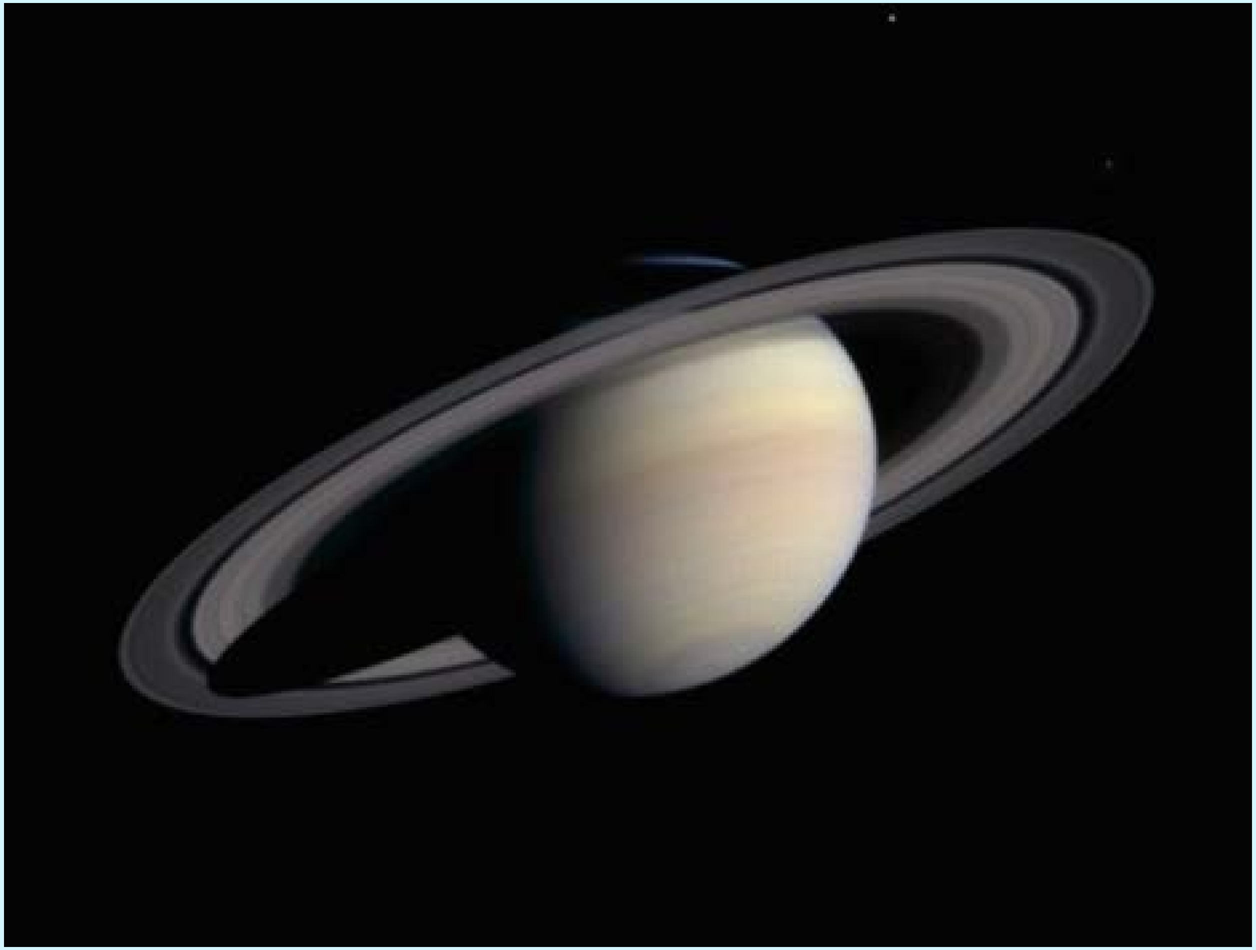
The Interior Structure of Saturn



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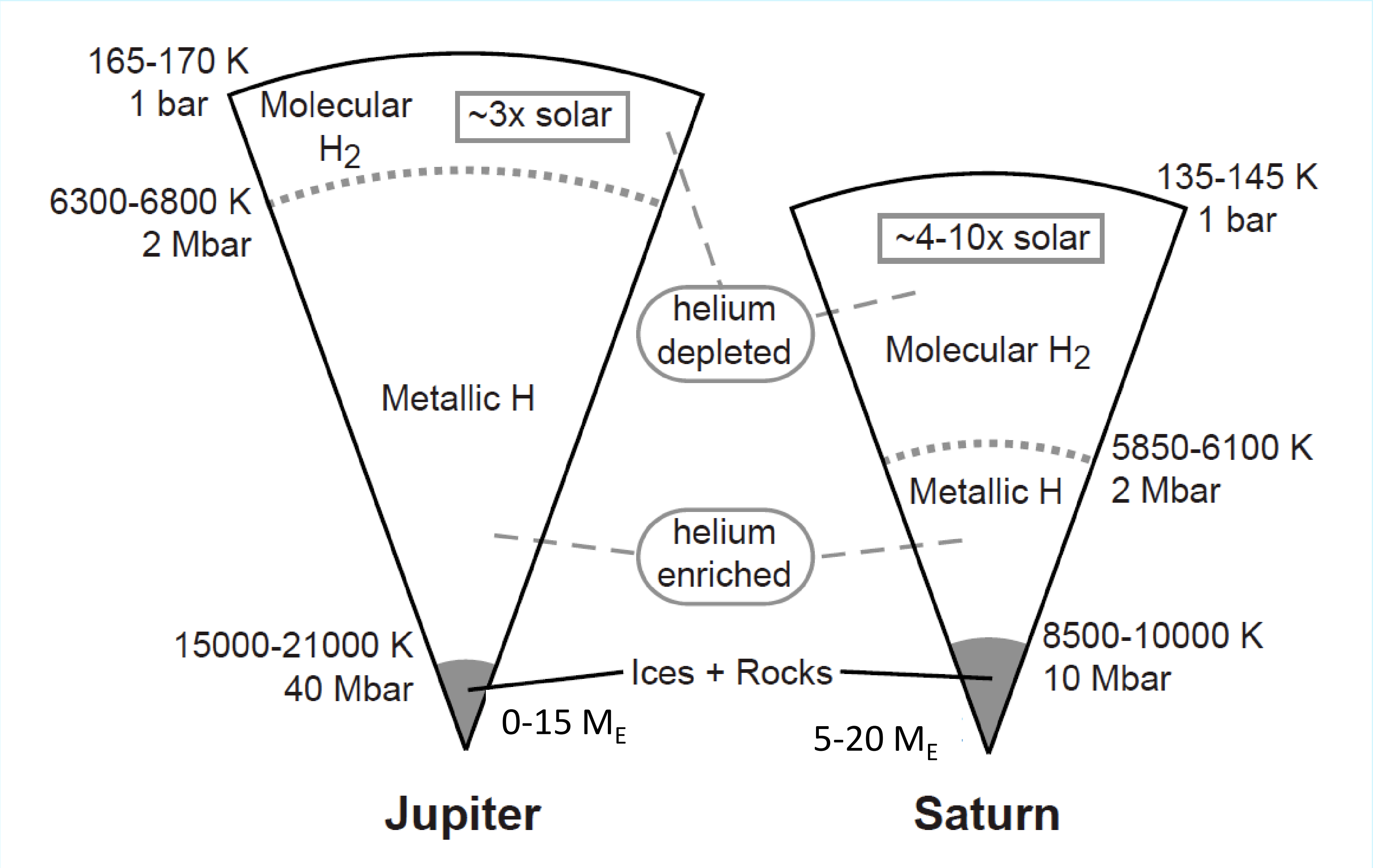
Main Science Questions

- What is the heavy element enrichment of Saturn, compared to the Sun, and Jupiter?
- Are these heavy elements mostly in a core?
- If so, how distinct is this core?
- What is the current temperature and composition structure, as a function of depth?
- How has the planet evolved with time?
- What is the state of interior rotation?

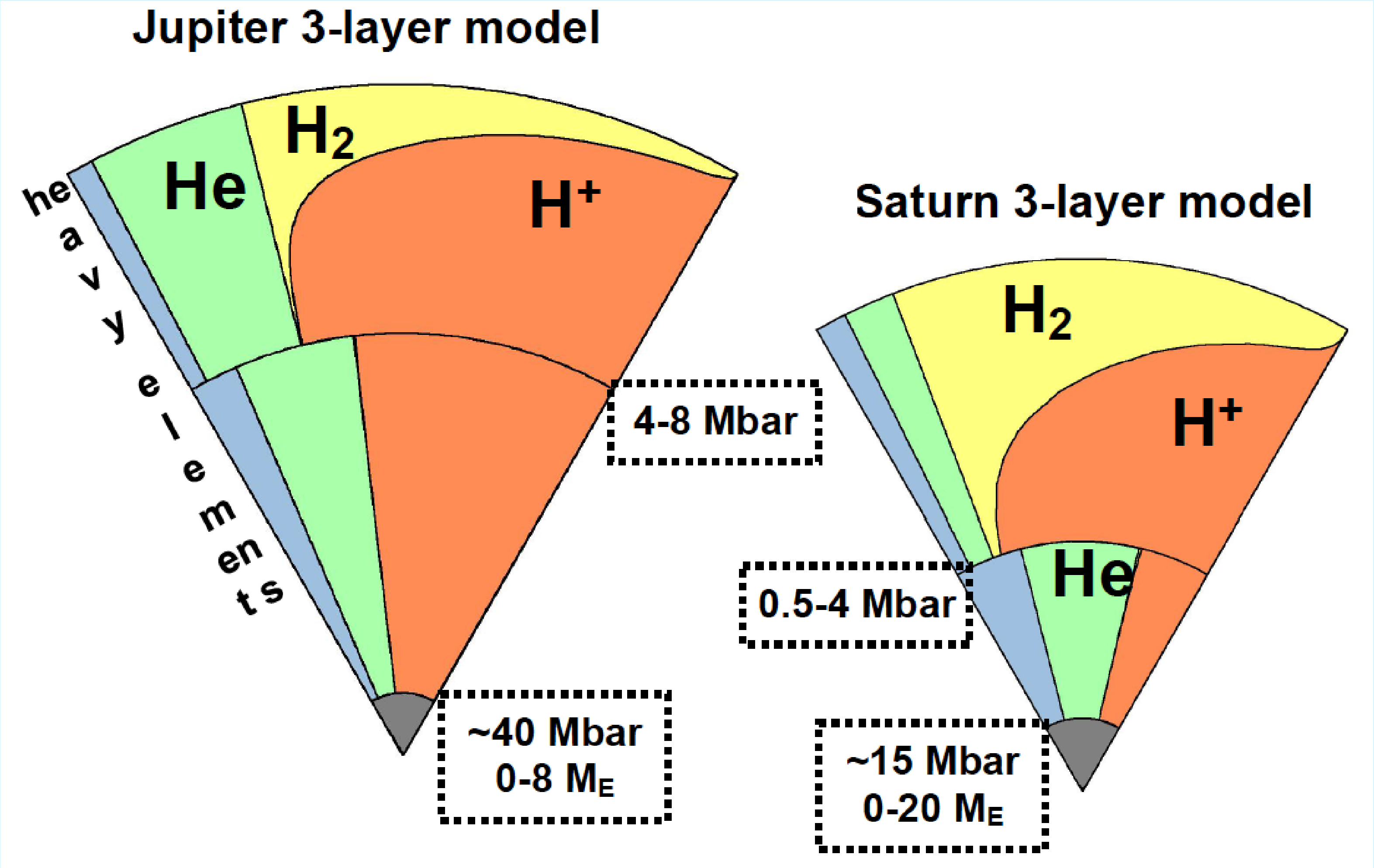
Our Gas Giant Prototypes: Jupiter and Saturn



