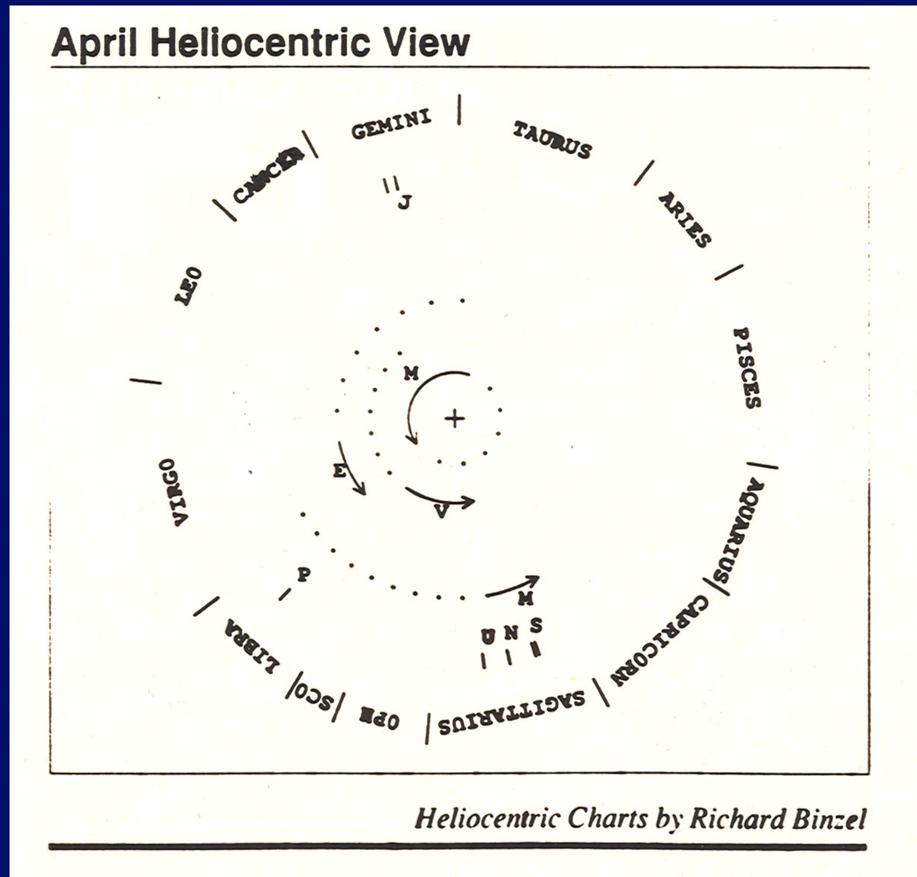
Origin of Planets

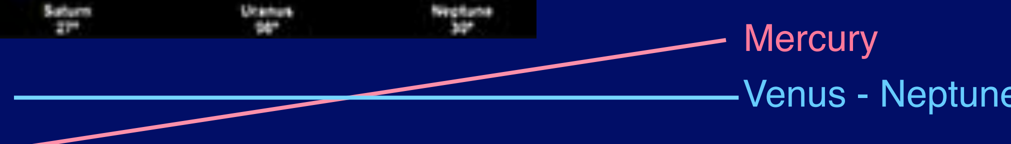
Our Solar System as Example

- We know far more about our solar system than about any other
- It does have (at least) one planet suitable for life
- Start with facts about the solar system
- Then discuss theories of planet formation

General Properties of the Solar System

- Dynamical Regularities
  - Planets orbit in plane, nearly circular
  - Planets orbit sun in same direction (CCW as seen from North Pole)
  - Rotation axes perpendicular to orbit plane
    - Uranus is the exception
  - Planets contain 98% of the angular momentum
  - The Sun contains 99.9% of the mass

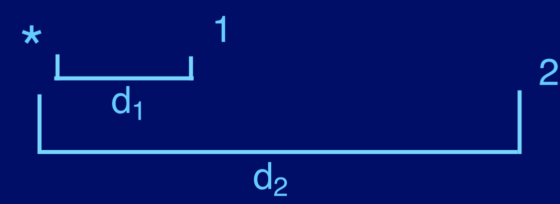

April Heliocentric View
GEMINI
TAURUS
ARIES
PISCES
AQUARIUS
CAPRICORN
SAGITTARIUS
SCO
LIBRA
VIRGO
LEO
CANCER
Heliocentric Charts by Richard Binzel


