PRESOLAR AND SOLAR SYSTEM DUST

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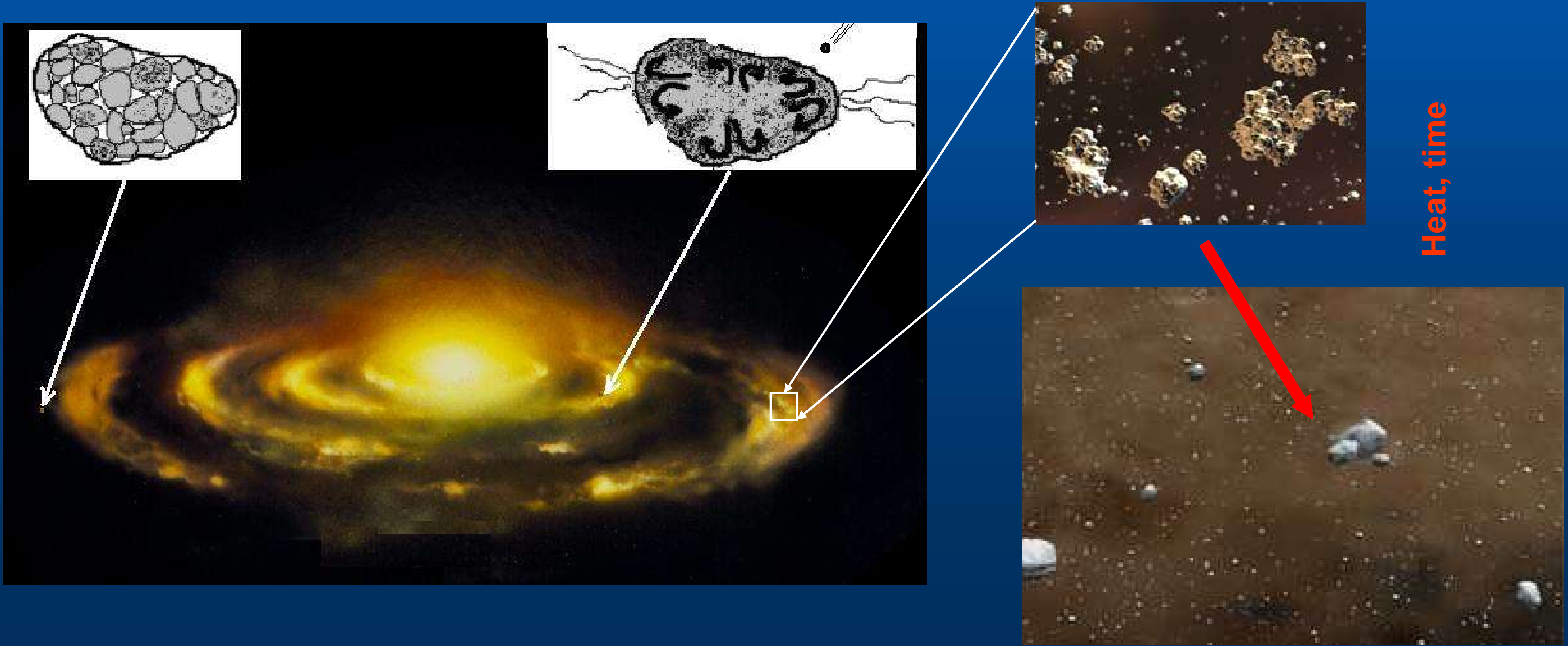
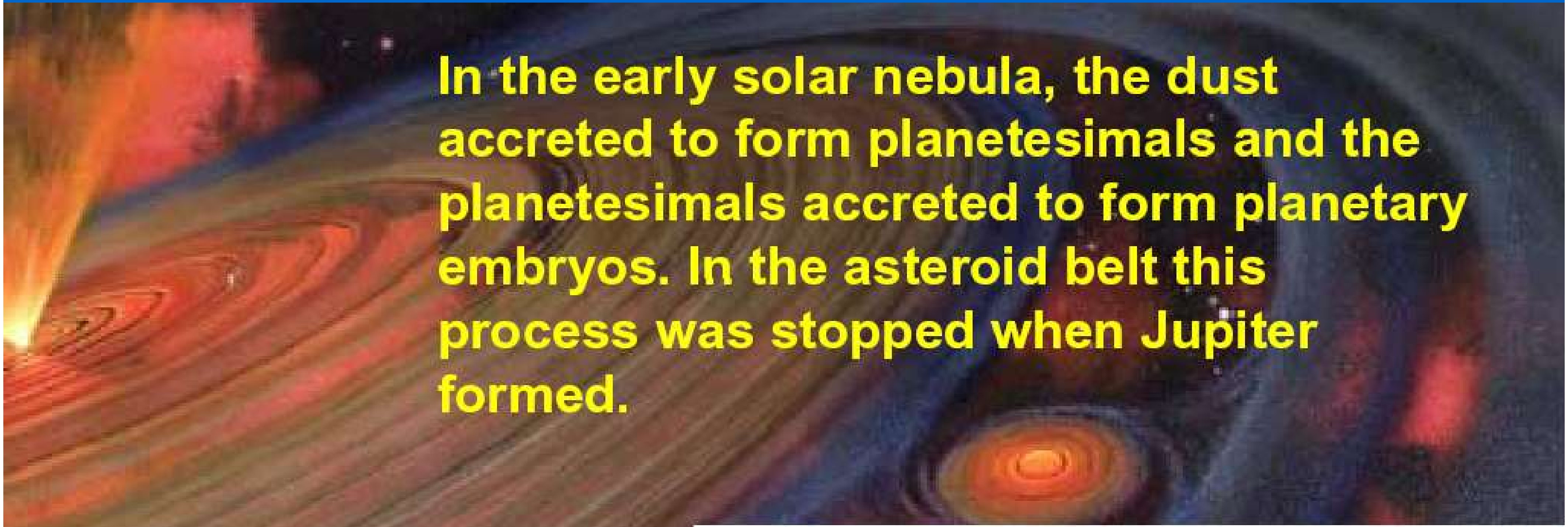


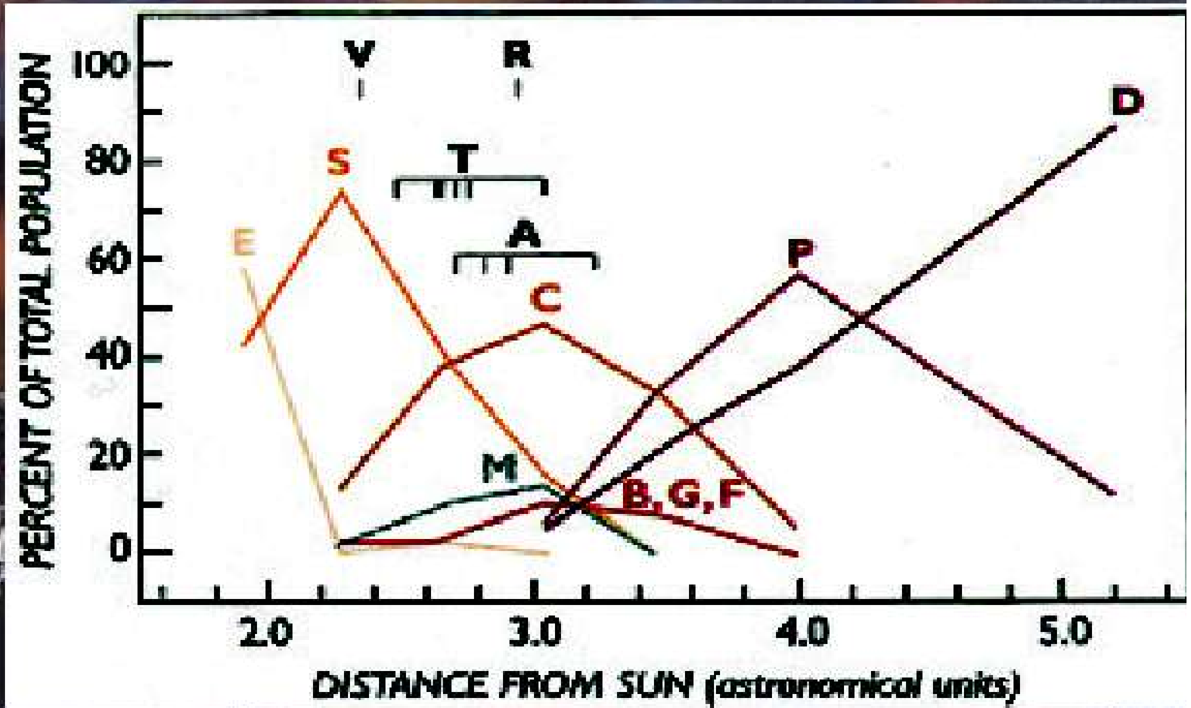
OUTLINE

- **Presolar grains, solar system minerals, and accretion**
- **Interplanetary Dust Particles (IDPs)**
- **Primitive bodies: challenge and opportunity…**
    - Physical properties of comets
    - The importance of comets in the origin of volatiles
    - Implications for sample-return missions
- Comet 81**P/Wild 2 results from Stardust (NASA)**
  - – First sample-return mission from a body different to the Moon
  - – What we learned about primitive materials from the outer disk?
  - – Composition of comets versum meteorites
- **Future spacecraft exploration**

FIRST SOLIDS IN THE OUTER DISK…

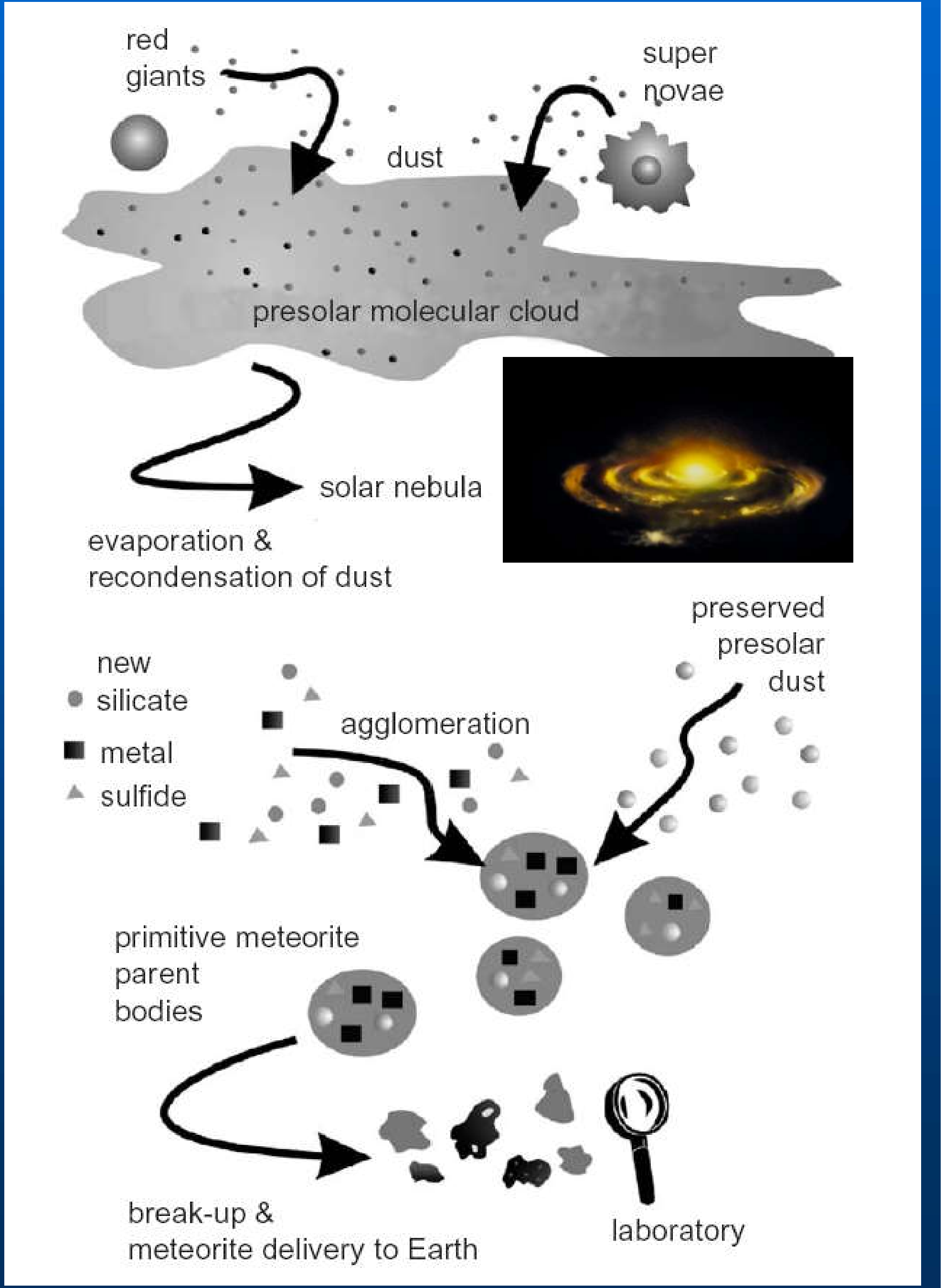


In the early solar nebula, the dust accreted to form planetesimals and the planetesimals accreted to form planetary embryos. In the asteroid belt this process was stopped when Jupiter formed.



STELLAR COMPONENTS

- The Sun and the protoplanetary disk formed in an environment rich in stellar products.
  - Growing evidence of the SS formation in a rich stellar cluster
- A small part of the materials were not processed in the solar nebula, and are “presolar”:
  - Presolar (stellar) grains
  - Radioisotopes
    - In the components
    - Trapped in the matrix
  - Isotopic anomalies
- Principal sources:
    - Circumstellar shells of red giants
    - AGBs
    - Novae and SN ejecta
- Clues from undifferentiated bodies:
  - Comets and carbonaceous asteroids



Adapted from Lodders and Amari (2005)

A SN OR A MASSIVE AGB STAR IN THE SOLAR SYSTEM ORIGIN?

- **Often it is argued the presence of a SN injecting radionuclides in the solar nebula**
- **But other stars exhale as well: AGB stars contributed significantly to the SS**
- **We found a 6.5 $M_{\odot}$ AGB star of solar metallicity as a good candidate to enrich the SS in short-lived nuclides (SLN)**
- **SLN abundances found in meteorites are explained with such type of AGB star:**
  - **Our model matches the abundances of ^{26}Al, ^{41}Ca, ^{60}Fe, and ^{107}Pd inferred to be in the solar nebula by using a dilution factor of 1 part of AGB material per 300 parts of original solar nebula material**
  - **Such a polluting source does not overproduce ^{53}Mn, as SN models do, and only marginally affects isotopic ratios of stable elements**

Image Gabriel Pérez Diaz (IAC)

Publication details:

Trigo-Rodríguez J.M., D.A. García-Hernández, M. Lugaro, A. I. Karakas, M. van Raai , P. García Lario, and A. Manchado (2009) Meteoritics and Planetary Science 44, 627.

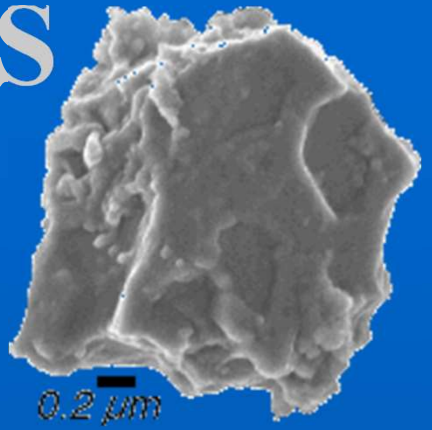
SOURCES OF RADIONUCLIDES

- **In particular short-lived nuclides (SLN) were important for planetesimals internal heating**
- **They incorporated from the vapor phase into the minerals forming chondritic components**

Parent	Daughter	Detected Presence	Half-Life (10^6 yr)	Likely stellar source(s)
^{10}Be	^{10}B	CAIs (McKeegan et al., 2000)	1.5	Spallation product
^{26}Al	^{26}Mg	CAIs (Lee et al.,1966) and chondrules (Galy et al. 2000)	0.73	SN, massive AGBs
^{41}Ca	^{41}K	CAIs (Srinivasan et al., 1994)	0.1	AGBs
^{53}Mn	^{53}Cr	CAIs (Birk and Allègre, 1985), chondrules, etc	3.7	AGBs
^{60}Fe	^{60}Ni	CAIs, eucrites (Shukolyukov and Lugmair, 1993)	1.5	SN, massive AGBs
^{87}Rb	^{87}Sr	CAIs	48,800	Massive AGBs

Adapted from Zinner (2002)

TYPES OF STELLAR GRAINS

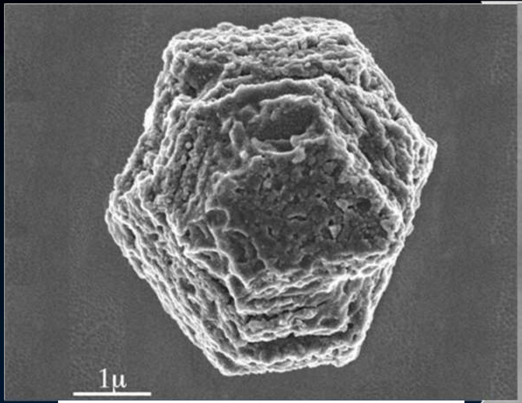


- **Usually called "presolar" because:**
  - **These grains are suspicious to be formed in stellar outflows of late-type stars and in ejecta of stellar explosions**
  - **Their stellar origin is identified by their anomalous isotopic compositions compared to SS materials**

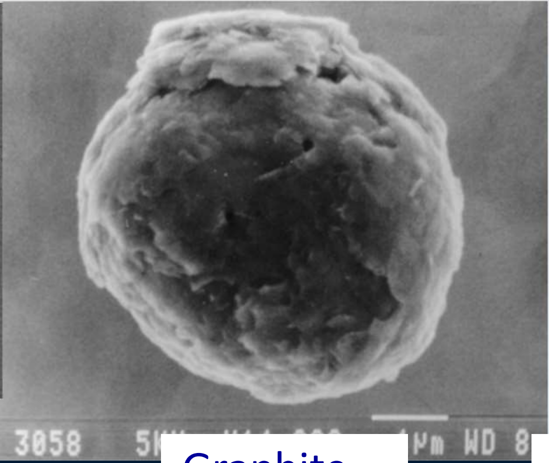
refractory

Grain type	Typical size	Abundance	Stellar sources
Diamond	2 nm	1,000 ppm	AGB?, SNe
Silicon carbide	0.1-20 µm	10 ppm	AGB, SNe, J-stars, novae
Graphite	1-20 µm	1-2 ppm	RG, AGB, SNe
Oxides	0.15 – 3 µm	1 ppm	SNe, AGB
Silicon nitride	0.3 – 1 µm	~ 3 ppb	SNe, AGB
Ti-, Fe-, Zr-, Mo-carbides	10-200 nm	< 1 ppb	SNe
Kamacite, iron	~10-20 nm	?	SNe
Olivine	0.1-0.3 µm	?	RGB, AGB, SNe?

