Nuclei in the Cosmos School
2025

COSMOCHEMISTRY

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Cosmochemistry: Presolar Grains/Stardust

Part 4: Presolar Grain Classification

Dr. Sheri Singerling

NIC School 2025

Day 2

Classifying Presolar Grains

- We group presolar grains based on: 1) mineral type, 2) isotopic compositions

Mineral types

Carbonaceous

- Nanodiamond (C)
- Silicon carbide (SiC)
- Graphite (C)

Oxides

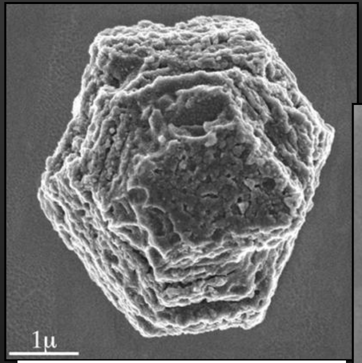
- Spinel ($MgAl_2O_4$)
- Corundum (Al_2O_3)
- Titanium oxide (TiO_2)
- Hibonite ($CaAl_{12}O_{19}$)
- Chromite ($FeCr_2O_4$)

Silicates

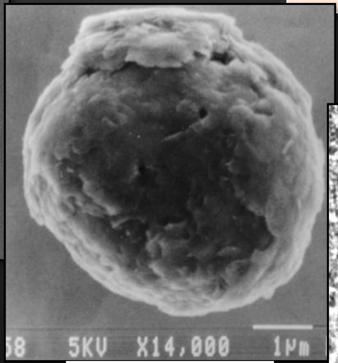
- Olivine $(Mg,Fe)_2SiO_4$
- Pyroxene $(Ca,Mg,Fe)_2Si_2O_6$
- Non-stoichiometric

Minors/Subgrains

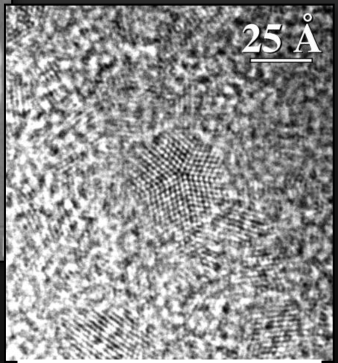
- Refractory carbides (TiC, ZrC, MoC, FeC)
- Silicon nitride (Si_3N_4)
- Titanium nitride (TiN)
- Magnetite (Fe_3O_4)
- Fe,Ni metal
- Silica (SiO_2)
- Sulfides (FeS, CaS)



Silicon Carbide

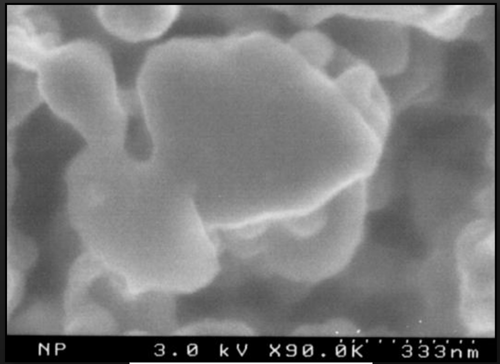


Graphite



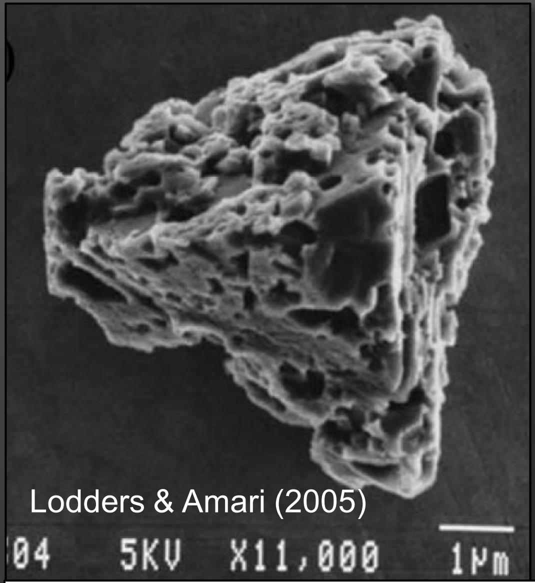
Nanodiamond

Oxides



Silicates

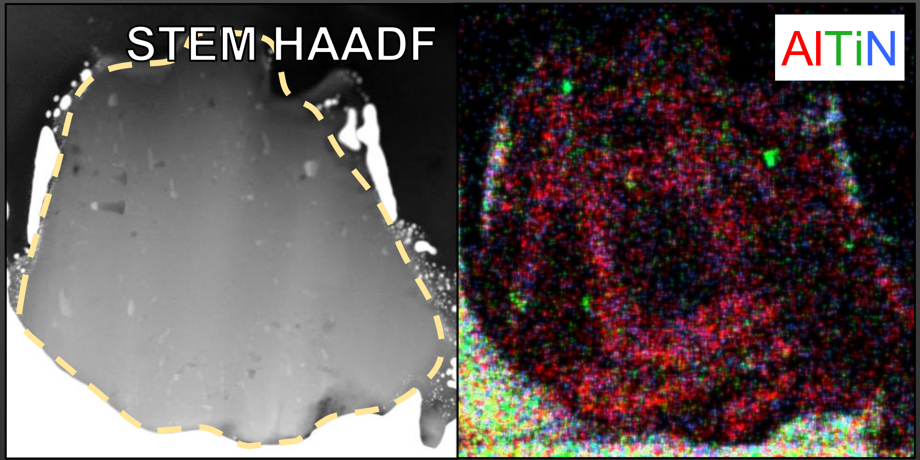
SiC

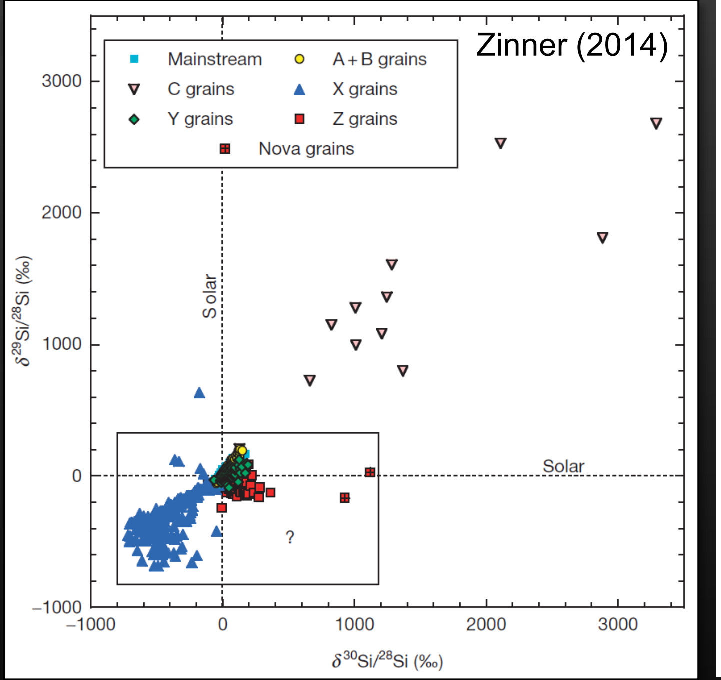


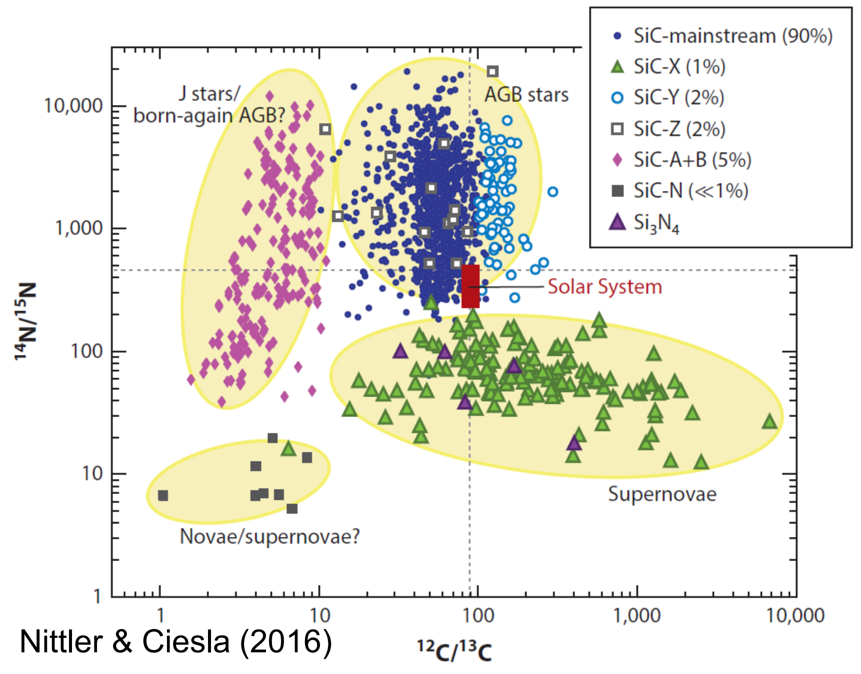
Groups	
AGBs	• Mainstream
AGBs; Low metallicity	• Y
AGBs; Low metallicity	• Z
Type II SNe	• X
Type II SNe	• C
Type Ia SNe	• PNG
Exotic stars? (Wolf Rayet, J)	• AB

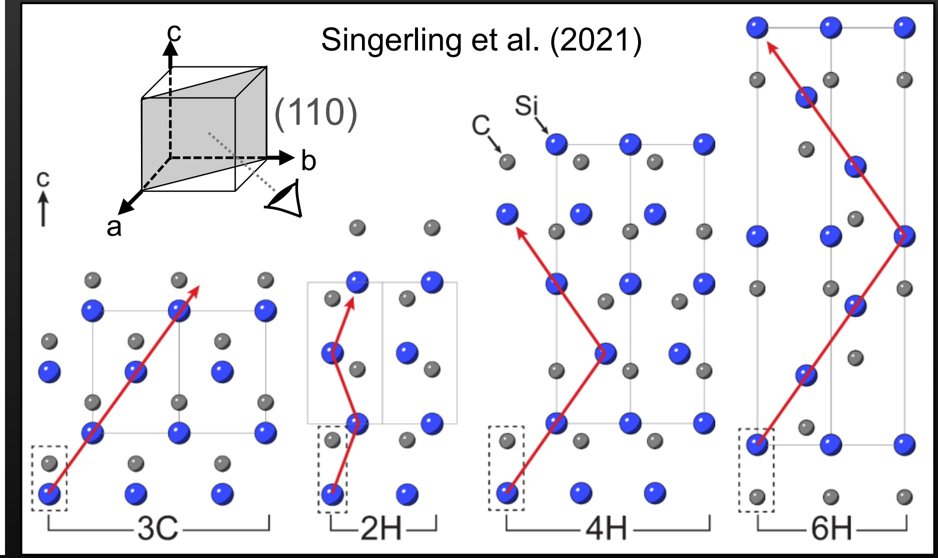
Common Textural/Elemental Features

- Subgrains = TiC and/or Fe,Ni metal
- Polytypes almost always 3C or 2H









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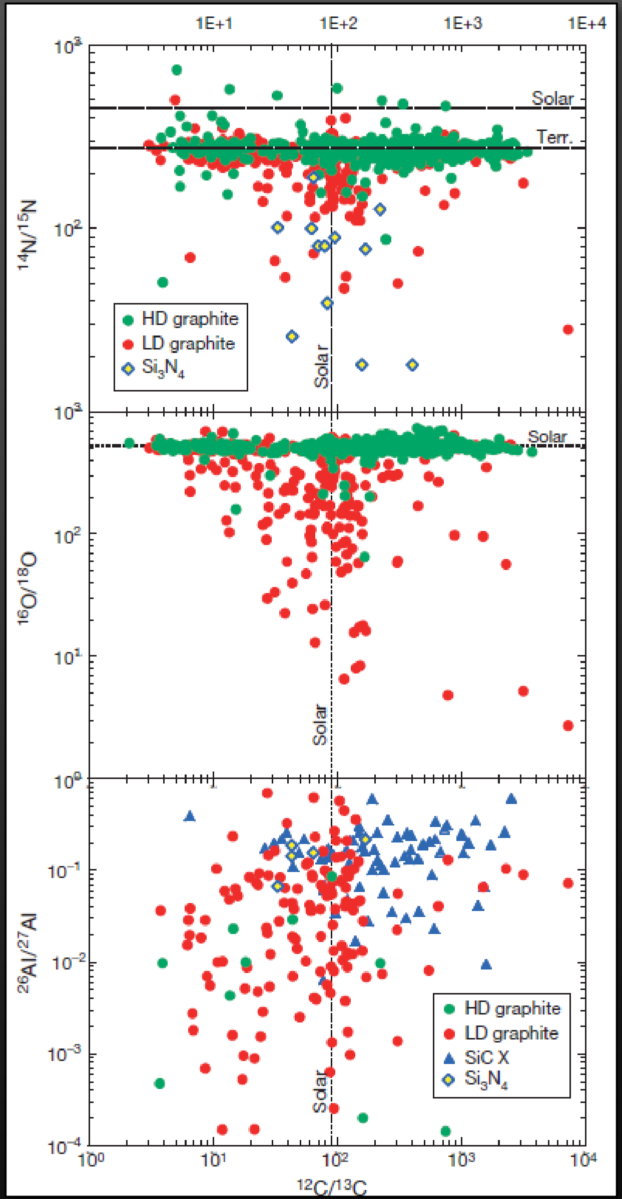


Zinner (2014)

