# Laboratory Studies of Interplanetary Dust


Scott Messenger

Lindsay Keller

Keiko Nakamura-Messenger

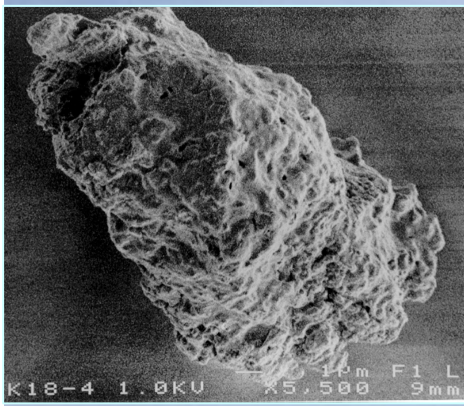
Ann Nguyen

Robert M Walker Laboratory for Space Science

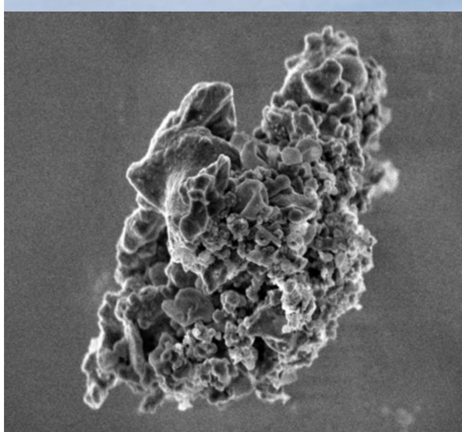
Astromaterials Research and Exploration Science

NASA & ESCG Johnson Space Center

# Interplanetary Dust Particles (IDPs)



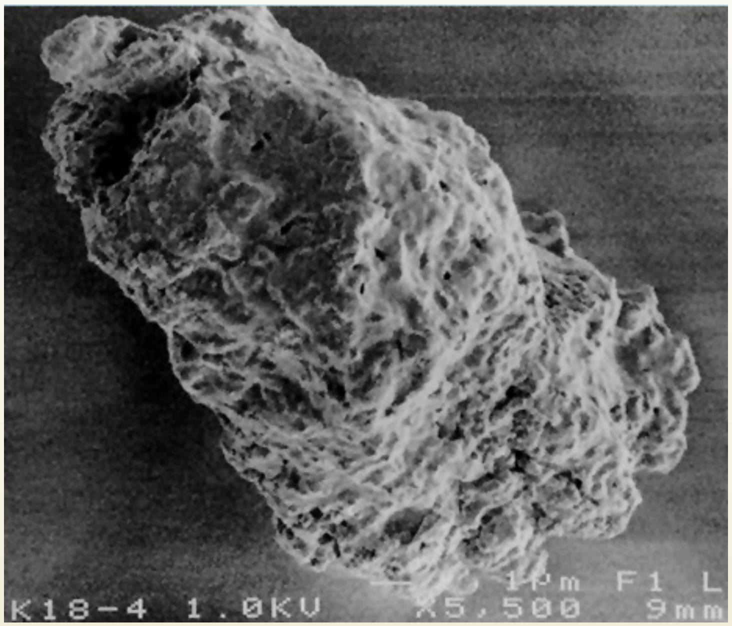

- “**Asteroidal**”:
  - Hydrated mineralogy



- “**Cometary**”
  - Anhydrous, unequilibrated mineralogy
  - Carbon-rich
  - Volatile element-rich
  - Porous, extremely fragile

Some (mostly anhydrous) IDPs have been linked to comets by inferred high eccentricity orbits – based on peak atmospheric entry T measured from the thermal release profiles of solar wind He (Nier & Schlutter).

# Hydrated IDPs – Samples of Asteroids?




- Spectrally distinct from comets
- Low atmospheric entry velocity
  - low eccentricity (asteroidal) orbits
- Main mineral components:
  Smectite, serpentine, carbonate, Ni-rich sulfides
- Some affinities to CI/CM chondrite meteorites
- Carbon rich
  - distinct from meteorites

<u>Probable Origins</u>

Carbon/volatile-rich outer-belt asteroids

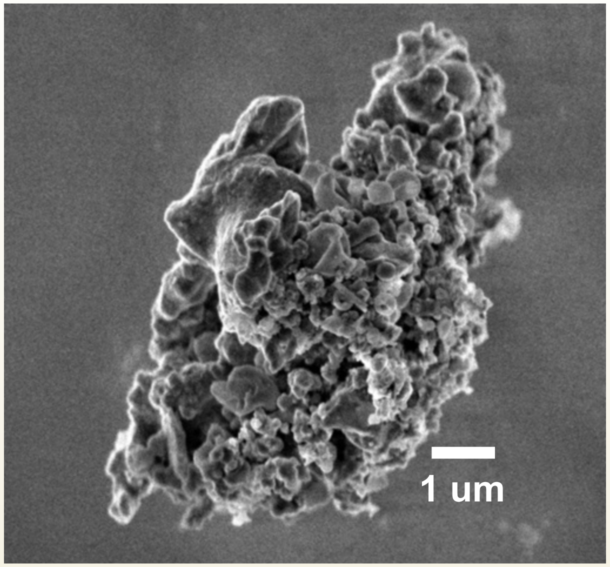
# Primitive Characteristics of Anhydrous IDPs

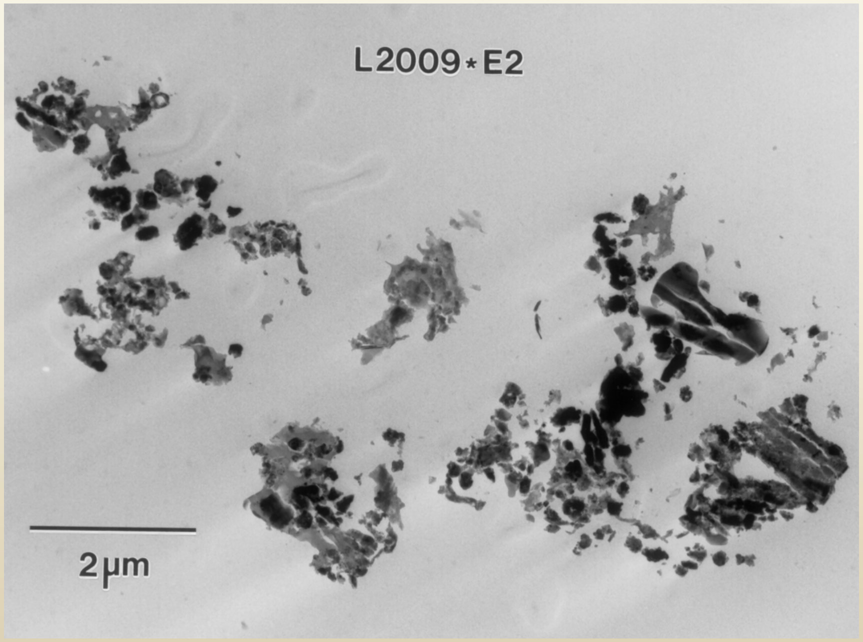
- **Structure**
  - **Porous (up to 70%), 0.3-6 g/ $cm^3$, fragile, fine grained**

- Chemistry
  - C- and N-rich (~3XCI)
  - Volatile trace element-rich

- Mineralogy
  - Anhydrous mineralogy
  - Unequilibrated, GEMS
  - Pre-accretional irradiation

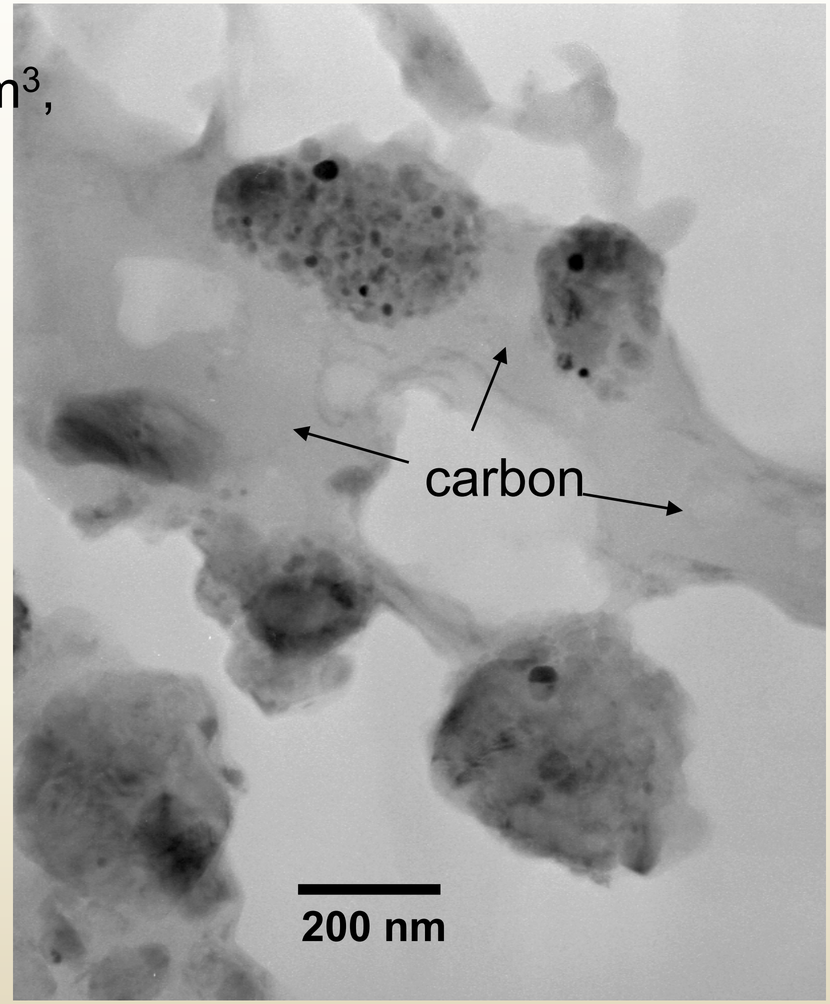
- Isotopes
  - stardust
  - molecular cloud material



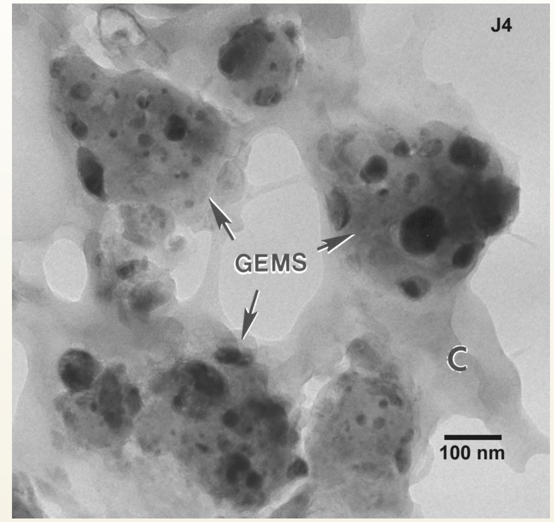
# Primitive Characteristics of Anhydrous IDPs

