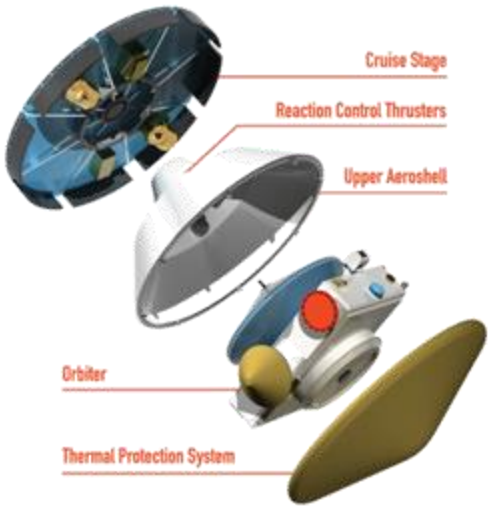
Aerocapture Solutions for Flagship-class Uranus Orbiter and Probe



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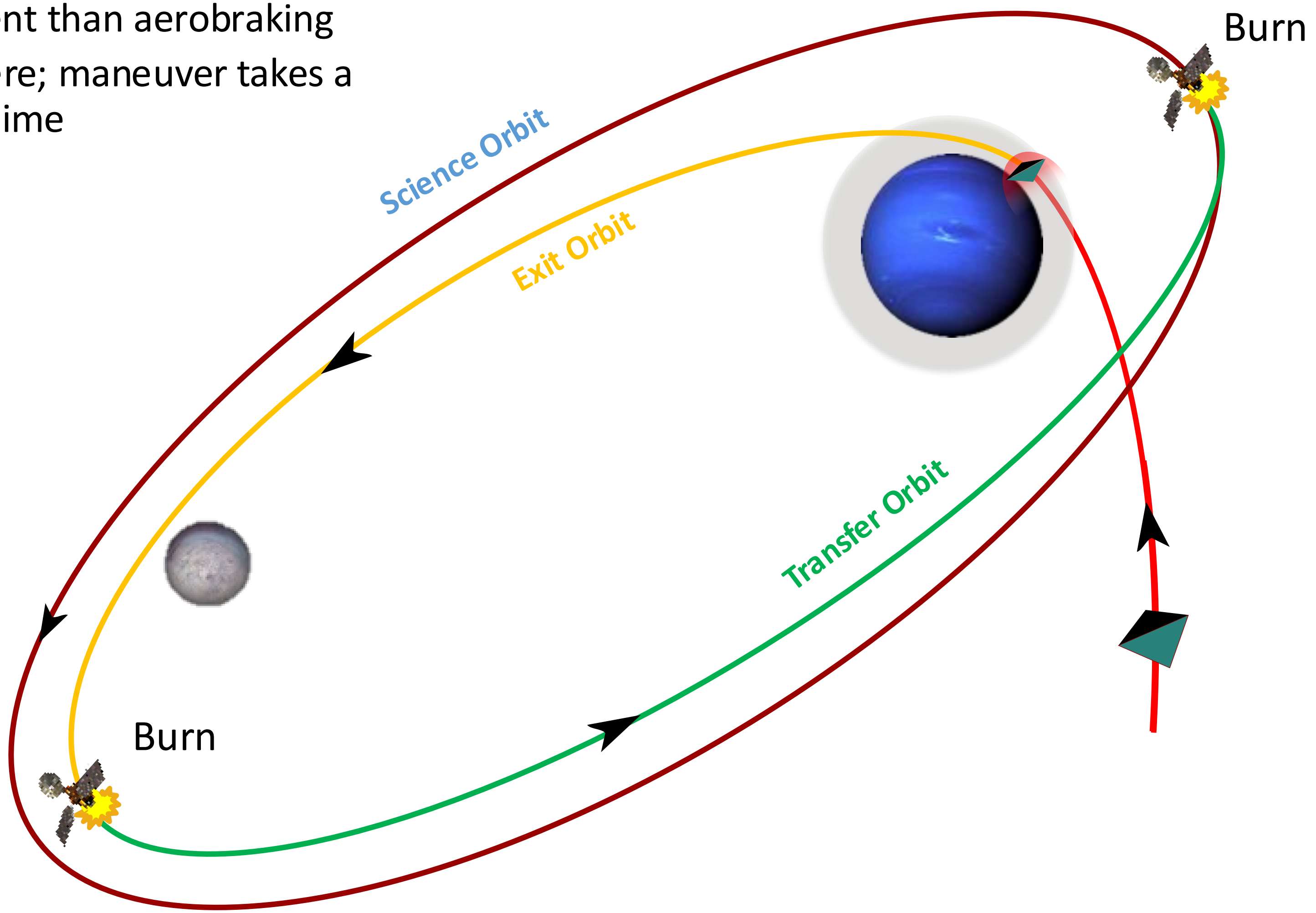
AIAA SciTech 2025, Orlando FL
January 6-10, 2025

What is Aerocapture?

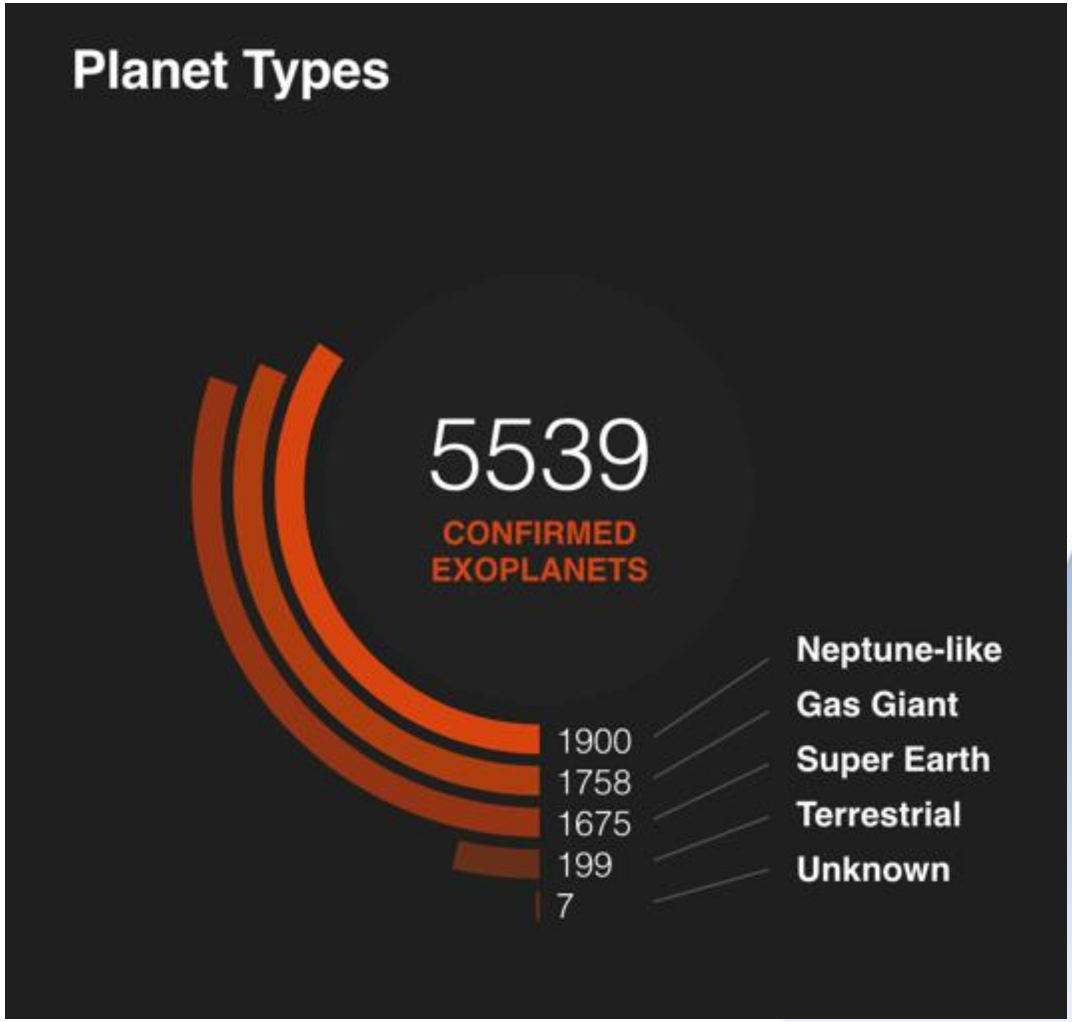
Aerocapture is different than aerobraking
Which skims atmosphere; maneuver takes a long time



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/Neptune like
- **Uranus is the top flagship class mission destination in the 2023-2032 Planetary Science Decadal Survey**
  - Scientific desire to get to Uranus before the 2049 Equinox
- **Decadal Survey also mentions aerocapture as a technology that should be incentivized**



