Comets: Formation and early evolution

Hans Rickman

Comet formation

- ***For sure:***
- *Time & place*: the solar nebula, beyond the snow line!
- *Identity*: icy planetesimals!

- ***Under debate:***
- *Mechanism*: pebble swarm or slow accretion?
- *Material*: pre-solar grains or condensates?

Properties: **Porosity**

- ***67P/Churyumov-Gerasimenko (****Rosetta****)***

- *Density:* 0.533 ± 0.006 g/cc (RSI+OSIRIS)
- *Dust/Gas Ratio:* 4 ± 2 (Giada+OSIRIS)

  This is very large; even 6 has been suggested

- ***Porosity = density / compact density*** ⇒ 72–74% (Pätzold et al. 2016)

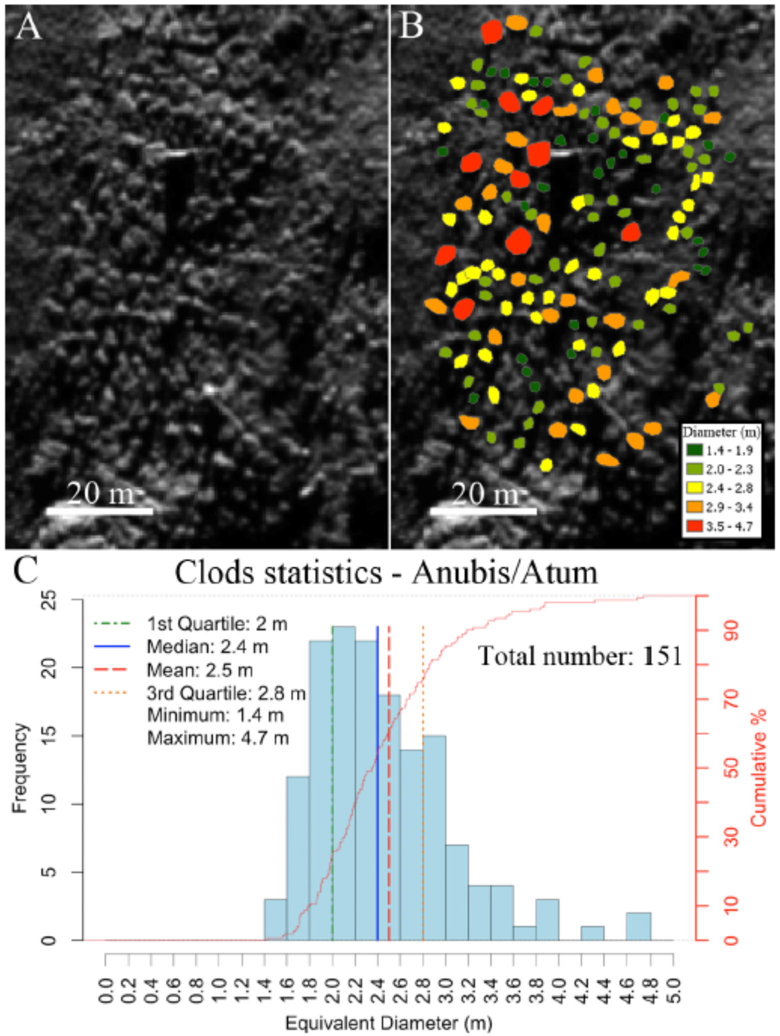
This is mainly micro-porosity (no large voids)

Properties: **Being pristine**

- ***Risks of modification:*** *Radiogenic heating* (^{26}Al, ^{40}K); *Collisions at high speed*

- ^{26}Al heating may purge km-sized comets of super-volatiles, contrary to observations
- But this is *strongly dependent on the time of formation*!
- *Low-velocity accretion* is required to avoid compaction yielding too high density

Davidsson et al. (2016)



"goosebumps"

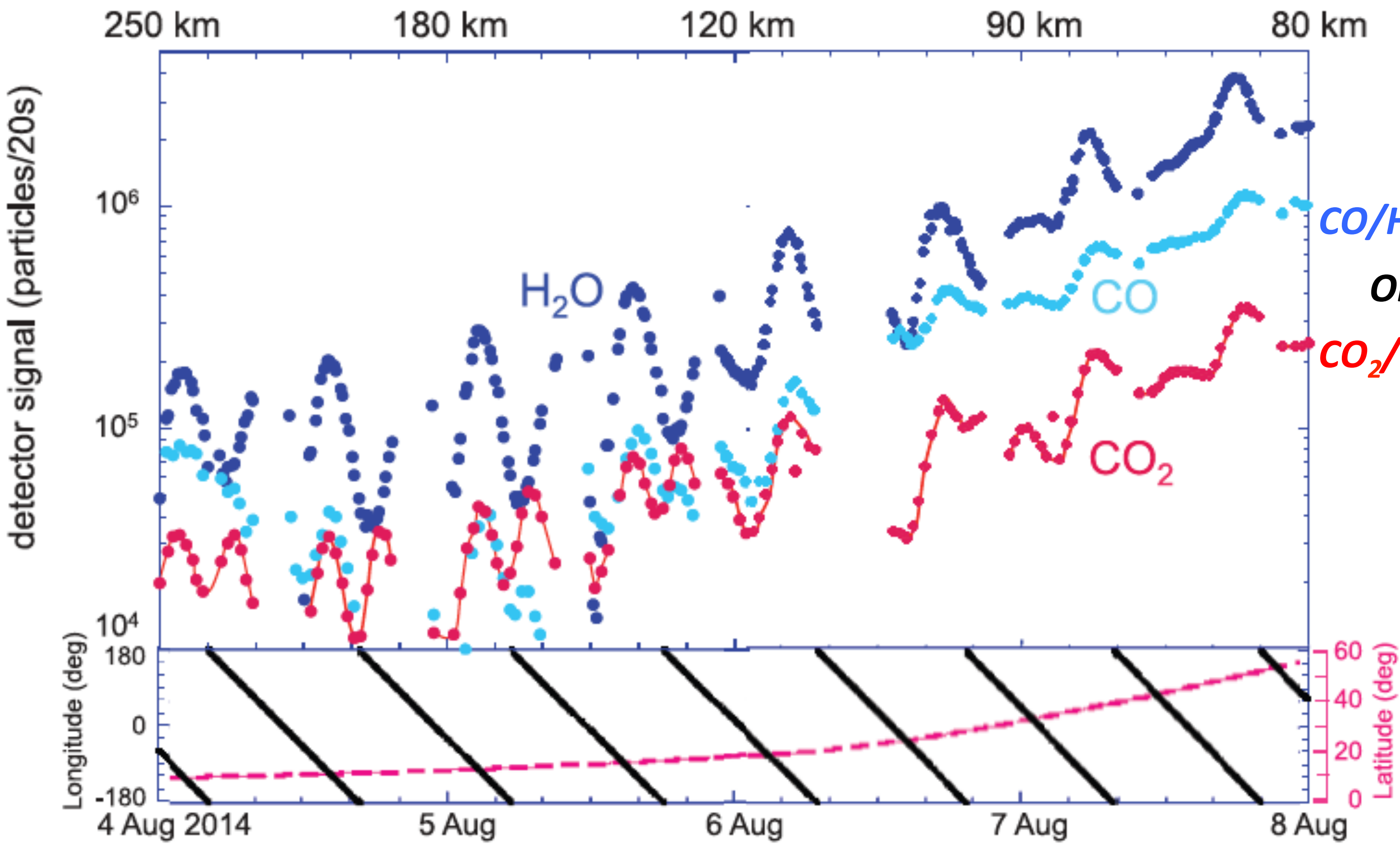
Possibly, original structural units: St ≈ 1

