Interstellar Ice Grain Chemical Composition retained in a Comet?

Complex Organics as Tracers of a Comets Formation and Evolution History

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Comet Formation Paradigm After Rosetta, Sofia, Bulgaria, June 19-23, 2017

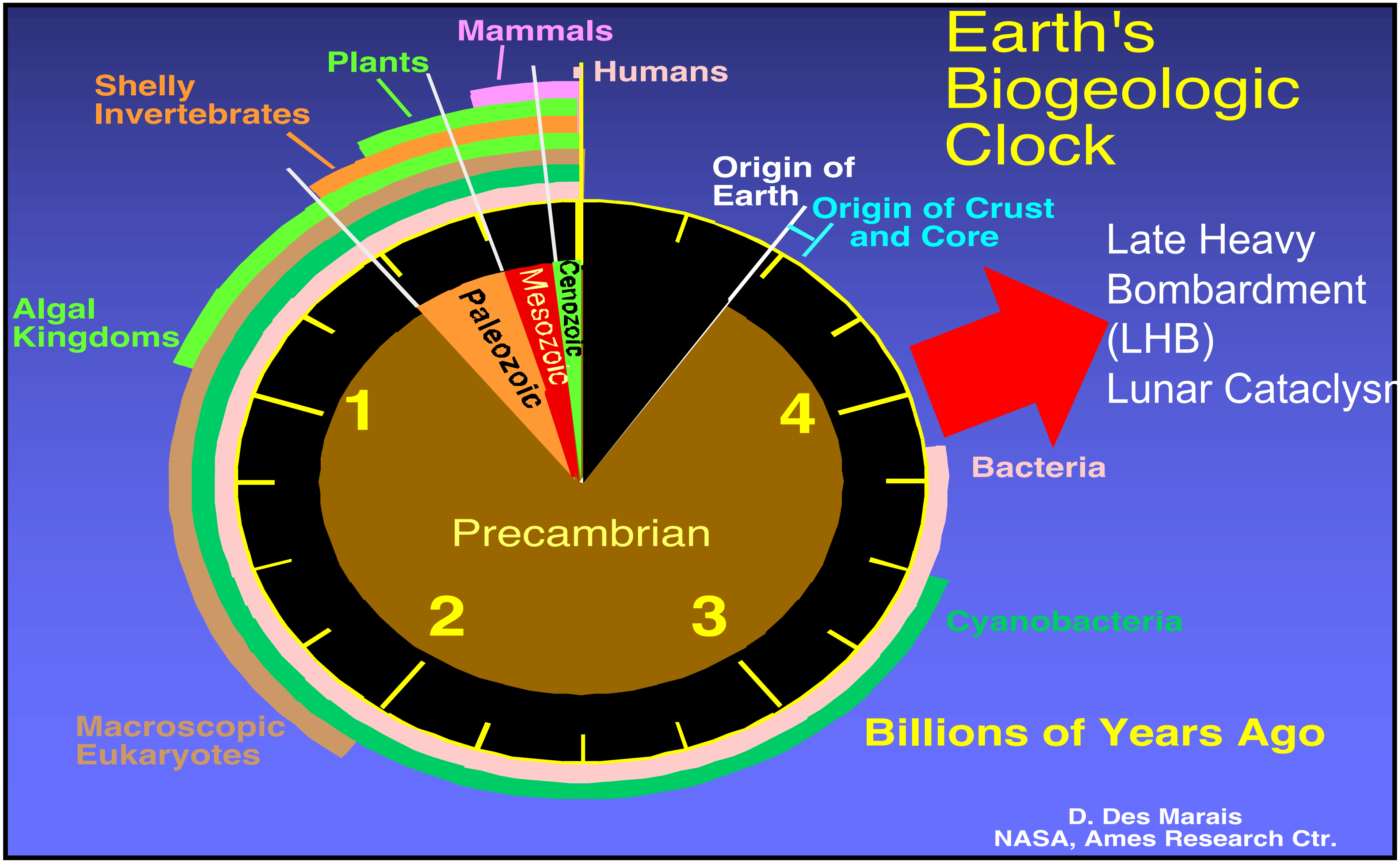
Did Comet and Asteroid Bombardment Trigger the Origin of Life on Earth?

What was the Composition of Comets around 4 Billion Years ago?

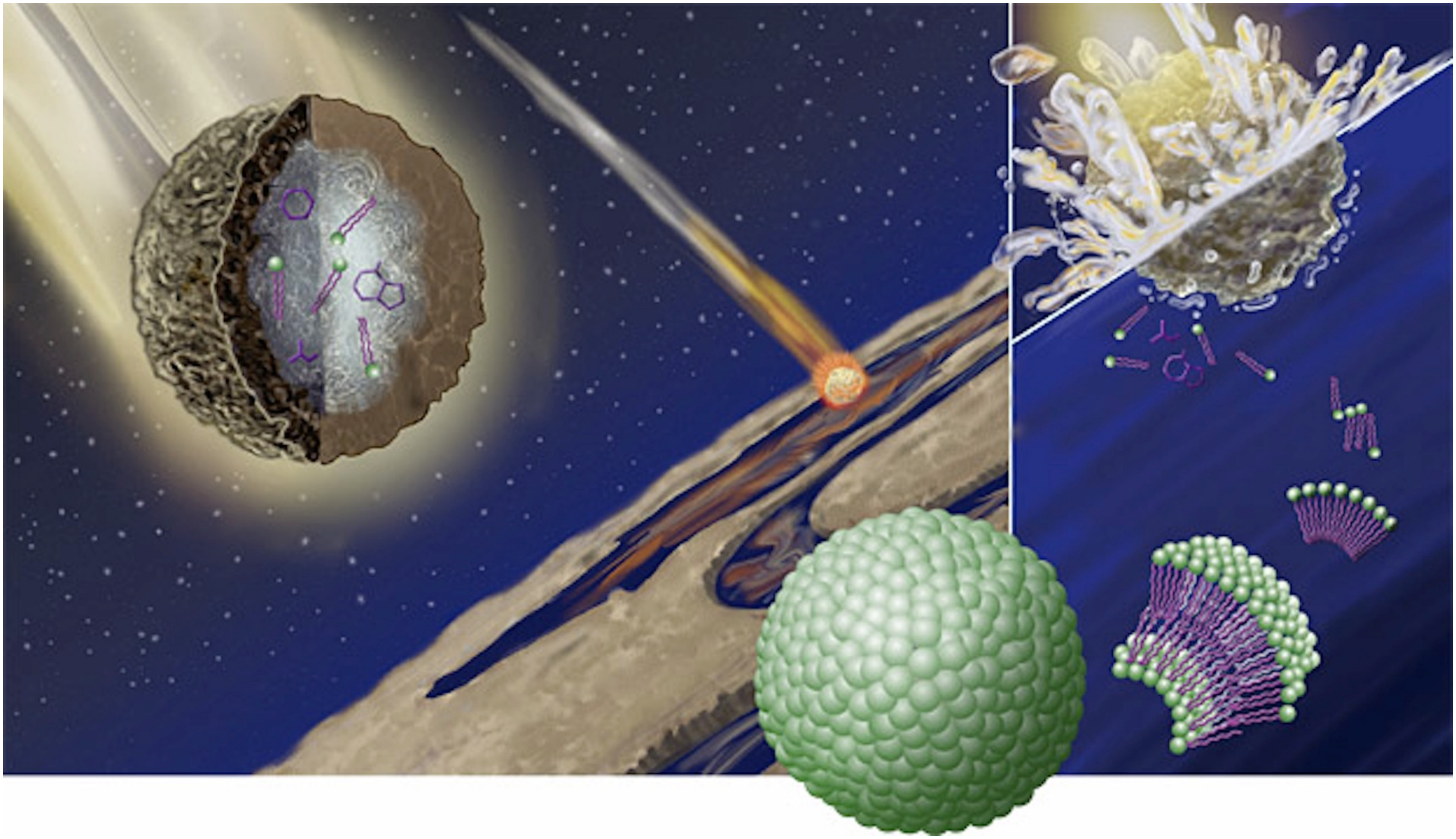
Did Cometisimals Retain or Lost their Memory of Interstellar Ice Grains during the Protoplanetary Stage?

Earth, Comets & Asteroids, and Life

Water & Organic Matter delivered to Earth by Comets/Asteroids ~4 Billion Years Ago



The Origin(s) of Life – Role of Comets

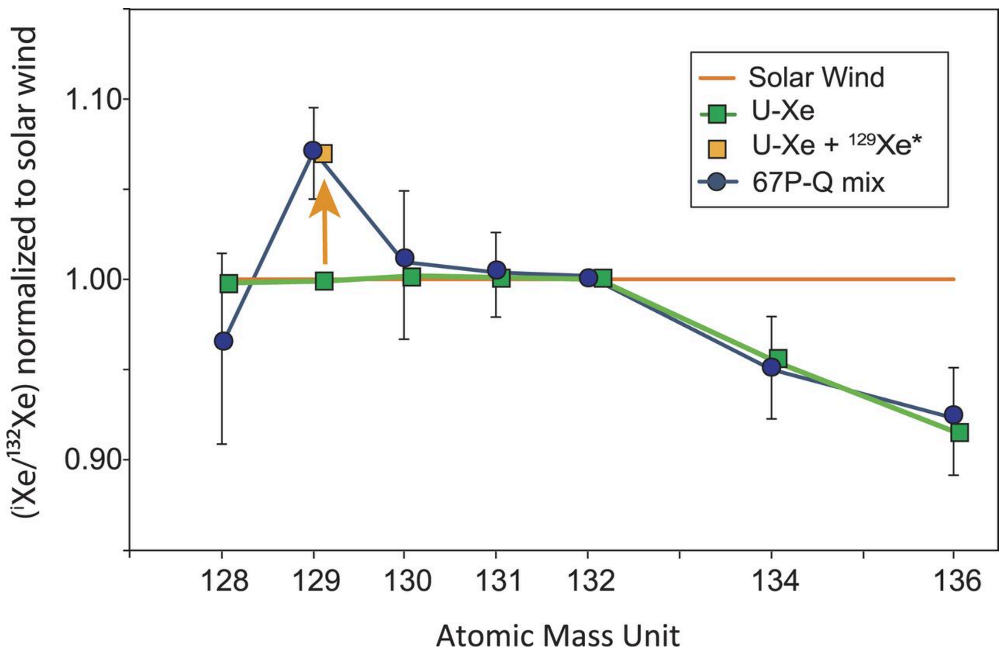


Did Organics Survive Comet Entry and Impacts on Earth?
Do we fully understand Comets? (Deep Impact, Epoxi, Rosetta)

Indication that Comets brought Xe to Earth

Xenon isotopes in 67P/Churyumov-Gerasimenko show that comets contributed to Earth's atmosphere

by B. Marty, K. Altwegg, H. Balsiger, A. Bar-Nun, D. V. Bekaert, J.-J. Berthelier, A. Bieler, C. Briois, U. Calmonte, M. Combi, J. De Keyser, B. Fiethe, S. A. Fuselier, S. Gasc, T. I. Gombosi, K. C. Hansen, M. Hässig, A. Jäckel, E. Kopp, A. Korth, L. Le Roy, U. Mall, O. Mousis, T. Owen, H. Rème, M. Rubin, T. Sémon, C.-Y. Tzou, J. H. Waite, and P. Wurz