"Solar mix" is 1.4% heavy elements by mass
Saturn is ~12-21X solar – highly enriched

Fortney, Baraffe, & Militzer (2010) "Exoplanets" book, Arizona Space Science Series

Our Gas Giant Prototypes: Jupiter and Saturn



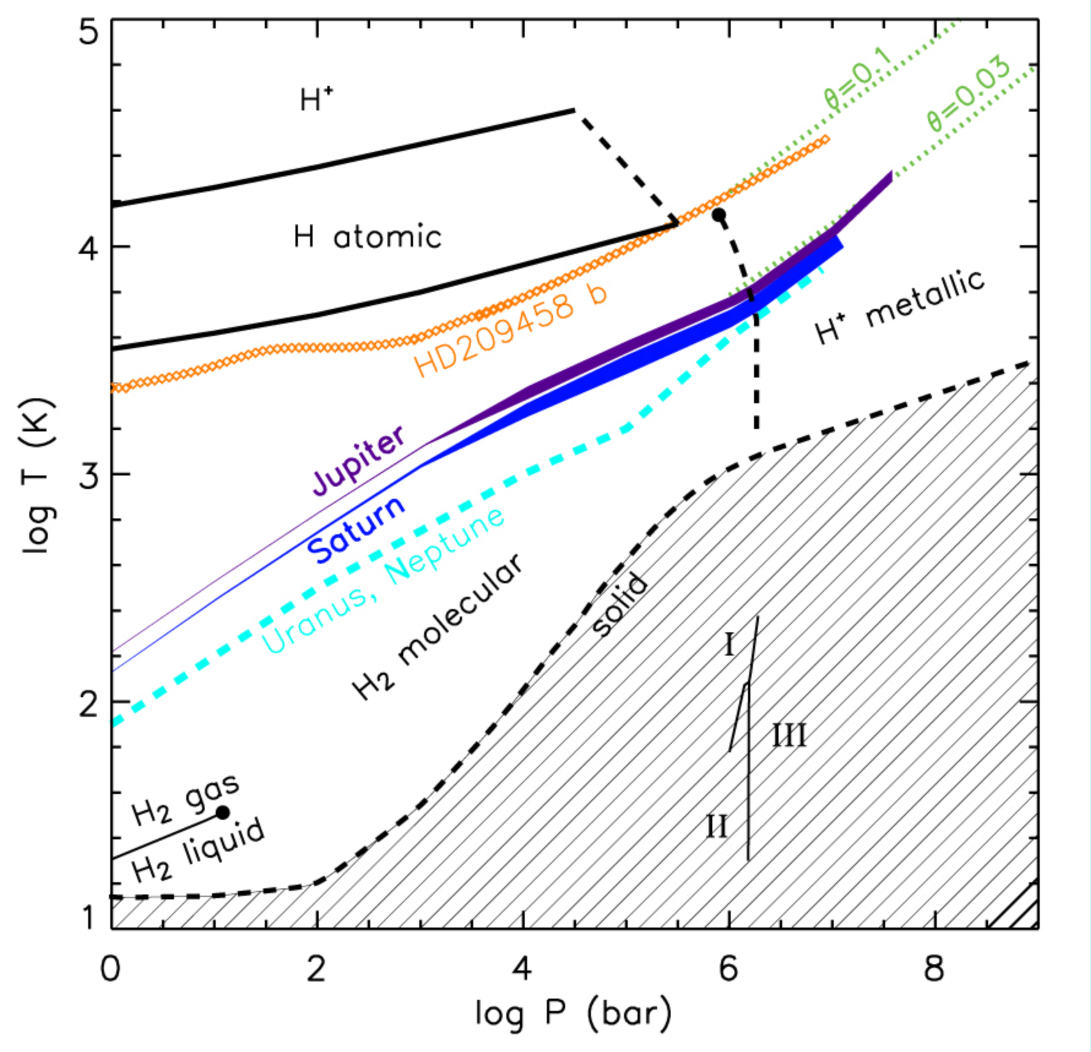
Slide courtesy of Nadine Nettelmann

High Pressure Hydrogen

H in fluid plasma phase (liquid metal)

Plasma is strongly coupled
$\Gamma = e^2/ak_bT$

Plasma is degenerate
$\theta = T/T_F$

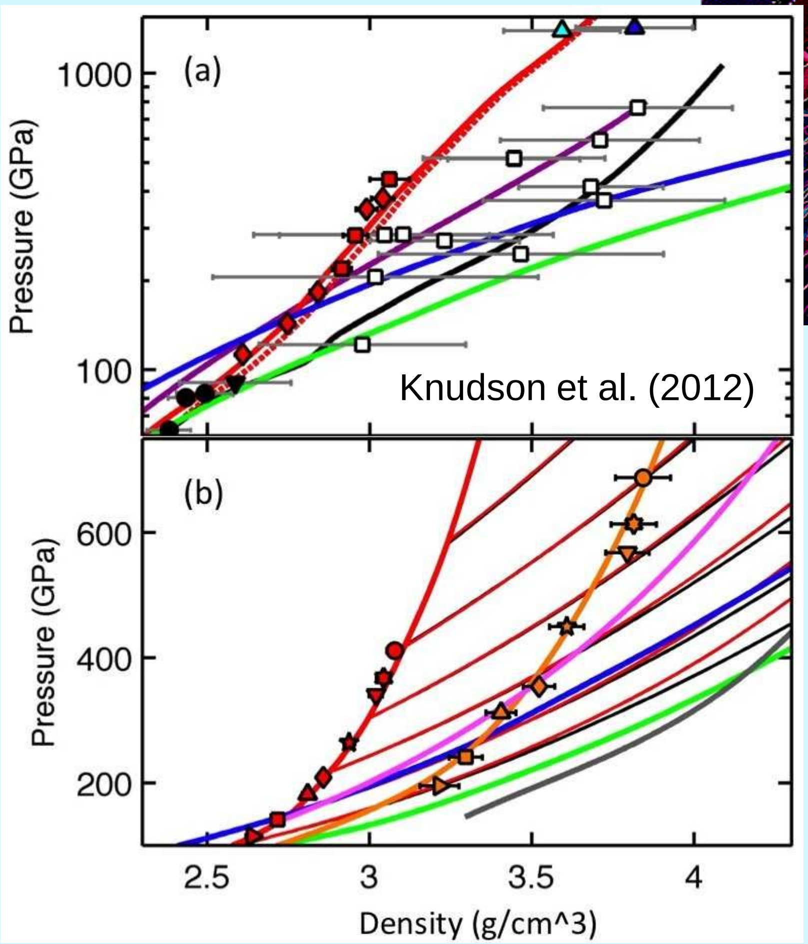


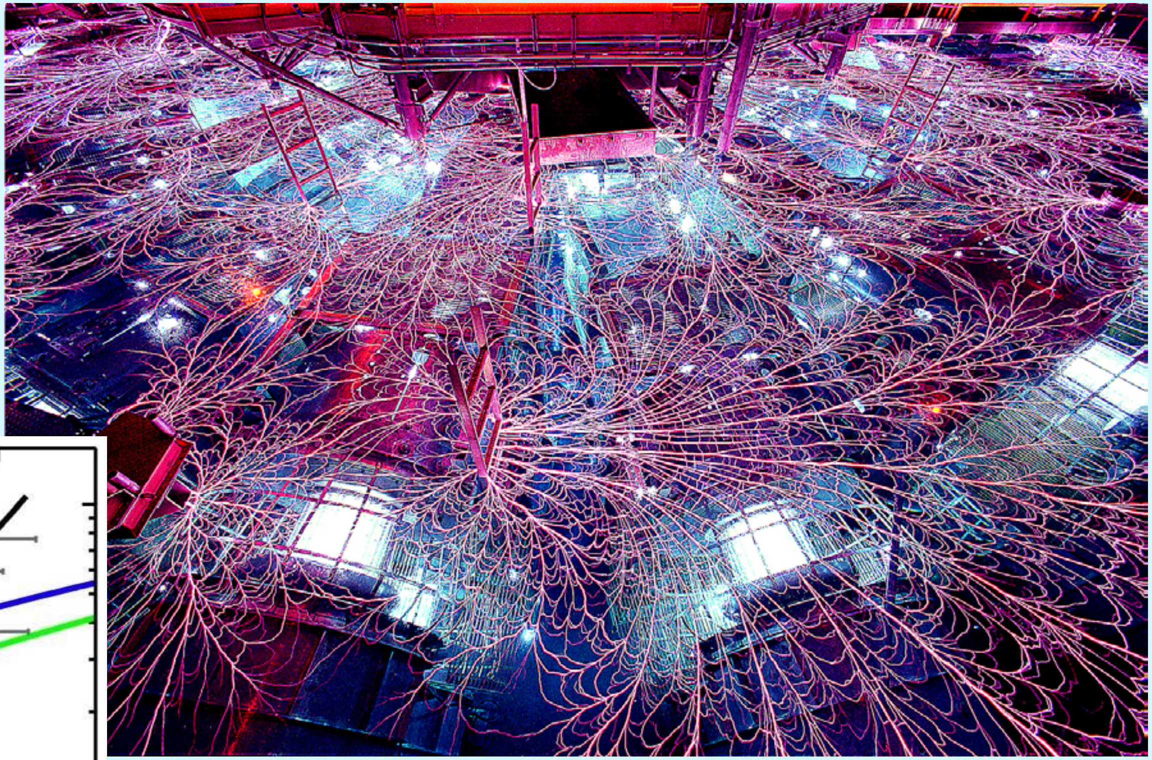
Guillot (2005)

For Saturn

$$\Gamma = \frac{e^2}{ak_BT} \sim 20\text{–}30, \qquad \theta = \frac{T}{T_F} \sim 0.02,$$

