ISO, LPC, NEO Science

Karen Meech

Enabling Fast Response Missions to NEOs, ISOs and LPCs

KISS workshop: October 24, 2022

C/2006 P1 McNaught, S. Deiries

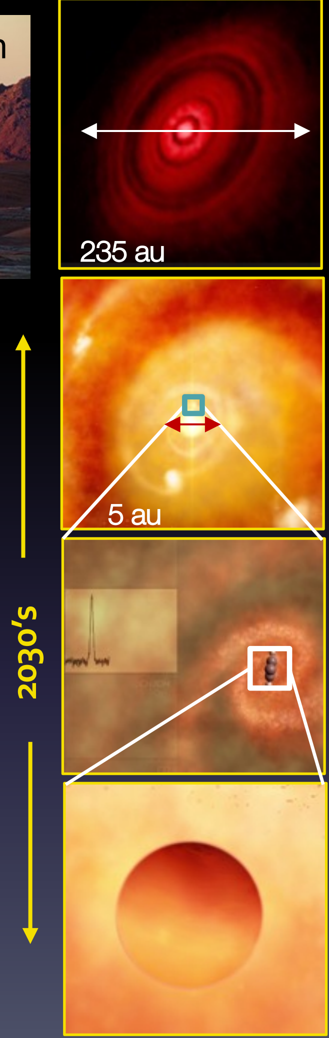
Transformative science in the 2030's

Life Requires water . . . . .

- Astrobiology seeks to understand how habitable worlds are made
- Habitability = water, organics, rocky planet, the right temperature

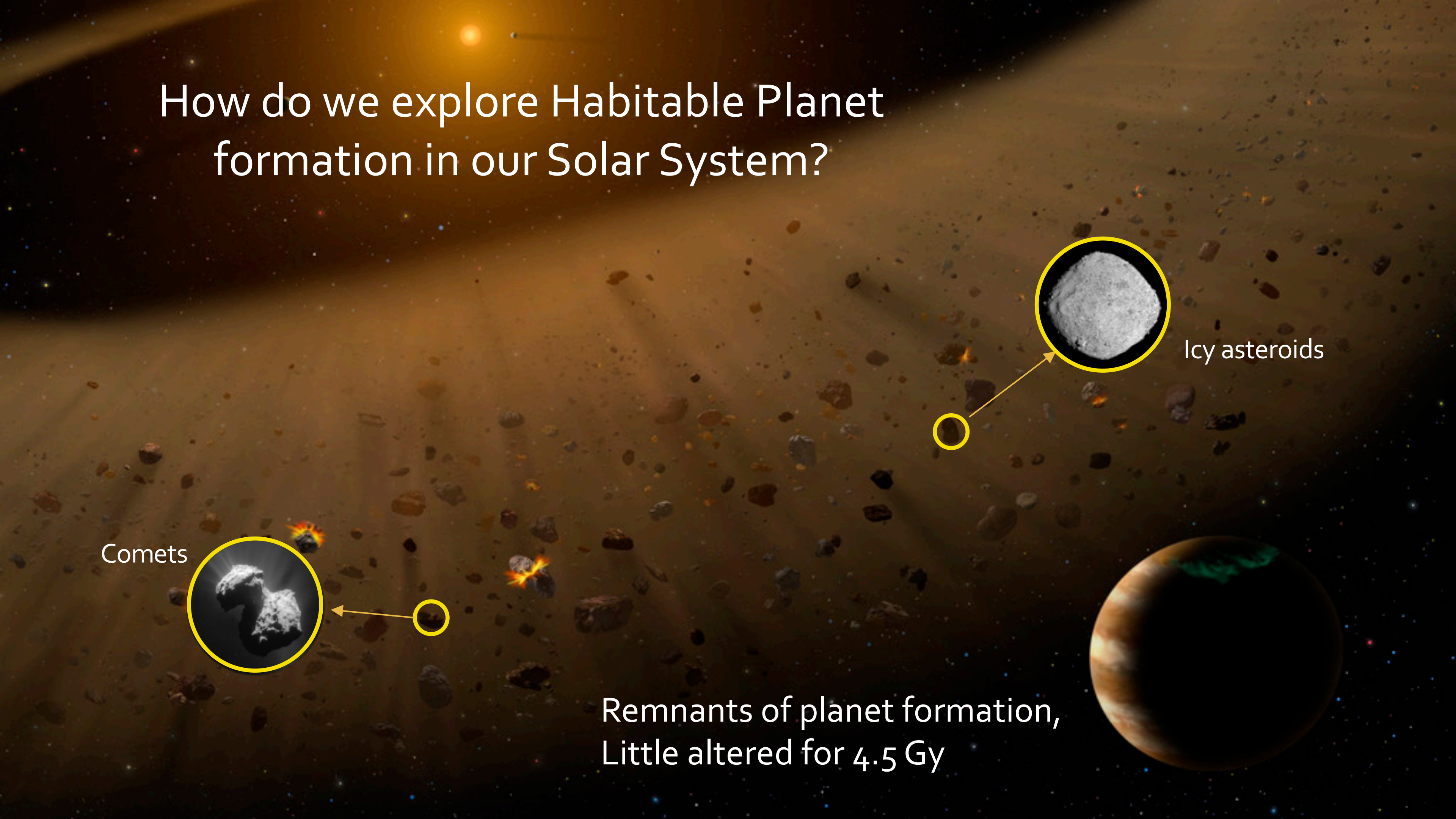
As of Oct 24, 2022: ~50 potentially habitable planets
5,190 confirmed, 8,954 candidates, 3,882 planet systems, 190 terrestrial planets

Credit: NASA/JPL-Caltech



Credits: ALMA, ngVLA

How do we explore Habitable Planet formation in our Solar System?

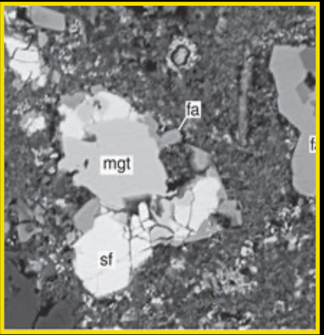


Remnants of planet formation,
Little altered for 4.5 Gy

Primitive Tracers

A. Meteorites (well-studied)
   - Contain water, have been altered
B. Icy asteroids & NEOs (largely unexplored)
   - Formed locally, or migrated from farther out
   - Contain unaltered material that can provide clues
C. Comets (many missions, ground, but new classes)
   - Formed cold, remained cold, untraceable dynamics
D. Icy satellites (Cassini)
   - Formed cold, have been heated – evolved
E. Interstellar objects (unexplored....)

A



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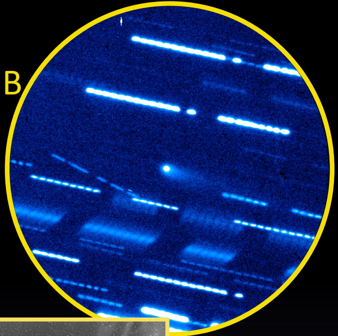

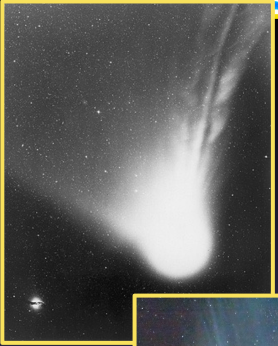

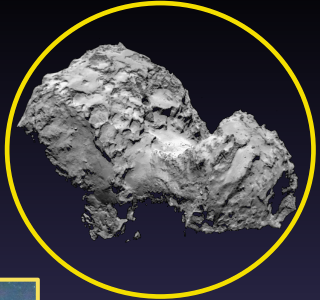

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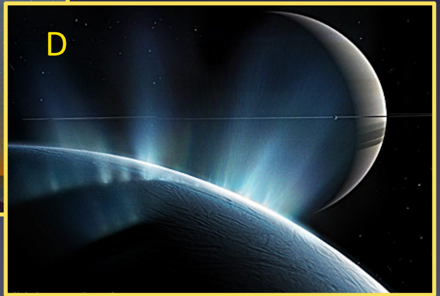
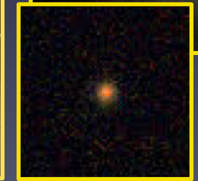
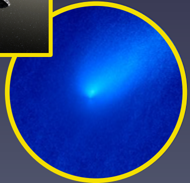
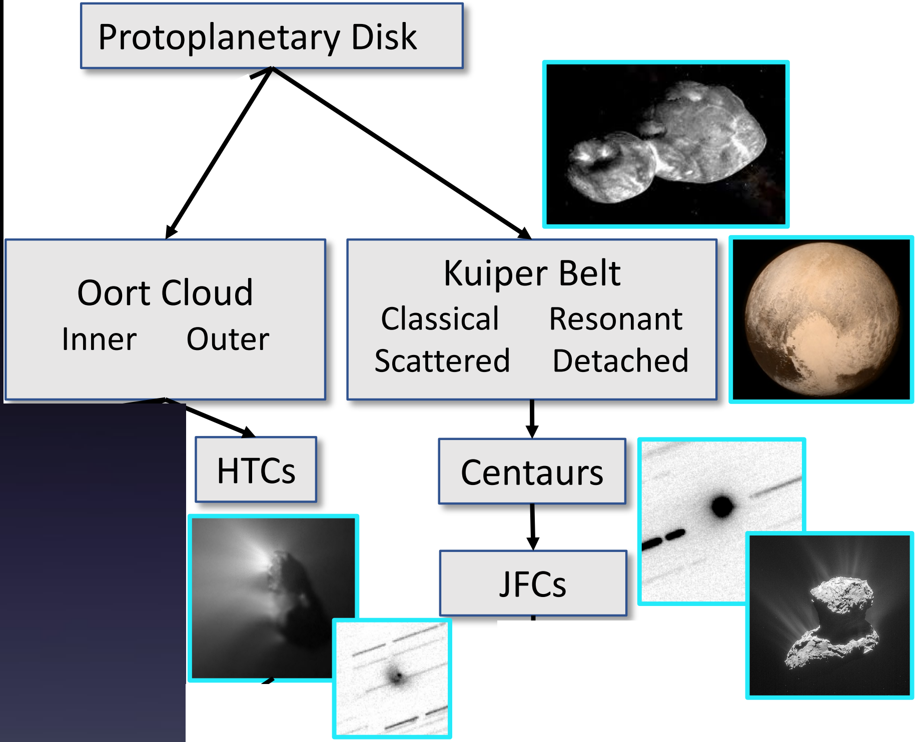