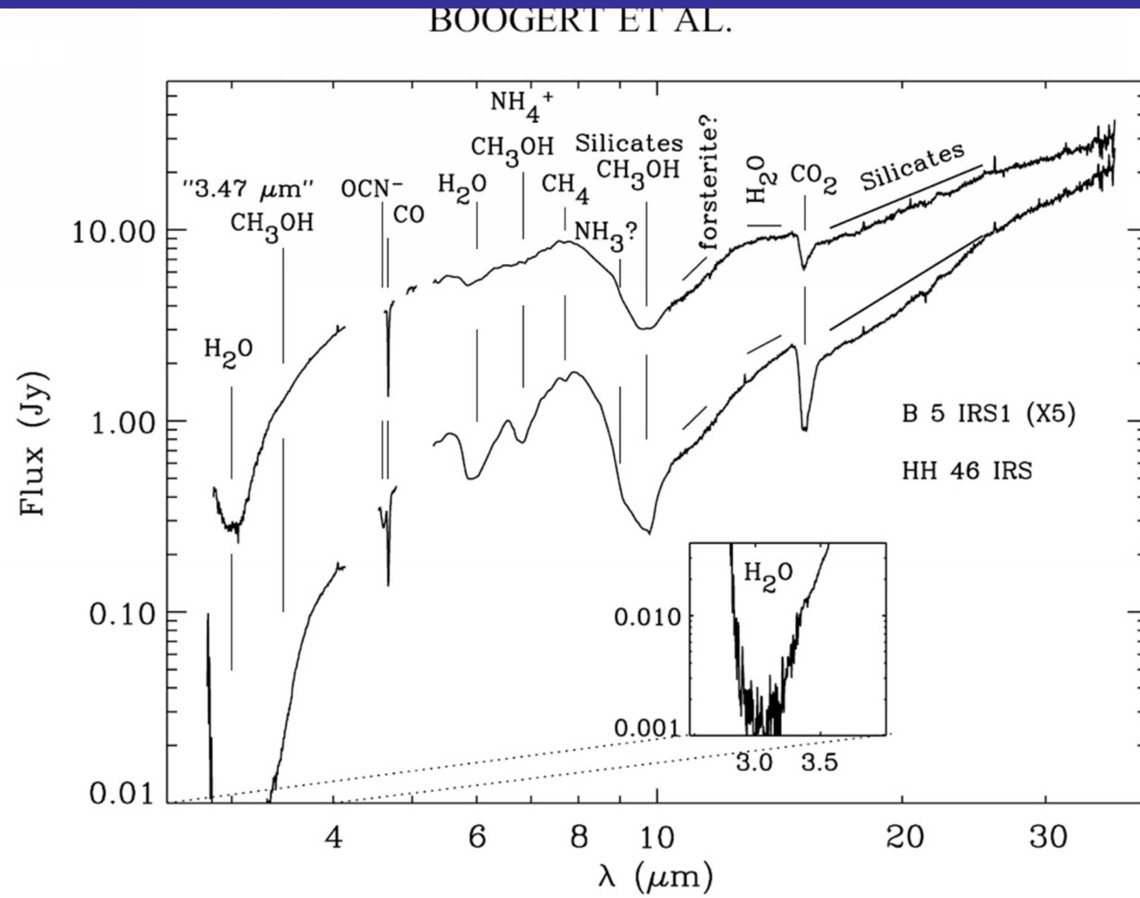


Science
Volume 356(6342):1069-1072
June 9, 2017

Interstellar Ice Grains: Loaded with Organics

How much ice-grain (not gas-grain) chemistry occurred in the ISM/DMC by Cosmic Rays, UV, e^- ?

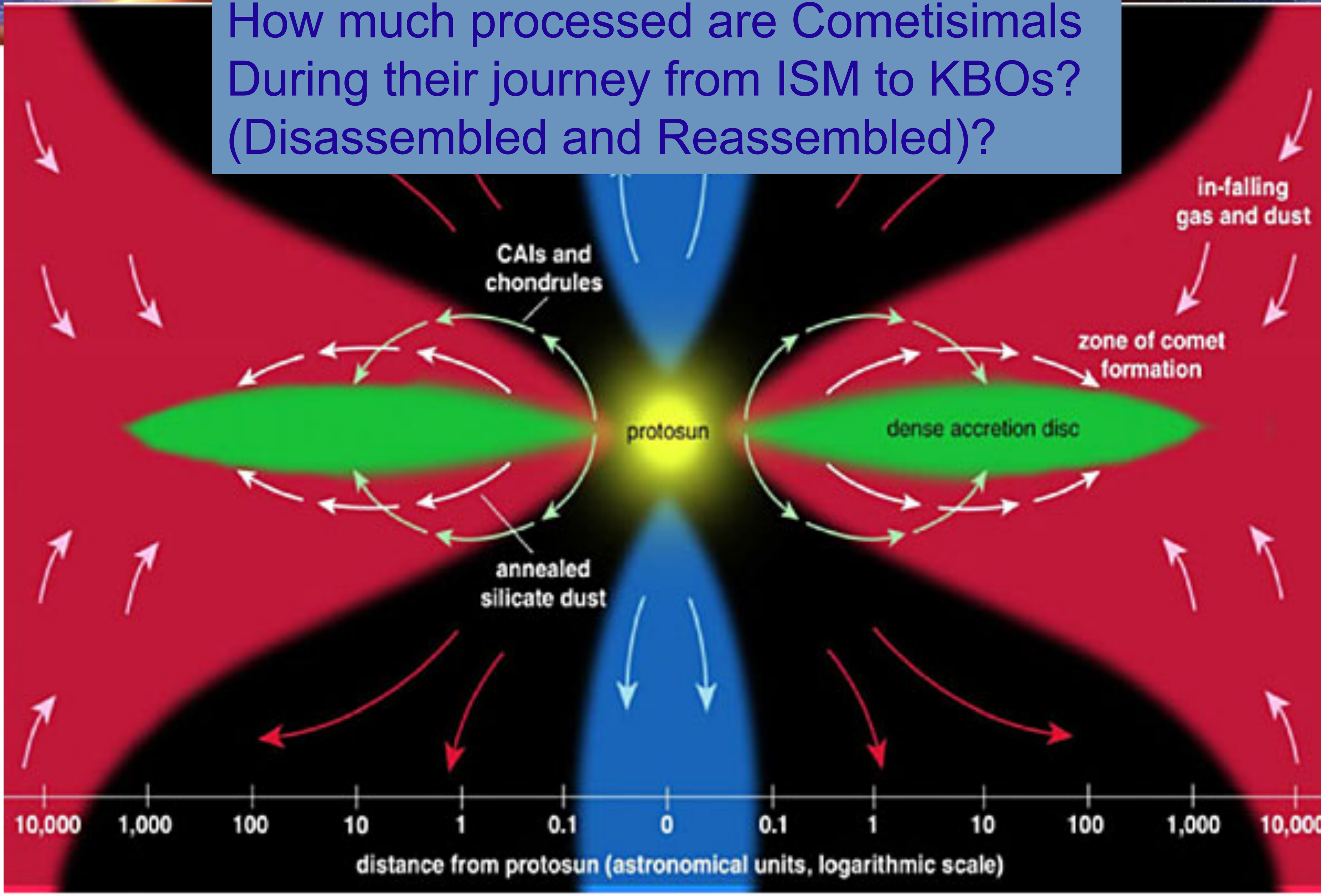
Dense Molecular Clouds (The Eagle Nebulae)



HH 46 IRS (YSO)

Birth of a Sun (Protoplanetary Disk)

How much processed are Cometisimals During their journey from ISM to KBOs? (Disassembled and Reassembled)?



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)

Questions: Pre KBO Journey of Cometisimals

We need observational data, lab work, and modeling to answer:

- Shock Waves:
  How far (10 AU?) and how much heating (up to 150K?)
- Lateral (inward and outward) movement of gas, dust, and ice?
- Vertical transport from the radiation edge into the midplane?
- Crystalline vs. amorphous silicates?
- Gas accretion on the dust?

Klaus Jokers and Maria Drozdovskaya

The Journey of an Interstellar Ice Grain

KBOs ≠ comets

Interstellar Ice Grain (amorphous)

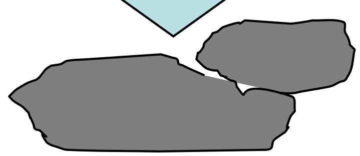
Complete Sublimation and Re-accretion of Ice & Volatiles

Solar Nebula & Protoplanetary Disk

Loss of Super Volatiles and Re-accretion

Parked in KBOs (<50 K)

Present-day Comets



We need Tracers of Each Pathway

Comet – Physical Composition

Comet - Chemical Composition

Comet – Molecules and Ice-Phase as Tracers of a Comet's Evolution History

Physical Composition of Comets

Physical Properties of Comets

Dust/Ice = 0.4 – 2.6; Porosity = 75 -85%

Density = 532 $\pm$ 7 kg m^{-3}

Crystalline water-ice = 920 kg m^{-3}
Amorphous water-ice = ~500 - 800 kg m^{-3}
Carbonaceous chondrites = ~3 to 3.7 kg m^{-3}

Surface Thermal Inertia:85$\pm$35 J $m^{-2}K^{-1}s^{-1/2}$

Thermal gradient?
How Deep to reach <30 K?
Thermally Equilibrated to the Core?

