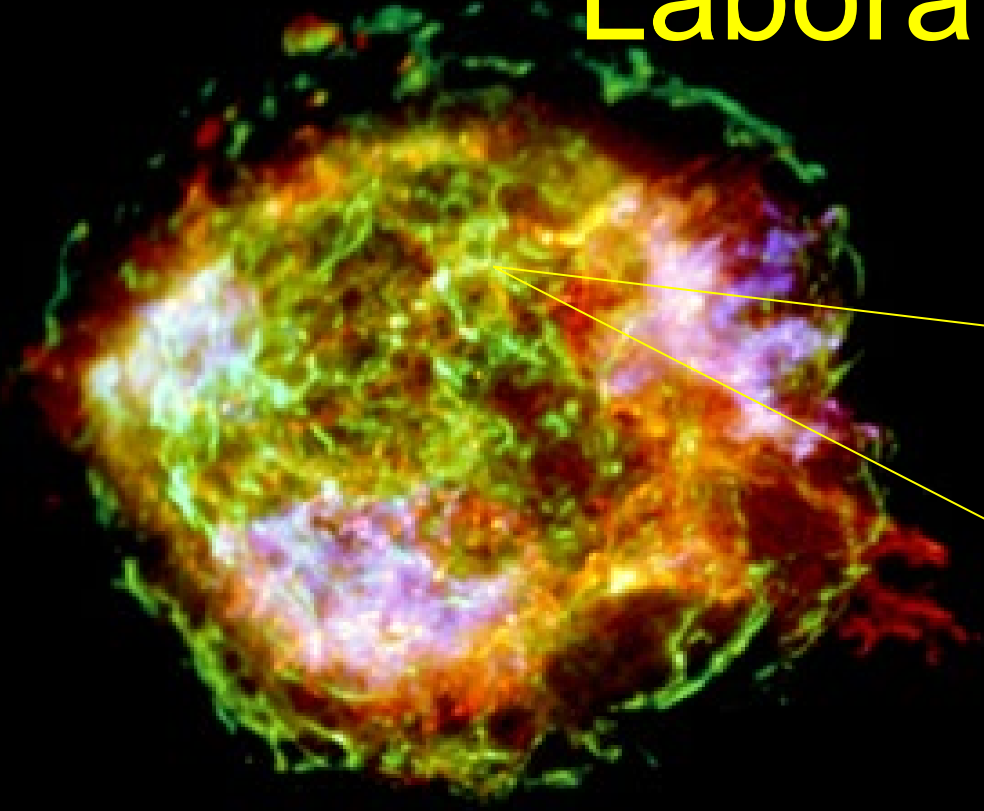
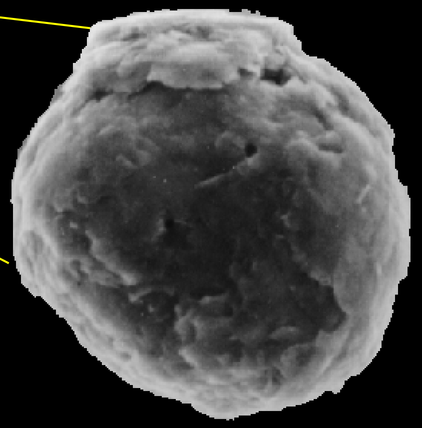
Presolar Cosmic Dust in the Laboratory

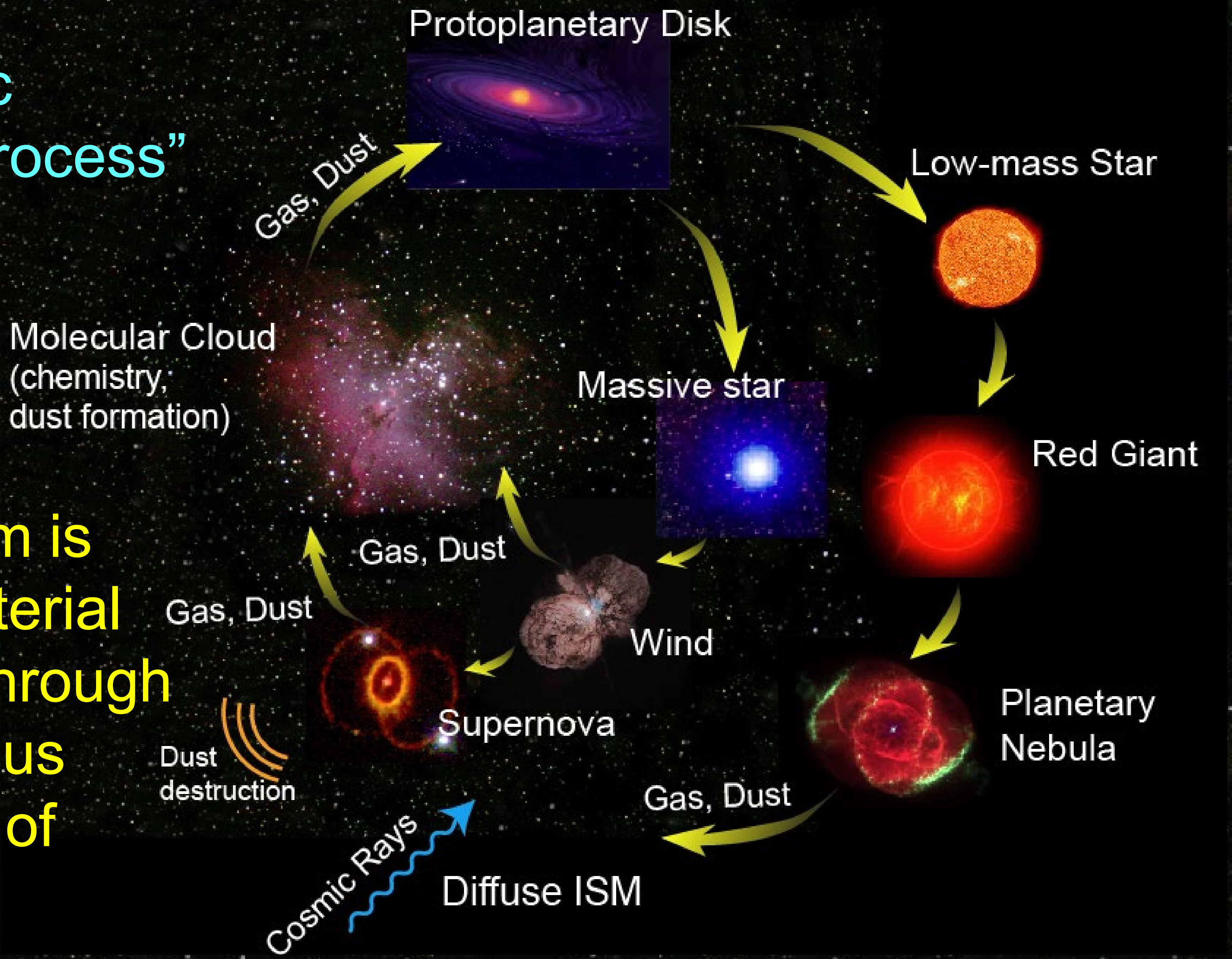




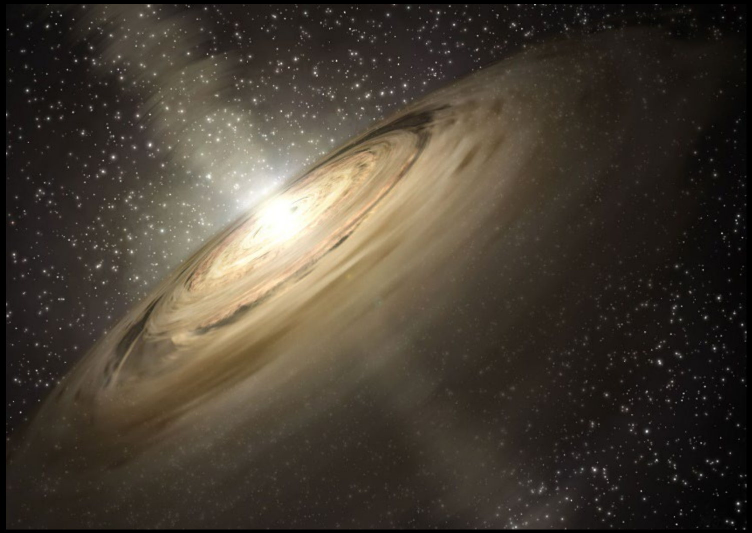
Larry R. Nittler
School of Earth and Space Exploration
Arizona State University

SCHOOL OF EARTH & SPACE EXPLORATION
ARIZONA STATE UNIVERSITY

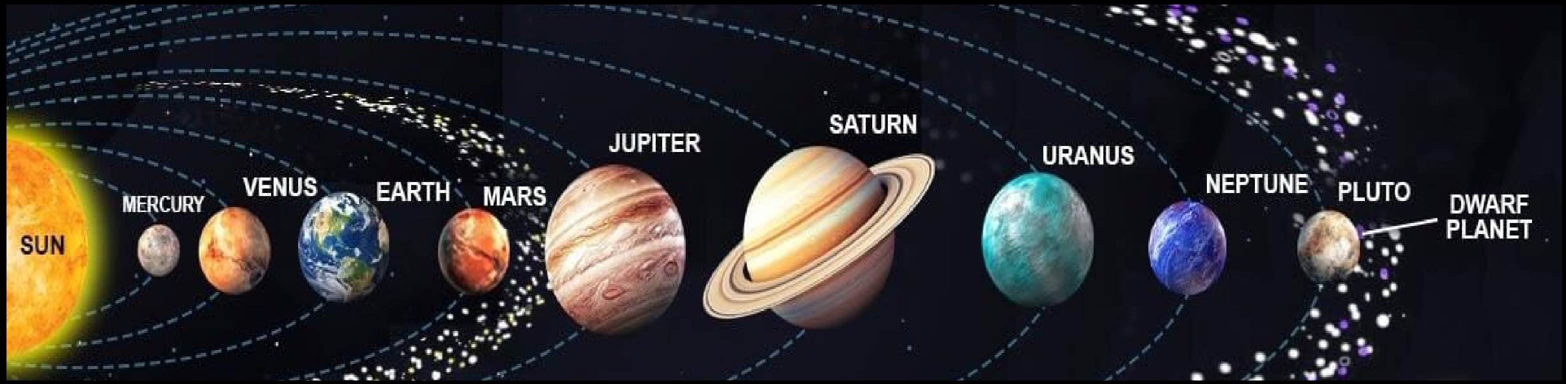
"The Cosmic Recycling Process"



Solar System is made of material processed through many previous generations of stars