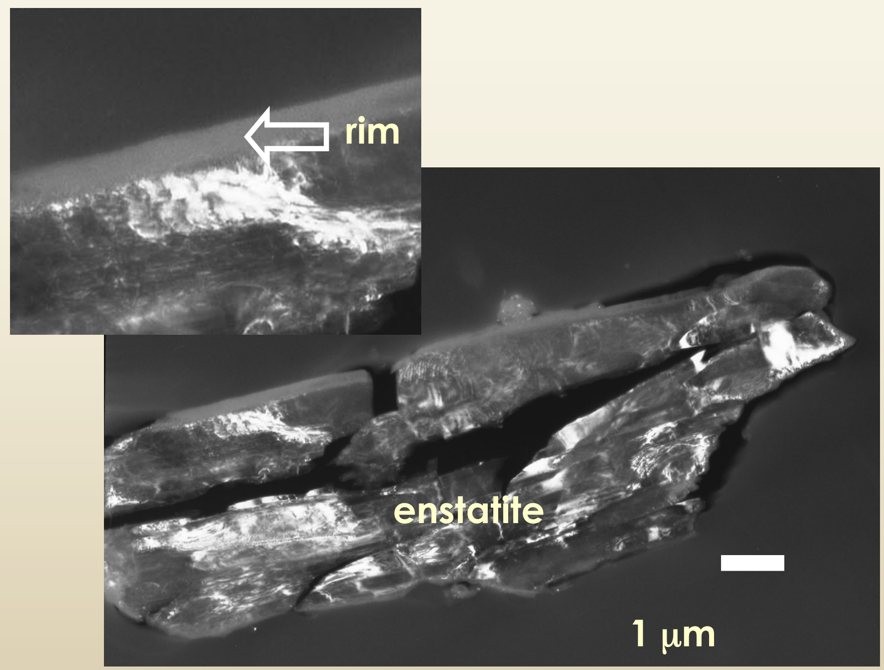
- Structure
  - Porous (up to 70%), 0.3-6 g/cm$^3$, fragile, fine grained
- **Chemistry**
  - **C- and N-rich (~3XCI)**
  - **Volatile trace element-rich**
- Mineralogy
  - Anhydrous mineralogy
  - Unequilibrated, GEMS
  - Pre-accretional irradiation
- Isotopes
  - stardust
  - molecular cloud material



# Primitive Characteristics of Anhydrous IDPs

- Structure
  - Porous (up to 70%), 0.3-6 g/cm$^3$, fragile, fine grained
- Chemistry
  - C- and N-rich (~3XCI)
  - Volatile trace element-rich
- **Mineralogy**
  - **Anhydrous mineralogy**
  - **Unequilibrated, GEMS**
  - **Pre-accretional irradiation**
- Isotopes
  - stardust
  - molecular cloud material



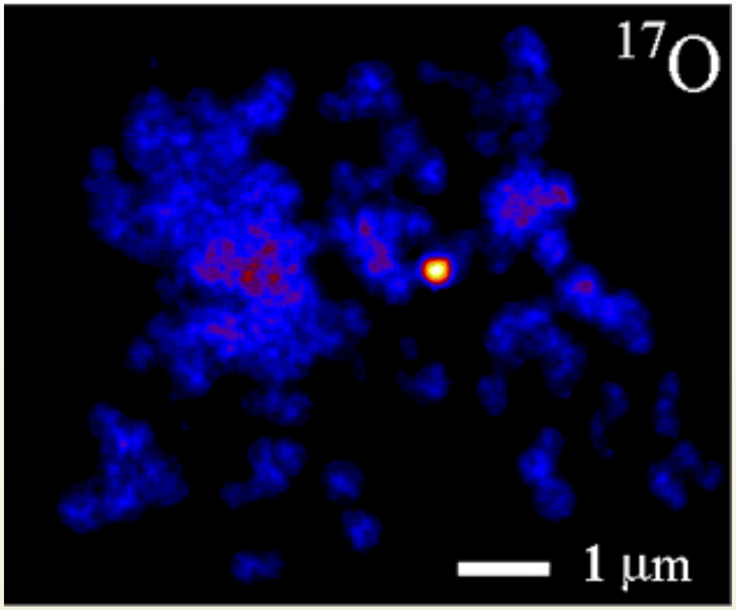



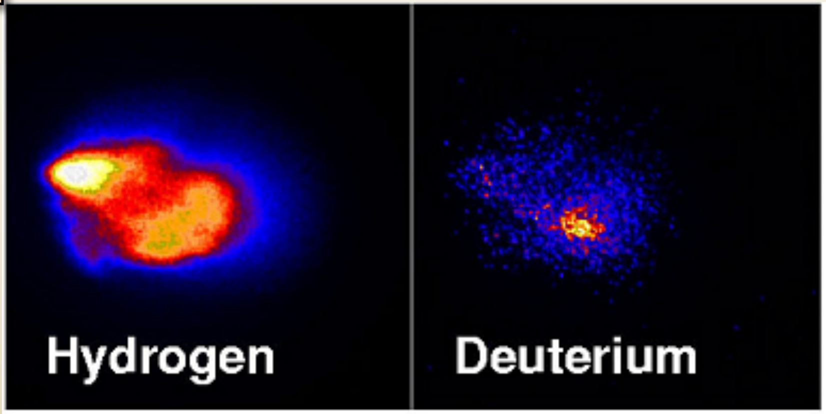
# Primitive Characteristics of Anhydrous IDPs

- Structure
  - Porous (up to 70%), 0.3-6 $g/cm^3$, fragile, fine grained
- Chemistry
  - C- and N-rich (~3XCI)

Presolar grains i.e. stardust and interstellar organic materials are identified by their **exotic isotopic compositions**

  - Not hydrothermally altered
  - Unequilibrated, GEMS
  - Pre-accretional irradiation
- **Isotopes**
  - **stardust**
  - **molecular cloud material**



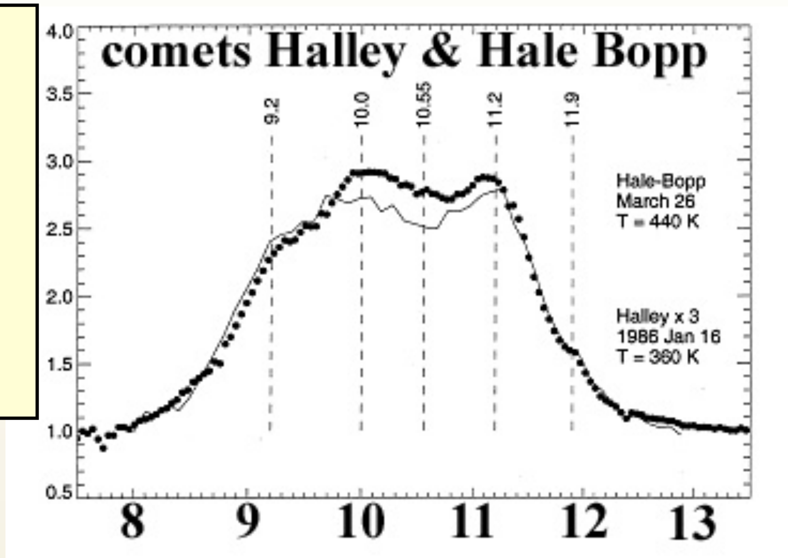



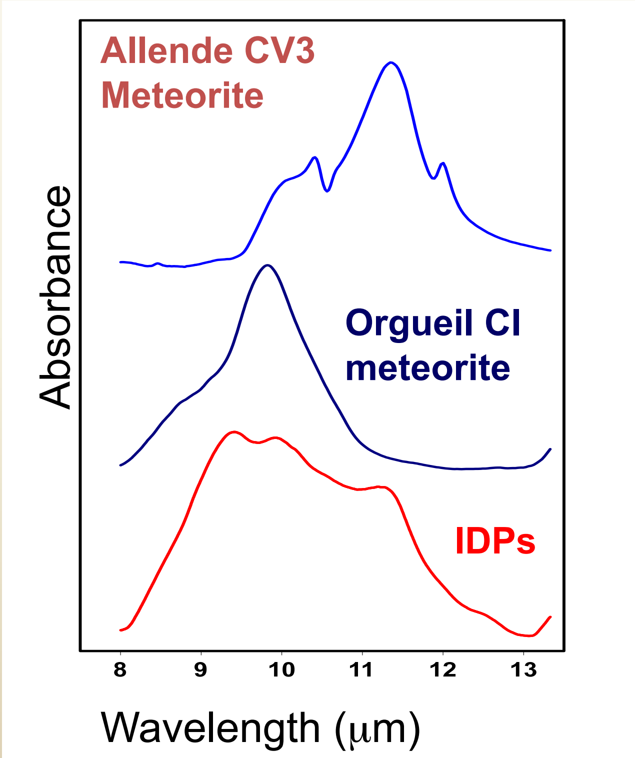

Ion Images of L2009 Clu. 7 D5

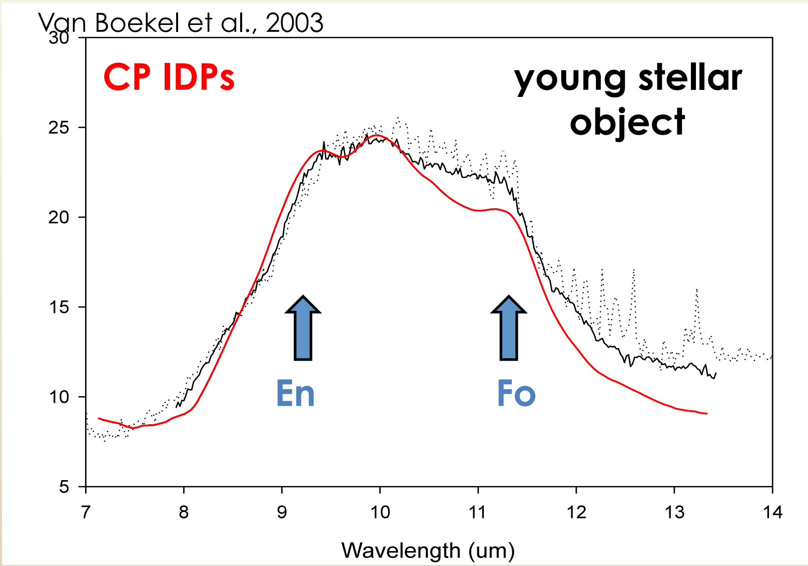
# Silicate Astromineralogy

**IDPs provide insight into these questions:**

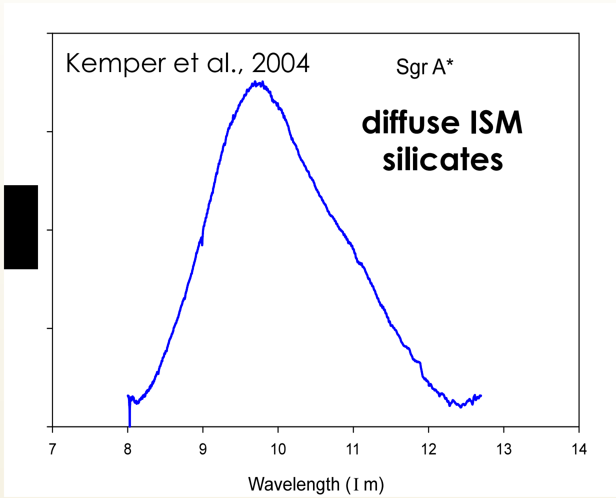
- What is the nature of interstellar dust? – the building blocks of the Solar System
- What are the origins of the crystalline silicates in comets?
- Are comets mostly pristine or mostly processed?

