Manufacture of odd-shape small bodies in space

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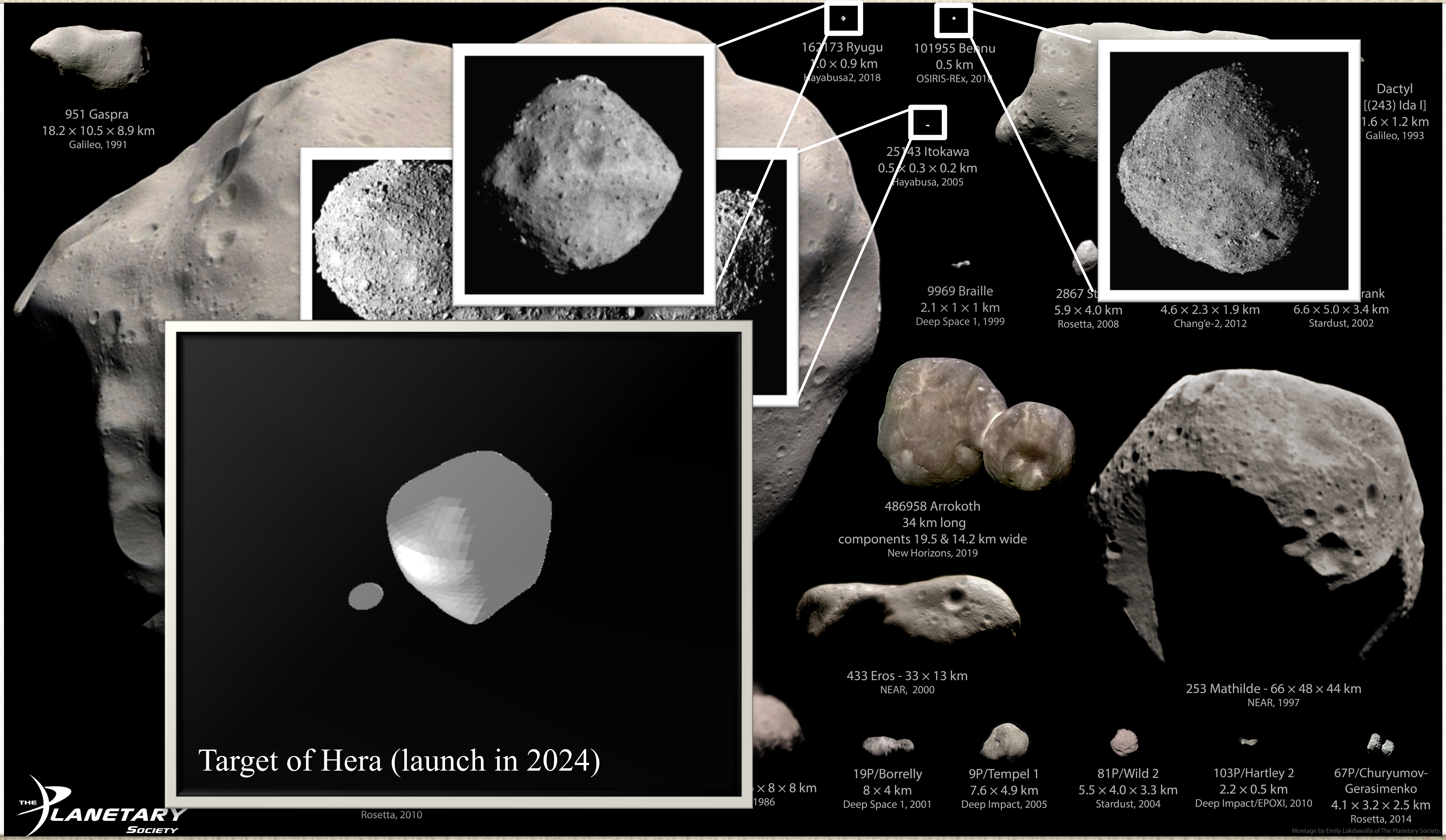
Small bodies that have been visited by spacecrafts



Mechanisms responsible for changing small body shapes

- *Primordial survivors*

  Low-velocity accretion in the proto-planetary disk (e.g., Kataoka et al. 2013 A&A)

- *Collisional evolution*

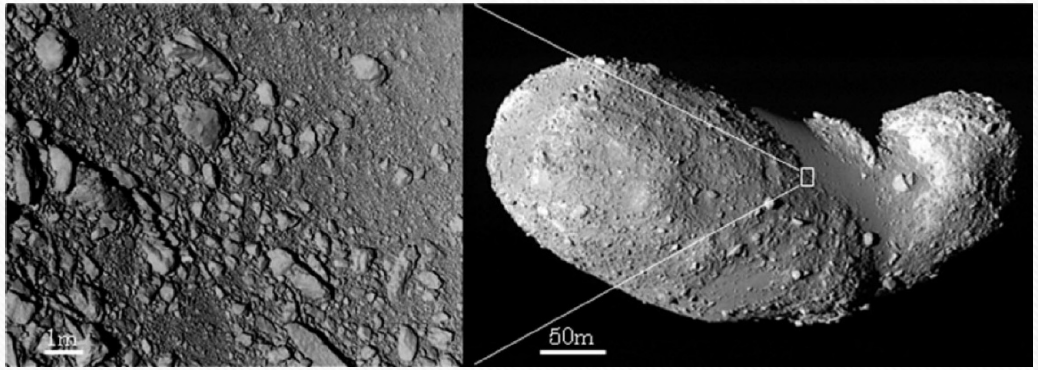
  Comets and asteroids would have experienced a high number of catastrophic collisions and could not have survived with the initial shape (e.g., Tanga et al. 2009 ApJ; Morbidelli & Rickman 2015 A&A)

- *Rotational reshaping and fission due to YORP*

  Radiation recoil (YORP) torques can alter the spin states of small bodies and lead to structural failure after reaching their spin limit (e.g., Lowry et al. 2007 Sci.; Walsh et al. 2008 Nat.)

- *Tidal distortion and disruption*

  In a close approach to planets or stars, rubble-pile small bodies can be dramatically modified, and even catastrophically break up (e.g., Asphaug & Benz 1994 Nat.)



Itokawa (Fujiwara et al. 2006 Sci.)

Mechanisms responsible for changing small body shapes

- *Collisional evolution*

  A SPH hydrocode including a porous material model is used to simulate the **fragmentation phase**

  The gravitational *N*-body code PKDGRAV is used to compute the **gravitational phase**

- *Rotational reshaping and fission due to YORP*

  PKDGRAV including a predefined spin variation path is used to simulate the YORP spin-shape evolution

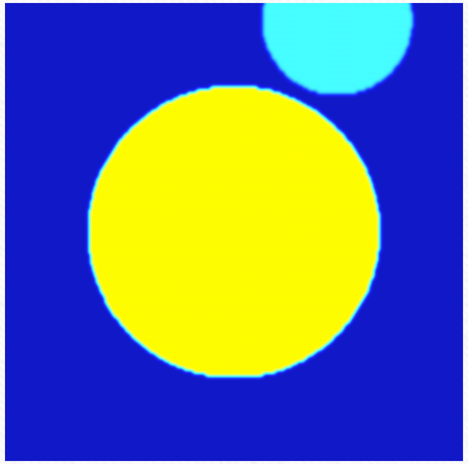
- *Tidal distortion and disruption*

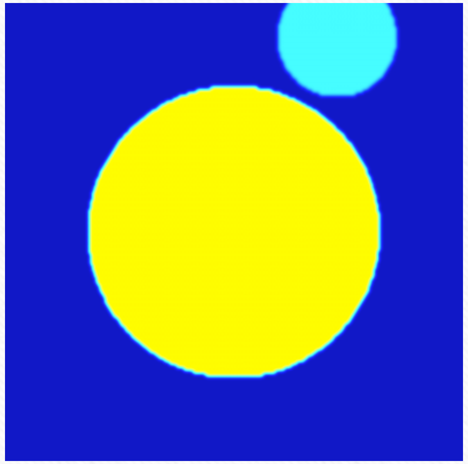
  PKDGRAV is used to simulate the encounter of a rubble pile with a planet/star

Numerical methodology: Simulating hyper-velocity collisions

- **3D SPH hydrocode**
  - Includes a **model of brittle failure** (Benz & Asphaug 1994 Icarus) and the **Drucker-Prager yield criterion** (shear strength dependency on pressure via the angle of friction)
  - Includes a **model of porosity** (Jutzi et al. 2008 Icarus) based on the P-alpha model (increased density of the material via pore-crushing through pressure)
  - Tillotson Equation Of State:
    - **Pressure** = *f* (internal energy, density)
    - **Temperature** computed from the internal energy with **temperature-dependent heat capacity** (Jutzi & Michel 2020 Icarus)

Non-porous target





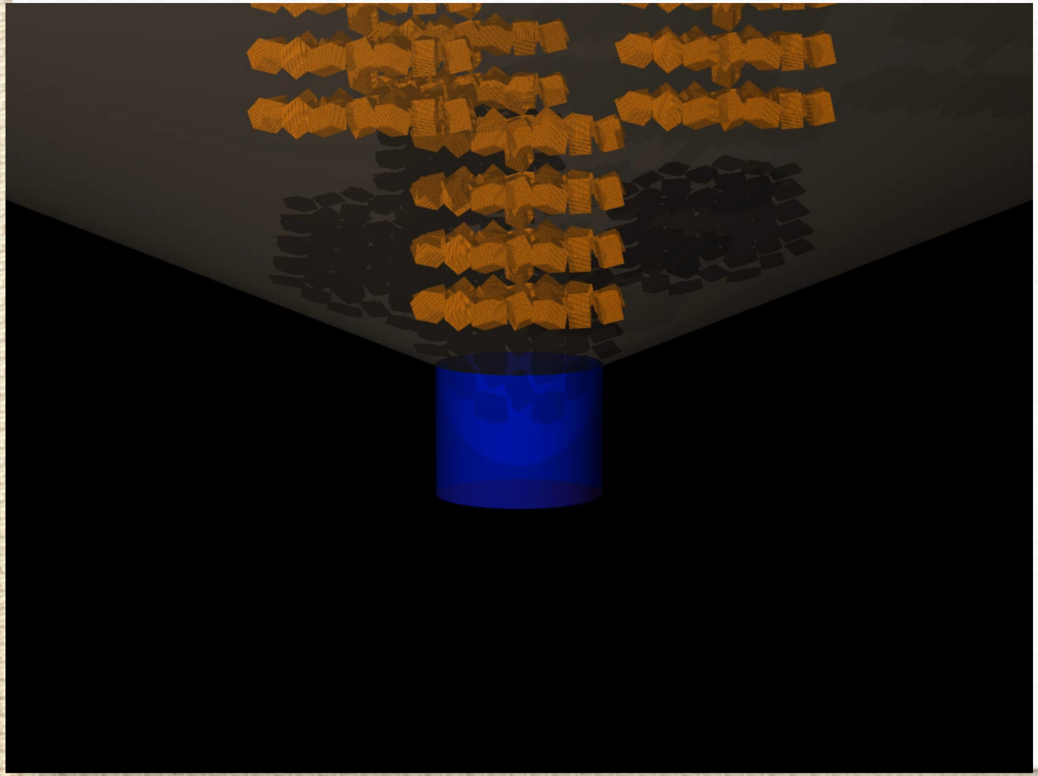
Porous target

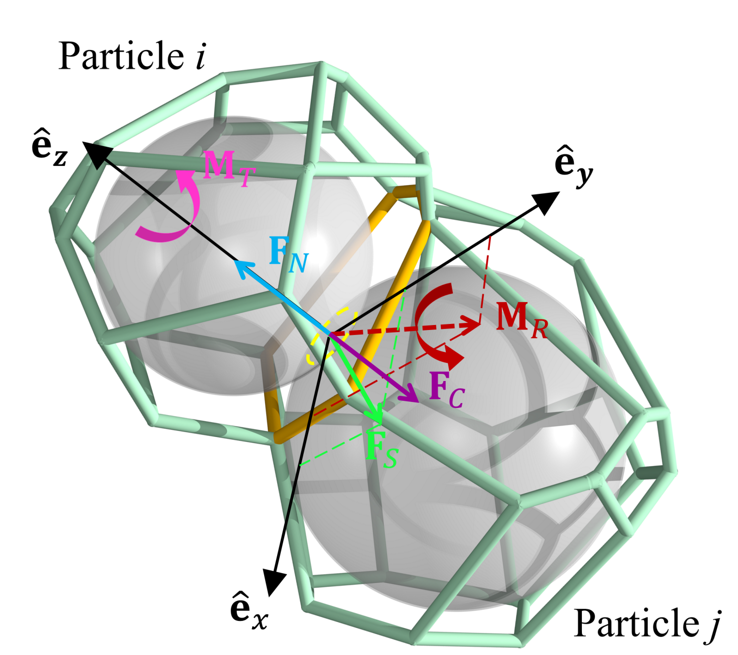
Same bulk density (1.3 g/cc)

