The Outer Planets and the H-He-C-O system

Dense and Astrophysical Plasmas, SCCS 2025, Stateline/NV

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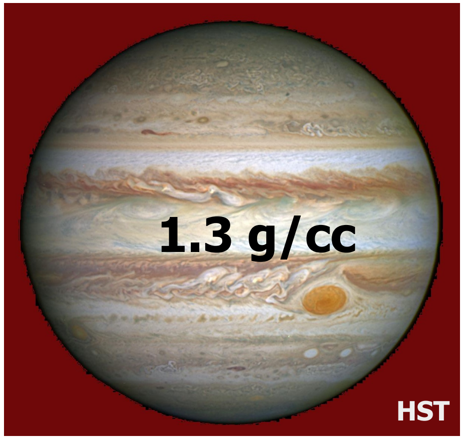
Collaborators: Mandy Bethkenhagen (LULI, USorbonne), Jonathan Fortney (UCSC), Nicola Tosi (DLR), Marina Cano Amoros (DLR), Dominik Kraus (URostock)

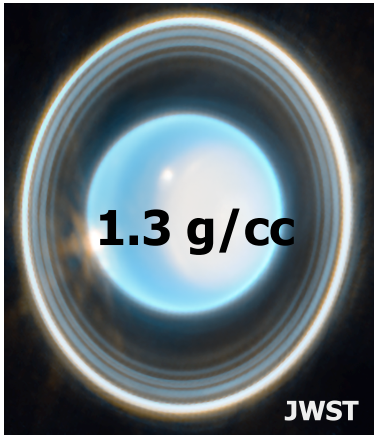


Radius=0.1 R_{Sun}
Mass=0.001 M_{Sun}

P_{CMB}~40 Mbar
T_{core}~14-20,000 K

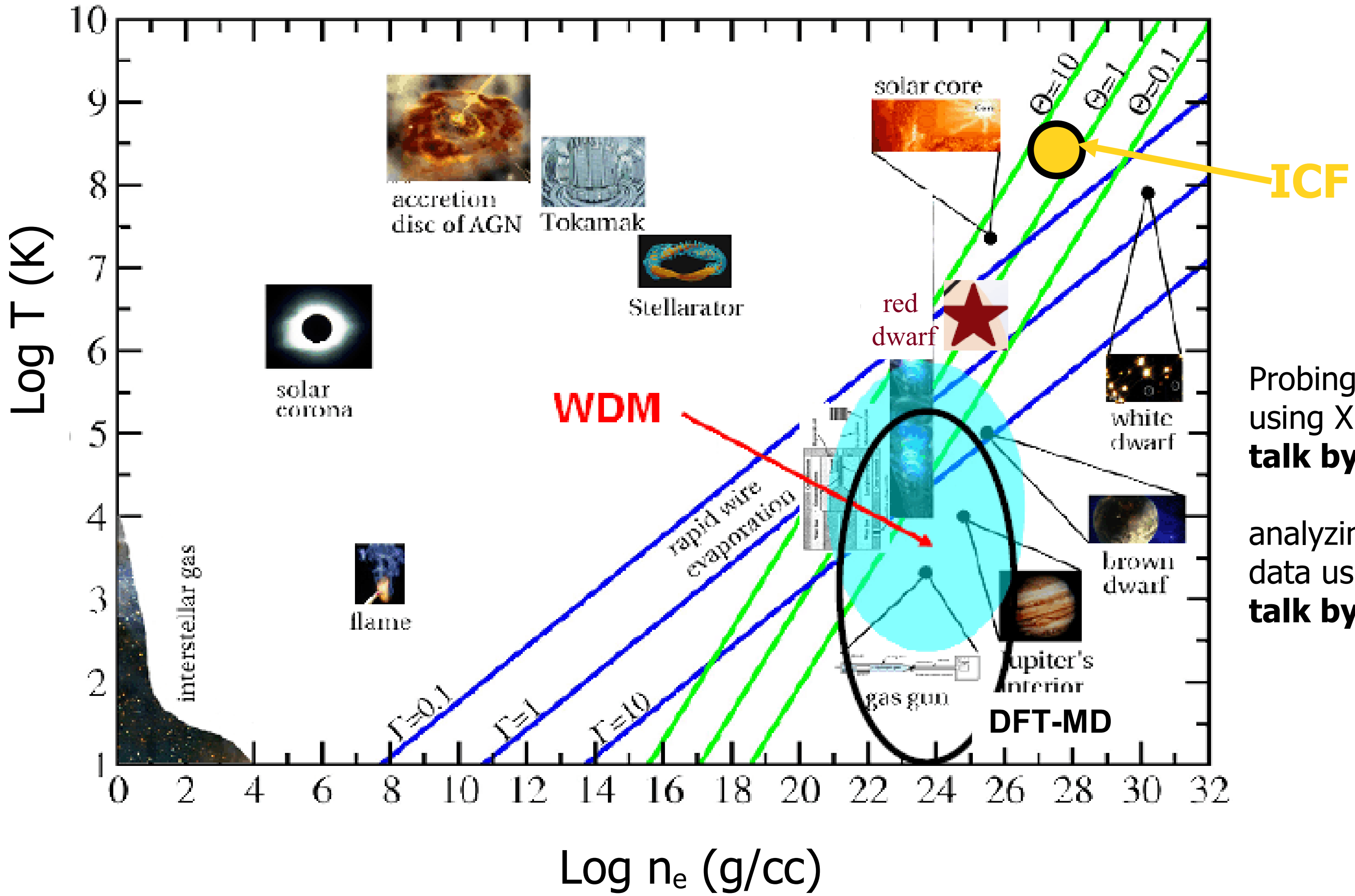
R=0.36 R_J =4 R_E
M=0.05 M_J =15 M_E

P_{CMB}~7 Mbar
T_{core}~4-10,000 K



Acknowledgement:
Juno Participating Scientist Program (NASA), German Science Foundation (DFG),

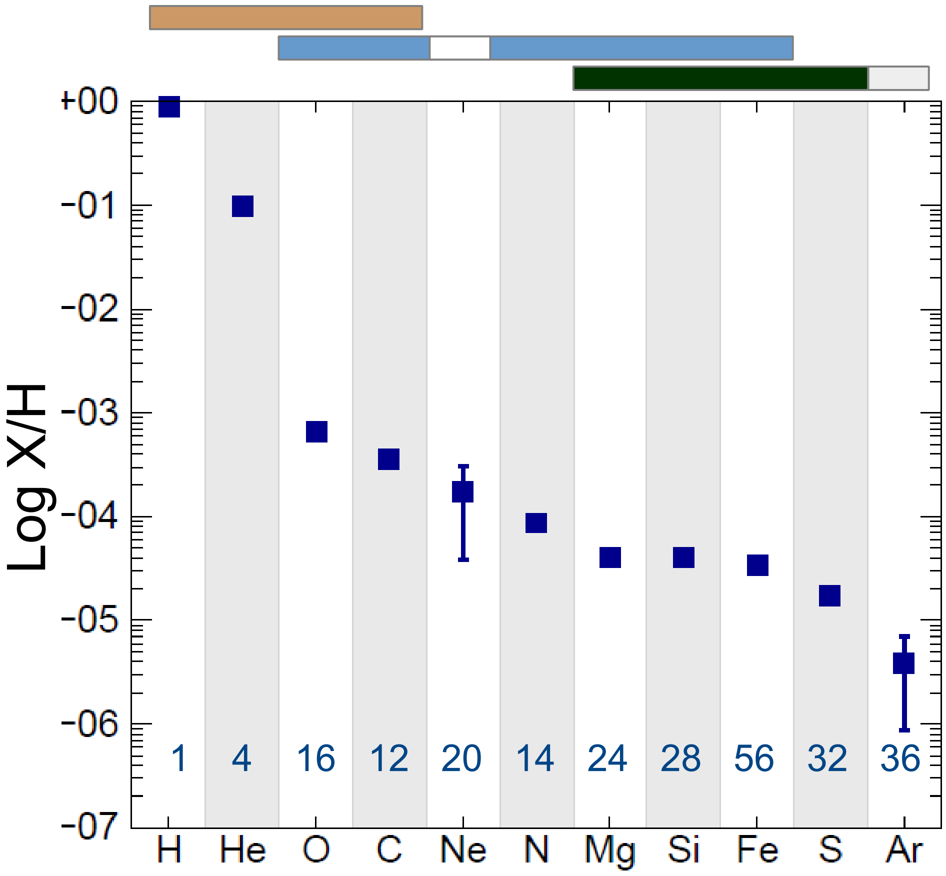
Temperature – Density plane



Probing WDM using XRTS: **talk by M. Böhme**

analyzing XRTS data using TD-DFT: **talk by A. White**

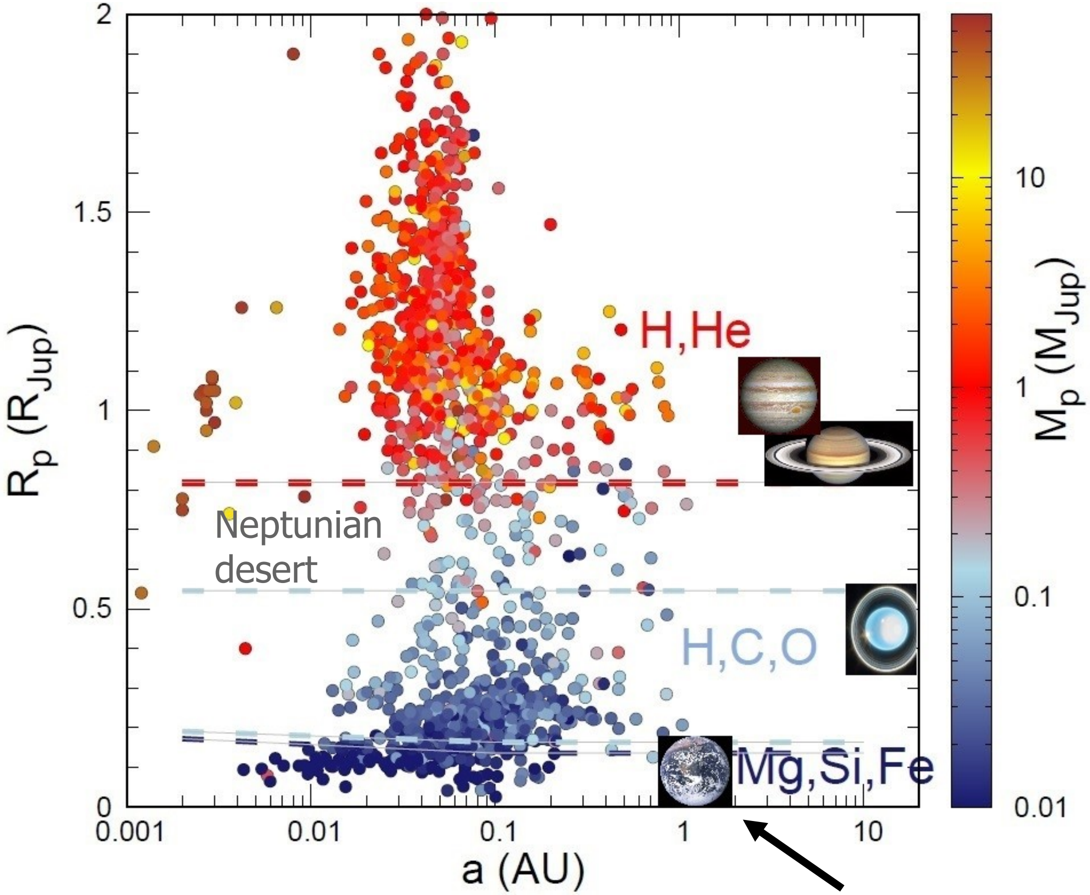
Solar System abundances



Lodders (2021)

- Deviations from solar system abundances (isotopes, I/R, O/H) indicate how planets formed
- Outer planets are macroscopic natural systems of H—Ar under a wide range of P-T conditions
- Interior & evolution models constrain EOS and phase diagrams

~1450 Exoplanets with measured Mass and Radius



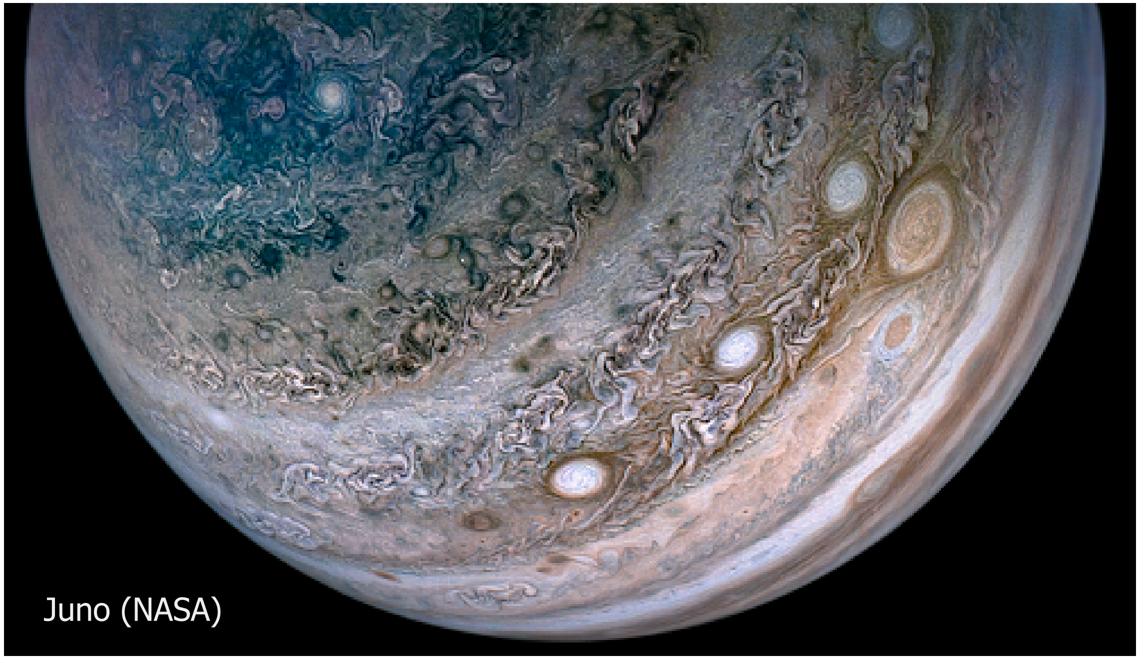
poster by S.S. Prins
thermal conductivity in Fe-alloys, important for core solidification and magnetic field

