The Far-Reaching Implications of KBO Observations from a Spacecraft in the Outer Solar System

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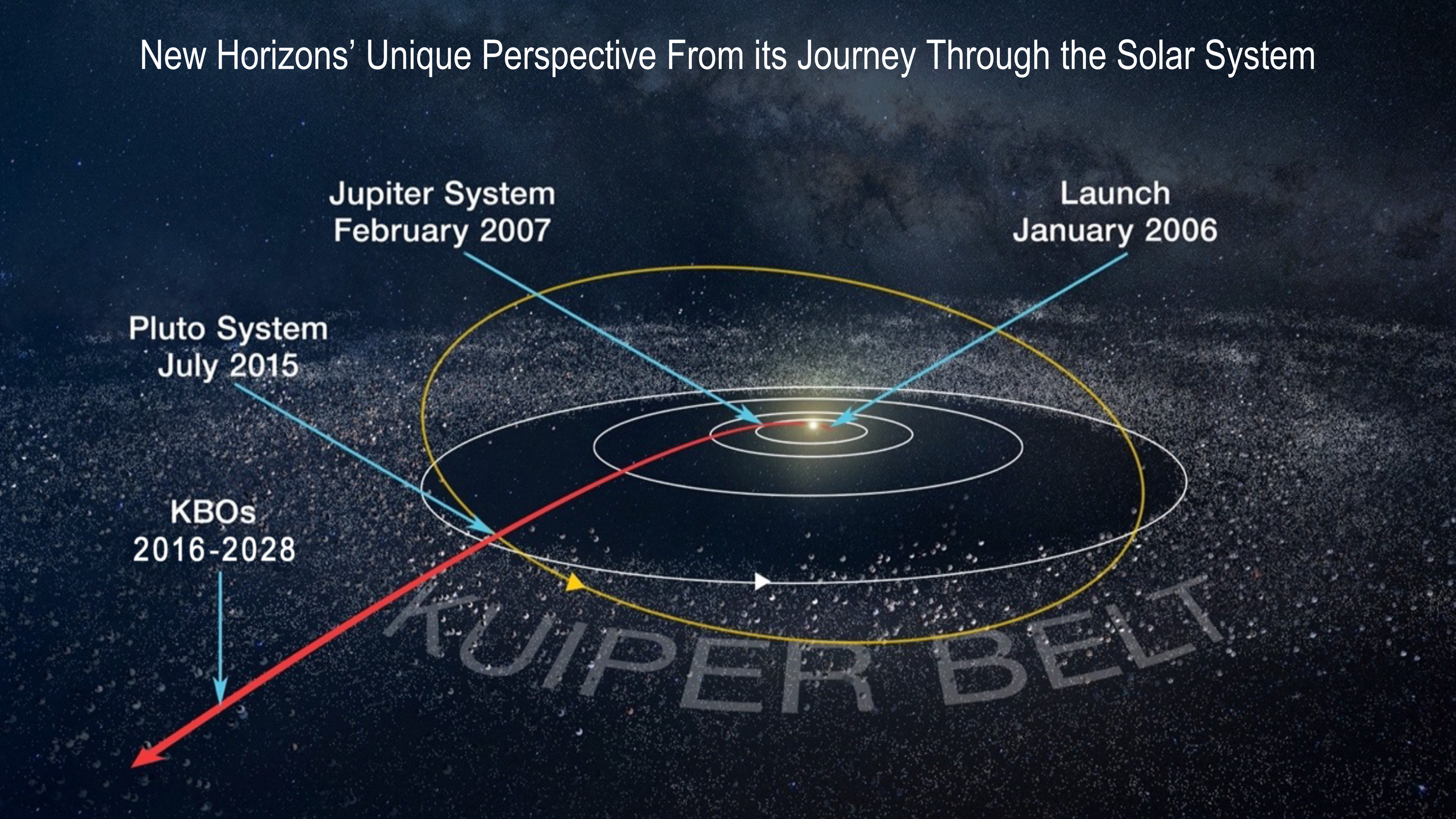
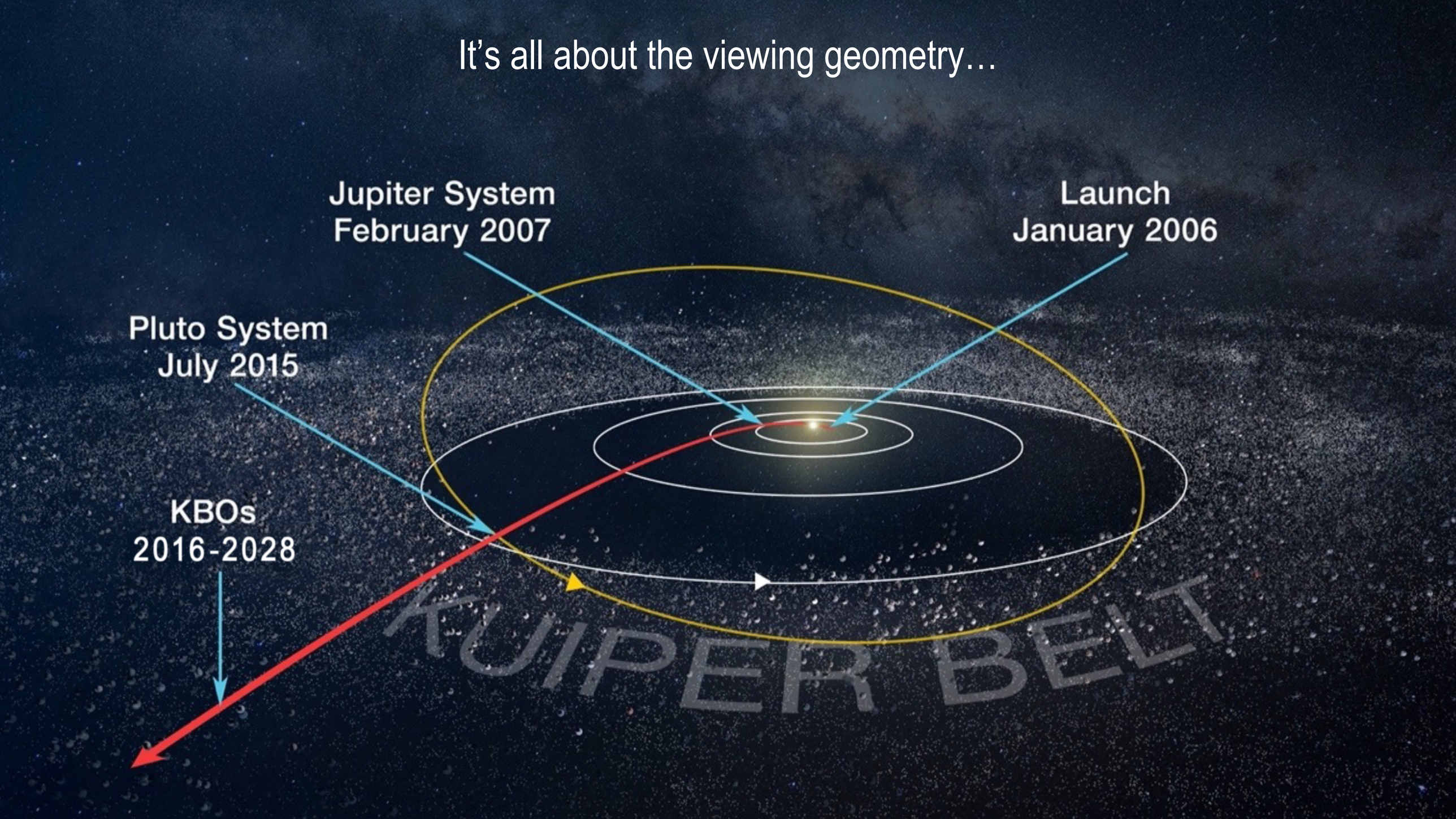
New Horizons Kuiper Belt Extended Mission

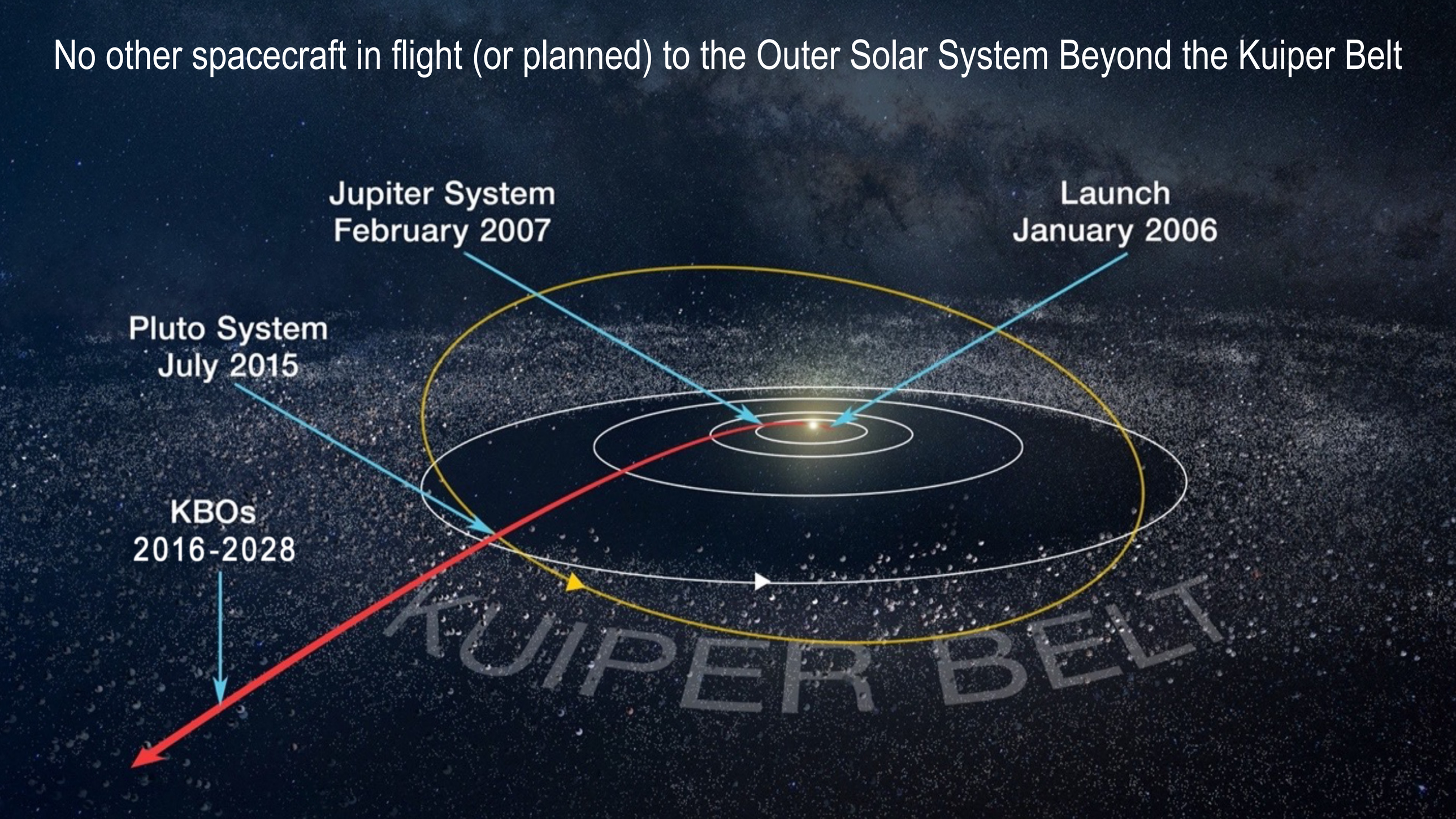
New Horizons' Unique Perspective From its Journey Through the Solar System



