The formation of the outer Solar System

ASTR 507, spring 2011

Planet formation

- How do planets form??
  - By what mechanism?

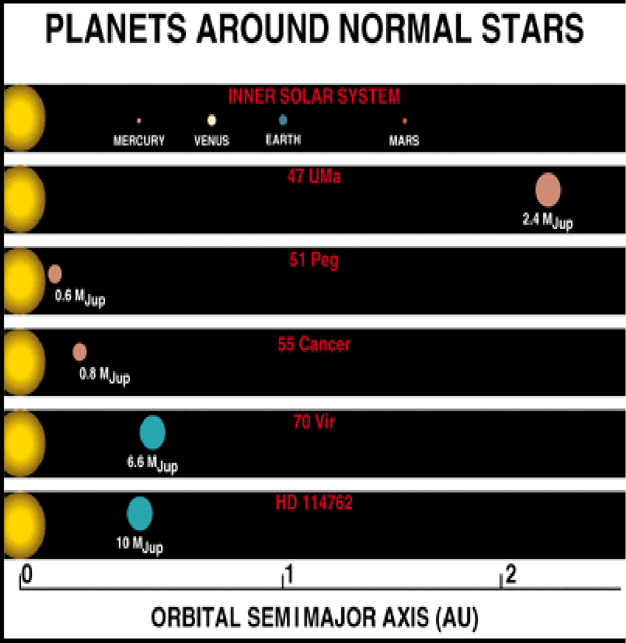
(Painting by William K. Hartmann. Used with permission.)

Planet formation

- How do planets form??
  - By what mechanism?
  - How long does it take?
    - Inner: tens of Myr
    - Outer : 10 --hundreds of Myr

(Painting by William K. Hartmann. Used with permission.)

Planet formation



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  - By what mechanism?
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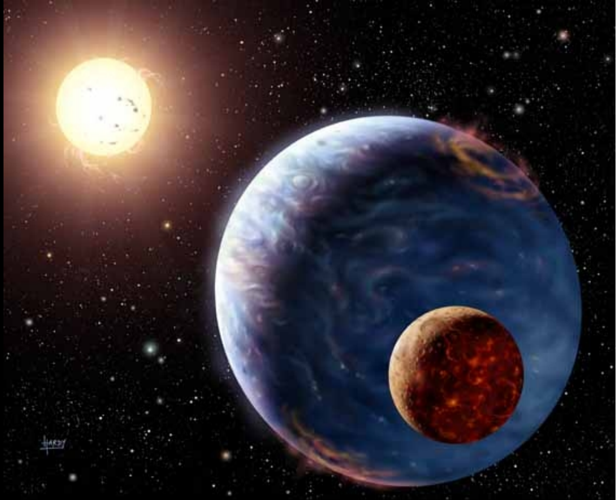
  - Is it the same for all planets?
    - for all planetary systems?

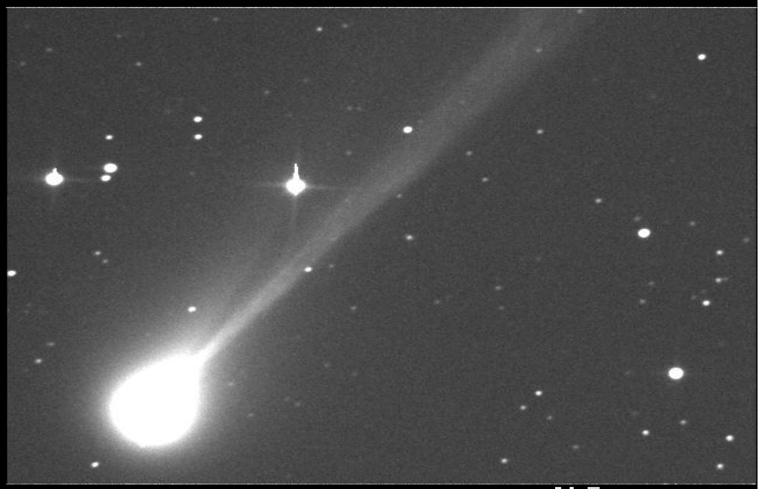
Planet formation



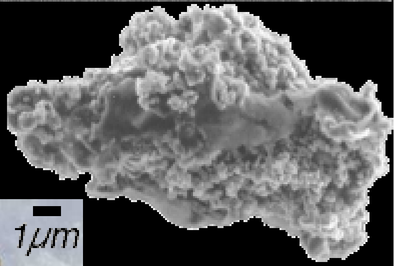
- How do planets form??
  - By what mechanism?
  - How long does it take?
  - Is it the same for all planets?
    - for all planetary systems?
- Where do we get constraints from?
  - properties of the planets (tough)
    - current positions/sizes/chemistry primordial? NO. Evolved. But some...

Constraints from small bodies

- Comets and Asteroids
  - much more primitive
  - Easier to sample



- Physical properties
- Orbital distribution



BOTH tell us about what was going on during planet formation

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

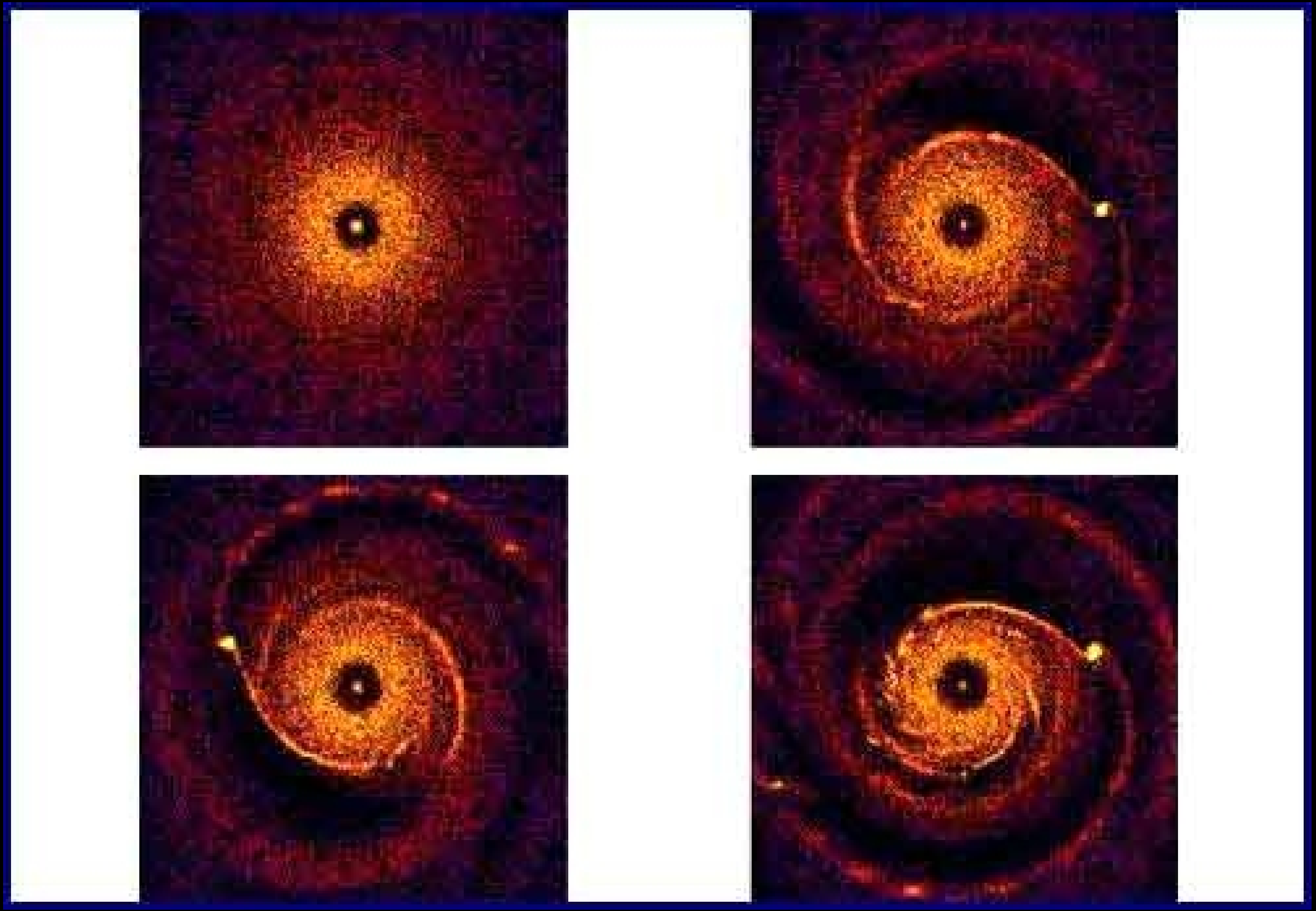
planets/moons

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
     - appealing for gas giants

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

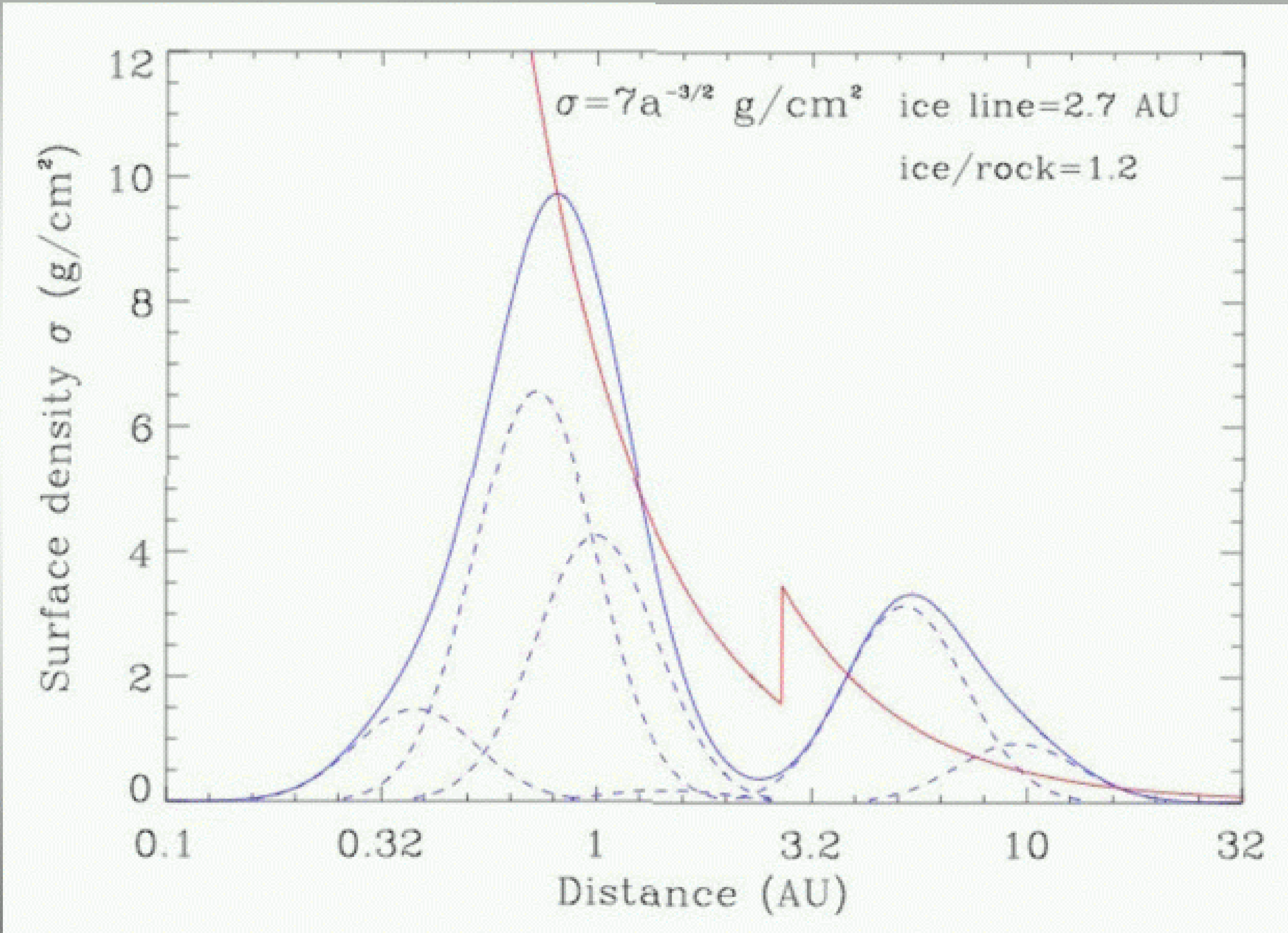
(same as inner)

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

Terrestrial planet cookbook: follow these easy steps

1) Dust sedimentation to midplane in protosolar nebula (turbulence)

Mass Distribution in the Planetary System



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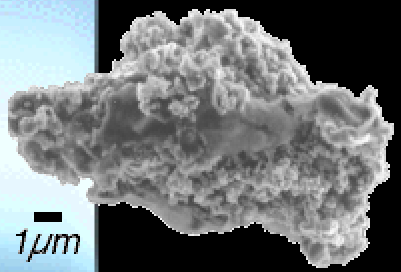
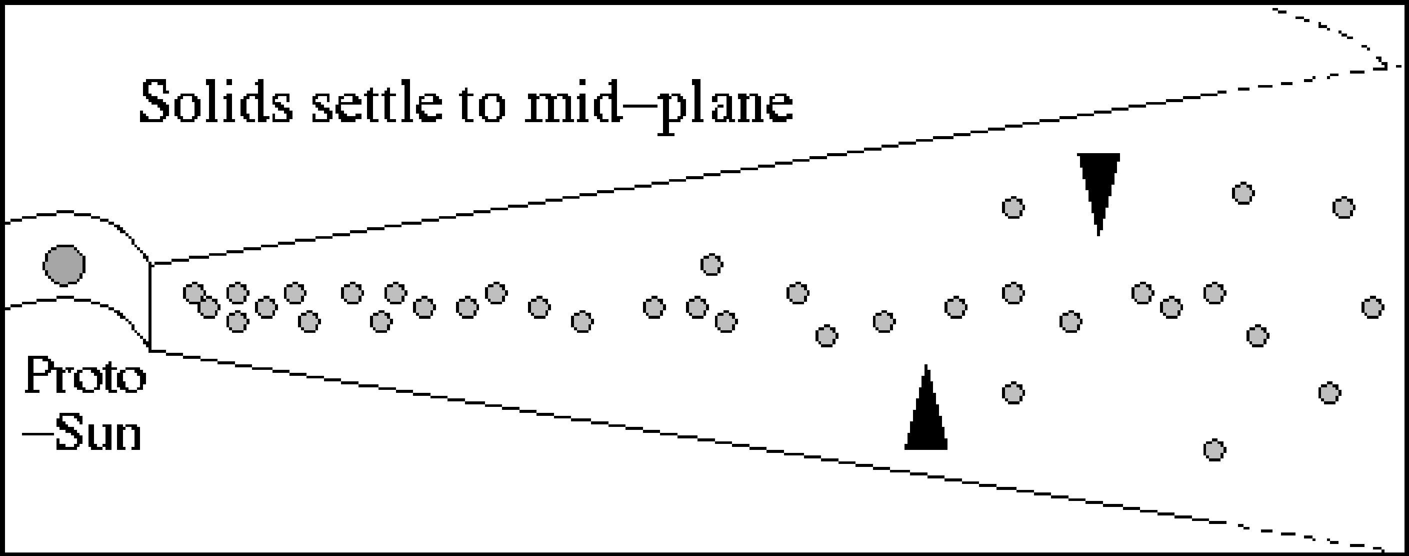
4) embryos coalesce into final planets (e and i of formed planets high)