Jupiter

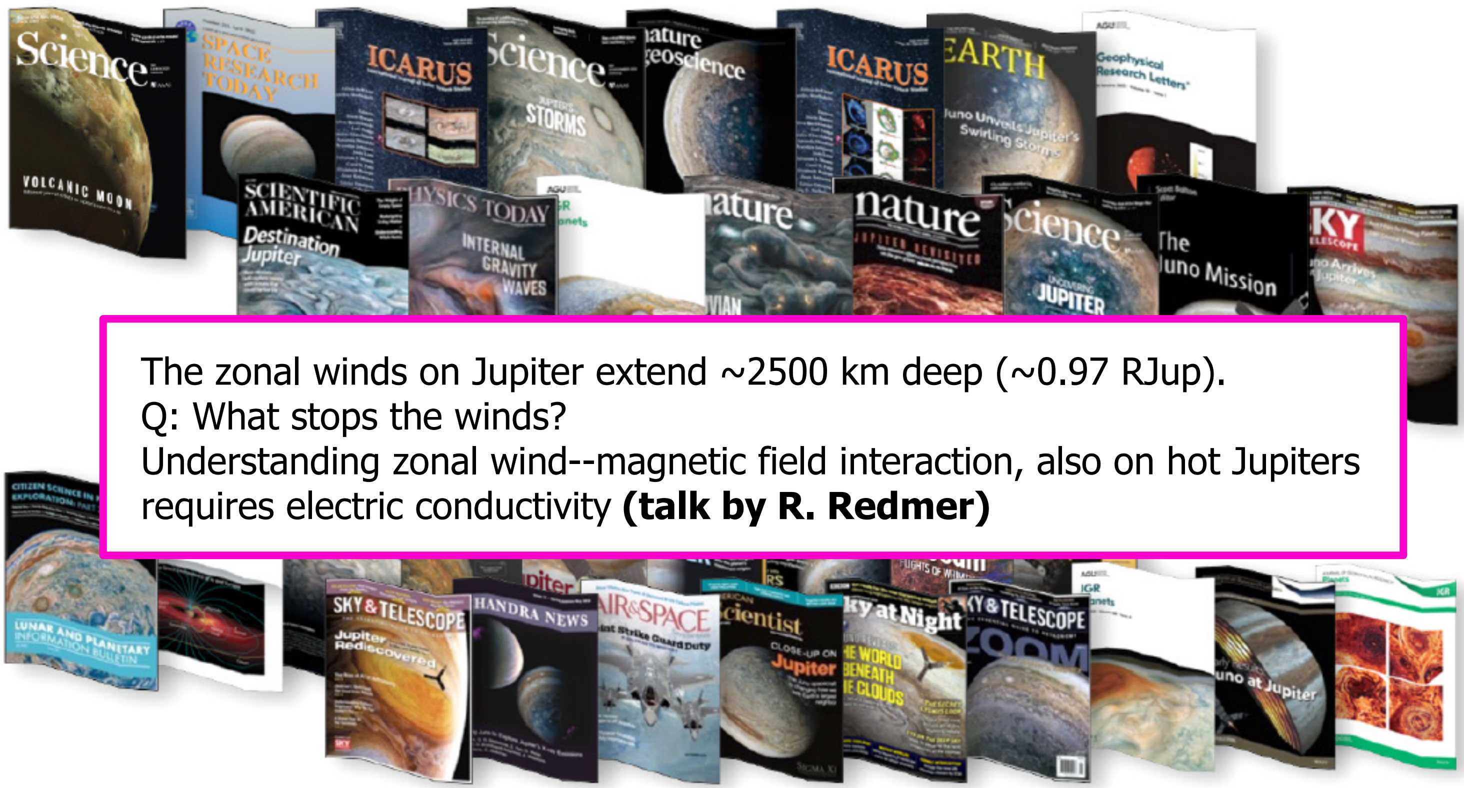
Key achievements

Current challenge

Solution pathways



Key achievements



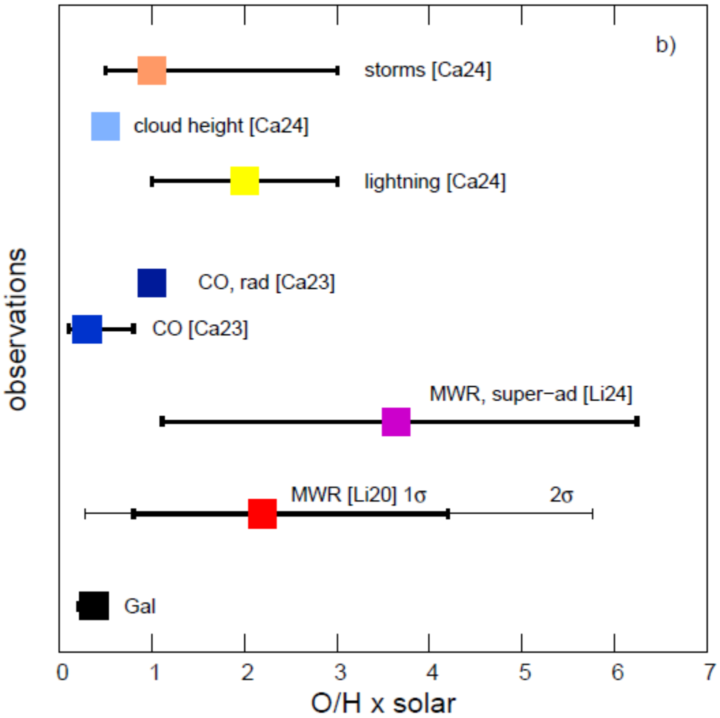
The zonal winds on Jupiter extend ~2500 km deep (~0.97 RJup).
Q: What stops the winds?
Understanding zonal wind--magnetic field interaction, also on hot Jupiters requires electric conductivity **(talk by R. Redmer)**

Figure 3-1. *A sampling of Juno's notable publications in science journals and the popular press.*

Juno EM2 Proposal (S. Bolton)

Observed water abundance

Observed O/H: 0.5-5x solar (Z_{atm}= 1-4 x solar)

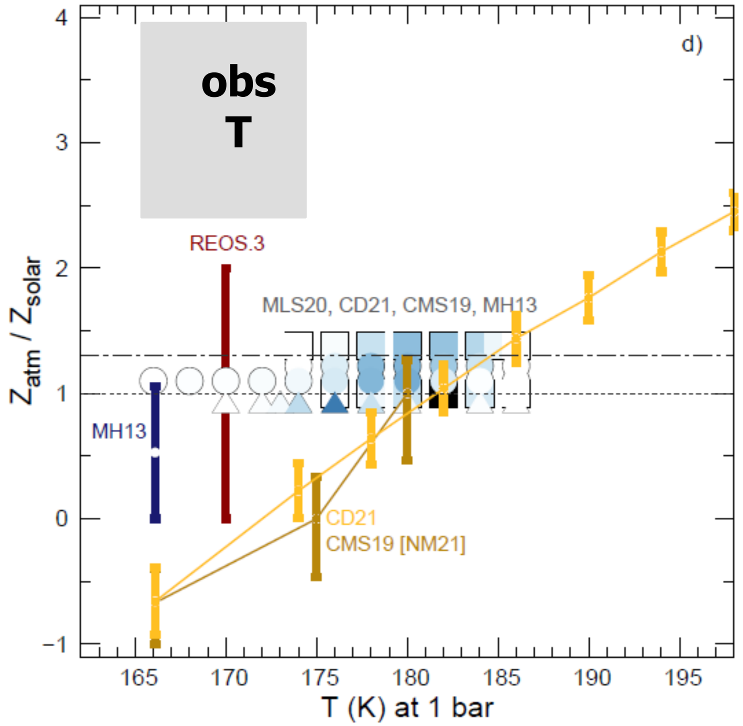


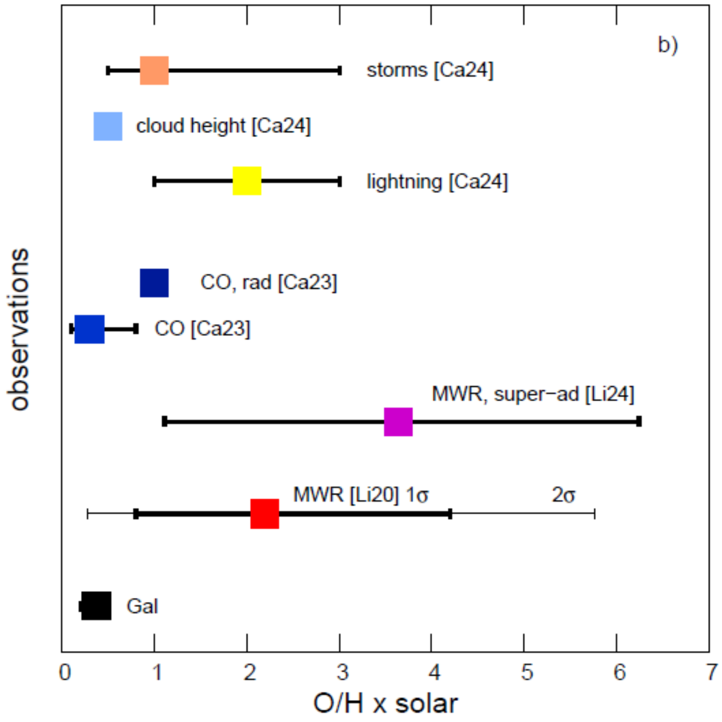
Nettelmann & Fortney (2025)

Current challenge: Z_{atmos}

Interior models: Z_{atm}= 0-1 x solar

Observed O/H: 0.5-5x solar (Z_{atm}= 1-4 x solar)



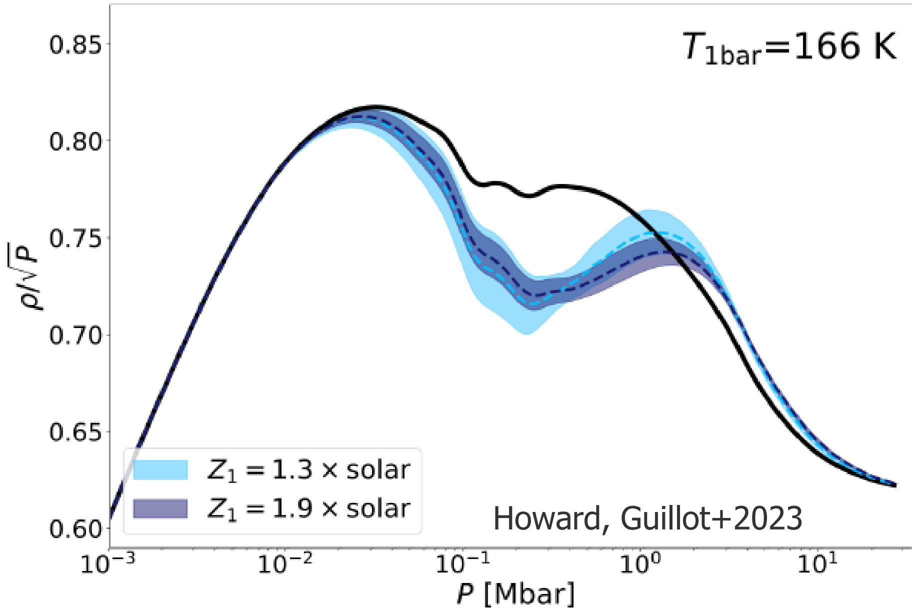


All adiabatic interior models struggle to reach 1x solar for observed T_{1bar}, regardless of which (PBE-based) H/He-EOS is used.

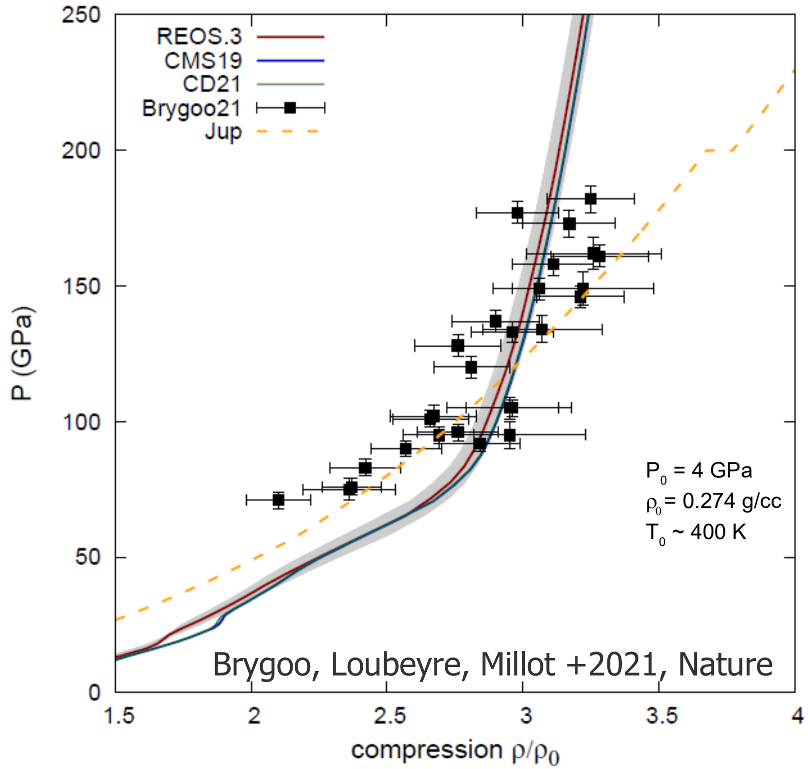
Nettelmann & Fortney (2025)

Solution pathway 1: stiffer **H/He EOS** at ~50 GPa

A decrease in density by 5-10% in the 0.1-1 Mbar region along the adiabat is required for 1.3 x solar.



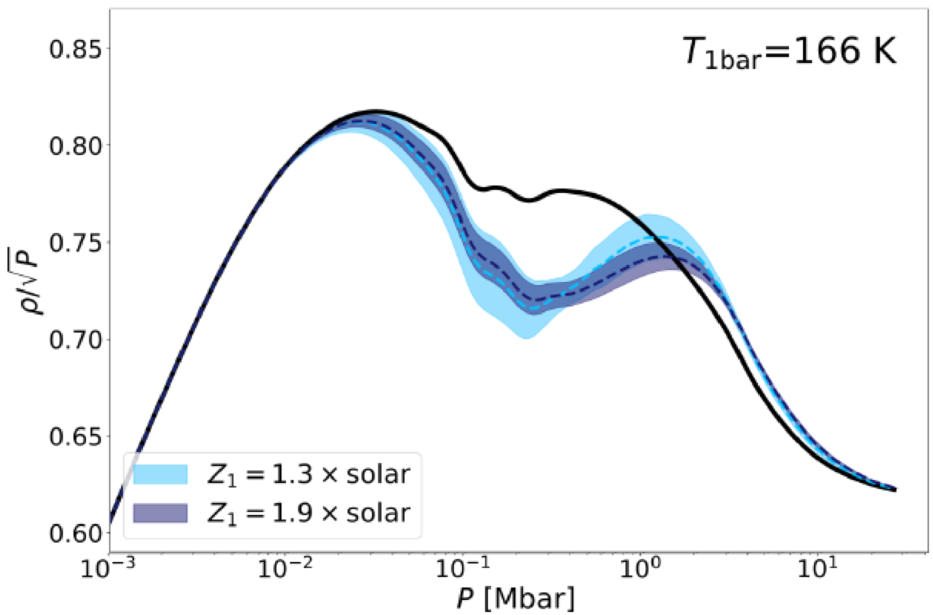
H/He-Hugoniot: DFT-MD-PBE based theories deviate from data at P<0.8 Mbar.



Needed: accurate (<2%) **H/He-**Hugoniot at 10-50 GPa to constrain H/He-EOS.

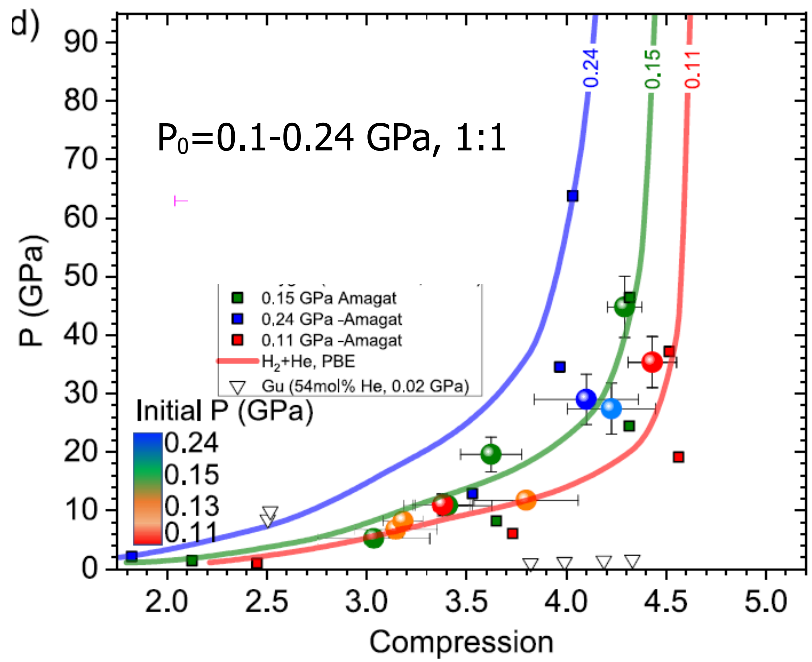
Solution pathway 1: stiffer **H/He EOS** at ~50 GPa?

A decrease in density by 5-10% in the 0.1-1 Mbar region along the adiabat is required for 1.3 x solar.



