INTERSTELLAR PROBE

A Mission to the Heliospheric Boundary and Interstellar Medium for the Next Decade

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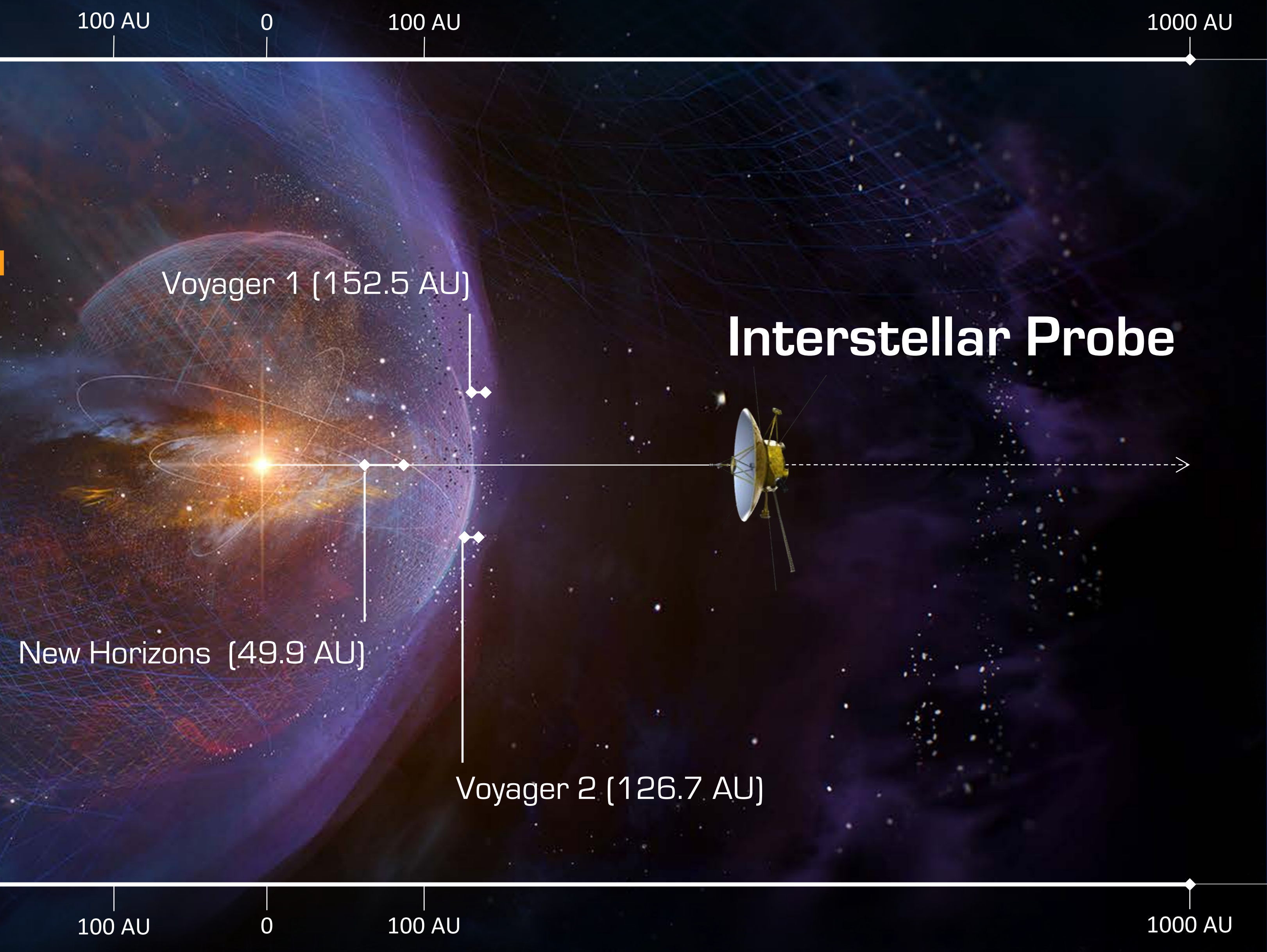
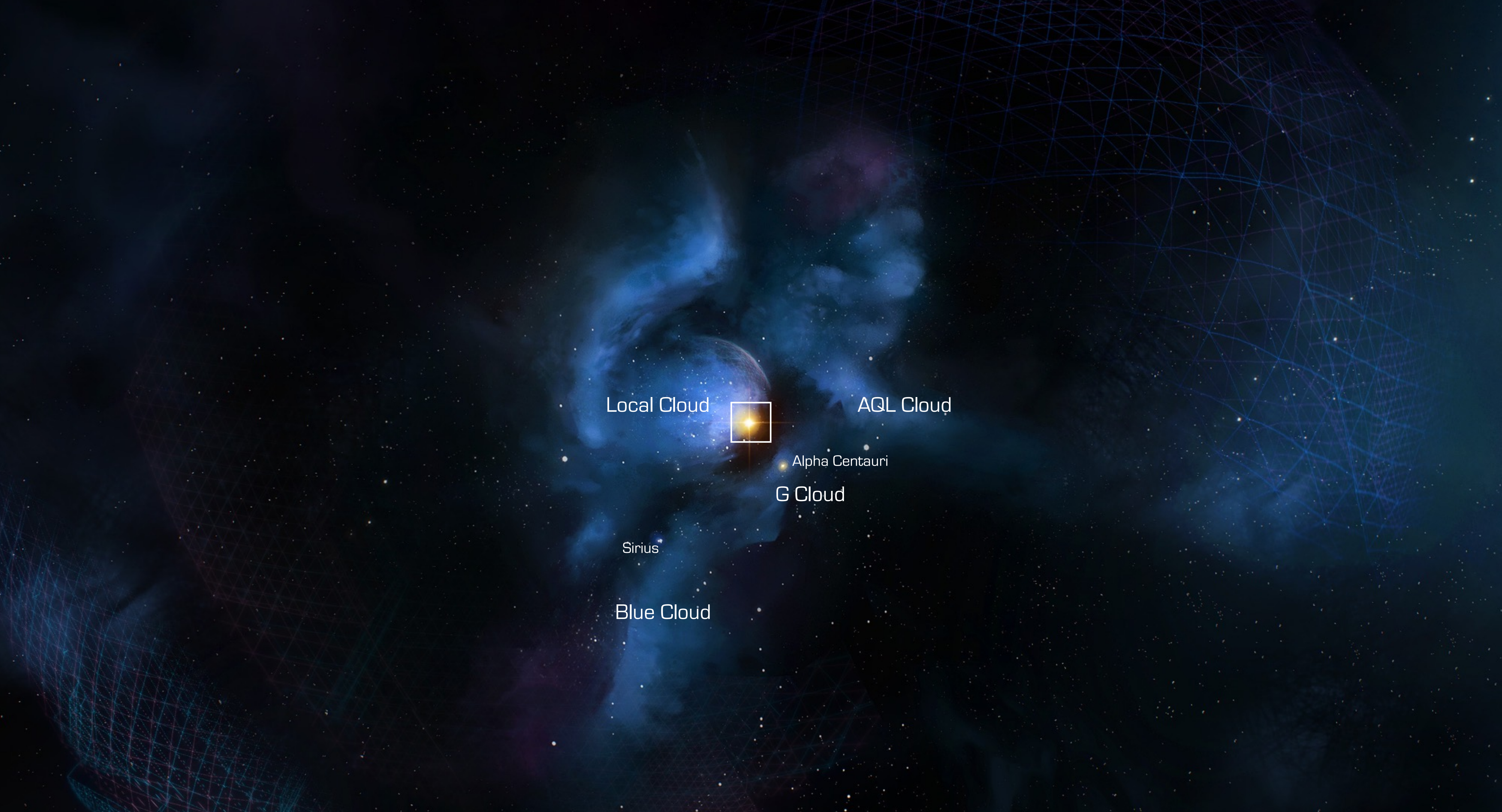
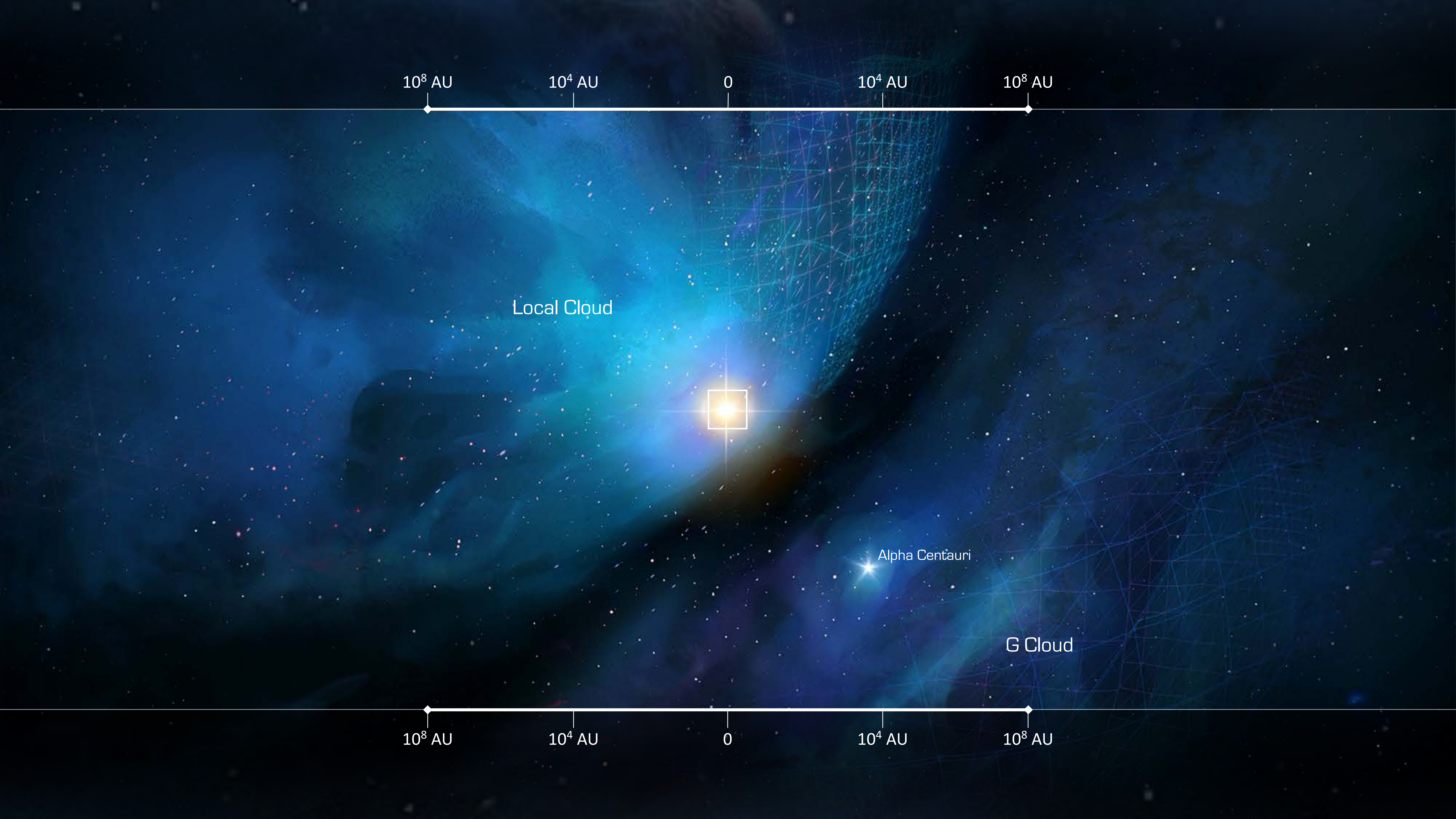
26 April, Virtual




