It came from outer space: Interstellar visitor 1I/'Oumuamua

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The Open University

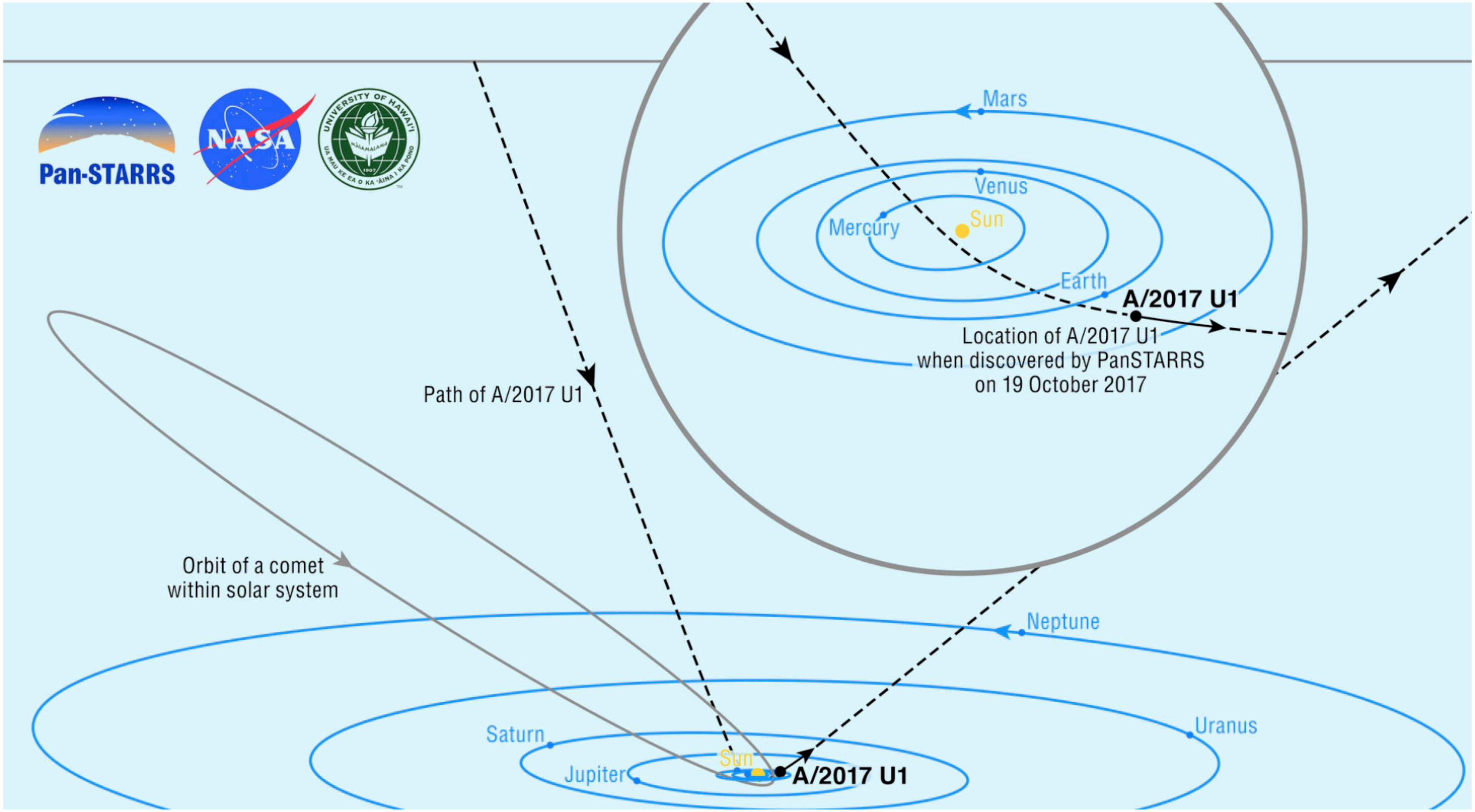
Outline

- Discovery, orbit, (e of comets, Oort cloud, why unusual)
- Reaction, challenges, observations, lots of arxiv posts
- Results
  - Lack of activity
  - Spectrum, comparison with known objects
  - Lightcurve, shape (vs albedo effects), tumbling?
- Expectations, how many interstellar visitors, why they should be comets
- Thermal model, ice survival (age), strength, comparison with comets
- Where did it come from?
- Expected discovery rate with LSST

Discovery

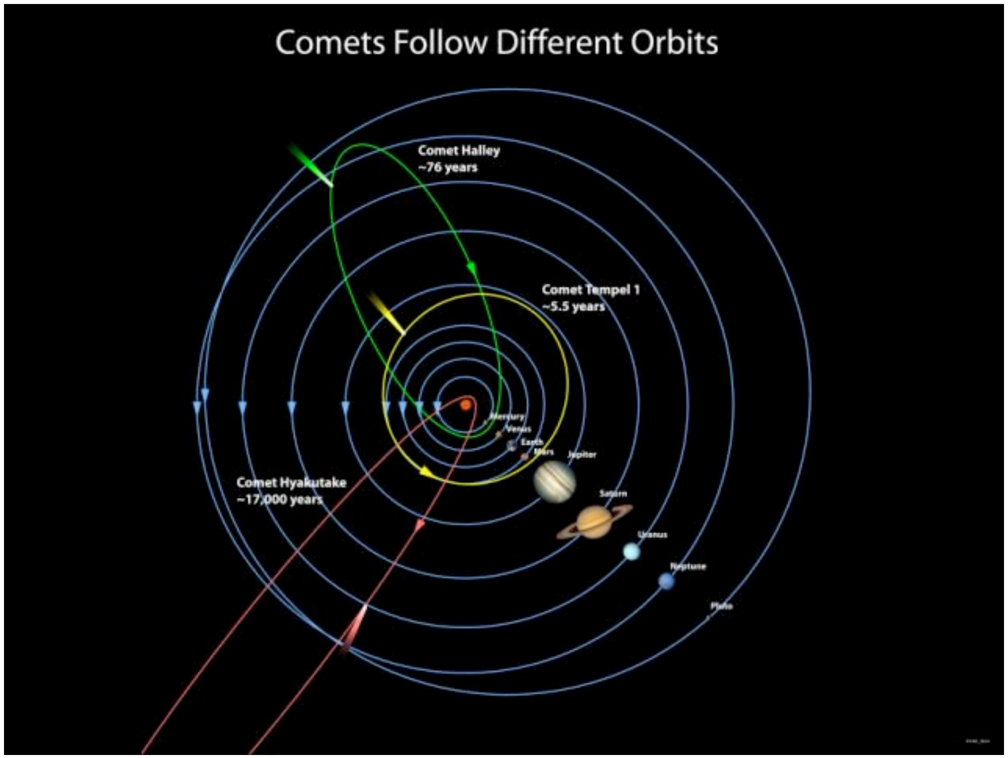
- Discovered 18 October 2017 by Pan-STARRS survey
  - Unusual initial orbit solution prompted follow up (search for earlier data not found automatically, new observations with CFHT)
- By 25th October a hyperbolic orbit with eccentricity 1.2 was confirmed, discovery announced as comet C/2017 U1 (PANSTARRS)
- Passed perihelion at q=0.25 AU in early September, relatively close approach to Earth (0.16 AU) in mid-October
- Outbound at discovery, fading fast

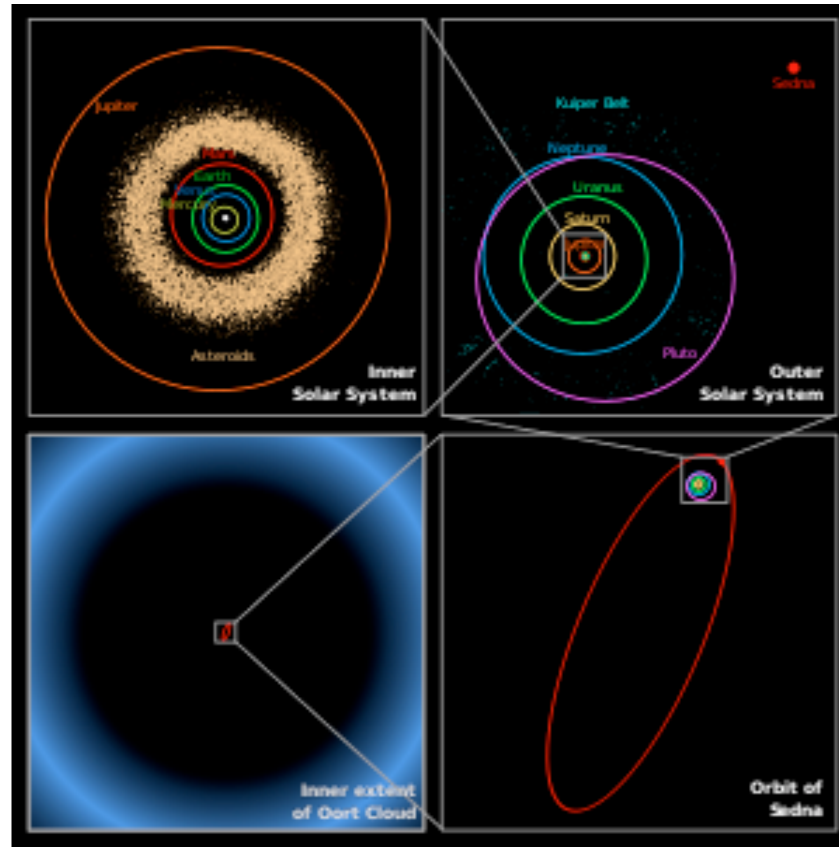
Orbit

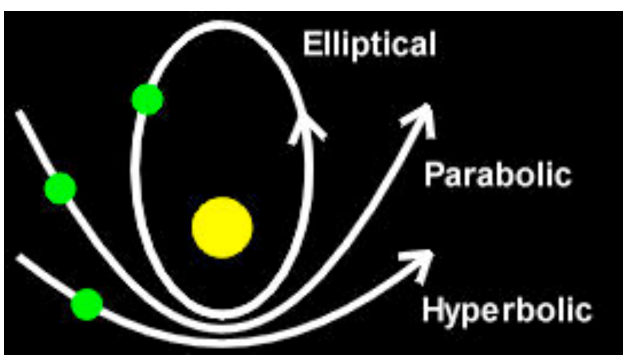


Pan-STARRS
NASA
Mars
Venus
Mercury
Sun
Earth
A/2017 U1
Location of A/2017 U1
when discovered by PanSTARRS
on 19 October 2017
Path of A/2017 U1
Orbit of a comet
within solar system
Neptune
Uranus
Saturn
Jupiter
Sun
A/2017 U1

Comet orbits

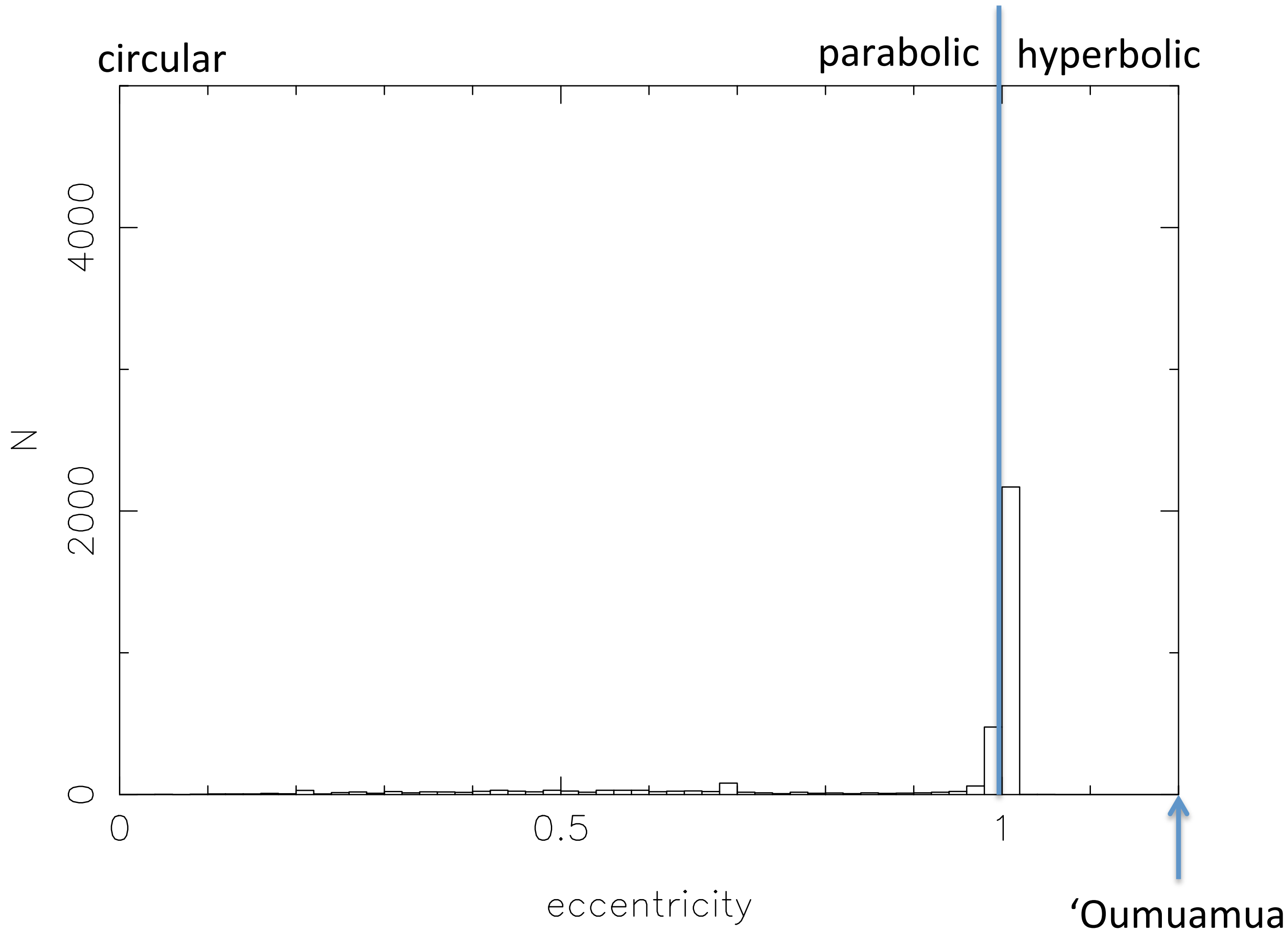






Jupiter family: short period (< 10yr), e~0.5
Halley type: ~100yr, e~0.9
Oort cloud comets: > 10,000yr, e~1

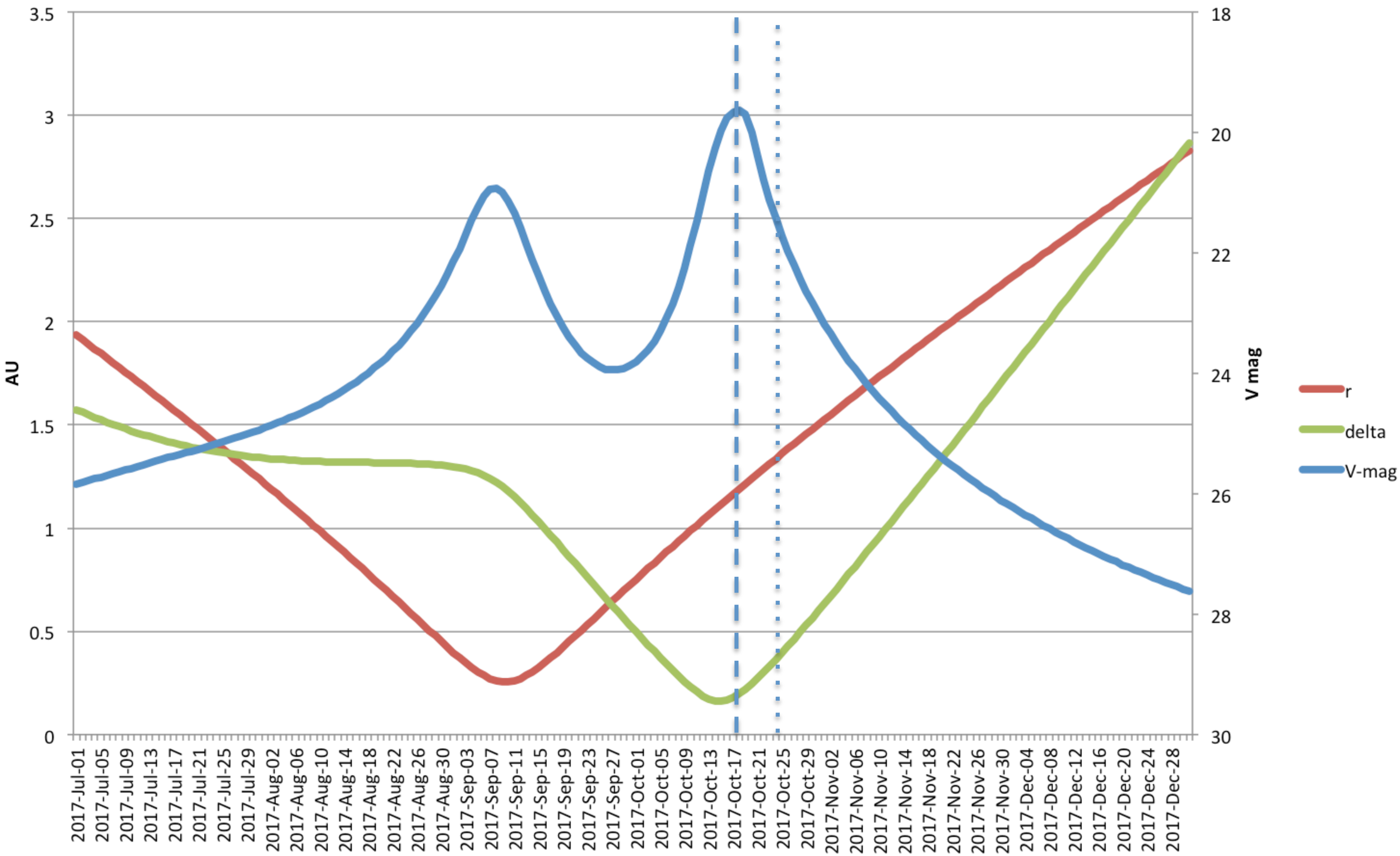
Comet orbits



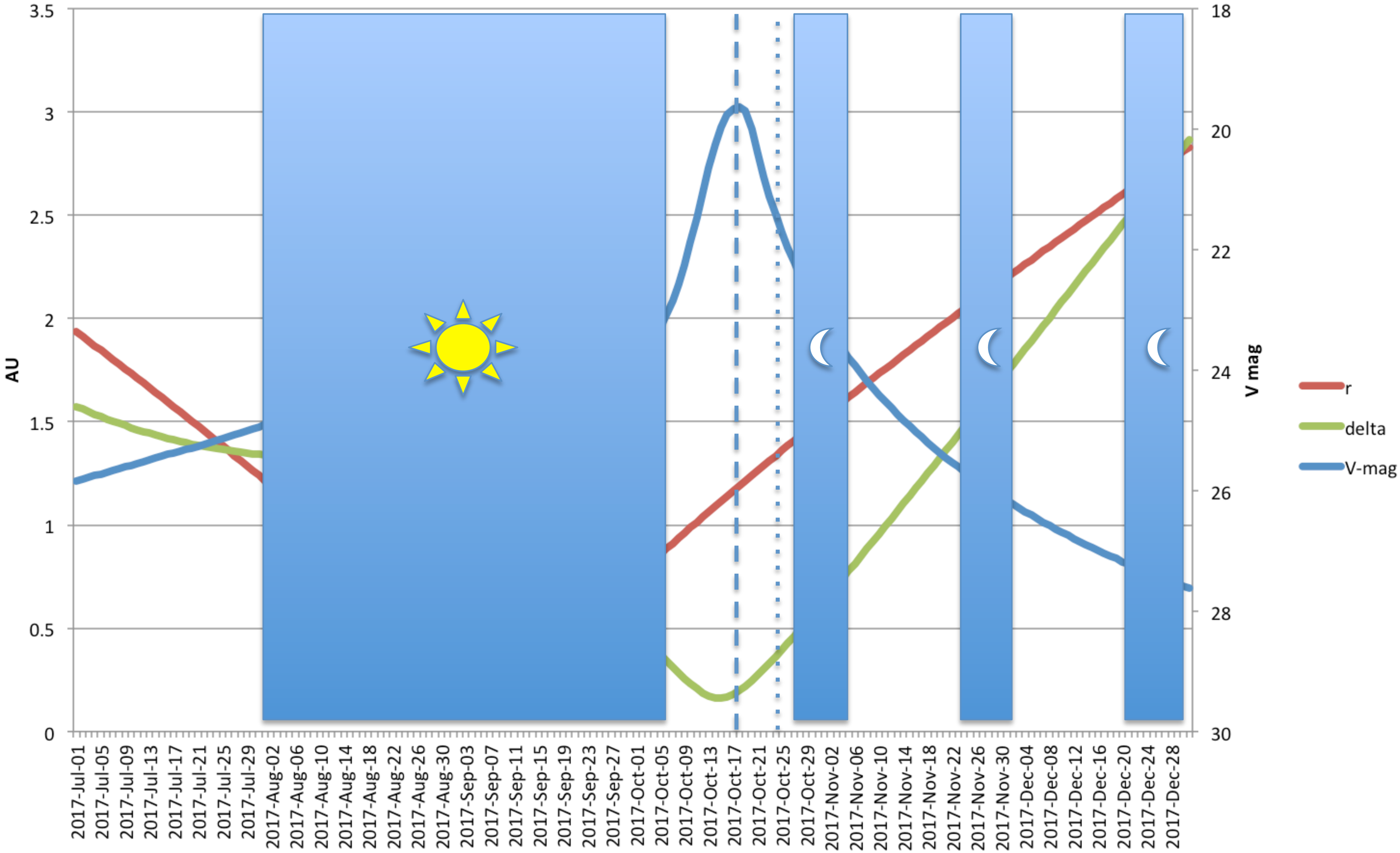
Rapid reaction

- Scramble for telescope time.
  - HST, VLT (FORS), Gemini, CFHT, UKIRT (Meech et al)
  - LT, WHT (Fitzsimmons et al)
  - VLT (X-shooter) (Snodgrass et al)
  - Gemini (Bannister et al, Drahus et al)
  - Palomar 200” (Masiero, Ye et al)
  - DCT (Knight et al)
  - APO (Bolin et al)
  - NOT, WIYN (Jewitt et al)
  - Spitzer (Trilling et al)