Properties: **Composition**

- ***67P Rosetta measurements***

- *Main contributors so far:*
- *Volatiles:* ROSINA orbiting mass spectrometer
- *Refractories:* VIRTIS near-IR spectrometry of the nucleus surface (mainly organics)
- *Bulk:* *DGR* from production rates of solids and gases measured by different instruments

Hässig et al. (2015) **ROSINA**



CO/H_2O=0.13

On average

CO_2/H_2O=0.08

Both CO and CO_2 are major, oxidized volatiles

Minor gaseous species

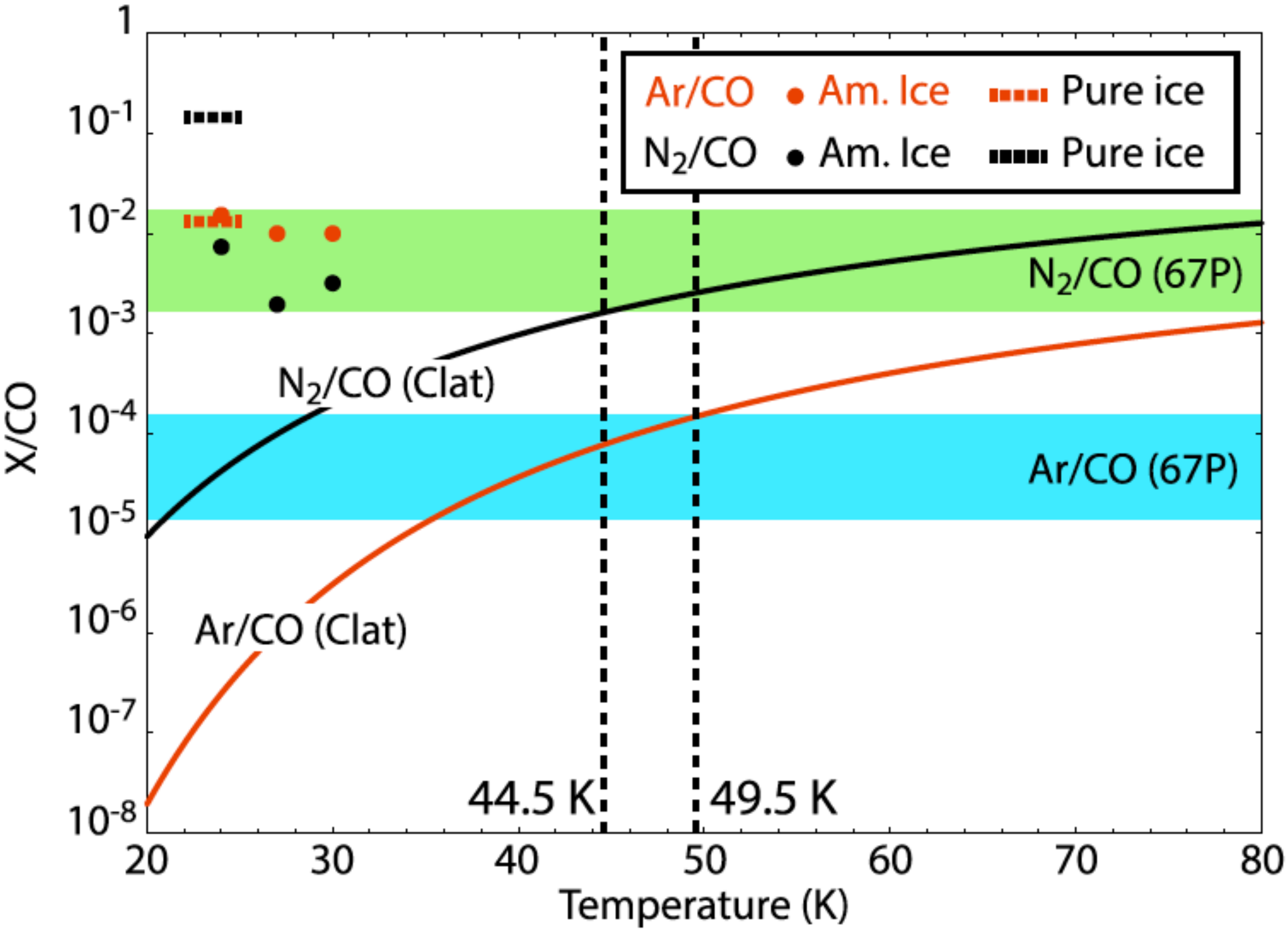
- ***Data from ROSINA in 67P:***

  First detections!