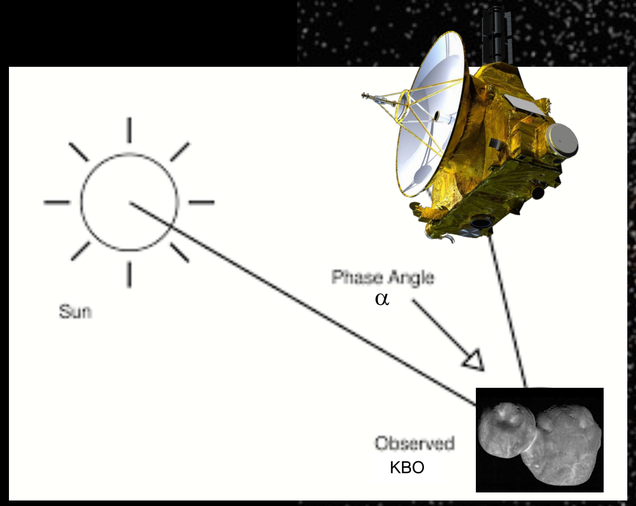
It’s all about the viewing geometry…



No other spacecraft in flight (or planned) to the Outer Solar System Beyond the Kuiper Belt



New Horizons is NASA's Observatory in the Kuiper Belt



Since 2007, New Horizons has made unresolved observations of dwarf planets and other Kuiper Belt Objects (KBOs) at unique viewing geometries only possible from a spacecraft in the outer solar system

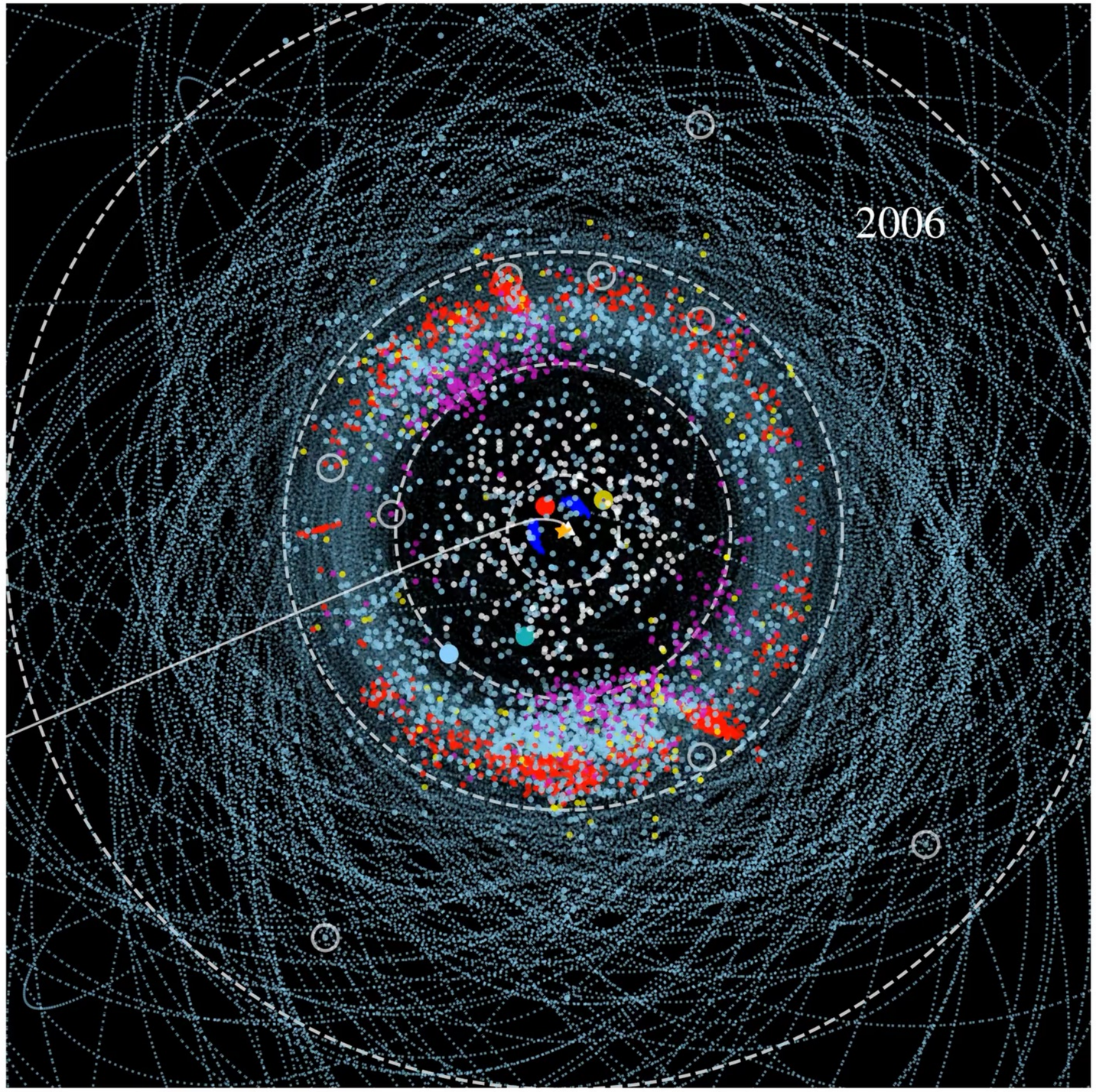
- Solar phase curves characterize surface microphysical properties
- Enable searches for binarity
- Rotation (light) curves at high solar phase angles constrain period and shape
- Astrometry enables Earth-based occultation observations by small KBOs → shape and size → albedo

▲ New Horizons Spacecraft Location

★ Sun

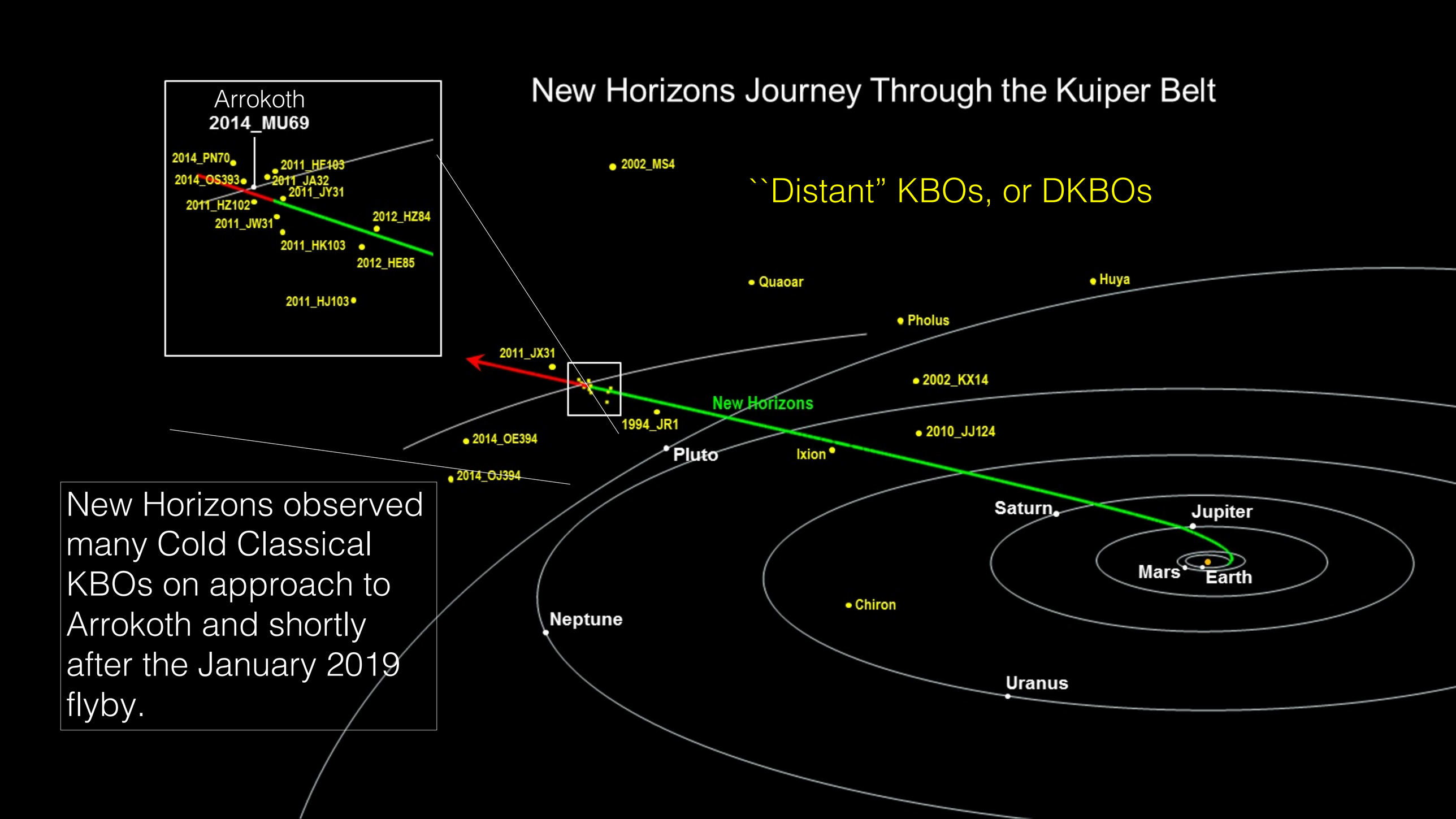
◯ Dwarf Planet Large KBO

● Neptune



Cold Classical KBOs
Plutinos
Centaurs
Jupiter Trojans
Scattered Disk
(other) Resonant KBO

