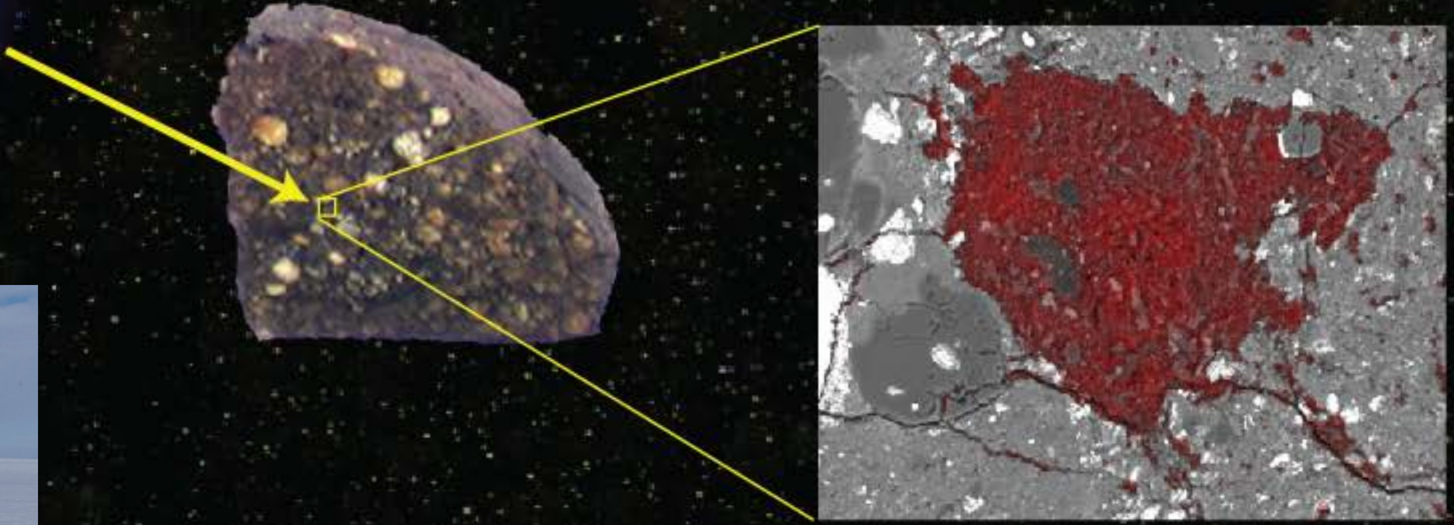
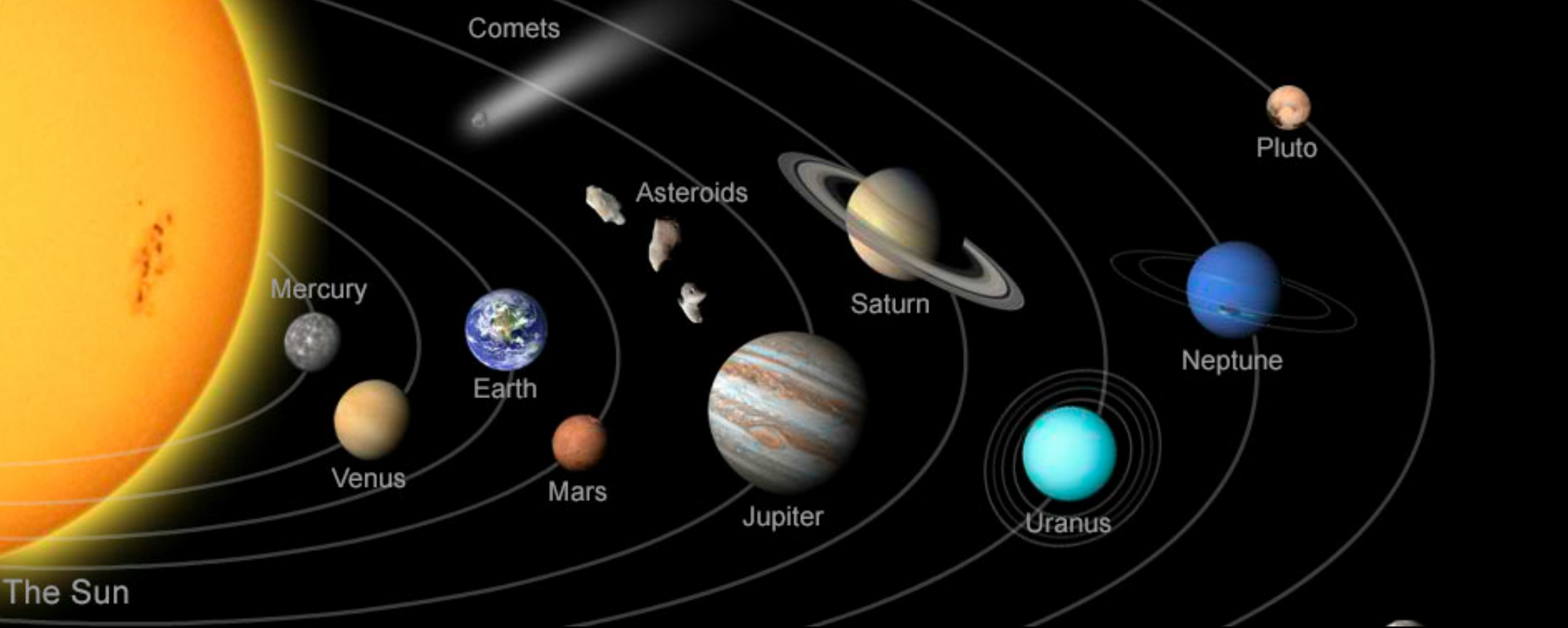
A cometary fossil inside an asteroidal meteorite



Rhonda Stroud **Naval Research Lab**

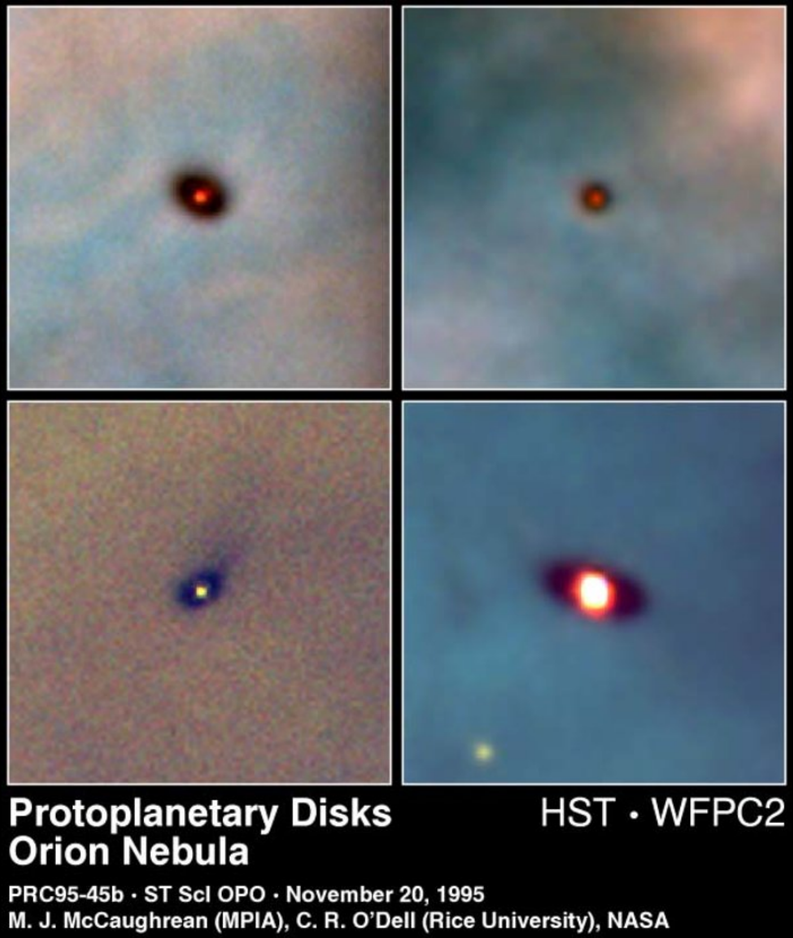
and Larry R. Nittler

Carnegie Institution of Washington

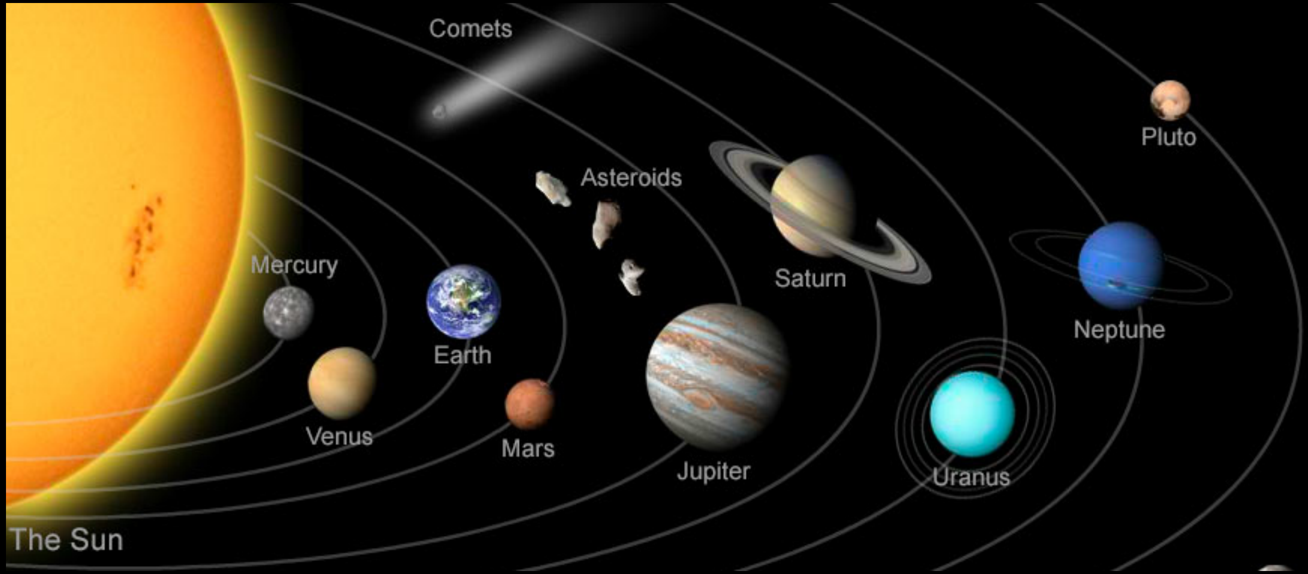


The Solar System today

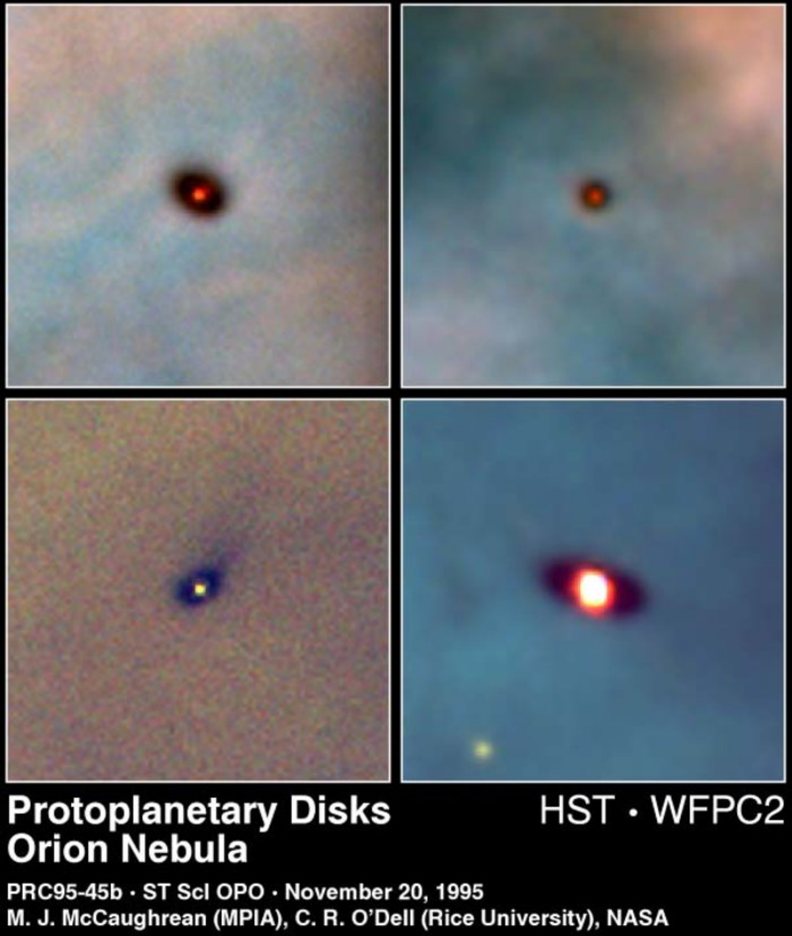
The Solar System 4.6 billion years ago

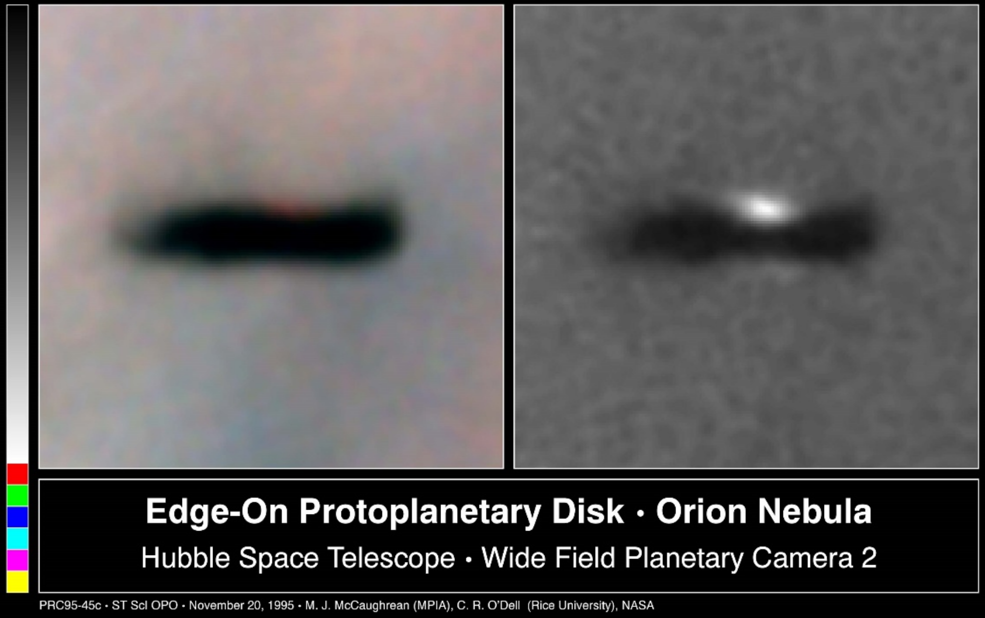


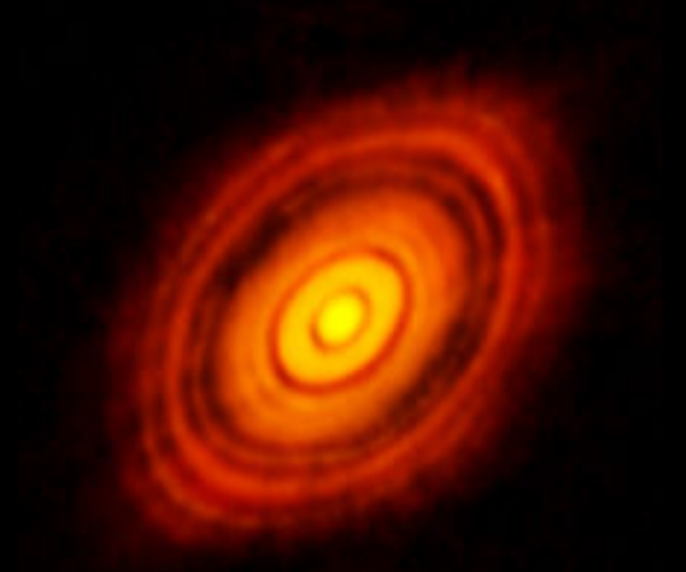
How did we get here?



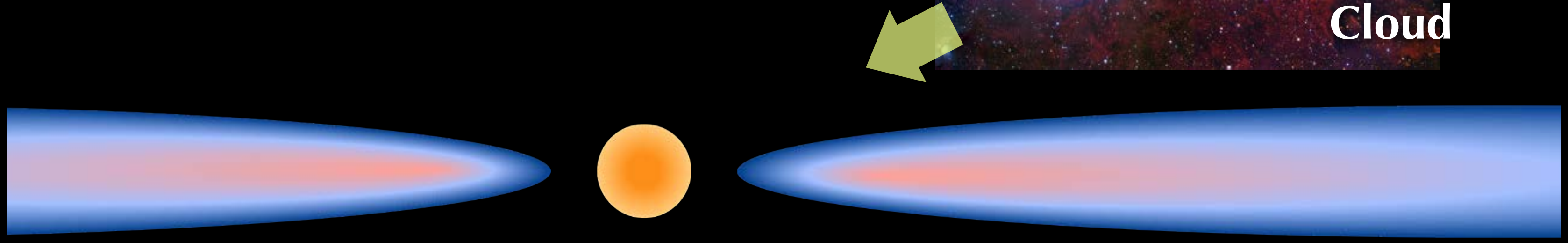
Planets are born in disks of gas and dust