Colors: speed scale

Numerical methodology: Simulating gravity and granular physics

- **PKDGRAV: "Parallel *k*-D tree GRAVity code"**
  - Combine parallelism and hierarchical tree code to compute forces rapidly
  - Soft-Sphere Discrete Element Method (Schwartz et al. 2012 Granular Matter)
  - Rotational resistance (Zhang et al. 2017 Icarus)
  - Van der Waals cohesive forces (Zhang et al. 2018 ApJ)





Interparticle force: $\vec{F}_i = \sum_{j=1, j\neq i}^{N} \vec{F}_{ij}^{(g)} + \sum_{j=1}^{N_C} \vec{F}_{ij}^{(c)}$

Mutual gravity **Contact force**

Mechanisms responsible for changing small body shapes

- *Collisional evolution* 67P/Churyumov-Gerasimenko

  A SPH hydrocode including a porous material model is used to simulate the fragmentation phase

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- *Rotational reshaping and fission due to YORP*

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- *Tidal distortion and disruption*

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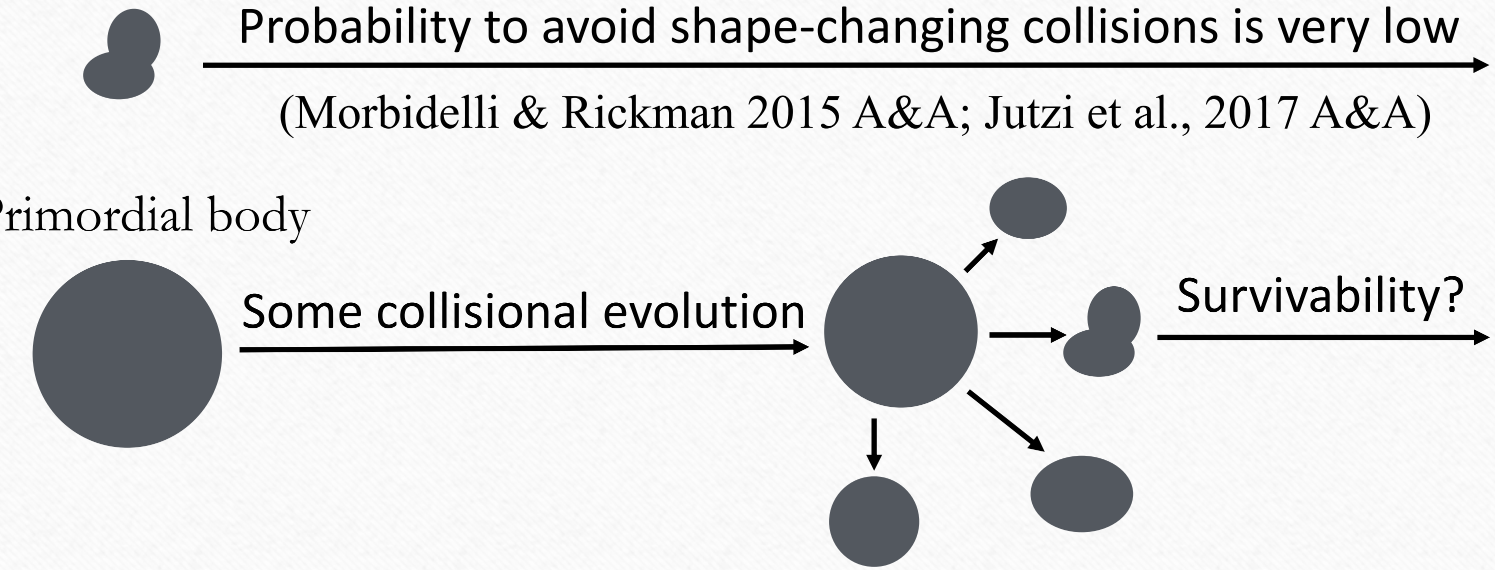
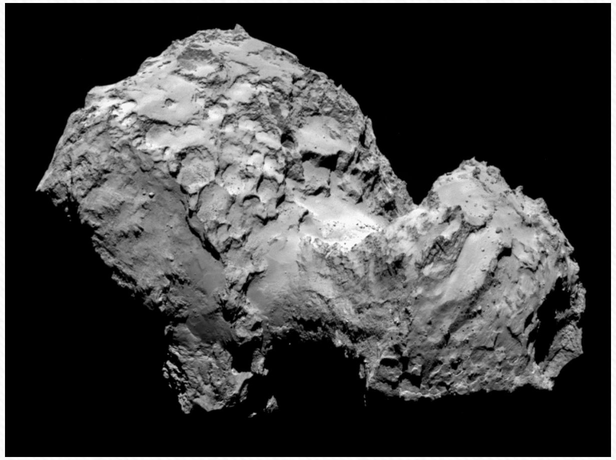
Collisional evolution: Formation of bi-lobed 67P/C-G-like Comets

Observations and close visit show:

- cometary nuclei have a bi-lobed shape
- significant rotation
- High porosity + super volatiles

Can such objects be the outcomes of catastrophic disruption & reaccumulation?





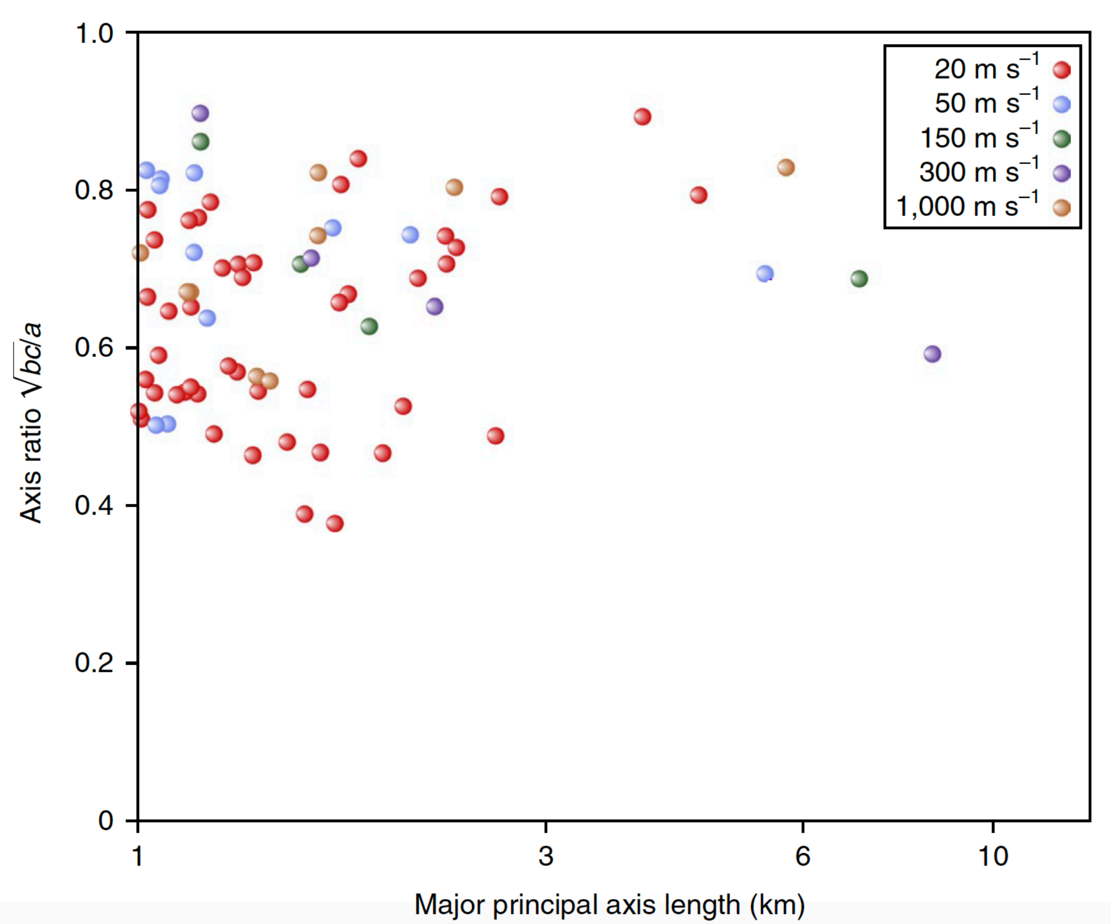
67P/C-G visited by ESA Rosetta Spacecraft in 2014

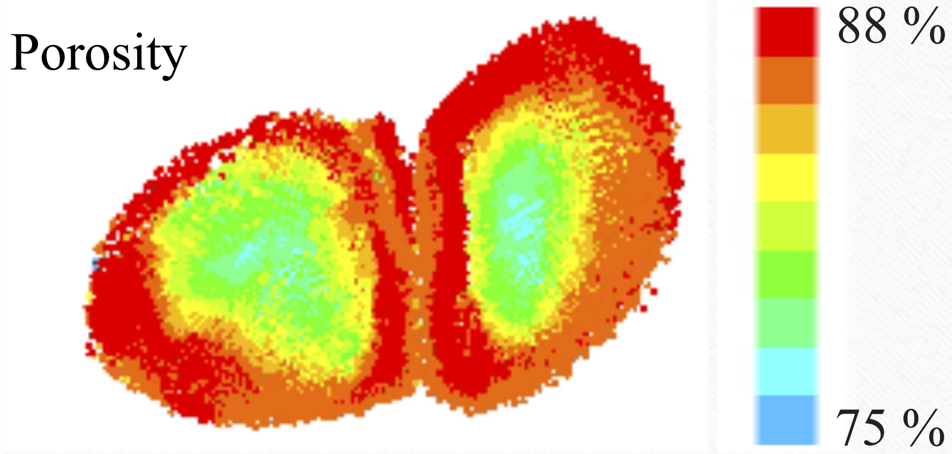
Modeling

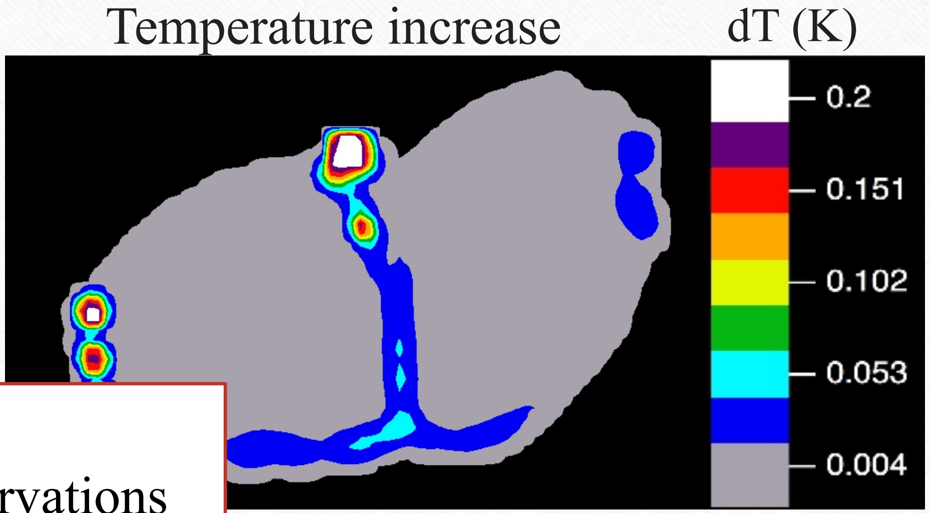
High-speed collision: Smooth Particle Hydrodynamics (SPH) code
Fragments evolution and reaccumulation: *N*-body code

Collisional evolution: Formation of bi-lobed 67P/C-G-like Comets

Collisional disruption & reaccumulation







- Reaccumulation leads to addition of macroporosity
- Relatively homogenous density distribution, consistent with observations
- Very little heating – volatiles can be preserved

(Schwartz et al. 2018 Nat.Astron.)

