Meteorites, Asteroids and Sample Science

Dionysis Foustoukos with George Cody & Conel Alexander

Earth & Planets Laboratory
Carnegie Institution of Washington

Road map for this presentation:

1) Why do we study meteorites and asteroids? What can we learn about early Solar System evolution?

2) **Asteroid Bennu:** Important for life ingredients in the soluble organic fraction extracted from returned samples.

3) **Asteroid Bennu:** A thermo-aqueous history through the lenses of the molecular structure and elemental/isotopic compositions of organic solids (H, C, N).

Carbonaceous chondrites (e.g. Murchison): Stony meteorites and contain large abundancies of H, C, N, S and O. They are considered the most primitive remnants of early Solar System.

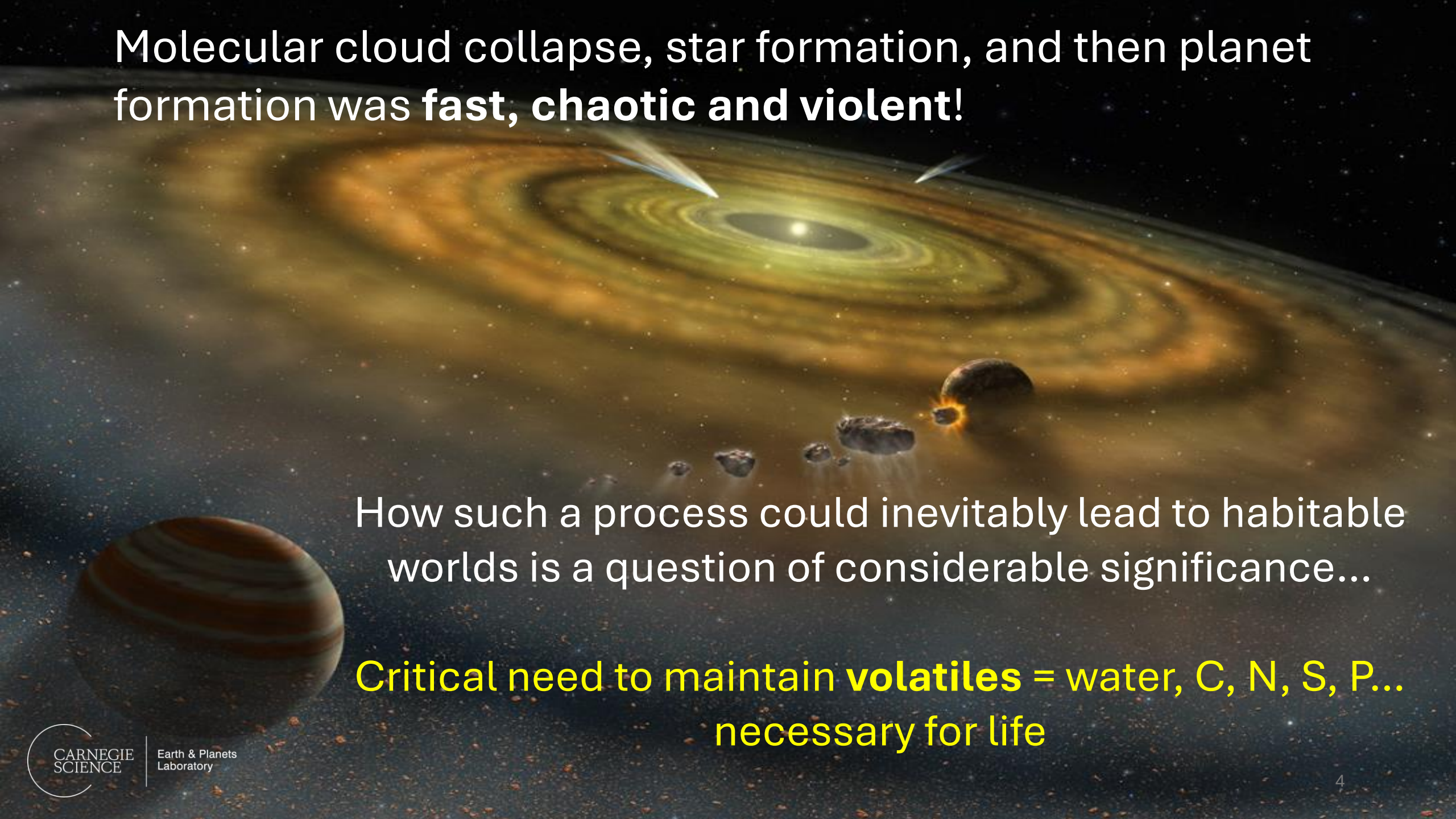
Asteroids (e.g., Bennu, Ryugu): Rocky bodies that are found mostly in the main asteroid belt between Mars and Jupiter. Some of them are classified as Near-Earth Objects (0.3 AU, 28 million miles). Remnants of early Solar System.

Stable Isotopes of H, C, N: Same element but with an +1 neutron; Measured as ratios (deuterium/hydrogen; $^{13}C/^{12}C$, $^{15}N/^{14}N$) and expressed in parts per thousand (‰) difference from a standard. The notations are $\delta D(‰)=(R/R_{std}-1) \times 1000$ (R=D/H).

Elemental Ratios: Here, these are described as weight or atomic ratios, e.g., N/C (at.) = (wt.% N/14)/(wt.% C/12). Measured by Elemental-Analyzer Isotope Ratio Mass Spectroscopy.

Functional Groups: a group of atoms with characteristic chemical properties, e.g. R-OH (alcohols)

Nuclear Magnetic Resonance: Spectroscopy based on the magnetic properties of nuclei (e.g., ^{13}C, ^{1}H): Probing nuclear spin states by imposing external magnetic fields. The frequency spectra show the variations imposed on local magnetic field around nuclei.



Molecular cloud collapse, star formation, and then planet formation was **fast, chaotic and violent**!

How such a process could inevitably lead to habitable worlds is a question of considerable significance…

Critical need to maintain **volatiles** = water, C, N, S, P… necessary for life

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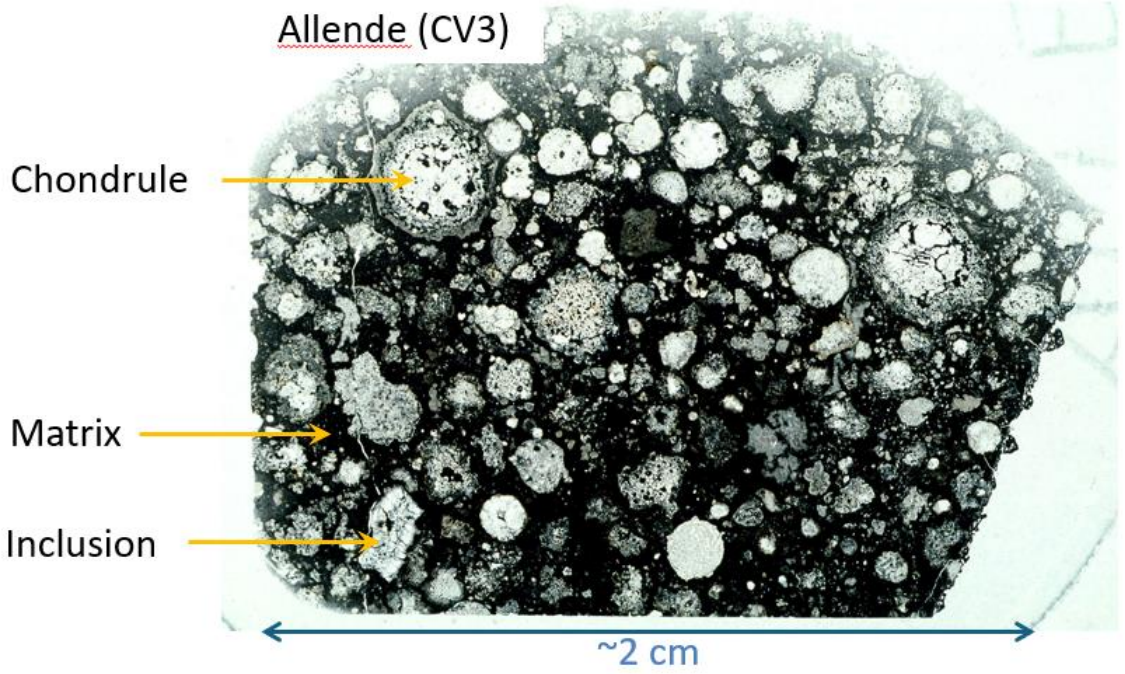
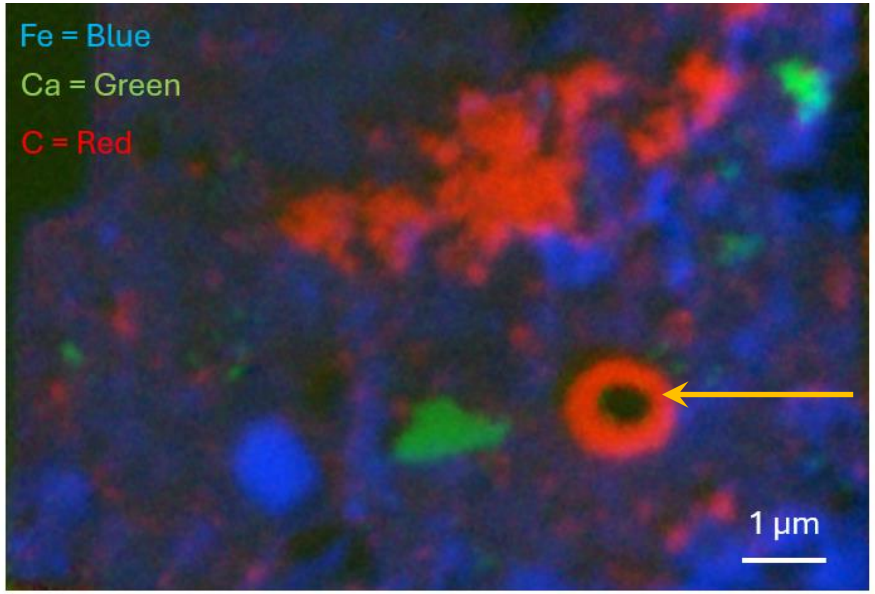
Photomicrographs Courtesy Adrian Brearley

Chondritic Meteorite is a Remnant of a Planetesimal: "cosmic sediment"

ALLENDE METEORITE A fragment of the Allende meteorite collected by Brian Mason and Roy Clarke shortly after it fell in northern Mexico on February 8, 1969. Allende is a CV3 carbonaceous chondrite. The white, fuzzy-looking features in it are calcium-aluminum inclusions, or CAIs, some of the first solids to condense in the solar system. Learn more about Allende here. *Chip Clark, Smithsonian Institution*

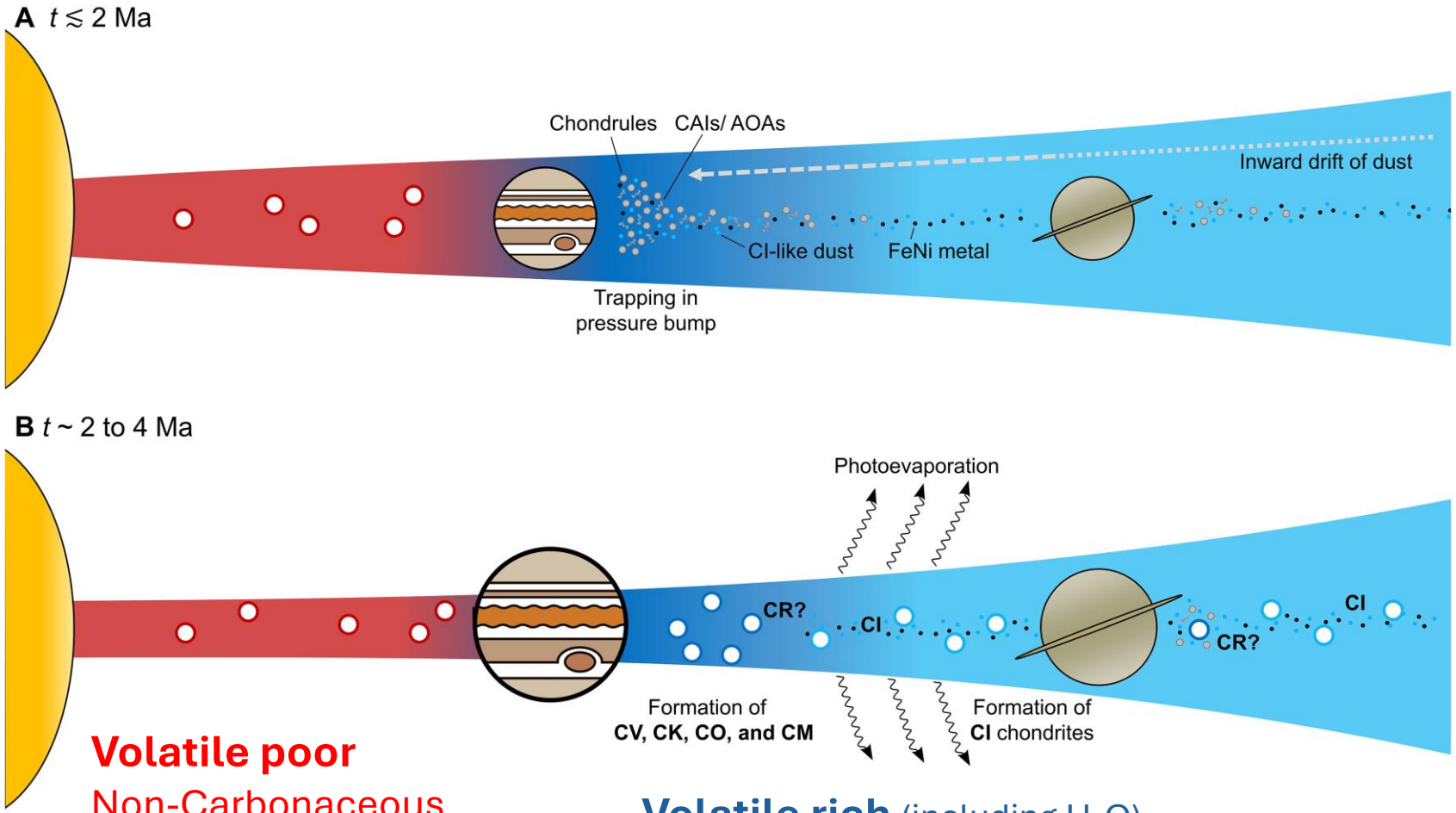




Organic Solids (Insoluble Organic Matter)

Scanning Transmission X-ray Image (**STXM**) (Cody et al. 2011)

Inner and Outer Solar System: All started in a narrow-time period



Volatile poor
Non-Carbonaceous Chondrites (Enstatite and Ordinary)

Volatile rich (including H_2O)
Carbonaceous Chondrites (e.g., CM, CI, CR)
contain abundant carbonaceous and organic material

CM (Mighei-like):
chondrules, 50 % matrix,
~ 2 wt.% C, 1wt.% H

CI (Ivuna-like):
no chondrules, 100 % matrix,
~ 3.7 wt.% C, 1.5 wt. % H
Chemical composition similar to solar photosphere

CR (Renazzo-like):
chondrules, 30 % matrix,
~ 1.2 wt.% C, 0.5 wt.% H

(Review: Alexander 2017)

