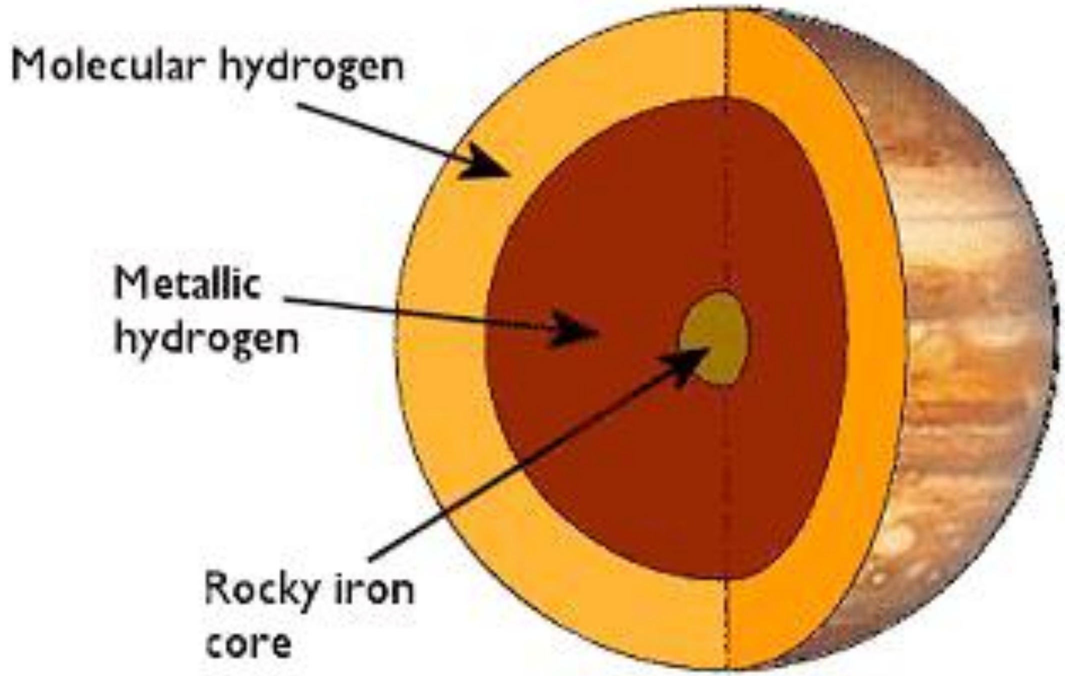
Does Jupiter have a Heavy Element Core?



Dave Stevenson
Caltech

CDPF Conference, Un. Michigan, Oct 14, 2014

…or to state the question more precisely:

Can we determine the mass or existence of Jupiter’s core even if we have ***perfect*** knowledge of the equation of state (EOS)

(The previously imperfect knowledge/ disagreements about the EOS is a major reason for different estimates, ranging from ~0 to ~15 Earth masses)

Some Definitions

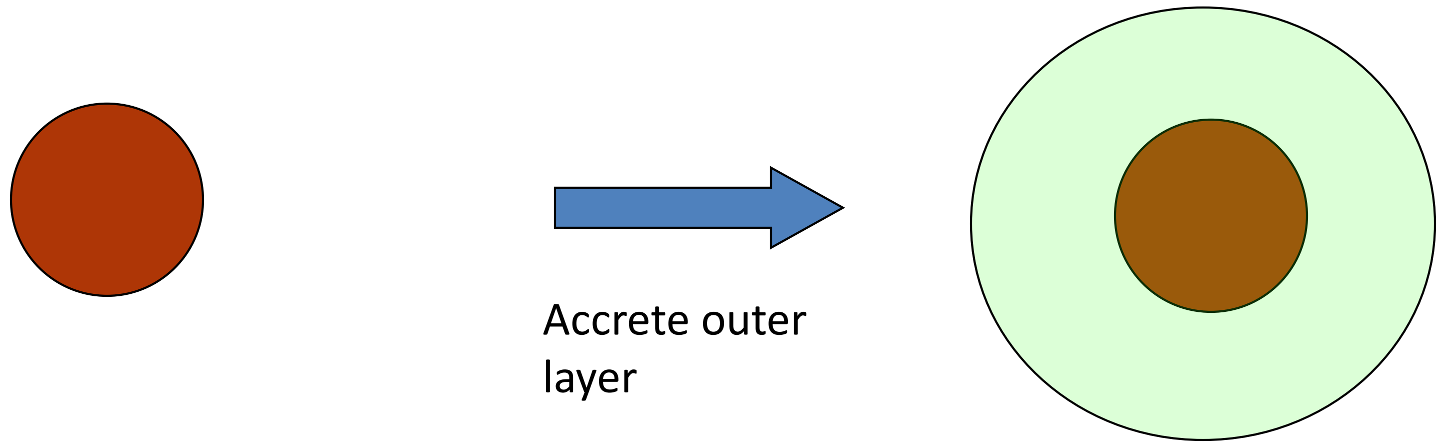
- By “core” I mean a central concentration of elements heavier that H and He
- This core does not have to be solid (it probably is not)
- This core does not have to be rock & iron (it could also contain ice)
- This core need not have a sharp boundary (it probably does not)- in this respect it is ***fundamentally*** different from earth’s core
- This core could contain some H and He mixed into it (and I will argue that it does)

Why is this an Interesting Question?

