Aerocapture as an Enabling Technology for the Ice Giants

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Langley/Ames EDL Summer Student Seminar
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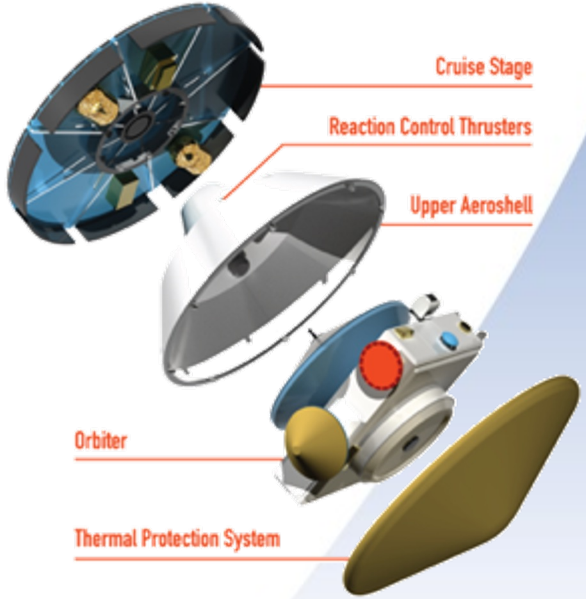
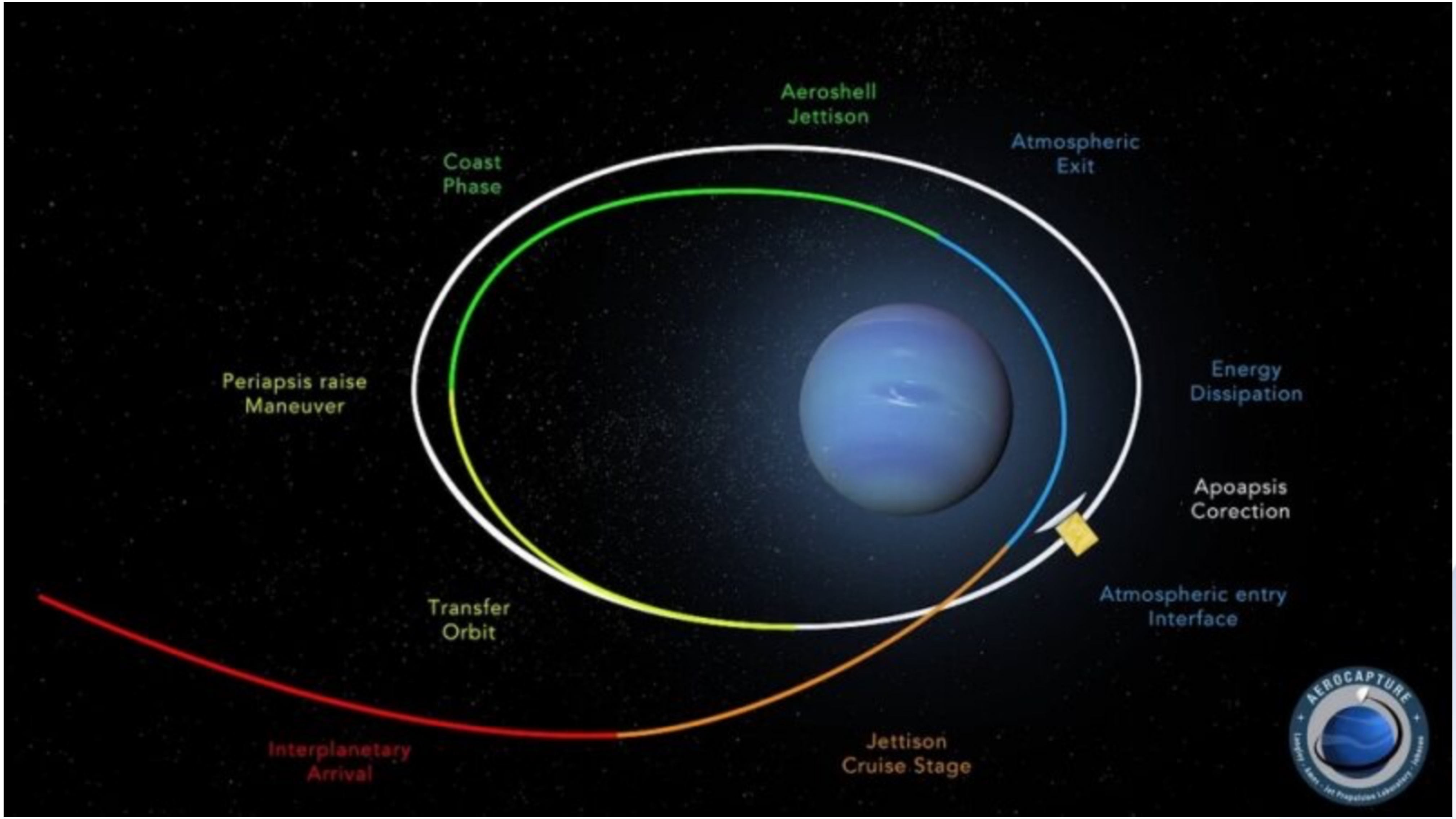
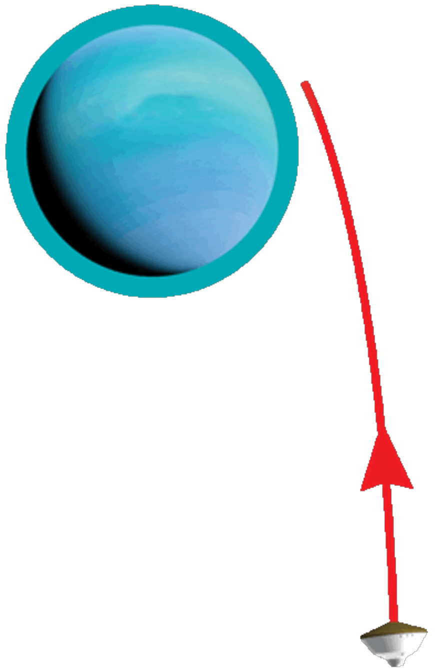


Introduction Video



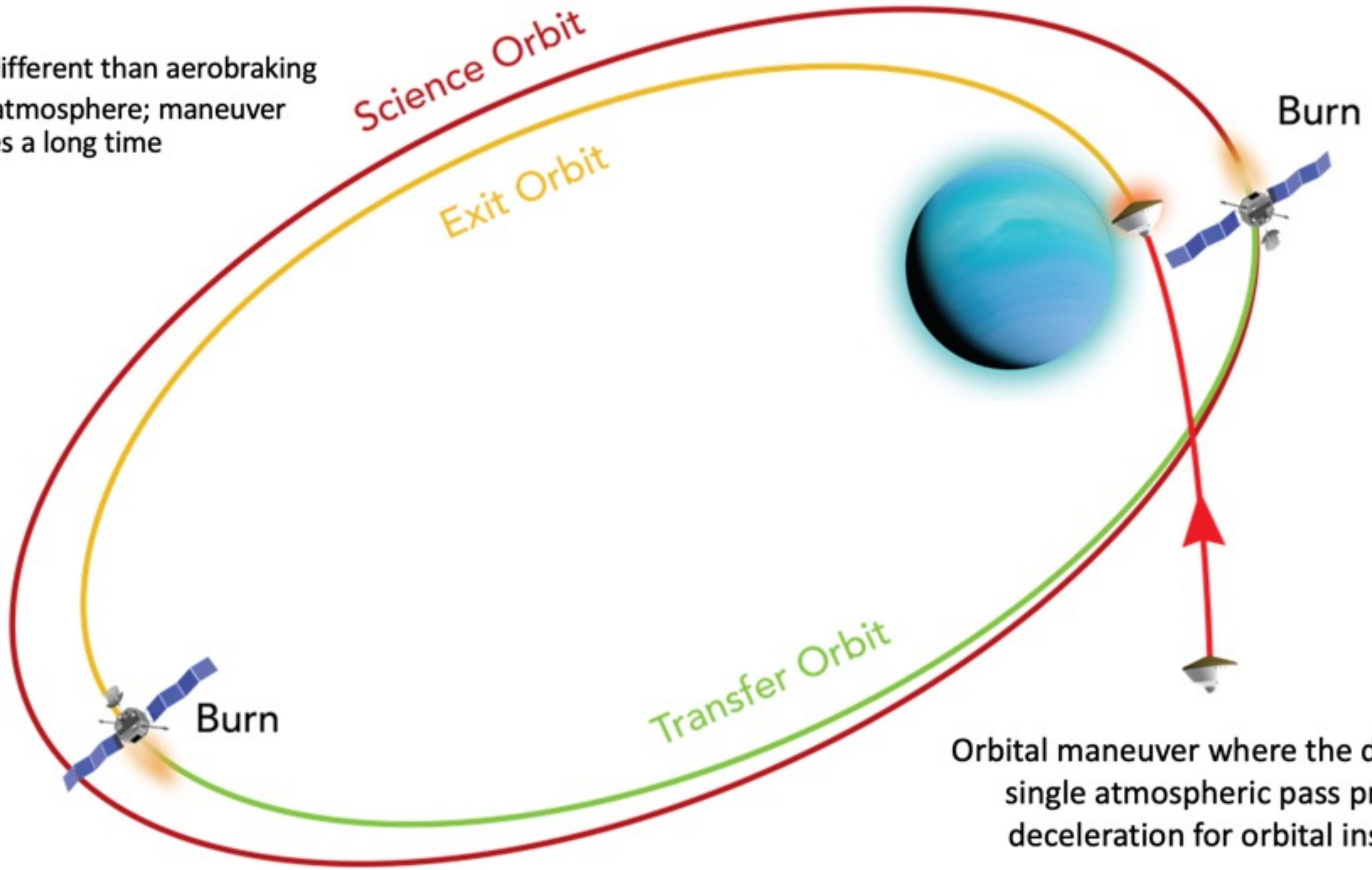
What is Aerocapture?



Orbital maneuver where the drag from a single atmospheric pass provides deceleration for orbital insertion

What is Aerocapture?

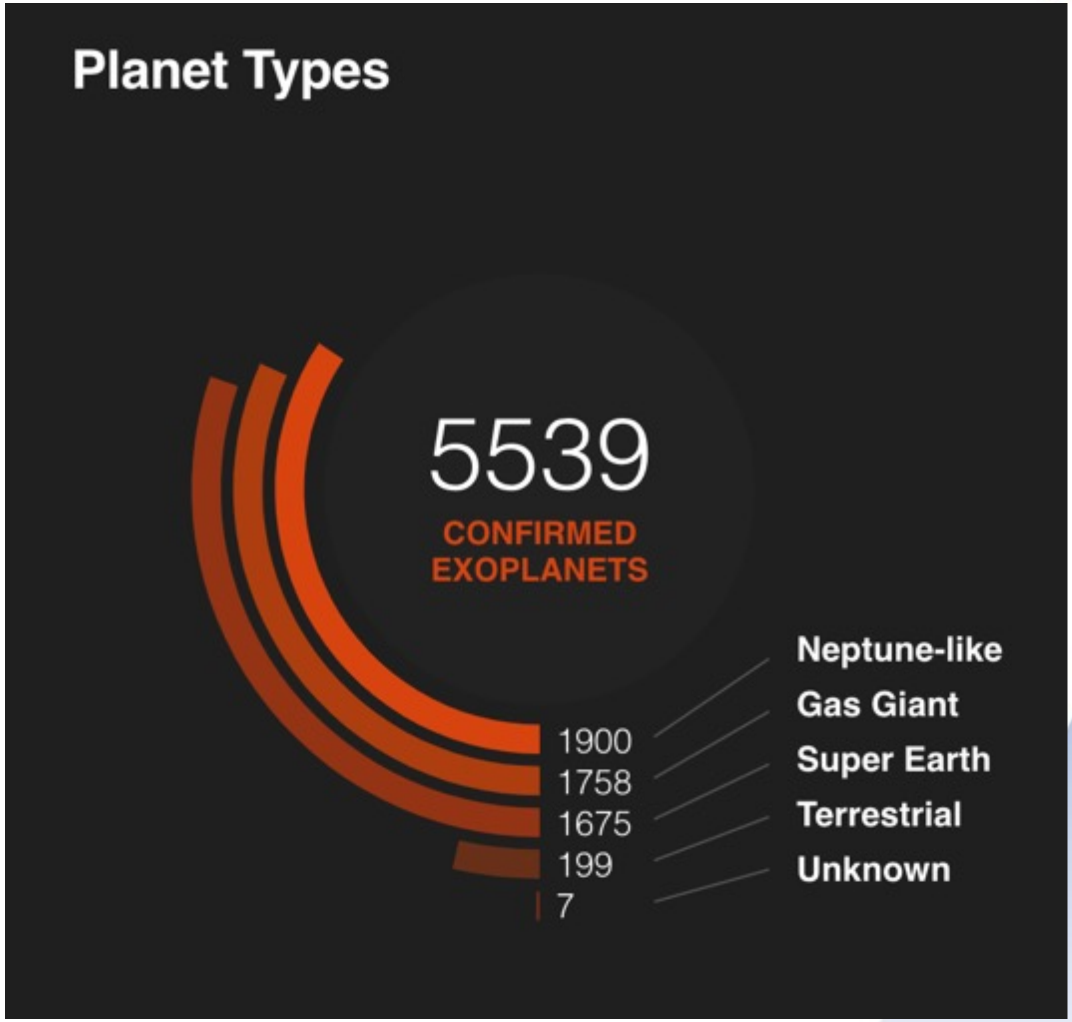
Aerocapture is different than aerobraking
Which skims atmosphere; maneuver takes a long time



Orbital maneuver where the drag from a single atmospheric pass provides deceleration for orbital insertion

Why the Ice Giants?

- Uranus and Neptune (Ice Giants) have only been visited by Voyager 2 through a flyby
- Uranus has interesting obliquity; Neptune has interesting moon: Triton
- Many exoplanets are Uranus and Neptune like
- **Uranus is the top flagship class mission destination in the 2023-2032 Planetary Science Decadal Survey**
  - Uranus Spring Equinox in 2049. Scientific desire to observe Uranus prior to 2049 to see the planet in a posture not seen by Voyager 2
- **Decadal Survey also mentions aerocapture as a technology that should be incentivized**

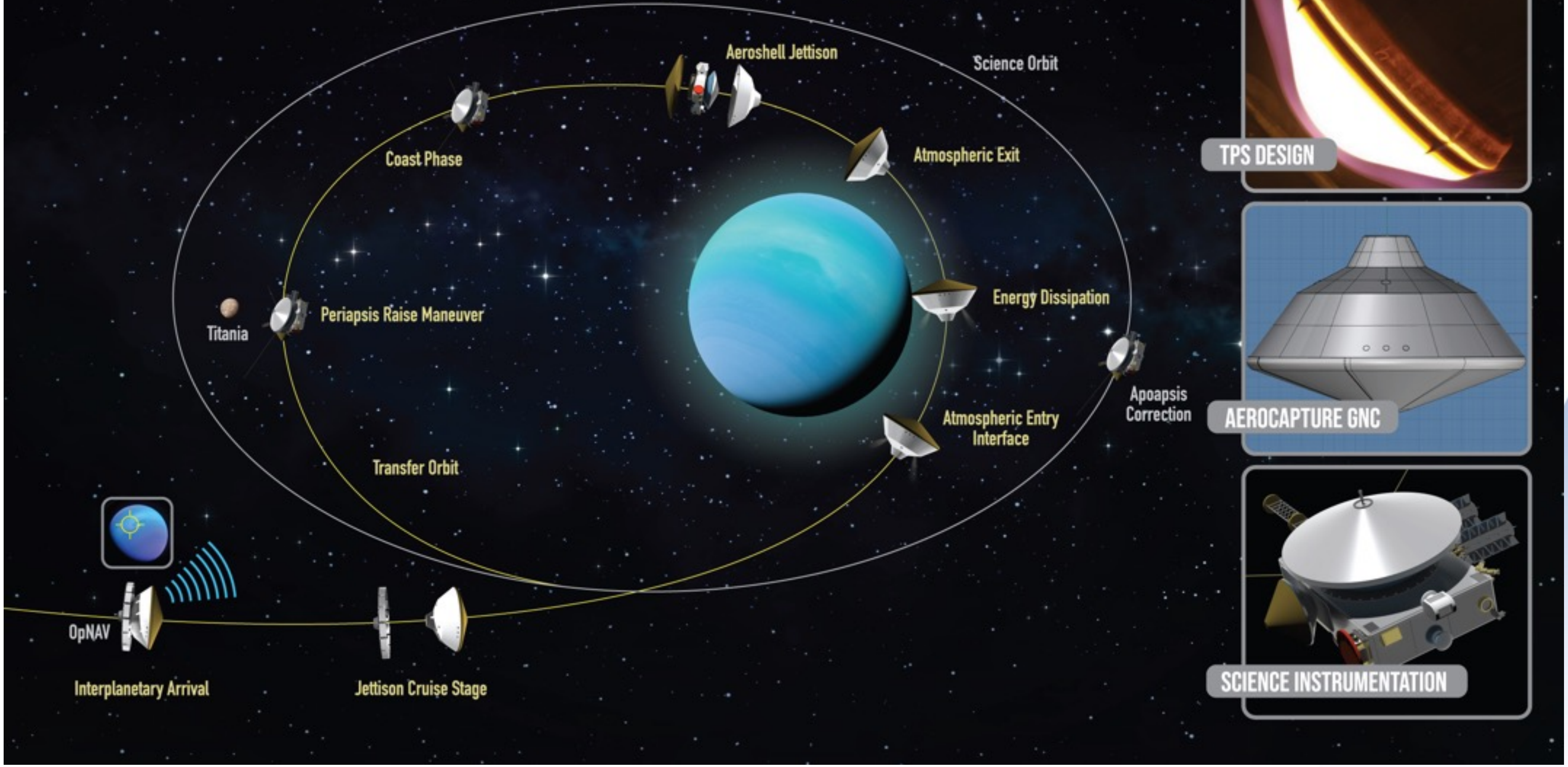


Credit: Exoplanets.nasa.gov (accessed Nov. 27, 2023)

Uranus selected as the point design for Year 1 efforts

Key Technological Thrusts for Aerocapture

TPS = Thermal Protection System
GNC = Guidance, Navigation, and Control
OpNAV = Optical Navigation

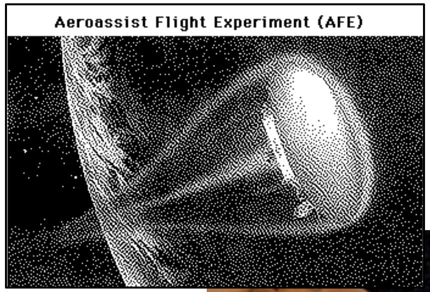


Outline

- Aerocapture and Ice Giants Introduction
- Project Objectives
- Gaps Addressed and Anticipated Benefits
- Aerocapture Sensitivities
- Team Organization
- Project Management
- Key Milestones
- Future Plans
- Publications

