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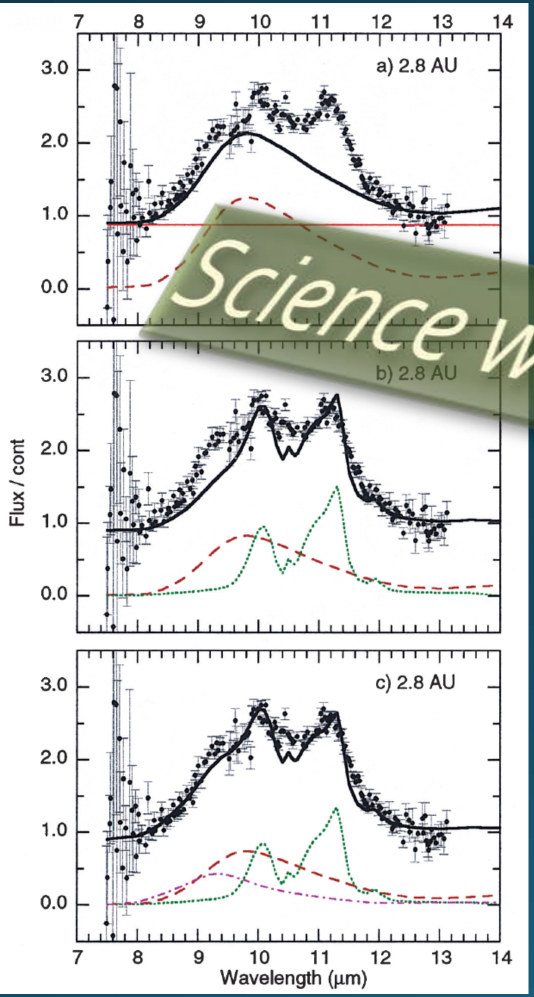
Comet Dust Composition and Astrophysical Connections

SOFIA Community Tele-talk, 2014 Sep 17

A variety of techniques are used to study comet dust: lab analysis, in situ analysis, telescopic (under a variety of geometric circumstances).



Science with a finely sharpened knife!

Comet Dust

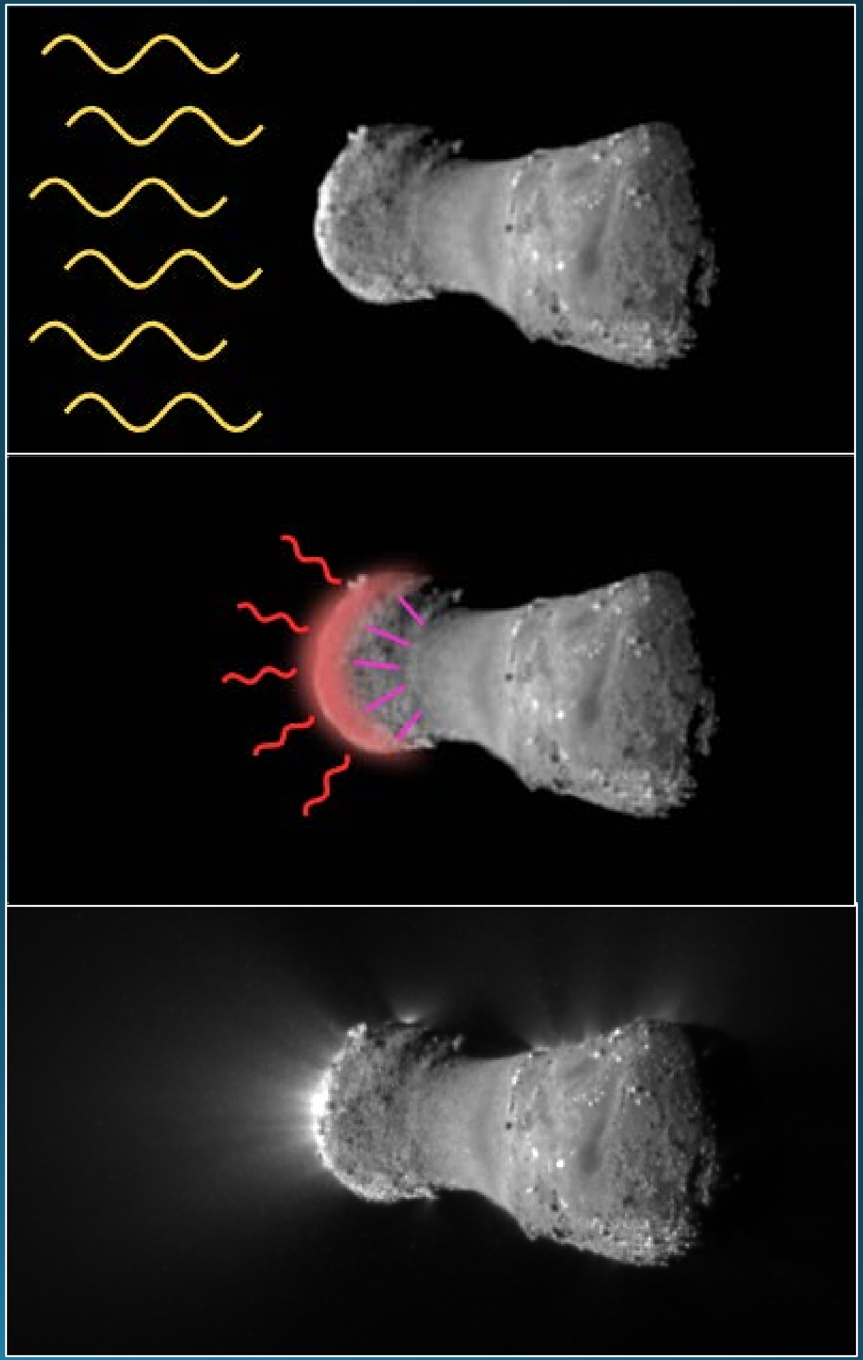
- Origin of dust
- Size, structure, and composition
  - Interplanetary dust particles and *Stardust* samples
  - Thermal emission from comet dust
- Evolution of dust and comets

Origin in the nucleus, and the Solar System

Comet dust origins

- Comets are aggregates of
  - ICE,
  - ROCK (dust), and
  - ORGANICS (refractory and volatile).

- As a comet approaches the Sun,
  - Surface temperature increases,
  - Energy propagates inward,
  - Ice sublimates,
  - Escaping gases drag out the dust.



The *Deep Impact* mission gave us a look inside a comet.

It demonstrated that:

- Volatiles are located very close to the surface (few meters),
- Volatiles are buried beneath a ~1m layer of dust (Kadono et al. 2007),
- Ice and dust are mixed on meter scales, but not at the micrometer scale (Sunshine et al. 2007).

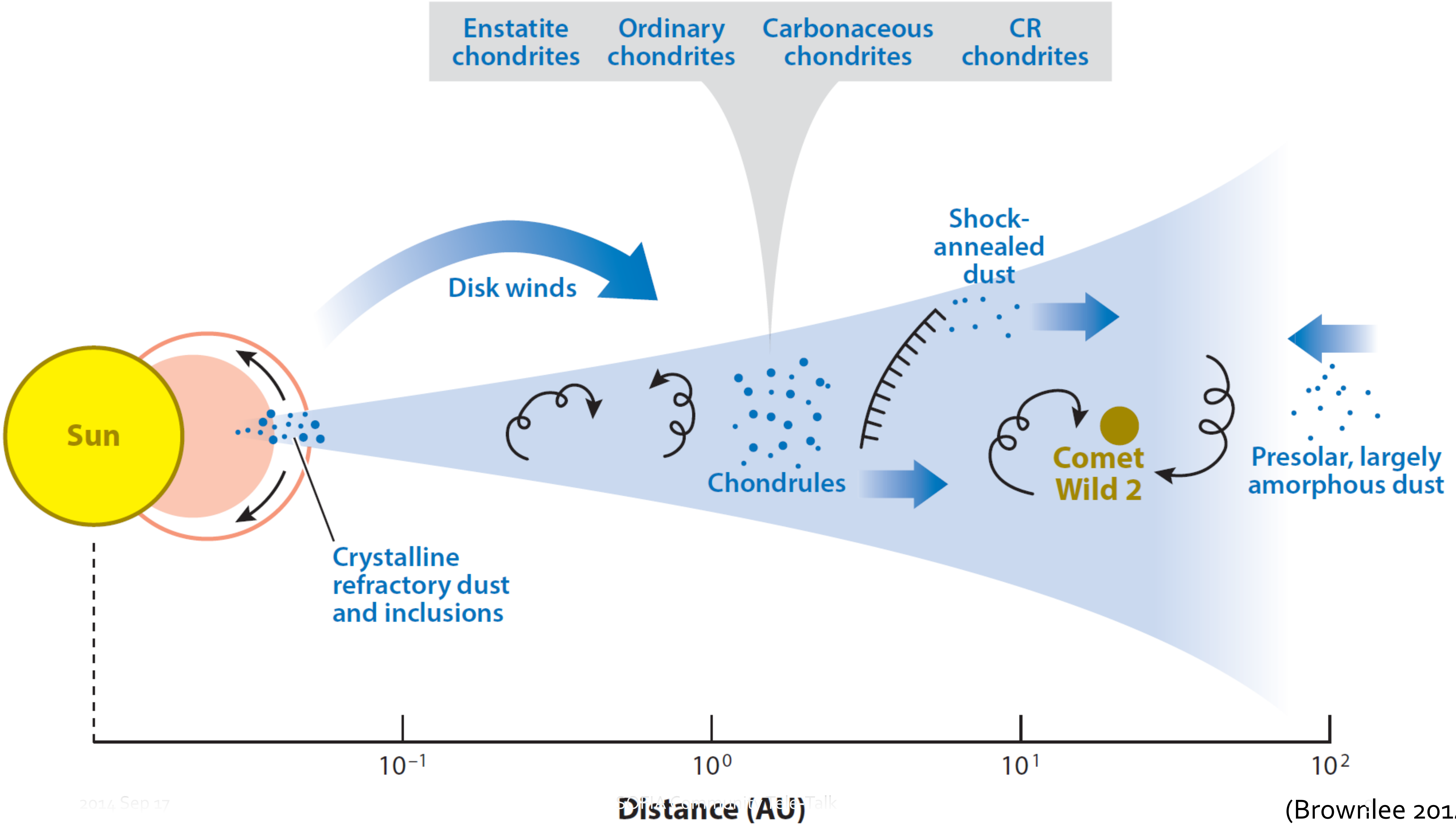
Dust in comet comae may originate from that upper-layer, or may be more directly from the interior.