Surface Strength

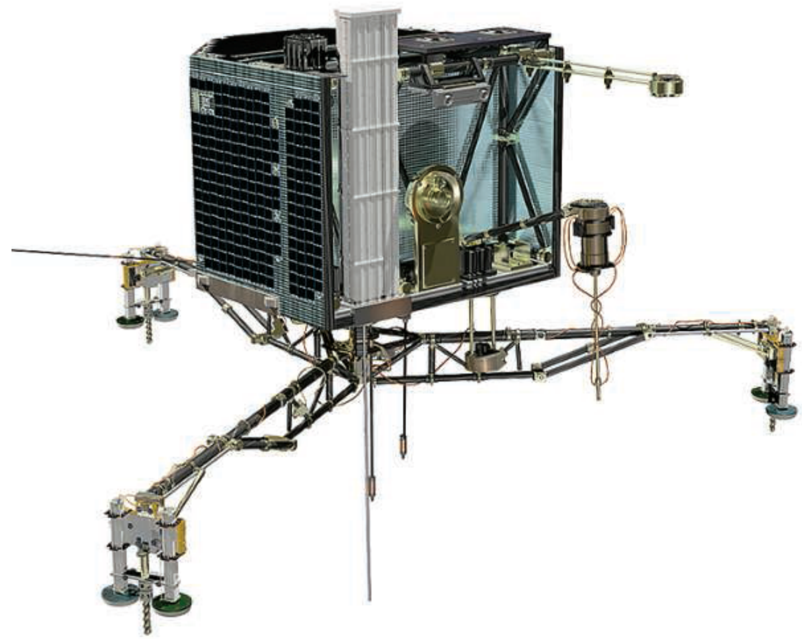
Science, 349, aaa9816, 2015

COMETARY SCIENCE

The landing(s) of Philae and inferences about comet surface mechanical properties

Jens Biele,[1*] Stephan Ulamec,[1] Michael Maibaum,[1] Reinhard Roll,[3] Lars Witte,[2] Eric Jurado,[9] Pablo Muñoz,[5,12] Walter Arnold,[10] Hans-Ulrich Auster,[6] Carlos Casas,[5,12] Claudia Faber,[4] Cinzia Fantinati,[1] Felix Finke,[1] Hans-Herbert Fischer,[1] Koen Geurts,[1] Carsten Güttler,[3] Philip Heinisch,[6] Alain Herique,[8] Stubbe Hviid,[4] Günter Kargl,[7] Martin Knapmeyer,[4] Jörg Knollenberg,[4] Wlodek Kofman,[8] Norbert Kömle,[7] Ekkehard Kührt,[4] Valentina Lommatsch,[1] Stefano Mottola,[4] Ramon Pardo de Santayana,[5,12] Emile Remetean,[9] Frank Scholten,[4] Klaus J. Seidensticker,[4] Holger Sierks,[3] Tilman Spohn[4]

The Philae lander, part of the Rosetta mission to investigate comet 67P/Churyumov-Gerasimenko, was delivered to the cometary surface in November 2014. Here we report the precise circumstances of the multiple landings of Philae, including the bouncing trajectory and rebound parameters, based on engineering data in conjunction with operational instrument data. These data also provide information on the mechanical properties (strength and layering) of the comet surface. The first touchdown site, Agilkia, appears to have a granular soft surface (with a compressive strength of 1 kilopascal) at least ~20 cm thick, possibly on top of a more rigid layer. The final landing site, Abydos, has a hard surface.

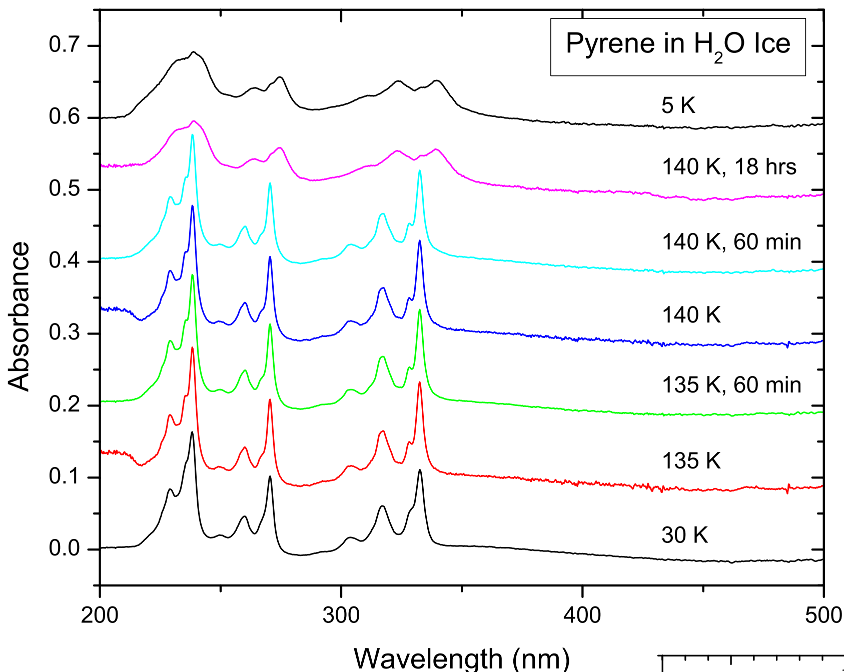


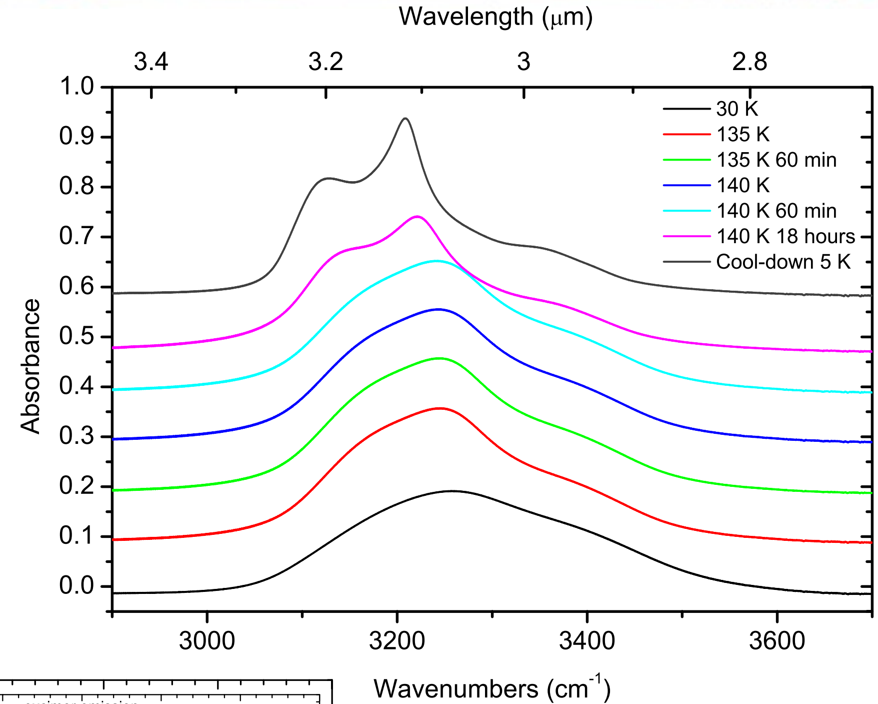
~20 cm granular (soft)
Below hard crust

How thick is the crust – cm range or m range?
If no hard-crust, can other properties also be accounted for?

Simultaneous UV & IR Absorption + Fluorescence

Pyrene in H2O Ice

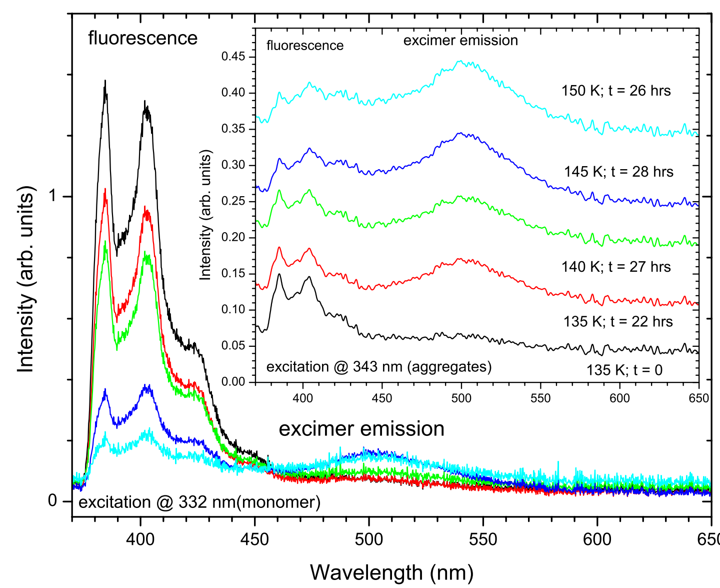




UV - PAH

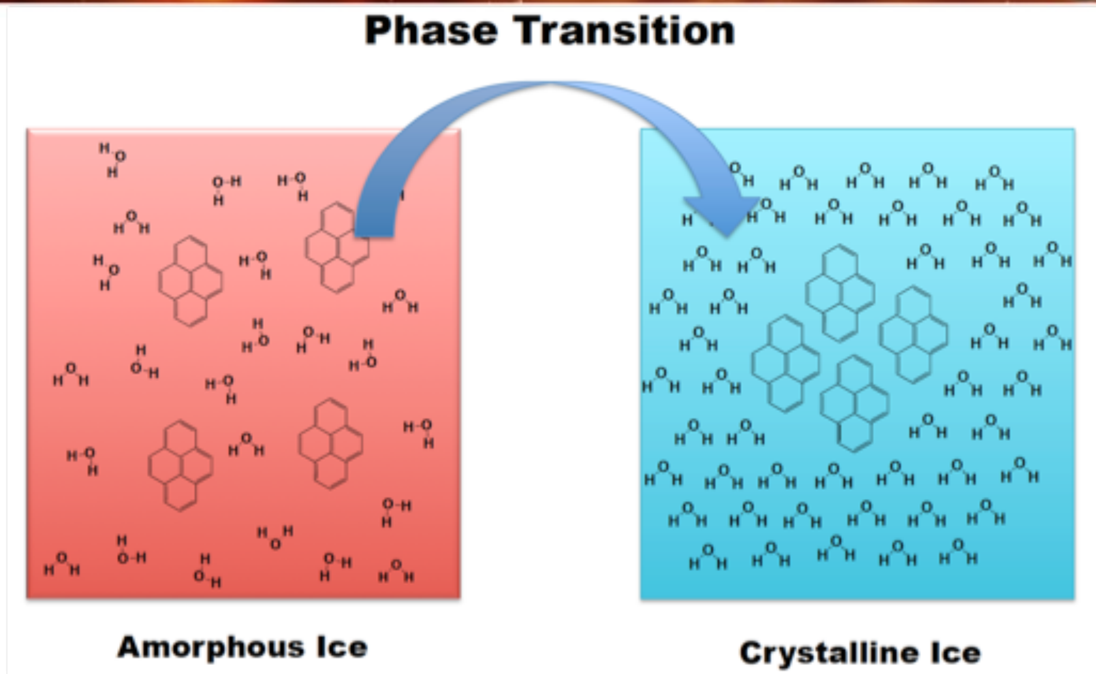
IR - Ice

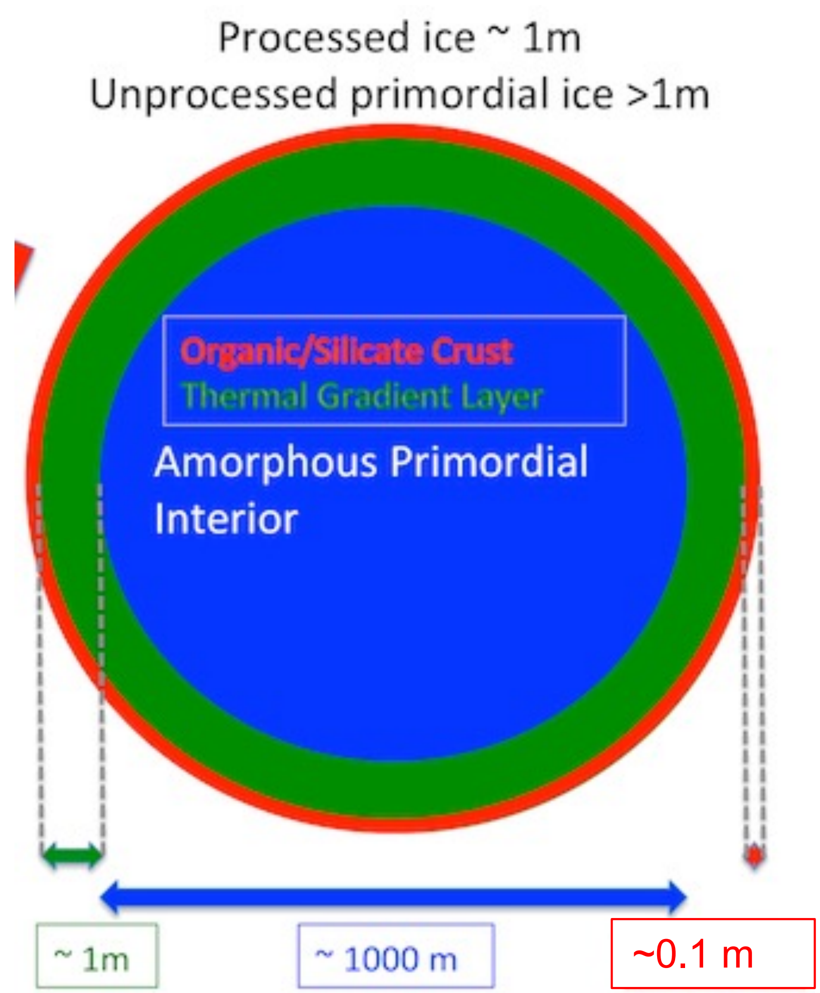
Flu - PAH



Lignell & Gudipati
J. Phys. Chem A.
119 (2015) 2607

Are Comets Like Deep Fried Ice Cream?





