Aerocapture as an Enabling Technology for Ice Giants

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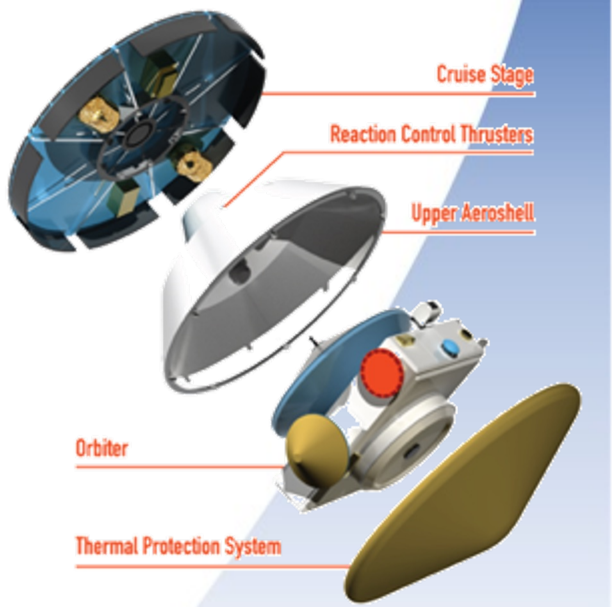
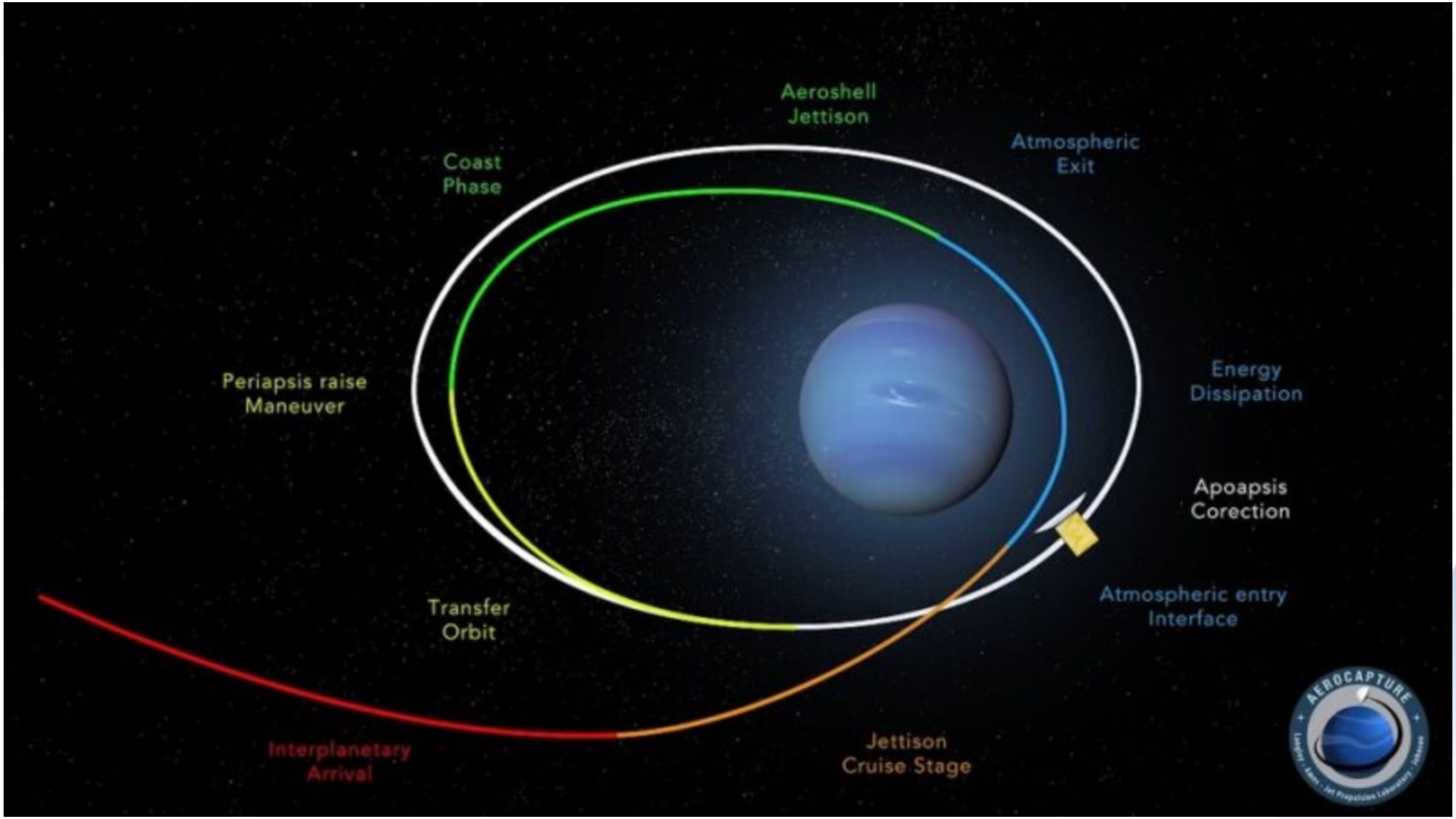
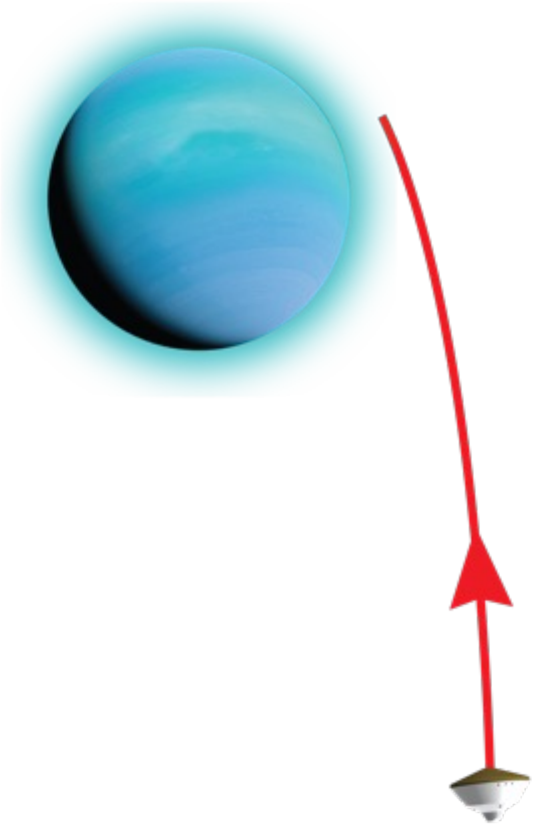


Introduction Video



What is Aerocapture?



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

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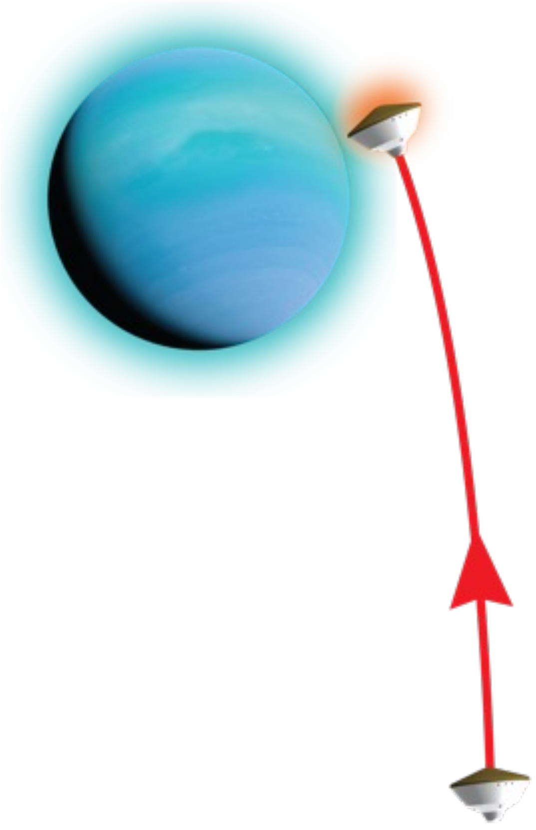

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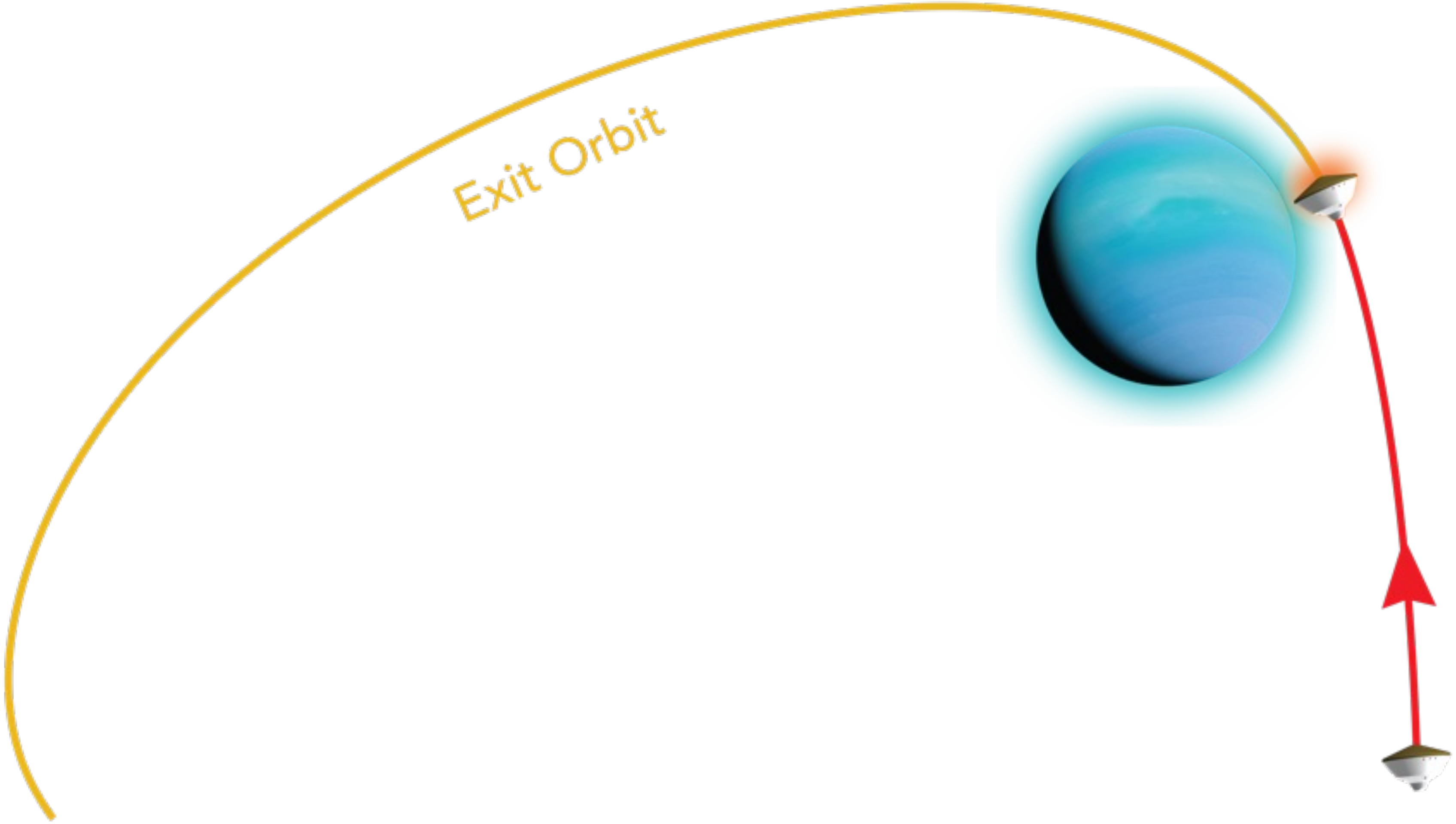

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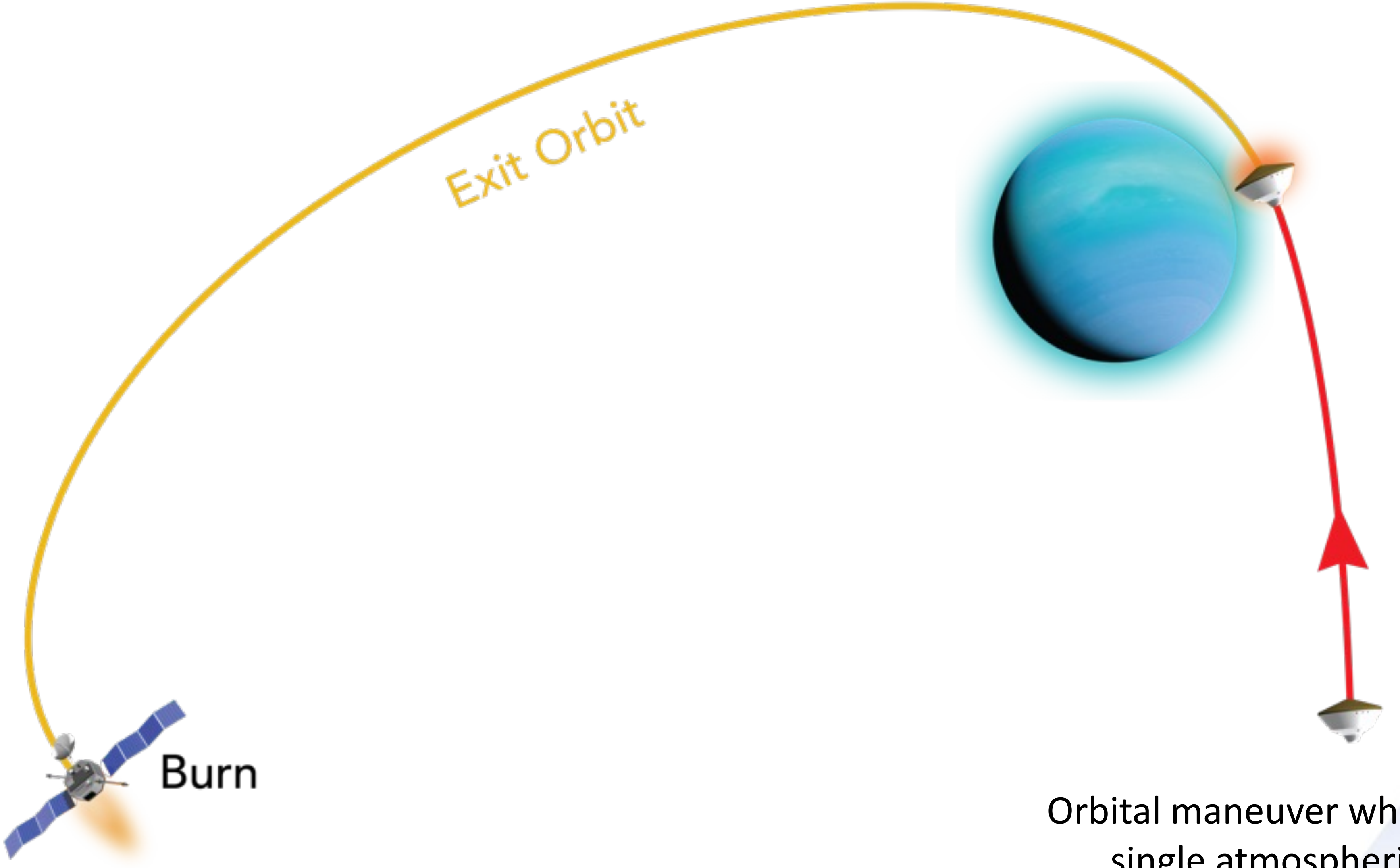