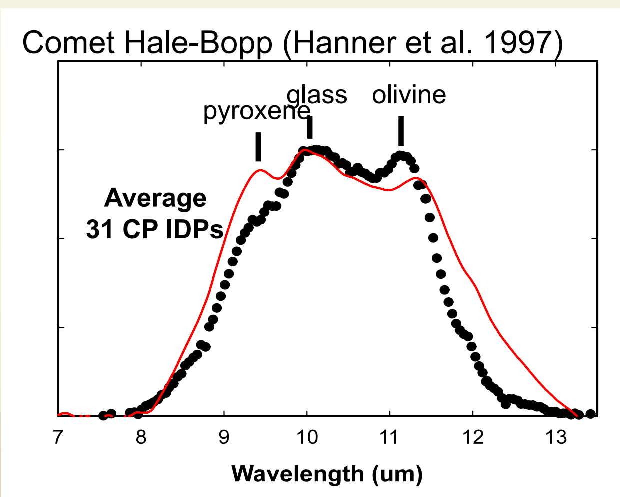


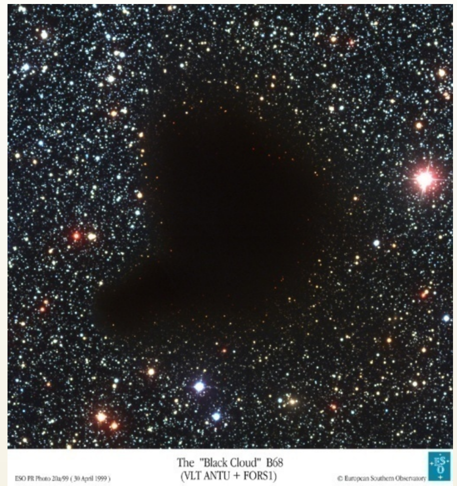



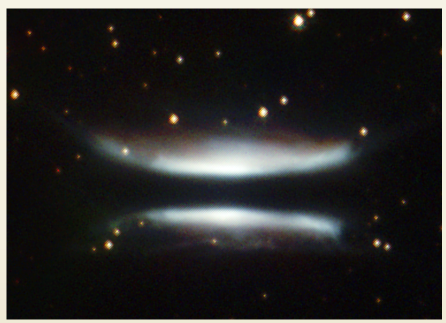



# Evolution of Silicate Dust Mineralogy



## Silicate Mineralogy from 10 μm Feature

| | Crystallinity |
|---|---|
| Evolved stars | 10 – 20 % |
| Diffuse ISM | < 1 % |
| Dense clouds | < 1 % |
| Young stellar disks | 1 – 5 % |
| Comets | > 10 % ? |
| Meteorites | *dominant* |

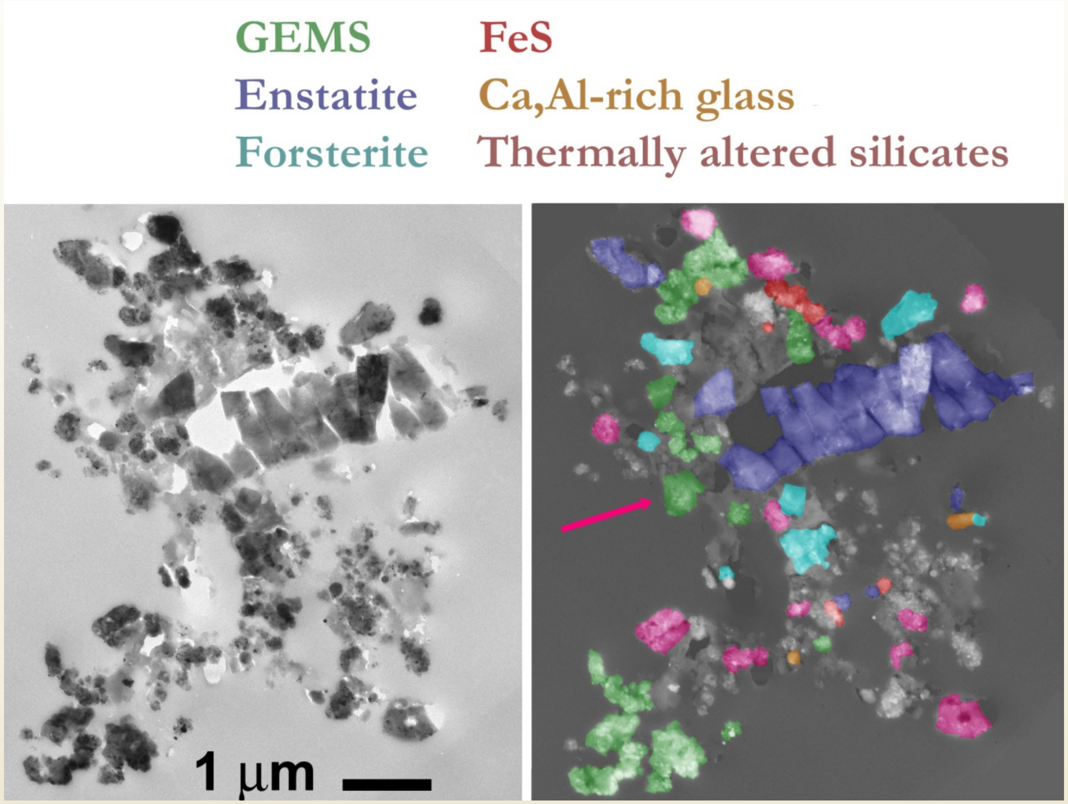
## Astrophysical Implications

**Crystalline silicates rapidly destroyed or rendered amorphous in ISM**

**Are crystalline silicates in YSO disks formed by annealing of ISM amorphous silicates or direct condensation?**

**What is the fate of ISM dust in young stellar systems?**

# Coordinated Isotopic/Mineralogical Study of IDPs




Thin section of IDP studied by TEM with typical anhydrous mineralogy

**Mineralogy:**

**Common components in 'cometary' IDPs have highly variable abundances**

**Analytical challenges:**

TEM analysis should be performed first

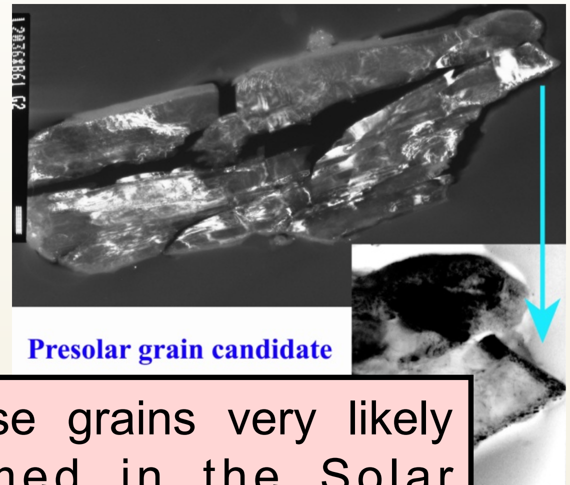
Many grains in IDPs are too small (<200 nm) for isotopic analysis

Isotopic signal from small grains contaminated by surrounding material

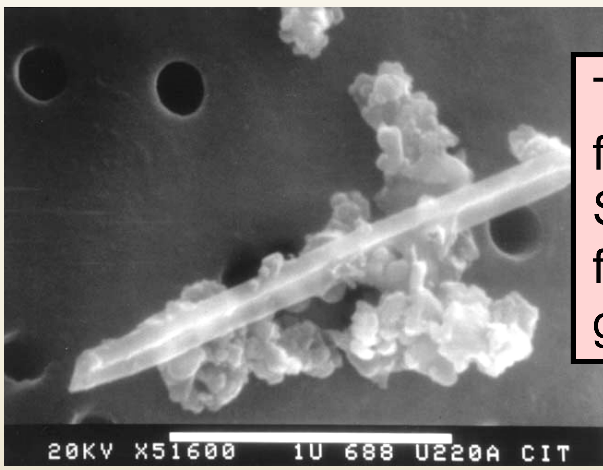
# Isotopically Solar Crystalline Silicates

**Common properties:**

- Forsterite, enstatite often have high Mg# >95%, Mn-rich
- Rounded single crystals, whiskers, and platelets

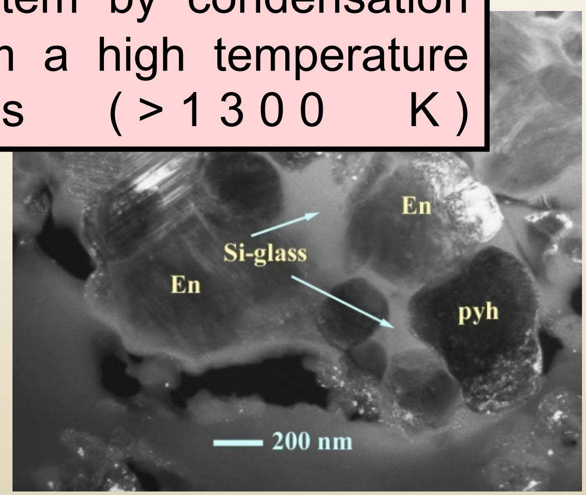



**Radiation-damaged grains**
Isotopically solar – formed in the Solar System



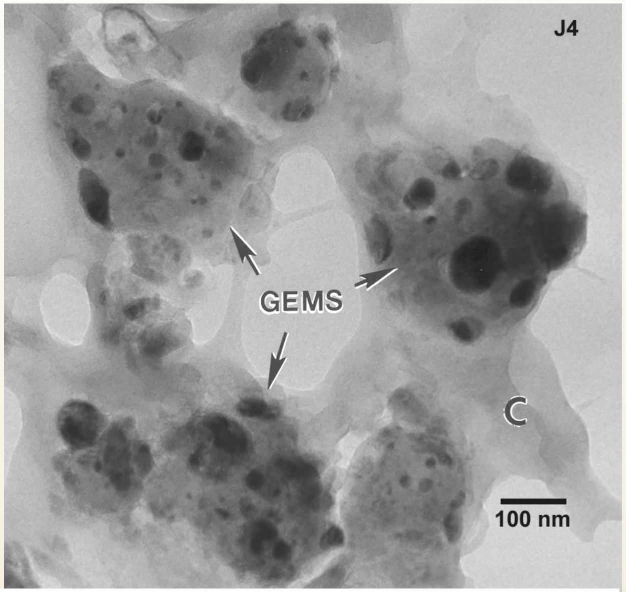

**Whisker morphologies** and axial screw dislocations suggest vapor phase growth. Bradley *et al*. 1983

These grains very likely formed in the Solar System by condensation from a high temperature gas (>1300 K)

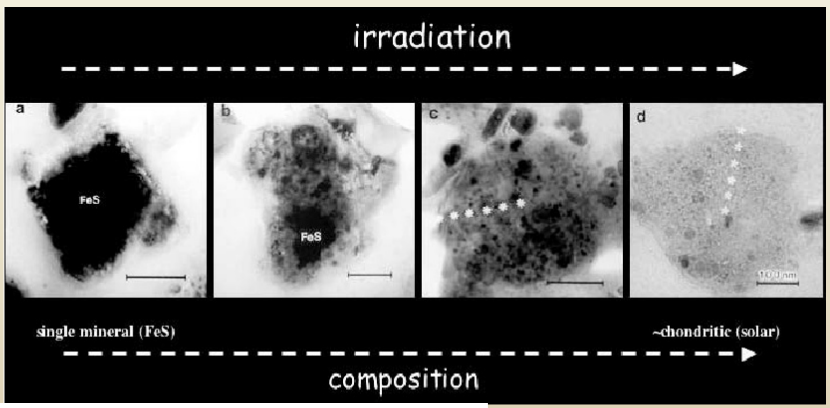



**Equilibrated aggregates** probably formed by thermal annealing –precursors?

Amorphous Silicates Grains in Cometary IDPs
"GEMS" Glass with Embedded Metal and Sulfides.