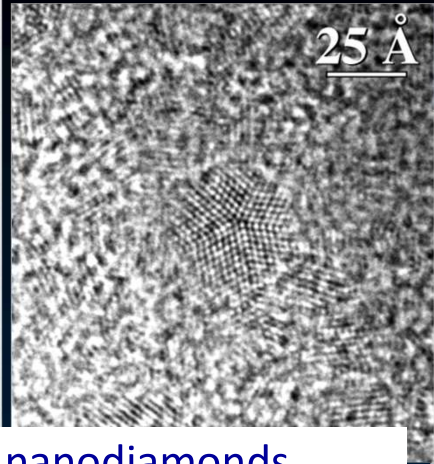
compiled from: Zinner, (2003) and Lodders and Amari (2005)



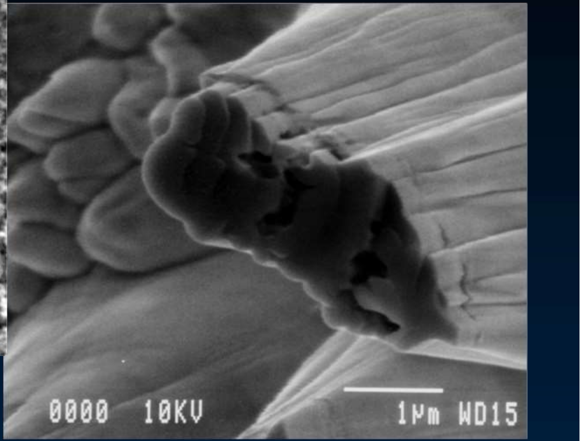
Silicon Carbide



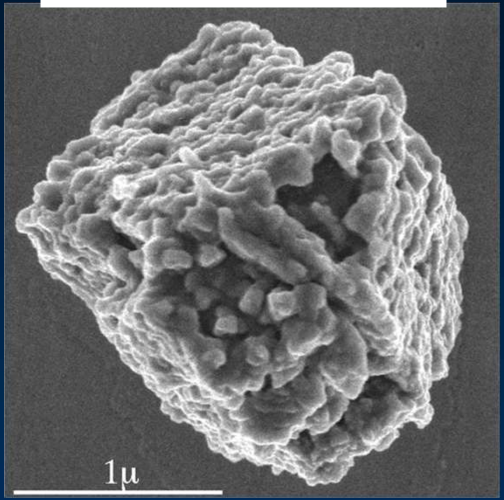
Graphite

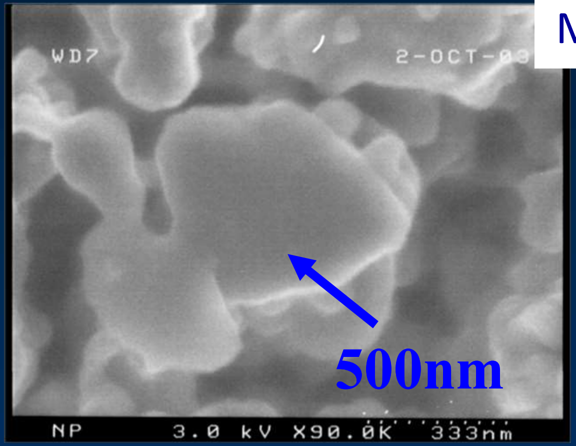


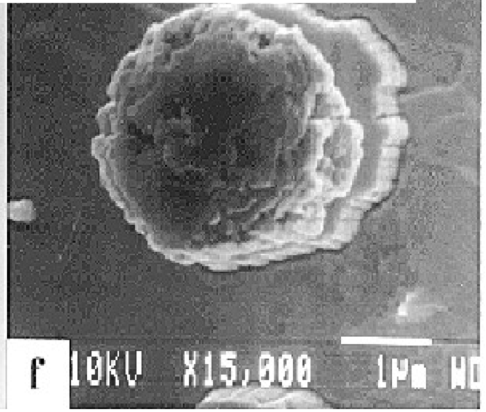
nanodiamonds



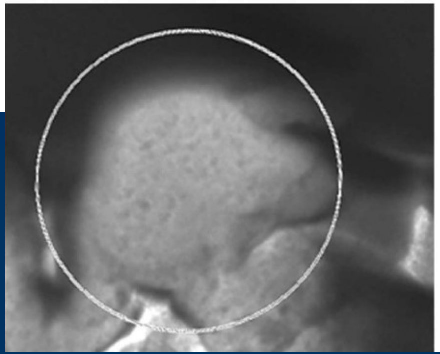
Oxides(Al_2O_3, $MgAl_2O_4$, Ti O_2 …)







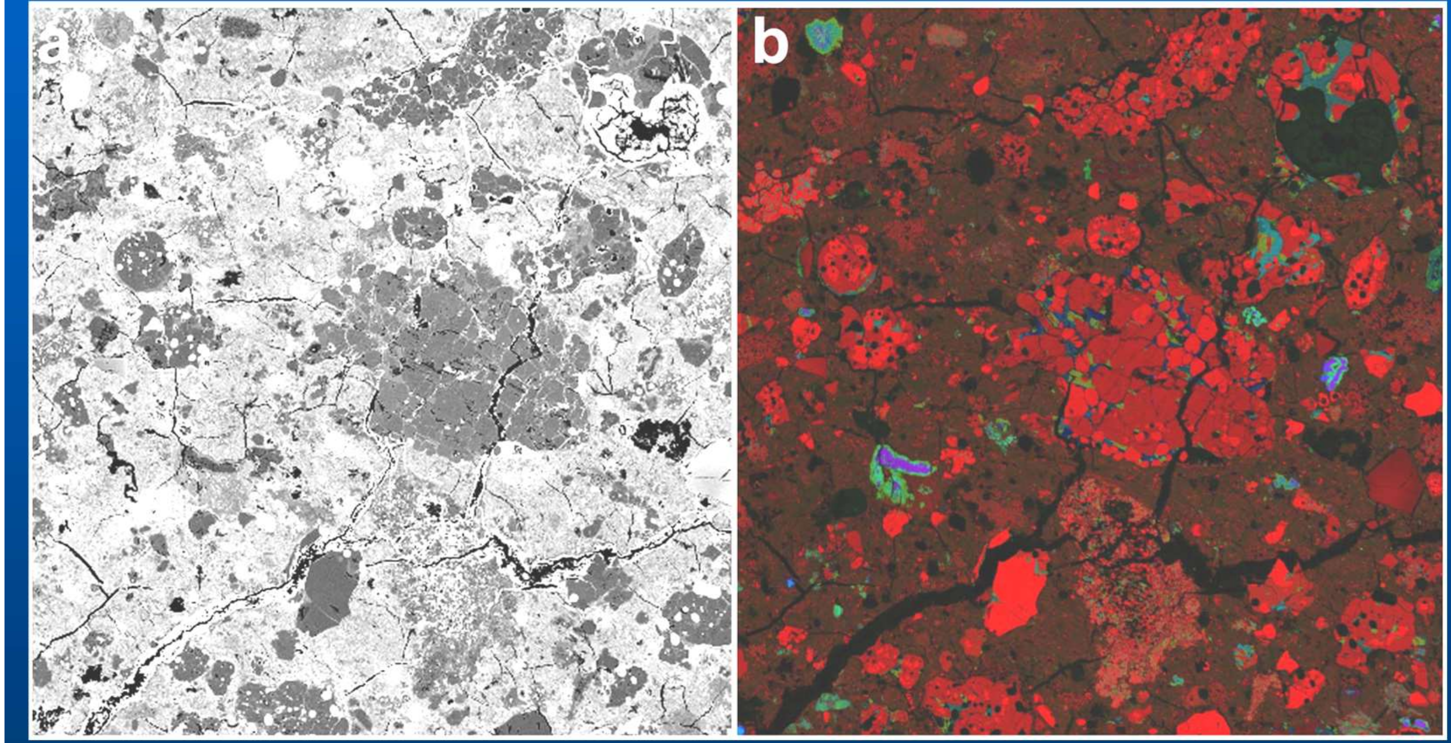
Silicates (Glass, $MgSiO_4$ …)



PRESOLAR GRAINS ARE AMAZING, BUT RARE!

- Tiny mineral grains (e.g. silicates, SiC, Al_2O_3 …) with extreme isotopic anomalies (e.g. Clayton & Nittler ARAA 2004)
- Rare component of meteorites (~100 ppm) and IDPs (400-1000 ppm)

IN SITU IDENTIFICATION OF PRESOLAR GRAINS



A mm^2 area of the primitive chondrite Acfer 094. a) SEM image showing the fine texture of the matrix. b) Composite RGB ion microprobe image where red=Mg, green=Ca and blue=Al. Presolar silicate grains are typically of the size of the fine dust that is forming the matrix.

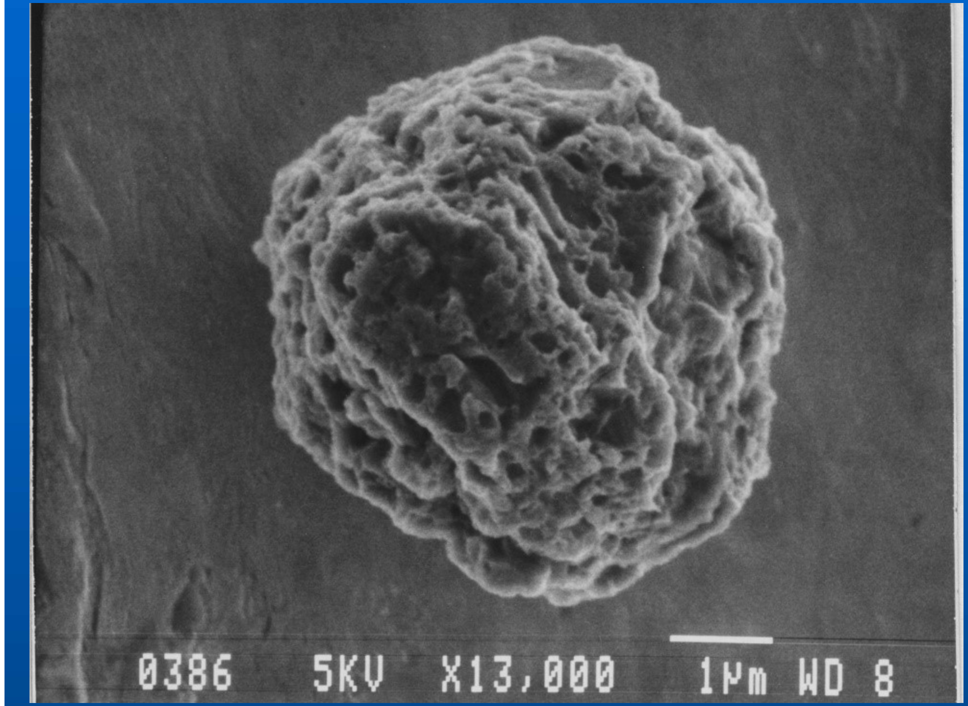
(Trigo-Rodríguez & Blum, 2009)

- New advance in reference with the “classical” chemical extraction
- Major and trace element chemistry can be used to identify stellar grains
- Presolar grains are usually identified in micro- and nano-probe X-ray maping by their often huge excesses or deficits in isotopic compositions (relative to normal terrestrial abundances)

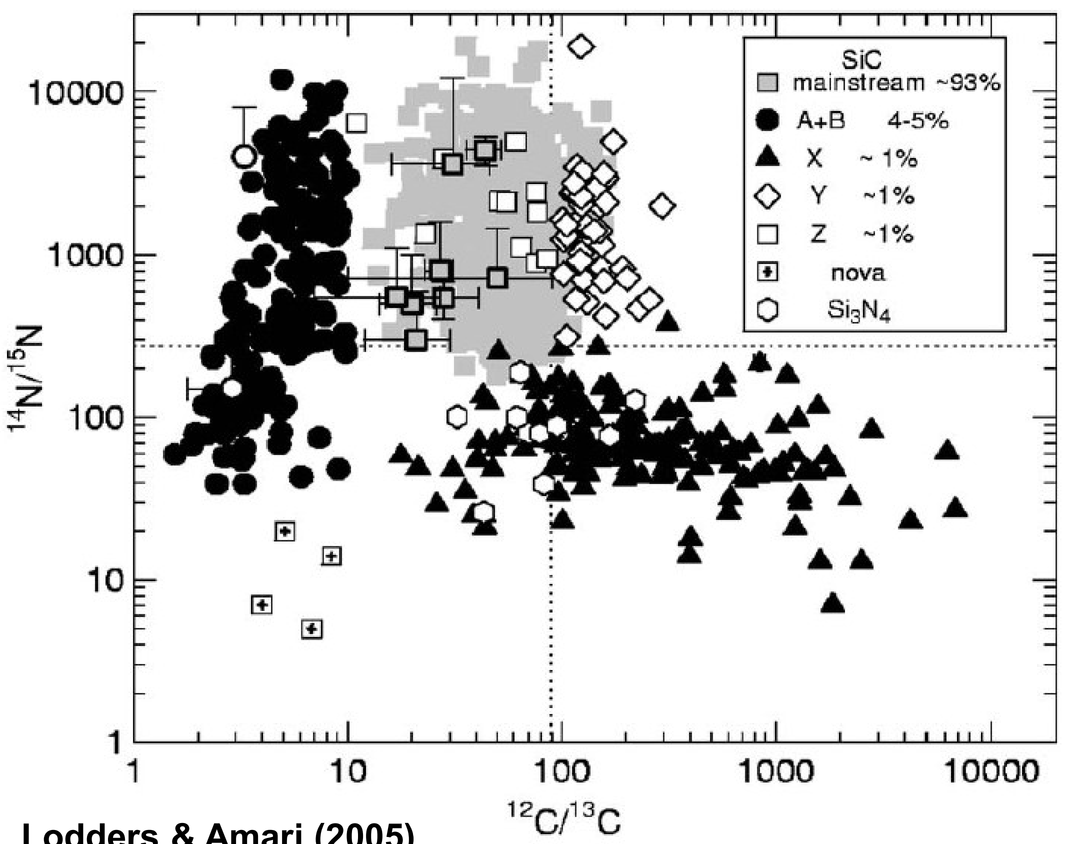
PRESOLAR COMPONENTS RETAINED IN PRIMITIVE SOLAR SYSTEM MATERIALS

- Short-live radionuclides
  - They were incorporated during condensation on mineral phases in the solar nebula: CAIs, chondrules, etc
  - A few (e.g. noble gases) were retained in the matrix during the early accretion of planetesimals
- Presolar grains
- Fine-dust materials:
  - Carbonaceous materials with chemistry and isotopic anomalies inherited from the IM

SILICON CARBIDE GRAINS



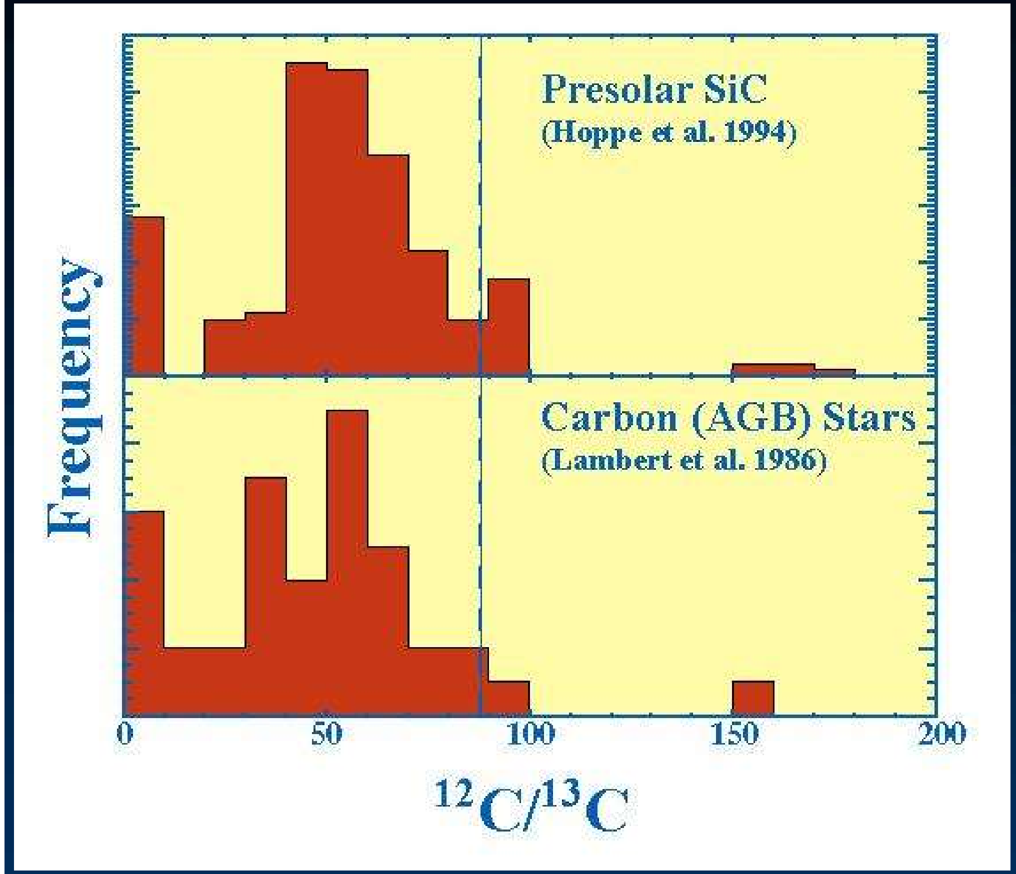
Chemically-extracted SiC grain, courtesy Sachiko Amari (2009)

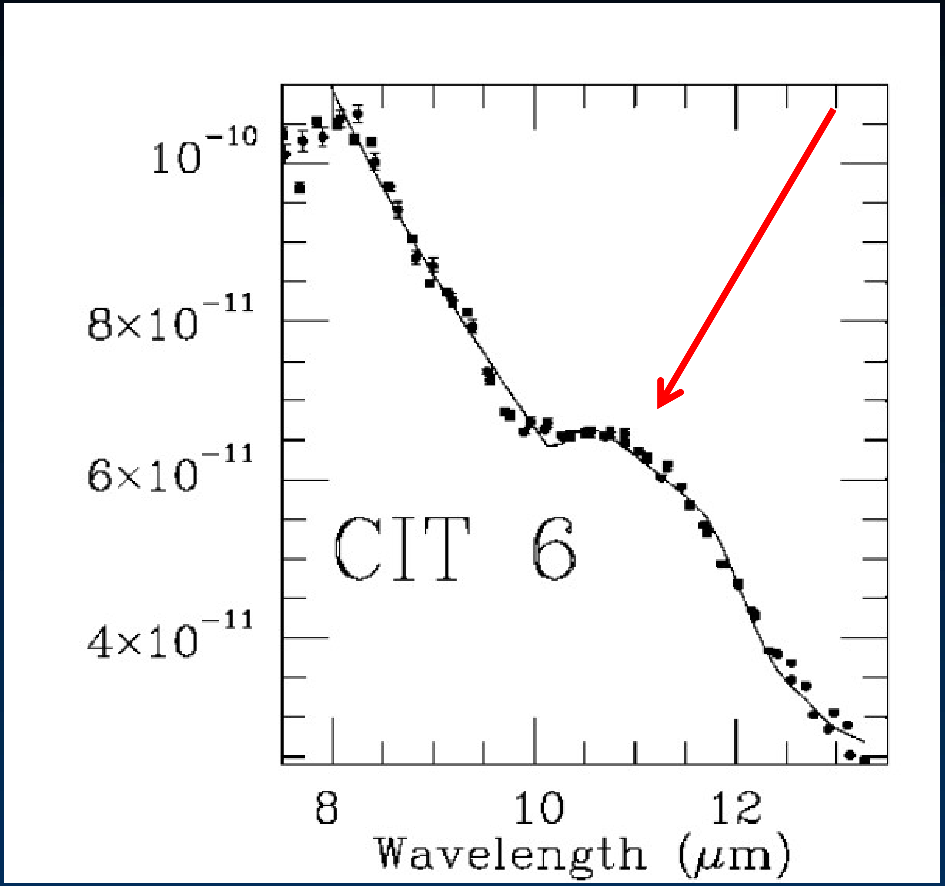


Lodders & Amari (2005)

- The different classes trace the variety of stars that were in the solar neighborhood
  - Mainstream grains and probably Y and Z classes are coming from AGB stars
  - In particular the Y may have origin (contain enrichments in s-process elements) in intermediate mass AGB stars (García-Hernández et al., 2006)
  - Products from J-type C-stars overlap with the A+B grains isotopic ratios.
  - A few grains detected have the imprints of Novae: low $^{12}C/^{13}C<10$ (José and Hernanz, 1998; José et al., 2001, 2004)

Mainstream SiC (>90%)



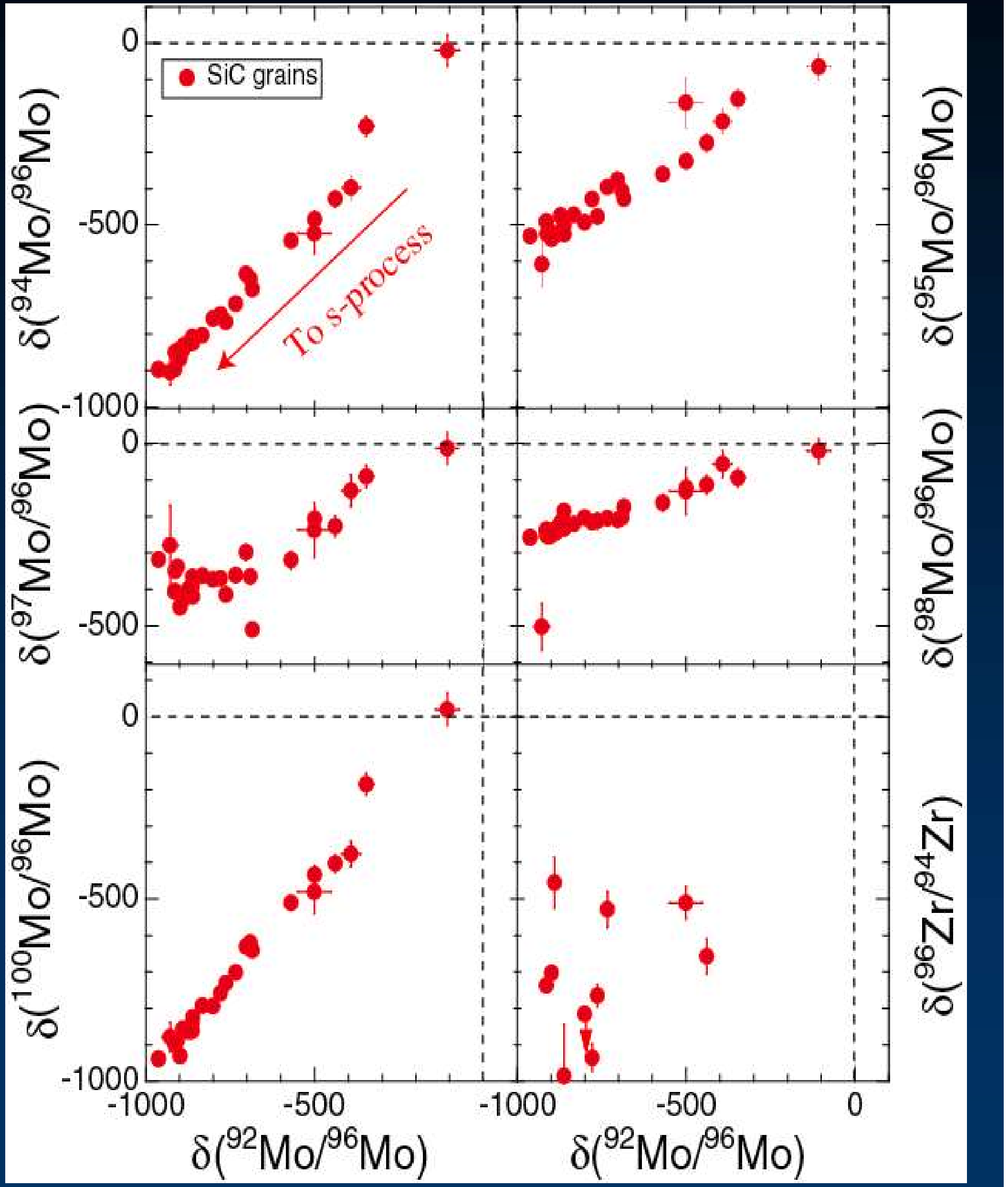


Formed in AGB stars!

