Giant planets:

far out, close-in, and deep inside

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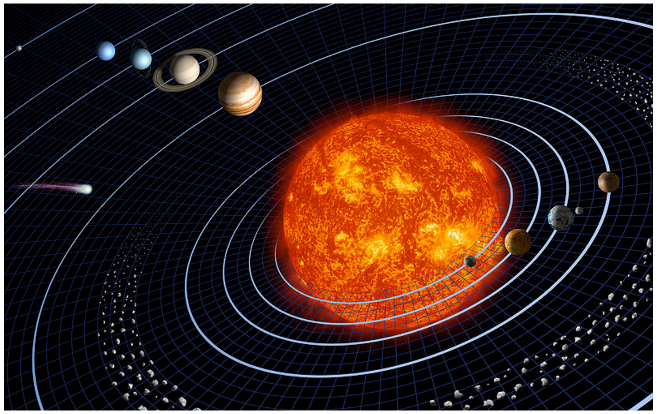


Outline

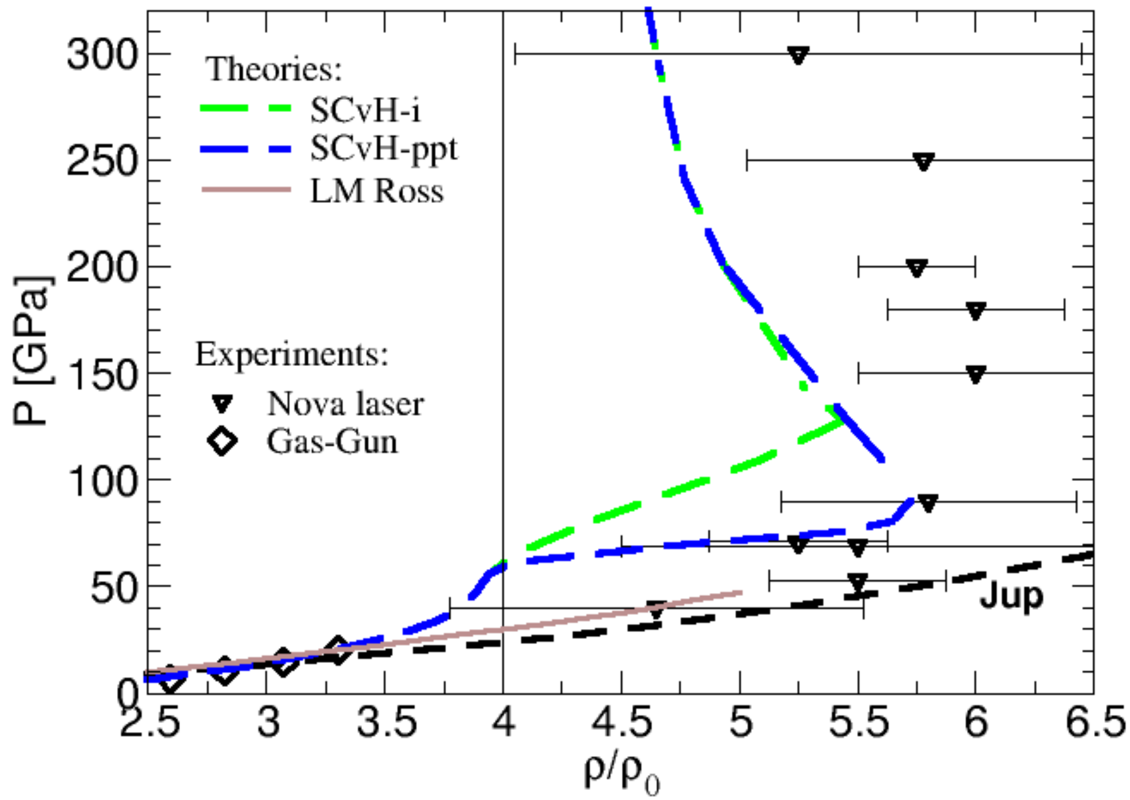
- H-EOS and Jupiter in 1995-‘99
- H-EOS and Jupiter in 2008-‘09
- H-EOS and Jupiter in 2010-‘11

  ⟶ primary objectives for CY11, CY12
- H/He demixing and Saturn
- ices in Uranus & Neptune
- ice in close-in big planets?

  ⟶ future project objectives for CY12+

H EOS in 1995-'99

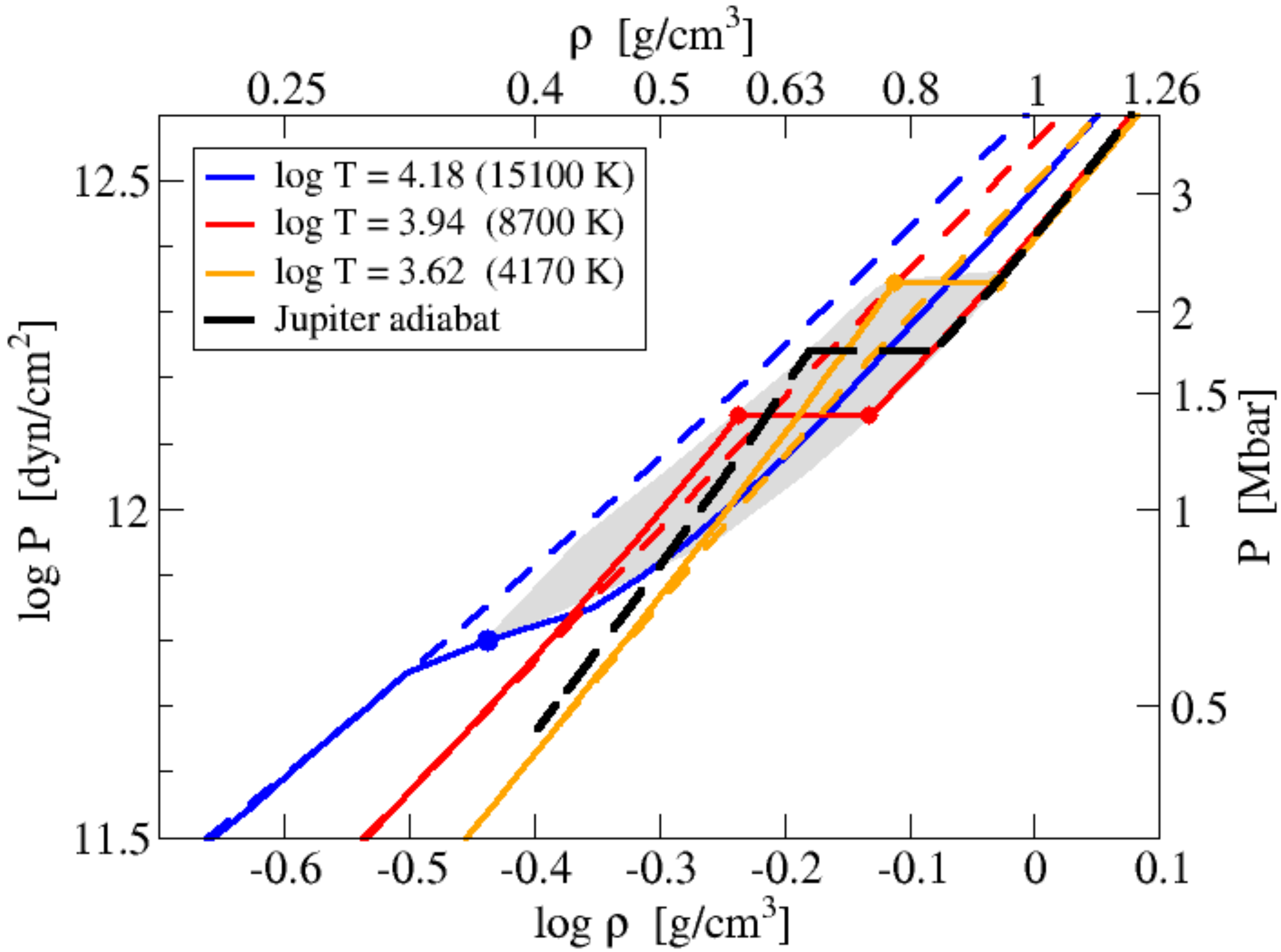
Experimental and theoretical principal Hugoniots predict a high maximum compressibility ~ 5.5.