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

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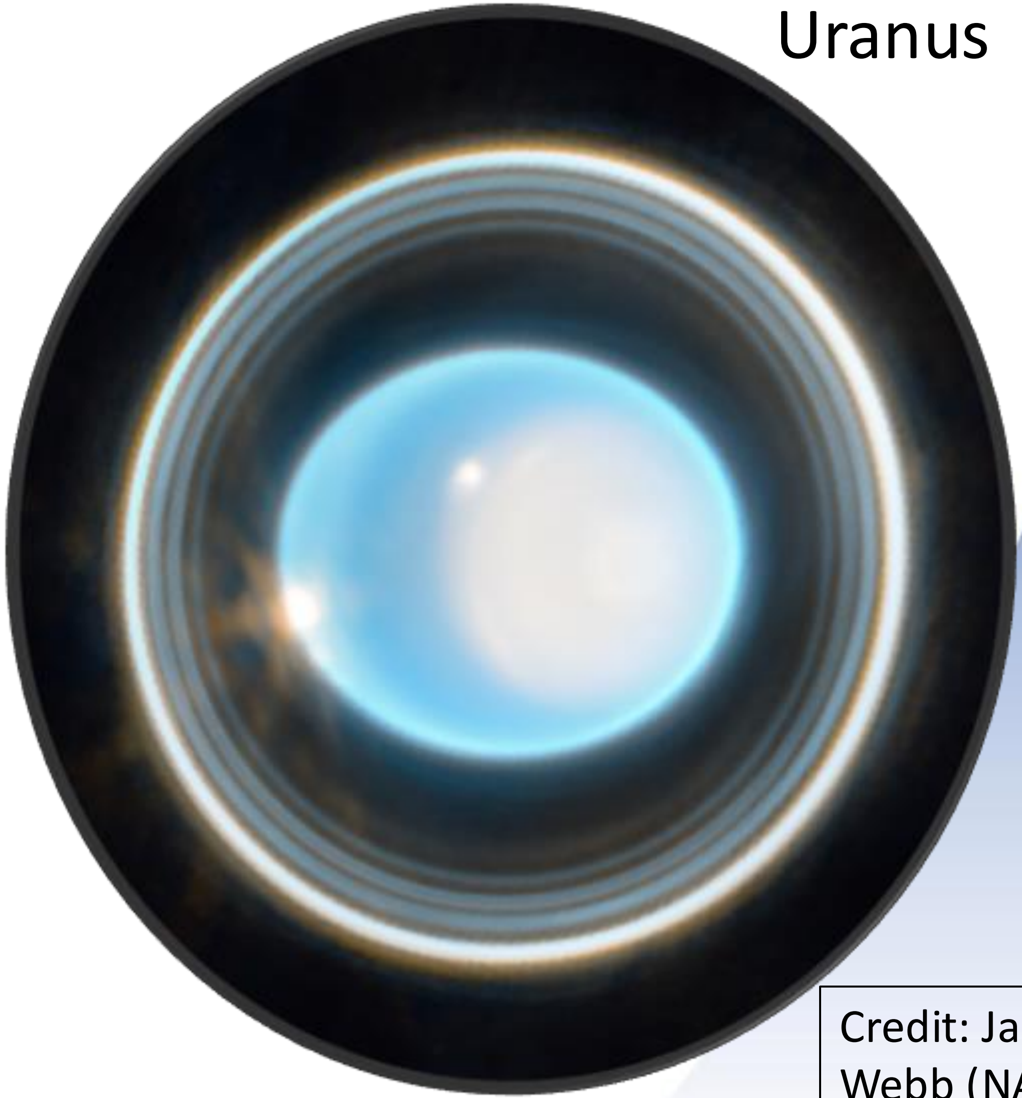
  - Scientific desire to get to Uranus before the 2049 Equinox
- **Decadal Survey also mentions aerocapture as a technology that should be incentivized**
- **Uranus chosen as the target planet for the study**

Uranus

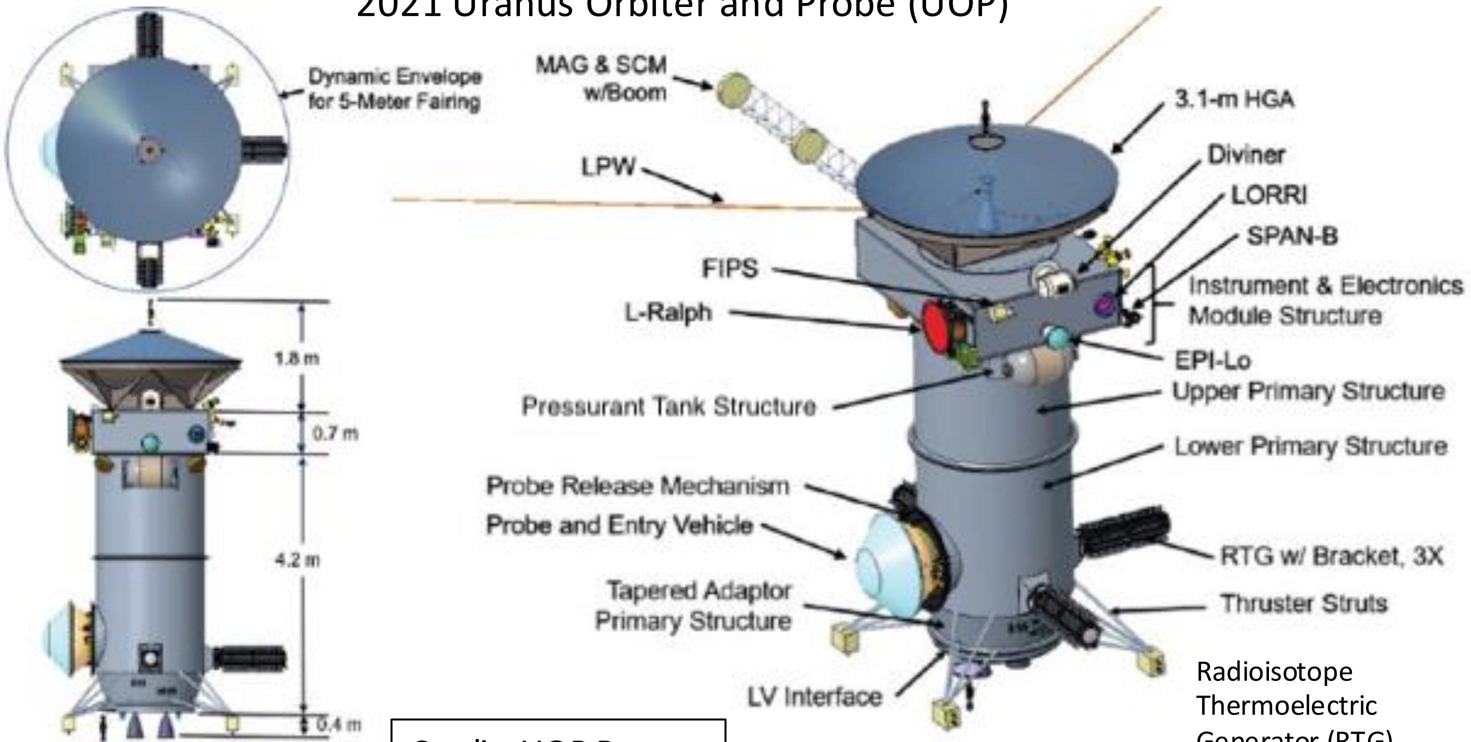


Credit: James Webb (NASA)

Uranus Flagship Concept

- **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

2021 Uranus Orbiter and Probe (UOP)



Radioisotope Thermoelectric Generator (RTG)

Credit: UOP Report

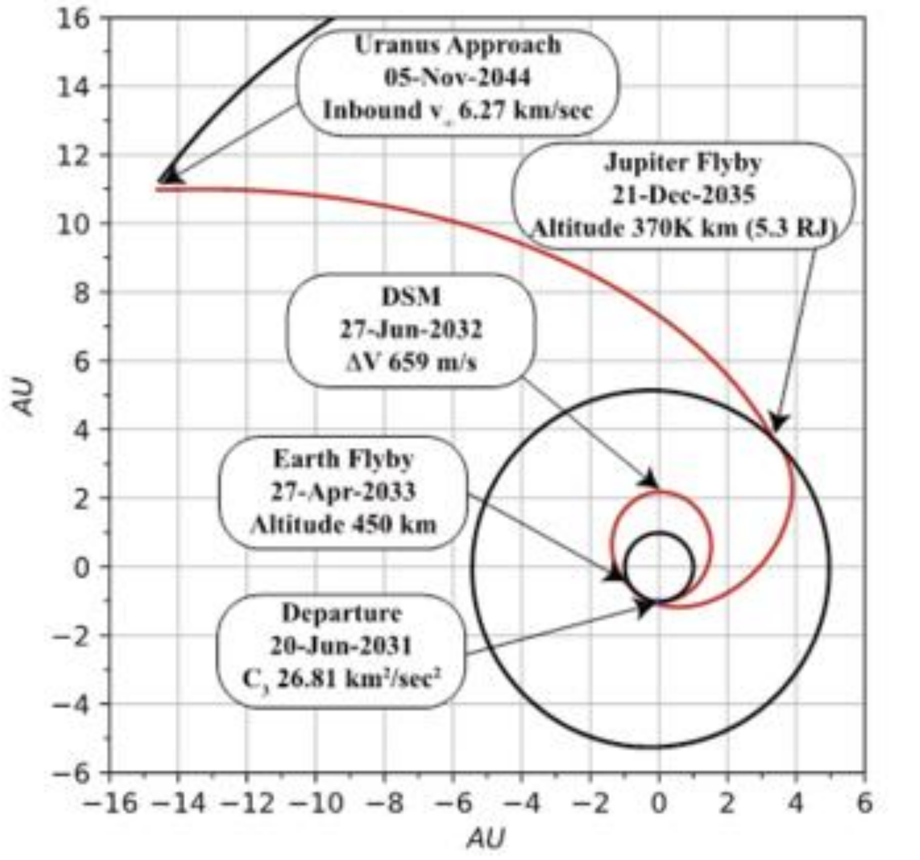
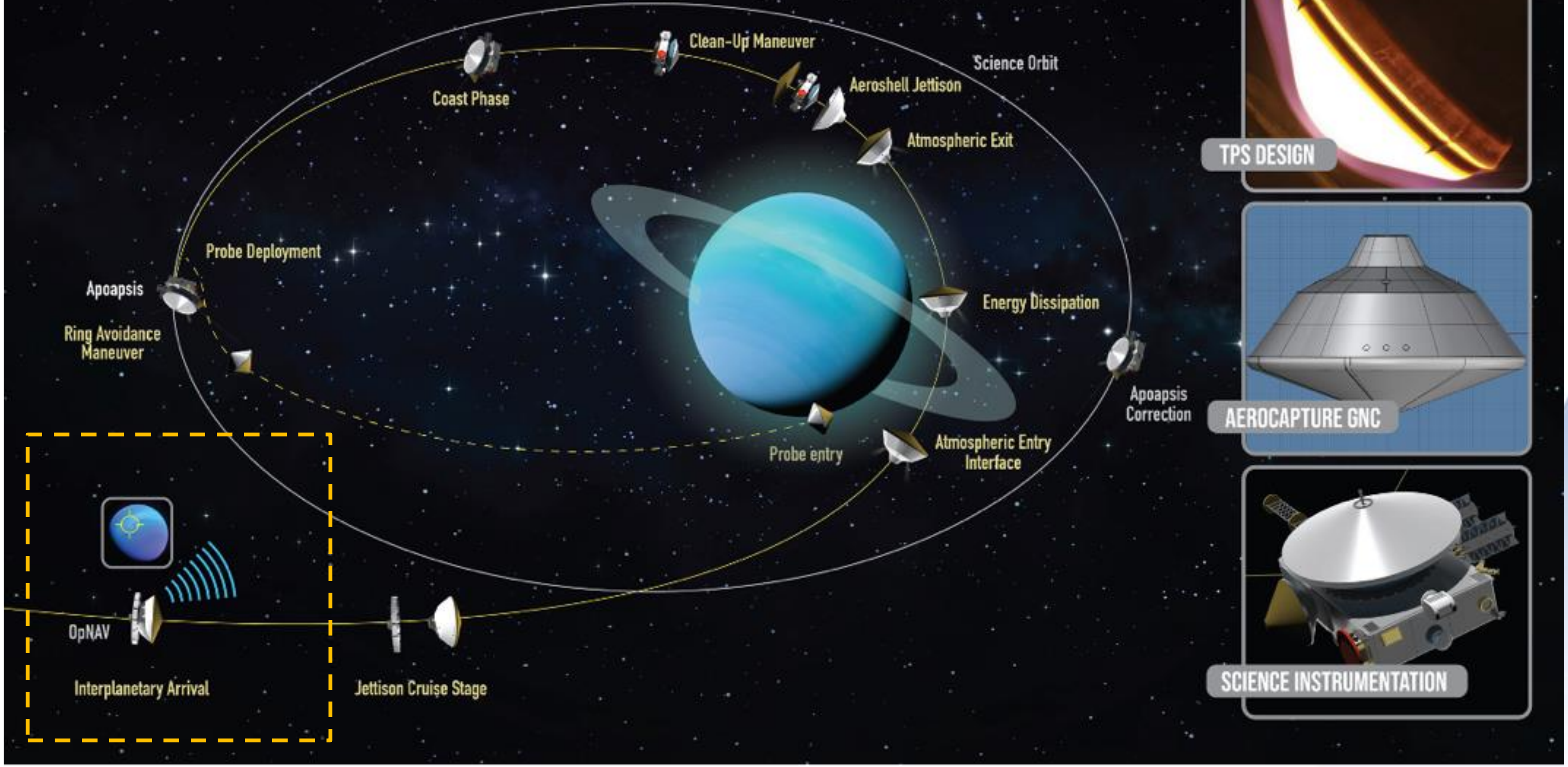


