“The Nature of Interstellar Organics and Their Relationship to the Solar System”

A talk given at the SSERVI Carbon Workshop on April 25th, 2018

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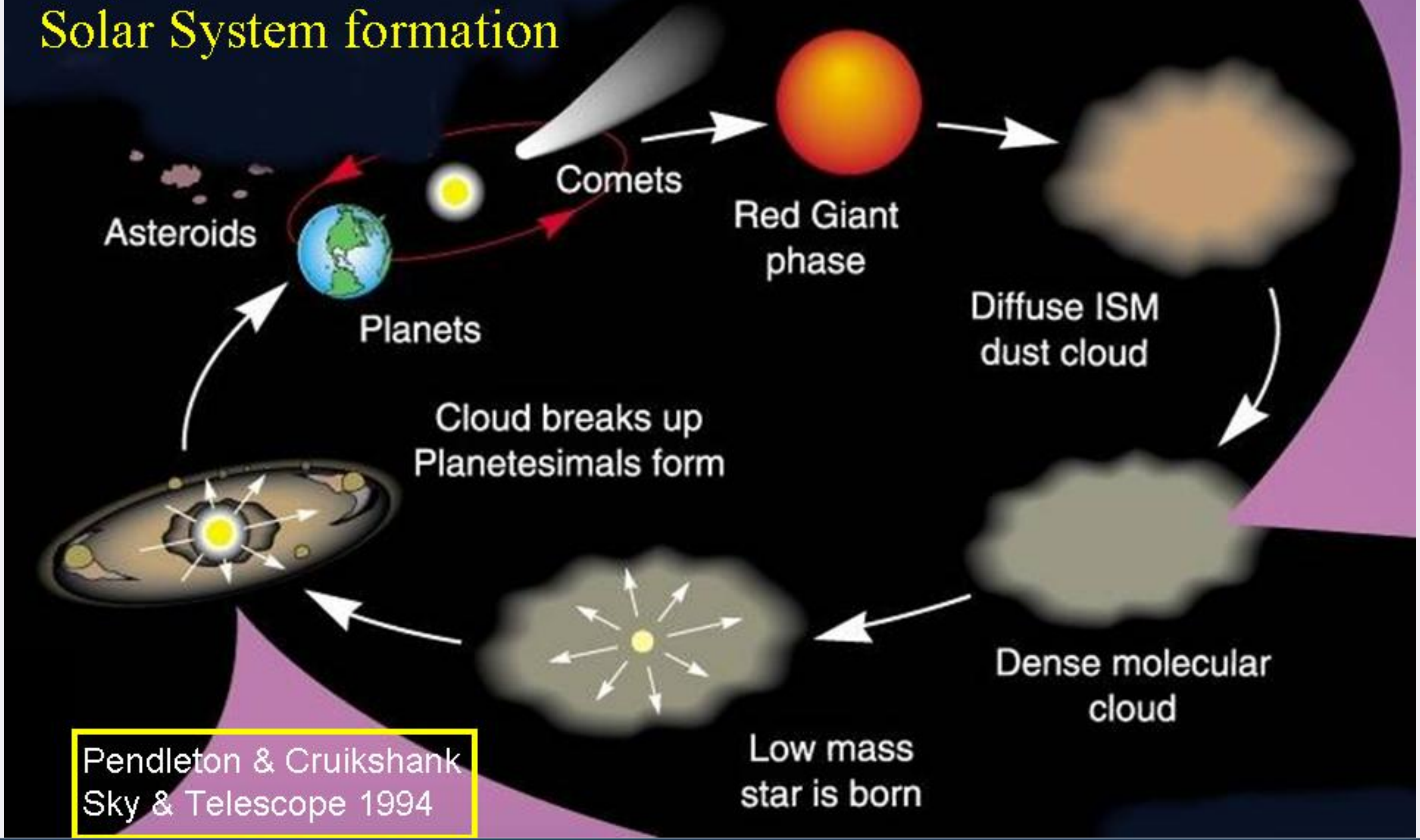
Key Questions

- What are the primordial sources of organics and volatiles and what are the processes that govern their formation, evolution and delivery throughout the Solar System?

- Once we identify the problems of interest, can we work collaboratively to bring together theoretical modelling, laboratory experimentation, and astronomical observations?

Volatile and robust carbon compounds in interstellar clouds were recycled during Solar System formation

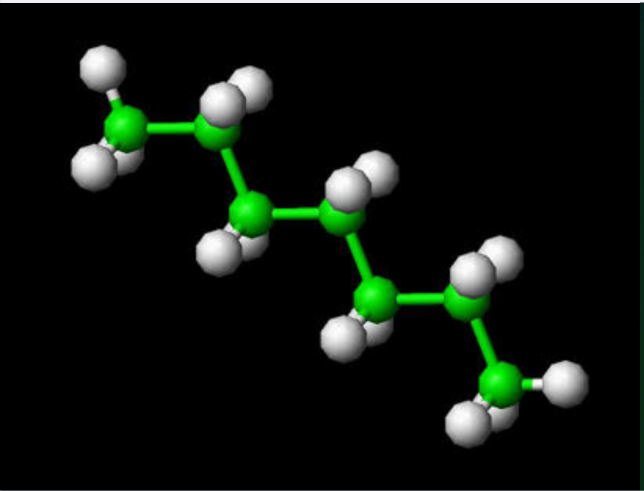


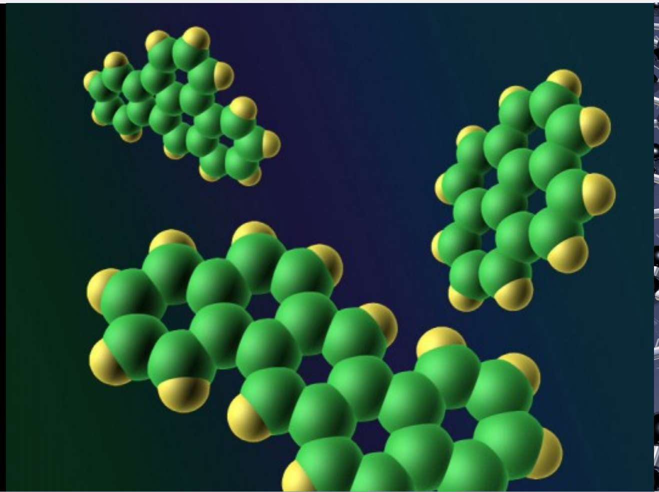
Interstellar Medium (ISM) Organics

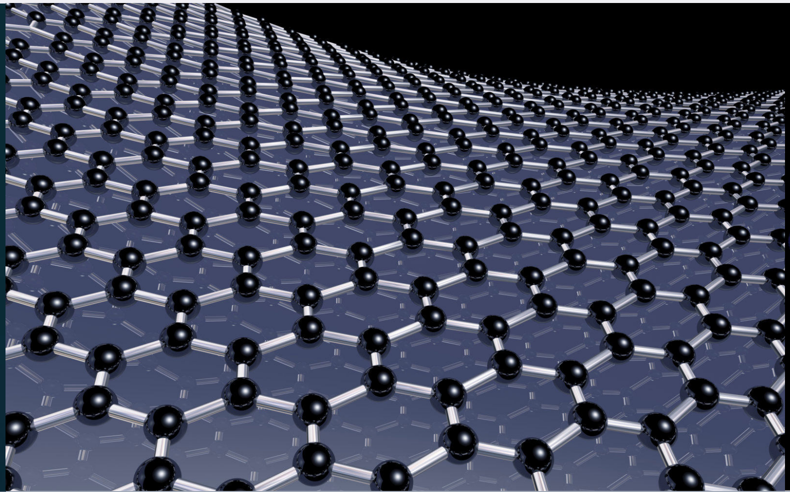
Evolved stars eject Carbon-rich products into the diffuse ISM. The ejected material cools as it travels away from the star. Infrared **absorption** bands reveal small aliphatic hydrocarbon chains in the diffuse ISM; ~10% of the elemental C in the ISM is locked up in these chains of hydrocarbons.

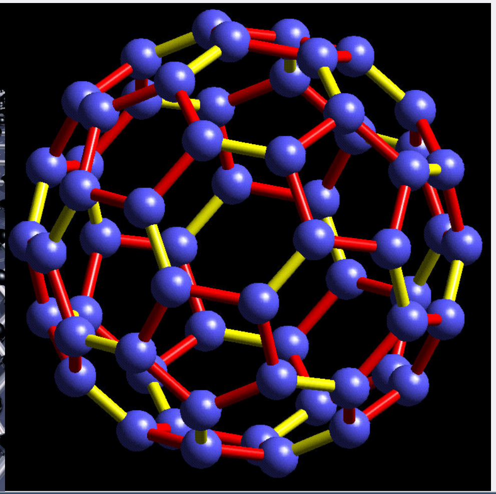
Polycyclic Aromatic Hydrocarbons (PAHs up to ~50 C atoms) and fullerenes (C60) are observed in many different environments in **emission**; ~5% of the C is locked up in PAHs.