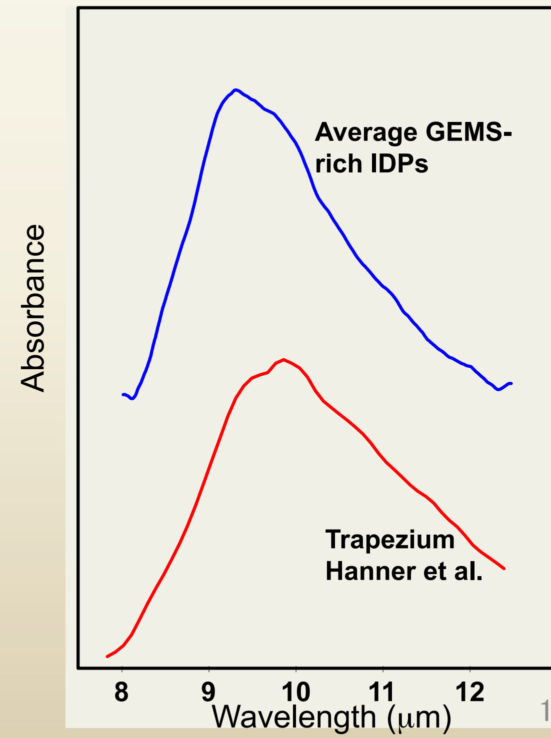

GEMS grains in an IDP, bound by C




Proposed ISM alteration sequence

**GEMS Properties**

- 0.1 – 0.5 μm diameter
- amorphous silicates
- ~ solar elemental abundances
- IR spectral match to ISM dust
- only found in IDPs
- **proposed products of interstellar grain recycling**




Bradley & Dai (2004) ApJ 617, 650

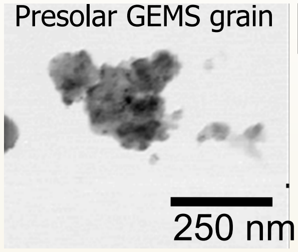
# Silicate Stardust Mineralogy

## Silicate Stardust Mineralogy Determined by TEM

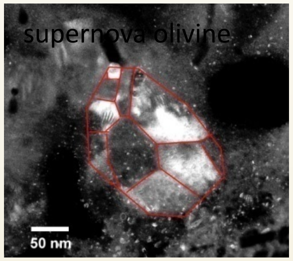
- IDPs & Micrometeorites [1-4,7,9,10]
  - 4 olivine
  - 8 GEMS grains
- Meteorites [5,6,8,11-13]
  - 2 olivine
  - 1 MgSi perovskite
  - 1 amorphous enstatite stoichiometry
  - 5 amorphous/nanocrystalline
  - 6 amorphous nonstoichiometric or GEMS-like

- Amorphous/crystalline silicate stardust ~ 2
- ISM amorphous/crystalline silicates > 50

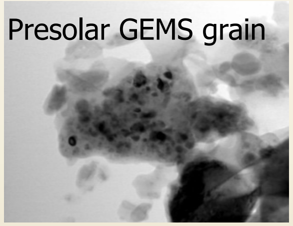
Amorphous silicate stardust is either preferentially destroyed, <250 nm, or isotopically solar




9



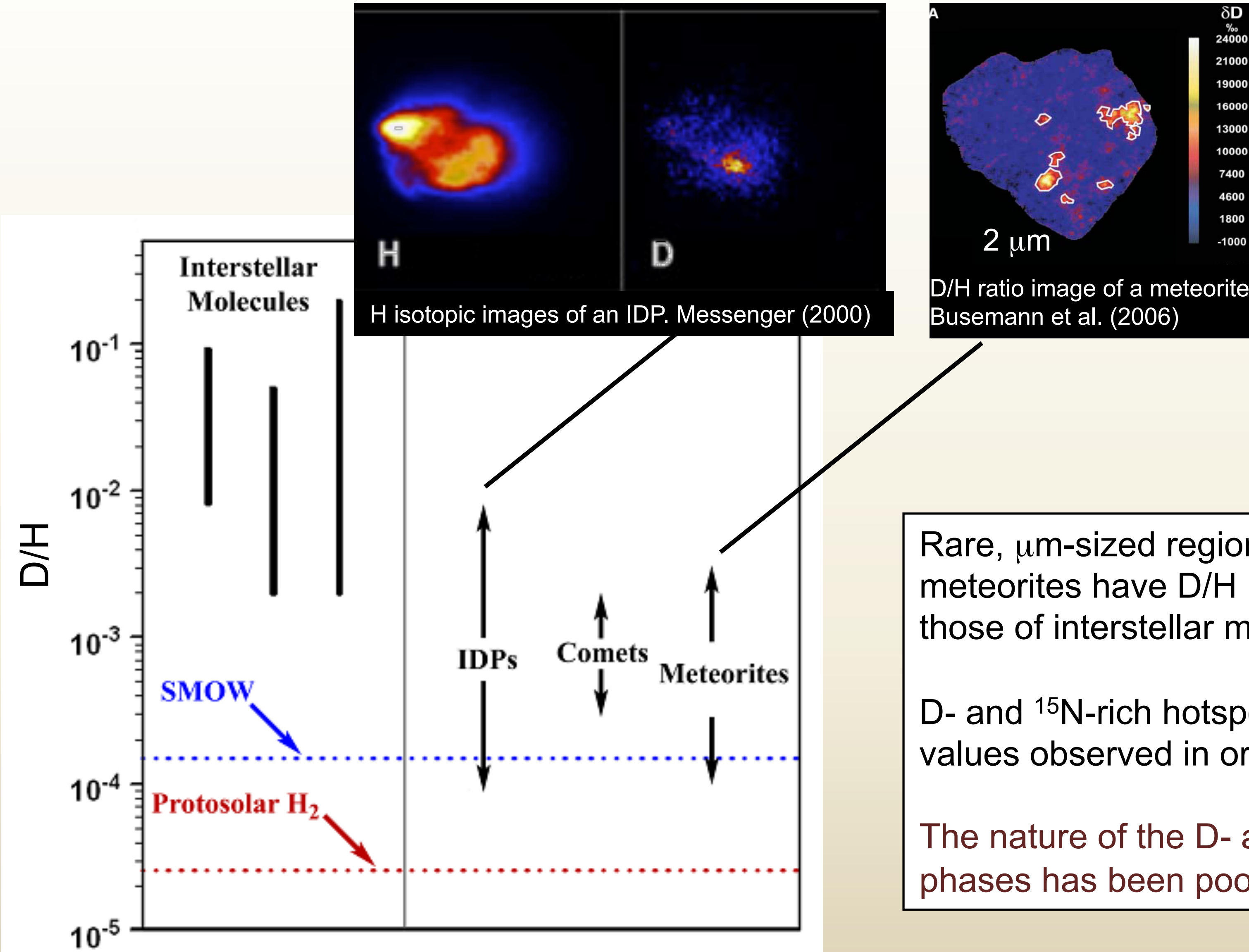

2




3

1: Messenger et al. 2003 2: Messenger et al. 2005 3:Yada et al. 2005 4: Floss et al. 2006 5: Nguyen et al. 2007 6: Vollmer et al. 2007 7: Keller et al. 2008 8: Stroud et al. 2008 9: Messenger et al. 2008 10: Messenger et al. 2009 11: Stroud et al. 2009 12: Vollmer et al. 2009 13: Nguyen et al. 2010

# Interstellar organic grains

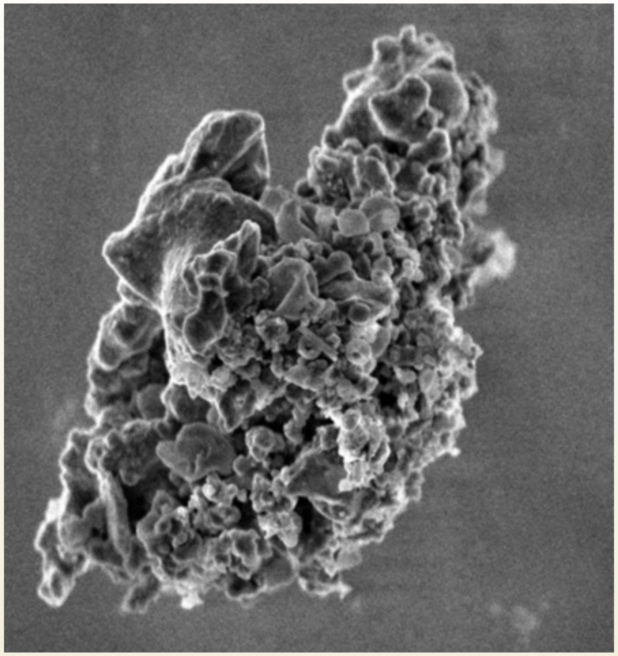



Rare, μm-sized regions of IDPs and meteorites have D/H ratios that reach those of interstellar molecules

D- and $^{15}$N-rich hotspots far exceed values observed in organic extracts

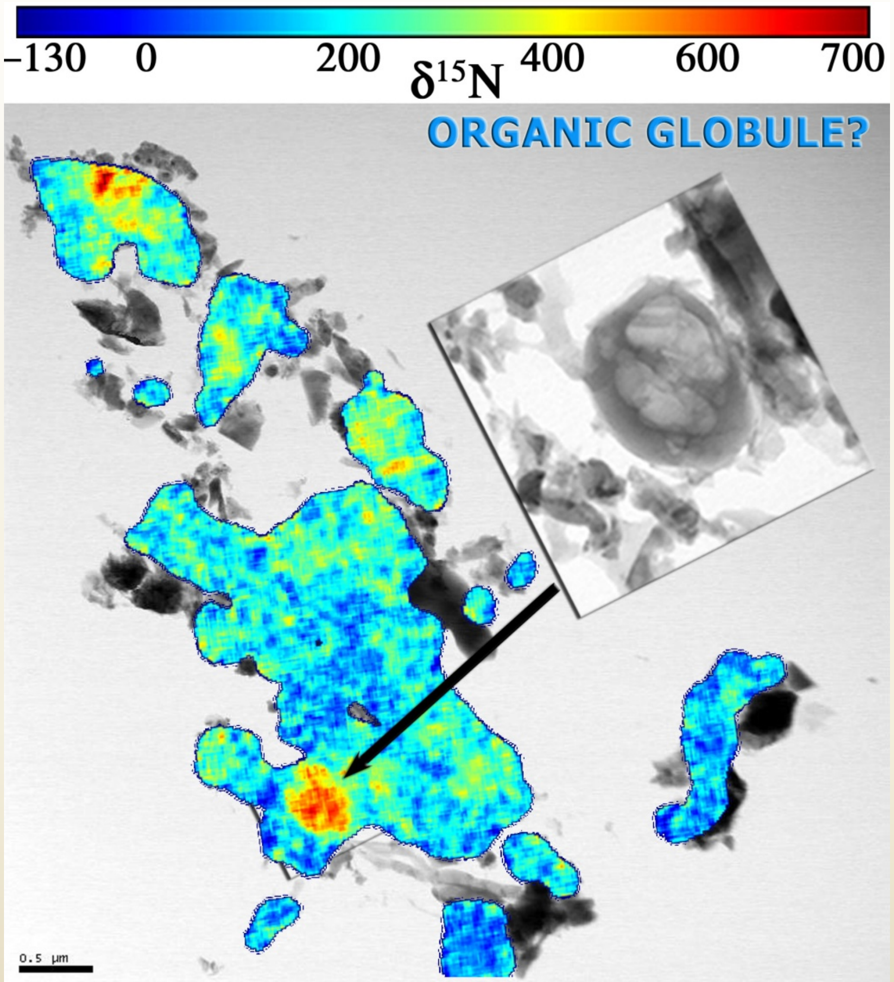
The nature of the D- and $^{15}$N-rich phases has been poorly known