What does the presence of ice imply?

- Nuclei formed well beyond the "snow line."
- The presence of highly volatile molecules (CO, CH_4, others) indicates interiors have remained cold, $T \ll 180$ K, since formation.
- Consequently:
  - Radiogenic heating never occurred, or
  - That energy was easily lost.

All comet interiors are pristine:

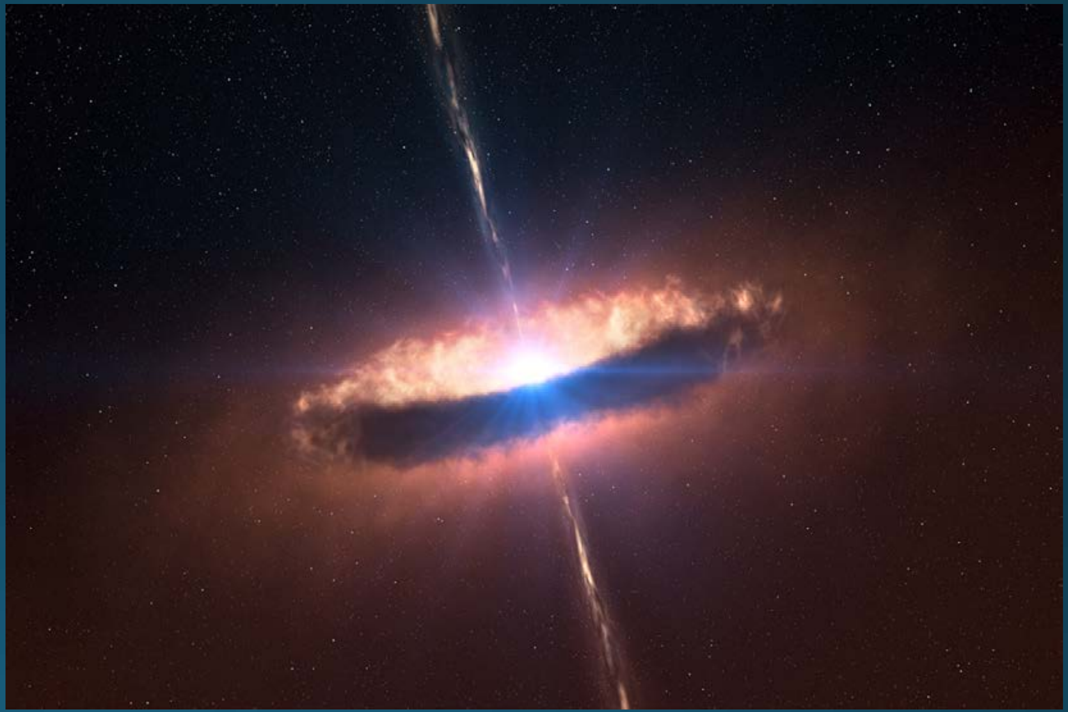
Dust is thermally stable and not aqueously altered.



(Brownlee 2014)

Comet dust origins

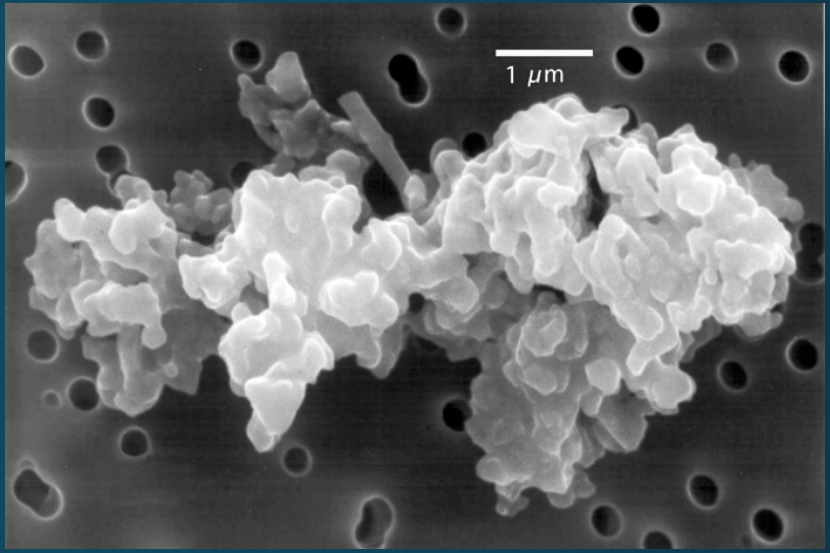
- The formation of dust in the early Solar System is a messy process.
- That newly formed dust is transported out to the comet formation zone.
- Comet interiors have been well preserved for the past 4.5 Gyr.
- Dust comae originate from the (near-)surface of the nucleus.

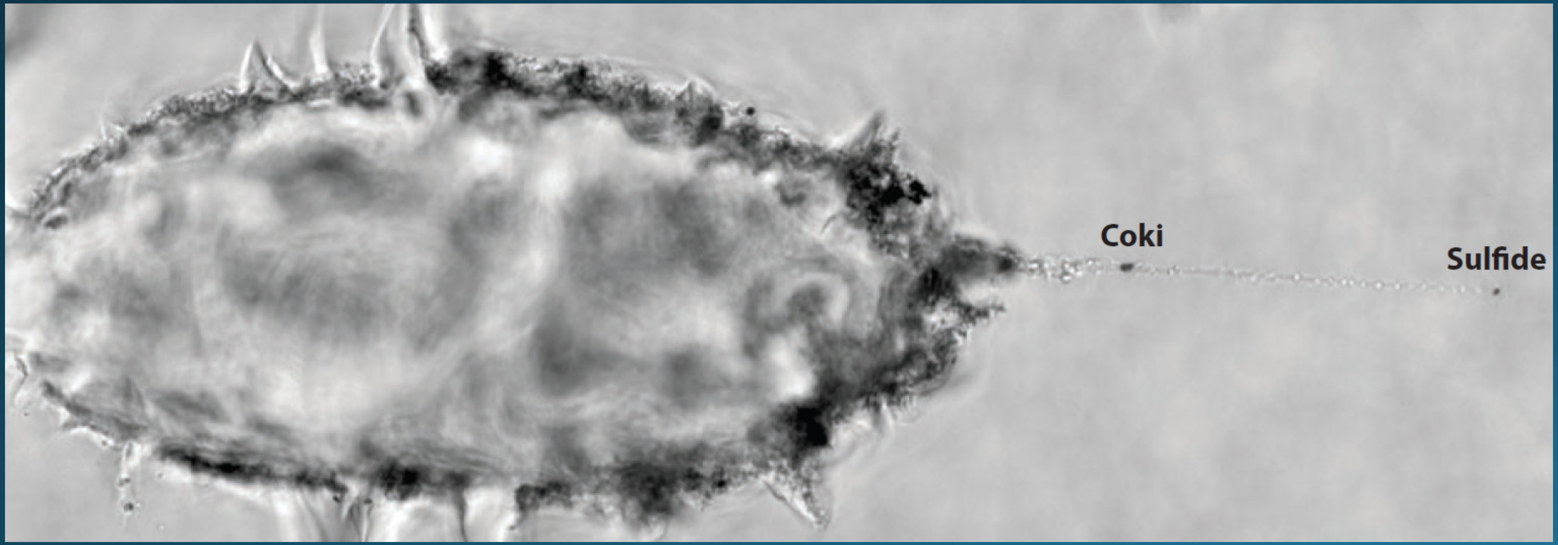


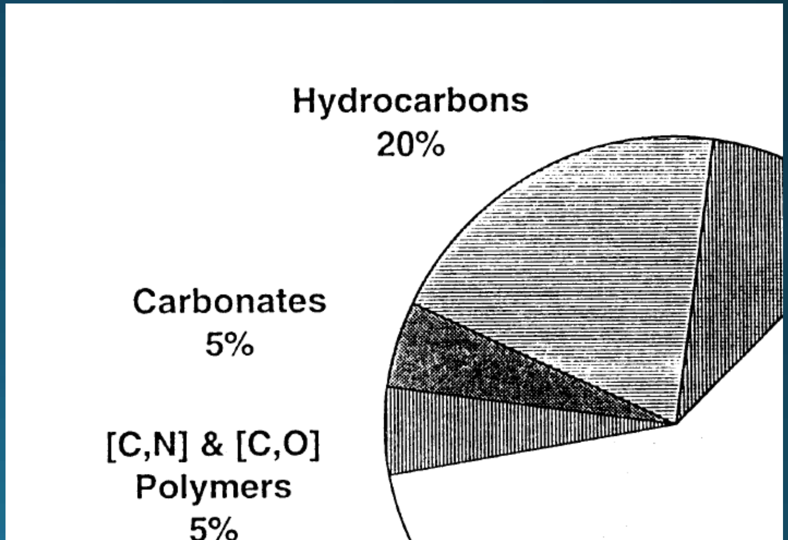
(ESO/L. Calçada/M. Kornmesser)