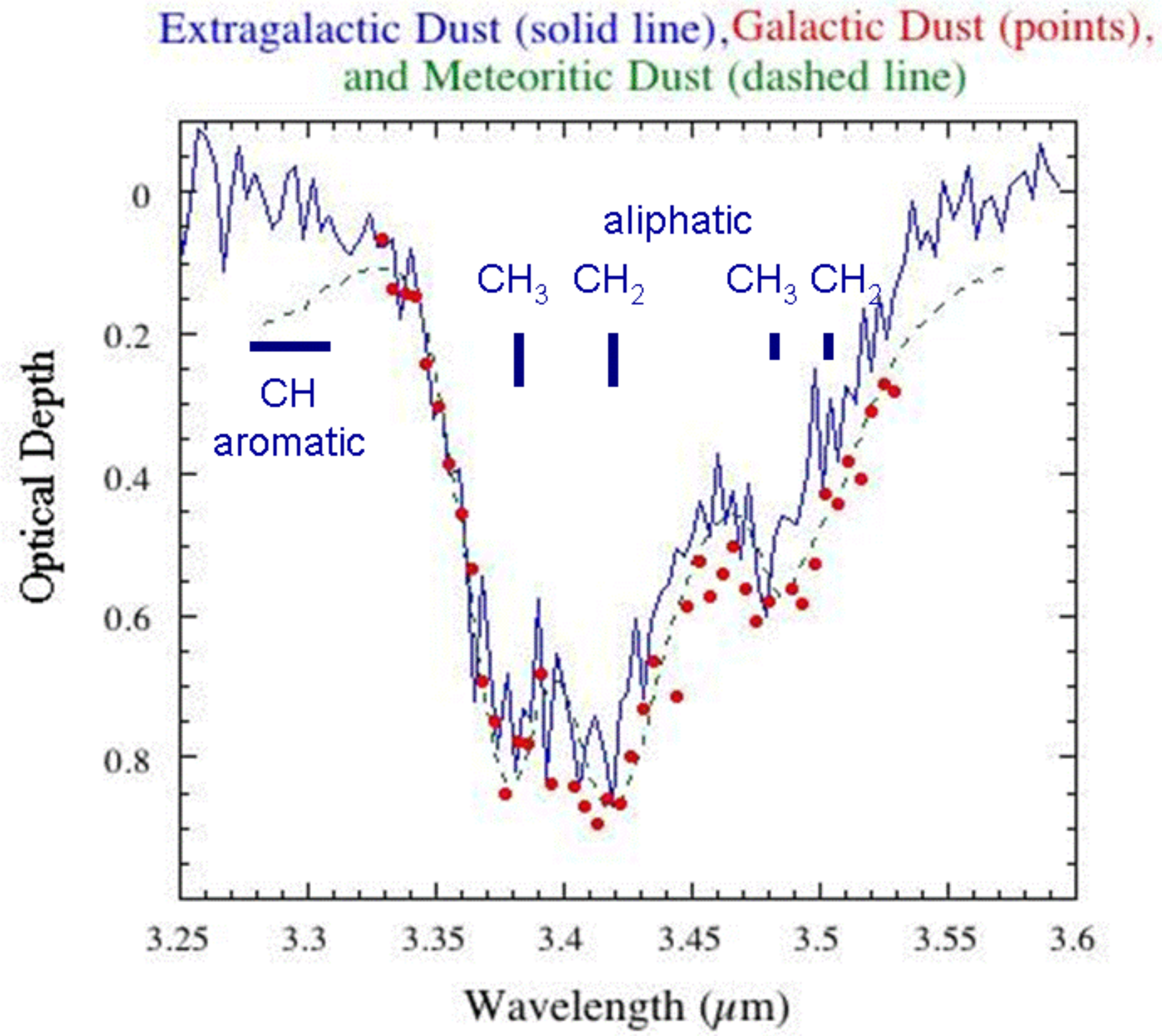
C60 is very stable and is found close to stars. Hard to form C60 there, so C60 is likely formed through the destruction of PAHs. How does this happen? First H bonds break and graphene sheets are formed. Then C bonds break to form small chains and cages. Following this, some of the cages join together to form fullerenes (C60).







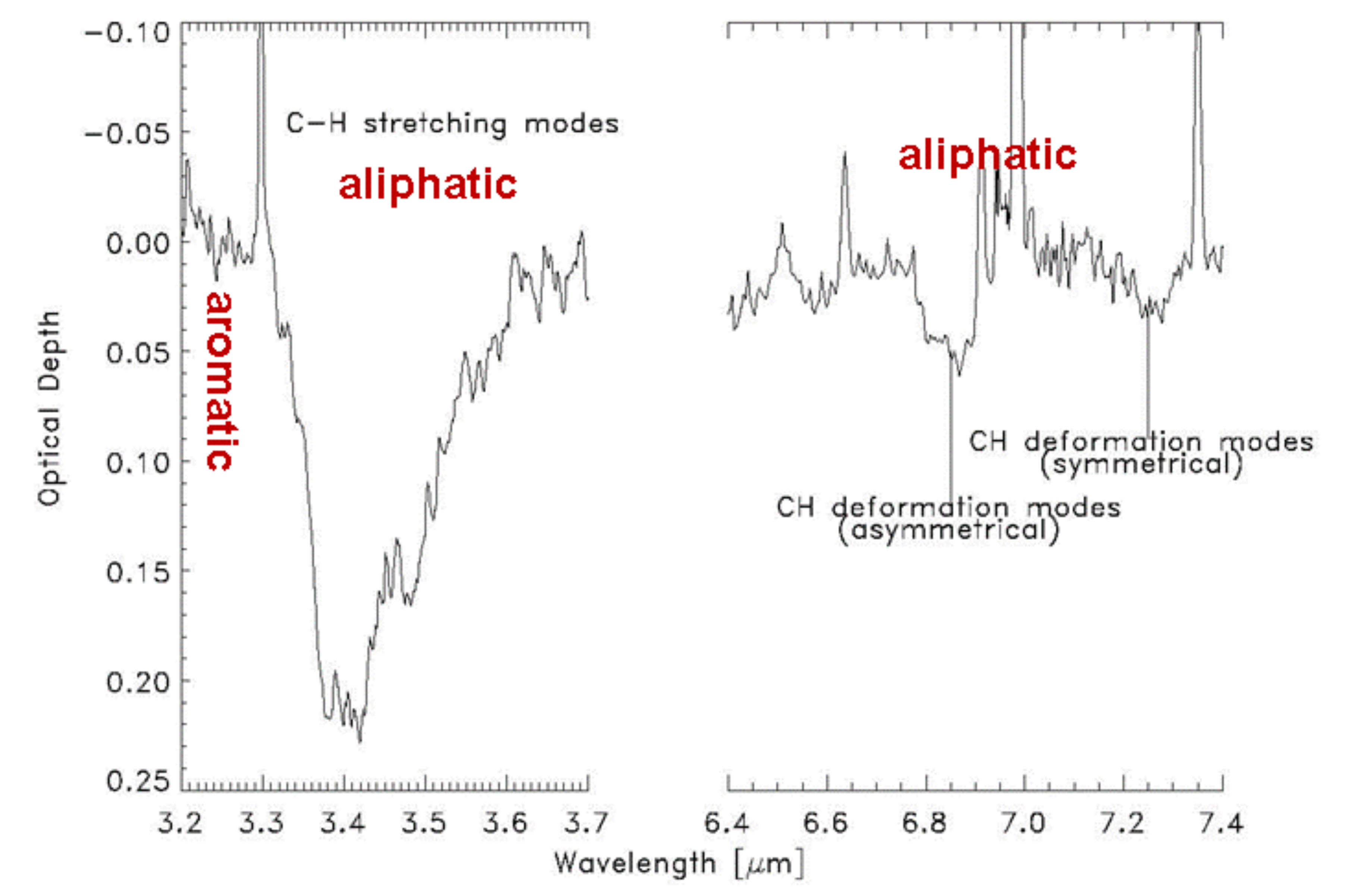




Dust in our Galaxy and other galaxies contains aliphatic hydrocarbons similar to those found in the Murchison meteorite.

Pendleton, Y. J. 1997, "Detection of Organic Matter in Interstellar Grains", Origins of Life and Evolution of the Biosphere, 27, 53-78.

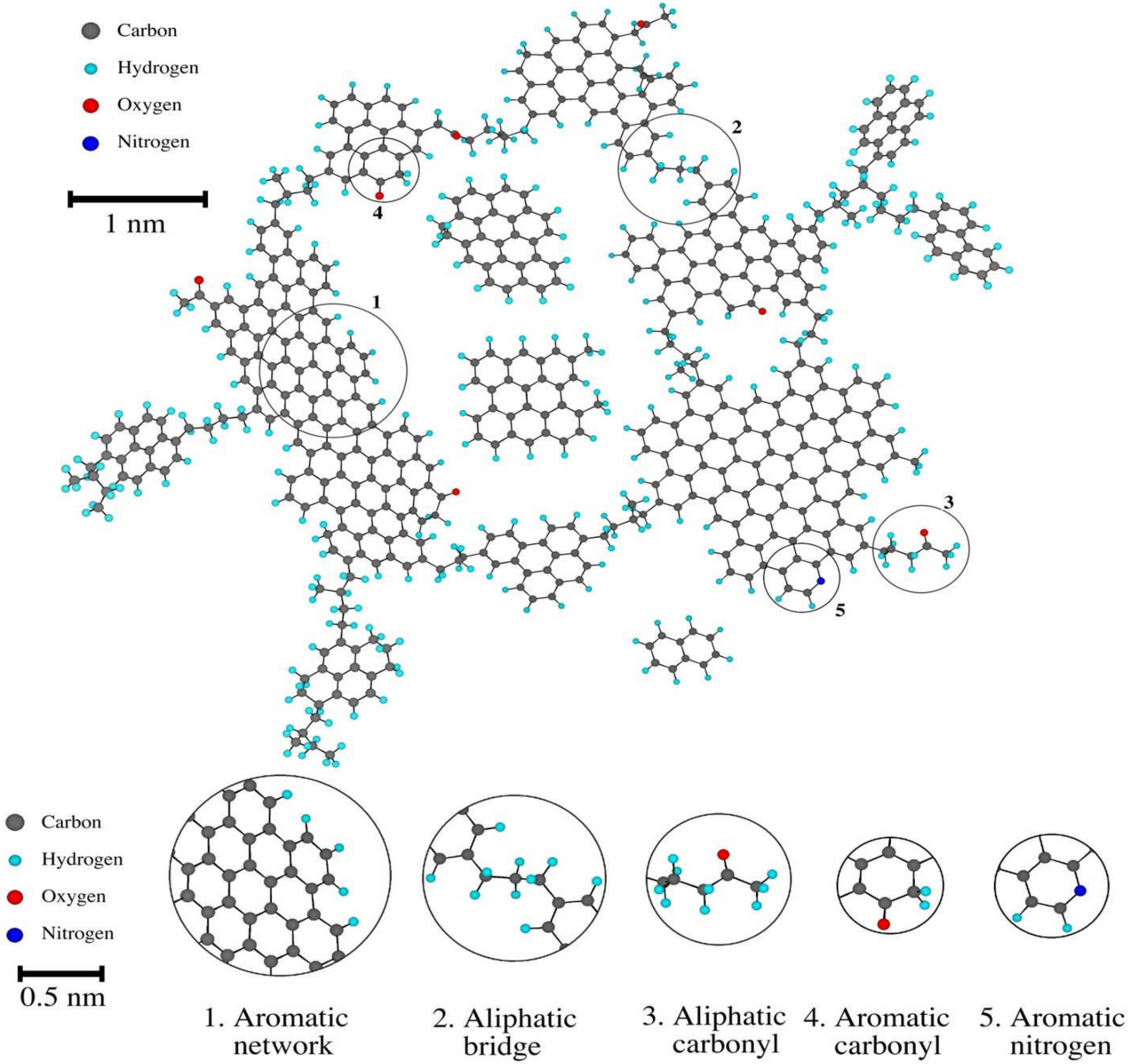
Diffuse ISM Dust along two sightlines



Only functional groups can be seen in *near-infrared* spectra.

