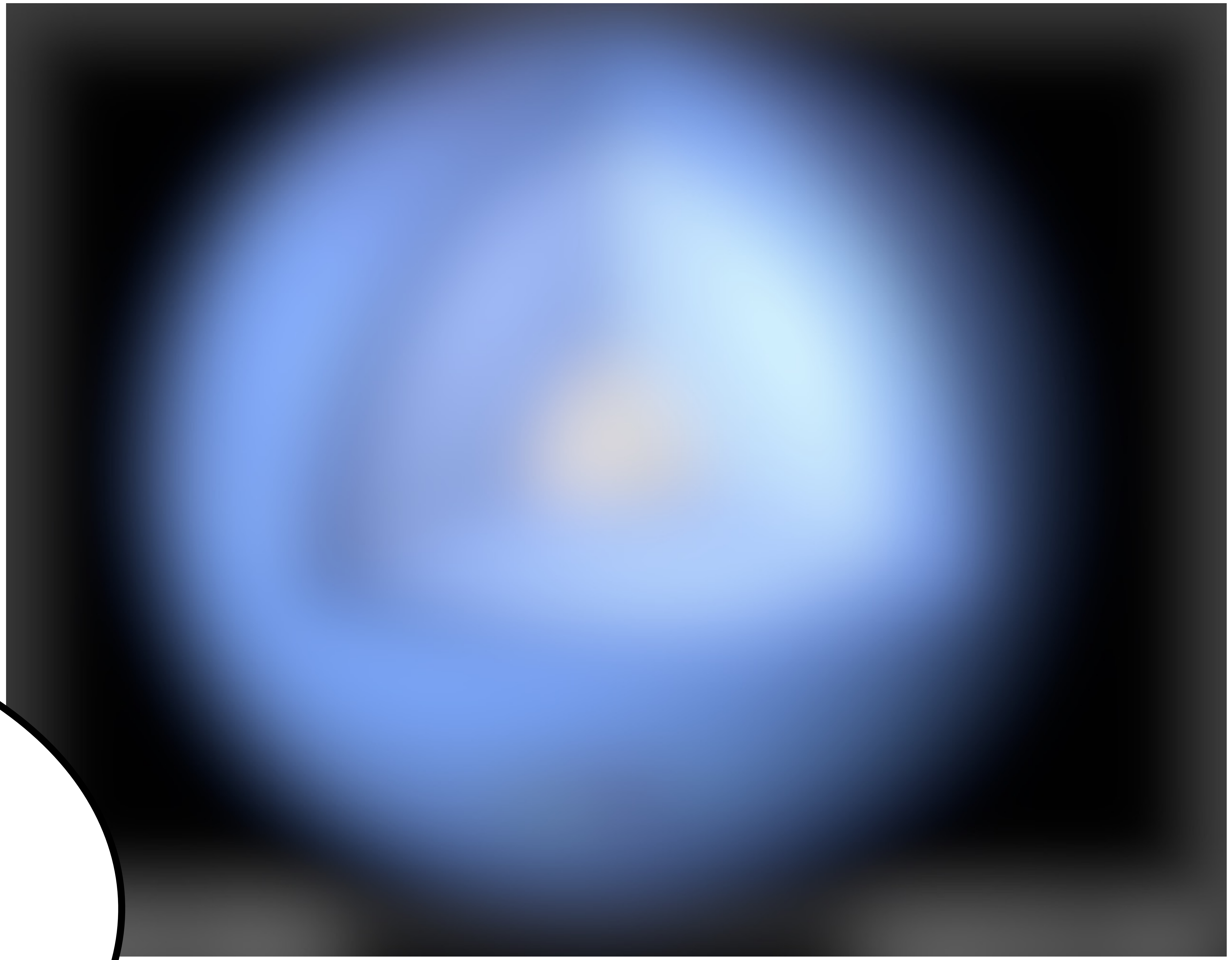
Interior Structure and Energy Balance of Uranus and Neptune

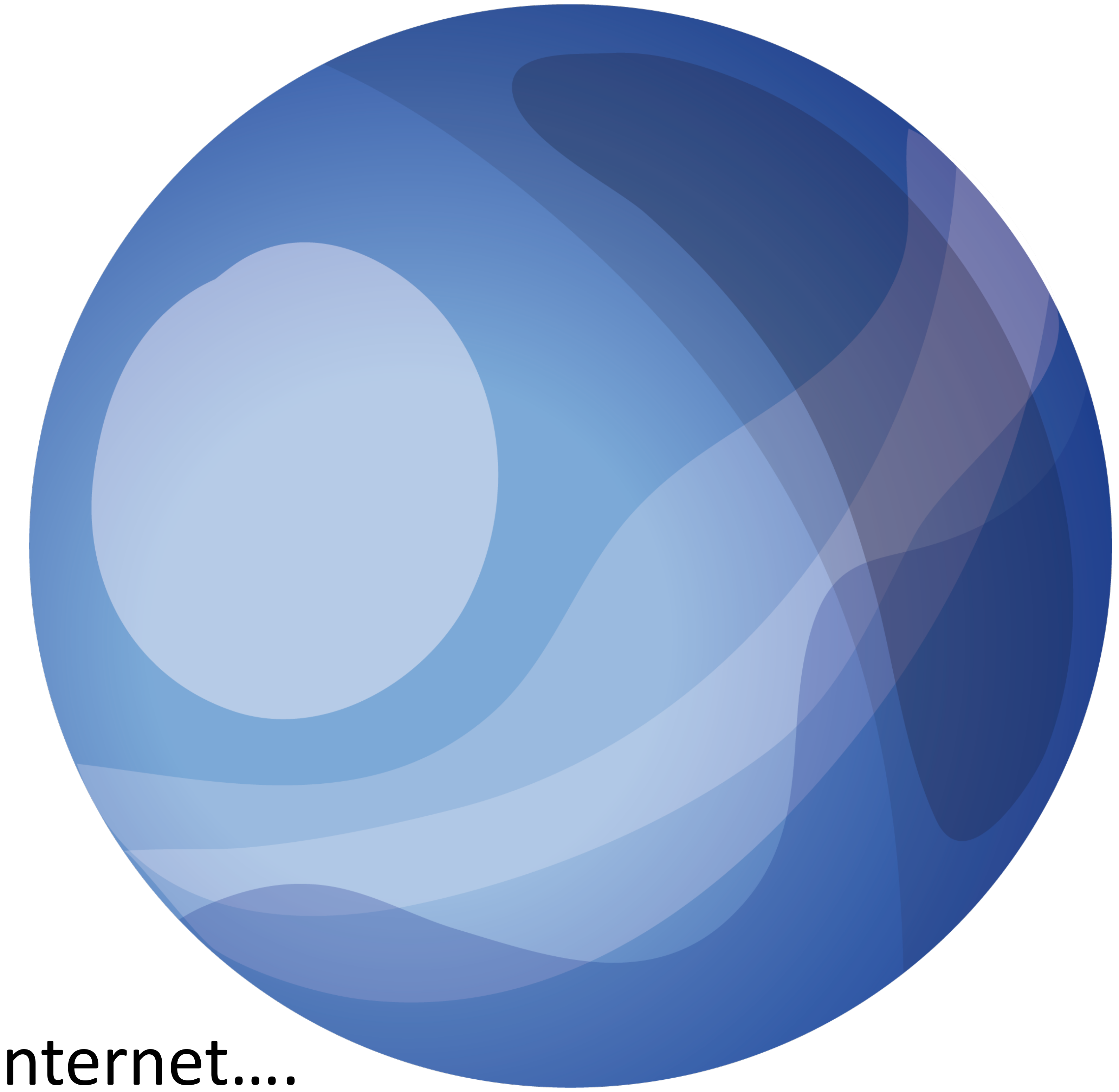


OWL
OTHER WORLDS
LABORATORY

Jonathan Fortney
OWL, University of California, Santa Cruz

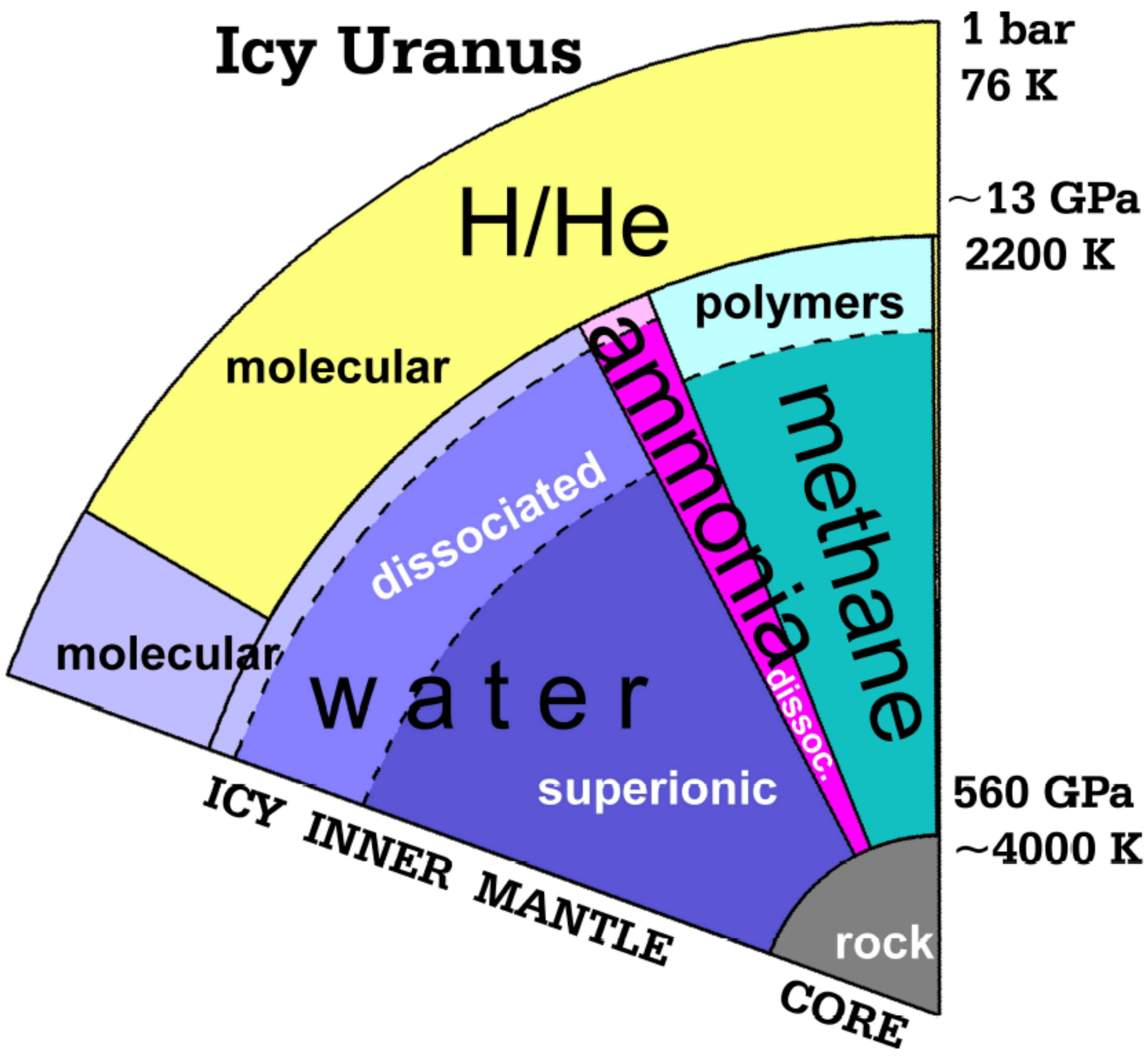
Talk Outline

- Interior Structure Models and Their Current Limitations
- Heat Flow Measurements and Their Implications for the Planets
- What can we measure or calculate to improve the situation?



Fun clip art from the internet….