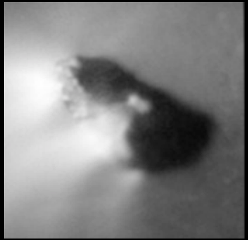
E

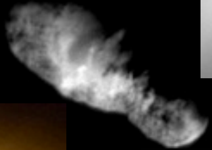


Icy Body Evolution in our Solar System



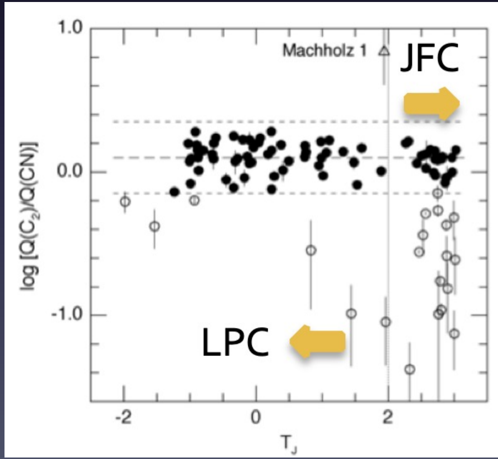
JFCs – Missions & Ground-Based

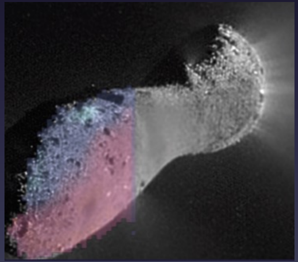




- Nucleus
  - Sizes collisional, small ones missing
  - Very low density, thermal conductivity → pristine
  - Dust shows movement in disk
  - Very little surface ice, low albedo
  - CO_2 a driver of activity

- Formation Implications
  - Chemistry not linked to dynamical regimes
    - Comparing JFC & LPCs
    - C-poor, C-normal comets
  - D/H uncorrelated with dynamics
    - Other Isotopes ?





A'Hearn et al 1995.

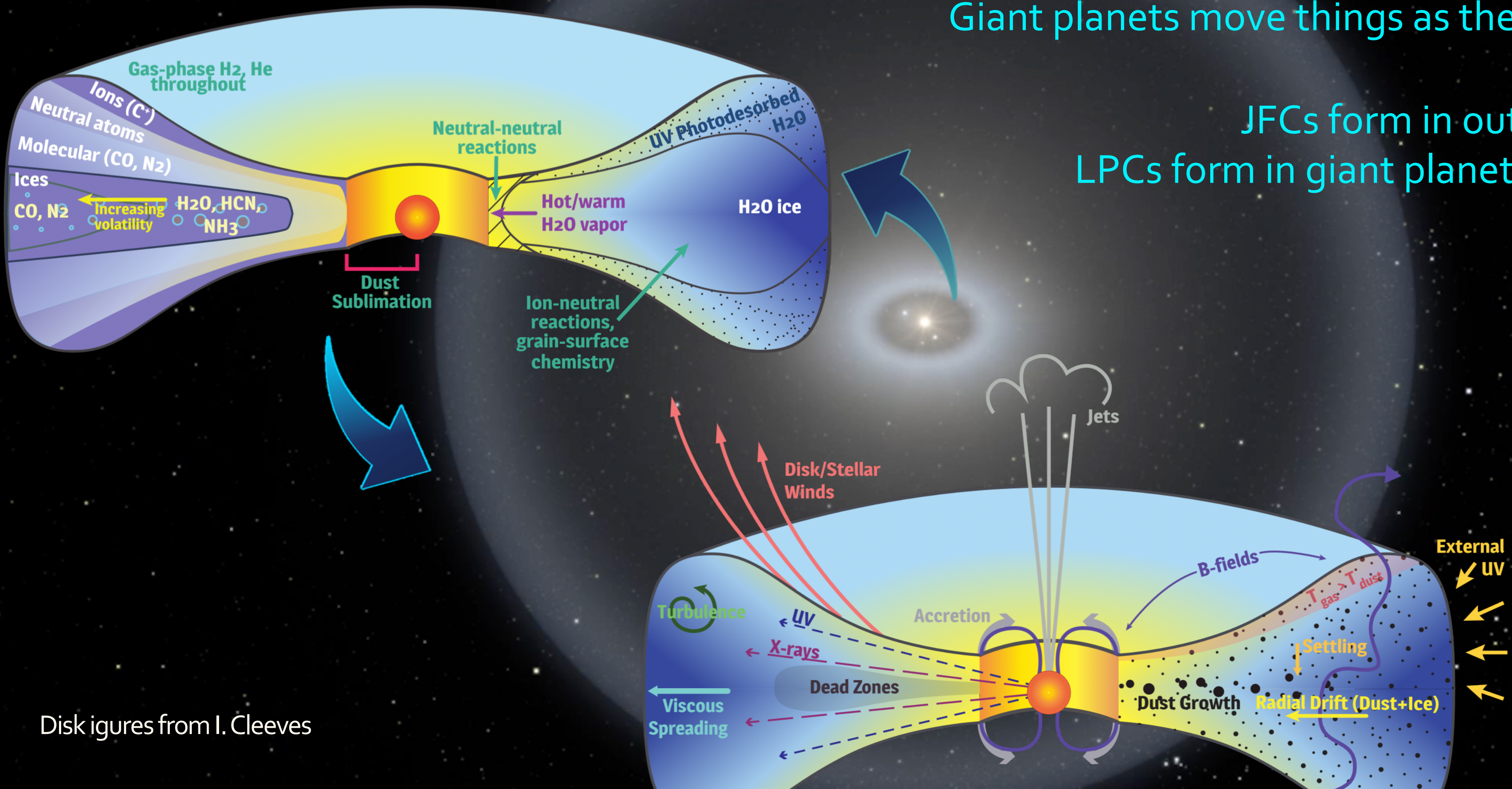
JFCs – Rosetta

- Rosetta is the most ambitious and productive comet mission to date
  - Comets have heritage from their formation, but it is a really mixed reservoir
    - Comets form over a wide range of distances outside snowline
  - New insight into how comets work (thermal inertia, porosity, where the ice is)
    - Interior structure relatively uniform
  - Rich array of pre-biotic chemical species
  - Comets may represent primordial planetesimals (density, porosity, low T ices)
- Questions
  - What is primordial and what is the effect of insolation?
  - How and where do comets form?
  - What role do comets play in bringing volatiles to the inner solar system – i.e. Earth?

Solar System formation

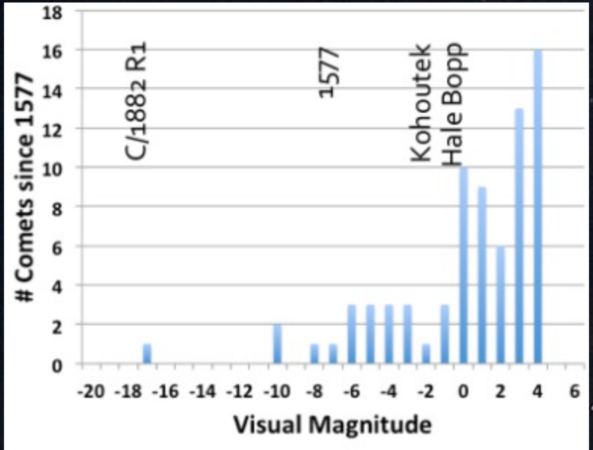
Chemistry is set by temperature
Giant planets move things as they grow

JFCs form in outer disk
LPCs form in giant planet region



Disk igures from I. Cleeves

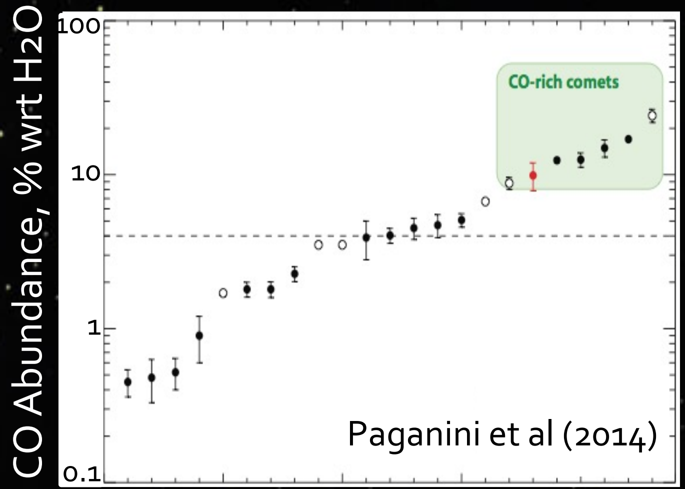
Long Period Comets



- Very bright comets are Rare
  - 12 very bright comets in ~270 yrs
  - Brighter than 0 mag every ~15 yrs

C/2006 P1 (McNaught)
q = 0.17 AU
Photo: firo002/Flagstarrotos

- Nucleus
  - Very little known
- Chemistry
  - Organic abundance not correlated with dynamical regimes
  - Only LPCs seem to be rich in CO



