Nuclei in the Cosmos School
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COSMOCHEMISTRY

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Cosmochemistry: Presolar Grains/Stardust

Part 6: Presolar Grain Processing in the Interstellar Medium

Dr. Sheri Singerling

NIC School 2025

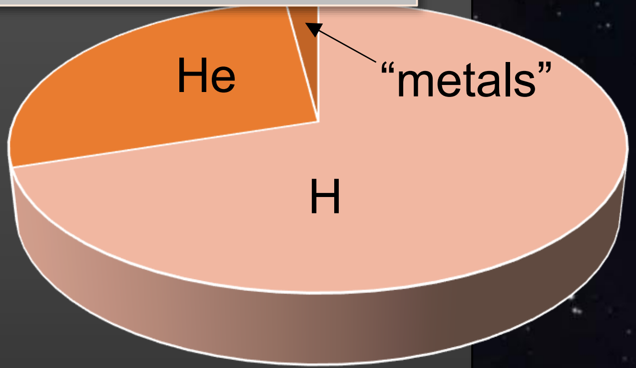
Day 3

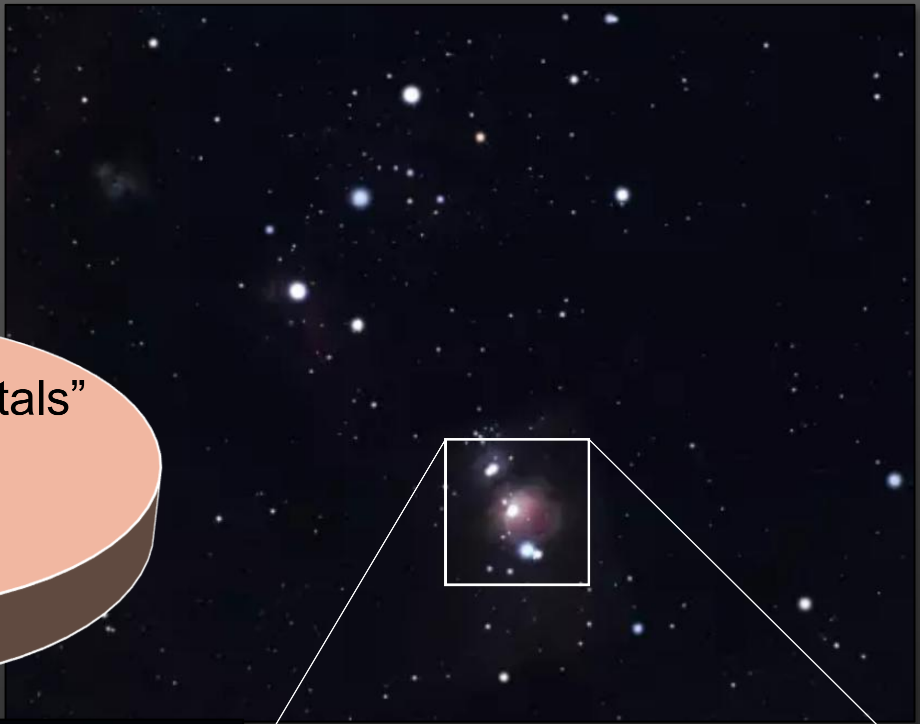
Schwiete CosmoLab
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Interstellar Medium (ISM)

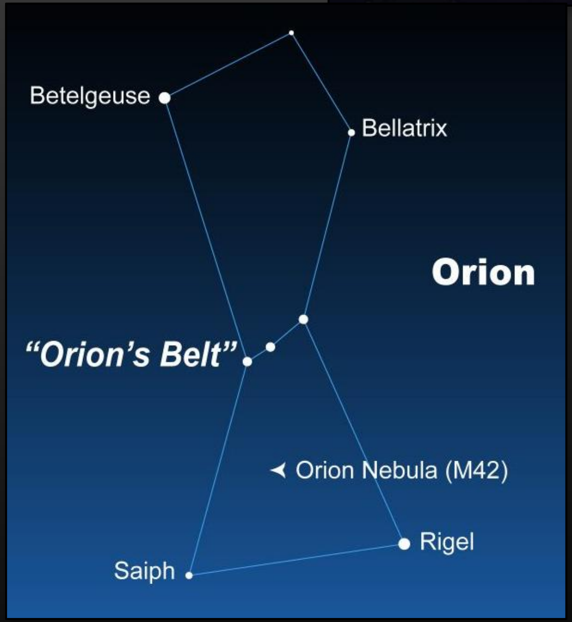
Tenuous collection of gas and dust that pervades the space between star systems

- It might seem empty…
  - It is filled with gas (70% H, 28% He, 2% "metals") and dust!





- It might seem quiet and calm…
  - It is violent and active!
  - A lot of processes are happening that are invisible to human perception

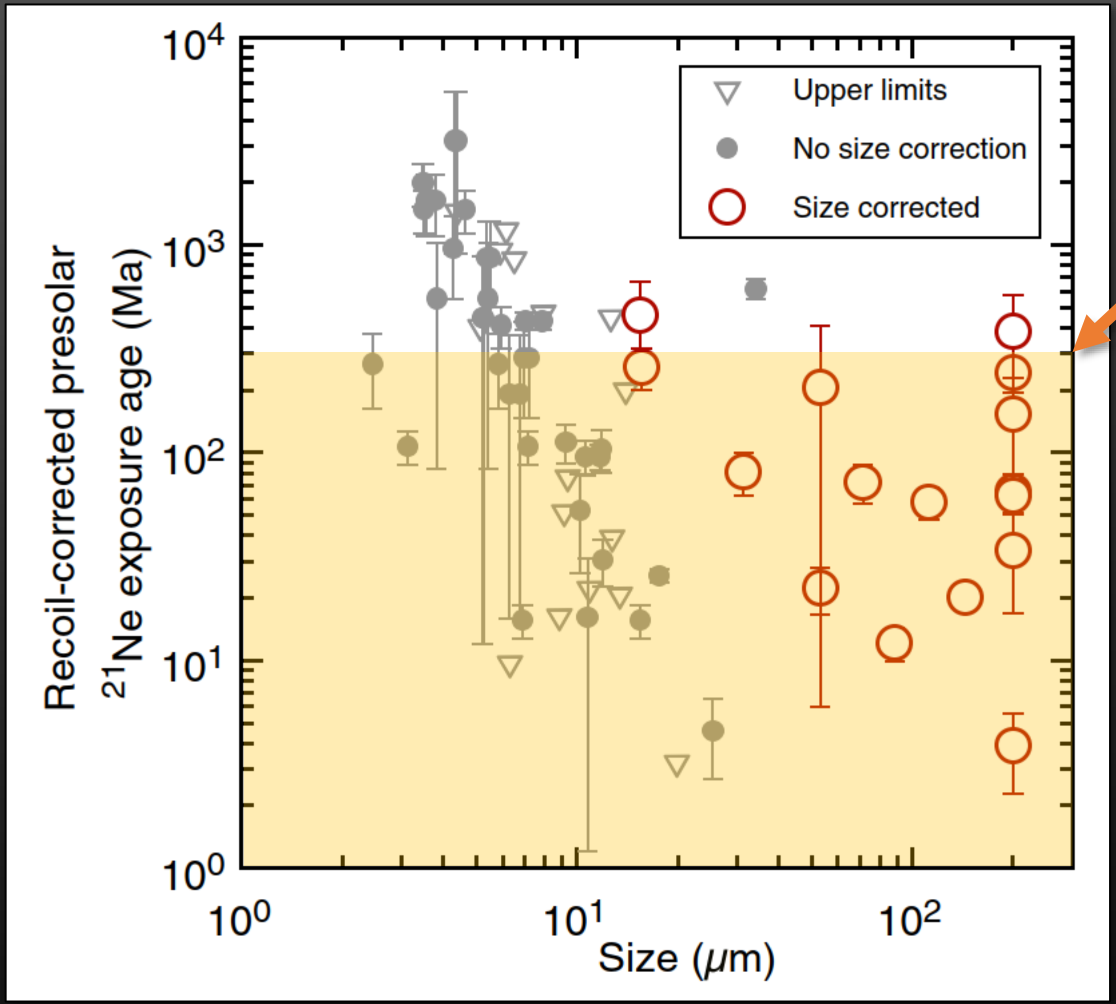


Significance

- The ISM is the reservoir of material for star formation
- More specifically to presolar grains:
  - ***Possible*** site of presolar grain formation?
  - ***Definite*** site of presolar grain processing!

Presolar Grains in the ISM

- Presolar grains that form within the ISM are theorized to exist



Heck et al. 2020

Cosmic ray exposure ages mostly <3 x 10^8 (300,000,000) years

Stardust lifetime ~4 x 10^8 (400,000,000) years

= Dust is quickly destroyed in the ISM

AND

Stardust injection timescale ~2 x 10^9 (2,000,000,000) years = Dust is only slowly injected into the ISM

Dust must also form in the ISM!

Presolar Grains in the ISM

- Presolar grains that form within the ISM are theorized to exist…BUT they have not been definitively identified in meteorites

Expected Features

- Non-stellar signatures
- Isotopic compositions of local ISM

=

For those in our Sun's parent molecular cloud, the local ISM equals the Solar System

=

No isotopic anomalies, making it impossible to distinguish these presolar grains from normal Solar System materials

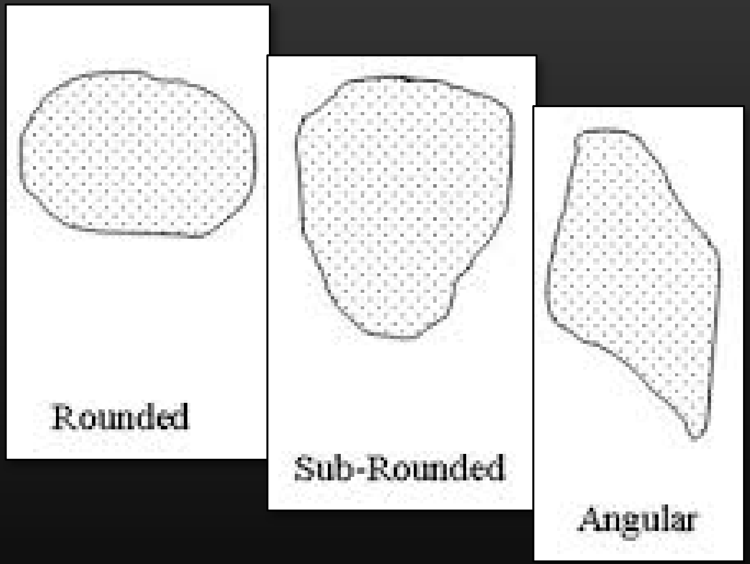
ISM Processes

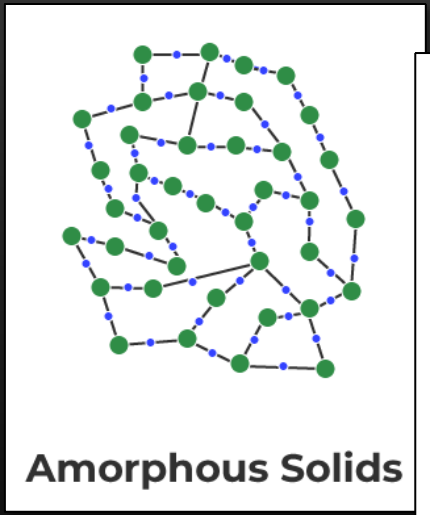
- Let us talk about what we do know...circumstellar presolar grains can be changed as they travel through the ISM!

