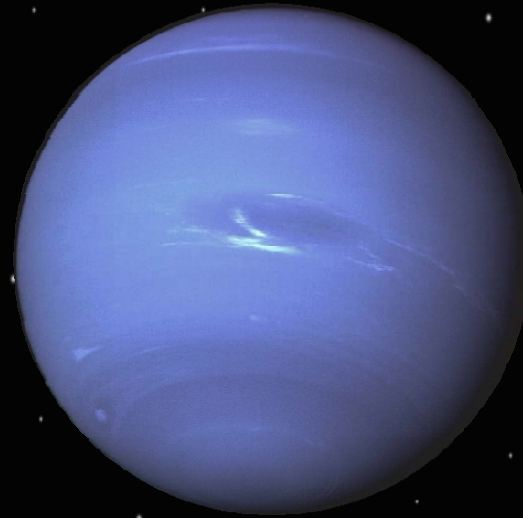


# Neptune Mission Concept



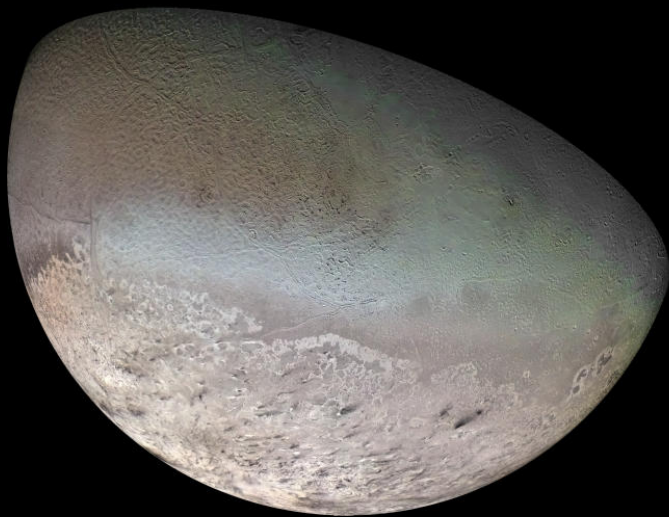
## A Voyage Through the Outer Solar System

Candice Hansen (JPL), Don Banfield (Cornell), E. Bierhaus (LMA), Mike Brown (CIT), Josh Colwell (UCF), M. Dougherty (IC), Amanda Hendrix (JPL), Krishan Khurana (UCLA), Alfred McEwen (UAz), Dave Paige (UCLA), Chris Paranicas (APL), Britney Schmidt (UCLA), Mark Showalter (ARC), Linda Spilker (JPL), Tom Spilker (JPL), John Stansberry (UAz), Nathan Strange (JPL), Matt Tiscareno

# Argo: a New Frontiers 4 Mission Concept

*A small body explorer doing exceptional ice giant science*

- Flyby Neptune
- Close flyby of Triton
- Flyby a Kuiper Belt Object
- Gravity assist from Jupiter and Saturn

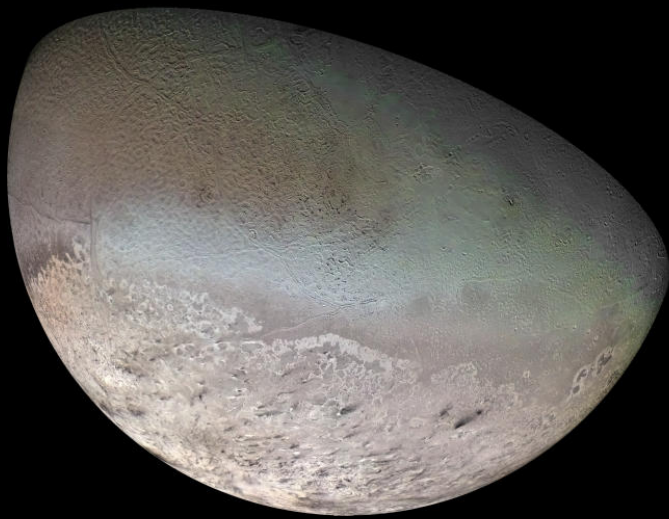


Exploration of Neptune has been stymied by the perception that a flagship-class orbiter is required to make scientific progress



A Neptune flyby mission is

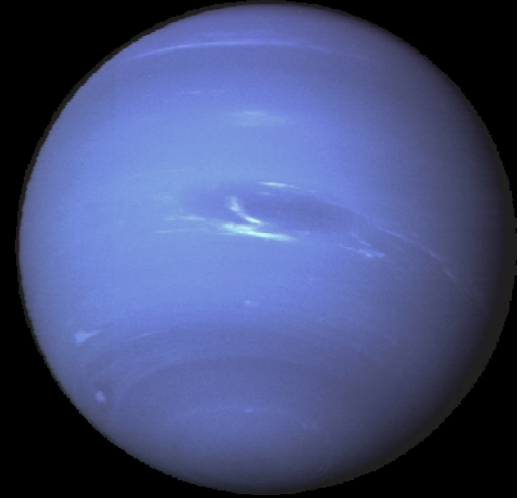
**a Pragmatic approach  
... with rich science  
results**



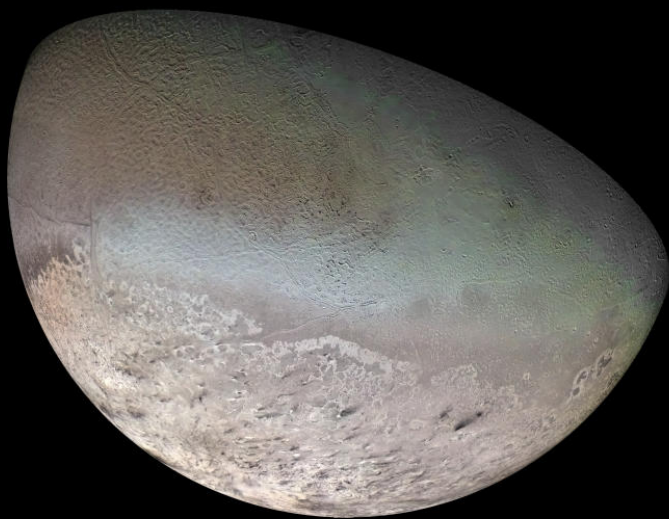
**Key Characteristics:**

- Focused science mission
- Simple mission profile
- Current instrument technology
- Current spacecraft technology
- Capable payload
- Nuclear power**

A Neptune flyby mission is not  
in competition with a flagship  
orbiter



Rather, it plugs a ~50 year gap  
in our study of Neptune



1989  
Voyager

> 2045  
Flagship  
orbiter



2029  
Argo

# Presentation Outline

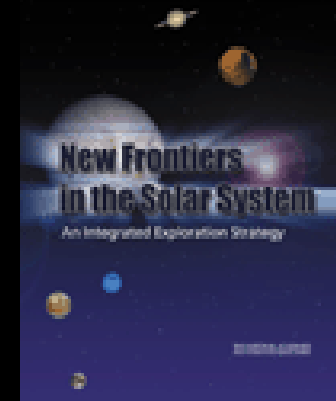
- Community support for a Neptune / Triton mission
- Science
- Mission, Payload, Spacecraft
- Observational timeline
- Summary

# academy interest in **neptune**

2003 planetary decadal survey explicitly discusses neptune

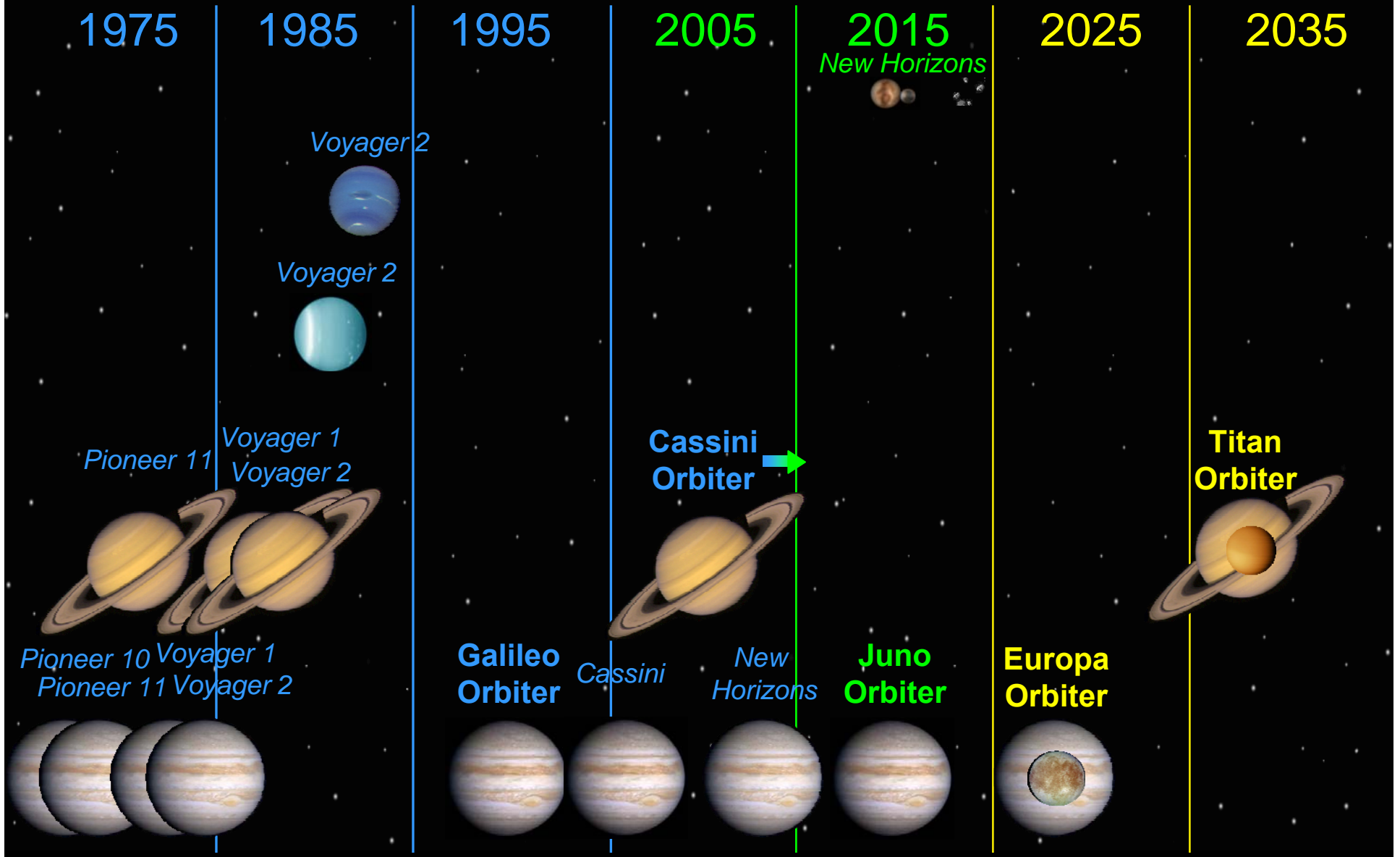
but Neptune set **three decades out (post 2035)** because