Full molecular identification awaits the acquisition of longer wavelength, moderate-resolution *mid-infrared* spectra.

Pendleton and Allamandola, 2002, Astrophysical J., Supp. 138, 75-98.



From Pendleton, Y.J. and Allamandola, L.J. (2002). The Organic Refractory Material in the Diffuse Interstellar Medium:Mid-IR Spectroscopic Constraints. *Astrophys J. Supp. Ser.*, **138**, 75-98.

A notional depiction of the basic structural and molecular character of carbonaceous interstellar dust, based on spectroscopic observations of dust in many environments.

Shows the relative abundances of C, H, O, and N. The specific geometries of aromatic plates and aliphatic components simply represent a likely scenario.

Diagram Credit: Max Bernstein

Newborn stars are embedded in these pillars of glowing interstellar dust and gas, sculpted by the intense wind and radiation from Eta Carinae.

Photo credit: Spitzer Space Telescope.

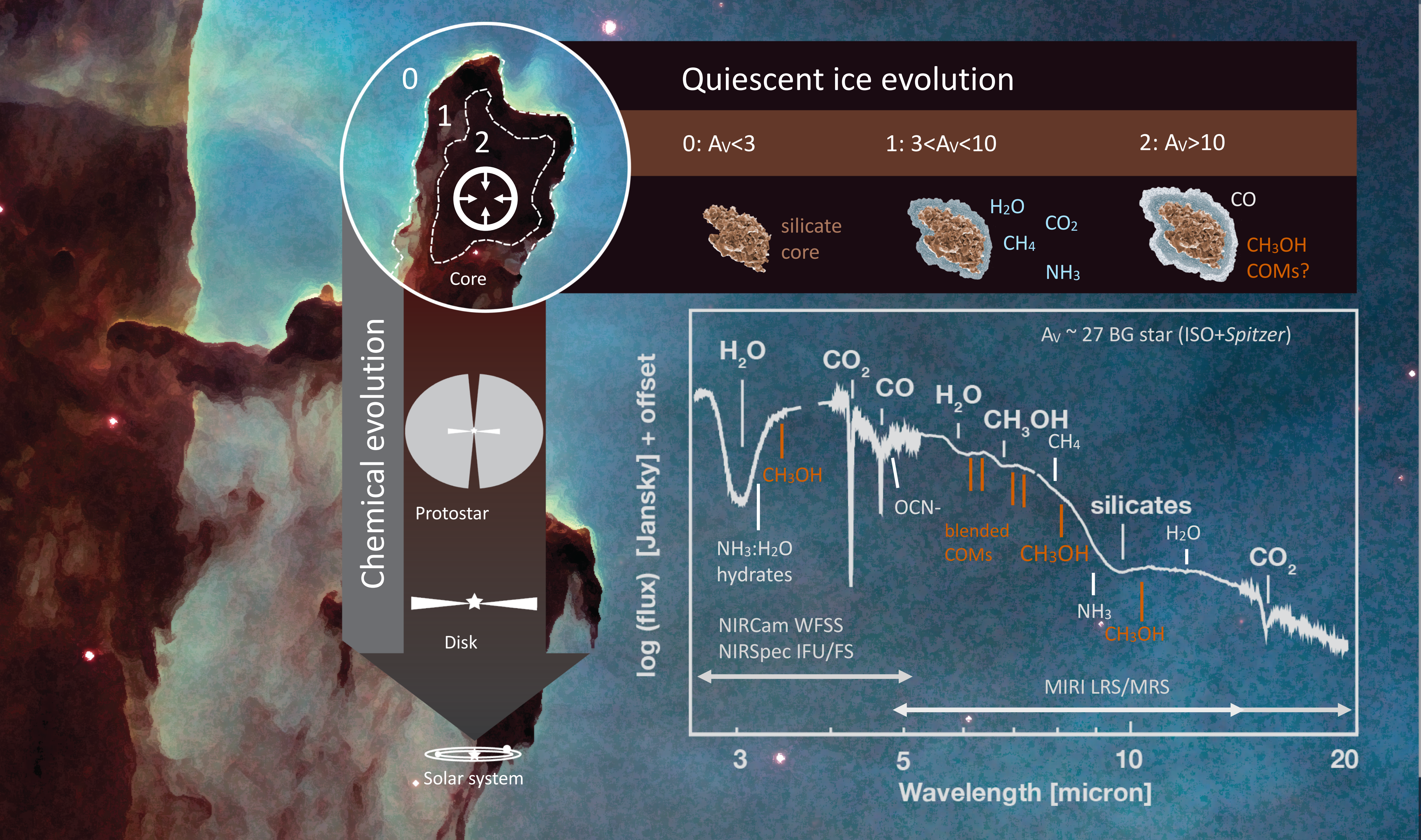
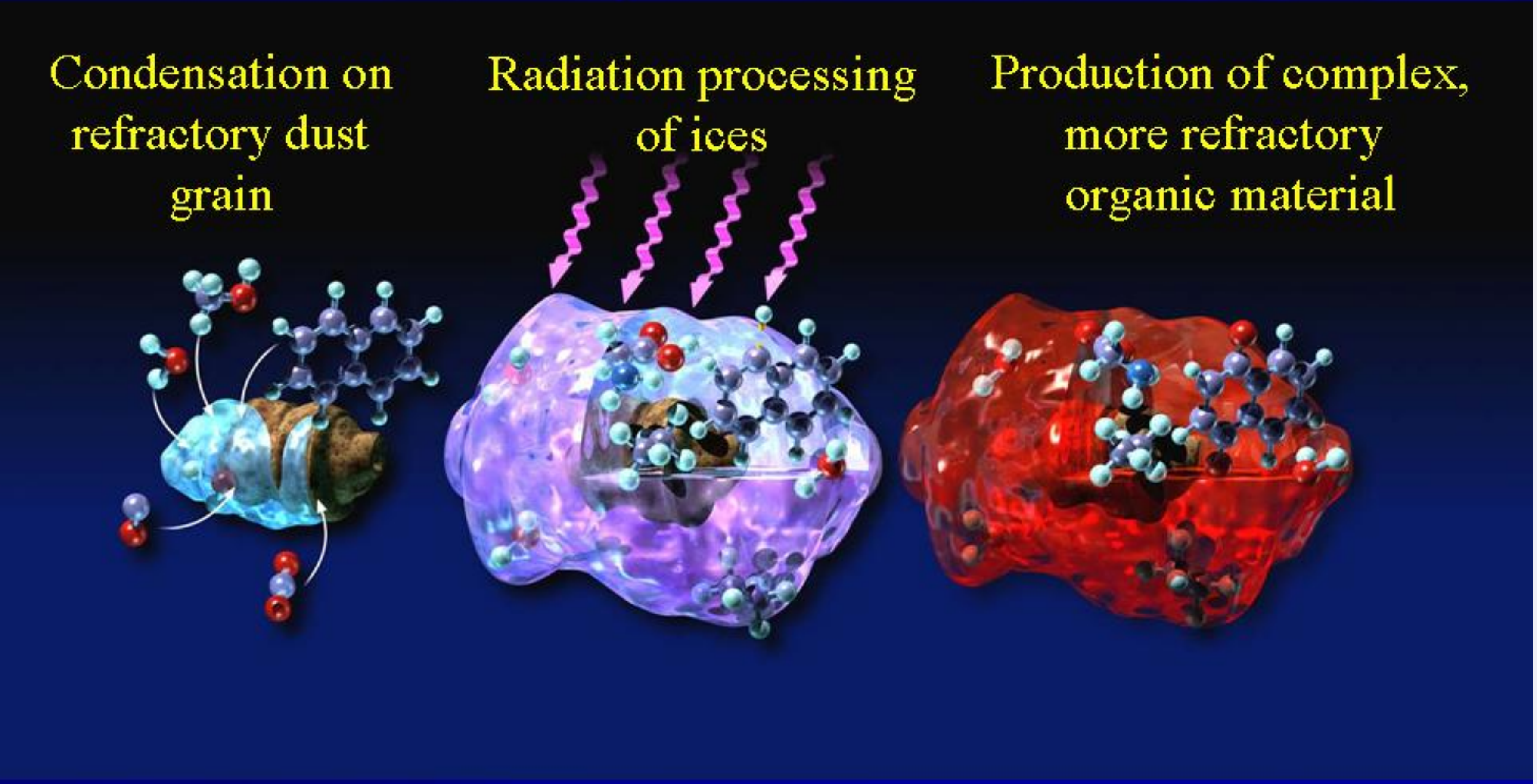


Figure Credit: Melissa McClure

Formation Pathways for Creating Organics

- ~40 yrs ago it was thought that ion-molecule chemistry in the gas phase governed the chemistry of the interstellar medium. But this locks up all the C in CO and CO tends to be unreactive in the gas phase, so where did the more interesting chemistry come from?
- Over the last 20 years, we have learned to fully appreciate the material injected from evolved stars. As these products are returned to the diffuse ISM, they cool down, break apart, and provide the feedstock for newly forming dense clouds.
- Ice grains, and the energetic processing of their components, are a critical step for more complex organic molecules to form.
- We now know there is a complex layering of ices and organics on dust grains before stars even form.
- Regardless of the processing methods within the ice, getting to methanol is key because it will later be released to the gas when the star forms.

Formation of complex organics in ice-covered interstellar dust particles



Bernstein, M., Sandford, S. and Allamandola, L. Scientific American, Vol. 281, 42-57 (1999).

