Planet formation

- Is accepted to occur in an accretion disk of gas and dust around the star
- Two main models

1) Aggregation via planetesimal accretion

* seems only

way for rocky

planets/moons

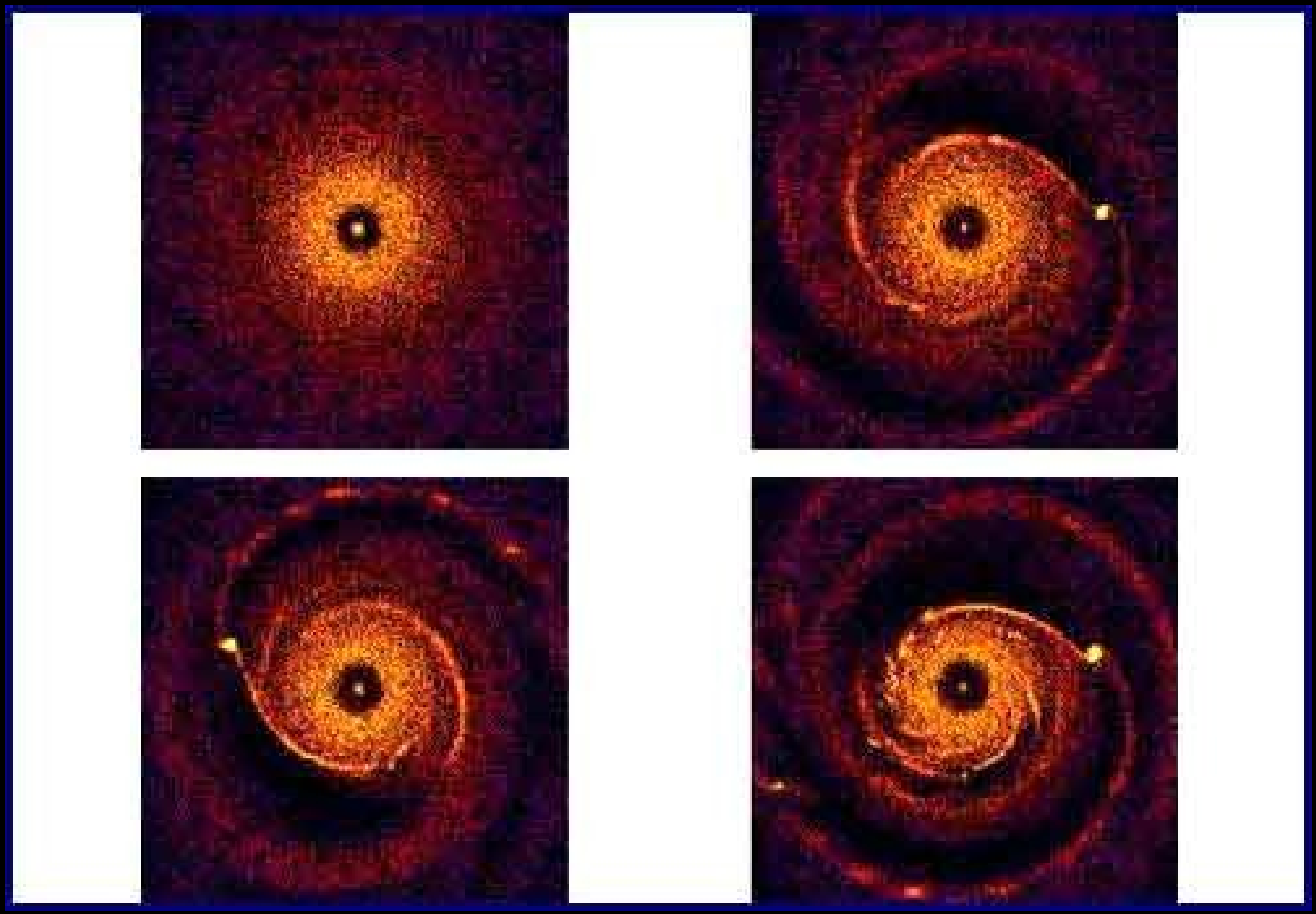
Planet formation

- Is accepted to occur in an accretion disk of gas and dust around the star
- Two main models

1) Aggregation via planetesimal accretion
2) Direct collapse at the planetary scale via gravitational instability
   - Has appeal for gas giants, but currently less favoured

Planet formation

- Direct collapse at the planetary scale via gravitational instability: did it happen here?



Armitage and Hansen (1999)

Solar System has 3 'types' of planetary bodies

- Rocky inner (terrestrial) planets

2 GAS 2 ICE

- Giant outer planets

- Pluto (same as inner)

(*nothing* is to scale in the picture above!)

Terrestrial planet cookbook: follow these easy steps

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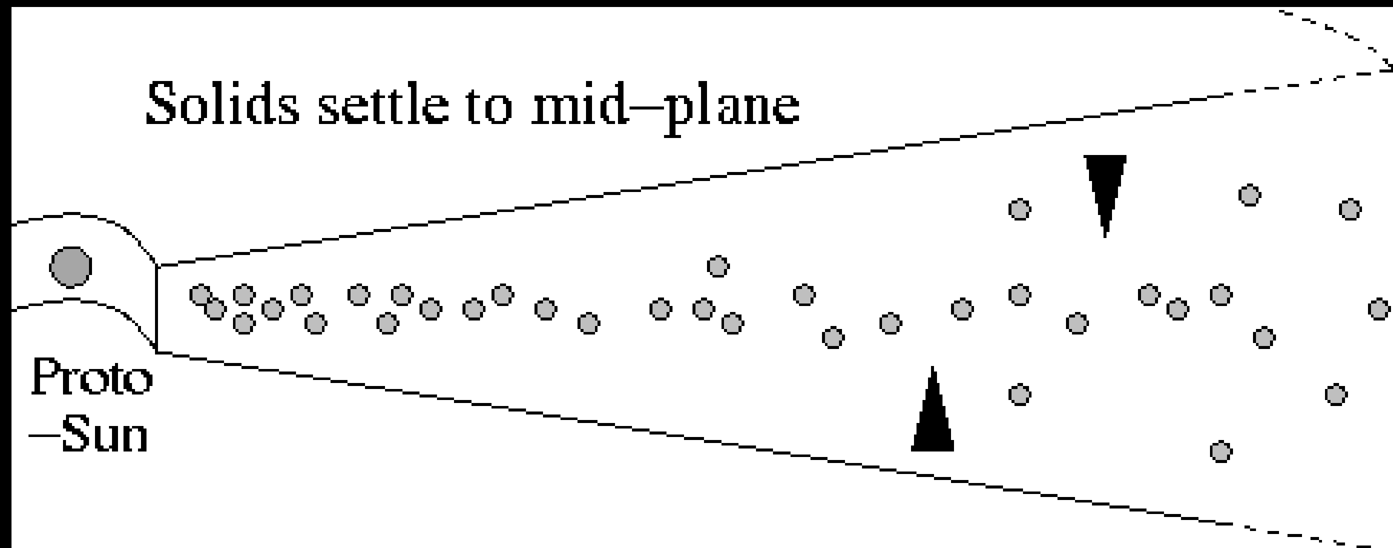
4) embryos coalesce into final planets (e and i of formed planets high)

1) Dust sedimentation



1) No direct planetesimal creation
2) 10-100 μm grains settle to midplane
3) Grains stick together to build macroscopic (~cm and larger) objects