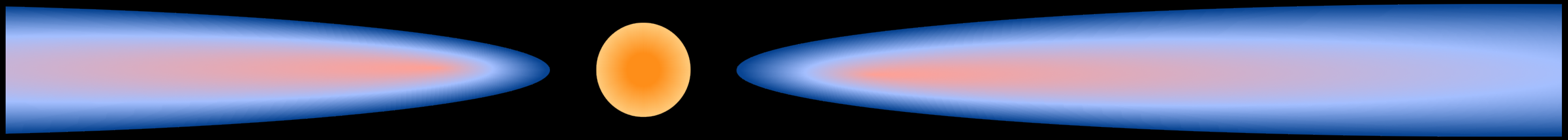


Solar System formation

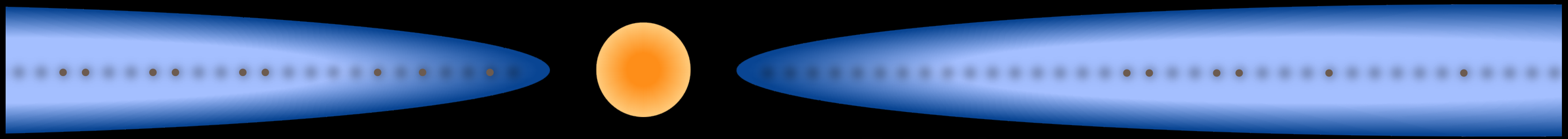


Solar System formation

Molecular Cloud

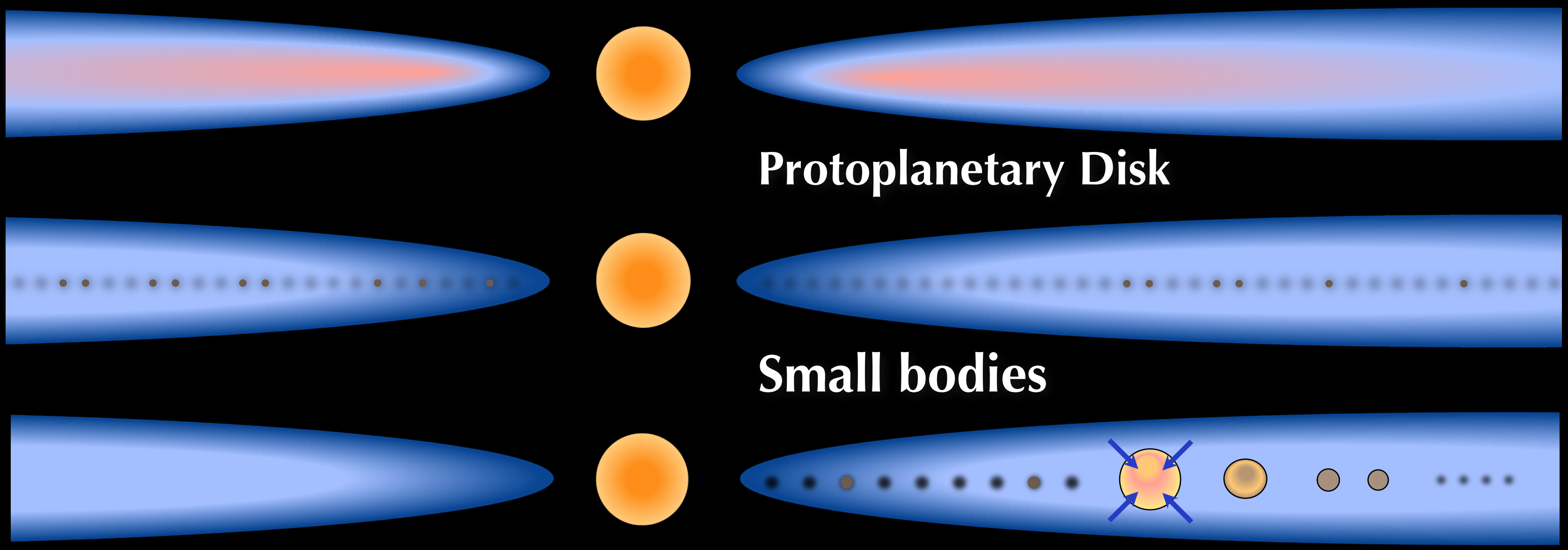


Protoplanetary Disk

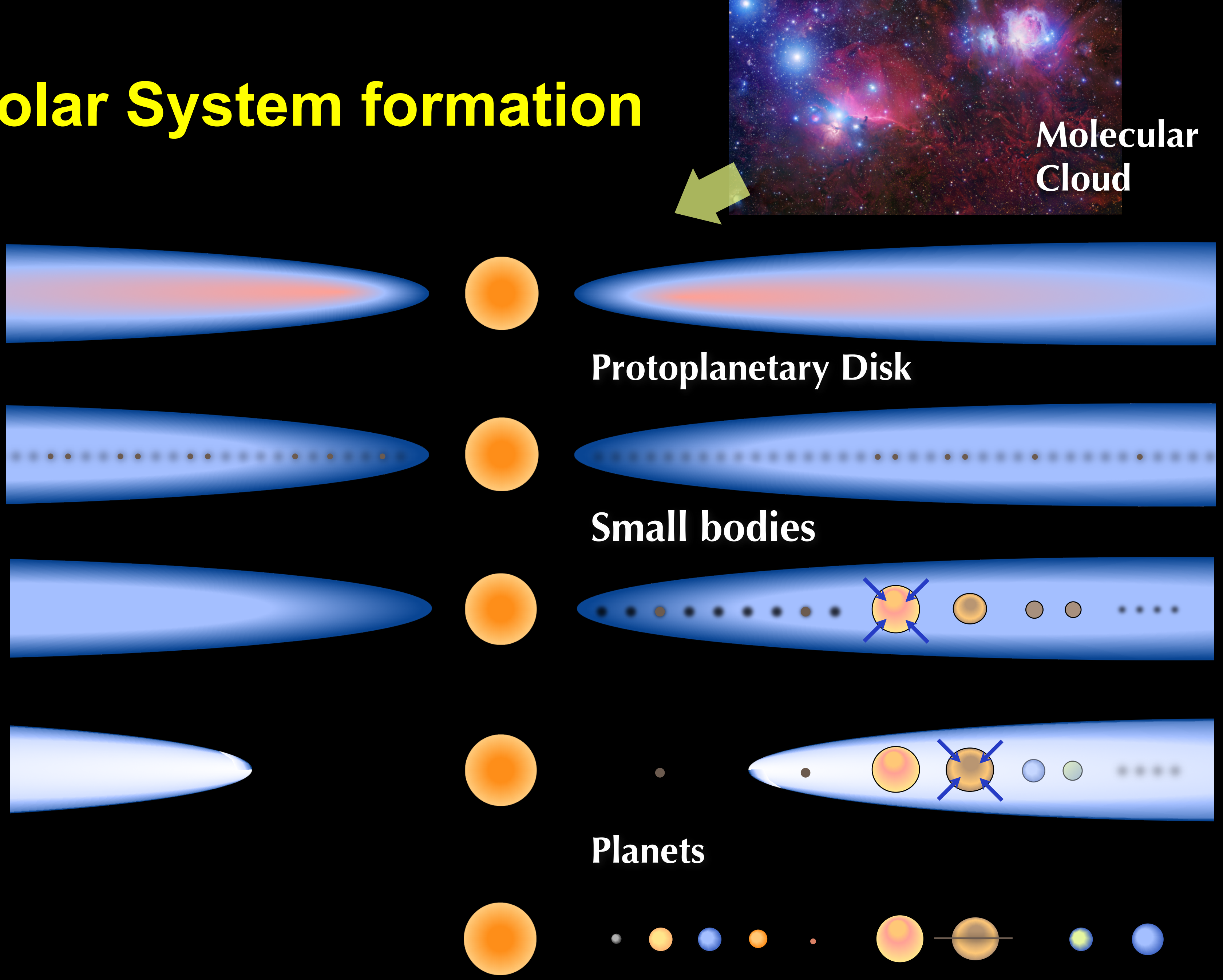


Small bodies

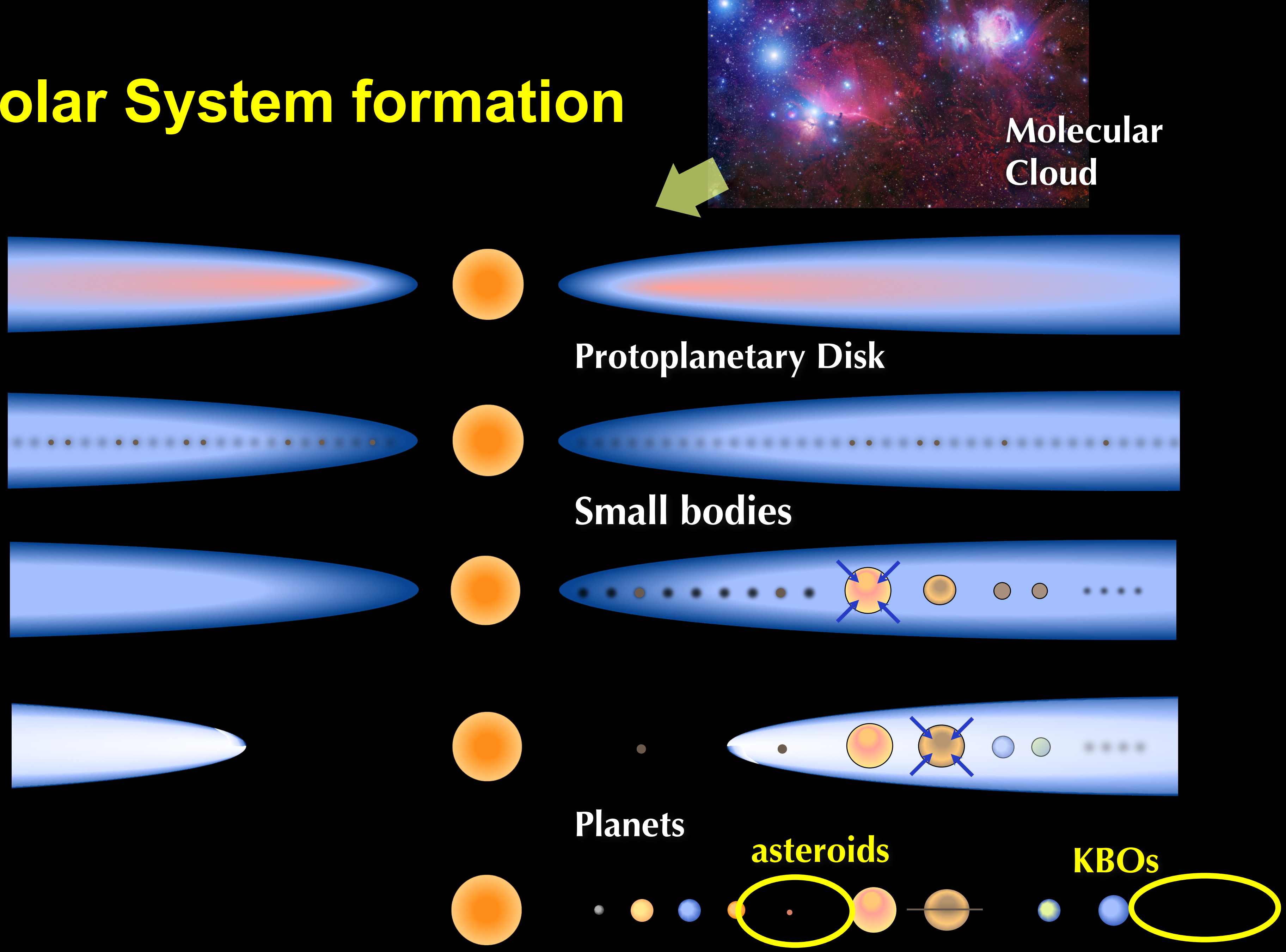
Solar System formation



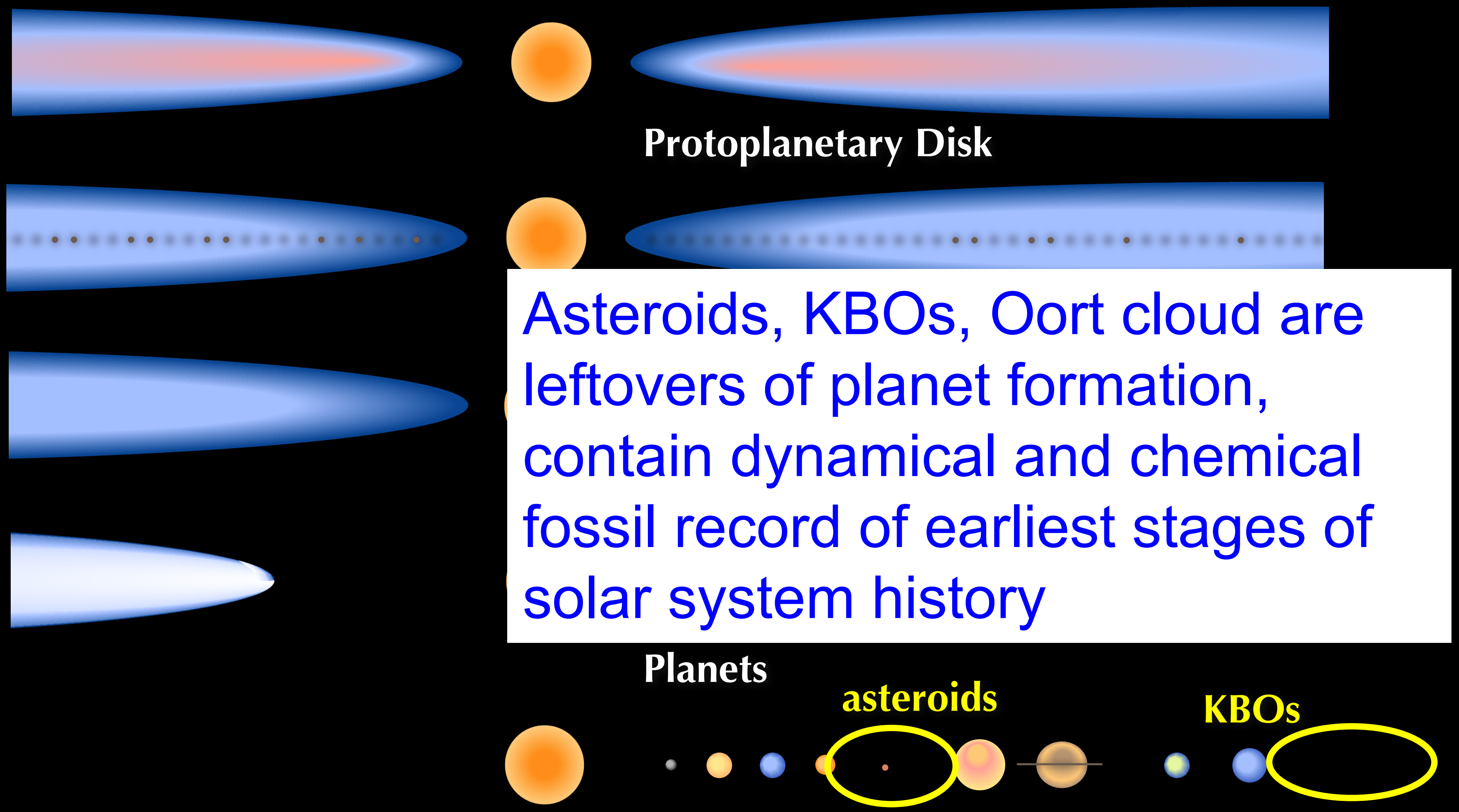
Solar System formation



Solar System formation

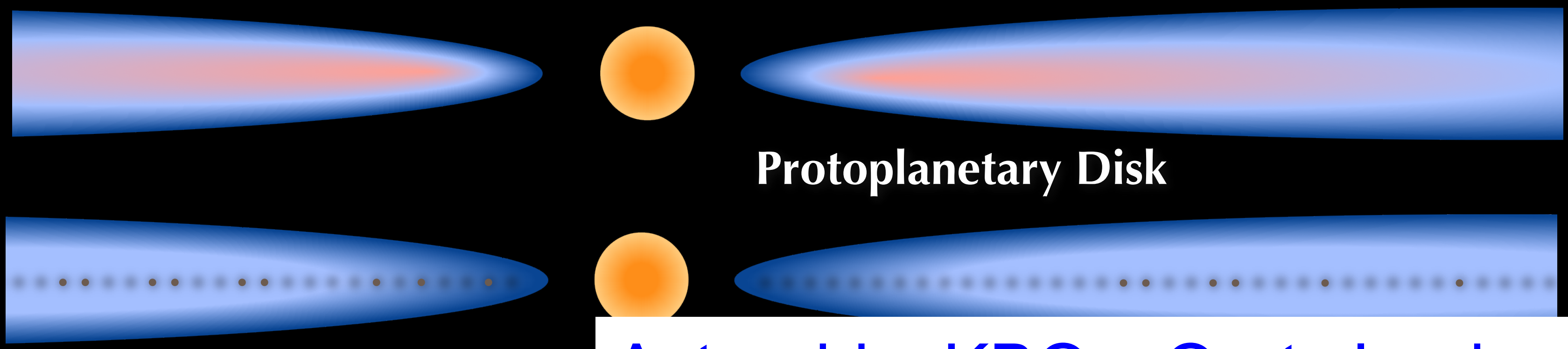


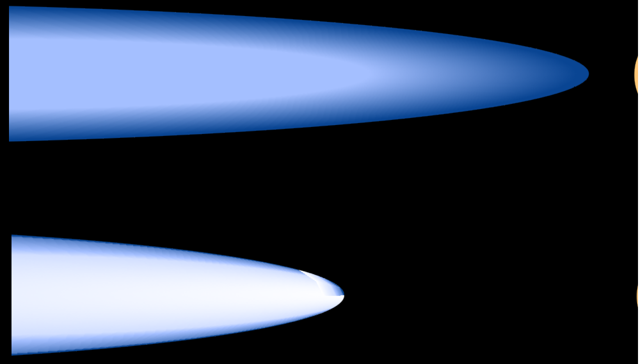
Solar System formation



Asteroids, KBOs, Oort cloud are leftovers of planet formation, contain dynamical and chemical fossil record of earliest stages of solar system history

Solar System formation

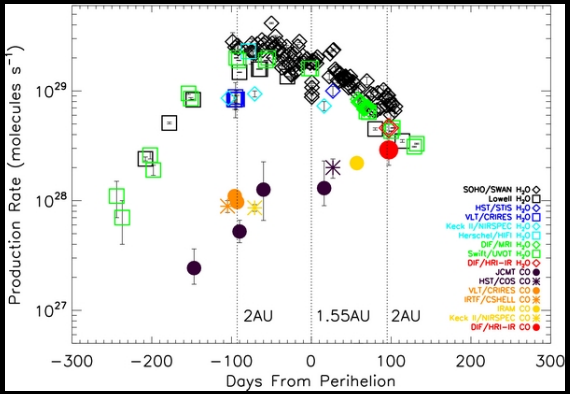


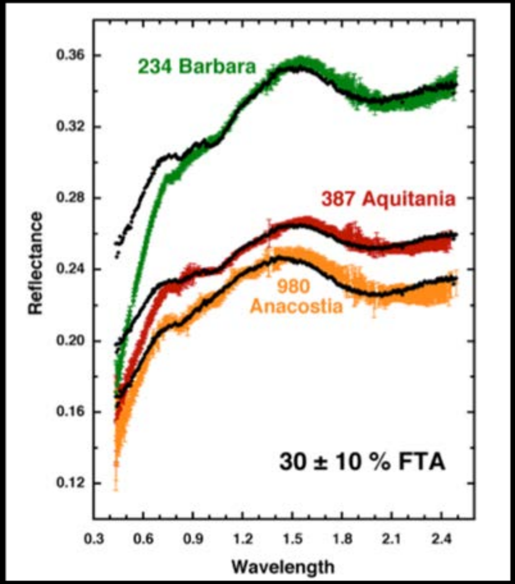


Asteroids, KBOs, Oort cloud are leftovers of planet formation, contain dynamical and chemical fossil record of earliest stages of solar system history

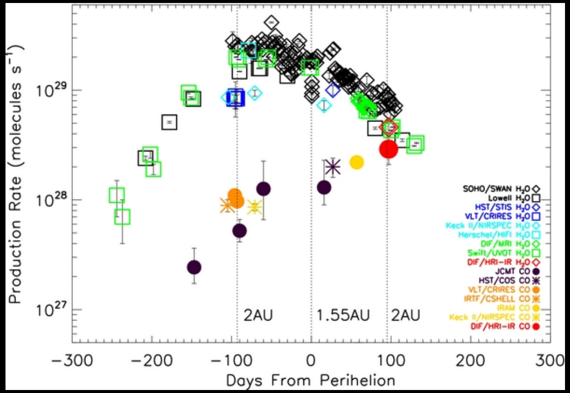
How can we study them?

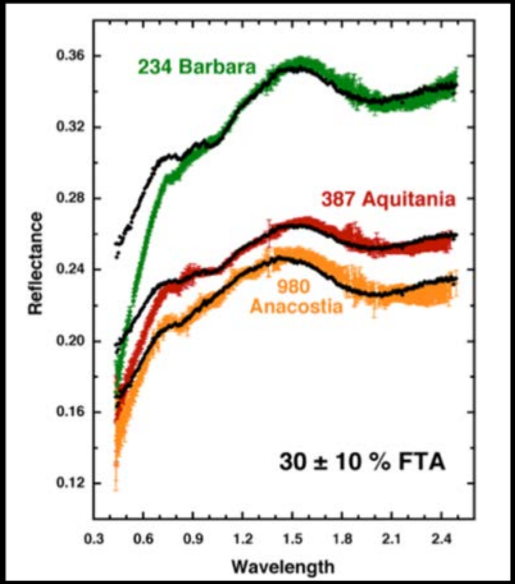
Astronomical Observations



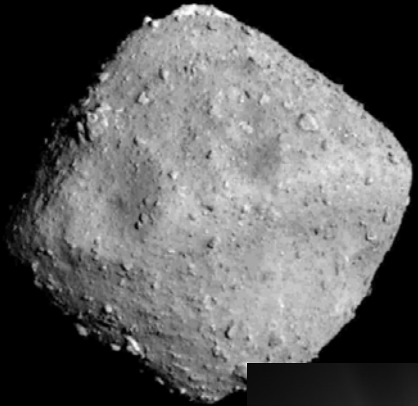


Astronomical Observations



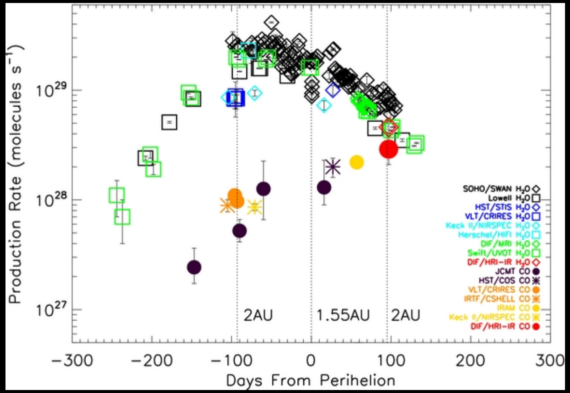


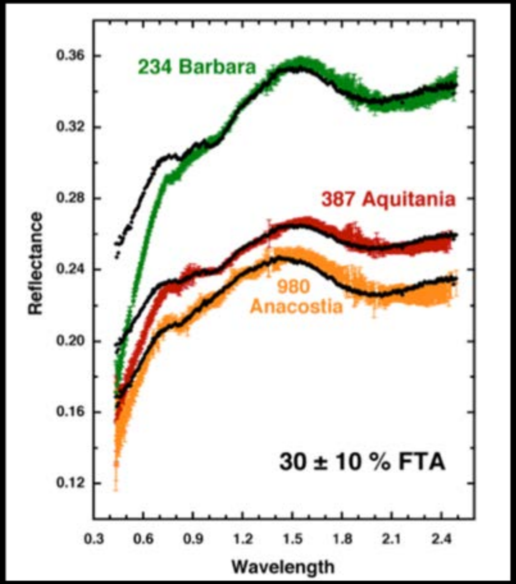
Spacecraft Observations



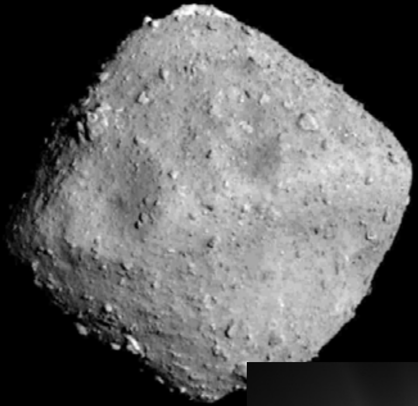
NASA/JHUAPL/SwRI/Thomas Appéré

Astronomical Observations



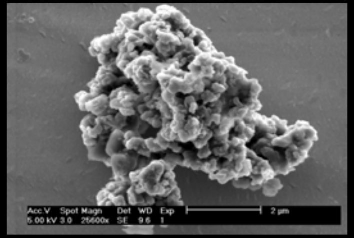


Spacecraft Observations

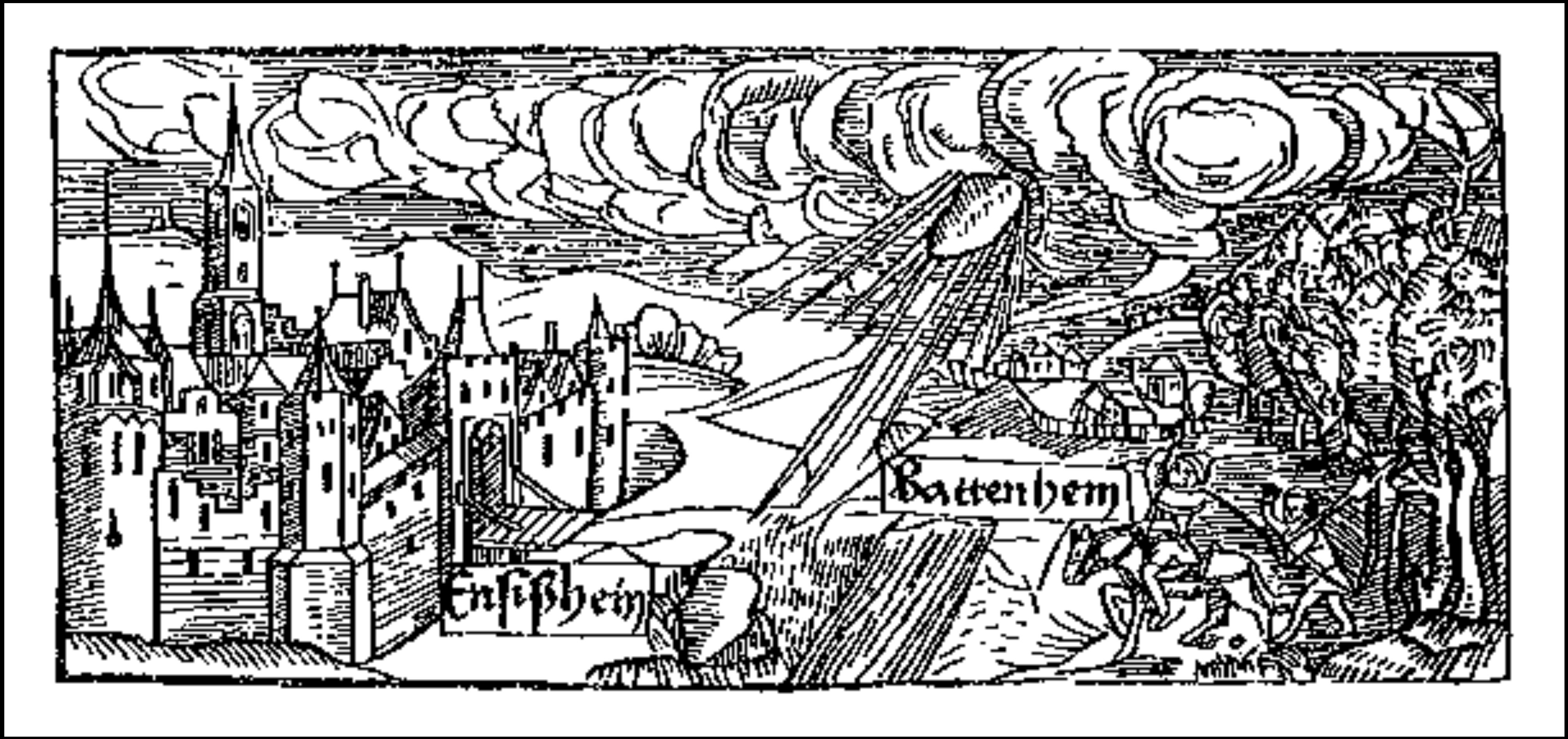


NASA/JHUAPL/SwRI/Thomas Appéré

Laboratory analysis of extraterrestrial samples



Meteorites (Rocks from Space!)



Ensisheim meteorite, France, November 7, 1492

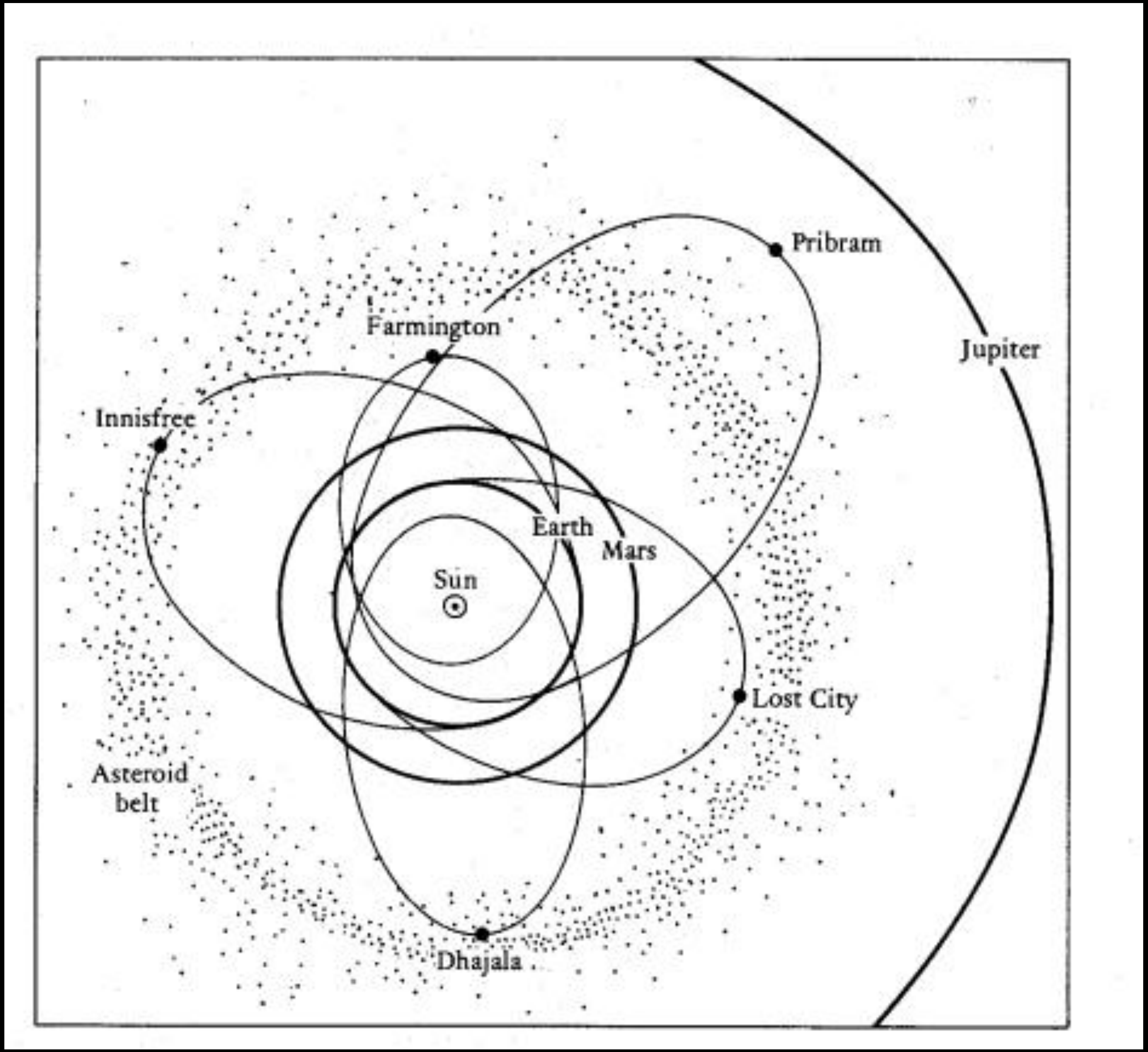
Peekskill meteorite

New York, October 9, 1992

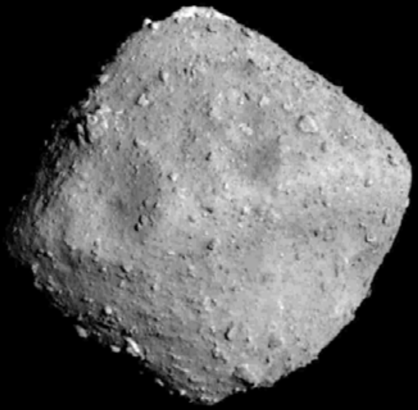
Where are they found?

