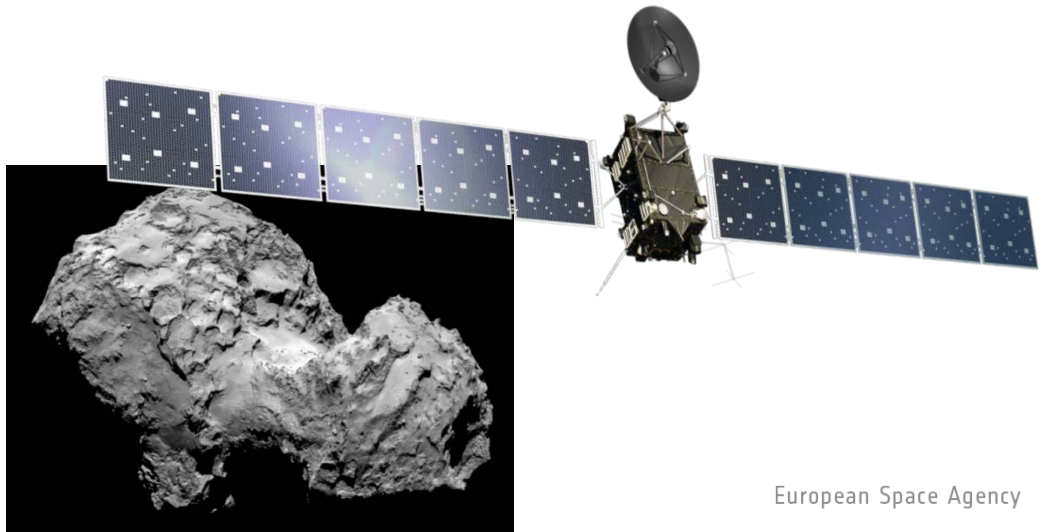
Comets and the Rosetta mission

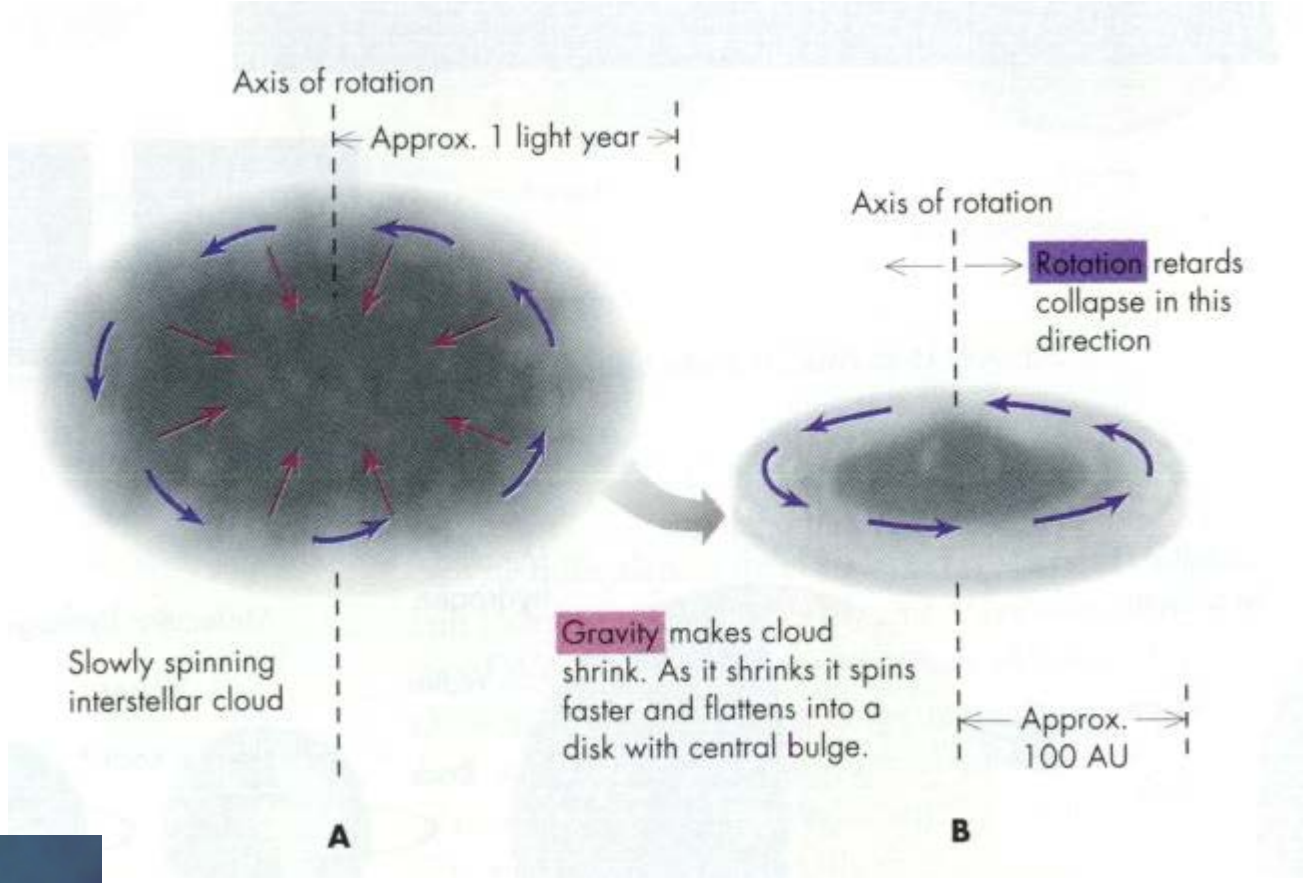
1. Comets and Formation of the solar system
2. Properties of comets
3. Cometary Science questions
4. Cometary missions before Rosetta



Phases of Solar system formation

1 Protosolar nebula

- It starts with a cloud of interstellar gas and dust
- Cloud collapse is triggered by external influence
  - E.g. shock wave from supernova
- Collapsing cloud forms fast-spinning disk

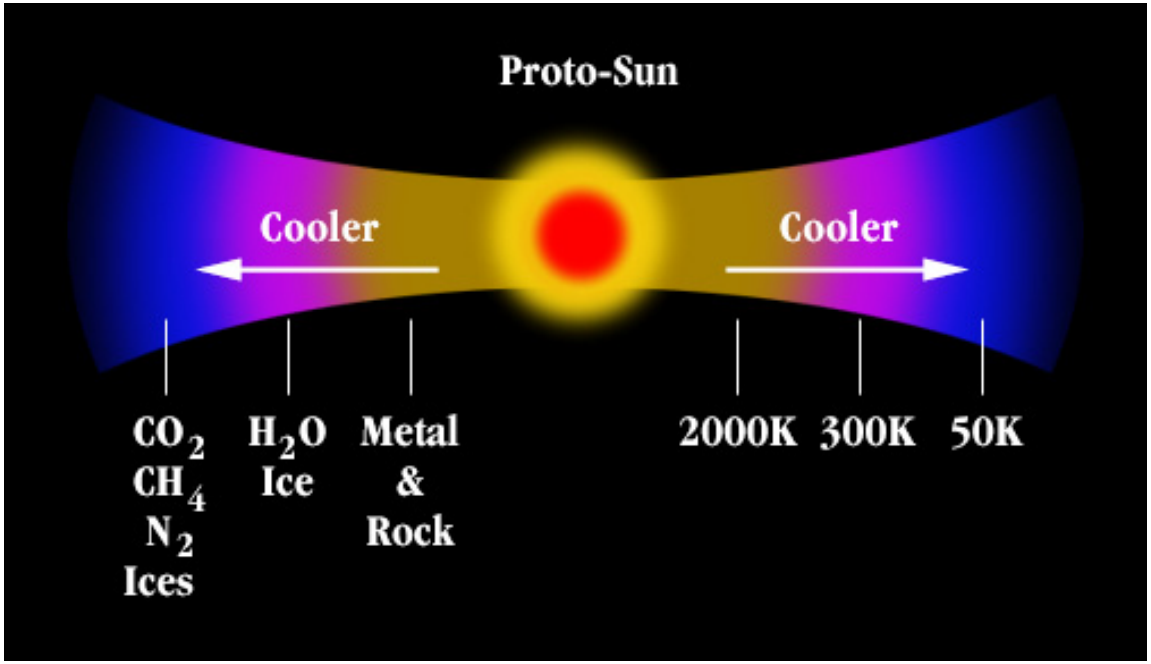


HST image of a protoplanetary nebula

Phases of Solar system formation

2 Protoplanetary disk

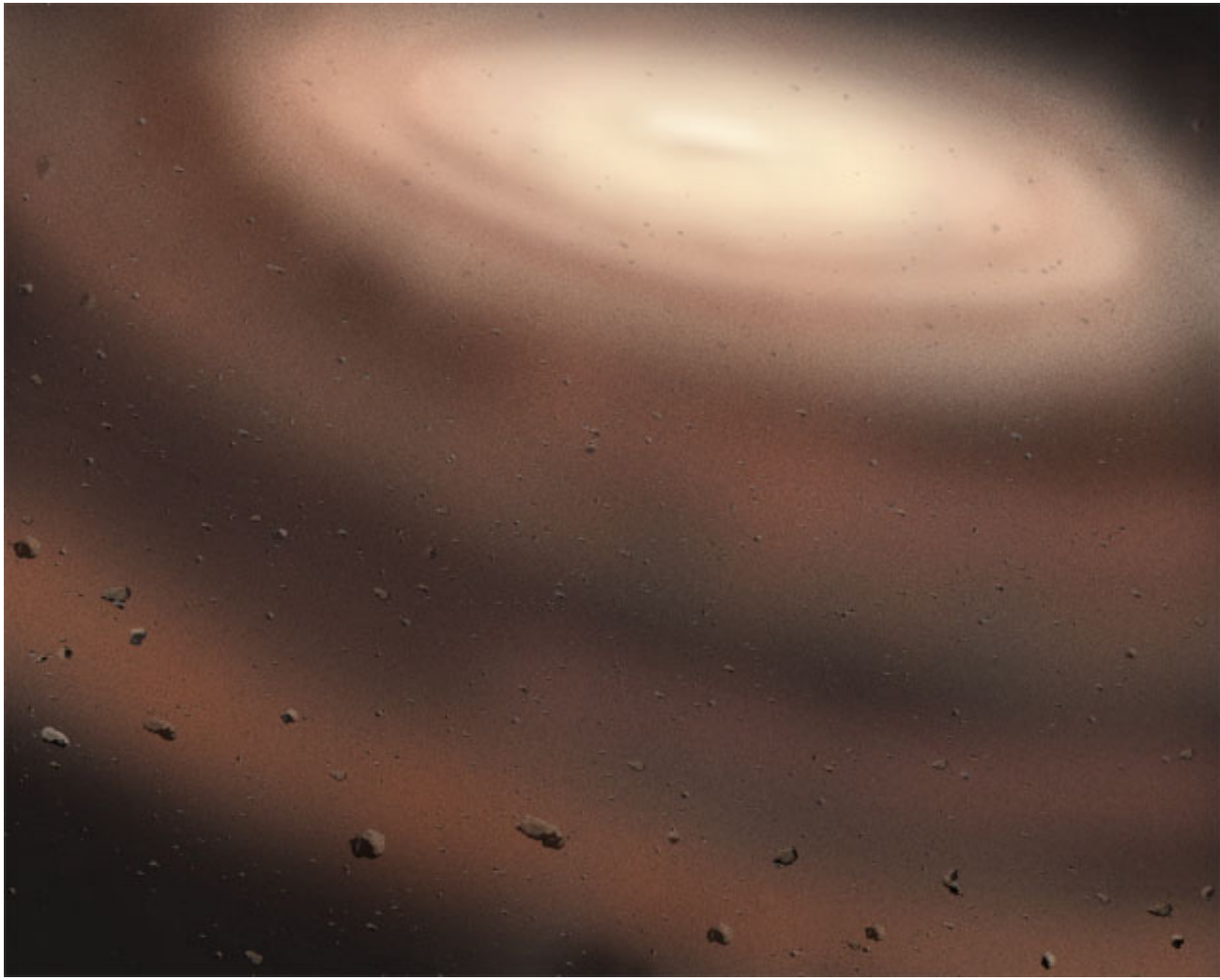
- Once the density in the inner part of the disk reaches a critical value, and nuclear fusion starts
  - The sun forms
- Sun heats up the now denser nebula, strong temperature decrease with distance
  - Metals and silicates condense in the inner part, ices in the outer part