C/2013 US10, Dec 7, 2015. F. Hemmerich

LPC Paradigm is Changing

- Activity levels
- Formation location

Hale-Bopp, 1995, Mag -2

McNaught 2006;
Mag -7

C/2007 N3 – mag 4

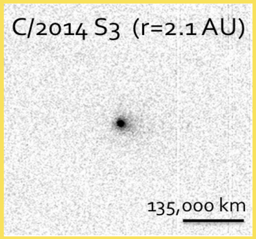
Lovejoy, 2011
Mag -6

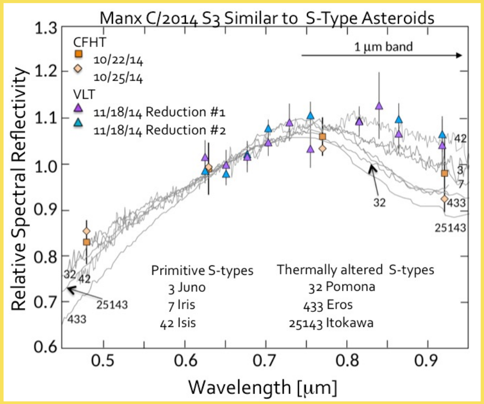
C/2010 US10 – mag 6

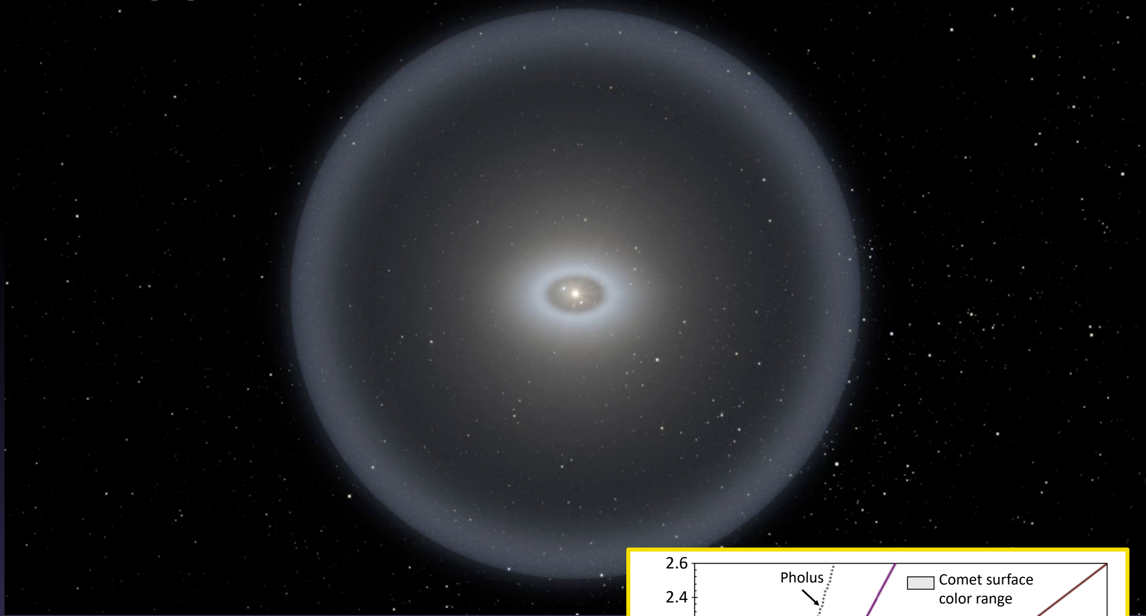
C/2014 Q2 Lovejoy, 2014 – mag 4

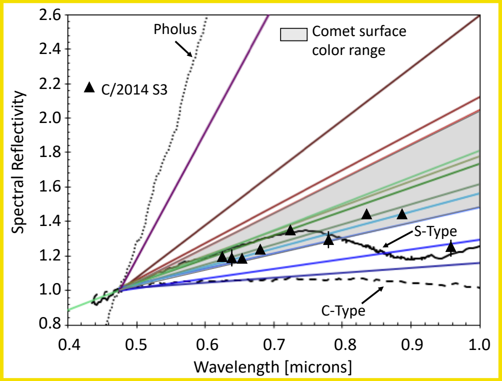
C/2016 R2 – mag 8

A New type of LPC: –Manxes



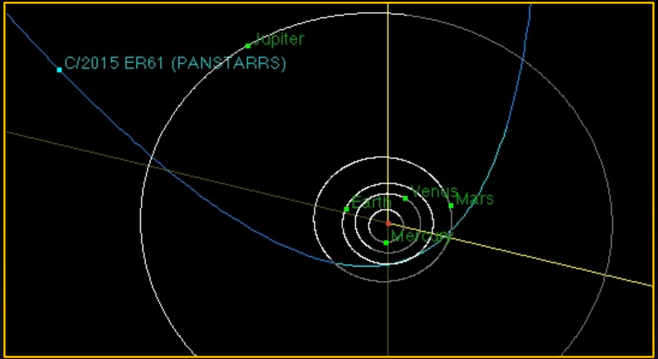


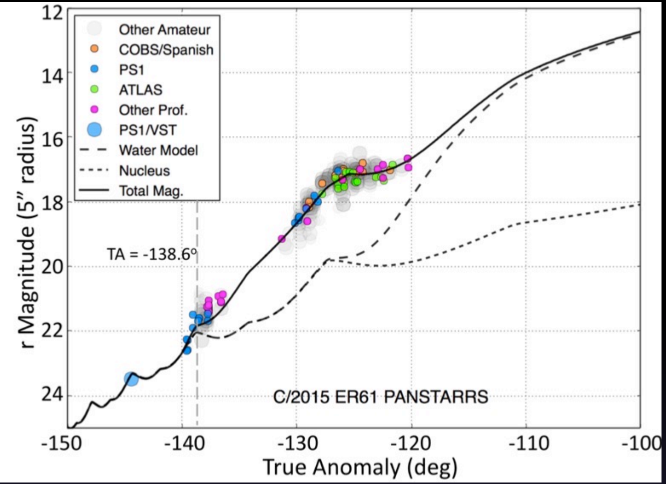




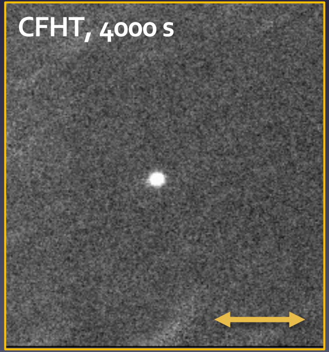
- Aug 2013 Pan-STARRS1 Survey discovers unusual LPC
  - Very inactive near perihelion
  - Spectrum consistent with inner solar system rocky asteroids
  - May have formed near the SS snowline, ejected to Oort cloud early

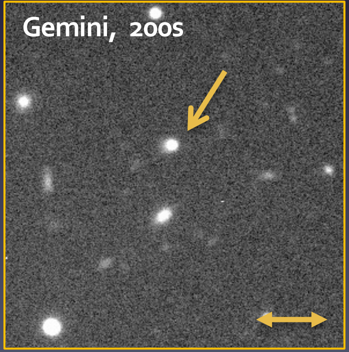
Comet Turn on: C/2015 ER61 PanSTARRS

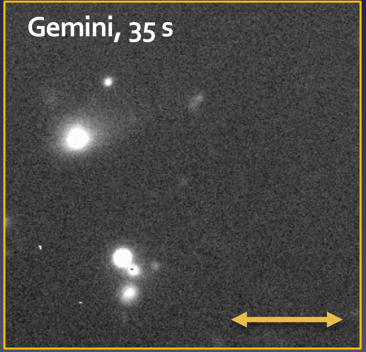


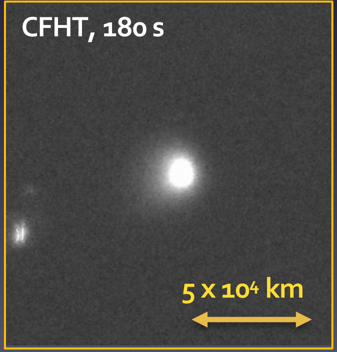


- Long period comet orbit
  - discovered Mar 14, 2015
  - Inactive at *r* = 8.44 au
  - A very large Manx? → no
  - CO2-driven activity began at 8.8 au, then water began around 5 au