Mechanisms responsible for changing small body shapes

- *Collisional evolution* **67P/Churyumov-Gerasimenko** **Bennu & Ryugu**

  A SPH hydrocode including a porous material model is used to simulate the fragmentation phase

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- *Rotational reshaping and fission due to YORP* **Effects of material properties**

  PKDGRAV including a predefined spin variation path is used to simulate the YORP spin-shape evolution

- *Tidal distortion and disruption*

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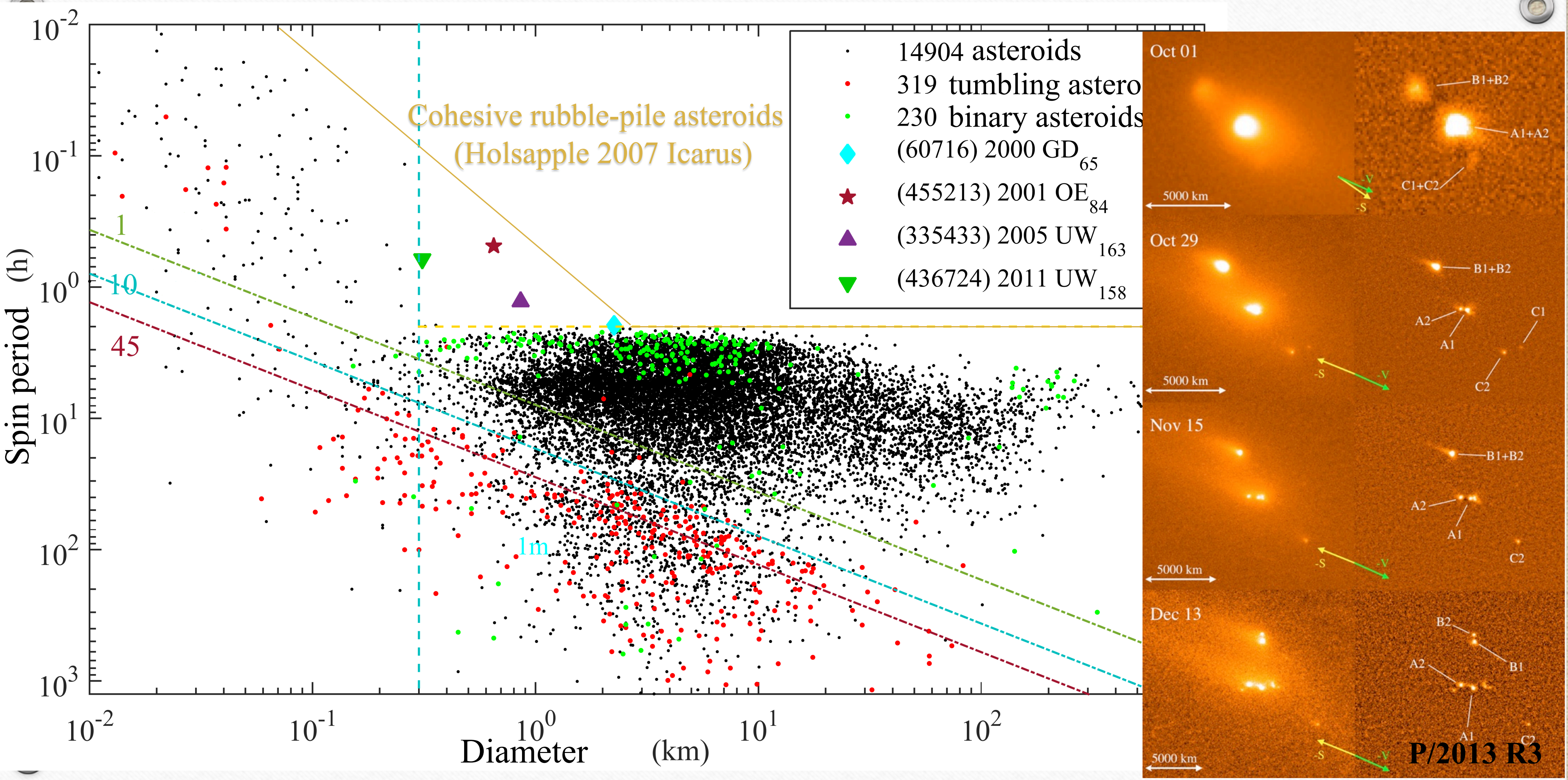
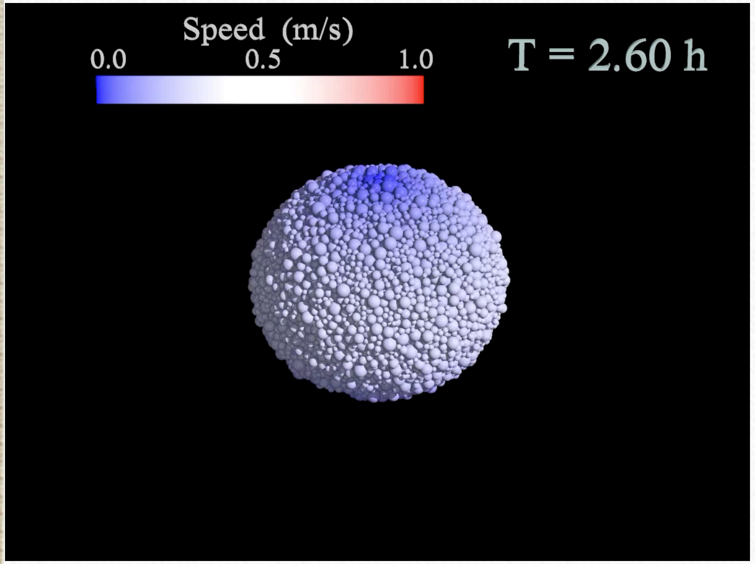
Rotational reshaping and fission due to YORP



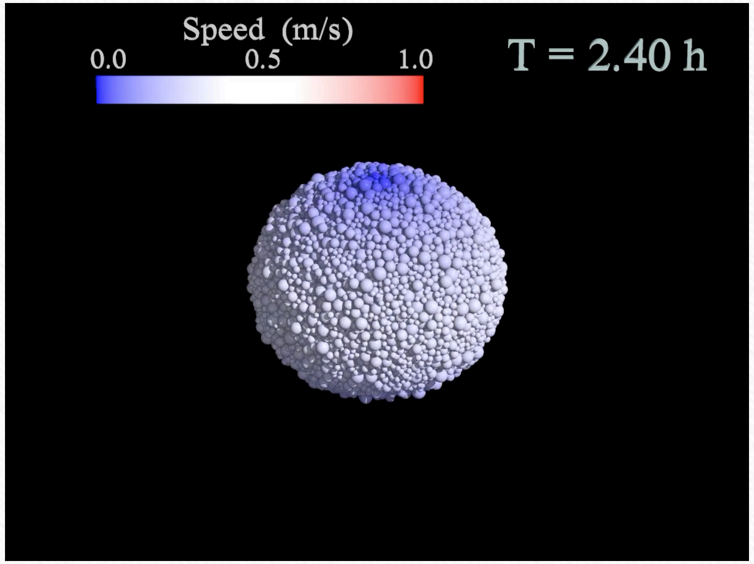
Rotational reshaping and fission due to YORP

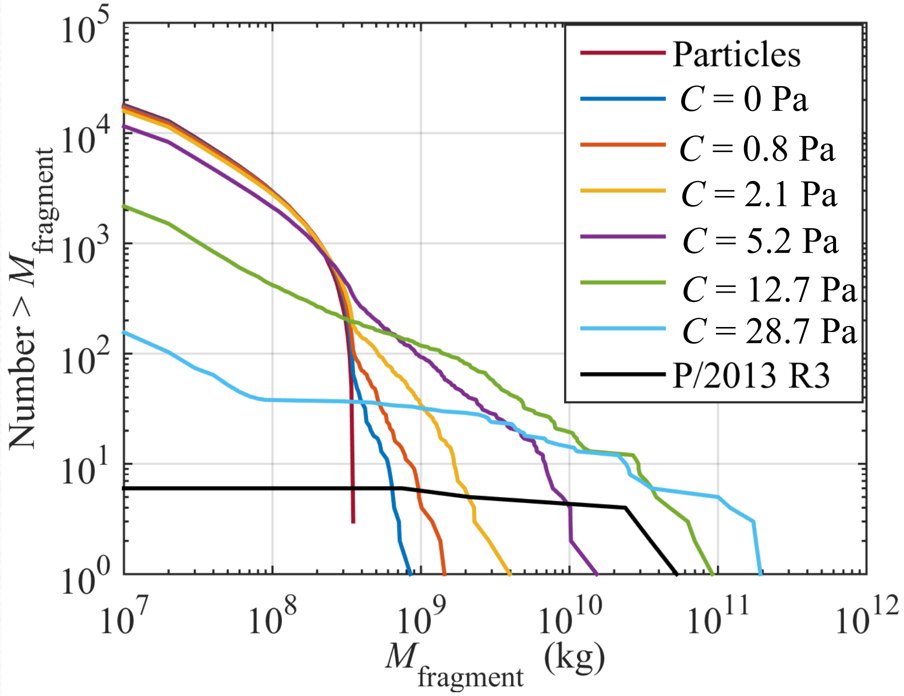
Effect of material cohesive strength on the rotational reshaping

$C = 0$ Pa



$C = 12.7$ Pa





A small amount of material cohesion can significantly improve the structural strength of an asteroid, and change its failure behavior

The cohesive strength of Asteroid P/2013 R3 is larger than 10 Pa

(Zhang et al. 2018 ApJ)

