A DEEP, WIDE SEARCH FOR SOLAR SYSTEM OBJECTS

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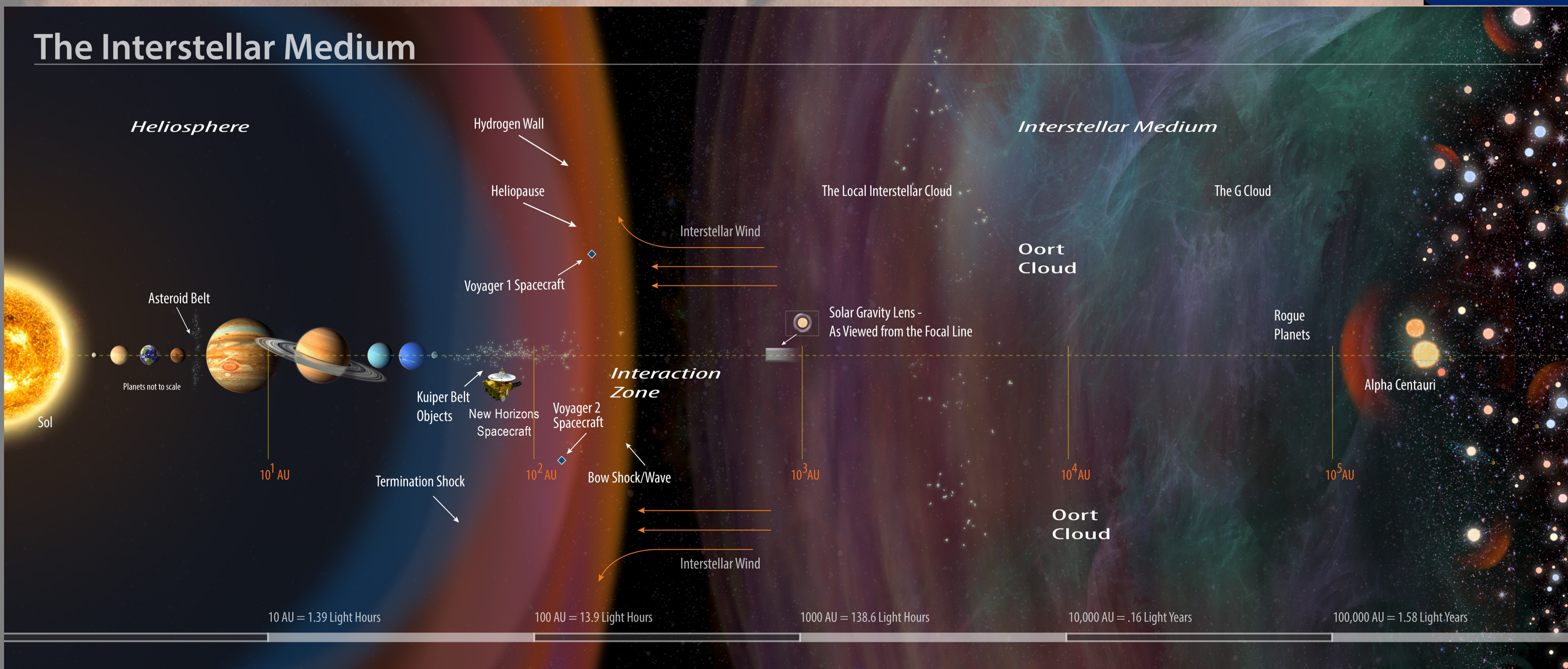
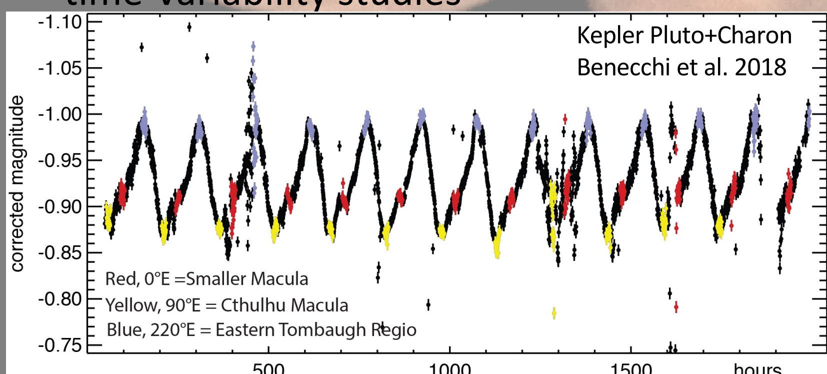
Perspective



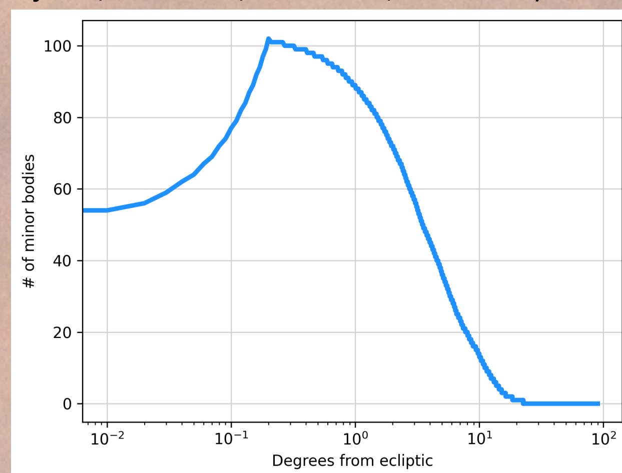
By Charles Carter/Keck Institute for Space Studies - https://web.archive.org/web/20190617075031/https://www.nasa.gov/feature/jpl/interstellar-crossing-the-cosmic-void/. (See also https://kiss.caltech.edu/final_reports/ISM_final_report.pdf), Public Domain, https://commons.wikimedia.org/w/index.php?curid=147469703

Motivation

- Roman is **uniquely** placed to study moving bodies in our solar system
  - Above Earth's atmosphere → stable PSF, deep imaging (F146W stacks): M=28.0 in 1 hour, M=30.5 in 43 hours
  - High resolution → identify binaries
  - Wide field (1 Roman field ~200x JWST NIRCam)
  - Filter range allows for diagnostic spectrophotometry (0.5-2.25 μm)
  - Removes 24-hour earth rotation aliasing for time-variability studies



- Discovery/study various dynamical populations
  - Near Earth asteroids (planetary defense)
  - Main belt objects
  - Trojans
  - Long-period/dynamically new comets
  - Interstellar objects (ISOs)
  - Dwarf planets
  - Transneptunian Objects (2 populations of "classical" objects, resonant, scattered, detached)



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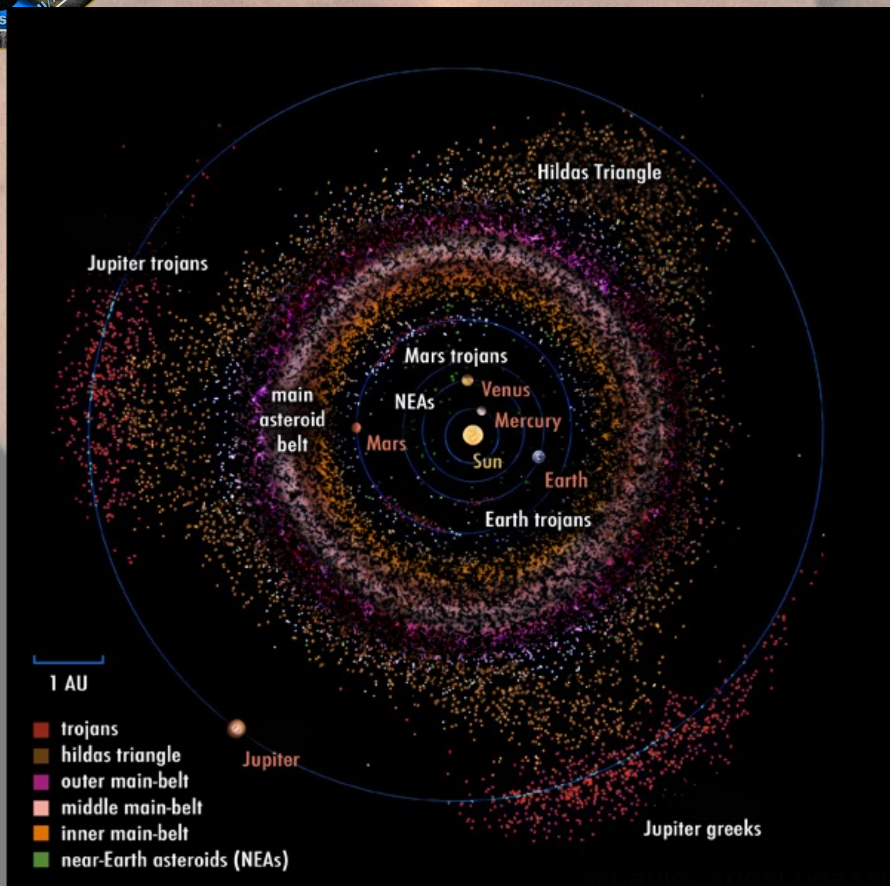
Current Solar System