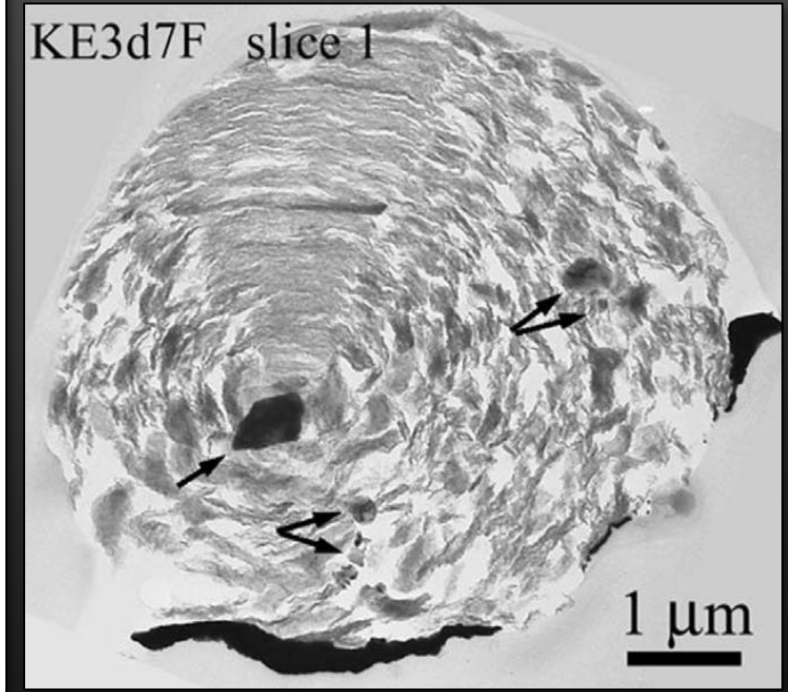
AGBs ← • High density (HD)

Type II SNe ← • Low density (LD)

Groups
• High density (HD)
• Low density (LD)

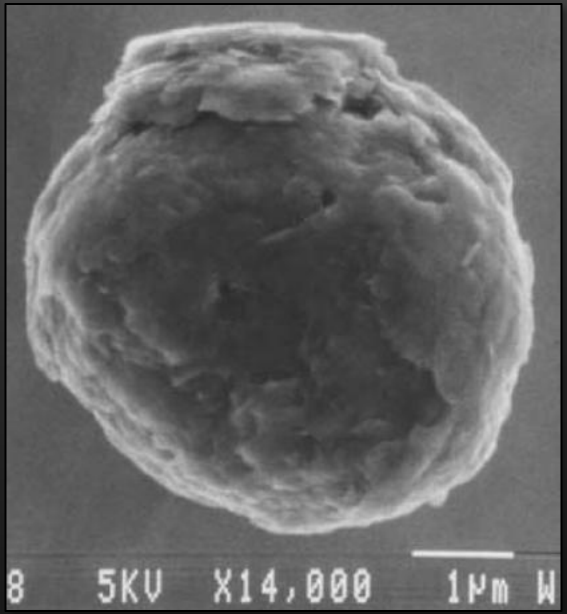
Common Textural/Elemental Features

- Subgrains = TiC, ZrC, and/or MoC
- Textural groups:
  - Cauliflower = LD, poorly crystallized
  - Onion = HD, well-crystallized

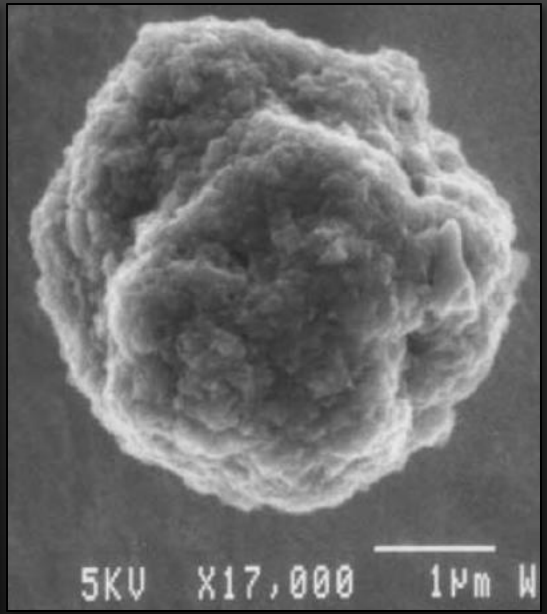


Croat et al. (2003)

Onion

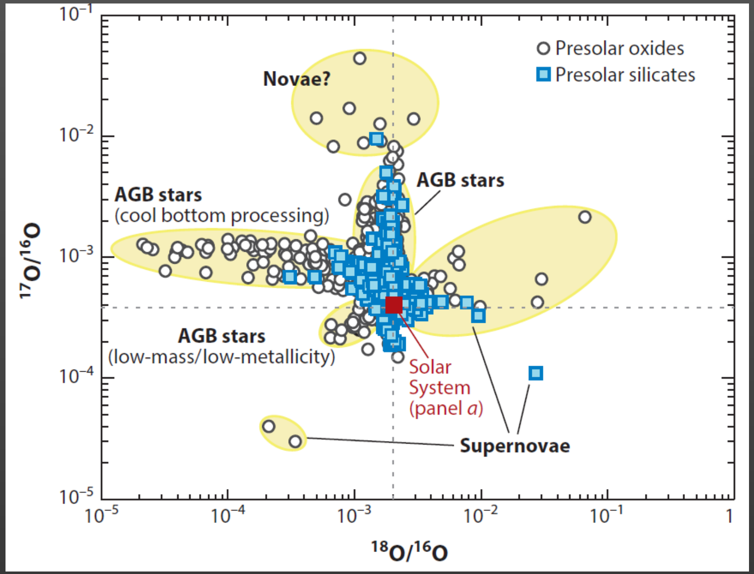


Cauliflower



Lodders & Amari (2005)

Oxides



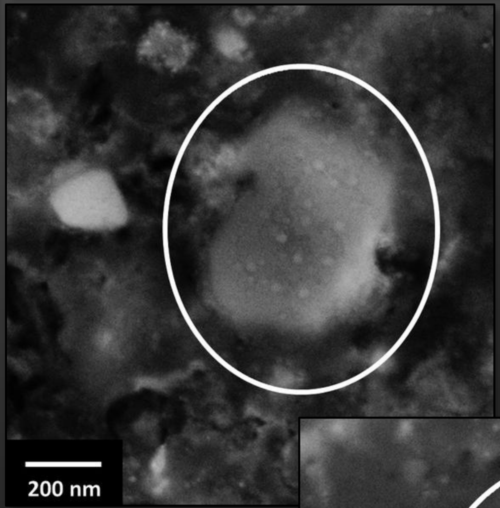
Nittler & Ciesla (2016)

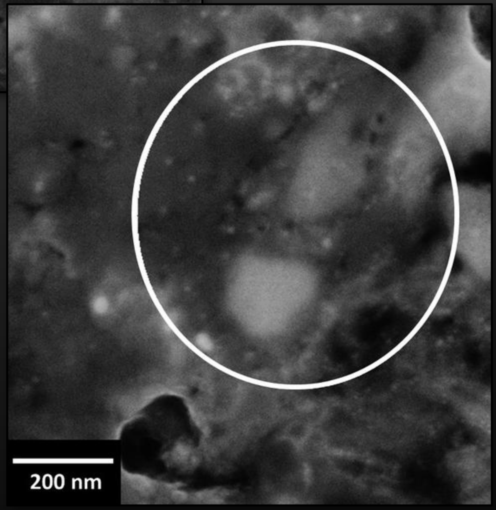
	Groups
Type Ia SNe?	Extreme 1
RGBs and AGBs	1
AGBs with CBP and/or low mass	2
AGBs with low mass and metallicity	3
AGBs with low mass + 3DUP, AGBs with high metallicity, or Type II SNe	4

Groups 2, 3, 4: AGBs

Common Textural/Elemental Features

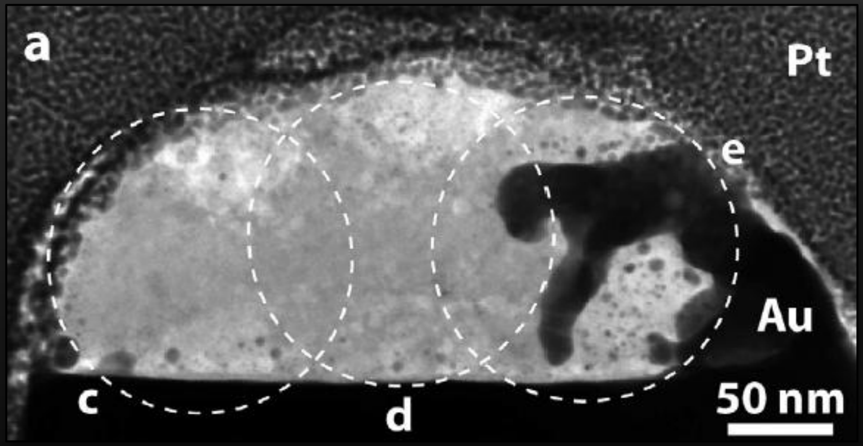
- Subgrains and compositional heterogeneities are rare
- Tend to be crystalline rather than amorphous/glassy

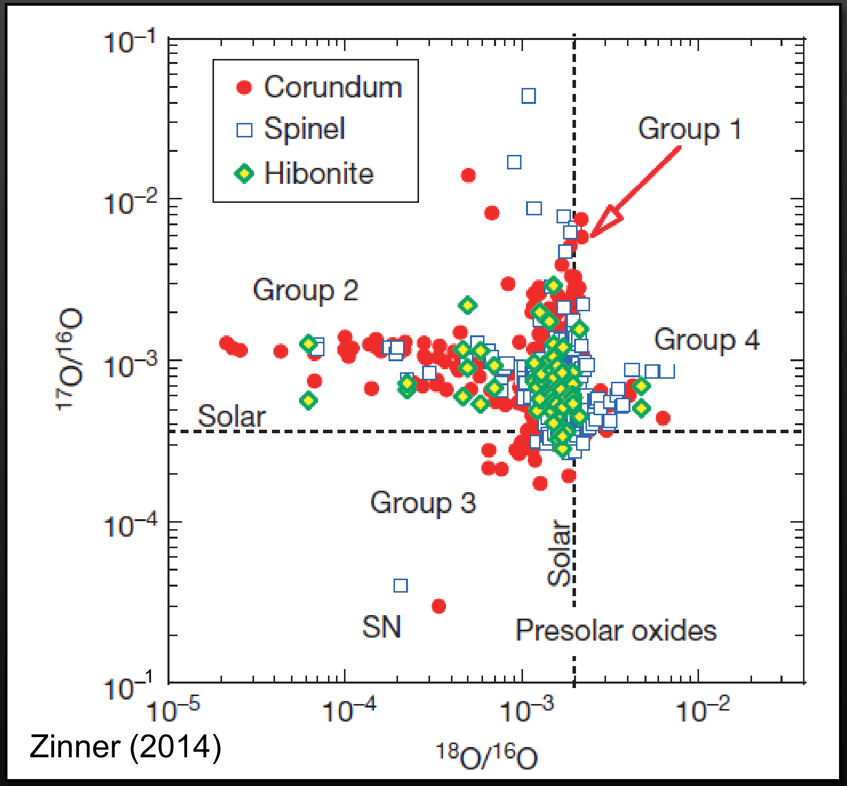




Leitner et al. (2020)

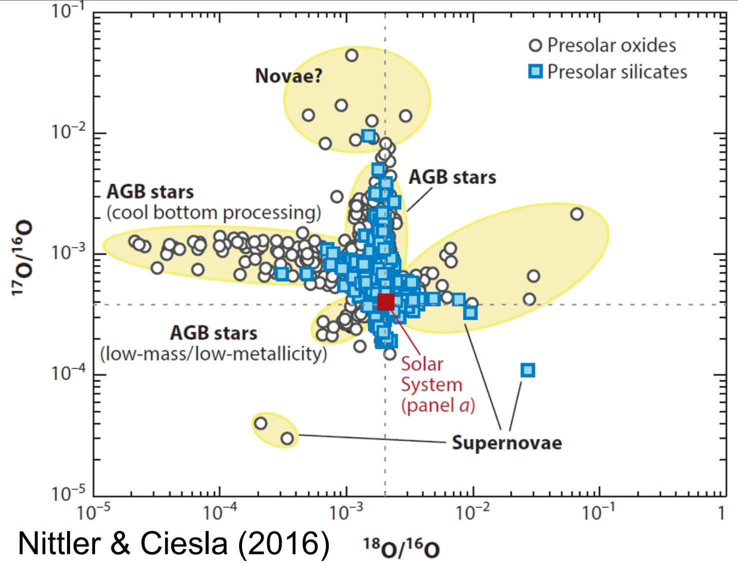
Zega et al. (2014)





Zinner (2014)

Silicates

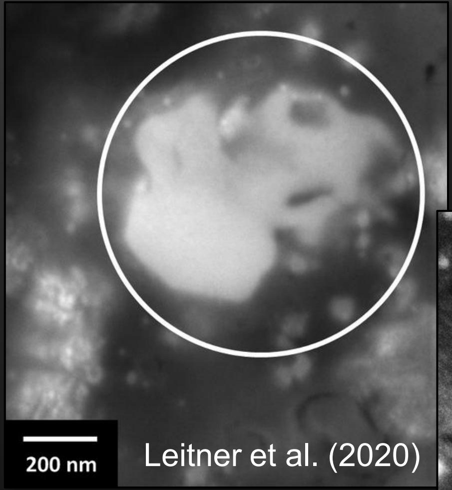


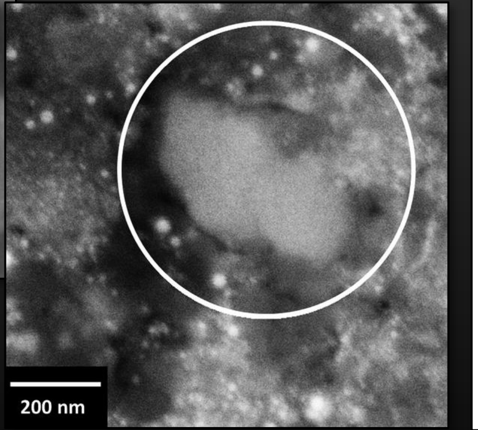
Nittler & Ciesla (2016)

Groups	
Type Ia SNe?	• Extreme 1
RGBs and AGBs	• 1
AGBs with CBP and/or low mass	• 2 (AGBs)
AGBs with low mass and metallicity	• 3 (AGBs)
AGBs with low mass + 3DUP, AGBs with high metallicity, or Type II SNe	• 4 (AGBs)