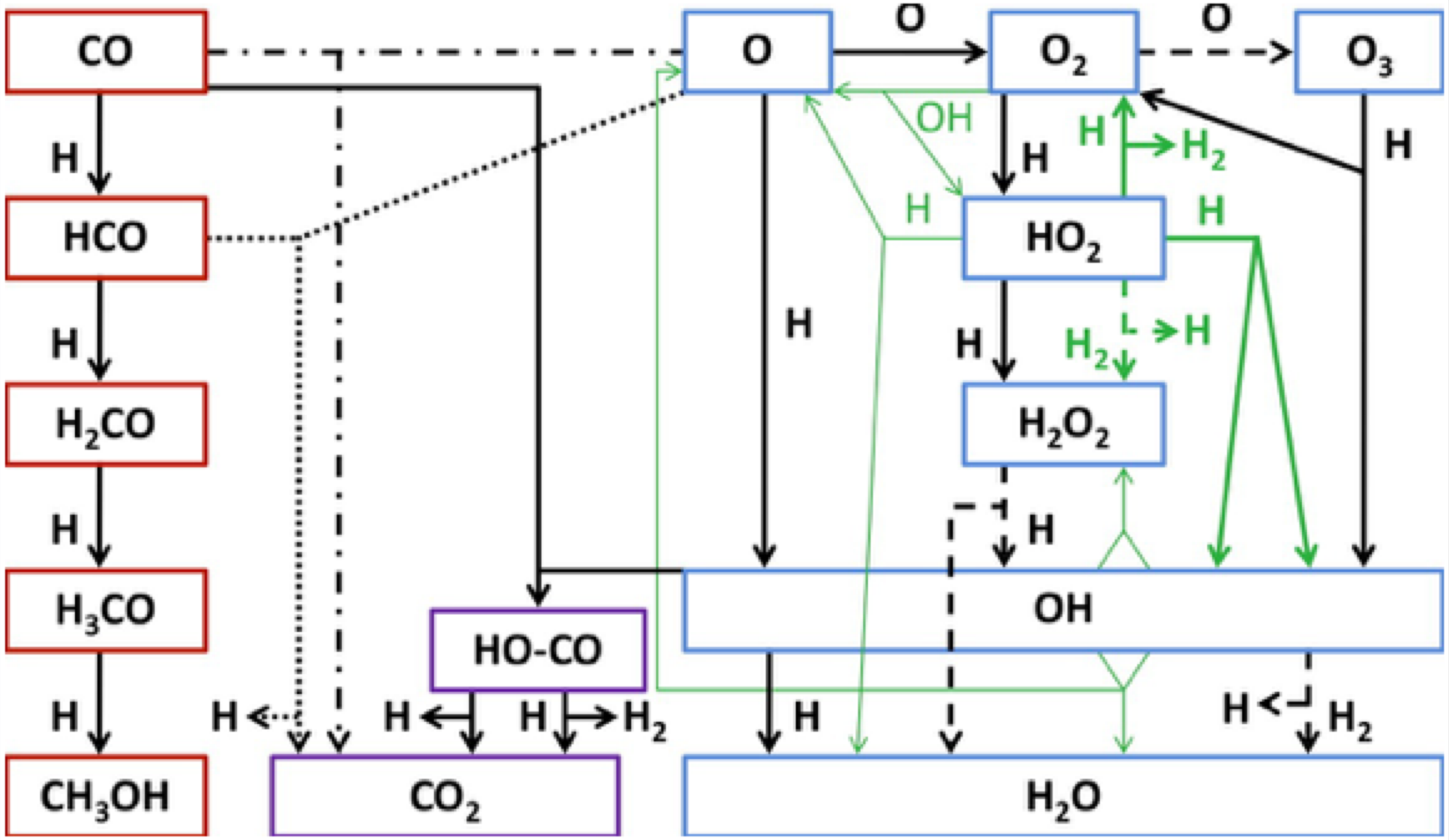
Dust grains are the meeting places where species come to mate

- The accretion of gas phase species starts an active surface chemistry that converts atomic O into H_2O and N and C into NH_3 and CH_4.
- CO accretes a little later and is then hydrogenated to formaldehyde (H_2CO) and methanol (CH_3OH).
- **A complex mixture and layering of ices is created before stars even form.**
- Timescale is about 10^4 years which is close to the timescale for massive star formation. Once the star forms, those ices nearby release their COMs back into the gas.
- Now instead of CO in the gas you have methanol.
- CH_3OH likes to transfer methyl groups to a wide range of receptors, leading to the formation of, for example, dimethyl ether (CH_3OCH_3) and methyl formate ($HCOOCH_3$ from H_2CO or HCOOH); both have been detected by the Atacama Large Millimeter/submillimeter Array (ALMA).

Grain Surface Reactions: getting to methanol is key!

- Hydrogenation & oxidation
- Quantum Tunneling
- Deuteration

Tielens & Hagen, 1982, A&A, 114, 245

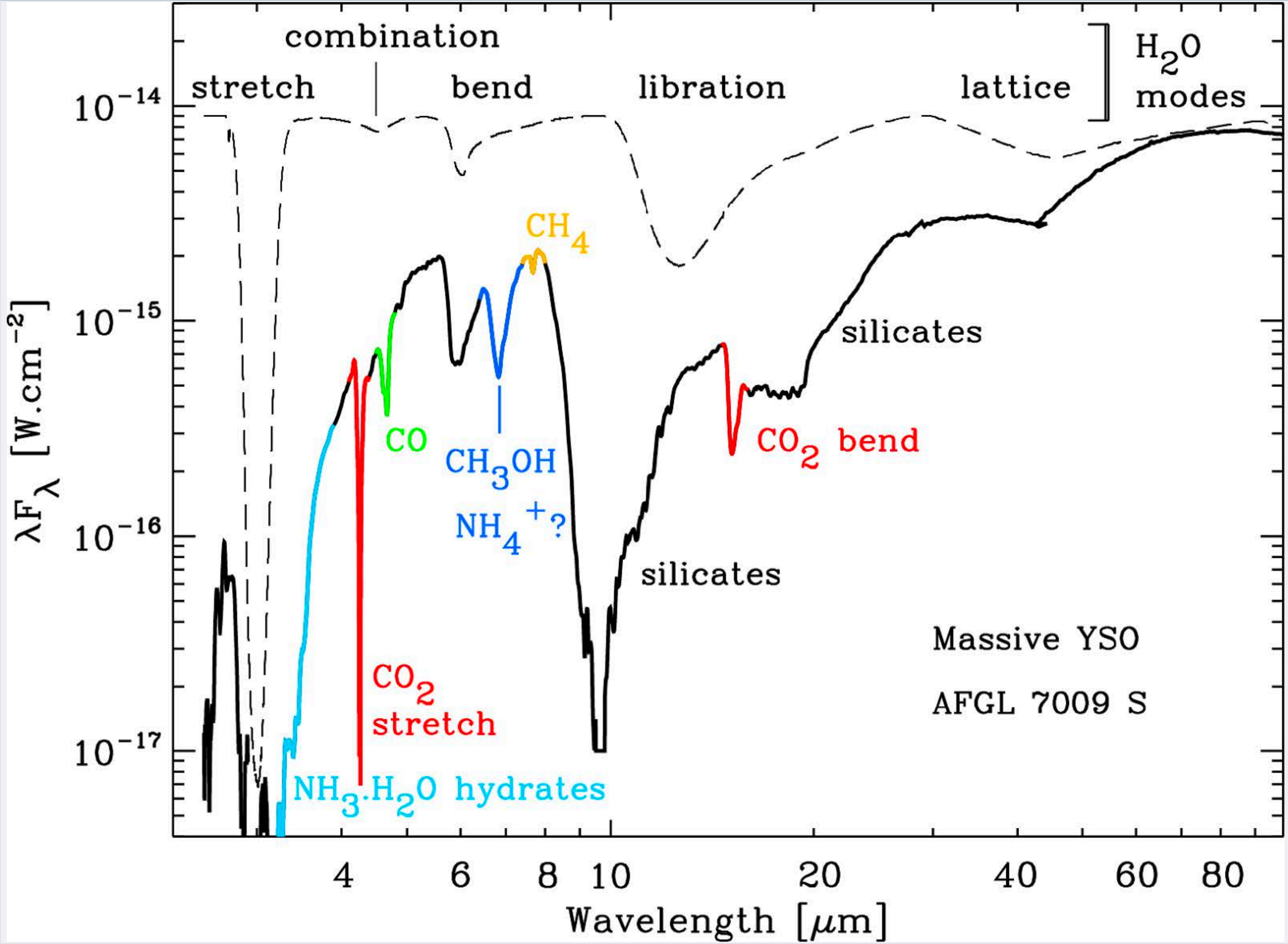


H2CO/CH3OH

Fuchs et al 2009, A&A, 505, 629; Hidaka et al, 2004, ApJ, 614, 1124; 2009, ApJ, 702, 291; Hiraoka et al 1998, ApJ, 498, 710; Ioppolo et al. , 2008, ApJ, 686, 1474

H2O

Ioppolo et al. , 2008, ApJ, 686, 1474; Dulieu et al 2010, A&A, 512, A30; Hiraoka et al 1998, ApJ, 498, 710; Miyauchi et al 2008, Chem Phys Lett, 456, 27; Mokrane et al, 2009, ApJ, 705, L195