Minimum Mass Solar Nebula

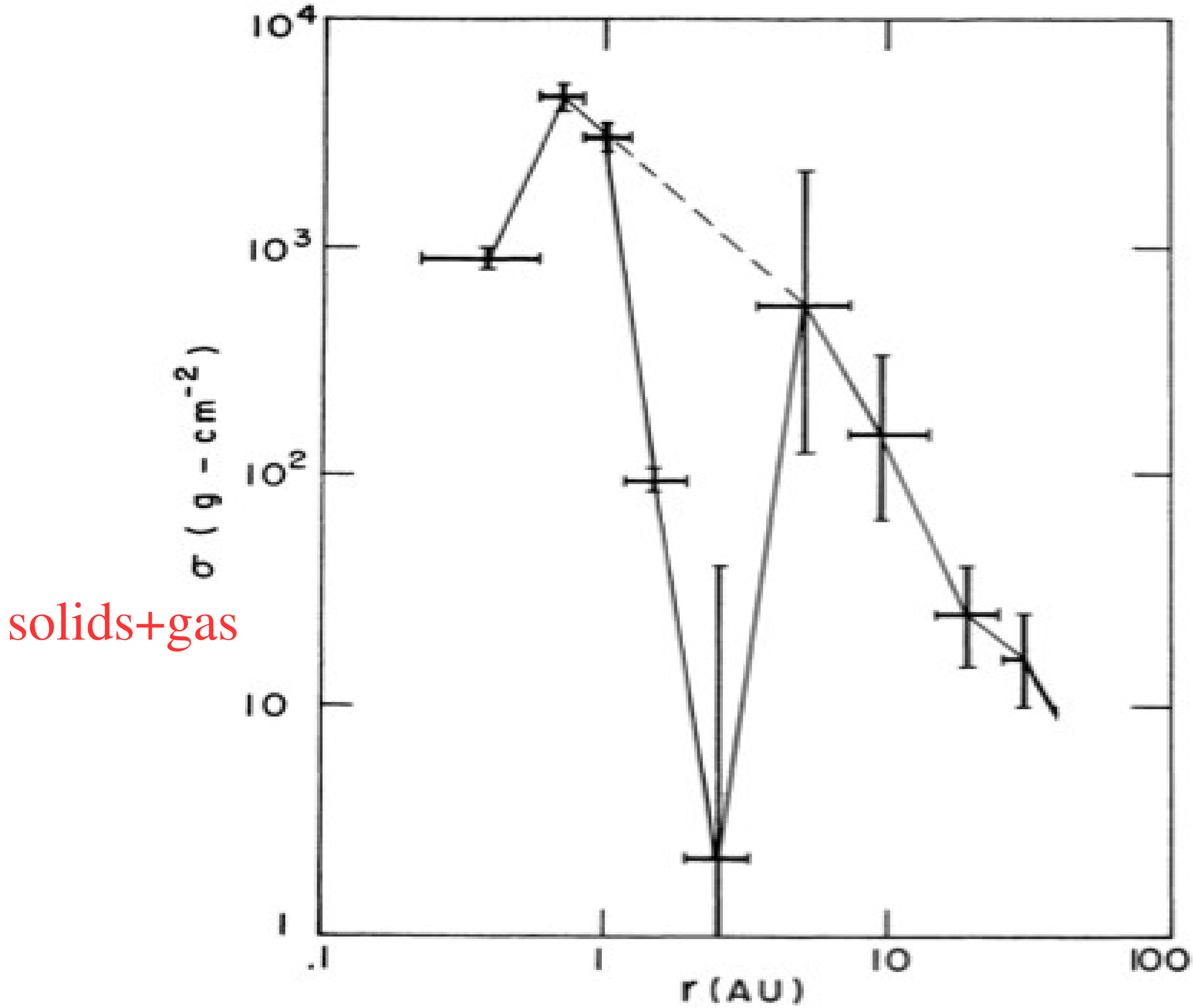


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits.

The solids are then augmented back to solar composition to include gas.

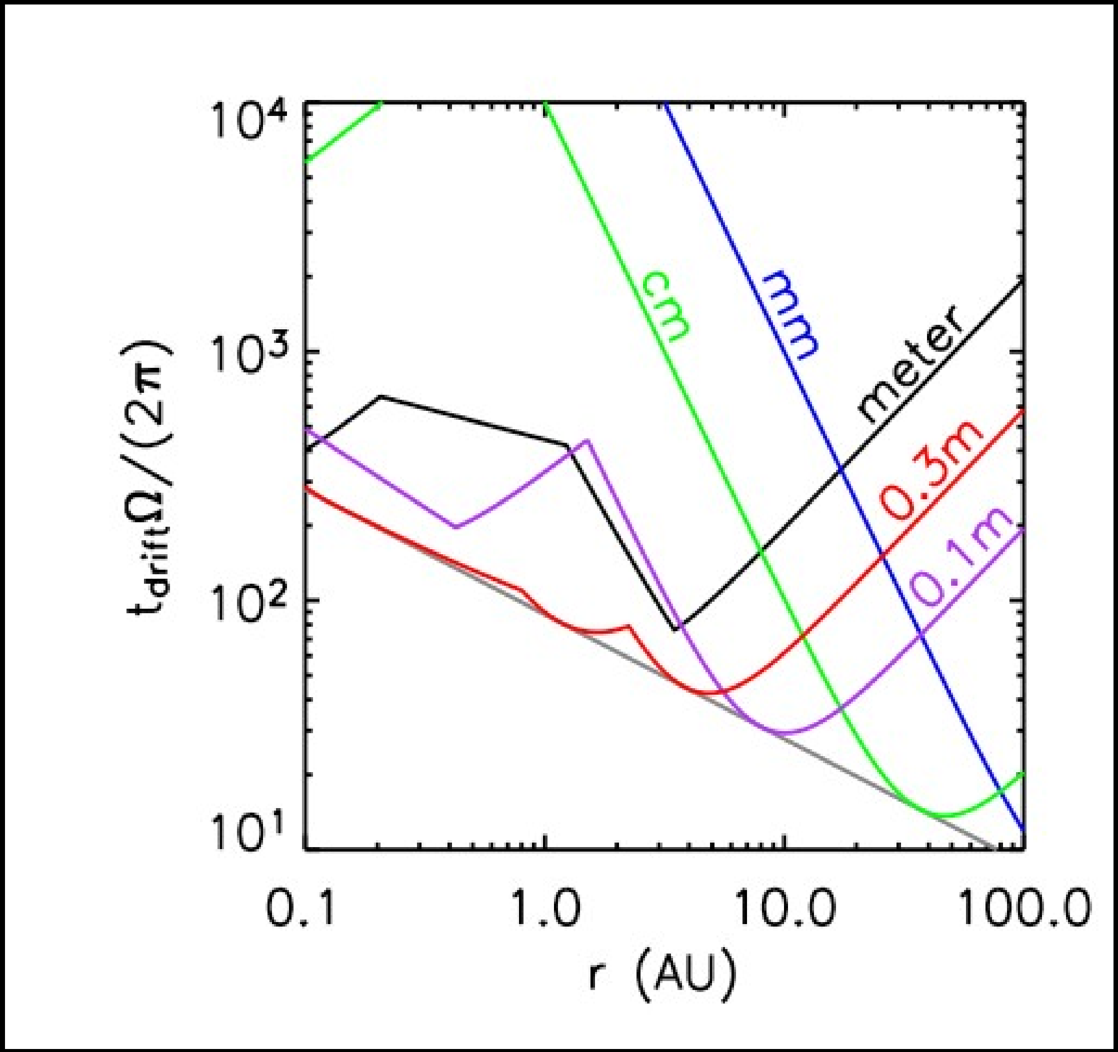
2) Planetesimal creation

1) Need ~1-km objects (decouple from gas)
2) The 1-meter barrier, unresolved
3) Concentration in small local vortices?

The problem of drag

Pressure support of disk means that the planetesimals see a 'headwind', causing frictional drag.

Figure : time scale for 1/e drop of 'a' in terms of orbital period



1) In the inner part of the nebula meter-scale bodies spiral towards the star in just tens of orbital periods.