- Nova Laser (LLNL): Collins et al. 1998, Ph. Pl.
- Gas-Gun (LLNL): Holmes et al. 1995, PRB
- SCvH EOS: Saumon et al. 1995, ApJ
- LM Ross: Ross 1998, PRB

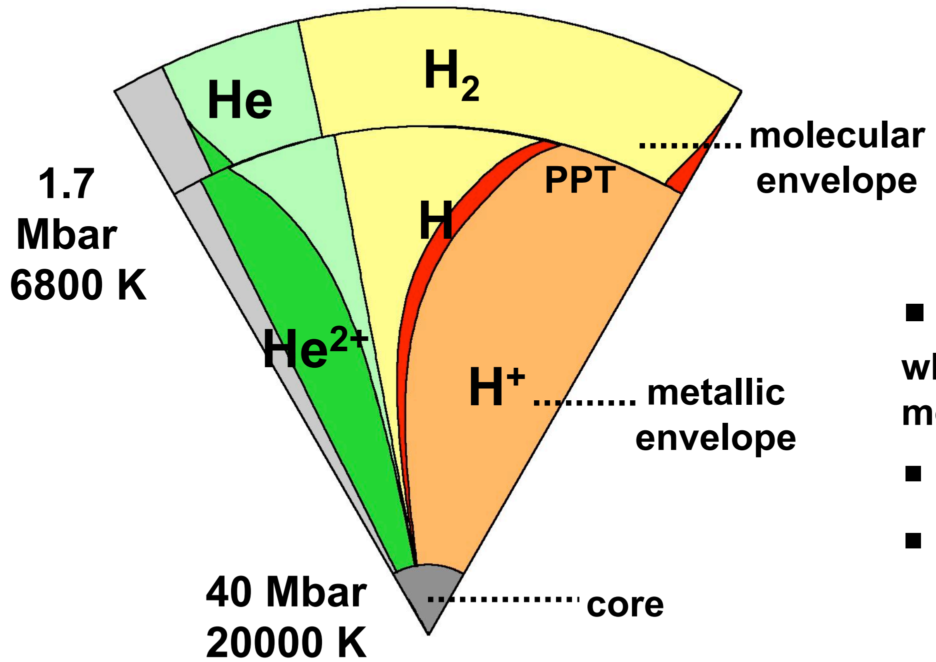
H EOS in 1995: SCvH-ppt/-i

The SCvH-ppt EOS predicts a PPT in Jupiter at 1.7 Mbar and 6800 K.



Jupiter in 1995-'99

Jupiter according to SCvH-ppt EOS



- layer boundary where metallization begins (1.7 Mbar)
- core mass 5-10 M_E
- SCvH-i: core mass 0-5 M_E

Models:

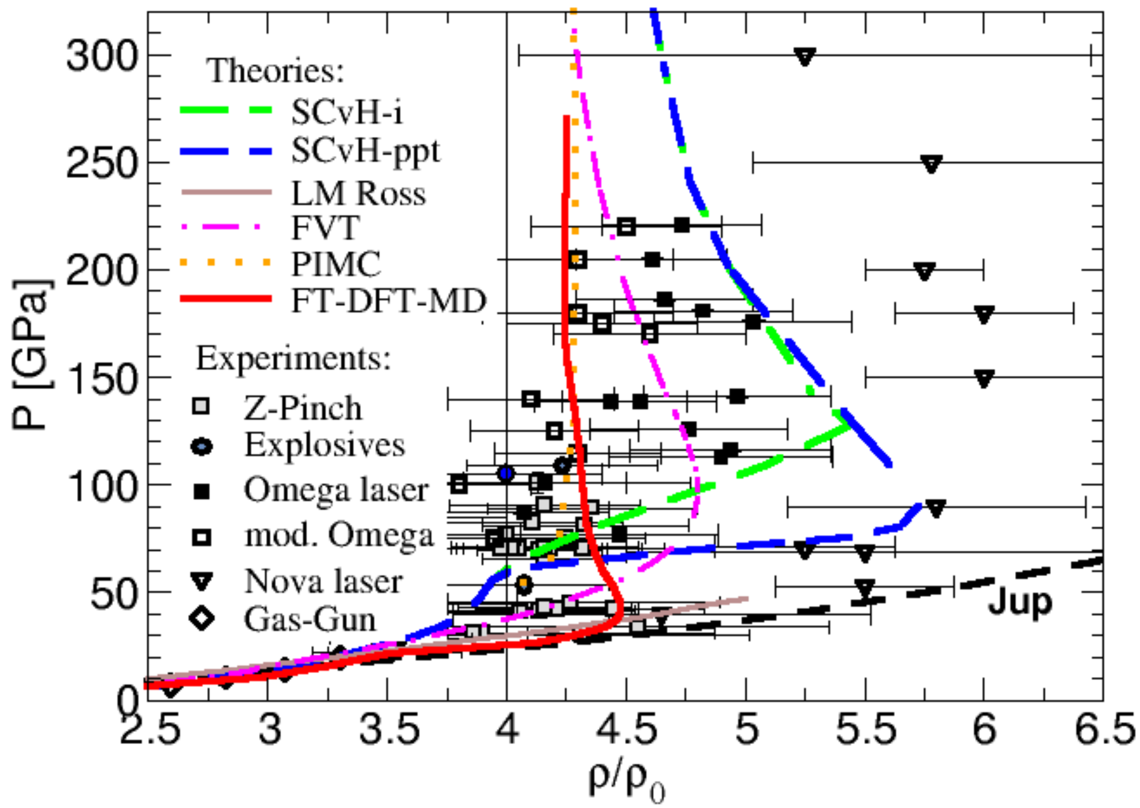
- Guillot (1999a,b), Science, P&SS
- Guillot et al. (1994a,b) Icarus
- Chabrier et al. (1992), ApJ
- Nettelmann et al. (2008), ApJ

EOS:

- Saumon, Chabrier et al. (1992, 1995), ApJ

H EOS in 2009

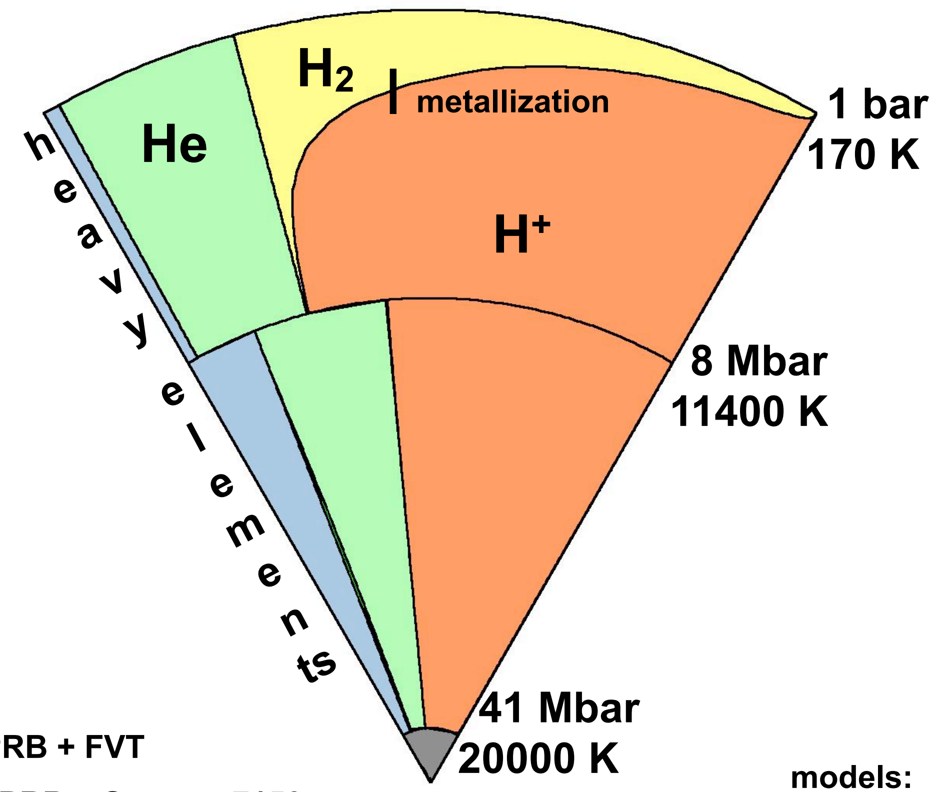
The overall shape of the Z-pinch data and the modified Omega laser data is best reproduced by FT-DFT-MD simulation data.