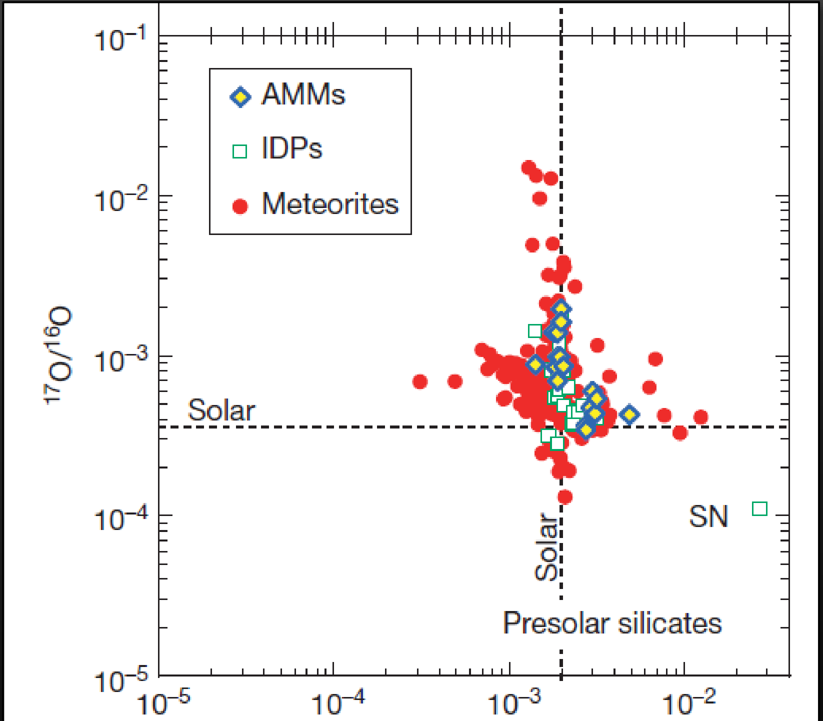
Common Textural/Elemental Features

- Subgrains rare
- Compositional heterogeneities not uncommon

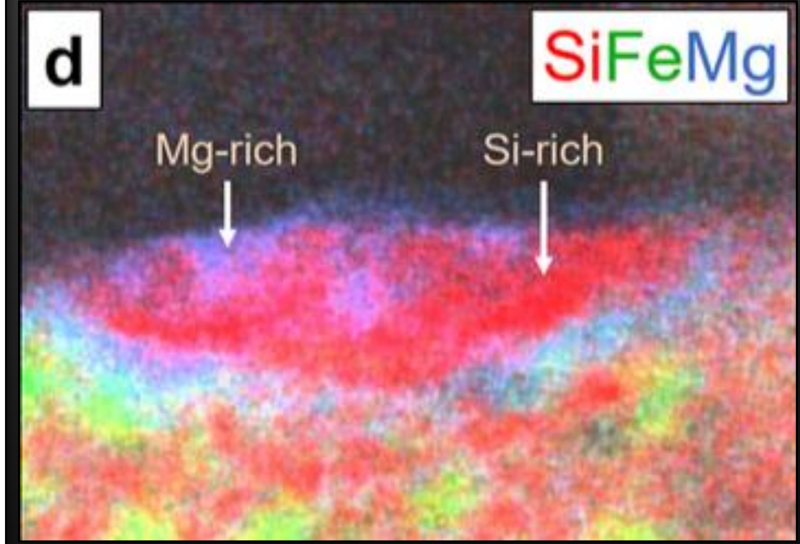




Leitner et al. (2020)

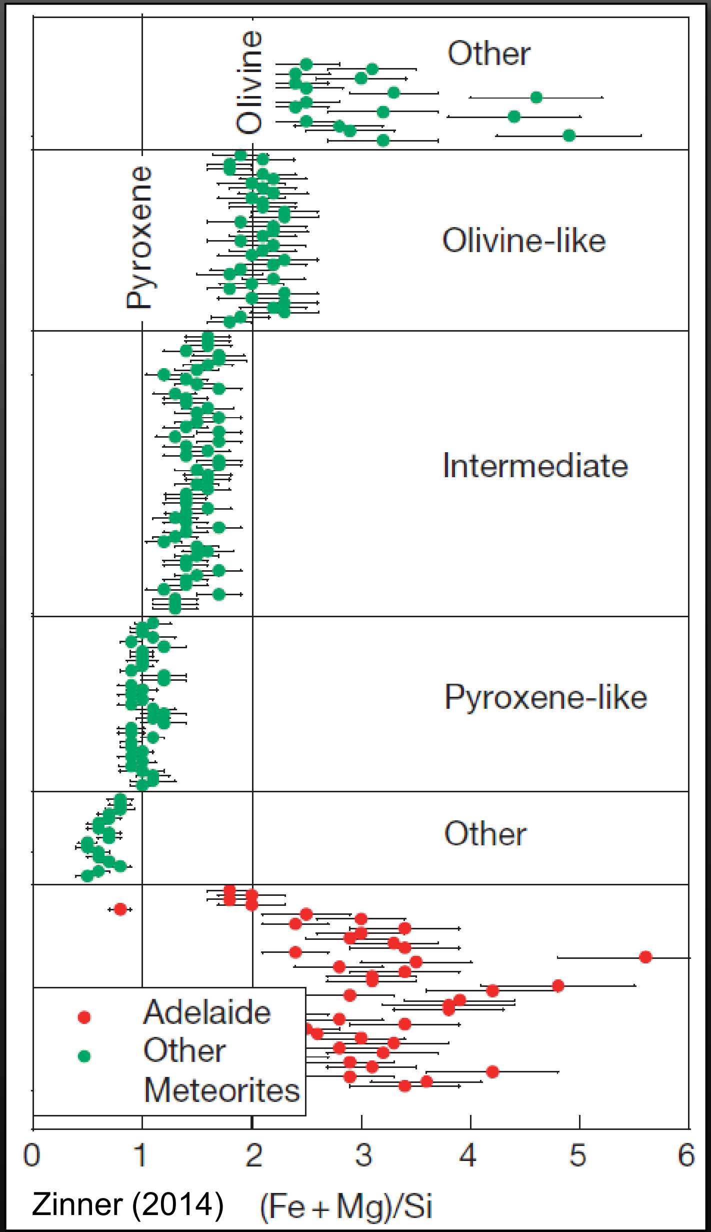


Zinner (2014)



Singerling et al. (2022)

Silicates



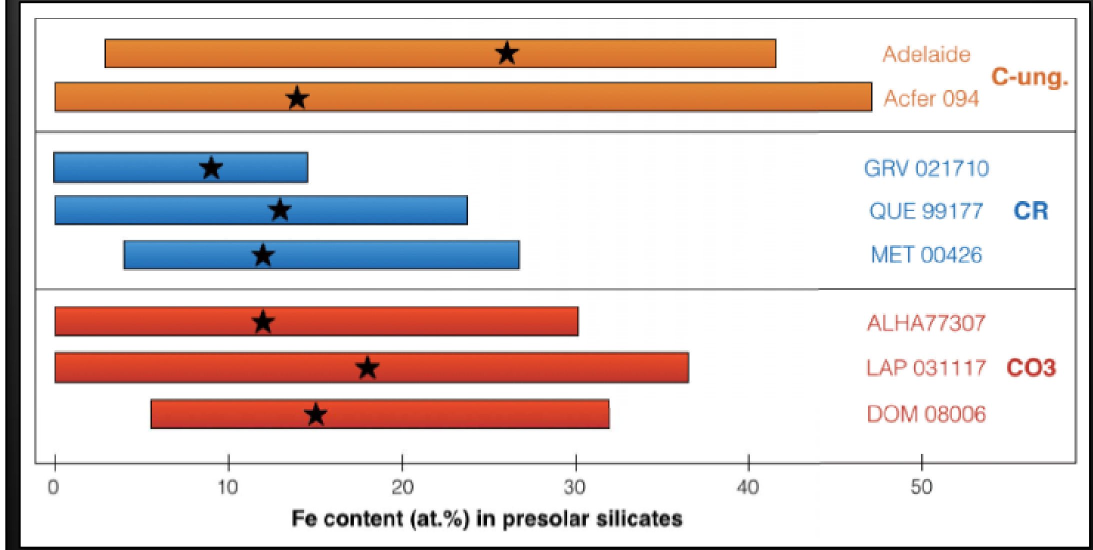
Zinner (2014)

Groups	Common Textural/Elemental Features

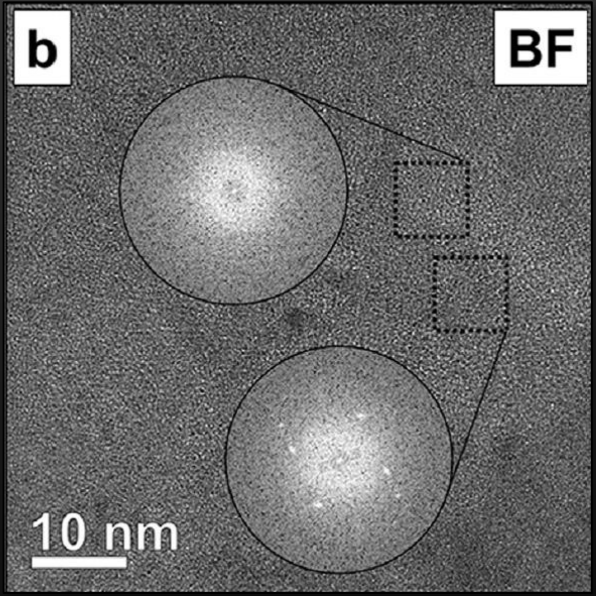
- Type Ia SNe? ← Extreme 1
- RGBs and AGBs ← 1
- AGBs with CBP and/or low mass ← 2 (AGBs)
- AGBs with low mass and metallicity ← 3 (AGBs)
- AGBs with low mass + 3DUP, AGBs with high metallicity, or Type II SNe ← 4 (AGBs)

Common Textural/Elemental Features

- Subgrains rare
- Compositional heterogeneities not uncommon
- Crystalline and amorphous/glassy
- Olivine more common than pyroxene by factor of 2–3
- Some non-stoichiometric silicates
- High Fe concentrations



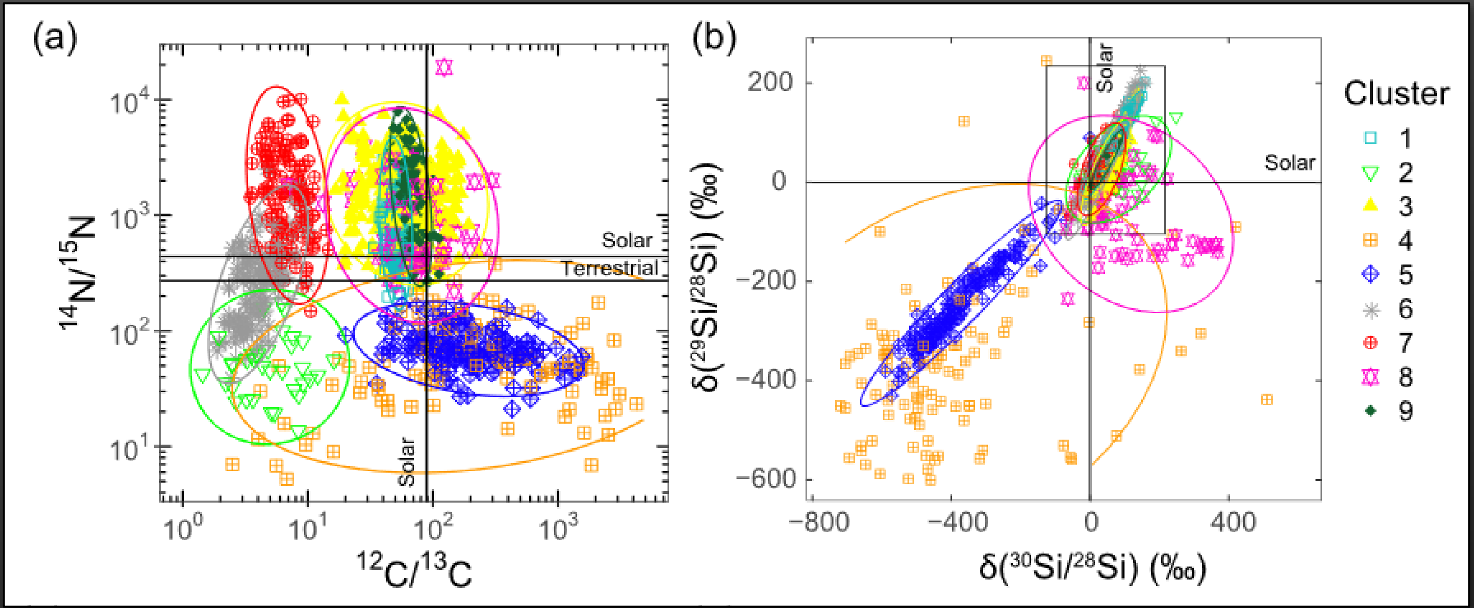
Floss & Haenecour (2016)



Singerling et al. (2022)

Big Data

- Some recent studies have used cluster analysis to group presolar SiC



Boujibar et al. (2021)

Pros
• More quantitative way to group presolar grains • Can find new groups previously overlooked

Cons
• Requires a large dataset (only SiC so far) • Could lead to misinterpretations if the algorithm is improperly understood by researchers using it

A promising tool for presolar grain researchers that could even lead to a new classification system!