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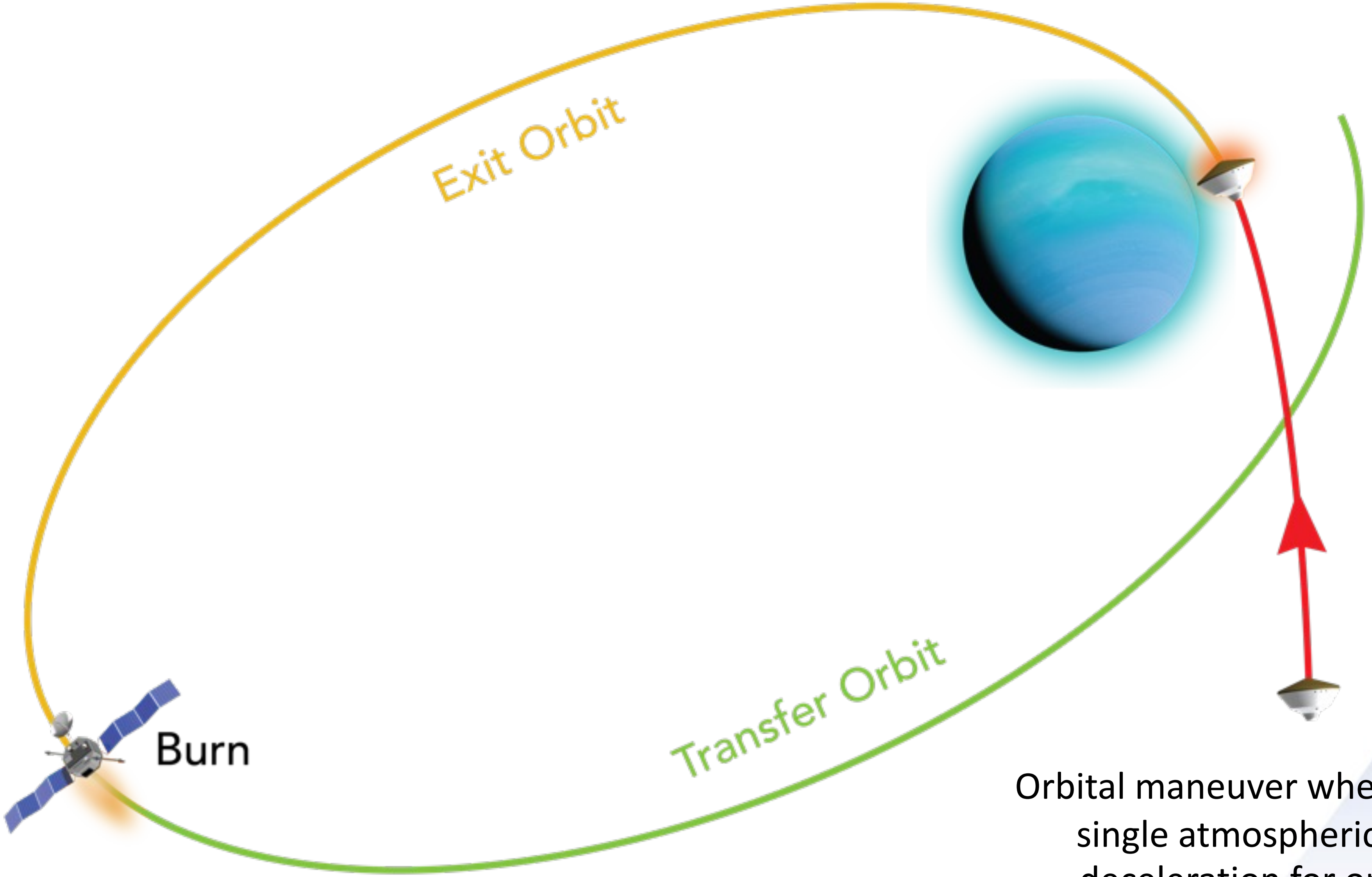

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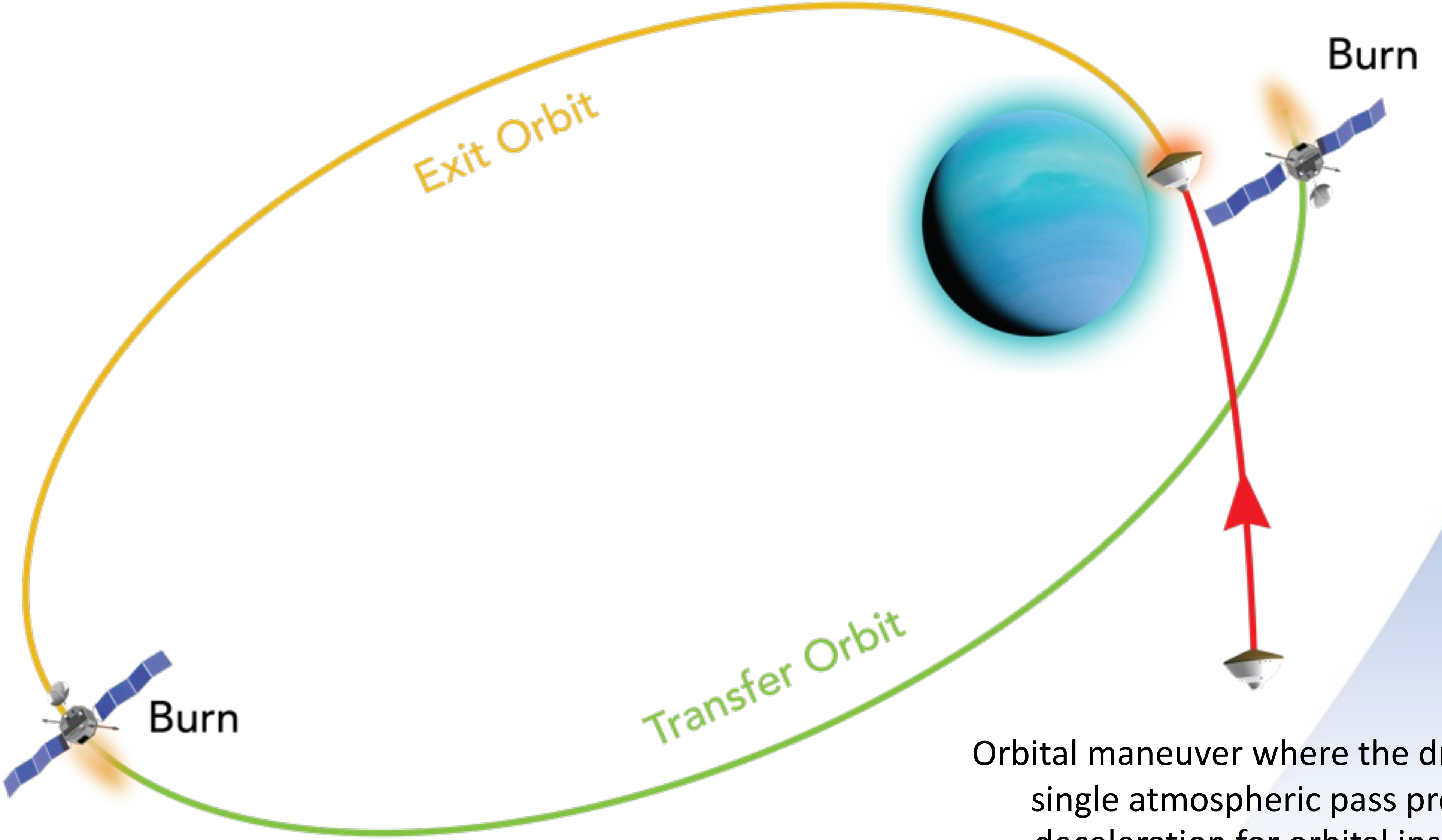

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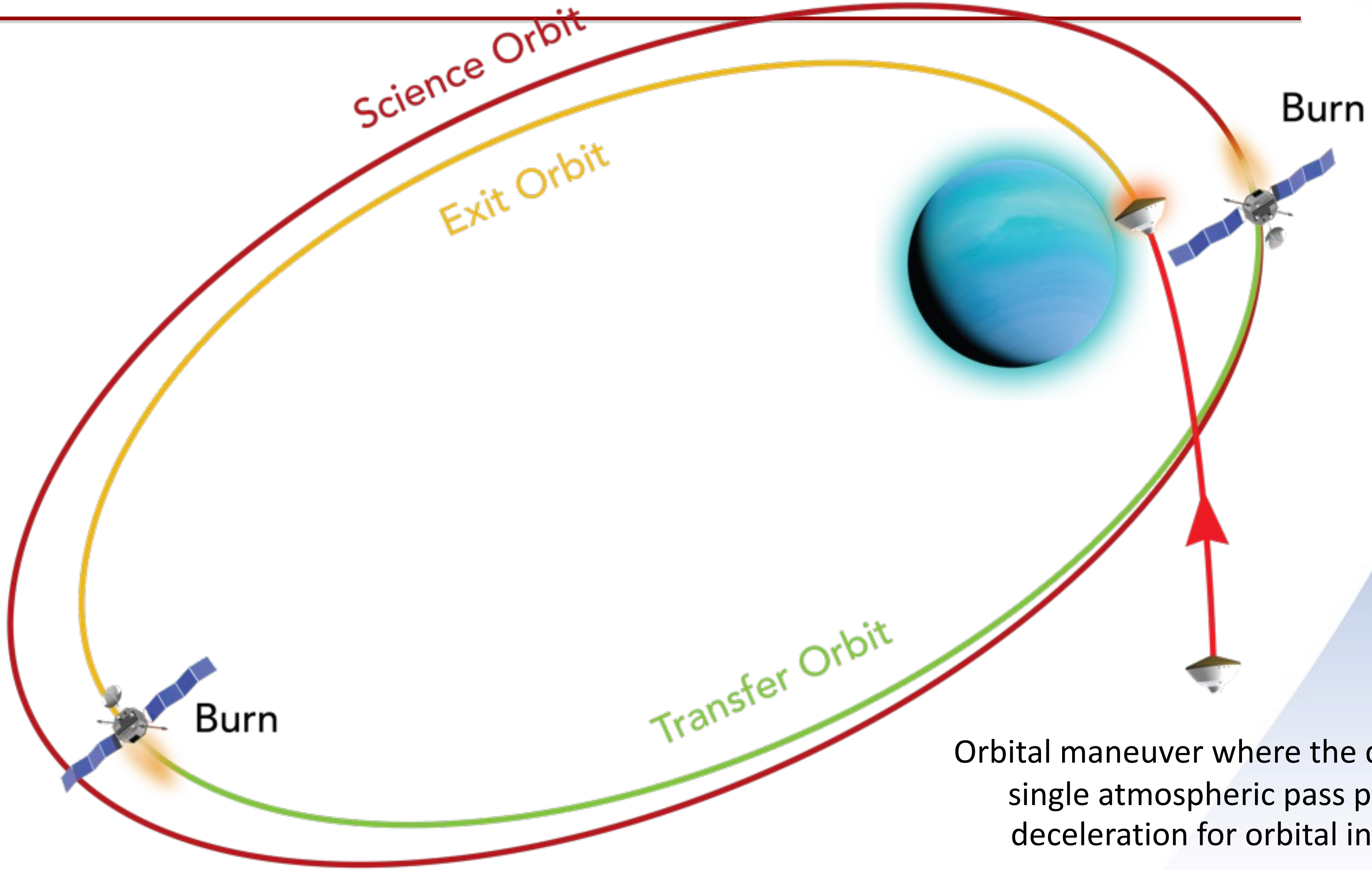
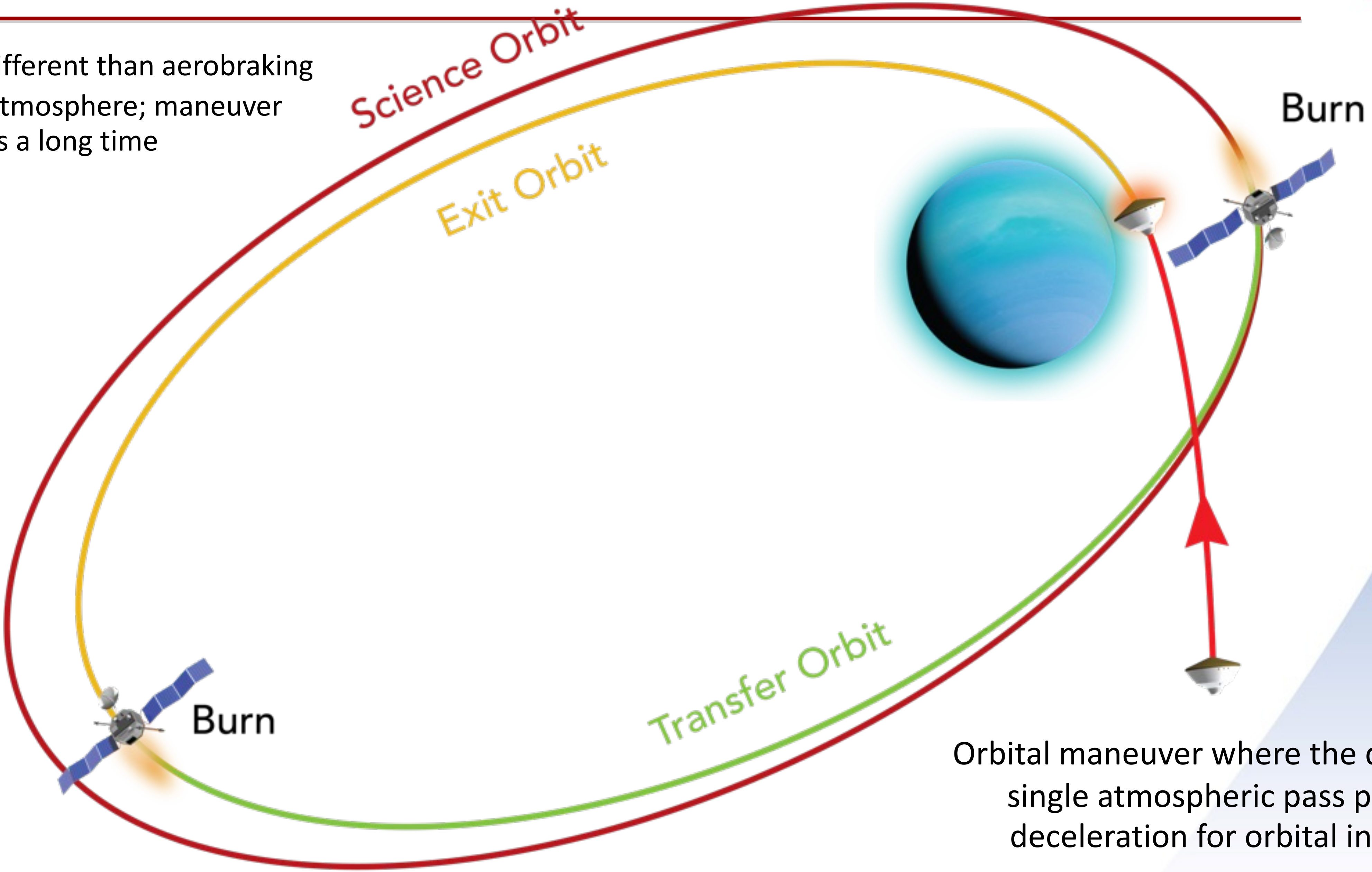


Orbital maneuver where the drag from a single atmospheric pass provides deceleration for orbital insertion

What is Aerocapture?