- **Z-machine (SNL): Knudson et al. 2004, PRB**
- **Omega laser (Rochester): Hicks et al. 2009, PRB.**
- **modified Omega data: Knudson & Desjarlais 2009, PRL**
- **FVT: Juranek & Redmer 2000, JCP**
- **PIMC: Militzer & Ceperley 2000, PRL**
- **FT-DFT-MD: Holst et al. 2008, PRB**

Jupiter according to LM-REOS-2008

- layer boundary
  free parameter
- continuous metallization
- $Z_1 << Z_2$



EOS:

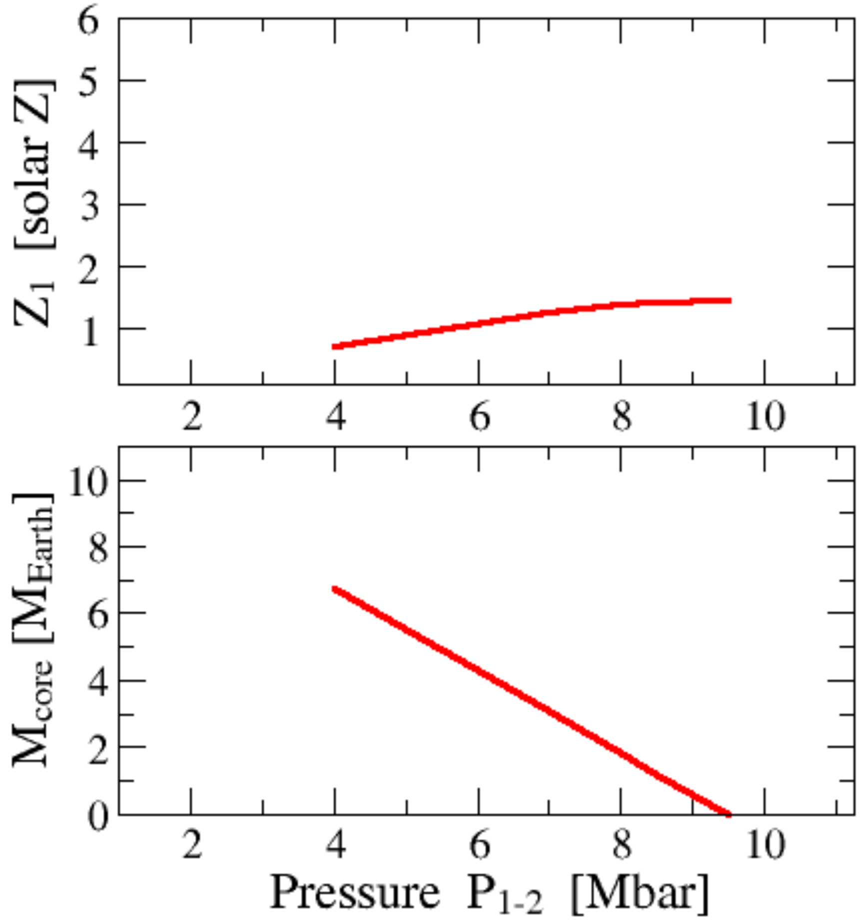
- Holst et al. 2008, PRB + FVT
- French et al 2009, PRB + Sesame 7150
- Kietzmann et al. 2007, PRL + Sesame 5761
- Nettelmann et al. 2008, ApJ

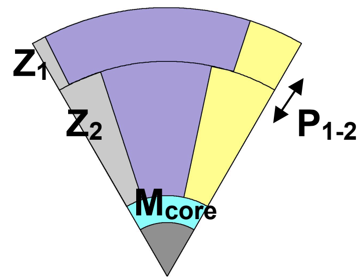
models:

- Nettelmann et al. 2008, ApJ
- Fortney & Nettelmann 2009, SSR

Jupiter in 2008- ’09 (H-REOS-2008)

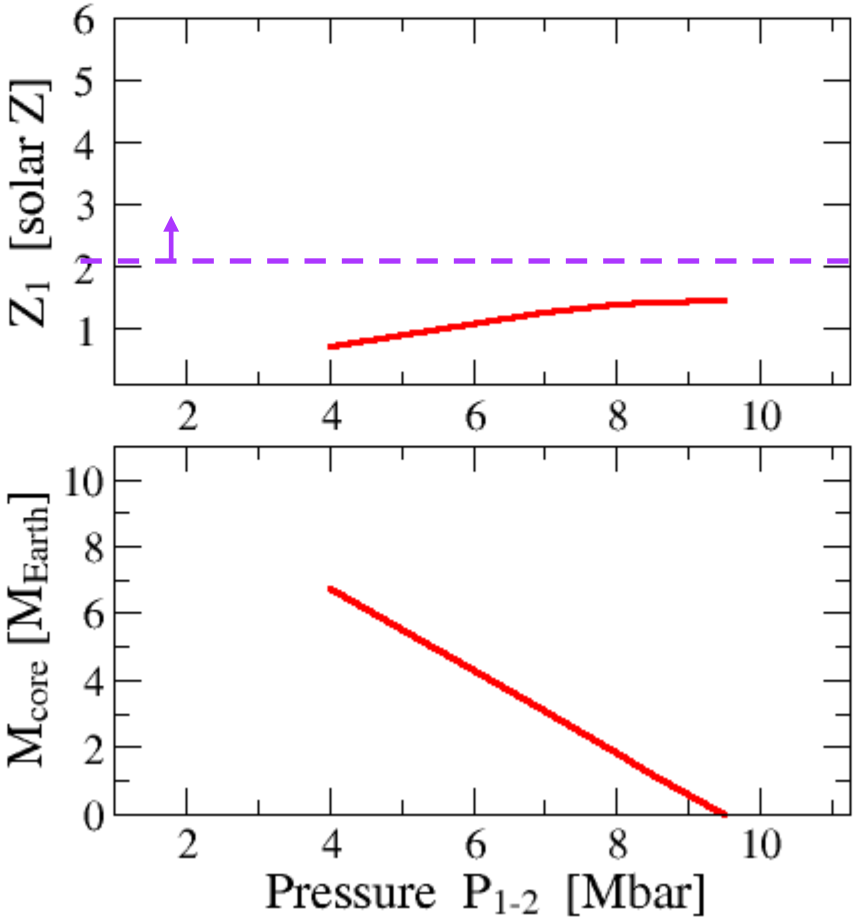
zero-mass core implies maximum envelope metallicity



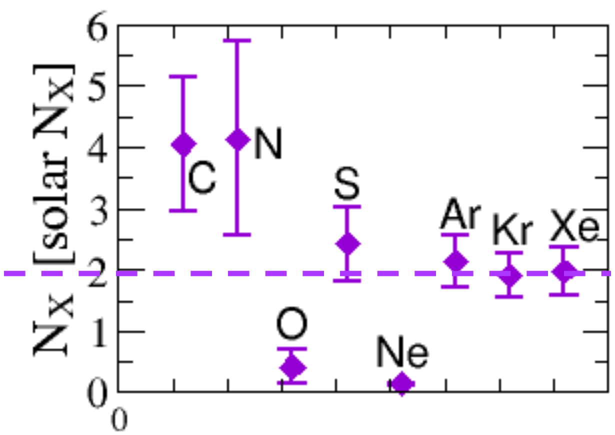


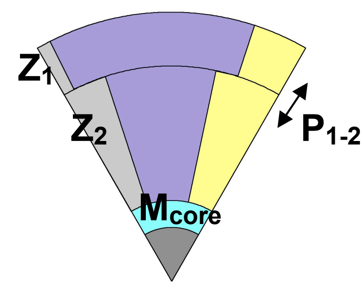
Jupiter in 2008- ’09 (H-REOS-2008)