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

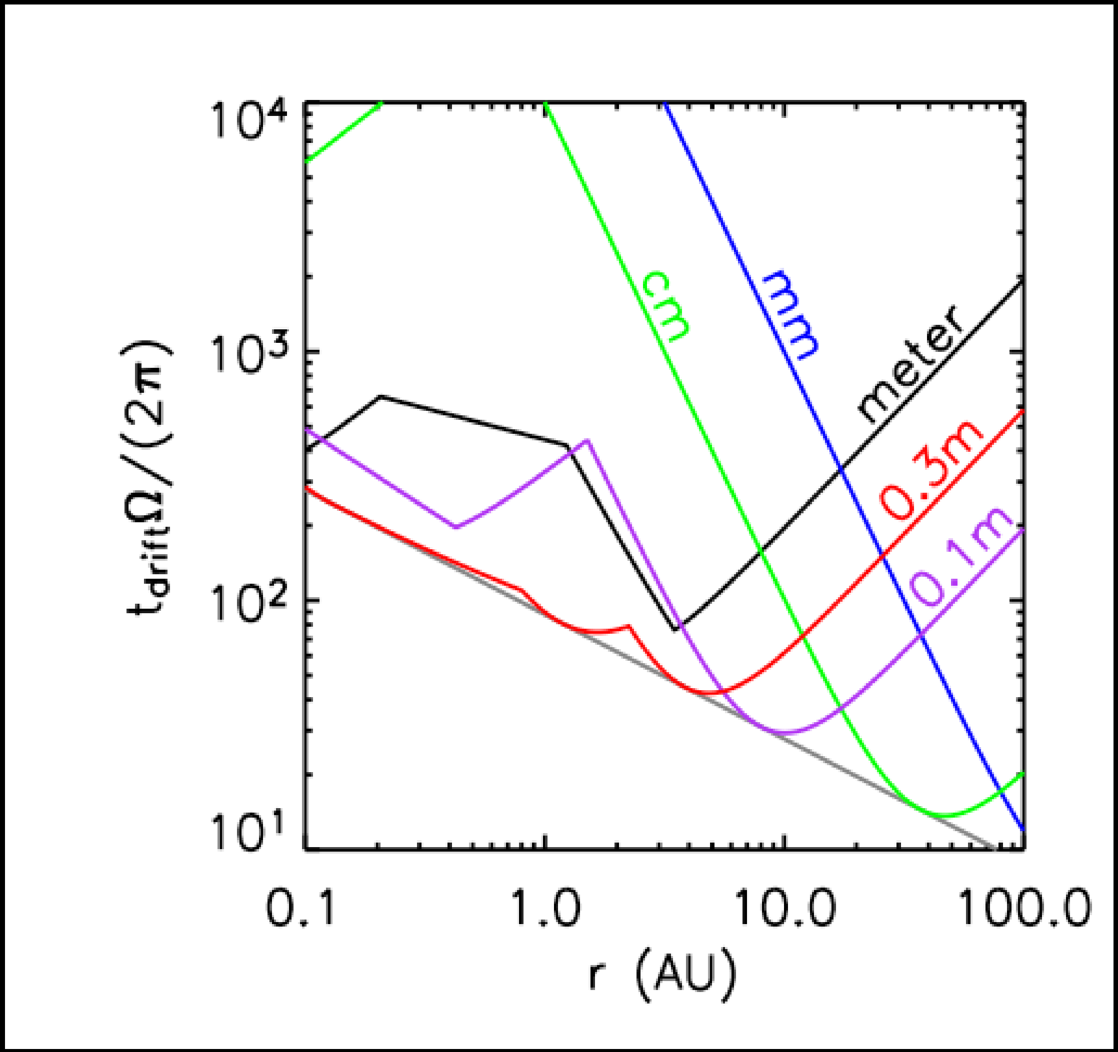
2) Planetesimal creation

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.

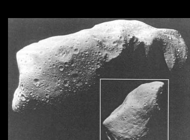
Figure : time scale for 1/e drop of 'a' in terms of orbital period



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

3) Form planetary embryos via local 'runaway'

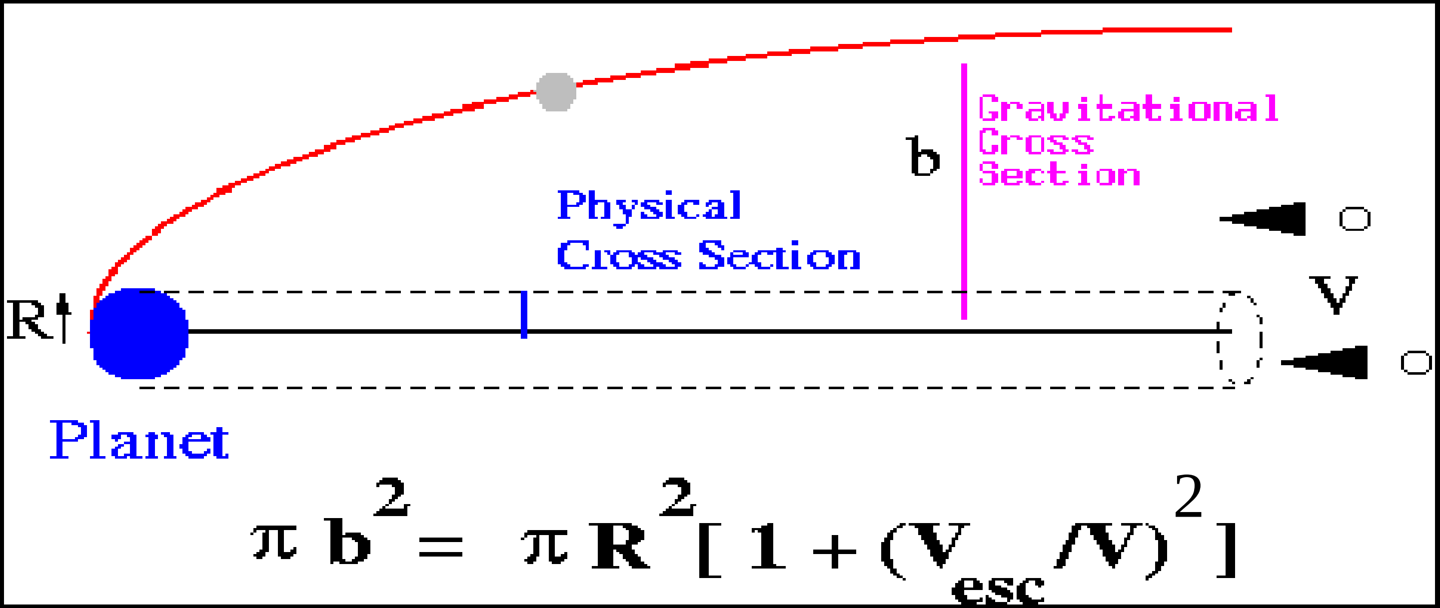
1) Well understood analytically+numerically
2) Planetesimal swarm on very circular and low inclination orbits
3) The biggest objects get bigger faster (simple to understand)
4) In inner S.S., go from 'asteroids' to Moon



$>>10^9$ in mass$>>$

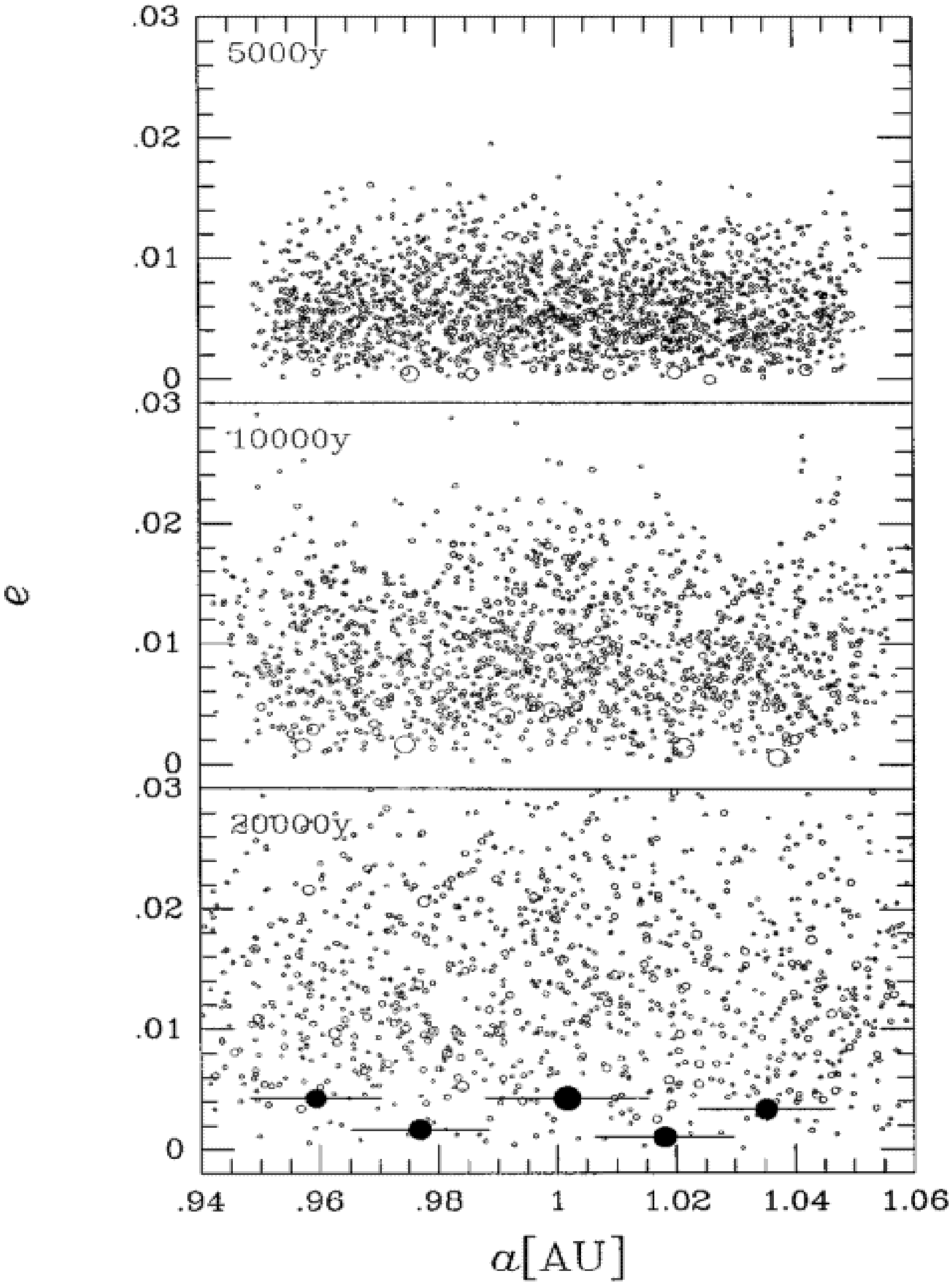
3) Runaway accretion, cont'd

1) Increase in physical cross-section



- Growth rate proportional to radius

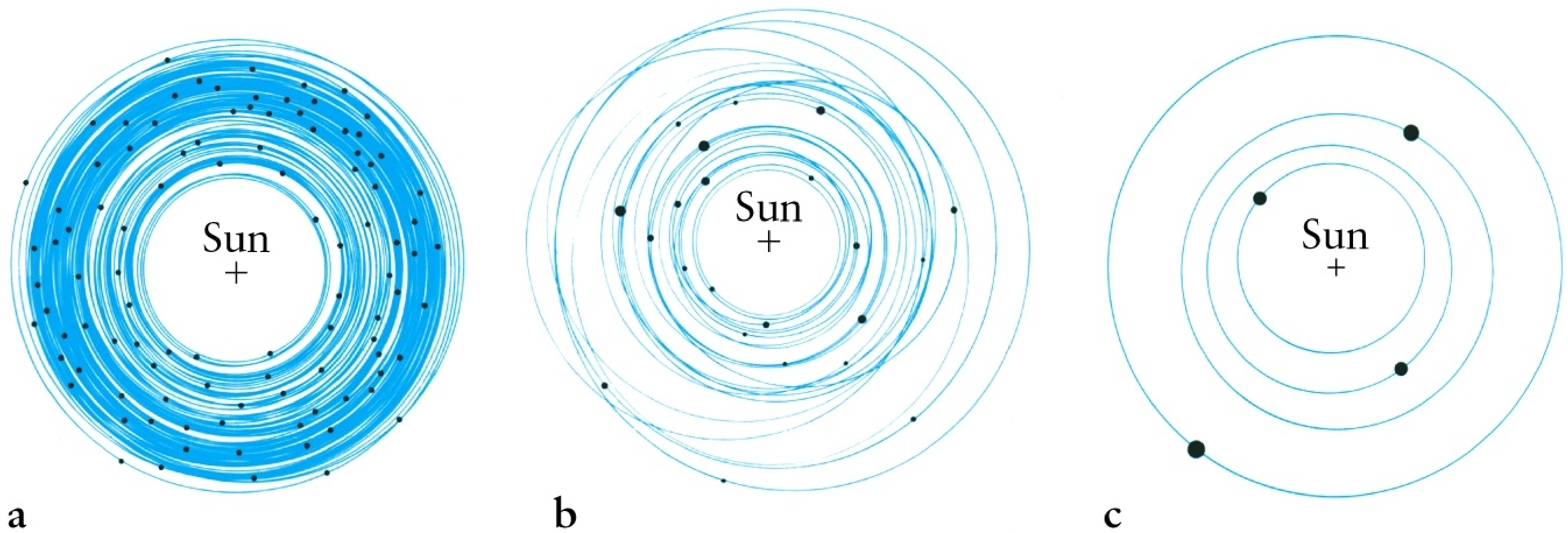
At any given distance, one object (embryo) sucks up most of the mass



Near 1 AU, reach lunar size

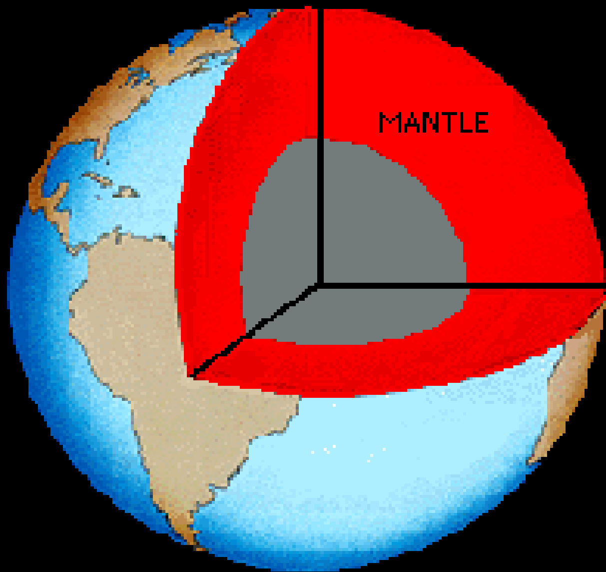
1) Finish with 'nested' set of embryos
2) Note embyros on low-e orbits (dynamical friction)
3) Ready for next stage

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...

