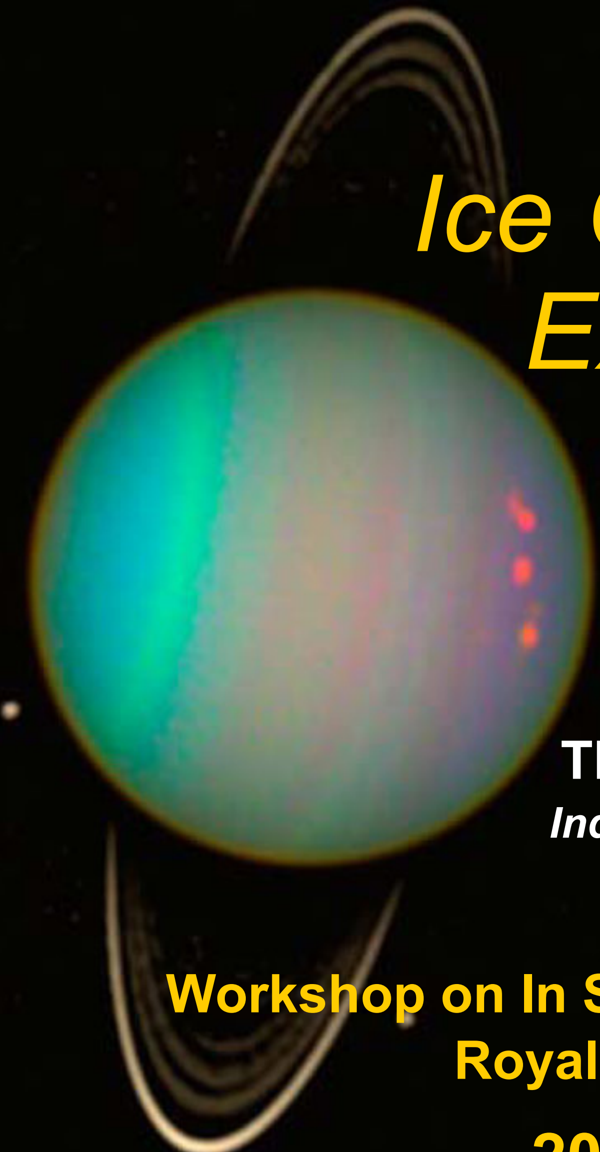
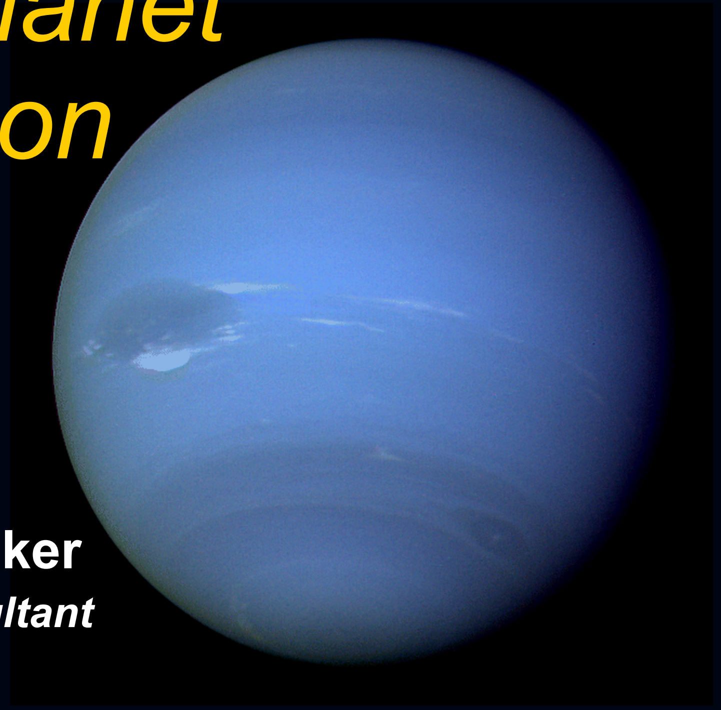




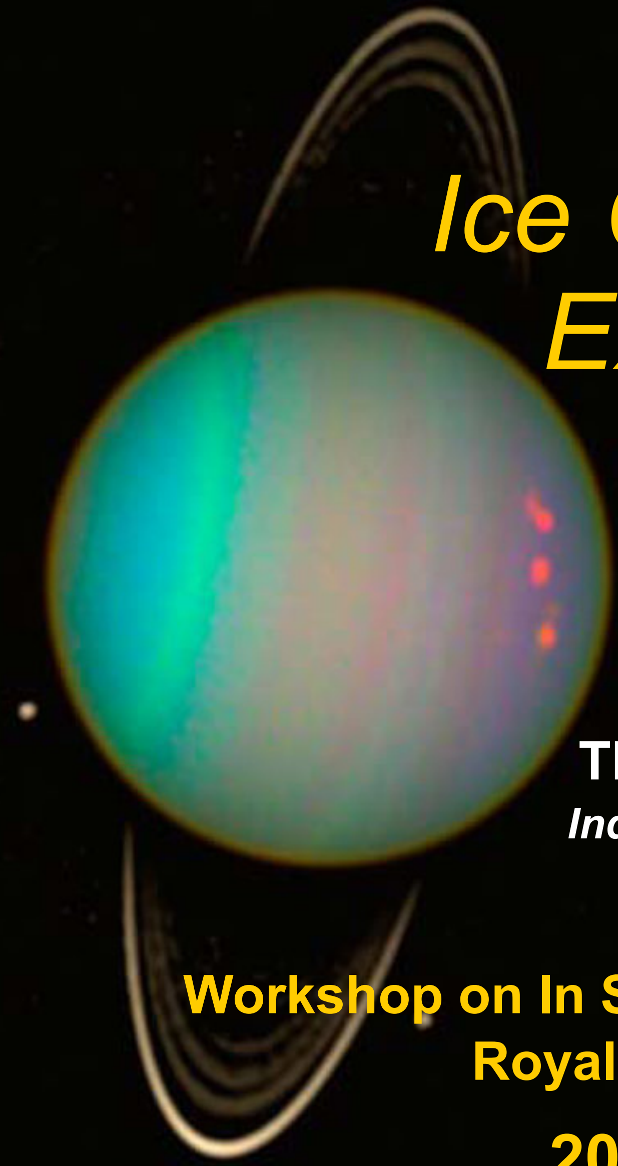
Enabling Technologies *for* *Ice Giant Planet Exploration*

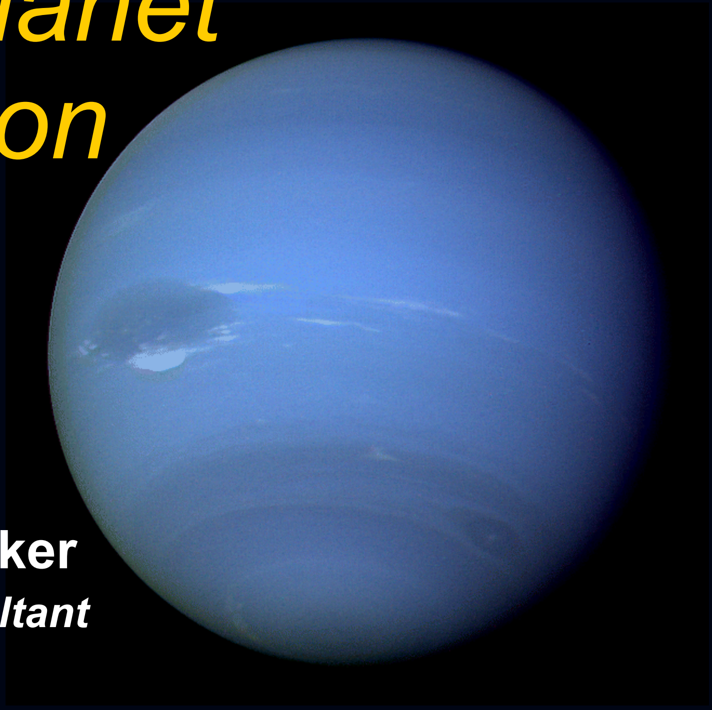
Thomas R. Spilker
Independent Consultant

