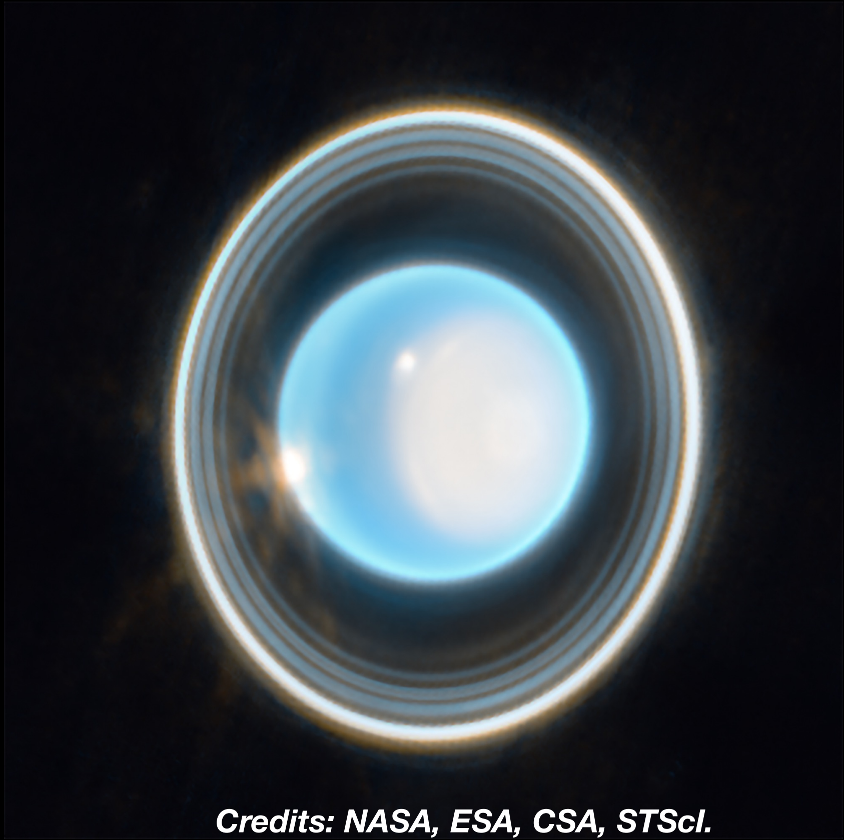
Uranus' Evolution & Current Structure

Ravit Helled
Institute for Computational Science
Center for Theoretical Astrophysics & Cosmology
University of Zurich



Credits: NASA, ESA, CSA, STScI.
Image processing: J. DePasquale (STScI)

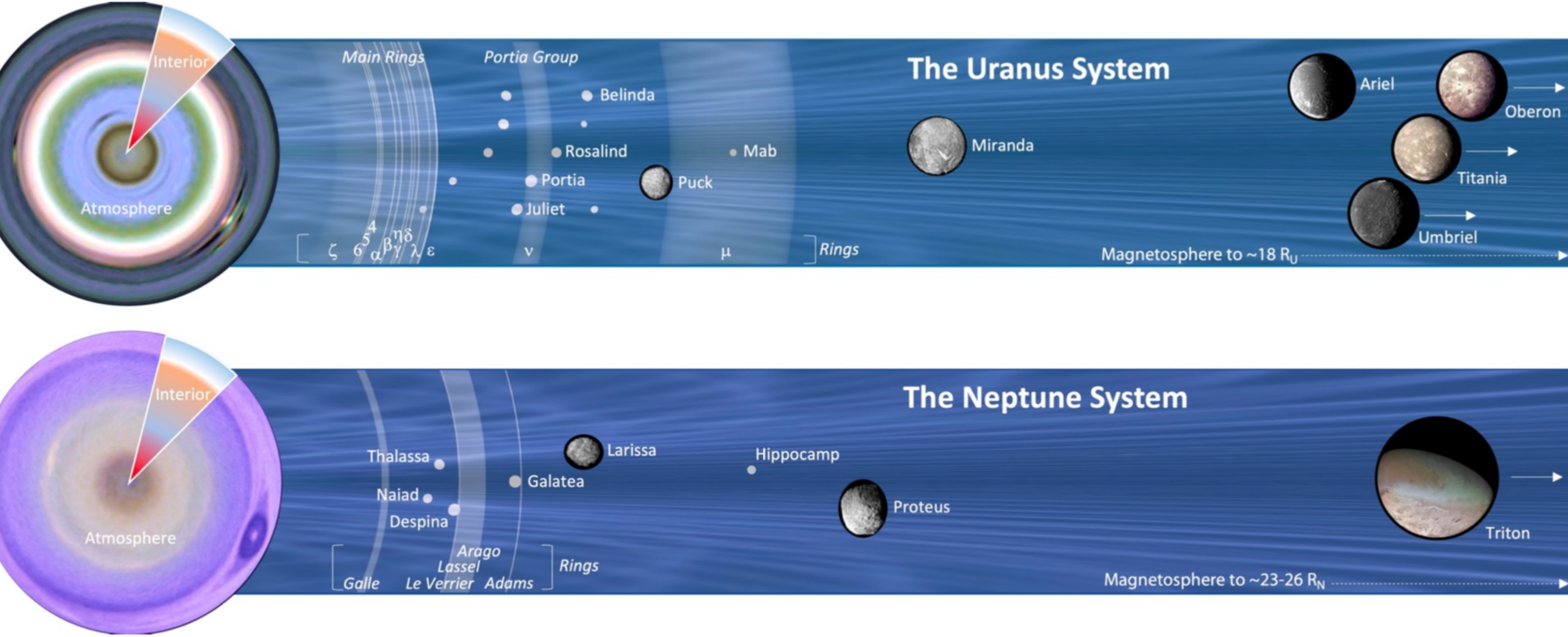
See recent reviews: Helled et al., 2020, Helled & Fortney, 2020

Uranus (and Neptune) represents a unique unexplored planetary class

Open fundamental questions:

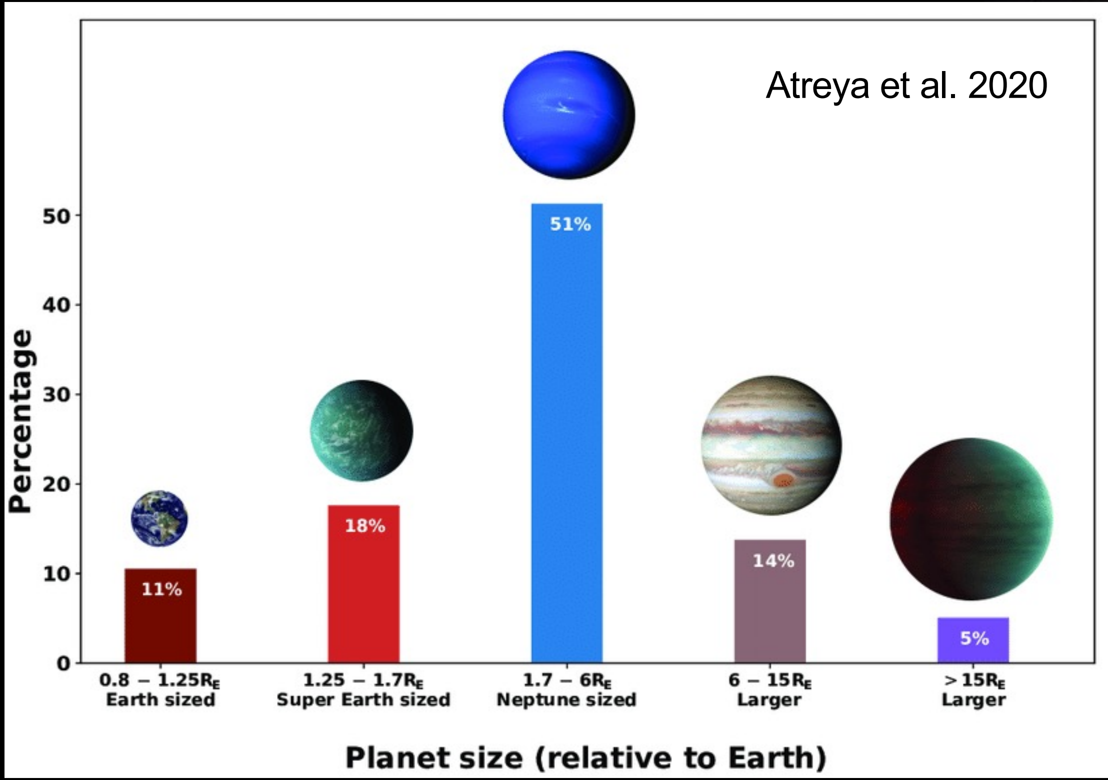
- How do planets like Uranus form & evolve?
- What is Uranus made of?

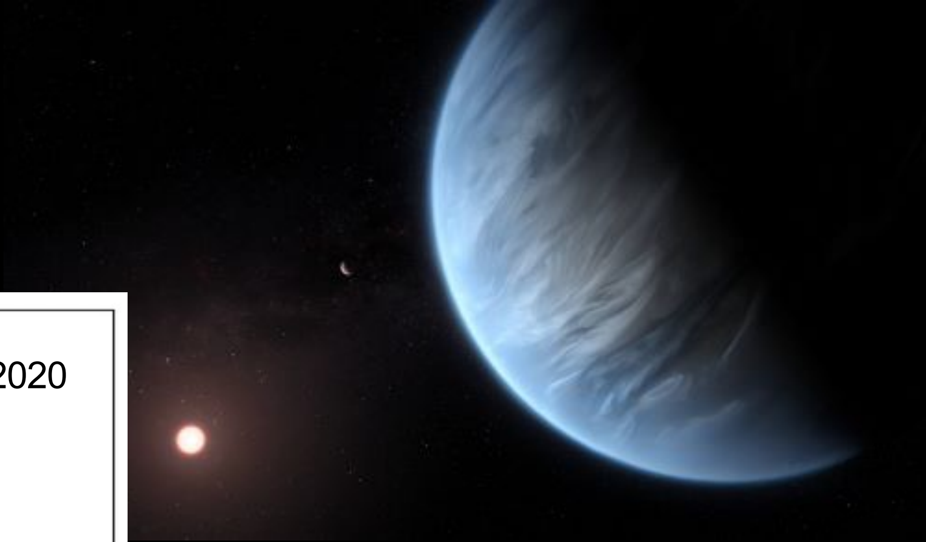
Both Uranus and Neptune exhibit rich systems from the mysterious interiors, atmospheres and magnetospheres, to diverse satellites and rings