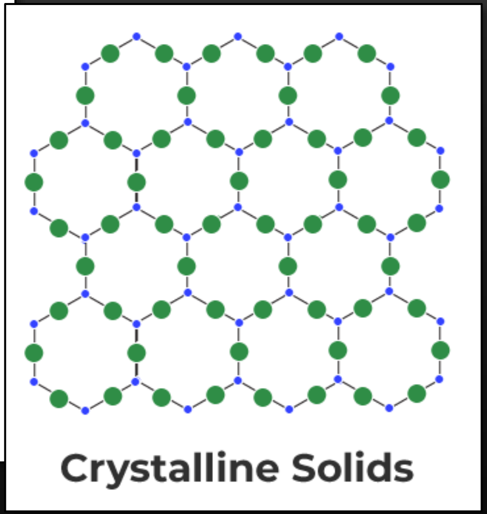
Heck et al. (2020) calculated the grains they analyzed were ***3–30x*** larger before their transit through the ISM

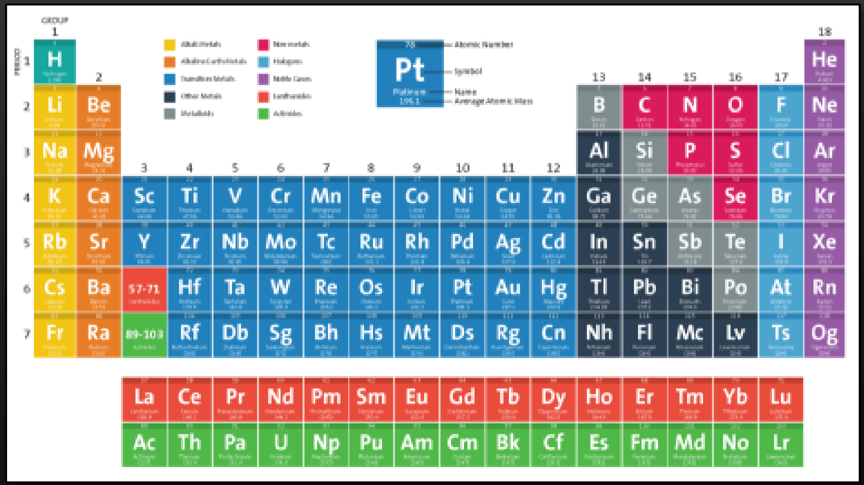
And that is just a change in size. What about other characteristics like…

- Shape
- Crystallinity
- Compositions









ISM Processes

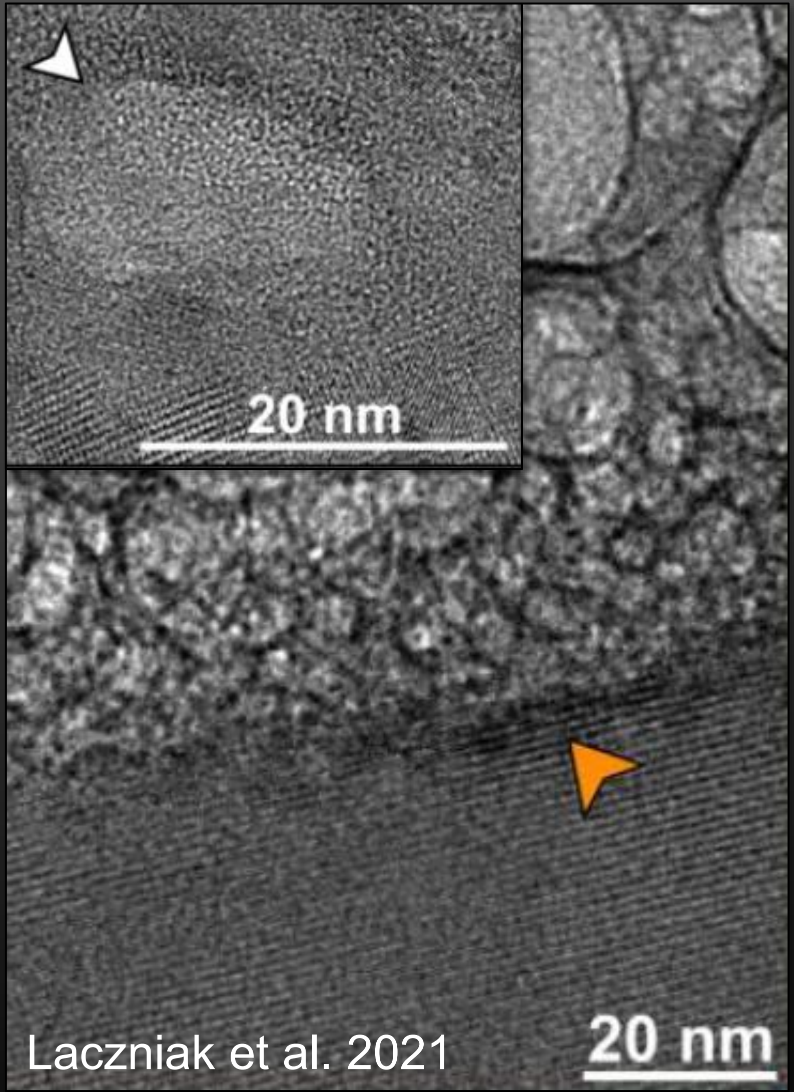
Dominant Processes Affecting Dust

Grain-Grain Collisions

Collisions between interstellar dust due to turbulent motions in the ISM (shock waves from supernovae explosions, stellar winds, etc.)

Effects:

- Sputtering (small particles ejected from surface)
- Fragmentation
- Aggregation
- Compaction
- Alteration of surface properties



Laczniak et al. 2021

Irradiation

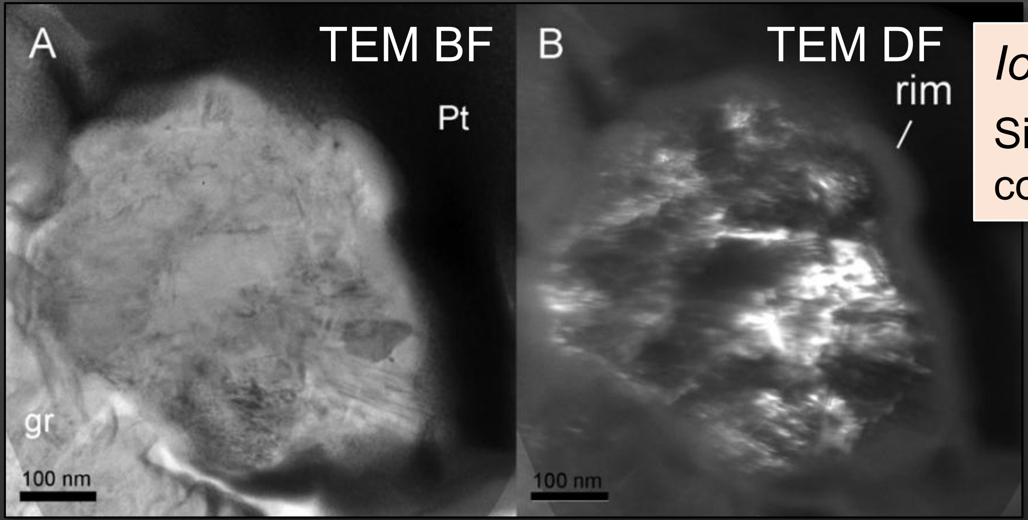
Bombardment of dust by high-energy (100 MeV–1 TeV) particles (~99% H^+ and He^+ nuclei and ~1% electrons) from cosmic rays or UV radiation from nearby stars

Effects:

- Structural defects (up to amorphization)
- Heating
- Implantation
- Change in isotopic compositions

Observations of ISM Processing

So…have we found evidence for bona fide ISM processing?

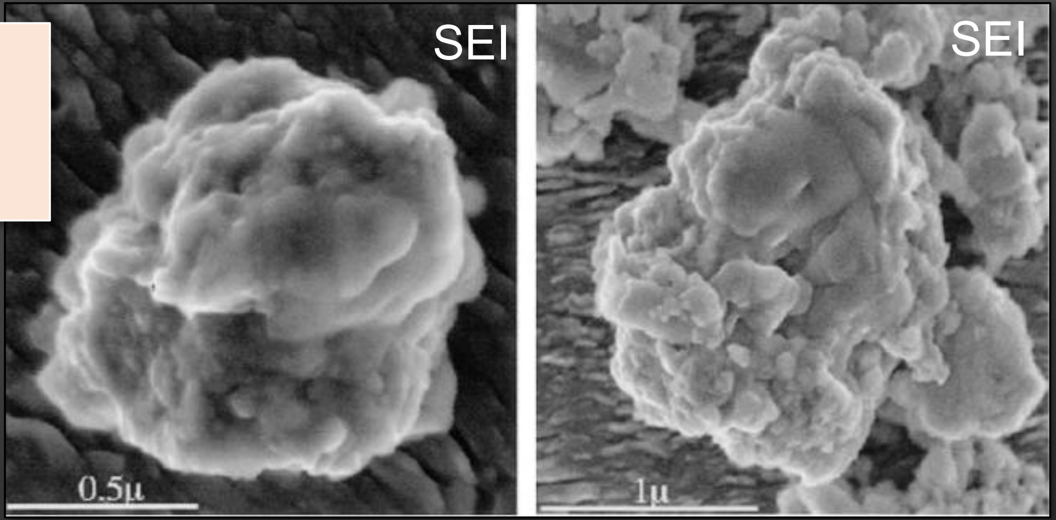


Stroud 2005

Ion Irradiation?