Credit: Wes Fraser

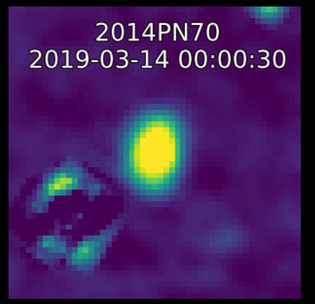

New Horizons Journey Through the Kuiper Belt
Arrokoth
2014_MU69
2014_PN70
2014_OS393
2011_HF103
2011_JA32
2011_JY31
2011_HZ102
2011_JW31
2011_HK103
2012_HZ84
2012_HE85
2011_HJ103
2002_MS4
``Distant" KBOs, or DKBOs
Quaoar
Huya
Pholus
2011_JX31
2002_KX14
New Horizons
1994_JR1
2010_JJ124
2014_OE394
Pluto
Ixion
2014_OJ394
Saturn
Jupiter
Mars
Earth
Chiron
Neptune
Uranus
New Horizons observed many Cold Classical KBOs on approach to Arrokoth and shortly after the January 2019 flyby.

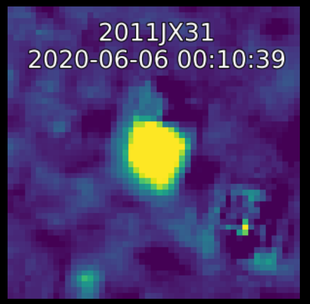
New Horizons ‘Distant’ KBOs & Dwarf Planets
(unresolved, point source observations)

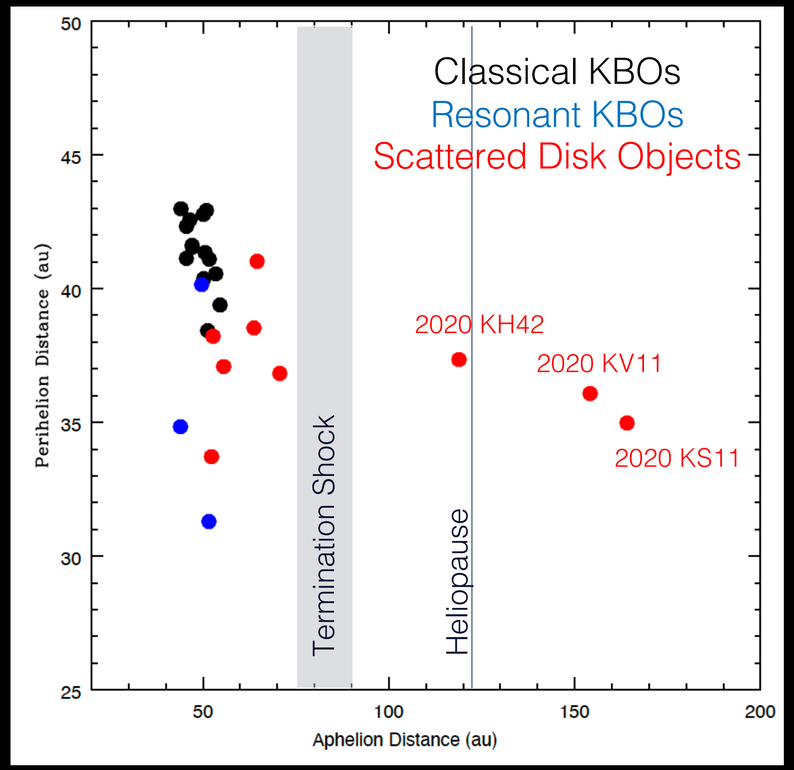
Cold Classical	Hot Classical	Scattered Disk	Resonant	Large KBO ($H_V < 5$)	Dwarf Planet	Centaur
2004 LW_{31}	2012 HZ_{84}	2011 HK_{103}	2012 HE_{85}	Quaoar	Eris	Chiron
2011 HF_{103}	2011 HJ_{103}	2014 OJ_{394}	2018 MG_{13}	Ixion	Makemake	2010 JJ_{124}
2011 HZ_{102}		2020 KV_{11}	2020 KS_{11}	2014 OE_{394}	Haumea	
2011 JA_{32}		2020 KP_{11}		2002 KX_{14}		
2011 JW_{31}		2020 KH_{42}		2002 MS_4		
2011 JX_{31}		2020 KT_{11}				
2011 JY_{31}						
2014 OS_{393}						
2014 PN_{70}						
2018 MF_{13}						
2020 KR_{11}						

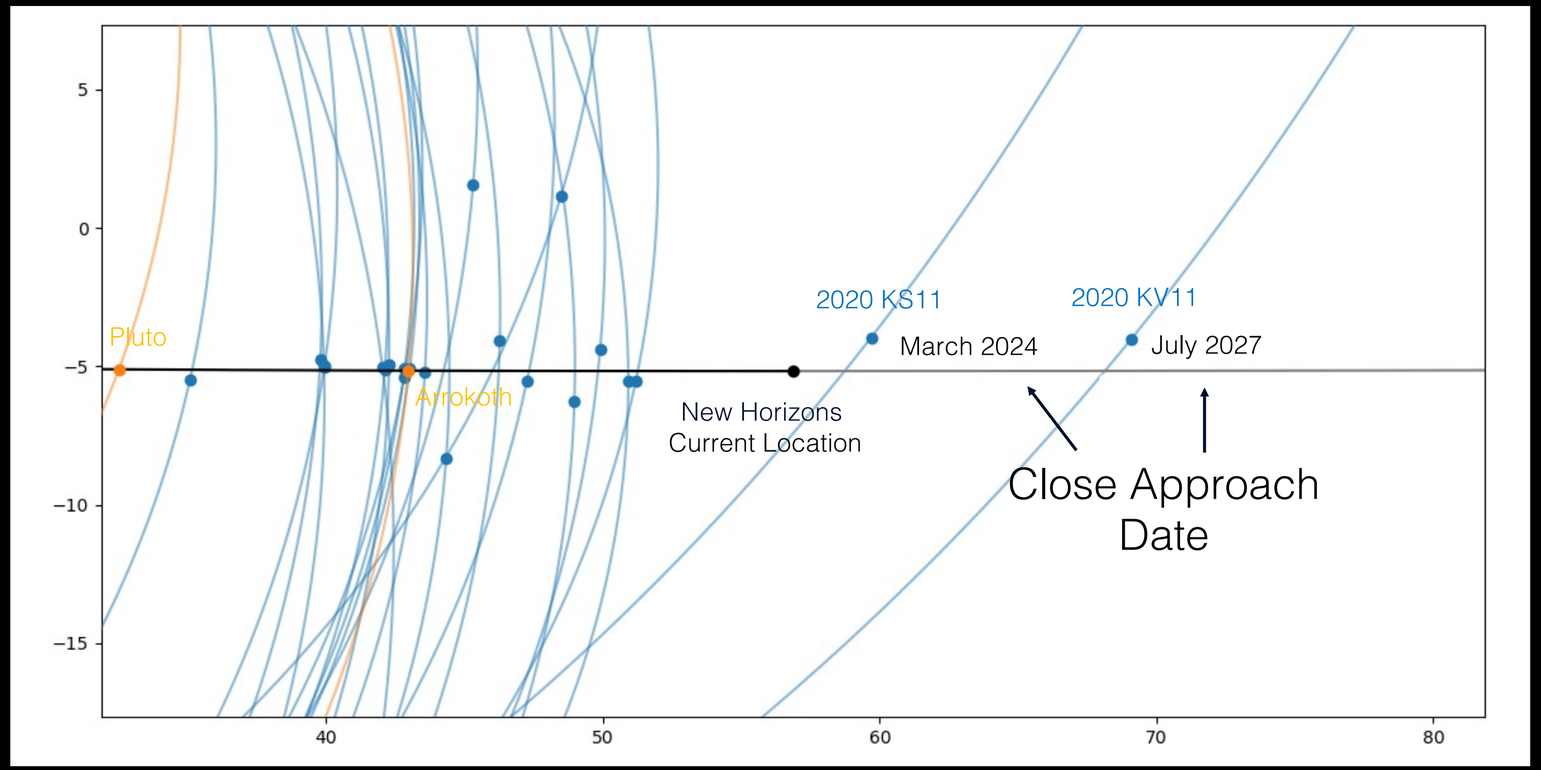
New Horizons KBO Survey

- >30 KBOs, dwarf planets observed so far: 13 classical, 6 scattered (SDO), 3 resonant, 8 large (dwarf planets), 2 centaurs
- New Horizons is currently at 58 au and will be sampling more SDOs until it leaves the Kuiper Belt
- Going forward, bias towards bigger KBOs that will have longer observation windows, giving broader phase coverage