The 'planetesimal hypothesis'

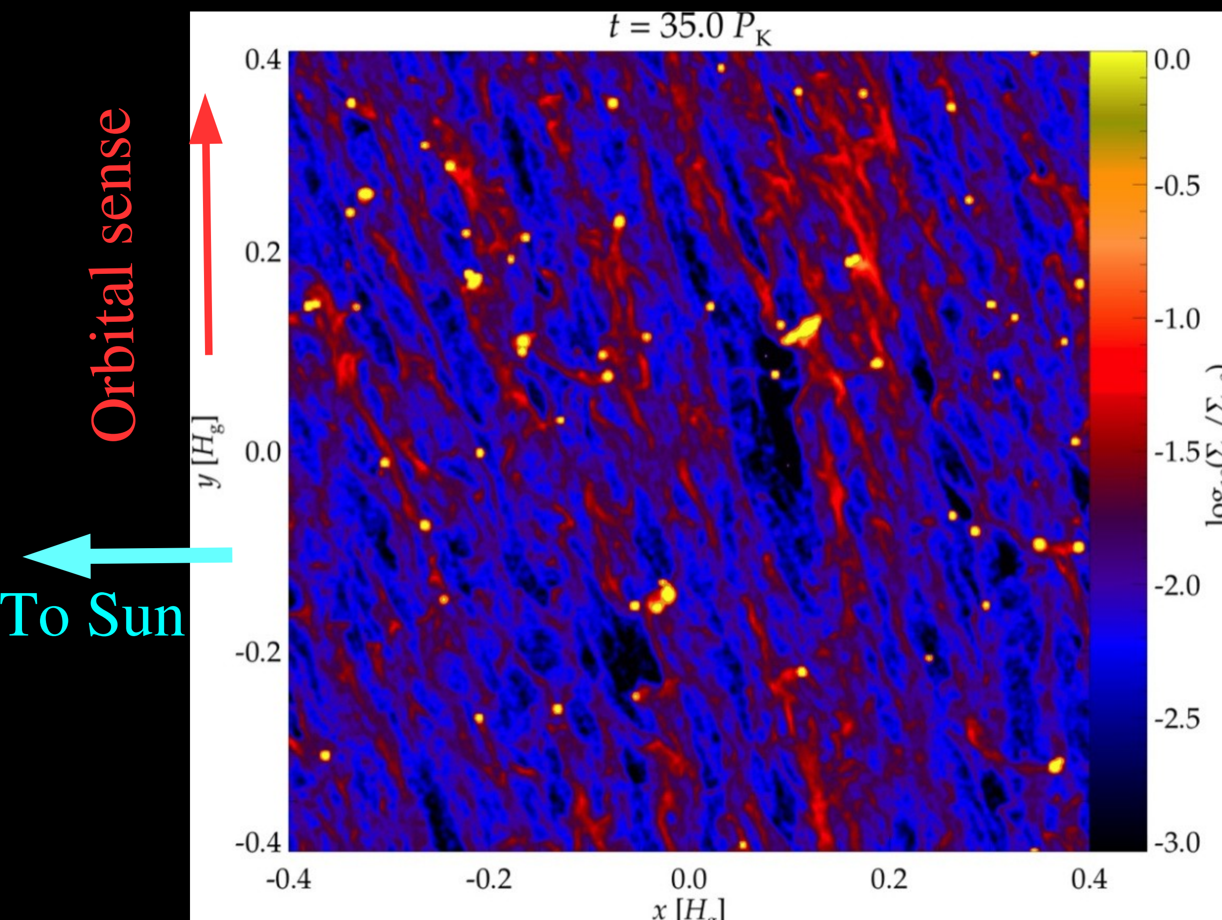
- The 'meter barrier problem' and the fact that meteorites imply that 'asteroid parent bodies' assembled rapidly imply there is some physics that quickly collects <cm sized sedimented solids into >km scale objects
- The Goldreich-Ward (1973) hypothesis: Solid disk becomes so thin it becomes dynamically unstable to clumping
  - Not now favoured; turbulence too strong!
- Today's favorite: Streaming instabilities

Streaming Instability

- Once sufficiently concentrated to midplane, instabilities in the gas cause gas clumping and drag concentrates solid particles

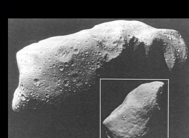
- Numerical simulation of coupled solid and gas dynamics in small patch of protosolar nebula.

- Colour bar is dust/gas surface density ratio.



3) Form planetary embryos via local 'runaway'

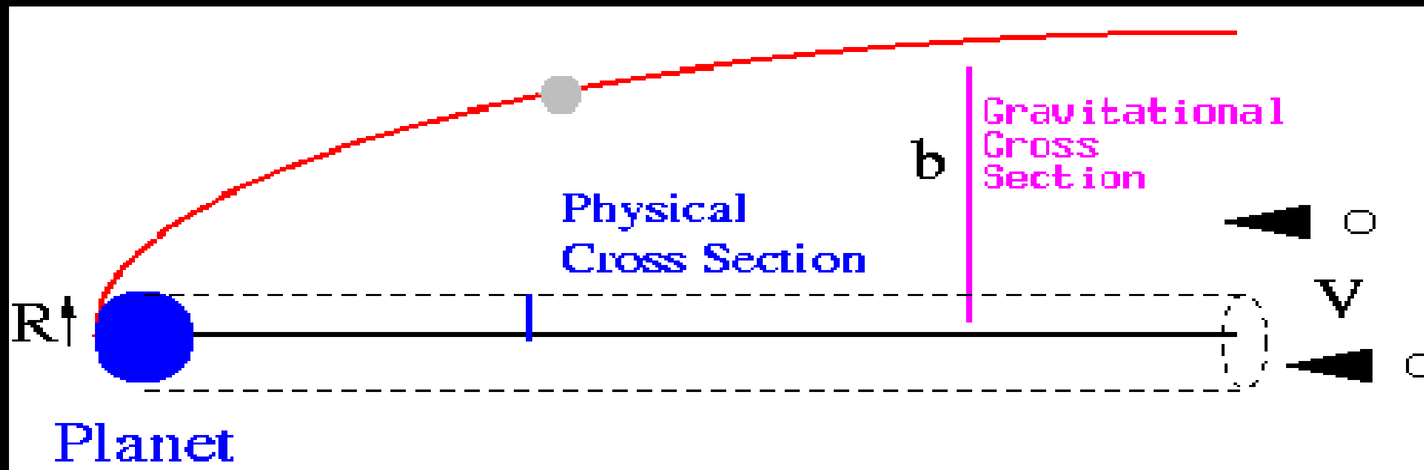
1) Well understood analytically+numerically
2) Planetesimal swarm on very circular and low inclination orbits
3) The biggest objects get bigger faster (simple to understand)
4) In inner S.S., go from 'asteroids' to Moon



