1I/`Oumuamua

Interstellar Small Body of Mystery

(aka 1I/2017 U1)

Edwin L. Turner

Department of Astrophysical Sciences, Princeton University
The Kavli Institute for the Physics and Mathematics of the Universe, University of Tokyo
Program in Interdisciplinary Studies, Institute for Advanced Study

+++++++++++++++

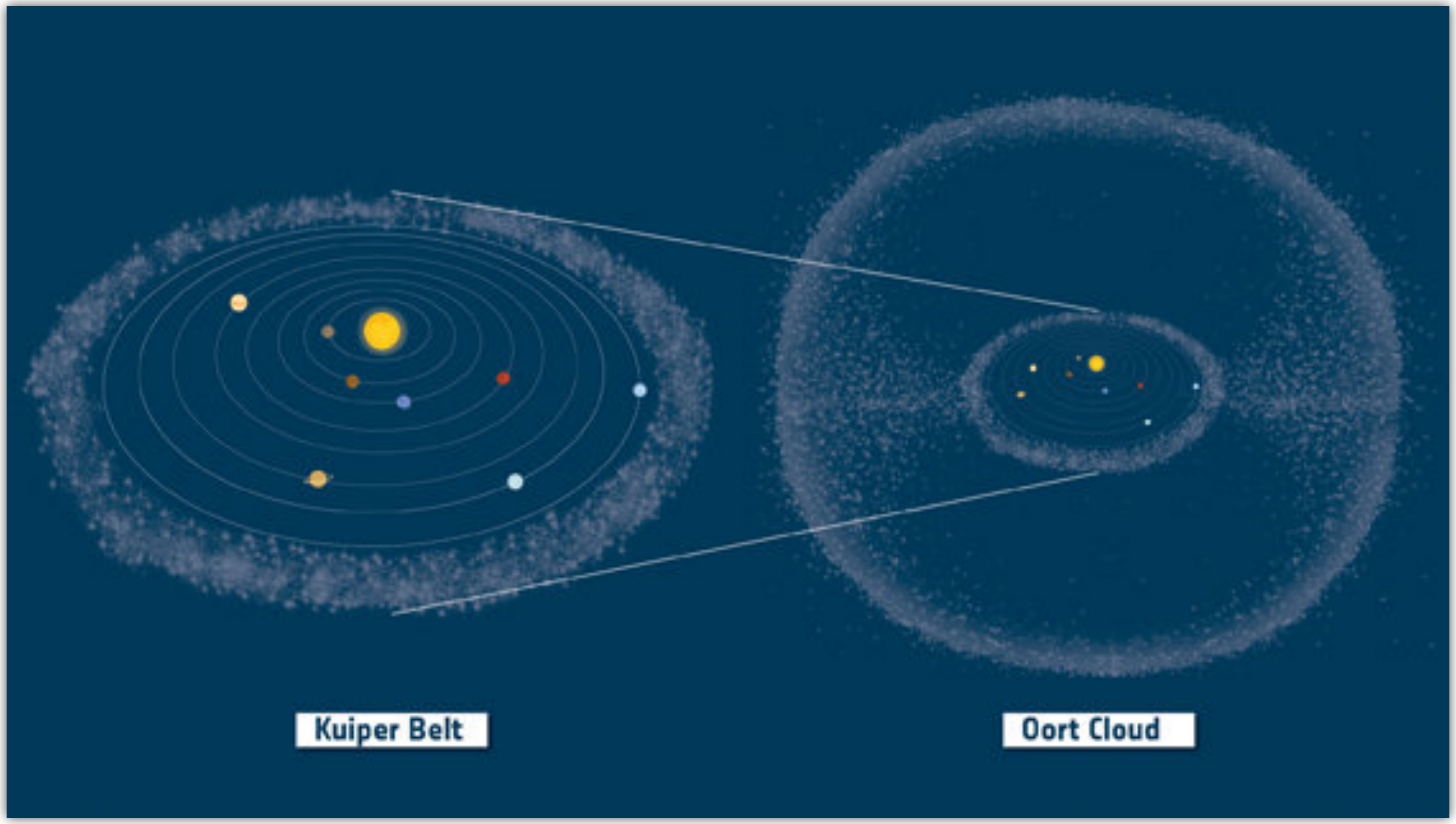
@ Kavli IPMU – June 10, 2019

J. Forbes (CfA) – provided some slides

Interstellar Small Bodies (Comets)

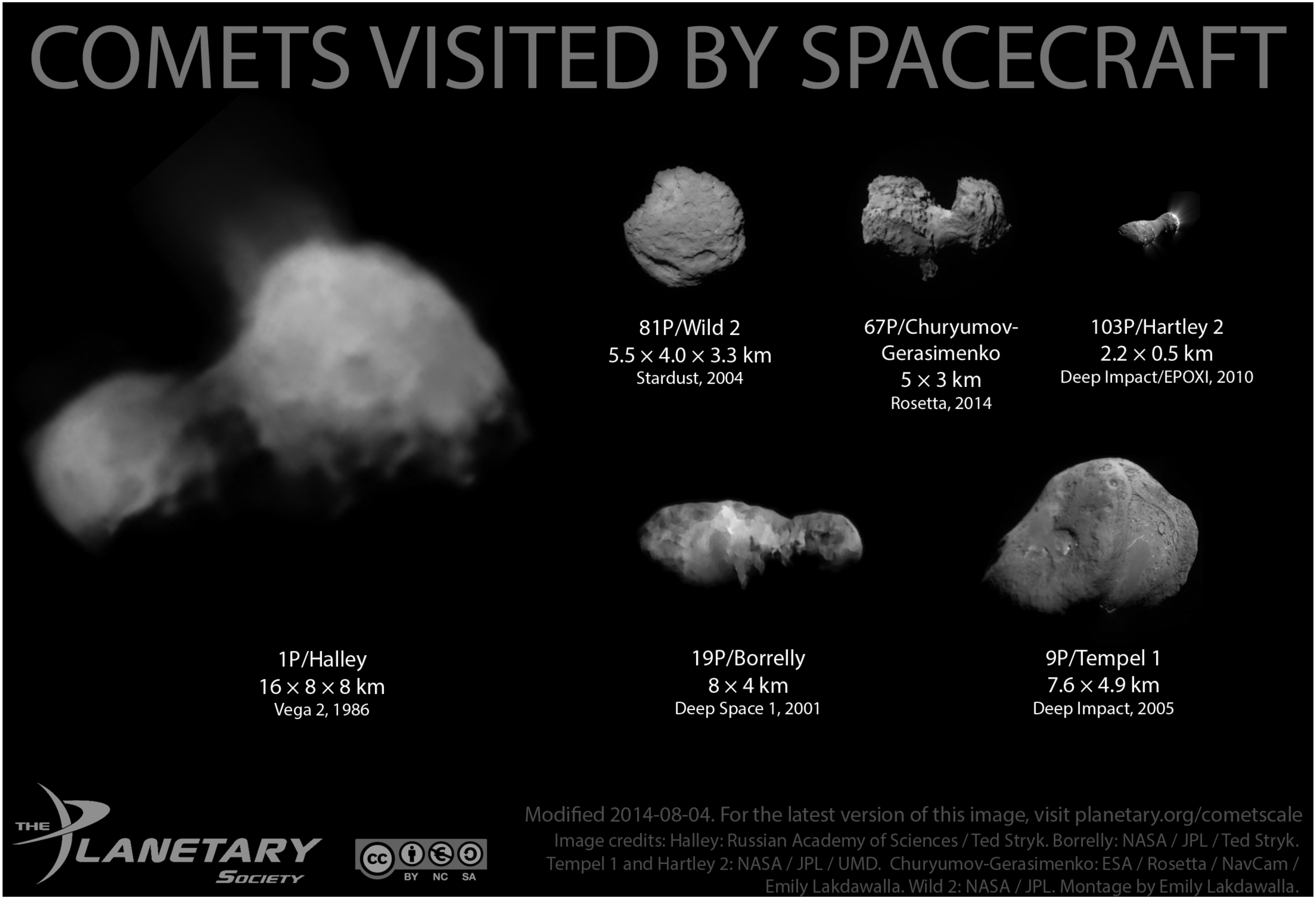
- Long predicted (1^{st} papers in ‘70s & ‘80s)
- ~1 km sized planetesimals ejected in huge numbers during planetary system formation & evolution
- Oort Cloud (of comets) => SS ejected 10^{12-15} of them
- Expected number density in the ISM VERY uncertain, but VERY much more common than stars or planets
- Some will pass through the SS occasionally & should be easily recognized due to strongly unbound orbits.
- Expected to resemble long period SS comets from the Kuiper Belt and/or Oort Cloud except for their orbits
- First ever detected: *1I/`Oumuamua*