final stage of low-mass (<8Msun) evolution

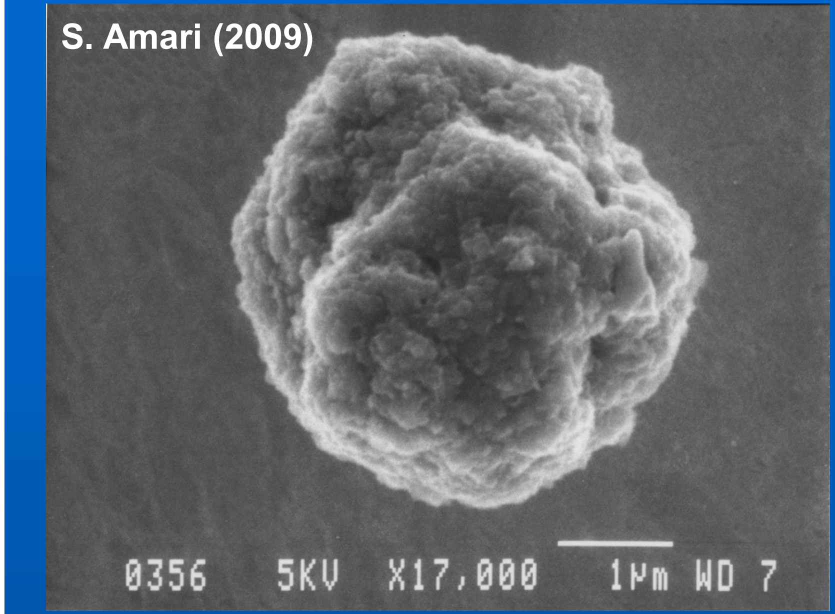
Heavy elements in AGB SiC

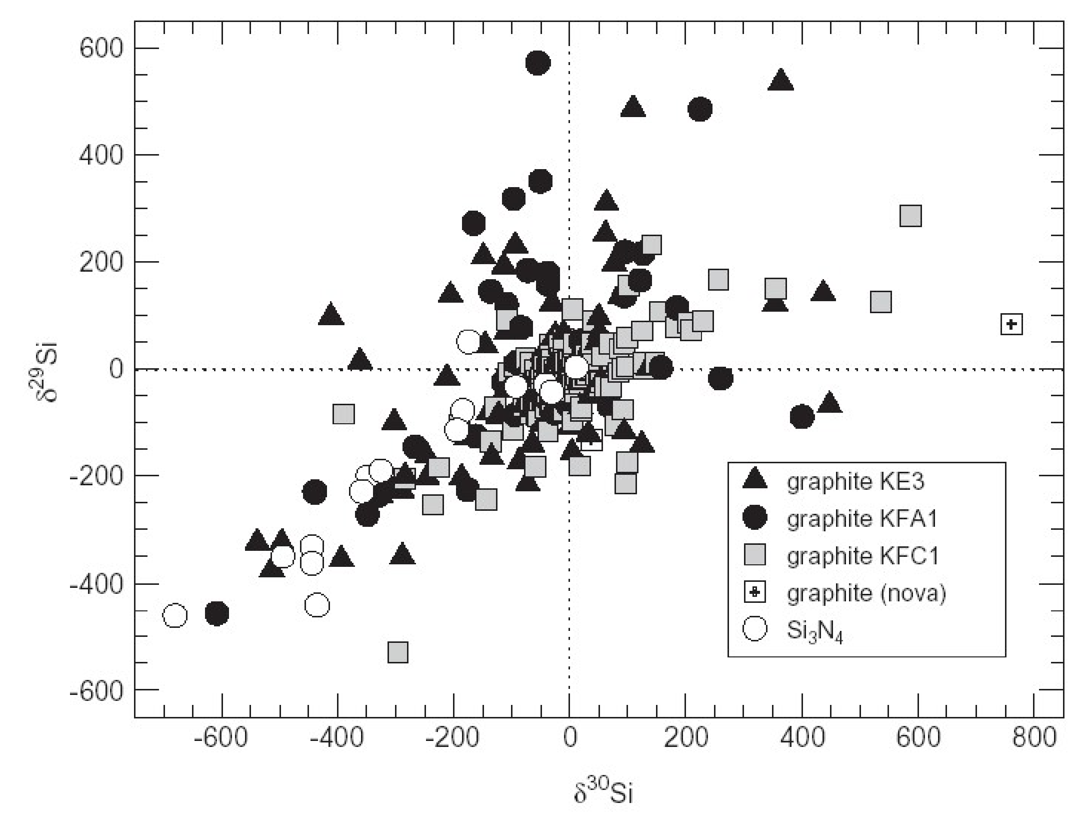
- Mo, Zr, Sr, Ru, Ba isotopes in single SiC grains
  - Clear *s*-process signature
  - Confirms AGB origin and *s*-process as “real” process in nature



Data from Argonne/Chicago group

STELLAR GRAPHITE

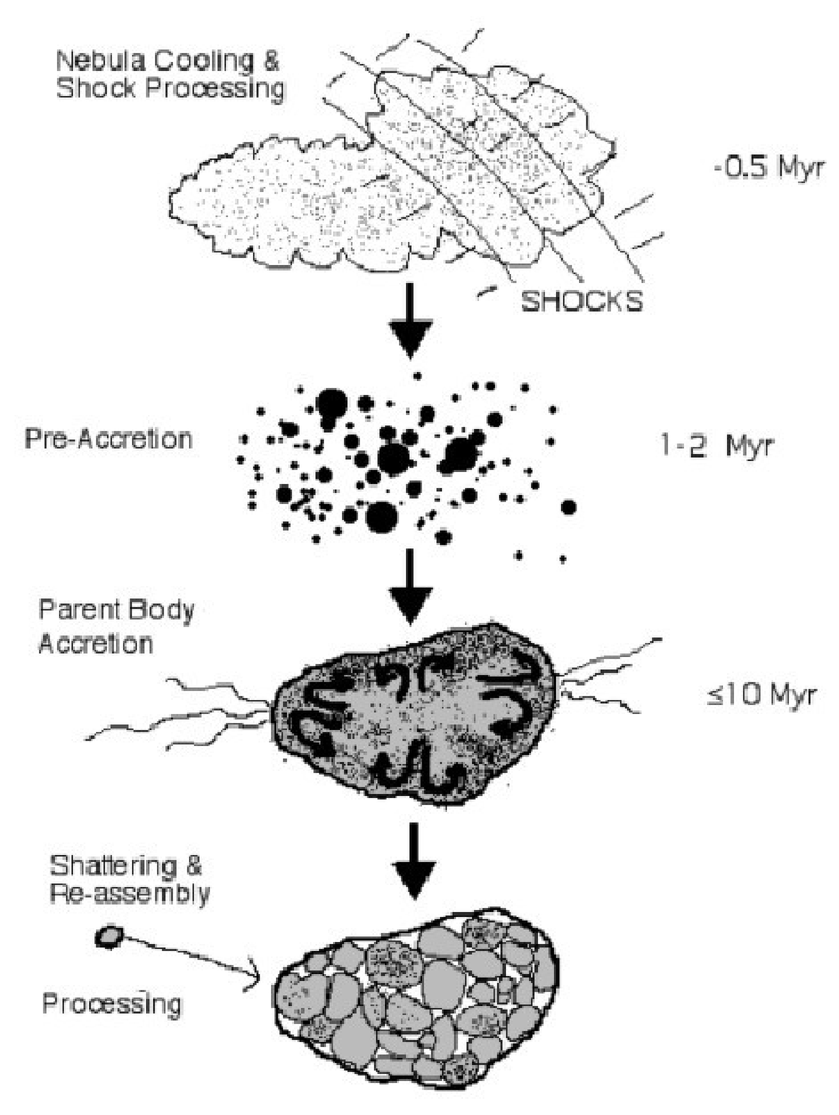




- There are no equivalent designations for the different graphite populations
- It is still unknown how many types of stars are needed to account for the presolar graphite
  - KE3 and KFA1 from SNe
  - KFC1 grains from low-metallicity AGB stars
  - A few are from Novae
- Low trace elements contents make isotopic analyses challenging

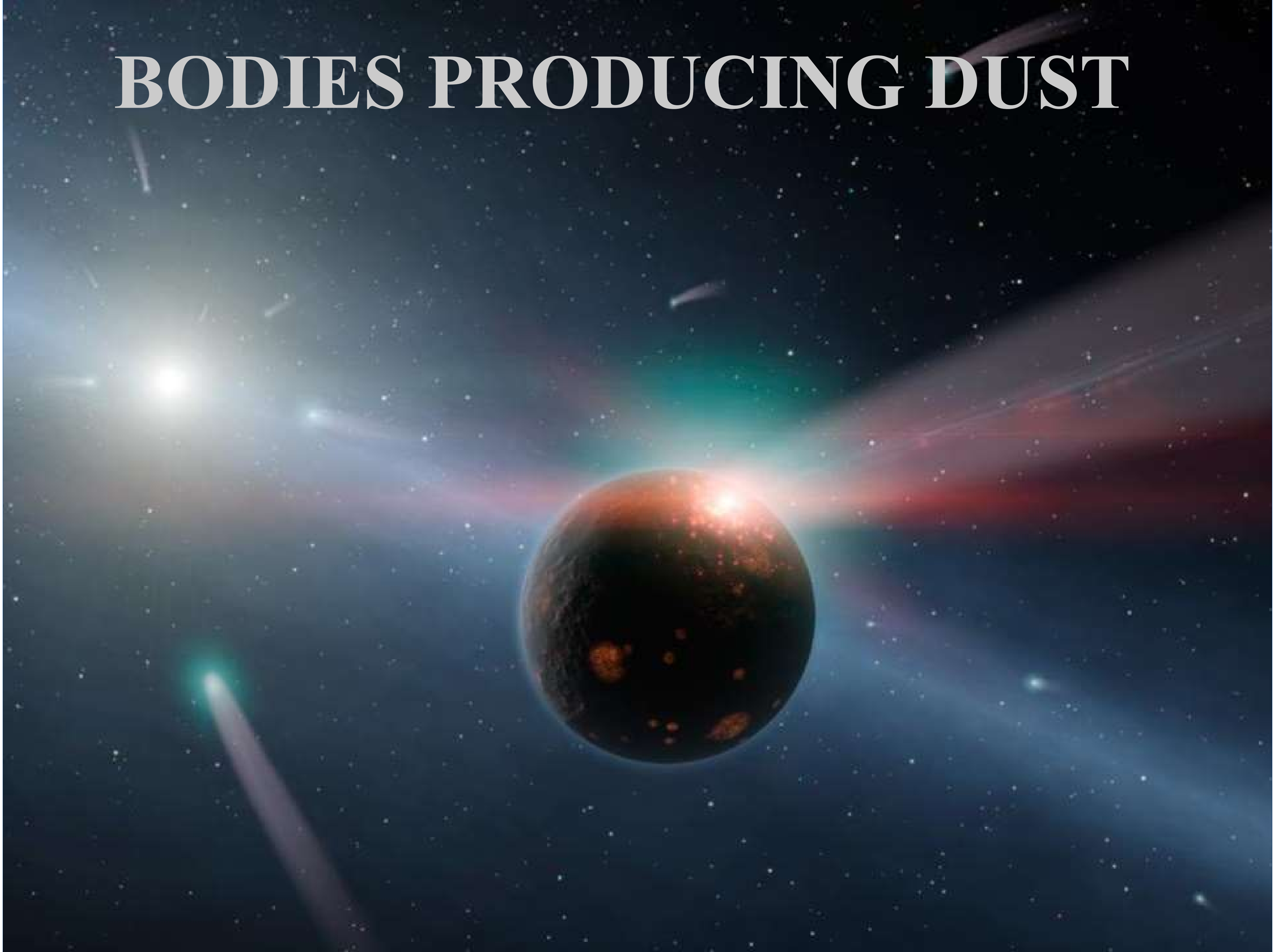
SUMMARY: FORMATION SCENARIO OF THE SOLAR SYSTEM

- ≈4.6 Gyr ago the solar nebula started its collapse
  - Presolar grains were embedded in the dust
  - In the hot nebular regions the first refractory minerals formed by evaporation, recondensation and melting of presolar dust grains, and SS condensates
- At ~4567 Myr: CAIs formed incorporating radionuclides from the stellar environment
- At ~4566 Myr: chondrule formation begins and continues for about 1-2 Myr
- Between 4565-4564 Myr the different components accrete to form the chondritic asteroids: first planetesimals
- Since then: Collisional compaction, and aqueous alteration have participated in processing the rock-forming materials of minor (undifferentiated) bodies

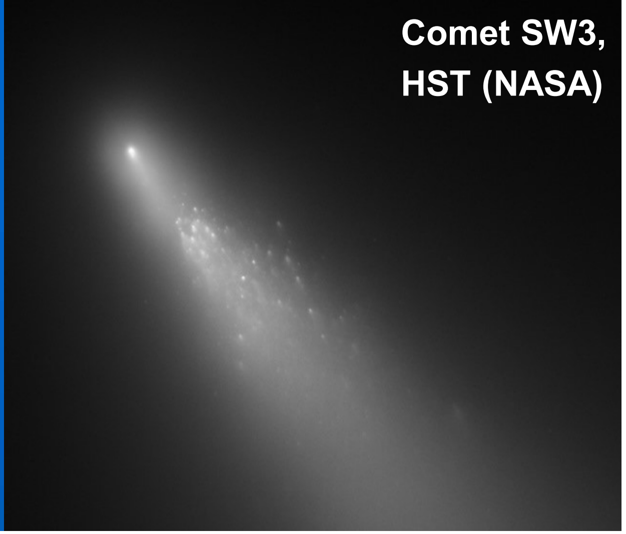


Jewitt et al. (2008)

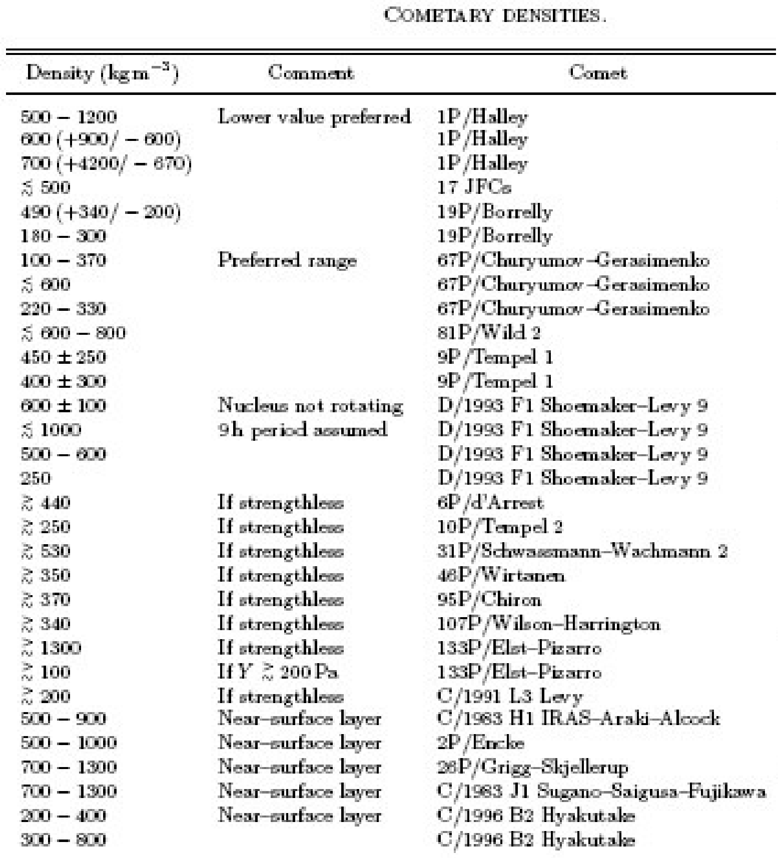
BODIES PRODUCING DUST



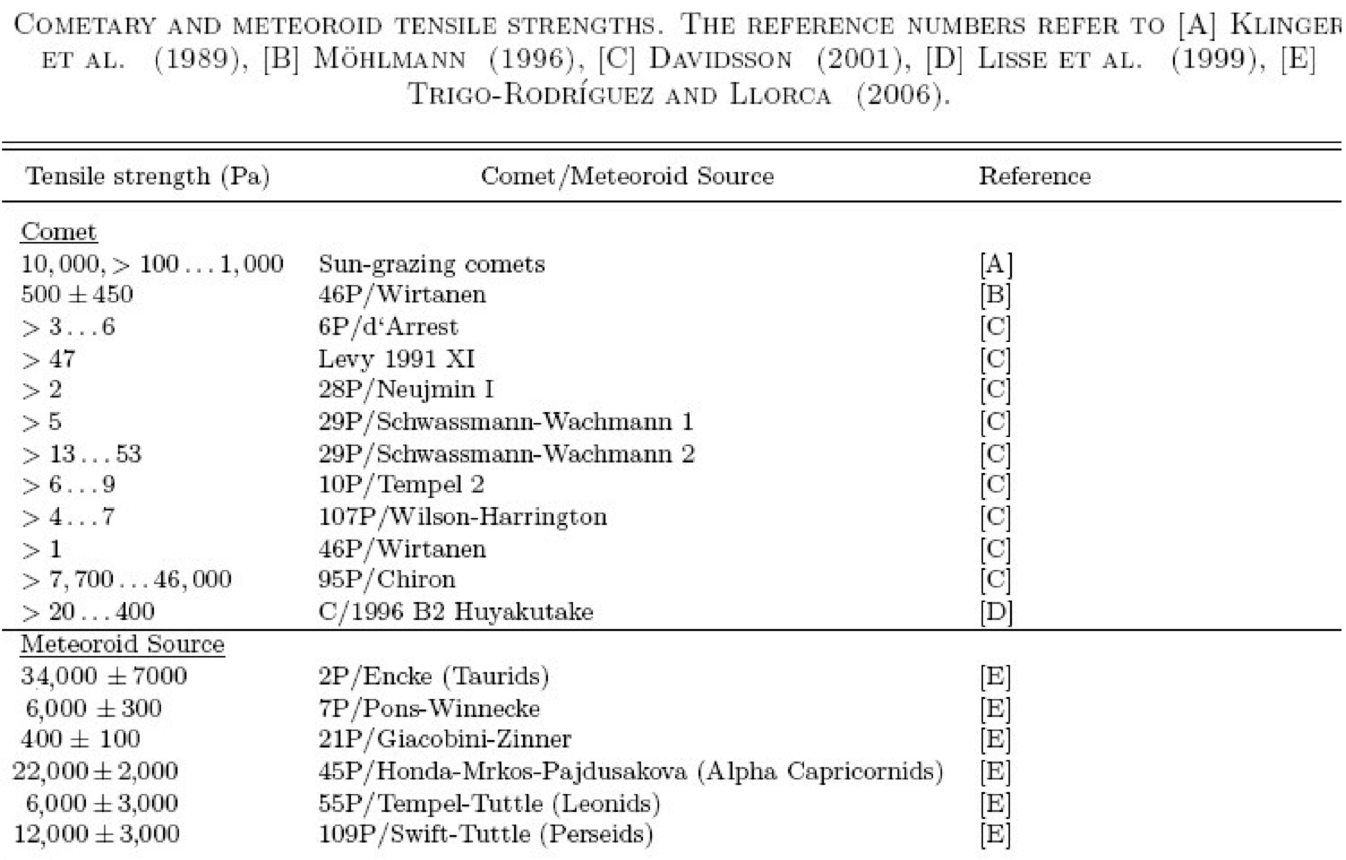
COMETS AS SOURCE OF DUST


Comet SW3, HST (NASA)

Blum et al. (2006) ApJ, in press.


Cometary densities.