Cosmochemistry: Presolar Grains/Stardust

Part 5: How to Study Presolar Grains

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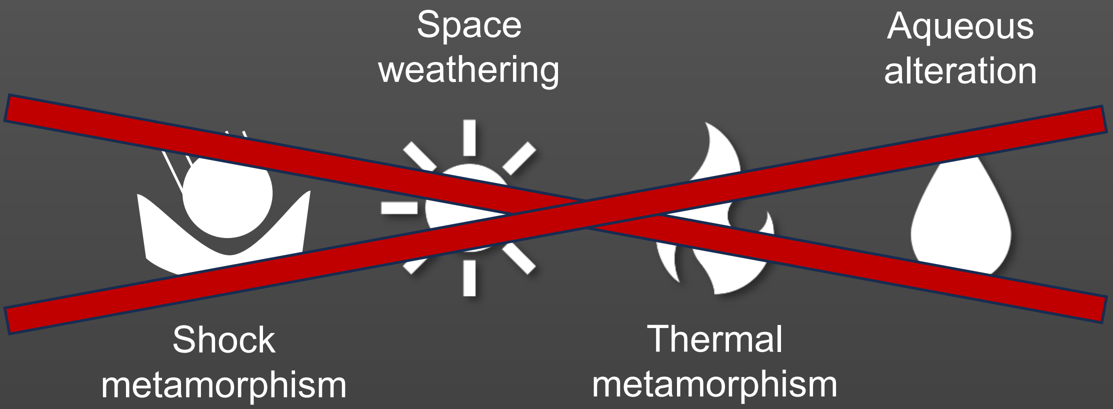
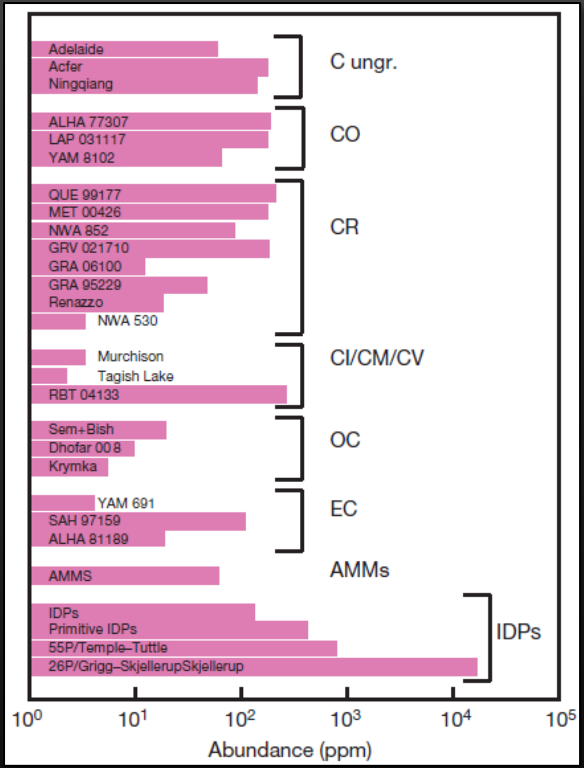
NIC School 2025

Day 2

Finding the Presolar Grains

- We find presolar grains in *pristine* samples of asteroids (meteorites) and comets (interplanetary dust particles, IDPs)





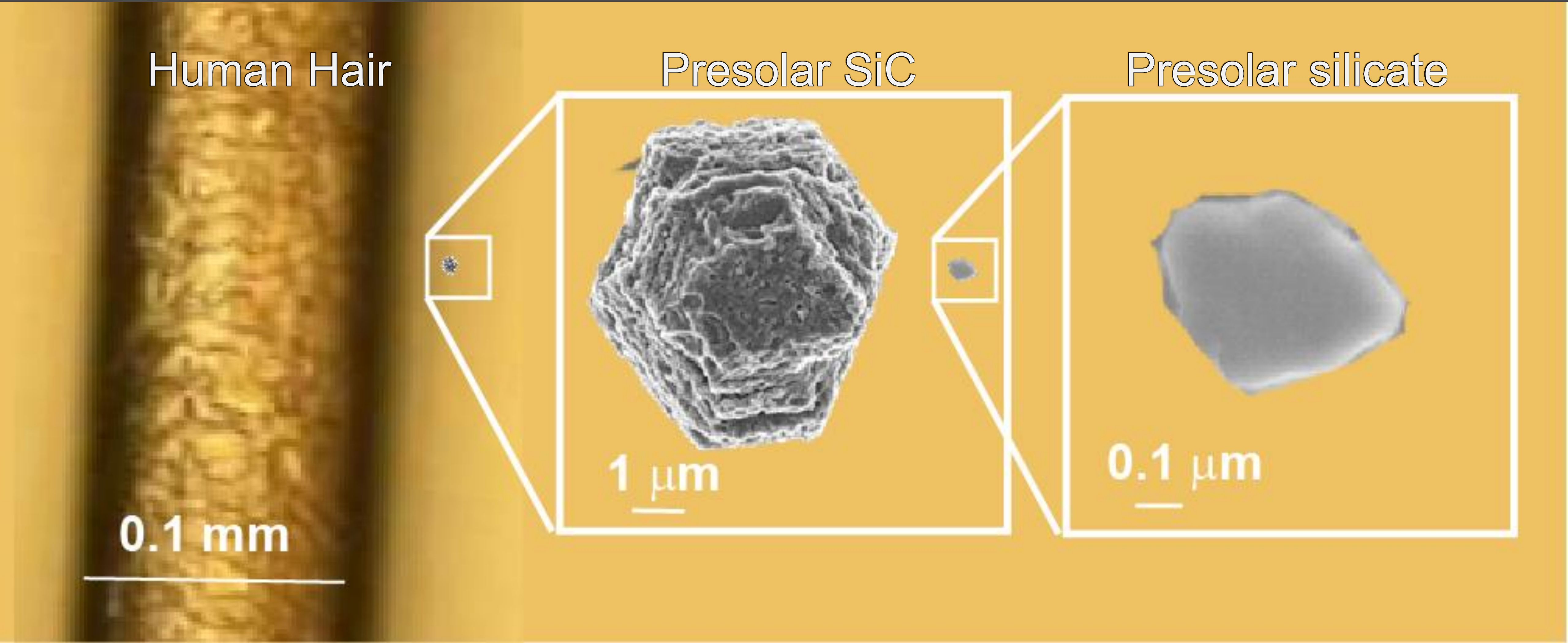
Zinner (2014)

Chondrite meteorites and IDPs are especially "rich" in presolar grains as they have **not**:

- Melted completely like the building blocks of planets
- Been heated (thermal metamorphism) from the radioactive decay of certain isotopes
- Interacted with fluid (aqueous alteration) from ices that melted during heating

Finding the Presolar Grains

- Presolar grains are small



Finding the Presolar Grains

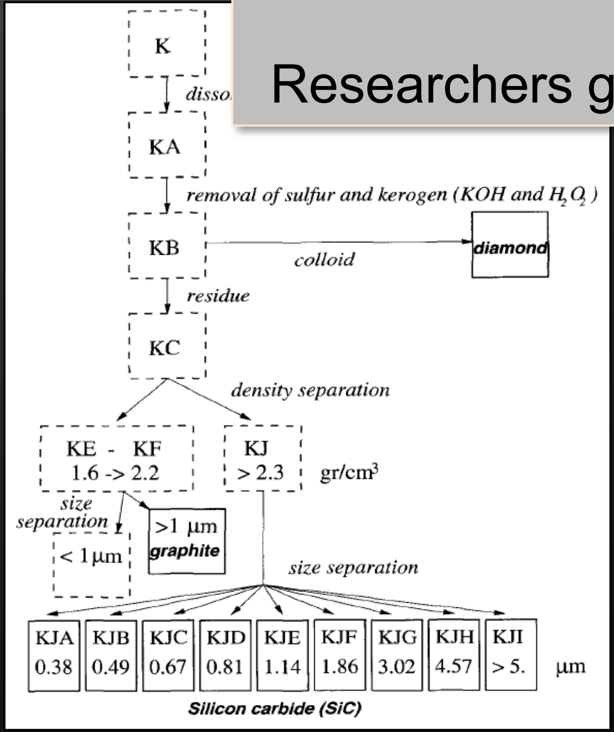
Ex situ

- How presolar grains were first found
- Burning down the haystack to find the needle
- Remove all the material that is not presolar

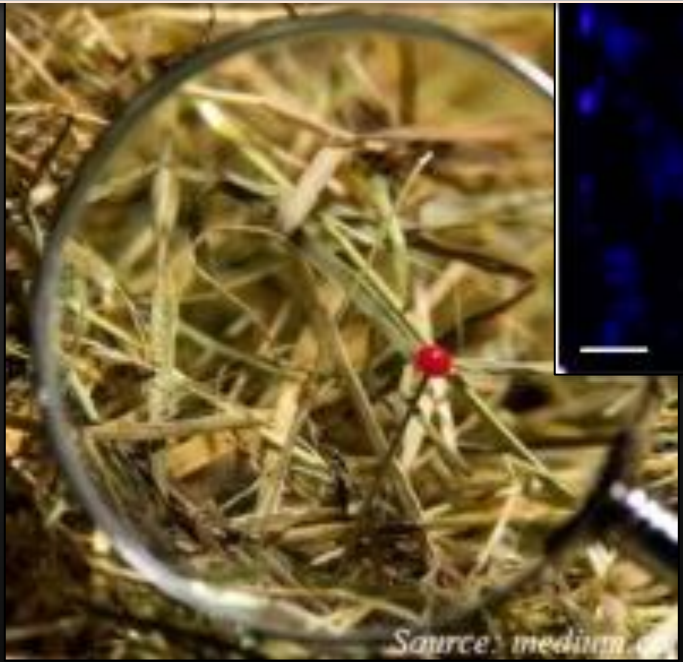
In situ

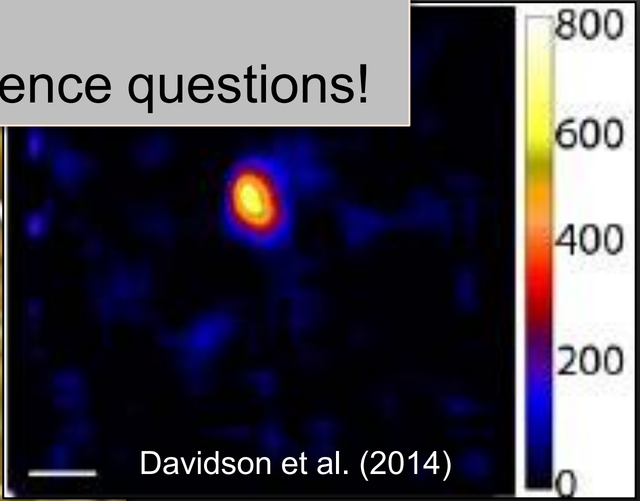
- How many presolar grains are studied now
- Find the needle in the haystack
- Use isotopic mapping to find anomalies

Both techniques have their pros and cons.
Researchers go with whichever can best help them answer their science questions!



Lugaro (2005)





Davidson et al. (2014)