Exhibit 3-25. Baseline interplanetary trajectory (launch period center case).

Credit: UOP Report

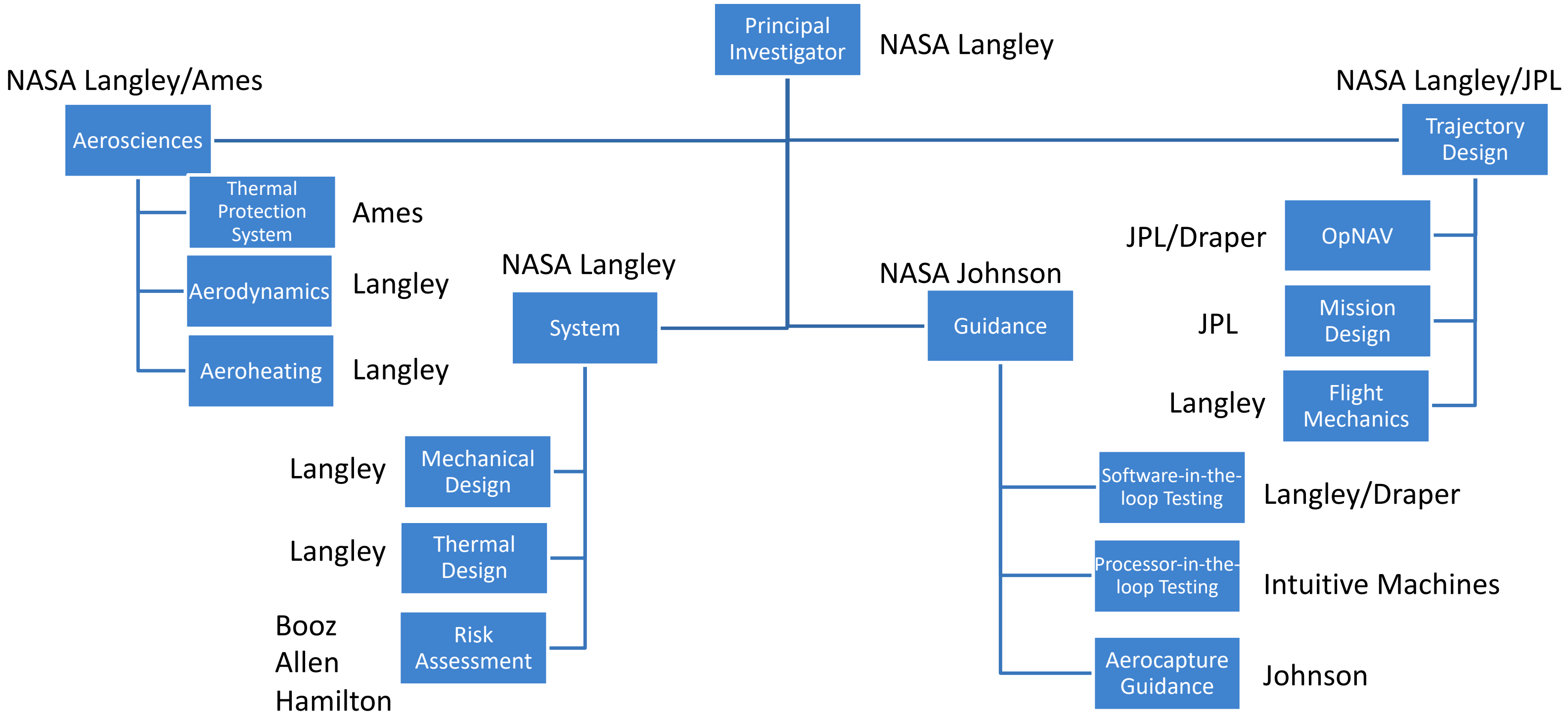
Four Key Technological Thrusts for Aerocapture

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



Aerocapture for Uranus Project

- Early Career Initiative (ECI) sponsored by NASA Space Technology Mission Directorate
- Multi-centered, multi-disciplinary team to design an end-to-end aerocapture concept
- **Objective: Use heritage entry vehicle configurations to provide a feasible aerocapture concept to take a mature Uranus orbiter and probe concept to orbit**



1. 1:20 – 1:40 pm: Mission Design/Interplanetary Navigation
2. 1:40 – 2:00 pm: 6-DOF Trajectory
3. 2:00 – 2:20 pm: Aeroheating
4. 2:20 – 2:40 pm: Aerodynamics
5. 2:40 – 3:00 pm: Thermal Protection System
6. 3:30 pm – 3:50 pm: Mechanical System
7. 3:50 pm – 4:10 pm: Aerocapture Guidance
8. 4:10 pm – 4:30 pm: Guidance Study
9. 4:30 pm – 4:50 pm: Navigation Analysis

Outline

- Aerocapture and Ice Giants Introduction
- Comparison of UOP with Aerocapture Concept
- Timeline of this Study
- Differences from Past Studies
- Key Findings in Year 2
- Summary

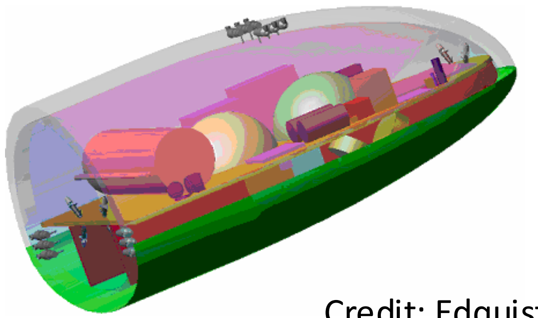
Timeline of This Study

Aerocapture Academic Research based on the 2004 study

Apr. 2022
Planetary Decadal Survey

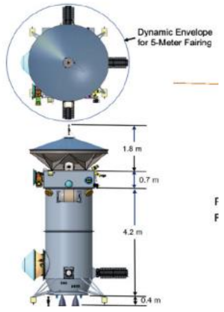
Oct. 2022-Sep. 2024
STMD funds Aerocapture Early Career Initiative