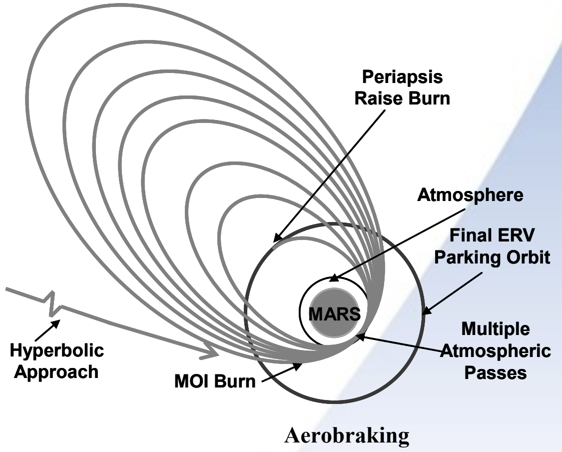
Existing Challenges

- Aerocapture proposed as the baseline for past missions
  - AFE, Mars Surveyor 2001, CNES Mars Sample Return Concept
- No aerocapture flights; mission cancellations due to non-aerocapture technological issues
- Perceived as risky orbit insertion method by mission proposals
  - Descoped or not considered by future planetary missions
  - Alternatives are baseline methods
    - Fully-propulsive orbit insertion – **large propellant mass**
    - Solar Electric Propulsion – **not effective at higher AU destinations**
    - Aerobraking - another atmospheric based orbital insertion method which is **longer time consuming** and has been estimated to have a higher risk posture
- Aerocapture has been in the roadmap of several mission types: cargo missions to support humans on Mars, small satellites, and robotic missions with high incoming speed



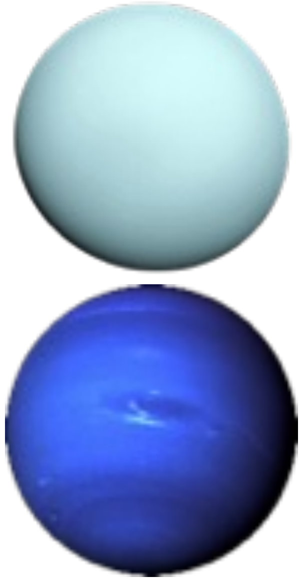
(proposed)


Mars Surveyor 2001 (proposed)



Aerobraking – Aerocapture alternative used for many missions but has higher risk Percy et al., 2005

Gaps



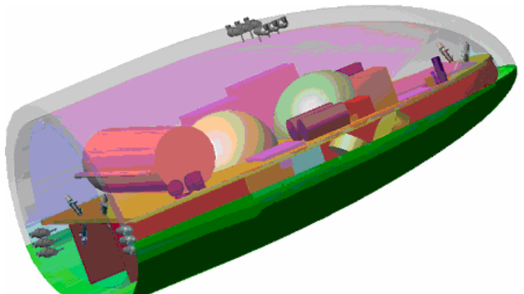
Typical Fully-Propulsive Mission

- Fast interplanetary speeds for outer planets
- **Need 50% or more mass** for fully-propulsive orbit insertion (requires ΔV of 1-2 km/s)
- Typical mission **require long cruise phase** (13-17 years)

Aerocapture directly infusible to top destinations for the next Decadal Survey

Aerocapture Enabled Mission

- Reduced propellant need; **increase on-orbit mass by 40%**
- Aerocapture less sensitive to faster interplanetary trajectories – **reduce trip time by 3-5 years**
- Savings used for launch vehicle choice or increased on-orbit science payload
- Fit a larger cap mission into smaller cap. e.g., **Flagship class mission in New Frontiers cap**



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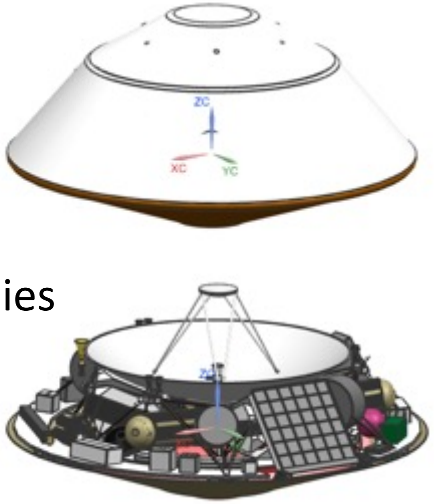

Heritage Blunt Bodies

Credit: Elliot et al. 2020

Utilize proven, heritage entry configurations

- Past aerocapture concepts had needed new entry configuration – limited thermal protection system options
- Mission design showed need for higher lift-to-drag and controllability
- Heritage entry configurations coupled with modern guidance techniques can perform aerocapture successfully

Goals

- Via systems analysis, **show a viable aerocapture-based system** that can accomplish an orbit insertion maneuver for Ice Giants missions and **place a mature science concept into a desired science orbit**
- Development in four key technological areas:
  1. Aerocapture Guidance and Control algorithm maturation for existing entry vehicle configuration
  2. Demonstration feasible Thermal Protection System design for aerocapture environments
  3. Development of Optical Navigation and Autonomous Navigation System for improved interplanetary navigation
  4. Demonstration of entry vehicle packaging and sizing of existing Ice Giants orbiter and probe designs
- Key objectives of this proposal are:
  - Demonstrate the feasibility of using **existing, flight proven, entry vehicle configurations** for aerocapture missions to the Ice Giants
  - Conduct a probabilistic risk assessment to **quantify actual system risk**
  - Showcases the **mission enhancing benefits** of an aerocapture system for **future Ice Giant missions**


WHITE PAPER FOR THE
PLANETARY SCIENCE DECADAL SURVEY, 2023 - 2032

Aerocapture as an Enhancing Option for Ice Giants Missions

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24 Hampton University
25 European Space Agency – ESTEC

White Paper Submitted to National Academy's Planetary Science Decadal Survey 2023-2032

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- Aerocapture Sensitivities
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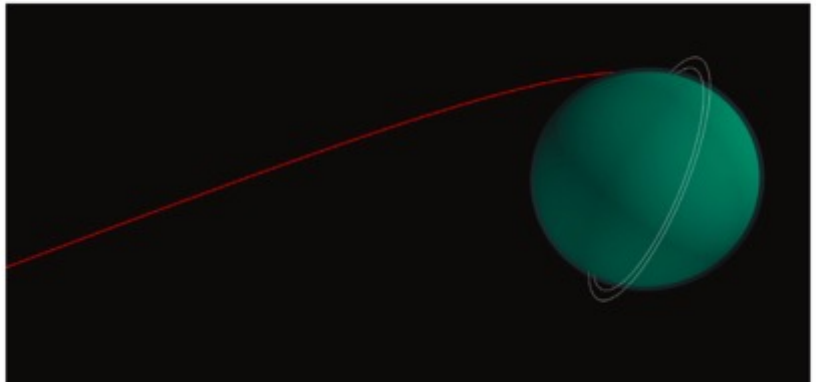
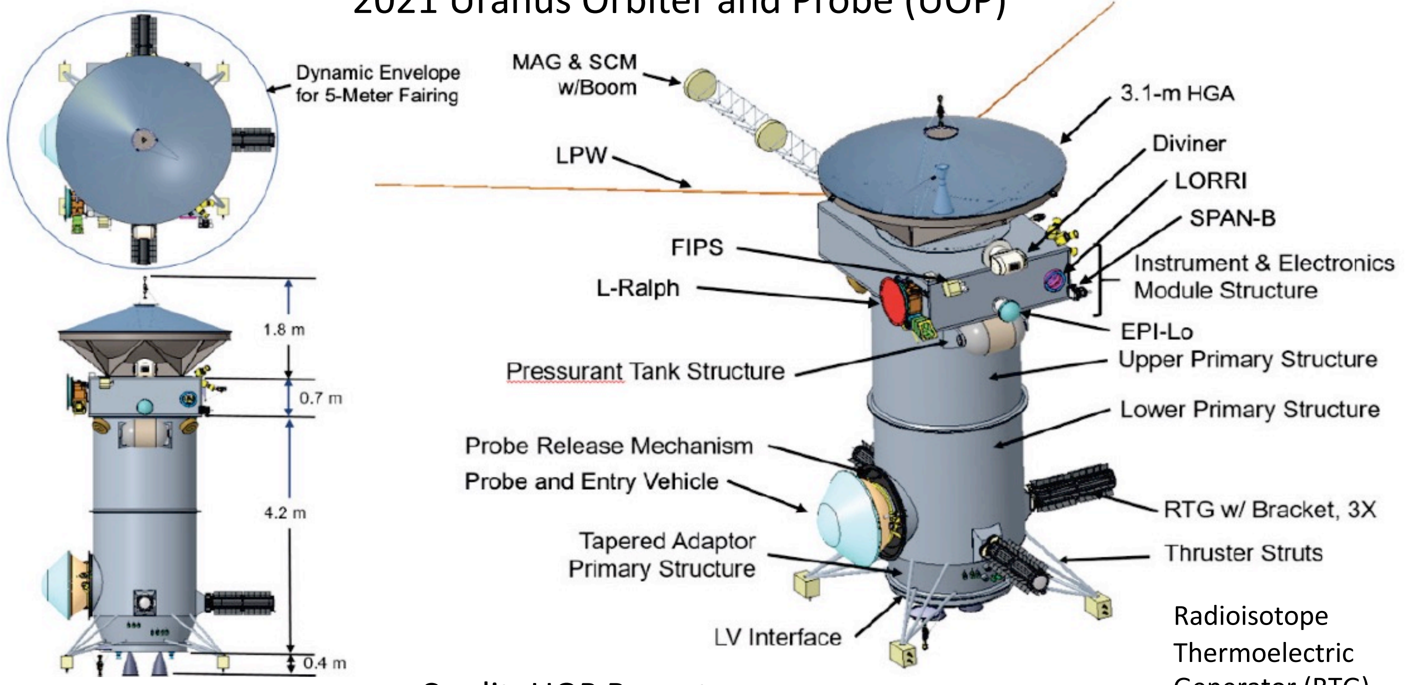
Uranus – Flagship Science Destination

- **2021 Uranus Orbiter and Probe (UOP) mission concept study**
  - 2023-2032 Planetary Decadal top flagship-class destination
  - 2031/2032 launch date; 13 years of transit
  - **1000 m/s ΔV for Uranus Orbit Insertion (1800 kg fuel)**
  - 60-70% of launch mass is fuel
  - Nuclear power source lifespan degrades after 17 years

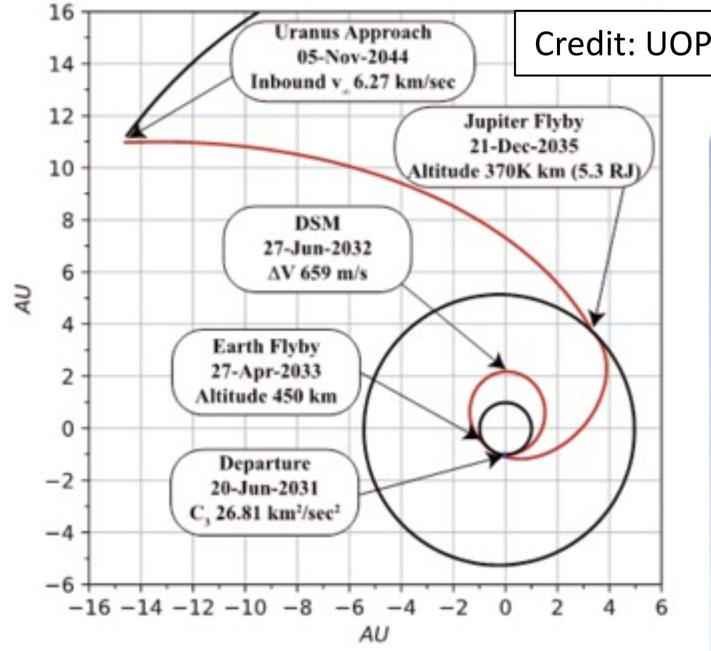


Credit: Girija 2022

2021 Uranus Orbiter and Probe (UOP)



Credit: UOP Report

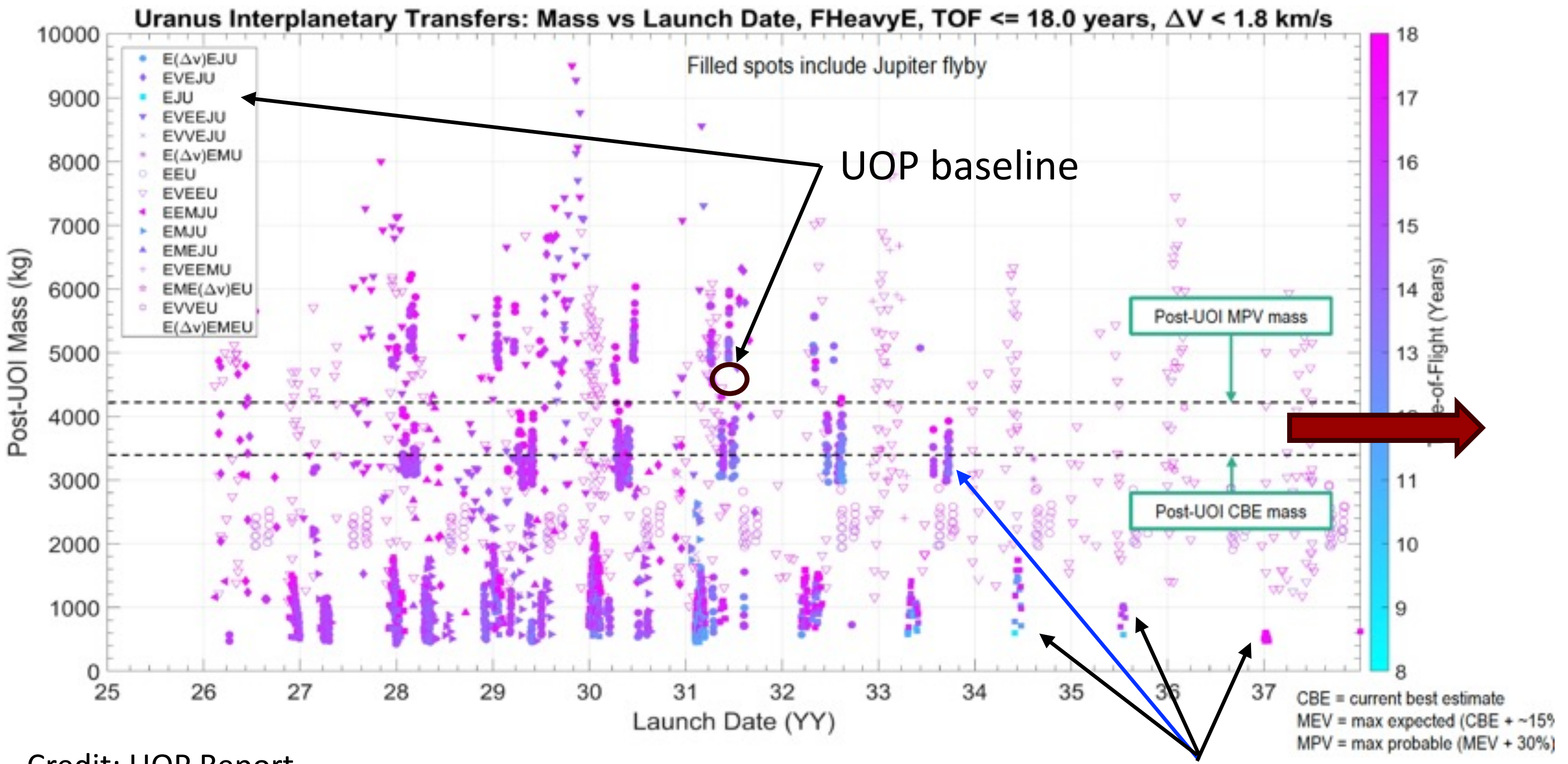


Credit: UOP Report

Exhibit 3-25. Baseline interplanetary trajectory (launch period center case).

Uranus Orbiter and Probe Challenges

- **Needed a 2031/2032 launch date to get to Uranus in 2044-2045**
  - Now in 2023, need a flagship mission, which has not been approved, to be ready in 8-9 years
- **Needed Jupiter fly-by**
  - Jupiter fly-by hard-to-impossible after a 2035 launch dates



Credit: UOP Report

UOP/propulsive limited by v_∞ arrival

Latest Jupiter options

Credit: UOP Report

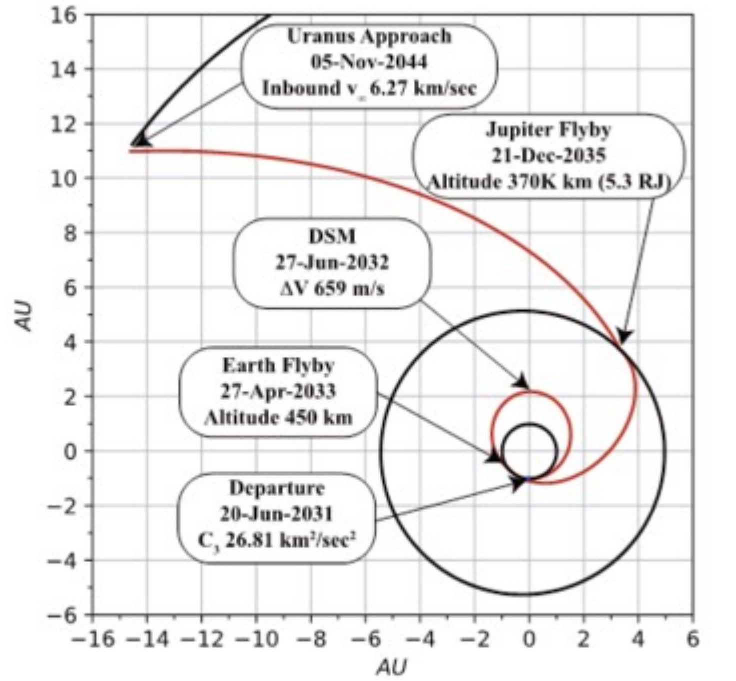
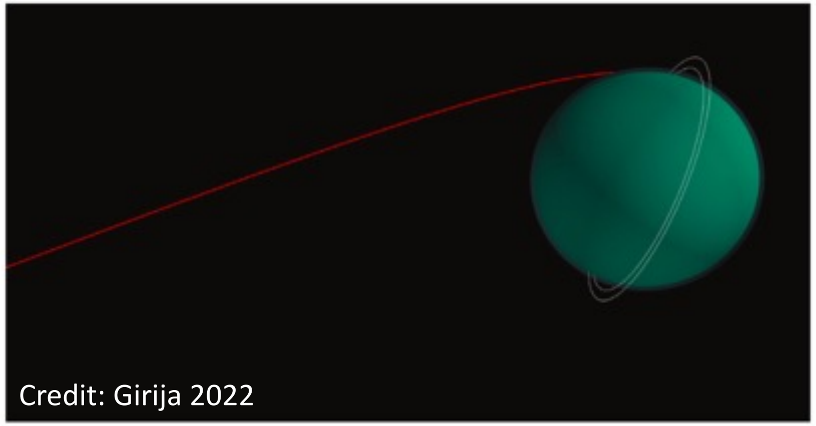


Exhibit 3-25. Baseline interplanetary trajectory (launch period center case).