Silicate rims/surface coatings on SiC grains

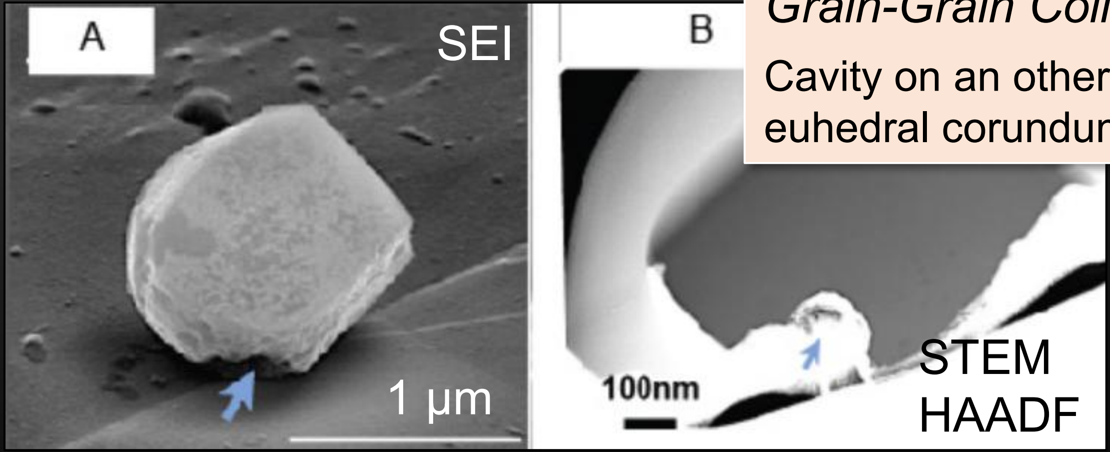
Could be solar nebula-related



Bernatowicz et al. 2003

Grain-Grain Collisions?

Cavity on an otherwise euhedral corundum grain



Takigawa et al. 2018

Maybe but…this is still an area of active research!

The **rarity** of presolar grains and **time-consuming nature** of sample preparation makes it **difficult** to perform systematic studies to search for **bona fide ISM processing features.**

Cosmochemistry:
Presolar Grains/Stardust

Part 7: Presolar Grain Processing in the Solar System

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The Solar System

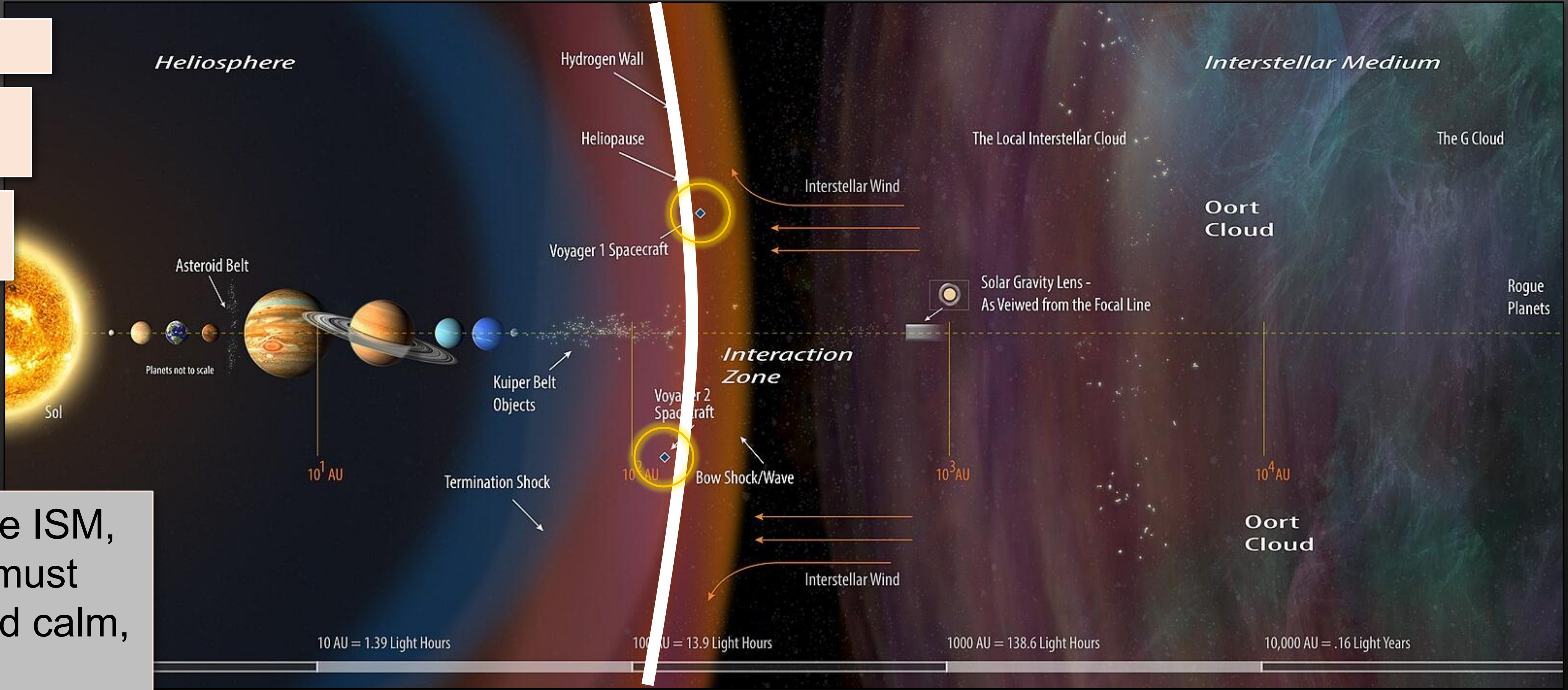
Where does the ISM end and the Solar System begin? → heliopause

- Let us define our Solar System = all matter influenced by the Sun's gravity

Planets/dwarf planets

Small bodies (asteroids and comets)

Dust (micrometeorites and IDPs)



So compared to the ISM, our Solar System must have been nice and calm, right? Nope!

Solar System Formation and Evolution

Molecular Cloud

↓

Protosun + Solar Nebula

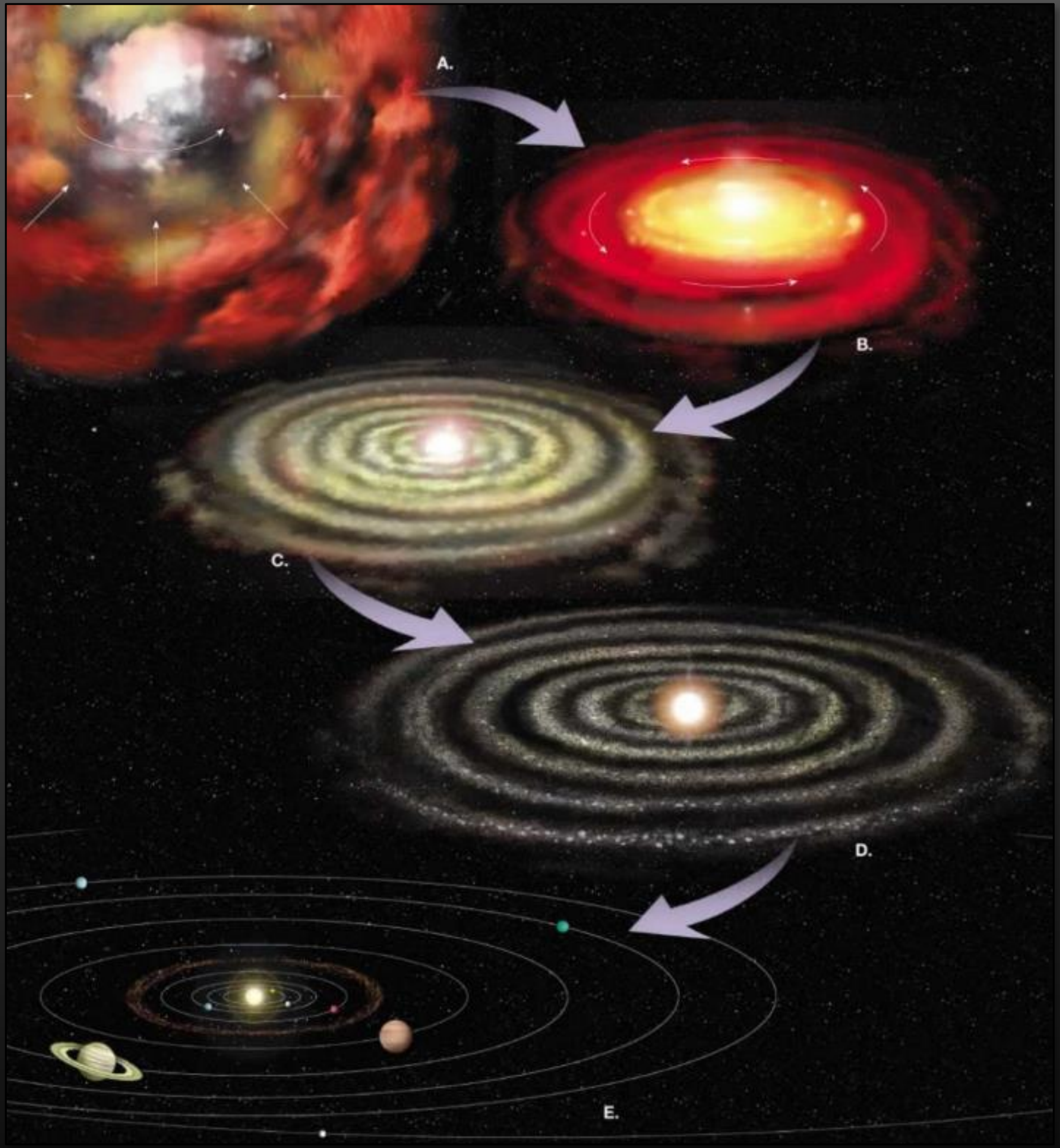
↓

Sun + Protoplanetary Disk

↓

Sun + Planets + Small Bodies
(asteroids and comets)

