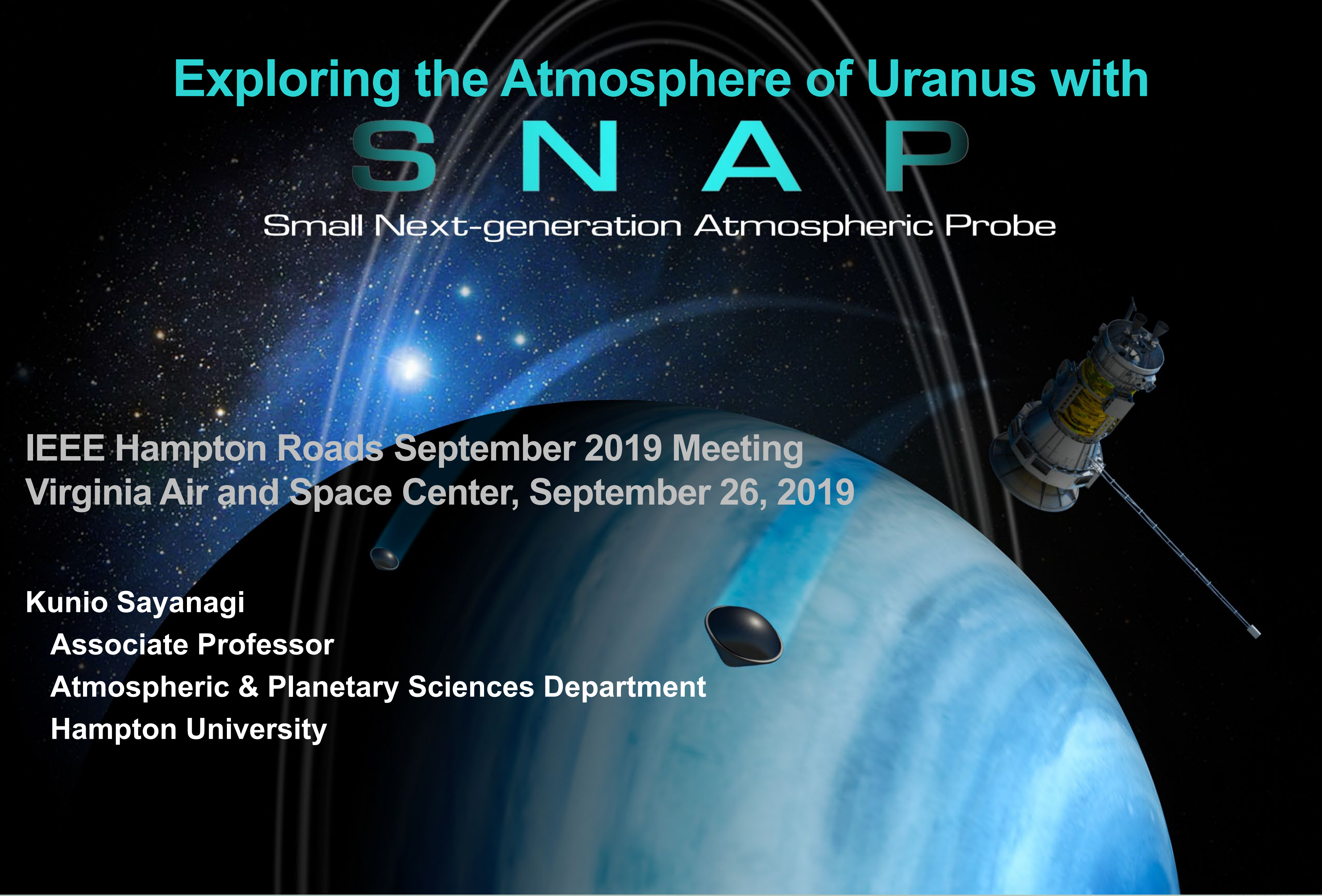
# Exploring the Atmosphere of Uranus with SNAP

## Small Next-generation Atmospheric Probe



IEEE Hampton Roads September 2019 Meeting
Virginia Air and Space Center, September 26, 2019

**Kunio Sayanagi**
Associate Professor
Atmospheric & Planetary Sciences Department
Hampton University

HAMPTON UNIVERSITY NASA Langley PURDUE UNIVERSITY NASA Goddard JPL Ames Research Center

# Study Team (All)

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(31 Team Members total)

[1]Atmospheric and Planetary Sciences Department, Hampton University (23 E Tyler St. Hampton, VA, 23668, kunio.sayanagi@hamptonu.edu), [2]NASA Langley Research Center, [3]Jet Propulsion Laboratory, California Institute of Technology, [4]Purdue University, [5]NASA Goddard Space Flight Center, [6]Planetary Mission Architect, [7]University of California, Berkeley.

**Mission Design Center:**

**NASA Langley Research Center Engineering Design Studio**

NASA Planetary Science DeepSpace SmallSat Program (PSDS3)

# Selected Proposals

**Venus**

Christophe Sotin, NASA's Jet Propulsion Laboratory, Pasadena, California: Cupid's Arrow
Valeria Cottini, University of Maryland, College Park: CubeSat UV Experiment (CUVE)

**Moon**

Suzanne Romaine, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts: CubeSat X-ray Telescope (CubeX)
Timothy Stubbs, NASA Goddard Space Flight Center, Greenbelt, Maryland: Bi-sat Observations of the Lunar Atmosphere above Swirls (BOLAS)

**Asteroids**

Jeffrey Plescia, Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland: Asteroid Probe Experiment (APEX),
Benton Clark, Lockheed Martin Space Systems Company, Littleton, Colorado: CubeSat Asteroid Encounters for Science and Reconnaissance (CAESAR)

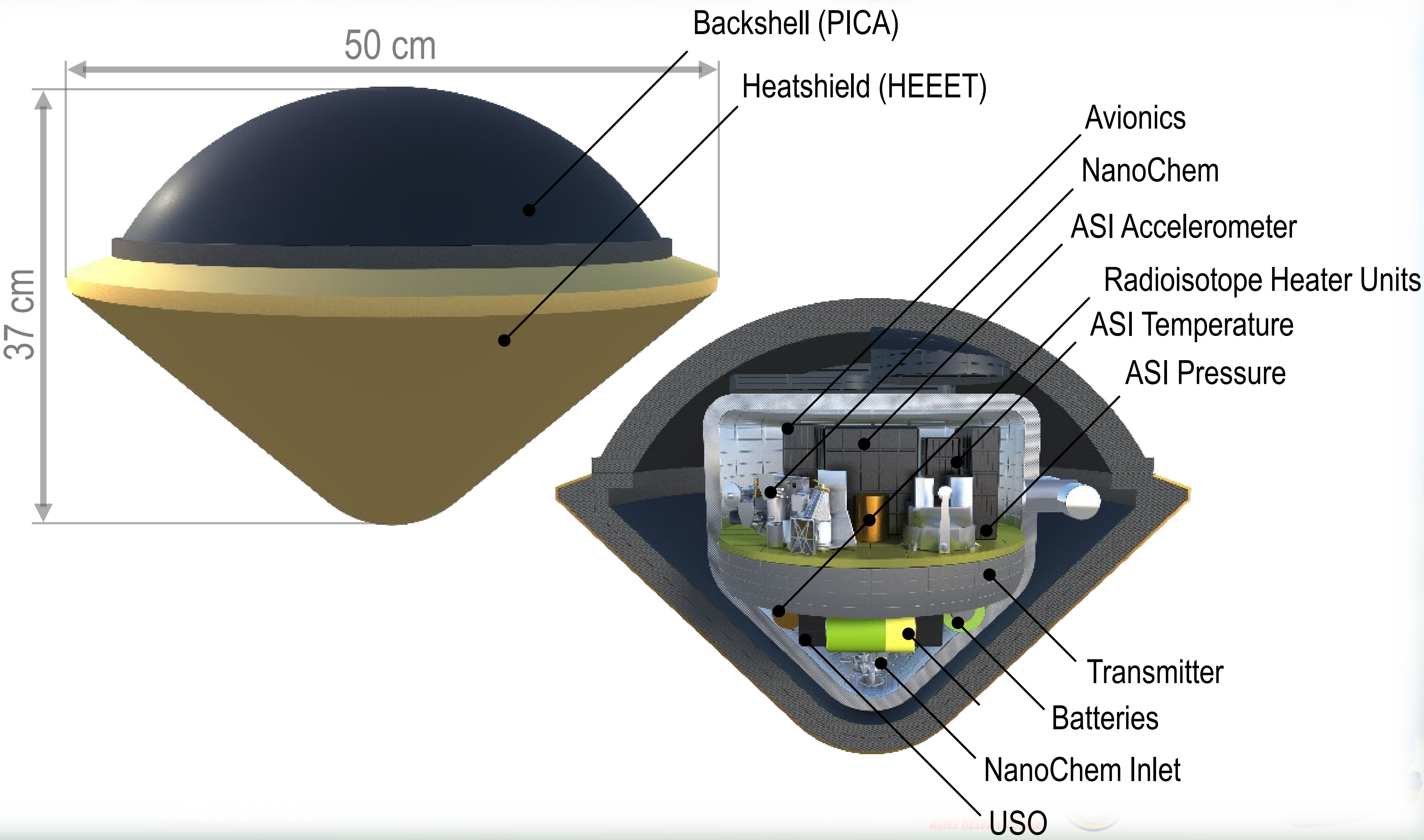
**Mars**

David Minton, Purdue University, West Lafayette, Indiana: Chariot to the Moons of Mars
Anthony Colaprete, NASA Ames Research Center, Moffett Field, California: Aeolus

**Icy Bodies and Outer Planets**

Kunio Sayanagi, Hampton University, Virginia: Small Next-generation Atmospheric Probe (SNAP)
Robert Ebert, Southwest Research Institute, San Antonio, Texas: JUpiter MagnetosPheric boundary ExploreR (JUMPER)

# SNAP Hardware Configuration



50 cm

37 cm

Backshell (PICA)

Heatshield (HEEET)

Avionics

NanoChem

ASI Accelerometer

Radioisotope Heater Units

ASI Temperature

ASI Pressure

Transmitter

Batteries

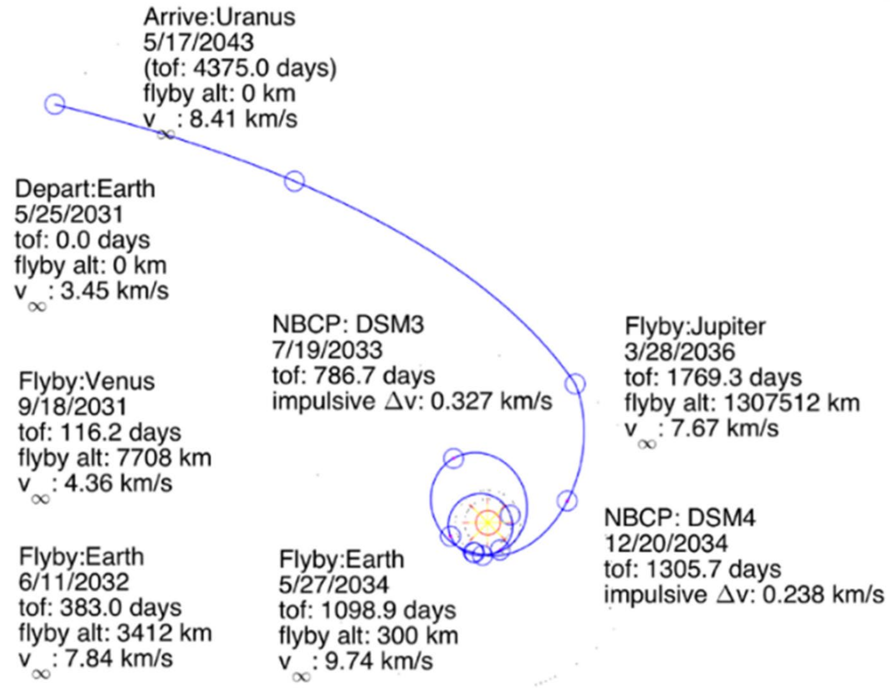
NanoChem Inlet

USO

# Baseline Carrier Mission

**Venus-Earth-Earth-Jupiter-Uranus Trajectory**

- Launch: 5/25/31, VEEJ gravity-assists + Two DSMs
- Launch Vehicle: Atlas V541,
  ~4450 kg $C_3 = 11.9\ km^2/s^2$
- 12-year cruise to UOI



**Uranus Arrival: May 17, 2043**

- Close to 2049 Equinox
- After 2028 Northern Summer Solstice
- Voyager flyby 1986 was during Southern Summer Solstice
- Periapsis $r_p = 1.05\ R_U$
- Capture orbit period = ~142 days

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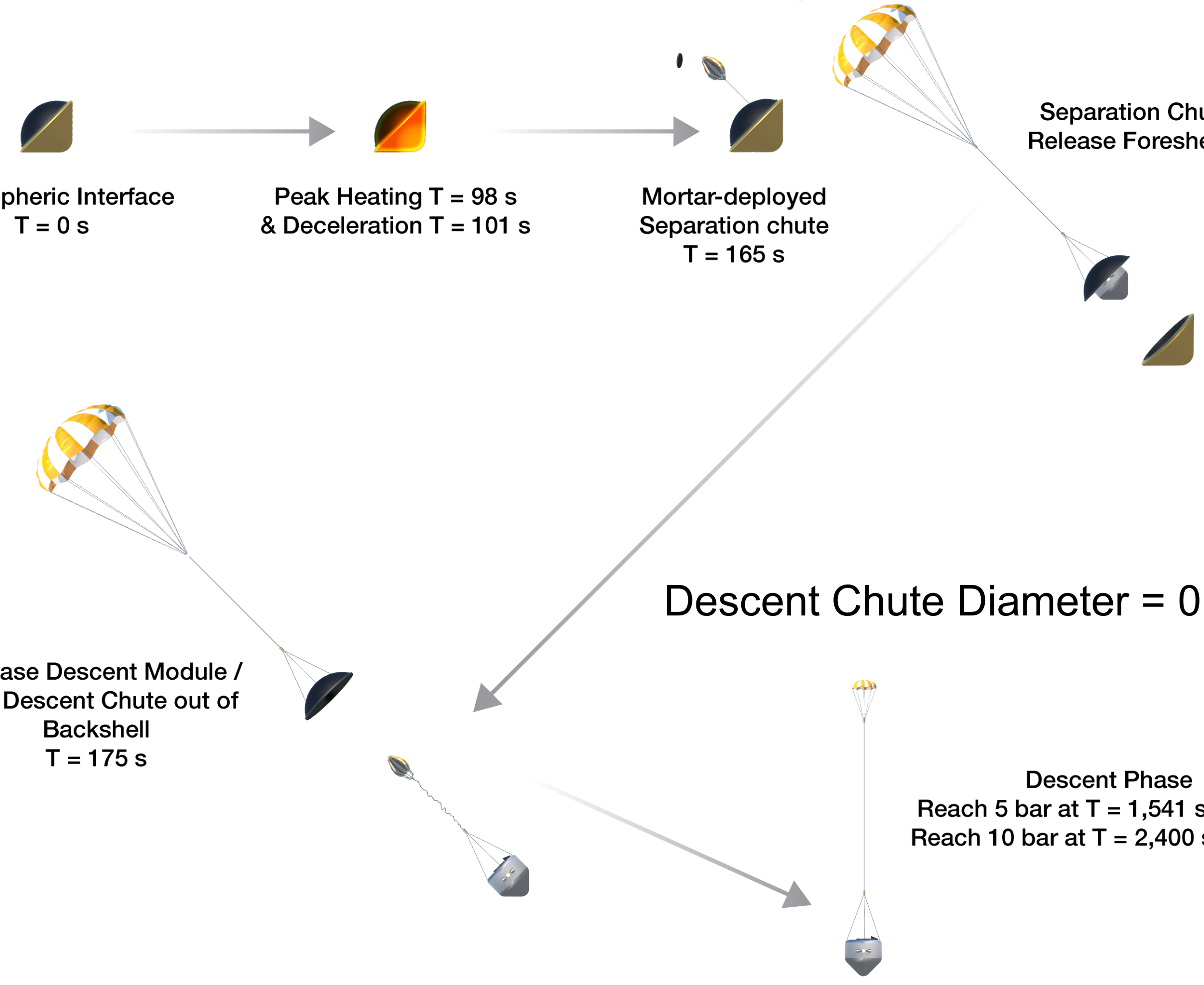
# Atmospheric Entry & Descent



Separation Chute Diameter = 1.5 m

Atmospheric Interface
T = 0 s

Peak Heating T = 98 s
& Deceleration T = 101 s

Mortar-deployed
Separation chute
T = 165 s

Separation Chute Opens,
Release Foreshell T = 170 s

Release Descent Module /
Pull Descent Chute out of
Backshell
T = 175 s

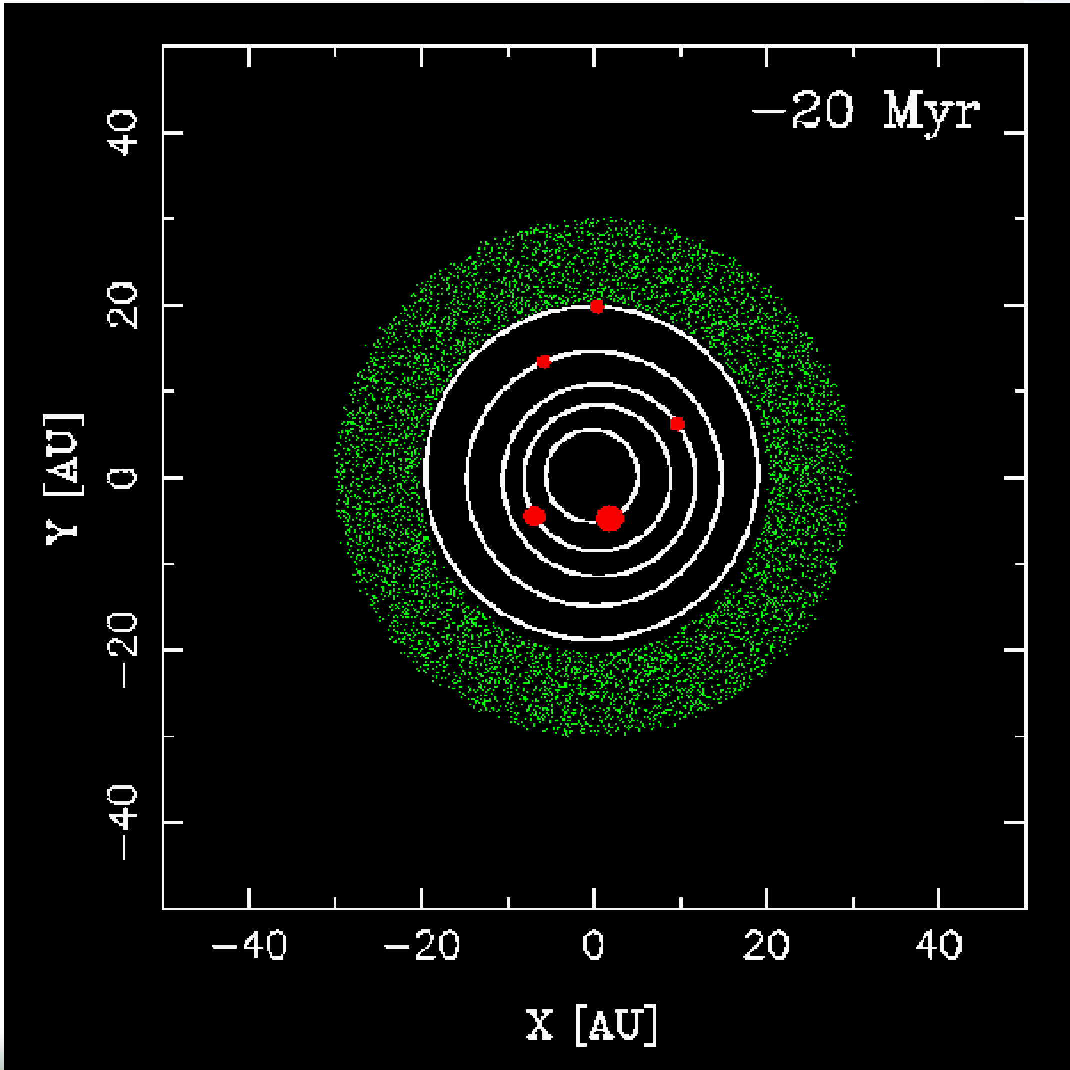
Descent Chute Diameter = 0.1 m Stabilizer