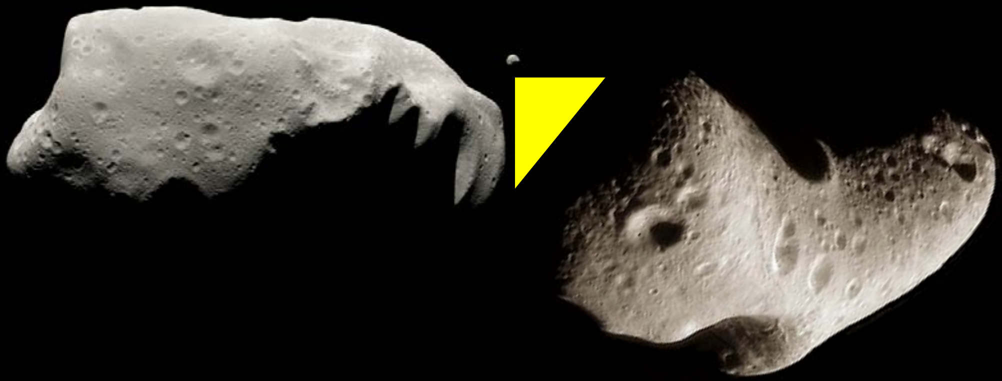
- All over the Earth, but deserts best due to long lifetimes against weathering

Where are they from?



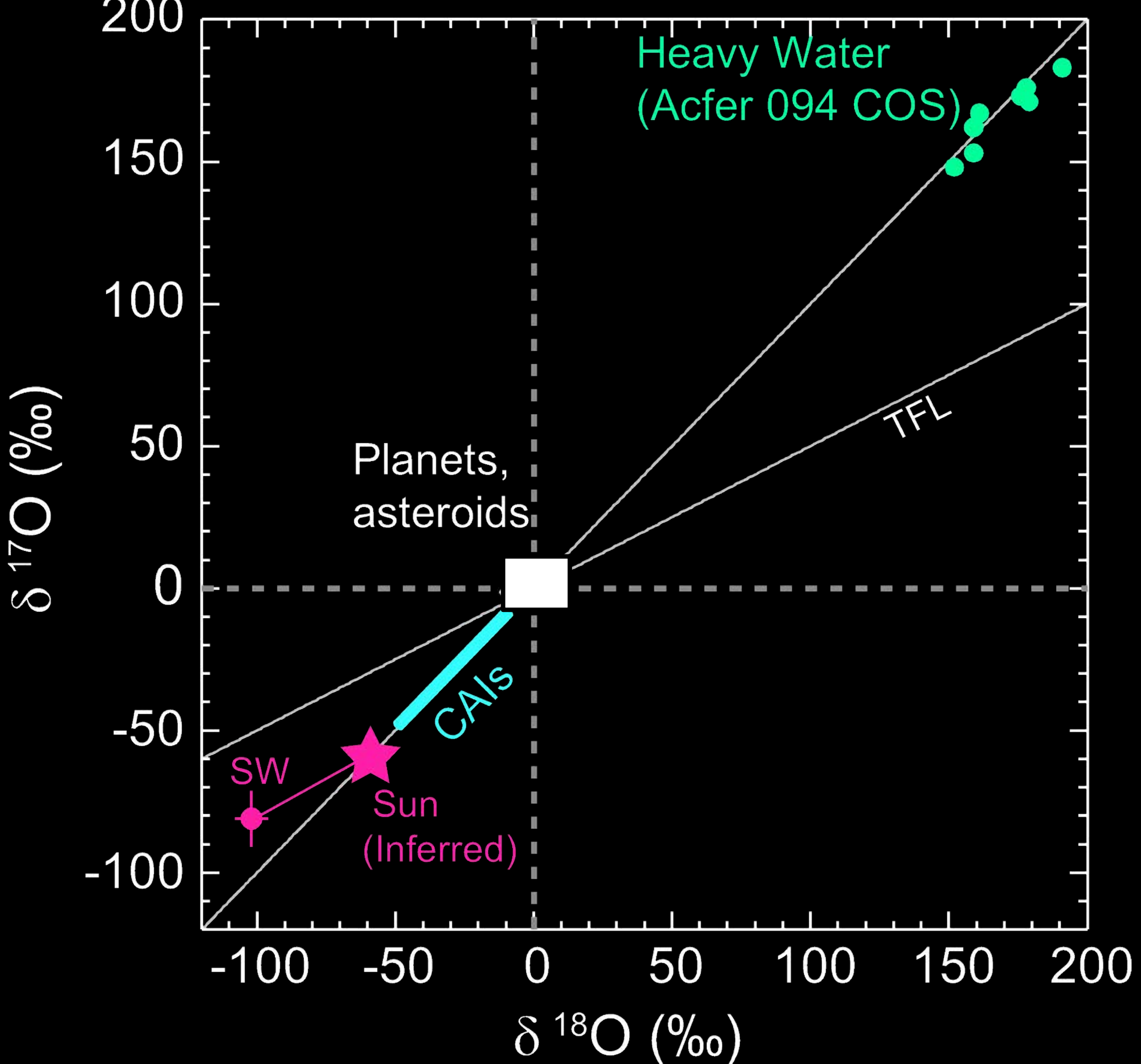
Asteroids!





Recorders of first few million years (Ma)

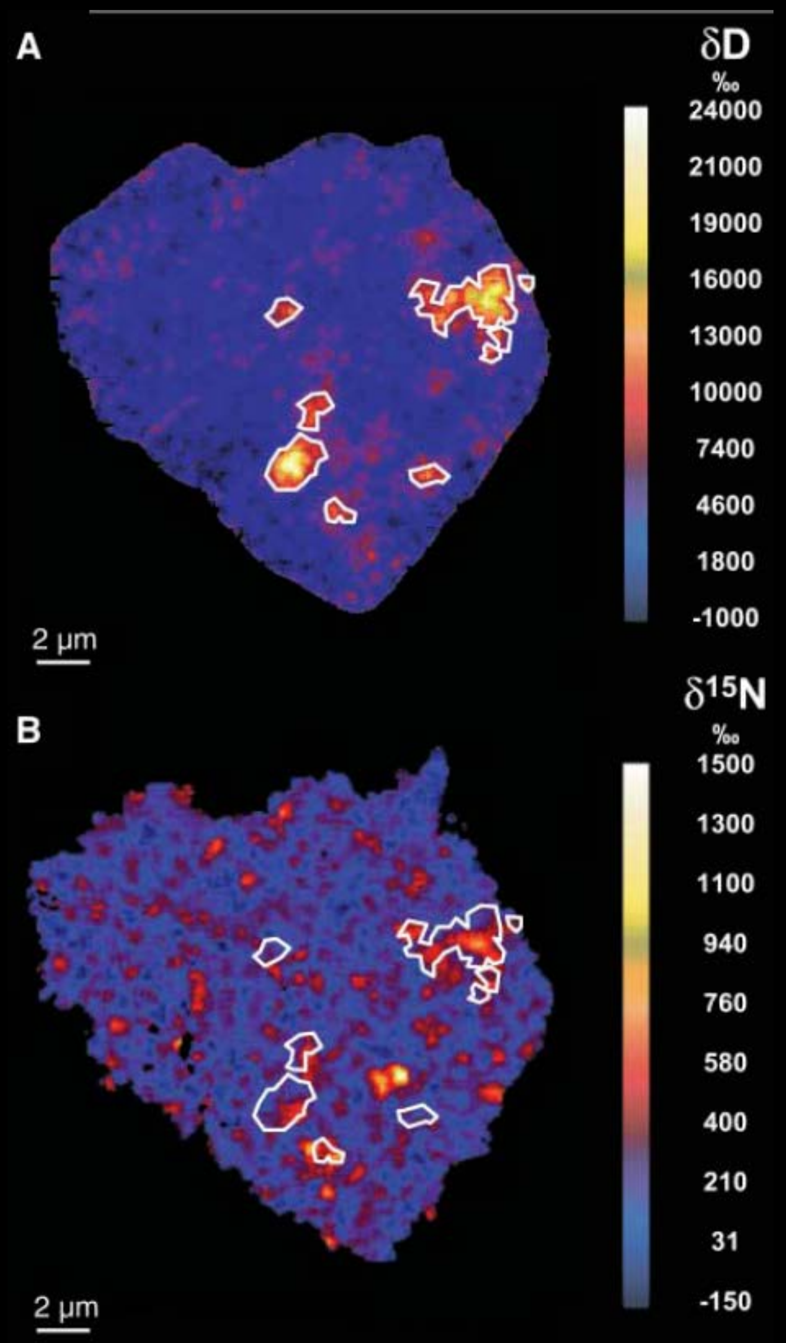
O isotopes in Solar System



- Planets "anomalous" –
  - ^{16}O-poor relative to bulk Sun
- This signature intermediate between Solar and an outer solar system ^{16}O-poor water composition, perhaps recorded by "COS" - cosmic symplectite in Acfer 094 meteorite
  - Photochemical self-shielding in disk or parental cloud?

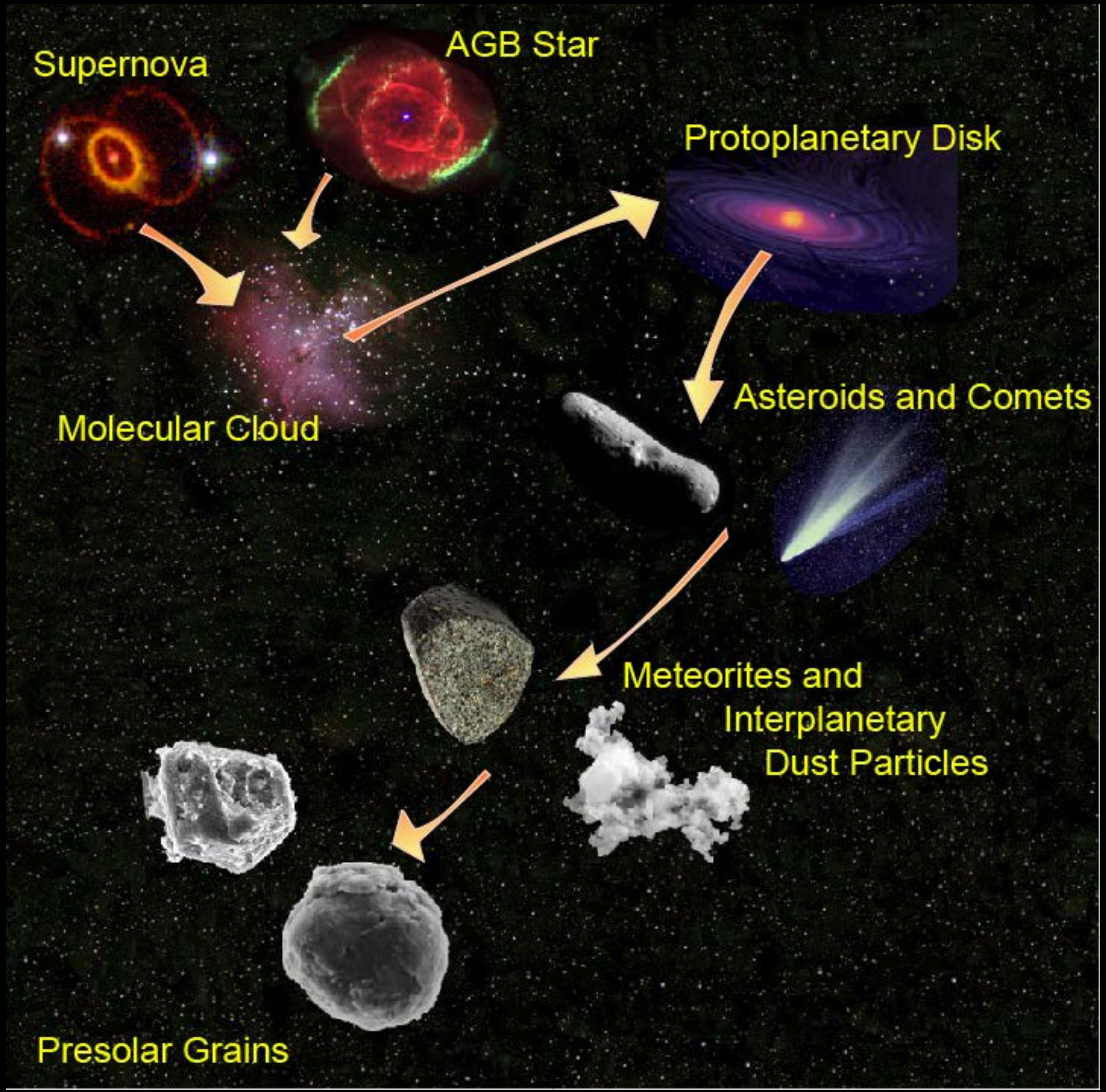
Meteoritic Organic Matter

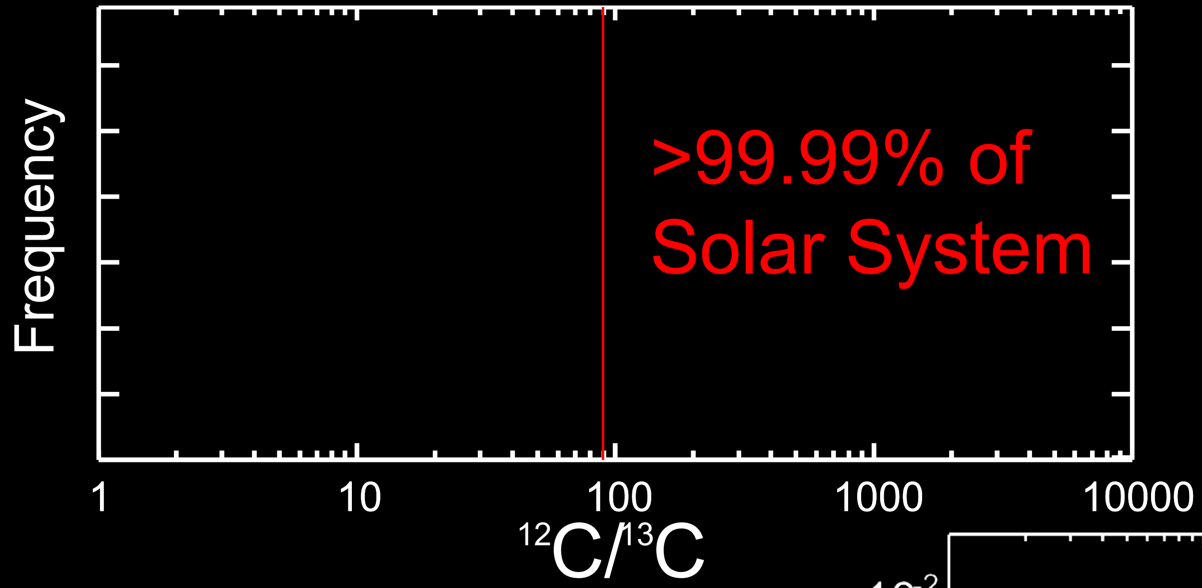
- Up to 2% of chondrites
  - Most is acid-insoluble, macromolecular (IOM)
  - Also wide suite of soluble organic molecules (amino acids, carboxylic acids, etc)
  - Isotopic anomalies suggest interstellar/outer solar system heritage



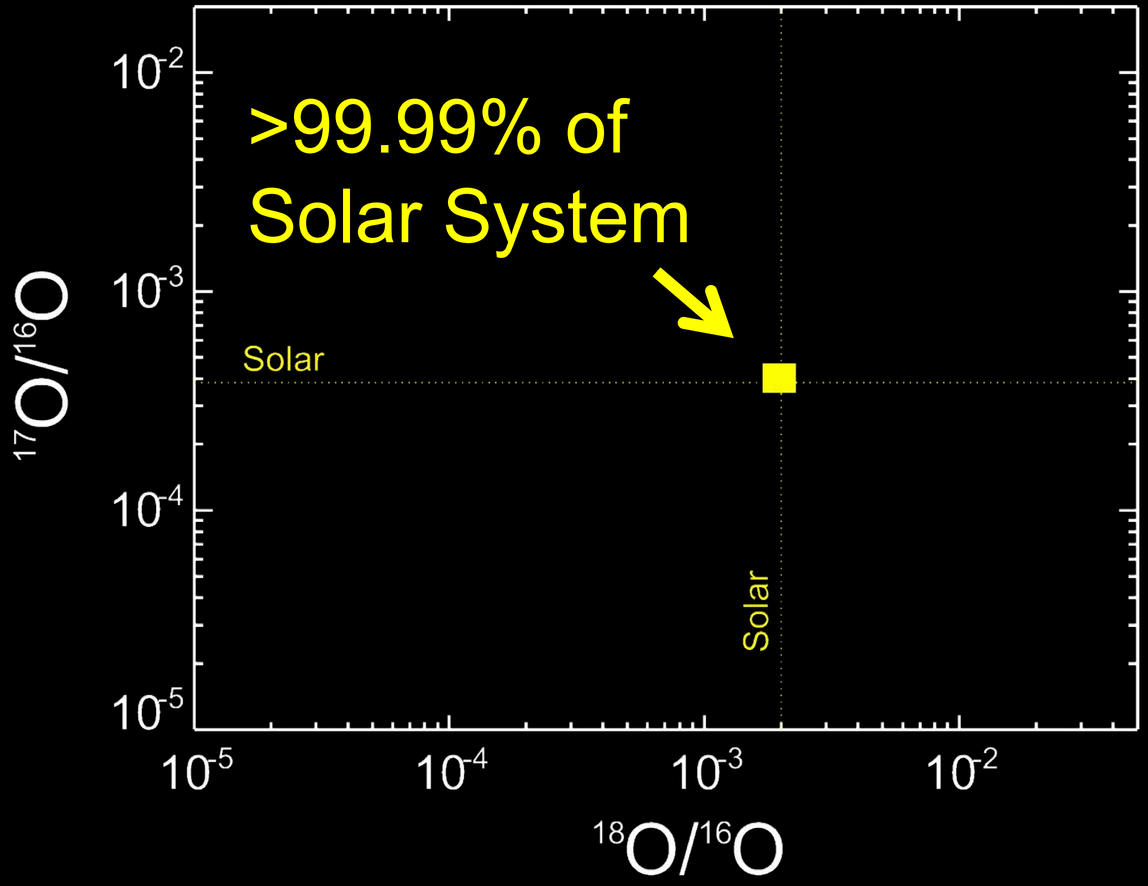
D and ^{15}N hotspots in meteoritic IOM (Busemann et al 2006)

Presolar Stardust in the Solar System

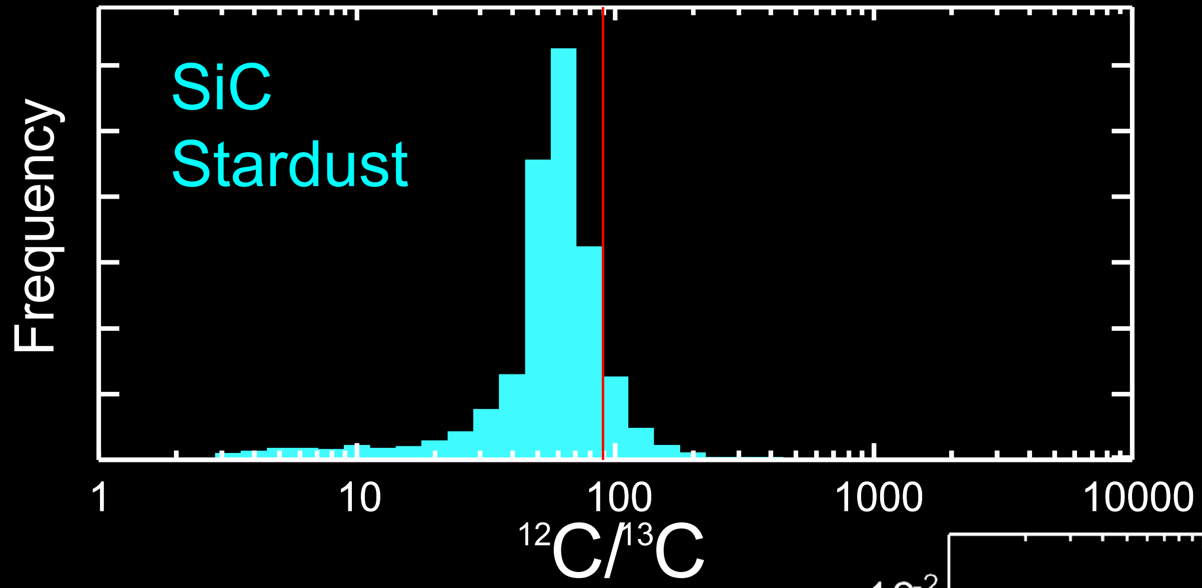




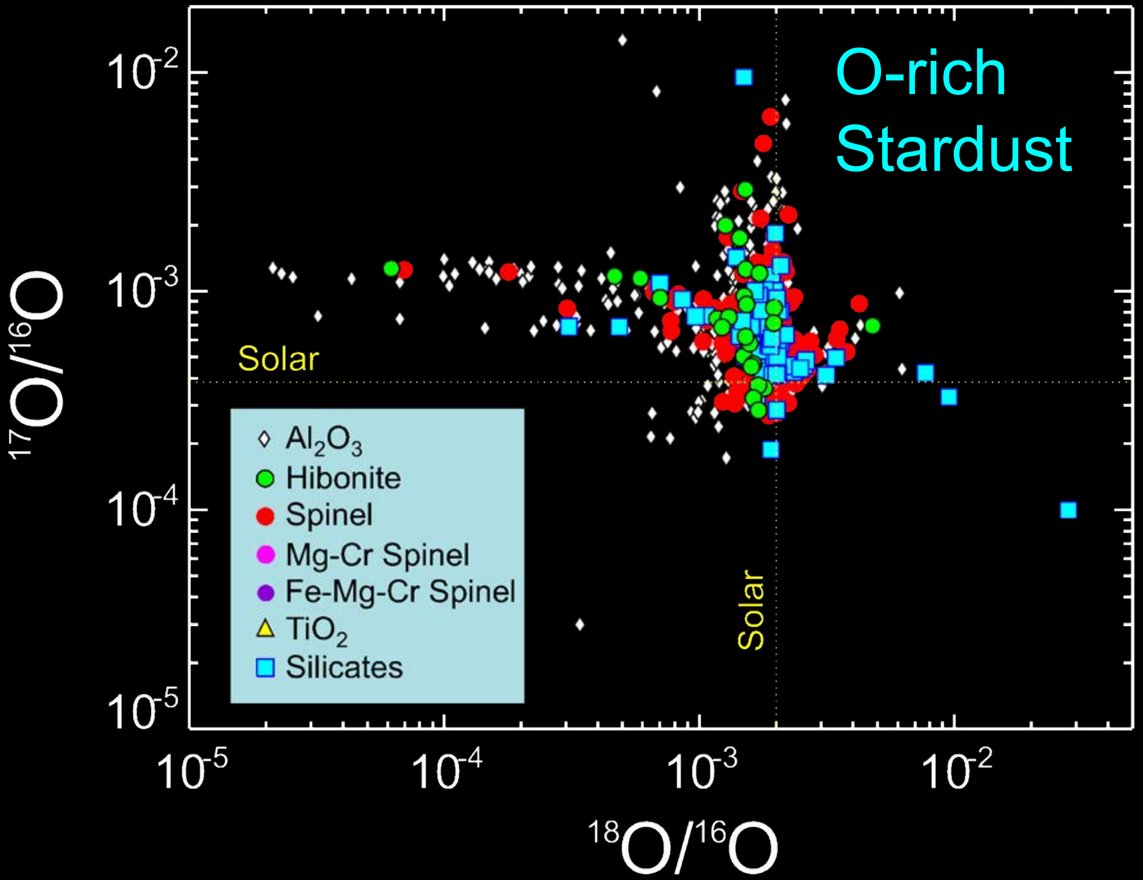
How do we know?



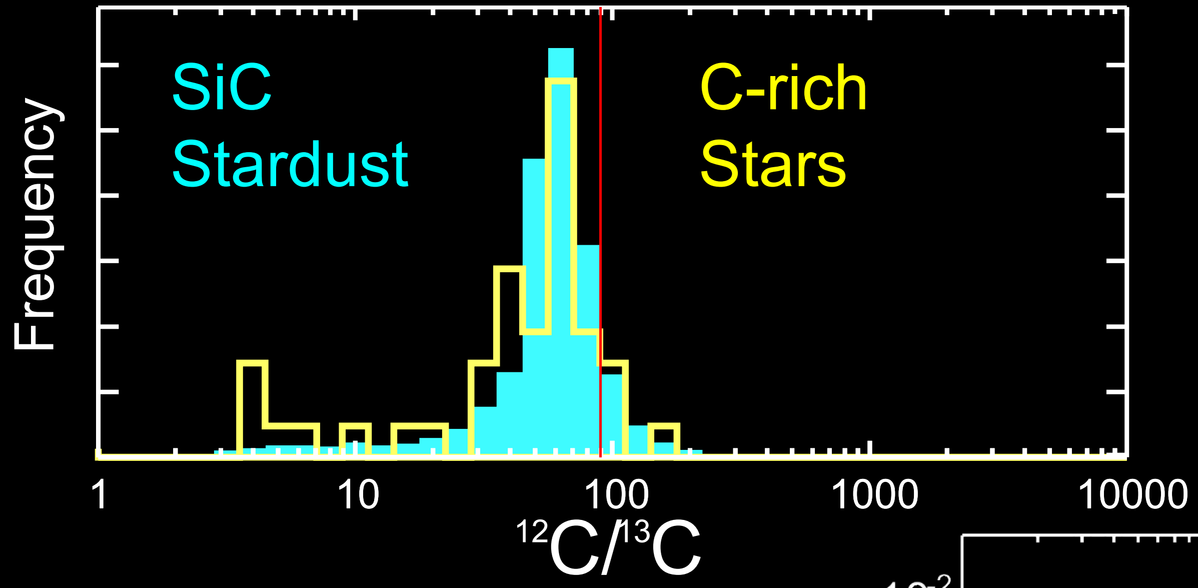
How do we know?