Local Cloud
AQL Cloud
Alpha Centauri
G Cloud
Sirius
Blue Cloud


10^8 AU
10^4 AU
0
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Local Cloud
Alpha Centauri
G Cloud
10^8 AU
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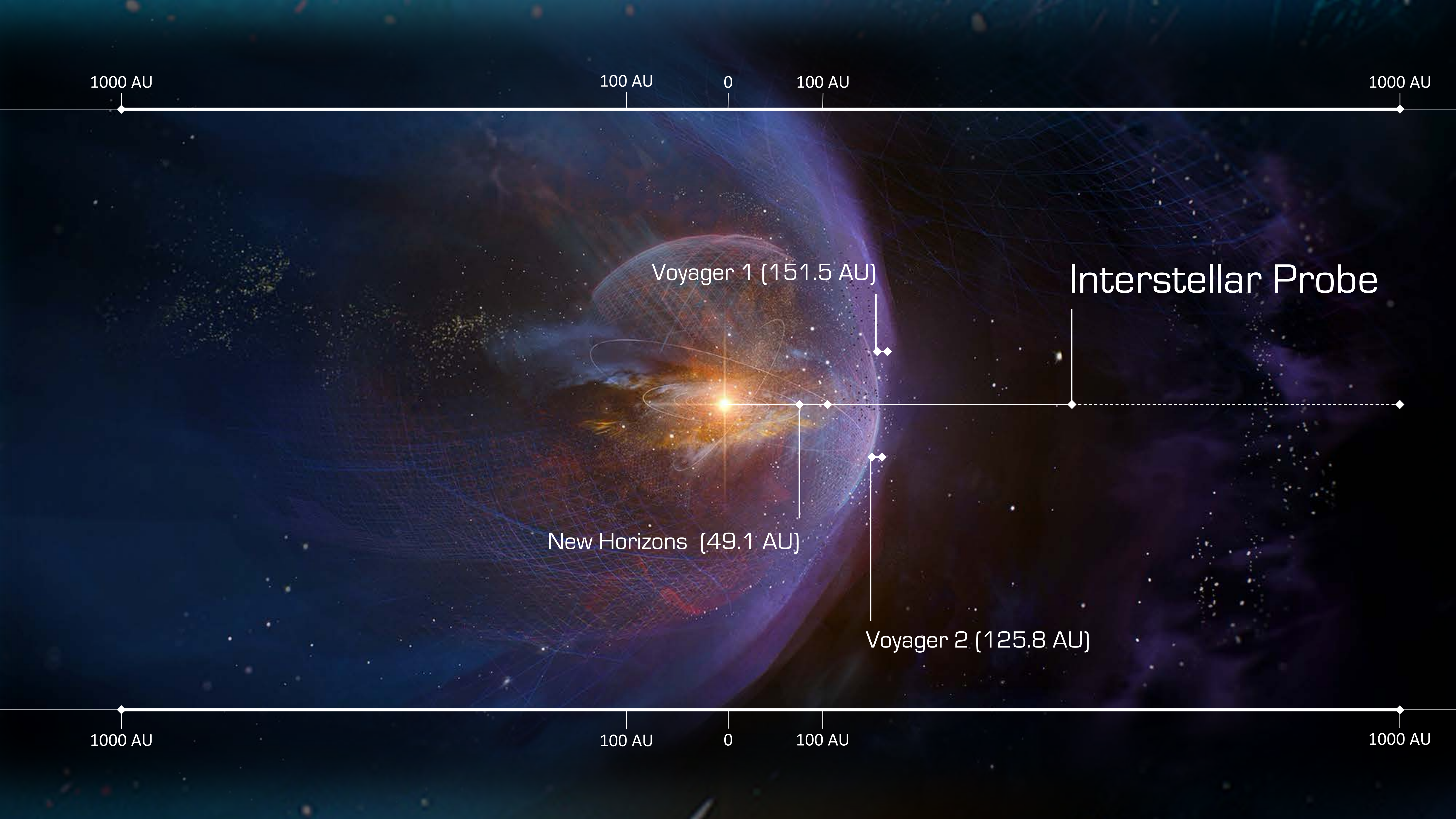
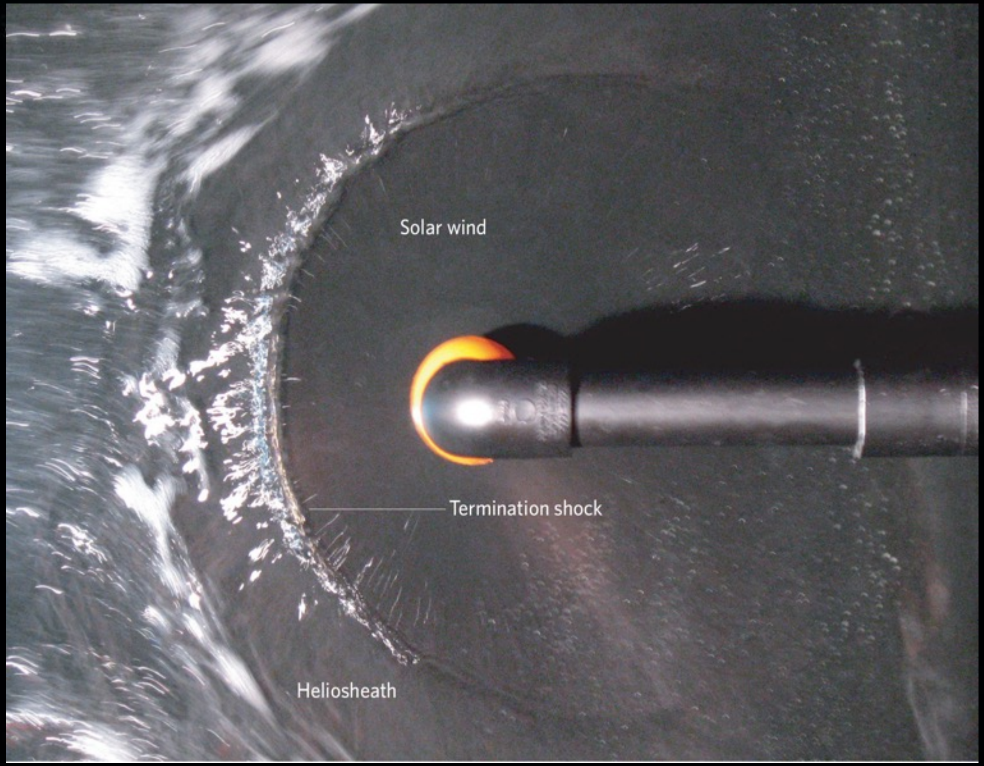