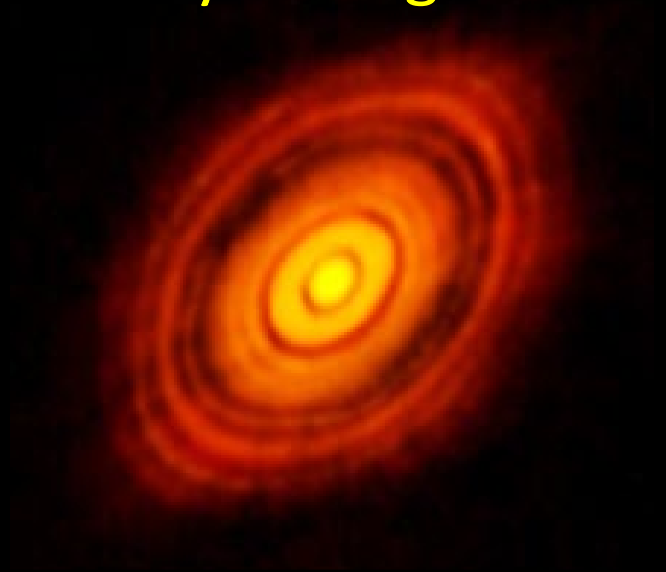


The Solar System 4.6 billion years ago



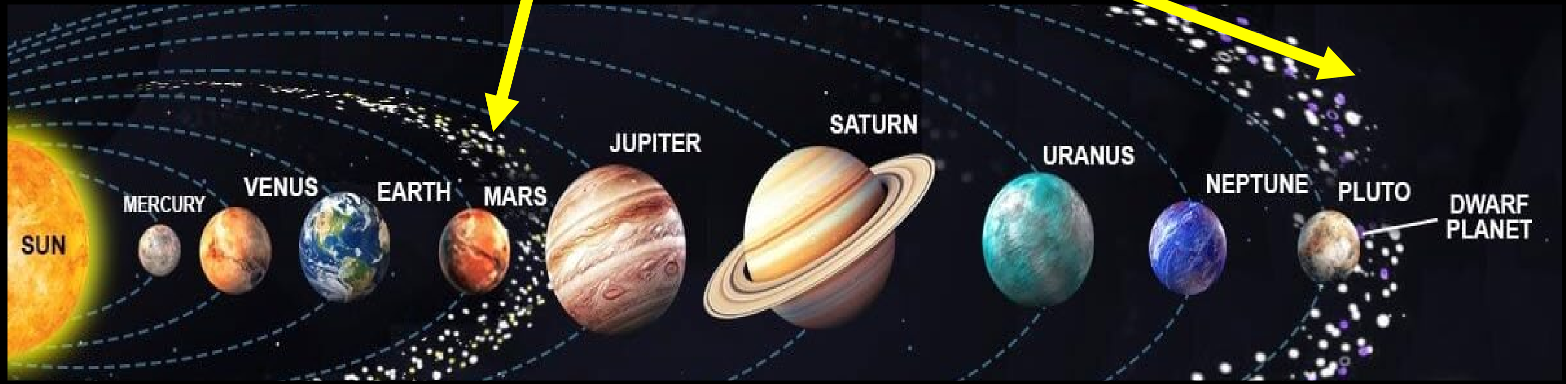
The Solar System Today

The Solar System 4.6 billion years ago

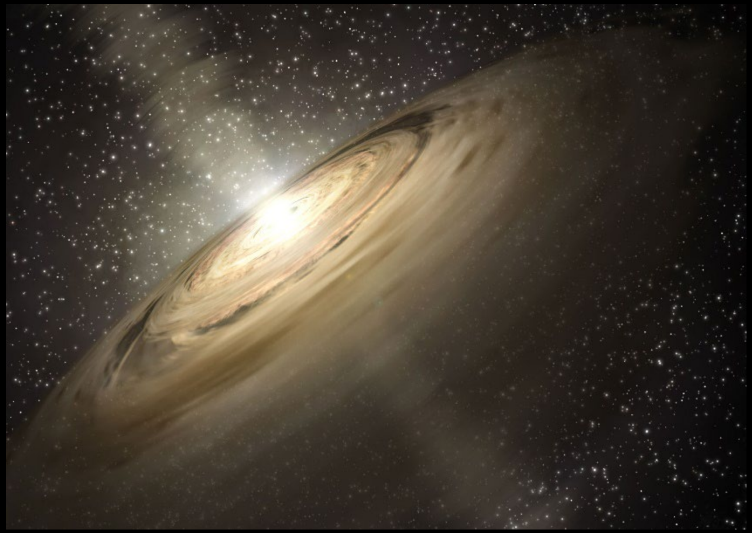


- Sun and planets formed from disk of gas/dust
- *Accretion*

  dust -> rocks-> planetesimals -> planets
- Asteroids and comets are surviving planetary building blocks



The Solar System Today



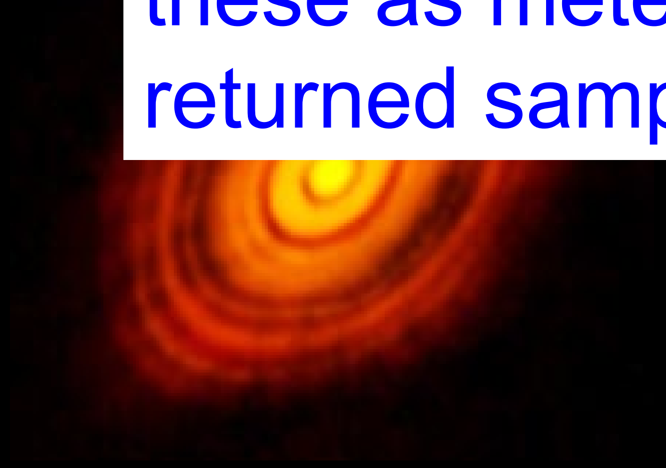
The Solar System 4.6
billio

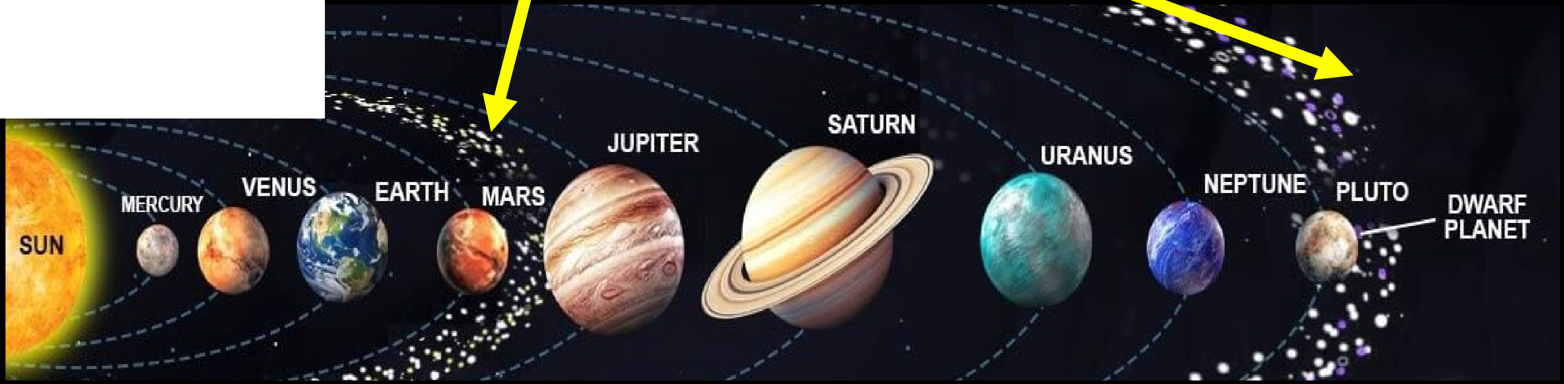
- Sun and planets formed from disk of gas/dust
- *Accretion*

  dust -> rocks-> planetesimals -> planets

- Asteroids and comets are surviving planetary building blocks

And we get samples of these as meteorites and returned samples!



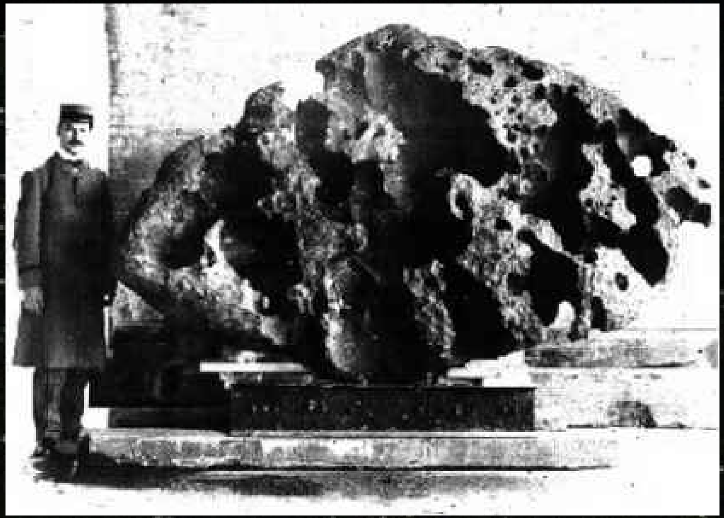


The Solar System Today

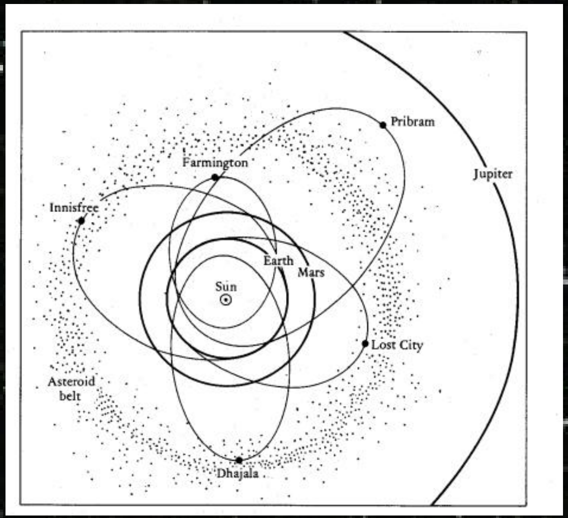
Meteorites

Fireball over Yellow Springs, Ohio
Credit: John Chumack

Meteorite on Antarctic ice (L. Nittler)

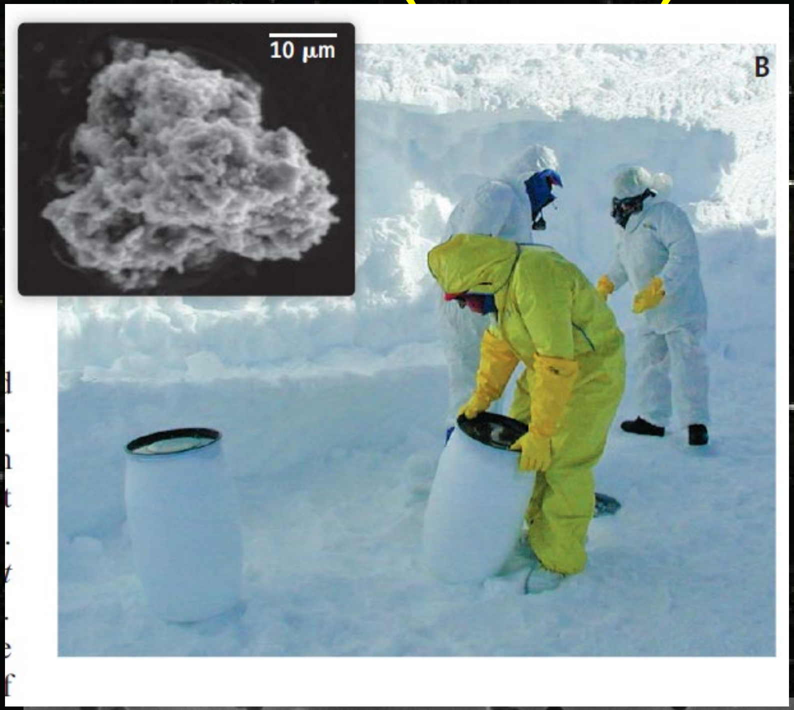


Willamette iron meteorite

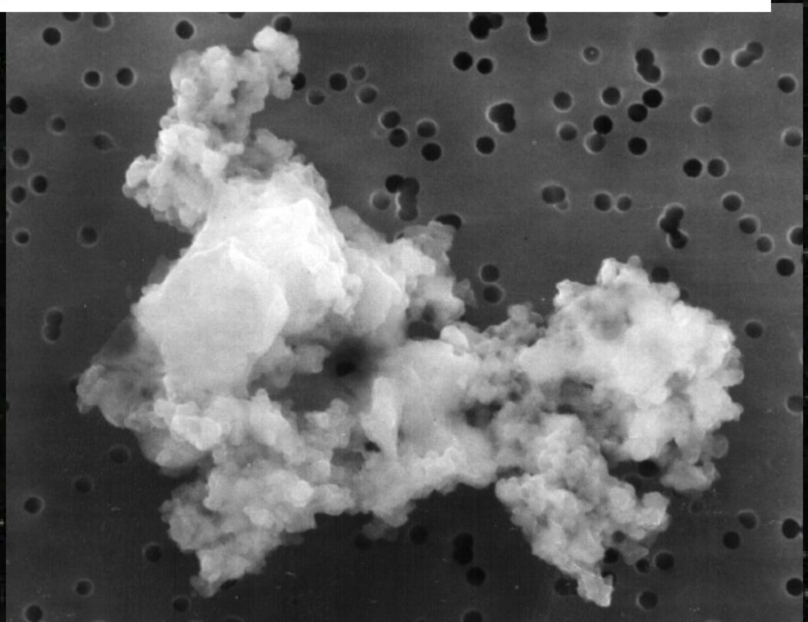


Orbit trajectories indicate origin in asteroid belt

Interplanetary Dust Particles (IDPs)



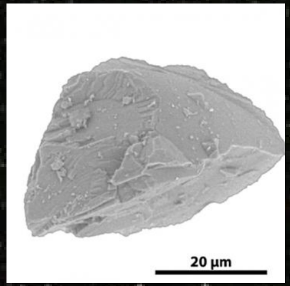
- Collected in stratosphere by modified U2 spy planes and in Antarctica by melting/filtering snow
- Originate in comets and asteroids



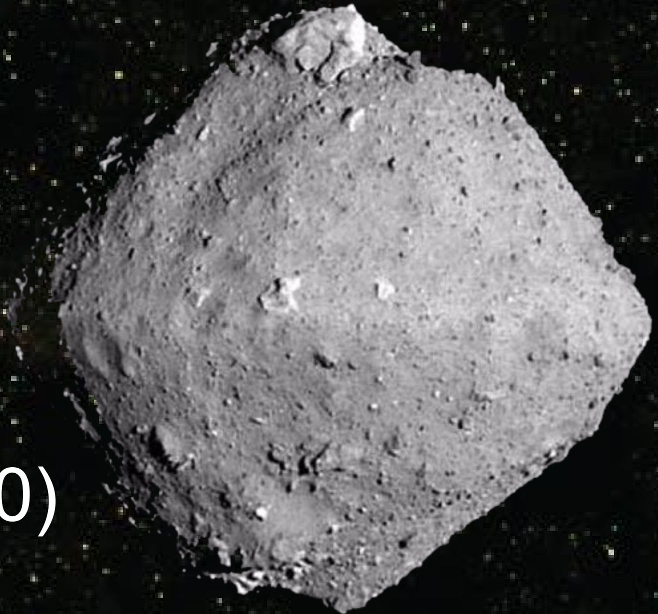
Returned samples

Itokawa

Hayabusa (2010)