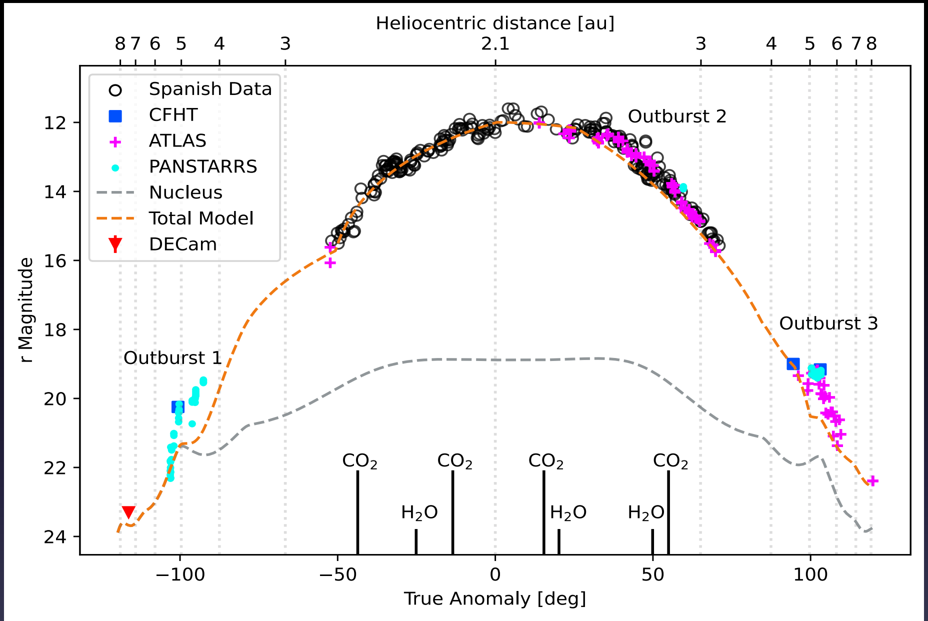


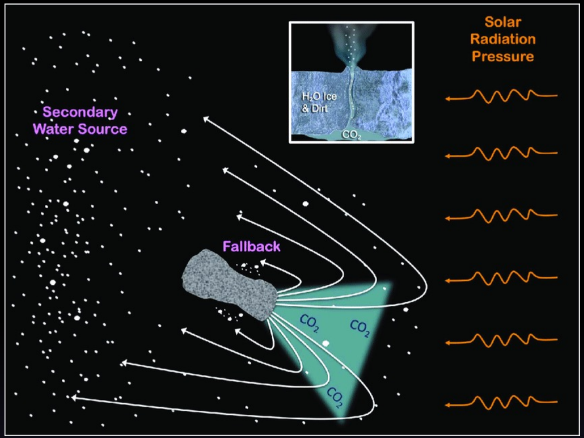


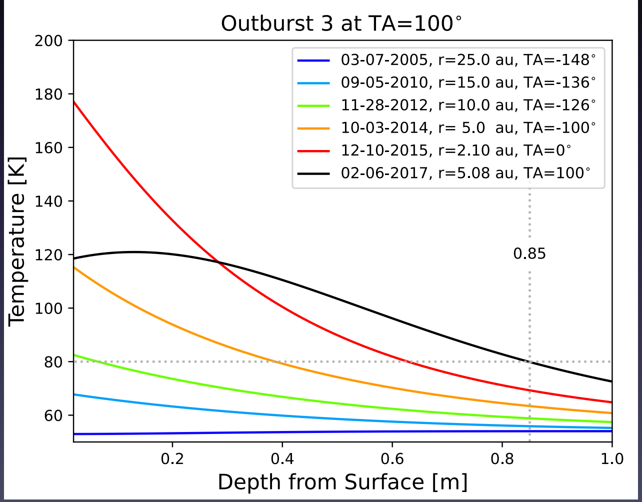




C/2014 S2 (PANSTARRS)



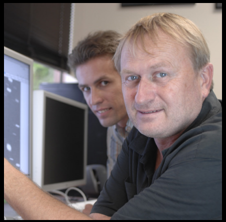




- Activity controlled by CO2
- Ejects large icy “grains” → H2O production
- Outbursts from ice at depths of 0.3-0.8 m

C. Urasaki et al (in prep).

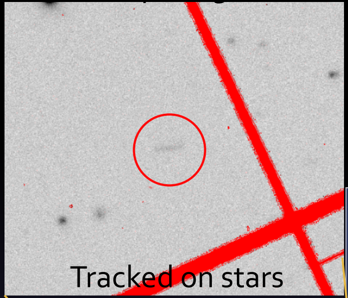
R. Weryk

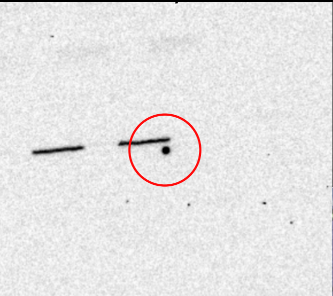


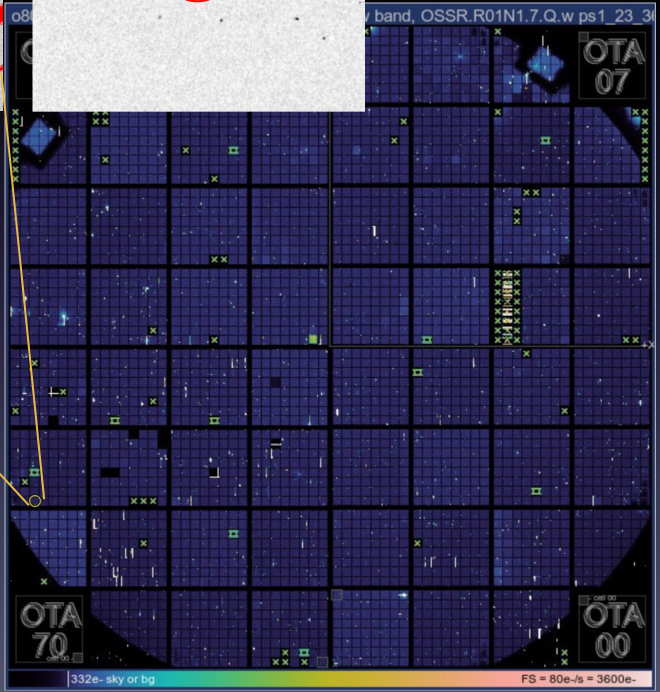
M. Micheli, R. Wainscoat

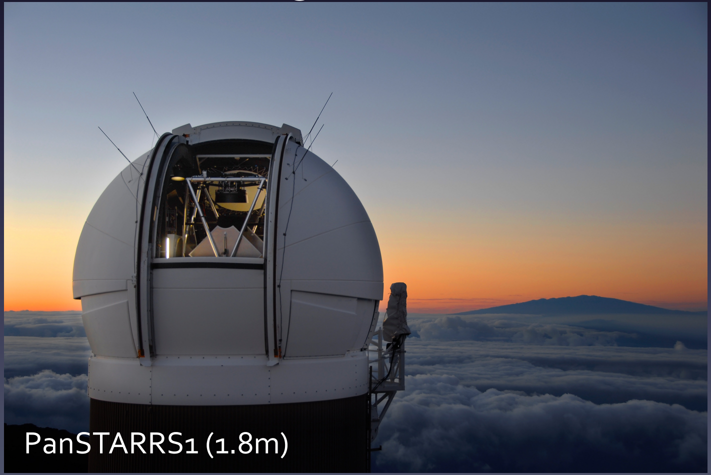
ISOs – LPCs from another Solar System

- 10/19 – Discovered by PS1 → P10Ee5V
- 10/18 – Prediscovery in Pan-STARRS data
- 10/20,22 – Follow up → e = 1.19
- 10/24 – Orbit on MPC
- 10/26 – Designated A/2017 U1

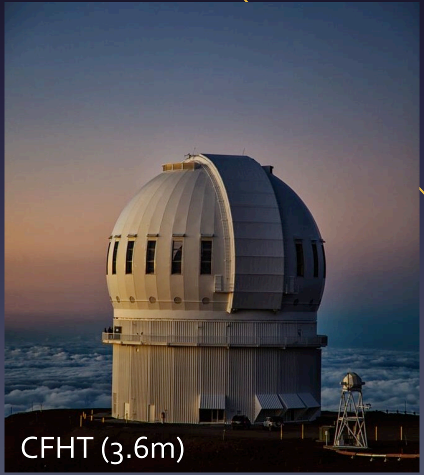




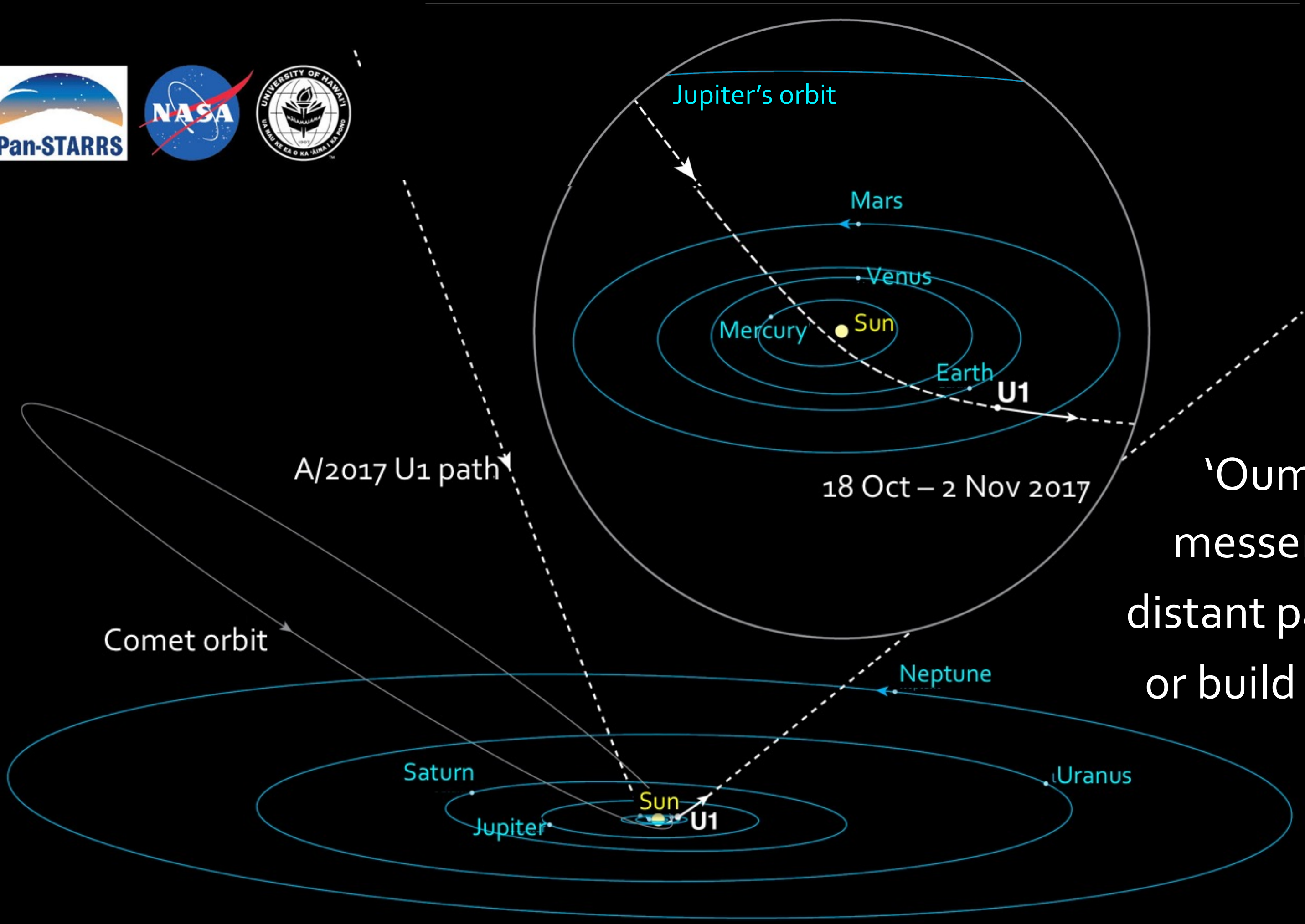




PanSTARRS1 (1.8m)