Comet dust samples

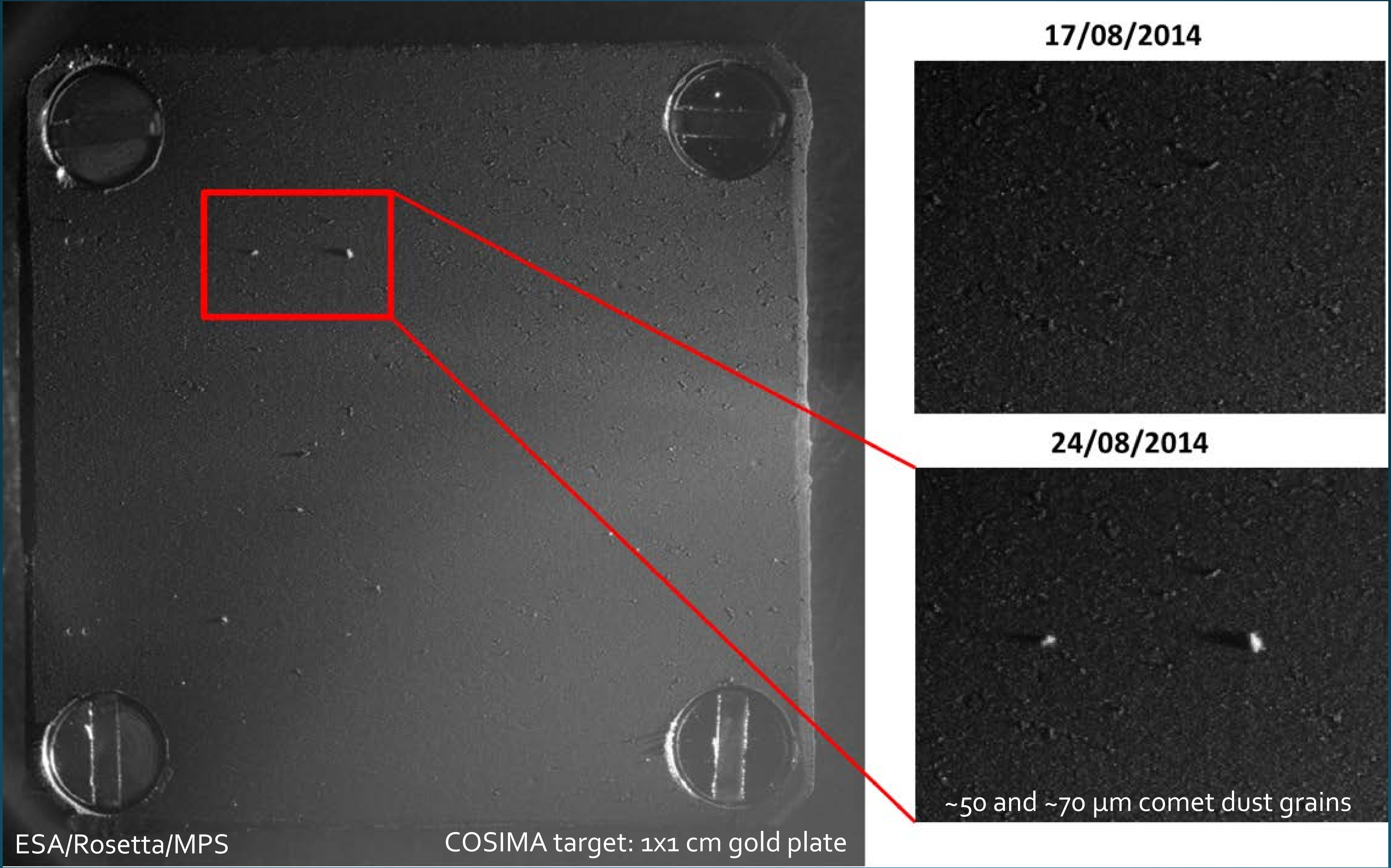
- Interplanetary dust particles collected in the stratosphere,
- Samples returned from comet Wild 2 by *Stardust*.
- In situ analysis of comet Halley, and soon comet Churyumov-Gerasimenko,





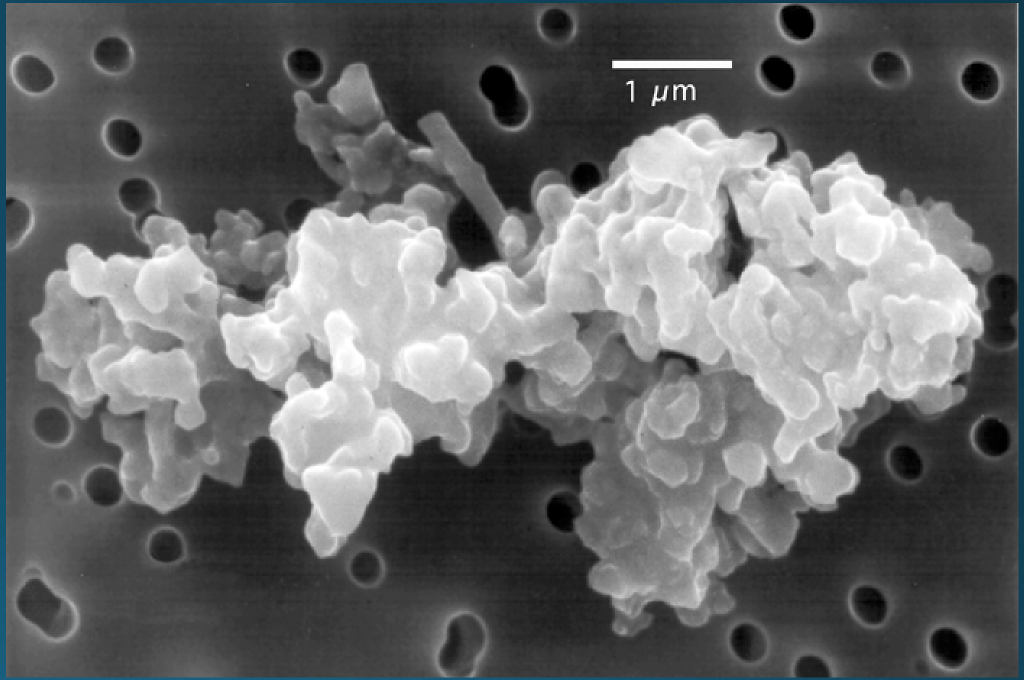


(Fomenkova 1999)


17/08/2014
24/08/2014
~50 and ~70 µm comet dust grains
ESA/Rosetta/MPS
COSIMA target: 1x1 cm gold plate

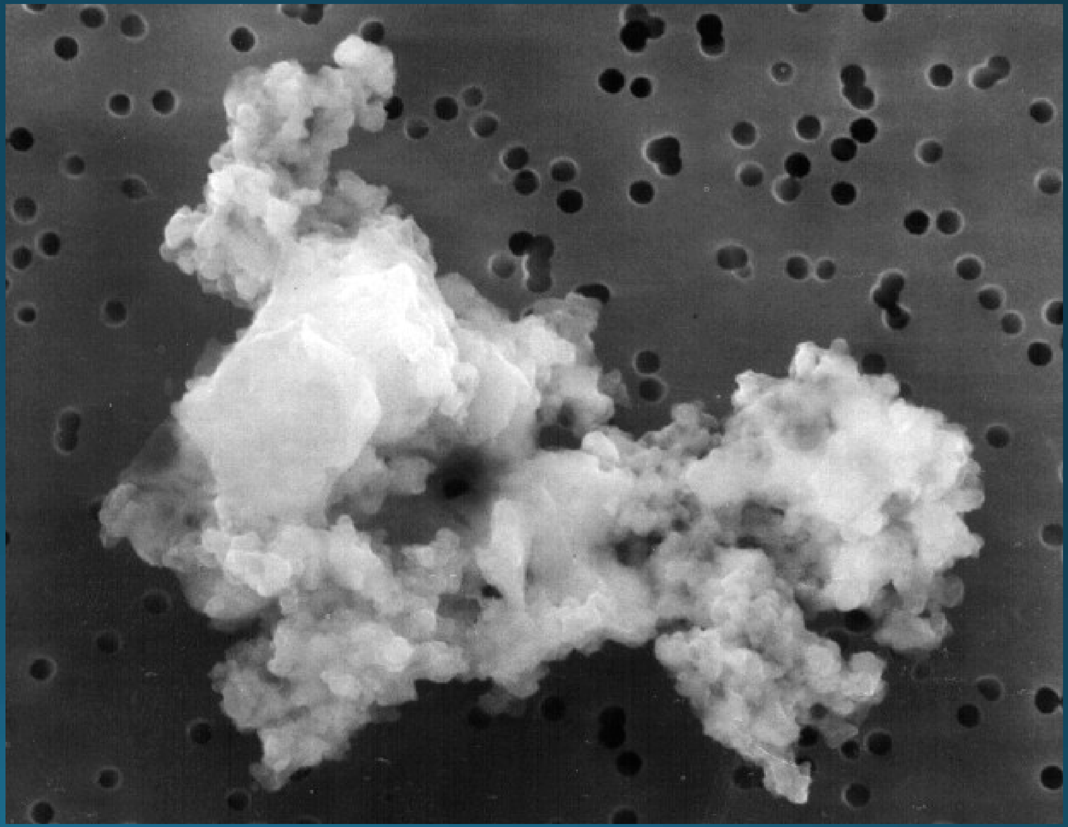
Interplanetary dust particles

- Summaries based on Wooden (2002), Hanner & Zolensky (2010).
- Two relevant types: chondritic porous (CP) and chondritic filled (CF)
  - Chondritic: close to solar elemental abundance,
  - Porous: >90% vacuum,
  - Filled: more solid
- Based on entrance velocities, CP IDPs are more likely cometary in origin.
- Based on the presence of hydrated silicates, CF IDPs are less likely cometary in origin.



Interplanetary dust particles

- CP IDPs are aggregates of smaller units.
- Large grains (0.1-10 μm) are
  - Anhydrous silicates (olivine, pyroxene),
  - Refractory iron sulfides
- Fine-grained (<0.1 μm) matrix consisting of
  - Silicates and carbon,
  - Silicates without carbon (GEMS), or
  - Carbonaceous material.

