University of Zurich[UZH]

URANUS AND NEPTUNE:
FROM ORIGIN TO CURRENT-STATE STRUCTURE

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See recent review by Helled et al., 2019, arXiv:1909.04891

URANUS & NEPTUNE

-- How do planets like Uranus/Neptune form?

-- How do these planets evolve?

-- What are Uranus and Neptune made of?

-- Are they different? If yes, in what? composition? heat transport? formation/evolution?

Uranus and Neptune represent a unique planetary class

URANUS & NEPTUNE: BASIC FACTS

Uranus: Mass = 14.5 $M_\oplus$ @ 19.2 AU

Neptune: Mass = 17.1 $M_\oplus$ @ 30 AU

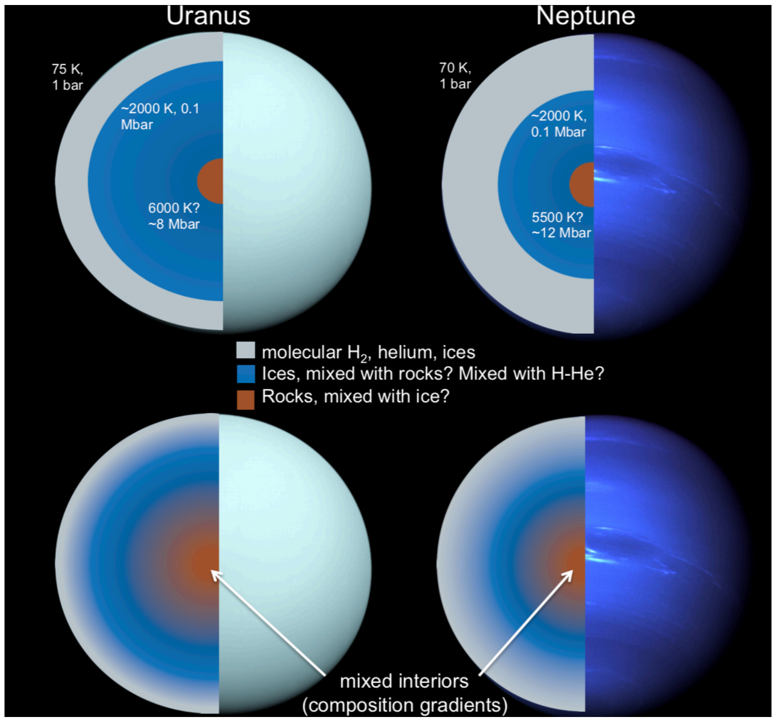
Temperature at 1 bar:

76 ± 2 K (U); 72 ± 2 K (N)

Y= 0.275 (proto-solar, very uncertain)

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

Water-rich planets?
Failed giant planets?
Where did they form?



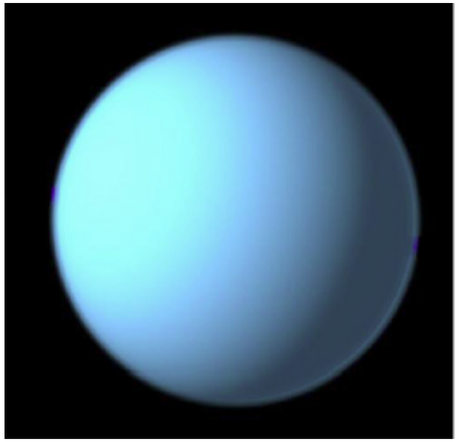
Similarities:

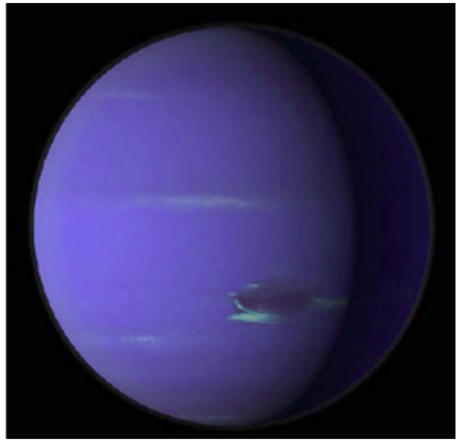
mass, radius, rotation,

radial distance

Differences:

flux, tilt, atmospheric composition, satellite system, atmosphere dynamics?





OBSERVATIONAL CONSTRAINTS

How well do we know those?

Mass

Radius (usually equatorial)

Angular velocity ω

Gravitational Moments (only J_2, J_4)

1 bar temperature

Atmospheric composition (only sometimes…)

(shape, MOI, magnetic fields dynamos, internal dynamics heat transport mechanism)

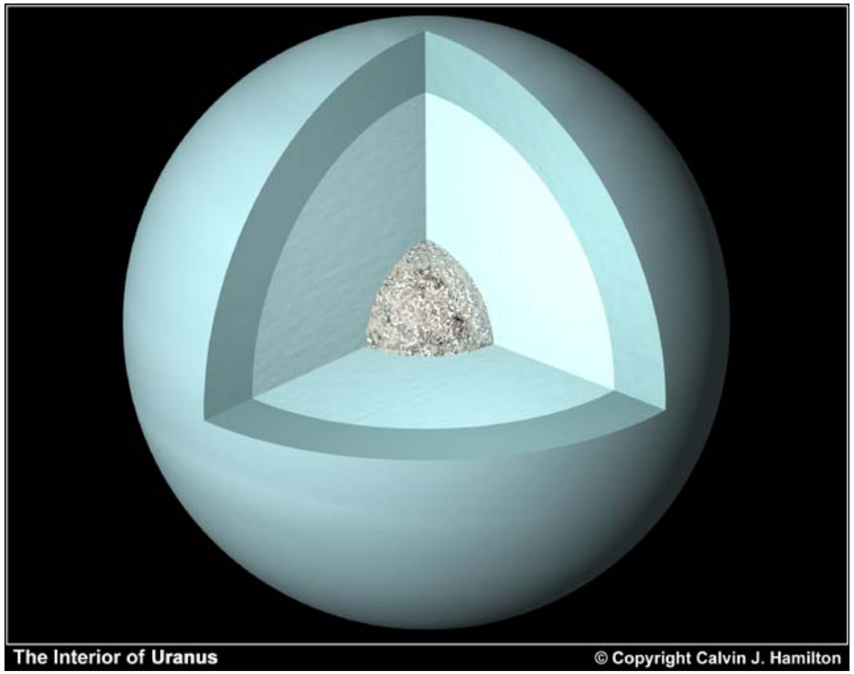
Yes, we need a space mission… preferably to both planets ☺

MAKING AN INTERIOR MODEL

Assumptions:
spherical symmetry & hydrostatic equilibrium

Interior parameters:
density, pressure, temperature

Planetary basic equations:
mass conservation, hydrostatic equilibrium, heat transport, energy conservation, EOS

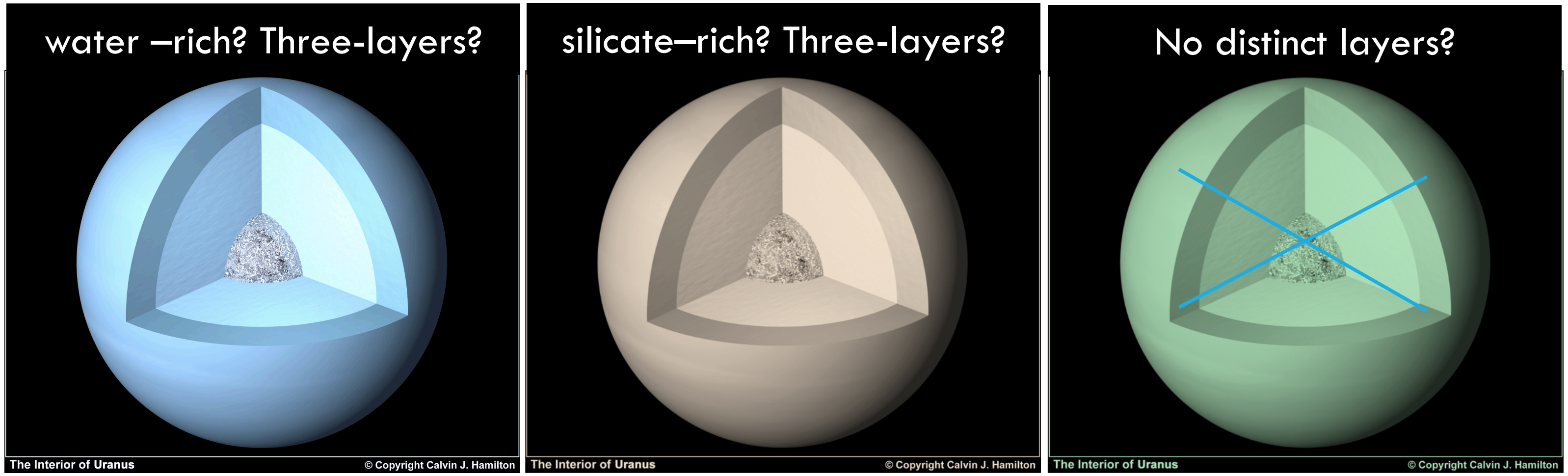


URANUS AND NEPTUNE

Only J_2 and J_4 are available with large uncertainties

→ a large range of possible internal structures.