- $Q(O_2)/Q(H_2O) = 3.8\%$ (Bieler et al. 2015)
- [In retrospect, $Q(O_2)/Q(H_2O) = 3.7\%$ in 1P/ Halley]
- $Q(N_2)/Q(CO) \approx 1\%$ (Rubin et al. 2015)
- $Q(Ar)/Q(N_2) \approx 1\%$ (Balsiger et al. 2015)

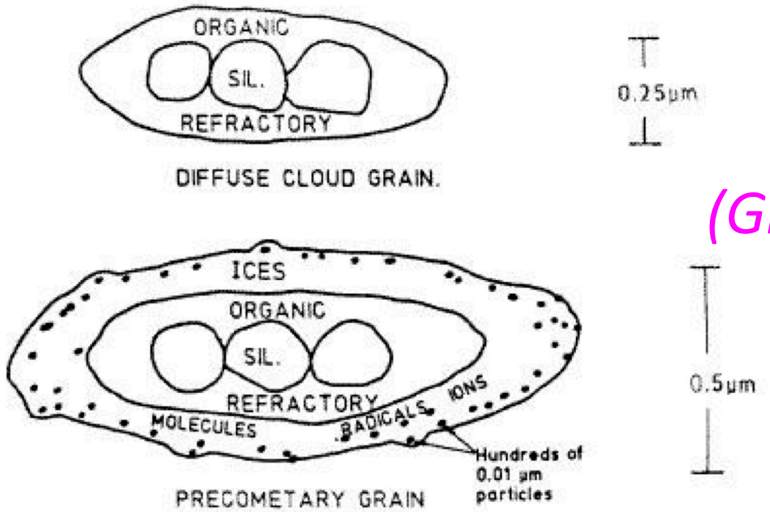
We cannot extrapolate to other comets!

Mousis et al. (2016)



Favored structure: crystalline clathrate

Cometary ice evolution



(Greenberg & Hage 1990)

Mousis et al.:

(1) Pre-solar core-mantle grains with likely amorphous ice
(2) Ice evaporation due to heating in the solar nebula
(3) Ice re-condensation at low T in opaque mid-plane layer
(4) Clathrate formation upon further cooling (?)

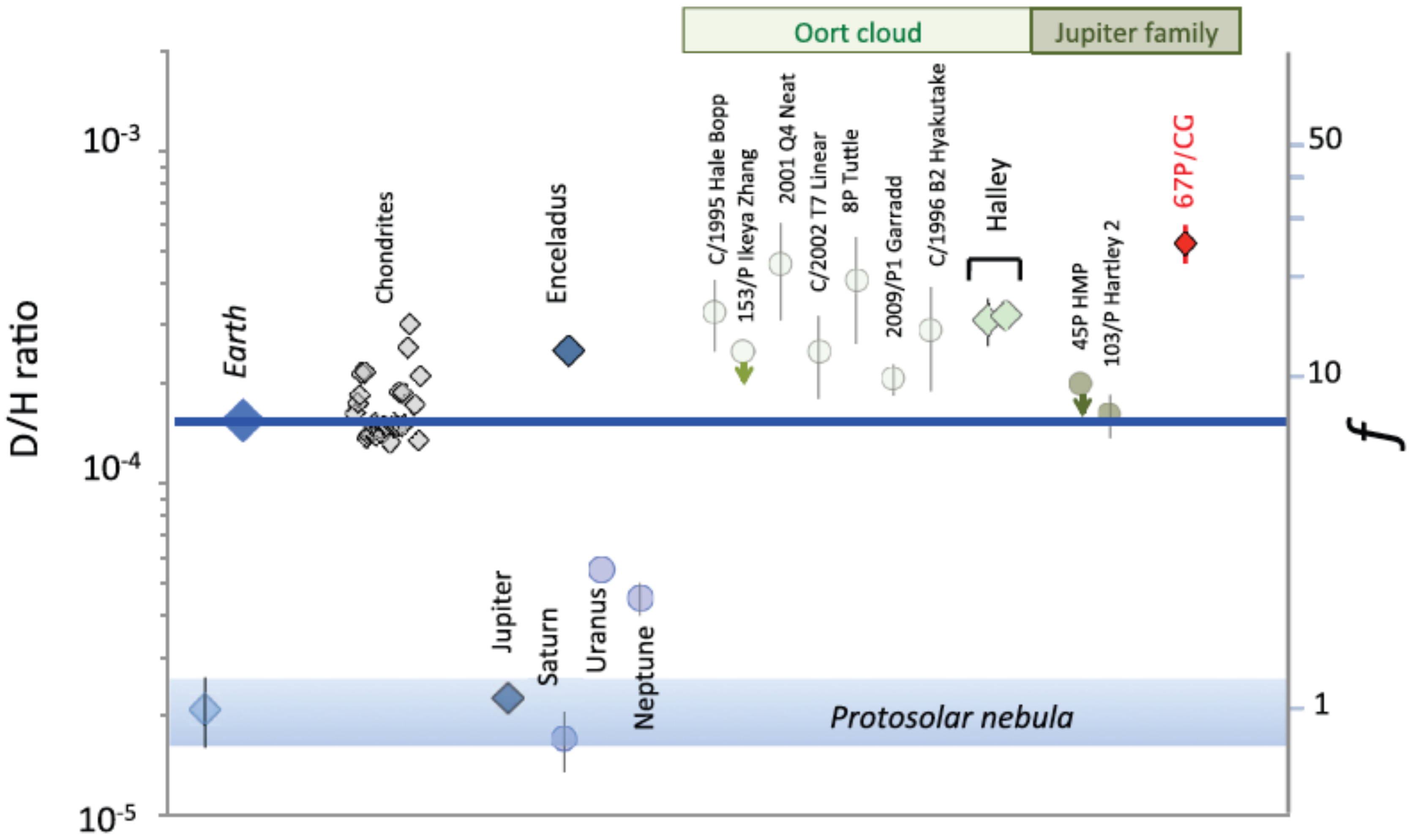
All this depends on heliocentric distance!