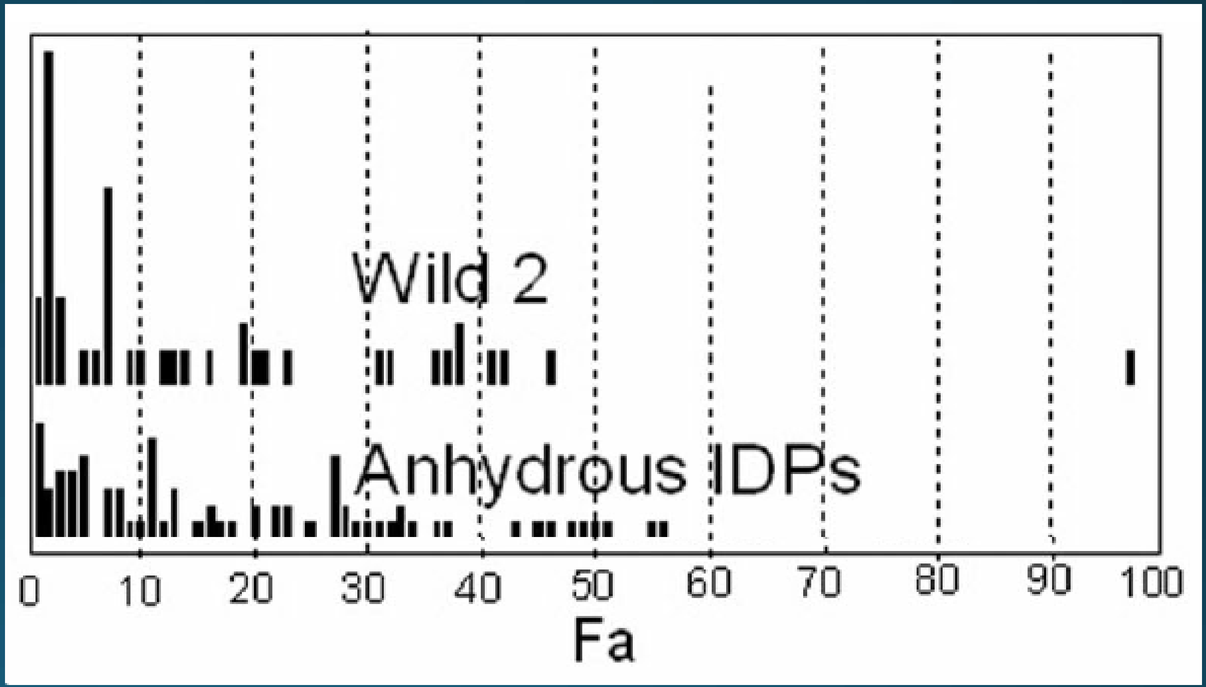


Crystalline silicates have a range of compositions.

A distributed Mg/Fe is found, but Mg-rich is preferred:

- Forsterite (Mg_2SiO_4), and
- Enstatite ($MgSiO_3$).

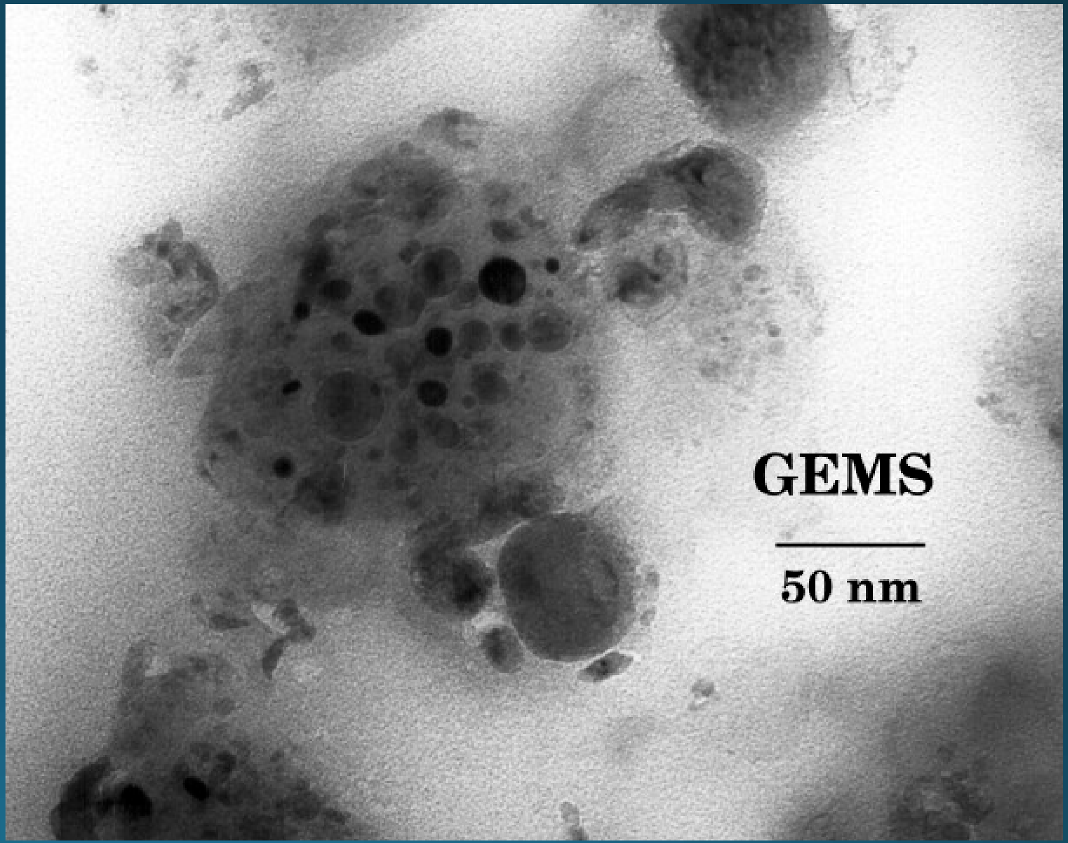
Mg/Fe is a clue from their formation. Mg-rich grains are typically preferred in nebular condensates, cf. solar Mg/Fe ~ 1.



(Zolensky et al. 2008, edited)

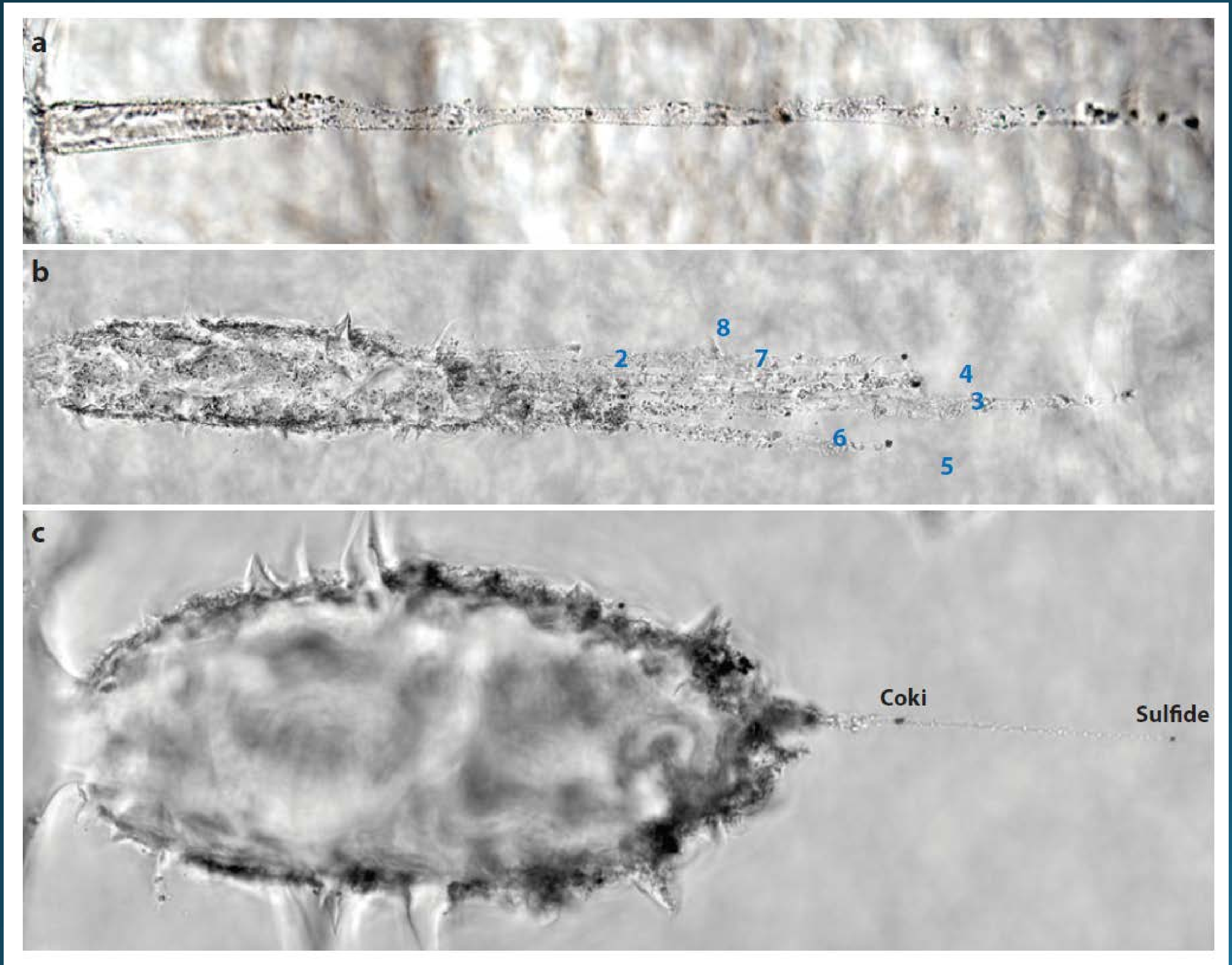
GEMS: Glass with Embedded Metal and Sulfides