Comet CG/67P

Lignell & Gudipati J. Phys. Chem A. 119 (2015) 2607

Physical Properties: Critical Work Ahead

Thermal Modeling/Lab-Work of Comet Nucleus

Thermal Conductivity

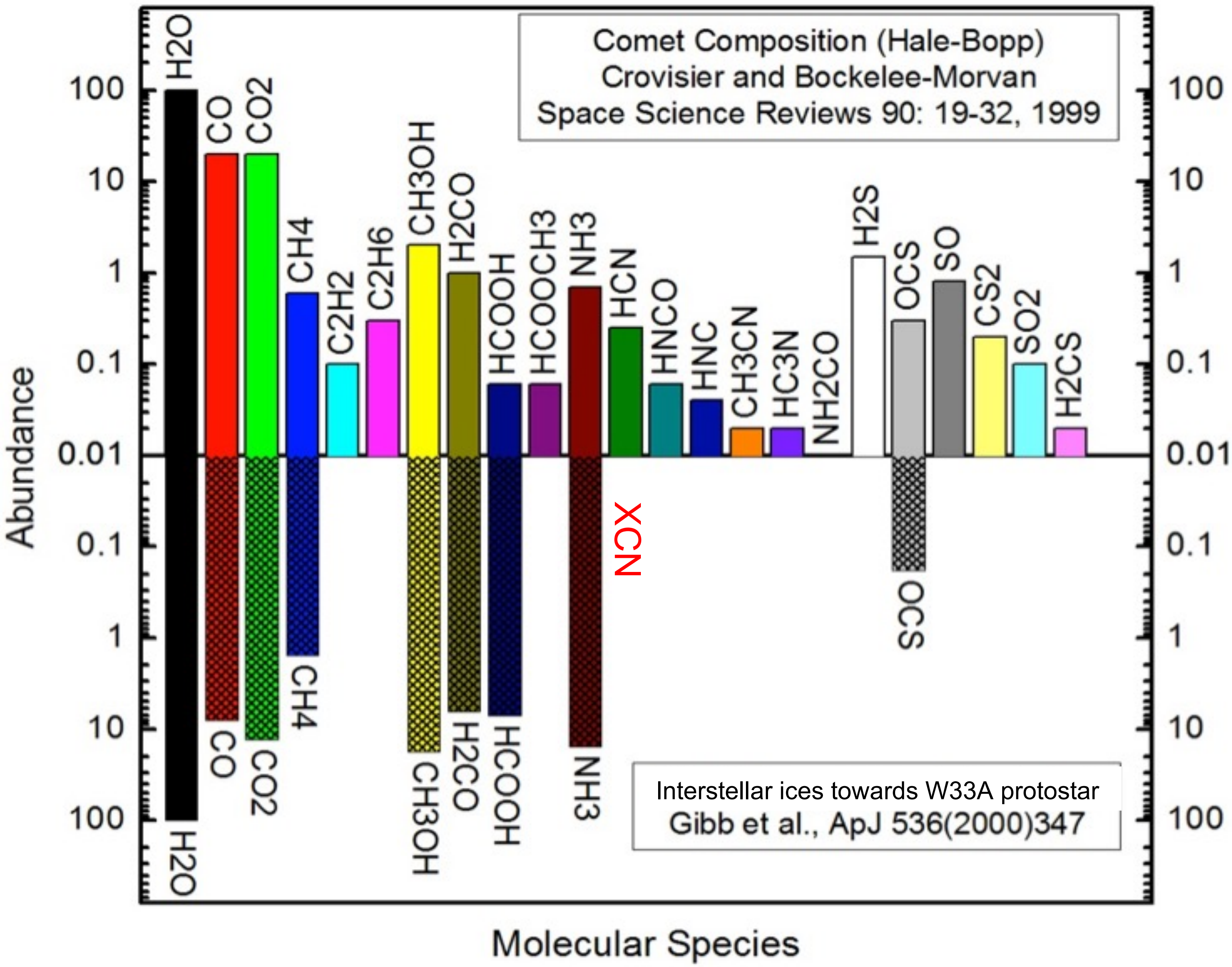
Thermal Wave Propagation

Thermal Equilibrium at Meters Depths

Near Surface Ice/Dust Hardness

Chemical Composition of Comets

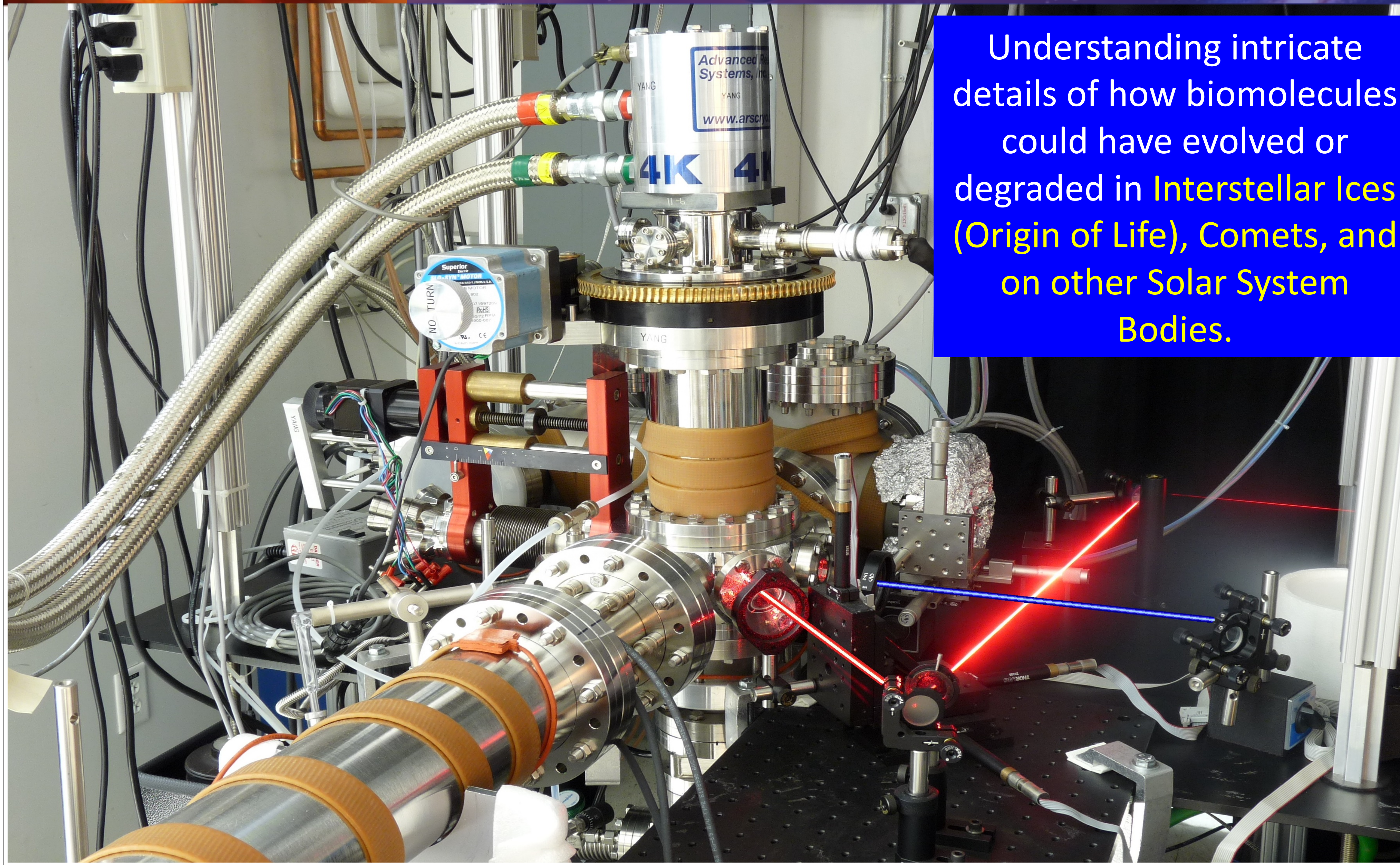
Similar Composition: Comets and Interstellar Ice Grains