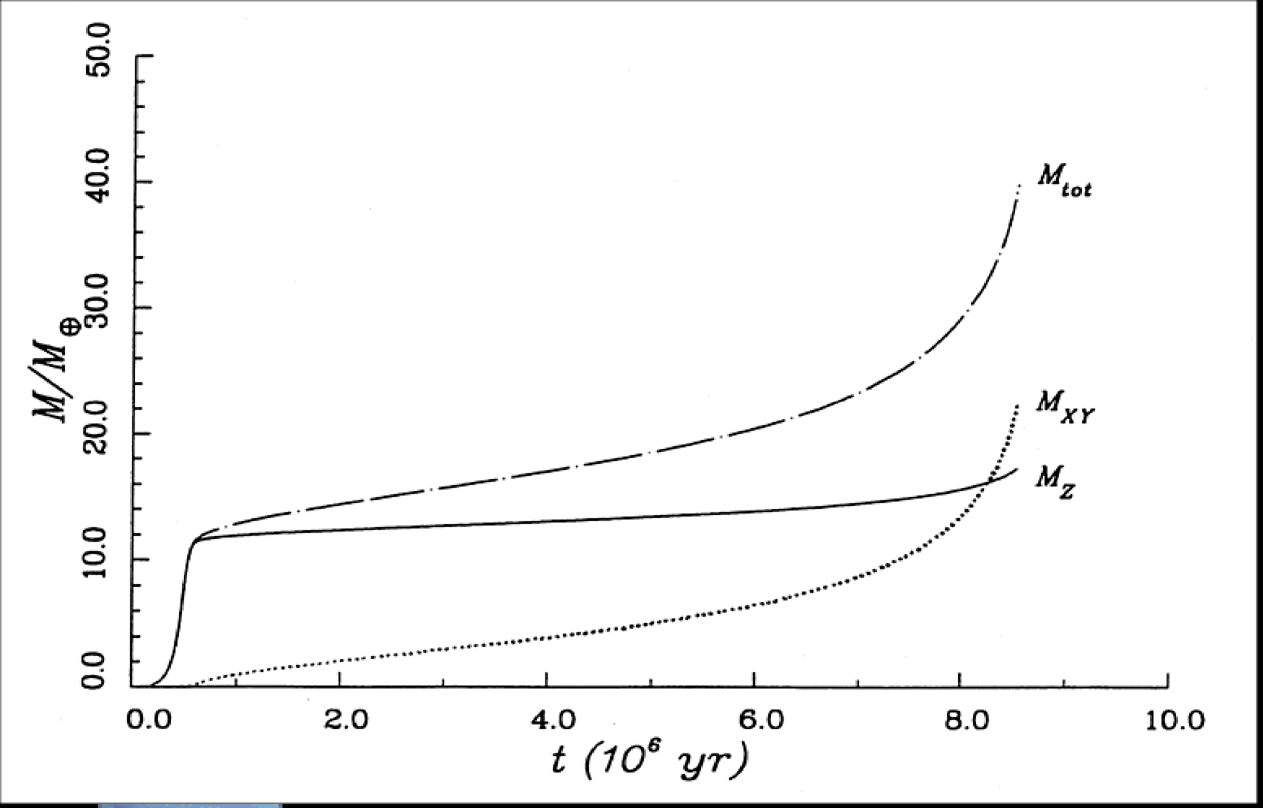
Time scale



- Isotopic evidence (eg: from the terrestrial mantle) indicates the Earth had formed its core at most 100 Myr (likely less)
- 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

- While runaway mass is bigger outside 5 AU, it's NOT 10 Earth masses

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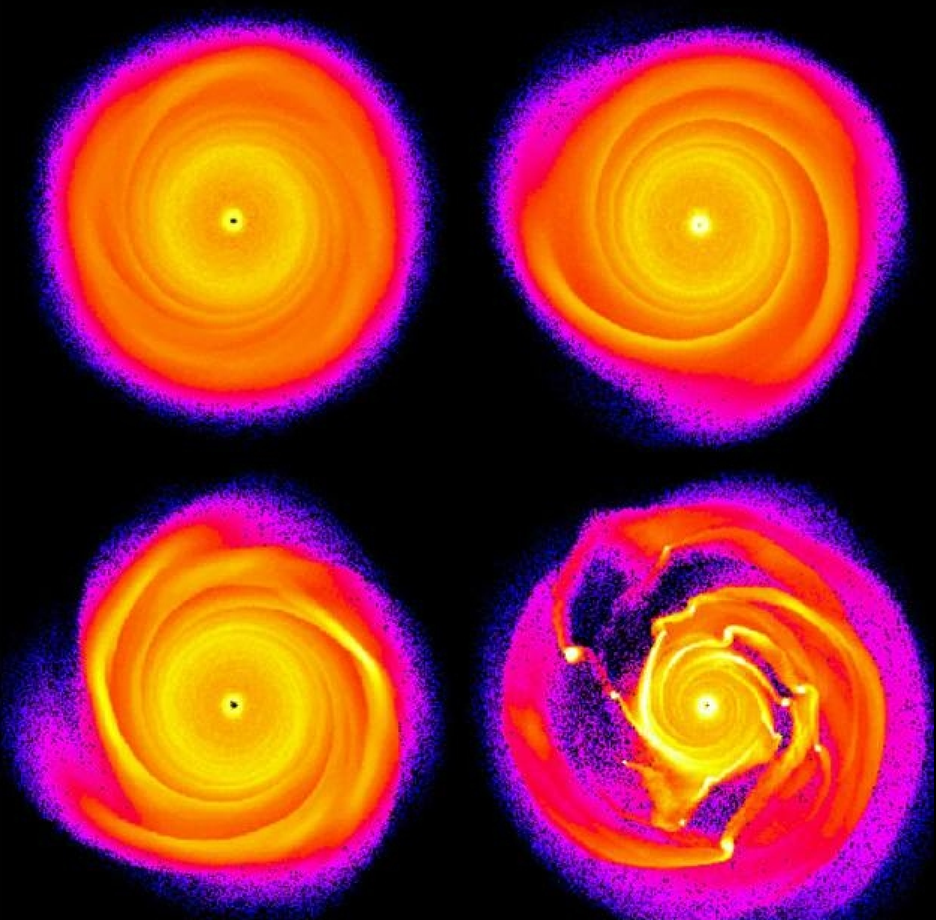
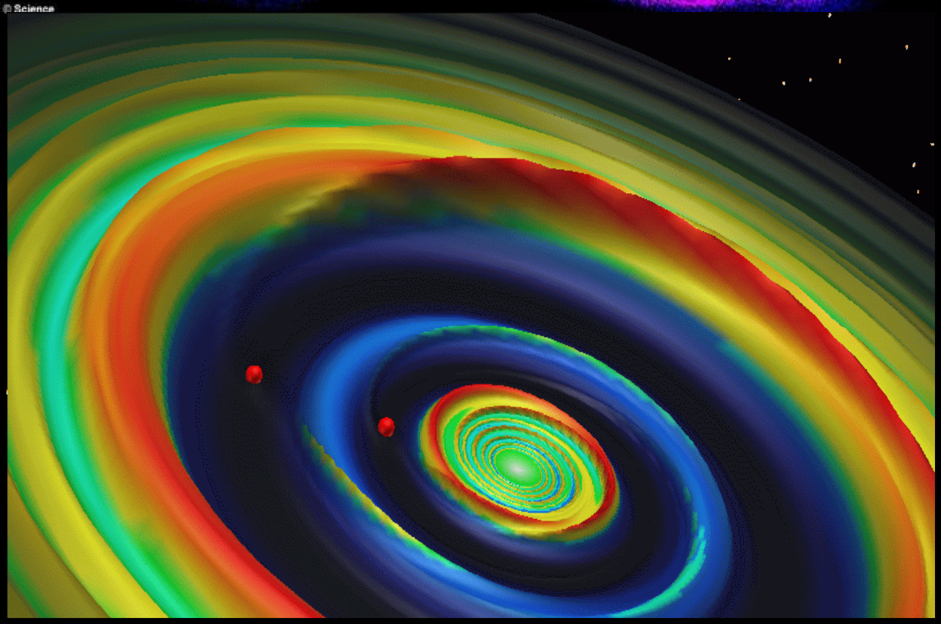
- It takes too long to build the Uranus and Neptune cores (gas disk leaves!)
- Why should gas inflow stop???





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

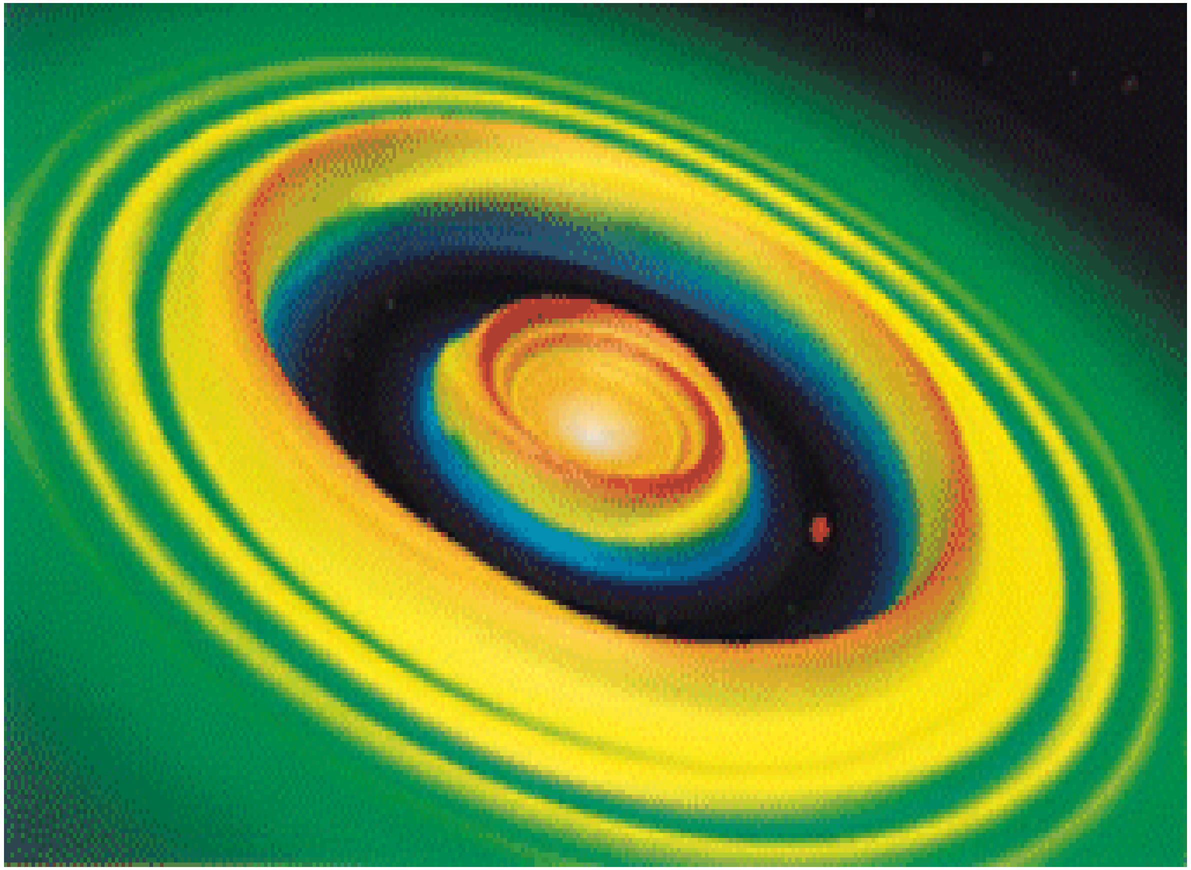
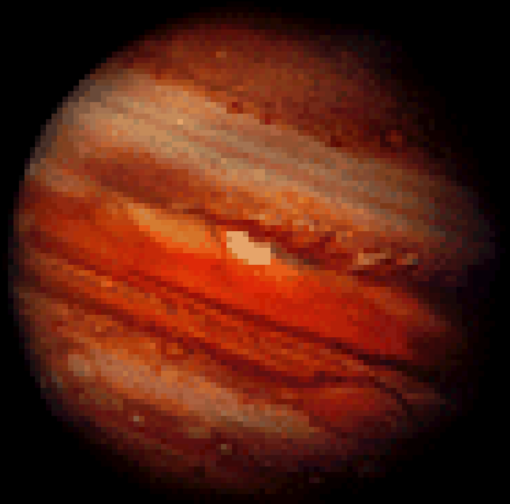


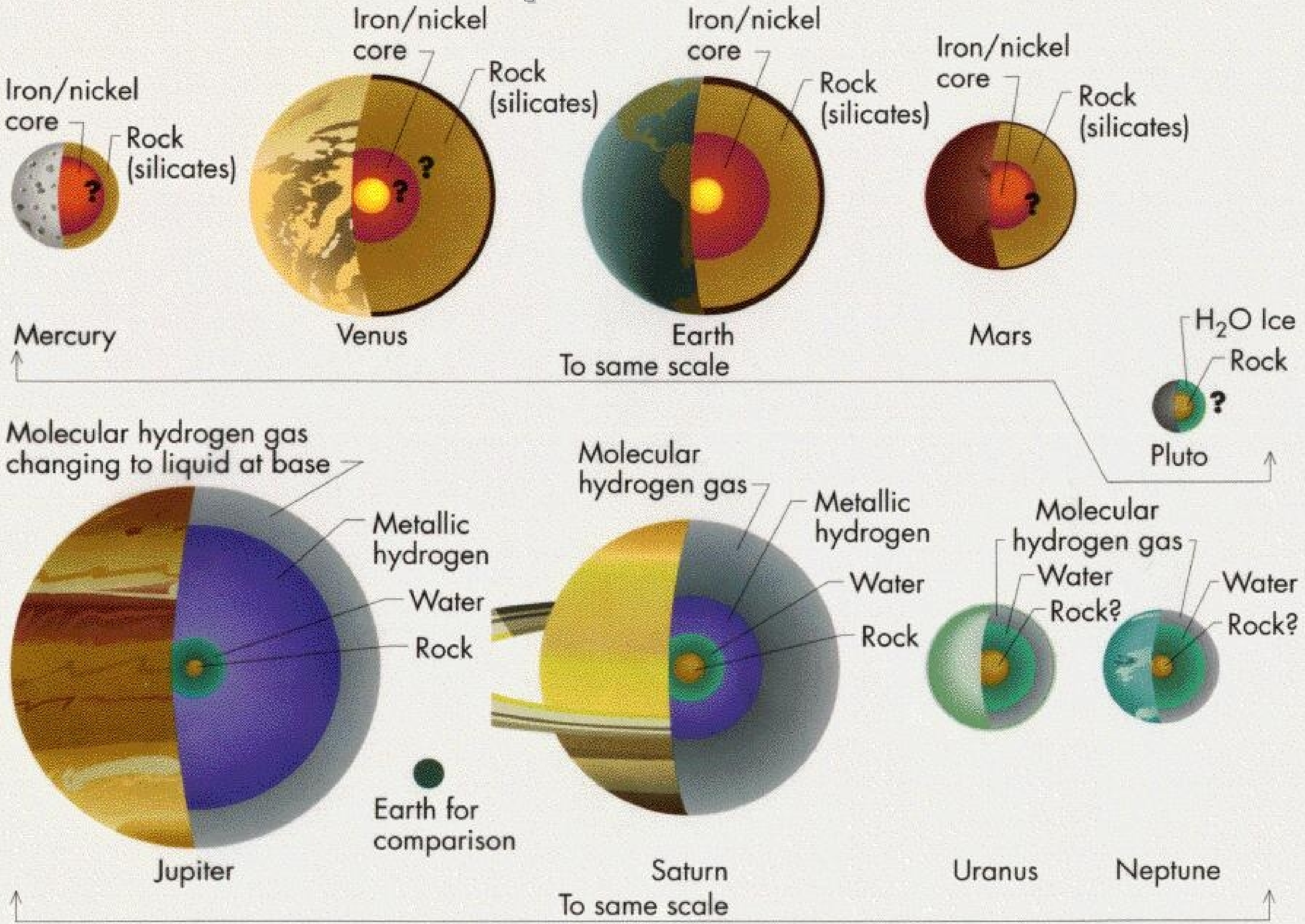
Figure 2 As shown in this simulation (Geoff Bryden, personal communication), young planets are expected to carve out low column density "gaps" in their parent disks. Observations of gaps may provide an indirect means of detecting young planets and inferring their formation masses and orbital radii.



