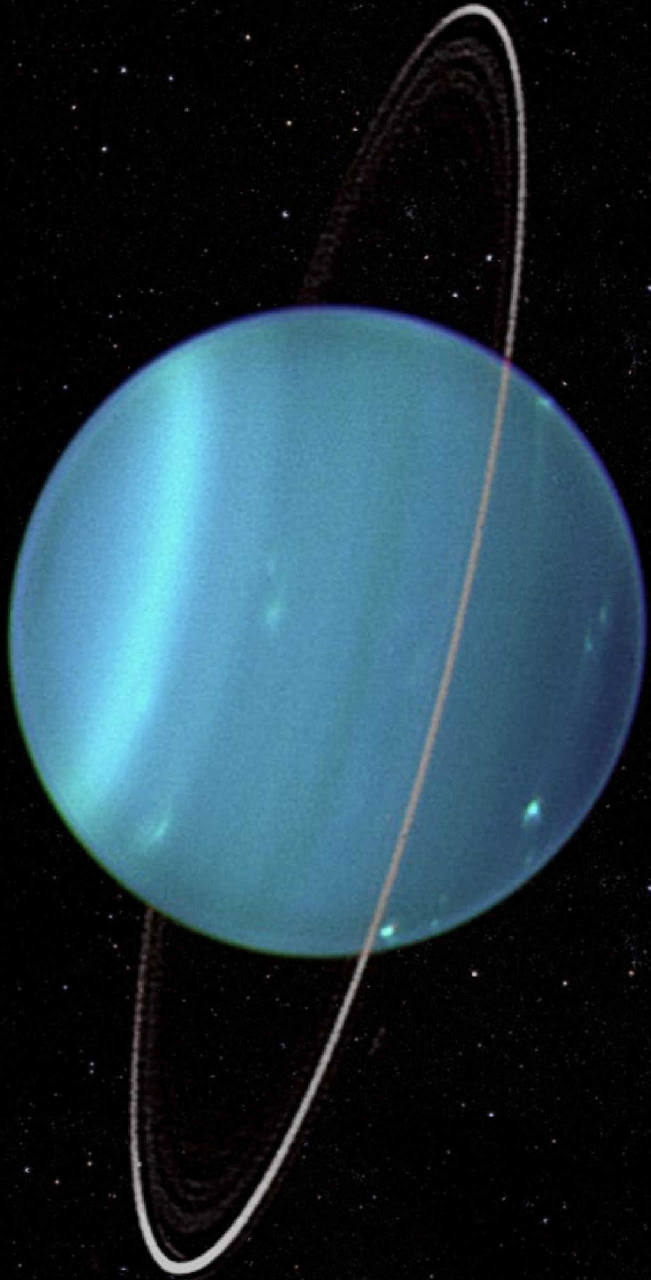
Uranus Orbiter and Probe

Exploring the mysteries of our nearest Ice Giant System

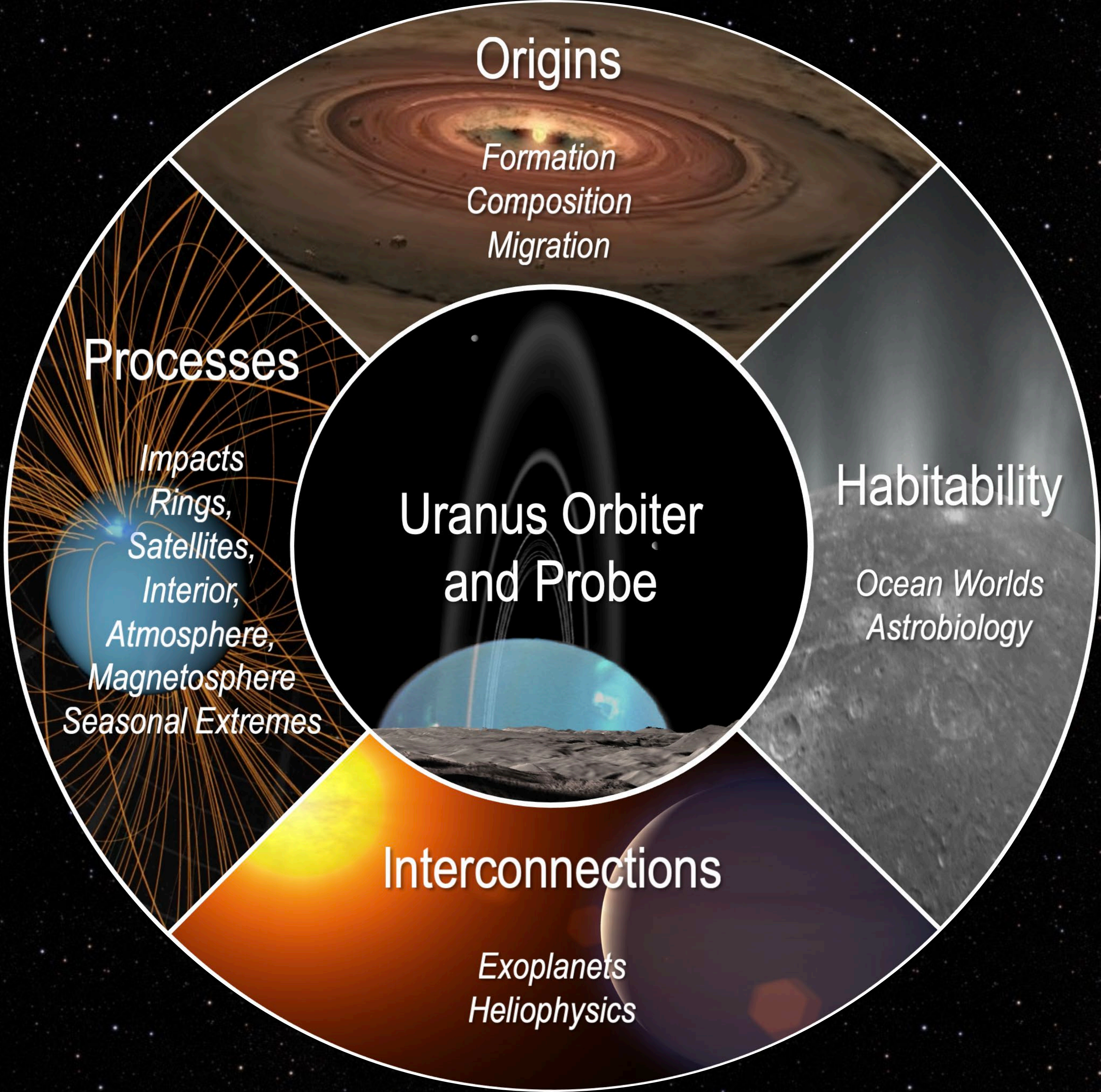


Decadal Study Leads:

Science Champions: A. Simon (NASA GSFC), F. Nimmo (UCSC)
Study Systems Lead: R. Anderson (APL)
Flight Dynamics: M. Ozimek (APL), J. Arrieta (Nabla Zero)
And many others…

Exploring our nearest ice giant system:

- *Uncovering the formation of ice giant-sized worlds*
- *Understanding the responses of the atmosphere, moons, and rings to extreme seasons*
- *Investigating ocean worlds*
- *Inspiring the next generation of planetary explorers*

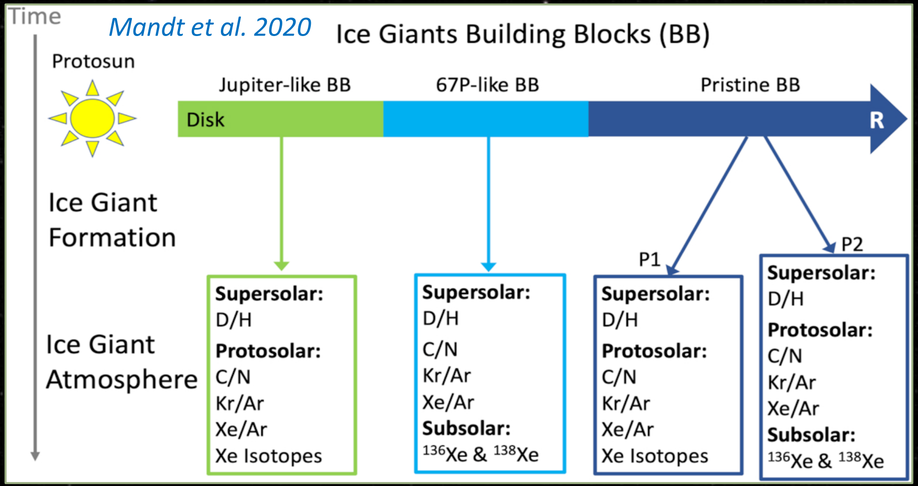


Overarching Science Goals (and example questions)