Phases of Solar system formation: Formation of planets and small bodies in the protoplanetary disk

- Dust particles in the disk collide and stick together
  => mm - decimeter sized partilces

- Larger particles do **not** easily stick together
  - ❑ Different hypotheses how particles continue to grow beyond cm size
  - ⇒ Comet research can test those theories
- Once larger bodies are formed (km-sized planetesimals), the biggest ones grow through collisions



Phases of solar system foramtion: T Tauri phase of the sun and formation of Oort cloud

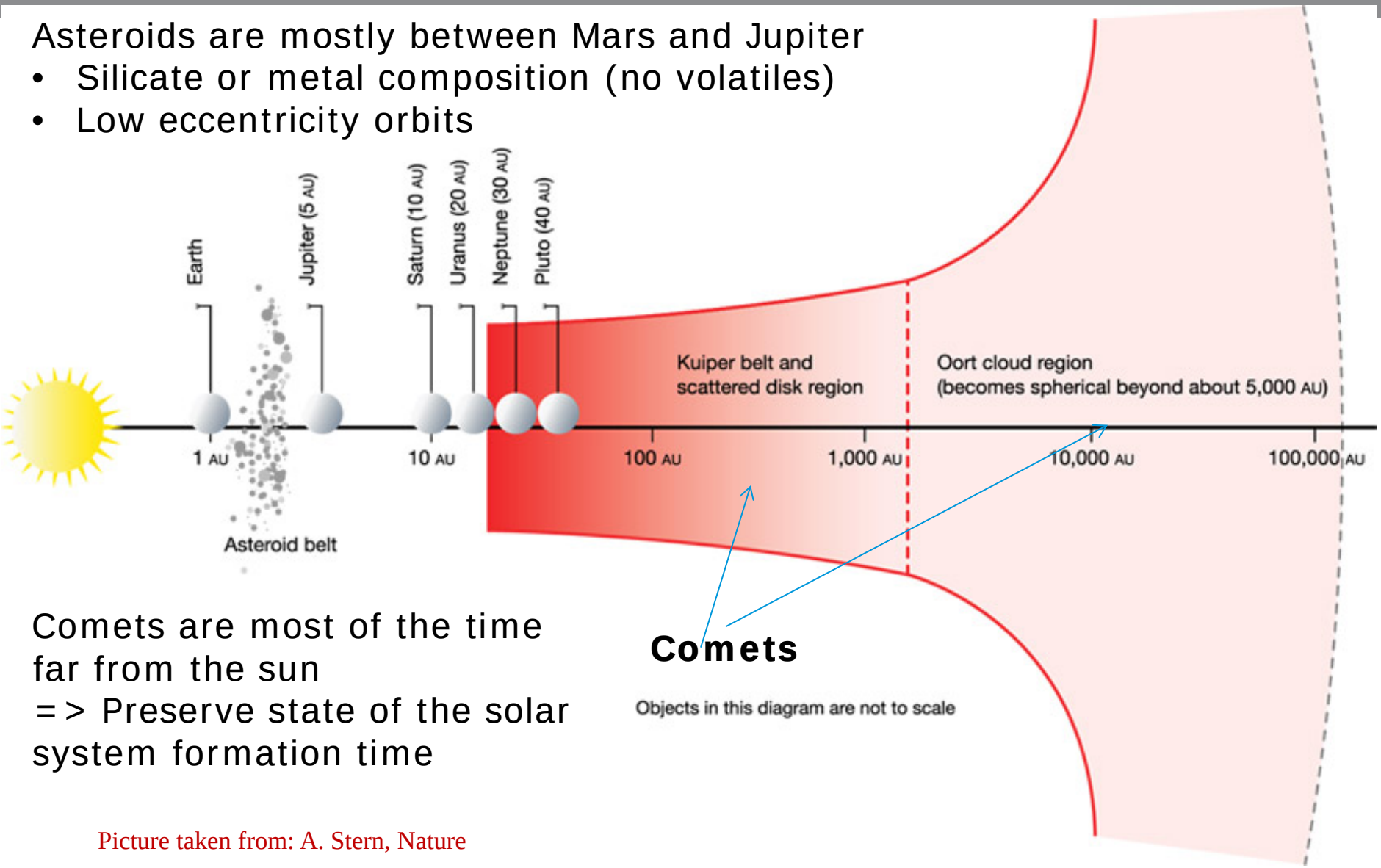
- After ~100000 years, sun becomes a highly active T Tauri star
  - Gas and dust are blown away by strong wind
- Small bodies (comets) in the outer planet region are ejected into the Oort cloud

T Tauri

Small bodies in the solar system today

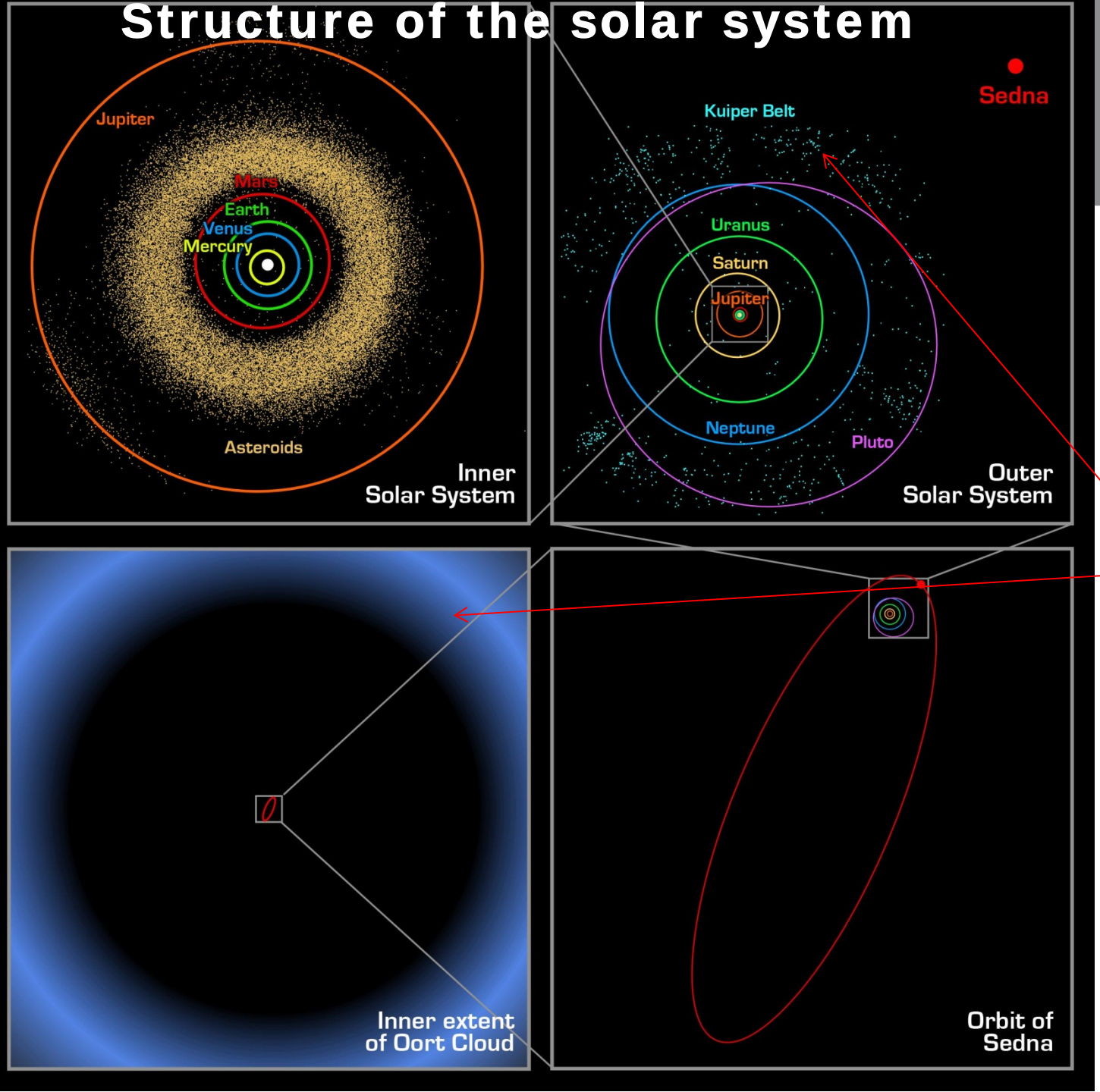
Asteroids are mostly between Mars and Jupiter

- Silicate or metal composition (no volatiles)
- Low eccentricity orbits



Comets are most of the time far from the sun
=> Preserve state of the solar system formation time

Picture taken from: A. Stern, Nature



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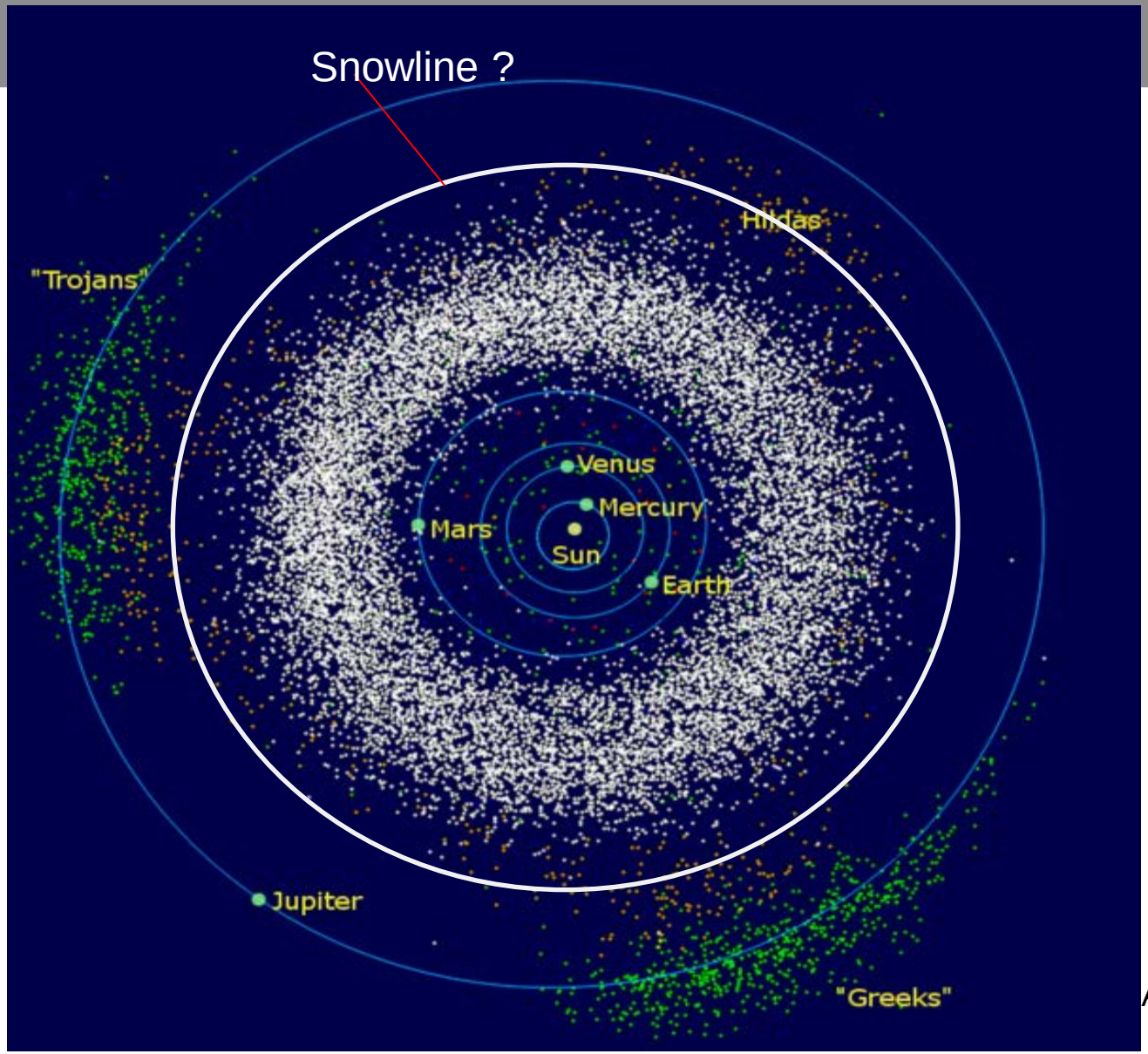
Comets