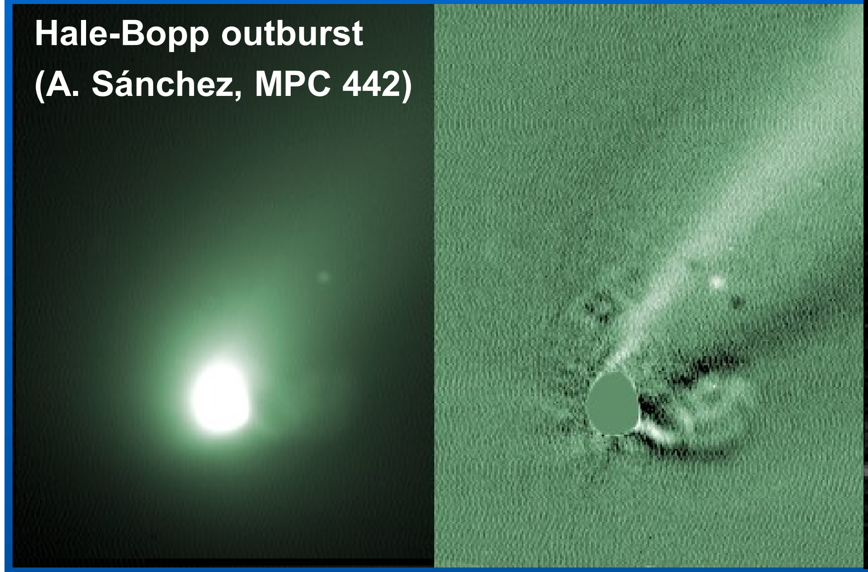
Density (kg m^{-3})	Comment	Comet
$500 - 1200$	Lower value preferred	1P/Halley
$600\ (+900/-600)$		1P/Halley
$700\ (+4200/-670)$		1P/Halley
$\lesssim 500$		17 JFCs
$490\ (+340/-200)$		19P/Borrelly
$180 - 300$		19P/Borrelly
$100 - 370$	Preferred range	67P/Churyumov–Gerasimenko
$\lesssim 600$		67P/Churyumov–Gerasimenko
$220 - 330$		67P/Churyumov–Gerasimenko
$\lesssim 600 - 800$		81P/Wild 2
450 ± 250		9P/Tempel 1
400 ± 300		9P/Tempel 1
600 ± 100	Nucleus not rotating	D/1993 F1 Shoemaker–Levy 9
$\lesssim 1000$	9 h period assumed	D/1993 F1 Shoemaker–Levy 9
$500 - 600$		D/1993 F1 Shoemaker–Levy 9
250		D/1993 F1 Shoemaker–Levy 9
$\gtrsim 440$	If strengthless	6P/d'Arrest
$\gtrsim 250$	If strengthless	10P/Tempel 2
$\gtrsim 530$	If strengthless	31P/Schwassmann–Wachmann 2
$\gtrsim 350$	If strengthless	46P/Wirtanen
$\gtrsim 370$	If strengthless	95P/Chiron
$\gtrsim 340$	If strengthless	107P/Wilson–Harrington
$\gtrsim 1300$	If strengthless	133P/Elst–Pizarro
$\gtrsim 100$	If $Y \gtrsim 200$ Pa	133P/Elst–Pizarro
$\gtrsim 200$	If strengthless	C/1991 L3 Levy
$500 - 900$	Near–surface layer	C/1983 H1 IRAS–Araki–Alcock
$500 - 1000$	Near–surface layer	2P/Encke
$700 - 1300$	Near–surface layer	26P/Grigg–Skjellerup
$700 - 1300$	Near–surface layer	C/1983 J1 Sugano–Saigusa–Fujikawa
$200 - 400$	Near–surface layer	C/1996 B2 Hyakutake
$300 - 800$		C/1996 B2 Hyakutake

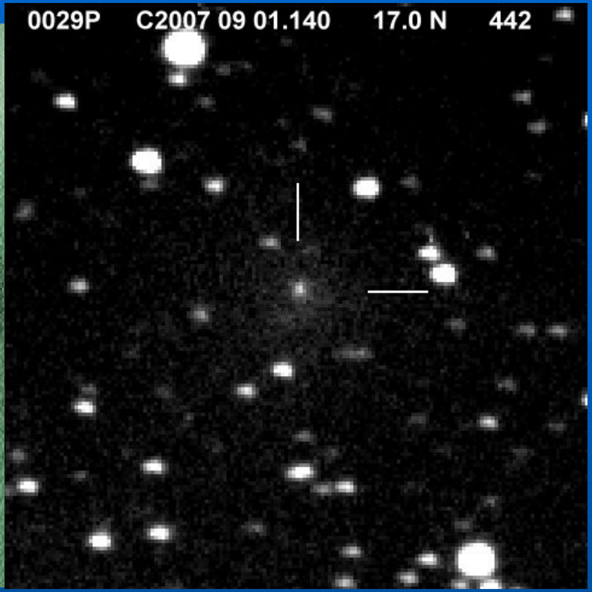

Cometary and meteoroid tensile strengths. The reference numbers refer to [A] Klinger et al. (1989), [B] Möhlmann (1996), [C] Davidsson (2001), [D] Lisse et al. (1999), [E] Trigo-Rodríguez and Llorca (2006).

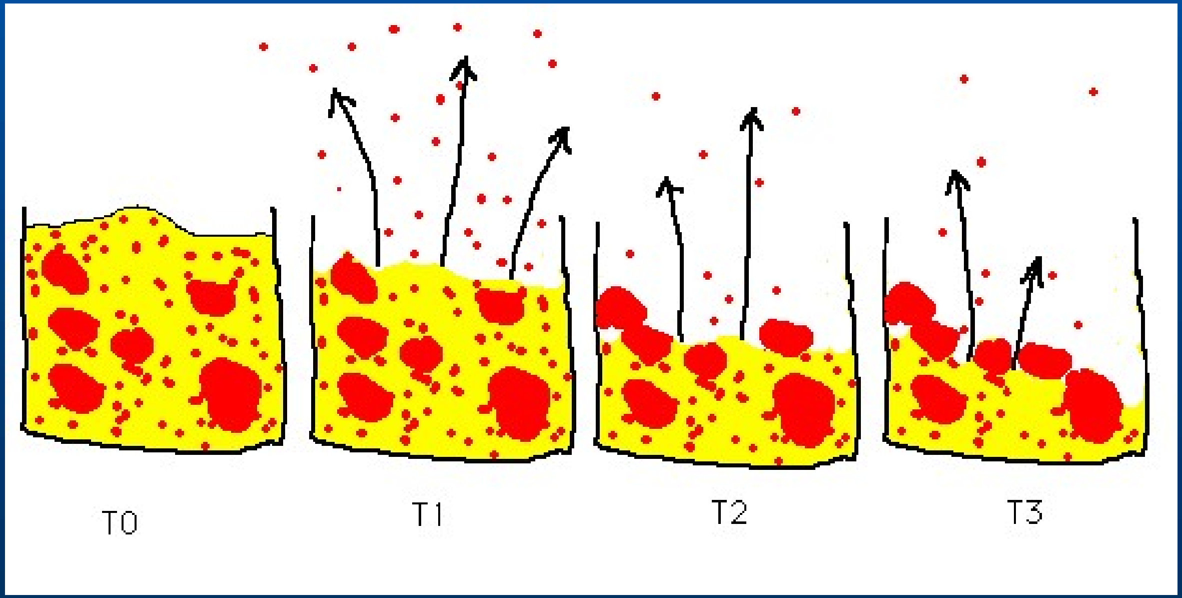
Tensile strength (Pa)	Comet/Meteoroid Source	Reference
Comet		
$10,000, > 100 \ldots 1,000$	Sun-grazing comets	[A]
500 ± 450	46P/Wirtanen	[B]
$> 3 \ldots 6$	6P/d'Arrest	[C]
> 47	Levy 1991 XI	[C]
> 2	28P/Neujmin I	[C]
> 5	29P/Schwassmann-Wachmann 1	[C]
$> 13 \ldots 53$	29P/Schwassmann-Wachmann 2	[C]
$> 6 \ldots 9$	10P/Tempel 2	[C]
$> 4 \ldots 7$	107P/Wilson-Harrington	[C]
> 1	46P/Wirtanen	[C]
$> 7,700 \ldots 46,000$	95P/Chiron	[C]
$> 20 \ldots 400$	C/1996 B2 Huyakutake	[D]
Meteoroid Source		
$34,000 \pm 7000$	2P/Encke (Taurids)	[E]
$6,000 \pm 300$	7P/Pons-Winnecke	[E]
400 ± 100	21P/Giacobini-Zinner	[E]
$22,000 \pm 2,000$	45P/Honda-Mrkos-Pajdusakova (Alpha Capricornids)	[E]
$6,000 \pm 3,000$	55P/Tempel-Tuttle (Leonids)	[E]
$12,000 \pm 3,000$	109P/Swift-Tuttle (Perseids)	[E]

- **Porosity, bulk density and strength are key properties to decipher how pristine is a body!**

ACTIVE AND DORMANT COMETS







Surface activity is evolving with time (Jewitt, 2006)

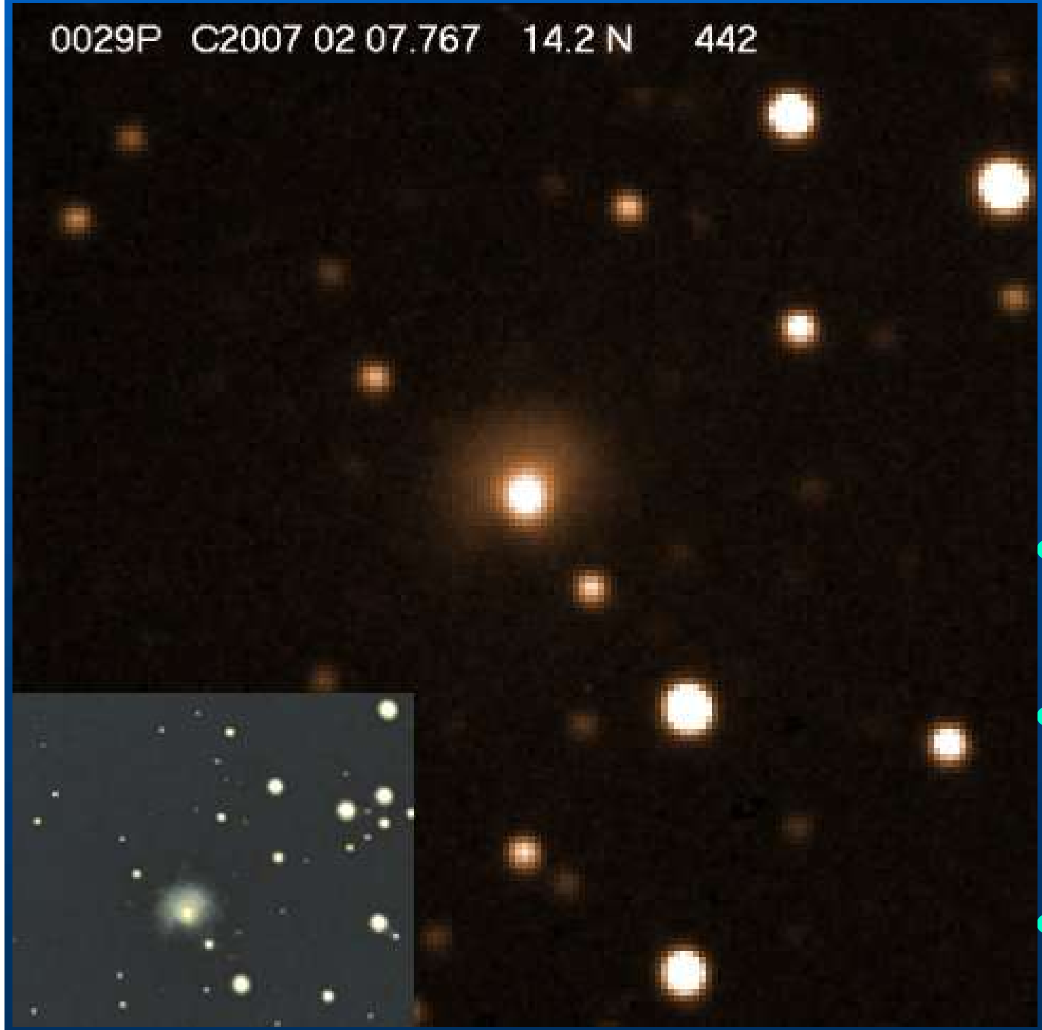
- In any case, don’t forget that we call comets to bodies of different nature, and in different stage of evolution
- Water was widely present all behind the “snow-line”, so it was incorporated into primordial objects
- Asteroids in cometary orbits (Tj>3) are evidence that some comets can have high-strength interiors
- Different cometary families:
  - Main Belt Comets like e.g. 133P/Elst-Pizarro (Hsieh & Jewitt, 2006)
  - Jupiter Family Comets
  - Halley Family Comets
  - Long Period comets
- We should be cautious when generalizing or extrapolating results among comets (!)

NASA

THE PHYSICS BEHIND DUST RELEASE

$$\frac{S_{\odot}(1-A)\cos\zeta(t)}{r_{\mathrm{h}}^{2}} = \varepsilon\sigma T^{4} + L\cdot p_{\mathrm{sat}}\sqrt{\frac{m_{\mathrm{H_2O}}}{2\pi kT}} - \kappa\frac{\mathrm{d}T}{\mathrm{d}x}$$

ENERGY BALANCE EQUATION



- Cometary dust is ejected by the pressure of the gas generated by sublimation

  The solar radiation absorbed at a comet nucleus surface is dissipated by thermal reradiation into space, sublimation of surface ice, and conduction into the interior
  - S_O=1367 J m^{-2} s^{-1} is the solar constant,
  - A=0.04 is a representative Bond albedo,
  - ζ(t) is the time--dependent solar zenith angle,
  - ε=1 is a representative emissivity,
  - σ is the Stefan-Boltzmann constant,
  - P_{sat}(T)=3.56·10^{12} exp(-6141.667/T) [Pa] (Fanale and Salvail, 1984) is the saturation pressure of water vapor,
  - m_{H2O} is the water molecule mass,
  - k is the Boltzmann constant,
  - L=2.6·106 J/kg is the latent heat,
  - κ is the conductivity.
- For r= 6 AU considering negligible heat conduction:
  - Noon T≈160 K is obtained.
- At that T, 99.5% of the absorbed energy is reradiated thermally and the water sublimation rate is 8.7·10^{-8} kg m^{-2} s^{-1}. Almost negligible compared to the sublimation rate of 4.6·10^{-4} kg m^{-2} s^{-1}, at r=1 AU
- For CO and CO_2 the same high sublimation rate would take place at temperatures as low as T=38 K and T=113 K, respectively.

ASTEROIDS AS SOURCE OF DUST:
Ice and Organics on 24 Themis & 65 Cybele

- A significant fraction of Main Belt Asteroids are also dust producers
- Ice sublimation and impacts release significant amounts of dust

nature Vol 464|29 April 2010|doi:10.1038/nature09029

LETTERS

Water ice and organics on the surface of the asteroid 24 Themis

Humberto Campins[1], Kelsey Hargrove[1], Noemi Pinilla-Alonso[2], Ellen S. Howell[3], Michael S. Kelley[4], Javier Licandro[5,6], T. Mothé-Diniz[7], Y. Fernández[1] & Julie Ziffer[8]

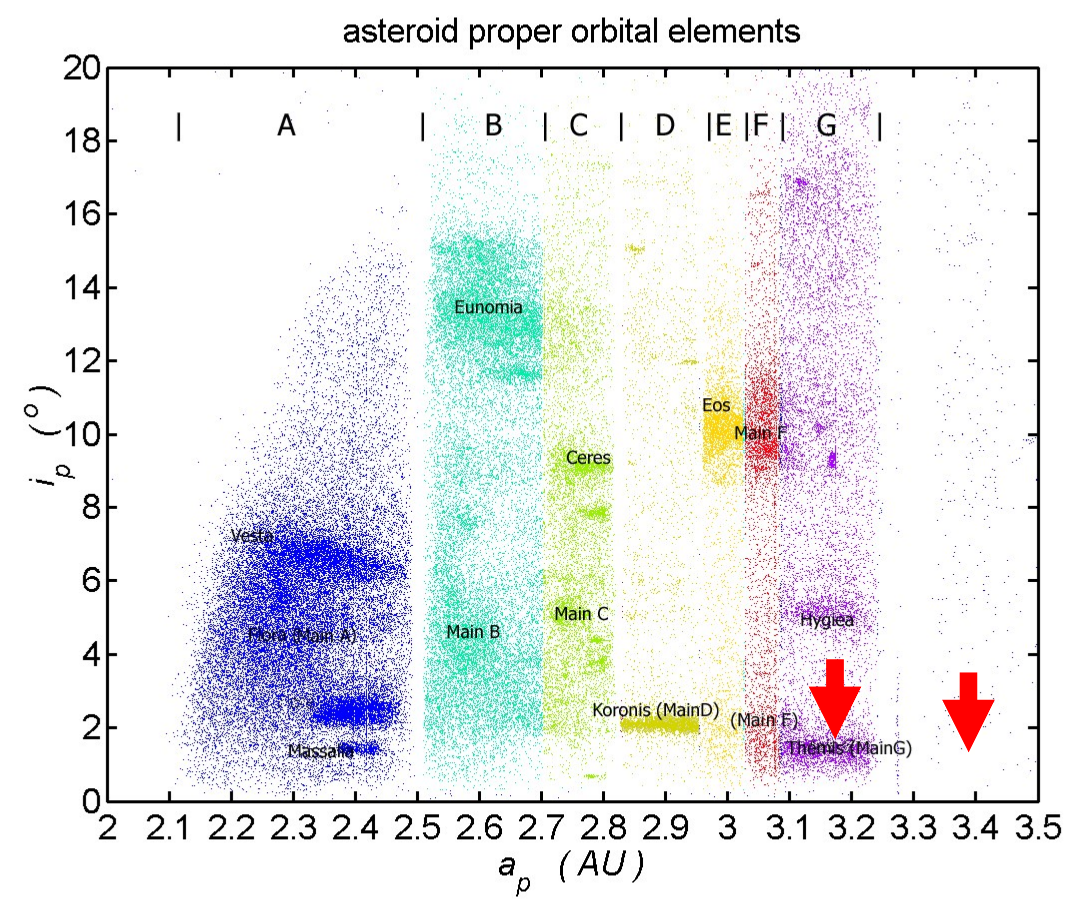
nature Vol 464|29 April 2010|doi:10.1038/nature09028

LETTERS

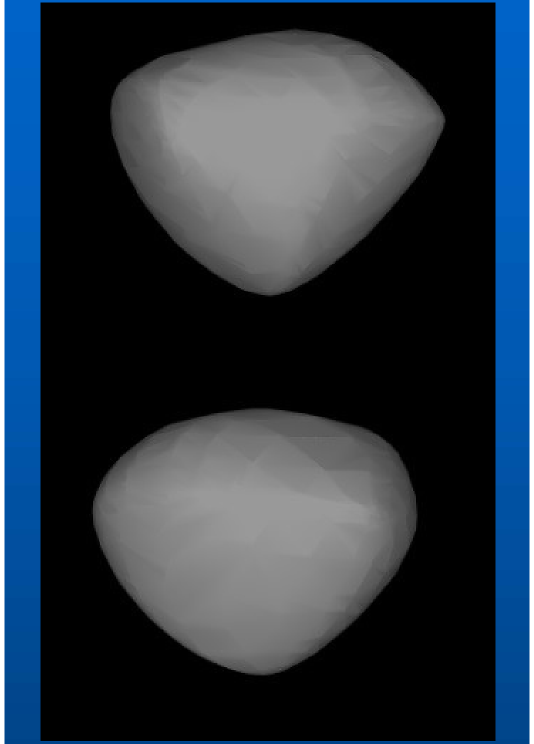
Detection of ice and organics on an asteroidal surface

Andrew S. Rivkin[1] & Joshua P. Emery[2]

EXAMPLE OF TRANSITIONAL ASTEROIDS



Ligthcurve model 65 Cybele (Franco & Pilcher, 2015)



24 Themis

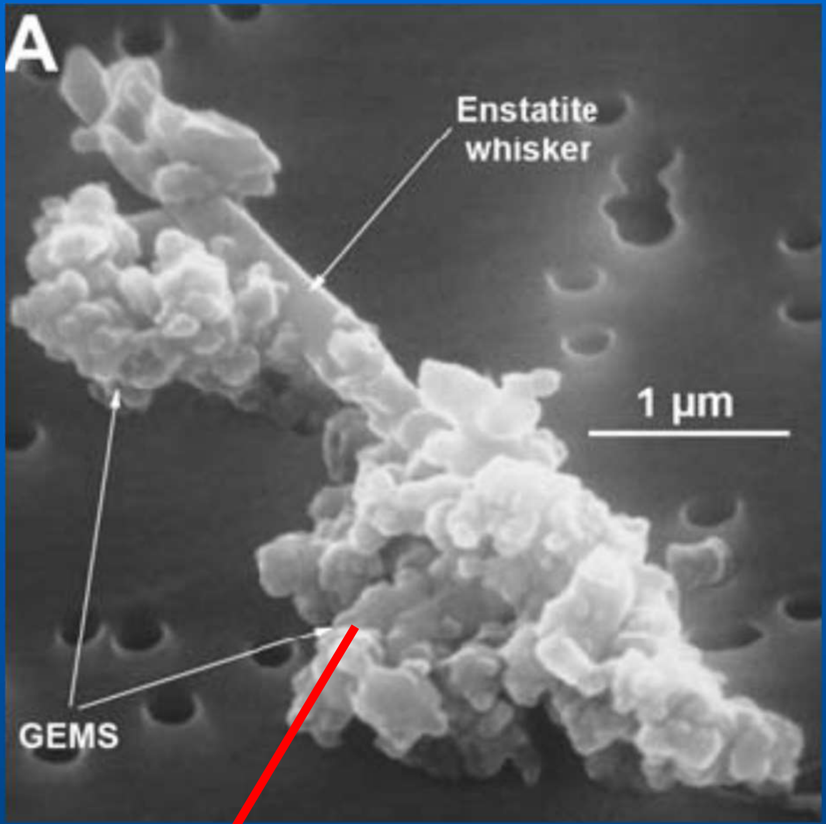
- Largest fragment of a family
- Orbiting near 3.2 AU
- Diameter ~ 200 km
- Geometric Albedo of 0.07
- Rotational period: 8.4 h

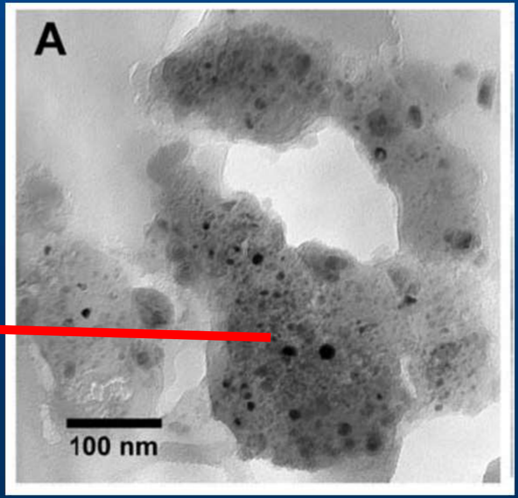
65 Cybele

- Largest of dynamical group between 3.3 - 3.7 AU
- Orbiting near 3.4 AU
- Diameter ~ 300 km
- Geometric Albedo of 0.07
- Rotational period: 4.0 h