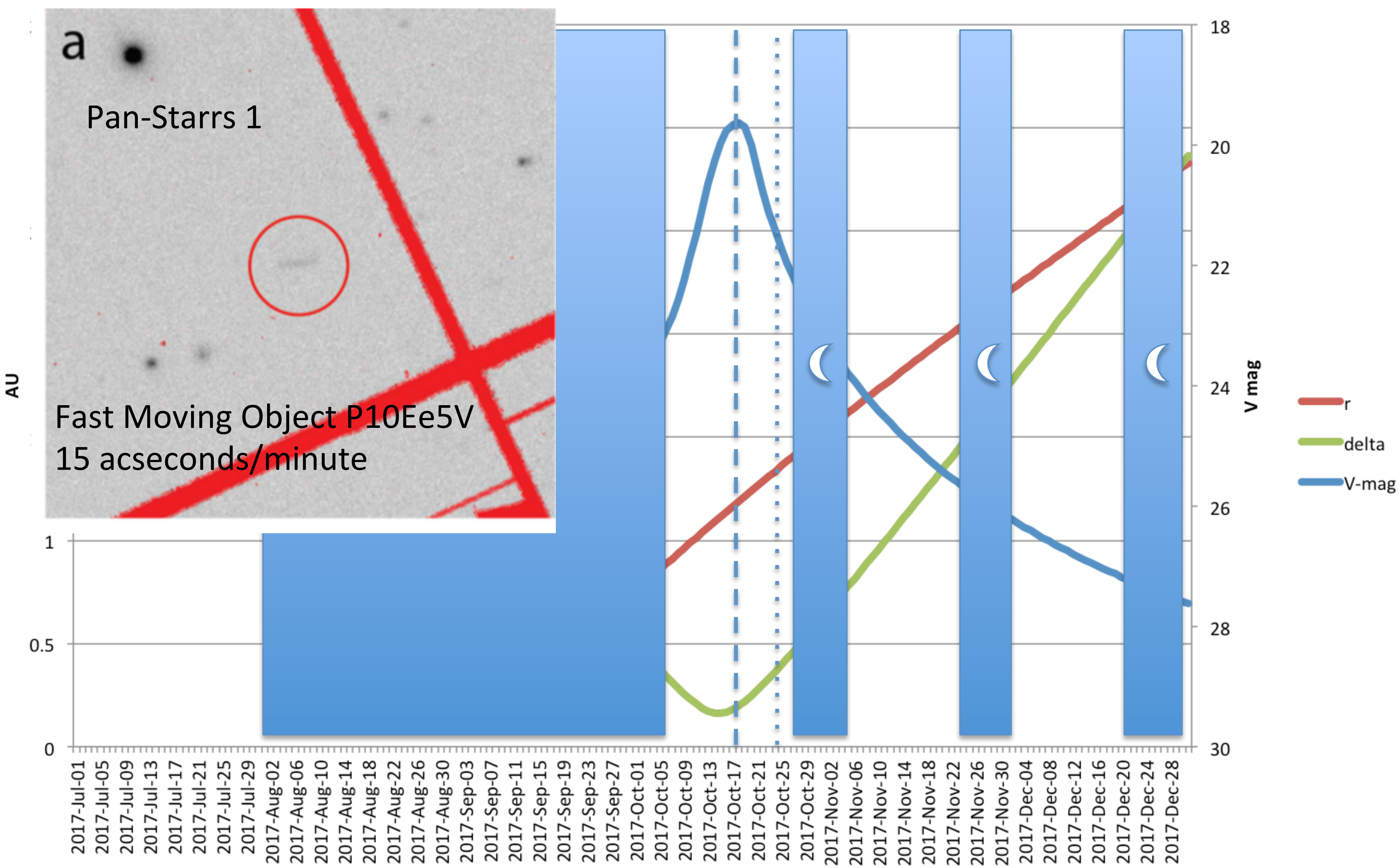
Narrow window for observations



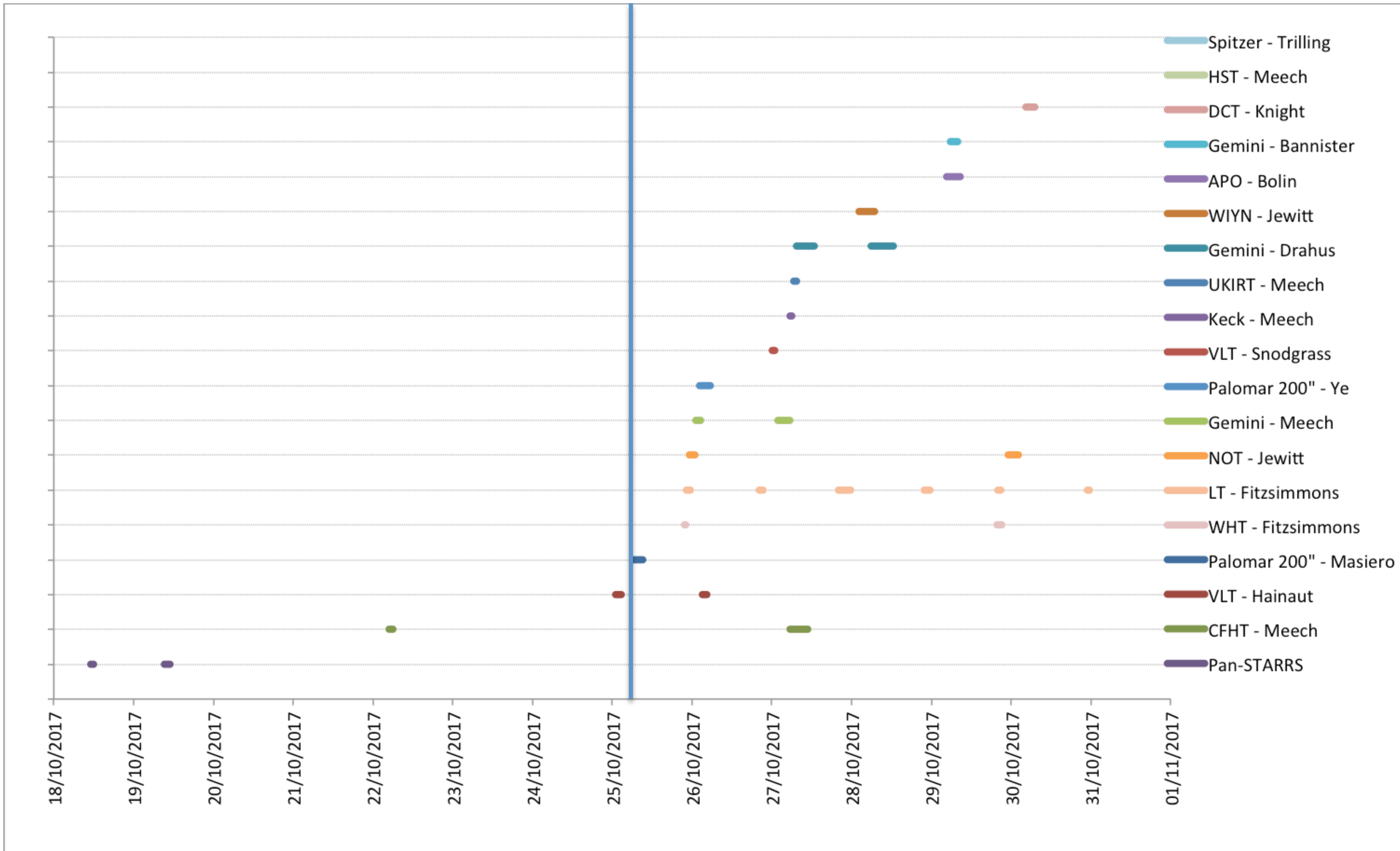
Narrow window for observations



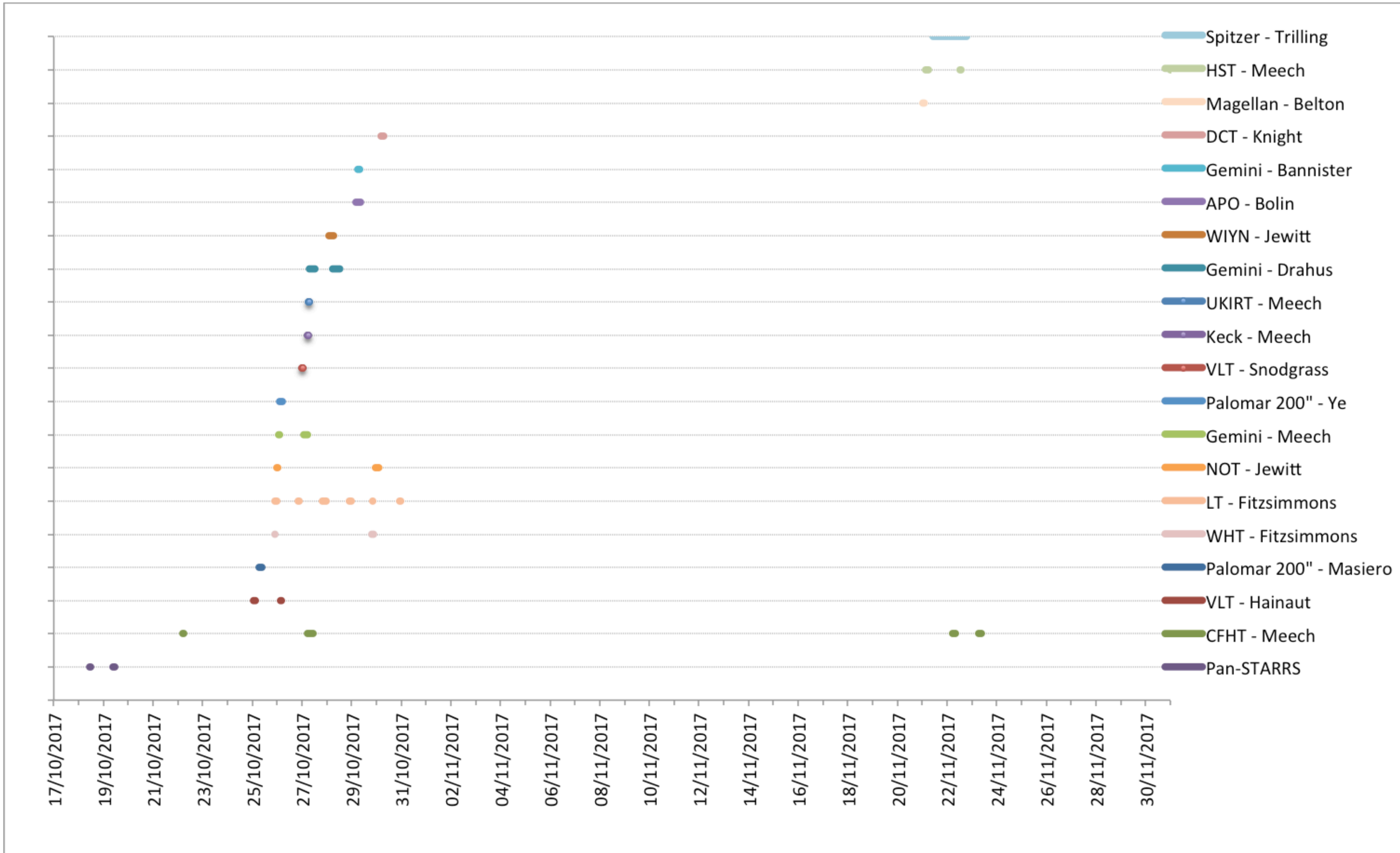
Narrow window for observations



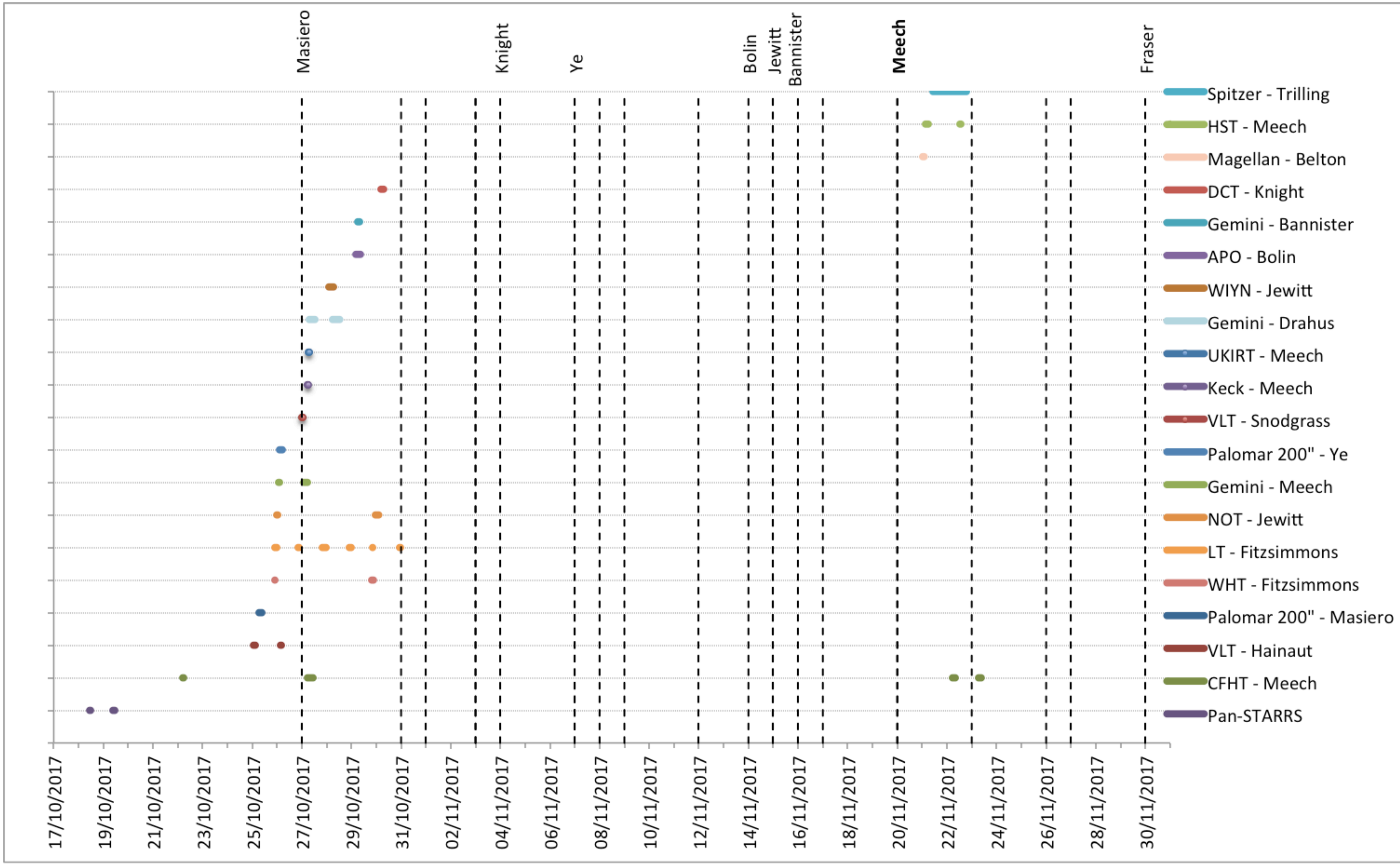
Rapid Reaction (2)



Rapid Reaction (2)



Rapid Reaction (2)



1710.09977	Masiero	Palomar Optical Spectrum of Hyperbolic Near-Earth Object A/2017 U1
1710.11364	Mamajek	Kinematics of the Interstellar Vagabond 1I/'Oumuamua (A/2017 U1)
1711.00445	de la Fuente Marcos	Pole, Pericenter, and Nodes of the Interstellar Minor Body A/2017 U1
1711.01300	Gaidos	Origin of Interstellar Object A/2017 U1 in a Nearby Young Stellar Association?
1711.01344	Trilling	Implications for planetary system formation from interstellar object 1I/2017 U1 (`Oumuamua)
1711.01402	Knight	The rotation period and shape of the hyperbolic asteroid A/2017 U1 from its lightcurve
1711.02260	Laughlin	On the Consequences of the Detection of an Interstellar Asteroid
1711.02320	Ye	1I/2017 U1 (`Oumuamua) is Hot: Imaging, Spectroscopy and Search of Meteor Activity
1711.03155	Hein	Project Lyra: Sending a Spacecraft to 1I/'Oumuamua (former A/2017 U1), the Interstellar Asteroid
1711.03558	Zwart	The origin of interstellar asteroidal objects like 1I/2017 U1
1711.04348	Cyncynates	Could 1I/'Oumuamua be macroscopic dark matter?
1711.04927	Bolin	APO Time Resolved Color Photometry of Highly-Elongated Interstellar Object 1I/'Oumuamua
1711.05687	Jewitt	Interstellar Interloper 1I/2017 U1: Observations from the NOT and WIYN Telescopes
1711.05735	Schneider	Is 1I/2017 U1 really of interstellar origin ?
1711.06214	Bannister	Col-OSSOS: Colors of the Interstellar Planetesimal 1I/2017 U1 in Context with the Solar System
1711.06618	Dybczynski	On the dynamical history of the recently discovered interstellar object A/2017 U1 - where does it come from?
1711.07535	Ferrin	1I/2017 U1 (Oumuamua) Might Be A Cometary Nucleus
1711.08800	Feng	`Oumuamua as a messenger from the Local Association
1711.09397	Zuluaga	A general method for assessing the origin of interstellar small bodies: the case of 1I/2017 U1 (Oumuamua)
1711.09599	Raymond	Implications of the interstellar object 1I/'Oumuamua for planetary dynamics and planetesimal formation
Nature	Meech	A brief visit from a red and extremely elongated interstellar asteroid
1711.01153	Fraser	1I/'Oumuamua is tumbling
1712.00437	Drahus	Tumbling motion of 1I/’Oumuamua reveals body’s violent past
1712.01823	Cuk	1I/`Oumuamua as a Tidal Disruption Fragment From a Binary Star System