Properties: **D/H ratio**

- We express this in units of VSMOW (likely terrestrial value)
- **In 67P: D/H ≈ 3** (ROSINA - Altwegg et al. 2015)
- **In 103P: D/H ≈ 1** (Herschel – Hartogh et al. 2011)
- **In Halley, Hyakutake & Hale-Bopp: D/H ≈ 2**
- Both *Jupiter Family* and *Long-period* comets show a spread, roughly from 1 to 3

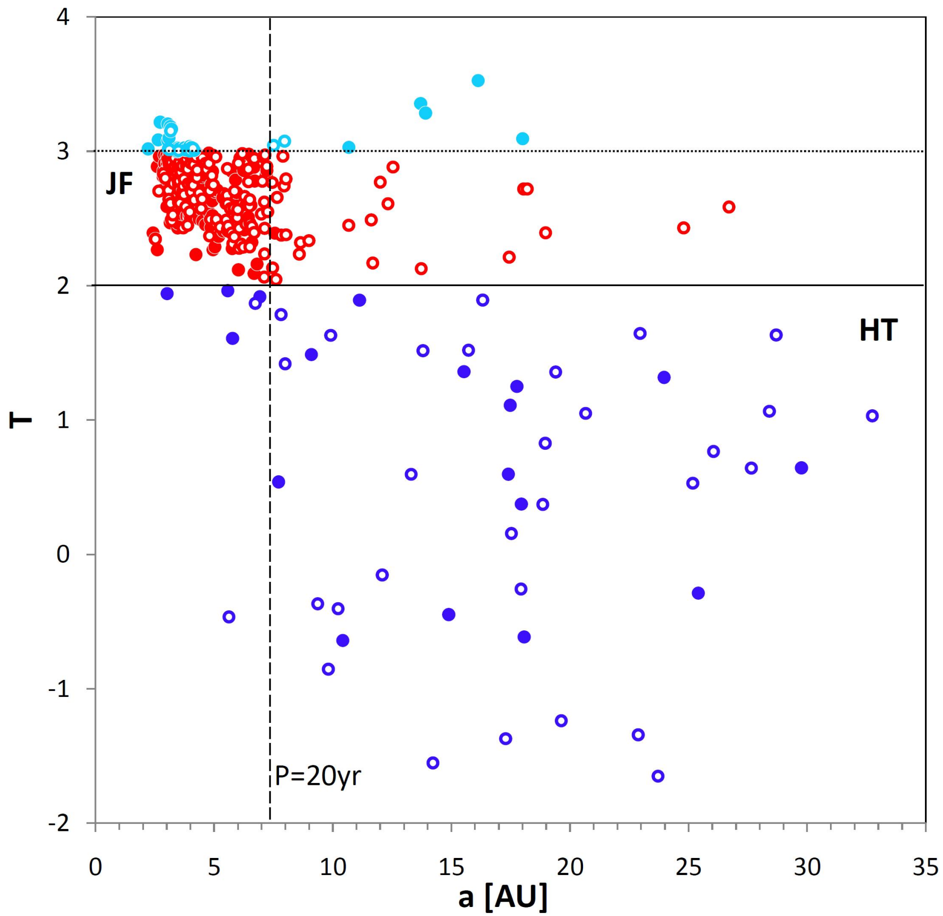
Comets of different types are similar

Altwegg et al. (2015)



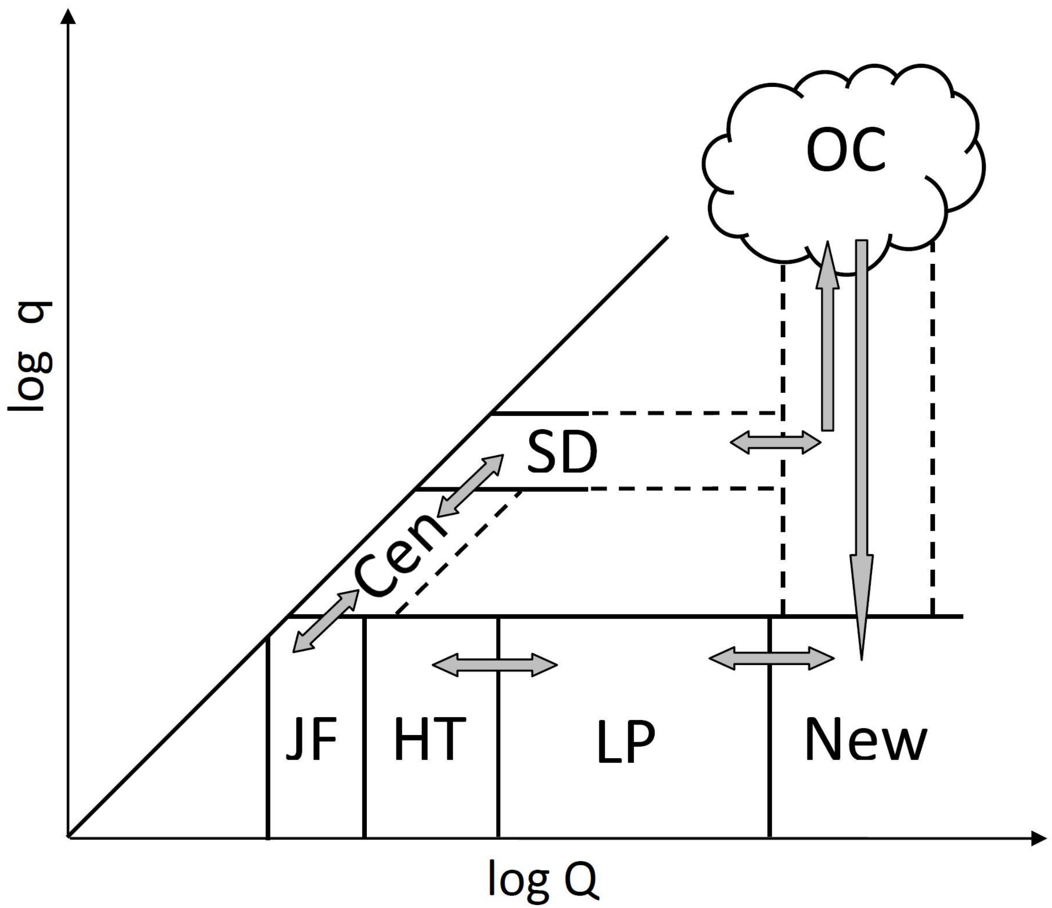
Earth's water was delivered as carbonaceous chondrites