IDPs COLLECTED FROM THEM

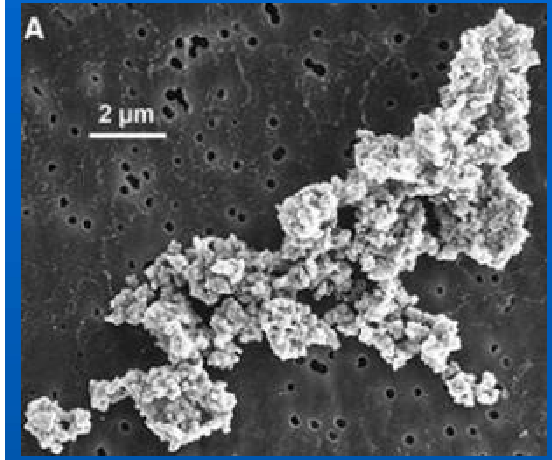
- Examples of pristine materials collected in the stratosphere
- Usually are 1-60 μm in size
- Asteroidal and cometary sources (based on inferred entry velocities)
- “Chondritic-porous” IDPs likely cometary:
  - Fine-grained (nm to μm grains)
  - Unequilibrated, anhydrous mineralogies
  - C,N- rich
  - Isotopically anomalous
  - Rich in presolar grains
  - Primordial materials



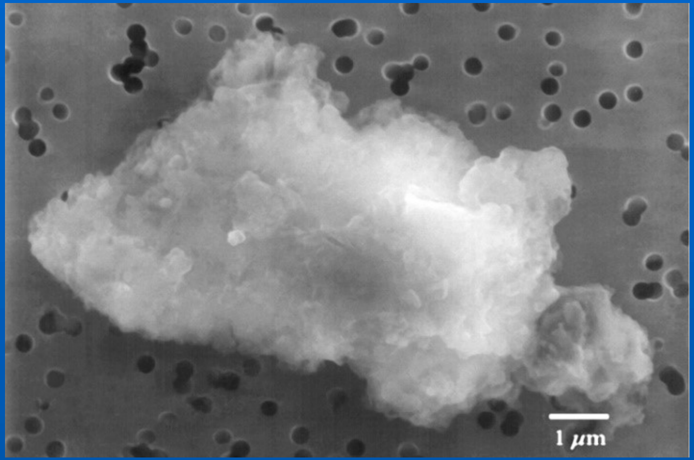


“GEMS” (Glass with Embedded Metals & Sulfides; J. Bradley)

ANHYDROUS AND HYDRATED IDPs

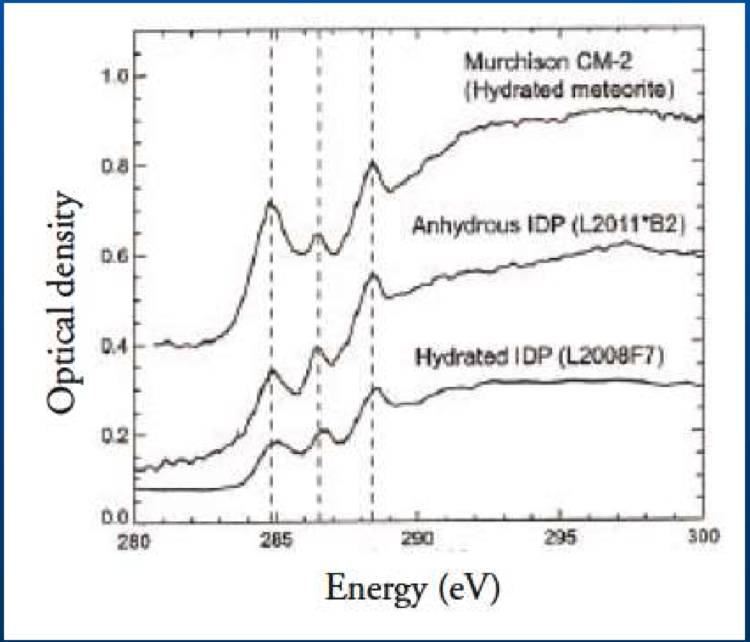


Unhydrated IDP

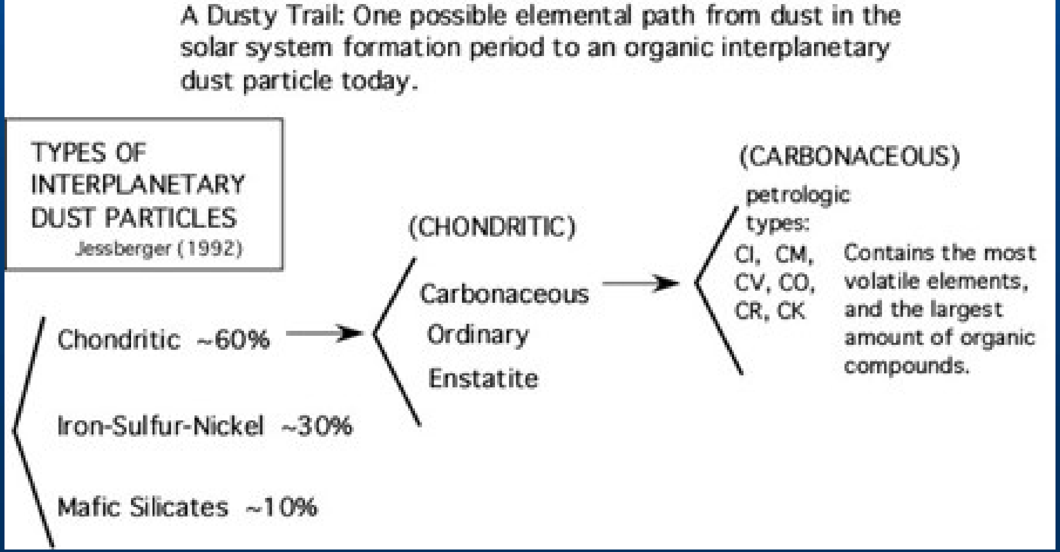


Hydrated IDP (NASA)

- **There are 2 major IDP types.**
  - **Hydrated that are linked to carbonaceous chondrites parent bodies (Tomeoka & Buseck, 1985)**
  - **Unhydrated that are basically linked to most pristine objects like e.g. Non-evolved comets**



IDPs can be differentiated by using XANES spectra (Flynn et al., 2000)



A Dusty Trail: One possible elemental path from dust in the solar system formation period to an organic interplanetary dust particle today.

TYPES OF INTERPLANETARY DUST PARTICLES
Jessberger (1992)

Chondritic ~60% → (CHONDRITIC) Carbonaceous → (CARBONACEOUS) petrologic types: CI, CM, CV, CO, CR, CK — Contains the most volatile elements, and the largest amount of organic compounds.

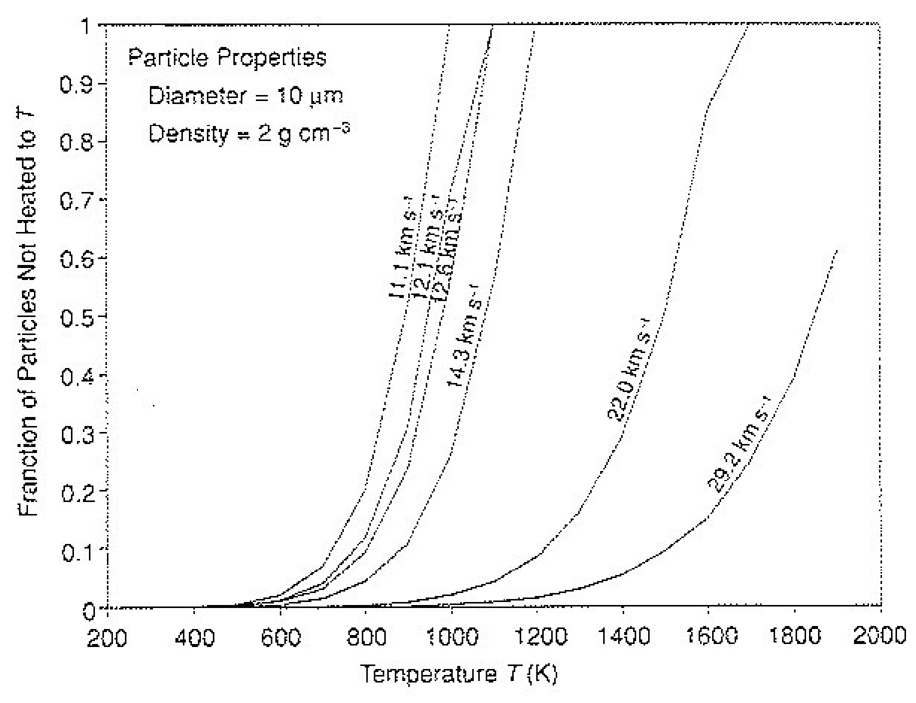
Ordinary

Enstatite

Iron-Sulfur-Nickel ~30%

Mafic Silicates ~10%

ATMOSPHERIC ENTRY HEATING

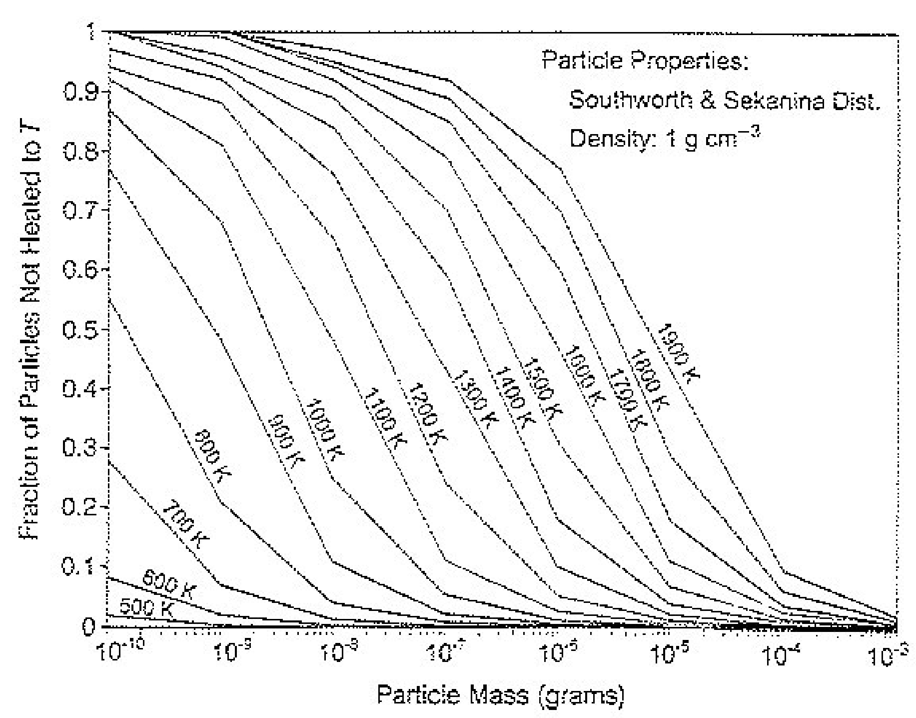


Flynn (2001)

- **Flynn (1989) first developed entry simulations to better understand atmospheric entry heating of interplanetary dust**
  - **He used the Zook (1975) analytical fit to the flux particle distribution (for v>11.1 km/s):**

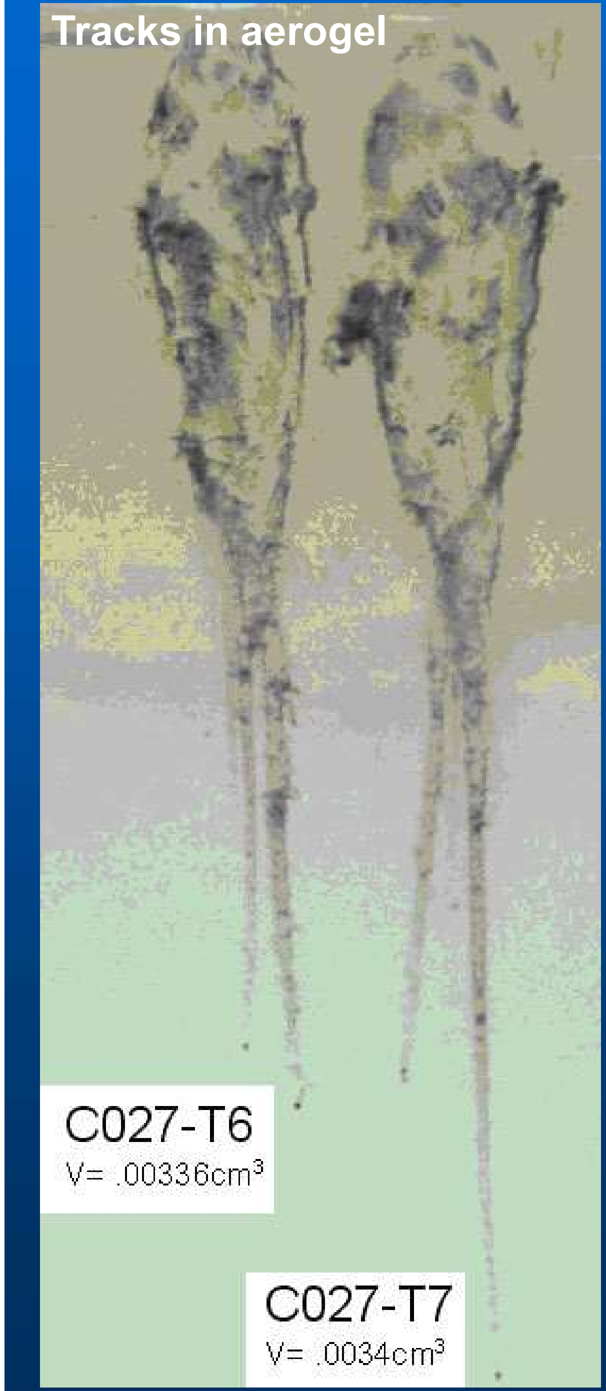
$$F(v) = 3.822\, e^{-0.2468\, v}$$

  - **He obtained different diagrams that allow to make some estimations of the rang of sizes and velocities that allow survival of IDPs**

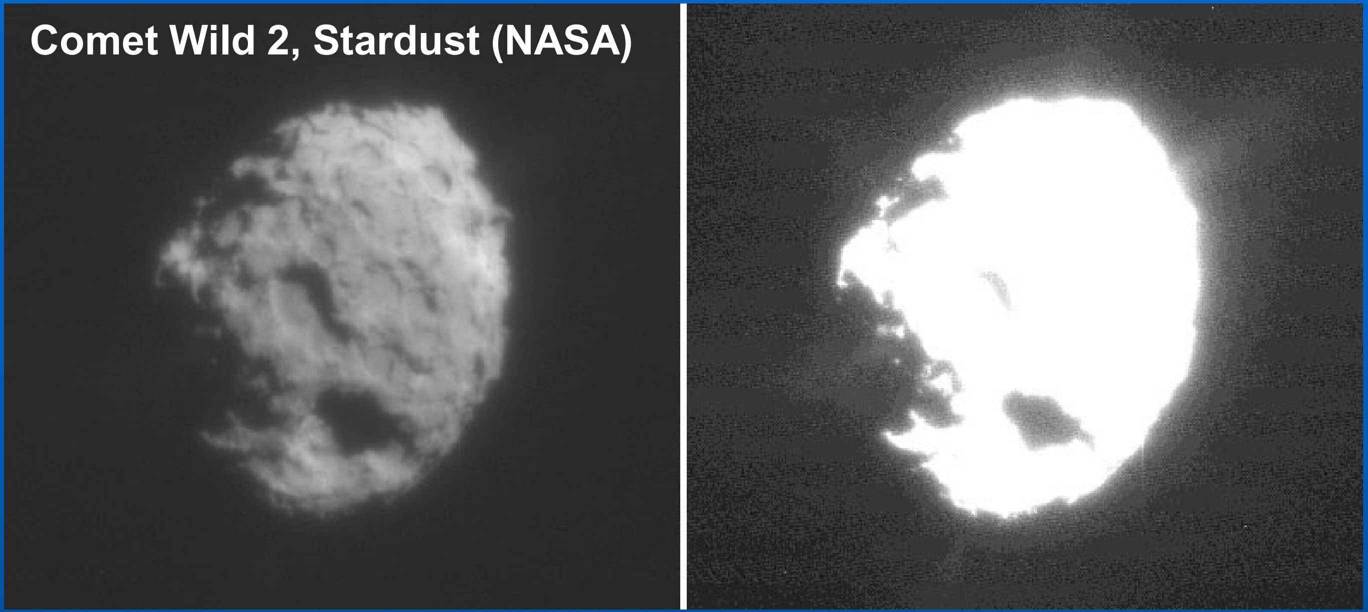


Flynn (2001)

STARDUST MISSION TO 81P/WILD 2



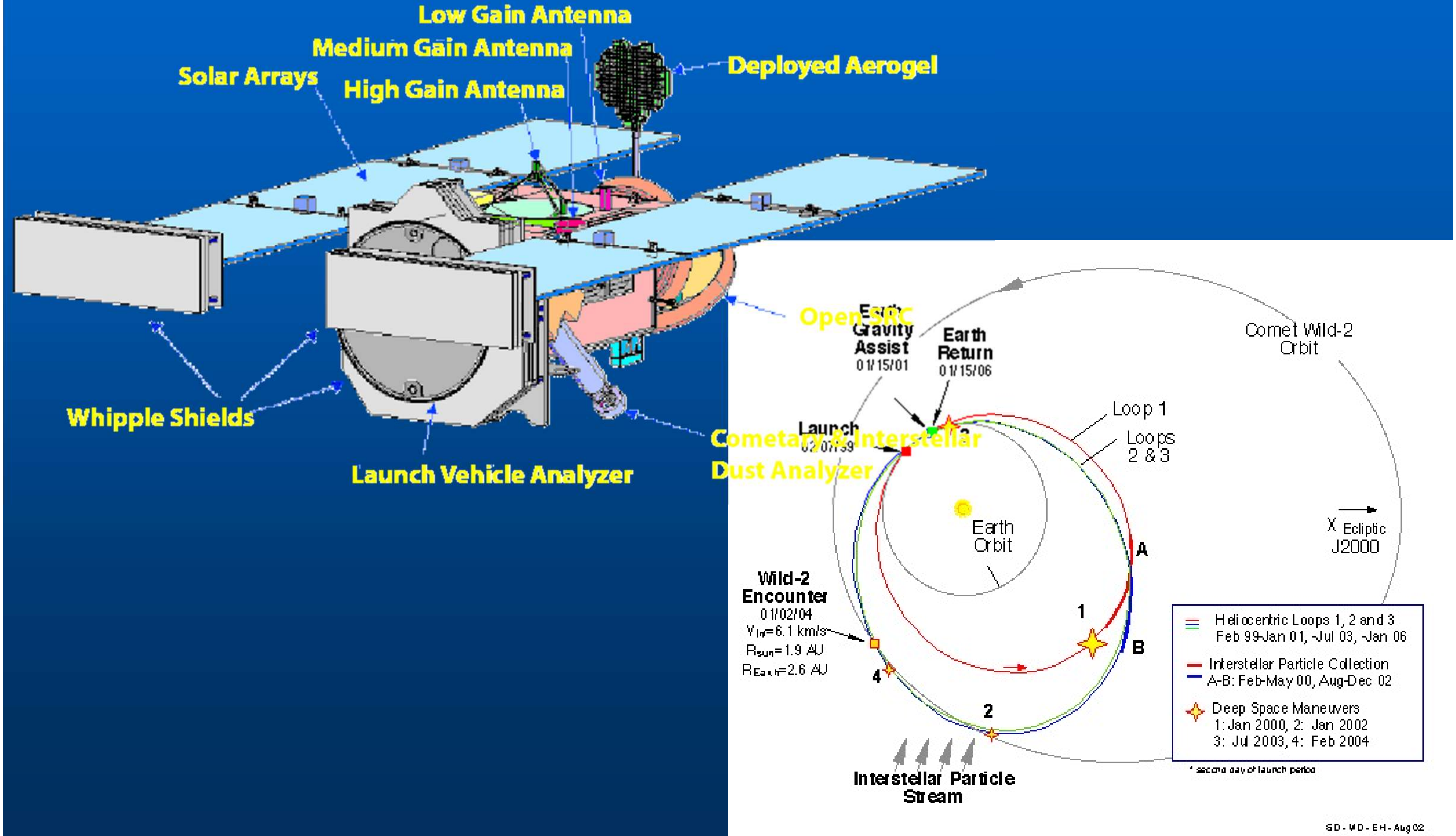
Tracks in aerogel



Comet Wild 2, Stardust (NASA)

- First sample return mission to a body different to the Moon
- Thousands of 81P/Wild 2 particles decelerated from 6 km/s
- In the *Preliminary Examination Team* we have studied the physics and mineralogy of the particles during deceleration
  - They were fragile aggregates
  - Fine grain materials did not survive, but large mineral grains almost intact
    - About a thousand recovered: $\varnothing \sim 5$ to 300μm

Stardust Mission



Facts on comet Wild-2

- **Pristine Jupiter-family comet**
  - **probably formed outside Neptune’s orbit, in Kuiper belt**
- **“Fresh” comet: only entered inner Solar System for the first time in 1974**
- **Stardust Goal:**
  - **Determine the mineralogical, chemical, elemental and isotopic properties of Wild-2 materials at sub-micrometer scales in order to learn about the early solar system and compare with other ET materials**
  - **Collecting particles at 230 km from nucleus (6.1 km/s)**