the maximum envelope metallicity lies below the observational limit



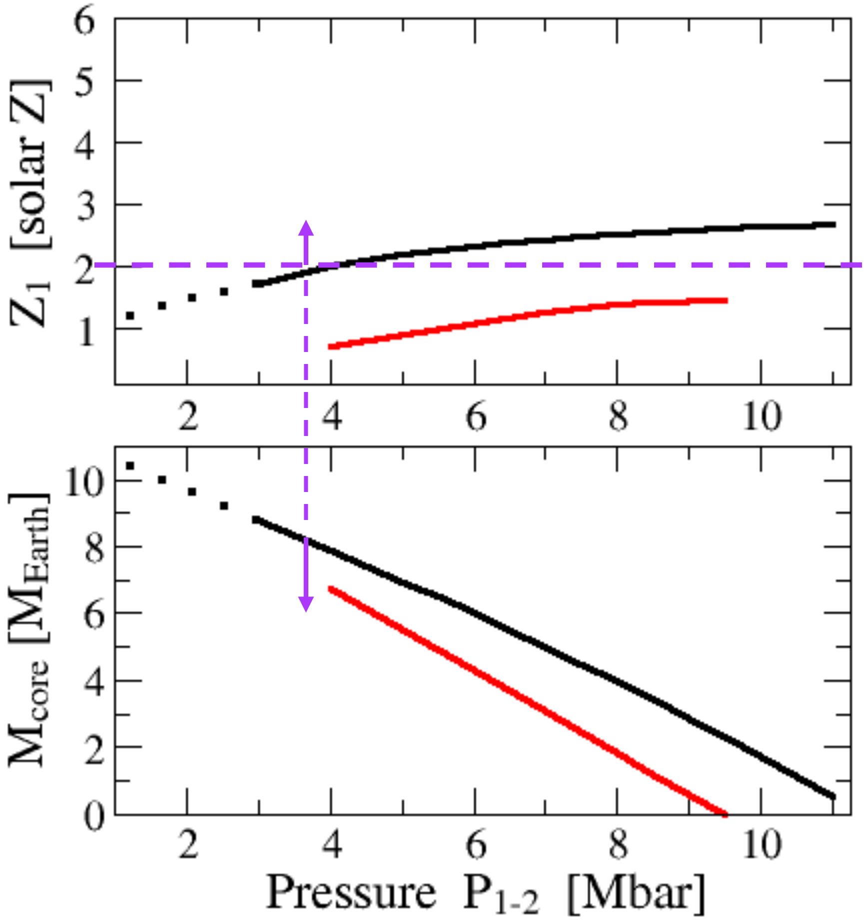
Galileo entry probe data



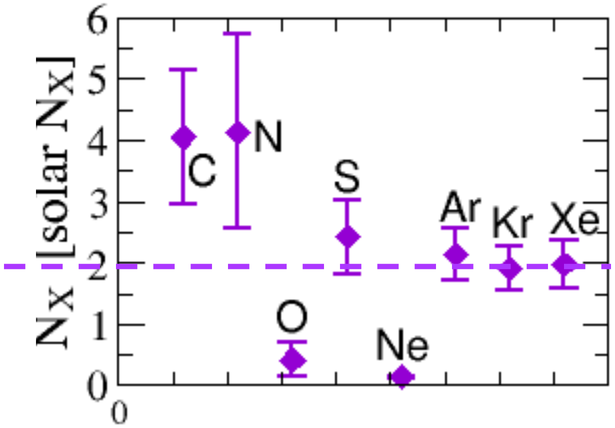


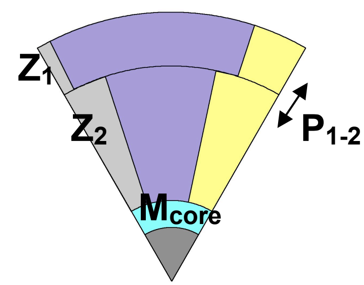
Jupiter in 2010- ’11 (H-REOS-2010)

the minimum metallicity implies a maximum core mass



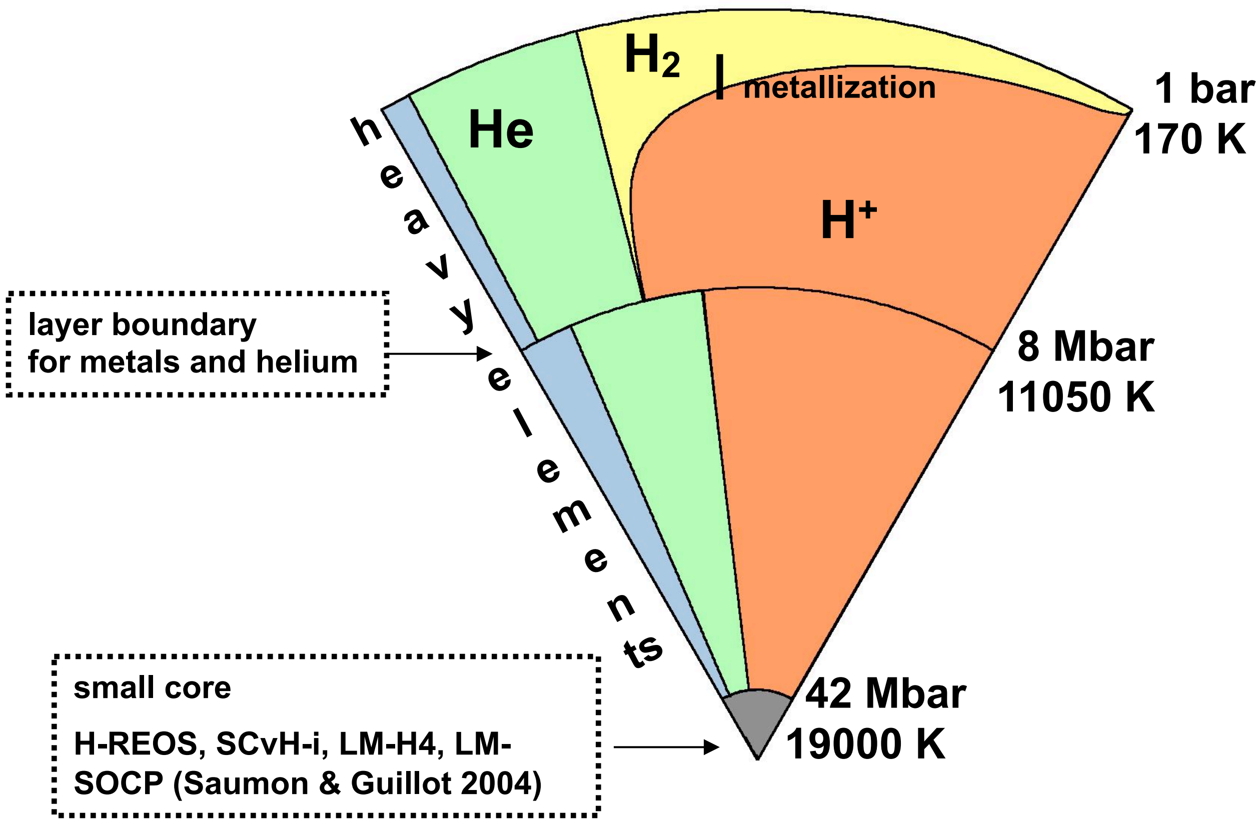
Galileo entry probe data





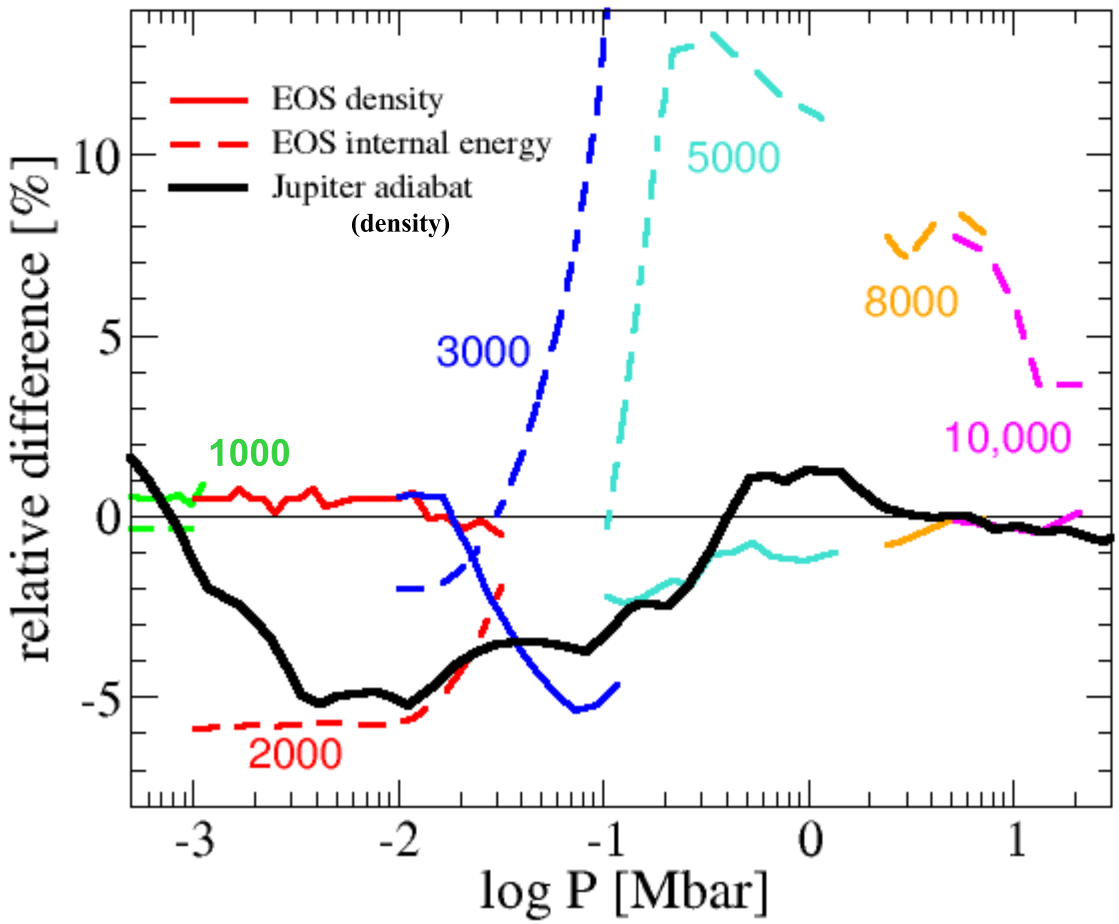
Jupiter in 2010-'11

Jupiter according to LM-REOS-2010



understanding the relation between H EOS and Jupiter adiabat... (wip)

The differences between H-REOS-2010 and H-REOS-2008 in ρ(p,T) and u(T,P) seem equally important for the Jupiter adiabat.