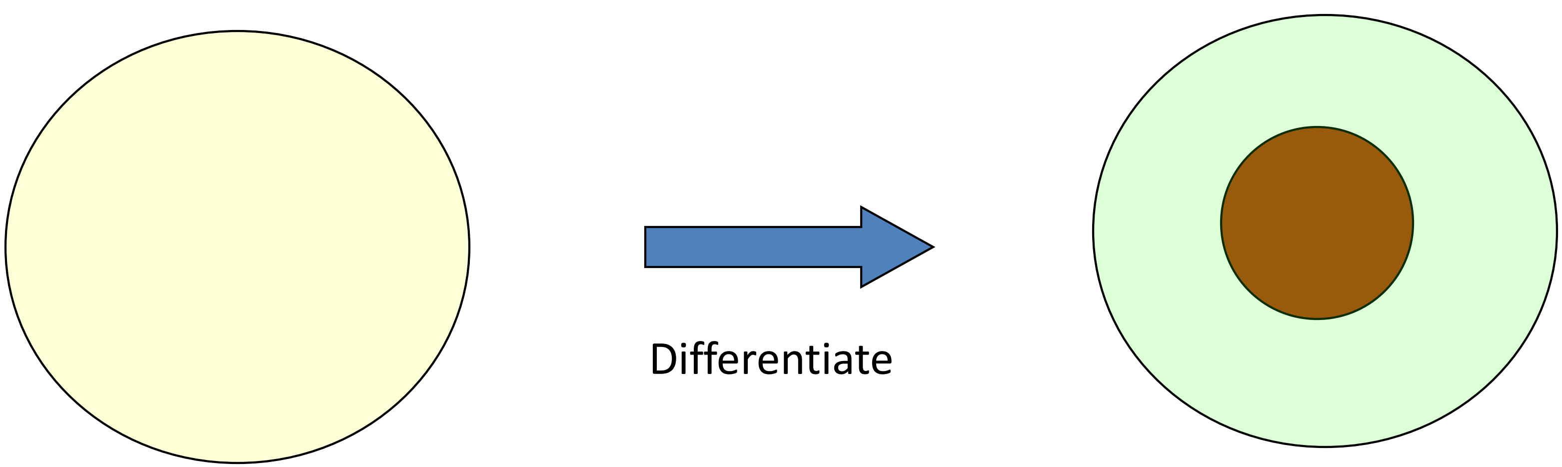
- Presence of core could tell us about the formation process
  - This was a major part of the justification for Juno, which will arrive at Jupiter on July 4, 2016.
  - Jupiter may define solar system architecture
- Persistence of a core may tell us thermodynamics of mixtures within Jupiter & the convective state
  - Relevant to the heat flow
  - Possibly relevant to the dynamo

Why might a Planet have a Core?

Bottom Up



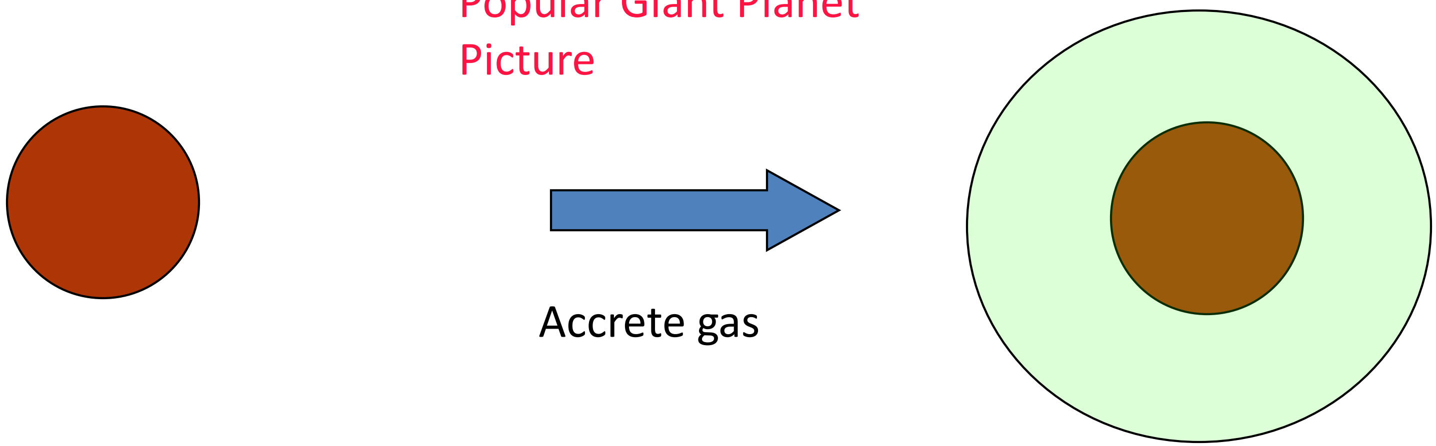
Top Down



Why might a Planet have a Core?