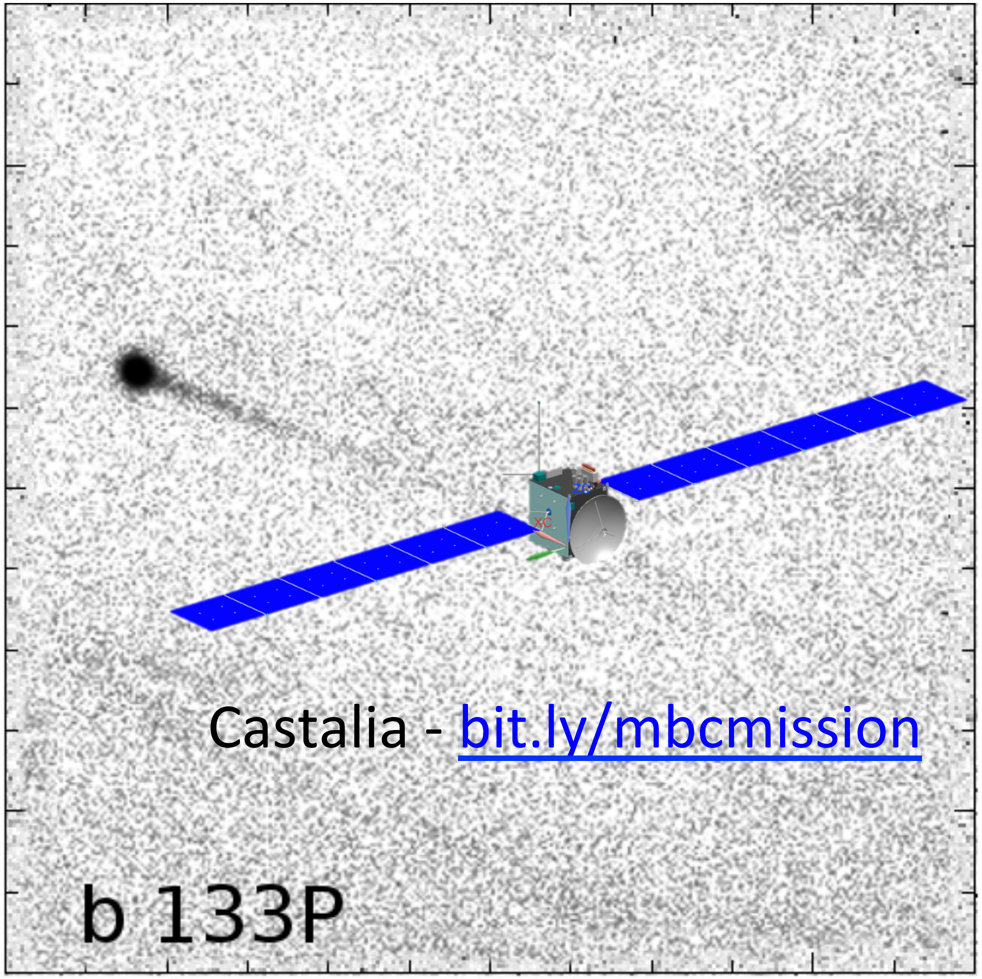
1712.04409	Domokos	Explaining the elongated shape of 'Oumuamua by the Eikonal abrasion model
1712.04435	Jackson	Ejection of rocky and icy material from binary star systems: Implications for the origin and composition of 1I/`Oumuamua
1712.06044	Wright	On Distinguishing Interstellar Objects Like `Oumuamua From Products of solar system Scattering
1712.06552	Fitzsimmons	Spectroscopy and thermal modelling of the first interstellar object 1I/2017 U1 'Oumuamua
1712.06721	Gaidos	What and Whence 1I/`Oumuamua?
1712.07247	Hansen	Ejection of material --"Jurads" -- from post main sequence planetary systems
1712.08059	Zhang	Prospects for Backtracing 1I/`Oumuamua and Future Interstellar Objects
1801.02658	Rafikov	1I/2017 'Oumuamua-like Interstellar Asteroids as Possible Messengers from the Dead Stars
1801.02814	Enriquez	Breakthrough Listen Observations of Breakthrough Listen with the GBT
1801.02821	Do	Interstellar Interlopers: Number Density and Origins of 'Oumuamua-like Objects
1802.00778	de la Fuente Marcos	Where the Solar system meets the solar neighbourhood: patterns in the distribution of radiants of observed hyperbolic minor bodies
1802.01335	Hoang	Spinup and Disruption of Interstellar Asteroids by Mechanical Torques, and Implications for 1I/2017 U1 (`Oumuamua)
1802.02273	Katz	Why is Interstellar Object 1I/2017 U1 (`Oumuamua) Rocky, Tumbling and Very Prolate?
1803.02840	Raymond	Interstellar Object ’Oumuamua as an Extinct Fragment of an Ejected Cometary Planetesimal
1803.07022	Seligman	The Feasibility and Benefits of In Situ Exploration of `Oumuamua-like objects
1803.09864	McNeill	Constraints on the Density and Internal Strength of 1I/’Oumuamua
1803.10187	Park	Search for OH 18 cm Radio Emission from 1I/2017 U1 with the Green Bank Telescope
1804.03471	Belton	The Excited Spin State of 1I/2017 U1 ‘Oumuamua
	Tingay	A Serendipitous MWA Search for Narrowband Signals from ‘Oumuamua

WHAT IS IT? COMET, ASTEROID?

SPACESHIP…?

Comets v asteroids

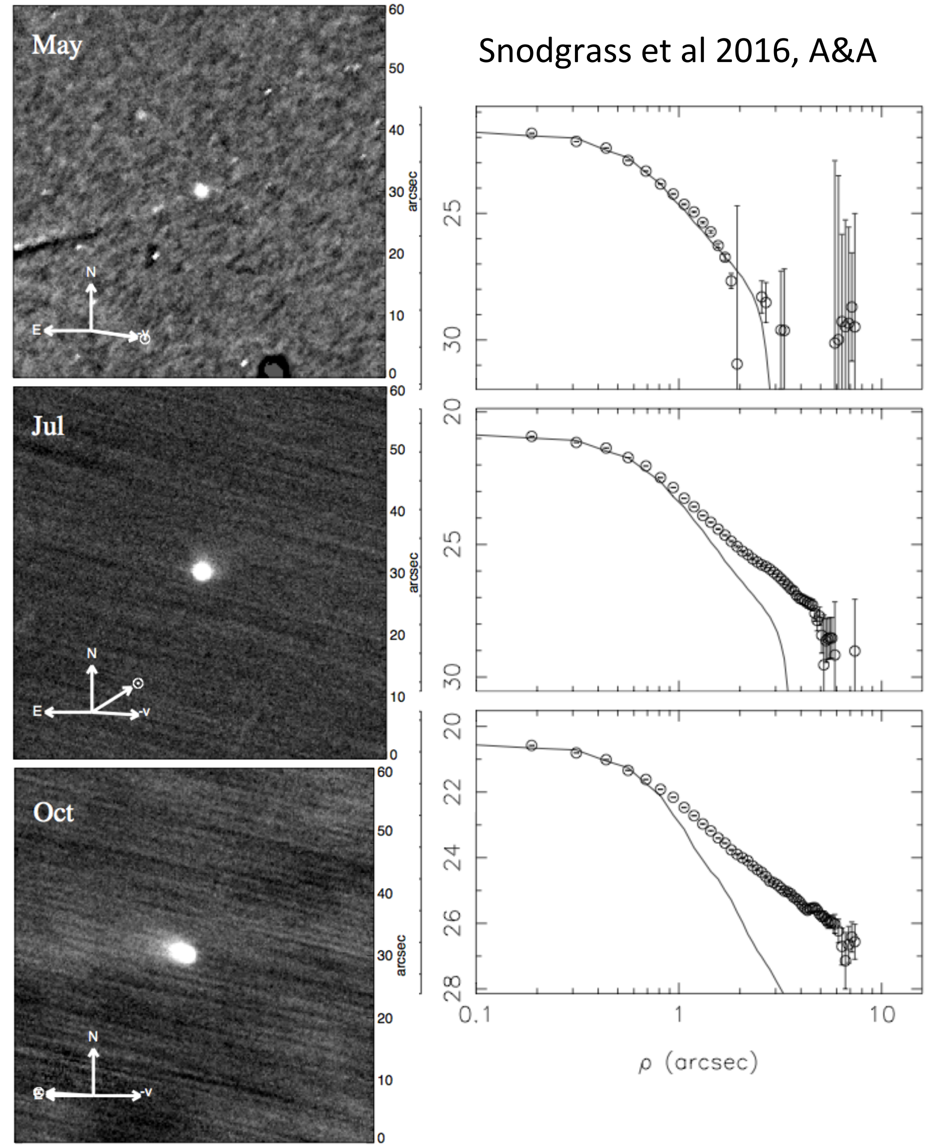
- Comets:
  - Icy, eccentric orbits, show activity (coma/tails)
- Asteroids:
  - Rocky, circular orbits, no activity
- Recent picture is more confusing
  - Active asteroids (main belt comets)
  - Damocloids/Manx comets
  - Extinct comets



Castalia - bit.ly/mbcmission

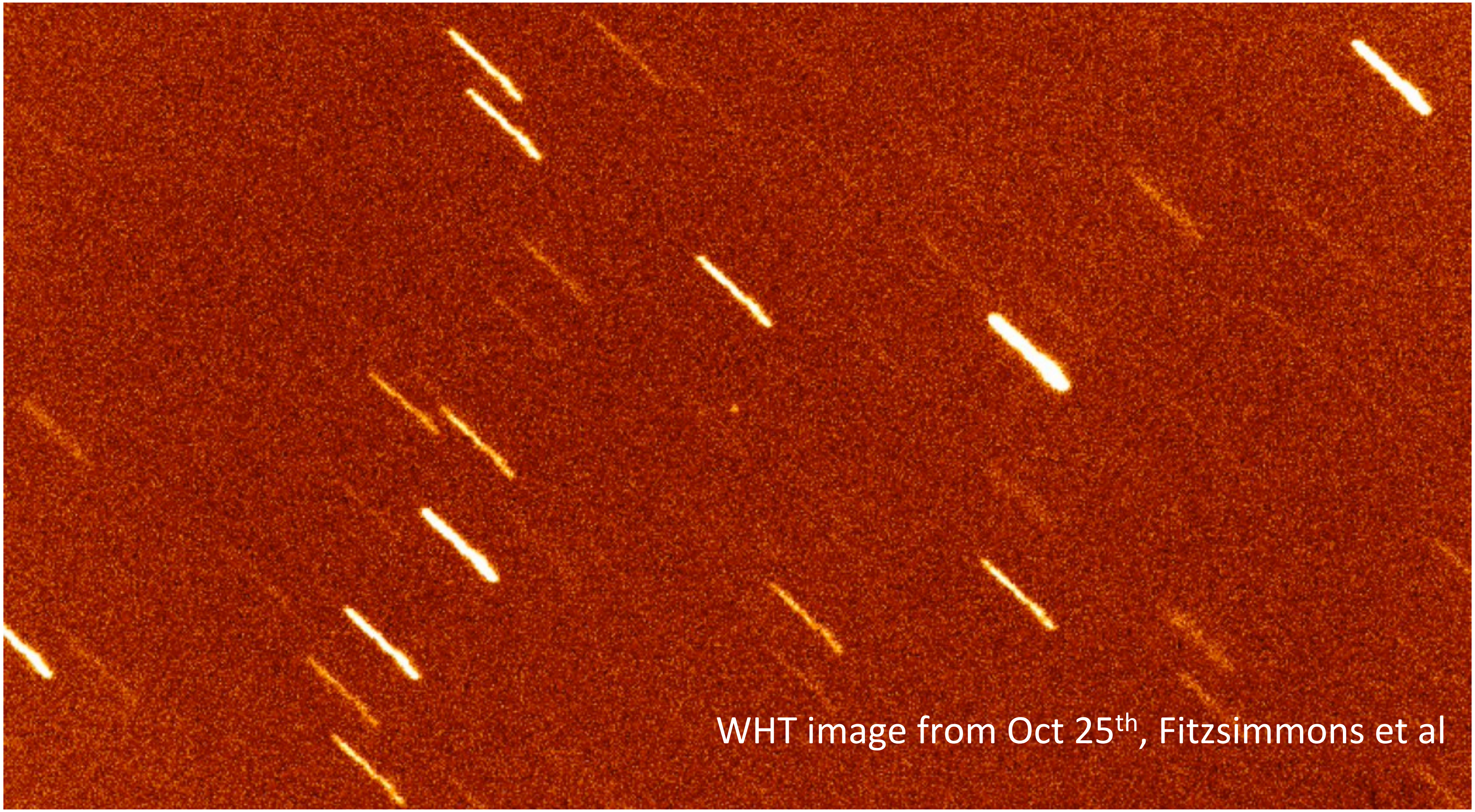
Comets v asteroids

- Observationally, comets have extended profile
- Comparison of surface brightness profile with PSF (from stars) reveals faint coma
- Example shows start of activity in 67P
- Can reveal activity fainter than is visible by eye in image
- Can still hide weak activity within seeing disc

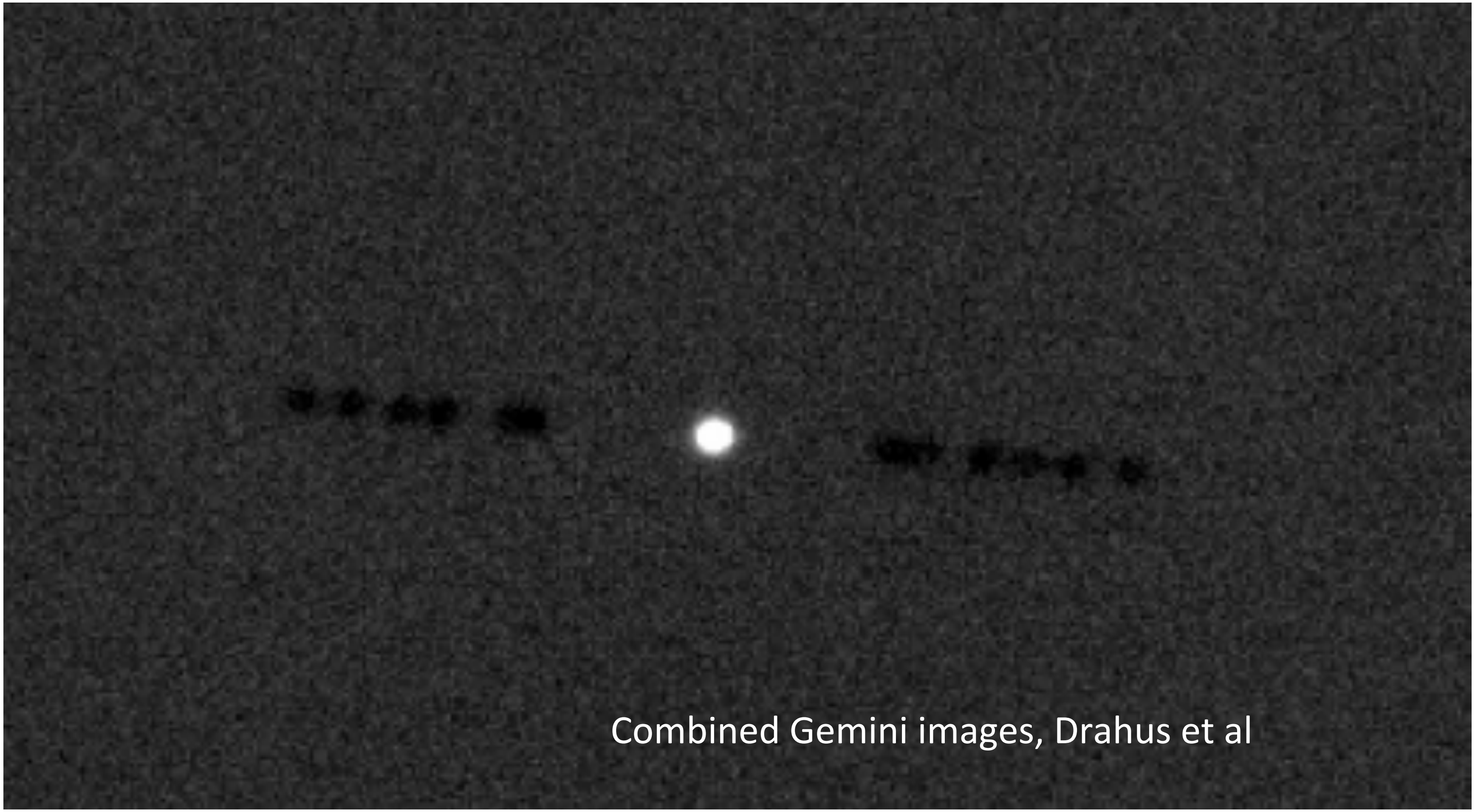


Snodgrass et al 2016, A&A

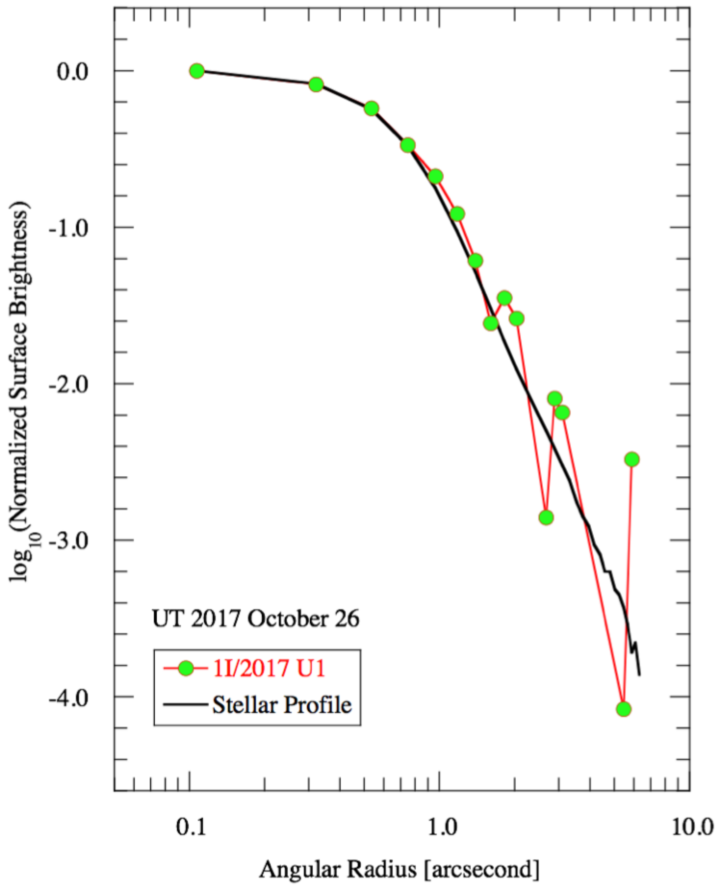
Asteroid?

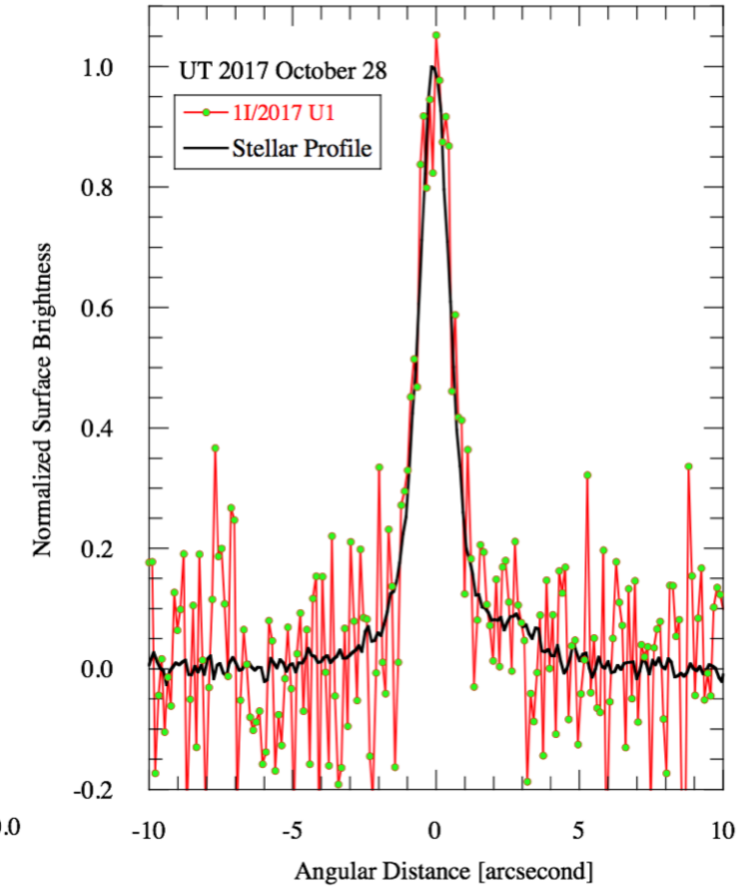


Asteroid?



No activity in profile – asteroid?