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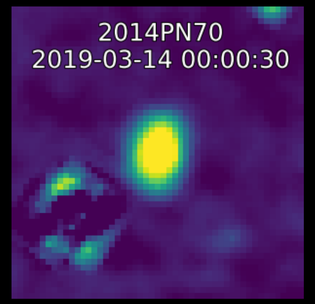
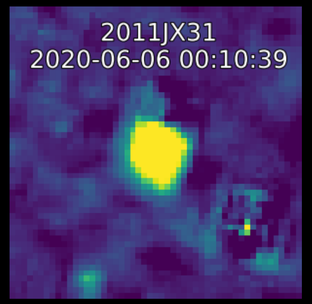
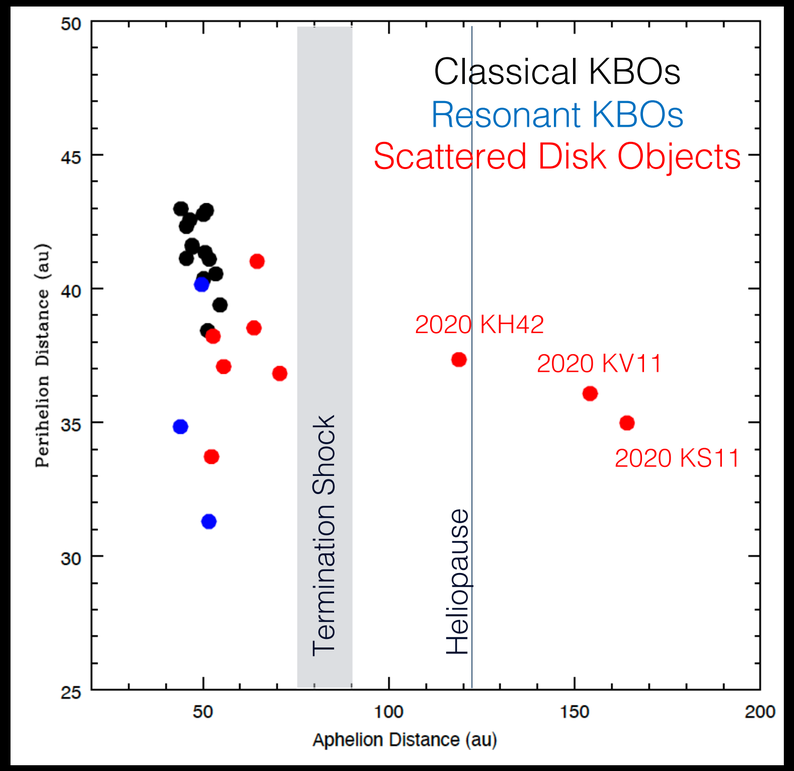
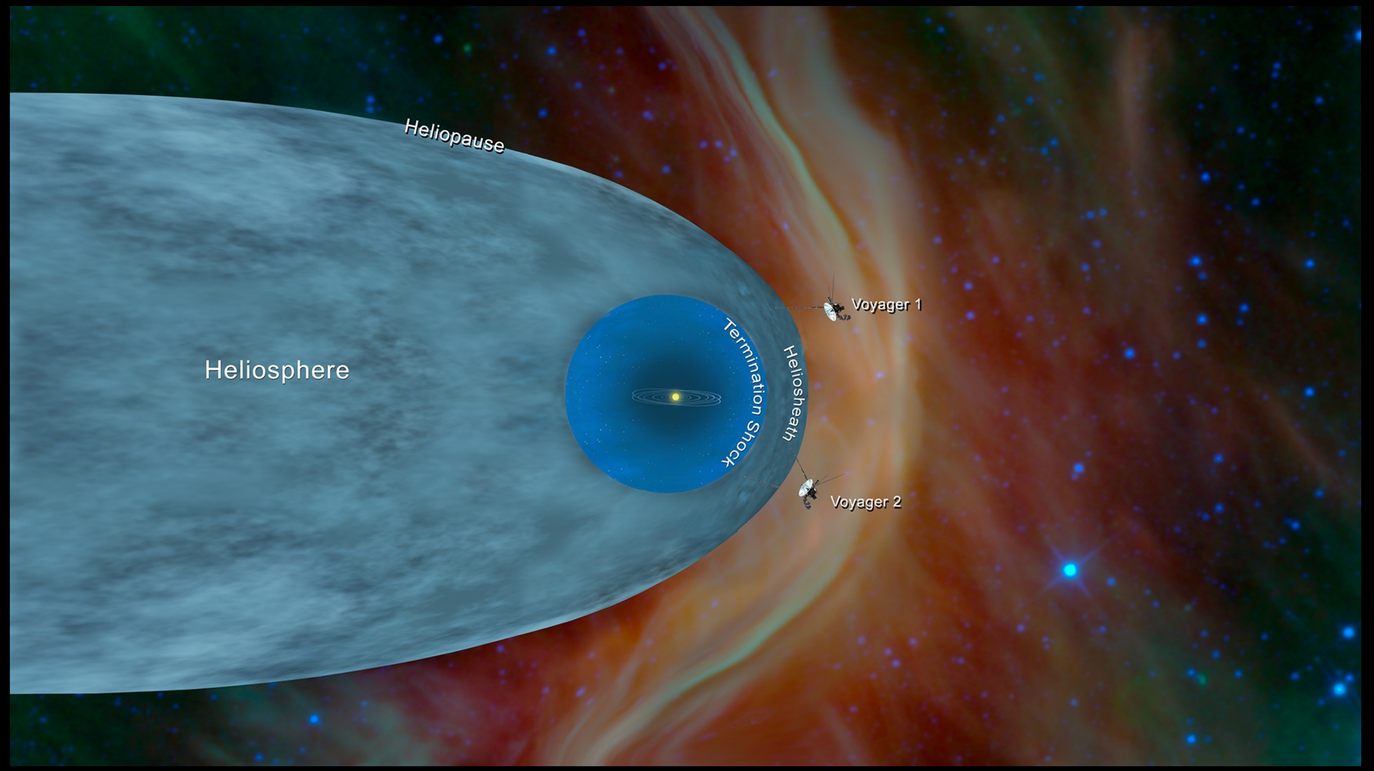
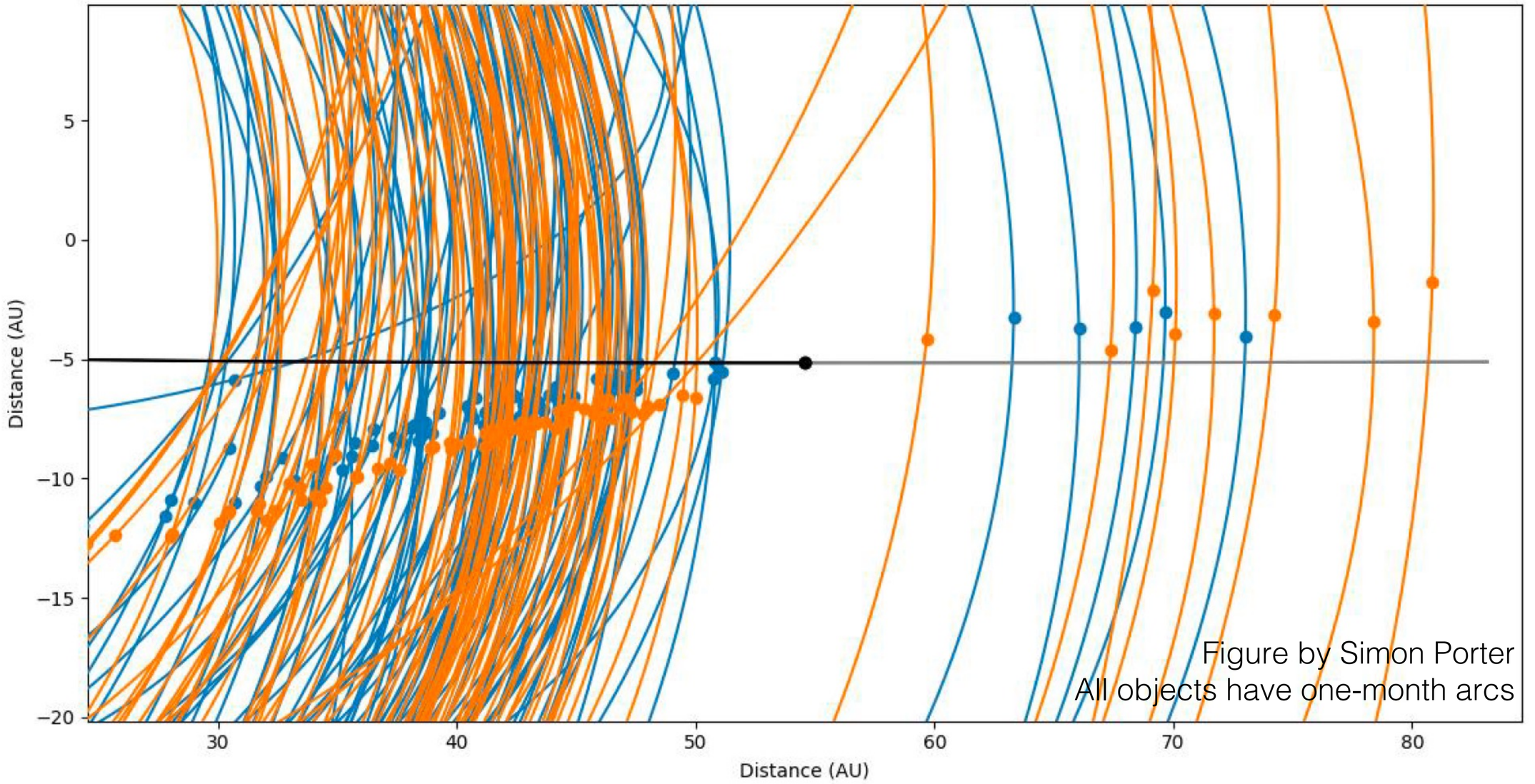








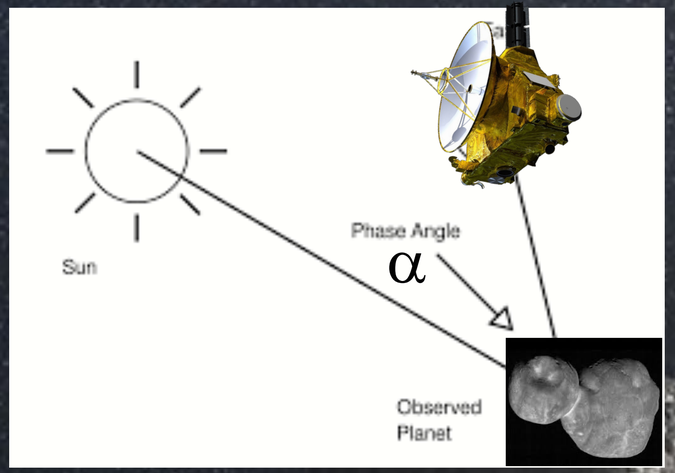
Preliminary Result: KBOs Discovered by Subaru HSC in 2021 and 2022



176 KBOs discovered in 2021 and 2022 (orange and blue dots, respectively) at the point on their orbits (orange and blue lines) when the New Horizons spacecraft is closest to them. Black line is the spacecraft trajectory with the current heliocentric position shown by the black dot at 55 au. The spacecraft will pass 60 au in October 2024.