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)

Where do constraints come from?

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

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

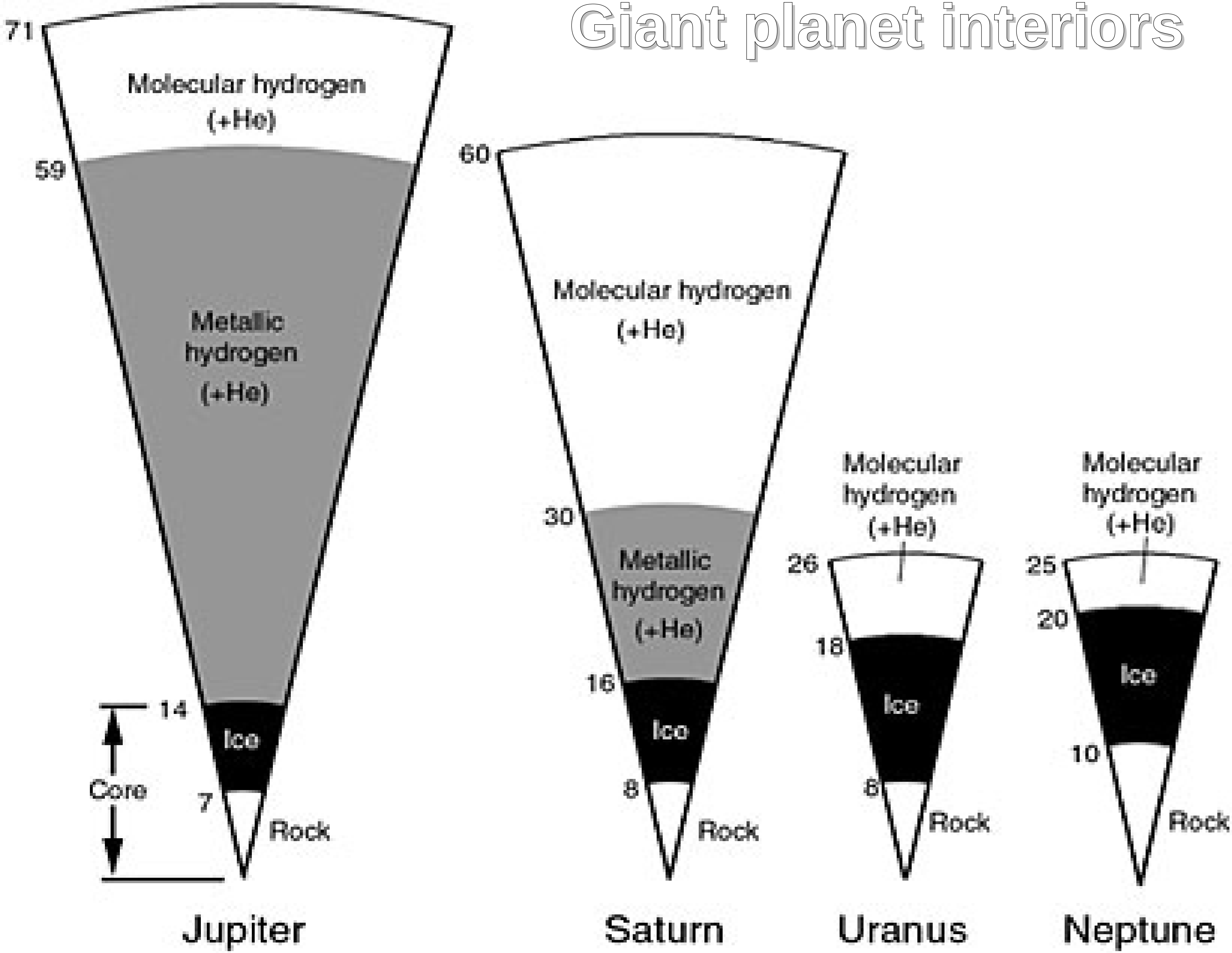
4) H/He ratio at upper layers
5) Chemisty at upper layers

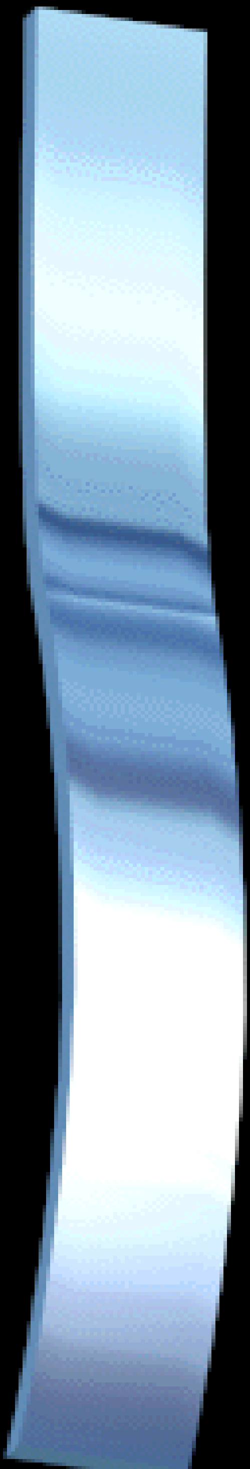
These allow constraints on total core mass and the total abundance of heavy elements