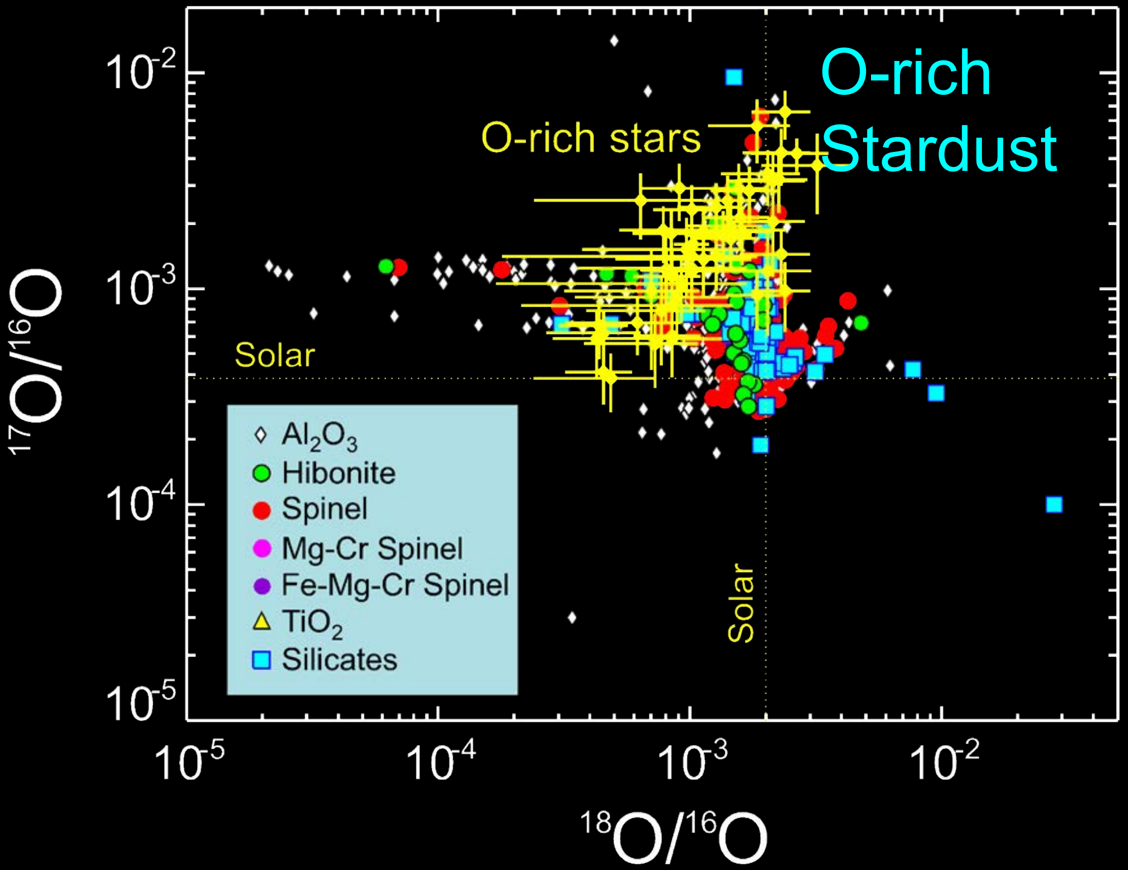
- Isotopic ratios in grains extremely unusual and distinct from ranges found in solar system material
- Too large to explain by physical/chemical processes



How do we know?



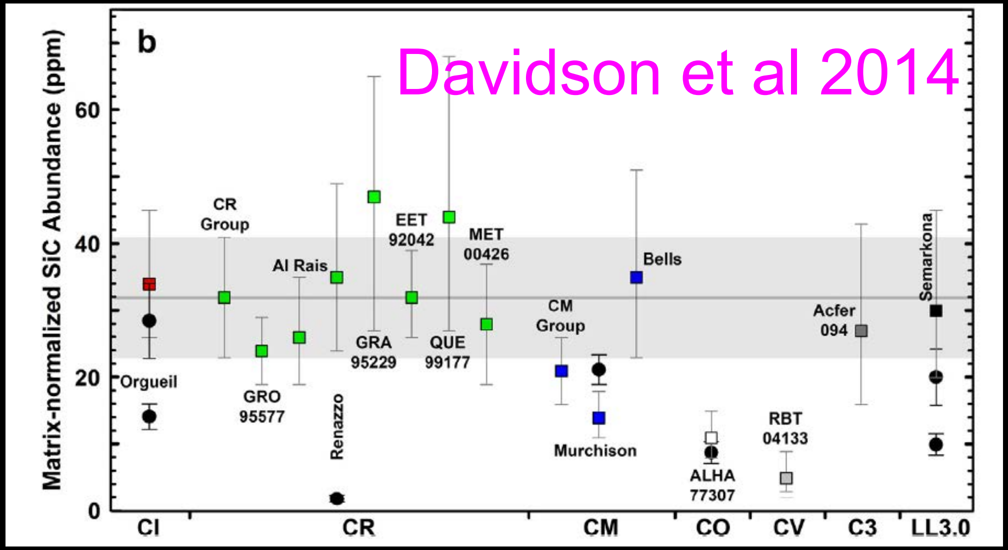
- Isotopic variations require *nuclear* processes.
- Origin in STARS



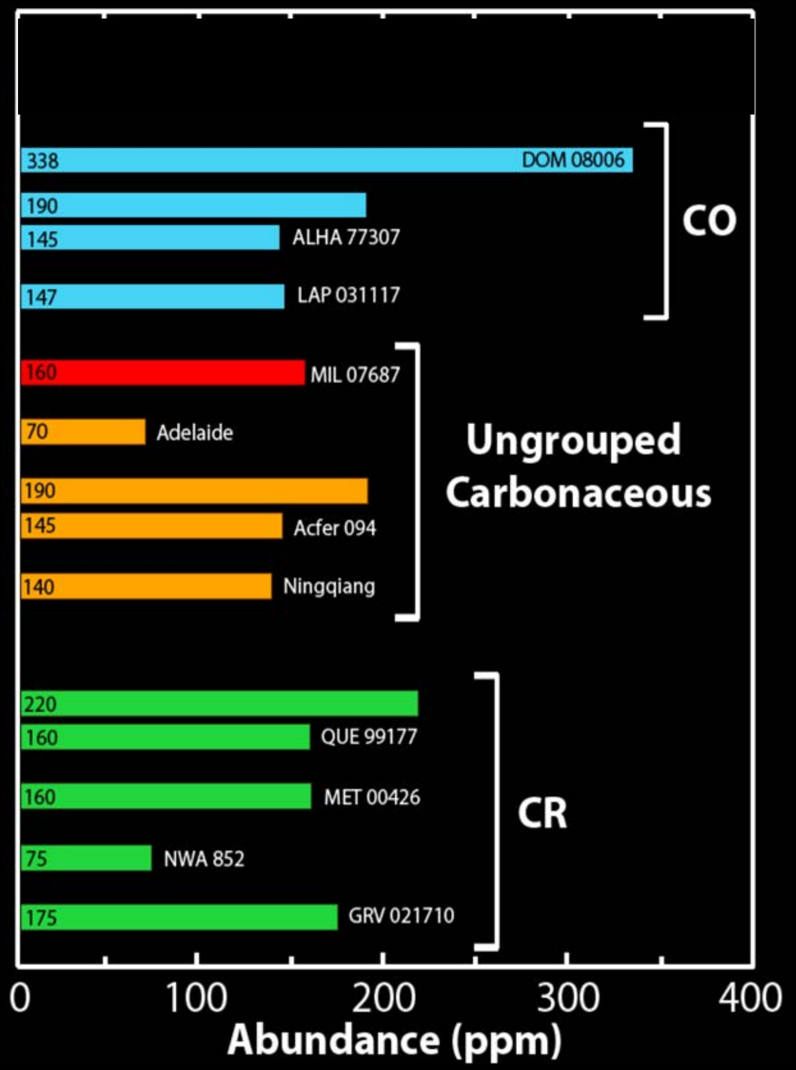
Pristine nature of presolar grains makes them useful probes of:

- Cosmology
- Stellar nucleosynthesis
- Stellar evolution and mixing
- Galactic chemical evolution
- Dust formation in stellar environments
- Dust processing in the interstellar medium
- Sources of material for Solar System
- Early Solar System processes (disk and planetesimal)

Presolar grain abundances

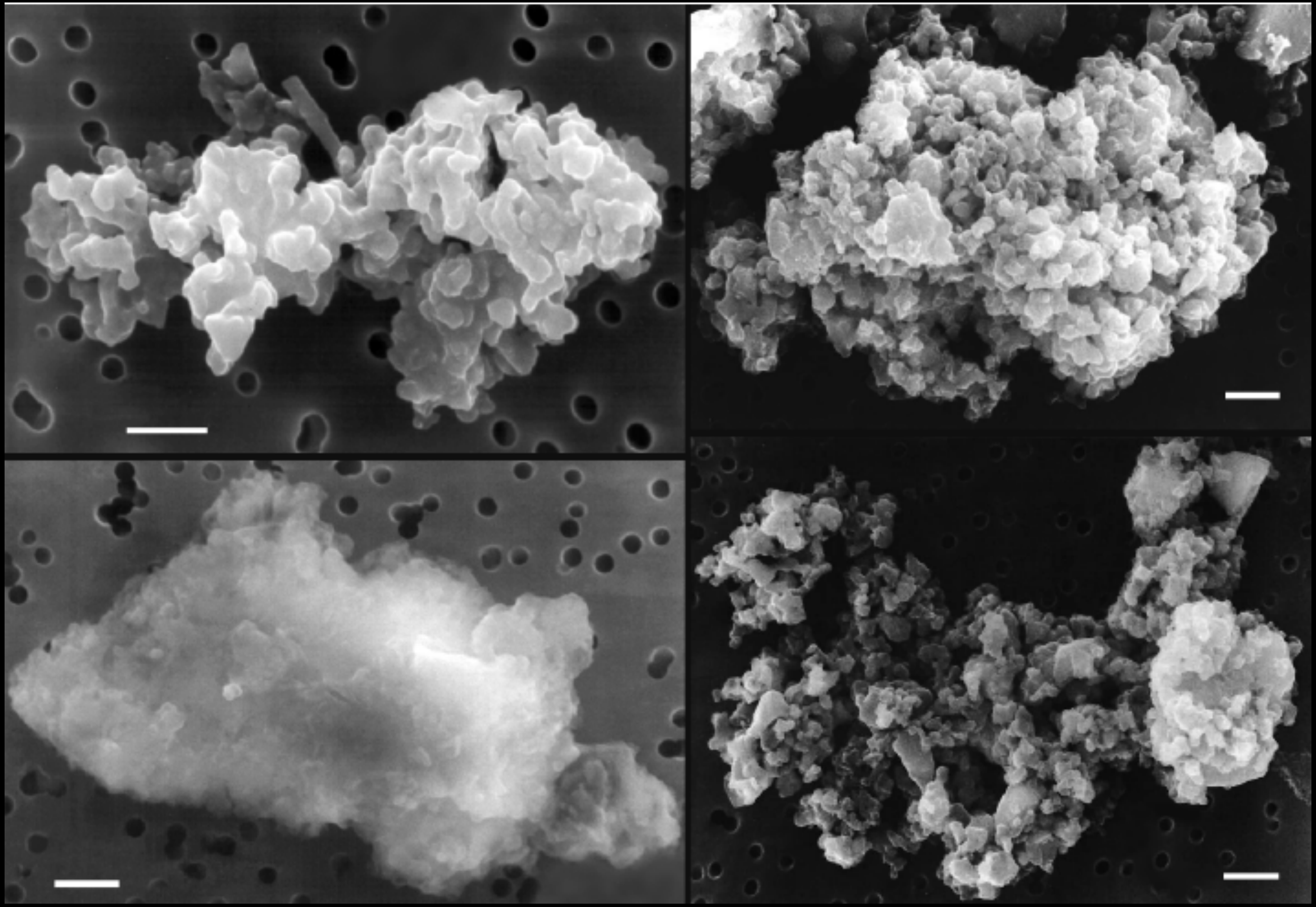


- SiC roughly constant across chondrite groups
- Silicates strongly sensitive to parent-body processing



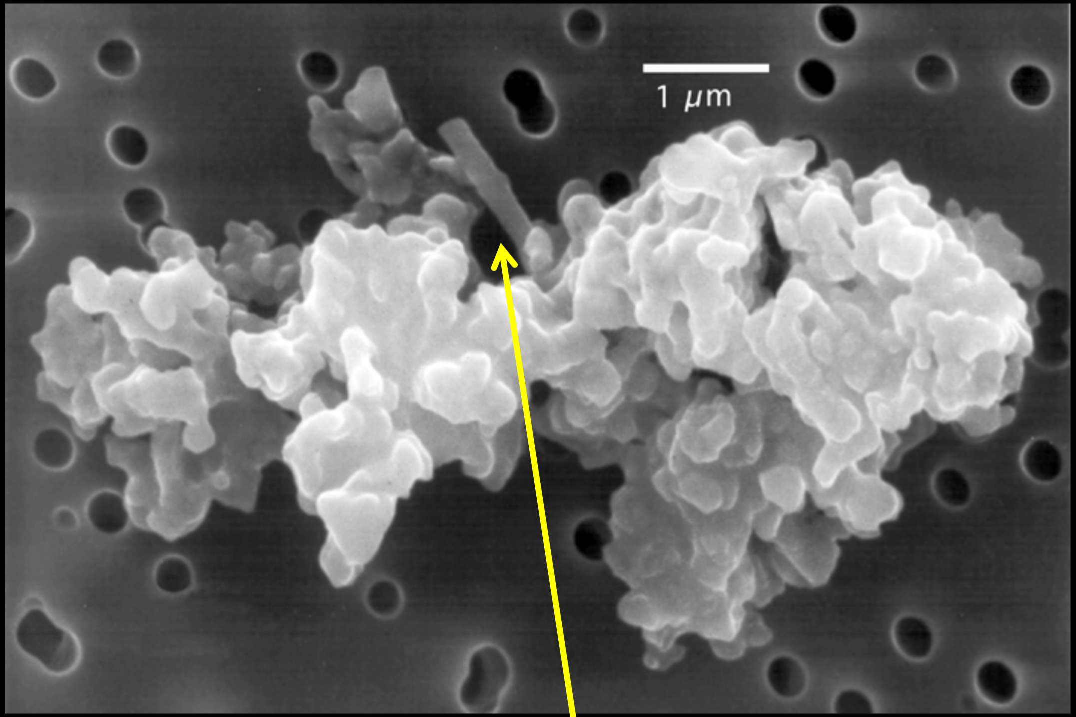
Floss, Nittler, Davidson, Leitner, Nguyen, others

Interplanetary Dust Particles (IDPs)



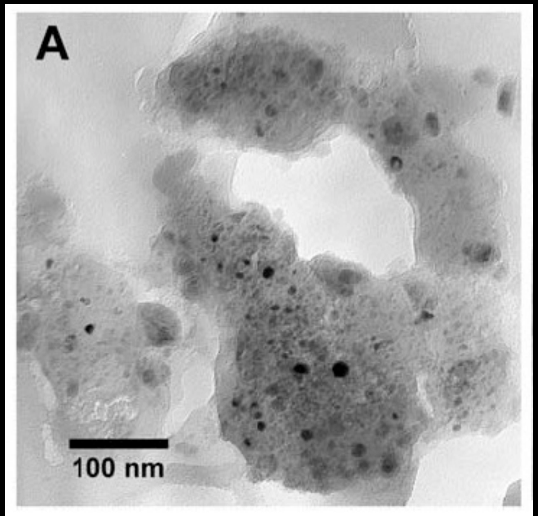
- Very tiny meteorites collected in stratosphere by aircraft
- 1-60 μm in size
- Asteroidal and cometary sources (based on inferred entry velocities)

Cometary IDPs



Enstatite ($MgSiO_3$) whisker

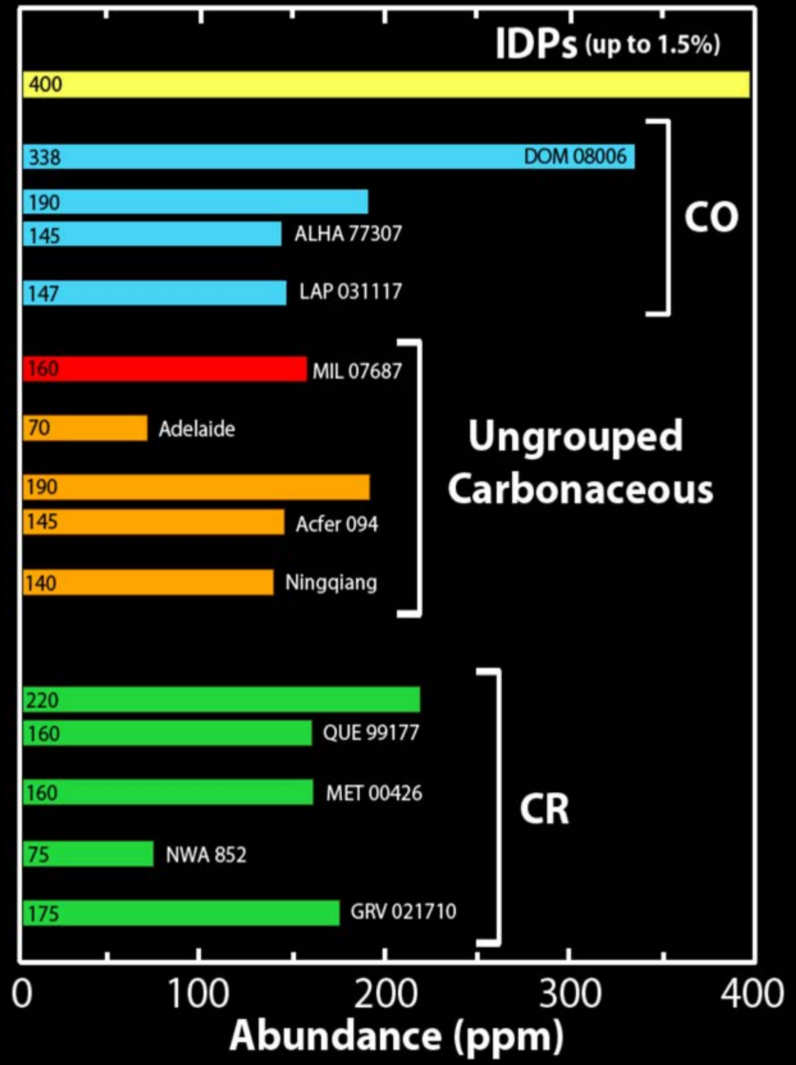
- Anhydrous
- C-rich (up to 50%)
- Ultra-fine-grained, unequilibrated
- Mix of crystalline and amorphous silicates

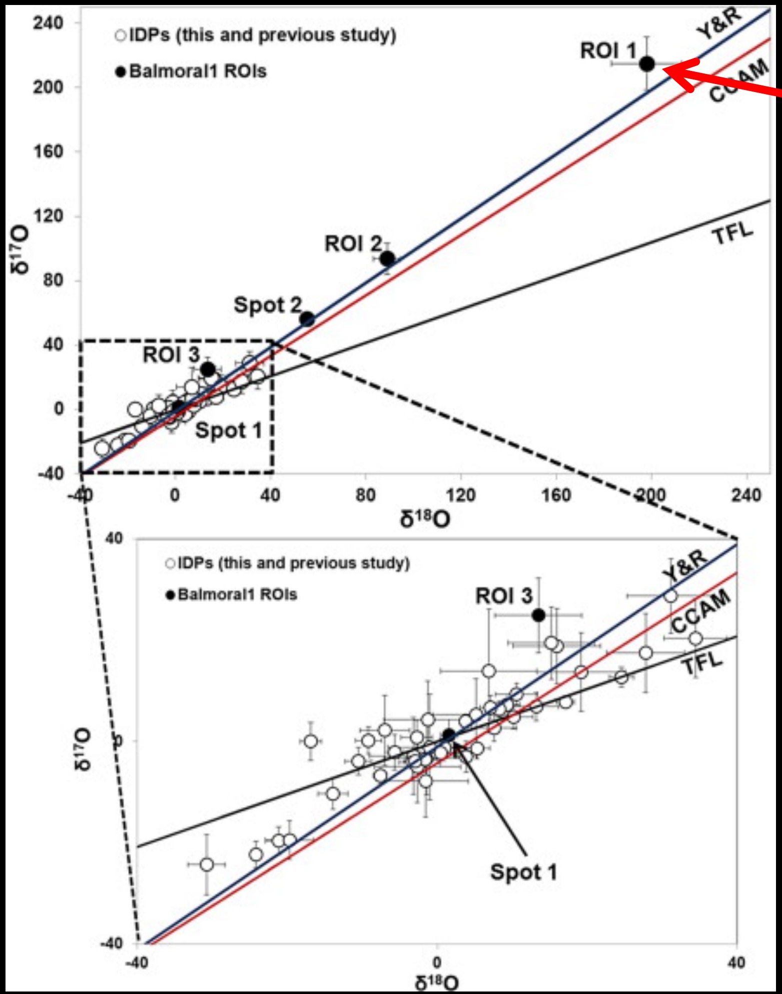


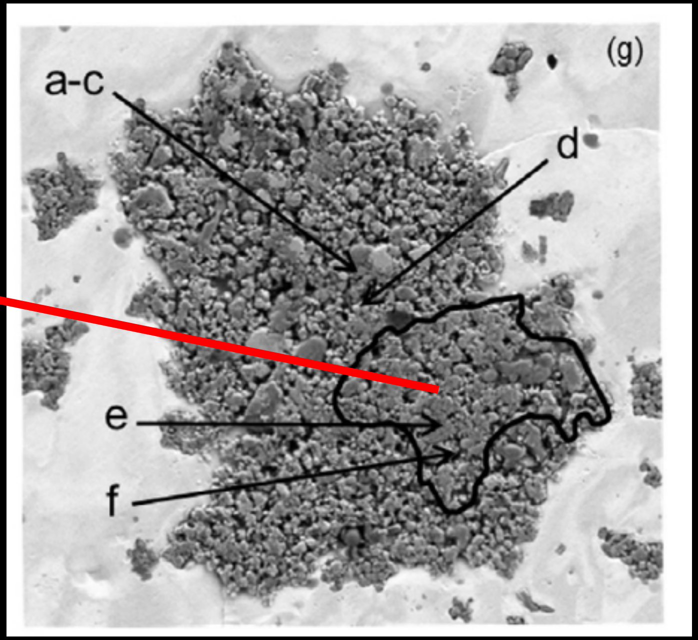
"GEMS" (Glass with Embedded Metals & Sulfides; J. Bradley)

Cometary IDPs

High presolar silicate abundance





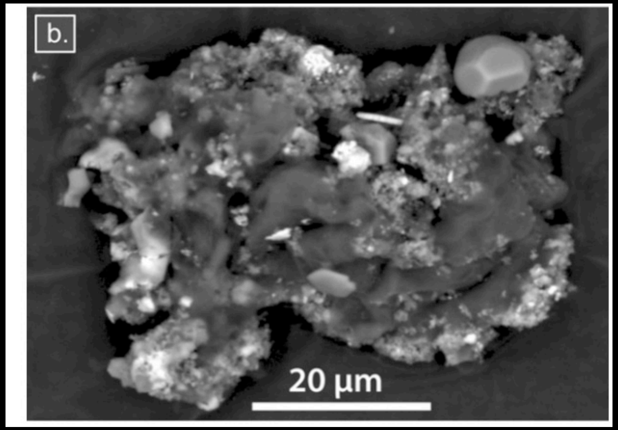


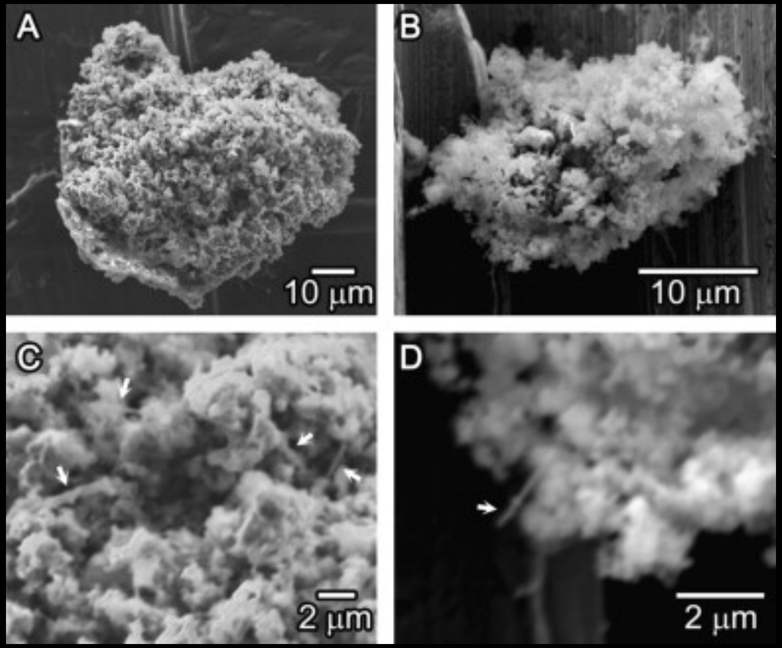
^{16}O-poor cosmic symplectite like signature (*Starkey et al. 2014)*

Antarctic Micrometeorites (AMMs)