Aerocapture is different than aerobraking

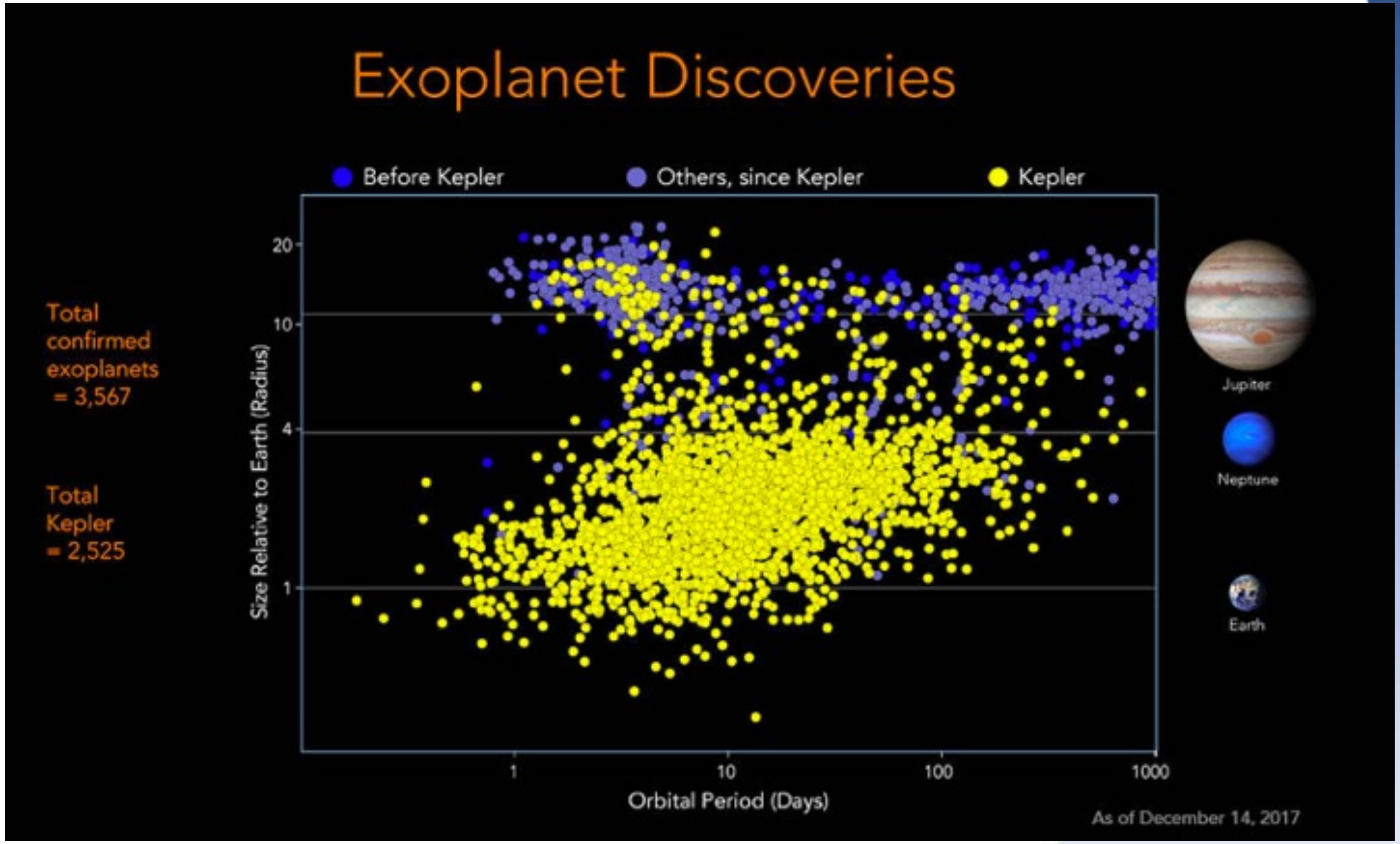
Which skims atmosphere; maneuver takes a long time



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

Why the Ice Giants?

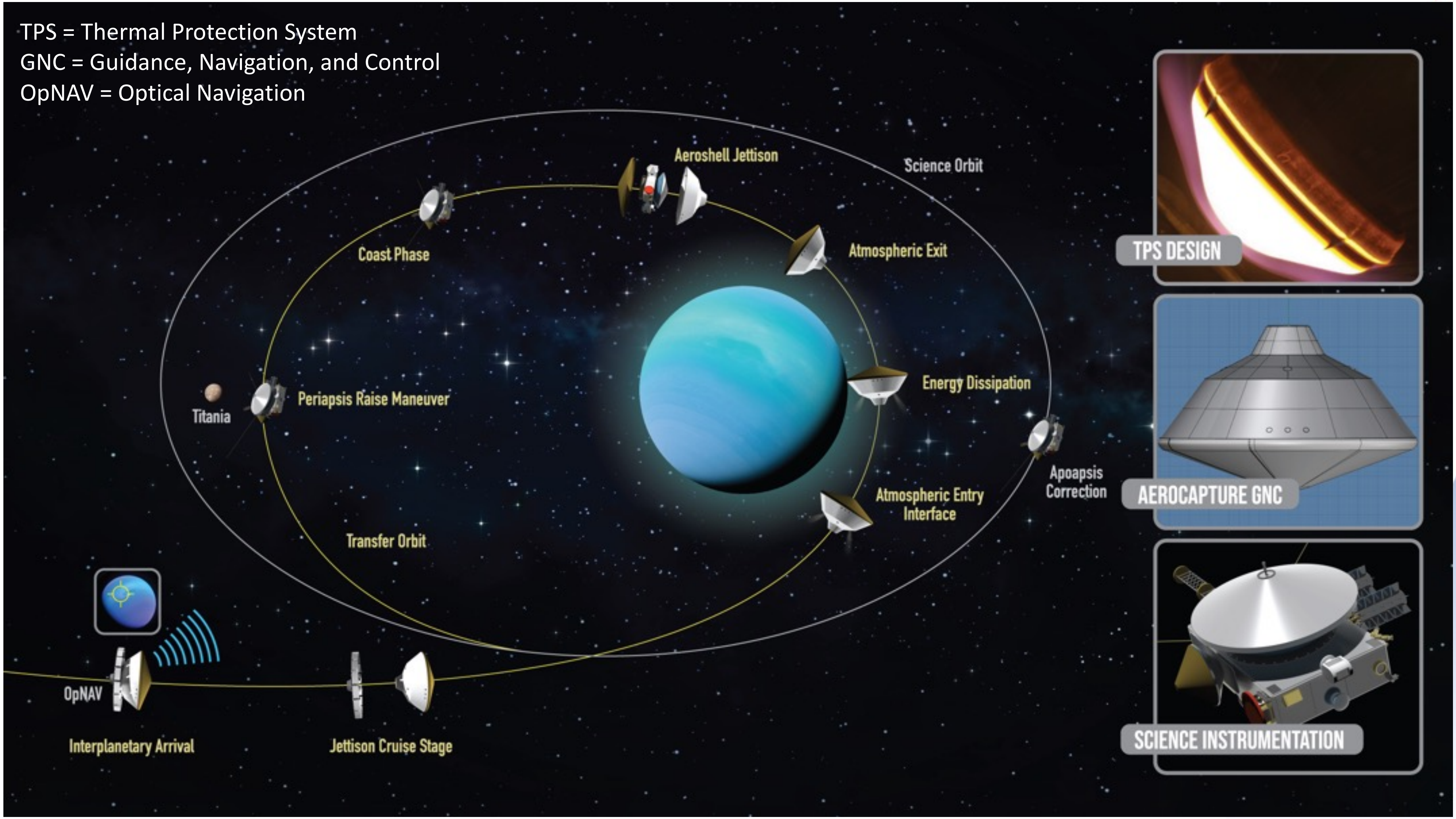
- Uranus and Neptune (Ice Giants) have only been visited by Voyager 2 through a flyby
- Uranus has interesting obliquity; Neptune has interesting moon: Triton
- Many exoplanets are Uranus and Neptune like
- **Uranus is the top flagship class mission destination in the 2023-2032 Planetary Science Decadal Survey**
- **Decadal Survey also mentions aerocapture as a technology that should be incentivized**



Credit: https://www.nasa.gov/image-feature/ames/exoplanet-discoveries

Uranus selected as the point design for Year 1 efforts

Key Technological Thrusts for Aerocapture

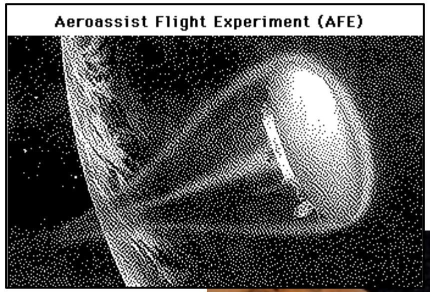


Outline

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

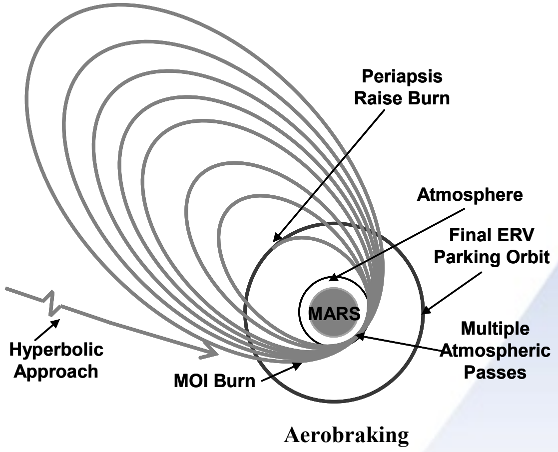
Existing Challenges

- 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



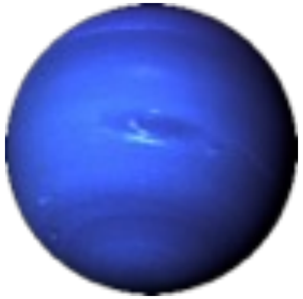
(proposed)

Mars Surveyor 2001 (proposed)



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

Gaps



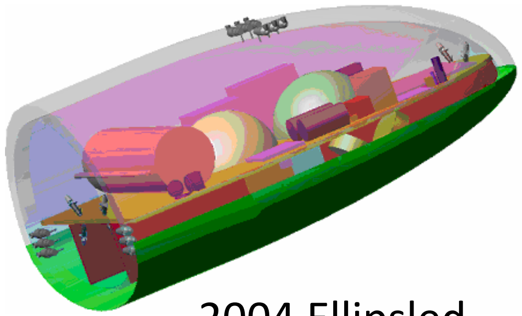
Typical Fully-Propulsive Mission

- 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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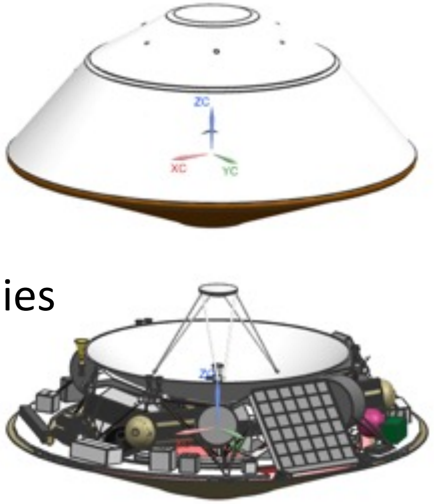

Heritage Blunt Bodies

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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8 John Hopkins University/Applied Physics Laboratory
9 NASA Langley Research Center
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11 University of Illinois, Urbana-Champaign
12 C.I.R.A. Italian Aerospace Research Centre
13 Purdue University
14 University of California, Los Angeles
15 NASA Johnson Space Center
16 University of Missouri
17 French National Centre for Scientific Research
18 San Diego State University
19 Kent State University
20 Aurora Technology B.V.
21 Mullard Space Science Laboratory, University College London
22 Institute of Structures and Design - German Aerospace Center (DLR)
23 Spacefaring Technologies Inc.
24 Hampton University
25 European Space Agency – ESTEC