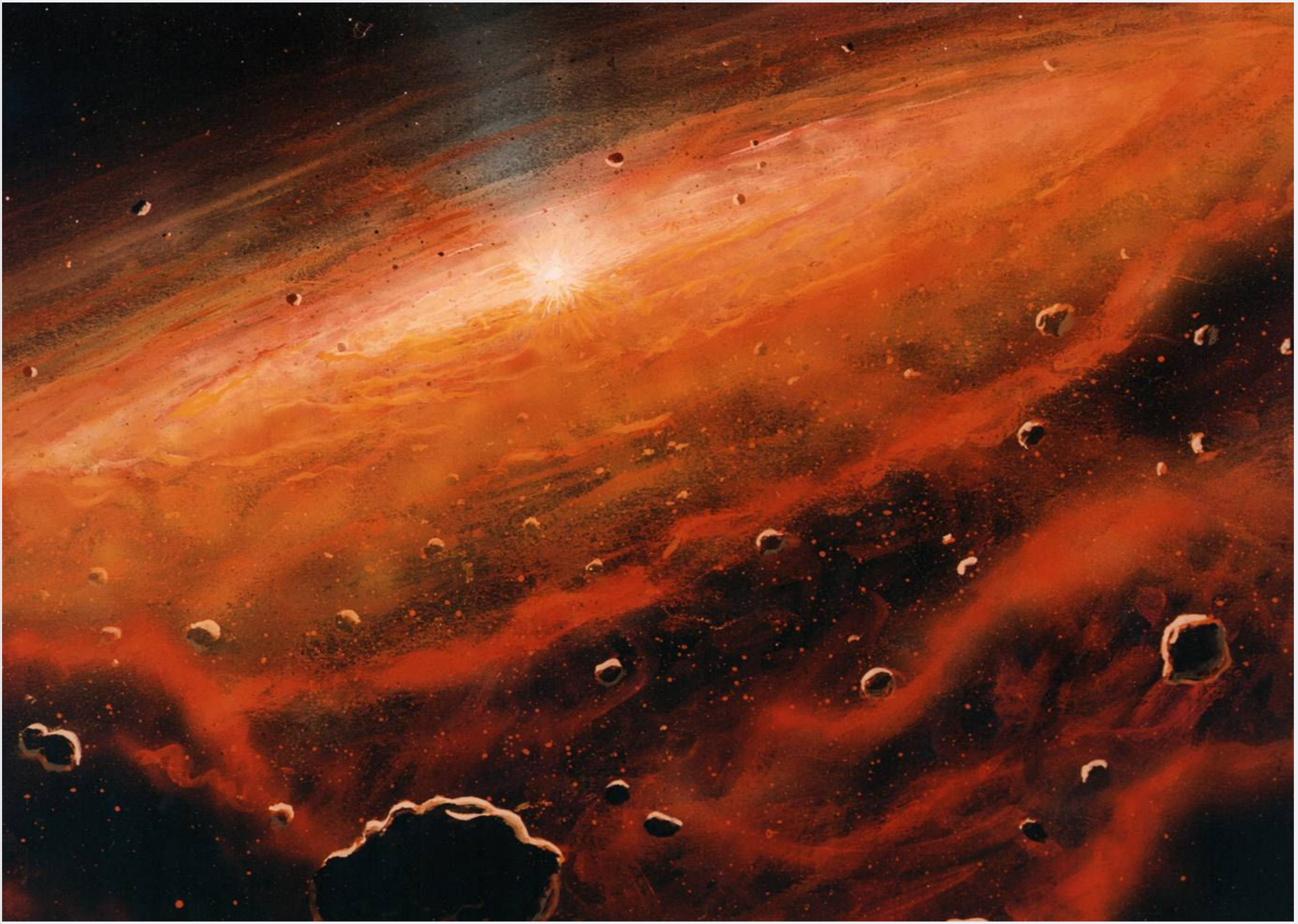


Overview of the strongest ice and dust features detected towards the Massive Young Stellar Object AFGL7009S (Dartois et al., 1998).

The calculated spectrum of pure H_2O ice spheres at 10 K is shown (dashed line) to indicate the multiple H_2O bands.

Figure from Boogert et al. 2015, ARAA, vol. 53, p.541-581

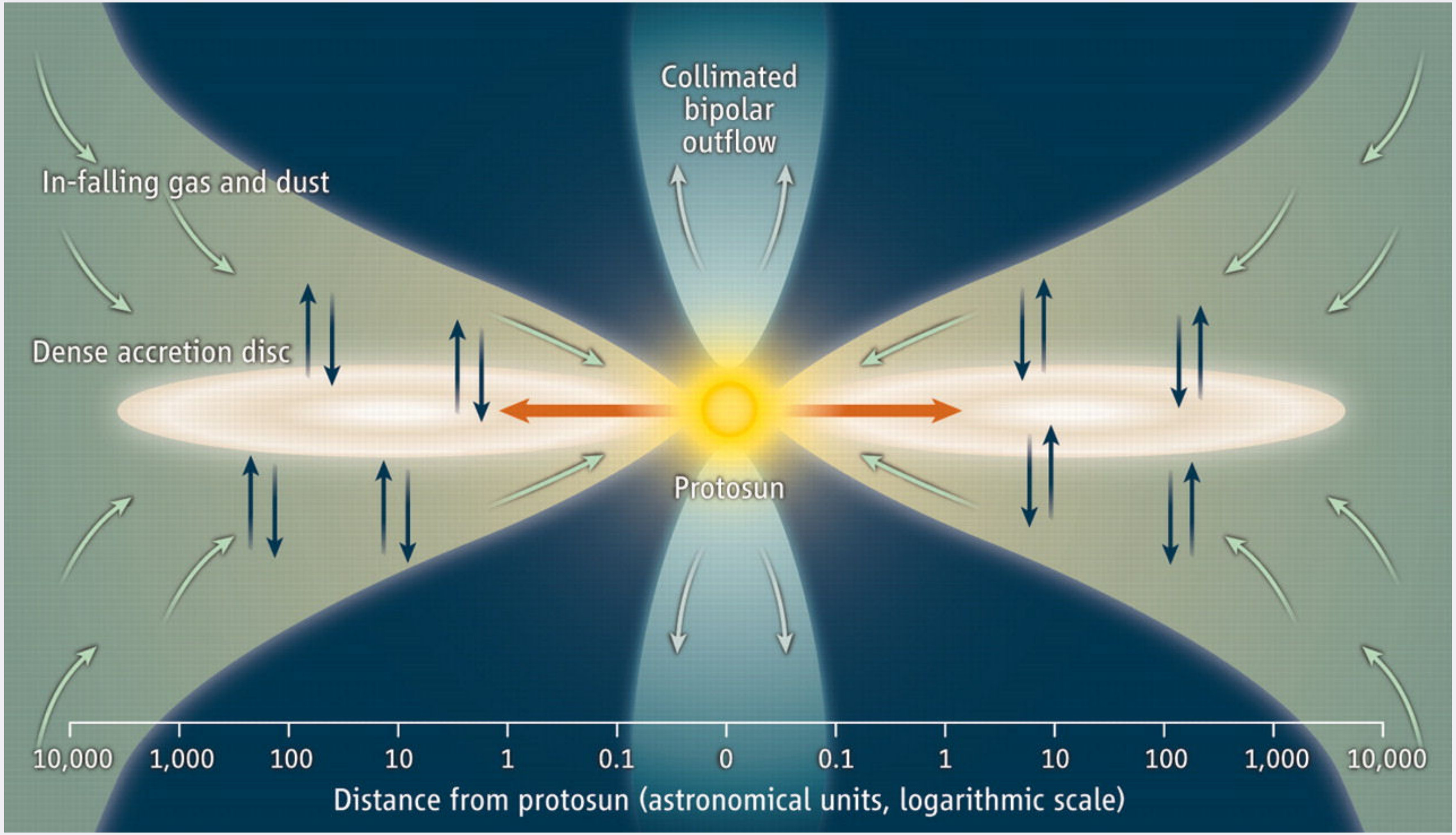
The Early Solar Nebula:
From what did those planetesimals form?



If the planetesimals scattered inward are primarily made of H Chondrite (stony, iron rich) material then the environment of the inner planets will be highly "reduced" (methane, ammonia, and water; Formaldehyde in the presence of ammonia, in a watery environment, plus energy, can yield amino acids.

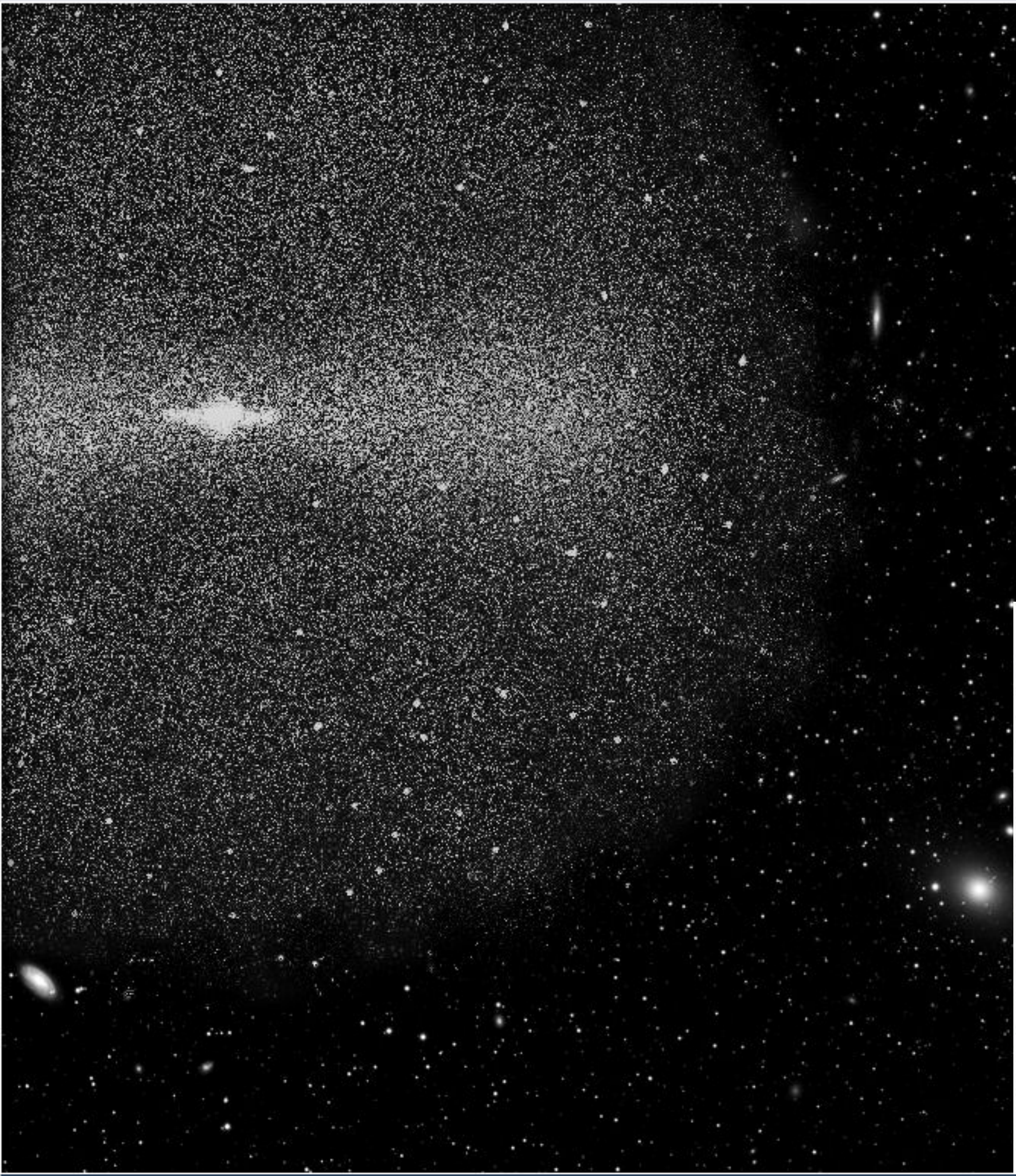
On the other hand, you could get a very oxidized environment (H_2 and CO_2) if the bombardment were from carbonaceous chondrites CI and in this case the additional building blocks of life have to be brought in from the outside.