1000 AU
100 AU
0
100 AU
1000 AU
Voyager 1 (151.5 AU)
Interstellar Probe
New Horizons (49.1 AU)
Voyager 2 (125.8 AU)
1000 AU
100 AU
0
100 AU
1000 AU

The Heliosphere

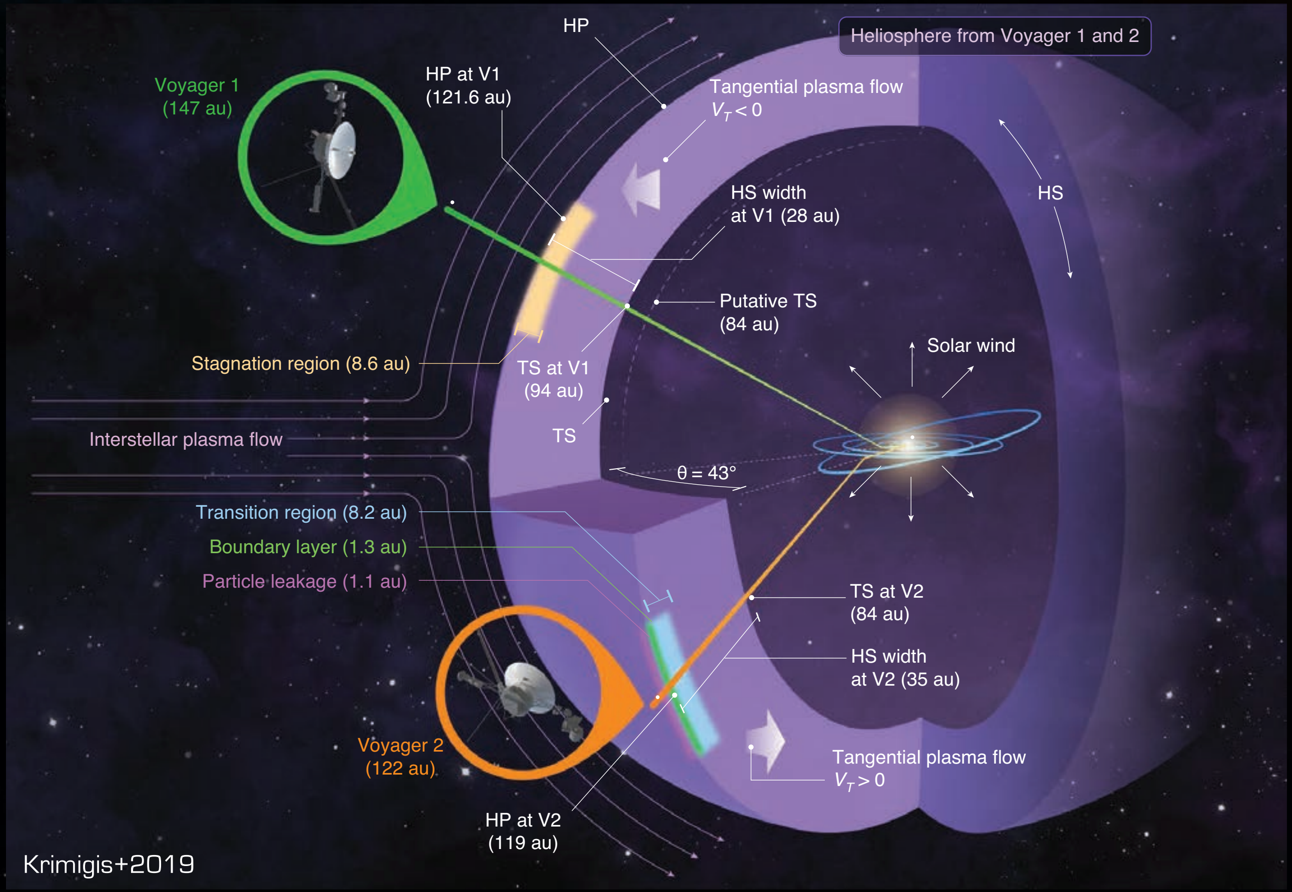
The very basics



- The Sun plows through the LISM with ~24 km/s
- The expanding solar wind meets the apparent flow of LISM
- The Termination Shock (TS) is where the outward solar wind flow is "terminated" and slowed creating a shock (this is where the water from the faucet piles up)
- The Heliosheath (HS) beyond the TS contains the slowed and shocked solar wind plasma that flows outward and bends around
- The Heliopause (HP) is theoretically where the solar wind stops and the LISM takes over (pressure balance)
- This hydrodynamic picture is intuitive, but after all it is just a sink…
- Interstellar Neutrals (ISNs) penetrate the heliosphere, ionizes and become Pick-Up Ions(PUIs) that are carried out with the solar wind mediating the shock conditions and the force balance…
- Therefore, the creation of the boundary already starts deep inside the heliosphere…

Current Understanding of the Heliosphere

We know a lot, but have just scratched the surface of a new regime



- Voyager 1 and 2 are the only spacecraft to have traversed the Heliopause (HP)
- While they determined the basic parameters in two directions, their limited payload left a range of mysteries
- IBEX and Cassini have imaged the boundaries from the inside and have brought the best global understanding to date, but still lack consistent interpretations
- Other observations include SOHO, Ulysses, New Horizons (and more) that have brought us remote information on interstellar neutrals and their critical interaction with the heliosphere
- IMAP (launch 2024) will provide order-of-magnitude better ENA imaging capabilities from 1 AU and guide the further formulation of the Interstellar Probe Science Investigation

Primary Goal: Understand our Habitable Astrosphere and its Home in the Galaxy

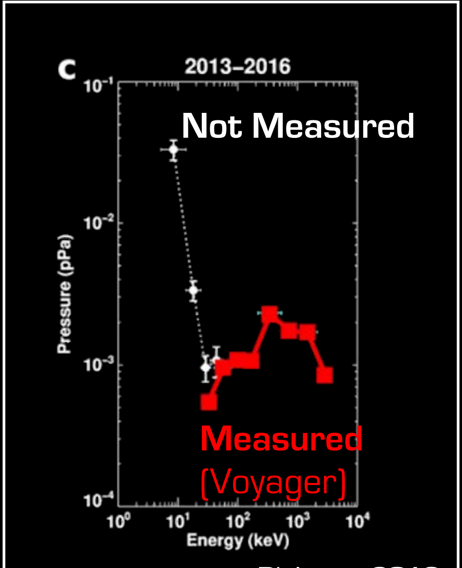
Objective 1: A Heliosphere Shaped by the Sun

Determine the physical processes that shape the heliosphere and how they manifest themselves globally

Processes Upholding the Shape

Probing the boundary to determine how solar wind plasma is heated to become the dominant force of the heliosheath. Measure directly the source and evolution of the critical Interstellar Pick-Up Ions (PUIs).

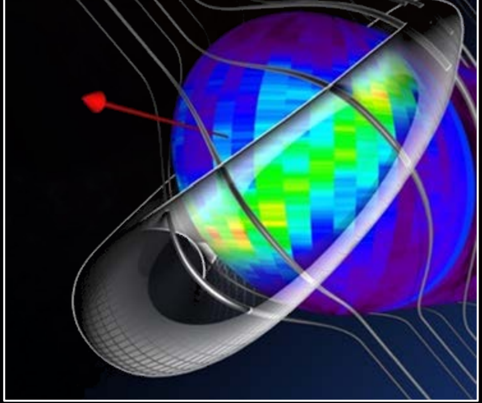
Voyager encountered a completely new regime of space plasma interactions. The expected heating of solar wind plasma across the termination shock was almost absent and the predominant energy appeared to be transferred to the so-called pick-up ions, not directly measured by Voyager.

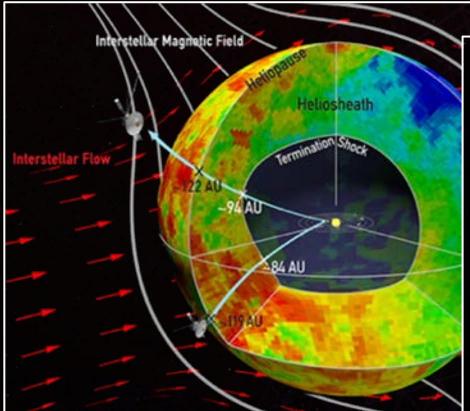


Dialynas+2019

Global Manifestation

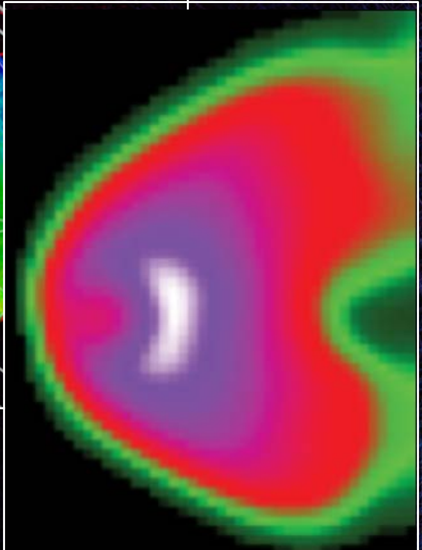
Global imaging from a changing vantage point and capture the first definitive picture from the outside


IBEX (McComas+2017)



Cassini (Dialynas+2017)

IBEX and Cassini have revealed what we know to date about the heliospheric shape, but both from a vantage point deep inside the heliosphere. This has made a unique interpretation difficult.