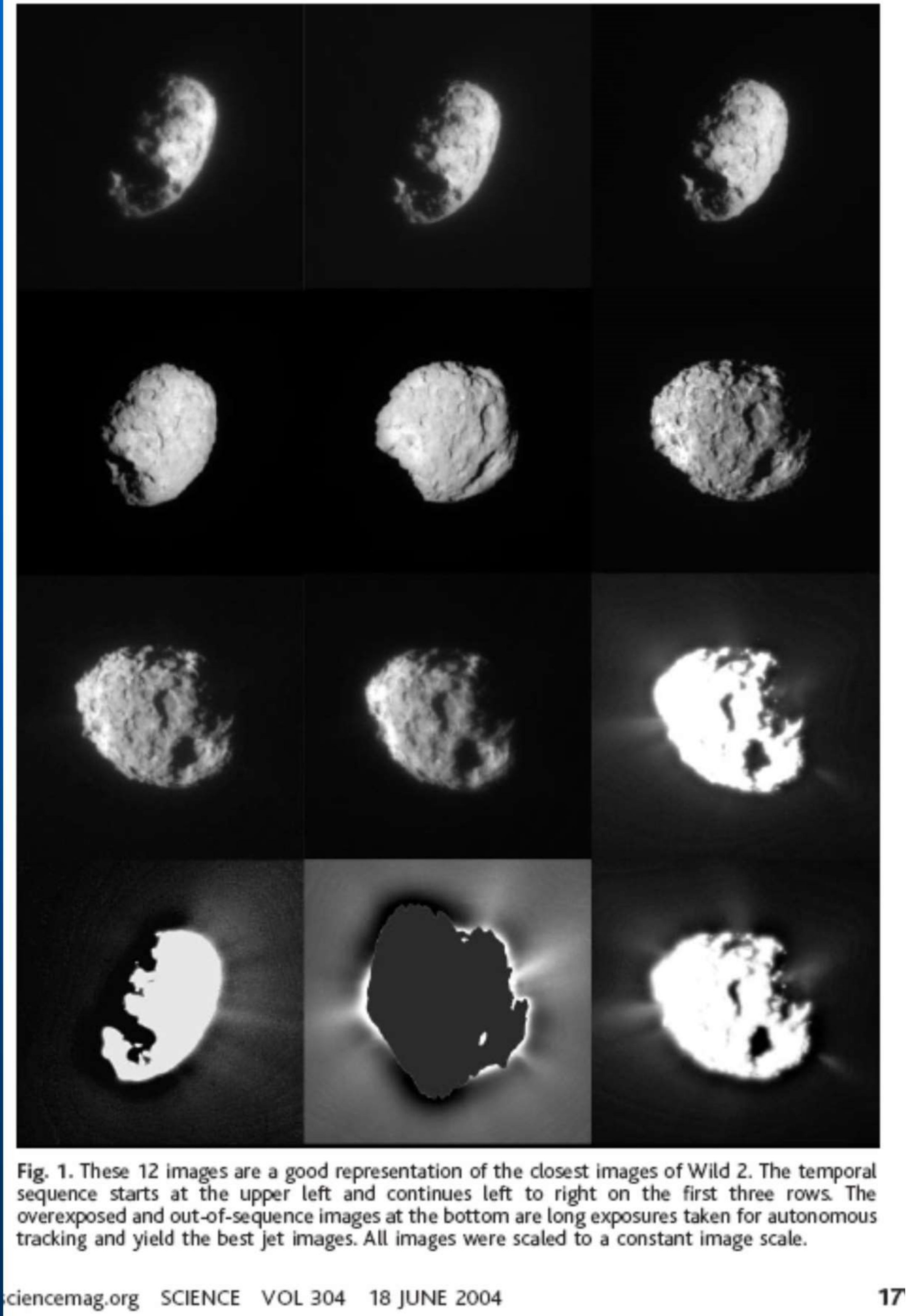


Fig. 1. These 12 images are a good representation of the closest images of Wild 2. The temporal sequence starts at the upper left and continues left to right on the first three rows. The overexposed and out-of-sequence images at the bottom are long exposures taken for autonomous tracking and yield the best jet images. All images were scaled to a constant image scale.

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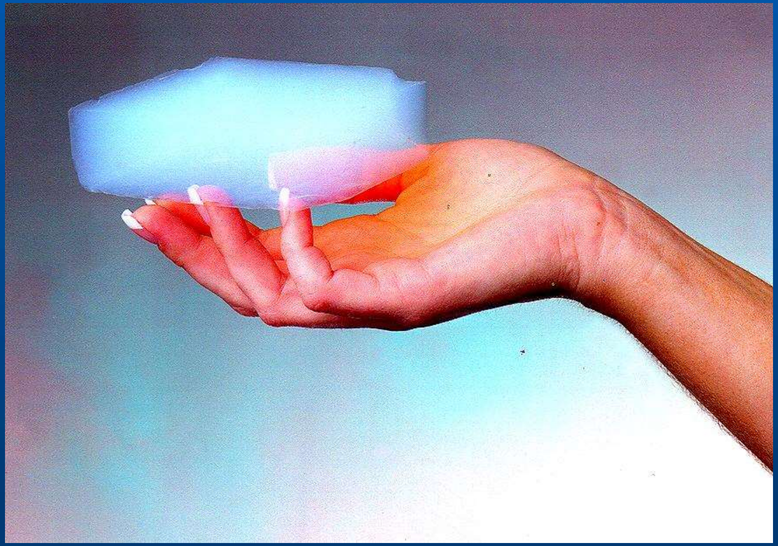
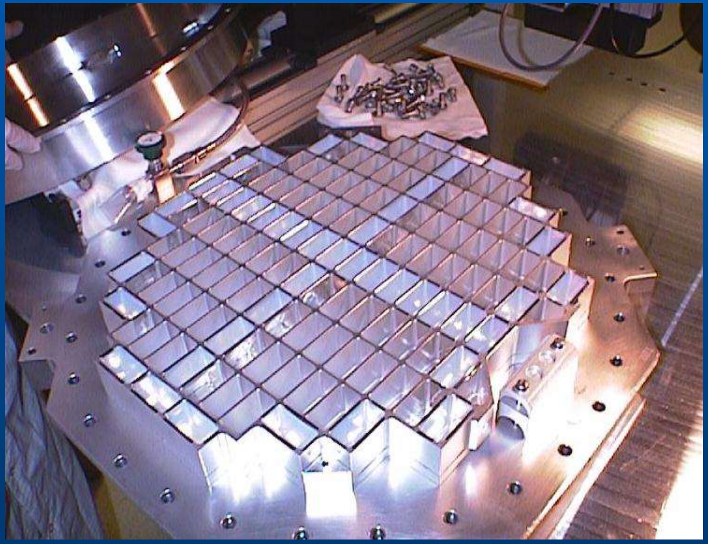
Stardust Dust Collection

- **Primary collector is "aerogel"**
  - Ultra-low density (~20 mg/cc) SiO_2 material
  - Particles stopped from 6.1 km/s to zero in few mm, with relatively little alteration





- Some samples "collected" as impact craters in Al foils between aerogel cells

Stardust Re-Entry
January 15, 2006
~3:00 am MST

Photo Courtesy @ Bruce Fischer
the Ogden Astronomical Society

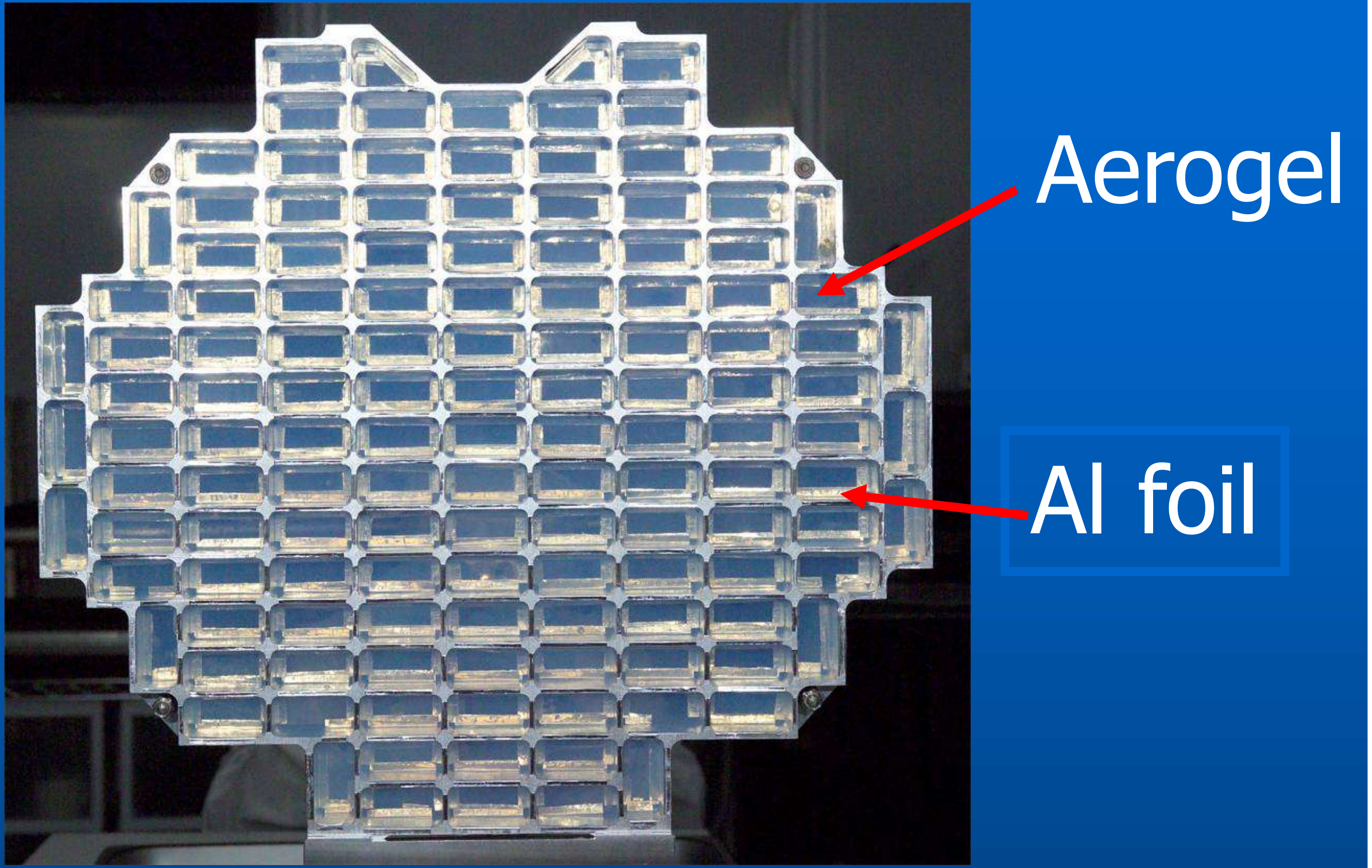
Stardust sample return capsule: safe and dry

✌ **Success!** ✌

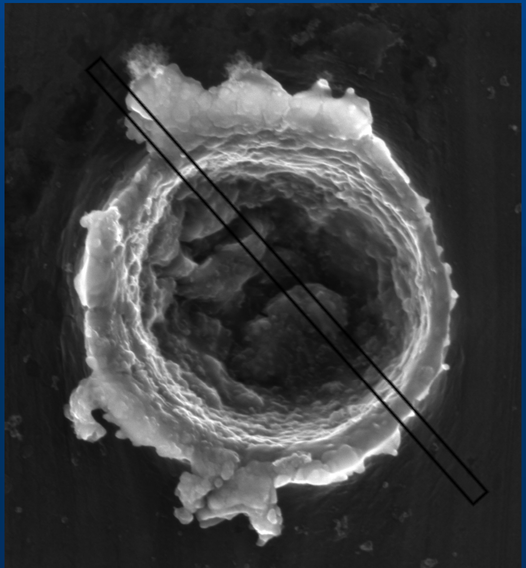
Intense effort by 100’s of members of the Stardust Team

Design - launch - operation - return - recovery - analysis

Collector Tray

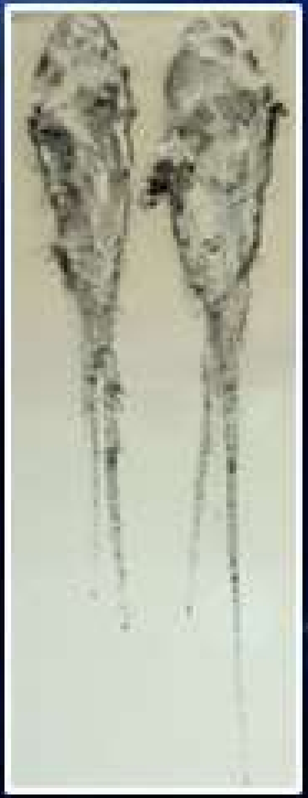


Crater in Al Foil



Tracks in Aerogel

Particle Track Profiles



8.5 & 11mm

11.7mm

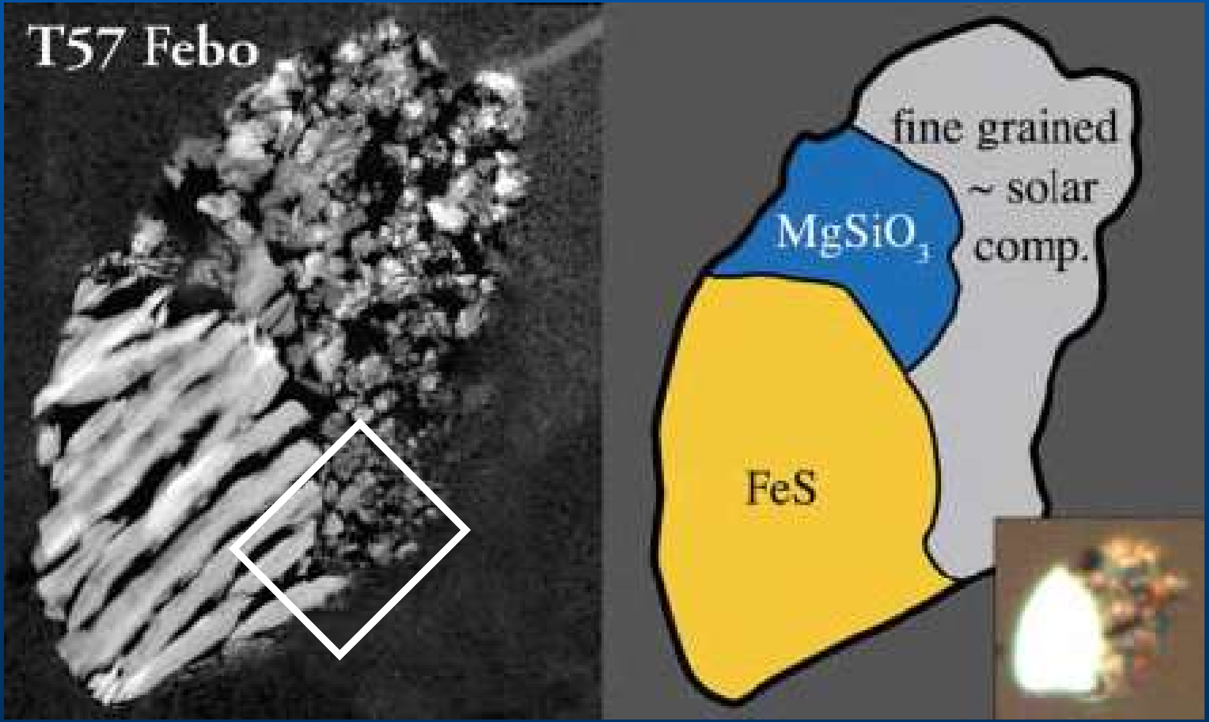
8mm

6mm

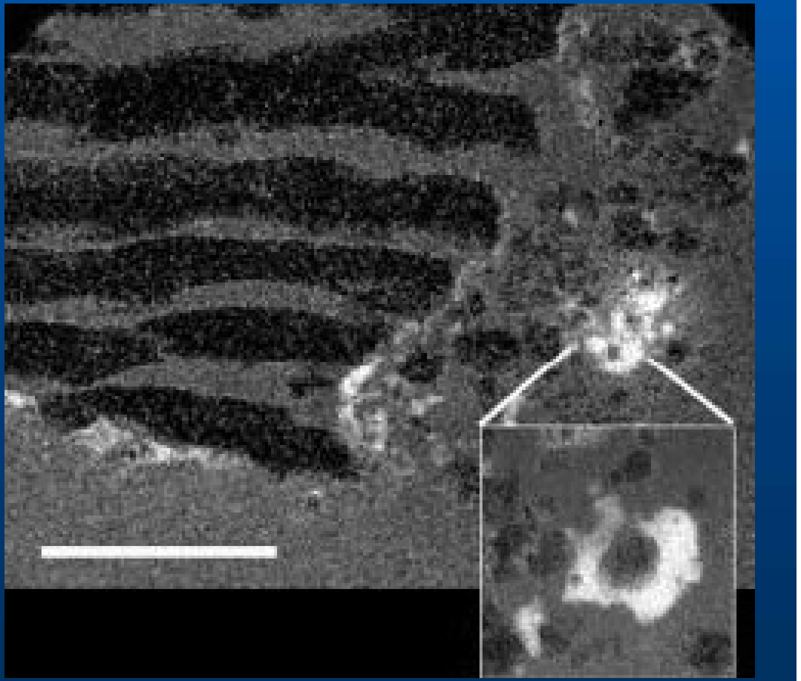
3.6mm

THE NATURE OF 81P/WILD 2

- At microscopic scale seems to be very pristine
- The largest recovered grains are ~1-15μm in diameter.
  - The toughest fragments that survived the capture process (biasing)
  - But some particles (like e.g. Febo) reveal that large grains are embedded in fragile aggregates similar to the matrix of carbonaceous chondrites, except for being highly porous
- This fine-grained component rich in organics contains important isotopic anomalies:
  - Detected enrichments in $^{15}N/^{14}N$
  - Such anomalies would be diluted under compaction, and aqueous alteration processes

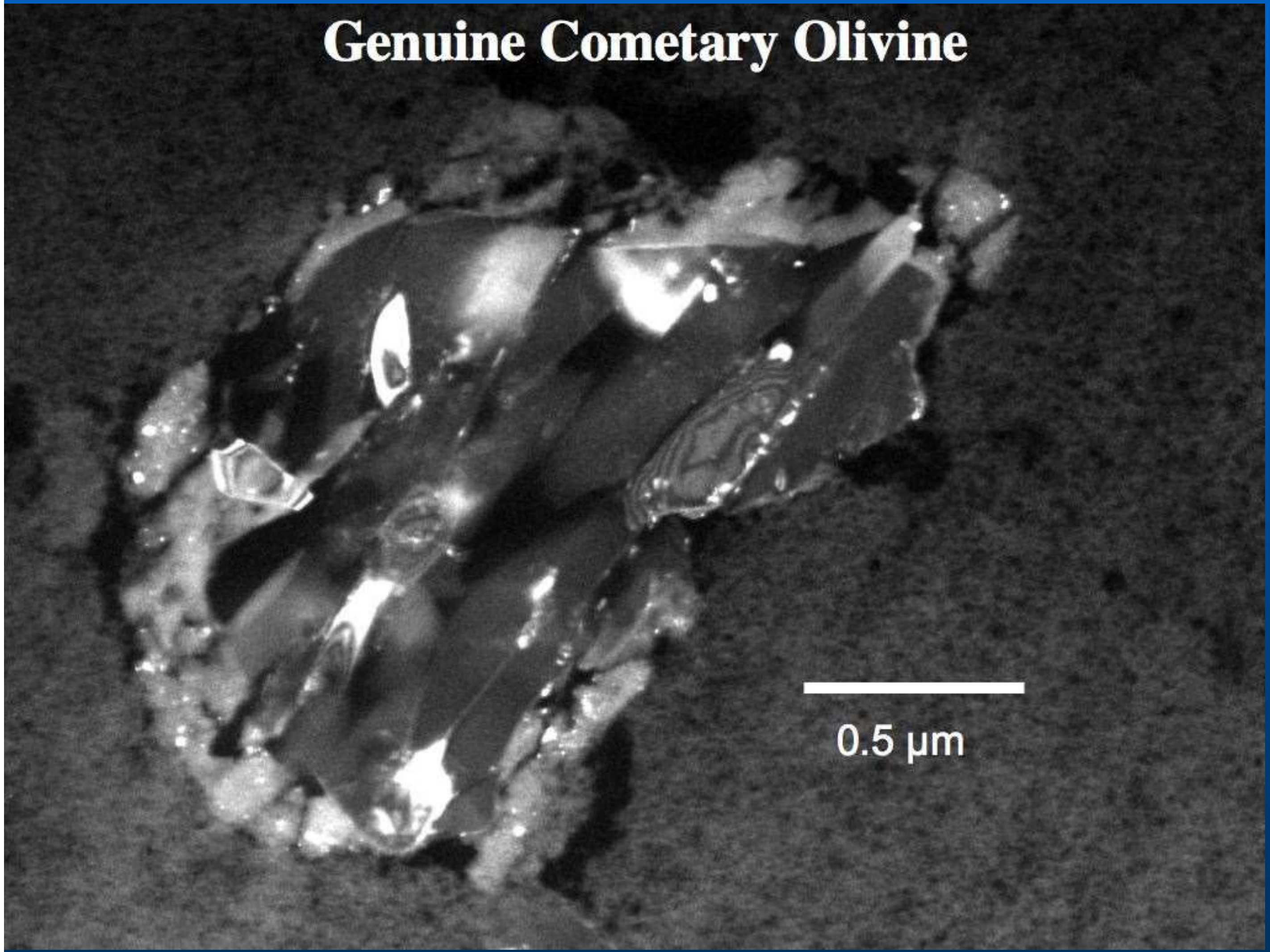


8 μm-size particle (FEBO) (Brownlee et al., 2006)



TEM image showing ^{15}N hotspot (PET/NASA)

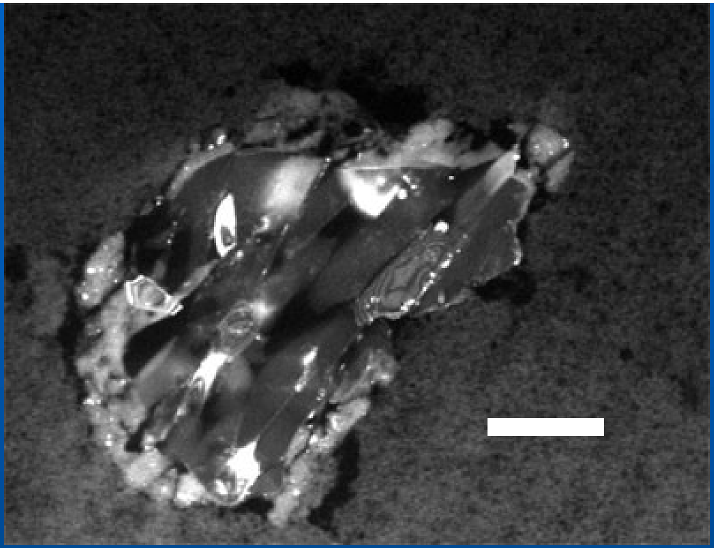
PROCESSED SILICATES INSIDE A KUIPER BELT COMET!