Let us go through each stage and talk about the processes that affect dust (*presolar grains*)



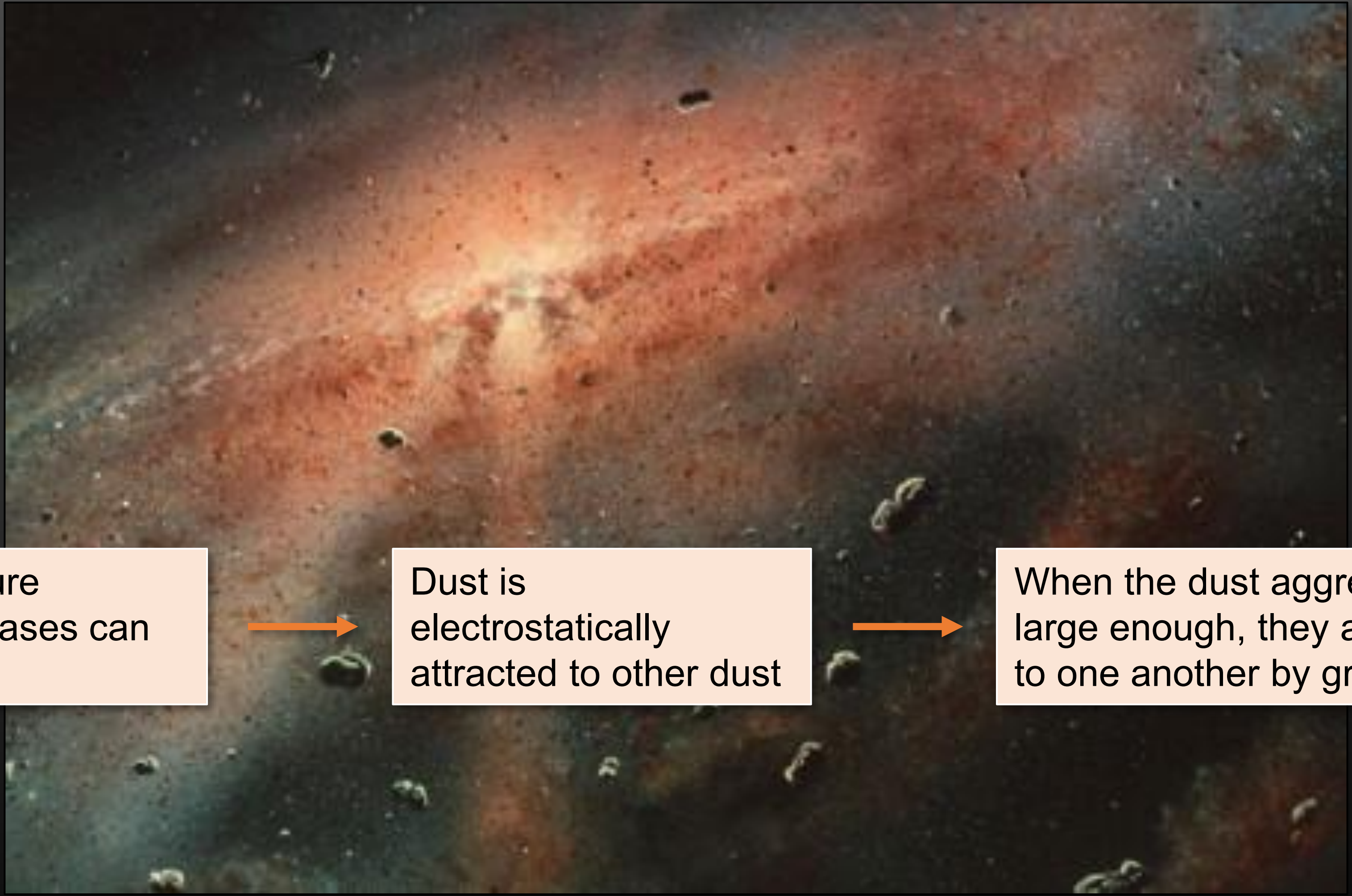
Molecular Cloud

Same processes as the ISM, so let us move on

Solar Nebula

Rotating disk of gas and dust surrounding the protosun

Remember, a protostar means thermonuclear fusion has not yet started



As temperature decreases, gases can condense → Dust is electrostatically attracted to other dust → When the dust aggregates are large enough, they are attracted to one another by gravity

Solar Nebular Processes

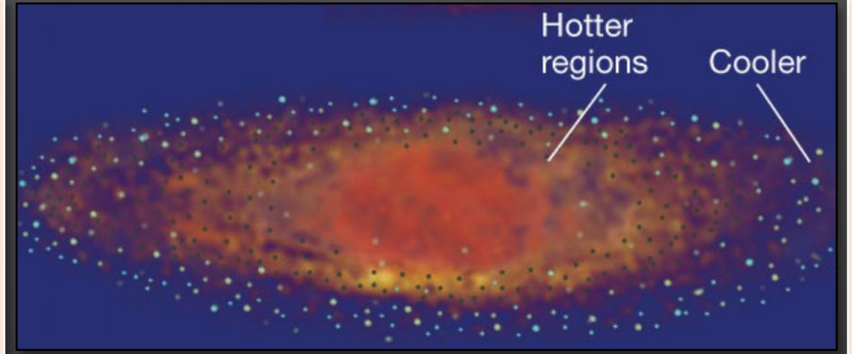
Dominant Processes Affecting Dust

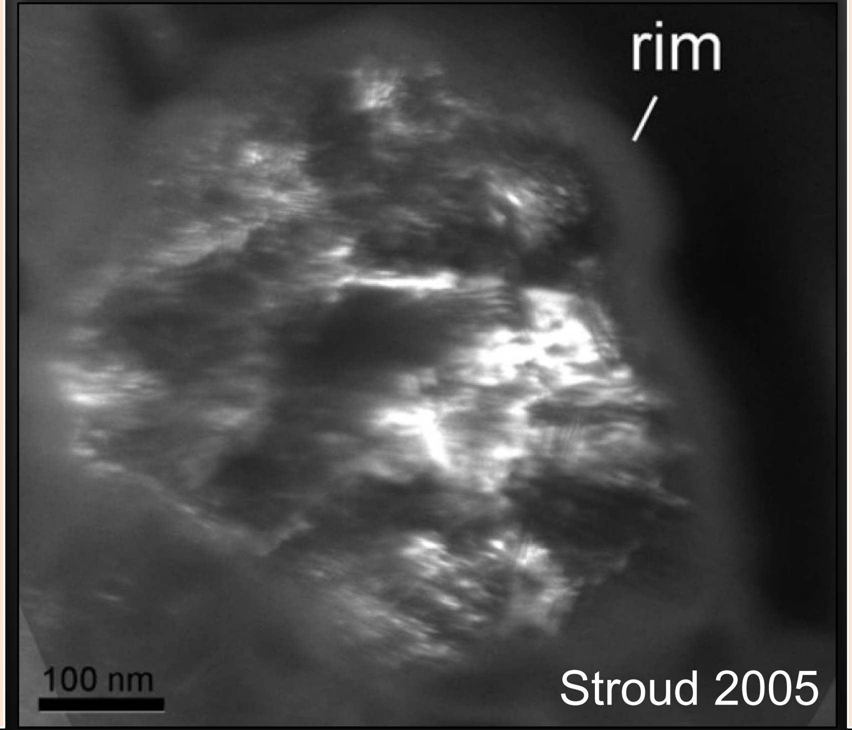
Gas-Phase Condensation

Solids condense from nebular gas and have solar isotopic compositions

Effects:

- Overgrowths of minerals with solar isotopic compositions on the presolar grains





Oxidation

The more O-rich environment and higher temperatures of the nebula, compared to the ISM, promotes oxidation

Effects:

- Oxidation of the surface of presolar grains

Solar Nebular Processes

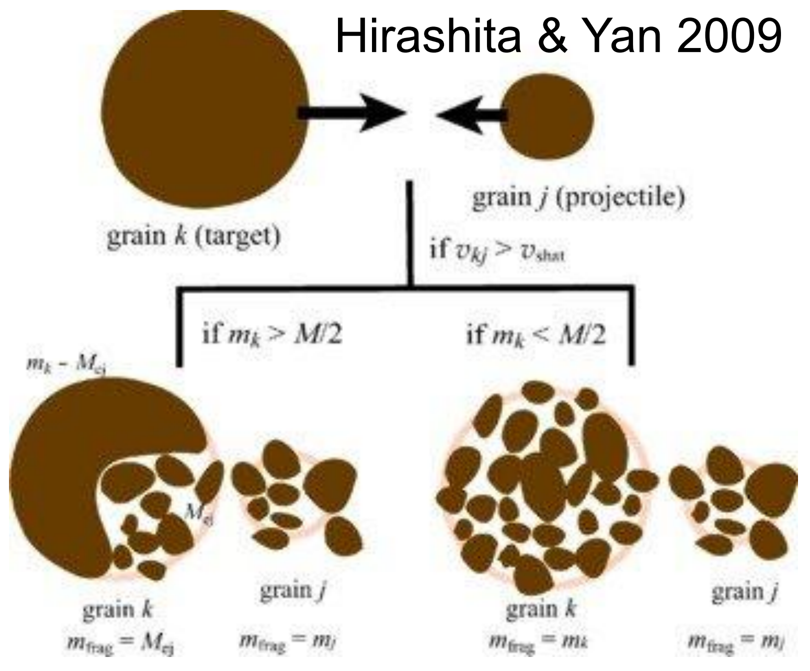
Dominant Processes Affecting Dust

Grain-Grain Collisions

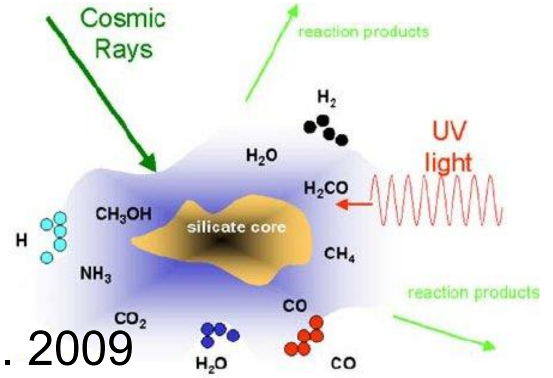
Collisions between nebular dust due to turbulent motions in the solar nebula (protosun in the T-Tauri stage is violent)