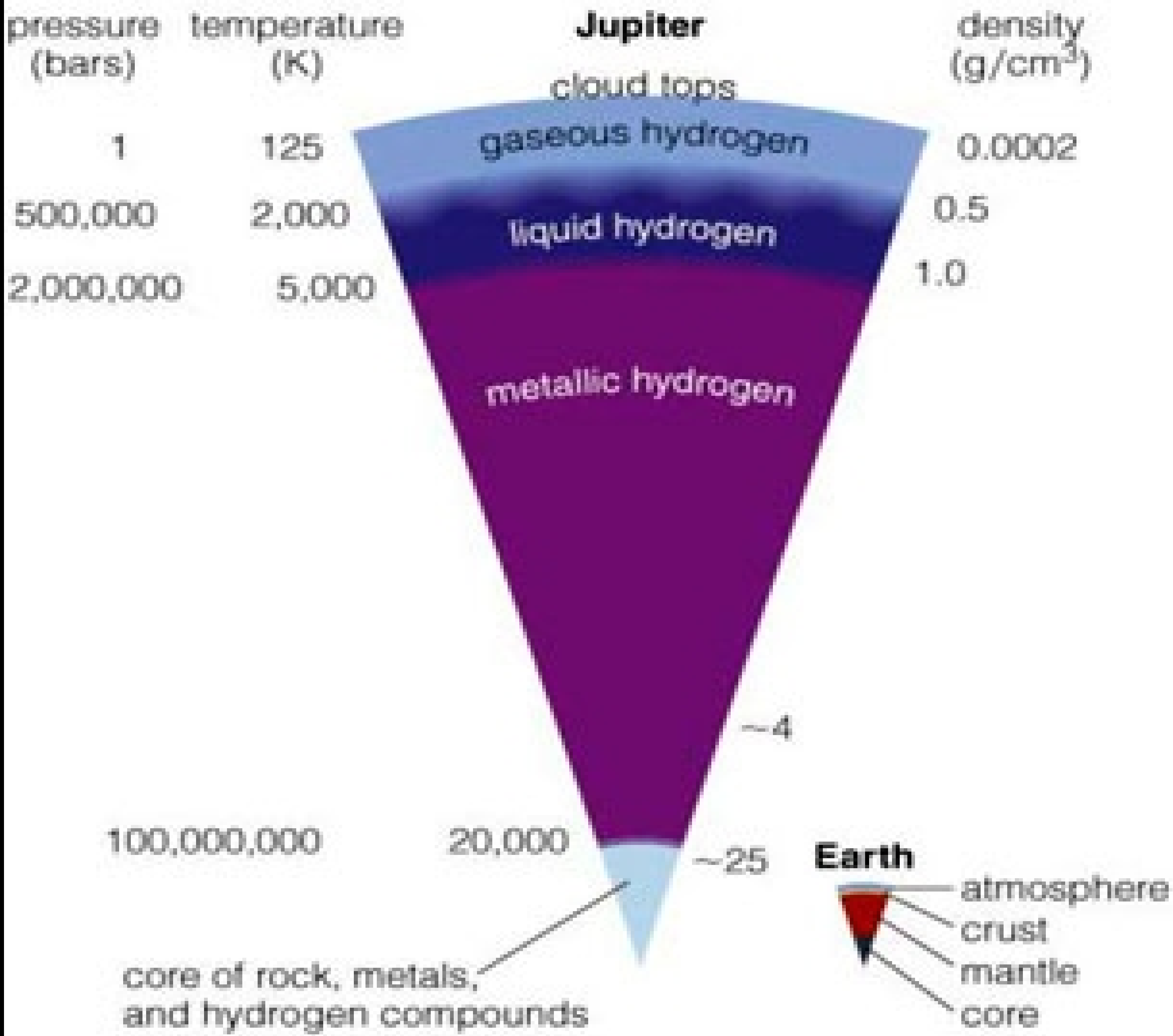
Interior models

- 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

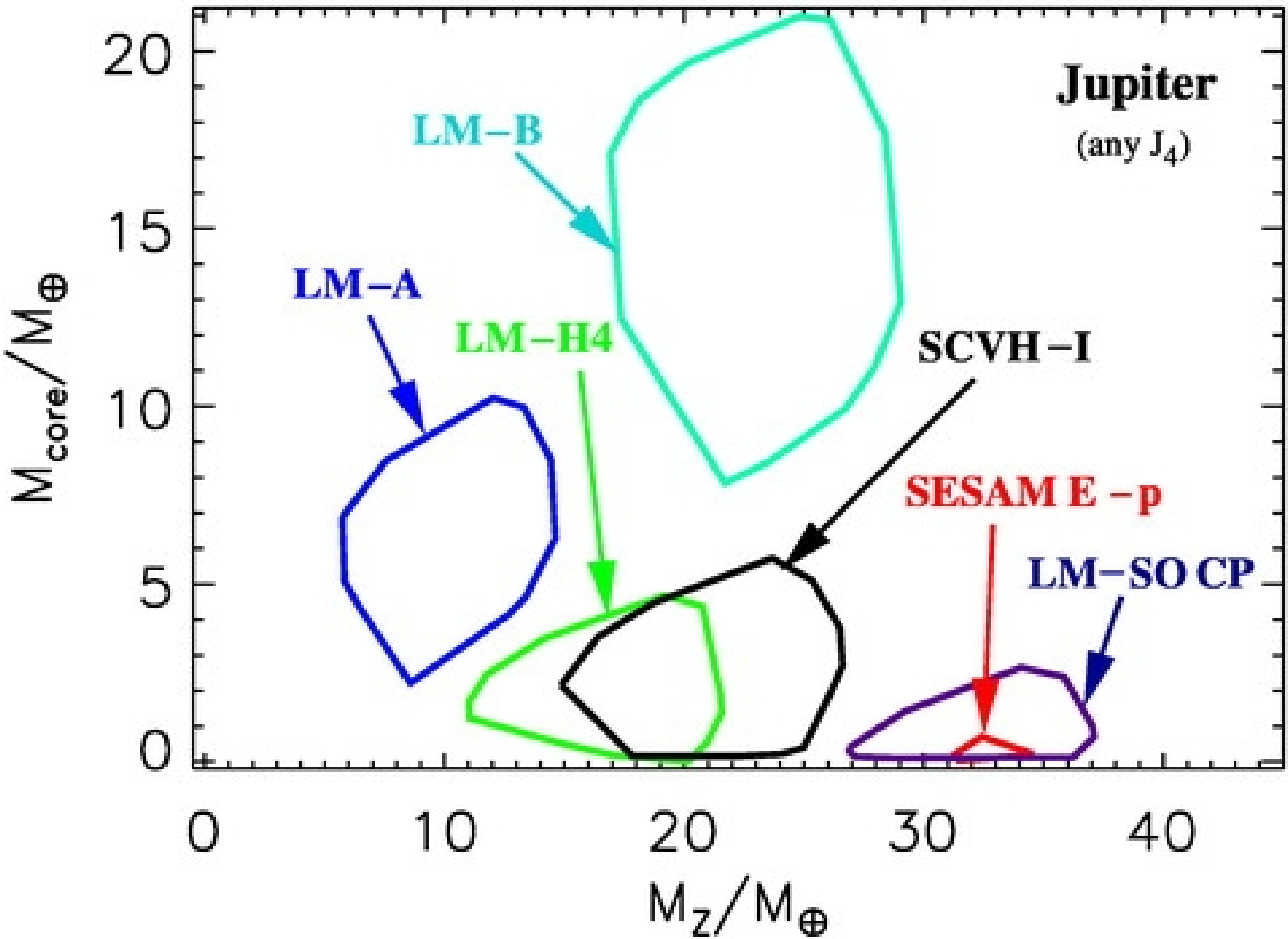


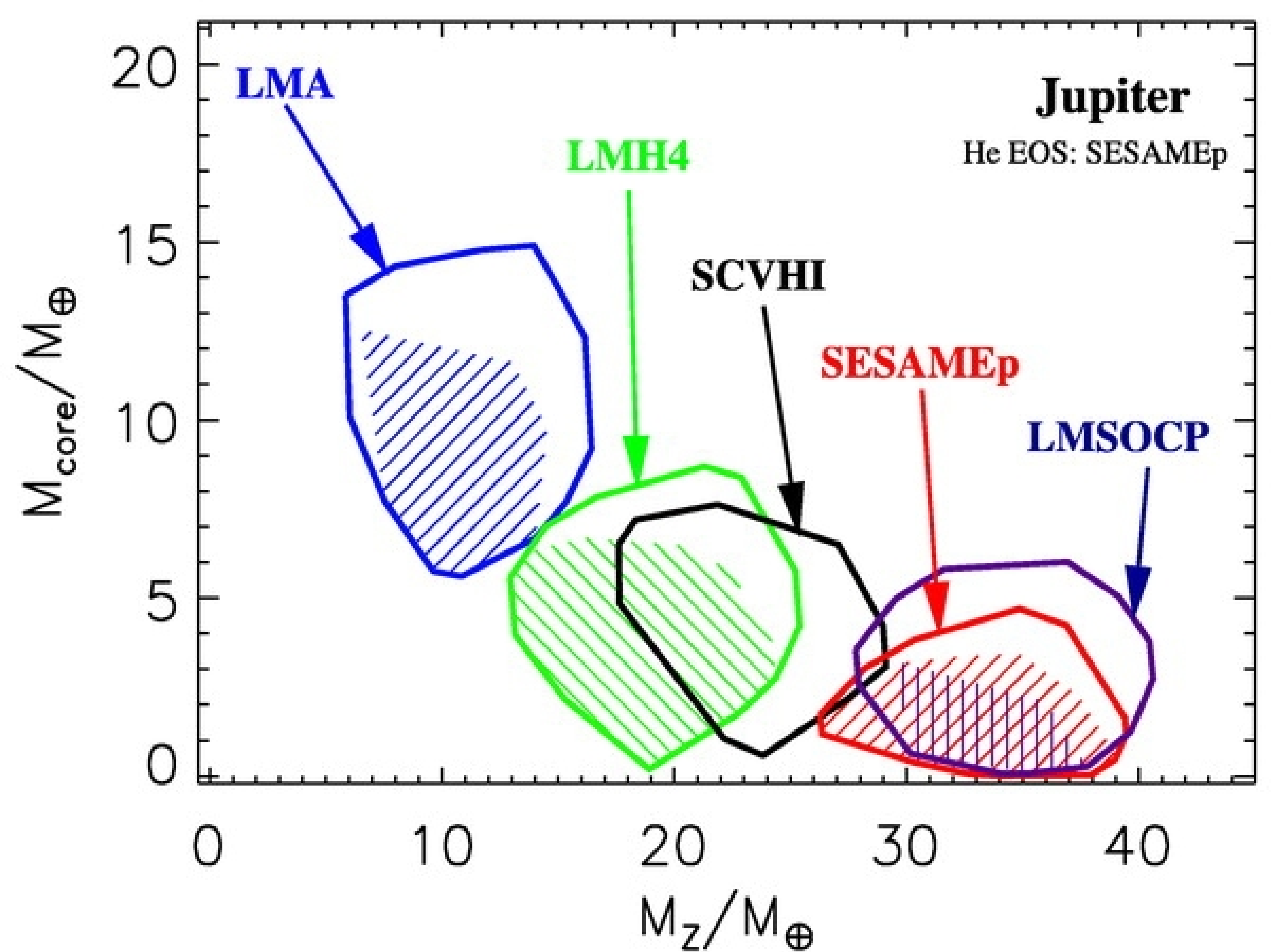




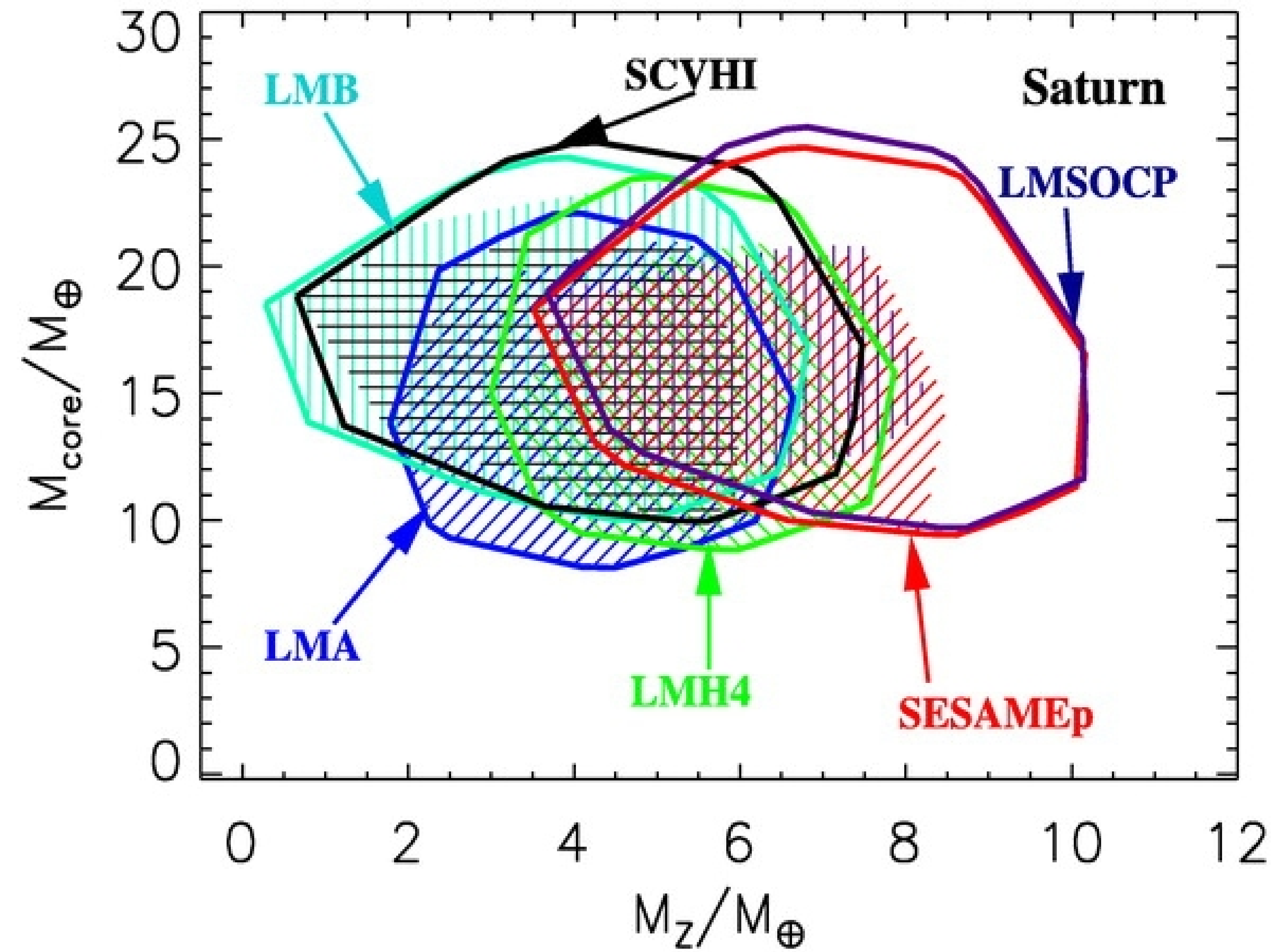
pressure (bars)
temperature (K)
Jupiter
density (g/cm^3)
cloud tops
gaseous hydrogen
1
125
0.0002
500,000
2,000
0.5
liquid hydrogen
2,000,000
5,000
1.0
metallic hydrogen
~4
100,000,000
20,000
~25
Earth
atmosphere
crust
mantle
core
core of rock, metals, and hydrogen compounds

- From Saumon and Guillot (2004)





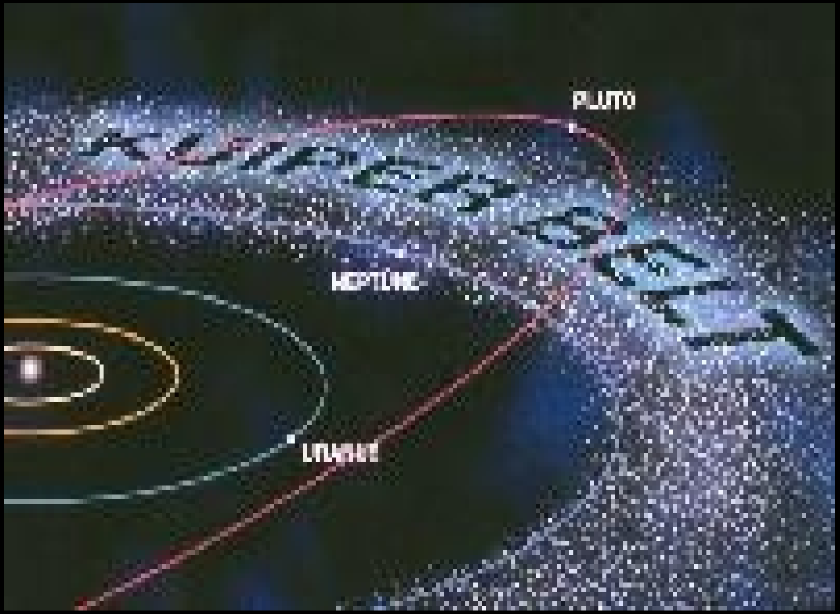
Jupiter
He EOS: SESAMEp
LMA
LMH4
SCVHI
SESAMEp
LMSOCP
$M_{core}/M_\oplus$
$M_Z/M_\oplus$
0
5
10
15
20
30
40



Saturn
SCVHI
LMB
LMSOCP
LMA
LMH4
SESAMEp
$M_{core}/M_\oplus$
$M_Z/M_\oplus$
0
5
10
15
20
25
30
0
2
4
6
8
10
12

How can we get more information?

- Back to small bodies
- Planetary satellites; regular and irregular
- Small bodies
  - Comets
  - The Kuiper Belt



Extrasolar Planetary Systems

- First discoveries in 1990s
-
- All are detected by 'indirect' methods
-
- Their orbits yielded a surprise!

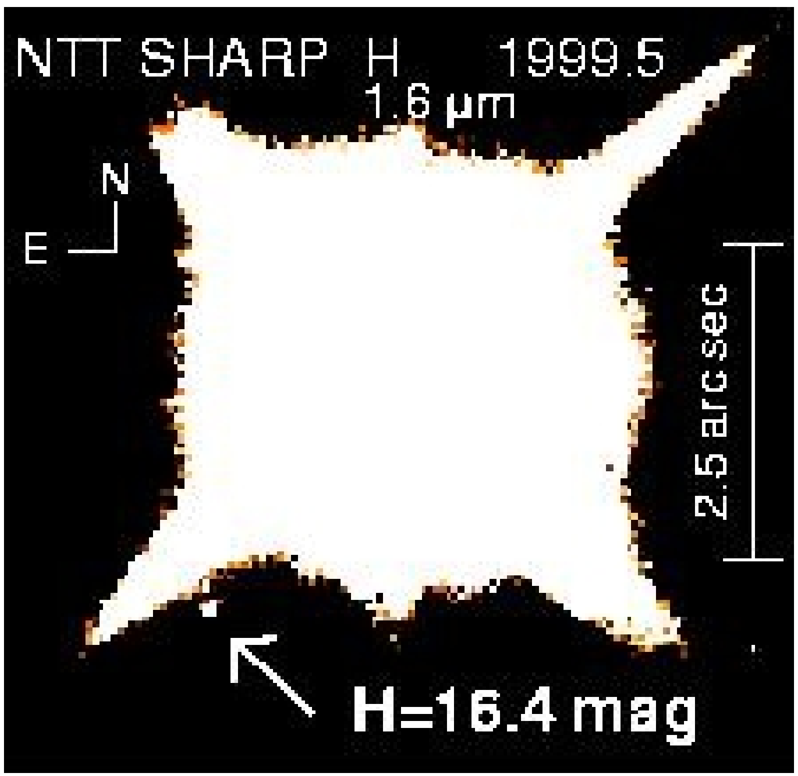
A long and checkered history

- Scientists have been trying to detect planets around other stars for a long time.
- There have been several erroneous claims.
- How can one detect such things?

Direct imaging?

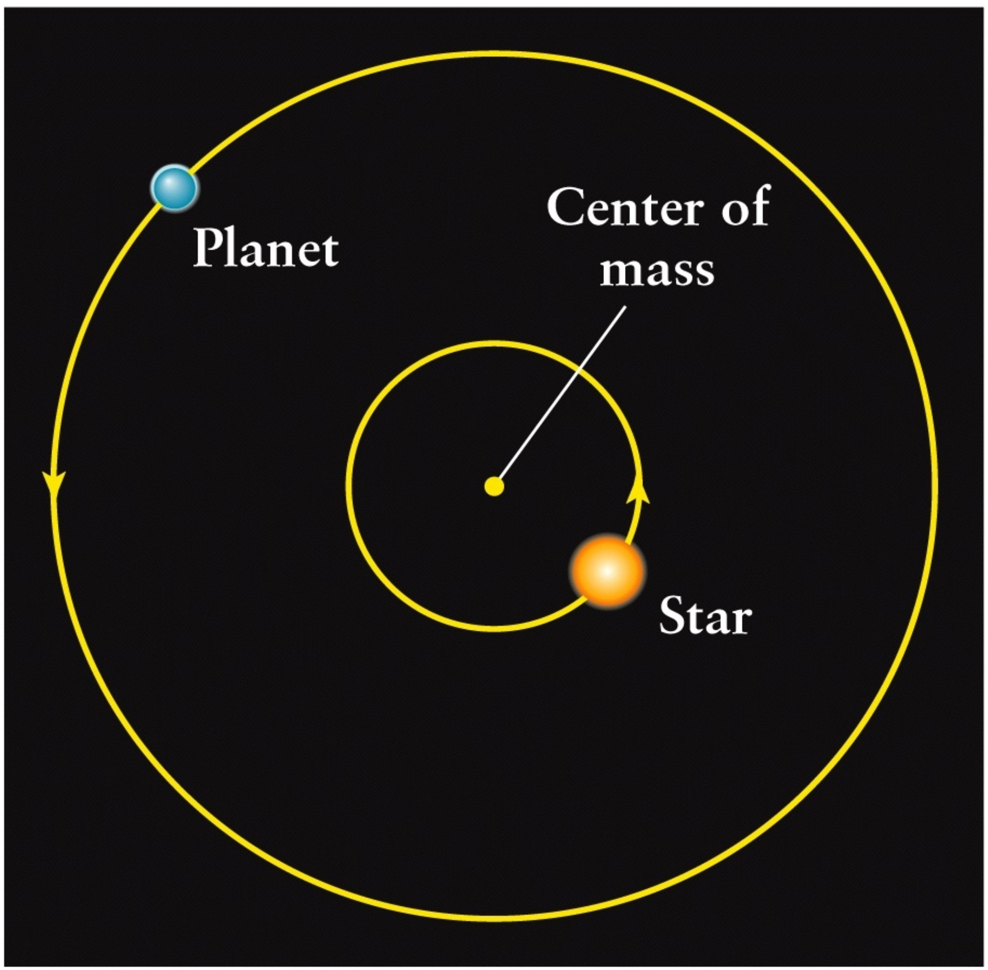
- Planets do not emit light in the optical
- All such light is reflected from the central star.
- But giant planets (being big) reflect a lot of light!

Direct imaging?