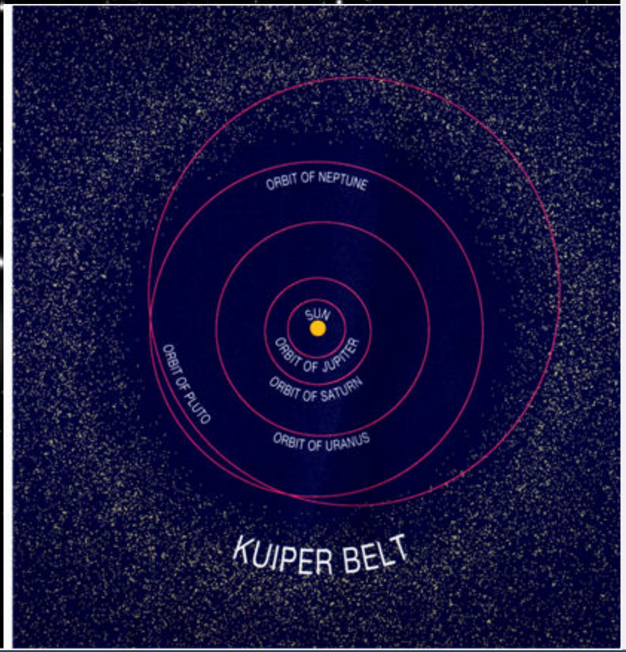
Painting Credit: William K. Hartmann



Models of the early solar nebula show that icy grains can travel via convection to high altitudes above the mid-plane, where the high UV fluence results in even more rapid conversion of ices into complex organics than occurs in the more opaque mid-plane of the nebula.

Ciesla, F. & Sandford, S., Science, 2012; Nuth, J. A., & Johnson, N. M., Science, 2012





Artistic representation of the current Solar System and the extended population of trans-neptunian bodies (TNOs).

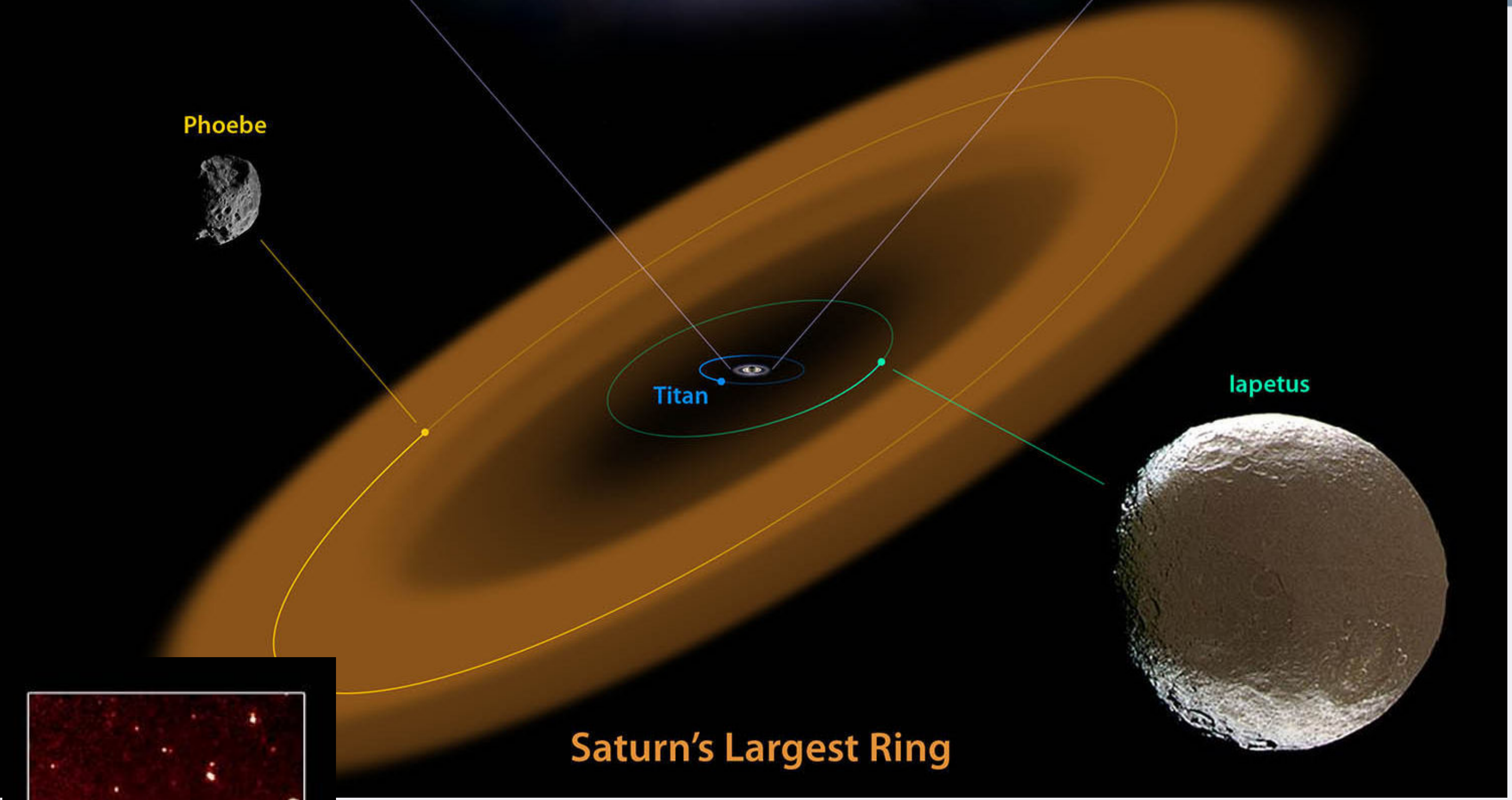
The Kuiper Belt *per se* encompasses the bodies that orbit the Sun close to the ecliptic plane, and range in average heliocentric distance from about 30 to about 55 AU.

Collisions and gravitational perturbations within the TNO population inject icy bodies into the inner Solar System where they can appear as comets.

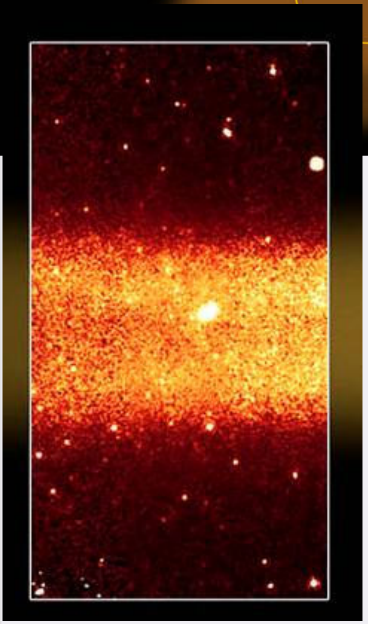
Pluto and Charon are the largest known members of the Kuiper Belt population; they consist of rock and ice and have differentiated by heating from the interior.

The red-brown colored materials on their surfaces result from local processing of the native ices and atmospheric gas (N_2, CH_4, CO) by UV and charged particles in the space environment.

New Horizons images of Pluto and Charon; Credit NASA, APL, SWRI



The Saturn system contains numerous smaller icy bodies, one of which is a captured Kuiper Belt object that brought with it an inventory of preserved primitive materials from the solar nebula.



Spitzer Space Telescope image of the Phoebe dust ring

Dust ejected from a relatively recent collision on Phoebe spirals toward Saturn, coating the surfaces of Iapetus (leading hemisphere) and Hyperion with material from its interior (Tamayo et al. 2011).

Summary

The origin and evolution of organic material, from evolved stars to the interstellar medium to dense clouds forming new stars, provides feedstock for our solar nebula.

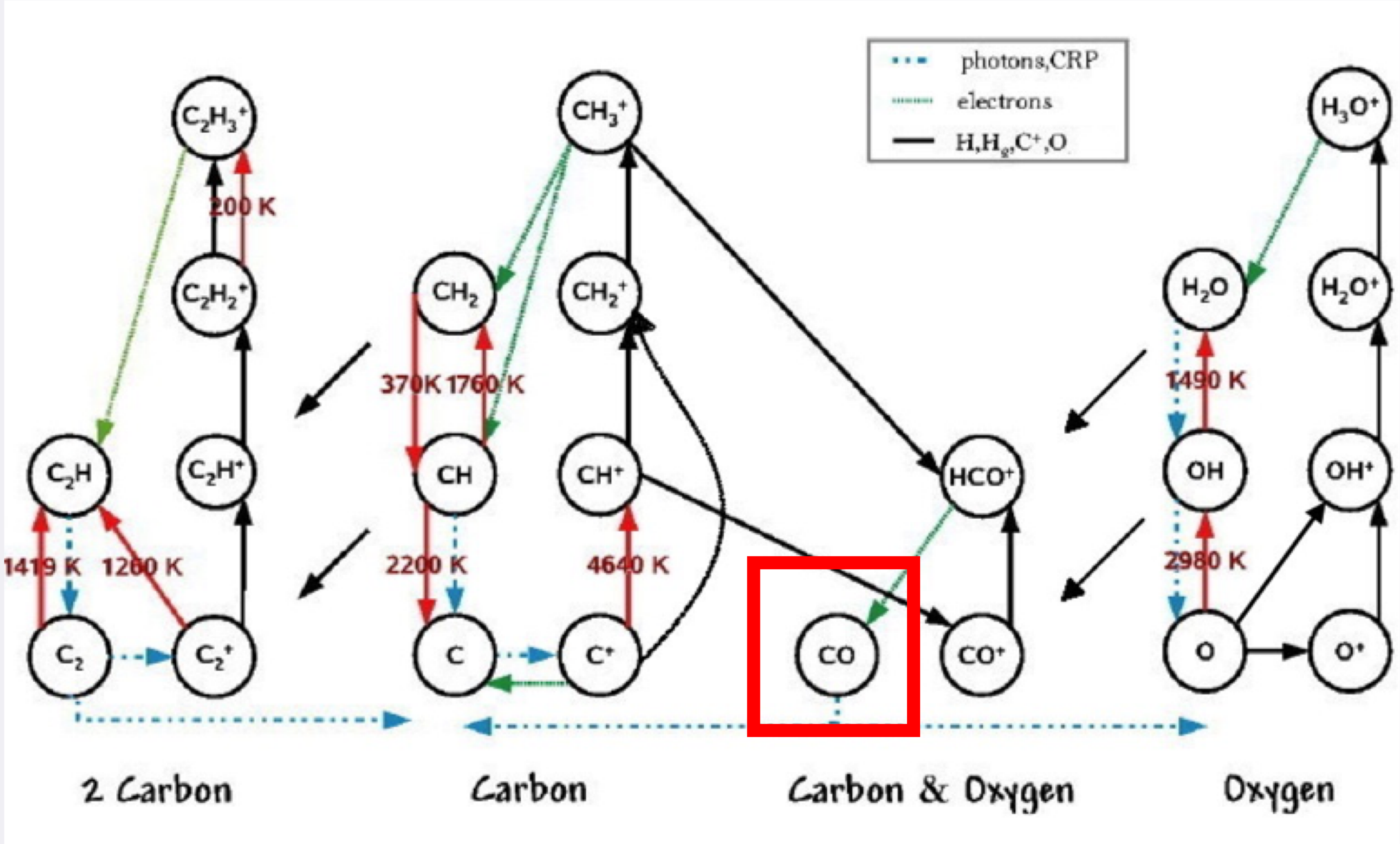
A complex layering of ices and organics exist even before a star forms.