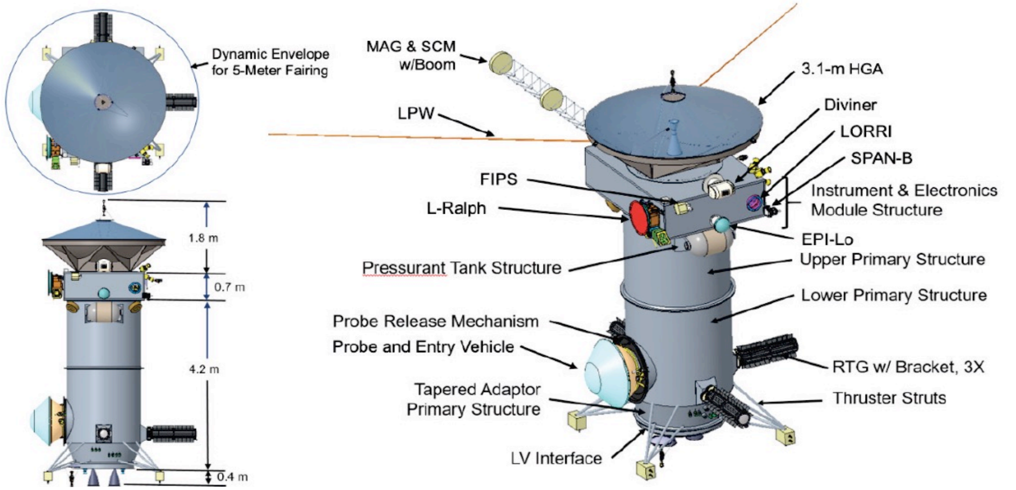
Aerocapture Solutions to Uranus Flagship

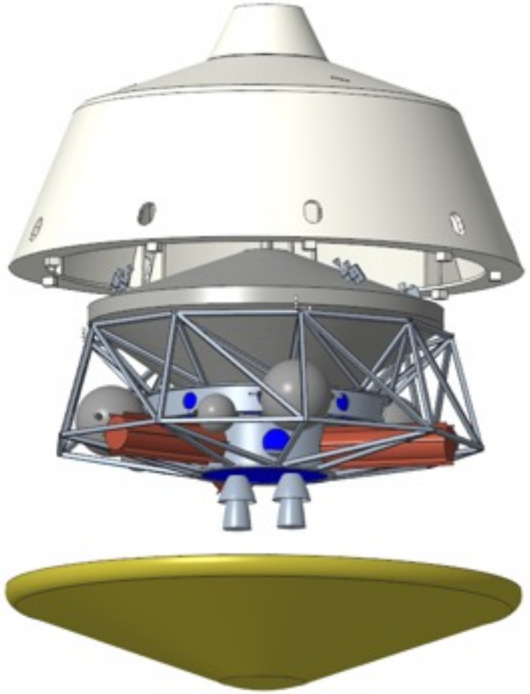
- 2021 Uranus Orbiter and Probe (UOP) mission concept study
  - 2023-2032 Planetary Decadal top flagship-class destination
  - 2031/2032 launch date; 13 years of transit
  - **1000 m/s ΔV for Uranus Orbit Insertion (1800 kg fuel)**
  - 60-70% of launch mass is fuel
  - Nuclear power source lifespan degrades after 17 years
- **Recent aerocapture studies have shown UOP payload can fit in heritage aeroshell and have feasible Guidance, Navigation, and Control (GNC) and Thermal Protection System (TPS) solutions**
  - Transit to Uranus in 7-9 years; save 1000 kg in fuel in orbit insertion
  - **Can we enable Flagship class science in New Frontiers budget?**


Credit: Girija 2022

2021 Uranus Orbiter and Probe (UOP)

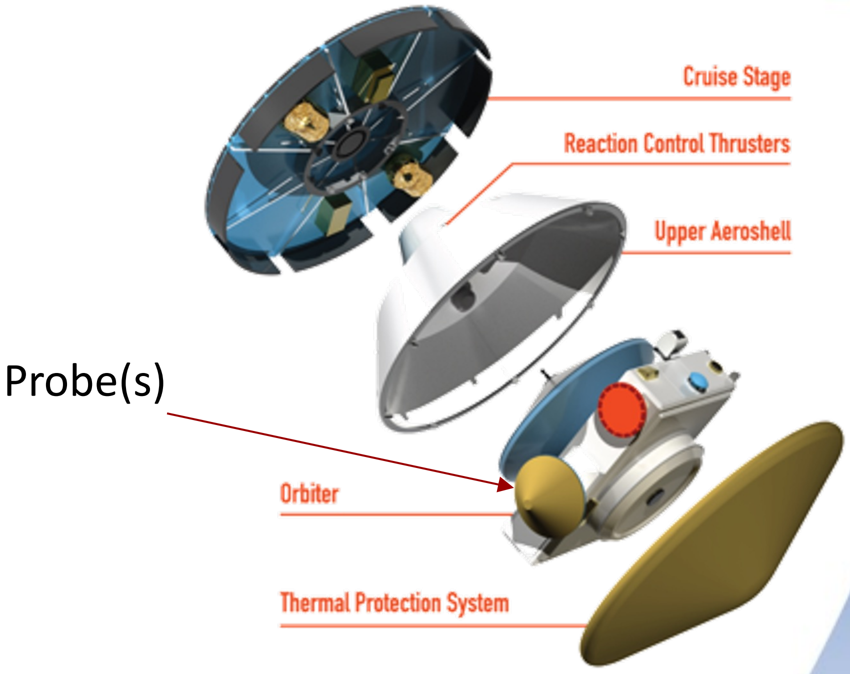
Credit: UOP Report



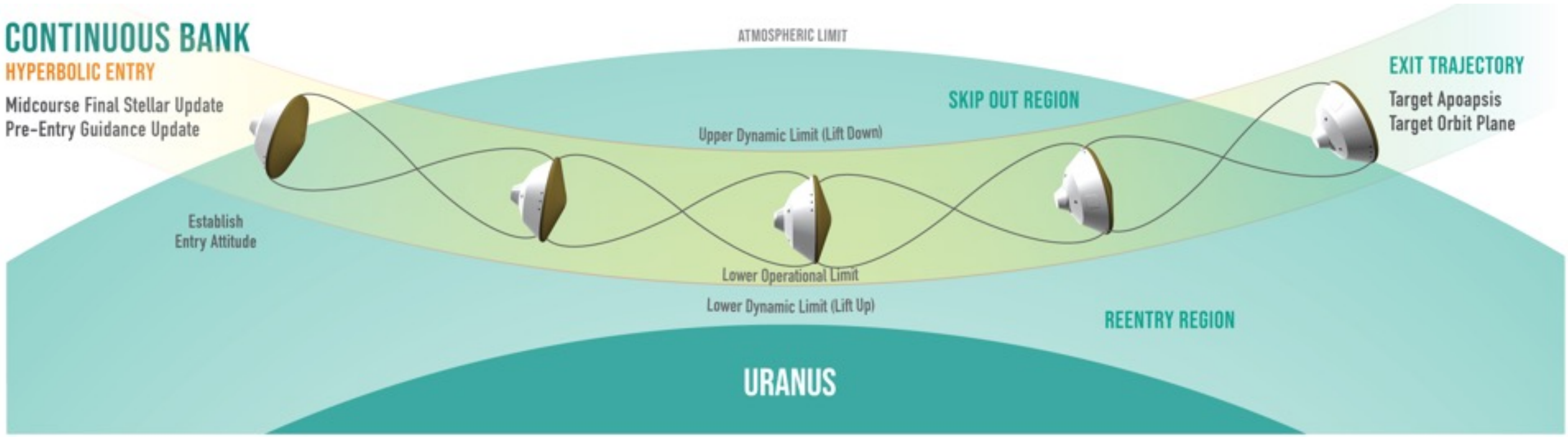


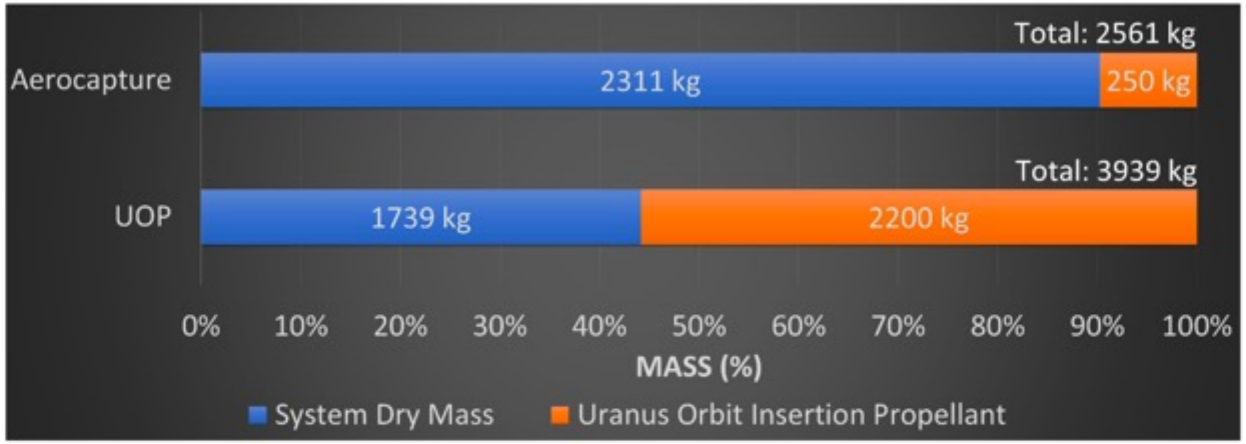
Aerocapture Sensitivities

- **Atmospheric Sensitivities**
  - Uranus atmosphere is under characterized
  - Can aerocapture-based system survive
- **Science Accommodations**
  - Packing orbiter within an aeroshell
  - Science and commissioning during the transit
    - Solutions with window accommodations
- **Faster/non-Jupiter options**
  - Jupiter fly-by unachievable after certain launch dates
    - Aerocapture can do a more direct route to Uranus (higher interplanetary speeds)
    - Achieve the desired arrival at Uranus for the equinox (by 2048-2049) time period
- **Probe(s) accommodation**
  - Can probe(s) be part of an aerocapture-based orbiter mission
    - The mass savings from aerocapture system can accommodate one or more probes



Heritage Guidance and Control Solution



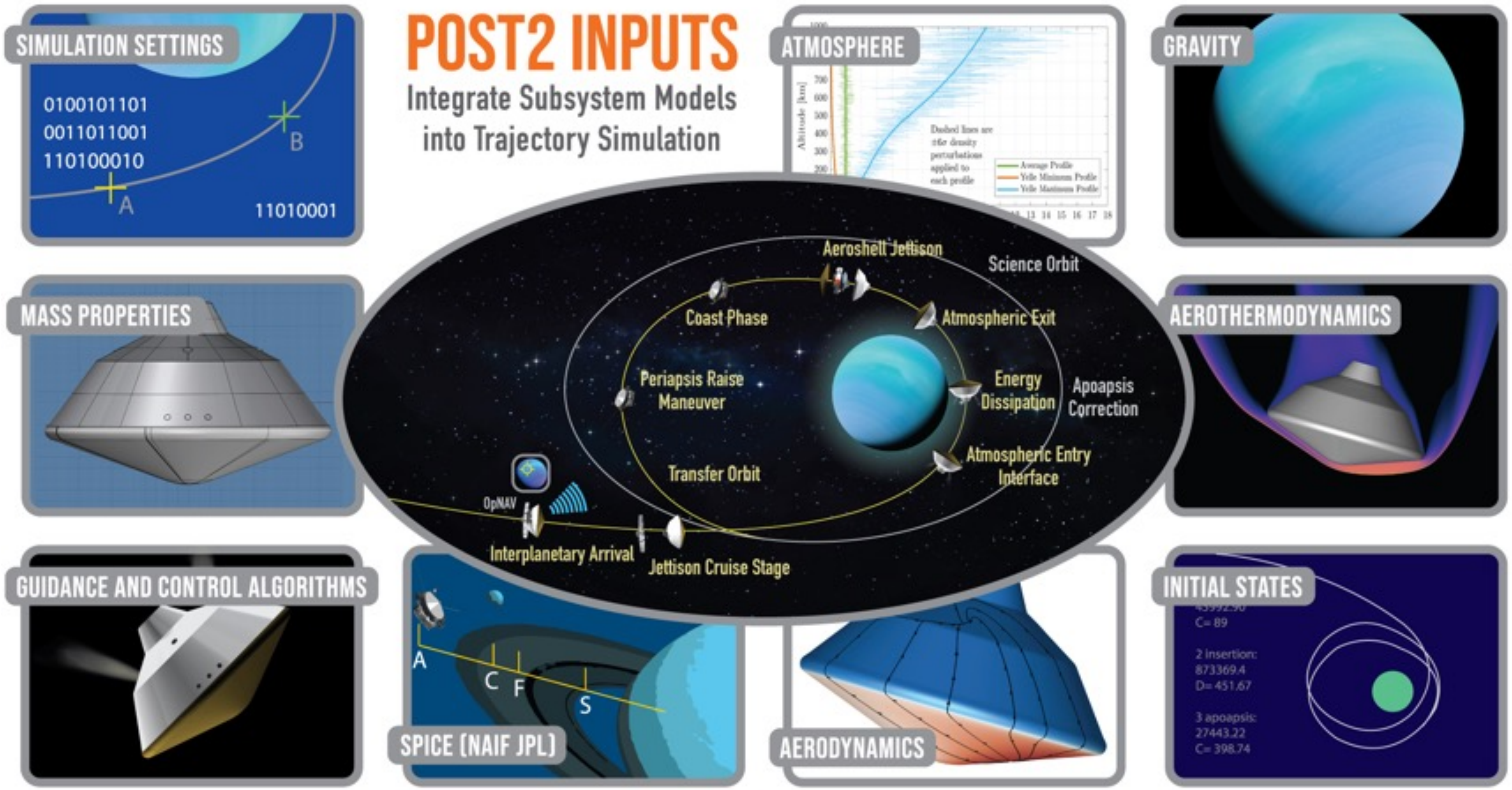


- Current baseline utilizes bank angle modulation control mechanism that has been demonstrated on Earth and Mars
- Guidance scheme uses predictor-corrector architecture flown on Earth missions
- Simulations show more than 1400 kg (35% mass savings) while achieving orbital insertion success

Aerocapture Performance under Atmospheric Uncertainty

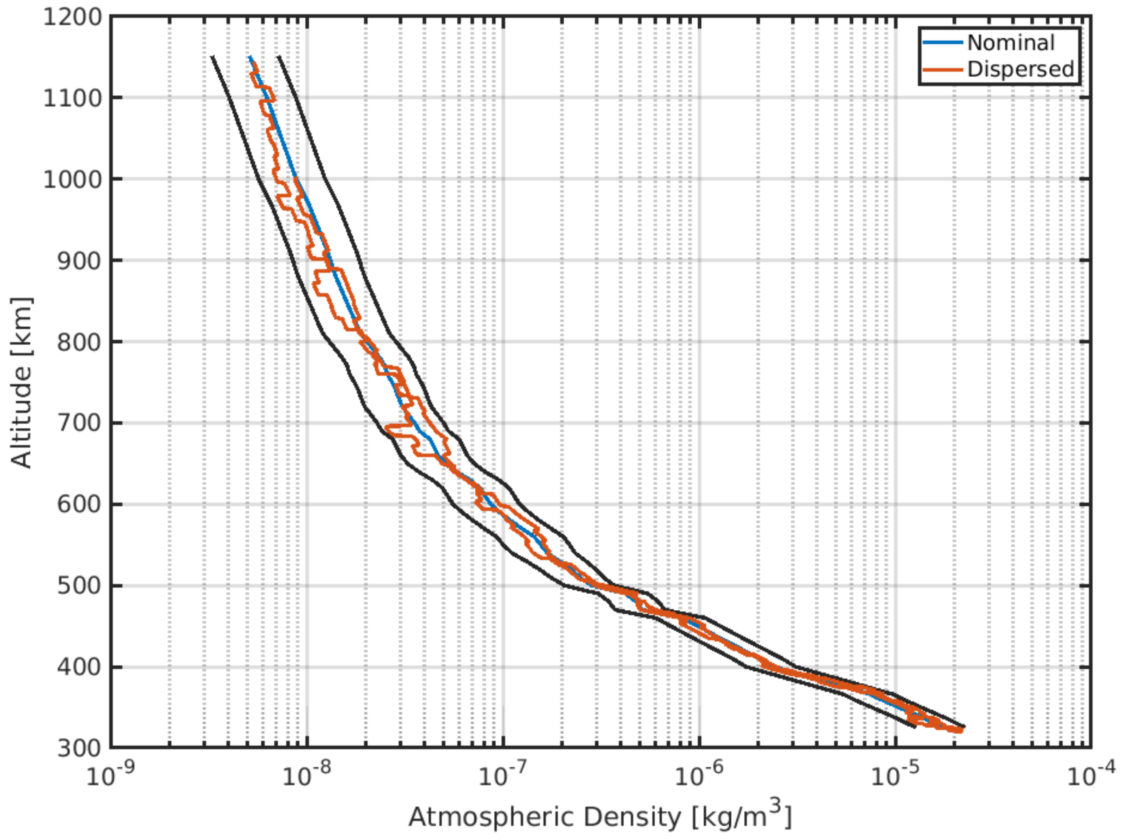
- **End-to-end aerocapture simulations use similar modeling standards that are used for flagship and other planetary scale missions**

POST2 = Program to Optimize Simulated Trajectories II



Aerocapture Performance under Atmospheric Uncertainty

- **End-to-end aerocapture simulations use similar modeling standards that are used for flagship and other planetary scale missions**
- **Robust solutions to atmospheric uncertainties in current best available Ice Giants models**
- **Atmospheric scientist joined team in late FY23 to provide updated atmospheric tables for Uranus**
  - Same person who is updating Uranus for the Global Reference Atmospheric Model (GRAM) project



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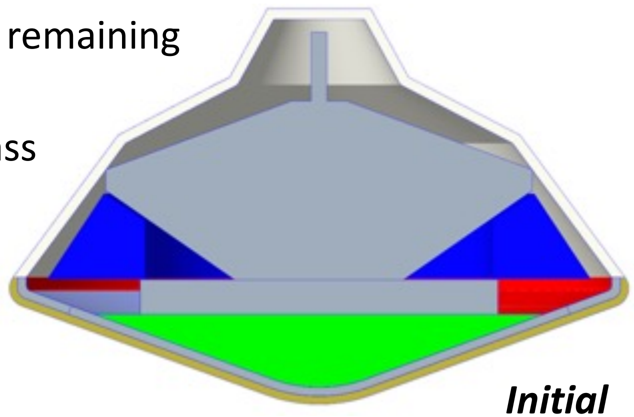
  - Science and commissioning during the transit
    - Solutions with window accommodations