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

- Aerocapture and Ice Giants Introduction
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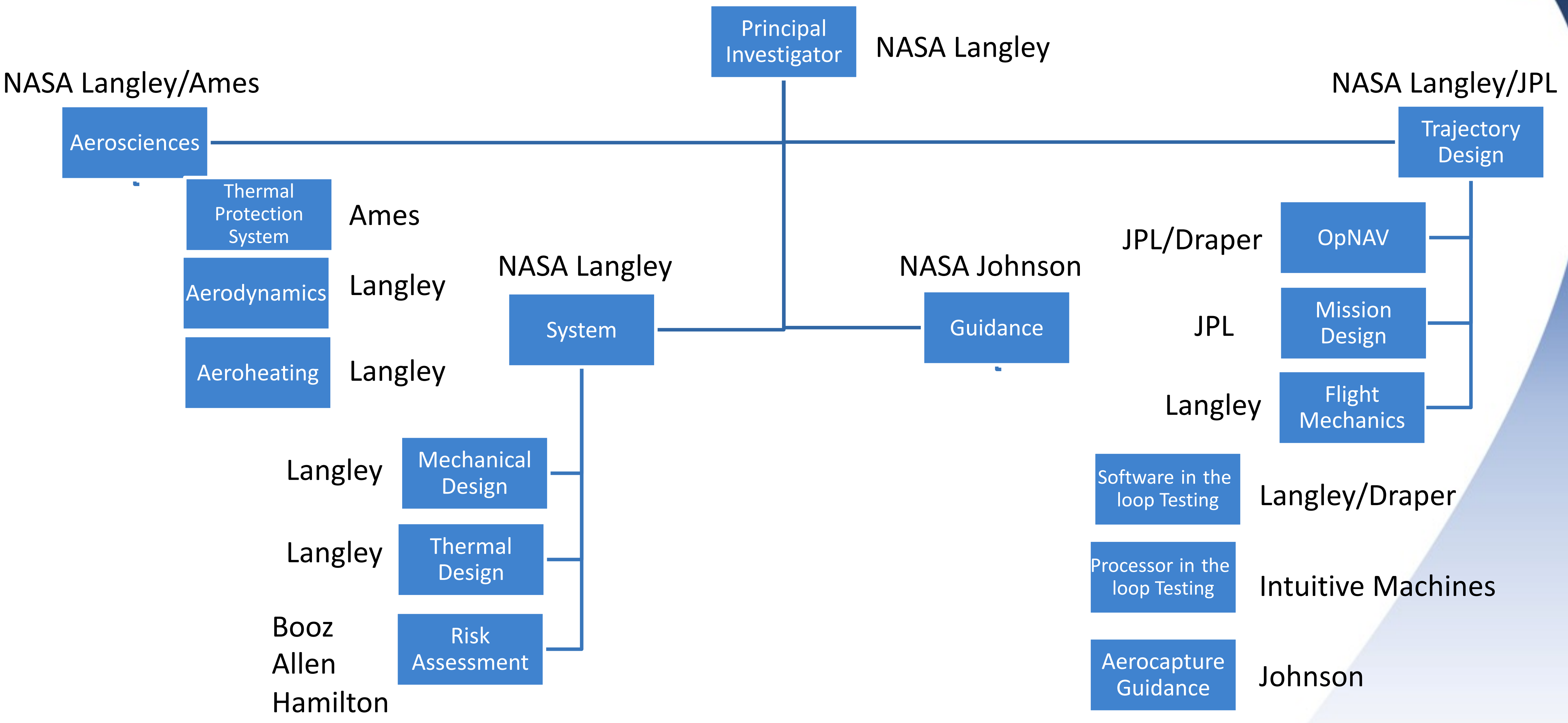
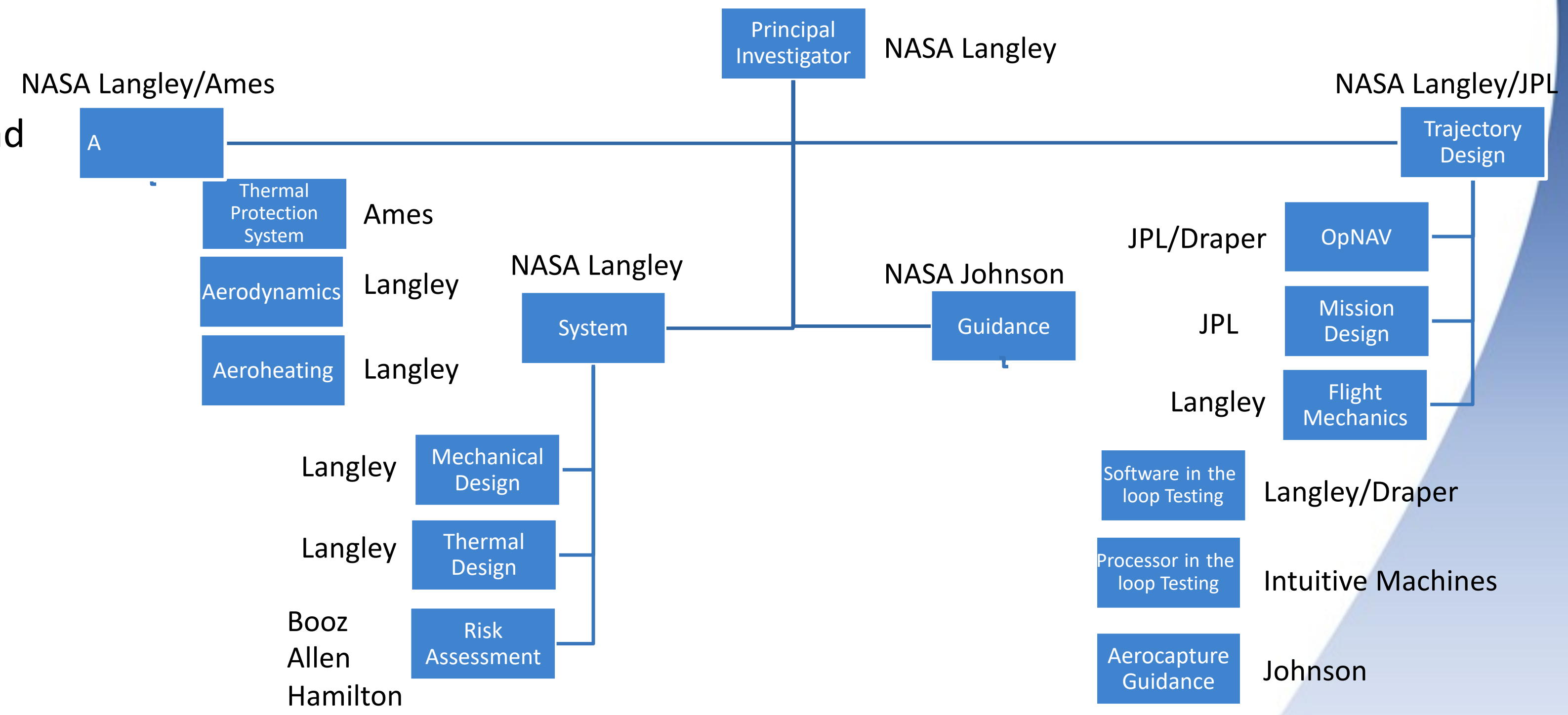
Organization



Team Members

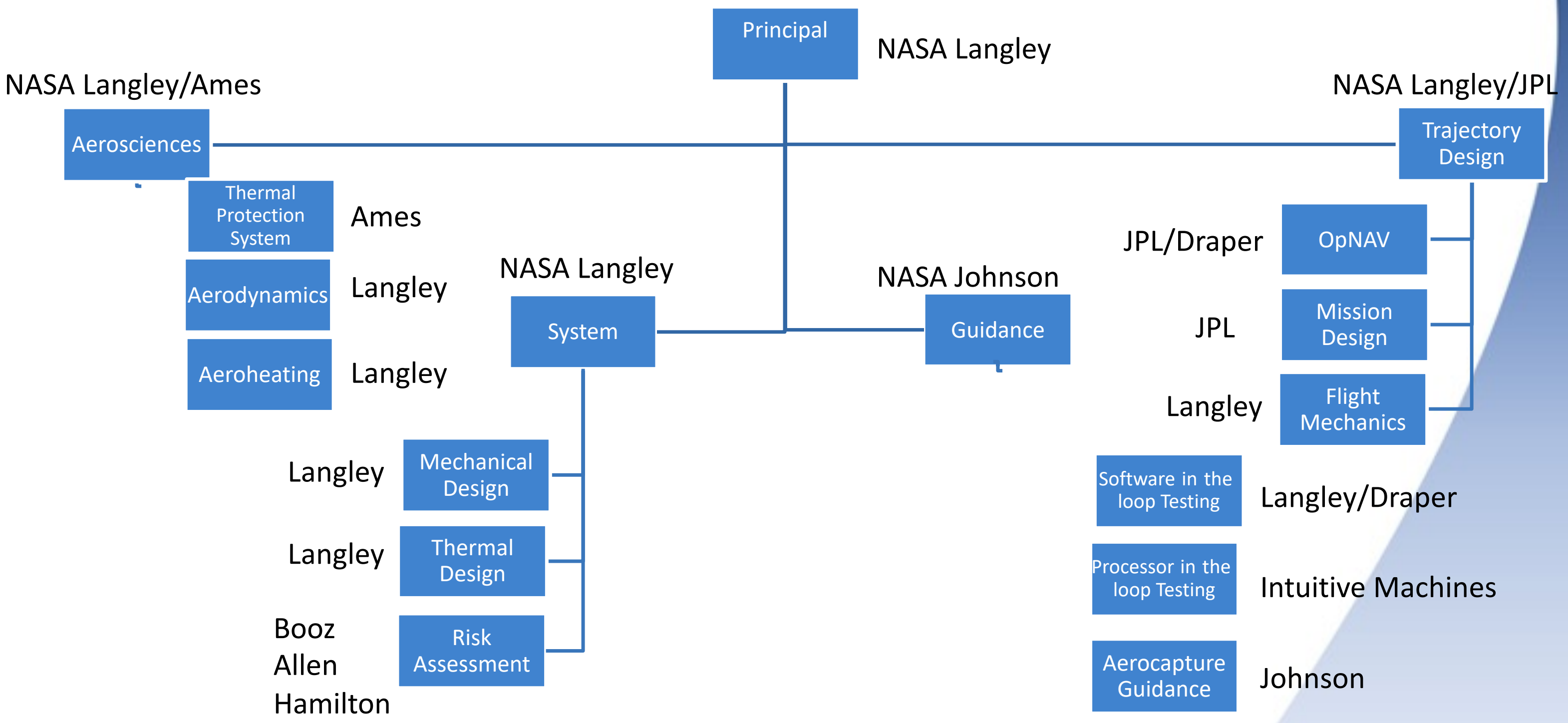
- **Langley Research Center (LaRC)**
  - Soumyo Dutta – Principal Investigator
  - Rohan Deshmukh – Flight Mechanics Lead
  - Eli Shellabarger – Aerodynamics Lead
  - JB Scoggins – Aerothermodynamics Lead
  - Andrew Gomez-Delrio – Mech. Design Lead
  - Rafael Lugo – Flight Mechanics
  - Sai Chadalawada – 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 (January start)**
  - Louis Breger – GNC IV&V
  - Thomas Palazzo – GNC IV&V
  - Lylia Benhacine – OpNAV IV&V
- **Booz Allen Hamilton (January start)**
  - Kasey Phillips – Agile Project Management
  - Chris Munk – Agile Project Management
  - Jean Ni – Probabilistic Risk Assessment
- **Intuitive Machines (March start)**
  - Lucas Ward – GNC Simulation
  - Shaun Stewart – GNC and Flight Dynamics
  - James Blakeslee – Software
  - Wyatt Johnson – GNC

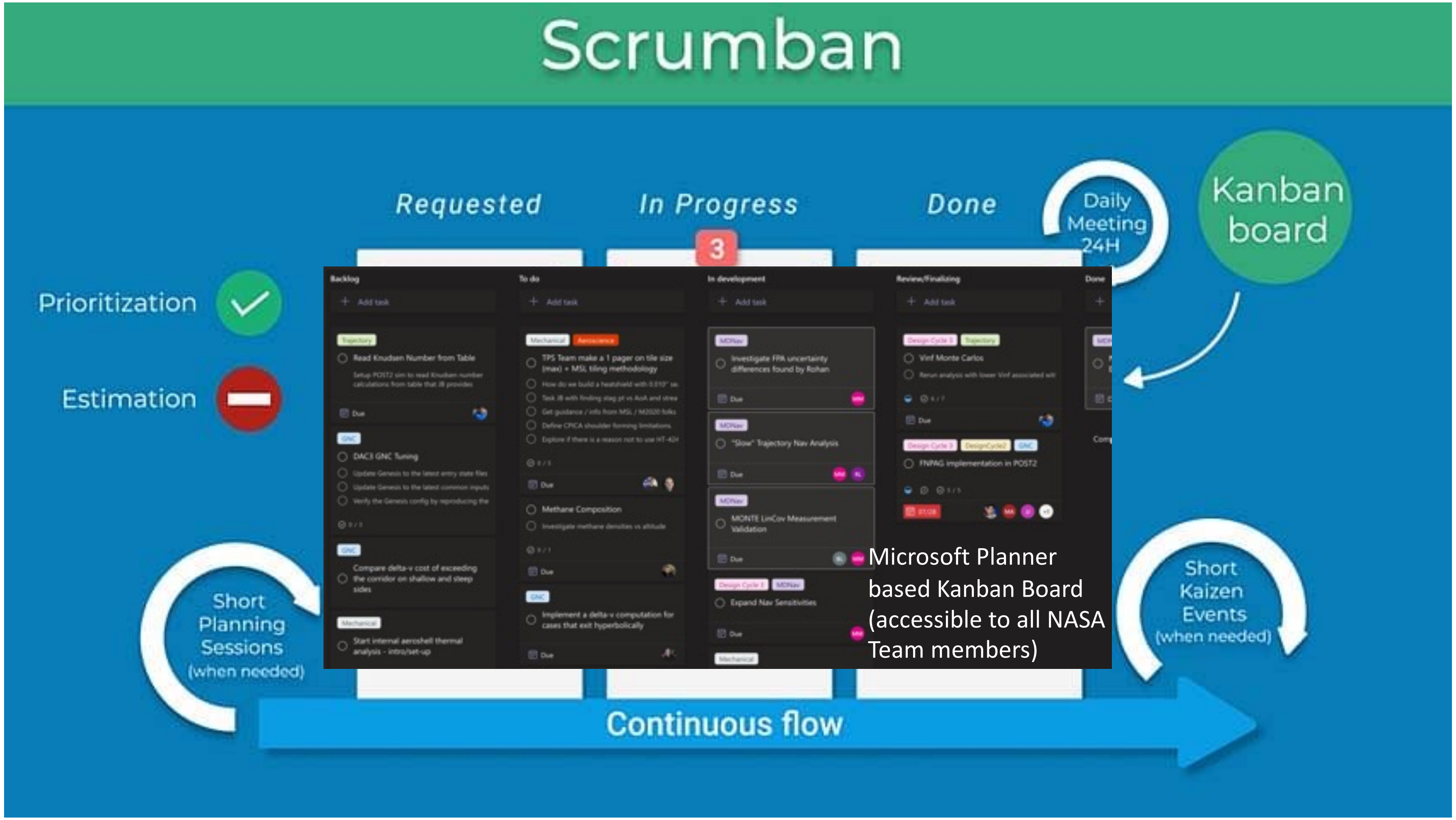


GNC = Guidance, Navigation, and Control
IV&V = Independent Validation and Verification