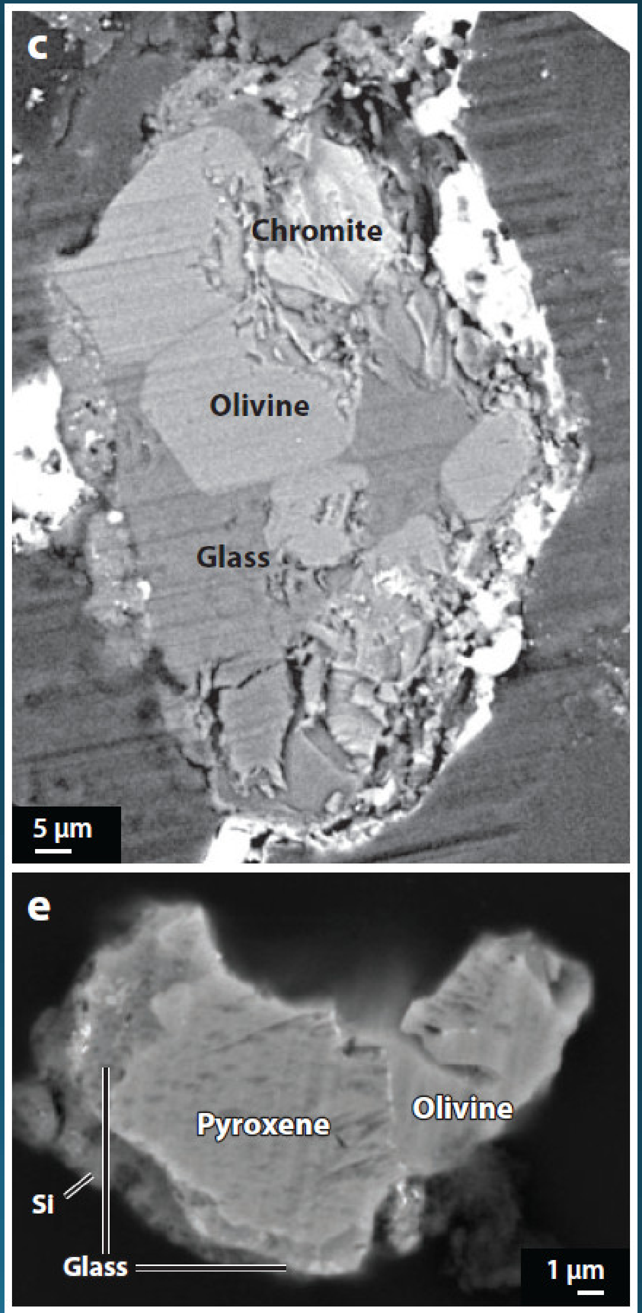
- Dominate the amorphous silicate component.
- Are possibly interstellar in origin (still being debated).
  - Tend to have O isotopic compositions indistinguishable from terrestrial materials and chondritic meteorites (Keller and Messenger 2011)
  - Petrology and mineralogy of isotopically anomalous GEMS are indistinguishable from others (Bradley 2013) suggesting a common origin.



Stardust

- One of the few spacecraft missions to return samples of a specific object:
  - Moon
  - Sun
  - Itokawa
  - Wild 2
- Collection was in 2004, sample return in 2006.





(Brownlee 2014)

Stardust

Returned

- >~ µm-sized grains and aggregates,
- Crystalline silicates consistent with CP IDPs,
- Chondrule fragments, of a range of compositions.

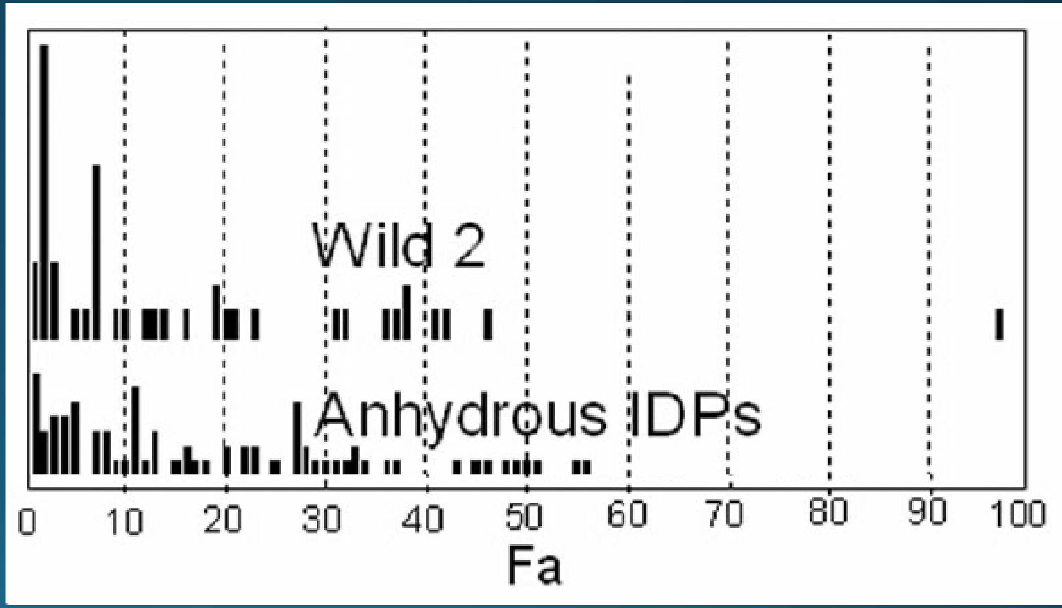
Did not return

- The smallest dust grains,
- Lower temperature species (e.g., phyllosilicates, amorphous silicates),
- GEMS clearly identifiable as cometary.

Select *Stardust* conclusions
Brownlee 2014

The IDP and *Stardust* collections are representative of comets.

The similarity between the two suggests the *Stardust* results can be generalized, at least to first order.



(Zolensky et al. 2008, edited)

Select *Stardust* conclusions
Brownlee 2014

Comet dust formed close to the Sun

- A wide variety of materials are found in Wild 2
    - CAIs and other “first condensates”
    - Crystalline silicates
    - A range of chondrule fragments
- Given this wide range, annealing of amorphous silicate grains to crystalline silicate grains is not needed to explain their high abundance in comets.

Select *Stardust* conclusions
Brownlee 2014

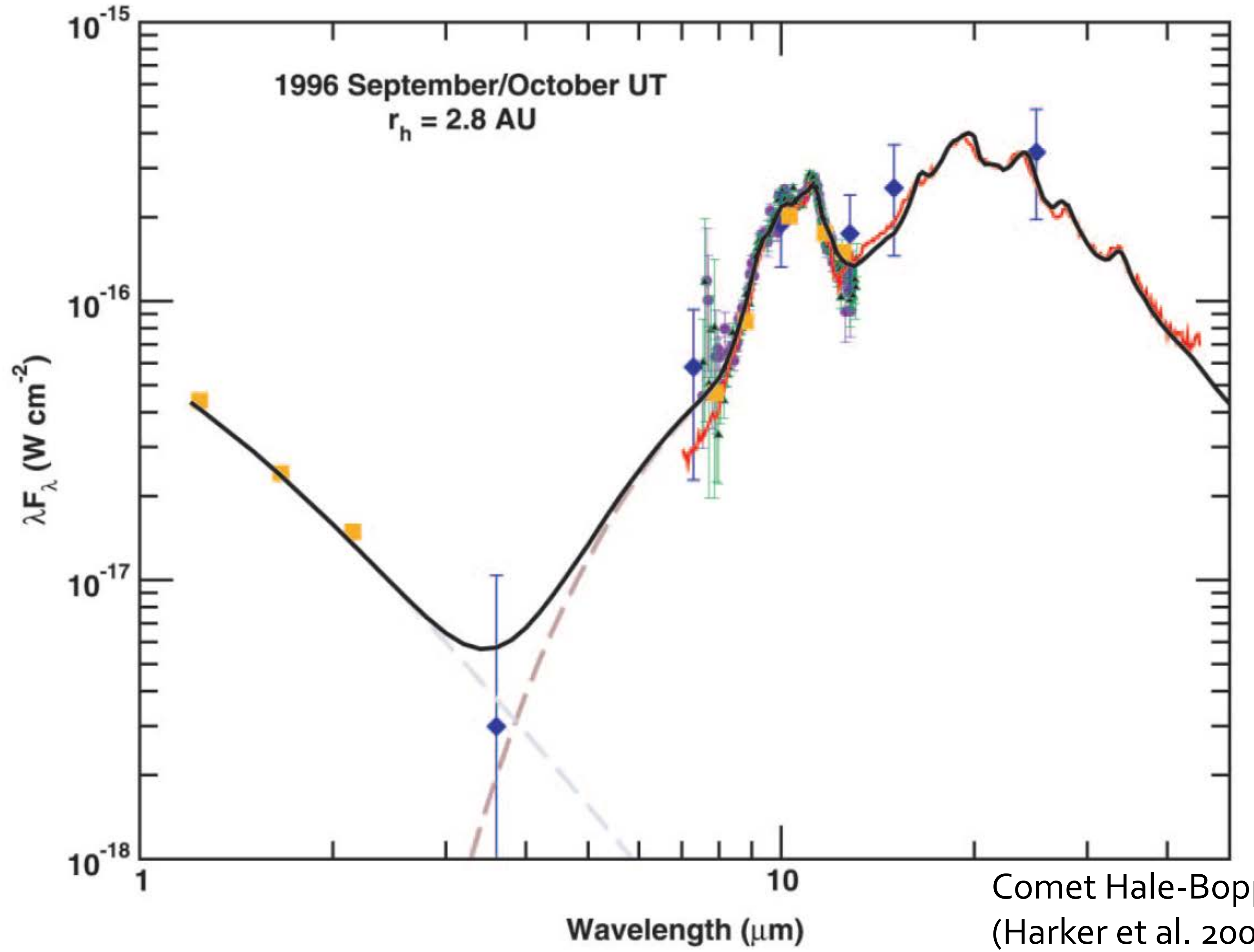
Pre-solar grains are not in abundance in the Wild 2 collection.

- 600-830 ppm for O-rich grains.
- ~375 ppm is primitive IDP mean.
- Up to 150-200 ppm in meteorite matrix.

- Sampling bias? Most ISM grains are small, amorphous
  - *Stardust* could not directly collect small grains, and
  - Difficult to distinguish amorphous grains from melted aerogel.

Summary of the Harker, Wooden, Woodward, Kelley approach.