Spitzer et al., 2024

Outer Solar System objects are rich in organics

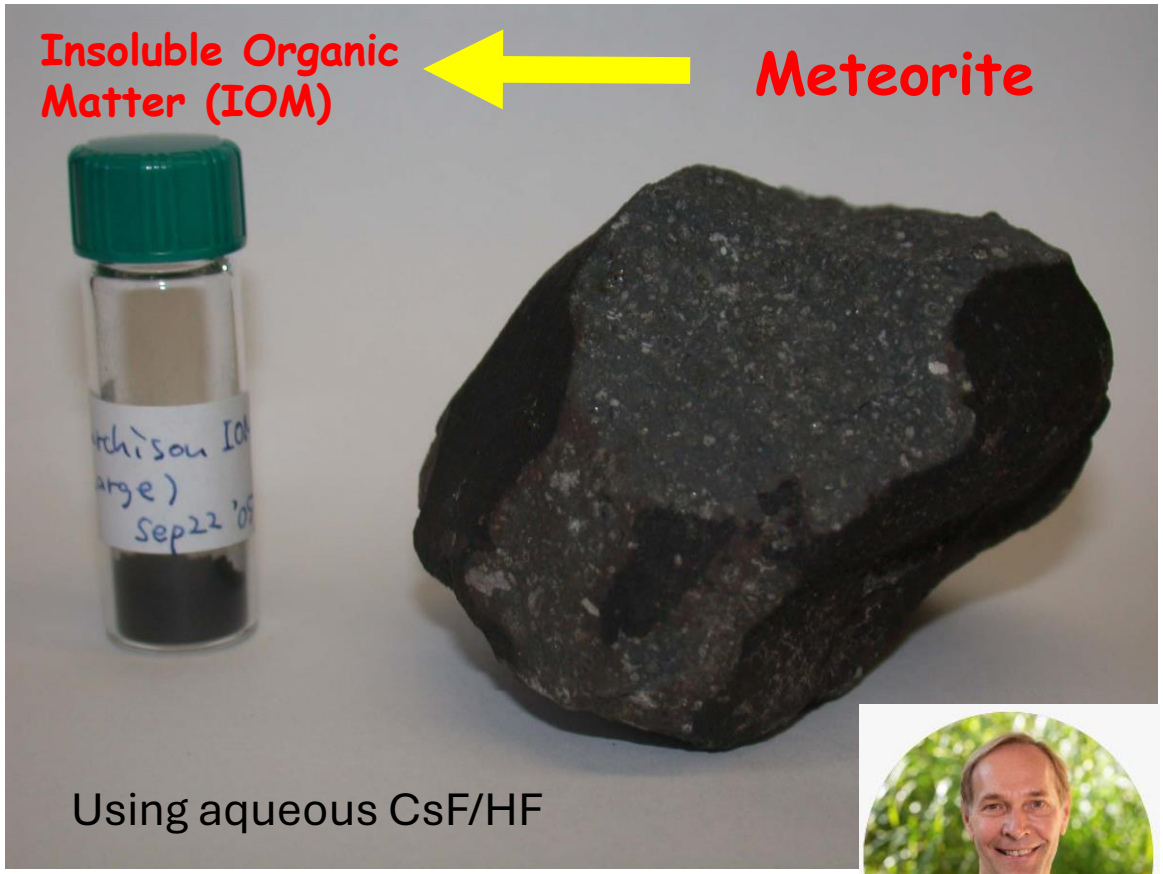
Insoluble Organic Matter (IOM)	Abundance
Macromolecular material ($C_{100}H_{70}N_3O_{12}S_2$)	70-99% total organic C
Murchison (CM2)	
Soluble Organic Matter (SOM)	**Concentration (ppm)**
Carboxylic acids	>300
Polar hydrocarbons	<120
Sulfonic acids (organoS)	67
Amino acids (92 named)	60
Dicarboxymides	>50
Aliphatic hydrocarbons	>35
Dicarboxylic acids	>30
Polyols (sugars)	30
Aromatic hydrocarbons	15-28
Hydroxy acids	15
Amines	13
Pyridine carboxylic acids	>7
N-heterocycles	7
Phosphonic acids	2
Purines and pyrimidines	1

Updated Table from *Meteorites and the Early Solar System II, (*2006) Pizzarello, S., Cooper, G. W., and Flynn, G. J., pp. 625-651, eds. D. S. Lauretta and H. Y. McSween

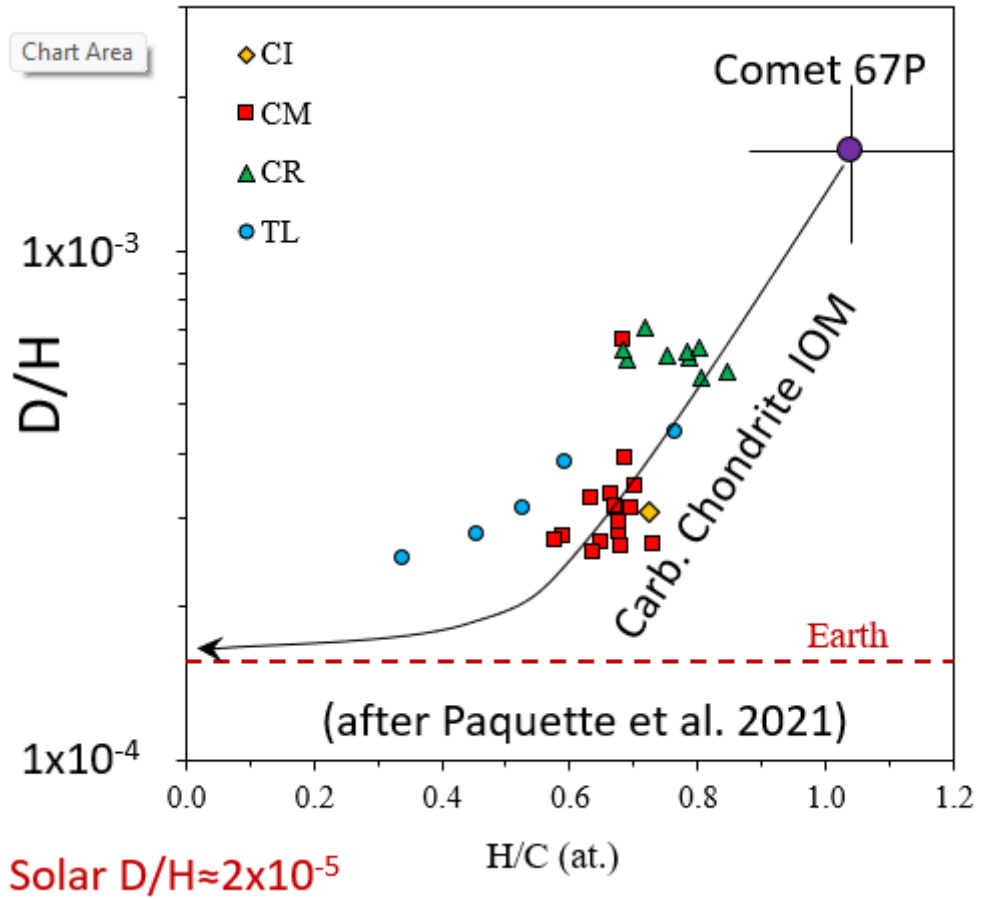
- Carbonacous chondrites (e.g., CI,CM,CR) contain complex varied suites of soluble organic compounds (>10,000) with almost complete structural diversity (e.g., numerous amino acids).
- Some of compounds or their precursors may have interstellar heritages (enriched in D and ^{15}N) (e.g., Glavin et al. 2018).
- **But**, aqueous-thermal activity (including NH_3, HCN & CO_2) has modified the original materials to unknown extents.

Insoluble organic matter (IOM)

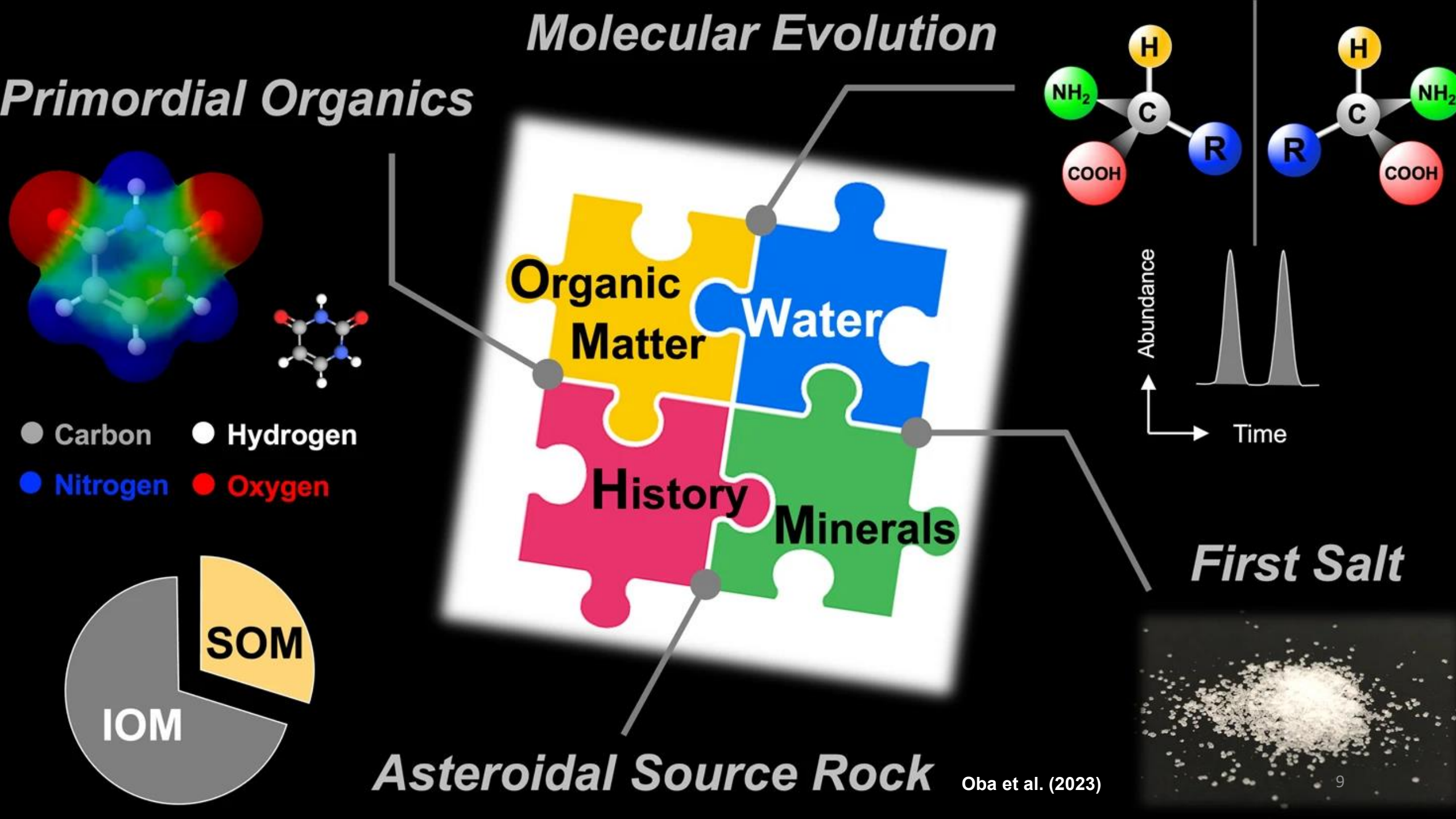
Complex, macromolecular C composed of aliphatic, aromatic and carbonyl functional groups.
Chemically like a mature coal: $C_{100}H_{60\text{-}80}O_{10\text{-}20}N_{3\text{-}4}S_{2\text{-}3}$
Similar to comets Halley and 67P.



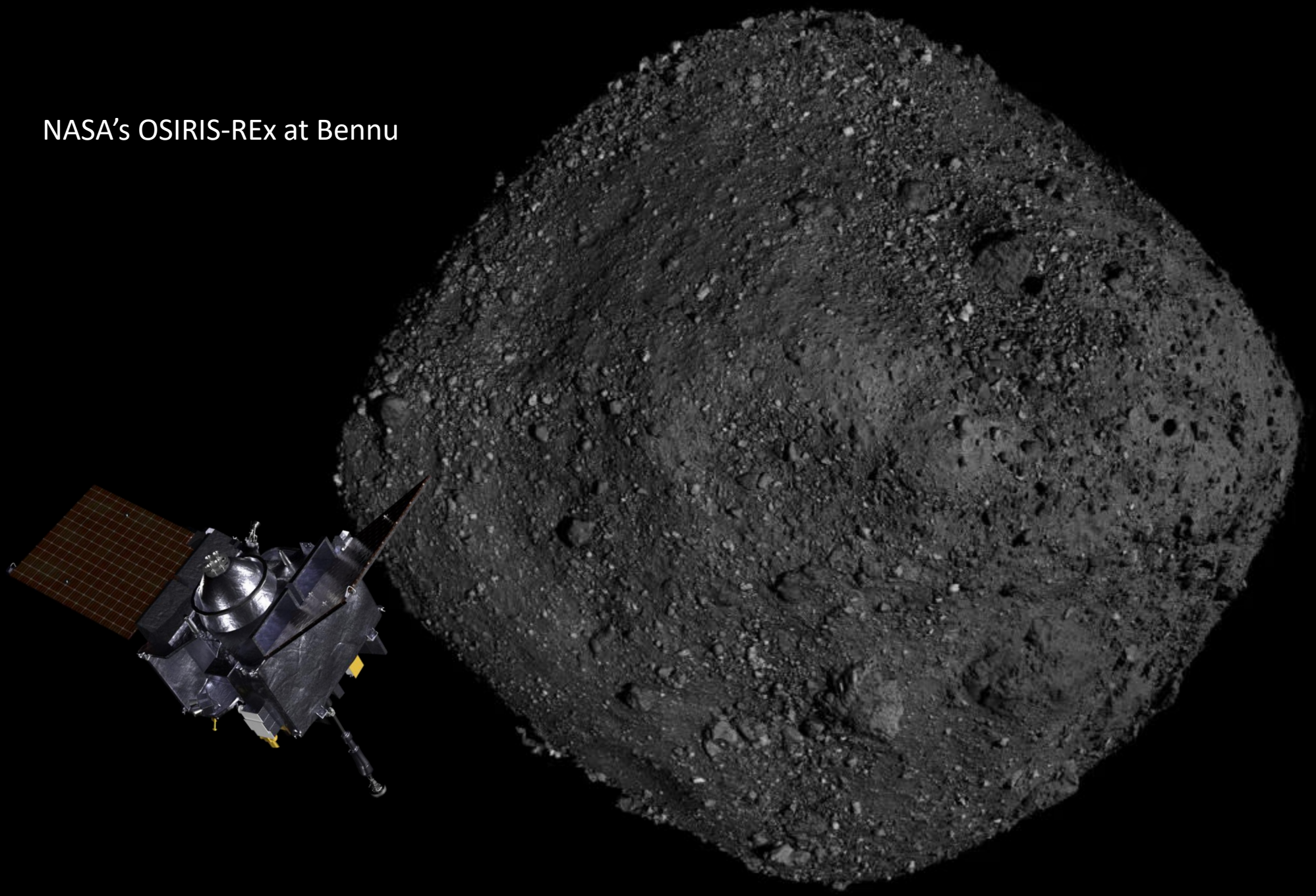
Conel Alexander



(Review: Alexander 2017)


Molecular Evolution
Primordial Organics
Organic Matter
Water
History
Minerals
Carbon
Hydrogen
Nitrogen
Oxygen
SOM
IOM
Abundance
Time
First Salt
Asteroidal Source Rock
Oba et al. (2023)