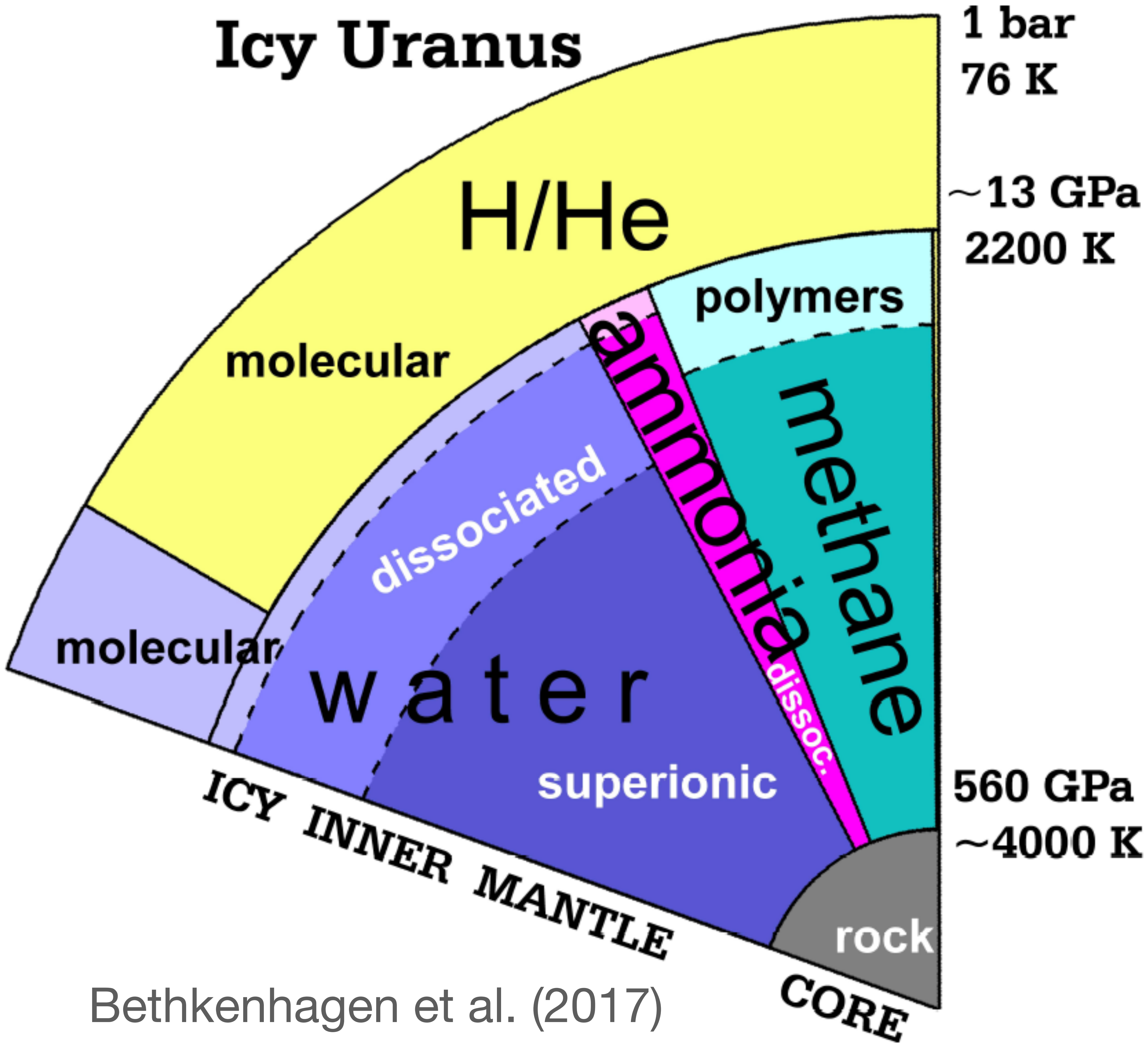
Interior Models: Vital Points



Bethkenhagen et al. (2017)

- 3-layer structure paradigm
  - H/He layer, atop fluid ice layer, atop rocky core
  - Nice visual!
- Outer layers denser than H/He — significant “metal” enrichment
- Inner layers typically a bit less dense than ices
- Are layers real anyway?
  - Model assumptions / convenience important in our “understanding”

Interior Models



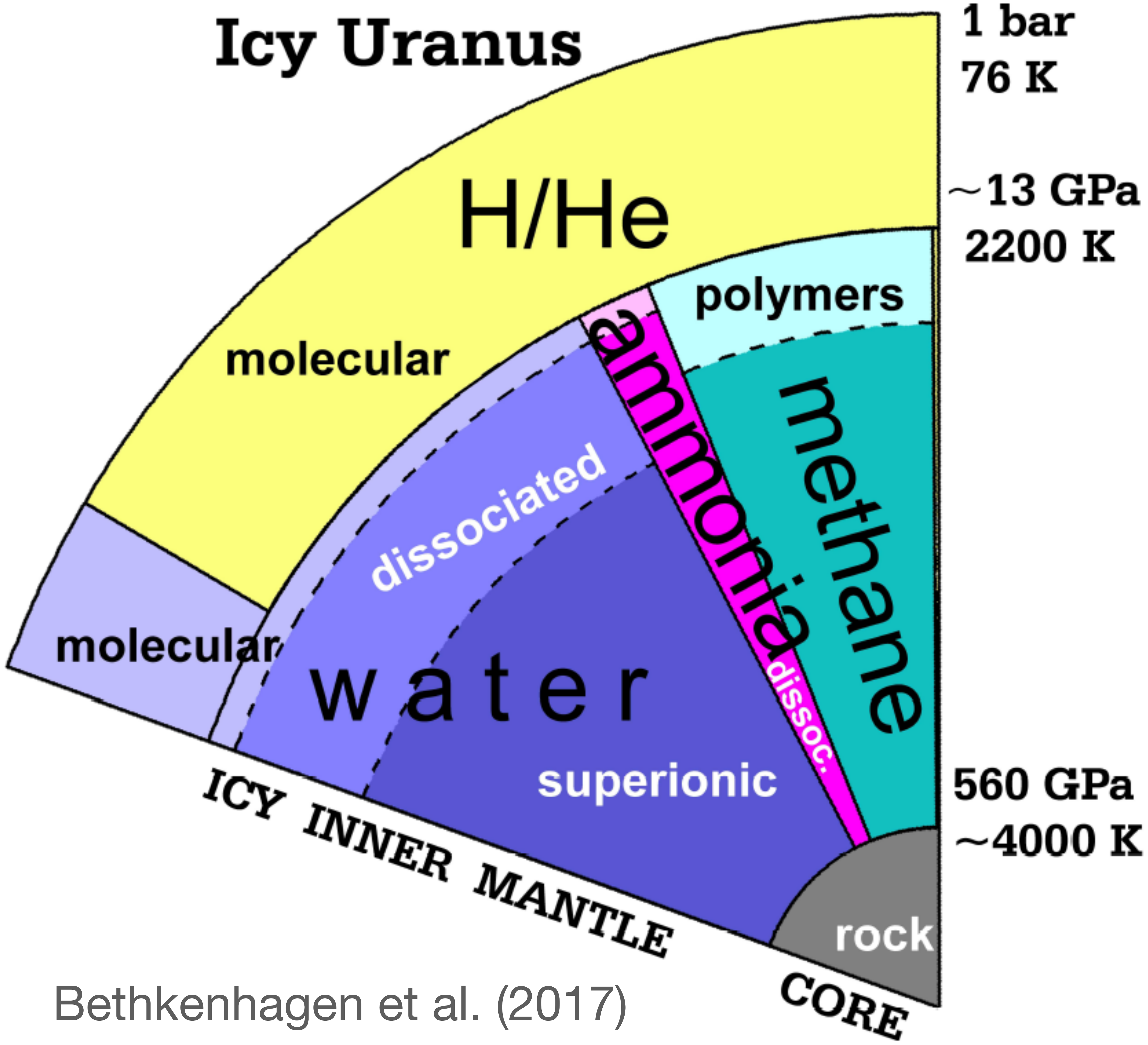
Bethkenhagen et al. (2017)

- Bulk densities of both planets *suggest* "watery" interiors
  - But high pressure rock + H/He can also mimic density of water
- **Standard models find interior ice:rock ratios of ~3:1 to 20:1 (!)**
  - Very strongly suggests that such a simple picture is not reality
  - Icy satellites suggest more like 1:1?
  - (Pluto is 70% rock)

Nettelmann, Helled, Fortney & Redmer (2013)

Parameter	U1	N1
Z_1	0.17	0.30
Z_2	0.915	0.833
M_c ($M_\oplus$)	0.61	3.15
T_c (K)	6000	5500
P_c (Mbar)	5.5	6.0
P_0 (Mbar)	8.3	16.4
M_Z ($M_\oplus$)	12.4	14.4
I:R	19.2	3.7

Interior Models: Room for Flexibility



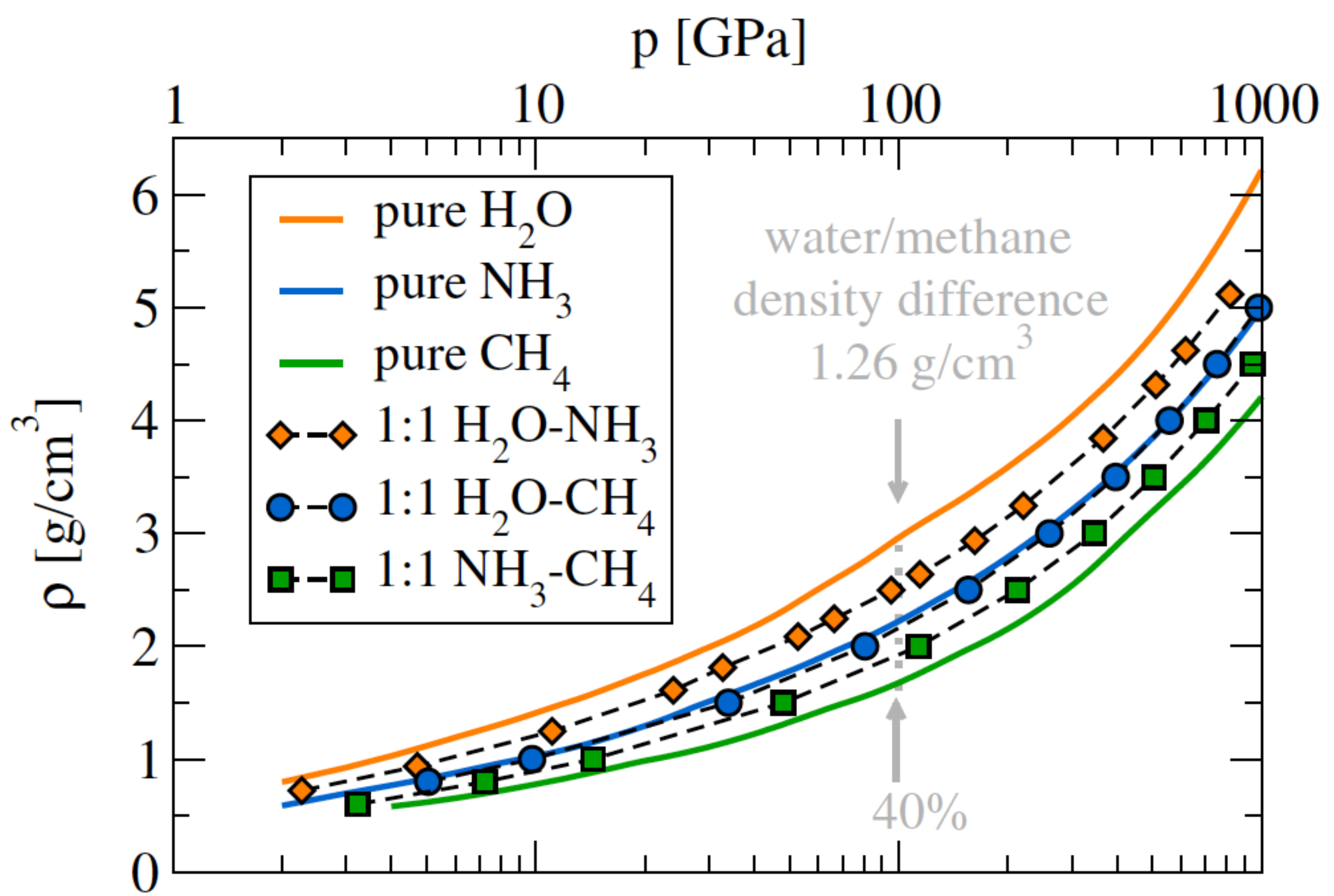
Bethkenhagen et al. (2017)

- Large disparity in heat flow between the two (factor of at least 10) suggests interior gradients possible, which can alter flux carried to the surface
  - Potentially much hotter interiors, leading to lower densities, allowing more rock
  - Mixtures between H/He and water, and water and rock, allow for more rocks