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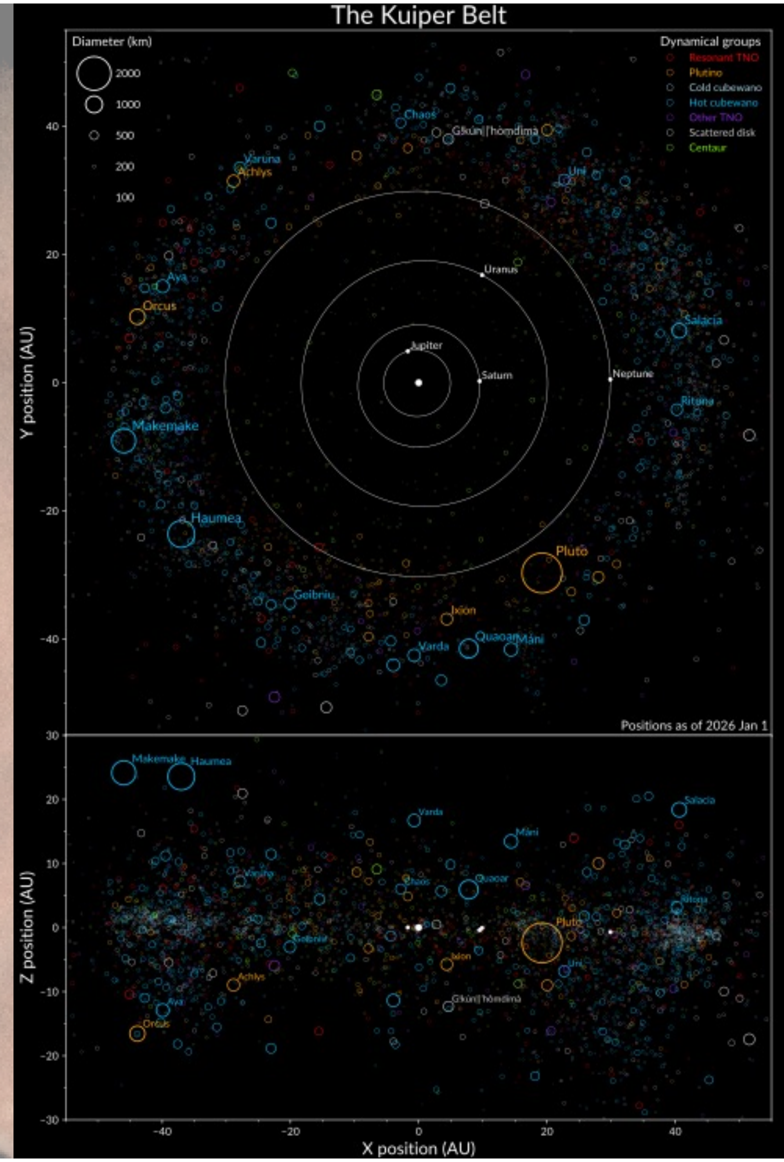

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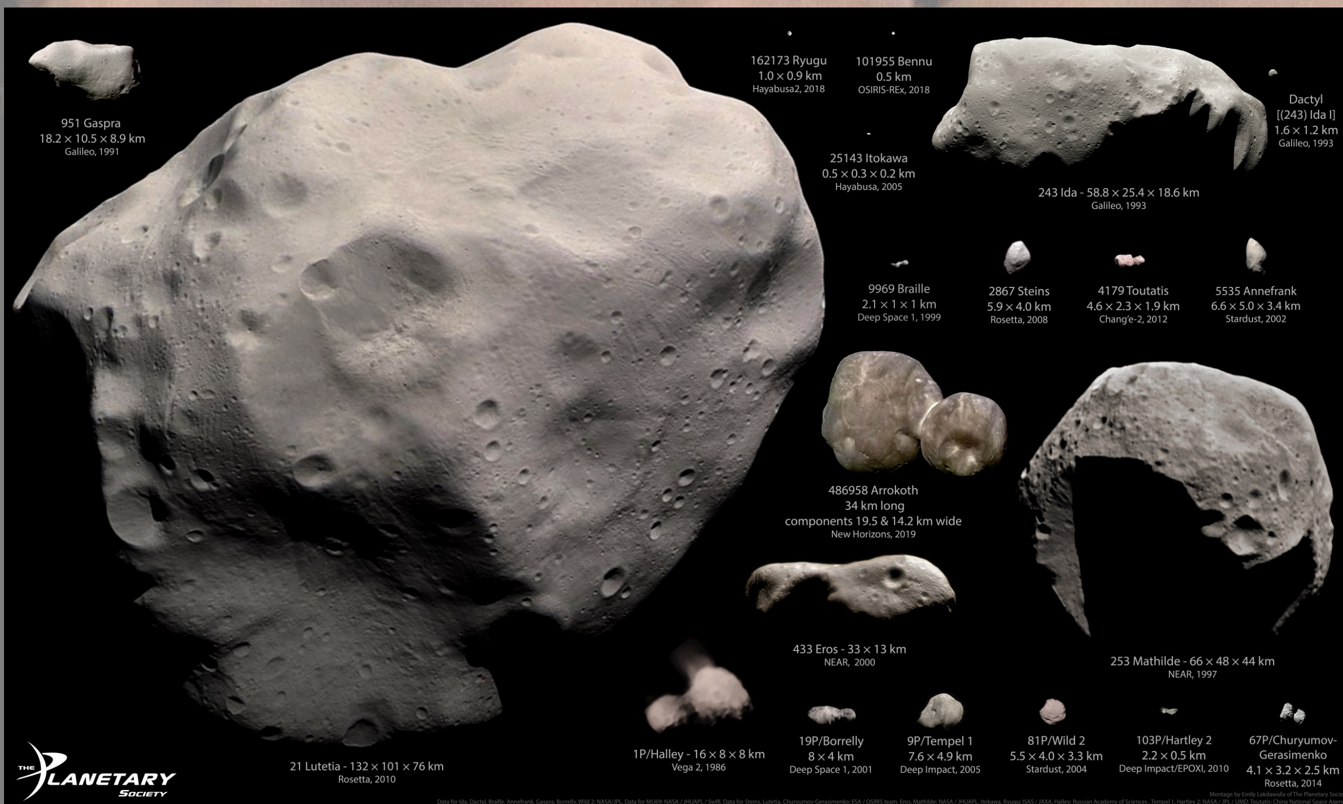
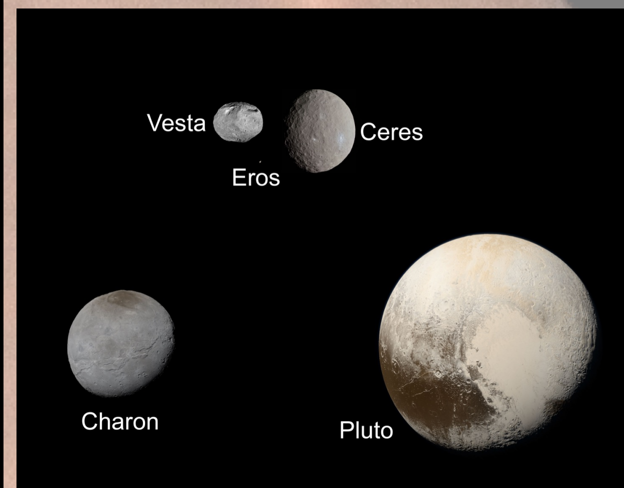
Many Different Shapes and Sizes



By Montage by Emily Lakdawalla for The Planetary Society. Data from NASA / JPL / JHUAPL / SwRI / UMD / JAXA / ESA / OSIRIS team / Russian Academy of Sciences / China National Space Agency. Processed by Emily Lakdawalla, Daniel Machacek, Ted Stryk, Gordan Ugarkovic / Thomas Appéré - https://www.planetary.org/space-images/asteroids-and-comets-visited-2018, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=113248764



By Ceres image: Justin CowartEros image: NASA/JPLVesta image: NASA/JPL-Caltech/UCAL/MPS/DLR/IDAPluto and Charon images: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute/Alex Parker - Ceres - RC3 - Haulani Crater Justin CowartWholeEros.jpgVesta full mosaic.jpgFile:Pluto in True Color - High-Res.jpgFile:Charon in True Color - High-Res.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=42852401