Photometric Properties of Kuiper Belt Object (KBO) Surfaces:

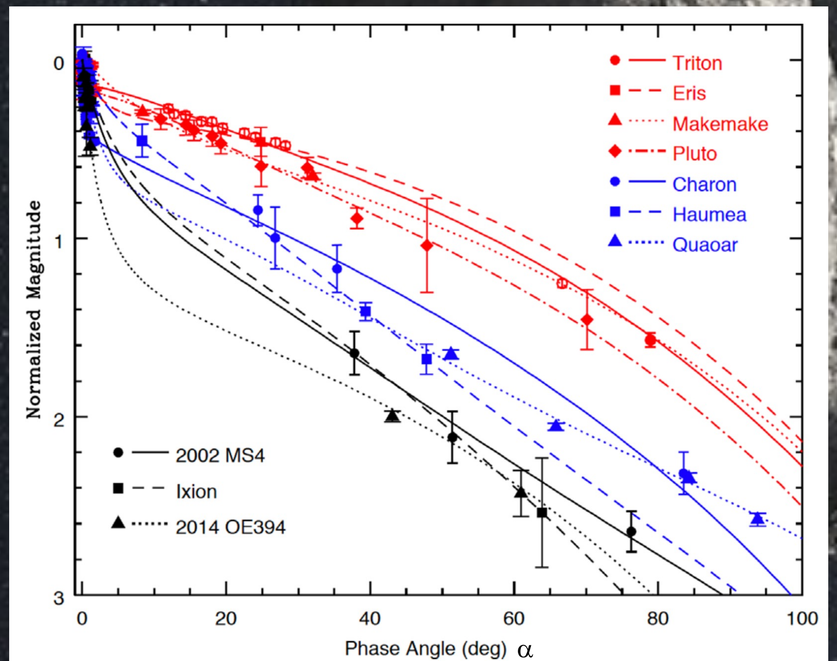
Determine physical surface properties by measuring reflected sunlight at multiple viewing and illumination geometries



The success with which a photometric model can determine physical surface properties depends upon the availability of observations at the broadest range of solar phase, incidence, and emission angles.

'Disk'-integrated, or 'whole-disk' solar phase curves – reflectance vs. solar phase angle (α)

'Disk'-resolved observations from close flybys by a spacecraft



Hapke (2012) Photometric Parameters:

- Single scattering albedo (scattering:extinction efficiency)
- Opposition effect (increase in reflectance as $\alpha \rightarrow 0°$) width and amplitude (porosity, particle transparency)
- Macroscopic roughness (mean topographic slopes)
- Directional parameters (backward or forward scattering) for Single Particles
  - particle transparency (internal scatterers)
  - euhedral (smooth), irregular (rougher) particles

Photometric Properties of Kuiper Belt Object (KBO) Surfaces

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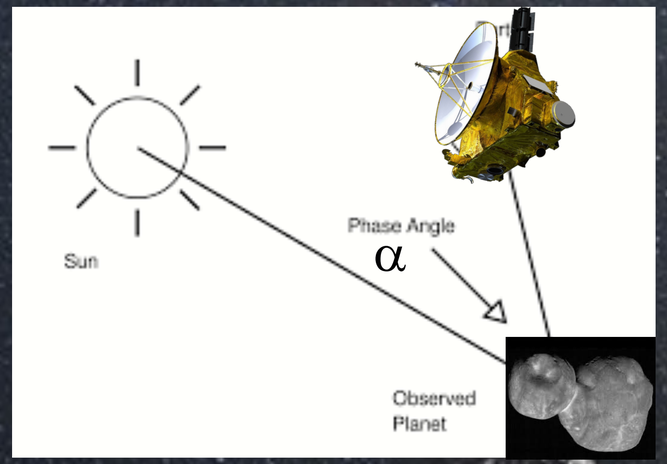
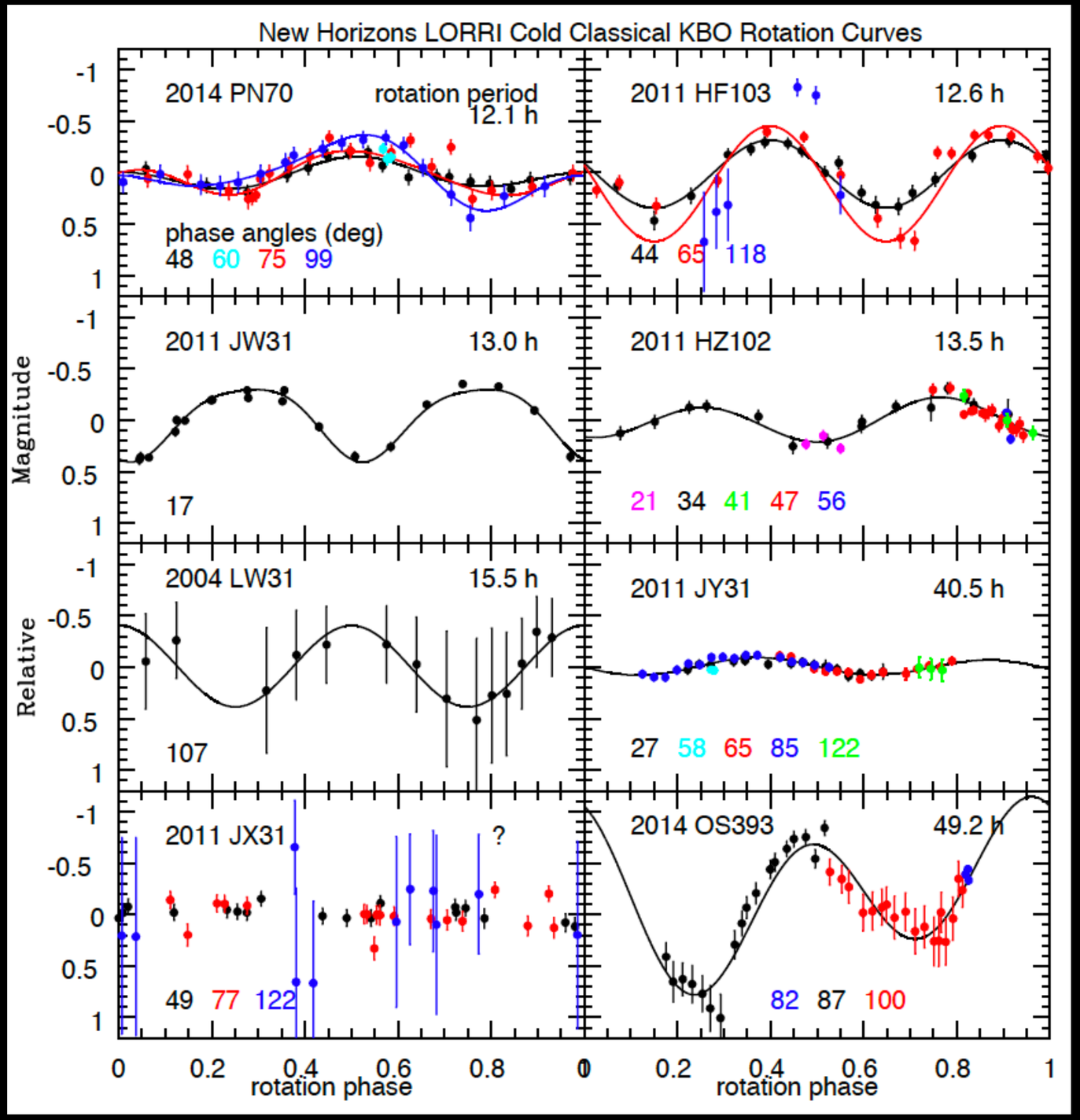


Reflectivity, or albedo

- Provides first, rudimentary measure of surface composition
  - Bright → volatiles, ices
  - Dark → tholins, amorphous C, non-volatiles

Geometric albedo, *p*, defined as reflectivity at opposition (phase angle $\alpha = 0°$) relative to a flat, perfectly diffusing disk *of the same size*

- How to measure size?
  - Direct imaging: s/c flyby; larger KBOs (HST)
  - Infer size from apparent magnitude to get absolute magnitude
  - Stellar occultations (e.g. Arrokoth, dwarf planets) + shape
  - Thermal emission (*Herschel, Spitzer*, ALMA)
    - ALMA – already observed 2 out of 3 planned NH KBOs:
      Plutino (15810) Arawn – May 2018 – 200 km diameter
      SDO 2014 OJ394 - December 2023 - analysis ongoing
      Classical 2014 OE394 - TBD