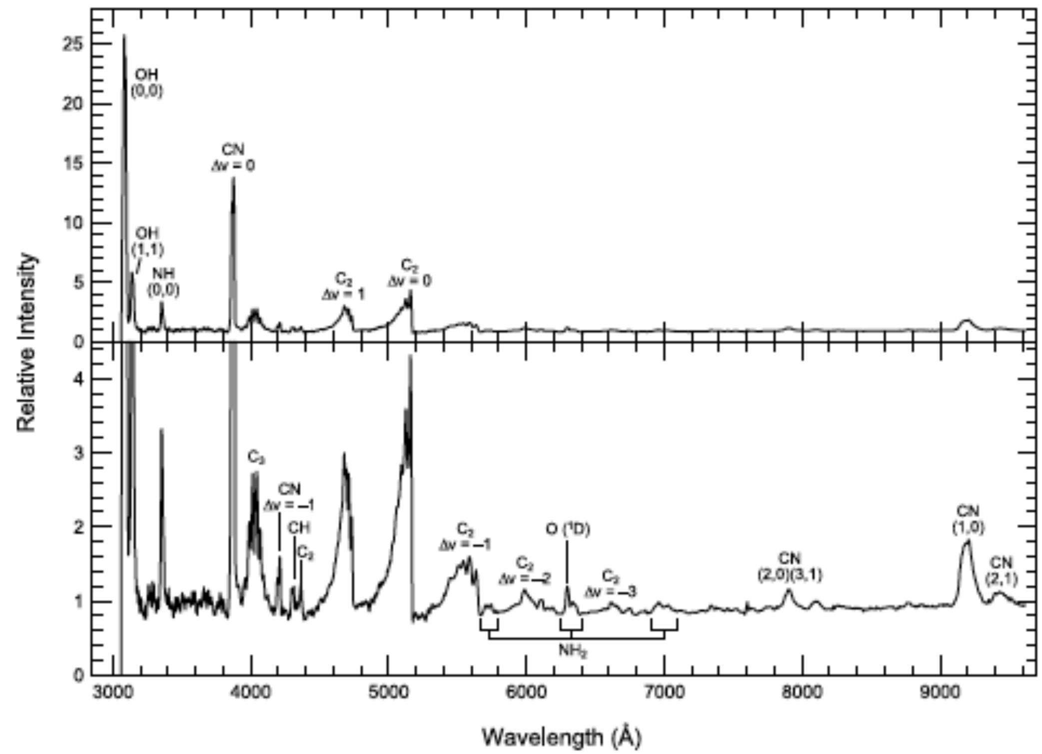




Jewitt et al

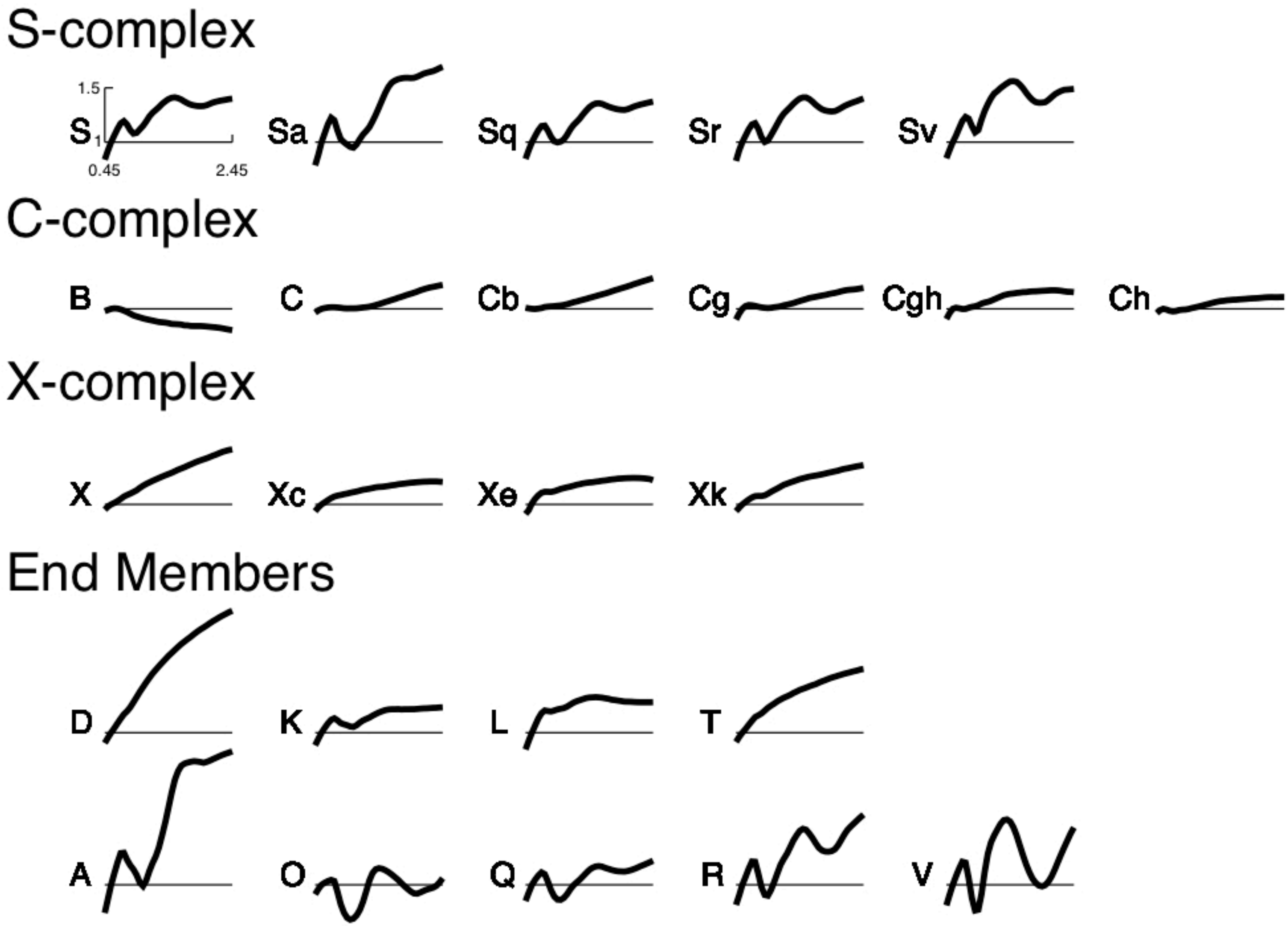
Composition

- Can also test for asteroid- or comet-like composition
- Spectroscopy reveals composition
  - emission features in gas coma (comets)
  - Solid-state absorption features in reflected continuum (asteroids)
  - E.g. bands at ~0.7 μm due to phyllosilicates, or ~0.95 μm (pyroxines and olivines)



Comet spectrum (Feldman et al 2004)

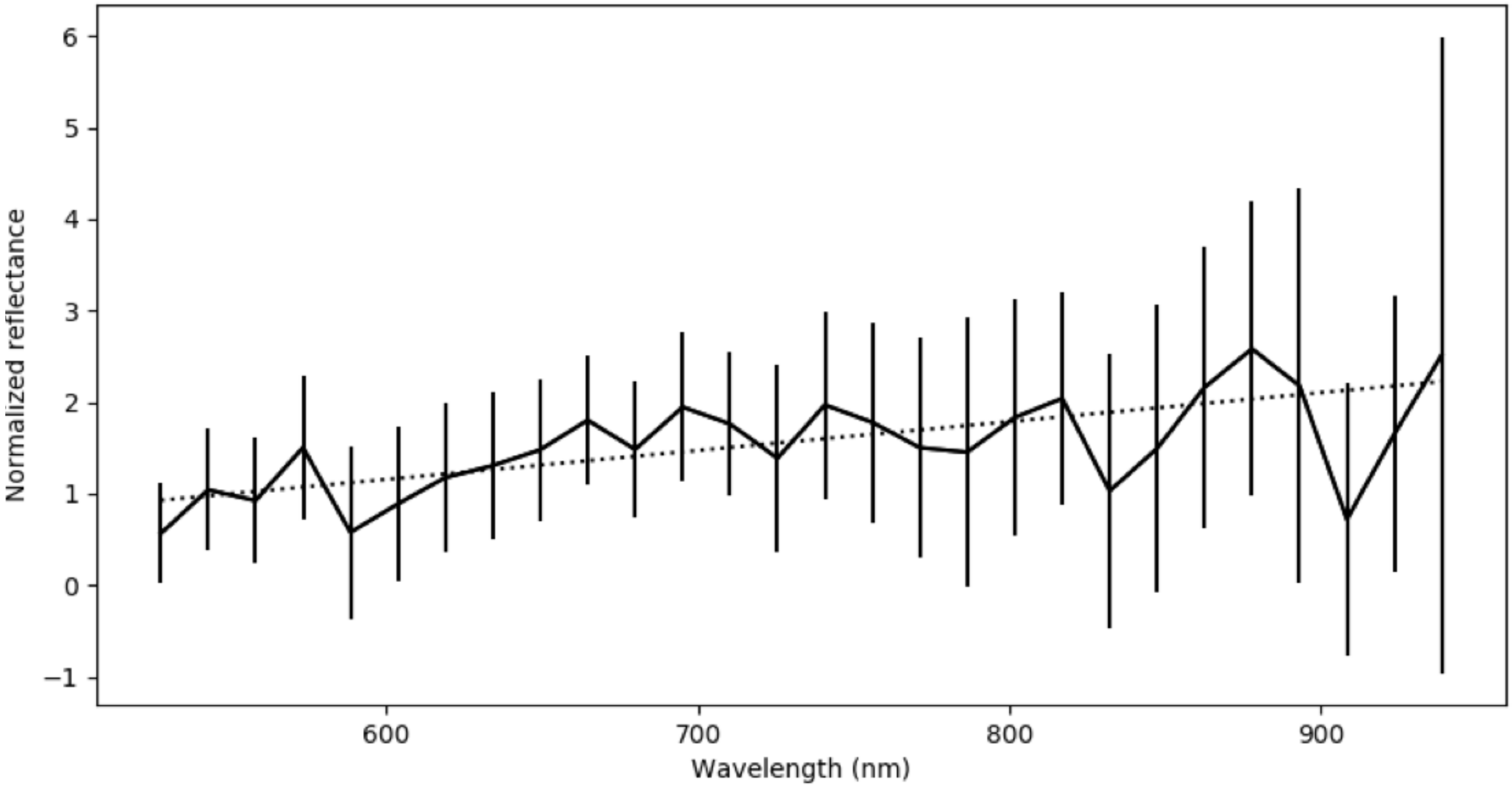
Bus-DeMeo Taxonomy Key



http://smass.mit.edu/busdemeoclass.html

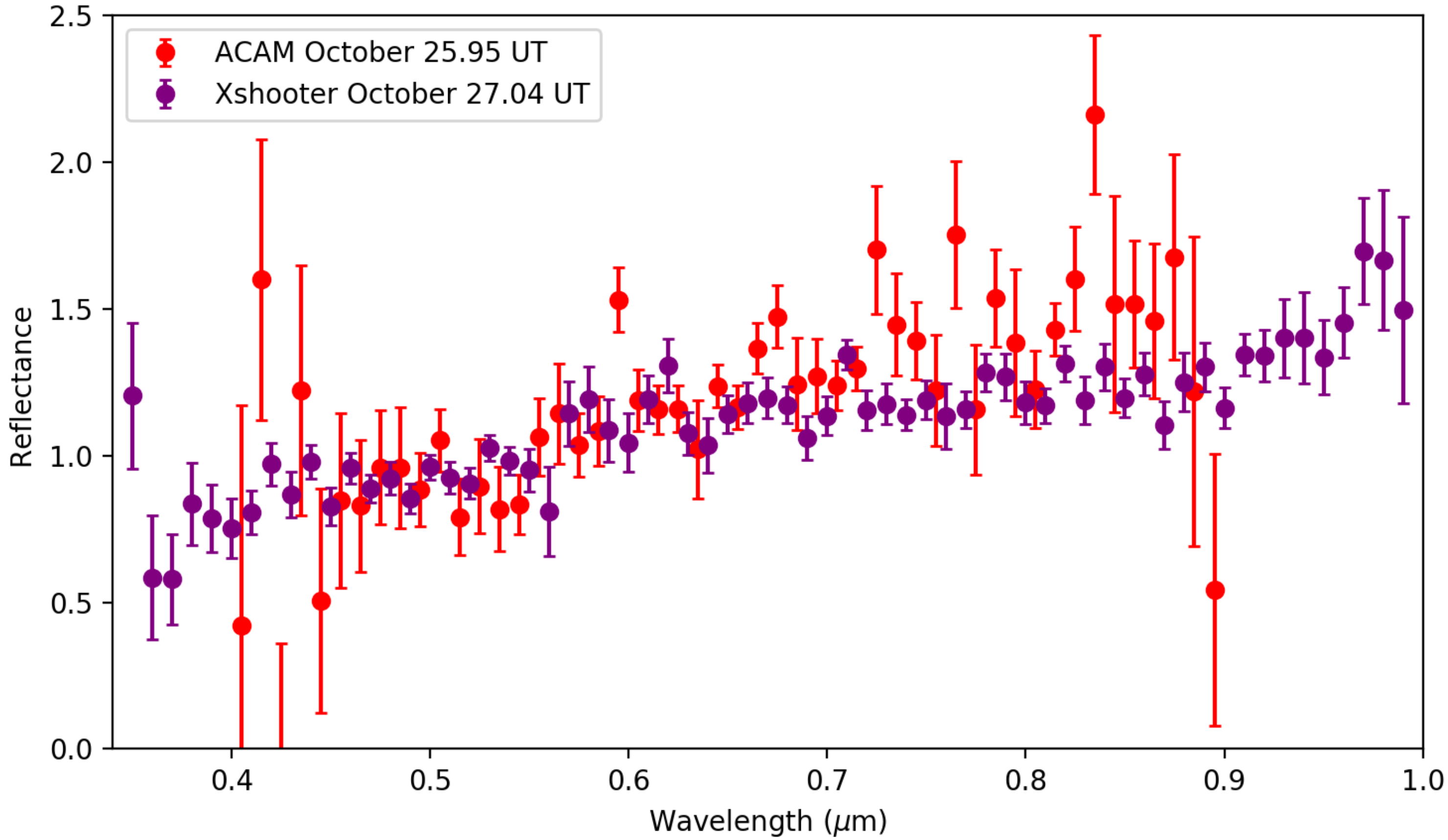
F. E. DeMeo, R. P. Binzel, S. M. Slivan, and S. J. Bus. Icarus 202 (2009) 160-180