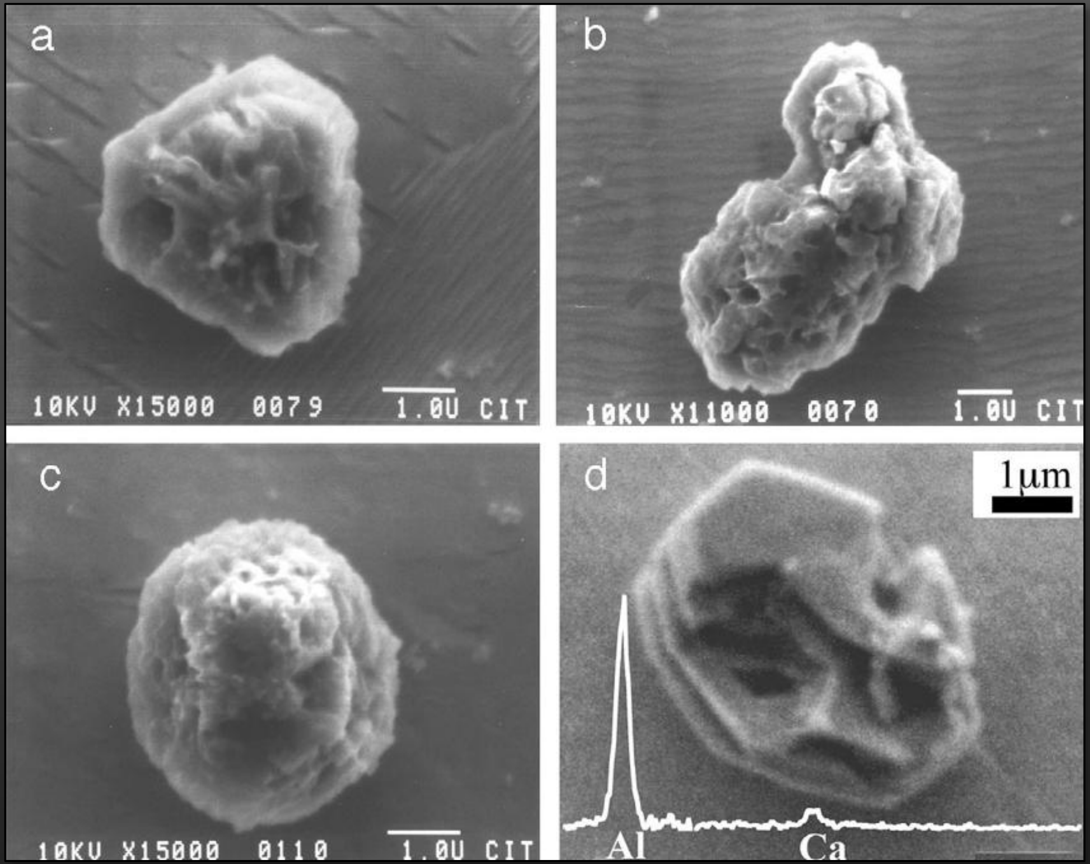
Ex situ

Pros

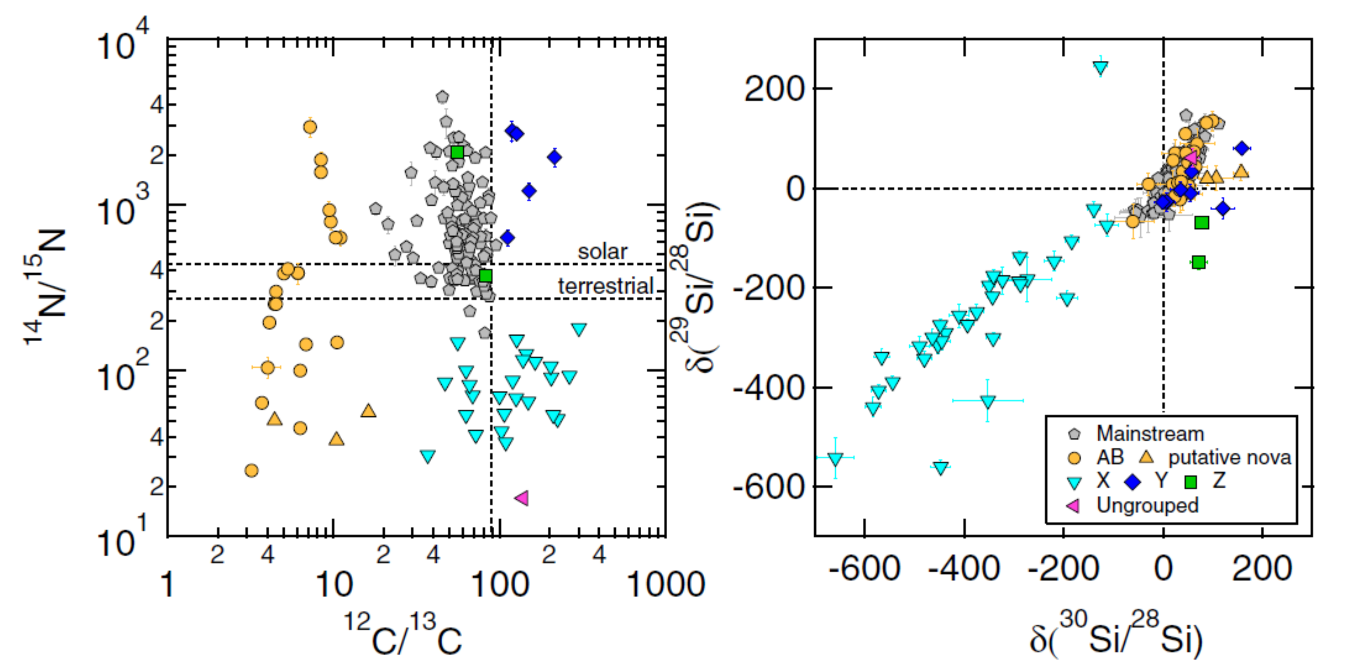
- Can get a lot of presolar grains together = more rapid isotopic analyses and better statistics

Cons

- Lose the petrographic context of the sample
- Could have reacted away parts of the sample without knowing it
- Destroys some presolar grain types (e.g., oxides and silicates)



Choi et al. (1999)



Liu et al. (2017)

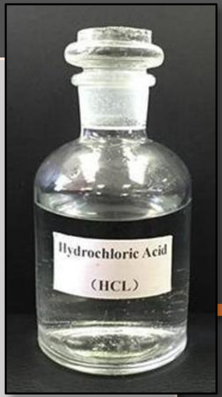
Ex situ

1. Choose samples

Select meteorite types with high abundances of presolar grains

2. Acid digestion

Dissolve meteorite matrix using strong acids for several hours or overnight



3. Filtration

Pass dissolved solution through filter paper and collect solid residue

4. Density separation

Mix solid residue and liquid with a density that separates meteorite matrix from presolar grains

5. Collection

Rinse presolar grains and prepare them for analyses


Lodders & Amari (2005)

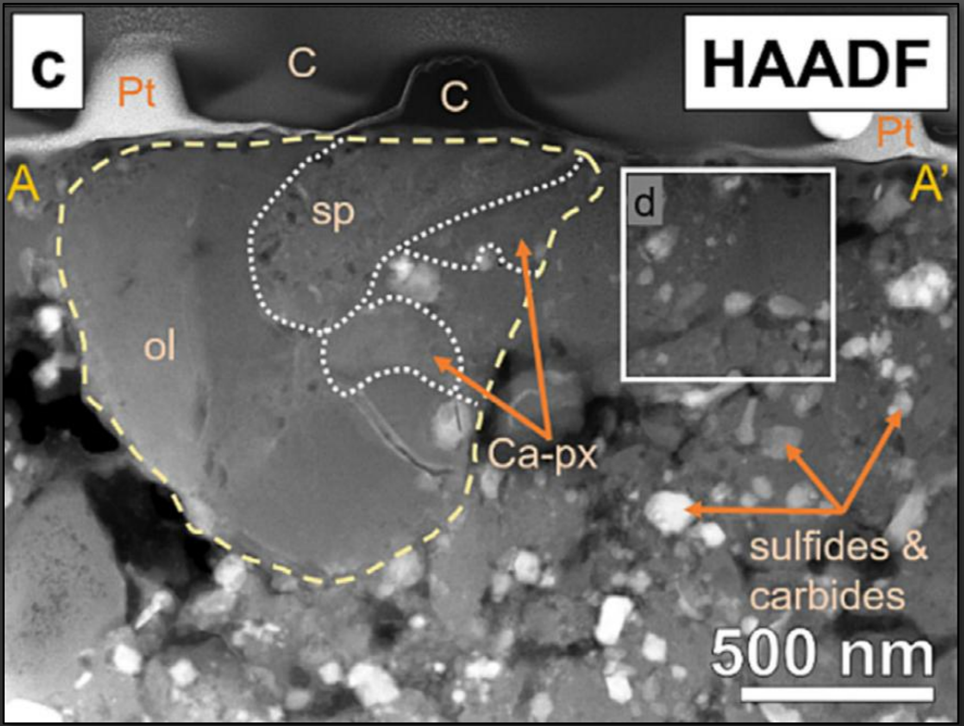
In situ

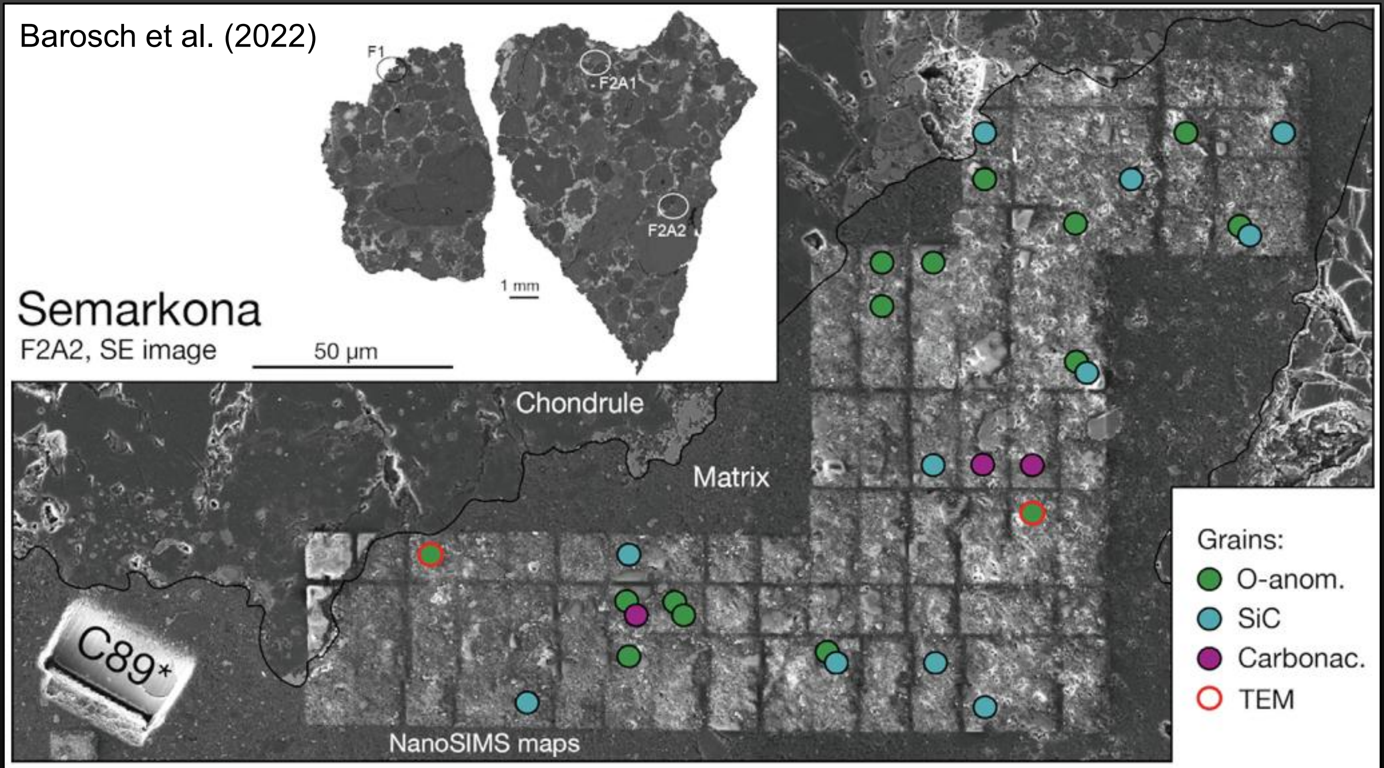
Pros

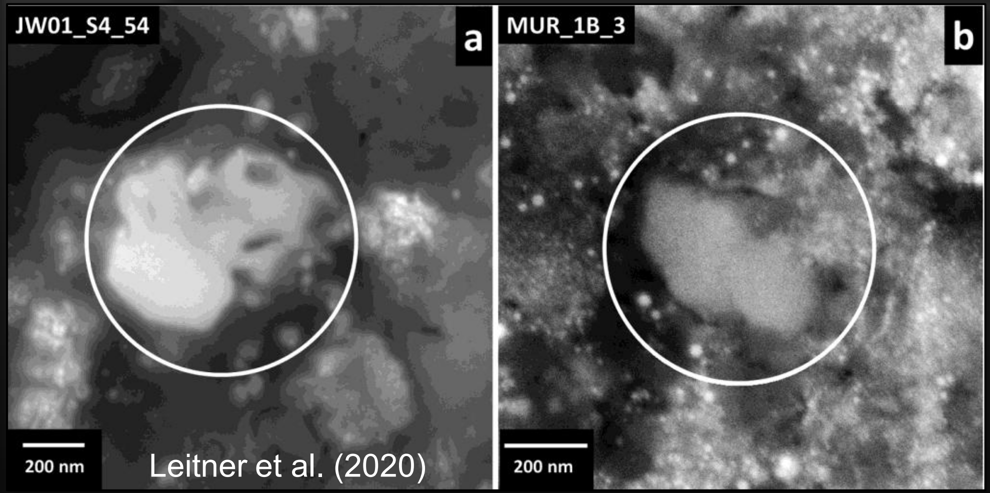
- Maintain petrographic context
- Do not react away parts of the sample
- Allow us to analyze other types of presolar grains (e.g., oxides and silicates)

Cons

- Takes a long time to find grains and collect isotopic data
- Harder to interpret mineralogic/petrologic findings (overlapping materials)
- Harder to prepare for TEM analyses







In situ

1. Choose samples

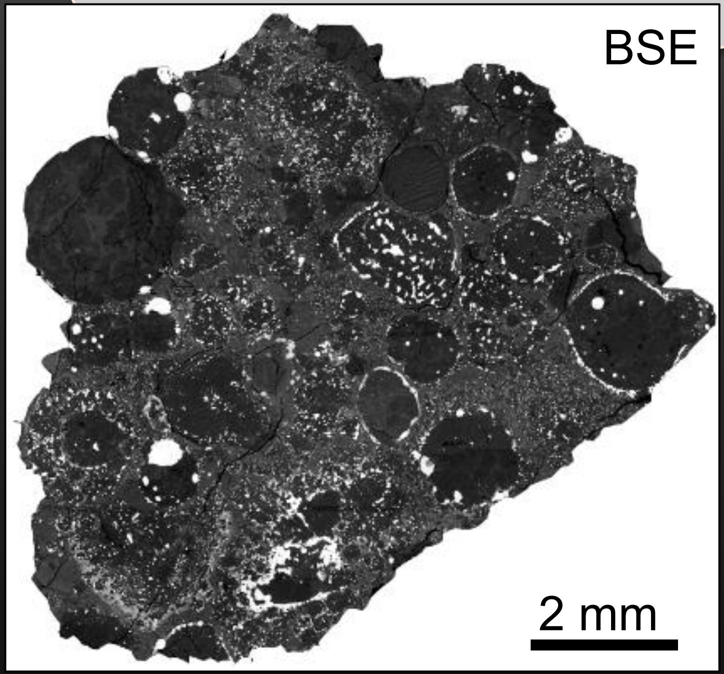
Select meteorite types with high abundances of presolar grains