Jupiter Family vs Halley Types



$$T = \frac{a_J}{a} + 2\sqrt{\frac{a}{a_J}(1-e^2)}\cos i$$

Roadmap of comet dynamics



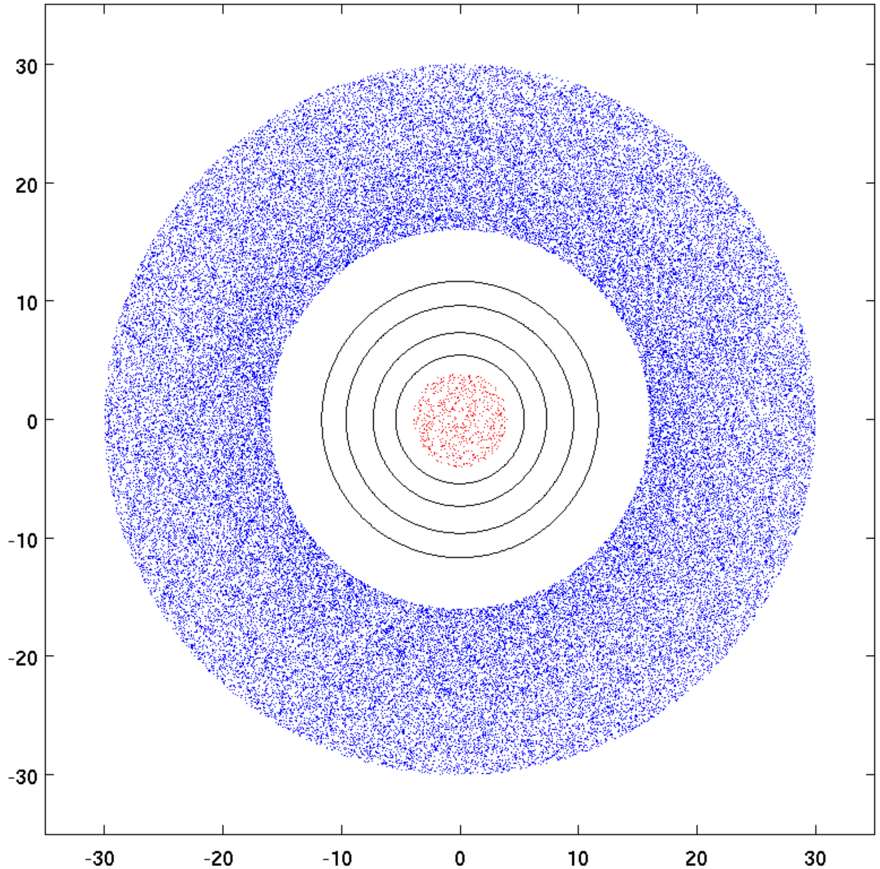
Observed comets

Source regions:

Jupiter Family: Scattered Disk

Halley Types: Oort Cloud

After dispersal of the solar nebula

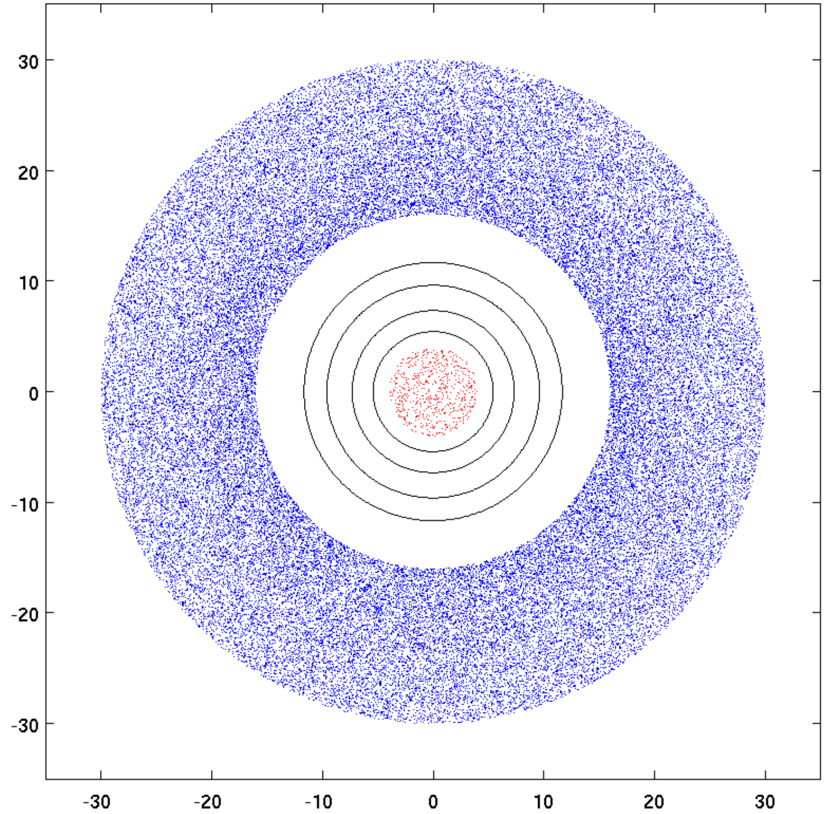


Rocky planetesimals

Icy planetesimals

Where did the GP stray planetesimals go?