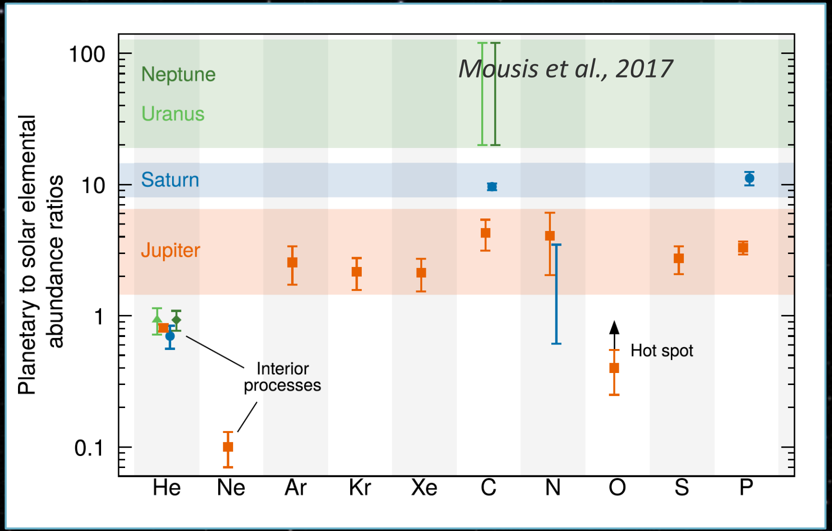
- Origins: Addresses OWL Thematic Q1-Q3, Q12
  - When and where did Uranus form in the protosolar nebula?
  - Did Uranus and Neptune migrate or swap positions?
  - Did a catastrophic giant impact tilt Uranus, rearrange its interior, and form satellites?
- Processes: Addresses OWL Thematic Q4-Q8, Q12
  - What mechanisms are transporting heat / energy in the planet and satellites today?
  - How do all the components in the Uranian system interact with each other?
  - What external factors are altering the planet, satellites, and ring compositions?
  - How does the solar wind interact with Uranus's complex magnetosphere?
- Habitability: Addresses OWL Thematic Q10, Q11
  - Did any of Uranus's moons have oceans in the past?
  - Are any of the moons presently ocean worlds?

The Uranus Orbiter and Probe mission enables broad multi- and cross-disciplinary science across nearly all Decadal thematic questions.

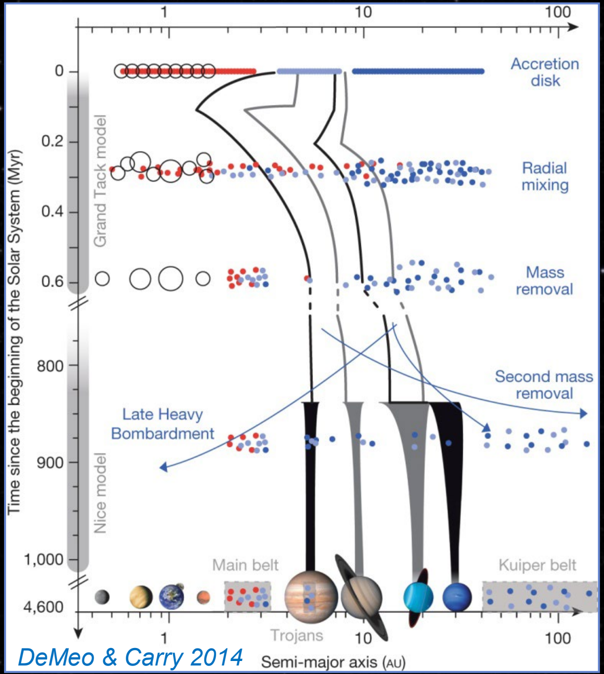
Origins



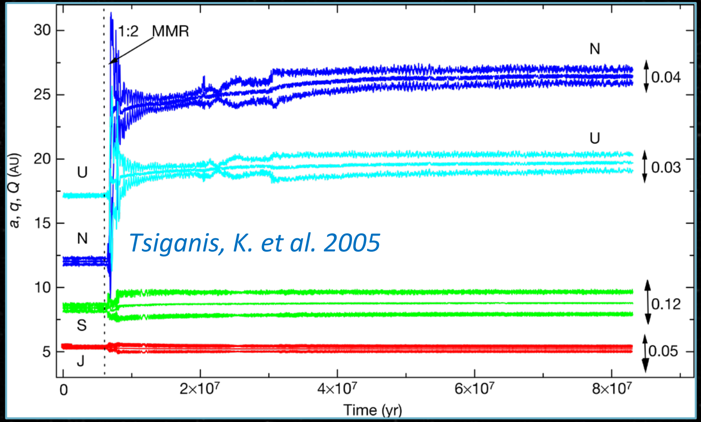
Uranus composition measurements help constrain protosolar nebula and accretion models

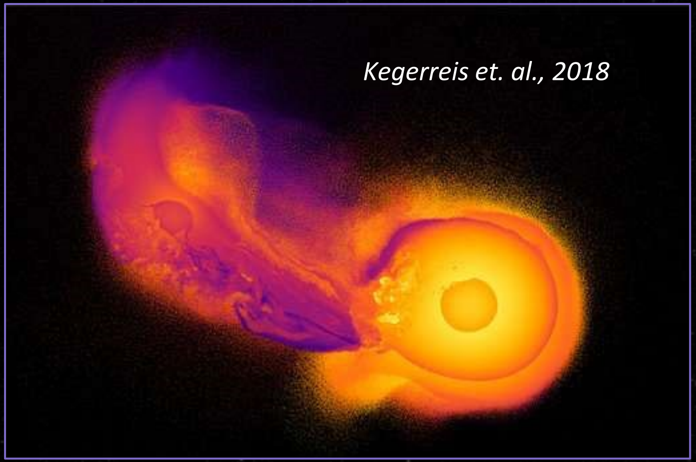


In situ composition and gravity measurements also answer questions about Uranus's formation and evolution, the role of giant impacts in its obliquity, interior structure, and internal heat

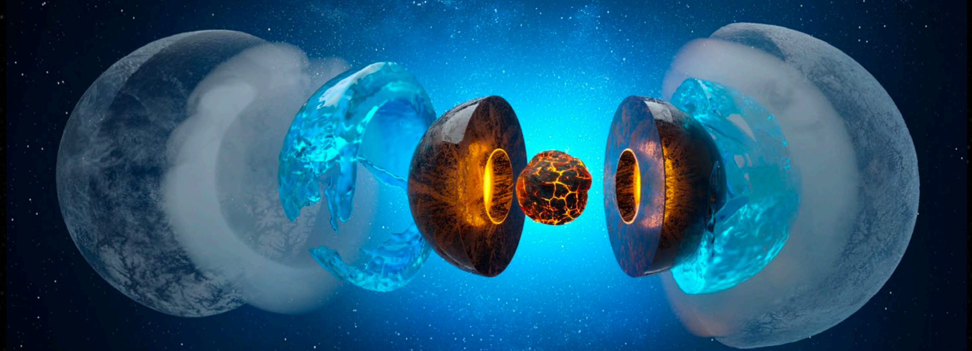


Uranus & Neptune swap positions in ~50% of Grand Tack simulations; isotope and noble gas measurements can tell us when & where they formed