Spectrum



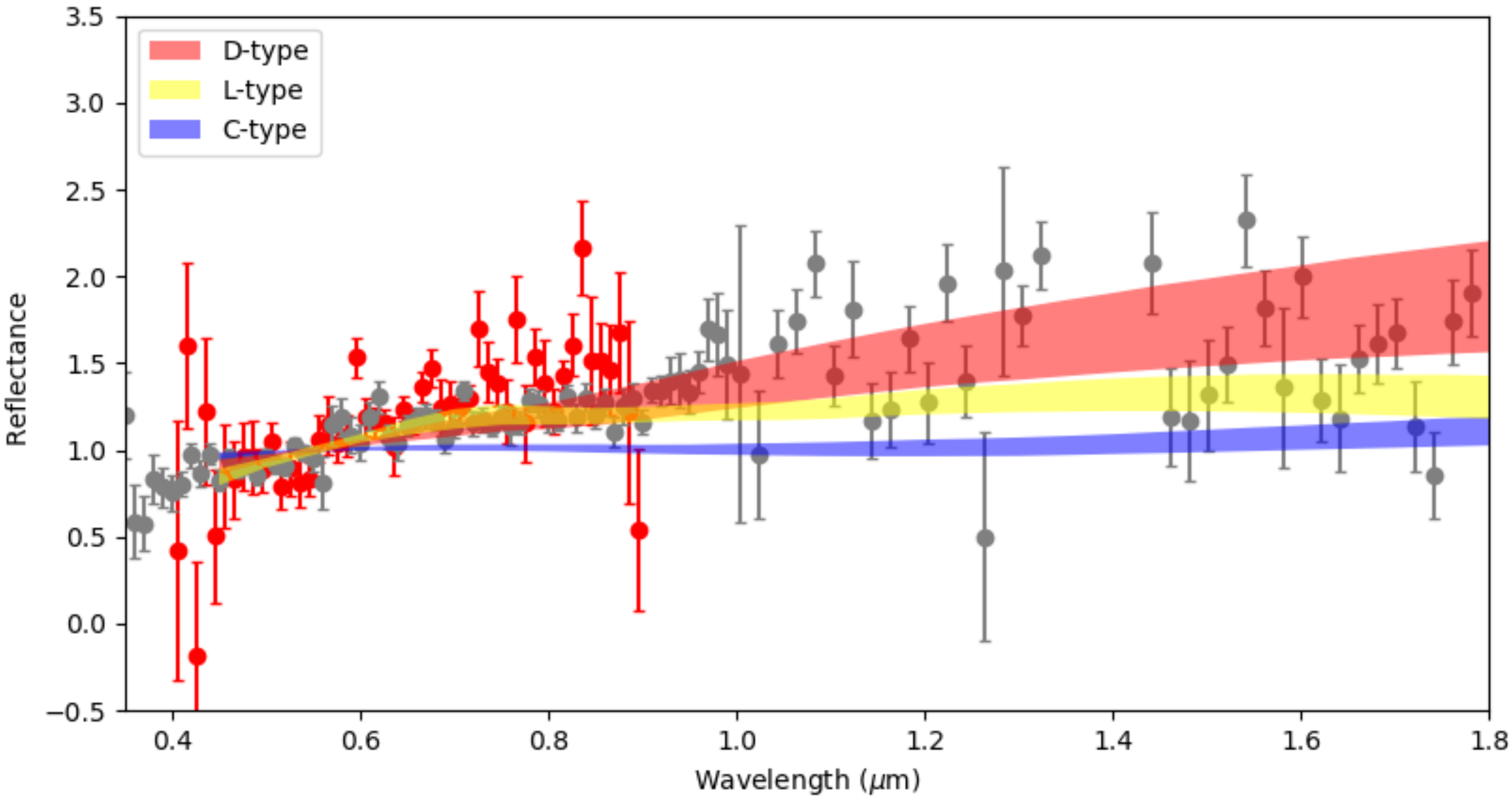
Palomar 200”, Masiero

Spectrum



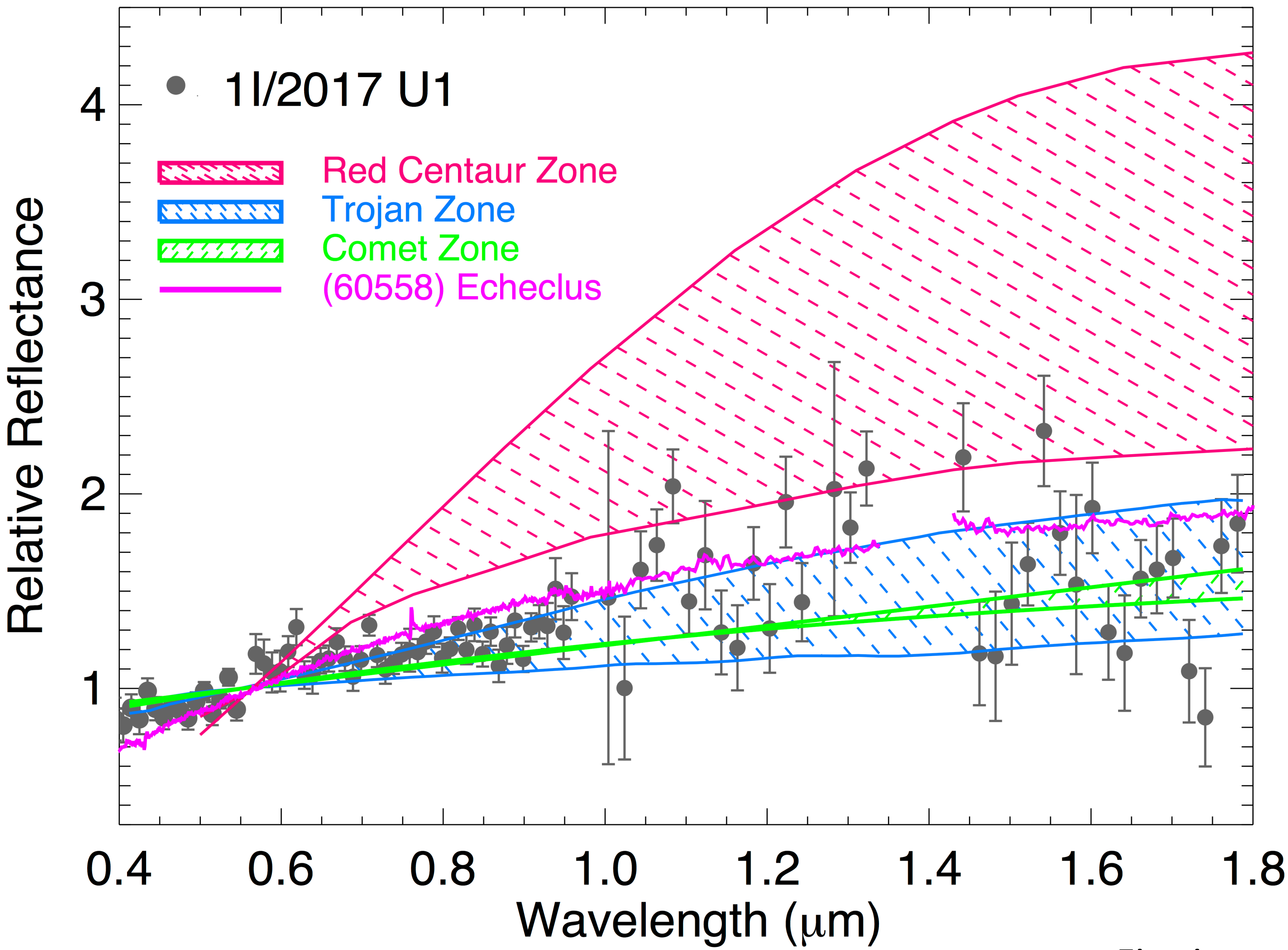
Fitzsimmons et al

Spectrum



Fitzsimmons et al

Spectrum



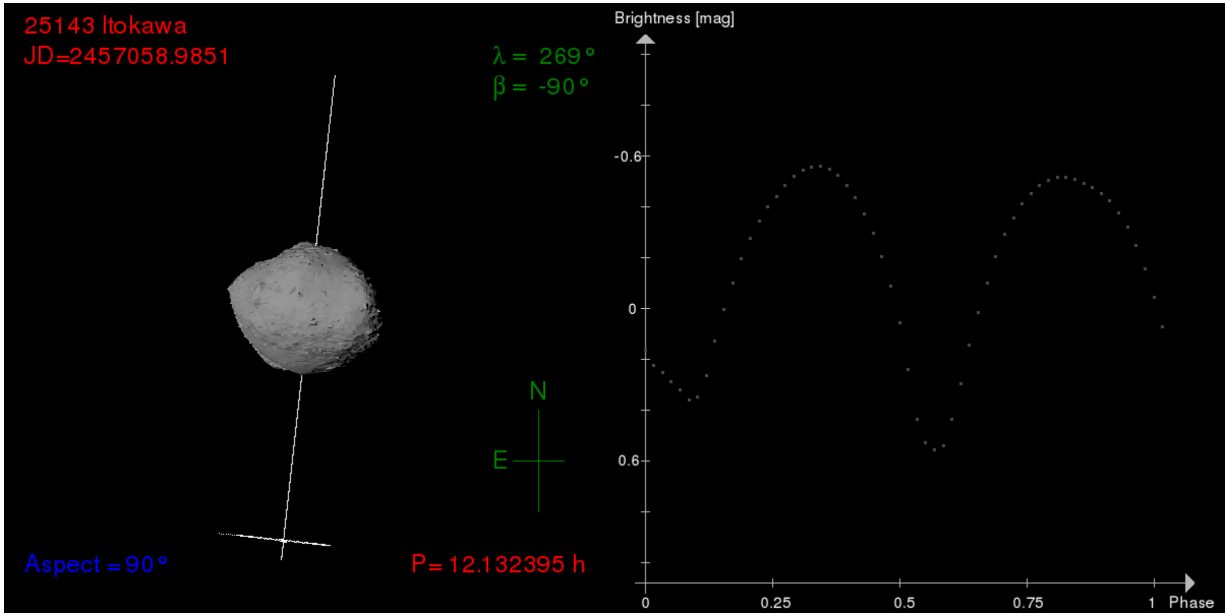
Fitzsimmons et al

Size, shape, physical properties

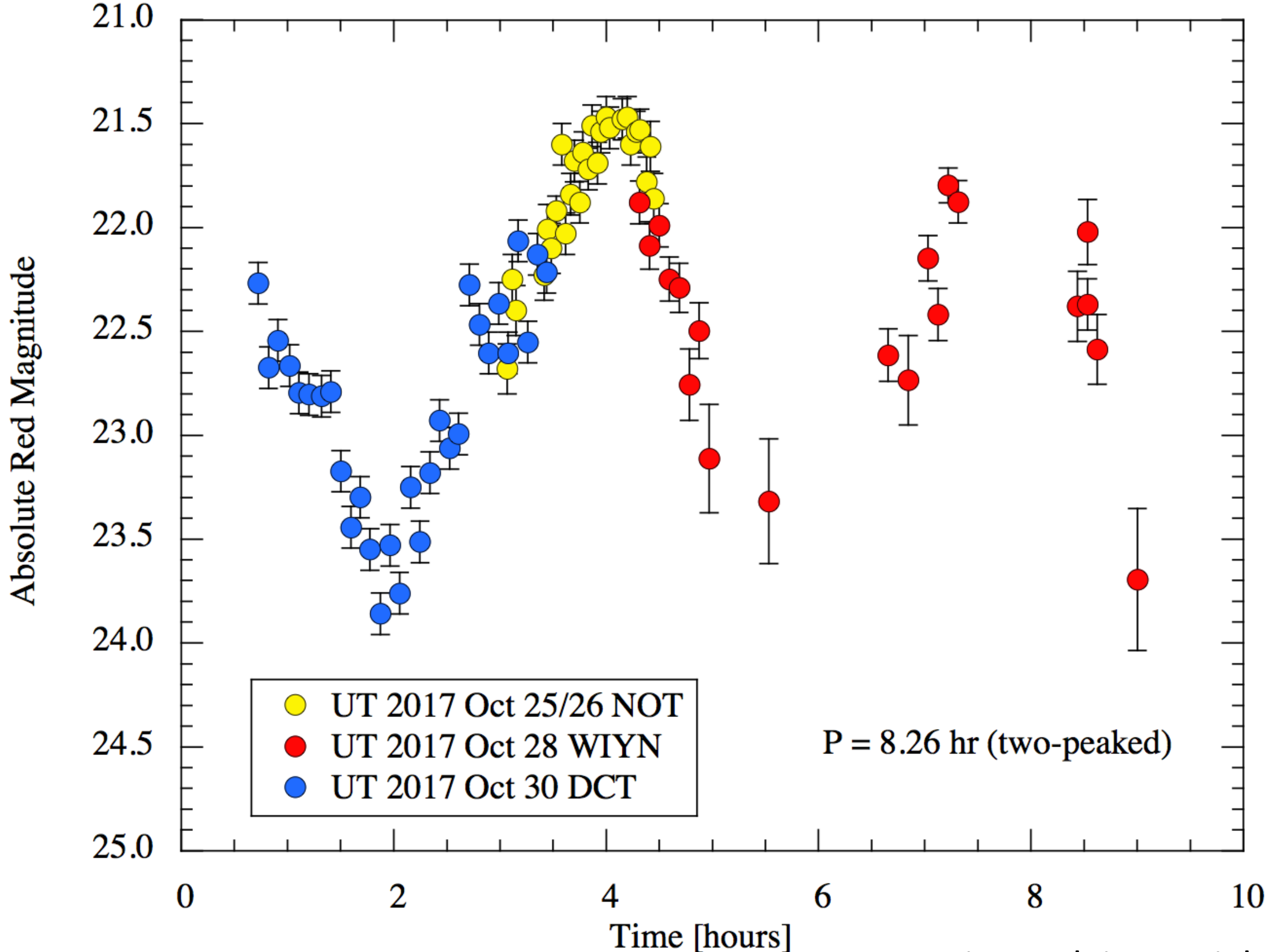
- Calibrated gives size (assuming albedo) from reflecting area
- Relative photometry over time-series (lightcurve) gives
  - Rotation rate from periodicity
  - Shape from lightcurve amplitude
  - Constraints on density / strength of material (balance of centrifugal and gravity forces)

$$\frac{a}{b} = 10^{0.4\Delta m}$$

- Colour photometry can complement spectra



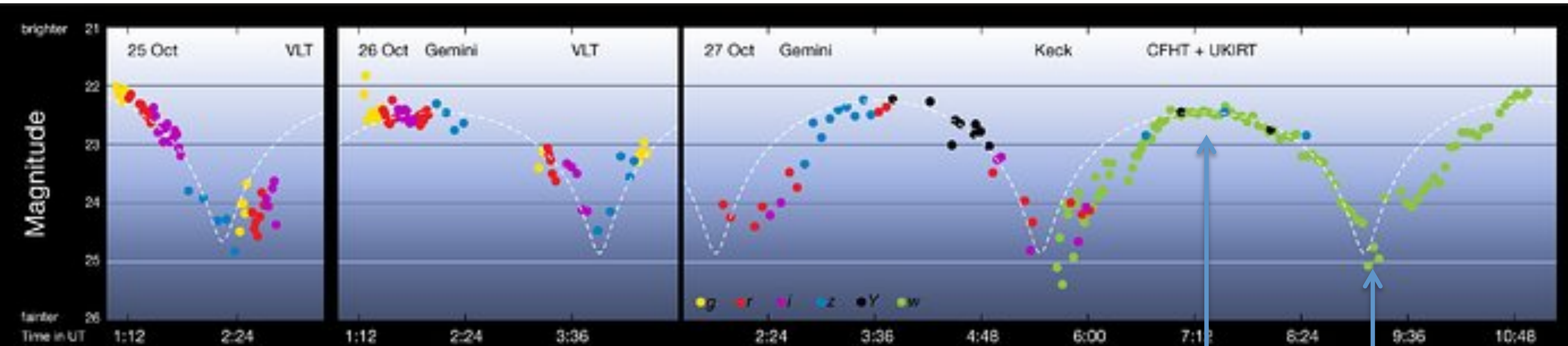
Lightcurve

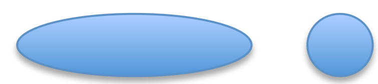


Jewitt et al, inc. Knight et al data

Lightcurve

Meech et al

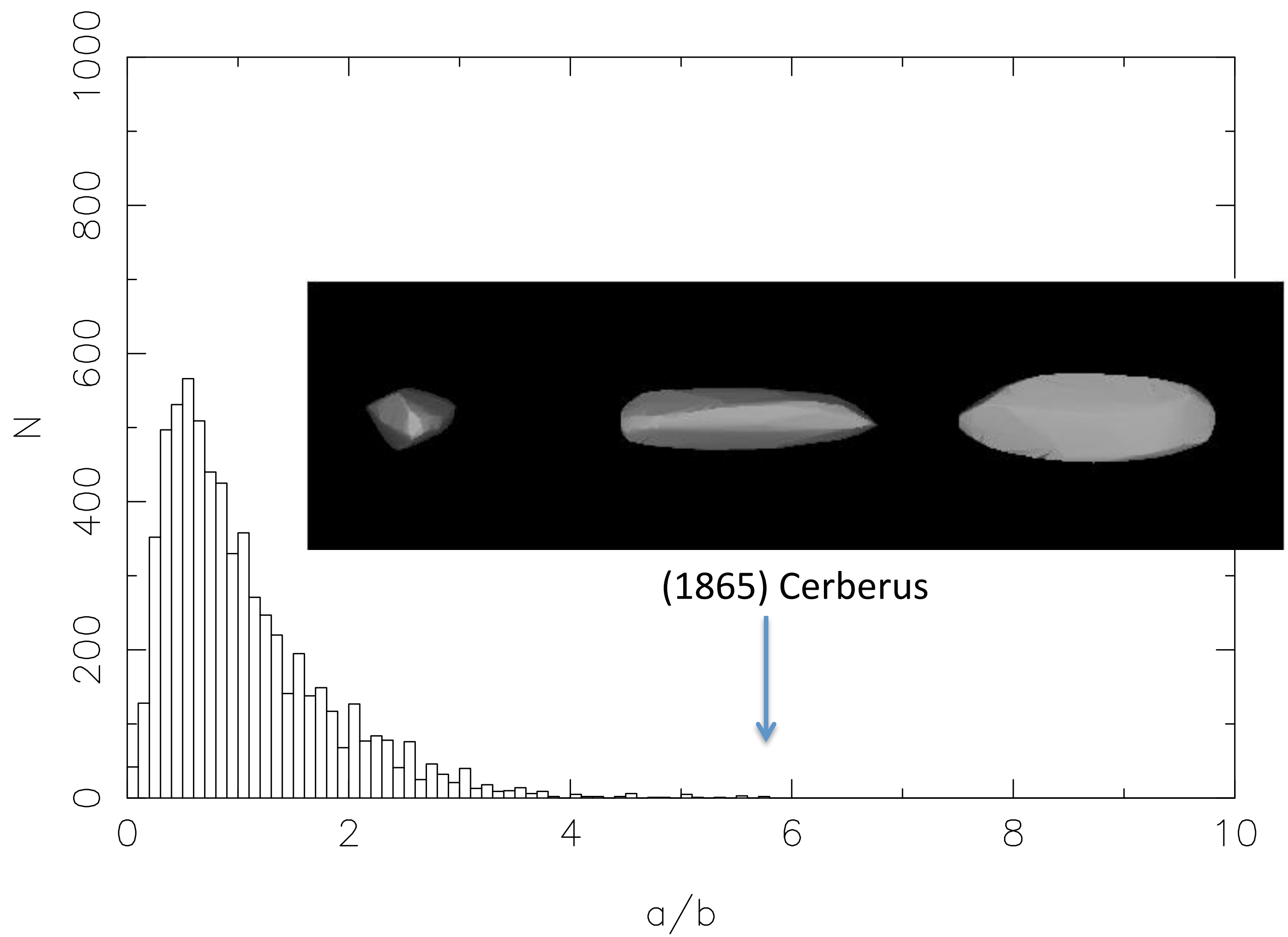




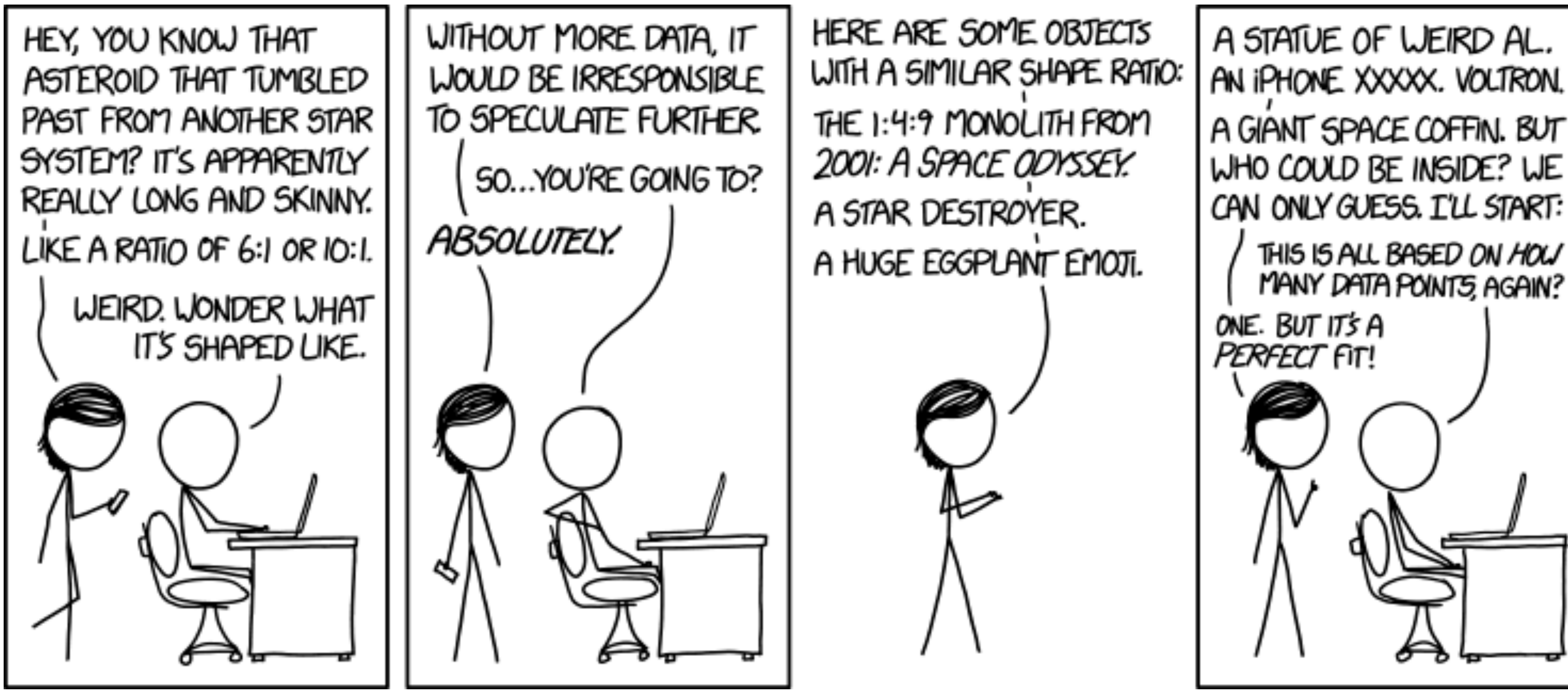
- Various lightcurve studies give period 7-8 hours
- Knight et al first partial lightcurve (on arXiv Nov 5)
- Meech et al one first to be published, combines multiple observations
- Lightcurve amplitude very large (2.5 mag)
- Implies a highly elongated body

$$\frac{a}{b} = 10^{0.4\Delta m} \approx 10$$

Lightcurve

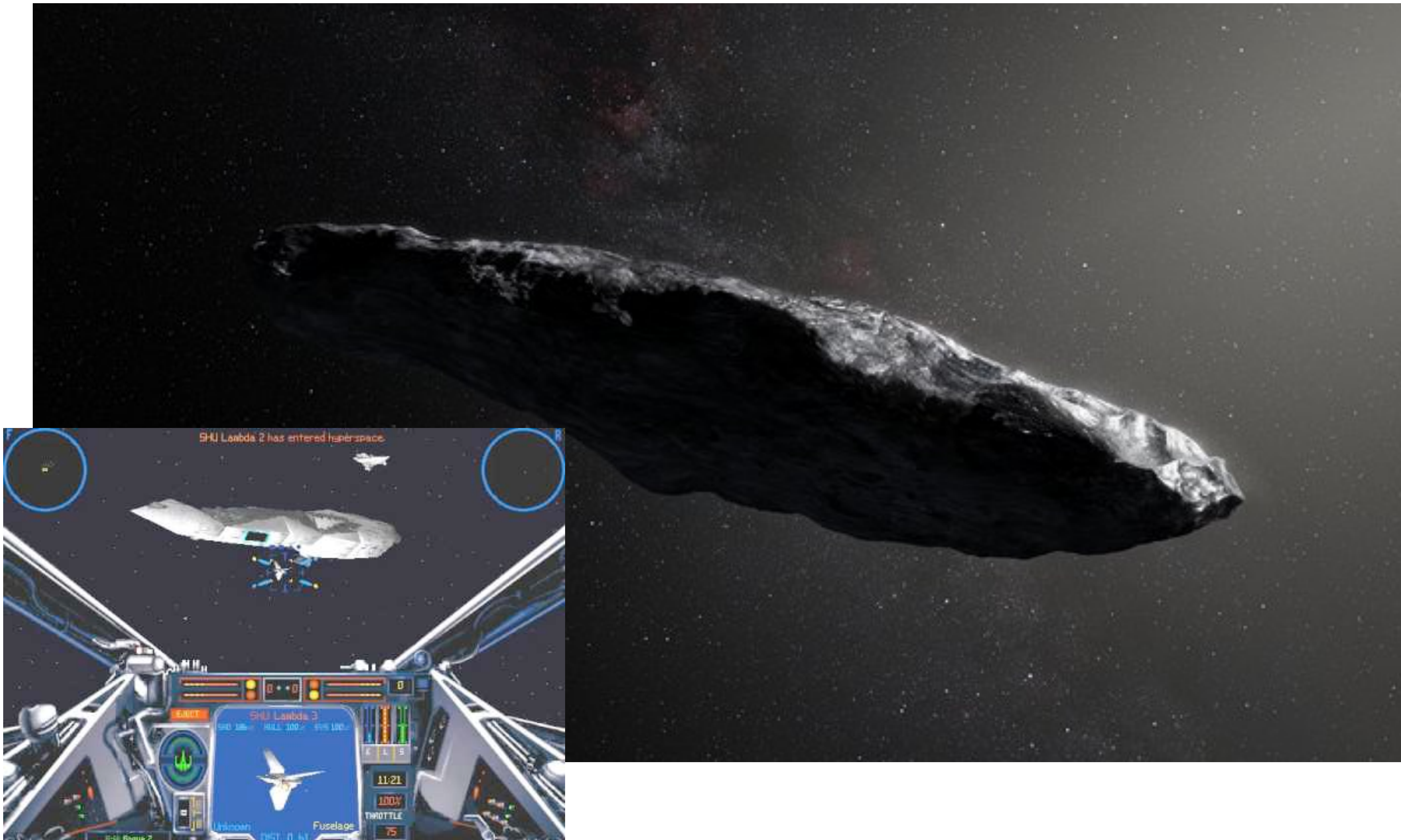


WTF?



https://xkcd.com/1919/ 22nd Nov

WTF?


