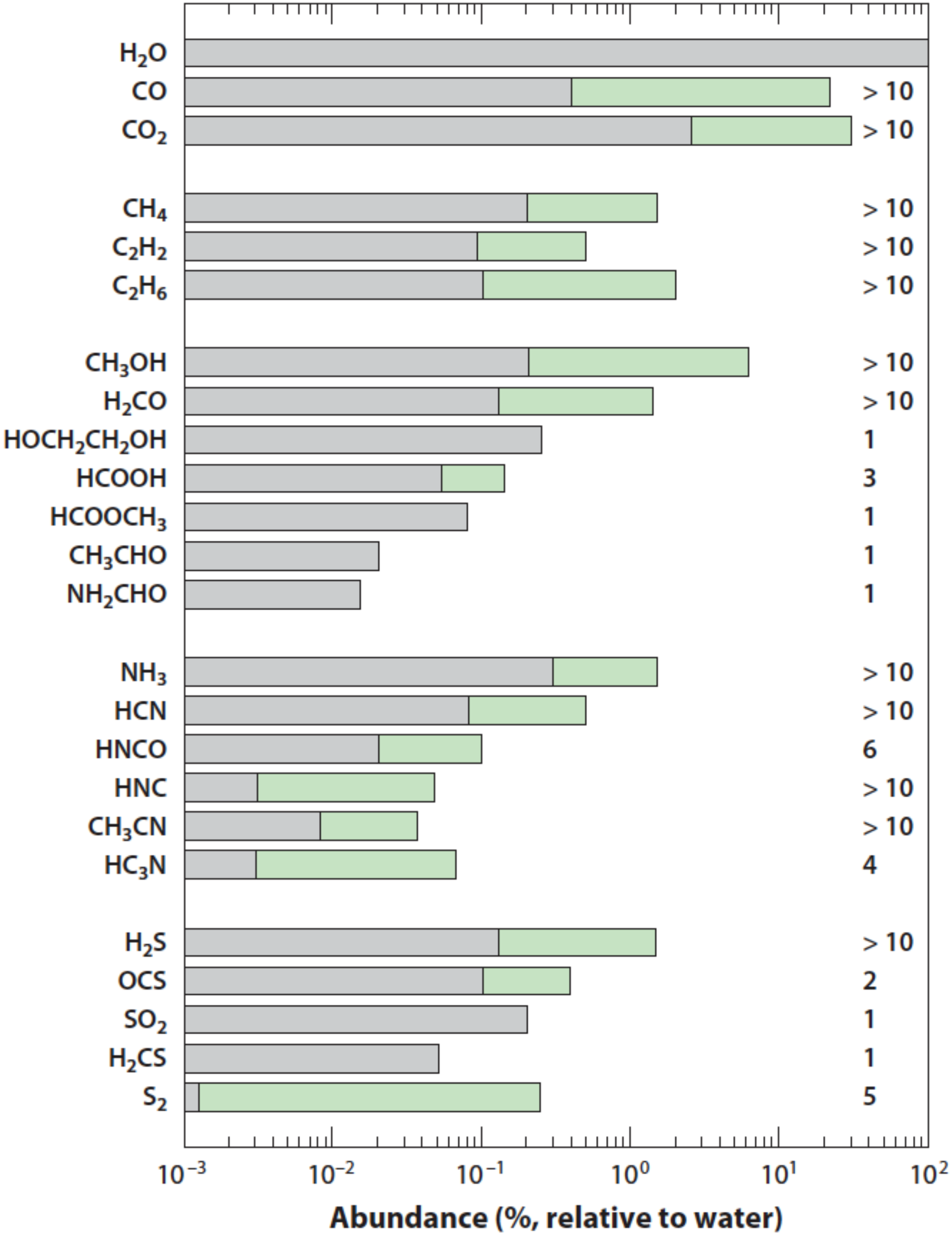
Infrared spectroscopy gives access to pivotal non-polar species (CO_2, CH_4), and in many cases, water.