**flagship-class orbiter assumed to be next step**

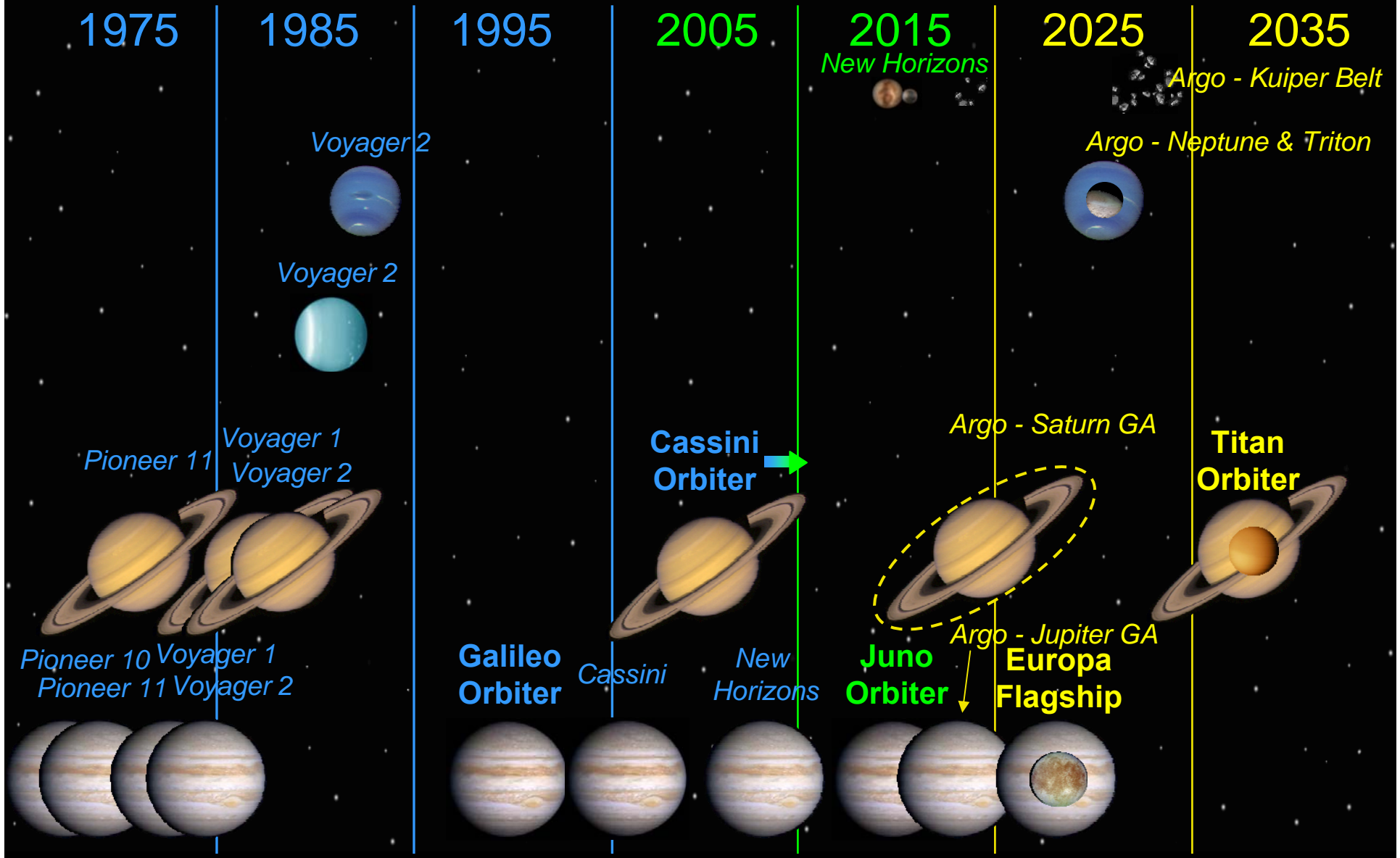


Our experience exploring Jupiter and Saturn belies this notion

# Past, Present, and Future of Outer Solar System Exploration



# Past, Present, and Future of Outer Solar System Exploration



# academy midterm report on decadal

Committee on **a**ssessing **S**olar **S**ystem **e**xploration

**nasa activity** on science question 2 (giant planet formation) **graded C**

with the **specific recommendation:**

“the *[next]* solar system exploration decadal survey should address the objectives and merit of a

**neptune/triton mission”**

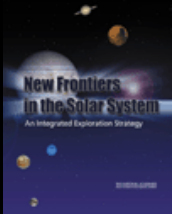
# Presentation Outline

- Community support
- Science
- Mission, Payload, Spacecraft
- Observational Timeline
- Summary

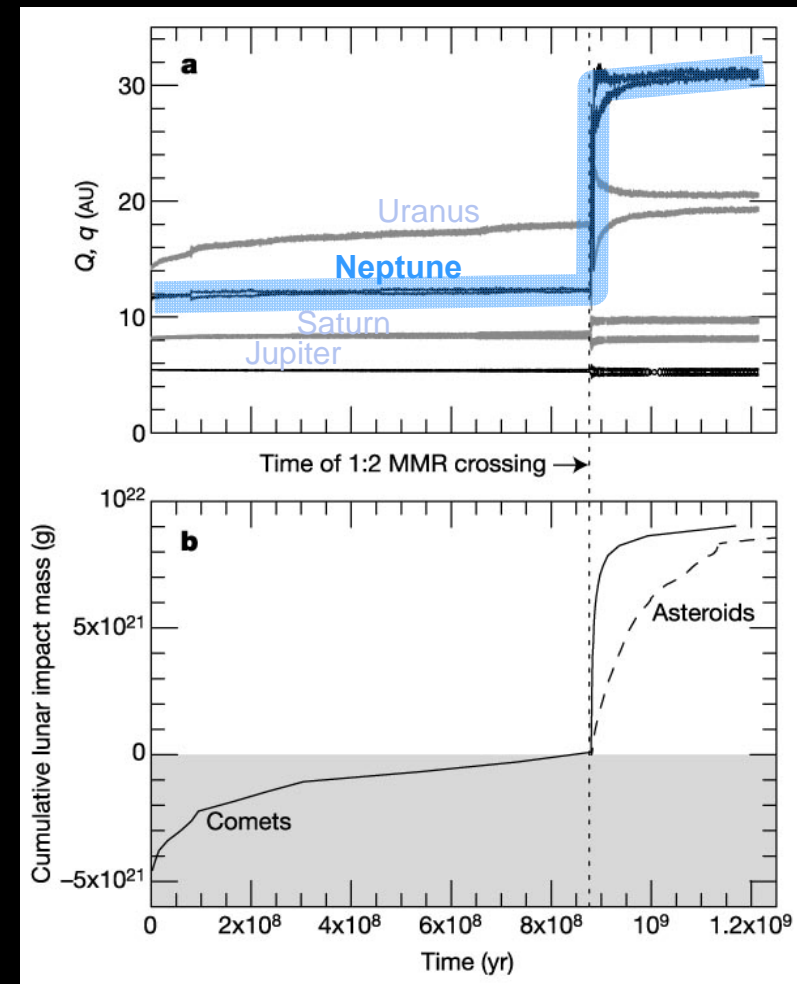
# Why study Neptune? Local Outlook

- Relevance to life and habitability
  - "The giant planet story is the story of the Solar System." \*
  - Direct implications for habitability
  - Delivery of volatiles to inner solar system

\* From the NAS NRC study: *New Frontiers in the Solar System: An Integrated Exploration Strategy*, often called the "Planetary Decadal Survey"

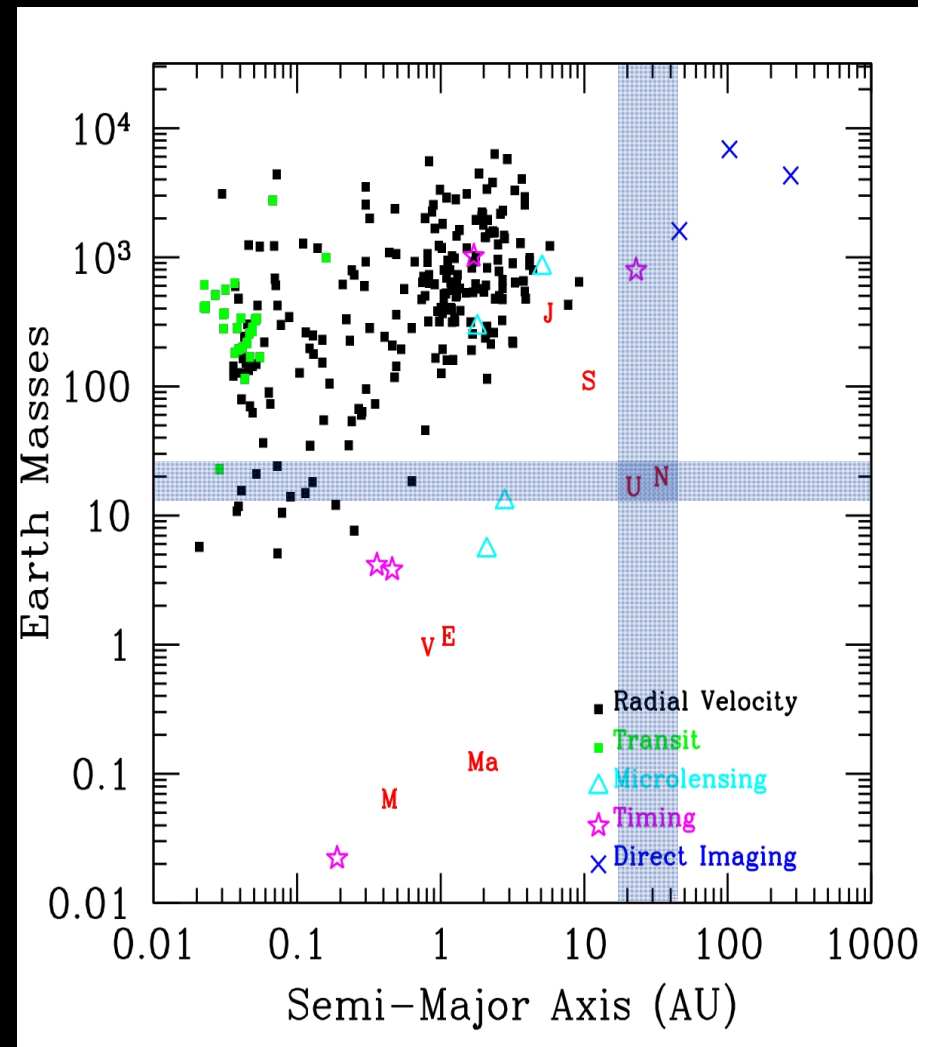


From "Origin of the cataclysmic Late Heavy Bombardment period of the terrestrial planets," R. Gomes, H. F. Levison, K. Tsiganis and A. Morbidelli 2005. *Nature* 435, 466-469.



# Why study Neptune? Broader Perspective

- Planetary System Architecture
  - Exoplanet population increasing dramatically
    - Growing number of ice-giant-mass objects
    - Pushing towards U/N equivalent distances in near future
      - Microlensing
      - Near-IR radial velocity
  - Knowledge of local ice giants extremely limited
    - Earth-based efforts extraordinarily challenging compared to J & S
      - Ice giants smaller
      - Ice giants much more distant
      - Ice giants colder



# Focus on Neptune

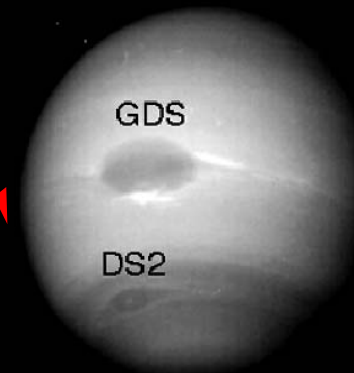


# neptune's dynamic atmosphere

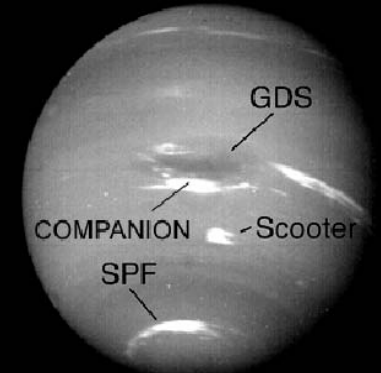
*Nearly all aspects of Neptune detectable from Earth have **changed significantly** since Voyager fly-by in 1989*

- Neptune's atmosphere shows fundamental differences in large-scale structure
  - GDS gone (all of them)
  - significant atmospheric evolution on <5-yr timescale

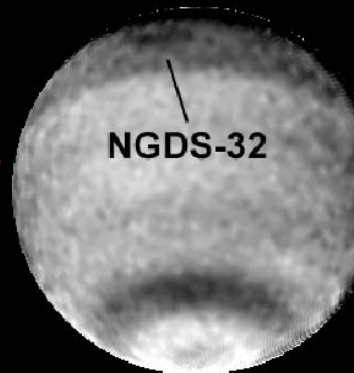
Voyager c. 1989  
compared with  
Hubble c. 1994