Fuente: Wikipedia/NASA/JPL

Comet Reservoirs (Classical picture)

1. Kuiper belt and scattered disk
   - Kuiper belt comets formed outside the giant planets
   - Source of Jupiter-family and Halley type comets
     - Get into inner solar system through perturbations by giant planets
     - Halley can be considered “Neptune family”
2. Oort cloud
   - Oort cloud comets formed in the giant planet region
   - Removed by gravity of giant planets
   - Occasional return to inner solar system due to nearby stars or molecular clouds passing by

Volatile rich and inert (rocky) bodies



Classical picture:
Snowline in the solar system somewhere between asteroid main belt and Jupiter's orbit:

- Giant planets and comets are icy
- Terrestrial planets and asteroids are dry
  - Earth oceans come from outer solar system !?

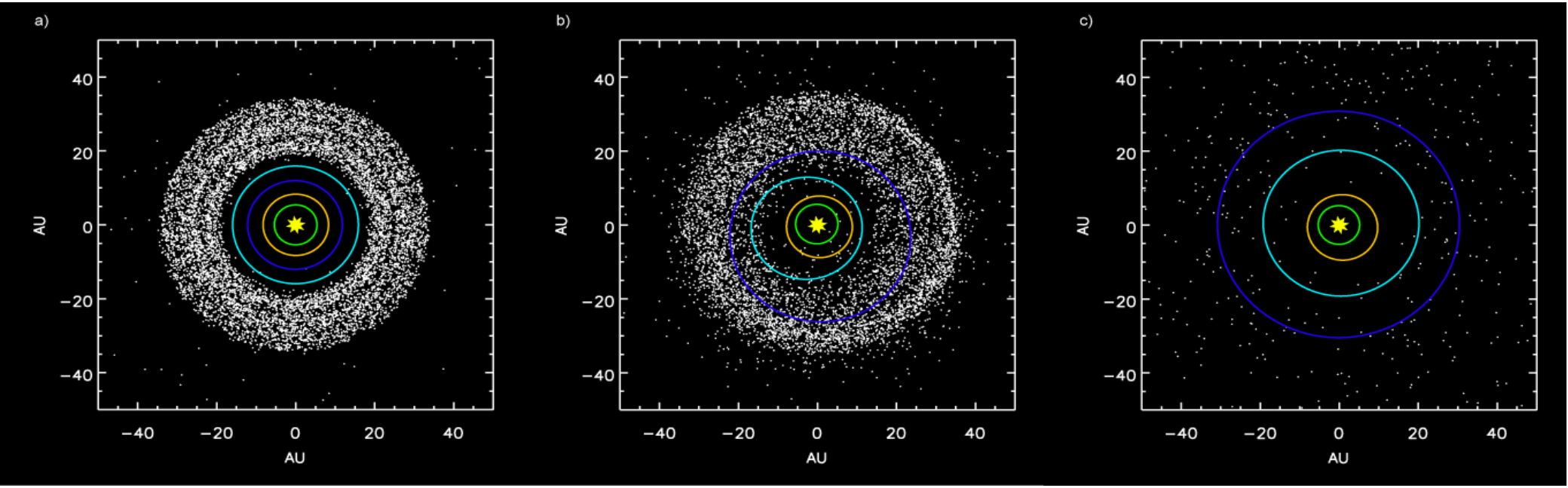
After: Wikipedia

Limitations of the classical picture: Planetary Migration (Nice model)

Before migration

3 Mys after start of migration

200 Mys after start of migration

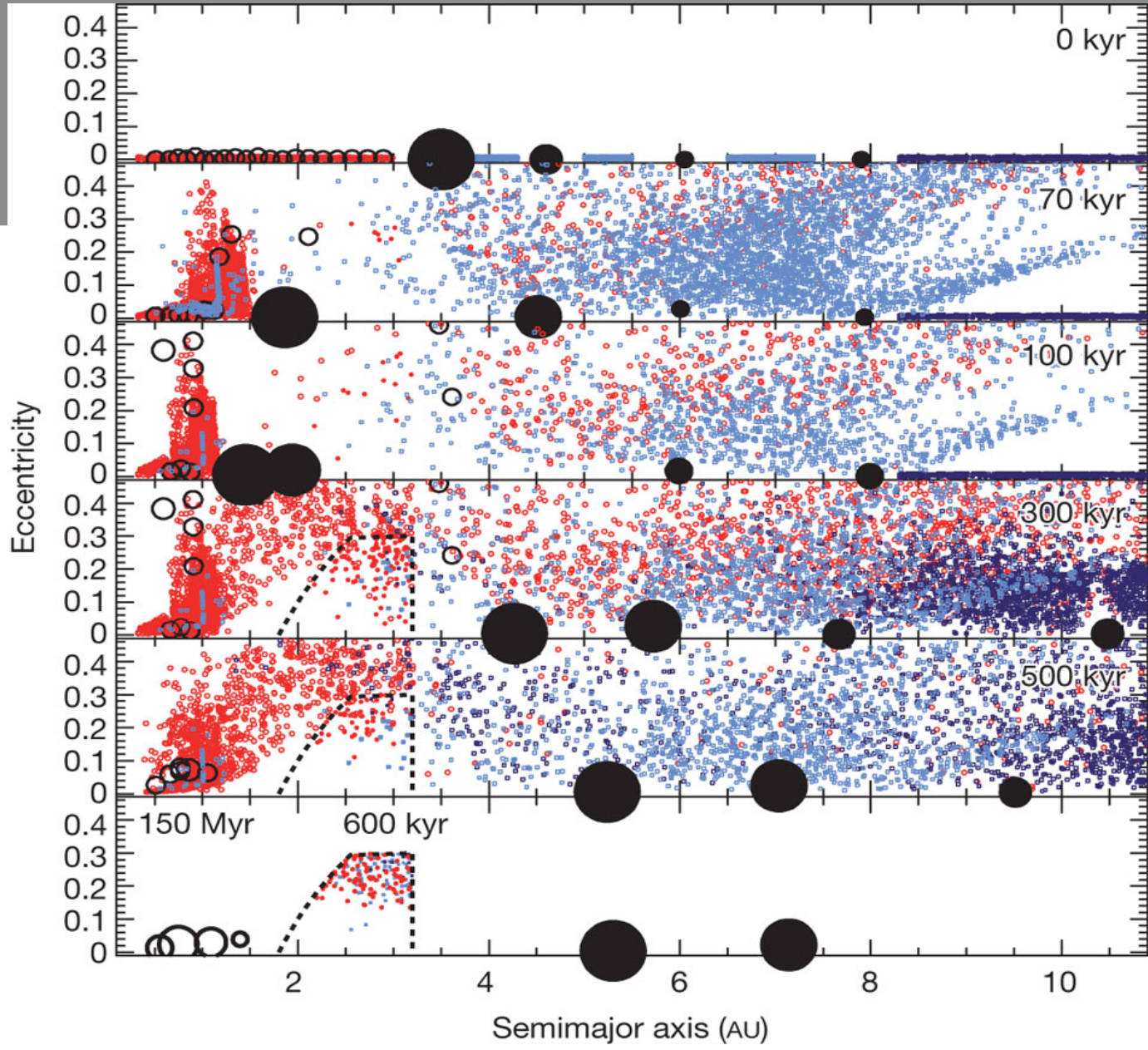


Source: Wikipedia, after Gomez et al. 2005

Migration implies that objects may cross the snow line

Some minor bodies may cross the snow line!

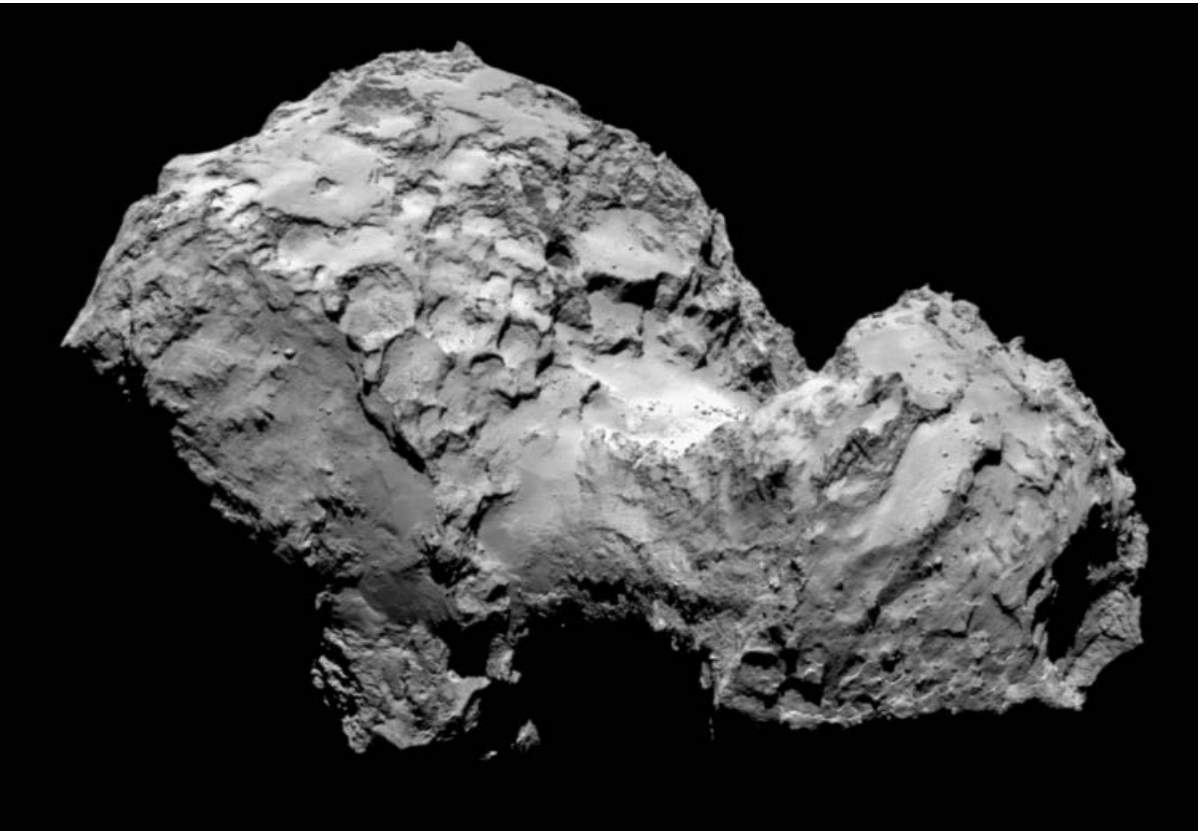
Ice may then survive until today in the interior of those bodies



From: Walsh et al. 2011

Cometary Science topics (related to formation)