>>10^9 in mass>>

3) Runaway accretion, cont'd

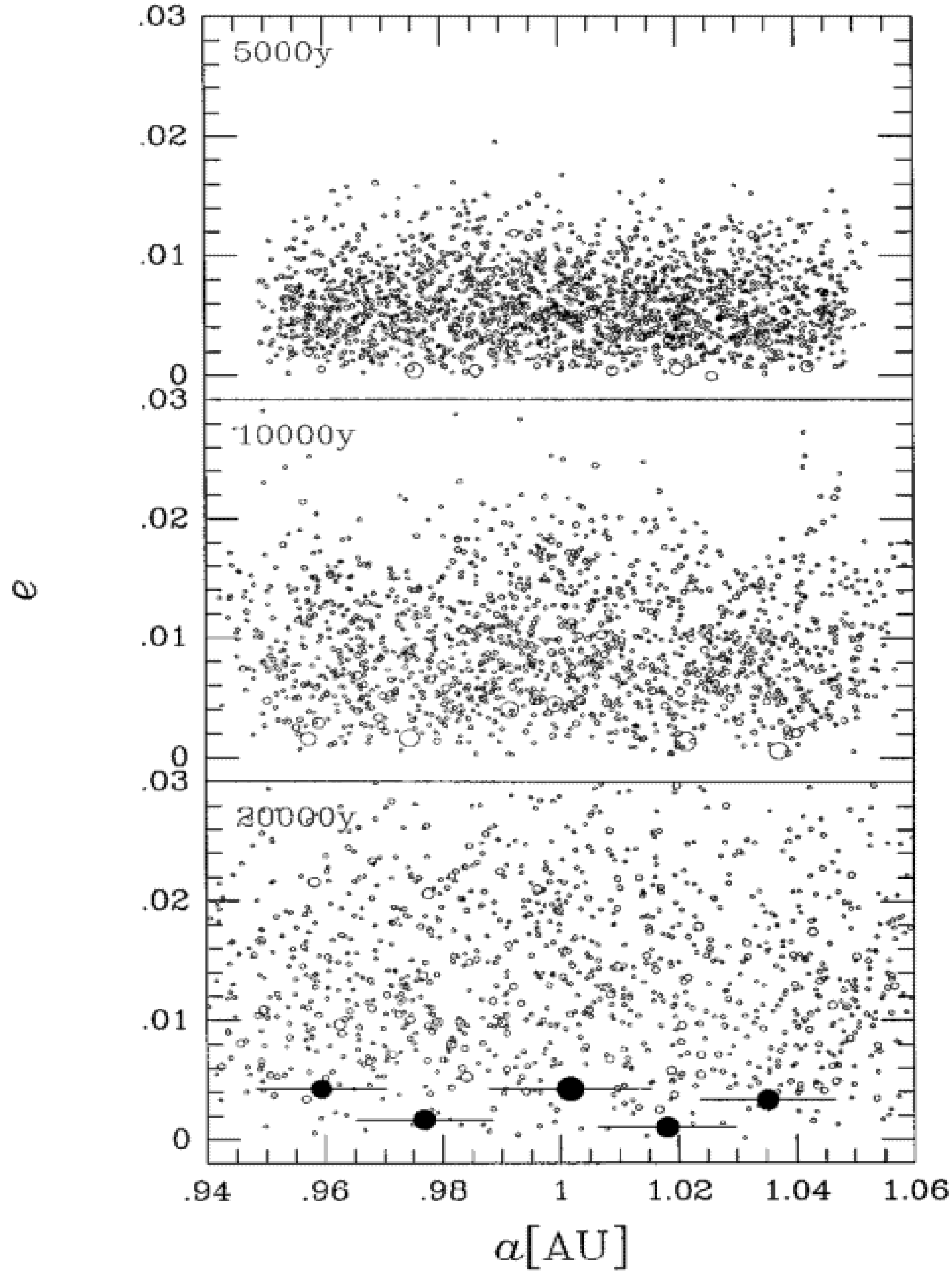
1) Increase in physical cross-section



$$\pi b^2 = \pi R^2 [1 + (V_{esc}/V)^2]$$

- Once an object gets large enough, its growth rate proportional to radius

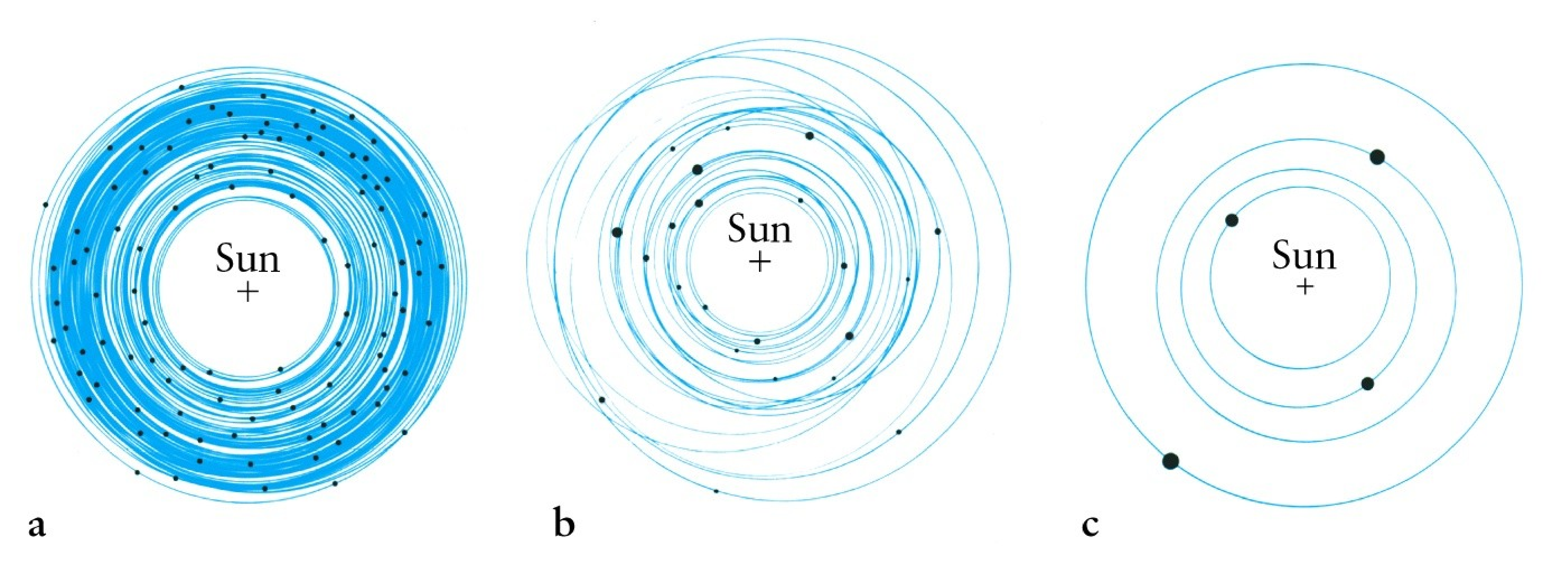
At any given distance, one object (embryo) sucks up most of the mass
in a 'runaway' accretion until it 'isolates'



Near 1 AU, reach lunar size

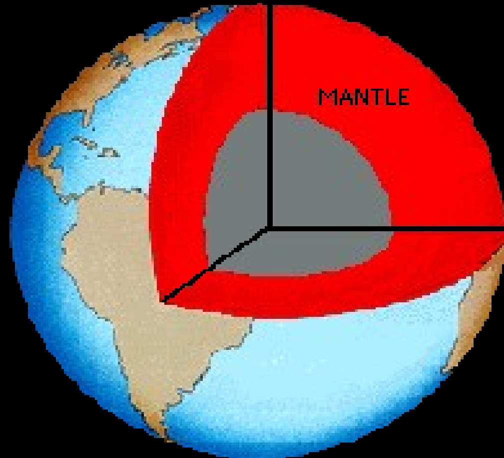
1) Finish with 'nested' set of embryos
2) Note embyros on low-e orbits (dynamical friction)
3) Ready for next stage

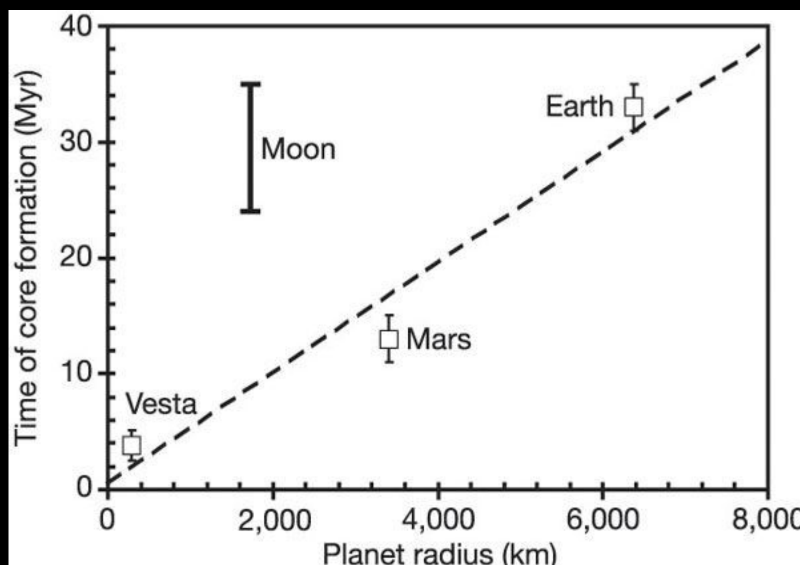
4) Put the lunar embryos together



- One gets planets at the end!
  -Number and location is stochastic, but basically correct outcome.
  Caution: orbital e and i too high...