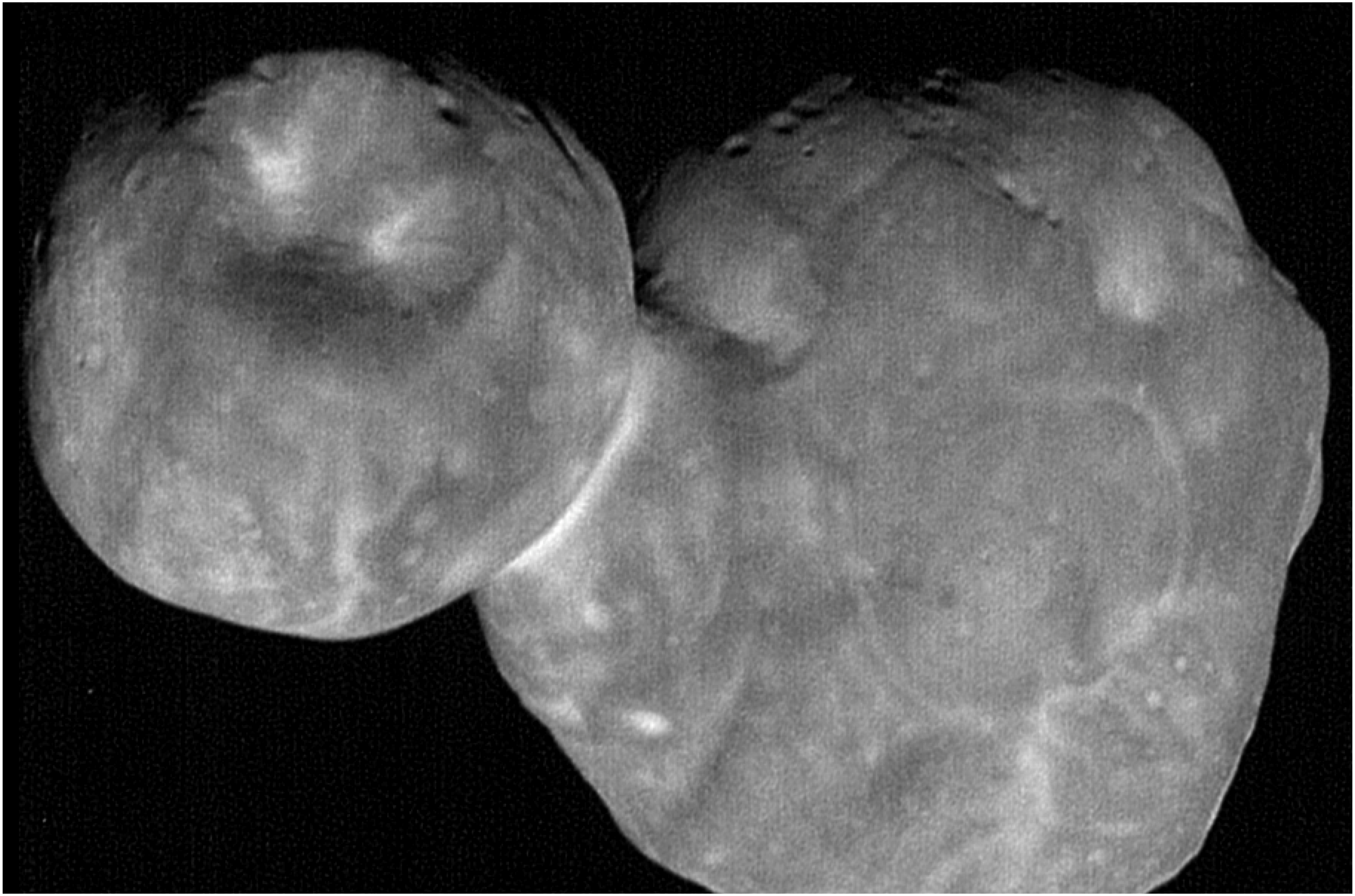
Kuiper Belt & Oort Cloud
SS Comets



NB - Oort Cloud is MUCH further out than shown in diagram…about 10^3-10^4 further than Kuiper Belt

Typical SS Long Period Comets Exhibit Prominent Coma & Tails


COMETS VISITED BY SPACECRAFT
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
67P/Churyumov-Gerasimenko
5 × 3 km
Rosetta, 2014
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
1P/Halley
16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
THE PLANETARY SOCIETY
BY NC SA
Modified 2014-08-04. For the latest version of this image, visit planetary.org/cometscale
Image credits: Halley: Russian Academy of Sciences / Ted Stryk. Borrelly: NASA / JPL / Ted Stryk. Tempel 1 and Hartley 2: NASA / JPL / UMD. Churyumov-Gerasimenko: ESA / Rosetta / NavCam / Emily Lakdawalla. Wild 2: NASA / JPL. Montage by Emily Lakdawalla.

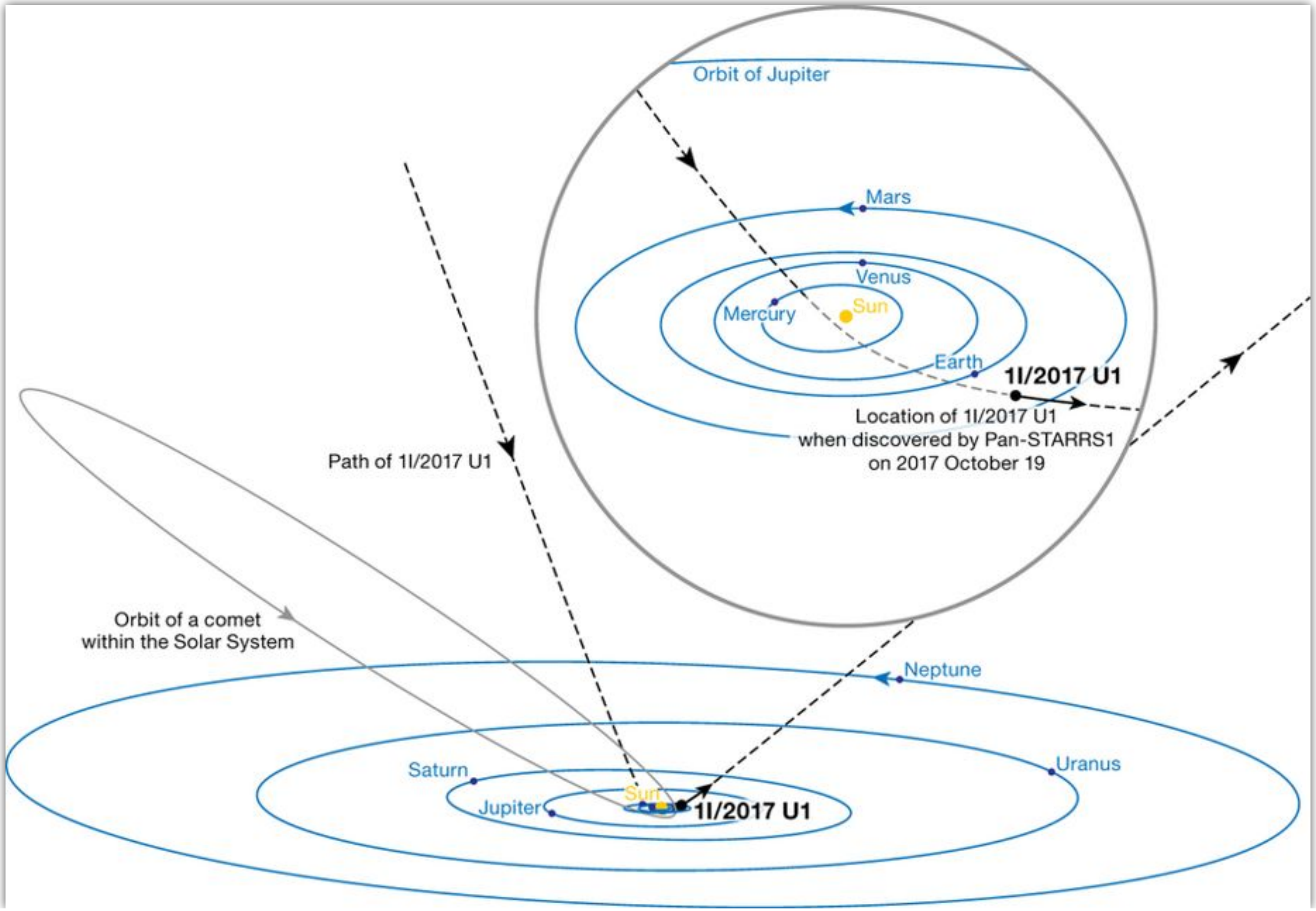


Ultima Thule from the New Horizons Probe

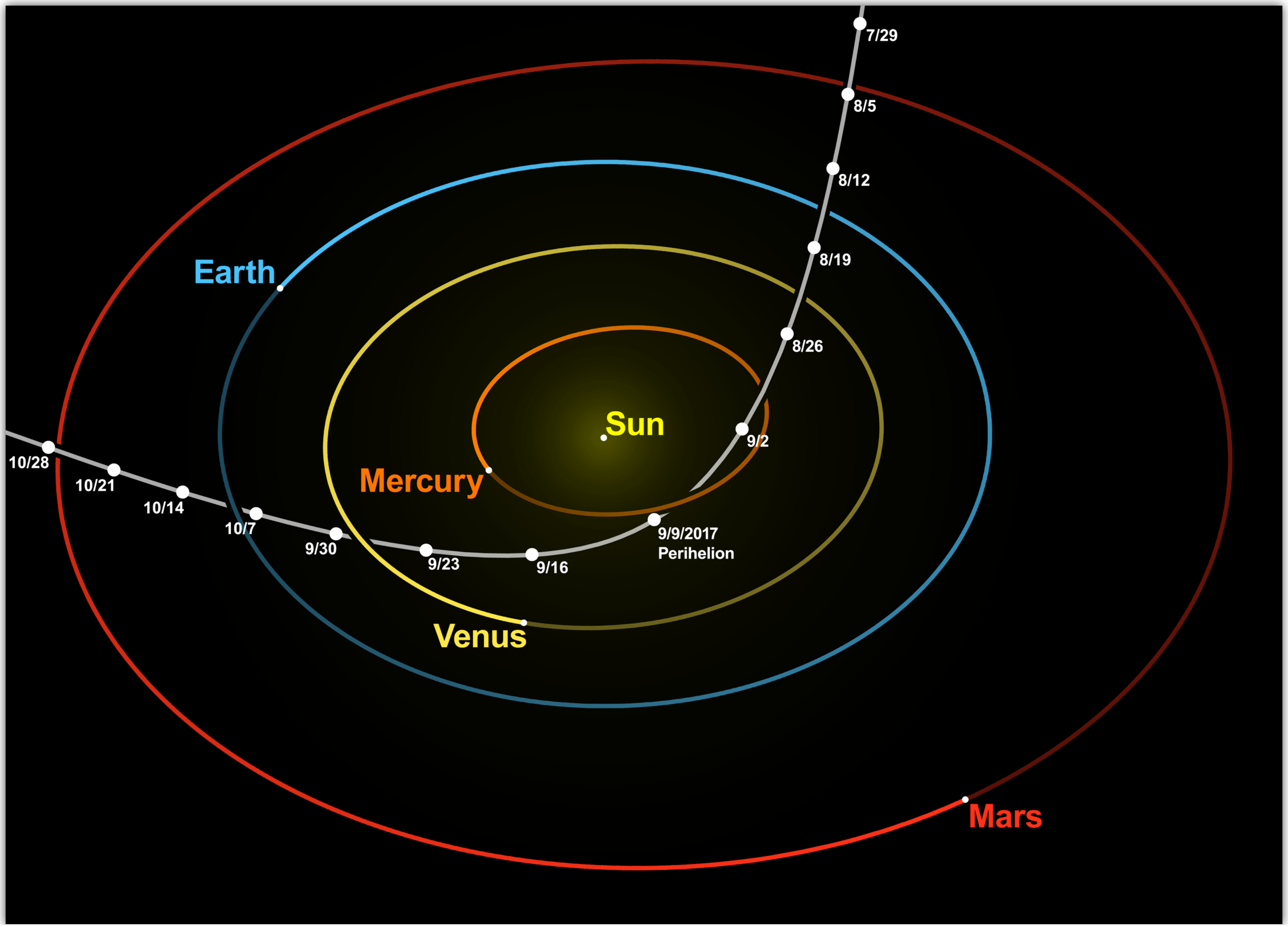
1I/`Oumuamua = 1I/2017 U1

- Discovered 19 October 2017 by Pan-STARSS1
- Soon recognized as interstellar due to its highly unbound orbit (high velocity)
- Unfortunately noticed after closest approach to the Sun on Sept 9, 0.25 AU (within the orbit of Mercury), and after its closest approach to the Earth on Oct 14, 0.16 AU.
- Observed intensively by multiple observatories (ground & space) until it became too faint to detect even with HST in early January 2018.
- Trajectory unsurprising
- Colors & spectra unusual but not uniquely so
- Still the subject of many studies with a growing literature of scientific publications.