Ryugu

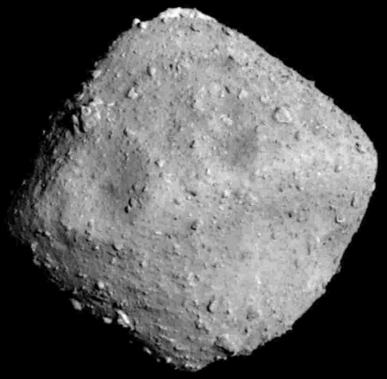


Hayabusa2 (2020)

Bennu

OSIRIS-Rex (2023)

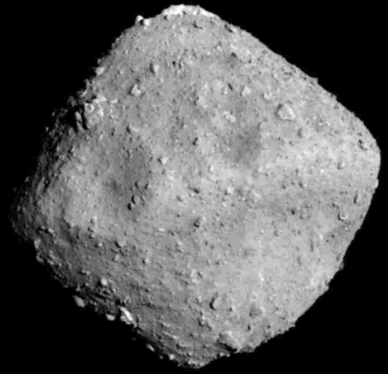
Primitive Extraterrestrial Samples



- Non-biological “fossils,” containing a record of:
  - Starting materials of the Solar System
  - What the Solar System was like at beginning
  - Earliest stages of planetary processes
  - Timescales for early processes
- Amenable to detailed analysis by ever-improving laboratory techniques

Laboratory Astronomy/Astrophysics

Primitive Extraterrestrial Samples



- Non-biological "fossils," containing a record of:
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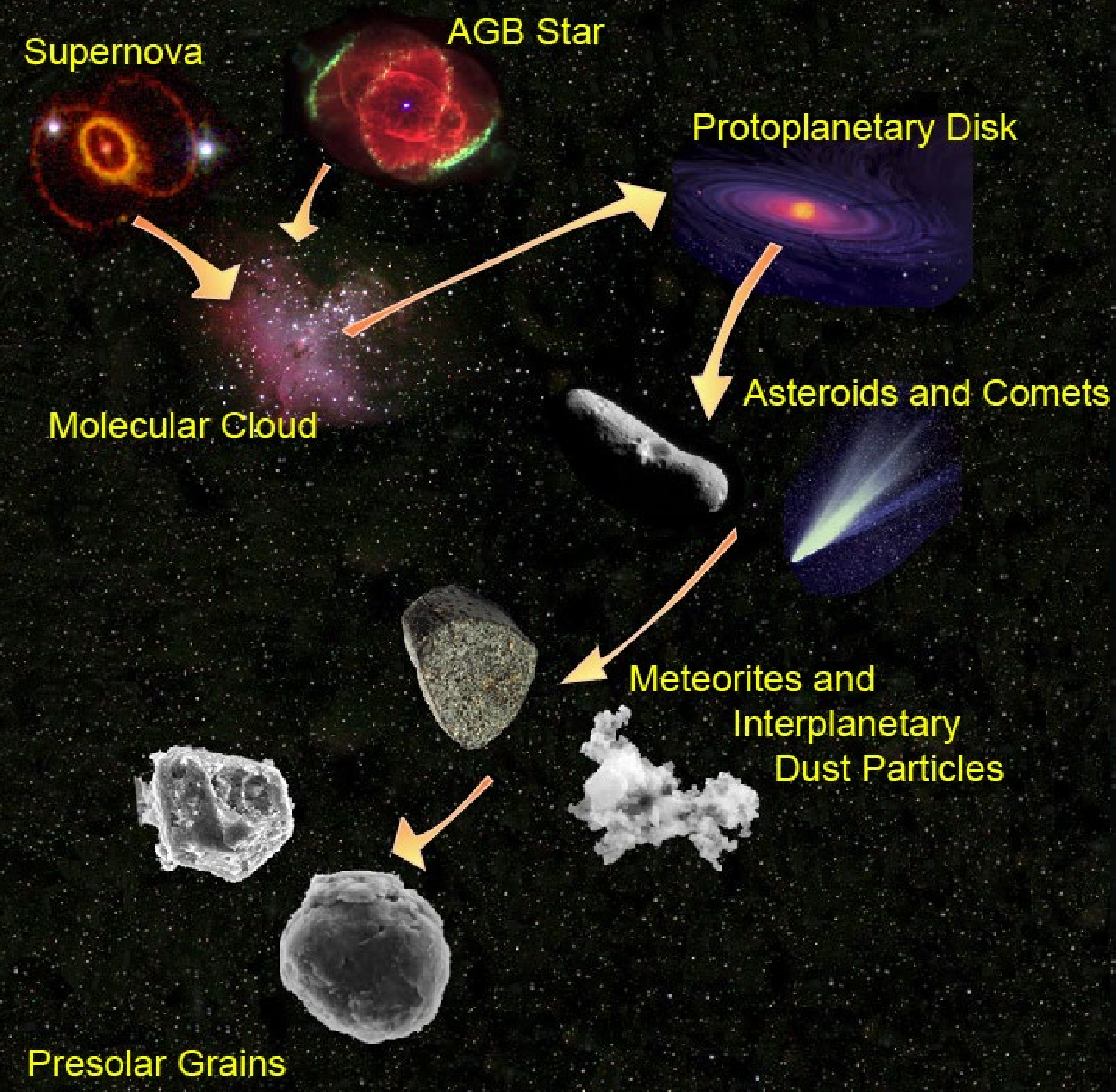
Laboratory Astronomy/Astrophysics

Presolar Stardust in the Solar System



- Bona-fide stardust from ancient dead stars
- Survived interstellar processes and solar system formation
- Found today surviving in meteorites and interplanetary dust particles
  - <~100 ppm

How do we know?

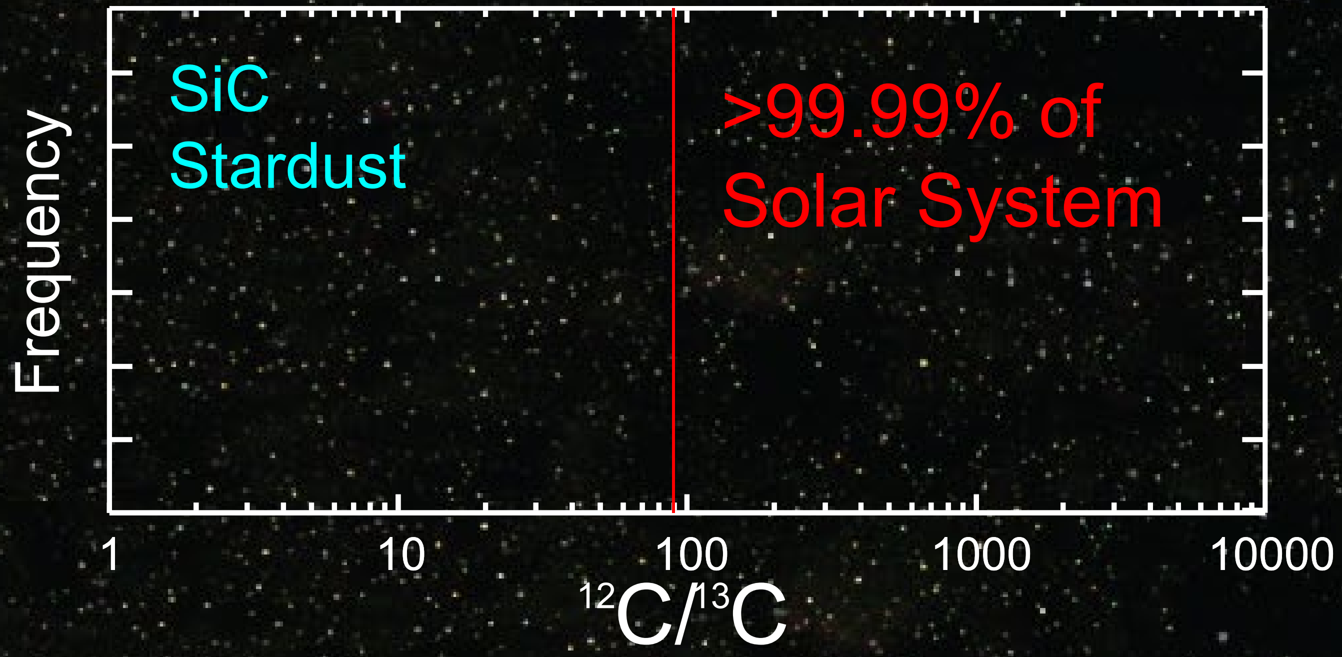
Isotopes are key!

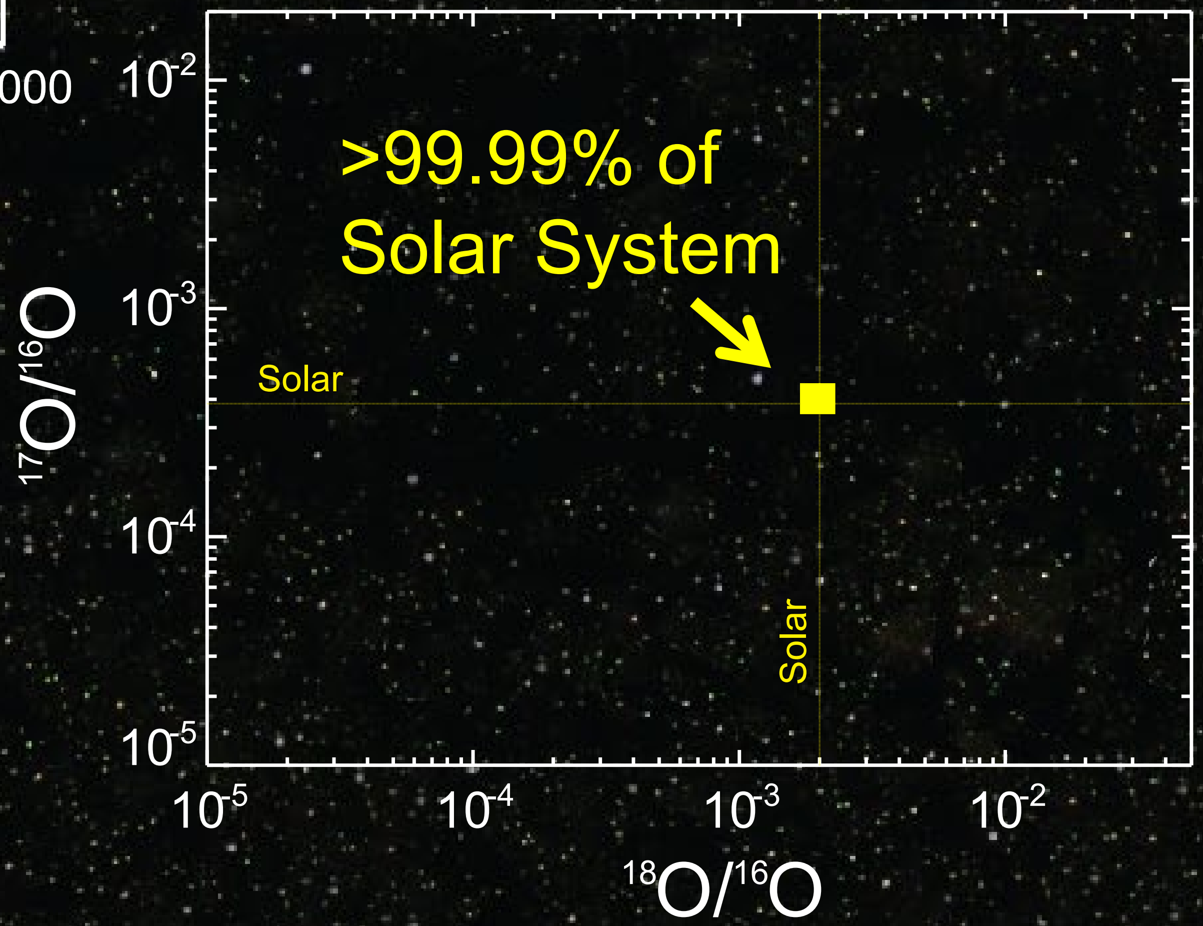
- Up until the 1960s prevailing wisdom was that the solar nebula was very hot and any preexisting dust from the presolar era would have been vaporized and the disk completely isotopically homogenized

- Largely true – for most elements *Sun ~ Earth ~ Jupiter ~ comets, etc (<% variations seen from physical/chemical processes)*