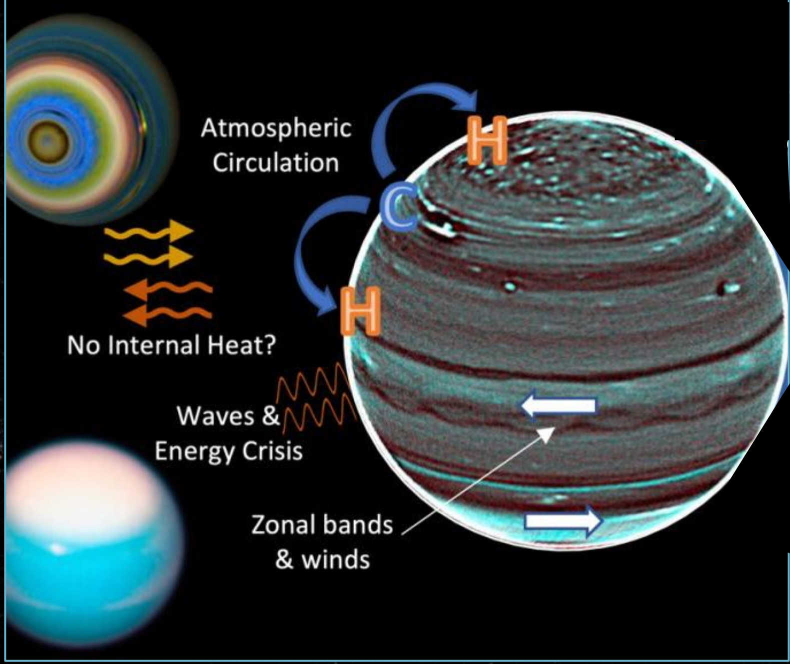


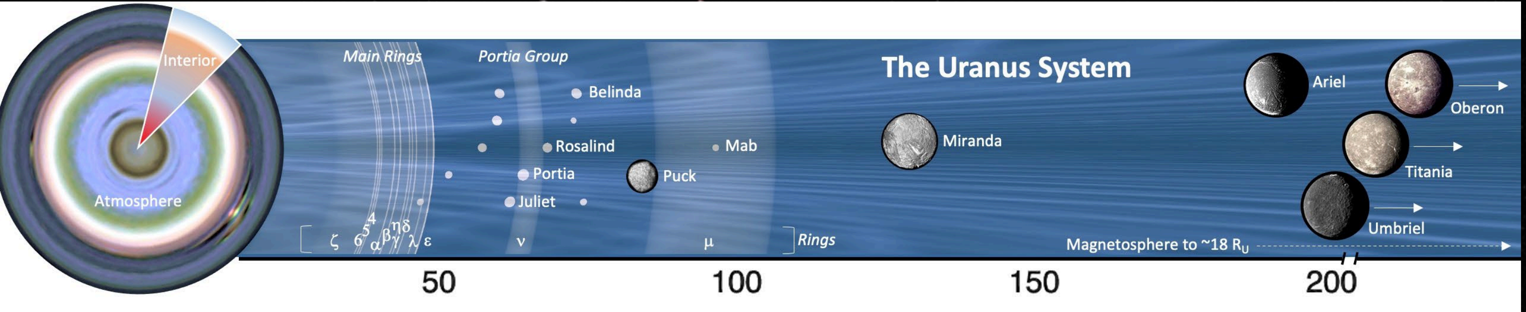


Processes

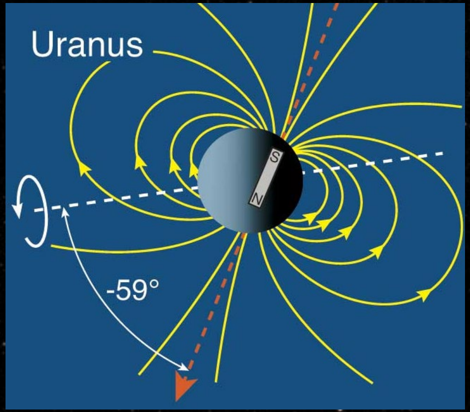


What is Uranus's interior structure?

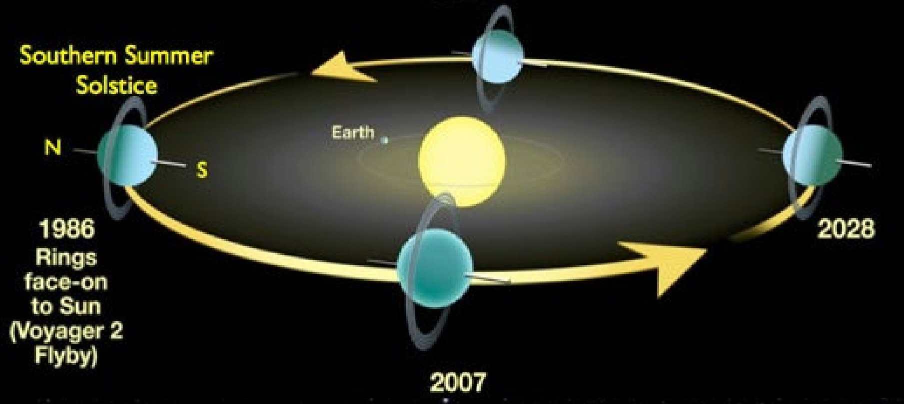




Regular satellite and ring system, young surfaces

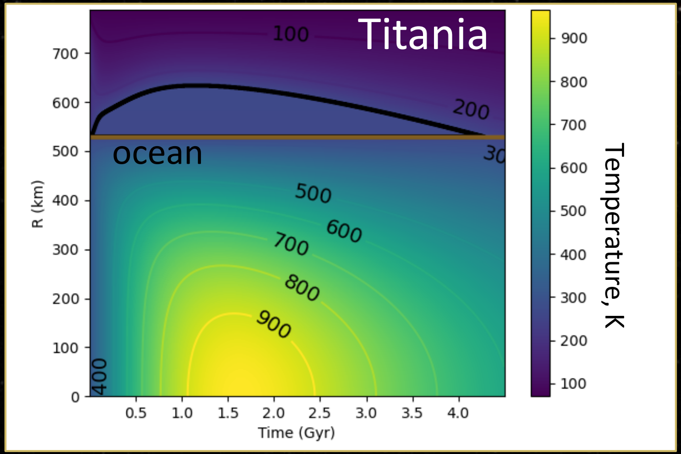


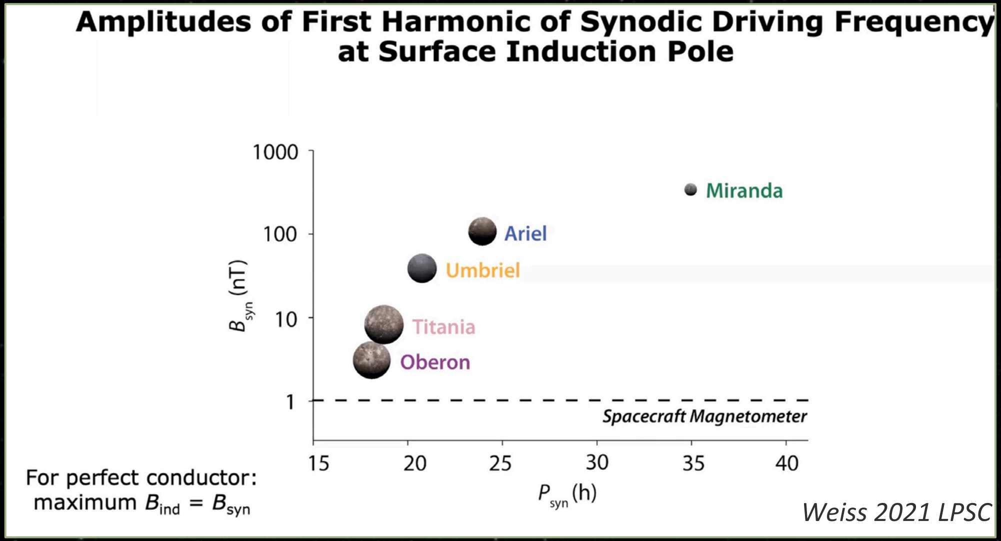
How/where is the dynamo generated? Magnetosphere is offset and tilted, interacts with rings and satellites, atmosphere (aurorae), solar wind



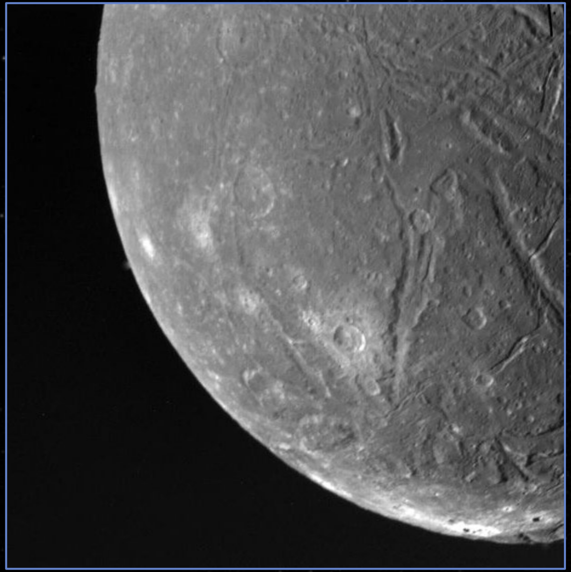
Extreme seasons, dynamic weather

Habitability



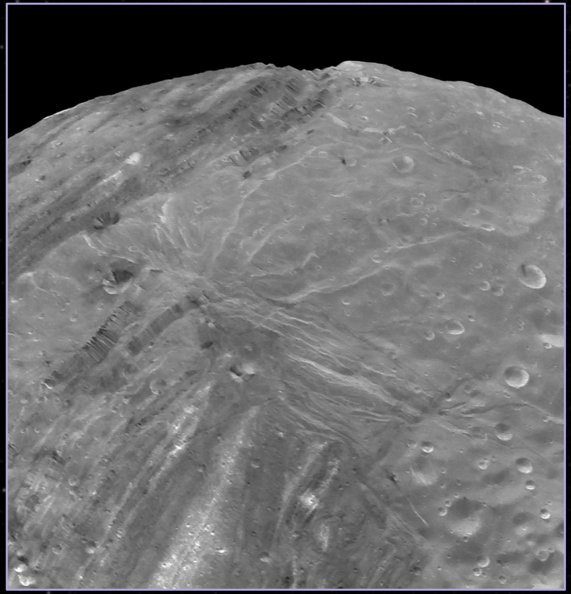


Are there active plumes or substantial internal heat and oceans now?