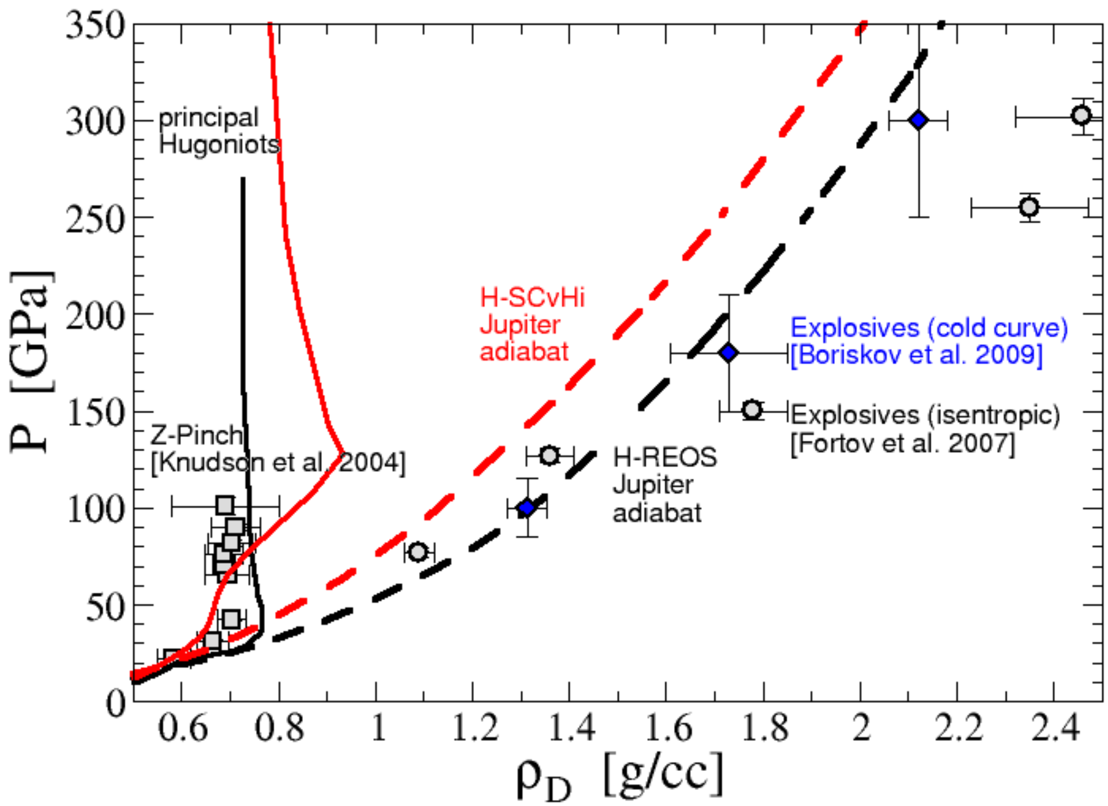


simulations with N particles per box:

H-REOS 2008: N=64

H-REOS 2010: N=512

experimental data for H

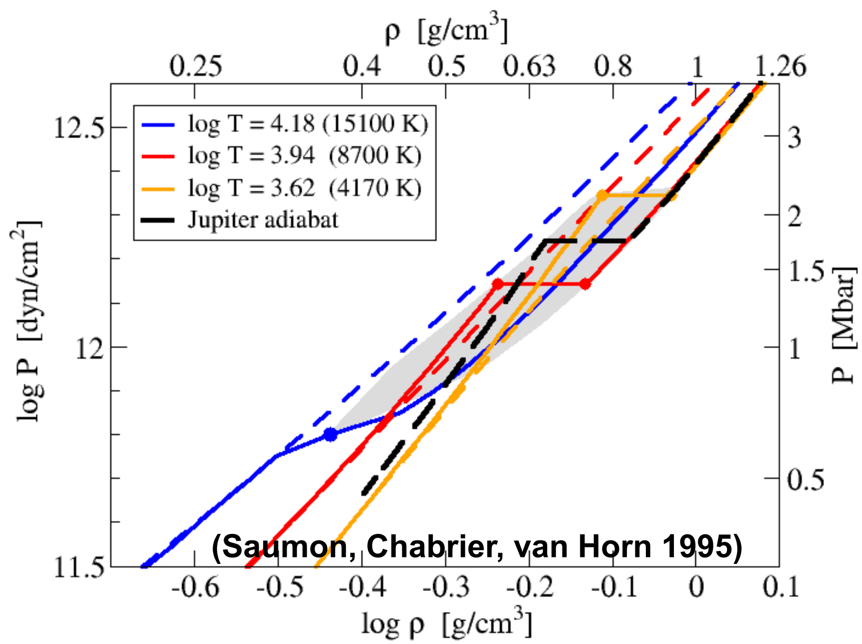


Proposal 01/2011, primary objective:

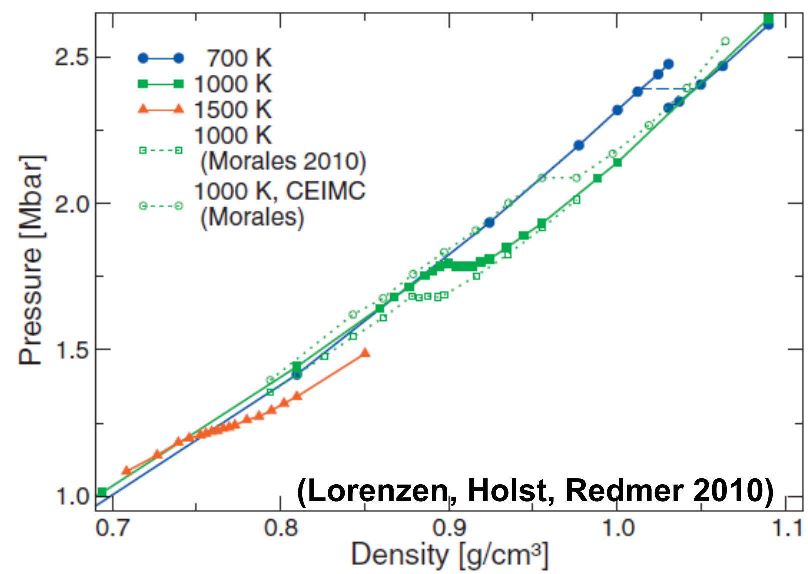
Measure the H EOS at ~1 Mbar and ~5000 K (~0.55 g/cc) to high accuracy.

ab initio H EOS 2010

SCvH-ppt:
1^{st} order phase transition
with T_{crit}=15000 K



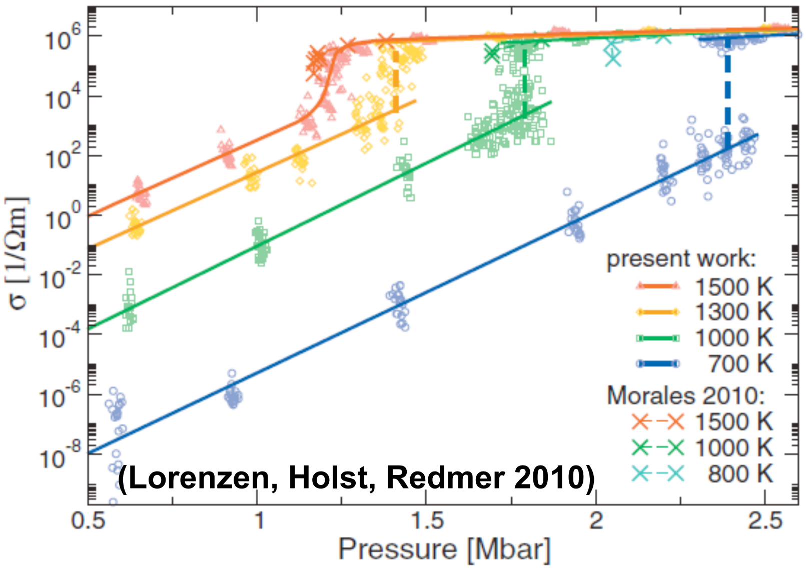
H-REOS 2010:
1^{st} order phase transition
with T_{crit}=1500 K