J. Duprat

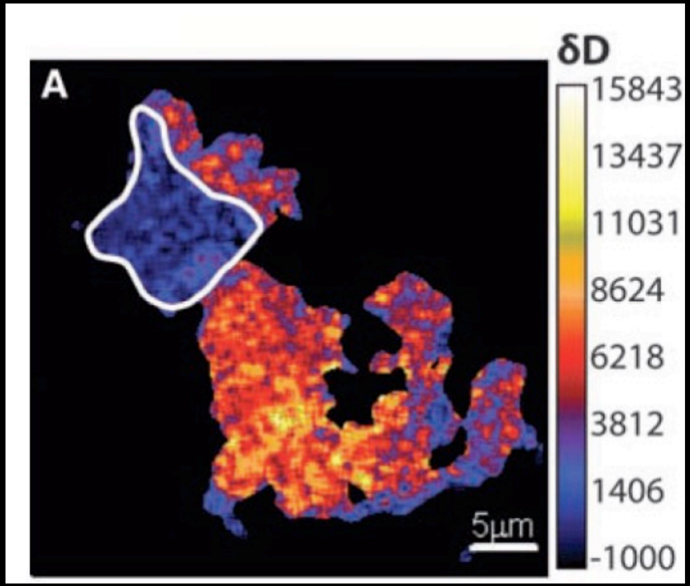
- 10s to 100s μm
  - Collected by filtering snow- or ice-melt
  - Fraction is anhydrous and porous
- Subset are very C-rich
  - Ultracarbonaceous (UC) AMMS (Duprat et al, 2010)



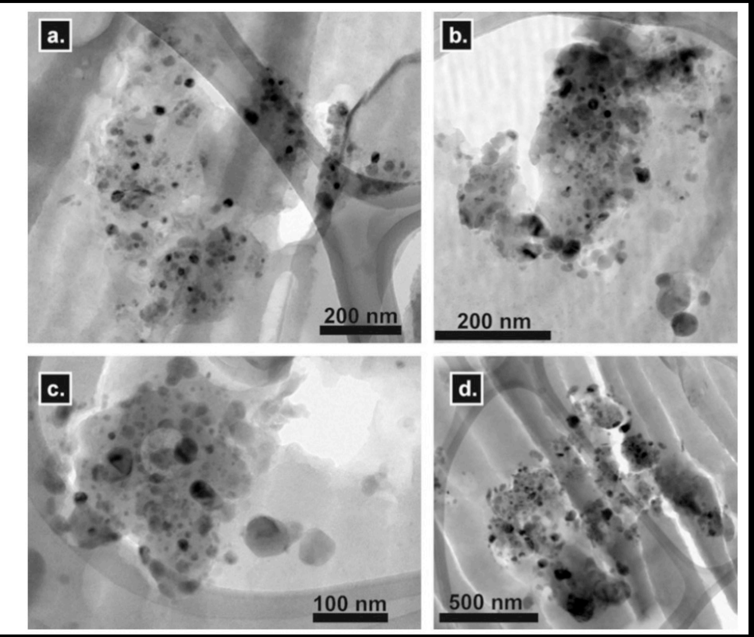


Noguchi et al. 2014

Ultracarbonaceous Micrometeorites



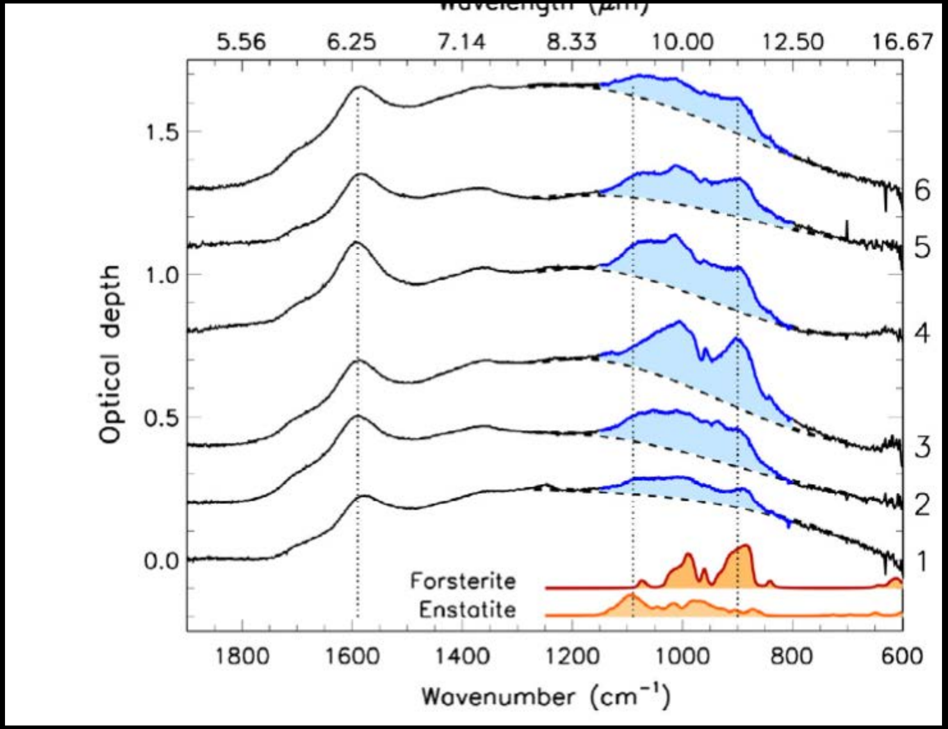
Some very D-rich



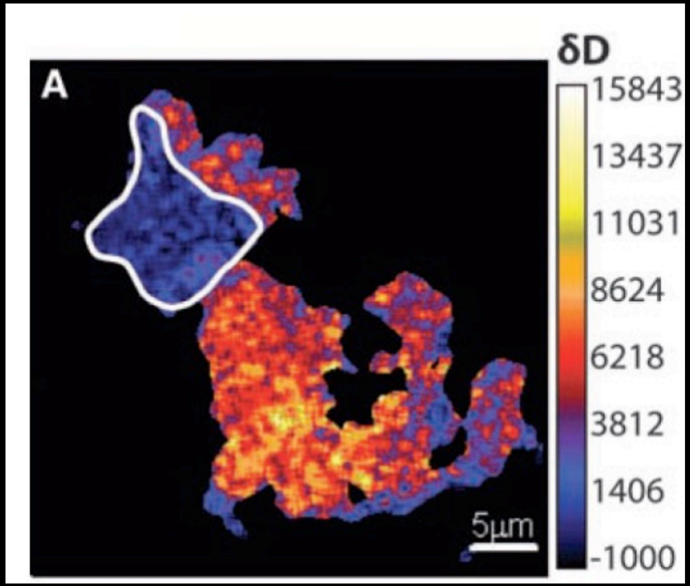
Contain GEMS

(Duprat et al. 2010, Dartrois et al. (2013,2018), Dobrica et al. (2012), Yabuta et al. (2018)

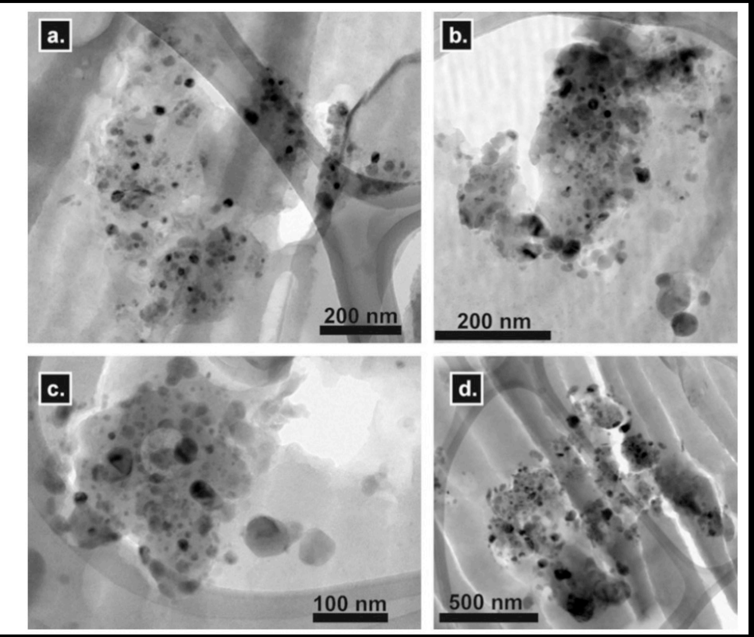
Some contain very N-rich OM



Ultracarbonaceous Micrometeorites

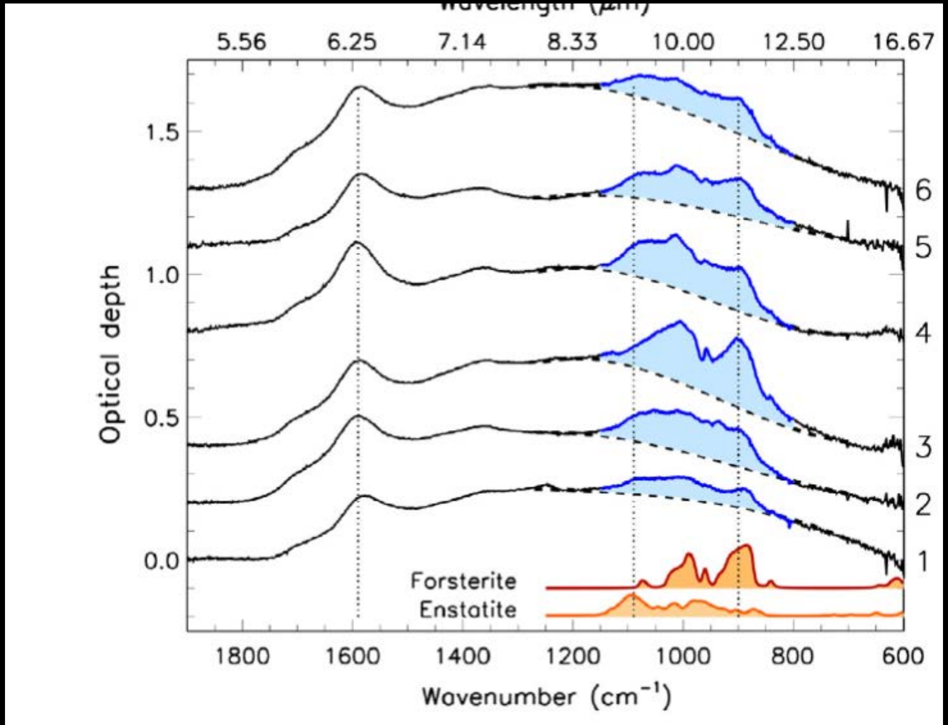


Some very D-rich



Contain GEMS

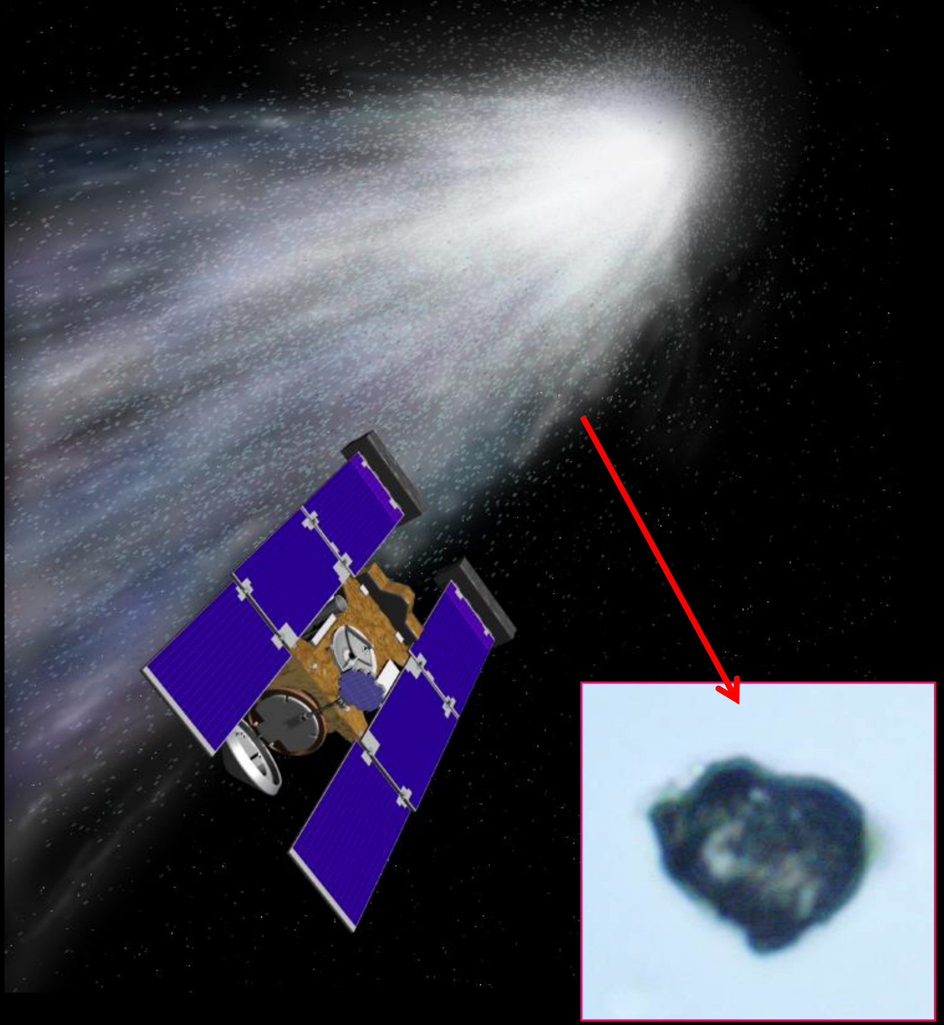
Proposed origin in comets/KBOs



Some contain very N-rich OM

(Duprat et al. 2010, Dartrois et al. (2013,2018), Dobrica et al. (2012), Yabuta et al. (2018)

Comet Wild-2 samples



STARDUST
NASA's COMET SAMPLE RETURN MISSION

- STARDUST mission returned solid samples from JFC Wild-2
- Collected in silica aerogel
- Bear similarities to both primitive meteorites and IDPs
  - Fine-grained crystalline and amorphous silicates
  - Organic matter
  - CAIs/chondrule fragments

nature astronomy

ARTICLES

https://doi.org/10.1038/s41550-019-0737-8

A cometary building block in a primitive asteroidal meteorite

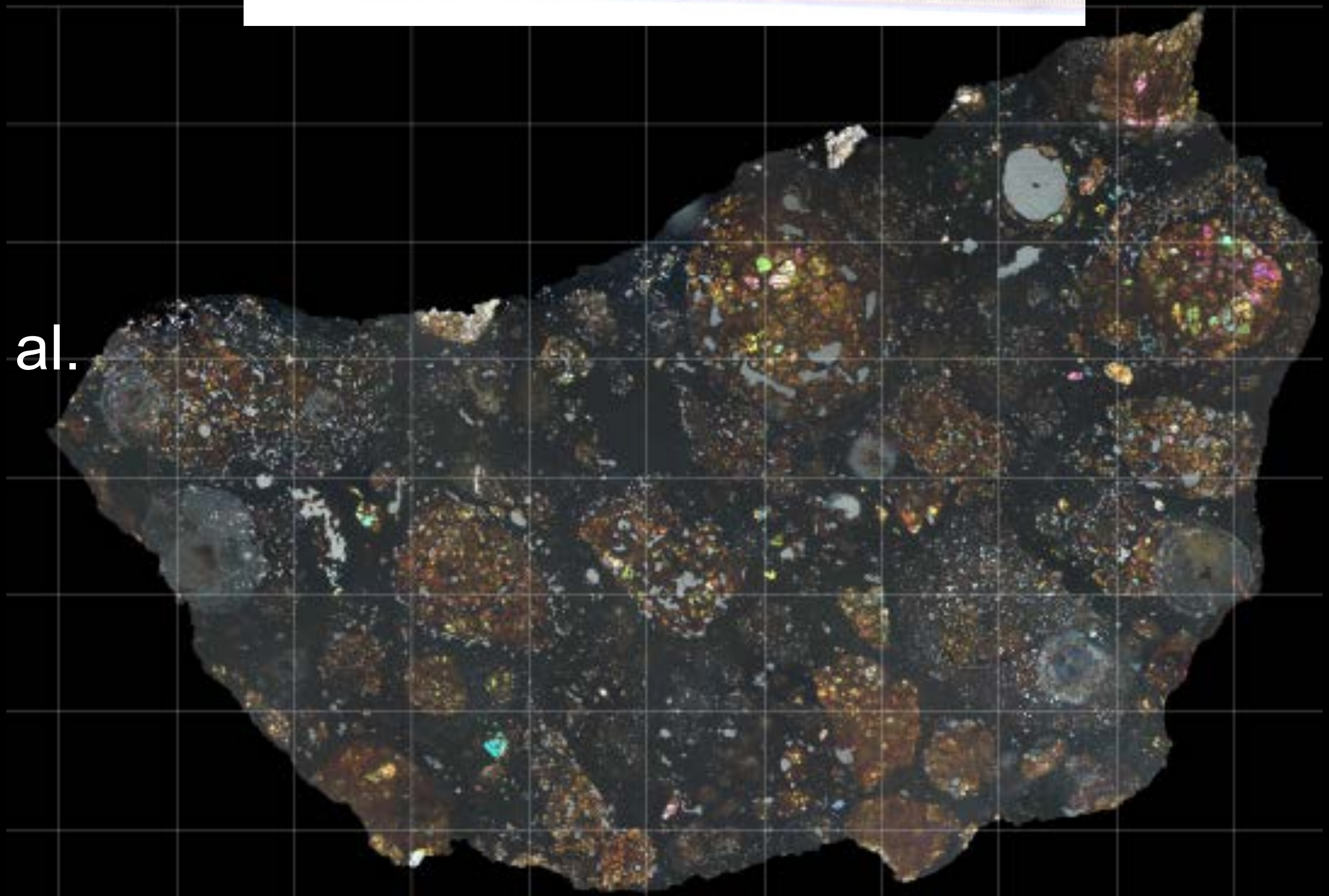
Larry R. Nittler[1*], Rhonda M. Stroud[2], Josep M. Trigo-Rodríguez[3,4], Bradley T. De Gregorio[2], Conel M. O'D. Alexander[1], Jemma Davidson[1,5], Carles E. Moyano-Cambero[3,4] and Safoura Tanbakouei[3,4]

Meteorites originating from primitive C-type asteroids are composed of materials from the Sun's protoplanetary disk, including up to a few per cent organic carbon. In contrast, some interplanetary dust particles and micrometeorites have much higher carbon contents, up to >90%, and are thought to originate from icy outer Solar System bodies and comets. Here we report an approximately 100-μm-diameter very carbon-rich clast, with highly primitive characteristics, in the matrix of a CR2 chondrite, LaPaz Icefield 02342. The clast may represent a cometary building block, largely unsampled in meteorite collections, that was captured by a C-type asteroid during the early stages of planet formation. The existence of this cometary microxenolith supports the idea of a radially inward transport of materials from the outer protoplanetary disk into the CR chondrite reservoir during the formation of planetesimals. Moreover, the H-isotopic composition of the clast is suggestive of a temporal evolution of organic isotopic compositions in the comet-forming region of the disk.

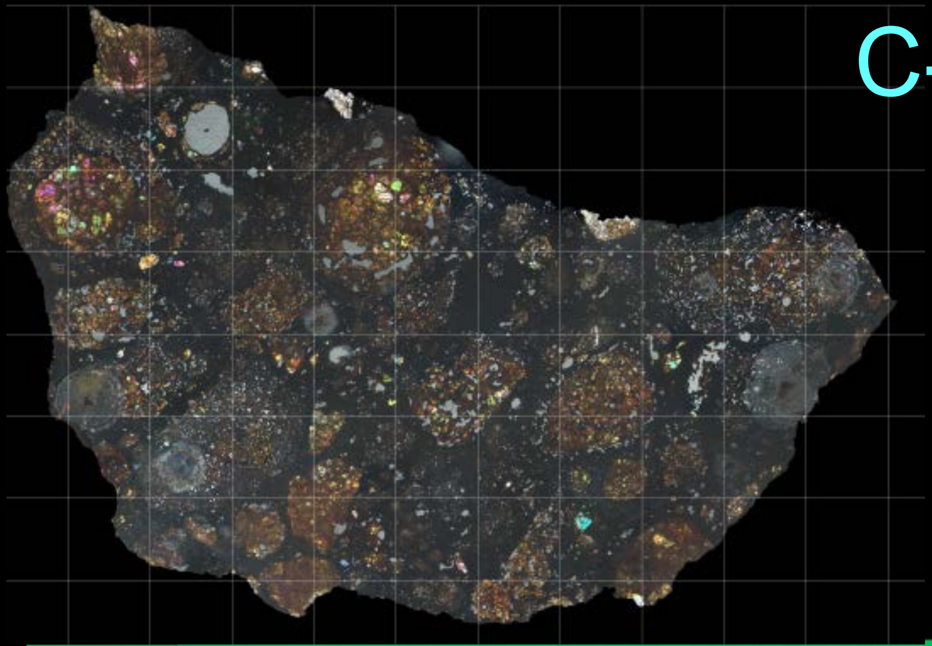
LaPaz Icefield (LAP) 02342

- 42 g Antarctic CR chondrite

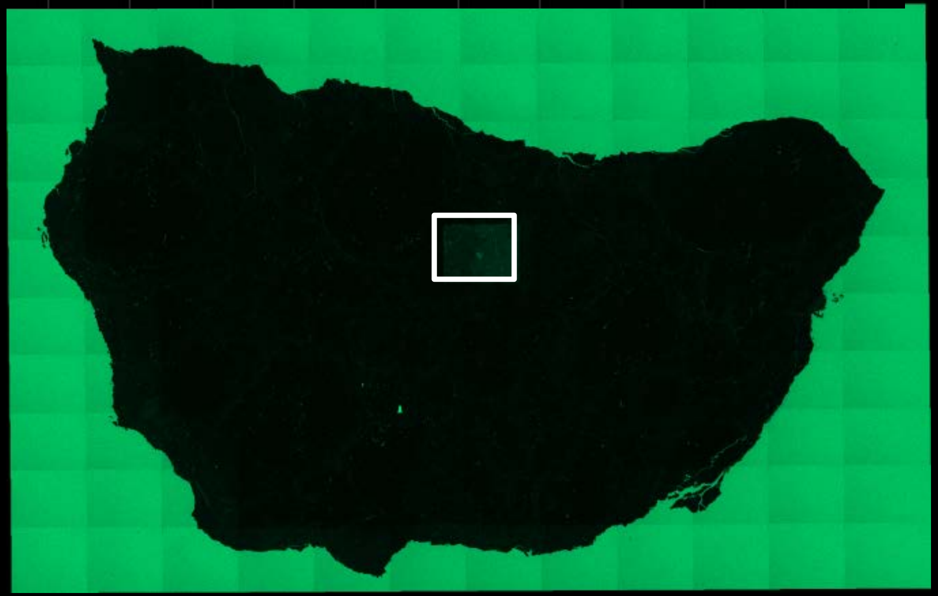
- Initial work identified interesting features and heterogeneous aqueous alteration (Trigo-Rodríguez et al. LPSC 2013)