Spectral data will investigate surface composition including organics

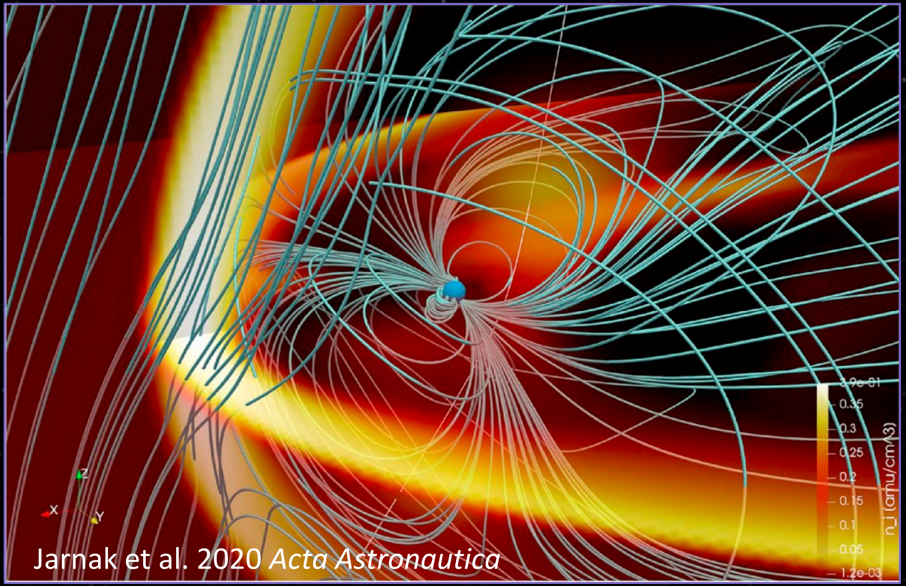
Possible subsurface oceans on several moons, plus evidence of past resurfacing.



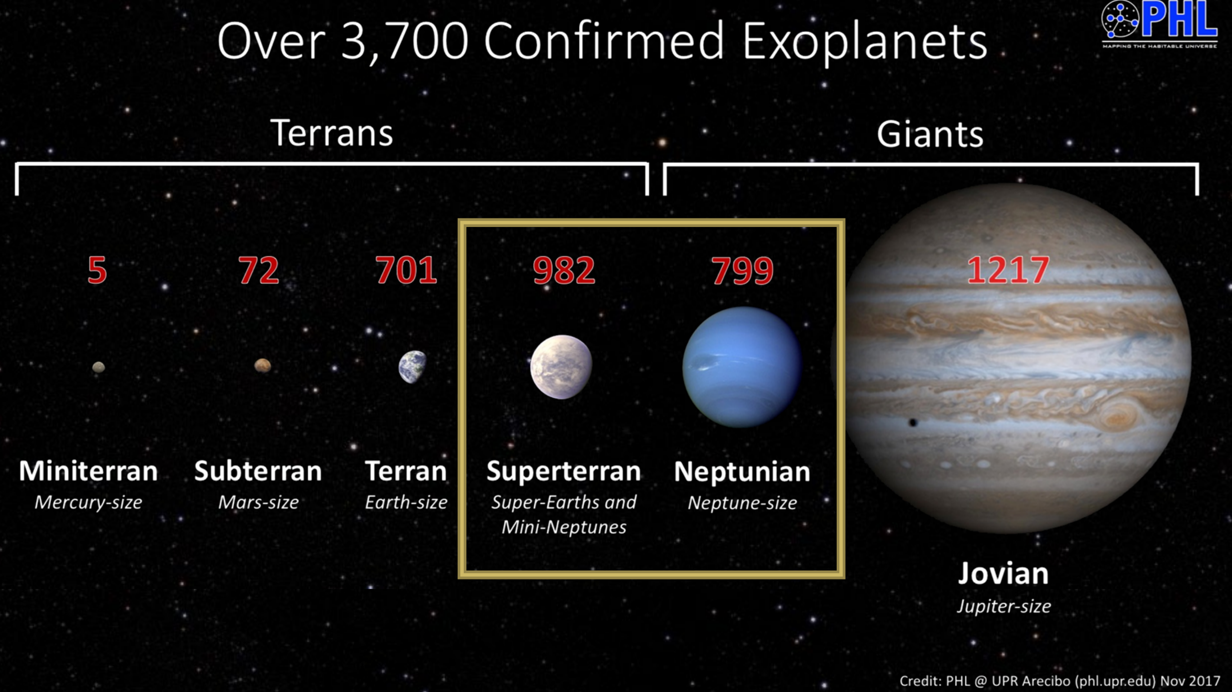
Implications of habitable worlds so far from the sun?

Interconnections

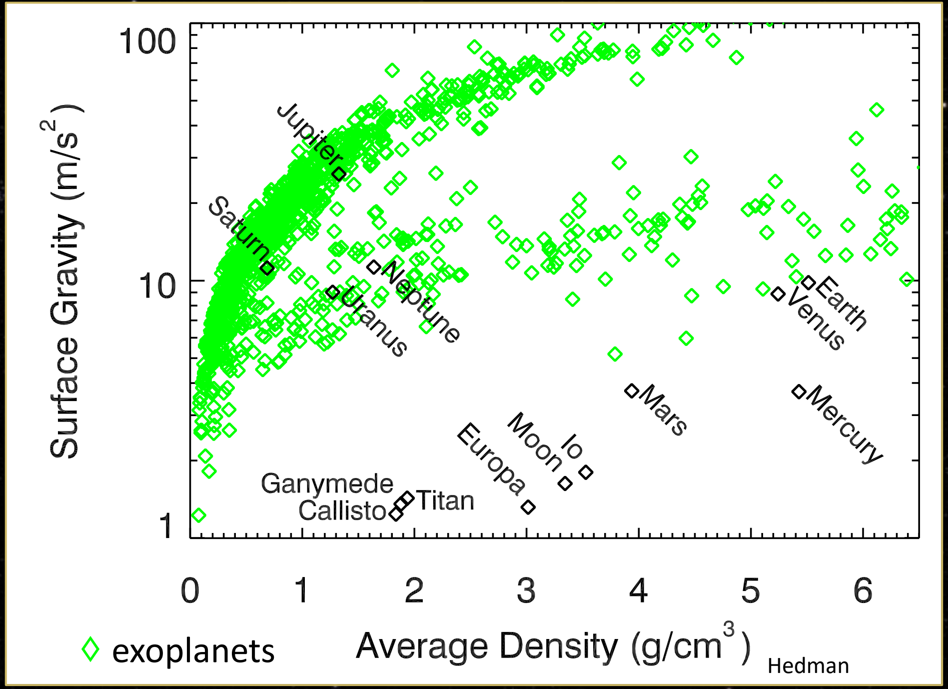
"… the Solar Wind-Magnetosphere Interactions panel's highest priority in planetary magnetospheres is a mission to orbit Uranus," 2013 Solar and Space Physics Decadal



Complex, tilted magnetosphere interacts with the solar wind in intriguing ways



Uranus and Neptune are in a different class than Jupiter & Saturn, and relevant to a different set of exoplanets (based on mass and radius)



Data from exoplanetarchive, filtered to remove high uncertainty data points

Science Traceability (by discipline)