Howard, Guillot+2023

H/He-Hugoniot: DFT-MD agrees with the Sandia-Z Hugoniots



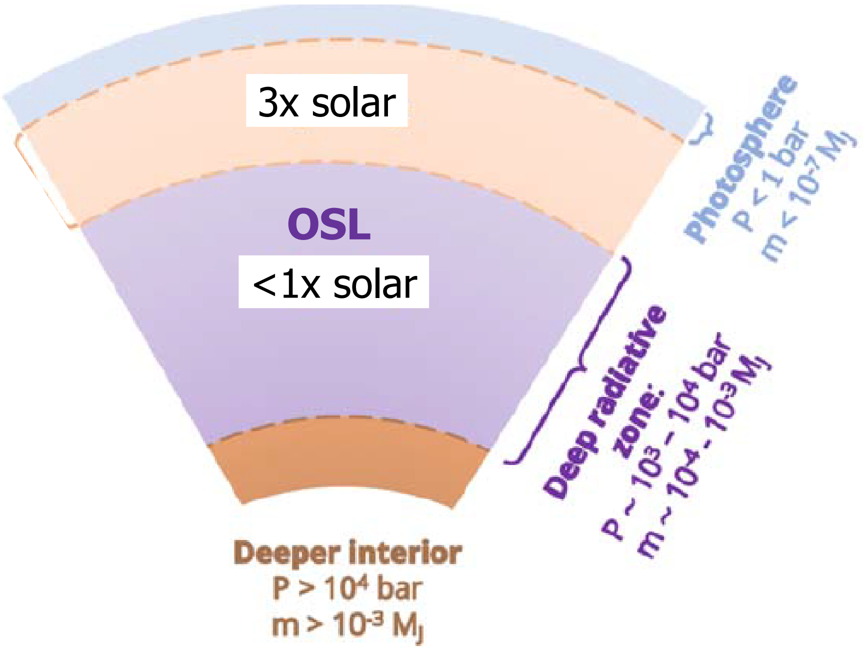
Duwal, Clay, Knudson +2024, BRB

Solution pathway 2: **OSL** with inverted Z-gradient (Zurich group)

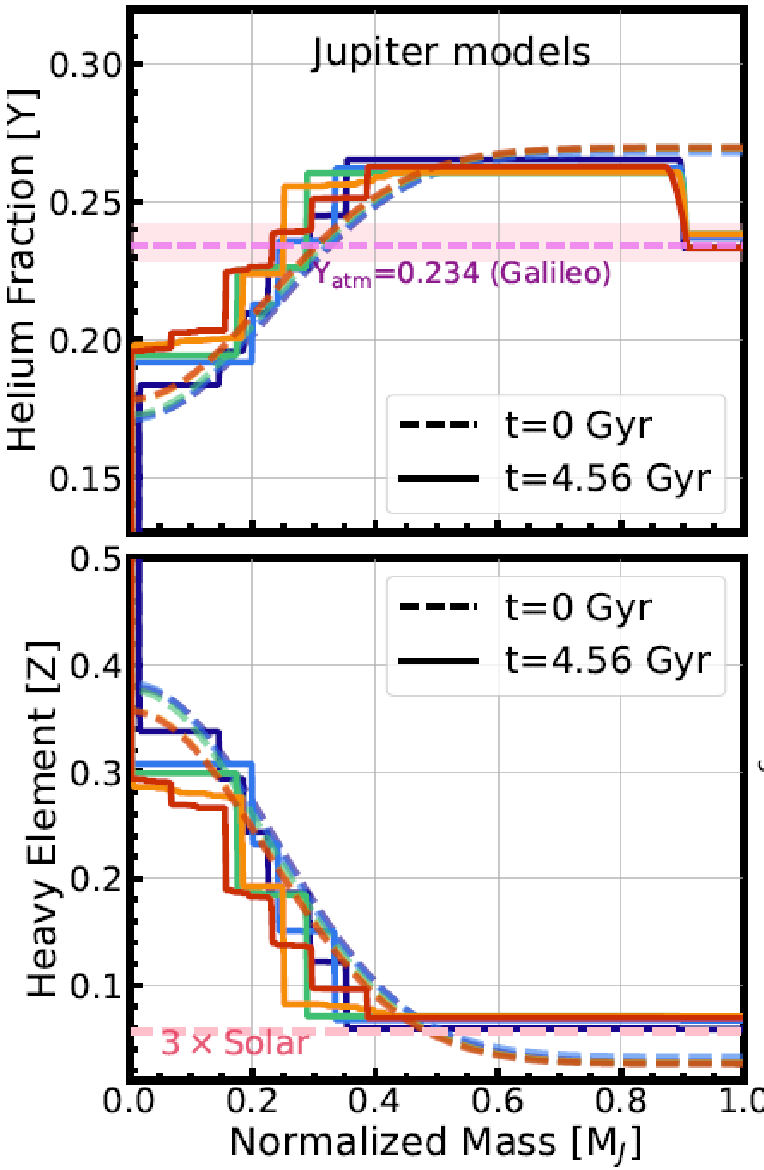
Sub-adiabatic **O**uter **S**table **L**ayer (OSL) prevents efficient mixing.

Dust infall of 10^{-4} M_{Earth} would enrich the atmosphere to 3x solar.

Opacity in OSL at ~1 kbar / 2000 K must be factor 0.1 reduced.



Müller & Helled 2024, ApJ



Solution pathway 3: warmer interior

Models with a **stable, super-adiabatic He-rain region at 1-2 Mbars** with 8000 K at 2 Mb (adiabatic+1500 K) leads to lower H/He-densities that allow for **3x solar Zatm**.

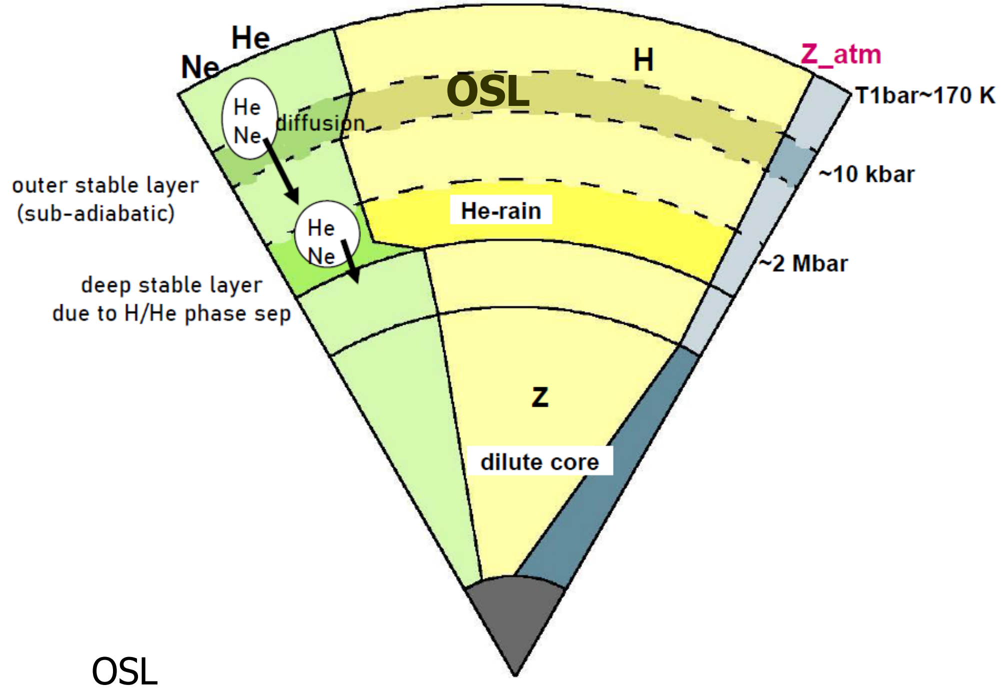
Modeling milestone (Princeton group)**:**
Evolution w simultaneous treatment of eroding core, He-rain, gravity field

Sur, Burrows, Tajeda Arevalo 2025, arXiv:2506:19041

Caveat: inconsistent temperature--heat flux relation (too warm)

Solution pathway 4: cold interior, due to **OSL** (UCSC group)

up to 3x solar atmospheric Z



OSL
- radiative, requires low opacity
- alkali metal depletion 0.001
- electron screening

Nettelmann & Fortney (2025) PSJ

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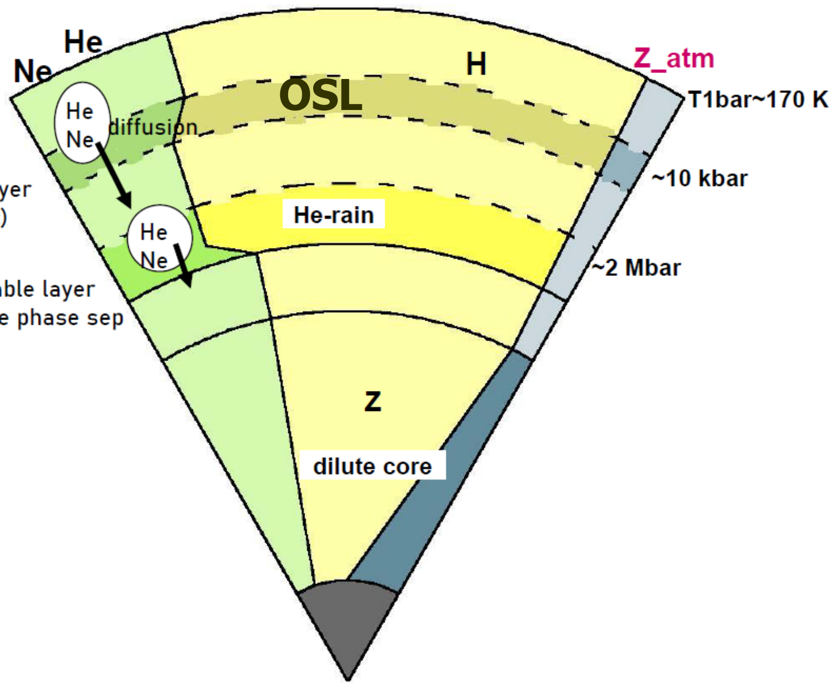

OSL
- radiative, requires low opacity
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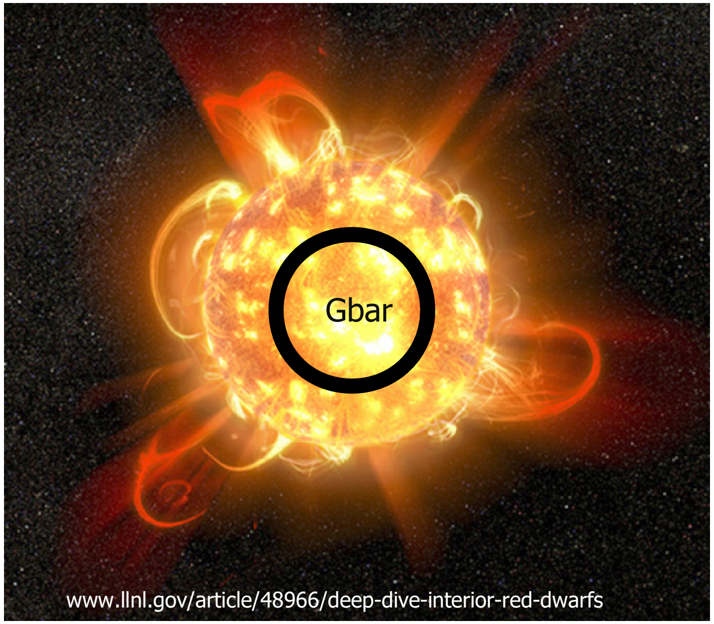
Nettelmann & Fortney (2025) PSJ

Red dwarf stars:
size of radiative core depends on absorption from free-free transitions in H.
(talk by S. Schumacher)



Lütgert, Bethkenhagen +2022, PoP

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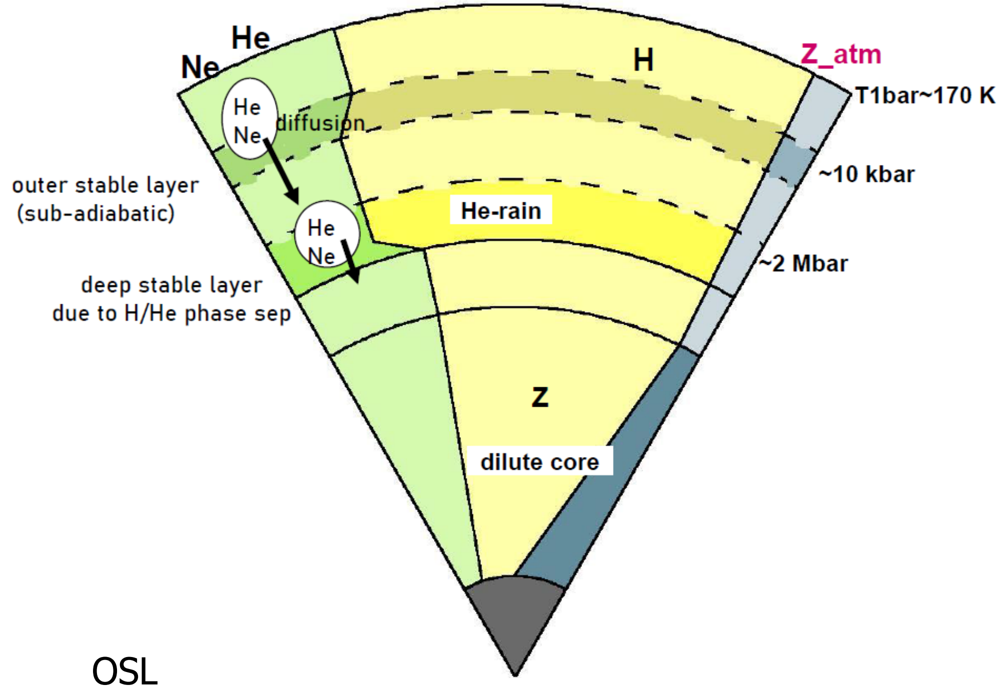
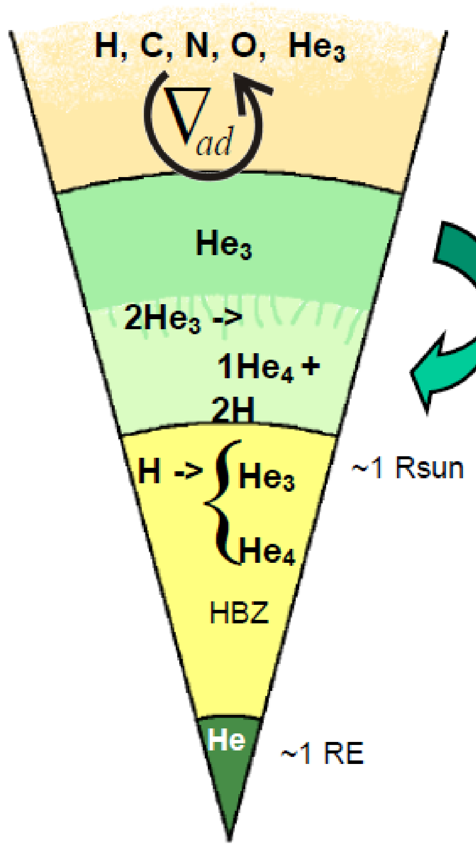