EOS at High Pressure: New Calculations and Precise Measurements



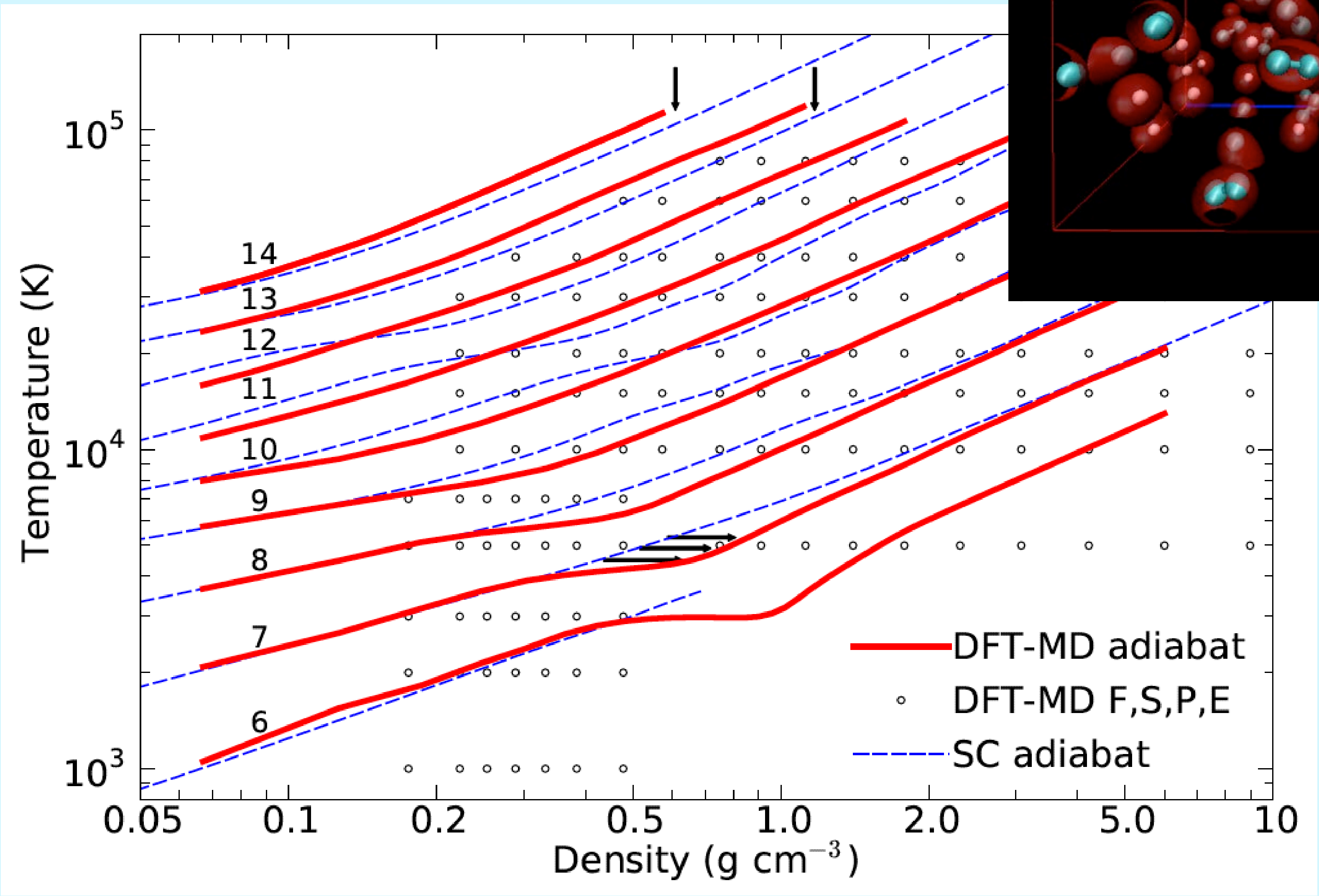


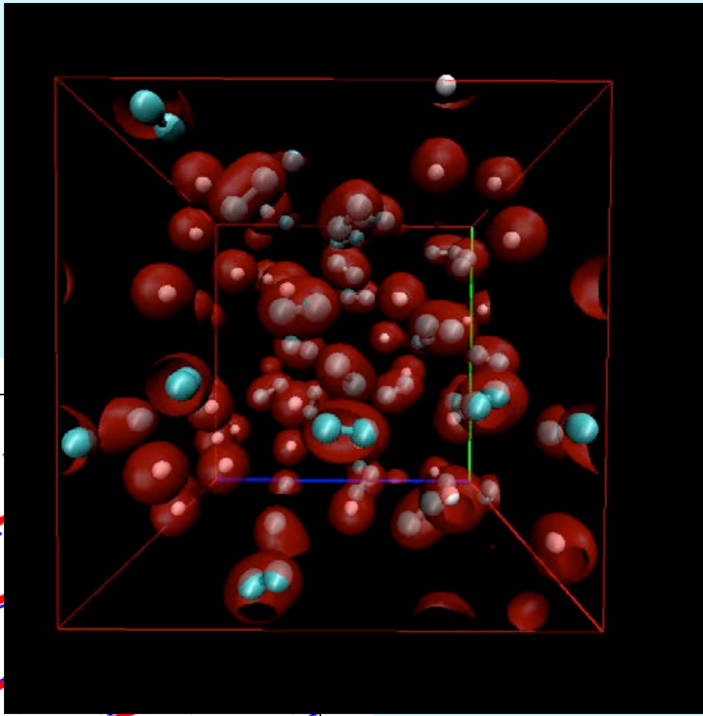
Sandia National Laboratory Z Machine

- After many decades of effort, we are now in an era of detailed first-principles calculations of the equation of state (EOS)
- Precision EOS measurements are also now available

French et al. (2009) water EOS

Militzer & Hubbard (2013): New H/He adiabats show dramatic differences in the phase space of Saturn & Jupiter

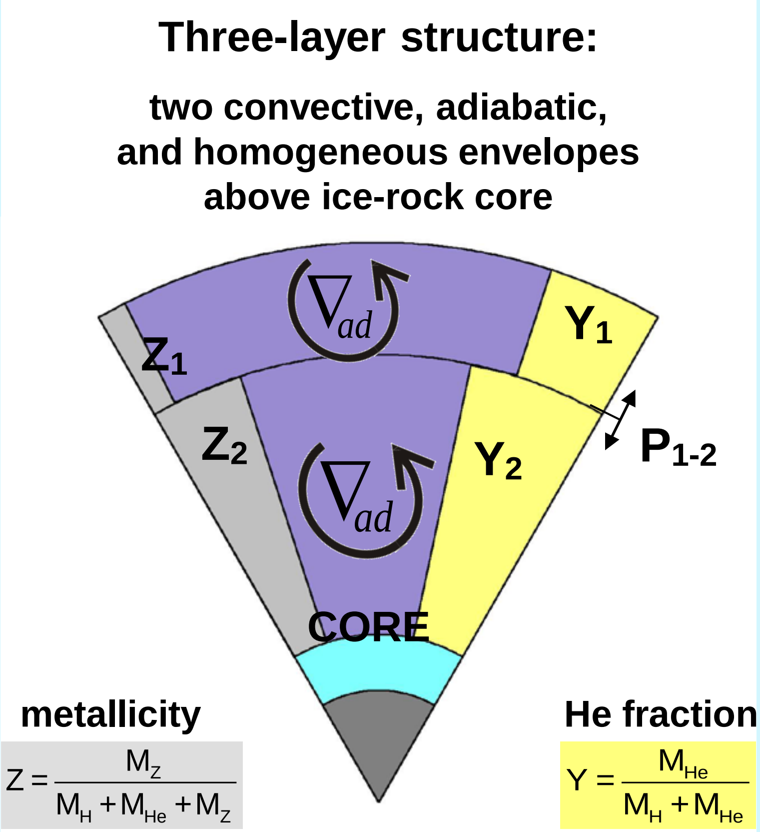




State of Interior Physics

- We are in a new era for first-principles calculations of the EOS, and their validation against experiment
- These EOS are for H, He, H/He mixtures, water, and rocks.
- They are just beginning to be used in Saturn models – room for growth in the next few years

Modeling the Solar System's Giant Planets

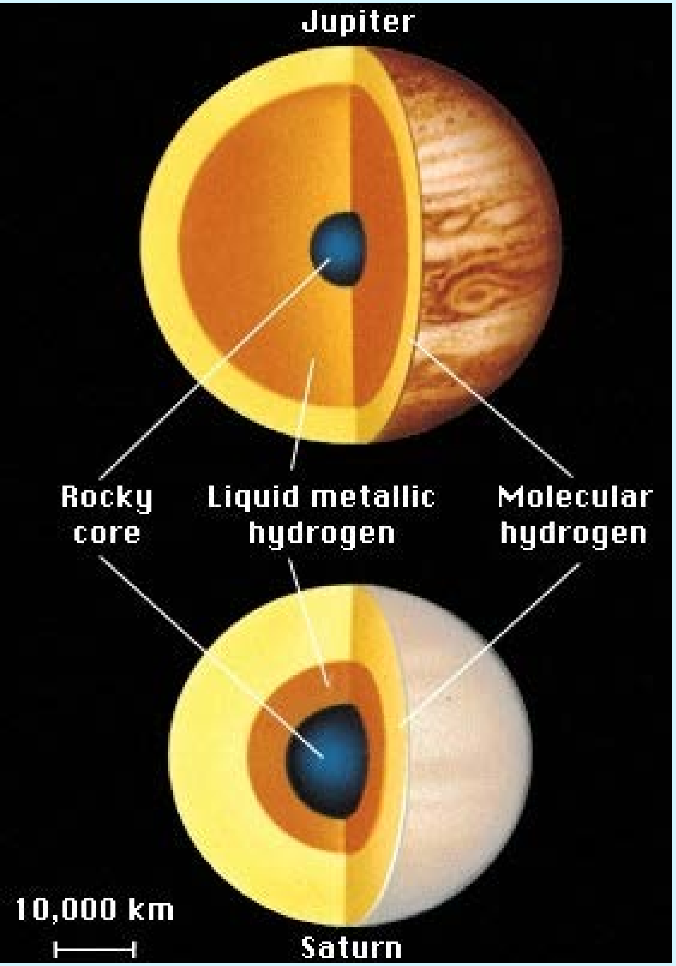


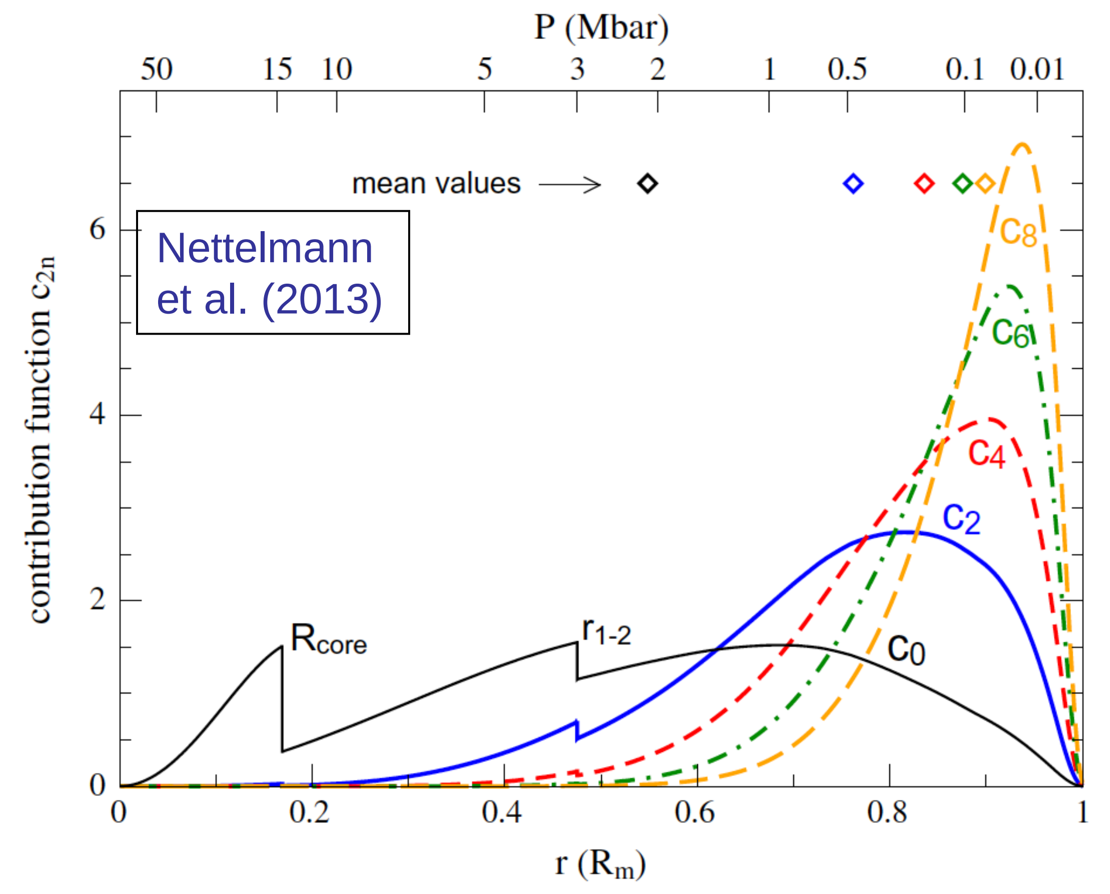
observational constraints		
explicitly	to be adjusted	fitting parameters
M_p	R_p	M_{core}
Y_{atm}	Y	Y_2
$T_{1\ bar}$	J_2	Z_2
ω	J_4	Z_1
age	T_{eff}	PAP