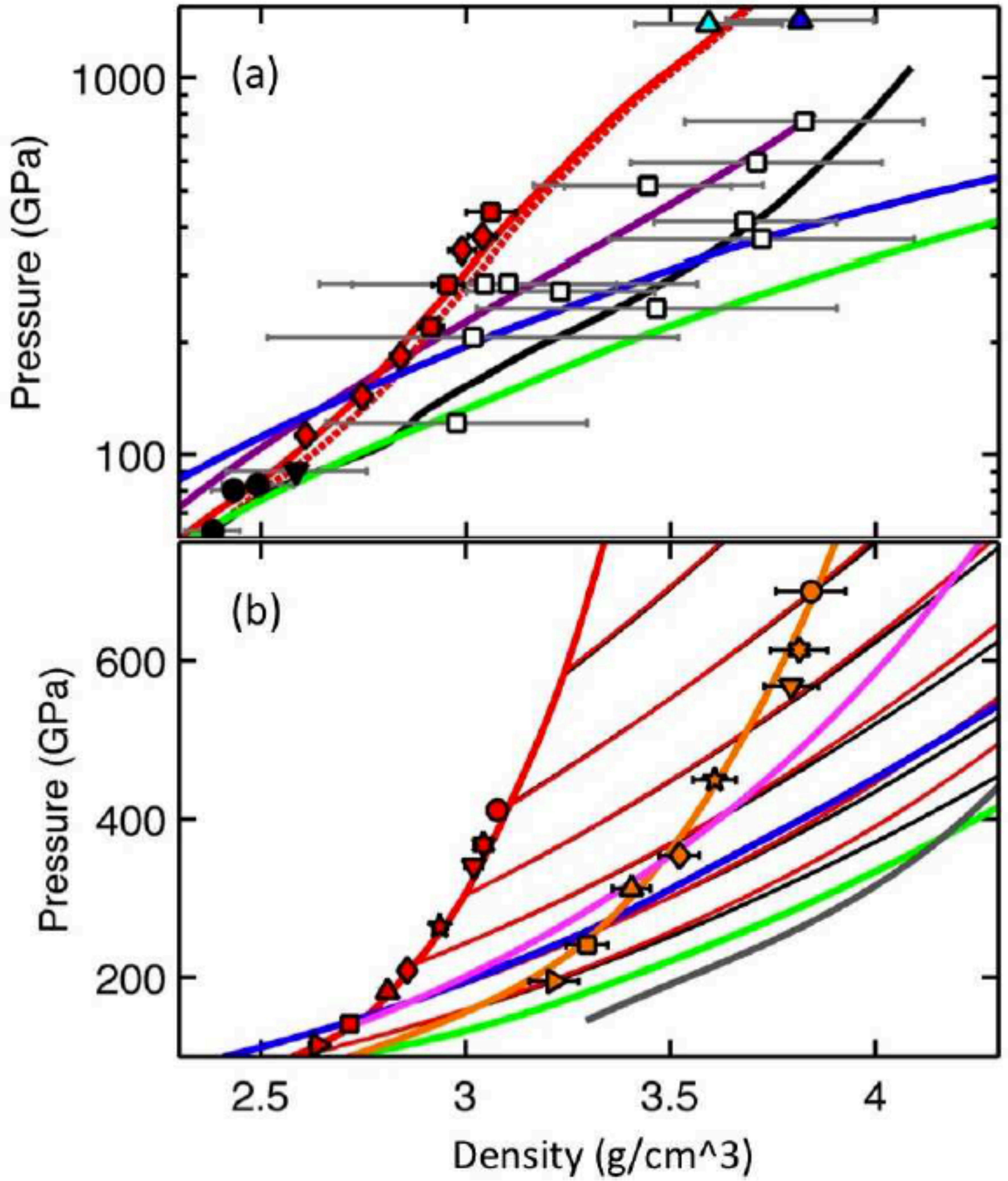
Interior Models: EOS Improvements

- We have recently seen essential advances in the equations of state (EOS) of water, ammonia, methane
- Still room for new work on their mixtures, phase separation, and “high pressure chemistry”
- One can use these EOS for improved models, but only up to a point, as their use still relies on modeling assumptions

First principles EOS, being validated

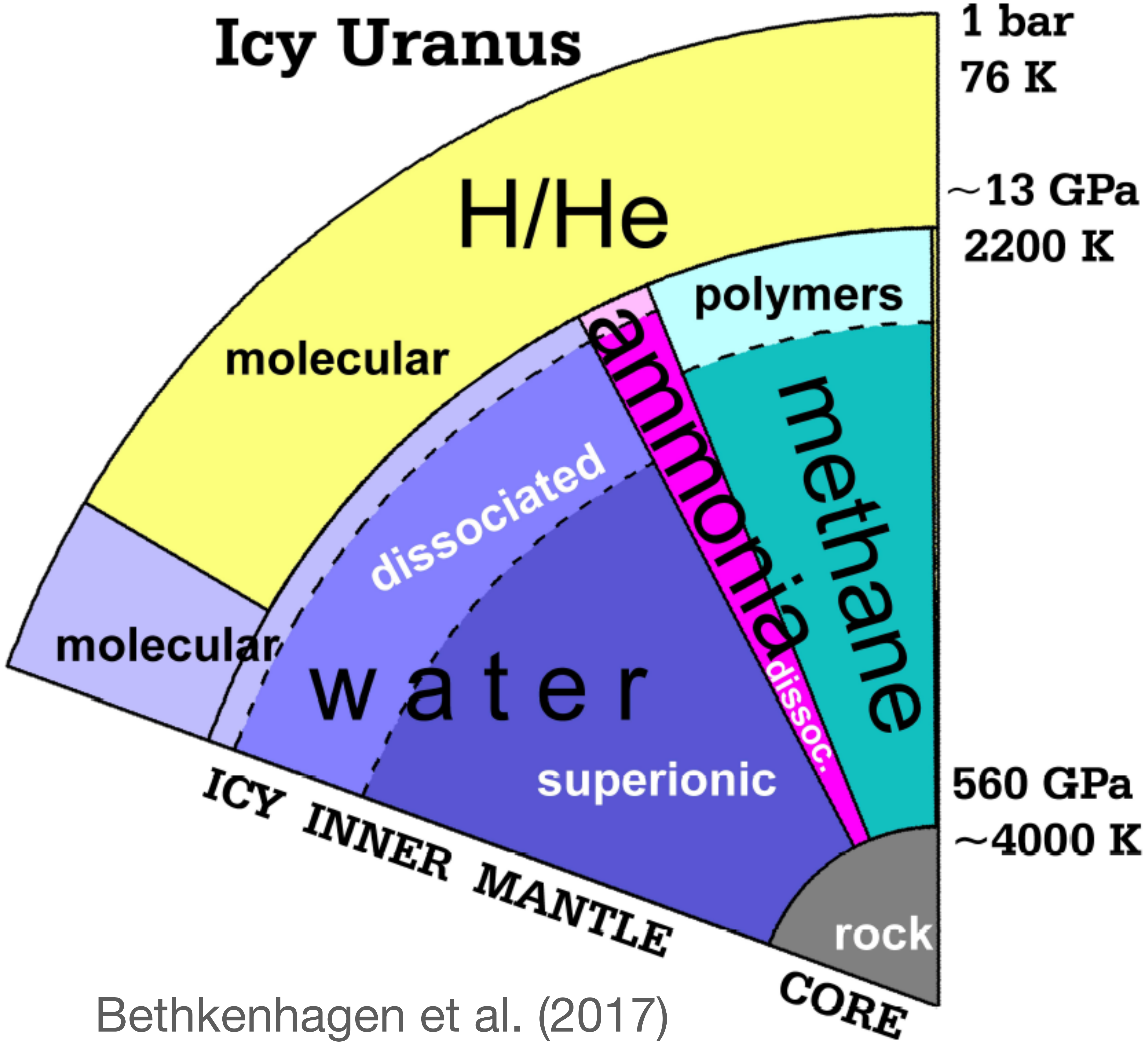


Bethkenhagen et al. (2017): Ab initio simulations of high-pressure fluid icy mixtures



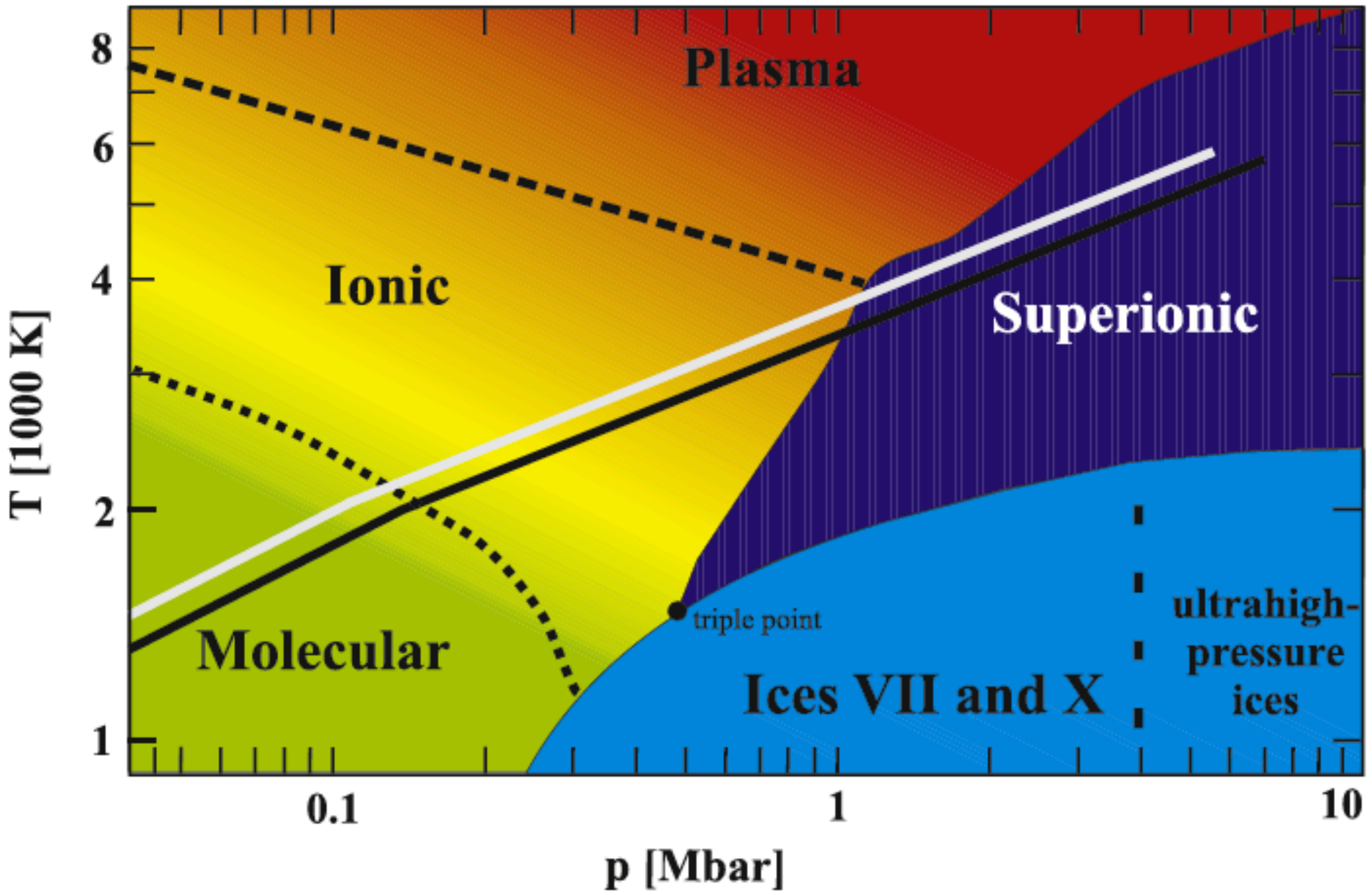
Knudson et al. (2012): Shocked water to 7 Mbar validates ab initiation water EOS

Strange Phases of Matter



Bethkenhagen et al. (2017)

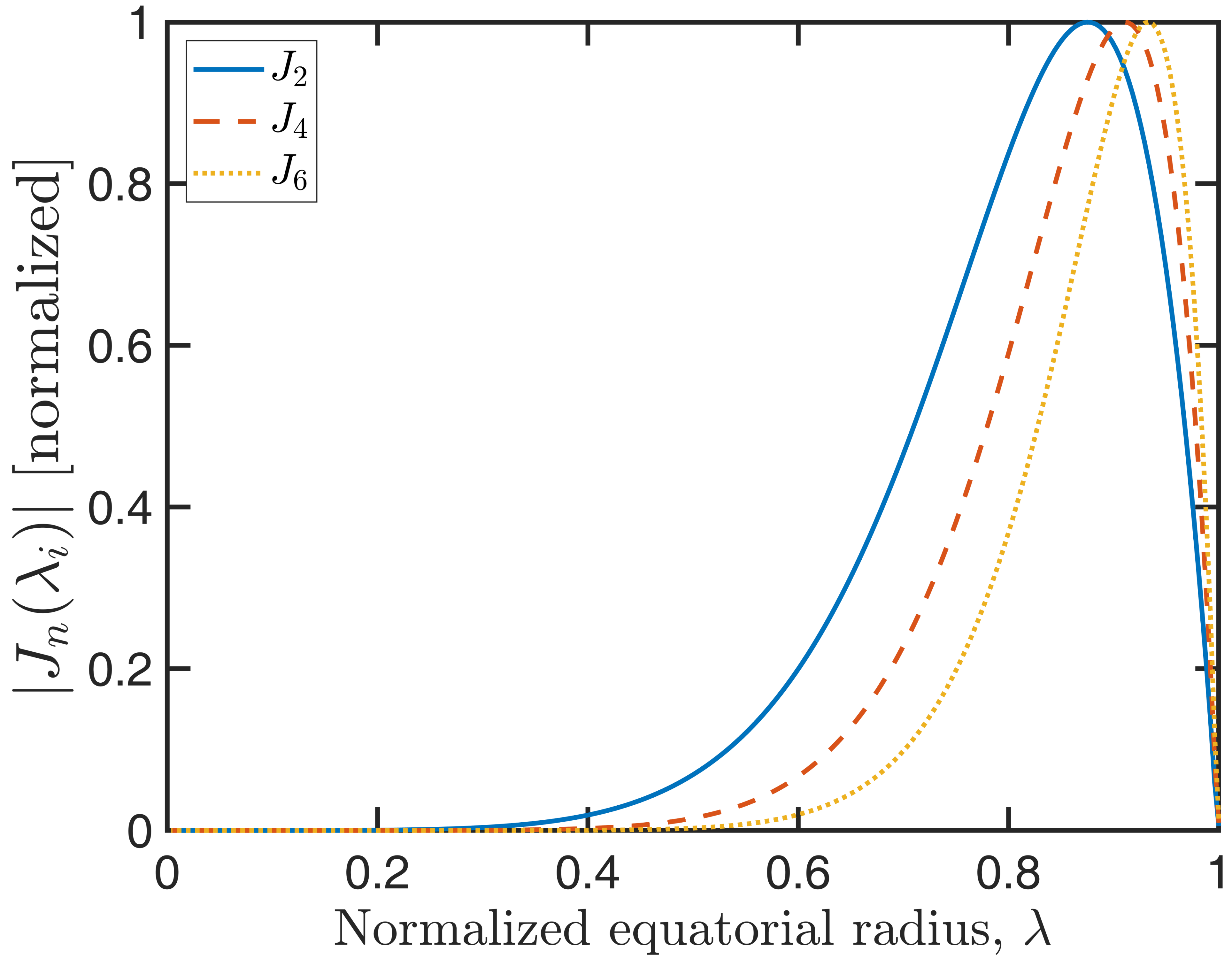
Redmer et al. (2011)