Thermal emission



Comet Hale-Bopp (Harker et al. 2002)

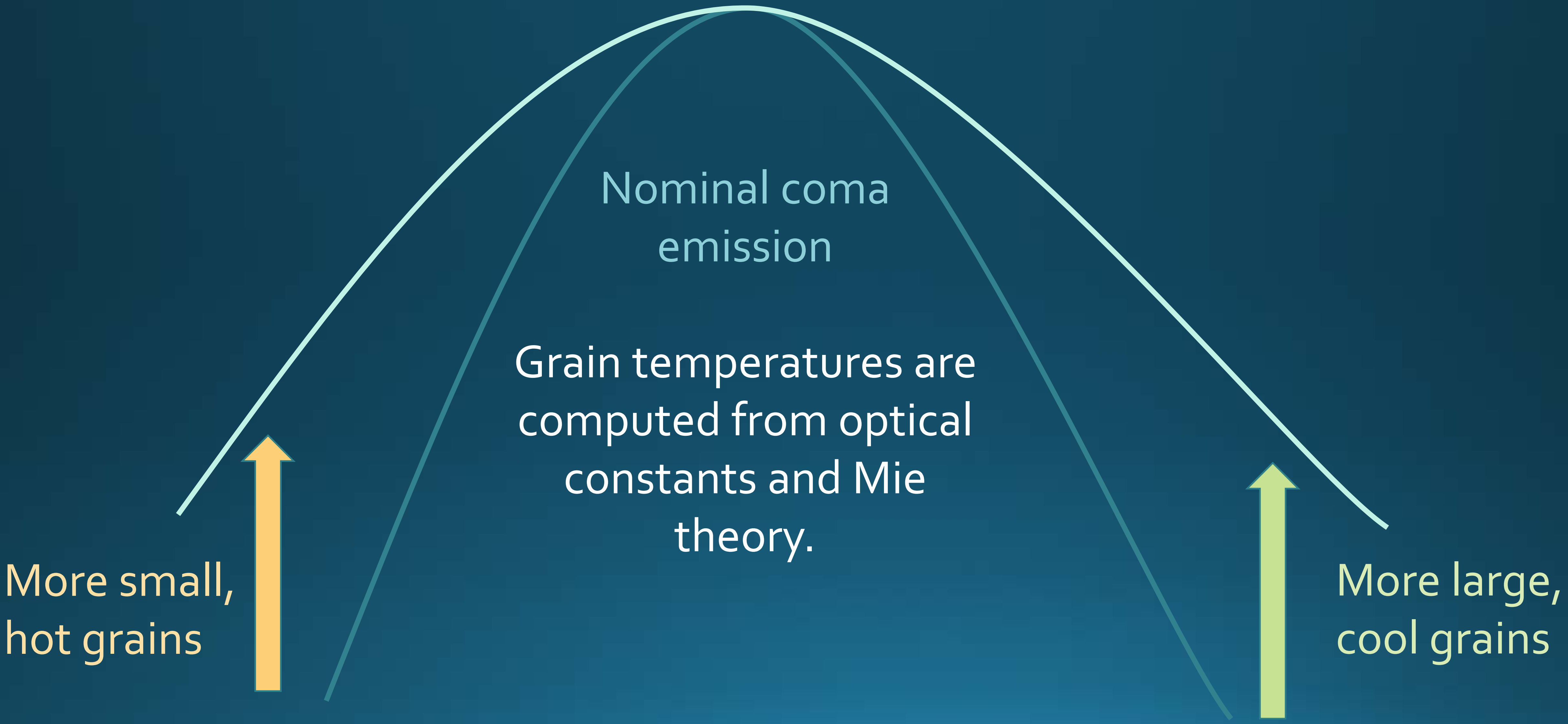
Comet spectral energy distributions are a combination of

- reflected sunlight, and
- thermal emission.

The shape of the thermal emission is sensitive to the dust:

- Size,
- Structure (shape, porosity), and
- Composition.

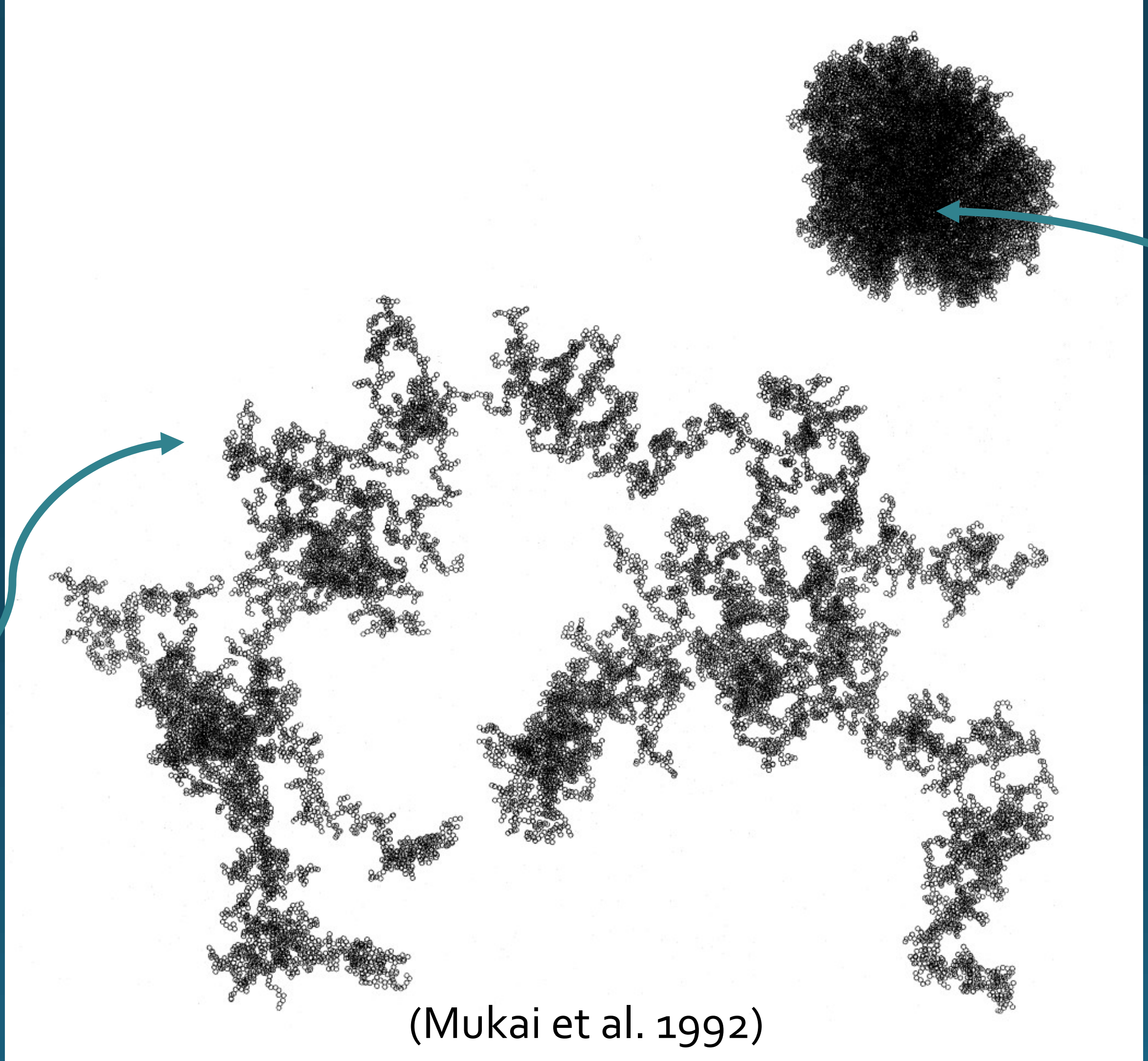
Grain size distribution



Grain temperatures are computed from optical constants and Mie theory.

Structure (porosity)

Grain structure addressed with effective medium theory: mixing vacuum into grains at the optical constant level.

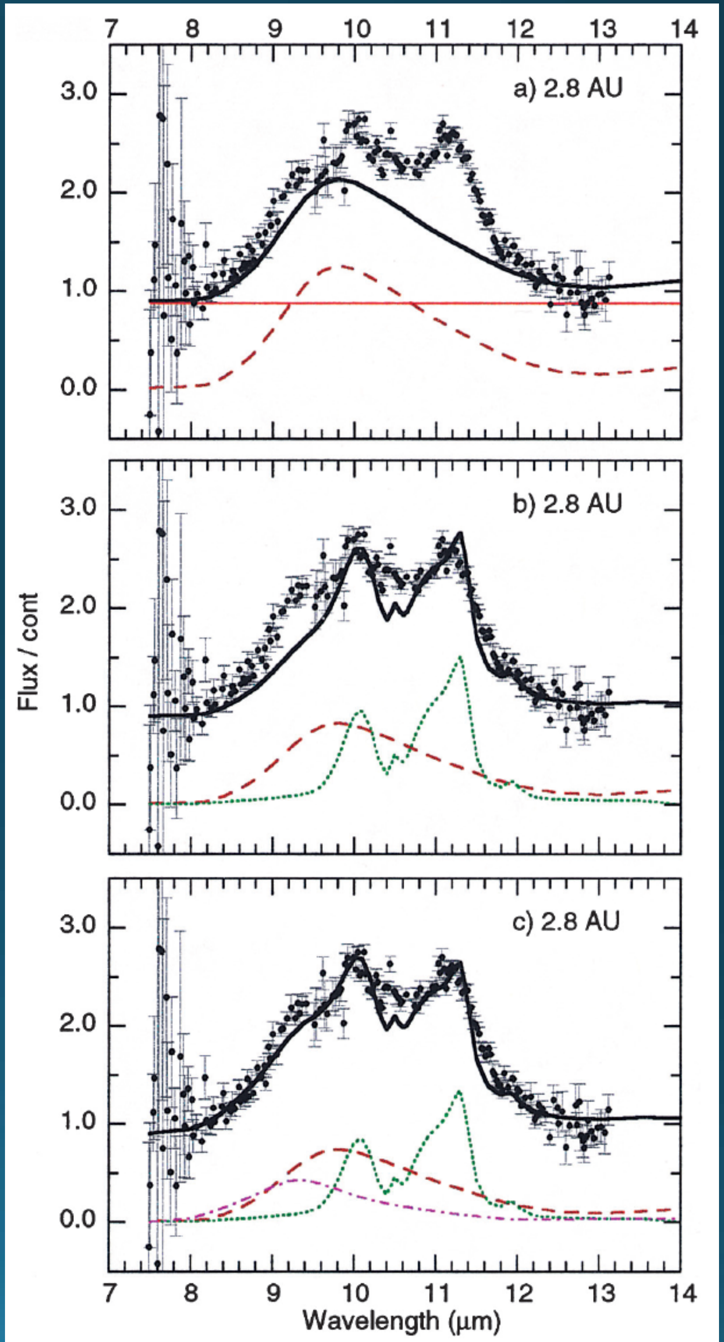


Fluffy aggregate, radiates more like a collection of individual grains.