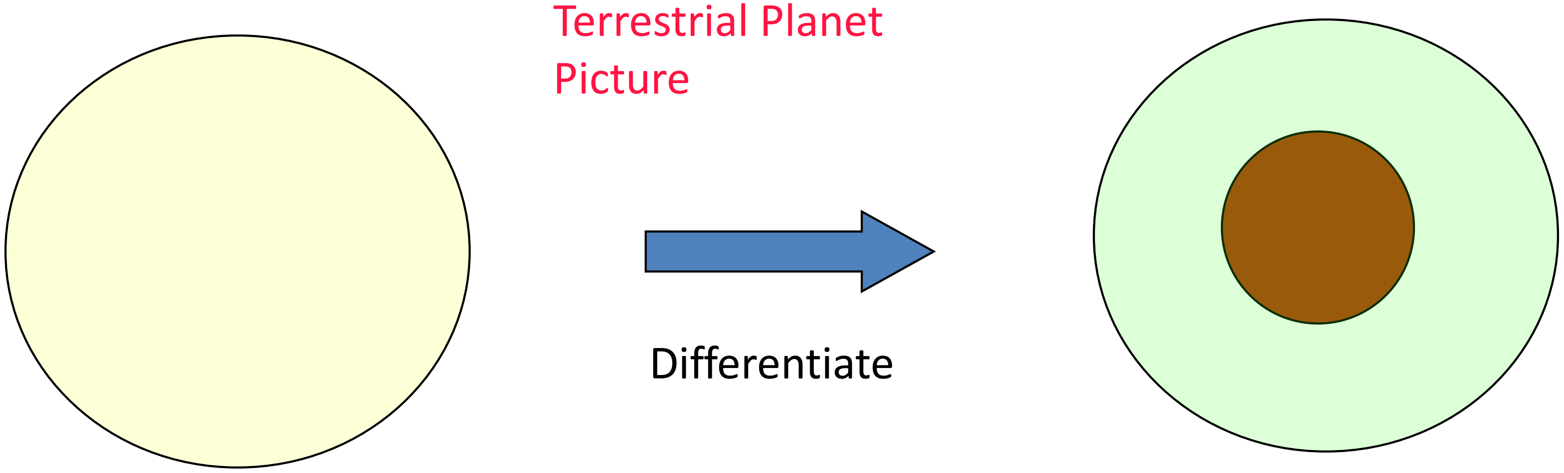
Bottom Up

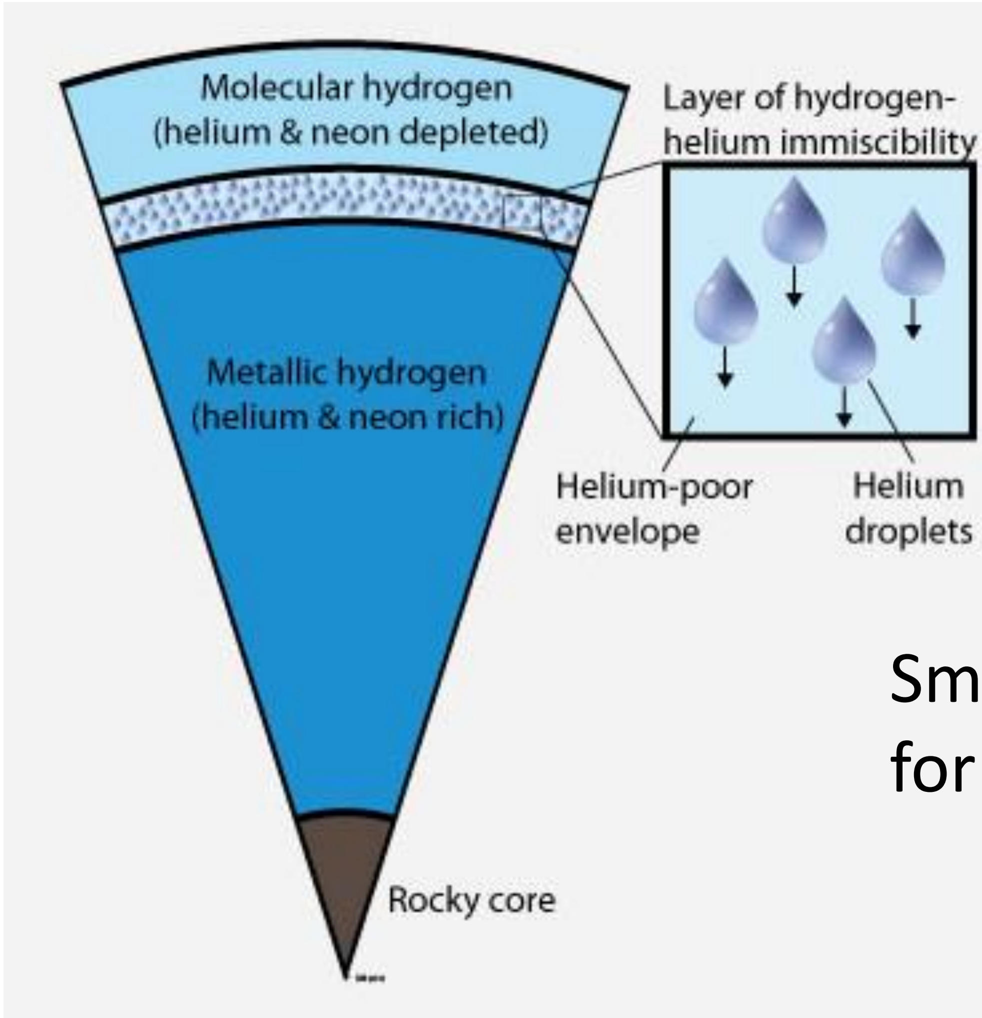
Popular Giant Planet Picture



Top Down

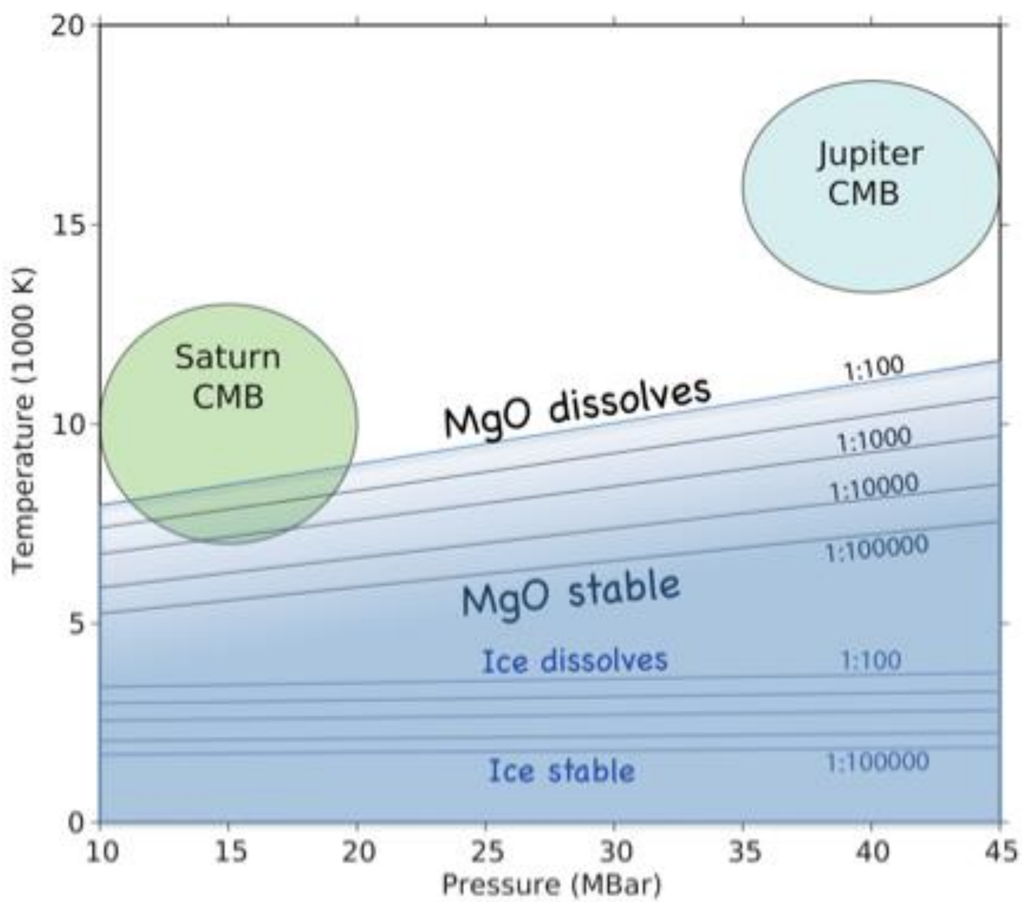
Well established Terrestrial Planet Picture