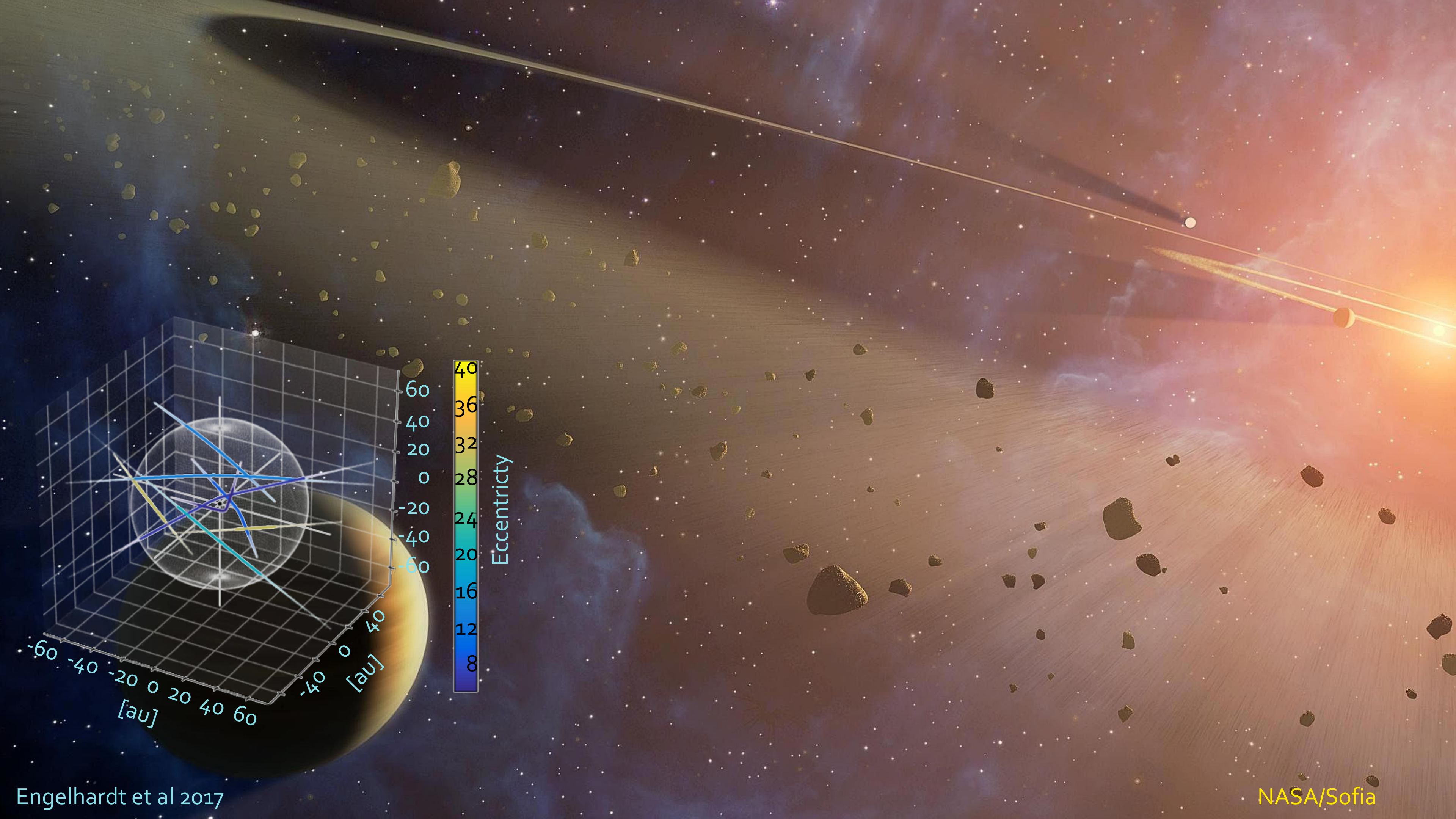


CFHT (3.6m)



ʻOumuamua: Scout or messenger sent from our distant past to reach out to us or build connections with us

Proposed Oct 29,
Official Nov 6.



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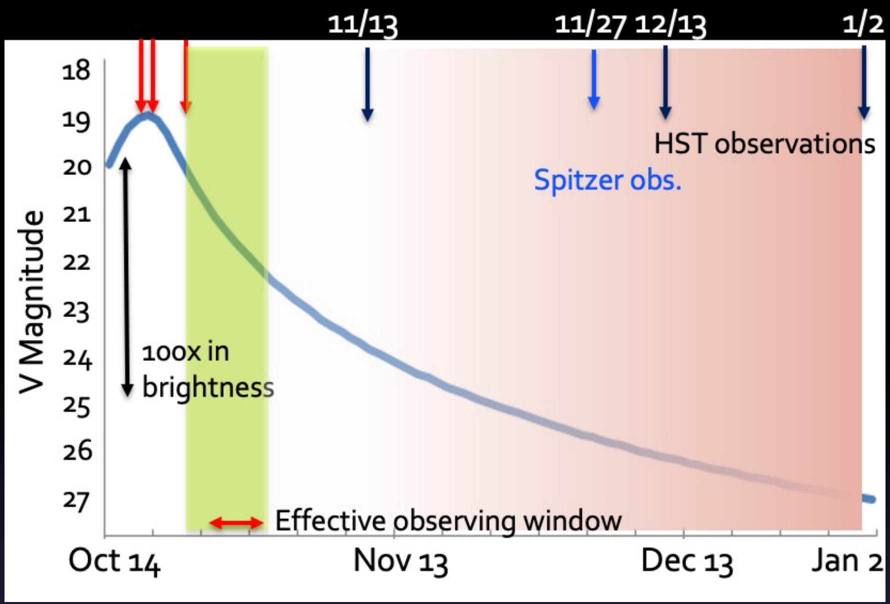
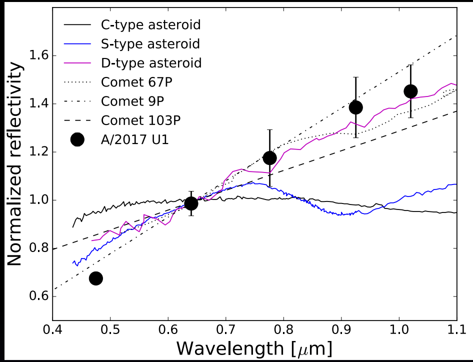
Eccentricty
Engelhardt et al 2017
NASA/Sofia

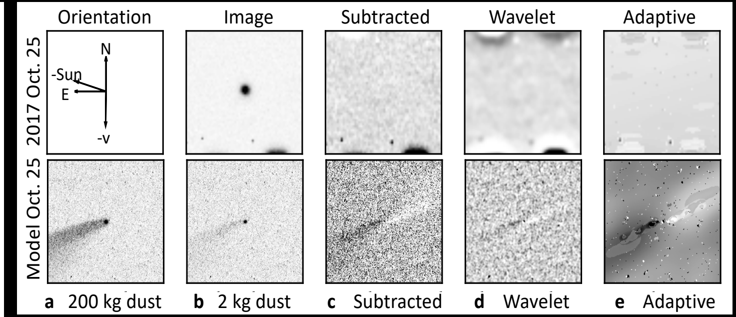


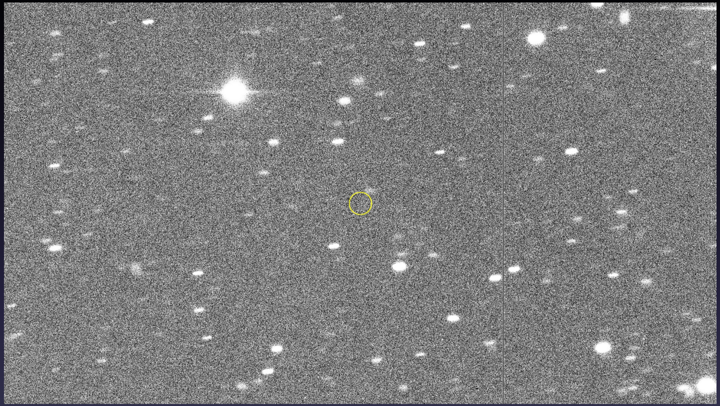
- What do we want to know?
  - What are its characteristics?
    - Size & shape, mass, density, rotation
  - What is it made of?
    - Color, spectral features?
    - Comet or asteroid?
    - Gas chemistry? Isotopes?
  - Where does it come from?
- Resources
  - 15 large telescopes/satellites, 100+ hrs of time

Sun	Mon	Tue	Wed	Thu	Fri	Sat
← Sep 9-q, 14- close Earth	16	17	18-PS1 Pre-covery	19-PS1 Discovery	20-Astrometry	21-Astrometry
22- Hyperbolic orbit confirm	23-VLT, GS prop; VLT Approve	24- GS prop Ap-prove; MPEC orbit	25-VLT ✭, HST prop submit, UKIRT DD	26- VLT, GS ✭; HST Approve; PR	27- GS,CFHT, UKIRT, Keck ✭	28- UKIRT ✭
29 – Hawaiian name	30- Name to IAU	31- Nature paper submit	1	2	3	4
5	6-Referee Rpt. IAU Name OK	7	8-Resubmit paper	9	10-Paper in production	→ Published 11/20

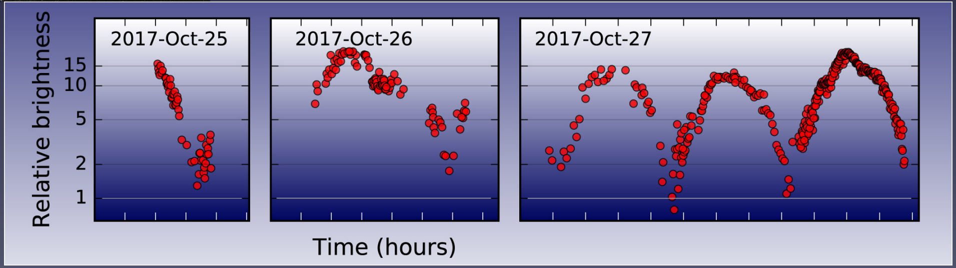
1I/'Oumuamua Characteristics







- Size, Albedo
  - Avg radius ~ 100 m for 4% reflectivity
  - Surface is red, Albedo not measured
- Shape & Rotation
  - Complex rotation
  - Very elongated
- No dust, no gas
  - maximum mass ~1-2 kg
  - μm sized dust within 750 km

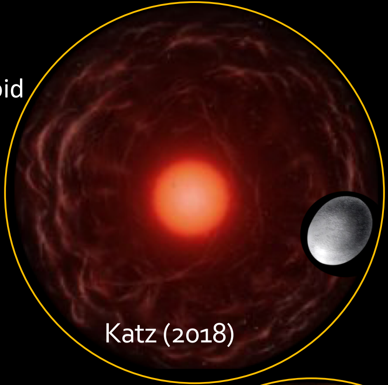


Origin of the Shape?