- Were comets formed in the protoplanetary disk or are they the product of collisions in the Kuiper belt?
  - Main “observable” difference is the impact/collision velocity



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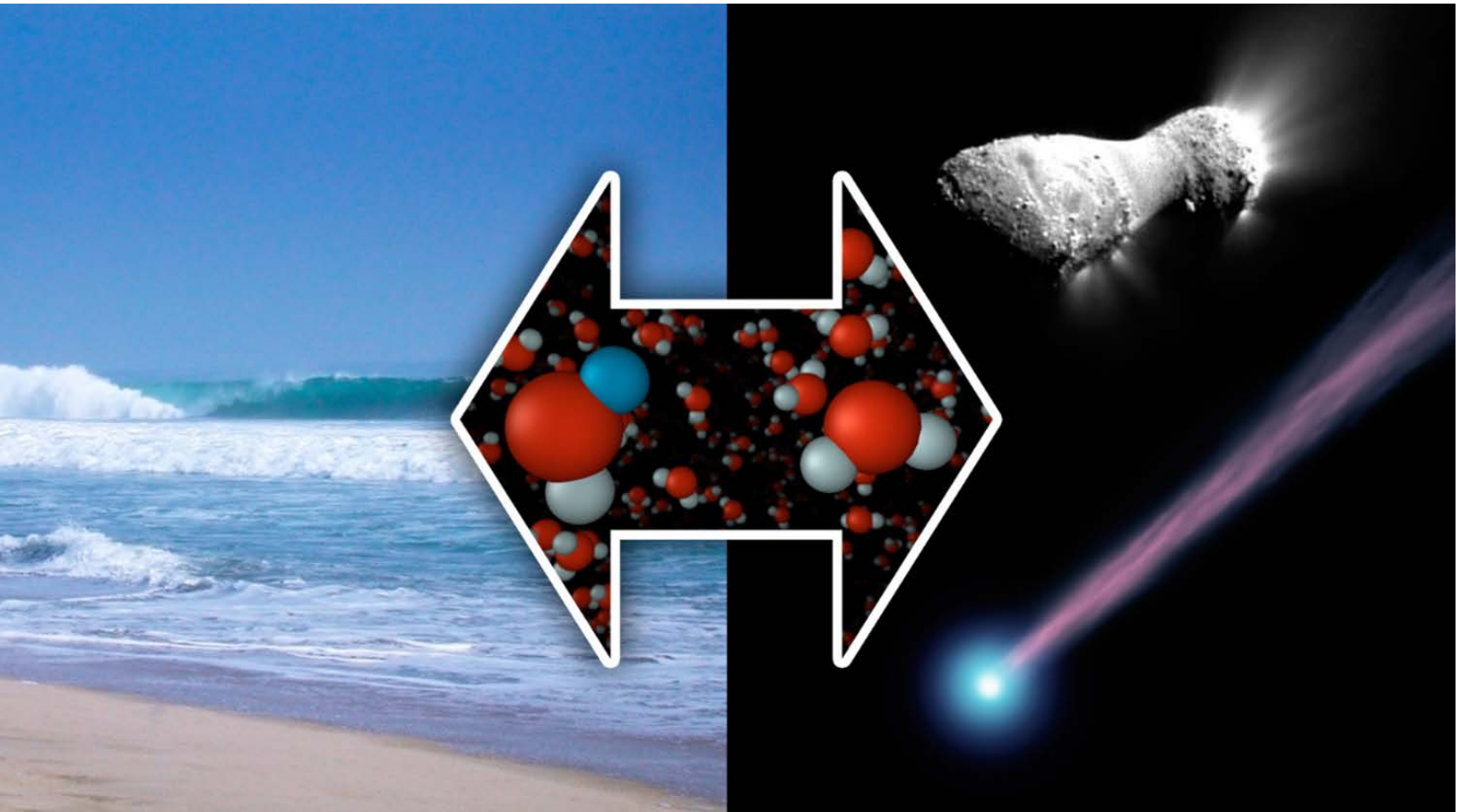
Did comets bring water and organics to Earth?

- Earth did form inside the snowline
  - ❑ Where does the water come from?



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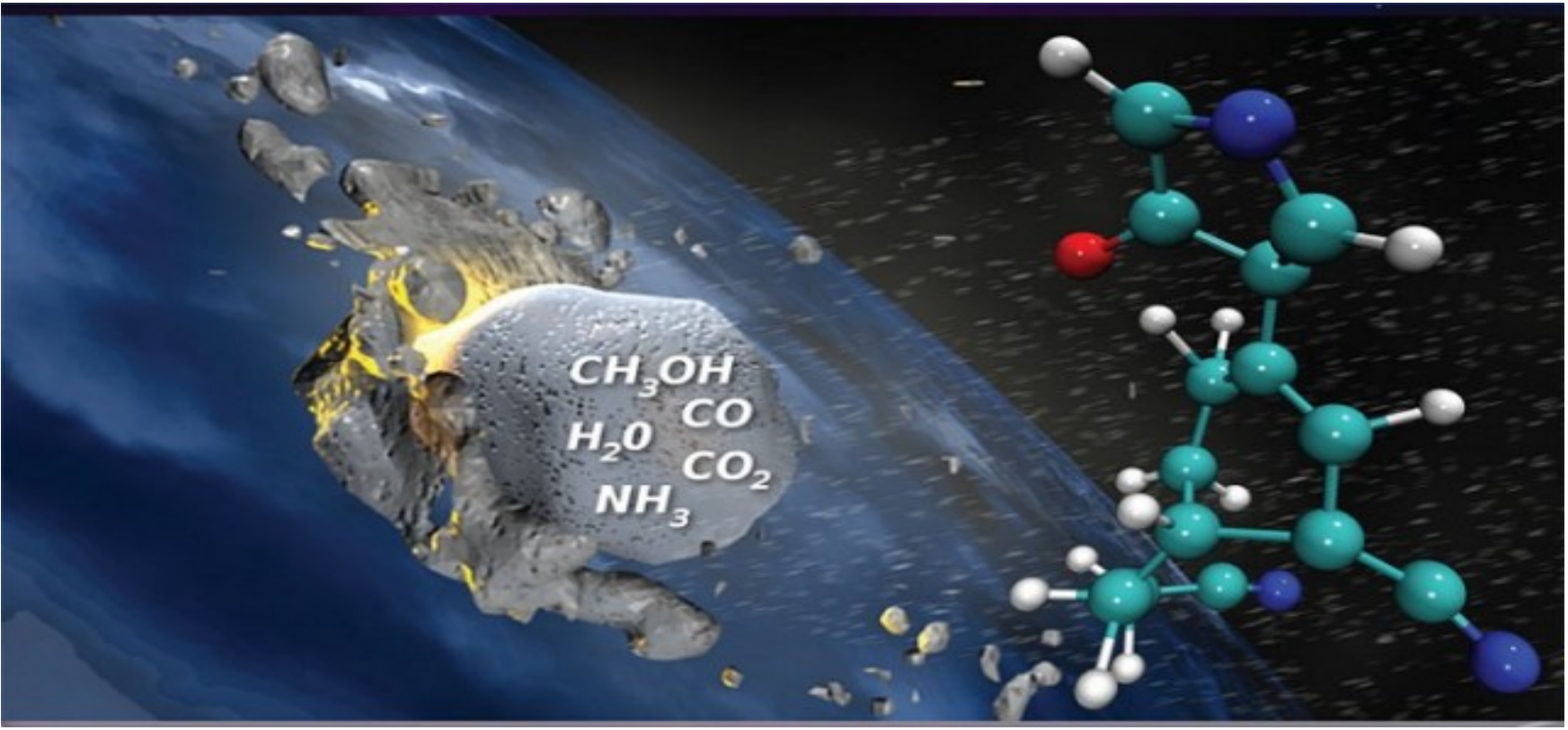
Did comets bring organic material to Earth (building blocks of life)?



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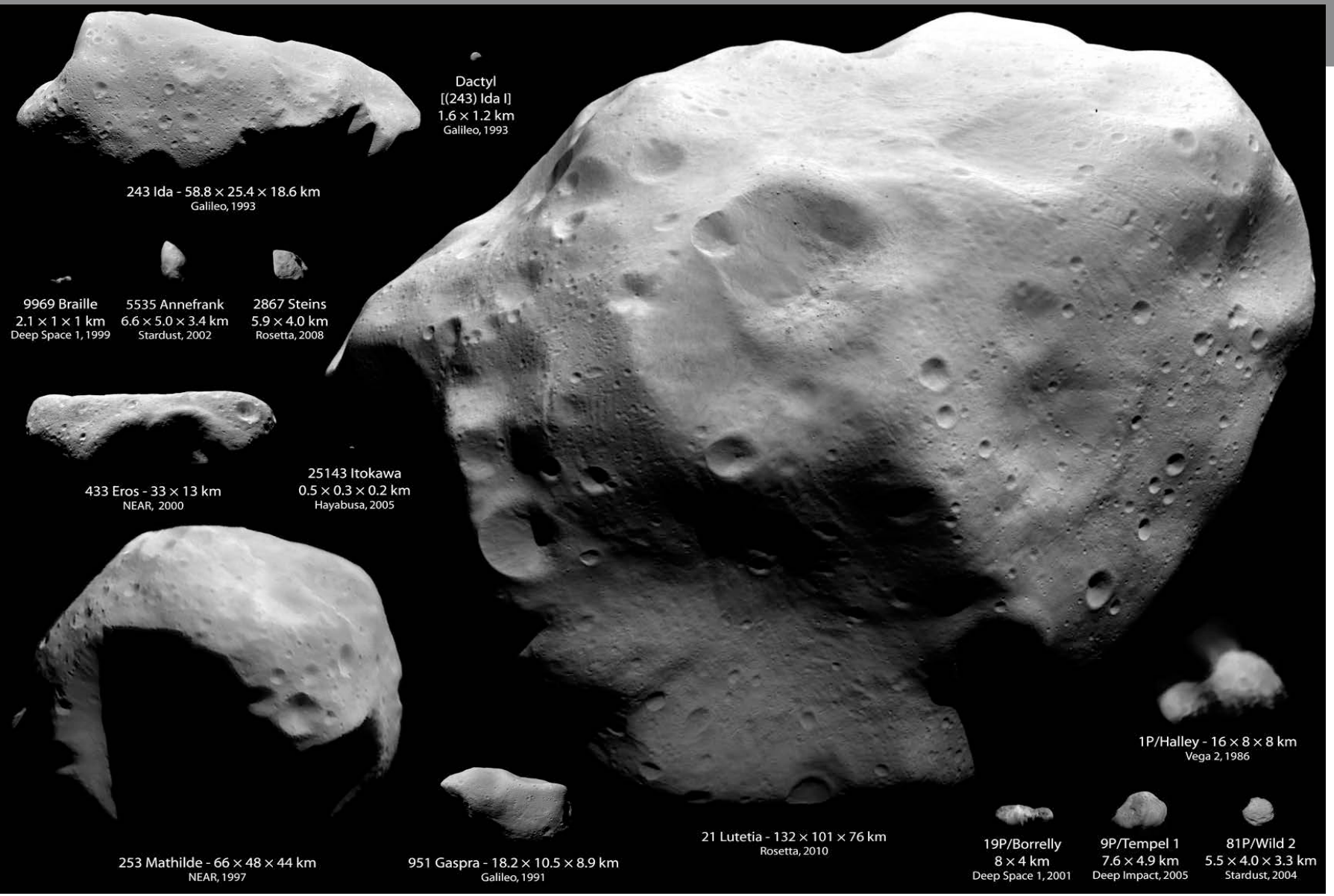
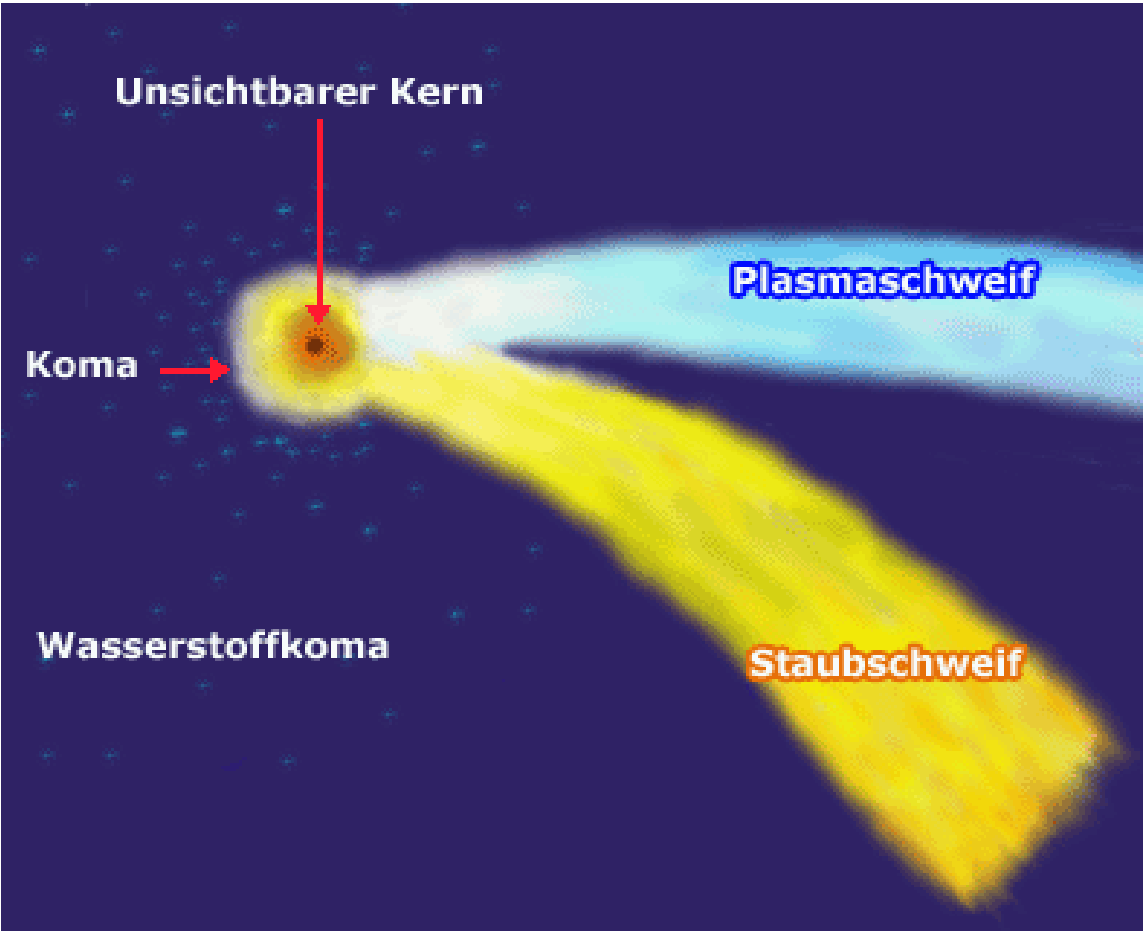
Asteroids and Comets overview (spacecraft visits)