Superionic Water: The O is a lattice but the H is a fluid

Interior Models: Exploring Uncertainties

- Given that so much of our current constraints are based upon given modeling frameworks, is there a way to more efficiently explore phase space?

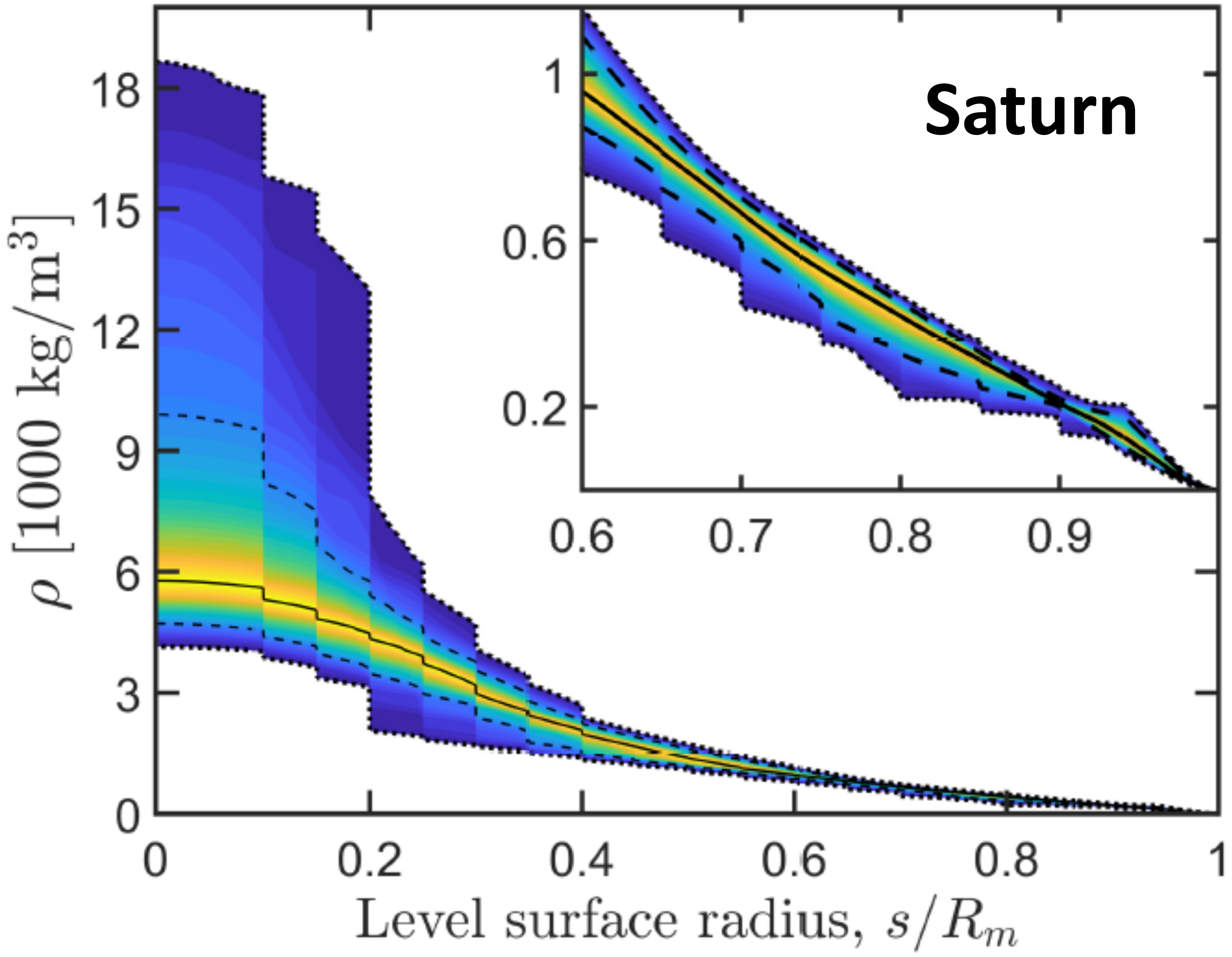


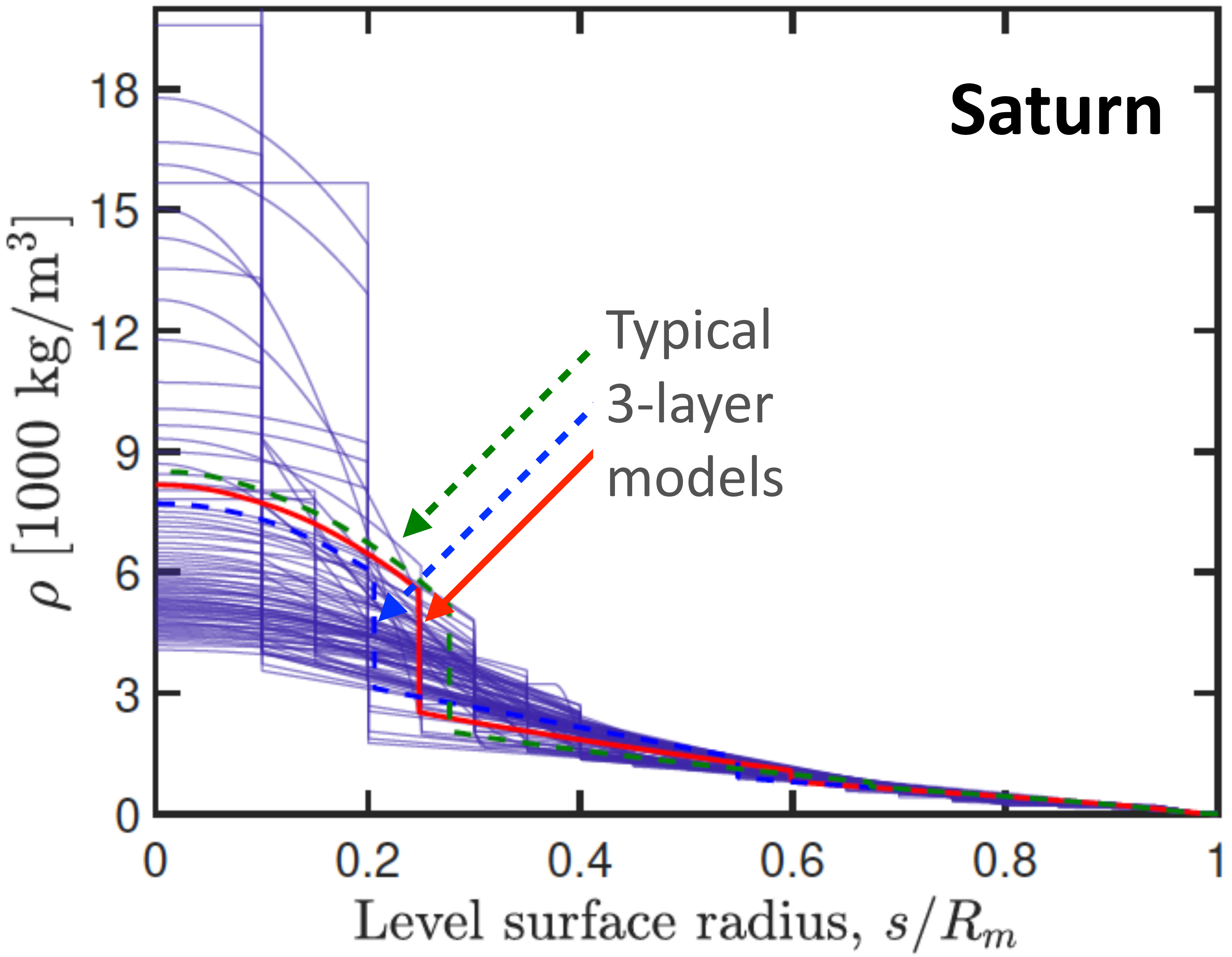
$$
\begin{aligned}
M &= \iiint \rho(r,\theta) d^3\tau, \\
J_{2i} &= -\frac{1}{M R_{\mathrm{eq}}^{2i}} \iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau,
\end{aligned}
$$

J_n gravitational moments are integrals only over density

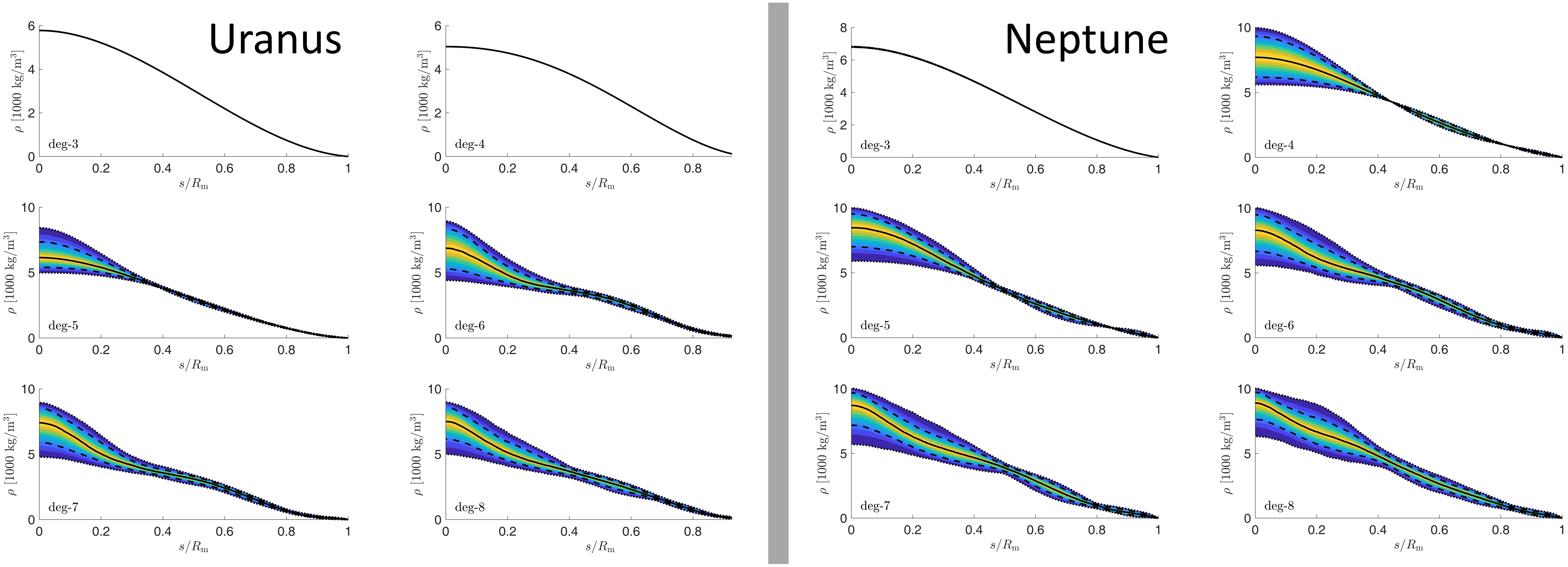
New Methods of Interior Modeling: A Truer View of Uncertainty

- A Bayesian MCMC-driven method to explore all possible interior density profiles that are consistent with gravity data, without needing EOS or a particular modeling framework
- Movshovitz, Fortney, et al. (2019), *Cassini* Grand Finale data for **Saturn**
- Majority of solutions point to a lower density “dilute” core



