Exploring the Expanding Frontier from New Horizons

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The Expanding Frontier of the Outer Solar System

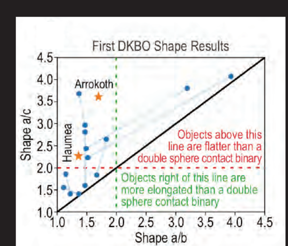
New Horizons in the Kuiper Belt

New Horizons uses its LORRI camera to uncover intruiging trends of the growing number of KBOs that hold unprecedented implications for planetesimal and planetary system formation, and perhaps even for KBO interactions with the interstellar medium.

Binaries are the Common End State

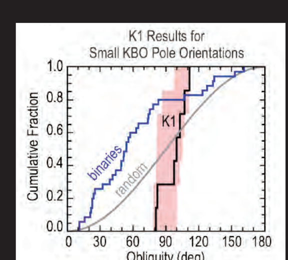
Since the surprising discovery that Arrokoth is a contact binary Arrokoth, 31 distant KBO (DKBO) observations have been completed from New Horizons. Porter et al. (2023) analyzed so far seven of these in detail. Despite being a relatively small data set the results already imply that binaries may represent a common end state of KBO evolution (Porter et al. 2023) and has forced a revision of fundamental planetesimal formation theory.

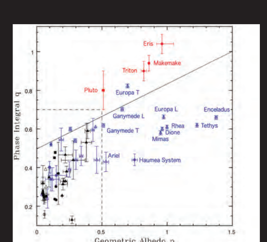
The technique relies on the unique distant position of New Horizons that provides varying Sun phase angle to KBOs as the spacecraft travels outward that cannot be achieved by any other observation from the inner solar system or Earth. Measuring the resulting light variation as the KBO slowly rotates offers insight into the shape, rotation rate, and pole axes orientations of the KBOs.



Rotation Poles are Similar

All of the KBOs analyzed by Porter et al. (2023) have rotational poles that are at very high obliquities with respect to their heliocentric orbits (pink band) and contrasts strongly with a random distribution (gray curve). The orientations of binary KBO mutual orbits (blue curve, Grundy et al. 2019) are very similar to the orientation distribution of angular momentum vectors from streaming instability (Nesvorný et al. 2019), but are completely different from the small KBO obliquity distribution.



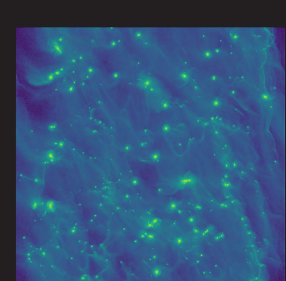


Different Surface Properties

Hot Classical KBOs and scattered objects have distinctly different surface properties from Cold Classical KBOs (Verbiscer et al. 2019, 2022). This may be a result of forming in a region of the nebula where the chemistry was different.

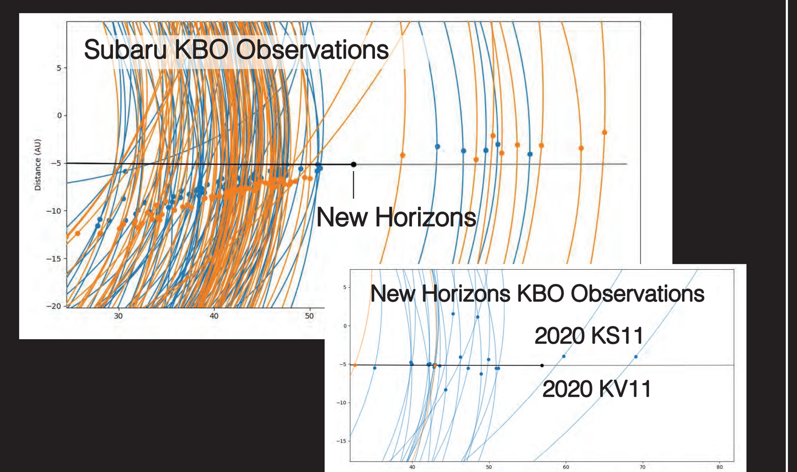
Far-Reaching Implications

McKinnon et al. (2020) suggested that Arrokoth formed initially as a close, but separated, binary directly from the protoplanetary disk through the mechanism of the streaming instability. Nesvorny et al. (2019, 2021) proposed that the streaming instability is the primary means of forming KBOs, and is very likely to form KBOs initially as separated binaries.