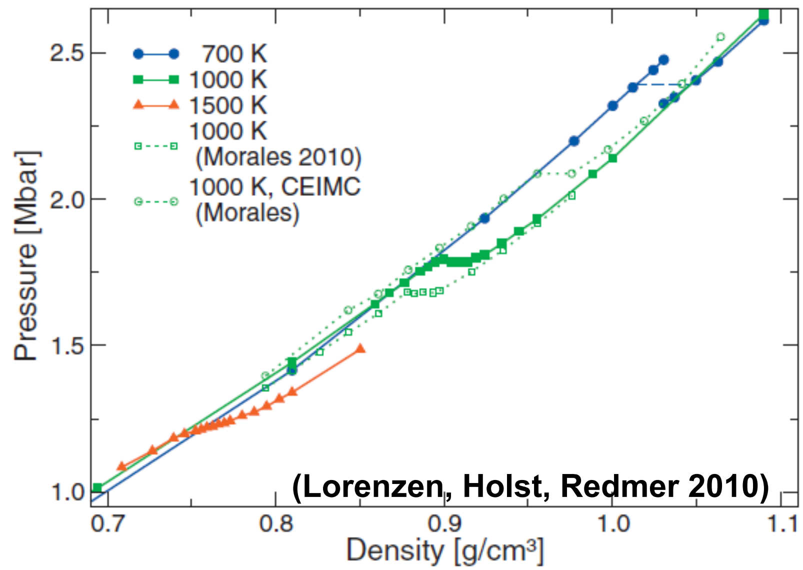
- **both EOS: plasma phase transition at P=1 - 3 Mbar, ρ=0.5 - 1 g/cm³**
- **H-REOS: PPT at T < T_{crit} = 1500 K cannot be a reason for the layer boundary**

ab initio H EOS 2010

The steep rise in electric conductivity indicates a non-metal-to-metal transition



H-REOS 2010:
1st order phase transition
with T_{crit}=1500 K



Proposal 01/2011, primary objective:

Test the prediction of a first order liquid-liquid phase transition.

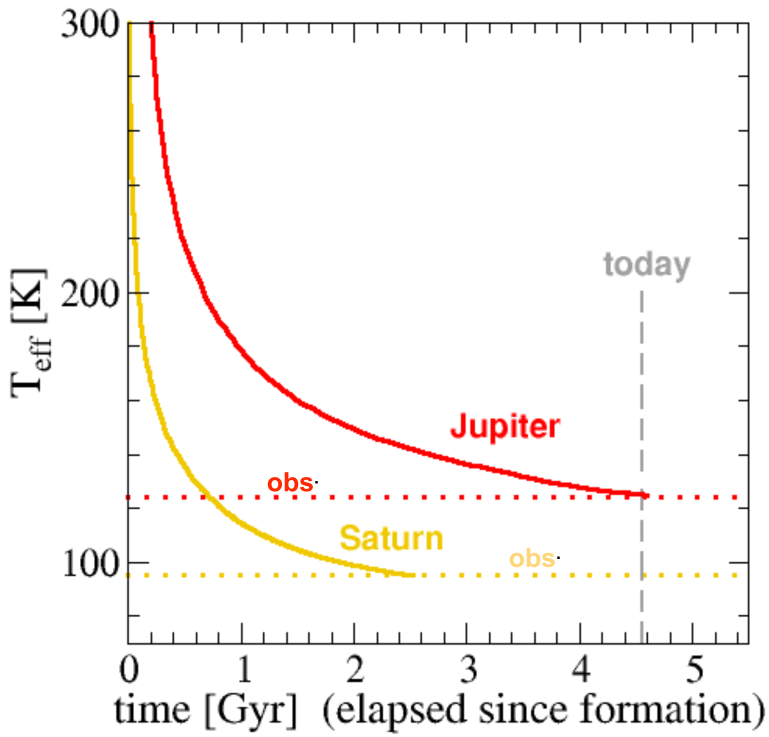
Saturn

- mass: 95 M_{Earth} , radius: 9 R_{Earth}
- orbital distance : 9.5 AU

Saturn, cooling curve

Energy balance: $$L - L_{\odot} = \frac{dE_{int}}{dt}$$ **with** $$L = 4\pi R_p^2 \sigma T_{eff}^4$$

Saturn is unusually luminous.



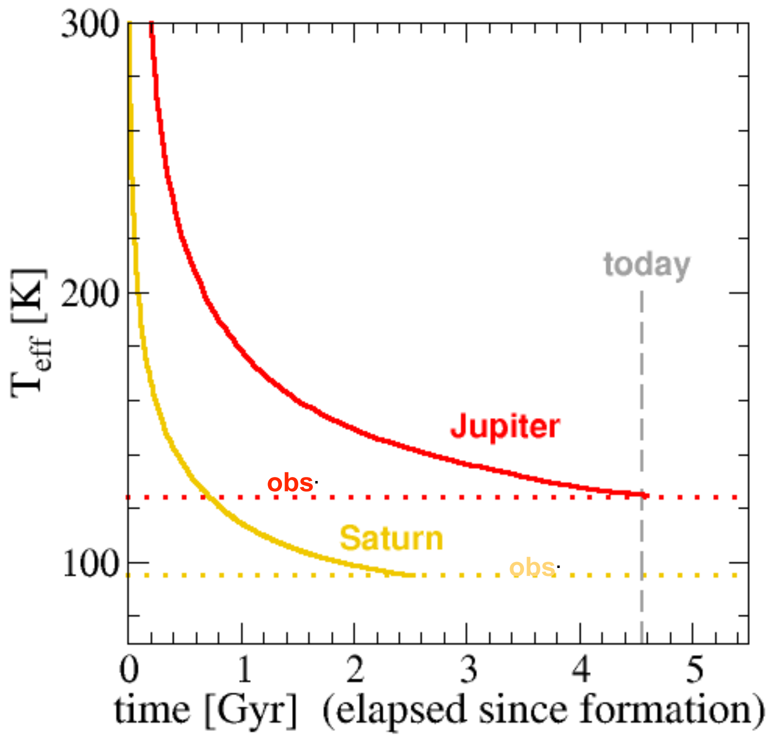
- **Stevenson & Salpeter (1977), ApJ**
- **Saumon et al. (1992), ApJ**
- **Fortney & Hubbard (2003), Icarus**
- **Fortney et al. (2011), ApJ**

Saturn, cooling curve

Energy balance:

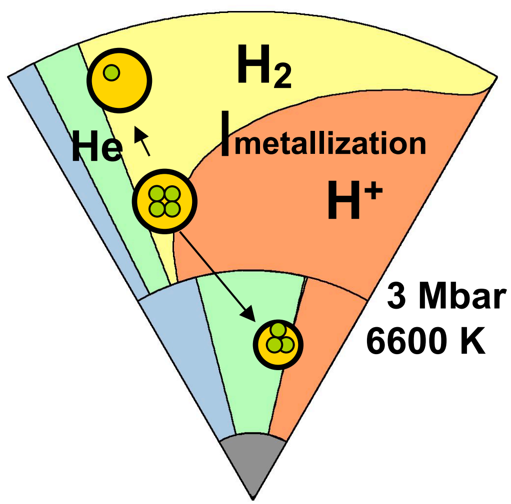
$$4\pi R_p^2 \, \sigma \, (T_{eff}^4 - T_{eq}^4) = \frac{dE_{int}}{dt}$$

Saturn is unusually luminous.



Solution:

Helium sedimentation leads to additional energy release

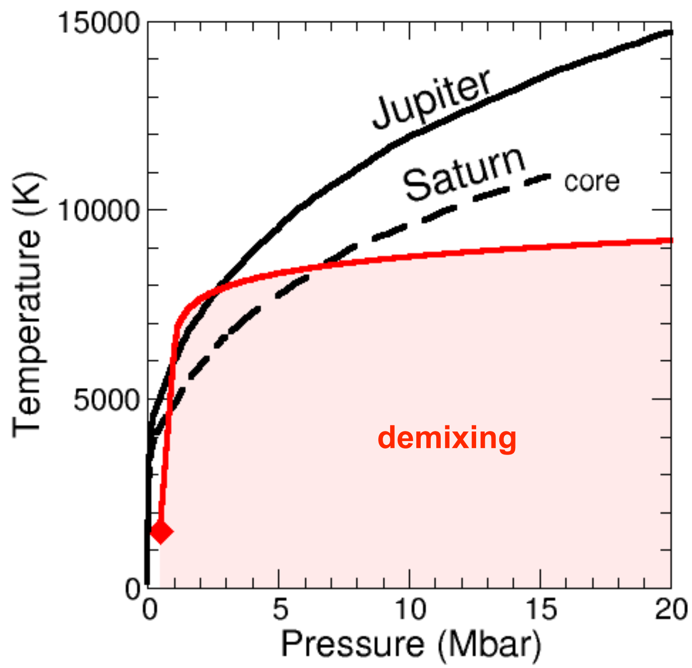


H/He demixing in Saturn

Energy balance:

$$4\pi R_p^2 \sigma (T_{eff}^4 - T_{eq}^4) = \frac{dE_{int}}{dt}$$

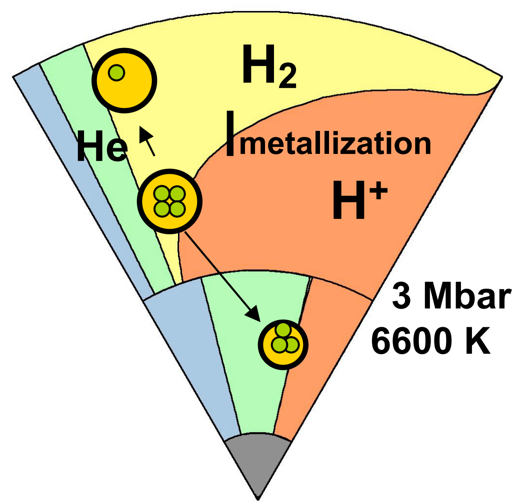
Simulations of H/He mixtures predict demixing in Saturn