Water "spin" temp.~25 K



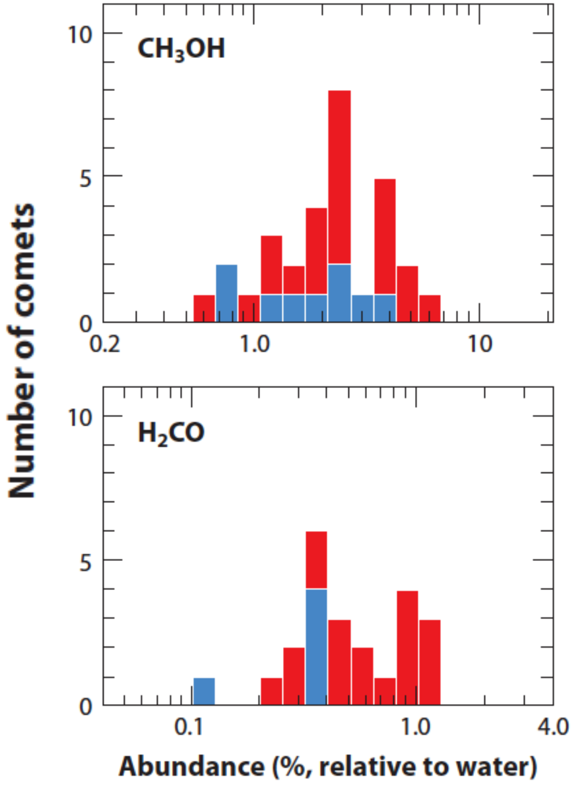


Ground-based data can also provide constraints, on a much larger number of comets, but must fight through the Earth's atmosphere!