DeMajistre+2019
Galli+2019

Capturing an image from outside heliosphere will provide the definitive observation of its global manifestation (simulation from 250 AU)

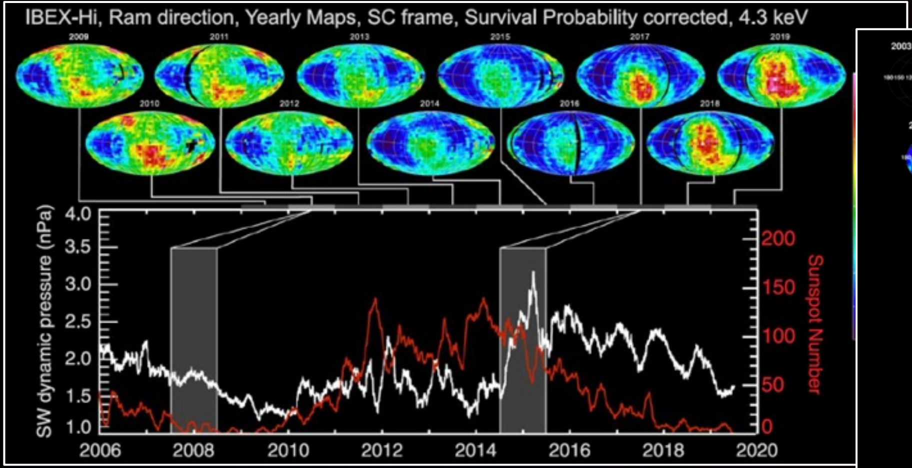
Primary Goal: Understand our Habitable Astrosphere and its Home in the Galaxy

Objective 2: A Variable Sun in a Changing Interstellar Environment

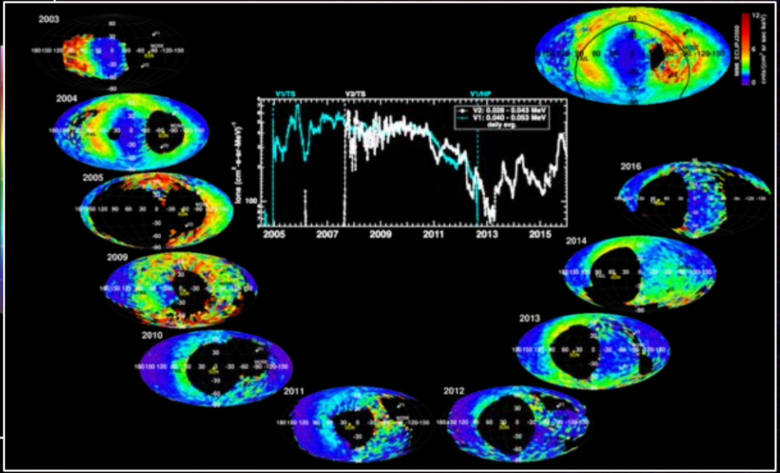
Determine how the Sun's activity, the interstellar medium and its possible inhomogeneity influence the dynamics and evolution of the global heliosphere

The Breathing Heliosphere Harboring a Variable Sun

In-situ measurements of solar wind disturbances propagating through the heliosphere and heliosheath. Imaging of global response along the outward trajectory.



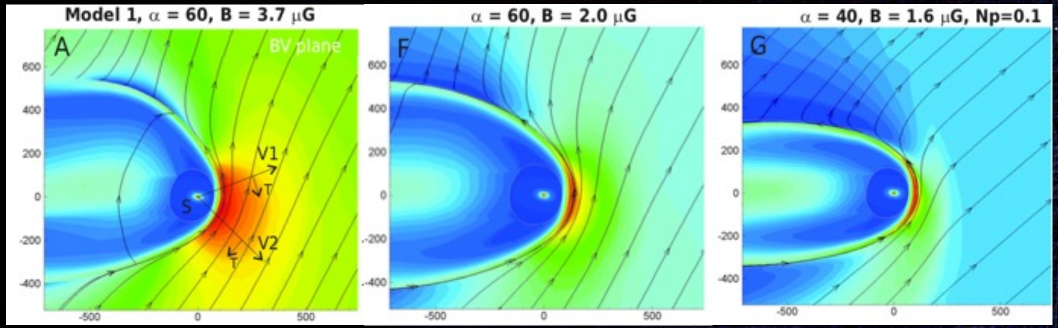
McComas+2020



Cassini (Dialynas+2017)

The Changing Heliosphere Through an Inhomogeneous ISM

Detailed measurements at the boundary and in the VLISM to understand how the heliosphere would respond once the Sun encounters the new environments of the neighboring interstellar cloud

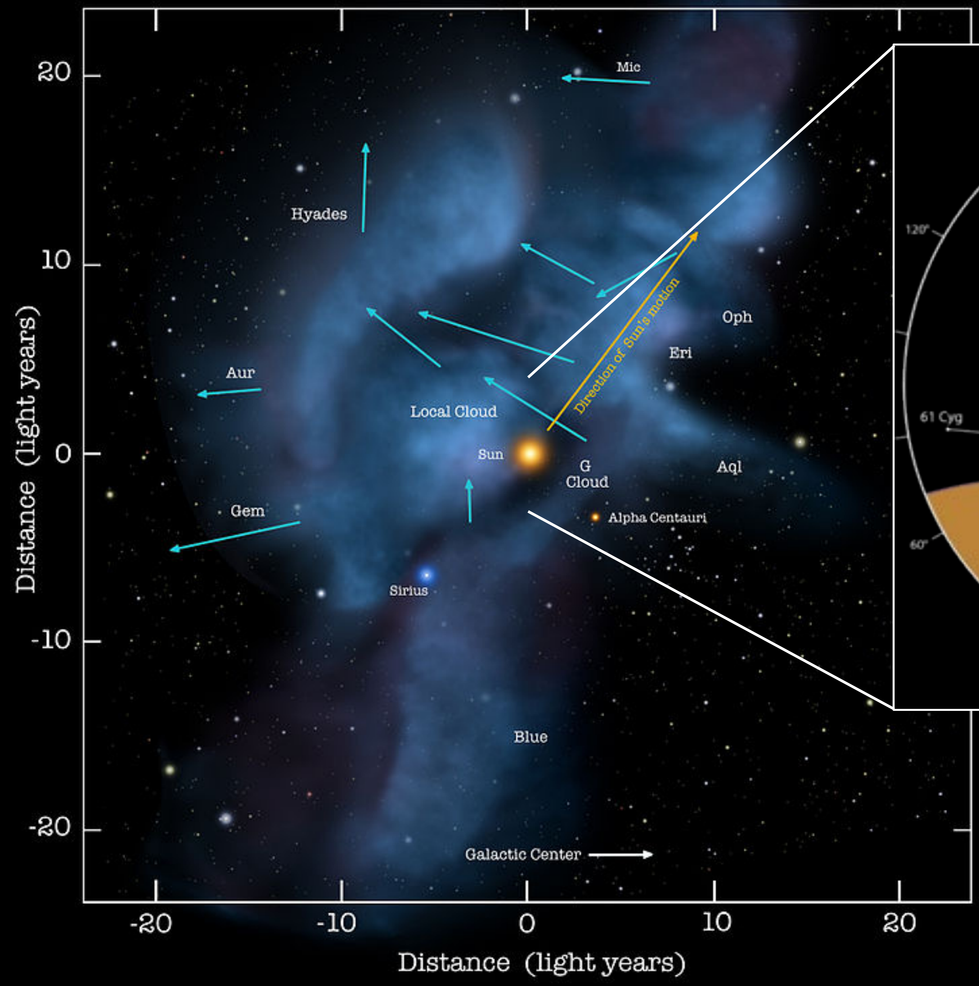


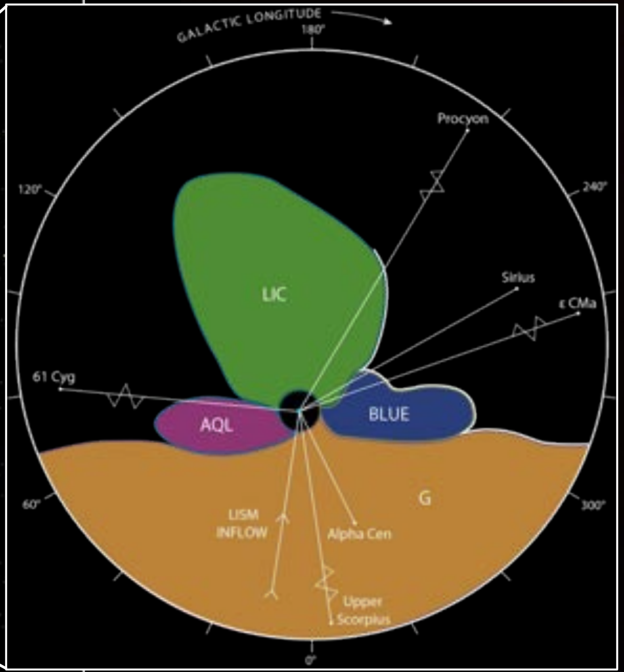
LIC conditions largely determine what our heliosphere look like (Izmodenov & Alexashov 2020)