Small effect
for Jupiter

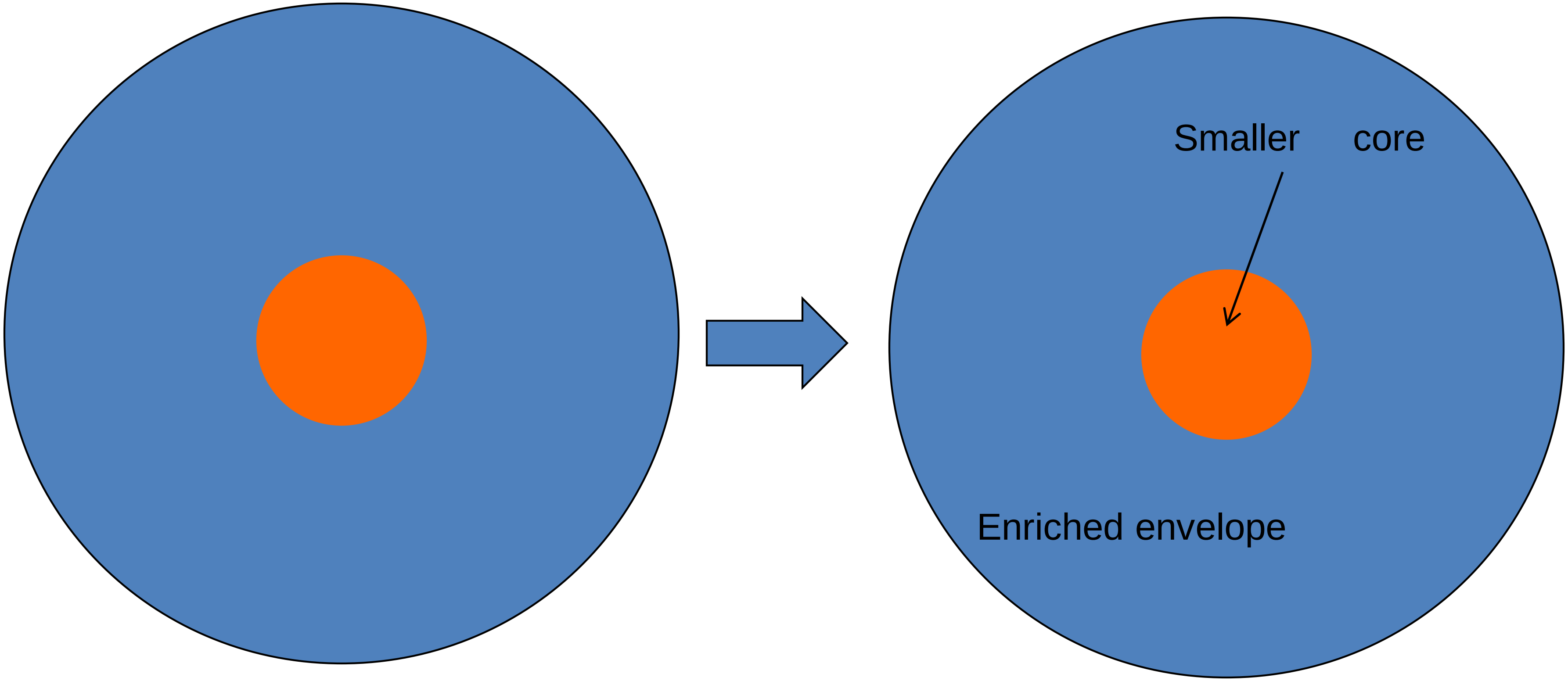
“Oh that this too too solid flesh would melt,
Thaw and resolve itself into a dew!”
-Shakespeare, *Hamlet*



Wilson & Militzer, 2011,2012

Two Reasons Why the Core is not Sharply Defined

- It was not sharply defined during accretion because the accretion temperatures predict that incoming planetesimals will break up and dissolve in the planetary envelope
- It is even less sharply defined because convection will mix up material from the core during subsequent evolution
  - Double diffusive convection (cf. Stevenson, 1985; LeConte and Chabrier, 2012)

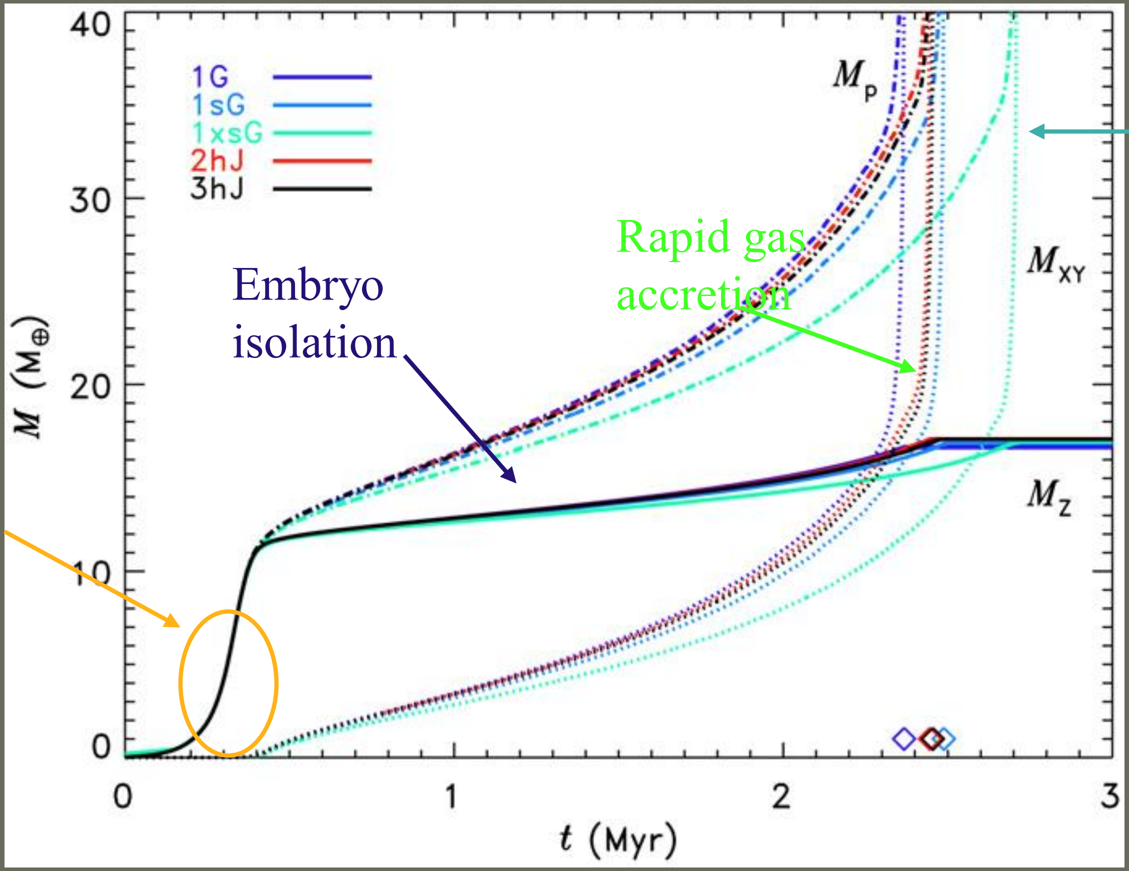


We would like to know the structure at early time (end of accretion)