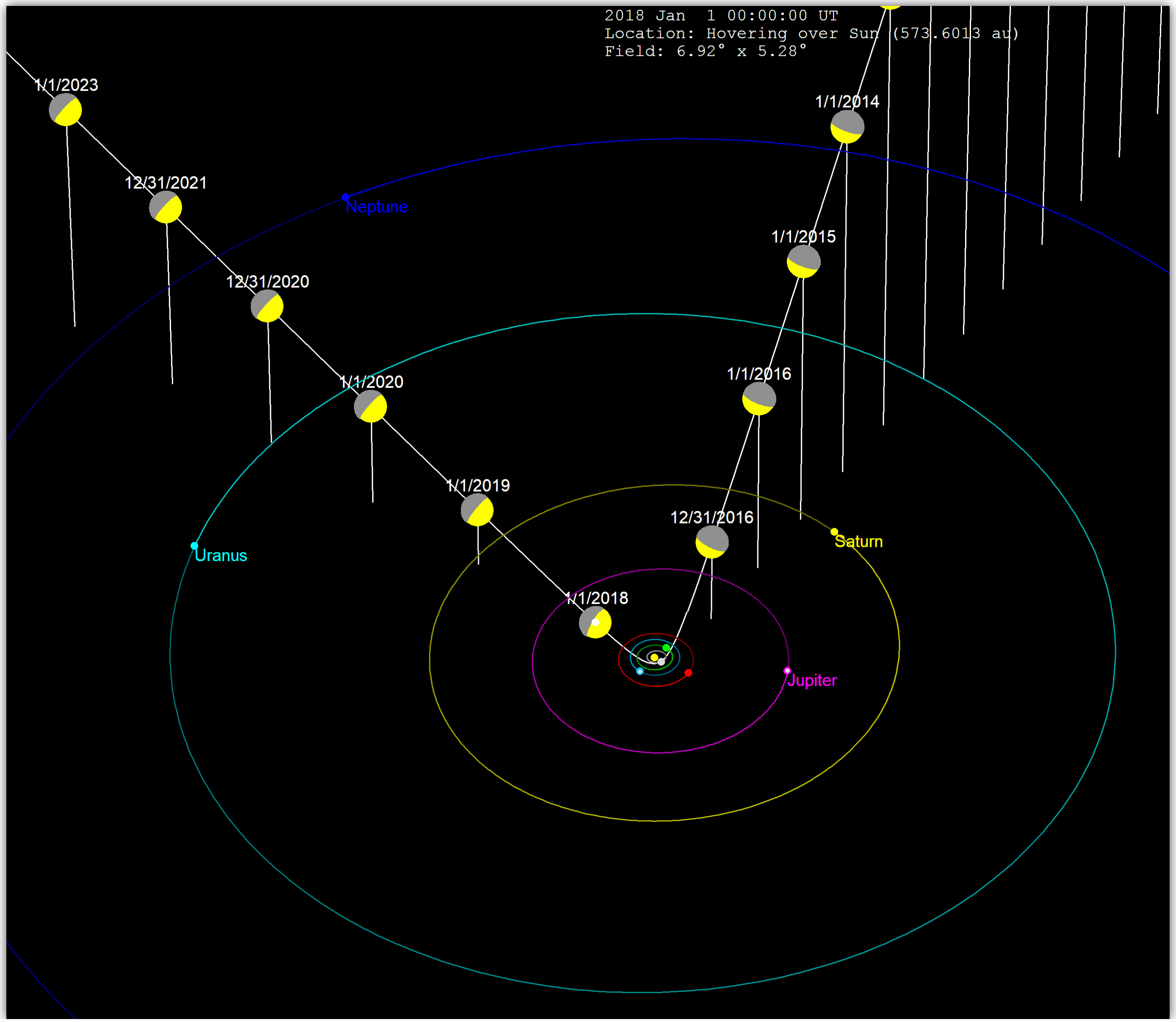
1I/`Oumuamua Trajectory



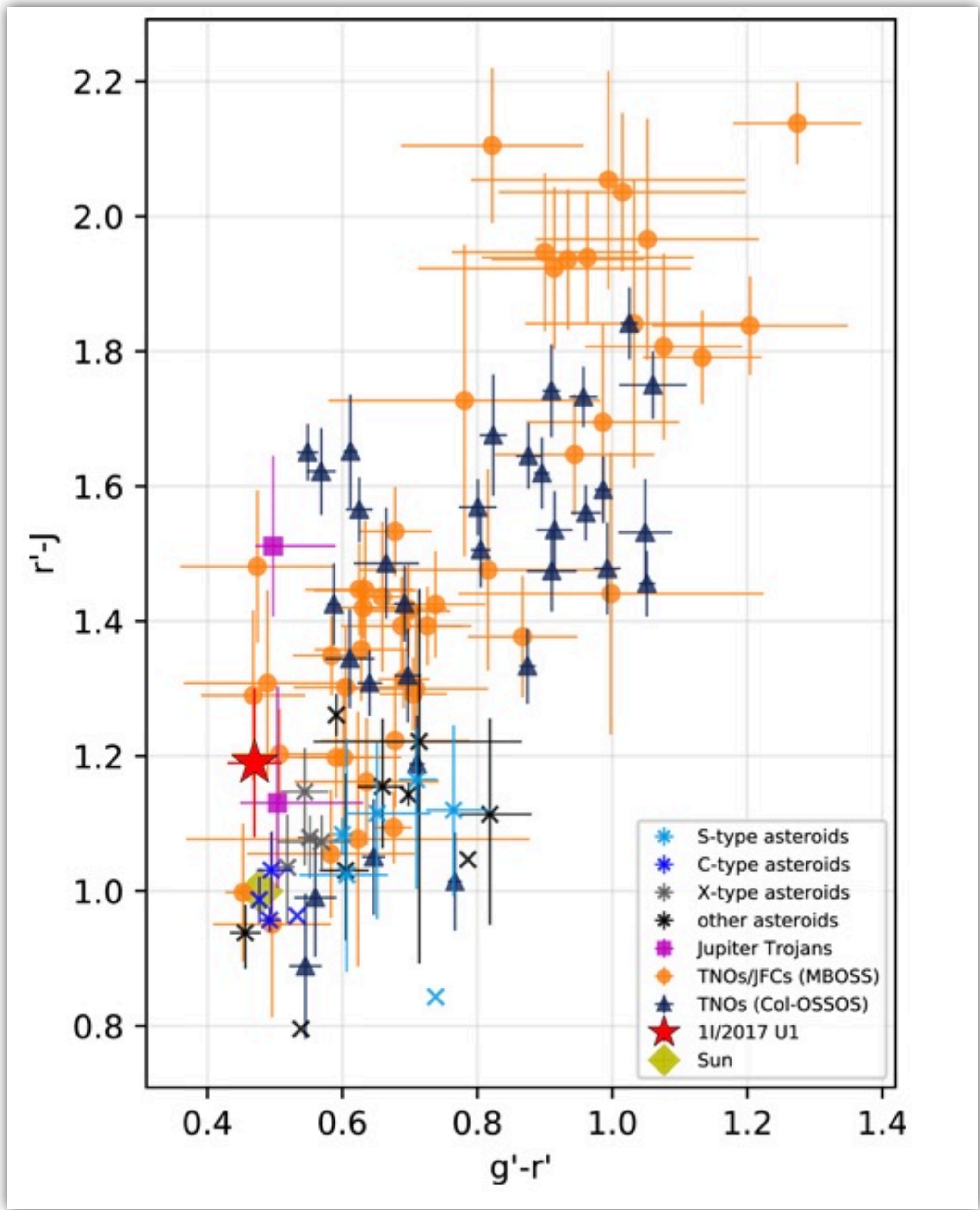
1I/`Oumuamua Trajectory



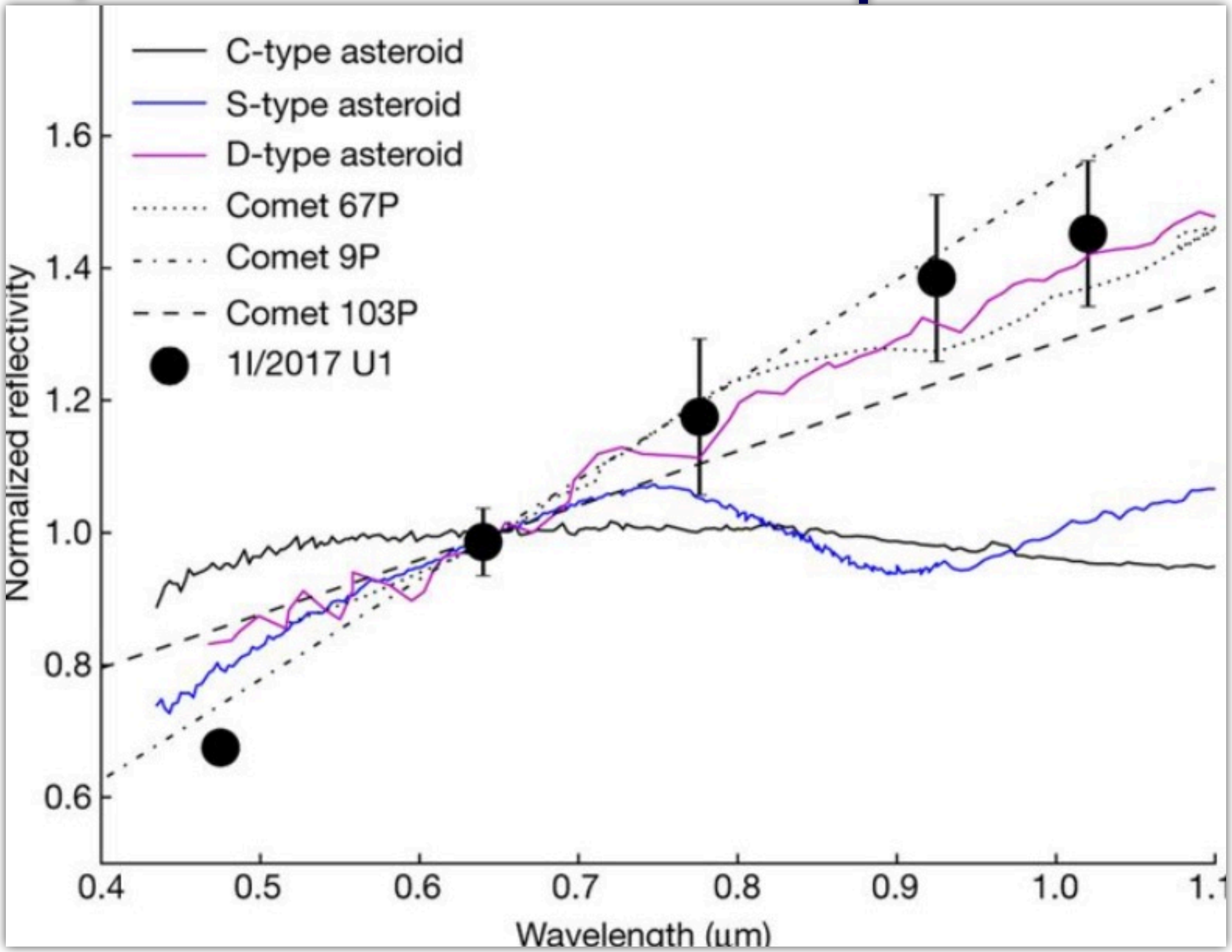
1I/`Oumuamua Trajectory



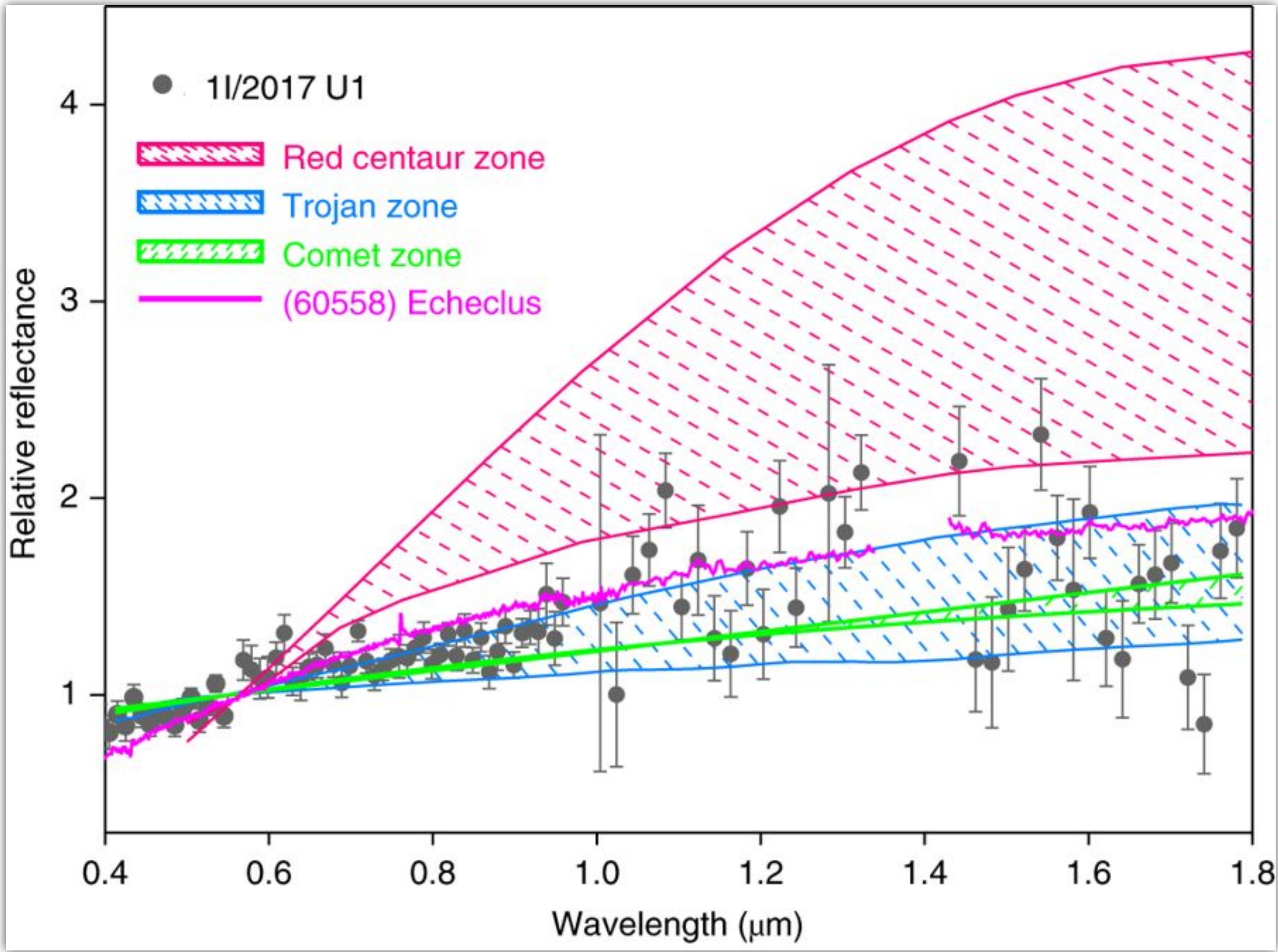
1I/`Oumuamua Colors



1I/`Oumuamua Spectrum



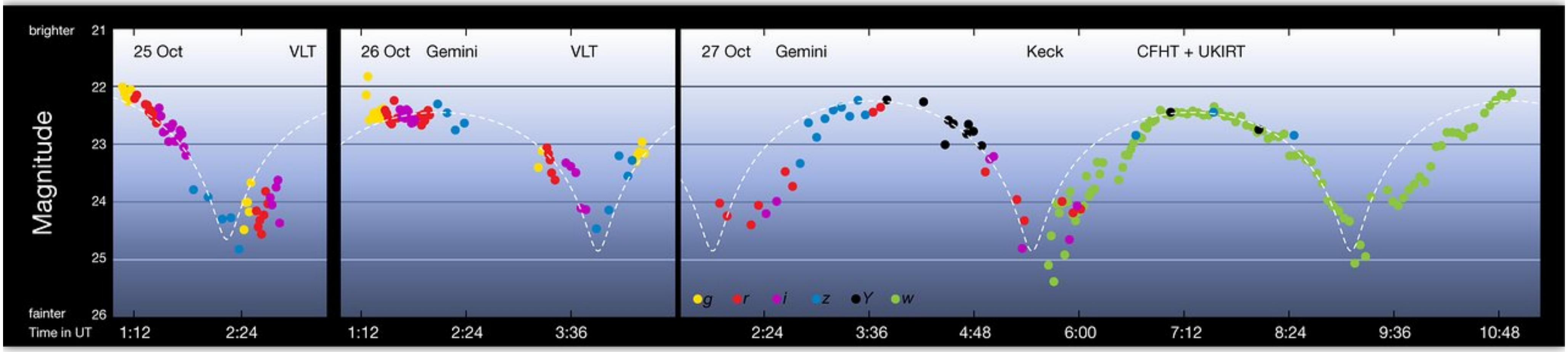
1I/`Oumuamua Spectrum



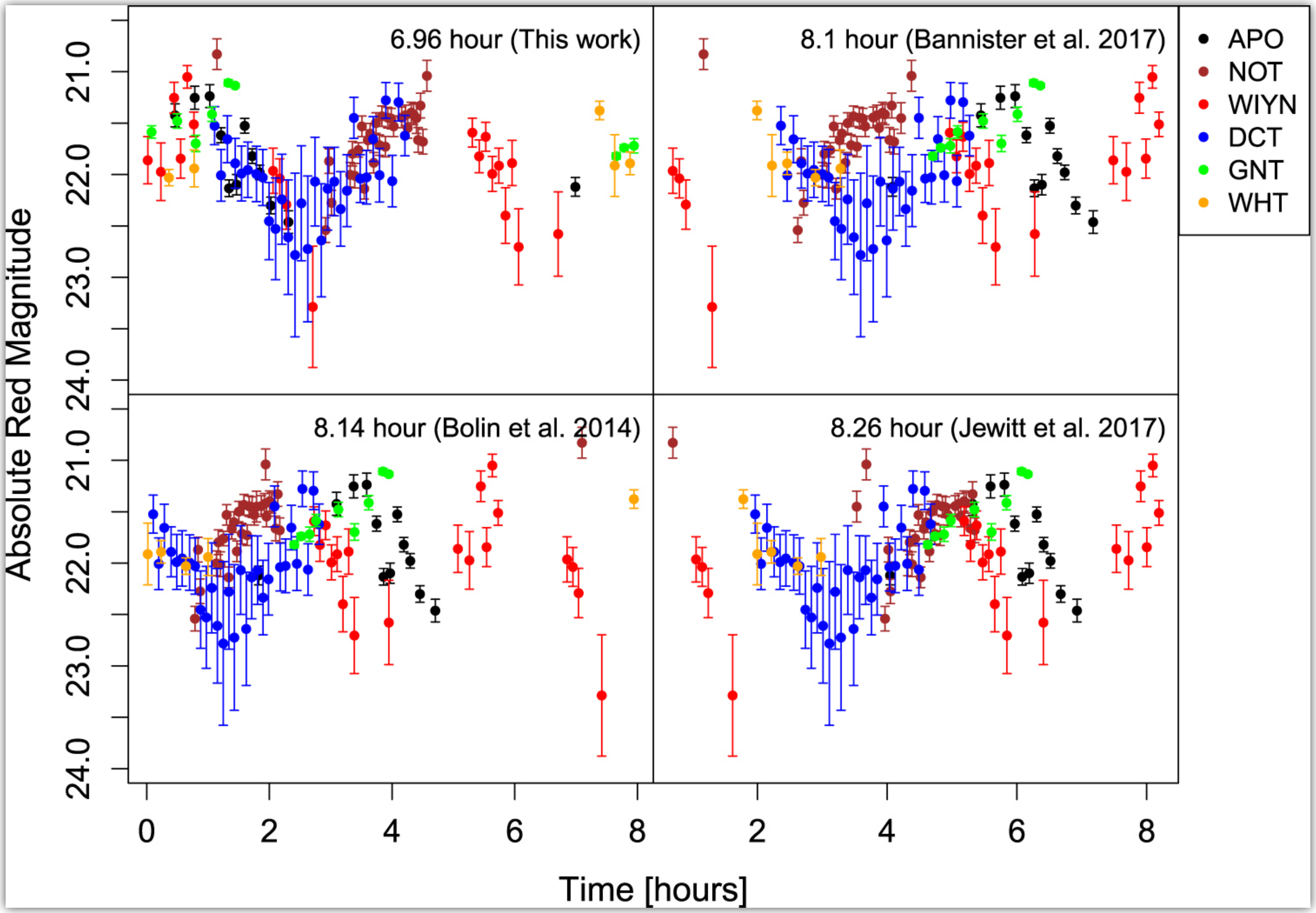
First Big Surprise: Light Curve

- Typical small body albedo => size ~100-200 meters
- Factor ~10 brightness variations, unprecedented in SS small bodies (all less than ~3:1 & most much less)
- Short period of a bit under 8 hours
- Period not entirely stable, sometimes significantly shorter or longer, suggesting tumbling
- Shape of brightness variations unusual, briefly faint, bright most of the time
- If surface all has roughly the same albedo (and is not changing) and is convex on large scales, it implies a highly elongated object
- Centrifugal forces impose significant limits on the object's internal structural strength (against tension)