Primary Goal: Understand our Habitable Astrosphere and its Home in the Galaxy

Objective 3: Into the Unknown Interstellar Cloud

Discover and quantify directly the properties of the unexplored VLISM





Linsky and Redfield 2019
Frisch and Mueller 2013

The Unexplored Interstellar Cloud

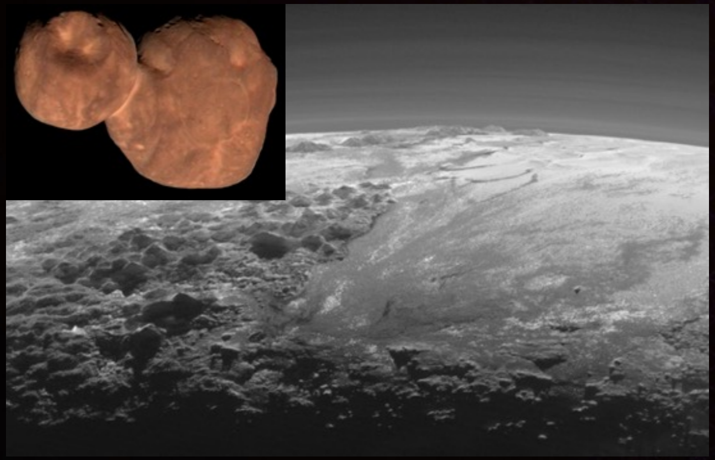
The first direct sampling of density, temperature, composition and fields beyond the heliopause would provide decisive information on the heliospheric interaction, and also on the chemical evolution of the galaxy.

All knowledge of the unperturbed LISM are average basic properties inferred from absorption spectra towards the nearest stars, and from measurements of interstellar gas, Pick-Up Ions (PUIs) and dust penetrating the heliosphere. New evidence is mounting that the heliosphere is in contact with four interstellar clouds with different properties and is leaving the Local Interstellar Cloud within relatively short galactic time scales - a "galactic event" of sorts.

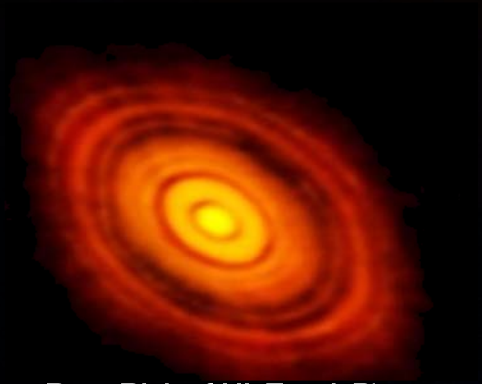
Supporting Goal: Understand The Origin and Evolution of Planetary Systems

Planets, KBOs and Circum-Solar Dust Disk

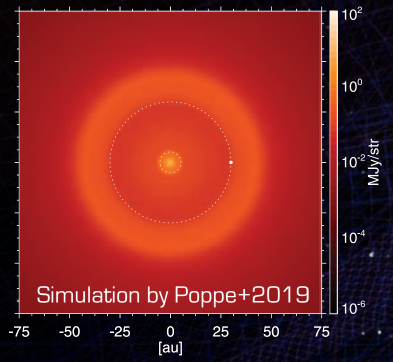
- **KBOs and (Dwarf) Planets:**
  - Current state of evolution: Geophysics and composition
  - Collisional, orbital and geological history: Shape, size distribution, orbit
  - Atmospheres: Structure and composition
  - Giant Planets Science: Observations during JGA
- **Circum-Solar Dust Disk:**
  - Dust processing in the Solar nebula: Dust compositional distribution
  - Dust production mechanisms: Dust size distribution
  - Large-scale dynamics: Disk structure associated with planets, asteroids, KBOs, solar activity
- **Exoplanetary Analogues**
  - Solar System Observations from afar: Phase curves, transit spectra, etc to help better infer characteristics of exoplanetary systems



130 dwarf planets and over 4000 KBOs. Any direction defined by Heliophysics offers a at least one compelling flyby.



Dust Disk of HL-Tauri: Planetary formation at 1 million years!? A solar system infant?

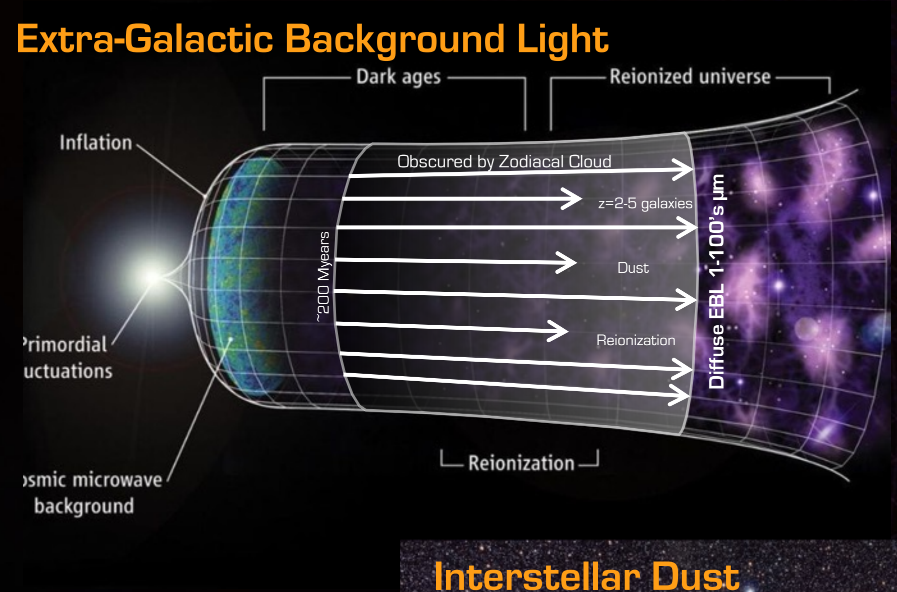


Sol: 4.6 billion years. Never seen. Not enough data to simulate accurately.