SHU Laabda 2 has entered hyperspace.
EJECT
SHU Laabda 3
11:21
100%
THROTTLE
75
SPEED
Fuselage
Rogue 2

WTF?

Questions

- What is it made of?
  - Comet or asteroid?
- Why the unusual shape?
- Where did it come from?
- How many are out there?

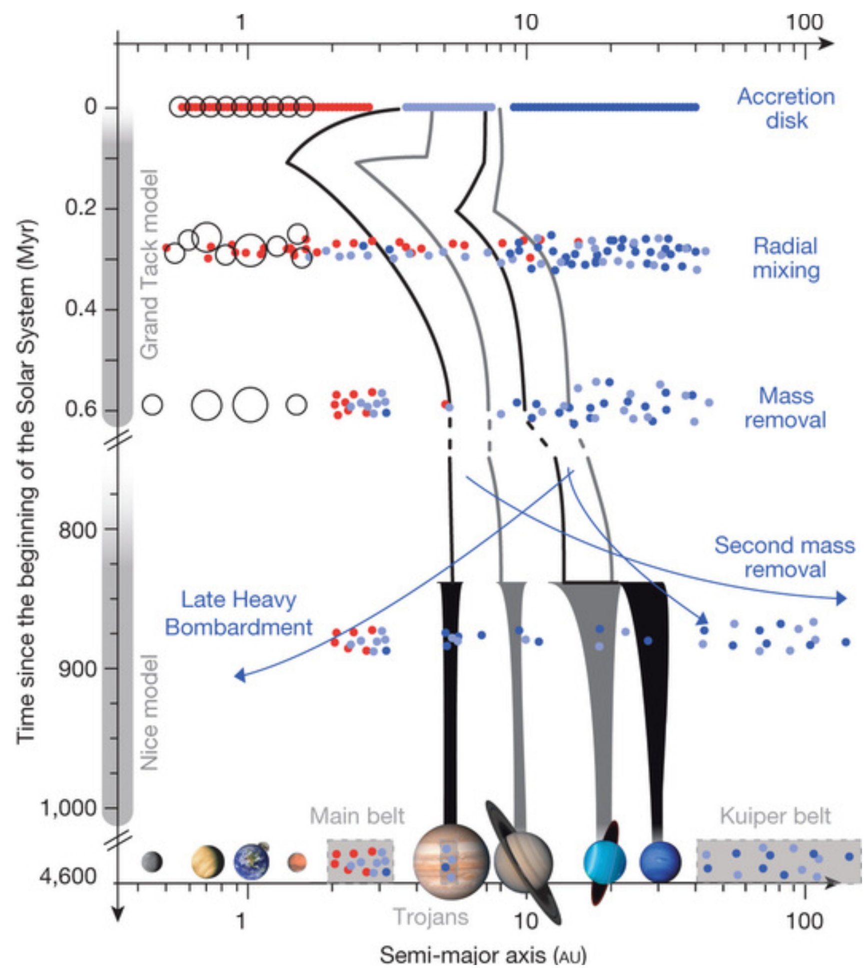
COMPARISON WITH EXPECTATIONS

Expectations

- Various studies estimating expected rate of discovery
- Most recent (pre `Oumuamua) by Engelhardt et al. (2017, AJ 153:133), inc. PS1 etc. survey efficiencies
- Detection rates depend on many things, including size distribution and comet/asteroid like behaviour
- Much easier to detect comets at same size, due to activity (larger reflecting area -> brighter)

Formation of ISOs

- Two ways of forming ISOs:
  - Direct ejection due to gravitational interaction with (giant) planet
  - Escape from Oort clouds due to stellar encounters
- Modern planet formation models include migration and eject a lot of planetesimals
- In both cases, most ISOs will be icy
  - Planetesimals forming near giant planets will be icy
  - Oort cloud mostly icy bodies



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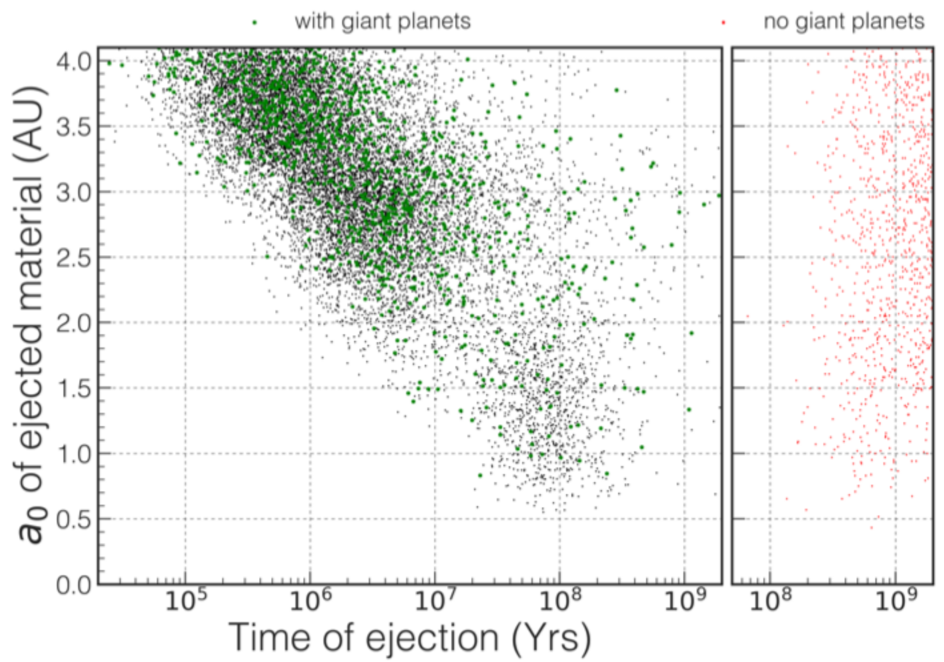


Barclay et al 2017 (ApJ 841:86)

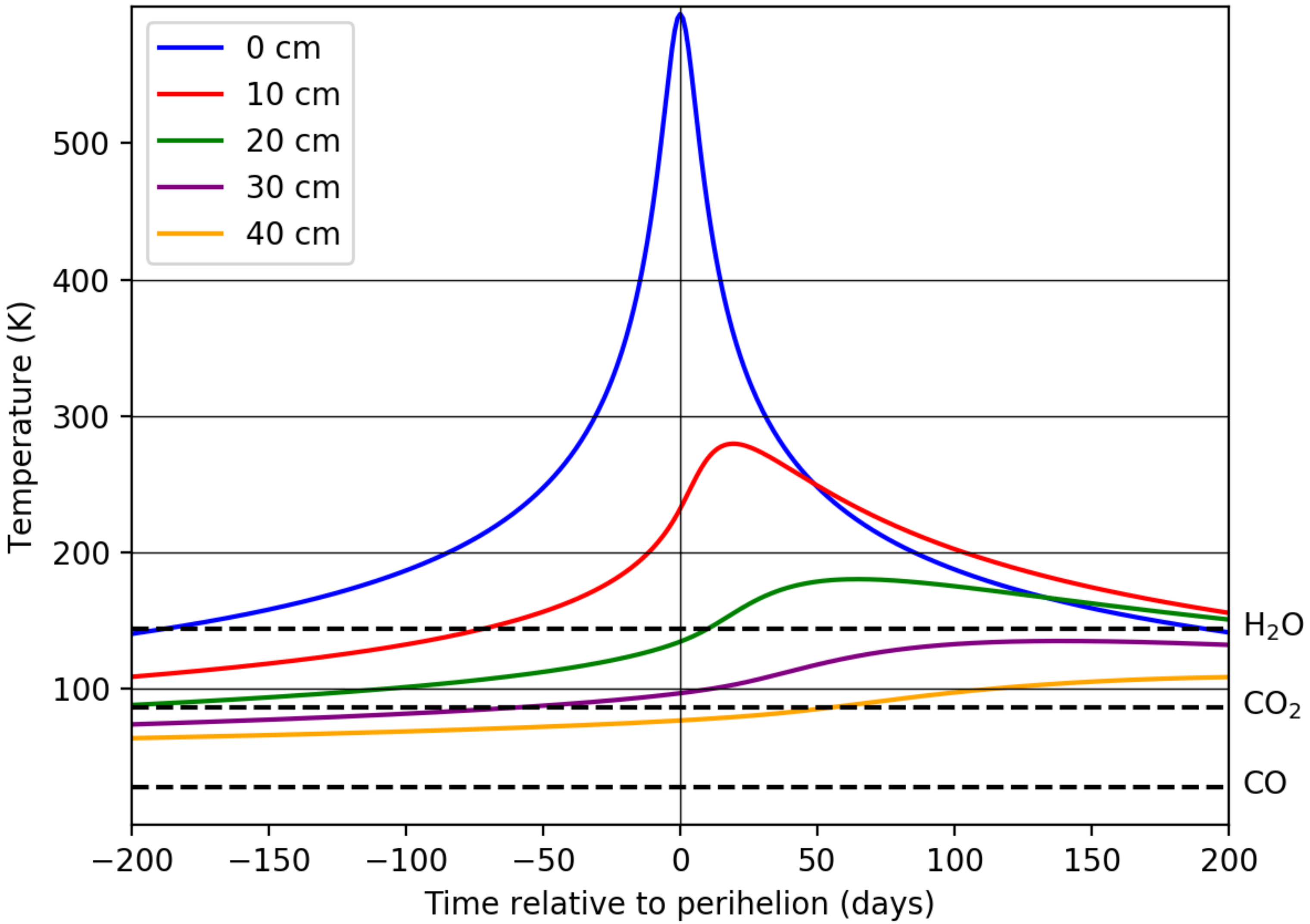
- Most planetesimals ejected early and from initially larger distance from star
- Most are small bodies

Can it be icy?

- Spectrum looks like an icy body
- Expectation that bringing an icy body to 0.25 AU will cause activity
- No activity seen

- Comets have low thermal inertia
- This thing was going fast
- Can ice survive under insulating layer?

Can it be icy?

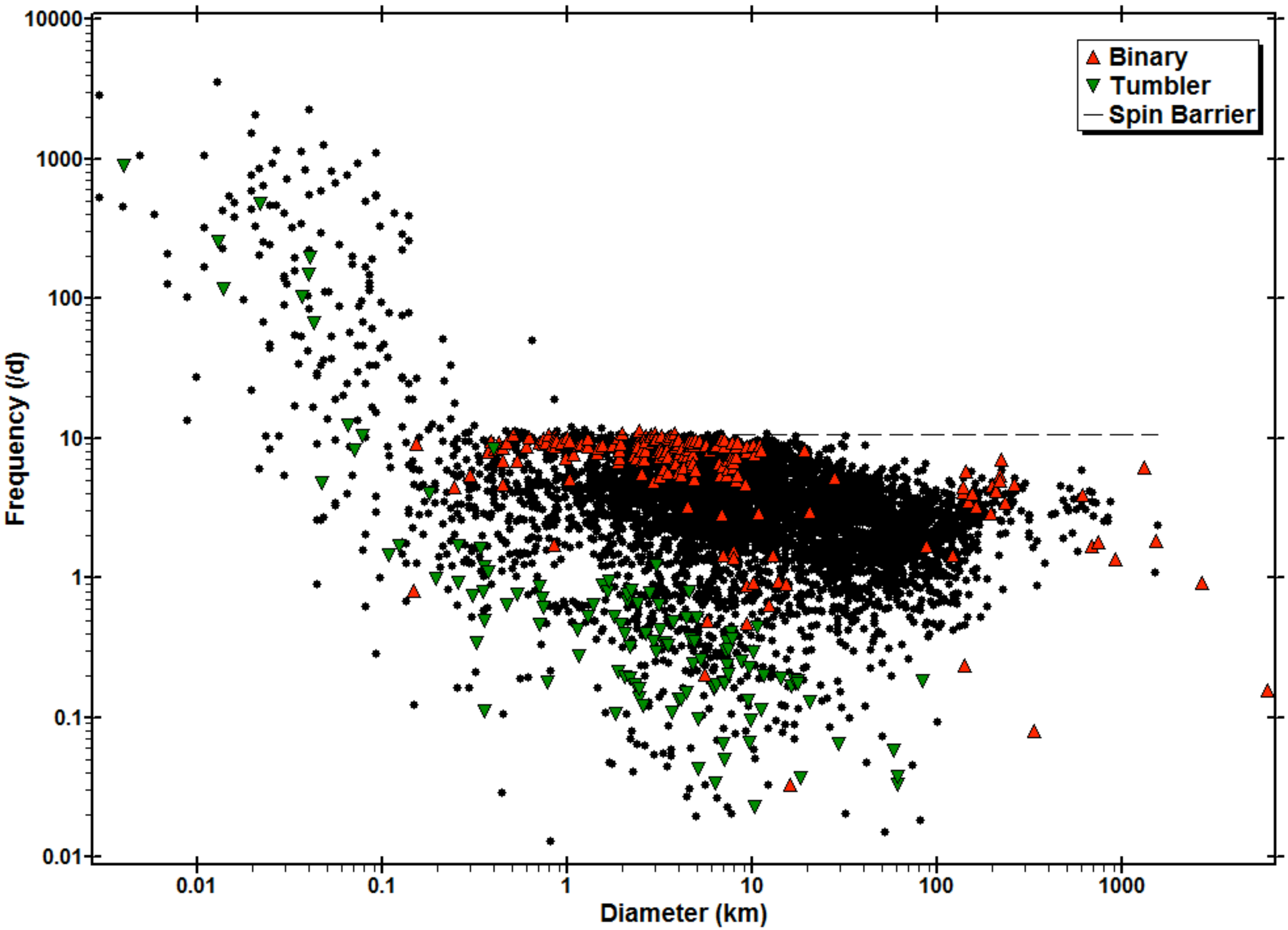


Fitzsimmons et al

Can it be icy?

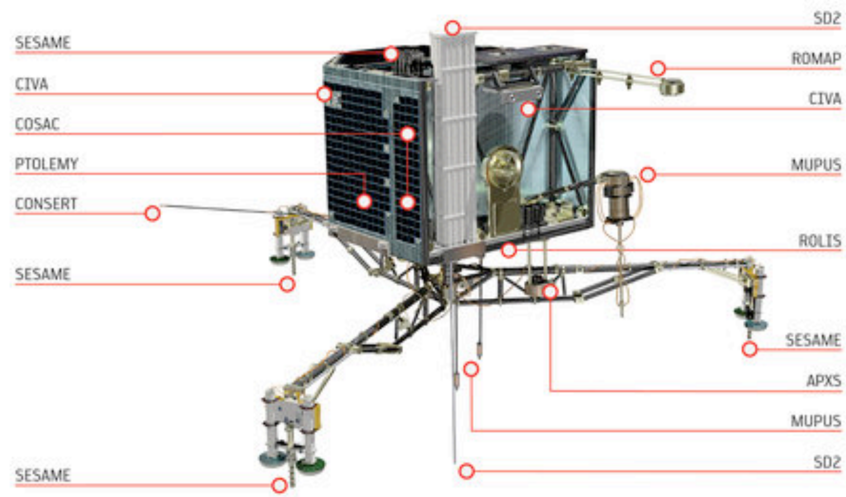
- Lack of activity doesn't rule out sub-surface ice
- Comet surfaces are expected to build up mantle / de-volatised layer over long periods of cosmic ray bombardment
- Predictions 10cm – 2m (Guilbert-Lepoutre et al 2015, SSR 197:271)
- Compatible with this, but can ice support the odd shape?
  - Implied density (if rubble pile) ~ 2000 kg/m^3 (not ice)
  - Small enough to be monolith? Strength?

Strength of asteroids



Strength

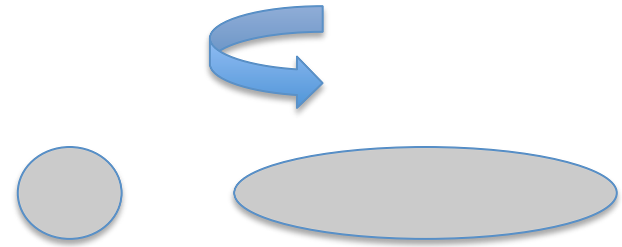
- Required strength for ~1000 kg/m^3 is only few Pa
- Talcum powder has strength of ~10 Pa
- How strong is a comet?
- Bulk comets thought to be strengthless
  - E.g. modelling of breakup of SL9 around Jupiter
- Rosetta results show strength on scales of cliffs (up to km) of 3-15 Pa, locally > 2 MPa (MUPUS)



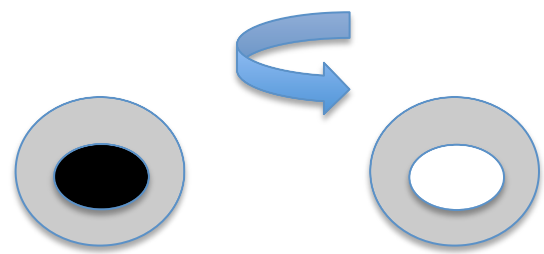
IS IT REALLY CIGAR-SHAPED?

Lightcurves

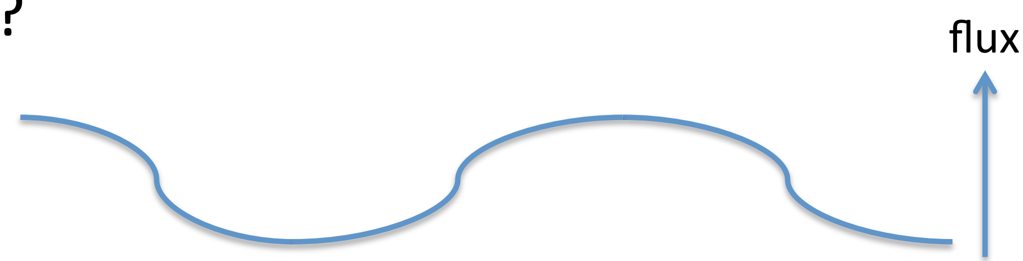
- Lightcurve variation not necessarily due to shape
- In most small bodies, shape controlled lightcurve is a reasonable assumption
  - Very few seen to have clear albedo variations
- Should ISOs be the same?
- Moderate elongation and associated albedo variation (ends v sides)??