How long did this last?



Did the Nice Model instability happen early or late?

Timing of the NM instability

- Traditionally, associated with the start of the Late Heavy Bombardment 4.1-4.2 Gyr ago
- But the NM does not depend on this timing, and the existence of the LHB is not certain
- Fine tuning is needed to explain the TP orbits with late instability (Kaib & Chambers 2016)
- Jumping Jupiter scenario is anyway needed to explain MB asteroid orbits (Toliou et al 2016)

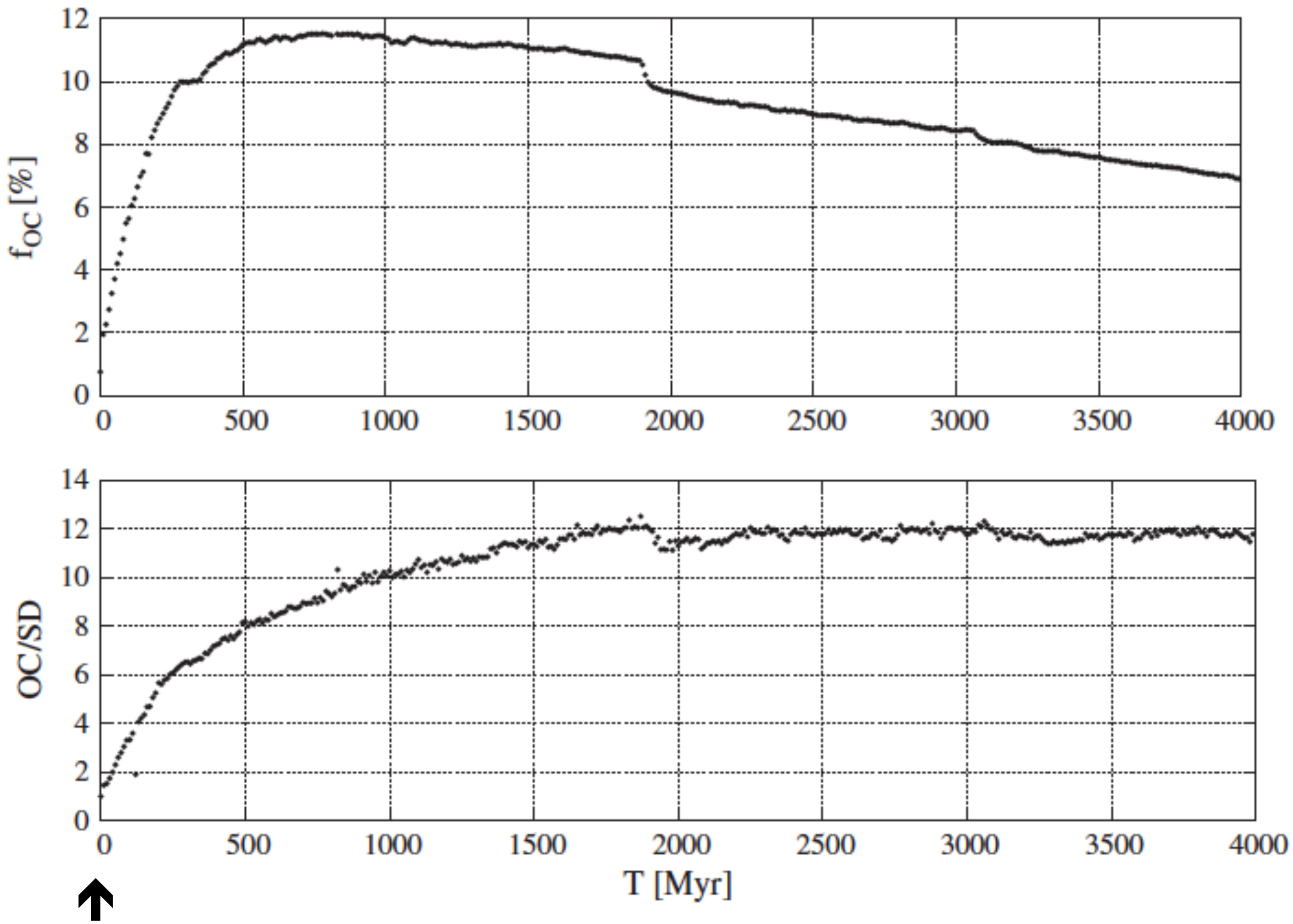
Very early or late instability: Open issue

Consequences of the instability

- ***Migration of ice giants*** through the disk of icy planetesimals $\Rightarrow$ Dispersal by grav. scattering

- ***Outward scattering*** $\Rightarrow$ ***Scattered Disk*** subject to energy diffusion
- ***External grav. torques*** $\Rightarrow$ ***Decoupling*** from planetary influence; storage into high-q orbits
- Thus, ***formation of an Oort Cloud***

Brasser & Morbidelli (2013)



End of migration

Currently, $M_{OC} \approx 7\%$ of M(disk)
_M_{SD} is 12 times less_

Nice Model inferences

- ***All comets stem from the icy planetesimal disk***
- Gradients in chemical composition or D/H ratio will be seen as scatter of similar extent among JF and LP/HT (SD and OC) comets
- This seems to agree with observations

Collisional evolution of comets?!