- Guillot 1999, PSS
- Chabrier, Saumon, Hubbard, Lunine 1992, ApJ

Slide courtesy of Nadine Nettelmann

Structure Models





$$V(r,\theta) = -\frac{GM}{r}\left[1 - \sum_{n=1}^{\infty}\left(\frac{R_{eq}}{r}\right)^n J_n P_n(\cos\theta)\right],$$

$$J_{2i} = -\frac{1}{MR_{eq}^{2i}}\iiint \rho(r,\theta) r^{2i} P_{2i}(\cos\theta) d^3\tau,$$

- Measurements of the planets' gravity fields give us a window into their interiors

Saturn's internal structure models

Rotation period of 10h 39mn 22.4s

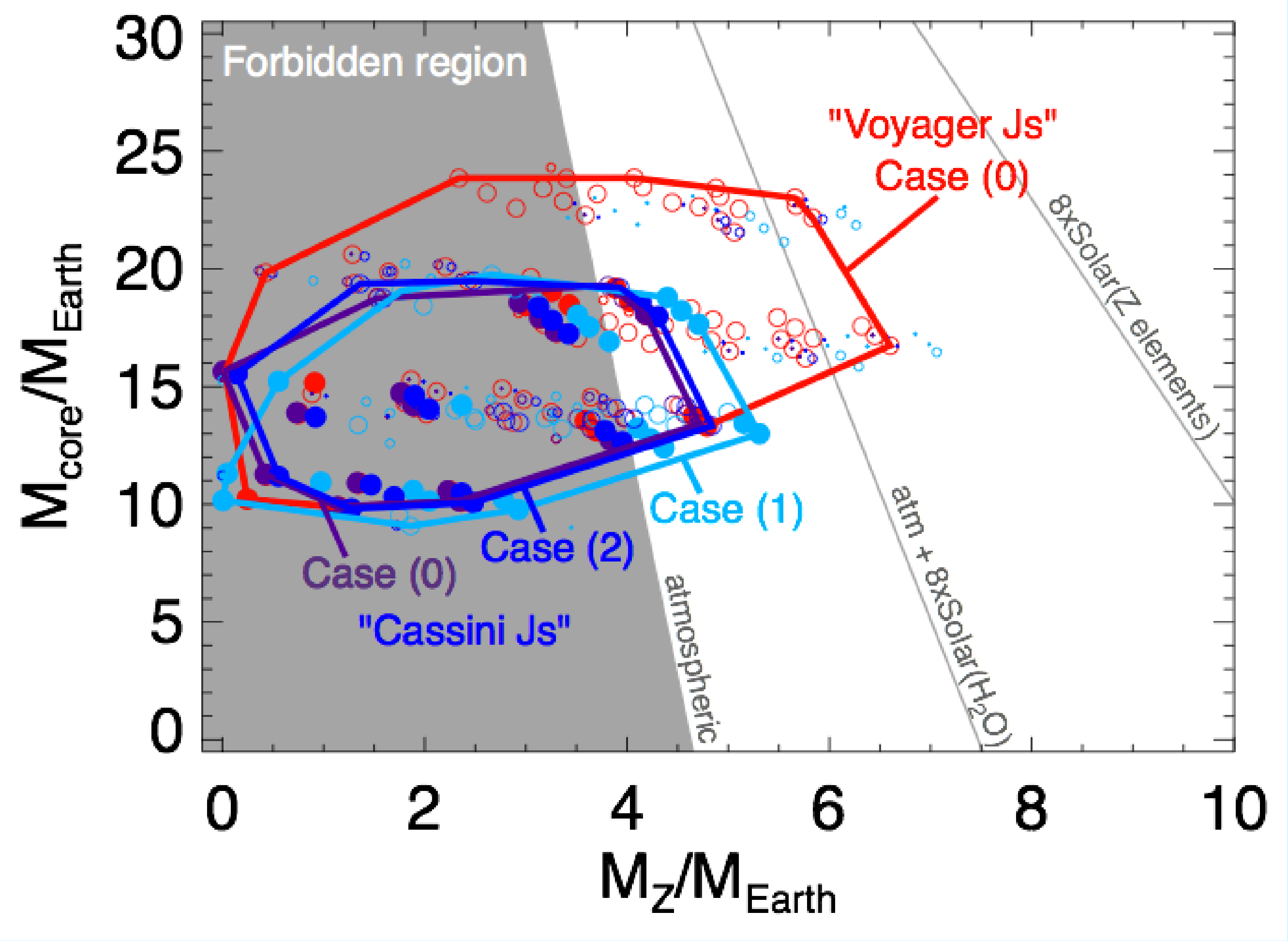
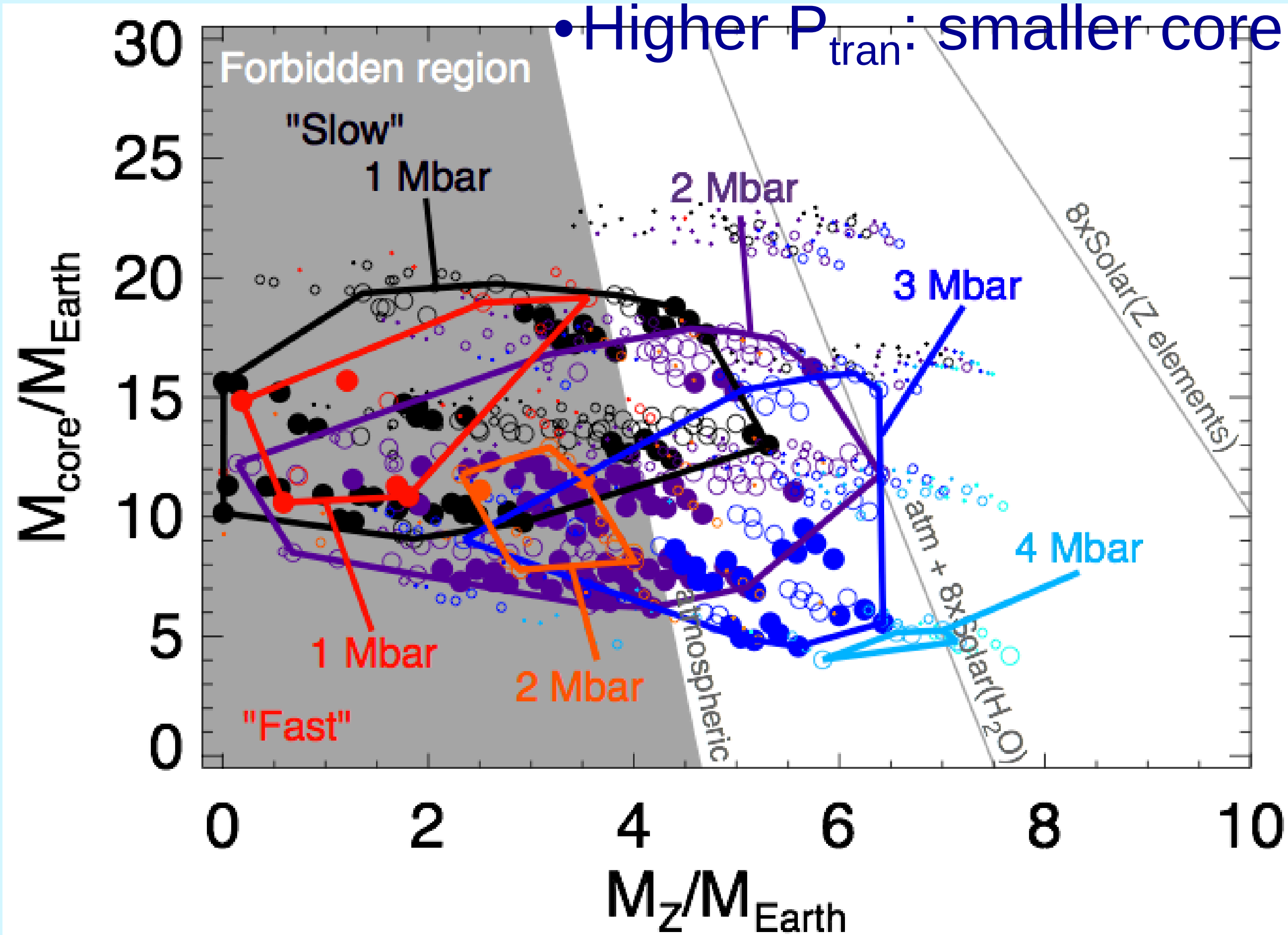


Figure courtesy of Ravit Helled (Helled & Guillot, 2013)

Saturn's internal structure models

Rotation period of 10h 39min vs. 10h 32min

- Rotation period affects internal structure inferences
- Fast rotation: metal-poor atmosphere
- Higher P_{tran}: smaller core mass



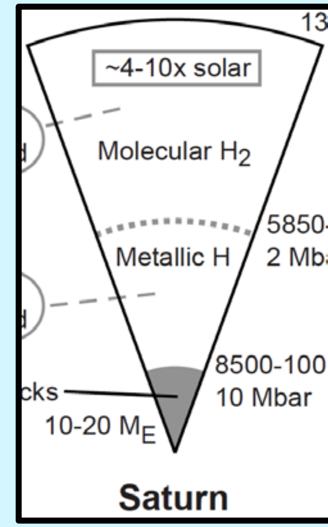
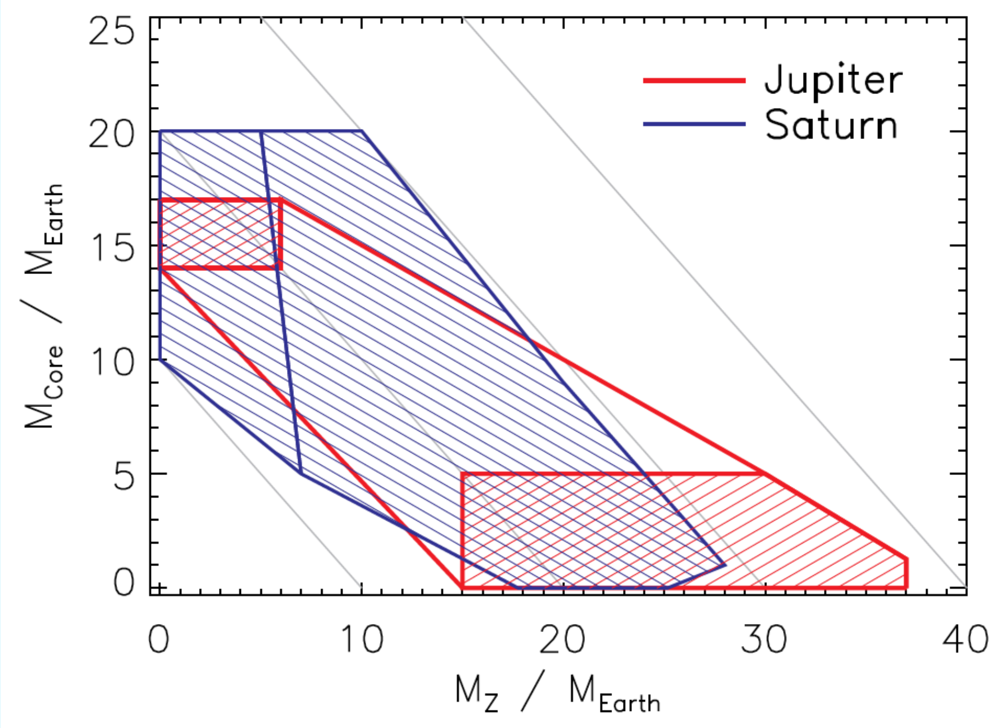


Figure courtesy of Ravit Helled (Helled & Guillot, 2013)

Metal-Enrichment of Giant Planets

Given our appreciation of the **difficulty to ascertain the current core masses**, and our lack of knowledge of the **relation between any current core mass and initial core mass**, it can make sense to really just think about **the total heavy element enrichment** in giant planets

This total enrichment is the only thing we'll be able to measure for the vast majority of transiting planets



Current constraints for Jupiter and Saturn from adiabatic interior models.