Gravity data are insufficient to constrain the composition and internal structure.



Helled et al., 2011.

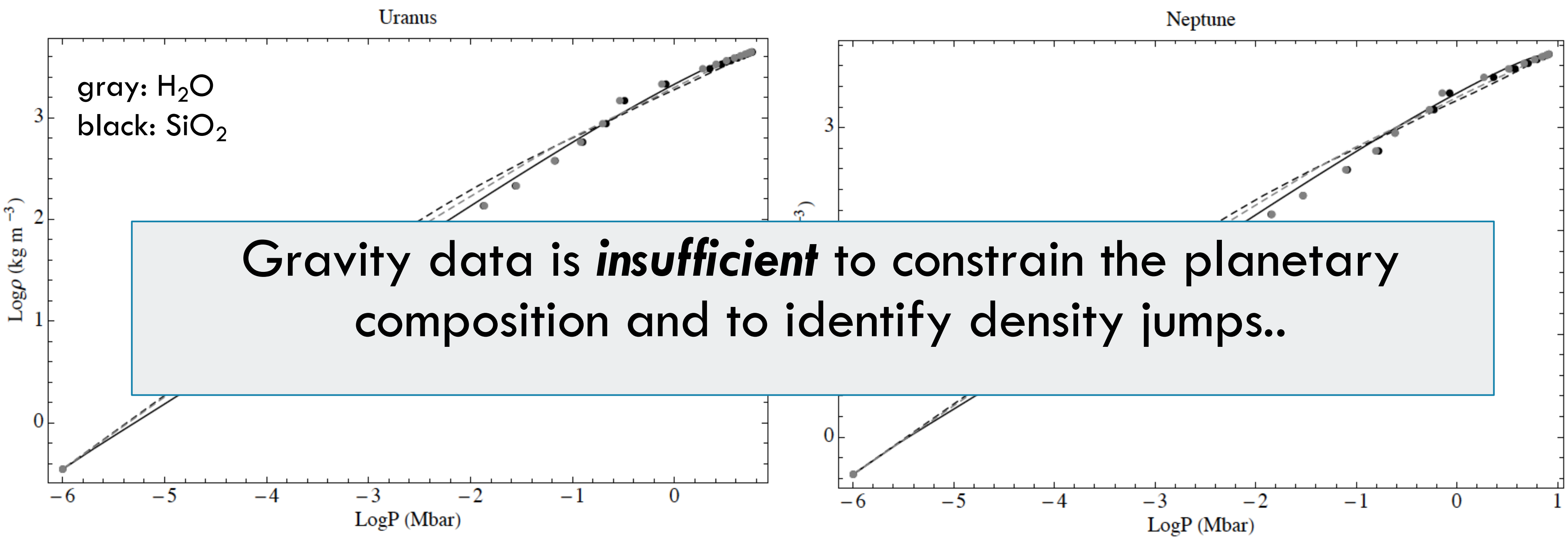
Reasons to believe U&N are water-rich:

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

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

URANUS AND NEPTUNE: COMPOSITION

The large error bars on J_{2n} allow a large range of possible internal structures.



Gravity data is ***insufficient*** to constrain the planetary composition and to identify density jumps..

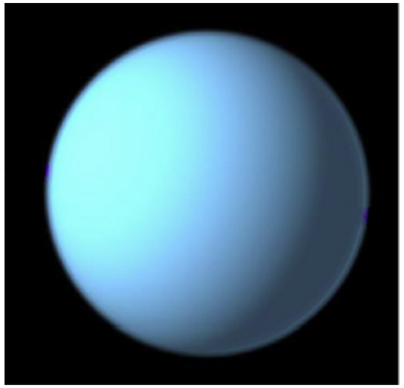
Helled et al., 2011

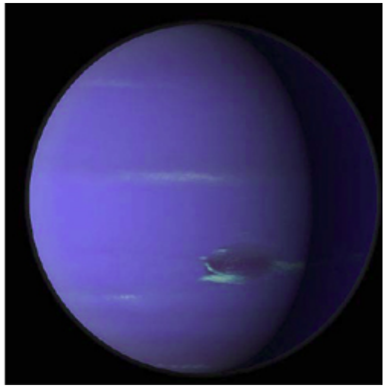
Remember (!):

- **Constraints on the *density profile* of the planets**
- **High-order harmonics provide information on outer regions**

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

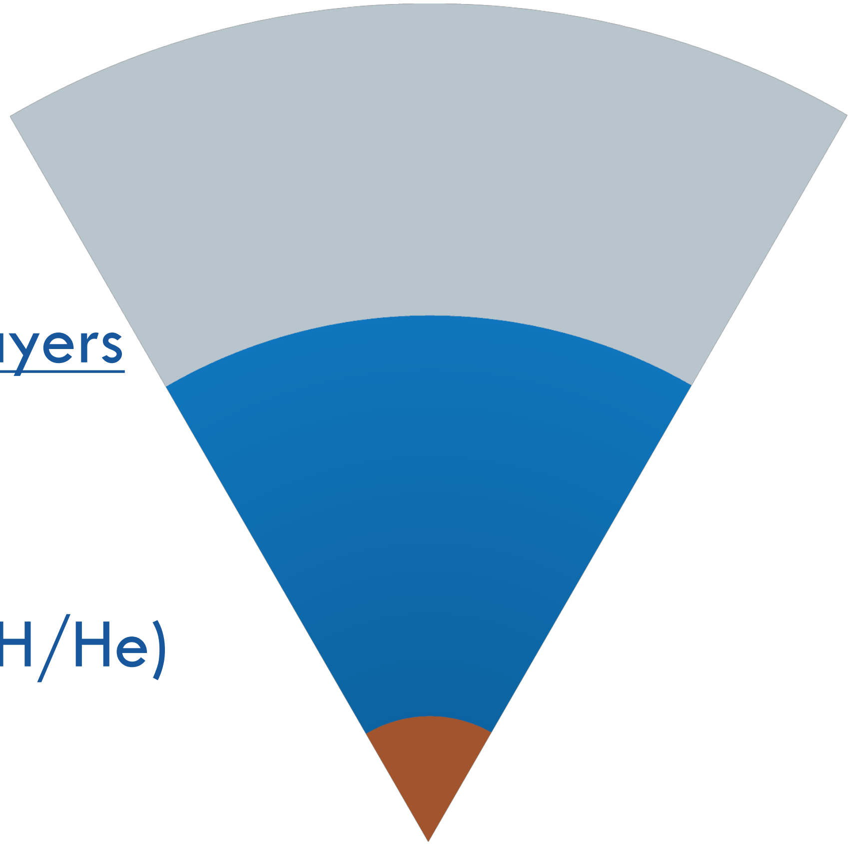
$$
\begin{aligned}
M &= \iiint \rho(r,\theta) d^3\tau, \\
J_{2i} &= -\frac{1}{M R_{\mathrm{eq}}^{2i}} \iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau,
\end{aligned}
$$





URANUS AND NEPTUNE: INTERNAL STRUCTURE

Basic idea of interior models: observations as constraints
more accurate measurements → less freedom in modeling



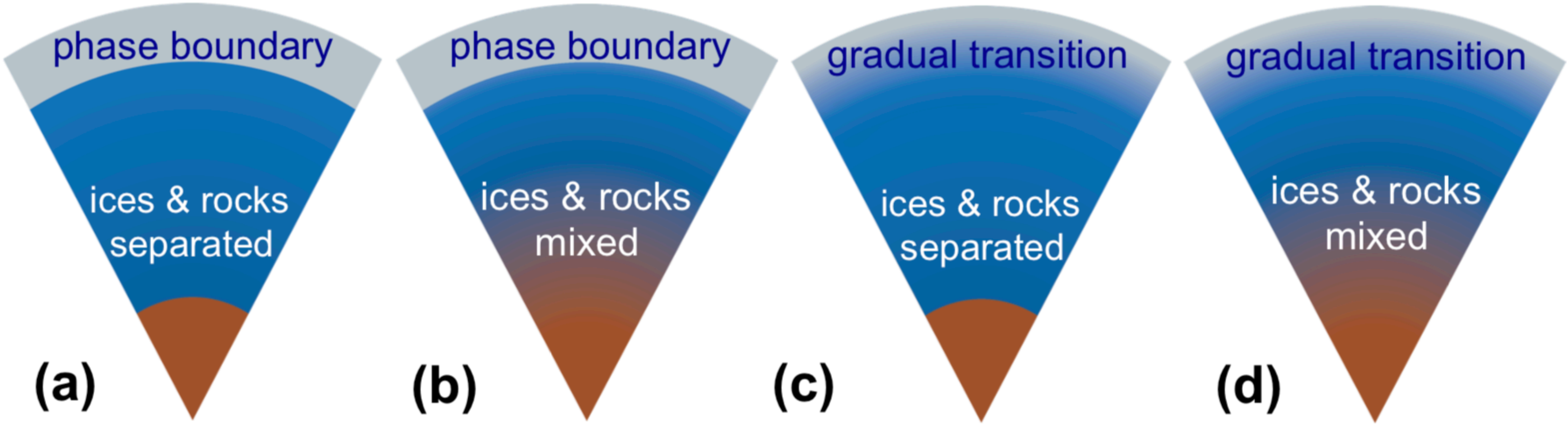
<u>Traditional** modeling icy planets: 3 layers</u>

1. Central Core (rocks)
2. Inner Envelope (ices)
3. Outer Envelope ('atmosphere' – H/He)

**where is it coming from?

ACTUALLY, THESE STRUCTURES MIGHT BE MORE REALISTIC…

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



IMPORTANT: 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!