Some outer Solar System bodies may preserve the original material from which they formed, including captured objects such as Saturn’s moon, Phoebe. They can help us understand the composition and degree of processing of that nebular material.

Understanding the initial conditions when planetesimals formed can better feed theoretical models and new lab experiments as we try to discern which planetesimals went where and what they brought with them.

Tracing carbon throughout the Solar System today can help us “unscramble the egg”, better understanding other planetary systems as well as our own.

Back Up Slides



Gas phase chemistry drives C to CO

How do we get get this carbon “reactive” ?

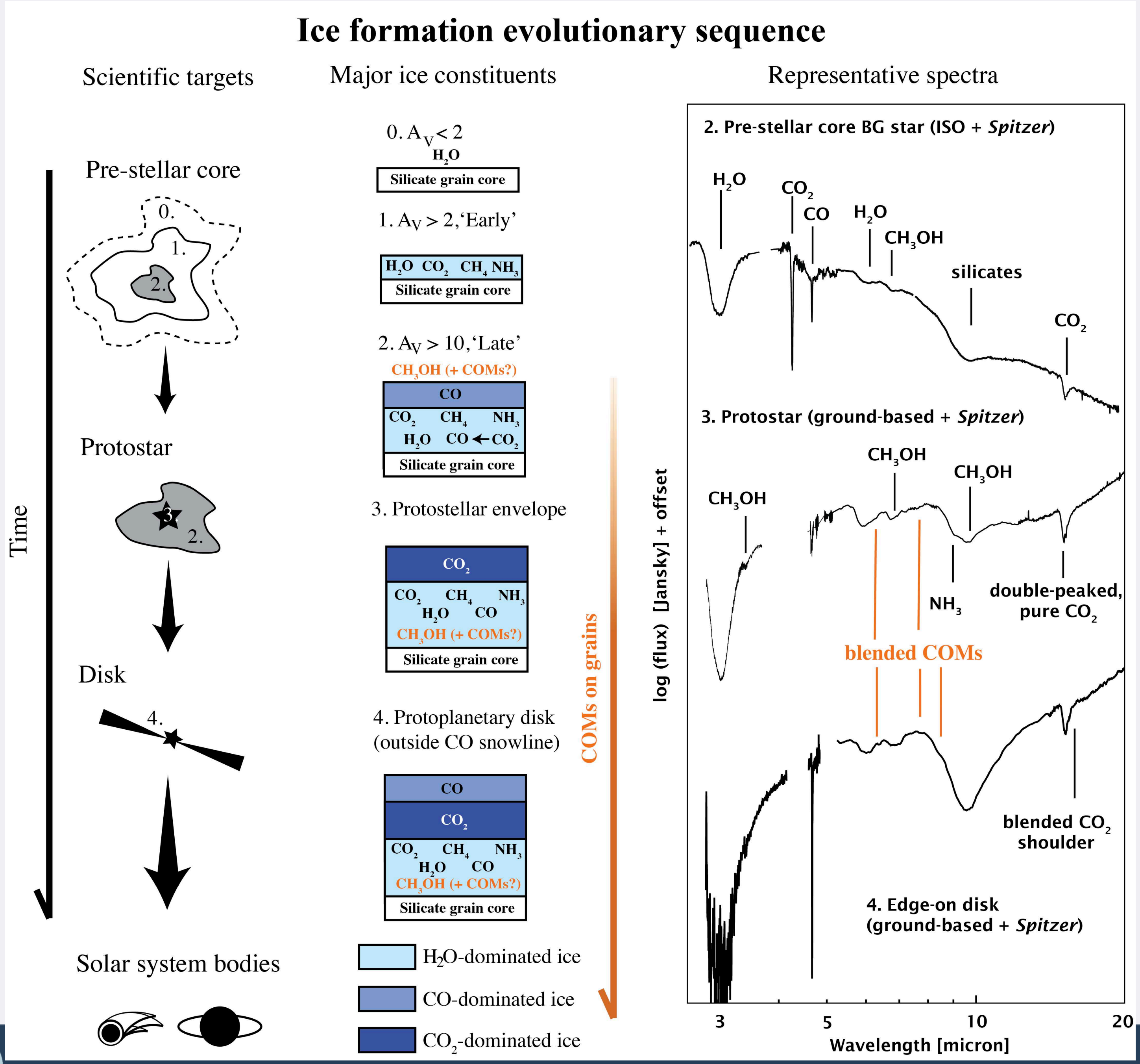
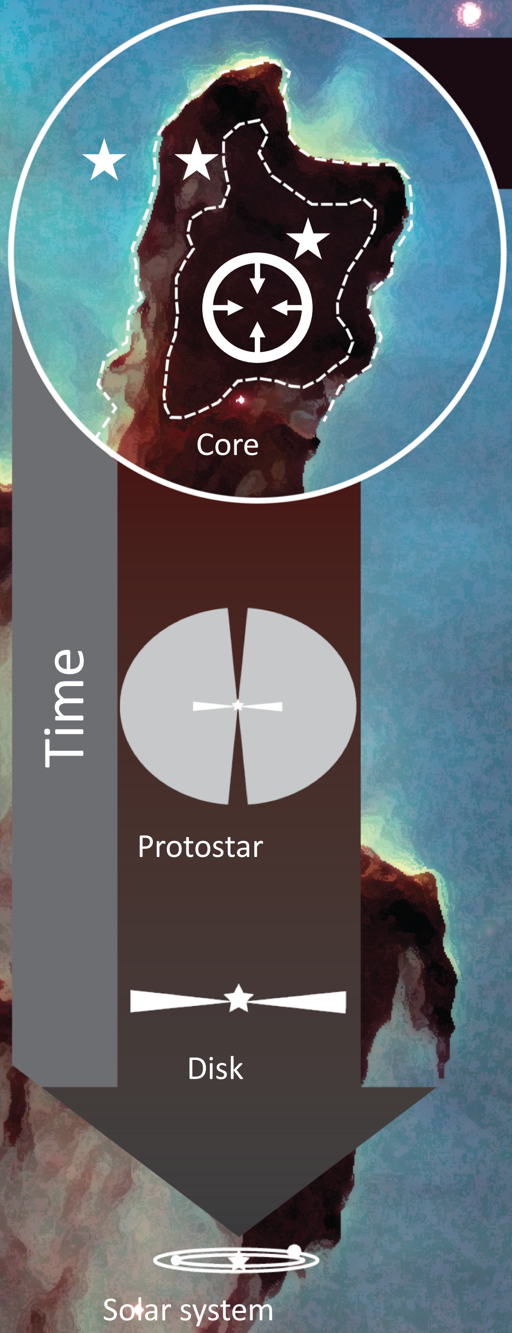
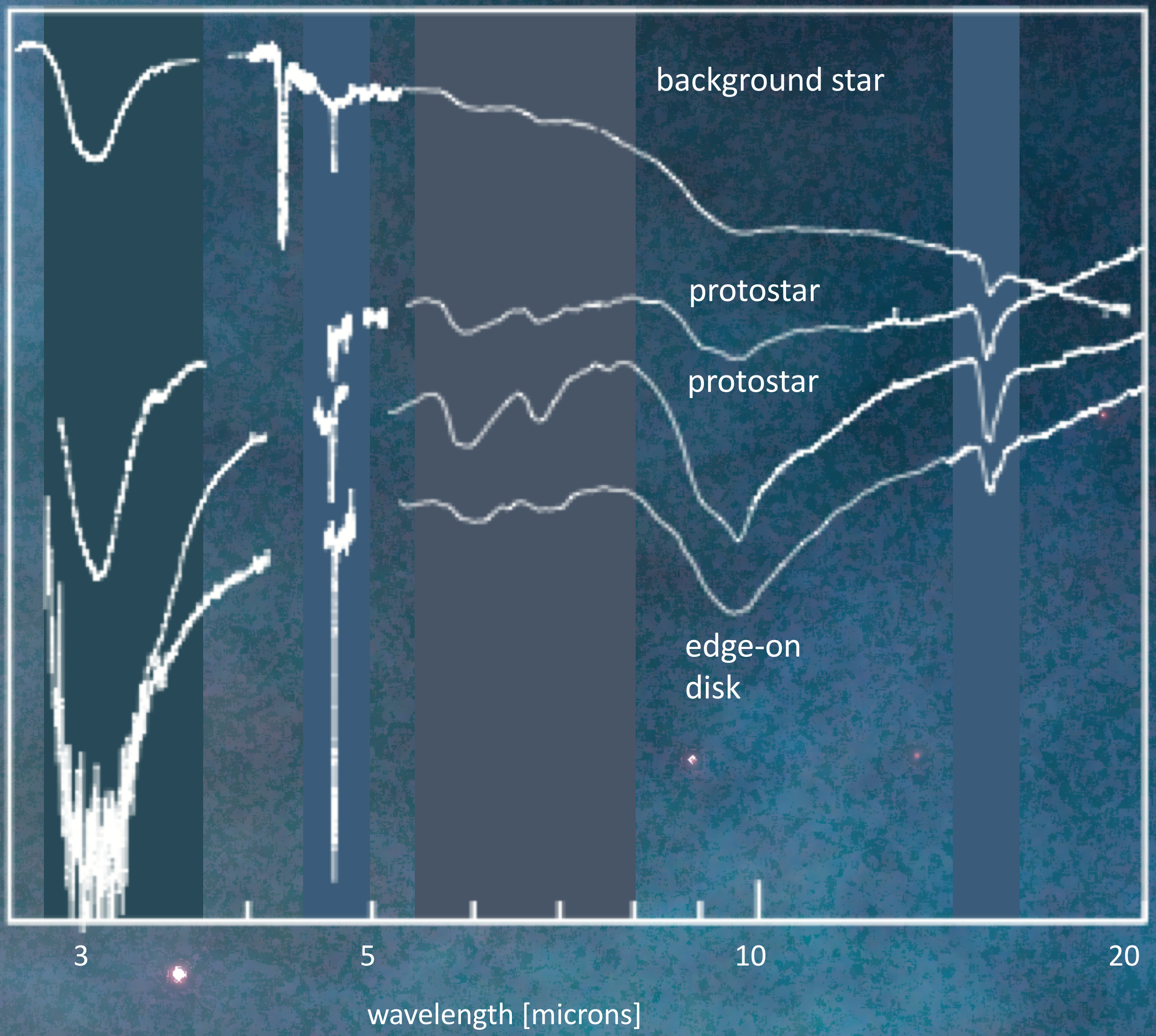