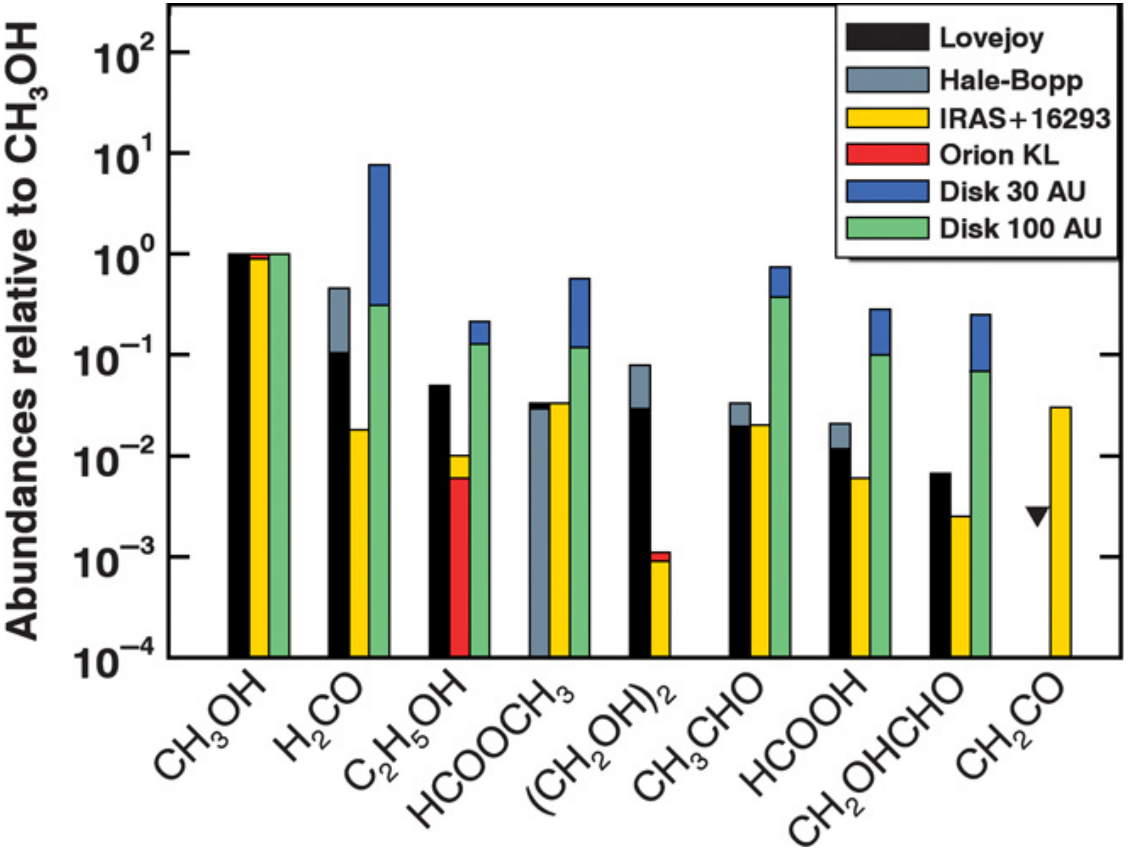


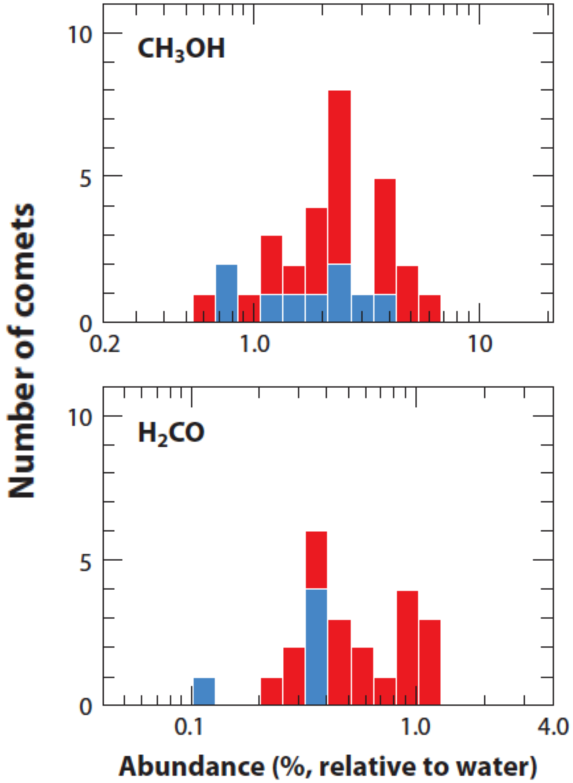
Mumma & Charnley, ARAA

From a combination of IR and mm-wave campaigns, we now have handfuls of comets with small molecule data. Plenty of variability!



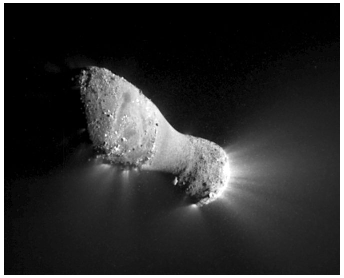
Nicolas Biver et al. Sci Adv 2015;1:e1500863



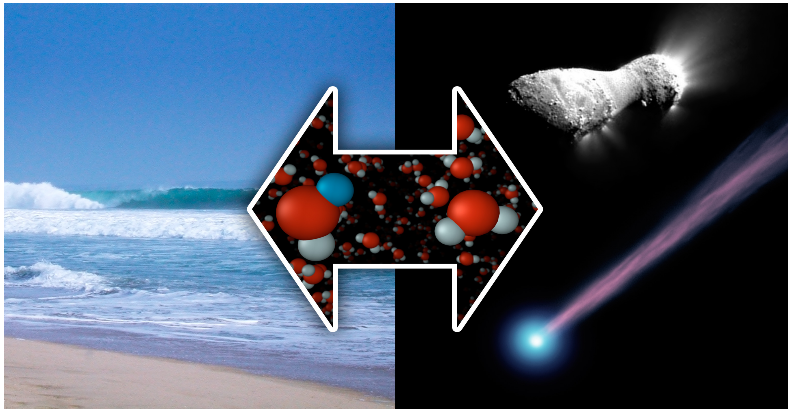


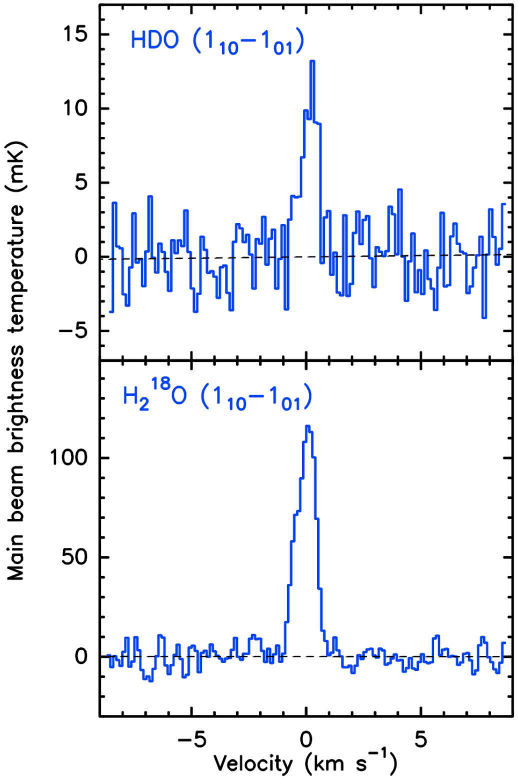
‘Complex’ organics? Still small by chemistry stds., can compare comets versus that seen in the dense ISM (not yet disks).