See poster by D. Soyuer

MAGNETIC FIELDS - INTERIORS

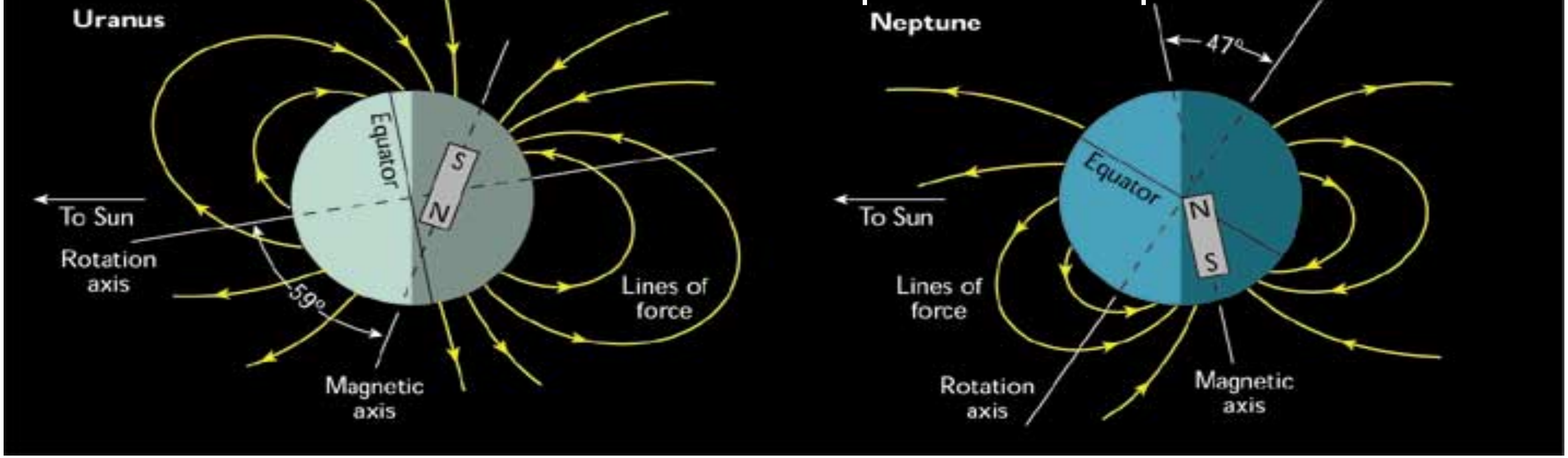
Complex multipolar nature of magnetic fields

Where are the magnetic fields generated?

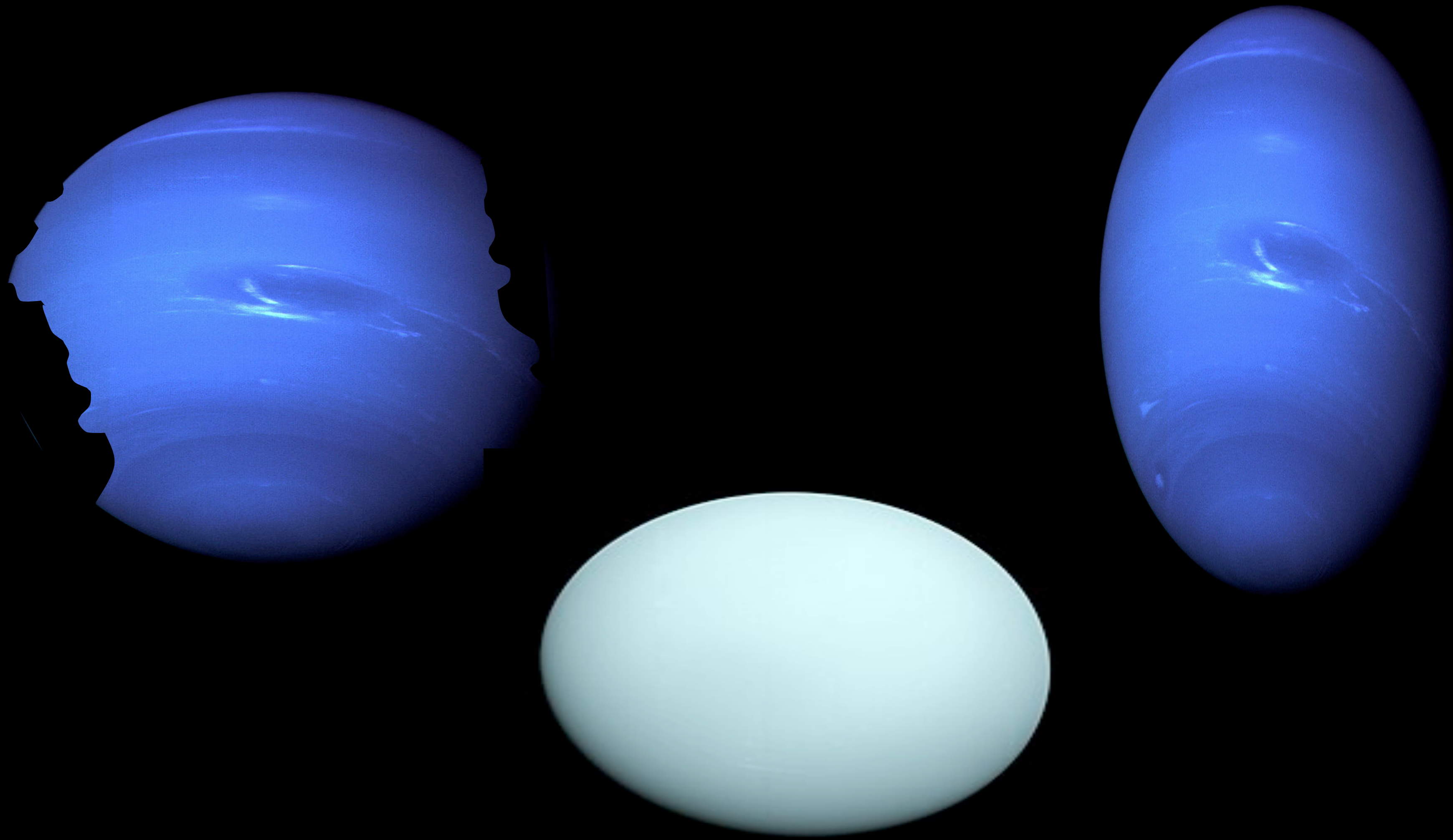
What is the depth of the winds and how is connected to the structure?

Constraints on interior: convective layer +conducting material (talk by Krista)