- **Lorenzen et al. (2009), PRL**
- **Morales et al. (2009), PNAS**

Solution:

Helium sedimentation leads to additional energy release



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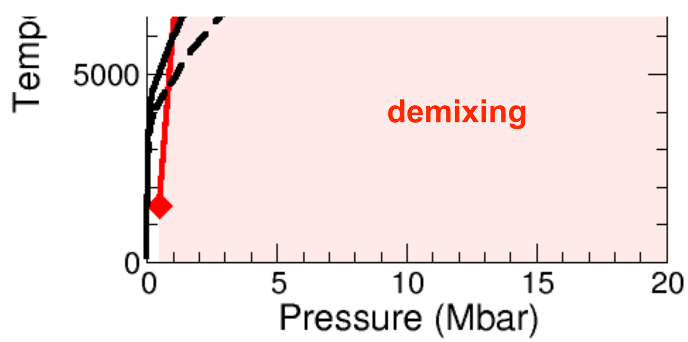
Simulations of H/He mixtures predict demixing in Saturn

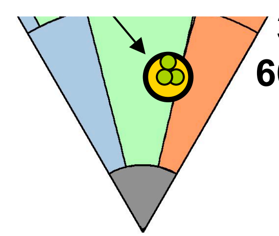
Solution:

Helium sedimentation leads to additional energy release

Future proposal objective:

Confirm demixing of hydrogen and helium at conditions relevant to Jovian planets



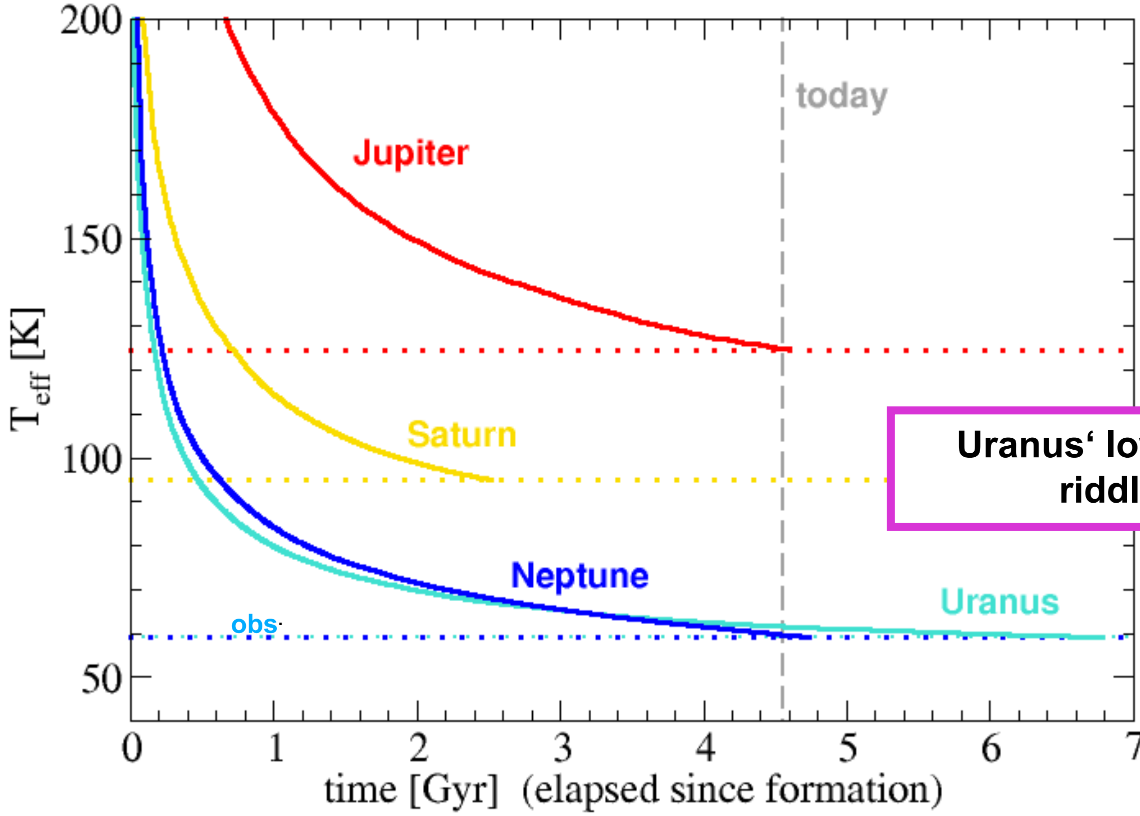


Voyager II flyby 1986

- Mass: 14.5 M_{Earth} , Radius: 4 R_{Earth}
- orbital distance : 19.2 AU

Uranus, cooling curve

Uranus` luminosity is unusually low.



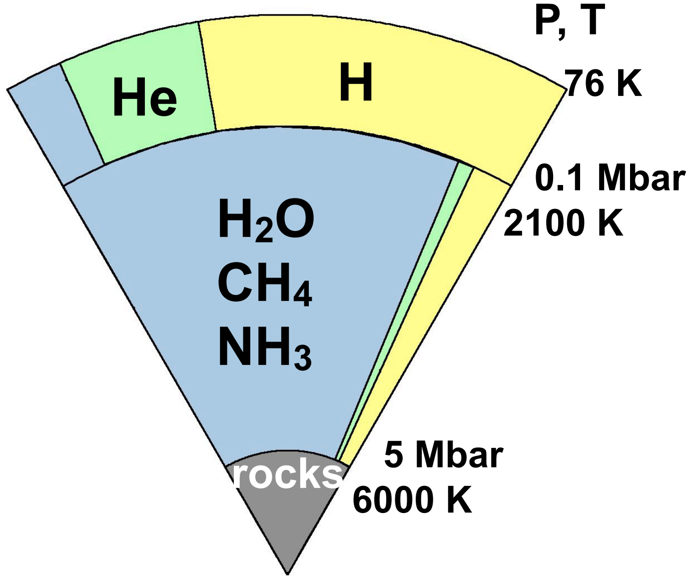
Explanations?

energy flux
$F_{diffusion} << F_{convection}$

Uranus' low luminosity is an important riddle of planetary science.

Uranus, composition

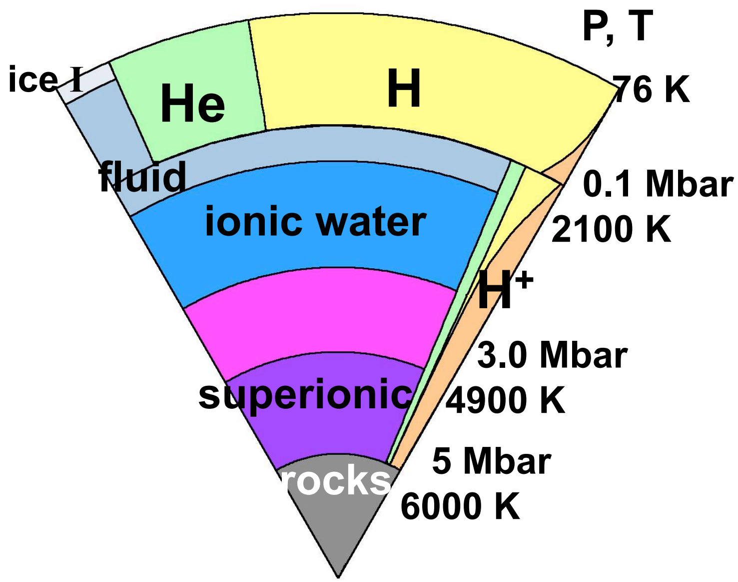
Uranus interior model
(Neptune similar)



The ice mass fraction can be up to 85%
(Neptune similar).