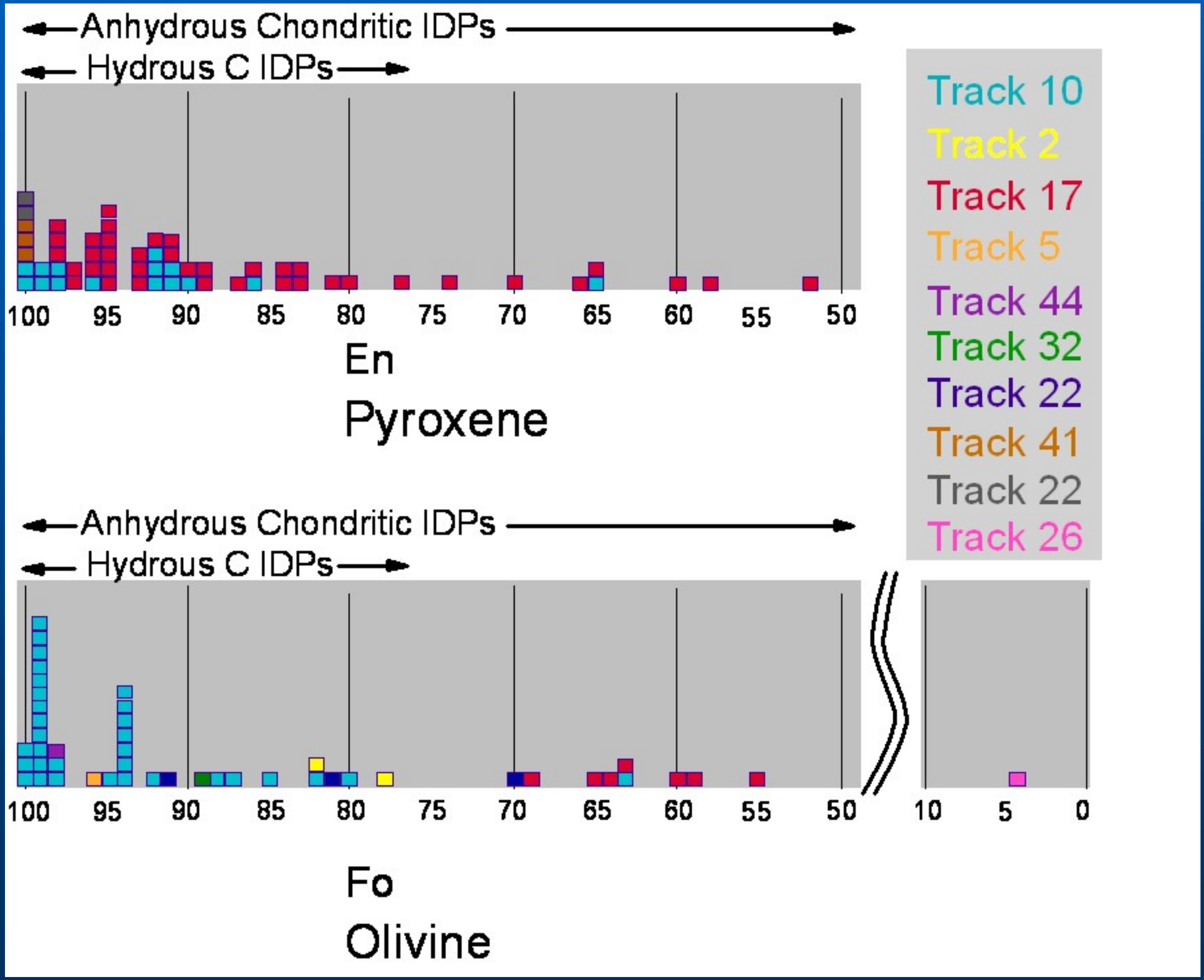
- Many mineral grains recovered larger that 1 μm are olivine and pyroxene
  - Synthesized nearby the Sun!
    - Confirmation of important radial turbulence in the protoplanetary disk (Bockelée-Morvan et al, 2002).
  - Wild 2 silicates were formed in the inner solar system:
    - New picture
- This results are consistent with the heterogeneity observed in meteoroids from a same comet

Comet Mineralogy: olivine and pyroxene

Crystalline olivine (Fo99)



0.5 µm



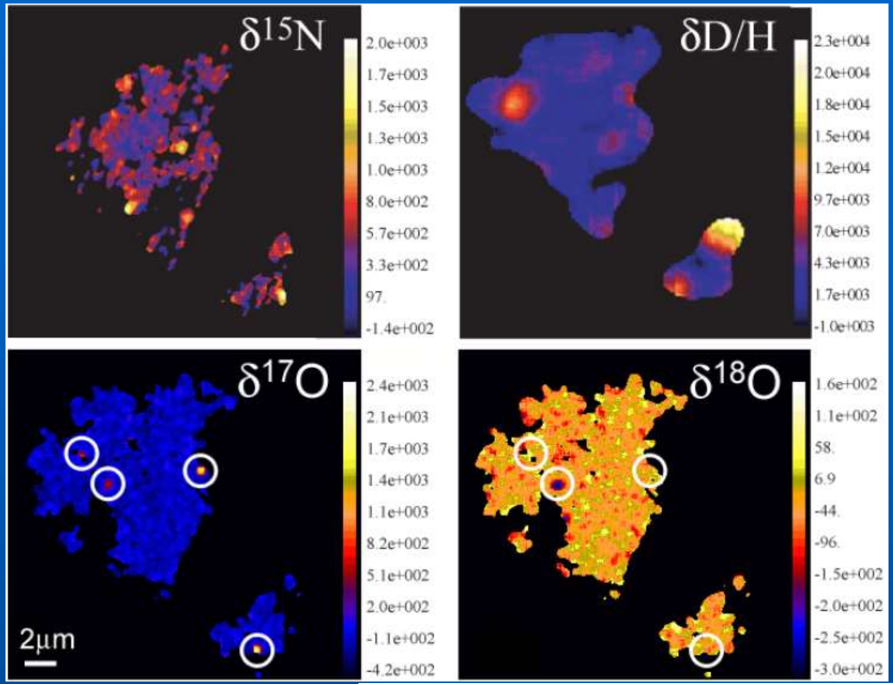
Very wide range of compositions,
highly unequilibrated materials

IDPs FROM 26P/GRIGG-SKJELLERUP

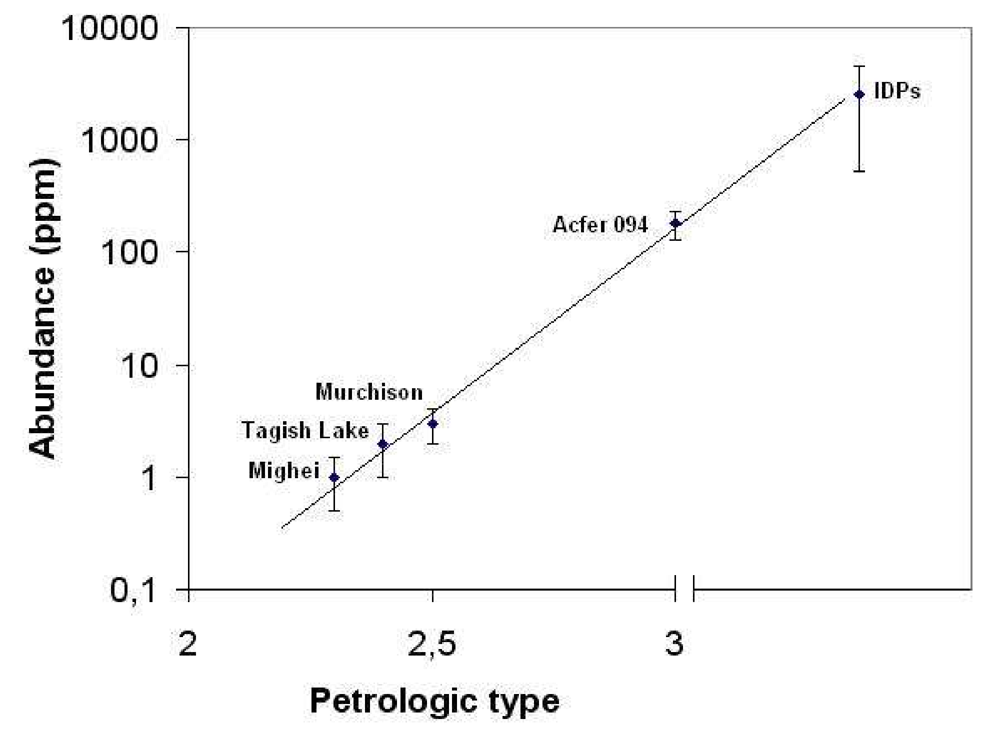
- IDPs also preserve isotopic anomalies, particularly in N, H and O presumably associated with molecular cloud chemistry

- Isotopic anomalies are heterogeneously distributed, mostly surrounding presolar grains

- Some comets have preserved the solar system "starting" materials
  - They not experienced significant collisional compaction and aqueous alteration



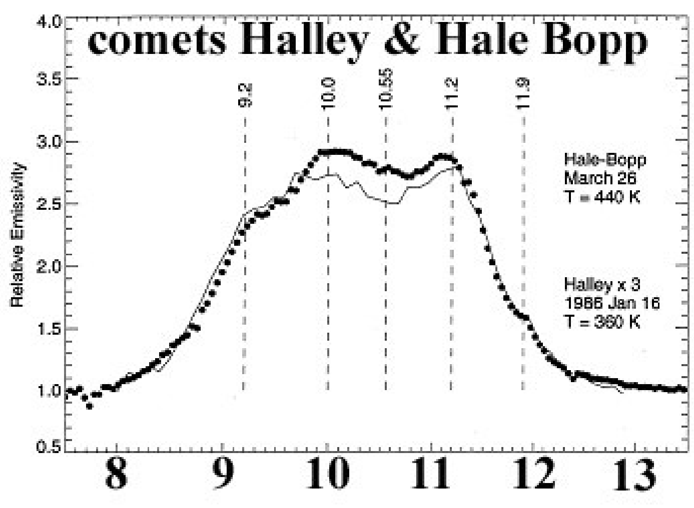
Isotopic ratio images of IDP L2054 E1
Likely from comet 26P
(Nguyen et al., 2007)



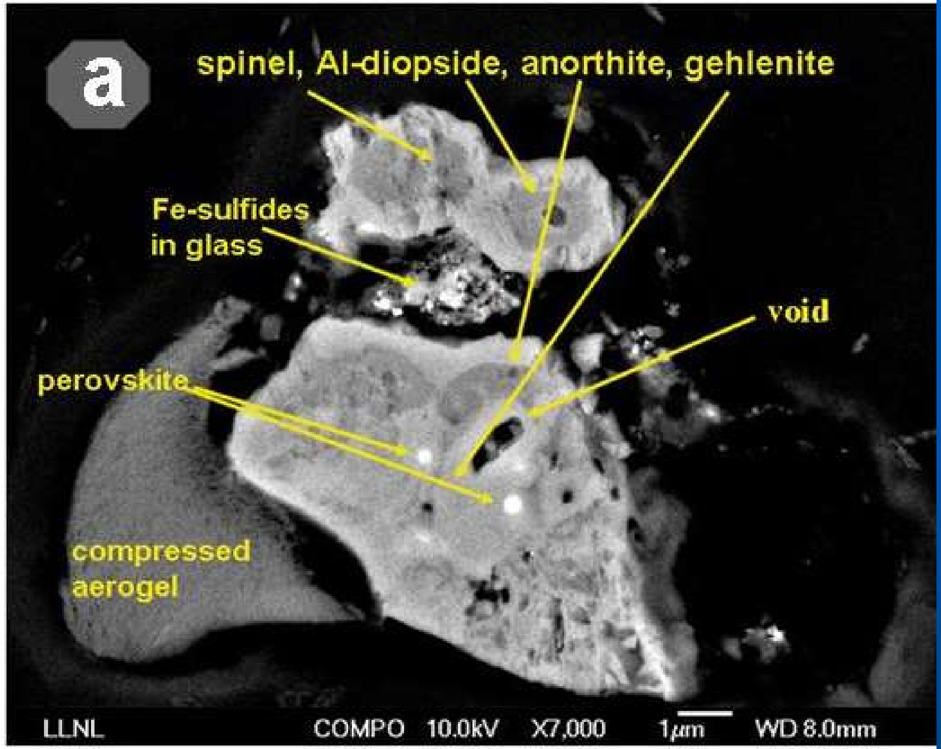
Presolar grains abundance
as a function of petrologic type
Trigo-Rodríguez & Blum (2009)

Forsterite: Mg_2SiO_4

- Common in Wild-2 samples, and IDPs, rarer in meteorites
  - Similar to meteoritic forsterite in isotopic and minor element composition
- Very refractory (T_{melt}=2200, T_{cond}=1400K)
- IR evidence in comets and disks
- Most likely formed in inner solar system
  - *Not* annealed interstellar silicate
  - Radial transport in disk



Refractory Minerals in Comets (CAIs)



Particle "Inti"

Diopside $CaMgSi_2O6$

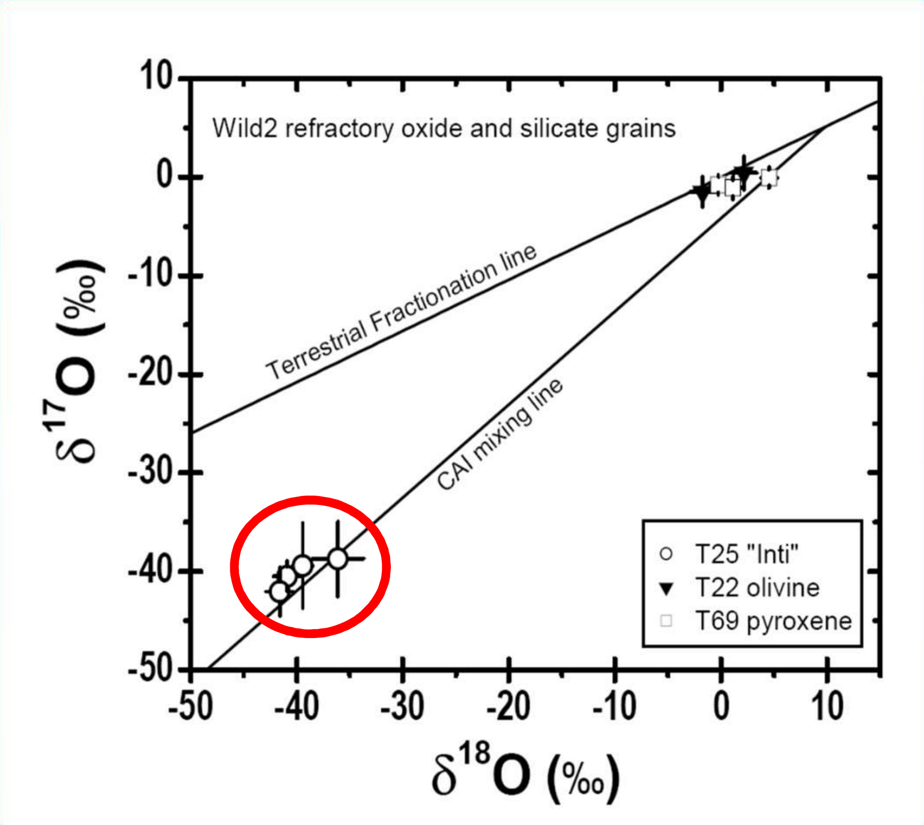
Anorthite $CaAl_2Si_2O8$

Spinel $MgAl_2O_4$

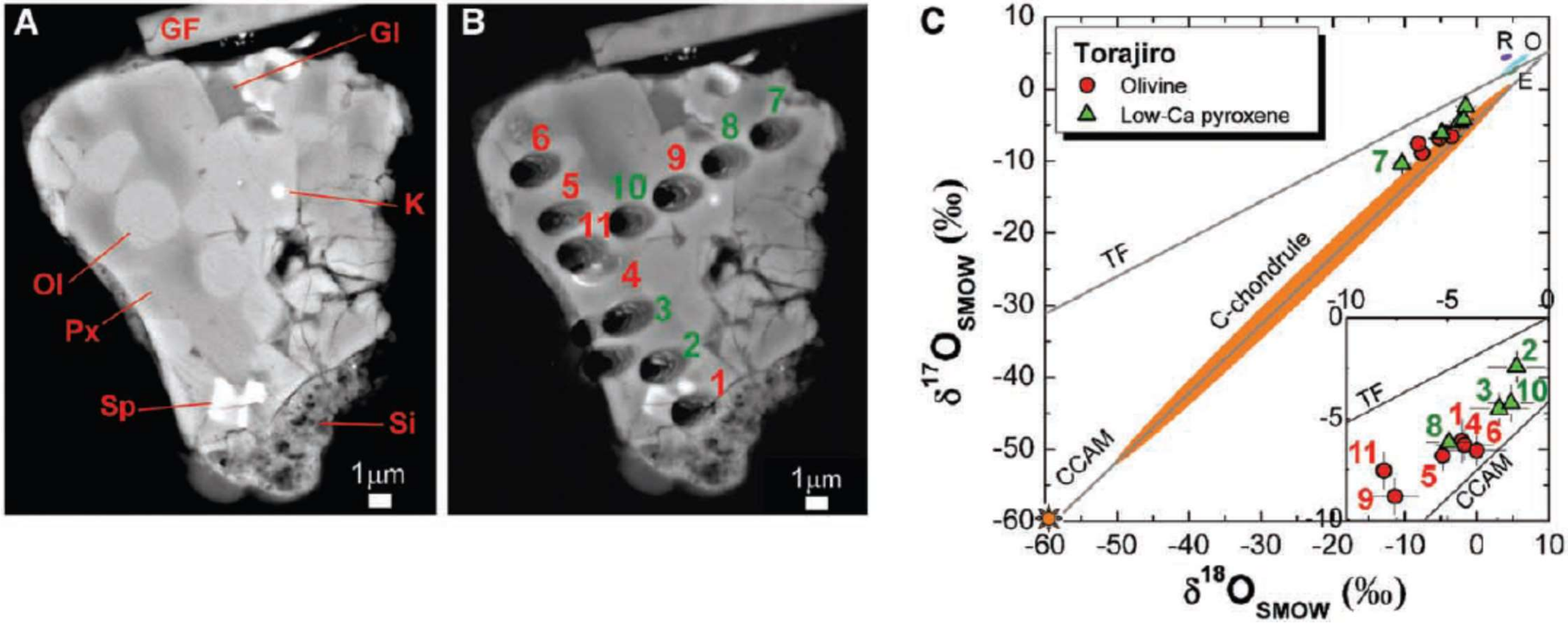
Gehlenite $Ca_2Al(AlSi)O_7$

V-Osbornite (Ti,V)N (forms at ~3300K)

- Similar to Ca-Al-rich Inclusions (CAIs) from chondrites:
  - Oldest objects in solar system
  - Formed at high T
  - ^{16}O-rich
- But comets accreted at T ~ 40 K!



Chondrules in Wild-2?



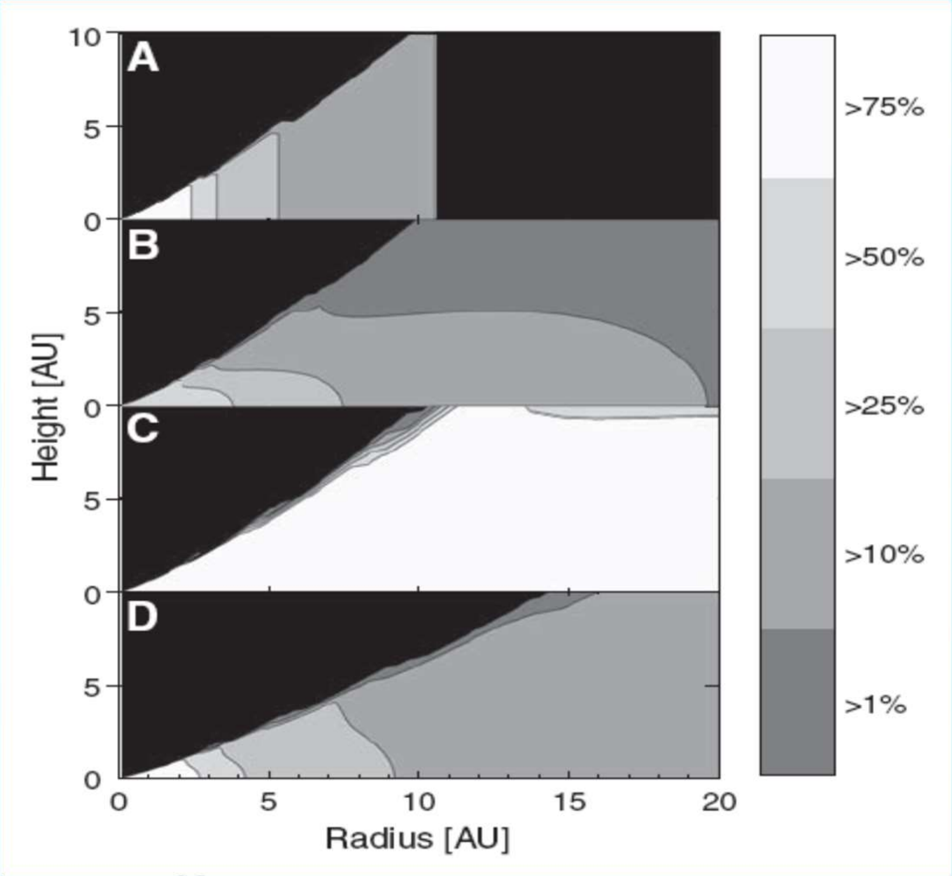
- **Nakamura et al (*Science* 2008) report 4 grains with similar mineralogy, chemistry and O-isotopes to chondrules found in meteorites**
  - **Evidence for significant radial transport in the disk**

Radial Transport in proplyds

- Wild-2 dust contains High-T materials, similar to asteroidal meteorites
  - e.g., CAIs, High T olivine, chondrules
- Not pristine aggregate of interstellar dust (bona fide presolar grains rare)
- Indicates large-scale transport of material in early Solar System
  - Turbulent Diffusion along midplane?
  - Ballistic Transport above disk?