NASA’s OSIRIS-REx at Bennu

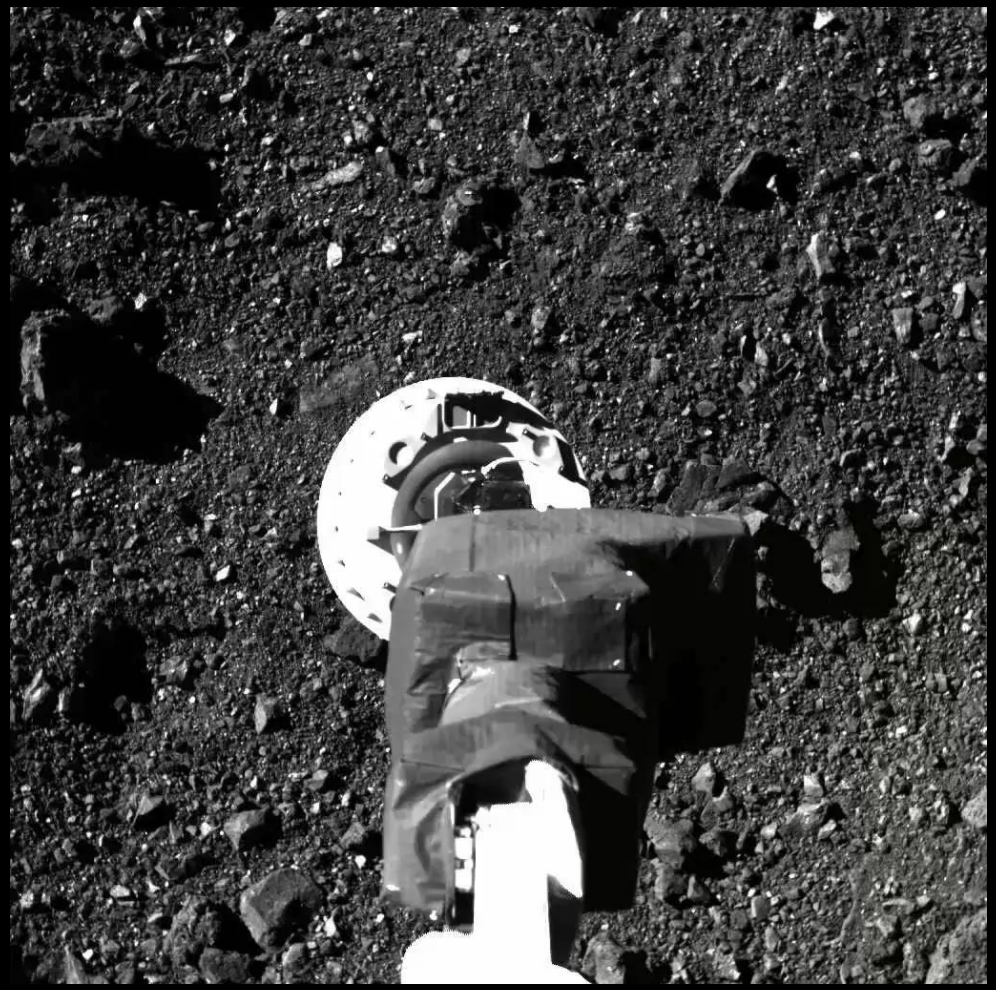


0.3 miles
(490 m)

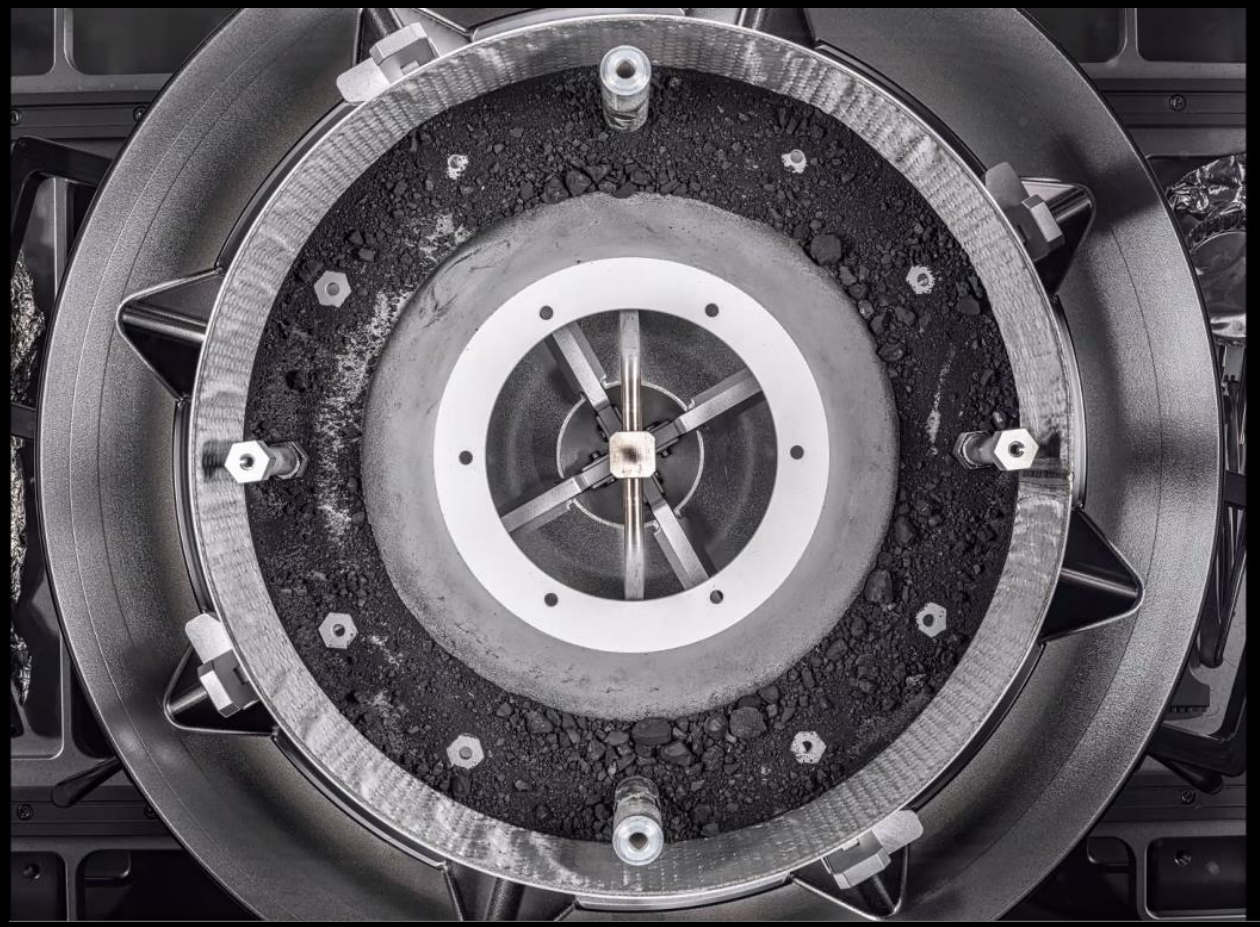
Derived from Flight Data

BENNU'S JOURNEY

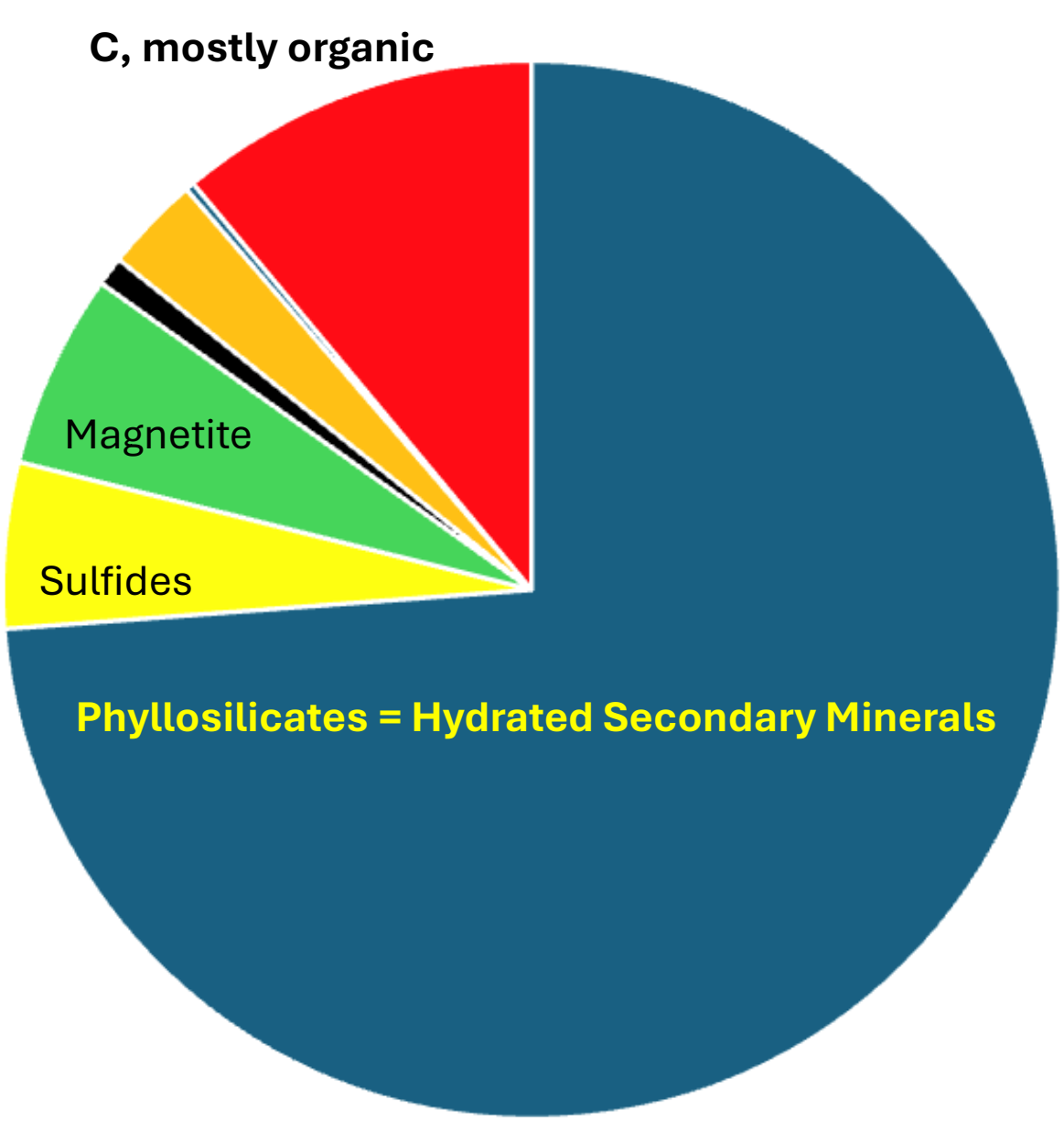
Sampling: Oct. 2020

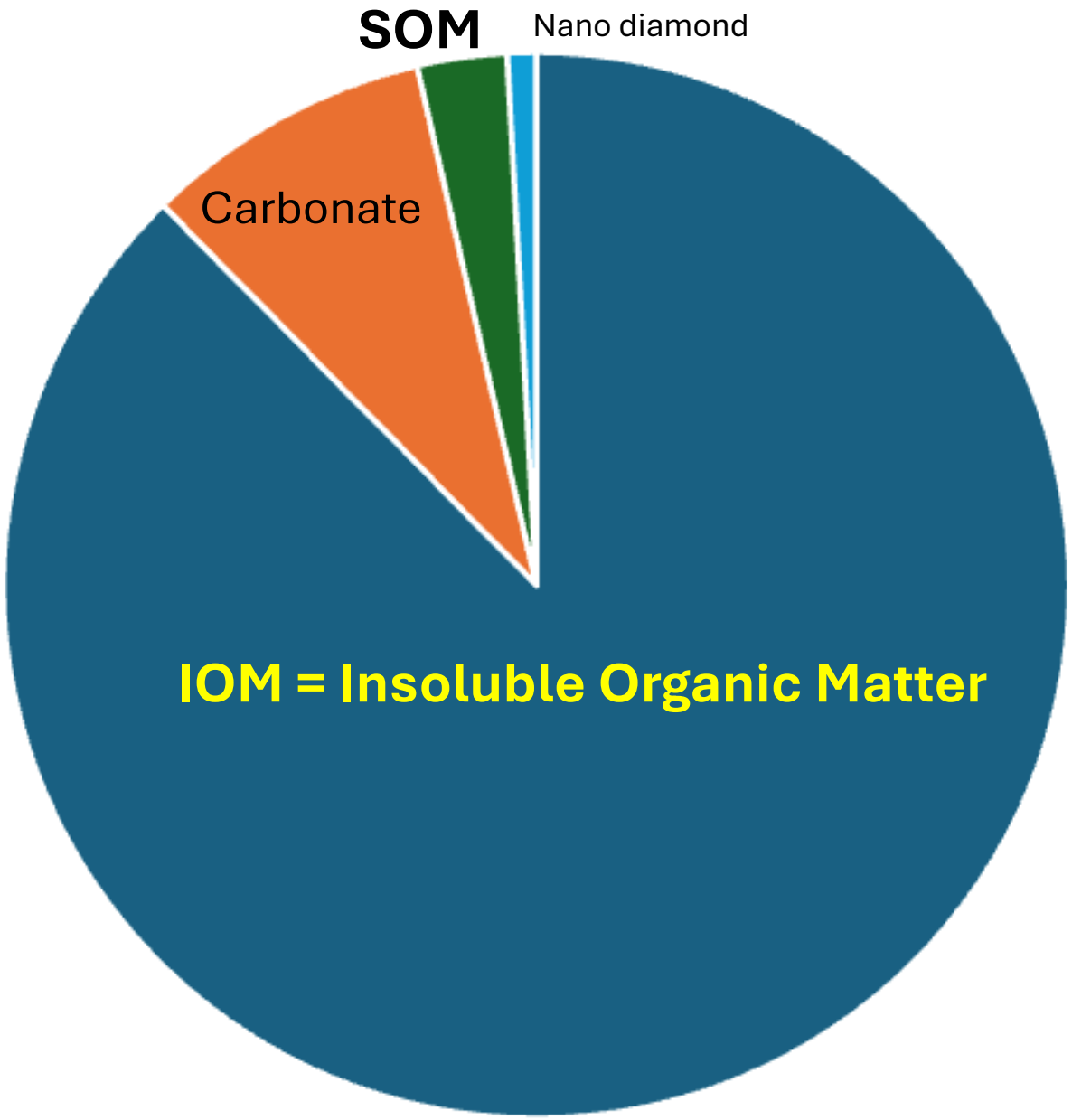


126 g of sample returned



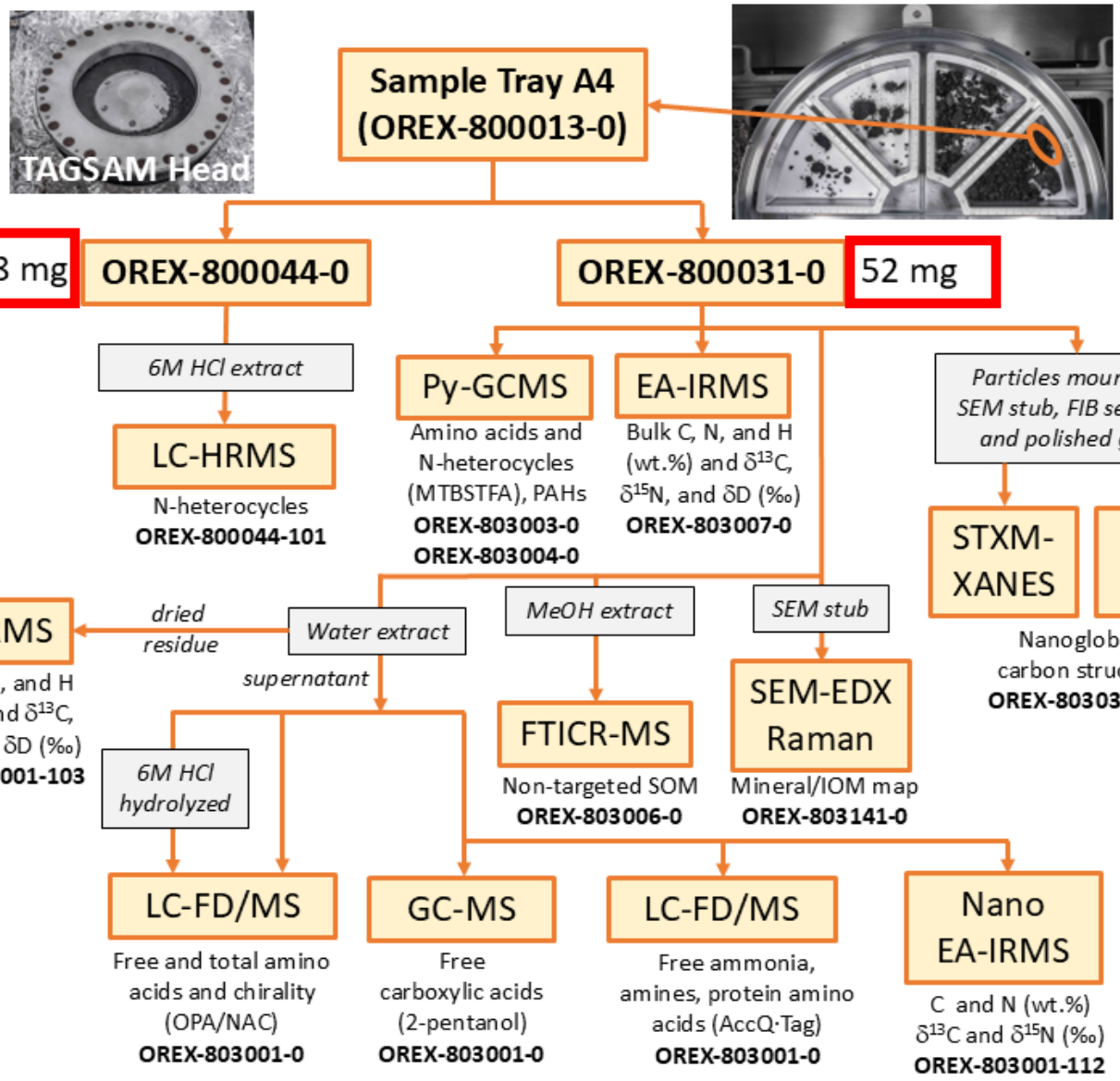
Bennu: An altered object with abundant C (~ 4 wt.%)