water in Uranus

Uranus interior model assuming all ices are H_2O



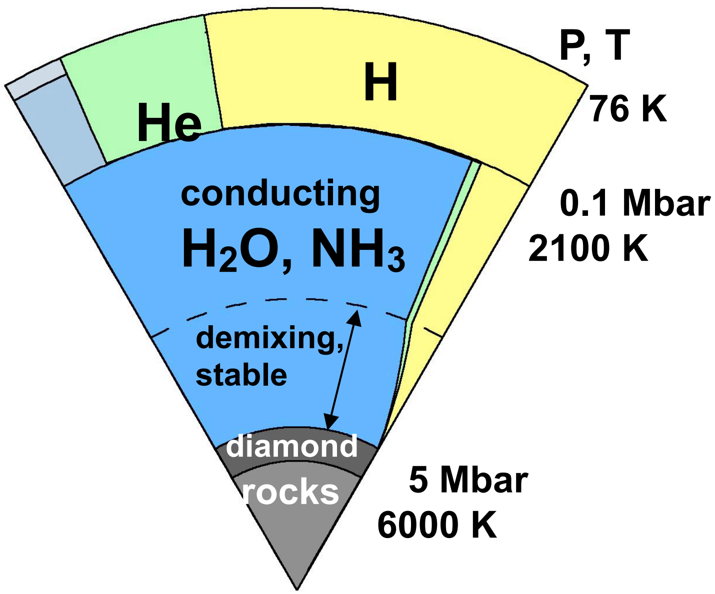
- the ionic shell is consistent with magnetic field models
- a superionic layer alone does not explain a stable interior

➢ Redmer, Mattsson, Nettelmann, French (2011), Icarus

The ice mass fraction can be up to 85% (Neptune similar).

ices in Uranus

Uranus interior model with diamond sedimentation



CH_4 phase seperation into H_2 (rising) and diamond (sinking) may cause

- a diamond layer
- an inhomogeneous, stable layer

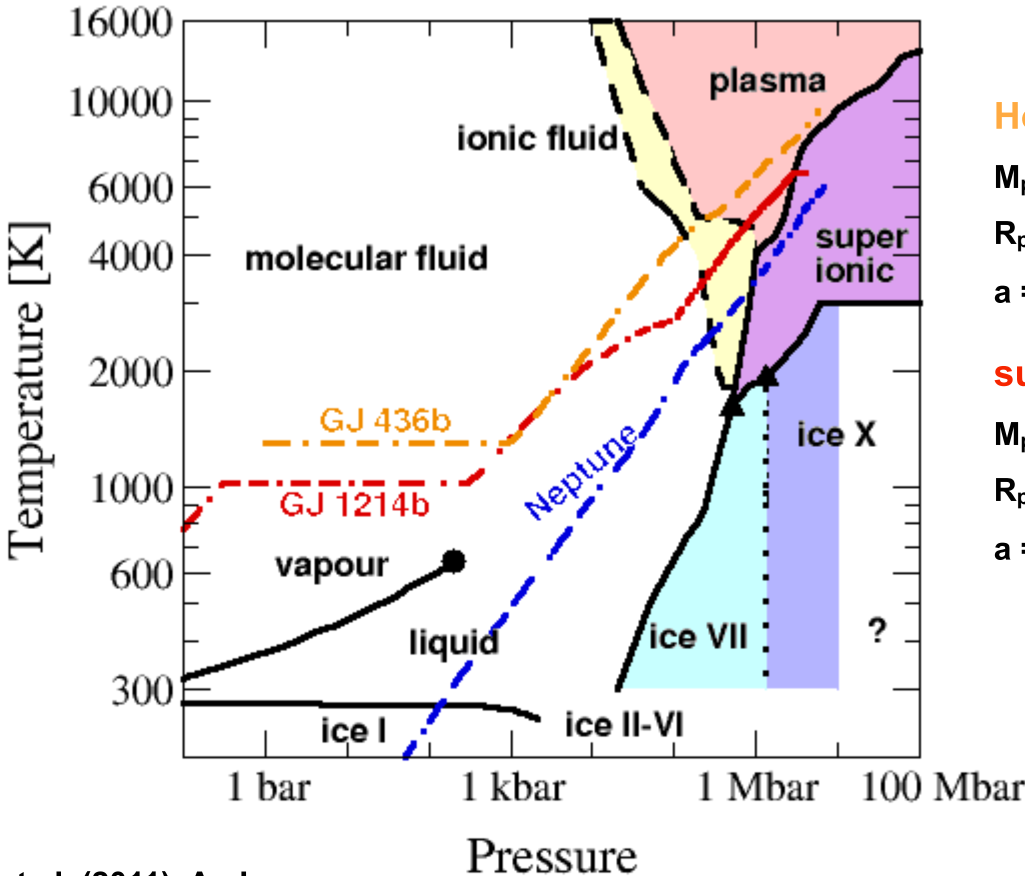
- **Knudson & Desjarlais (2008)** (exp. & sims. on carbon)
- **Hirai et al. (2009), PEP** (diamond anvil exp. on methane)
- **Chau et al. (2011), Nat. comm.** (sims. on synthetic Uranus mixtures)

Future proposal objective:

Measure carbon clustering in water-methane mixtures at 6000 K and 1 Mbar.

Water in close-in exoplanets

Water-ice most likely does not occur in the interior of any known big planet.



Hot Neptune GJ436b:

M_p = 23.2 M_E

R_p = 4.2 R_E

a = 0.03 AU

super-Earth GJ1214b:

M_p = 6.5 M_E

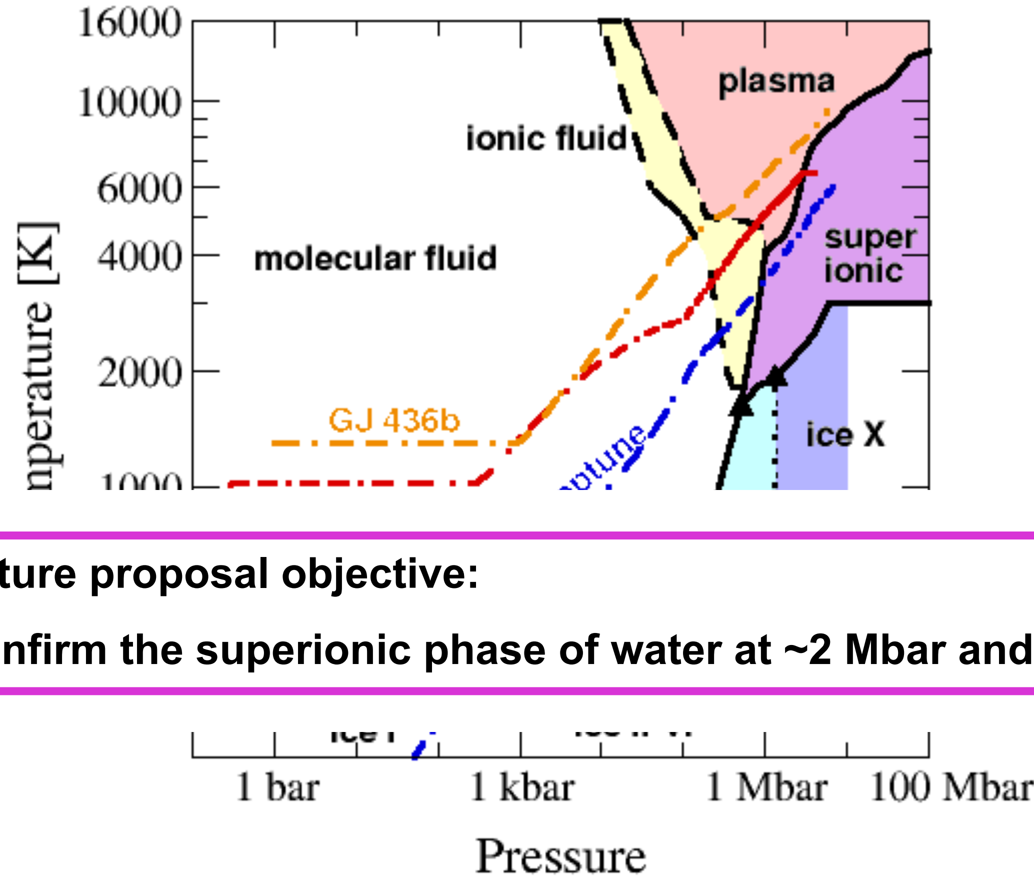
R_p = 2.7 R_E

a = 0.017 AU

- **Nettelmann et al. (2011), ApJ**

Water in close-in exoplanets

Water ice most likely does not occur in the interior of any known big planet.



Future proposal objective:

Confirm the superionic phase of water at ~2 Mbar and ~4000 K.

Summary

Uncertainties in the Jupiter adiabat around 1 Mbar are mapped onto different Jupiter interior models.

proposal: perform multiple shock compression on pre-cooled D_2 at Z

Ab initio H EOS predict a PPT at low temperatures off the Jupiter adiabat

proposal: perform shock-ramp compression (on N_2) and measure T, σ

Saturn‘s high luminosity may be explained by He rain

proposal: confirm experimentally H/He phase separation

Uranus low‘ luminosity may be explained by diamond rain

proposal: develop diagnostics for detecting diamond in water

Water in close-in exoplanets is not in an ice phase.

proposal: confirm experimentally the existence of superionic water