Supporting Goal: Understand Galaxy and Star Formation

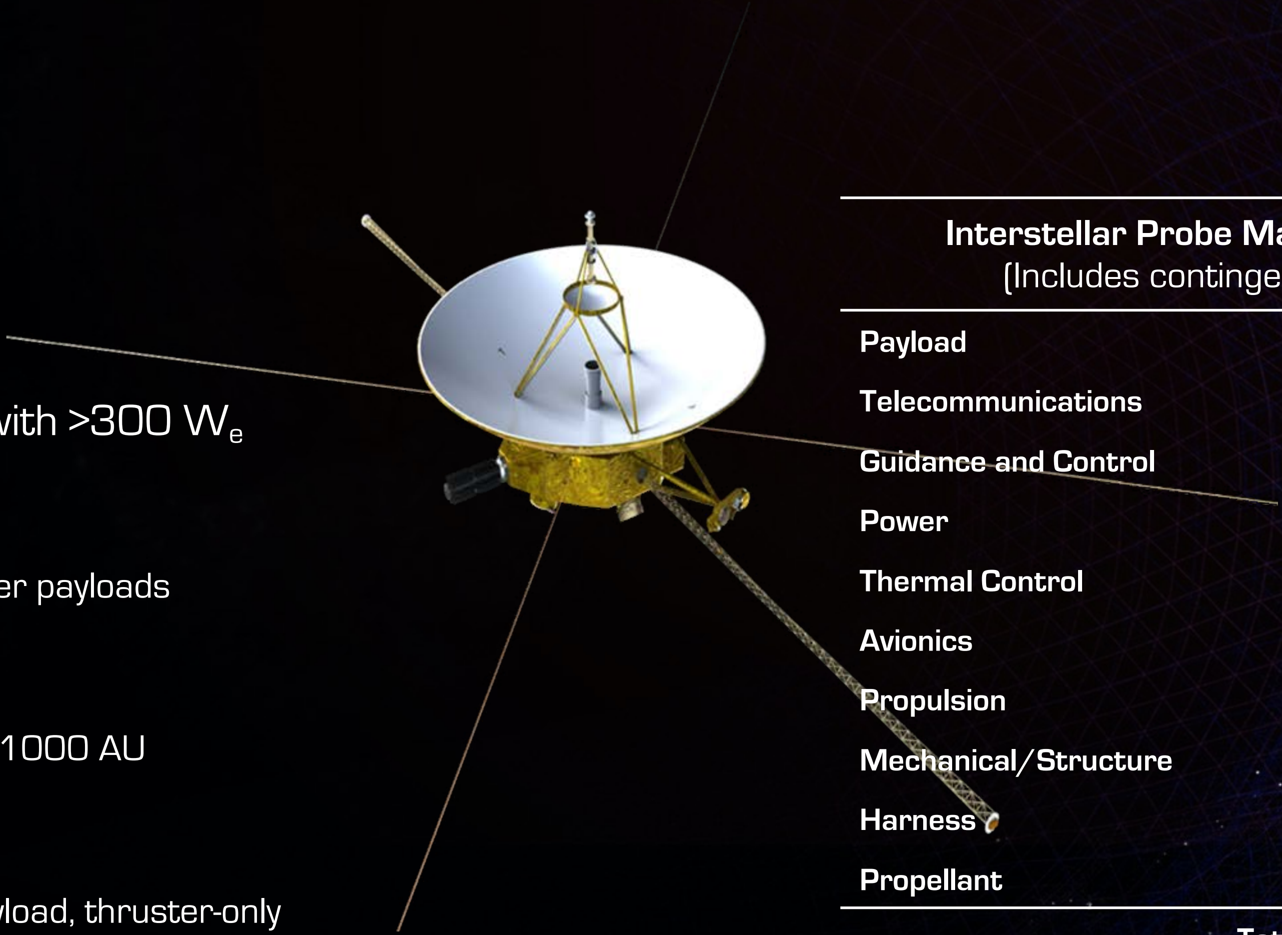
Extragalactic Background Light (EBL), Interstellar Dust (ISD), Nucleosynthesis and Constraints on Big Bang

- **Extragalactic Background Light:**
  - Diffuse red-shifted light emitted by all stars and galaxies from ~200 My after Big Bang
  - IR spectrum completely obscured by the Zodiacal cloud
  - Critical information on energy release and galaxy formation in the early universe
- **Interstellar Dust Grains:**
  - Composition and Evolution of the Near and Distant ISM: Remote IR observations and in-situ measurements of ISD properties
  - Chemical Evolution of the Galaxy: In-situ ISD elemental and isotopical composition
- **Recent Nucleosynthesis:**
  - In-situ isotopic ratios of D/H, ^{3}He/^{4}He, ^{13}C/^{12}C, ^{18}O/^{16}O, ^{22}Ne/^{20}Ne, ^{38}Ar/^{36}Ar
- **Constraints on Cosmology:**
  - ^{2}H, ^{3}He, and ^{4}He abundances in the VLISM



Mission Architecture

- Study Requirements
  - Nominal Design Lifetime: 50 years
  - Ability to operate at 1000 AU
  - Readiness by 1 January 2030
- Mass: 850-950 kg
- Power: Two Next Generation RTGs with >300 W_e (total) after 50 years
- Payload
  - Mass: ~85 kg, trading lighter and heavier payloads
  - Two examples
- Telecommunication
  - X-band to achieve 500 bps downlink at 1000 AU
  - Large fixed dish (5m for X-band)
- Control
  - Spinning or three-axis depending on payload, thruster-only control
  - Pointing and control requirements driven by telecom



Interstellar Probe Mass (kg) (Includes contingency)	
Payload	105
Telecommunications	83.4
Guidance and Control	16.8
Power	169
Thermal Control	70.8
Avionics	12.8
Propulsion	37.2
Mechanical/Structure	150
Harness	29.3
Propellant	106
Total	793
Margin	80
Launch Mass	873

Notional Operations Scenarios

Driving Mission Architecture Designs

Baseline Scenario
(concluding now)

- Spin stabilized
- 50m PWS wire antennas

Inner Heliosphere Phase
1-90 AU

- In-situ measurements of magnetic fields, solar wind and PUI
- ENA and Ly-a imaging from a changing vantage point
- PWS observations of 2.5 kHz emission

Heliosheath Phase
90-120 AU

- In-situ measurements through boundary region
- ENA and LYA imaging
- PWS Observations

Interstellar Phase
>120 AU

- In-situ measurements of ISM gas, neutrals and dust
- External ENA and Ly-α imaging
- In-situ measurements of ribbon

Augmented Scenario
(under study)

- 3-axis stabilized
- Rigid PWS antennas

Circum-Solar Dust Disk
- IR imaging of Circum-Solar Dust

KBO/Dwarf Planet Flyby
- Flyby of Quaoar
- Transition to spin mode after flyby

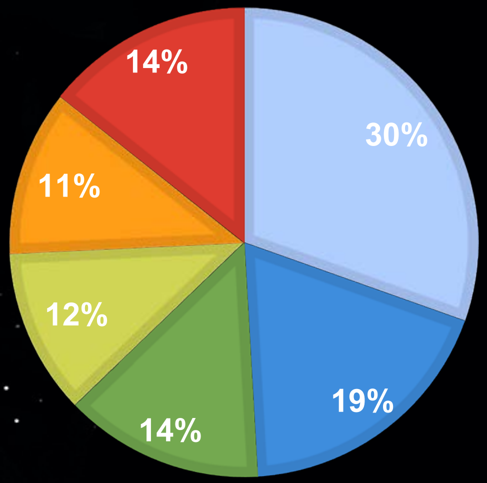
Extragalactic Background Light
- IR imaging of EBL beyond the Circum-Solar Dust Disk

Example Model Payloads

Baseline

87.4 kg
86.7 W

- Charged Particles
- Fields and Waves
- ENA Imaging
- Dust
- Neutrals
- Ly-alpha



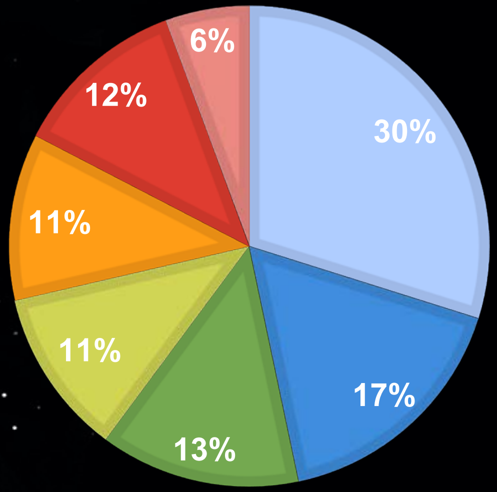
Instrument (Heritage)	Measurement Requirements		Mission Requirements	Science Driver
Magnetometer (MAG) (MMS/DFG)	0.01 - 100 nT; 0.01 nT (10^{-8} nT^2/Hz turb.)	≤60 s; (100 Hz)	Two FG, 10m boom	LISM (turbulence)
Plasma Waves (PWS) (Van Allen/EFW)	~1 Hz – 1 MHz; Δf/f≤4% ≤0.7 μV/m @ 3 kHz	≤60 s (≤ 4 s at TS)	4x50 m wire; spin plane	LISM n_e, T_e (QTN), turbulence
Plasma Subsystem (PLS) (PSP/SWEAP/SPAN-A)	~eV to 10's keV e, H+, He+, C+, N-O+	~4π; ≤60 s	Spinning	Flows, n_e, T_e, n_i, T_i Force balance
Pick-up Ions (PUI) (Ulysses/SWICS)	0.5-78 keV/q H, ^{3}He, ^{4}He, C, ^{14}N, ^{16}O, ^{20}Ne, ^{22}Ne, Mg, Si, Fe (charge states)	iFOV: 60°	Spinning	Interstellar, inner PUI Force balance
Energetic Particles (EPS) (PSP/EPI-Lo)	10's keV – 1's MeV H, ^{3}He, ^{4}He, C, O, Ne, Mg, Si, Fe (Li/BeB)	~4π; ≤60 s	Spinning	S/W, HS and ACRs Force balance
Cosmic Rays (CRS) (PSP/EPI-Hi, new development)	H to Sn; ≤1 GeV/nuc; Δm= 1 amu electrons; ≤10 MeV	≥2 directions; daily	Spinning	ACRs, GCRs LiBeB cosmic story
Interstellar Dust Analyzer (IDA) (IMAP/IDEX, new development)	1-500 amu; **m/Δm:** ≥ 200	iFOV: 90°	Ram direction Co-boresighted NMS	ISDs, galactic heavy ion composition
Neutral Mass Spectrometer (NMS) (LunaResurs/NGMS, JUICE/NMS)	H to Fe, m/Δm > 100 (1σ) 1 – 300 u/e	iFOV: 10°; weekly	Ram direction Co-boresighted IDA	LISM composition
ENA (ENA) (IMAP/Ultra, new development)	~1-100 keV; H (He, O goal)	iFOV: 170° x 90°	Spinning, 2 heads	Shape, force balance, ribbon/belt
Lyman-Alpha Spectrograph (LYA) (MAVEN/IUVS, new development)	120-130 nm; 0.004nm	iFOV: 5°; 140° monthly	Spinning	LISM and heliosheath H

