On the Formation of Comets

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Current popular ideas

- Comets formed in streaming instabilities
  - Blum *et al.* (2014, *Icarus* **235**, 156); Wahlberg Jansson & Johansen (2014, *A&A* **570**, A47); Lorek *et al.* (2016, *A&A* **587**, A28); Poulet *et al.* (2016, *MNRAS* **462,** S23)

- Comets experienced violent collisions
  - Morbidelli & Rickman (2015, *A&A* **583**, A43); Rickman *et al.* (2015, *A&A* **583**, A44); Jutzi *et al.* (2017 *A&A* **597**, A61); Jutzi & Benz (2017 *A&A* **597**, A62)

- Discuss problems with these ideas and offer alternative

Streaming instabilities

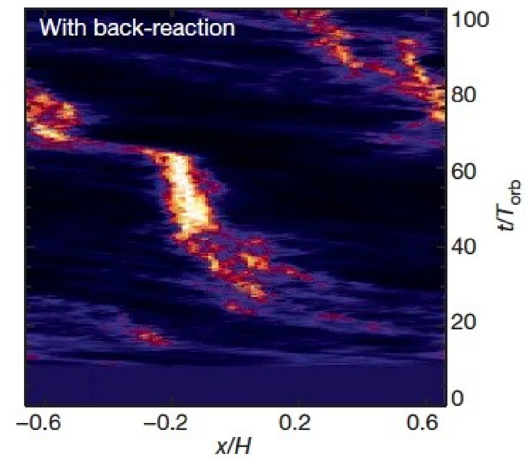
Hit/stick growth to mm-cm sized *pebbles*

Pebble swarms grow due to
the streaming instability
(Youdin & Goodman 2005, *ApJ* **620**, 459)

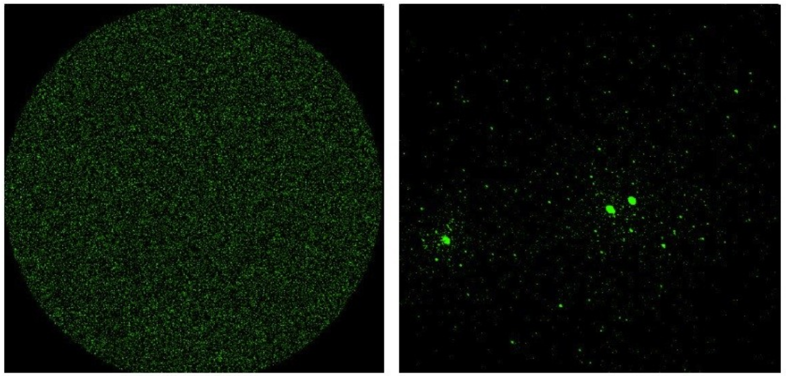
Swarms collapse gravitationally
to *large* bodies on *short* timescales

Efficient producer of (*ultra)wide binaries*

High fraction of (ultra)wide binaries
among dynamically cold TNOs
(Stephens & Noll 2006, *Astron. J.* **131**, 1142)



Johansen *et al.* (2007). *Nature* **448**,1022



Nesvorny *et al.* (2010). *Astron. J.* **140**, 785

^{26}Al heating; compression

Hydrostatic equilibrium: D<150km bodies have ρ<750 kg m^{-3}

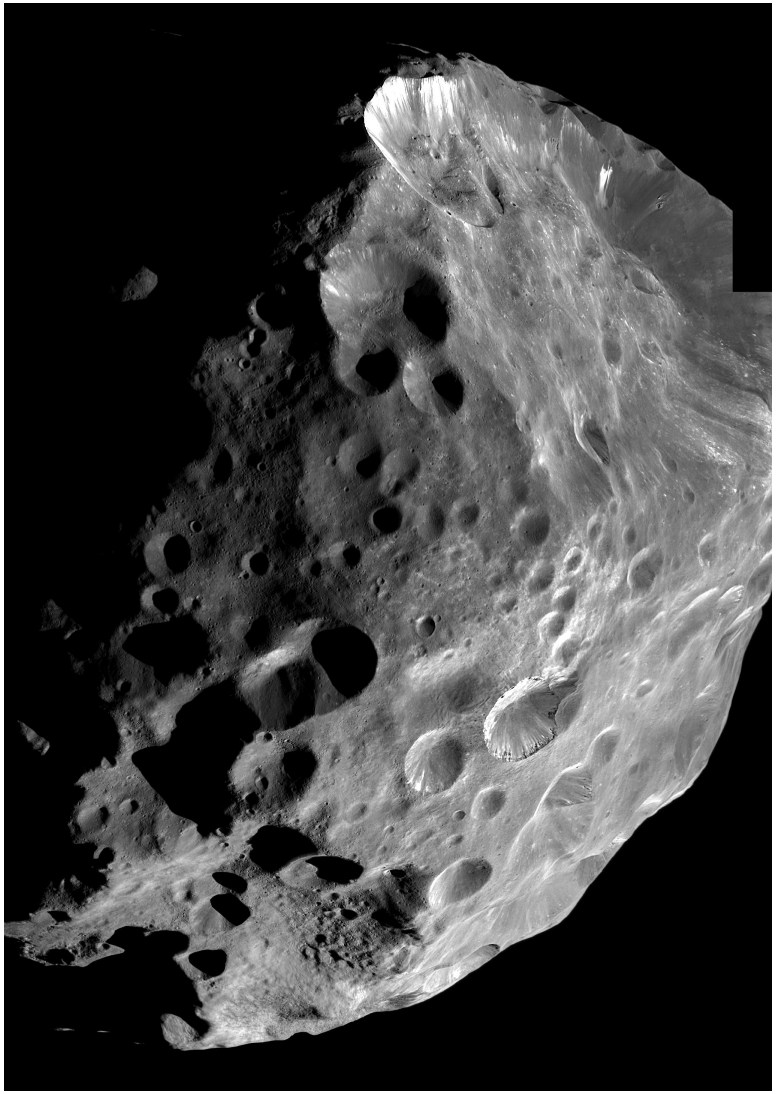
<u>Cold Classical TNOs:</u>
Binary masses known to within ~2%
Herschel & Spitzer radiometric diameters & geometric albedos:

2001 QW_{322}: D=108km, ρ=1270 kg m^{-3}
(66625) Borasisi: D=126km, ρ=2100 kg m^{-3}
ρ>1000 kg m^{-3}
(Petit *et al.* 2008, *Science* **322**, 432)
(Vilenius *et al.* 2014, *A&A* **564**, A35)

<u>Phoebe; captured by Saturn</u>

D=217.7 ± 1.5 km; ρ<1000 kg m^{-3} irregular body expected.