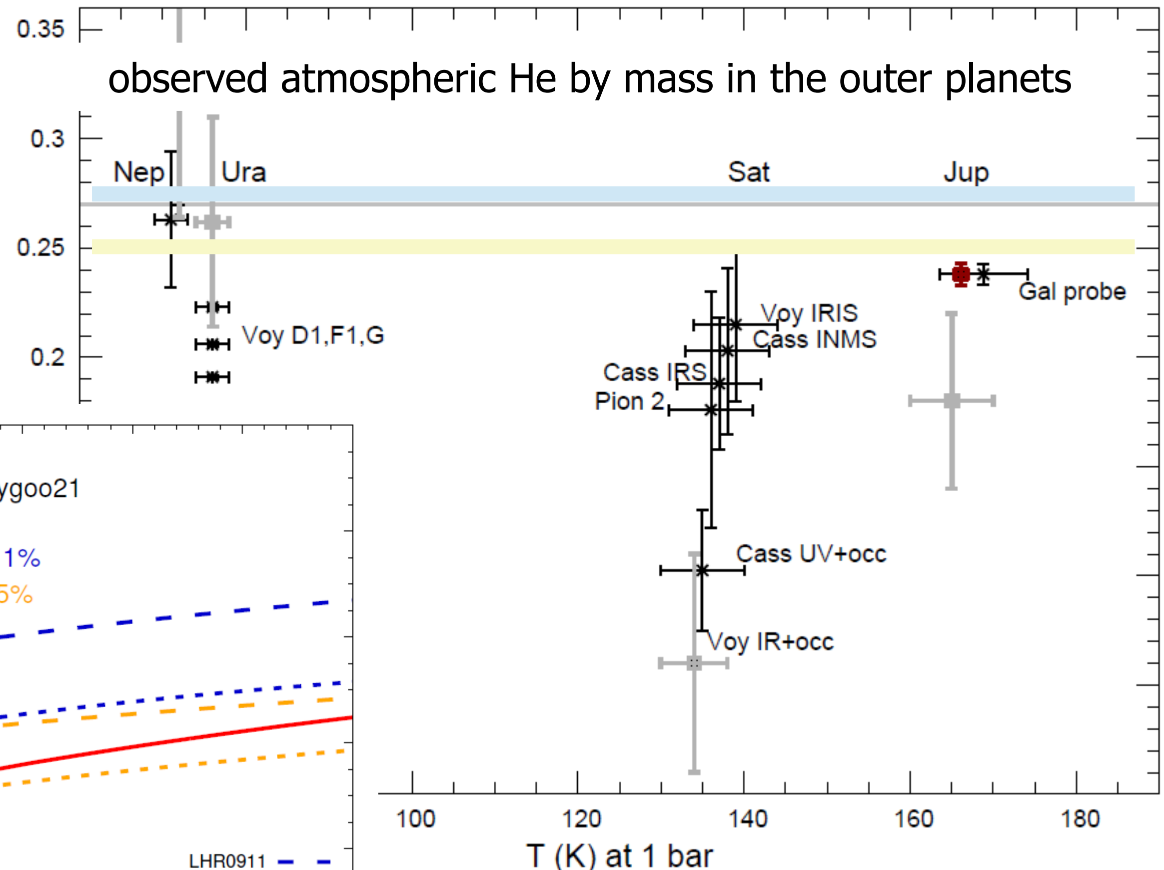
OSL
- double-diffusive, for He-Ne transport

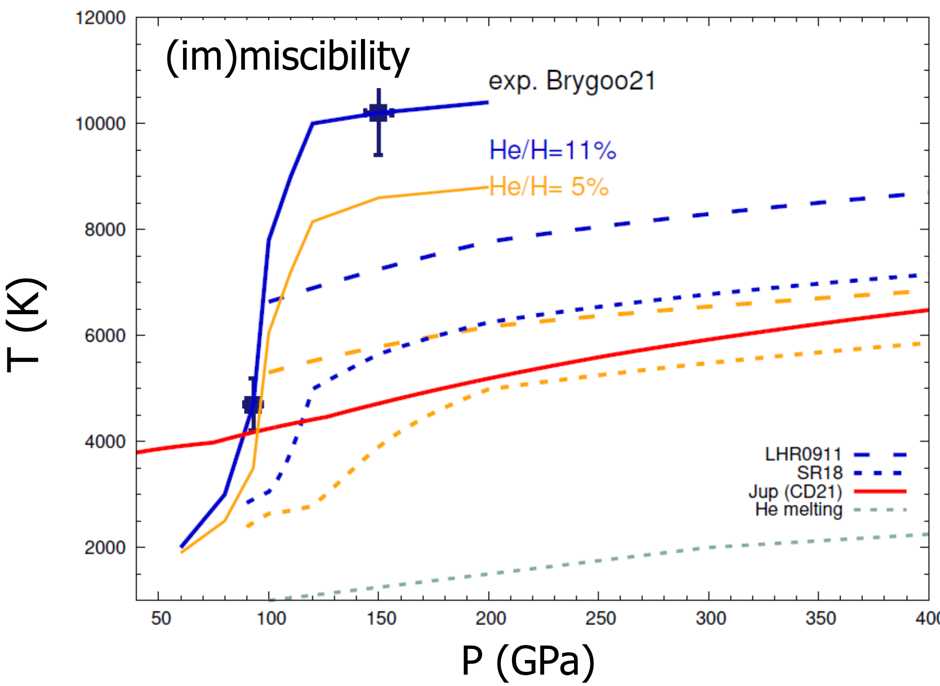
Red giant stars:
double-diffusive convection proposed to explain atmospheric He-isotopes



Nettelmann & Fortney (2025) PSJ

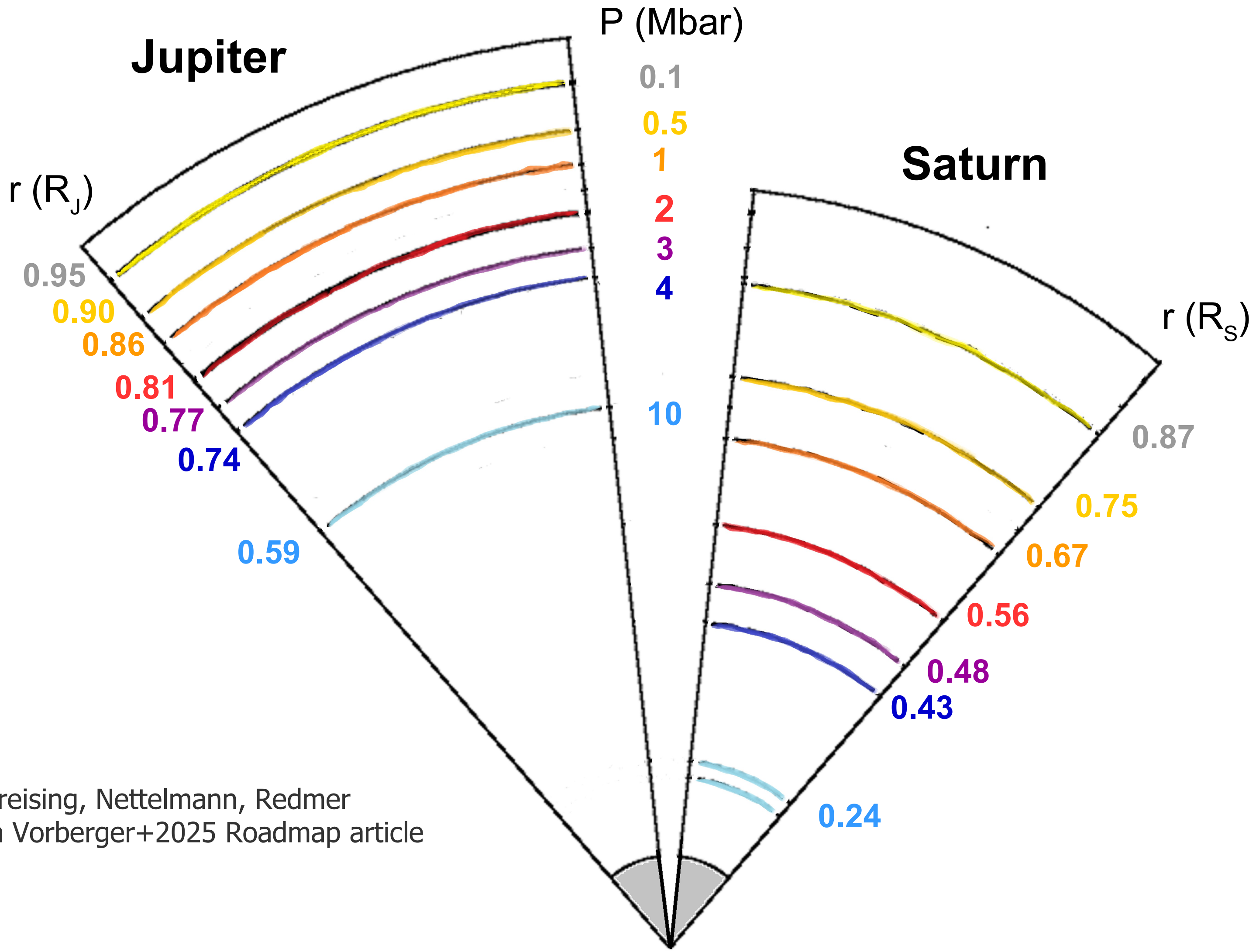
Current challenges: H/He





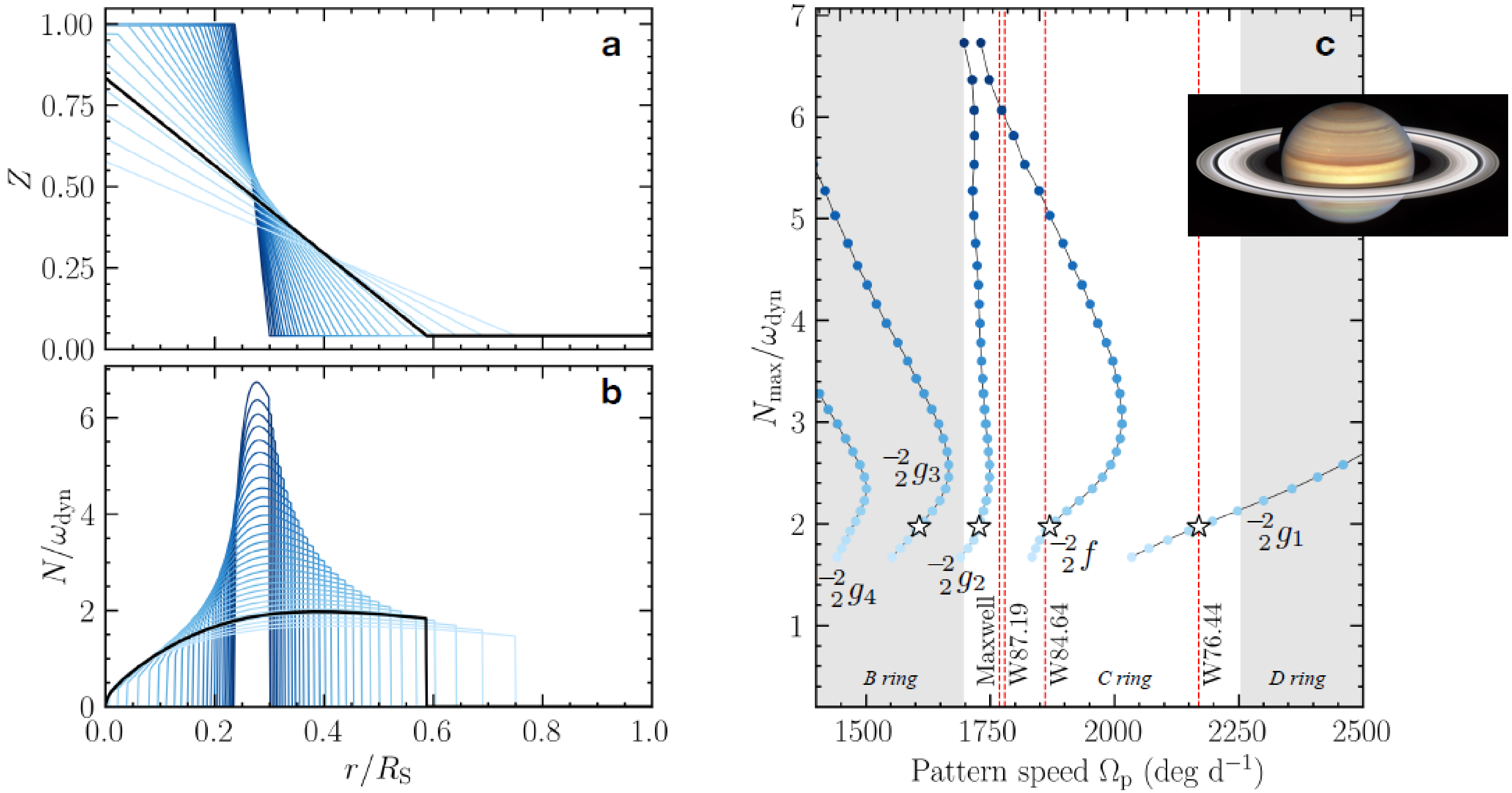
Brygoo, Loubeyre, Millot 2021, Nature
Schöttler & Redmer 2018 PRL
Lorenzen, Holst, Redmer 2009,2011
Chen, Zeng 2024, Nat. Comm
Nettelmann, Cano Amoros+2024, SSRv

interior pressure-radius relation



Preising, Nettelmann, Redmer
in Vorberger+2025 Roadmap article

Key achievement: extended dilute core inferred from ring seismology

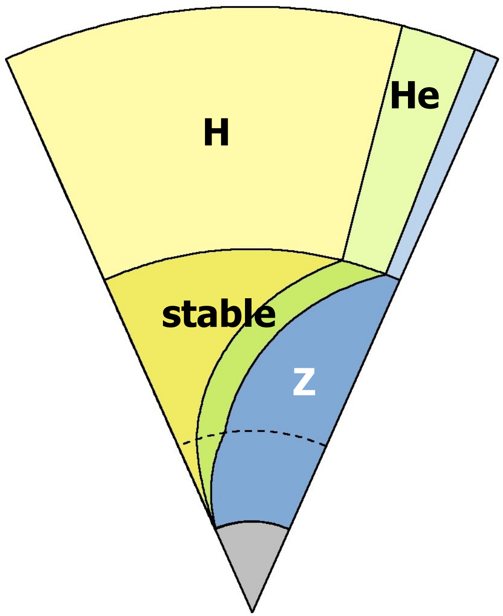


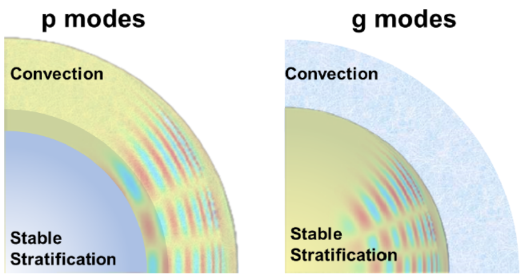
Mankovich & Fuller 2021, Nat Ast
Hedman & Nicholson 2013, AJ

Cassini Observations:
30 frequencies in Saturn's rings
that result from resonant coupling to planetary f-/g-modes.

Saturn?