Fletcher, Helled et al., 2021

Exoplanet context





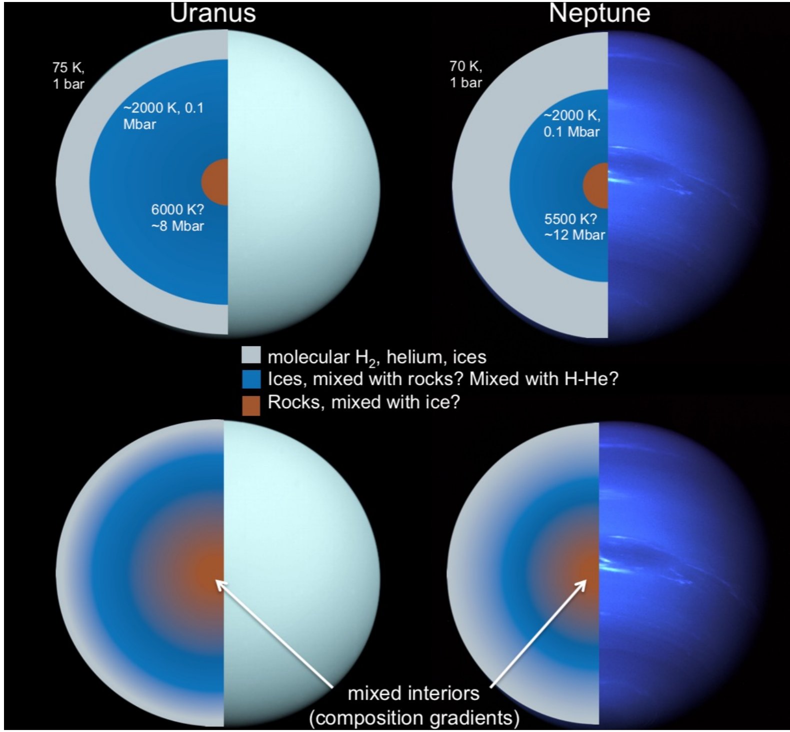
ESA/Hubble, M. Kornmesser


The National Academies of
SCIENCES · ENGINEERING · MEDICINE
ORIGINS,
AND
Planetary Decadal Survey says it's time for a mission to Uranus
Robin Canup and Philip Christensen, Co-chairs
A Decadal Strategy for Planetary Science & Astrobiology
2023–2032
Cover by P. Byrne and J. Tuttle Keane

Uranus: Basic Facts

- Mass = 14.5 $M_{\oplus}$ @ 19.2 AU
- Temperature at 1 bar: 76 ± 2 K
- Y= 0.275 (proto-solar, very uncertain!)
- Fast rotation, strong winds

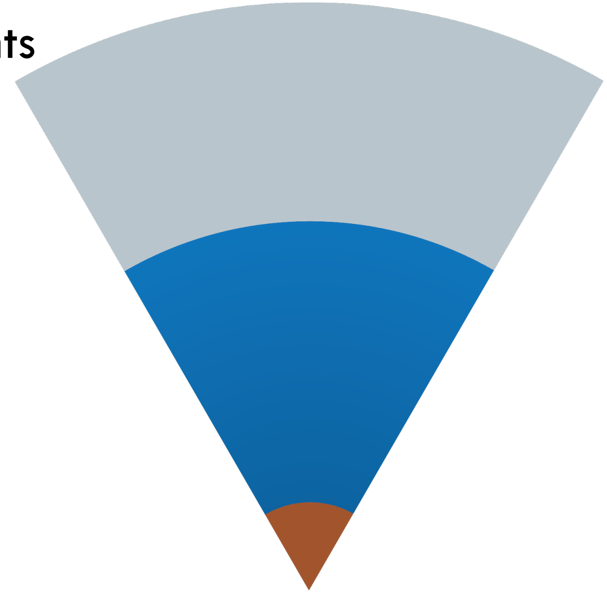
Water-rich?
Distinct layers?
Where & how did it form?



Making an interior model

Basic idea of interior models: observations as constraints

more accurate measurements → less freedom in modeling



Assumptions:

spherical symmetry & hydrostatic equilibrium

Interior parameters:

density, pressure, temperature

Planetary basic equations:

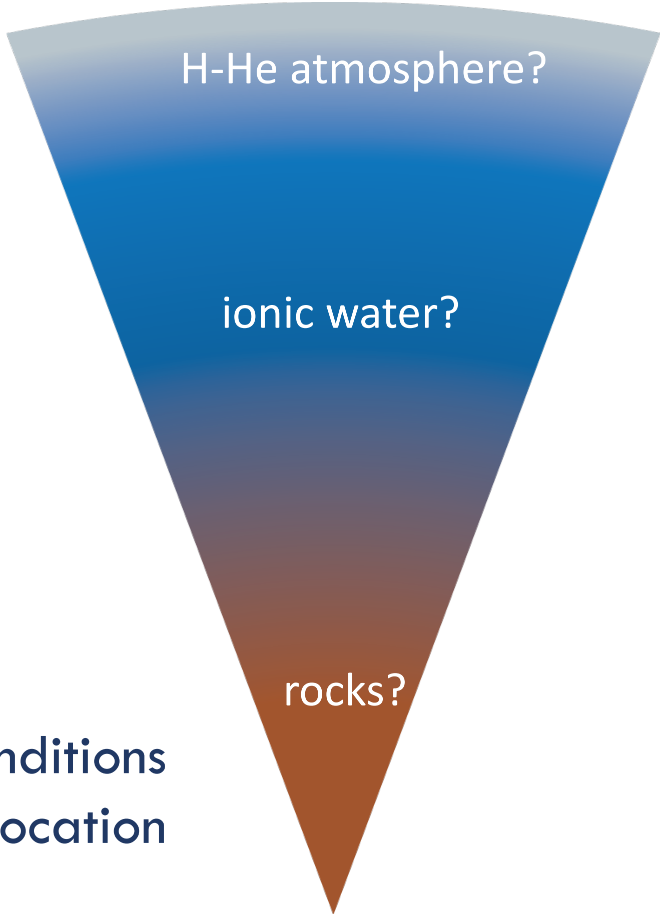
mass conservation, hydrostatic equilibrium, heat transport, energy conservation, EOS

Traditional 3-layer models:

1) Central Core (rocks)
2) Inner Envelope (ices)
3) Outer Envelope (H-He+Z)

Observational Constraints

- Mass
- Radius (shape)
- Rotation rate
- Gravitational Moments
- 1 bar temperature
- Atmospheric composition (if available)

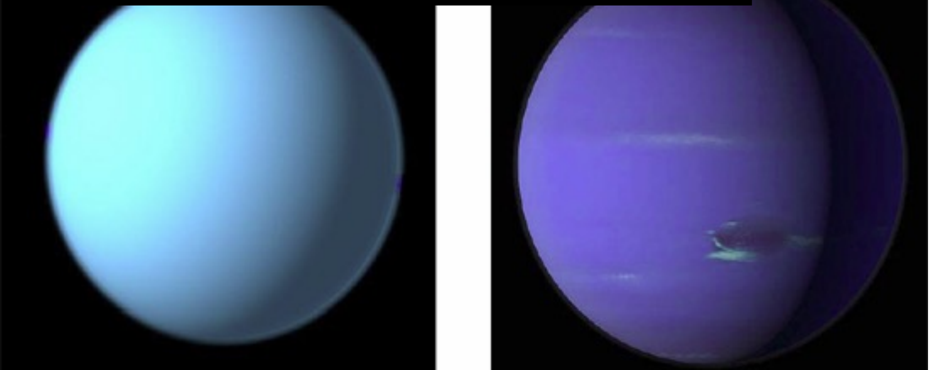


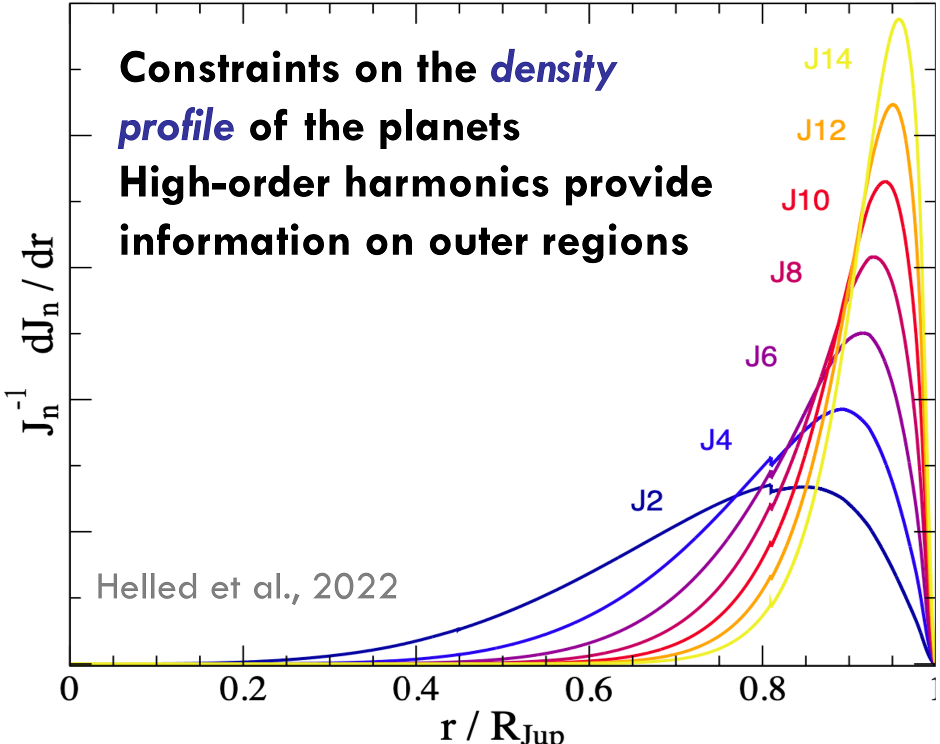
→ Composition provides constraints on (1) the conditions in the solar nebula, (2) the planetary formation location and (3) formation timescale.

- Gravity data are insufficient to constrain the composition & internal structure.