VGR CLEAR



VGR ORANGE



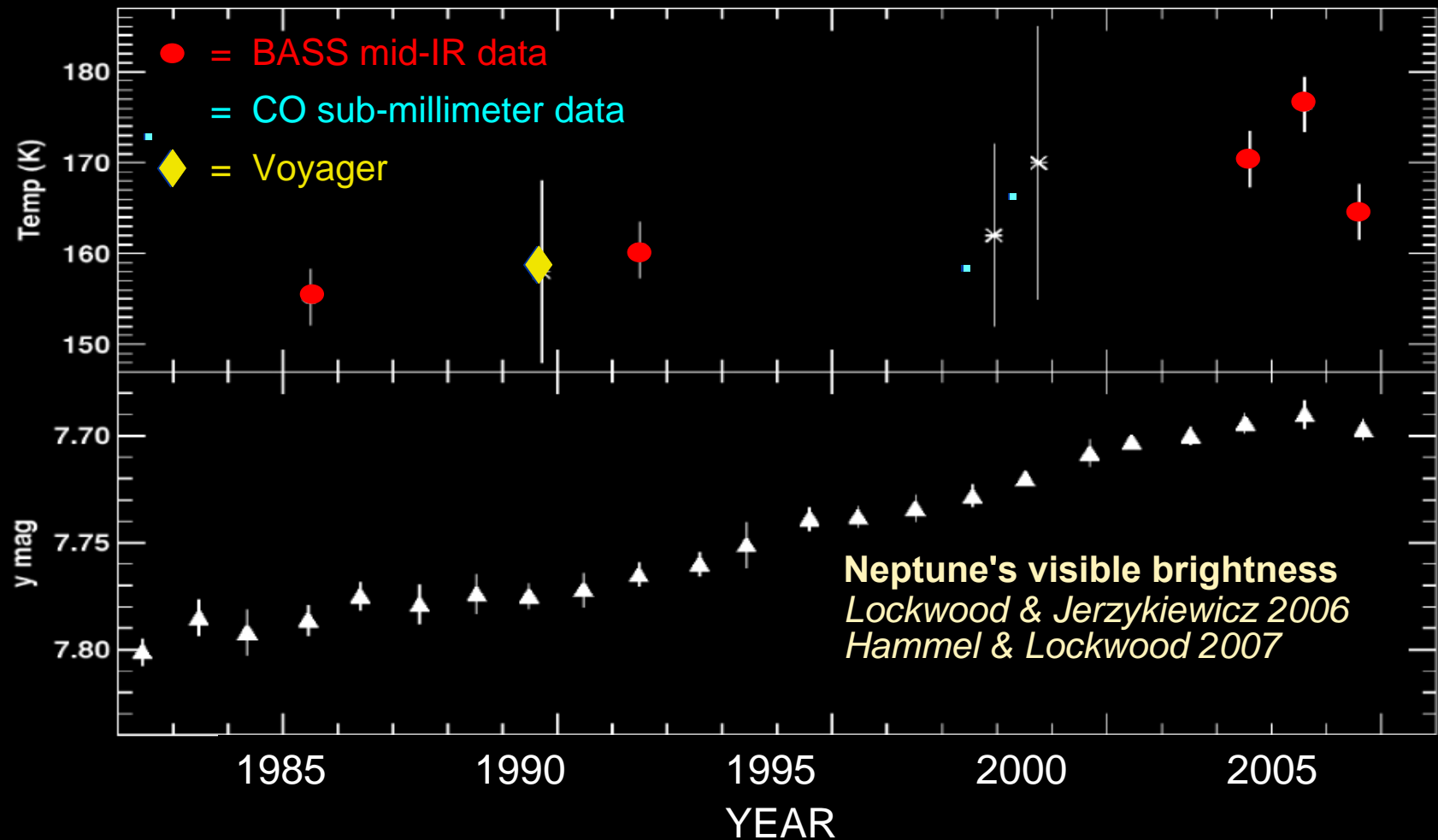
WFPC2 467M



WFPC2 673N

# neptune's energy balance

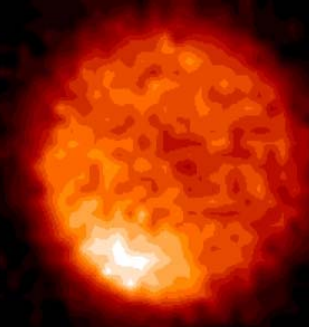
Evidence for stratospheric heating since Voyager



# Neptune mid-IR



Gemini/Michelle at 11.7  $\mu\text{m}$   
Ethane Emission  
from the stratosphere



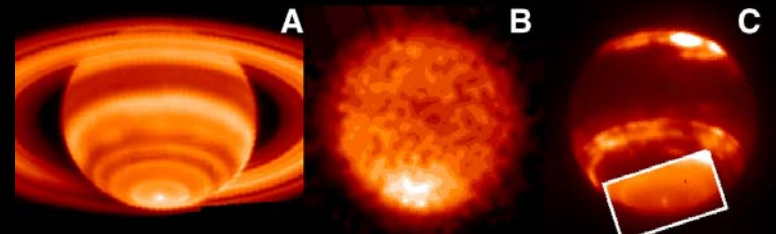
Gemini/Michelle at 7.7  $\mu\text{m}$   
Methane Emission  
from the stratosphere



Keck/NIRC2+AO at 1.6  $\mu\text{m}$   
Sunlight Scattering from  
tropospheric Clouds



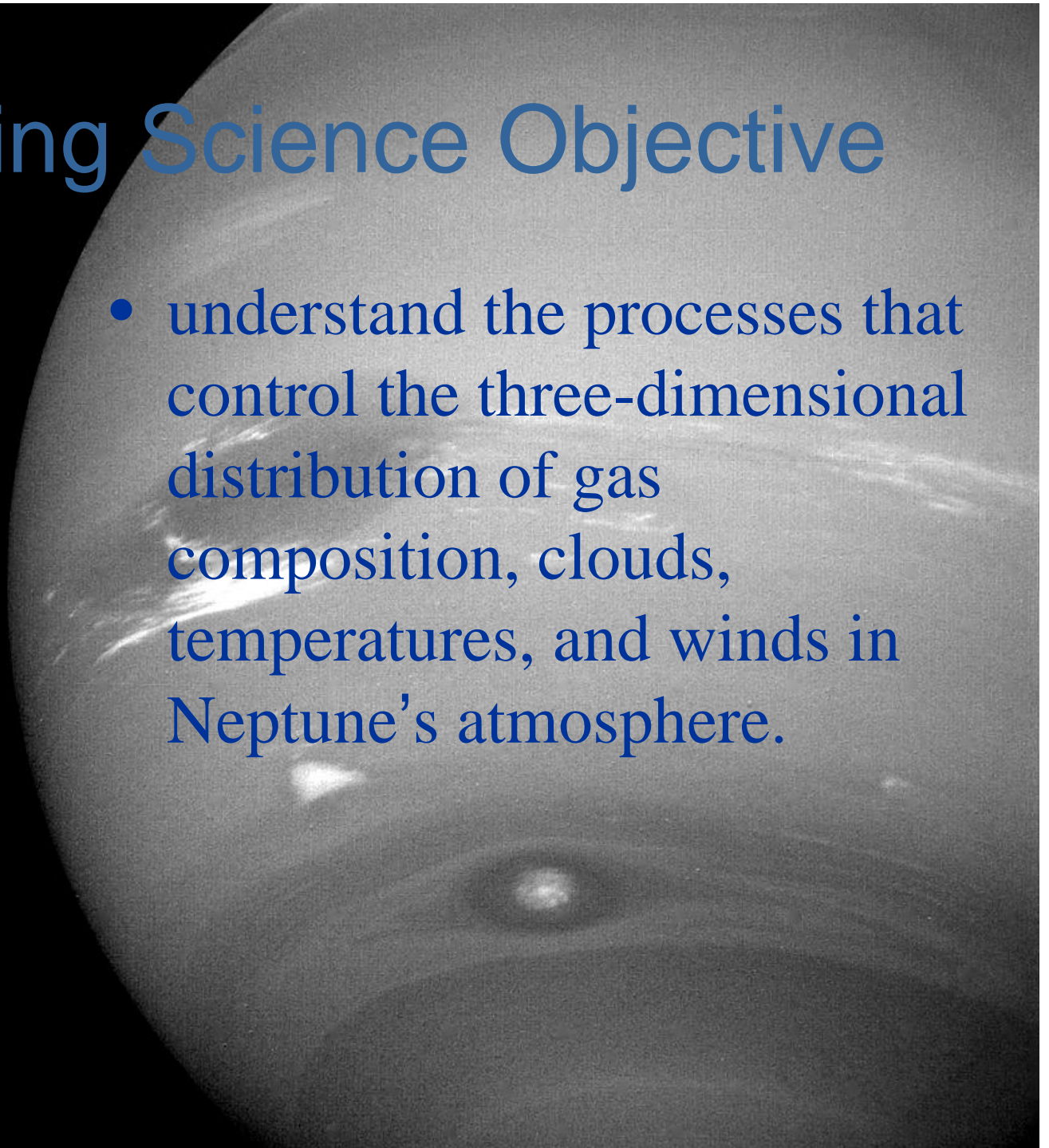
All 3 images  
taken within a  
few minutes on  
5 July 2005



Hammel et al. (2007)

# Overarching Science Objective

- understand the processes that control the three-dimensional distribution of gas composition, clouds, temperatures, and winds in Neptune's atmosphere.



# Level 1 Science Investigations

- Question - Does the conversion of hydrogen from its ortho- to para- state supply energy and modulate excess thermal IR radiated from neptune?  
(Smith and Gierasch 1995)
- Observation - map ortho- and para-hydrogen as a function of altitude, latitude, and time via NIR spectroscopy

# Level 1 Science Investigations

- Question - Why are wind speeds faster at Neptune than Jupiter and Saturn? Is it because atmospheric turbulence is less, because less power is available? Less turbulence allows the large-scale winds to coast along without dissipation of energy. (Ingersoll et al 1995)
- Observation - Map and make movies of convective patterns and zonal circulation in the thermal IR

# Level 1 Science Investigations

- Question - What is *Neptune's temperature field*; how does it affect Neptune's internal heat flux? What powers the winds? Ground-based midIR images show emission primarily from the south polar region. Need to develop model for Neptune's global energy balance.
- Observation - Map and make movies of convective patterns and zonal circulation in the near IR. Map thermal emission as a function of altitude, latitude and time

# Level 1 Science Investigations

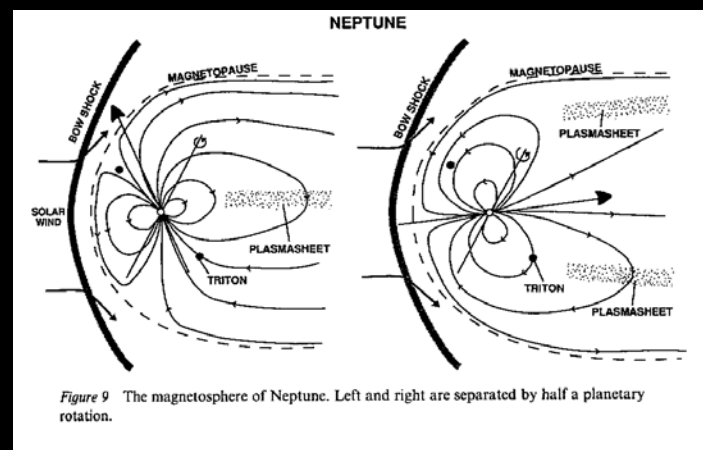
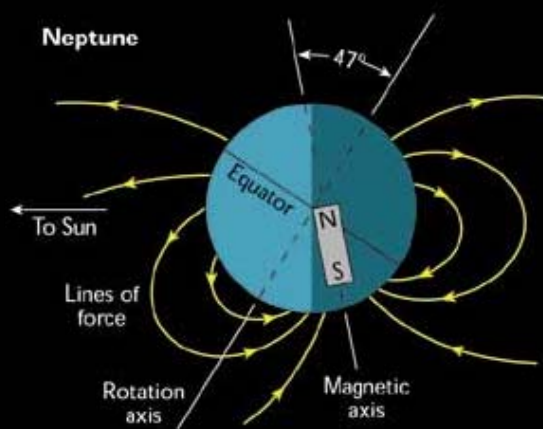
- Question - What is the *tropospheric aerosol composition and particle size* in discrete features? What is the *aerosol composition and particle size in the stratosphere and upper troposphere*? The bulk of Neptune's atmosphere is H and He. CH<sub>4</sub>, NH<sub>3</sub>, H<sub>2</sub>S, and H<sub>2</sub>O, condense or chemically combine in the atmosphere of Neptune to form clouds.
- Observation - Image atmospheric features at high resolution in near IR and UV wavelengths. Stellar occultations will reveal haze layers; visible and near IR observations at a variety of phase angles yield particle sizes

# What a neptune flyby can do

- Neptune Measurement Goals
  - new visible and first-ever near-ir mapping of small-scale cloud dynamics and evolution
  - first detailed spatially-resolved spectroscopic mapping of cloud composition
  - first auroral ultraviolet images
  - first detailed infrared map
  - gravitational moments refined for interior models

# Neptune's Magnetosphere

- Magnetic dipole is highly tilted and offset from the planet's center
- Changes in the magnetosphere are dramatic as the planet rotates and different parts of the field encounter the solar wind



Not like Jupiter or Saturn  
Undetectable from Earth

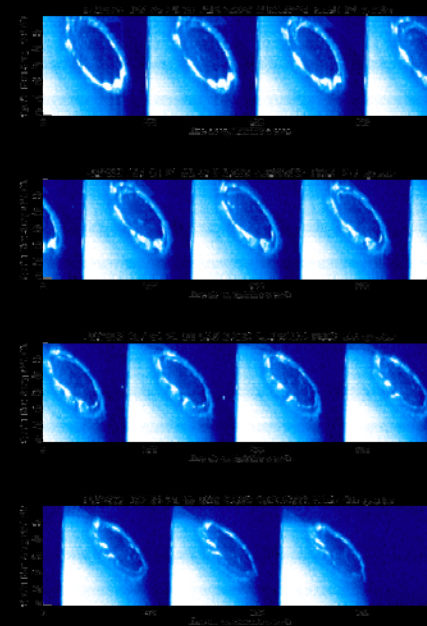
# Level 1 Science Investigations

- Question - What is the generation mechanism of Neptune's unusual field?
- Observation - Improve quadrupolar and octopolar terms of the magnetic field by flying by Neptune at a different latitude / longitude than Voyager, preferably over the south polar region