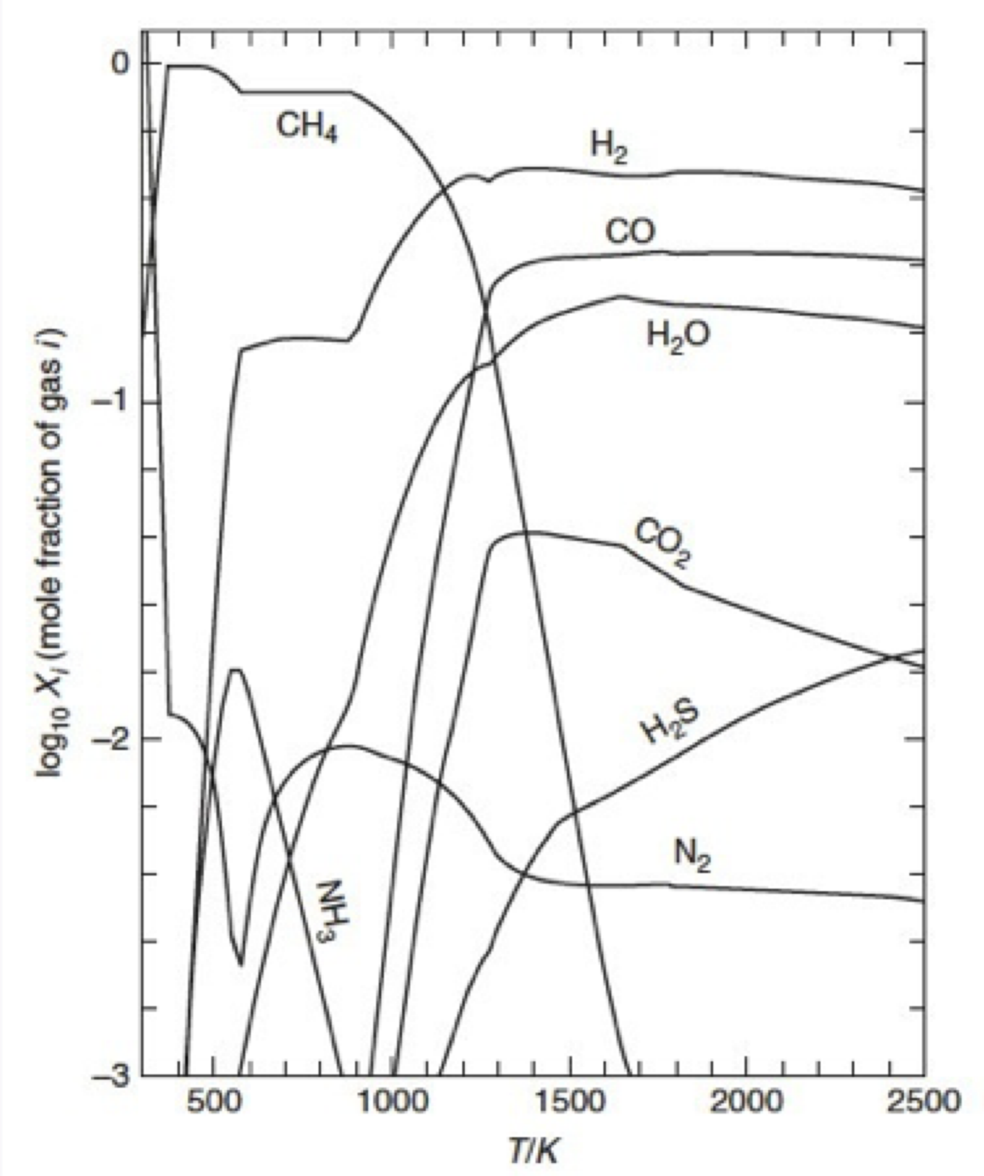
Illustration credit: Melissa McClure

Ice evolution sequence



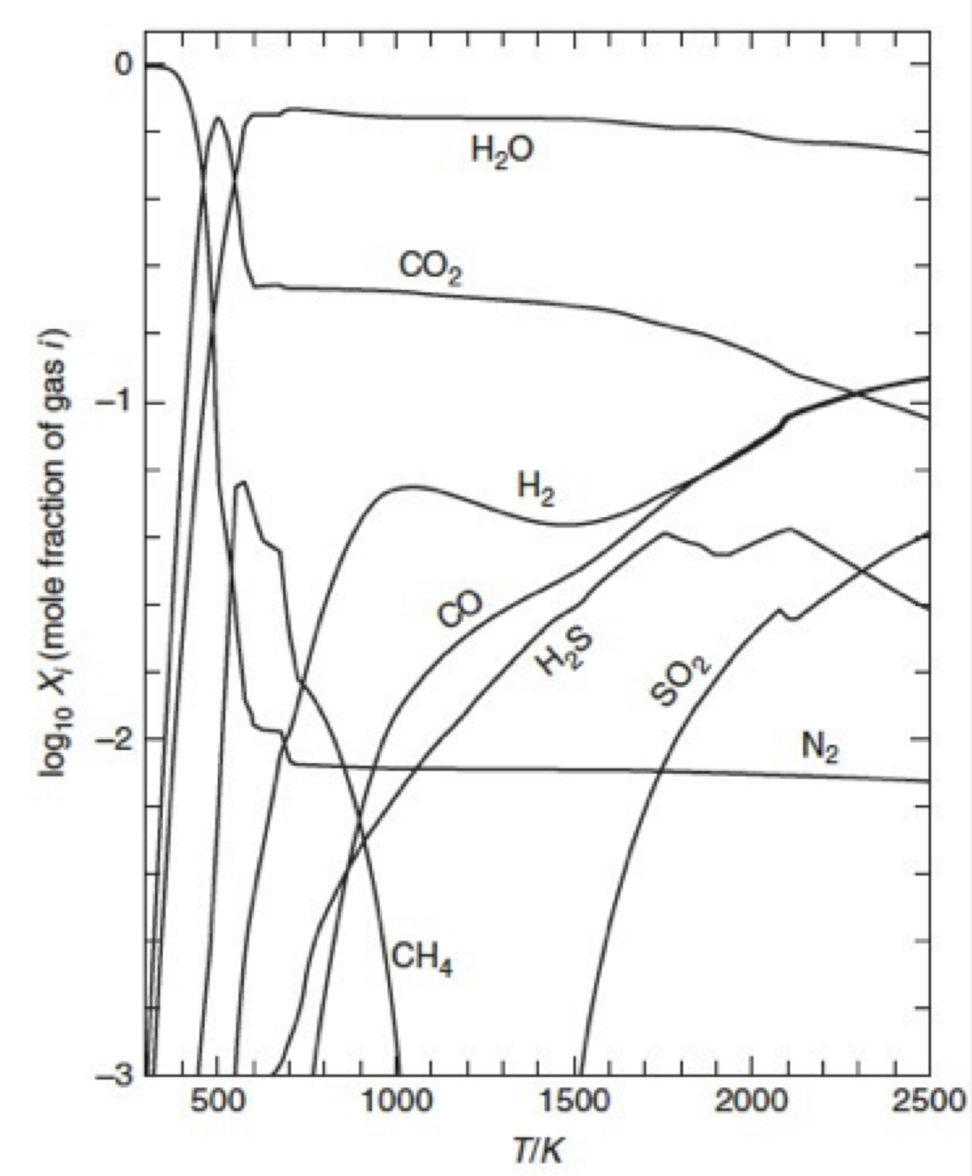


“reduced” initial composition



H chondrite

“oxidized” initial composition



CI chondrite

From Stardust to Planetesimals

Theoretical models (many groups) reveal that planetesimals form in a few thousand years.
An initial group of rocky planetesimals form close to the new star, with icy bodies further away, and in many cases the icy bodies can be perturbed inward so that you get a mixture at different times.

By 200M years the inner region has been cleared; by 800M years Jupiter and Saturn get into resonance, scattering the remaining planetesimals both inward and outward. These models illustrate that the system can transport planetesimals from outer regions to the inner portion which could be a common process for planetary systems.

If the planetesimals scattered inward are primarily made of H Chondrite (stony, iron rich) material then the environment of the inner planets will be highly "reduced" (methane, ammonia, and water; think Miller-Urey environment). Formaldehyde in the presence of ammonia, in a watery environment, plus energy, can yield amino acids.

On the other hand, you could get a very oxidized environment (H2 and CO2) if the bombardment were from carbonaceous chondrites CI and in this case the additional building blocks of life have to be brought in from the outside.

Background to Boogert ice figure:

The vast majority of interstellar and circumstellar ice studies target the stretch and bend mode vibrations in the 3–16-μm range, because below 3μm the signals are weak as a result of dust continuum extinction (in contrast to Solar System studies, which often observe the combination modes at 1–2μm), and above~30μm the availability and capability of instrumentation are limited.
The Boogert figure shows a selection of ice features detected outside the Solar System. The widths vary dramatically, from 1.5 cm−1(0.0034μm) for 13CO to 400 cm−1(0.38μm) for the H2O ice bands. Also, many band profiles (e.g., those of CO and CO2) contain substructures at the level of a few cm−1. Thus, ice studies benefit significantly from the availability of medium resolution IR spectrometers (R=λ/λ≥500). For many features, the positions and widths vary considerably across objects. These variations are often well studied and have led to empirical decompositions. The components are listed, and are further discussed in Section 4. Indirect constraints on the ice composition are provided by observations of gas-phase rotational lines at (sub)millimeter wavelengths. First, low gas-phase abundances (depletions) of specific molecules in clouds imply their presence in the ices (Bergin & Tafalla 2007). Second, gas-phase species observed in hot core regions surrounding YSOs originate from sublimated ices, either directly or after gas-phase chemical reactions (Blake et al. 1987, Herbst & van Dishoeck 2009). Third, some gas near cloud edges originates from photodesorbed ices (Oberg et al. 2009a).