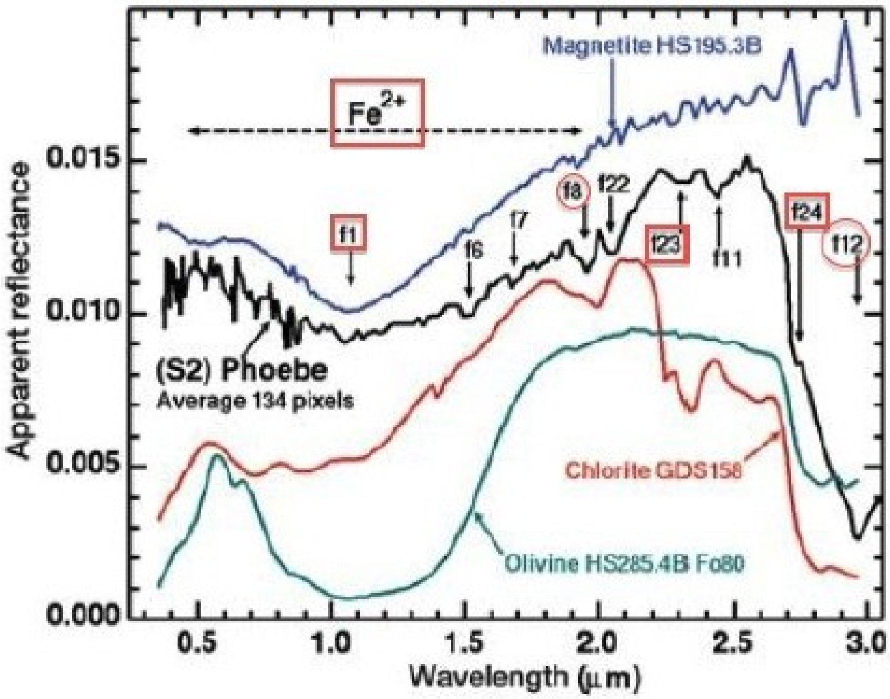
ρ=1634 ± 46 kg m^{-3}
Oblate shape: a/b=0.93
(Matson *et al.* 2009, Saturn from Cassini-Huygens)



Credit: JPL/Space Science Institute

Aqueous alteration

Credit: Clark *et al.* (2005, *Nature* **435**, 66)



<u>Phoebe, Cassini:</u>
Phyllosilicates (squares)
Metal-OH absorption: 2.16μm, 2.3μm
OH stretch fundamental: 2.72μm

Water bound in phyllosilicates (circles)
1.5μm, 1.95μm, 2.95μm
Clark *et al.* (2005, *Nature* **435**, 66)

<u>Phyllosilicates: 0.7μm</u>

Seen in 11 of 16 Jovian irregular satellites, including Himalia, and D= 6-8km Callirrhoe, Megaclite, Themisto.

Uranus irregular satellite Caliban
Vilas *et al.* (2006, *Icarus* **180**, 453)

Centaur (10199) Chariklo
Lederer *et al.* (2004, *Earth Moon Planets* **92**, 193)

Plutinos: 2003 AZ_{84}
Fornasier *et al.* (2004, *A&A* **421**, 353)
2000 GN_{171} and 2000 EB_{173}
Lazzarin *et al.* (2003, *Astron. J.* **125**, 1554)

<u>Al/Mg-rich OH-bearing minerals: 1.4μm, 2.28μm</u>

Centaur 1999 DE_9
Jewitt & Luu (2001, *Astron. J.* **122**, 2099)
Plutino 2000 EB_{173}
de Bergh *et al.* (2004, *A&A* **416**, 791)

Comets: no aqueous alteration

All ≳20-30km bodies born within Solar Nebula lifetime (streaming instabilities) expected to be aqueously altered!

<u>R=35km body with 20% ice:</u>
Most ice vaporized/melted
if formed t<=6.5 Myr after CAI
(Mousis *et al.* 2017, arXiv:1703.04227v1)

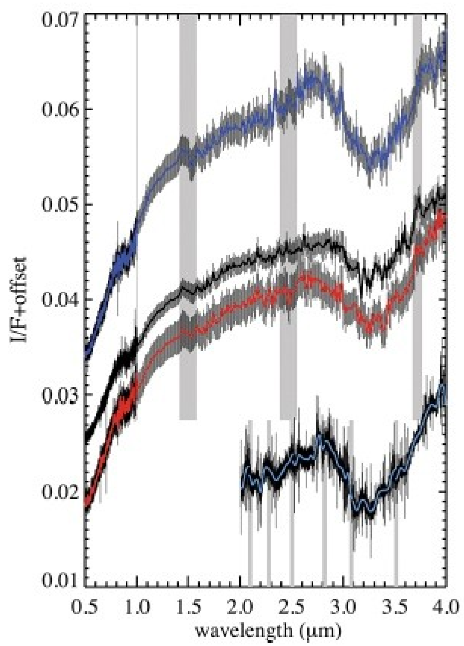
<u>Gas disk lifetimes in open clusters:</u>

Object	Age [Myr]	#disks[%]
NGC2024	0.3	80
NGC2264	2-3	50-70
Tr 37	4	48
NGC2362	5	12

(Haisch *et al.* 2001, *ApJ* **553**, L153)
(Sicilia-Aguilar *et al.* 2006, *ApJ* **638**, 897)

<u>End of Solar Nebula:</u>
Age of Iapetus constrained to
t=3.4-5.4 Myr after CAI
(Castillo-Rogez *et al.* 2009, *Icarus* **204**, 658)

<u>Stardust:</u>
Phyllosilicates rare or absent
(Brownlee *et al.* 2012, *Meteo. Planet. Sci.*, **47**, 453)
(Roskosz & Leroux 2015, *Astrophys. J.*, **801**, L7)



Credit:
Capaccioni *et al.* 2015,
Science, **347**, aaa0628

<u>Rosetta:</u>
VIRTIS: spectrum inconsistent with CI/CM/CR meteorites
OSIRIS: no 0.7 μm absorption
no phyllosilicates