Need to determine rotation period of the planets

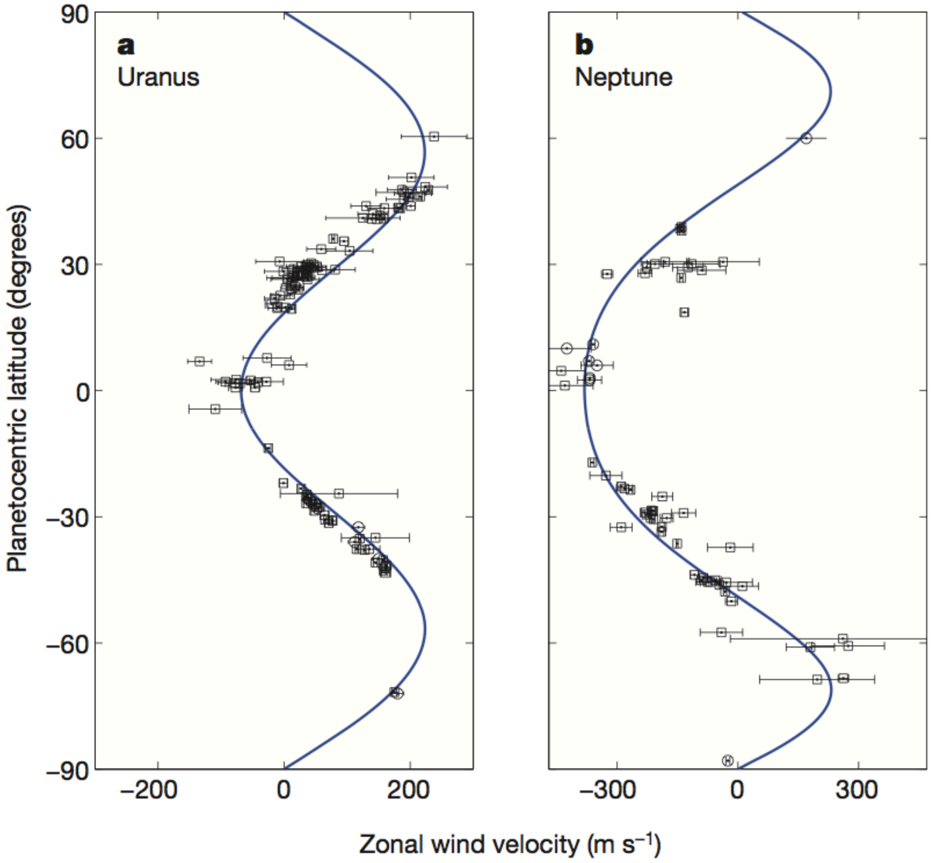


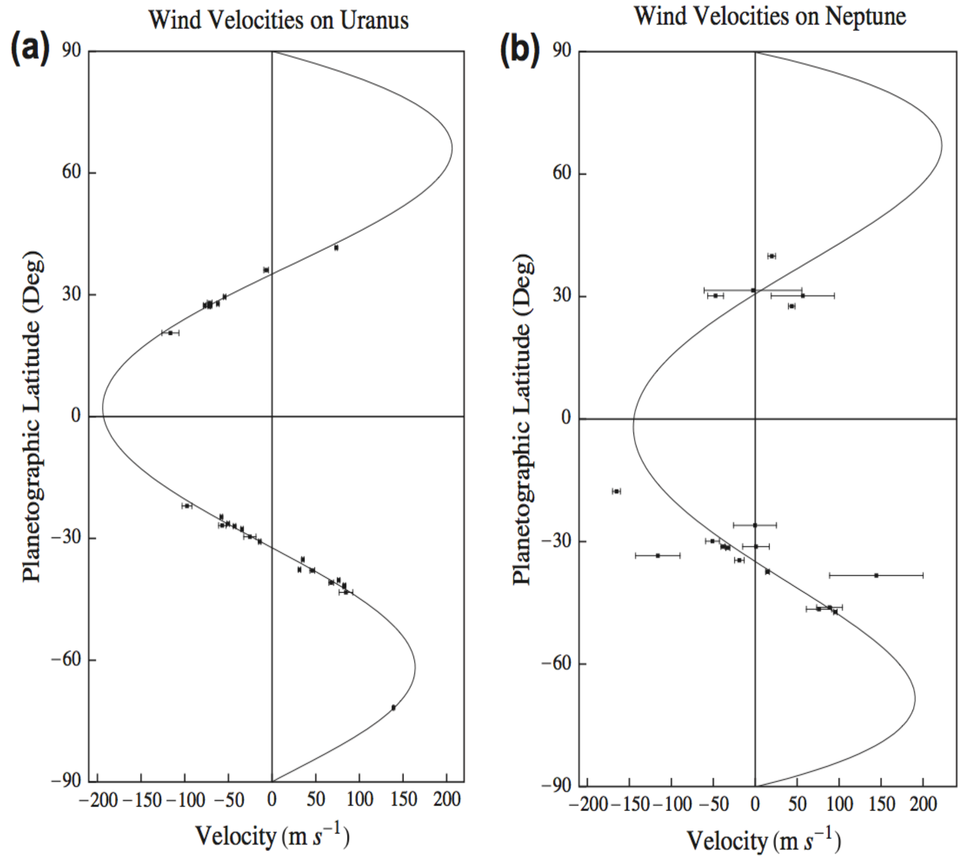
PLANETARY SHAPE AND ROTATION SHOULD ALSO BE USED TO CONSTRAIN INTERNAL STRUCTURE



Modified shapes & rotation periods for Uranus and Neptune

Uranus: 17.24 hr (P_{Voy}: 16.58 hr); Neptune: 16.11 hr ($P_{voy:}$ 17.46 hr)





UNCERTAINTY IN ROTATION → WIND VELOCITIES

Helled et al., 2010

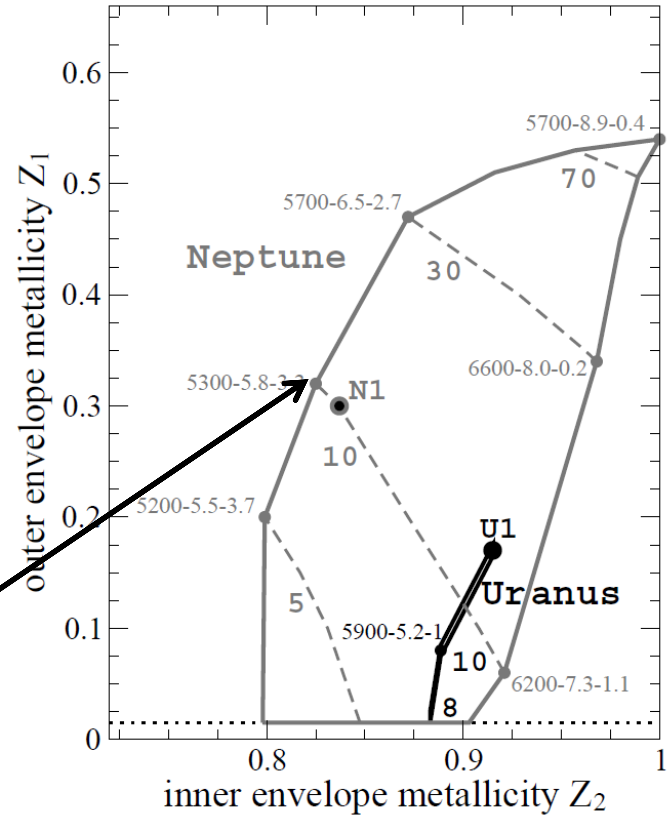
SHAPE – ROTATION- INTERIOR

New rotation periods & shapes for Uranus and Neptune (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, Helled, Fortney & Redmer, 2013

ARE URANUS AND NEPTUNE "ICY"?

ARE URANUS AND NEPTUNE "TWIN PLANETS"?

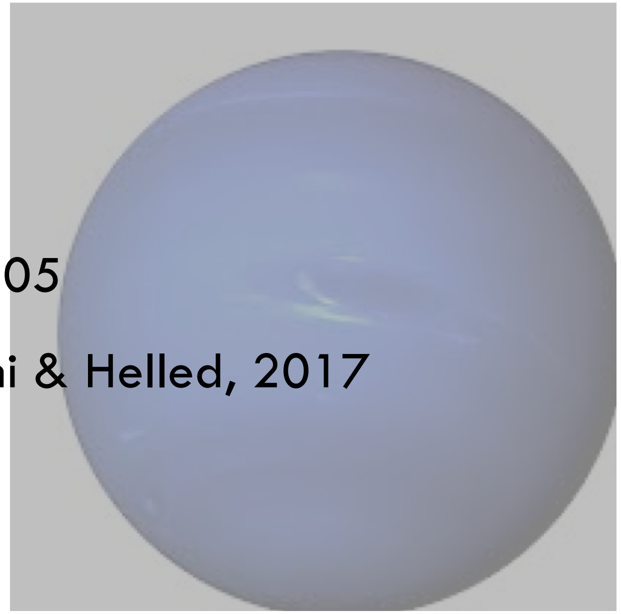
FORMATION OF URANUS & NEPTUNE

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

Similar formation process like J&S but slower: "failed giant planets"???

- On one hand, must form before the gas dissipates.
- On the other hand, should not become gas giant planets.

The fine-tuning problem in UN formation



In situ formation? Thommes et al. 1999; Tsiganis et al. 2005

Pebbles/planetsimals? Lambrechts et al. 2014 , Venturini & Helled, 2017

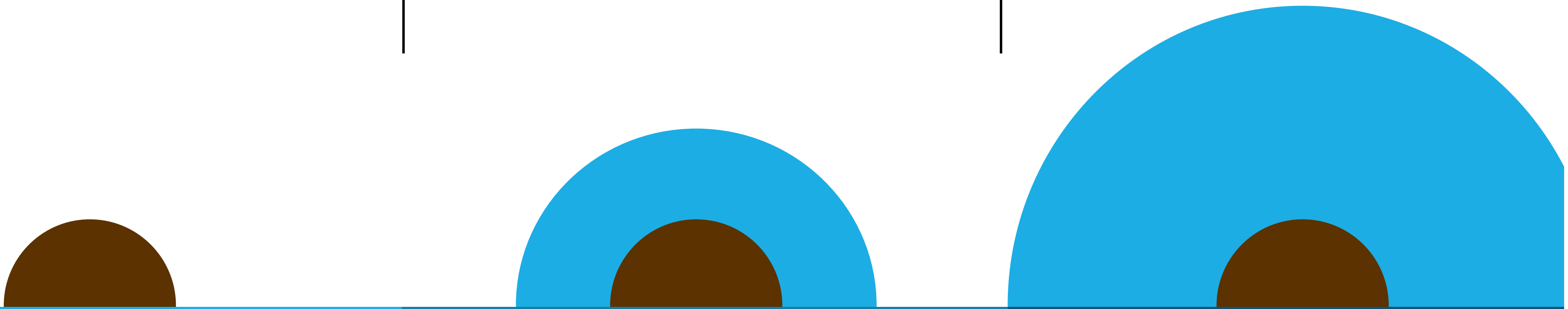
Collisions of embryos? Izidoro et al. 2015

The Core Accretion Model – failed giant planets?