Workshop on In Situ Exploration of the Ice Giants
Royal Society, London, UK

2020 January 21

Enabling Technologies *for* *Ice Giant Planet Exploration*





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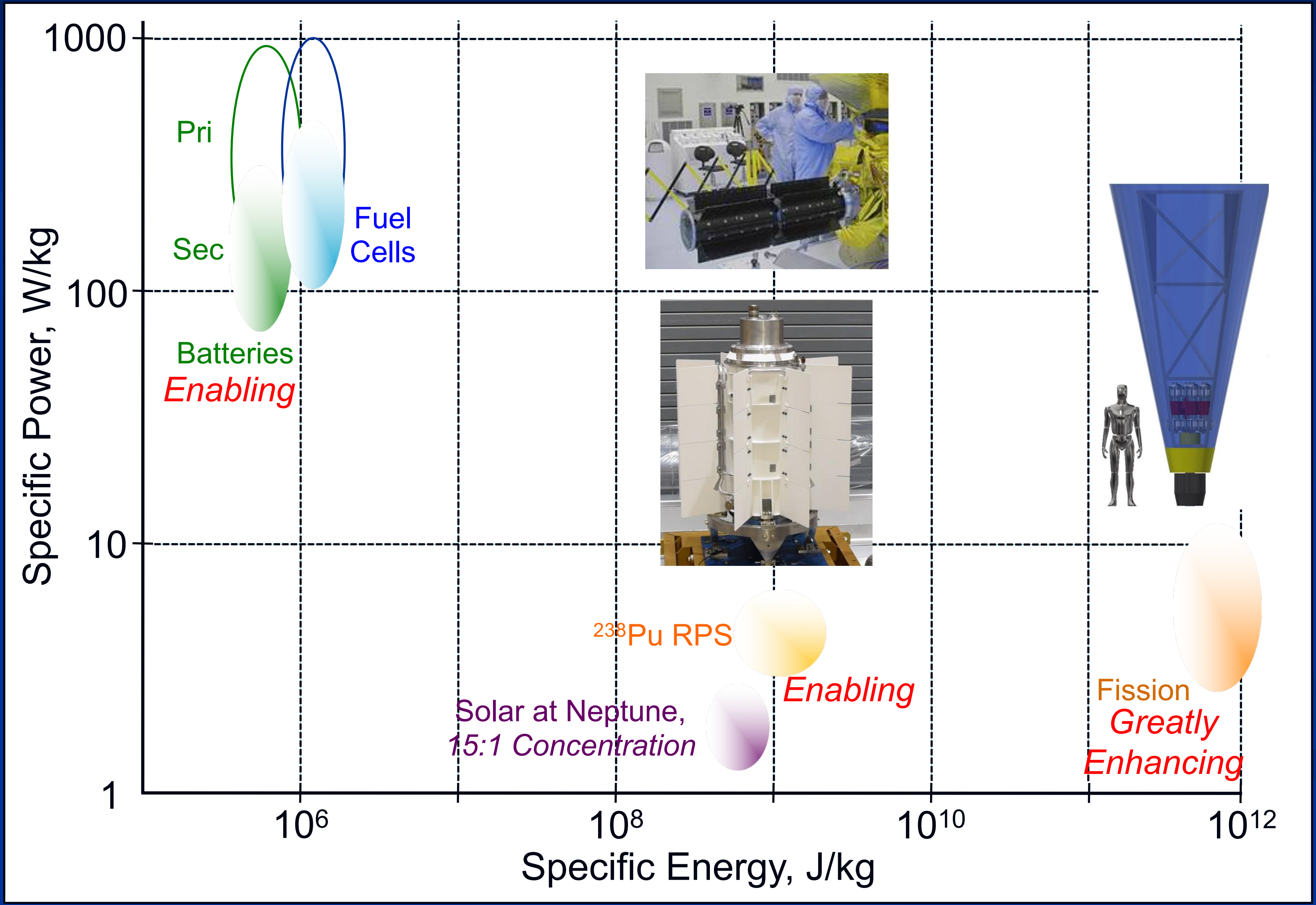
Ice Giant Characteristics That Result in Technological Challenges

- They're a long distance from the sun
  - Low insolation: cold, low solar energy density
  - Long climb out of the deep solar gravity well; long travel times
    - High approach velocities
- They're a long distance from Earth
  - Telecommunications challenges
- They have fairly high planetary masses
  - High orbital velocities near the planet
  - High atmospheric entry velocities
- Their atmospheres have low average molecular masses
  - Large scale heights
  - Large distances from the tropopause to the clouds

Primary Technological Challenges Facing Missions to the Ice Giants

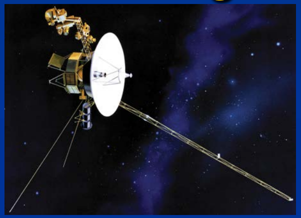
- Four general challenges arising from large heliocentric distance:
  - Providing sufficient electric power
  - Providing telecommunications of sufficient rate
  - Maintaining an acceptable thermal environment
  - Accommodating large propulsion requirements
- Additional challenges for atmospheric entry probes:
  - Maintaining survival temperatures during “coast”
  - Extreme hypersonic atmospheric entry
  - Telecommunications: data relay link
  - Duration of tropospheric descent phase
- Tour design challenges:
  - Highly seasonal arrival circumstances at Uranus
  - Retrograde orbit of Neptune’s only large satellite

Specific Energies and Powers of Candidate Electric Power Sources



Telecommunications Challenges

- All communications will be electromagnetic
  - Existing (*enabling*) technology: radio
  - Emerging (*enhancing*) technology: optical
  - At large distances, spherical divergence reduces supportable rates