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

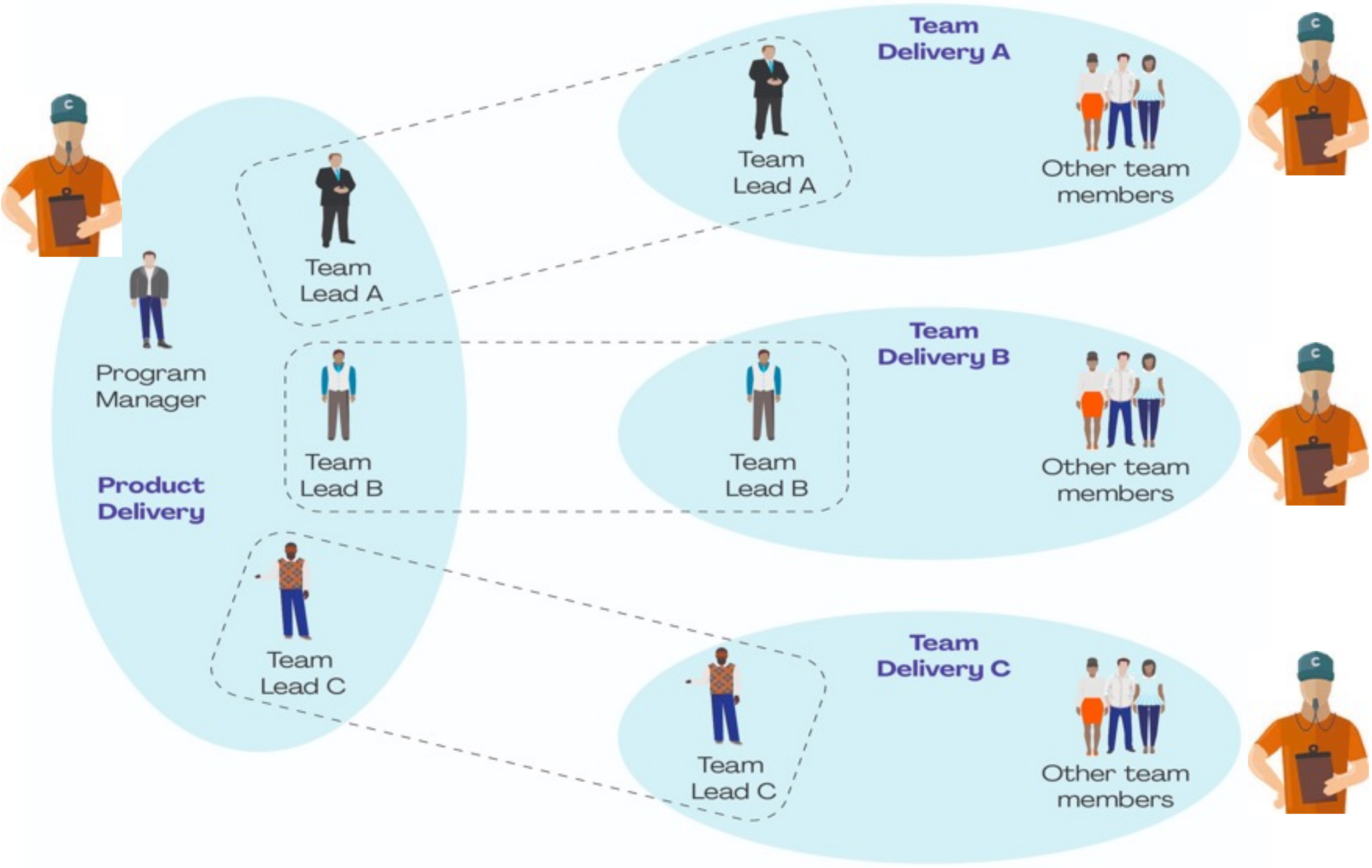
Project Management



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

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

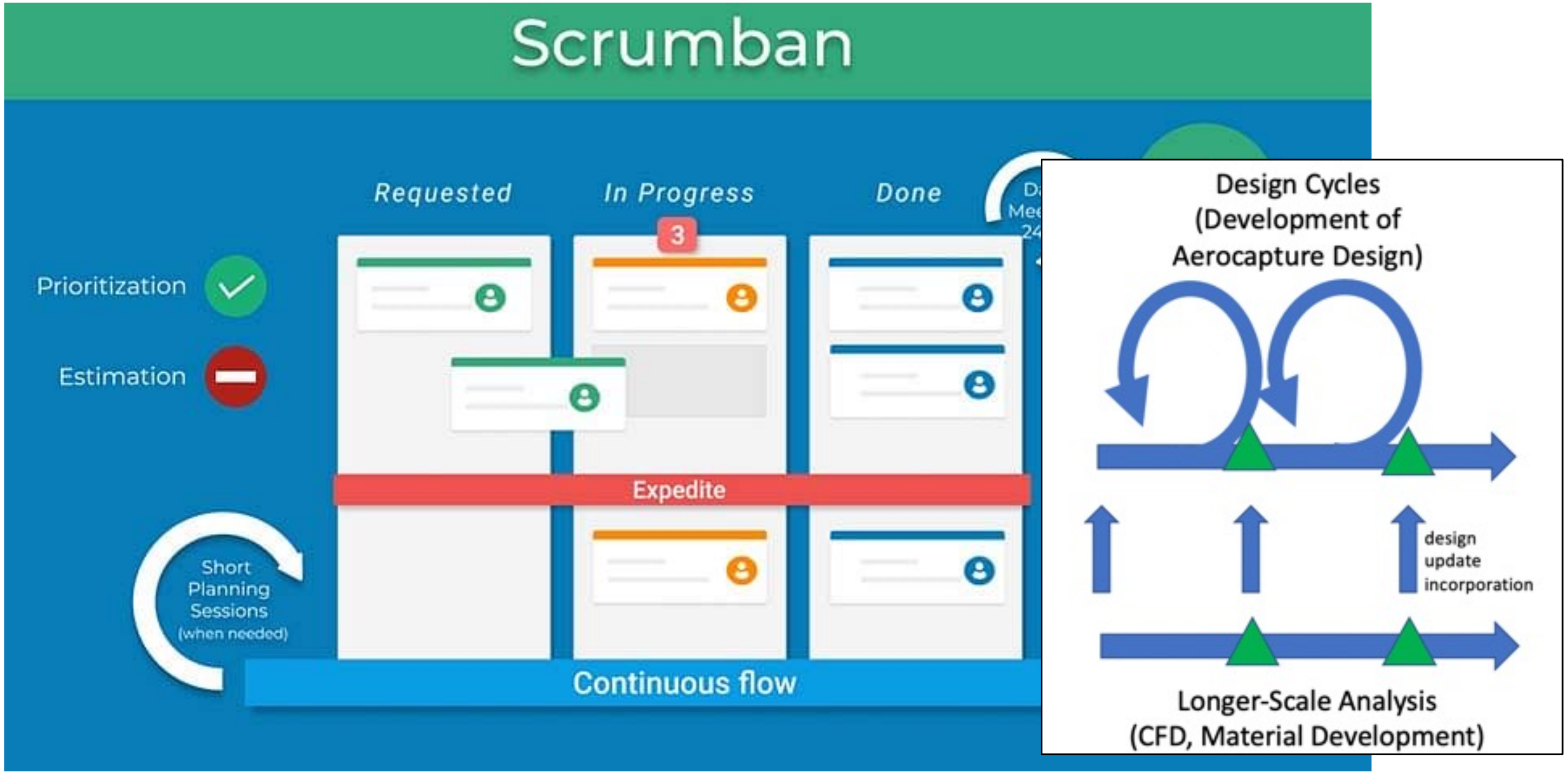
Project Management



- 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

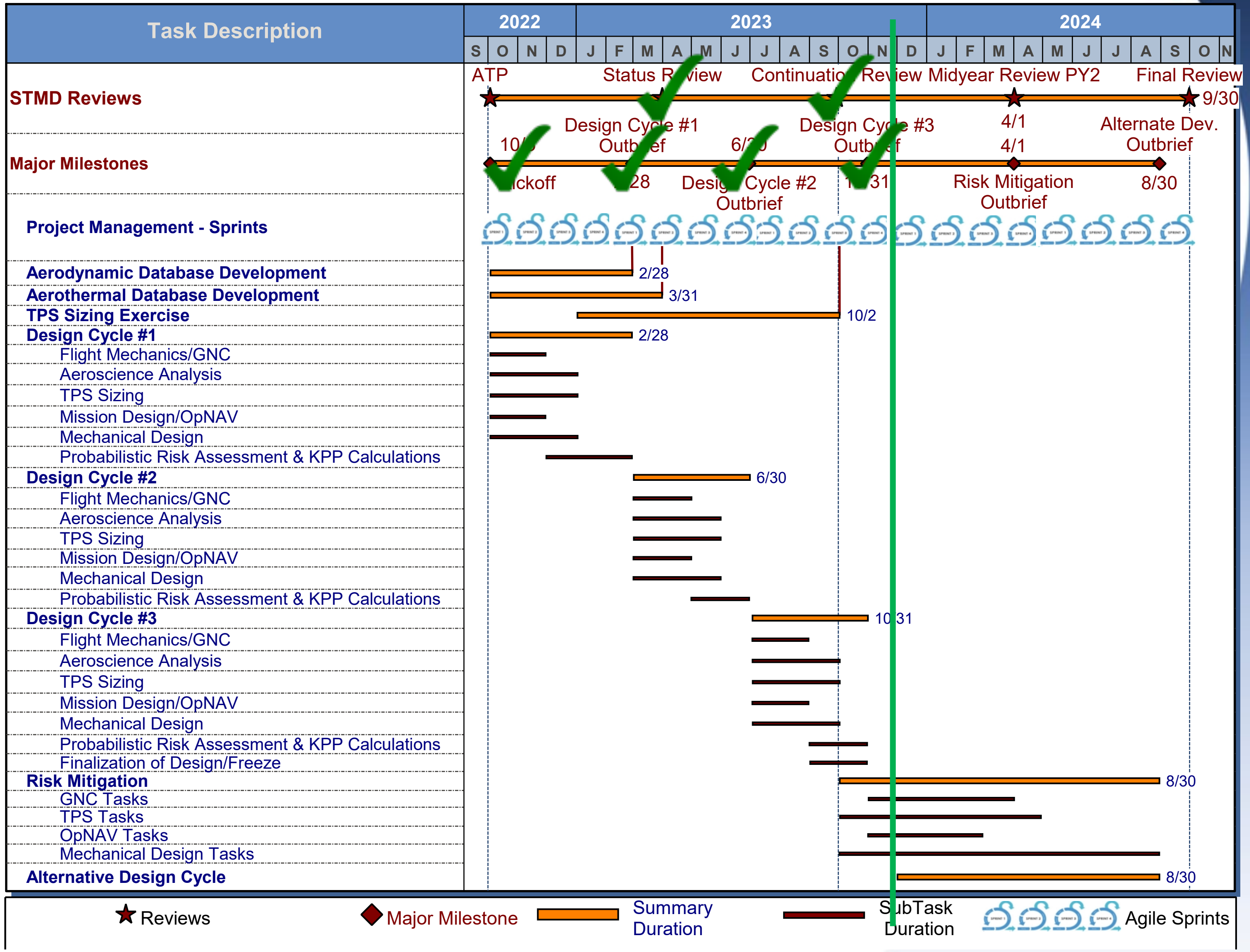
Credit: https://www.simplilearn.com/what-is-scrumban-article

CFD = Computational Fluid Dynamics

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

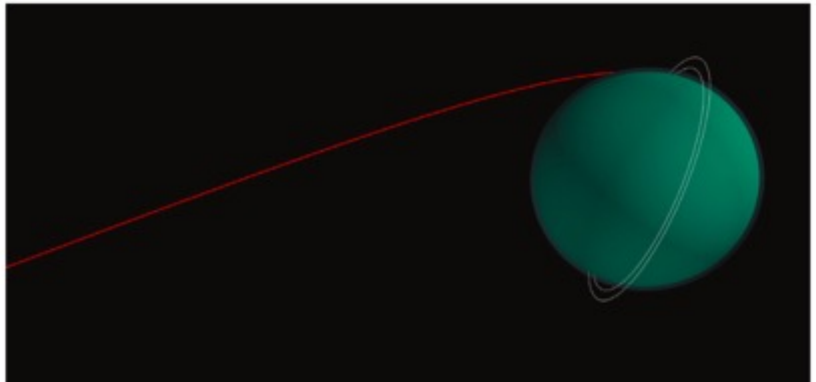
Key Milestones

- **Year 1 divided into three design analysis cycles (DAC)**
- **Incremental design update – three reviews completed**
  - DAC # 1: March 2023
  - DAC # 2: June 2023
  - DAC # 3: November 2023
- **Year two divided into two large cycles**
  - Risk mitigation
  - Alternatives development



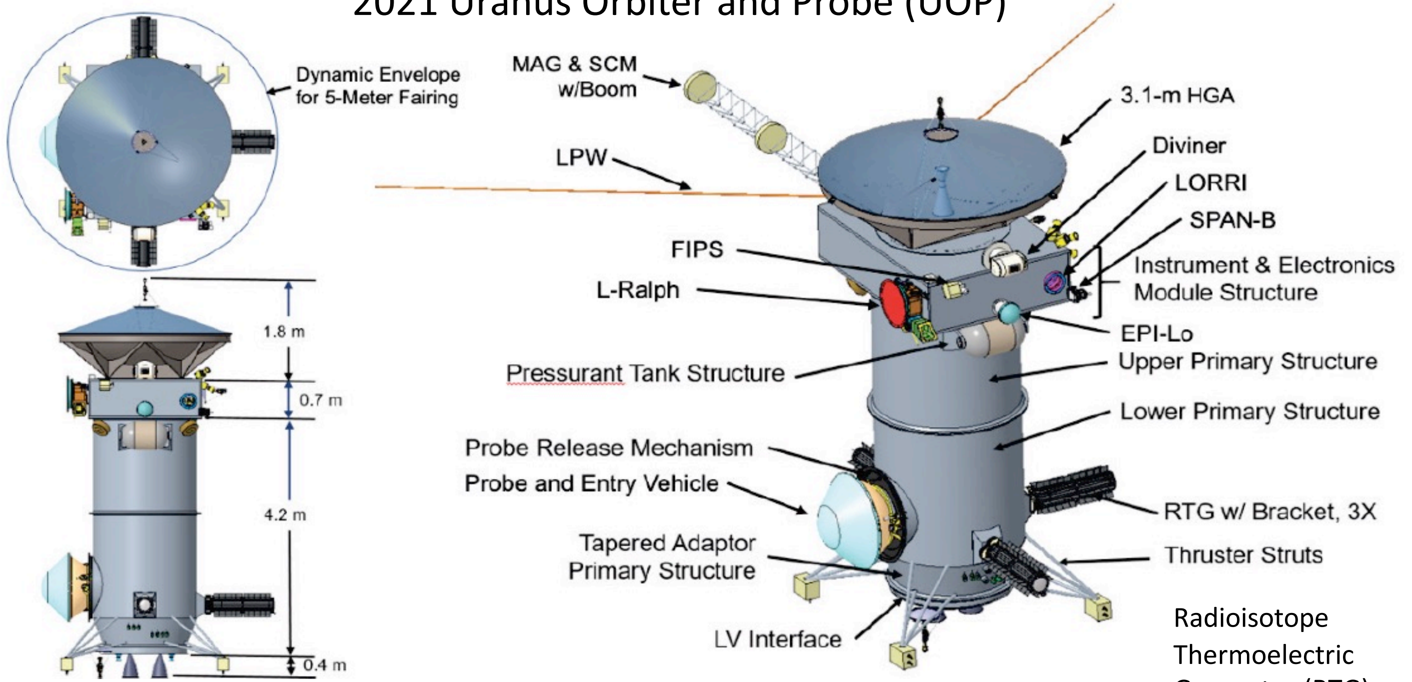
Uranus – Flagship Science Destination

- **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



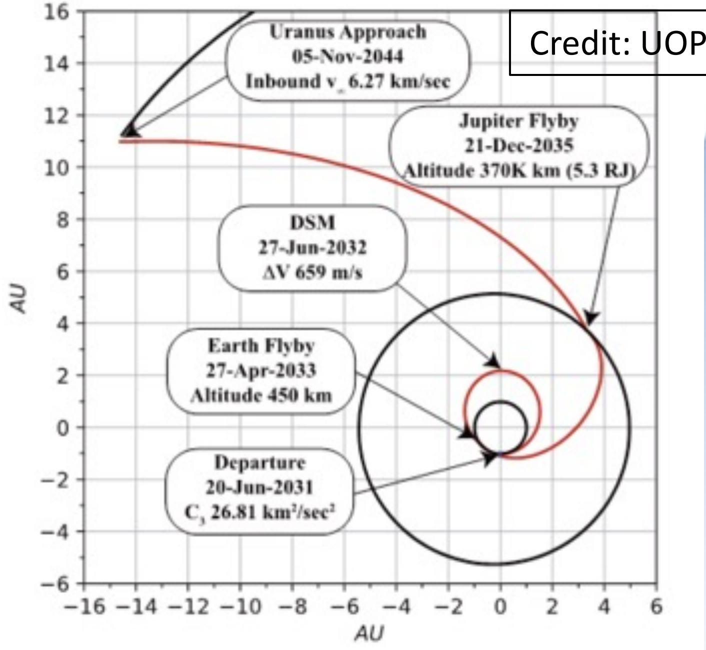
Credit: Girija 2022

2021 Uranus Orbiter and Probe (UOP)



Radioisotope Thermoelectric Generator (RTG)