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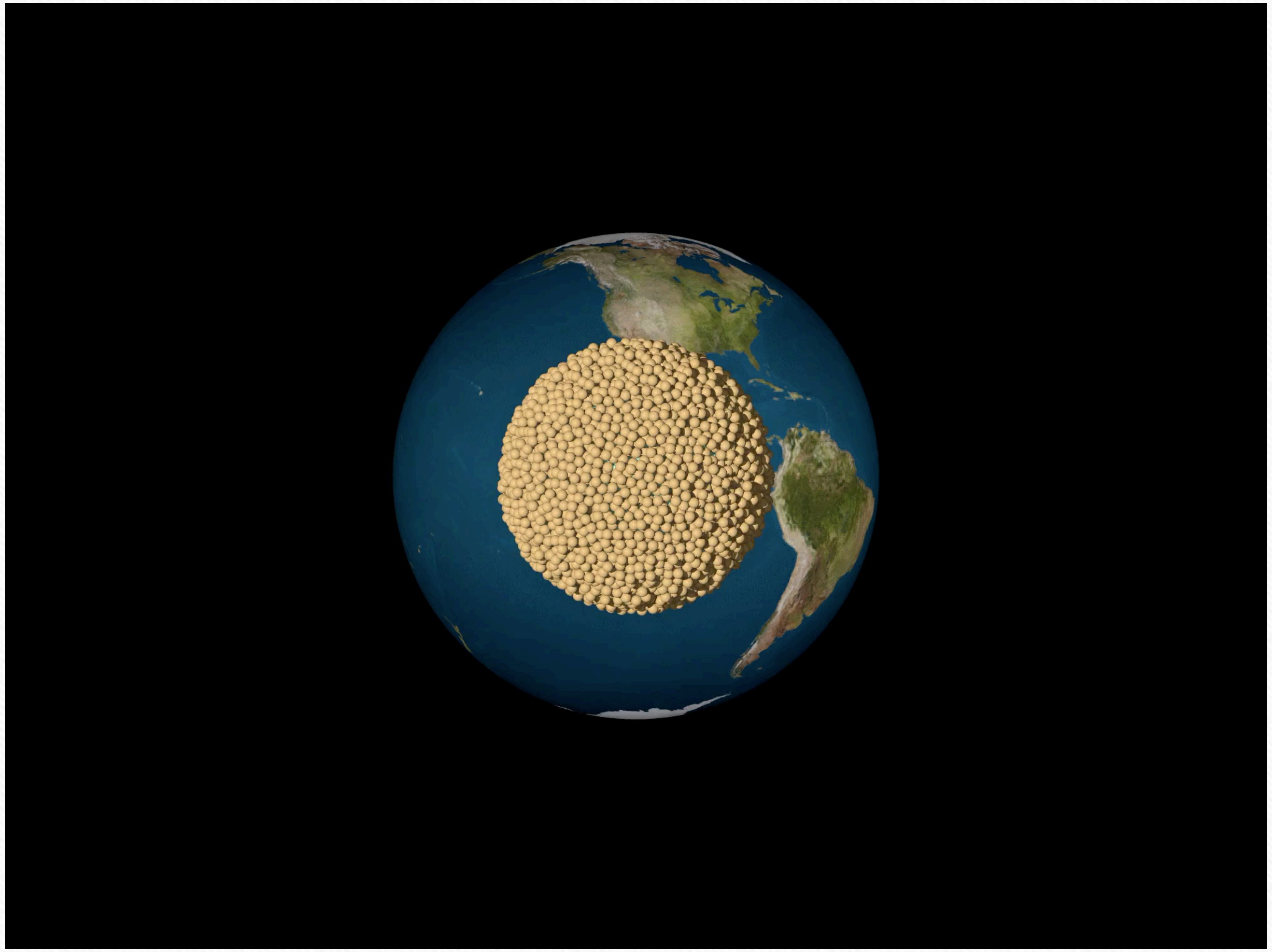
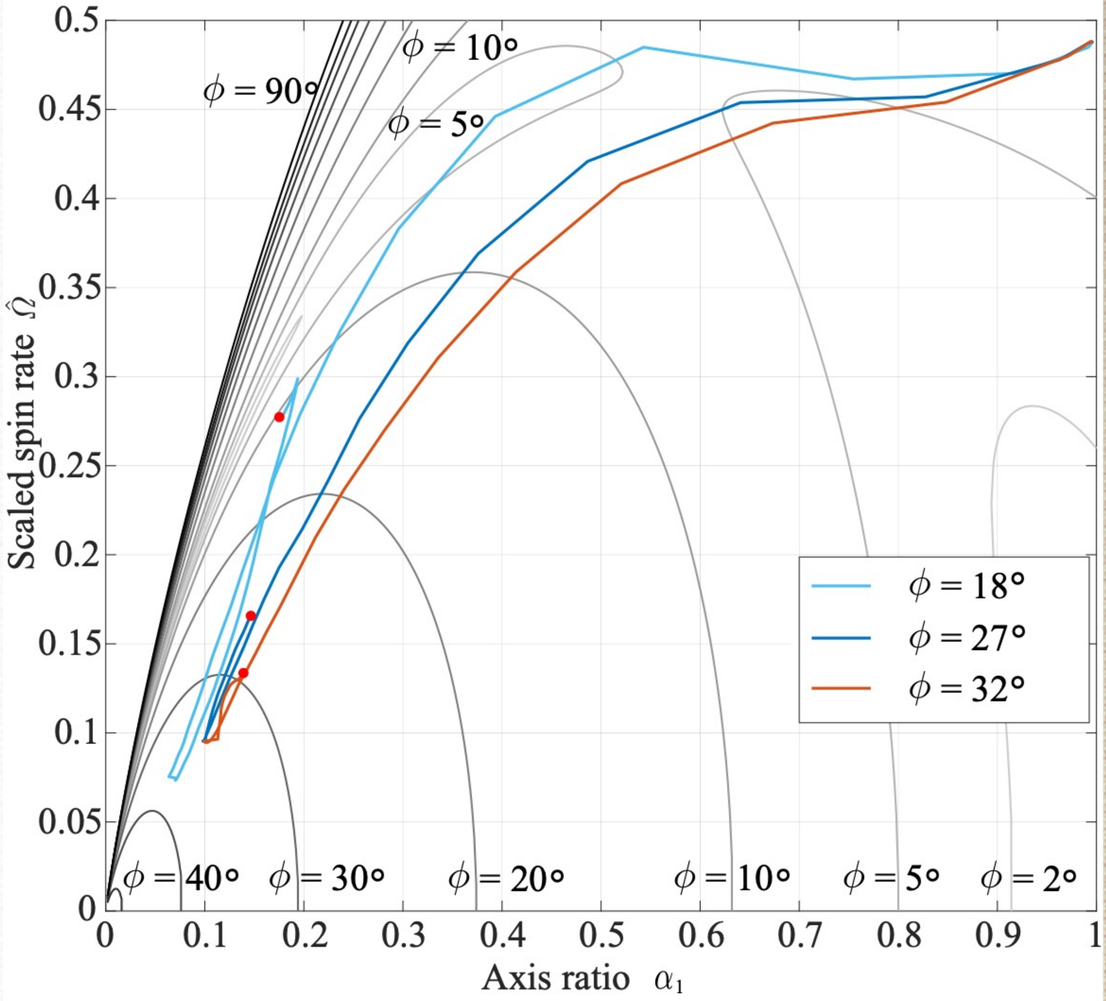
- *Tidal distortion and disruption* **Elongated near-Earth asteroids** **1I/'Oumuamua**

  PKDGRAV is used to simulate the encounter of a rubble pile with a planet/star

Tidal distortion and disruption: Formation of elongated objects

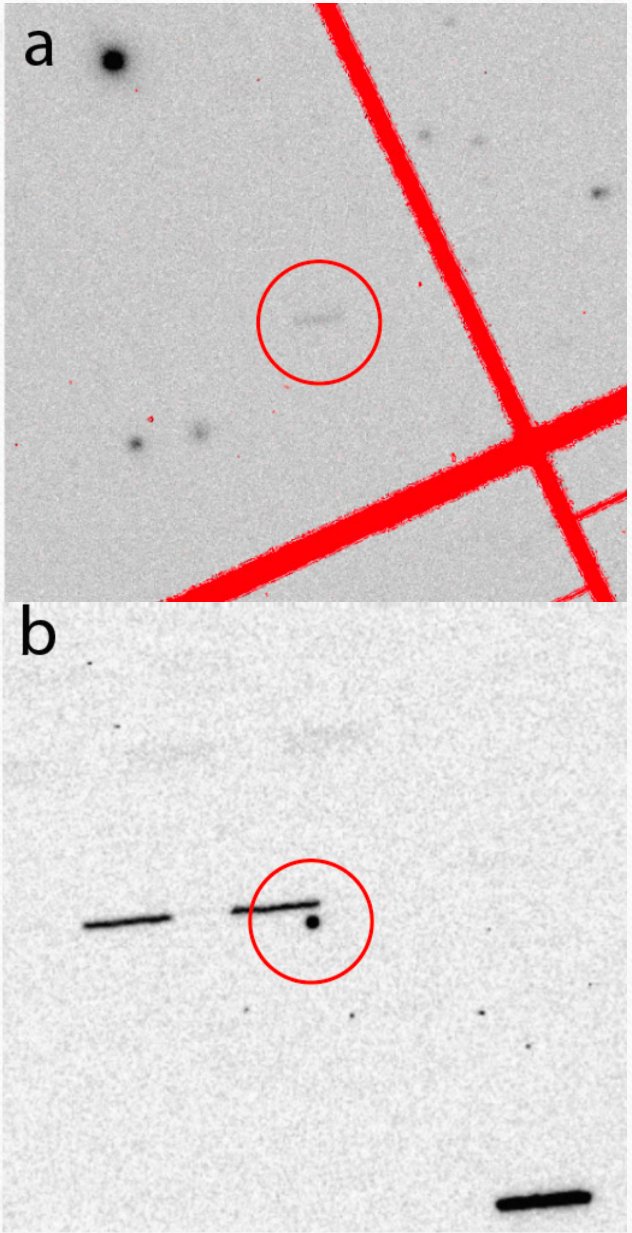




A rubble pile flies by the Earth with a distance of $1.6R_{\text{Earth}}$

(Zhang & Michel 2020 A&A)

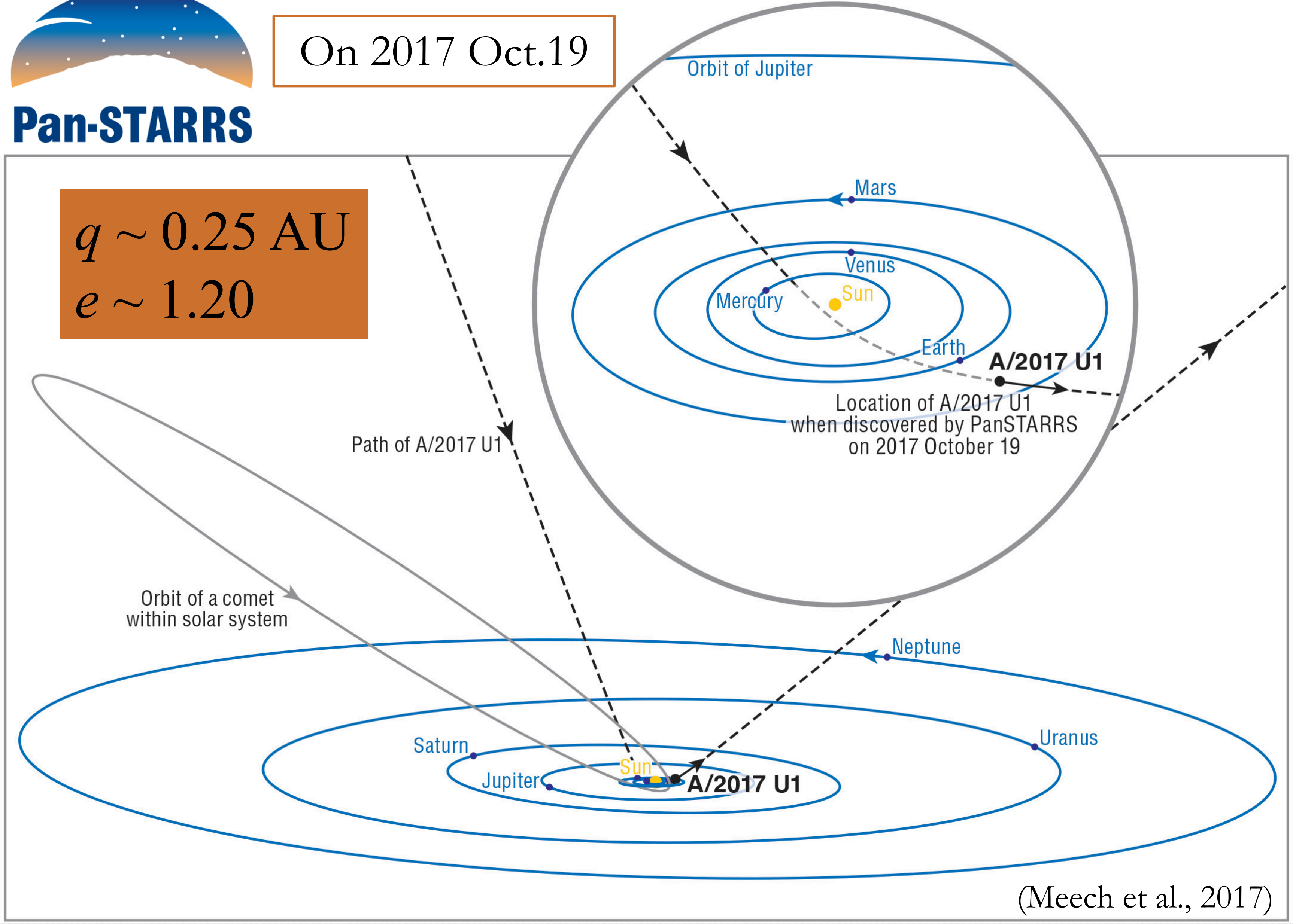
Discovery of the first interstellar object ‘Oumuamua