Example Model Payloads

Augmentation

89.1 kg
90.2 W

- Charged Particles
- Fields and Waves
- ENA Imaging
- Dust
- Neutrals
- Flyby Imaging
- IRM



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Magnetometer (MAG) (MMS/DFG)	0.01 - 100 nT; 0.01 nT (10^{-8} nT^2/Hz turb.)	≤60 s; (100 Hz)	Two FG, 10m boom	LISM (turbulence)
Plasma Waves (PWS) (PSP/FIELDS, Van Allen/EFW, in development)	≤10 kHz; Δf/f≤15% ≤0.7 μV/m @ 3 kHz	≤60 s (≤ 4 s at TS)	4x2.5m rigid + sounder (4x50 m optional)	2.5 kHz, n_e (T_e, turbulence)
Plasma Subsystem (PLS) (PSP/SWEAP/SPAN-A)	~eV to 10's keV e, H+, He+, C+, N-O+	~4π; ≤60 s	Spinning	Flows, n_e, T_e, n_i, T_i Force balance
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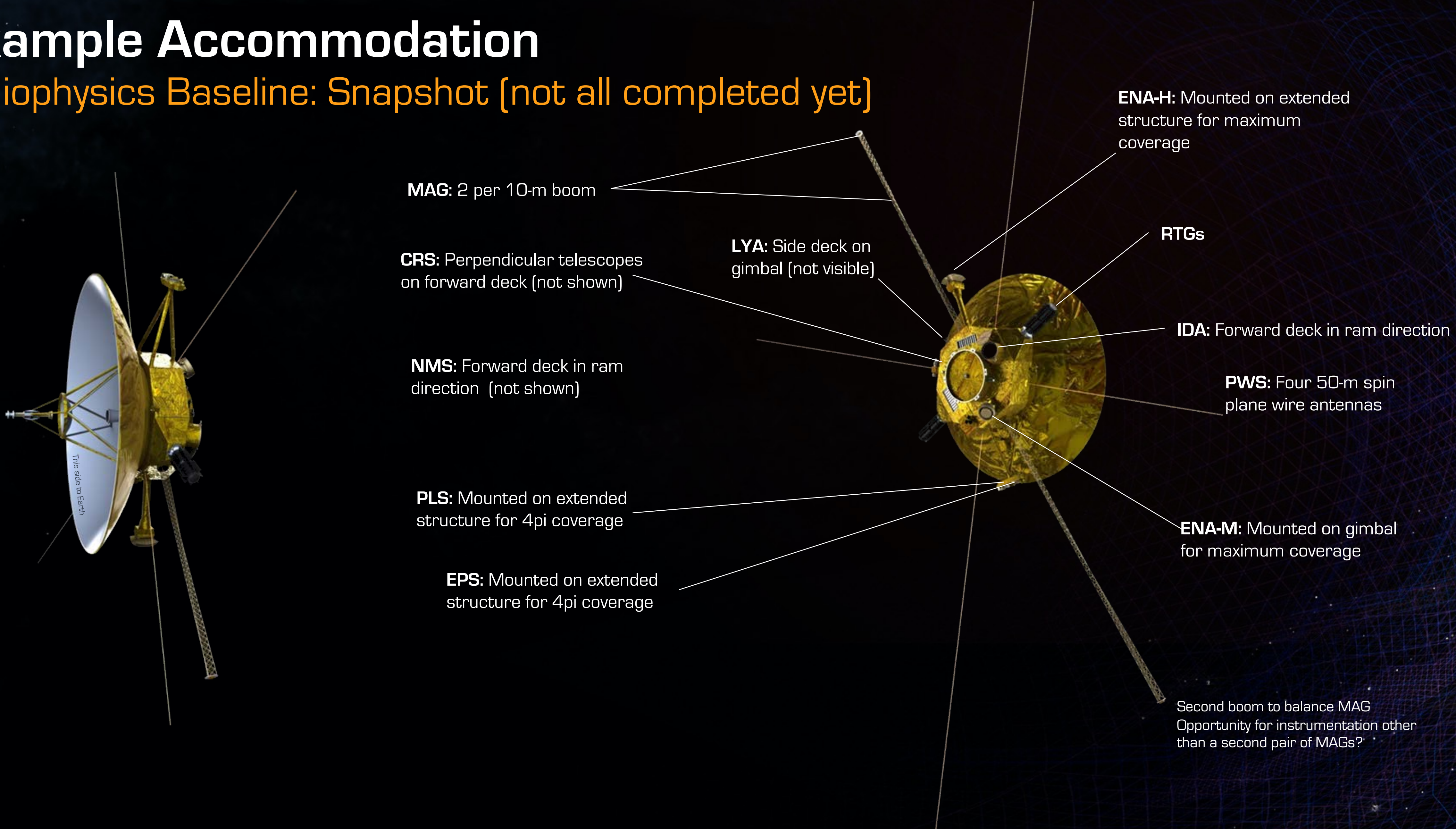
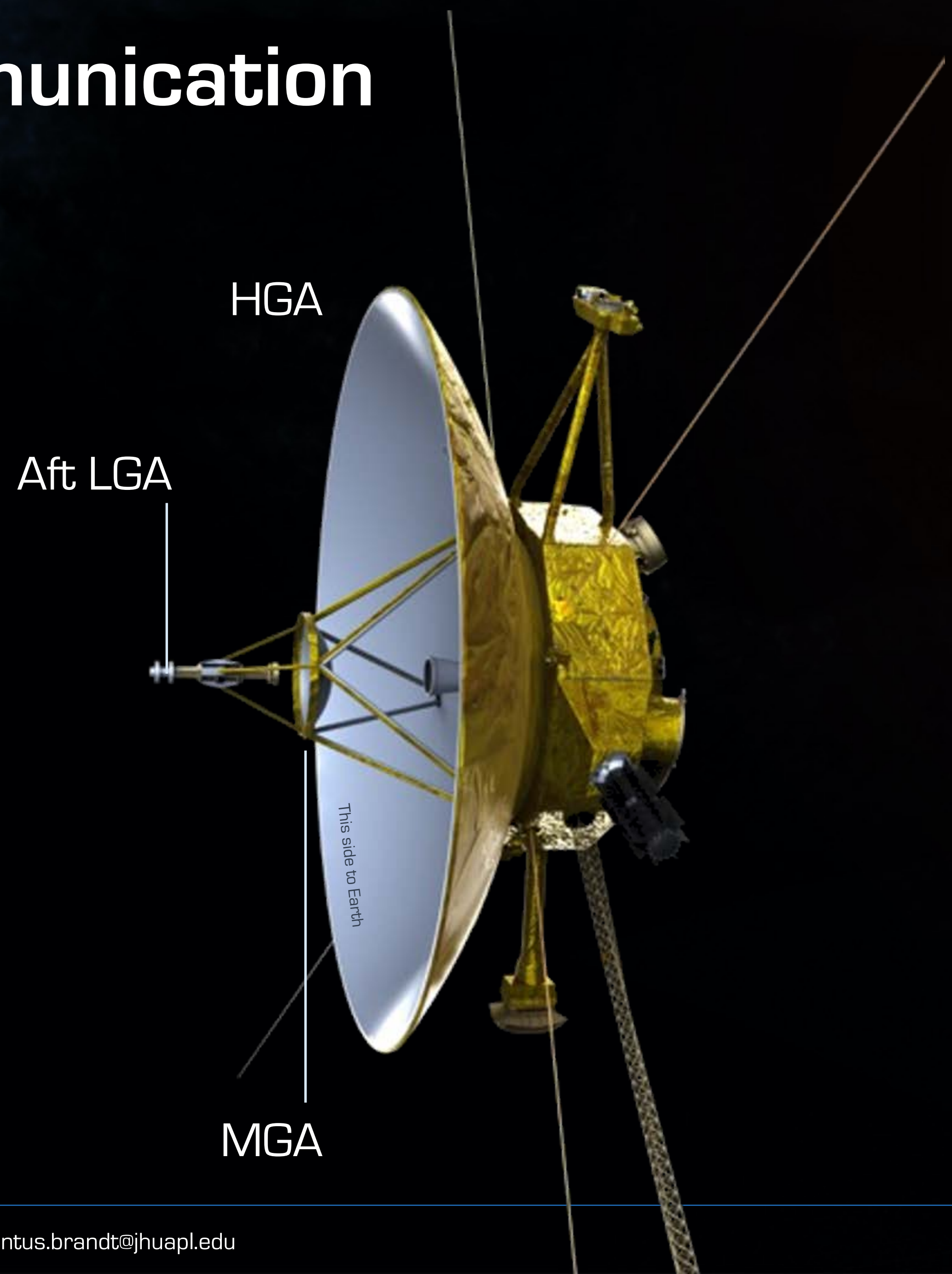
ENA (ENA) (IMAP/Ultra, in development)	~1-100 keV; H (He, O goal)	iFOV: 170° x 90°	Spinning, 2 heads	Shape, force balance, ribbon/belt
Visible-Near-IR (VIR) (New Horizons/Ralph)	0.4-4 μm; 5 ch. ≤0.975 μm; >240 ch. >0.975 μm	Pixel: 10 μrad FOV: 2.3°x1.2°	3-axis Co-boresighted IRM	Flyby features/composition, distant KBOs, astro
Visible-IR Mapper (IRM) (New Horizons/LEISA, CYBER-II, in development)	0.5-15 μm 30-60 μm	52 μrad/1.8° 1.3 mrad/0.07°	3-axis; perp. to spin Co-boresighted VIR	Dust Disk, surface comp., ISM dust, CBL