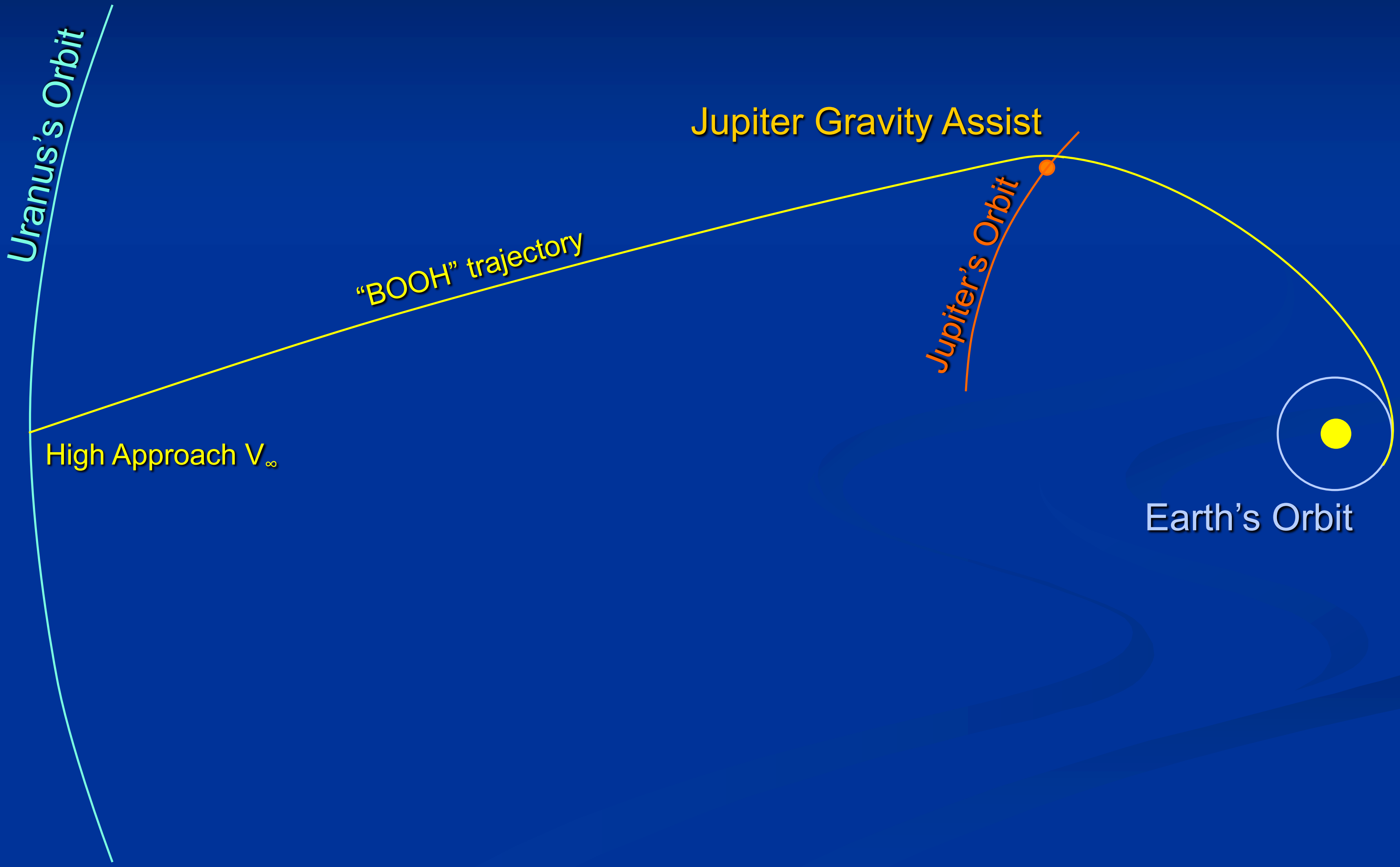


- Radio
  - Voyager X-band from Neptune
    - 19 W RF through a 3.6-m HGA to a 70-m ground station: *3 kbps*
  - Ka-band can do about a factor of four to five better
  - One downlink pass per day might be insufficient
- Optical
  - Successful lunar demos outperformed Ka-band radio with less power
  - Demo on the Psyche mission to be launched in mid-2023, 250 Mbps
  - Requires exquisitely accurate, *leading* pointing
  - Currently only experimental ground stations exist

Propulsion Challenges

- Three applicable primary propulsion types
  - Chemical
    - Energy supplied by an internal chemical reaction
    - Capable of high power (MWth), high thrust (10s to 1000s of Newtons)
    - Relatively low exhaust velocity (“specific impulse”), 2-3 km/s
  - Electric
    - Energy supplied by an external electric power source
    - Relatively high exhaust velocity, 20-40 km/s
    - *Low* thrust — *milli*Newtons
  - Aerodynamic
    - Energy *decreased* by atmospheric drag
    - Aero entry
    - Aerocapture
    - No primary propellant!

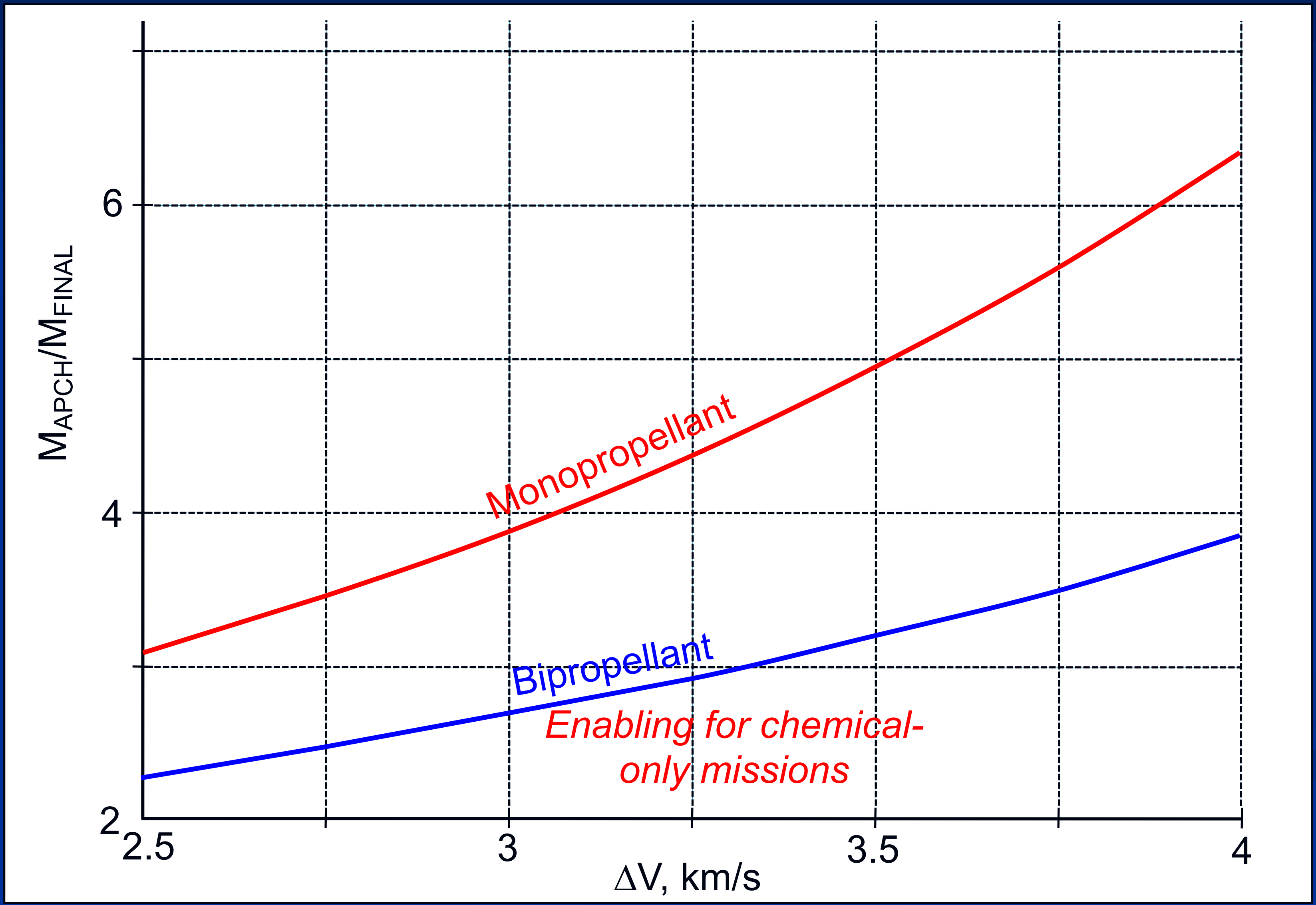
Gravity Assist Transfer Orbits to an Ice Giant