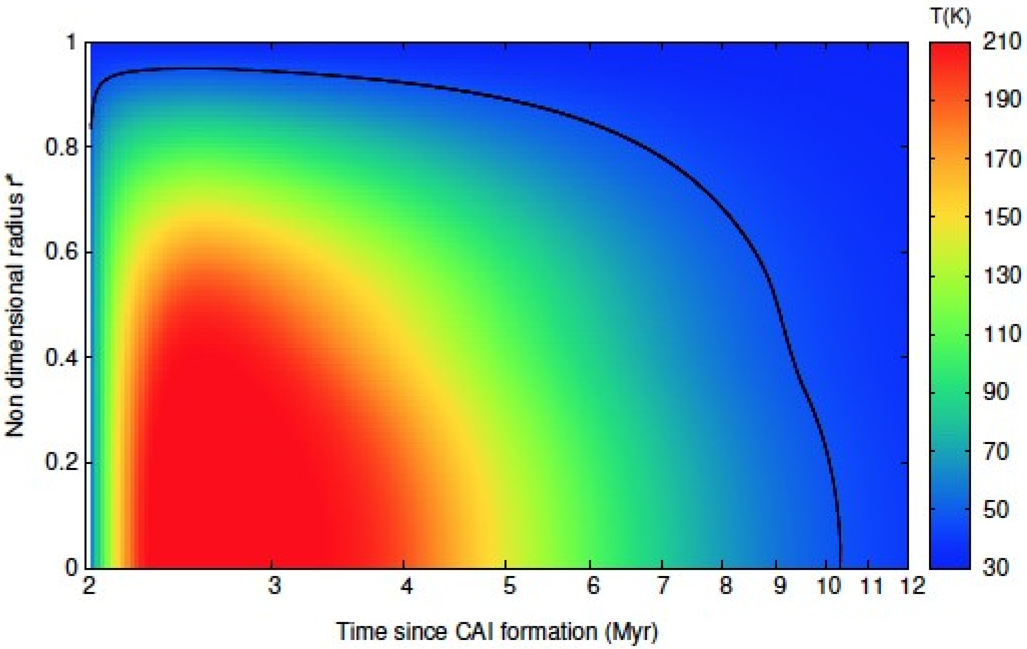
Collisional cascade unlikely

- Bodies a few times 10km born within the Solar Nebula lifetime expected to be substantially aqueously altered, compacted, supervolatile-poor
- Comets (high porosity, abundant supervolatiles, no phyllosilicates) cannot be their collision fragments
- One cannot build comets out of Phoebe
- Compare with comet-sized (D=6-8km) jovian irregulars Callirrhoe, Megaclite, Themisto: 0.7 μm absorption because they are break-up products of aqueously altered parents in a truly collisional environment

(Sheppard & Jewitt 2003, *Nature* **423**, 261)
(Vilas *et al.* 2006, *Icarus* **180**, 453)

Comets likely not formed by streaming instabilities

Credit: Mousis *et al.* 2017, arXiv:1703.04227v1



67P-sized comets, and particularly Halley-sized must reach their final size *after* dissipation of the Solar Nebula to avoid severe thermal processing.

This may disqualify streaming instabilities as a comet formation mechanism.

A D=2.6km body with 20% ice born 2Myr after CAI: severe internal vaporization

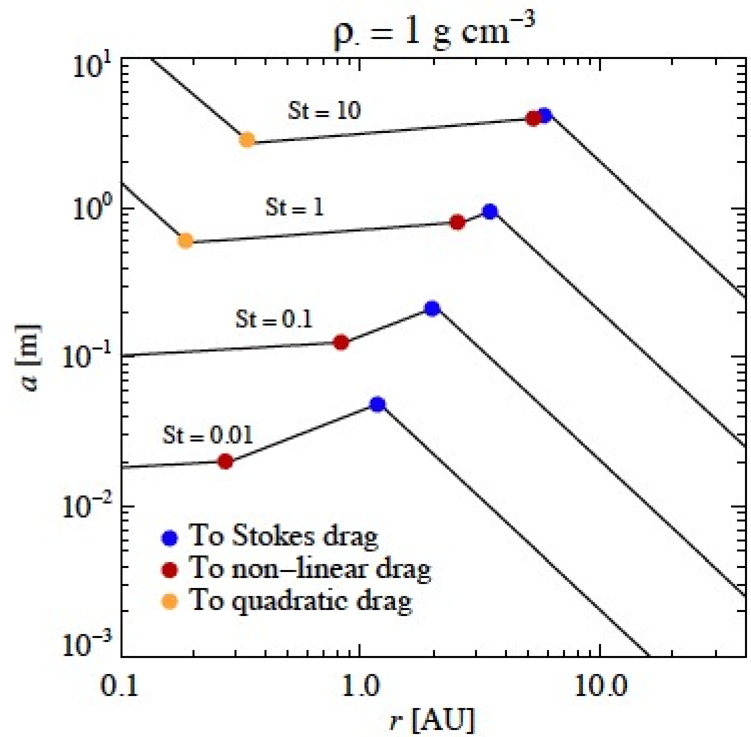
Avoiding water vaporization entirely requires birth >=4.5 Myr after CAI

Comets likely not formed by streaming instabilities

To minimize/avoid radiogenic heating: streaming instabilities form comets when solar nebula disperses?
(Johansen *et al.* 2009, *Astrophys. J.* **704,** L75)

If so, mm-cm pebbles must avoid drift and growth for up to 3-5 Myr.

Drift barrier:
Radial drift peaks (St=1) for
~1m at 1 AU,
~1cm at 30 AU,
~1mm at 100 AU.