NH LORRI Cold Classical KBO Rotation Curves

Double-peaked rotation curves

Rotation periods: 12.1 – 49.2 h

Total amplitudes: 0.2 – 2 magnitudes

Amplitudes vs. phase angle:

Increase: 2014 PN70, 2011 HF103

May Increase?: 2011 JX31, 2011 JW31, 2004 LW31, 2014 OS393, 2011 HZ102

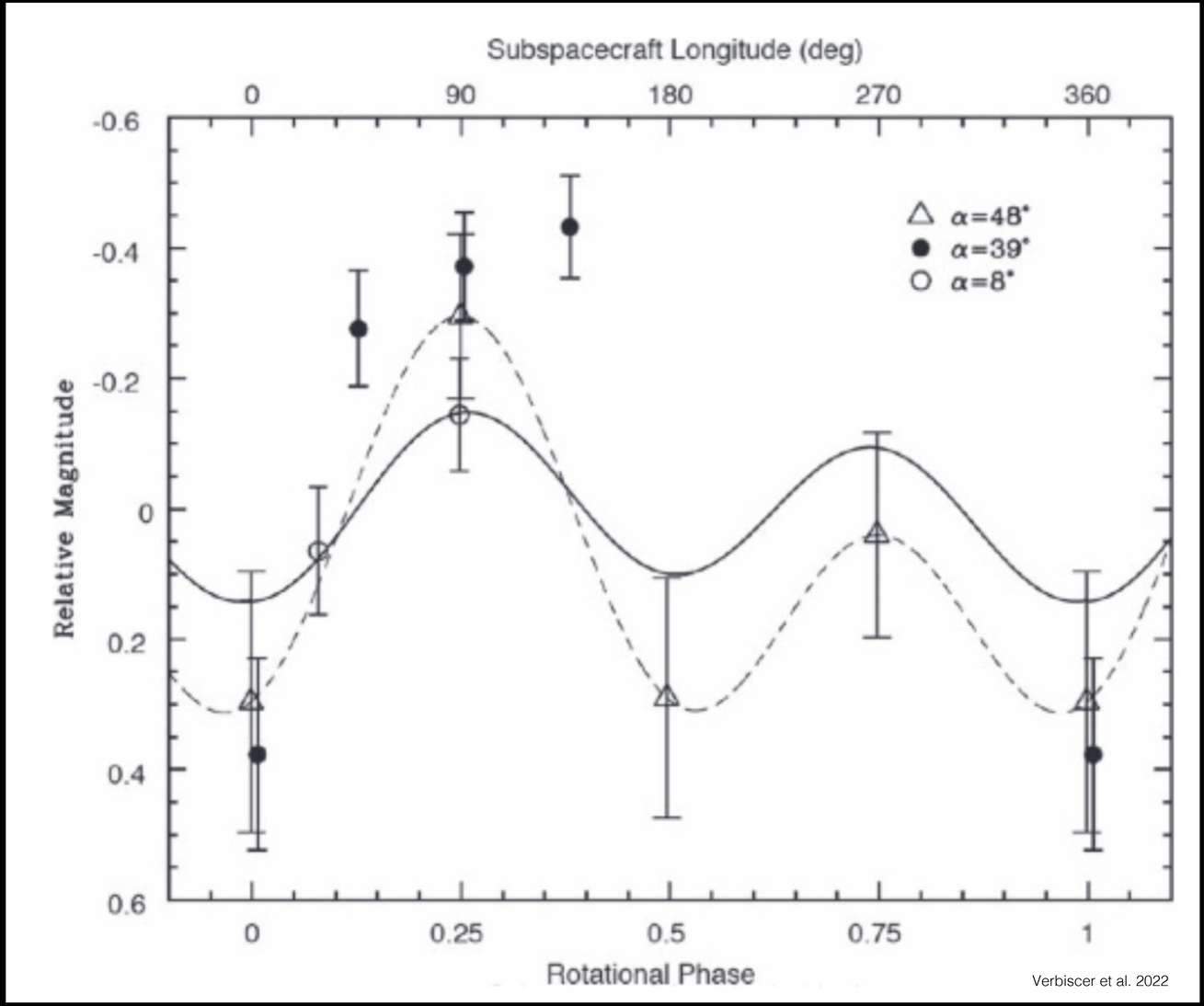
Constant: 2011 JY31 (Binary KBO, Weaver et al. 2022)

Note: 2014 OS393 images hinted at binarity; long rotation period!

Assuming uniform surface albedo, these curves constrain shape and rotation pole (Porter et al. LPSC 2022)

Rotation curves enable accurate placement of points on solar phase curves if cadence and sampling will throw off simply averaging all observations at a given α.