# Organic Globule in a Cometary IDP

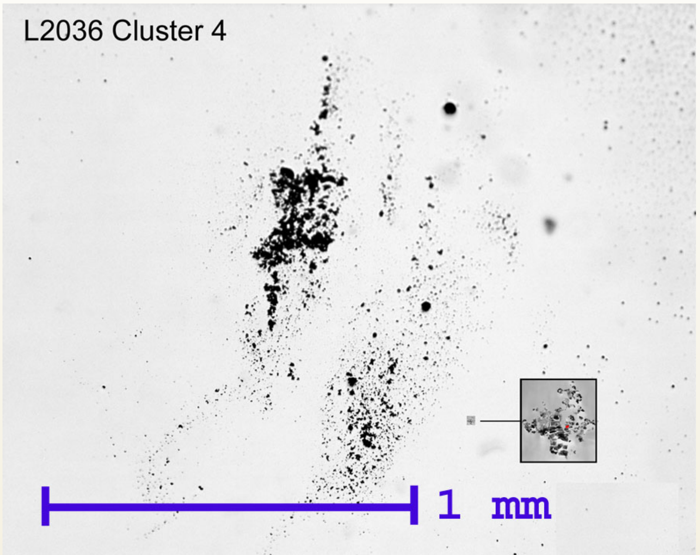


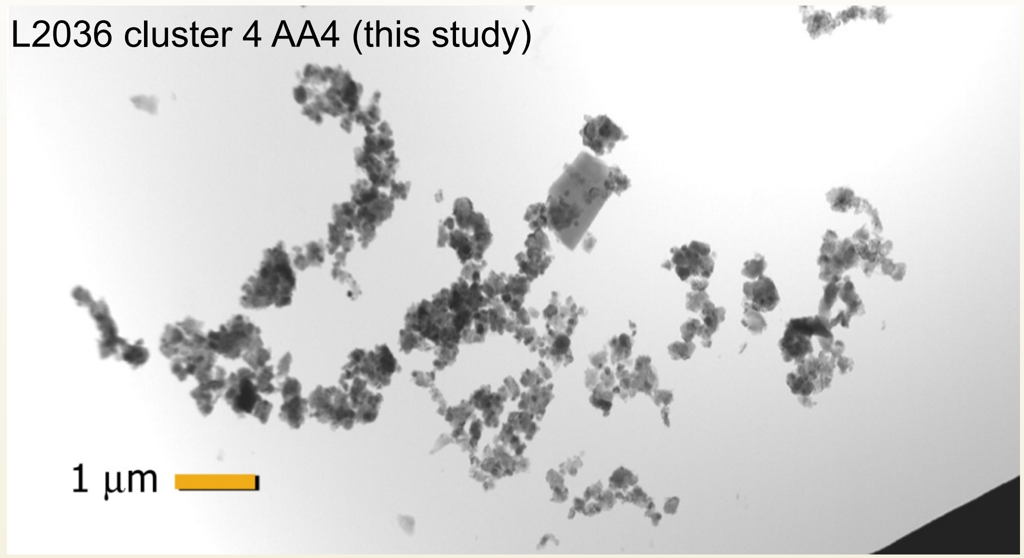
Anhydrous IDP: cometary dust?

- Unlike meteorites, anhydrous IDPs have not been hydrothermally altered
- IDPs are very C-rich (3 x CI)
- C is the matrix which binds IDPs together
- D/H and $^{15}N/^{14}N$-rich hotspots are common



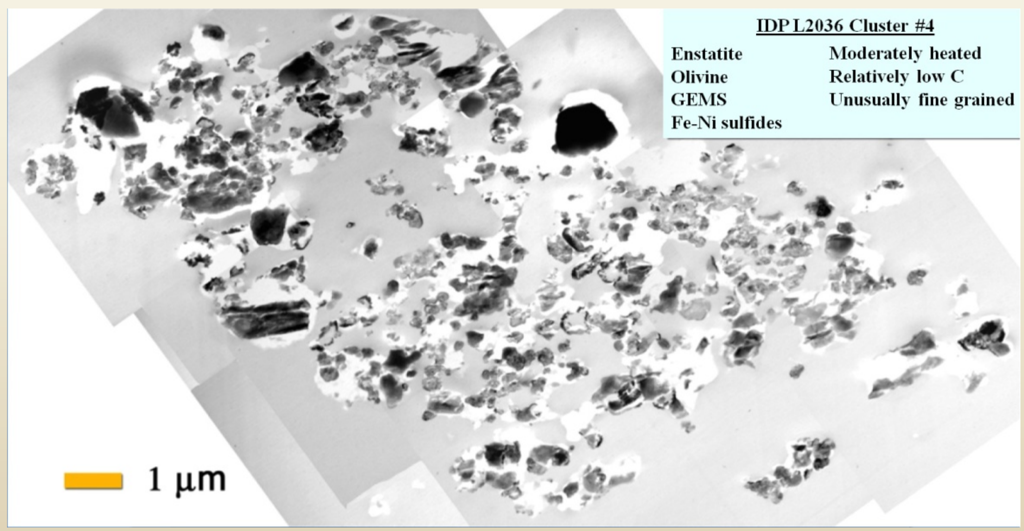
# Putting it all together: stardust-rich cluster IDP



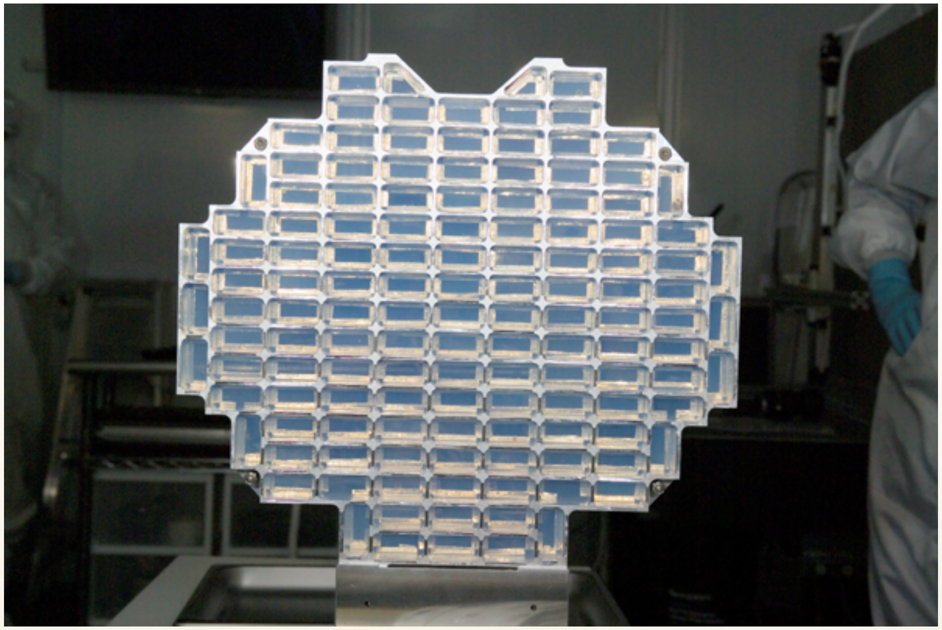




L2036 Cluster #4

- Large, mineralogically diverse cluster IDP
- Grain size 0.1 – 1.0 μm
- At least $10^6$ individual mineral grains
- Major components: amorphous silicates, enstatite, olivine, Fe,Ni sulfides, carbonaceous material
- Silicate stardust abundances ~2000 ppm
- **High-T condensates**, **annealed grains**, **circumstellar/interstellar dust**, **interstellar organic matter**