  -(Solution probably missing interactions with remaining small planetesmals)



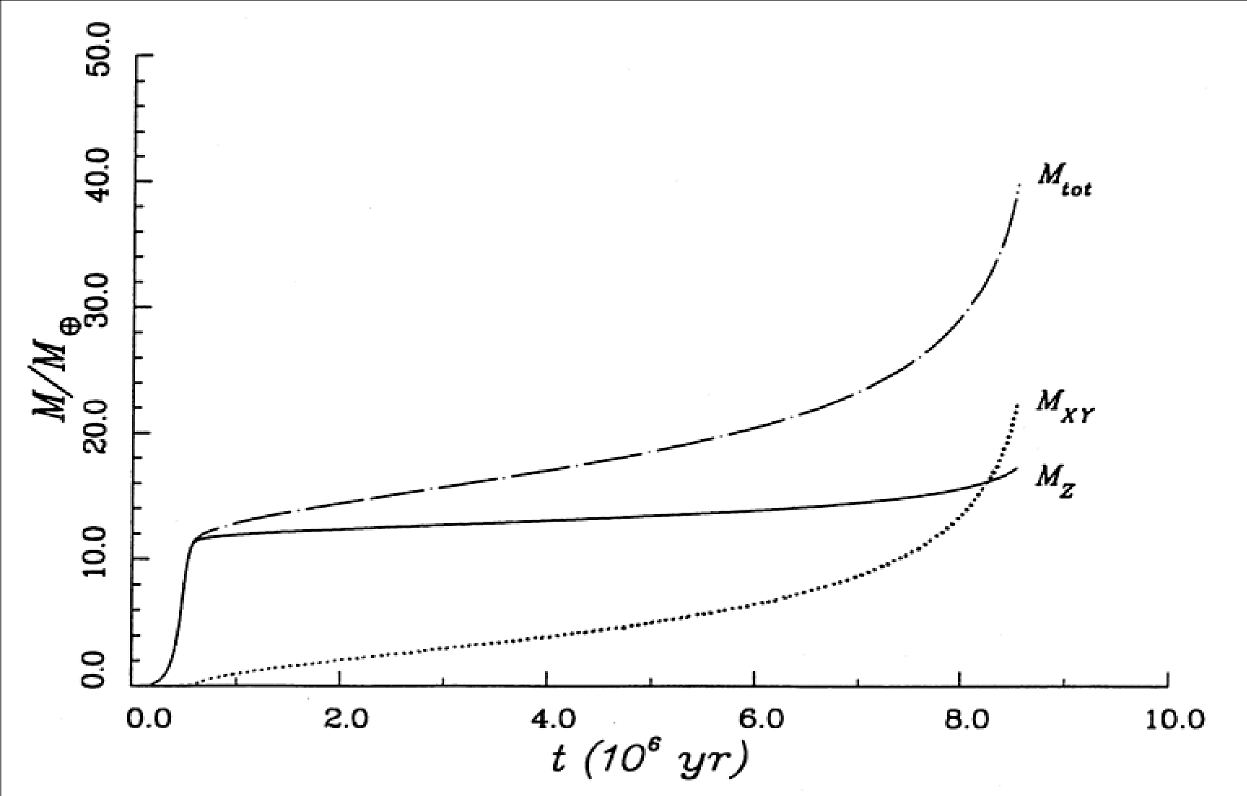


Time scale

- Isotopic evidence (eg: from the terrestrial mantle) indicates the Earth had formed its core at most 100 Myr (likely less)
- Left: Core formation from Hafnium/Tungsten cosmochronology
- T=0 here is defined relative to chondrule and CAI formation

So, the giant planets...

- This sequence of steps does NOT work for the giant planets
- Unlike terrestrial planets, giants have gas (majority for J/S, several Earth-mass for U/N)
- Standard way to get this is core-accretion



Core-Accretion models

- Build a roughly 10 Earth-mass core via runaway accretion (solid)
- Add gas slowly for millions of years while core cools, then quickly
- Jupiter/Saturn had full envelope collapse, while U/N had gas 'run out'?

PROBLEMS

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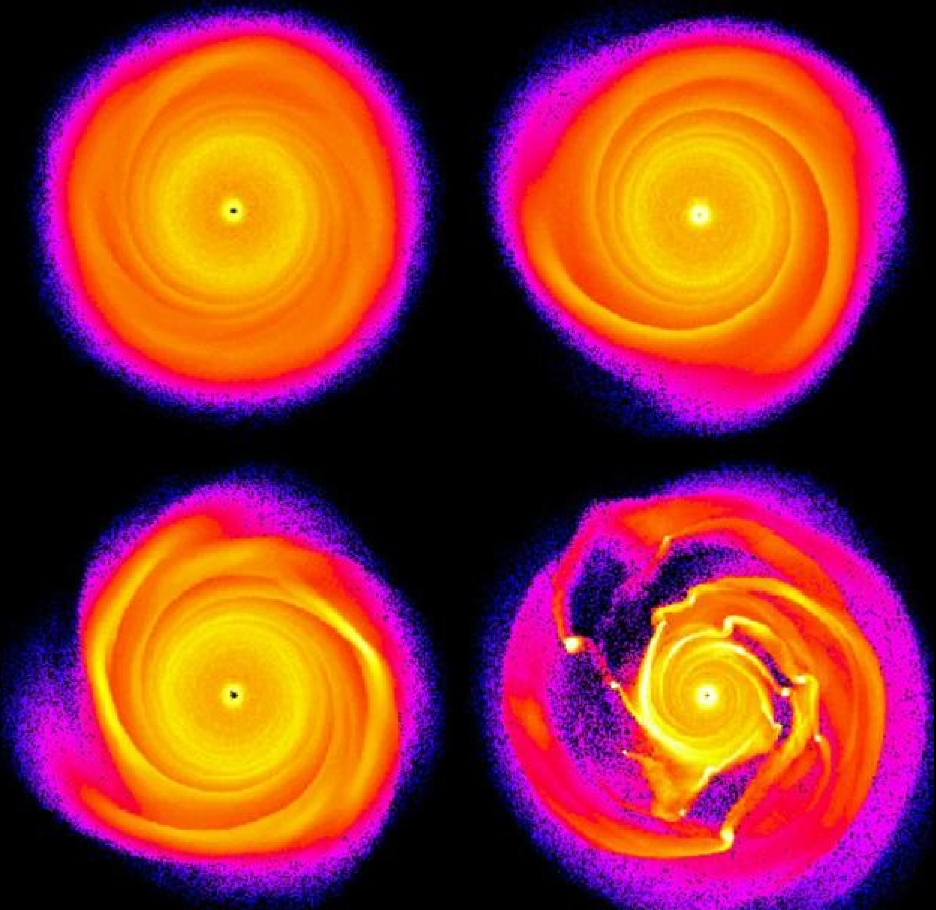
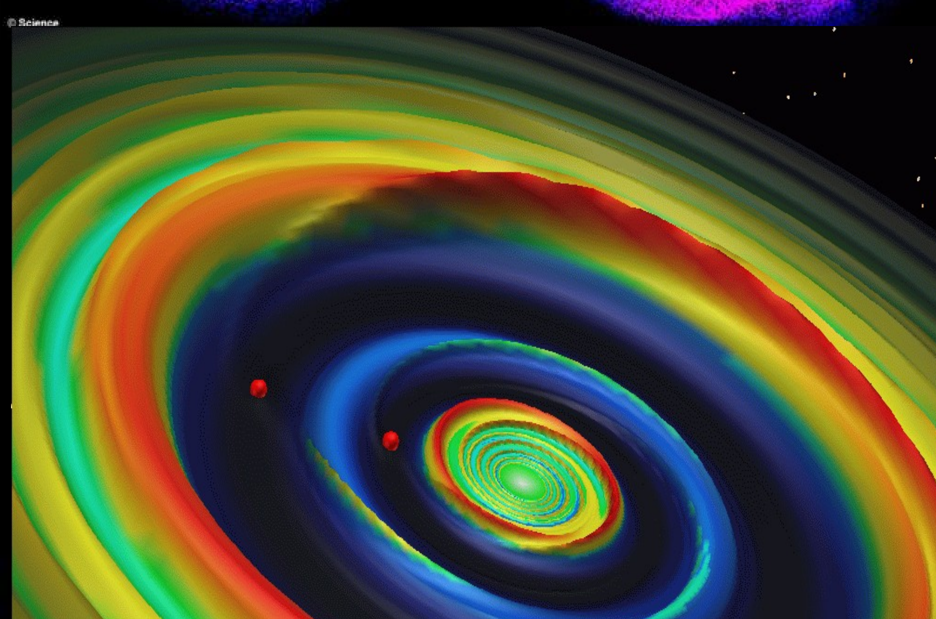
- It takes too long to build the Uranus and Neptune cores (gas disk leaves!)
- Why should gas inflow stop???

Instant solution?