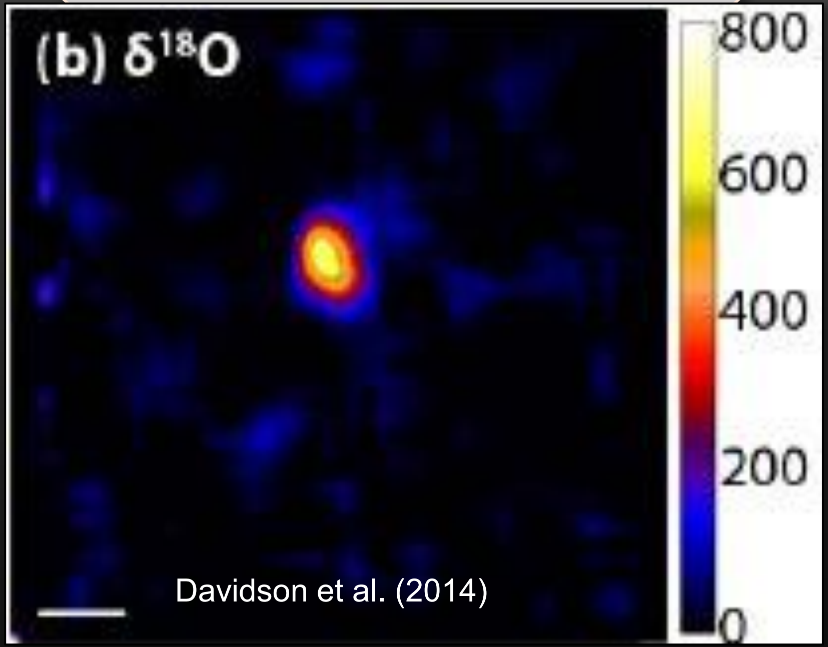
2. Request samples

Obtain a polished thin section of your meteorite(s) from a collection

3. Isotopic mapping

Collect isotopic maps and ratio them to observe isotopic anomalies

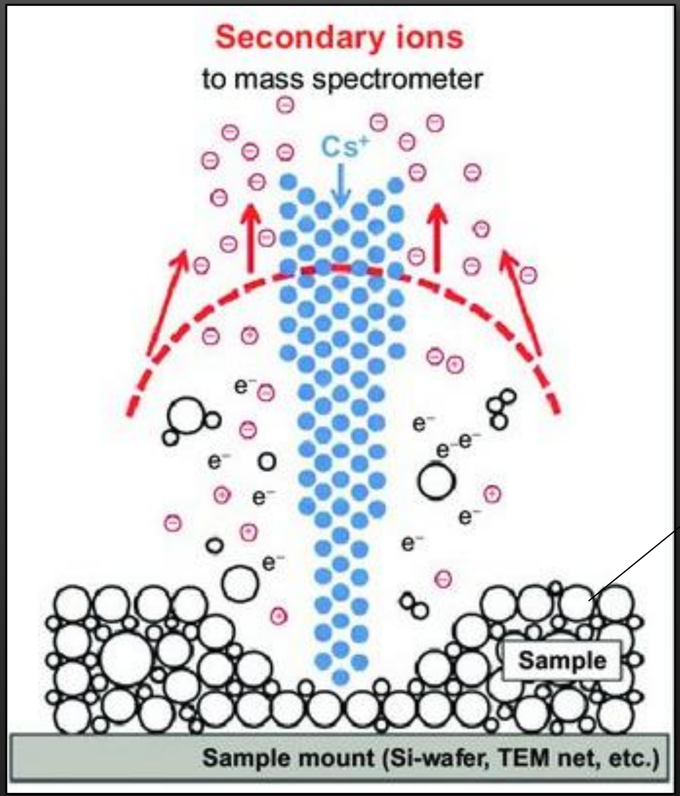


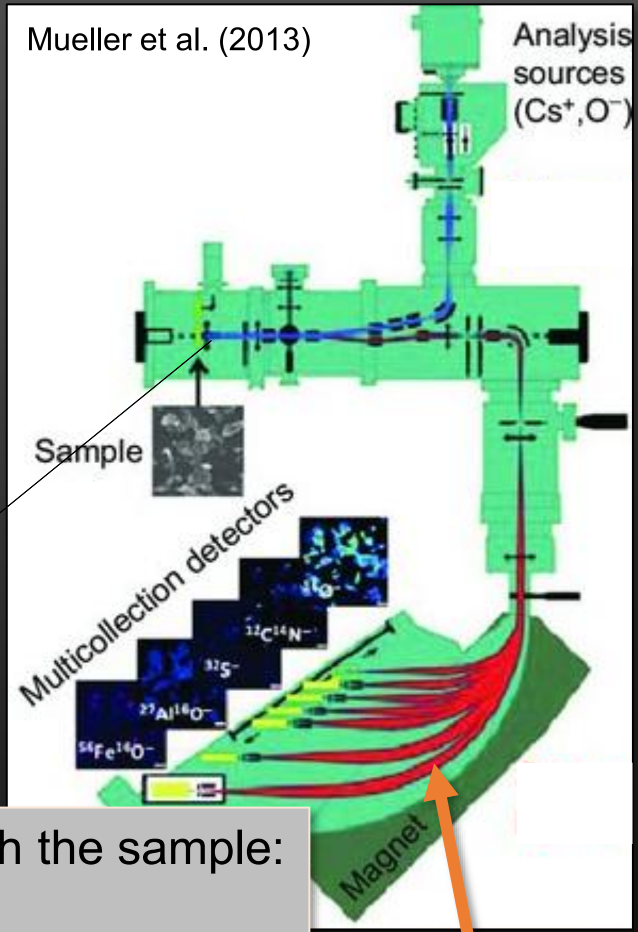


Davidson et al. (2014)

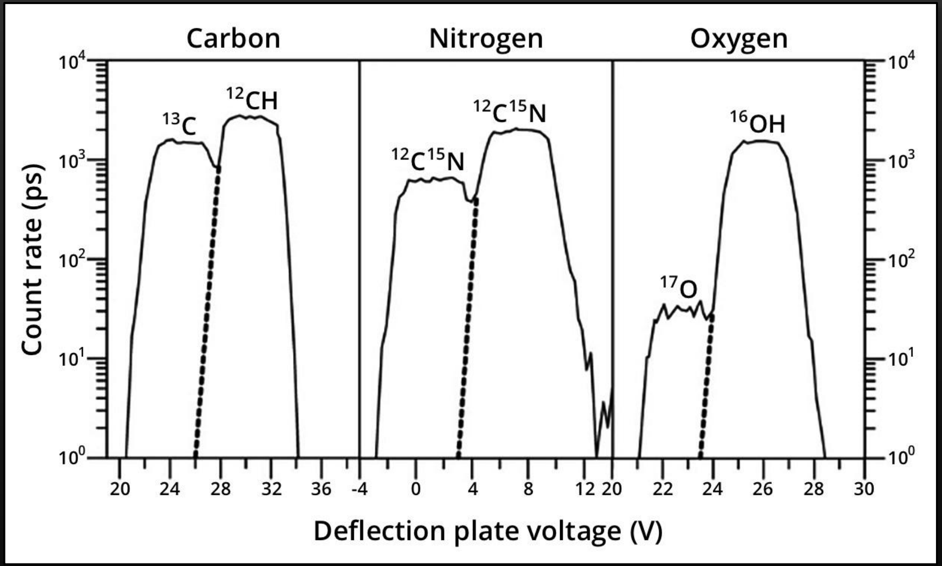
Isotopic Data—NanoSIMS (Nano Secondary Ion Mass Spectrometry)

- How does it work?





Different masses

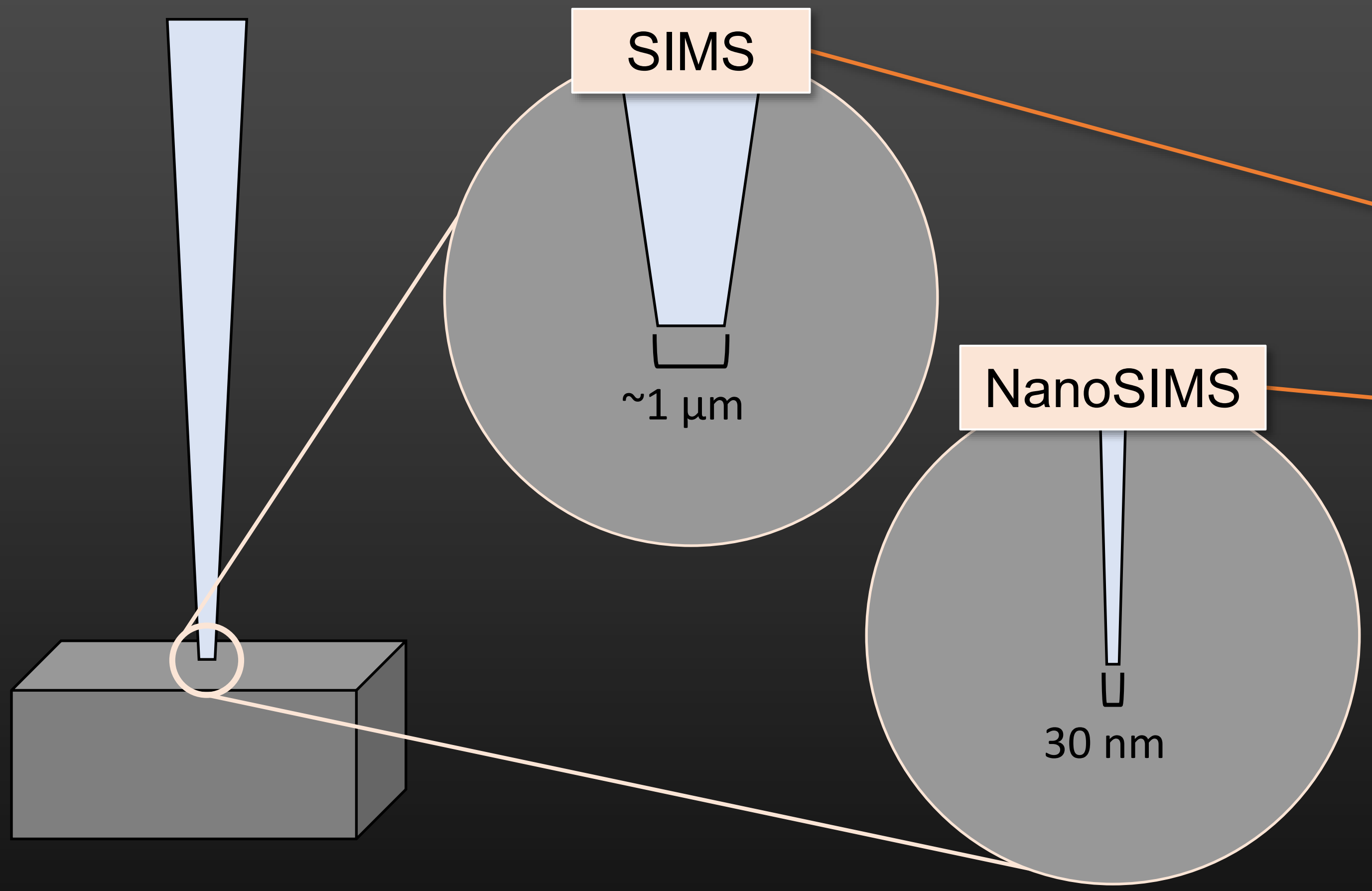


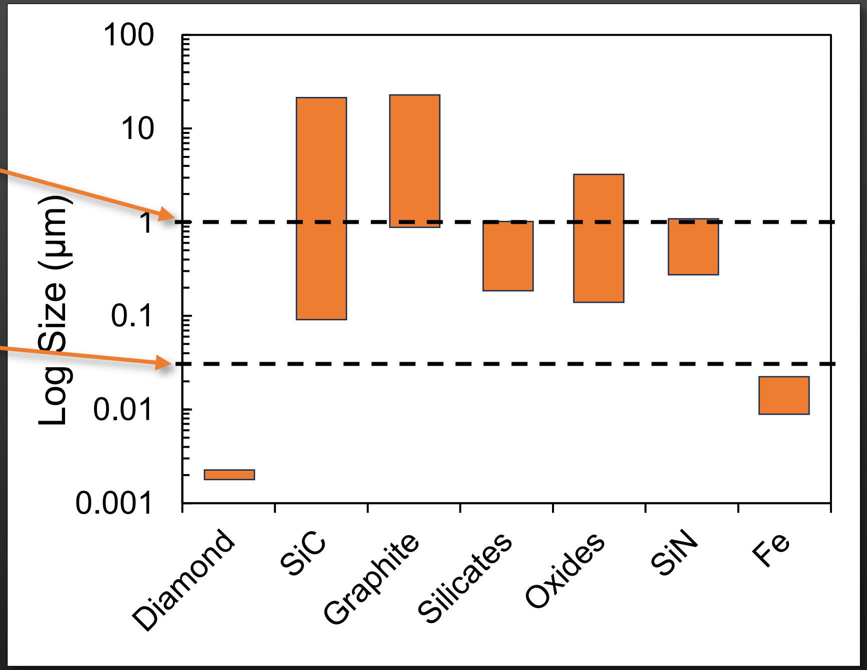
When primary ion beam interacts with the sample:

- Top layer is amorphized
- Primary beam ions are implanted into the sample
- Secondary ions are ejected from the sample

Isotopic Data—NanoSIMS (Nano Secondary Ion Mass Spectrometry)