2004
Neptune Aerocapture Study



Credit: Edquist 2004

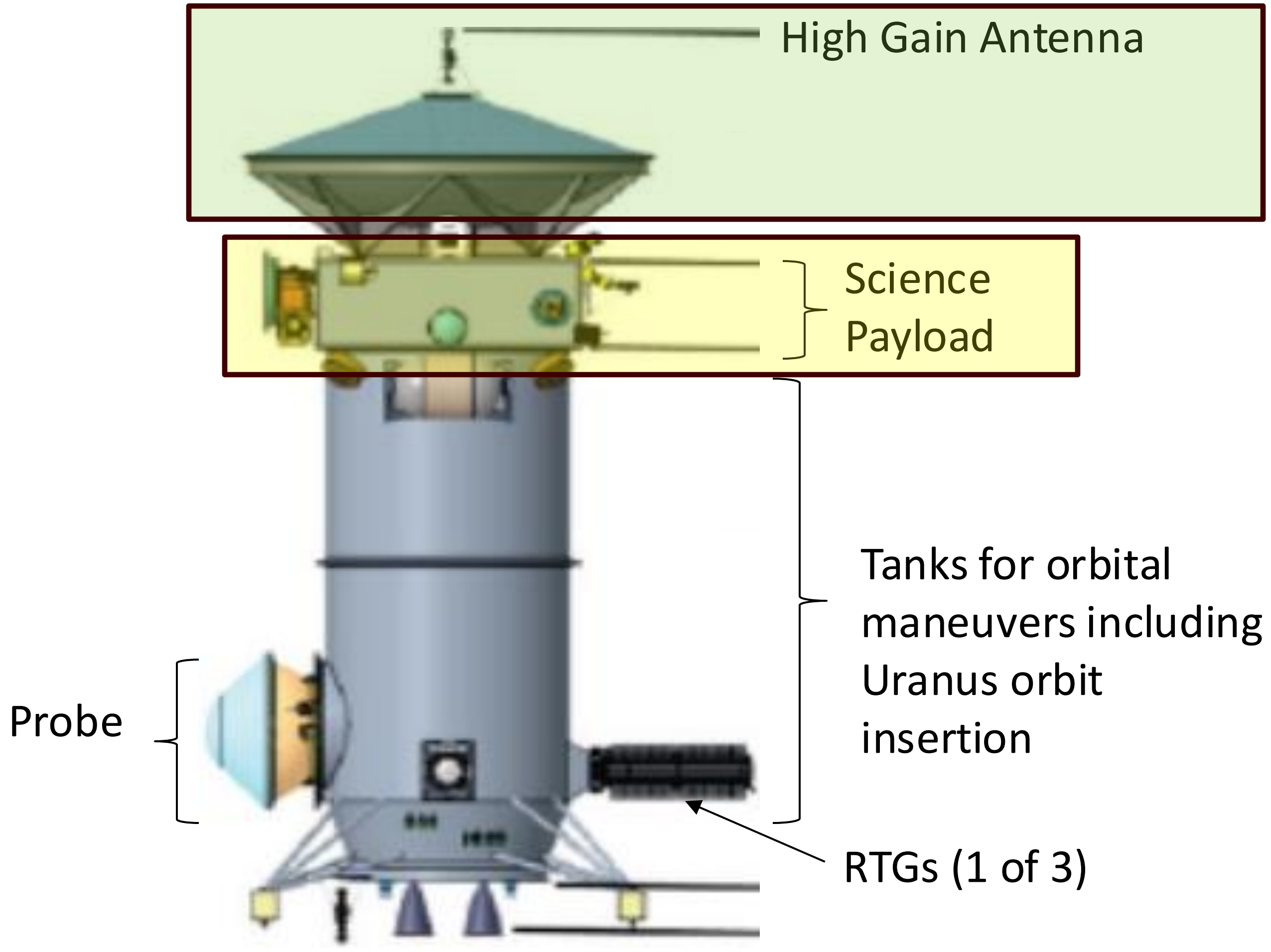
2021
Uranus Orbiter and Probe



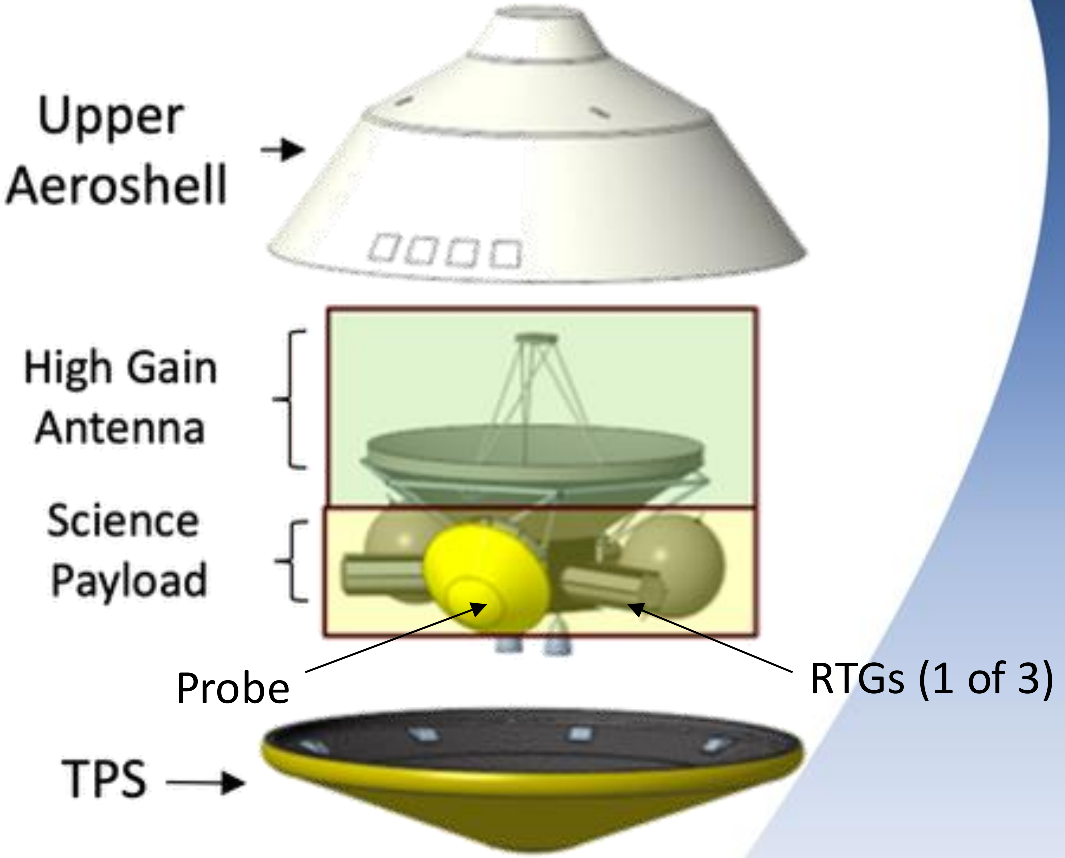
Credit: Simon 2021

2022-Feb. 2023
Aerocapture Demonstration Relevance Assessment Team (ADRAT)

Comparison of UOP with Aerocapture Concept



Uranus Orbiter and Probe



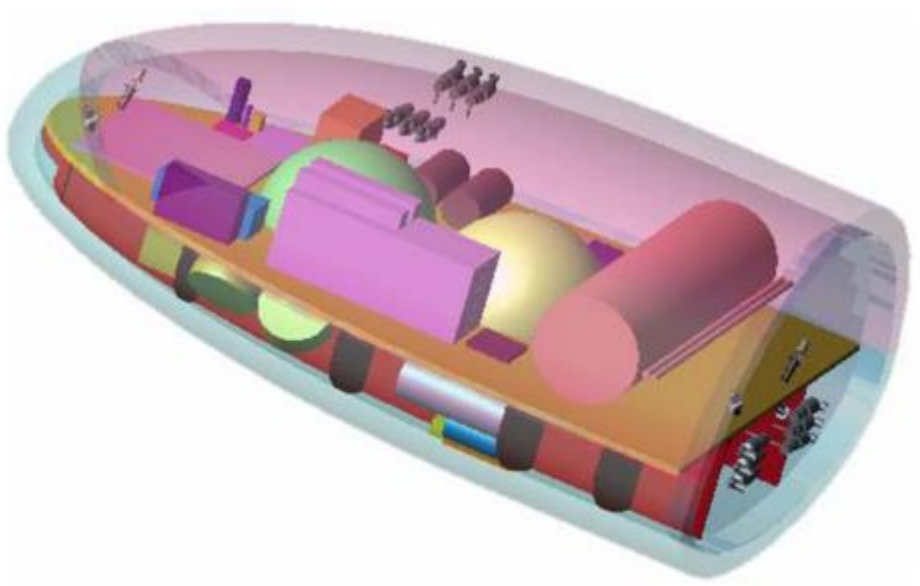
Current ECI Aerocapture Concept

Aerocapture Demonstration Relevance Assessment Team (ADRAT)

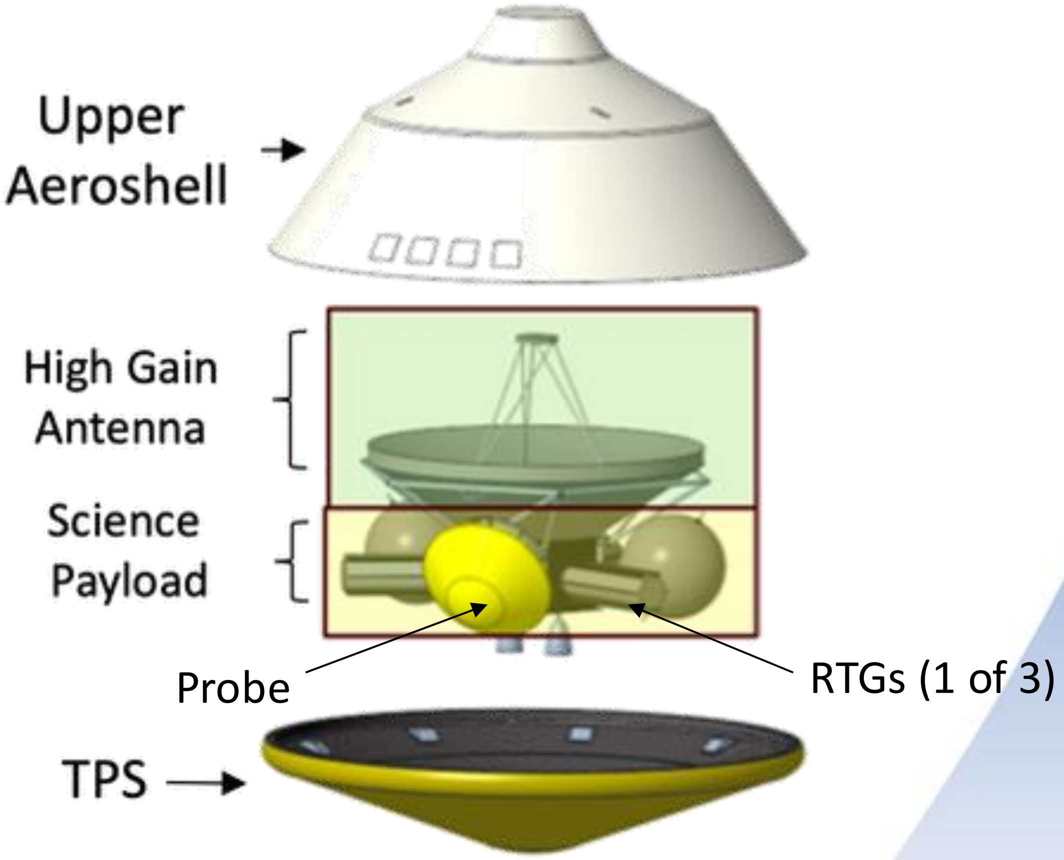
	Risk Statement	Type	Level of Risk
1	If the atmospheric density profile uncertainty is too large, then trajectory or flight-path calculations based on the blunt-body heritage would be in error.	Development	High
2	If the aerocapture implementation heat shield TPS performance and sizing requires more mass than studies assumed, then the dry mass will exceed the allocation.	Development	Low
3	If the aerocapture implementation requires more mass for ancillary systems (e.g., g-load mitigation, separation mechanisms, packaging, heat dissipation), then the dry mass will exceed the allocation.	Development	Medium
4	If the aerocapture uncertainties are too high, then the cost ($, mass) of implementation with sufficient capability will be too high.	Development	High
5	If the aerothermodynamics of the target body are not well understood/modeled, then heat shield performance will be compromised.	Mission	High
6	If the aerothermodynamics of the target body are not well understood/modeled, then the control actuators may not have sufficient control authority to maintain the flight path angle and the lift vector orientation.	Mission	Medium
7	If the entry heating (integrated heat flux and soak-back) cannot be accommodated, then components may overheat resulting in failures.	Mission	Medium
8	If autonomous optical navigation cannot correctly correlate the atmosphere altitude to the planet barycenter, then the density will not be as expected and may exceed the ability of the spacecraft to compensate.	Mission	Low