Mercury
Venus - Neptune

Side View

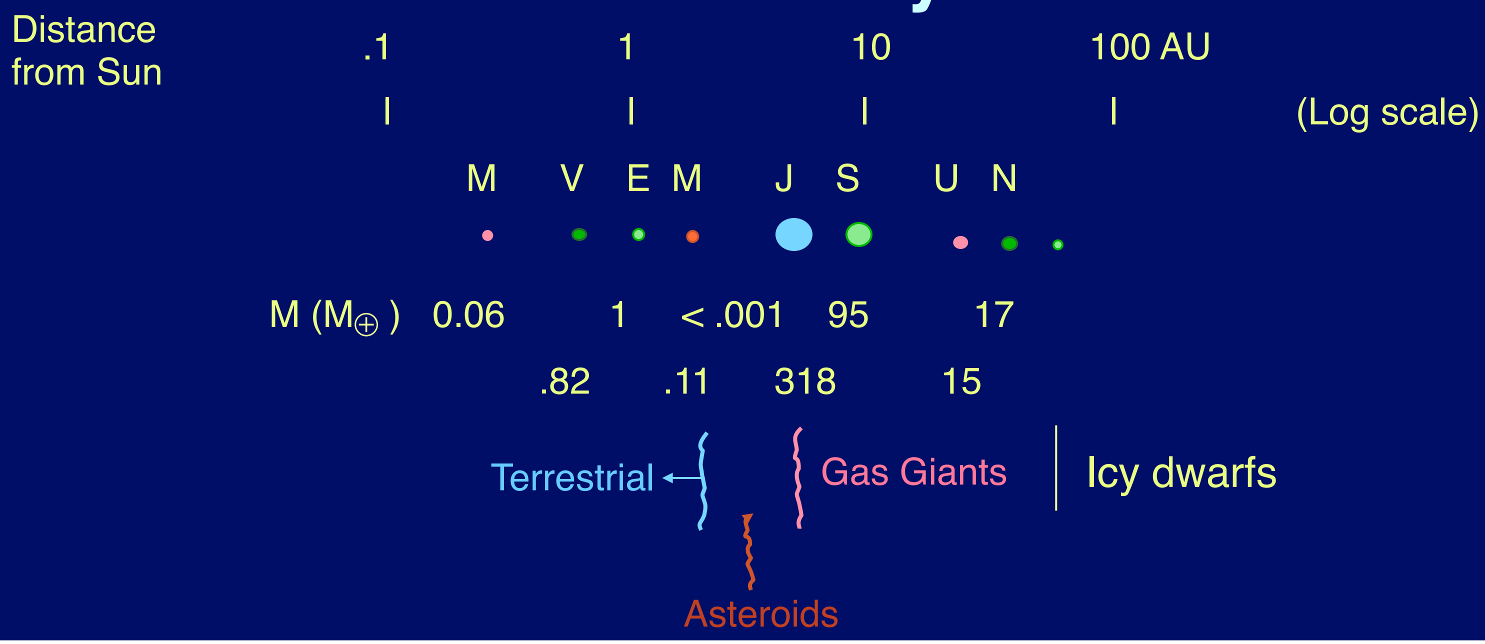
Spacing and Composition

- Spacing increases with distance
  - Evenly spaced if plotted logarithmically
  - Missing planet in asteroid belt
- Composition varies with distance
  - Inner 4 are "terrestrial"
    - Small, rocky, thin atmospheres
  - Outer 4 are "gas giants"
    - Gaseous, large, mostly atmosphere



$$\frac{d_2}{d_1} \simeq 1.5 - 2$$

The Solar System



Composition (%)

	Rocky	"Icy"	Gaseous	Enhancement to get ⊙ abundance
Terrestrial	100	<1	0	300-500
Jupiter	6	~13	~81	2-40
Saturn	21	~45	~34	10-60
Uranus	~28	~62	~10	30 –140
Neptune	~28	~62	~10	30-115
Comets	~31	~69	~0	

Rocky - iron, silicates, …

"Icy" - at time of formation (H_2O, NH_3, CH_4, …)

Gaseous - H, He

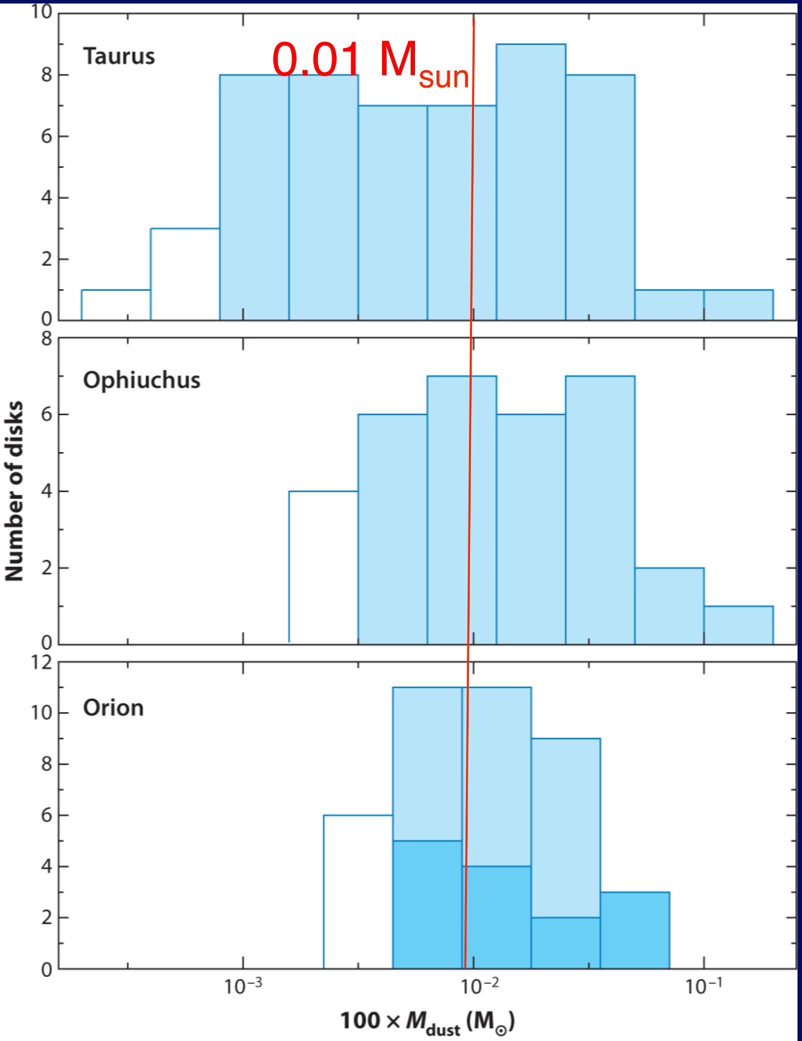
What is a Planet? I. Small end…

- Pluto much smaller than others (0.002 M_{earth})
- Other, similar objects found in Kuiper Belt
  - Including one similar to Pluto (Eris)
    - First named Xena, renamed Eris, goddess of discord, has a moon, Dysnomia, goddess of lawlessness…
- IAU voted in 2006
  - 1. Create a new category of dwarf planet
  - 2. Demote Pluto to a dwarf planet