Effects:

- Sputtering (small particles ejected from surface)
- Fragmentation
- Aggregation
- Compaction
- Alteration of surface properties



Hirashita & Yan 2009



Srama et al. 2009

Irradiation

Bombardment of dust by solar wind (1 keV–few MeV) (mostly H^+ with some He^+ nuclei and electrons) or UV radiation from the protosun (eV)

Effects:

- Structural defects (up to amorphization)
- Heating
- Implantation
- Change in isotopic compositions

UV radiation is mostly limited to the surface of the grains

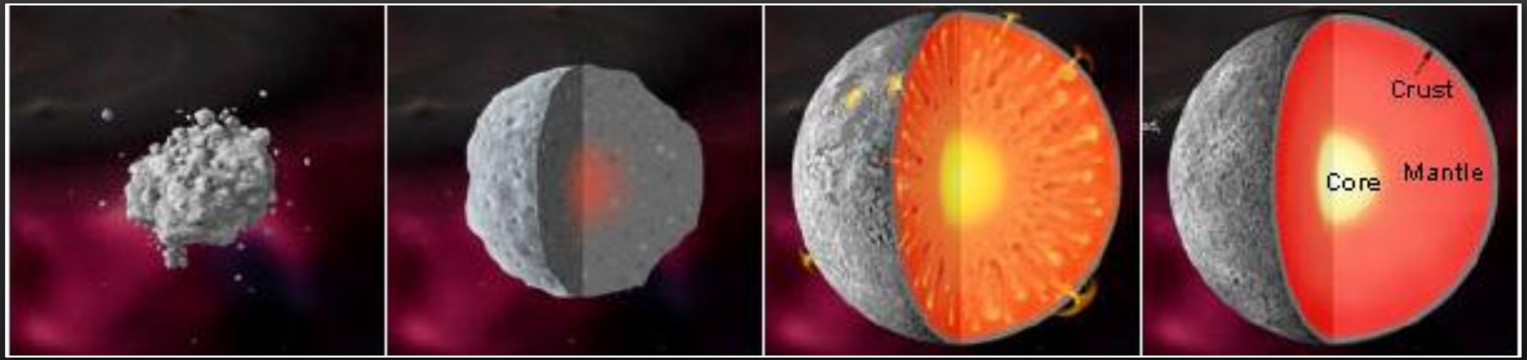
Small Bodies

Technically any body in the Solar System other than the Sun, planets, or dwarf planets

- But the sizes can range from 525.4 km in diameter (asteroid Vesta) down to 10s of kms
  - Which do we care about for presolar grains? → The small ones!...But why?

Differentiation

To preserve presolar grains, we need to *avoid* differentiation, which means looking at smaller bodies: **asteroids and comets**!



Radioactive decay of some short lived isotopes releases heat

$^{26}Al \rightarrow {}^{26}Mg$

→ Large bodies melt →

Heavy components (Fe and Ni) sink to the center of mass, forming the cores the cores

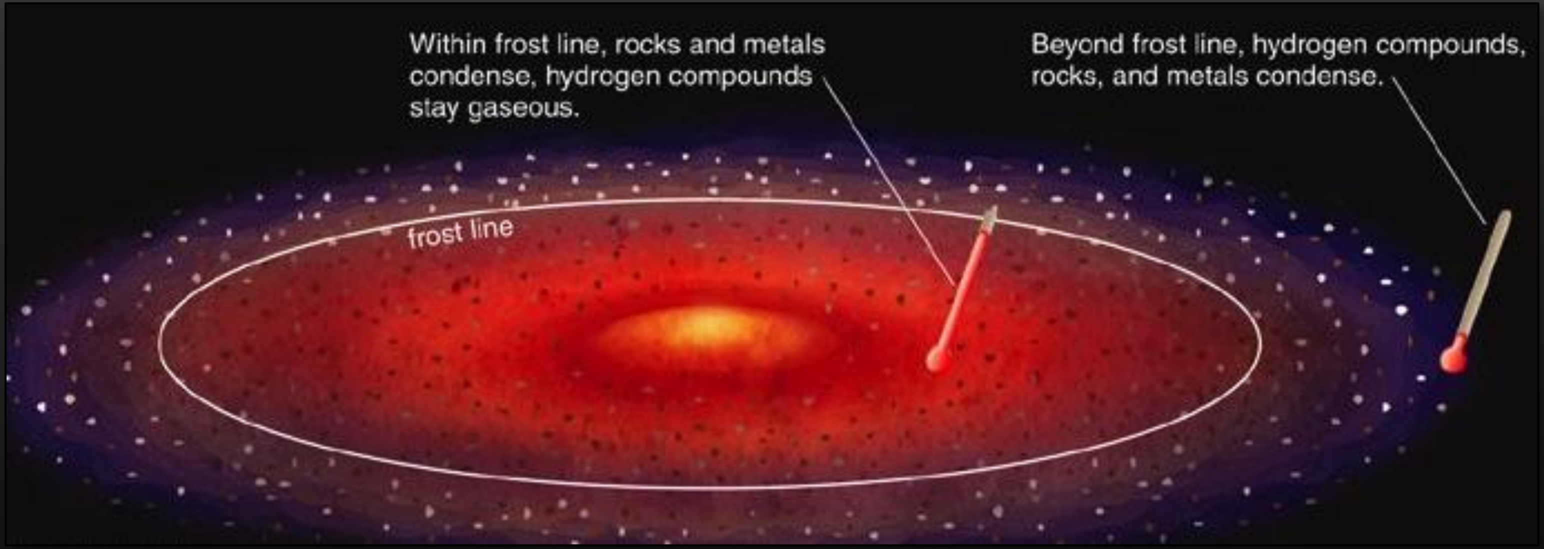
Lighter components form the mantle

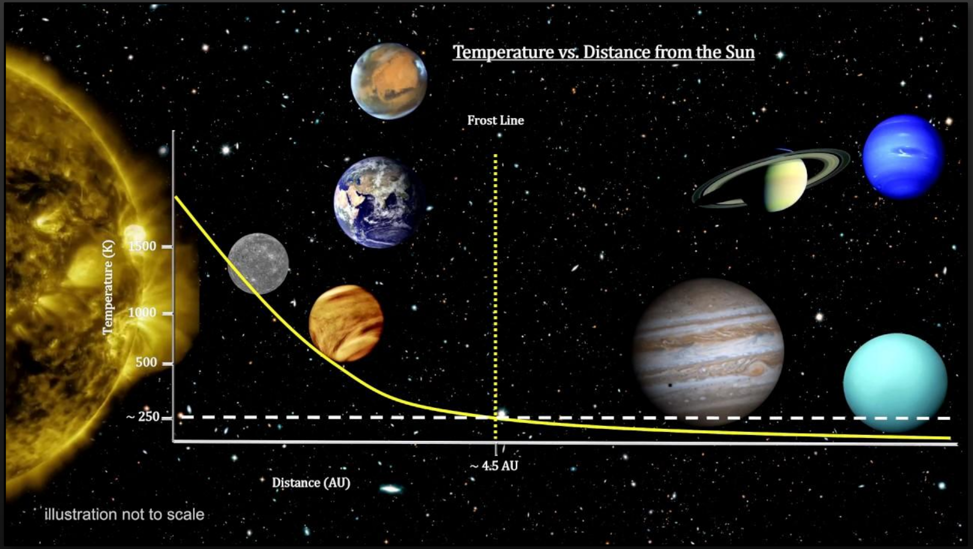
Asteroids and Comets (aka Parent Bodies)

Asteroids = **inner** Solar System **rocky** (mostly located between Mars and Jupiter aka the asteroid belt)

Comets = **outer** Solar System **icy** bodies with highly elliptical orbits (mostly come from the Kuiper belt)

Location of accretion/distance from Sun determines what material could form (e.g., water/water vapor vs ice)





Parent Body Processes

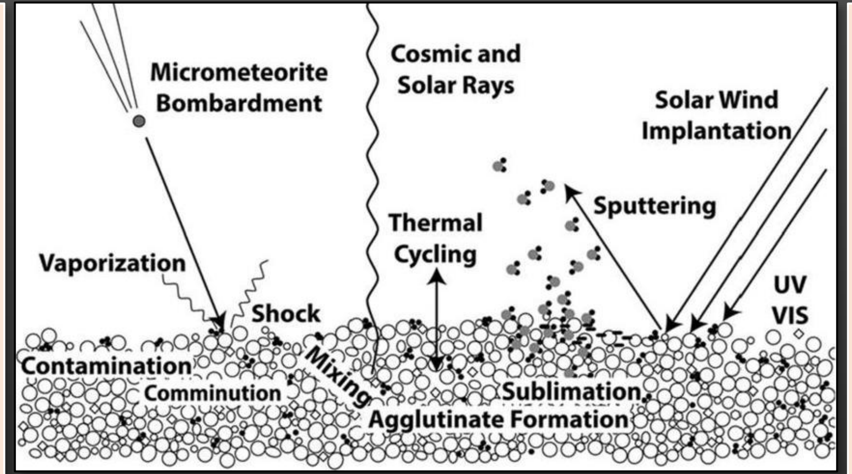
Dominant Processes Affecting Dust

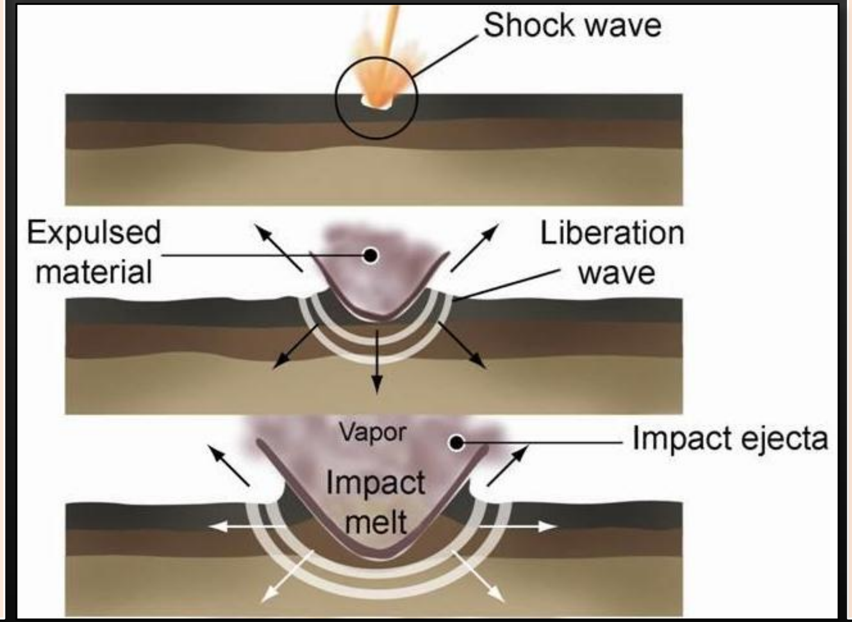
Space Weathering

Weathering (physical and chemical changes) that occurs on airless bodies

Effects:

- Amorphization
- Melting
- Loss of volatiles
- Fe nanoparticles





Shock Metamorphism

Rapid increases in temperature and pressure from impacts on airless bodies

Effects:

- Fragmentation
- Structural defects (up to amorphization)
- Phase transformations
- Diffusion and homogenization

Parent Body Processes

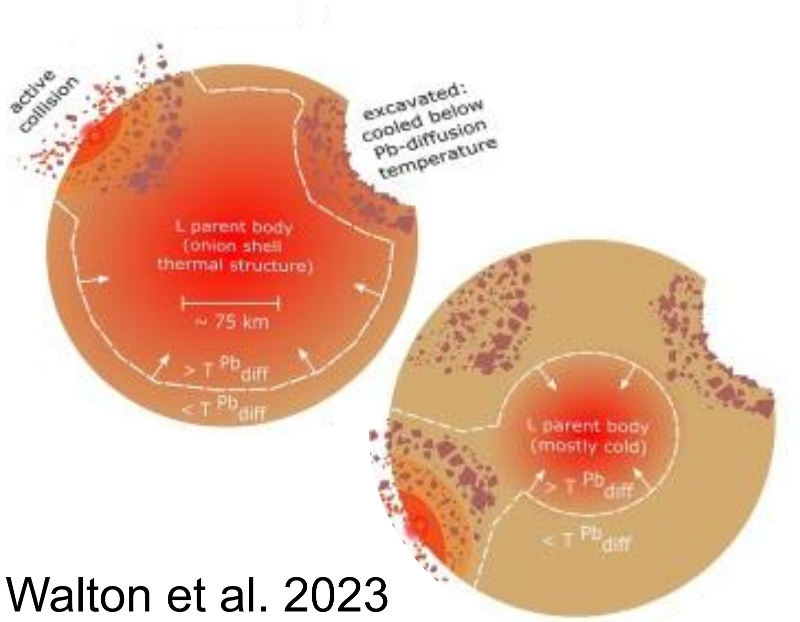
Dominant Processes Affecting Dust

Thermal Metamorphism

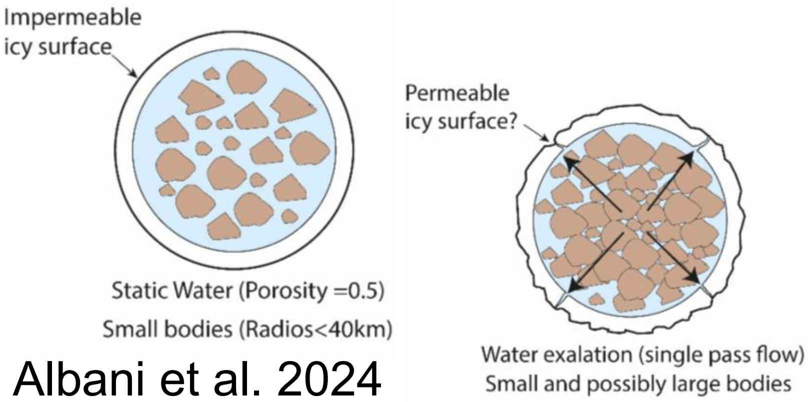
Heating (without melting) of rocky components from processes such as solar radiation, impacts, and <u>radioactive decay of certain isotopes</u>

Effects:

- Crystallization (of amorphous materials)
- Loss of volatiles (e.g., S, Zn, Pb)
- Diffusion and homogenization



Walton et al. 2023



Albani et al. 2024

Aqueous Alteration

Interaction of fluids (from melting of ice) with rocky components

Effects:

- Mobilization of certain elements (e.g., Fe, Mg, Ca)
- Mineral replacement
- Homogenization
- Porosity
- Veins and alteration rims

Observations of Solar System Processing

So…have we found evidence for bona fide Solar System processing?

Hydration?

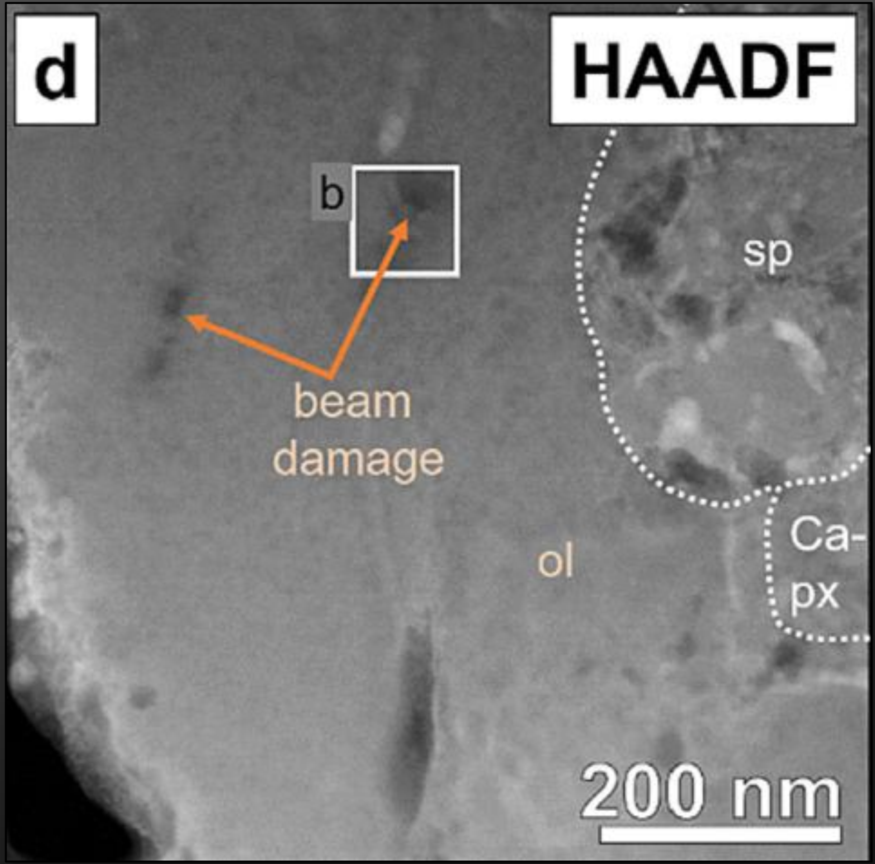
Beam damage/ amorphization during EDS on silicate grains

Perovskite – $MgSiO_3$
(Vollmer et al. 2007)

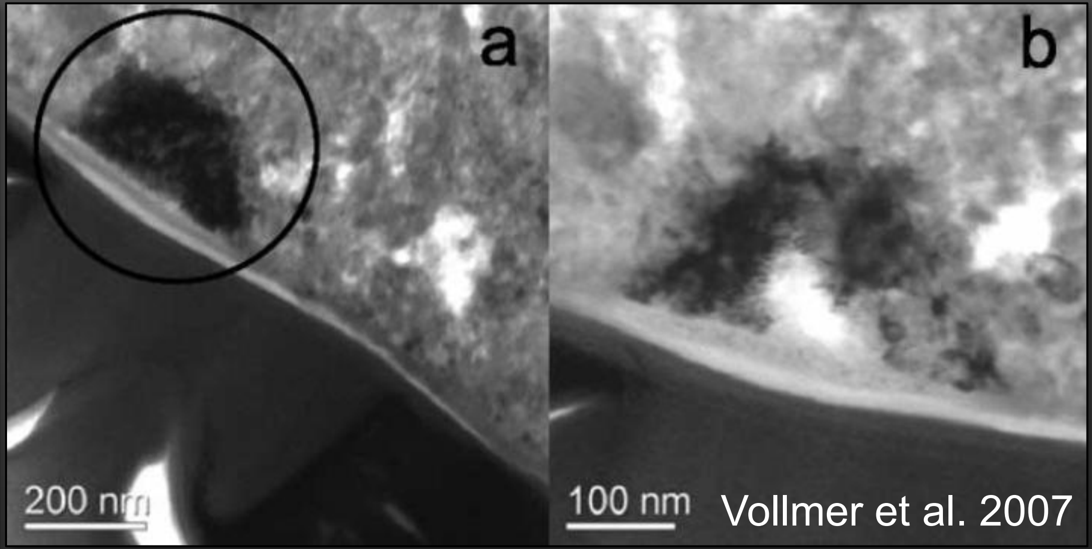
Enstatite – $Mg_2Si_2O_6$
(Vollmer et al. 2013, Nittler et al. 2020)

Olivine – $(Mg,Fe)_2SiO_4$
(Vollmer et al. 2009, Singerling et al. 2023)