Pan-STARRS

On 2017 Oct.19

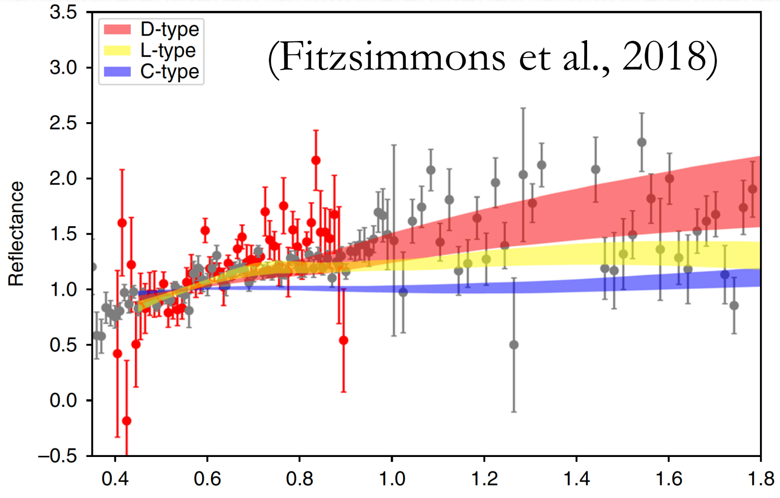
$q \sim 0.25$ AU
$e \sim 1.20$

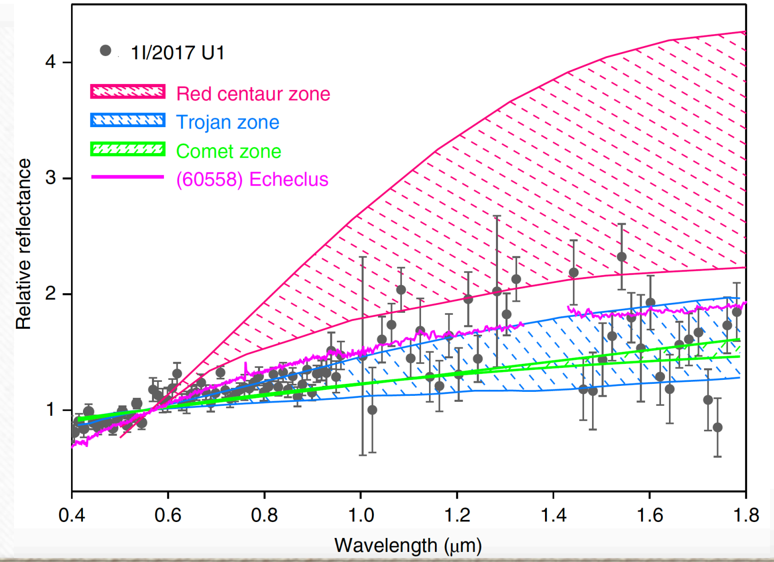


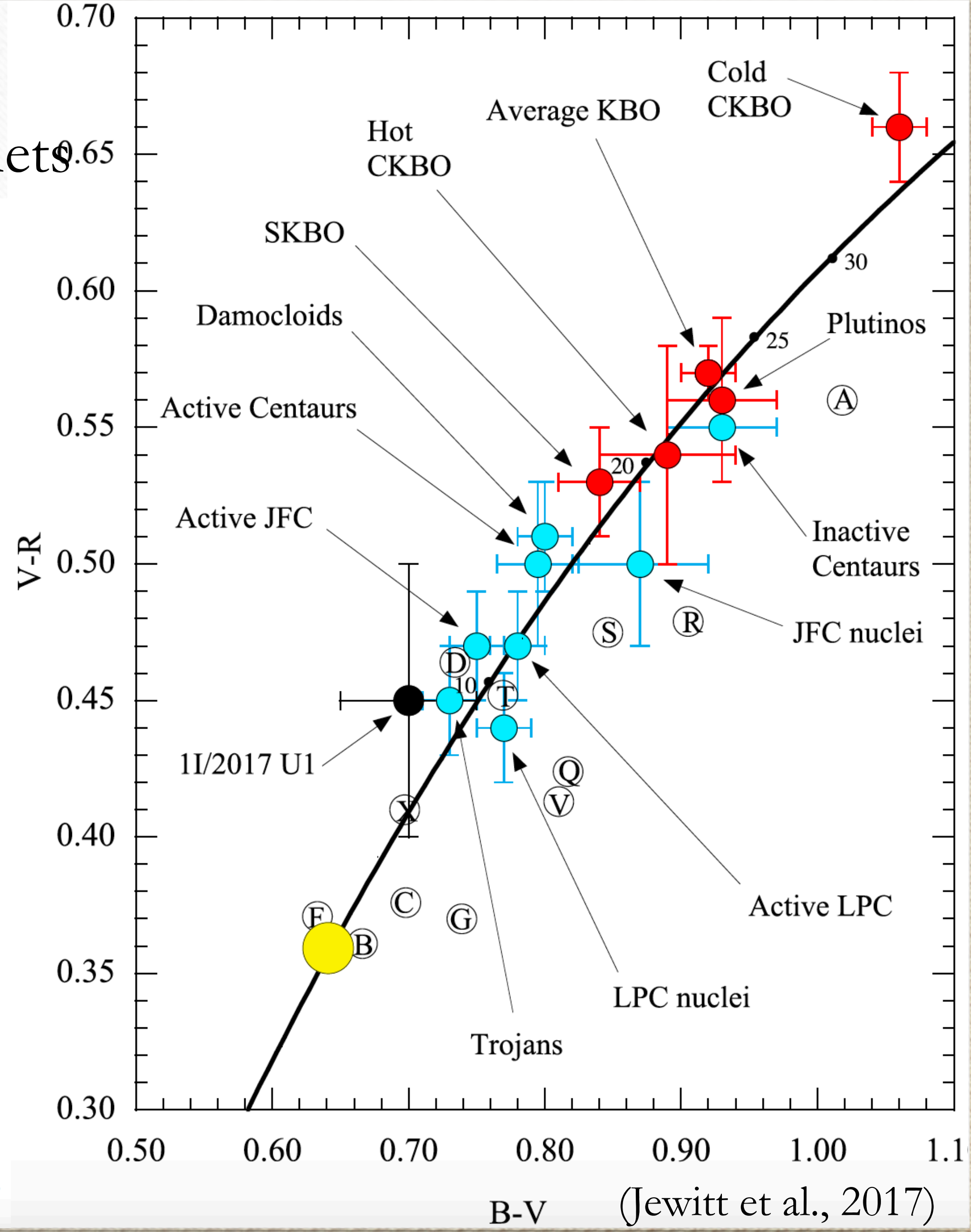
(Meech et al., 2017)

Characteristics of the first interstellar object 'Oumuamua

- Point source with no evidence of coma or gas
- Colors (red) consistent with some asteroids and comets







Characteristics of the first interstellar object 'Oumuamua

- Point source with no evidence of coma or gas
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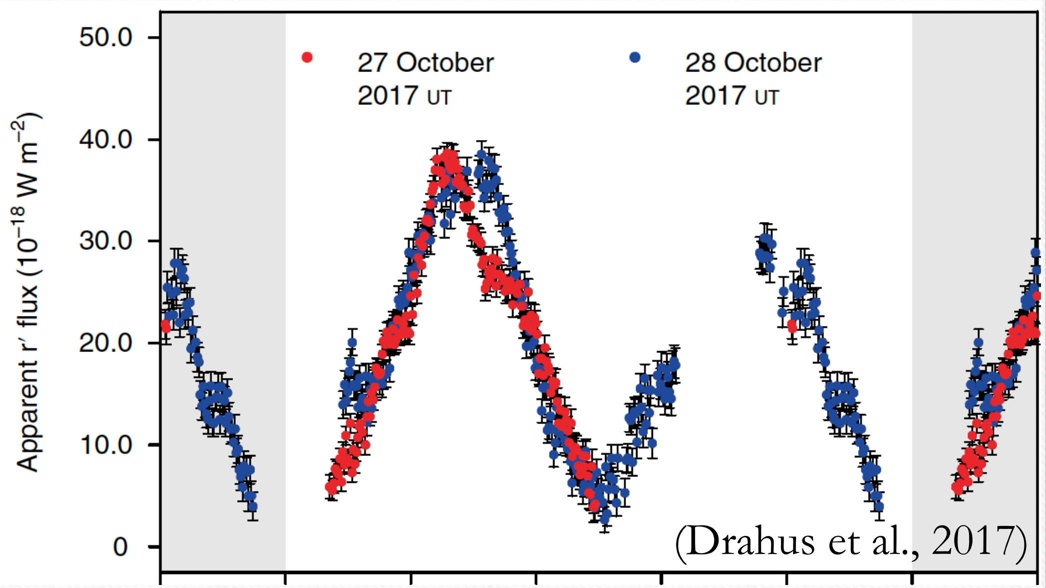
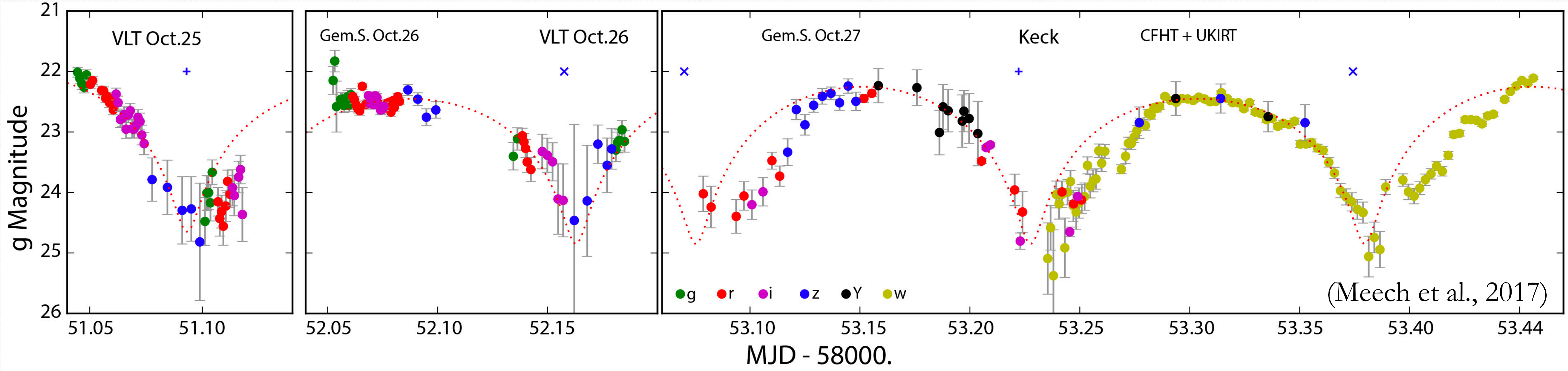
- Unusually large brightness range ($c/a < 1{:}6$, $a \sim 100$ m)
- Tumbling rotational state (period ~ 8 h)





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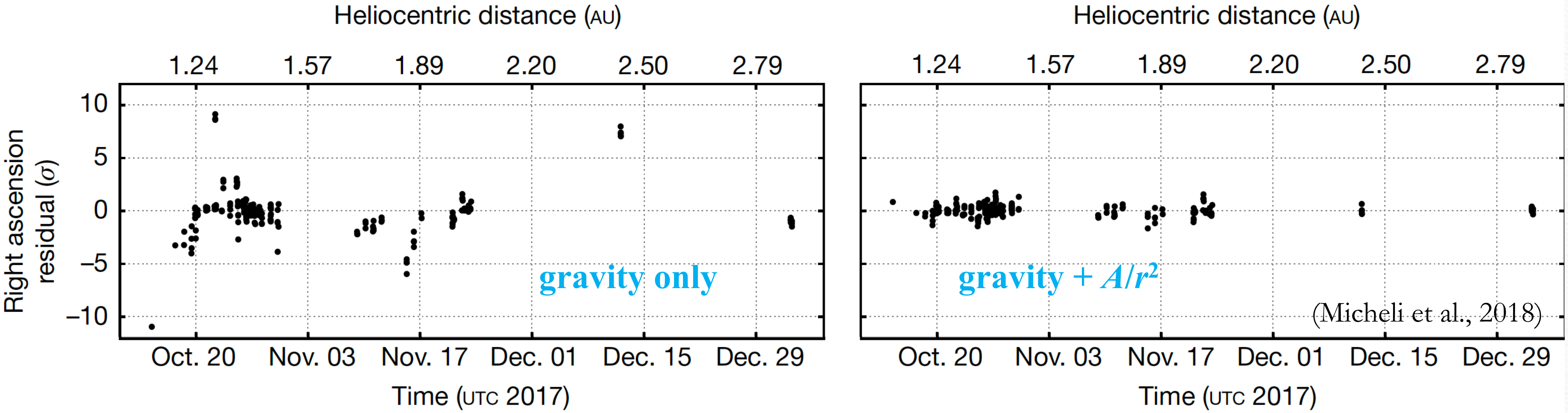
- Non-gravitational acceleration

$$a_{ng} = (4.92 \pm 0.16)\times 10^{-6} \left(\frac{r}{1\ \mathrm{AU}}\right)^{-2}$$



(Micheli et al., 2018)

Puzzles of the first interstellar object ‘Oumuamua

- Point source with no evidence of coma or gas
- Colors (red) consistent with some asteroids and comets
- Unusually large brightness range ($c/a < 1{:}6$, $a \sim 100$ m)
- Tumbling rotational state (period ~ 8 h)
- Non-gravitational acceleration