Complex Organics Delivered by Comets and Origin of Life

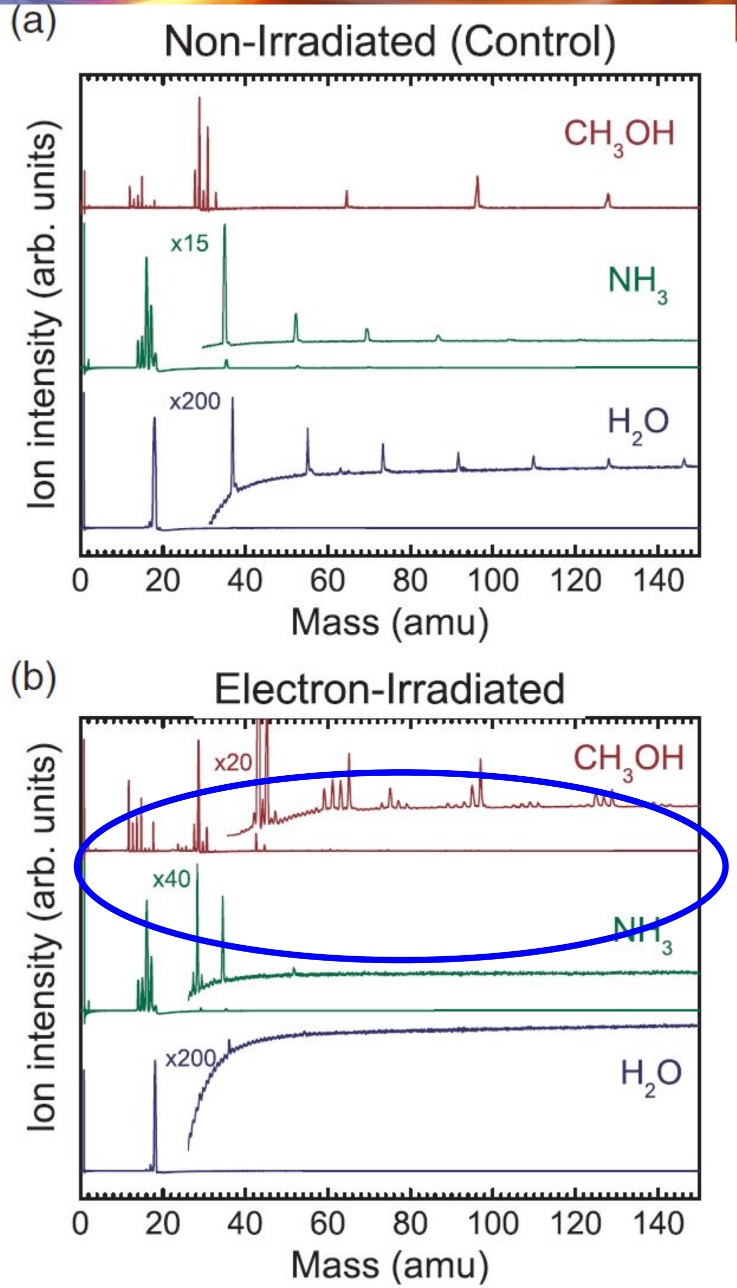
Understanding Prebiotic Chemistry in Comets

At Murthy's Ice Spectroscopy Lab (ISL) @ JPL



Understanding intricate details of how biomolecules could have evolved or degraded in Interstellar Ices (Origin of Life), Comets, and on other Solar System Bodies.

Pure Ice – Radiatioin Chemistry

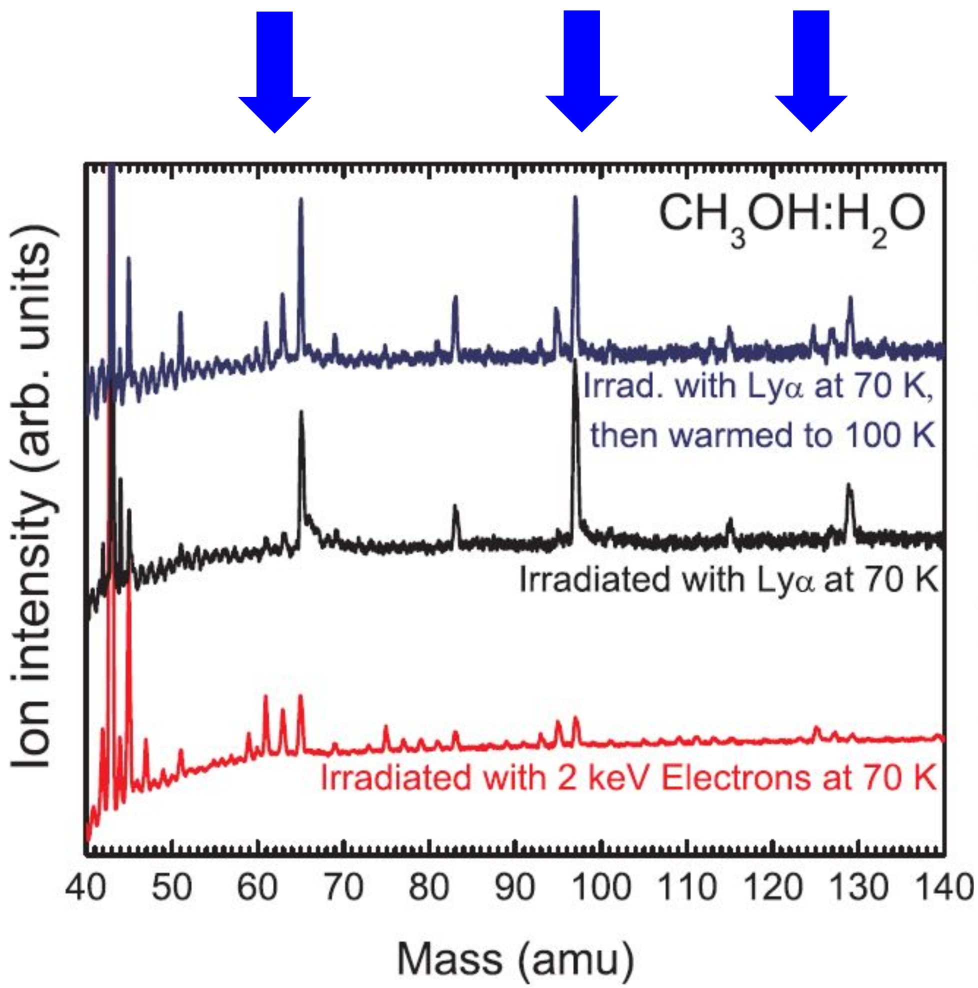


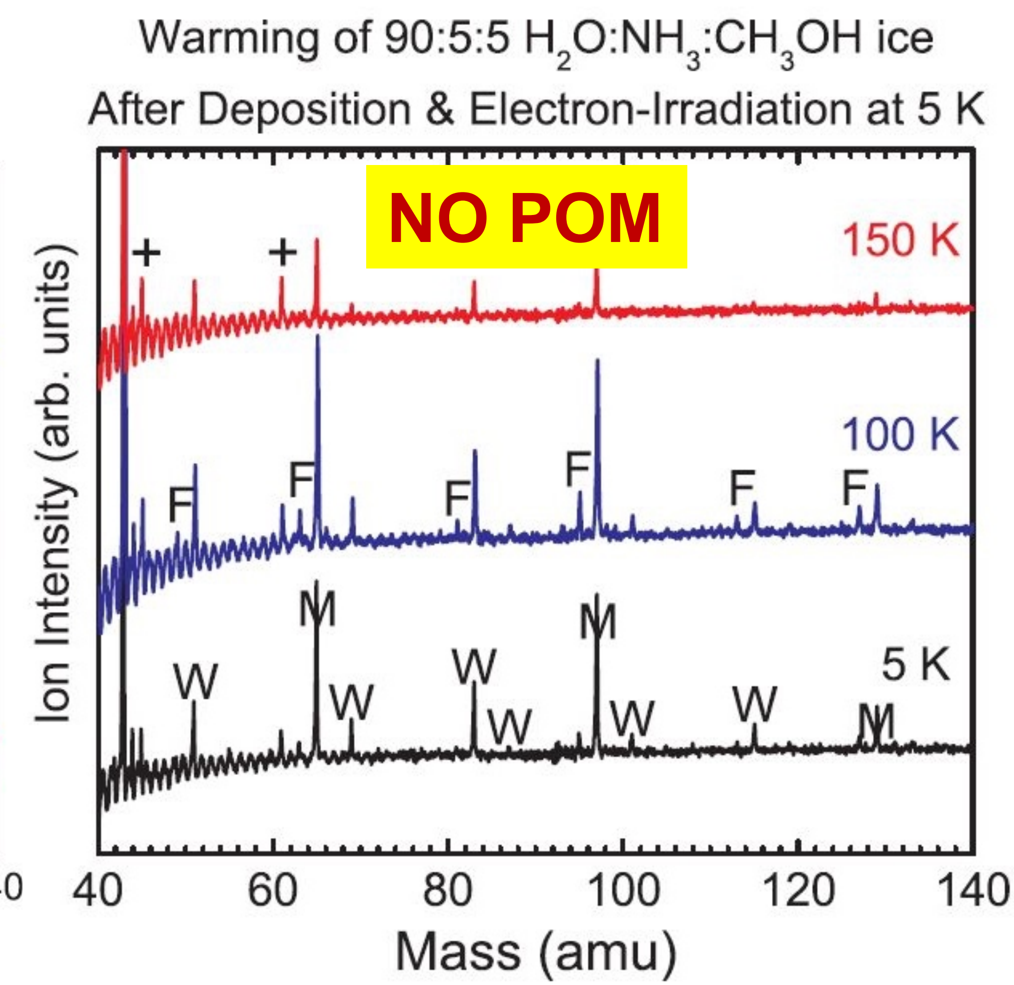
Methanol
most reactive & several products

Ammonia
Intermediates (N, NH, NH_2) & few products (H_2N_2)

Water
Intermediates (OH, H, O) & products (O_2, H_2O_2, O_3)