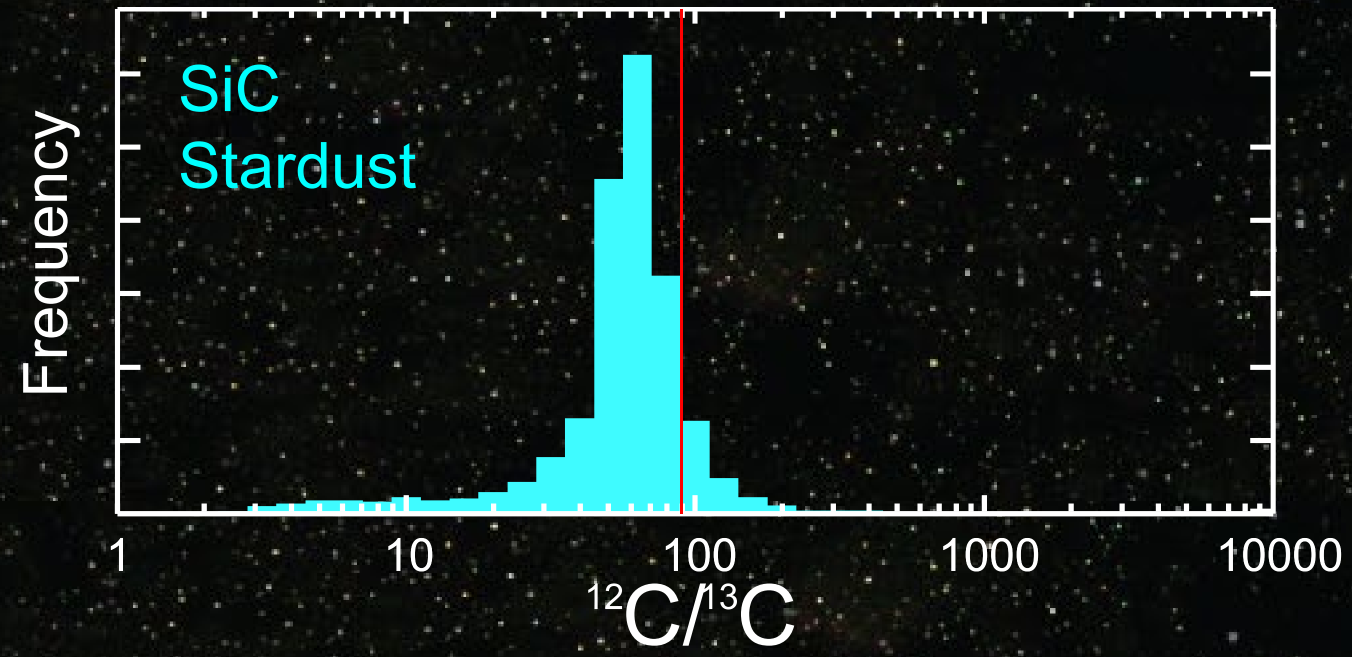
- *1960s: Discovery of isotopically anomalous noble gases in meteorites led to 20 years of experiments searching for presolar grains (success in 1987!)*

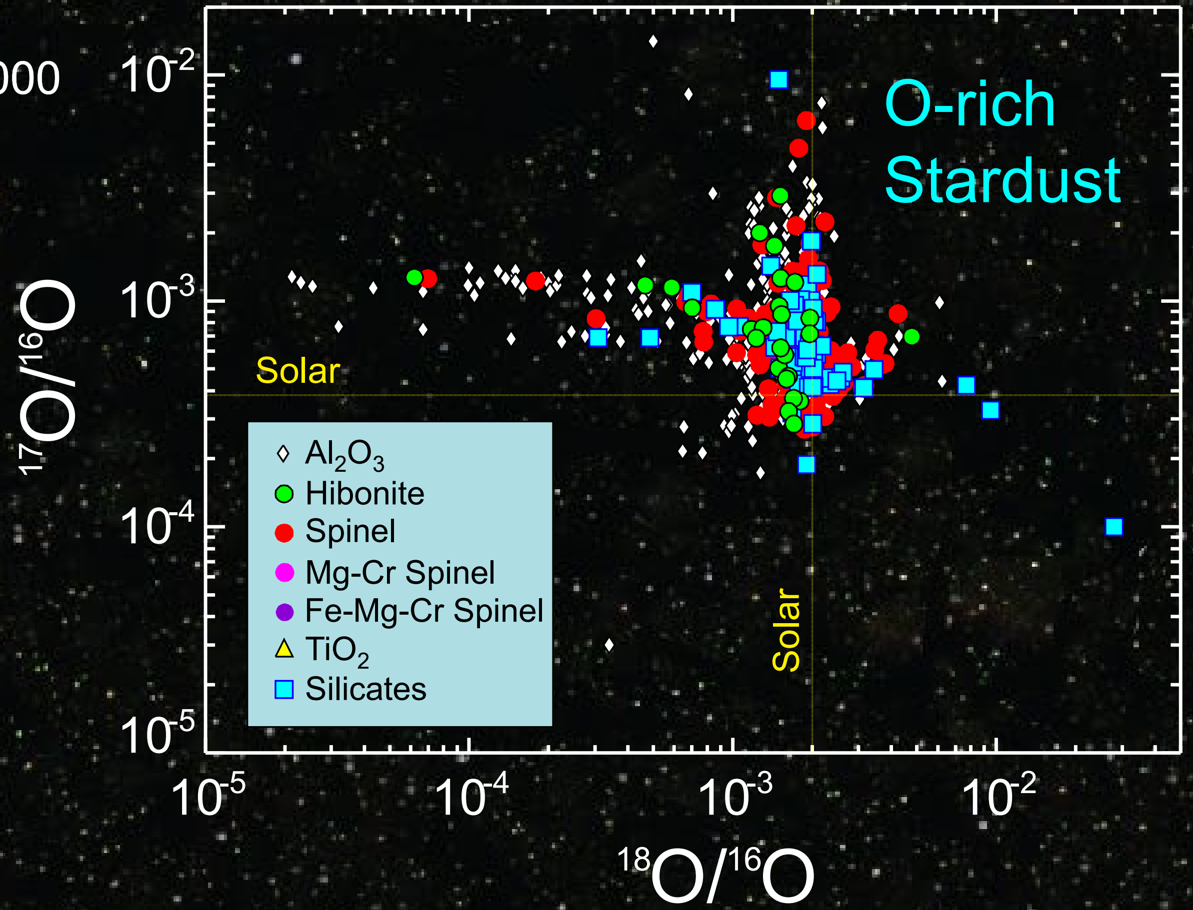
How do we know?



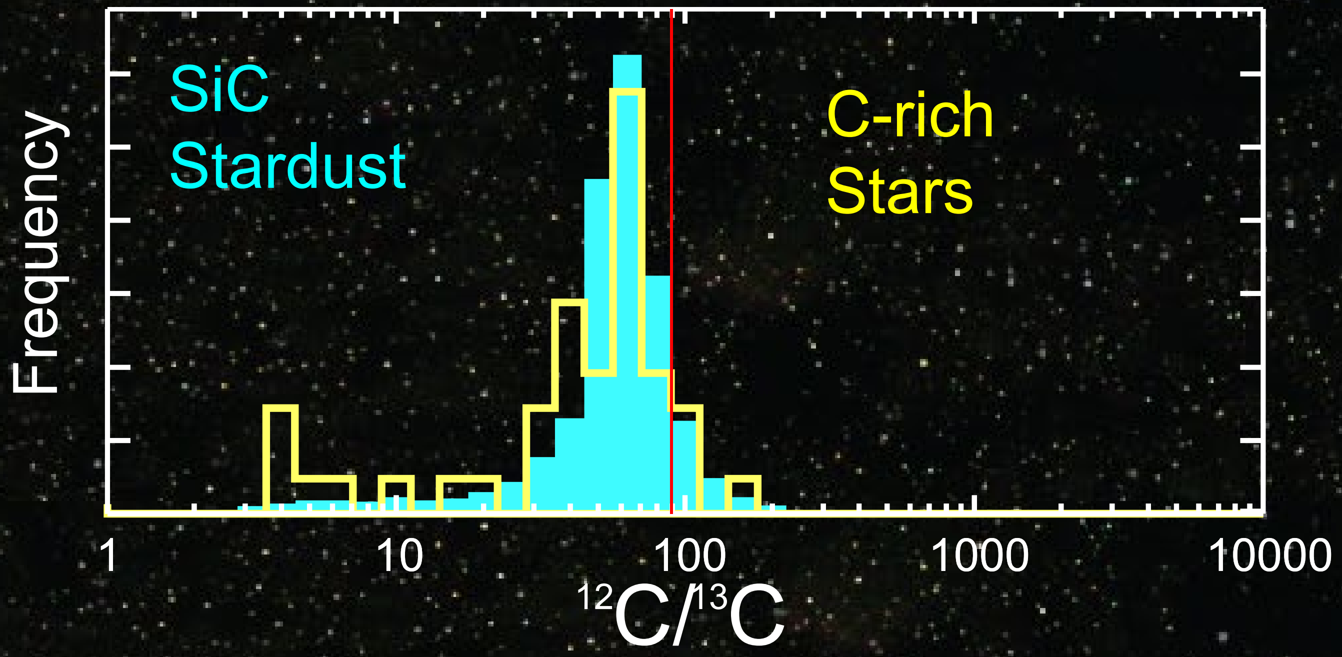


How do we know?





- Isotopic ratios in grains extremely unusual and distinct from ranges found in solar system material