Vehicle Design Evolution

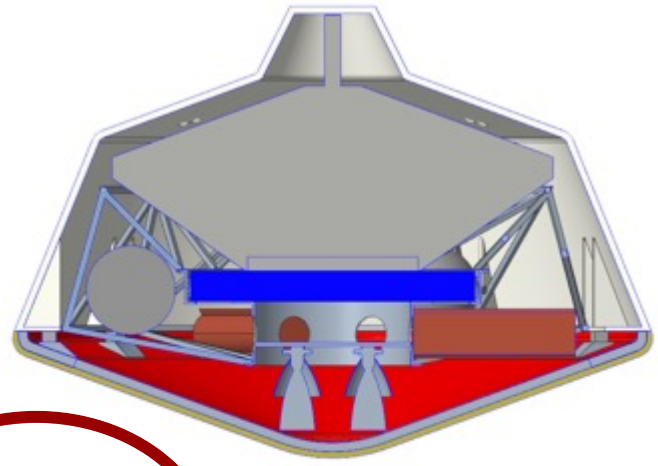
DAC 1

- HGA packaged in MSL aeroshell (**4.5 m diameter**)
- Generic volumes for remaining payload mass
- 2710 kg total dry mass



DAC 2

- Back shell angle/height modified, payload structure concept generated
- Steeper angle yields heating concerns
- No apparent volume for probe and release mechanism

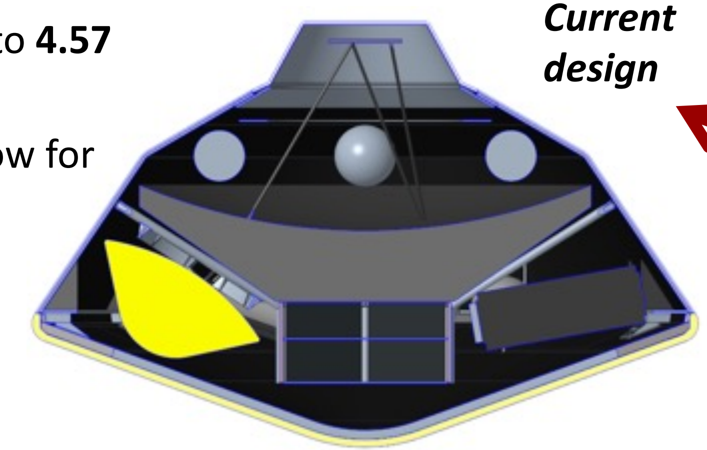


Initial design

Current design

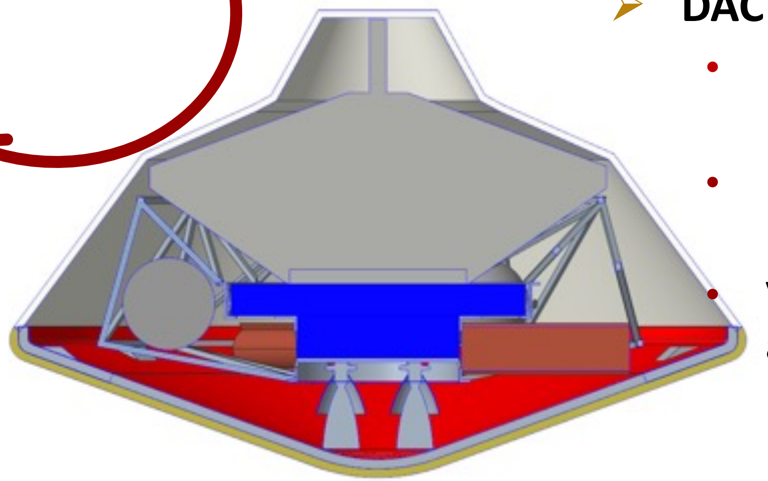
DAC 4

- Vehicle scaled down to **4.57 m** diameter
- Design maturities allow for tighter packaging
- 2616 kg dry mass
- 506 kg propellant



DAC 3

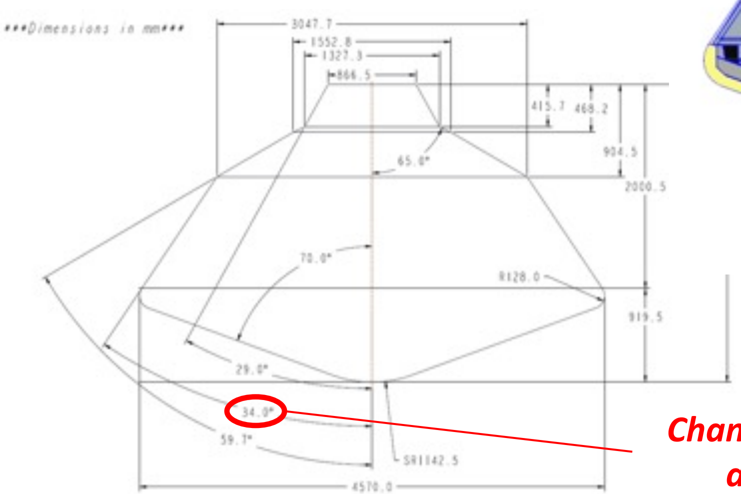
- MSL vehicle scaled up to **5.0 m** diameter
- Payload accommodated with margin
- Vehicle cannot fly on currently available launch vehicles



Vehicle Design Overview

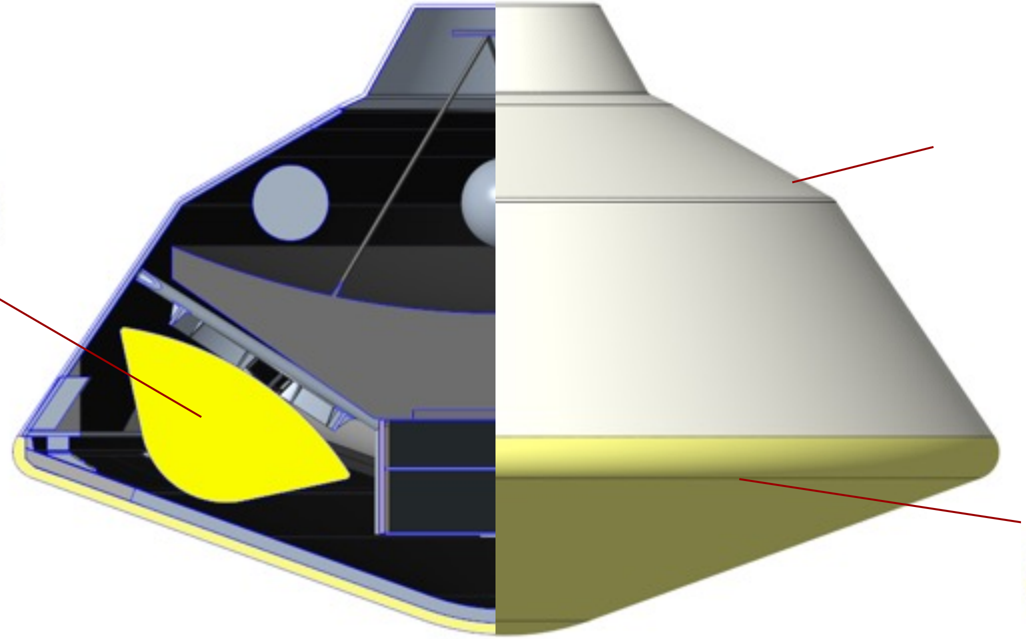
Payload

(1926 kg fueled)



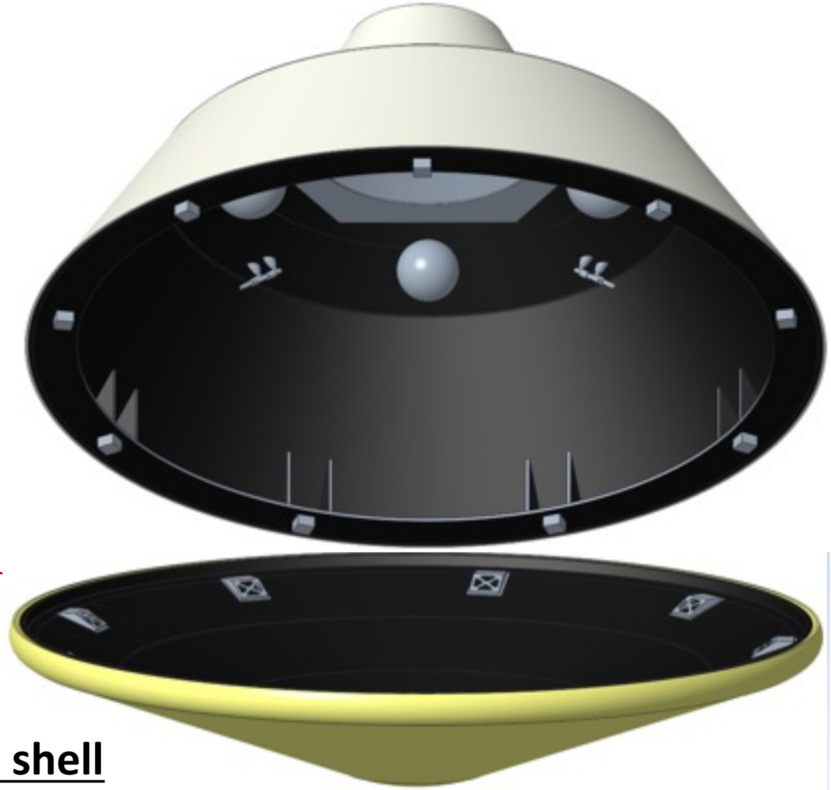
Changed from 37° (MSL) to accommodate HGA

4.57 m diameter MSL aeroshell
35% MGA + margin at 4064 kg MPV entry mass
(3122 kg wet mass CBE)



Back shell ***(600 kg + 150 kg ballast)***

- MSL TPS - 1.27 cm thick SLA-561V
- Separation mechanisms
- RCS engines + propellant/pressurant



Forward shell

(464 kg)

- 5.00 cm thick CPICA (sized by TPS team)
- Separation fittings

Aerocapture Sensitivities

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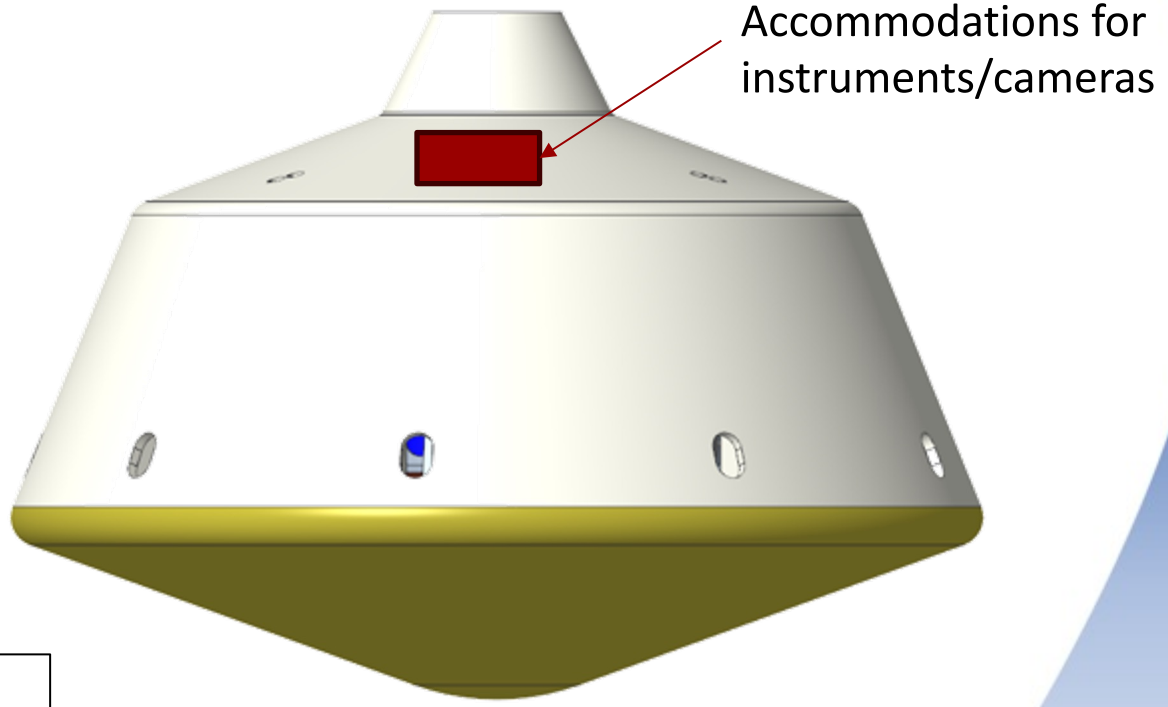
- **Science Accommodations**
  - Packing orbiter within an aeroshell
  - Science and commissioning during the transit
    - Solutions with window accommodations
    - Backshell that can be opened



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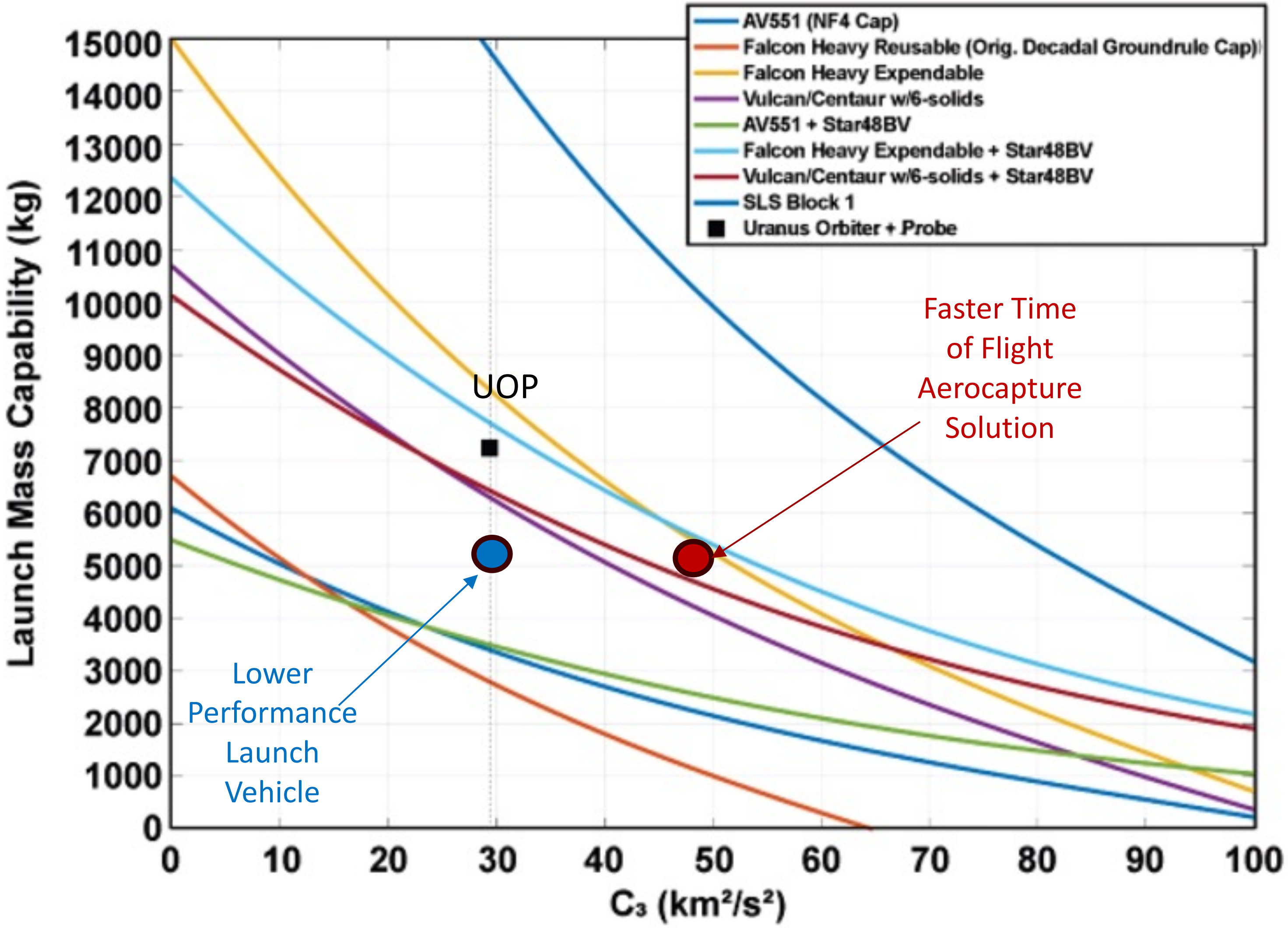
    - Achieve the desired arrival at Uranus for the equinox (by 2048-2049) time period