Discipline	Science Objective	Measurement
Atmospheres	**A1. How does atmospheric circulation function, from interior to thermosphere, in an Ice Giant?**	A. Cloud top zonal and 2D winds, waves to ~10 m/s resolution
		B. *In situ* vertical wind profile to 10-20 m/s resolution
		C. Resolved composition, disequilibrium species mapping (to P < 3 bars): CH_4, H_2S, H_3^+, C_2H_2, C_2H_6, etc., hydrogen ortho/para fraction to mixing ratio ±20%
		D. Depth of atmospheric winds (gravity moments)
	A2. What is the 3D atmospheric structure in the weather layer?	A. Cloud tomography and aerosols
		B. Vertical temperature profile to ±1K
		C. Global temperature variations in troposphere, stratosphere, thermosphere
	A3./I1. When, where, and how did Uranus form, and how did it evolve both thermally and spatially, including migration?	A. Noble gas (& isotopes of He, Xe) abundances to ± 5%
		B. Elemental (& isotopes of H, C, S, N & O (stretch goal)) abundances, lower bounds on CH_4, H_2S, NH_3, H_2O, and the variation with depth
		C. Global distribution of atmospheric composition
Interiors		D. Global energy balance (Bond albedo and thermal emission) to 1%
	I2. What is the bulk composition and its depth dependence?	A. Gravity field to at least J_8, uncertainties on J_2-J_6
	I3. Does Uranus have discrete layers or fuzzy core, and can this be tied to its formation and tilt?	A. Gravity field to at least J_8, uncertainties on J_2-J_6
		B. Ring oscillations
	I4. What is the true rotation rate of Uranus, does it rotate uniformly, and how deep are the winds?	A. Internal magnetic field structure
		B. Planet shape

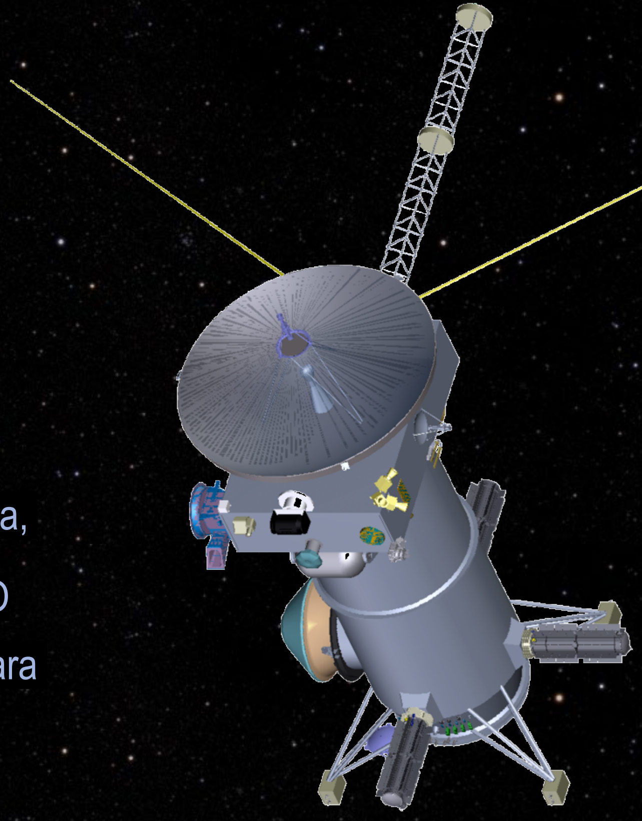
STM is very similar to that from 2010 V&V decadal, and post-decadal 2017 study

The mission enables transformative system science!

STM, continued…

Discipline	Science Objective	Measurement
Magnetospheres	**M1. What dynamo process produces Uranus's complex magnetic field?**	A. Internal magnetic field structure
	M2. What are the plasma sources & dynamics of Uranus's magnetosphere and how does it interact with the solar wind?	A. Particles & fields over range of space (distance, longitude, latitude, local time) and time (spin, solar wind variability)
	M3. How does the magnetosphere interact with Uranus's upper atmosphere and satellite surfaces?	A. Energetic particle fluxes at satellite orbital ranges
		B. Plasma/energetic particle fluxes over Uranus polar regions
Rings and Small Satellites	**R1. What processes sculpted the ice giant rings and small moons into their current configuration?**	A. Fine-scale structures in the dense rings at multiple times and longitudes
		B. Measure longitudinal variations in the ring structure (including normal modes and arcs)
		C. Inventory and shape of small moons > 0.5 km in radius within 500,000 km of the planet's center
	R2. What are the compositions, origins and history of the Uranian rings and inner small moons?	A. Ring (color) imaging at a wide range of phase angles
		B. Ring and small moon spectra (Cordelia to Mab), 1-5 μm
Large Satellites and Ocean Worlds	**S1. What are the internal structures and rock-to-ice ratios of the large Uranian moons? Which ones possess substantial internal heat sources or possible oceans?**	A. Magnetic field intensity and direction
		B. Static gravity coefficients
		C. Global shape
		D. Energy distribution of bulk plasma flow, 10eV-10 keV
		E. Plume/activity searches
		F. Satellite orbital positions
	S2. How do the compositions and properties of the Uranian moons and ring system constrain their formation and evolution?	A. Reflectance spectra from 0.8-5 μm, detect features 1% of continuum from 0.8-2.6 μm and 2% of continuum from 2.6-5.0 μm
		B. Static gravity coefficients
		C. Global shape
	S3. What geological history and processes do the surfaces record and how can they inform outer solar system impactor populations?	A. Distribution and topography of surface features
		B. Variations in surface composition
		C. Energy distribution of bulk plasma flow, 1eV-1 keV
		D. High-phase plume-search images
	S4. What evidence of exogenic interactions do the surfaces contain?	A. Energy distribution of bulk plasma flow, 10keV-10 MeV
		B. Variations in surface composition in reflectance spectra
		C. Evidence of radiation processing of surface ices

Mission Design Summary



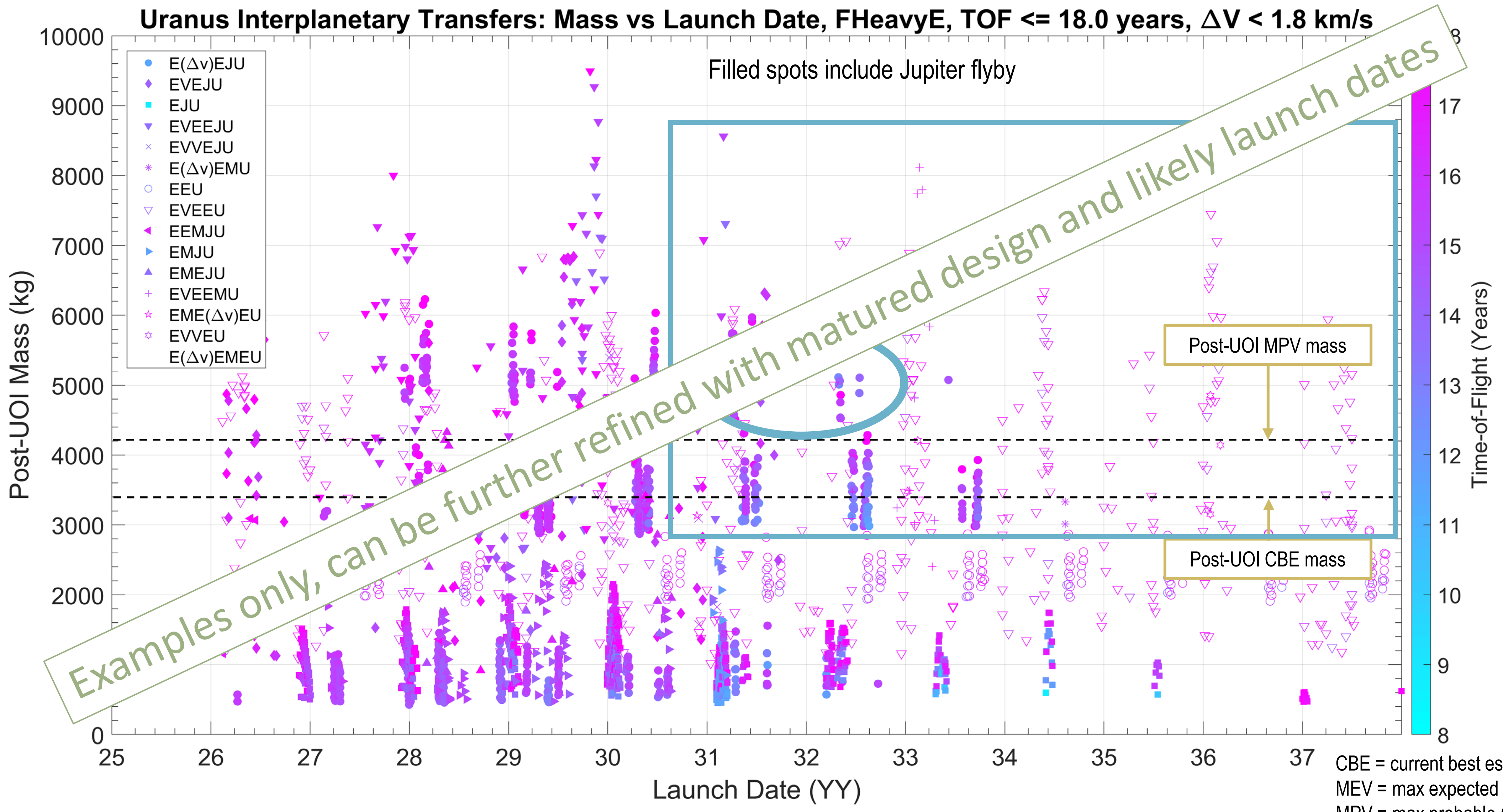
- UOP is feasible and flexible
  - No new technology is required
  - Lots of launch window and tour options
- Notional baseline science payload:
  - Orbiter: Magnetometer, Narrow Angle Camera, Wide Angle Camera, Thermal IR Camera, Visible-Near IR Imaging Spectrometer, Comprehensive Fields and Particle Suite, Radio Science with USO
  - Probe: Atmospheric Structure, Mass Spectrometer, USO, Ortho-para hydrogen Sensor
- Flight time: 11+ years, depending on trajectory chosen
  - Falcon 9 Heavy Expendable
  - Delivers ~4200 kg into orbit (including probe), margined
    - Stacked dry mass = 2756 kg (MPV), wet mass = 7235 kg
    - Leaves ~1100-kg margin on LV
  - Cruise trajectory to orbit insertion to probe release and orbital tour closes
    - First end-to-end trajectory design