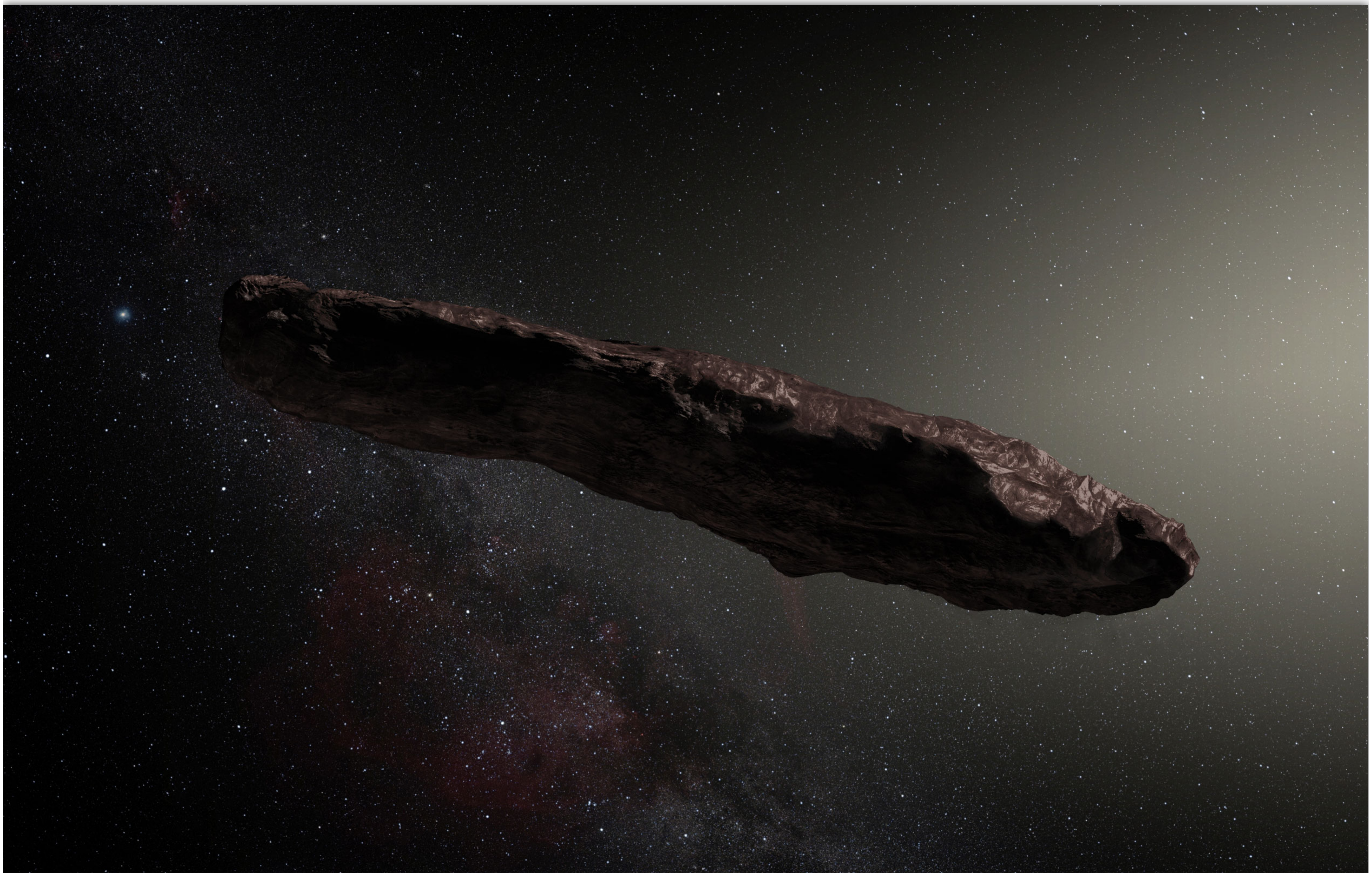
1I/`Oumuamua Light Curve



1I/`Oumuamua Light Curve



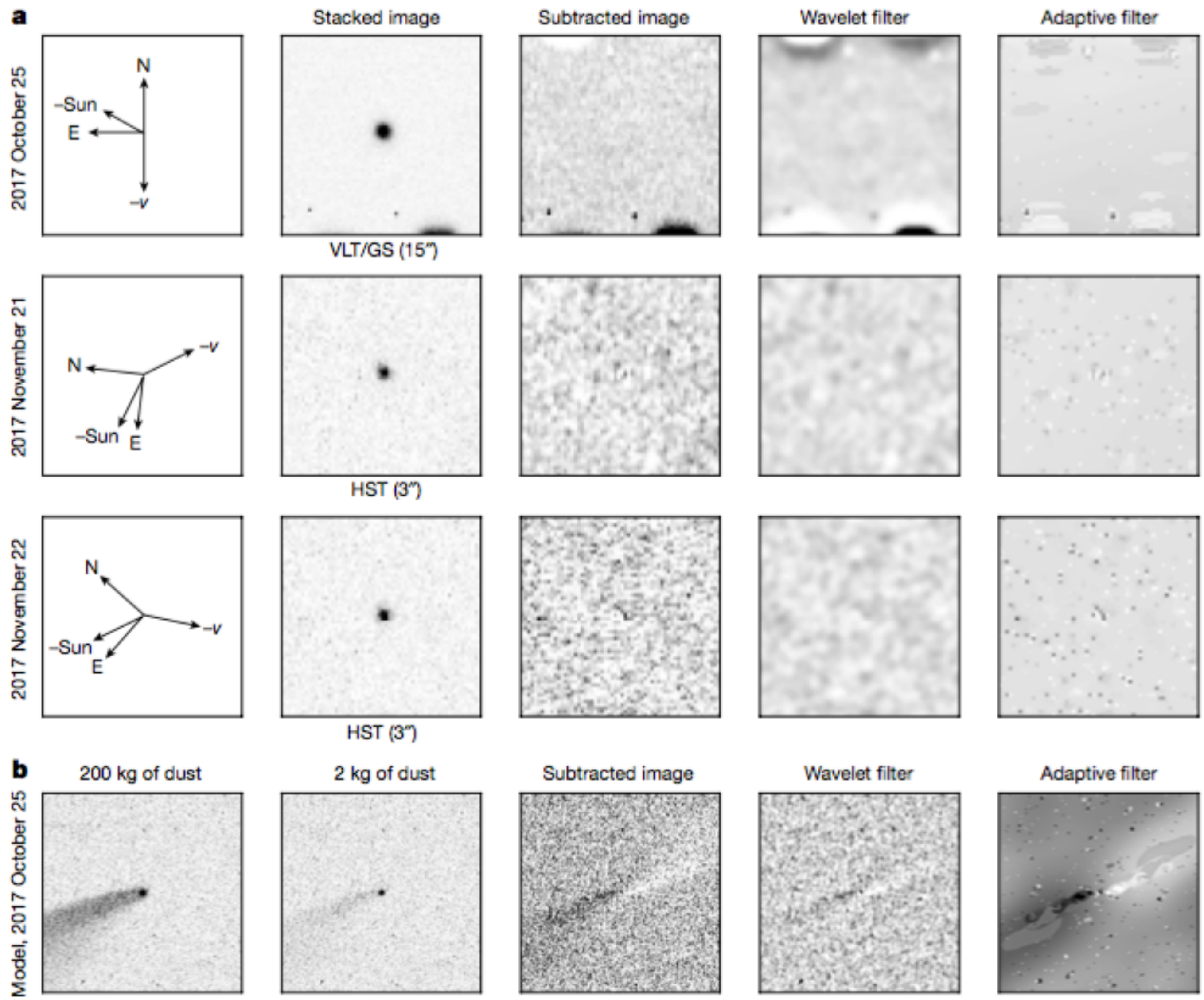
1I/`Oumuamua Artist Conception



Second Big Surprise: No Coma or Tail

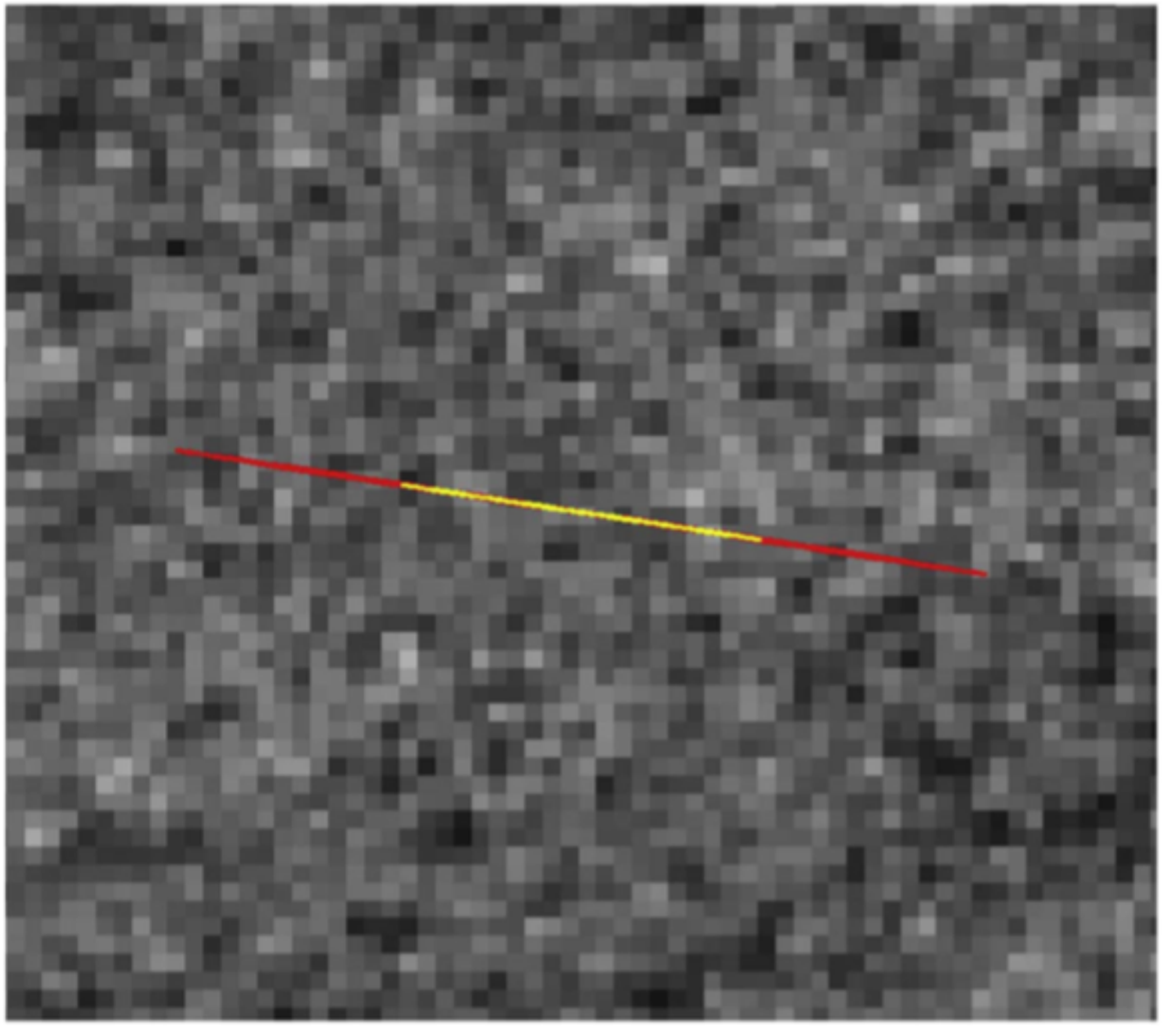
- Initially *assumed* to be a comet (icy object)
- But absence of expected coma & tail led to it being designated an asteroid (rocky object)
- Subsequent careful analysis of optical and infrared observations rule out even an extremely small amounts of coma (<1% of expected dust ejected)
- IR observations also rule out even a small amount of CO_2 gas being ejected
- "Large" dust grains also limited by IR null detection
- Makes the "Third Big Surprise" much harder to understand