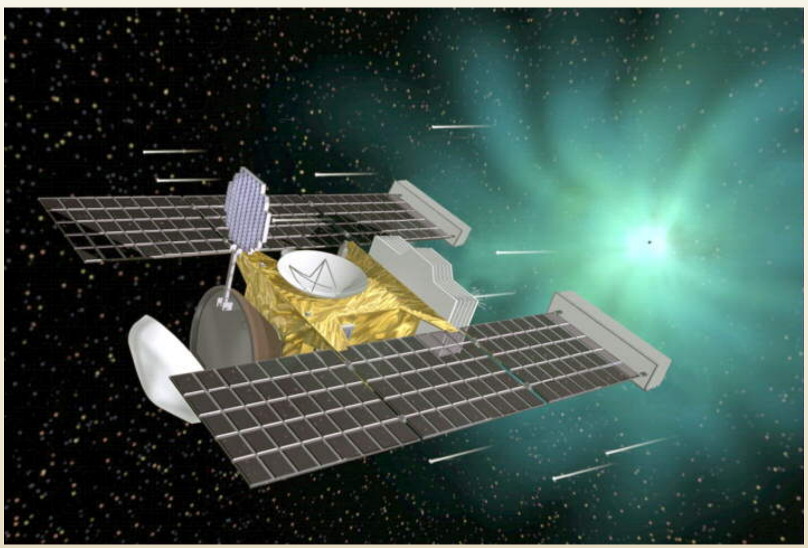


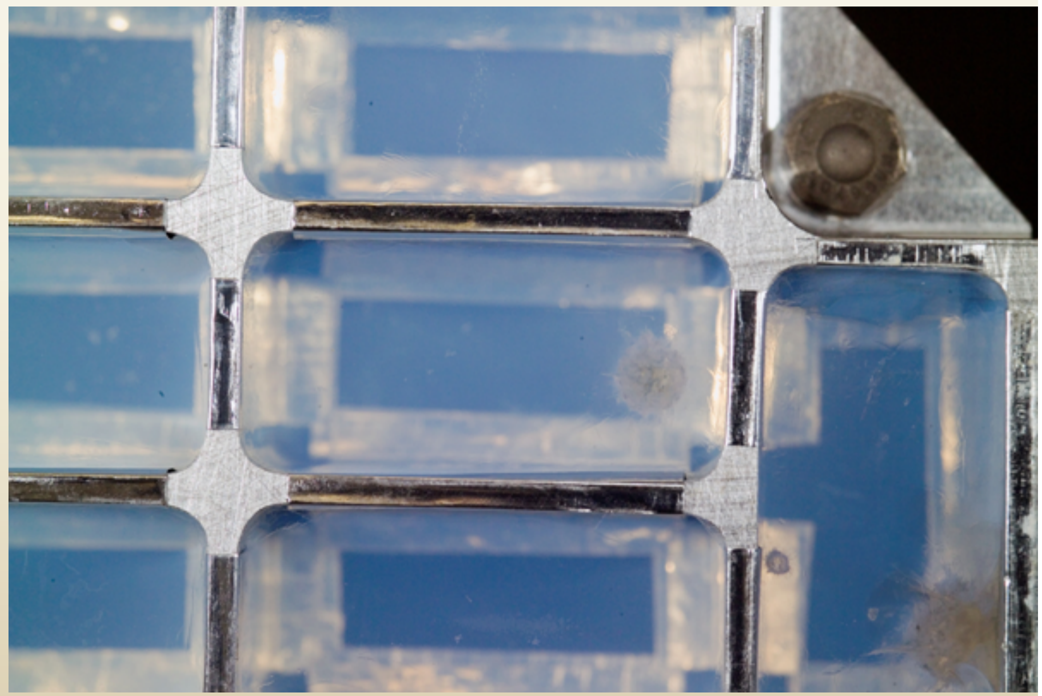

Fragment analyzed by Messenger et al. 2007 LPSC

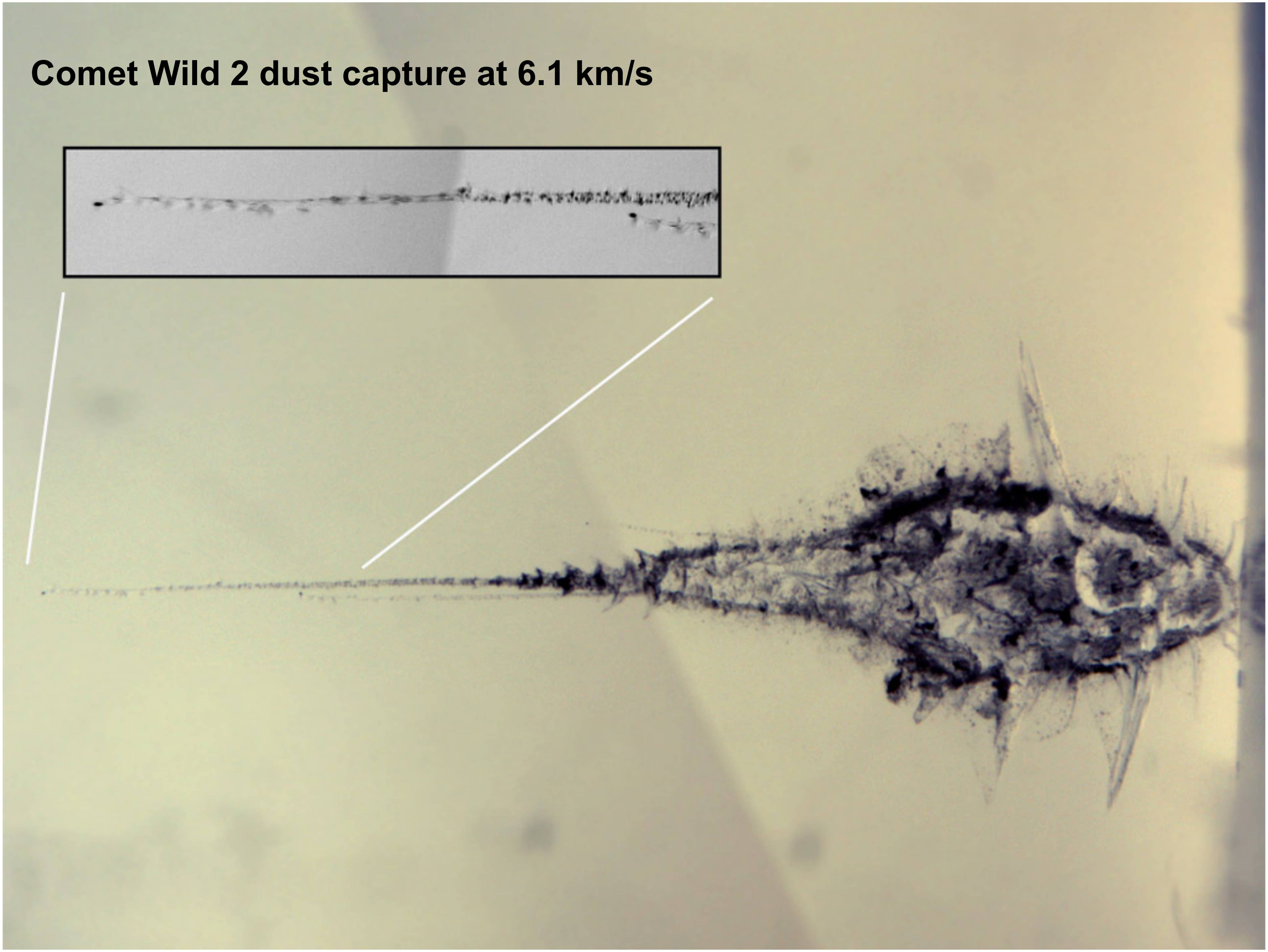


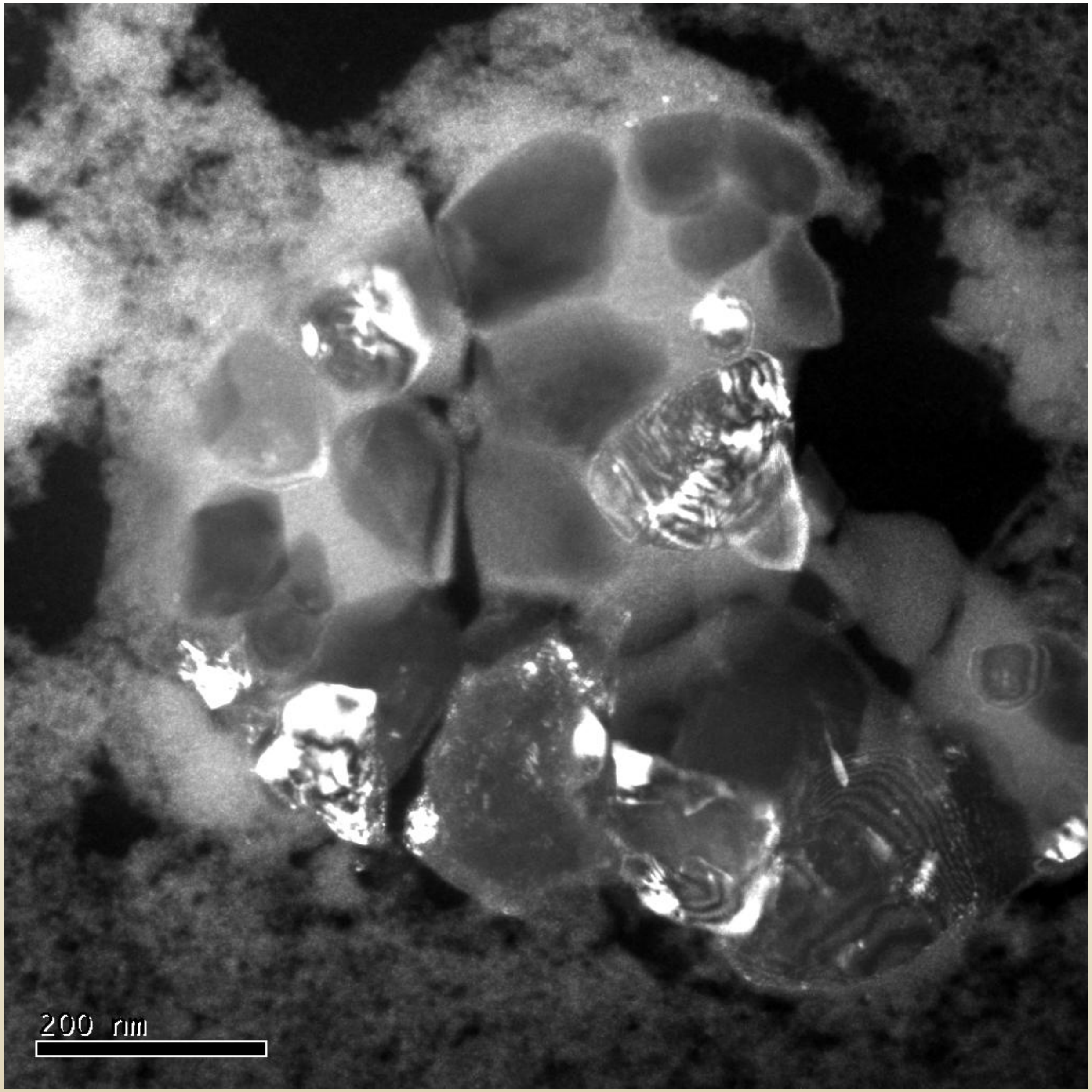
Stardust mission collected dust from a specific comet (Wild 2)

Comet Wild-2 particles captured in ultra low density silica aerogel – capture velocity ~6 km/s