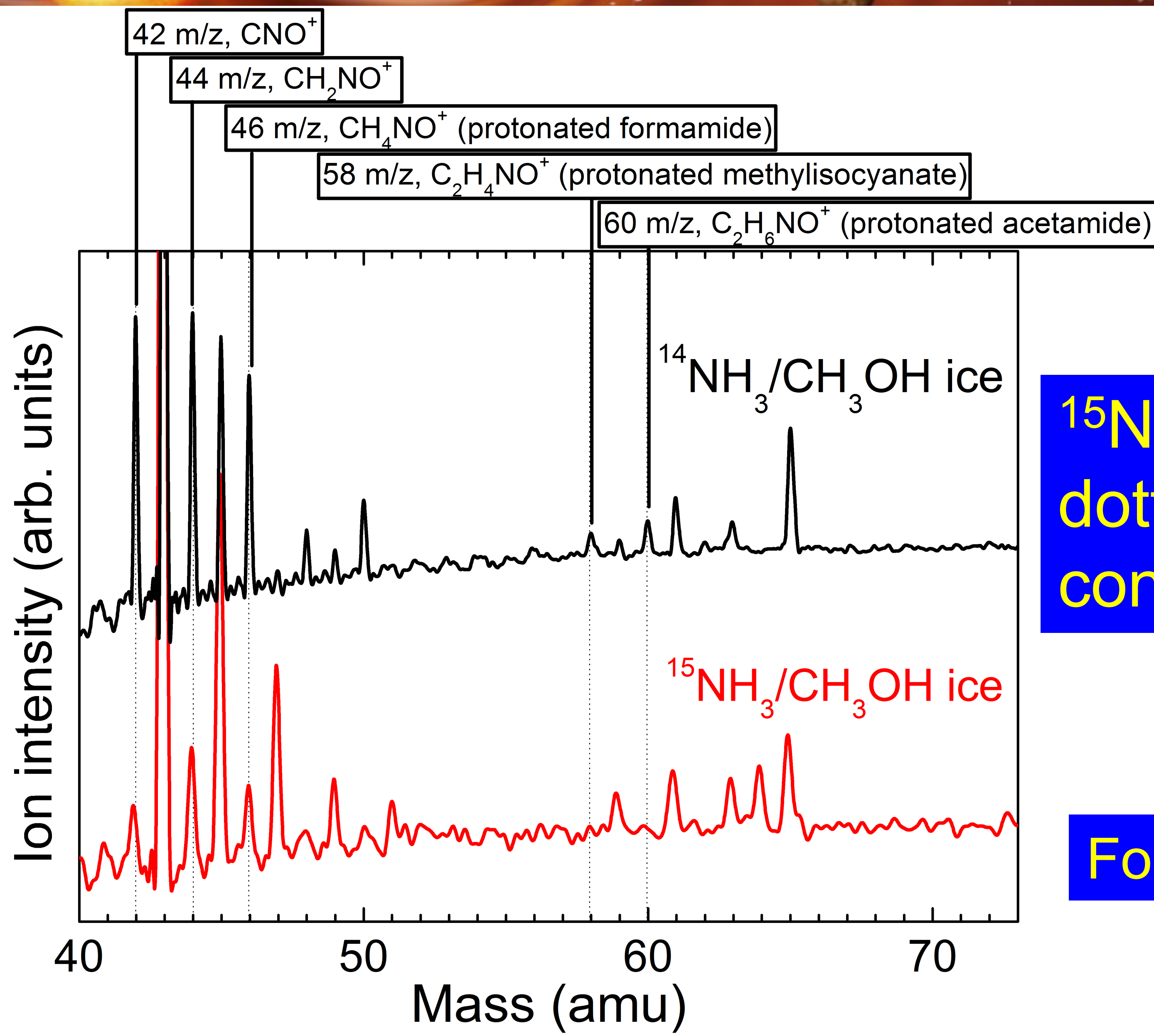
Molecules, Radiation, and Temperature





Formaldehyde formation 70 K – 100 K & disappearing >100 K

Isotopic Labeling $CH_3OH:NH_3$ ice



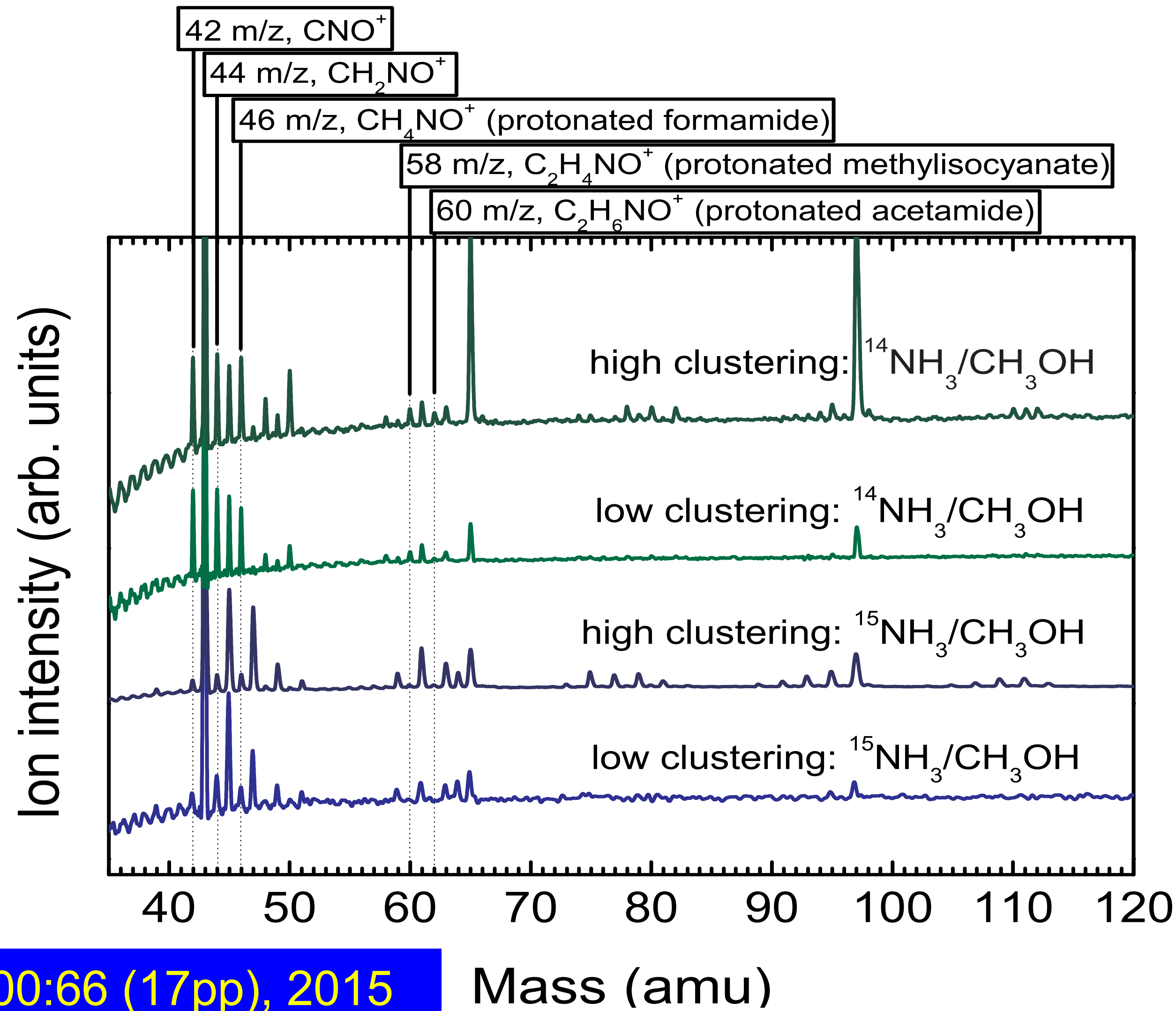
^{15}N labeling dotted lines confirm structure

Formamide Tracer?

Realistic Cometary/Interstellar Ice Analogs

Snapshots/Scooping the Evolution of Astrophysical Ice Analogs

Cometary Ice Analogs Produce Key Building Blocks Of Life upon Radiation Processing

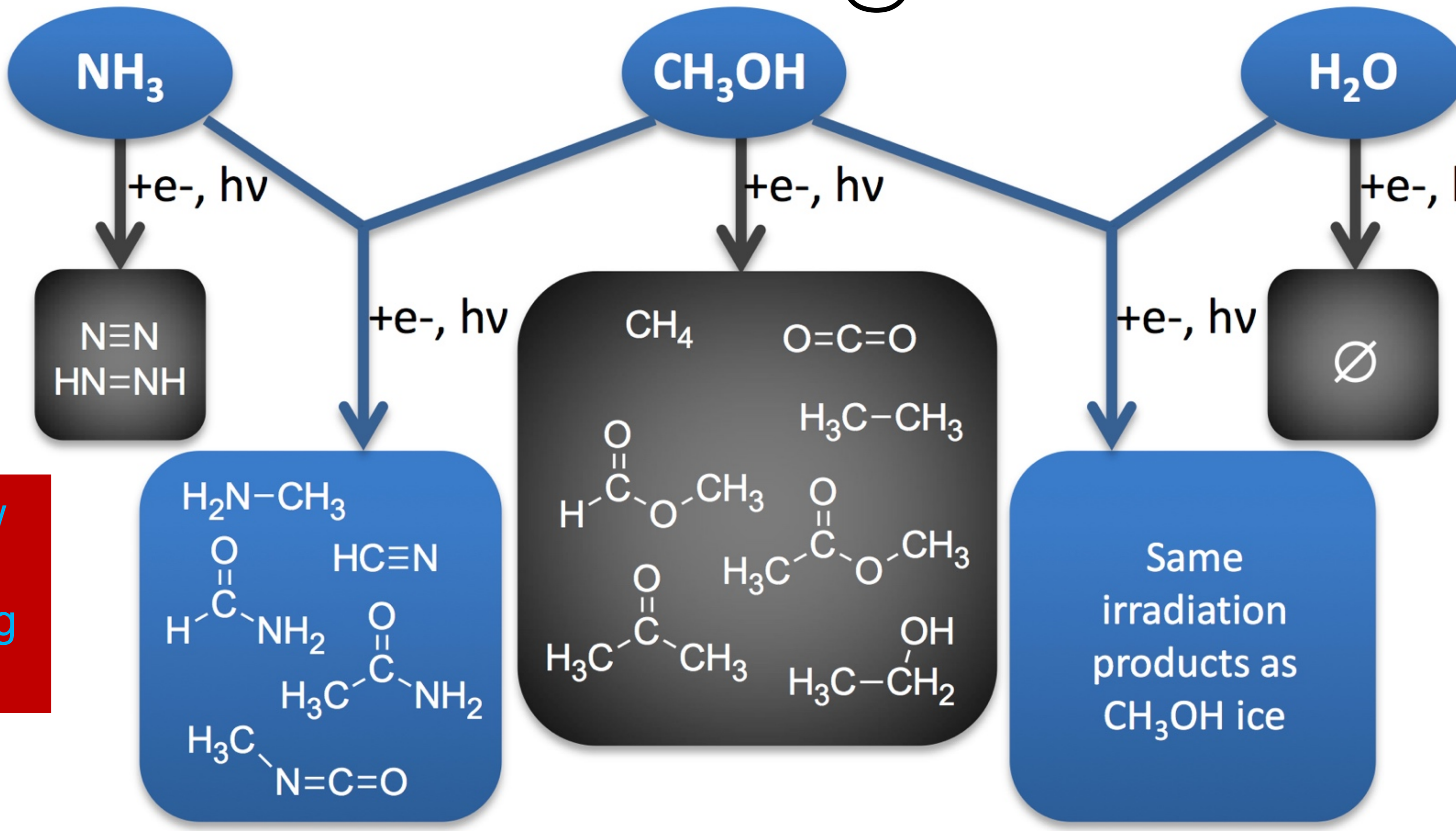


Tracer Molecules:
Formaldehyde
Formamide

Henderson and Gudipati ApJ - 800:66 (17pp), 2015

Molecules found in interstellar ice analogs

Irradiation Products of Single and Dual-Component Ices, 5 K
Enhancement @100 K



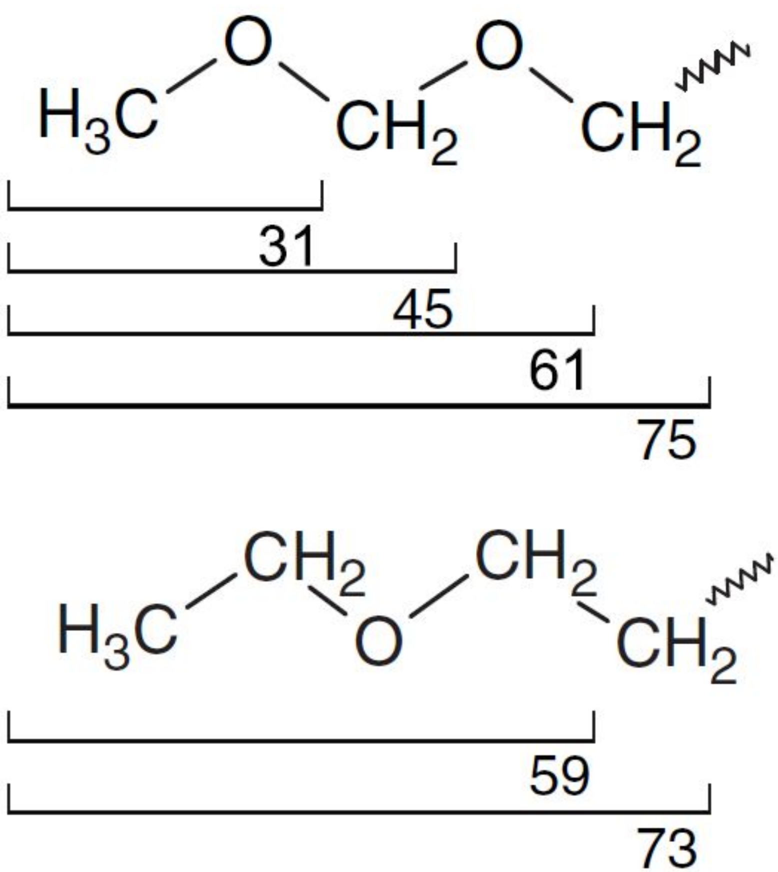
We are now working on S-containing Molecules