Shape variation



Albedo variation



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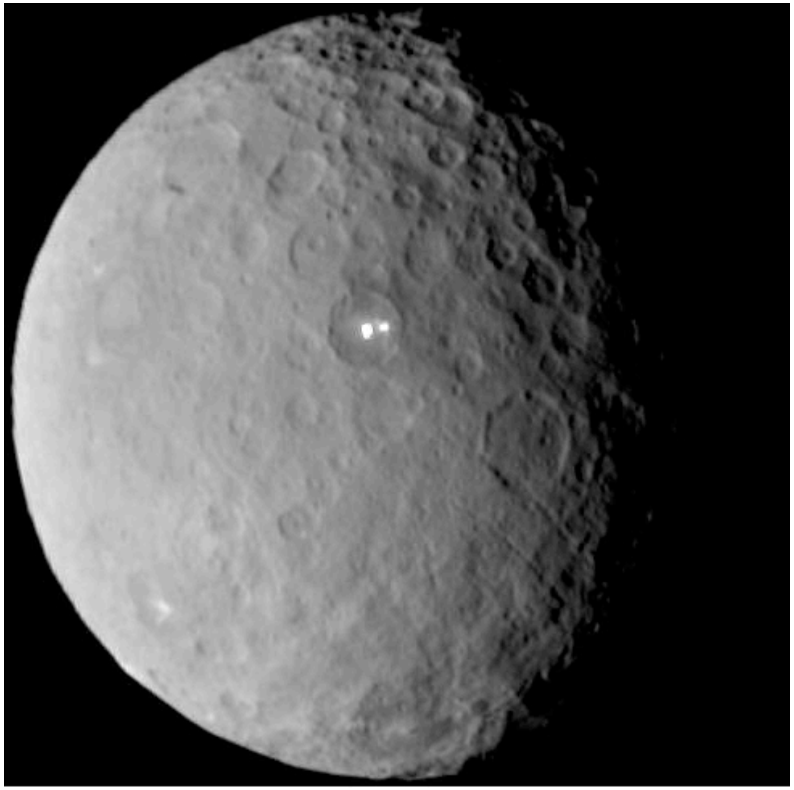
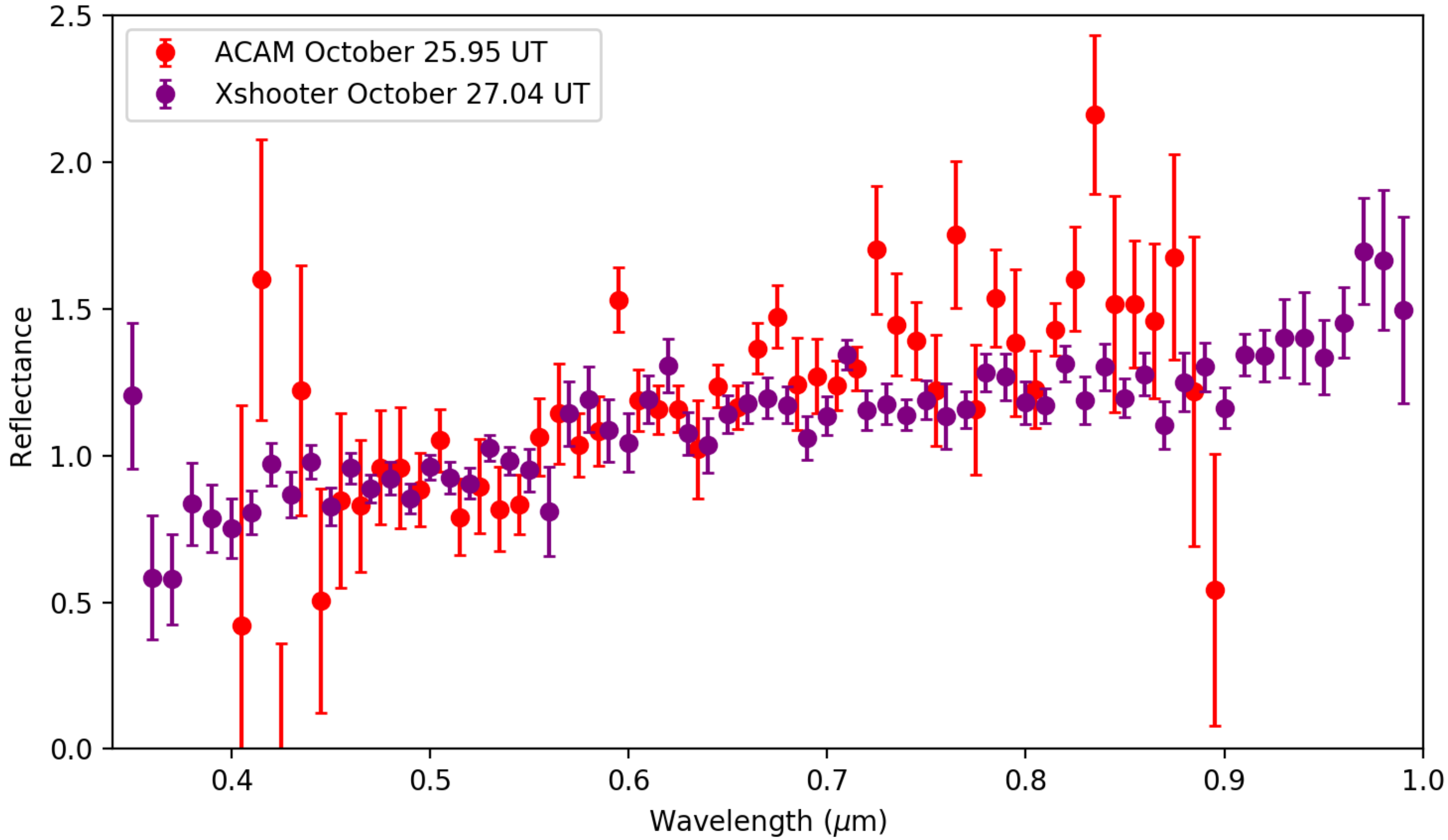


Lightcurves

`Oumuamua models (end members)

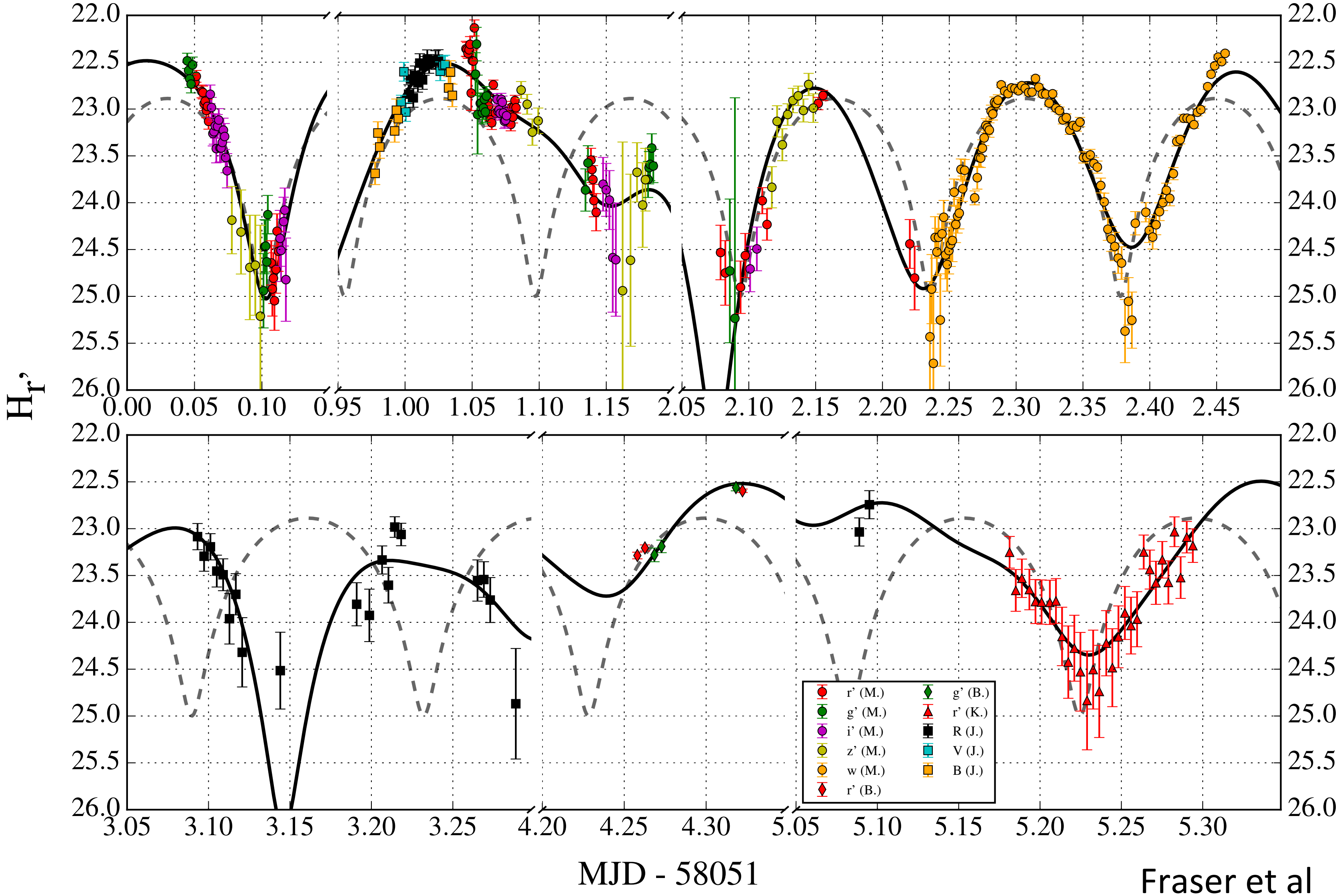
@lukedones

Rotational variation



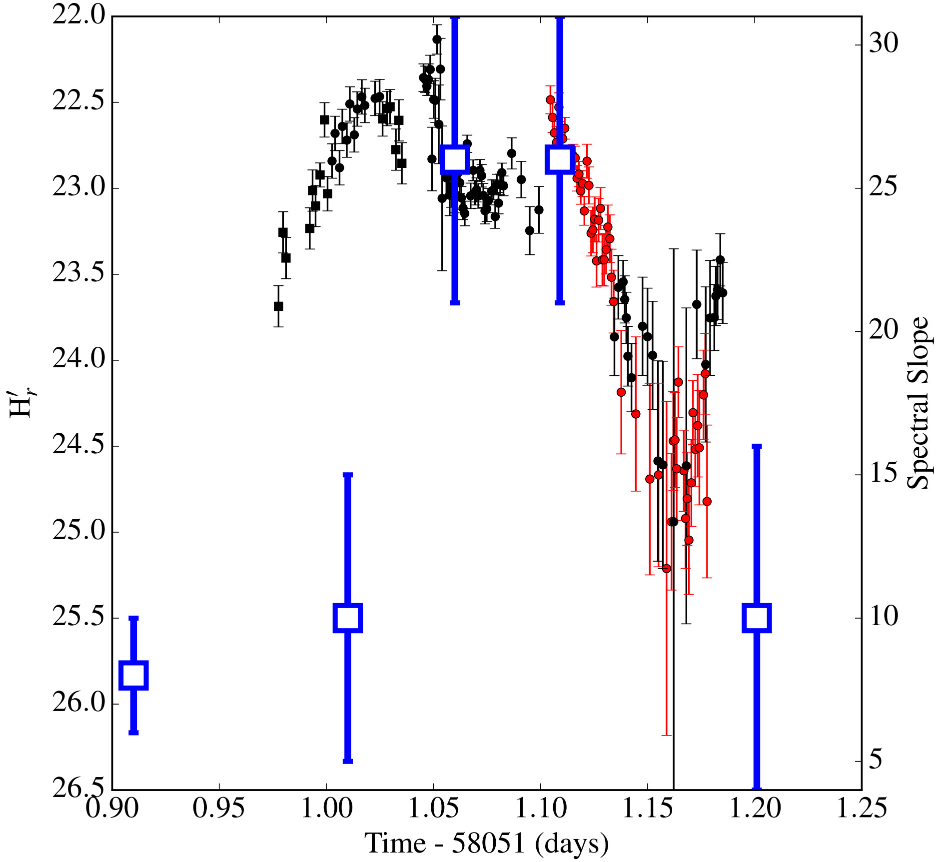
Fitzsimmons et al

All lightcurve data – it is tumbling



Fraser et al

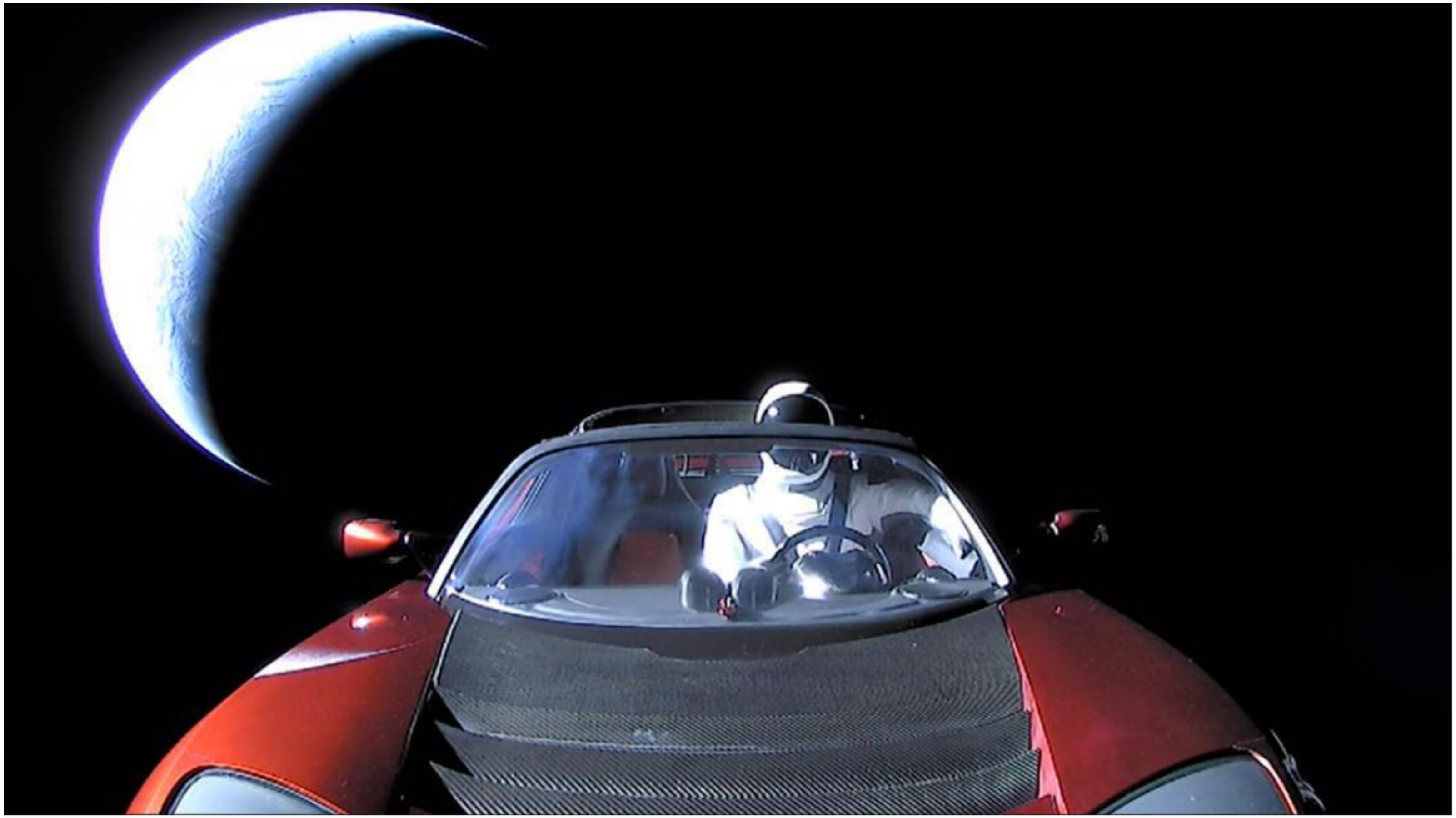
Tumbling, with red side(s)



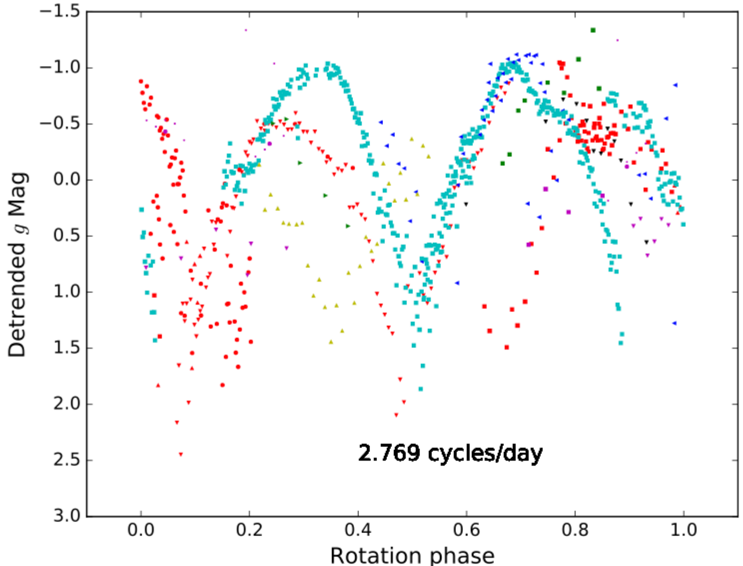
Fraser et al

- Tumbling interpretation means that phasing of colours is difficult to do
- Can't map differences
- Colours / spectroscopy around this peak show that difference can be due to red patch(es) and otherwise more neutral colours
- Also, tumbling model doesn't require such large elongation: a/b > 5

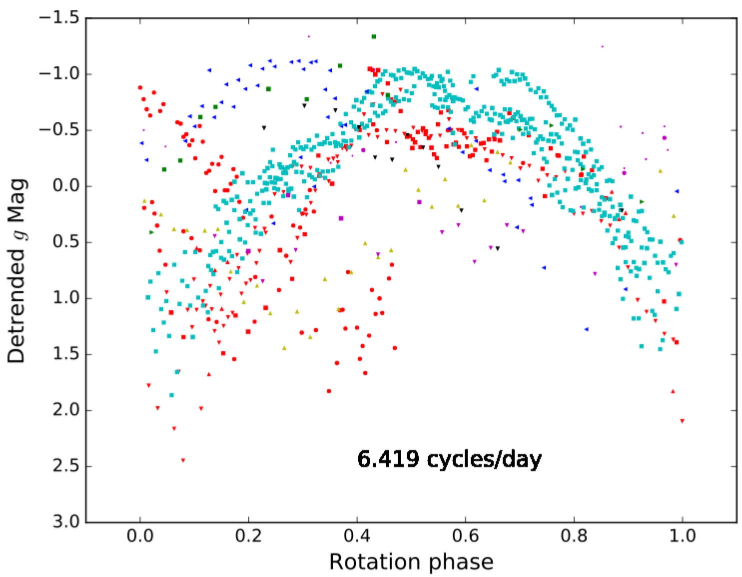
Tumbling, with red side(s)



Tumbling

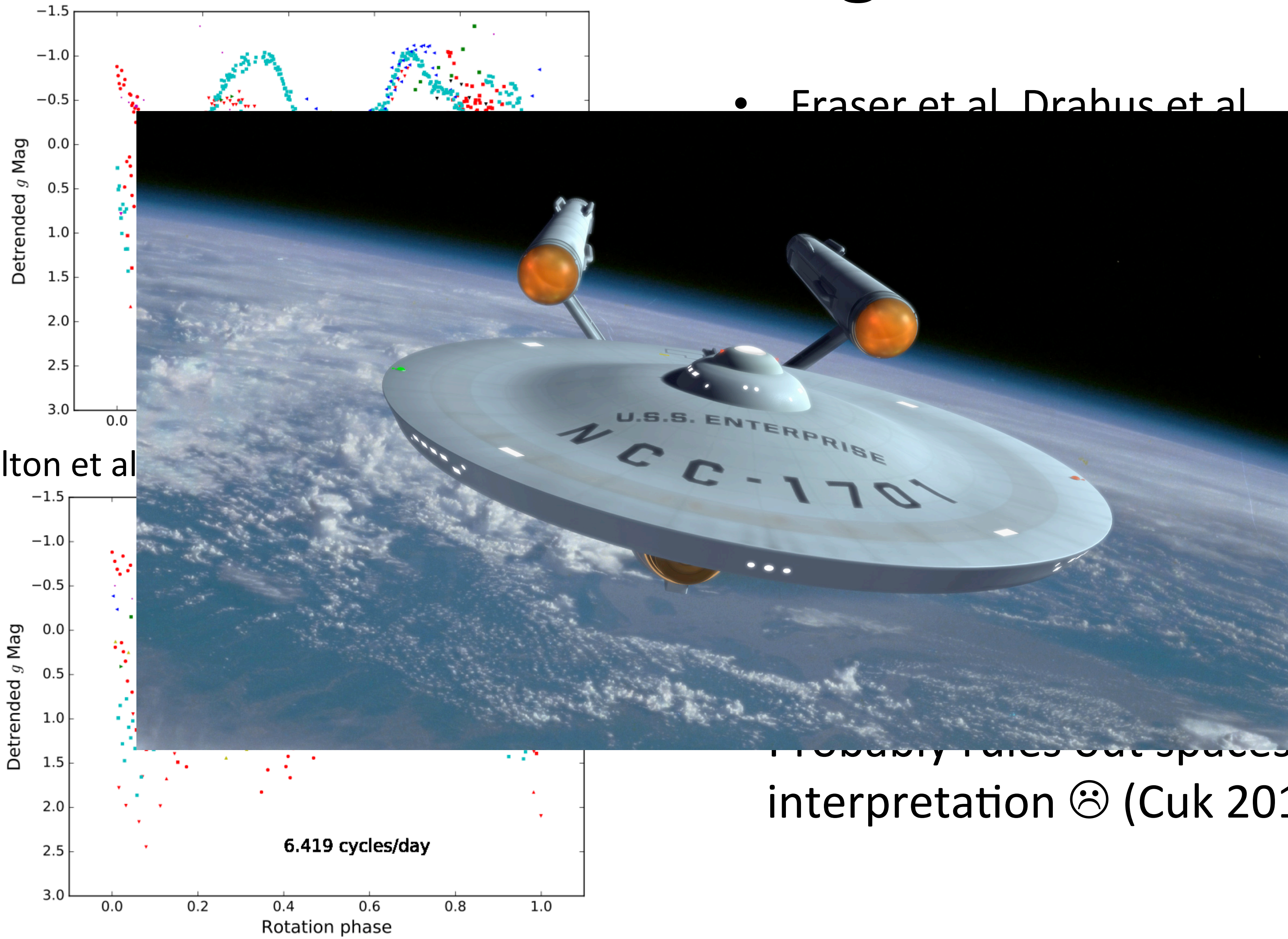


Belton et al



- Fraser et al, Drahus et al, independently find ‘Oumuamua to be tumbling
- Belton et al 2018 follow up with additional photometry from November
  - Find various possible frequencies and shape implications
  - SAM (minimum energy) = cigar
  - LAM = cigar to pancake (max energy)