No dust



Micheli+ (2018)

No CO, CO_2



Trilling+ (2018)

Third Big Surprise: Non-Gravitational Motion

- Very careful astrometric (sky position) measurements conclusively indicate an acceleration anomaly (away from the Sun) at a level of about 0.0008 solar gravity's inward acceleration => 10^5 km positional discrepancy
- Comets often display such accelerations (usually smaller though) due to evaporative jets of gas & dust
- But they produce coma/tails 100s of times brighter than the limits for 1I/`Oumuamua
- Also, such jets would be expected to change the spin period greatly, but not observed (?) – Rafikov 2018
- Pressure from solar radiation could produce such an effect only if the object has a VERY low surface density implying a thickness of <~1 mm for ordinary materials

LETTER

https://doi.org/10.1038/s41586-018-0254-4

Non-gravitational acceleration in the trajectory of 1I/2017 U1 (ʻOumuamua)

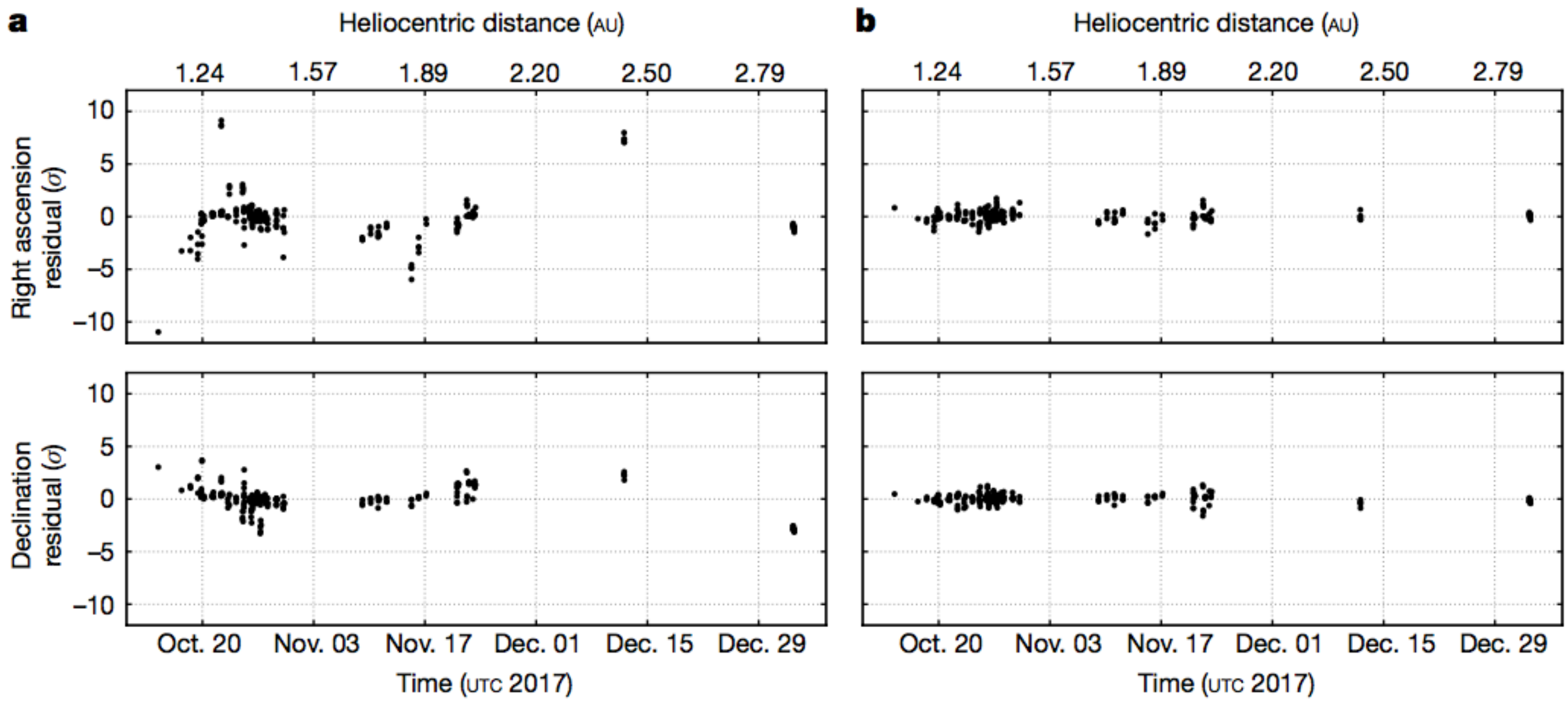
Marco Micheli[1,2]*, Davide Farnocchia[3], Karen J. Meech[4], Marc W. Buie[5], Olivier R. Hainaut[6], Dina Prialnik[7], Norbert Schörghofer[8], Harold A. Weaver[9], Paul W. Chodas[3], Jan T. Kleyna[4], Robert Weryk[4], Richard J. Wainscoat[4], Harald Ebeling[4], Jacqueline V. Keane[4], Kenneth C. Chambers[4], Detlef Koschny[1,10,11] & Anastassios E. Petropoulos[3]

Gravity-only

Gravity+

RA residuals

Declination residuals

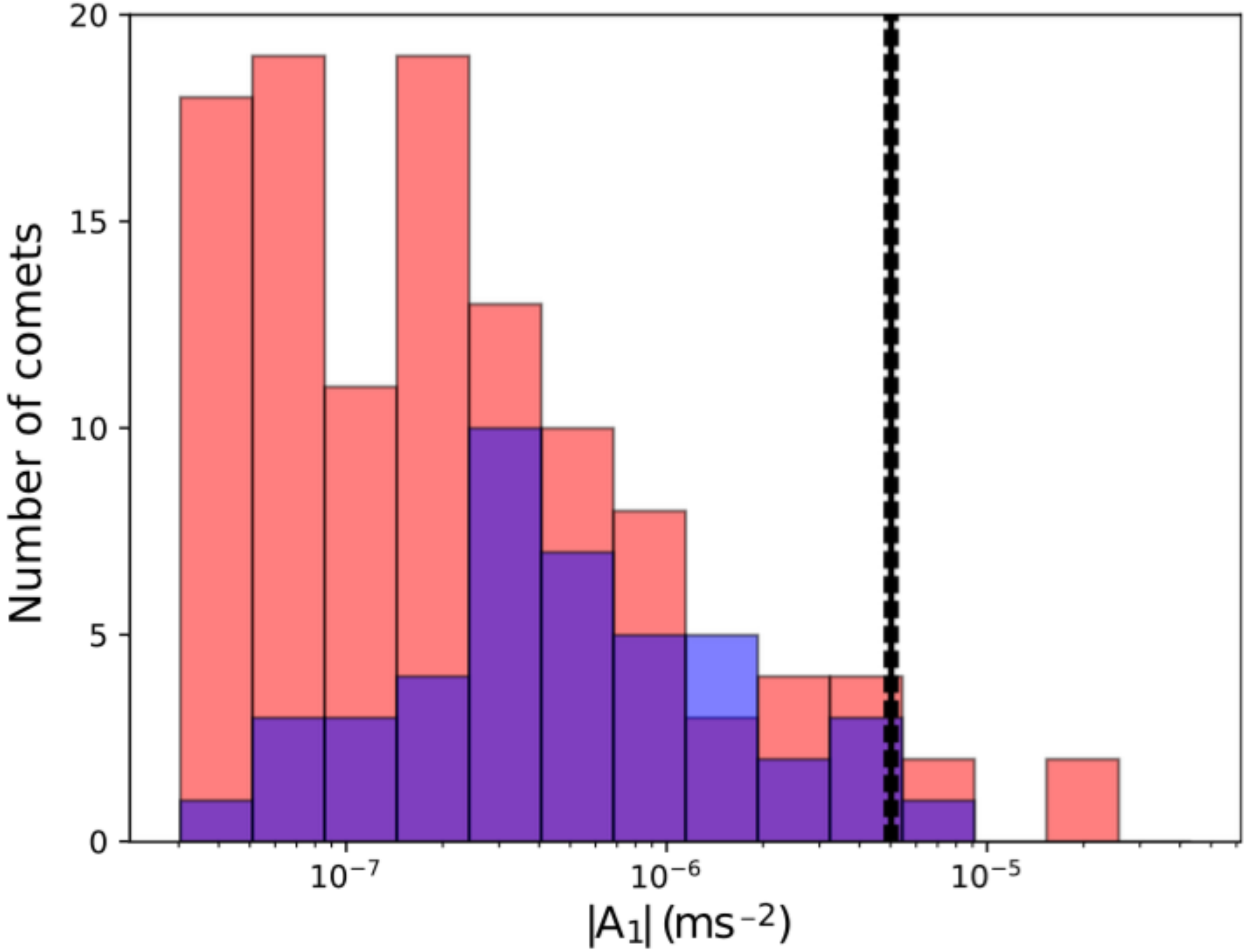


Micheli+ (2018)