Structure and chemical composition are inferred ***indirectly*** from the model (and strongly depend on the assumptions)

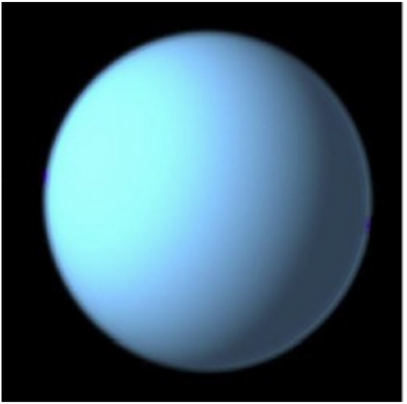
$$\begin{aligned} M &= \iiint \rho(r,\theta) d^3\tau, \\ J_{2i} &= -\frac{1}{M R_{\rm eq}^{2i}} \iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau, \end{aligned}$$

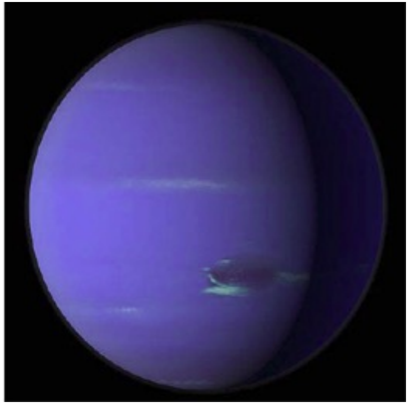


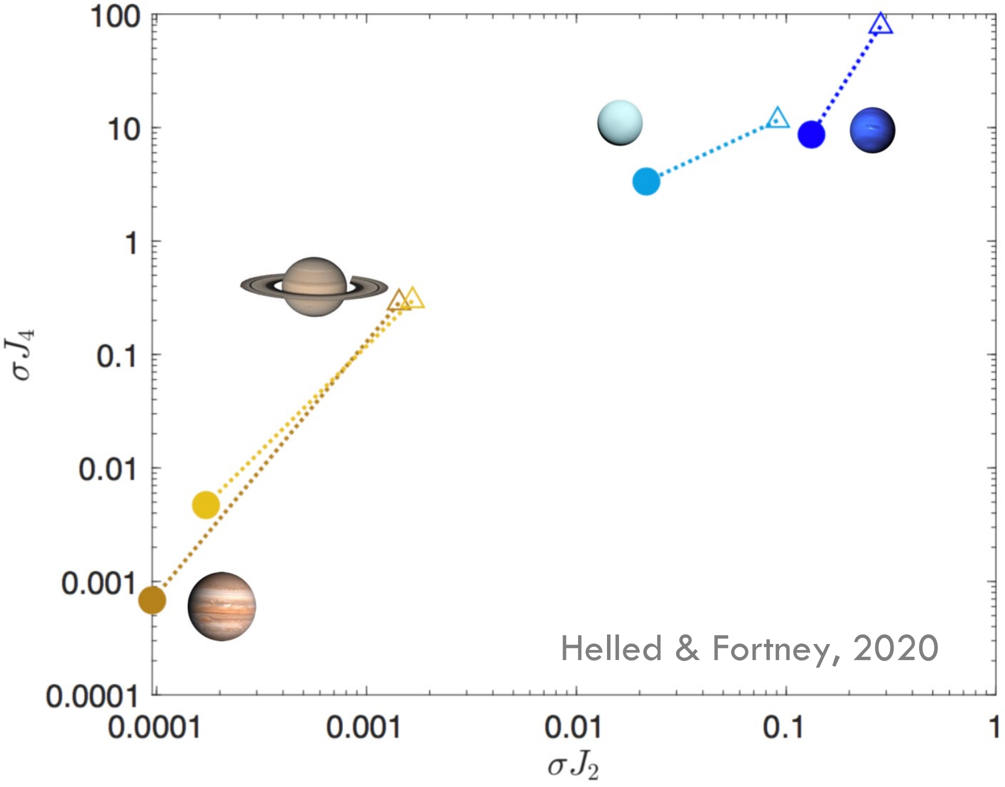


- Only J_2 and J_4 are available with large uncertainties

→ a large range of possible internal structures and compositions

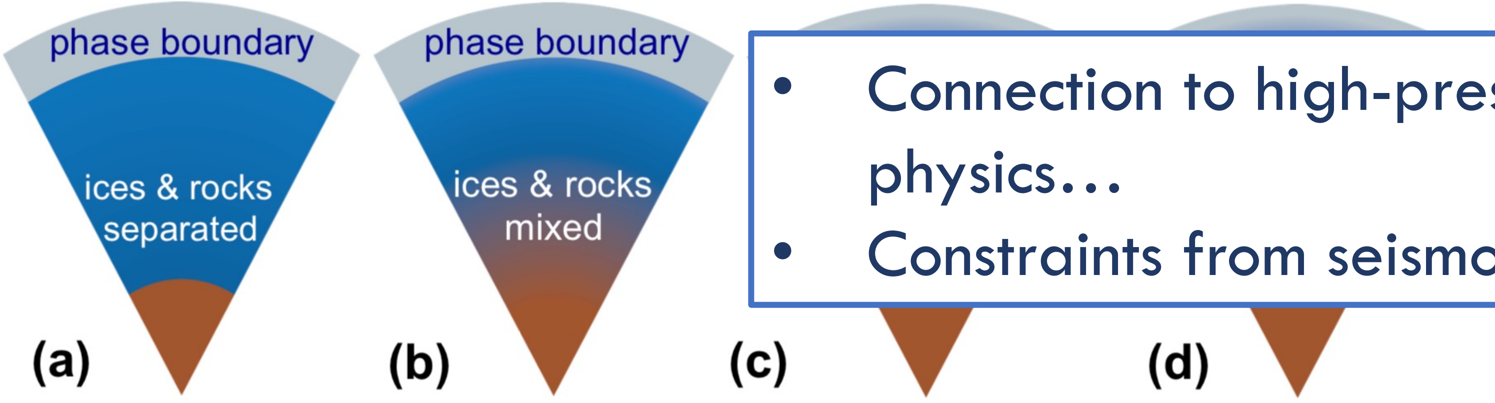






relative observational uncertainties

Do Uranus & Neptune have distinct layers?
What is the bulk composition?



- Connection to high-pressure physics…
- Constraints from seismology?

Given the data we have, Uranus and Neptune can also be rock-dominated

Uranus and Neptune are unique planets – they are different from the terrestrial planets and the gas giants. **We still not have a good modeling approach**!

e.g., Stevenson, 1985
Lozovsky, Helled et al., 2017
Helled & Stevenson, 2017
+....

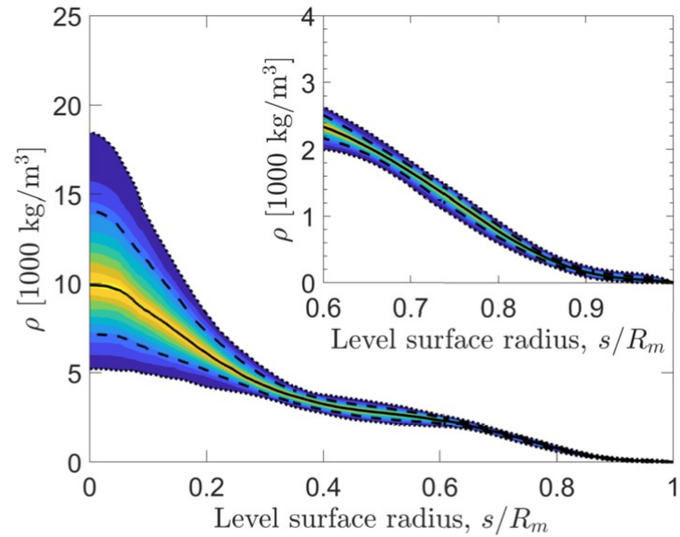
Empirical models

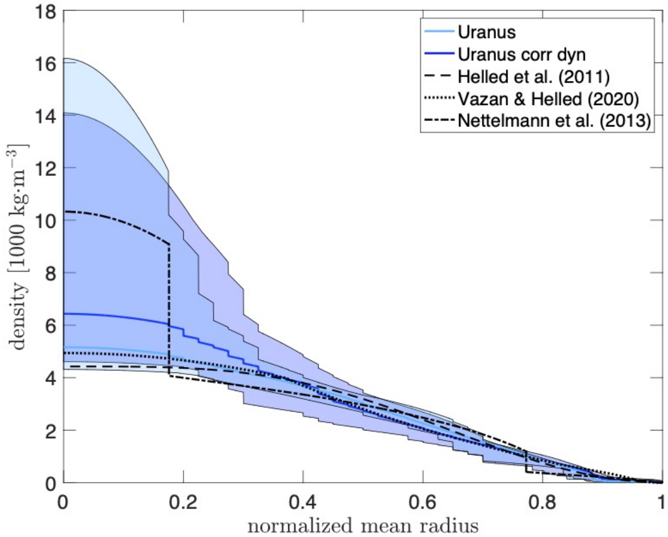
Uranus

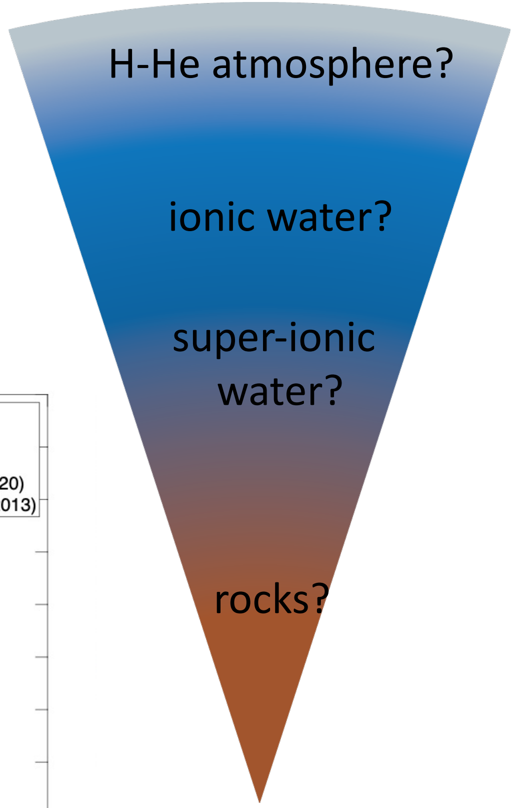
46.1 < $J6$ < 69.0

-17.8 < $J8$ < -8.4

0.218 < MoI < 0.227



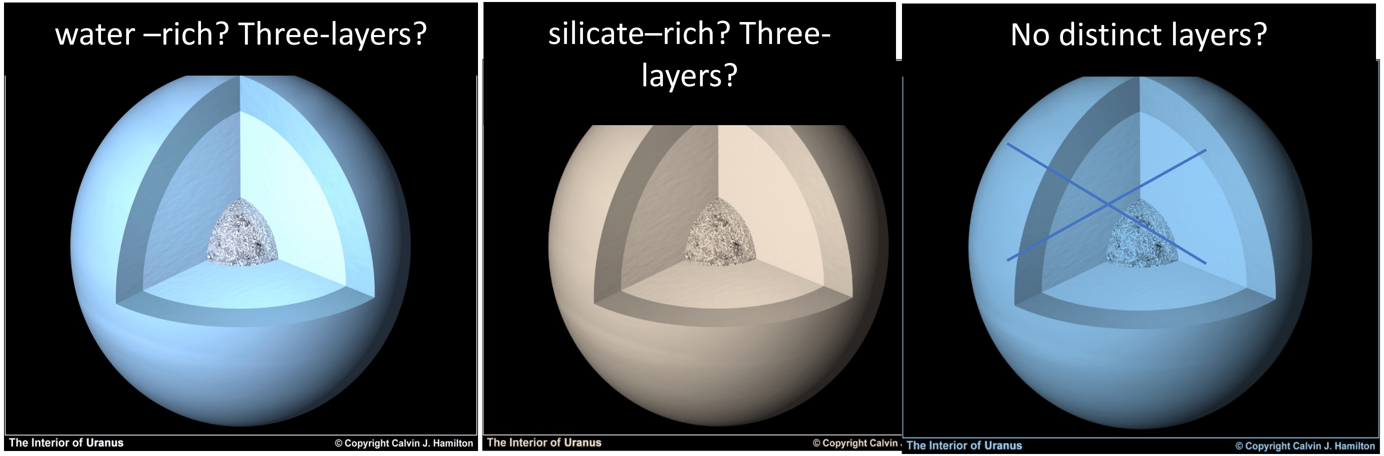




Movshovitz+2022, Neuenschwander & Helled, 2022

Ice or rock giant?