Compact aggregate, radiates more like a solid particle.

Composition

- Our thermal models are based on the compositions of IDPs and Hale-Bopp.
- Right: Building up the 10-µm silicate emission feature of comet Hale-Bopp (Wooden et al. 1999).
  - Spectrum normalized with a Planck function.
  - Top: Just amorphous olivine.
  - Middle: Add Mg-rich crystalline olivine.
  - Bottom: Add amorphous pyroxene



Crystalline fraction

Comet	f_{cryst} (%)	Source
C/2007 N3 (Lulin)	14 ± 4	Woodward et al. 2011
9P/Tempel 1	13 – 35	Harker et al. 2005
73P/S-W 3C	26 ± 4	Harker et al. 2011
C/2001 HT50 (LINEAR-NEAT)	28	Kelley et al. 2006
73P/S-W 3B	34 ± 10	Harker et al. 2011
17P/Holmes	60	Reach et al. 2007
C/2002 V1 (NEAT)	66	Ootsubo et al. 2007
C/2001 Q4 (NEAT)	70 – 71	Wooden et al. 2004, Ootsubo et al. 2007
C/1995 O1 (Hale-Bopp)	60 – 80	Harker et al. 2002

- How much inner-Solar System material mixed with ISM dust in the outer-disk?
- Several comets have been measured, and a couple surveys by our team will be published in the next few years.
- A wide range, 14% to 70%.
- Much more varied than T-Tauri disks: 10-20% (Oliveira et al. 2011).

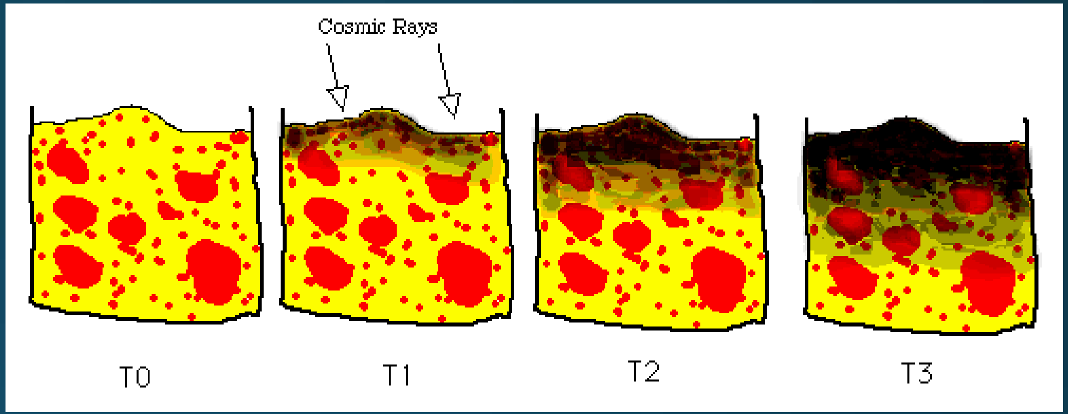
Is our Solar System unqiue/rare?

Are there small scale variations in T-Tauri disks not evident in *Spitzer* spectra?

Comet evolution

Cold storage

- Comet interiors are preserved, but not necessarily their surfaces.
- Galactic cosmic rays and a long residence in the Oort cloud will alter the upper few meters.
- Amorphize silicate crystals?
- Carbonize organics?



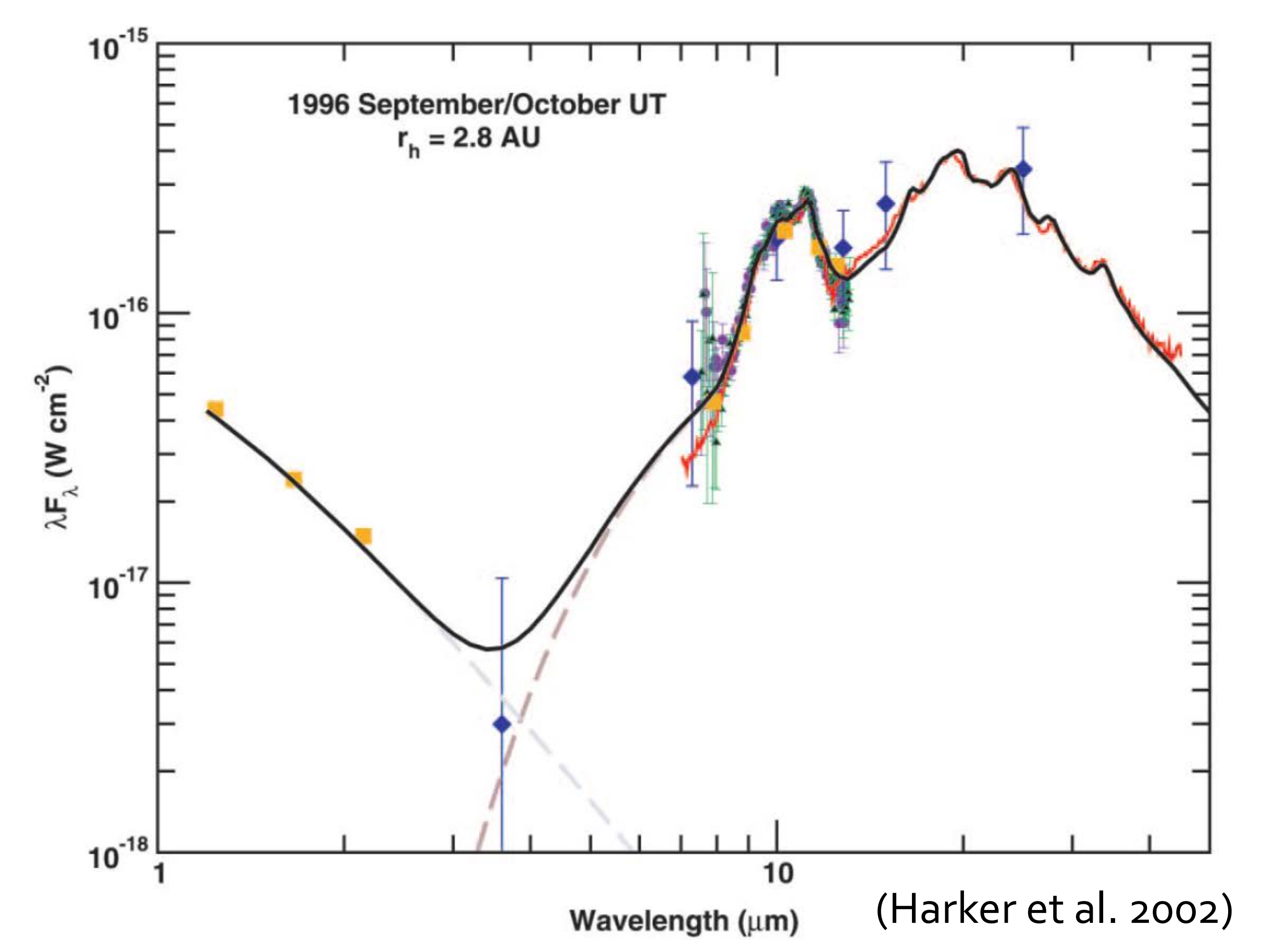
(Dave Jewitt)

Oort Cloud Comet Hale-Bopp

- Extreme dust properties, which seem to be rare in the comet population:
  - Strong amorphous and crystalline silicate features.
  - Strong thermal continuum at short wavelengths.
  - Nearly an optically thick coma at perihelion (tau <~ 1).

A preponderance of small, silicate rich dust grains

(Harker et al. 2002).



(Harker et al. 2002)

Old vs. New

- Reciprocal semi-major axis, computed before being perturbed by the planets, indicates the likelihood of a comet being on its first perihelion passage (Oort 1950).
  - $1/a_0 < 50 \times 10^{-6}$ AU^{-1} considered to be dynamically new
  - Jupiter's average kick is about 1000×10^{-6} AU^{-1}.

- Comet Hale-Bopp had been to the inner solar system several times:
  - $1/a_0 = 3800 \times 10^{-6}$ AU^{-1}

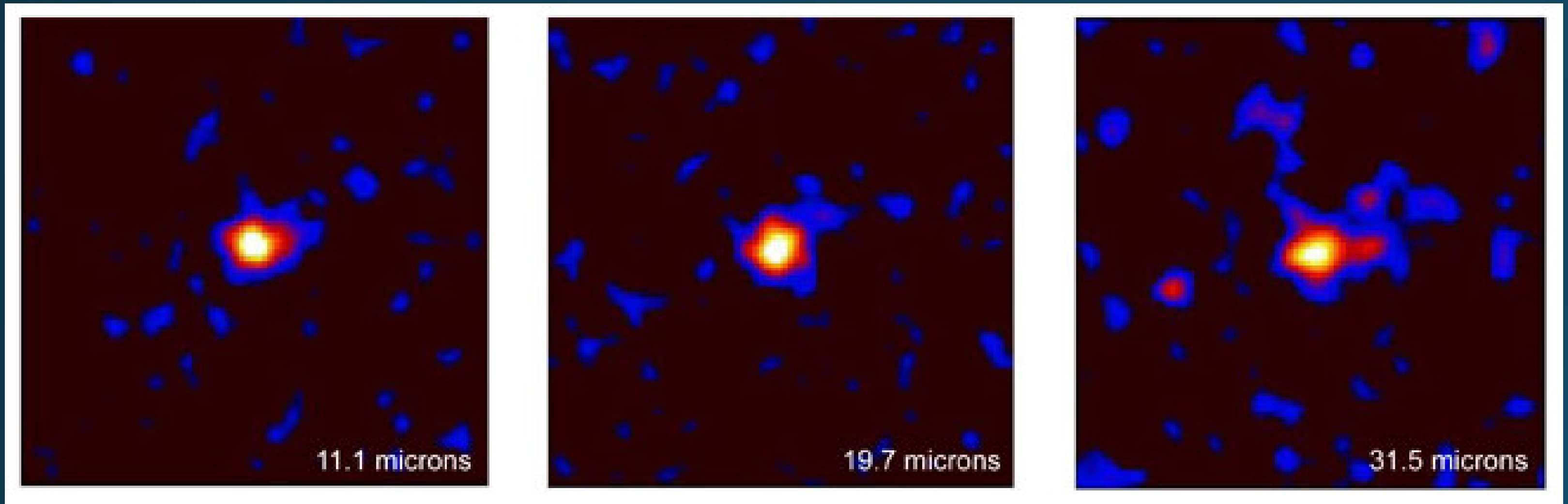
Hale-Bopp was pristine in the Solar System sense, but not a preserved relic from the Oort Cloud.