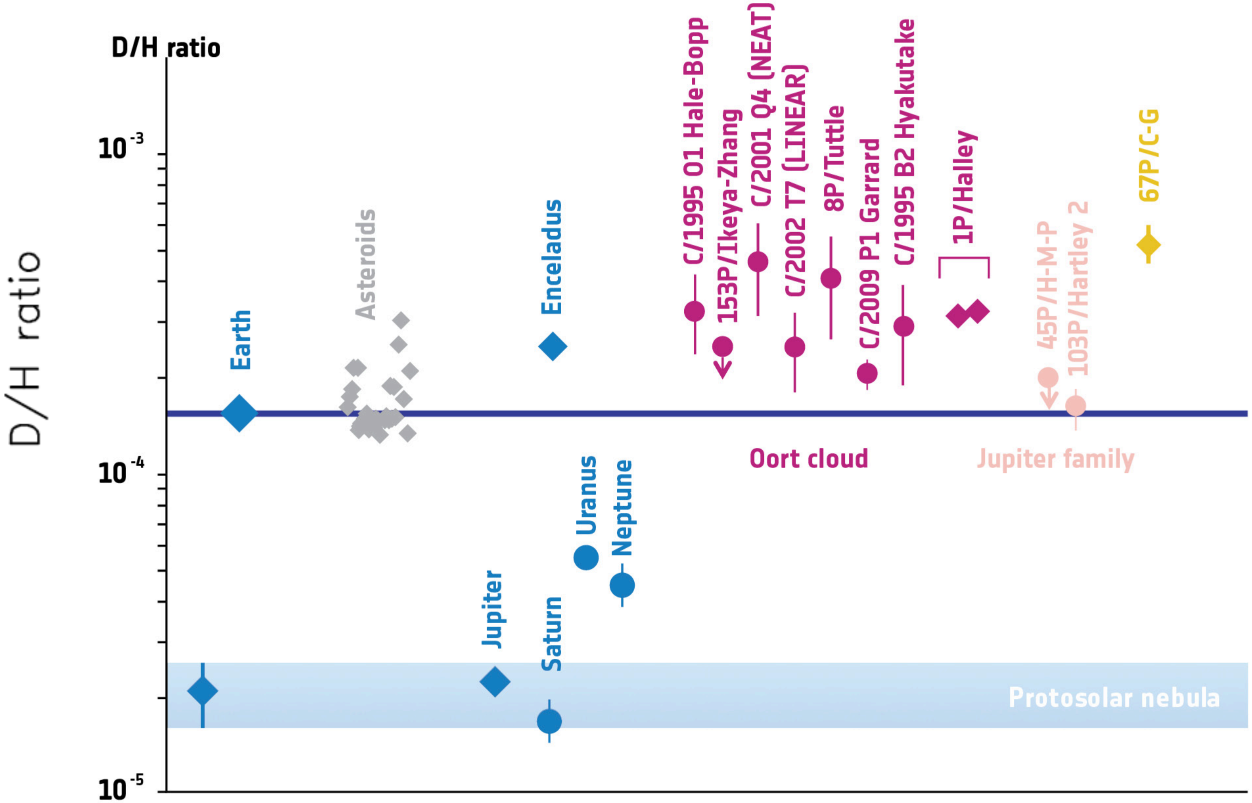
What studies of icy bodies could test dynamics?