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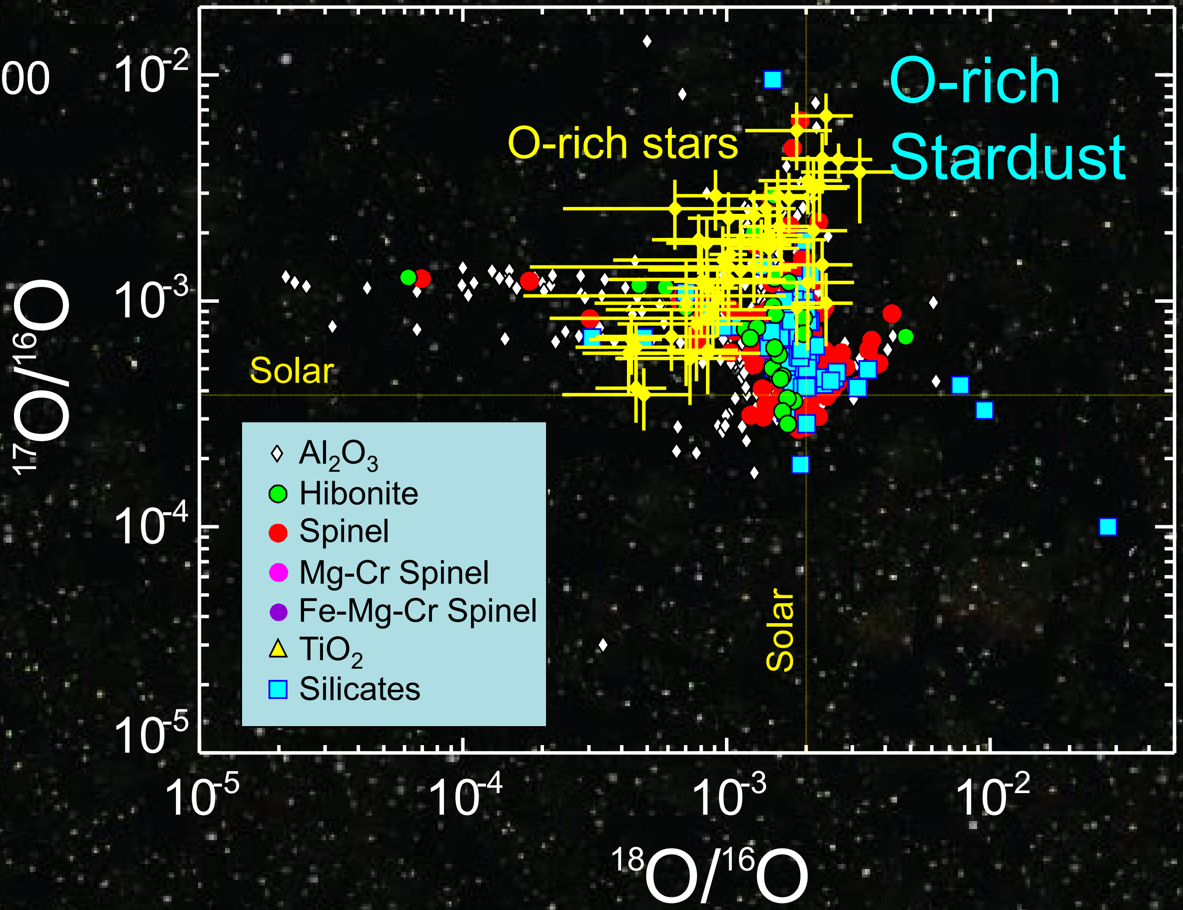
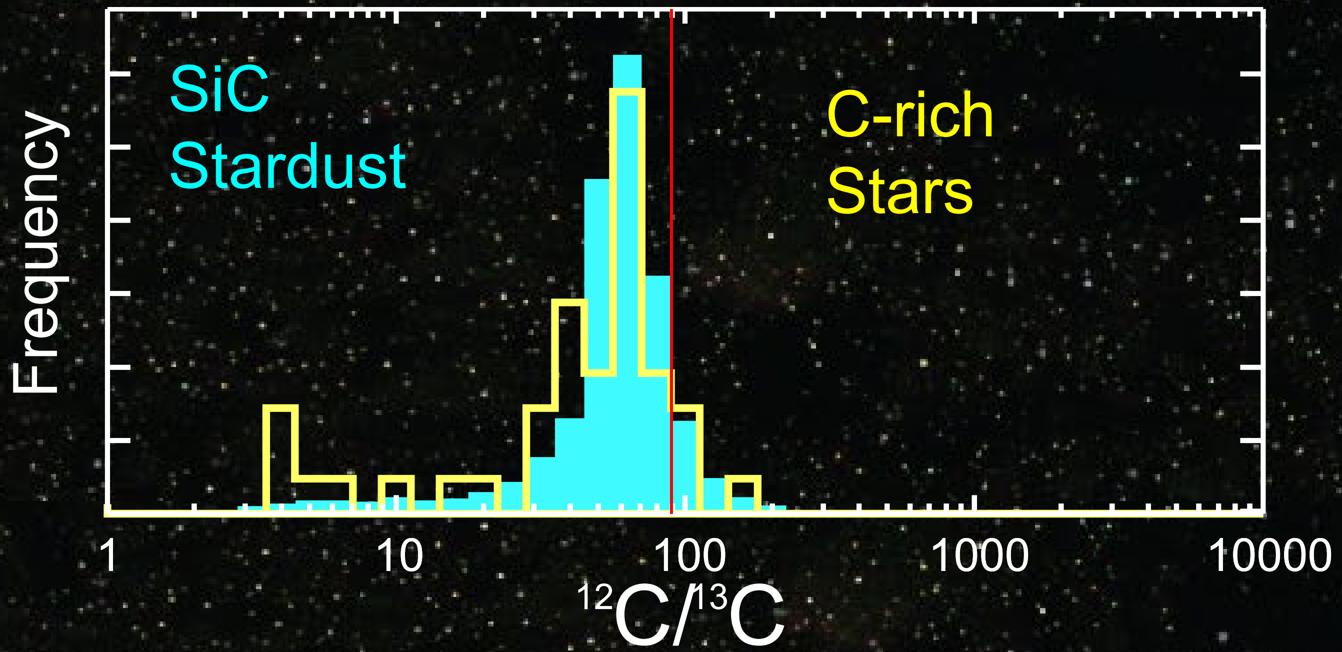
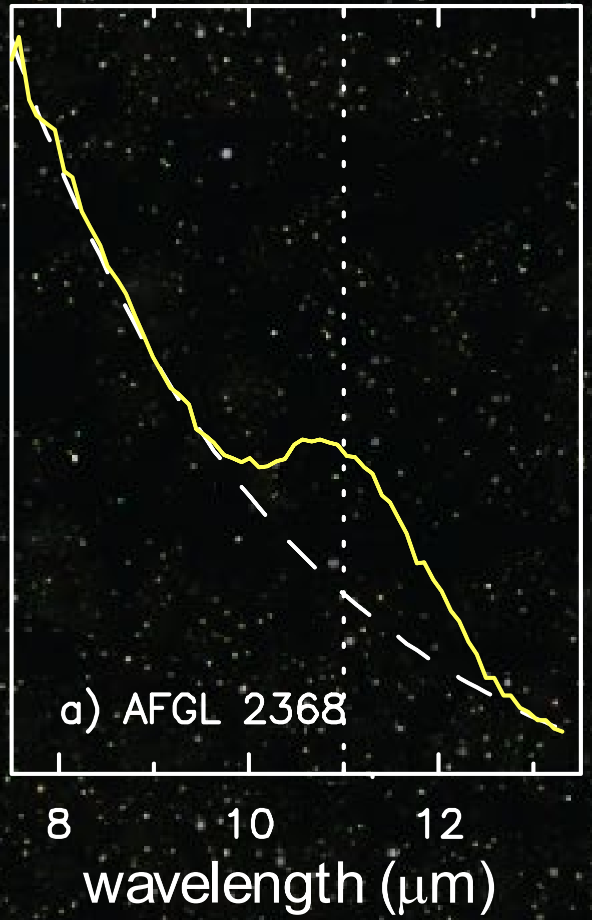
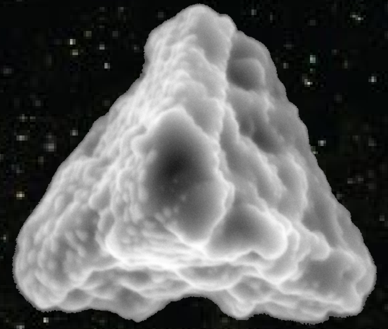


- Isotopic variations require *nuclear* processes.
- Origin in STARS

How do we know?



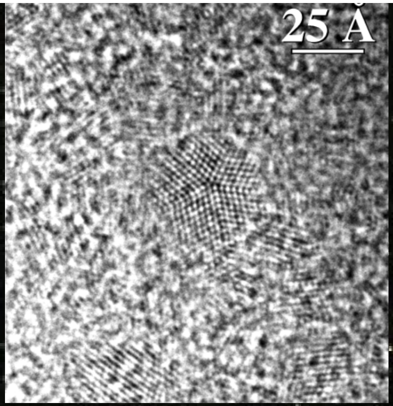




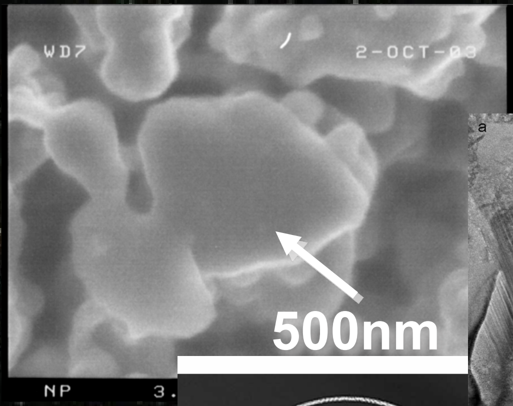
- Isotopic variations require *nuclear* processes.
- Origin in STARS

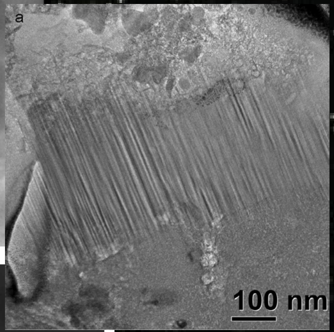
Types of Presolar Grains

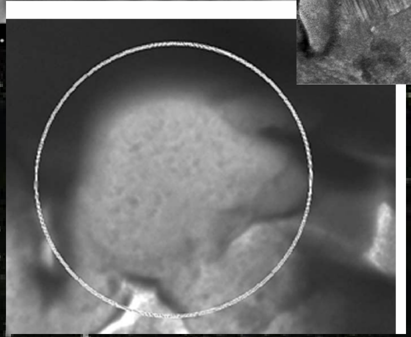
Nanodiamonds(?)
(1400 ppm)



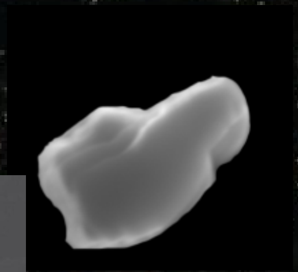
Silicates (wide range of minerals and non-stoichiometric phases)
(up to 300 ppm)

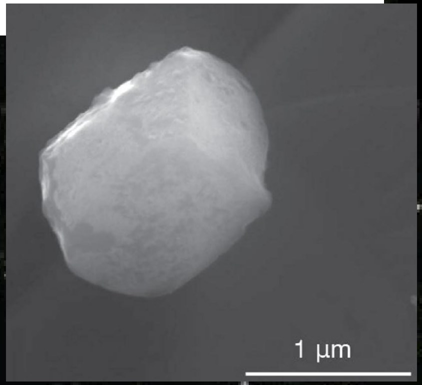




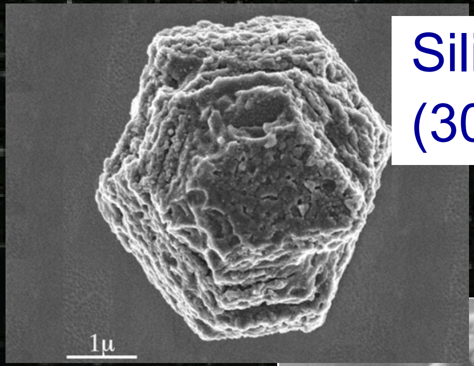


Oxides(Al_2O_3, $MgAl_2O_4$, $CaAl_{12}O_{19}$, TiO_2 …) (up to 10s ppm)

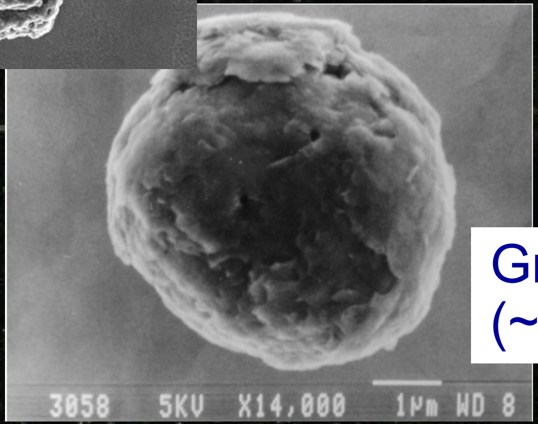




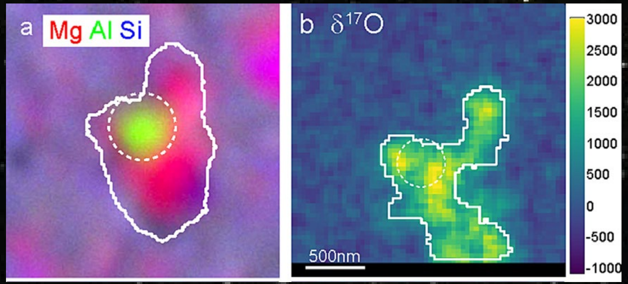
Silicon Carbide
(30 ppm)

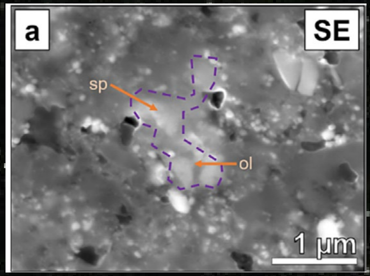


Graphite
(~1 ppm)