Credit: UOP Report



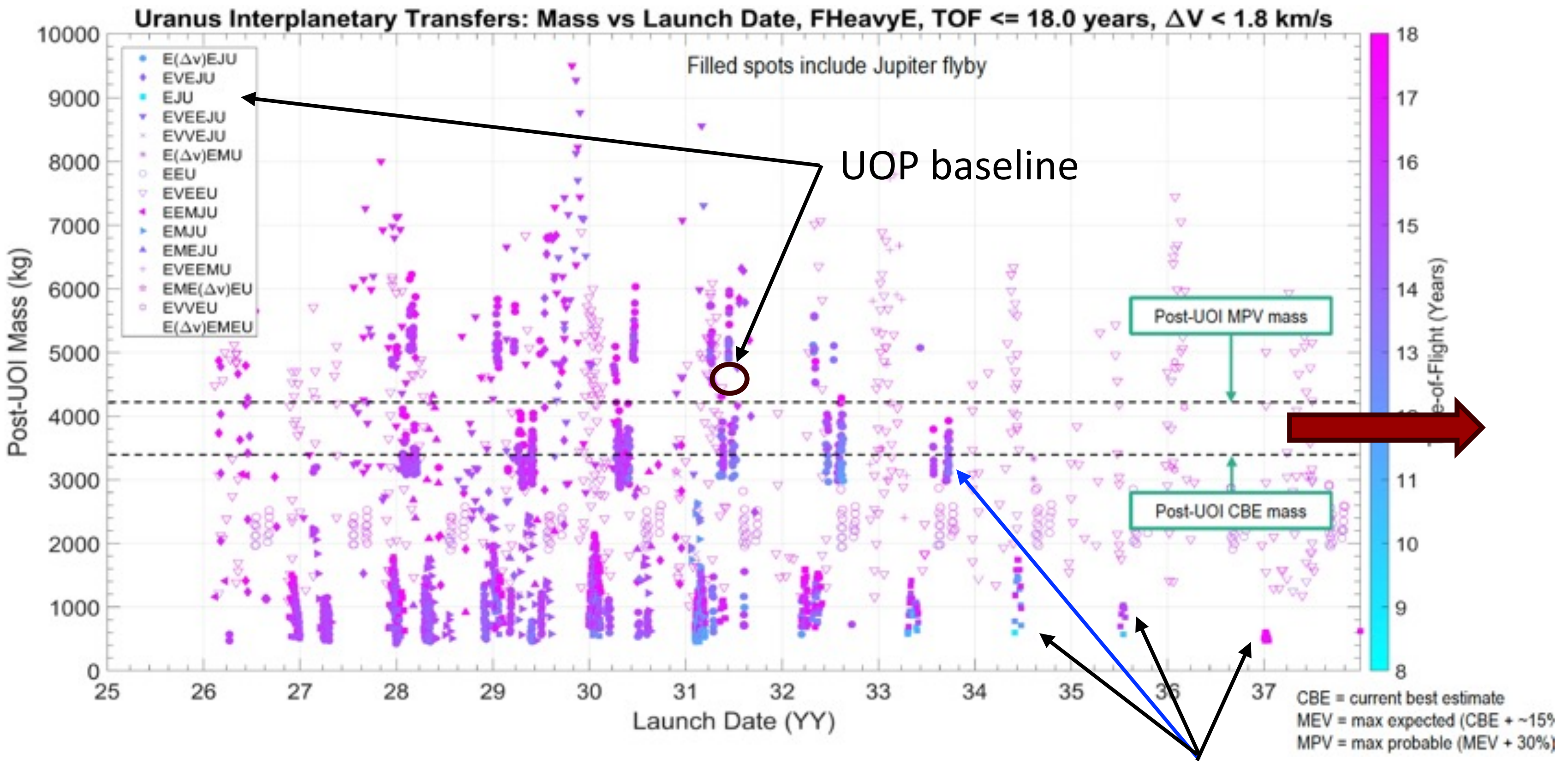
Credit: UOP Report

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



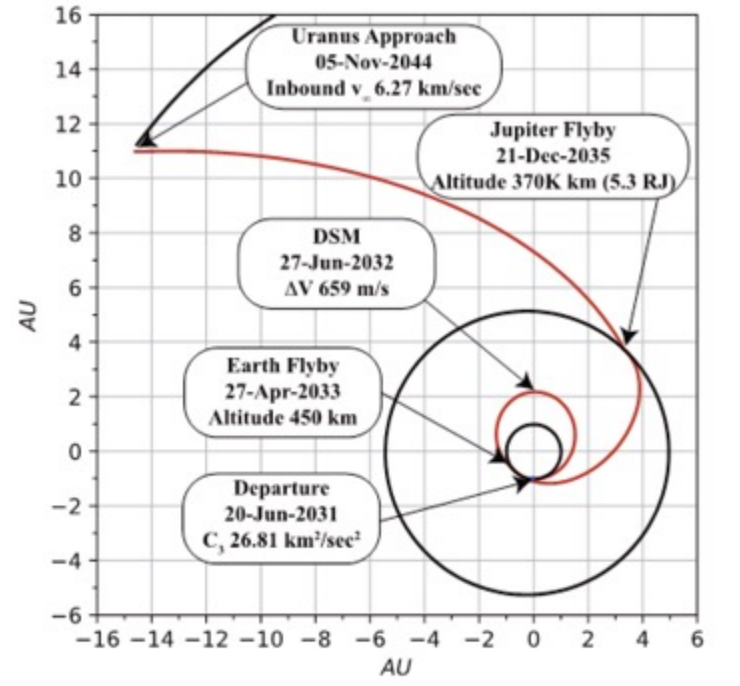
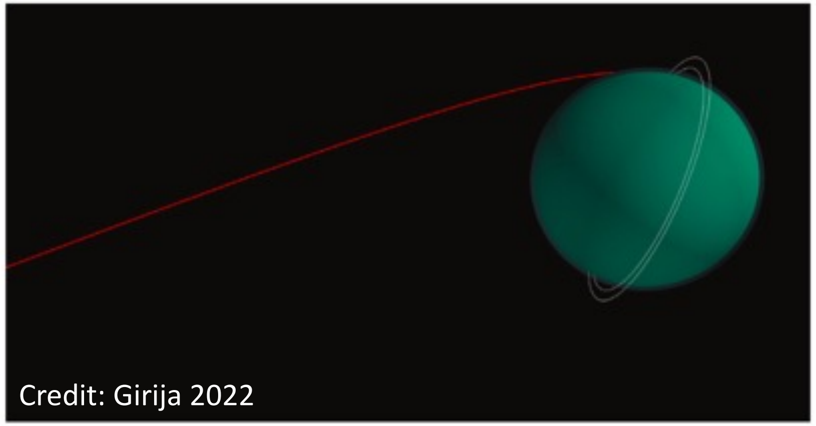


Exhibit 3-25. Baseline interplanetary trajectory (launch period center case).

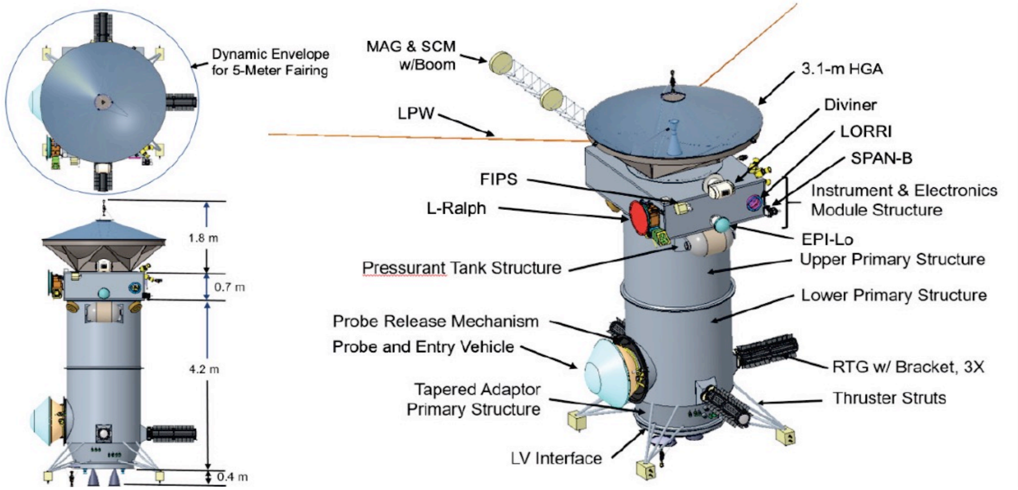
Aerocapture Solutions to Uranus Flagship

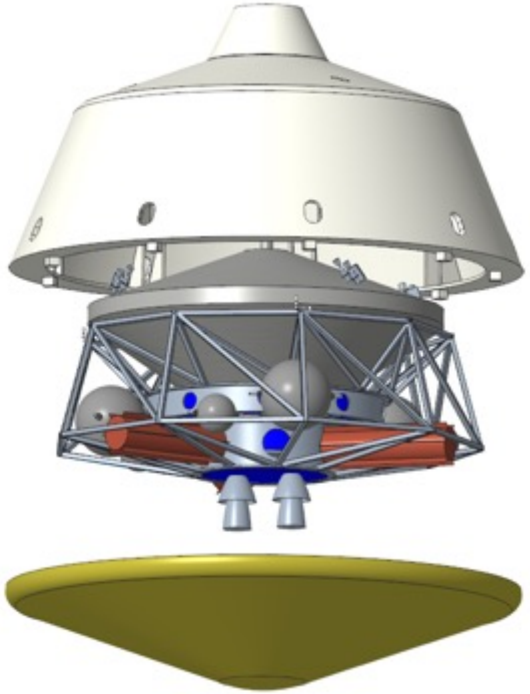
- 2021 Uranus Orbiter and Probe (UOP) mission concept study
  - 2023-2032 Planetary Decadal top flagship-class destination
  - 2031/2032 launch date; 13 years of transit
  - **1000 m/s ΔV for Uranus Orbit Insertion (1800 kg fuel)**
  - 60-70% of launch mass is fuel
  - Nuclear power source lifespan degrades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

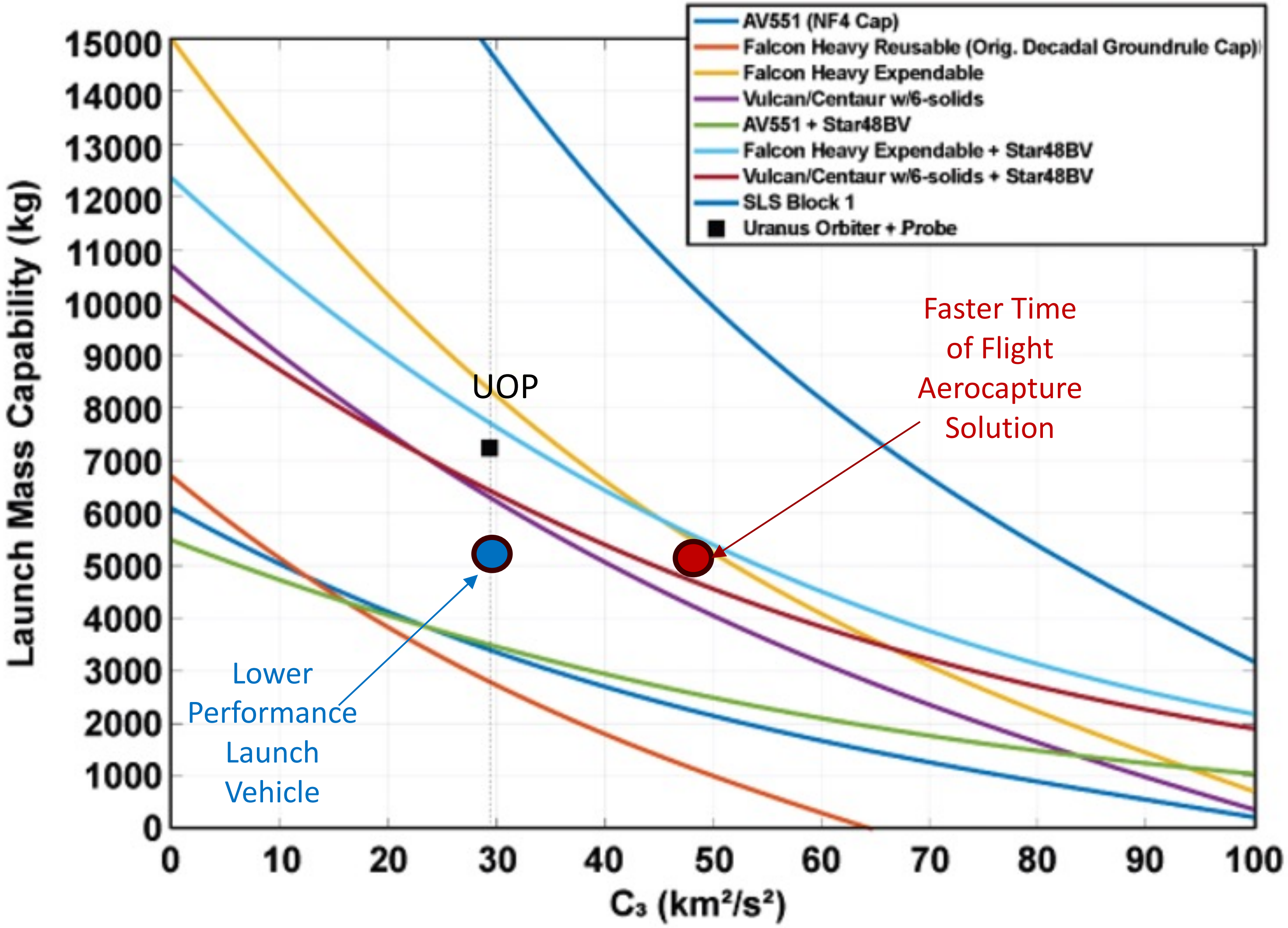
2021 Uranus Orbiter and Probe (UOP)