The structure we see now is not necessarily the same

Core accretion model ("Standard" Case)

Embryo formation (runaway)



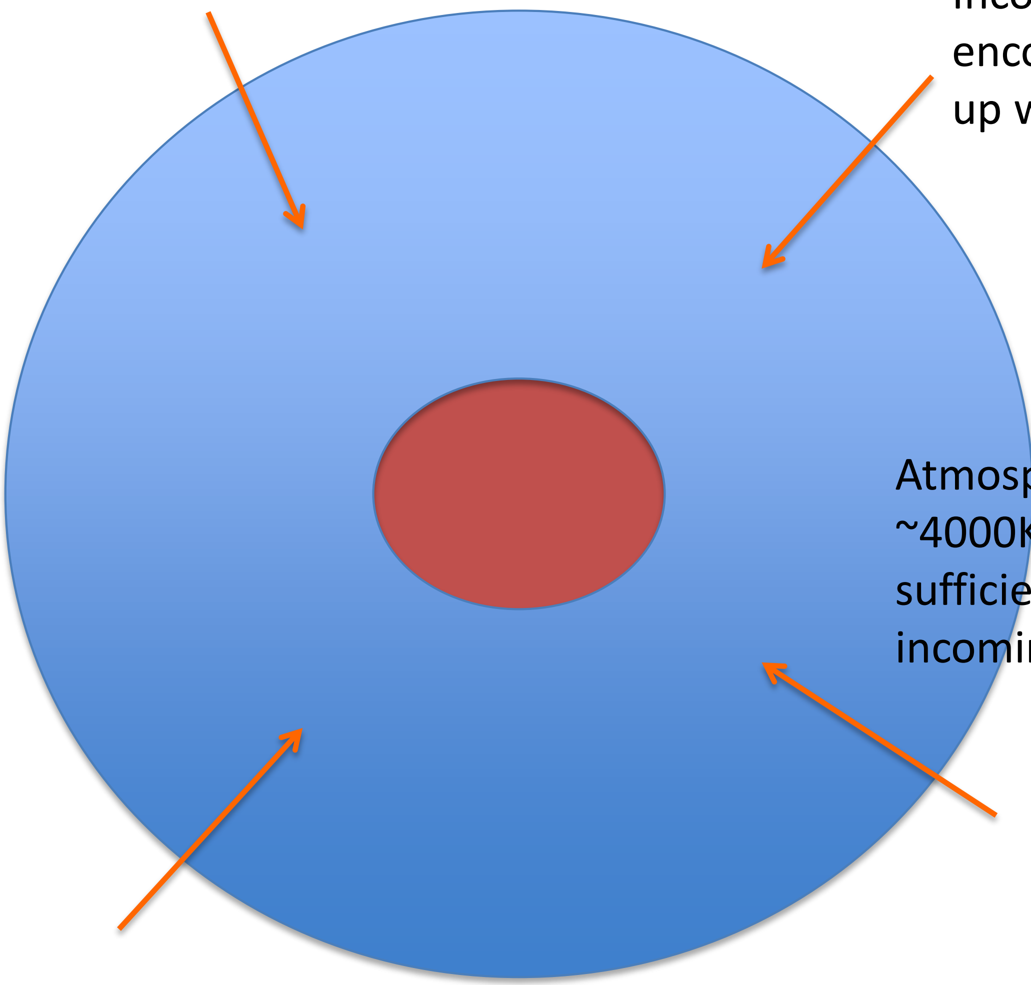
Truncated by gap formation

Pollack *et al*, 1996; Lissauer *et al* , 2009

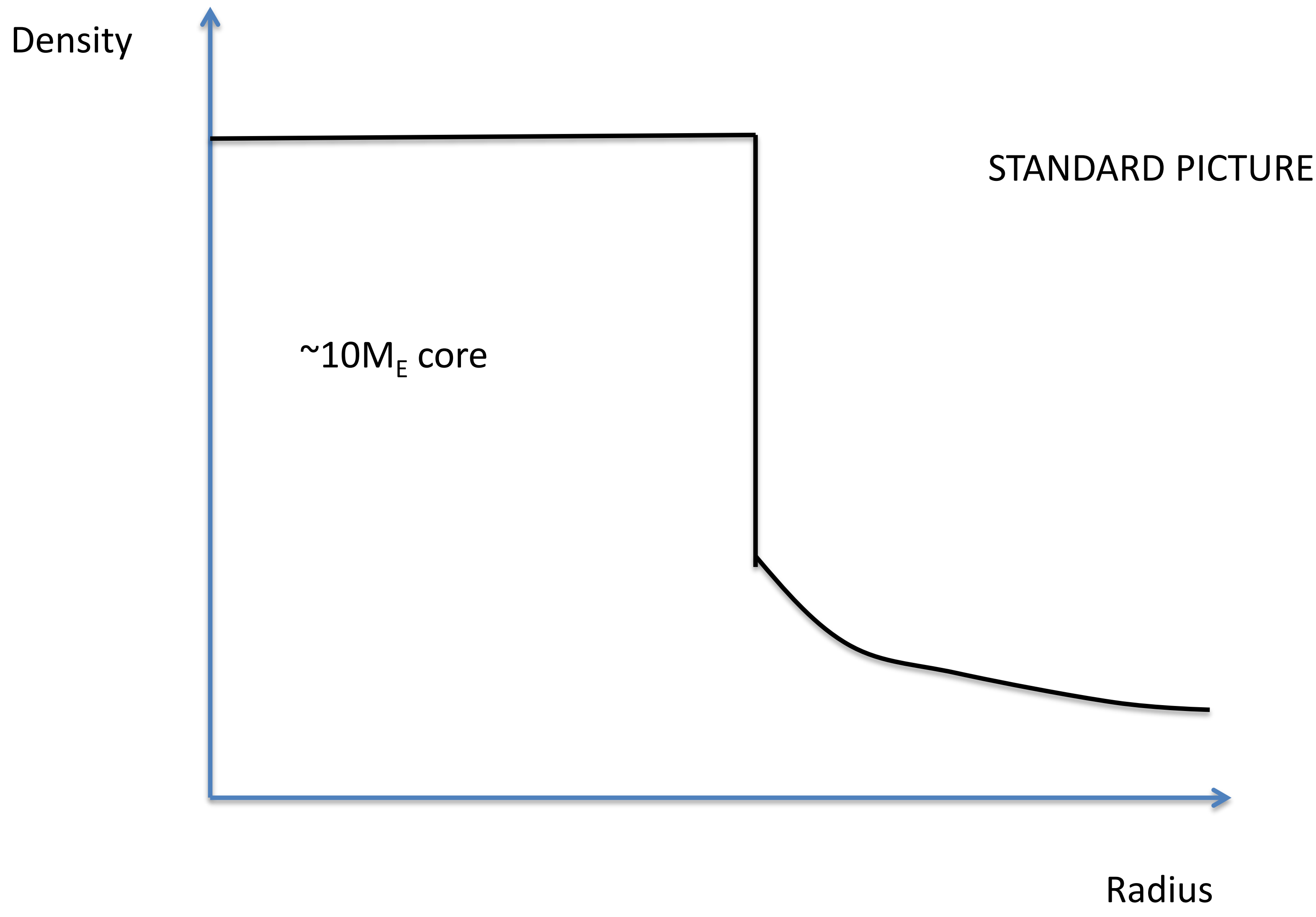
"Just the place for a Snark! I have said it twice:
That alone should encourage the crew.
Just the place for a Snark! I have said it thrice:
What I tell you three times is true.