Aerocapture Increases Transit Choices

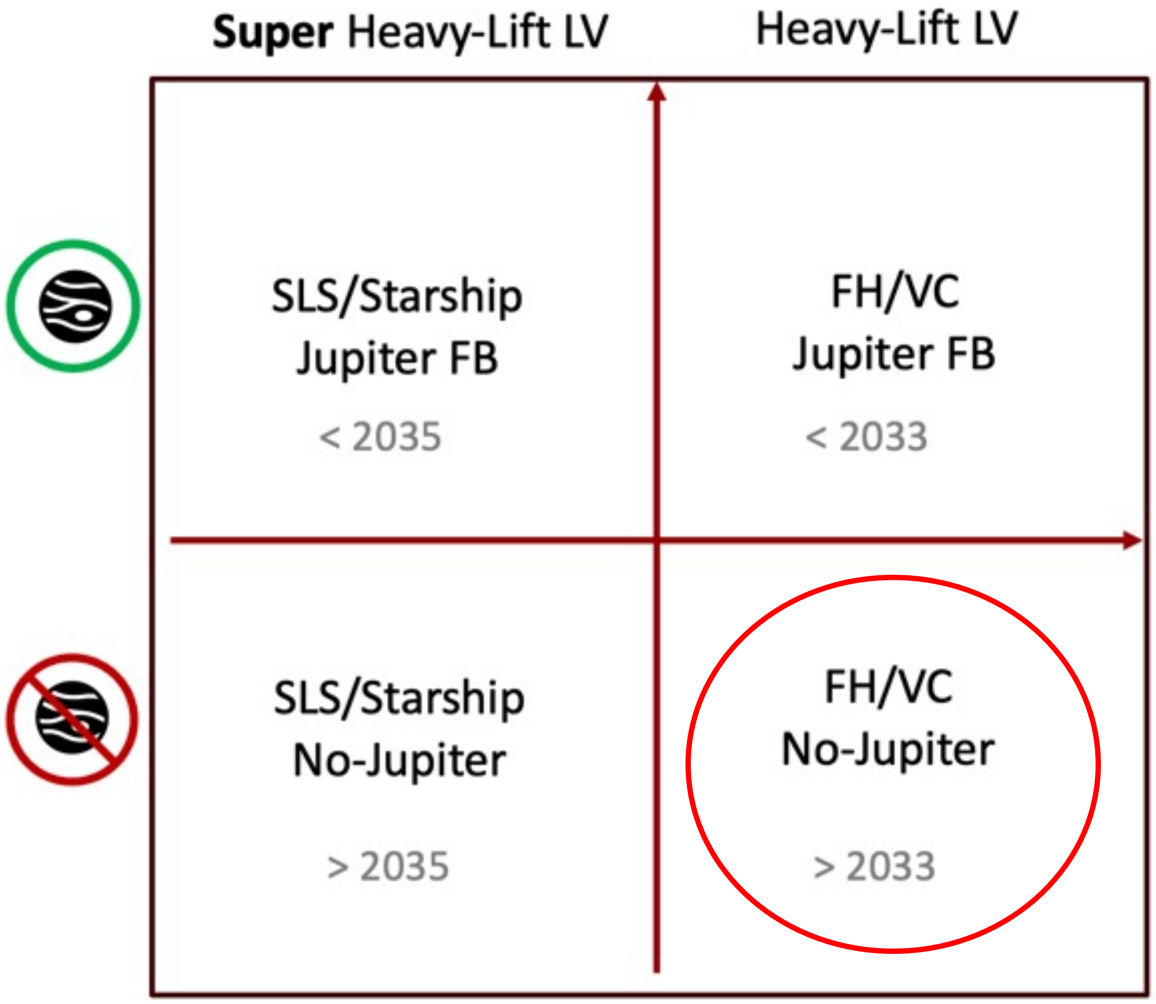


- **Current NASA baseline Uranus design requires higher performance launch vehicles**
- **Aerocapture design can:**
  - Achieve faster time of flight solutions with similar launch vehicle capability
  - Lead to a lower performance launch vehicle requirements with cost savings
- **Initial mission design solutions show feasible aerocapture solutions in 2035+ launch window that gets to Uranus in the late 2040's without a Jupiter fly-by**

Credit: Original C3 chart from UOP Report

Interplanetary Transit Choices

- **Move to a more Realistic/Conservative Configuration and Launch time.**
  - L: **> 2035**
  - LV: **FH**/VC
  - No Jupiter available
  - Search Leverage: Venus, Earth, Mars



Groups I and II: Aerocapture vs Fully Propulsive

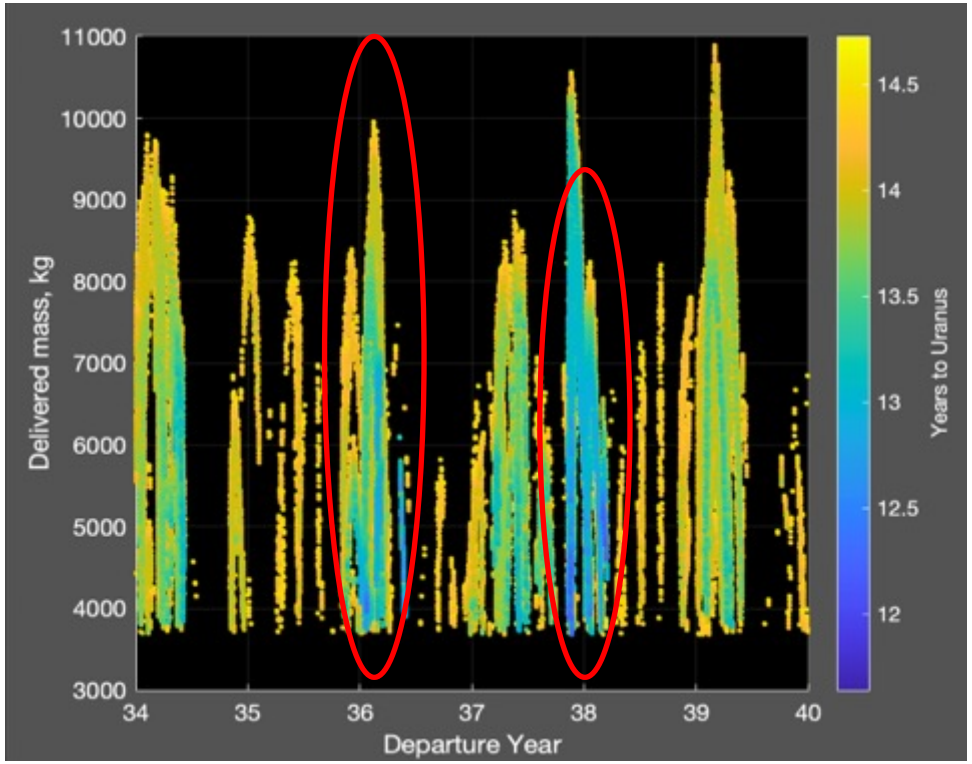
- **Fastest time of flight solutions for Groups I and II**
  - Launches between 2031 and 2038 that meet the UOP delivery mass requirements.
  - Aerocapture can reduced cruise time between 2.4 ~ 5.0 yrs., increase Jupiter availability by 1 year and add 2035 and 2037 launch opportunities.

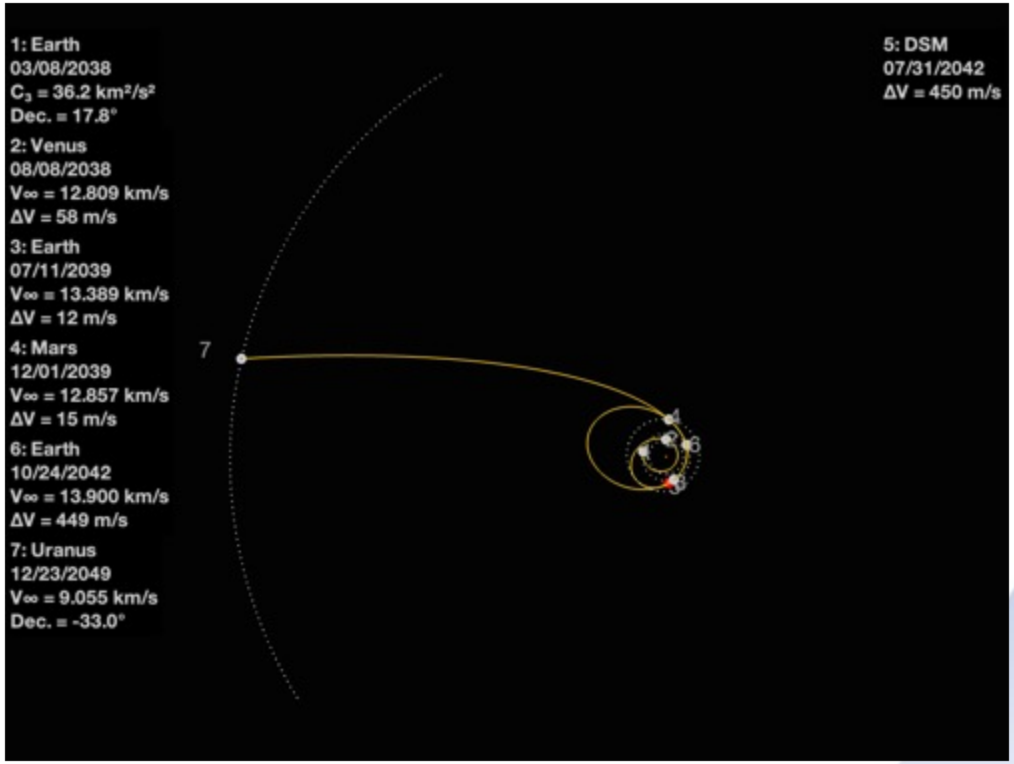
	Launch Year	Cruise (yrs.) UOP Propulsive		Cruise (yrs.) UOP Aerocapture
Jupiter	2031	13.4	Jupiter	9.8
Jupiter	2032	12.8	Jupiter	7.8
No-Jupiter	2033	15.3	Jupiter	10.2
No-Jupiter	2034	15.2	No-Jupiter	12.6
No-Jupiter	2035	-	No-Jupiter	13.5
No-Jupiter	2036	15.3	No-Jupiter	12.7
No-Jupiter	2037	-	No-Jupiter	12.9
No-Jupiter	2038	14.2	No-Jupiter	11.8

LV: Falcon Heavy Expendable.

No-Jupiter, No Super-Heavy + Late 2030 Launch

- **Interplanetary Search Space for: Falcon Heavy (FH) & No-Jupiter (> 2035)**
  - L:2036, ToF: 12, Delivery Mass: 5000 kg, FH: Several FBs solutions, e.g. V-E-M-E-U
  - L:2038, ToF: 11.8, Delivery Mass: 5000 kg, FH. Several FBs solutions, e.g. V-E-M-E-U





- Comparison to fully-propulsive UOP Solution for 2038 ToF: 14.2 yrs.**~2.5 yrs** ToF savings with Aerocapture, **~2.7 yrs** for 2036.
- $v_\infty \sim 9.0$ km/s

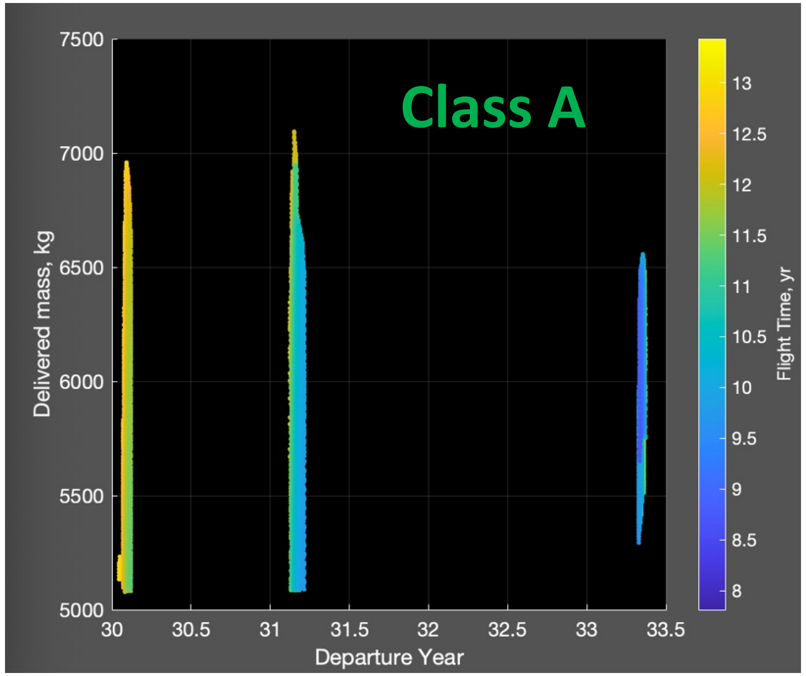
Groups III and IV: Super Heavy-Lift

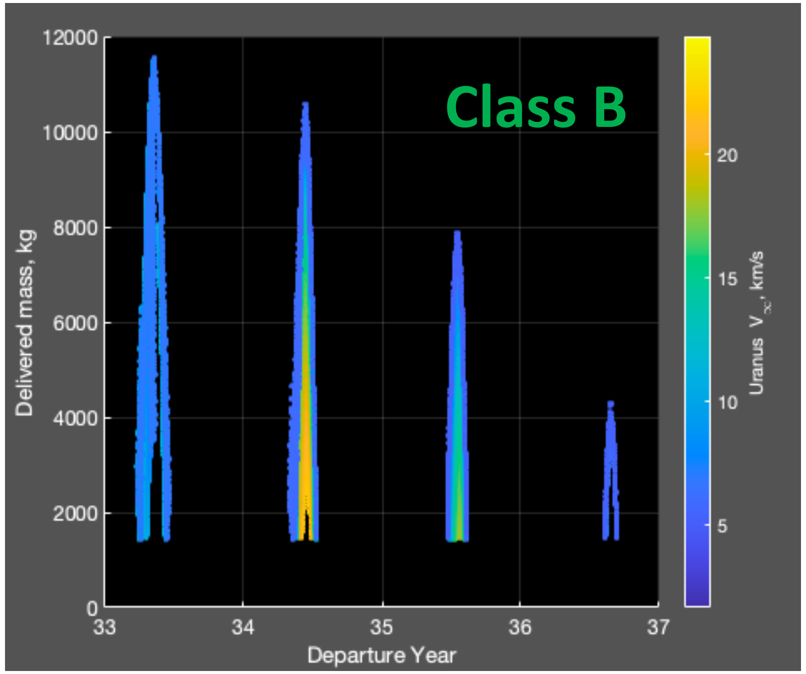
- **Some distinctions to make between vehicles:**
- **Class A (Available)**
  - SLS B1
  - Max C3 = 85 km^2/s^2 for 5500 kg of launch mass
- **Class B (In-development)**
  - SLS B2 (with upper stage)
  - Starship (with in-orbit refueling)
  - Max C3 = 160 km^2/s^2 for 5500 kg of launch mass

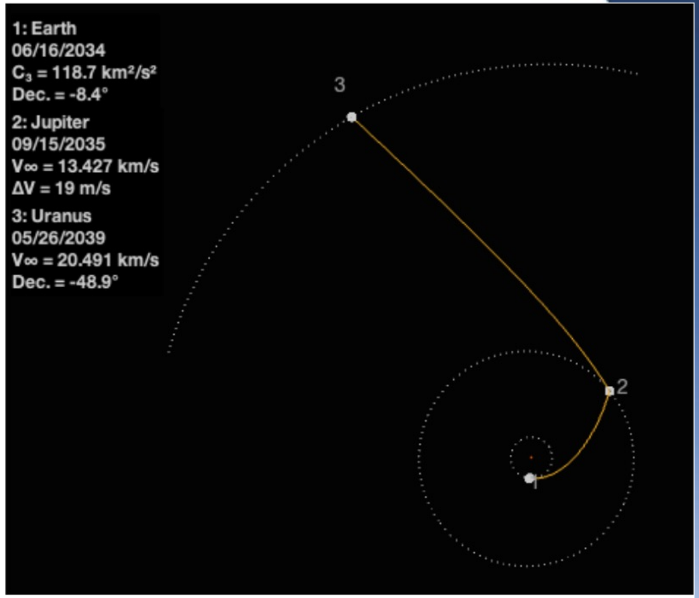
Heavy-Lift LV	I FH/VC Jupiter flyby ≤ 2033	II FH/VC No Jupiter > 2033
Super Heavy-Lift LV	III SLS/Starship Jupiter flyby > 2035(36)	IV SLS/Starship No Jupiter < 2035(36)

Group III: Super Heavy-Lift LV w/ Jupiter

- **Class A (Available): SLS B1**
  - Launch availability up to 2033
  - UOP Solutions with ~8 yrs. time of flight (~ 11 yrs. for UOP-prop)
- **Class B (In-development): SLS B2, Starship**
  - Launch availability up to 2035
  - UOP Solutions with ~5-6 yrs. time of flight



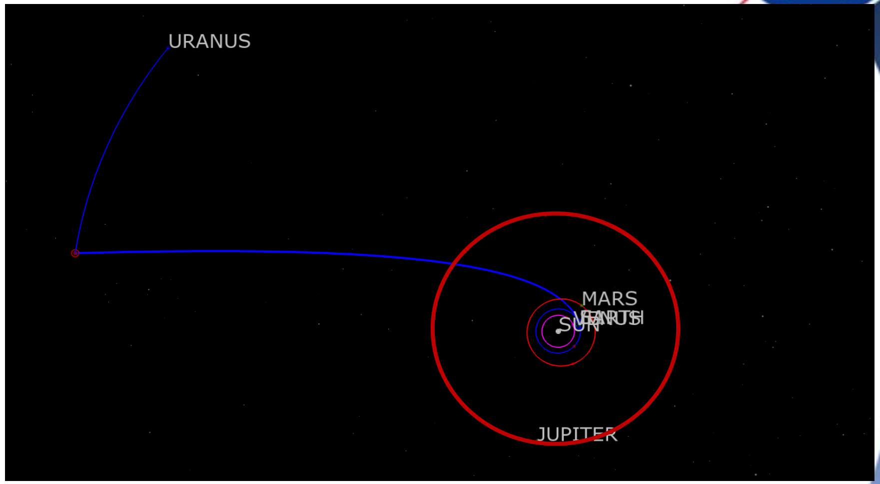




(b) Trajectory with 2034 launch, and 5 years cruise to Uranus with arrival v_∞ = 20.5 km/s

Group IV: Super Heavy-Lift LV no Jupiter

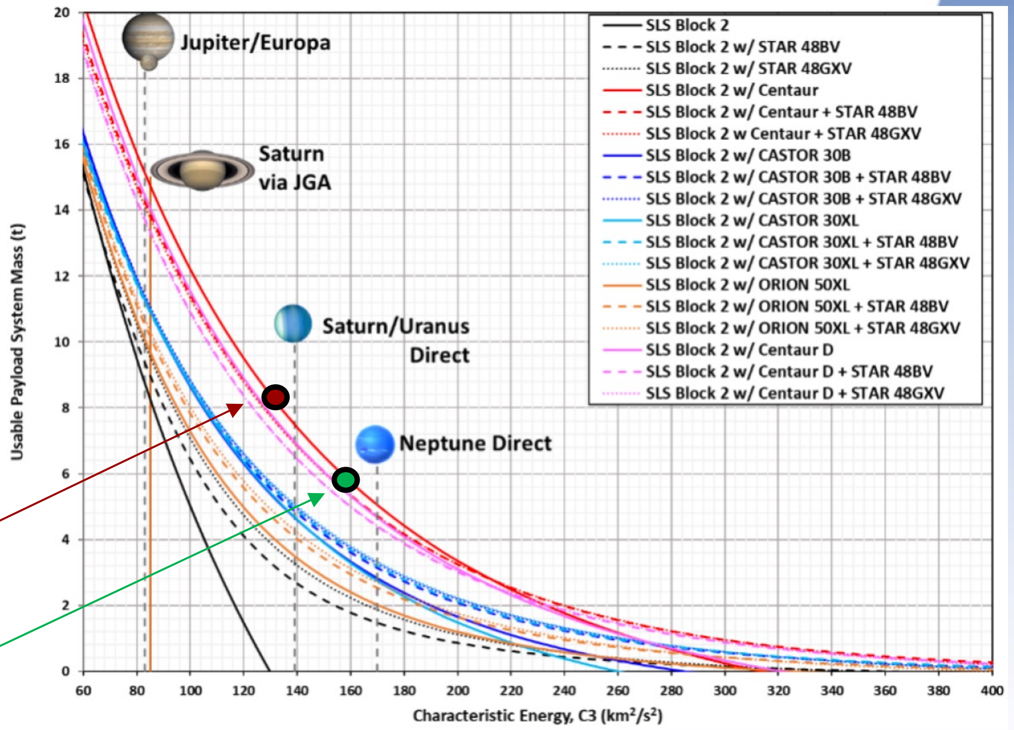
- **Class A & B LV inner tour trajectories available**
  - Both Class and
  - Time of flight typically 12-14 years
  - Unique 10 yr. ToF Earth-Earth-Mars-Uranus solution in 2034