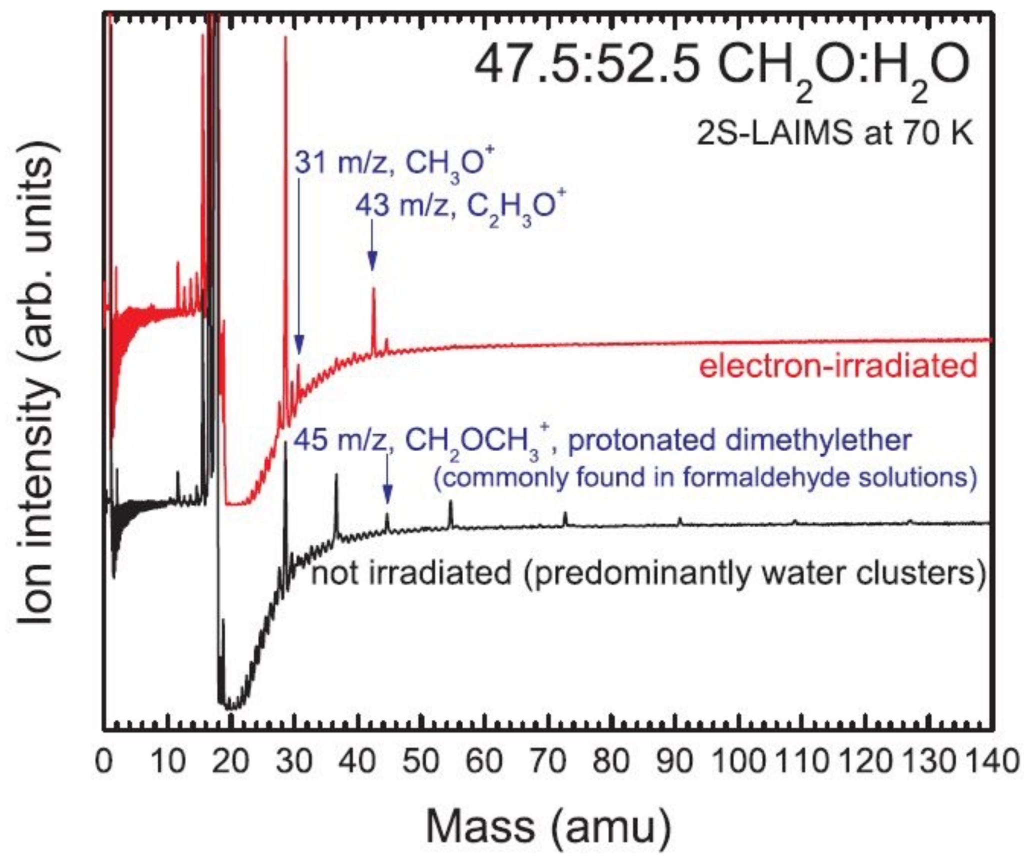
Many of these molecules are detected by Rosetta-ROSINA

NH_3 less reactive than CH_3OH under radiation

Polyoxymethylene (POM): Temperature Tracer

No POM detected at <150 K in Ice
POM was detected in room temp residues





Molecules and Ice-Phase as Tracers of a Comet's Evolution History

Molecular Tracers – Database Needed

- S_2 – Observed by ROSINA of Rosetta in 67P/C-G
- (Interstellar Ice needs to be retained?)

- OCS vs. H_2S (more in 67P/C-G vs. PPD) – Temperature?

- Lack of Observation of POM (Polyoxymethelene) in 67P/C-G and in the Labwork done at <100 K.

- Correlated co-existence of Complex Organics Database: e.g.: formamide and formaldehyde

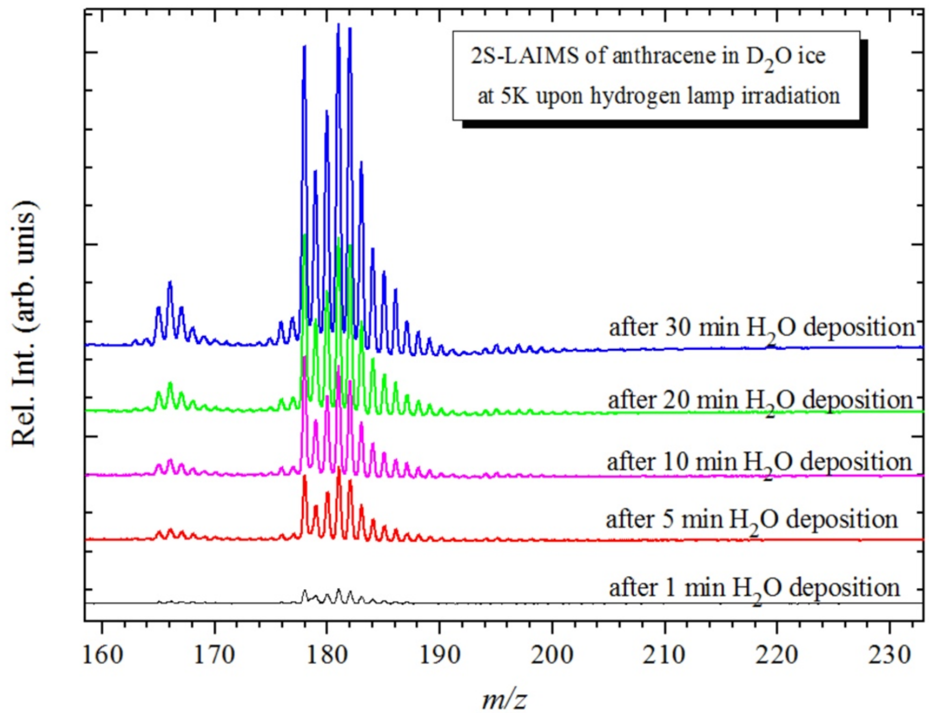
D/H Ratio As a Tracer – Careful

We should be careful with D/H ratio as a tracer

- Gas-Phase D/H alone may be distorted
- D/H ratio of solid may be enriched in D
- Photochemical (radiation) chemistry could alter D/H ratios.

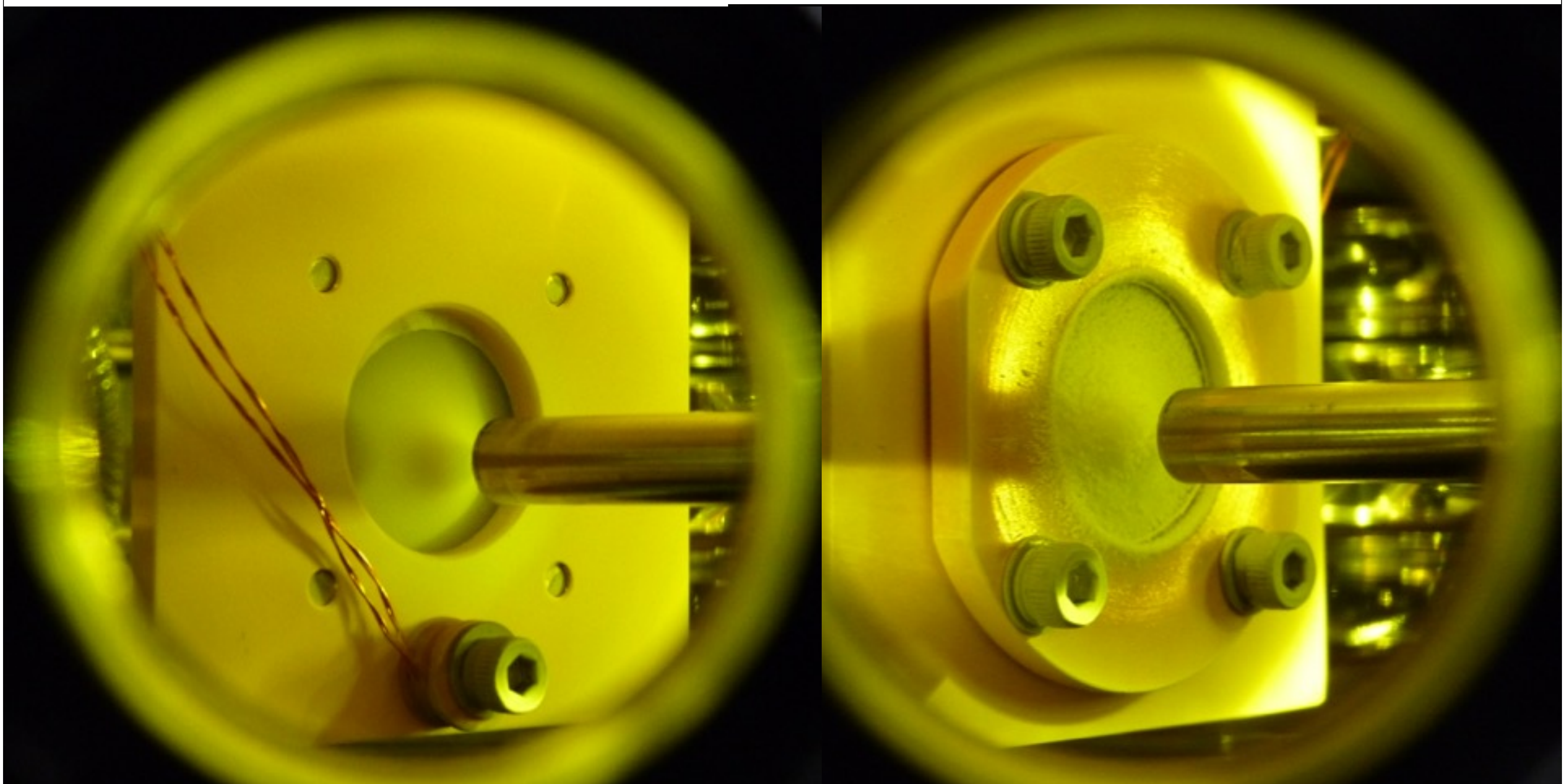
Nuclear isotopes are better Tracers(C,O, Ar, Kr, Xe, N, etc.)

PAH Anthracene
Photo-Deuteration
In D2O ice with Ly-α



A Comet’s Nucleus – What is it?
Amorphous, Crystalline, or Crystalline with Clathrates?