# Level 1 Science Investigations

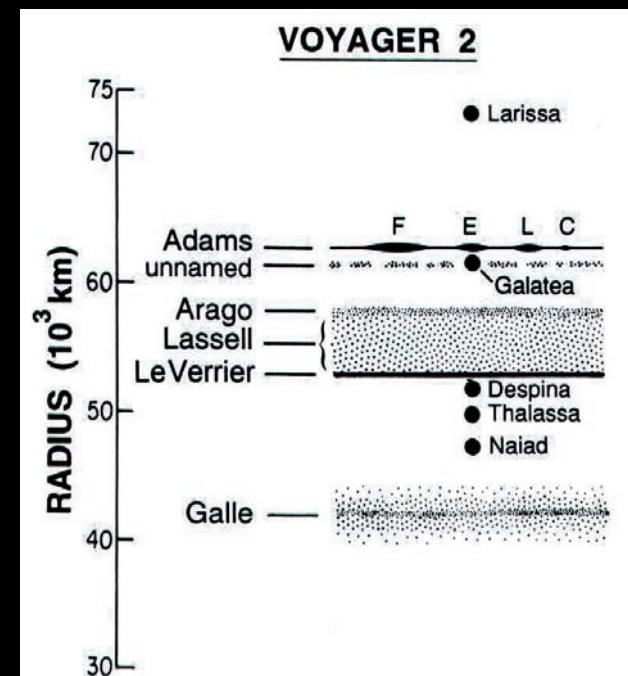
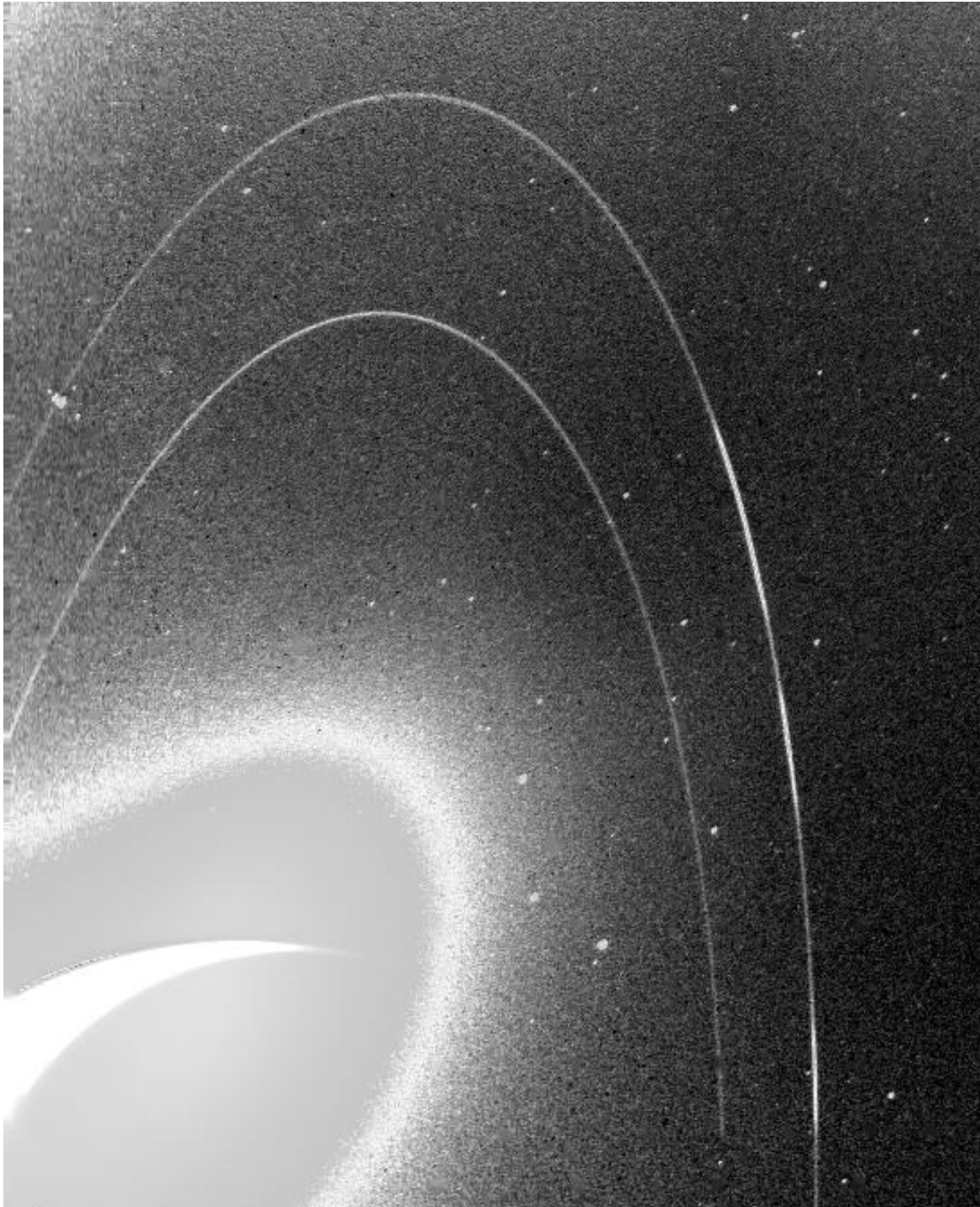
- Question - What are the *operational dynamics of a highly-tilted magnetosphere* that refills and empties over diurnal time scales? Is magnetic reconnection important for the motions of plasma?
- Observation - Measure field and plasma parameters along the spacecraft trajectory with modern instrumentation to understand plasma generation, convection, and diffusion processes.

The UV instrument will look for aurorae on Neptune and relate them to the reconnection electric field imposed by the solar wind.



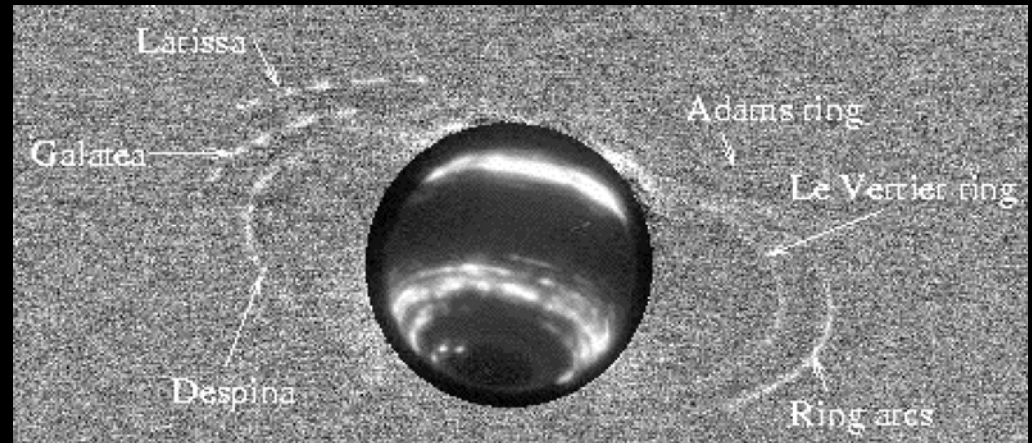
# Neptune's Rings

- Narrow rings
- Arcs
- Dust bands
- Small moons



# Neptune's Rings

*Nearly all aspects of the Neptune system detectable from Earth have changed significantly since Voyager fly-by in 1989*



The arcs have fallen behind their predicted location and definitively outside the resonance, contradicting the confinement model

The leading arcs have also shifted forward and decreased in brightness relative to the others

The trailing arc, Fraternite, is the most stable and seems to track at the exact resonance rate

The other arcs continue to evolve, with the leading arcs Courage and Liberte now almost completely gone

The narrow Le Verrier ring, interior to the Adams ring, has also brightened by a factor of four since Voyager

# Level 1 Science Investigations

- Question - Where are the arcs now? What is the *current configuration of the rings, dust disk, and ring arcs* and how has that configuration evolved since the Voyager flyby in 1989? Test confinement and resonance models by getting updated positions for the arcs, mapping their orbital motion since Voyager
- Observation - Map and make movies of ring arcs at high phase. Acquire images of the dust bands and narrow rings
- Question - What are the *particle size distributions* in the rings and ring arcs? Do larger parent bodies too small to be detected by Voyager populate and/or confine the ring arcs? Because dust lifetimes are short, identifying the full size distribution is critical to understanding the timescales for ring evolution.
- Observation - The combination of phase coverage from a flyby with the vastly improved capability of a modern imaging system will allow us to measure the phase curve in the visual and near-IR.

# Triton Science Objectives

*Triton Science Objective 1: Triton has a youthful surface, substantially modified when Triton was captured by Neptune. Argo will map the side of Triton seen only at a distance by Voyager (“terra obscura”) and more of the northern hemisphere. Near-global surface coverage will extend the post-capture cratering history and other modification of Triton’s surface.*

- More of Triton's northern hemisphere will be sunlit
  - Most of it was in seasonal darkness for Voyager

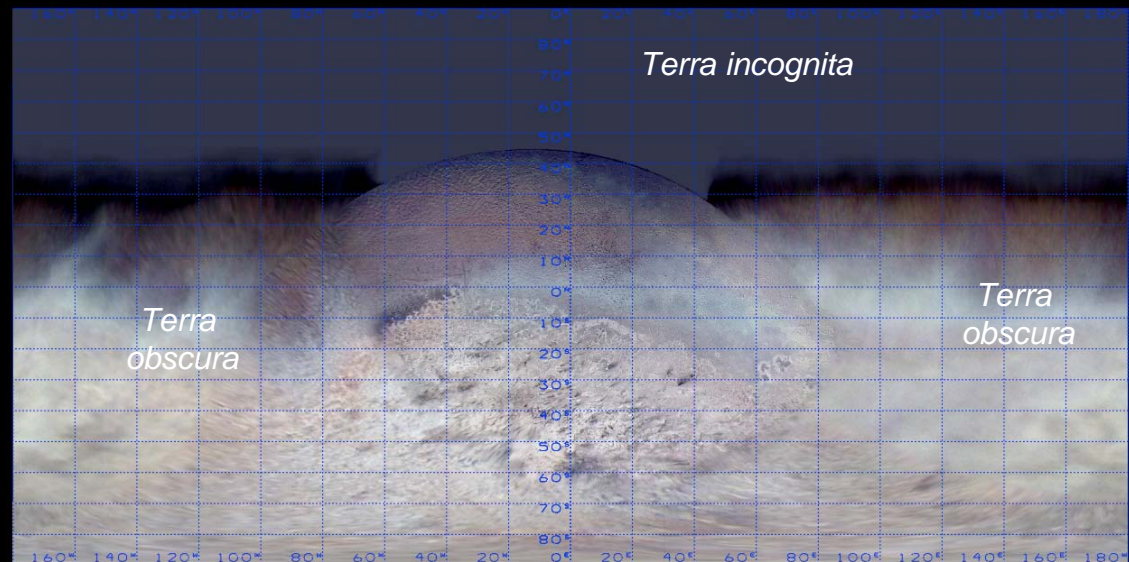
Terminator  
in 2027: 60° $\oplus$



Terminator in  
1989 for VGR  
flyby: 45° $\oplus$



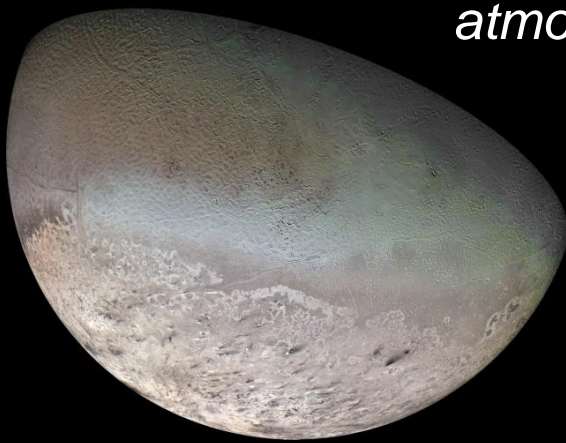
Image the hemisphere  
observed only at low  
resolution by Voyager



# Triton Science Objectives

*Triton Science Objective 2: Triton's climate is controlled by its nitrogen atmosphere in vapor equilibrium with surface frost. Argo will map the distribution of ices on Triton's surface and measure the atmospheric pressure to capture another point in time for modelling climate change on an icy body*

- Triton's atmosphere has changed significantly since the Voyager flyby in 1989
  - Nitrogen and methane ices move seasonally from hemisphere to hemisphere and the pressure of the atmosphere increases and decreases seasonally



Will Triton's enigmatic plumes still be active?  
Are they a seasonal phenomenon, like on Mars?