- Why not take a picture?
- A problem of *contrast;* trying to see something very faint just beside something very bright.
- Even around nearby stars we can only do this at distances of >100 AU.
- So astronomers must use *indirect methods*

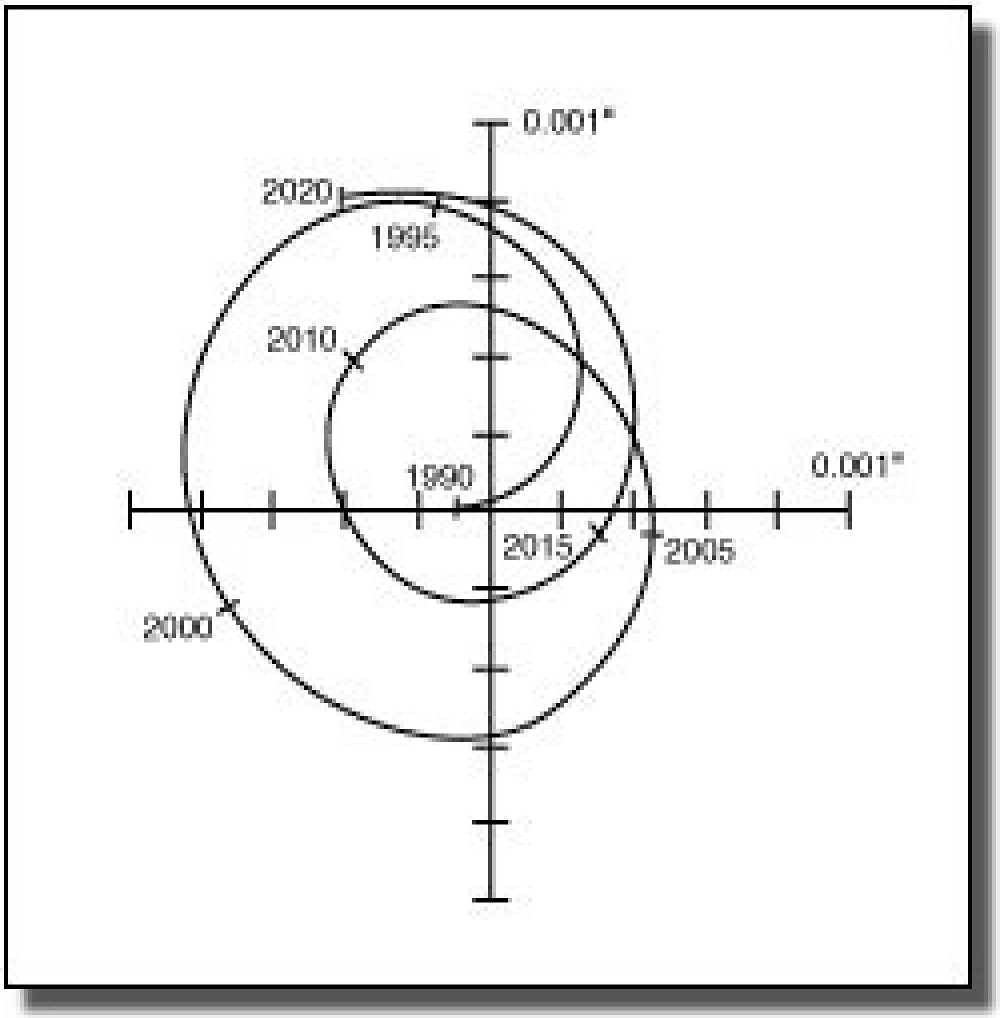
Reflex orbital motion



a

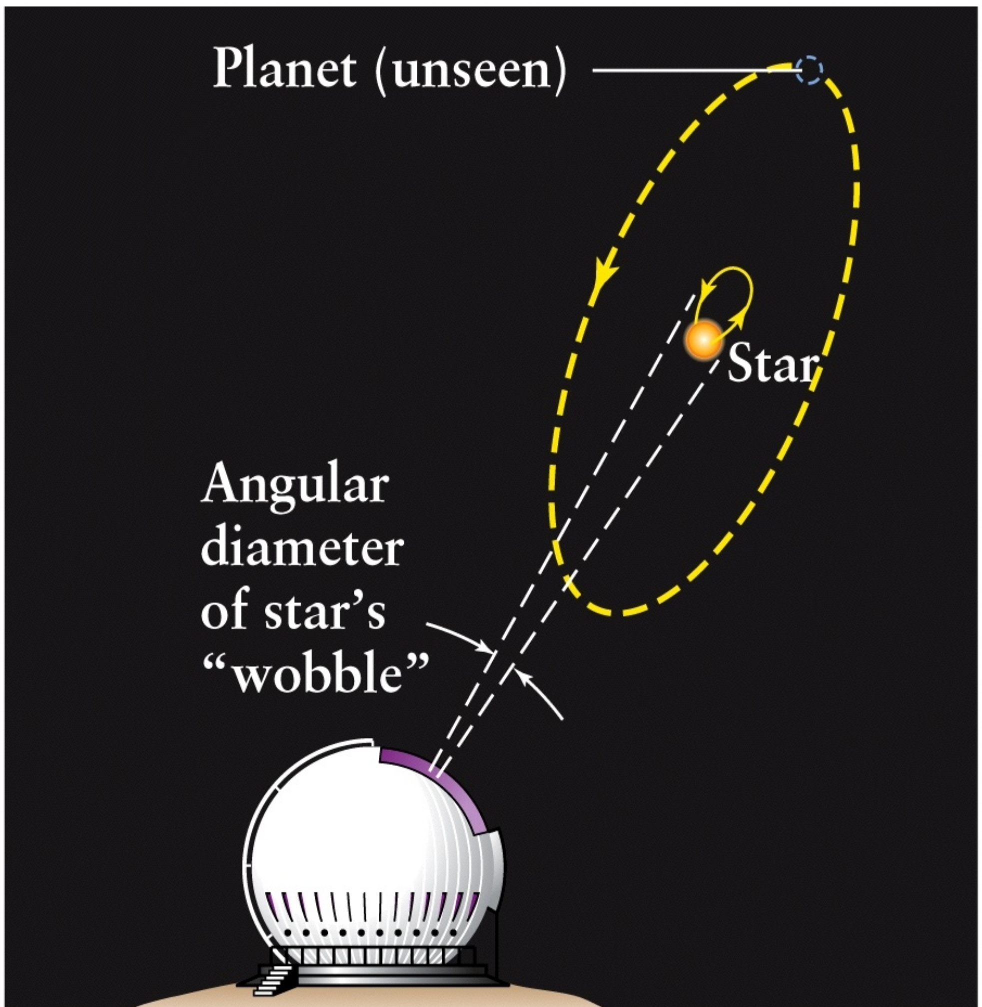
- When two objects orbit each other, they each orbit in a circle around their center of mass (com).
- The com is closer to the biggest object, as determined by their mass ratio.
- Earth/Moon : 81 in mass, so 1/81 of the way to Moon.

Astrometric motion?



- For the Sun-Jupiter system, c.o.m. is at surface of Sun.
- Figure shows the apparent trajectory of Sun's center during 30 years if viewed from a nearby star near the NCP.
- Motion is 0.001”, which is undetectable, although some claims were made.

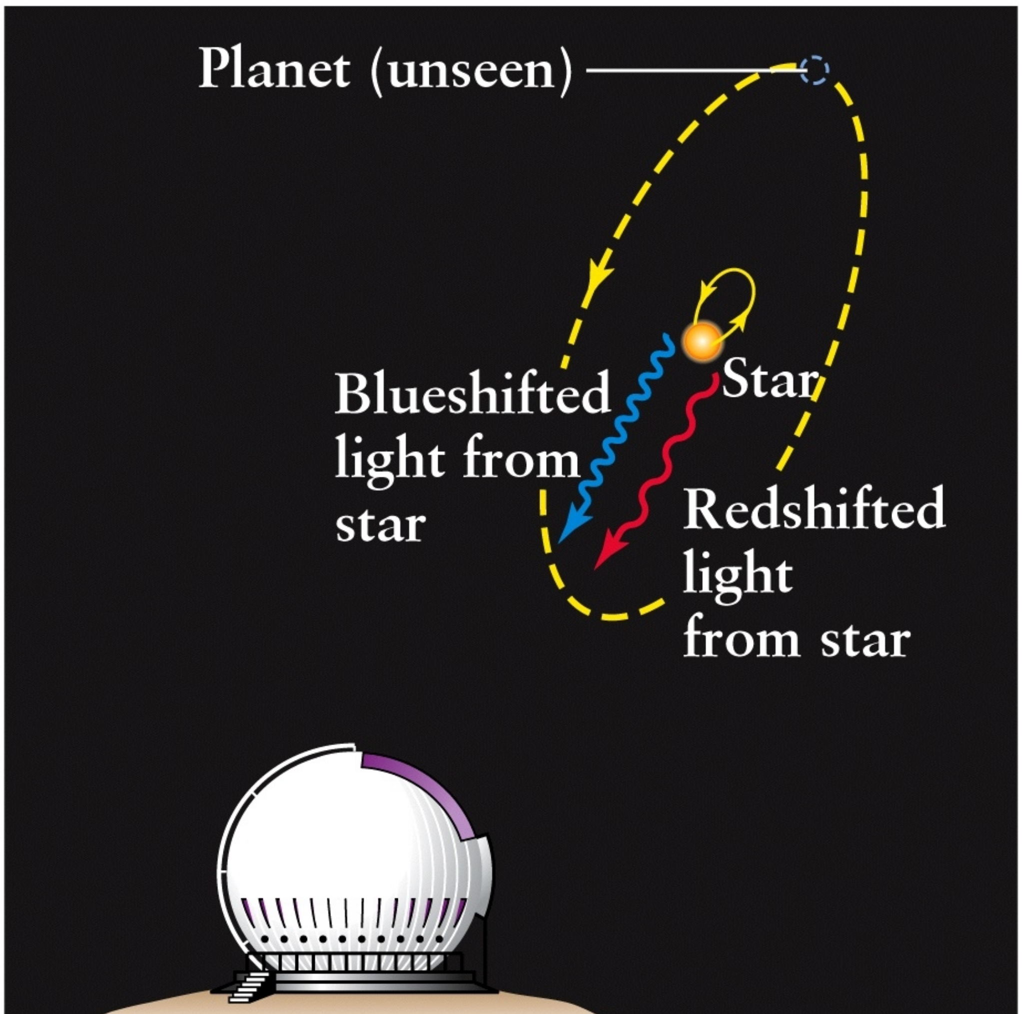
Size of the wobble



b

- The nearest stars are about 10 light-years away, which is about 700,000 AU
- The wobble back and forth for an edge-on system is about 0.005 AU
- So, the angle is d/D or 0.005/700,000 = 0.001"
- Again, this is very very hard to detect.
- What to do, what to do...?

Use the Doppler effect!



c

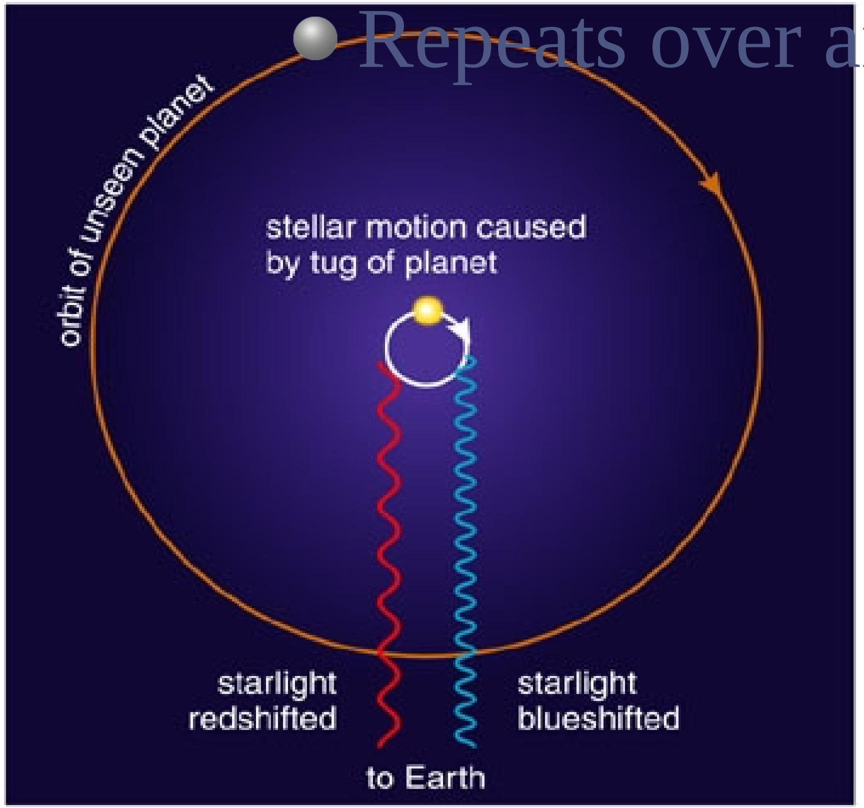
- Watch the spectrum of the central star
- Sometimes star approaching, other times receeding
- The Doppler effect causes spectral lines to shift back and forth, with amplitude proportional to mass of planet, and with the period of the planet's orbit!

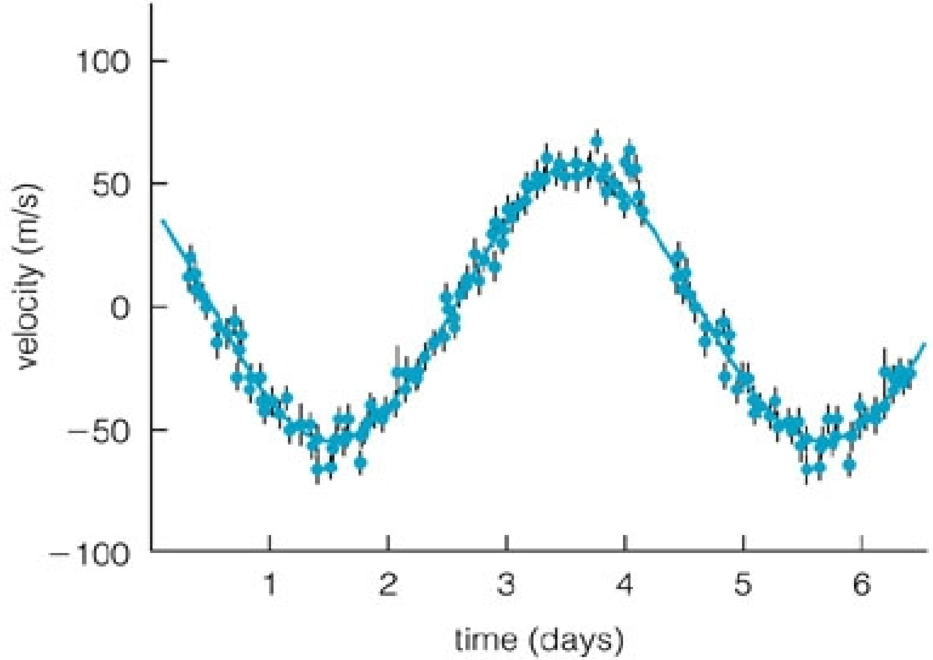
How big is the effect?