A Second Kuiper Belt?

Recent Results



Main Panel: Kuiper Belt Objects detected from the Subaru 2021 (blue) and 2022 (orange) observations (Fraser et al., 2023). The horizontal black line is the trajectory of New Horizons, the black dot represents the spacecraft's position on 2022-12-15. The colored dots show the locations of the discoveries at the point on their orbits when New Horizons is closest to them. For reference, the spacecraft will pass 60 au in October 2024. **Inset:** KBOs observed or planned from New Horizons.

Searching for new KBO Targets

Given the possible indication of a massive population of KBOs beyond the main belt, efforts are intensified to use ground-based and near-Earth facilities to do deep searches for KBOs (Fraser et al., 2023).

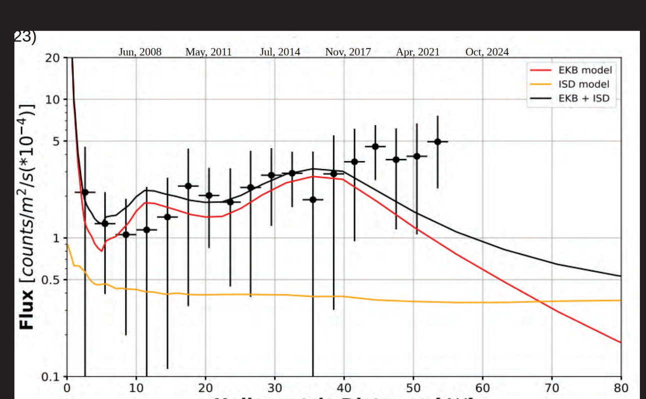
Two newly discovered KBOs are already known to be observable by LORRI in the coming years. Both are bright enough from New Horizons to obtain solar phase curves. By using ongoing ground-based searches, we expect that at least three to four more distant KBOs observable by LORRI will be discovered in the next couple years, and it is possible that some may appear bright enough to LORRI that rotational light curves can be obtained, providing shape constraints. These objects sample the dynamically excited subpopulations of objects that originally formed closer to the Sun before being perturbed outward early in solar system history, and this new Kuiper Belt population offers a major addition to the current data set.

Searching for new KBOs observable by New Horizons will first require intensified simulations of populations that would intersect the New Horizons trajectory (Kavelaars, Napier, et al.).

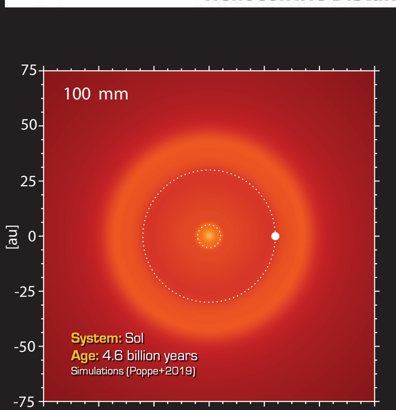
Current searches include the Subaru and Cerro Tololo Inter-American Observatories that have uncovered 242 KBOs 2020-2023, HST astrometry programs to enable potential DKBO observations and the OSSOS survey. The KBO discoveries have been delivered to the Minor Planet Center (MPC) and are publicly available.

Upcoming observatories such as JWST, Roman Observatory and Euclid are vital in this upcoming search to eventually find KBOs at distances of more than 60 au.

Circum-Solar Dust: Another Surprising Result!