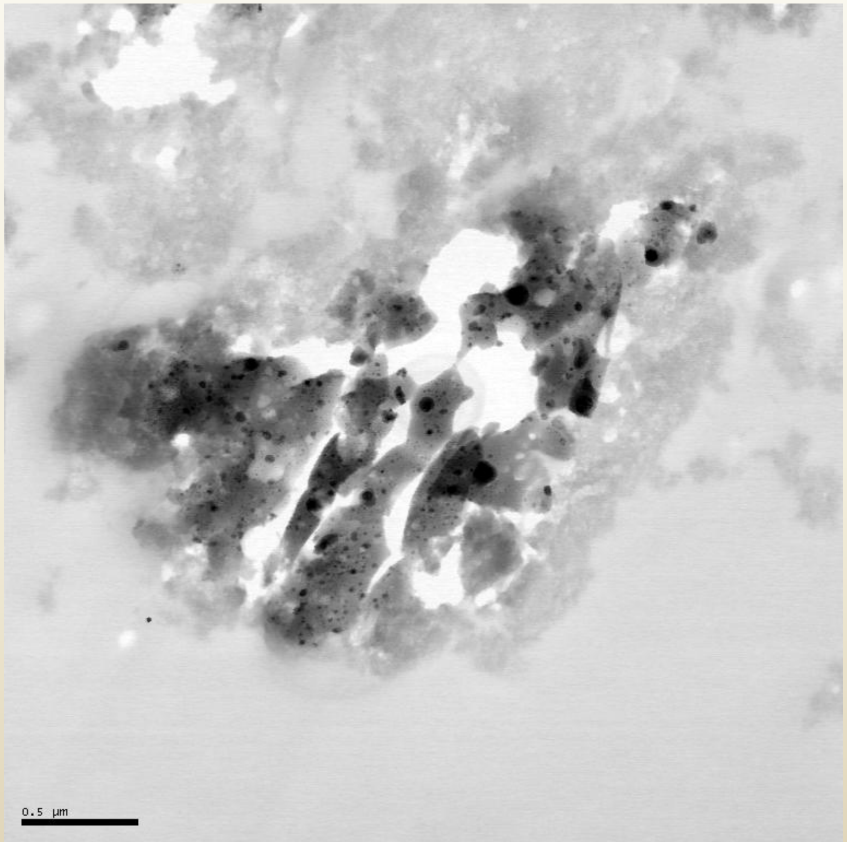

Comet Wild 2 dust capture at 6.1 km/s

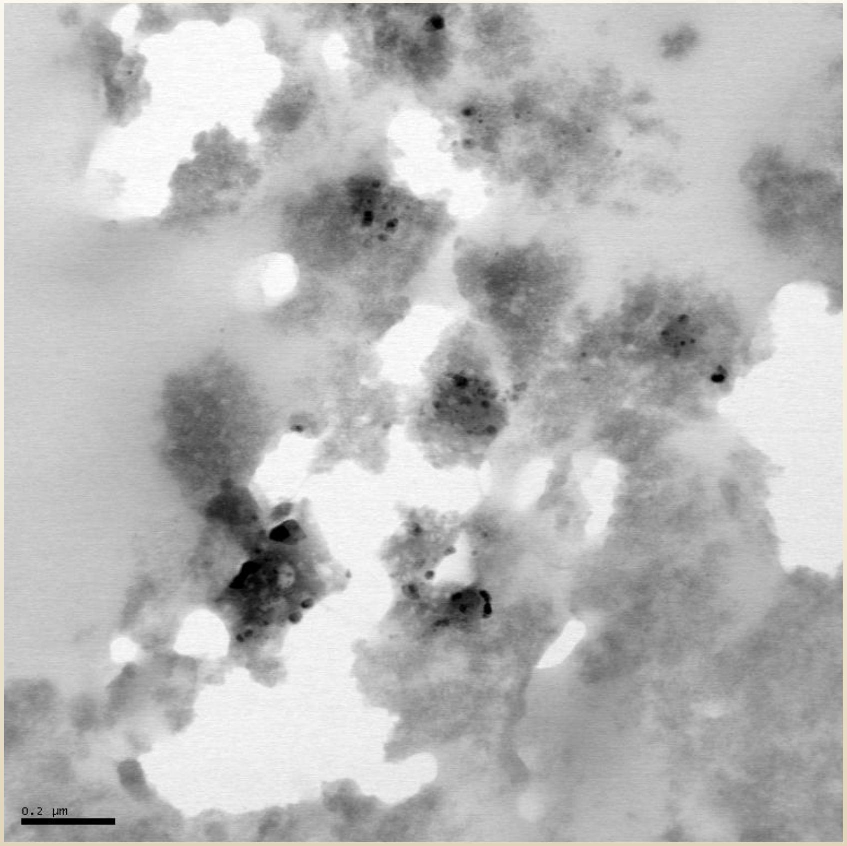



**Wild-2 Olivine**
**Orthopyroxene**

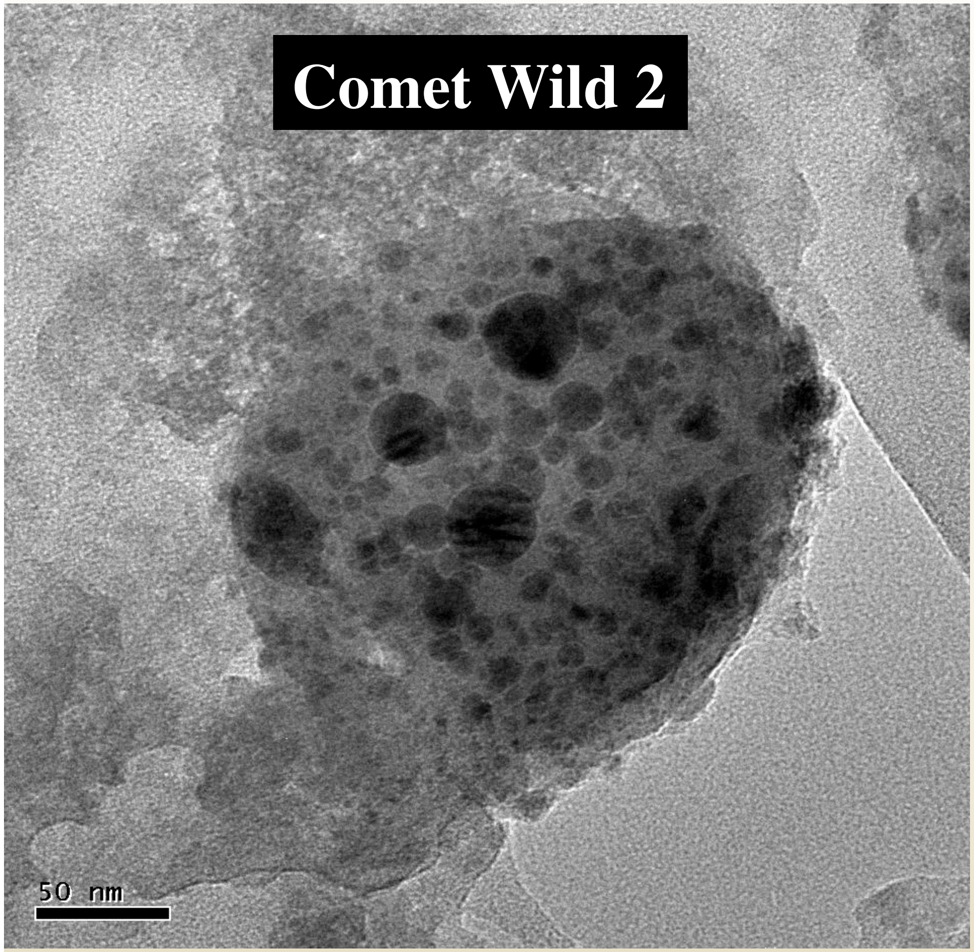
FC6,0,10,13,1

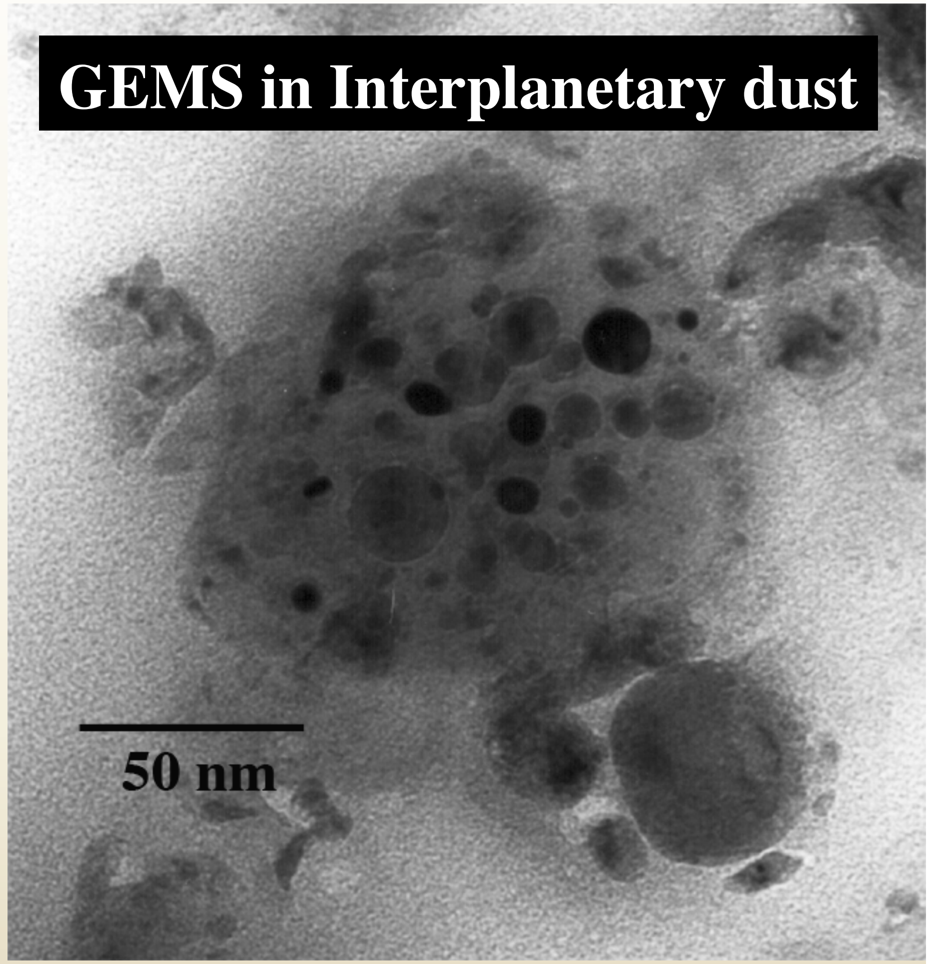
**_Amorphous silicates are abundant but appear to be thermally processed and intimately mixed with aerogel_**



# GEMS grains in Wild-2 samples?



# Stardust Mineralogy

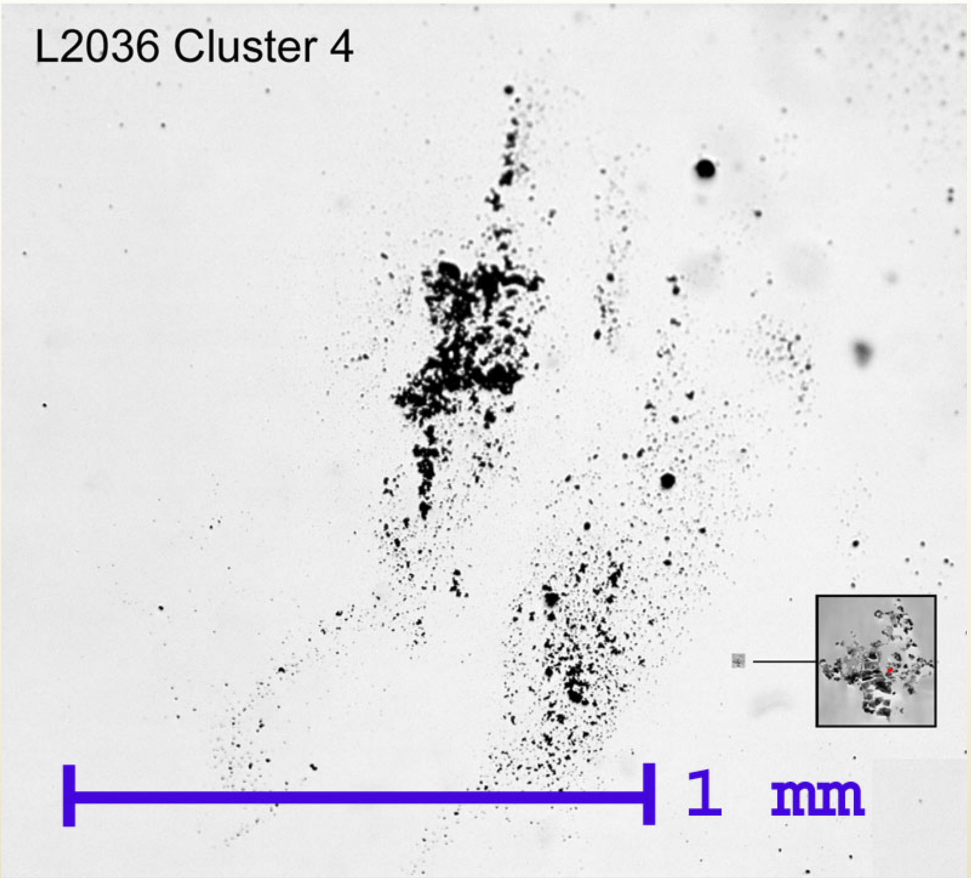
- Abundant crystalline silicates
- Intact amorphous silicates are rare
- CAI and chondrule-like materials observed
- Intact carbonaceous material is rare
- Intact fine-grained material is rare
- No hydrated silicates, but perhaps carbonates

The bulk composition of comet Wild-2
is a matter of vigorous ongoing
research and debate

# Dust in the Outer Solar System: Major Questions

| **Property** | | **Process** |
|---|---|---|
| • Is outer Solar System dust entirely anhydrous? | ⟹ | Did KBOs experience aqueous processing? |
| • What is the proportion of crystalline/amorphous silicates? | ⟹ | Extent of high T dust processing & mixing in the early Solar System? |
| • What is the abundance and state of carbon? | ⟹ | Did cometary organic matter originate in molecular clouds or in the solar nebula? |
| • Are there distinct populations of dust? | ⟹ | Is there compositional diversity in the Kuiper belt? |
| • Do outer SS dust particles retain ice? | ⟹ | Are mineral grains and ice mixed on microscopic scales? |