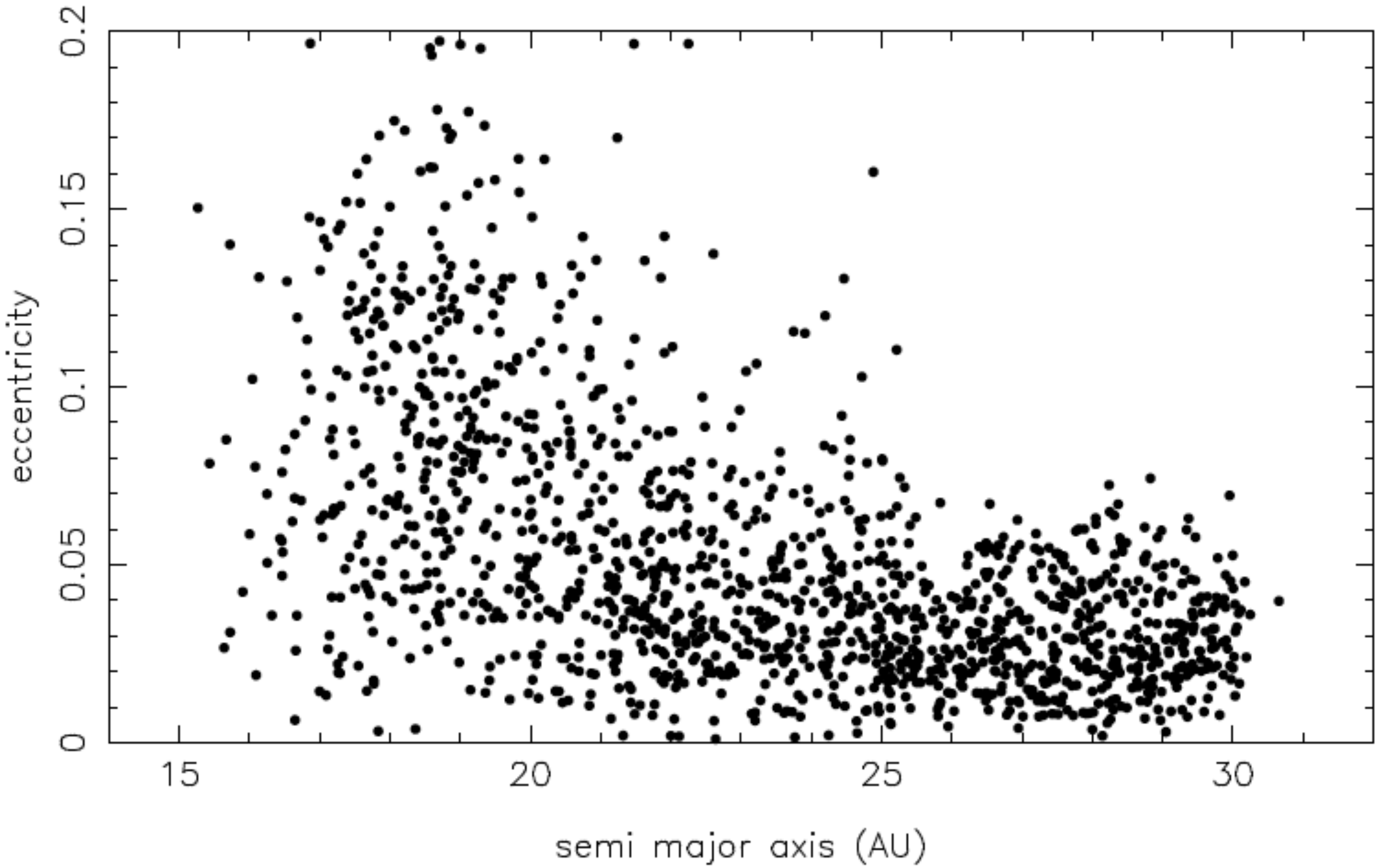
- *Davis & Farinella (1996):* Collisional evolution in the Edgeworth-Kuiper Belt $\Rightarrow$ comet-size objects are ***collisional fragments***
- *Stern & Weissman (2001):* During Oort Cloud formation out of planetesimals from the giant planet zone, the ***objects were destroyed***
- *Charnoz & Morbidelli (2003):* OC comets may be primordial, while ***SD objects are collisional fragments***

What about the Nice Model?

- ***Morbidelli & Rickman (2015)***

- We model the ***collisional evolution of comets in a Nice Model scenario*** from the beginning until the present: the *pre-instability disk* (400 My); the *disk dispersal stage* (SD formation, 350 My); the *SD residence time* (~4 Gy)

Excitation of the primordial disk



Disk state after 300 My according to Levison et al. (2011), self-excited by 1000 Pluto-size objects

Model parameters

- ***Disk population***
- SD formation ⇒ *$2{\times}10^{11}$ objects with $D > 2.3$ km at the start of disk dispersal* (Brasser & Morbidelli 2013)
- We divide this disk into three radial zones
- ***Collisional break-up condition***
- Specific disruption energy *$Q^*(R)$ from Benz & Asphaug (1999)* for “strong ice”

Pre-instability disruptions

Number of catastrophic collisions per 400 My for a target with R = 2 km (as appropriate for 67P)