Tumbling



- Fraser et al, Drahus et al

g

igar

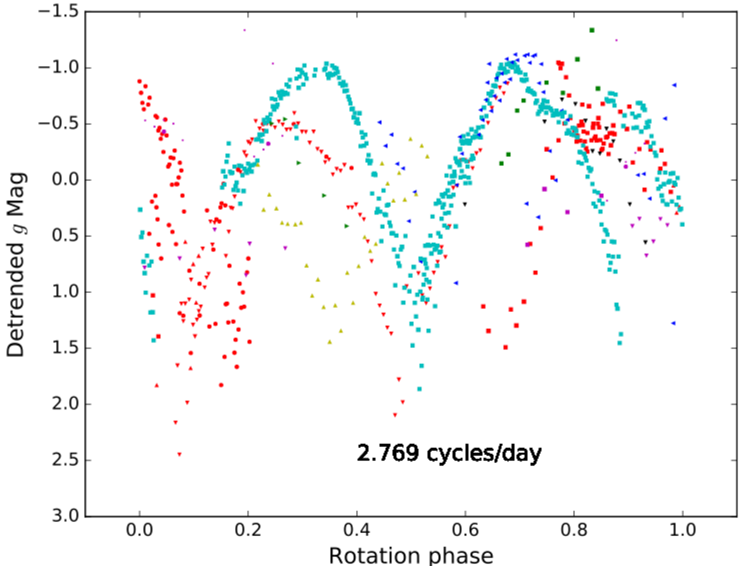
ax

yrs

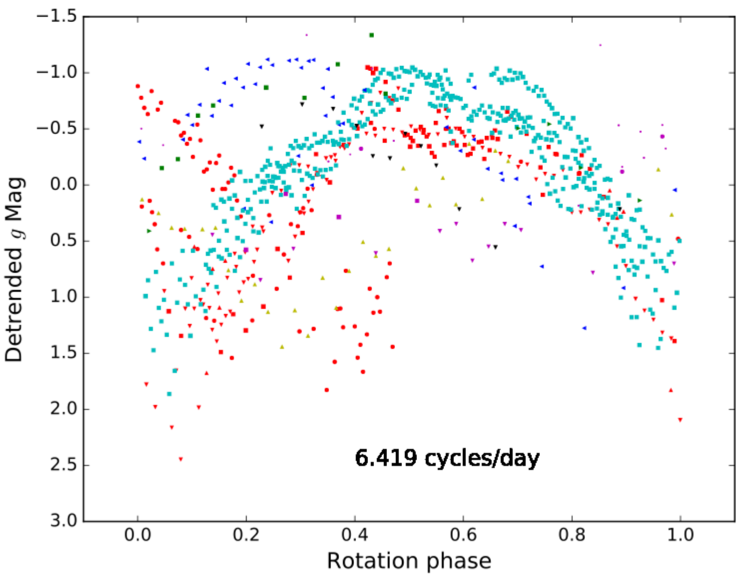
hip

interpretation ☹ (Cuk 2017)

Tumbling



Belton et al



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- Damping timescale > 10^{11} yrs
- Probably rules out spaceship interpretation ☹ (Cuk 2017)

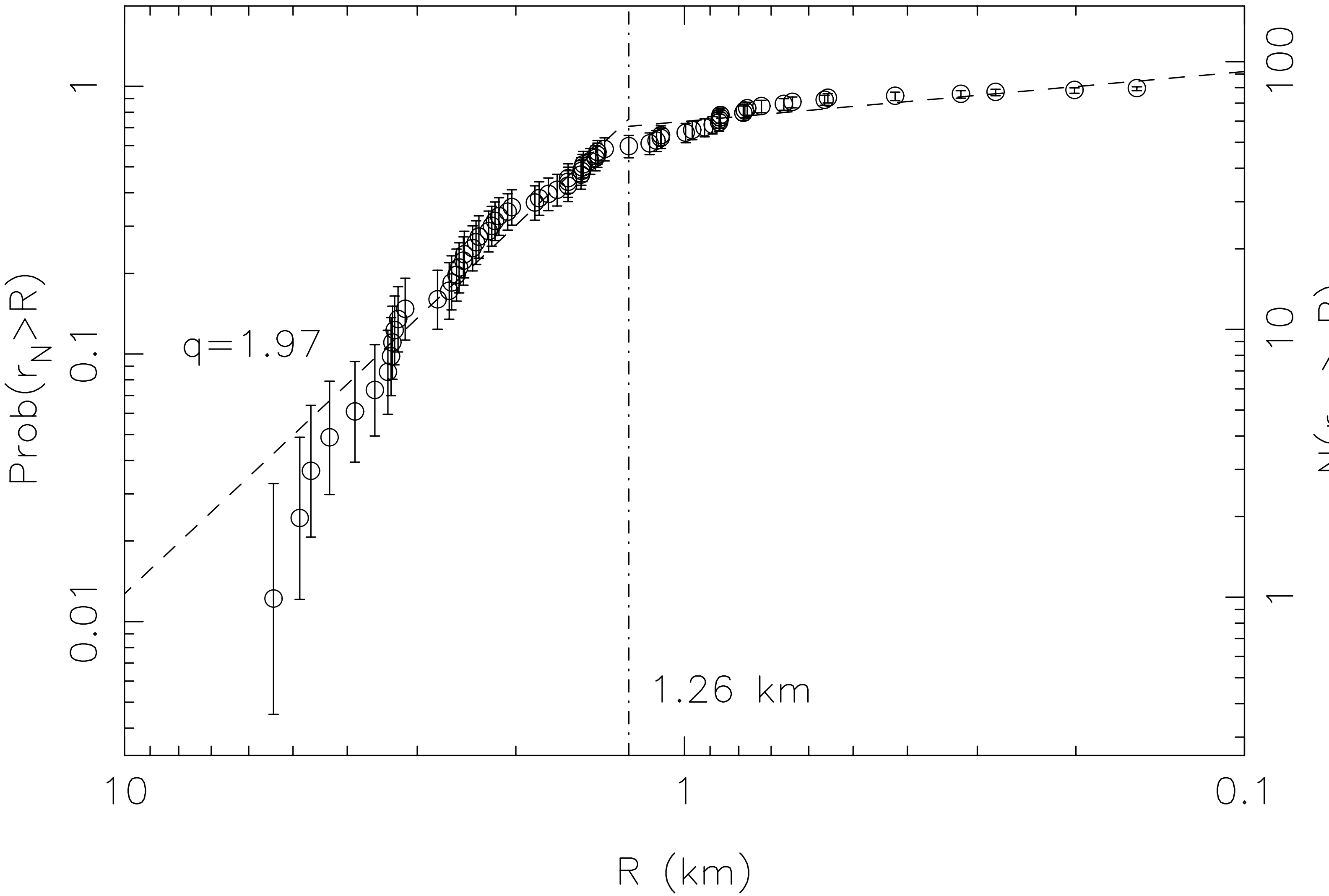
IMPLICATIONS

Comparison with comets

- Composition looks like icy body
- Other properties do not rule it out
- Is time spent in interstellar space unusual?
- Age is difficult to estimate, but can't be so ancient:
  - Universe only ~3x age of solar system
  - Planetary systems only form once there are metals (so not first generation of stars)
  - Also low speed w.r.t. LSR implies youth (Feng et al 2017)
- Probably not very different in age to Oort cloud comets
  - Oort cloud experiences similar cosmic ray rate
  - Oort cloud comets should be similar?

Oort cloud comet

Sizes of comets



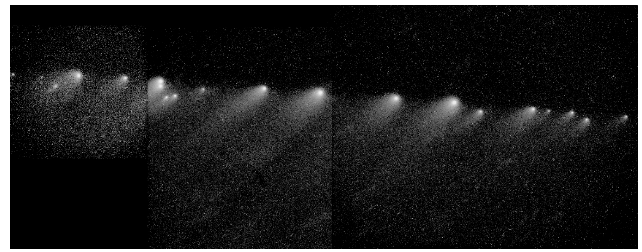
Snodgrass et al 2011

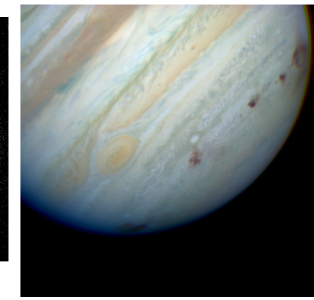
Implications for Oort cloud comets

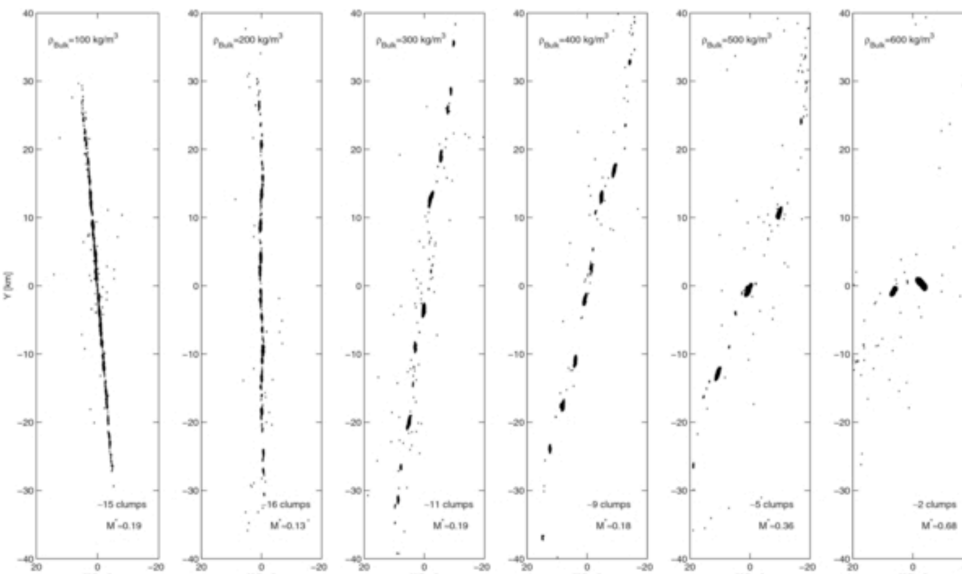
- `Oumuamua is much smaller than known comets (typically > 1km)
- Combined with elongation, nowhere is deeper than ~20m from surface
- Could be de-volatised
- Oort cloud comets of similar size will have had similar cosmic ray bombardment
- Should expect that there is a population of small and inactive ‘comets’ from Oort cloud

Loss of volatiles in its home system?

- Raymond, Armitage & Veras 2018:
  - 0.1-1% of comets have disruptive encounters with giant planets before ejection
  - Most then pass close to star before leaving
  - Could be devolatised, and potentially elongated
- Or, could be rocky body from binary system (Jackson et al 2018)

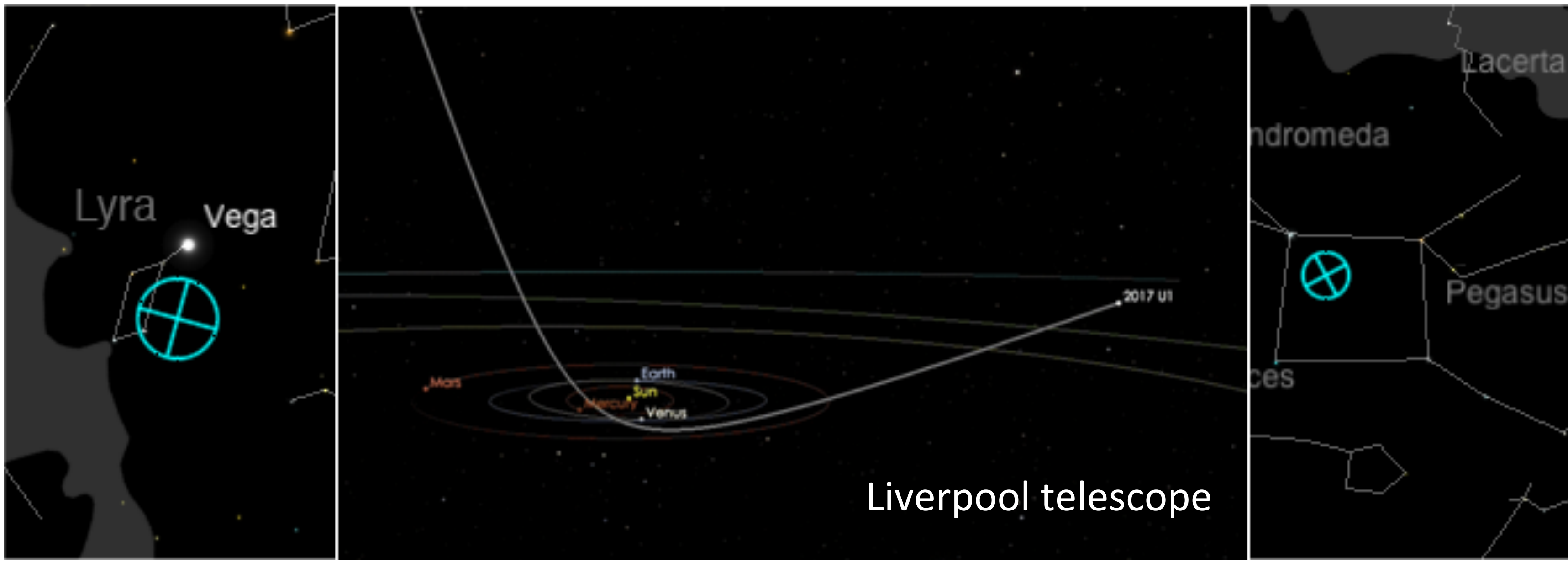






Movshovitz, Asphaug, & Korycansky 2012

Where did it come from?



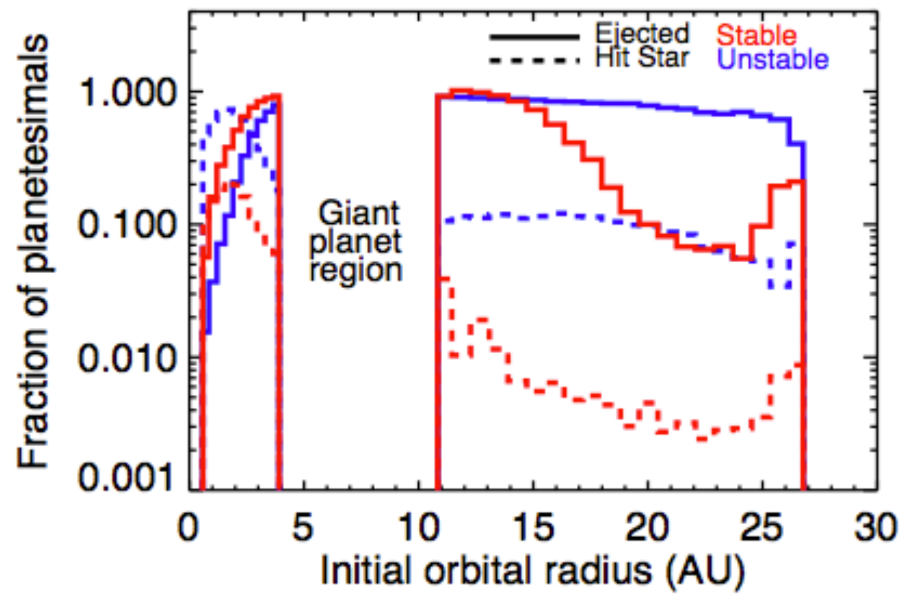
- Came from approx Solar apex, i.e. direction Solar system is moving relative to local standard of rest
- Speed (~30 km/s) similar to Sun motion – we ran into it
- From direction of Vega, but Vega wasn't there when it was
- Integration of trajectory and star motions doesn't find parent system (Dybcynski & Krolikowska, Ye et al, Zuluaga et al, Zwart et al, Feng & Jones, Zhang)

How many more are out there?

- Size distribution of asteroids or comets implies many more small bodies than larger one
- If they are inactive they are harder to detect
- Very approximate calculation (based on N=1 in 10 years of surveys) from Laughlin & Batygin 2017:
  - Space density of similar objects of order ~1/100 AU^{-3}
  - This implies ~2×10^{26} such objects in the galaxy
  - Galactic mass in such bodies is $M_{tot} \sim 10^{11}\ M_{\oplus}$ (for density of 1000 kg/m^3).
  - Ejection of these bodies implies more Jupiter-like (giant at a>5 AU) exoplanets to find

Implications for planet formation

- Papers from Trilling et al, Raymond et al.
- Around 1 $M_{\oplus}$ (0.1-10) of ISOs ejected per solar mass star
- Dominated (by number) by small and icy bodies, asteroid-like composition unlikely
- Systems with distant Jupiters more efficient, hot Jupiters don't eject bodies easily
  - E.g. Solar System models suggest > 10 $M_{\oplus}$ ejected, above average
  - True population depends on size distribution and ejection processes



Raymond et al 2017

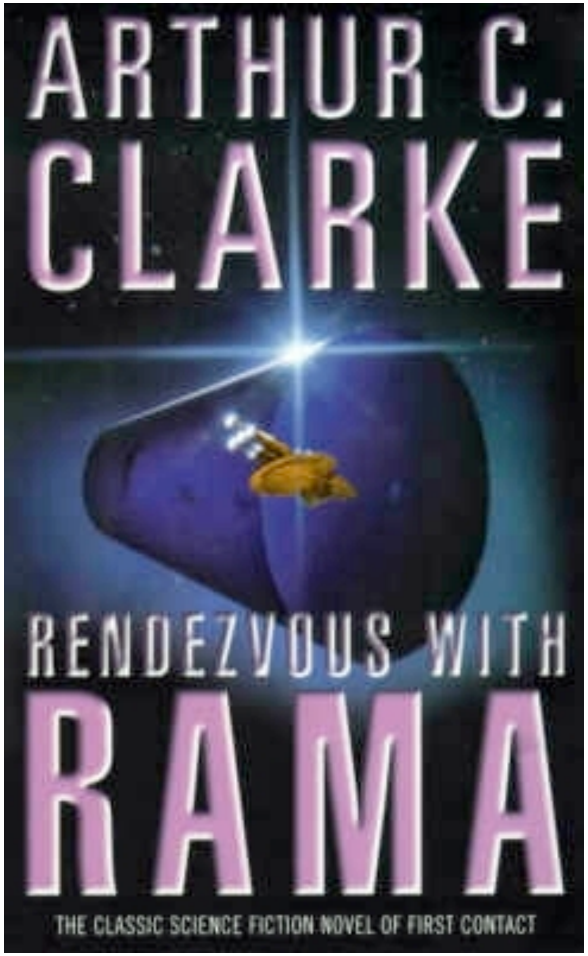
Future prospects

- Hein et al suggests a mission to intercept, catching up at ~100 AU…
- Can expect more ISOs
- Probably there are larger ones, but small ones more common
- Are they all inactive?
- Will be a surprise if they are all so elongated…
- **Predicted discovery rate for LSST is ~1/yr**
- Can expect to find some inbound, longer to study (and ELTs/JWST to respond with)
  - ~10 year wait for one suitable for intercept mission, if ready

Summary

- Rapid response to characterise 1st ISO during short observing window
- Surface properties match icy outer-Solar System bodies as expected, but no comet-like activity
  - Thermal model suggests that this can be explained by devolatised surface layer
- Lightcurve implies extremely elongated shape, tumbling
  - Comet-like strength enough to support this
- Small size could explain earlier loss of volatiles
- Implications for planet formation.
  - Currently, $N_{models} >> N_{data\_points}$
- Many more discoveries expected in LSST era

Only possible conclusion



'Big void' identified in Khufu's Great Pyramid at Giza

By Jonathan Amos
BBC Science Correspondent

8 hours ago | Science & Environment | 609