Composite (multi-phase) grains

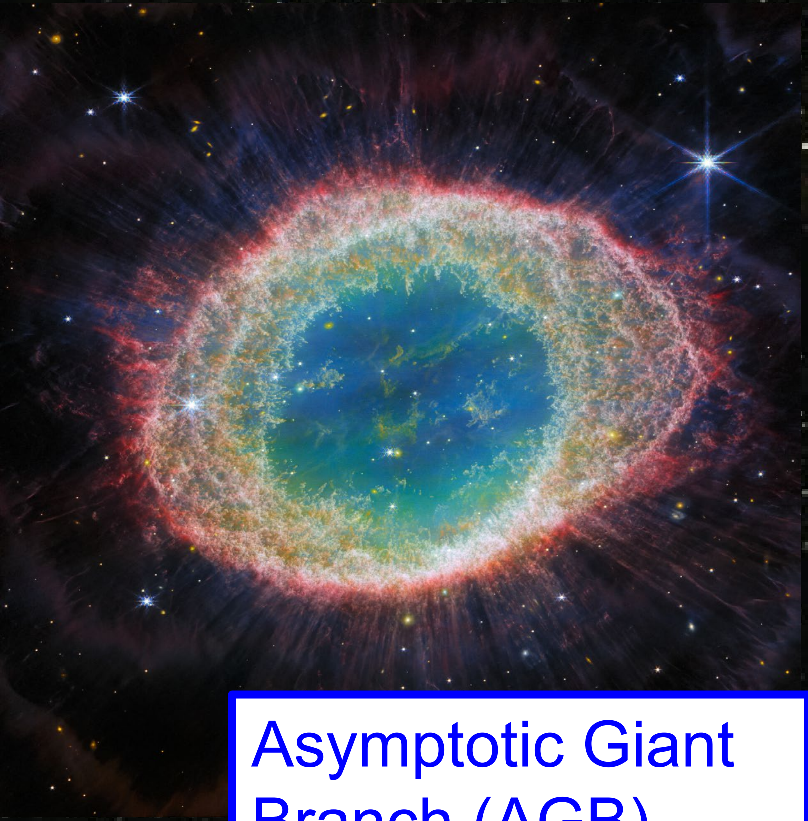




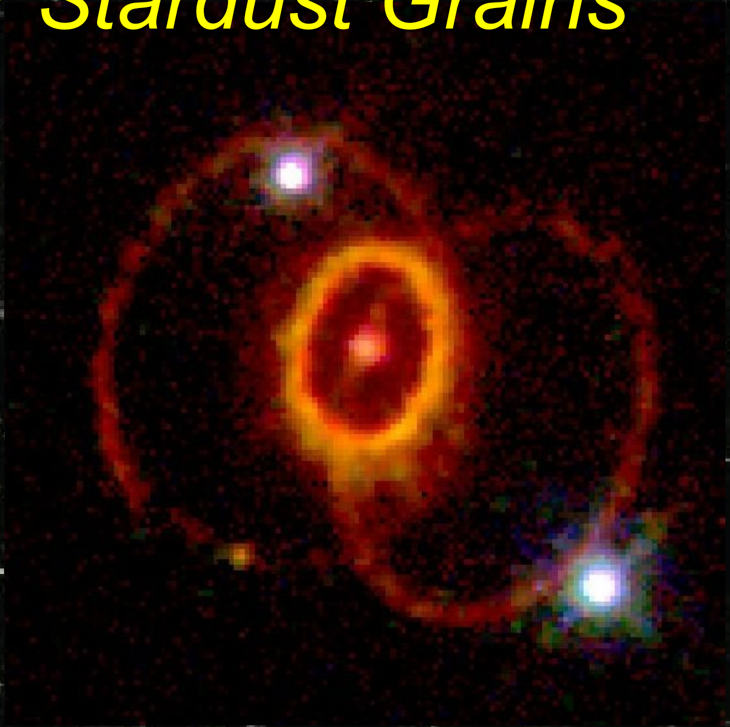
Information from presolar grains

- Cosmology
- Stellar nucleosynthesis
- Stellar evolution and mixing
- Galactic chemical evolution
- Dust formation in stellar environments
- Composition/mineralogy/processing of interstellar dust
- Sources of material for Solar System
- Early Solar System processes

Sources of Presolar Stardust Grains

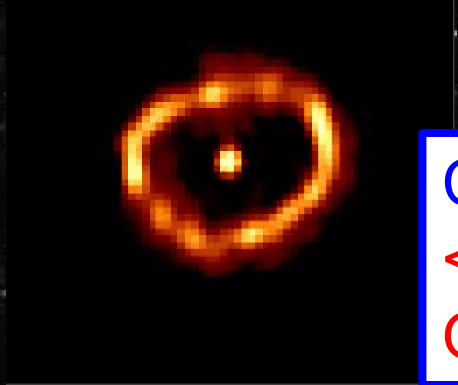


Asymptotic Giant Branch (AGB) stars:
>90% of SiC, Silicates, Oxides



Type II Supernovae
<10% of SiC, Silicates, Oxides, <50% Graphite, 100% Si_3N_4

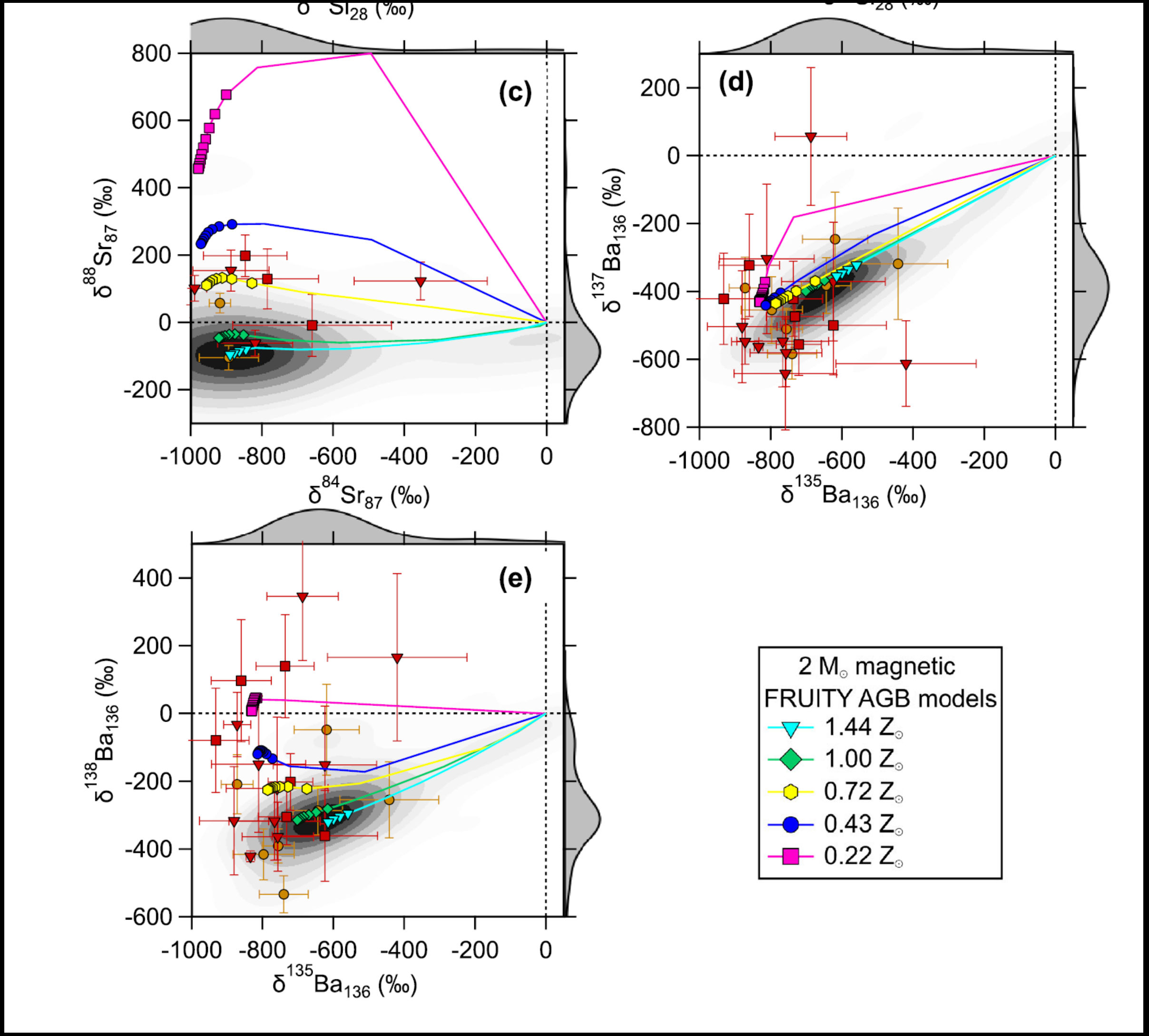
Nova Cygni 1992 (HST)



Classical Novae?
<1% SiC, Silicates, Oxides, Graphite

Lessons for Nuclear Astrophysics

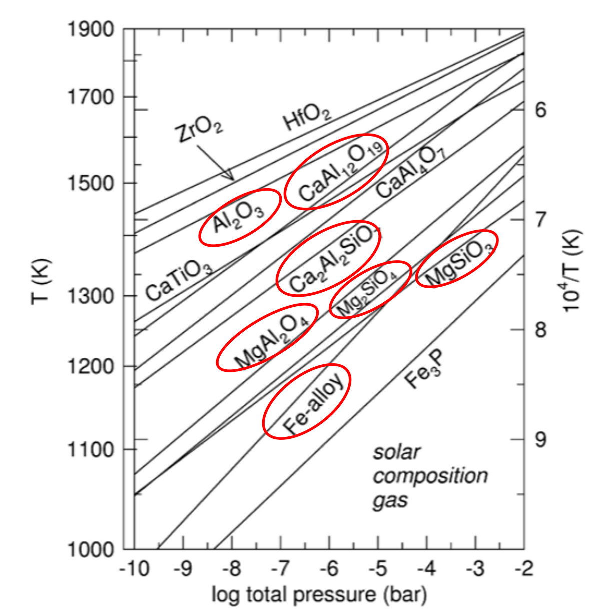
- Cam measure heavy trace element isotopes which are not possible astronomically (Ba, Mo, Zr, Sr, …)
- Can test stellar theory with very high precision



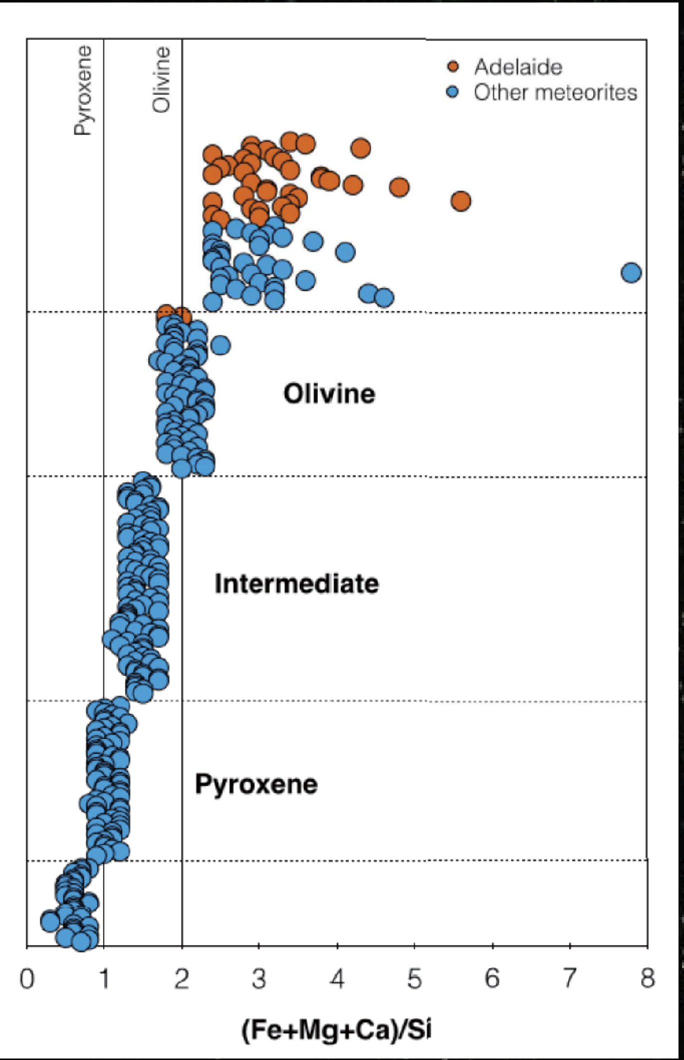
Liu et al., 2022

Lessons from presolar grains for dust aficionados

- Grain compositions:
  - Have both mineral phases predicted to condense from high-T (Al_2O_3, SiC, $MgSiO_3$) and wide range of non-stoichiometric phases, and composite grains
  - no "average" silicate composition