Credit: Johansen *et al.* 2014, *Protostars and Planets VI*

An alternative comet formation scenario

A&A 592, A63 (2016)
DOI: 10.1051/0004-6361/201526968

Astronomy & Astrophysics

The primordial nucleus of comet 67P/Churyumov-Gerasimenko

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I. Streaming instabilities consume majority of pebbles when growing large bodies in the Solar Nebula

II. Remaining pebbles grow very slowly through hierarchical agglomeration to form comets

III. Large TNOs and comets are separate populations, only connected through the pebbles.

An alternative comet formation scenario

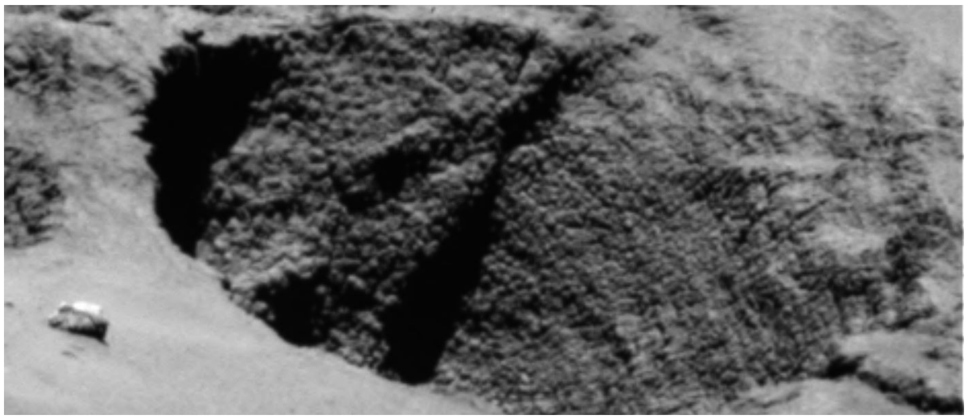
In the *solar nebula* (0-3 Myr after CAI)

- 13 $M_\oplus$ cm-sized pebbles form 50-400km "TNOs" in *streaming instabilities*
- ^{26}Al causes severe thermal processing, densification, aqueous alteration
- Remaining 2 $M_\oplus$ cm-sized pebbles form 0.1-1km cometesimals through *hierarchical agglomeration*.
- ^{26}Al heat dissipates; porosity, m-sized ψ_{macro}, supervolatiles, mineralogy preserved.

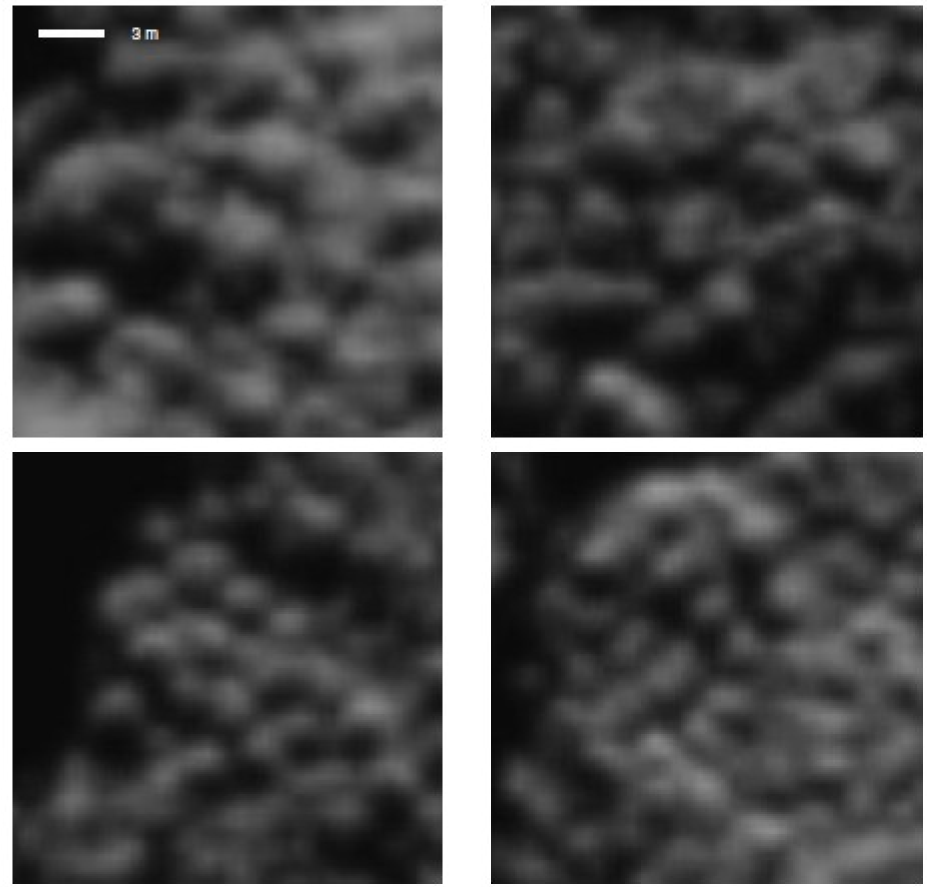
In the *primordial disk* (3-400 Myr after CAI)

- "TNO" runaway growth to $\lesssim$ Triton-size. Gradually stir the disk.
- Comet accretion intensifies: layering
- No gas drag: bi-lobe nucleus formation
- D$\gtrsim$50km comets form (Hale-Bopp) at >25Myr
- Low collision frequencies; *primordial rubble-pile nuclei survive.*

Signs of hierarchical growth: goose bumps



Credit: ESA/Rosetta/MPS for OSIRIS Team and Sierks *et al.* (2015, *Science* **347**, aaa1044).