A small solid (heavy-element) core is formed via planetesimal/pebble accretion

The heavy-element core is massive enough to accrete and retain gas (H-He).

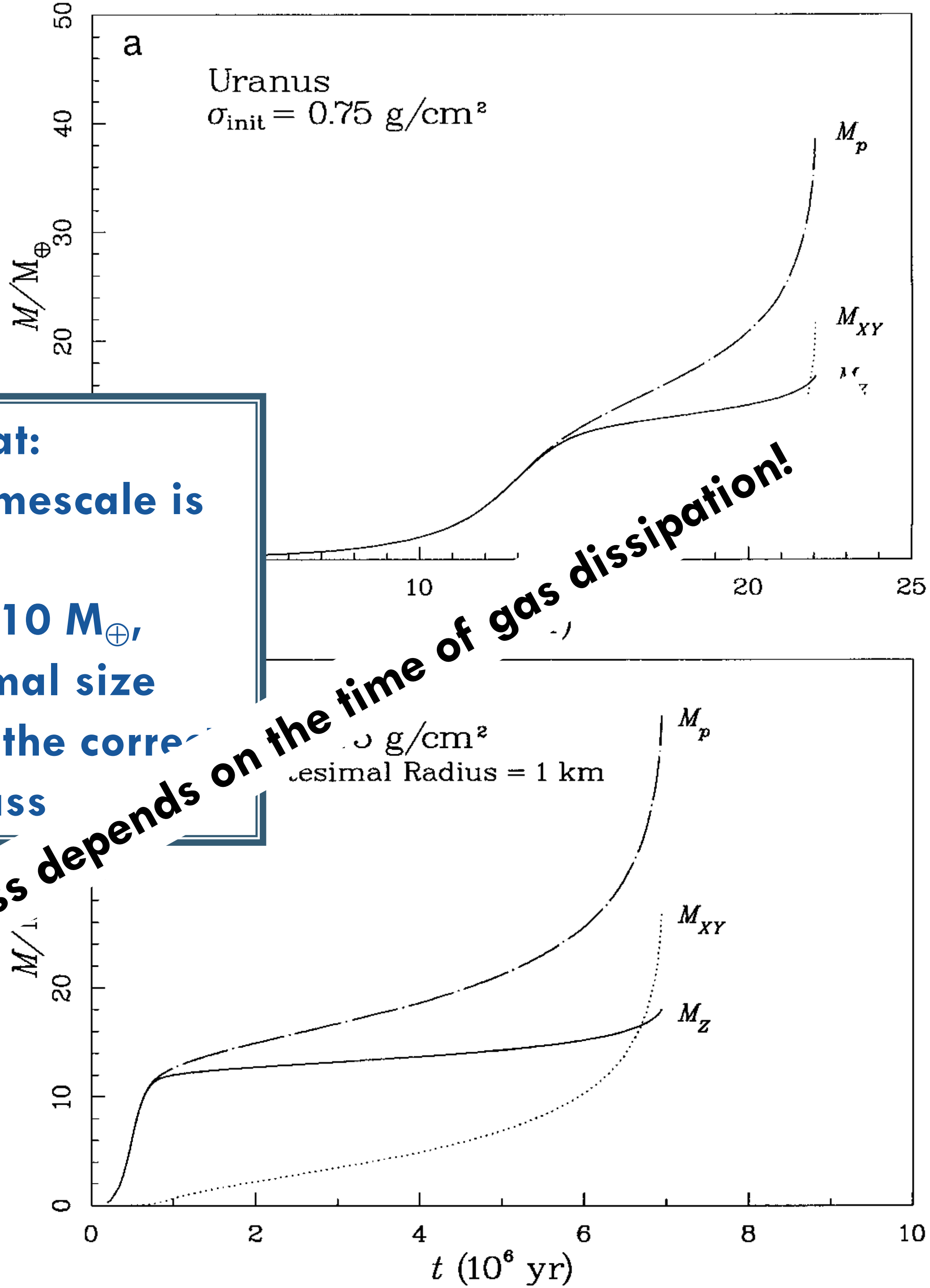
The gas accretion rate exceeds the solid accretion rate —> runaway growth



Phase 1
~ 0.5-1 Myr?

Phase 2
~5-10 Myr?

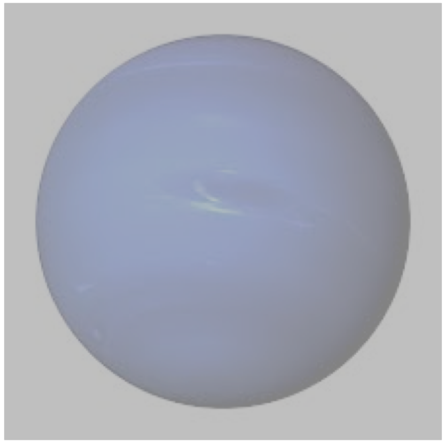
Phase 3
~0.1-0.5 Myr?



Note that:
(1) formation timescale is long
(2) M_{core} is ~10 $M_\oplus$,
(3) Planetesimal size
(4) we don't get the correct final mass

Final mass depends on the time of gas dissipation!

Pollack et al. 1996



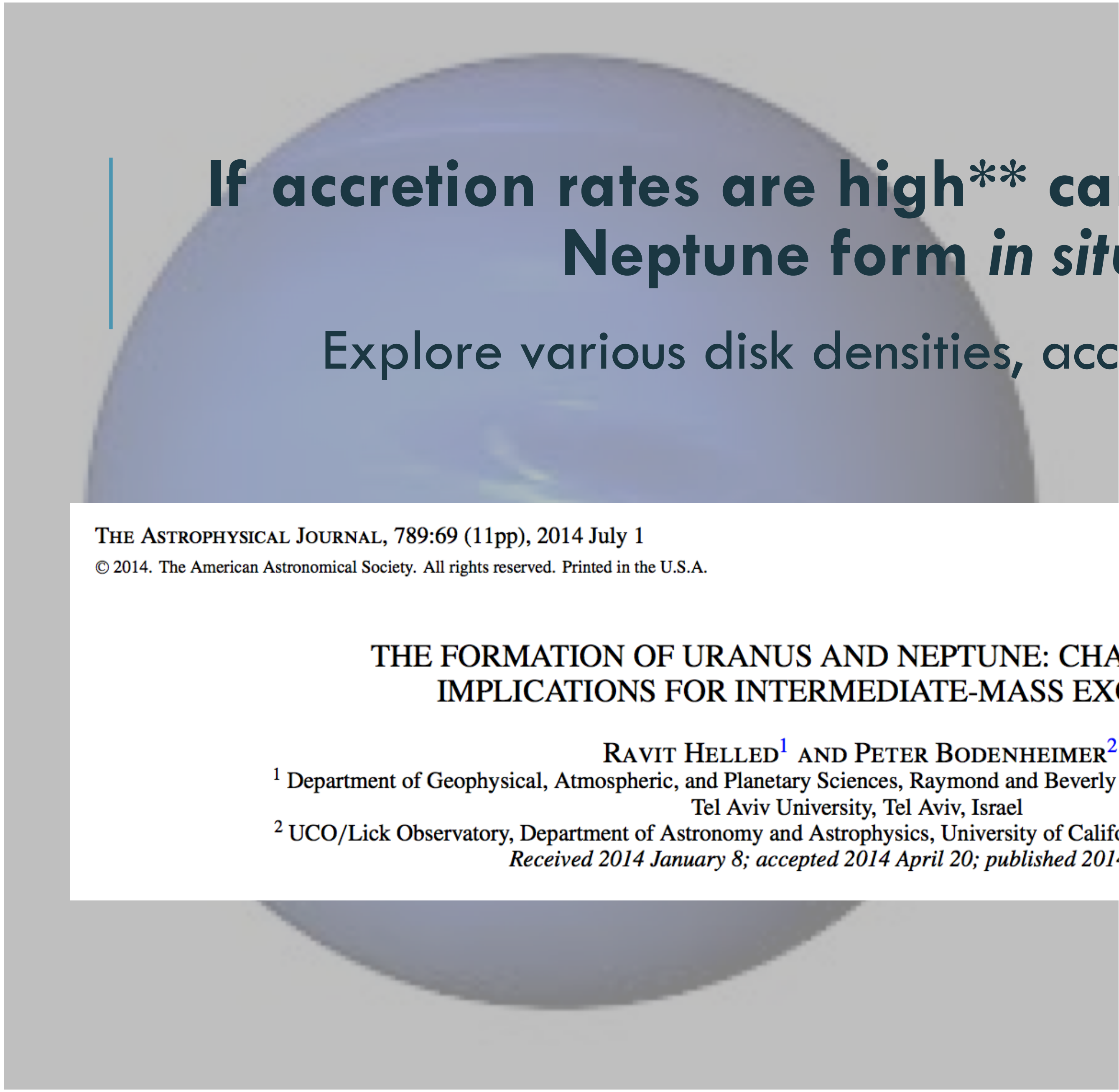
Problems/Challenges:

1. Formation timescale for in situ formation
2. Getting Uranus/Neptune-like final composition

Possible Solutions:

1. Formation closer to the sun (Nice Model)
2. Disk physics/chemistry – disk evolution, enhancing the solids
3. High accretion rates: dynamically cold planetesimal disk
4. Pebble Accretion
5. A combination…

What are the possible observations to discriminate among different scenarios?