Haumea Shape and Pole

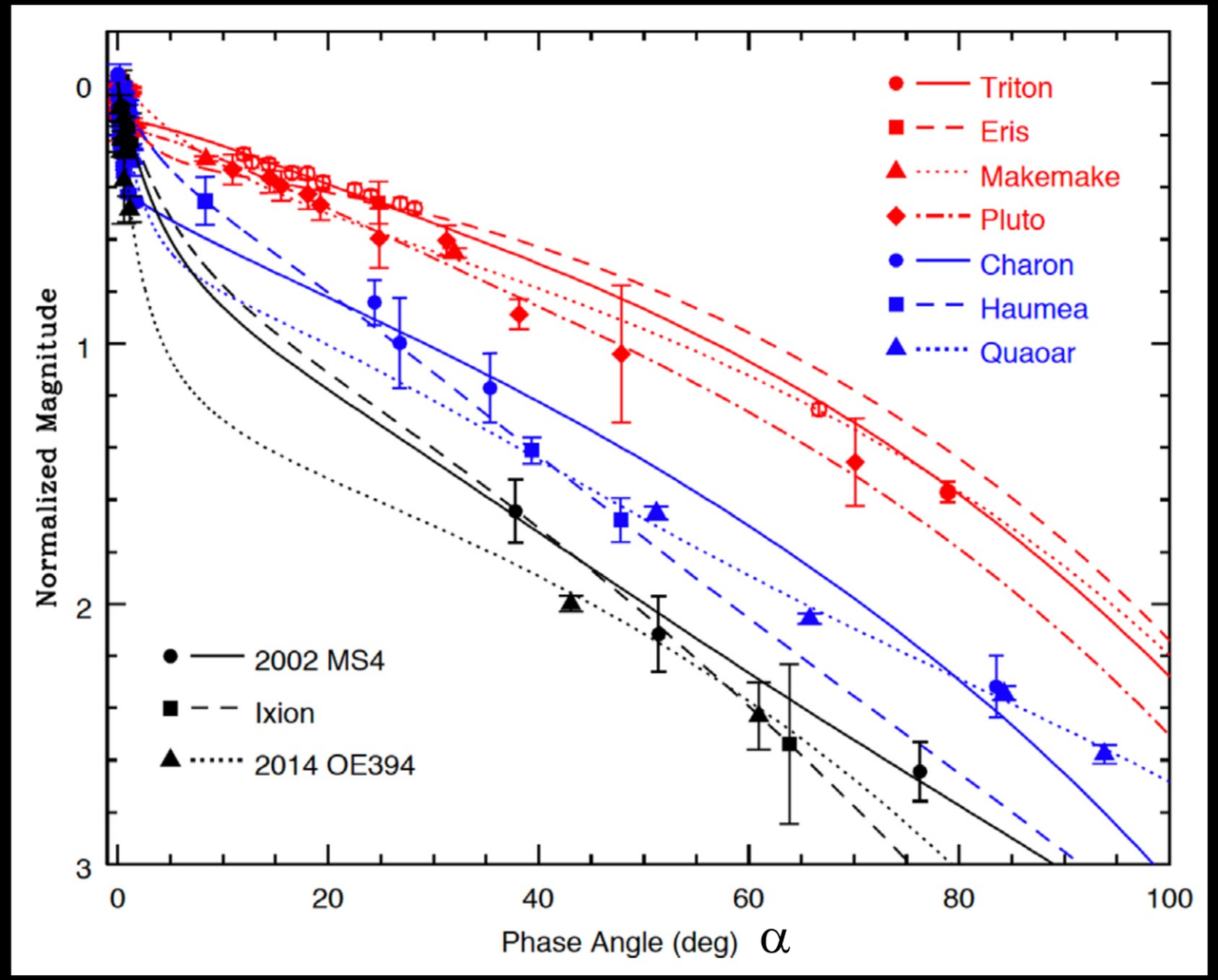


Verbiscer et al. 2022

Dwarf Planet Haumea
2100 x 1680 x 1074 km

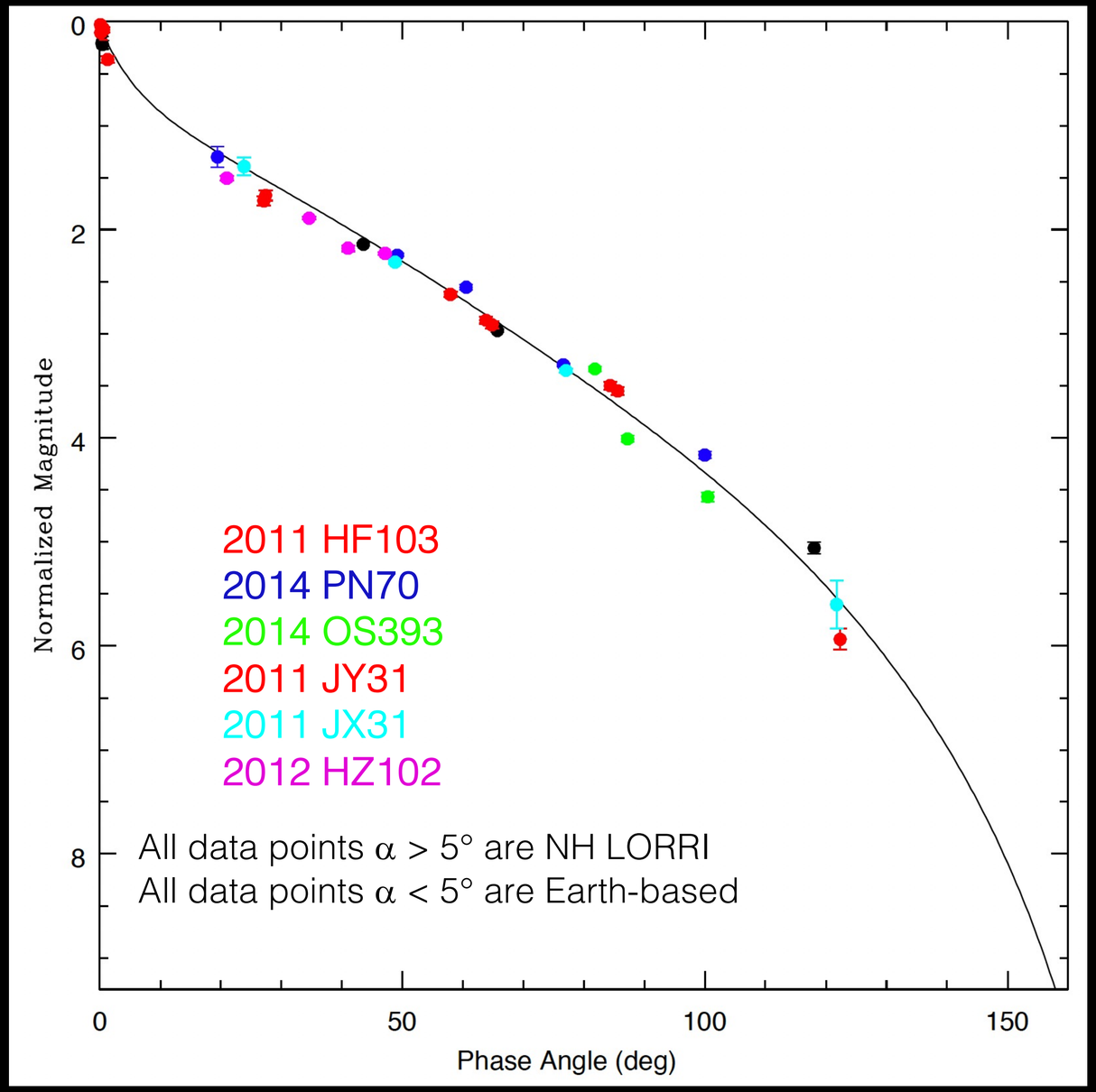
- New Horizons can acquire another Haumea rotation curve at a higher phase angle, α = 60°, in early 2027.
- Also extend Haumea's phase curve to 60°

Disk-Integrated Solar Phase Curves of KBOs at Large Phase Angles



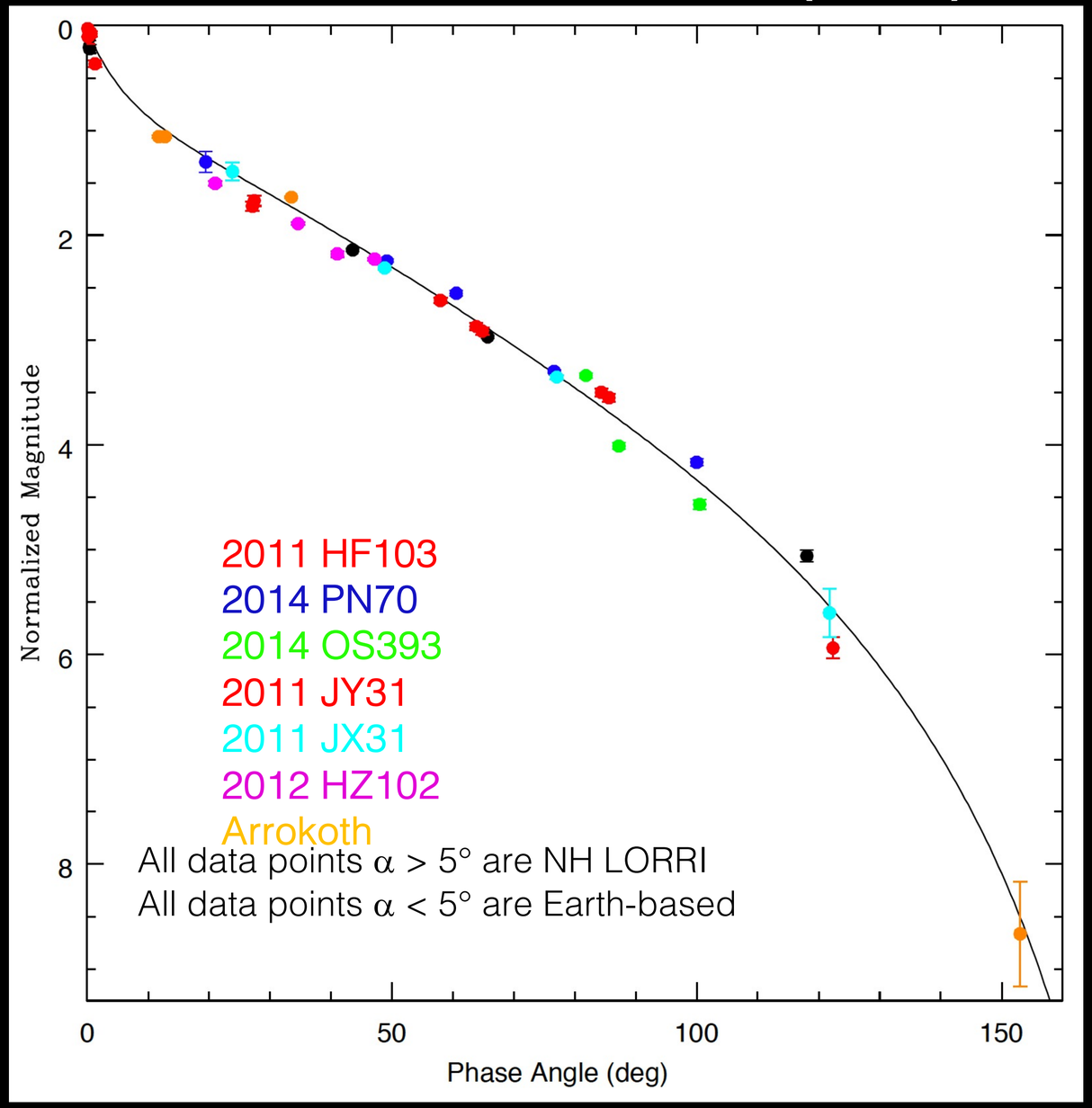
- All data $\alpha > 2°$ from New Horizons and Voyager 2 (Triton). All data normalized to magnitude 0 at opposition (to compare phase curve shapes)
- Solid lines are fits to Hapke (2012) photometric model
- Highly volatile ices (N_2, CH_4, etc.) have shallowest phase curve slopes (red).
- H_2O (blue) - intermediate slopes
- Non-volatile surfaces (black) have steepest slopes

Cold Classical (CC) KBO Solar Phase Curves



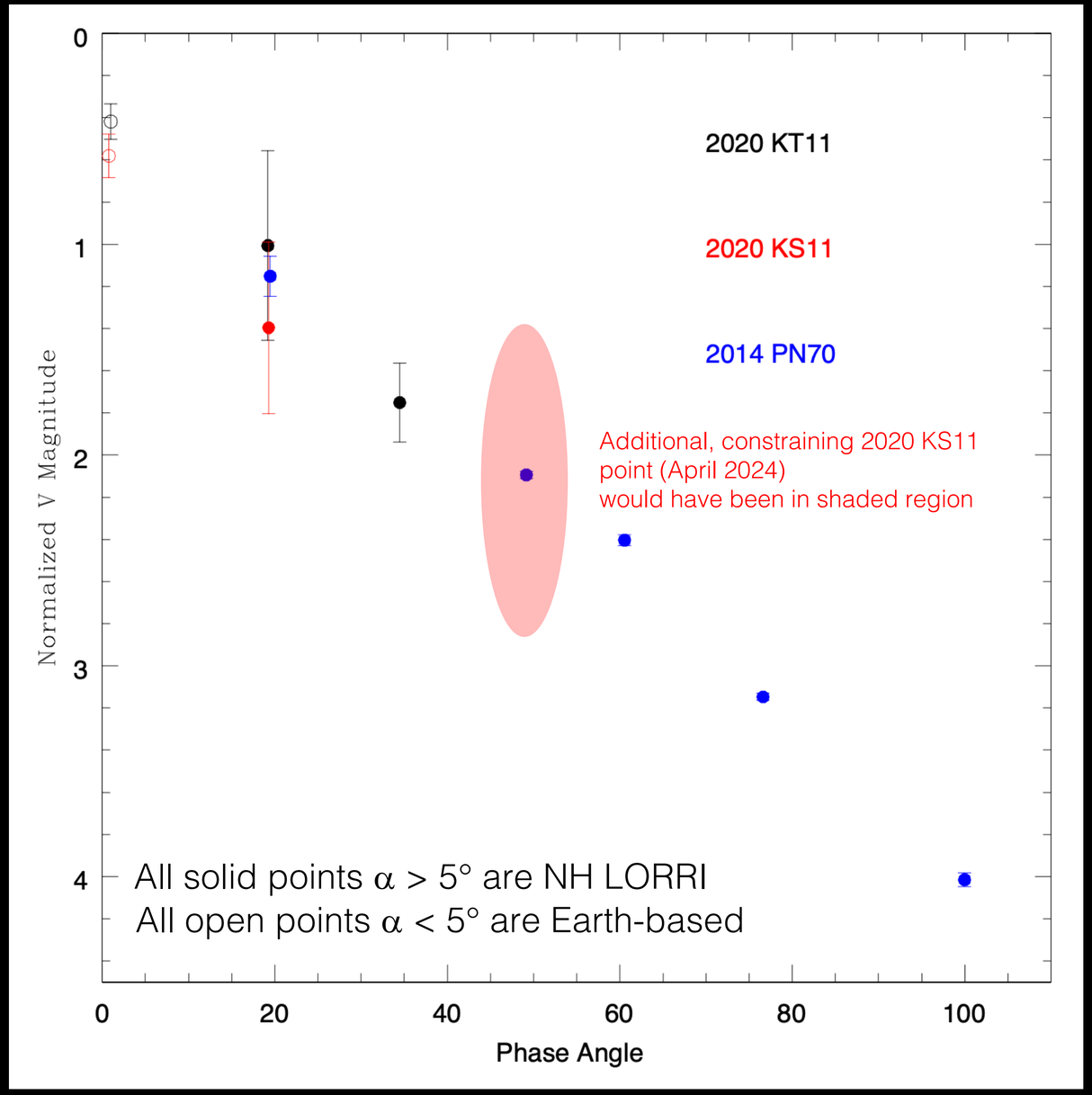
- NH CCKBOs have similarly-shaped solar phase curves. (Corrected for rotation light curves.)
- Solid line is fit to Hapke (2012) photometric model
  - Single scattering albedo = 0.09
  - Photometric roughness 25° (mean topographic slope angle)
- All data normalized to magnitude 0 at opposition (to compare phase curve shapes), but all geometric albedos are still assumed, not measured.