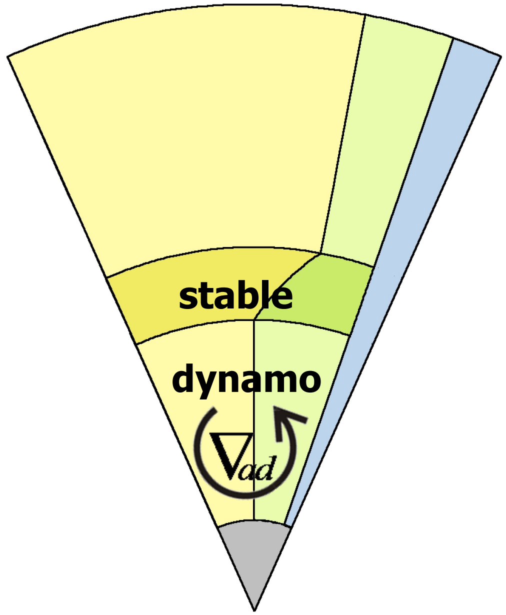
seismology

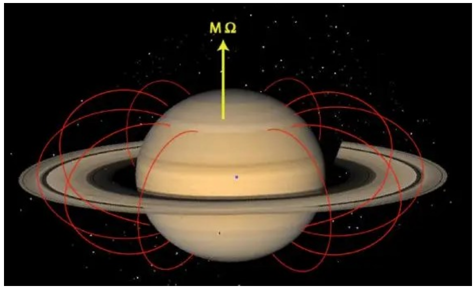




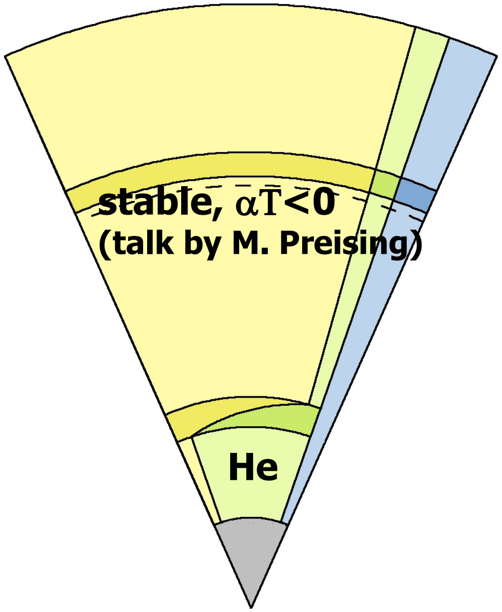
Mankovich, Parisi+2025, PSJ

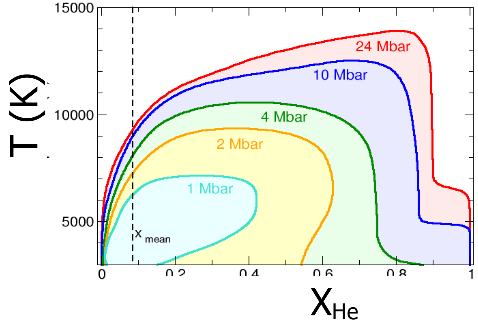
magnetic field



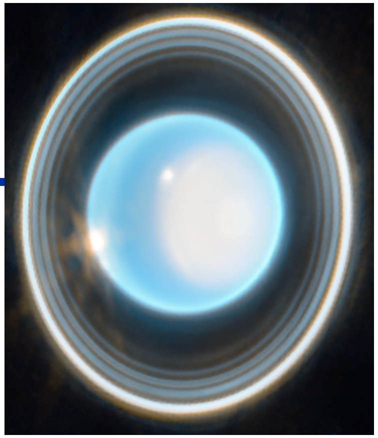


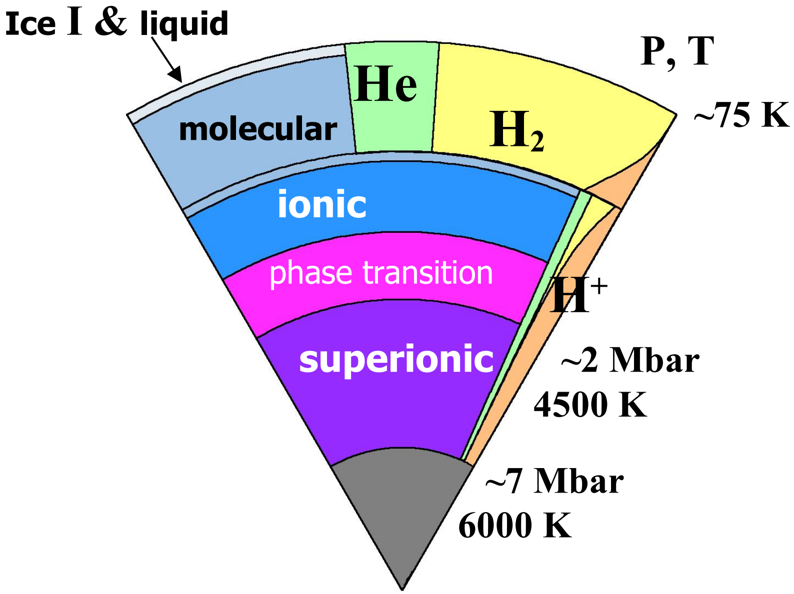
H/He phase diagram





Classical Ice giant model with water





(NN 2009)

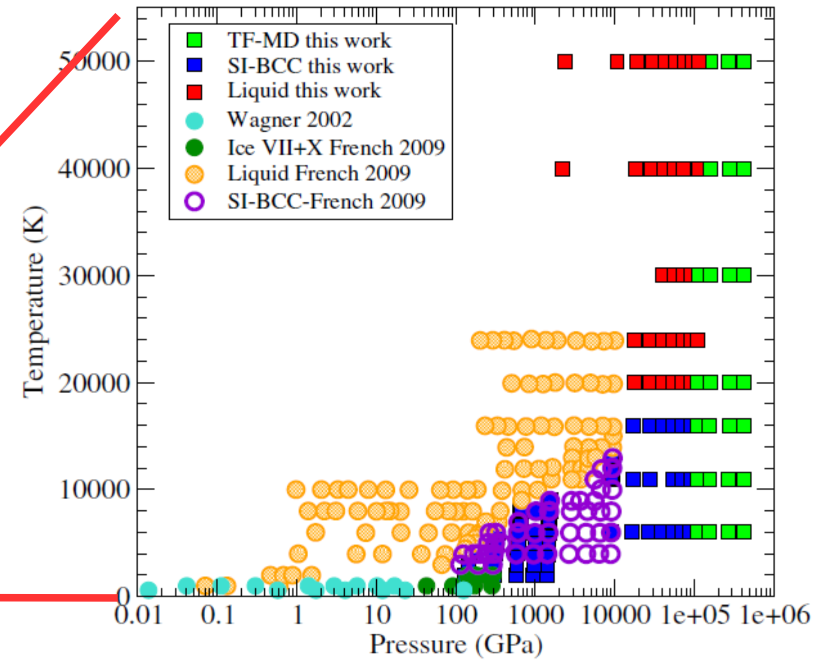
experimental investigation of SI water:
poster by L. Andriambariarijaona

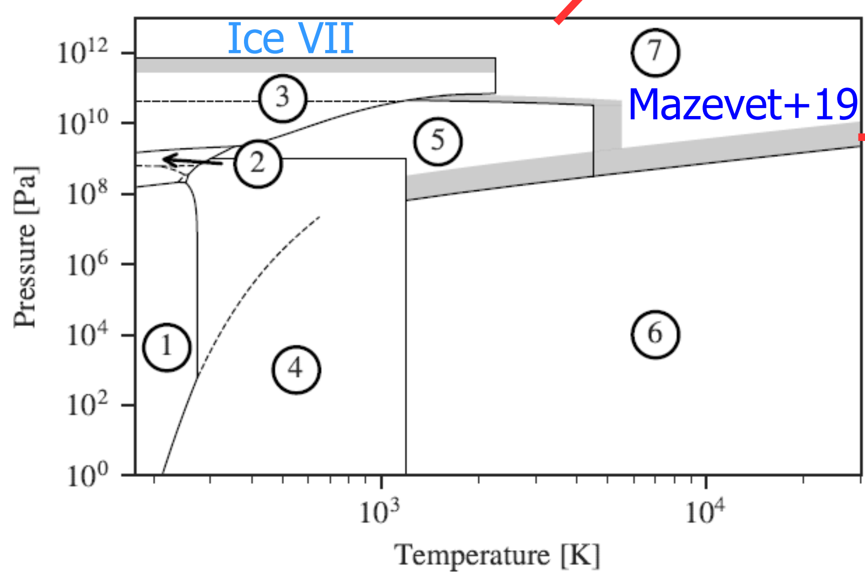
diffusion: **poster by E. Chu**

detection of SI phase: Millot, Coppari+2019, Nature

AQUA water EOS (Haldemann+2020, Bern group)

Fundamental problem
in astrophysical WDM physics:
large-scale water EOS with entropy

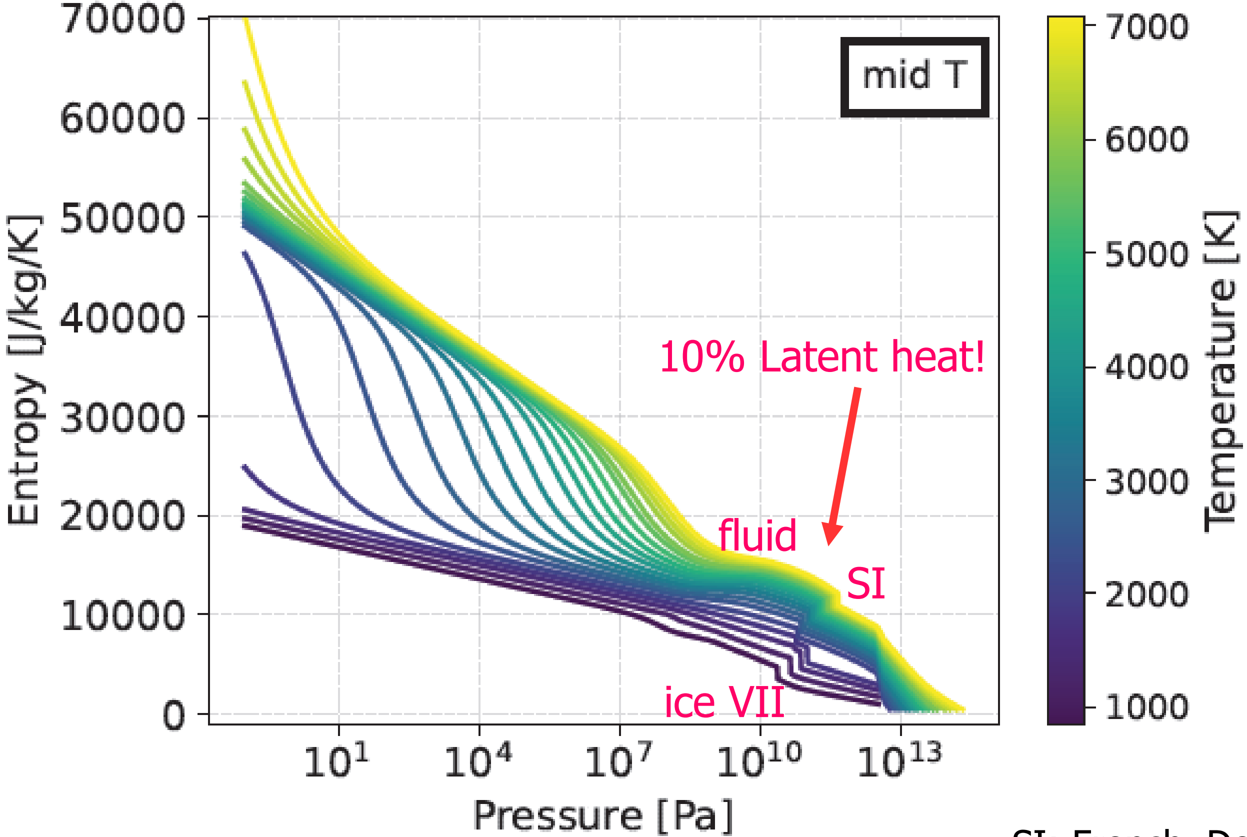




Free energy model to obtain S(T,P) + S_0
S_0 adjusted to Soubiran & Militzer (2015).
However, misprint in F leads to +/- 10%
error in S -> **revised AQUA**

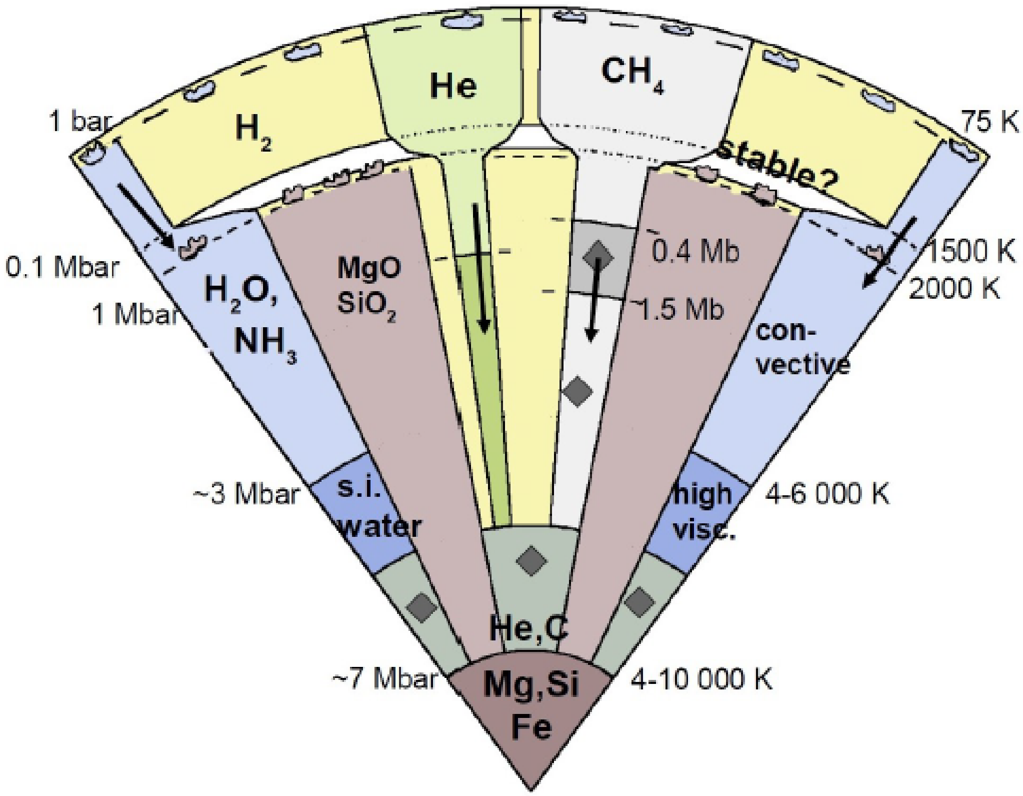
Cano Amoros+ (in prep)

revised entropy of AQUA EOS (Cano Amoros+, DLR group)



SI: French, Desjarlais+2016
ice VII: French & Redmer 2015

more than water: HHe, CNO, MgSiFe, ...

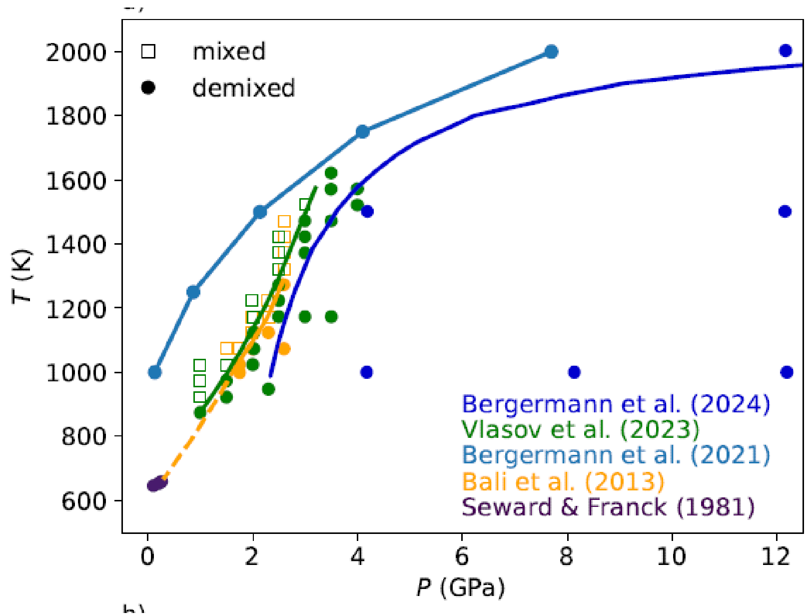


Vorberger, Graziane, Riley et al (2025) arXiv:2505.0249

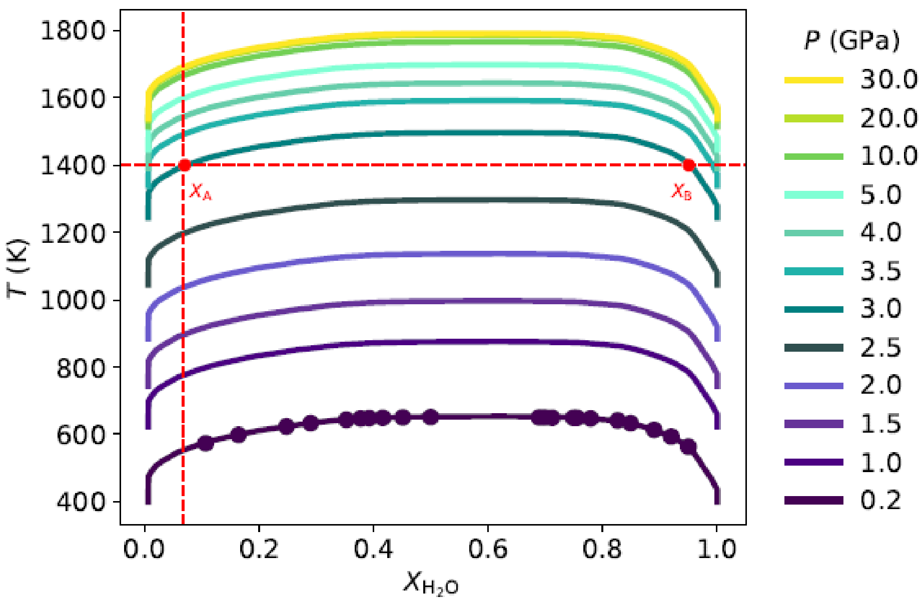
H2/H2O phase diagram

Significant advancement in astrophysical WDM physics:
confirmed experimental data; theory (DFT-MD simulations) and experiments (DAC) agree for 1:1.