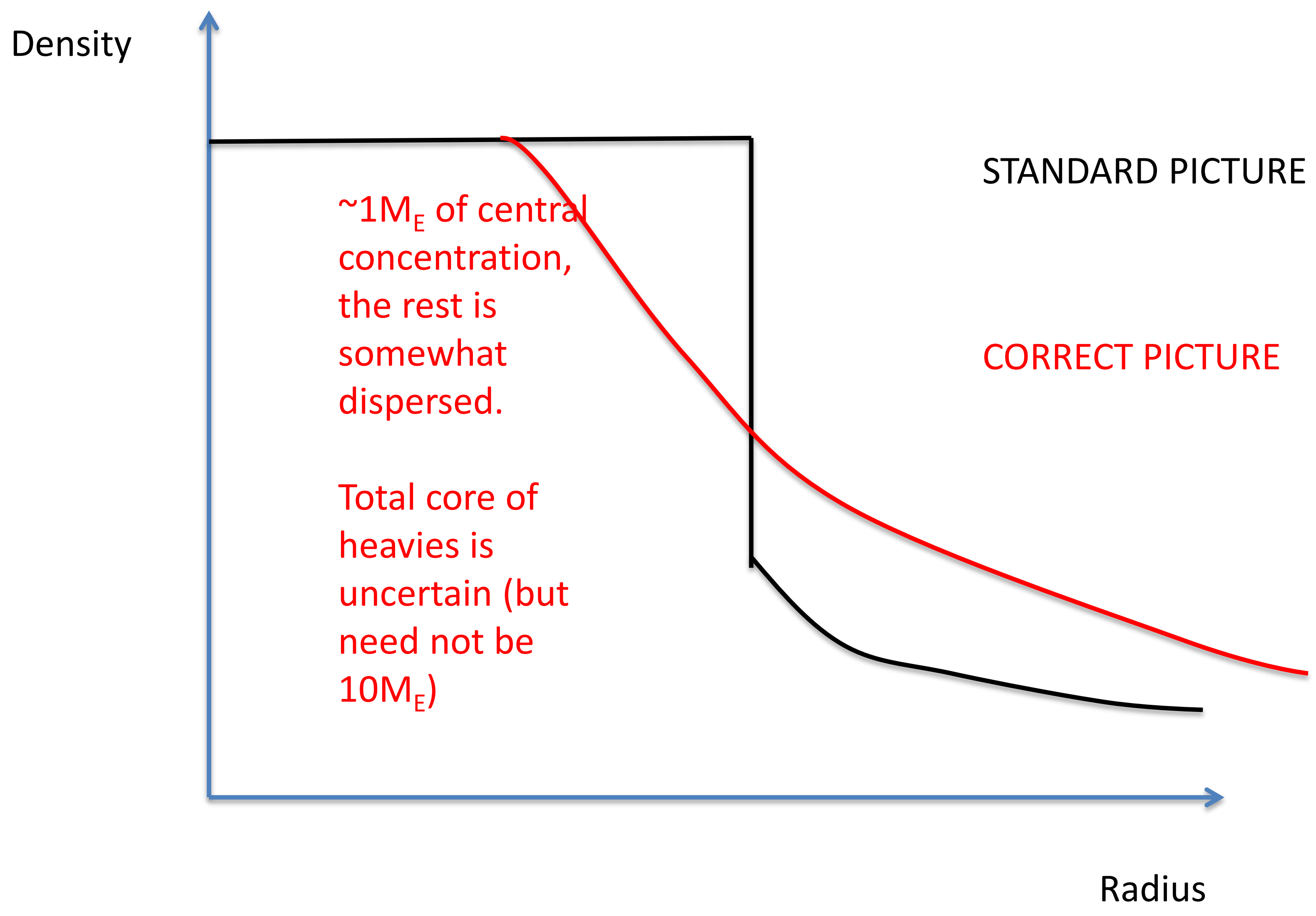
-Lewis Carroll

Incoming planetesimals encounter enough gas to break up when the core is only ~$1M_E$



Atmospheric basal T is ~4000K when core is $1M_E$, sufficient to dissolve all the incoming material


Density
STANDARD PICTURE
~10M$_E$ core
Radius



Density
STANDARD PICTURE
~1M$_E$ of central concentration, the rest is somewhat dispersed.
CORRECT PICTURE
Total core of heavies is uncertain (but need not be 10M$_E$)
Radius

- Energy of formation for $10M_E$ is enough to vaporize the ice and rock *ten times over.*
- Energy is enough to raise internal T to 120,000K
- Radiation into a vacuum creates a core "surface" T of ~1200K for the Lissauer et al model.
  - But it's not a vacuum: Nebula gas ensures a $T \sim GM\mu/4kr$ (Radiative zero solution, Stevenson, 1982). This is ~15,000K at the "surface"(of the core) for H/He.
  - But there's no surface! This T is well above vaporization (and critical T) for both ice & rock. This makes T even larger!