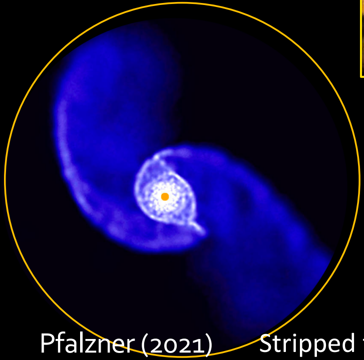
Post-main sequence stars
Hansen (2017)

Misaligned circumbinary disks
Childs & Martin (2022)

Fluidization to Jacobi ellipsoid
during red giant phase



Katz (2018)

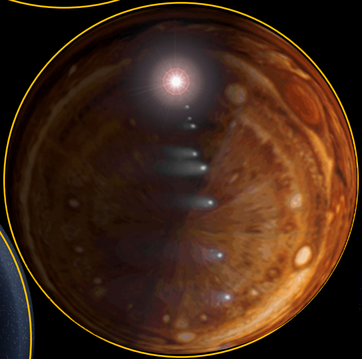


Pfalzner (2021)

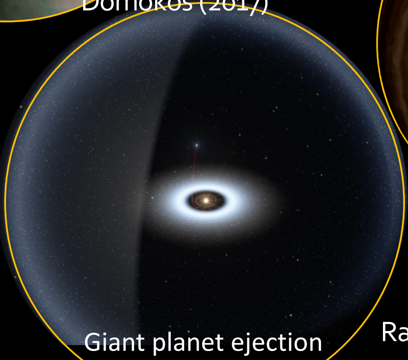
Stripped from star
during cluster phase

Interstellar ablation
Domokos (2017)

Molecular H2 iceberg
Seligman (2020)



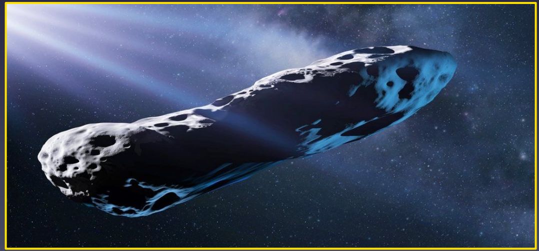
Tidal disruption by
giant planets
Raymond (2018)



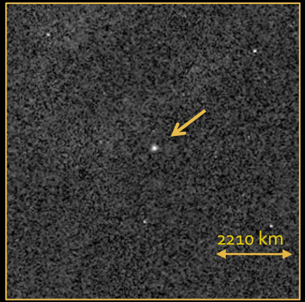
Giant planet ejection

Tidal disruption by white
dwarf star, or binary system

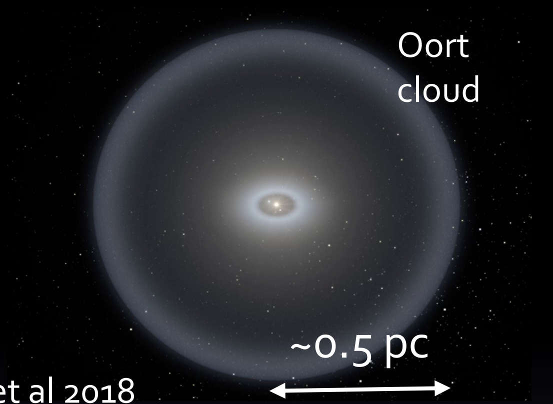
Cuk (2017), Rafikov (2017)

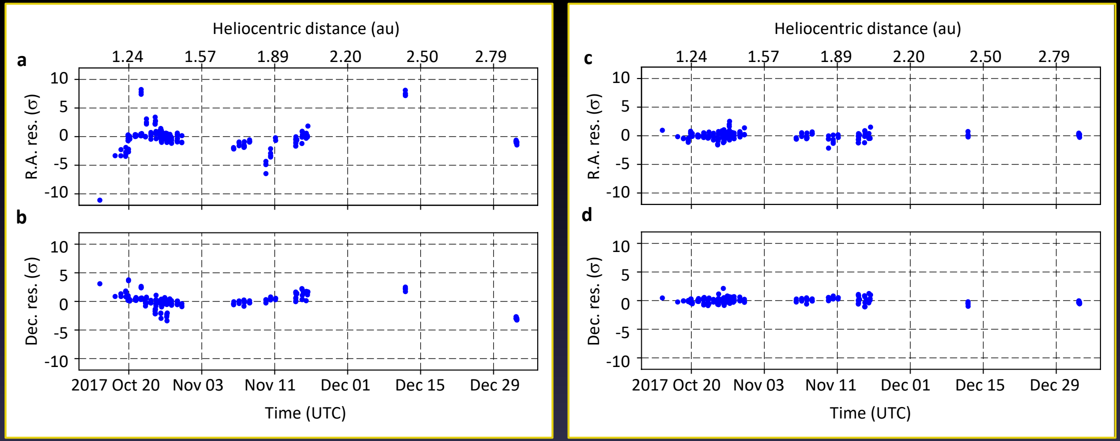


Nitrogen iceberg. Desch (2021)
CO sublimation, Seligman (2021)



Which Way home?



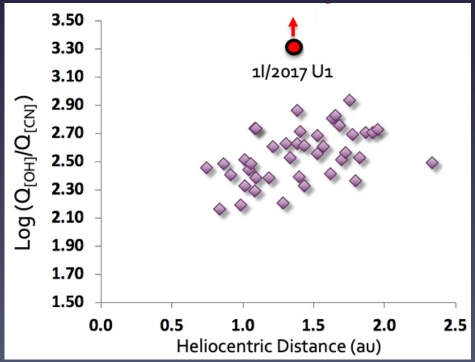


Micheli et al 2018

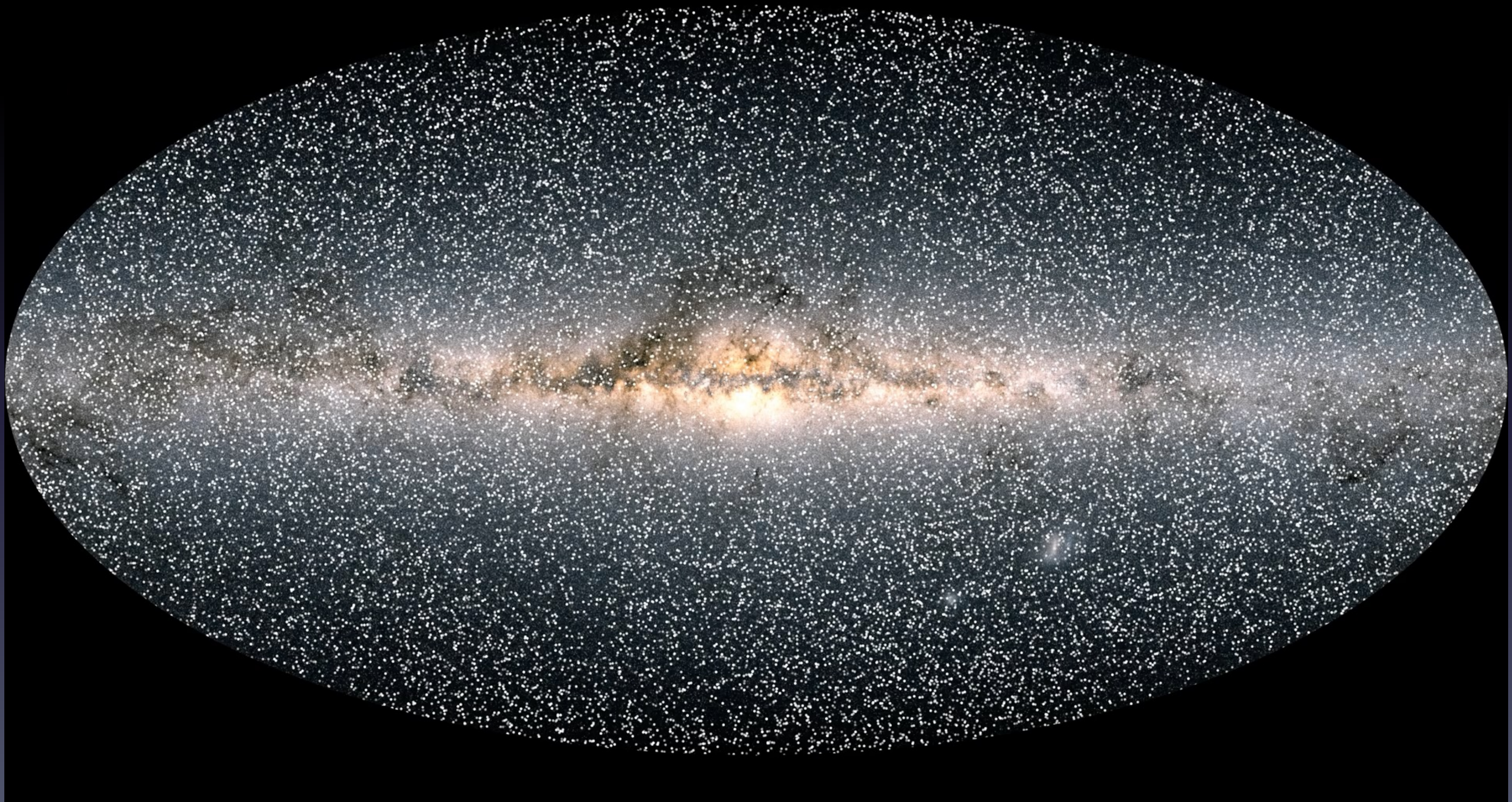
Bailer Jones et al 2018

Star	Type	Enc Dist	Enc vel	When
HIP 3757	M2.5 dwarf	0.6 pc	24.7 km/s	1 Myr
HD 292249	G5 dwarf	1.6 pc	10.7 km/s	3.8 Myr
Home 3		0.66 pc	14.3 km/s	1.1 Myr
Home 4		0.9 pc	18.0 km/s	1.1 Myr