If accretion rates are high** can Uranus and Neptune form *in situ*?

Explore various disk densities, accretion rates.

The Astrophysical Journal, 789:69 (11pp), 2014 July 1 doi:10.1088/0004-637X/789/1/69

THE FORMATION OF URANUS AND NEPTUNE: CHALLENGES AND IMPLICATIONS FOR INTERMEDIATE-MASS EXOPLANETS

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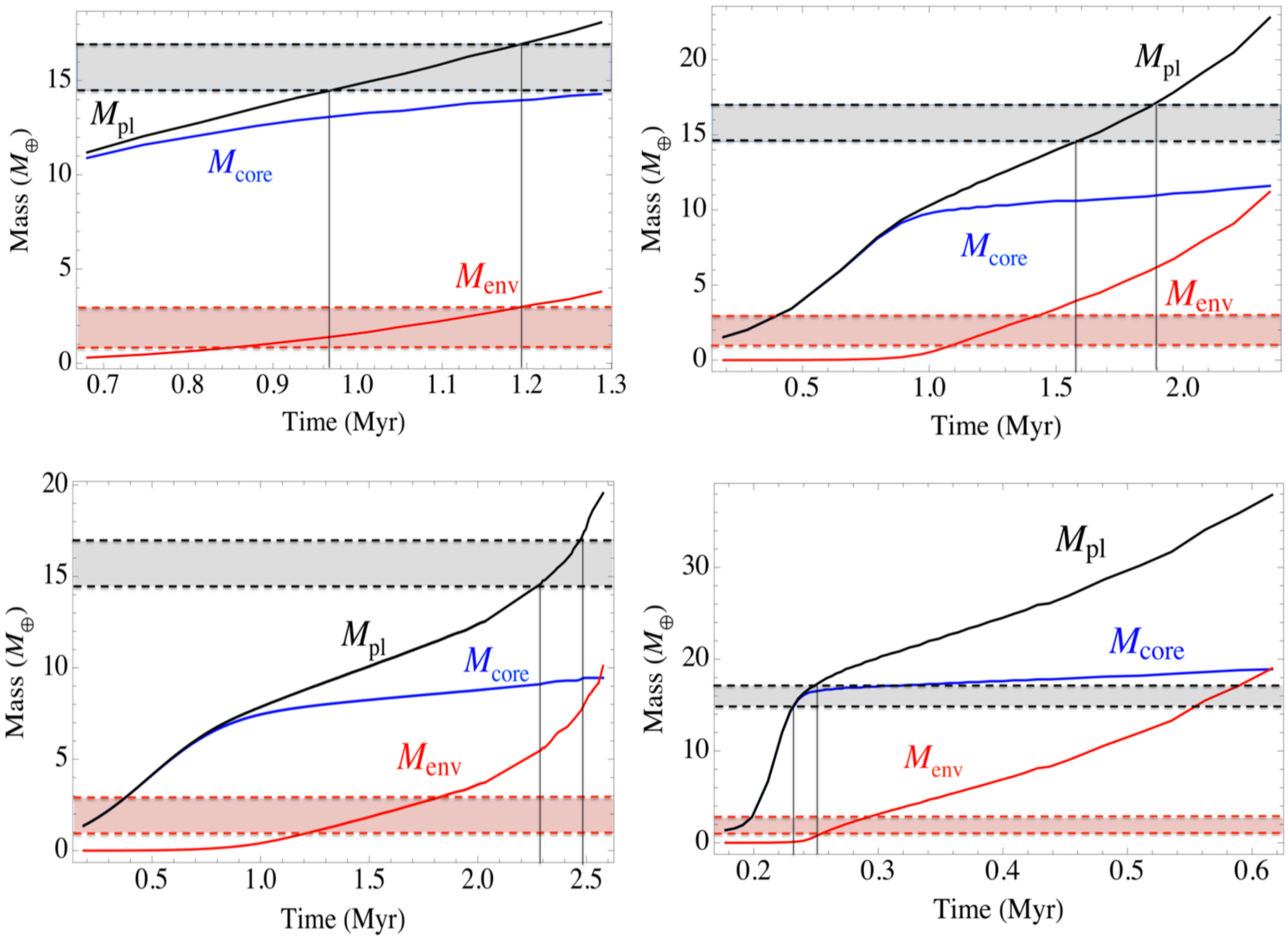
**dynamically cold small planetesimals (see e.g., Goldreich et al. 2003; 2004, Rafikov, 2011; Lambrechts & Johansen, 2012)

THE CHALLENGE IN FORMING URANUS & NEPTUNE

The challenge is to keep U&N small and from accreting too much gas and/or solids.

Getting the correct gas-to-solid ratio is not trivial

However: this naturally explains the diversity of intermediate-mass exoplanets.



Possible formation paths of U&N. The dashed black curves correspond to their masses, and the red dashed lines to the inferred H-He mass.

Formation models with different assumed solids, opacities, formation locations…

The Formation of Mini-Neptunes

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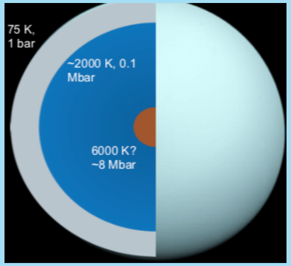
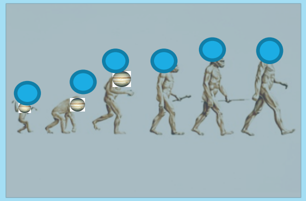
Conclusion: Uranus and Neptune are very difficult to form with pebbles or planetesimals. The only cases with relatively high occurrence rate of Neptunes (∼40%) are for planetesimal accretion, and disks with larger amounts of solids (i.e., 2–3 MMSN disk) coupled with larger dust opacities.

Planet Formation



Internal structure



Planet Evolution

The Formation process determines the primordial internal structure and composition which affects the long term evolution and the current-state structure!

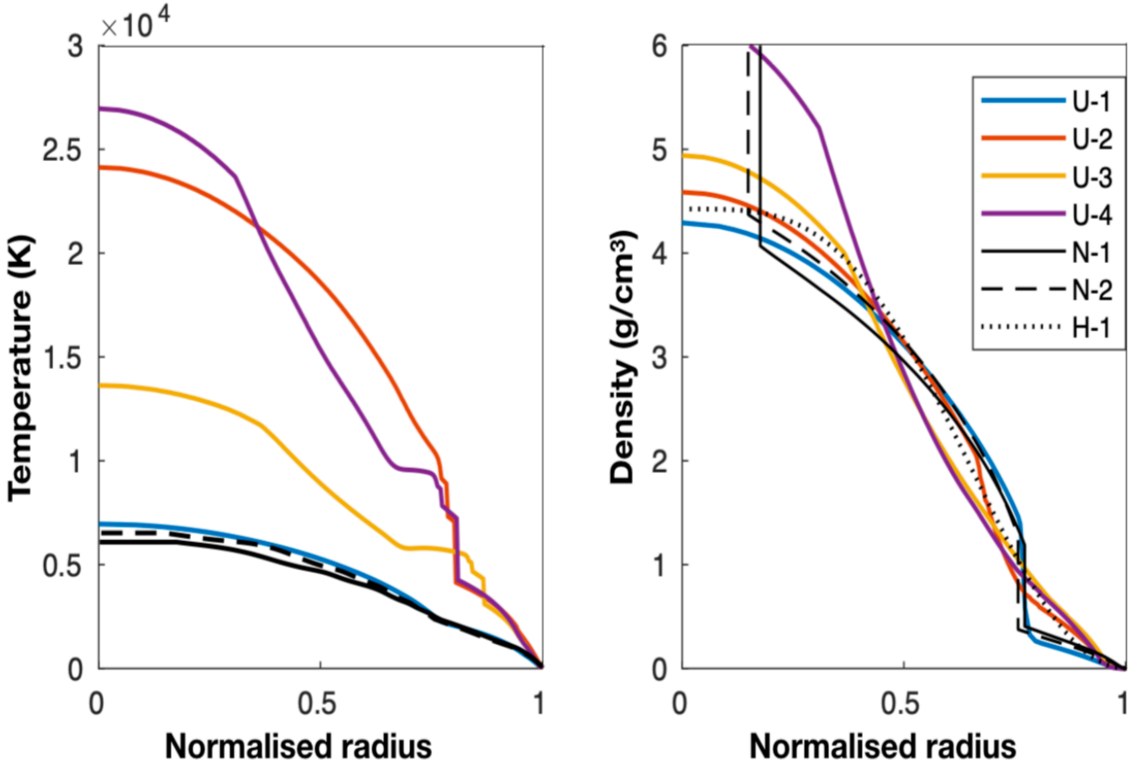
LONG-TERM EVOLUTION

Explaining the low luminosity of Uranus: A self-consistent thermal and structural evolution