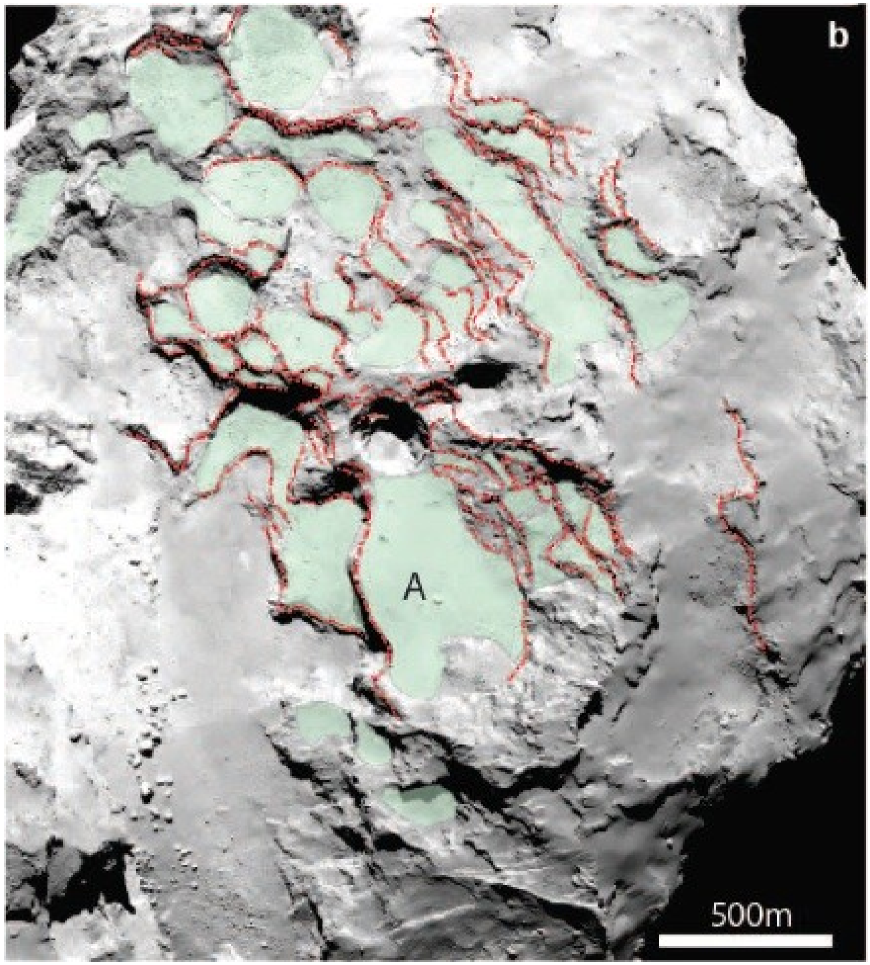


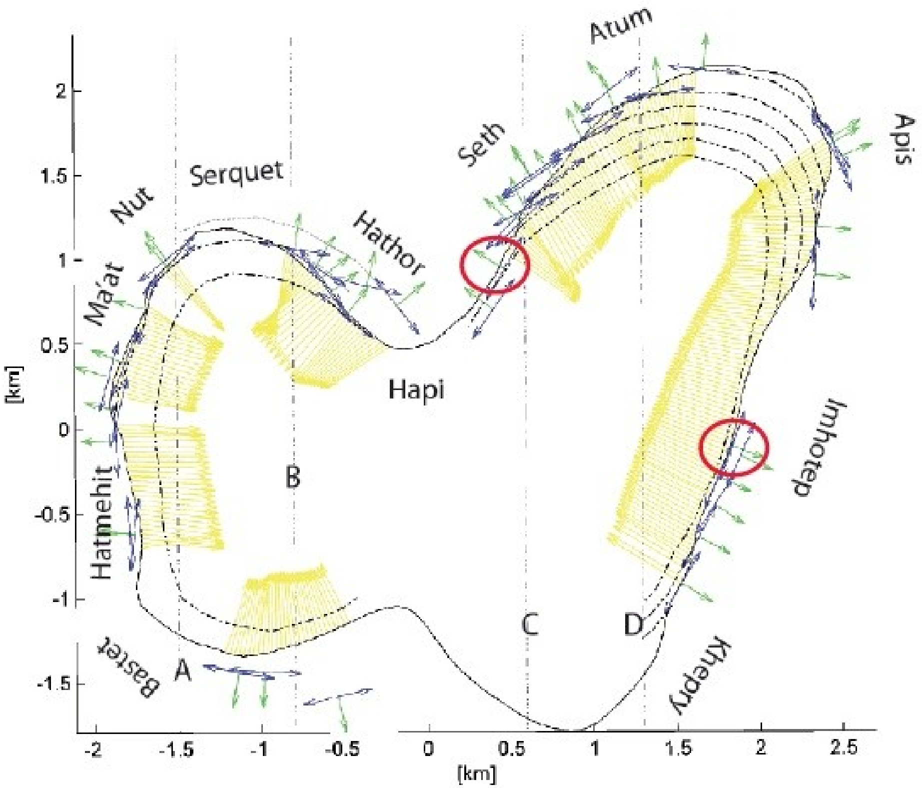
Credit: ESA/Rosetta/MPS for OSIRIS Team and Davidsson *et al.* (2016, *A&A* **592**, A63).

Mono-disperse size distribution (2.5m ± 1m)