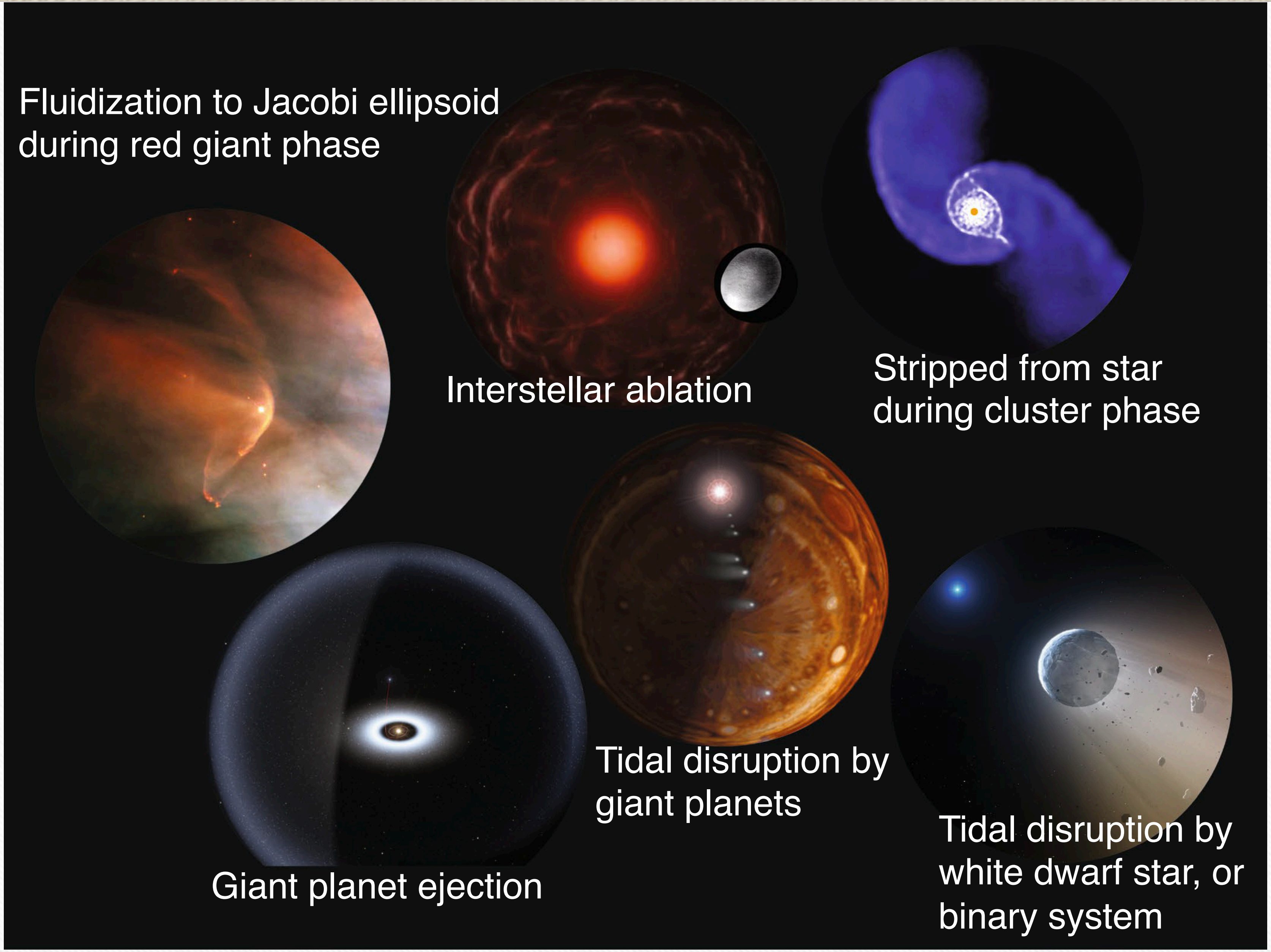
The fraction of cometary interstellar objects may be < 0.1 % (Do et al., 2018, Portegies Zwart et al., 2018)

The required number of density of asteroidal interstellar objects $3.5{\times}10^{13} - 2{\times}10^{15}\ \mathrm{pc}^{-3}$

Extremely elongated prolate or flat oblate shape, structural stability, large tumbling time scale

Solar-radiation pressure (bulk density < 1 kg/m^3) or outgassing (absence of coma)?

Origin of the first interstellar object 'Oumuamua



Formation and ejection of ‘Oumuamua by tidal disruptions

- Stellar encounter
- PKDGRAV

  (Granular contacts included)
- Parent body

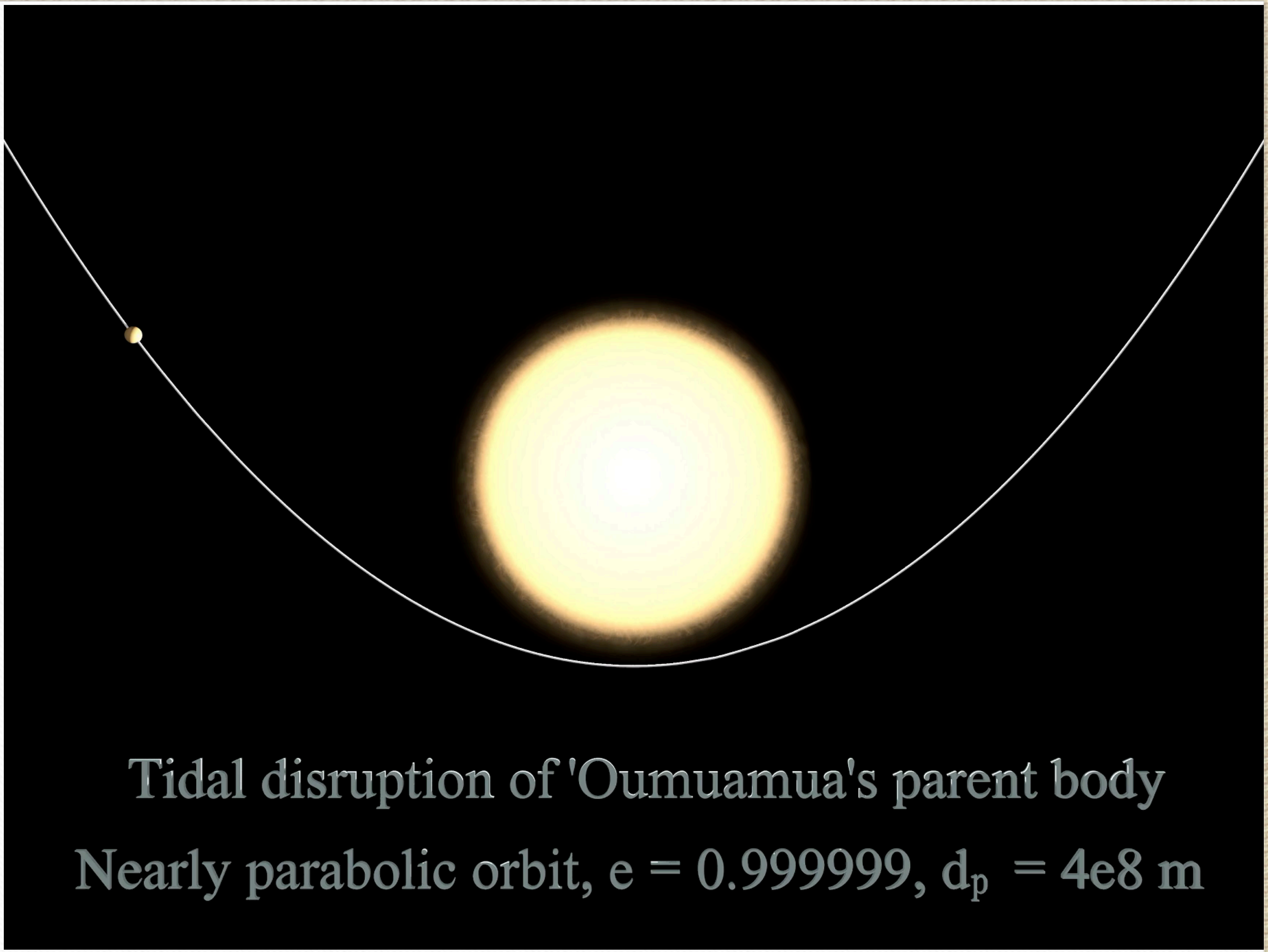
  Rubble-pile structure

  Near parabolic orbit

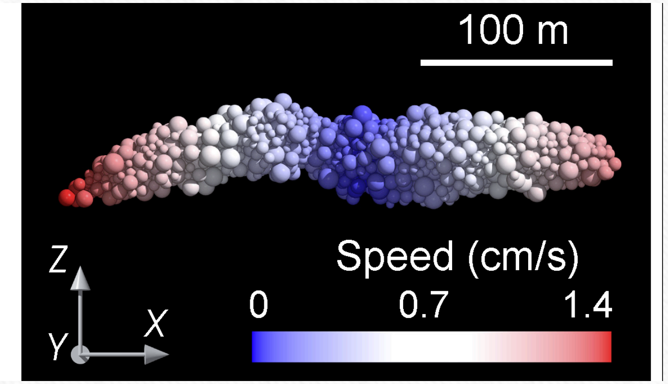
  Spherical

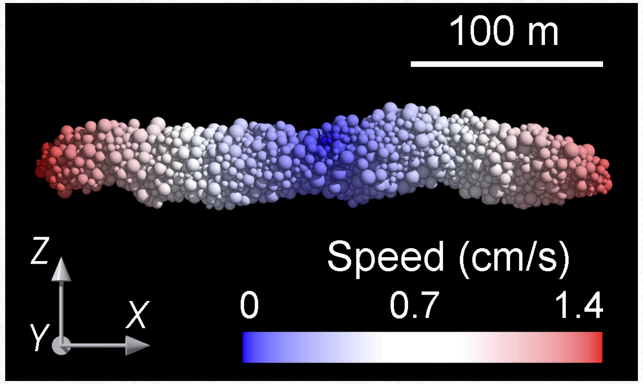
  $R_p = 100$ m

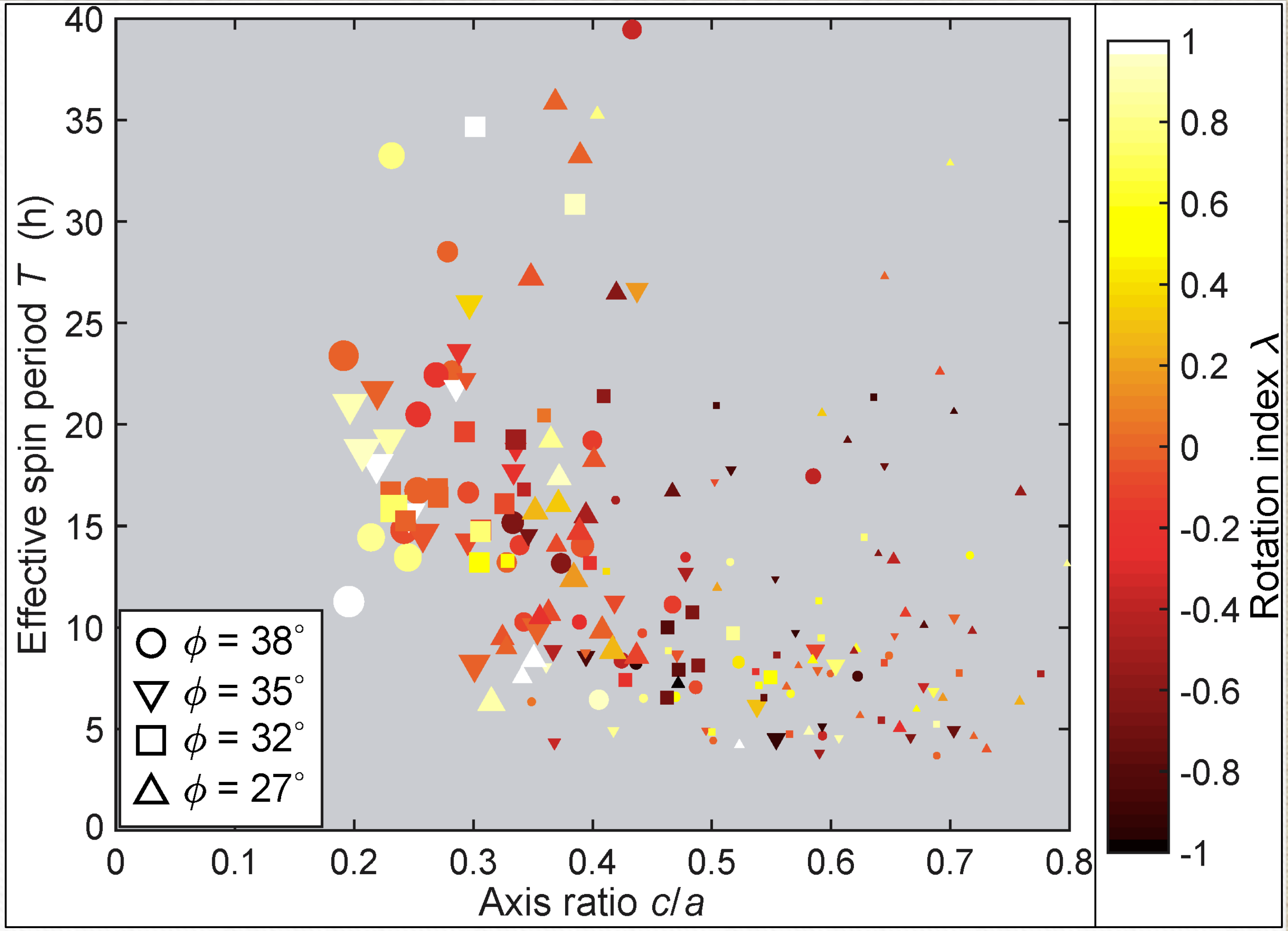
  $\rho_p = 2000$ kg/m^3
- Star mass $0.5M_\odot$