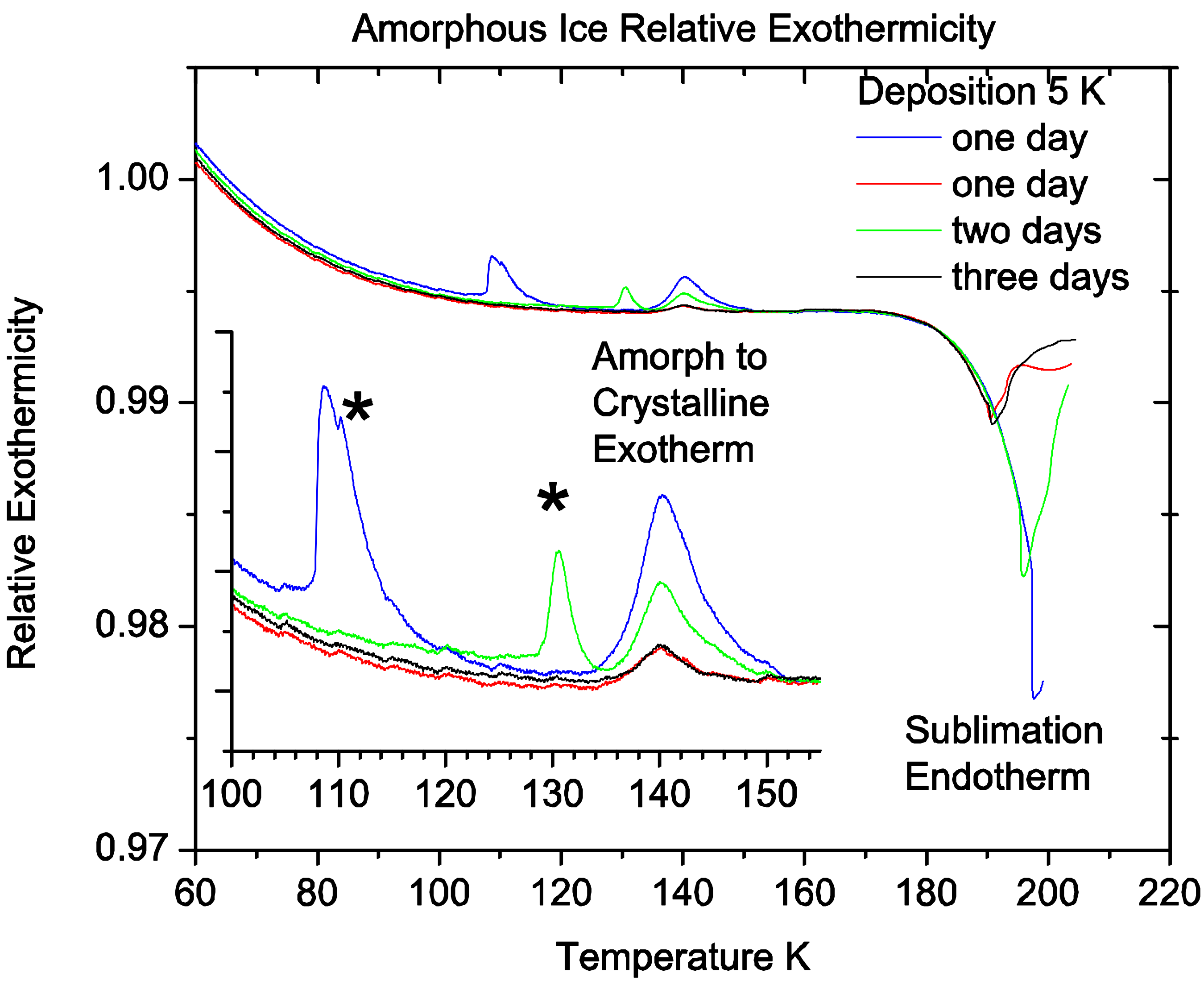
Macroscopic Amorphous Ices in the Lab: Simulating Interstellar & Comet Ices



150 K Deposition
(Crystalline)

5 K Deposition
(Amorphous)

Amorphous to Crystalline – Exothermic?

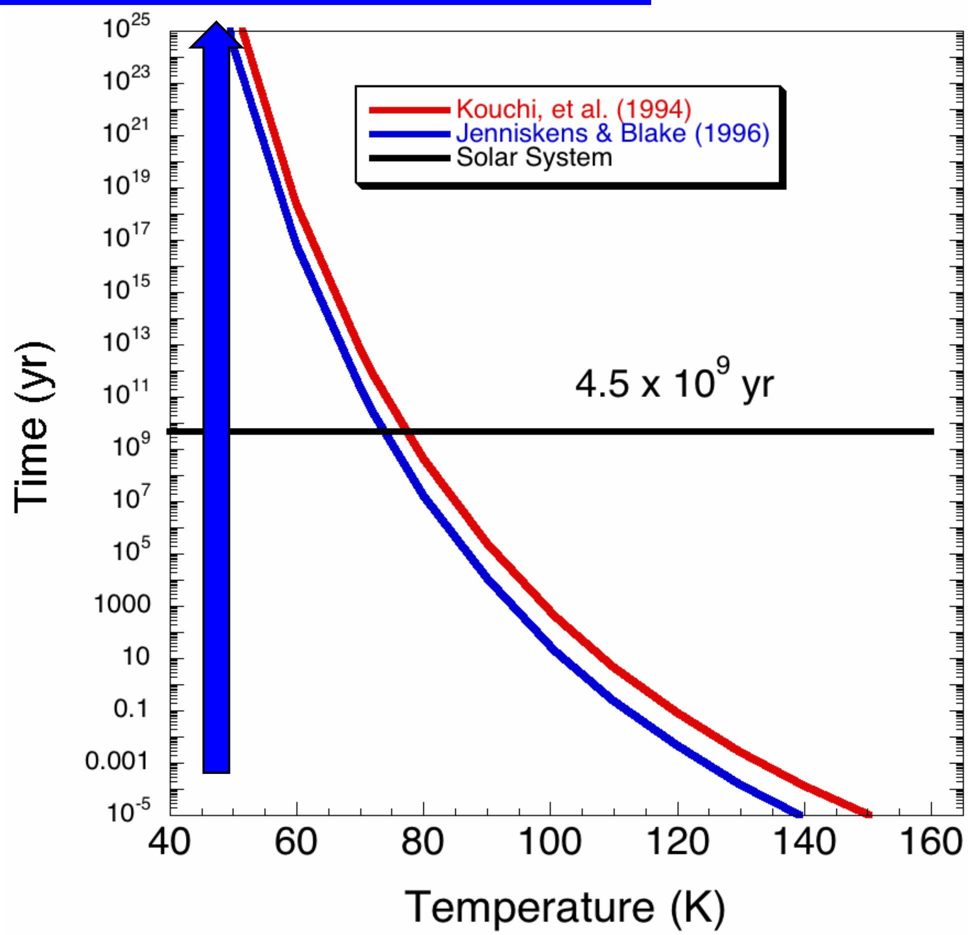


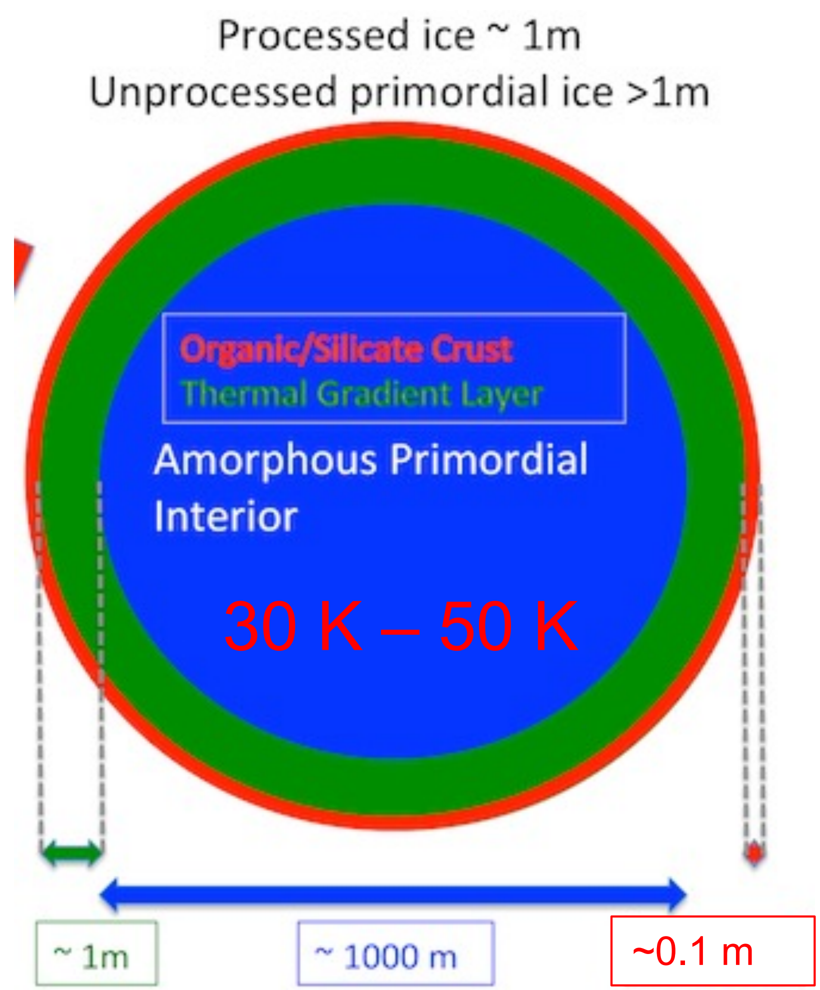
Impurities may change exothermic to endothermic (amorphous to crystalline) transition

Robert Wagner and Murthy Gudipti (2013) to be published

How Primitive is a Comet's Interior?

KBOs and Centaurs





Mastrapa, Grundy, Gudipati (Solar System Ices 2013)

Cryogenic Comet Nucleus Sample Return

Ultimate Answers to:
Amorphous, Crystalline, Or Clathrate Comet Nucleus?
Co-existence of supervolatiles and water-ice from ISM?

Will be answered ONLY through <40 K Sample Return!

CCNSR!

Conclusions

Retention of Interstellar Amorphous Ice Grain Structure and Composition in Cometary Nucleus Explains ALL Observations

Physical parameters on their own may not constrain cometary interior composition models.

Chemical composition from rare-gas isotopes to complex organics should be used as tracers to further constrain the modeling studies.

Ice phase: amorphous, crystalline, clathrates (low-temp or high-temp??) along with the thermal evolution of ice phase of cometary precursors from protoplanetary to present-day.

Post-Rosetta Cometary Science

Dig Deeper and Get the Cryogenic Samples

Better Understanding of Protoplanetary Disks (JWST?)

Better Thermal and Radiation Evolution Modeling of Cometary Nucleus.

How were the cometary nuclei @ Late Heavy Bombardment Time ~ 4 BY ago?

Ice Spectroscopy Lab (ISL) Crew 2017

Continuing Team-Effort of ISL since 2007

Thank You

Thank you for your time
Thanks to the SOC for the invitation
Thanks to the LOC for outstanding hospitality
Thanks to NASA and JPL for financial support