demixing temperature for 1:1 concentration



phase diagram with extrapolation

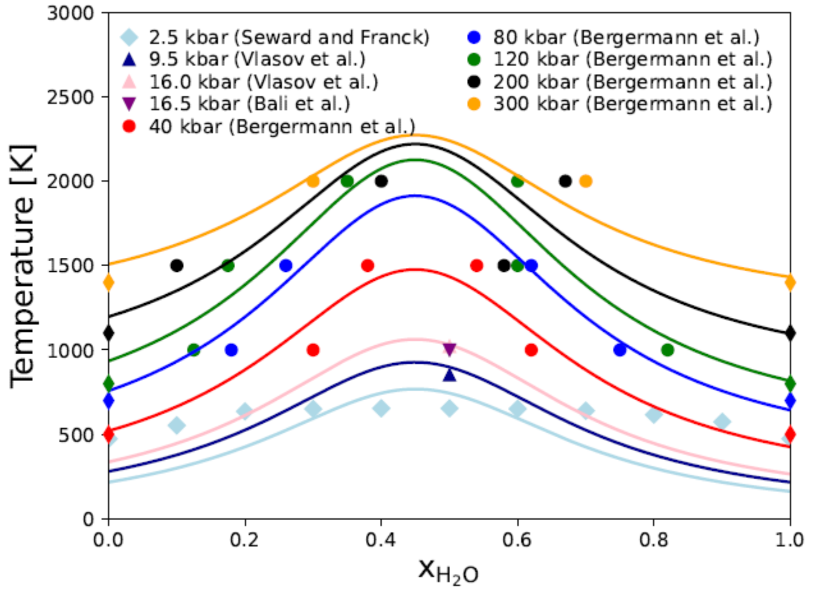


Cano Amoros, Nettelmann, Tosi et al 2024, A&A

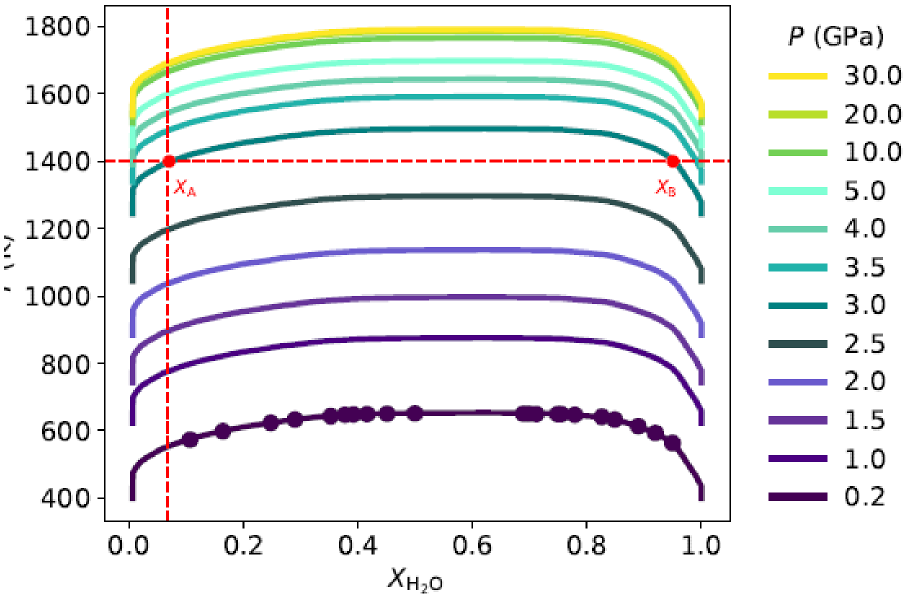
H2/H2O phase diagram

Key task: constrain H2-H2O phase diagram at P>4 GPa experimentally at different concentrations.

...based on DFT-MD simulations



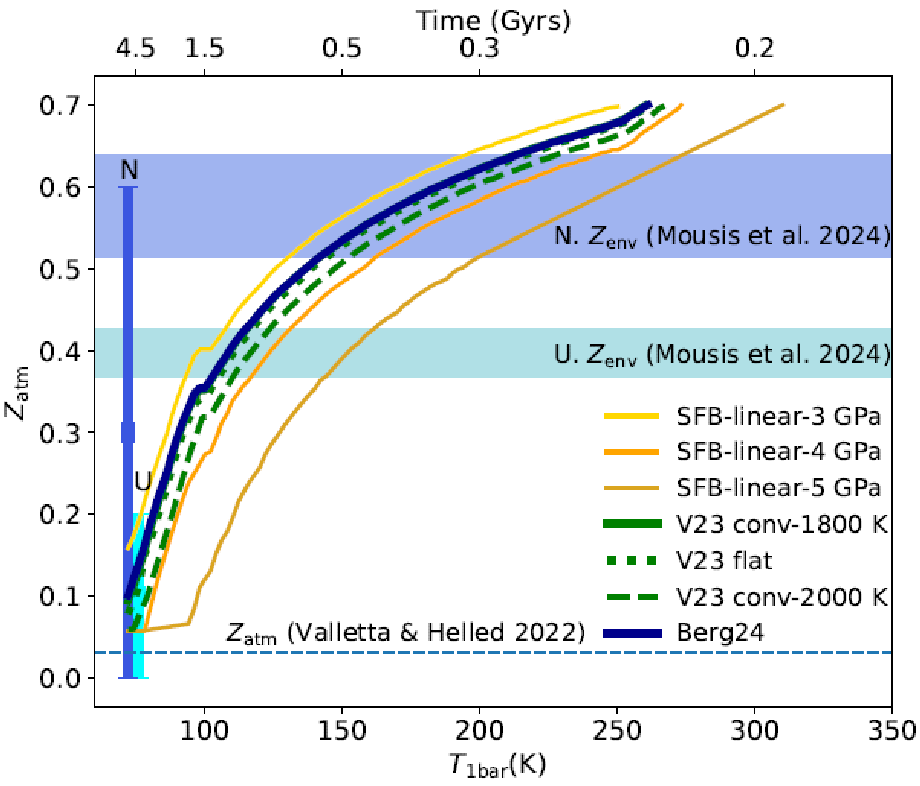
...with extrapolation beyond 0.2 GPa



Howard, Helled, Bergermann, Redmer, arXiv:2507.06288

Application of H2/H2O phase diagram to U&N

Our models predict strong rain-out, resulting in low (<20%) deep atmospheric water abundance Z_{atm}.



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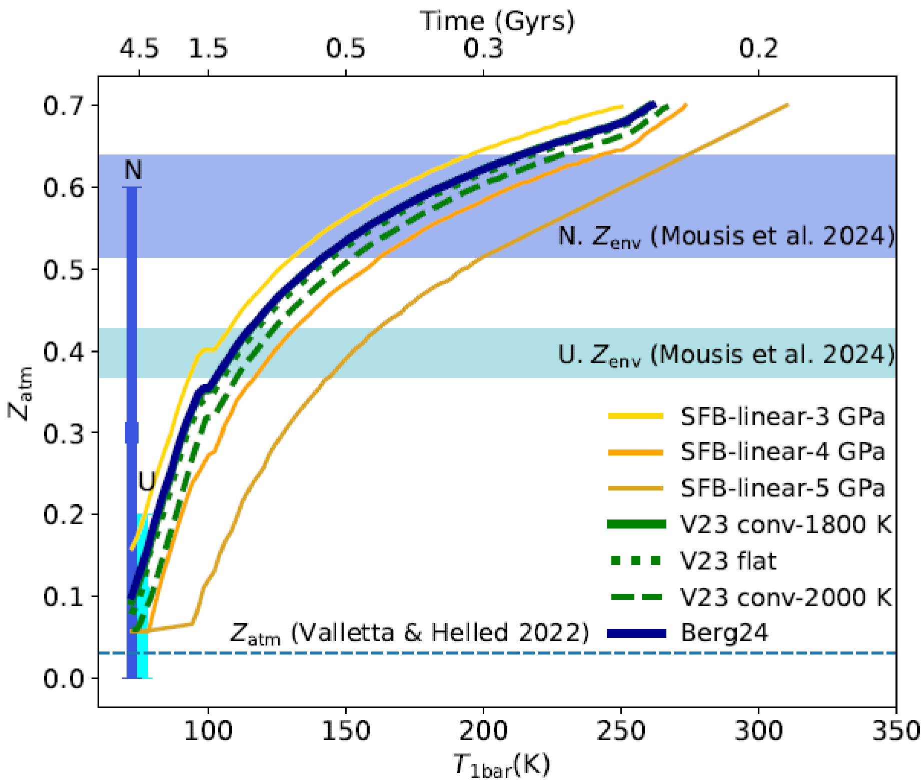
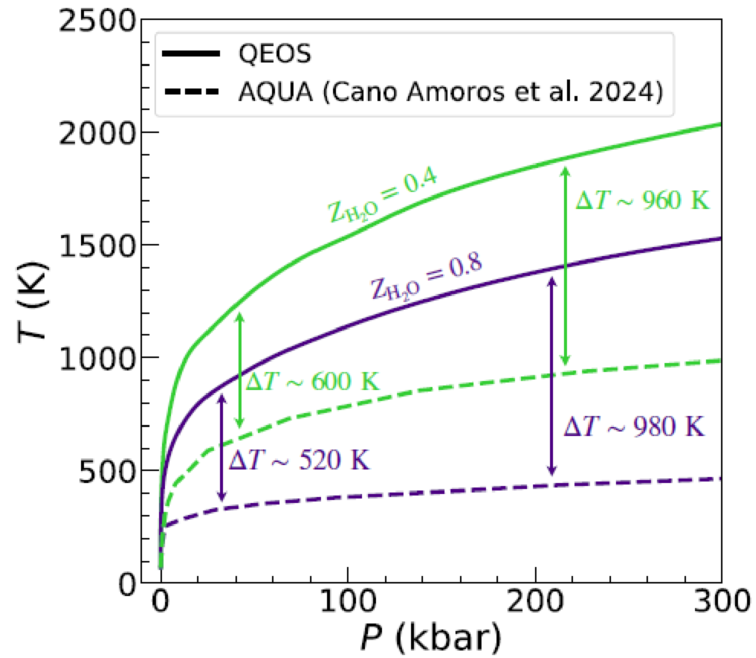


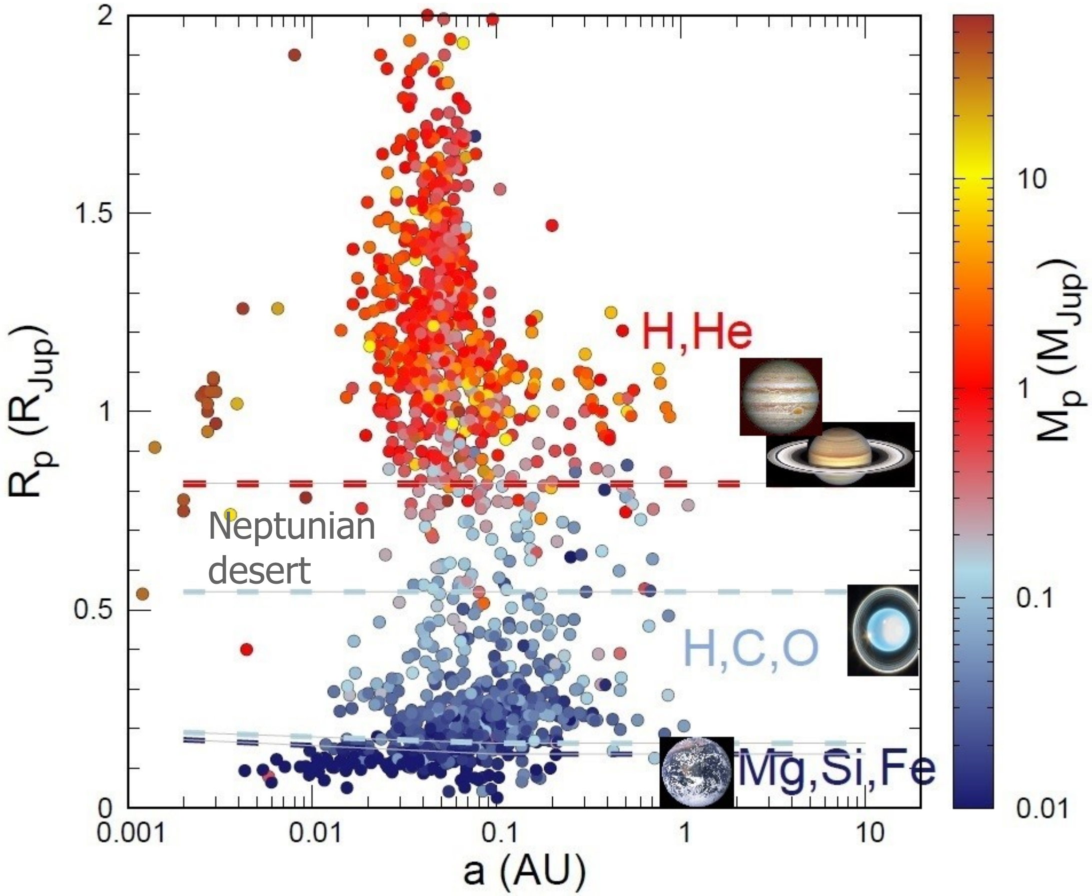
Cano Amoros, Nettelmann, Tosi et al 2024 A&A

The uncertainty in T(P) of 500-1000 K along planetary adiabat matters.
Key task: water EOS with entropy !



Howard, Helled, Bergermann, Redmer, arXiv:2507.06288

exo- and solar system planet diversity



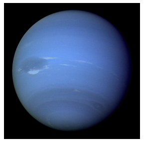
Exoplanets of same Mp, same orbital distance exhibit great diversity in Rp.

Are planets of same Rp-Mp similar ?

Individual: Venus, Earth, Jupiter, Saturn

Current challenge:
Are Uranus and Neptune “Ice Giants“, or are they dissimilar?

Similar or not ?