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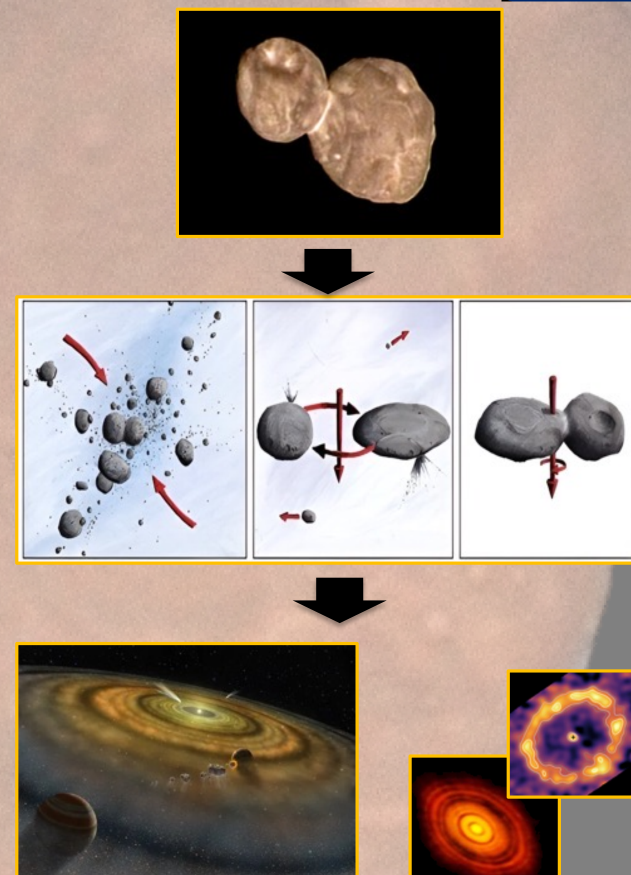
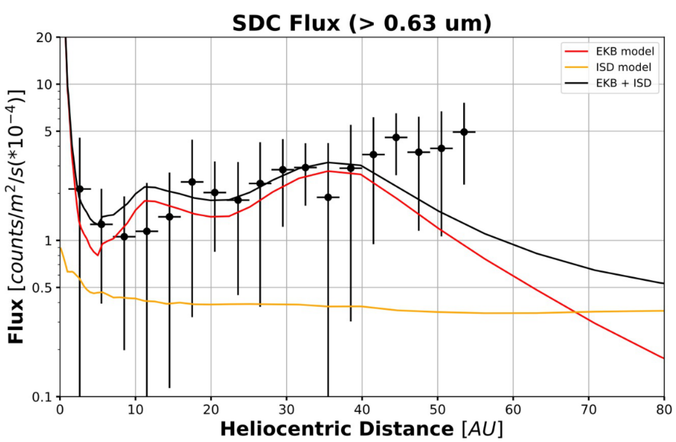
Impact of the *New Horizons* Mission

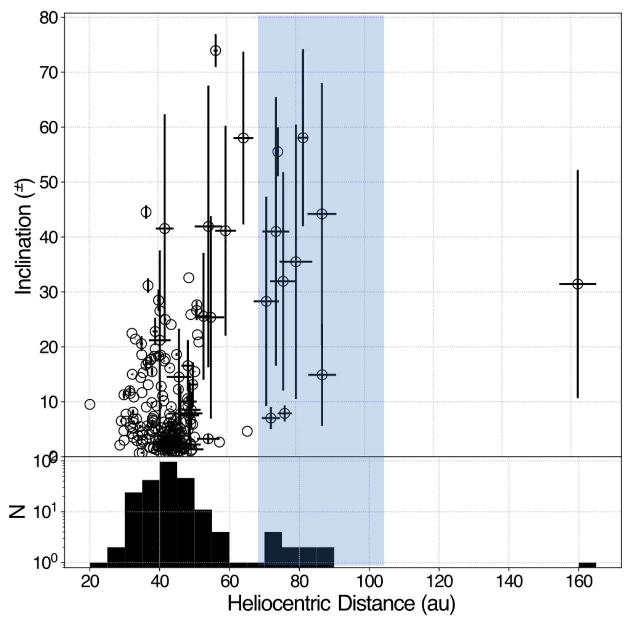
- The historic Arrokoth flyby revolutionized our understanding of planetesimal formation, and deciding the longstanding accretion mode in favor of pebble accretion.
- Multiple KBO observations from New Horizons continue to uncover large-scale characteristics critical for understanding planetary system formation here and elsewhere
- Indications of an extended Kuiper Belt amplifies the urgency for an enhanced KBO search now to find new targets that *New Horizons* can reach and observe



A flyby target in the distant Kuiper Belt?

- Two lines of evidence provide evidence for an extended Kuiper Belt: elevated dust fluxes from the NH SDC and Subaru search results.



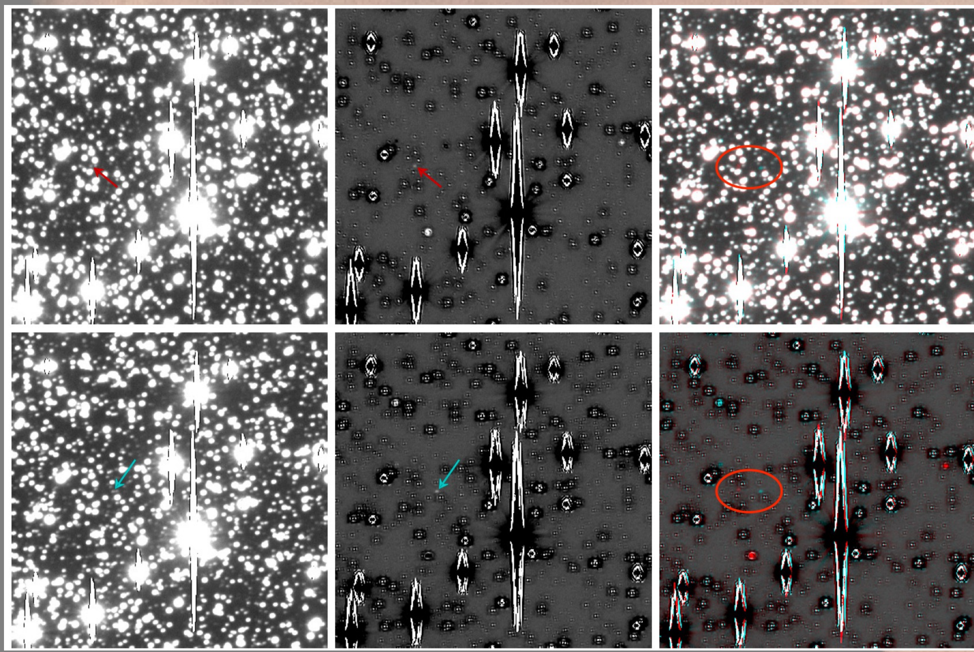


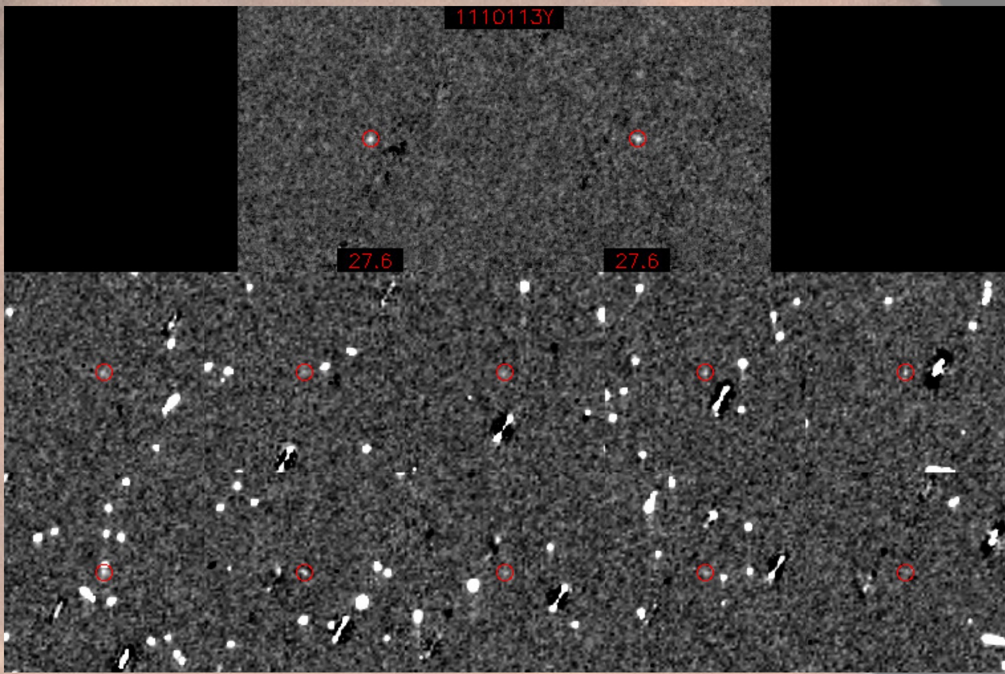
(left) Doner et al. 2024. ApJ Letters, Vol. 961, Issue 2, id. L38
(right) Fraser et al. 2024. PSJ, Vol. 5, Issue 10, id.227

- The next *New Horizons* flyby target will be 70-100 au from the Sun. (Arrokoth was at 44 au, where it formed).
- Study geology, geophysics, surface composition, post-formation evolution of KBO 2x farther from Sun than Arrokoth.
- The spacecraft has sufficient fuel and power to conduct another KBO flyby.