Descent Phase
Reach 5 bar at T = 1,541 s (26 min)
Reach 10 bar at T = 2,400 s (40 min)

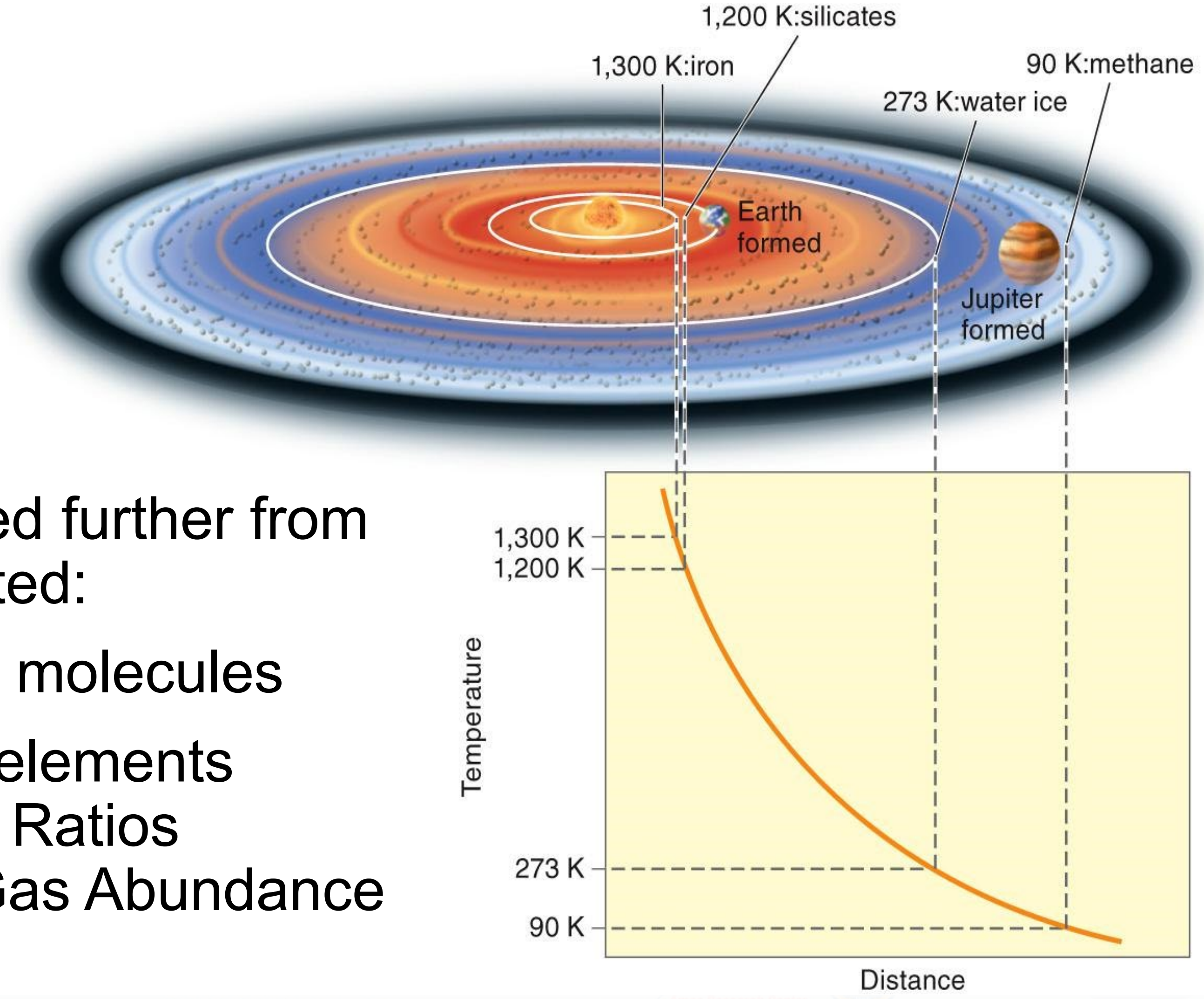
# Why Send Probes to Uranus?

# Where in Solar System did Uranus Form?

- “Nice Model” of Solar System Evolution
- Jupiter and Saturn pushed out Uranus and Neptune, and scattered many icy left-over materials.
- Did Uranus and Neptune form closer to the sun that they are today?



# Planetary Formation and Atmospheric Composition

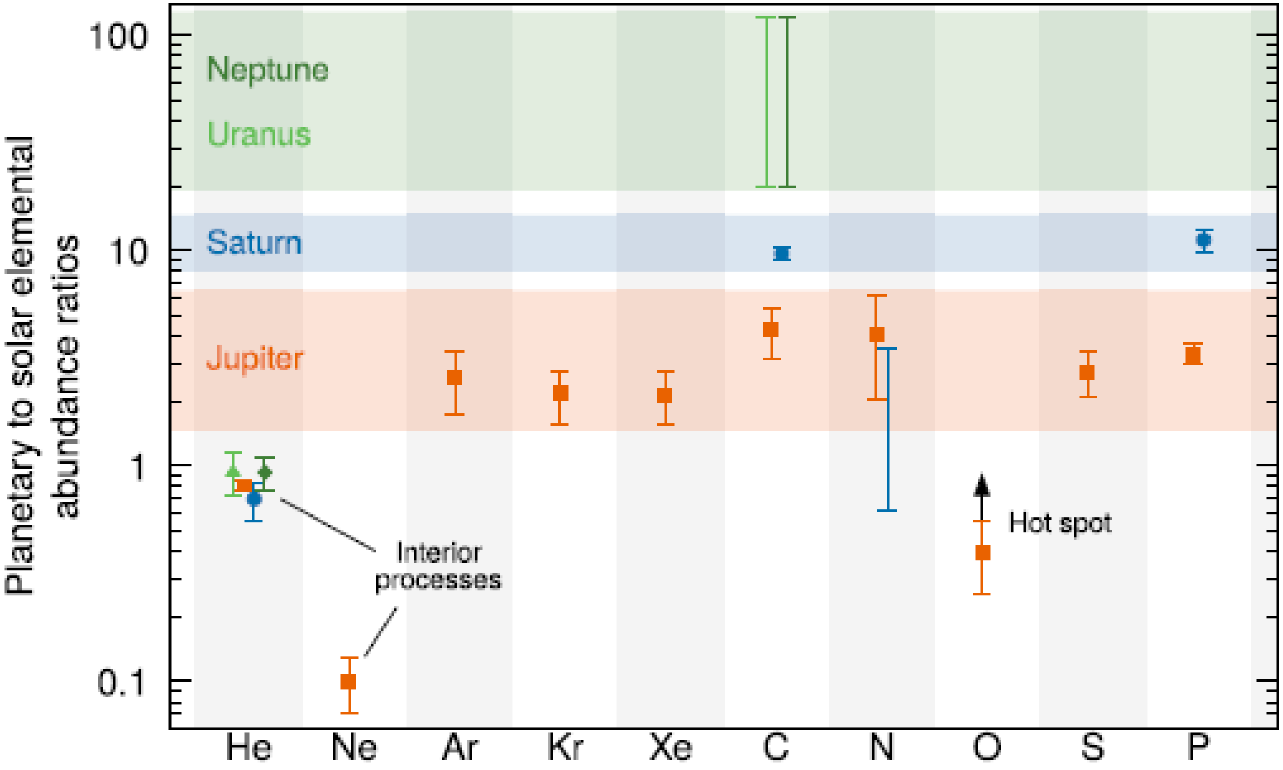


Public-domain figure

Planet that formed further from the sun collected:

- More volatile molecules
- More lighter elements
  - → Isotopic Ratios
  - → Noble Gas Abundance

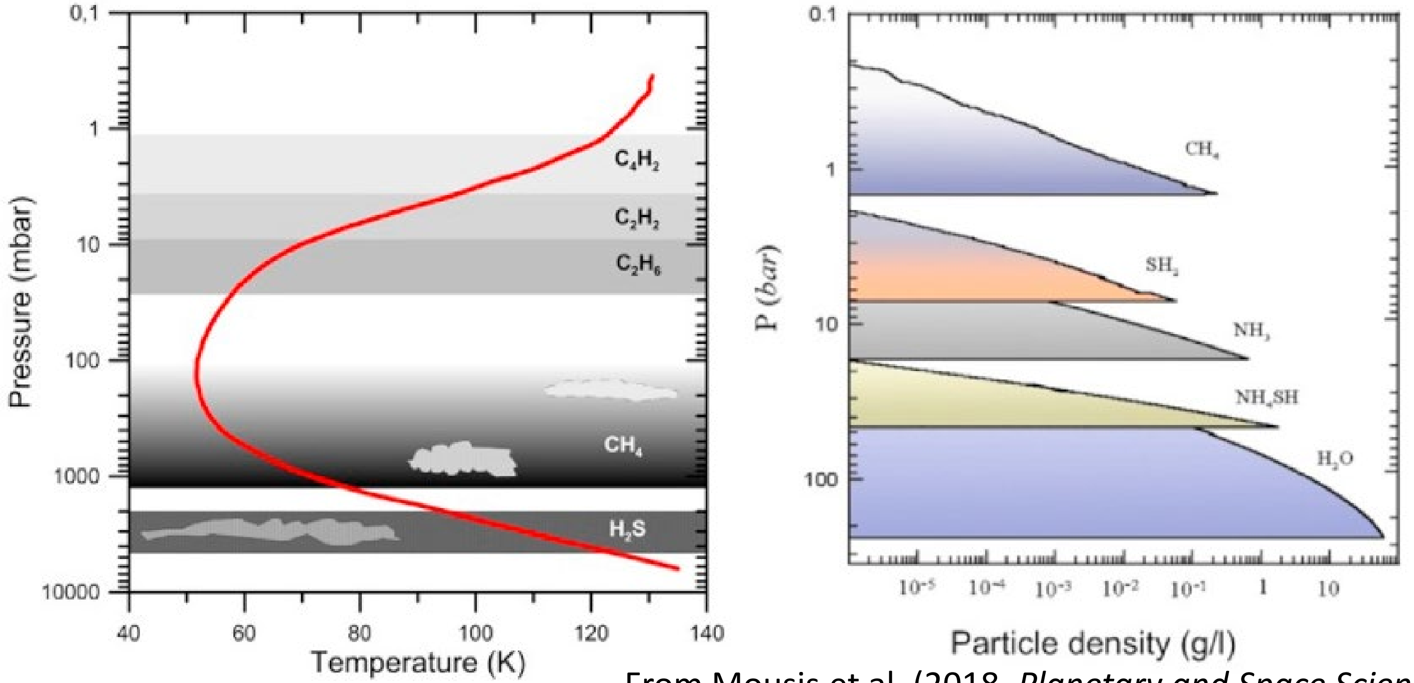
# Missing Key:
# Noble Gas and Isotopic Ratios



From Mousis et al. (2018, *Planetary and Space Science*)

Noble Gas and Isotopic Ratios have not been measured at Saturn, Uranus and Neptune

# How do clouds with 5 Condensibles Form Layers and Interact?

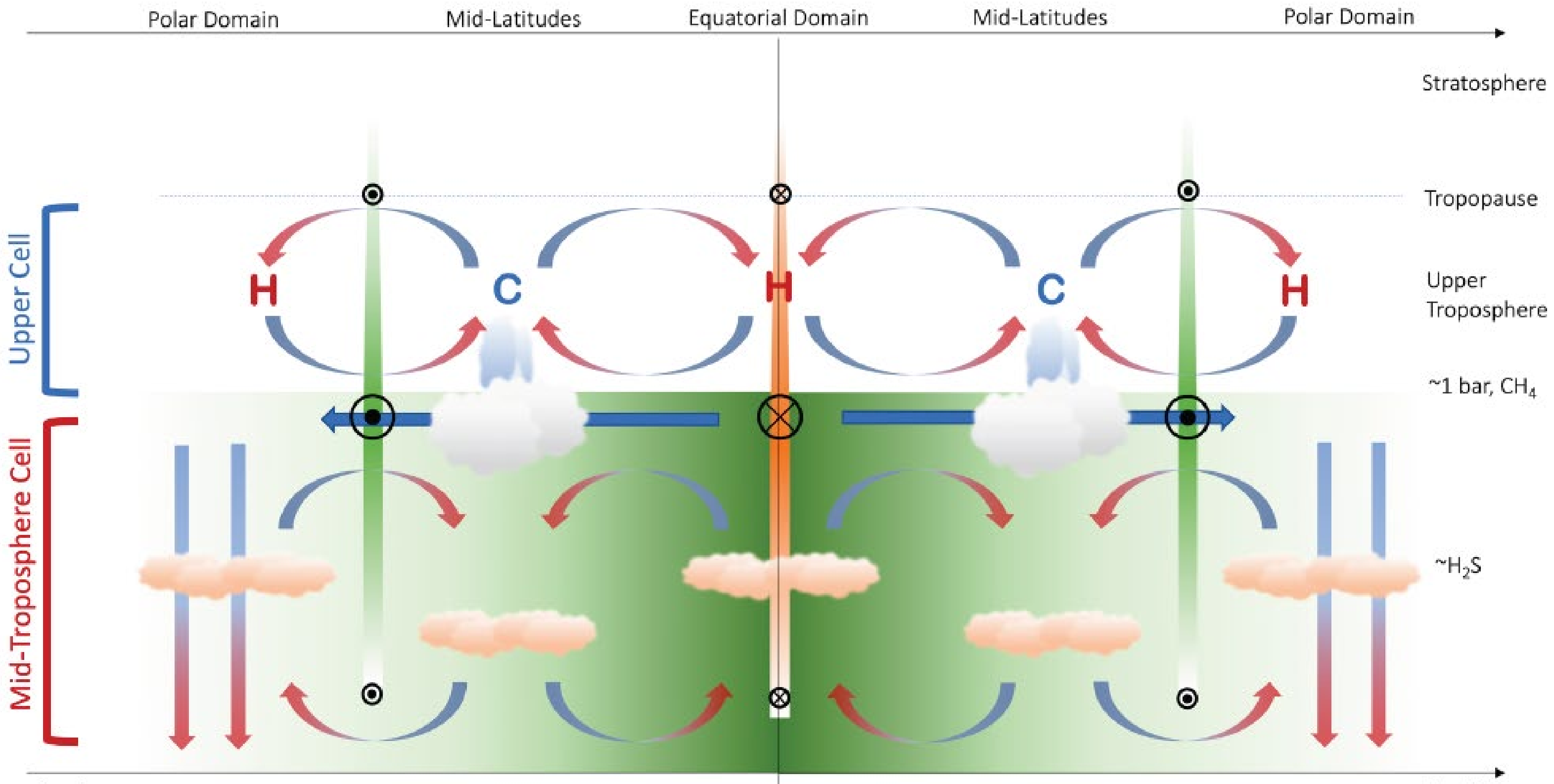


From Mousis et al. (2018, *Planetary and Space Science*)

There are 5 condensable species on Uranus:
$CH_4$, $SH_2$, $NH_3$, $NH_4SH$, $H_2O$

Earth has one ($H_2O$)!

# How does the Atmosphere Circulate on Uranus?

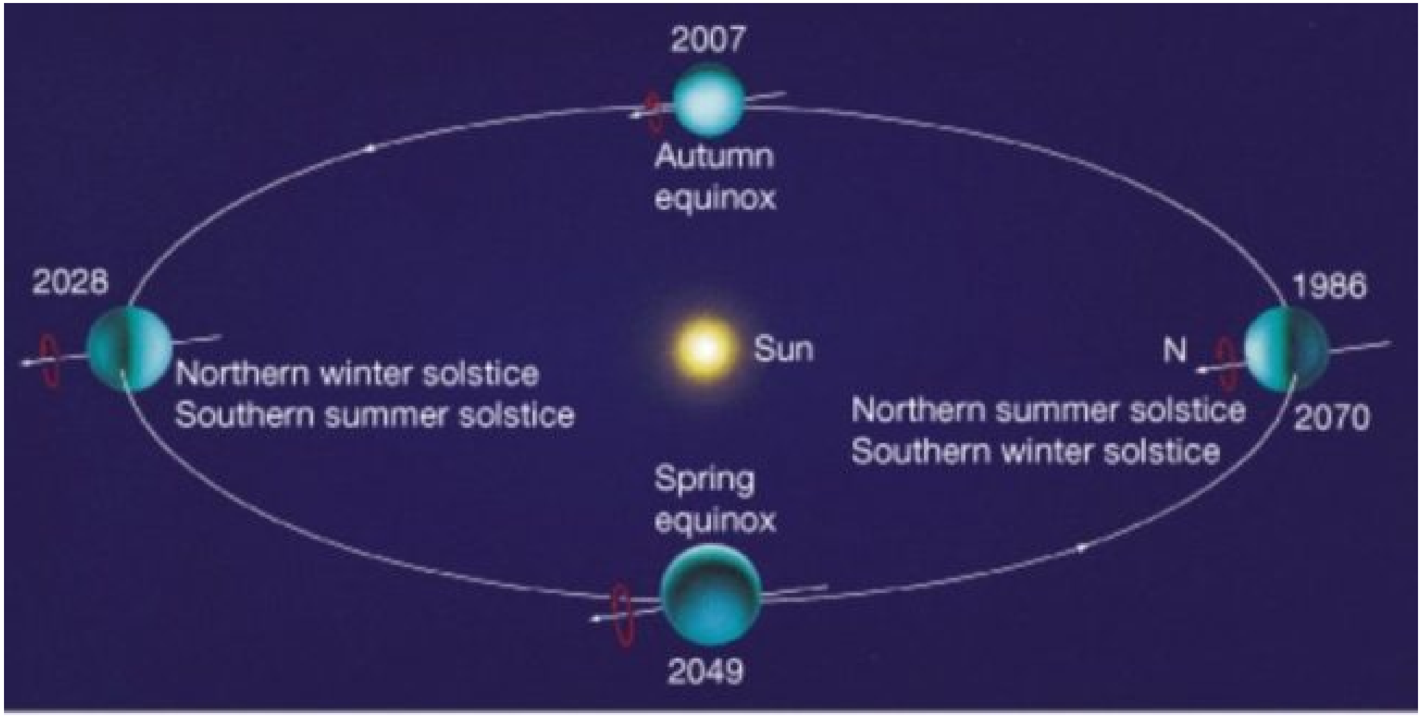


From Fletcher et al. (2019, *to be published in Space Science Reviews*)

Hypothesized stacked "Hadley"-like Circulation

→ How does the circulation evolve with season?