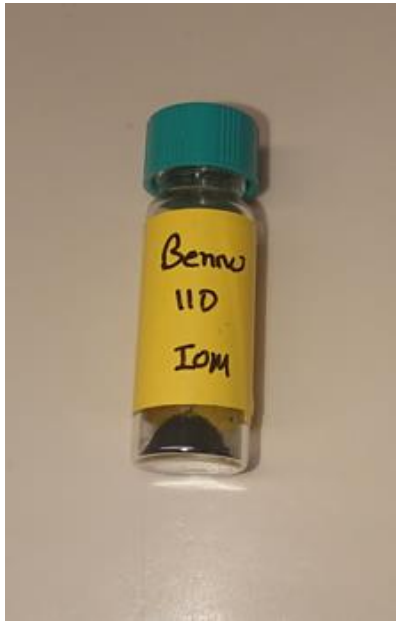


Connolly et al. (2025); Cody et al. (2025); Glavin et al. (2025); Lauretta et al. (2024), McCoy et al. (2025), Zega et al. (2025)

Coordinated Sample Analysis To Characterize the Organics

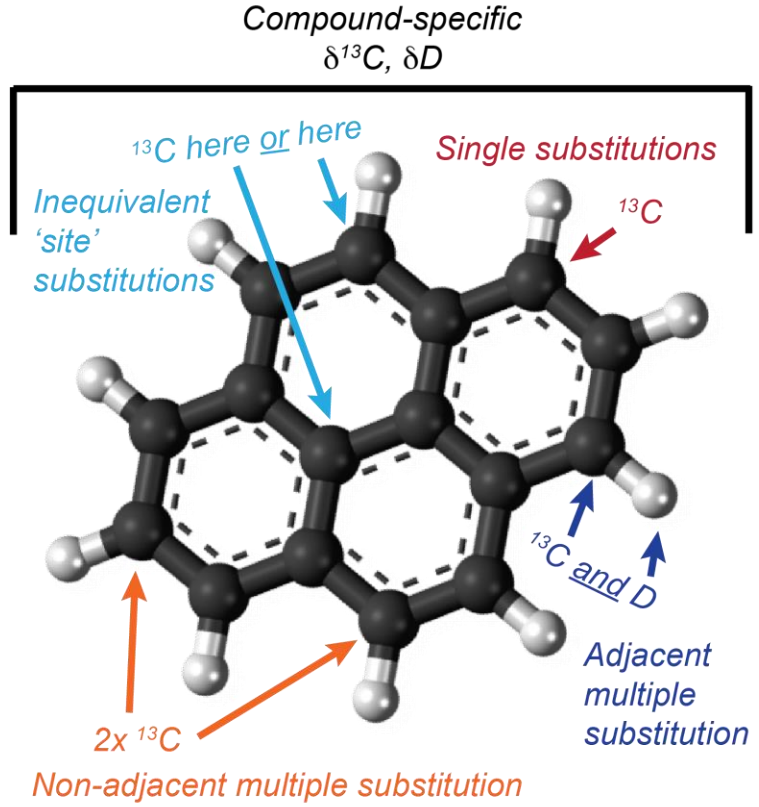


IOM extraction required ~ 1 g of bulk material for ~ 3% extraction efficiency



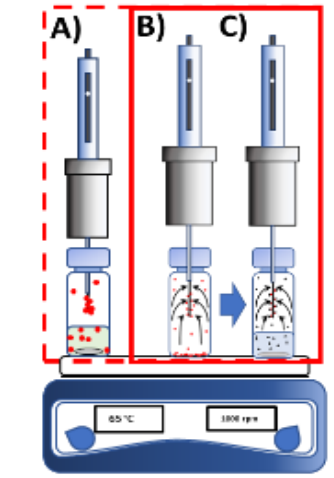
Glavin et al. (2025)

Compound-specific isotope analysis of organic molecules

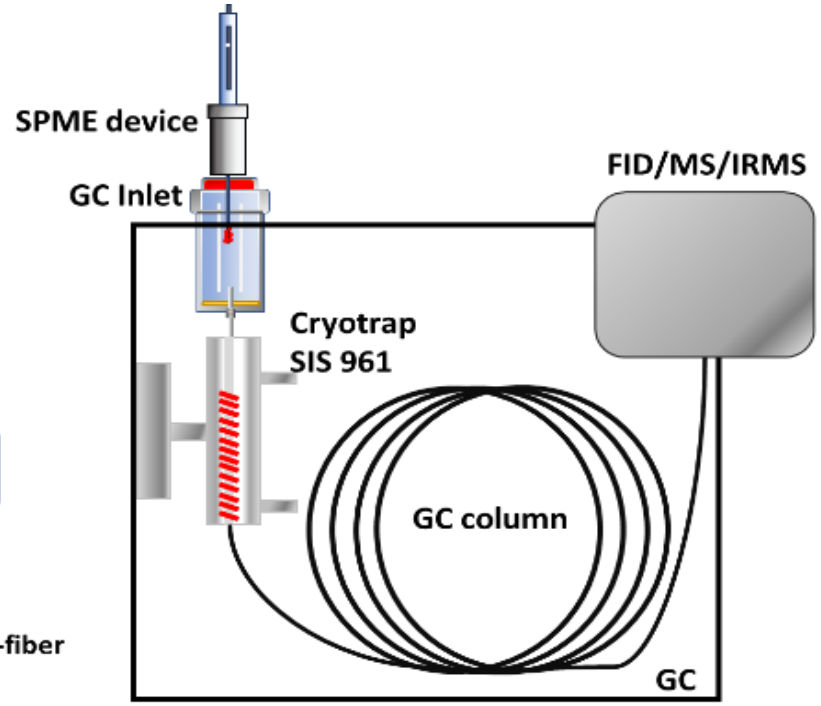


Amy Hofmann
(JPL)

Solid-phase microextraction of amines, NH_3 and analysis of hyper-volatiles (e.g., CH_3OH, alkanes)

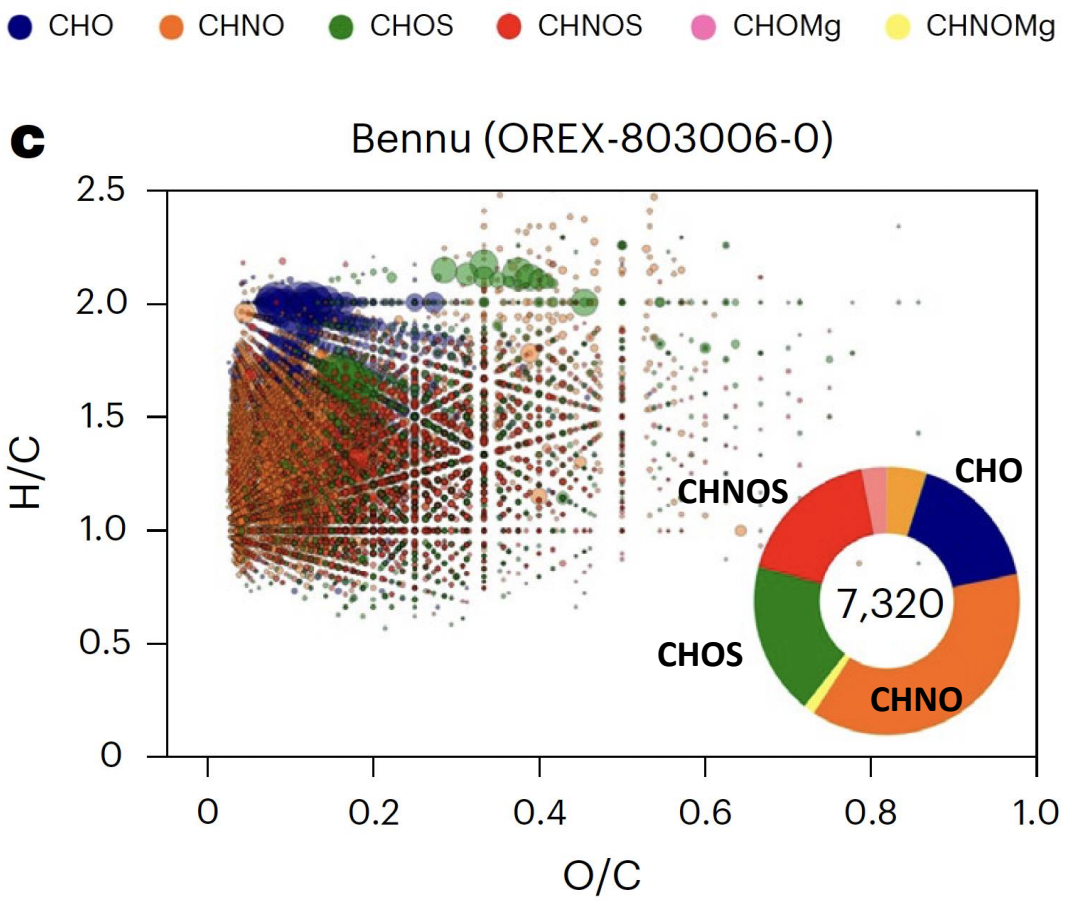


A) Direct SPME
B) Loading derivatizing reagent
C) Headspace SPME on-fiber derivatization

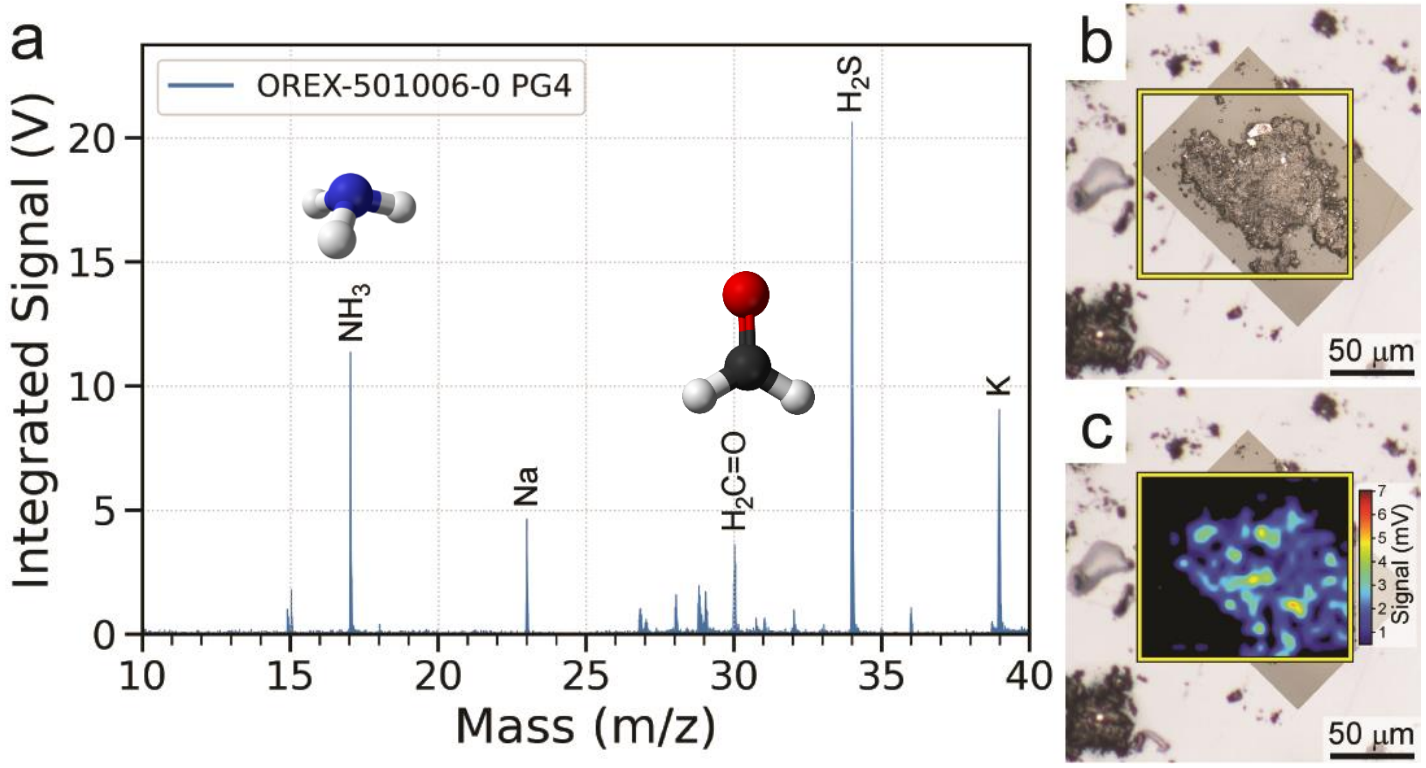


Yongsong Huang
(Brown Univ.)