Theories of Planet Formation

- All start with rotating disk
  - Mass $0.01M_\odot$ or more
    - Sum of planet masses $0.001\ M_\odot$
    - Consistent with observed disk masses
  - Temperature and Density decrease with distance from forming star
  - Dust plays crucial role

Many disk masses are large enough…



Williams JP, Cieza LA. 2011.
Annu. Rev. Astron. Astrophys. 49:67–117

And these masses measure only the small dust. Rocks are invisible to us.
But they are based on dust mass times 100.
We have less info on gas masses.

Annual Reviews

First Step: Accretion of Dust Grains

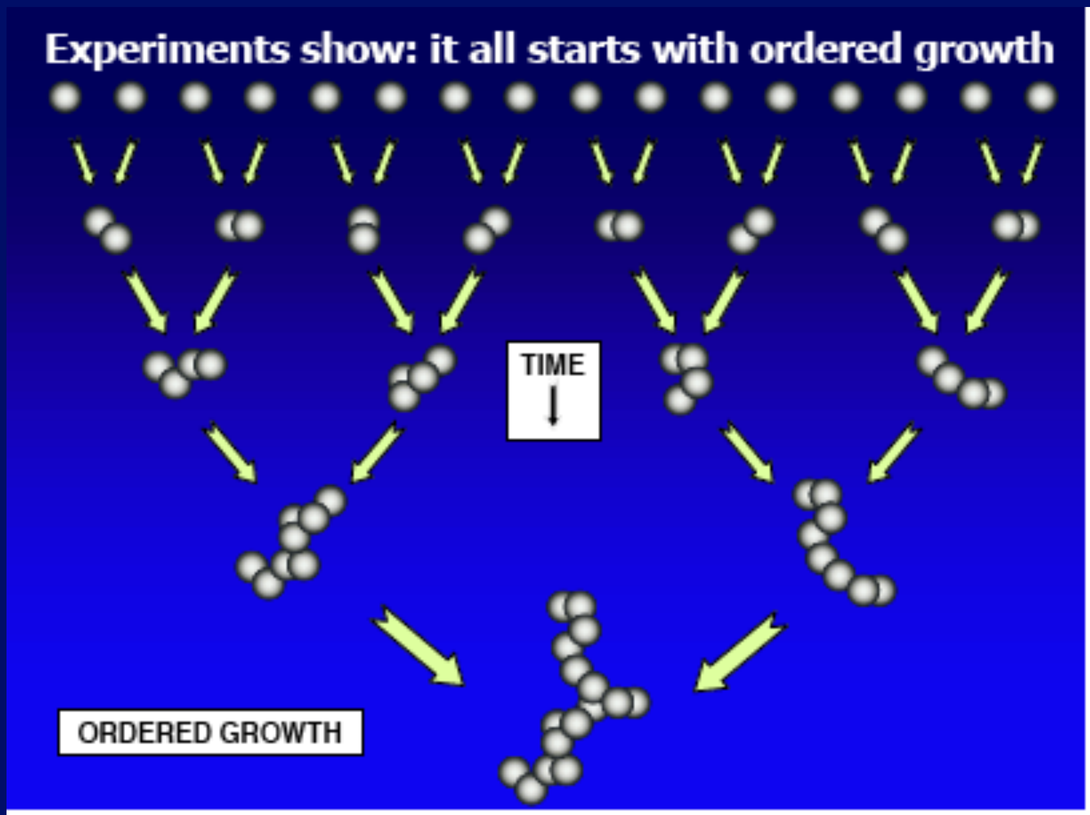
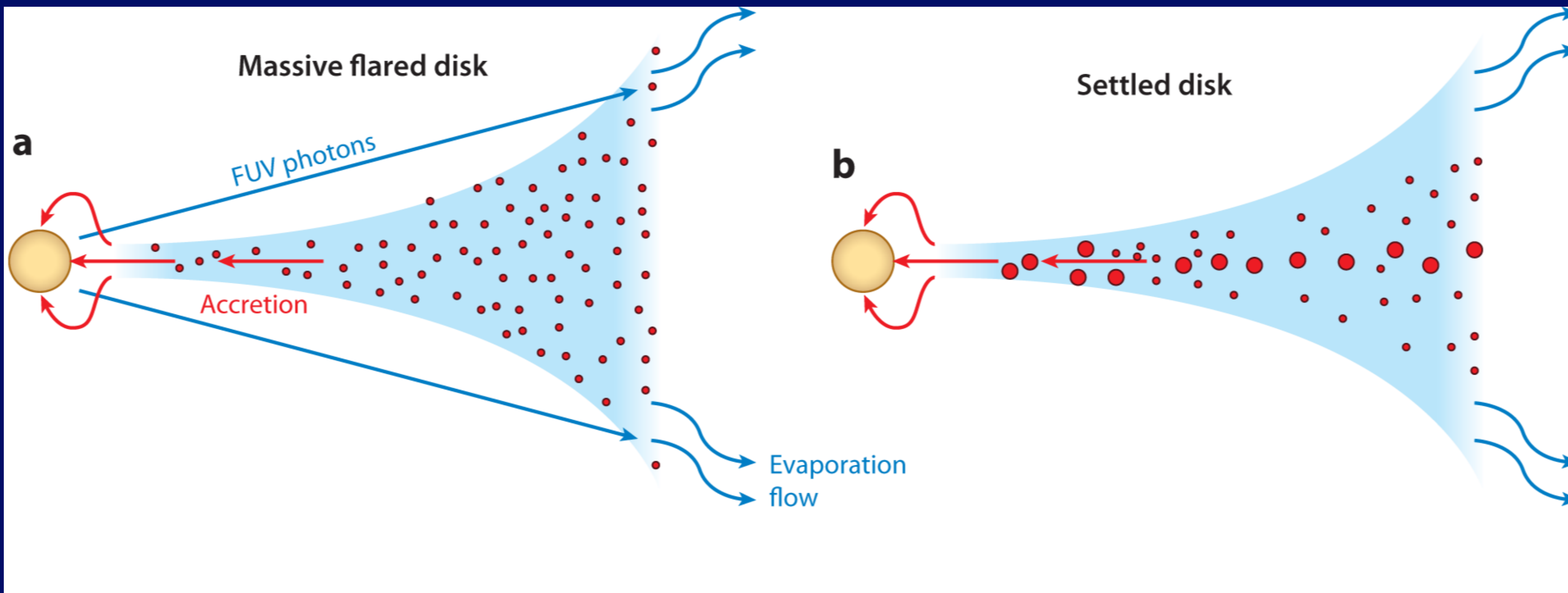