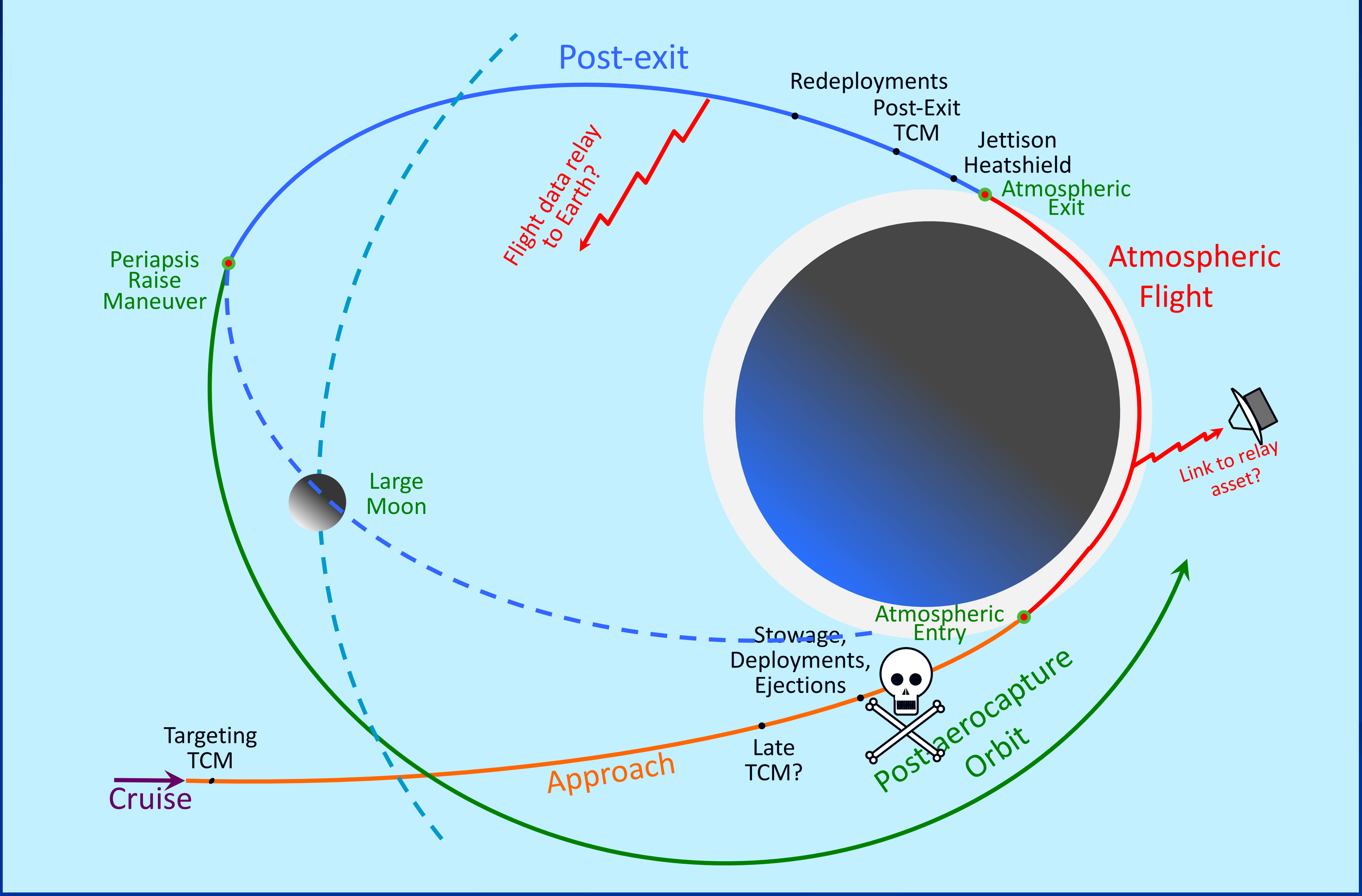
Simple SEP Transfer Orbit to an Ice Giant