Turbulent-driven diffusion of dust

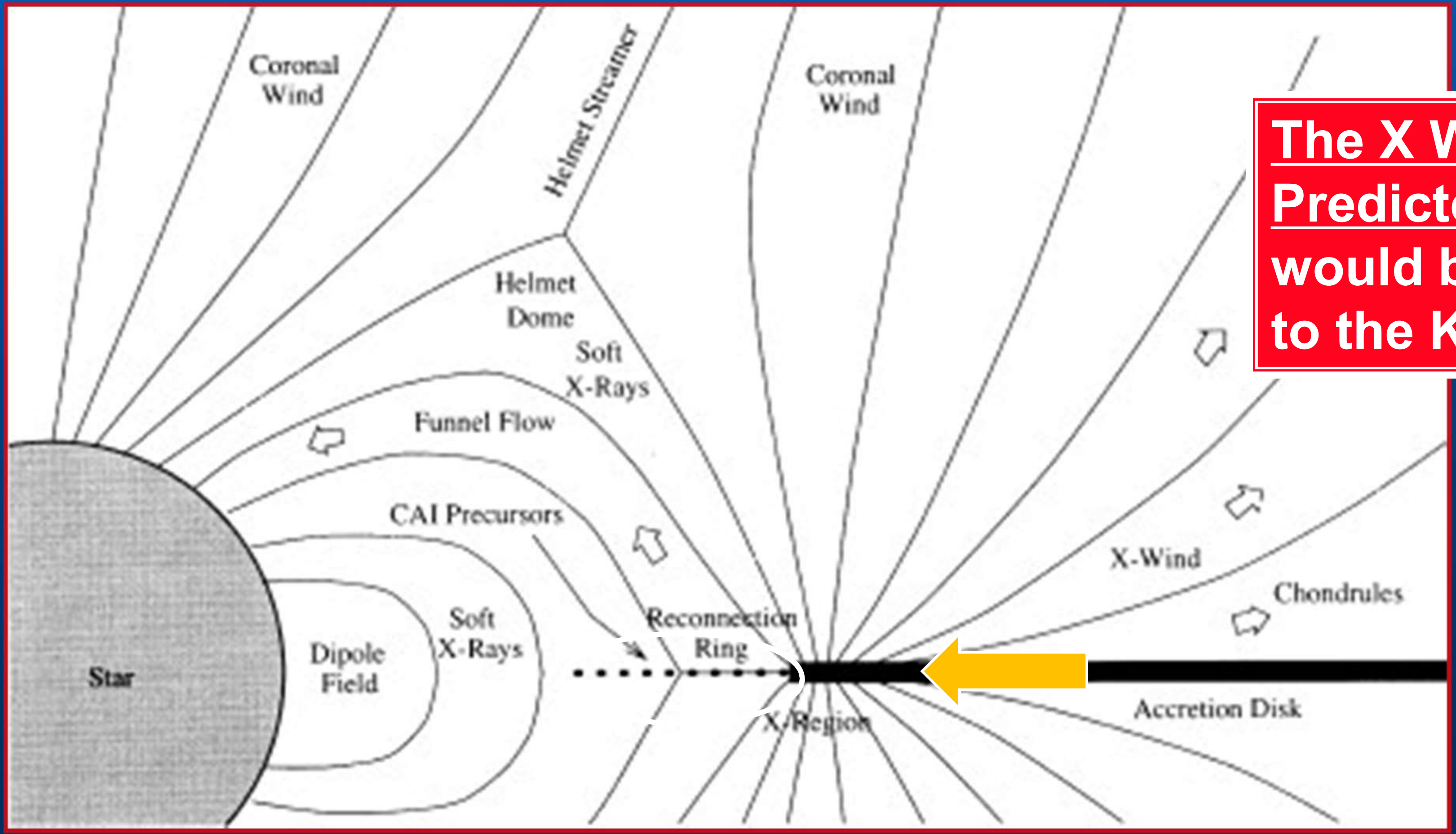
- **1-D models show transport inefficient (Bockelee-Morvan et al. 2002)**
- **2-D models show much higher efficiency (outward transport along midplane, inward transport above)**
  - **Ciesla, *Science* 2008**



Contour plots of silicate crystallinity fraction, Ciesla 2008

SCENARIO FOR CAI FORMATION

- **Shu et al. (1996, 2001) demonstrated with the X Wind model that CAIs can form as evaporative residues of "dustballs" in the context of his theory of magnetohydrodynamic X-winds stored in the reconnection ring**
- **Flares induced by the stressing of magnetic fields in the inner edge of the disk**
  - **Hard (2-10 keV) X-ray flares can lead to vaporization and melting of materials in t~30 yr**
  - **Materials in the reconnection ring can growth in such timescales**

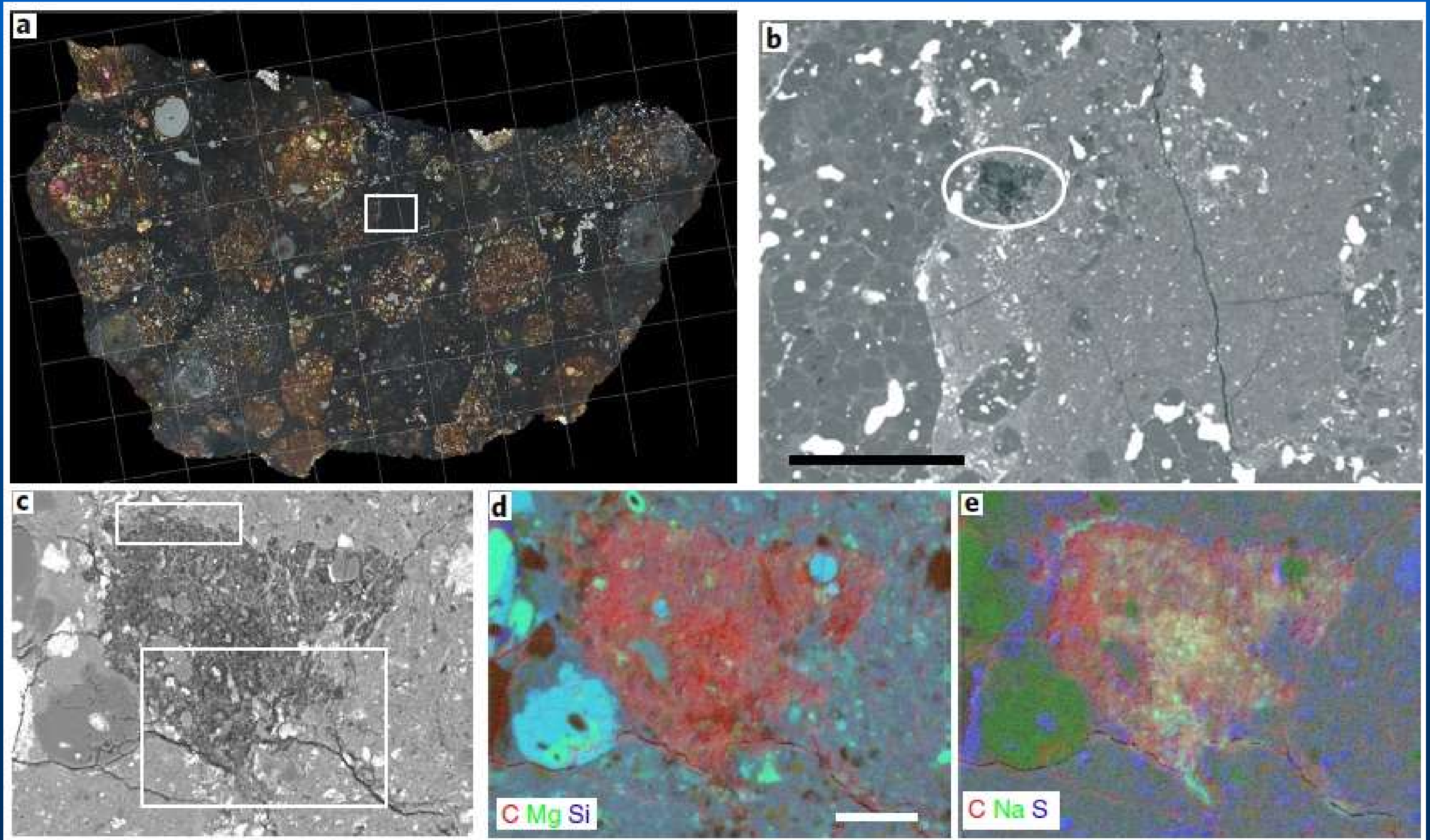


The X Wind model: Predicted that CAIs would be ejected to the Kuiper Belt!

Shu et al. (1996)

MATERIALS FROM KUIPER BELT OBJECTS: LA PAZ 02342 XENOLITH

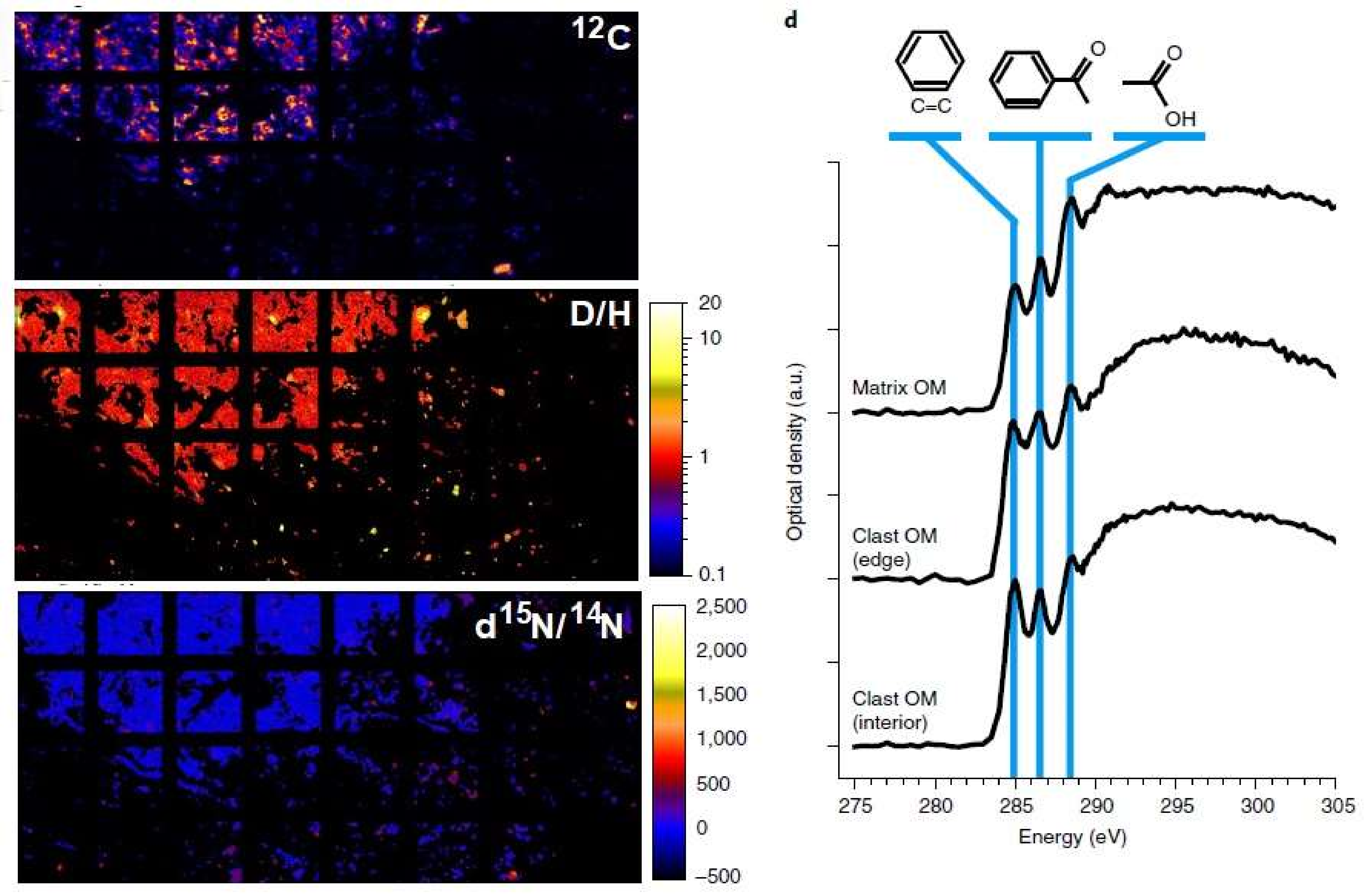
- **A clast contains evidence from an ancient comet with unknown chemistry**
- **a) LAP 02342 thin section in TL. b, SEM micrograph of the clast and nearby matrix. c) SEM of CRC. d,e) RGB/EDS maps**



ORGANICS IN THE XENOLITH

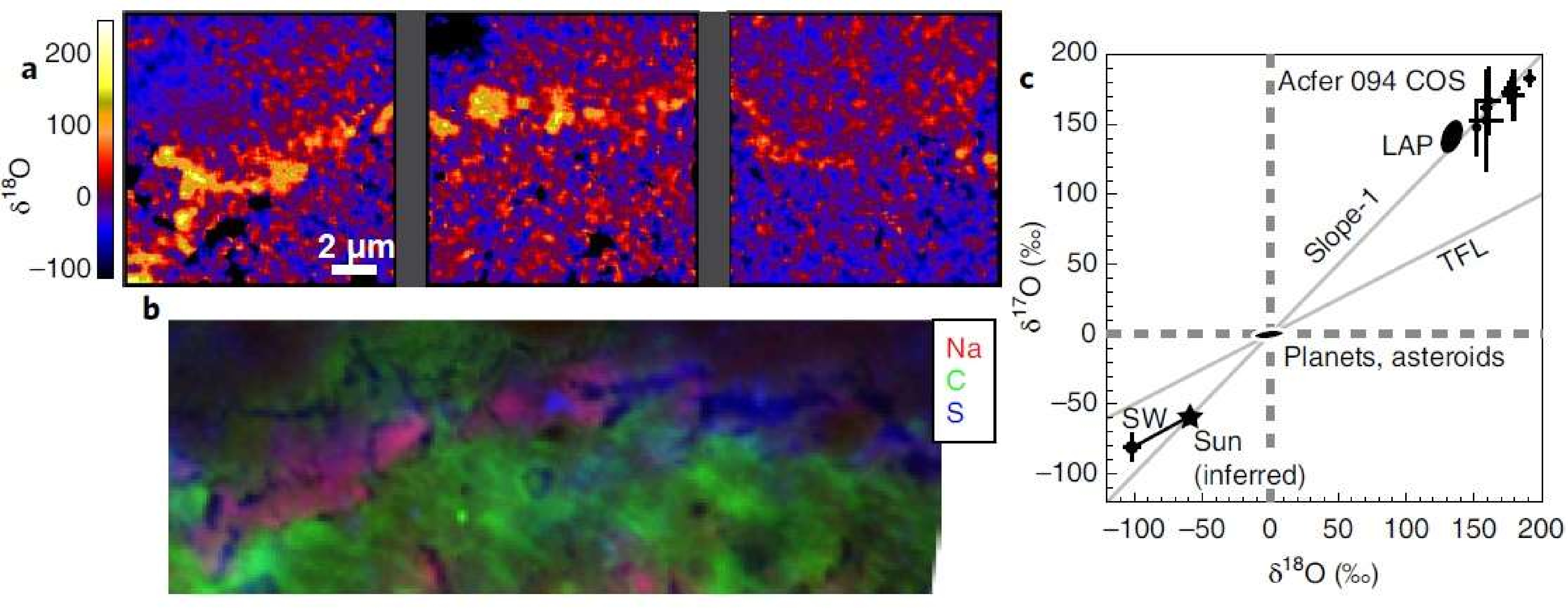
- **C-XANES reveals aromatic carbon, ketone functional groups & carboxyl**

X-ray absorption near-edge spectroscopy (XANES) (Nittler, Stroud, Trigo-Rodriguez et al.)



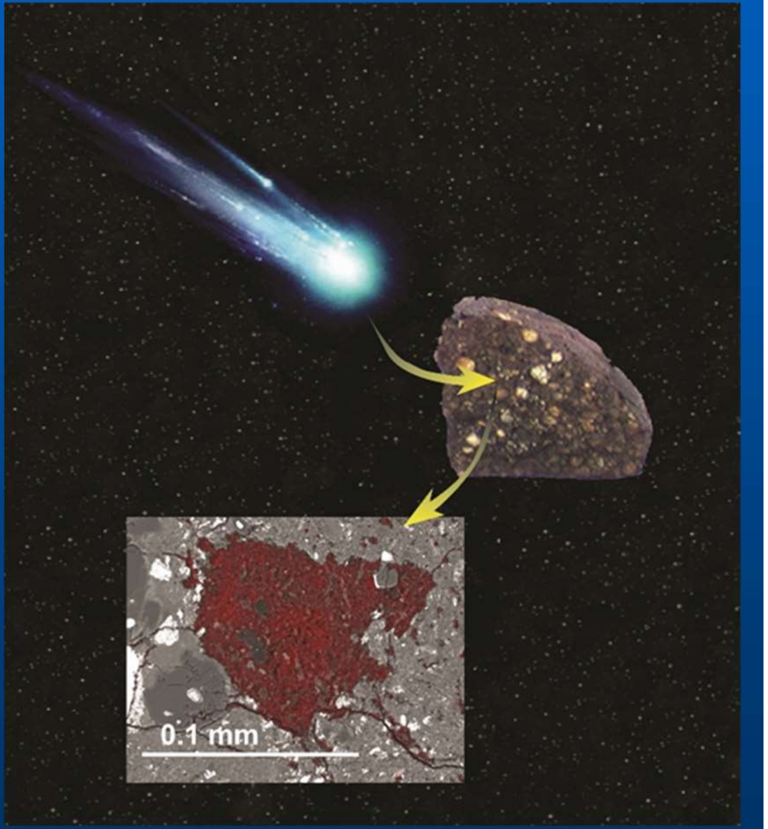
^{16}O POOR MATERIALS

- a) δ^{18}O images showing anomalous ^{16}O-poor grains near the upper border of the CRC
- b) SEM-EDS map. R=Na; G=C, and B=S. O anomalous materials are rich in Na and S, and STEM data revealed to be Na-rich sulfates.
- c) Oxygen three-isotope plot of the Solar System. ^{16}O-poor materials in LAP 02342 xenolith are represented by a 2σ mean error ellipse calculated from the 42 most anomalous grains identified in the NanoSIMS images.



ORIGIN OF THE XENOLITH

- **It came from the materials available in the outer disk where KBOs formed and represents a primordial building block of C-rich icy bodies.**
- **The lower D/H of the clast OM, compared with OM in CR chondrites and the most extreme UCAMMs and IDPs, may represent a temporal change in the composition of refractory OM in the outer Solar System: presolar or early-formed material was more D-rich, while material that formed more slowly, like e.g via UV processing of organic precursors, was less anomalous.**
- **If such a temporal evolution in cometary D/H exists, it would not be surprising for cometary materials sampled by CR chondrites to be less anomalous, since these meteorites have the youngest accretion ages.**
- **The presence of the CRC in LAP 02342 indicates that inward transport also affected the late stages of planetesimal accretion, and provides support for a connection between comets and C-asteroids.**



CONCLUSIONS

- Undifferentiated meteorites are a valuable source of information on the materials available at the time of solar system formation:
  - Less processed chondrites contain isotopic clues on the stellar sources of radionuclides
- Interplanetary Dust Particles (IDPs)
  - A small fraction of particles that survive atmospheric entry, from comets and asteroids
  - They sample primitive bodies not necessarily having similitude with chondrites
- If we wish to recover "pristine" materials to get direct information on the nature of early solar system:
  - Targets should be carefully selected: surface mineralogy vs. interior
  - Dynamical evolution: Backwards integration of the orbital elements can give clues on collisional, irradiative, and aqueous processing
- Cometary follow-ups can assess: thermal inertia, reflectance features, shape, and bulk density: useful to decipher how evolved is a comet
- Sample-return missions from primitive bodies are required to learn more:
  - Stardust NASA mission brought amazingly pristine material from 81P/Wild 2
  - C or D-class asteroids might be good targets: OSIRIS-Rex and Hayabusa 2

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