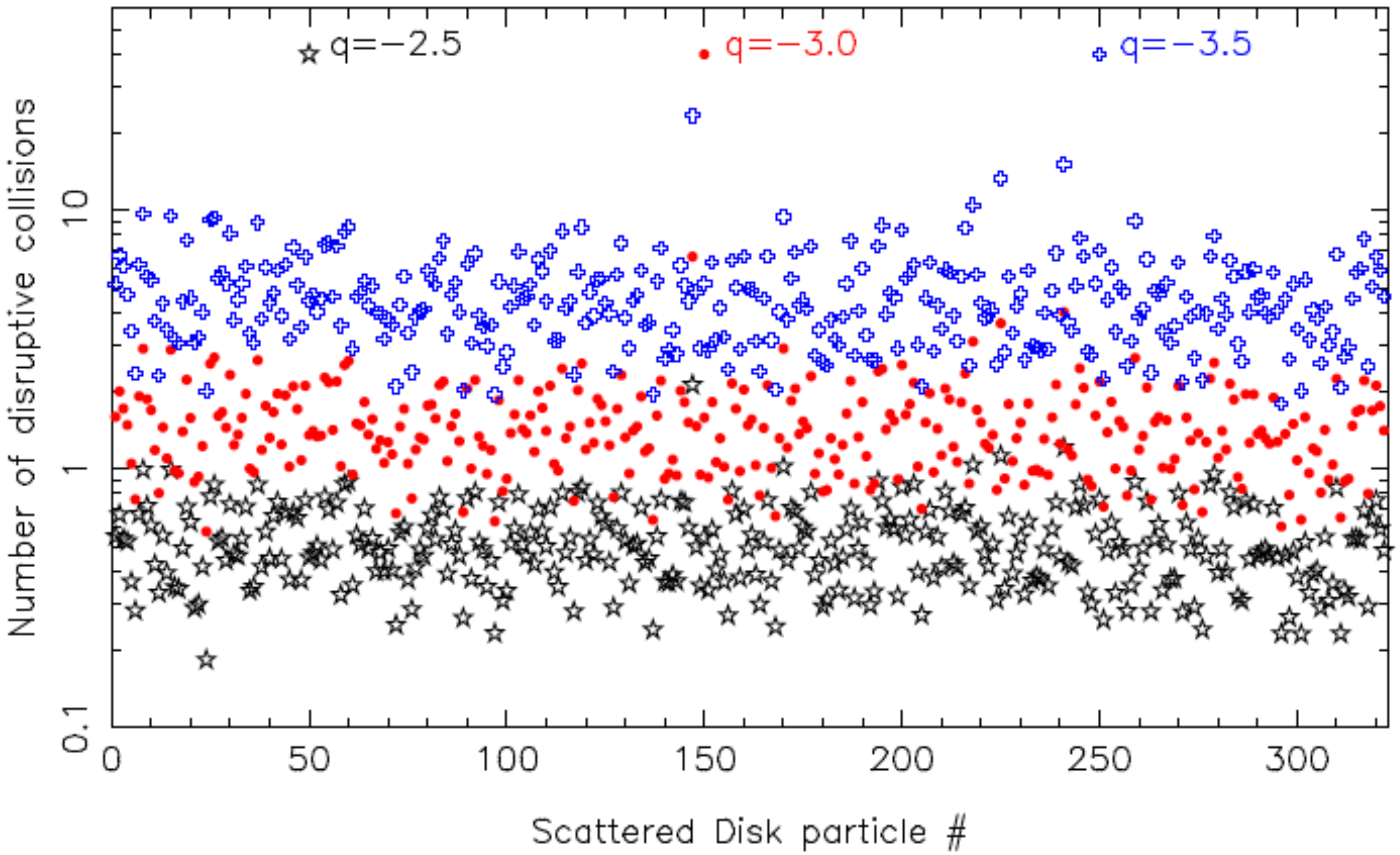
$q \backslash$ targetzone	I	II	III
-2.5	58.0 (51.2)	28.7 (20.7)	12.3 (9.6)
-3.0	94.5 (75.0)	39.7 (23.7)	12.1 (7.9)
-3.5	190.6 (137.7)	70.2 (35.3)	15.4 (8.2)

q is the power law index of the assumed differential size frequency distribution

Numbers in parentheses refer to the dynamical state after 100 My (lower eccentricities and velocities)

TZ III may be favored for 67P due to its high D/H ratio. However, the chance to avoid disruption is < 10^{-4} !

Dispersal stage disruptions

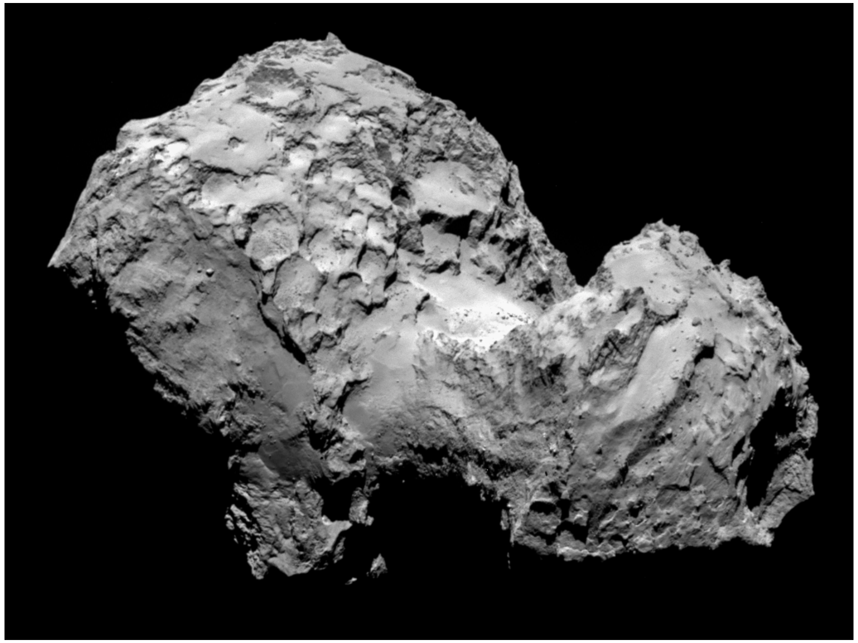


For a steep SFD, comets do not survive
The standard case (-3.0) is borderline
With a shallow SFD, comets tend to survive to a large degree

Collisional dilemma (?)

- A low-mass disk does not save comets from collisional destruction (Rickman et al. 2015)
- And ***67P does appear to be primordial!*** (highly porous, full of volatiles) …

Comet 67P (OSIRIS)



– Could the disk be slim enough to save the comets? ***No***

– Can comets stay primordial in spite of collisions? ***Yes***

An early instability would help…

Evidence for late instability?

- *Marty et al.* (2016) find *Ar abundance in 67P* consistent with a late veneer for the Earth's atmospheric argon, implying a comet input of *$3x10^{18}$ – $6x10^{20}$ kg*. Rickman et al. (2017) find *$3x10^{19}$ kg*.
- Abundant *water in lunar apatites (Greenwood et al. 2011)* may be difficult to explain, unless the mare forming projectiles were water rich.

There are still major, open issues!