103P Hartley 2,
5 hrs Herschel

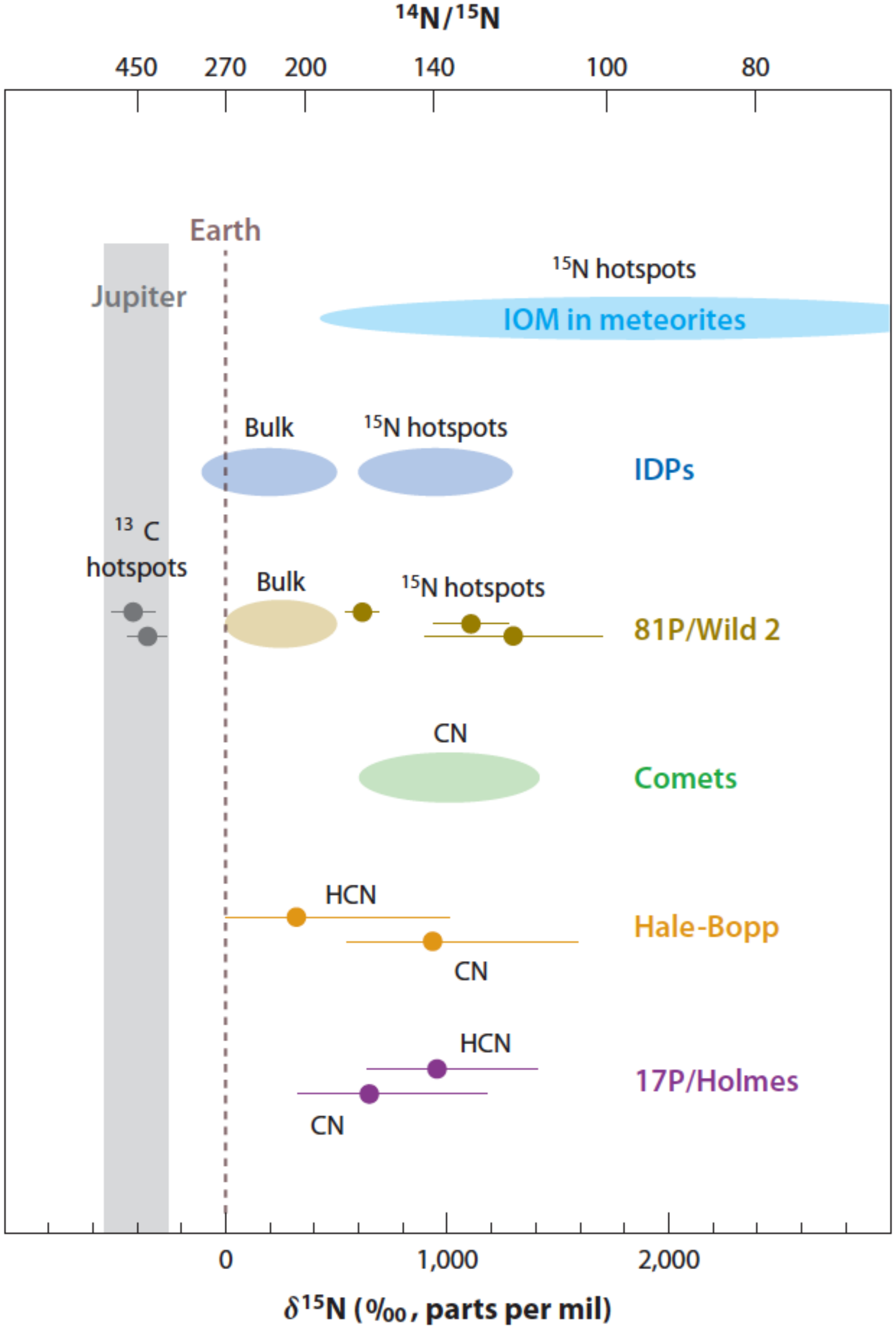




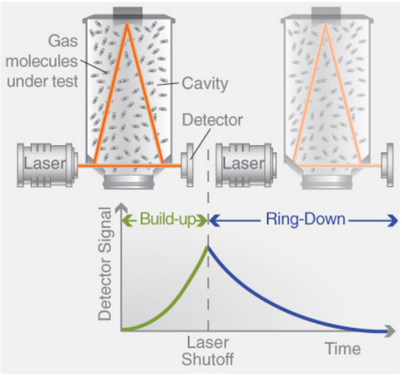


Isotopes & formation conditions?