Cold Classical (CC) KBO Solar Phase Curves



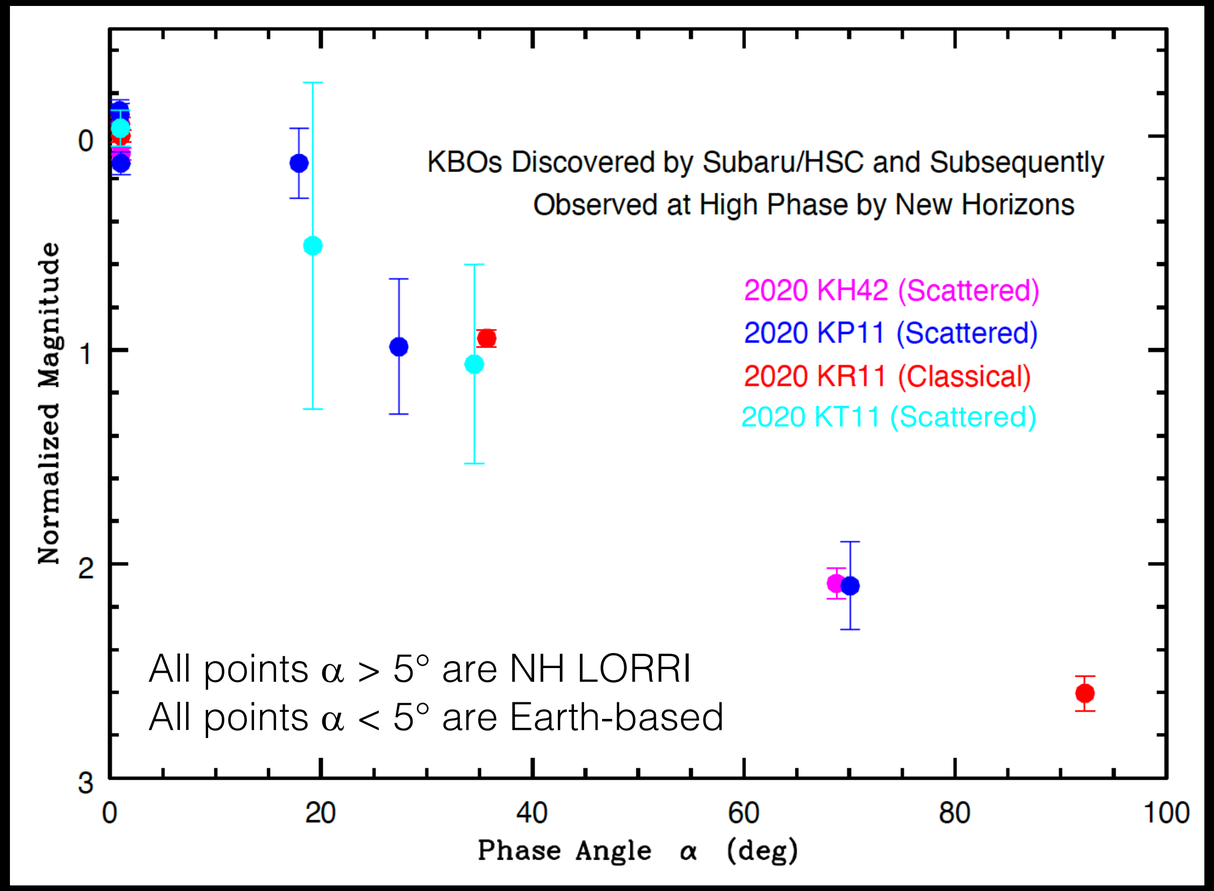
- Arrokoth's solar phase curve matches those of other cold classical KBOs
- New Horizons found no strong indication of H_2O ice on Arrokoth's surface, more CH_3OH, remnants of volatiles being removed (red color)

NH KBO Solar Phase Curves

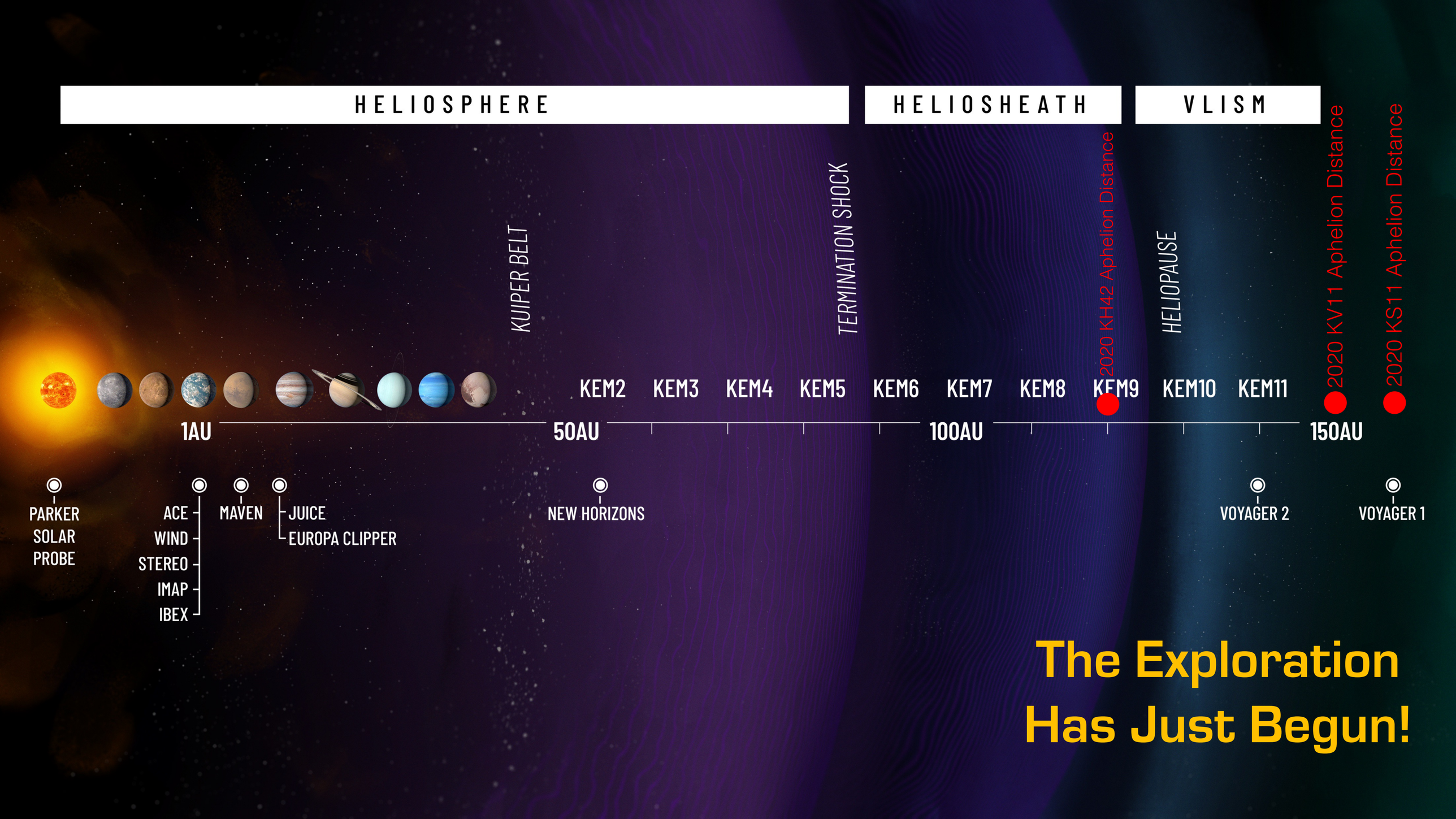


- No longer going to observe 2020 KS11 at closest approach in March 2024
- 2020 KS11 has the largest aphelion distance of all NH KBOs (so far)
- 2020 KV11 closest approach is July 2027

NH KBO Solar Phase Curves



- New Horizons can observe 2020 KV11 as early as November 2024 when the phase angle will be 1.8 degrees, *V* magnitude = 21.
- Phase angle increases, *V* magnitude decreases (until July 2027)
- Now the ONLY opportunity that we have in hand to study space weathering via disk-integrated phase curve modeling of a KBO that has ventured beyond the Heliopause.


HELIOSPHERE
HELIOSHEATH
VLISM
KUIPER BELT
TERMINATION SHOCK
HELIOPAUSE
2020 KH42 Aphelion Distance
2020 KV11 Aphelion Distance
2020 KS11 Aphelion Distance
KEM2
KEM3
KEM4
KEM5
KEM6
KEM7
KEM8
KEM9
KEM10
KEM11
1AU
50AU
100AU
150AU
PARKER SOLAR PROBE
ACE
WIND
STEREO
IMAP
IBEX
MAVEN
JUICE
EUROPA CLIPPER
NEW HORIZONS
VOYAGER 2
VOYAGER 1
The Exploration Has Just Begun!