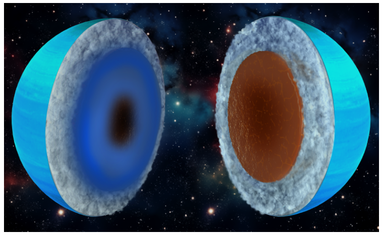


similar

Mass (M_E)	**14.5**	**17.1**	
Radius (**R_E**)	**4.0**	**3.85**	
magnetic field	**non-axial, multipolar, off-centered**		
rotation	**17.25 h**	**16.1 h**	
C / H (x solar)	**80** ± **20**	**80** ± **20**	
T_{1bar} (K)	**76**	**72**	Nettelmann 2025
T_{eff} (K)	**59**	**59**	Scheibe +2021 Stixrude +2021, 2025

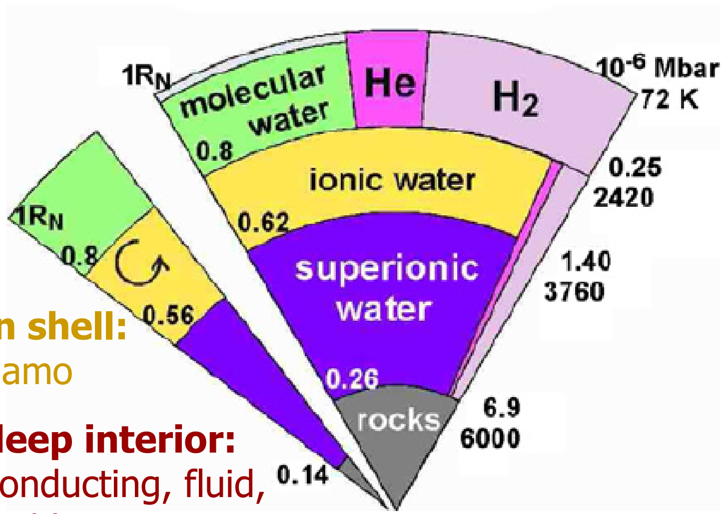
dissimilar

a (AU)	**19.1**	**30**	Nettelmann, Helled +2013
T_{eq} (K)	**59**	**46**	Helled & Fortney 2020
heat flux F ($erg/cm^2/s$)	**0 - 90**	**390 – 480**	
obliquity	**98°**	**28°**	



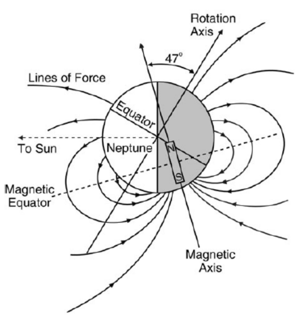
similar: **Ice Giant** magnetic field & HCON mixtures

Deep interior is superionic water. Stable?
(Redmer+2011)



thin shell:
dynamo

deep interior:
conducting, fluid,
stable
(Stanley & Bloxham 2004, 2006)



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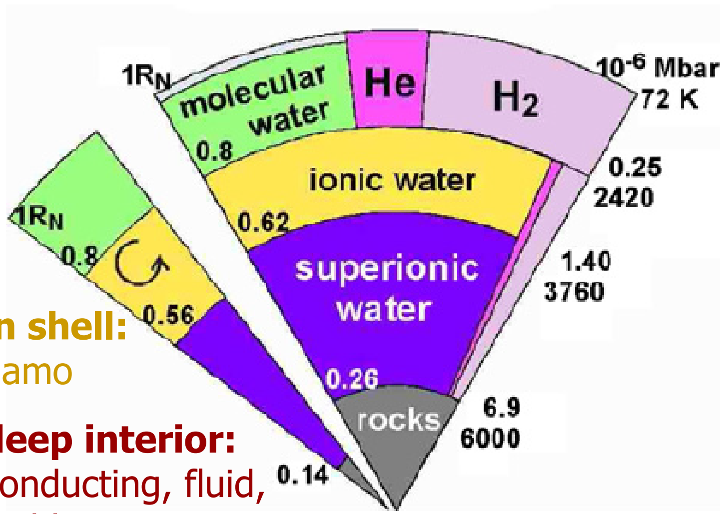

thin shell:
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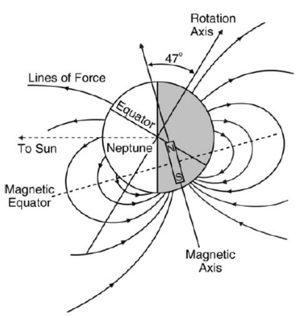
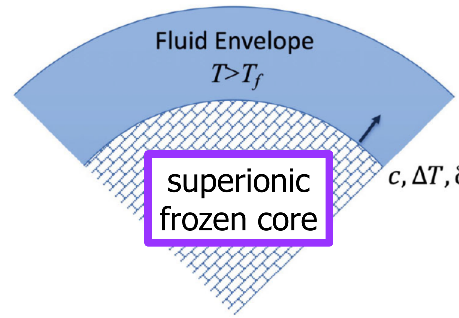
(Stanley & Bloxham 2004, 2006)



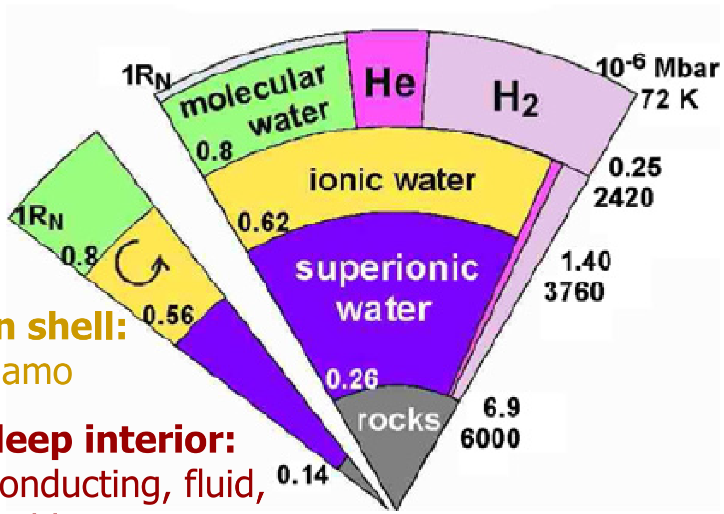
deep layer is SI water; stable, due to high viscosity (Stixrude+2021, PNAS)



deep interior is CNH
(Militzer 2024, PNAS)

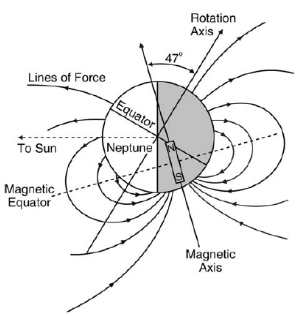
similar: **Ice Giant** magnetic field & HCON mixtures

Deep interior is superionic water. Stable?
(Redmer+2011)

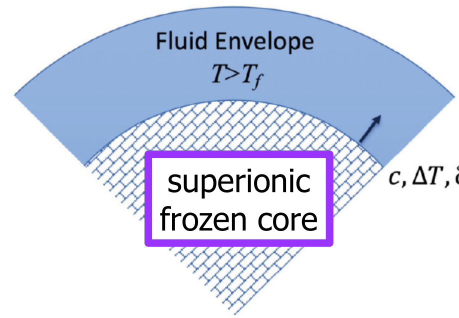


thin shell:
dynamo

deep interior:
conducting, fluid,
stable
(Stanley & Bloxham 2004, 2006)



deep layer is SI water; stable, due to high viscosity (Stixrude+2021, PNAS)

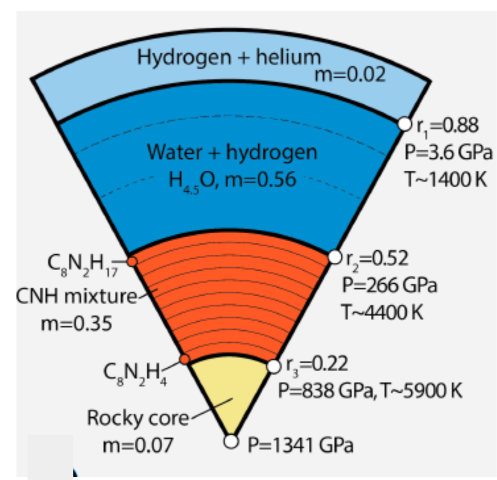


deep interior is CNH
(Militzer 2024, PNAS)

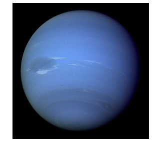
DFT-MD simulations of HCON w 540 atoms

phase separation into H-O and H-C-N fluids

C-C, C-N bonds, C-N-H clusters sink

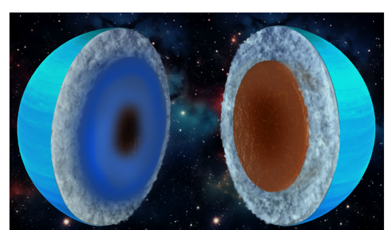


Similar or not ?

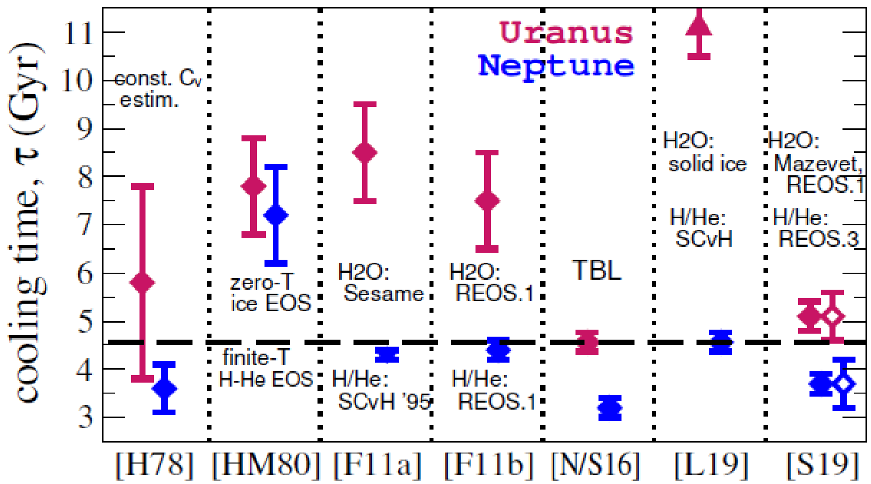


		Uranus	Neptune
similar	**Mass** (M_E)	**14.5**	**17.1**
	Radius (R_E)	**4.0**	**3.85**
	magnetic field	**non-axial, multipolar, off-centered**	
	rotation	**17.25 h**	**16.1 h**
	C / H (x solar)	**90** $\pm$ **10**	**90** $\pm$ **20**
	T_{1bar} (K)	**76**	**72**
	T_{eff} (K)	**59**	**59**
dissimilar	**a** (AU)	**19.1**	**30**
	T_{irr} (K)	**59**	**46**
	heat flux F (erg/cm^2/s)	**0 - 90**	**390 – 480**
	obliquity	**98°**	**28°**

Thermal Evolution



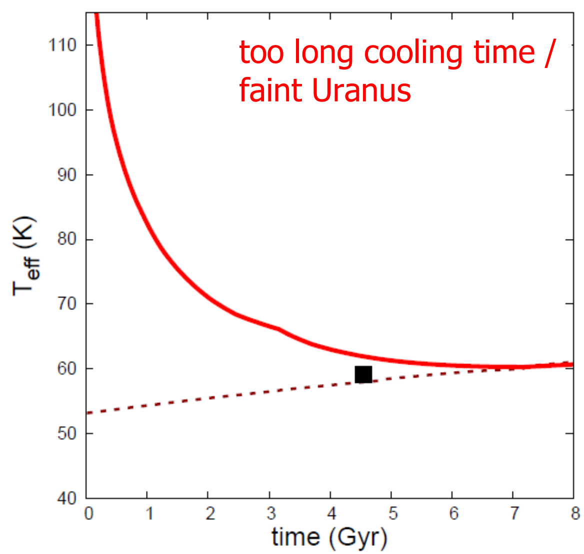
dissimilar: Thermal evolution

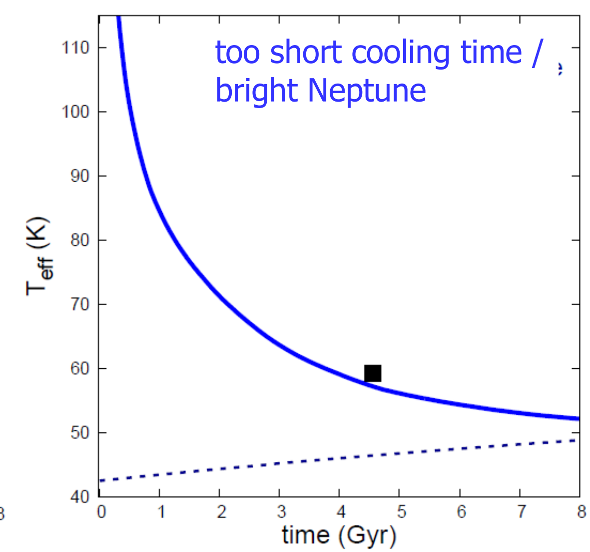


All adiabatic models fail to explain both planets:
Neptune cools quicker than Uranus

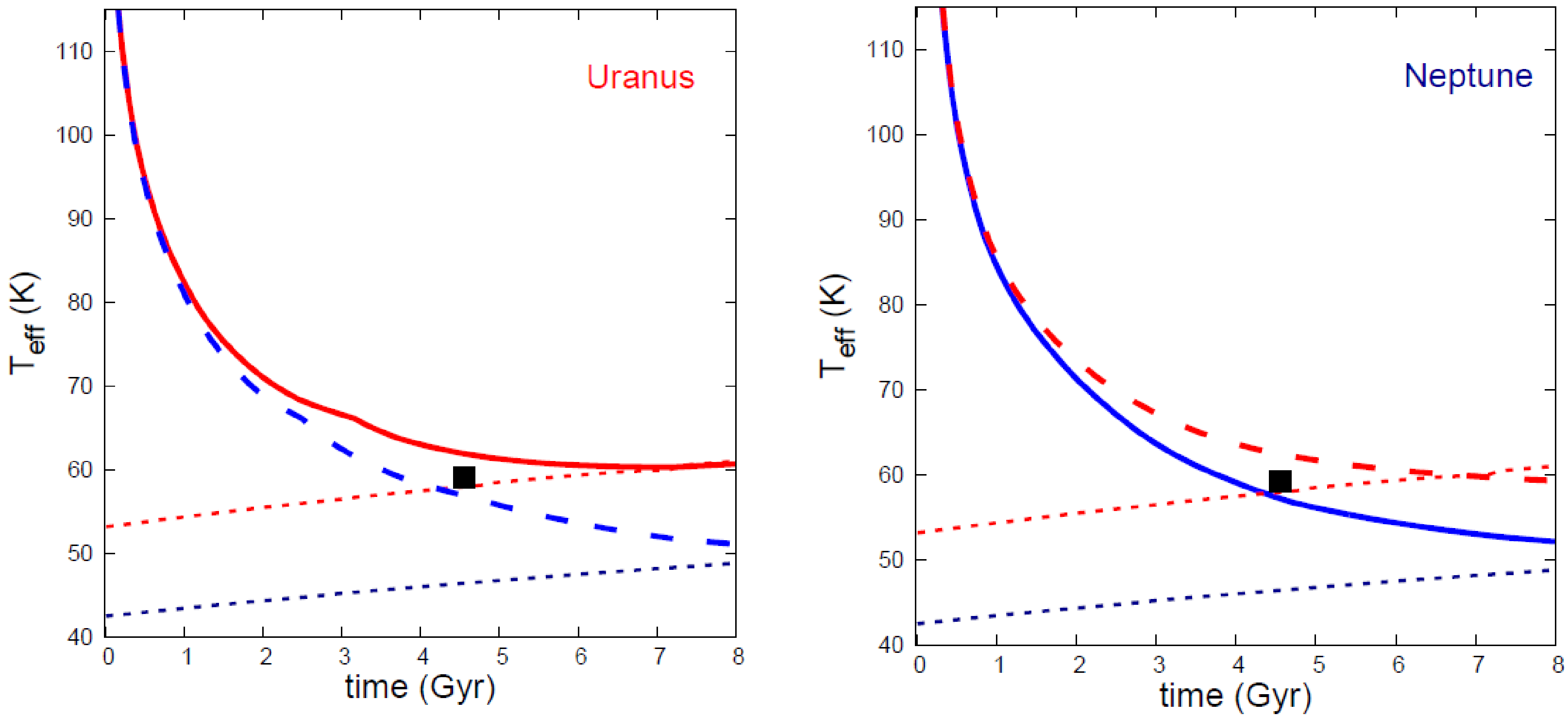
(Helled, Nettelmann, Guillot 2020, SSRv)

Adiabatic models suggest that
Uranus and Neptune are dissimilar.