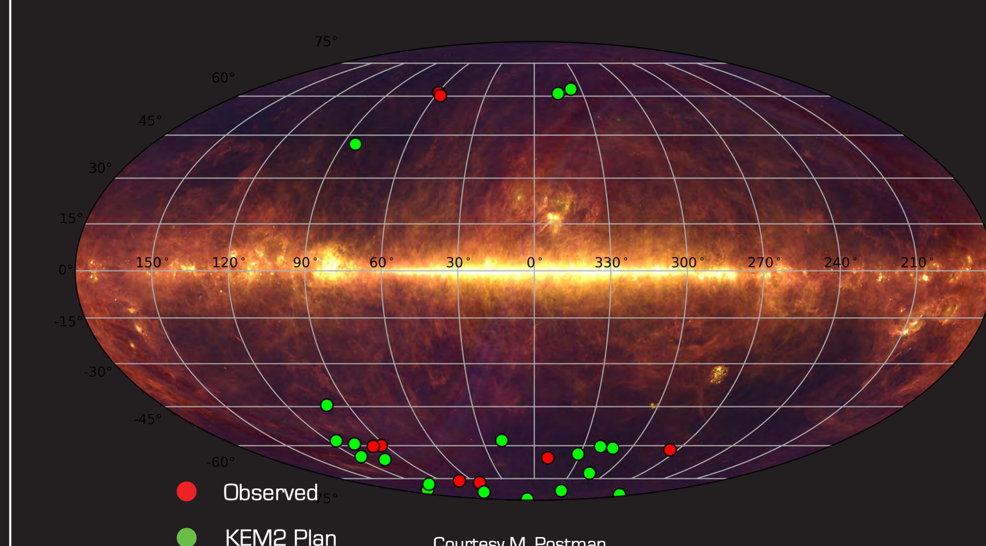
The most recent SDC flux estimates reported by Doner et al. (2023) now clearly show an increase in rather than the theoretically predicted decline, which is consistent with the notion of a massive KBO population beyond the main Kuiper Belt.
The figure shows the dust flux for particles with a radius greater than 0.63 μm from 1 to 55 heliocentric astronomical units. Each point is an average of the flux measured by each film across each 3 au traversed by the New Horizons spacecraft. The orange curve represents the ISD flux values calibrated from Ulysses measurements. While ISD grains are much smaller (~0.28μm),they are also traveling at higher velocities and as a result SDC interprets them as small IDPs (Bernardoni et al. 2022). red lineshows a model from (Poppe et al. 2019) that is normalized to the SDC measurements and assumesSDC is impacted only by IDPs. The black line is a sum of the orange and red models to provide a more comprehensive model of the total flux SDC is measuring.



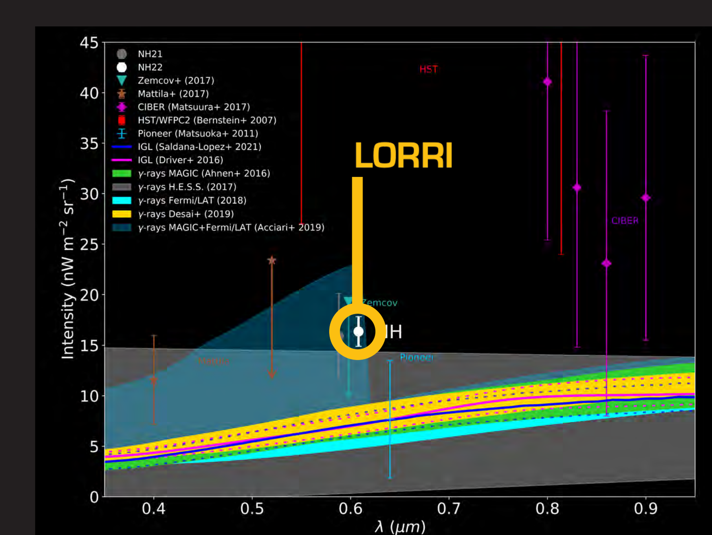
(Left) Models of the circum-solar dust disk predict a decline beyond the main Kuiper Belt, which appears now to be in direct contradiction to observations. Because of the very limited dust measurements in our solar system, we have little insight into what a mature circum-solar dust disk looks like. (Right) ALMA observations of young protoplanetary disks show highly structured disks that may indicate planetary formation at a very young age. SDC is currently the best dust measurement we have in the ecliptic plane of the outer solar system and therefore is vital for helping us understand planetary system formation in general.

Astrophysics Beyond

Excess of Cosmic Optical Background (COB)

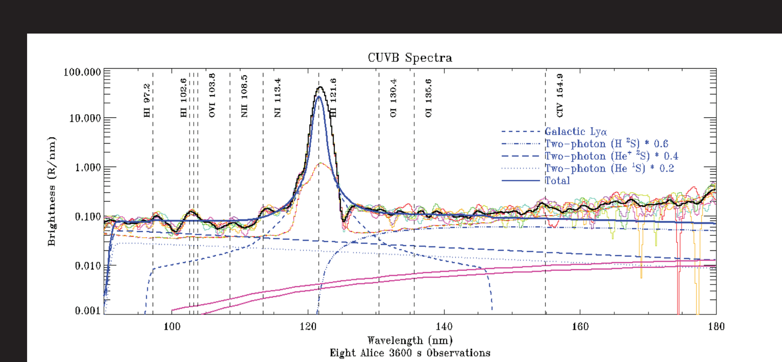


In the next year, New Horizons will obtain COB measurements of multiple fields (Figure 10b) to establish that the fluxes are sufficiently accurate to provide a strong test of the COB fluxes inferred from galaxy counts and the attenuation of cosmologically distant very high-energy λ-ray sources. The number of the fields also allows them to be tested for homogeneity of the COB, a key diagnostic for whether the unknown component is generated on cosmological scales.