# Seasons on Uranus



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# Review: Probe Scientific Objectives

**Atmos. Composition - Formation and Evolution**

- Noble Gas
- Isotopic Ratios

**Thermal Structure and Energy Balance**

- Temperature vs. Pressure
- Radiative Flux

**Role of Clouds/Haze/Aerosols**

- Composition & Light Scattering Properties of Aerosols
- Vertical Distribution of Aerosols and Vapors

**Atmospheric Dynamics**

- Zonal Circulation
- Meridional Circulation
- Vertical Mixing of Disequilibrium Species

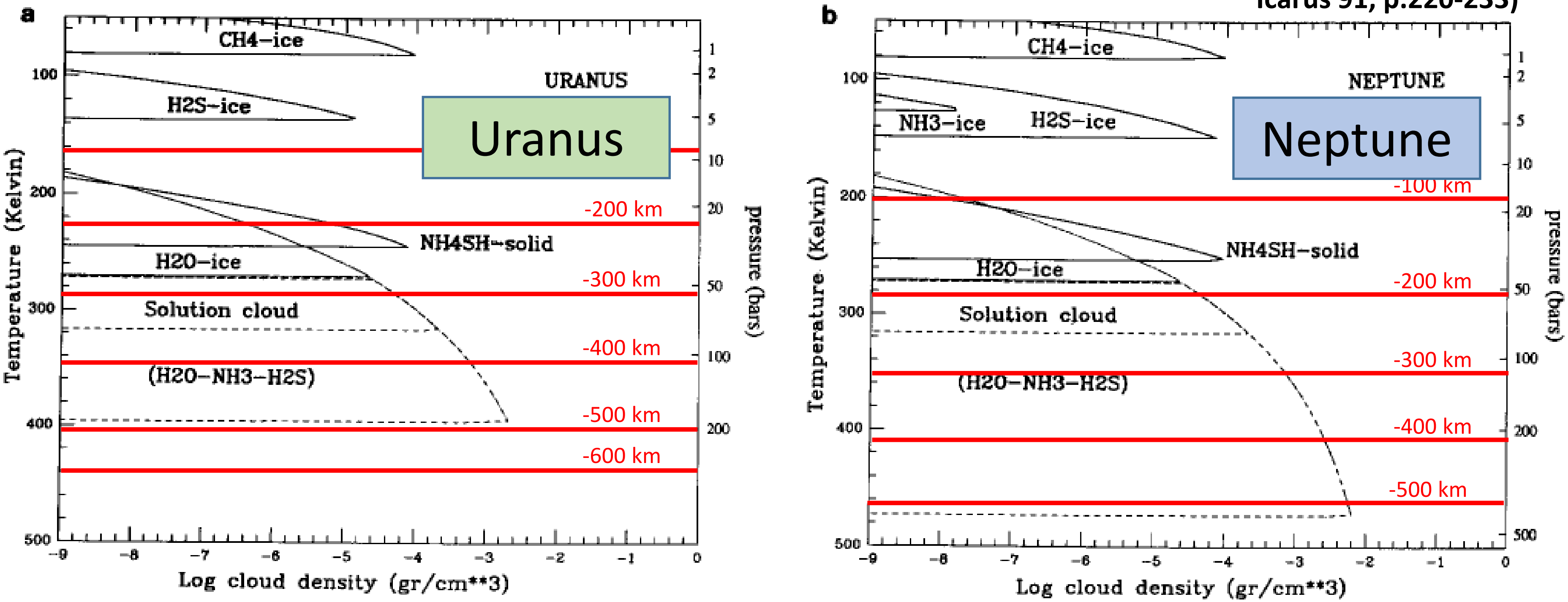
# Review: Key Observables

| →<br>Science Objectives:<br>→<br>↓ Observables ↓ | Atmospheric Composition | Formation & Evo. | Thermal Structure + Energy Balance | Clouds | Zonal Circ. | Meridional Circ. | Vertical Mixing | Local Turbulence |
|---|---|---|---|---|---|---|---|---|
| **Noble Gas Abundance** | X | X | | | | | | |
| **Isotopic Ratios** | | X | | | | | | |
| **Volatile Molecule Abundance** | X | | X | X | | X | X | |
| **Cloud/Haze/Aerosol Properties** | | | | X | | X | X | |
| **Disequilibrium Species Concentration** | | | | | | X | X | |
| **Temperature vs. Pressure/Density** | | | X | X | | | X | |
| **Radiative Flux** | | | X | X | | | | |
| **Horizontal Wind Speed** | | | | | X | | | |
| **Probe Descent Speed+Accel.** | | | | | | | X | X |

# Question #1: How deep do probe(s) need to reach?

**Predicted Altitudes and Densities of clouds in Uranus and Neptune**

de Pater et al. (1991
Icarus 91, p.220-233)

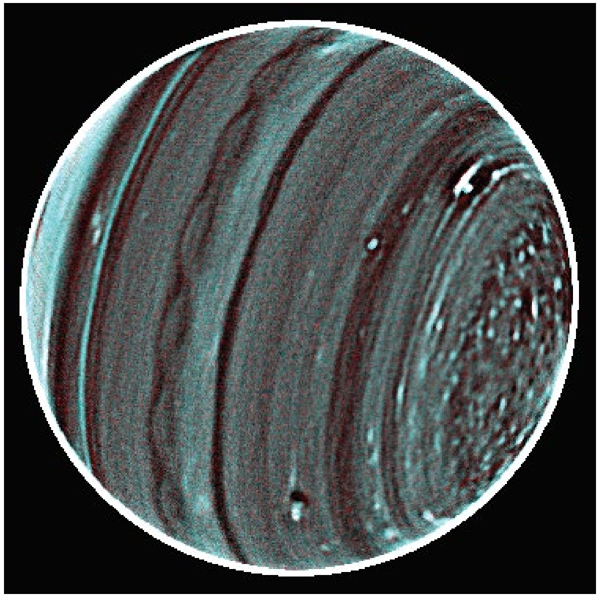


**Sampling CH4-ice and H2S-ice clouds is possible with 10-bar probes, <100 km below 1-bar.**
**Sampling H2O-ice requires ~50-bar, 200-300 km below 1-bar.**
**Reaching below all clouds requires descent to 200-500 bar pressure, >500km below 1-bar.**

# Question #2: Which Latitude(s)? How many probes?

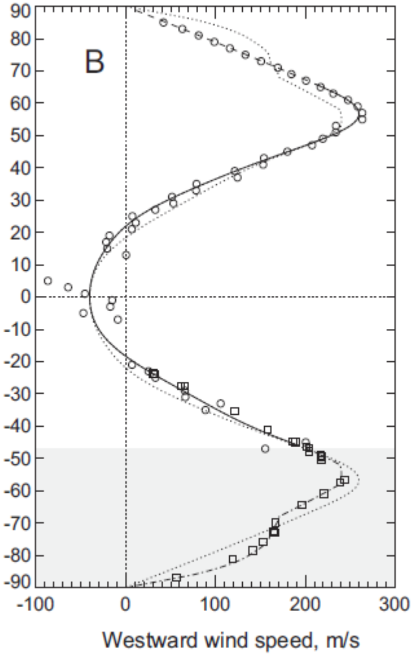
Example: Cloud bands and circulation on Uranus

Cloud Bands

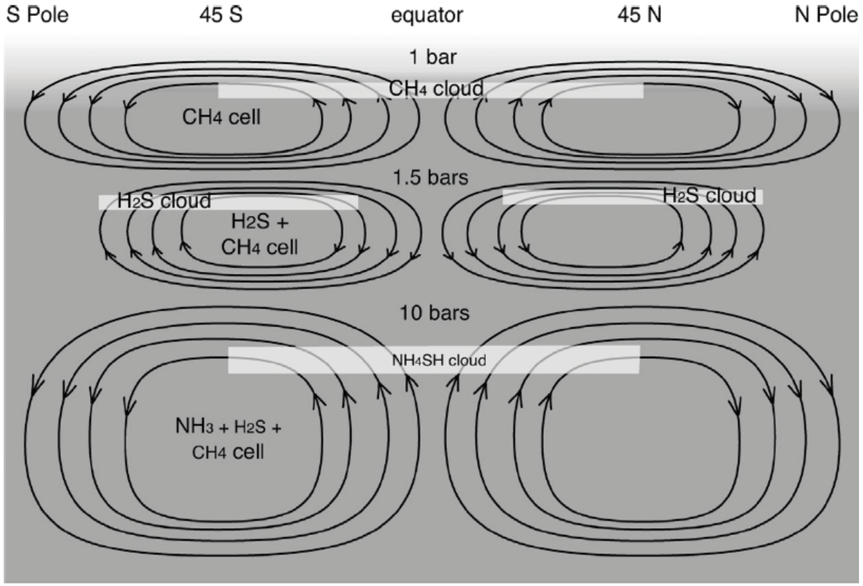


Sromovsky et al. (2015
Icarus 258, p.192–223)

Wind Bands



Meridional Circulation (Hypothesized)



Sromovsky et al. (2014
Icarus 258, p.137-155)

**Which cloud band(s) should we target?**
**Where do we best sample the zonal wind?**

**How do we best test meridional circulation?**
**What's the effect of Seasonal forcing?**

# Some quantities are Homogeneous

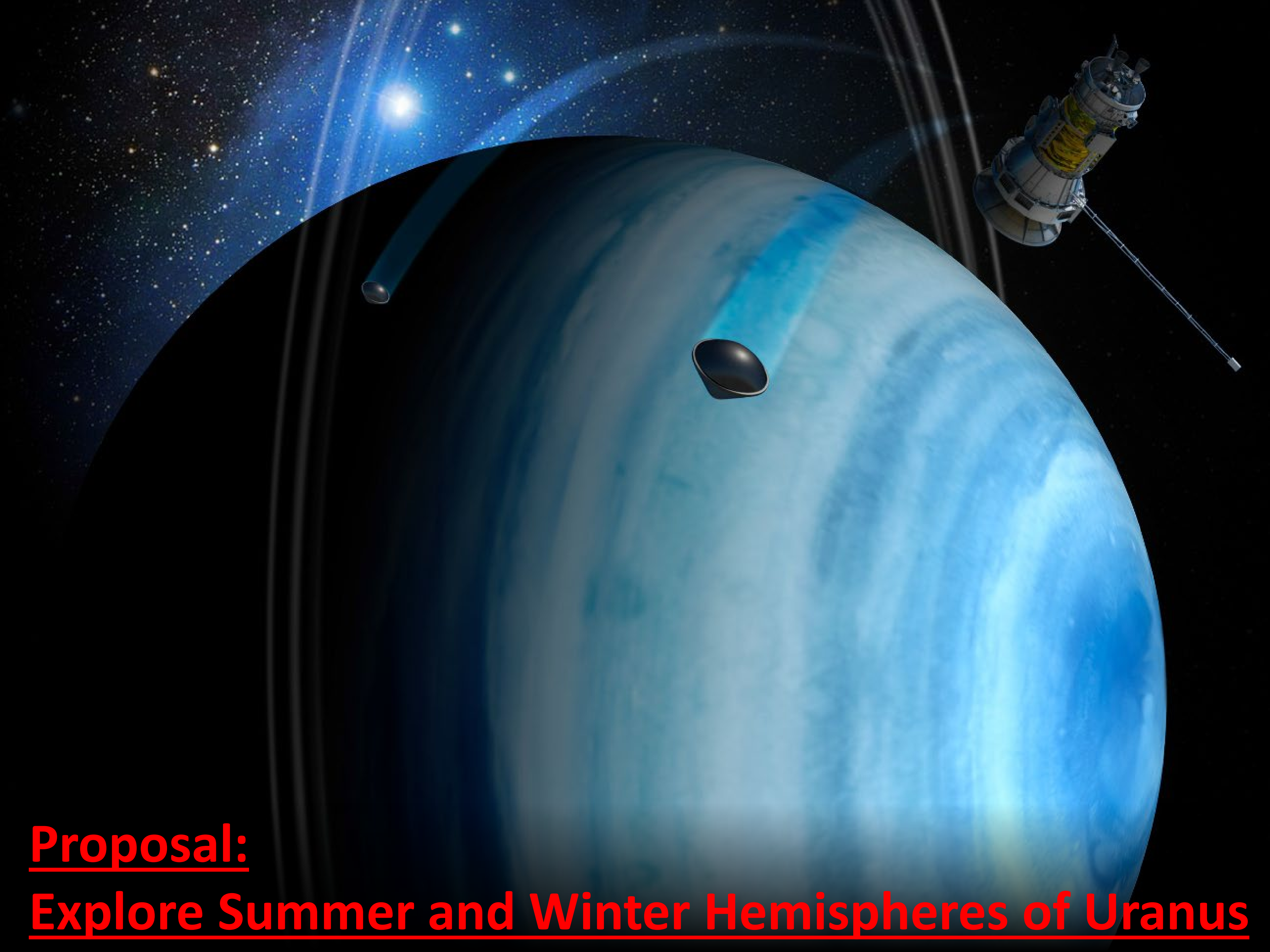
| Observable | Spatial Variation |
|---|---|
| Noble Gas Abundance | Spatially Homogeneous |
| Isotopic Ratios | |
| Volatile Molecule Abundance | Spatially Variable |
| Cloud/Haze/Aerosol Properties | |
| Disequilibrium Species Concentration | |
| Temperature vs. Pressure/Density | |
| Radiative Flux | |
| Horizontal Wind Speed | |
| Probe Descent Speed+Accel. | |
| Local Turbulence | |

**Spatially Homogeneous quantities do not need to be measured at multiple locations.**

# Review: Instruments

Red Letters = Usual Suspects

| Observable | Instruments |
|---|---|
| Noble Gas Abundance | Mass Spec, He Detector, Noble Gas Sensor |
| Isotopic Ratios | Mass Spec, TLS |
| Volatile Molecule Abundance | Mass Spec, TLS, Vapor Sensor |
| Cloud/Haze/Aerosol Properties | Nephelometer |
| Disequilib. Species Concentration | Ortho-Para Sensor, Vapor Sensor |
| Temperature vs. Pressure/Density | ASI |
| Radiative Flux | Net Flux Radiometer |
| Horizontal Wind Speed | USO/Doppler Wind Experiment |
| Probe Descent Speed+Accel. | ASI |



# Proposal:
# Explore Summer and Winter Hemispheres of Uranus

# Multi-Probe Missions

**Enable Future Multi-Probe Planetary Missions:**

- Advocated by Decadal Surveys
- Provide data on spatially varying atmospheric phenomena.
- **2003 Survey**: Advocated for a Jupiter Multi-Probe mission
- **2013 Survey:** Emphasized that a second probe can significantly enhance the scientific value of a probe mission
- Never realized due to perceived high-cost.
- SNAP Design applicable to Saturn, Uranus and Neptune (with possibilities for Venus)

**SNAP Enables Future Multi-Probe Missions**

**SNAP**

Small Next-generation Atmospheric Probe

# Multi-Probe Science Objectives

**Multi-Probe Shared Objectives:**

*Determine spatial variability in atmospheric properties:*

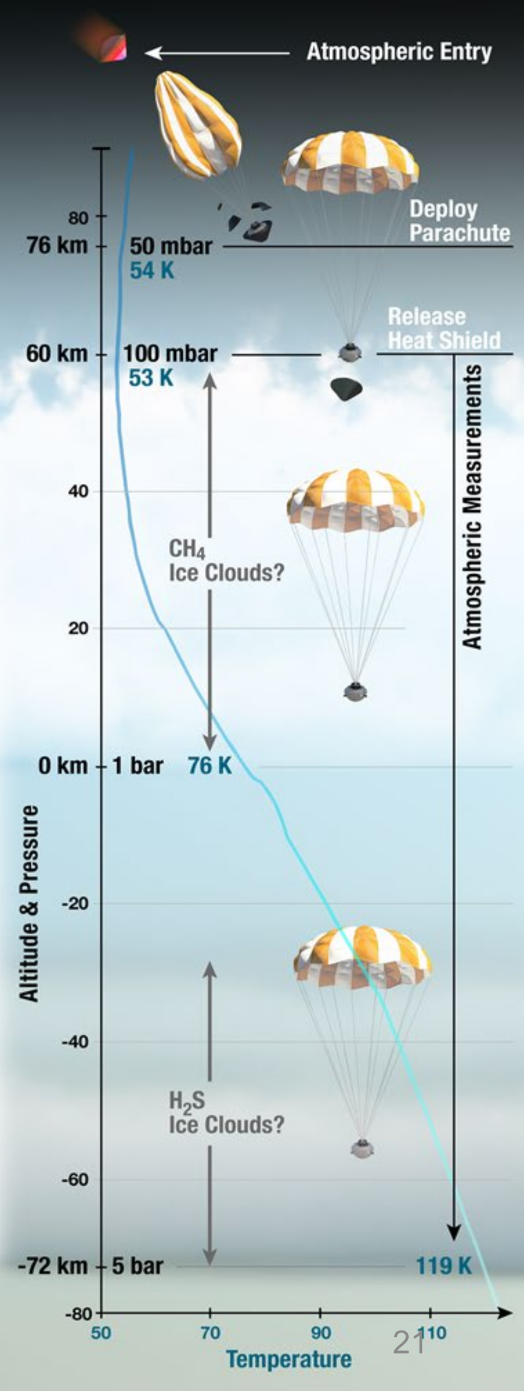
- Vertical distribution of cloud-forming molecules
- Thermal stratification and static stability
- Atmospheric dynamics as a function of depth

**Proposal: Probe Summer and Winter Hemispheres**

**Main Probe-only Objectives:**

*Determine Bulk Composition:*

- Measure abundances of the noble gases (He, Ne, Ar)
- Measure isotopic ratios of H, C, N, and S