Observations from Earth vs. Space

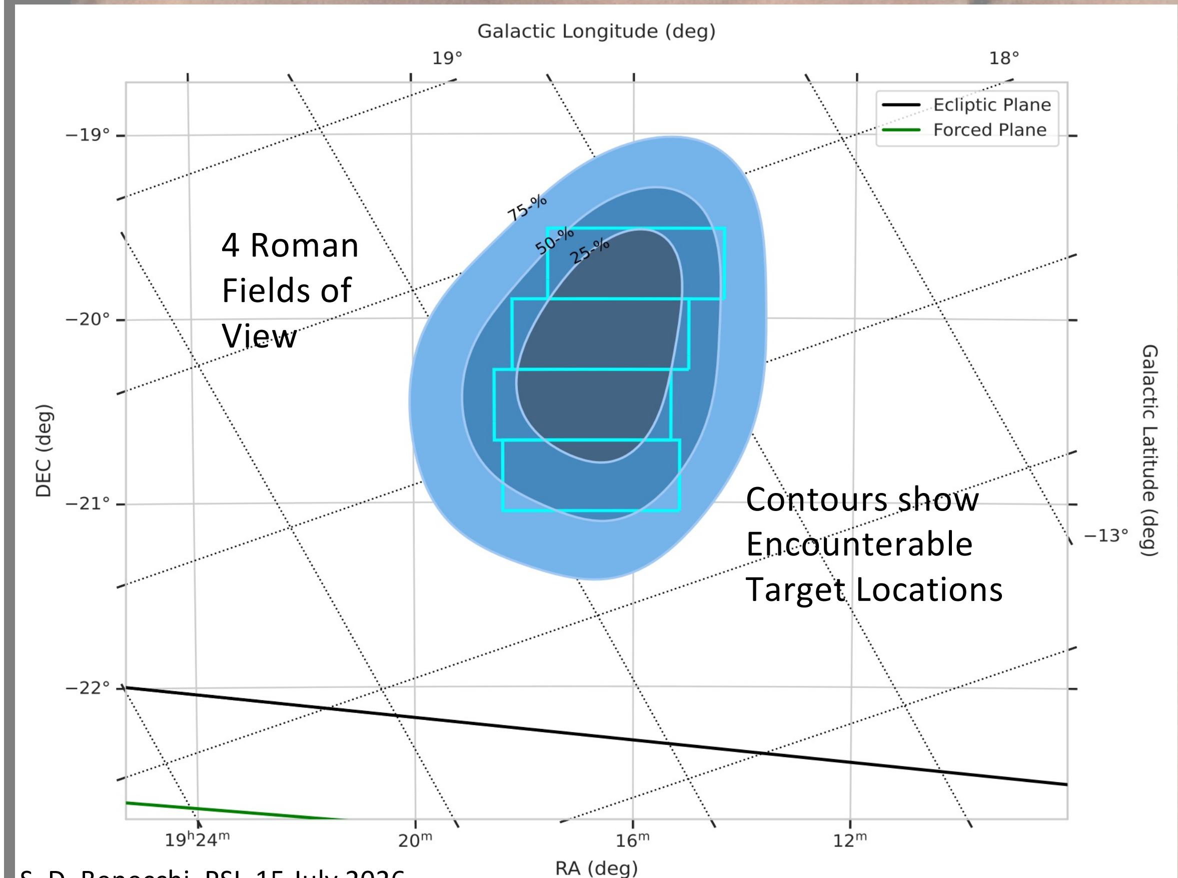
Subaru SuprimeCam Data, Buie et al. 2024





HST/WFC3: Discovery of Arrokoth, Buie et al. 2024

Potential Roman Contribution



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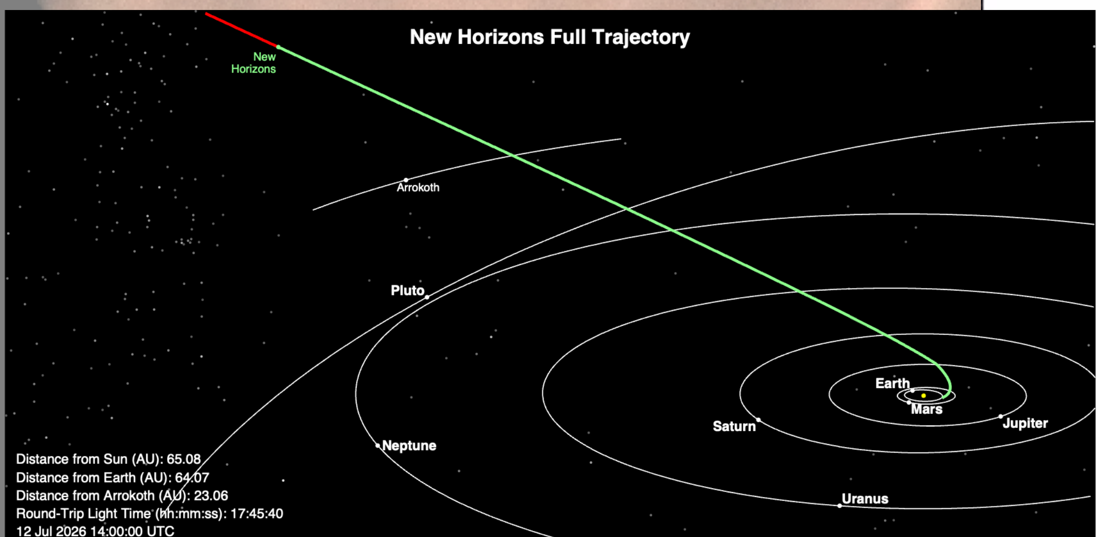
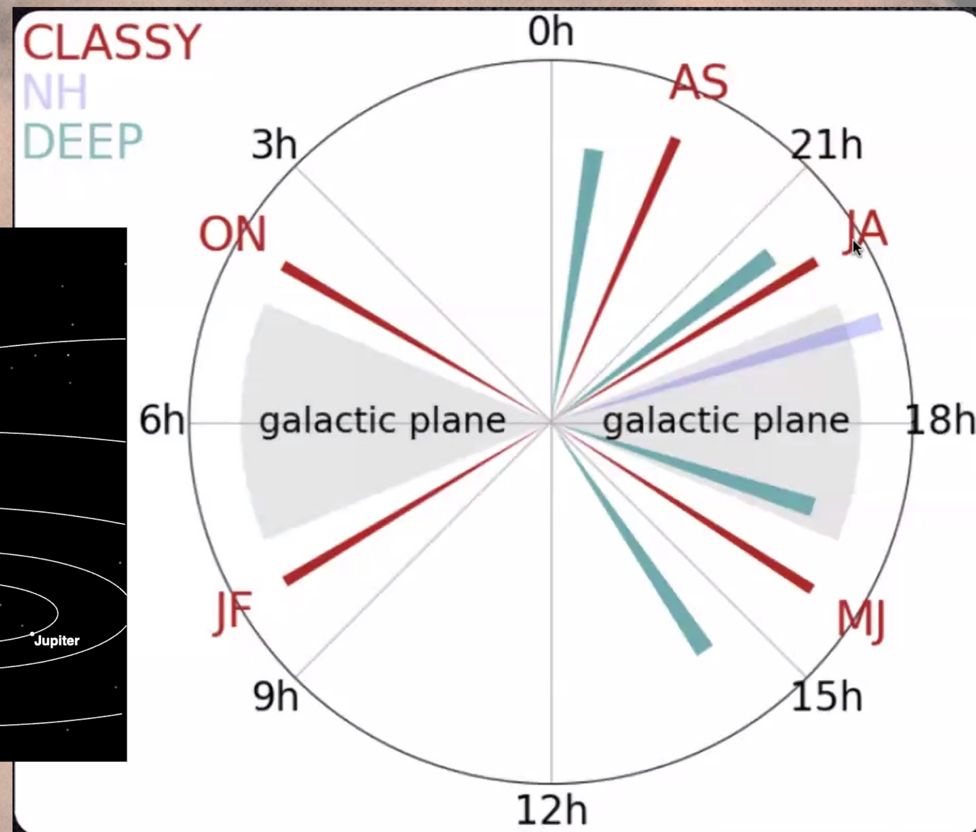
- A deep (r~30.5), 4-*Roman*-field search space, 1.12° sq, centered on *New Horizons*' trajectory 2027-2040.
- Integrate 43.5 hours for image shift+stack to M_{F146}=30.5
- Observing windows: March-May & Sept-Nov
- Paired observations, 6-months apart.

- 3.5% probability of discovering a flyby target → if found can compare surfaces/ structures of bodies from 1-100 au
- ~16 KBOs discovered within 1 au of *New Horizons* → Characterize their shape, rotation, surface properties with multiple high-phase observations from *New Horizons*. Search for satellites at spatial resolutions beyond *HST* and *JWST*