Effect of perihelion distance and friction angle





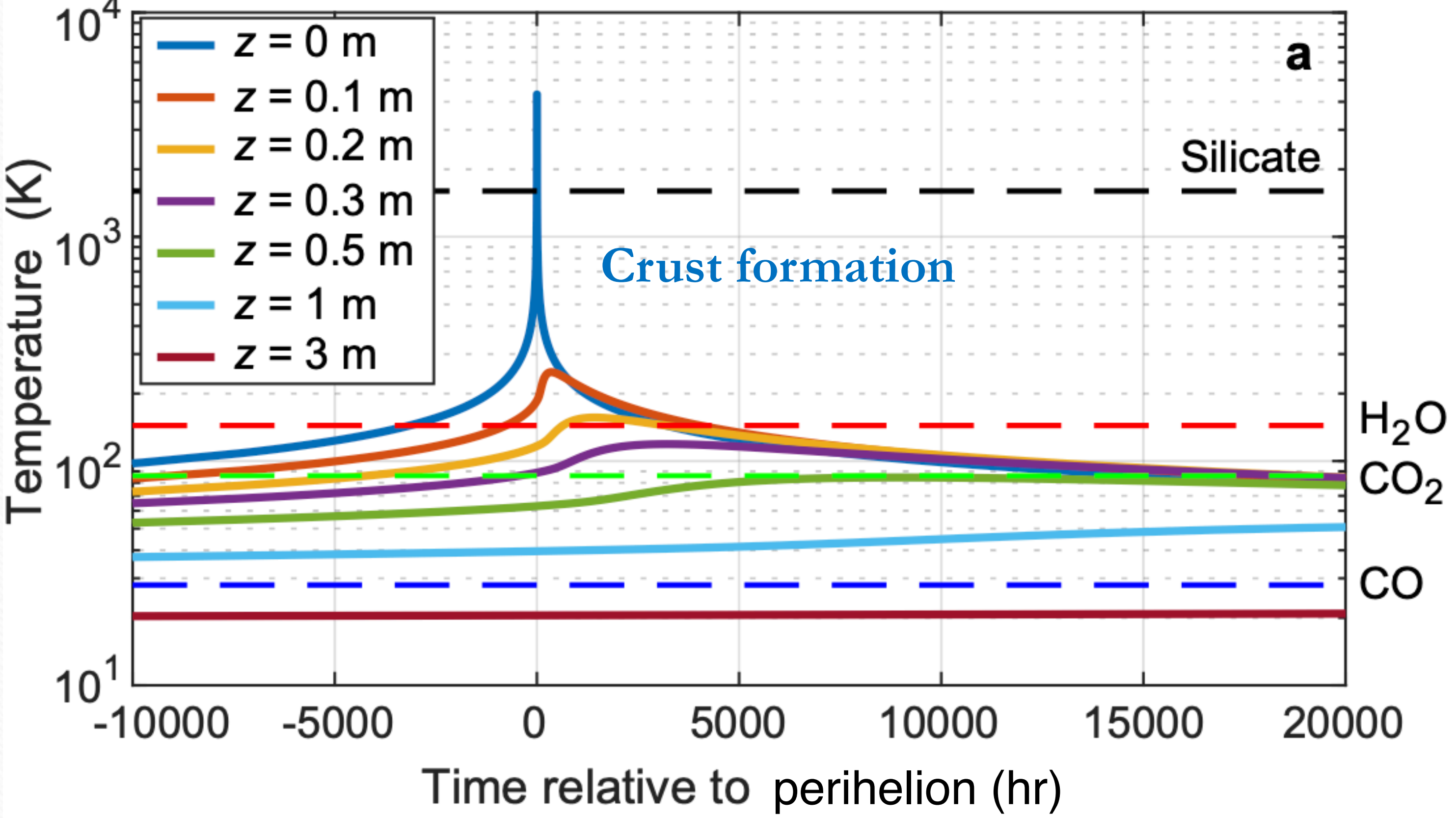


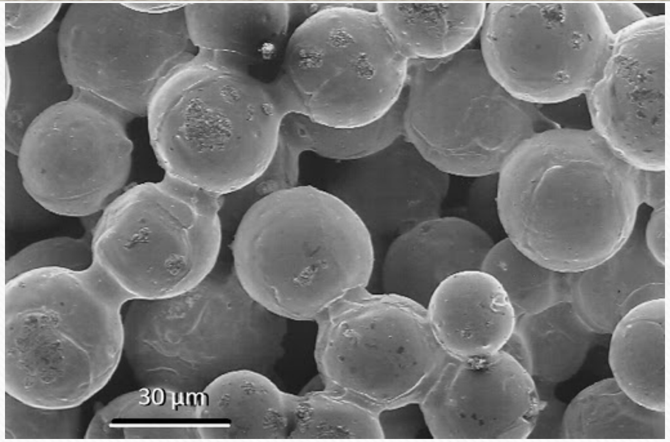
Fragmentation outcomes for various friction angles

The production of extreme elongated fragments through tidal disruptions is very common and very efficient.

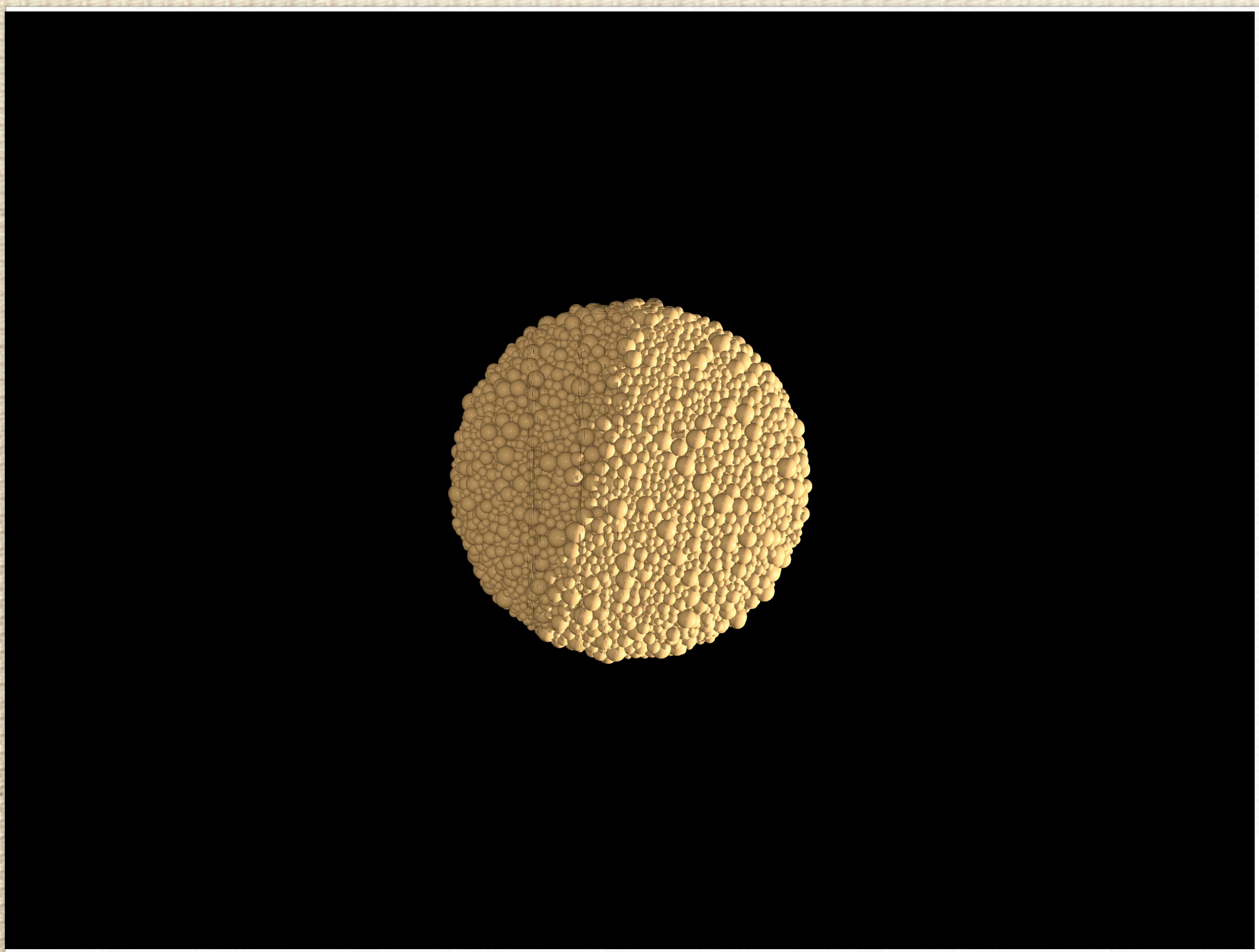
Temperature evolution during close stellar encounters