Jupiter: 3x to 8x solar
Saturn: 12x to 21x solar

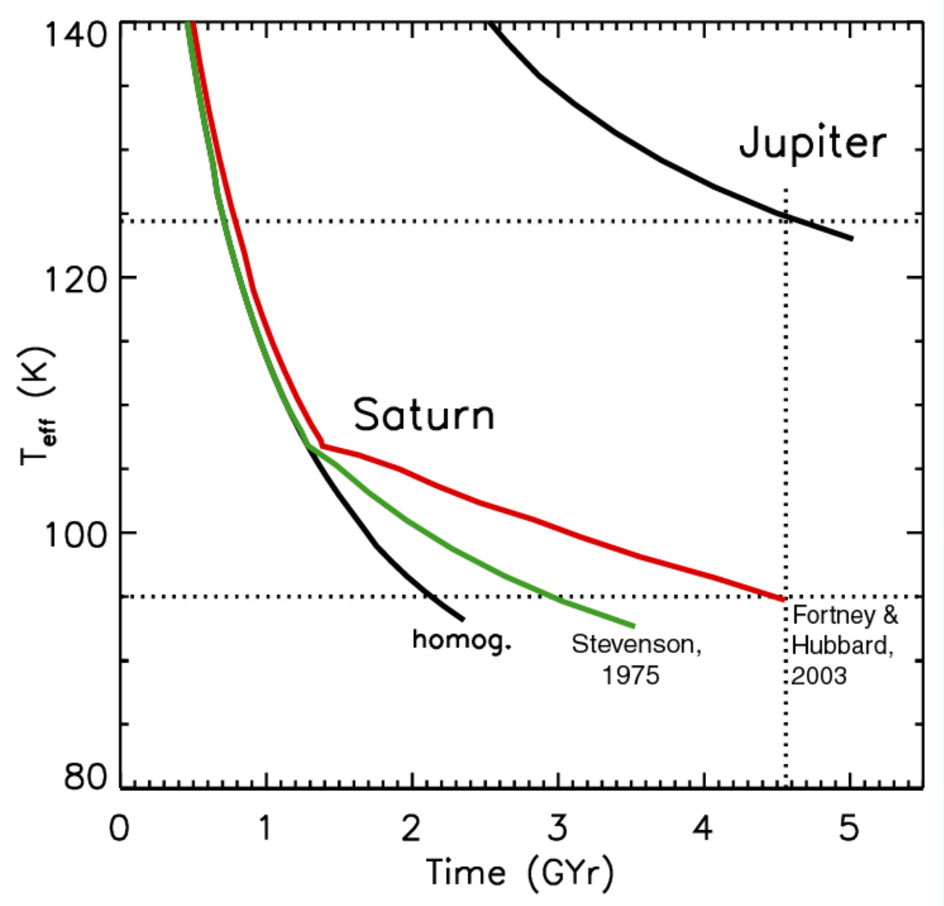
Similar amounts of heavy elements in each planet

State of Simple Models of Current Structure

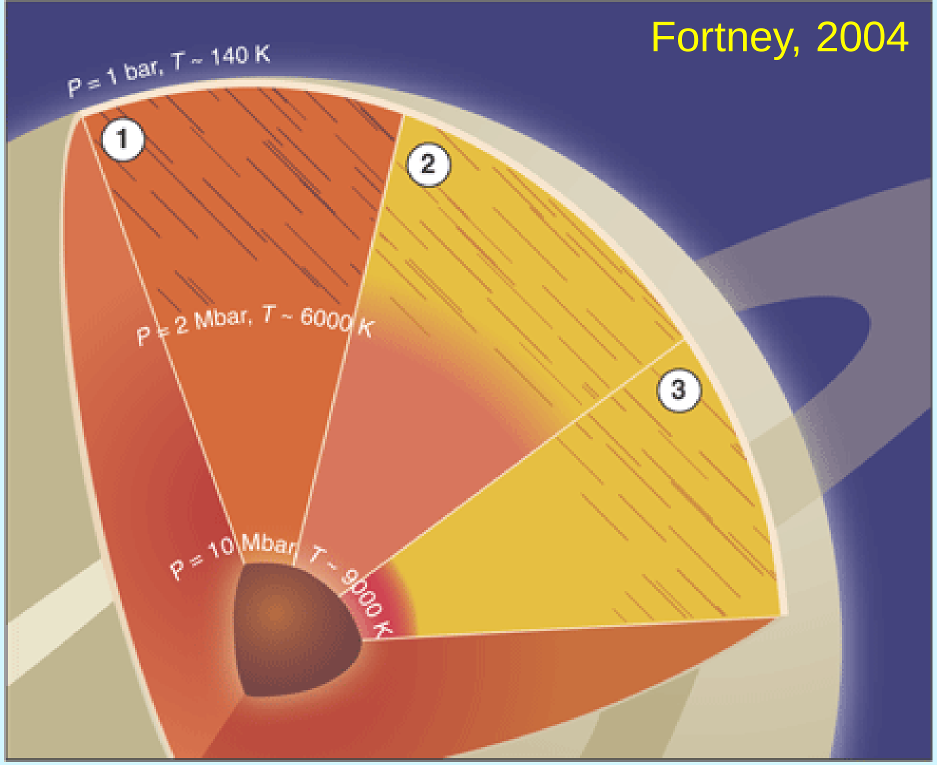
- Saturn and Jupiter have similar total amounts of heavy elements
- Strong evidence for a distinct core or very strong heavy element enhancement near center
- Some real tension between “metal-rich” atmosphere from spectroscopy, and metal-rich H/He envelope from gravity field
- Rotation period uncertainty is important!
- No models yet include results of interior He redistribution from real phase diagrams