Trajectories and Launch Windows

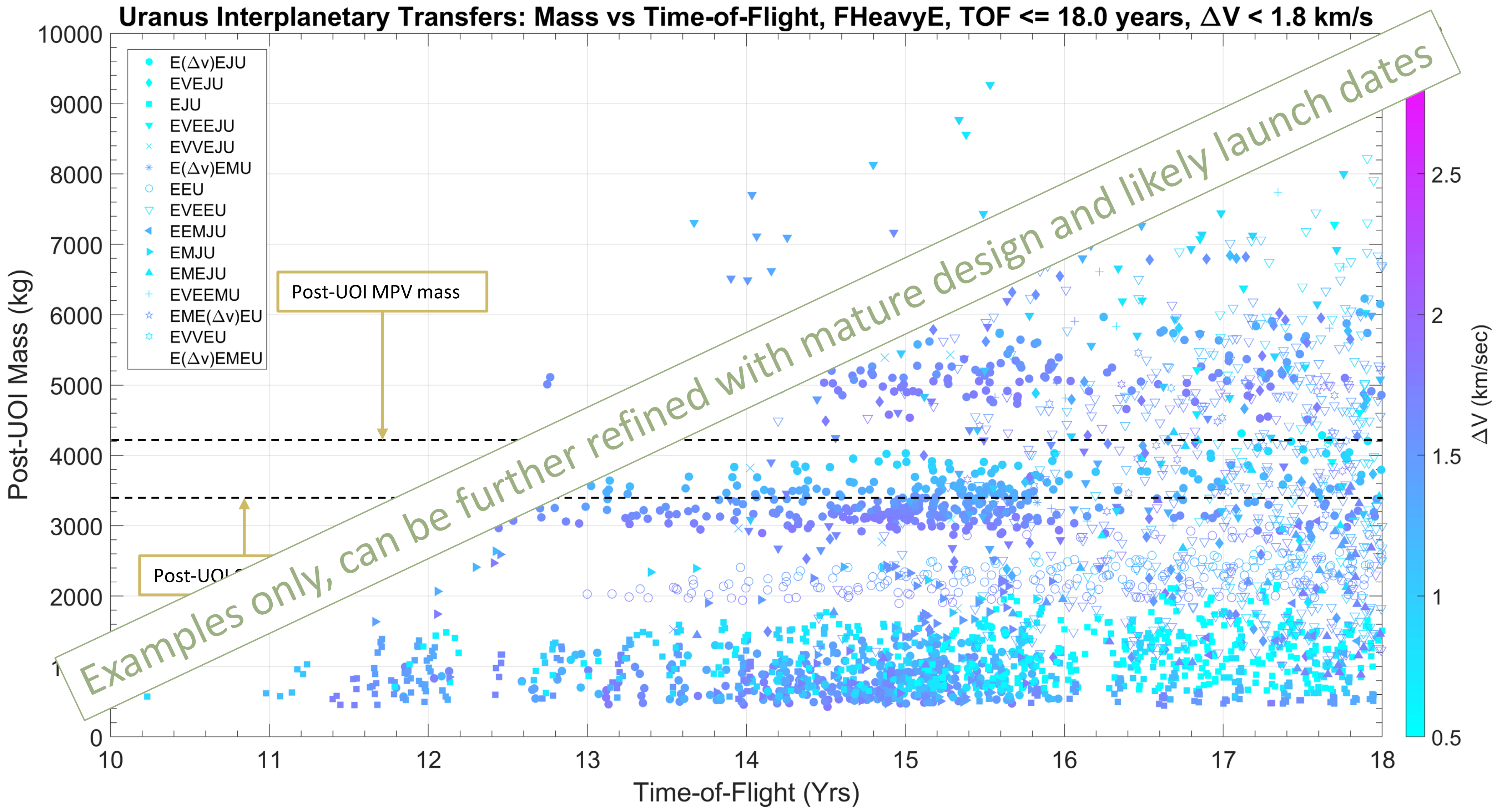
- Optimal launch dates in 2031-2032 include a Jupiter gravity assist
  - Most cost-efficient approach, but THIS IS NOT A SHOWSTOPPER.
  - There are many good opportunities with Venus & Earth flybys (trade space has thousands of options to sort through)

	Launch Date	C_3 (km^2/s^2)	Path	DSM (km/s)	UOI (km/s)	PLDV (km/s)	Post-UOI Mass (kg)	TOF (yrs)
Baselined window	6/13/2031	27.1	E(DV)EJU	0.773	1.011	1.783	4919	13.4
	6/15/2031	27	E(DV)EJU	0.717	1.251	1.968	4643.5	12.7
Backup	4/29/2032	28.8	E(DV)EJU	0.602	0.956	1.558	5111.5	12.8
Example windows w/o Jupiter flyby	1/8/2033	23.6	EVEEU	0.42	1.012	1.434	5933.3	15.3
	5/27/2034	23.1	EVEEU	0.68	0.946	1.629	5626.4	15.2
	2/28/2036	28.2	EVEEU	0.54	0.974	1.519	5240.5	15.3
	1/8/2038	35.5	EVEEU	0.00	1.307	1.307	4812.3	14.2

Nominal Trajectories: quick look shows many options over the decade



CBE = current best estimate
MEV = max expected (CBE + ~15%)
MPV = max probable (MEV + 30%)



Uranus Interplanetary Transfers: Mass vs Time-of-Flight, FHeavyE, TOF <= 18.0 years, ΔV < 1.8 km/s
Post-UOI Mass (kg)
Time-of-Flight (Yrs)
ΔV (km/sec)
E(Δv)EJU
EVEJU
EJU
EVEEJU
EVVEJU
E(Δv)EMU
EEU
EVEEU
EEMJU
EMJU
EMEJU
EVEEMU
EME(Δv)EU
EVVEU
E(Δv)EMEU
Post-UOI MPV mass
Examples only, can be further refined with mature design and likely launch dates

Trajectory Alternatives beyond 2031-2032 Jupiter Flyby

- Assuming Falcon 9 Heavy, all-chemical propulsion:
  - Same mass, arrival speed: use an inner cruise option (e.g., 2036 Venus-Earth-Earth) with likely few year time penalty
  - Lower post-UOI mass: more detailed point design may be more mass efficient, required margins will decrease with mission phase
  - Allow higher arrival velocity: have lots of mass margin currently for a bigger burn, if desired
- Vast Trade Space:
  - Literally thousands of options available, more can be used as mission matures
- Final mission formulation in Phase A will optimize the trajectory based on mass, budget, and launch date.