Pointing Relative to Other Studies





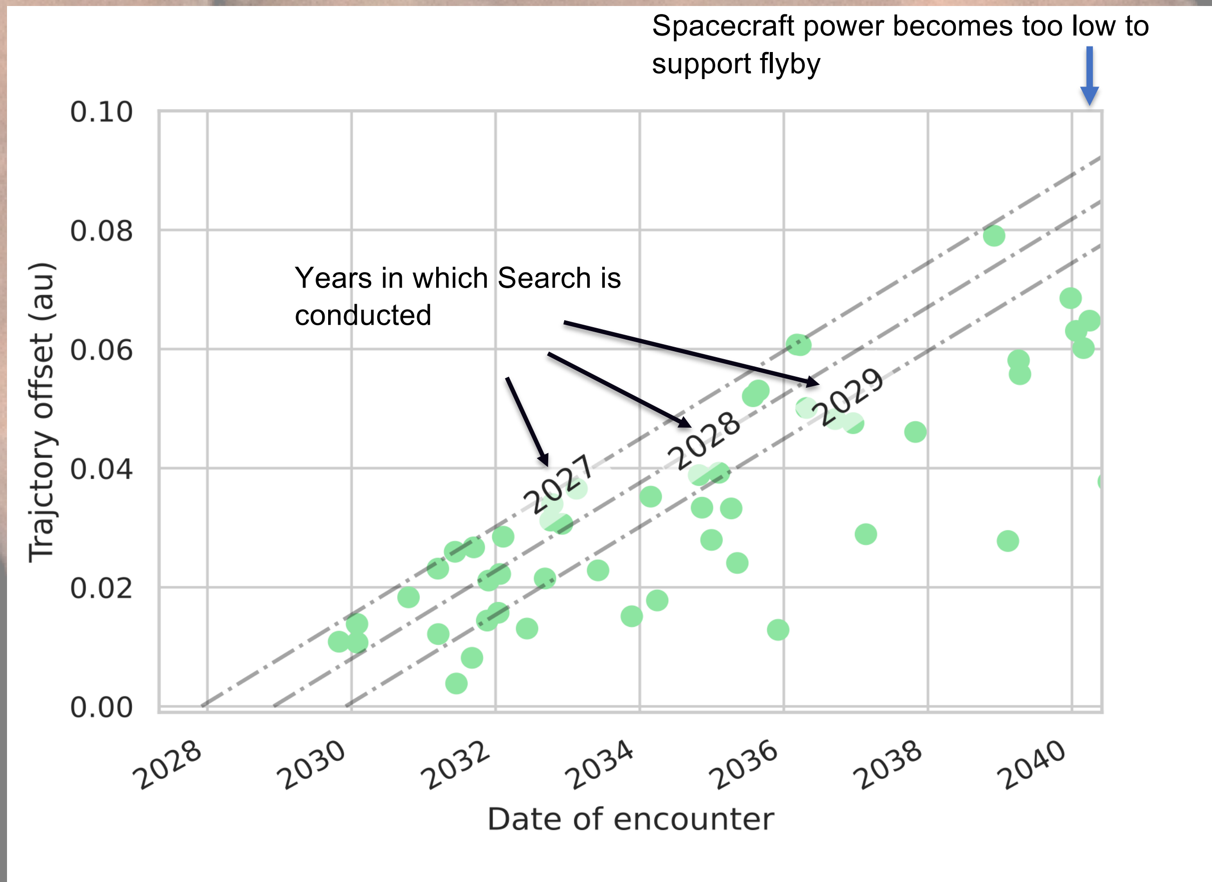
Fraser et al. 2022ff. CLASSY: the Classical and Large-A Solar SYstem survey

Time Critical Nature of Observations

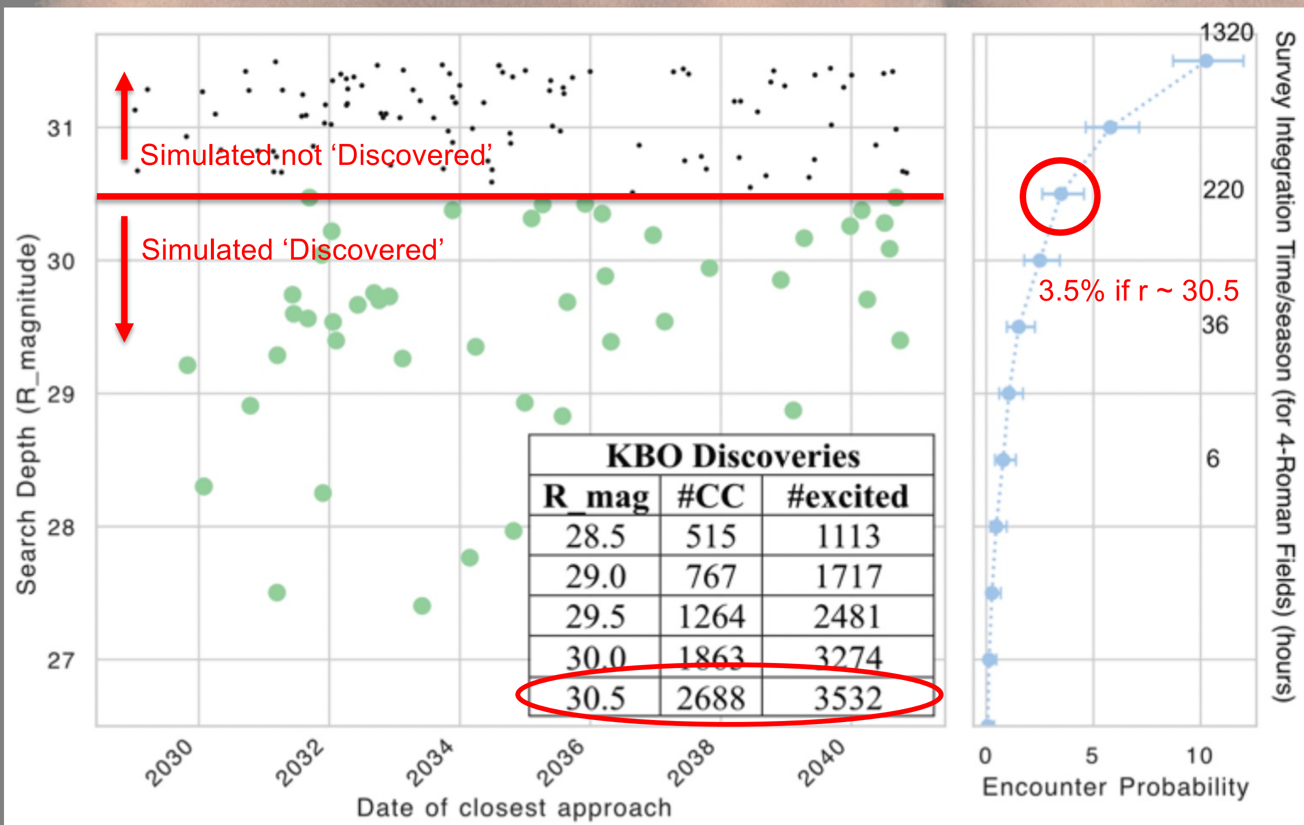
- Figure: The distance encounterable targets are today from *New Horizons*' trajectory vs. when a flyby would occur.
- The volume from which flyby targets can come is *significantly* reduced each year the search is delayed. i.e. the likelihood of finding flyby target *decreases by one third* for each year.

Assumptions:

- fixed D*V* ~30 m/s
- trajectory change 12 months post discovery
- spacecraft power becomes too low to support flyby after 2040

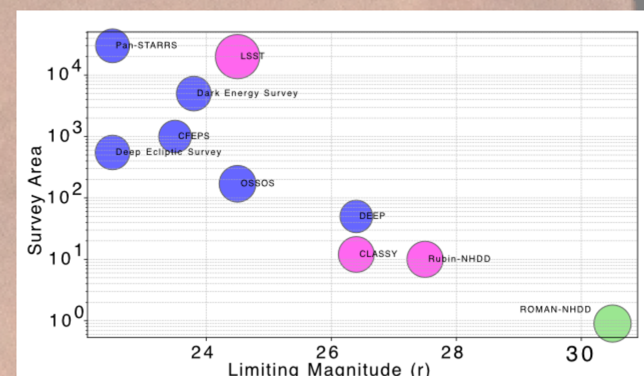


Encounterable *New Horizons* Roman Discoveries & Additional Survey Science Contributions



KBO Discoveries		
R_mag	#CC	#excited
28.5	515	1113
29.0	767	1717
29.5	1264	2481
30.0	1863	3274
30.5	2688	3532

Discover > 5000 small KBOs → Advance understanding of KBO size-frequency distribution



Left: Brightness of encounterable targets viewed from Earth today. Dots are simulated 'discovered' KBOs (green)and 'not discovered' (black).
Right: Probability of finding close flyby target as function of search depth. Probability is ~3.5% if the search reaches *r* ~ 30.5. Calculation uses most recent version of OSSOS++ TNO population model [2-5].

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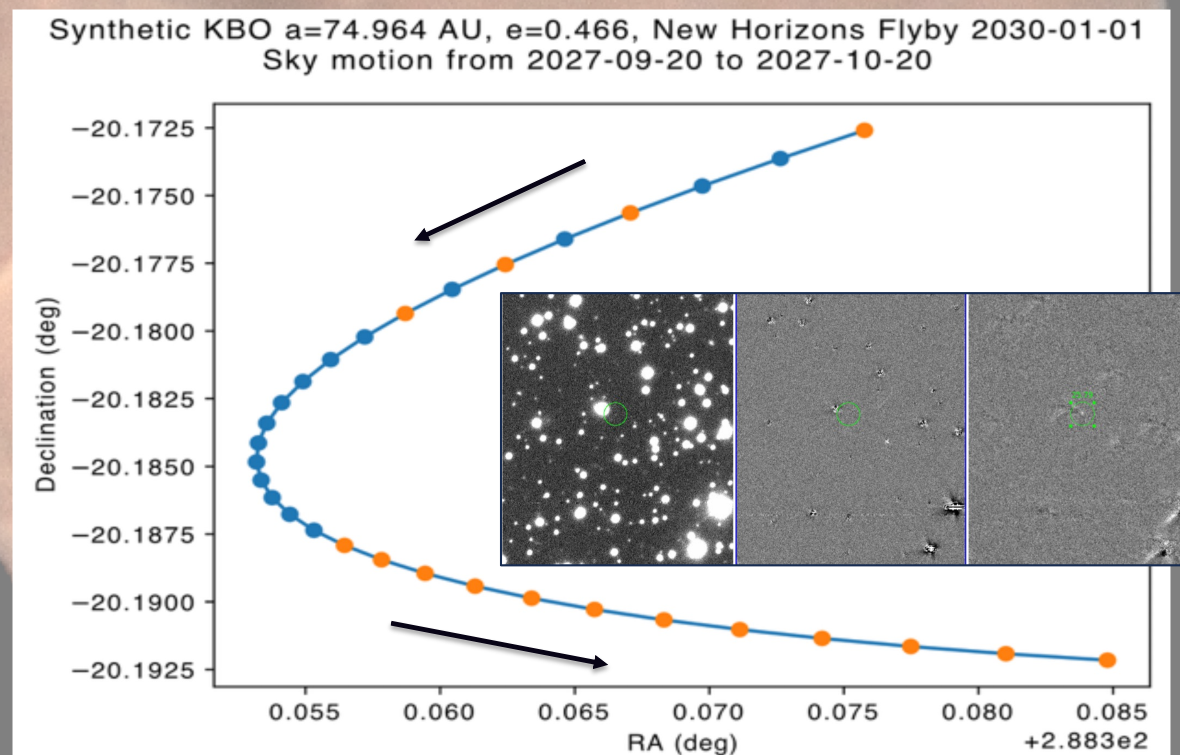
KBO motion over time