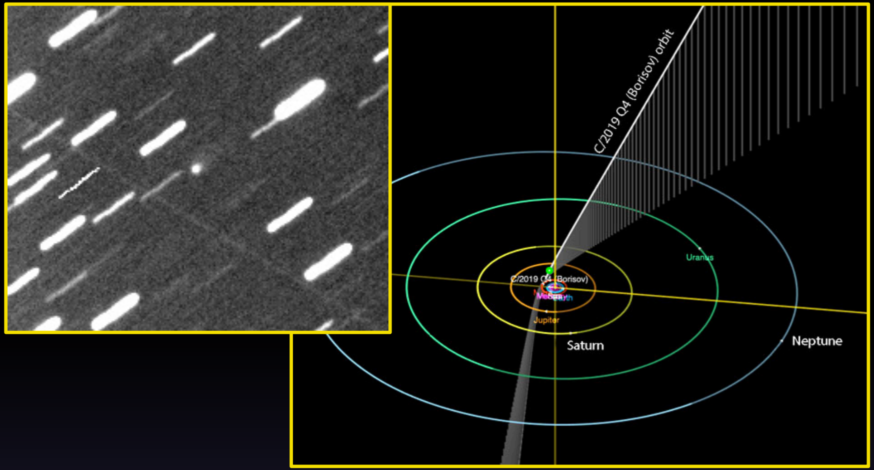
- Gravity only does not work
- Acceleration directed radially away from Sun (similar to that of comets): → $A_1\, g(r)$, $g(r) \propto r^{-2}$
- Inferences about chemistry



Why Finding “home” may be impossible
Gaia EDR3 release 40,000 stars within 100 pc, 1.6 Myr

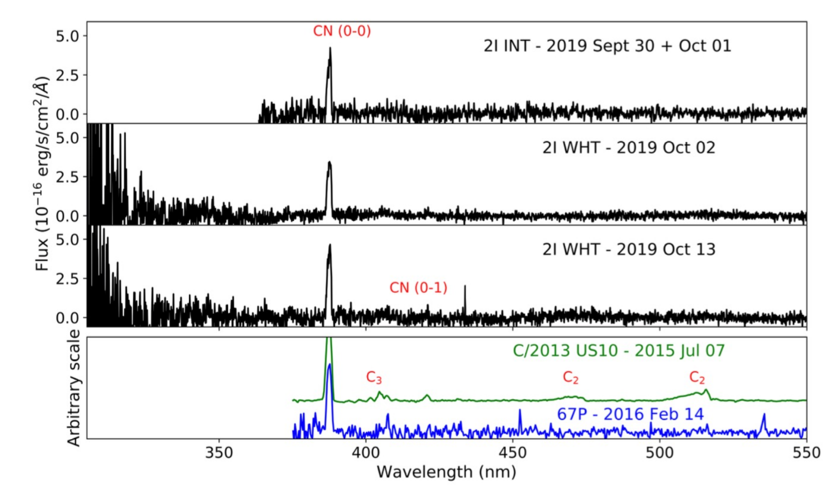


The Second ISO - 2I/Borisov



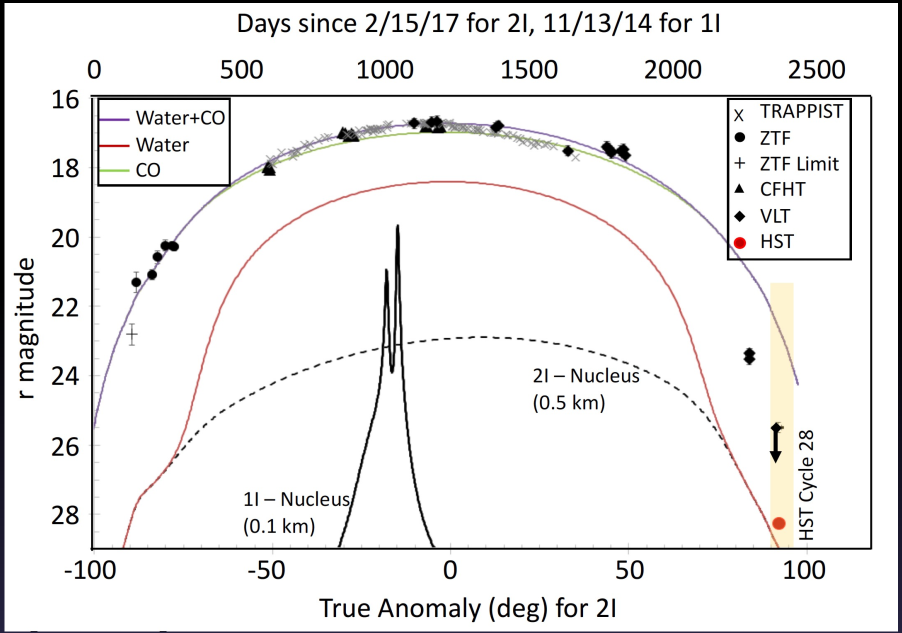
- C/2019 Q4, G. Borisov, Crimea
  - 8/30/2019 at 2.98 au, q = 2.006 au 12/8/19, e=3.36
  - Hyperbolic orbit on 9/11/19, Designated 2I on 9/24/19
- Characteristics
  - Red like 1I
  - CN detected 9/2019 (Fitzsimmons et al 2019)
  - Depleted in C-chain species (Opitom et al 2019)
  - HST: small radius 0.2-0.5 km (Jewitt et al 2020)

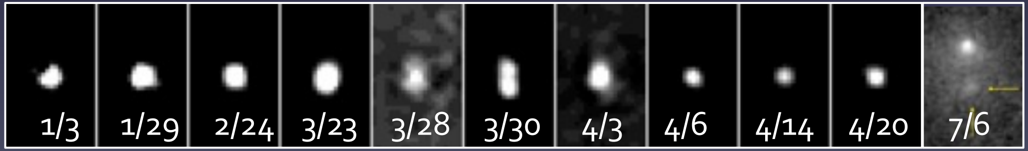
Our last HST observations were made Mar 2021, Mag > 27



Drivers of Activity

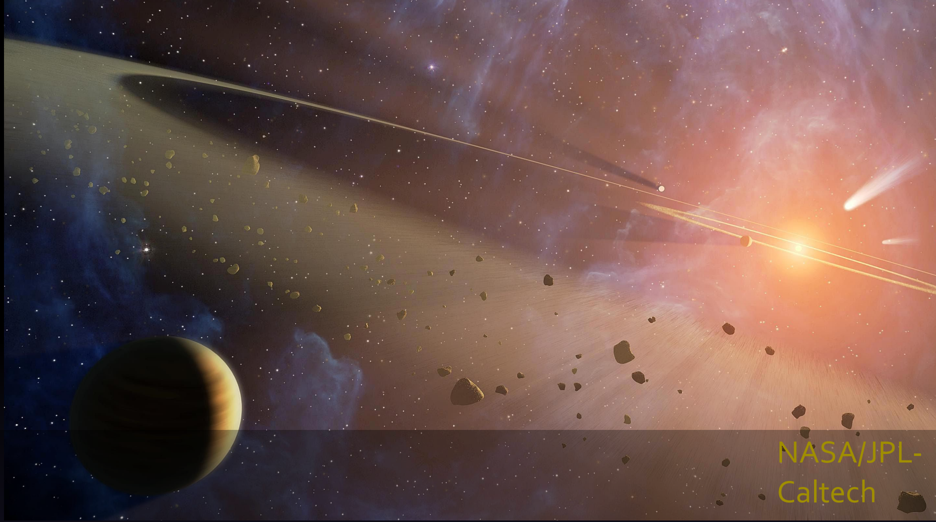
- Pre-discovery observations
  - Suggest CO-CO2 as driver
- HST, Swift, ALMA observations
  - CO/H2O = 130-155%
  - Different chemistry in home system?
- Activity Patterns
  - Water increased up to q, then dropped off
  - HST Mar 2020 split nucleus ~ 3 weeks after an outburst, and another split in July





(Ye et al. (2019), Bodewits et al, Cordiner et al. 2020)

The ISO "Legacy"