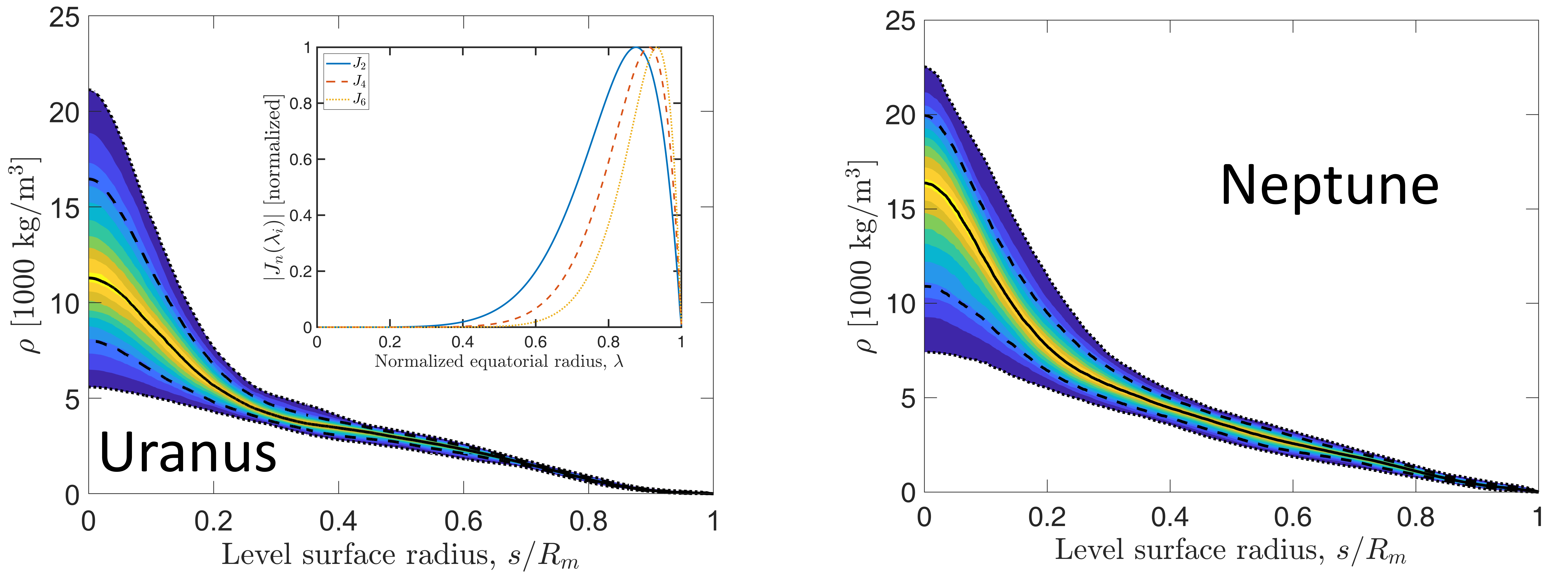


New Methods of Interior Modeling: Preliminary Uranus & Neptune



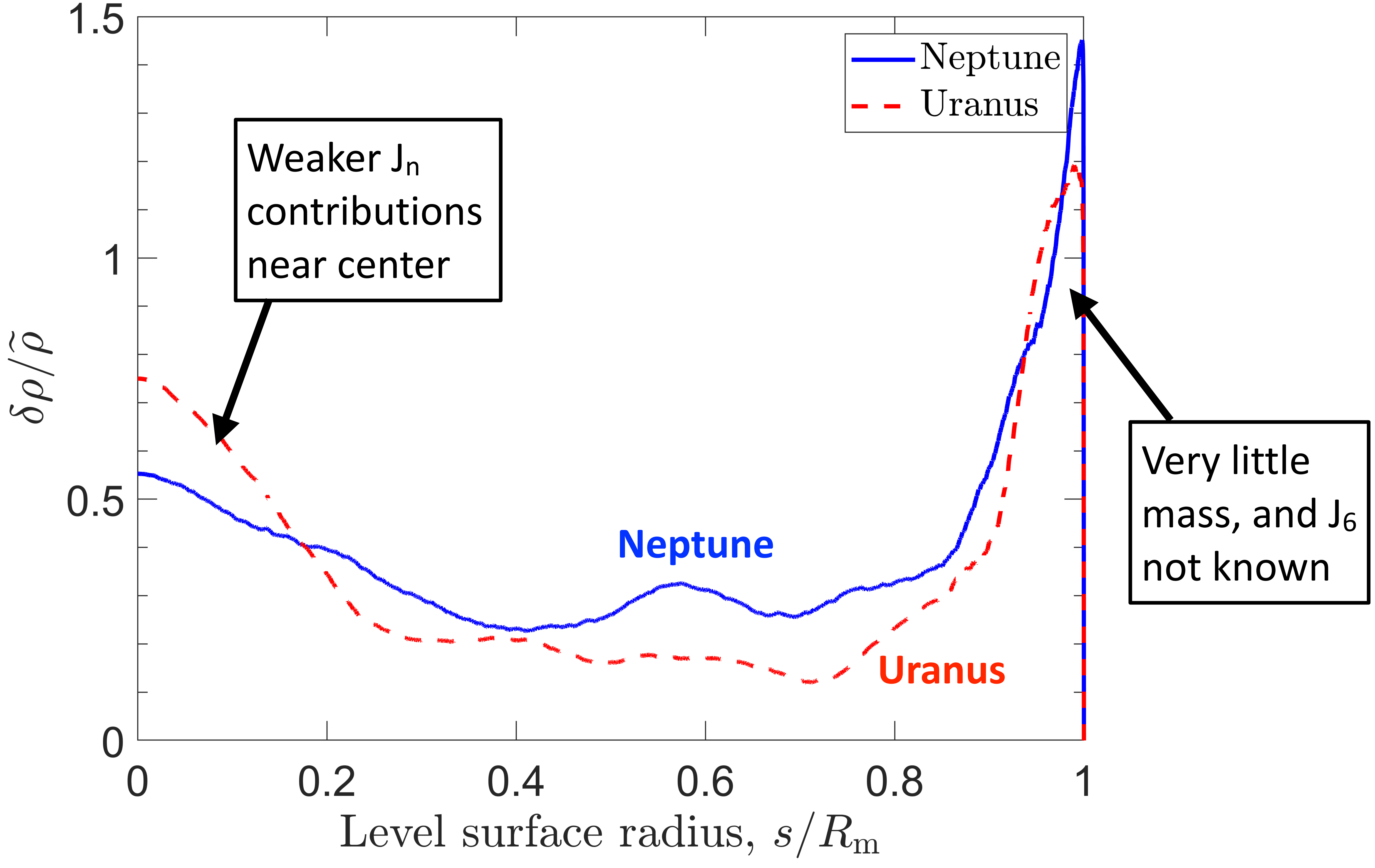
- An exploration of how polynomial degree effects ability to explore a wide phase space of solutions, motivated by work of Helled et al.

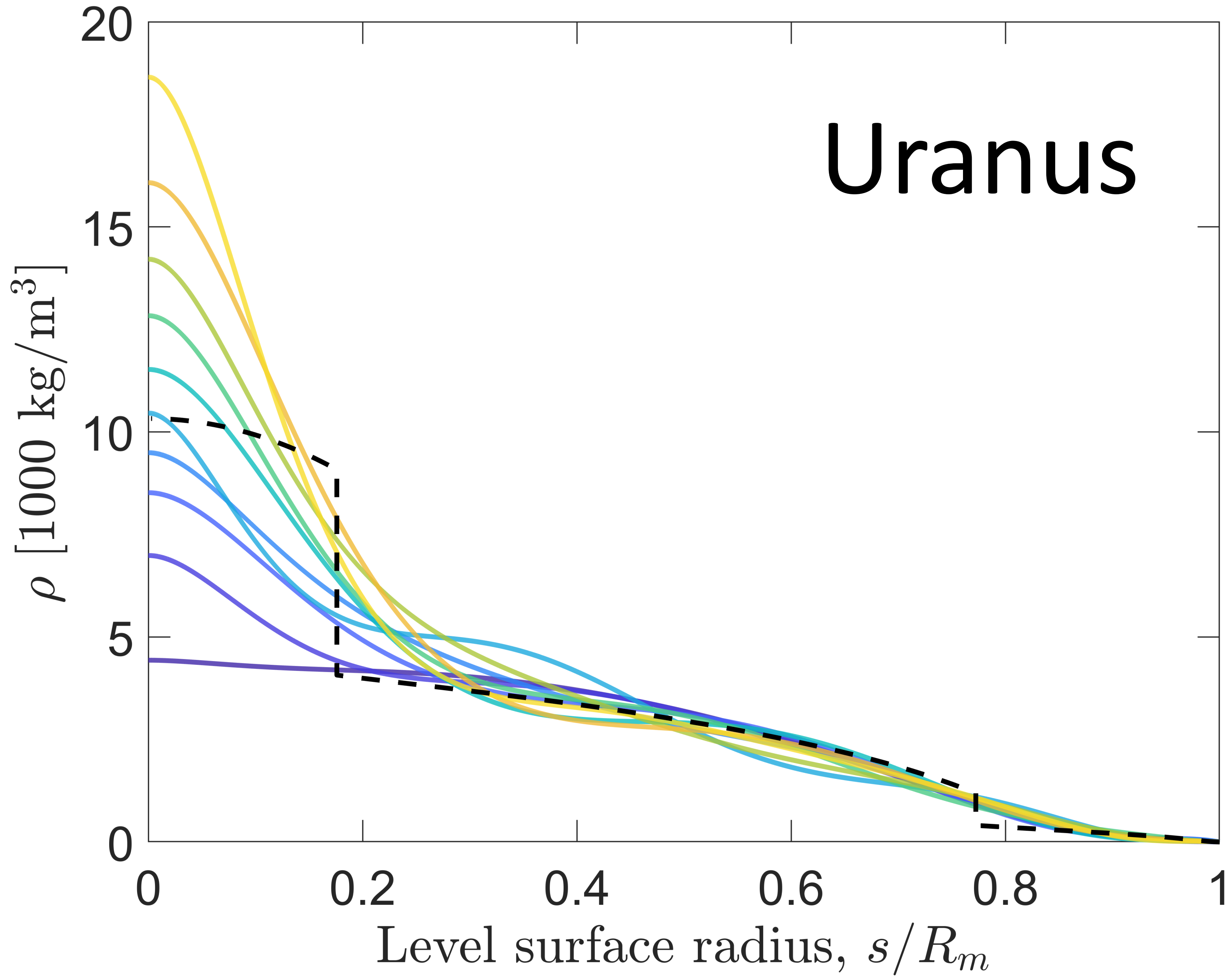
New Methods of Interior Modeling: <u>Preliminary</u> Uranus & Neptune

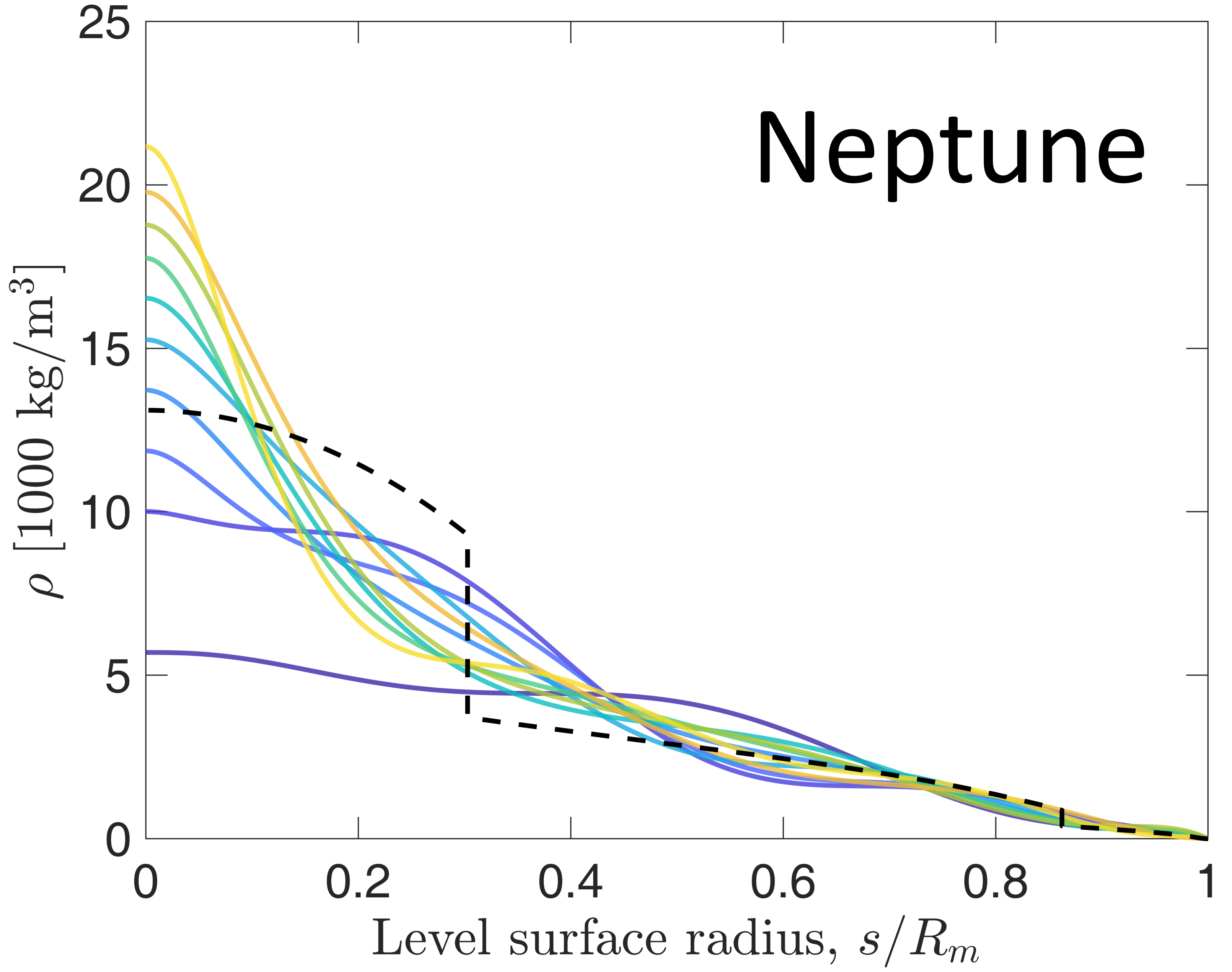


- Polynomial interior density profiles above shown to 8th degree
- Uranus gravitational field is better determined — tighter constraints