Source:

E. Lakdawalla

❑ How do comets look like?



- Nucleus with diameter of few km
  - ❑ Made of ice (mostly water ice) and dust
- On approach to the sun, ice sublimates and carries dust with it
  (the coma forms)
- Gas is ionized by solar UV-radiation and carried away by the solar wind
- Dust is pushed away from the sun by solar radiation pressure

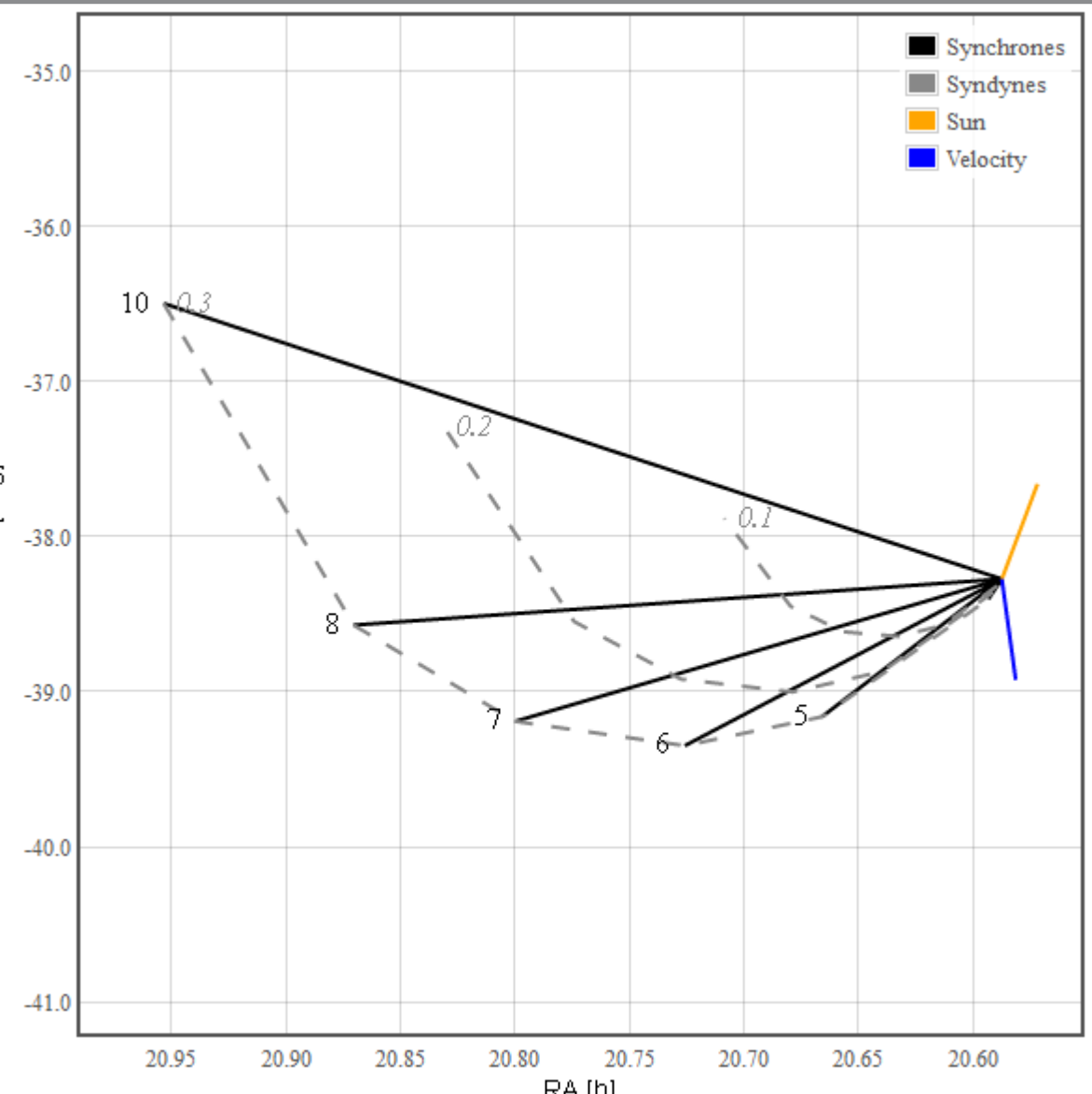
Dust tail: Synchrones and syndynes

- Particles in the dust tail are influenced by 2 forces:
  1. Solar gravity ~ mass
  2. Solar radiation pressure ~ surface area
- Neglecting ejection velocity, position of particle in tail depends on
  1. Time of ejection
  2. β = rad. pressure/ gravity ~ 1/(ρd) ρ: Density
     d: Size

Synchrones: Lines describing particles ejected at the same time

Syndynes: Lines describing particles of same β (~size)

Synchrones and syndynes (example comet Garrad 2006 P1)



Source J.-B. Vincent

Cometary nuclei visited by spacecraft

Overall, all look different: Different formation or different evolution?

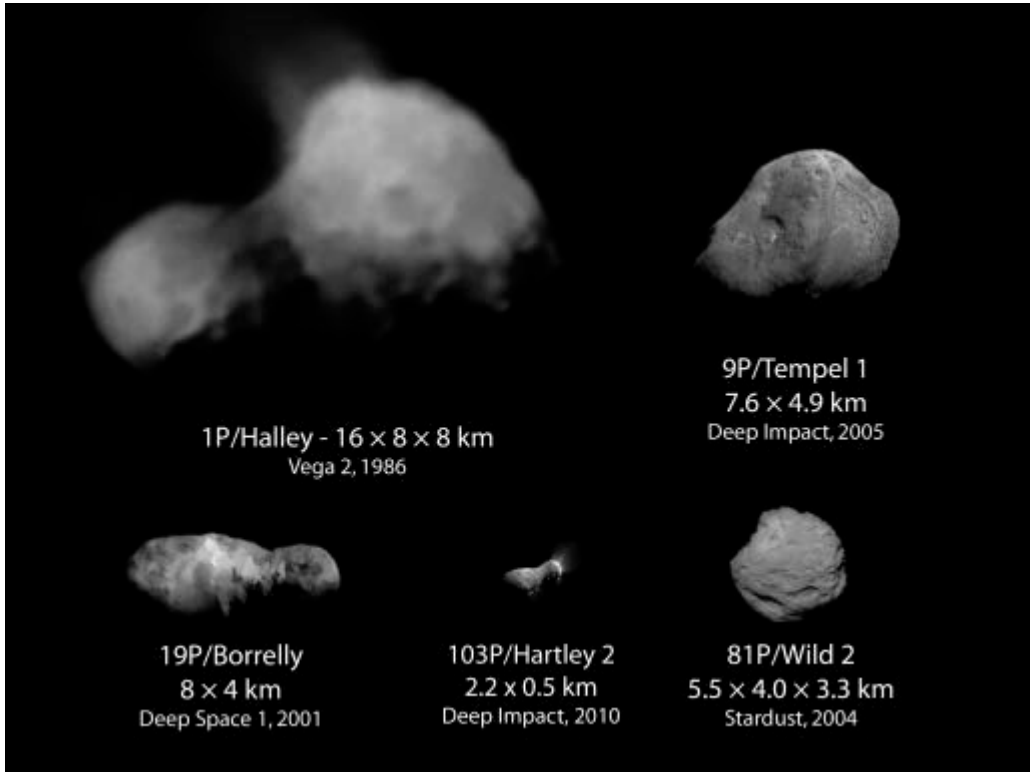


Image credit: L. Elenin

1P/Halley: Highly active, low albedo, relatively little geological information about the surface