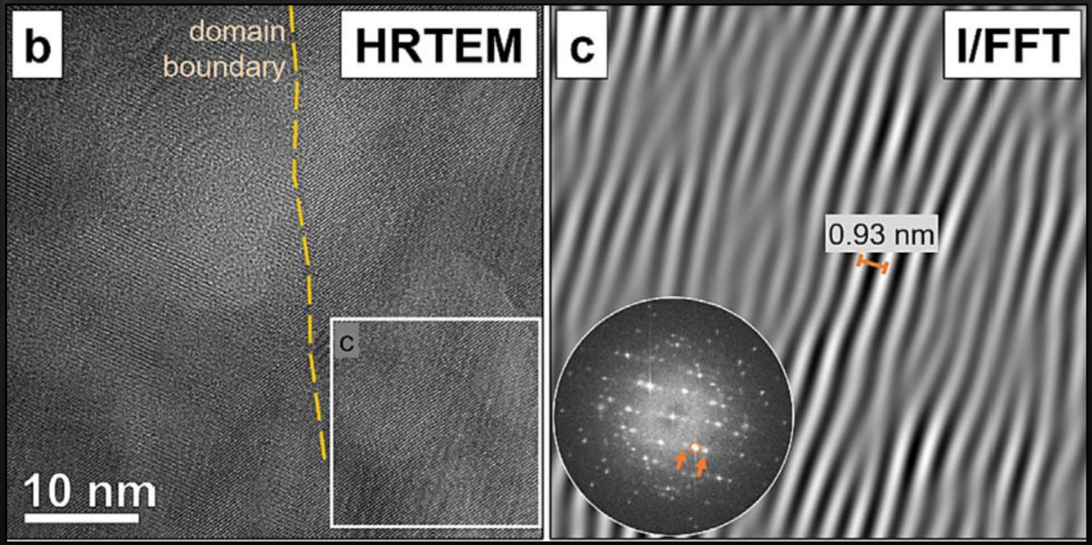
Modulations in olivine – $(Mg,Fe)_2SiO_4$
(Singerling et al. 2023)



Singerling et al. 2023



Vollmer et al. 2007



Observations of Solar System Processing

So…have we found evidence for bona fide Solar System processing?

Yes!

Mobilization of Fe?

Fe-rich rims on:

Compound grain
(Seifert et al. 2022)

Mg-Al spinel – $MgAl_2O_4$
(Zega & Floss 2013)

Non-stoichiometric silicate
(Singerling et al. 2022)

Fe-rich veins in:

Olivine – $(Mg,Fe)_2SiO_4$
(Singerling et al. 2023)

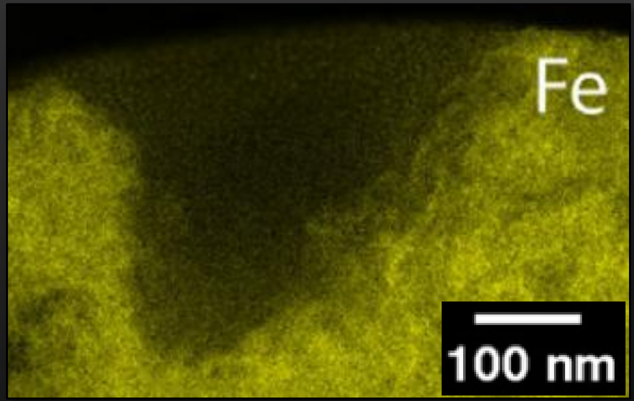
Hibonite – $CaAl_{12}O_{19}$
(Leitner et al. 2012)

Mineral Transformations?

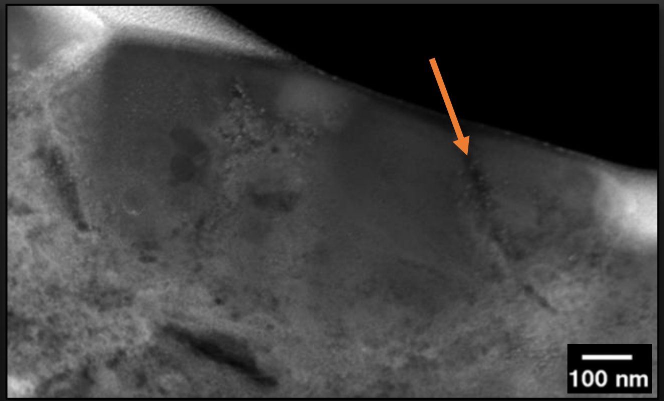
Mg-Al spinel → phyllosilicates

Formation of magnetite subgrains

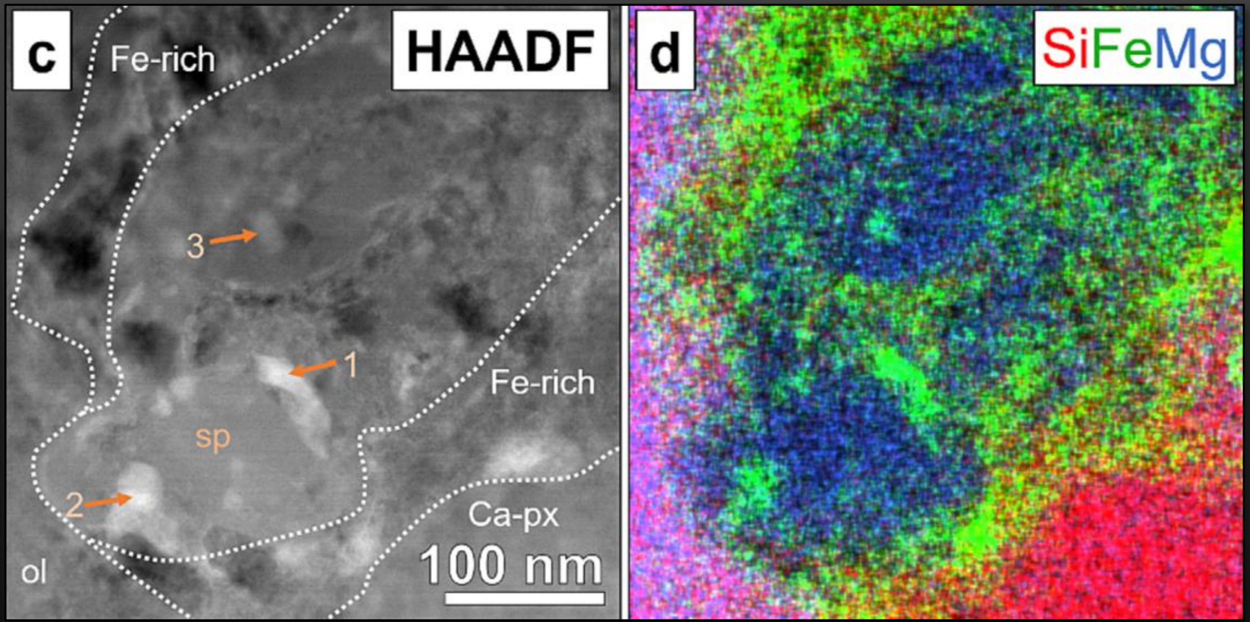
(Singerling et al. 2023)



Zega & Floss 2013



Leitner et al. 2012



Singerling et al. 2023

Cosmochemistry: Presolar Grains/Stardust

Part 8: Conclusions

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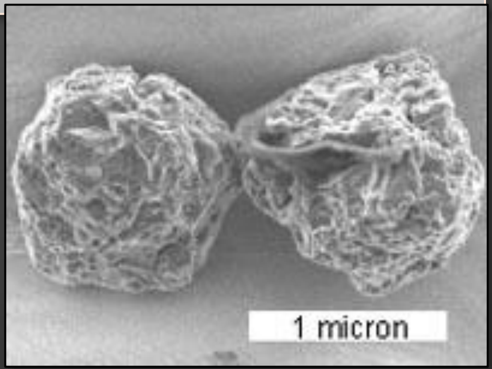
Day 3

How Presolar Grains Inform Astrophysics

What does astrophysics predict?

What do presolar grains tell us?

When do these two agree/disagree?



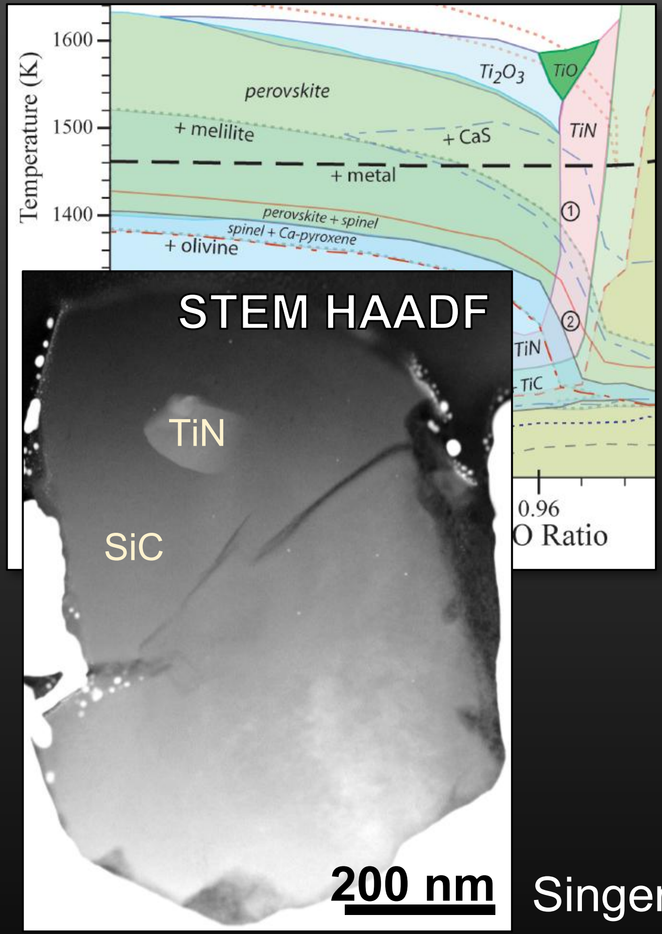
Astrophysics deals with many topics other than stars and dust—galaxies, black holes, cosmic inflation, dark matter/energy, and on and on. But we will focus on the astrophysics that concerns stars and dust.

This includes a few different fields/techniques such as:

- Theory/modeling
- Observational astronomy
- Lab-based experiments

Astrophysics vs Presolar Grain Findings

- Example 1: Circumstellar gas-phase condensation
  - Theory (thermodynamics) can predict whether minerals should condense around AGB stars
  - Do the expected (stable) minerals occur? What about unexpected (unstable) ones?