Fig. From talk by Jurgen Blum

Second Step: Dust settles to midplane

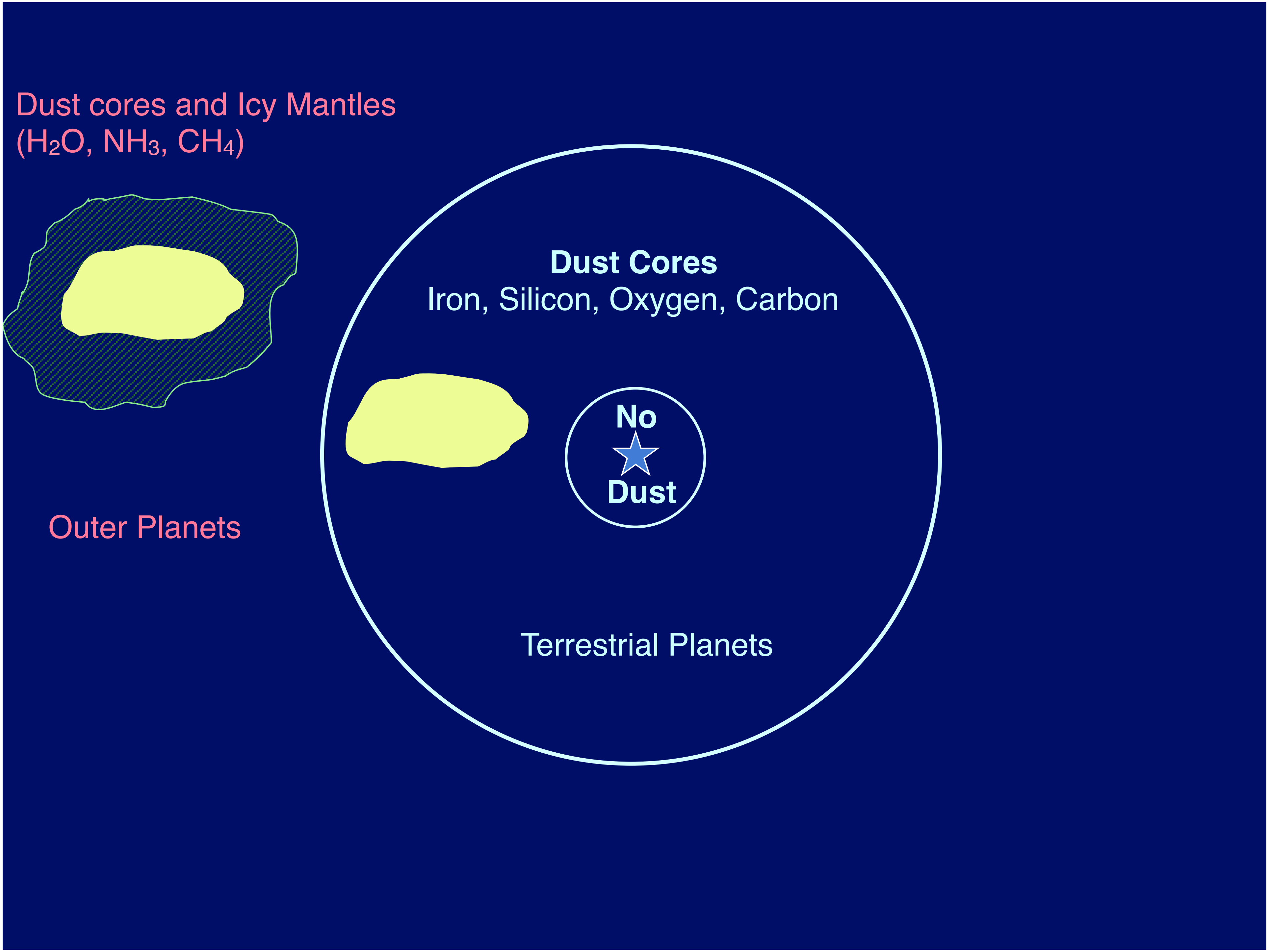


Williams and Cieza, Annual Reviews

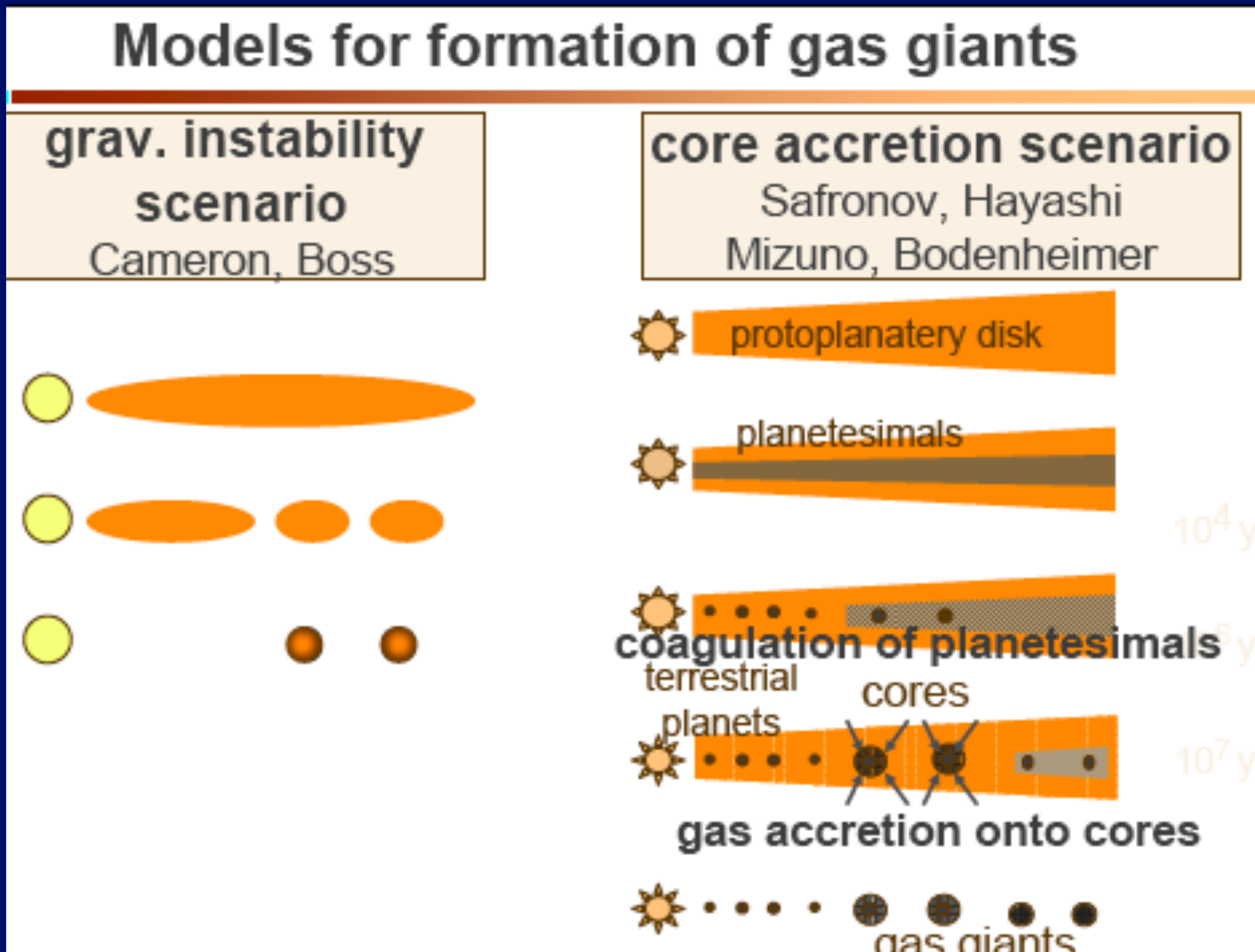
Step 3: Dust in midplane grows to rocks, boulders, …

Step 4: From Boulders to Planets

- Boulders grow to planetesimals
- Planetesimals collide, grow larger
  - Some dust returned in collisions
- Icy dust in outer part of disk
  - Builds bigger, icier planets
  - Internal heat turns ice to gas
- If rock-ice core massive enough
  - Gravitational collapse of gas
  - Gas giants with ring/moon systems


Dust cores and Icy Mantles
(H_2O, NH_3, CH_4)
Outer Planets
Dust Cores
Iron, Silicon, Oxygen, Carbon
No
Dust
Terrestrial Planets