Saturn's Evolution

Fortney & Hubbard, 2003



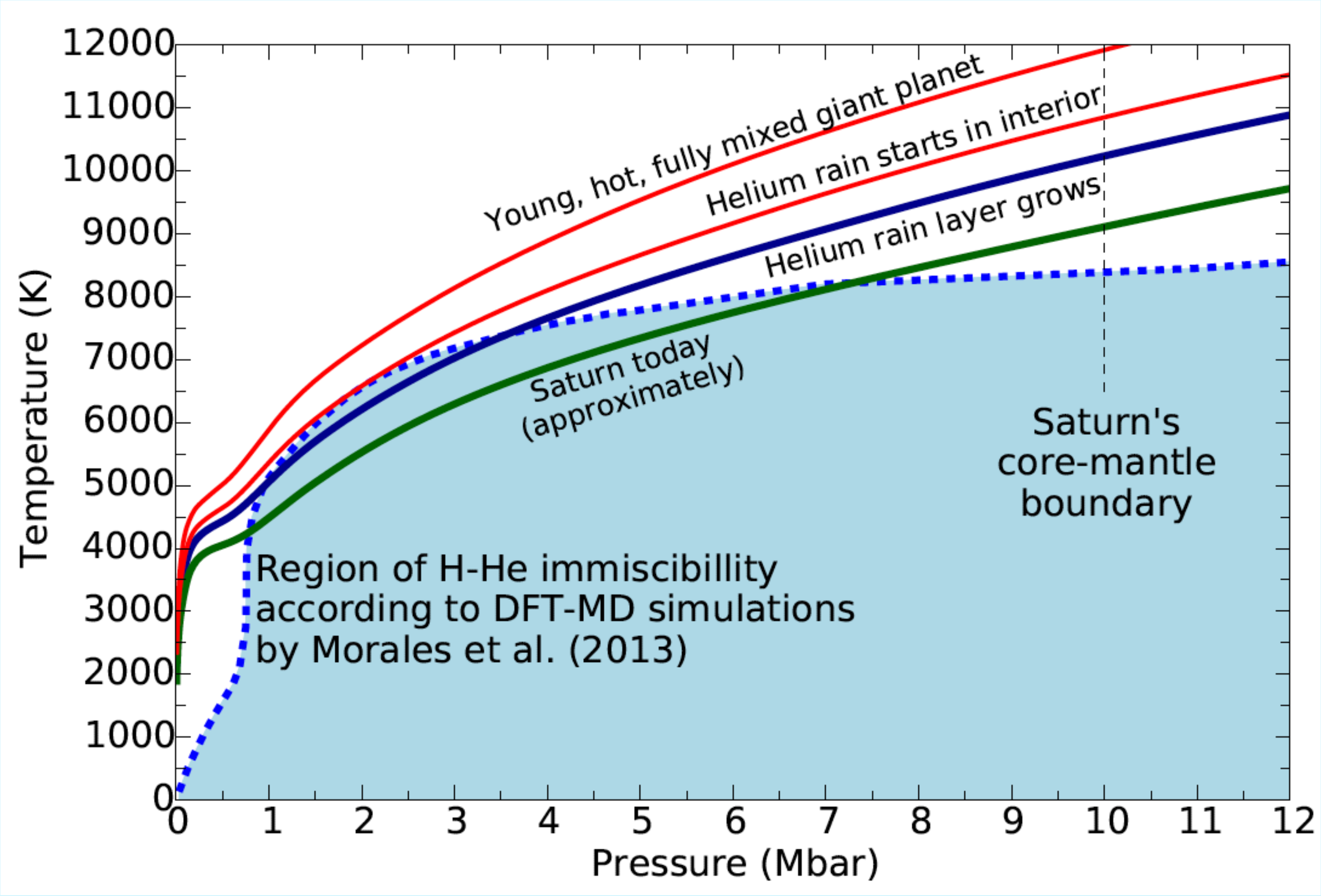
Fortney, 2004



Helium Phase Separation

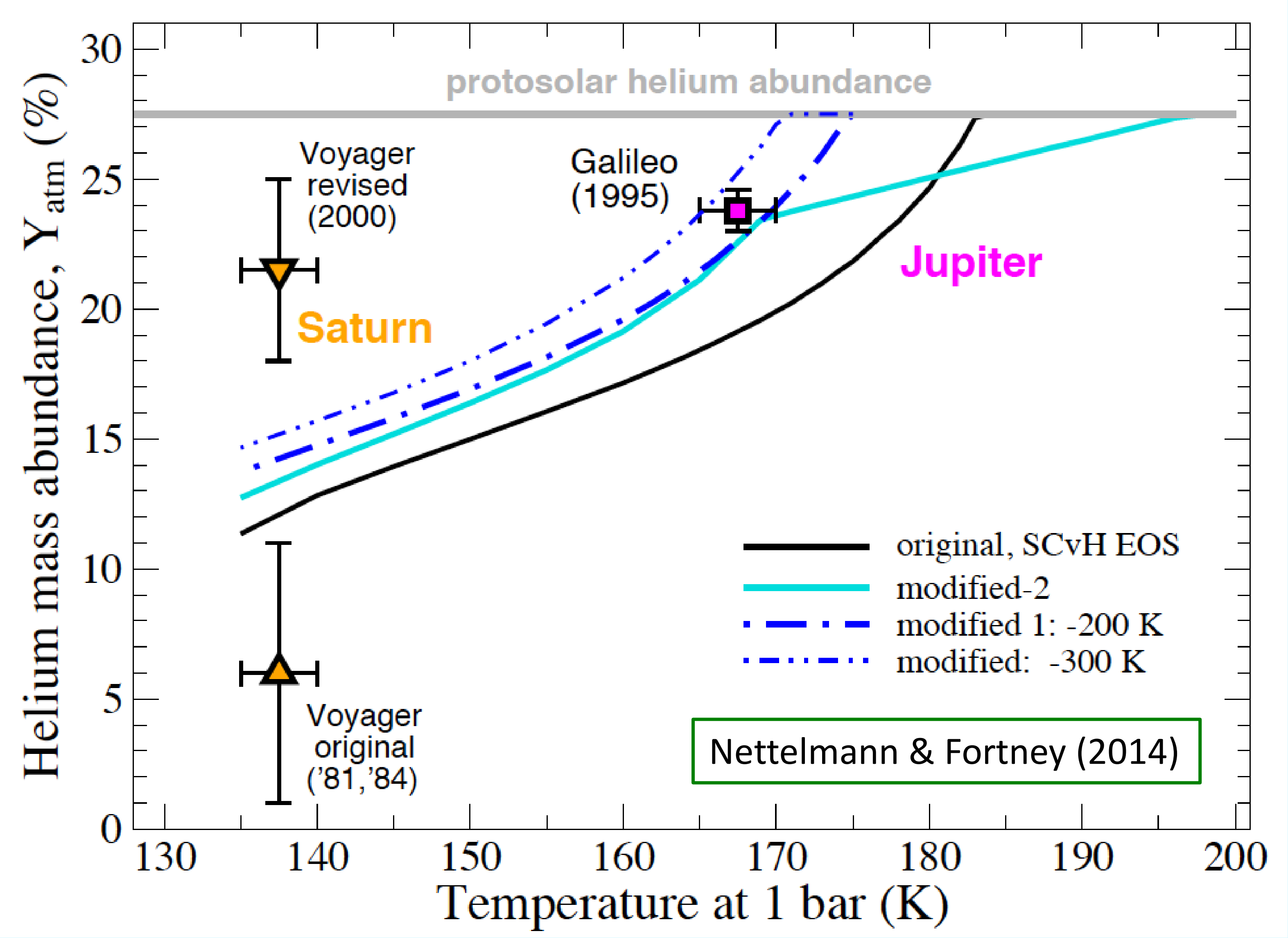
- A variety of work (Stevenson & Salpeter, 1997; Fortney & Hubbard, 2003) show that He rain can provide the necessary energy to explain the planet's luminosity
- We lack any clarity on the details

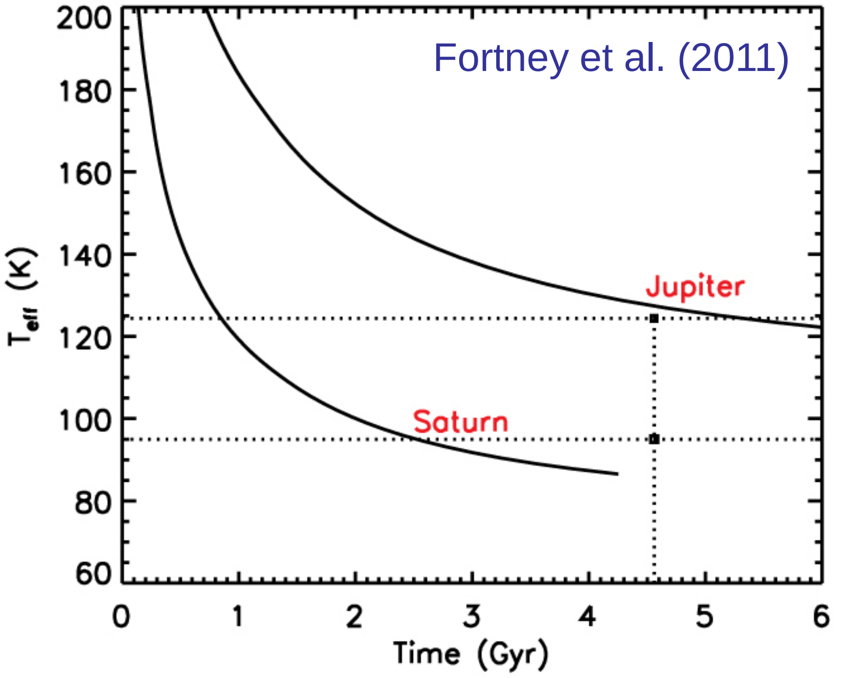
After many years of hard work on first-principles calculations, there is now good agreement on the H/He phase diagram



Shape of phase diagram appears robust (calculated by 2 different groups), but onset temperature uncertain ~500 K

Jupiter's Y_{atmos}~0.234, and Published Phase Diagrams Suggest Saturn's Y_{atmos}~0.14



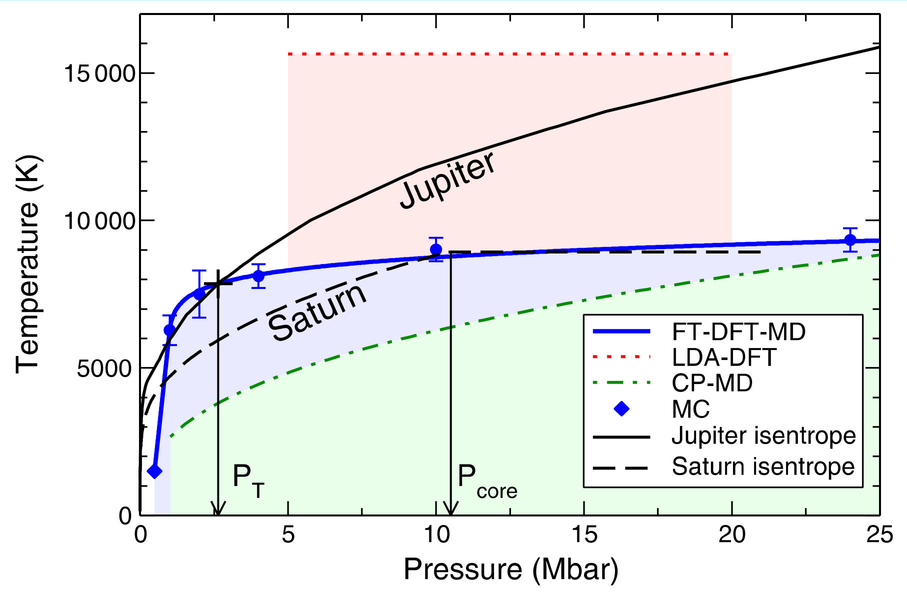


Homogeneous Evolutionary Models

The "shortfall" in models of Saturn's evolution has long been known (Pollack, et al. 1977, Stevenson & Salpeter 1977, Grossman, et al. 1980)

Saturn is currently over 50% more luminous than homogeneous evolutionary models predict.

Lorenzen et al. (2009)



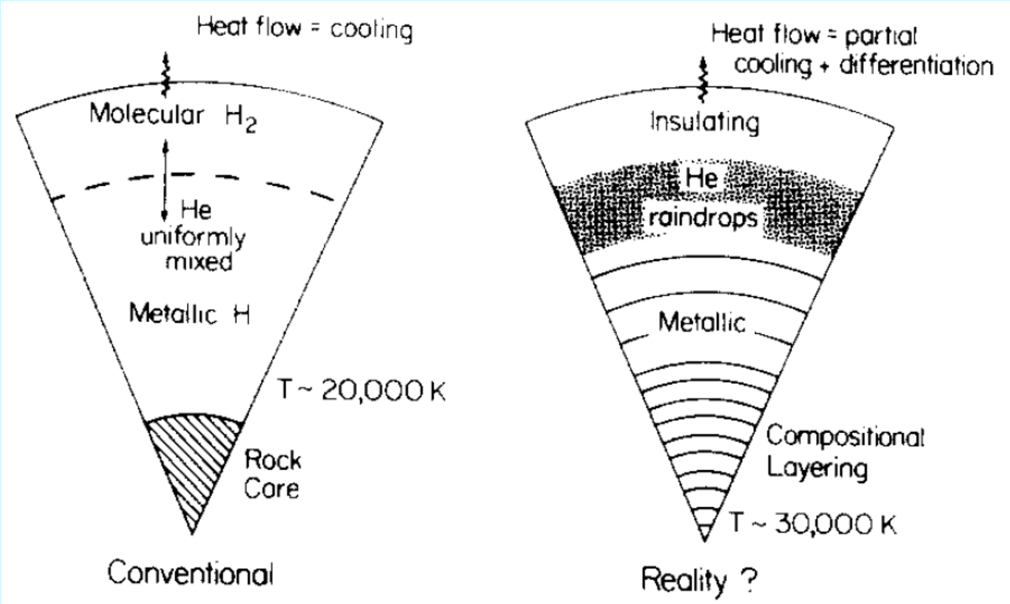
Saturn's "excess" luminosity is potentially due to the phase separation and subsequent "rain" of helium within the planet.