Other Example Chemical Trajectory Solutions

	Launch Date	C3 (km^2/s^2)	Path	DSM (km/s)	UOI (km/s)	PLΔV (km/s)	Post-UOI Mass (kg)	TOF (yrs)
	9/30/2029	13.7	EVEEJU	0.00	1.221	1.221	7865.2	14.5
	10/31/2029	11.3	EVEEJU	0.00	1.901	1.901	6665.4	13.1
	3/7/2031	17.5	EVEEJU	0.05	1.722	1.771	6068.7	12.5
	4/3/2031	28.6	E(ΔV)EJU	0.65	1.033	1.68	4934.7	13.5
ACE Run baseline	6/13/2031	27.1	E(ΔV)EJU	0.77	1.011	1.783	4919	13.4
	6/15/2031	27	E(ΔV)EJU	0.72	1.251	1.968	4643.5	12.7
	7/18/2031	19.8	EVEJU	1.07	1.763	2.834	4089.3	11.6
	8/1/2031	18	EVEJU	1.05	1.374	2.426	4855	12.3
	8/9/2031	20.2	EVEJU	1.06	1.504	2.561	4433.5	12
ACE Run backup	4/29/2032	28.8	E(ΔV)EJU	0.60	0.956	1.558	5111.5	12.8
	5/3/2032	29.2	E(ΔV)EJU	0.76	1.147	1.904	4527.2	12.2
	8/15/2032	49.5	E(ΔV)EJU	0.42	1.302	1.726	3056.3	11.8
Example windows w/o Jupiter flyby	1/8/2033	23.6	EVEEU	0.42	1.012	1.434	5933.3	15.3
	5/27/2034	23.1	EVEEU	0.68	0.946	1.629	5626.4	15.2
	2/28/2036	28.2	EVEEU	0.54	0.974	1.519	5240.5	15.3
	1/8/2038	35.5	EVEEU	0.00	1.307	1.307	4812.3	14.2

Lighter colors = best solutions

High-level Mission Phases for Trajectory Design

Cruise Phase | *Science Phase*

Interplanetary Cruise | Capture/Probe Deploy | Science Focused Tour

20 June 2031
Launch

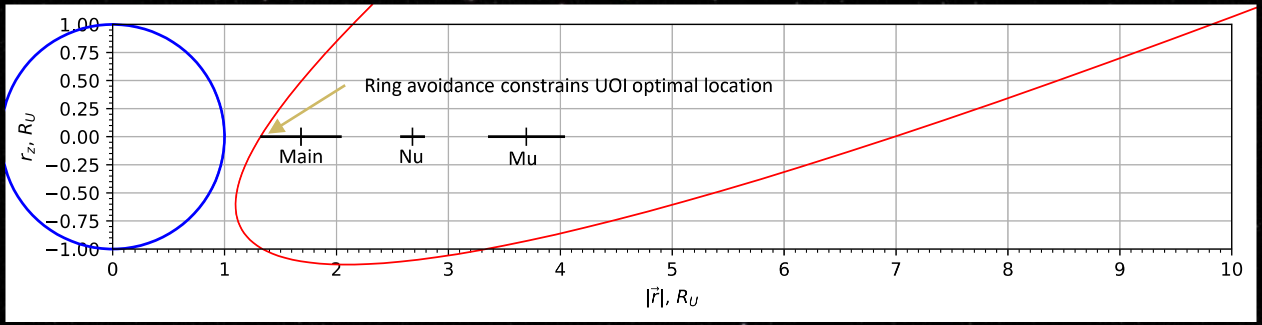
5 Dec 2044
UOI

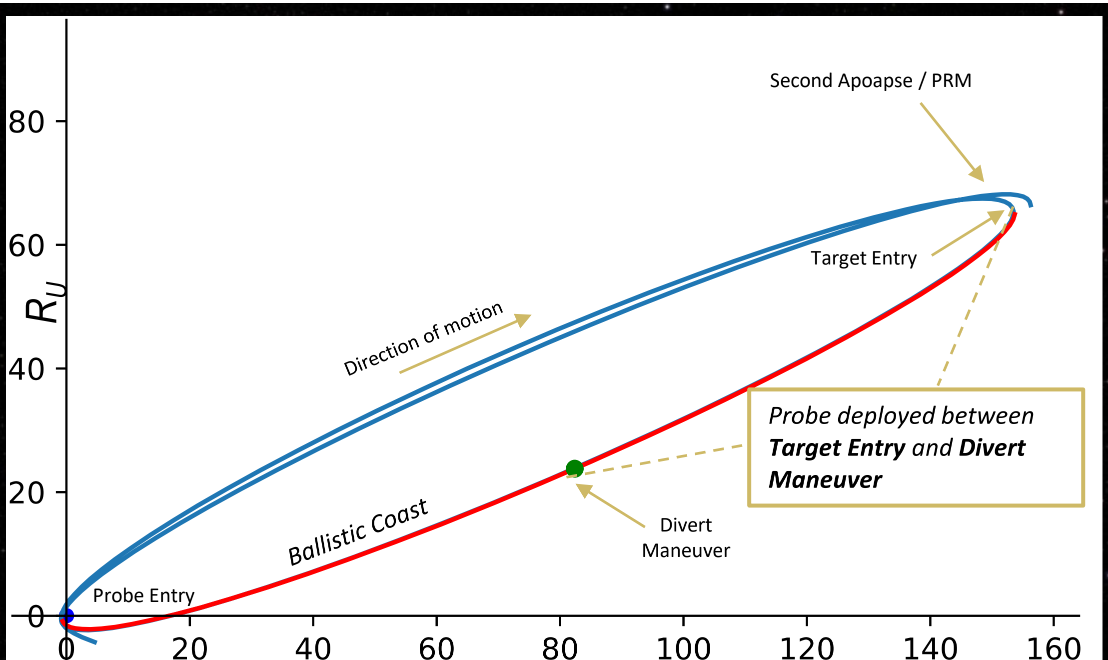
6 Apr 2045
Probe Entry

6 July 2045
Tour starts

EOM

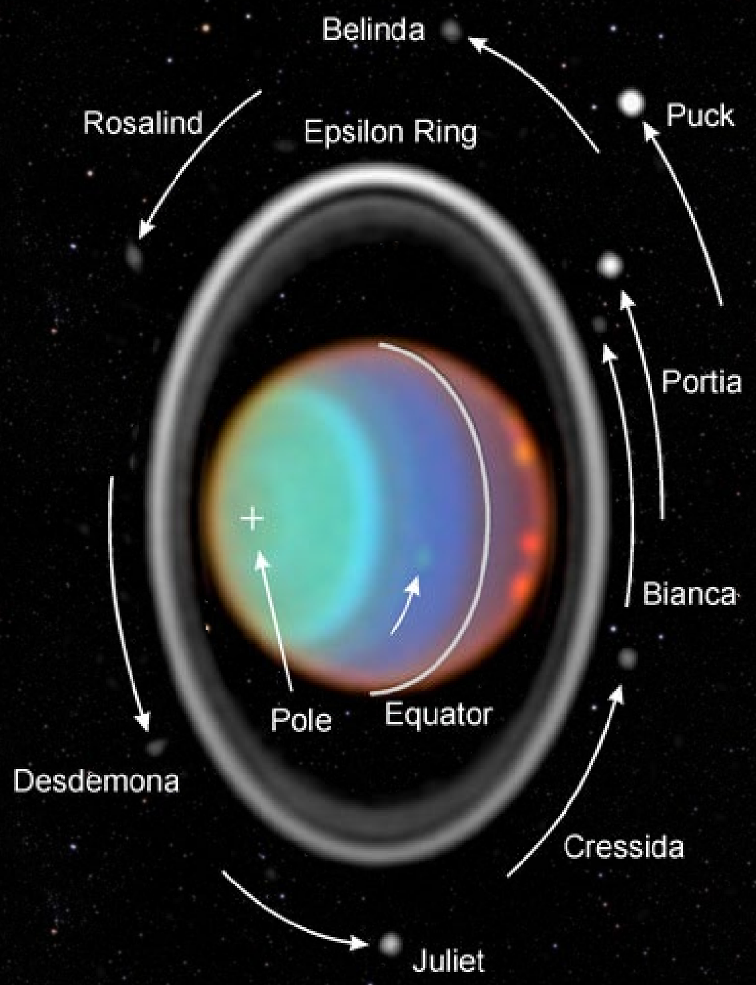
Parameter	Value
Earth Departure	20-Jun-2031
Departure C_3	26.81 km^2/s^2
DSM	27-Jun-2032
DSM Δv	659.320 m/s
Earth Flyby	27-Apr-2033
Flyby Altitude	450 km
Jupiter Flyby	21-Dec-2035
Flyby Altitude	369550 km
Uranus Approach	05-Nov-2044
Inbound v_∞	6.267 km/s
TOF	13.462 yr