N-rich and S-rich Chemistry of the SOM in Bennu



FTICR-MS data from P. Schmitt-Kopplin and M. Liss

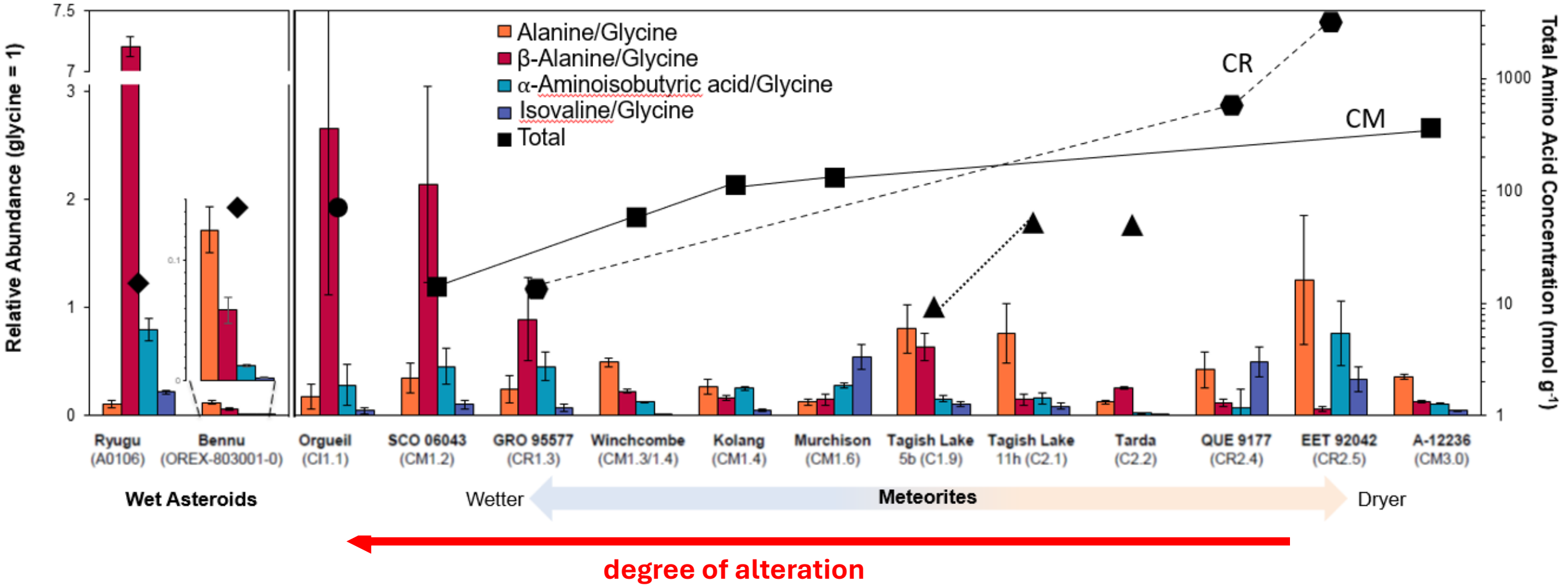


µ-L²MS data from S. Clemett

ammonia, formaldehyde: precursors of prebiotic organics

Glavin et al. (2025)

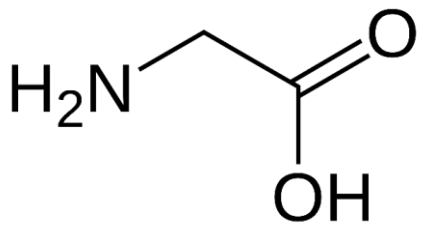
Tremendous diversity amongst 'primitive' extraterrestrial samples: Bennu is less altered than some



Diversity linked to varying alteration conditions (T, pH, etc.), nature (dry/aqueous) and/or heterogeneity of precursors?

Glavin et al. (2025)

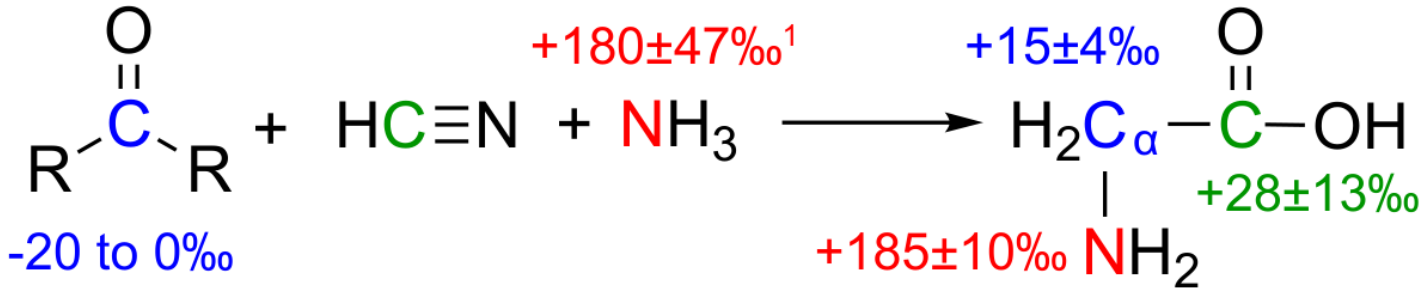
Isotopes reveal origins for glycine



Baczynski, **Ophelie McIntosh, Kate Freeman** et al.(PNAS, in review)

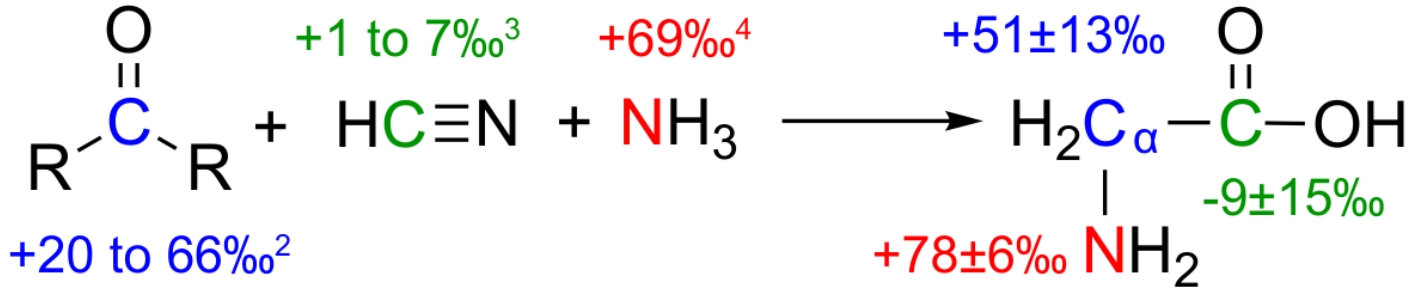
Bennu:
outer Solar System (Icy)

Bennu (OREX-800107-183)



Murchison:
planetary processes (wet)

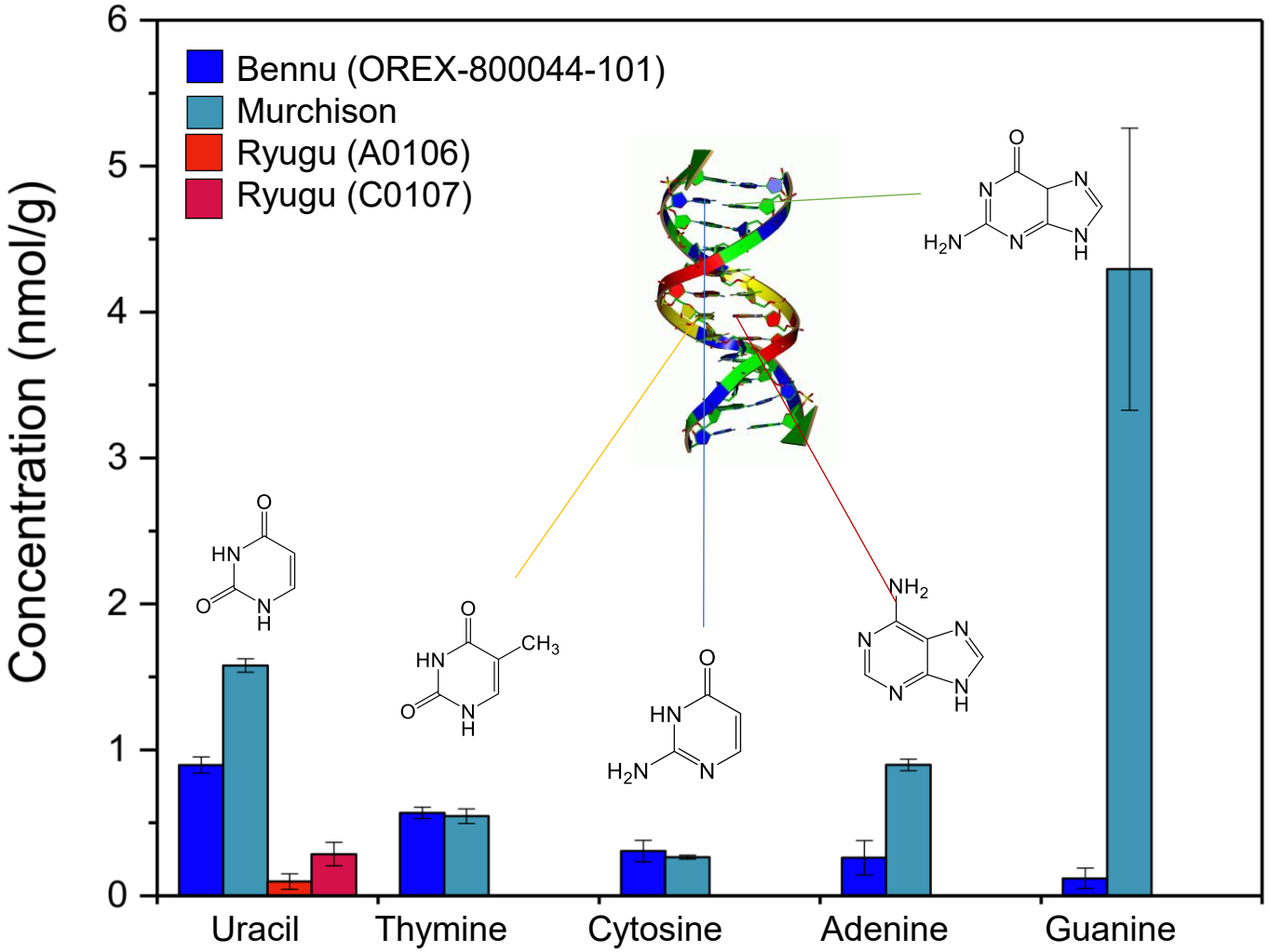
Murchison



[1]Glavin and Dworkin et al., 2025; [2]Simkus et al., 2019; [3]Pizzarello 2014; [4]Pizzarello et al., 1994

All 5 biological nucleobases found in Bennu

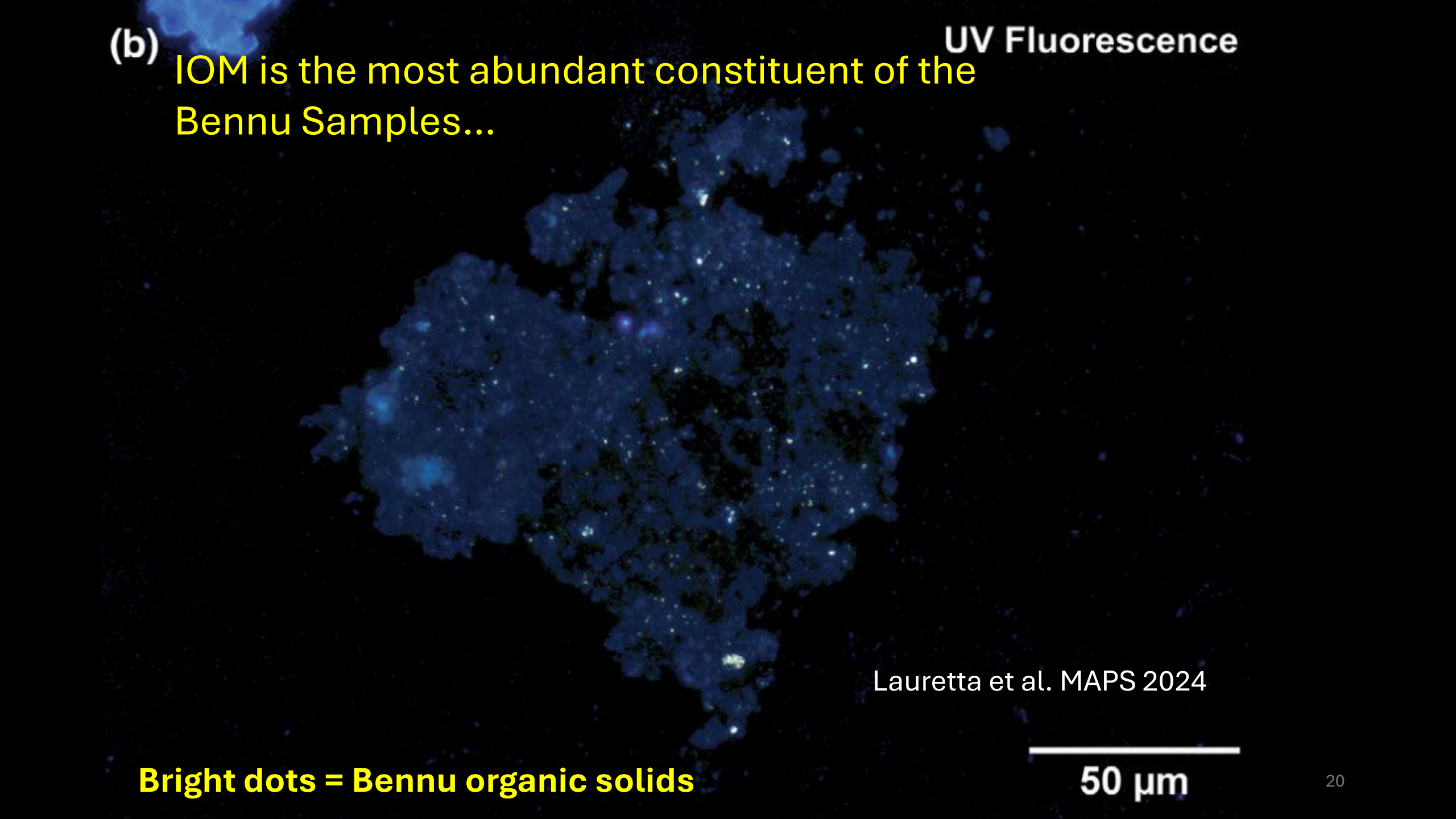
Koga et al. (2024), Oba et al. (2023), Glavin et al. (2025)



Murchison uracil $\delta^{13}C$=44.5±2.3‰ (Martins et al. 2008)

23 N-heterocycles that are crucial components of DNA and RNA found in Bennu with total concentration of ~5 nmol/g which is 5-10 x higher than in Ryugu but much less than in Murchison.

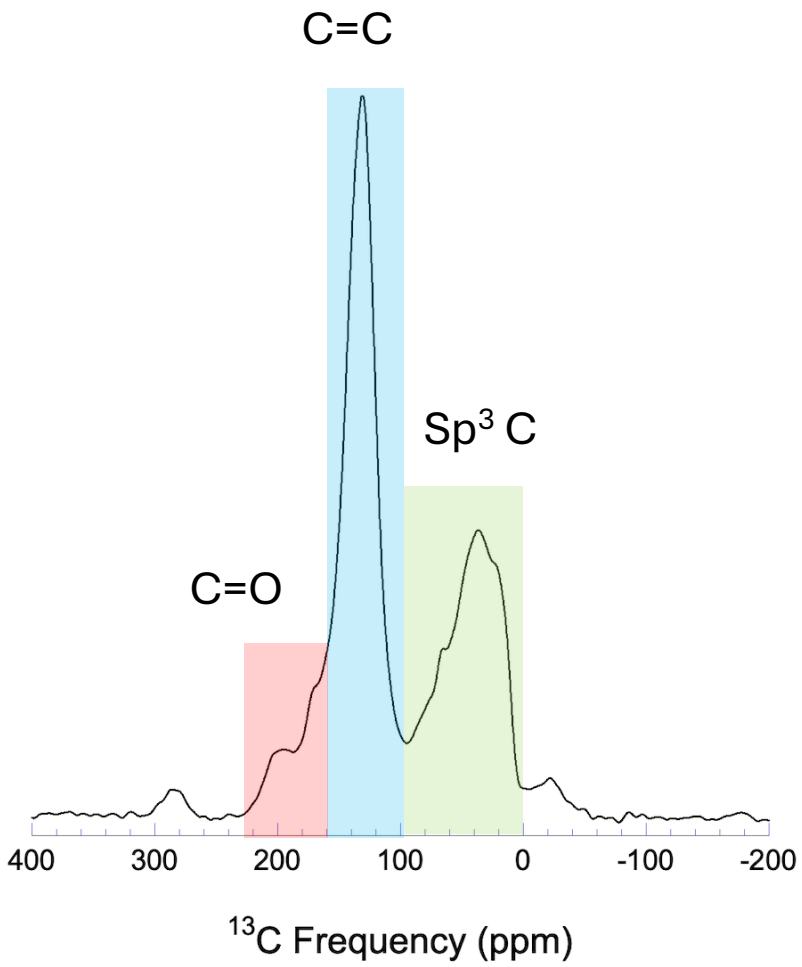
Elevated *pyrimidine:purine* ratio in Bennu (1.8) compared to Murchison (0.4) may be due to differences in parent body chemical compositions and/or alteration histories.