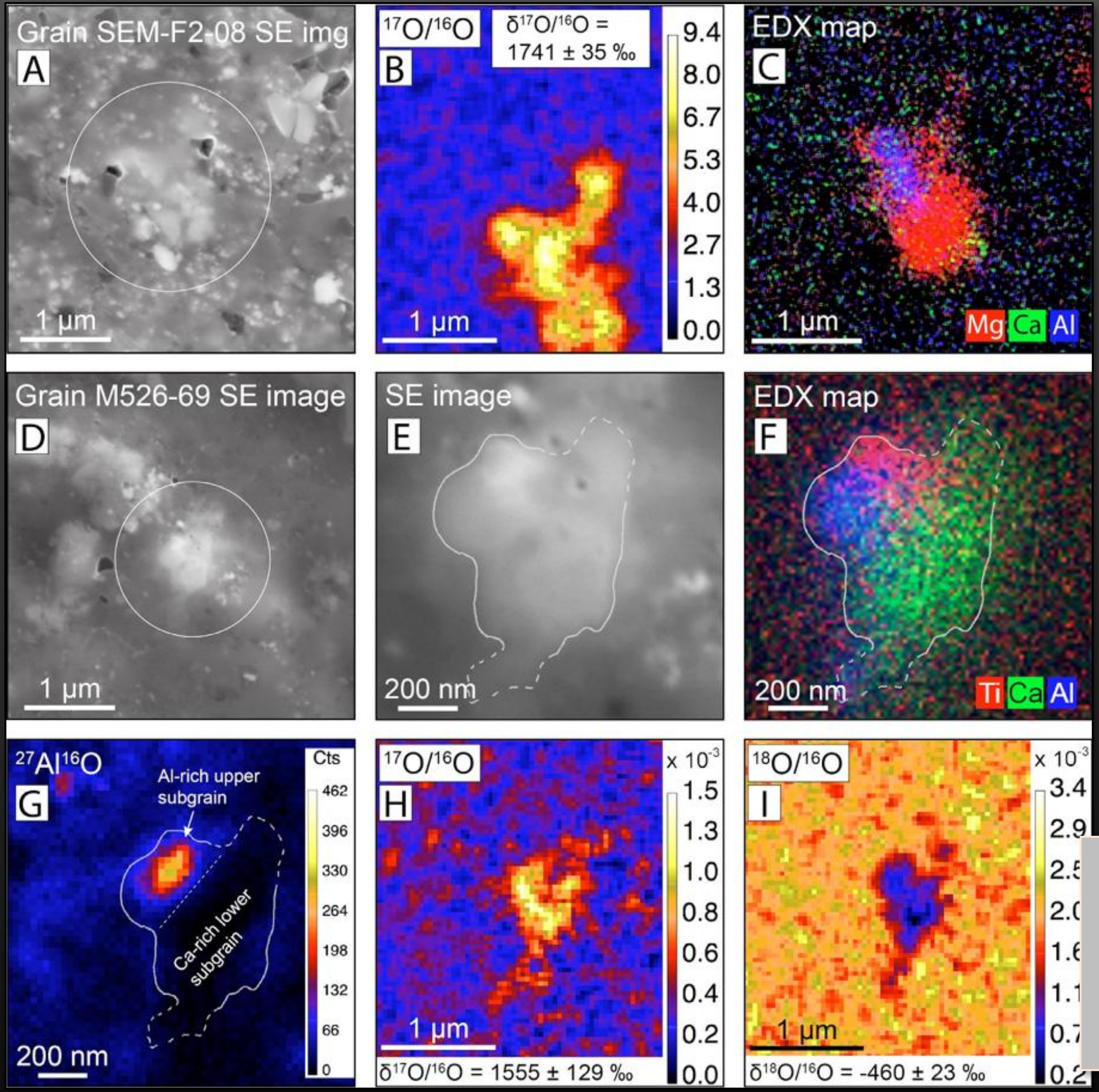
- SIMS vs NanoSIMS

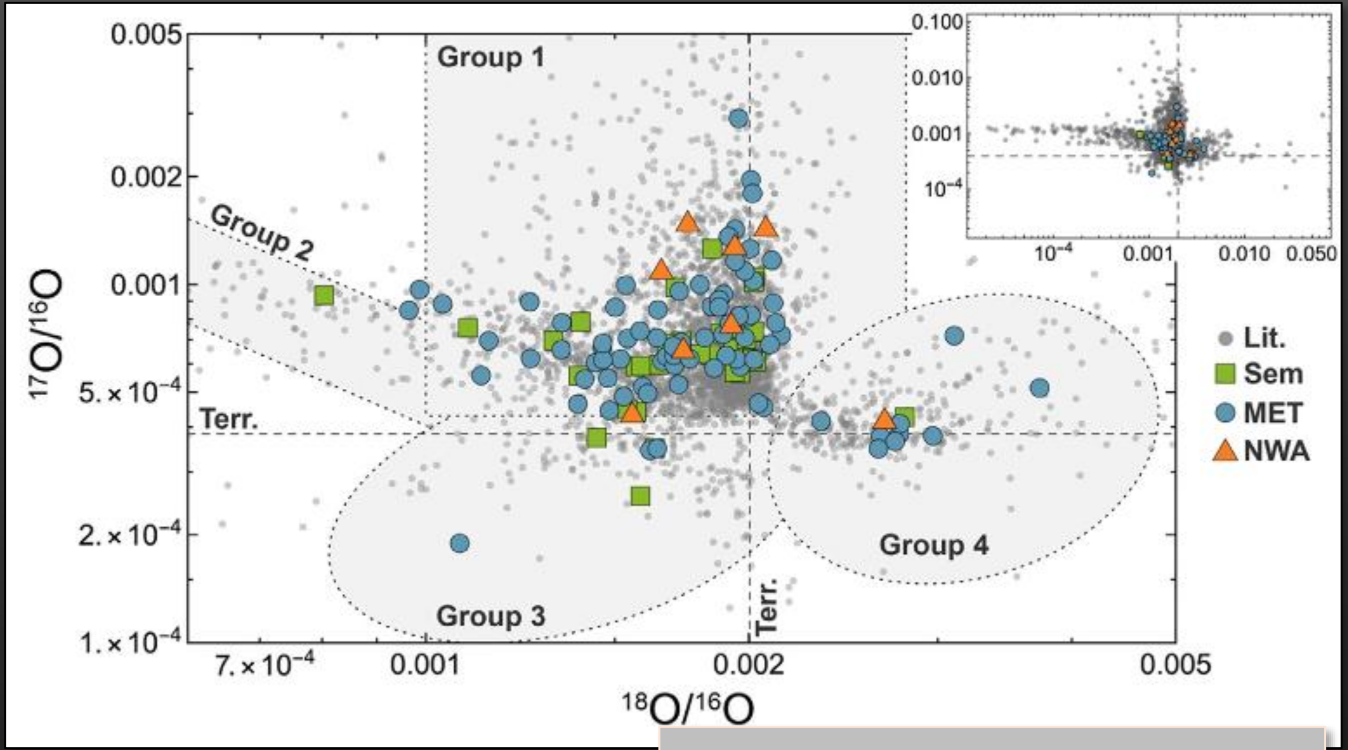




Isotopic Data—NanoSIMS (Nano Secondary Ion Mass Spectrometry)

- What do we get from it?





Barosch et al. (2022)

Maps:

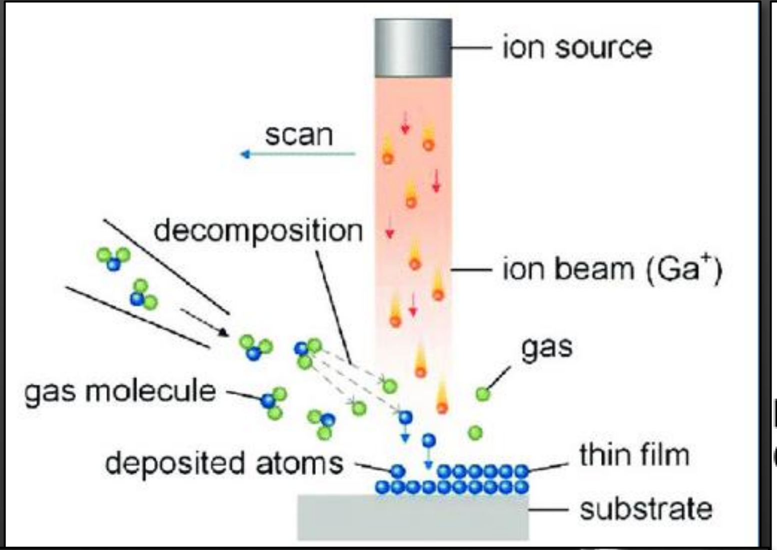
- Help us find the grain and show us isotopic heterogeneities

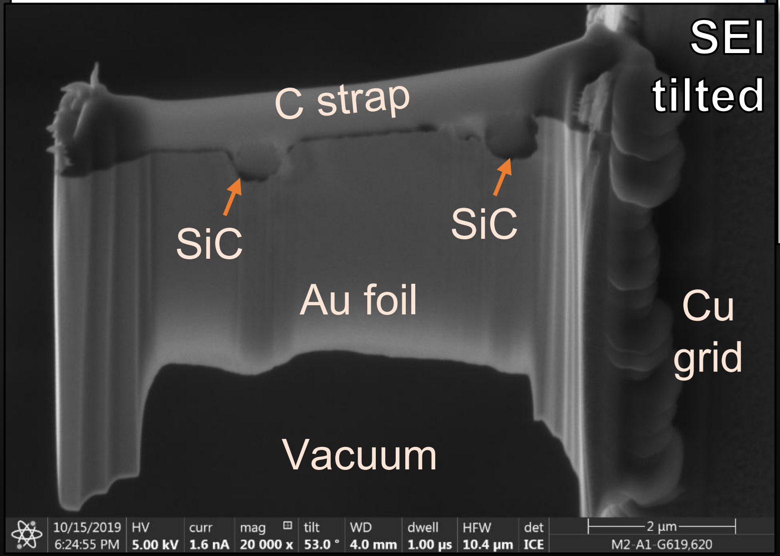
Plots:

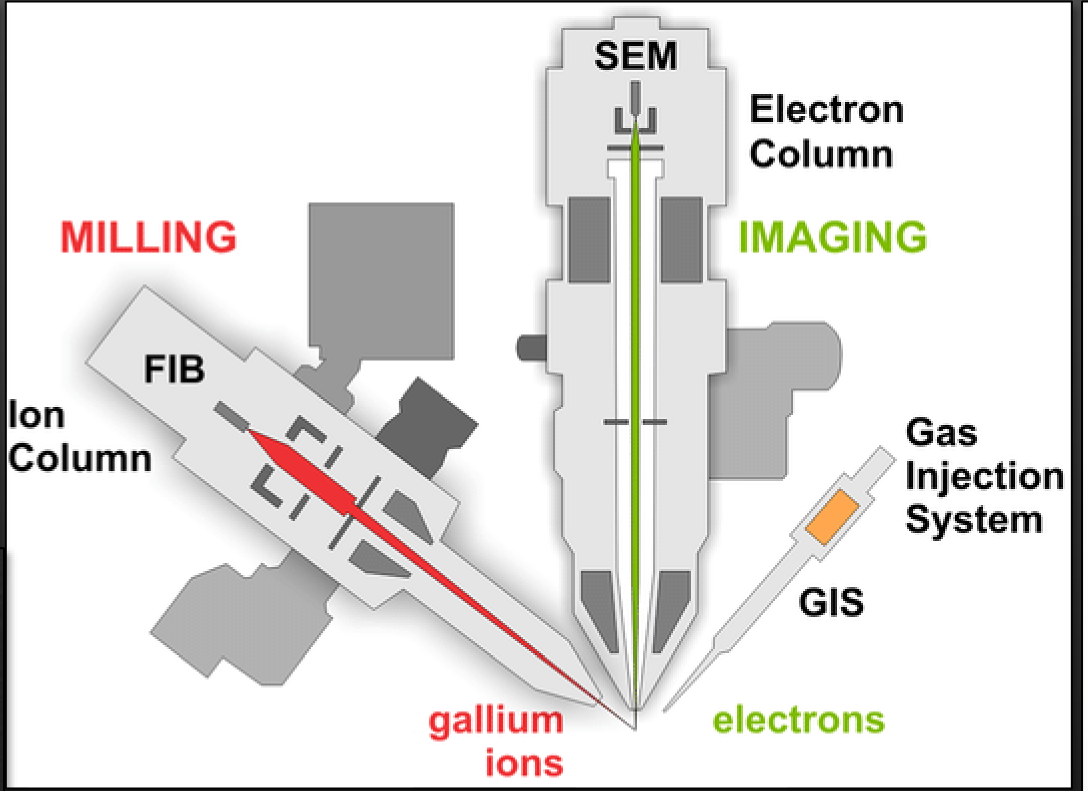
- Give us information on formation environments and conditions

Preparation—FIB-SEM (Focused Ion Beam-Scanning Electron Microscopy)

- How does it work?



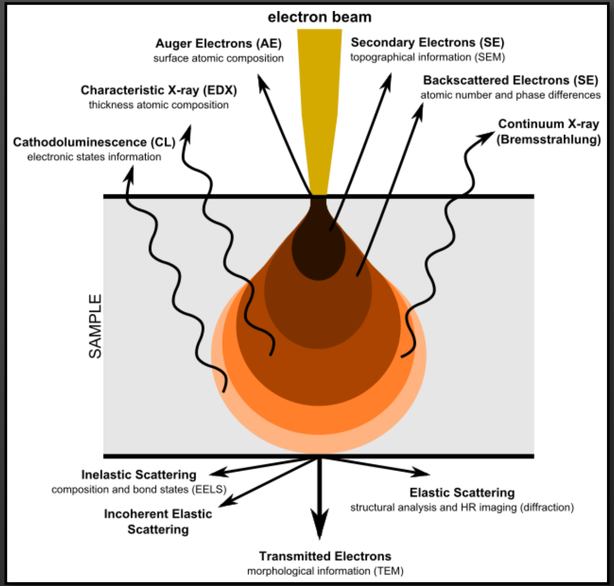




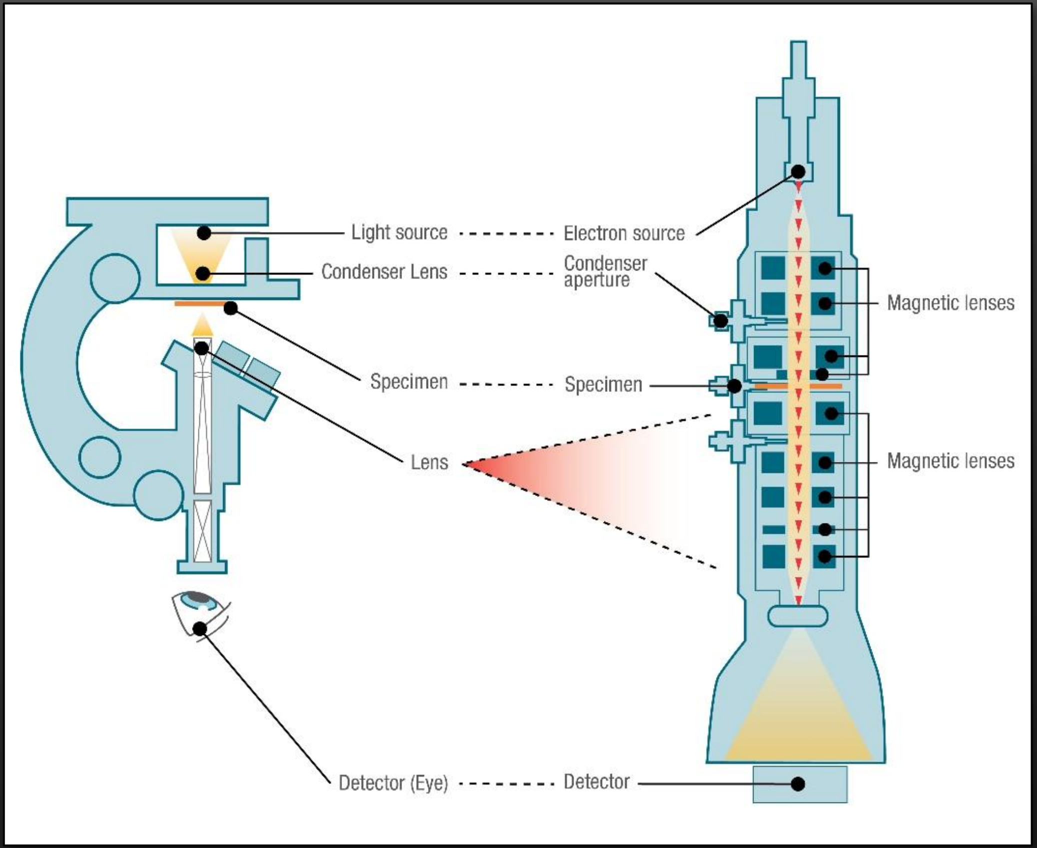
Need to thin samples down to 100 nm

Nanoscale Analyses—TEM (Transmission Electron Microscopy)

- How does it work?