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SNAP

Small Next-generation Atmospheric Probe

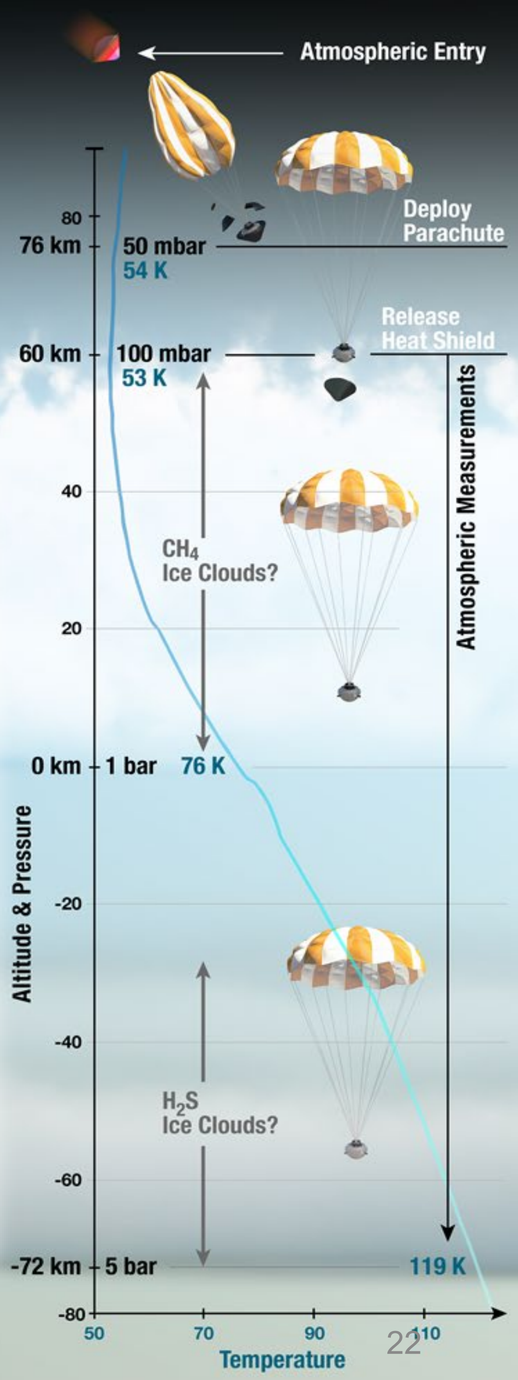
# Science Instruments

**Mass Spectrometer:**
Noble gas abundance and isotopic ratios

**NanoChem Atmospheric Composition Sensor:**
Vertical distribution of cloud-forming molecules

**Atmospheric Structure Instrument (ASI):**
Thermal stratification and static stability

**Ultra-Stable Oscillator (USO):**
Atmospheric dynamics as a function of depth
(Through Doppler Wind Experiment)

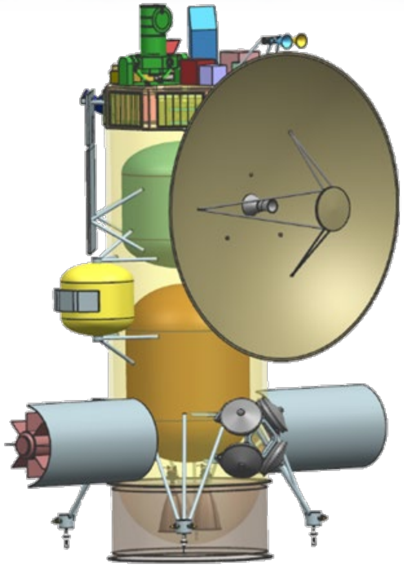


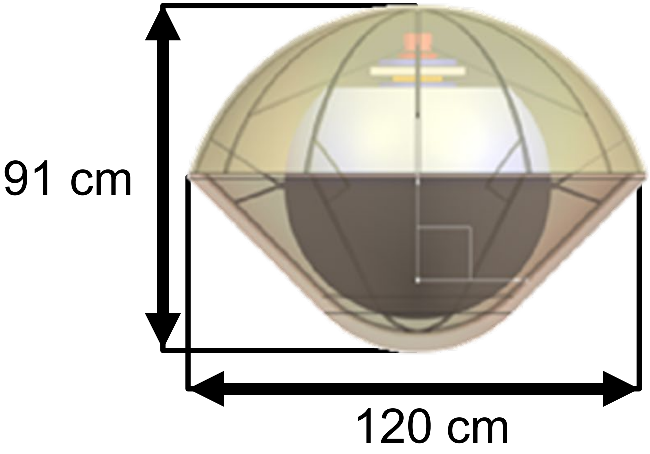
# Mission Design Assumptions

1. Baseline Carrier Mission: Uranus Orbiter with Probe Mission Architecture #5 by Ice Giants Flagship SDT:
    - 1913 kg Uranus Orbiter
    - All-chemical Propulsion (no SEP)
    - 50 kg Science Payload on Orbiter
    - 321 kg Probe (= Primary Probe = PP)
2. Add SNAP as a Second Probe
3. Deliver PP and SNAP at Uranus with large spatial separation
4. PP/SNAP and CRSC trajectories must enable data relay

# NASA’s Uranus Mission in 2030s

## From Ice Giant SDT Study





**Orbiter (CRSC)**

- Mass in orbit: 1913 kg
- Payload Mass: 50 kg
- UOI $r_p$: 1.05 $R_U$
- Orbital Period: ~142 days

**Primary Atm. Probe (PP)**

- Mass: 321 kg
- Diameter: 1.2 m, 45° sphere-cone
- 10-bar* pressure altitude
- Probe release: ~60 days
- EPFA: -20° to -50°

**Baseline Orbiter and Probe: Ice Giant SDT Architecture #5**

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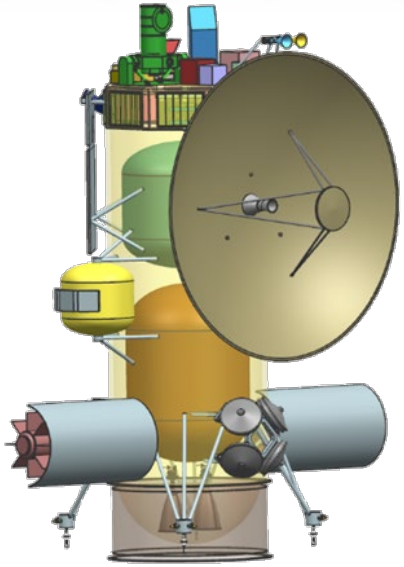
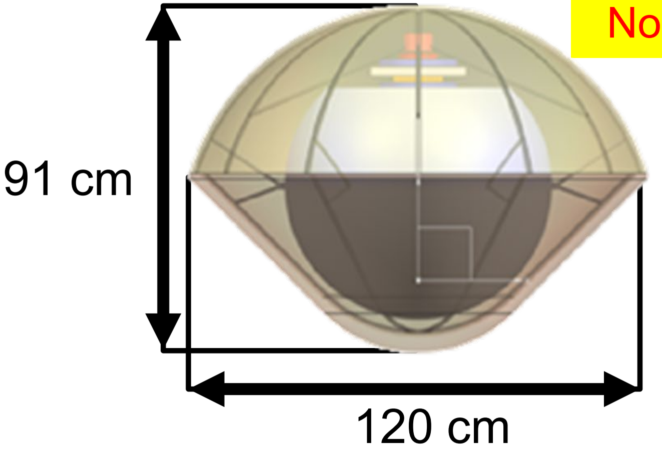
*10-bar is requirement for hardware operation for margin, science objective is to reach 5-bar.

# Add SNAP as a Second Probe

**From Ice Giant SDT Study**





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- Diameter: 1.2 m, 45° sphere-cone
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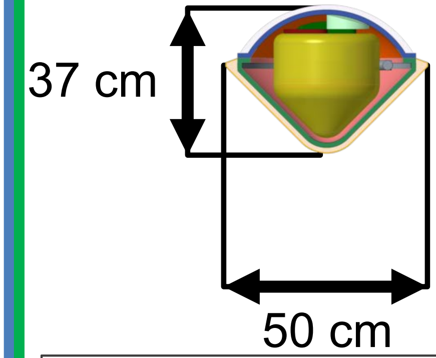
Baseline Orbiter and Probe: Ice Giant SDT Architecture #5

**SNAP**

Not to scale with Orbiter



**SNAP**

- Mass: 30 kg
- Diameter: 0.5 m, 45° sphere-cone
- 10-bar* pressure altitude
- Probe release: 30–60 days
- EPFA: -20° to -50°

*10-bar is requirement for hardware operation for margin, science objective is to reach 5-bar.

# Challenges of Multi-Probe Missions

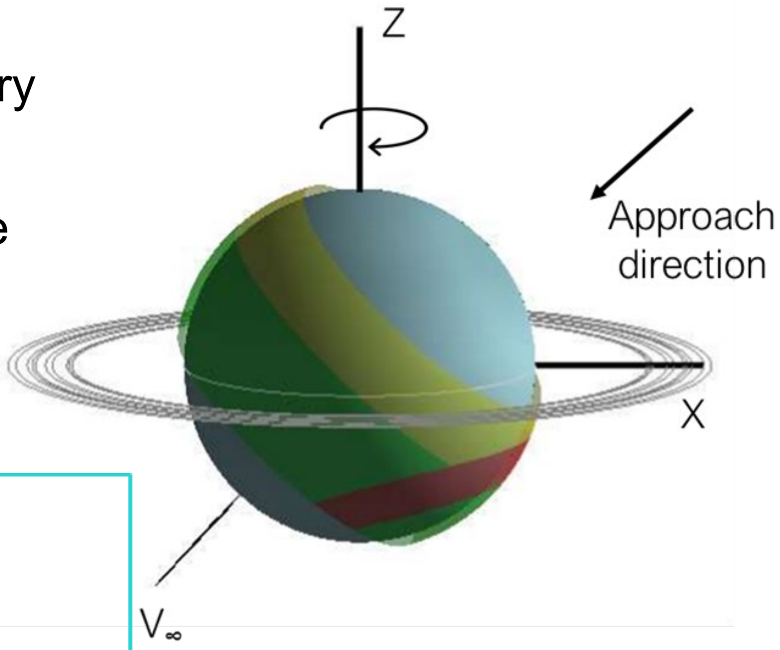
- Deliver Primary Probe and SNAP at two significantly different locations (**latitude**, longitude, time-of-day)

- During each probe’s atmospheric descent:
  - Orbiter used to receive data from probe, relay to Earth
  - Orbiter must be within 30 degree comm. cone around zenith.
  - Each probe must reach at >5-bar while Orbiter is in 30-deg cone.

# Uranus Entry Locations

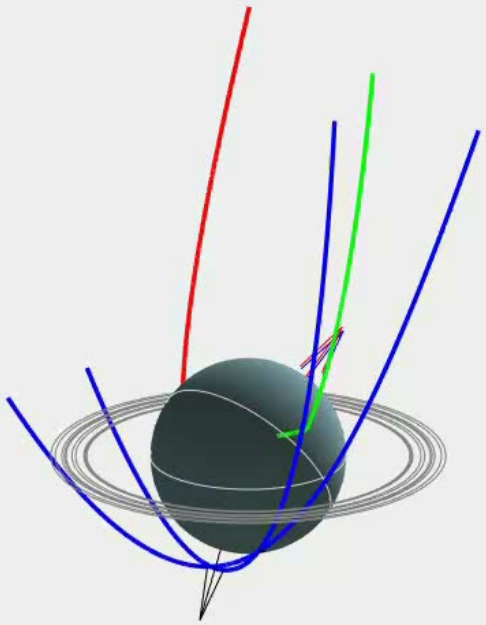
**Accessibility of Entry Locations**

- Trajectory gives access to a wide range of latitudes and spatial distribution for the entry probes
- One probe can enter the night side and the other on the day side (After 2028 Northern Summer Solstice)



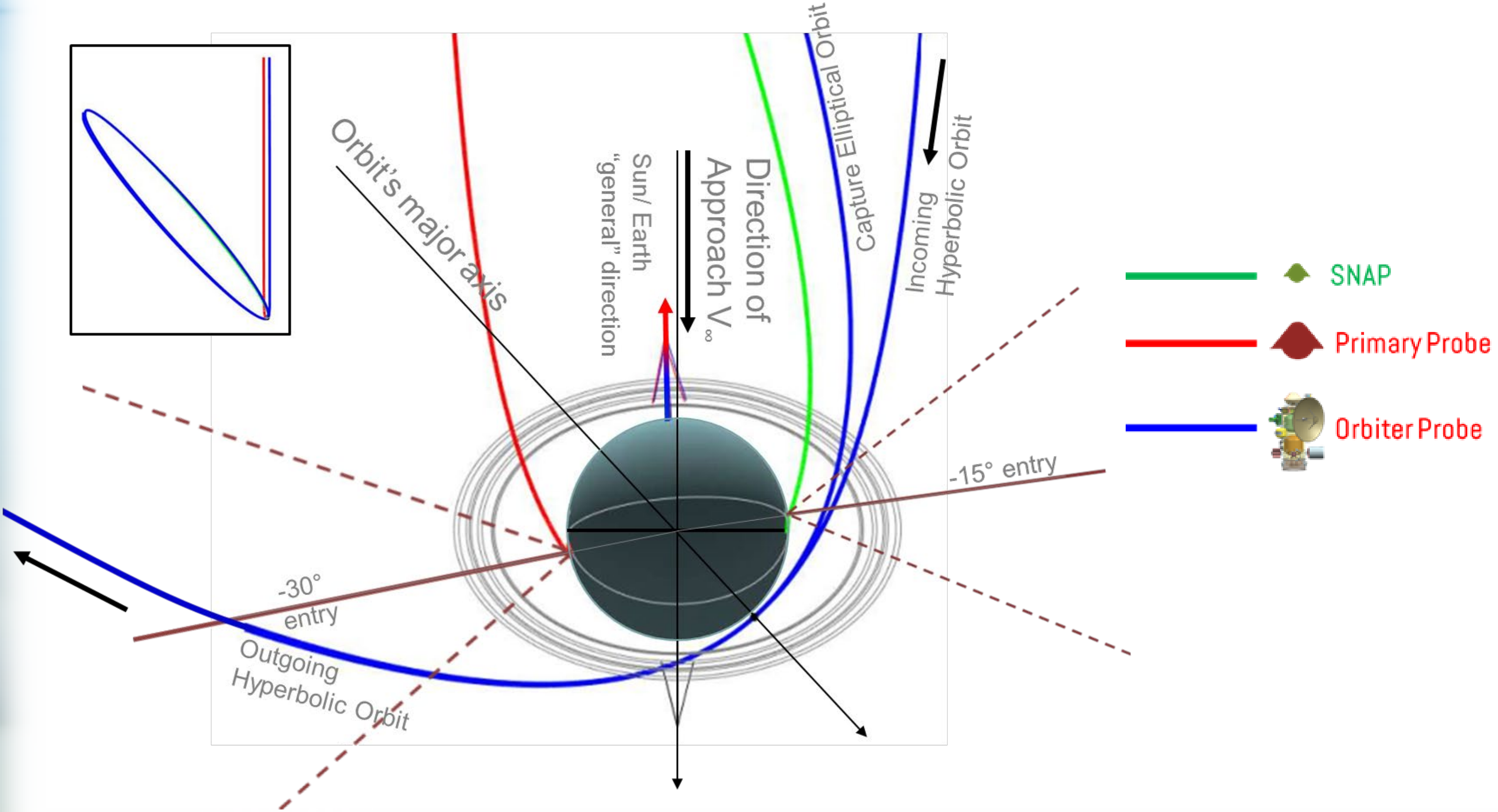
Red: Crosses rings
Yellow: Exceeds 200g during entry
Green: Feasible

# Dual Probe Delivery Trajectory

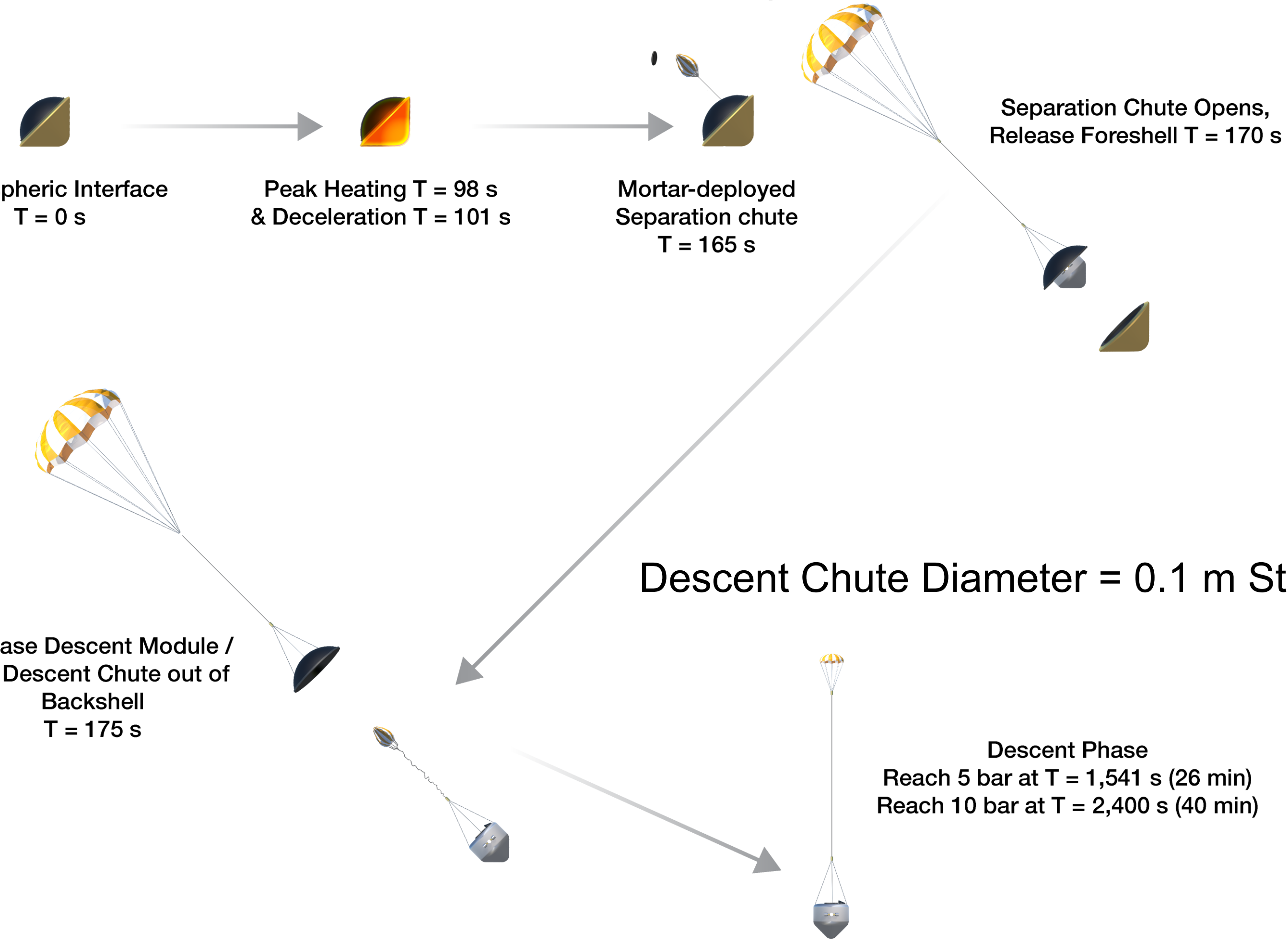


# Dual-Probe Delivery Trajectories

## Trajectory Solution to add SNAP to Ice Giant SDT Architecture #5



# Atmospheric Entry & Descent



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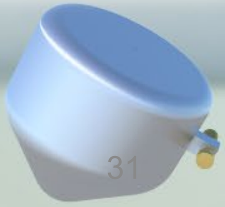
Descent Chute Diameter = 0.1 m Stabilizer

Descent Phase
Reach 5 bar at T = 1,541 s (26 min)
Reach 10 bar at T = 2,400 s (40 min)