(b)
UV Fluorescence
IOM is the most abundant constituent of the Bennu Samples…
Lauretta et al. MAPS 2024
50 µm
Bright dots = Bennu organic solids

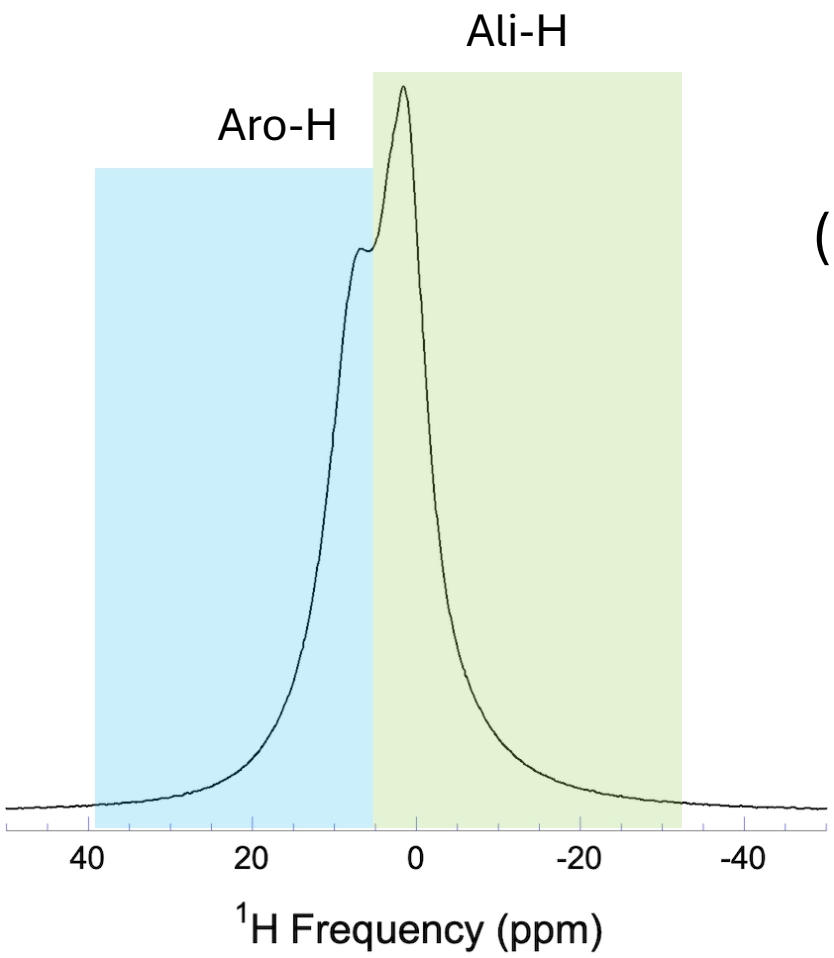
The Anatomy of IOM: Solid State ^{13}C & ^{1}H NMR

George Cody

^{13}C ssNMR



^{1}H ssNMR



Aliphatic Moieties

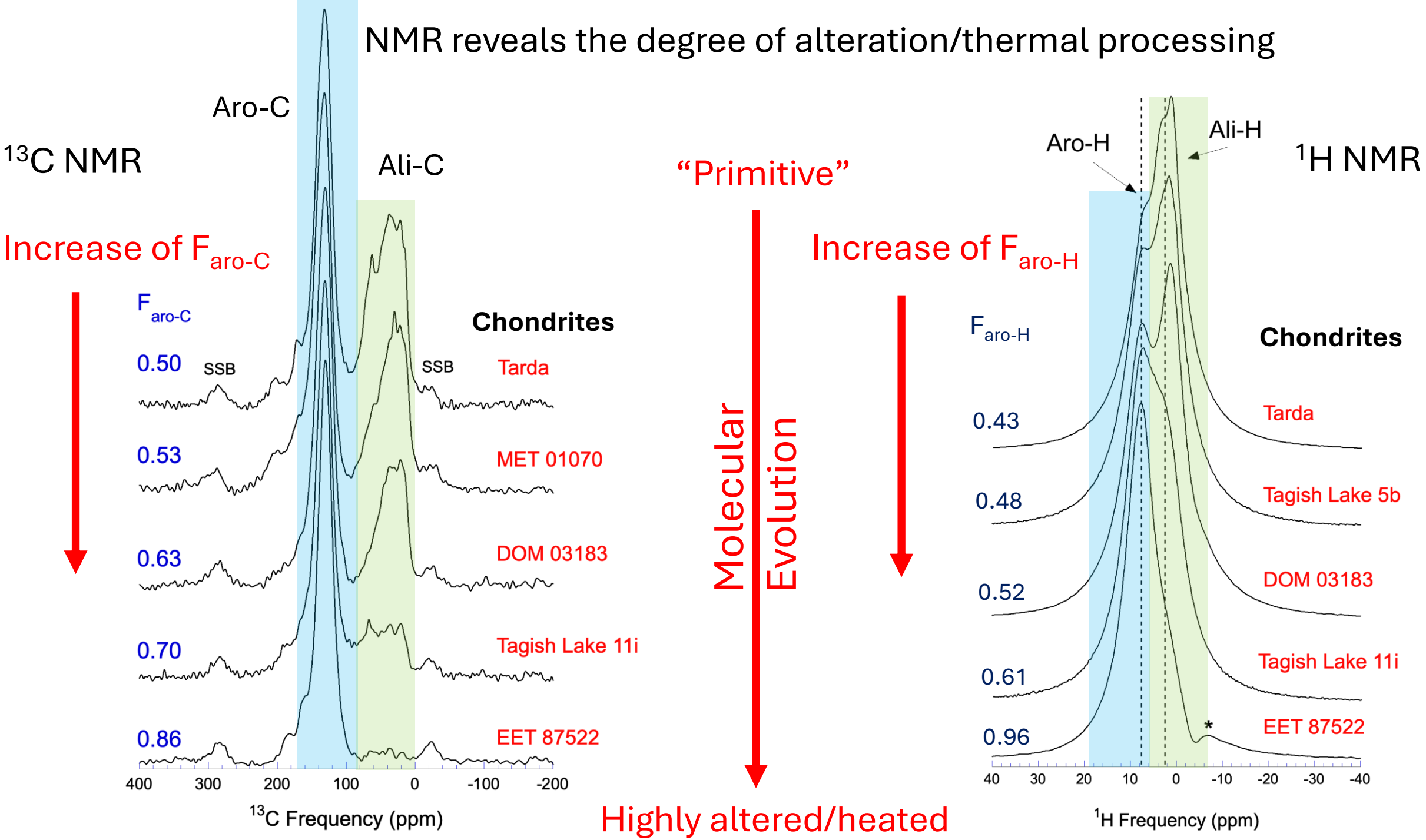
($-CH_3$; $-CH_2-$; $-CH$; $CH_{x=0-2}O$)

Aromatic Moieties

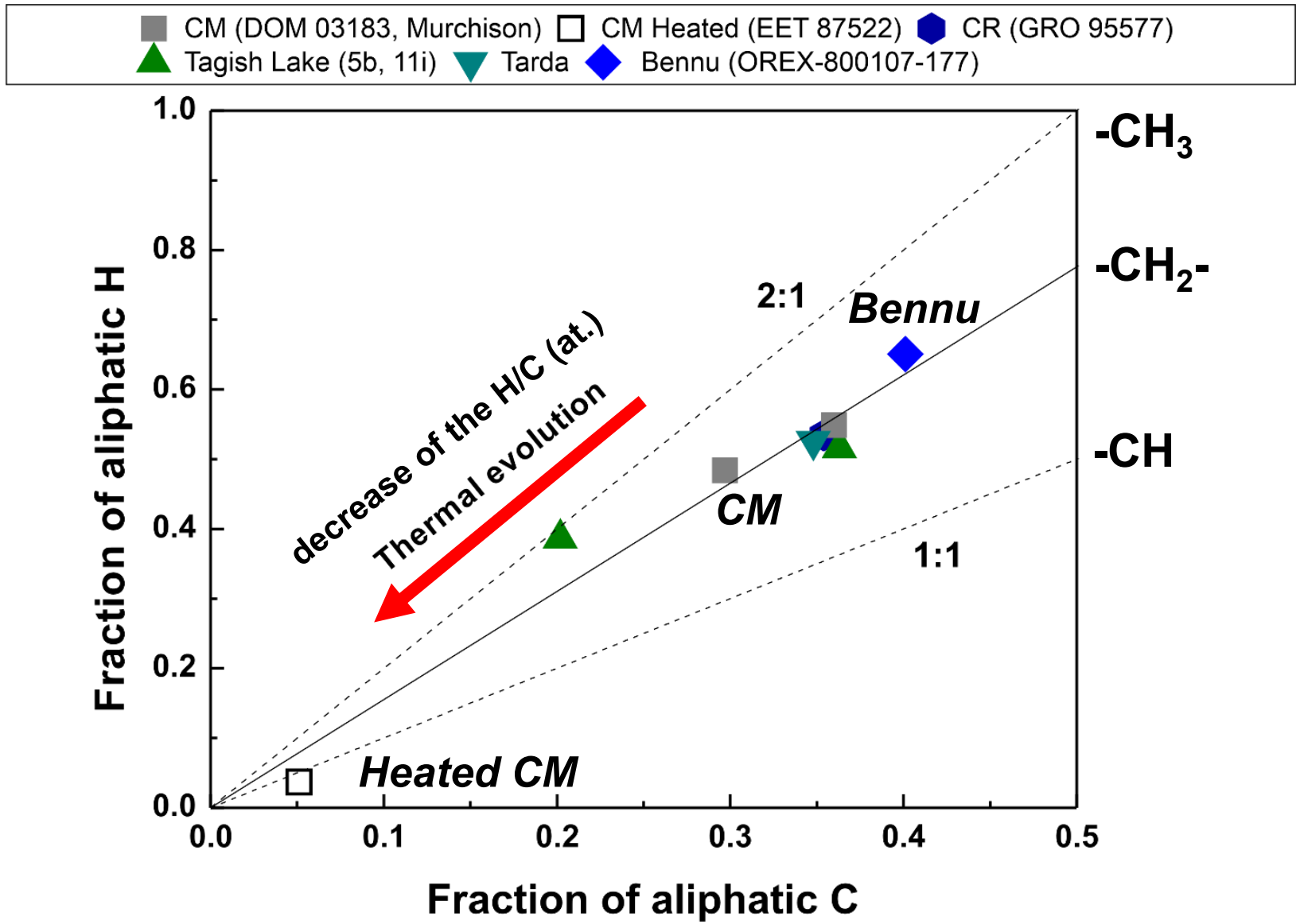
(C=C)

Fraction of Aromatic and Aliphatic C, H

NMR reveals the degree of alteration/thermal processing

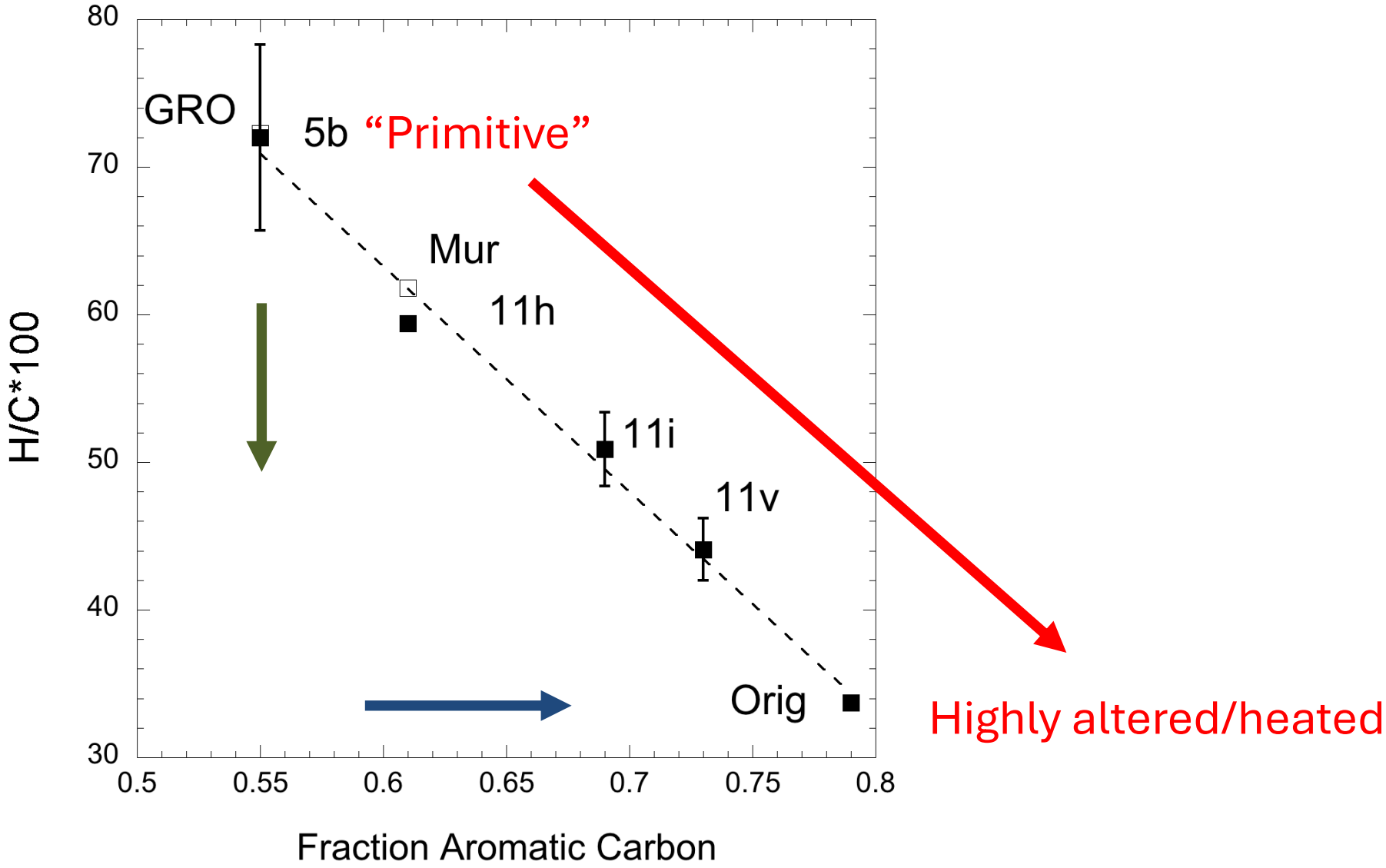


Loss of aliphatic C: -CH_2- functional groups



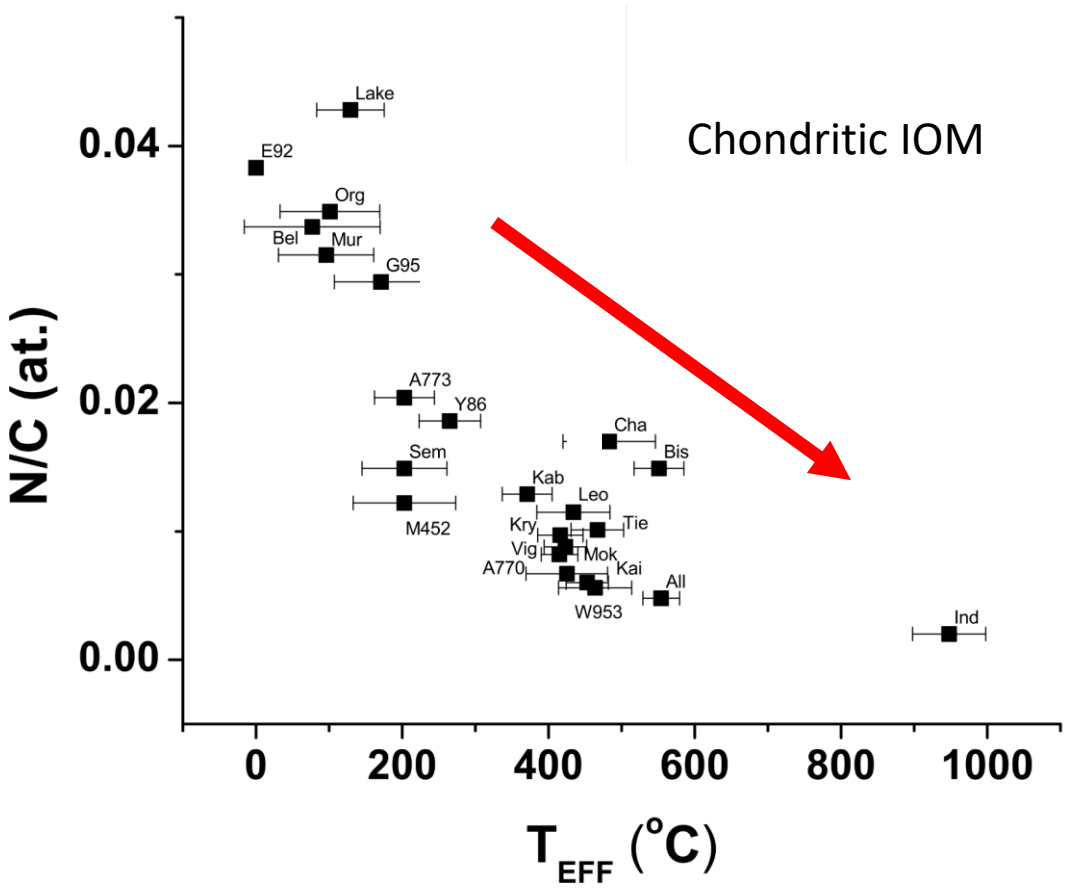
Foustoukos et al. (2025)