Simple REP or NEP Transfer Orbits to an Ice Giant

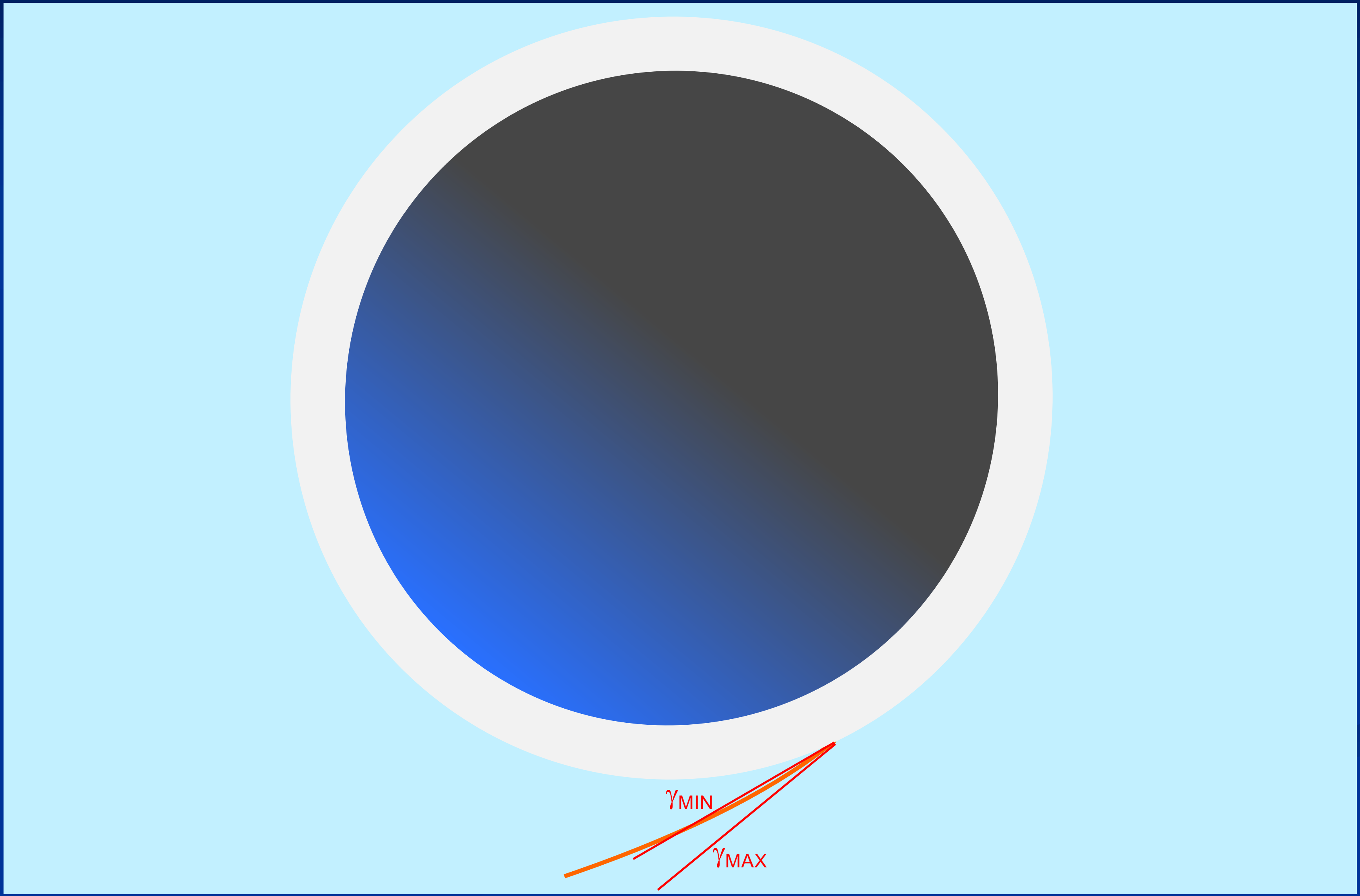
Chemical Bipropellant vs Monopropellant



What Is Aerocapture?



Aerocapture *Entry Corridor*



Surprising Characteristics of Aerocapture

- All else held constant, the higher the V
  thus the higher the atmospheric entry s
  entry corridor
  - For trajectory control, *faster entry is more fo*
  - Faster entry generally means the trip time is
  - *But* … faster entries put greater demands o

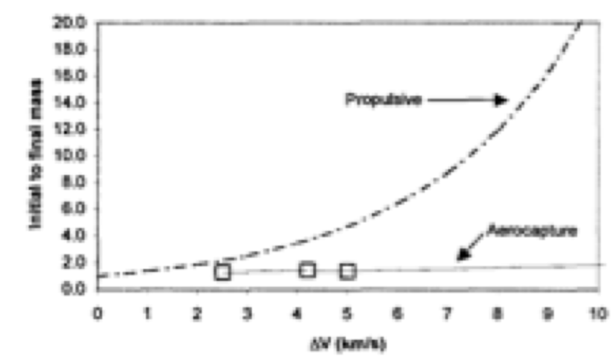
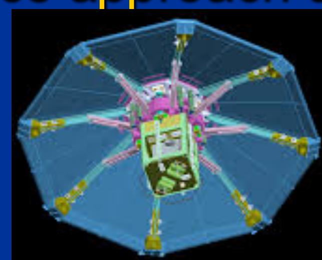


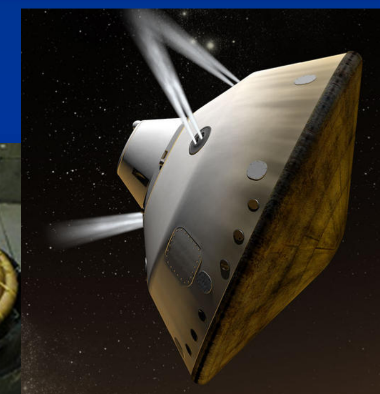
Figure 1. Comparison of Aerocapture to Propulsive Orbit Insertion Mass Ratios (Initial To Final)

- While the propellant mass of an impulse propulsion system goes up quasi-exponentially with ΔV, the mass of an aerocapture system goes up only quasi-linearly with ΔV
  - For low ΔVs, propulsive is less massive than aerocapture
  - For high ΔVs, aerocapture is far less massive than propulsive
  - The crossover point (in ΔV) depends on the propulsive and aerocapture technologies being compared.
- Like NEP, aerocapture is *not* enabling, but might be greatly enhancing

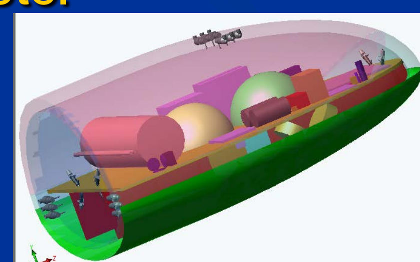
Critical Technologies for Aerocapture

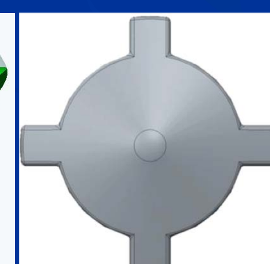
- Navigation
  - High accuracy approach navigation
  - Planetary ephemerides
- Guidance
  - Algorithms for the guidance approach used
  - High capacity computing

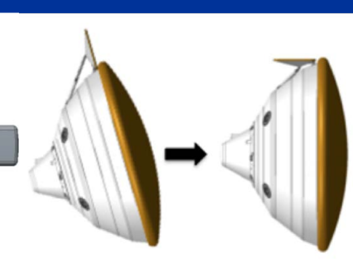




- Control
  - Aeroshell designs
  - Effectors: drag skirts, flaps, etc.







- Aeroshell materials (TPS)
  - HEEET
  - Heritage carbon phenolic (Galileo Probe) no longer available

Radioisotope & Fission Electric Propulsion

- General characteristics
  - Very high total ΔV capability
  - Very low acceleration magnitudes
- Better suited for Earth-to-destination transfers…
- … but can be useful for orbital tours

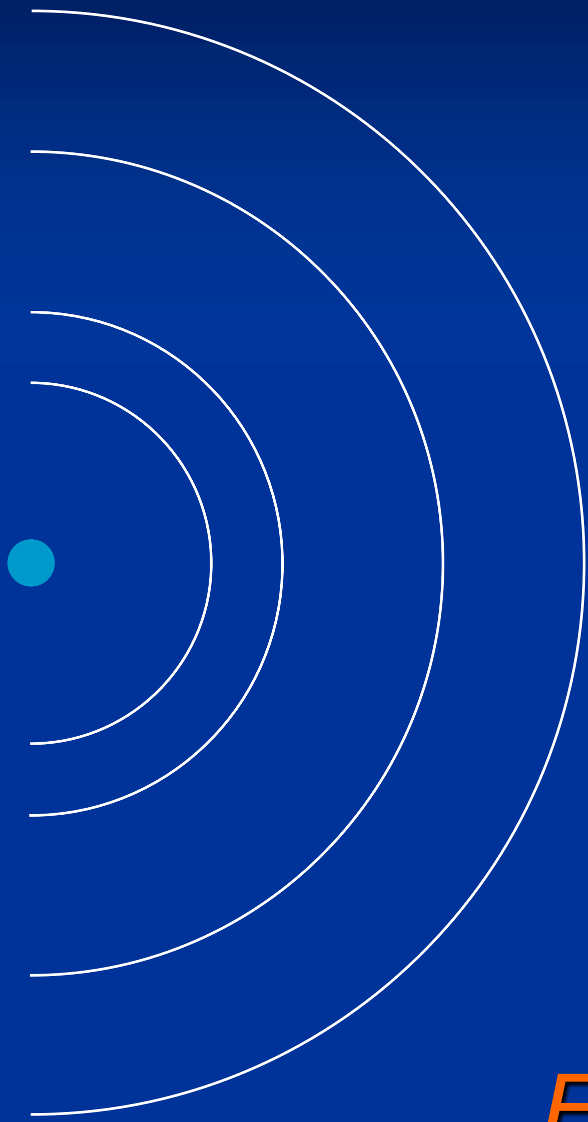
Thermal Challenges

- Enabling technologies already well in hand
  - Waste heat from nuclear power sources
    - Radiative coupling
    - Heat pipes
    - Pumped heat loops
  - Radioisotope heater units
    - Heat without an external power source
  - Electric heaters
    - Inefficient use of electric power but fast & accurate control
  - Heat loss control
    - Multi-layer insulation (“MLI”)
    - Variable louvers
    - Low-conductivity structural materials
- Primary message: *Thermal design up front, not as an afterthought*