# Neptune flyby enables KBO science

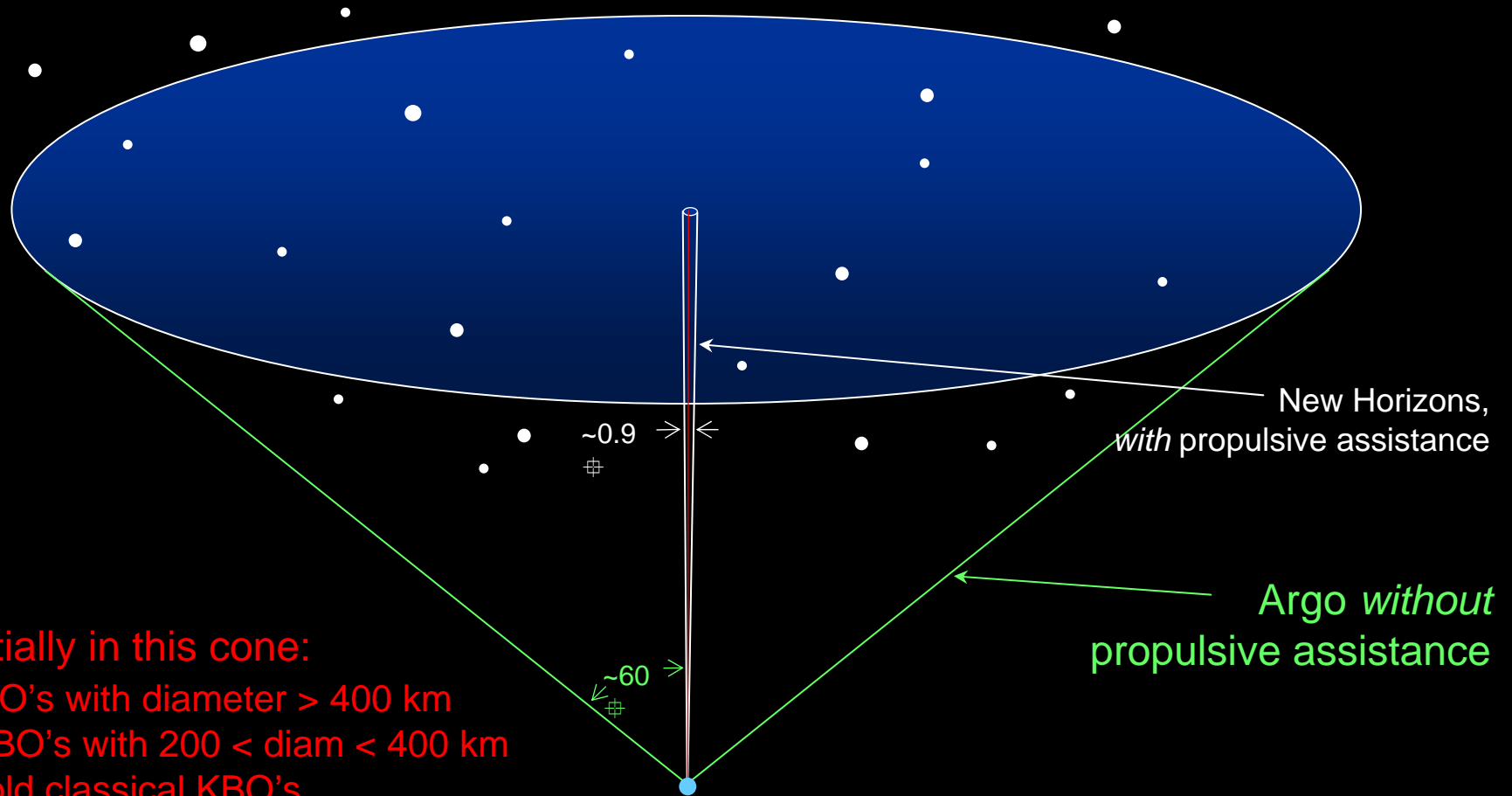
- **Opportunity** to continue on to a KBO! □!
- Potential KBO Targets
  - The cone of accessibility includes ~40 of the largest KBOs
  - Several binary KBOs
  - Many objects in the cold classical disk
- **Neptune flyby permits selection of KBO with highest scientific interest**



Address evolution of the solar system...

# Access to Kuiper Belt Objects

Argo's accessible volume is ~4000x that of New Horizons  
Flight time to KBO is just ~1.5 - 3 years (KBO at 35-39 AU)



Potentially in this cone:

9 KBO's with diameter > 400 km

40 KBO's with  $200 < \text{diam} < 400$  km

18 cold classical KBO's

# KBO Science Objectives

- Reconnaissance of primitive solar system body that is member of a much larger population
- Determine comparative properties of captured KBO Triton and a KBO *in situ*
- Expand the diversity of volatile-rich small bodies explored in the outer solar system
  - Between Argo and New Horizons (shown here) we will double the number of explored KBOs
    - Pluto
    - New Horizons *in situ* KBO
    - Triton
    - Argo *in situ* KBO

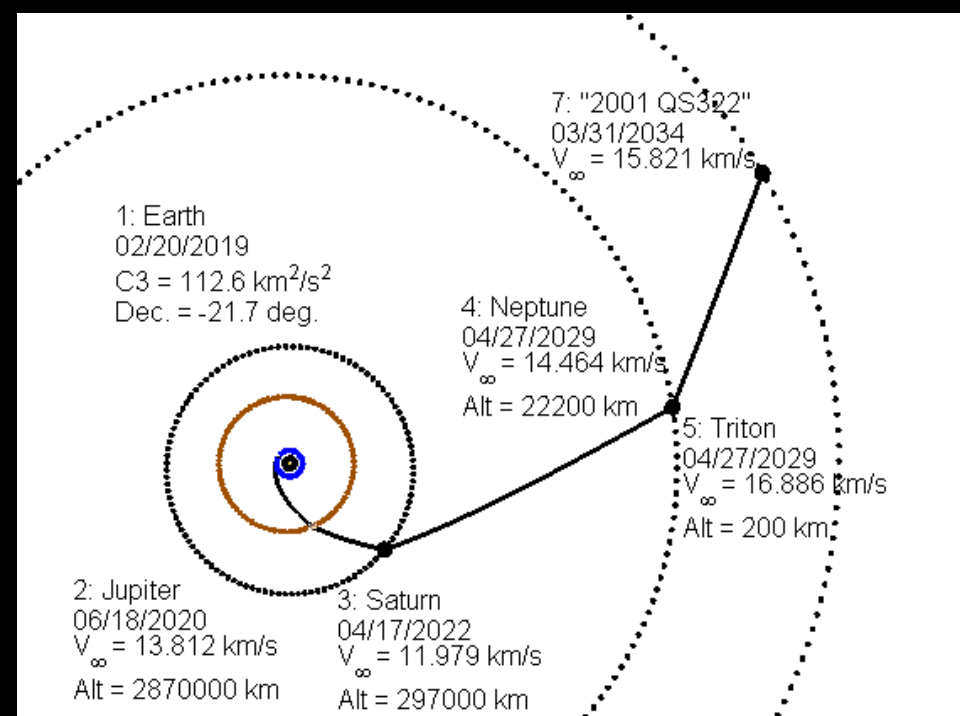
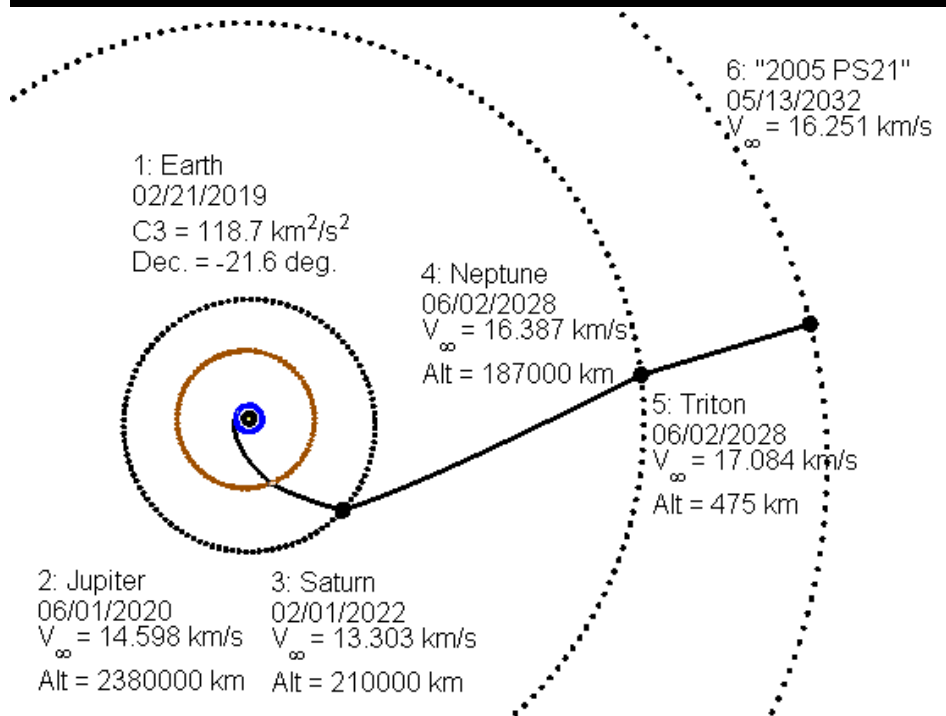


# Presentation Outline

- Community support
- Science
- Mission, Payload, Spacecraft
- Observational Timeline
- Summary

# Example 2019 Launch Options

Voyager-like flight times to Jupiter and Saturn;  
even faster to Neptune

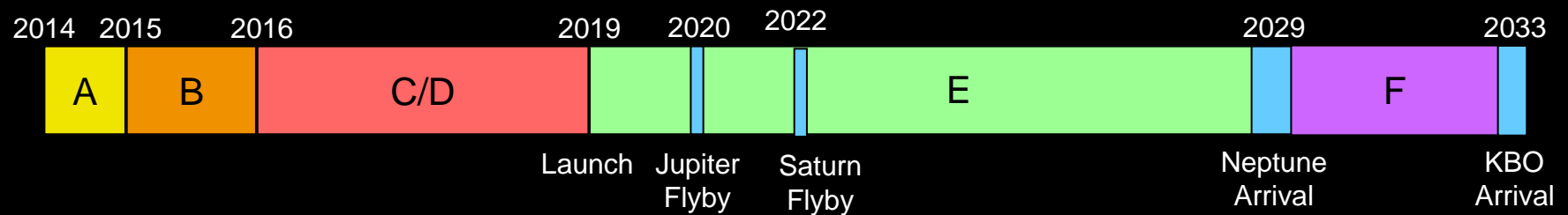


Time of Flight = 9.3 yr  
Neptune flyby 2028  
38S Neptune periapsis  
KBO: 2005 PS21

Time of Flight = 10.2 yr  
Neptune flyby 2029  
21N Neptune periapsis  
KBO: 2001 QS 322

# Project Timeline

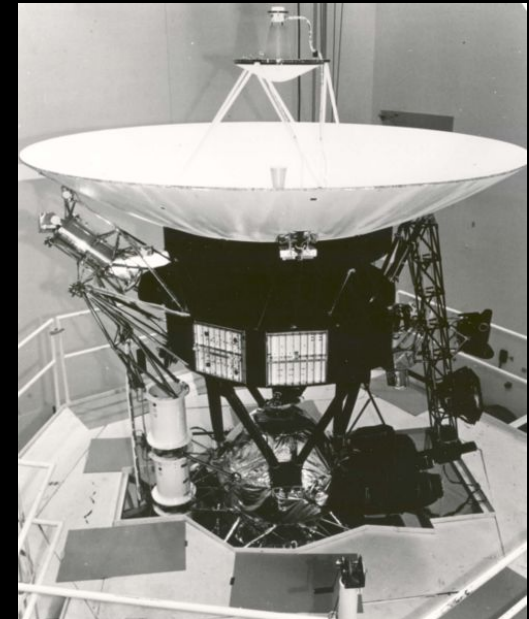
- Phases A, B, C/D, E, F (with science windows)



- Project start in 2014 for 2019 launch, ~9-year flight, 6-month Neptune science phase
- Launch opportunities occur between 2015 and 2019; such windows only occur every 12 years
- KBO arrival date depends on which KBO is selected

# Modern Technology

- *Voyager launched* in 1977
- Voyager technology now >35 years old!
- Technology that could fly on Argo **today** (no technology development needed)
  - Visible camera with a CCD, not a vidicon
  - Near-IR array, not single channel bolometer
  - UV multi-pixel imaging, not single channel
  - Solid-state recorders, not tape recorders
  - Ka band for telecom and radio science



# Spacecraft

- Envision a spacecraft similar to New Horizons spacecraft
  - Similar total mass and mass distributions (~400 kg dry mass)
  - Similar power needs (200 W)
- **Must use nuclear power**
- By maintaining similar scope we expect to remain in the New Frontiers budget envelope

# Notional Argo Payload

Preliminary suite based on science traceability matrix

- High resolution visible camera - New Horizons (NH) level
- Near-Infrared spectrometer - NH heritage
- UV solar & stellar occ. spectrometer - reduced Cassini heritage
- Far-infrared linear radiometer - Diviner heritage
- Magnetometer - ST5 (UCLA)
- Charged particle spectrometer – Messenger heritage
- Gimballed high-gain antenna - heritage radio science instrument

Beyond this: explore trade space for other instrumentation in terms of science, cost, power, and mass

# Payload mass

8.6 kg	Lorri
10.5	Ralph
5.0	UV
12.0	Diviner
10.0	Magnetometer w/ boom
3.5	Charged particle spectrometer
1.5	USO
<b>51.1 kg</b>	<b>Total</b>



Figure 1. The MCS flight instrument photographed during calibration at JPL. Major elements of the instrument are identified.