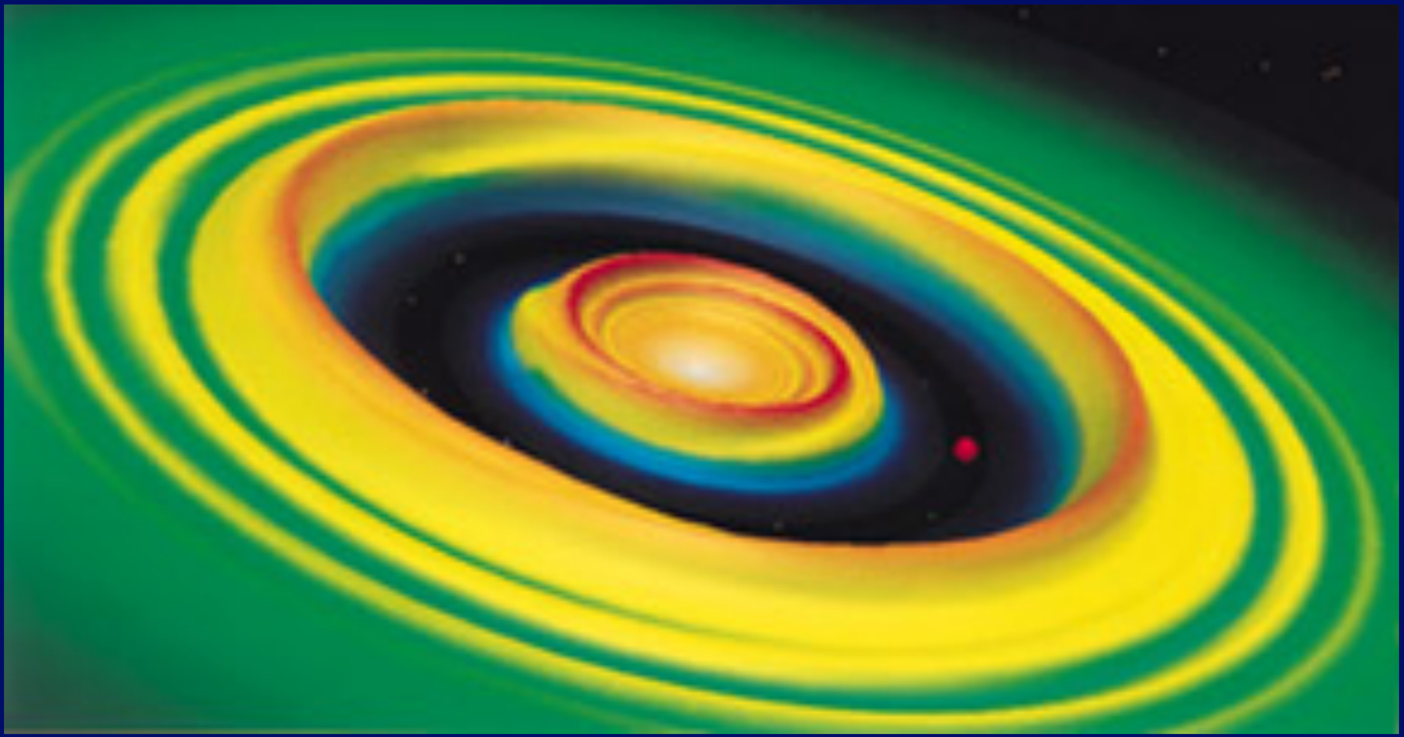
Formation of Gas Giants (Jupiter, Saturn)



Predictions from Models

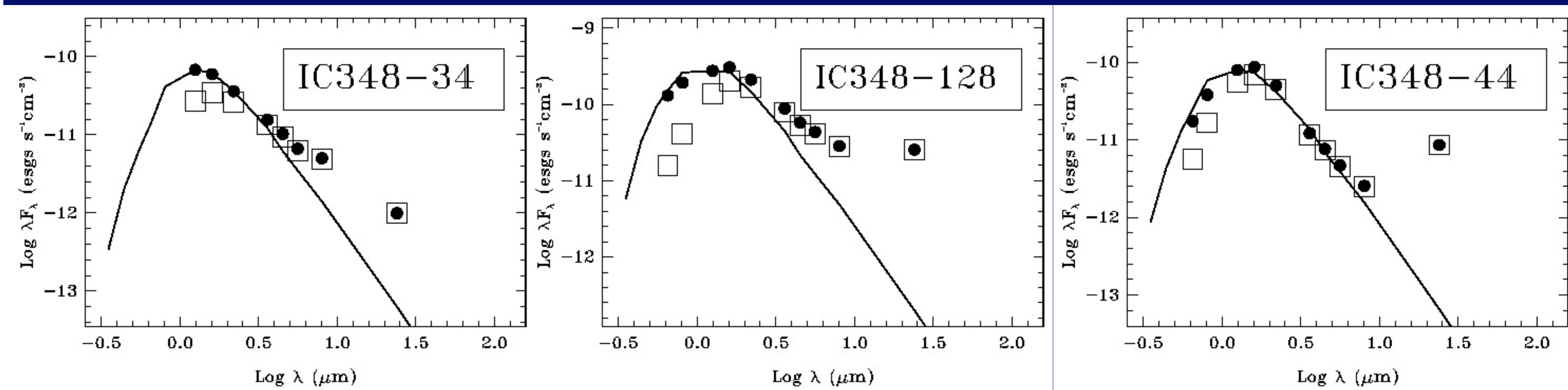
- Formation in rotating disk with icy dust can explain many facts about our solar system
- If we can generalize, expect planetary systems common
- Expect (?) about 10 planets, terrestrial planets in close, giant planets farther out, spaced roughly logarithmically
- May still be typical, but not universal…
- Big planets may clear a gap in disk

Theory Predicts Forming Planets Clear a Gap



Can we observe such gaps?