Comet C/2012 S1 (ISON)

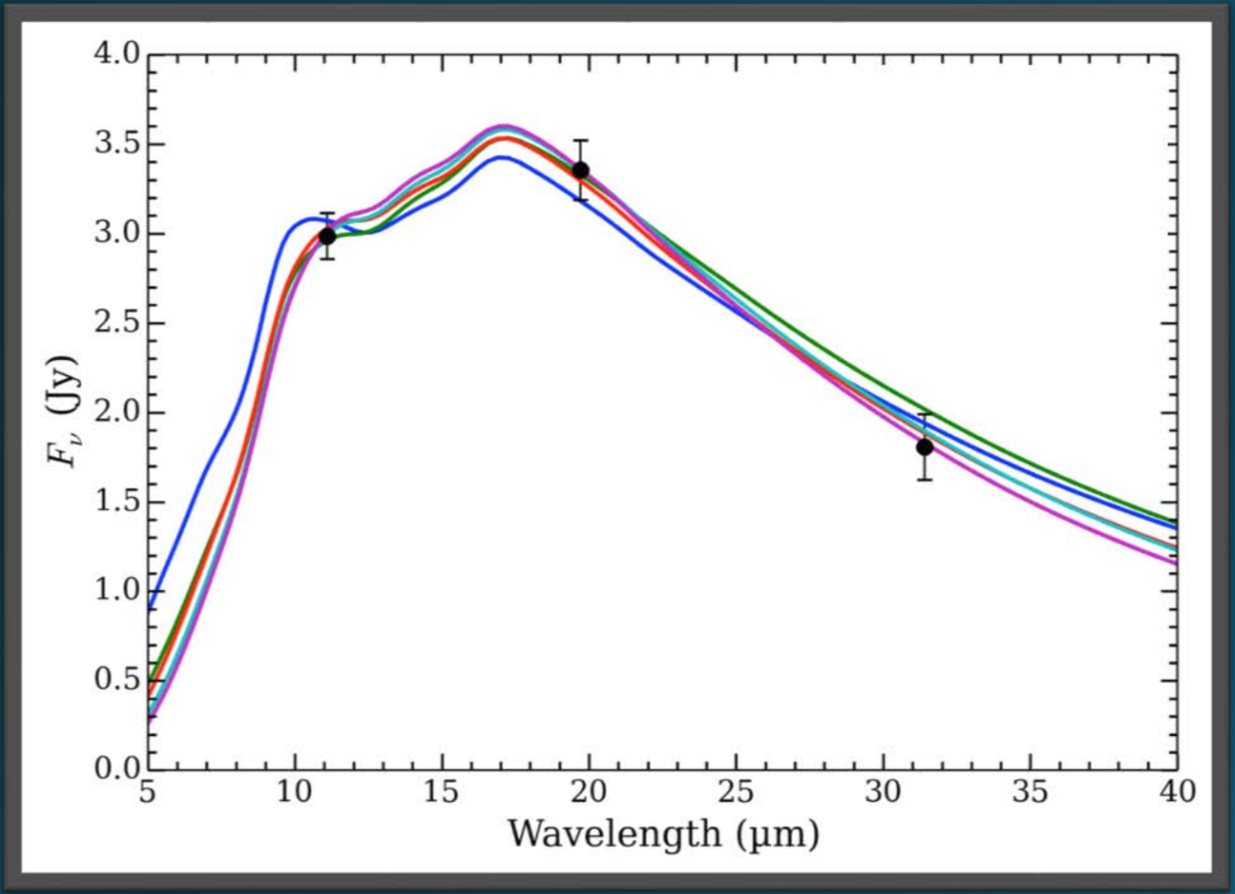
- A dynamically new sungrazing comet discovered at 6 AU.
- It appeared to be on its first inner-Solar System passage since being placed in the Oort cloud.
- As a sungrazer it could easily lose 10's of meters of material: the irradiated mantle would be lost in one perihelion passage.
- Thus an opportunity to compare the irradiated mantle to the deeper interior.

(Hubble Heritage)

Comet C/2012 S1 (ISON)



11-, 20-, and 32-µm filter photometry of comet ISON with SOFIA/FORCAST.



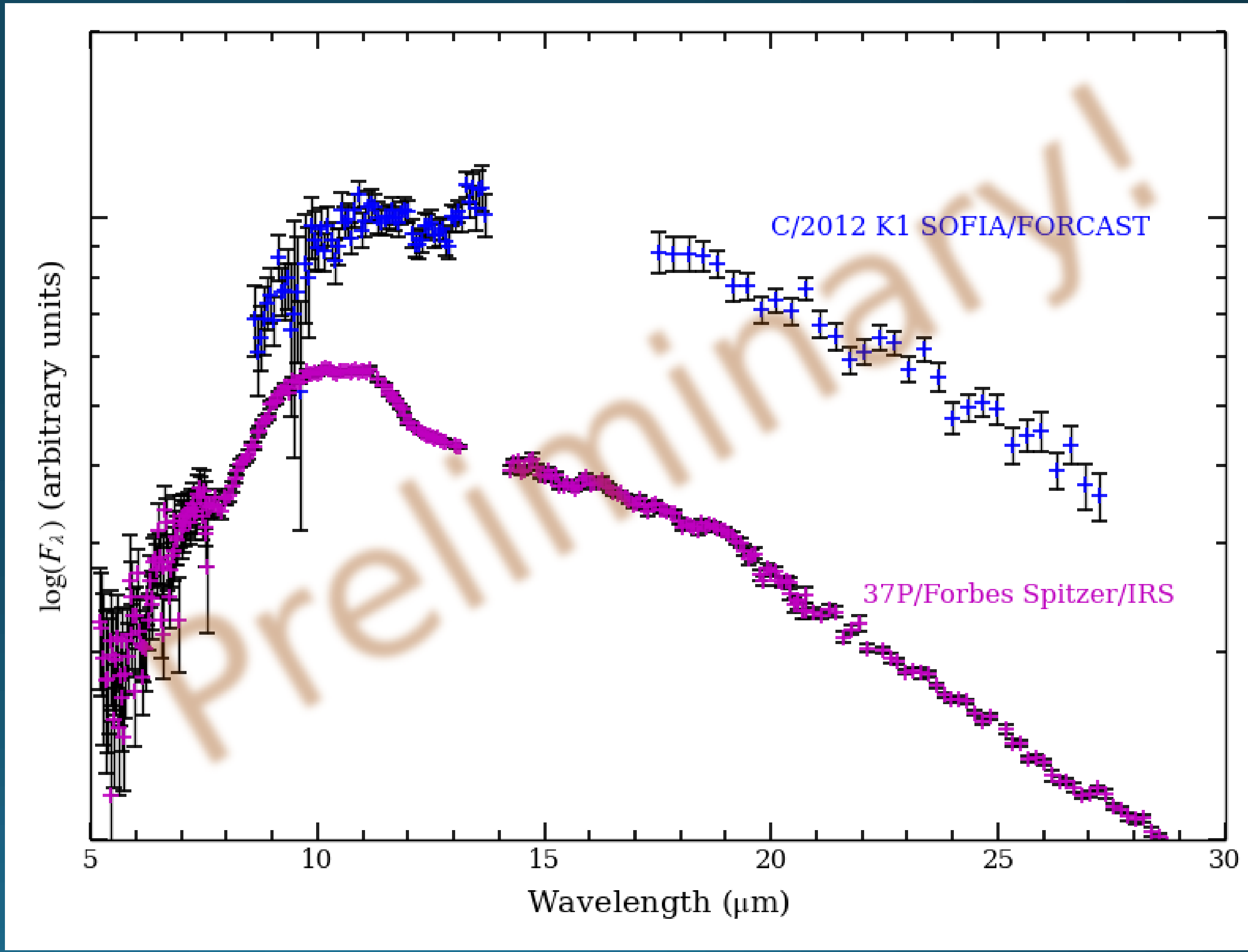
Wooden et al. in preparation

- We fit the SED along with two constraints from Subaru/COMICS (Ootsubo et al., in prep.):
  - continuum temperature, and
  - silicate feature strength.
- A family of models is obtained, the most plausible suggest:
  - Narrow size distribution (mono-disperse) with a preponderance of 1-µm grains, and
  - Low silicate mass fraction (<20%).
- Post-outburst mid-IR spectra show a more typical comet (Russell et al., in prep.).

Did we observe the irradiated mantle?

C/2012 K1 (PanSTARRS)

- Also a dynamically new comet.
- Observed with SOFIA/FORCAST in June 2014.
- Spectral extractions calibrated based on our ground-based and Kuiper Airborne Observatory experience.
- Data look great! Analysis is ongoing. More details at the DPS Meeting in Tucson (Woodward et al.).



Summary

- Comet dust grains are relics from our Solar System's formation.
  - They simultaneously represent the *inputs* and the *outputs* of planetesimal formation.
- Our knowledge of their compositions are guided by laboratory and in situ analyses.
  - Telescopic observations are still needed to give us bulk coma properties and an understanding of comet-to-comet variations.
- Comet dust grains originate from a wide variety of processes:
  - Interstellar medium grain growth and processing,
  - Chondrule formation,
  - Grain condensation.
- Mid-infrared spectra reveal a diversity not seen in T-Tauri disks.
  - Statistically significant comet surveys will address if the mean comet agrees with the mean T-Tauri disk.