Credit: ADRAT Report

Differences from Previous Aerocapture Studies

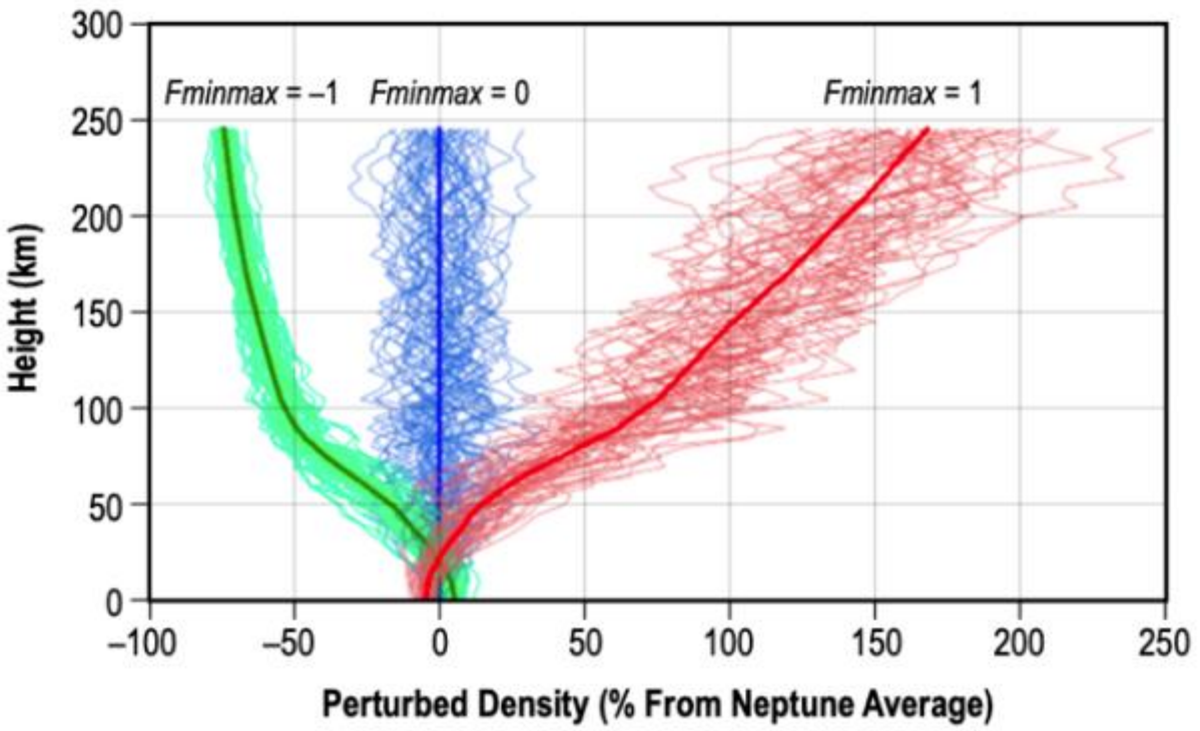


2004 Aerocapture Concept

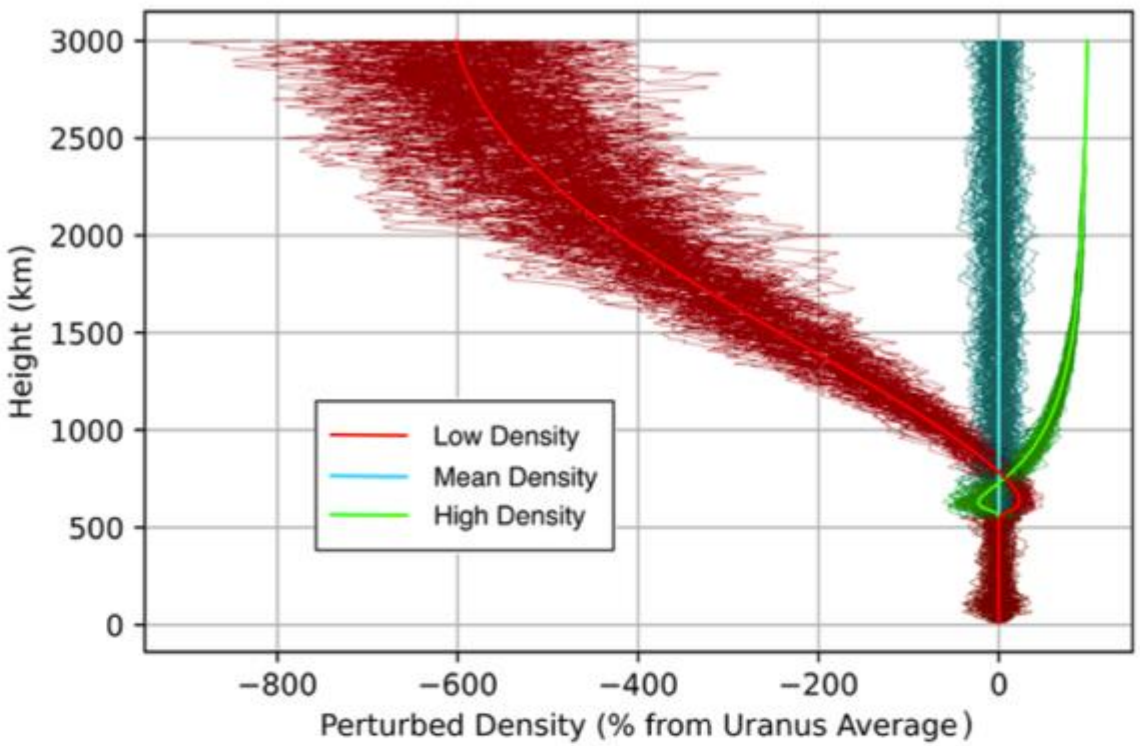


Current ECI Aerocapture Concept

Differences from Previous Aerocapture Studies



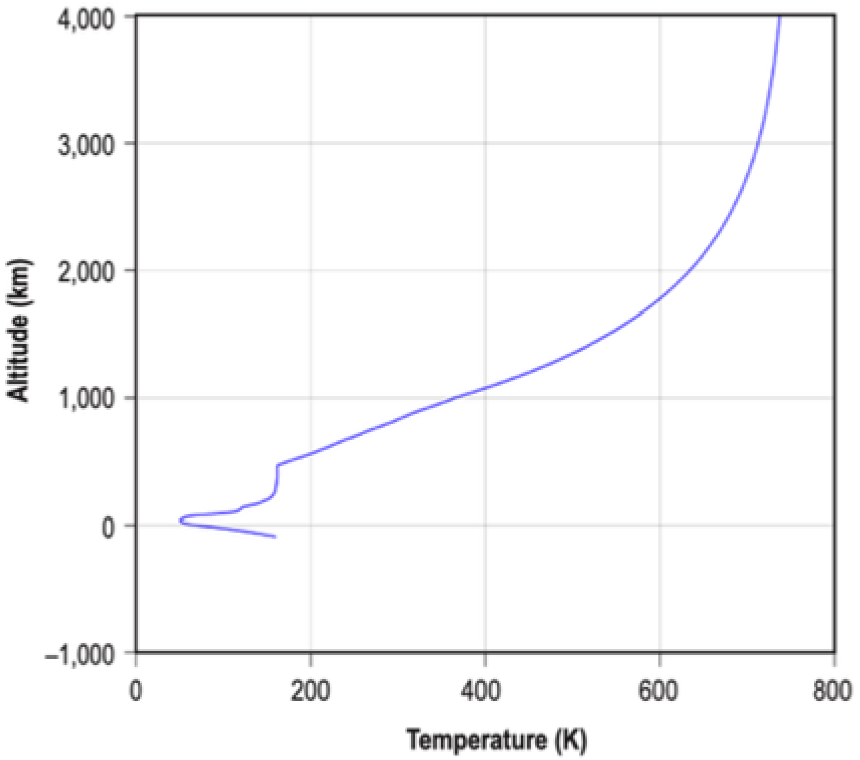
Neptune GRAM Density Deviations (used by 2004 study)