Technological Challenges for Entry Probes

- Coast thermal
  - Not a problem if you have RHUs
  - *If you don't…*
  - Battery mass can be large — high specific energy batteries needed
- Surviving entry conditions
  - Need a high-performance TPS material — currently, HEEET
  - Some approaches use steep entries
    - High inertial loads — custom components & instruments? *££££!*
- Data relay link
  - Direct-to-Earth (DTE) generally infeasible from ice giants
  - Low antenna gains
  - Atmospheric attenuation at deeper levels
  - Distances are much smaller than for Galileo Probe
- Descent duration
  - For deeper probes, drag management

Tour Design Challenges: Uranus



When normalized by
planetary radius
or planetary mass
the Uranian system
(minus Miranda)

dynamically
looks similar
to

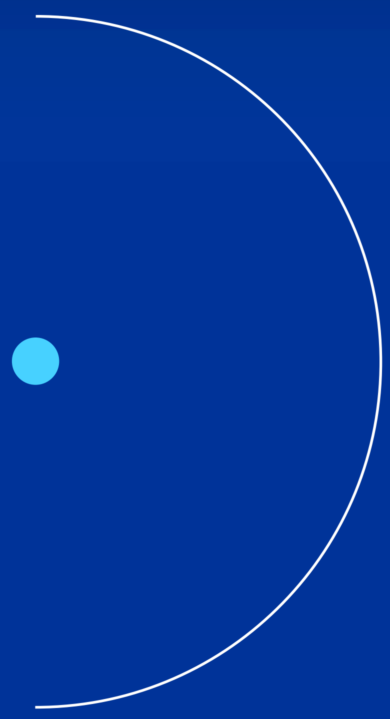
the Jovian system
(*Galileo*-like tours
are possible)

EXCEPT THAT…

It's Tipped On Its Side!

- Transfer orbit approaches vary seasonally & can be anywhere from equator-on to pole-on (i.e., *declination of the approach asymptote* from 0° to 90°)
- Galileo-like tours require very low orbit inclinations
- High approach declinations make it very difficult to get into a low-inclination orbit unless you have REP or NEP

Tour Design Challenges: Neptune

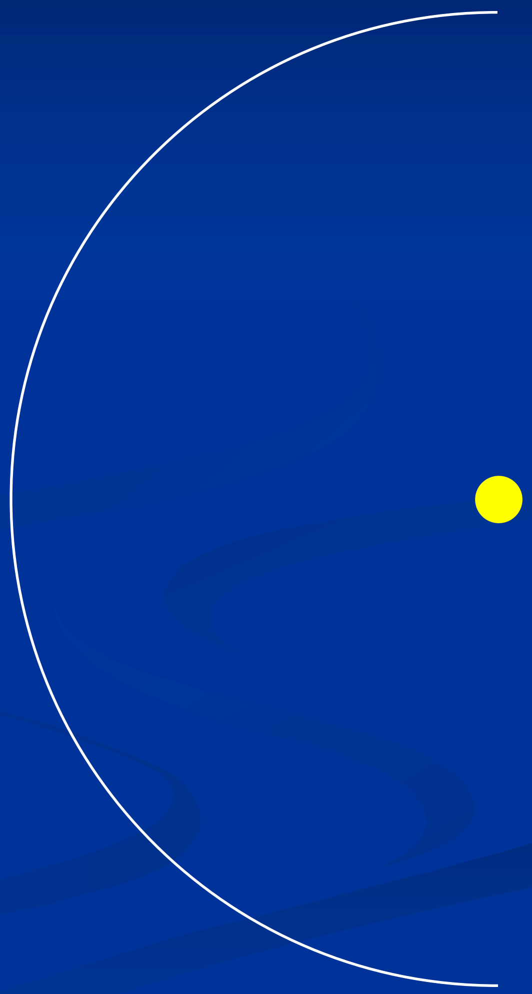


When normalized by
planetary radius
or planetary mass
the Neptunian
system

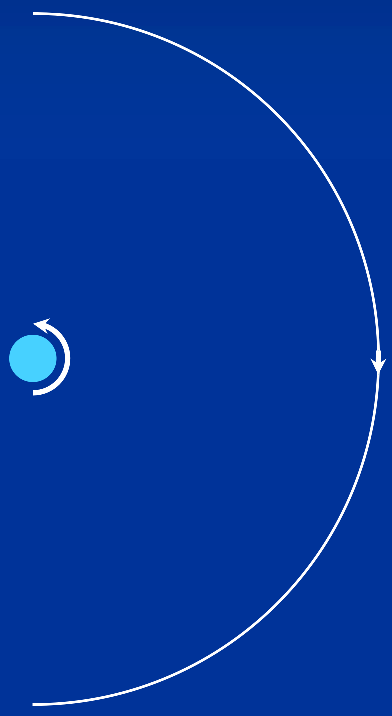
dynamically
looks similar
to

the Saturnian system
(*Cassini*-like tours
are possible)

EXCEPT THAT…



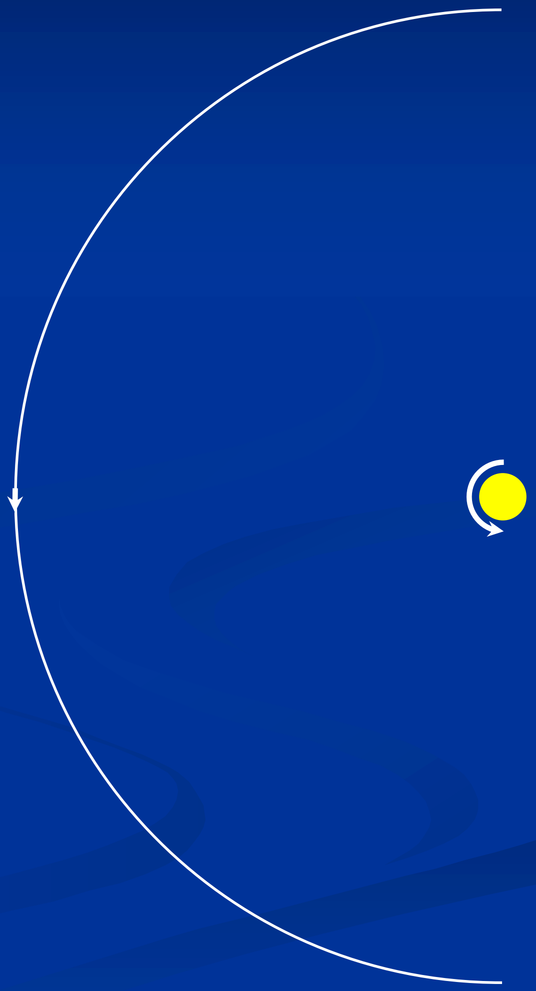
Tour Design Challenges: Neptune



When normalized by
planetary radius
or planetary mass
the Neptunian
system

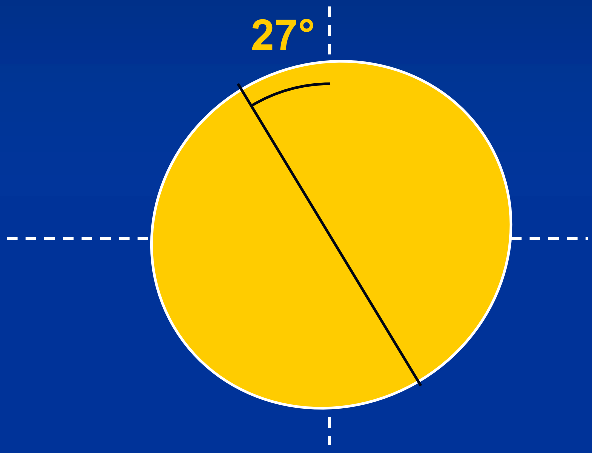
dynamically
looks similar
to

the Saturn system
(*Cassini*-like tours
are possible)