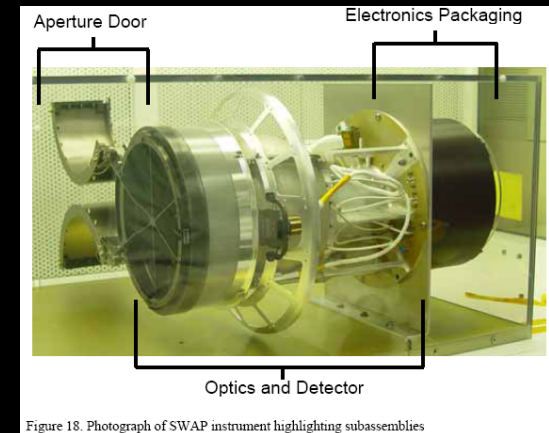


Figure 18. Photograph of SWAP instrument highlighting subassemblies

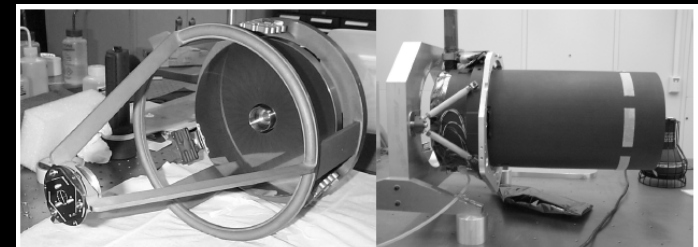


Figure 1 (left) LORRI telescope assembly, showing SiC mirrors and metering structure; (right) LORRI composite baffle and flexure mount on test stand

# Telecommunication Options

- Use existing DSN facilities with flight-proven high gain antenna
- X-band downlink to a 70-m DSN station
  - Voyager 2 transmitted 21 kbps from Neptune (with arraying)
  - NH will send 0.7-1.2 kbps from Pluto
- Ka-band downlink
  - 14-16 kbps to a 70-m DSN station; ~4 kbps to 34-m
    - Assuming smaller 2 - 2.5 m HGA
- Design for simultaneous observation and downlink (gimballed high gain antenna)
  - Significantly improves science yield for one-time science opportunities
  - Saves costs in Phase E

# Presentation Outline

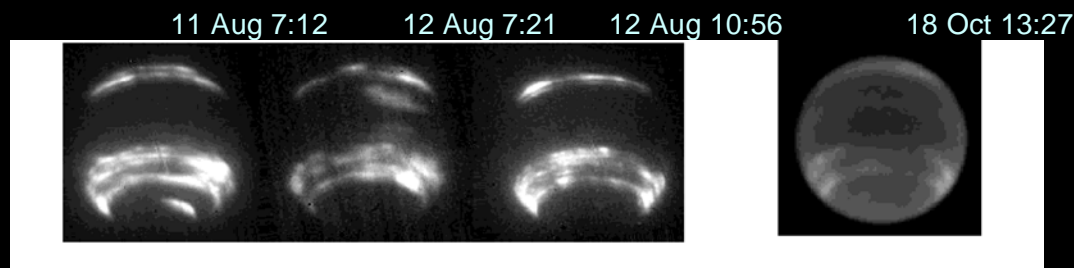
- Community support
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# Observational Timeline

## *Atmospheric Movies*

- Beginning at closest approach - 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths.
- Receding from Neptune, from closest approach to + 6 months observe Neptune every 36 deg of longitude, in visible, near IR and thermal wavelengths

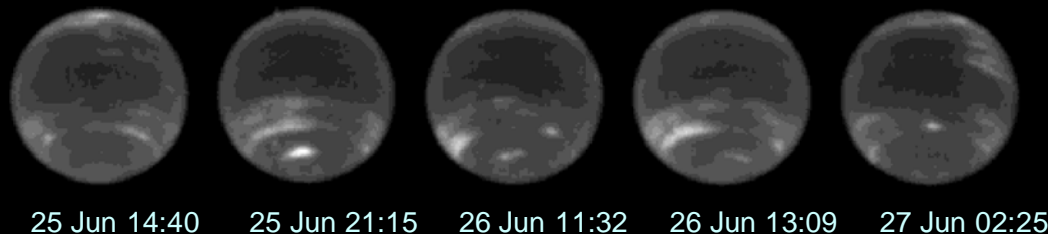
2000



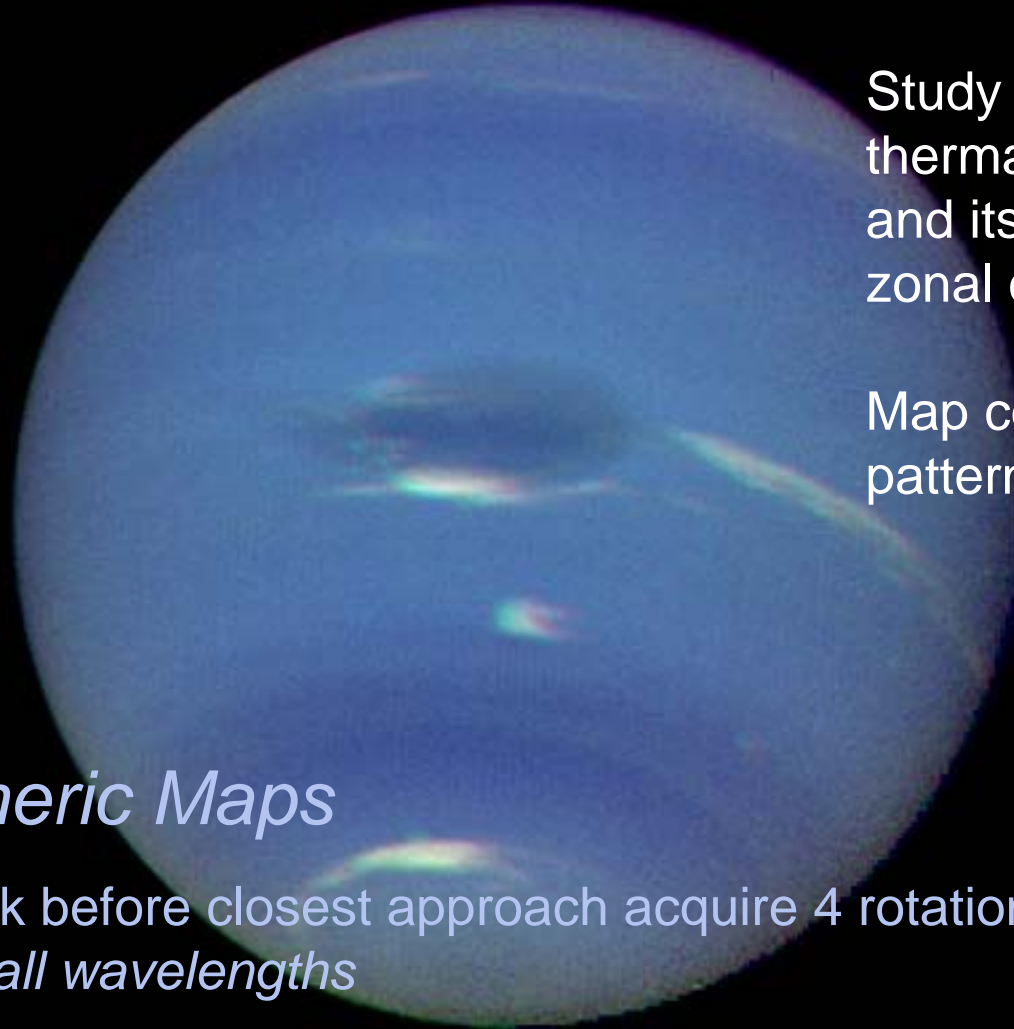
Study Neptune's  
dynamic atmosphere  
on short timescales

Map zonal winds

2001



# Observational Timeline



Study Neptune's thermal emission and its effect on zonal circulation

Map convective patterns

## *Atmospheric Maps*

- One week before closest approach acquire 4 rotations of global maps *at all wavelengths*
- Particularly important in the thermal IR

# Observational Timeline

Study composition

Determine aerosol  
particle sizes

Map convective  
patterns in storms

## *Atmospheric Features, high altitude structure*

- In the days before and after closest approach acquire closeup views of all Neptune's storms, observe stellar occultations, radio occultation of earth
- All wavelengths
- Variety of phase angles

# Observational Timeline

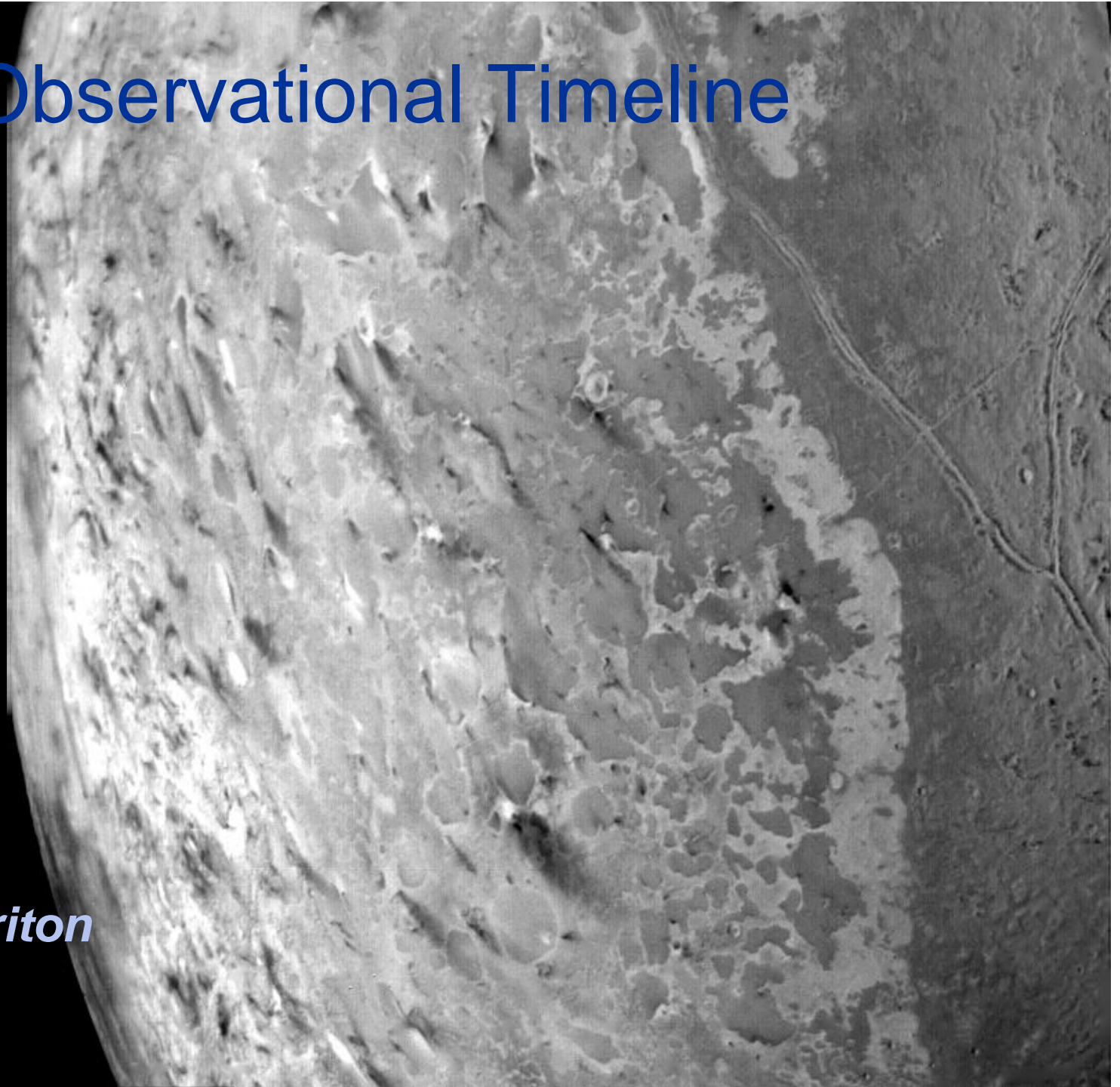


## *Ring structure*

- after closest approach acquire closeup views of Neptune's rings, ring arcs and dust bands; observe stellar occultations
- All wavelengths
- Variety of phase angles

# Observational Timeline

*Encounter Triton*



# Presentation Outline

- Community support
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- Summary

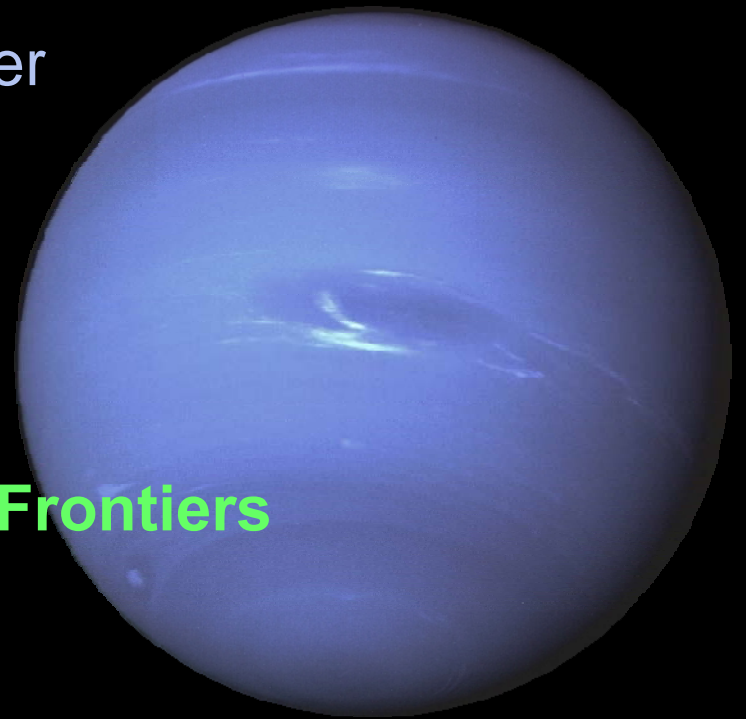
# Academy and Community Interest

- **2003 Planetary Decadal Survey** explicitly discusses Neptune
  - Flybys/orbiters in “Giant Planets,” “Large Satellites,” and “Primitive Bodies”
  - Community Papers highlight Neptune Atmosphere and System Exploration
  - Set in third decade because **Flagship-class orbiter assumed**
- NASA Vision Missions: **Two independent Neptune studies**
- NASA’s **2006 Solar System Exploration Roadmap** explicitly discussed Neptune
  - Again, late in the queue because **Flagship-class orbiter assumed**
- Would engage a **broad swath of the planetary community**
  - Rich scientific return: thick atmosphere, thin atmosphere, rings, satellites, surface geology, magnetospheres, interiors, KBOs...