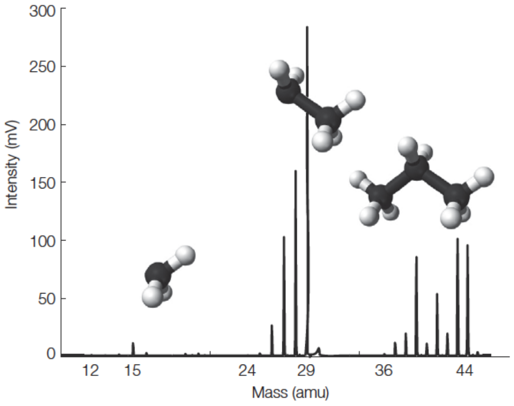
What new science can in situ or sample return missions drive?



CRDS

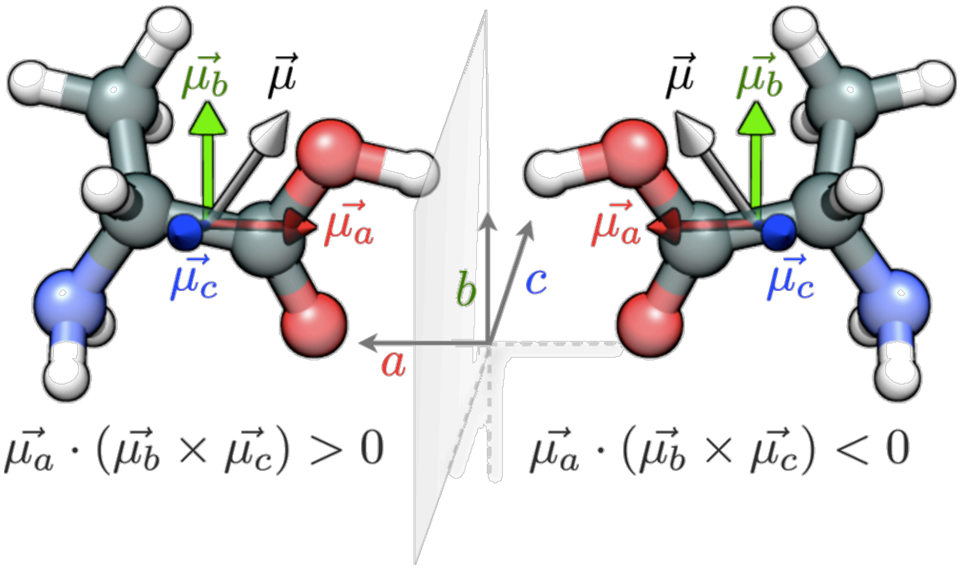


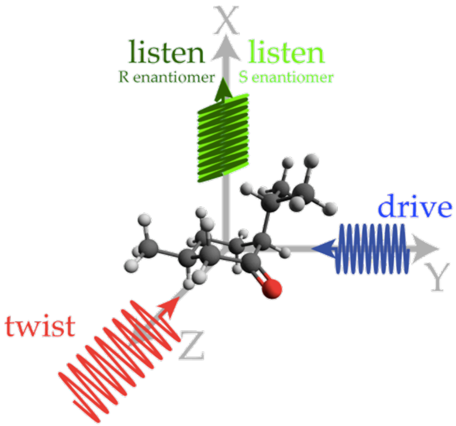
FT-MS

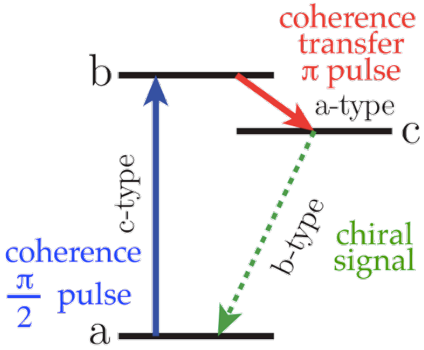


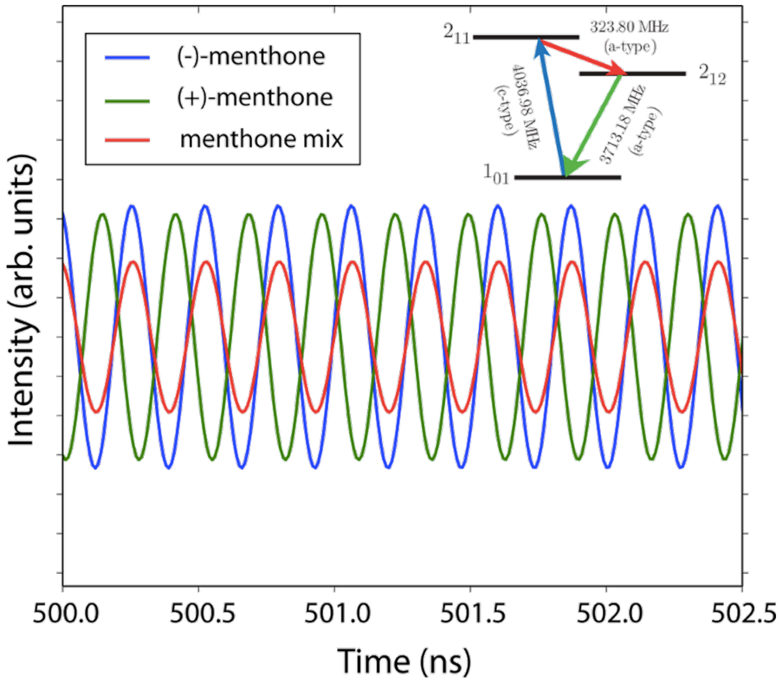
For small molecules, site specific stable isotopes to <1 per mil!

What new science can in situ or sample return missions drive?



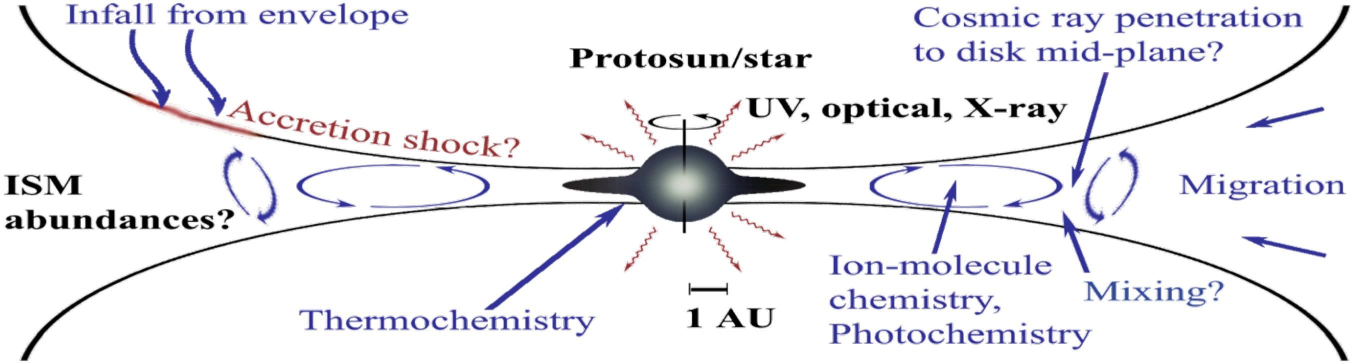


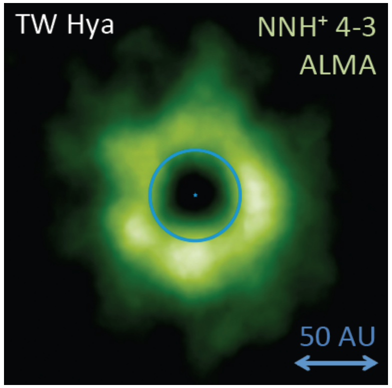


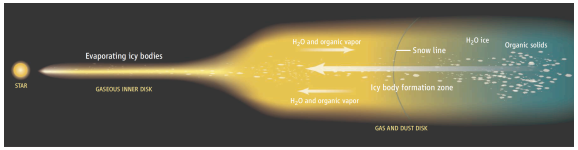


For more complex molecules, much better detection limits and, where appropriate, chiral enantiomeric excesses.

Disks & Cometary Precursors - Conclusions







- With ALMA and the next generation of optical/IR telescopes we can now image the birth of solar systems directly.
- We can measure snow line locations vs. t, and examine dust aggregation. For C, N cannot simply follow the water.
- Large samples of comets can be studied remotely, to provide context/distributions.
- Does the process of planetesimal formation have chemical consequences?