# Interplanetary Dust Particles: Micro-rocks



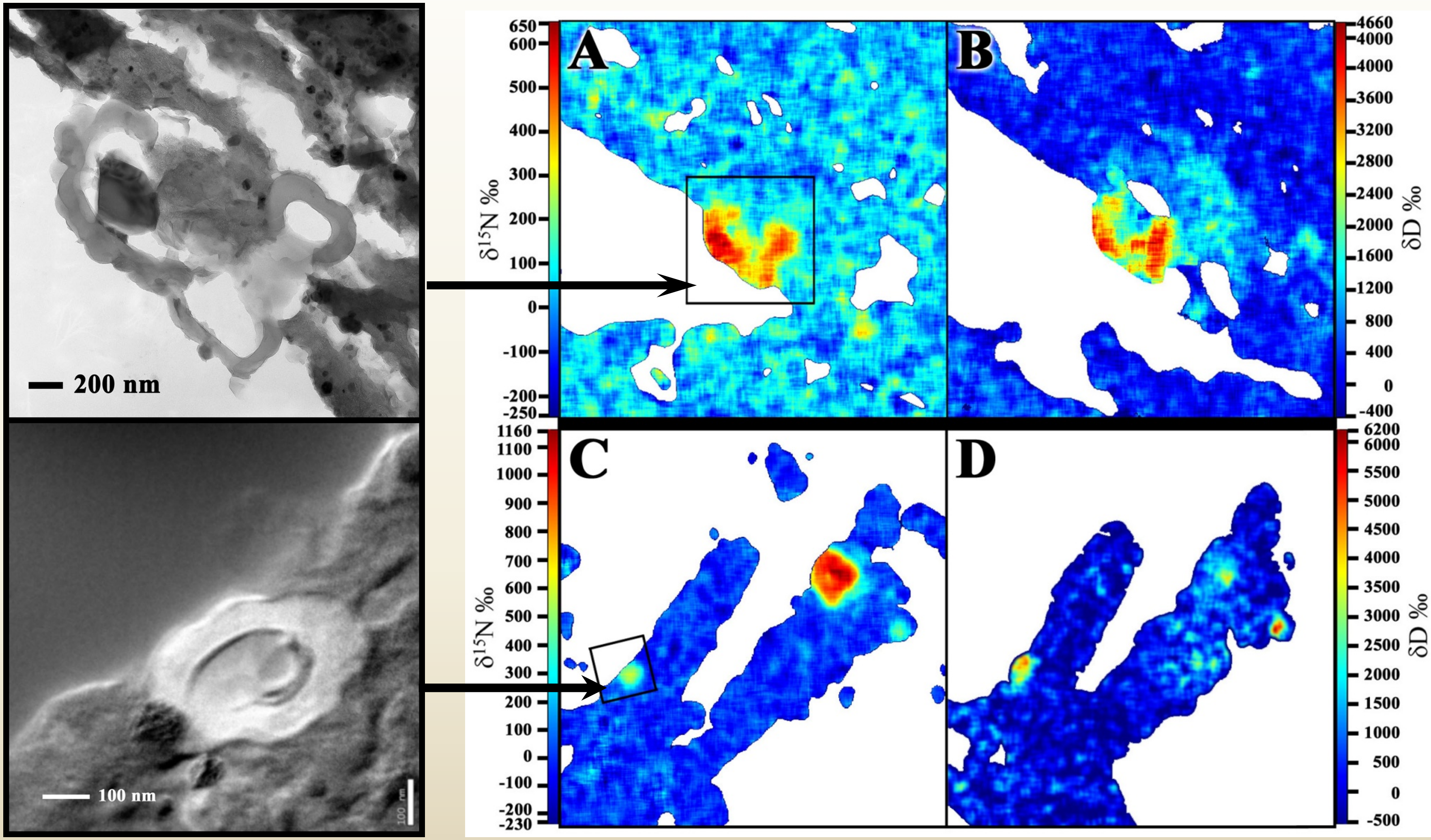

IDP sizes: 5 – 100 μm

Grain size: 50 – 1000 nm

Number of grains in an IDP:
$10^4$ - $10^6$

Silicate stardust grains in an IDP:
10 – 1,000

# H and N Isotopic Anomalies in Organic Globules




Top: Brightfield TEM image
Bottom: Energy filtered C image

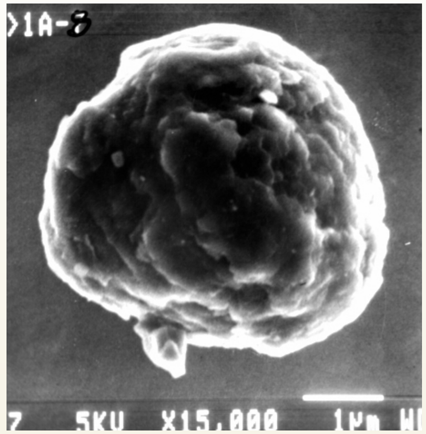
D/H ratios of the globules are 2.5 – 9 x terrestrial

Nakamura-Messenger et al. (2006) Science

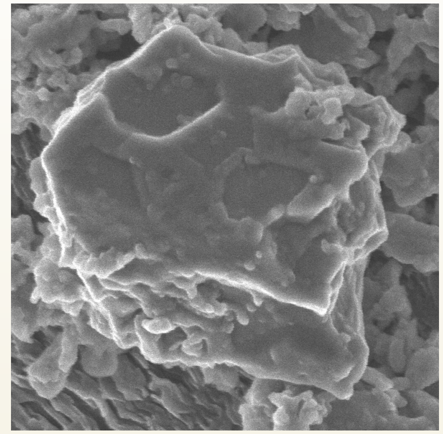
# Stardust from Meteorites and Cosmic Dust

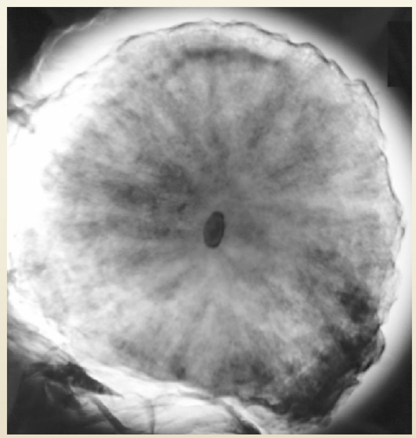
- SiC
- $Si_3N_4$
- Graphite
- Nanodiamonds
- $Al_2O_3$
- $TiO_2$
- Hibonite
- Spinel
- Olivine
- Pyroxene
- Amorphous silicate

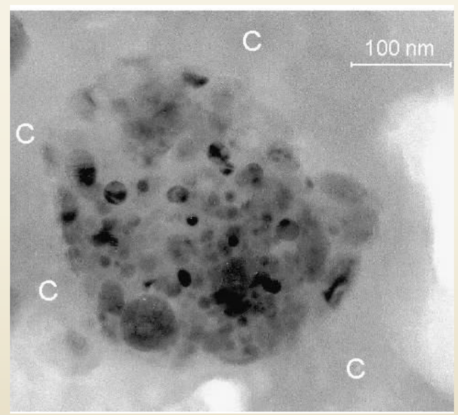
Stardust Microstructure
Internal grains
Pristine: Primary growth features
Processed: annealing, radiation



Graphite


Silicon Carbide


**Carbides *Within* Graphite**



Amorphous Silicate

Typical size: 0.1 - 1 μm Abundance: 1 – 1,000 ppm

Original discovery team: S. Amari, T. Bernatowicz, R. Lewis, E. Anders, E. Zinner

# Silicate and Oxide Stardust

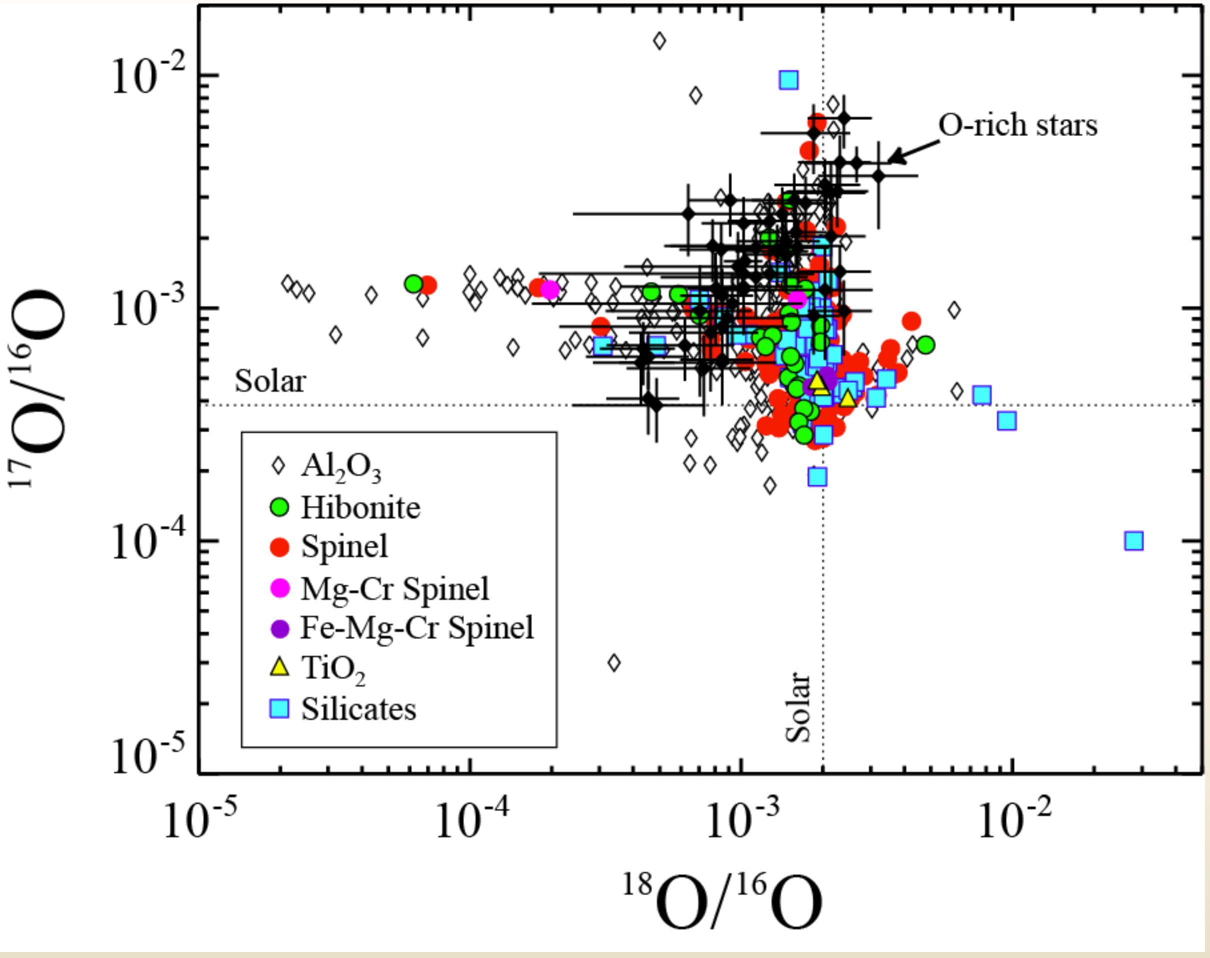


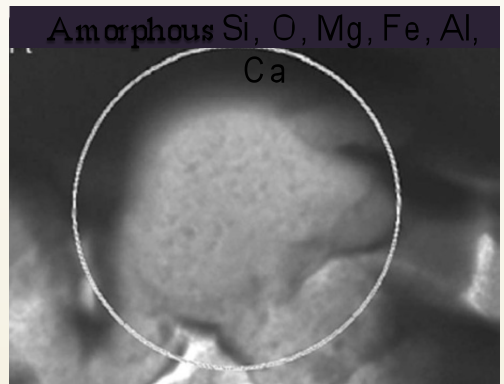

Figure courtesy L. Nittler

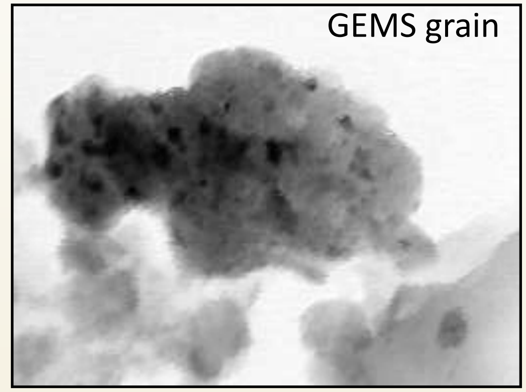
- >100 presolar silicates and oxides found so far
- ~99% originate from RG/AGB stars
- Supernova dust is rare (~1%)

# Amorphous Silicate Stardust: Properties and Histories

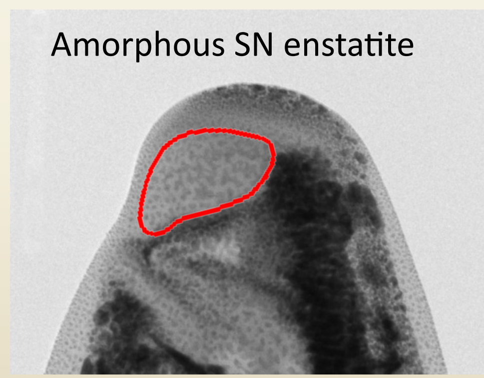
- Compositionally diverse
- nm-scale chemical heterogeneity
- Non-chondritic element abundances

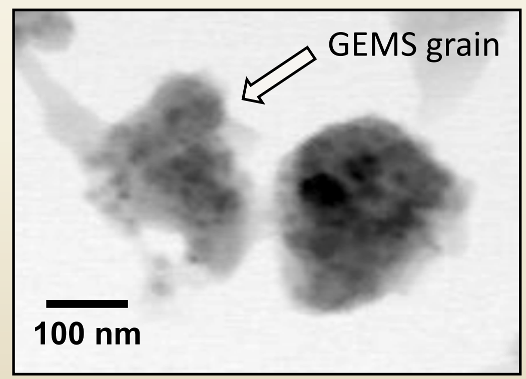
Radiation processed, but not chemically homogenized




Nguyen et al. 2007




Keller et al. 2008