- Why not direct collapse?
- Dynamicists can create anything...
- Uranus/Neptune didn't; why have 2 mechanisms?
- Requires very massive disk
- Such planets migrate
- Outer planet atmospheres too rich in 'metals'



Giant planets accrete gas until gap formation slows it to a trickle

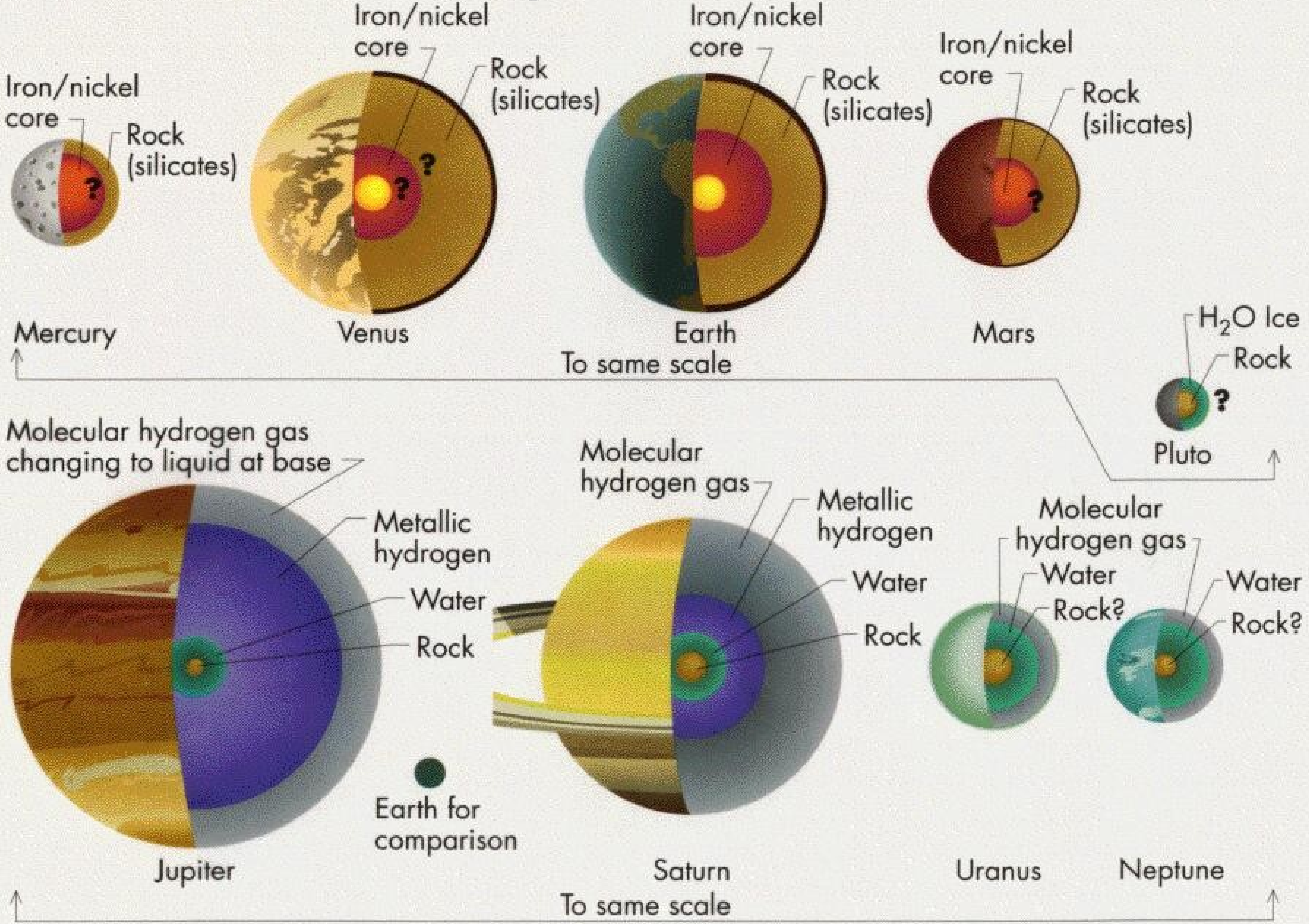
- Can have 'type II' migration

Figure 2 As shown in this simulation (Geoff Bryden, personal communication), young planets are expected to carve out low column density "gaps" in their parent disks. Observations of gaps may provide an indirect means of detecting young planets and inferring their formation masses and orbital radii.

Heavy element overabundance

- The Galileo probe showed that the upper atmosphere of Jupiter is enriched relative to solar abundance
- This doesn't make sense in a direct collapse scenario
- After Jupiter forms it is very bad at capturing more planetesimals

Giant planet interiors



Where do constraints come from?

1) Total mass, radius, shape
2)

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1) Total mass, radius, shape
2) Heat flow at `surface' (1 bar)
3) moments of intertia and gravity moments
    1) C/MR^2
    2) Jn

$$V(r,\theta) = \frac{GM}{r}\left[1 - \sum_{n=0}^{\infty}\left(\frac{R_{eq}}{r}\right)^{2n} J_{2n}P_{2n}(t)\right], \qquad (6)$$

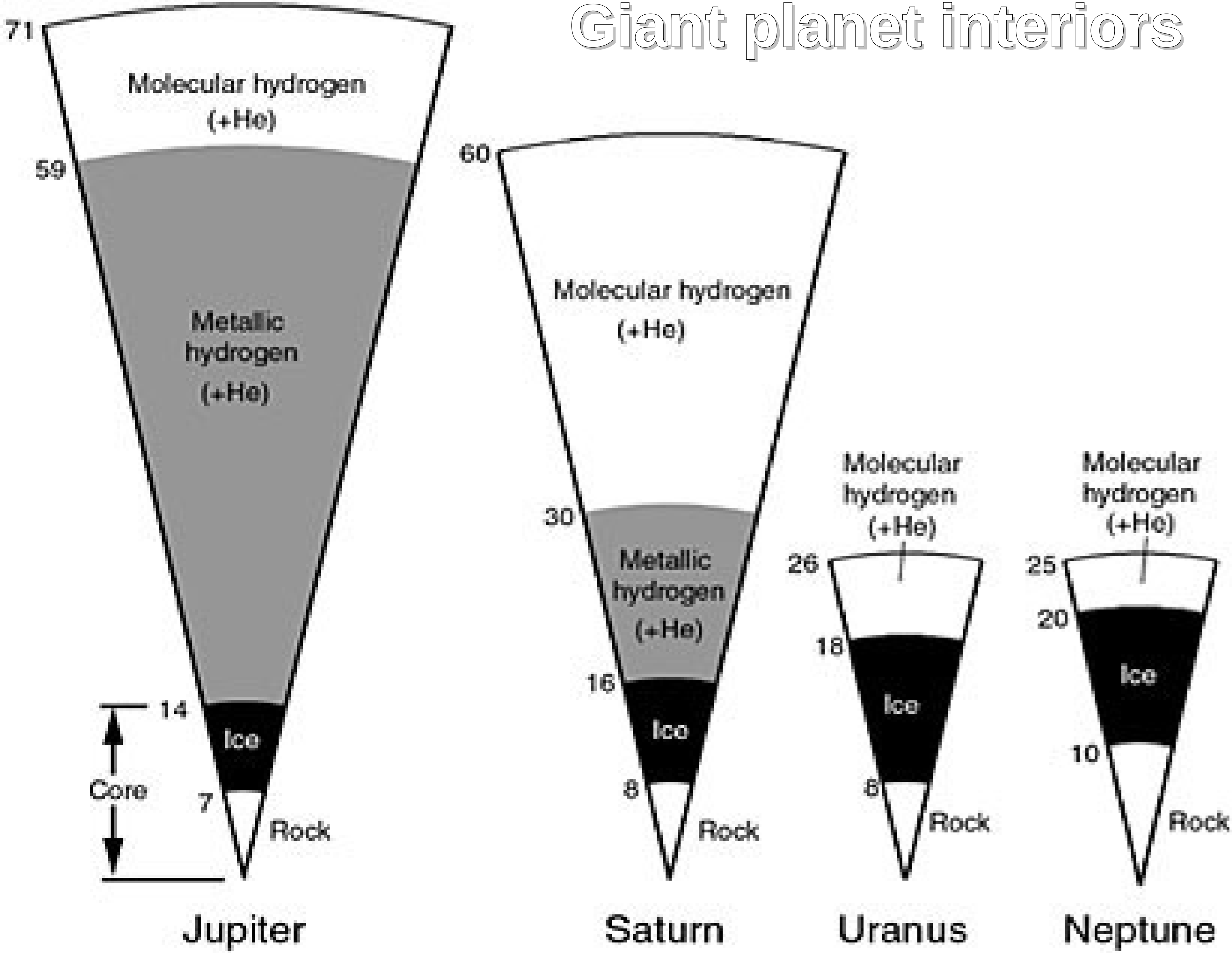
4) H/He ratio at upper layers
5) Chemisty at upper layers