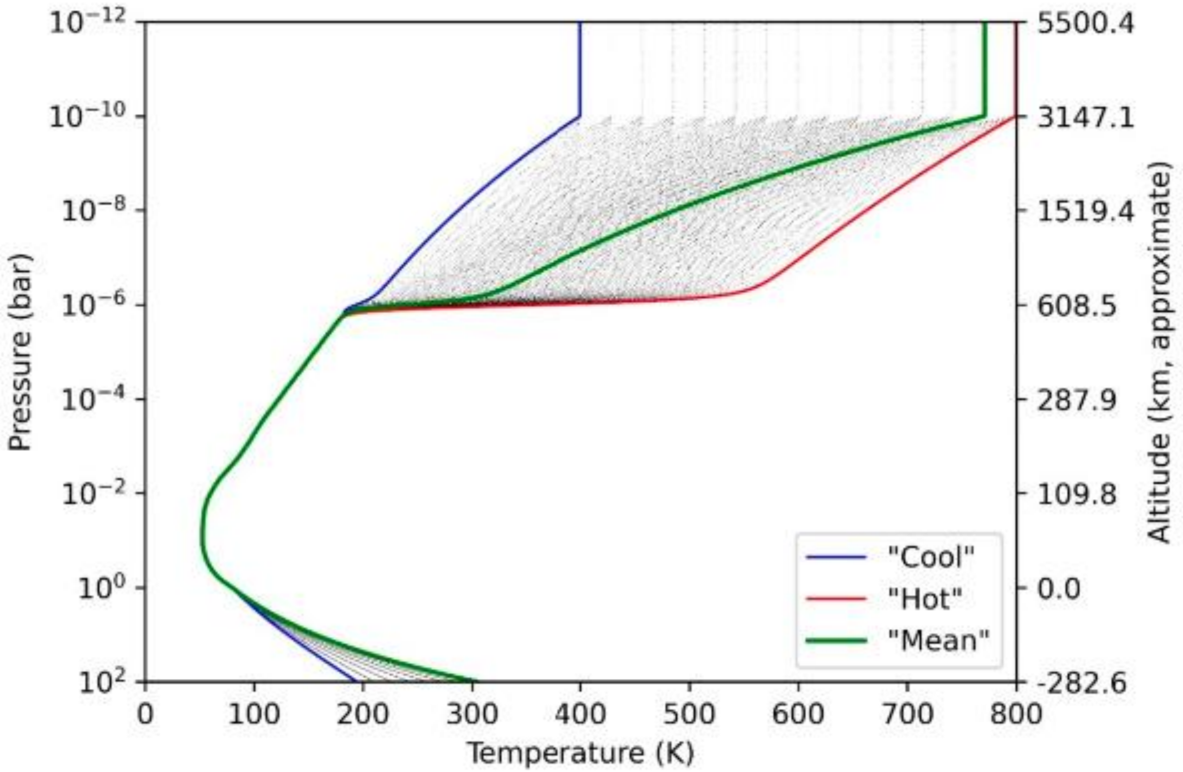
Uranus GRAM Density Deviations (used by current ECI study)

- **Similar to Neptune study, the aerocapture study considered various profiles for the planet**
- **Density deviations were similar in various areas of interest**

Differences from Previous Aerocapture Studies



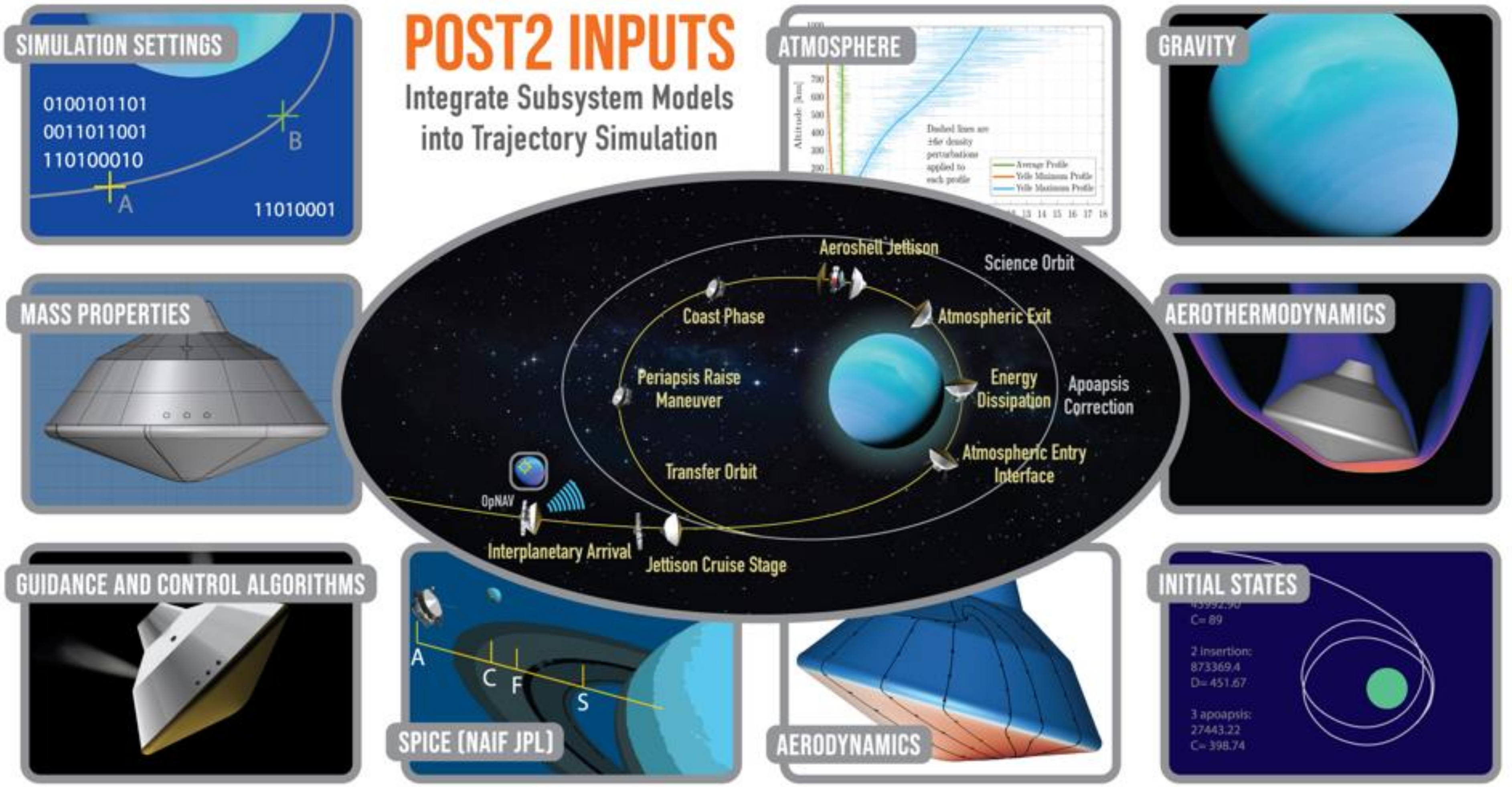
Neptune GRAM Temperature Deviations
(used by 2004 study)



Uranus GRAM Temperature Deviations
(used by current ECI study)

- **Year 2 of the study also updated the Uranus atmospheric profiles to capture larger uncertainties in the models**

Aerocapture Trajectory Simulation



POST2 – Program to Optimize Simulated Trajectories II

SPICE – Spacecraft, Planet, Instrument, C-matrix, Events (Planetary Ephemeris)

NAIF – Navigation and Ancillary Information Facility

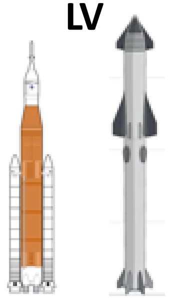
Interplanetary Trajectories Broad Search

- **Interplanetary Broad Searches:** Use *Star* (a Patch Conic tool). Good candidate solutions are optimized on high-fidelity (Copernicus & Monte)
- **Search Space Drivers:**
  - Launch Vehicle (LV):
    - Heavy-Lift: Falcon Heavy (FH)/Vulcan(VC)
    - Super heavy-lift: Space Launch System (SLS), Starship
  - Launch mass (LV Performance- C3)
  - Uranus arrival velocities (or v_∞) allowed
  - Interplanetary bodies gravity assist:
    - - Jupiter, - Inner cruise, - direct
  - Propulsion systems:
    - Chemical
    - ~~Solar Electric Propulsion~~
    - ~~Nuclear Thermal propulsion~~