- Recall that : $\Delta\lambda/\lambda = v/c$, where
  - λ is the wavelength of light being used
  - $\Delta\lambda$ is the change in the wavelength of the spectral line
  - v is the velocity that the star is moving
    - CAN BE TOWARDS OR AWAY
  - c is the speed of light
- Can show (done on board in class):
  - vmax = 13 m/s * sqrt(5 AU/a)
  - For 1 Jup-mass planet orbiting star like Sun at 5 AU

What do you see?

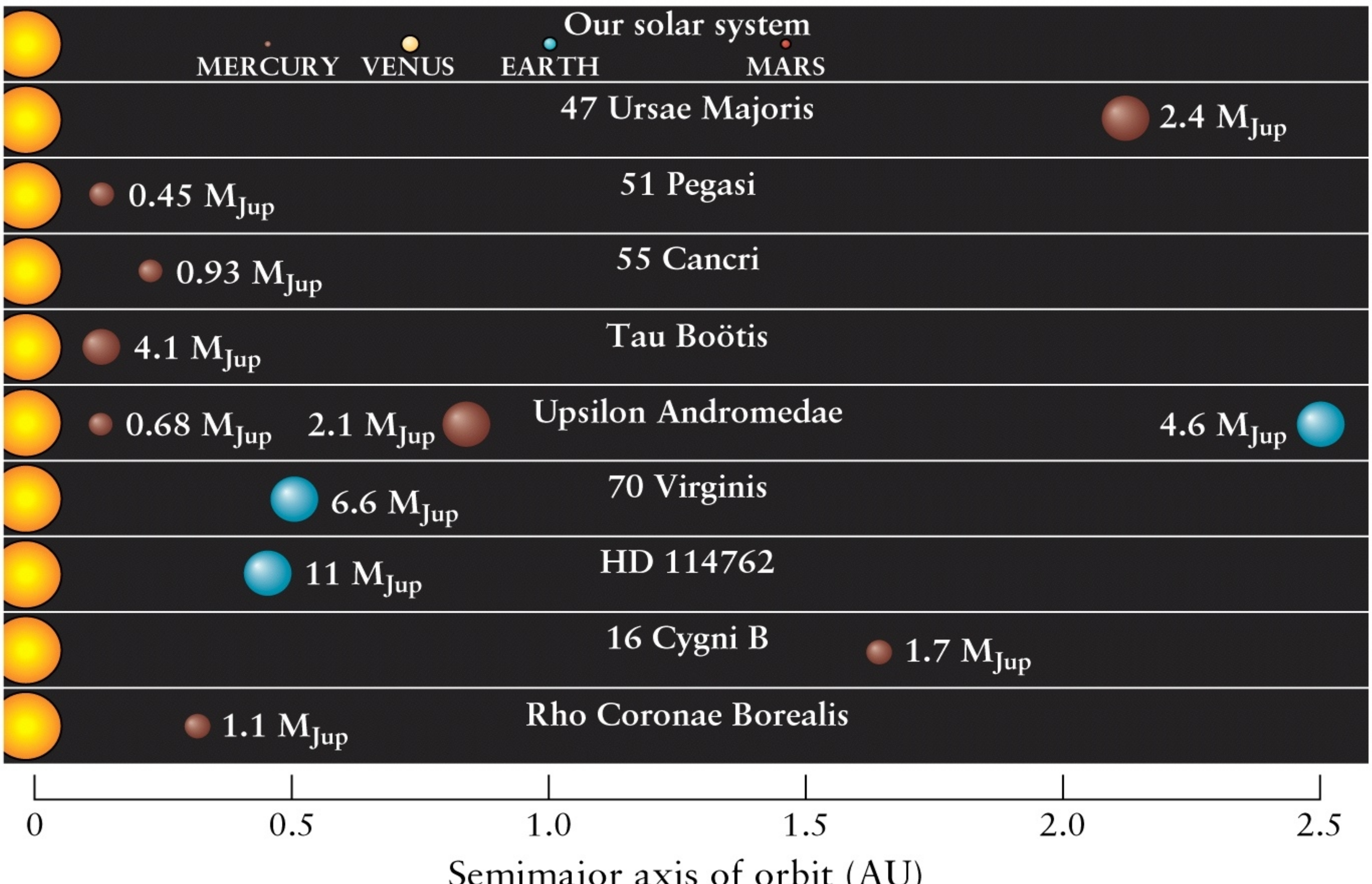
- You can get the line-of-sight speed of the star from the amplitude of the effect.
- Repeats over and over again.





Many systems discovered this way

- The BIG surprise : Planets the mass of Jupiter or larger very close (0.1 – 2.0 AU) to their star.



The M sin(i) problem

- In fact, you only really measure the mass of the planet TIMES sin(i), where i is the inclination of the orbit (i=0 for 'face on', 90 deg for 'edge-on')
- So, do you get a LOWER LIMT or UPPER LIMIT on the mass of the planet???

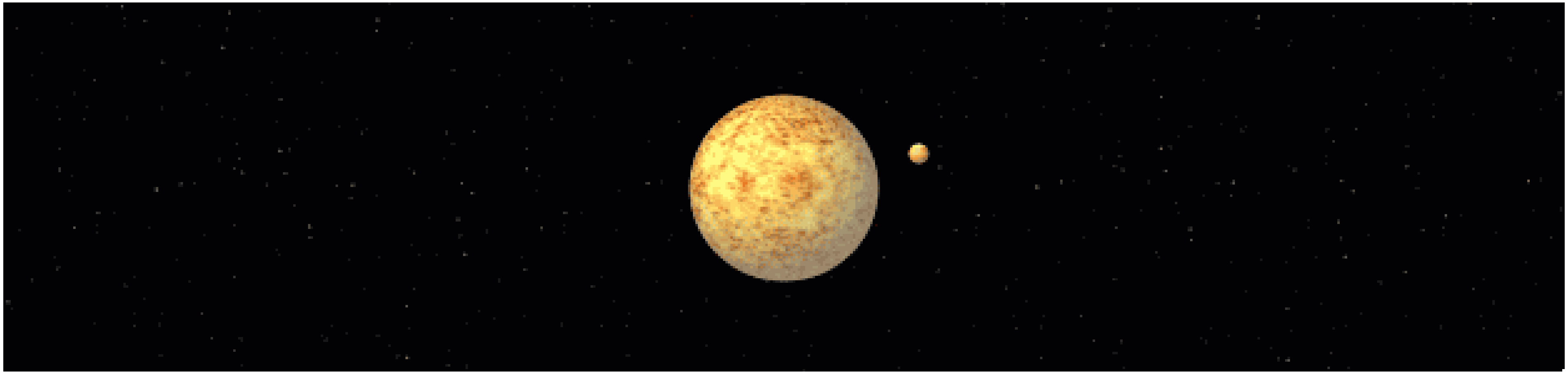
A) A LOWER LIMIT

B) AN UPPER LIMIT

The M sin(i) problem

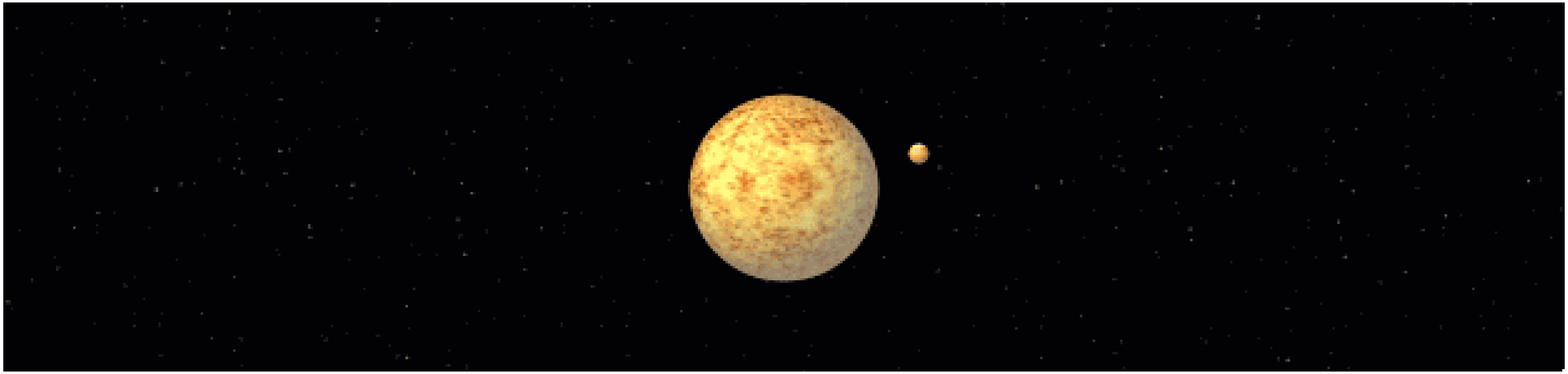
- In fact, you only really measure the mass of the planet TIMES sin(i), where i is the inclination of the orbit (i=0 for 'face on', 90 deg for 'edge-on')
- Example : Suppose M sin(i) = 1 Jupiter mass
  - It COULD be that sin(i)=0.5 and M = 2 Jup. mass
  - OR that sin(i)=0.1 and M=10 Jupiter-mass
- How can you know the inclination?
  - In general, you can't....but...

If you're lucky...

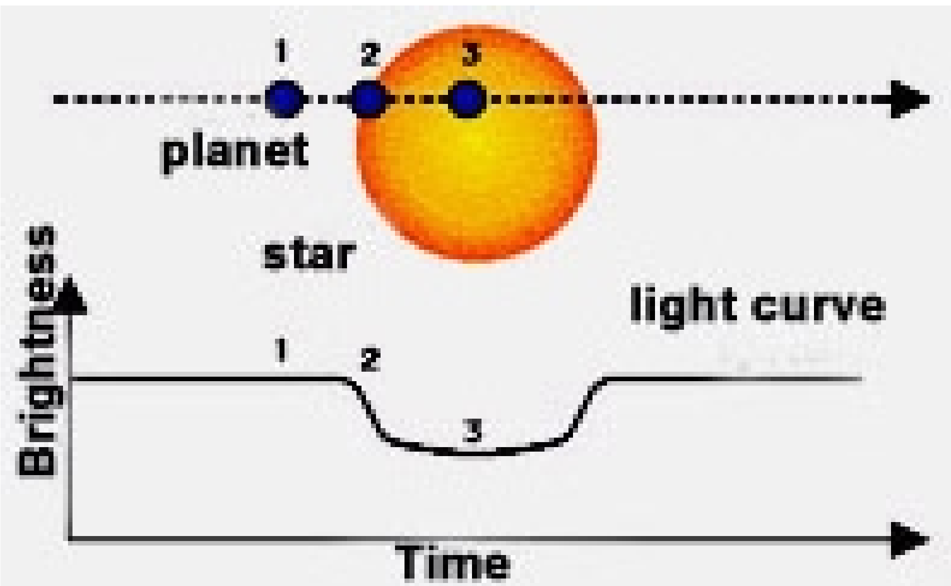


If you're lucky...

- A TRANSITING system has the planet's orbit crossing in front and behind the star
- This means that i=90 degrees and you get the mass of the planet.
- What can you see in such a case?

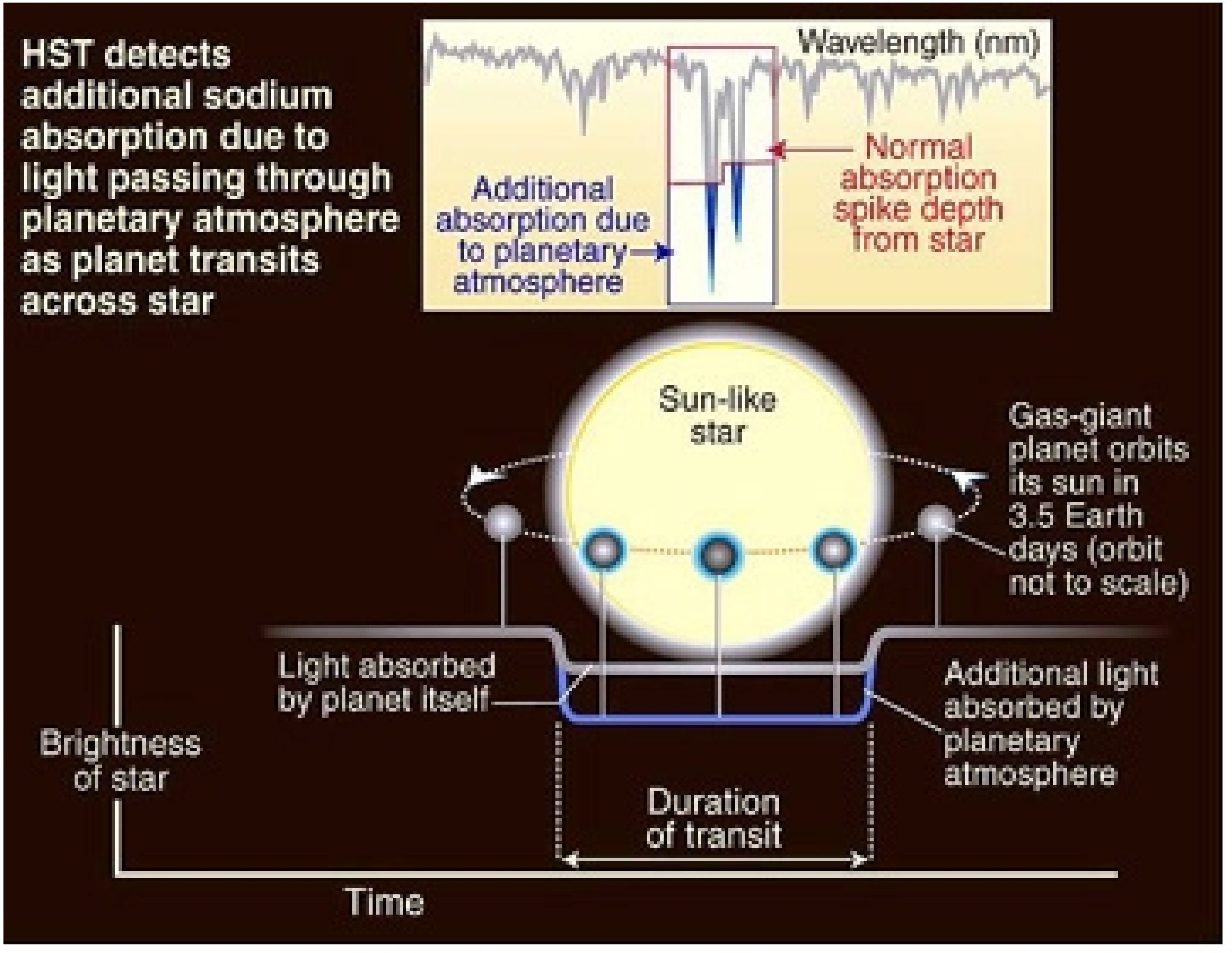


You can see the partial eclipse.



- When planet passes in front of the star, it blocks some of the light of the star.
- (Just the geometrical fraction of the disk that it blocks, which can be around a percent).
- This GIVES the radius of the planet (why?)