*A flyby mission addresses important science objectives, is much less expensive and less complex than an orbiter, and is achievable within New Frontiers resources*

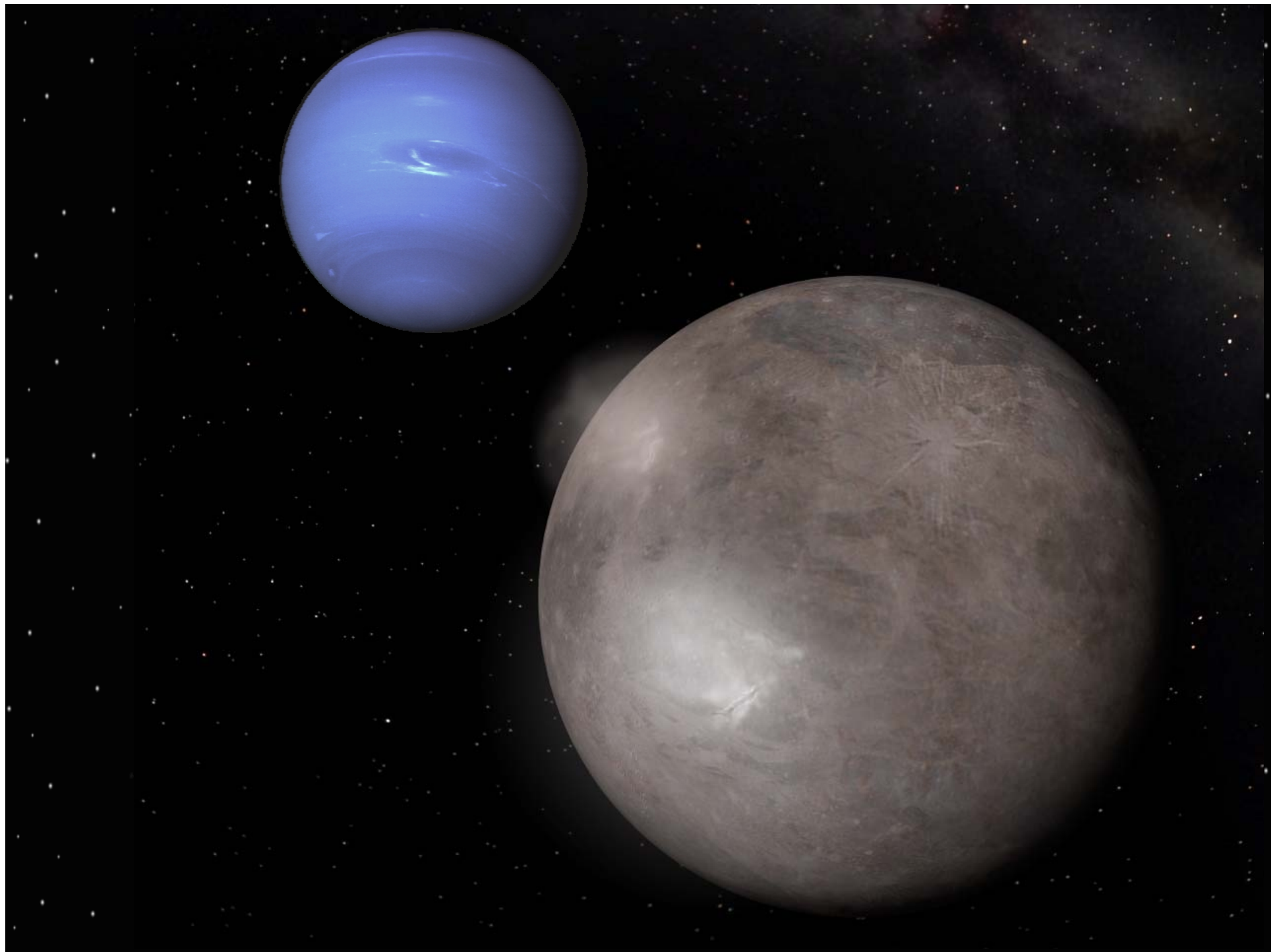
# Summary

- **Neptune and Triton are compelling flyby targets**
  - Dynamic worlds, rich opportunities for new science discoveries
  - Trajectories identified with reasonable trip times and approach velocities
- A **KBO encounter** explores another primitive outer solar system body
  - Triton / KBO comparison
  - Pluto / KBO comparison
  - Numerous potential targets
- This **Mission is feasible for New Frontiers**
  - Key science addressed by instrument package based on New Horizons heritage
  - Avenues available for additional cost savings in development, operations, and launch vehicle
  - Mission can be accomplished within New Frontiers cost cap





Backup Slides



# NRC Midterm Report

- The Committee on Assessing the Solar System Exploration (CASSE) Program gave NASA a “C” in its 2008 Report, on Science Question #2\*, and made the specific recommendation:
  - “The next solar system exploration decadal survey should address the objectives and merit of a Neptune/Triton mission”
- NF4 can raise this grade without a flagship

\* How long did it take the gas giant Jupiter to form, and how was the formation of the ice giants (Uranus and Neptune) different from that of Jupiter and its gas giant sibling, Saturn?

# Argo Mission Statement

Argo is the next step for outer solar system exploration, illuminating the genesis and evolution of the solar system by

- characterizing Kuiper Belt objects with diverse evolutionary paths ranging from captured KBO Triton to an *in situ* KBO, and
- accomplishing ground-breaking science at Neptune by opening a window on the dynamical nature of the atmosphere, rings, and magnetic field, and laying the groundwork for future ice-giant missions.

# Why Now?

- Launch opportunity window from 2015 - 2019
  - Such windows occur every 12 years due to Jupiter gravity assist
- Waiting for flagship, or next window, will result in ~50-year gap in observations of a Triton dynamic system
- Neptune / Triton Flyby is **complementary** to eventual Neptune system orbiter
  - Outstanding ice giant science can also be obtained on the way to the KBO
- Exoplanetary Neptunes are now known to exist
  - Knowledge of local ice giants is substantially less than gas giants
- Current technology far surpasses Voyager-era technology
- **Need time to resolve nuclear power issues**

## NF3 vs. NF4

New Frontiers 3		New Frontiers 4
AO out	2009	
	2010	
	2011	
	2012	
	2013	AO comes out 54 months after NF3 AO, write proposal
	2014	Downselect, Step 2 = Phase A
	2015	Phase B
	2016	Phase C/D
	2017	Phase C/D
	2018	Phase C/D
	2019	Launch in February
	2020	Backup launch in January

The schedule for NF4 is tight but not out of the question

# Argo Launch Vehicle Requirements

- Criteria for launch vehicle choice
  - Desired trip time
  - Spacecraft mass
  - Launch trajectory  $C_3$
- For a **given launch vehicle**:
  - higher  $C_3$  → faster trip time BUT smaller spacecraft mass that vehicle can launch

$C_3$  (km<sup>2</sup>/sec<sup>2</sup>) ≡ square of the hyperbolic excess velocity

hyperbolic excess velocity ≡ craft's speed when it "breaks free of Earth's gravity" (i.e., has just climbed out of Earth's gravity well)

Example trajectories aimed at Jupiter gravity assists (to Neptune, for instance)

$C_3$	Trajectory	Launch Vehicle and Mass	Trip time to Jupiter
25	Delta-VEGA (Propulsive Deep Space Maneuver, single Earth gravity assist)	<i>Smallest Atlas V can propel &gt;1000 kg to this <math>C_3</math></i>	4-5 years
80	Direct Earth-to-Jupiter, "just barely getting there"	<i>Mid-sized Atlas V can propel &gt;500 kg to this <math>C_3</math></i>	2-2.5 years
162	New Horizons, high-speed Jupiter gravity assist to Pluto	<i>Largest Atlas V with an additional Star-48 upper stage to propel 478 kg to this <math>C_3</math></i>	13 months

- Currently examining trades among launch mass capacity,  $C_3$ , and trip time to Neptune (next slide)

# Argo **Discovery** Opportunities

*These measurement objectives are accessible to a flyby, but are impossible from L2, from near-Earth orbit, and from Earth even with a 30-m telescope*

- Neptune
  - Small-scale cloud distribution
  - Atmospheric lightning
  - Magnetic field measurements in completely different orientation
  - First detailed compositional/spectral map
  - First detailed infrared map
  - Gravitational moments refined for interior models
- Overall unique viewing geometry
  - High-phase angle observations of atmospheres of Neptune & Triton, rings
- Triton & in situ KBO
  - Geologic mapping (and for Triton: mapping expanded beyond Voyager with improved resolution)
  - Surface evolution & atmospheric structure
  - Magnetic field
  - First compositional/spectral map
  - First detailed infrared map
- Nereid and perhaps other moons
  - First detailed images
- Ring system
  - Detailed structure and evolution

# Presentation Outline

- Context
- Science
- Mission
- Cost
- Summary

# Of \$1B Boxes and Bricks

“I heard that a joint NASA study by JPL and APL said **NASA couldn't send any mission to the outer Solar System for less than \$1B.**” **This is wrong.**

The “Titan and Enceladus \$1B Mission Feasibility Study” *actually* said:

Pg 1-1: “**no missions to Titan or Enceladus that achieve at least a moderate understanding beyond Cassini-Huygens** were found to fit within the cost cap of 1 billion dollars (FY'06).”

Relevance to Neptune: None

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“But I also heard that the study said **NASA couldn't even send a BRICK (spacecraft with no instruments) to the outer Solar System for less than \$800M.**” **This is only partially correct.**

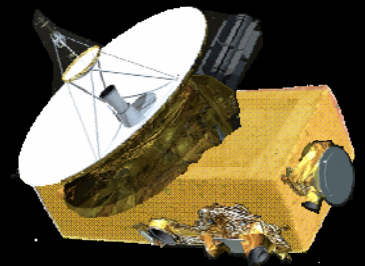


**CORRECT** Pg 1-11: “Even the lowest cost mission studied [Enceladus flyby], without the cost of science payload, has a minimum **expected cost of ~\$800M.**”

**HOWEVER** Pg 2-4: “[The Enceladus flyby's] design (and therefore cost) was uniquely derived using **actual cost data from the NH mission.**”

Neptune cost mitigators: Can use an Atlas 541 instead of a 551.  
Do not require Star-48 upper stage. Other savings under study.