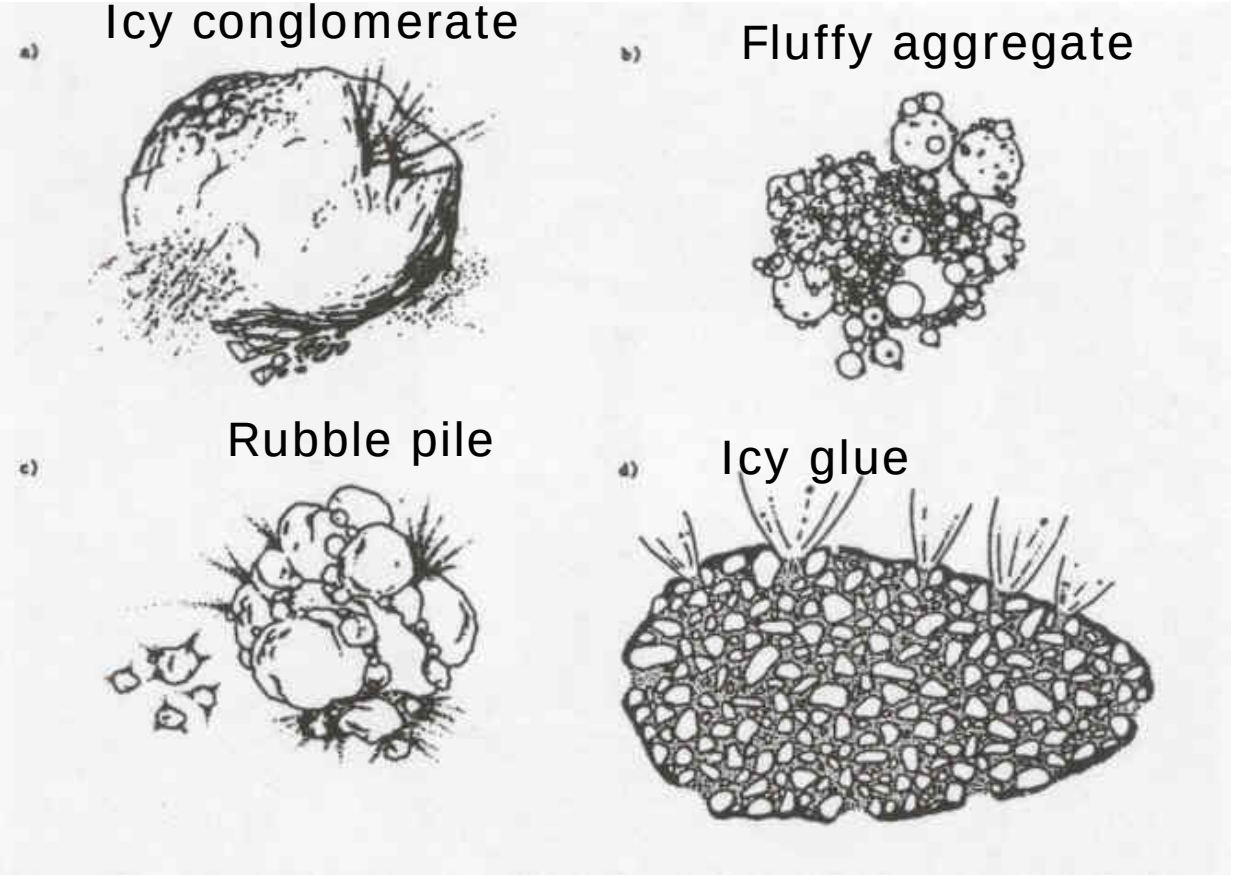
19P/Borrelly: Diverse geology, different types of terrain, no ice found on surface!

81P/Wild: Rugged terrain, impact craters ?

9P/Tempel 1: Diverse terrain, primordial layers found?, impact craters ?, very little ice found on surface

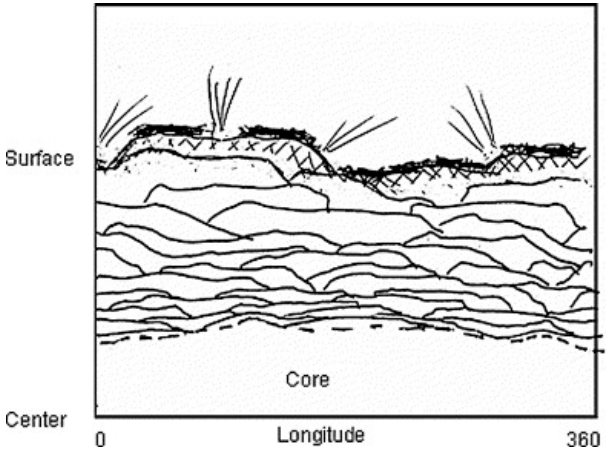
103P/Hartley 2: Hyperactive, diverse terrain, extreme shape, ice blocks (cm-dm sized) emitted from nucleus

Models of comet nuclei structure and formation (before Rosetta)



Credit: Donn et al., Weissman

- Models are quite different, but we cannot distinguish which is correct
  - ❑ Deep Impact mission added a fifth model (primordial layers)



Credit: Belton et al.

How does cometary activity work?

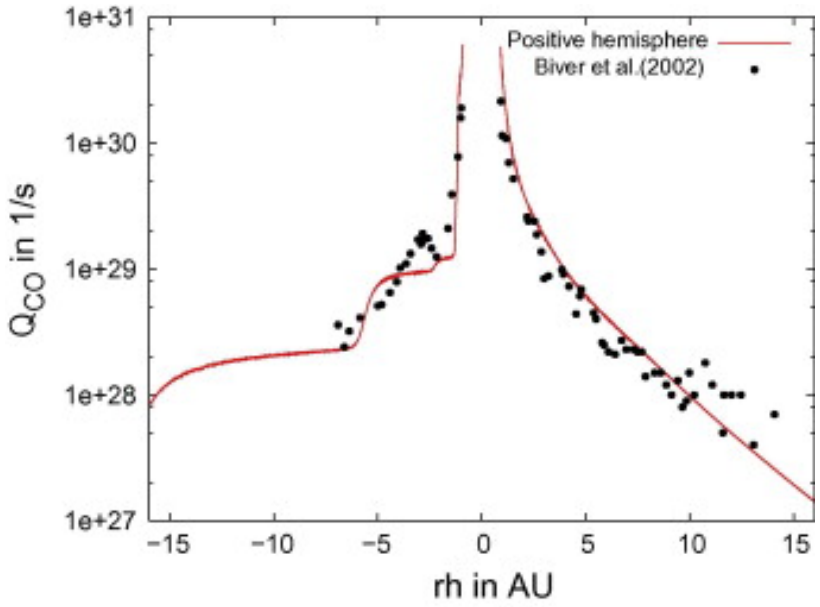
- Basic idea:
  - Comet is an ice/dust mixture
  - On approach to the sun, ice evaporates and carries dust with it

But:

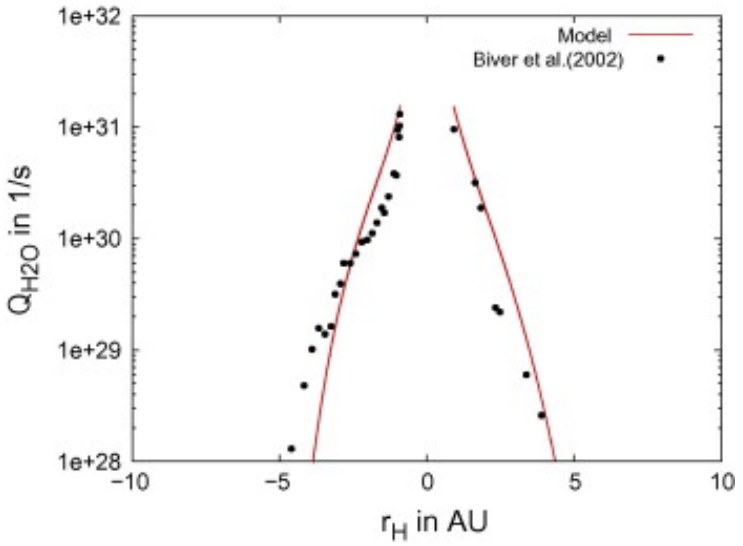
- Little or no surface ice found on cometary nuclei
- However, subsurface activity difficult to sustain
  - Too much dust carried away by gas: Sublimation front moves towards to the surface
  - Not enough dust carried away by gas: Dust layer above ice becomes larger and larger => activity is choked
- Also, evolution of activity of comet Hale-Bopp with distance from the sun appears most consistent with surface activity
- How do the ice blocks seen on Hartley 2 fit in the picture?

Comet Hale-Bopp: Measured vs. modelled production rate

CO



water

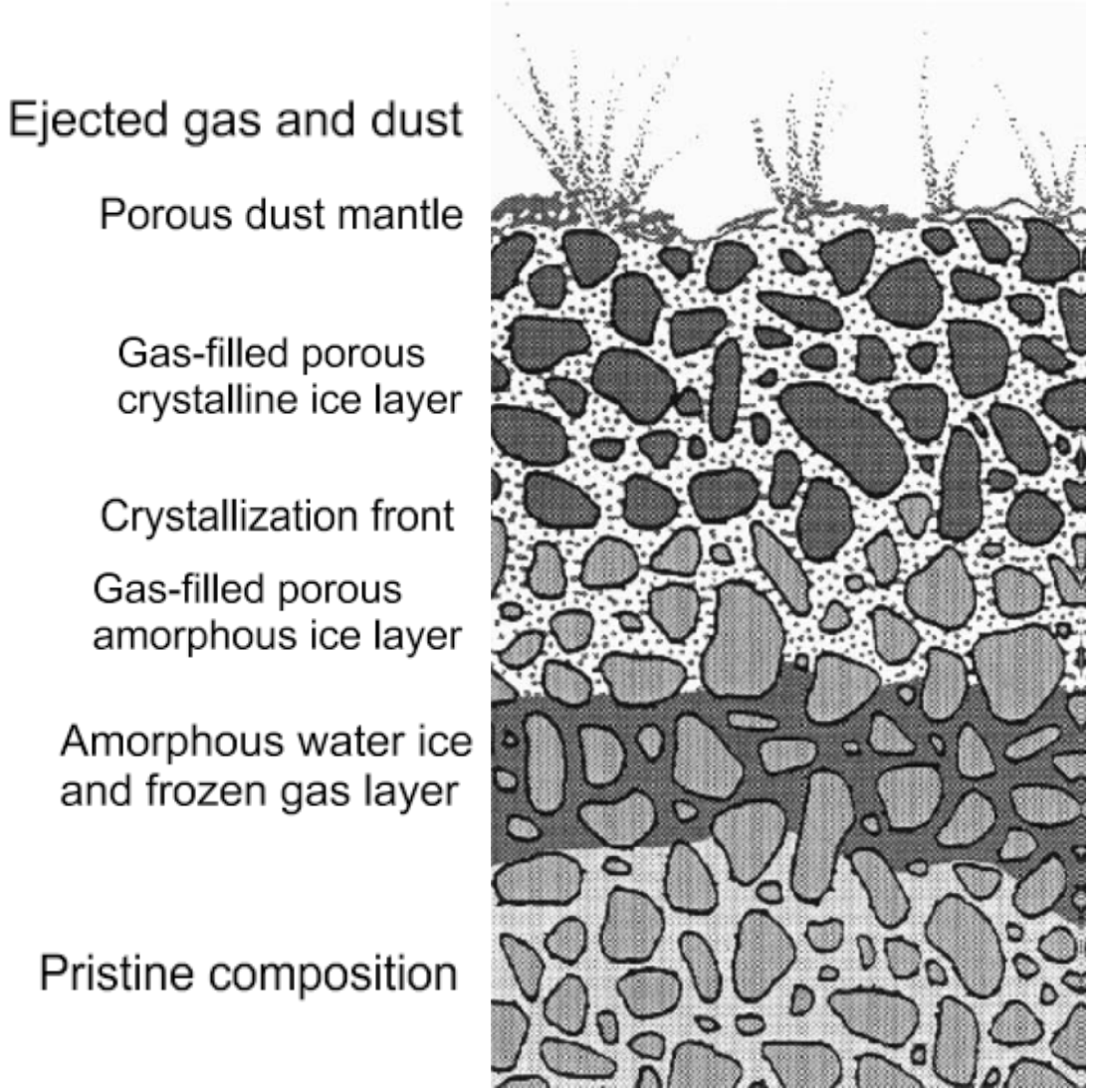


This is the best model fit achieved, sublimation happens at the (very near) surface

Image credit:
Gortsas et al.