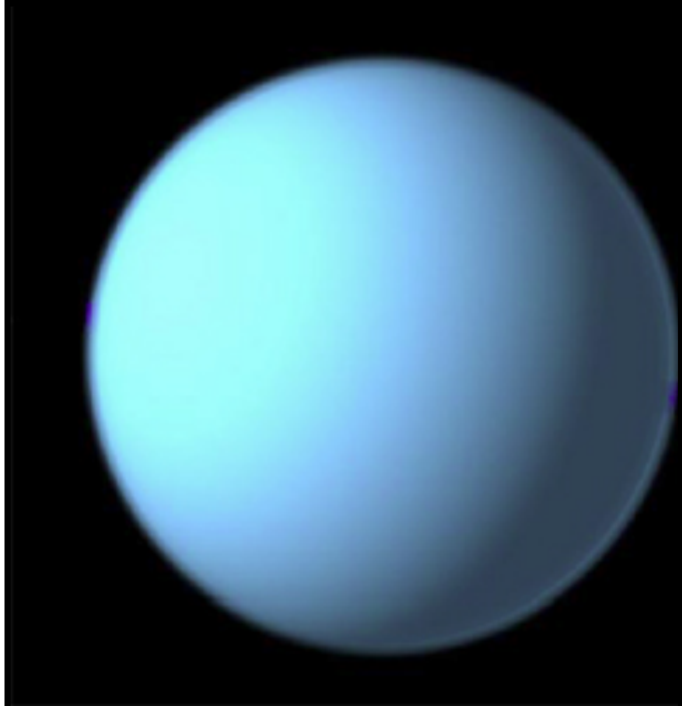
Allona Vazan[1,2] and Ravit Helled[1]

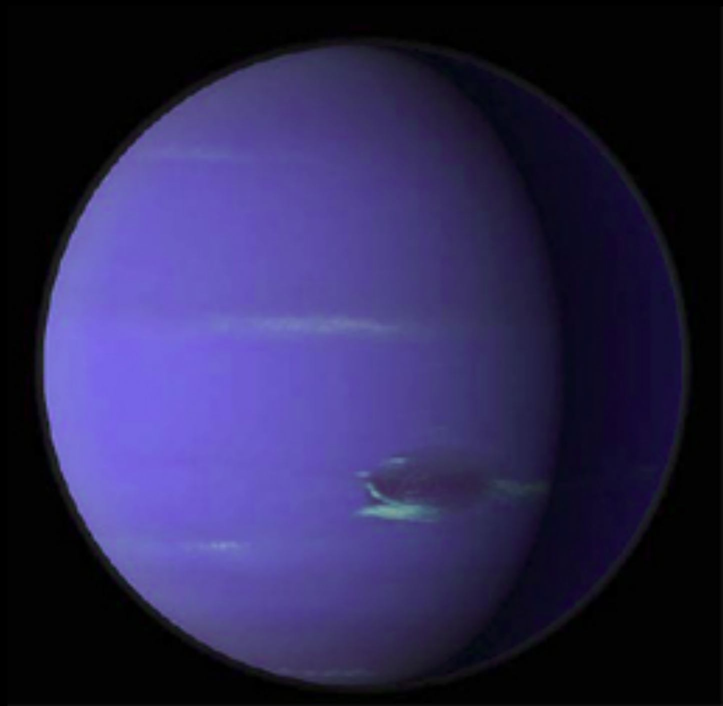
Non-adiabatic interior+evolution of Uranus.

- 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.



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



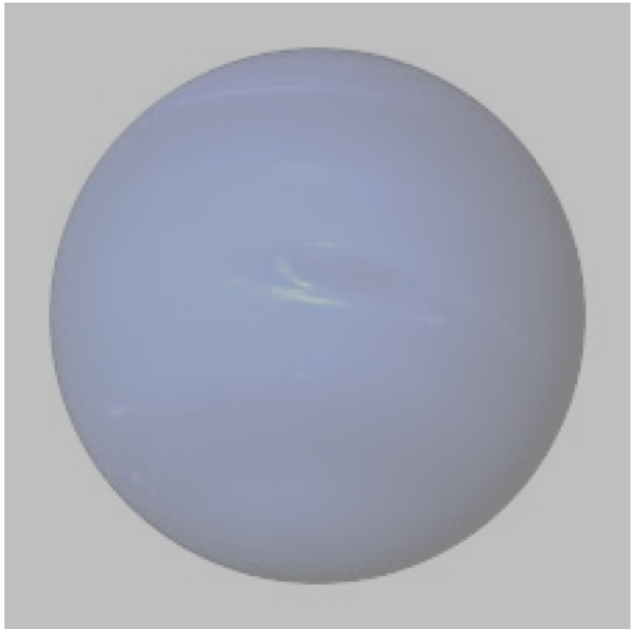


Stevenson, 1986
Podolak & Helled, 2012
Reinhardt et al., 2020

CONNECT INTERNAL STRUCTURE WITH EVOLUTION

Despite the similar masses Uranus and Neptune they differ in:

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



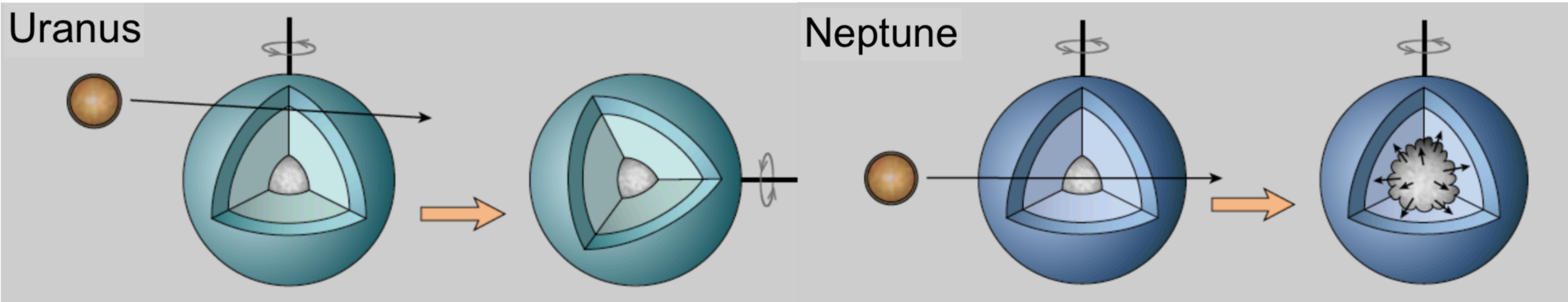
More from Alice on Wed…

GIANT IMPACTS:

tilt, internal flux and atmospheric composition, satellite formation

Uranus: Oblique Collision

Neptune: Radial Collision

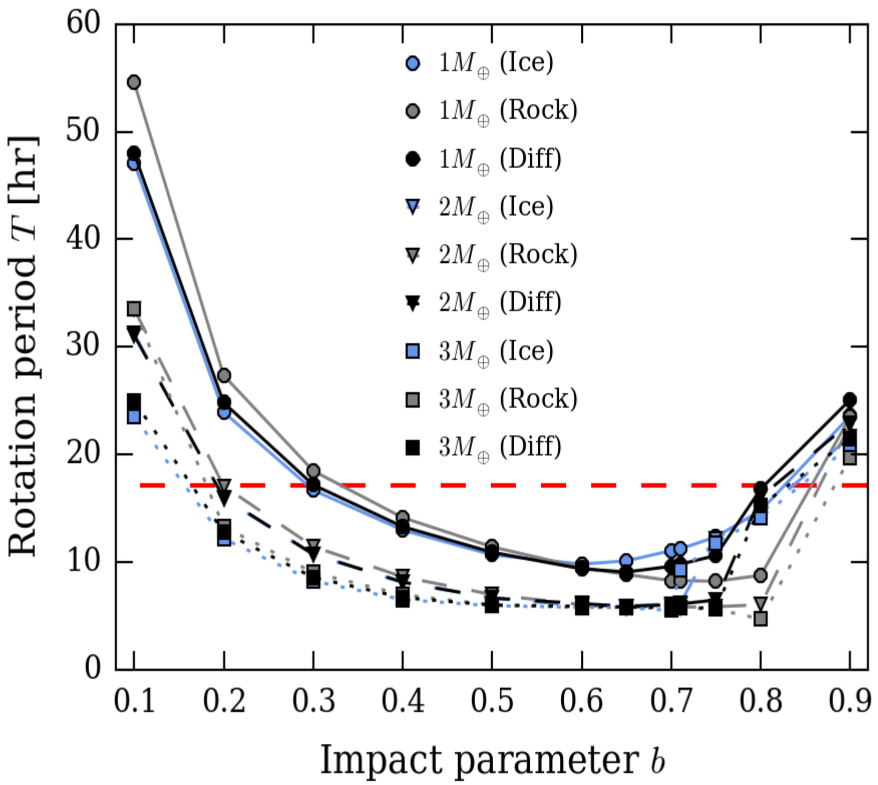


tilt its spin axis and eject enough material to form a disk where the regular satellites are formed.