- Given the data we have, Uranus could also be rock-dominated



Helled et al., 2011.

Reasons to believe U&N are water-rich:

(1) Magnetic fields **– is it really?**

(2) Water is abundant at these distances **– what about Pluto?**

Magnetic fields - Interiors

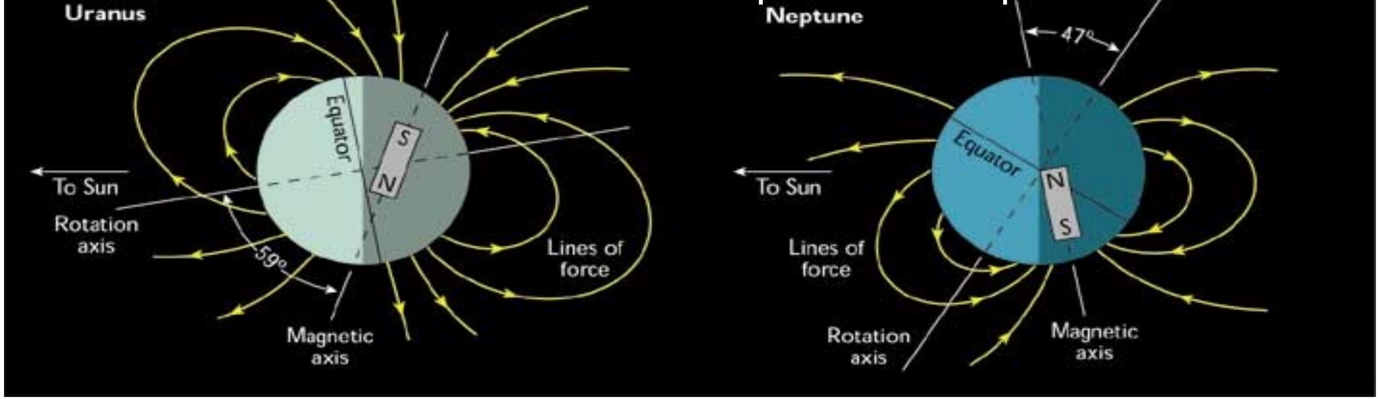
- Complex multipolar nature of magnetic fields

Where are the magnetic fields generated?

What is the depth of the winds and how is connected to the structure?

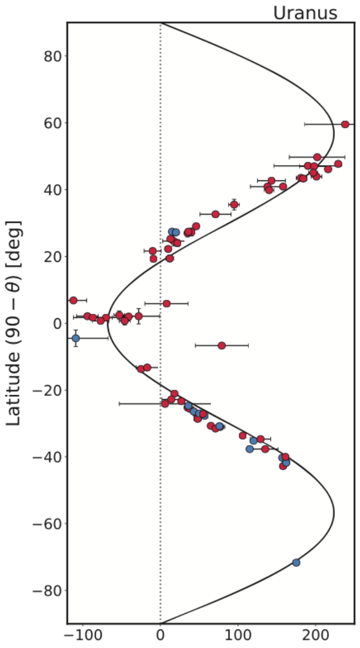
Constraints on interior: convective layer +conducting material

Need to determine rotation period of the planets



What is the rotation rate of Uranus?
What is the shape of Uranus?

Uncertainty in rotation → wind velocities

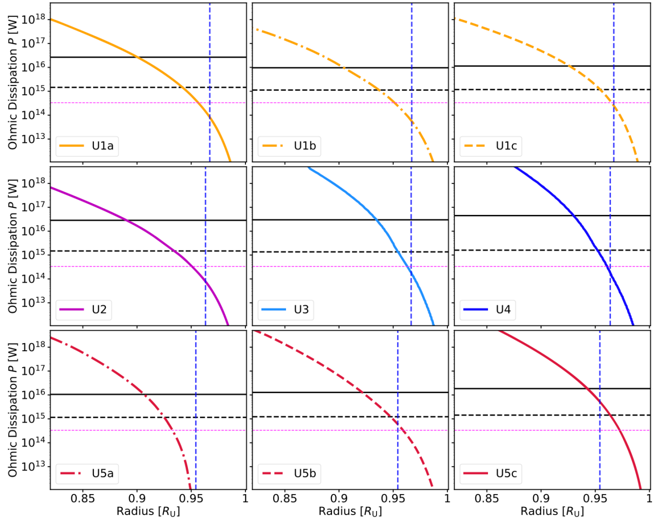


wind speeds (m/s)

P_{Voy}:
16.58 hr
Suggested (theory*):
17.24 hr
*Helled+10

How deep are the winds?

Kaspi et al. 2013
Soyuer et al., 2020



wind penetration to ~0.93–0.97 R_U (~1000 km)

Shape – rotation- interior

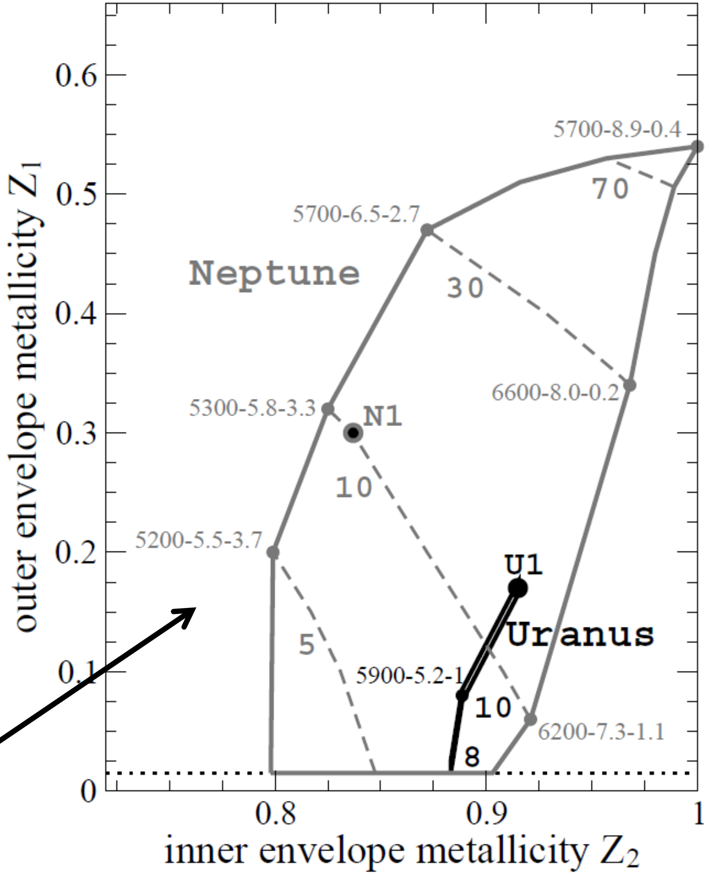
Modified rotation periods & shapes

(Helled et al., 2010)

Uranus: 17.24 hr (P_{Voy}: 16.58 hr)

Neptune: 16.11 hr ($P_{voy:}$ 17.46 hr)

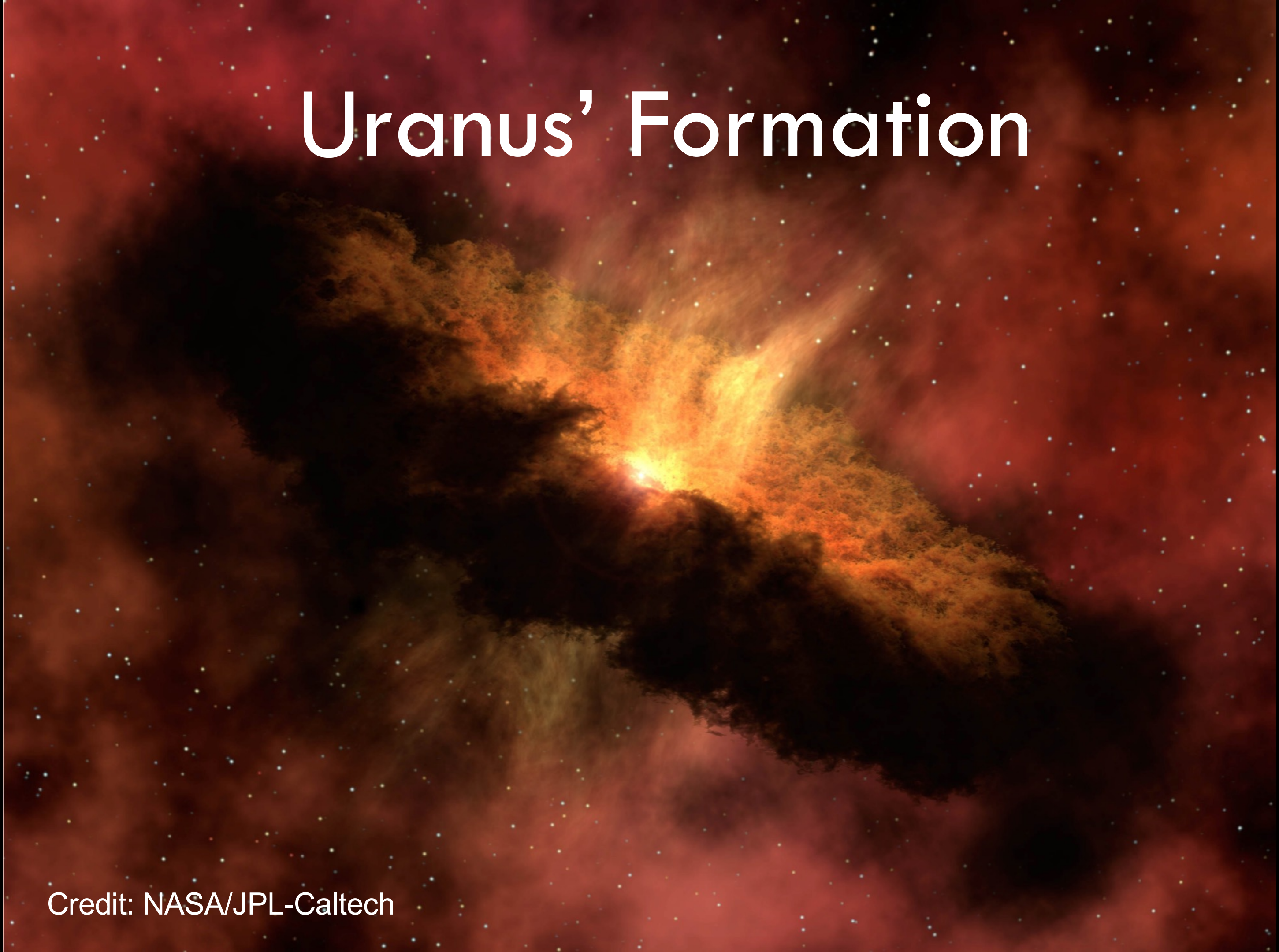
Interior models with modified data:



T_c (K), P_c (Mbar), M_{core} / M_{Earth}

Nettelmann,+2013

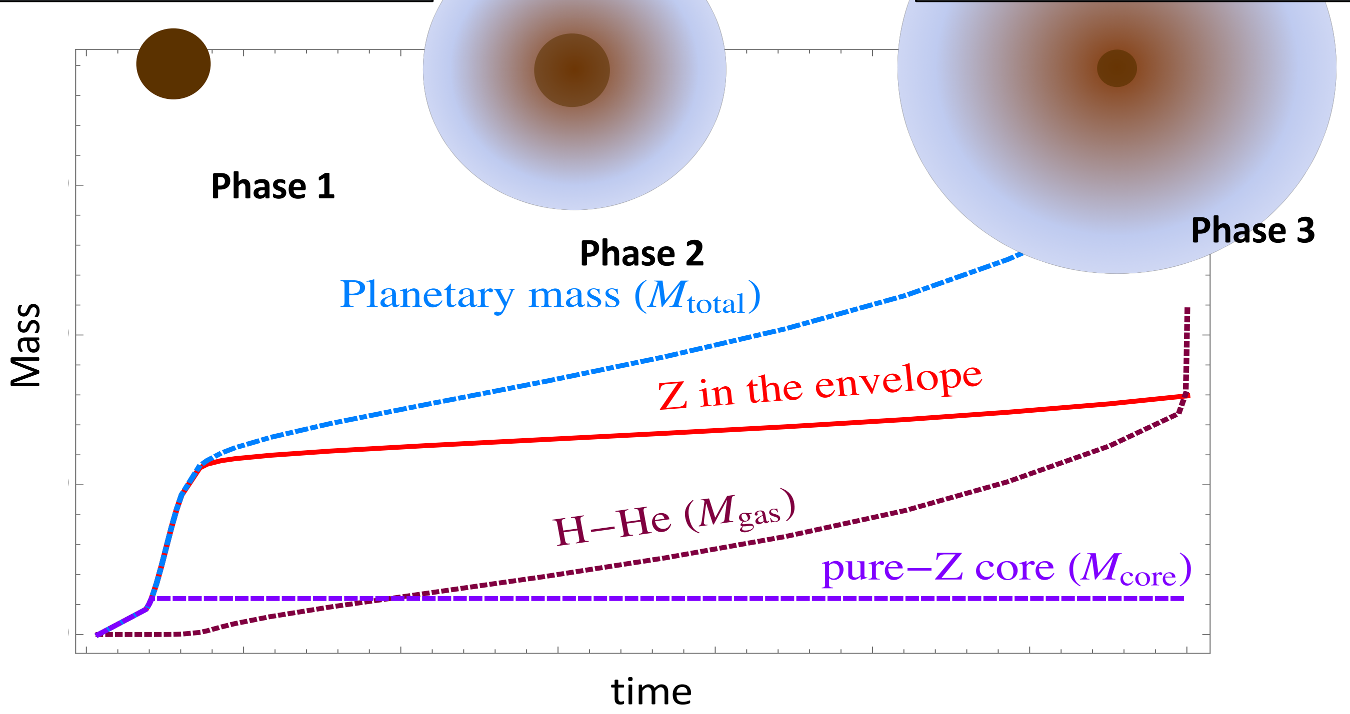
Uranus' Formation



Credit: NASA/JPL-Caltech

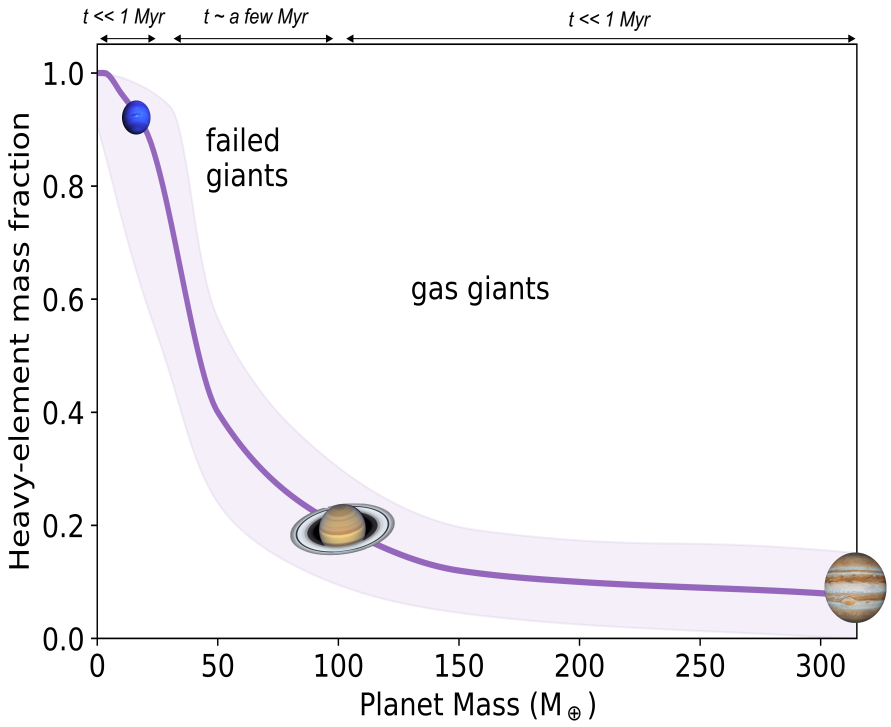
Planet Formation 101

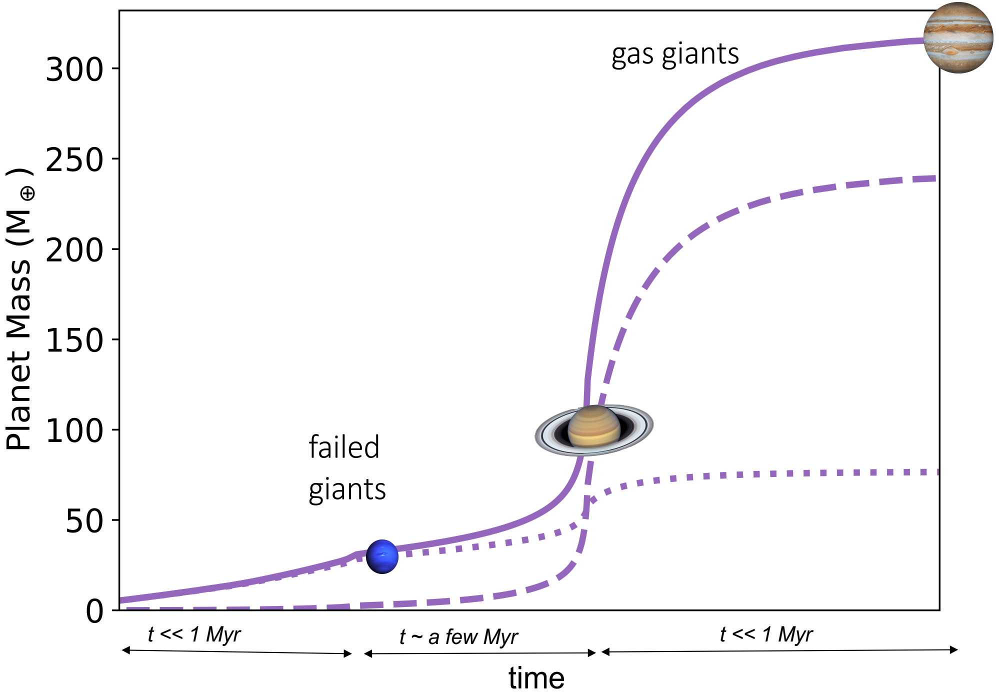
Terrestrial planets	Neptunes, mini-Neptunes	Gas giants
Formation of a heavy-element core via planetesimal/pebble accretion	The core is massive enough to accrete and retain gas (H-He)	The gas accretion rate exceeds the solid accretion rate → runaway growth



Helled & Morbidelli, 2021

Are Uranus and Neptune failed giant planets?



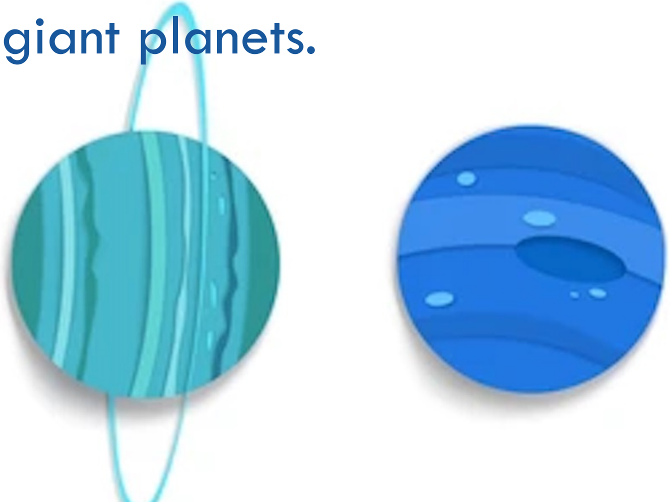


Helled, A&A, 2023

Formation of Uranus & Neptune

Uranus and Neptune have 2 $M_\oplus$ and 3 $M_\oplus$ of H-He, respectively. Metallicity of ~ 85% (but model dependent).