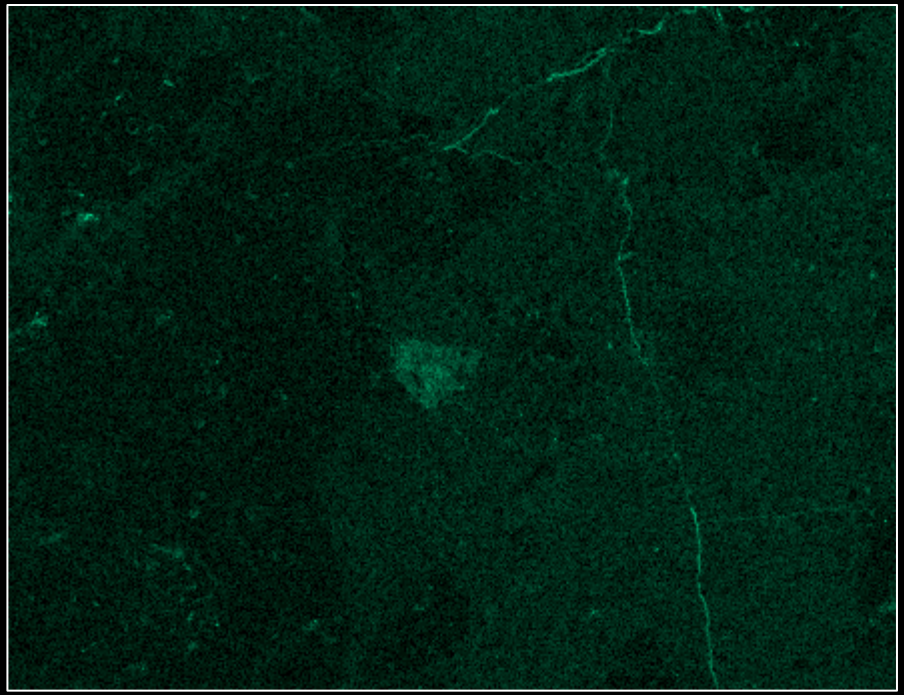
C-rich clast



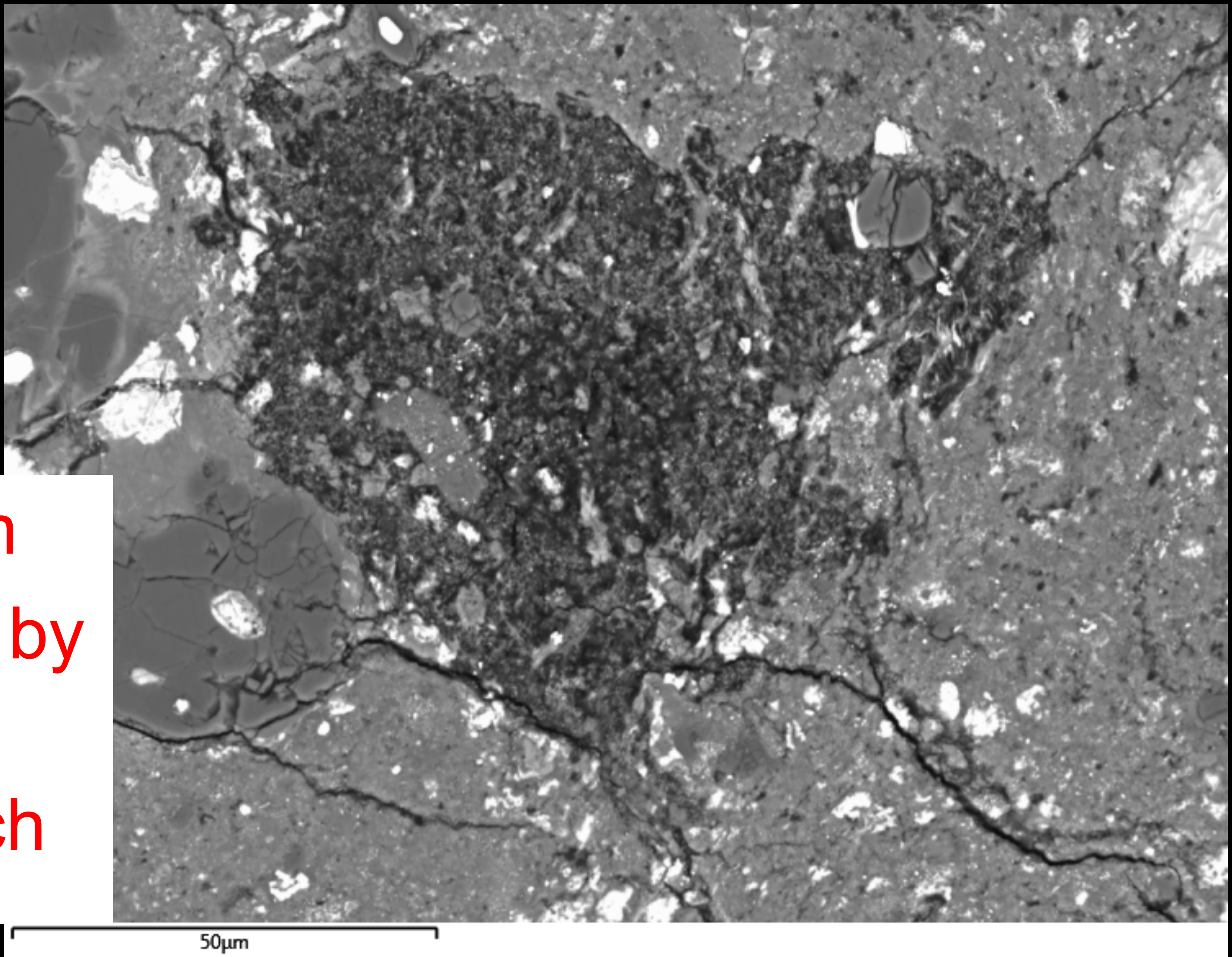
– Noticed unusual C-rich region of thin section; targeted for additional analysis



C X-ray map



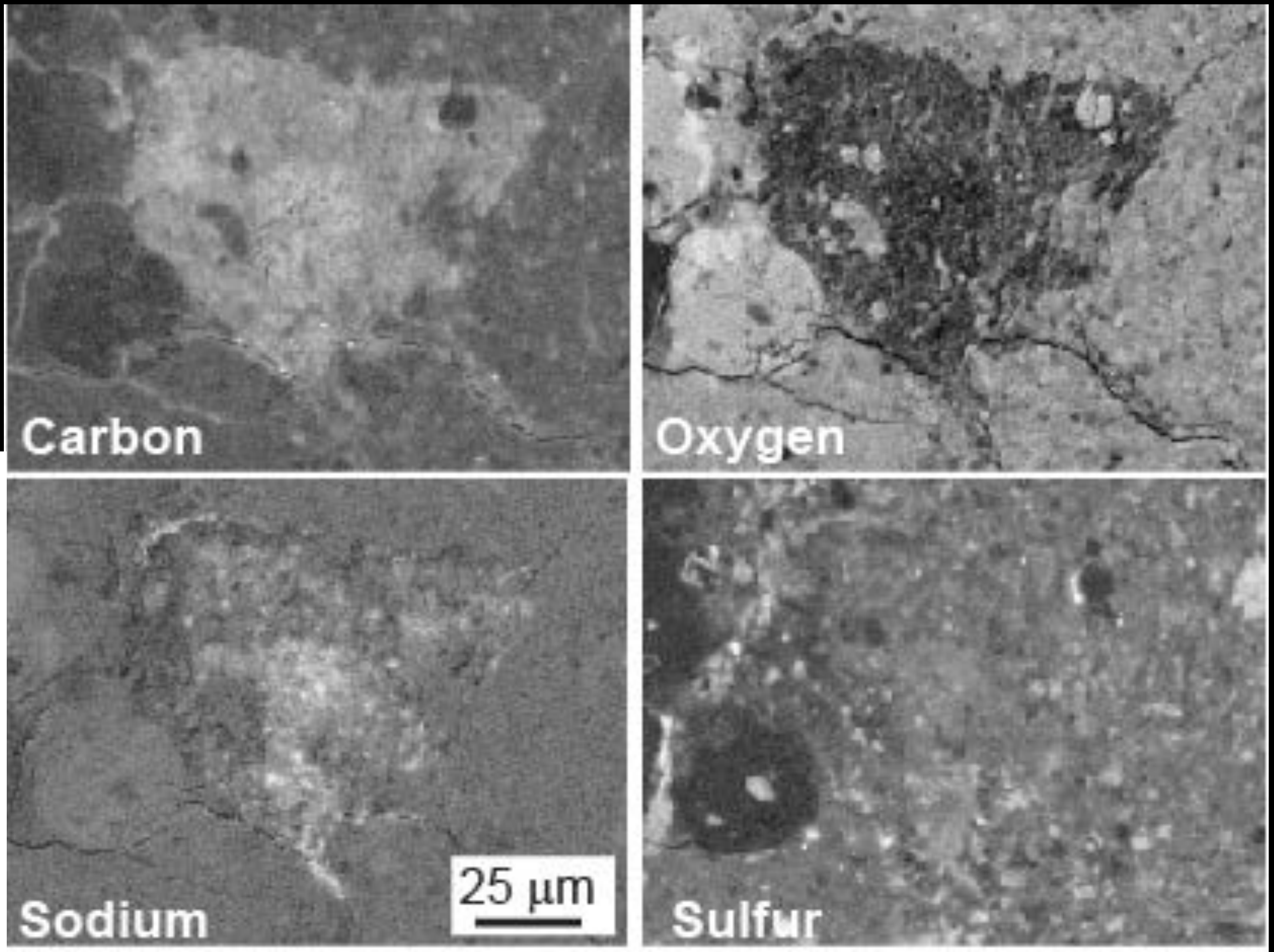
C-rich Clast



- ~100-µm
- >70% C by area
- Na, S rich

C-rich Clast

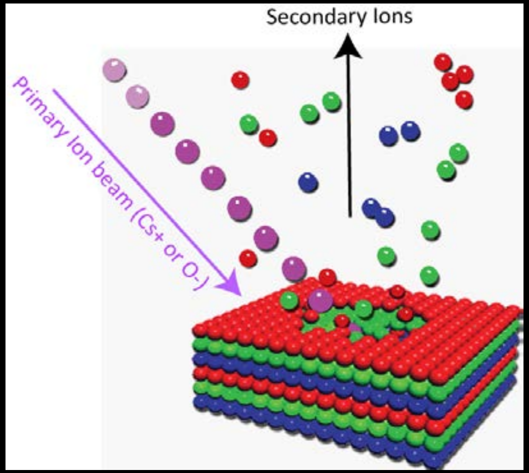
- ~100-μm
- >70% C by area
- Na, S rich

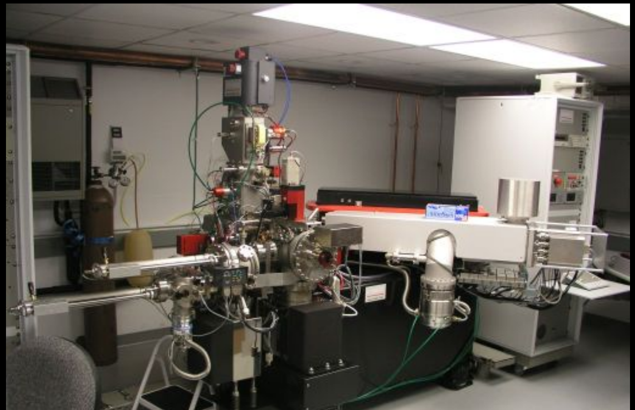


Methods

Secondary Ion Mass Spectrometry (SIMS)

- Major/minor element isotope ratios (>100nm)





Carnegie Inst. NanoSIMS

Scanning Transmission Electron Microscopy

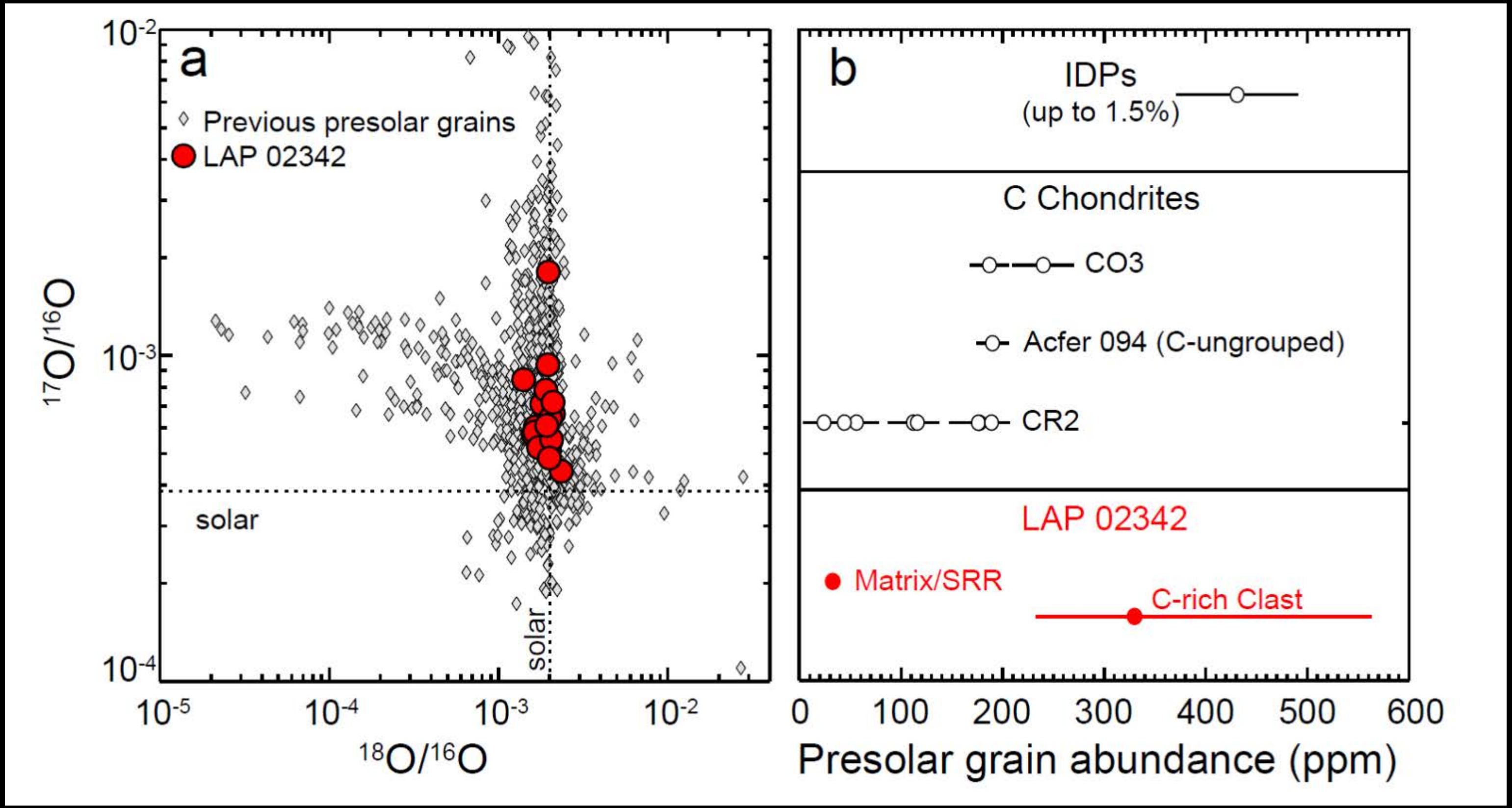
- Morphology/ mineralogy/ microstructure (<1Å)

NION UltraSTEM 200-X
Naval Research Lab

X-ray Absorption Near-Edge Spectroscopy (Synchrotron-based transmission X-ray microscopy provides information about chemical bonding

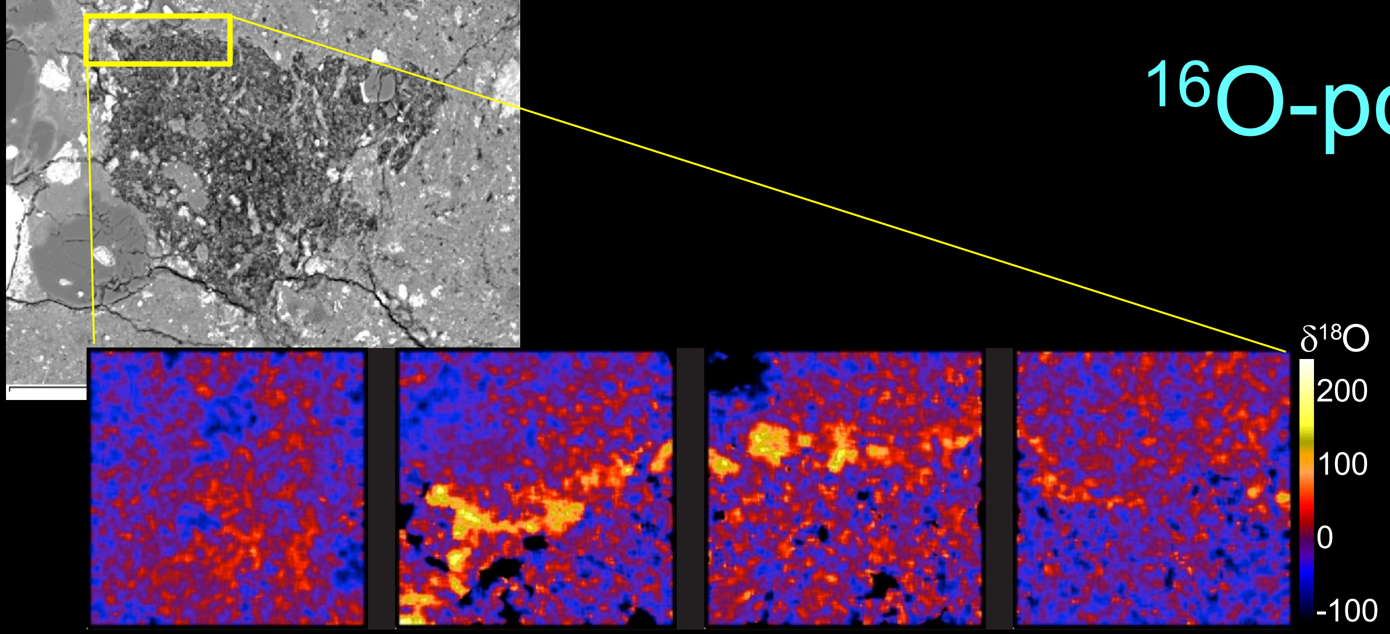
Advanced Light Source (LBNL)

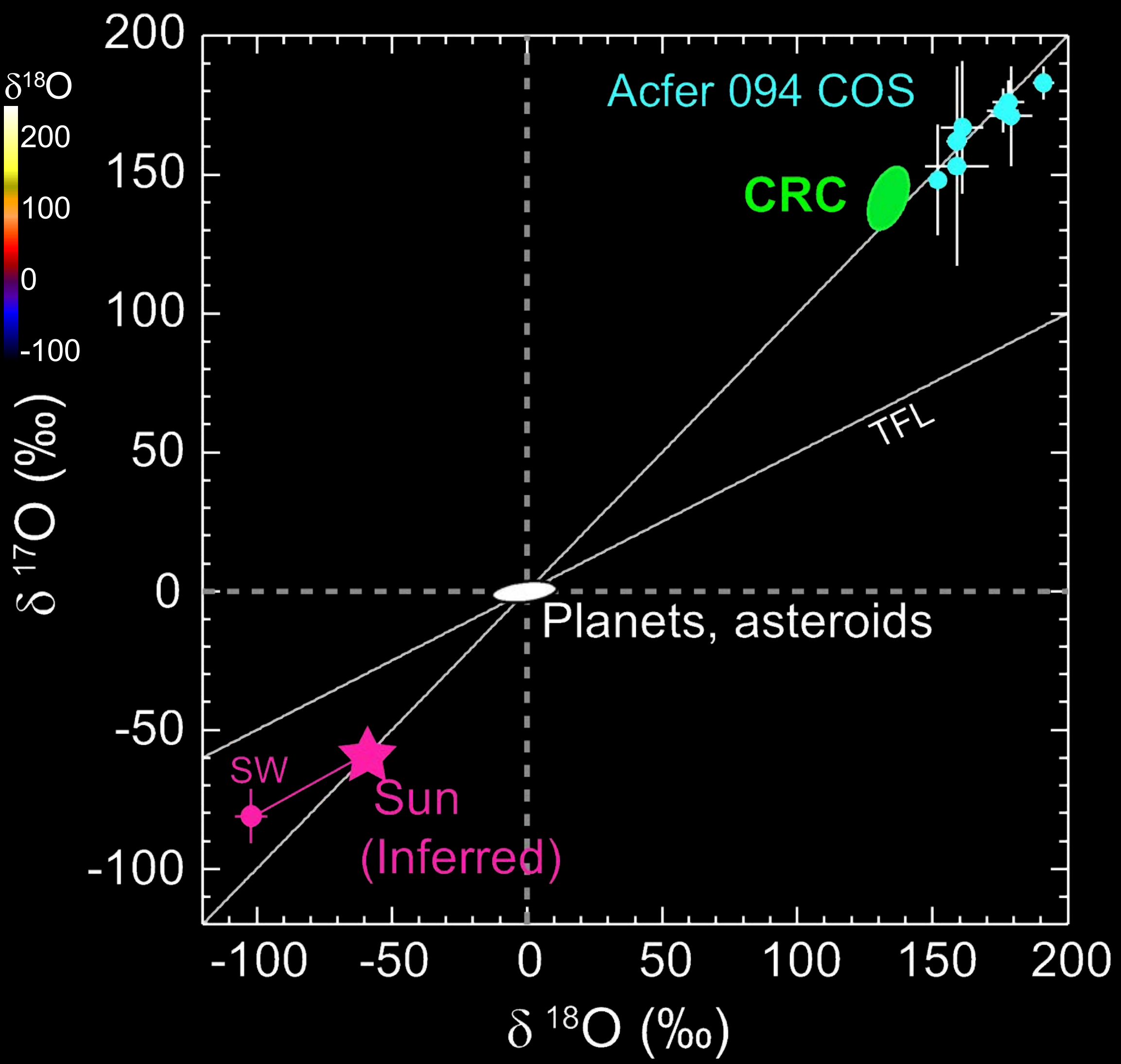
Presolar Grains



- Matrix presolar silicate abundance at low end for CR chondrites
- C-rich Clast abundance much higher, comparable to the most primitive meteorites and IDPs

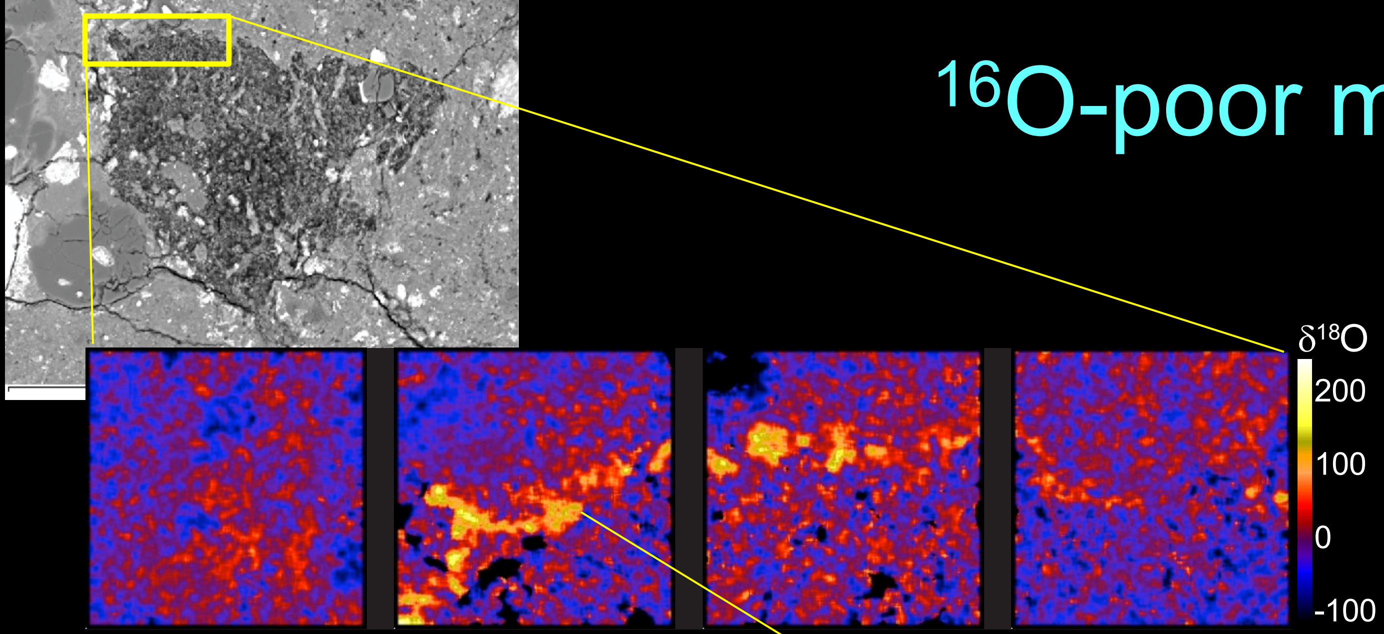
^{16}O-poor material

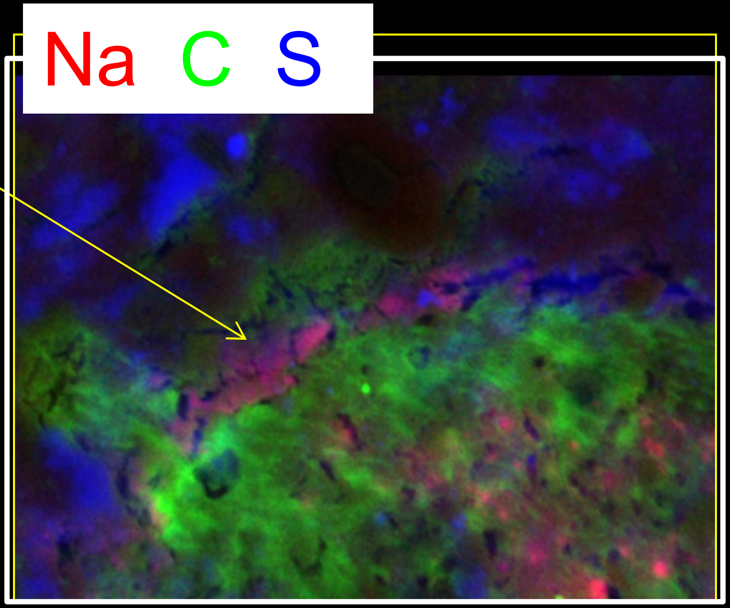




- Related to Acfer 094 COS?
  - Outer-solar system water?