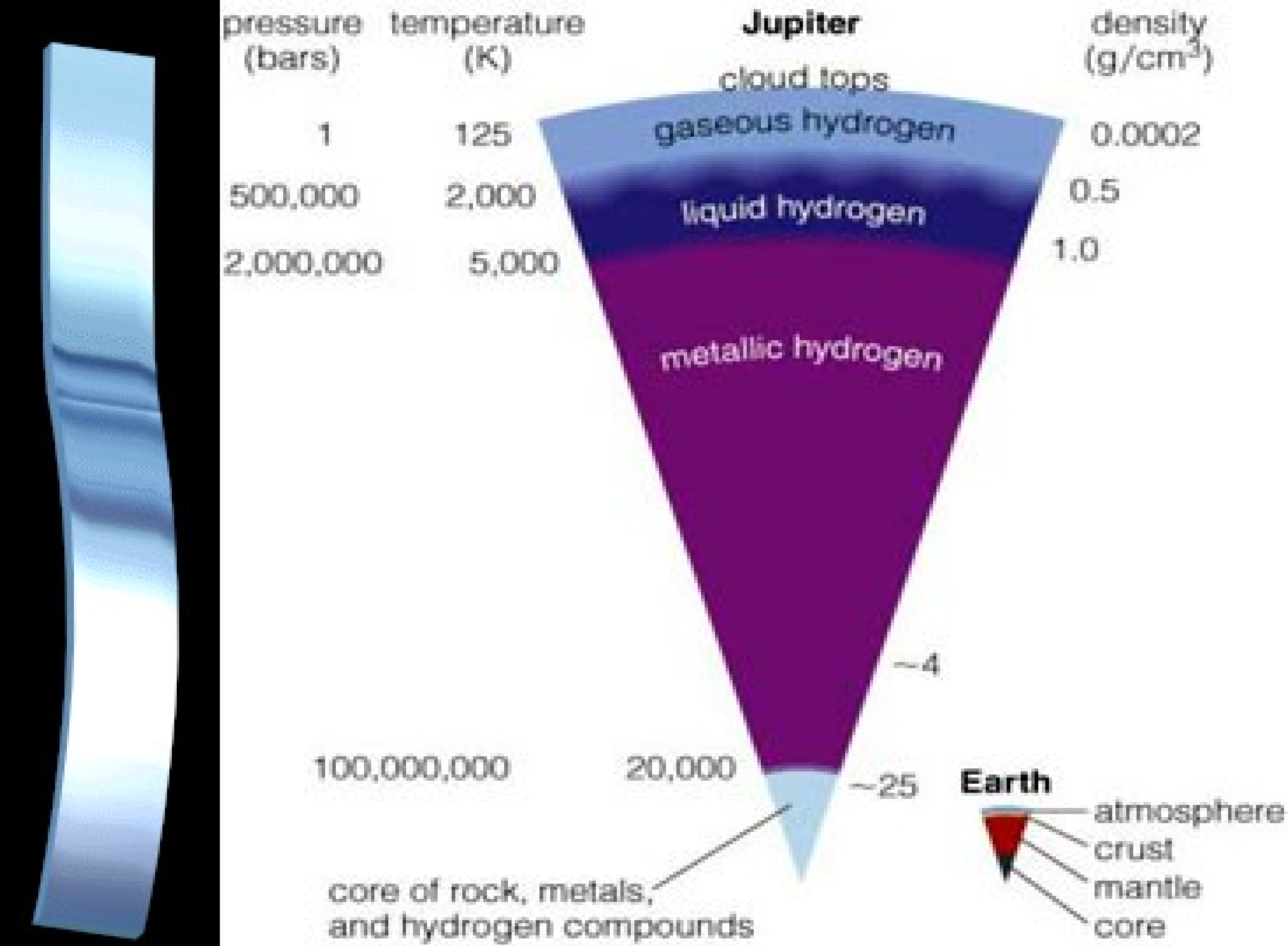
These allow constraints on total core mass and the total abundance of heavy elements

Interior models

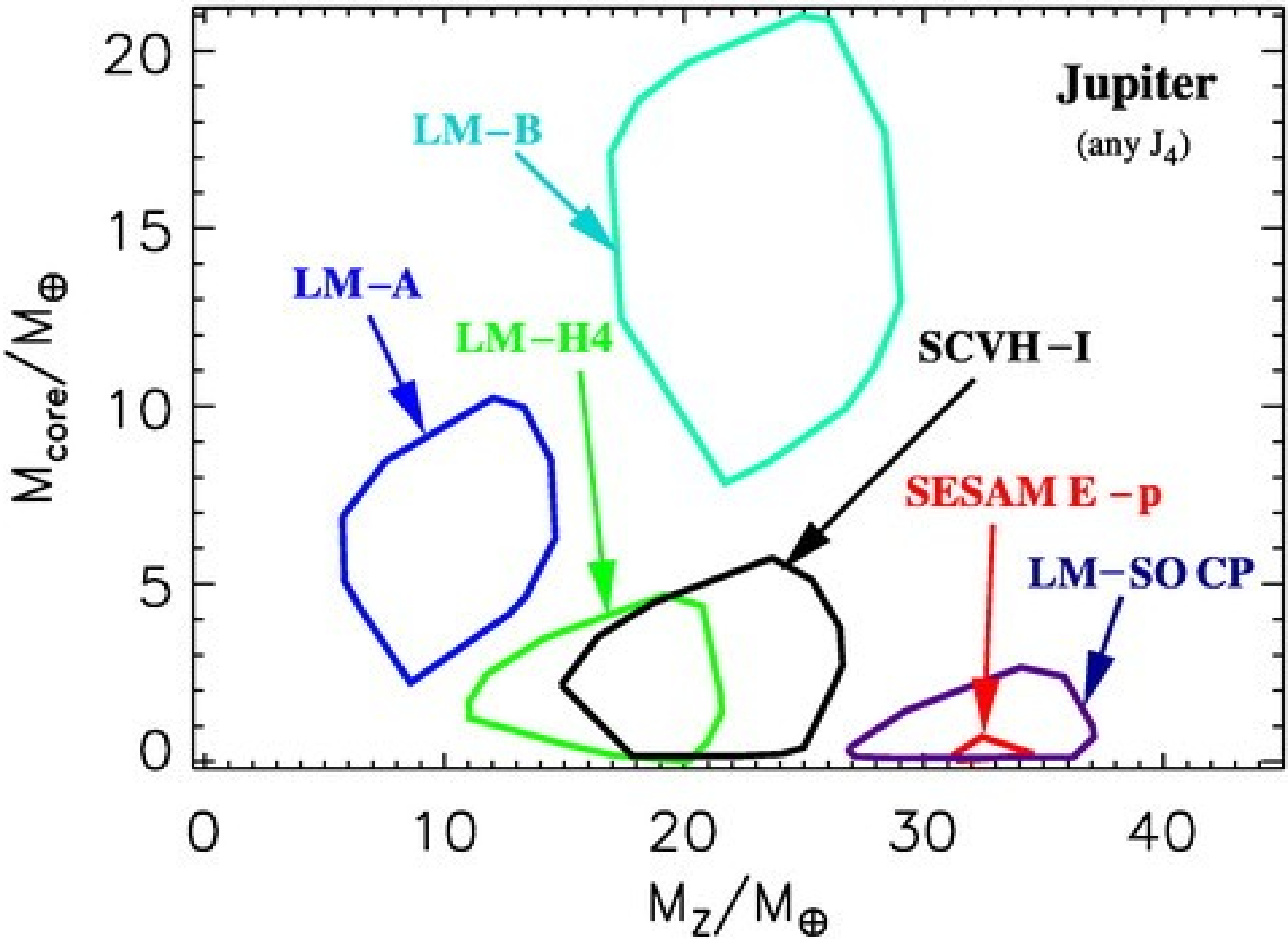
- Give a range of possible core masses and metal contents
- Jupiter/Saturn have metallic hydrogen layers
- uncertainties dominated by unknown equations of state for H and He at Mbar pressures