Preliminary Uranus & Neptune





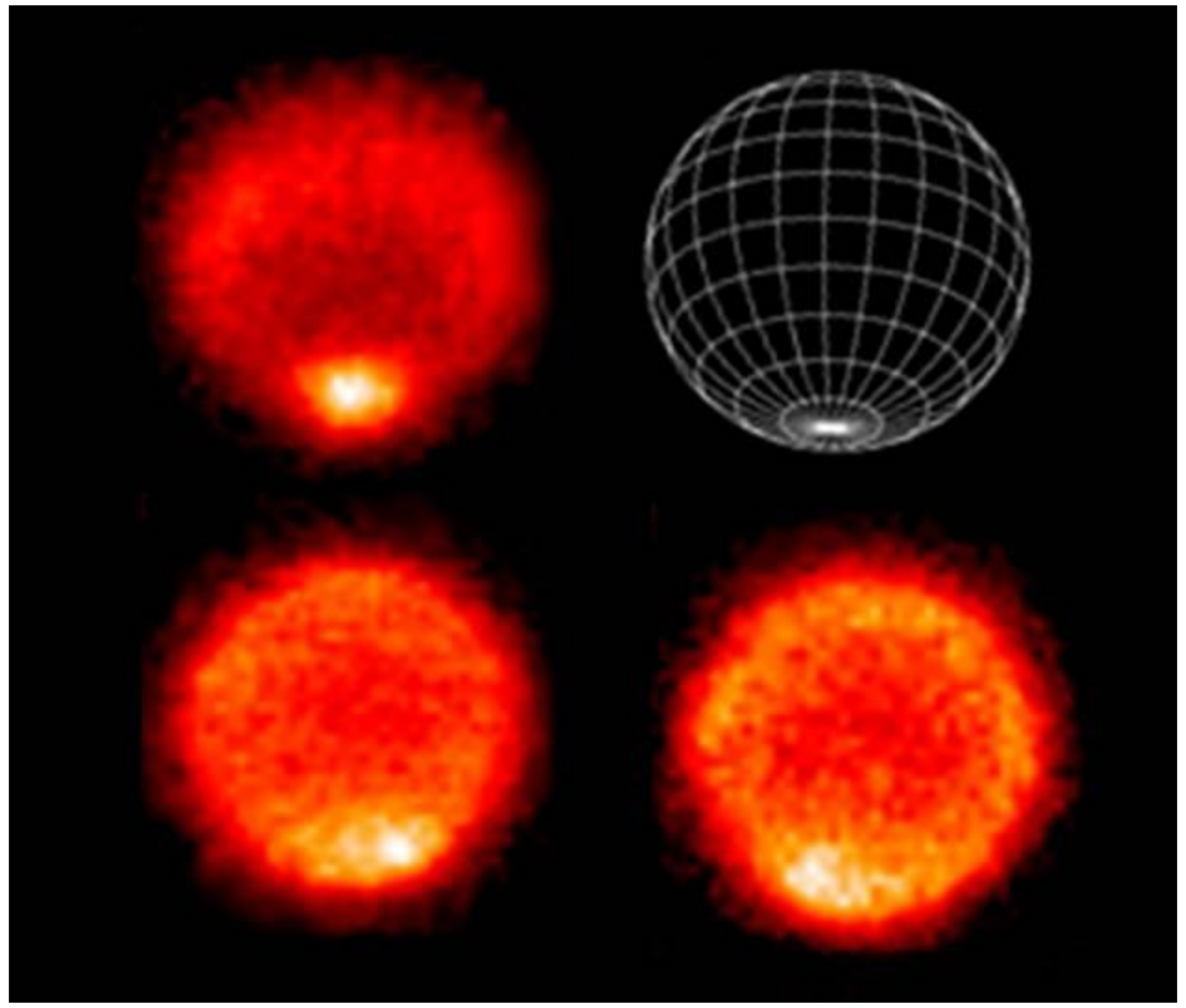


- Neptune's density is less well constrained
- Uranus's gravitational field is better determined

Energy Balance: A Complementary Observable

$$T_{\mathrm{eff}}^{\,4} = T_{\mathrm{eq}}^{\,4} + T_{\mathrm{int}}^{\,4}$$

- **Total Thermal Flux**
- Measurable!



Neptune, Orton et al. (2007) from the VLT

- **Thermal Flux Due to Absorbed and Re-Radiated Sunlight**
- Depends on the Bond Albedo, A_B: the ratio of reflected Solar Power to the Incident Power
- A_B requires observations *over all wavelengths and all phase angles*

- **Thermal Flux from the Planet's Interior**
- Can only be determined if T_{eq} is known

Energy Balance: A Complementary Observable

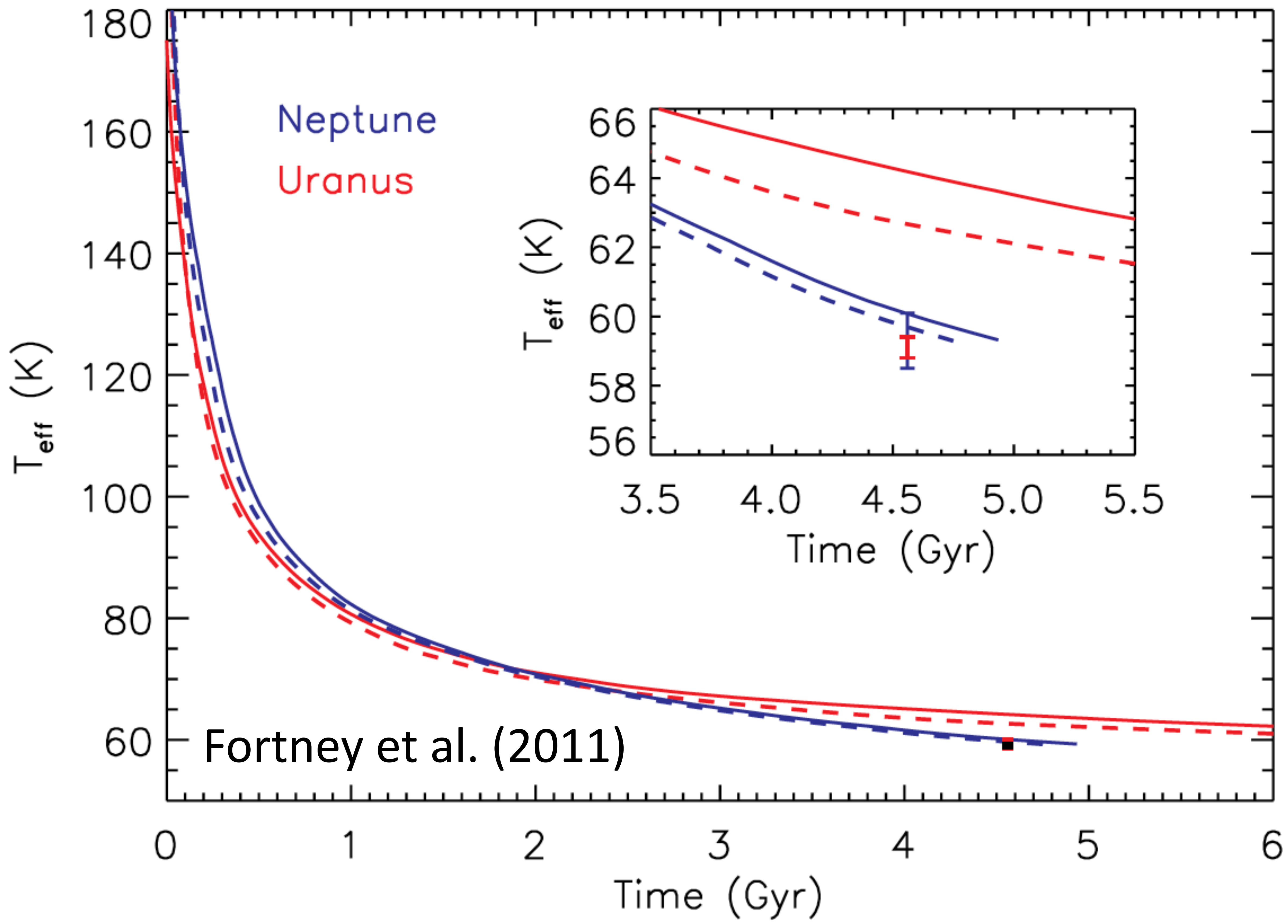
PEARL AND CONRATH: THE ENERGY BALANCE OF NEPTUNE 18,929

TABLE 7. The Energy Balance of the Outer Planets, as Determined From Voyager IRIS Data

Parameter	Jupiter[a]	Saturn[b]	Uranus[c]	Neptune[d]
Geometric albedo[e]	0.274 ± 0.013	0.242 ± 0.012	0.215 ± 0.046	0.215 ± 0.050
Phase intergral	1.25 ± 0.1	1.42 ± 0.1	1.40 ± 0.14	1.35 ± 0.16
Bond albedo[e]	0.343 ± 0.032	0.342 ± 0.030	0.300 ± 0.049	0.290 ± 0.067
Absorbed power,[e] 10^{16} W	50.14 ± 2.48	11.14 ± 0.50	0.526 ± 0.037	0.204 ± 0.019
Equilibrium temperature,[e] K	109.5 ± 1.4	82.4 ± 0.9	58.2 ± 1.0	46.6 ± 1.1
Emitted power, 10^{16} W	83.65 ± 0.84	19.77 ± 0.32	0.560 ± 0.011	0.534 ± 0.029
Effective temperature, K	124.4 ± 0.3	95.0 ± 0.4	59.1 ± 0.3	59.3 ± 0.8
Energy balance[e]	1.67 ± 0.09	1.78 ± 0.09	1.06 ± 0.08	2.61 ± 0.28
Internal power, 10^{16} W	33.5 ± 2.6	8.63 ± 0.60	0.034 ± 0.038	0.330 ± 0.035
Internal energy flux, 10^{-4} W/cm^2	5.44 ± 0.43	2.01 ± 0.14	0.042 ± 0.047	0.433 ± 0.046
Internal power/unit mass, 10^{-11} W/kg	17.6 ± 1.4	15.2 ± 1.1	0.392 ± 0.441	3.22 ± 0.34
Luminosity: $\log(L/L_0)$	−9.062 ± 0.034	−9.651 ± 0.030	$-12.054^{+0.327}_{-\infty}$	−11.025 ± 0.044