Hierarchical growth collision velocities peak when growing meter-sized objects

Signs of hierarchical growth: layering

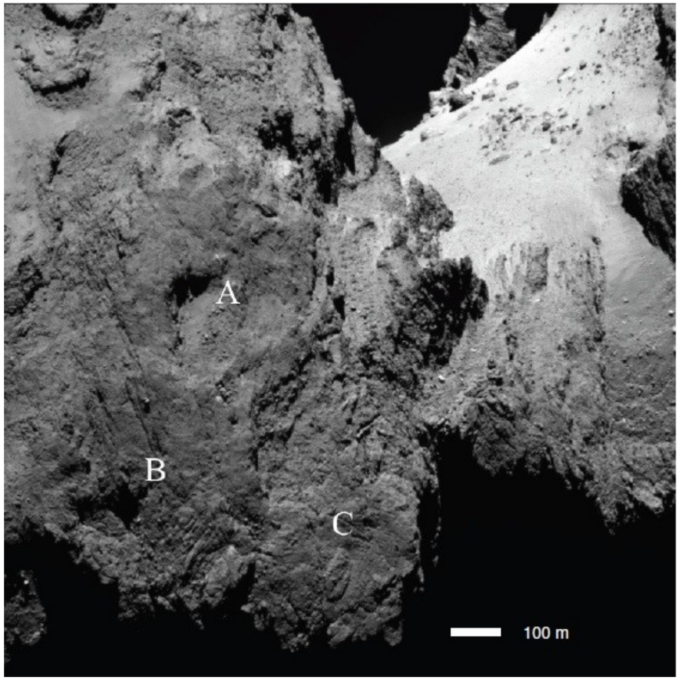


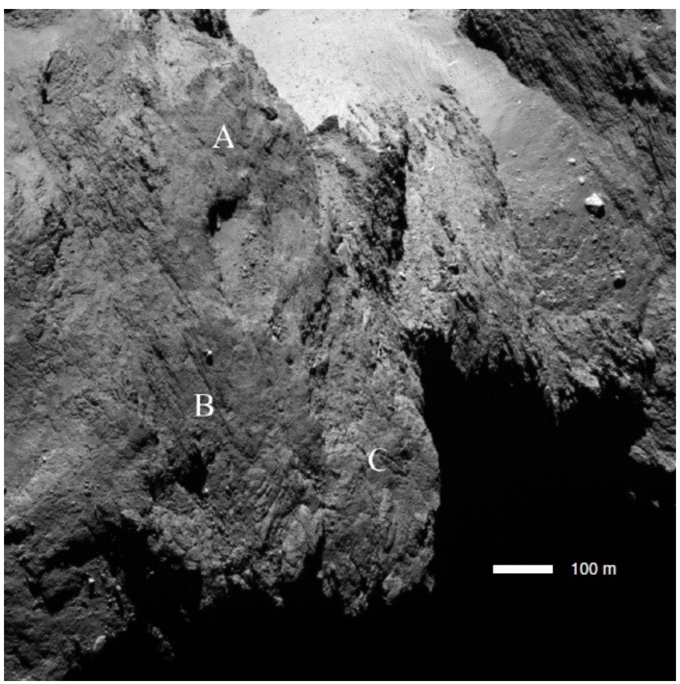


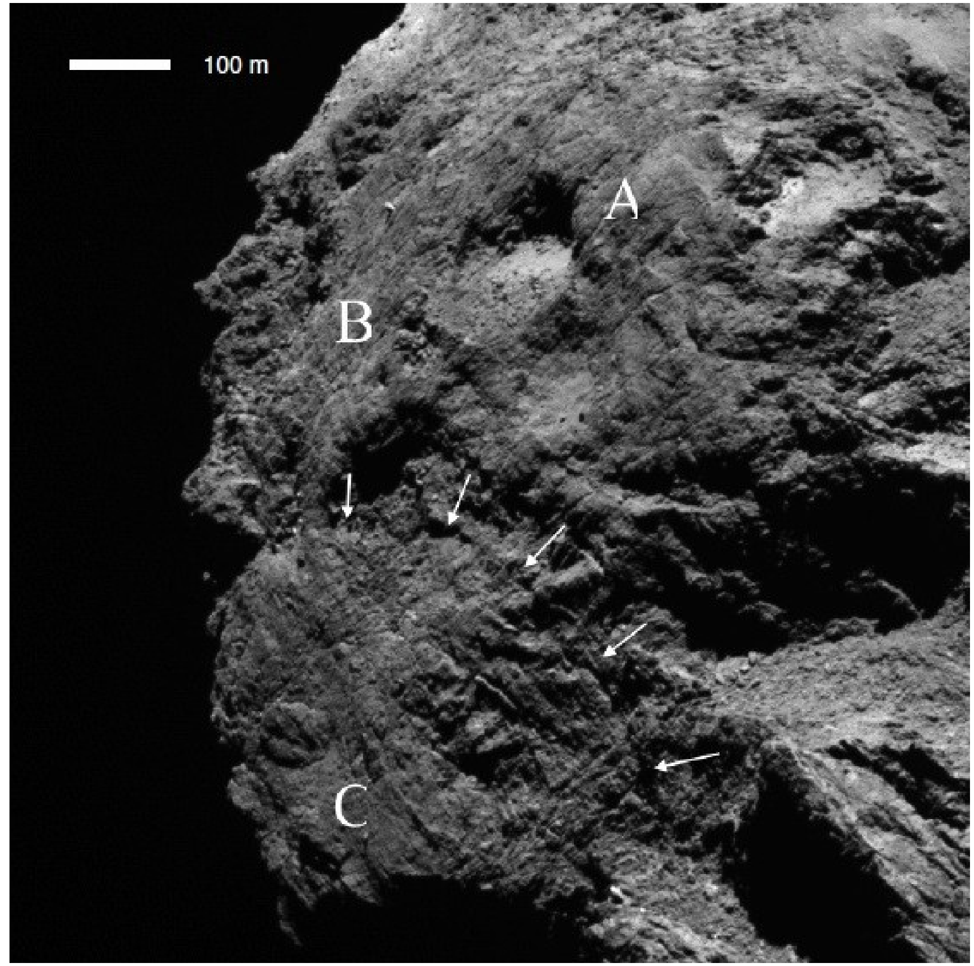
Credit: Massironi *et al.* (2015, *Nature* **526**, 402)

Numerous terraces: onion-shell stratification
Lobes are *individually* layered: merger of two bodies
At least 650m thick in places
The "talps model" of Belton *et al.* (2007 *Icarus* **187**, 332):
smeared-out cometesimals during primordial accretion