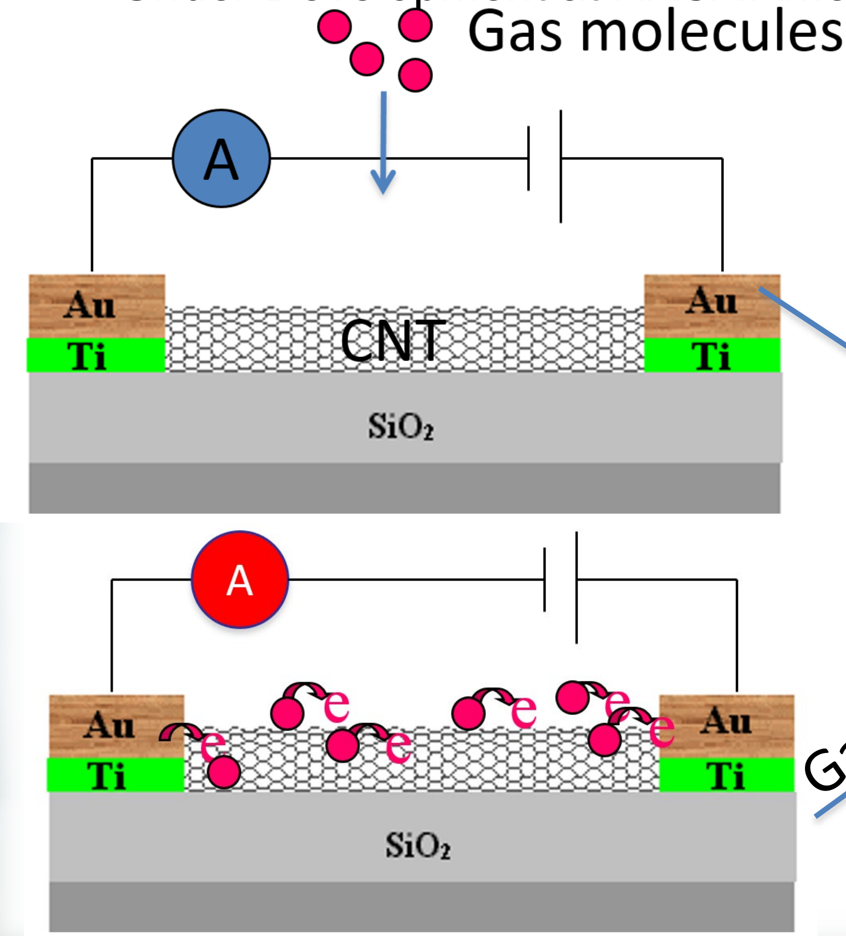
# Science Instruments

| Instrument | Measurement | Mass | Power | SNAP Data Return |
|---|---|---|---|---|
| **NanoChem** | Atmospheric Composition | 1.0 kg | 1 W | 0.6 Mbit |
| **Atmospheric Structure Instrument** | Pressure<br>Temperature<br>Acceleration | 1.3 kg | 5 W | 4.5 Mbit |
| **Ultra-Stable Oscillator** | Doppler Wind Experiment | 1.7 kg | 3 W | 0.03 Mbit (Housekeeping Only) |
| **Total** | | **4 kg** | **9 W** | **5.1 Mbit** |



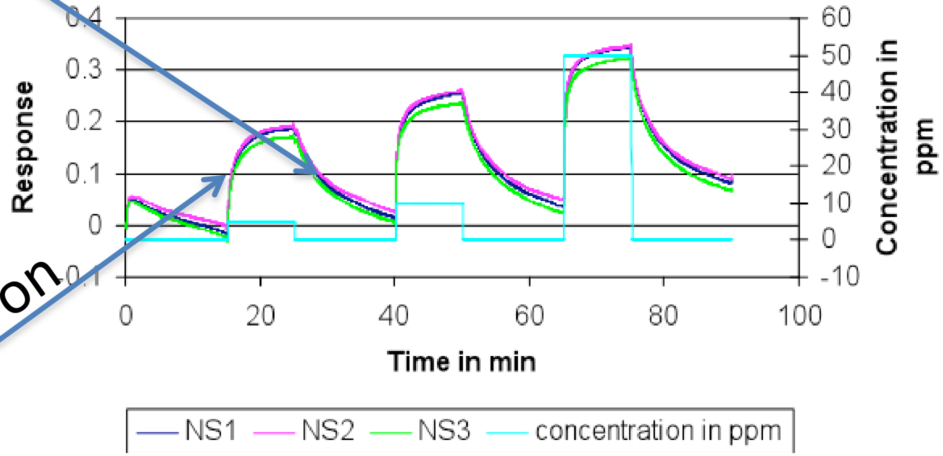
# NanoChem: How it works

- Measures <u>Changes in Resistivity</u> in response to vapor concentration
- Sensor Heads can be arrayed up to 16 x16 grid on a single chip
- Under Development at NASA Ames (PI: Jing Li)



**<u>NanoChem Advantages:</u>**

- Small Sensor Package
- Low Mass, Lowe Power
- Can operate without Vacuum Pump



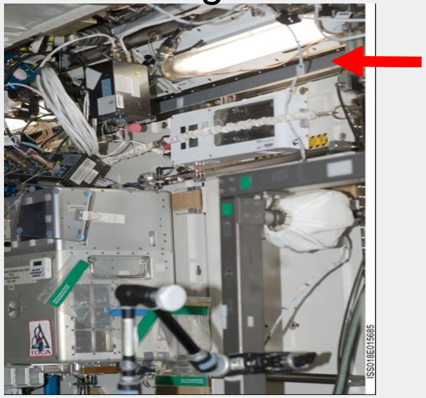
NanoChem response to ammonia

# NanoChem: TRL = 4 Today

**Launched and Operated in Space**

Navy MidSTAR-1 satellite in 2007

Environmental Monitoring on ISS



Sensitivity demonstrated for:

… $CH_4$, $H_2O$, and $NH_3$, among others

… in Mars and Earth conditions

Need to

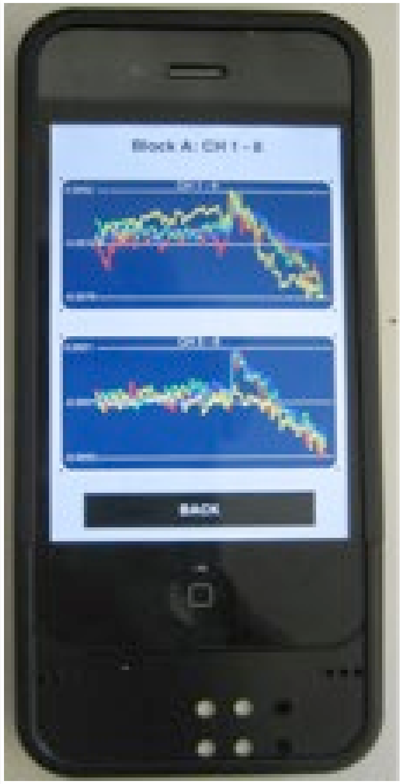
…develop sensitivities for $H_2S$

… demo in Giant Planet Conditions

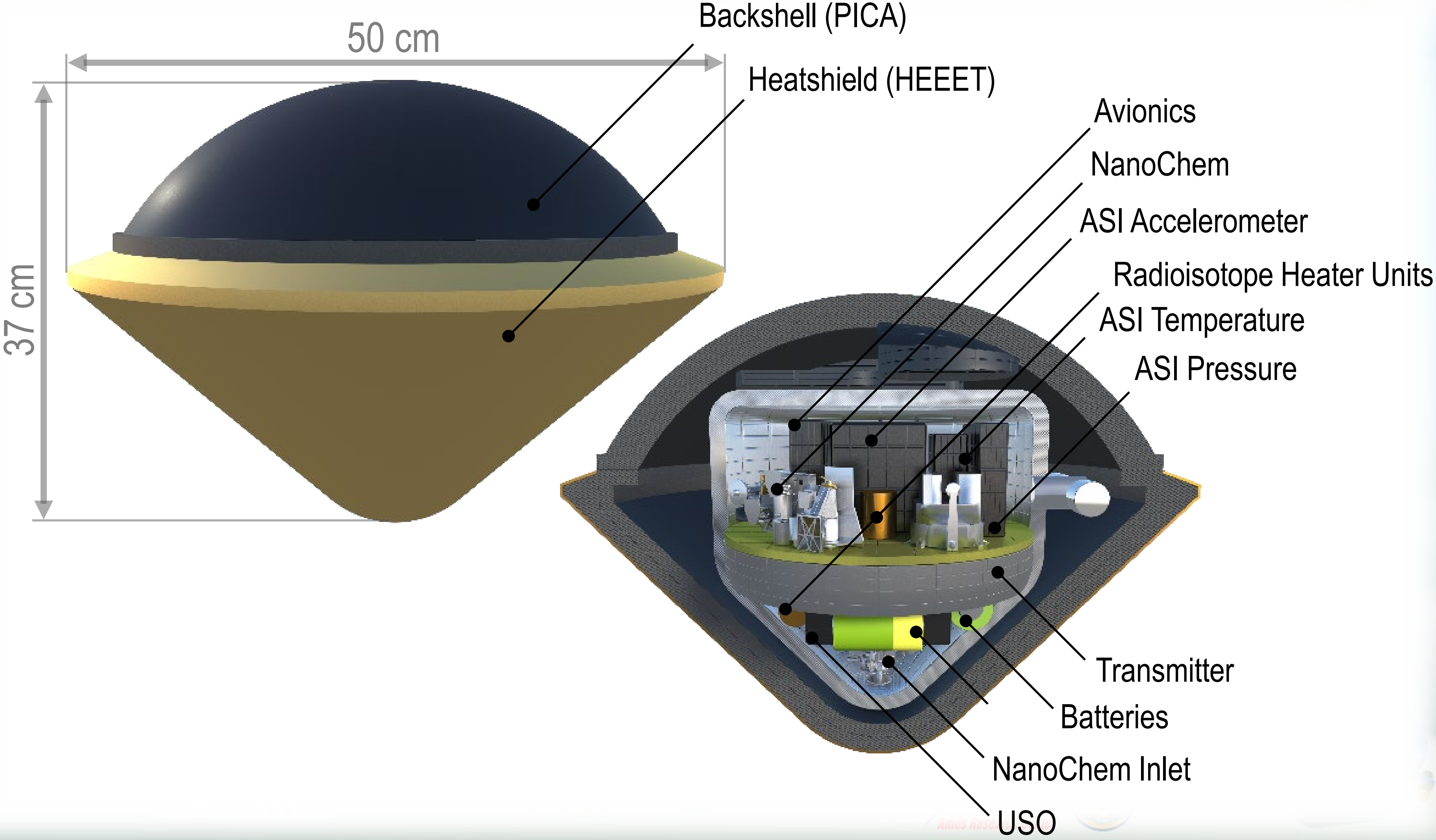
| Analyte | Sensitivity/Detection Limit |
|---|---|
| $CH_4$ | 1 ppm in air |
| Hydrazine | 10 ppb tested |
| $NO_2$ | 4.6 ppb in air |
| $NH_3$ | 0.5 ppm in air |
| $SO_2$ | 25 ppm in air |
| HCl | 5 ppm in air |
| Formaldehyde | 10 ppb in air |
| Acetone | 10 ppm in air |
| Benzene | 20 ppm in air |
| $Cl_2$ | 0.5 ppm in $N_2$ |
| HCN | 10 ppm in $N_2$ |
| Malathion | Open bottle in air |
| Diazinon | Open bottle in air |
| Toluene | 1 ppm in air |
| Nitrotoluene | 256 ppb in $N_2$ |
| $H_2O_2$ | 3.7 ppm in air |

# NanoChem Commercialization

- Development at NASA Ames
  PI: Jing Li
- A/D on NanoChem Attachment
- Power from Phone (~mW)
- Processing on the Phone
- High sensitivity – ppb to ppm
- Data Transmission through
  Cellular Network



# Baseline Hardware Configuration



50 cm

37 cm

Backshell (PICA)

Heatshield (HEEET)

Avionics

NanoChem

ASI Accelerometer

Radioisotope Heater Units

ASI Temperature

ASI Pressure

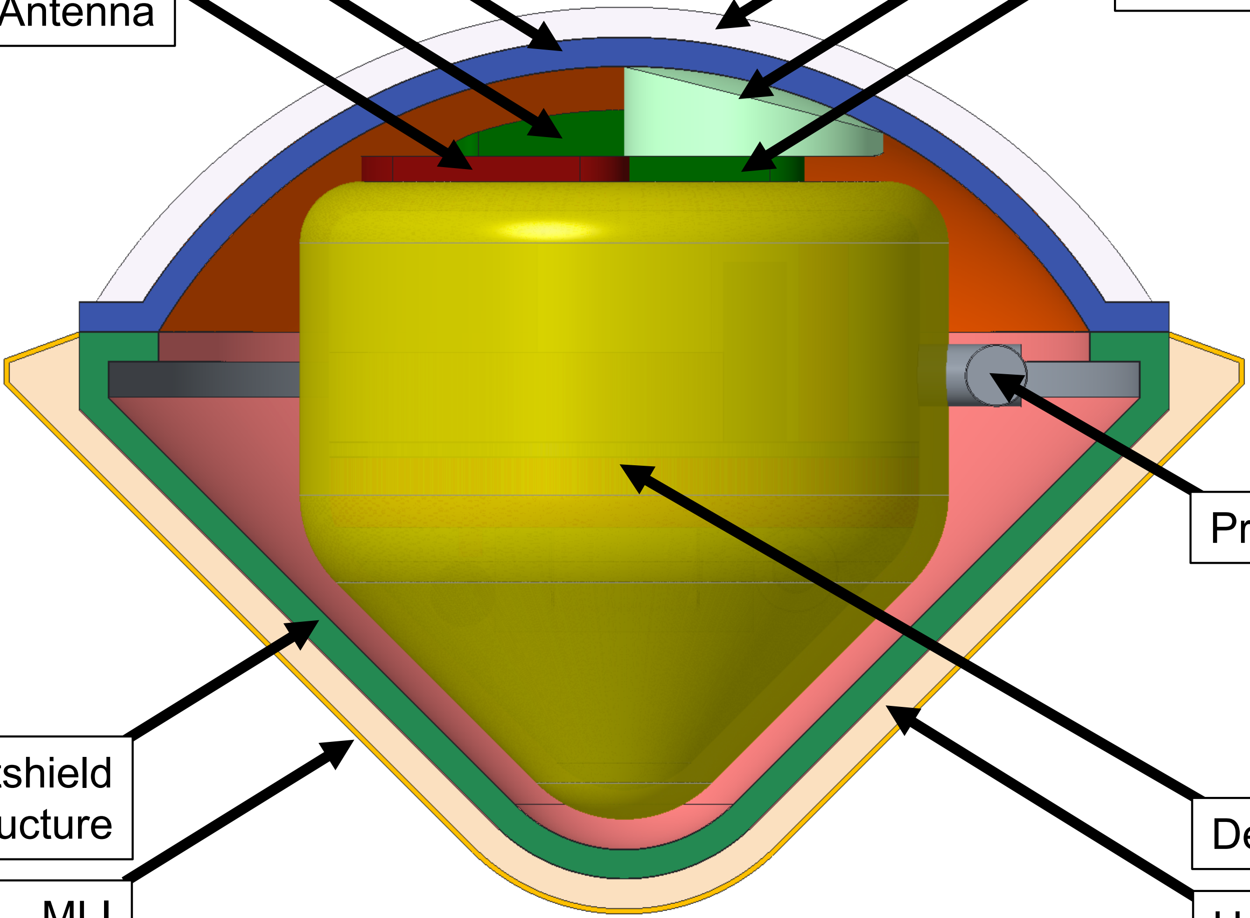
Transmitter

Batteries

NanoChem Inlet

USO

# Baseline Hardware Configuration



Backshell Structure

Descent Chute

Antenna

Heatshield Structure

MLI

Backshell (PICA)

Separation Chute

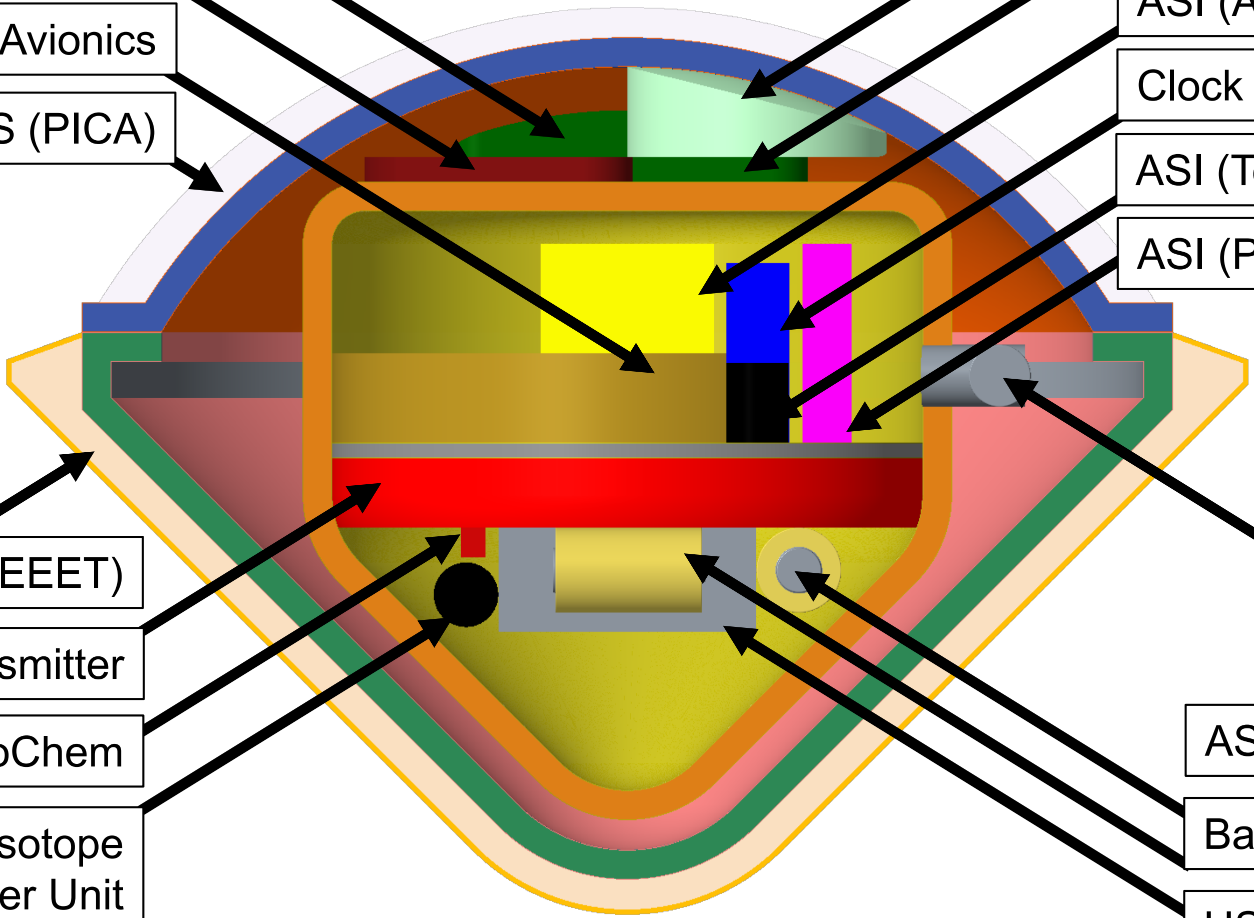
Chute Mortar

Pressure Sensor

Descent Module

Heatshield (HEEET)

# Baseline Hardware Configuration



Descent Chute

Antenna

Avionics

TPS (PICA)

TPS (HEEET)

Transmitter

NanoChem

Radio-Isotope
Heater Unit

Separation Chute

Chute Mortar

ASI (Accelerometer)

Clock

ASI (Temperature)