Table 1 | Fits for different non-gravitational models

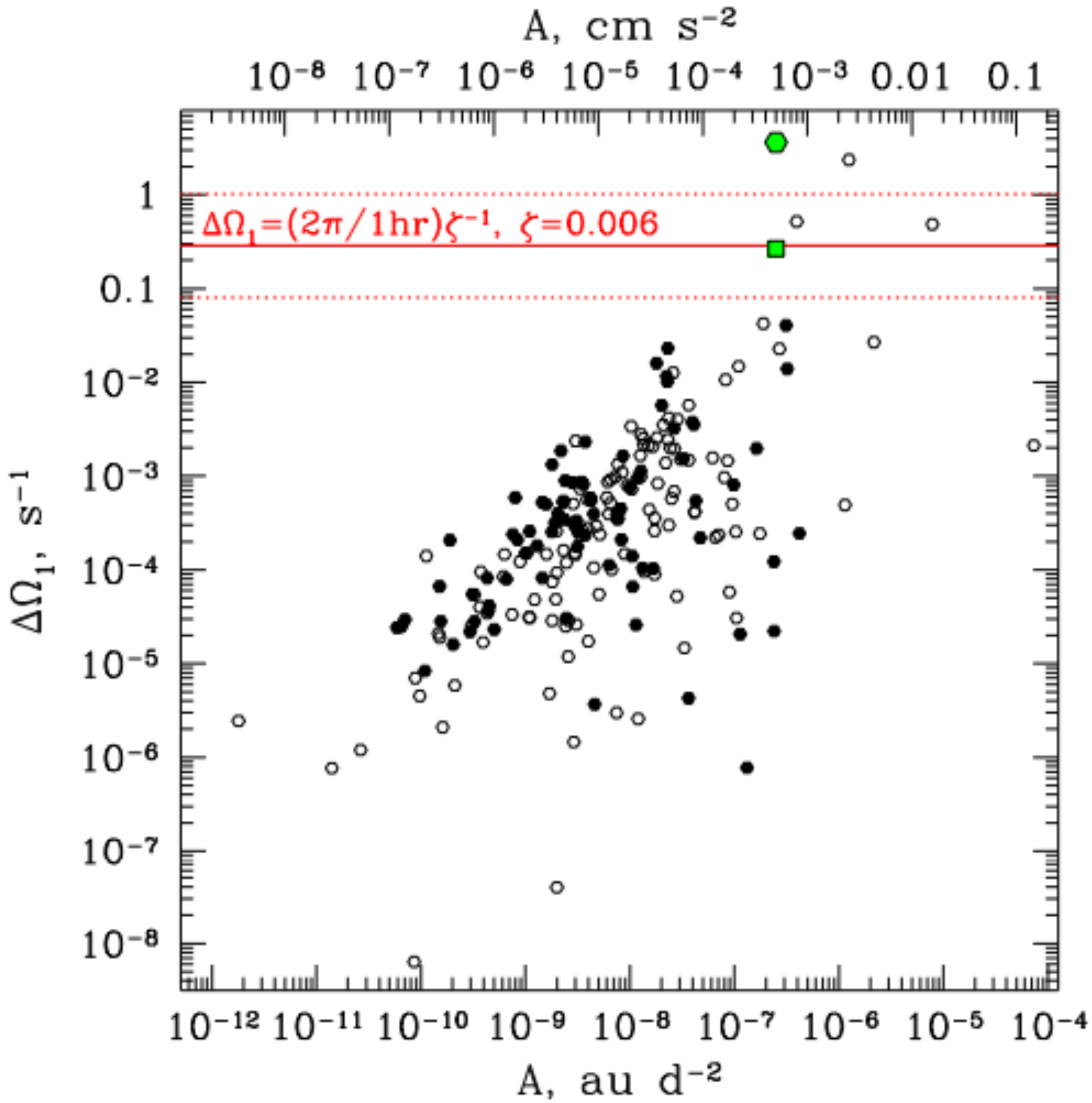
Model	Number of parameters	χ^2	χ_ν^2
Gravity-only	6	1.031×10^3	2.53
(1) Impulsive change in velocity	10	117	0.29
(2) Pure radial acceleration, $A_1 g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	7	99, 80, 81, 98	0.24, 0.20, 0.20, 0.24
(3) RTN decomposition, $[A_1, A_2, A_3] g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	9	90, 80, 78, 87	0.22, 0.20, 0.19, 0.21
(4) ACN decomposition, $[A_A, A_C, A_N] g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	9	104, 85, 77, 83	0.26, 0.21, 0.19, 0.21
(5) Pure along-track acceleration, $A_A g(r) \propto r^{-k}, k \in \{0, 1, 2, 3\}$	7	1.031×10^3, 1.025×10^3, 1.002×10^3, 963	2.53, 2.52, 2.46, 2.37
(6) Constant, inertially fixed acceleration vector	9	116	0.29
(7a) Pure radial acceleration, $A_1 g_{CO}(r)$	7	84	0.21
(7b) Pure radial acceleration, $A_1 g_{H2O}(r)$	7	111	0.27
(7c) RTN decomposition, $[A_1, A_2, A_3] g_{CO}(r)$	9	79	0.19
(7d) RTN decomposition, $[A_1, A_2, A_3] g_{H2O}(r)$	9	89	0.22
(7e) RTN decomposition, $[A_1, A_2, A_3] g_{H2O}(r), \Delta T$	10	86	0.21

Micheli+ (2018)



Micheli+ (2018)

Catastrophic spin-up?



Rafikov 2018c

Solar-radiation pressure. A simple radial dependency of the non-gravitational acceleration, decaying as r^{-2} with the heliocentric distance, is allowed by the dataset for $A_1 = (4.92 \pm 0.16) \times 10^{-6}$ m s^{-2}. If interpreted as solar-radiation pressure on the projected area of the object exposed to sunlight, then this A_1 value would correspond to an area-to-mass ratio between about 0.5 m^2 kg^{-1} and 1 m^2 kg^{-1} Given the range of possible sizes and shapes of 'Oumuamua[1], and assuming a uniform density and an ellipsoidal shape for the body, this estimate of the area-to-mass ratio would correspond to a bulk density of the object between about 0.1 kg m^{-3} and 1 kg m^{-3}, three to four orders of magnitude less than that of water. Alternatively, to be composed of materials with densities comparable to normal asteroidal or cometary matter, 'Oumuamua would need to be a layer, or a shell, at most a few millimetres thick, which is not physically plausible.

Unless 'Oumuamua has physical properties that differ markedly from those of typical Solar System bodies within the same size range, the interpretation of the non-gravitational acceleration being due to solar-radiation pressure is therefore unlikely.

Micheli+ (2018)

Small Surprises/Facts

- Initial velocity (far from the Sun) was VERY close to the local standard of rest (LSR), as close as one nearby star in a few hundred.
- Estimates of the interstellar number density of such objects (assuming random motions and based on the one detection) are at the VERY high end of the range expected (but quite uncertain), $\sim 10^{15}/pc^3$ (or per local main sequence star), ~1 AU mean separations.
- If number density is that high and such objects are moving randomly, more should be detected in coming years, especially in the LSST survey.
- No radio emission detected by Breakthrough Listen to a VERY low power level (in the bands observed).
- Very difficult/expensive but maybe possible to send a probe to get a close look…would take a few decades.

THE ASTROPHYSICAL JOURNAL LETTERS, 868:L1 (5pp), 2018 November 20 https://doi.org/10.3847/2041-8213/aaeda8

CrossMark

Could Solar Radiation Pressure Explain 'Oumuamua's Peculiar Acceleration?

Shmuel Bialy and Abraham Loeb
Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA; SBialy@cfa.harvard.edu
Received 2018 October 26; revised 2018 October 30; accepted 2018 October 31; published 2018 November 12

PREPERIHELION OUTBURSTS AND DISINTEGRATION OF COMET C/2017 S3 (PAN-STARRS)

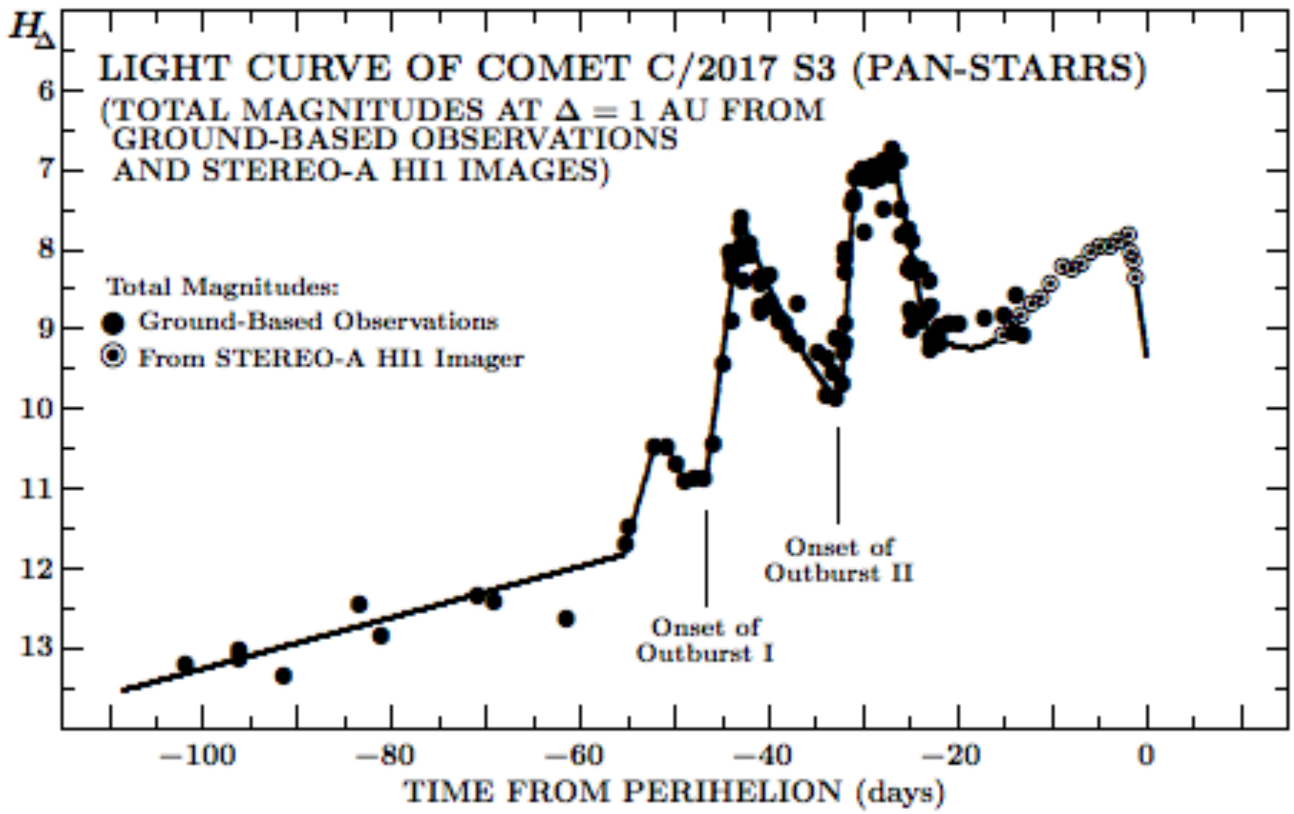
ZDENEK SEKANINA[1] & RAINER KRACHT[2]
[1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A.
[2]Ostlandring 53, D-25335 Elmshorn, Schleswig-Holstein, Germany
Version 3 of Paper First Posted on December 17, 2018