A Likely Picture

- Incoming planetesimals disrupt because of ram pressure overcoming self-gravity (or strength). Occurs at $P \sim 0.1$bar $(R/10\mathrm{km})^2$
- Constituents sublime (ice higher up, rock deeper down). Only very large bodies can go all the way.
- Result is probably a stable molecular weight gradient , high molecular weight at the base; T ~tens of thousands K.
- Compositional gradient prevents direct convection but double –diffusive convection is possible.
- Much larger hydrogen addition as well as heavy elements.

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A new vision on giant planet interiors: the impact of double diffusive convection

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Abstract

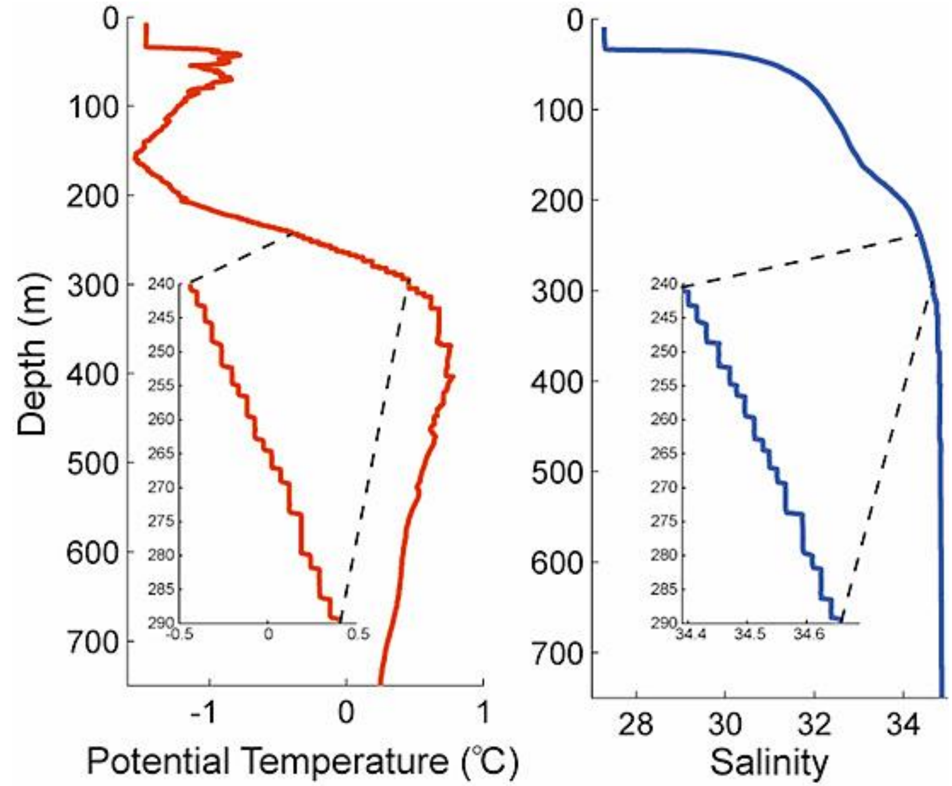
While conventional interior models for Jupiter and Saturn are based on the simplistic assumption of a solid core surrounded by a homogeneous gaseous envelope, we derive new models with an inhomogeneous distribution of heavy elements, i.e. a gradient of composition, within these planets. Such a compositional stratification hampers large scale convection which turns into double-diffusive convection, yielding an inner thermal profile which departs from the traditionally assumed adiabatic interior, affecting these planet heat content and cooling history.
To address this problem, we develop an analytical approach of layered double-diffusive convection and apply this formalism to Solar System gaseous giant planet interiors. These models satisfy all observational constraints and yield a metal enrichment for our gaseous giants up to 30 to 60% larger than previously thought. The models also constrain the size of the convective layers within the planets. As the heavy elements tend to be redistributed within the gaseous envelope, the models predict smaller than usual central cores inside Saturn and Jupiter, with possibly no core for this latter.
These models open a new window and raise new challenges on our understanding of the internal structure of giant (solar and extrasolar) planets, in particular on the determination of their heavy material content, a key diagnostic for planet formation theories.

Key words. Double diffusive convection; Planet internal Structure; Jupiter; Saturn

Double-Diffusive Staircase

An example of thermohaline convection in Earth's oceans

The steps develop naturally and evolve over time so that transport of both heat and composition are much enhanced over pure molecular diffusion.



Thermal Evolution

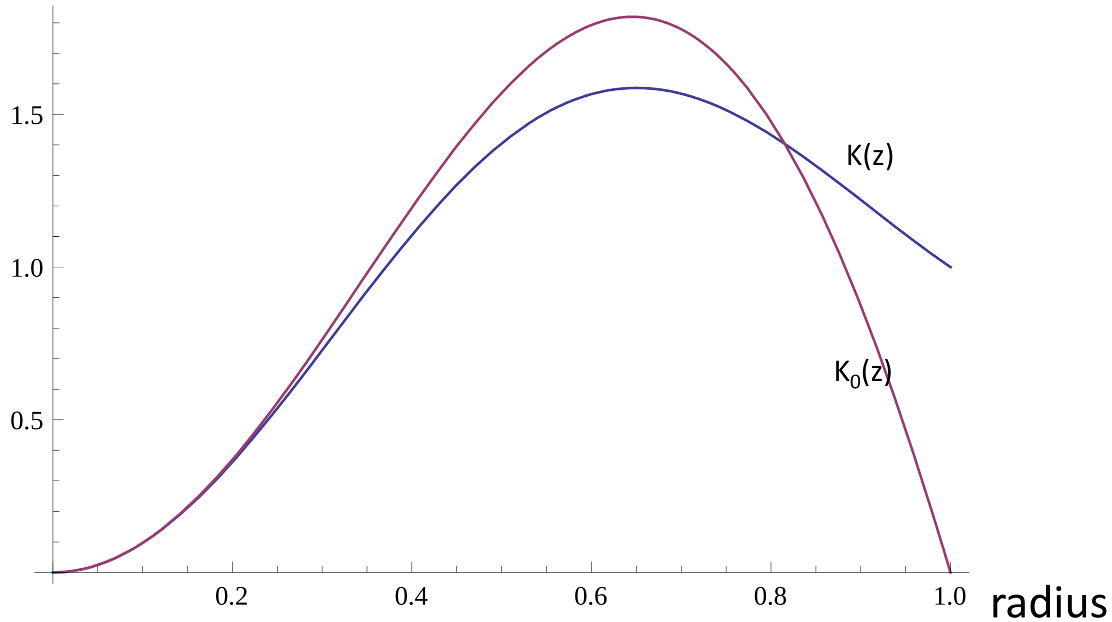
- It seems that Lord Kelvin was right for Jupiter (but not for earth or for the Sun)…we can understand the heat flow now simply by assuming a hot start. Timescale ~ heat content/luminosity. But even for Jupiter, one suspects this is somewhat fortuitous.
- For Jupiter with a core, $E_{grav} \cong -0.75(1+2M_c/M)GM^2/R$ (nearly exact for n=1 polytrope)
- Mixing up this core requires the equivalent of cooling the planet by at least 1000K, mass averaged (probably much more) and so is unlikely