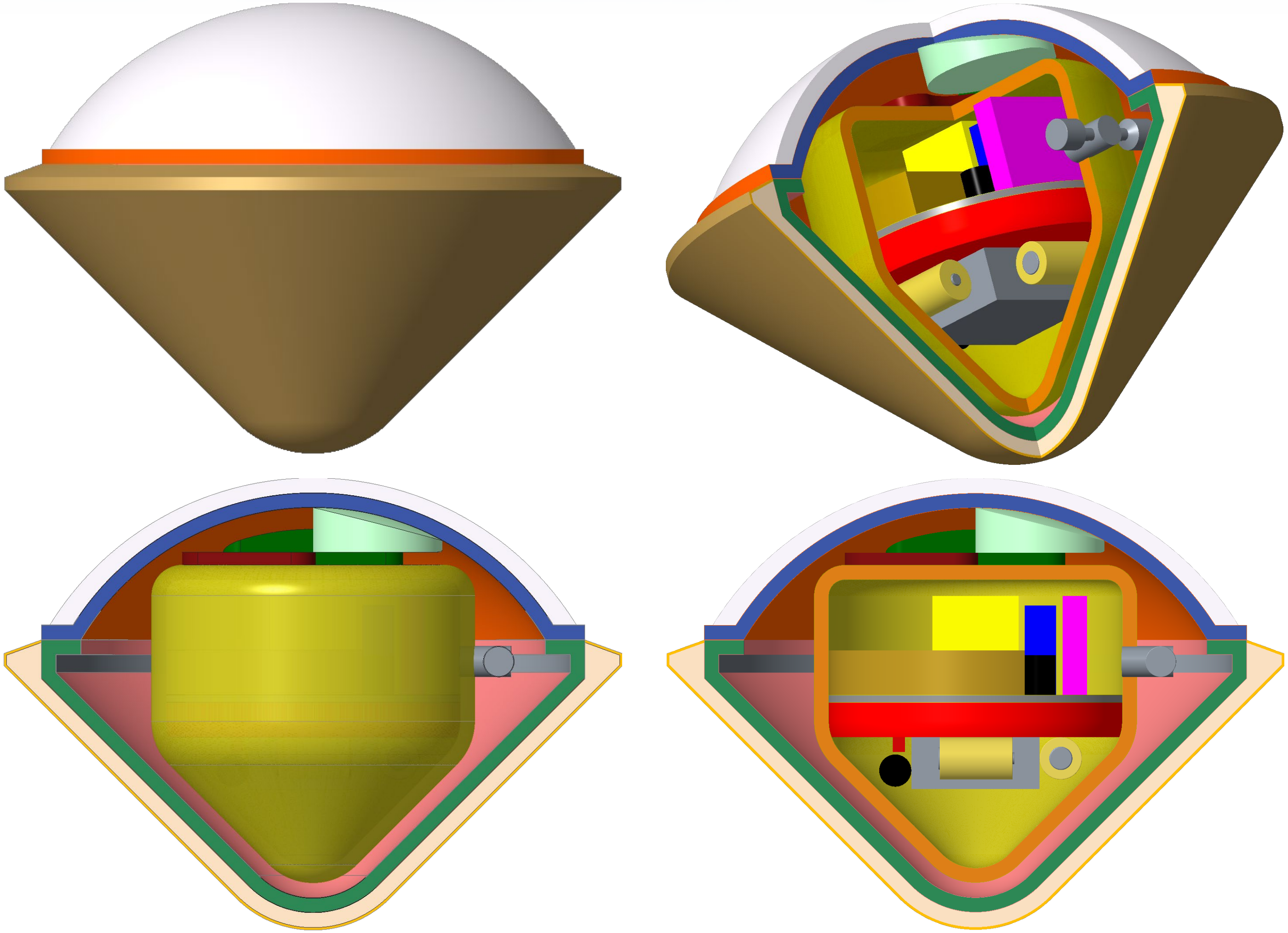
ASI (Pressure)

ASI Inlet Mast

Batteries

USO

# Baseline Hardware Configuration



# Probe Mass Summary

| Subsystem | CBE (kg) | +30% MGA (kg) | +15% Margin (kg) |
|---:|---:|---:|---:|
| Forebody TPS (HEEET) | 3.7 | 4.9 | 5.6 |
| Forebody Structure | 2.0 | 2.6 | 3.0 |
| Backshell TPS (PICA) | 0.7 | 0.8 | 1.0 |
| Backshell Structure | 1.4 | 1.8 | 2.1 |
| Separation Parachute & Mortar | 1.3 | 1.7 | 1.9 |
| Separation System | 0.8 | 1.0 | 1.2 |
| Aeroshell Total | 9.9 | 12.9 | 14.8 |
| Descent Module Structure | 1.4 | 1.8 | 2.1 |
| Descent Parachute | 0.4 | 0.6 | 0.6 |
| Science Instruments | 4.4 | 5.7 | 6.6 |
| Engineering Systems | 3.93 | 5.1 | 5.9 |
| Descent Module Total | 10.2 | 13.2 | 15.2 |
| Total Mass Entry Mass | 20.1 | 26.1 | 30.0 |

# SNAP Design Summary

**Dual-Probe Trajectory Solutions Found**

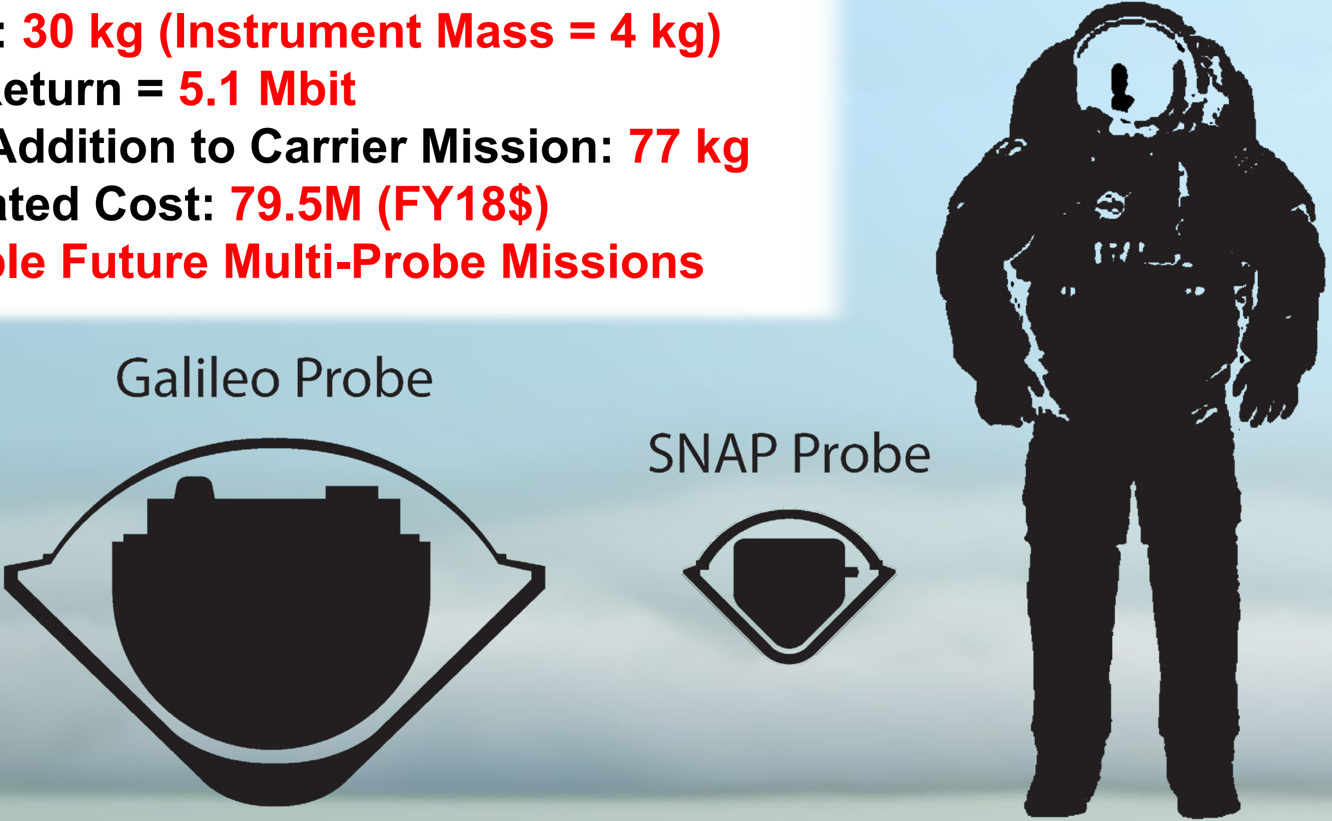
**SNAP Mass: 30 kg (Instrument Mass = 4 kg)**

**Total Data Return = 5.1 Mbit**

**Total Mass Addition to Carrier Mission: 77 kg**

**Total Estimated Cost: 79.5M (FY18$)**

**SNAP: Enable Future Multi-Probe Missions**

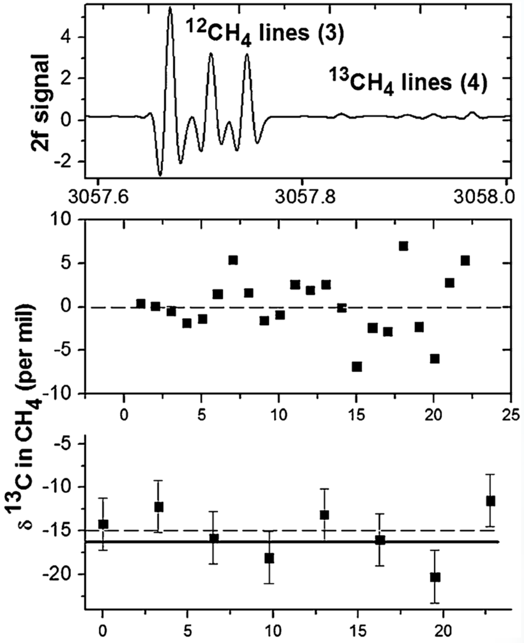


# A little bit about
# Tunable Laser Spectrometer (TLS)

- Shoot a tunable laser through gas sample
- Scan wavelength around an absorption line
- (Usually) One tunable laser required for one target gas molecule

**Table 10** TLS measurement capability

| Channel | Wavelength | Scan name | 15 minute predicted capability |
|---|---|---|---|
| 1-IC laser | 3.3 µm | Methane | to 0.3 ppbv<br>$\delta^{13}$C to 2 per mil |
| 2-Near IR laser | 2.785 µm | Carbon dioxide | to 0.2 ppmv in $CO_2$ and $H_2O$<br>$\delta^{13}$C to 2 per mil<br>$\delta^{18}$O to 3 per mil<br>$\delta^{17}$O to 5 per mil |
|  | 2.783 µm | Water | $H_2O$ to 0.1 ppmv<br>$\delta$D to 2 per mil<br>$\delta^{18}$O to 3 per mil<br>$\delta^{17}$O to 5 per mil |

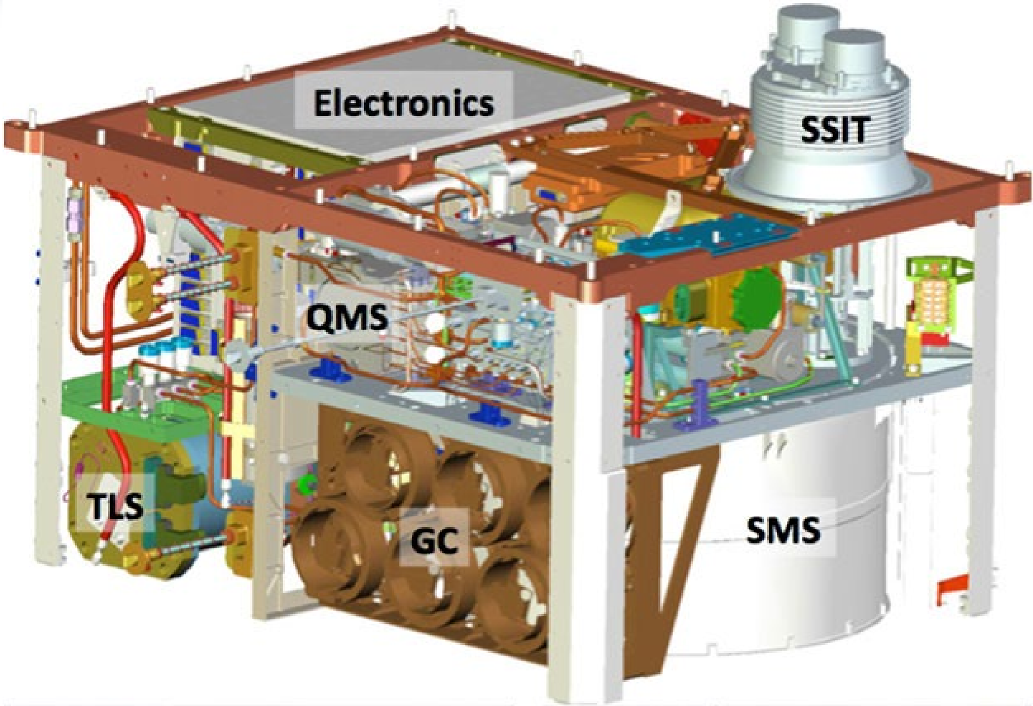


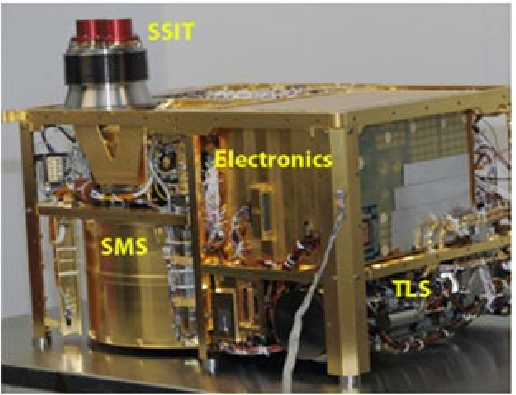
Example: Mars Curiosity SAM instrument (Mahaffy et al. 2012)

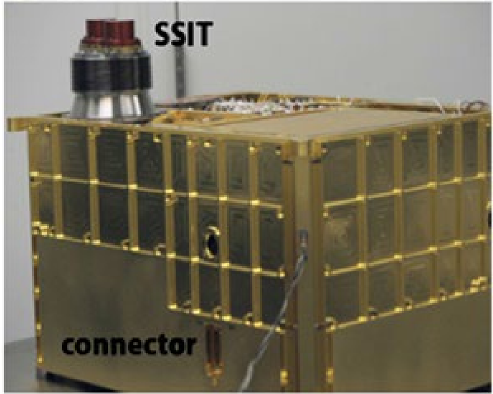
# Mars Curiosity SAM:
# State-of-the-Art Atmospheric Composition Instrument

Curiosity Sample Analysis at Mars (SAM):

- Combination of:
    - Quadrupole Mass Spec.
    - Gas Chromatograph
    - Tunable Laser Spec.
    - Solid Sample Inlet Tube
    - Solid Manipulation System
- 40 kg instrument mass
- Curiosity's Total Inst Mass = 75 kg
- SAM was >50% of total instr mass
- Curiosity total mass = 899 kg





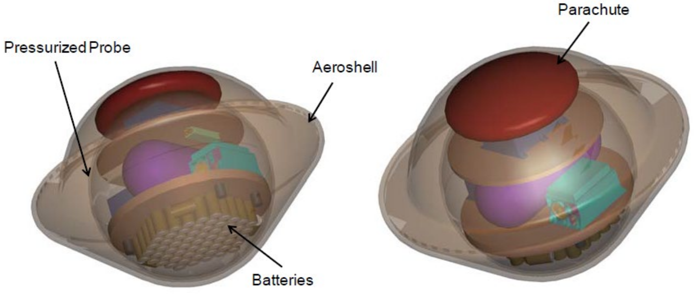


Mars Curiosity SAM instrument
(Mahaffy et al. 2012)

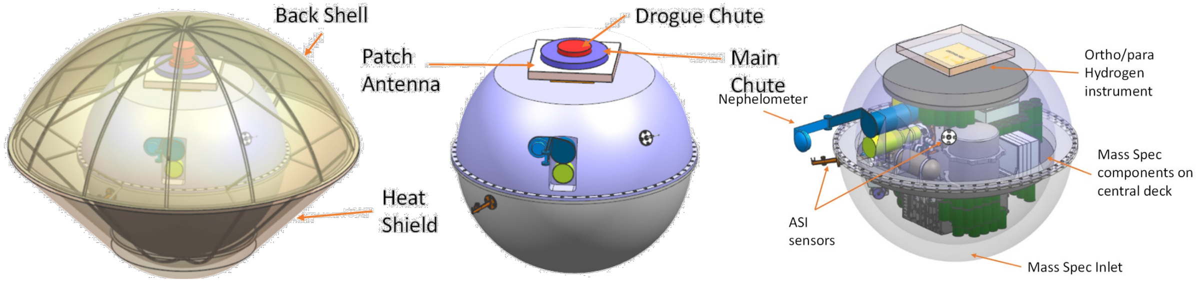
# Probe Design Comparison

- Design Considerations:
  - Instruments
    - Usual Suspects: Mass Spec, ASI, USO …
    - Mass Spec has large impact on probe mass.
  - Entry Latitude & Depth
- Design Comparisons
  - Galileo Probe
  - Huygens
  - 2010 Decadal Uranus Orbiter and Probe
  - 2017 Ice Giant SDT Study
  - SNAP

2010 Decadal Uranus Orbiter and Probe



2017 Ice Giant SDT Study



# Probe Mass Comparison

| Missions | Atmos. Entry Mass | Entry Sys. | Descent Module | | | | |
|---|---|---|---|---|---|---|---|
| | CBE +Conting. +Margin | Aeroshell + Chutes | Instruments | Inst. Mass | Mass Spec Mass | Non-MS Inst. Mass | Battery |
| Galileo Probe | 335 kg | 219 kg (65%) | MS, ASI, USO, HAD, Neph, NFR, Lightning, Energetic Particles | 35 kg (10 %) | 13.2 kg | 21.8 kg | 7.5 kg ($\text{Li-SO}_2$, 2.2%) |
| Huygens | 318 kg | 118 kg (37%) | GCMS, ASI, USO, DISR, Surface Sci. | 48 kg (15%) | 17.2 kg (+6 kg pyrolizer) | 24.2 kg | 13 kg ? ($\text{Li-SO}_2$, 4%) |
| 2010 Uranus Study | 127.1 kg | 40.8 kg (46%) | MS, ASI, Neph, USO | 17.1 kg (13%) | 9.2 kg | 7.9 kg | 11.3 kg ($\text{Li-SOCl}_2$, 9%) |
| 2017 IG SDT | 320.7 kg | 147.0 kg (46%) | GCMS, ASI, Neph, Ortho-Para | 32.5 kg (10%) | 17.4 kg | 15.1 kg | 17.1 kg (Li-Ion, 5.3%) |
| 2019 SNAP | 30 kg | 14.8 kg (49%) | NanoChem, ASI, USO | 6.6 kg (22%) | (No Mass Spec) | 6.6 kg | 0.34 kg (Li-CFx, 1.1 %) |

# Probe Mass Comparison

| Missions | Atmos. Entry Mass | Entry Sys. | Descent Module | | | | |
|---|---|---|---|---|---|---|---|
| | CBE +Conting. | Aeroshell | | Inst. | | Non-MS Inst. | Battery |
| Galileo Probe | | | | | | | 7.5 kg (Li-SO$_2$, 2.2%) |
| Huygens | | | | | | | 13 kg ? (Li-SO$_2$, 4%) |
| 2010 Uranus Study | | | | | | | 11.3 kg (Li-SOCl$_2$, 9%) |
| 2017 IG SDT | | | | | | | 17.1 kg (Li-Ion, 5.3%) |
| 2019 SNAP | 30 kg | 14.8 kg (49%) | NanoChem, ASI, USO | 6.6 kg (22%) | (No Mass Spec) | 6.6 kg | 0.34 kg (Li-CFx, 1.1 %) |

Mass Spec Design Trade should be an important component of future mission studies.