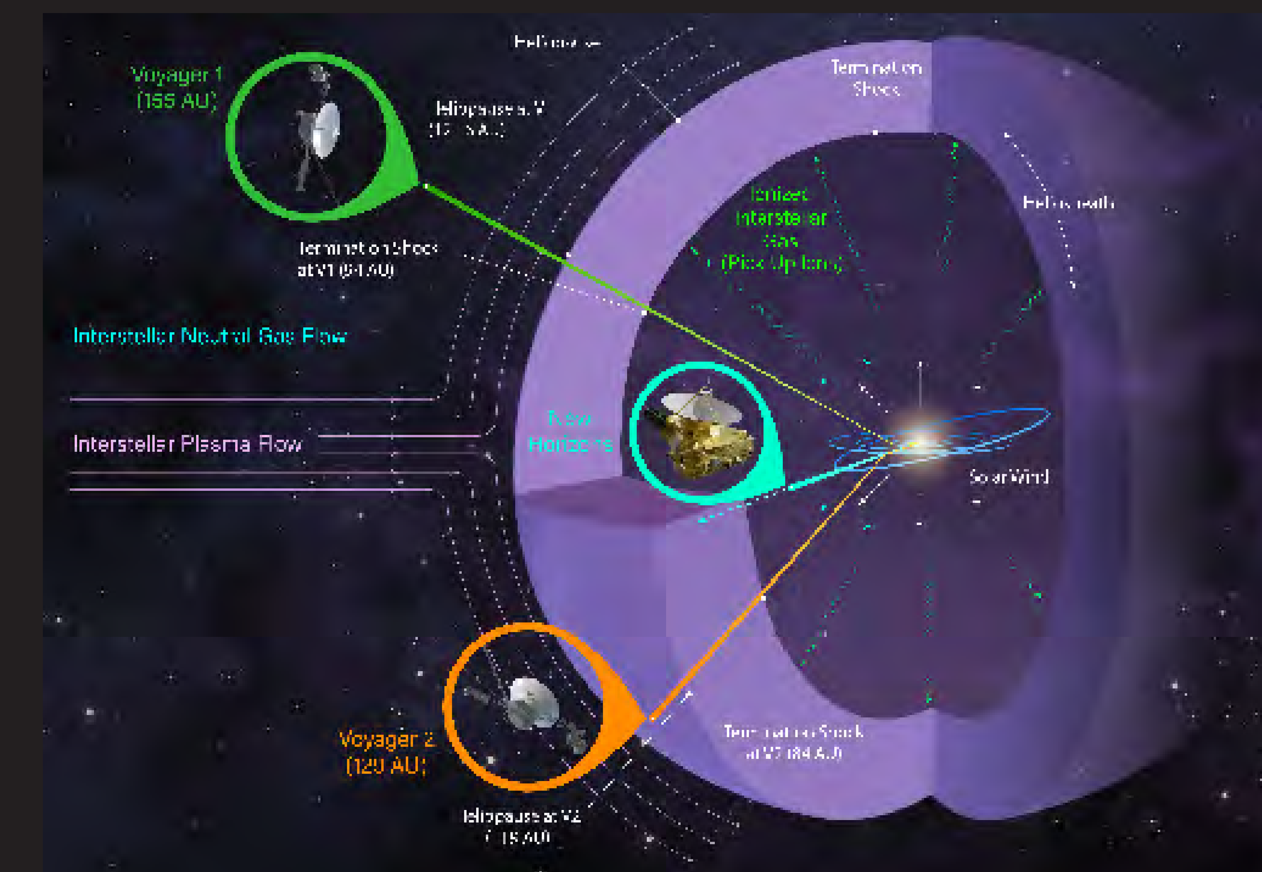
New Horizons' great distance from the Sun allows unprecedentedly sensitive measurements of the COB, because the spacecraft is far beyond most solar-illuminated dust. Using LORRI observations, Lauer et al. 2022 derived a COB flux of 15.36 ± 1.40 nW m−2 sr−1, which is in ~5 sigma conflict with the hypothesis that the integrated light of external galaxies (IGL) can account for the COB, as well as with the simplest models of the gamma-ray attenuation. The excess over the IGL may validate arguments that the present galaxy counts have not included the full variety of stellar systems.