- **Class B direct-to-Uranus trajectories very promising**
  - Hohmann transfer available yearly
  - 5500 kg and high v_∞ arrival enables: ToF = 7 yrs

Propulsive Mass

Aerocapture Mass

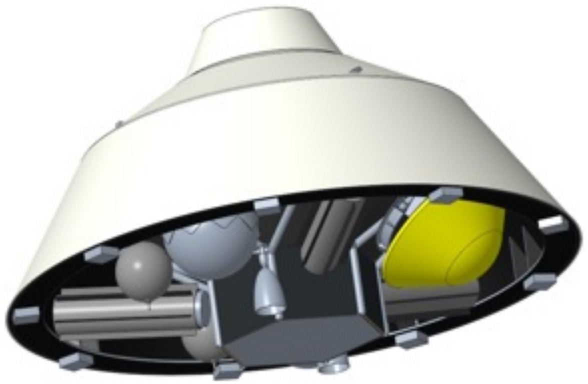


Aerocapture Sensitivities

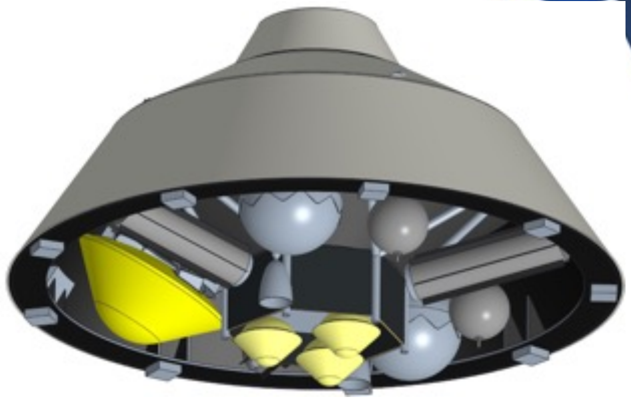
- Atmospheric Sensitivities
  - Uranus atmosphere is under characterized
  - Can aerocapture-based system survive
- Science Accommodations
  - Packing orbiter within an aeroshell
  - Science and commissioning during the transit
    - Solutions with window accommodations
- Faster/non-Jupiter options
  - Jupiter fly-by unachievable after certain launch dates
    - Aerocapture can do a more direct route to Uranus (higher interplanetary speeds)
    - Achieve the desired arrival at Uranus for the equinox (by 2048-2049) time period
- **Probe(s) accommodation**
  - Can probe(s) be part of an aerocapture-based orbiter mission
    - The mass savings from aerocapture system can accommodate one or more probes

Probe Accommodations

- **Additional smaller probes increase mission scientific value**
  - Enables observation of atmospheric variability and global seasonal effects
  - SNAP probe design can be accommodated by aerocapture vehicle with no major design changes
  - 45° EV with 50 cm diameter (30 kg)
- **Multiple probe configurations available**
  - Combinations of 1-2 UOP probes, 0-7 SNAP probes
  - Conops consideration: when to release each probe and DV cost



Baseline configuration with single 1.25 m UOP probe

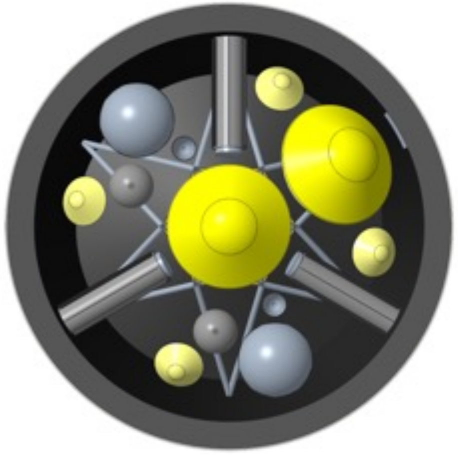


0.5 m SNAP probe array added

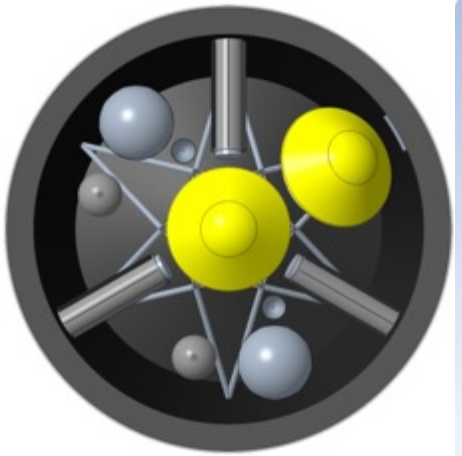
Baseline (1 UOP probe)

1 UOP + 6 SNAP

1 UOP + 3 SNAP

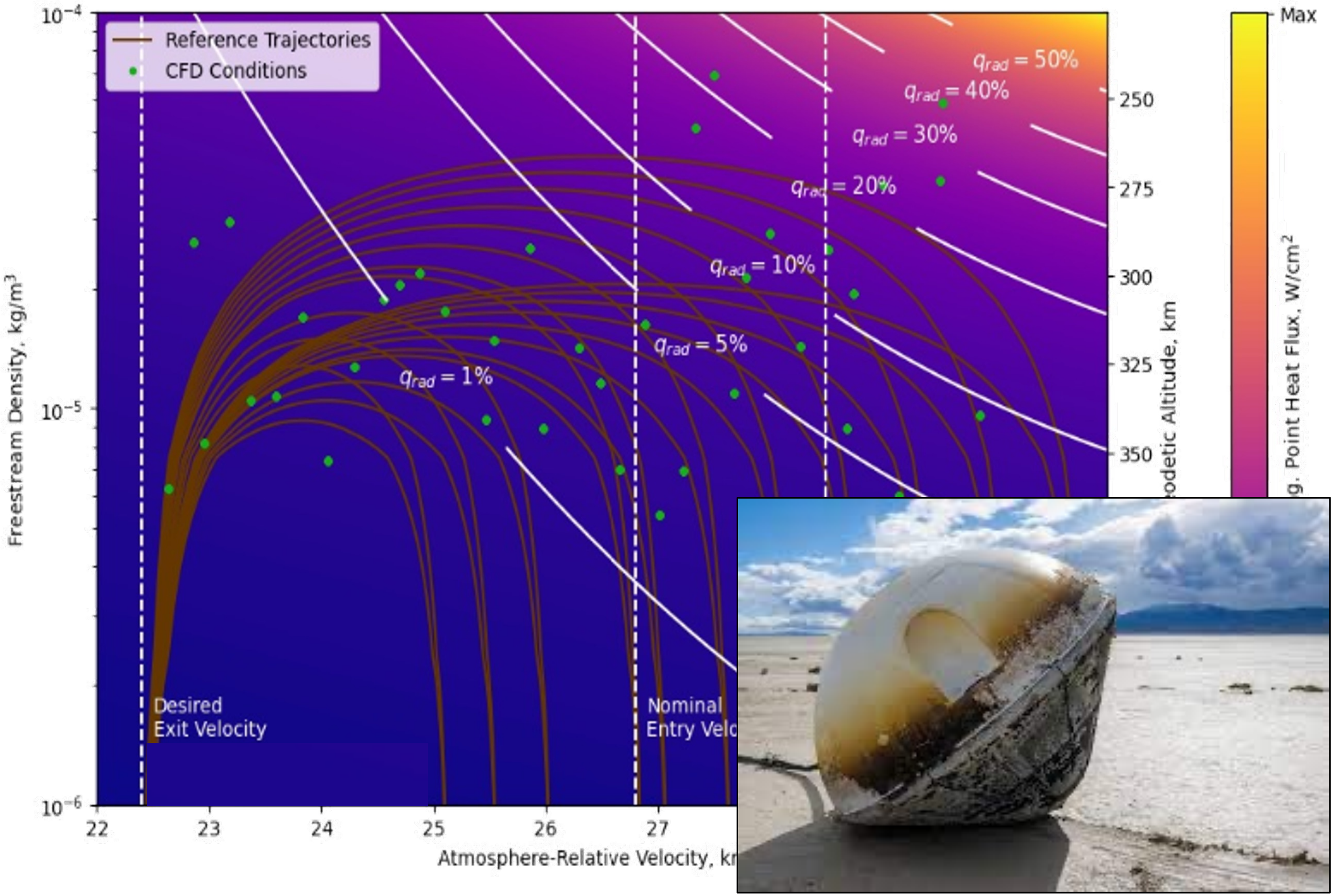


2 UOP + 4 SNAP



2 UOP

Aerosciences and Thermal Protection System Solutions



- **ECI project developing computational capabilities for Giant planet missions**
  - No atmospheric missions since Galileo mission to Jupiter (launched in 1989)
  - Lessons learned from other ECIs
- **Aerocapture has much lower maximum heating conditions than direct entry probes**
  - Radiative heating insignificant for most conditions
- **Conformal PICA – lightweight solution available for Thermal Protection System**

Credit: Varda

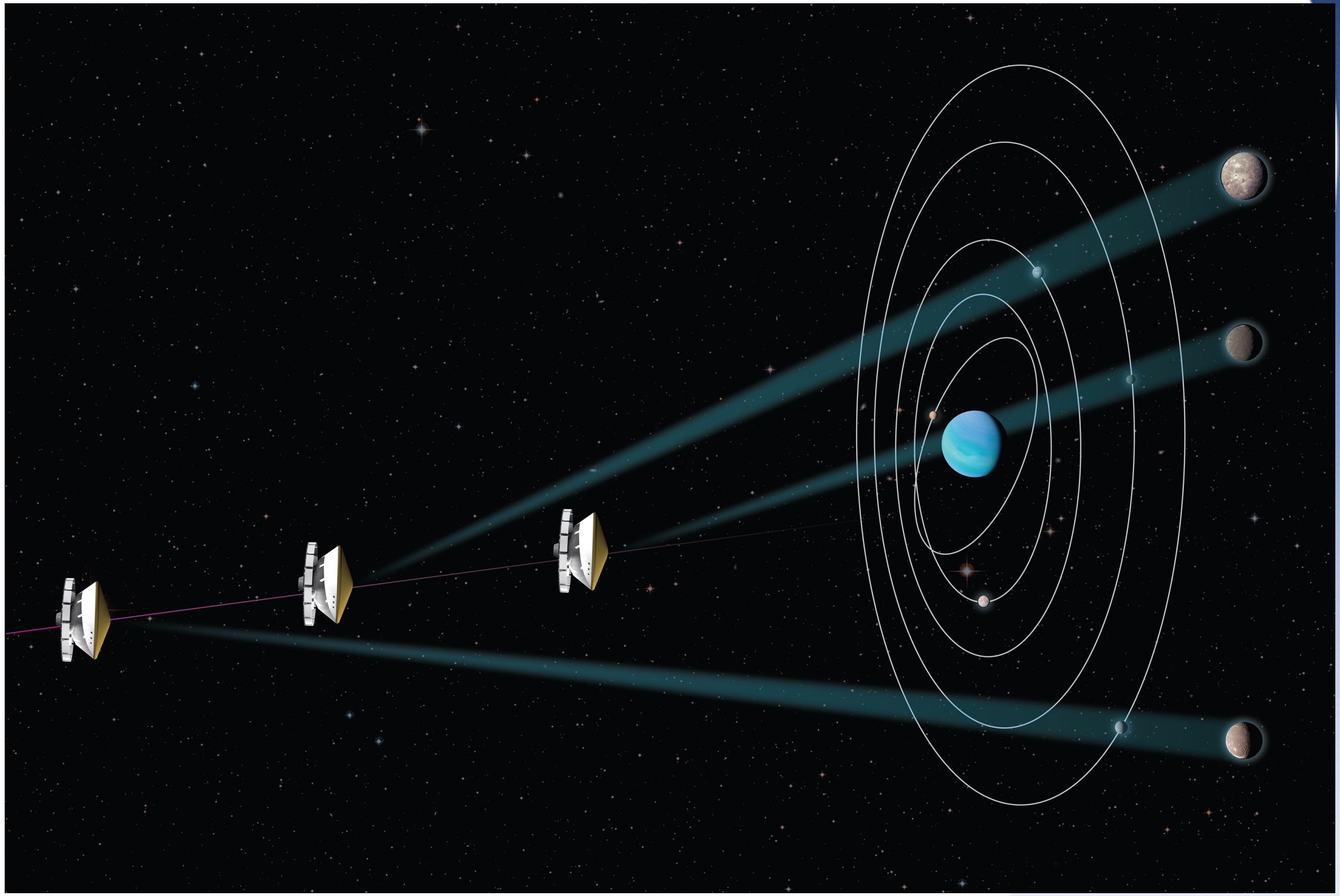
Navigation Solution

OpNAV Approach Campaign

- Uranus is a challenging OpNAV target
  - Fills spacecraft camera (LORRI) field of view ~8 days from entry
  - No features to register and planetary atmospheres are known to introduce errors to limb-scanning
- Plan is to use Uranus satellites as beacons to indirectly observe correlated to Uranus position

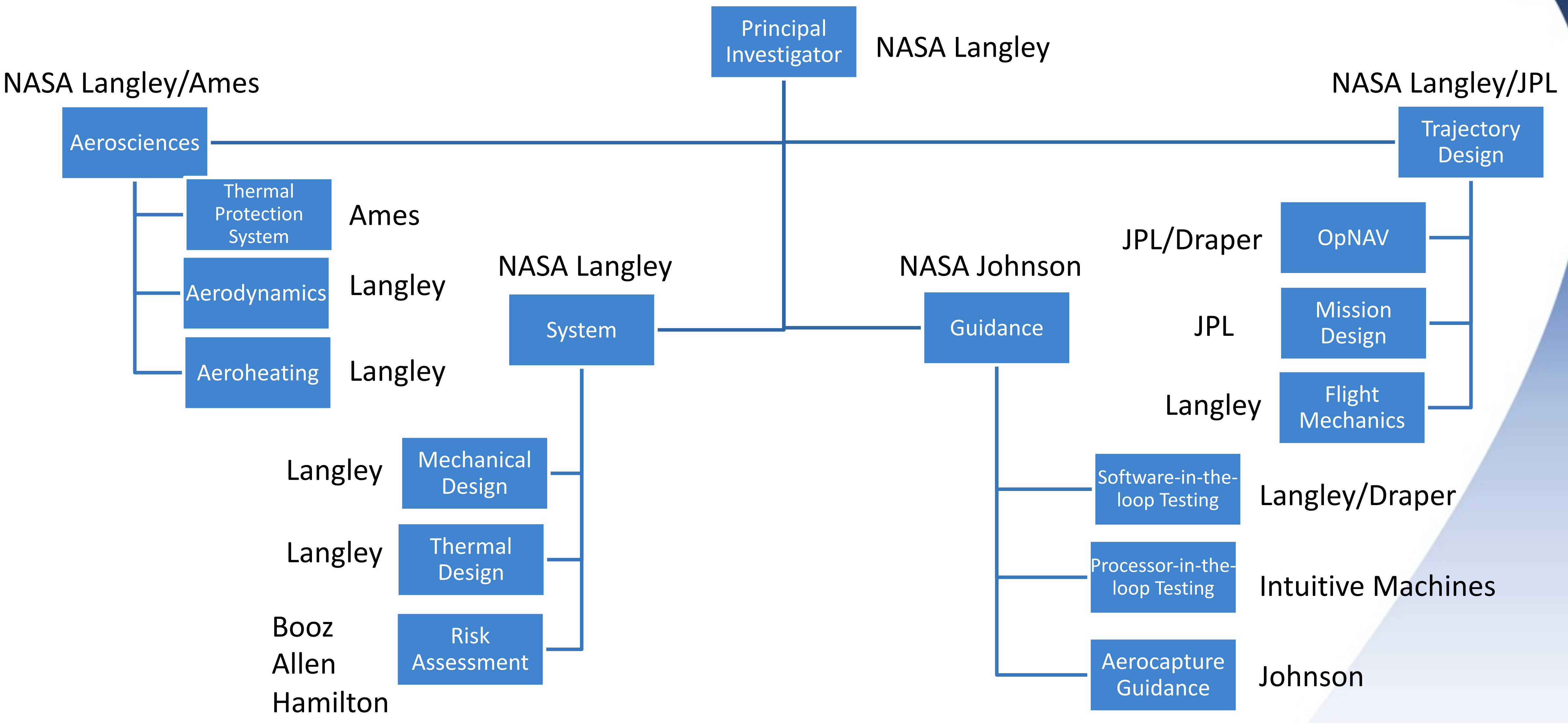
Initial analysis shows no need for AutoNAV

- Ground-in-the-loop (even with 8 hours two-way light speed) produces desired entry accuracy



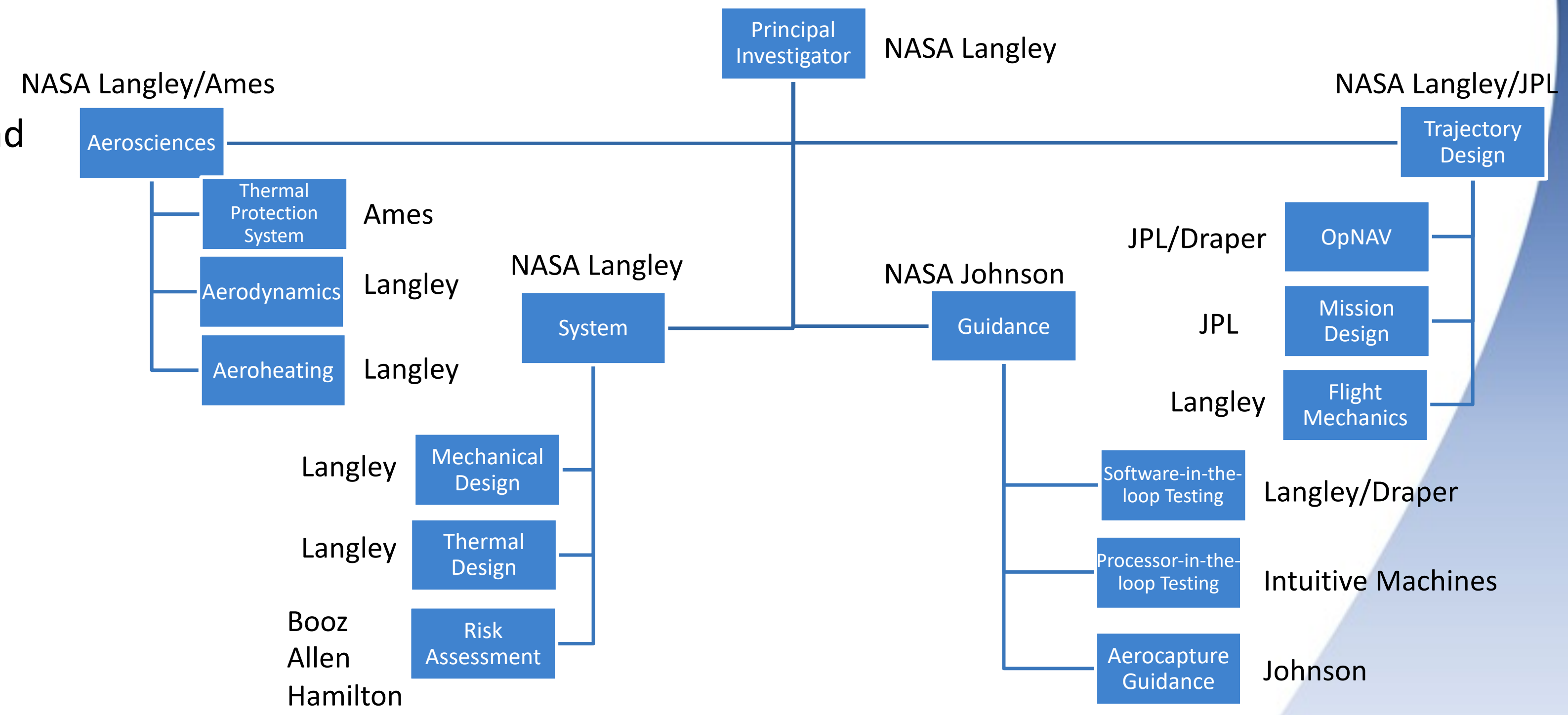
- Aerocapture and Ice Giants Introduction
- Project Objectives
- Gaps Addressed and Anticipated Benefits
- Aerocapture Sensitivities
- **Team Organization**
- **Project Management**
- **Key Milestones**
- **Future Plans**
- **Publications**