How does activity work? Possible solutions

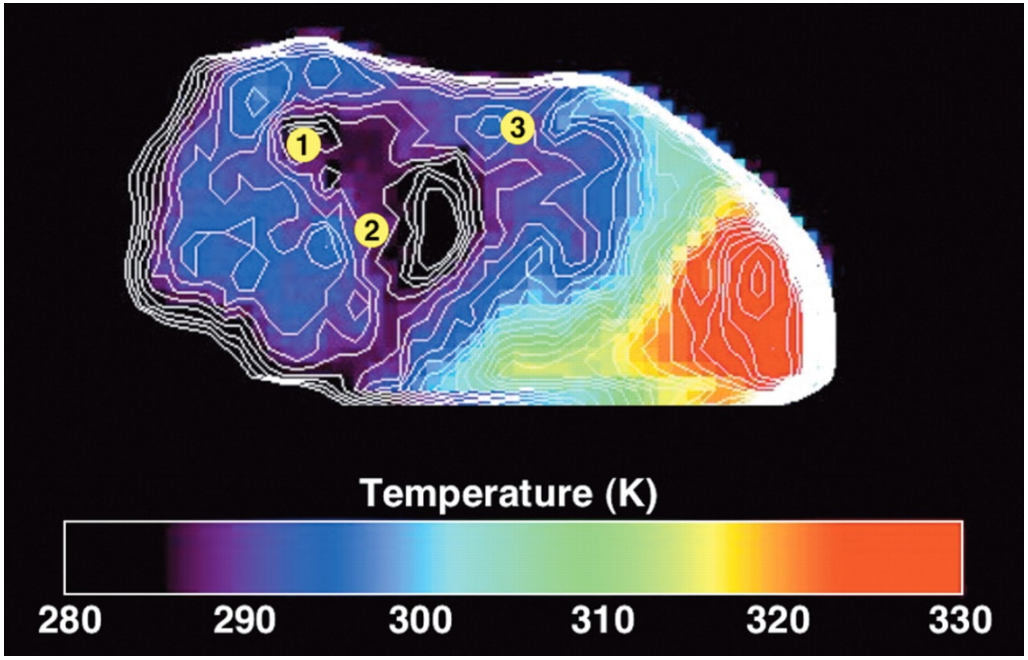
- 1) “Explosive” processes: e.g. Exothermal transformation of amorphous in crystalline ice
  - Allows to maintain subsurface activity
  - Difficult to explain heliocentric variation
    - In those models CO activity does not change much over the orbit



Credit: D. Prialnik

How does cometary activity work? Possible solutions

- 2) Rapid removal of the surface layer
  - Removed more quickly than the interior is heated up
  - Why no surface ice?
    - Dust just above the surface hides view?
    - Intimate mixture of ice and dust hides spectral signature of ice?
    - But difficult to explain surface temperature distribution for Tempel 1



- Region where ice is detected on Tempel 1 are colder
- Not expected for intimate mixture
- Recondensation?

Credit: Sunshine et al.

Additional problem: Gas pressure needs to overcome gravity and tensile strength of dust

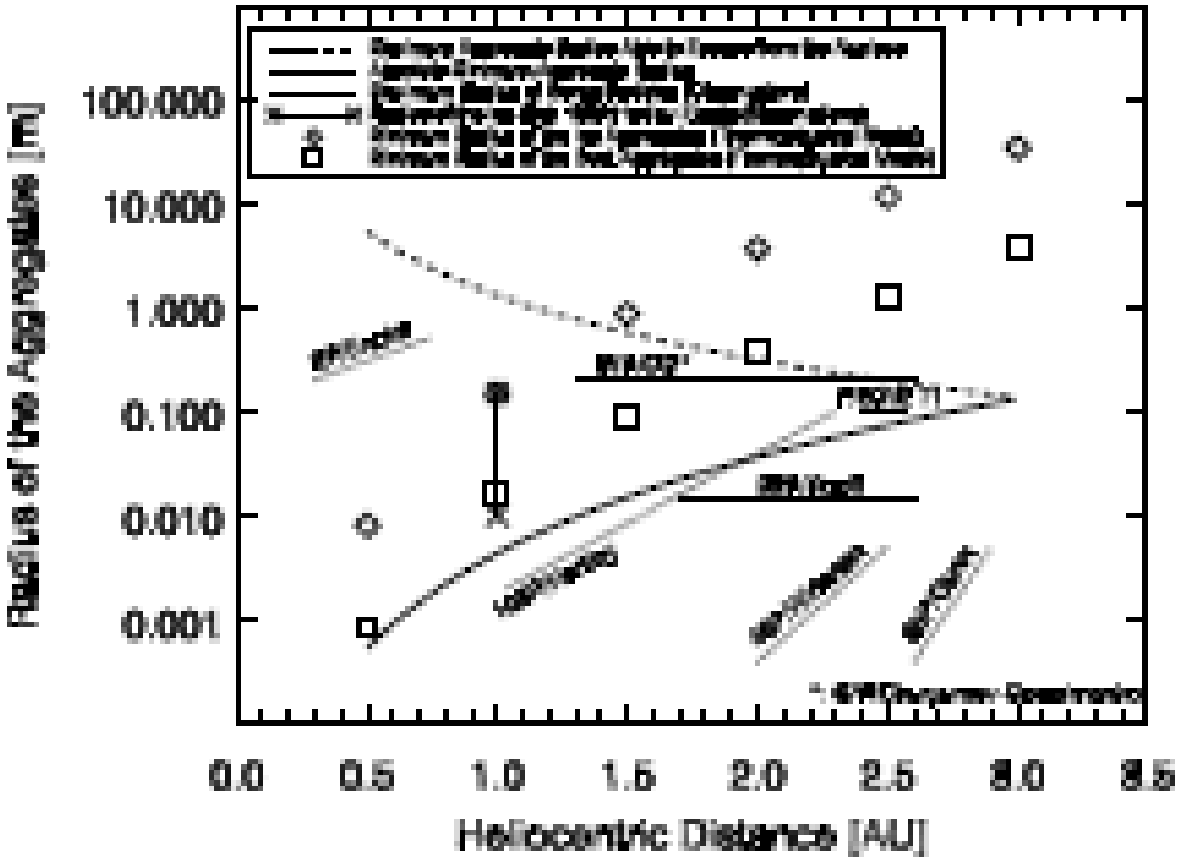
- Pressure ~r^2, gravity ~r^3
  => Largest liftible particle

- Tensile strength decreases with size
  => Smallest liftible particle

Shows:
Pressure from water sublimation is insufficient!

More volatile gases (CO, CO_2) create somewhat higher pressure, nevertheless:

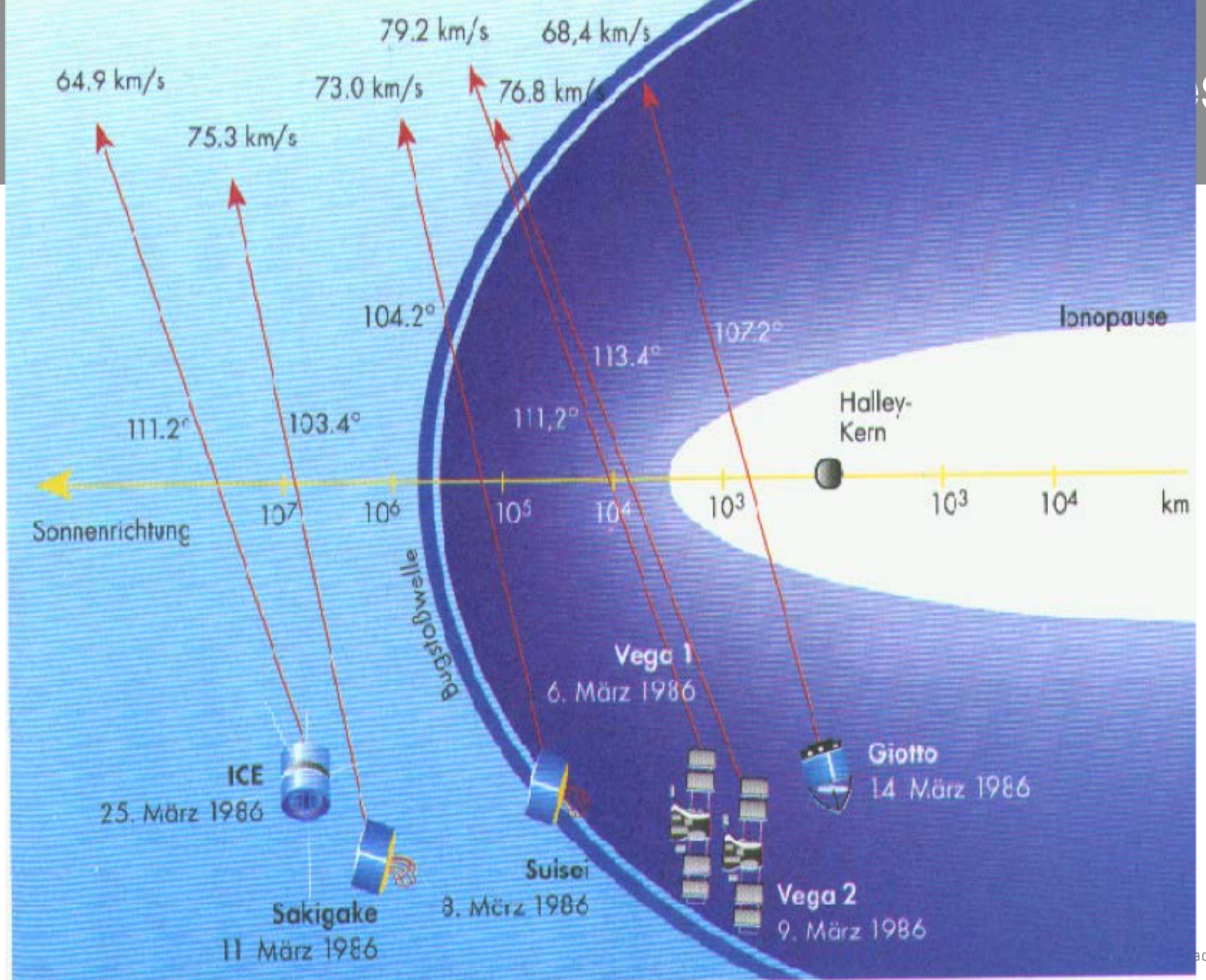
Activity is not really understood



Blum et al. 2014, 2015

Missions to comets before Rosetta

- First comet missions were the “Halley armada” in 1986
  - ESA, Russian, and Japanese spacecraft flew by comet Halley
- Further flybys over the years
  - Deep Space 1 at Borelly (2001)
  - Stardust at Wild 2 (Comet coma sample return)
  - Deep Impact (extended mission) at Hartley 2 in 2010
- Flyby + Impact by Deep Impact in 2005 (Comet Tempel 1)