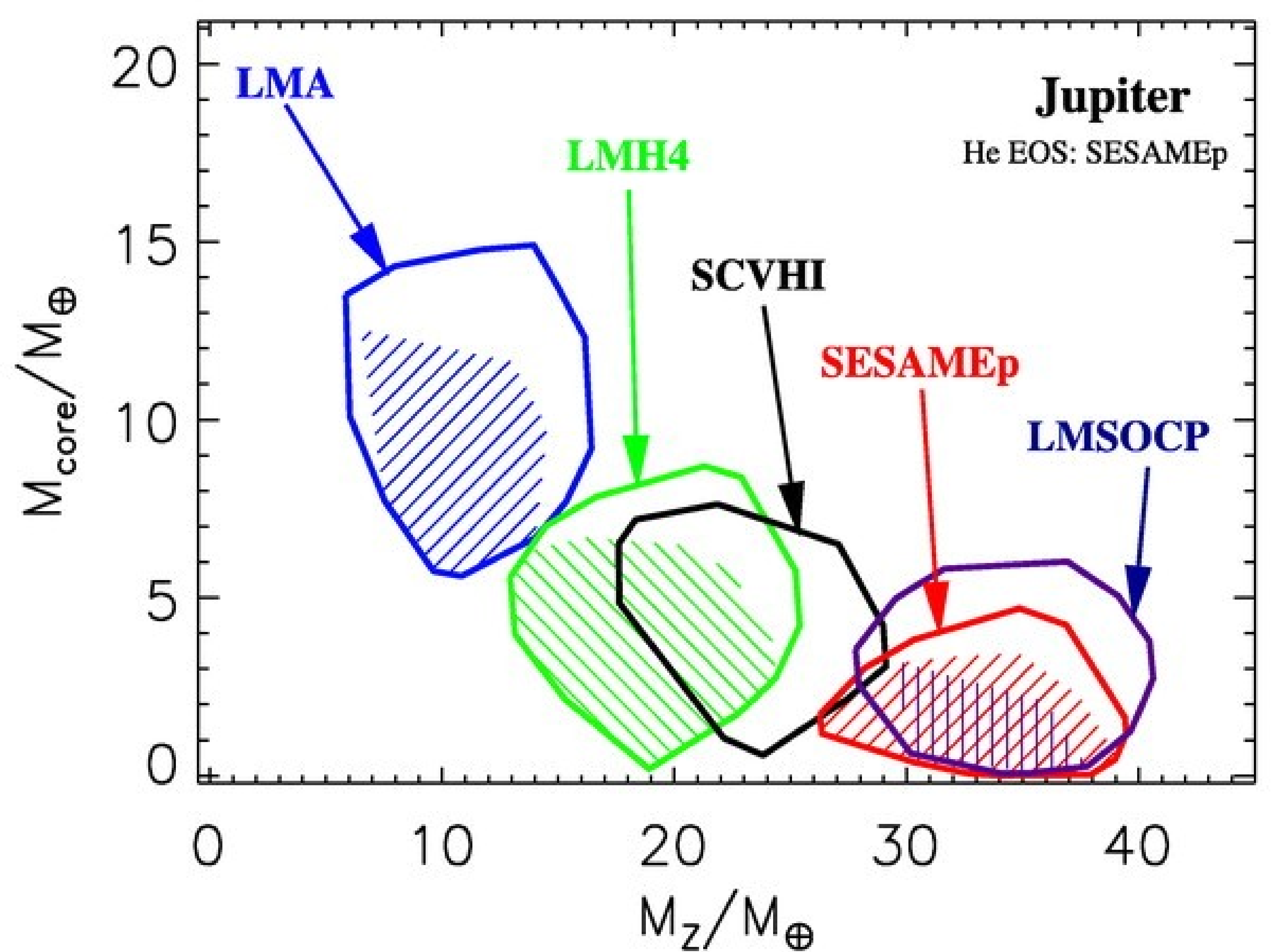
Giant planet interiors



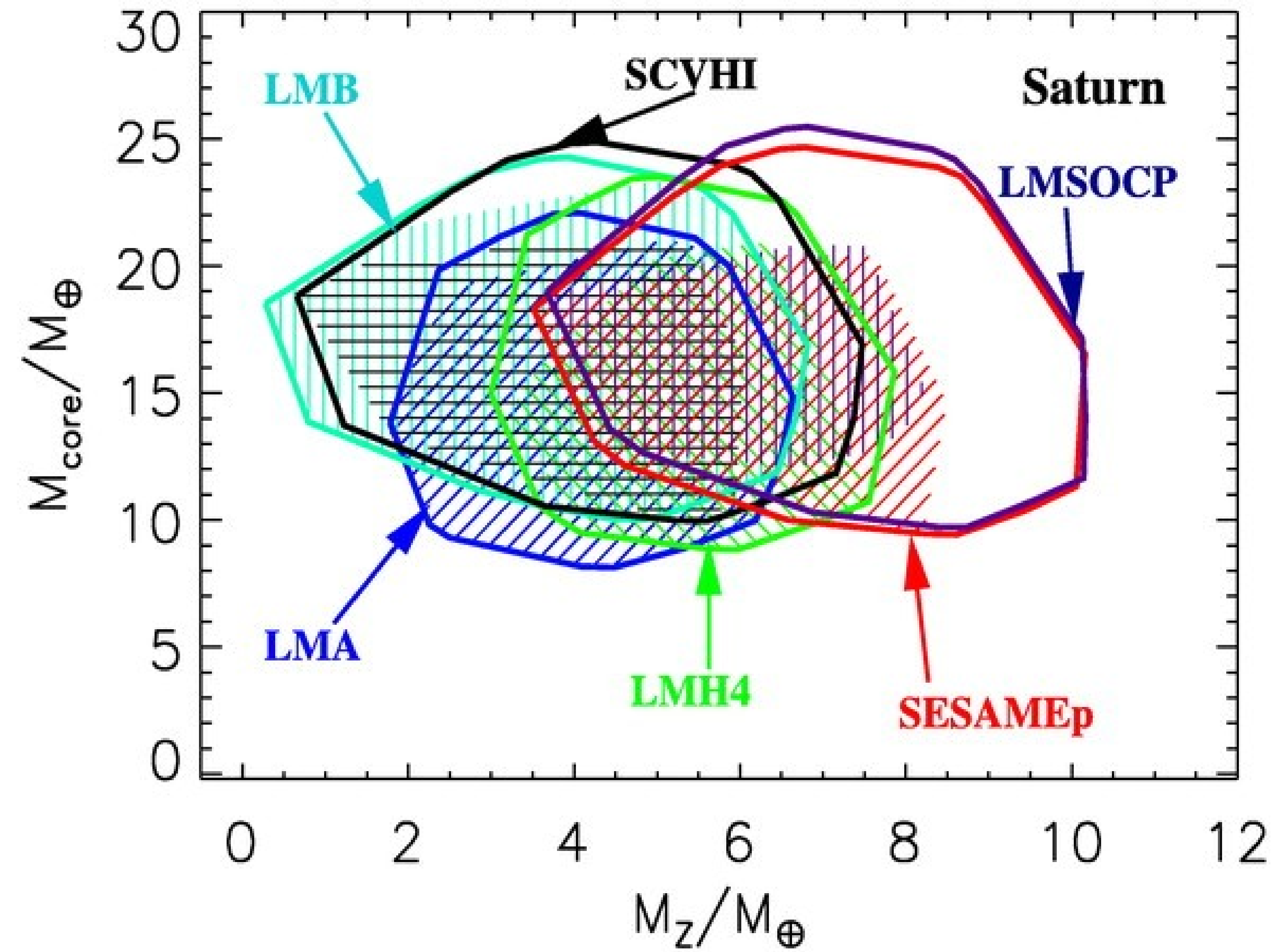

pressure (bars)
temperature (K)
Jupiter
density (g/cm^3)
cloud tops
gaseous hydrogen
1
125
0.0002
500,000
2,000
0.5
liquid hydrogen
2,000,000
5,000
1.0
metallic hydrogen
~4
100,000,000
20,000
~25
core of rock, metals, and hydrogen compounds
Earth
atmosphere
crust
mantle
core

- From Saumon and Guillot (2004)





LMA
LMH4
SCVHI
SESAMEp
LMSOCP
Jupiter
He EOS: SESAMEp
20
15
10
5
0
0
10
20
30
40
$M_{core}/M_{\oplus}$
$M_Z/M_{\oplus}$



SCYHI
LMB
Saturn
LMSOCP
LMA
LMH4
SESAMEp
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6
8
10
12
$M_{core}/M_{\oplus}$
$M_Z/M_{\oplus}$