Detecting Disk Gaps



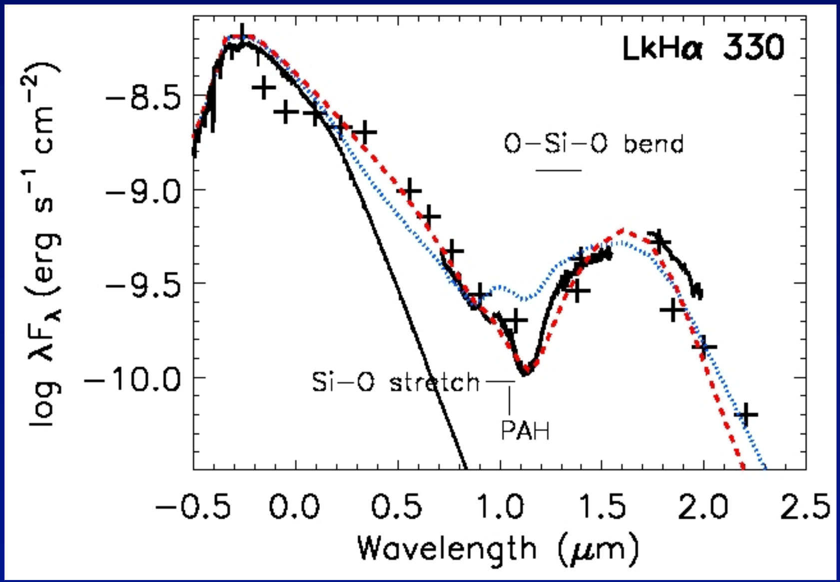
Disk with little dust

Disk with little hot dust, more cool dust

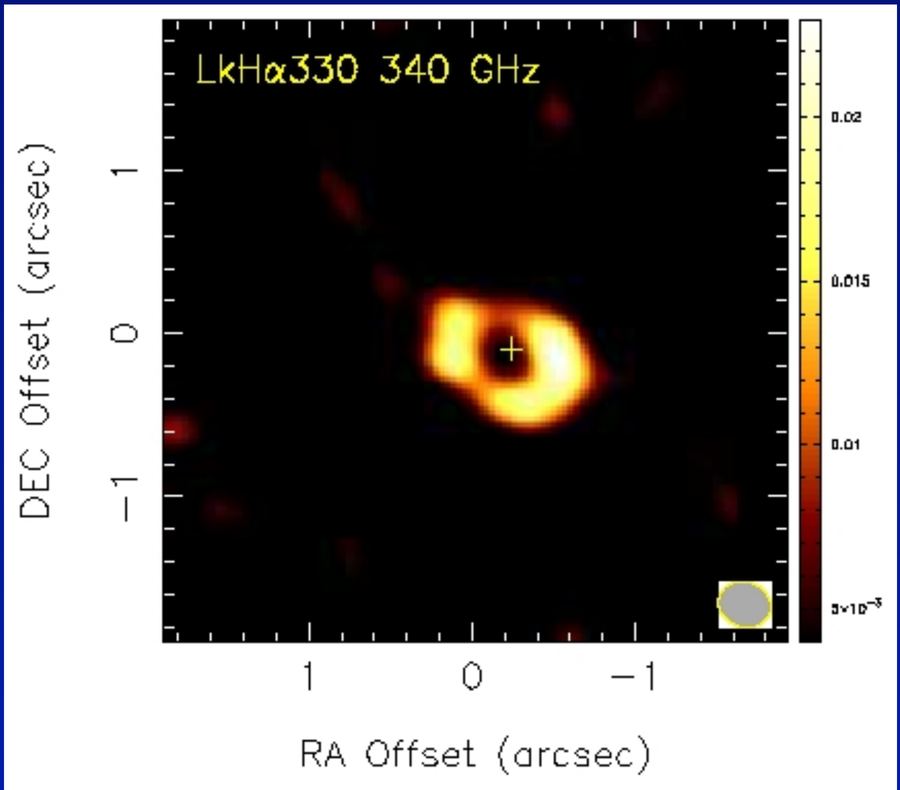
Disk with almost no hot dust, but a lot of cool dust

Star emission peaks at visible/near-infrared wavelengths. Dust in disks emits in infrared (an excess). Near-infrared if hot (close to star), mid-infrared if cooler. Some excesses start only at long wavelengths but are substantial. These fit models with gaps.