79.2 km/s
68,4 km/s
64.9 km/s
73.0 km/s
76.8 km/s
75.3 km/s
104.2°
113.4°
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Ionopause
111.2°
103.4°
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Halley-
Kern
Sonnenrichtung
10^7
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10^5
10^4
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10^3
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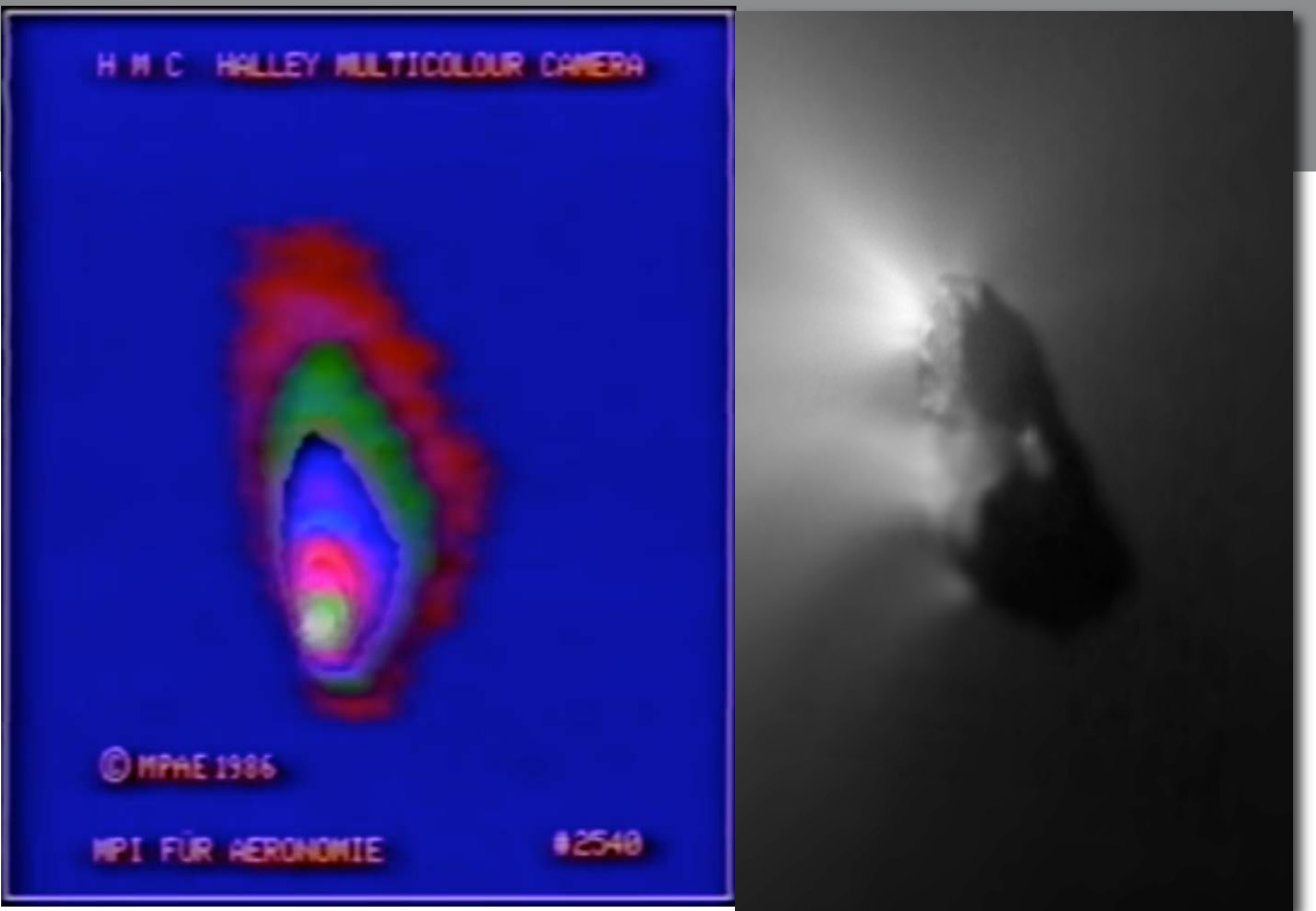
km
Bugstoßwelle
Vega 1
6. März 1986
Giotto
14. März 1986
ICE
25. März 1986
Suisei
8. März 1986
Vega 2
9. März 1986
Sakigake
11. März 1986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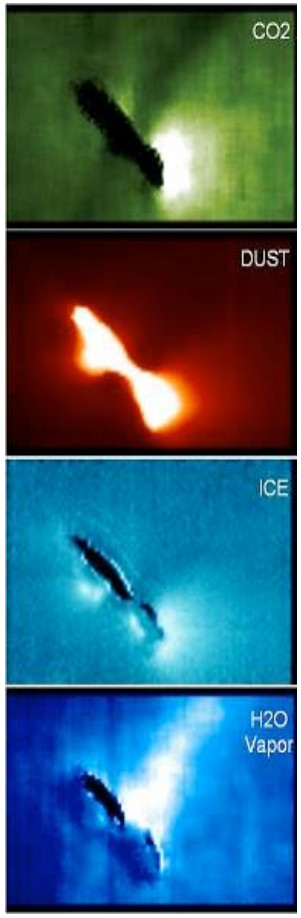
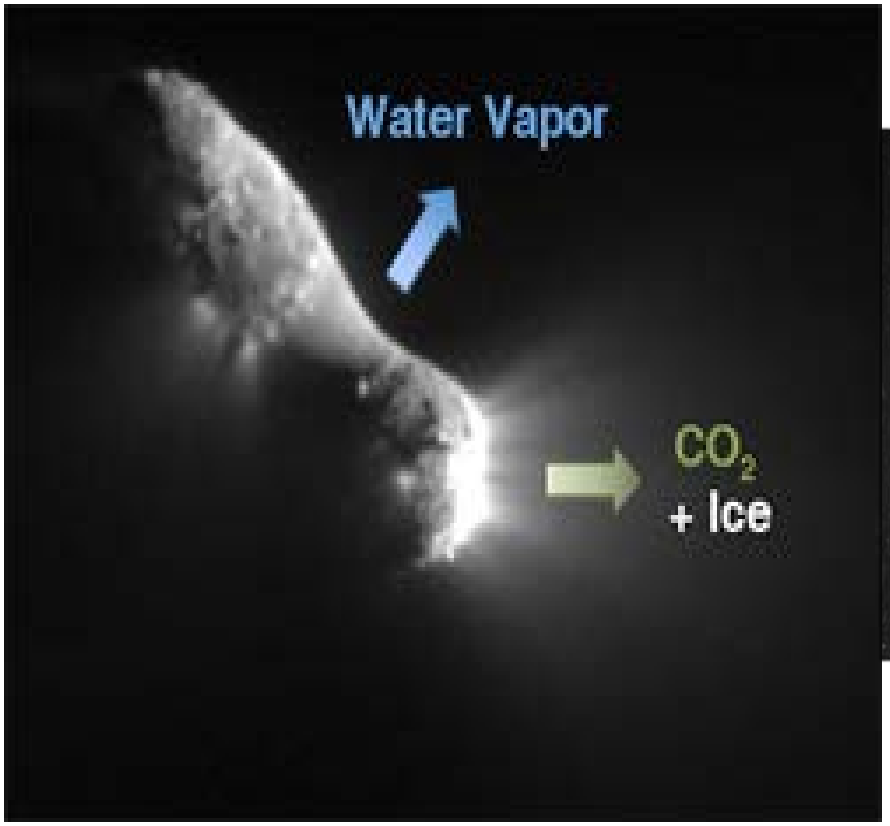
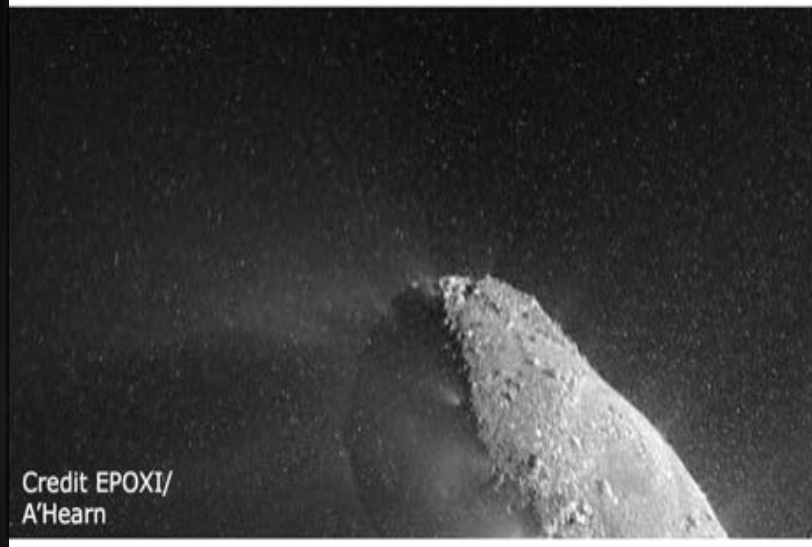
Comet Hartley 2: Inhomogeneous activity



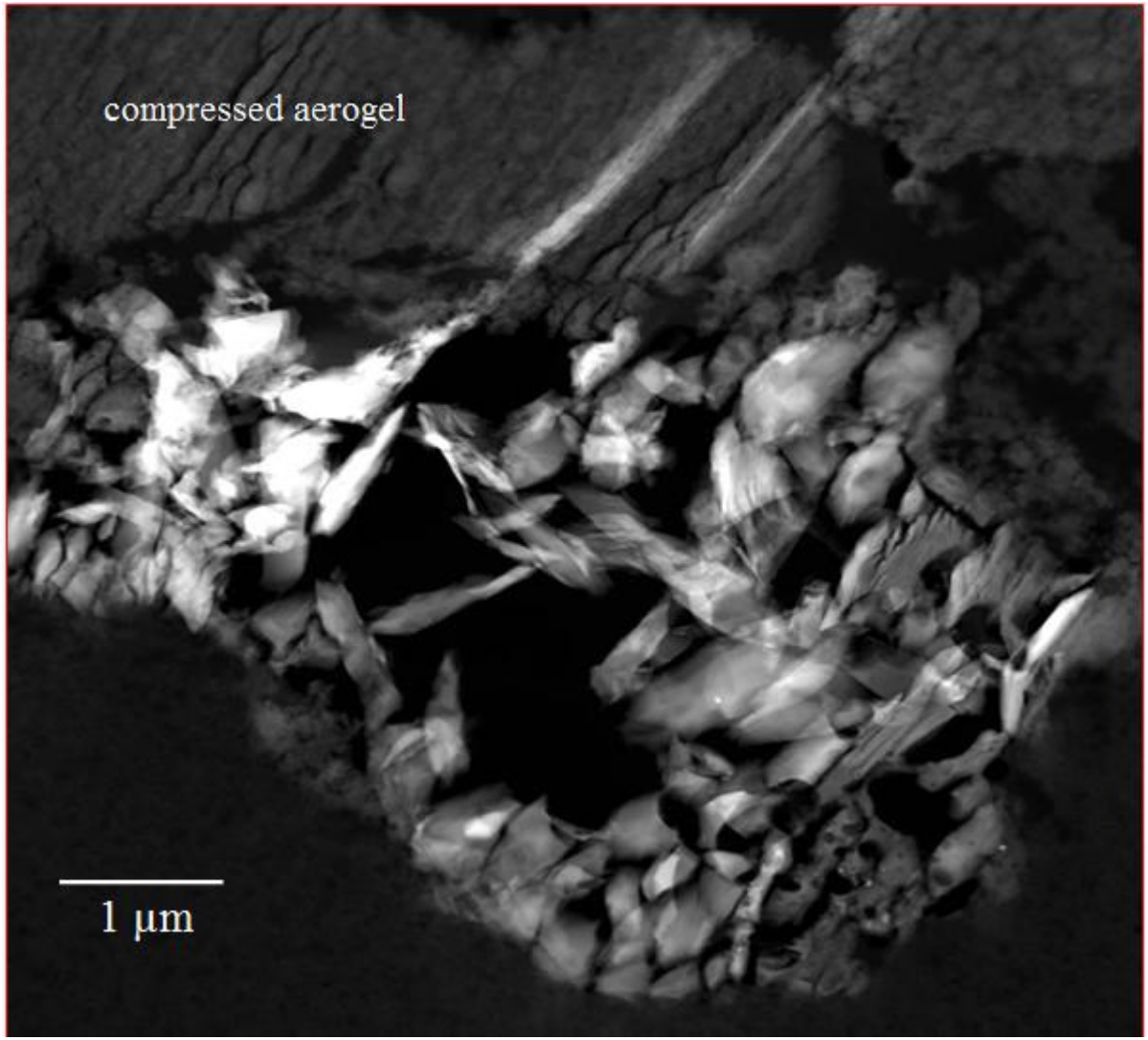




Stardust: High temperature material found in comet coma

- Calcium Aluminium rich Incusions (CAIs) found that form at high temperatures

=> Comet contains material from the inner solar system!



Summary

- Comets are remnants of planet formation
- Major science questions:
  - Did comets form in its current size/shape in the protoplanetary disks or are they collision products from the Kuiper belt?
  - Did comets bring water and the building blocks of life to Earth?
  - What is the structure of the nucleus?
  - How does cometary activity work?