Analysis is done with a non-linear shift and stack methodology.

- Recovery of this orbit using the nominal 16 points in orange with an accuracy of 40 mas
- Leads to projected positional uncertainty of ~60 mas (~100000 km) in the next season ~6 months later - sufficient to enable an object discovered in one of the seasons to be directly recovered in the other.

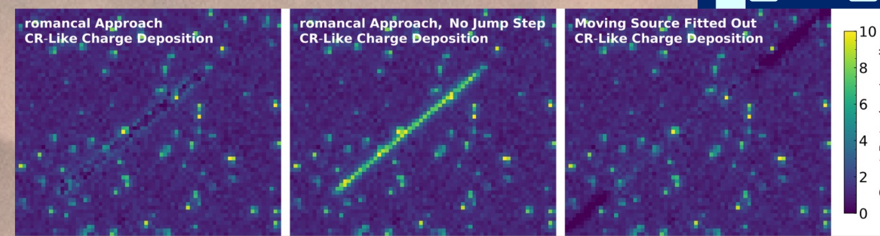
→ Know what population of the Kuiper Belt new discoveries fall into with high precision.

Sky motion of a KBO discovered by *Roman*. Each dot is one day.

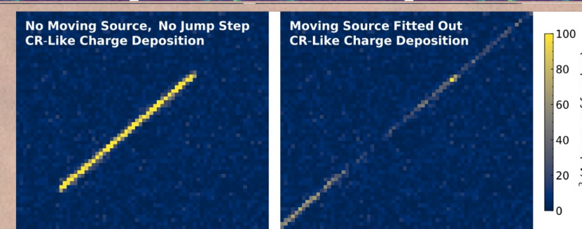


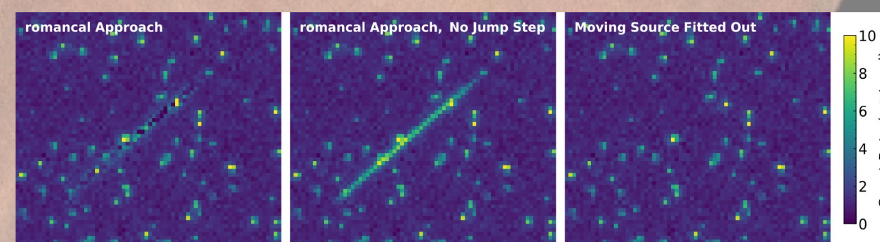
Aside: Contribution to Roman Astrophysics

- The current "Romancal" pipeline (L1→L2) does not properly ID and model moving objects, it assumes CRs.
- Knowing WHERE small bodies are located allows one to properly model and subtract these objects (~1 obj/det/exp in HLWAS, near ecliptic ~3 obj/det/exp)
    - ➔ more accurate photometry
    - ➔ more accurate positions
    - ➔ far fewer false positives