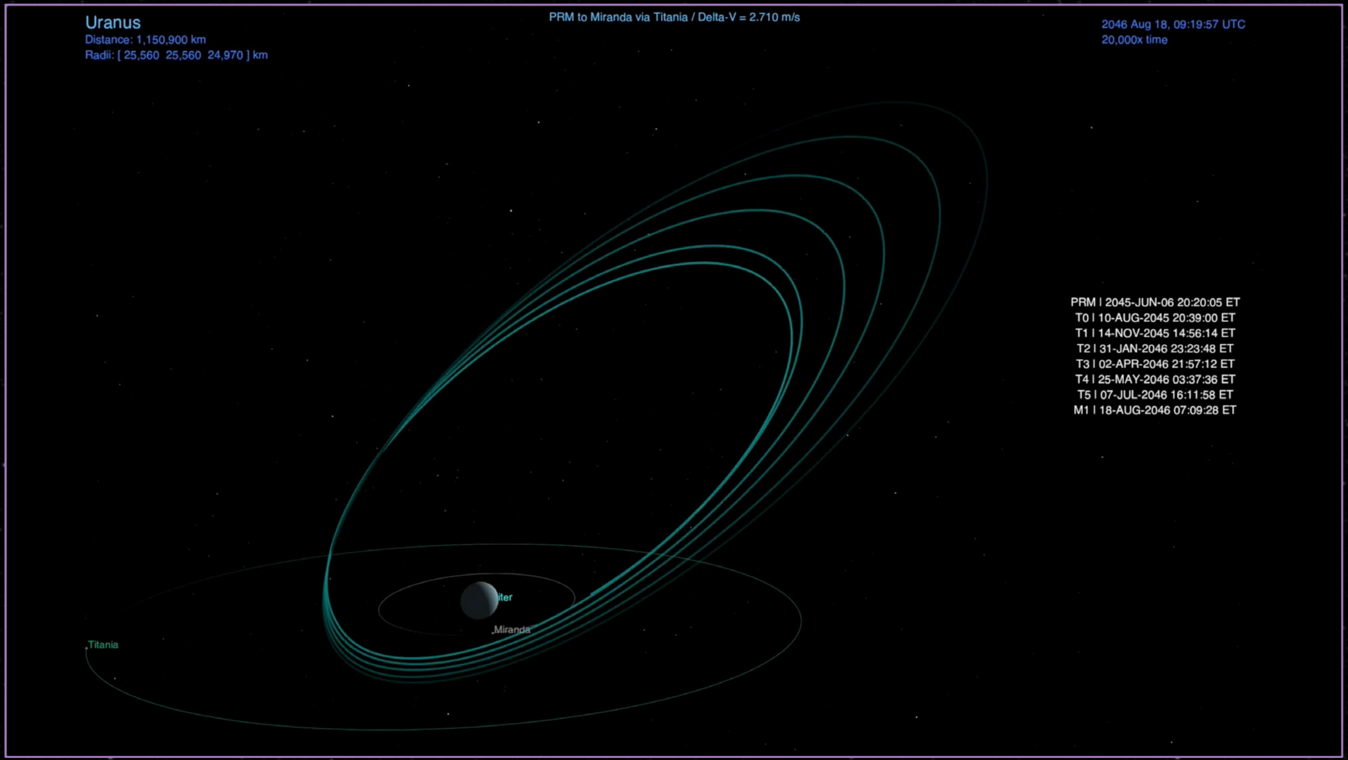
Concept of Operations

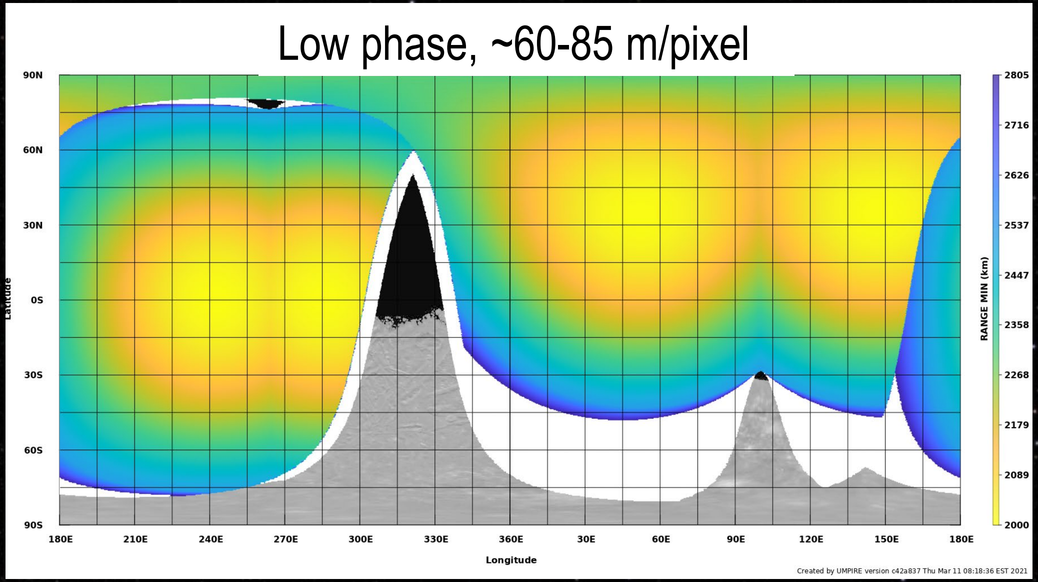
- Orbital period during tour ~34 days
  - Start in polar orbit, use Titania to pump down to equatorial
- General data strategy
  - Tour - Ka-band science downlink, one 8-hr pass /day
  - Possible additional passes for critical events and nav purposes
  - Compression assumption – average, assuming 2:1
- Onboard Storage of all science data and housekeeping
  - Some instruments also have their own storage
- Solar conjunction not a problem during any of the critical events
- Considered 4 orbit types, all have sufficient downlink to achieve science goals
  - Uranus/Rings Remote sensing focused
  - F&P and Mag focused
  - Satellite flyby w/ remote sensing focused
  - Multiple satellite flyby focused (equatorial phase)



Tour Science Coverage

- Orbits start polar and are pumped down, using Titania, to equatorial for a satellite tour
- Most science objectives met in the high inclination phase
  - Additional satellites objectives fulfilled in satellite tour phase
  - Satellite flybys ≲ 4 km/s
- Tour has lots of flexibility, this example closes
  - Slight tweaks may be desired for highest spatial resolution rings and small moons imaging





Example Ariel imaging coverage

Mission descopes

Category	Baseline Requirement	Threshold Requirement
Orbital tour	4 Years	2 Years
	Polar phase, followed by low inclination phase	Polar only
Satellite flybys	3 targeted, 2 non-targeted, flybys of each of the major moons @ <10 km/s	2 targeted,1 non-targeted, flybys of each of the major moons @ <10 km/s
	Targeted and non-targeted flybys of small moons	Non-targeted flybys only
	Polar and low inclination passes	Polar only
Uranus orbits	Close (1.1 R_u) polar & low inclination dayside passes	Polar only
Probe depth range	From 0.1 to 5 bars (10 bars preferred, but not a driver)	From 0.1 to > 1 bar
Payload	Full complement	Remove WAC from orbiter and ortho-para sensor from probe

These can be revisited as concept matures and payload is defined

Special Considerations

- No new technology is required for this mission
- Optimal launch windows are before ~2033 to include a Jupiter gravity assist
  - This is the most cost-efficient approach, but a JGA is NOT required
  - Mission Phase A formulation can update trajectory to include Venus flybys or SEP, as needed for launch window, but there may be cost, mass, or cruise duration penalties
- This concept study assumed the use of the Falcon 9 Heavy Expendable
  - Lower performance launch vehicles may also be feasible, with optimization
- Assumes 3 Next-Gen mod 1 RTGs are available

Summary

- All mission studies since 2010 have converged on the same general design as the most science value per dollar
  - A moderately instrumented orbiter with an atmospheric probe
  - Science traceability is stable – spectacular system science awaits!
- New Decadal study shows that the mission closes with a variety of launch windows
  - No new technology is needed
  - Critical event timing issues resolved, moving probe release to after orbit insertion, connected to an orbital tour that precesses to the equatorial plane
  - Even without optimization, mission closes on a Falcon 9 Heavy with lots of margin
- Pre-formulation study needed
  - Point design can now be optimized within likely launch windows and constraints
  - Trajectory trade space will grow as design becomes more efficient and as required margins decrease

Decadal concept study report can be found at: https://tinyurl.com/2p88fx4f

Summary and Next Steps

- UOP promises fantastic, high priority, Decadal science!
  - Broad system exploration
  - Great opportunities for cross-disciplinary work and early career involvement
  - Concept is ready for pre-formulation study of final point design and optimized trajectory
- Briefings, Special Sessions, and Workshops since the Decadal
  - OPAG (June & Nov. 2022)
  - In Situ Exploration of the Giant Planets II (July 2022)
  - AGU and DPS sessions (Fall 2022)
- Upcoming Workshops:
  - Uranus Flagship: Investigations and Instruments for Cross-Discipline Science, (25-27 July 2023 Pasadena)
  - Keck Institute for Space Studies Workshop (~November 2023)
  - AGU Special Session (December 2023)

Questions?