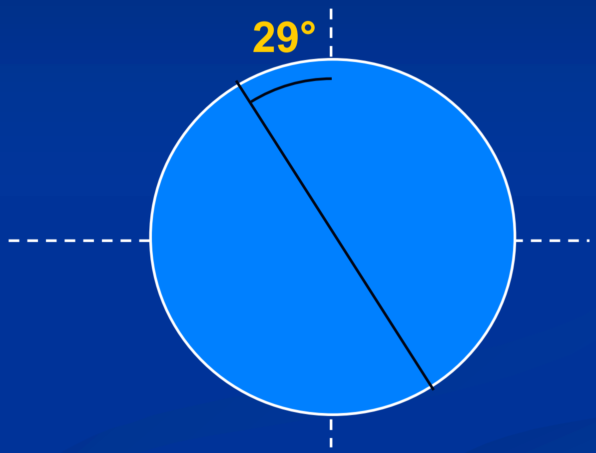


Triton's orbit is Retrograde!

At Least Its Obliquity Isn't Crazy!



Saturn



Neptune

Questions?

Bulk Characteristics of the Giant Planets

Planet \ Characteristic	Mass (Earth masses)	Equatorial radius (km)	Mean mass density (gm/cm^3)
Jupiter	317	71490	1.32
Saturn	95	60330	0.68
Uranus	14.5	25500	1.27
Neptune	17.1	24770	1.64

Typical Atm-Relative Entry Speeds At the Giant Planets

Color-coded entry velocity indicators assume shallow entry angle

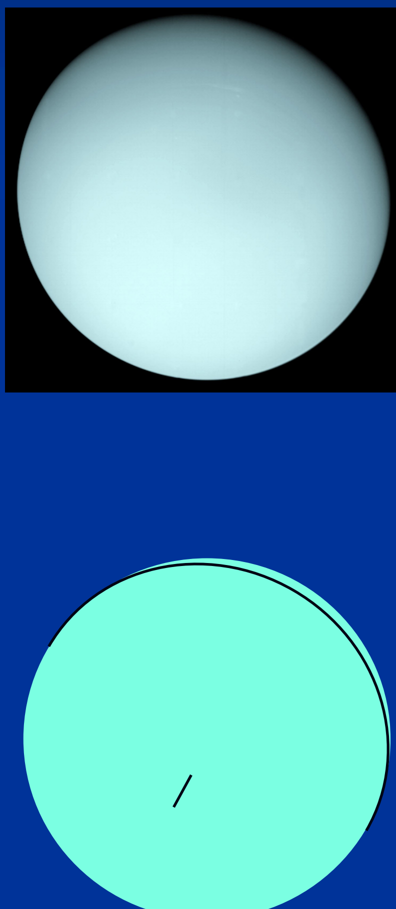
Speeds in km/s; assume "typical" hyperbolic approach V_∞

Destination \ Entry Orbit Inclination	0° (prograde)	90° (polar)	180° (retrograde)
Jupiter	47.4	61.1	72.2
Saturn	26.5	37.5	46.2
Uranus	21.6	24.1	26.7
Neptune	25.4	28.2	30.8