Signs of hierarchical growth: PRFs in Bastet



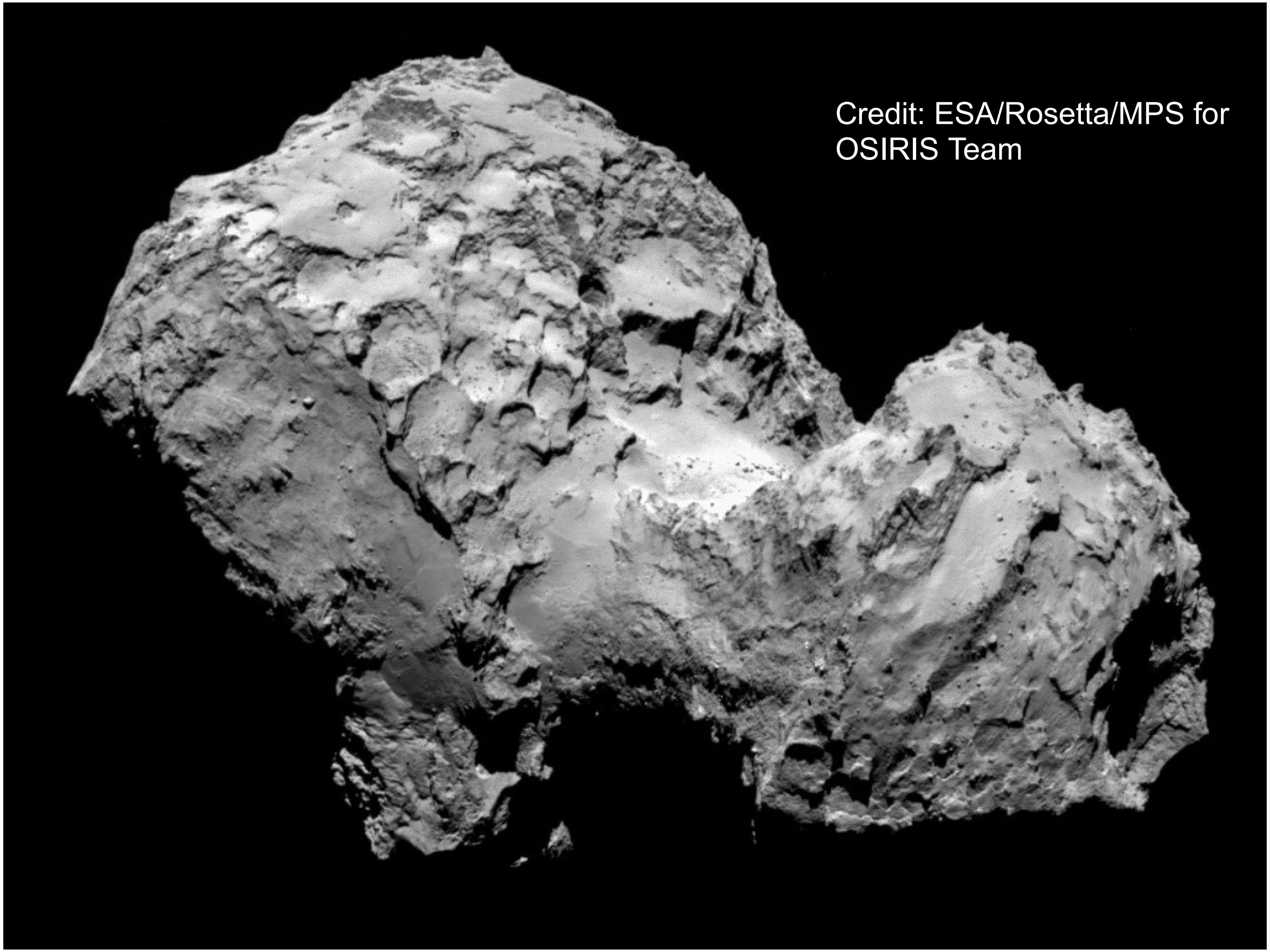




Positive Relief Features (PRFs): spherical caps, possibly intact cometesimals, each 320-450 m across.

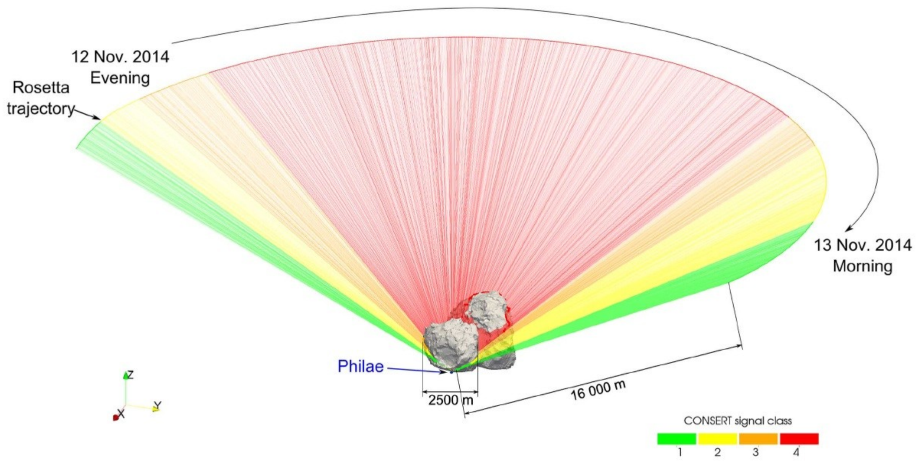
Credit: ESA/Rosetta/MPS for OSIRIS Team and Davidsson *et al.* (2016, *A&A* **592**, A63).

Signs of hierarchical growth: bi-lobed nucleus



Small lobe: 2.70 x 2.24 x 1.64 km
Large lobe: 4.20 x 3.22 x 1.80 km (Jorda *et al.* 2016, *Icarus* **277**, 257-278).

Nucleus interior structure



Credit: Kofman *et al.* (2015 *Science* **349**, aab0639)

No volume scattering:
~10m-scale homogeneity

But: “Two or three well-defined propagation paths could indeed be potentially due to the presence of a large structure inside the nucleus”

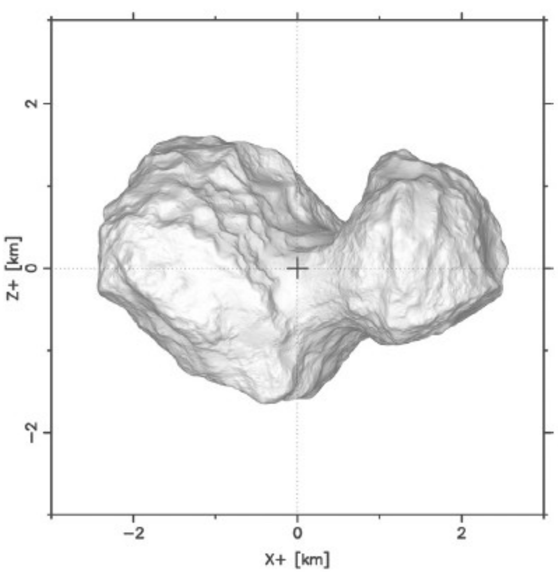
Dielectric constant ε=1.27 ⟹ porosity 75-85%

Density gradient

CONSERT: porosity increase by ~10-20% in upper 150m. Shallow regions denser than interior by a factor 1.2-2.0.
(Ciarletti *et al.* 2015, *A&A* **583**, A40
Brouet *et al.* 2016, *MNRAS,* doi:10.1093/mnras/stw2151)

Lobes have different densities?

COM/COF off-set {18,-32,16} meters
Principal axis tilts 4.0° ± 1.9° wrt z-axis
(Jorda *et al.* 2016, *Icarus* **277**, 257)



ρ_{big}=540-570 kg m^{-3}?

ρ_{small}=445-515 kg m^{-3}?