Cosmic UV Background (CUVB)

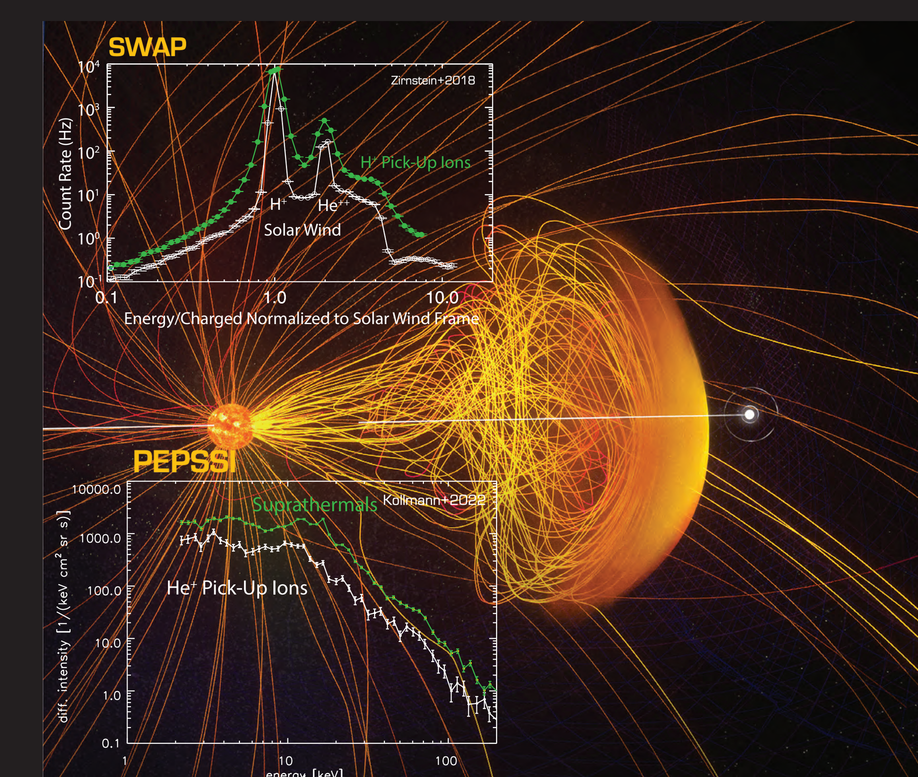


New Horizons' large heliocentric distance also opens a unique window into cosmical UV background radiation from outside the heliosphere. The background UV spectrum observed is a combination of contributions from the outer heliosphere, the Local Interstellar Medium, and more distant sources out to z<~1, which New Horizons can help to disentangle with a combination of Lyman-α imaging and spectroscopy. Data from the Galaxy Evolution Explorer (GALEX) in the range of 130 to 180 nm obtained at 1 au suggested significant emission from unknown sources, although Kulkarni et al. argues that about two-thirds of this unknown component can be explained as emission from weak shocks, H2 fluorescence, or two-photon continuum emission. Given its distant position, New Horizons can test these contributions using Alice to obtain deep spectra at several fields.

The Heliosphere and Interstellar Medium



As the Sun plows through the VLISM, the solar wind carves out a vast magnetic bubble—the heliosphere—which interacts with galactic cosmic rays, ISD, plasma, and gas. Over the next several years New Horizons is nearing the inner edge of the heliosphere, the Termination Shock. In this region so-called interstellar Pick-Up Ions (PUIs) dominates over the solar wind pressure, and ultimately play the leading role in upholding the entire heliosphere. New Horizons is now the only spacecraft now in the outer heliosphere, with the Voyager mission in the interstellar medium - a historic, unique constellation for investigating the complex propagation of solar disturbances from the Sun, through the outer heliosphere and into the unknown interstellar medium (Hill et al., 2020, Brandt et al., 2023). Figure adapted from Krimigis et al., 2019.



PUI observations by New Horizons. Upper graph, in addition to measuring the solar wind, SWAP measures the proton PUIs and how they are preferentially accelerated by an interplanetary shock. The white curve denotes conditions before the shock, and the orange curve denotes conditions after shock passage (Zirnstein et al., 2018). Lower graph, PEPSSI measures He+ PUIs and how they respond to a passage of CIR. The white curve d notes conditions before CIR passage, and the orange curve denotes conditions during CIR passage (Kollmann et al., 2023).