n=1 polytrope
(new results)

$$\frac{R}{R_o} \cong 1 - \frac{M_Z}{M}$$

$$\frac{\alpha}{\alpha_o} \cong 1 - 1.5\frac{M_c}{M}$$

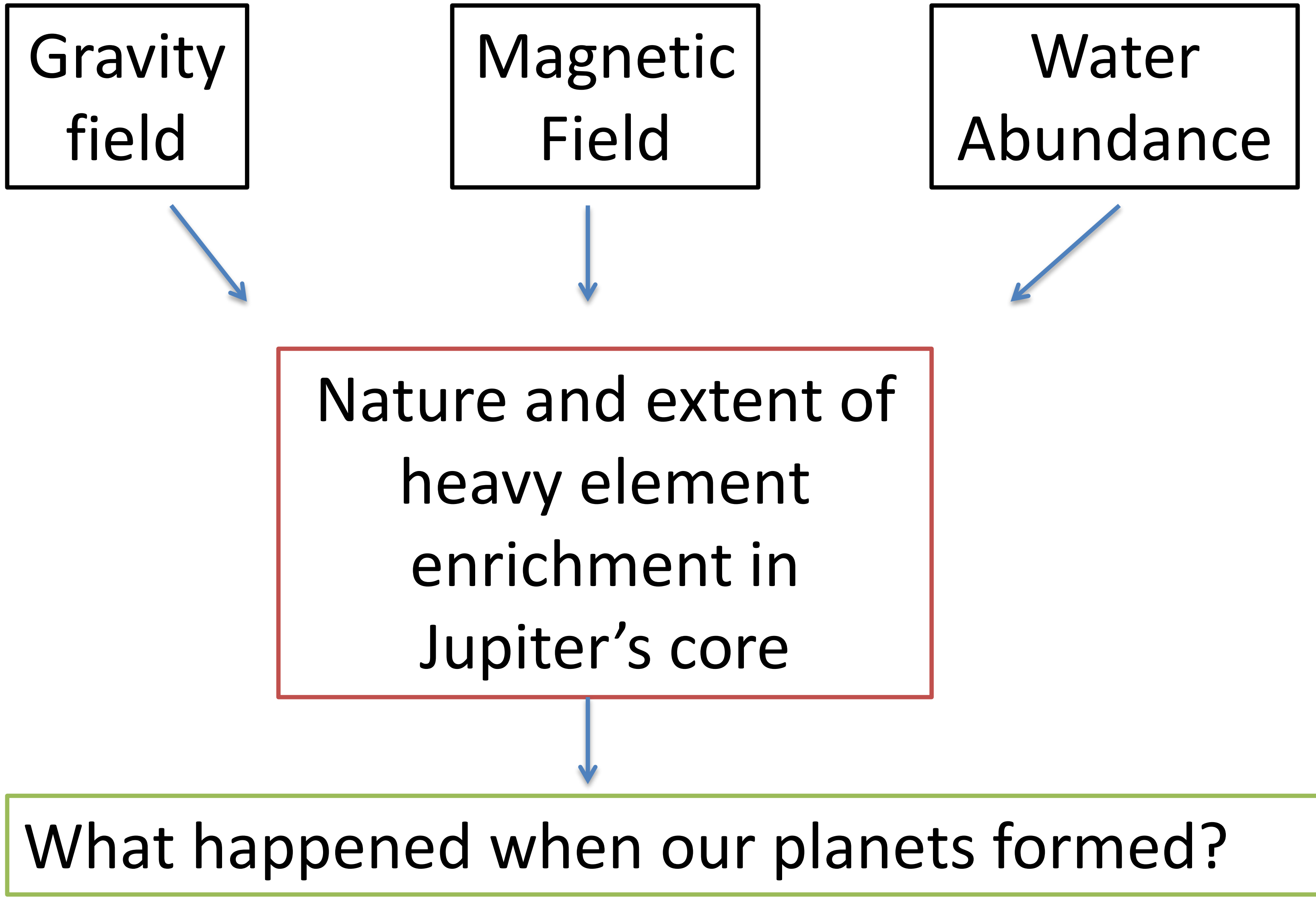
R=radius
R_o=radius for pure H-He
M_Z= total mass of heavies (core & envelope)
$\alpha = C/MR^2$; α_o =value fro pure H-He ($\cong 0.262$)
M_c =core mass *defined to be only the original enrichment of heavies!*



$$\delta = \frac{1}{\pi}\int_0^{\pi} y(z)K(z)dz$$

$$\bar{y} = \frac{1}{\pi}\int_0^{\pi} K_o\,(z)y(z)dz$$

Change in planet radius is remarkably insensitive to the distribution of heavy elements


Gravity field
Magnetic Field
Water Abundance
Nature and extent of heavy element enrichment in Jupiter's core
What happened when our planets formed?

Conclusions

- We will be able to tell whether Jupiter has a core and even establish the mass of that core *provided we define the core to be the excess of heavy elements*
  - Assumes good understanding of hydrogen equation of state
- We will <u>not</u> be able to establish the nature of that core with any confidence (i.e., the extent to which it is dispersed rather than concentrated) by "conventional" techniques (gravity moments)
  - Unconventional includes tidal response, normal modes and perhaps magnetic field