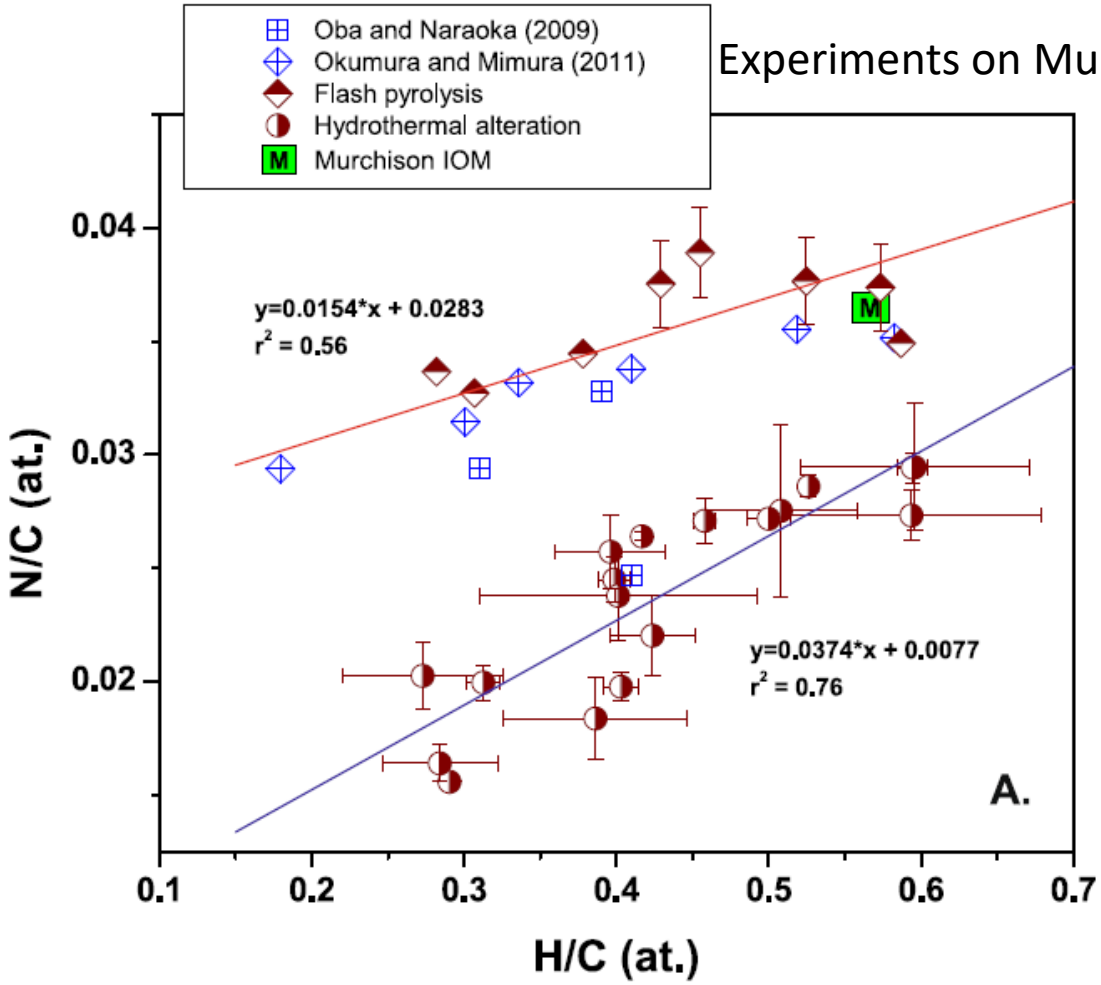
Molecular and Chemical Evolution: When aliphatic H is lost, the H/C (atomic) ratio decreases and the fraction of aromatic C increases.



Cody et al. (2023)

The effect of thermal alteration on the H, C and N elemental abundancies: N is more resistant (less labile) than H

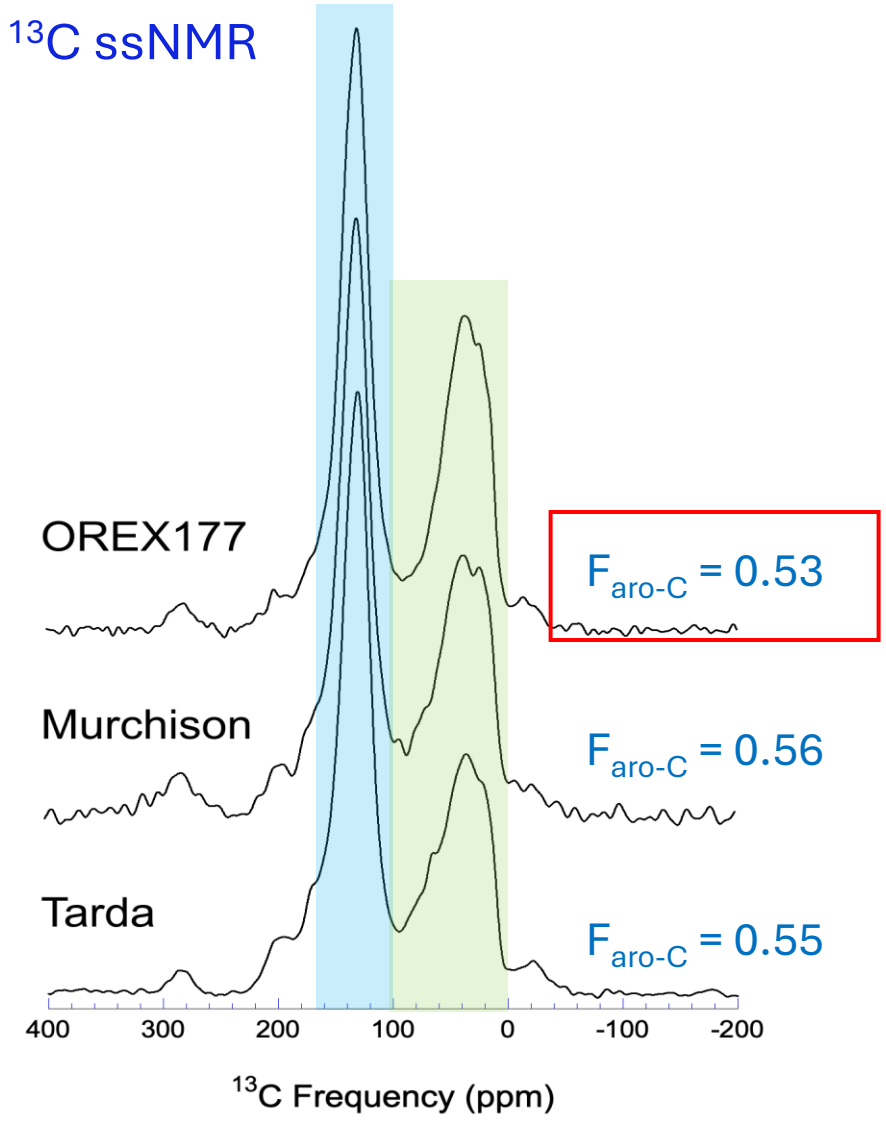


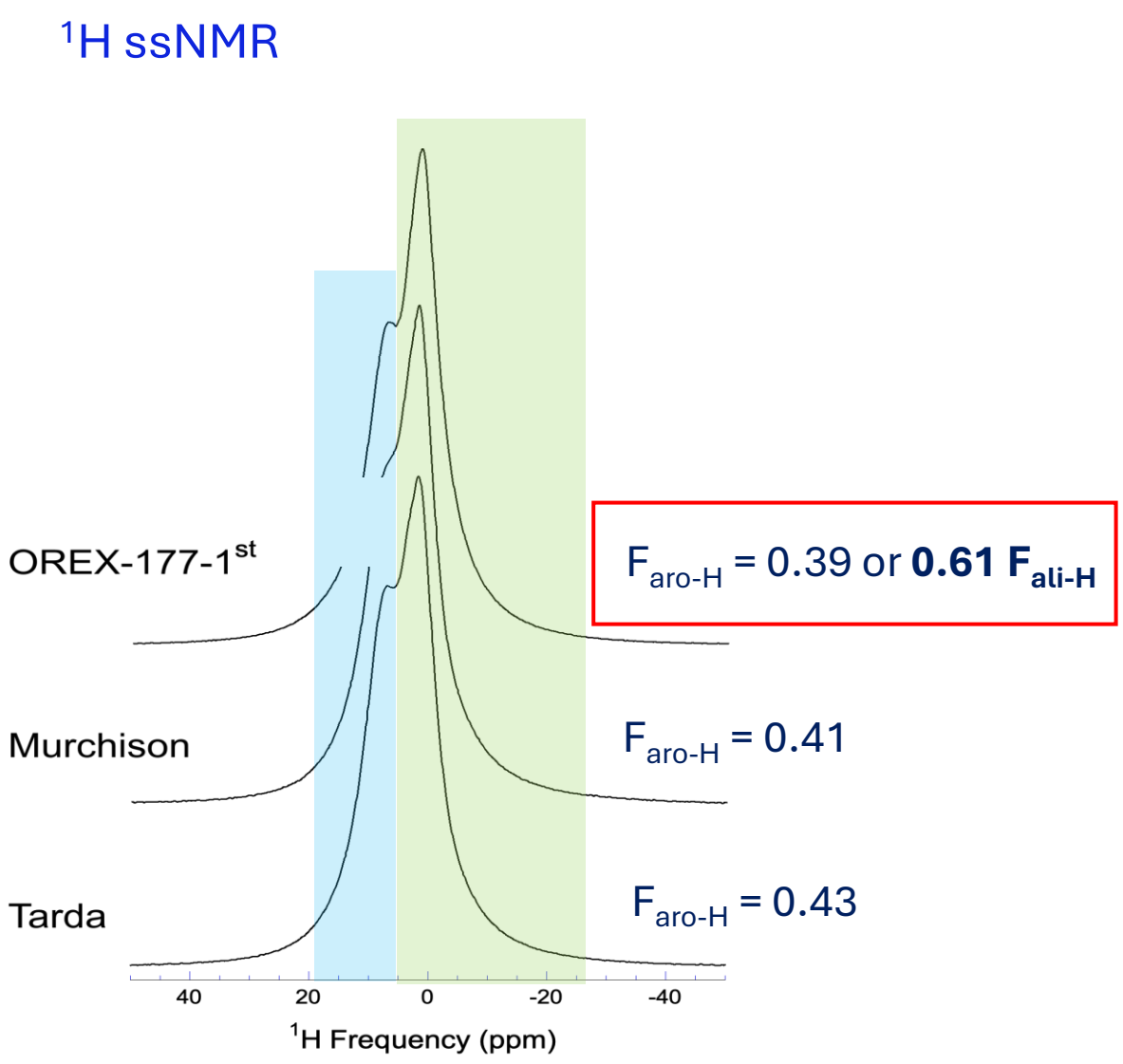


Alexander et al. (2007), Cody et al. (2008), Foustoukos et al. (2021)