Credit: UOP Report





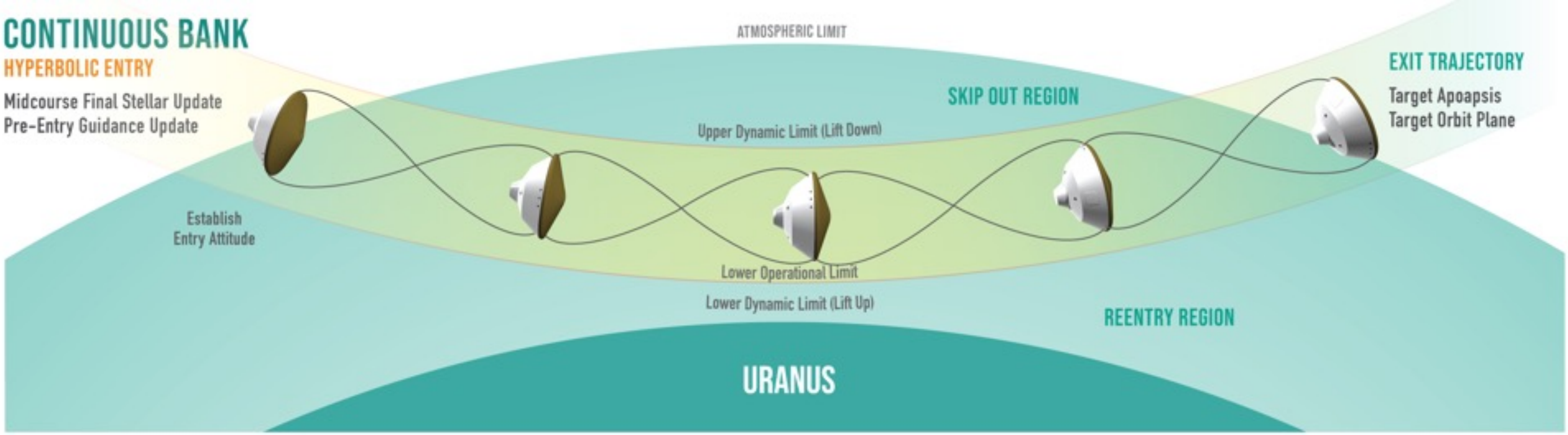
Aerocapture Increases Transit Choices

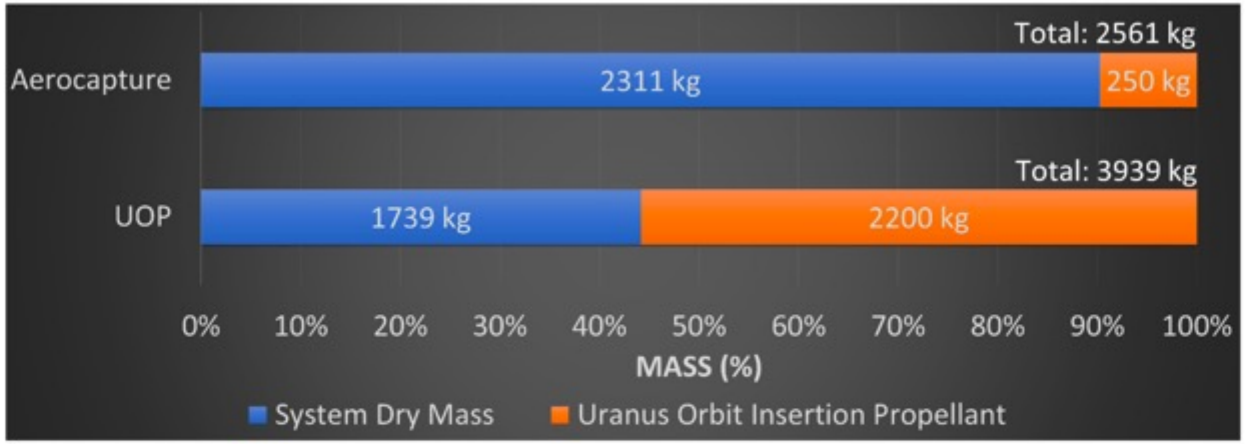


- **Current NASA baseline Uranus design requires higher performance launch vehicles**
- **Aerocapture design can:**
  - Achieve faster time of flight solutions with similar launch vehicle capability
  - Lead to a lower performance launch vehicle requirements with cost savings
- **Initial mission design 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

Heritage Guidance and Control Solution



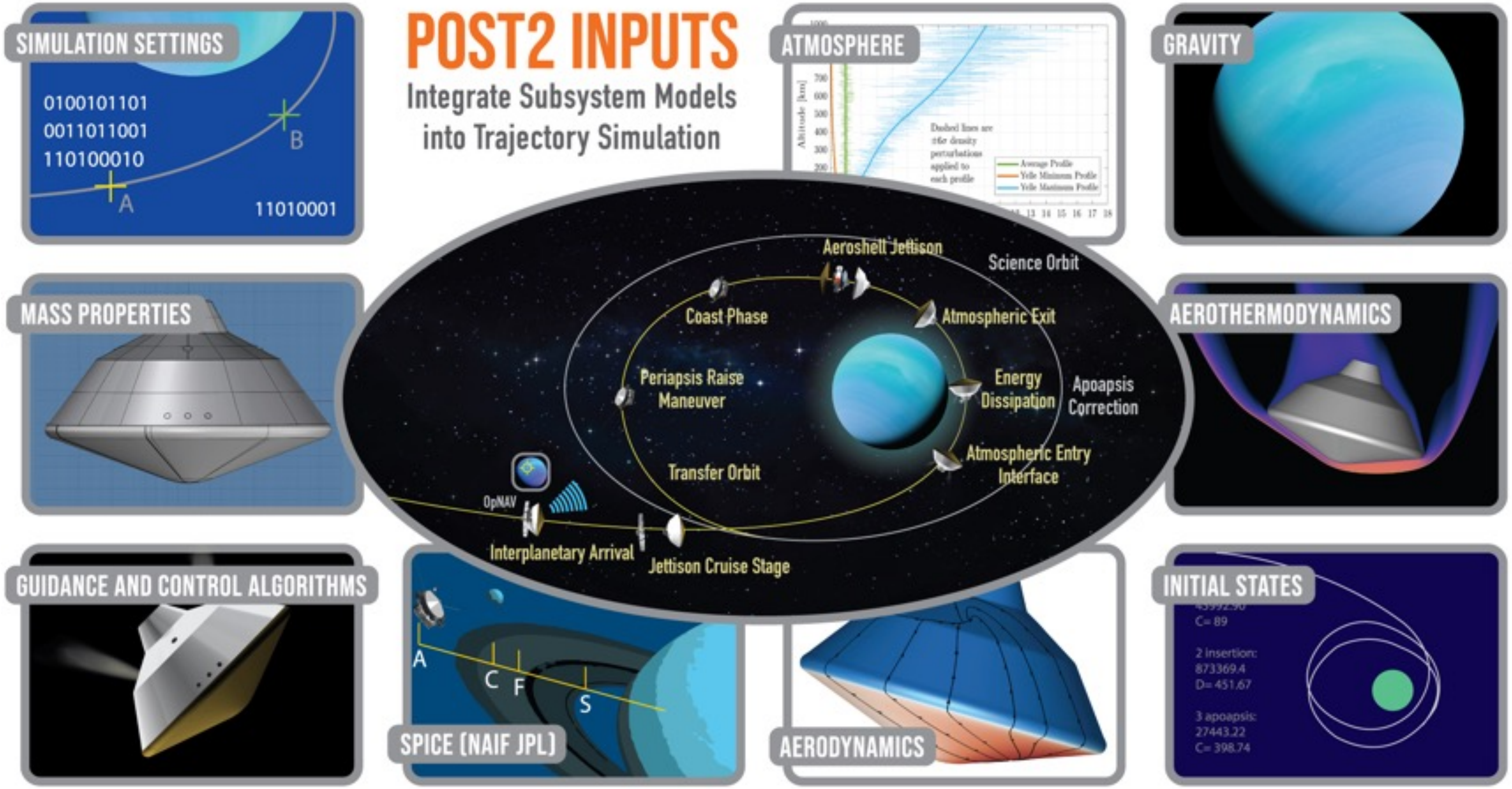


- Current baseline utilizes bank angle modulation control mechanism that has been demonstrated on Earth and Mars
- Guidance scheme uses predictor-corrector architecture flown on Earth missions
- Simulations show more than 1400 kg (35% mass savings) while achieving orbital insertion success

Aerocapture Performance under Atmospheric Uncertainty

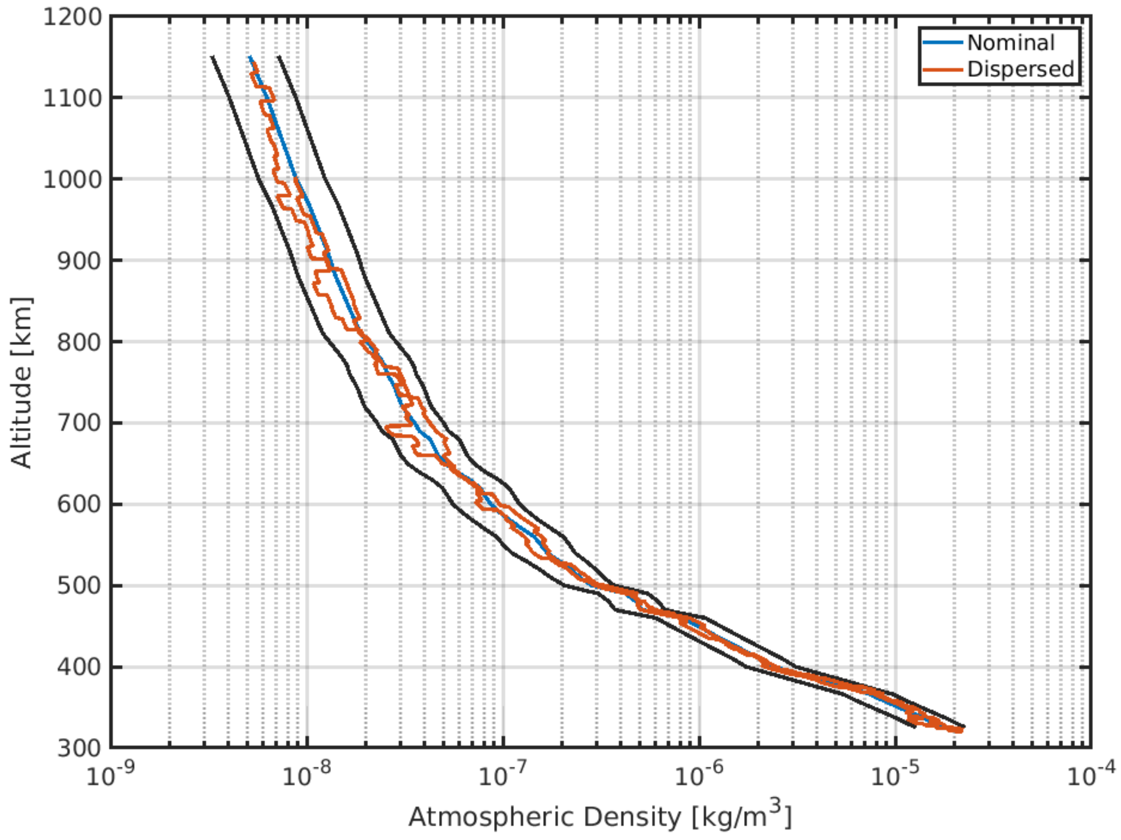
- **End-to-end aerocapture simulations use similar modeling standards that are used for flagship and other planetary scale missions**