Organization



Team Members

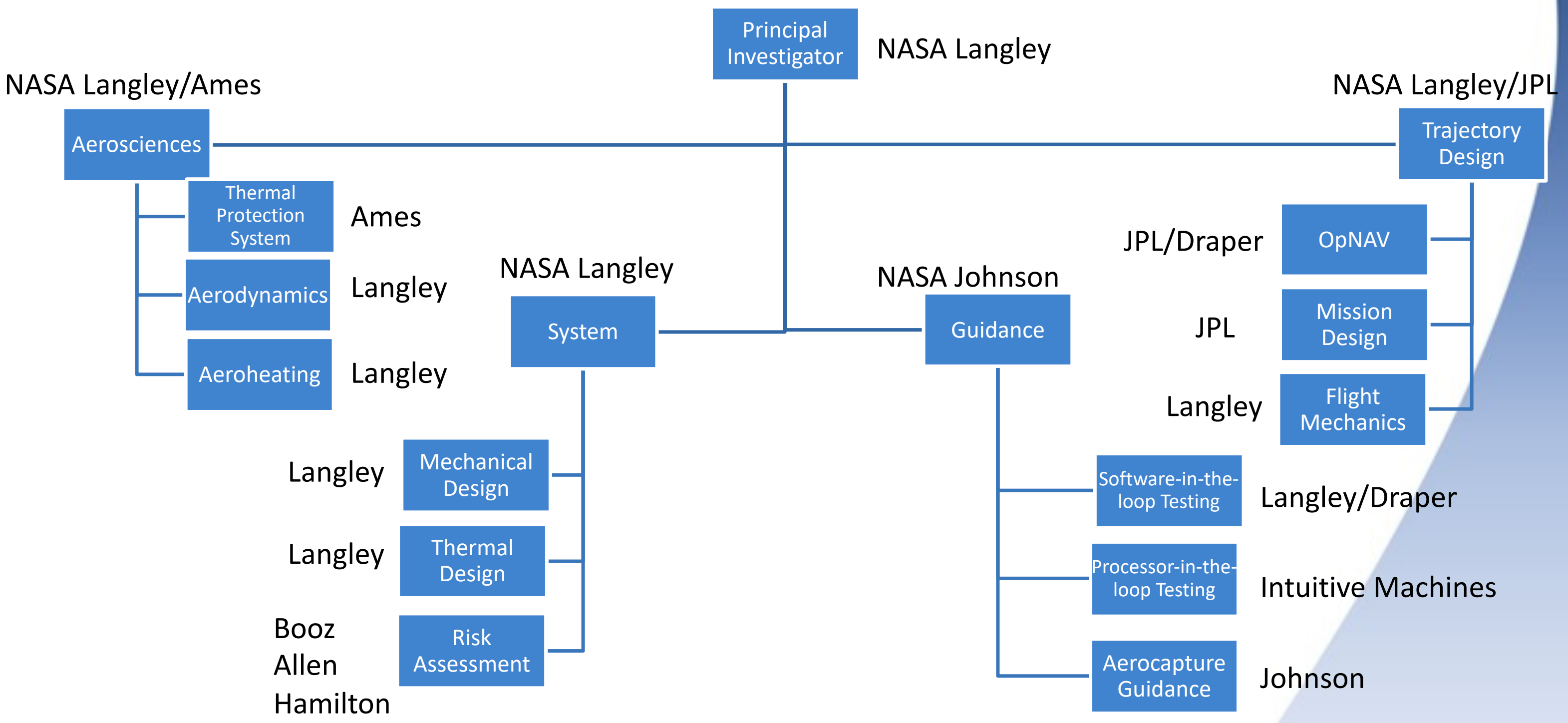
- **Langley Research Center (LaRC)**
  - Soumyo Dutta – Principal Investigator
  - Rohan Deshmukh – Flight Mechanics Lead
  - Eli Shellabarger – Aerodynamics Lead
  - JB Scoggins – Aerothermodynamics Lead
  - Andrew Gomez-Delrio – Mech. Design Lead
  - Rafael Lugo – Flight Mechanics
  - Sai Chadalawada – Flight Mechanics
- **Ames Research Center (ARC)**
  - Joseph Williams – TPS System, ARC Lead
  - Jonathan Morgan – TPS Design
- **Johnson Space Center (JSC)**
  - Breanna Johnson – GNC co-Lead, JSC Lead
  - Dan Matz – GNC co-Lead
  - Josh Geiser – GNC
- **Jet Propulsion Laboratory (JPL)**
  - Declan Mages – OpNAV, JPL Lead
  - Ricardo Restrepo – Mission Design



TPS = Thermal Protection System
GNC = Guidance, Navigation, and Control
OpNAV = Optical Navigation

External Partners

- **Draper Laboratories**
  - Louis Breger – GNC IV&V
  - Thomas Palazzo – GNC IV&V
  - Lylia Benhacine – OpNAV IV&V
- **Booz Allen Hamilton**
  - Kasey Phillips – Agile Project Management
  - Chris Munk – Agile Project Management
  - Jean Ni – Probabilistic Risk Assessment
- **Intuitive Machines**
  - Lucas Ward – GNC Simulation
  - Shaun Stewart – GNC and Flight Dynamics
  - James Blakeslee – Software
  - Wyatt Johnson – GNC

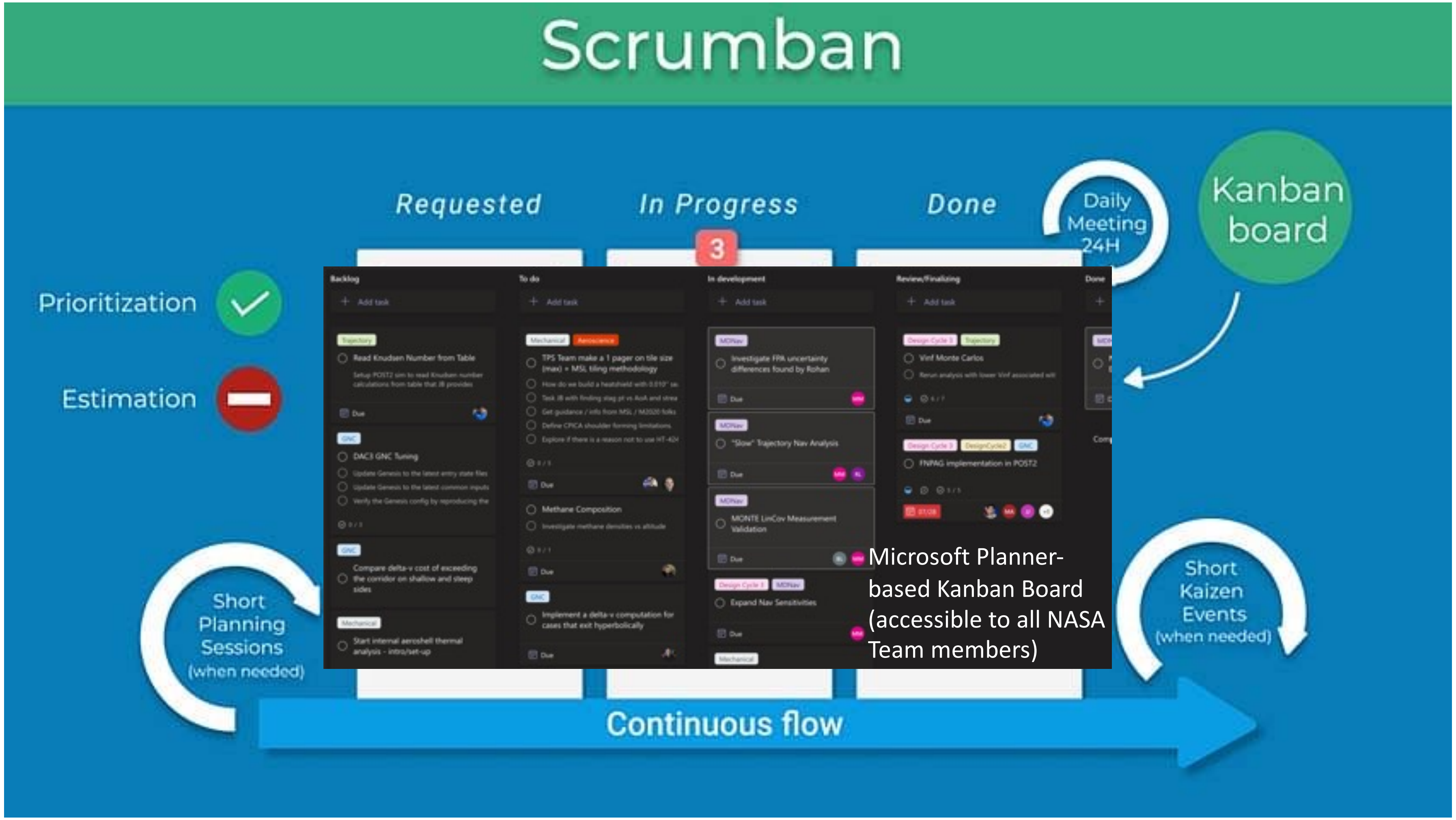


GNC = Guidance, Navigation, and Control
IV&V = Independent Validation and Verification

Mentors

- **Neil Cheatwood (LaRC)**
  - PI for LOFTID and led development of entry technology, such as HIAD
  - Mentor PI/PM in technology development roles
- **Karl Edquist (LaRC)**
  - Aerodynamics and Aerothermodynamics lead on several planetary projects
  - Mentor aerosciences team
- **Raj Venkatapathy (ARC)**
  - Led development of entry technology, such as ADEPT and HEEET
  - Extensive background in TPS design
  - Mentor TPS team and PI/PI in tech development roles
- **Shyam Bhaskaran (JPL)**
  - Many years experience in OpNAV/AutoNAV development
  - Supervisor of Outer Planet Navigation group
  - Mentor for OpNAV and AutoNAV team

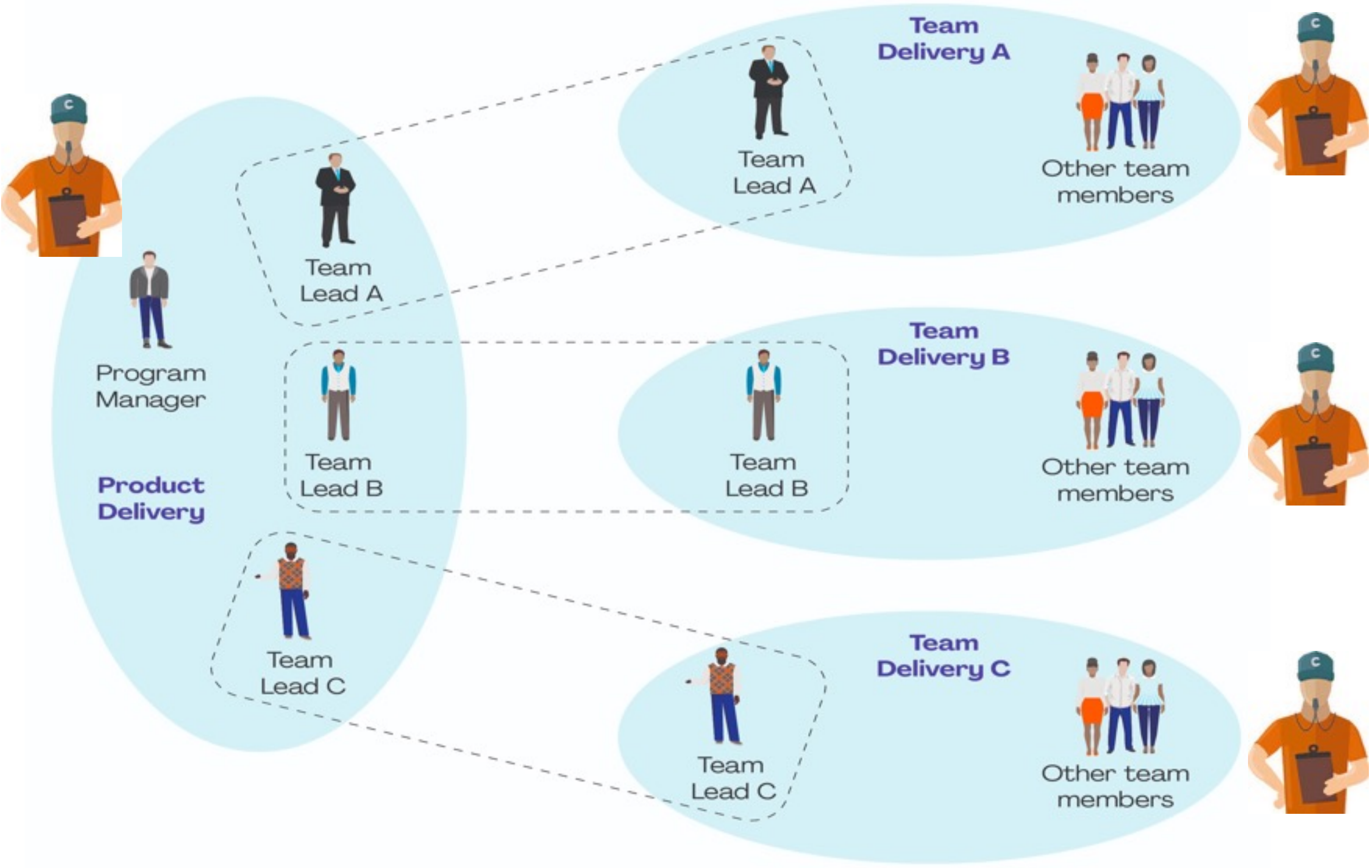
Project Management



- **Hybrid Agile Development Philosophy**
- **Scrumban = combining scrums and Kanban visualization**

Credit: https://www.simplilearn.com/what-is-scrumban-article

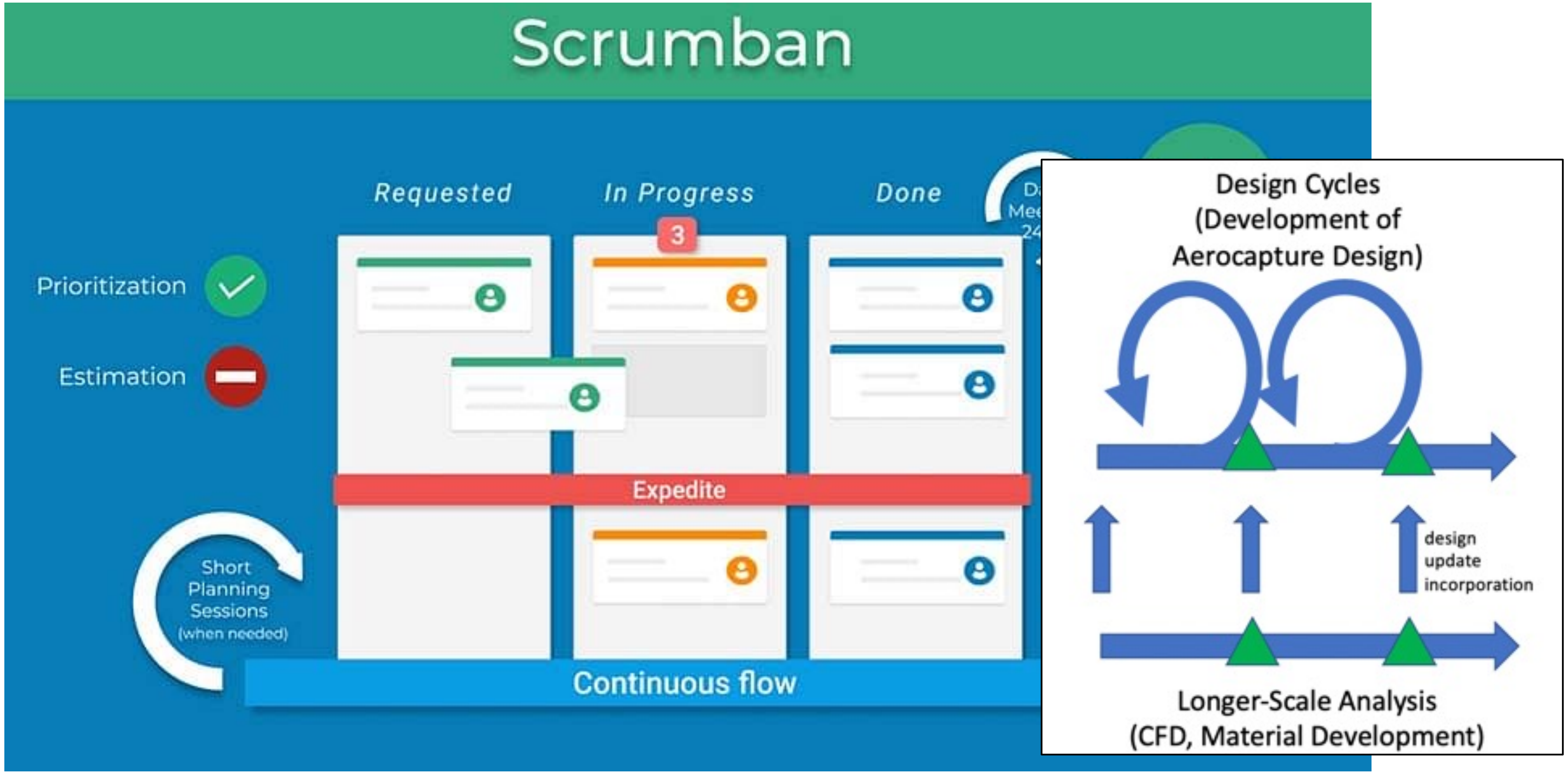
Project Management



- Hybrid Agile Development Philosophy
- Scrumban = combining scrums and Kanban visualization
- Group of Agile teams utilized with frequent Agile project management support