Heavy-Lift LV

Falcon Heavy

Super Heavy-Lift LV



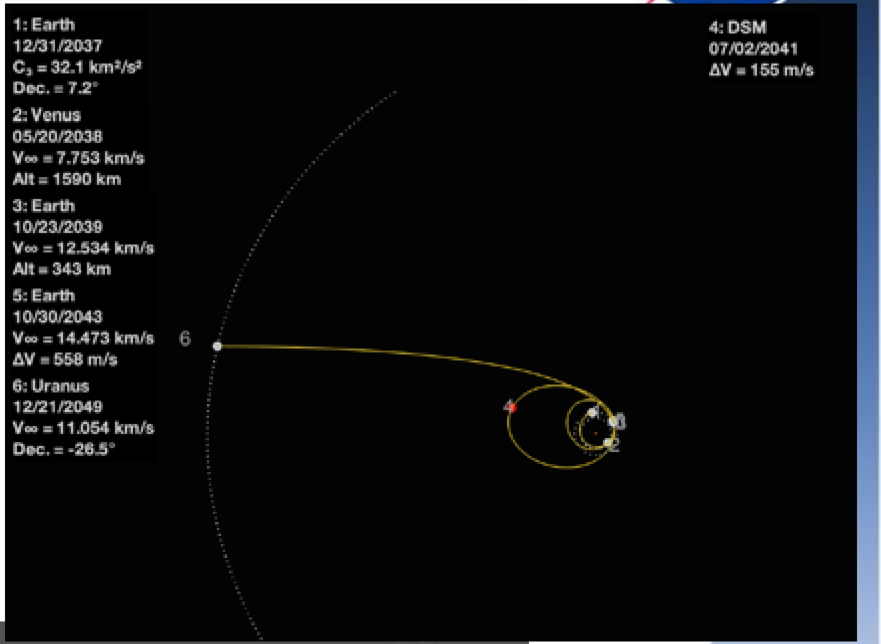
SLS Starship

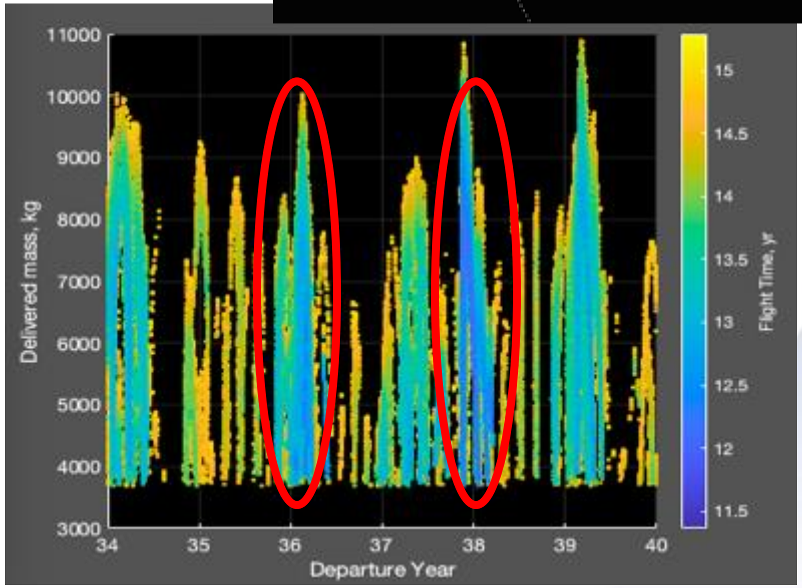
Heavy-Lift LV	I UOP-Prop FH/VC Jupiter flyby ≤ 2033 DAC2/3	II FH/VC No Jupiter > 2033 DAC4/5
Super Heavy-Lift LV	III SLS/Starship Jupiter flyby < 2035	IV SLS/Starship No Jupiter > 2035

Group II: Heavy Lift no Jupiter

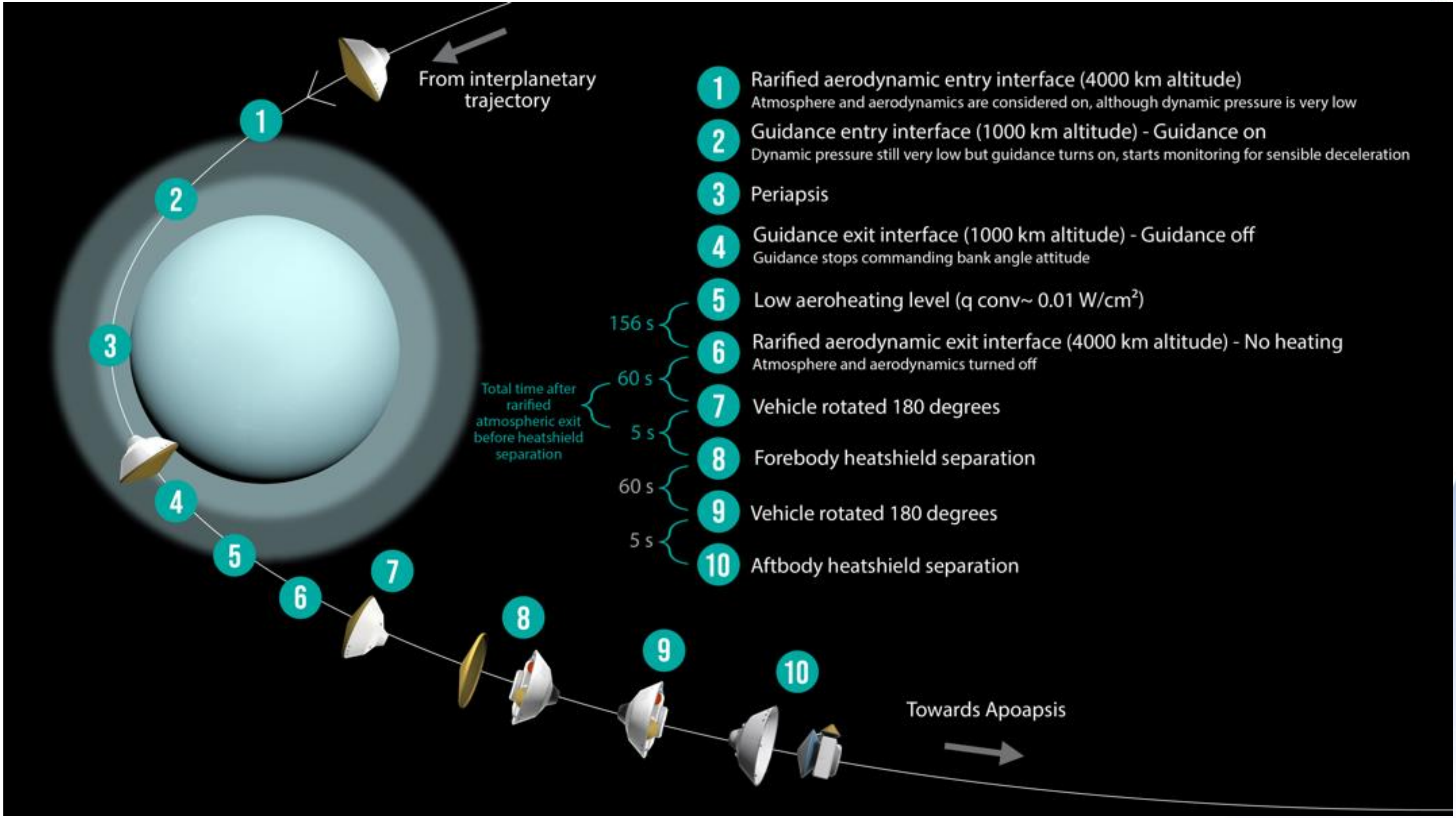
FH & no Jupiter (> 2033)

- For 5500 kg max C3 = 48 km^2/s^2
- Searched 2034-2040. Includes Venus, Earth, Mars.
- 2036 Launches:
  - v_∞ :   8 – 11.4 km/s
  - Launch: Jan – Mar 2036,
  - Arrive : Sept – Dec 2048
  - Time of flight (ToF): **12.8 yrs.** (UOP: 15.3 yrs) 2.8 yrs saving
- 2038 Launches:
  - v_∞ :   9 – 11.0 km/s
  - Launch: Dec 2037 – Mar 2038
  - Arrive : Nov – Dec 2049
  - ToF: **11.8 yrs**. (UOP ~ 14.2 yrs.) 2.4 yrs. Saving