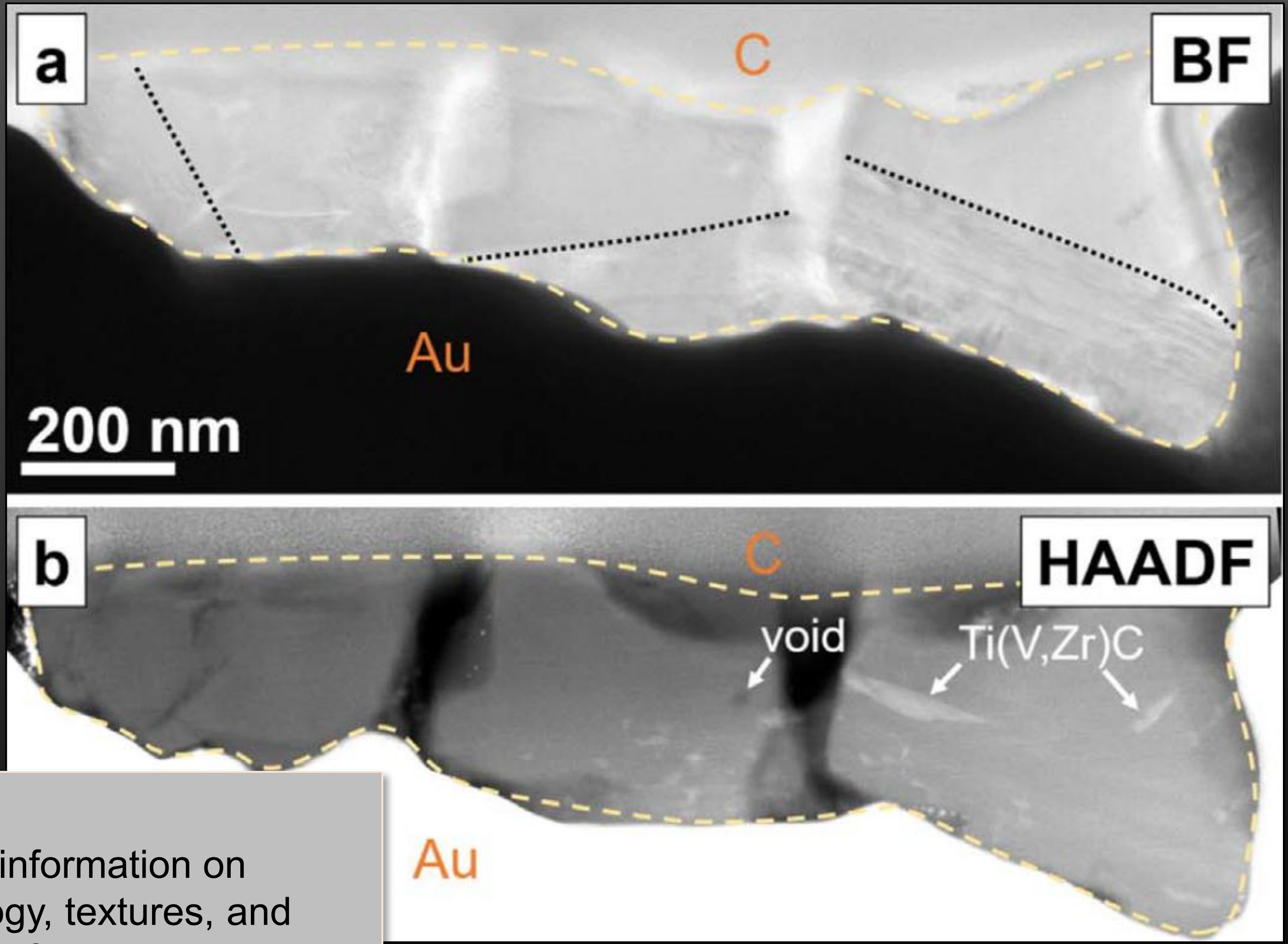


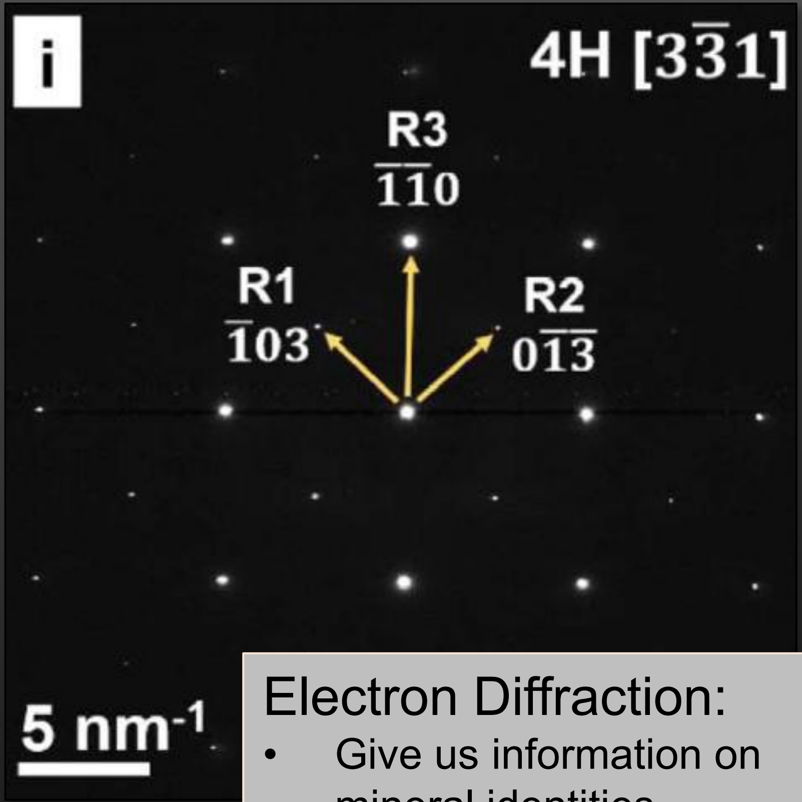
Electron beam goes through the sample



Nanoscale Analyses—TEM (Transmission Electron Microscopy)

- What do we get from it?



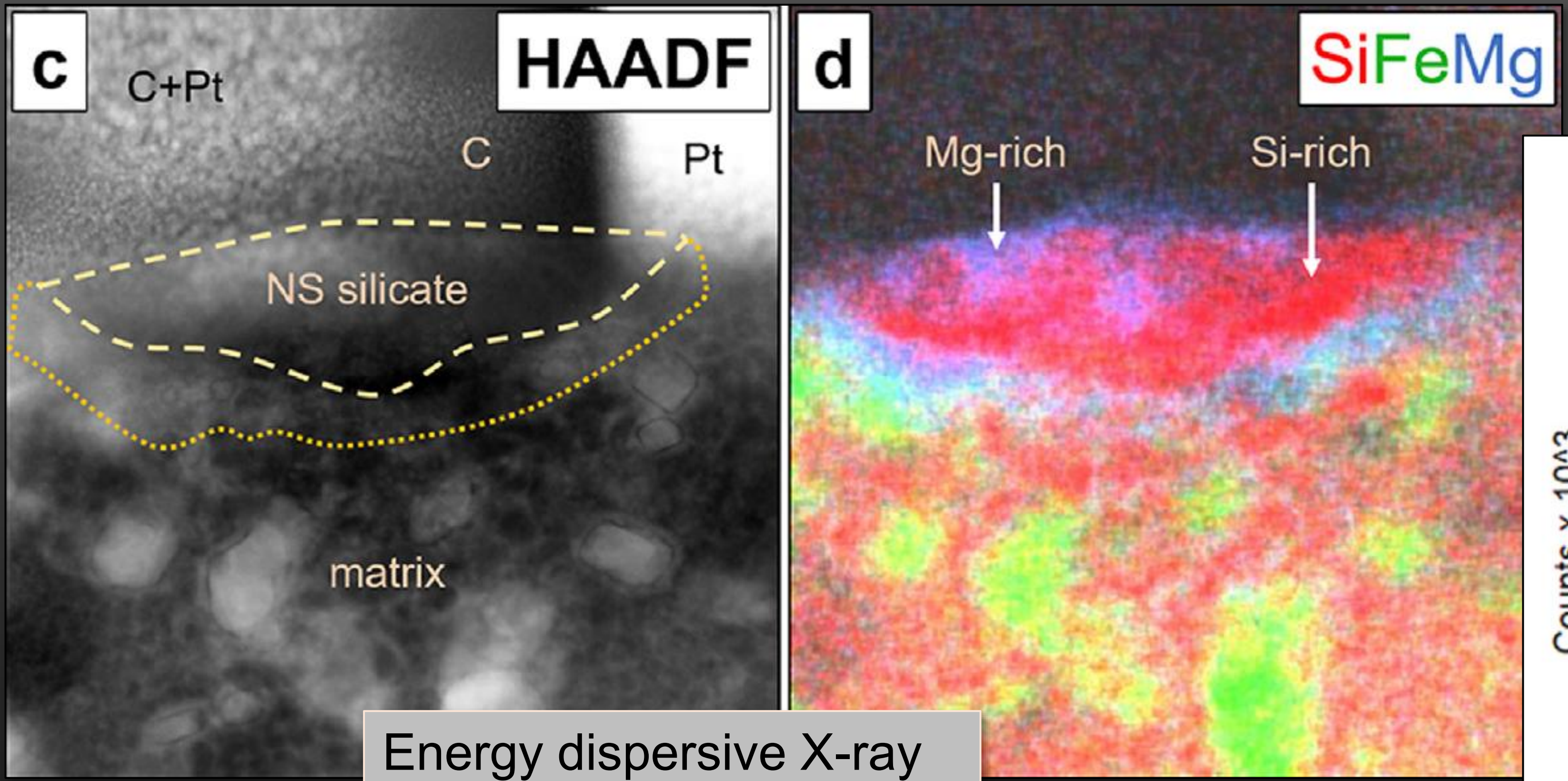


Images:
- Give us information on mineralogy, textures, and structural features

Electron Diffraction:
- Give us information on mineral identities, orientation relationships, and crystallinity

Nanoscale Analyses—TEM (Transmission Electron Microscopy)

- What do we get from it?

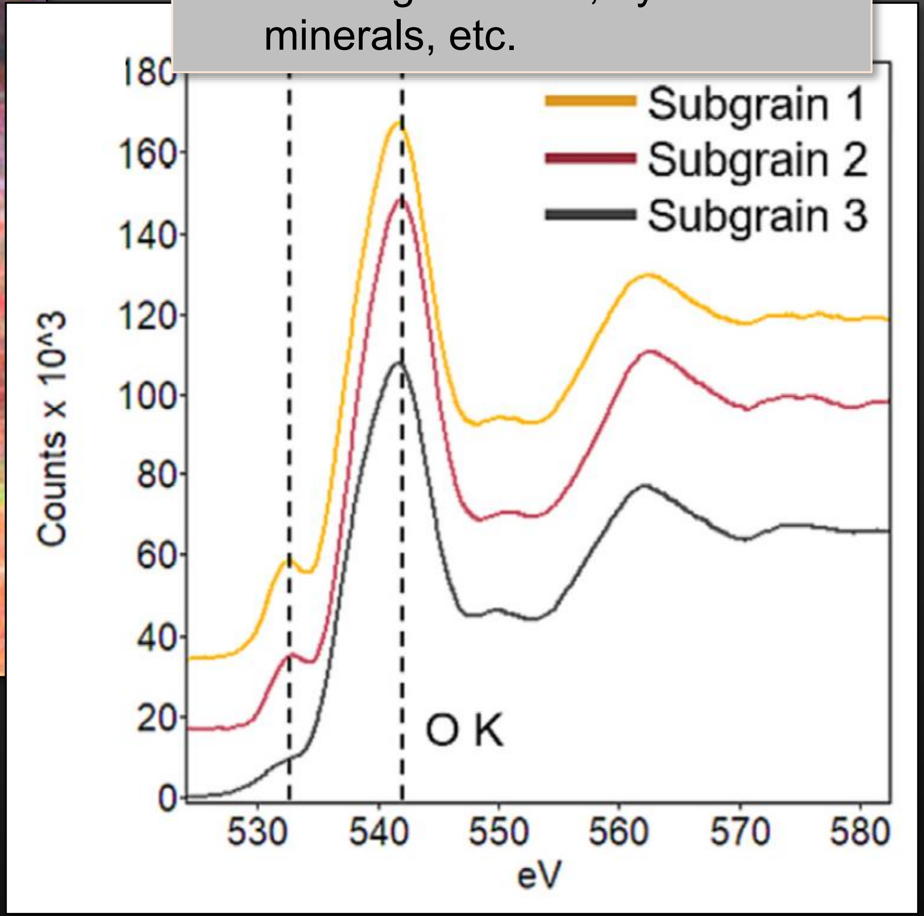


Energy dispersive X-ray spectroscopy (EDS):

- Help us identify mineral types and show us elemental heterogeneities

Electron energy loss spectroscopy (EELS):

- Help us determine valence state (e.g., Fe^{2+} or Fe^{3+}), bonding behavior, hydration of minerals, etc.



Day 2 Summary

We **classify** presolar grains based on their **mineral types** and **isotopic compositions**.

The **compositions** and **textures** of the grains can tell us about their parent star.

We use **isotopic (NanoSIMS)** and **microscopic (TEM)** instrumentation to investigate the grains and learn more about their history.