- **Similar formation process like J&S but slower:**
  - On one hand, must form before the gas dissipates.
  - On the other hand, should not become gas giant planets.

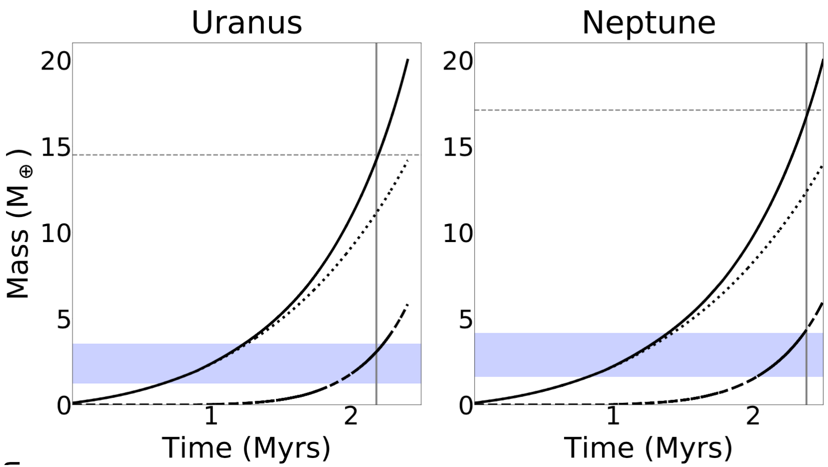


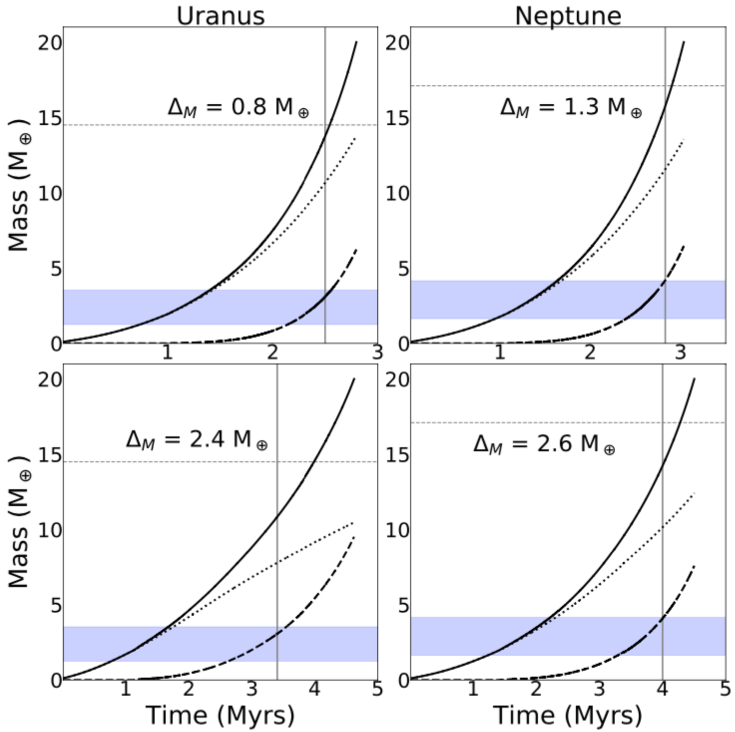
see Helled & Fortney, 2020 and Helled+2020 for recent reviews

Potential Formation paths:

1. Formation closer to the sun (Nice Model)
2. Disk physics/chemistry – disk evolution, enhancing the solids
3. High accretion rates: pebble accretion, dynamically cold planetesimal disk
4. Formation via impacts of ~5 $M_{\oplus}$ embryos
5. …

In-situ Formation of Uranus & Neptune





U&N can from in-situ within the disk timescale and have the correct final masses and compositions

Often a few $M_\oplus$ of heavies is missing
→ Post-formation giant impacts?

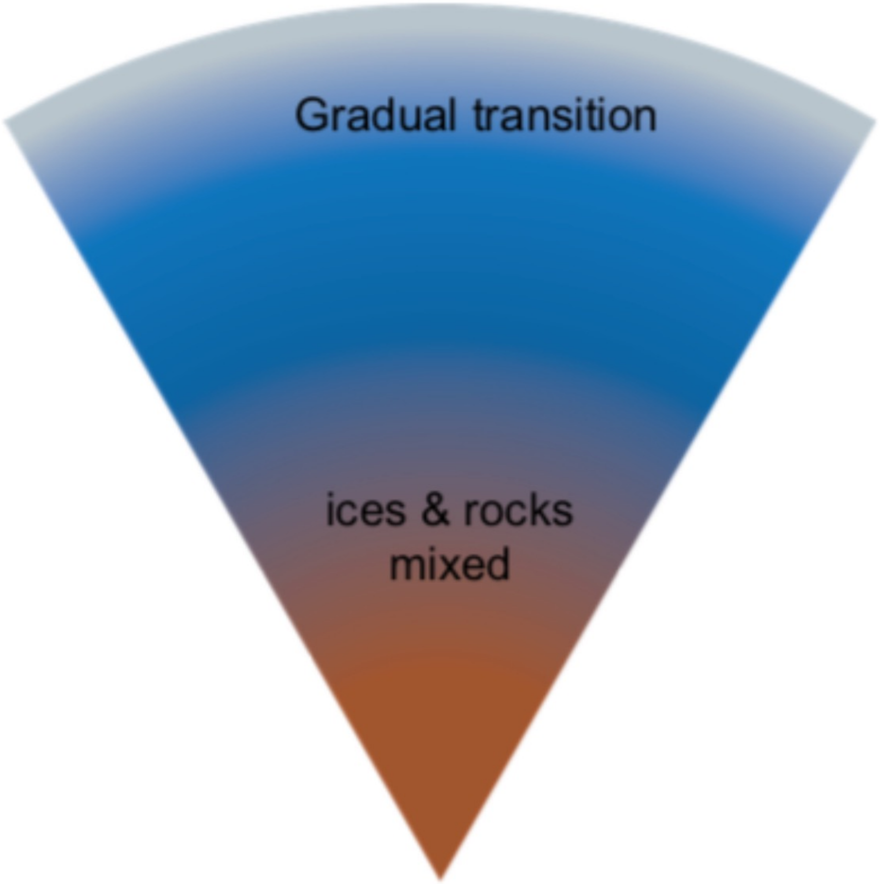
Valletta & Helled, 2022

Connecting the internal structure with growth history

The heavy-element profile within the planet's deep interior (before runaway) reflects its accretion history!

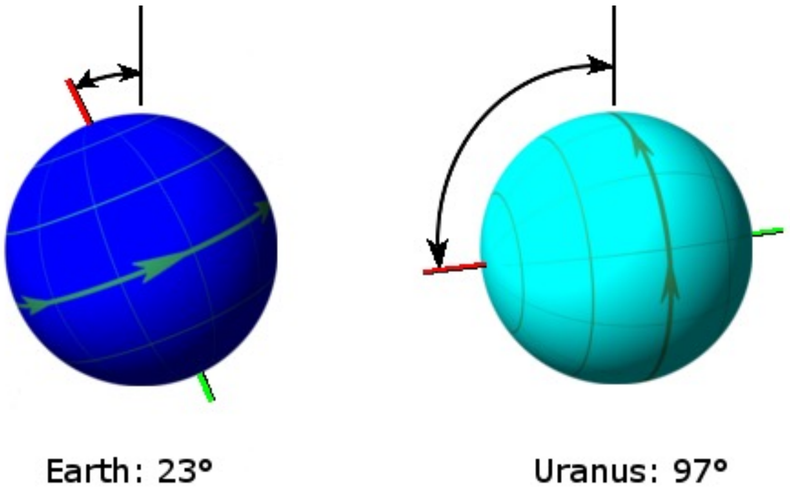
$$Z(m) \sim \frac{\dot{M}_{Z,env}(M)}{\dot{M}_{xy}(M) + \dot{M}_{Z,env}(M)},$$

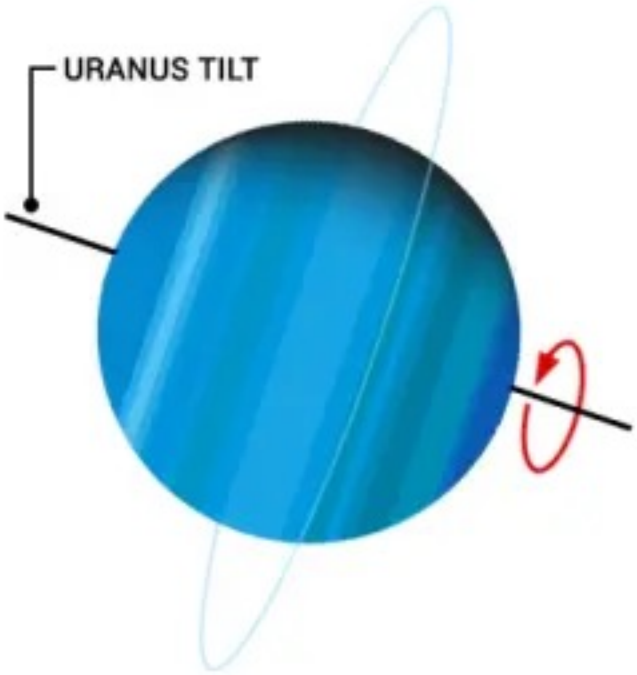
Helled & Stevenson 2017
Valletta & Helled, 2020, 2022



Diversity of intermediate-mass/size exoplanets

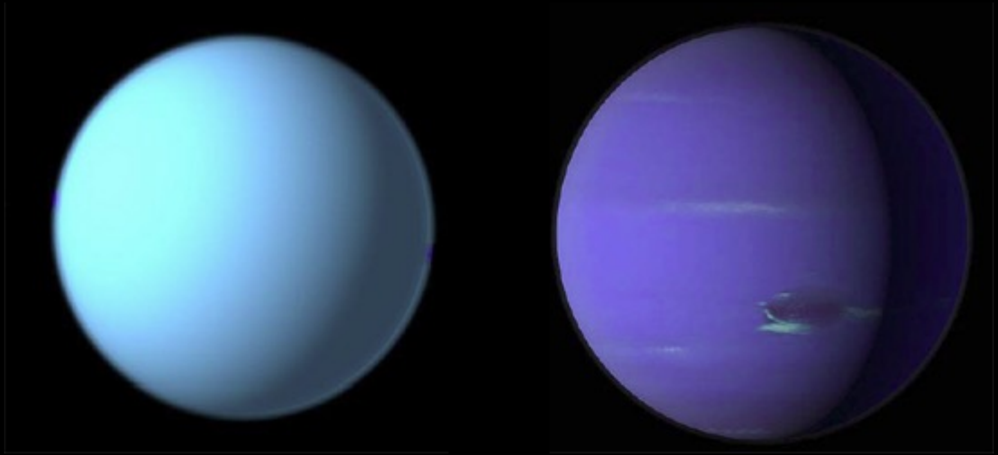
Uranus’ strange tilt (and moons)