N/C and H/C atomic ratios derived from the wt.% N, C and H

The molecular structure of Bennu's IOM reveals limited evolution

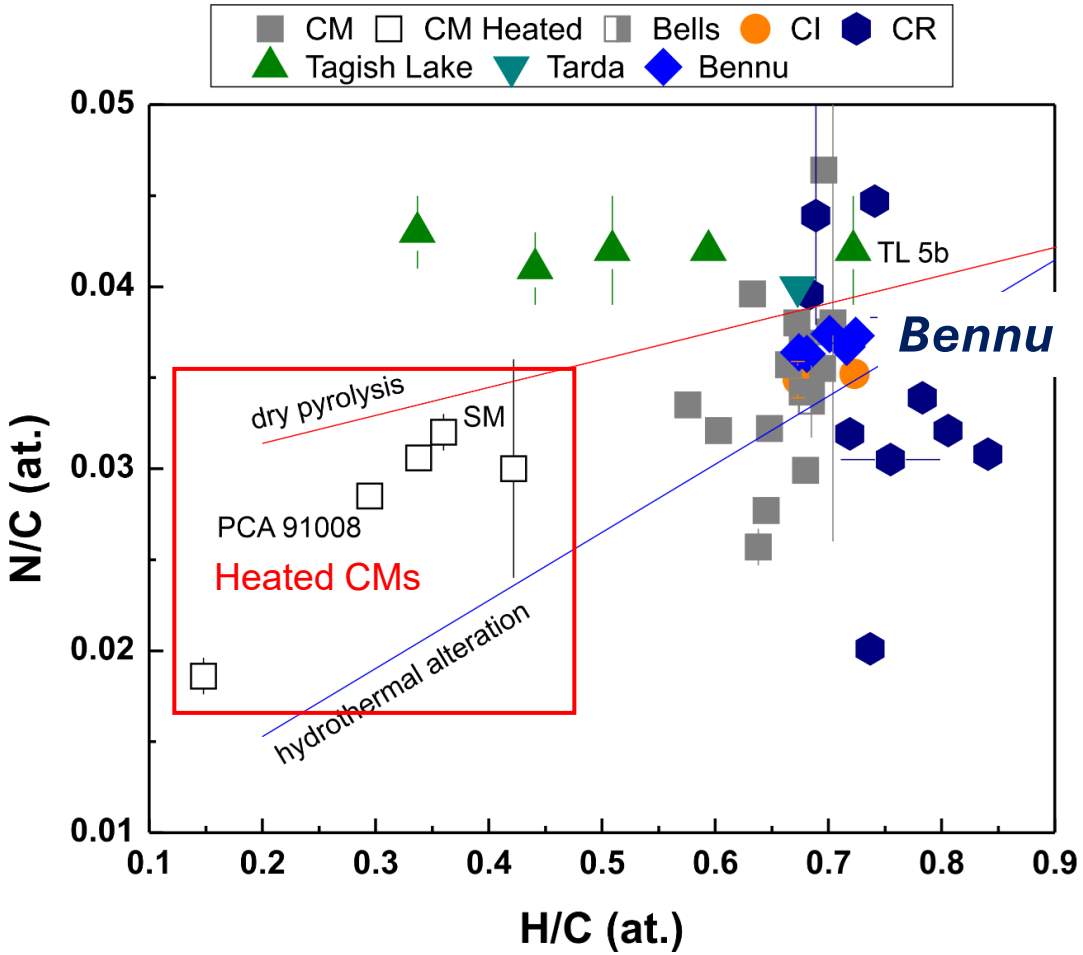




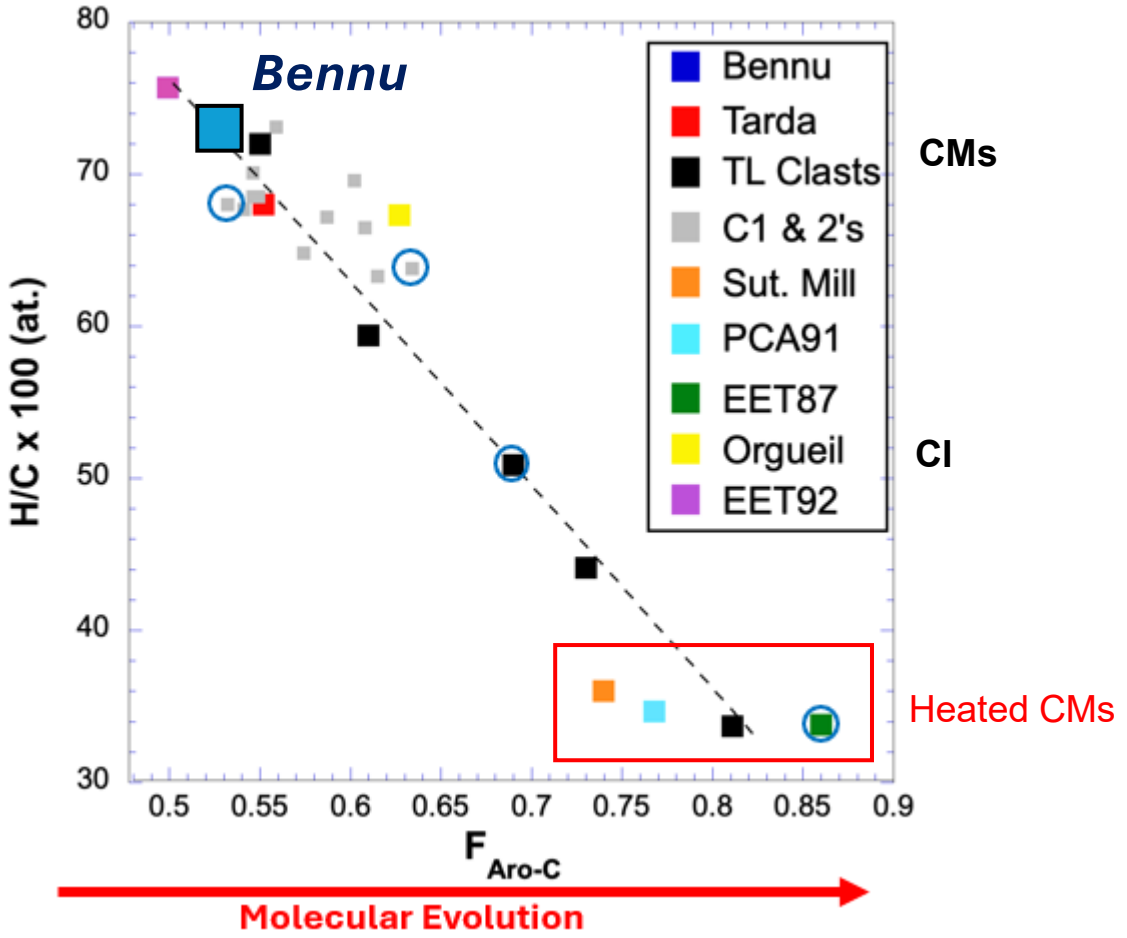
Cody et al. (2025)

Bennu IOM seems to be one of the least evolved

Low-degree thermal alteration (<400 °C – short thermal event?) similar to some of the pristine IOMs



Foustoukos et al. (2025)



Cody et al. (2025)

Evidence of D/H exchange between H_2O and Bennu IOM under aqueous-thermal conditions

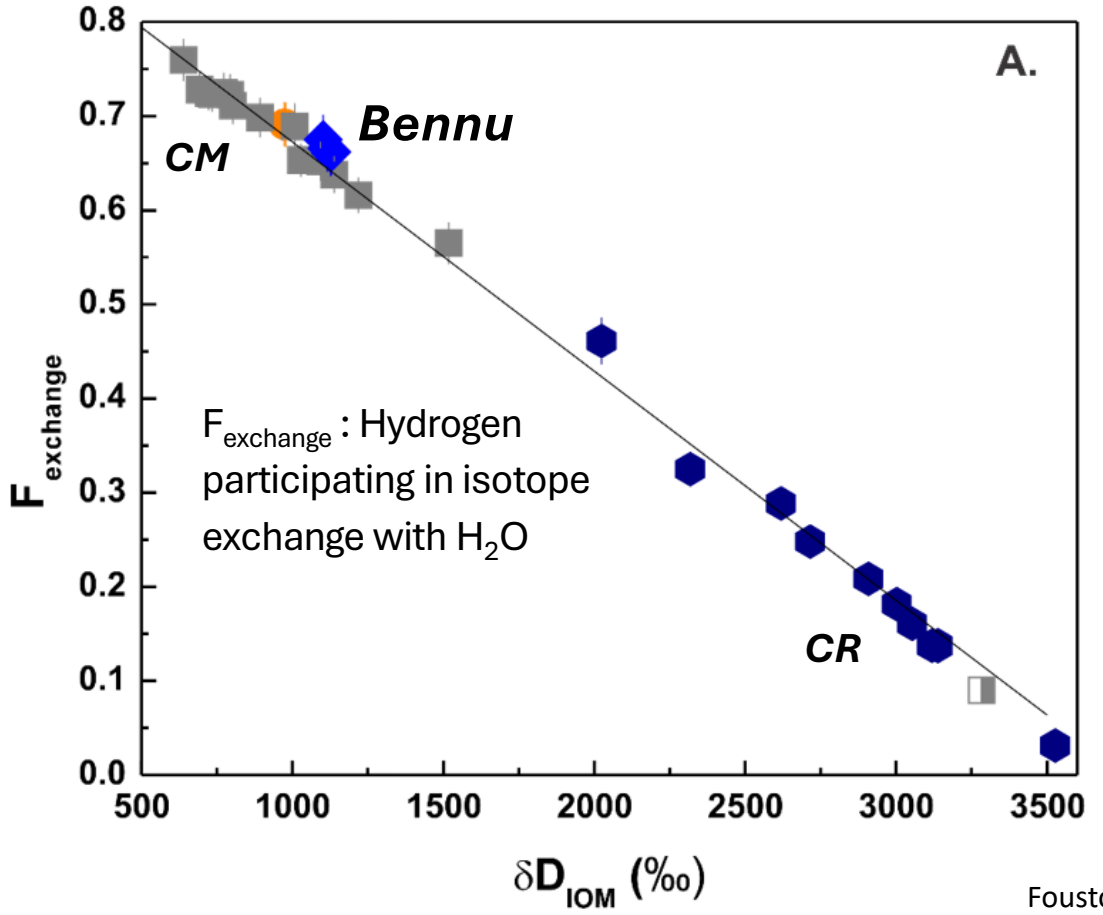
Precursor /primitive IOM
δD = ~ 3500 ‰

D/H isotope exchange

H_2O
δD = ~ -450 ‰

Chondritic IOM (CM, CI, Bennu?)
δD = ~ 500 - 1500 ‰

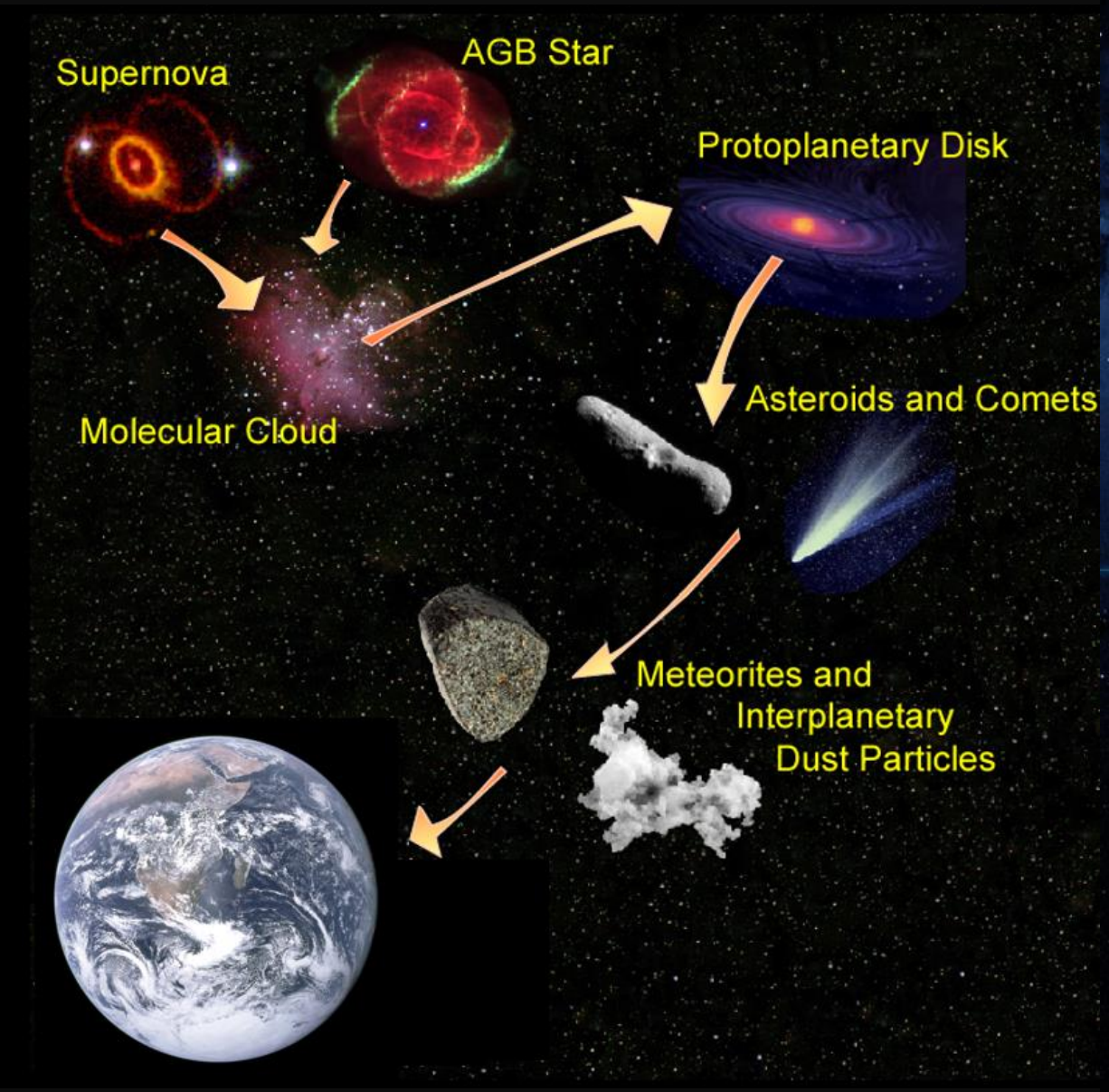
Alexander et al. (2012)

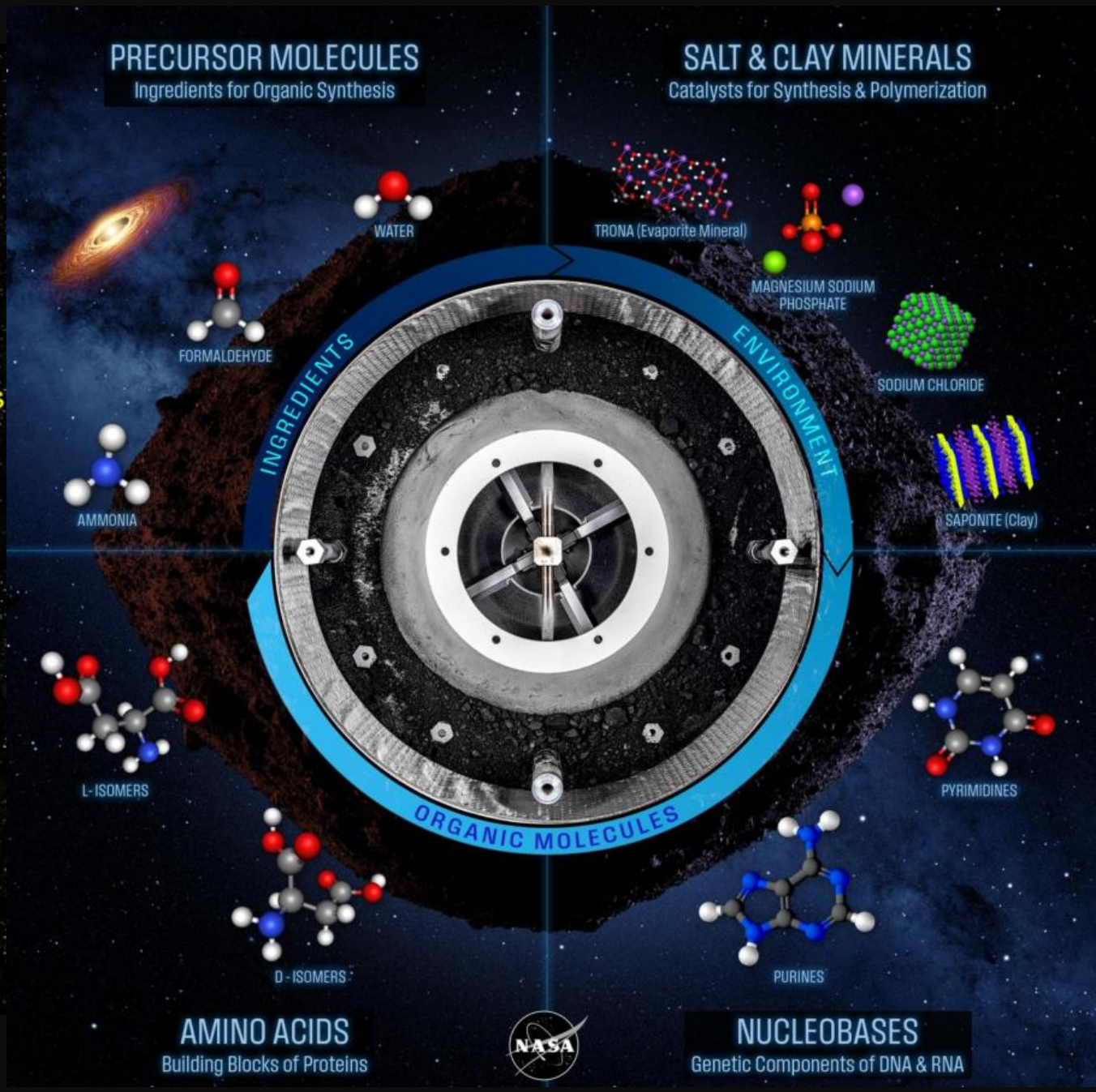


Foustoukos et al. (2021, 2025)

H isotope systematics: $F_{exchange}$ ~ 0.65
Molecular structure: $F_{ali\text{-}H}$ ~ 0.6

McCoy et al. (2015)


Supernova
AGB Star
Protoplanetary Disk
Molecular Cloud
Asteroids and Comets
Meteorites and
Interplanetary
Dust Particles


PRECURSOR MOLECULES
Ingredients for Organic Synthesis
SALT & CLAY MINERALS
Catalysts for Synthesis & Polymerization
WATER
TRONA (Evaporite Mineral)
MAGNESIUM SODIUM PHOSPHATE
FORMALDEHYDE
SODIUM CHLORIDE
INGREDIENTS
ENVIRONMENT
AMMONIA
SAPONITE (Clay)
L-ISOMERS
PYRIMIDINES
ORGANIC MOLECULES
D-ISOMERS
PURINES
AMINO ACIDS
Building Blocks of Proteins
NUCLEOBASES
Genetic Components of DNA & RNA