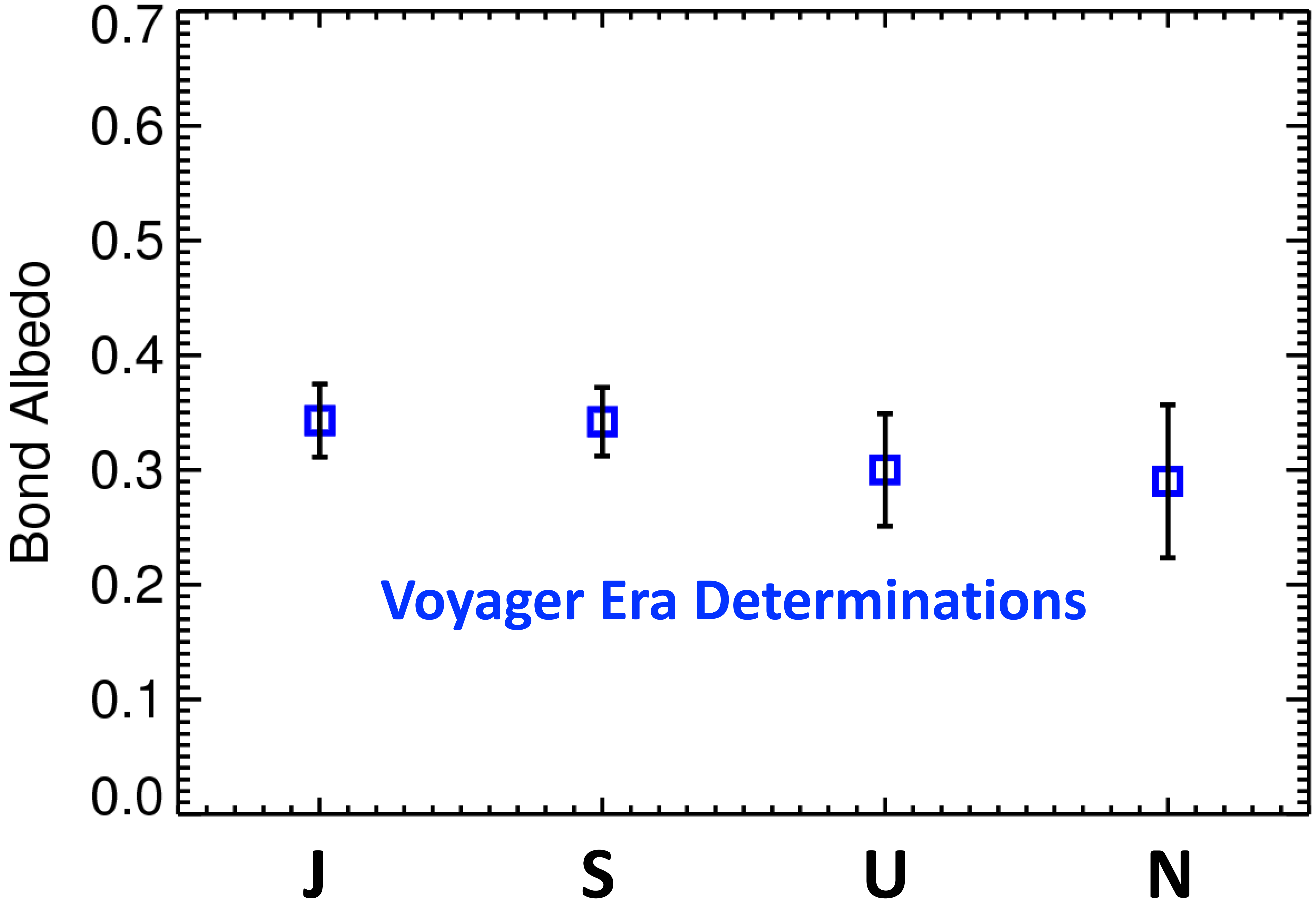
A Fantastic Legacy of the Voyager Missions

Thermal Evolution Models Aim to Match T_{eff} at 4.5 Gyr

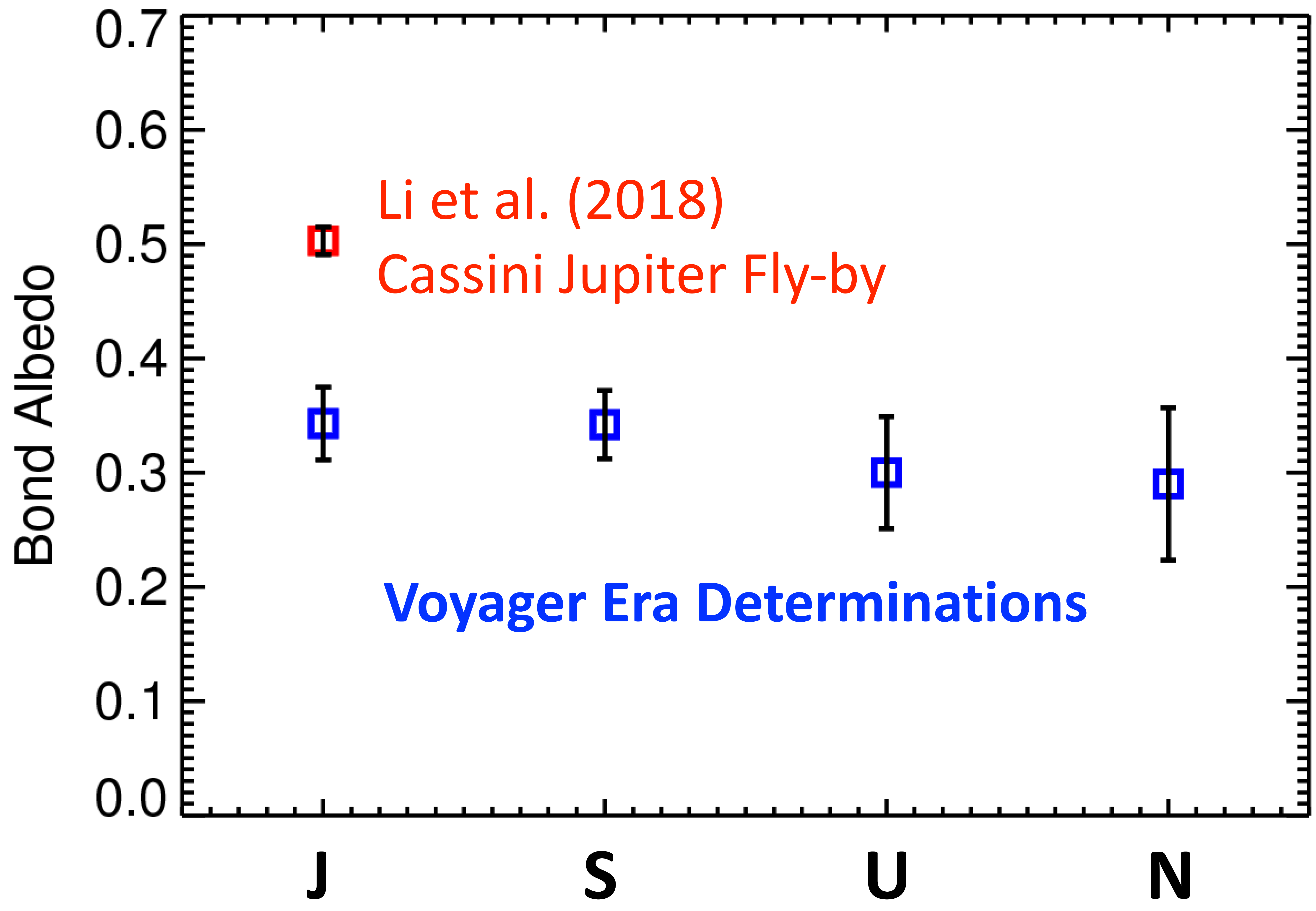


- Improved physics led Fortney & Nettelmann (2010) and Fortney et al. (2011) to find a good match for Neptune, and the “typical” poor match for Uranus, with “standard” 3-layer adiabatic models
- The interior model matters, and the energy balance values matter

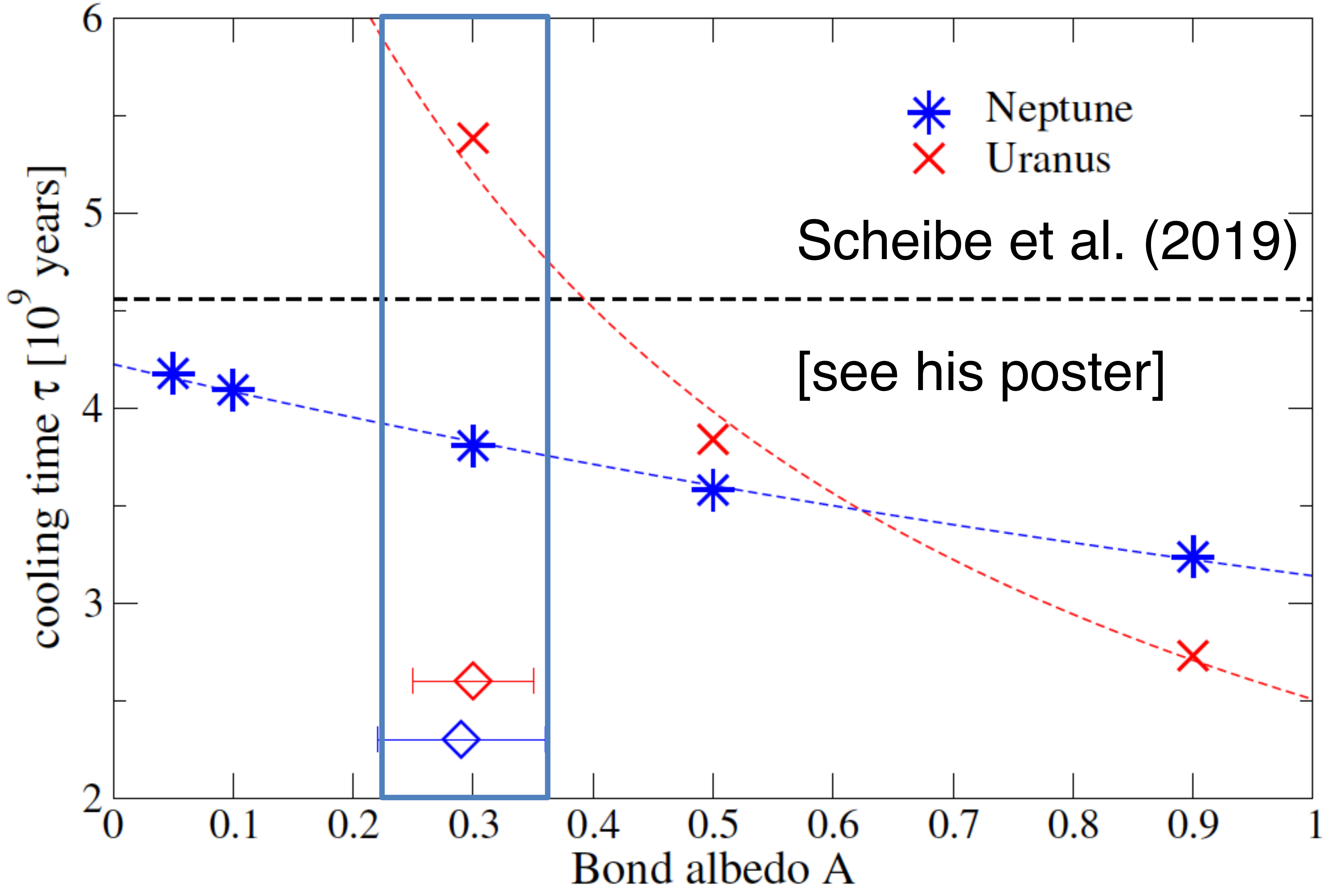
Bond Albedos: Revisions in Order?



Bond Albedos: Revisions in Order?