Singerling et al. (2021)

Titanium nitride (TiN)

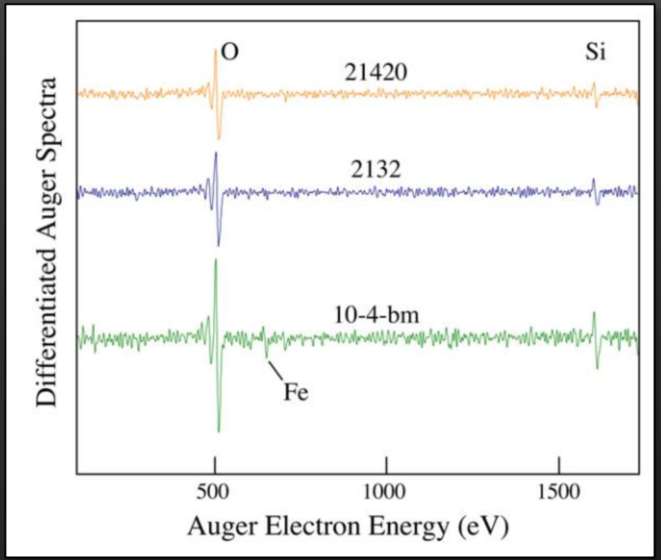
- Theory/modeling = stable and should condense
- Observational astronomy = not observed
- Presolar grain studies = observed

We do not observe it via telescopes because it is so small and only occurs as a subgrain

Silica (SiO_2)

- Theory/modeling = unstable and should not condense
- Observational astronomy = observed
- Presolar grain studies = observed

Theory does not account for non-equilibrium condensation



Bose et al. (2012)

Astrophysics vs Presolar Grain Findings

- Example 2: Mineral abundances
  - Theory can predict what the relative abundances of certain minerals should be
  - How do the abundances of two of the most common silicates—olivine ($(Mg,Fe)_2SiO_4$) and pyroxene ($(Ca,Mg,Fe)_2Si_2O_6$)—compare?

Olivine vs pyroxene

- Theory/modeling = olivine > pyroxene
- Observational astronomy = pyroxene > olivine
- Presolar grain studies = olivine > pyroxene

We need more data to resolve this discrepancy!

Possible explanations

1. Olivine > pyroxene but olivine is more readily destroyed by secondary processing (in the ISM and/or Solar System)

Caveat: Would require our presolar grain population to be non-representative…

2. Observational data are not accurate because infrared spectra peaks are in error. Features like grain size, shape, crystallinity, and variations in composition (e.g., Fe vs Mg) can affect the peak positions.

Future Directions

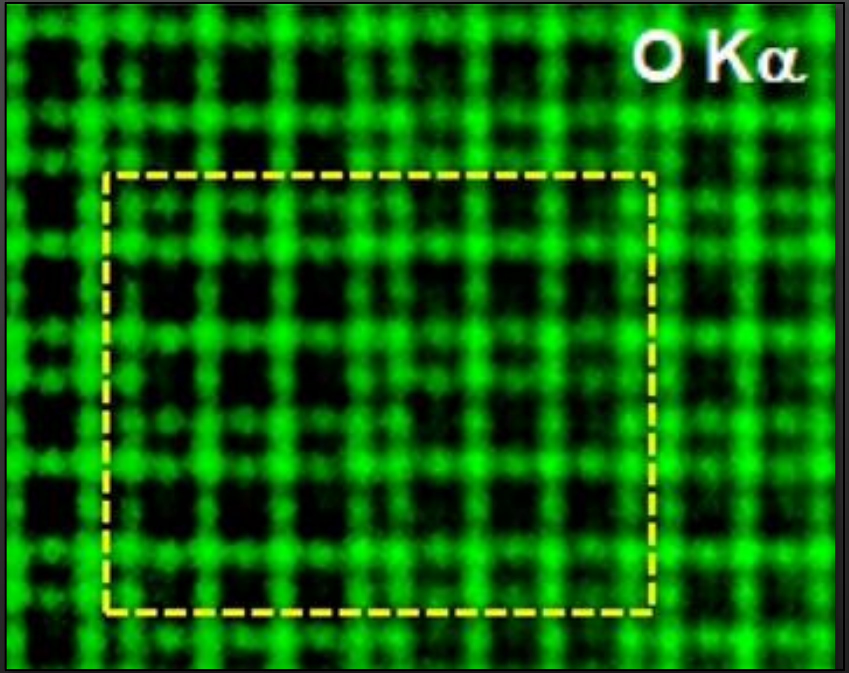
Where do we go from here? What are the most promising avenues for how we can advance of our understanding of these rare and precious specimens?

1. Expanding sample collections

- Seeking new sources of presolar grains, such as cometary samples
- Sample return missions!

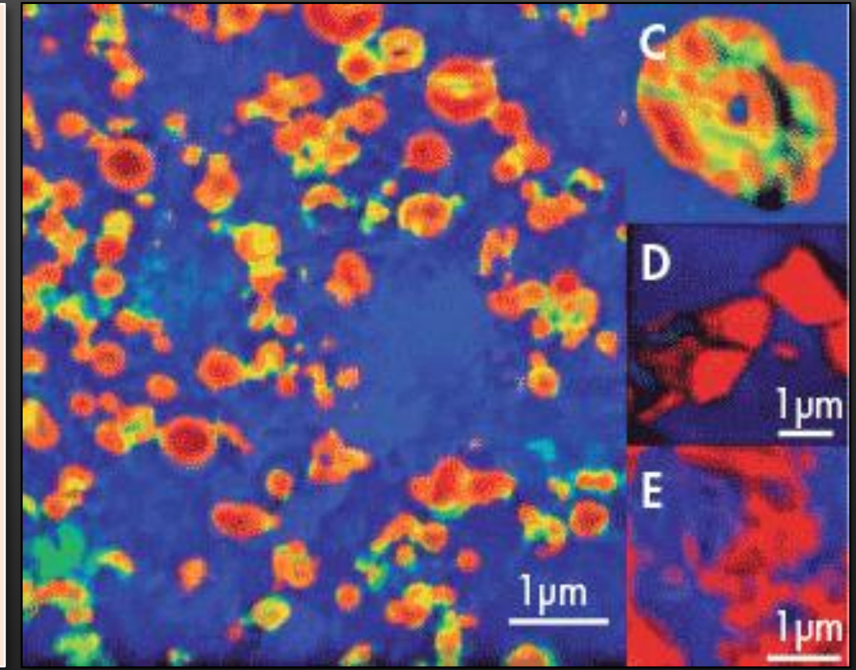
Future Directions

Where do we go from here? What are the most promising avenues for how we can advance of our understanding of these rare and precious specimens?



2. Making improvements to analytical techniques

- Higher resolution and higher sensitivity everything—telescopes, microscopes, spectrometers
- Faster sample preparation, data collection, and data processing/interpretation



Future Directions

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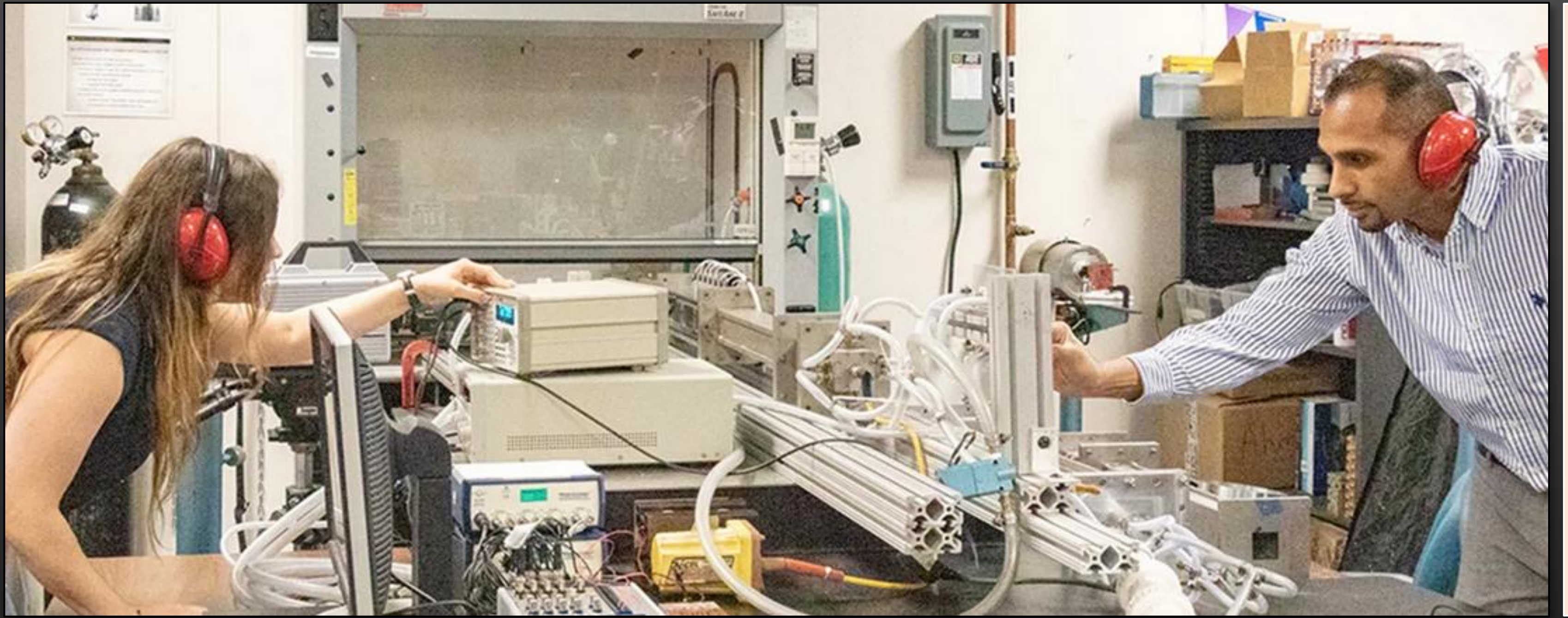

3. Fostering interdisciplinary studies

- Encouraging more collaborations between astrophysicists and cosmochemists to address open questions

Day 3 Summary

There are numerous **post-formation processes** that can affect presolar grains, both in the **ISM** and the **Solar System**.

Astrophysical and cosmochemical studies compliment one another.

Even when the two disagree, studying the **contradictions** enables us to make the most **profound advances** in our understanding of the **Universe**!