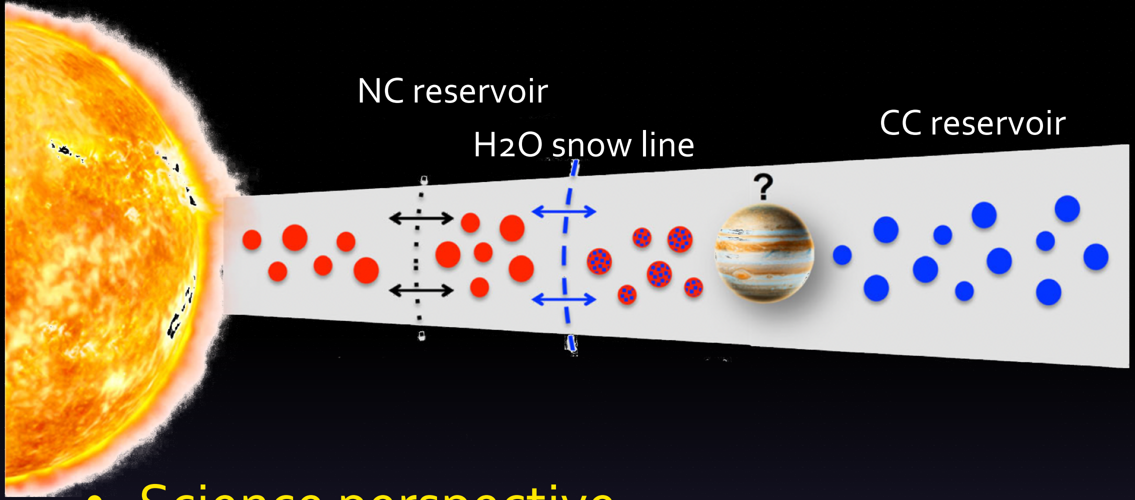
Characteristics

- 1I: Very small (102 m for 4% albedo), red, excited rotation, no dust/gas seen, non-grav. accn.
- 2I: Small (200 – 500 m), red, cometary, CO-rich, C-chain depleted

Future studies of ISOs – sampling chemistry of other star systems

- Unlikely we will be able to back-track the path to home star
- Capture of interstellar comets into the young solar system & Oort cloud?
- Have we already seen interstellar material in our solar system?
- Some answers will require in-situ investigation → missions

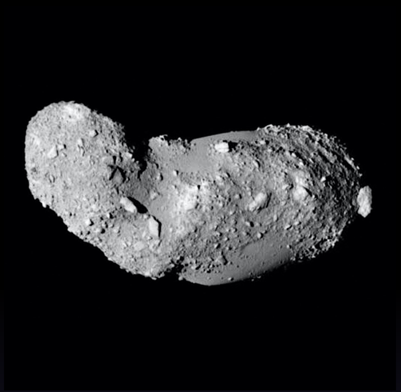
NEOs

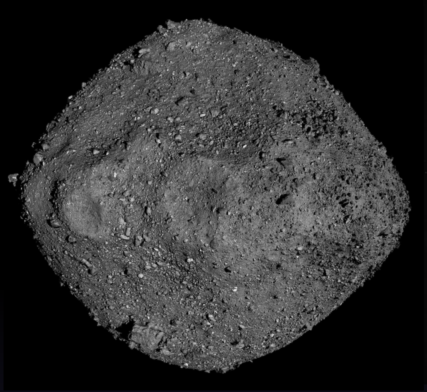


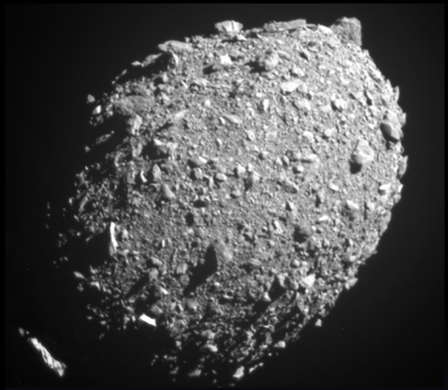
Bermingham, K.R. et al. 2020

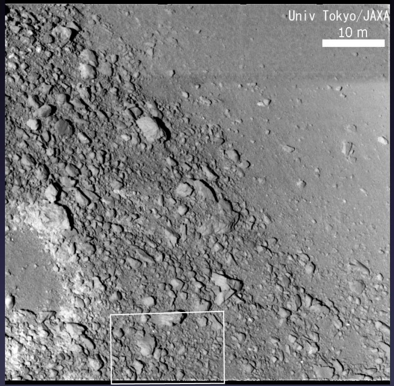
- Science perspective
  - Migrated from asteroid belt – variety of spectral types (origins)
  - Ryugu – like CCs, low T (37C) aqueous alteration 1-2 Myr after CAI
- Planetary Defense Science Perspective
  - Rubble piles, high microporosity
  - Minimal internal strength
  - Surface regolith – lack substantial surface sub-cm material

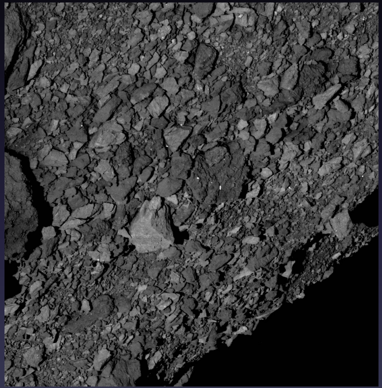
NEOs Up Close











Itokawa (256 m radius)
1.9 g/cm^3
S type

Ryugu (480 m)
1.3 g/cm^3
C type

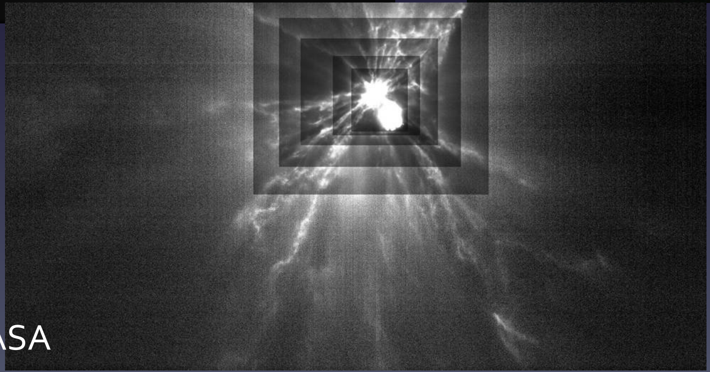
Bennu (243 m)
1.2 g/cm^3
B type

Dimorphos (84 m)
2.7 g/cm^3 (assumed)
S type

DART Kinetic Impactor Test

ASI/NASA

CTIO/NOIRLab/SOAR/NSF/AURA/T. Kareta, M. Knight

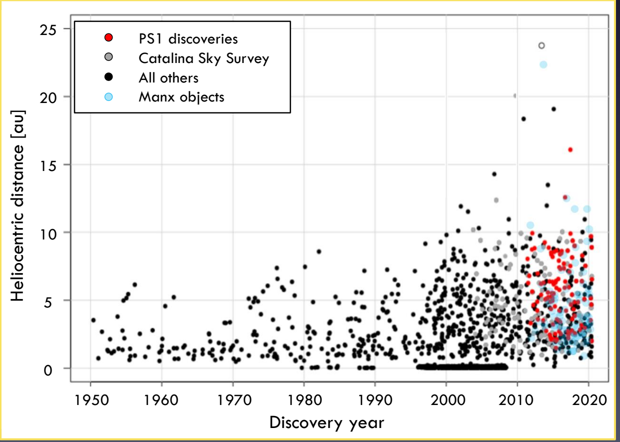


ASI/NASA

NASA, ESA, J.-Y Li , J. Depasquale

Discovery, Characterization, Warning Timescales

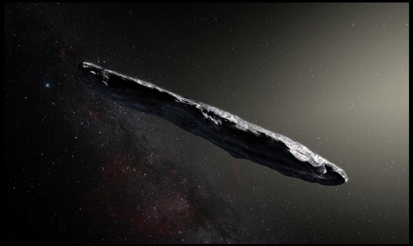
- Large all-sky surveys
  - Enable LPC discovery ~ 10 yrs pre-q
- Rubin Telescope
  - First light: Engineering Q4 2022, System Q3 2023
  - Survey begins 2024 Q3
  - Single visit – good S/N detections to mag 24



Meech, Yang, Kleyna (2016)

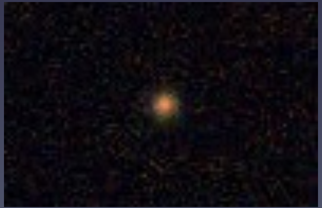
May 15, 2022

Key Questions



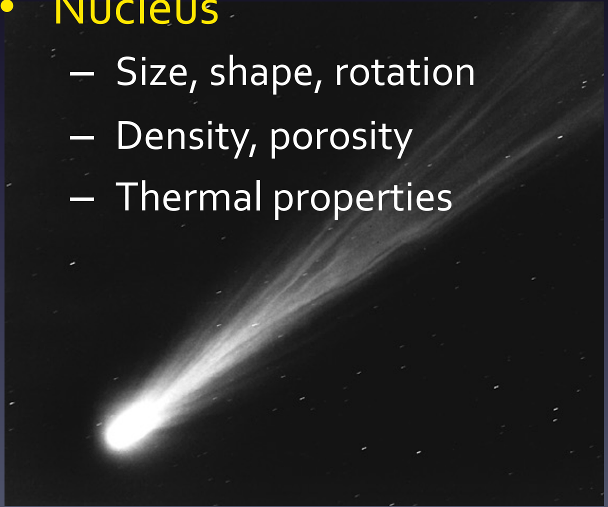
ISOs

- Chemistry
  - Volatiles & Isotopes
  - Dust
  - Surface materials vs bulk
- Nucleus
  - Size, shape, rotation
  - Density, porosity
  - Thermal properties
- Trajectory?

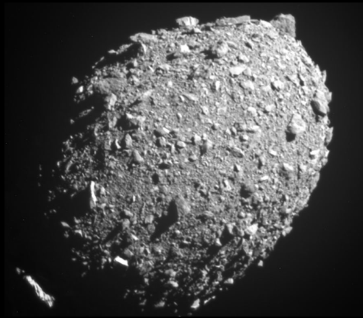


LPCs

- Chemistry
  - Volatiles & Isotopes
  - Dust
  - Surface materials vs bulk
- Nucleus
  - Size, shape, rotation
  - Density, porosity
  - Thermal properties



NEOs



- Nucleus
  - Mass, speed
  - Density, porosity, strength
  - Internal structure
- Composition
  - Ice, dust
  - Surface materials vs bulk