1I/'OUMUAMUA AS DEBRIS OF DWARF INTERSTELLAR COMET THAT DISINTEGRATED BEFORE PERIHELION

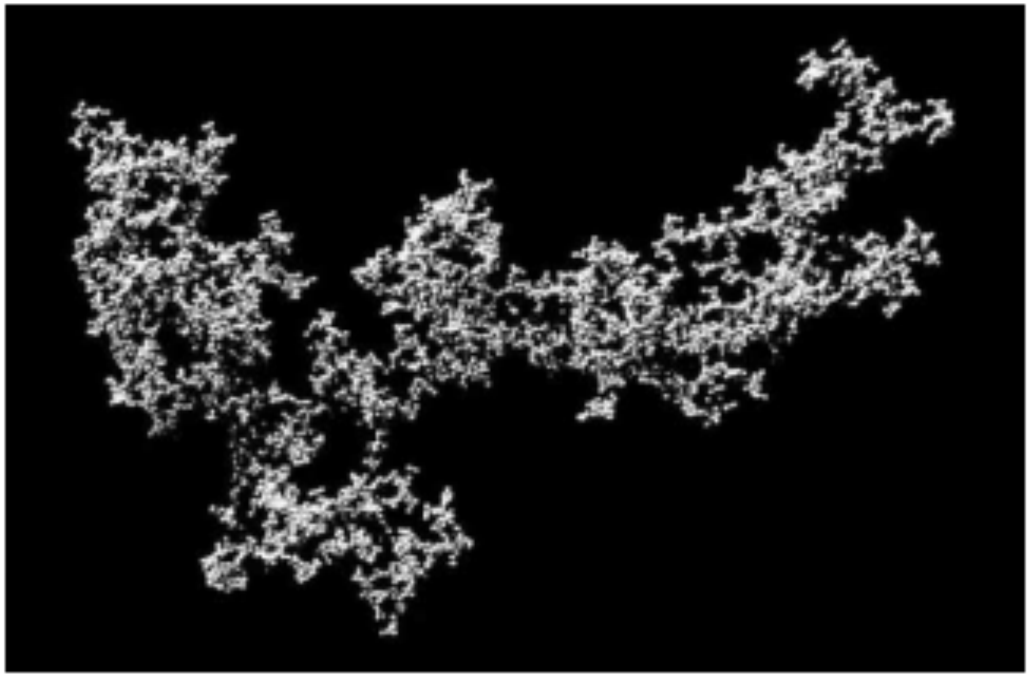
ZDENEK SEKANINA
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, U.S.A.
Version January 31, 2019

COULD 1I/'OUMUAMUA BE AN ICY FRACTAL AGGREGATE EJECTED FROM A PROTOPLANETARY DISK? A FLUFFY RADIATION-PRESSURE-DRIVEN SCENARIO

AMAYA MORO-MARTÍN[1]
Draft version February 13, 2019

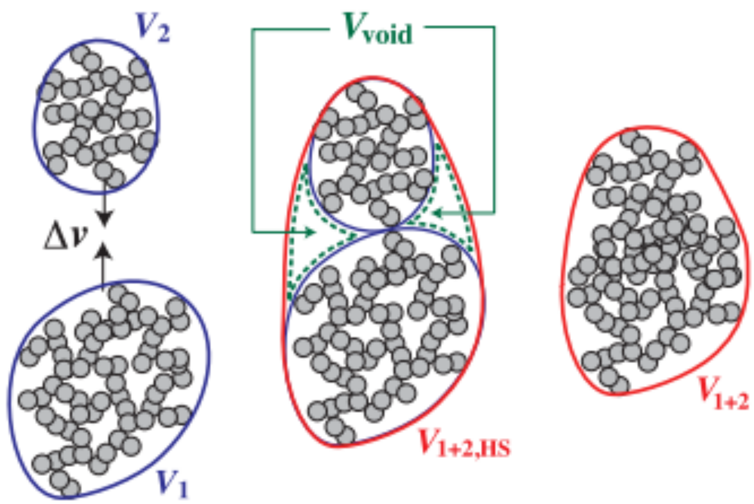


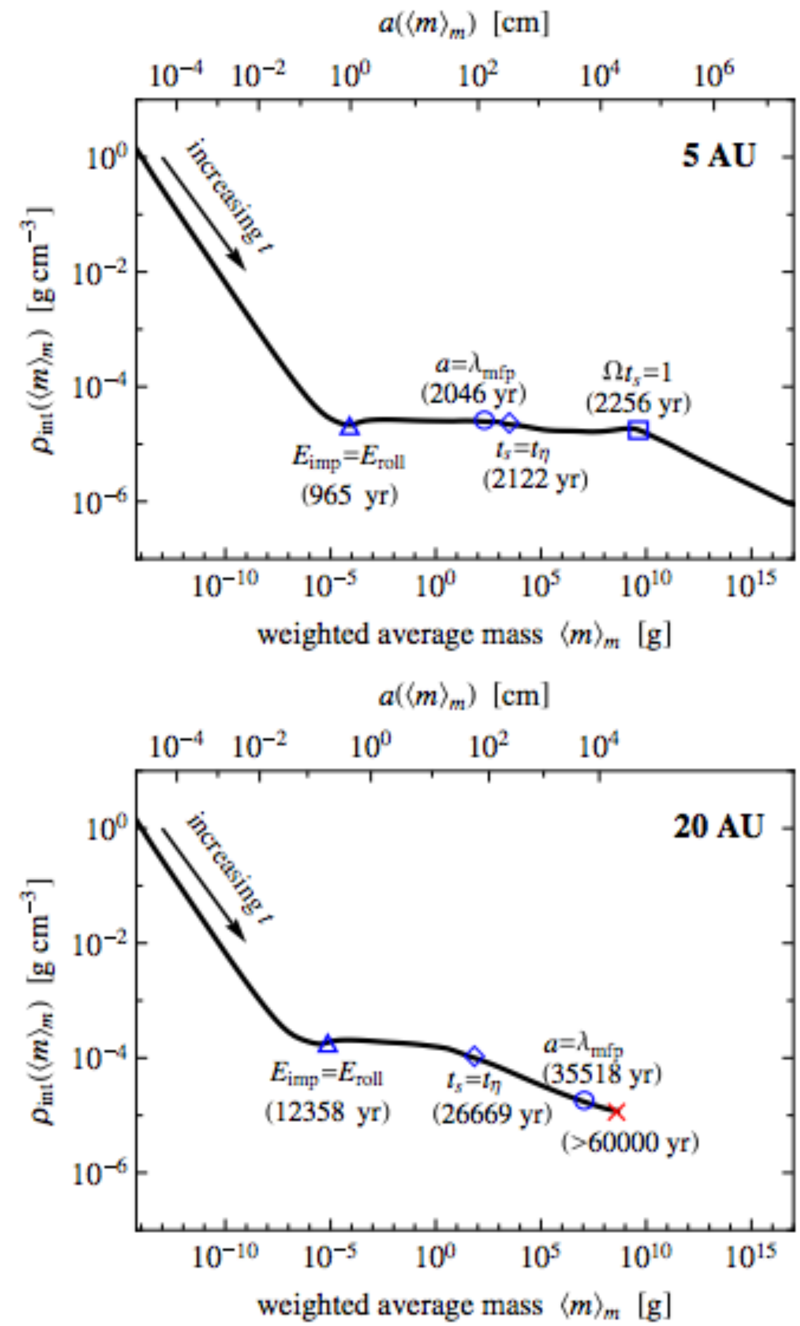
Sekanina & Kracht (2018)



Sekanina & Kracht (2018)

Icy aggregates (Moro-Martin)





Okuzumi+ (2012)

The Jet Scenario (mainstream view)

-Jets are common (typical A1)

- No sign of dust, carbon molecules, or cometary activity
  => Extremely low C abundance
- Possible catastrophic spin evolution
- Large quantity of mass lost

Aggregate Dust (Sekanina)

-Possible example: C/2017 S3
-No cometary activity

- Potentially fragile
- Difficult to form even in high-gas environment, but need to form in low-gas environment

Aggregate Ice (Moro-Martin)

- Could be easily formed in young system [consistent with low velocity]

- Potentially fragile
- Quick sublimation during pericenter

Light Sail (Bialy & Loeb)

- Nothing else seems satisfactory
- `Oumuamua is very unusual [high n density, low velocity, large axis ratio]

- Difficult to envision natural formation
- Why send a light sail at such a low velocity from so far away?

Is 1I/`Oumuamua An Alien Craft/Artifact?

- Some astronomers have suggested this possibility, one (A. Loeb) very vocally and controversially, and many discuss it at least semi-seriously in private.
- Excessive explanatory and insufficient predictive power to be a useful scientific hypothesis.
- Confirmation bias probably in play.
- How can we further investigate the possibility?
  - Rendezvous mission (very hard, probably won't happen)
  - Find more of them (but may not be the same type of object)
  - Watch the directions it came from and left toward (long shot)
  - Keep analyzing the data we have (but diminishing returns)
- Yet another example of the "alien tease", so not convincing. *I.e.*, very low Bayesian prior.

Thoughts

- The original Micheli analysis does not actually strongly favor any one acceleration model.
- The jet scenario requires a strange composition, but maybe that’s correct [origin outside Solar System or reprocessing by the Sun]!
- Sekanina makes a compelling argument that a close passage to the sun probably had a large effect on `Oumuamua[’s parent body].
- The aggregates seem tough to form and maintain

Summary

- 1I/`Oumuamua is the first interstellar object (small body) we have observed.
- It has properties that are quite unlike any known small body in the SS (asteroid or comet) in multiple ways, although it is similar to some of them in a few ways, especially its spectrum. (SS seems atypical of planetary systems in many ways.)
- Its properties are hard to interpret/understand physically based on our knowledge of the formation and role of planetesimals in planetary system formation.
- The possibility of it being an alien artifact of some sort is not ruled out and is suggested by the data in the view of some astronomers.
- We may or may not be able to learn significantly more about it or similar objects in the foreseeable future.