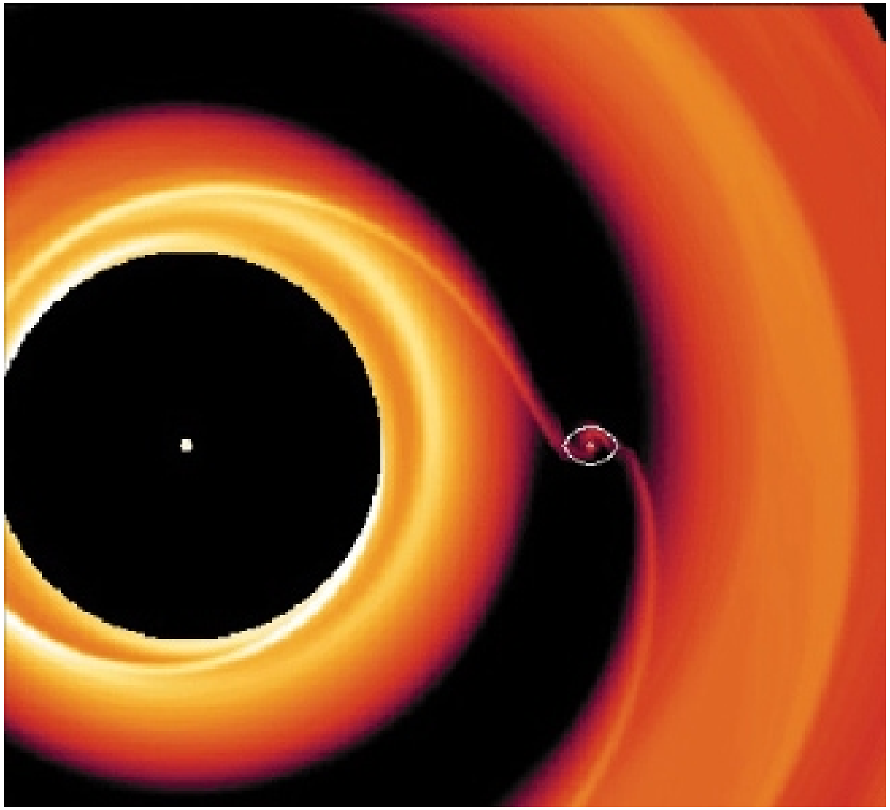
Can even see absorption spectrum of the planet's atmosphere!



Surprises, or not?

- We find such large planets so close
  - In nebular theory, expect them to form only outside of the 'frost line' near 5 AU.
  - How is this possible?

Big planets can interact with the disk



- Tides between the disk and the planet cause the planet to slowly spiral towards the star.
- So they can form near 5 AU and then migrate in to near the star.
- This pushes the inner disk into the star.

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- We DON'T see Jupiter-sized objects near 5 AU
  - Why?

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  - How is this possible? Migration
- We DON'T see Jupiter-sized objects near 5 AU
  - Why? Because their orbital periods are >10 years and we have only been doing this this long.
- We DON'T see Earth-sized objects near 1 AU.
  - Why?

Surprises, or not?

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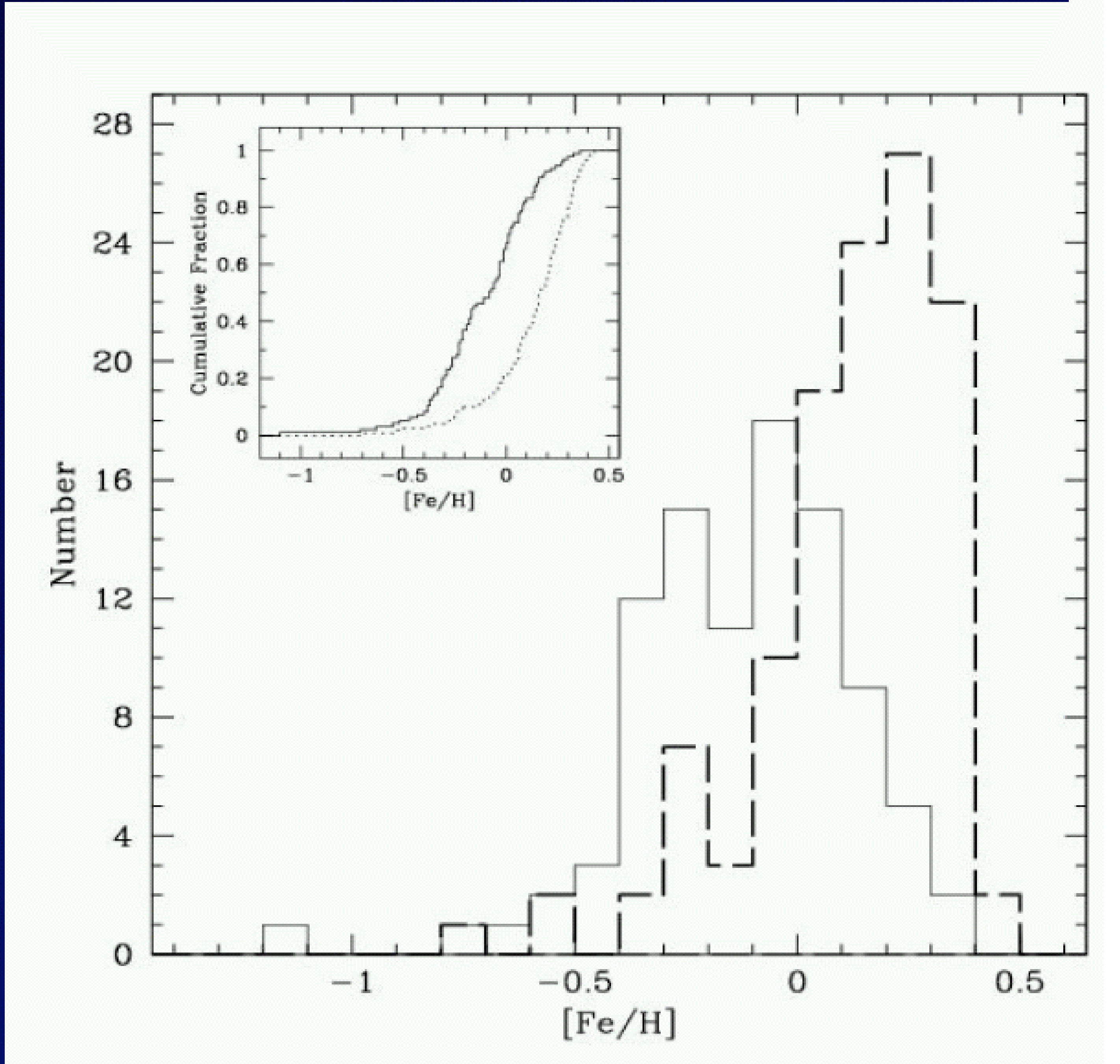
  - In nebular theory, expect them to form only outside of the 'frost line' near 5 AU.
  - How is this possible? Migration
- We DON'T see Jupiter-sized objects near 5 AU
  - Why? Because their orbital periods are >10 years and we have only been doing this this long.
- We DON'T see Earth-sized objects near 1 AU.
  - Why? They don't tug the star enough.

A recent advance: planet-bearing stars are more metal rich

Average difference 0.25dex

$P(KS) \sim 10^{-12}$



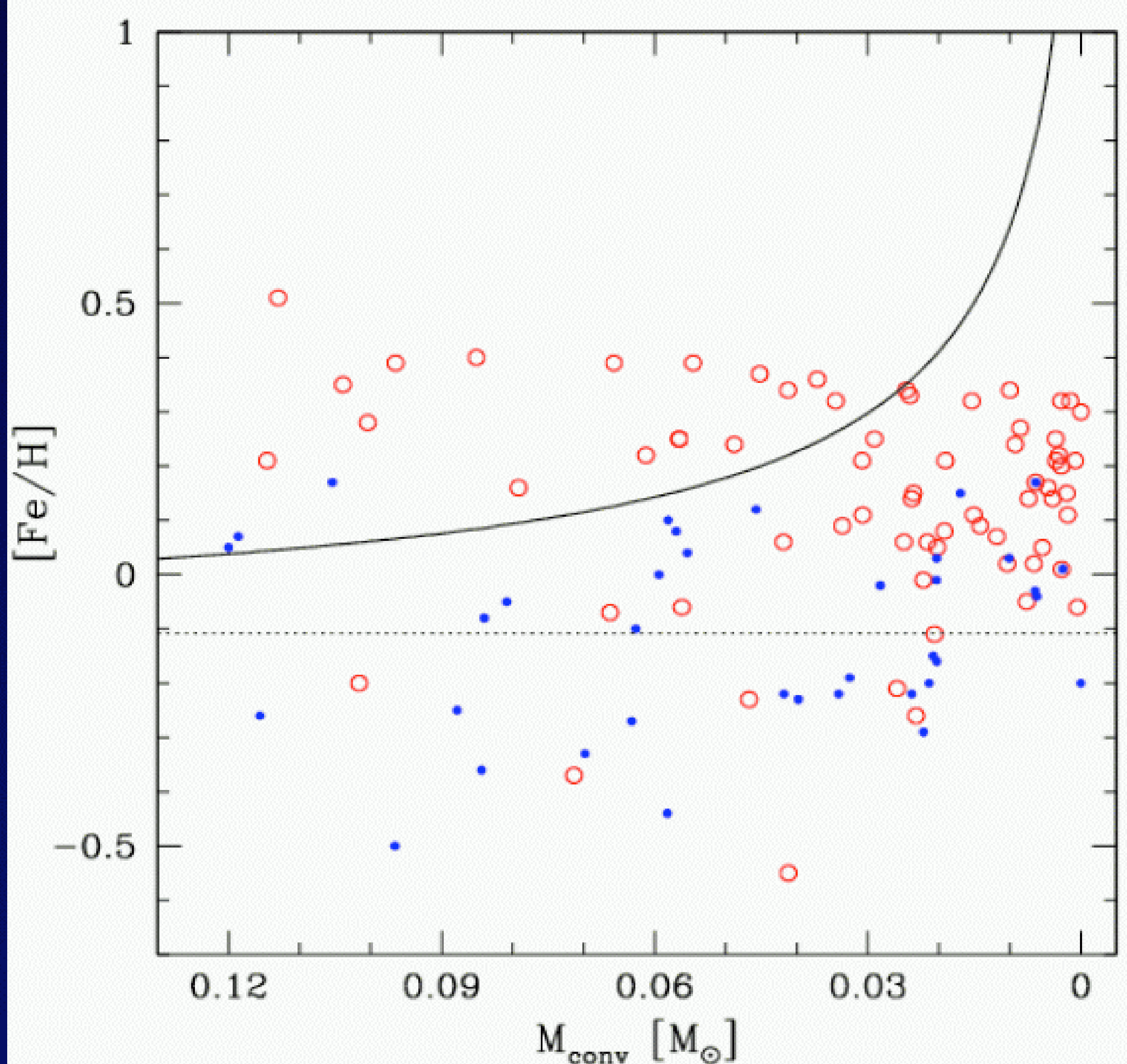
119 planet-hosts (Santos et al. 2005)

Couldn't migrating planets pollute the upper layers of star?

Pollution is probably not source of excess!

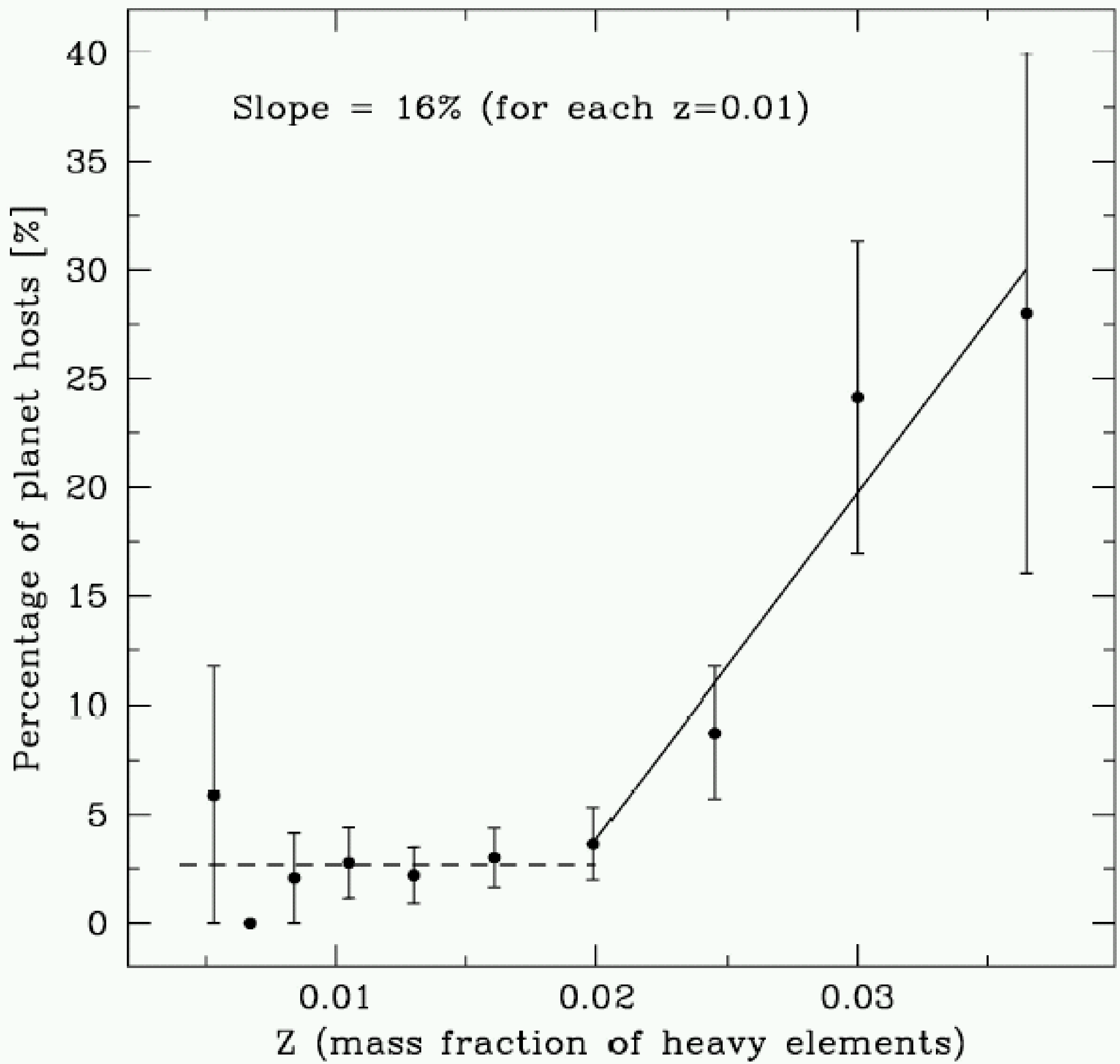
No Correlation!

Pinsonneault et al. (2001)
Santos et al. (2003)
Cody et al. (2004)



This means giant planets easier to build in metal-rich disks?

Two different populations, a flat tail, a ~z^2 dependence?



Santos et al. (2004)

Implications for models: Core accretion vs. disk instability

- Core accretion model: planet formation dependent on dust content (e.g. Ida & Lin 2004; Alibert et al. 2004)
- Disk instability model: not strongly dependent on metallicity (Boss 2002)

Observations are (more) compatible with core accretion model!