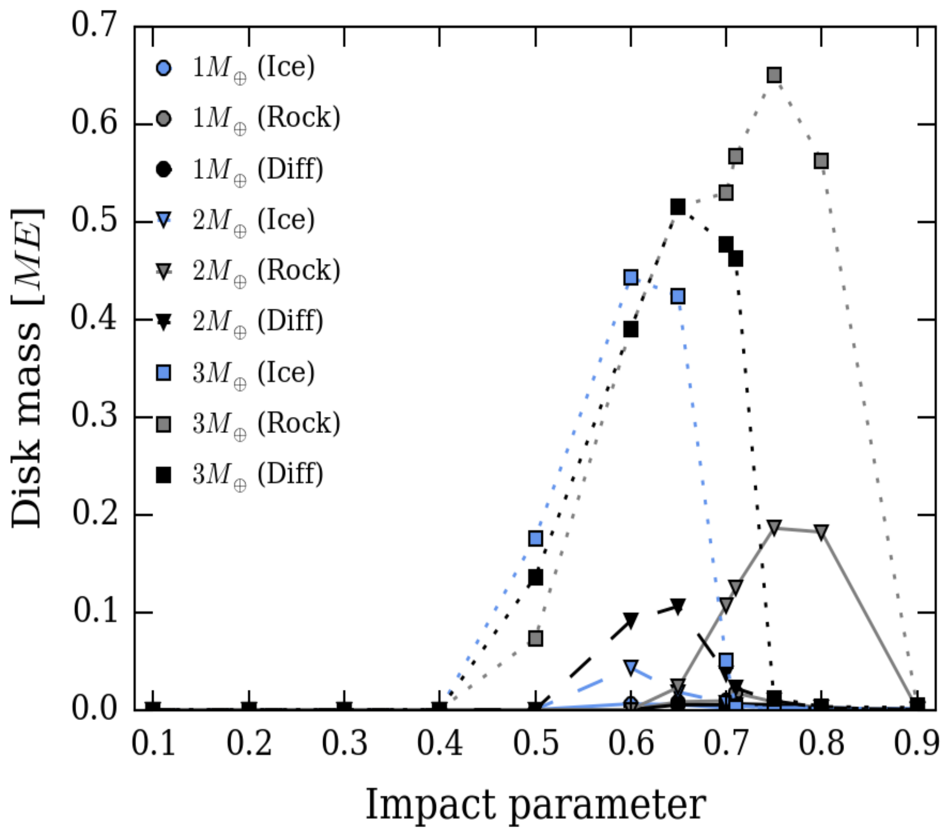
could deposit energy deep inside, mix its interior resulting in a nearly adiabatic interior.

TITING URANUS AND FORMING A DISK

A large range of impact parameters can lead to Uranus' rotation period



Disk 0.001 – 0.6 $M_\oplus$, up to 170 $R_\oplus$



Kegerreis et al. 2018

Reinhardt et al. 2020, in press.

HEAD-ON VS. OBLIQUE COLLISIONS

b=0.2, $M_{imp} = 2M_{\oplus}$ (12% rock, 88% ice), $v_{\infty} = 5$ km/s

b=0.7, $M_{imp} = 2M_{\oplus}$ (12% rock, 88% ice), $v_{\infty} = 5$ km/

More details in A. Chau's talk on Wed.

Head-on collision (b=0.2):

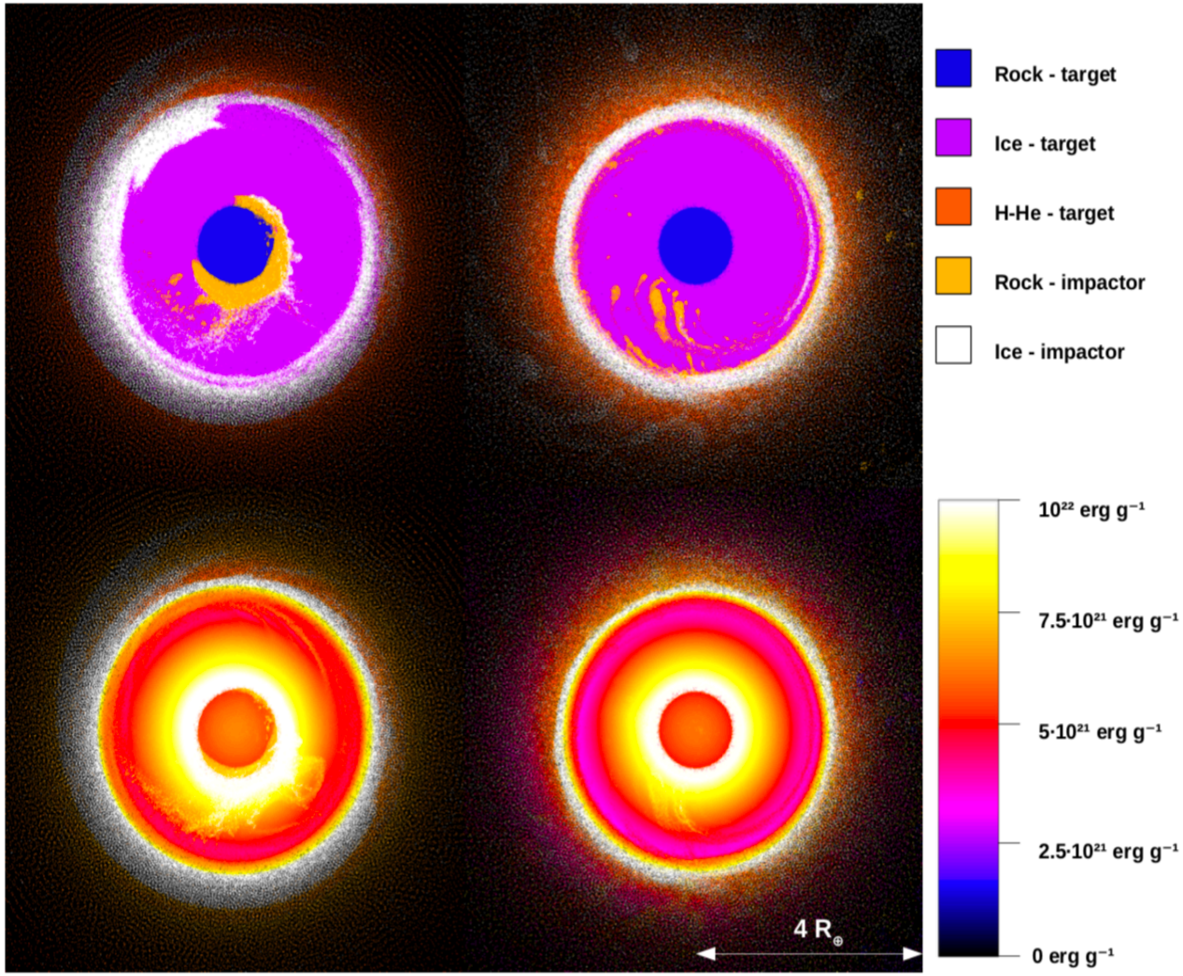
Impactor's material and energy are deposited in the deep interior → an adiabatic interior and high flux?

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…

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



b=0.2 b=0.7

Reinhardt et al., 2020

SUMMARY & FUTURE RESEARCH

IMPORTANT: facts vs. opinions/traditions/concepts – do we really we really know about Uranus and Neptune?

- How did Uranus and Neptune form?
- What are the compositions and internal structures of Uranus and Neptune?
- What is the importance of giant impacts on these planets?
- Connect **interior models** with **planetary formation** and **evolution models**
- Space mission (orbiters + probes?) to Uranus (and) Neptune to further constrain models
- Connection to exoplanets.