State of “Standard” Evolution Models

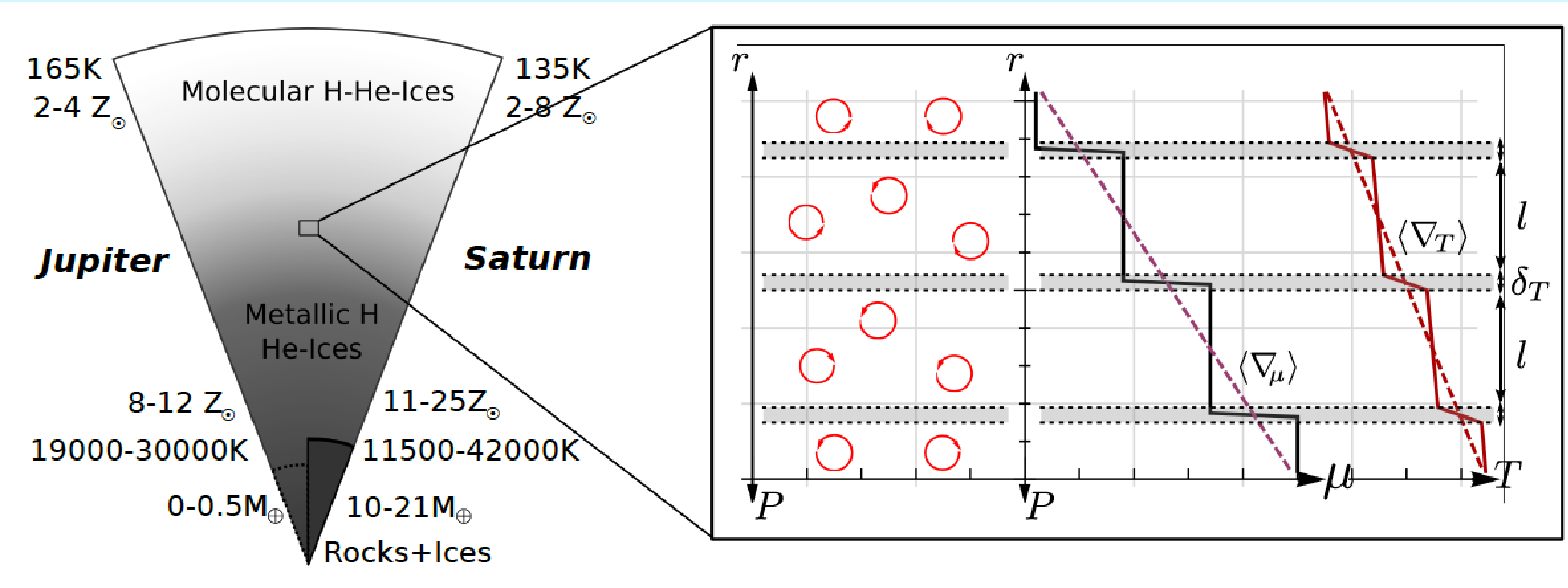
- Two groups (nearing 3) have calculated H/He phase diagrams in reasonably good agreement that show He composition gradients should be expected throughout Saturn’s interior
- Saturn cooling shortfall of 2-3 Gyr extremely robust, since 1977
- Calculated phase diagram shape + constraint from Jupiter suggest Saturn’s Y_{atmos}~0.14
- No published evolution models yet use new phase diagrams to consistently track He redistribution with time

Complexities?

- 2 layer models
  - 1 homogenous envelope + core
  - Not really viable given He phase separation
- 3 layer models (Nettlemann et al. 2013, Helled & Guillot 2013)
  - 2 layers of the envelope
    - He poor outer layer
    - He rich inner layer
    - Z-poor outer, Z-rich inner (Nettelmann et al.)?
    - (These still ignore the distribution of He within the planet)
- What about a less simple picture?



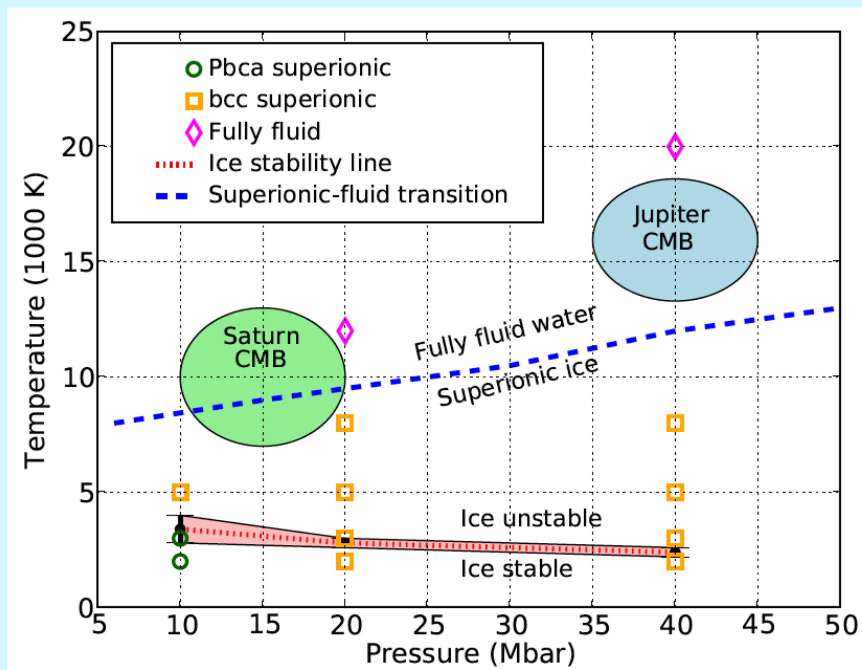
Stevenson (1985)



Leconte & Chabrier (2012)
based in part on 3D simulations of Garaud & collaborators

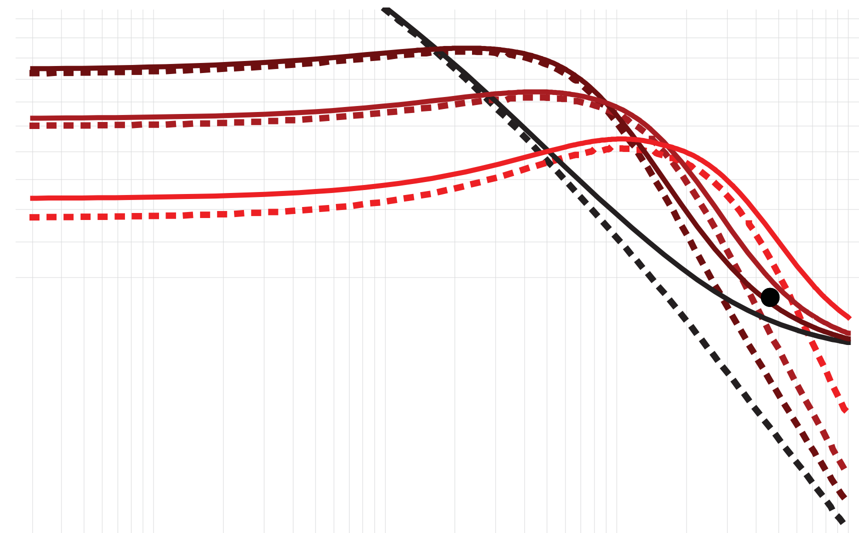
Giant Planets May Not be as Simple as We Might Hope Them to Be

The assumptions of fully convective interiors and distinct heavy element cores can now be examined



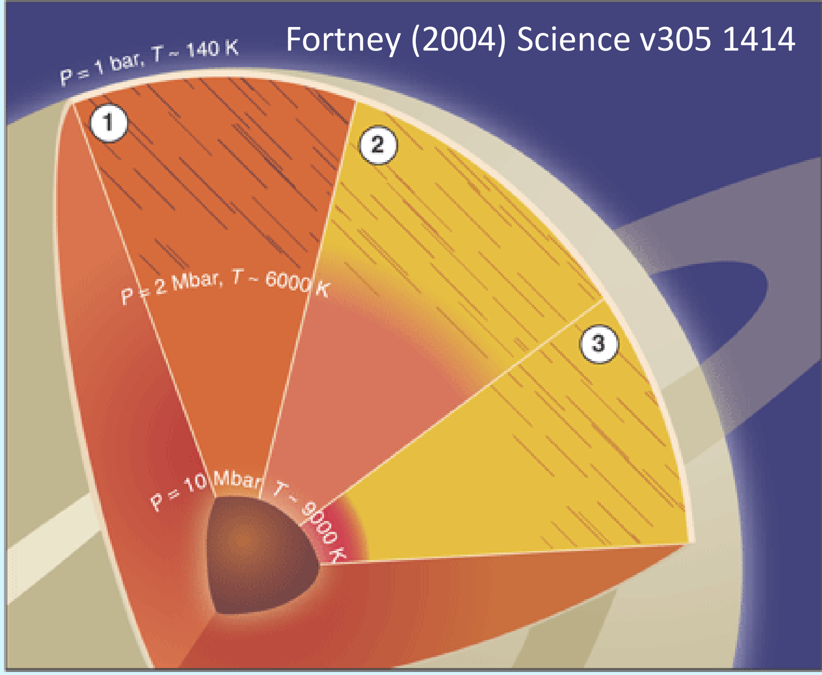
Wilson & Militzer (2012)

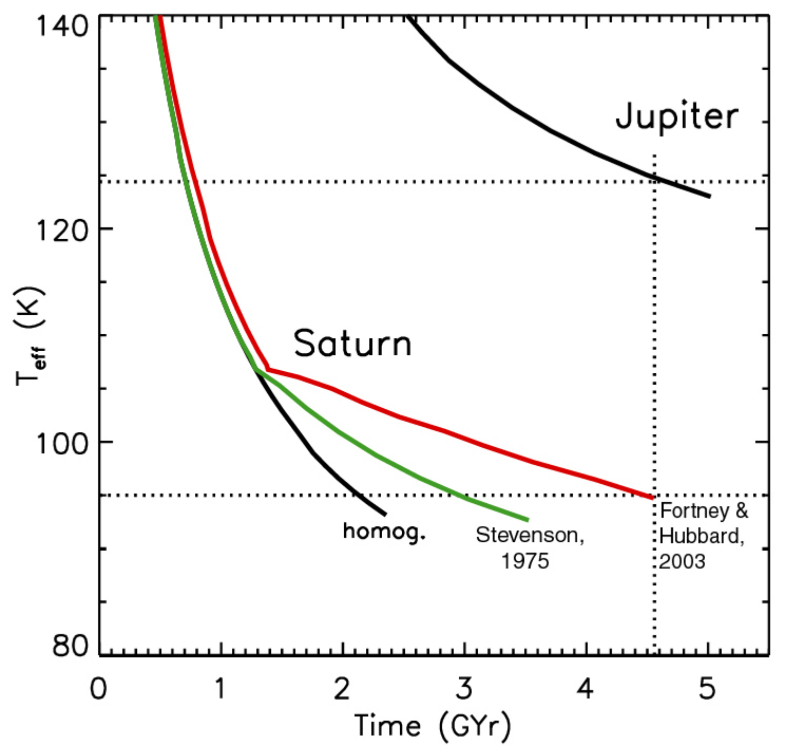
Evolutionary Histories with Composition Gradients can be Complex



Leconte & Chabrier (2013)

Anomalously large T_{eff} of Saturn could be due to helium rain, or altered cooling due to composition gradients, **or both**





Kronoseismology

- Seismology has dramatically altered our view of the Earth and Sun
- “Saturn’s Rings as a Seismograph”
- Marley (1991), Marley & Porco (1993)
- Hedman & Nicholson (2013, 2014) – clear identification of features in Saturn’s C-ring not due to resonances with any satellite orbits
- Fuller et al. (2014), Fuller (2014)
- Marley (2014)