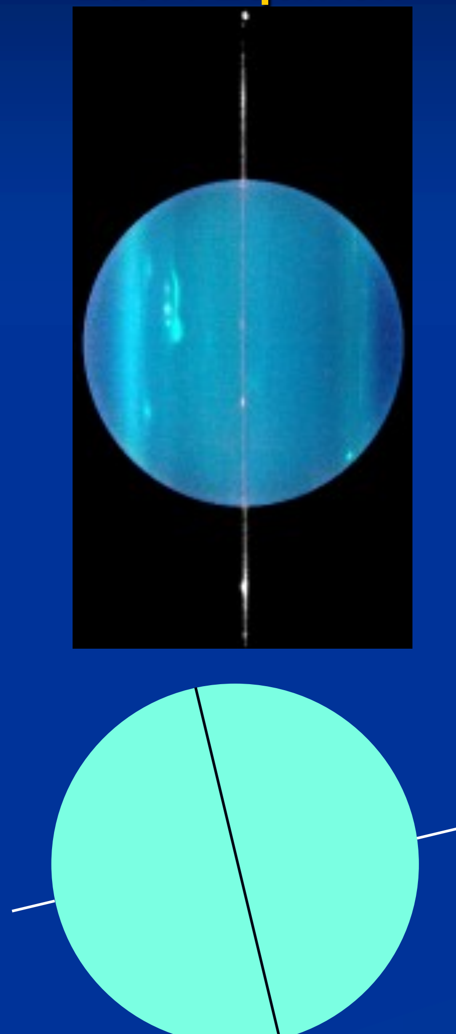
CRITICAL TECHNOLOGY: HIGH-PERFORMANCE TPS MATERIALS

Uranus Heliocentric Views With Time

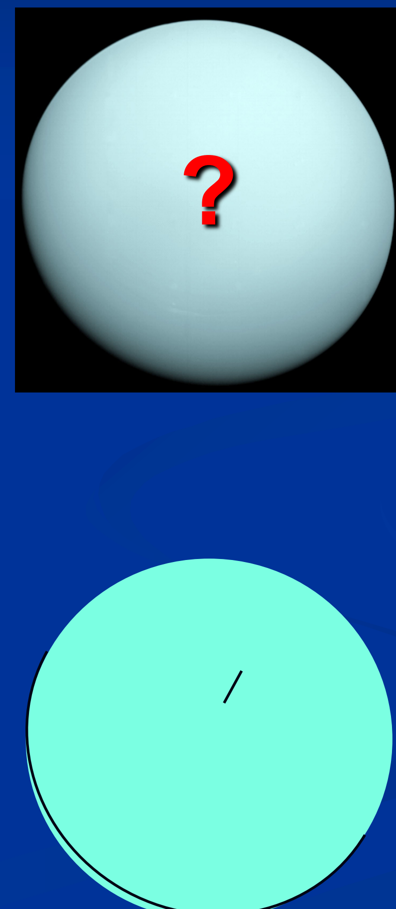
1986: *Voyager 2* View



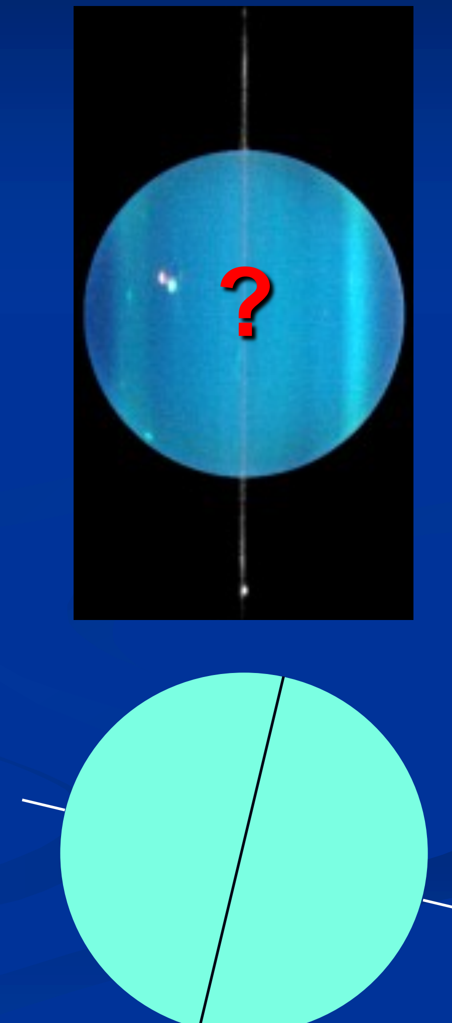
2007: Equinox



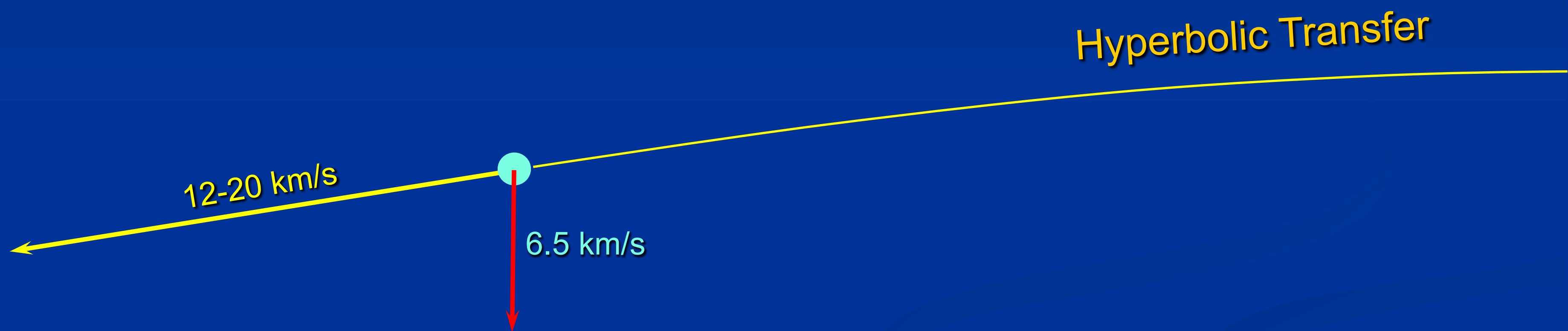
2028



2049: Equinox



Simple Transfer Orbits to Uranus

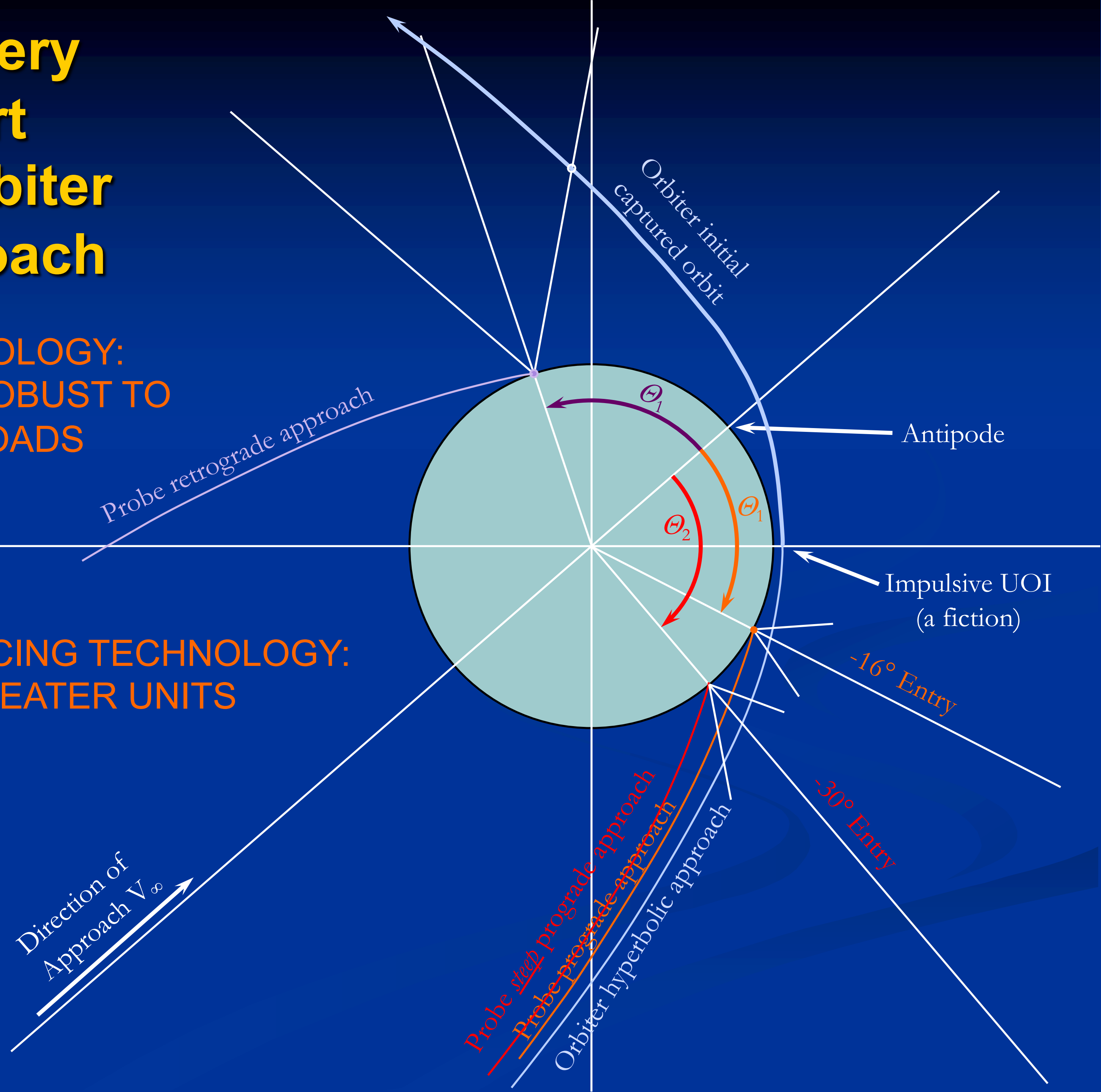


V_{ent} (assuming ideal orientation wrt rotation) is now
21.6 – 26.7 km/s

Probe Delivery And Support From an Orbiter Upon Approach

CRITICAL TECHNOLOGY:
INSTRUMENTS ROBUST TO
HIGH INERTIAL LOADS

GREATLY ENHANCING TECHNOLOGY:
RADIOISOTOPE HEATER UNITS



Equatorial Region Might Not Be Accessible