^{16}O-poor material

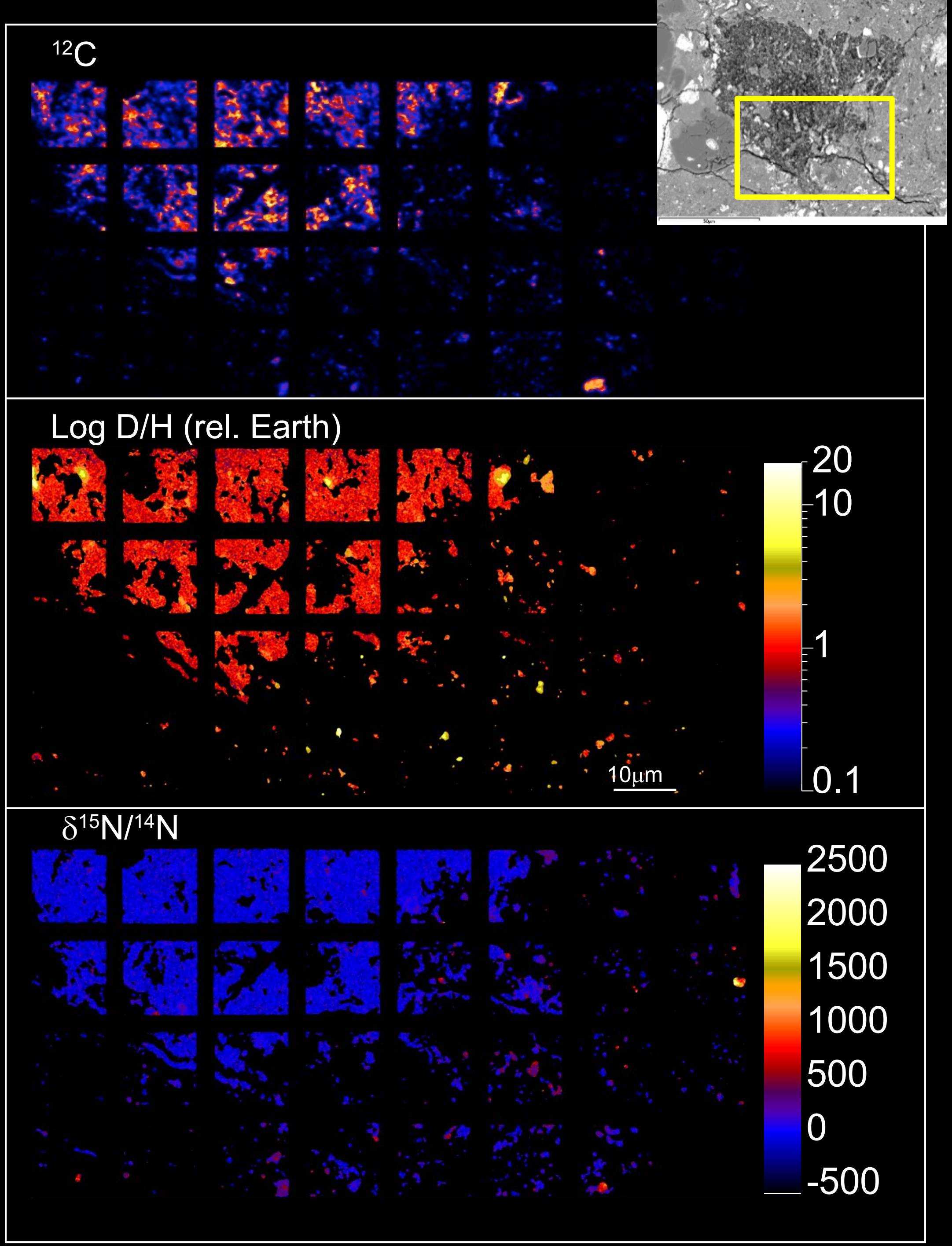




- SEM-EDS indicates grains rich in Na, S,O
  - Na sulfate(!)
  - Acfer 094 COS is magnetite-Fe sulfide

Organic Matter

- C-rich clast largely close to terrestrial but with some localized enrichments (“hotspots”) of D and ^{15}N



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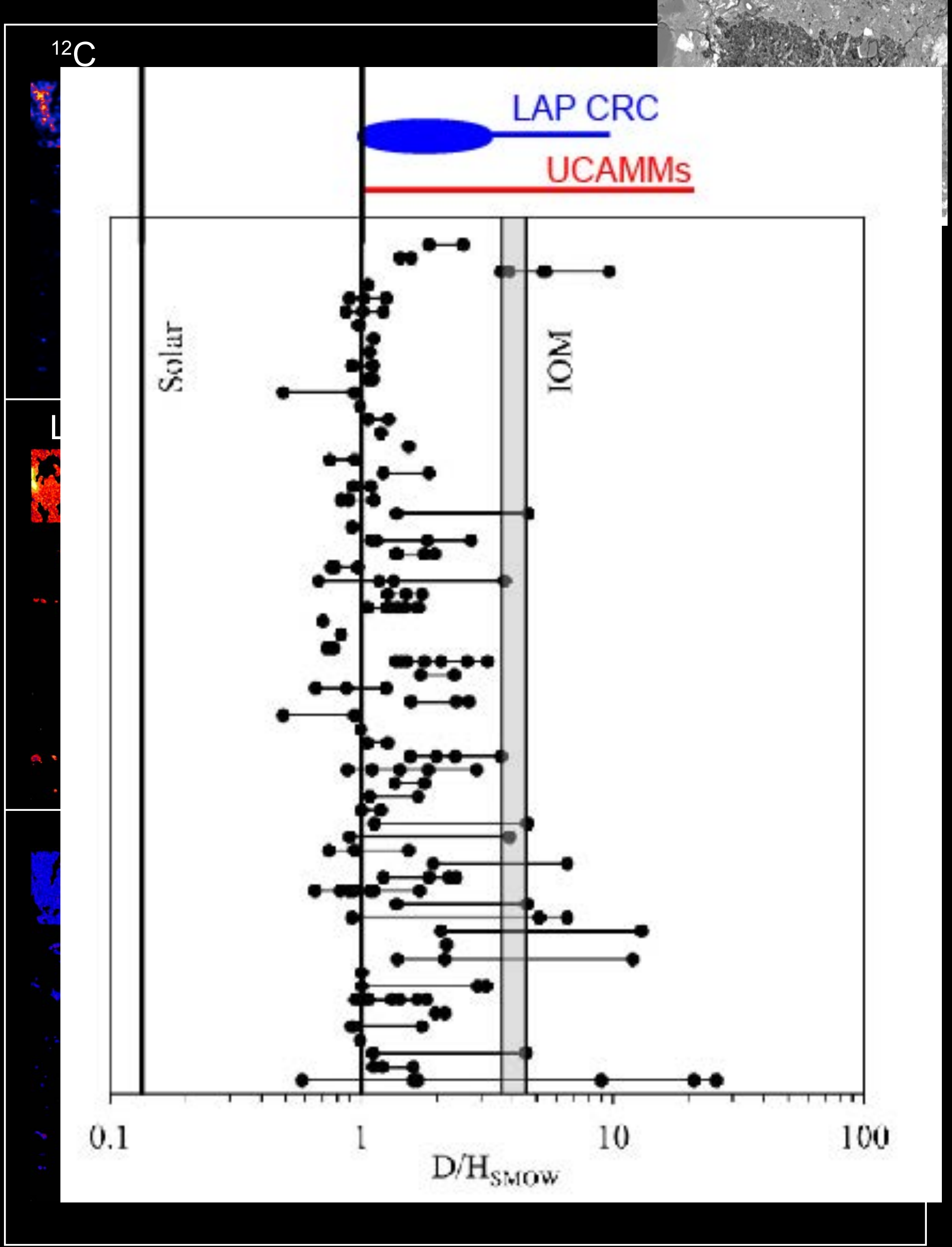
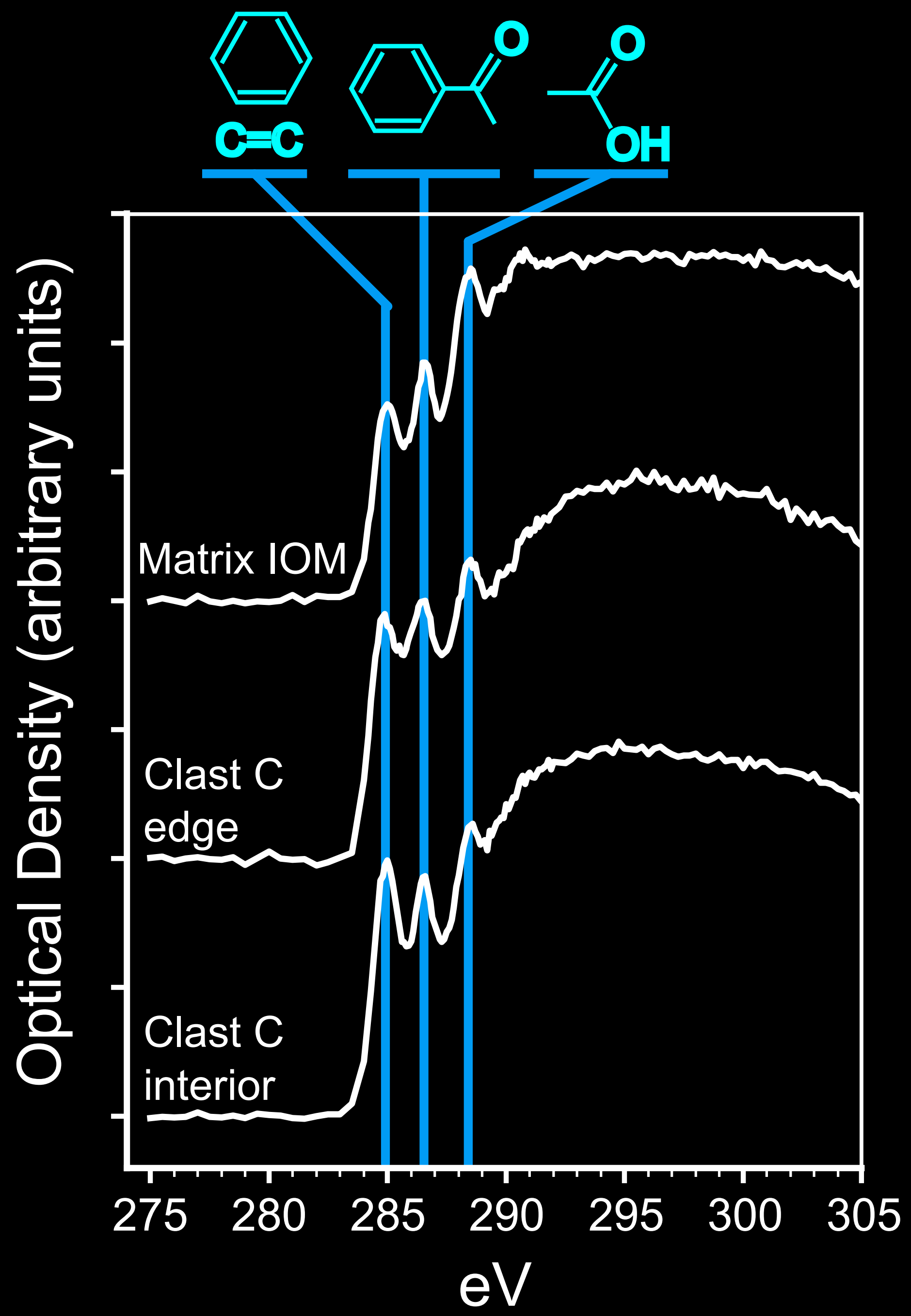
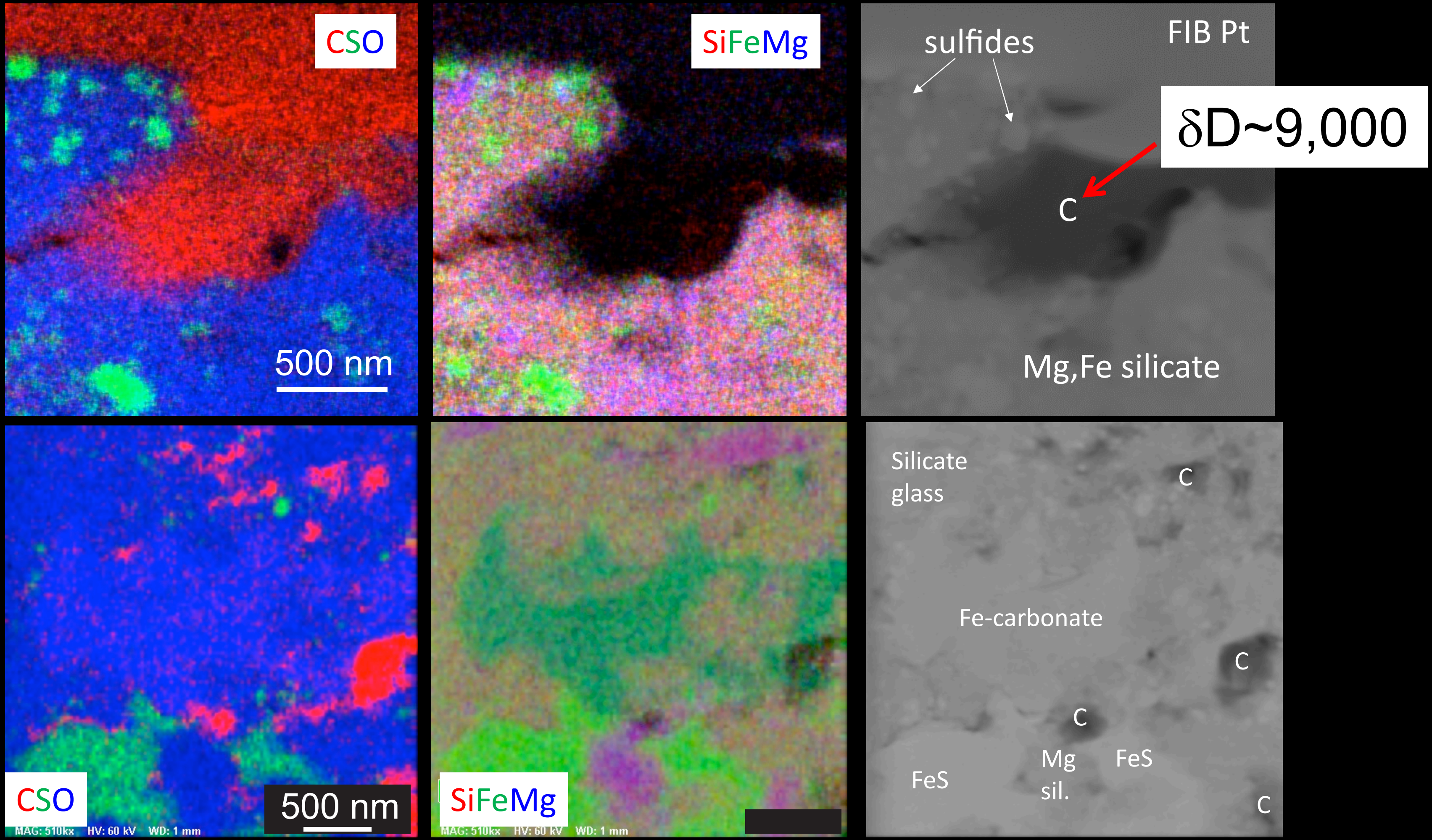


C-XANES

- Details of how material absorbs X-rays reflects chemical bonding
  - Matrix C has typical CR IOM spectrum
  - Clast shows lower abundances of O-bearing functional groups

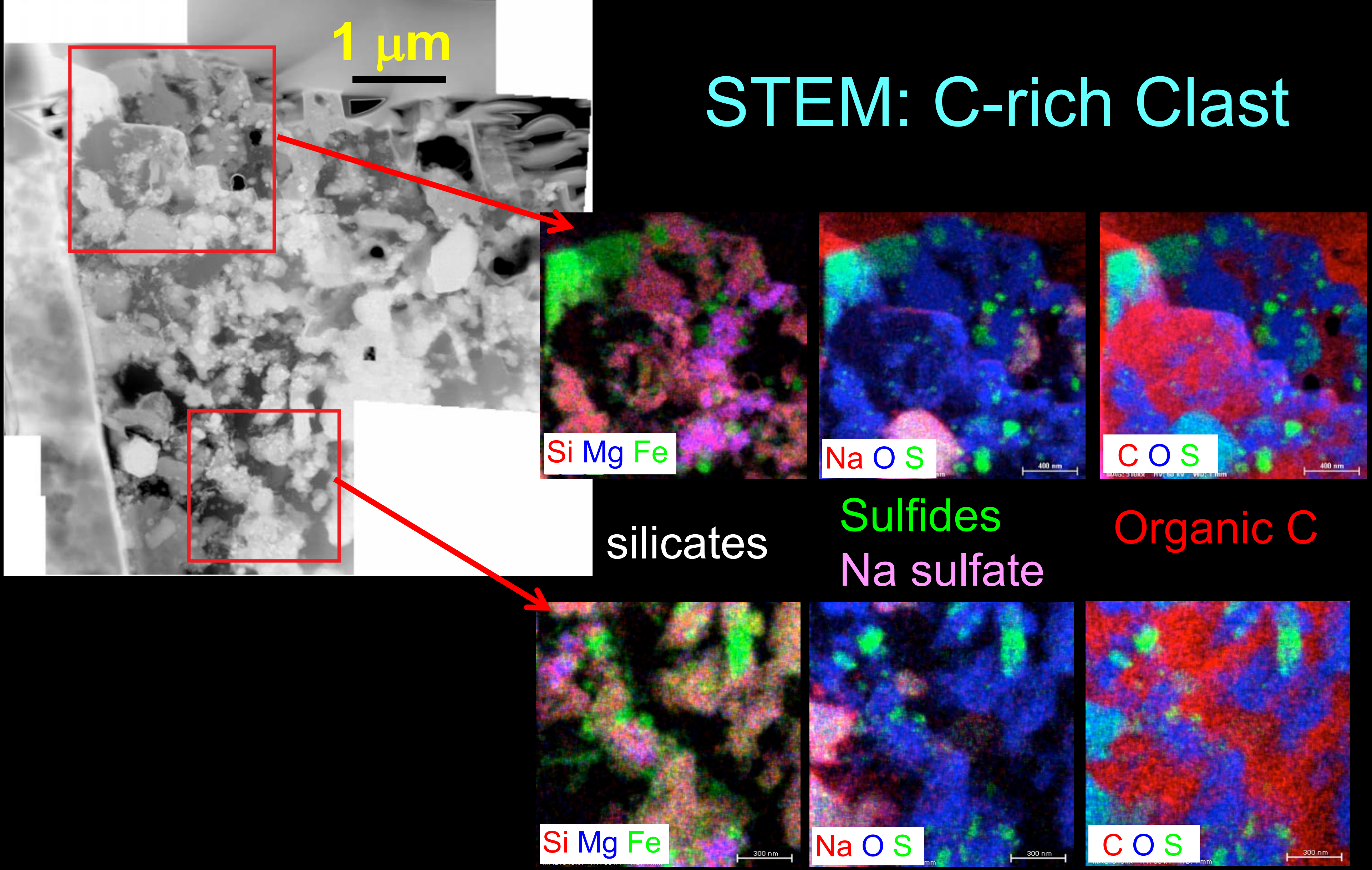


STEM: Matrix



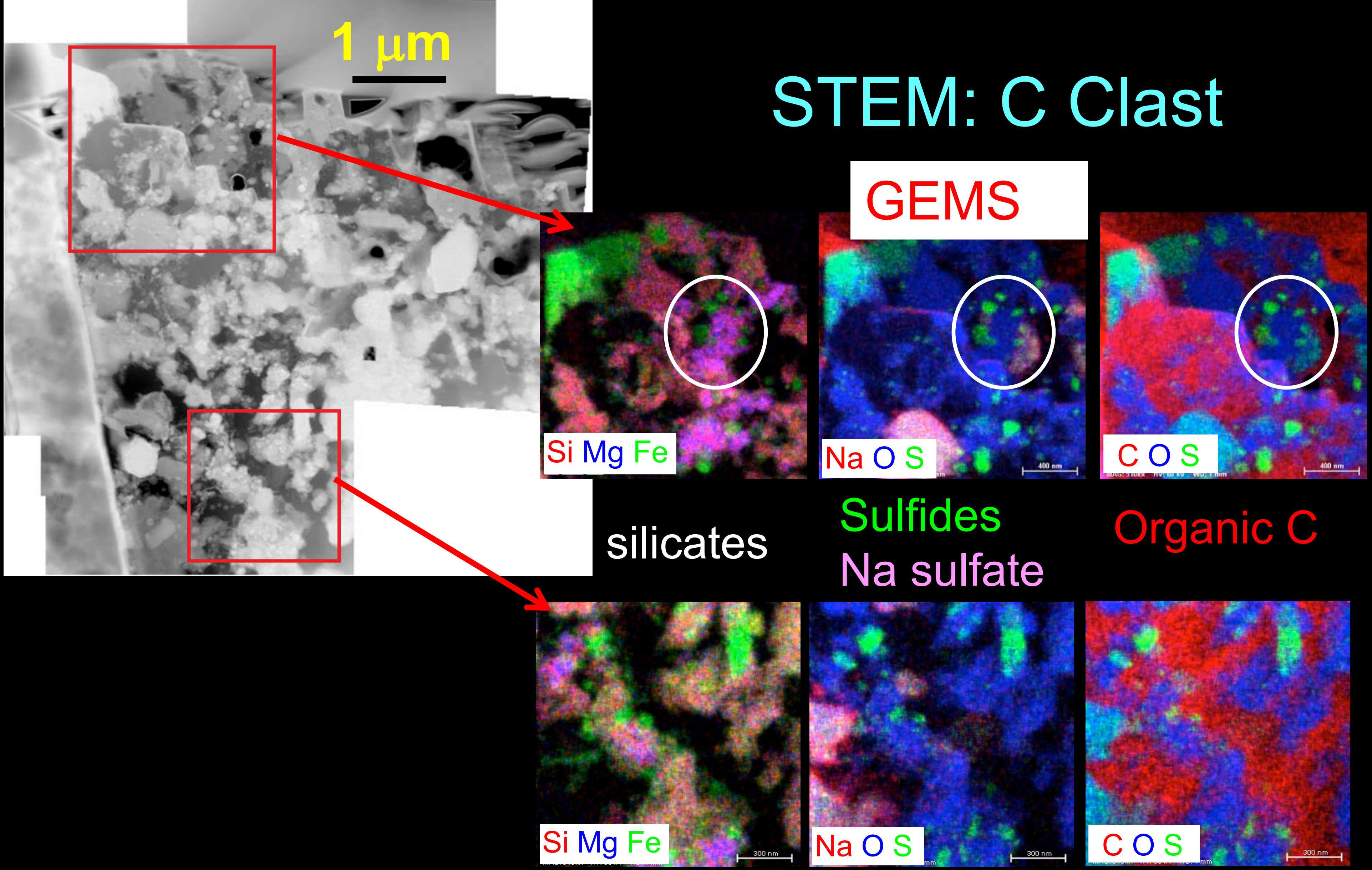
- Silicates, glass, sulfides, carbonates
- No sulfates

STEM: C-rich Clast



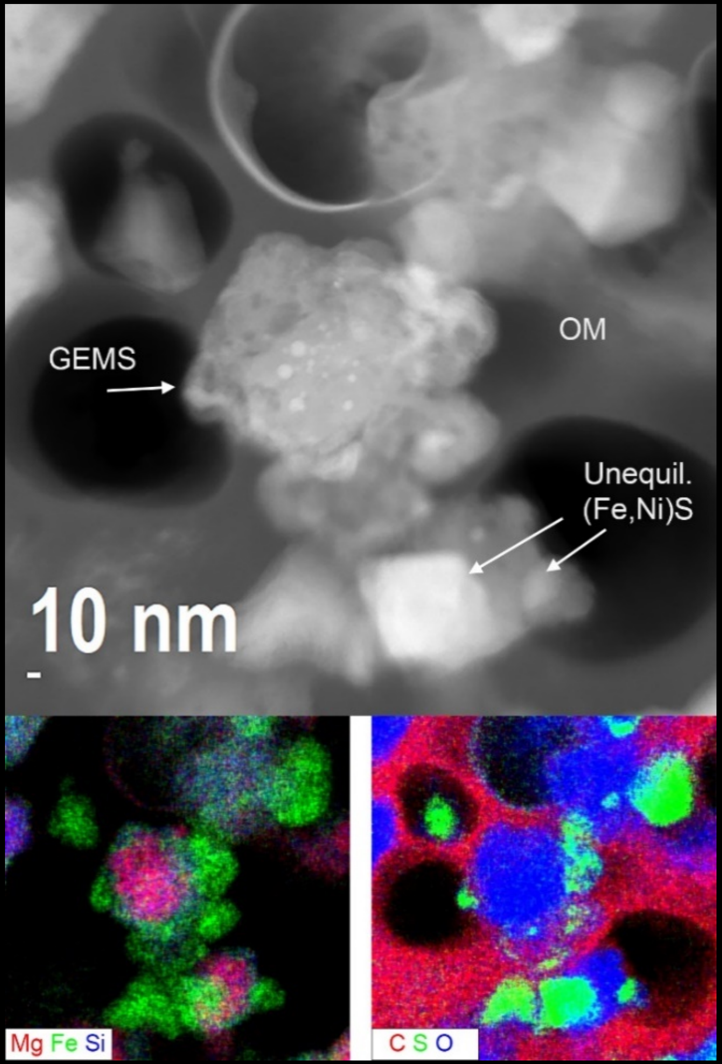
Extremely fine-grained and high porosity