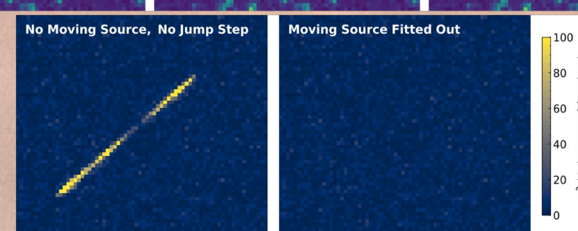


Fitting a Cosmic Ray in L1 Data



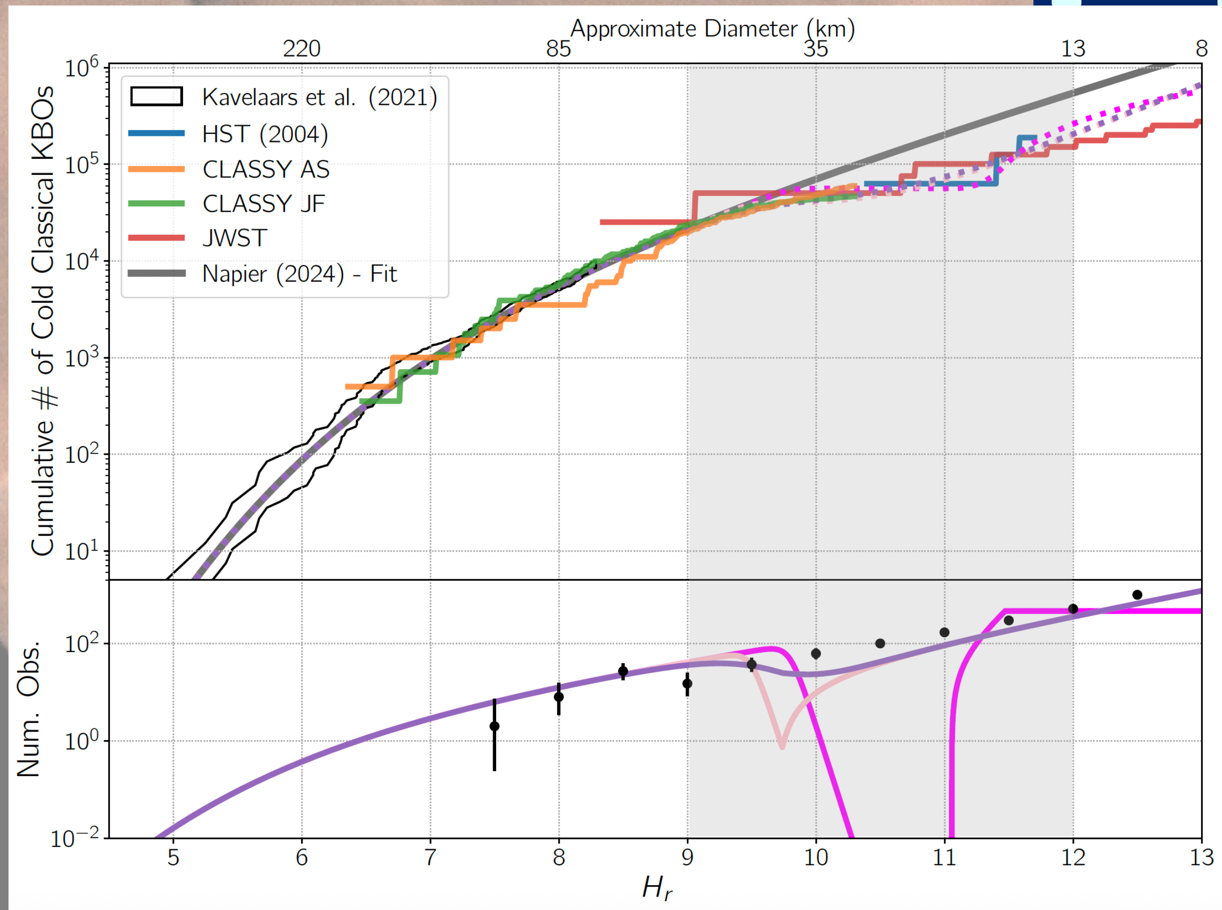


Fitting a Moving Object in L1 Data



Survey Science Goals: Beyond New Horizons

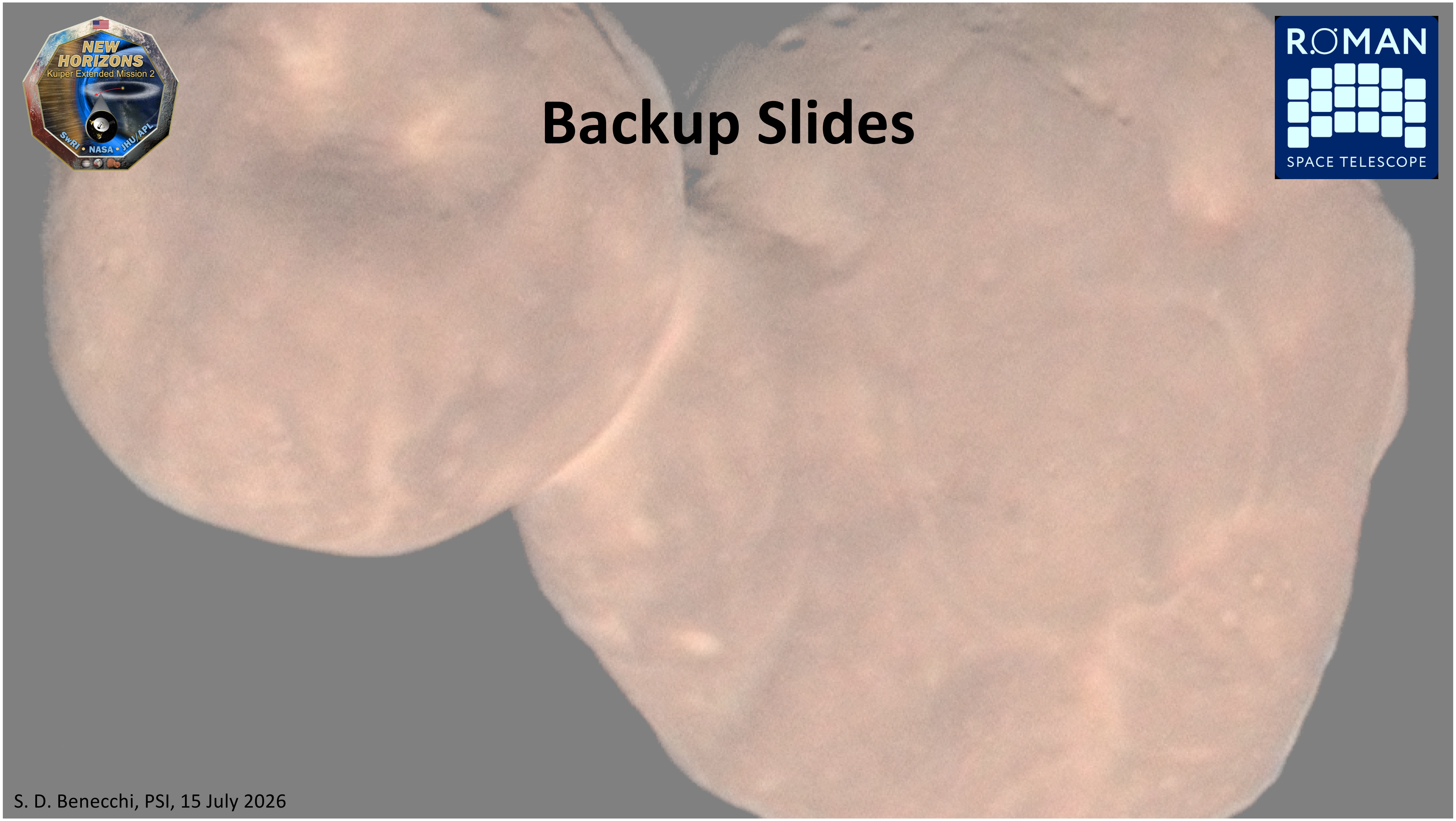
Measure the size frequency distribution in the Kuiper Belt at smaller sizes → investigate streaming instability model: timing of pebble cloud collapse and unaccreted ejecta. Currently all models are consistent with the available data.



Top: Measured cumulative Cold Classical Size Frequency Distribution from OSSOS [6], CLASSY [7], *HST* [8], and the *JWST* Pencil beam (GO-1568) [9] surveys. Solid grey curve is the fit of the exponential taper function to DEEP data [10]. Diameters assume spherical bodies with visible albedos = 0.12.
Bottom: Differential curves of the model absolute magnitude distributions, including contributions of the primary bodies formed during pebble cloud collapse and unaccreted ejecta. Curves show different variations in SFD slope of ejecta and smallest mass of accreted primary body in the model.

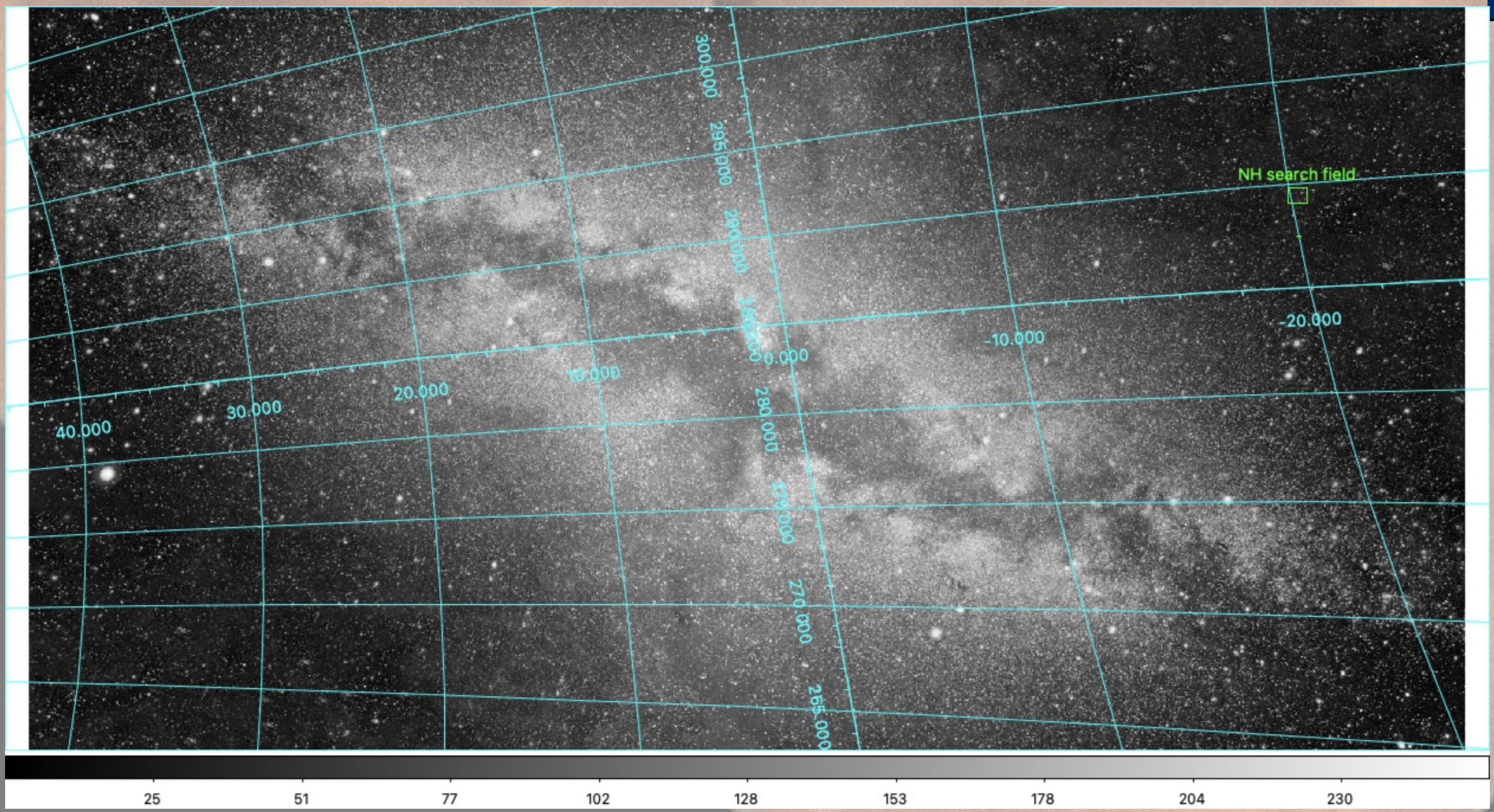
Take Aways

- Roman is a unique platform for Solar System Studies at **all** heliocentric distances
    - New Object discovery at sizes inaccessible from other facilities.
    - **Could** enable a fly-by of a KBO by *New Horizons*
    - Population statistics
    - Observation timing decoupled from Earth's 24-hour rotation
    - Physical studies (color, rotation, binarity)
    - Size Frequency Distribution → timing of object building in the solar nebula
- Astrophysics studies benefit from proper removal of foreground/solar system sources