POST2 = Program to Optimize Simulated Trajectories II

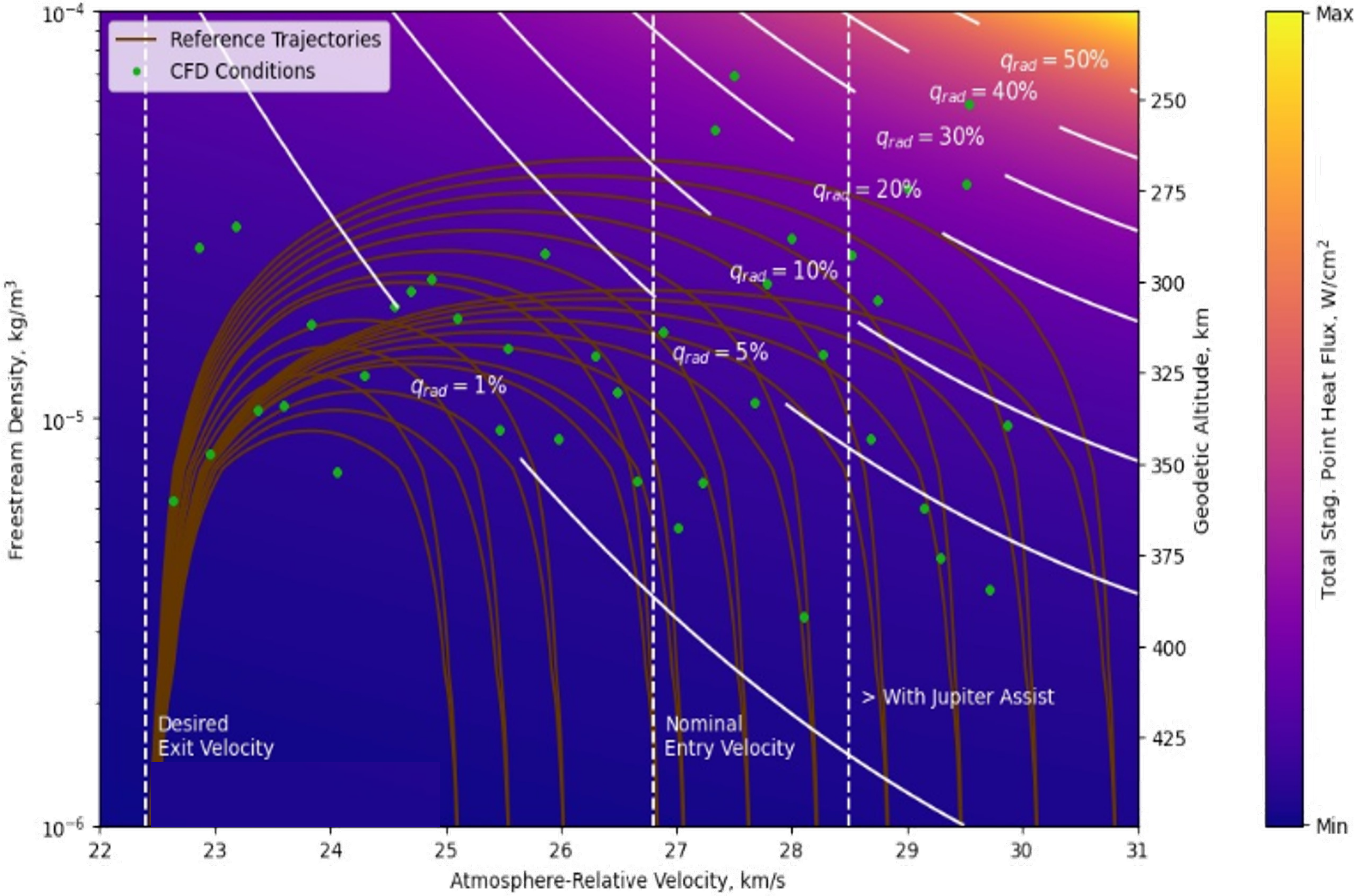


Aerocapture Performance under Atmospheric Uncertainty

- **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



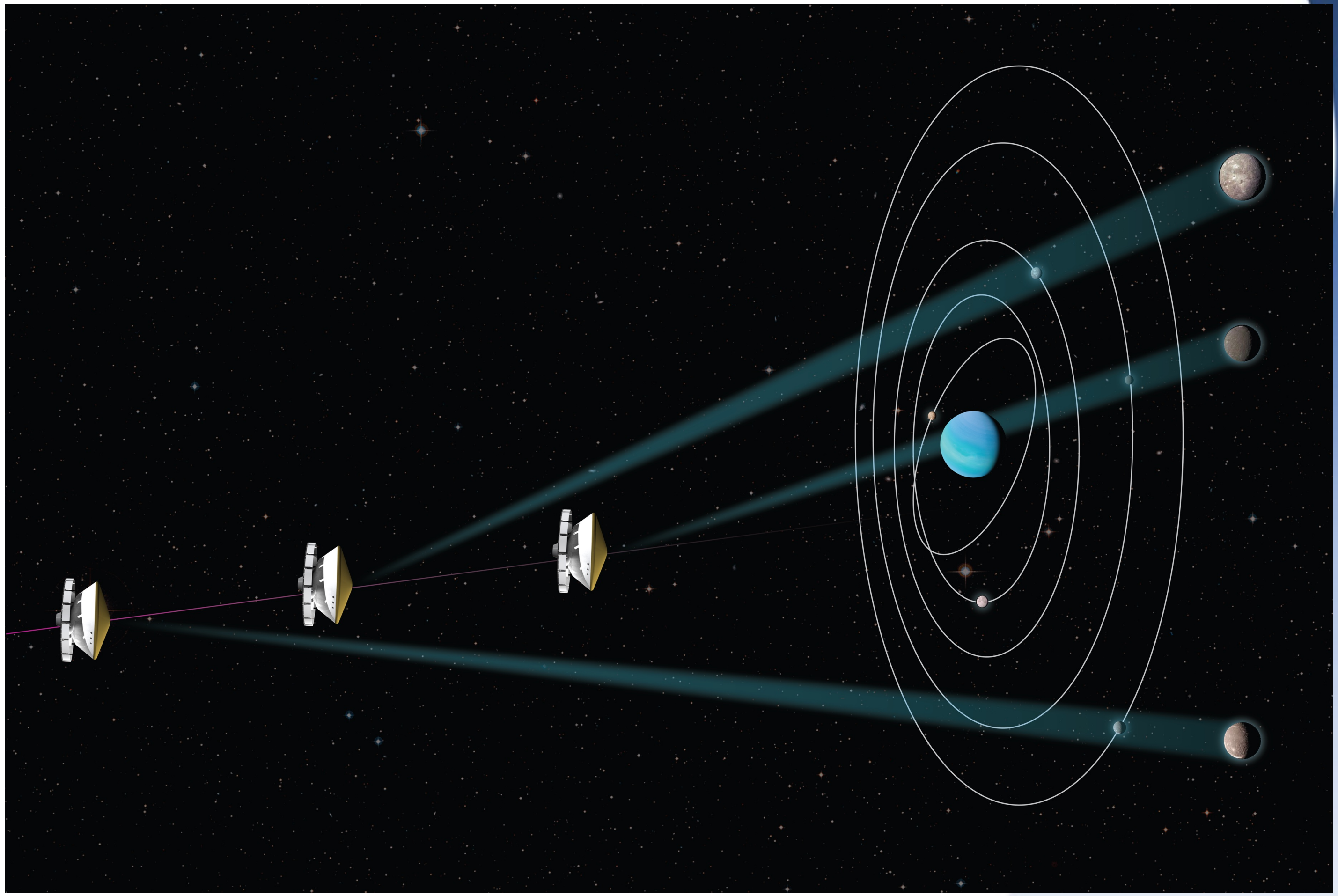
Aerosciences and Thermal Protection System Solutions



- **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**

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

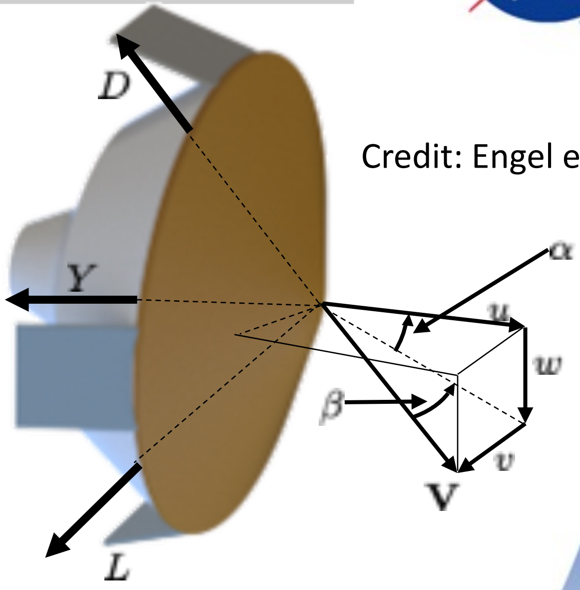


- Aerocapture and Ice Giants Introduction
- Project Objectives
- Gaps Addressed and Anticipated Benefits
- Team Organization
- Project Management
- Key Milestones
- **Future Plans**
- **Publications**
- **Challenges Encountered**

Plans for Second Year

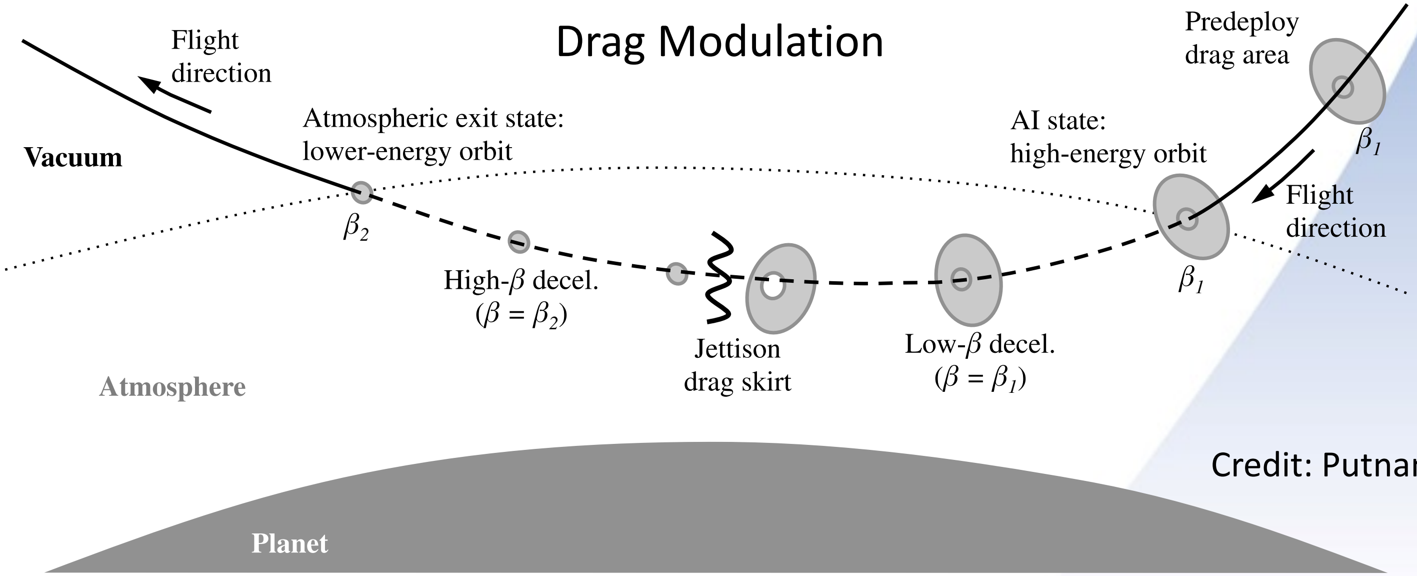
- Technological maturation of subsystem design for alternatives and risk mitigation
  - Identification of ways to lower risk for each subsystem flagged at the end of the year one efforts
  - Do development to improve the maturity of the subsystem
  - Show existing feasible alternatives for subsystems with risk
  - Explore if the risk can be lowered and feasibility can be enhanced for the full aerocapture design
- Alternative control mechanisms
- Different aerodynamic configurations

Direct Force Control



Credit: Engel et al.

Drag Modulation



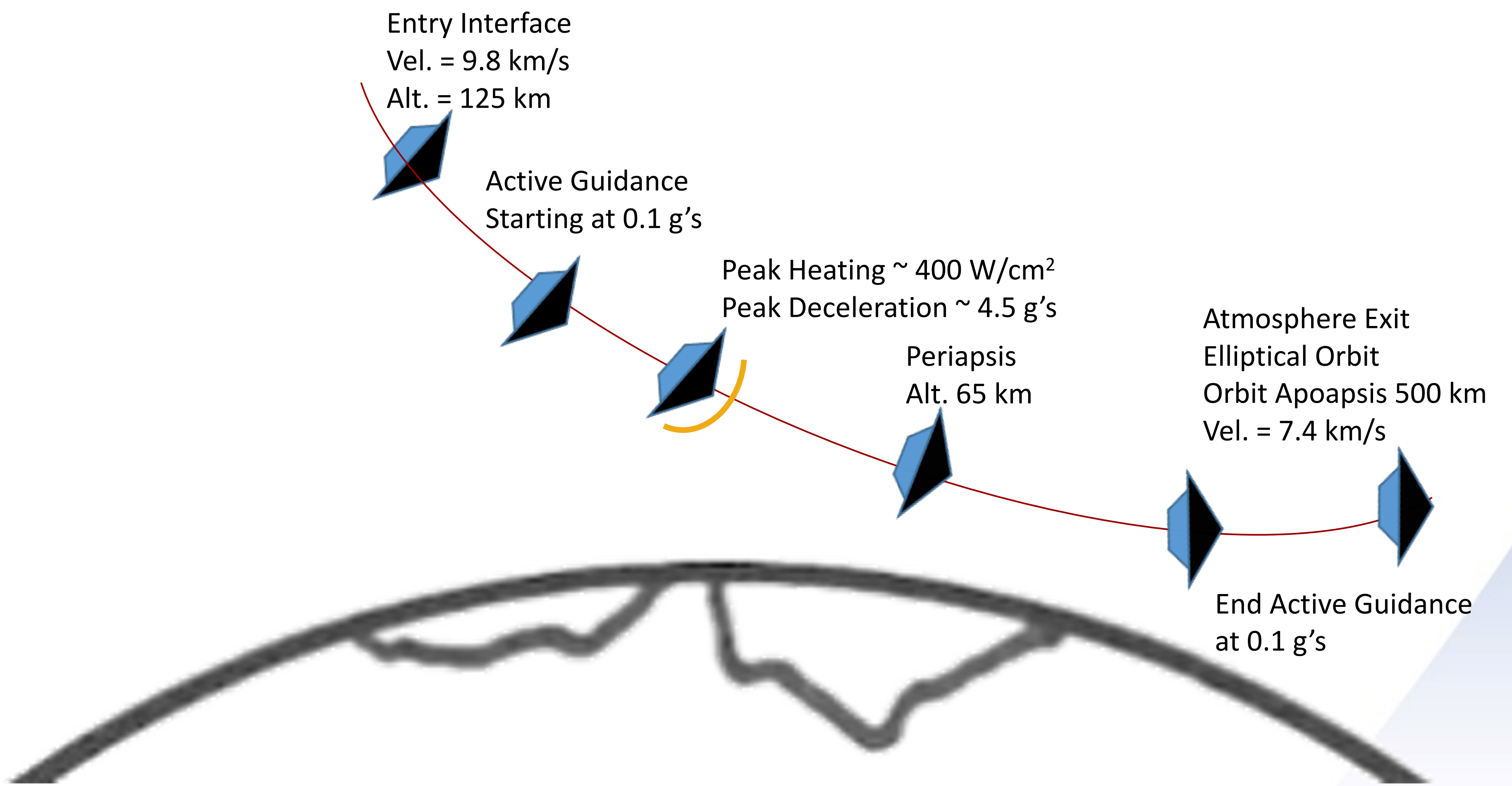
Credit: Putnam et al.

Publications List (Past and Future)

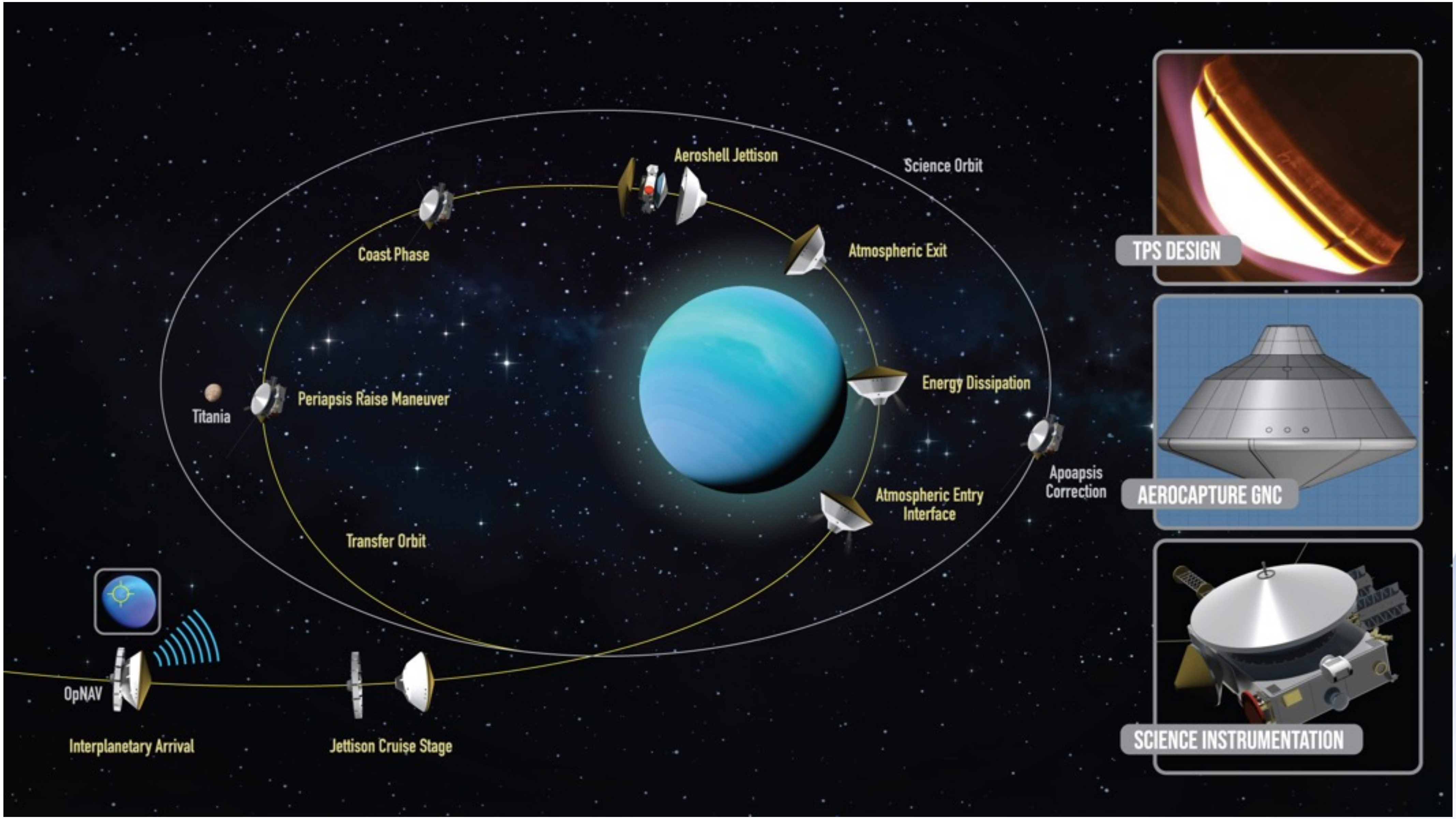
- Jan. 2023 – **NASA Tech Showcase** – Galveston, TX: Poster showcased aerocapture as an orbit insertion mechanism
- May 2023 – **Space Exploration Conference** – Turin, Italy: Invited talk discussing aerocapture for planetary missions
- July 2023 – **Uranus Flagship Workshop** – Pasadena, CA: One talk 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: One 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

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)



Questions


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