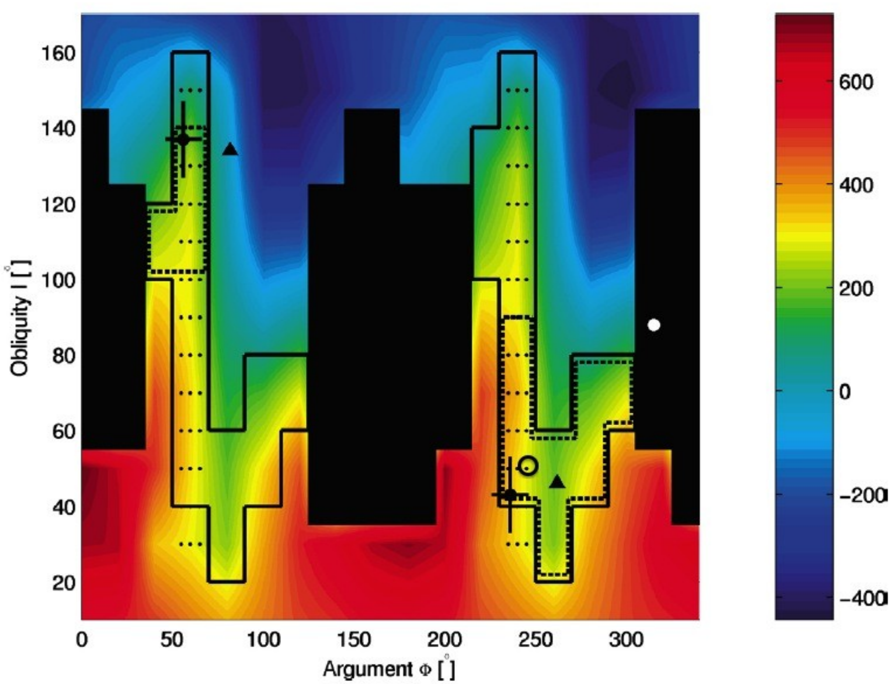
Credit: Jorda *et al.* 2016, *Icarus* **277**, 257

The mass, density, and porosity of 67P

Available online at www.sciencedirect.com
SCIENCE DIRECT
Icarus 176 (2005) 453–477
ICARUS
www.elsevier.com/locate/icarus

Nucleus properties of Comet 67P/Churyumov–Gerasimenko estimated from non-gravitational force modeling

Björn J.R. Davidsson [a,*], Pedro J. Gutiérrez [b]



For the spin axis orientation "CM" about 7° from correct one.

M=$1.1\cdot10^{13}$ kg
(range $0.9\text{-}1.4\cdot10^{13}$ kg)

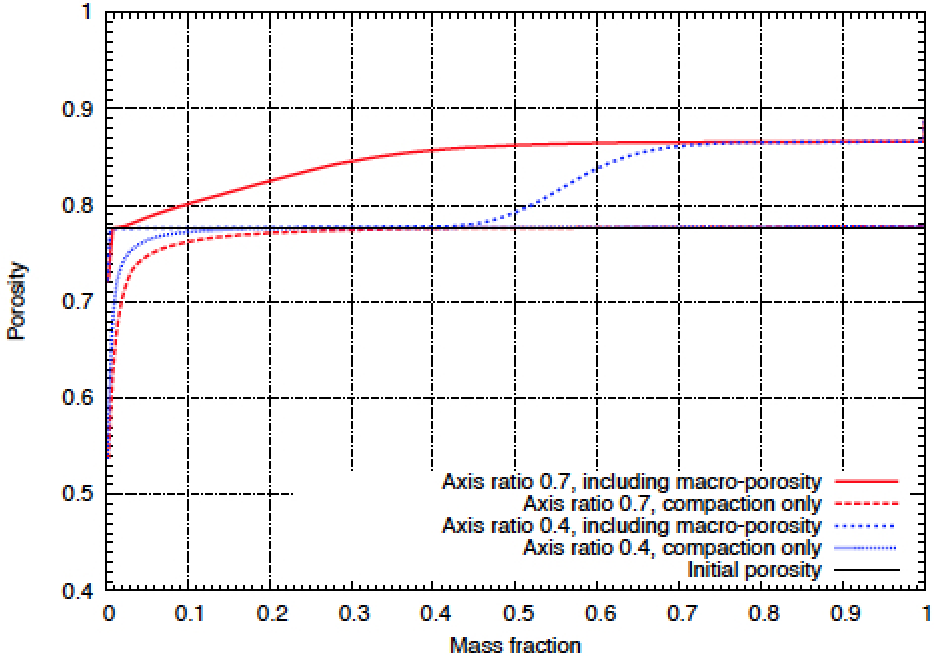
Corresponding density for *assumed* volume:
ρ=330 kg m^{-3}
(range 270-420 kg m^{-3})

In situ measurements by Rosetta/RSI (Pätzold *et al.* 2016, *Nature* **530**, 63)

M=$9.982\cdot10^{12}$ kg
ρ= 535 kg m^{-3} (correct volume)

Dust/ice mass ratio 4±2 (Rotundi *et al.* 2015, *Science* **347**, aaa3905): $\rho_{comp}\approx$1800 kg m^{-3}, porosity is ~70%!

Another problem with violent collisions



Credit: Jutzi & Benz 2017, *A&A* **597**, A62

One ~ 100 ms^{-1} collision: 1% of mass compacts to ρ=850 kg m^{-3}

Up to ~100 collisions; all mass compacted (Jutzi et al. 2017, *A&A* **597**, A63)

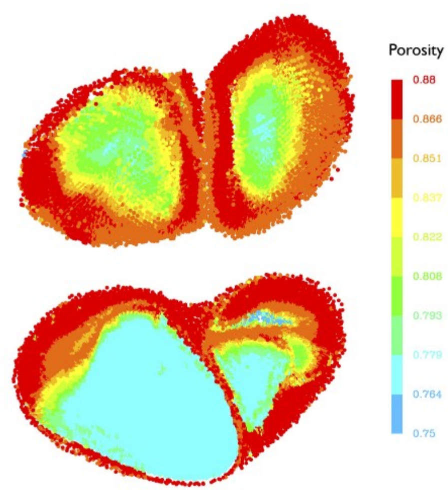
Claim: bulk density kept low by "new" 40% macroporosity

Collisional processing:
Micro-porosity transformed to macro-porosity. Target increasingly heterogeneous.

Possible consistency problems with CONSERT and goosebumps:

1. Porosity decrease with depth suggested, the opposite measured

2. Why would collisions exclusively produce meter-sized dense rubble?



Credit: Jutzi & Benz 2017, *A&A* **597**, A62

Summary

- The effects of radiogenic heating need to be taken seriously
- Collisional cascades mix down aqueously altered material to small sizes which seems incompatible with comet properties
- If comets reached their final size within the Solar Nebula lifetime it is very difficult to avoid thermal processing. They may need to grow on longer timescales than streaming instabilities can offer.
- The notion of a slowly grown primordial comet nuclei appear most consistent with spacecraft observations