Despite the similar masses/sizes Uranus and Neptune differ in:

- Large tilt (~97°) of Uranus and its satellites
- Large difference in observed heat flux
- Satellite systems
- (Inferred) Moment of Inertia

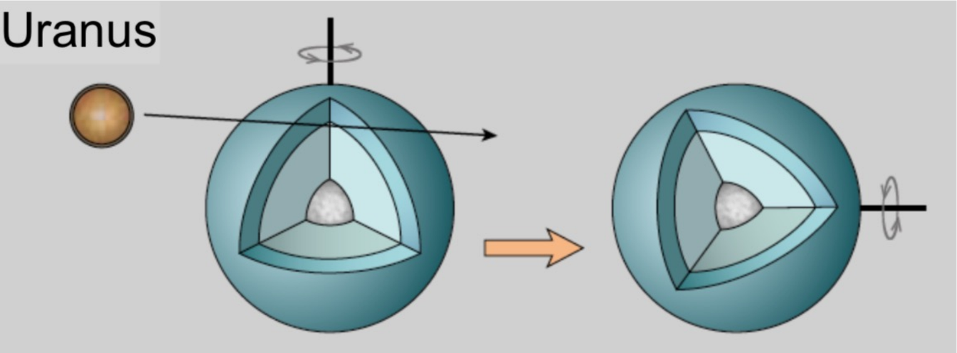


Maybe Uranus and Neptune were initially similar shortly after formation and the differences are a result of giant impacts?

Stevenson, 1986
Podolak & Helled, 2012
Reinhardt et al., 2020

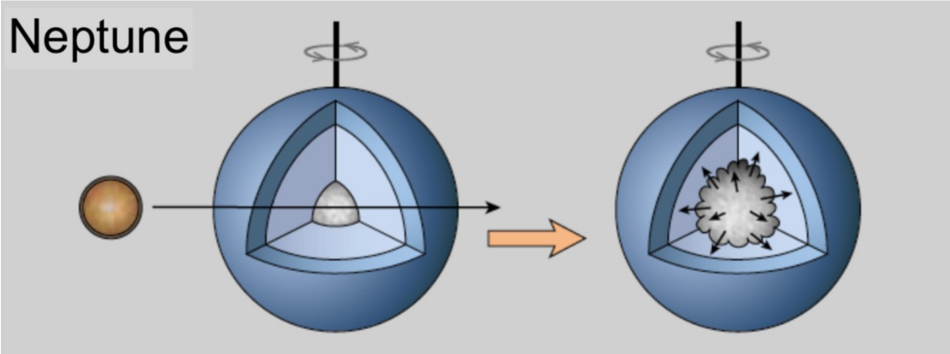
Giant Impacts:

Uranus: Oblique Collision



tilt its spin axis and eject enough material to form a disk where the regular satellites are formed.

Neptune: Radial Collision



could deposit energy deep inside, mix its interior resulting in a nearly adiabatic interior.

might also explain the missing heavy-element mass…

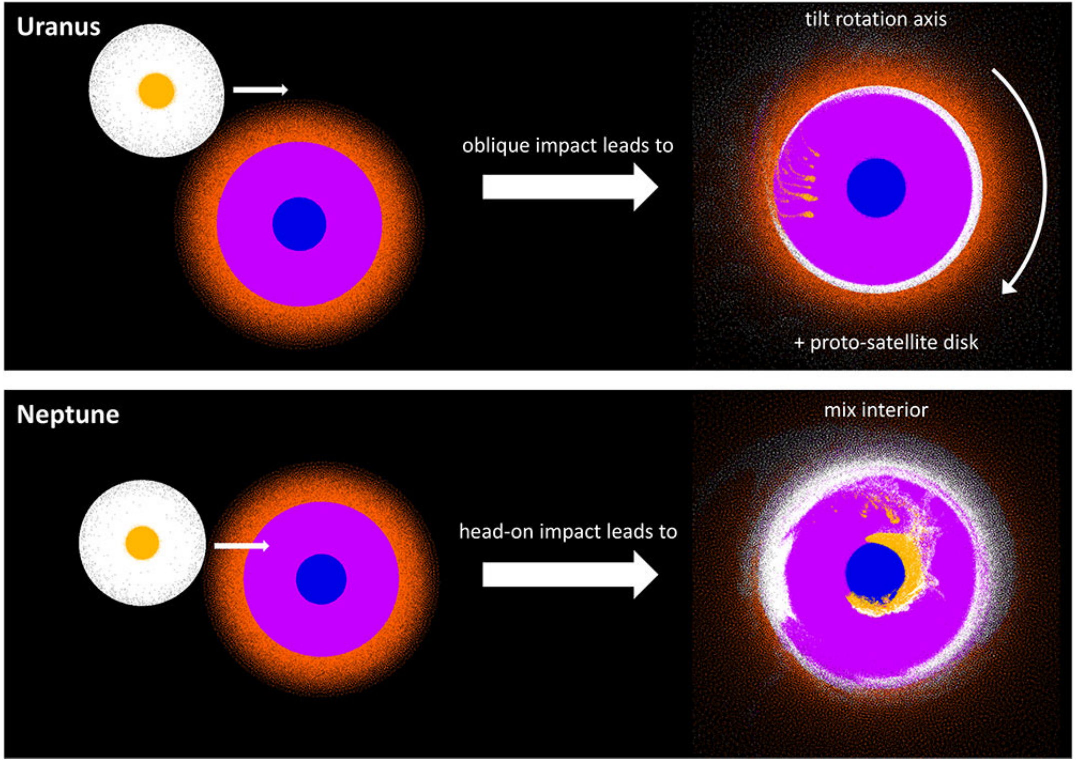
M_{tot}=14.5 $M_{\oplus}$, v_{∞}=5 km/s

Head-on collision (b=0.2):

- Impactor's material and energy are deposited in the deep interior → an adiabatic interior and high flux?

Grazing collision (b=0.7):

- Increase in angular momentum → change of tilt, disk formation, deep interior is relatively unaffected

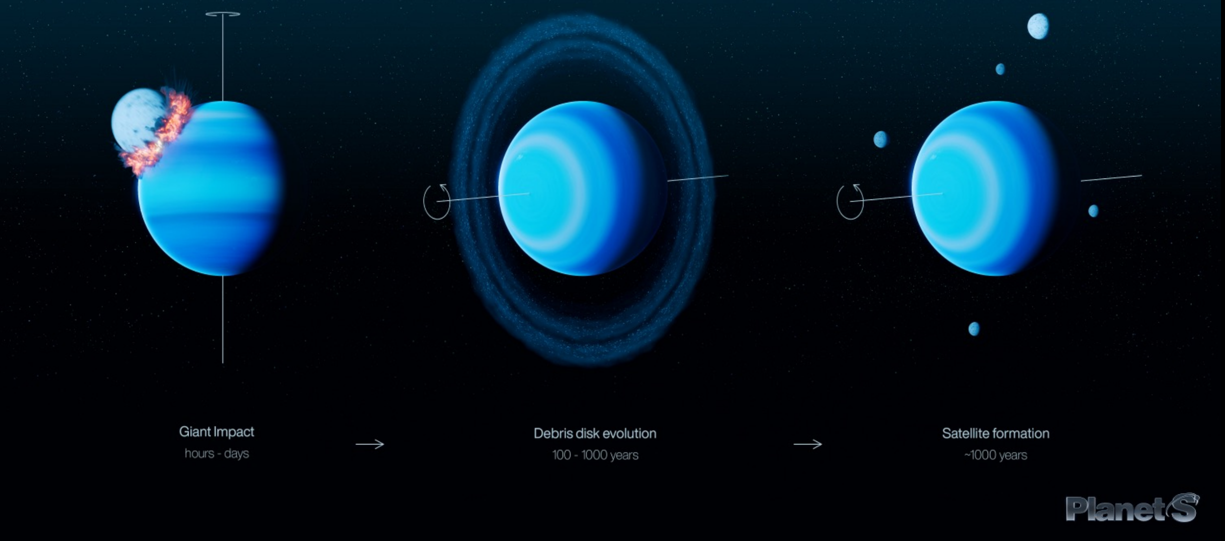


But much more work is needed...

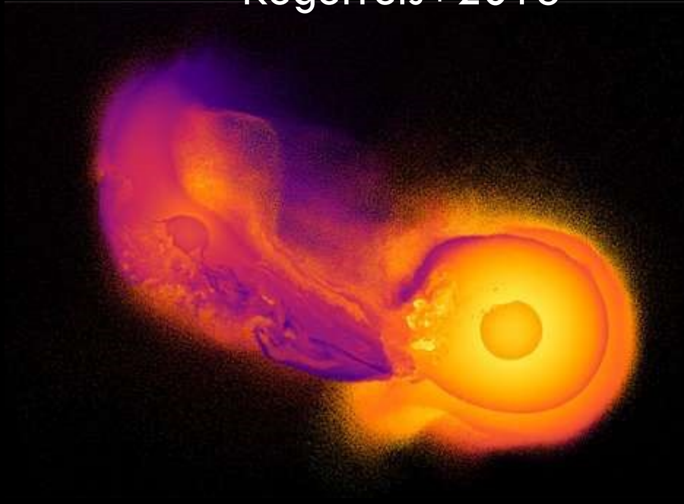
Reinhardt et al., 2020

Can Uranus' moons form from the post-impact disk?