Credit: Project Management Institute

Project Management



- Hybrid Agile Development Philosophy
- Scrumban = combining scrums and Kanban visualization
- Group of Agile teams utilized with frequent Agile project management support
- Parallel track development for longer-scale analysis

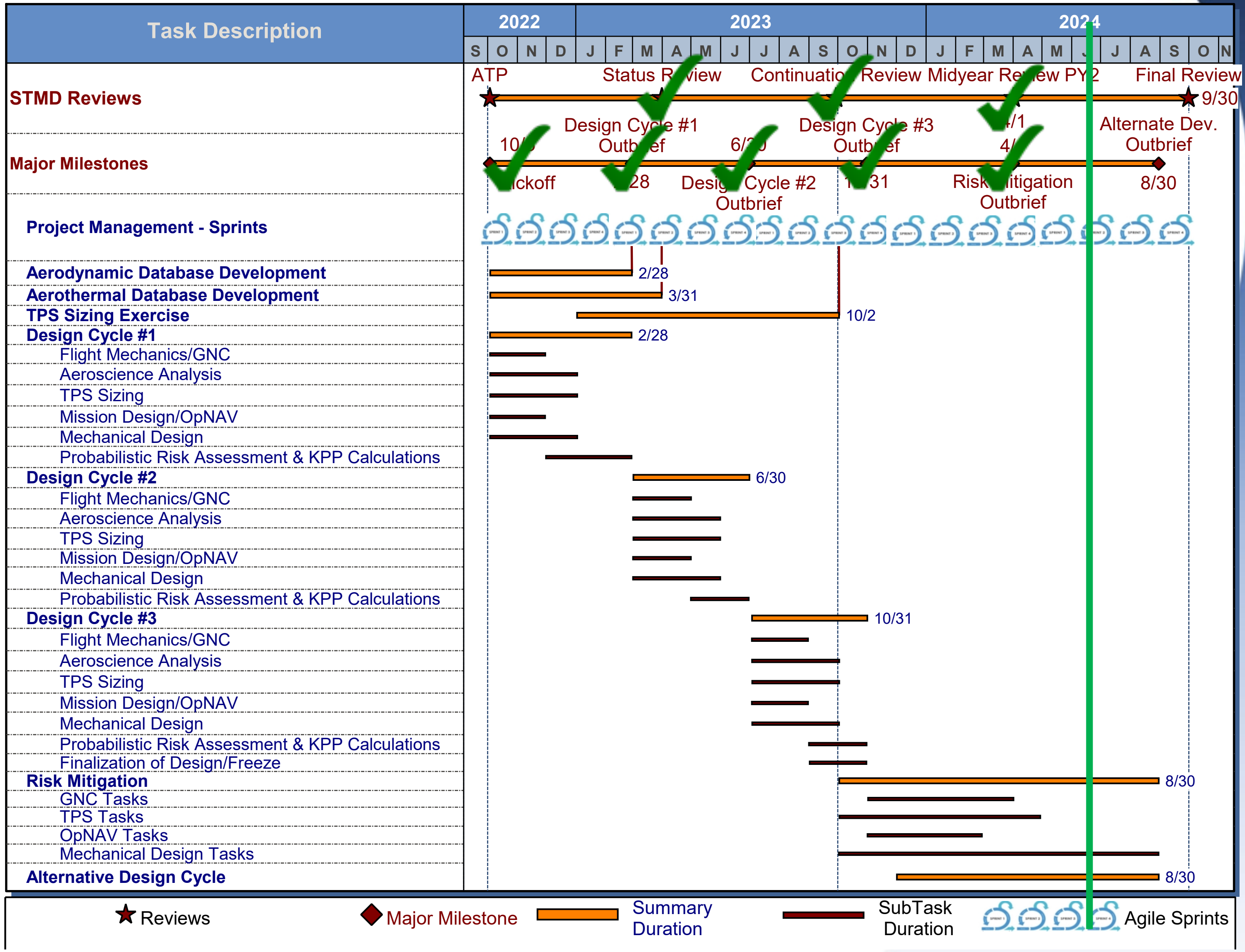
Credit: https://www.simplilearn.com/what-is-scrumban-article

CFD = Computational Fluid Dynamics

- Aerocapture and Ice Giants Introduction
- Project Objectives
- Gaps Addressed and Anticipated Benefits
- Aerocapture Sensitivities
- Team Organization
- Project Management
- **Key Milestones**
- **Future Plans**
- **Publications**

Key Milestones

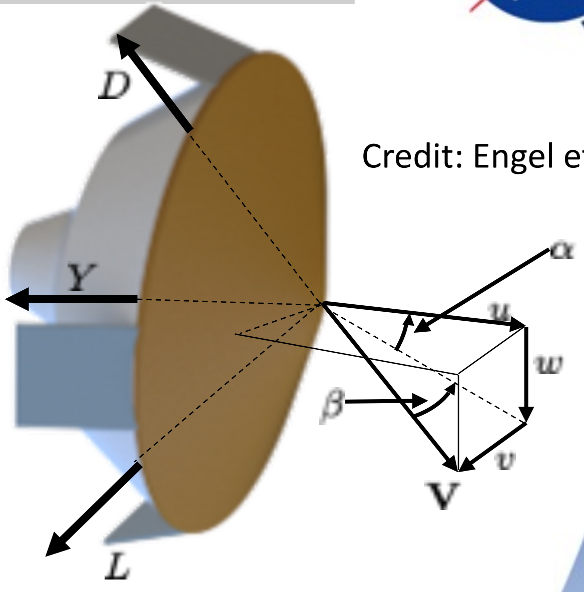
- **Incremental design update – three reviews completed**
  - DAC # 1: March 2023
  - DAC # 2: June 2023
  - DAC # 3: November 2023
  - DAC # 4: April 2024
  - DAC # 5: August 2024



Future Plans

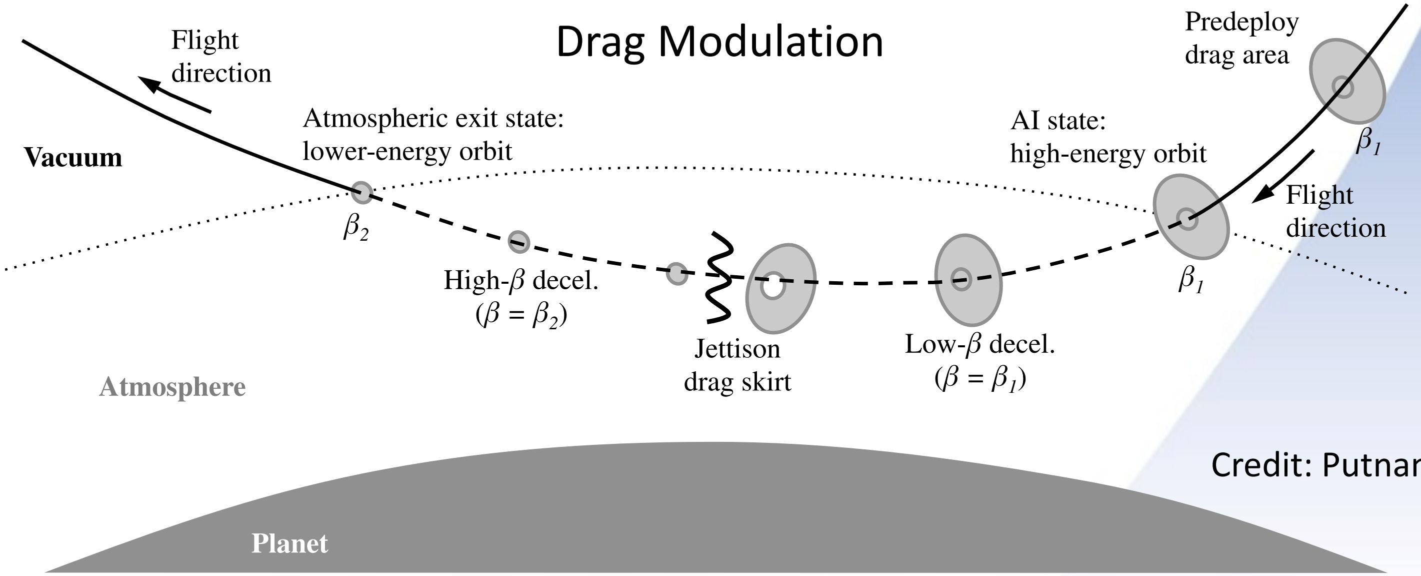
- Alternative control mechanisms
  - Primary control system used – Bank angle modulation
  - Direct force control (DFC) – control angle of attack and sideslip angle independently
  - Drag modulation – no lift generated, modulate ballistic coefficient/drag area for control
- Different aerodynamic configurations
  - Non-blunt bodies
  - Deployables

Direct Force Control



Credit: Engel et al.

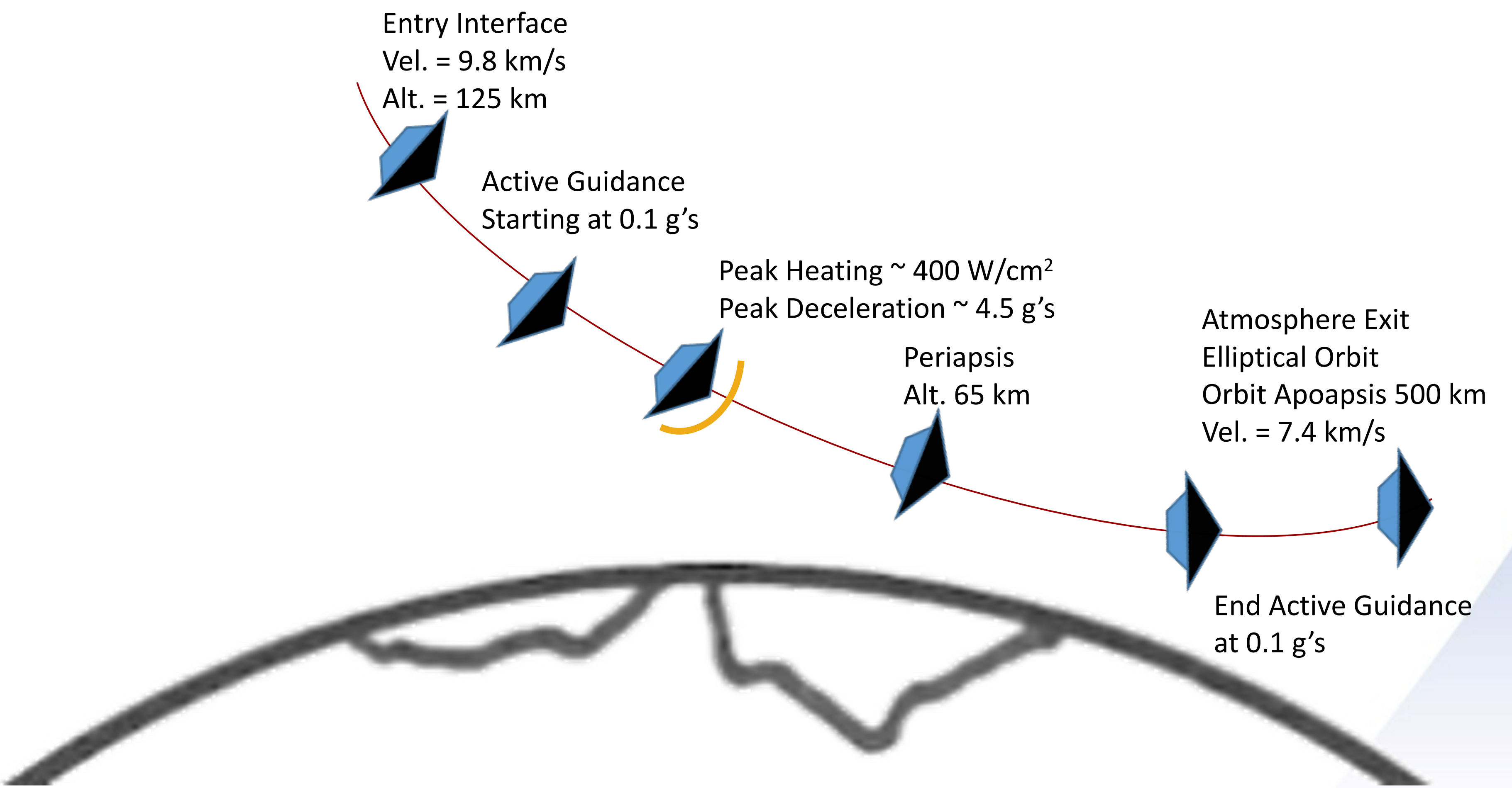
Drag Modulation



Credit: Putnam et al.

Transition Plan after ECI:
Earth Demonstration from Geostationary Transfer Orbit (GTO)

- Piggy-back on geostationary transfer launch
- Demonstrates direct force control and on-board guidance (ΔV ~ 2 km/s)
- High energetic entry – demonstrates heating objectives
- Total mission time ~ 30 hours (from separation at GTO apoapsis to end of mission)



Publications List (Past and Future)

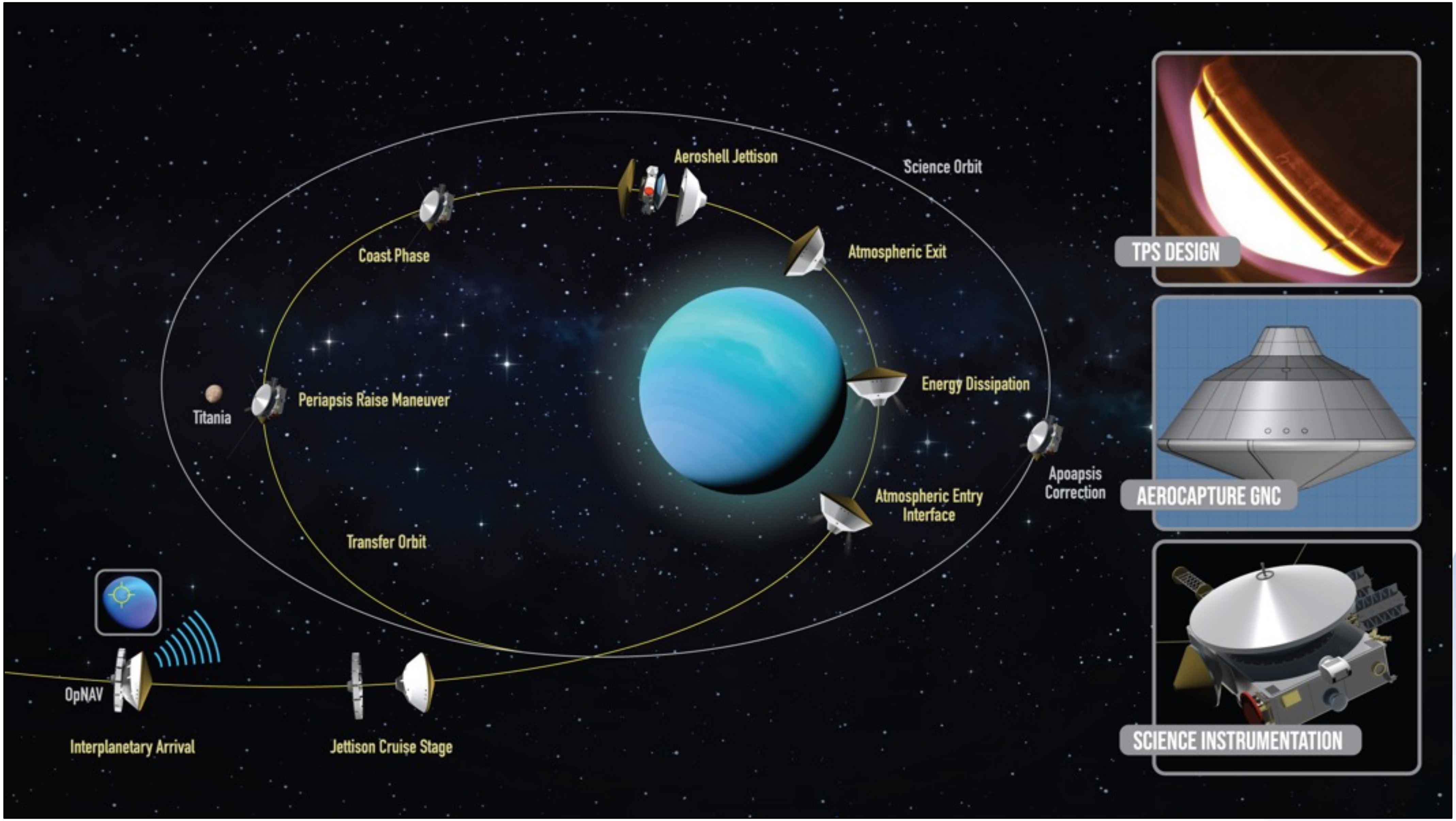
- Jan. 2023 – **NASA Tech Showcase** – Galveston, TX: Poster showcased aerocapture as an orbit insertion mechanism
- May 2023 – **Space Exploration Conference** – Turin, IT: Invited talk discussing aerocapture for planetary missions
- July 2023 – **Uranus Flagship Workshop** – Pasadena, CA: One talk and poster discussing aerocapture system and Thermal Protection System solutions
- Aug. 2023 – **International Planetary Probe Workshop** – Marseille, FR: Two talks and one poster discussing aerocapture system, trajectory, and aerosciences related to Uranus mission
- Aug. 2023 – **Thermal & Fluids Analysis Workshop** – College Park, MD: One talk on aerothermal implications of aerocapture at the Ice Giants
- Nov. 2023 – **Outer Planets Assessment Group** – Boulder, CO: Talk on aerocapture option for Uranus Flagship mission
- Jan. 2024 – **AIAA SciTech 2024** – Orlando, FL: 2 special sessions with 8 papers discussing in-detail aerocapture system design
- May 2024 – **Uranus Flagship Workshop** – Goddard, MD: one poster discussing aerocapture system
- June 2024 **– International Planetary Probe Workshop –** Williamsburg, VA: Two talks (6DOF trajectory and MDNAV solution) and two posters (system overview and Agile project management)
- June 2024 – **Outer Planets Assessment Group** – Ithaca, NY: One invited talk about aerocapture interplanetary trajectories
- Jan. 2025 – **AIAA SciTech 2025** – Orlando, FL: (potentially) special sessions with final results

Team Meetings

January 2024: SciTech 2024 in Orlando, FL

April 2024: DAC # 4 Review in Houston, TX

Questions



Aeroshell Jettison
Science Orbit
Coast Phase
Atmospheric Exit
TPS DESIGN
Energy Dissipation
Titania
Periapsis Raise Maneuver
Apoapsis Correction
Atmospheric Entry Interface
AEROCAPTURE GNC
Transfer Orbit
OpNAV
Interplanetary Arrival
Jettison Cruise Stage
SCIENCE INSTRUMENTATION