# Review: Probe Scientific Objectives

**Atmos. Composition - Formation and Evolution**

- Noble Gas
- Isotopic Ratios

**Thermal Structure and Energy Balance**

- Temperature vs. Pressure
- Radiative Flux

**Role of Clouds/Haze/Aerosols**

- Composition & Light Scattering Properties of Aerosols
- Vertical Distribution of Aerosols and Vapors

**Atmospheric Dynamics**

- Zonal Circulation
- Meridional Circulation
- Vertical Mixing of Disequilibrium Species

# Review: Instruments

**Red Letters = Usual Suspects**

| Observable | Instruments |
|---|---|
| Noble Gas Abundance | Mass Spec, He Detector, Noble Gas Sensor |
| Isotopic Ratios | Mass Spec, TLS |
| Volatile Molecule Abundance | Mass Spec, TLS, Vapor Sensor |
| Cloud/Haze/Aerosol Properties | Nephelometer |
| Disequilib. Species Concentration | Ortho-Para Sensor, Vapor Sensor |
| Temperature vs. Pressure/Density | ASI |
| Radiative Flux | Net Flux Radiometer |
| Horizontal Wind Speed | USO/Doppler Wind Experiment |
| Probe Descent Speed+Accel. | ASI |

# Take Home Message

**Atmospheric Composition Instruments are the Primary Driver for Total Mass of an Atmospheric Entry Probe**

**Current State-of-the-Art:**
- **Mass Spectrometer + TLS combination (e.g. Curiosity SAM)**

**Current Needs:**
- **Reduce Mass and Power of Gas Composition Instruments**

**Next generation:**
- **Miniaturized Mass Spectrometer?**
- **TLS without Harriot Cell? (e.g. LaRC's Diode Laser Hygrometer)**
- **Vapor Sensors?**

# BACK UP SLIDES

## SNAP IS A 30-KG ATMOSPHERIC PROBE
## THAT ENABLES
## **MULTI-PROBE MISSIONS**
## TO SATURN, URANUS AND NEPTUNE

# SNAP Study Goals

**Enable Future Multi-Probe Planetary Missions:**

- Advocated by past Decadal Surveys
- Provide data on spatially varying atmospheric phenomena.
- **2003 Survey**: Advocated for a Jupiter Multi-Probe mission
- **2013 Survey:** Emphasized that a second probe can significantly enhance the scientific value of a probe mission
- Never realized due to perceived high-cost.
- SNAP Design applicable to Saturn, Uranus and Neptune (with possibilities for Venus)

**SNAP Enables Future Multi-Probe Missions**

# Development Steps

**CML 1: Cocktail Napkin** – The science questions have been well articulated, the type of science observations needed for addressing these questions have been proposed, and a rudimentary sketch of the mission concept and high-level objectives have been created. The essence of what makes the idea unique and meaningful have been captured.

**CML 2: Initial Feasibility** – The idea is expanded and questioned on the basis of feasibility, from a science, technical, and programmatic viewpoint. Lower-level objectives have been specified, key performance parameters quantified and basic calculations have been performed. These calculations, to first-order, determine the viability of the concept.

**CML 3: Trade Space** – Exploration has been done around the science objectives and architectural trades between the spacecraft system, ground system and mission design to explore impacts on and understand the relationship between science return, cost, and risk.

**CML 4: Point Design** – A specific design and cost that returns the desired science has been selected within the trade space and defined down to the level of major subsystems with acceptable margins and reserves. Subsystems trades have been performed.

**CML 5: Baseline Concept** – Implementation approach has been defined including partners, contracting mode, integration and test approach, cost and schedule. This maturity level represents the level needed to write a NASA Step 1 proposal (for competed projects) or hold a Mission Concept Review (for assigned projects).

**CML 6: Integrated Concept** – Expanded details on the technical, management, cost and other elements of the mission concept have been defined and documented. A NASA Step 2 CSR is at this level of maturity. There is no corresponding milestone for assigned projects.

**CML 7: Preliminary Implementation Baseline** – Preliminary system and subsystem level requirements & analyses, demonstrated (& acceptable) margins and reserves, prototyping & technology demonstrations, risk assessments and mitigation plans have been completed. This is the maturity level needed for competed missions to hold their Preliminary Mission System Review (PMSR) and for assigned projects to hold their Mission Definition Review (MDR)

**CML 8: PDR (Integrated Baseline)** – Design and planning commensurate for a Preliminary Design Review (PDR).

**CML 9: CDR** – Design and planning commensurate for a Critical Design Review(CDR).

# Probe Mass Summary

| Subsystem | CBE (kg) | +30% MGA (kg) | +15% Margin (kg) |
|---:|---:|---:|---:|
| Forebody TPS (HEEET) | 3.7 | 4.9 | 5.6 |
| Forebody Structure | 2.0 | 2.6 | 3.0 |
| Backshell TPS (PICA) | 0.7 | 0.8 | 1.0 |
| Backshell Structure | 1.4 | 1.8 | 2.1 |
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| Separation System | 0.8 | 1.0 | 1.2 |
| Aeroshell Total | 9.9 | 12.9 | 14.8 |
| Descent Module Structure | 1.4 | 1.8 | 2.1 |
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| Science Instruments | 4.4 | 5.7 | 6.6 |
| Engineering Systems | 3.93 | 5.1 | 5.9 |
| Descent Module Total | 10.2 | 13.2 | 15.2 |
| Total Mass Entry Mass | 20.1 | 26.1 | 30.0 |

# Multi-Probe Missions

**Enable Future Multi-Probe Planetary Missions:**

- Advocated by National Academy Decadal Surveys
- Provide data on spatially varying atmospheric phenomena.
- **2003 Survey**: Advocated for a Jupiter Multi-Probe mission
- **2013 Survey:** Emphasized that a second probe can significantly enhance the scientific value of a probe mission
- Never realized due to perceived high-cost.
- SNAP Design applicable to Saturn, Uranus and Neptune (with possibilities for Venus)

**SNAP Enables Future Multi-Probe Missions**

# Interplanetary Trajectory Options

- A broad of catalog of ballistic chemical gravity-assist trajectory options
- SEP options not investigated due to high mass

| Launch Date | Launch Vehicle | Flyby Sequence | Launch $C_3$ ($km^2/s^2$) | Interplanetary Cruise (yrs) | DSM (m/s) | Arrival Mass (kg) | UOI ΔV (m/s) | Mass in Orbit (kg) |
|---|---|---|---|---|---|---|---|---|
| **5/25/2031** | Atlas V 541 | Earth-VEEJ-Uranus | 11.9 | 12 | 565 | 3582.5 | 1680 | 1850 |
| **7/18/2031** | Delta IV Heavy | Earth-VEJ-Uranus | 20.3 | 10.9 | 737 | 5265 | 2240 | 2393 |
| **4/6/2031** | Delta IV Heavy | Earth-VVE-Uranus | 25.5 | 11.5 | 1063 | 4751 | 1580 | 1885 |

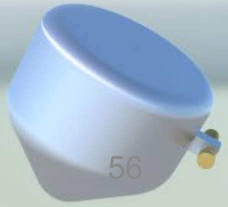
**Baseline**

**Dual probe delivery architecture possible for multiple interplanetary trajectory options**

HAMPTON UNIVERSITY NASA Langley PURDUE UNIVERSITY NASA Goddard JPL Ames Research Center

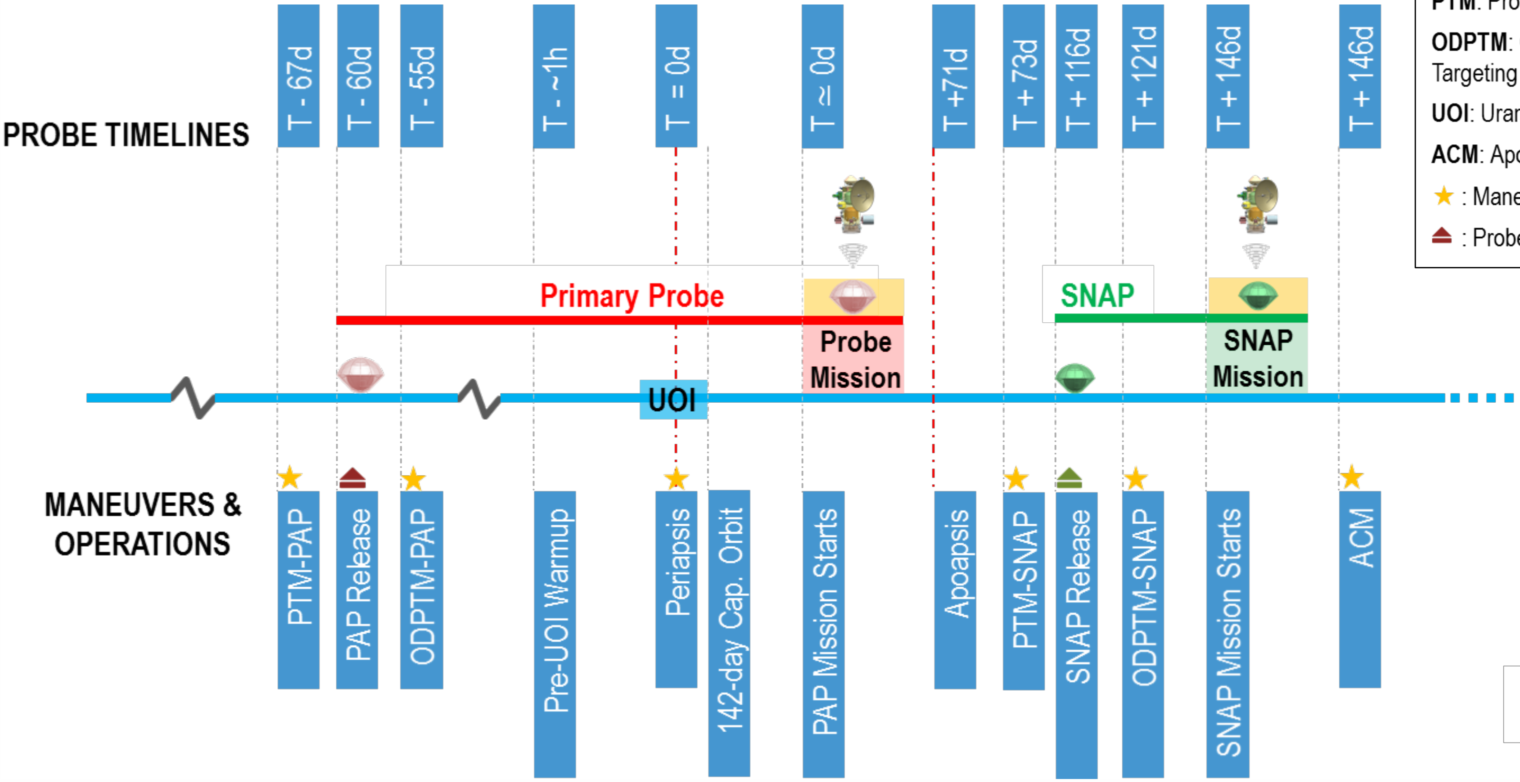
# Science Instruments

| Instrument | Measurement | Mass | Power | SNAP Data Return |
|---|---|---|---|---|
| **NanoChem** | Atmospheric Composition | 1.0 kg | 0.1 W | 1.08 Mbit |
| **Atmospheric Structure Instrument** | Pressure<br>Temperature<br>Acceleration | 1.3 kg | 5.7 W | 6.25 Mbit |
| **Ultra-Stable Oscillator** | Doppler Wind Experiment | 1.7 kg | 3.2 W | 0.05 Mbit<br>(Housekeeping Only) |
| **Total** | | **4 kg** | **9 W** | **7.35 Mbit** |



# Overall Mission ConOps

- Overall mission ConOps with critical events
- T = 0 day is UOI



**PAP**: Primary Atmospheric Probe

**SNAP**: Small Next-generation Atmospheric Probe

**PTM**: Probe Targeting Maneuver

**ODPTM**: Orbiter Divert and Periapsis Targeting Maneuver

**UOI**: Uranus Orbit Insertion

**ACM**: Apoapsis Correction Maneuver

★ : Maneuver

⏏ : Probe ejection event

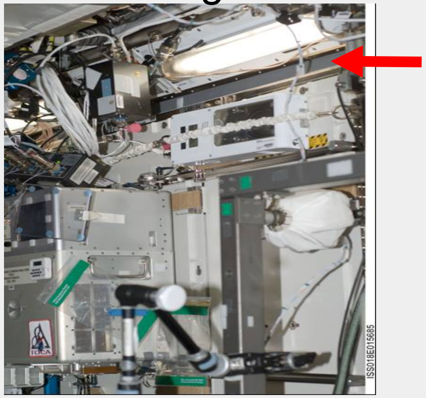
*Not to Scale*

# NanoChem: TRL = 4 Today

**Launched and Operated in Space**

Navy MidSTAR-1 satellite in 2007

Environmental Monitoring on ISS



Sensitivity demonstrated for:

… $CH_4$, $H_2O$, and $NH_3$, among others

… in Mars and Earth conditions

Need to develop sensitivities for:

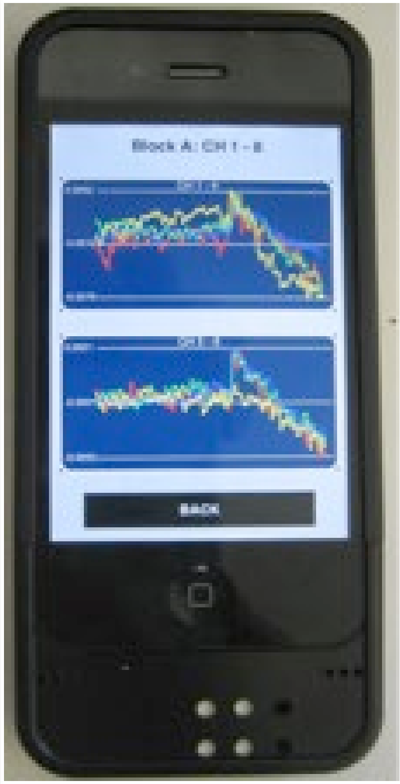
… $H_2S$

… in Giant Planet Conditions

| Analyte | Sensitivity/Detection Limit |
|---|---|
| $CH_4$ | 1 ppm in air |
| Hydrazine | 10 ppb tested |
| $NO_2$ | 4.6 ppb in air |
| $NH_3$ | 0.5 ppm in air |
| $SO_2$ | 25 ppm in air |
| HCl | 5 ppm in air |
| Formaldehyde | 10 ppb in air |
| Acetone | 10 ppm in air |
| Benzene | 20 ppm in air |
| $Cl_2$ | 0.5 ppm in $N_2$ |
| HCN | 10 ppm in $N_2$ |
| Malathion | Open bottle in air |
| Diazinon | Open bottle in air |
| Toluene | 1 ppm in air |
| Nitrotoluene | 256 ppb in $N_2$ |
| $H_2O_2$ | 3.7 ppm in air |

# NanoChem Commercialization

- Development at NASA Ames
  PI: Jing Li
- A/D on NanoChem Attachment
- Power from Phone (~mW)
- Processing on the Phone
- High sensitivity – ppb to ppm
- Data Transmission through Cellular Network



# Impact on Carrier Mission

Trajectory:

- Release SNAP after Uranus Orbit Insertion

Hardware:

- Mounting & deployment hardware
- Pre-deployment power & data connections
- Orbiter propellant

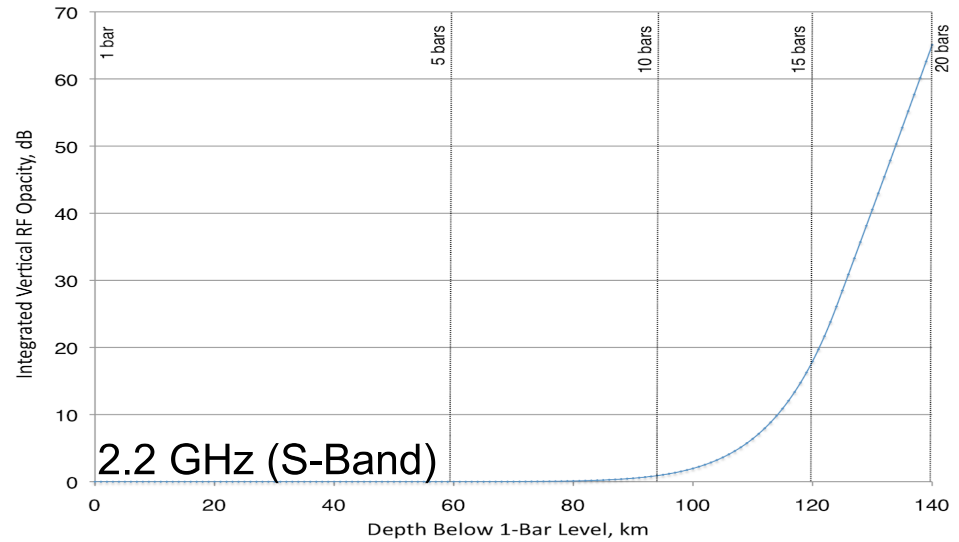
Software & operations:

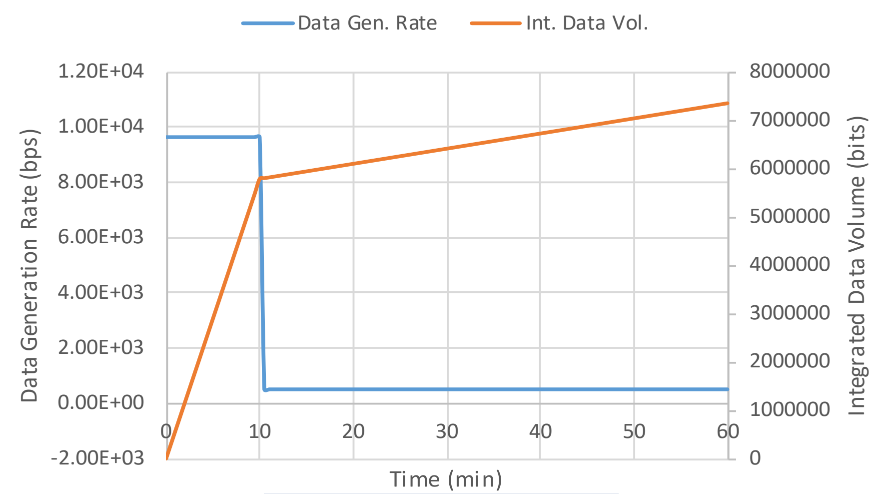
- Accommodate second probe delivery and data relay

# Link Analysis

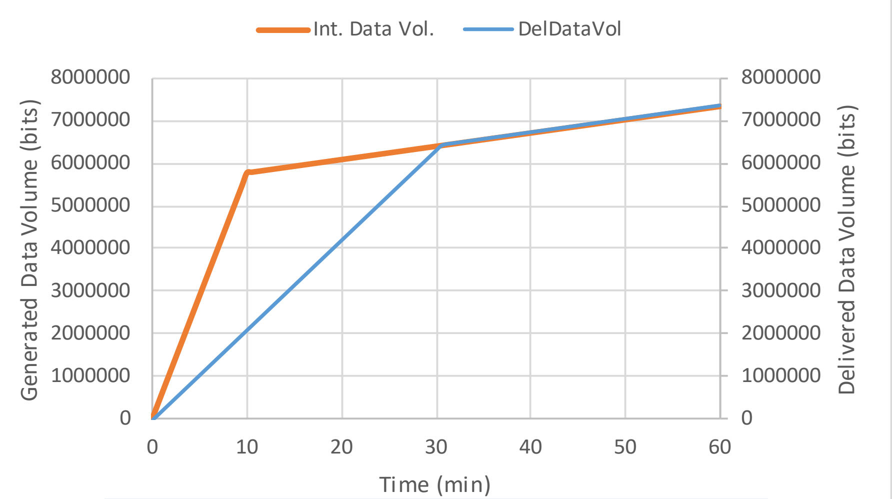
Link Analysis takes account of:

- Atmospheric Radio Absorption
  $(NH_3 + CH_4)$
- Attenuation through Link Range
- Transmitter/Receiver Antenna Gain
- Link Geometry
- Receiver Noise Model



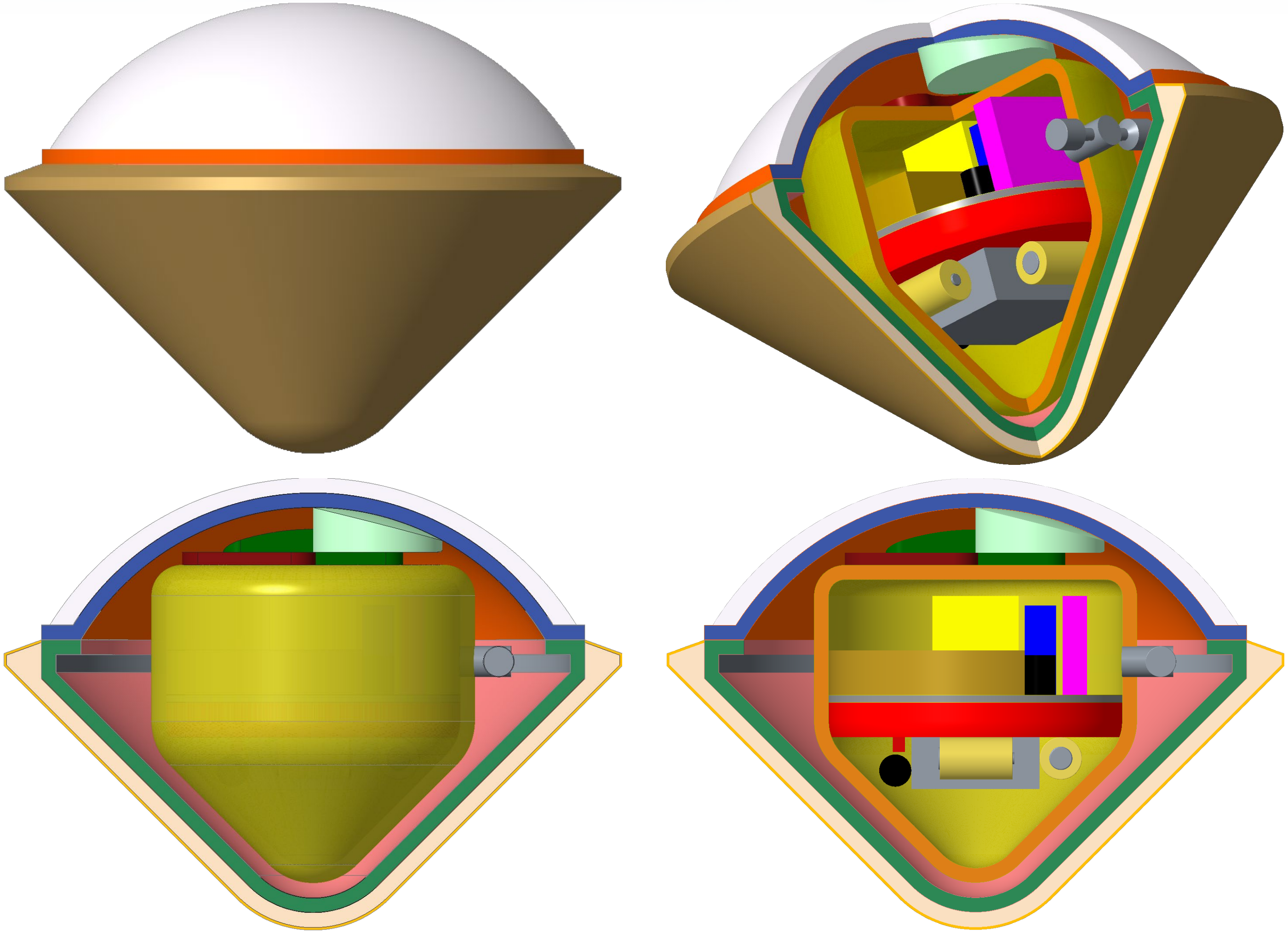


Data Generation



3500 bps Data Rate Worst-case

# Baseline Hardware Configuration



# Probe Mass Summary

| Subsystem | CBE (kg) | +30% MGA (kg) | +13% Margin (kg) |
|---:|---:|---:|---:|
| Heatshield TPS (HEEET) | 3.74 | 4.86 | 5.48 |
| Heatshield Structure | 2.0 | 2.6 | 2.9 |
| Backshell TPS (PICA) | 0.65 | 0.85 | 0.95 |
| Backshell Structure | 1.4 | 1.8 | 2.1 |
| 1st Parachute & Mortar | 1.3 | 1.7 | 1.9 |
| Separation System | 0.8 | 1.0 | 1.2 |
| Aeroshell total | 9.9 | 12.9 | 14.5 |
| | | | |
| Descent Structure | 1.4 | 1.8 | 2.1 |
| 2nd Parachute | 0.43 | 0.56 | 0.63 |
| Science Instruments | 3.85 | 5.0 | 5.6 |
| Engineering Systems | 4.9 | 6.4 | 7.2 |
| Descent Module total | 10.6 | 13.8 | 15.5 |
| | | | |
| Total Entry Mass | 20.5 | 26.6 | 30.0 |

# SNAP Probe Power Summary

| **Sub-system/ Instruments** | **Power** |
|---|---:|
| *Ultra-Stable Oscillator* | 3.2 W |
| *ASI* | 5.7 W |
| *Nano-Chem Sensor* | 0.1 W |
| Avionics | 4 W |
| Radio Transmitter | 50 W |
| Accelerometers | 0.1 W |
| **Total** | **63.1 W** |

In left, we assume use of x3 RHUs.

Battery-powered heaters are also possible.

After probe release until atmo. entry
→ SNAP needs 3W of heating.
For 30-day "coast"…
Li-Ion (current, 145 Wh/kg) = 21 kg
Li-Ion (future, 400 Wh/kg) = 7.5 kg
Li/CFx (639 Wh/kg) = 4.7kg

| Phase | Energy Requirement, Wh | Battery Mass, kg | Number of Batteries |
|---|---|---|---|
| SNAP Mission | 164 | 0.257 | 3 |

# Mass Impact on Carrier Mission by Addition of SNAP

- SNAP margined mass = 30 kg.
- Requires additional mass to baseline Uranus mission:
  - Probe Support Systems on the Orbiter
  - Propellant on the Orbiter

| Systems/ Subsystem | Mass, kg | Margined Mass, kg | Margin |
|---|---|---|---|
| **Probe Support Systems Total** | **4** | **5.3** | 30% |
| Spin ejection device | 3 | 4 | |
| Harness/ umbilicals | 1 | 1.3 | |
| **SNAP Mass** | **23.88** | **30** | **25%** |
| **Orbiter SNAP Support Propellant** | **30** | **36** | **30%** |
| **Total Mass Addition to Carrier Mission** | **58** | **72.3** | |

# Technology Needs

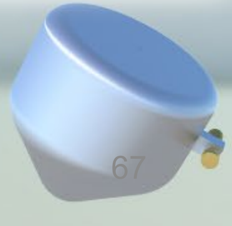
- Instrument/Sensor Technology
  NanoChem is TRL = 4 today (Under Dev. at Ames)
- Thermal Protection System:
  HEEET is needed for low density (Under Dev. at Ames)
- Power - Batteries:
  Low-temp., High Specific Energy Batteries alleviate need for RHUs
- Electronics:
  Low-survival temp will reduces heater power needs

# Study Team (Science Team)

| | |
|---|---|
| Kunio M. Sayanagi (PI) | Hampton University |
| Robert A. Dillman | NASA Langley Research Center |
| David H. Atkinson | Jet Propulsion Laboratory |
| Amy A. Simon | NASA Goddard Space Flight Center |
| Michael H. Wong | University of California, Berkeley |
| Thomas R. Spilker | Independent Consultant |
| Sarag Saikia | Purdue University |
| Jing Li | NASA Ames Research Center |
| Drew Hope | NASA Langley Research Center |
| W. Chris Edwards | NASA Langley Research Center |

**Mission Design Center:**

**NASA Langley Research Center Engineering Design Studio**

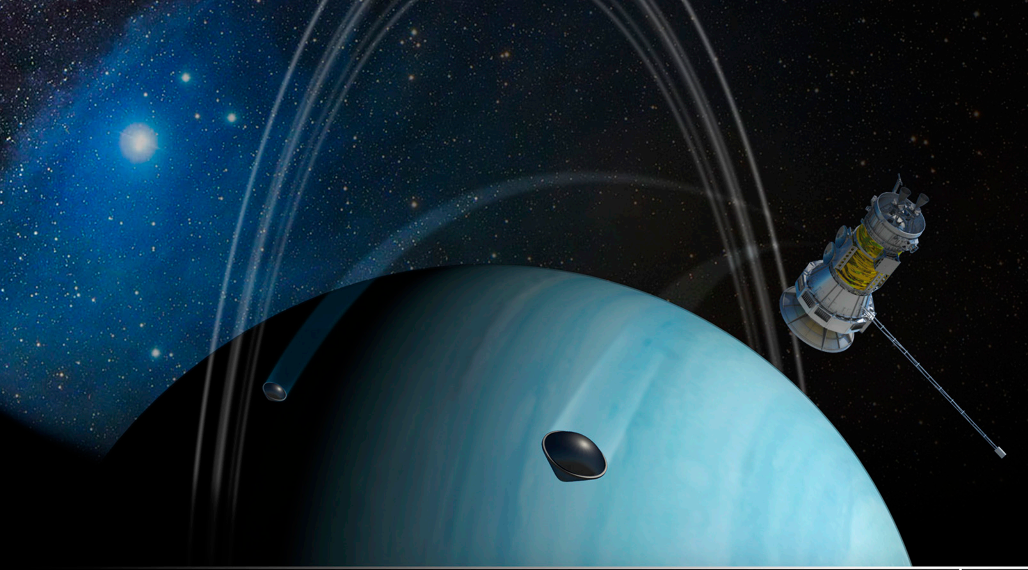


# SNAP

## Small Next-generation Atmospheric Probe

NASA HAMPTON UNIVERSITY

Planetary Science deep Space SmallSat Studies



## Team Members/Institutions

| | |
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Supported by: NASA Langley Research Center Engineering Design Studio

## Science Objectives:

*Tier-1 Objectives*: Determine spatial differences of the following atmospheric properties from the Main Probe entry site:

1. Vertical distribution of cloud-forming molecules
2. Thermal stratification
3. Wind speed as a function of depth

*Tier-2 Objectives*: Augment Main Probe Science Objectives:

4. Measure abundances of the noble gases (He, Ne, Ar)
5. Measure isotopic ratios of H, C, N, and S

## Mission Overview:

*Baseline Mission Configuration:*

Add SNAP to Uranus Orbiter and Probe Mission
Orbiter delivers Main Probe and SNAP to Uranus

*Baseline Spacecraft Configuration:*

Mass: 30 kg
Probe Diameter: 50 cm
Probe Power: Primary Batteries
Heatshield Material: HEEET

*Notional Payload:*

NanoChem: Detect cloud-forming molecules
Atmospheric Structure Instrument: Measure thermal profile
Ultrastable Oscillator: Atmospheric Dynamics

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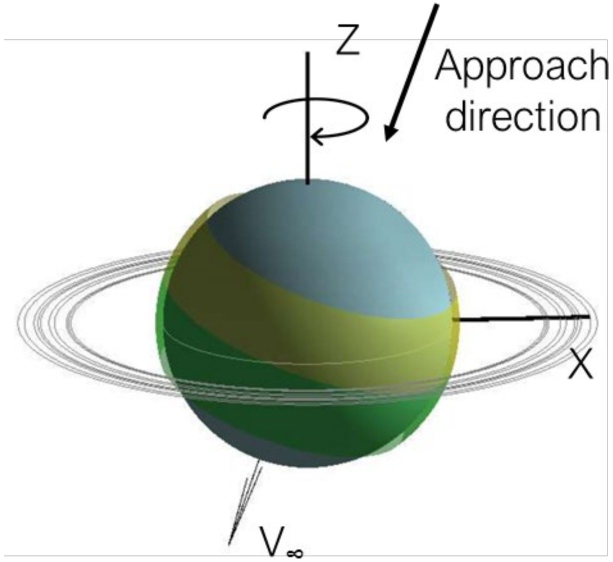
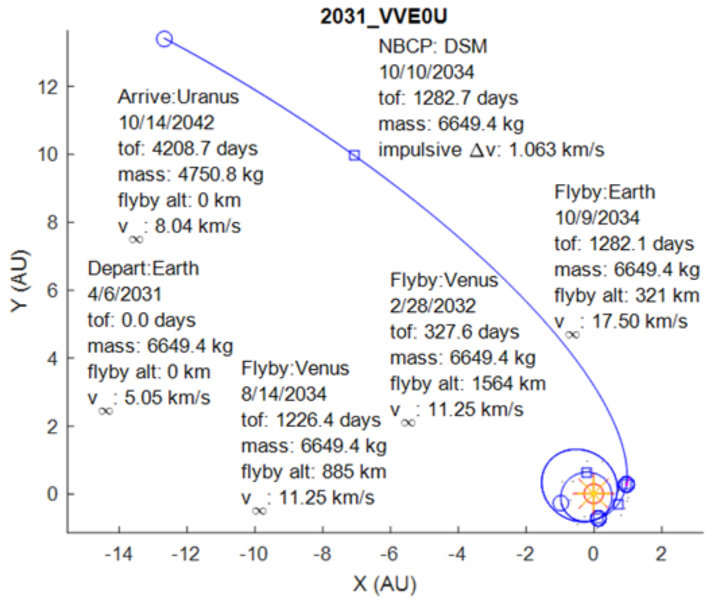
# Alternate Interplanetary Trajectories

- Dual probe delivery possible for multiple trajectory options
- SNAP mission concept is applicable to many interplanetary trajectories

| Launch date | Launch Vehicle | Flyby Sequence | Launch $C_3$ ($km^2/s^2$) | IP TOF (yrs) | DSM (m/s) | Arrival Mass (kg) | UOI $\Delta V$ (m/s) | Arrival $V_\infty$ (km/s) | Arrival Decl., deg | Mass in Orbit (kg) |
|---|---|---|---|---|---|---|---|---|---|---|
| 4/6/2031 | Delta IV Heavy | Earth-VVE-Uranus | 25.5 | 11.5 | 1063 | 4751 | 1580 | 8.04 | 71° | 1885 |



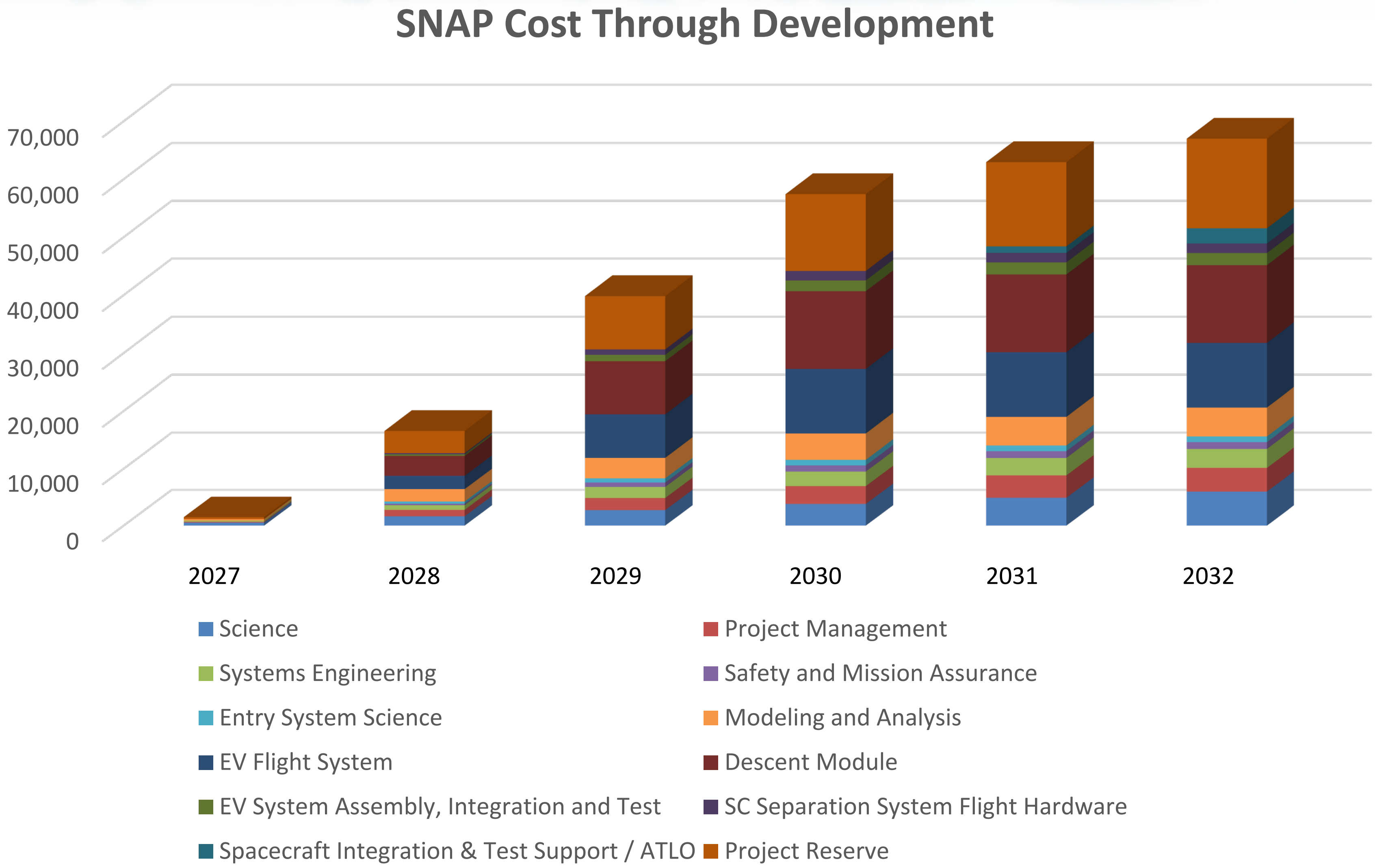
Accessibility of Entry Locations



# Concept-of-Operations: Dual-Probe Delivery

- Shows hyperbolic approach trajectories of orbiter + SNAP (blue, right) and primary probe (red)
- Shows elliptical captured orbit of orbiter (blue, left) and elliptical trajectory of SNAP (green)
- 30° Margined HWHM beam cone is centered around the negative of planet-relative velocity vector of the probes as they undergo entry and descent
- Orange cone: Ongoing probe entry mission but no orbiter-probe contact
- Green cone: When orbiter is in contact with the probe

# Cost Analysis



SNAP Cost Through Development