Woo et al, 2021



Kegerreis+2018

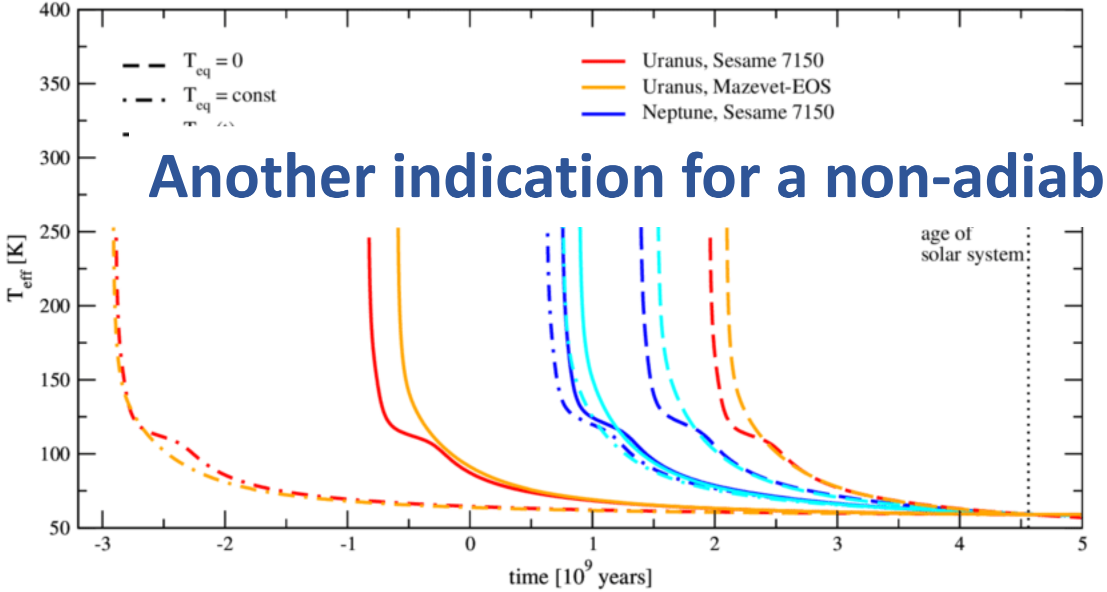


Artistic illustration of the formation of the largest moons of Uranus.
Image: Tobias Stierli

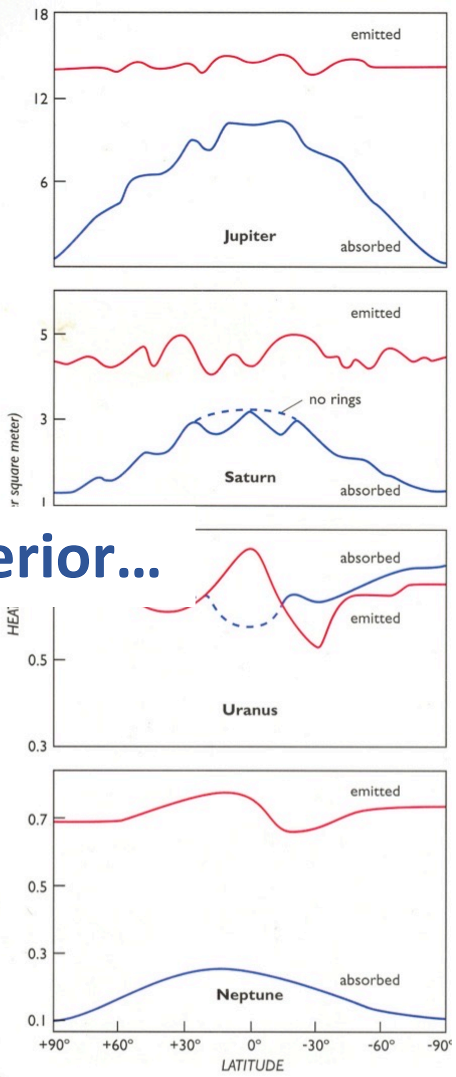
See also Salmon & Canup, 2022Rufu & Canup, 2022
Ida+2020, Kegerreis+2018 and references therein

Uranus’ strange luminosity

The low luminosity of Uranus challenges the assumption of adiabatic cooling…



Another indication for a non-adiabatic interior…

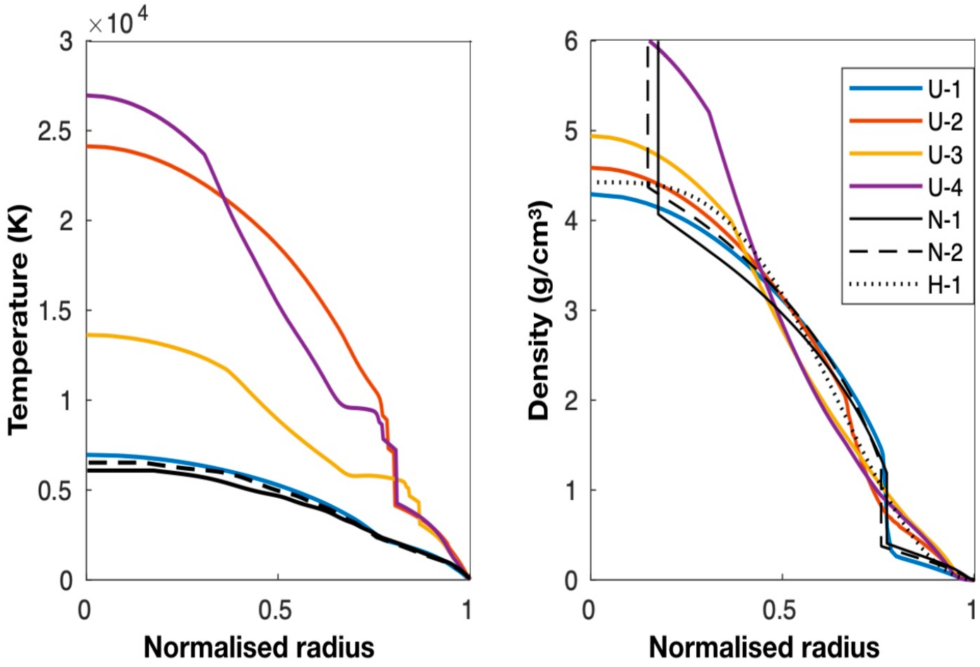


Scheibe et al., 2019

Uranus’ long-term non-adiabatic evolution

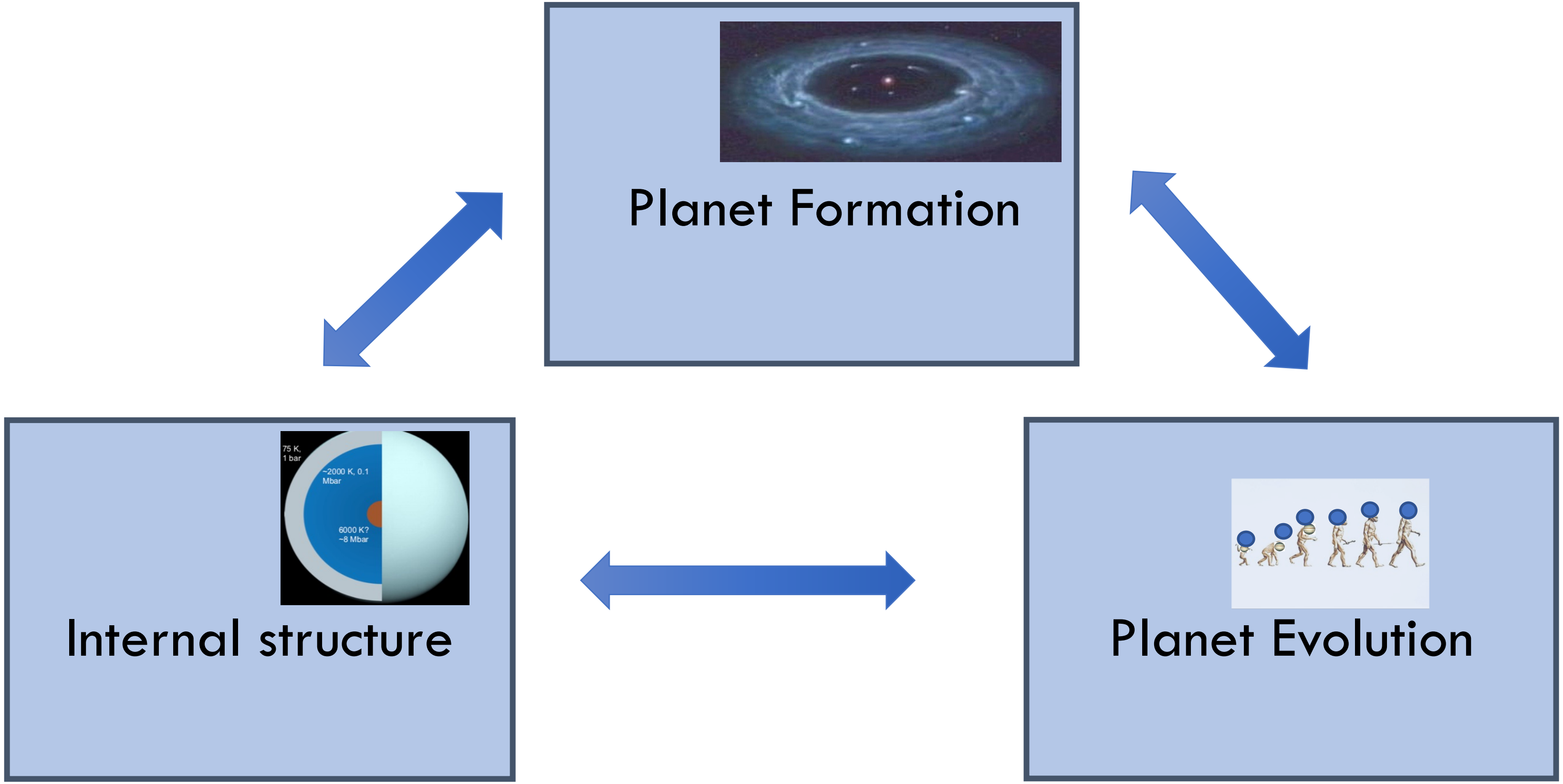
Non-adiabatic interior+evolution of Uranus.

- Convective mixing is limited to Uranus’ deep interior
- The composition gradient persists and can explain Uranus’ measured luminosity.
- Uranus’ interior could be **very hot**, despite its low luminosity.



Vazan & Helled, 2020

Connect **interior models** with **planetary formation** and **evolution models**



Summary & Future Research

- Key fundamental questions remain:
  - How did Uranus form and evolve?
  - What is the composition and internal structure of Uranus?
  - What is the rotation rates of Uranus? How deep do the winds go?
  - How different are Uranus and Neptune? What is the origin of these differences?
  - How is Uranus' magnetic field generated?

❖Uranus and Neptune could form in-situ.
❖The planetary structure can be complex.
❖Giant impacts might have played an important role in their evolution.

Future Research

- Understanding the behaviour of planetary materials, and their mixtures:
  - Further improvements in EOS calculations and experiments of volatile materials such as water, ammonia, methane, their mixtures, as well as their mixtures with rock or with hydrogen (and helium)

- Prepare for the upcoming space mission: identify the key measurements and develop the theoretical framework for the data interpretation

- Connection to exoplanets