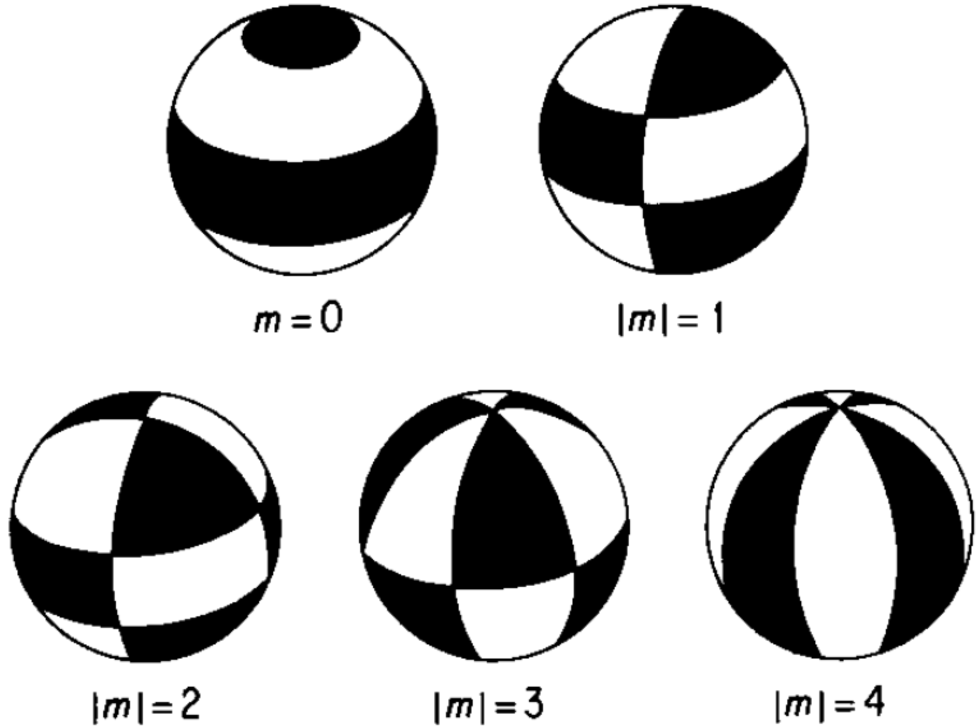
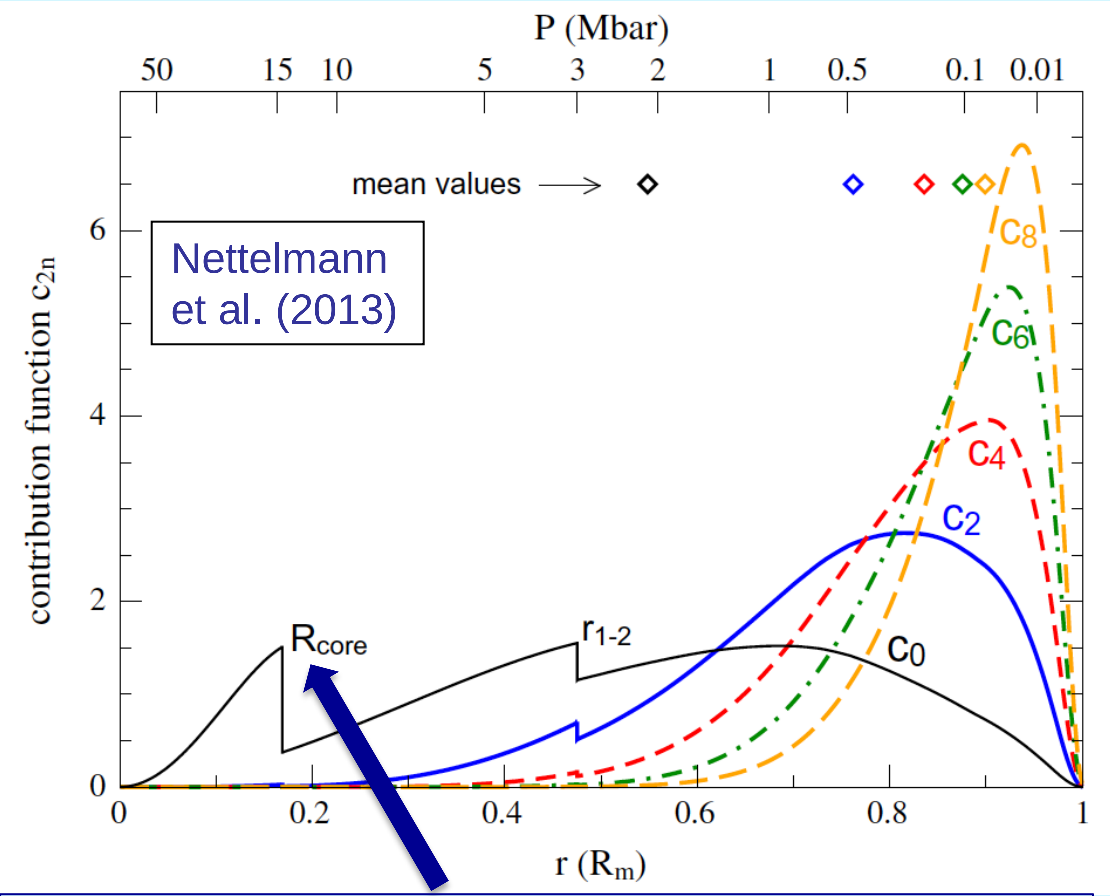


FIG. 1. Illustration of spherical harmonics for degree $l = 4$.

Kronoseismology

- Fuller (2014) find:
    - Evidence for a significant density enhancement below 0.3 R_{saturn}
    - Stably stratified region at ~0.25 R_{saturn}
- Reasonably good agreement with "simple" standard interior models
- Incredibly important additional information
- Suggestive of an ice-dominated core?



- Model used rock+iron EOS for core
- Choice of water or water+rock would yield larger core radius since $R \sim \rho^{-1/3}$
- 3x less dense core (compared to above) would give core radius of ~0.25 R_{saturn}

Juno and Cassini Grand Finale: Precise Gravity and Magnetic Field Constraints

- Current interior structure constrained by J_2, J_4, (and J_6, but with unhelpfully large error bars)
- Cassini Grand Finale, out of perhaps J_{10}
- Not sure on Saturn numbers, but Jupiter gravity field should be determined to within 1 part in 10^9
- Usual method of calculation of gravity field involved expansion of gravity in powers of "smallness parameter" *m*, which is ~0.1

$$m = \frac{3\omega^2}{4\pi G\rho}$$

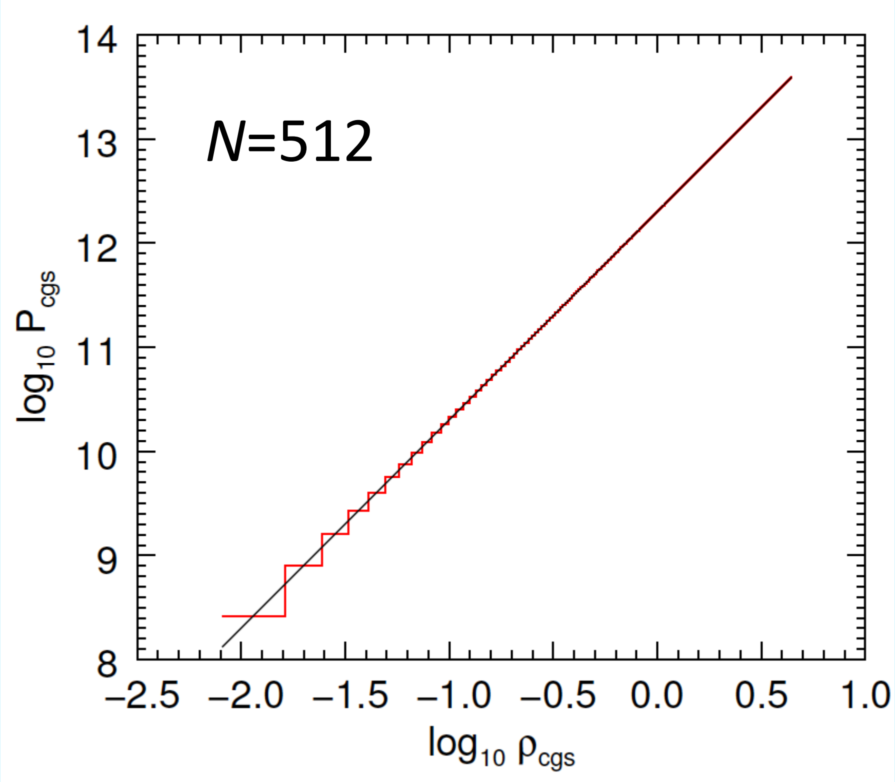
- Would need analytic expansion of theory of figures to at least 9th order (I personally have only heard of the equations expanded to 4th order and they are horrific)

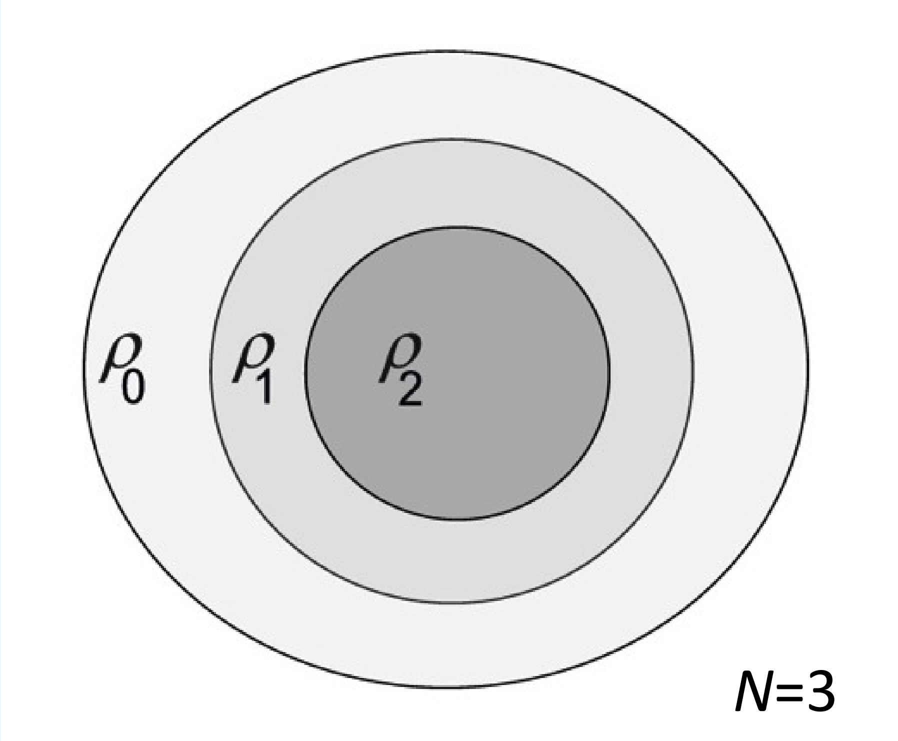
- Recent progress in better ways to calculate the gravity field of fluid planets!

New Methods for Calculating the Gravity Field

Kong et al. (2012, 2013a, 2013b)
Hubbard (2012, 2013)

- *Cassini Grand Finale* to yield gravity field out to ~ J_{10}
- How to calculate model J_n values accurately and efficiently?





- Hubbard's **"Concentric Maclaurin Spheroids" (CMS)**
- Replace continuous density distribution with nested constant density shells
- Can be generalized to multi-D

Preparation for Cassini Grand Finale

- Revised calculations of the H/He phase diagram
  - Needed to better understand He distribution within the planet
  - Not as simple as He-poor and He-rich
- New Saturn evolution models using the revised H/He phase diagram
  - Is He rain the only complication in interior models, or also heavy element gradients?
- Continued work on assessing ring seismology constraints
  - Unique information, but will certainly require years of additional work on what data are telling us
- New reference gravity models using best available constraints
  - Same depth of work need for Saturn models as has previously been done, and currently done, for Jupiter
  - Use constraints from seismology

Conclusions

- Input physics are significantly better than in previous decades
  - Still work to be done in applying this work to Saturn
  - He rain still looks promising
- Seismology already yielding important and novel constraints
  - We can certainly expect new insights from existing data
  - Strong hints of extremely complex behavior
- Gravity field from Cassini Grand Finale should significantly constrain H/He envelope which leads to overall better planet-wide constraints
- *A lot of the field is still limited by “modeling choices” but I can see this is really starting to change*