**Result: \$\$ available for Argo science payload within \$800M cap**



# Cost-Saving Options

- Use simple spacecraft with current (New Horizons) heritage
  - Experience base and corporate knowledge available
  - No miracle developments required
- Identify many trajectories, some of which offer mass relief
  - NH's Star 48 upper stage may not be needed
- Use smaller Atlas V launch vehicle
  - 541 instead of 551 -- promising for some trajectories
- Scale instrument requirements to available \$
- Use the market-based approach that Cassini followed for payload development (power, mass, dollars were trade-able)
  - No instruments over-ran or were descope from payload
- Science ops at Jupiter or Saturn will be a mission of opportunity
  - Under SALMON umbrella

# Argo Notional Cost

- Delta to New Horizons cost outline
  - \$566 M in real year dollars = NH Phase C/D cost including launch vehicle, ops to launch + 9 months

- Notional allocation for \$800M available:

\$ 200M *	Launch vehicle (Atlas V 551)	
105M	Power sources (assumes 3 MMRTGs)	
40M	9 yrs cruise ops	
27M	Neptune flyby ops, Operational Readiness Tests	
100M	Payload and Science Team	
320M	Project Management, Spacecraft and Launch approval	
8M	Education and Public Outreach	

*\* Atlas 541 is ~\$190M; if Star-48 upper stage not needed, then get additional ~\$10M savings*

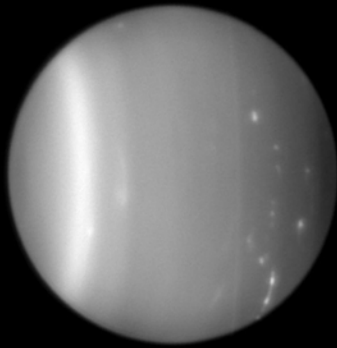
- Plan to size the requirements to the \$ available
  - Have identified options to explore to fit comfortably within NF budget resources (next slide)

# Cost-Saving Options

- Use simple spacecraft with current (New Horizons) heritage
  - Experience base and corporate knowledge available
  - No miracle developments required
- Use smaller Atlas V launch vehicle
  - 541 instead of 551 -- promising for some trajectories
- Identify trajectories which offer mass relief
  - NH's Star 48 upper stage likely not needed
- Use the market-based approach that Cassini followed for payload development (power, mass, dollars were trade-able)
  - No instruments over-ran or were descoped from payload
- Offer KBO flyby option as Phase F extended mission
  - Not part of primary mission
- Scale instrument requirements to available \$

# Which Ice Giant?

## Uranus



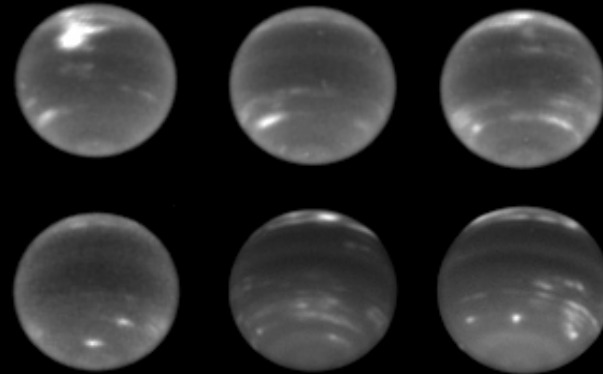
### Uranus Pros

- Closer; shorter trip time
- Full retinue of original satellites
- Dynamic ring system
- Interesting magnetic field

### Uranus Cons

- ☐♁♃♄♅♆♇♈♉♊♋♌♍♎♏♐♑♒♓♈♉♊♋♌♍♎♏♐♑♒♓  
♁ fly-by at equinox (2007, 2049)  
to get active atmosphere (see  
equinoctial above) and full

## Neptune



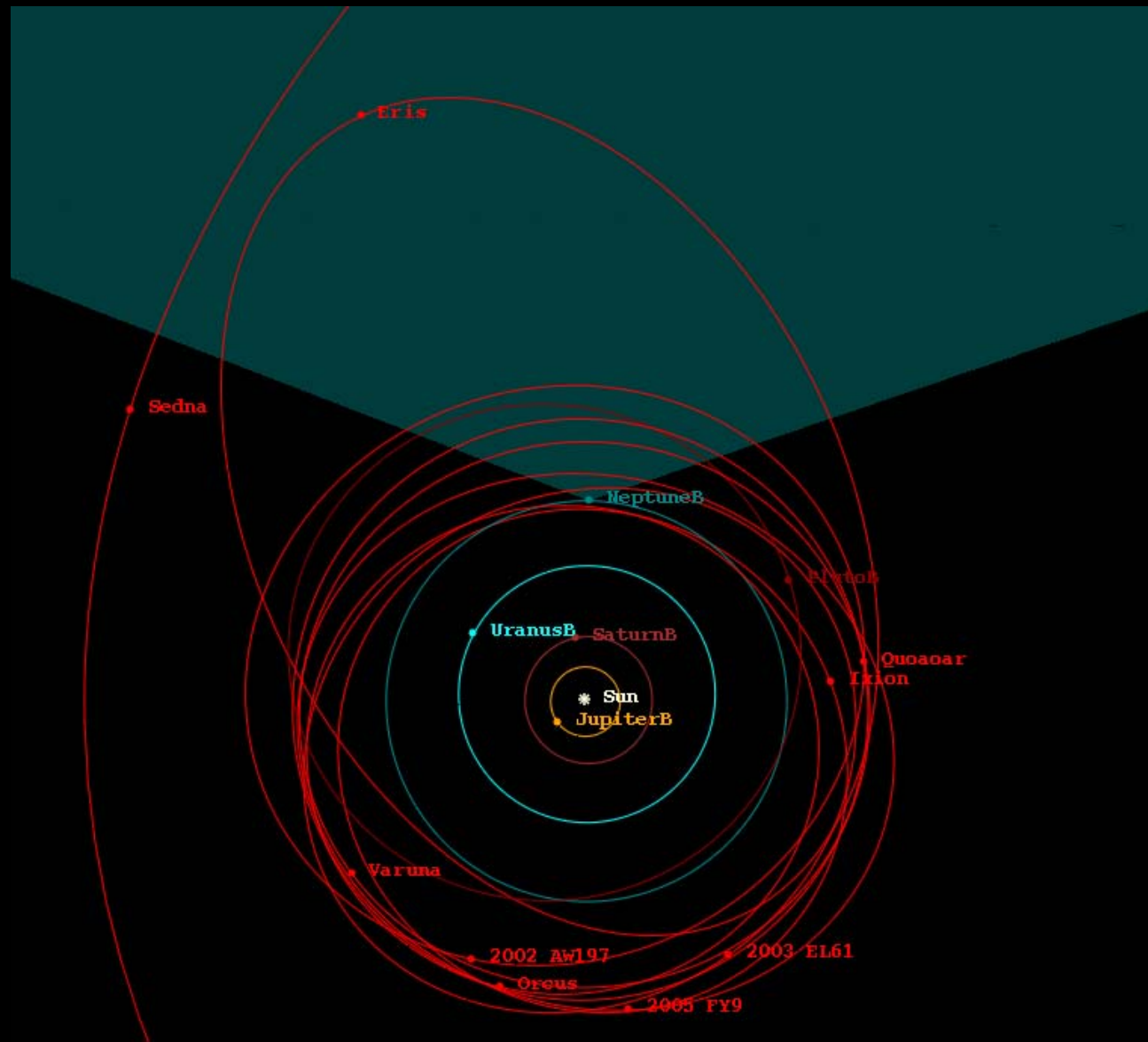
### Neptune Pros

- Triton (captured KBO[?], active)
- Atmosphere always active
- Dynamic ring system
- Interesting magnetic field

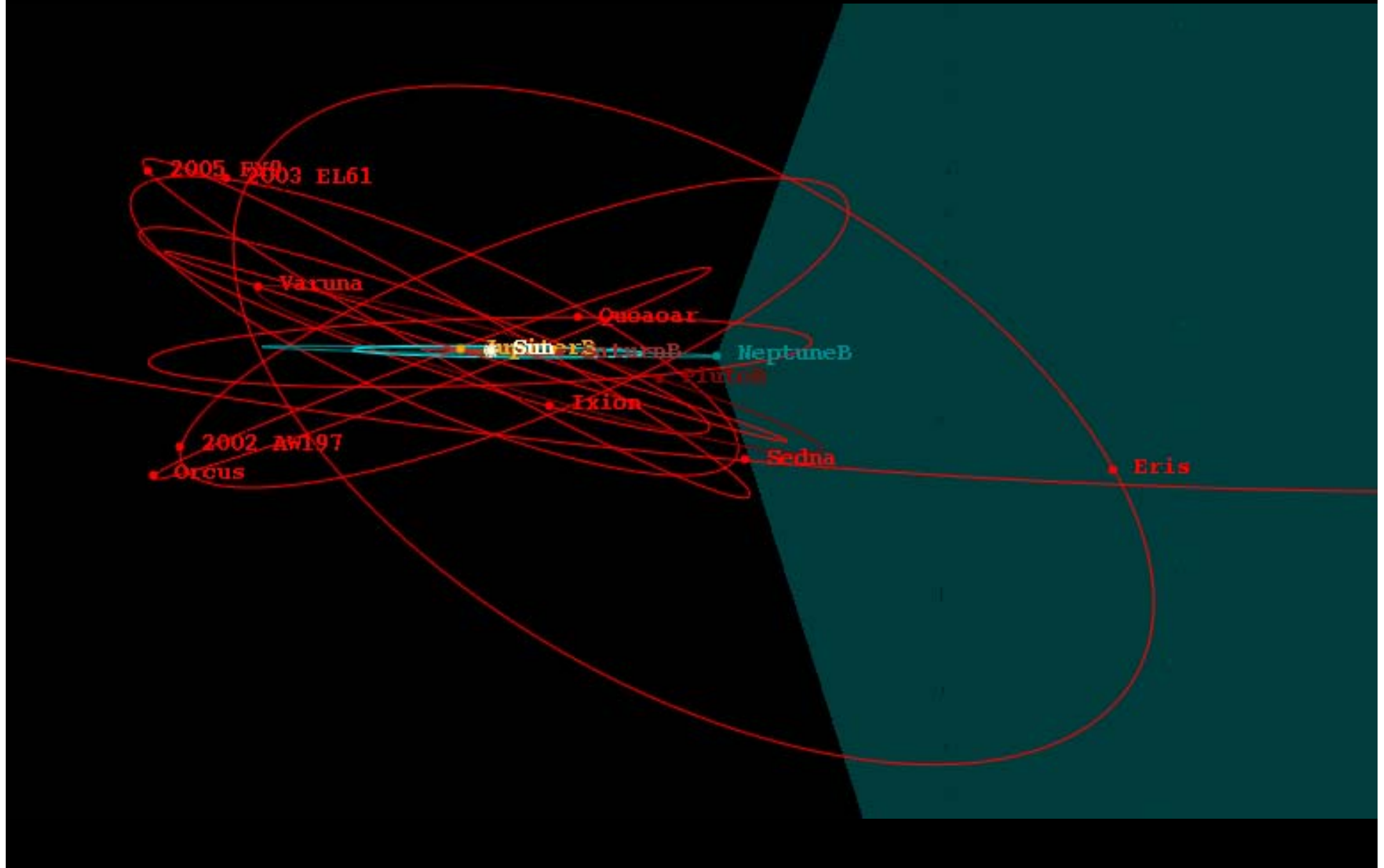
### Neptune Cons

- Farther away; longer trip time

# KBO Accessibility - top view



# KBO Accessibility - side view



# Decadal Priorities, 1 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	<b>Theme 1. ORIGIN AND EVOLUTION</b>					
	<i>Solar-System Giant Planets</i>					
<b>Paradigm altering</b>	How did the giant planets form?	x	xxx	xx	xx	xx
"	What are the orbital evolutionary paths of giant planets?	o	xxx	xxx	o	x
<b>Pivotal</b>	What are the elemental compositions of the giant planets?	x	xxx	xx	x	xx
"	What are the internal structures and dynamics of giant planets?	xx(1)	xxx	xxx	x	xx
	<i>Extrasolar Giant Planets and Brown Dwarfs</i>					
<b>Pivotal</b>	How can we use the giant planets in our solar system to calibrate spectroscopic observations (optical, infrared, radio) of extrasolar giant planets?	xx	xxx	xxx	x	xxx

# Decadal Priorities, 2 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	<b>Theme 2. INTERIORS AND ATMOSPHERES</b>					
	<i>Interiors</i>					
<b>Pivotal</b>	What is the nature of phase transitions within the giant planets?	xx(1)	xxx	xx	x	xx
"	How is energy transported through the deep atmosphere? Do radiative layers exist?	xx(1)	xxx	xx	x	xx
"	How and where are planetary magnetic fields generated?	x(1)	xxx	xxx	o	xxx
<b>Foundation building</b>	What is the nature of convection in giant planet interiors?	xx(1)	xxx	xxx	o	xx
"	How does the composition vary with depth?	x(1)	xxx	xx	o	xx

# Decadal Priorities, 3 of 3

Class of Question	Scientific Themes	Earth-Based Orbiting Facilities	Neptune POP	Analysis and Modeling	Lab	ARGO
	<b>Theme 2. continued:</b> <i>Atmospheres</i>					
<b>Pivotal</b>	What energy source maintains the zonal winds, and how do they vary with depth? What role does water and moist convection play?	x	xxx	xx	x	xxx
"	What physical and chemical processes control the atmospheric composition and the formation of clouds and haze layers?	x	xxx	xx	x	xxx
<b>Foundation building</b>	How and why does atmospheric temperature vary with depth, latitude, and longitude?	x	xxx	xx	x	xxx
"	How does the aurora affect the global composition, temperature, and haze formation?	x	x	xx	x	x
"	What produces the intricate vertical structure of giant planet ionospheres?	x	xx	xx	x	xx
"	At what rate does external material enter giant planet atmospheres, and where does this material come from?	x	o	xx	x	o
"	What can organic chemistry in giant planet atmospheres tell us about the atmosphere of early Earth and the origin of life?	x	x	xx	x	x

# Power Source Options

	BOL Electric Power (W)	EOL (14 yrs) Electric Power (W)	Unit Mass (kg)	Estimated Unit Cost	# Units Needed
MMRTG	115	103	44	\$35M	3 (or even 2)
ASRG	140	127	20	\$20M	2
GPHS-RTG (unit F-5)	300 *	228	55	?	1

\* New Horizons' GPHS-RTG used a mix of old and new Pu; BOL power for that unit was only 240 W

**If NF-03 AO excludes nuclear-powered missions, then no outer Solar System missions are possible other than flagship.**  
 If NF-03 AO is broader, missions may be possible (J-N-KBO; J-S-N-KBO).