Upholding the Heliosphere

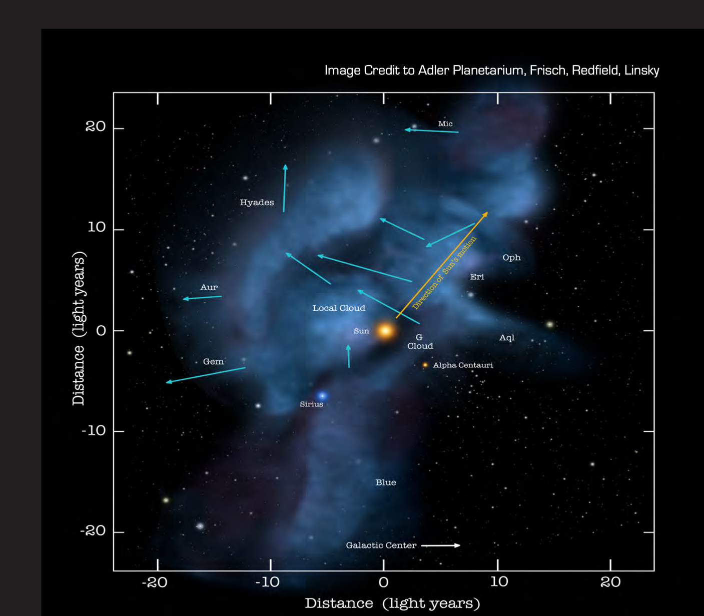
SWAP and PEPSSI measures a unique kind of particle, "Pick-Up Ions", explaining how the boundary is upheld as the heliosphere plows through interstellar space (Shrestha et al., 2023, Kollmann et al., 2023).

Evolution of the Solar Wind

SWAP and PEPSSI observes how the solar wind slows down as it starts sensing the interstellar medium and how solar shock waves propagate and accelerate particles (Elliott et al, 2019).

Galactic Cosmic Rays

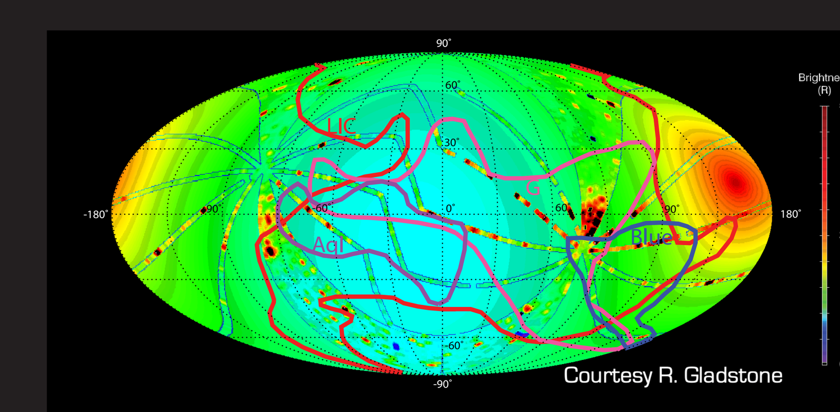
PEPSSI also detects the very high energy particles that manage to penetrate the magnetic barrier of the heliosphere and how they are modulated (Hill et al., 2020).



The Sun moves through a neighborhood of dense interstellar clouds. For the past 60,000 years it has been traveling through the Local Interstellar Cloud (LIC), but is at this very moment transitioning over to the lesser known G-Cloud (Redfield et al., 2008). Our knowledge of these clouds is derived from HST spectral observations toward nearby stars. Alice is giving us our first full sky map in the UV which will offer the opportunity to search for their large scale morphology.

Alice Ly-Alpha Skymap

Searching for the Hydrogen Wall and Interstellar Clouds



New Horizons' Alice has completed the first full Lyman-α sky maps with high resolution and sensitivity (expanding on the six great-circle scans and proof-of-concept 30°-wide contiguous sector shown here). The smooth background model includes multiple scatterings of solar Lyman-α and isotropic 43-R galactic background (Gladstone et al., 2021). New Horizons is uniquely positioned to reveal the large-scale structure of the H wall and LISM cloud signatures (colored outlines of LIC, G, Blue, Aql, mapped by Redfield et al., 2008)