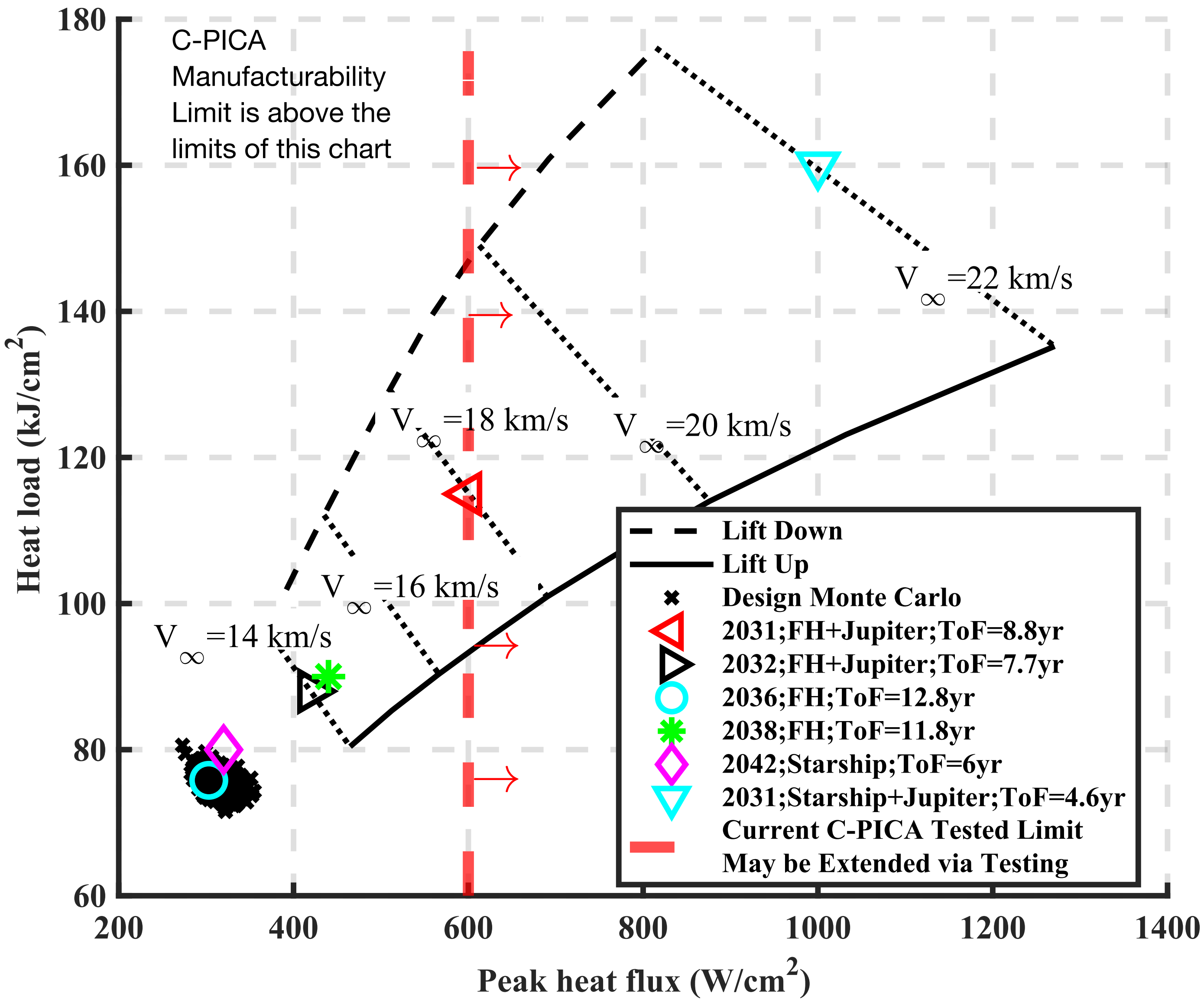




Post-Aerocapture Concept of Operations



Aerosciences and Thermal Protection System Solutions



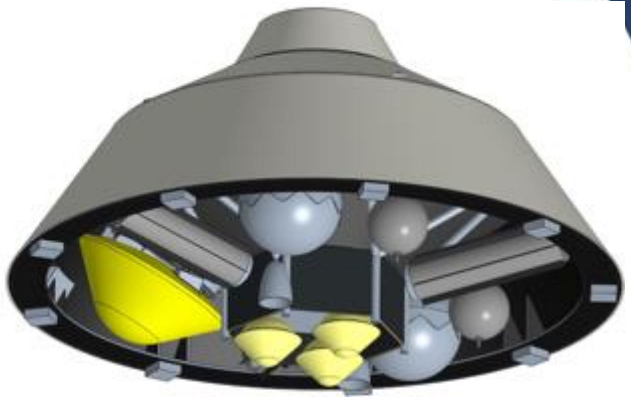
- **ECI project developing computational capabilities for Giant planet missions**
  - No atmospheric missions since Galileo mission to Jupiter (launched in 1989)
  - Lessons learned from other ECIs
- **Aerocapture has much lower maximum heating conditions than direct entry probes**
  - Radiative heating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

Credit: Varda

Potential Probe Accommodations

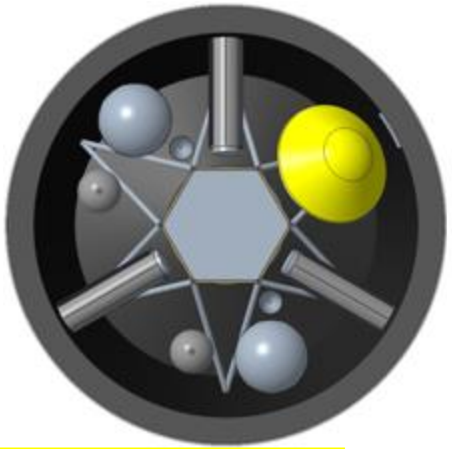
- **Additional smaller probes increase mission scientific value**
  - Enables observation of atmospheric variability and global seasonal effects
  - SNAP probe design can be accommodated by aerocapture vehicle with no major design changes
  - 45° entry vehicle with 50 cm diameter (30 kg)
- **Multiple 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*

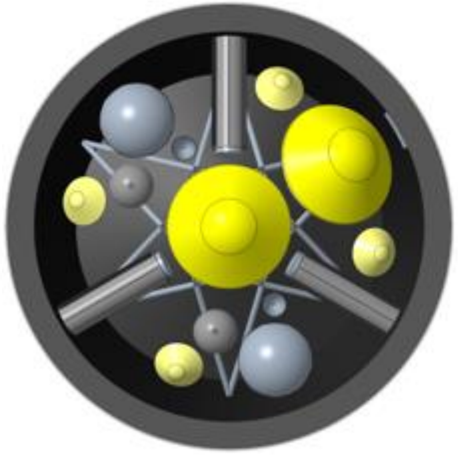
*Small Next-generation Atmospheric Probe (SNAP)



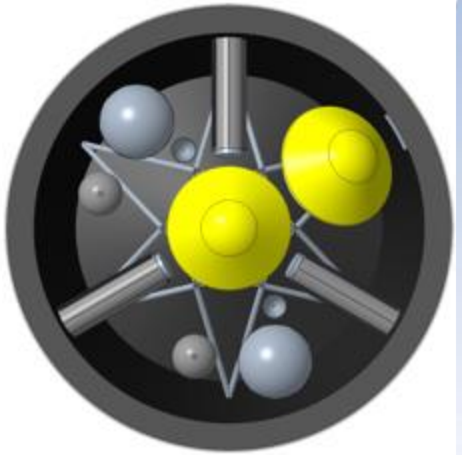
Baseline (1 UOP probe)

1 UOP + 6 SNAP

1 UOP + 3 SNAP



2 UOP + 4 SNAP



2 UOP

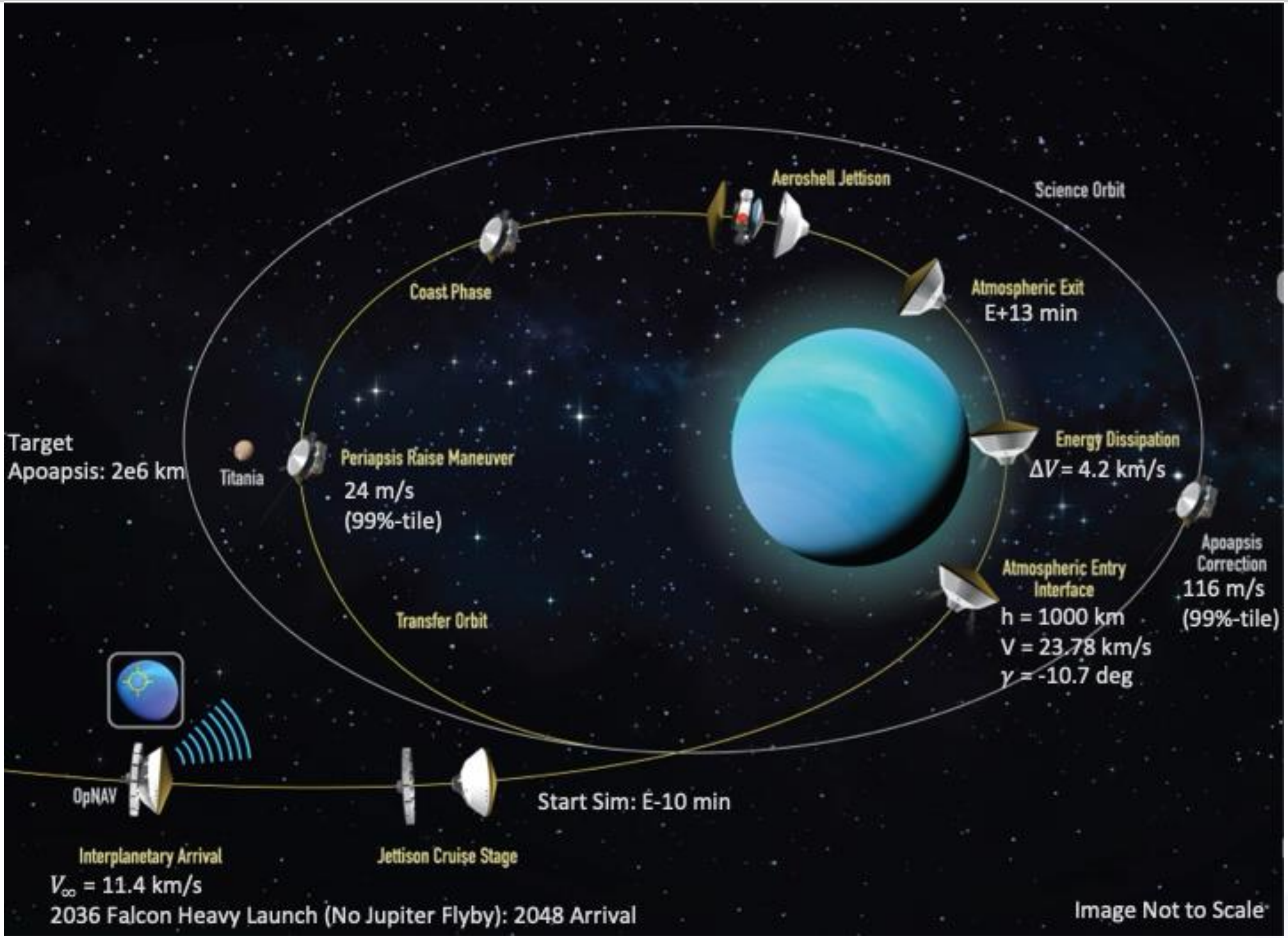
Summary

- Uranus is the prime Flagship-Class mission destination chosen by the Planetary Science Decadal Survey in 2022. Interest in visit to the planet before 2049 Spring Equinox
- Baseline Uranus mission from the Decadal Survey is a fully-propulsive orbit insertion concept called Uranus Orbiter and Probe. It takes 13 years to reach Uranus, has 60-70% of the launch mass as fuel, and needs launch dates in 2031 or 2032
- This Uranus Aerocapture study uses heritage, 70-deg. sphere-cone similar to Mars Science Laboratory and Mars 2020 to take the UOP payload to Uranus in 9 years or less with less fuel mass
- Aerocapture provides feasible means of conducting a Uranus Flagship-Class mission that utilizes 2036 and 2038 launch opportunities with short transit times to reach the planet before 2049
- Nine additional papers on Wednesday (Jan. 8th) sessions of the GNC/AFM-sponsored EDL GNC special sessions will explore the design of the aerocapture system more in-depth

Acknowledgments

- The work is funded by the NASA Space Technology Mission Directorate (STMD)'s Early Career Initiative (ECI)
- External partners include Draper Laboratories, Intuitive Machines, and Booz Allen Hamilton

Questions



Aeroshell Jettison
Science Orbit
Coast Phase
Atmospheric Exit
E+13 min
Target
Apoapsis: 2e6 km
Titania
Periapsis Raise Maneuver
24 m/s
(99%-tile)
Energy Dissipation
ΔV = 4.2 km/s
Apoapsis
Correction
116 m/s
(99%-tile)
Atmospheric Entry
Interface
h = 1000 km
V = 23.78 km/s
γ = -10.7 deg
Transfer Orbit
OpNAV
Start Sim: E-10 min
Interplanetary Arrival
Jettison Cruise Stage
V∞ = 11.4 km/s
2036 Falcon Heavy Launch (No Jupiter Flyby): 2048 Arrival
Image Not to Scale

Backup Slides