Newly Revised Physics, Standard Models, Revised Story



- Correct A_B value plays a large role in understanding Uranus thermal history
- Uranus is still underluminous today, but not that far off
- Neptune is overluminous today
- Still a large difference between the two, but neither is “simple”

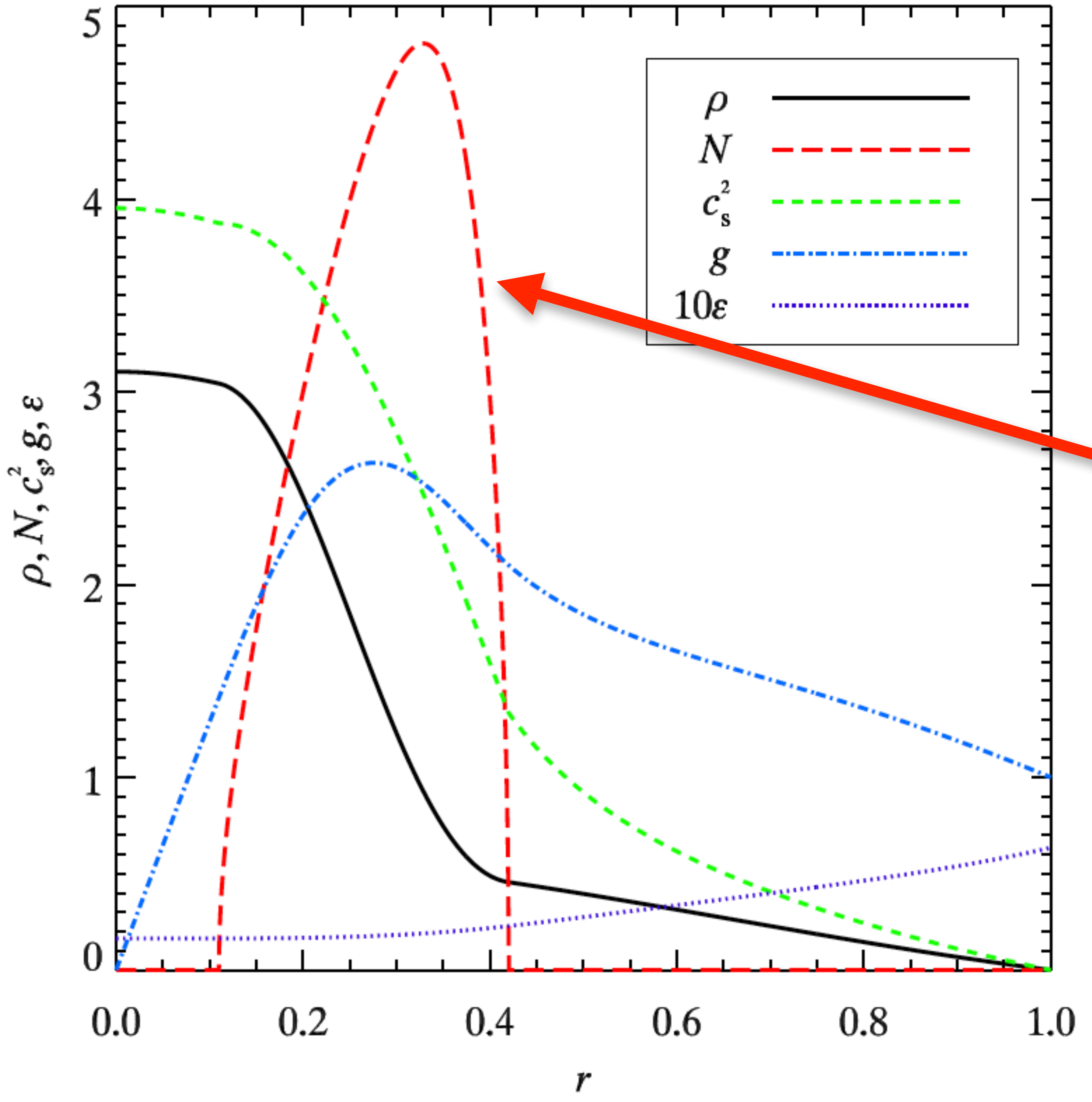
Paths Forward?

- Gravitational Field, for interior structure:
  - Uranus J_2 and J_4 already fairly precise
  - Neptune needs improvement in low order field
- Constrain deep atmosphere dynamics: J_6, J_8, + *[Soyuer poster]*
- Improved rotation rate and shape determination

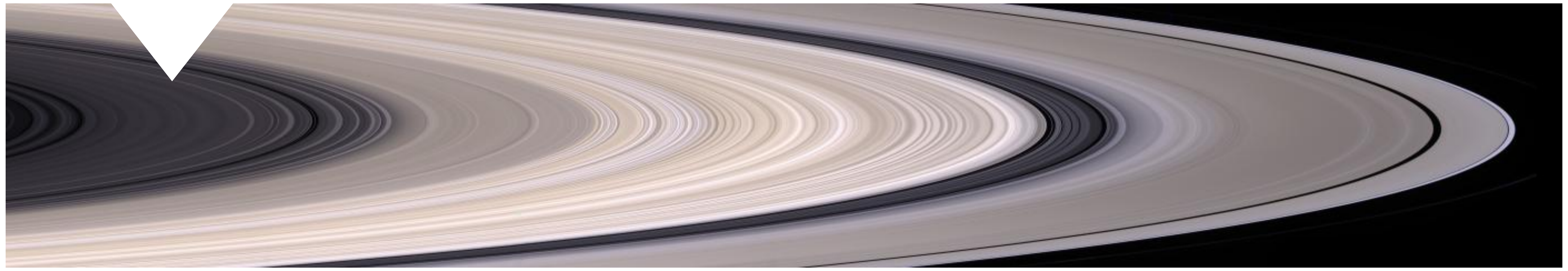
- Re-analysis of Voyager energy balance data + inclusion of high quality ground-based geometric albedo data *[Li poster]*

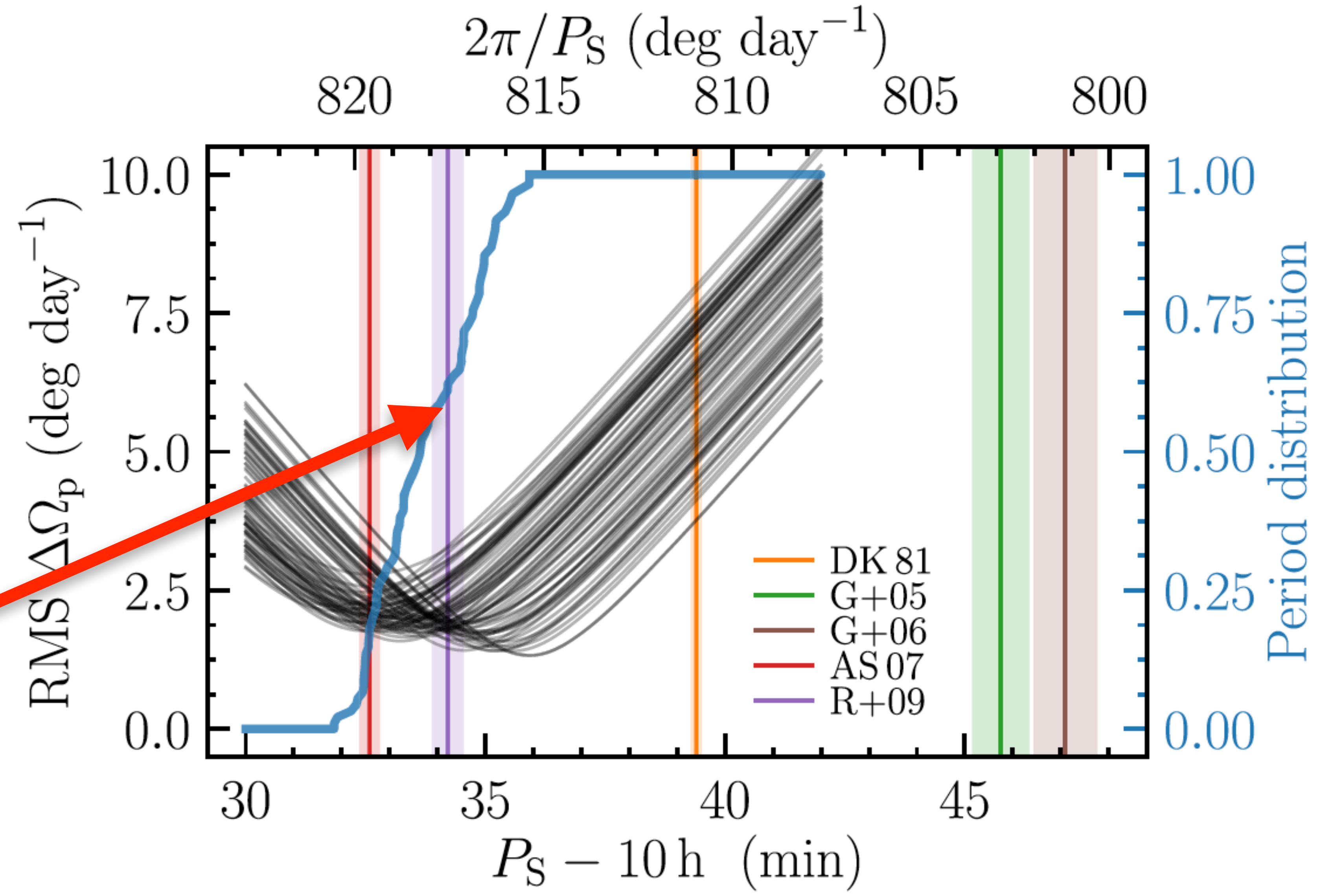
Additional Paths Forward?

- **Seismic investigations** for an entirely new axis for information on the interior
  - Location of layer boundaries (are there layer boundaries?)
  - Non-adiabatic regions that support g-modes *[Friedson & Hedman posters]*



Fuller (2014):
Eroded Core
in Saturn

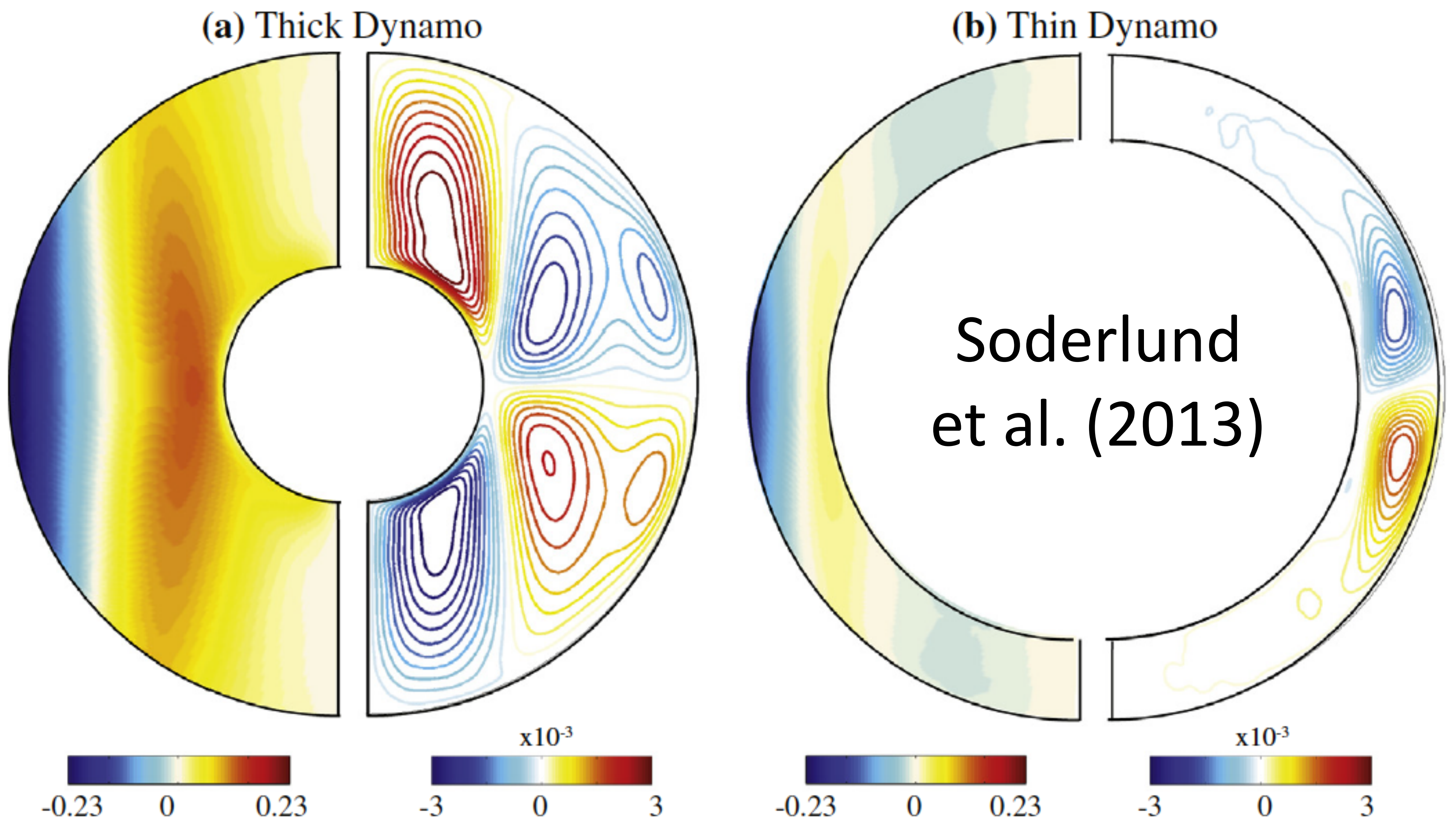




Mankovich et al (2019):
Precise Rotation Period

Additional Paths Forward?

- **Seismic investigations** for an entirely new axis for information on the interior
  - Location of layer boundaries (are there layer boundaries?)
  - Non-adiabatic regions that support g-modes *[Friedson & Hedman posters]*
- A much better understanding of the **magnetic field and dynamo** will feed back directly into improvements in knowledge of the structure



While challenging, a consistent picture involving the dynamo, interior conductivity, and interior convection will be necessary to get past our current lack of understanding

Additional Paths Forward?

- **Seismic investigations** for an entirely new axis for information on the interior
  - Location of layer boundaries (are there layer boundaries?)
  - Non-adiabatic regions that support g-modes *[Friedson & Hedman posters]*
- A much better understanding of the **magnetic field and dynamo** will feed back directly into improvements in knowledge of the structure
- **Entry probe** for temperature structure and atmospheric abundances
  - *Juno*-like microwave sounding for ~100+ bars?
- **More experiments and theoretical investigations of mixtures** and possible phase separation for mixtures relevant to the ice giants *[Millot talk, Weds]*