Backup Slides

NH Search Field Location



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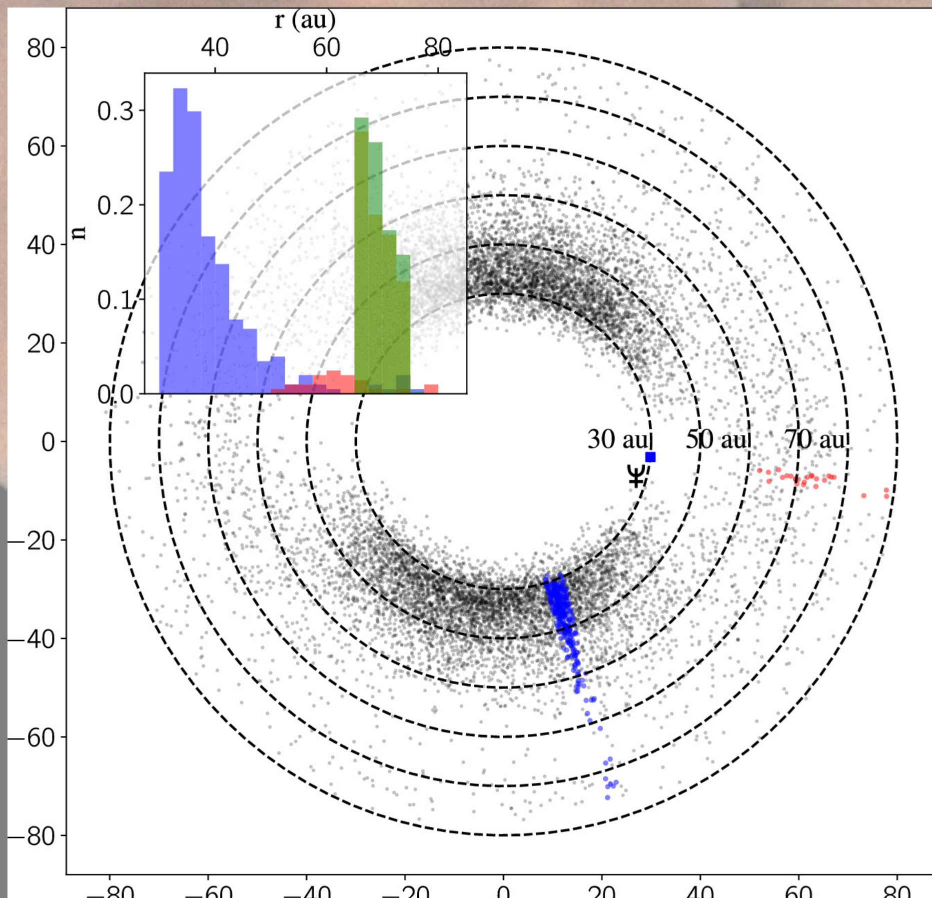
Survey Pointing & Discovery Bias



The spatial distribution of the model 5–2 resonant objects in the OSSOS++ model realized on Julian Date 2459874.5. The position of Neptune is shown by the blue square. Only those objects with $r < 27$ are shown. The realization is ~8× oversampled. Objects seen by the New Horizons and DEEP pointings are shown in blue and red, respectively, with color-matched histograms of each sample shown in the inset. As well, the inset also shows an example of a radial distribution of discoveries that would be discovered from an annulus model in the New Horizons (orange) and DEEP (green) pointings. The example is of an annulus centered at 70 au. The annuli histograms have been rescaled for clarity. Annuli centered at other distances merely move the histogram of simulated detections inward or outward accordingly. This figure demonstrates how strongly survey pointing can influence the density and distribution of detectable resonant objects, an effect that is not present in distributions that are longitudinally symmetric. From Fraser et al. 2024

Studies on Roman Level 1-> Level 2 Products

- Masiero, Joesph. “Technical Memo: The Impact of Nancy Grace Roman Telescope’s default image processing on the detectability of moving Solar system objects” 2025. https://arxiv.org/abs/2509.20469
- Holler, Bryan. “The Roman Space Telescope as a Planetary Defense Asset” 2025. PASP. Volume 137, Issue 10. https://arxiv.org/pdf/2508.14412
- Brandt, Timothy. “A Classic Nonlinearity Correction Algorithm for Detectors Read Out Up-The-Ramp” 2025. https://arxiv.org/pdf/2512.09132

Actions to Enable Single Image Streak Analysis

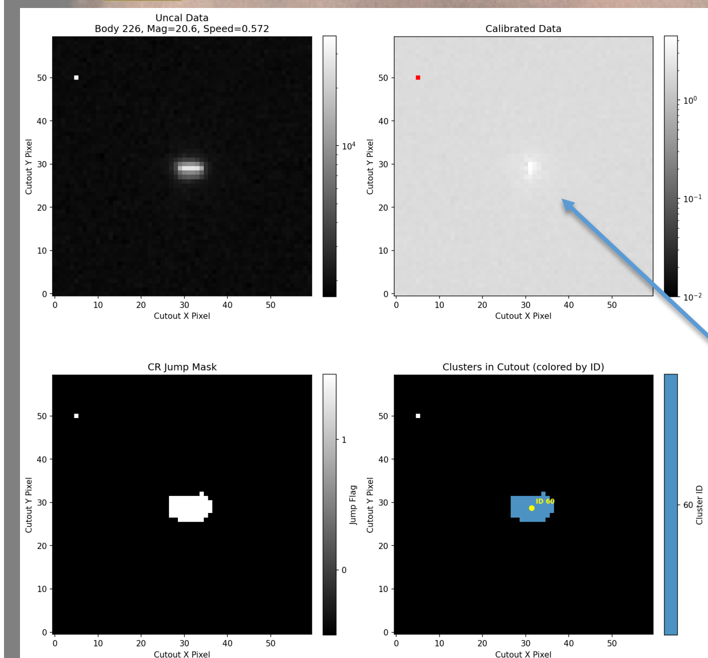
- Requires some additional information to be stored from Level 1-> Level 2 processing
  - DQ flags and CR jump locations up the ramp (2D DQ array vs 3D Resultant DQ Array)
  - Per-pixel chi-sq
  - Difference between uniform weight and optimal weight slope

- New tools in development (not in romanacal but could enhance the Roman mission):
  - Clustering algorithms to identify moving object streaks
    - Inputs required: DQ Array
  - Tim Brandt's new model and retrieval method
    - Inputs required: Initial guess of position/velocity of moving object

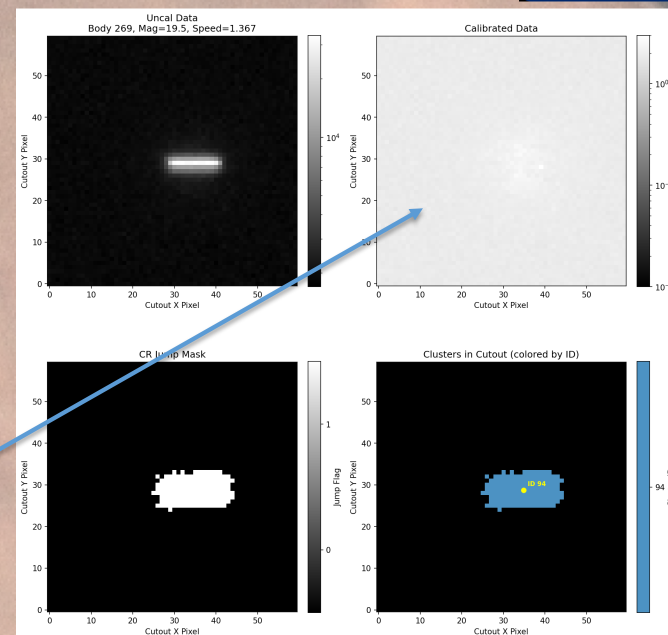
- Take away and next steps: Computationally fast clustering on the DQ array of a single image can provide the information need to locate and remove and most importantly preserve astrophysical information on solar system moving body streaks.

Clustering Algorithm

MBCs – Roman I-sim -> RomanCal – ARTIFACT/REMOVAL



- (Both) Top left: Roman I-sim L1 last resultant from uncalibrated data of moving body
- (Left) Top right: L2 calibrated image with romancal showing remnant artifact or ghost; not suitable for science
- (Right) Top right: L2 calibrated image with romancal showing streak is completely removed;



- RESULT (Both) Bottom row: 2D clustering of jump pixels in 2D DQ array can identify MBCs because pixel level changes in flux in time are identified as cosmic rays or jumps

Single Image Streak Analysis

- Tim Brandt New Method:
  - Calculate full maximum likelihood of a streak over all pixels with all resultants
  - Ansatz: static astronomical scene + point source moving at constant velocity
  - Outputs:
    - Best-fit static count rate for each pixel
    - Best chi squared for each pixel
    - Best-fit track of the moving object
    - Best-fit parameters of the moving object (x, y, vx, vy, flux)
  - Note: cosmic rays can make streaks, but not gradually over the entire exposure. They look different temporally in L1 data (next slide).

- RESULT modeling a moving source to minimize chi squared and remove it naturally returns scientifically valuable information about the source

What Additional Information to Save?

➔ resultant_dq or group_dq array

- As a small body streaks across pixels, changes in flux are flagged as cosmic rays
- Correlated positions in the flattened dq array can be used to cluster cosmic rays to identify streaking objects
- Further inspection of the **resultant dq array (not currently saved or available for analysis)** would correlate clustered cosmic ray flags in time up the ramp.
- 2D combined with 3D clustering would almost certainly associate groups of cosmic rays to actual moving bodies and remove most if not all of false positive cases by just inspecting the 2D dq array
  - Snowballs and oblique cosmic rays would not be observed up the ramp

Recommendation to RSC Project: Minimal Changes

- Decide on which approach provides the best information on initial guesses for moving object positions/velocity
  - DQ flags/jump locations (DQ extension of standard output)
  - Per-pixel chi-sq
  - Difference between uniform weight and optimal weight slopes
- Add/save selected keyword(s) and content (already calculated in the pipeline) to L1 outputs
  - Meta data about streak identification in image (Boolean), location (pixel coordinates and small cut-out region)
  - Unique DQ array flag – Moving Body Candidate (MBC)

➔ Brandt code available on Github

➔ Cosentino code available in SOC

➔ Key: The project now includes the needed inputs to avoid re-processing full images from L1 (saving significant NEXUS compute resources) - only "stamps" are required around desired locations to produce science results