Temperature evolution at different depths

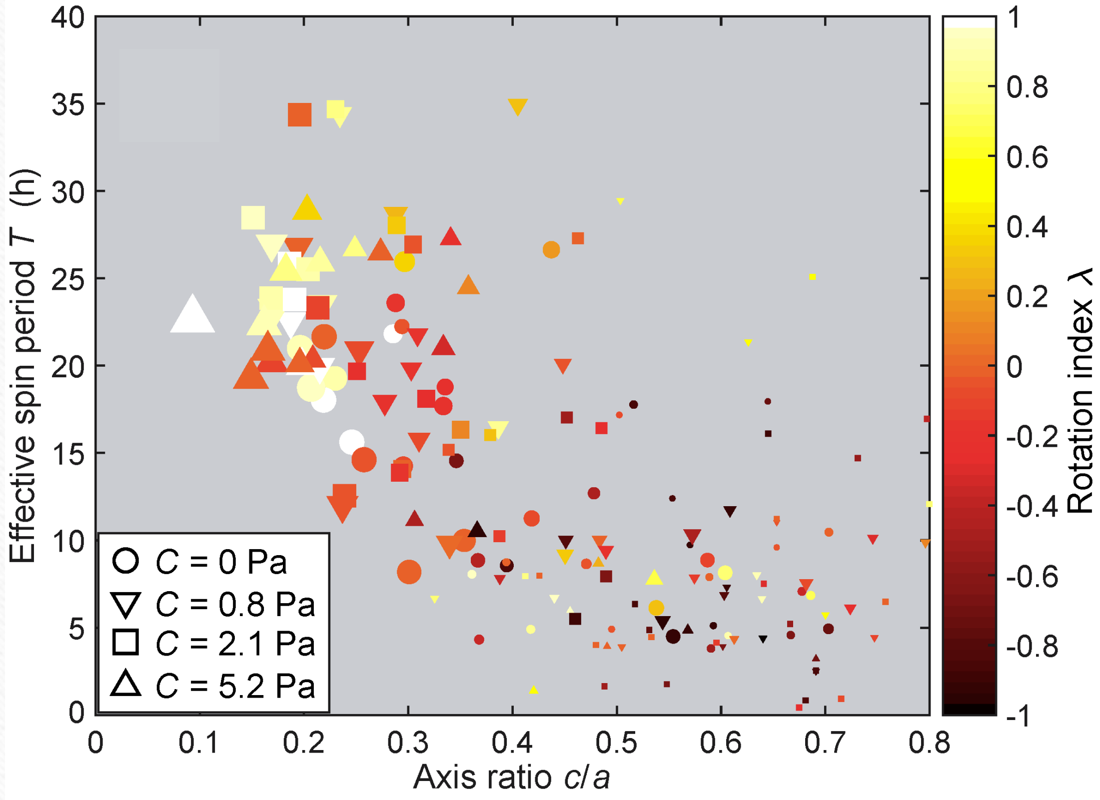


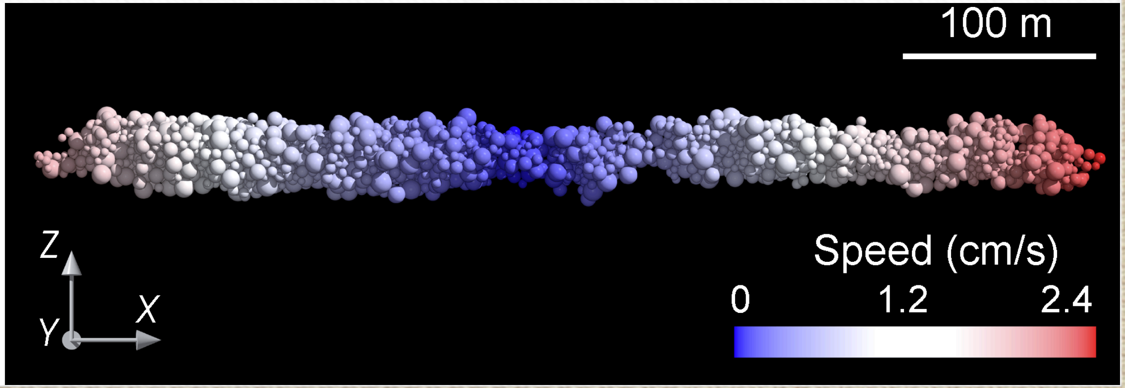


Effect of later-turn-on cohesive strength

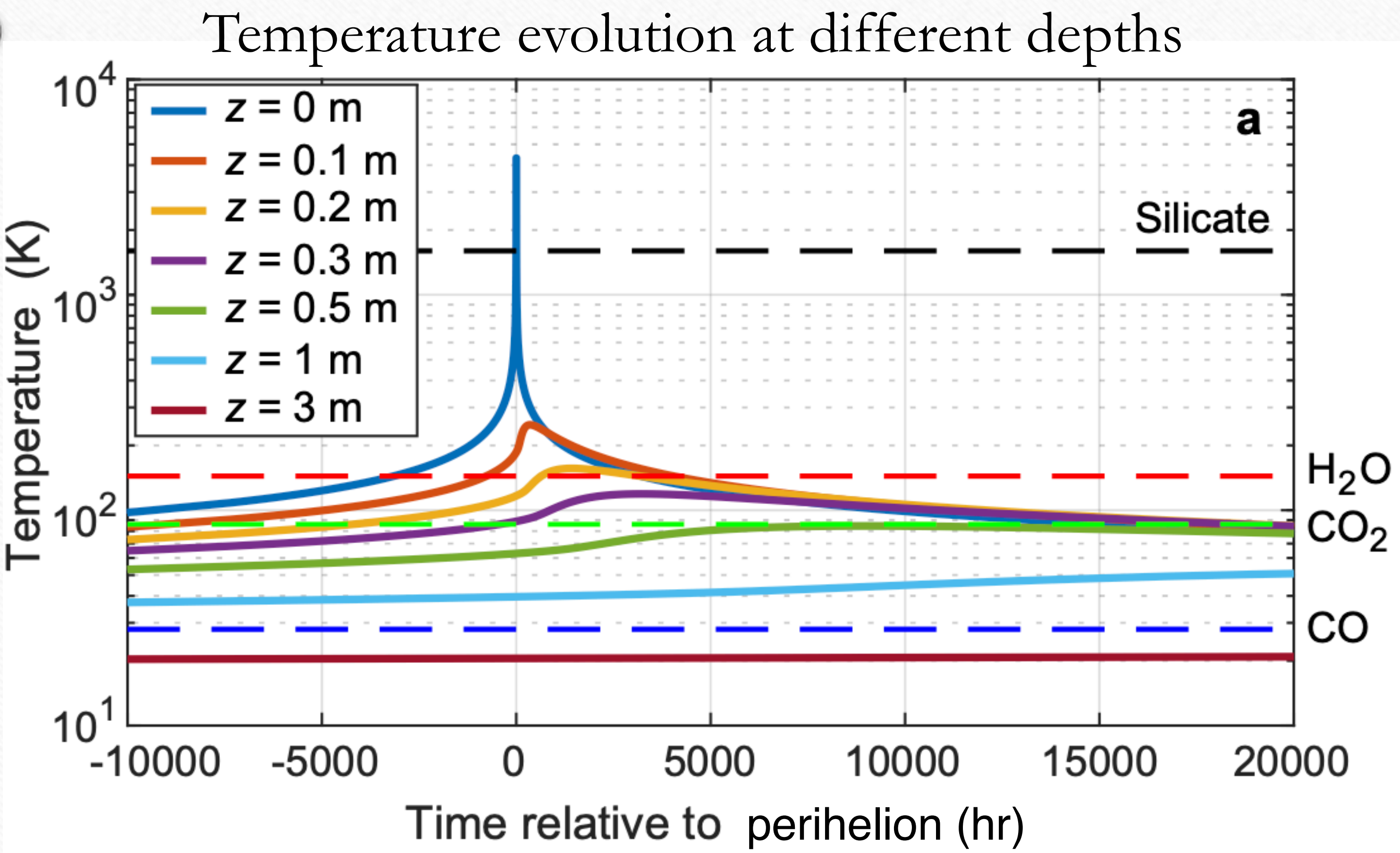


C = 0 Pa before crust formation at 3 hours post periastron and C = 5.2 Pa after the phase transition





Asteroidal surfaces and inventory of volatiles



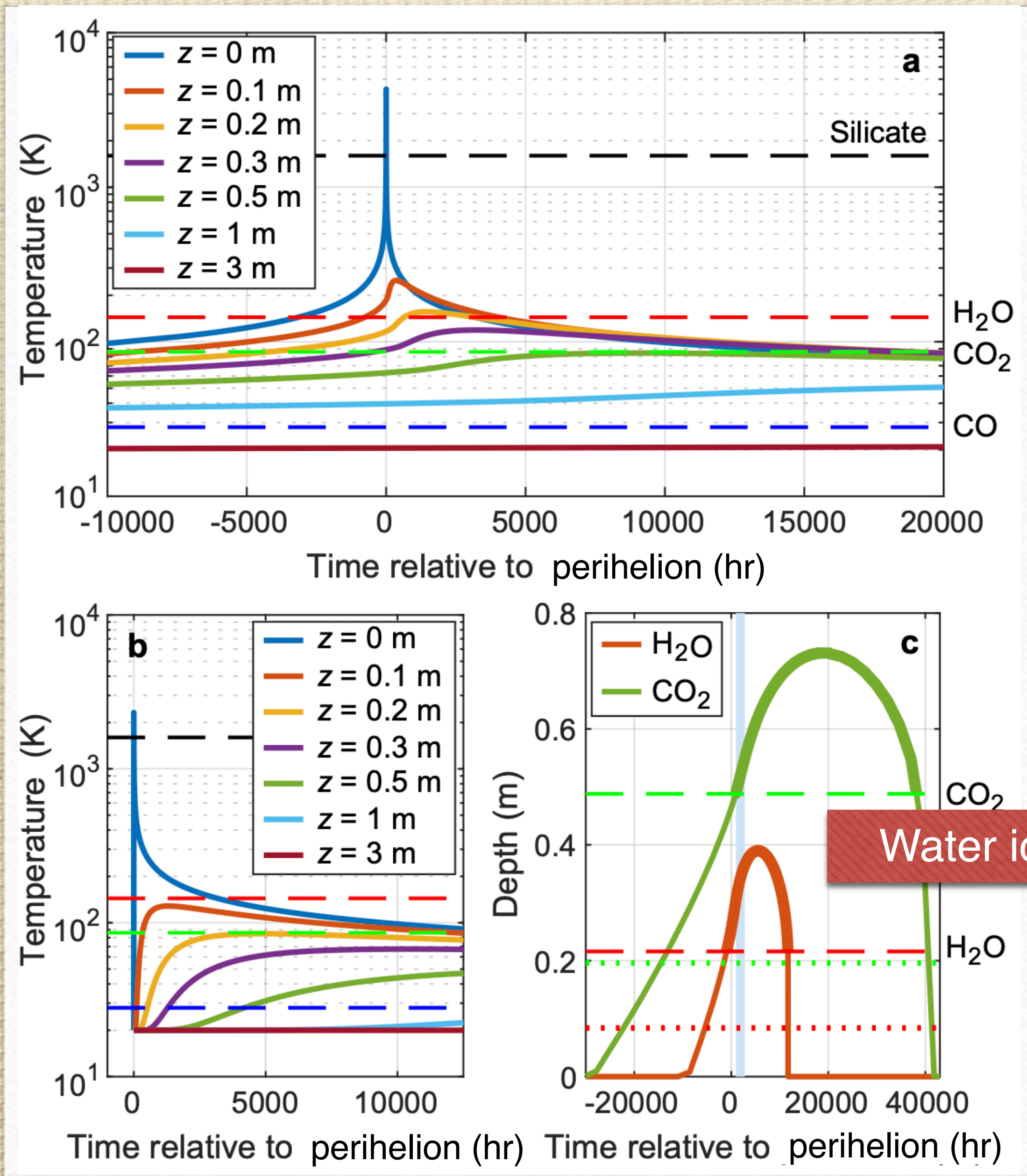
CO sublimation > 3 m

Consistent with 'Oumuamua's spectroscopic properties and the inferred "dryness" of the interstellar population

H_2O preserved at > 10~20 cm

CO_2 preserved at > 20~50 cm

Passage through the Solar System



Water ice inventory is sufficient

Quantity	Value Q(X) [molecules/s]
OH production	$< 1.7\times10^{27}$ @ 1.8 AU
CO production	$< 9\times10^{23}$ @ 2.0 AU
CO_2 production	$< 9\times10^{22}$ @ 2.0 AU
CN production	$< 2\times10^{22}$ @ 1.4 AU
C_2 production	$< 4\times10^{22}$ @ 1.4 AU
C_3 production	$< 2\times10^{21}$ @ 1.4 AU
Dust production [kg/s]	$< 1.7\times10^{-3}$ @ 1.4 AU < 10 @ 10^3 AU

$$a_{ng} = (4.92 \pm 0.16)\times10^{-6}\left(\frac{r}{1\ \mathrm{AU}}\right)^{-2}$$

$$Q_X \sim \frac{m_O a_{ng}}{v_{th}} = 0.7\ \mathrm{kg/s}@1\ \mathrm{AU}$$

$$Q_{H_2O} \sim 2.5\times10^{25}\ @\ 1\ \mathrm{AU}$$

$$Q_{CO_2} \sim 9.6\times10^{24}\ @\ 1\ \mathrm{AU}$$

$$Q_{H_2O}^{total} = 1.2\times10^{6}\ \ \mathrm{kg}$$

Solving the puzzles of ‘Oumuamua

- Shape and tumbling rotation state √
- No cometary activity is observed √
- Colors similar to objects with irradiated organic-rich surfaces √
- Non-gravitational acceleration probably due to outgassing √
- Required number of density √

The proposed tidal disruption mechanism can account for the formation and ejection of 1I/‘Oumuamua.

(Zhang & Lin 2020 Nat. Astron.)

Summary

- *Collisional evolution*

  Catastrophic disruption of a parent body leads to reaccumulated aggregates with different shapes

- *Rotational reshaping and fission due to YORP*

  Surface mass movement can be induced and form top shapes & binary systems

- *Tidal distortion and disruption*

  A pathway to form extremely elongated objects

Material strength play important roles in asteroid reshaping processes

Thanks for your attention!