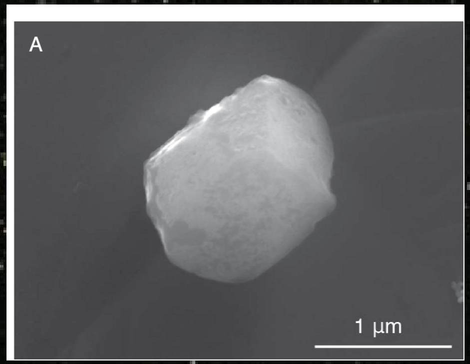
Lodders and Amari CdE 2005



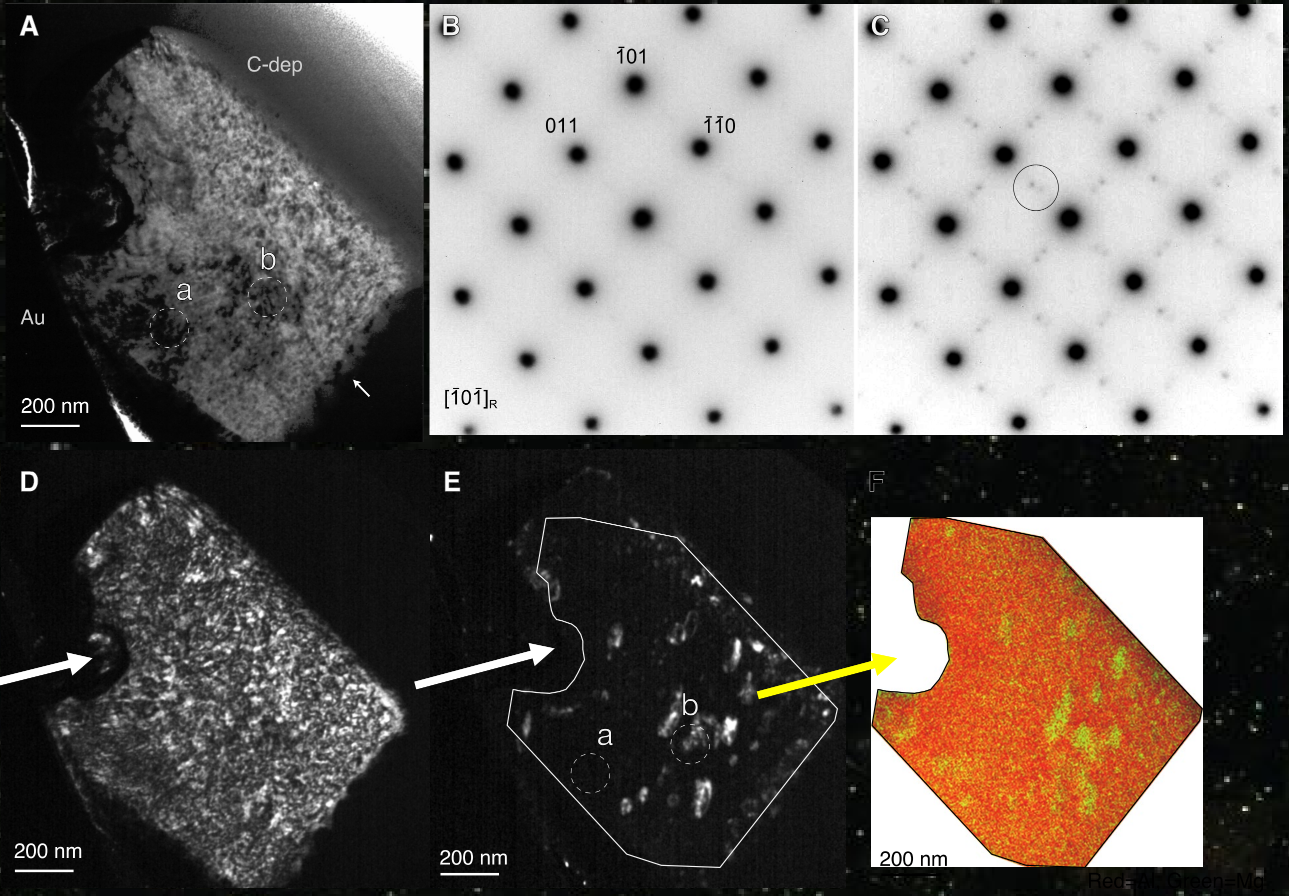
Floss and Haenecour, GJ, 2018

Lessons from presolar grains for dust aficionados

- Grain formation processes:
  - Detailed microstructures constrain condensation conditions and ISM processing
  - **See Stroud poster**



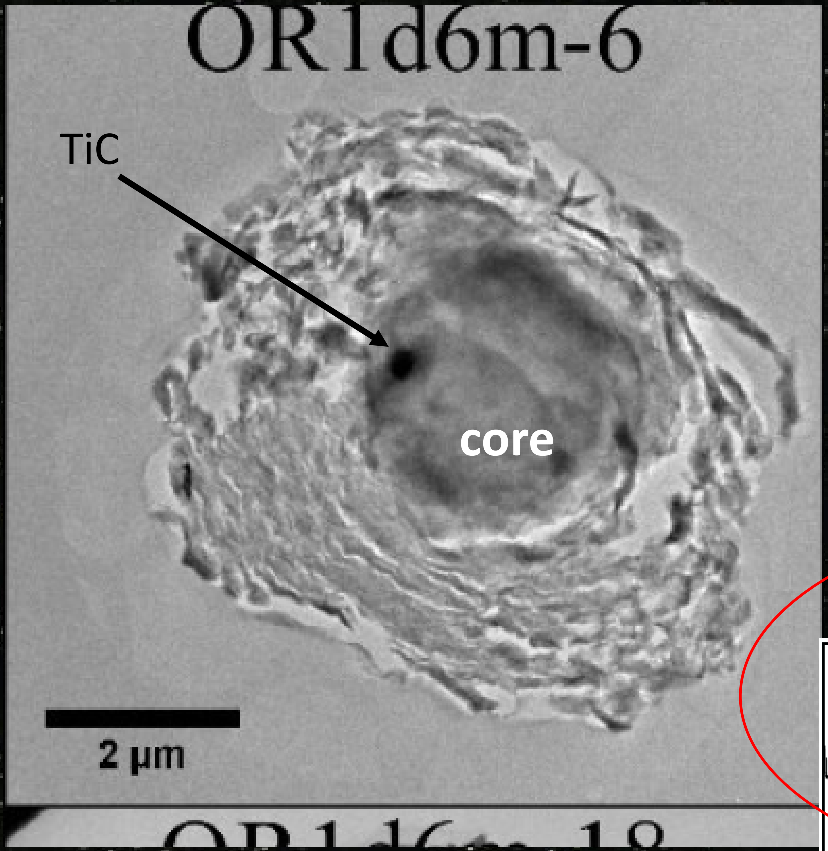
Interstellar impact crater?



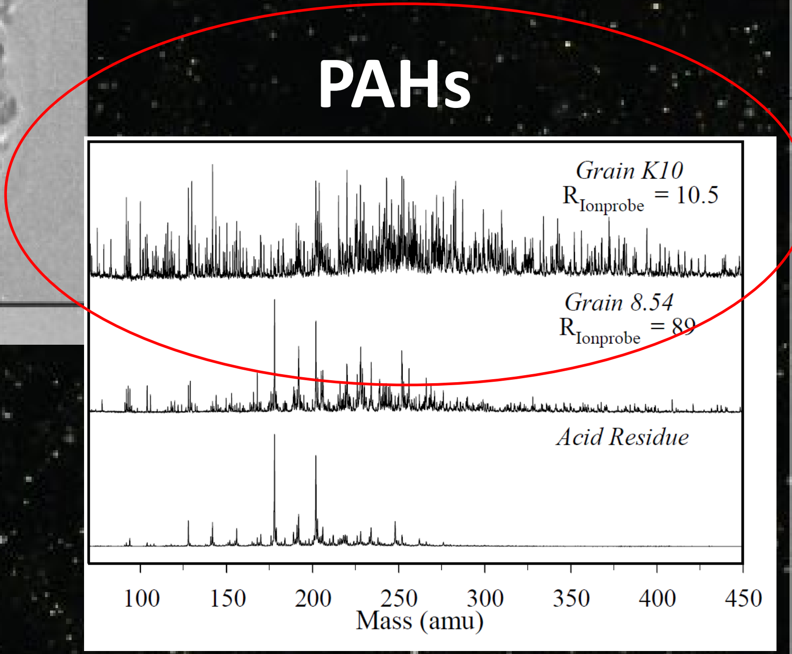
Detailed structure of AGB star corundum (Al_2O_3) grain
Takigawa et al. (ApJL 2018)

Lessons from presolar grains for dust aficionados

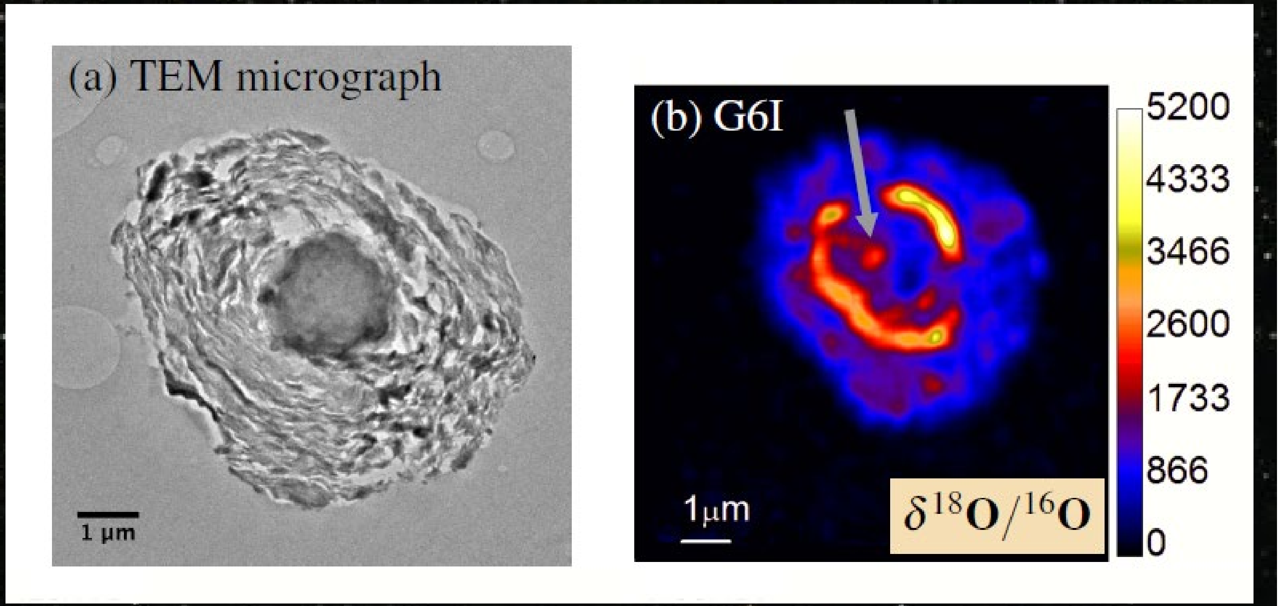
- AGB star "graphites"
- Often contain sub-grains of refractory carbides (TiC, MoC, …)
  - Put constraints on condensation conditions (Bernatowicz+ 1996, Croat+ 2005)
- Often contain nanocrystalline cores surround by well-crystallized graphite layers
- At least some cores contain PAHs (Messenger+ 1998)



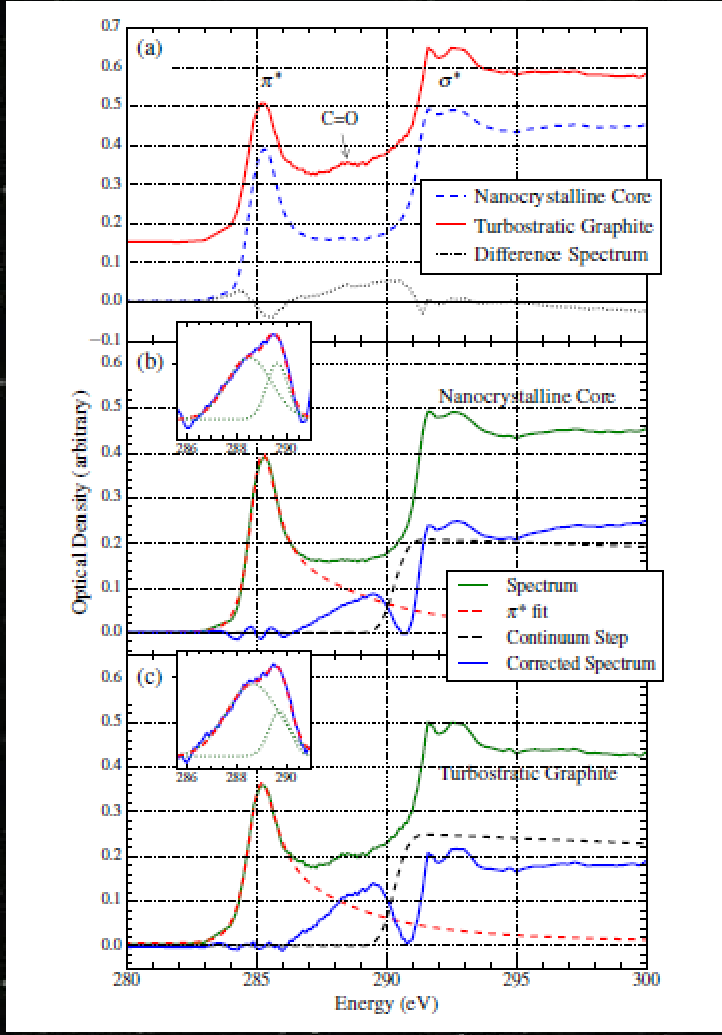
Core-mantle "onion" AGB graphite (Groopman et al 2017)



Lessons from presolar grains for dust aficionados



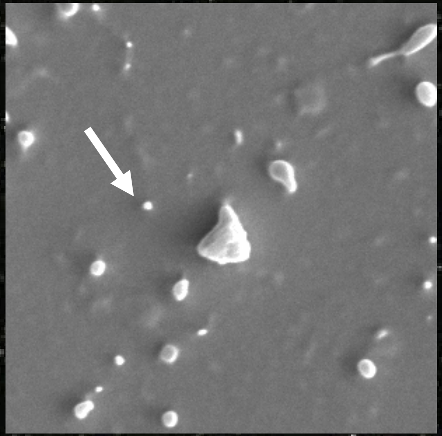
- Supernova graphite with nanocrystalline core, mantled by graphite shells
(Groopman, Nittler et al, 2014)
  - Structure/chemistry indicates changing chemical/physical conditions during grain growth



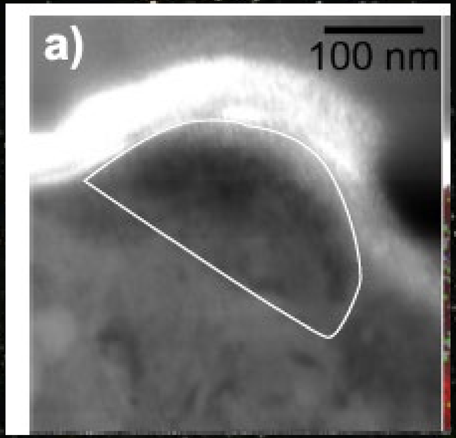
C-edge X-ray Absorption Spectra

Lessons from presolar grains for dust aficionados

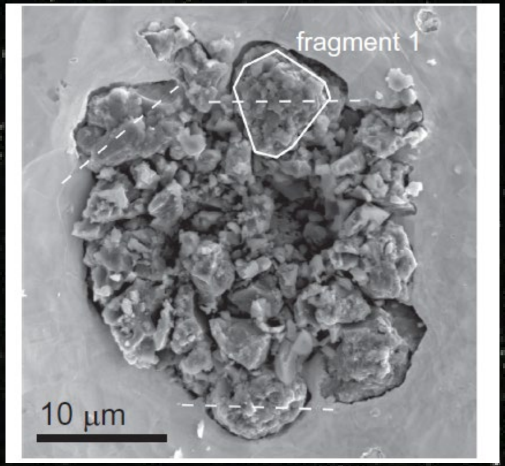
- Grain Sizes:
  - Stardust from both AGB stars and supernovae have wide size distributions, from 50-nm to 10s microns
  - ~100-200 nm average diameter in good agreement with IS dust, but grains can be LARGE!