Example Accommodation

Heliophysics Baseline: Snapshot (not all completed yet)



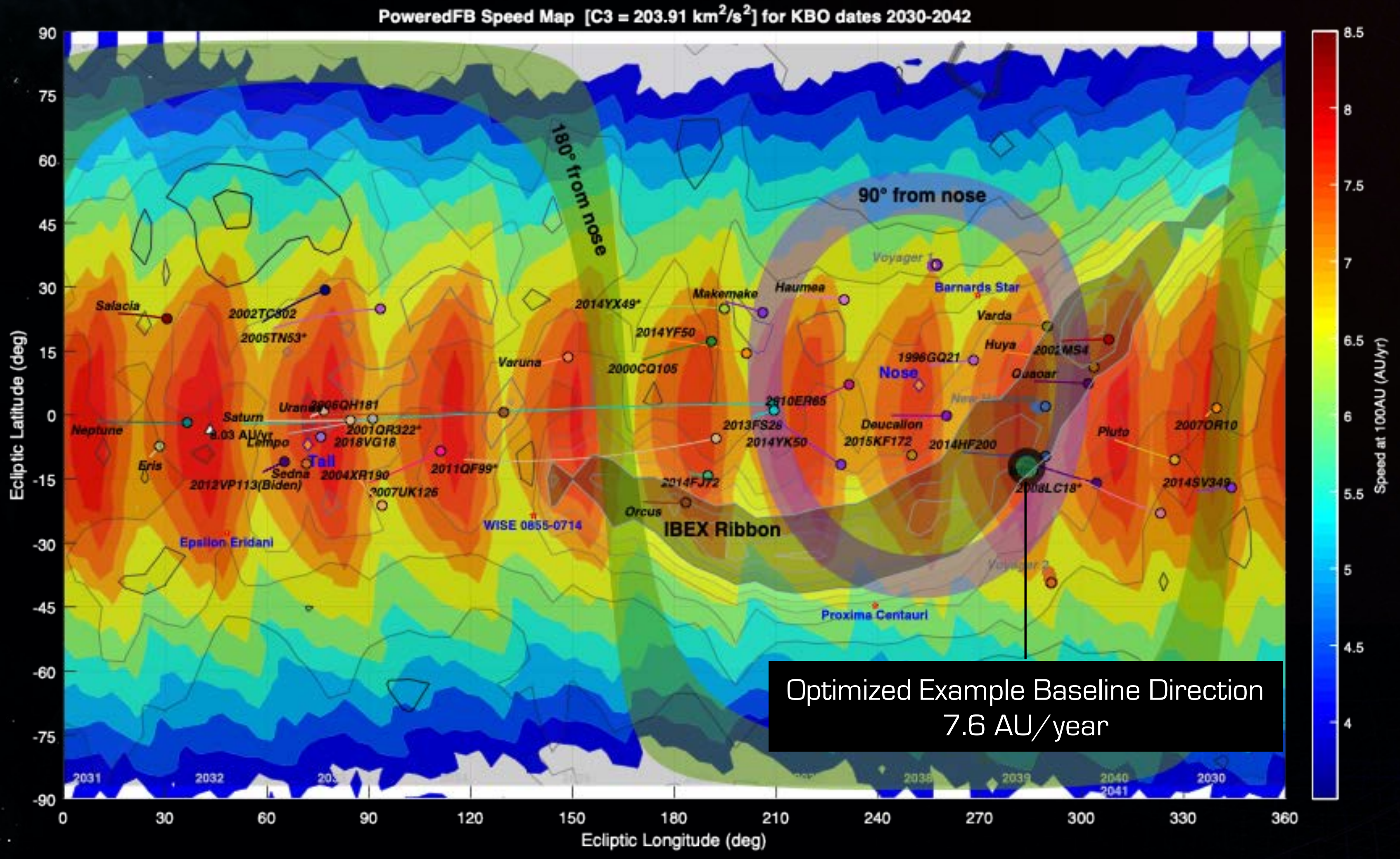
Communication



Interstellar Probe Communications Subsystems	
HGA	5m Solid Composite
MGA	0.37m Solid Composite
TWTA Power	52 W
Subsystem Mass (CBE)	72.9 kg HGA – 53.7 kg
Downlink Data Rate[1]	2592 bps (375 AU) 365 bps (1000 AU)
Uplink Data Rate[2]	2000 bps (375 AU) 250 bps (1000 AU)

1 – Turbo R1/6 encoding, ngVLA Ground Station
2 – DSN 70m station w/ 80 kW Tx, LDPC encoding

Baseline Trajectory

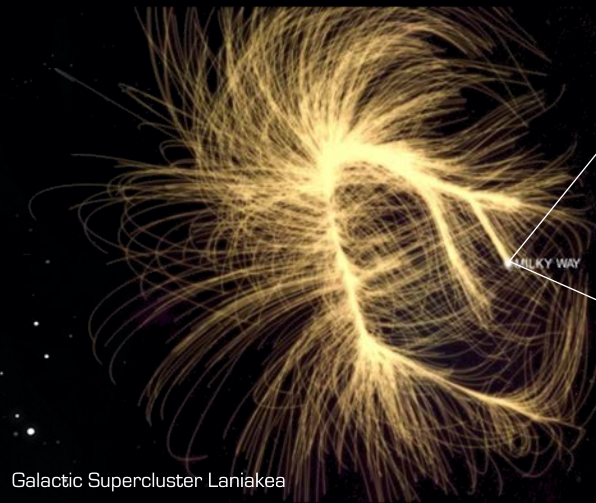


Direction Trades from 2019 Workshop

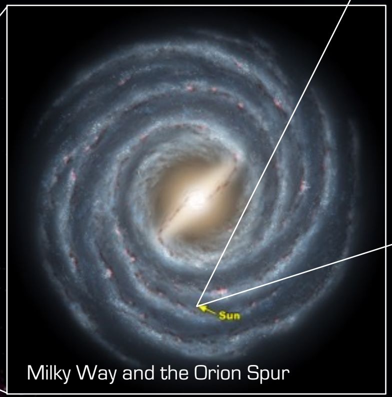
Direction	Heliophysics Trades
~45° off nose	• Through ribbon (~285° ELON) • Good for imaging from outside • Good for ISD
Nose	• Fast way to LISM • Stagnation, high-pressure region, force balance • Good for ISD • Not through max ribbon • Not optimal for imaging from outside
Flank (~90°)	• HP data point important for shape • ACR acceleration • May be longer to reach LISM • Not in the ribbon • Dust duty cycle limited
~135° off Nose	• Problematic for dust • Sufficiently close to the direction of CMA • Maximum outbound speed area
Tailward	• Problematic for dust • Sufficiently close to the direction of CMA
Off Ecliptic (U/N)	• Jets, turbulence • Towards EUV ionizing stars (CMA) • Not through ribbon (tailward)

Concluding Remarks

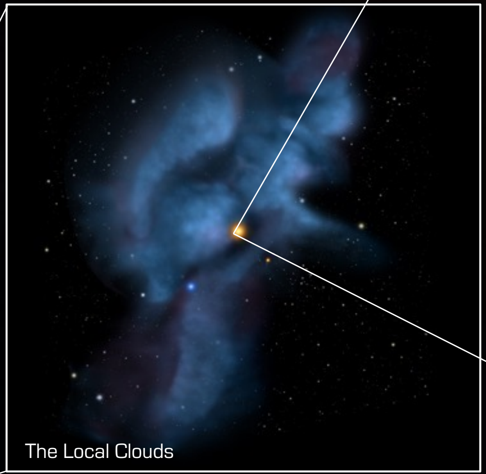
- Interstellar Probe is the beginning of Humanity's journey in to the galaxy
- We are there technically to take this first explicit step
- Interstellar Probe will take us to a completely unexplored region of space – Mare Incognitum* – to understand our home in the galaxy and find answers to questions we do not yet know how to pose



Galactic Supercluster Laniakea



Milky Way and the Orion Spur


The Local Clouds


Home

*Unknown Sea

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pontus.brandt@jhuapl.edu