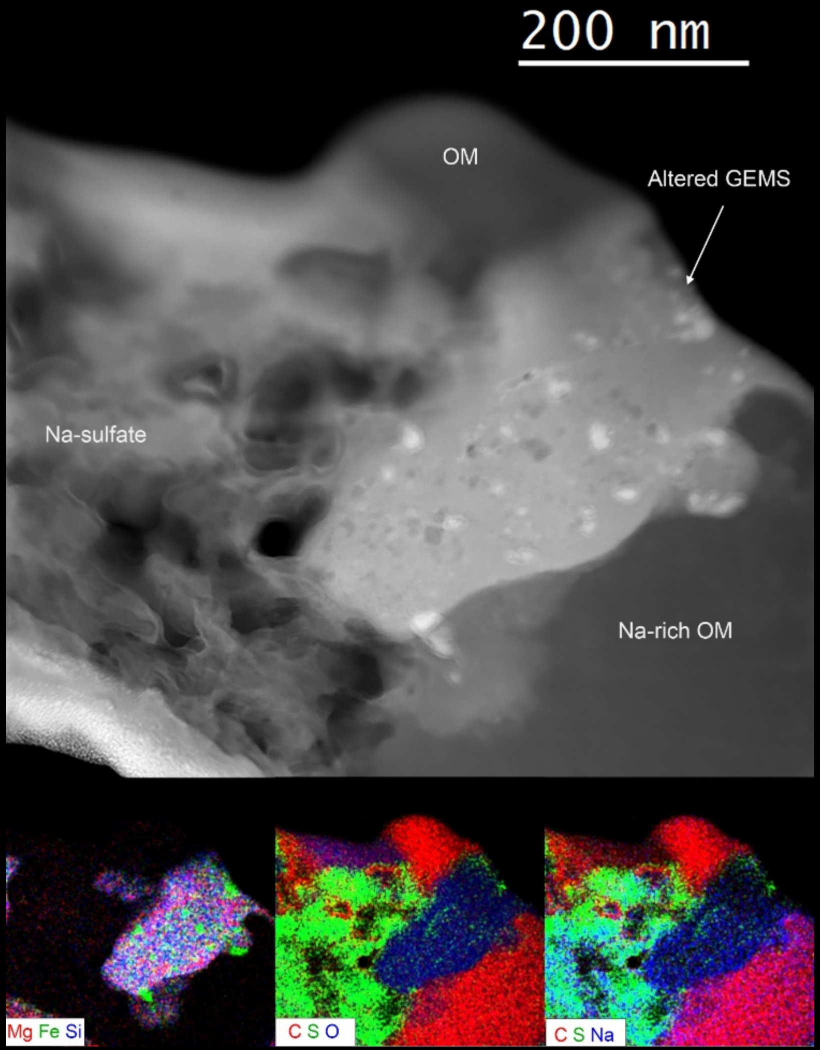
STEM: C Clast



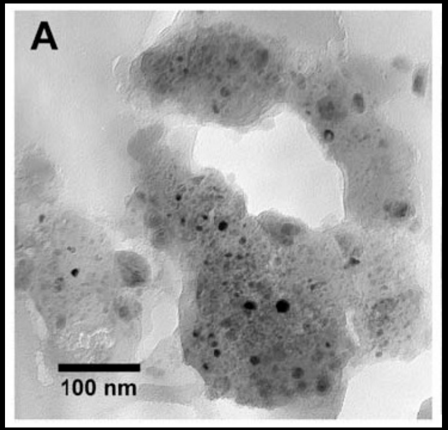
Extremely fine-grained and high porosity

GEMS (Glass with Embedded Metal and Sulfides)

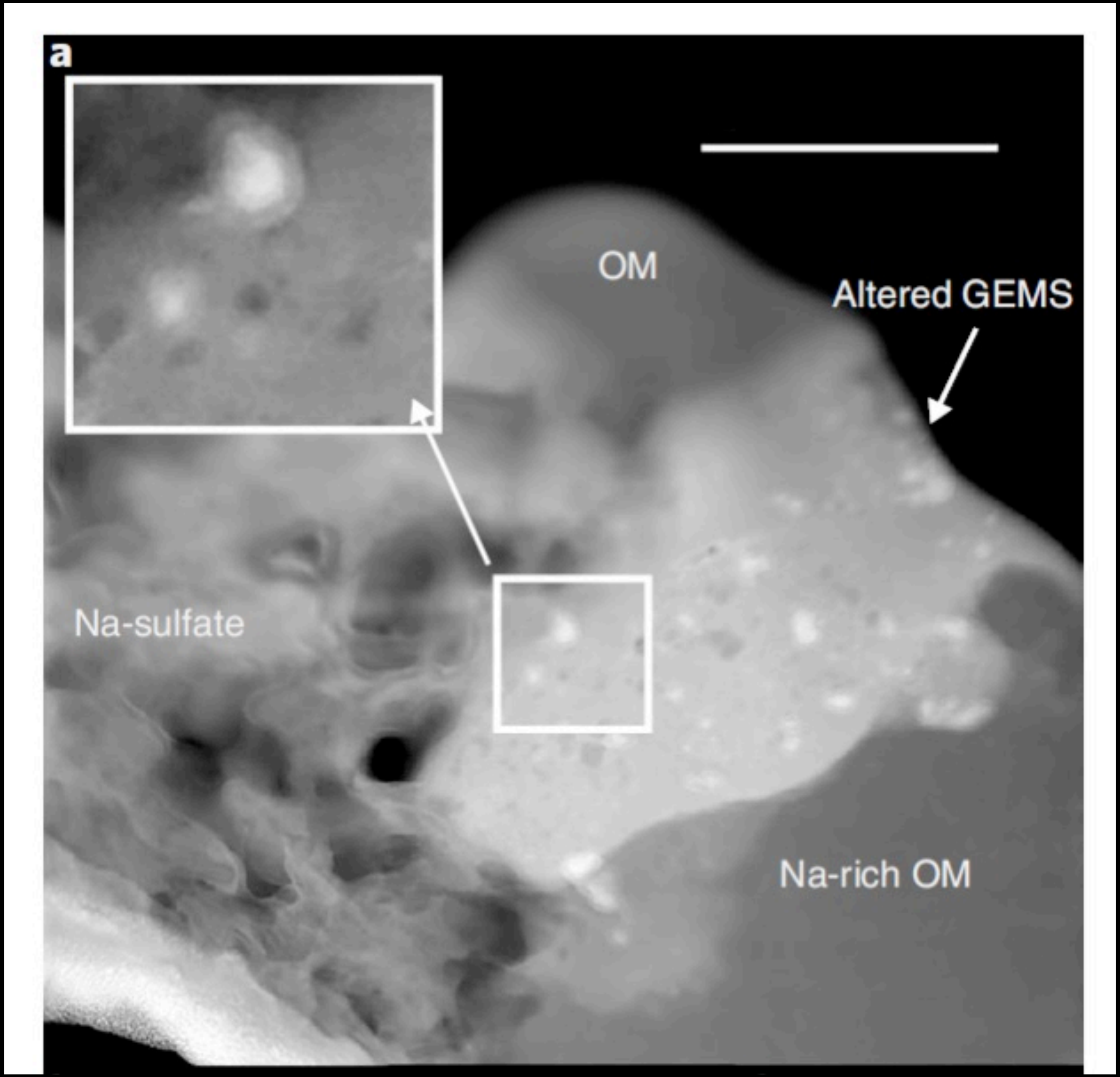




GEMS in IDP

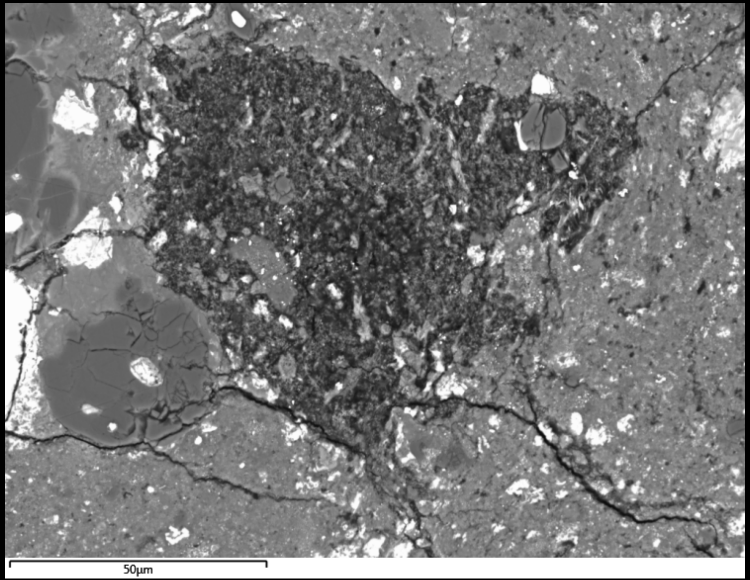


- Common in IDPs, ultracarbonaceous micrometeorites
- Extremely rare/absent in chondrites



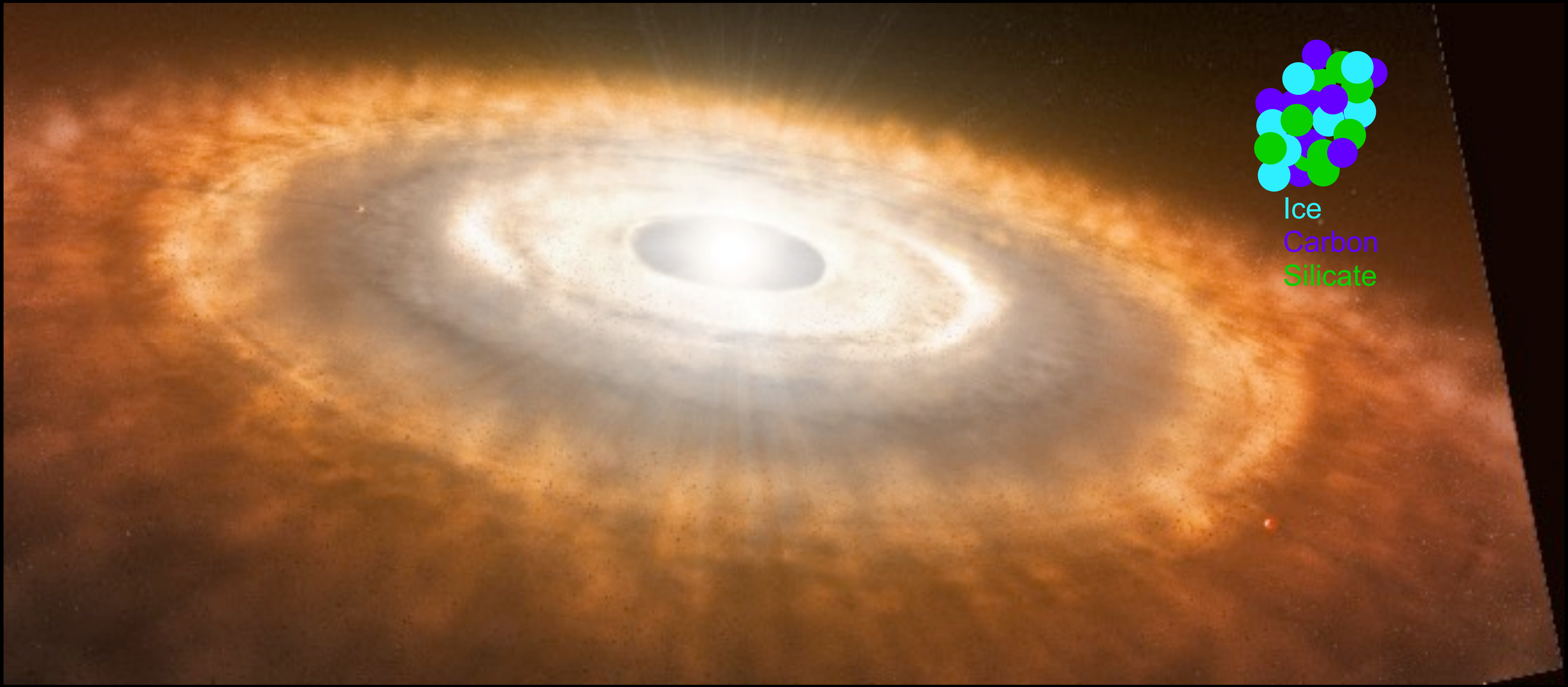
- Some early signs of aqueous alteration observed in some GEMS

C-rich Clast

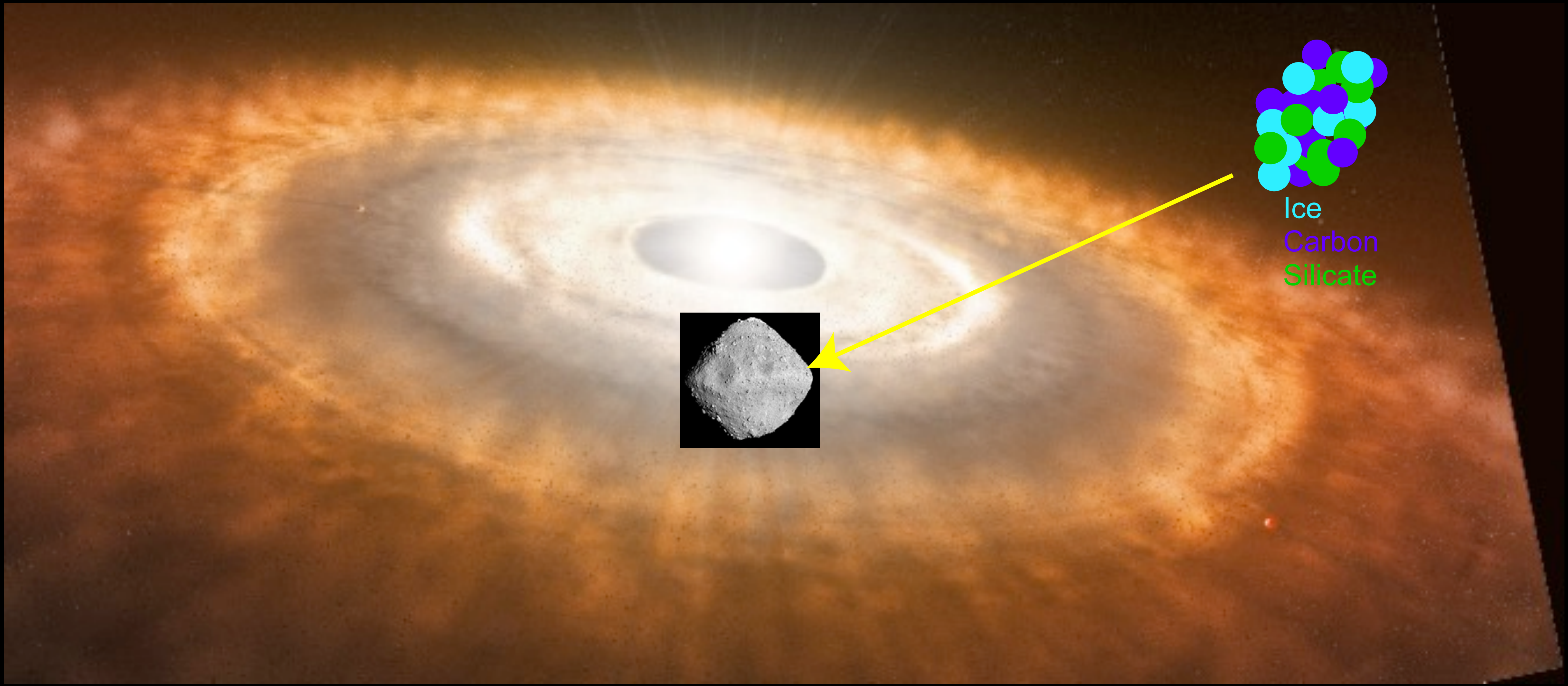


- Distinct from other matrix materials
  - >50 wt% C, highly porous
  - OM isotopically and chemically distinct from matrix OM
  - Higher abundance of presolar silicate grains
  - ^{16}O-poor Na-rich sulfates
  - GEMS
- Accreted onto a CR parent body as distinct object
- Looks ***a lot*** like UCAMMS, thought to be cometary in origin, but present in an asteroid!

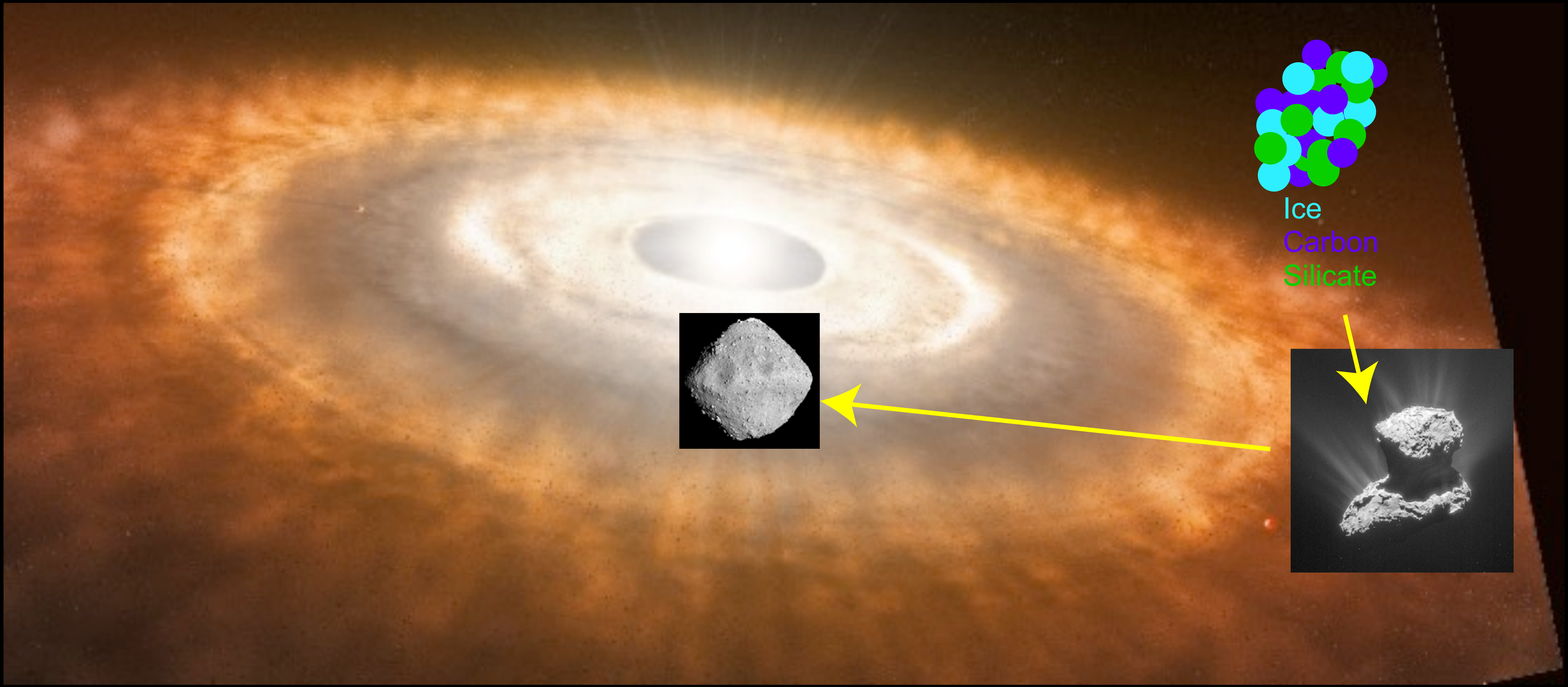
Origin of C-rich Clast



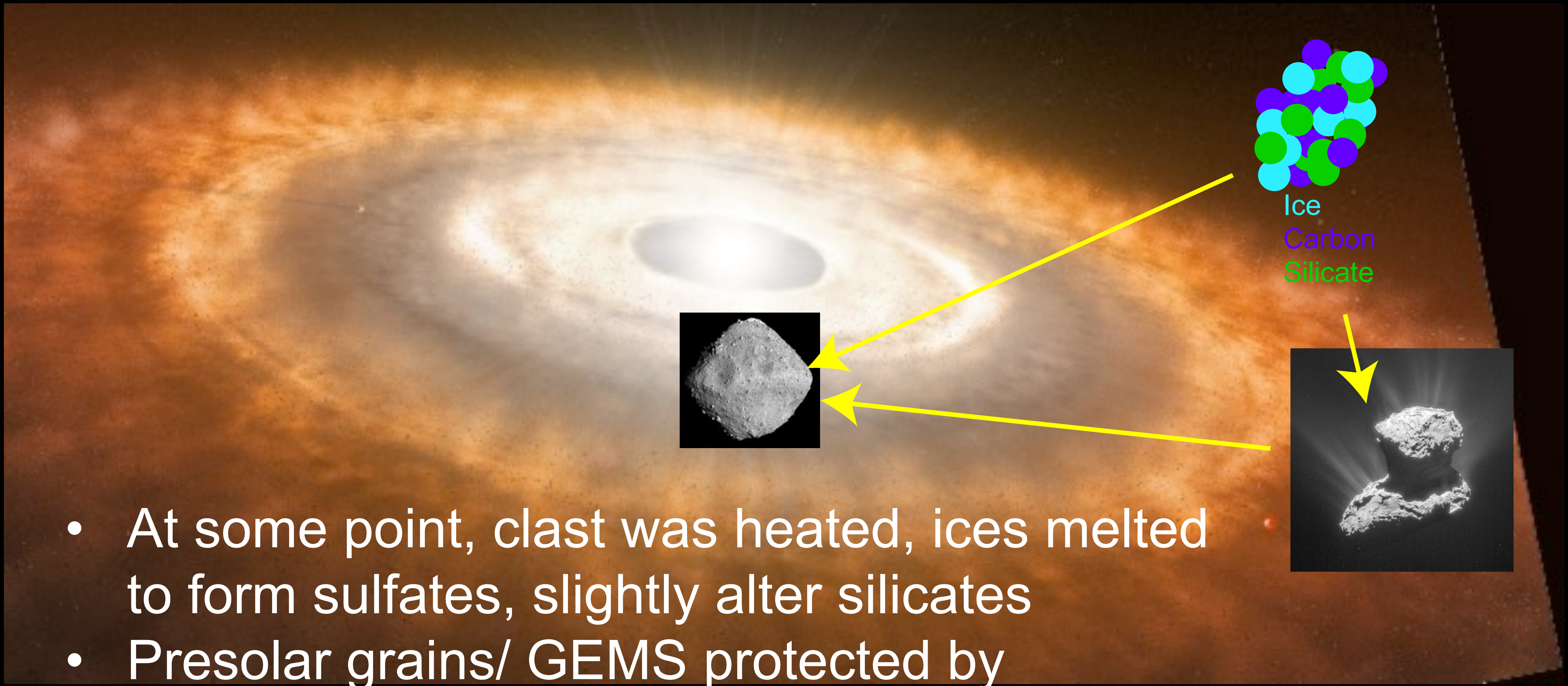
Origin of C-rich Clast



Origin of C-rich Clast

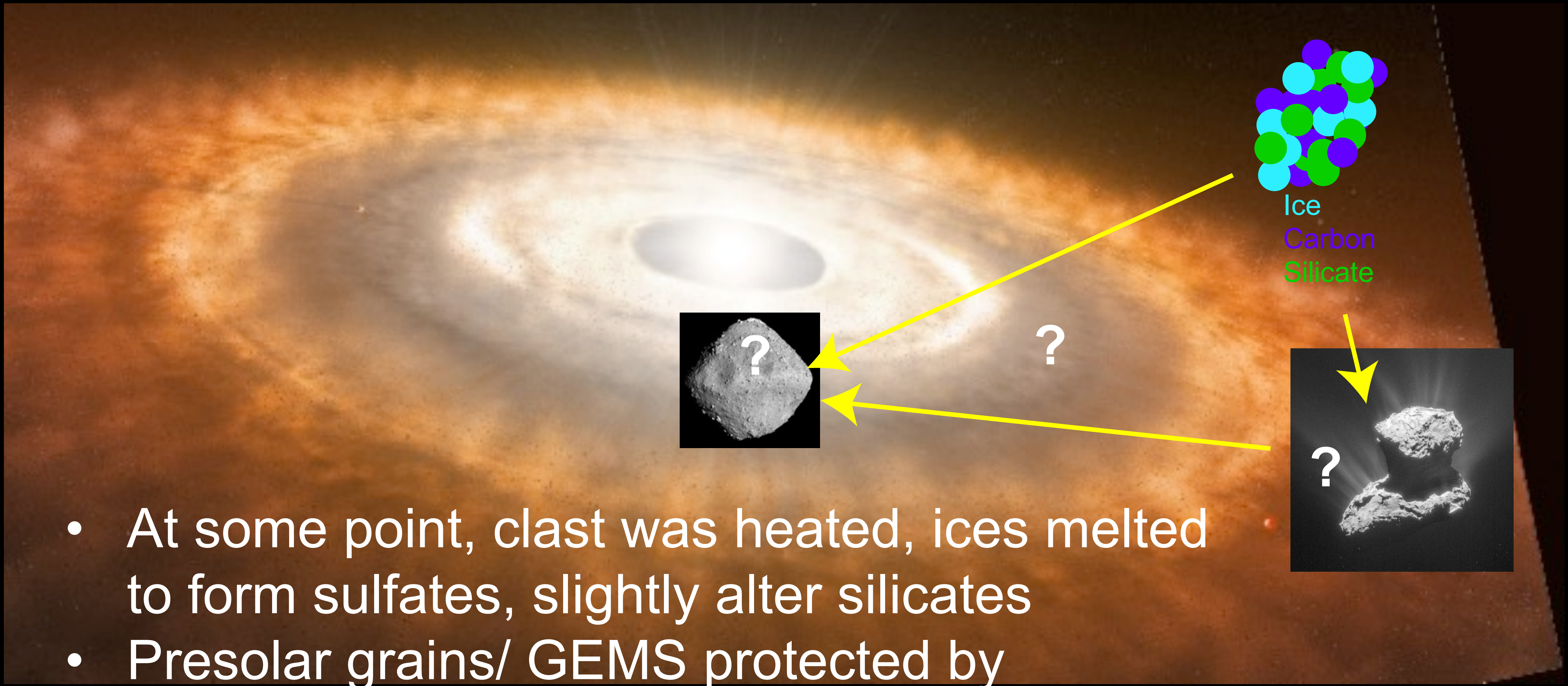


Origin of C-rich Clast



- At some point, clast was heated, ices melted to form sulfates, slightly alter silicates
- Presolar grains/ GEMS protected by abundant carbon

Origin of C-rich Clast



- At some point, clast was heated, ices melted to form sulfates, slightly alter silicates
- Presolar grains/ GEMS protected by abundant carbon

Implications

- Presence of cometary clast in a C chondrite indicates inward transport of C-rich icy dust during time of chondrite accretion
  - Outward transport of inner SS material to comet accretion region already well established from *STARDUST* results

- Preservation of chemically fragile materials (e.g., sulfates) with record of early solar system ices!
  - Such materials unlikely to survive atmospheric entry and/or extraction from Antarctic snow/ice in IDPs or UCAMMs

- Need dedicated searches for similar materials in other C chondrites (and material returned from asteroids Bennu and Ryugu by OSIRIS-REx and Hayabusa2!)

THANKS!