- 60-nm supernova ^{54}Cr-rich oxide
(Nittler et al. *ApJL* 2018)



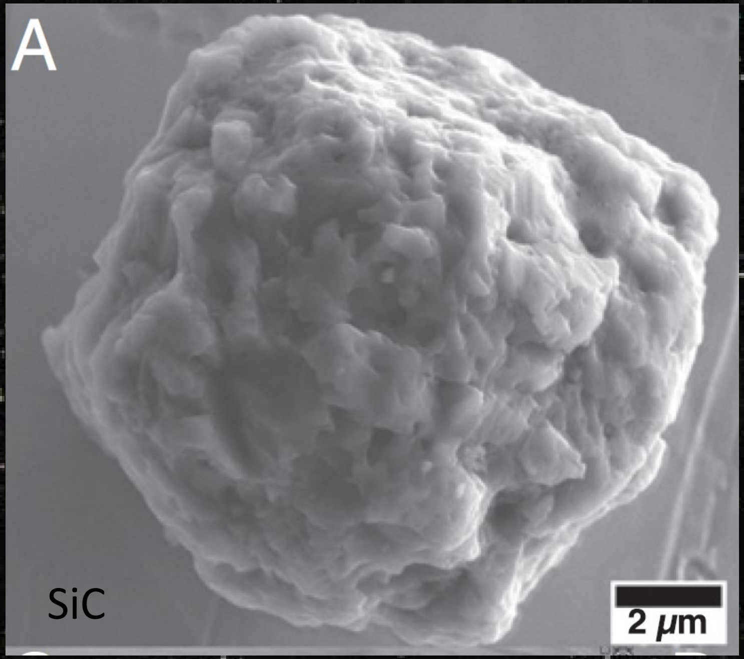
- 200-nm AGB silicate
(Nittler et al *GCA* 2018)



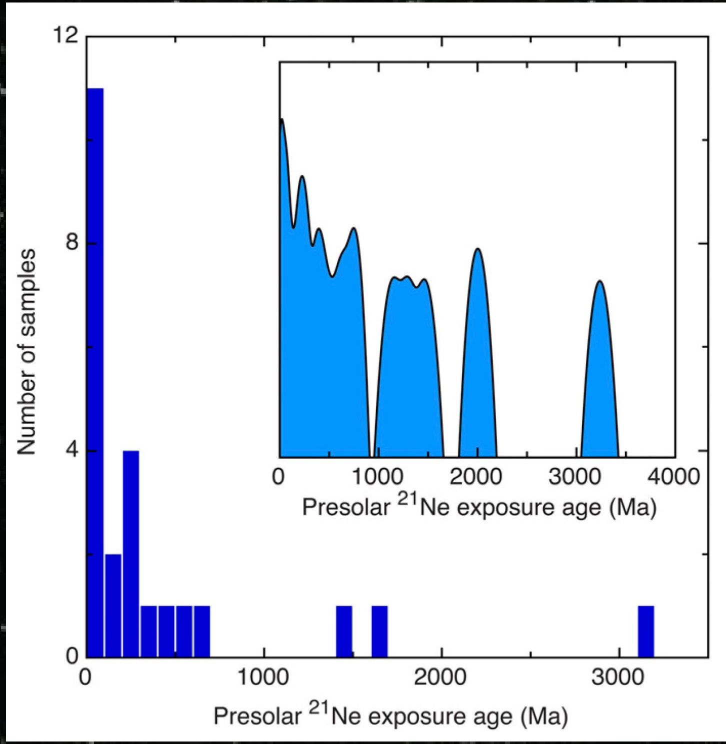
- 30-μm SiC X-grain
(Gyngard et al. *GCA* 2018)

Lessons from presolar grains for dust aficionados

- Grain Lifetimes
  - For largest grains can measure isotopic products of Galactic Cosmic Ray interactions (e.g., ^{21}Ne, produced by spallation of ^{28}Si) – tells us how long grain was in ISM before being trapped in meteorite



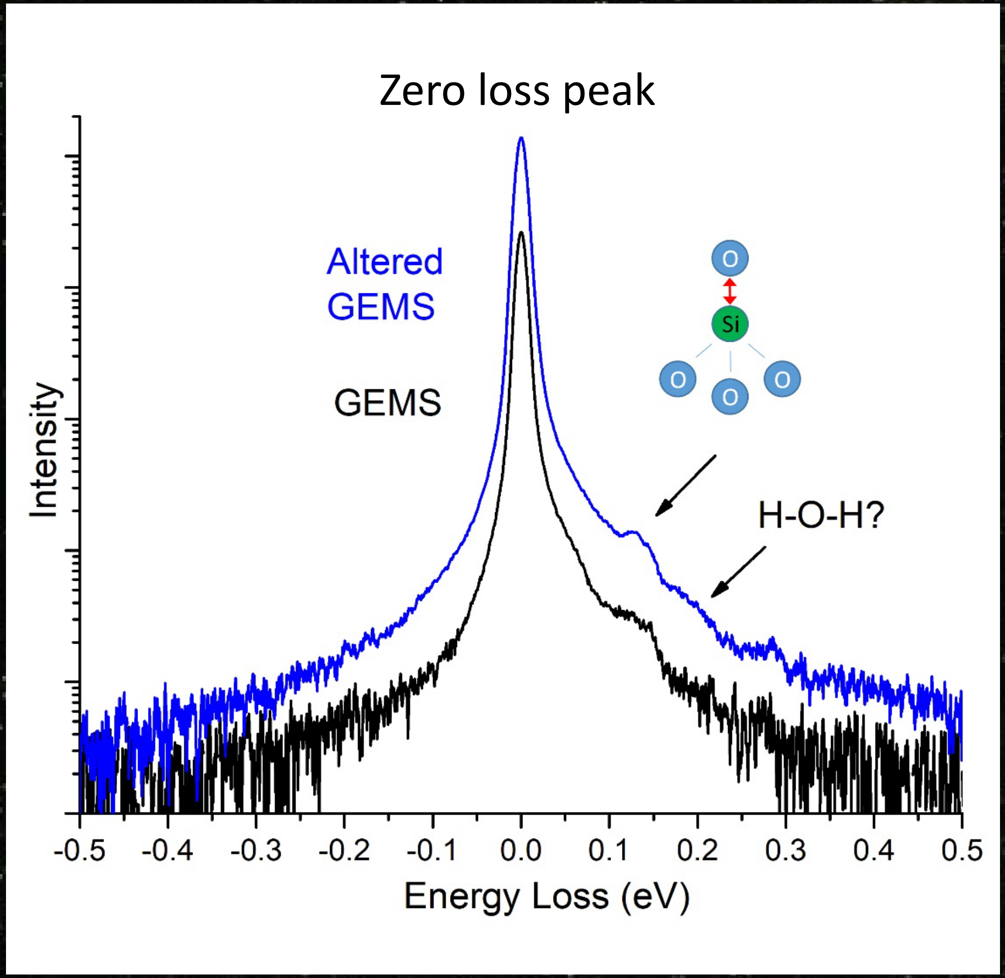
- Wide range of inferred grain ages (3 Myr to 3Gyr), majority <300 Myr



Heck et al., PNAS 2020

Future prospects: “IR” spectroscopy in the electron microscope?

- Monochromated Electron Energy Loss Spectroscopy
  - Monochromation of the STEM e-beam to ~10 meV now possible.
  - Allows detection of excited vibrational modes



Stroud et al. 2018

Future prospects: “IR” spectroscopy in the electron microscope?

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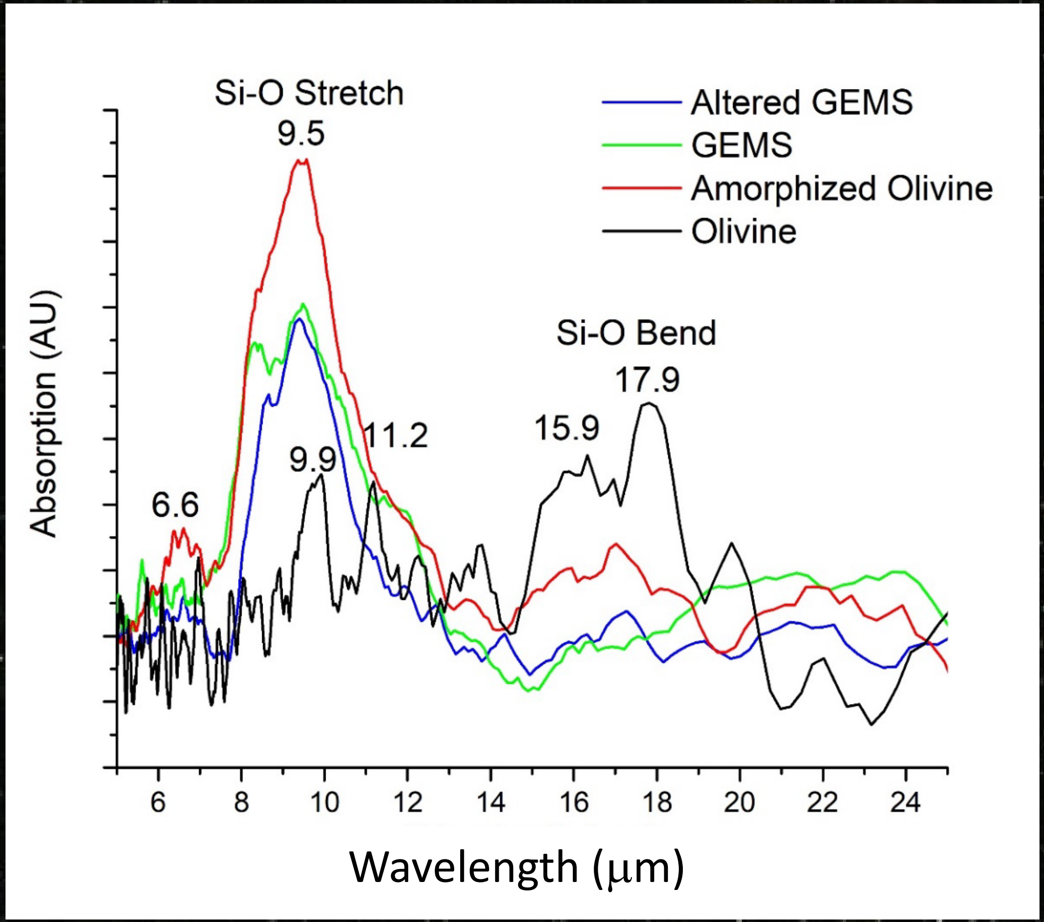
  - Monochromation of the STEM e-beam to ~10 meV now possible.
  - Allows detection of excited vibrational modes
- May allow direct determination of optical properties of presolar grains!



Stroud et al. 2018

Conclusions

- Primitive extraterrestrial materials (meteorites, IDPs, returned asteroidal and cometary samples) contain preserved dust grains from our protoplanetary disk
- These include presolar stardust grains from previous generations of stars
  - Provide unique information on types, sizes, ages, and processing histories of circumstellar and interstellar dust grains
  - Presolar (and by extension interstellar) silicates show huge range of compostions- there is no single “average” composition

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THANKS!