Thermal evolution on swapped orbits



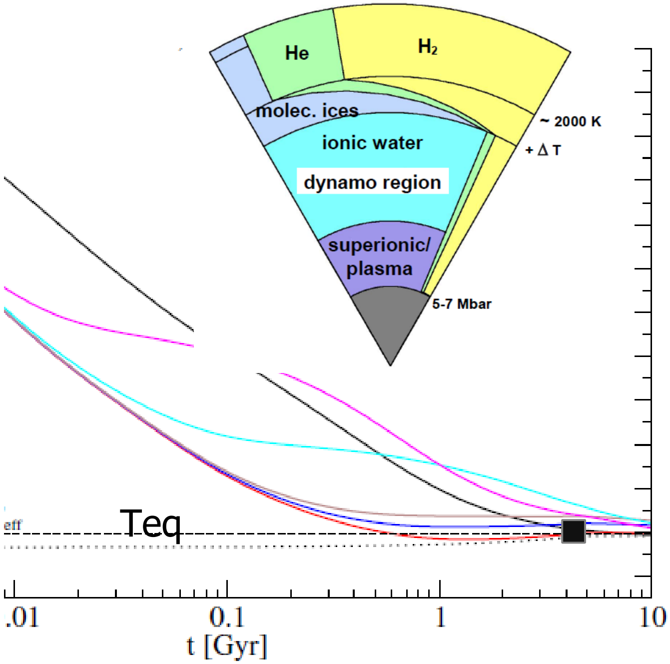
(Nettelmann 2025 in Oxford U Press)

Adiabatic models suggest that Uranus and Neptune are similar.
Adiabatic models suggest that the Ice Giants are not fully adiabatic.

Thermal Boundary Layer (TBL) at ice-poor/ice-rich transition

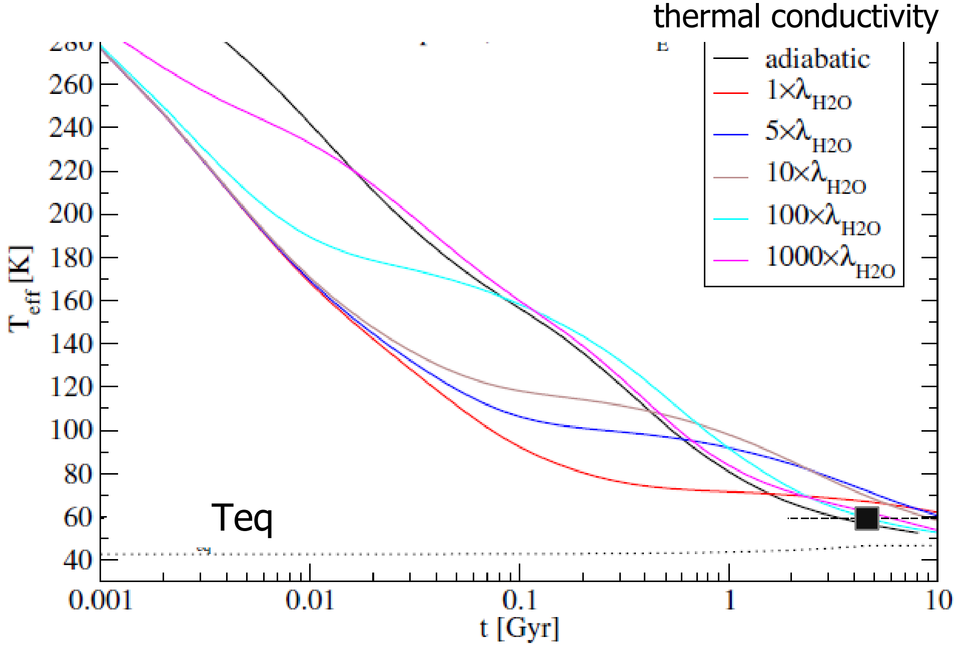
faint Uranus

TBL delays cooling of the deep interior.
Models with equilibrium evolution (Teff ~Teq) yield the observed luminosity.



bright Neptune

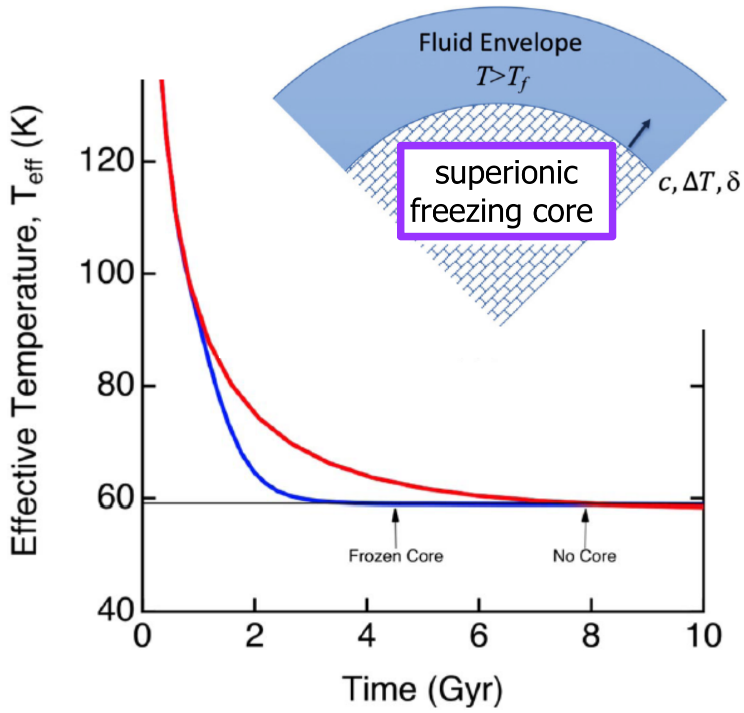
Similar models explain bright Neptune, depending on λ and TBL thickness.



Scheibe, Nettelmann, Redmer 2021, A&A

evolution with freezing SI core (Stixrude, LA group)

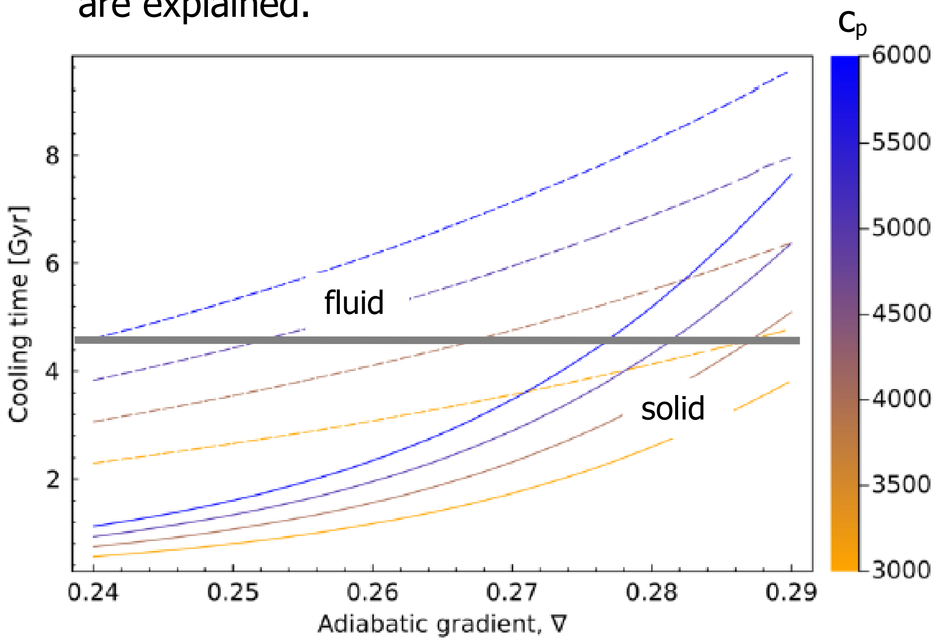
Uranus



Stixrude et al 2021, PSJ

Neptune

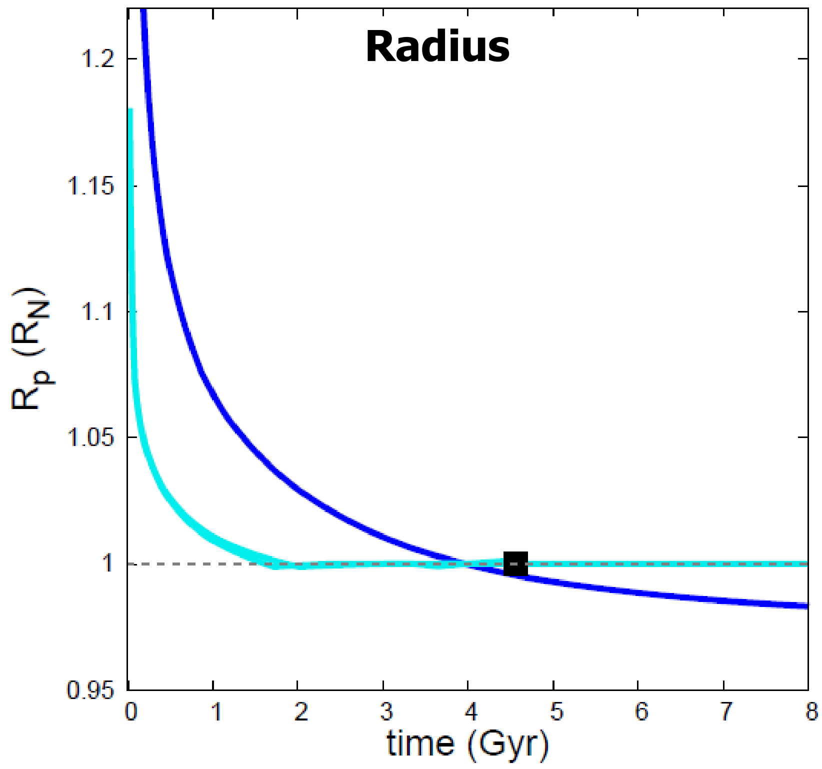
Depending on c_p and grad_ad, both planets are explained.

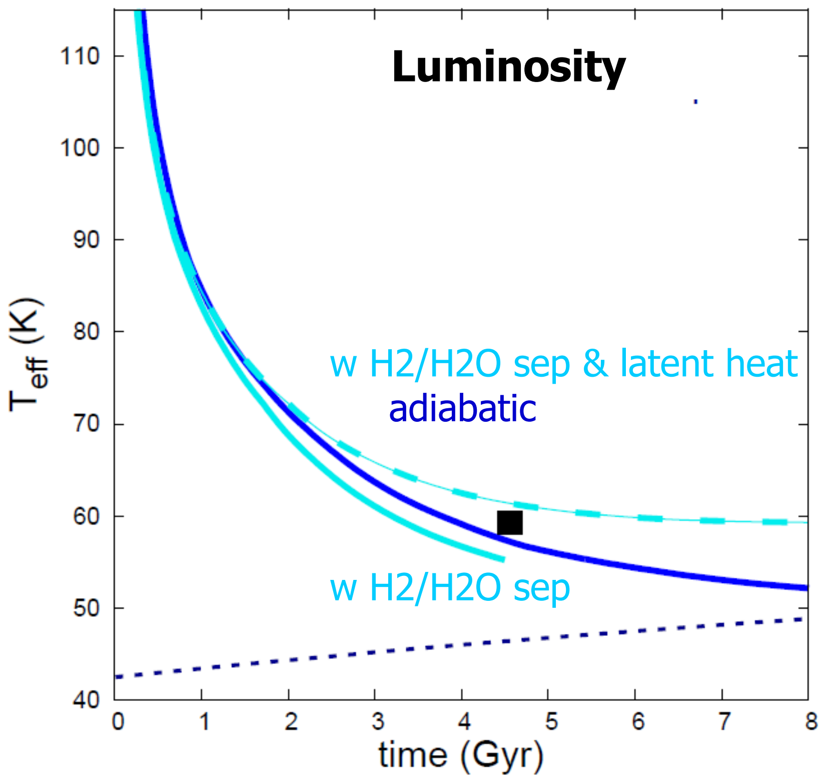


James & Stixrude 2024, SSRv

Neptune evolution with H2/H2O phase separation

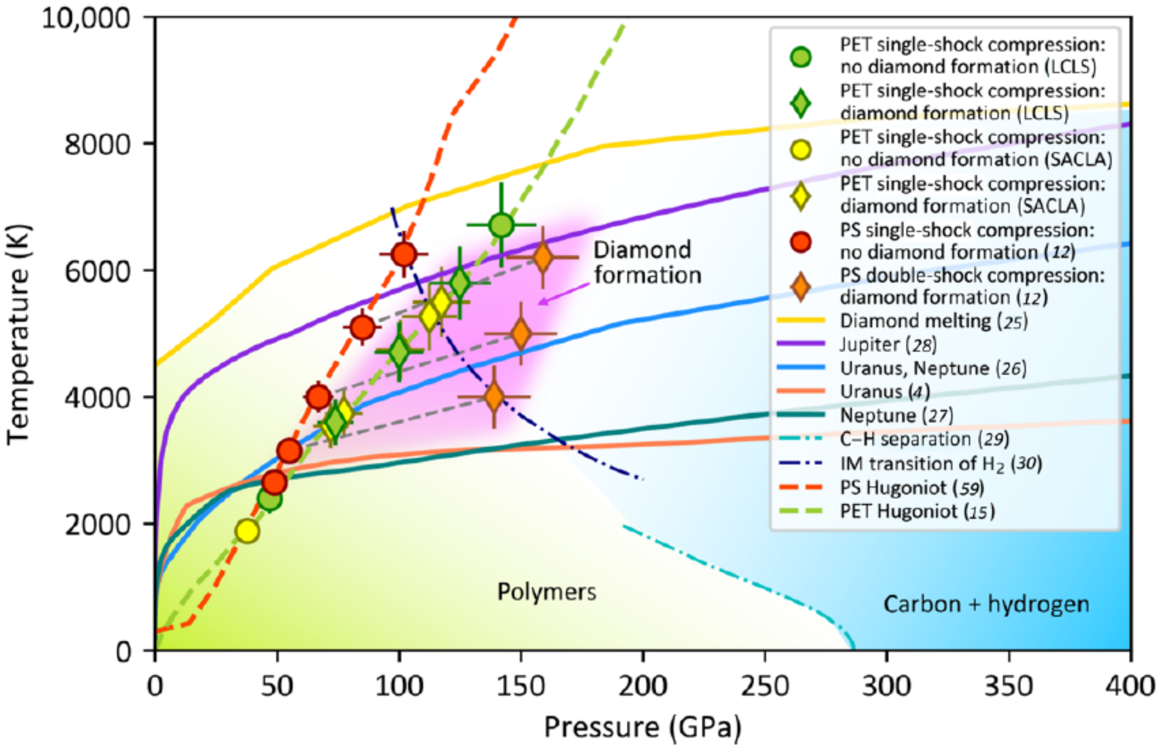
The combined effect of H2/H2O phase separation and latent heat from SI core freezing could explain Neptune's luminosity.





Cano Amoros, Nettelmann, Tosi (in prep)

Key achievement: Diamond under Ice Giant conditions



He, Rödel, Lütgert +2022, Sci Adv.

nano-diamonds are detected

-in various experimental set-ups:
laser-shock, double-laser shocks, DACs.

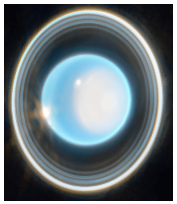
-using different sample materials:
C
C-H (eg PS)
C-H-O (PET, sugar wax, PLA, CA)
(talk by P. May)

O facilitates C-H phase separation

MD-results controversial:
yes: He+2022, Chang+2023,
no: Militzer 2024

diamond rain !?

Summary



H-O experiments & theory: uncertainties in the water EOS (**entropy!**) and phase diagram limit our understanding of the **Ice Giants**.

The **faintness of Uranus** can be explained if it harbors a **TBL,** or **H2/H2O phase separation**, and evolves in equilibrium with the strong solar irradiation.

The **brightness of Neptune** indicates a **heat source:** latent heat from superionic **core freezing, diamond rain**, or C-N polymers sinking.

Caution: it is not certain if SI water exists in Uranus and Neptune.

Experimental verification with **different set-ups i**s important for constraining the **EOS and miscibility gap in H-He-systems**

Jupiter & Saturn harbor **non-adiabatic, stable regions.**

Caution: there is still no consistent, widely-accepted model of Jupiter or Saturn.

Appendix