A Case Study LkHα330



Brown et al. 2007b

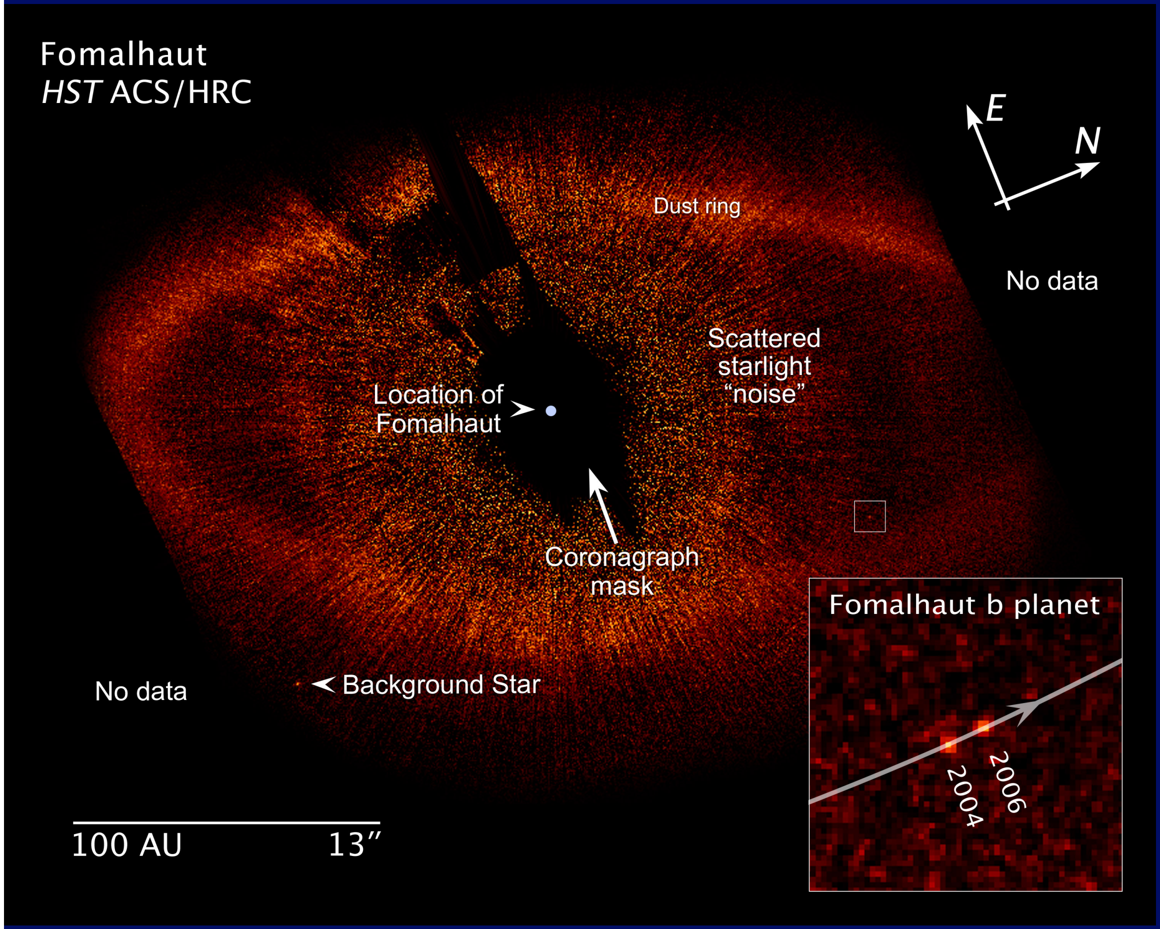


Some excess at short λ, but much more beyond 20 μm. Blue line has no gap, red has gap.

Implies large gap; models predict about 40 AU radius. Submm interferometer should show ring.

J. Brown et al. 2007

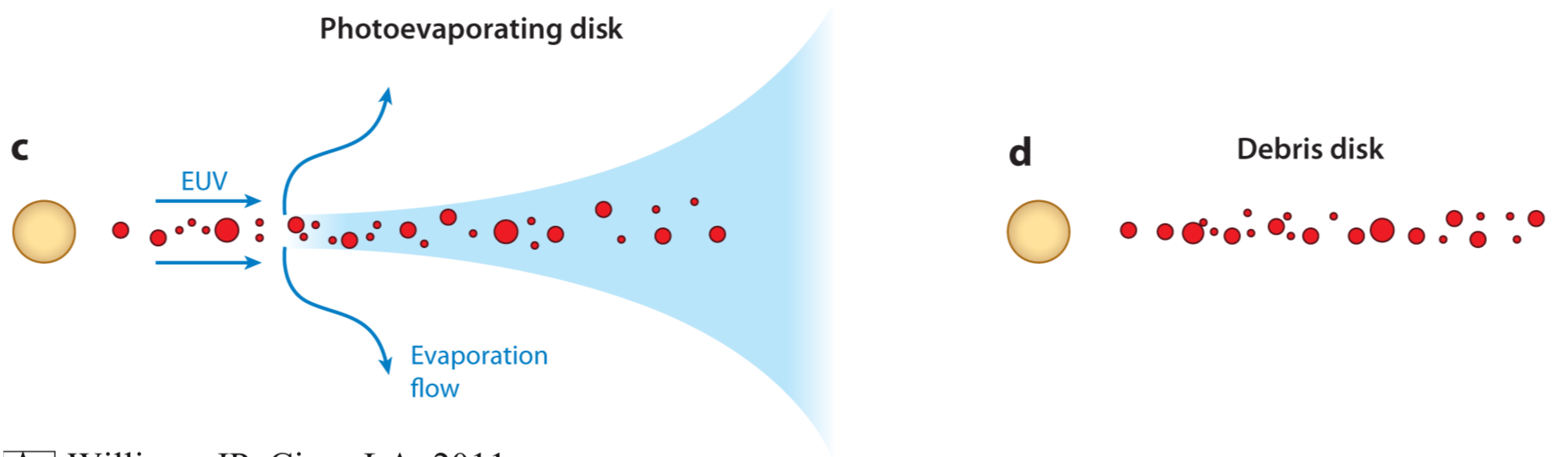
Detection of planet within disk



A planet just inside the dust ring around the star Fomalhaut. A coronagraph was used to block the star light and the Hubble Space Telescope avoids seeing. The faint spot in the box moves across the sky with Fomalhaut (proper motion), but with a slight shift due to its orbital motion (see inset). Announced by Kalas et al. Science, 2008, 322, 1345.

Planet about 3 $M_{jupiter}$ and 119 AU from star. Keeps inner edge of dust ring sharp. Light may actually be reflected off a circumplanetary disk.

Last Steps: Loss of gas, collisions lead to debris disk



Williams JP, Cieza LA. 2011.
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Annual Reviews

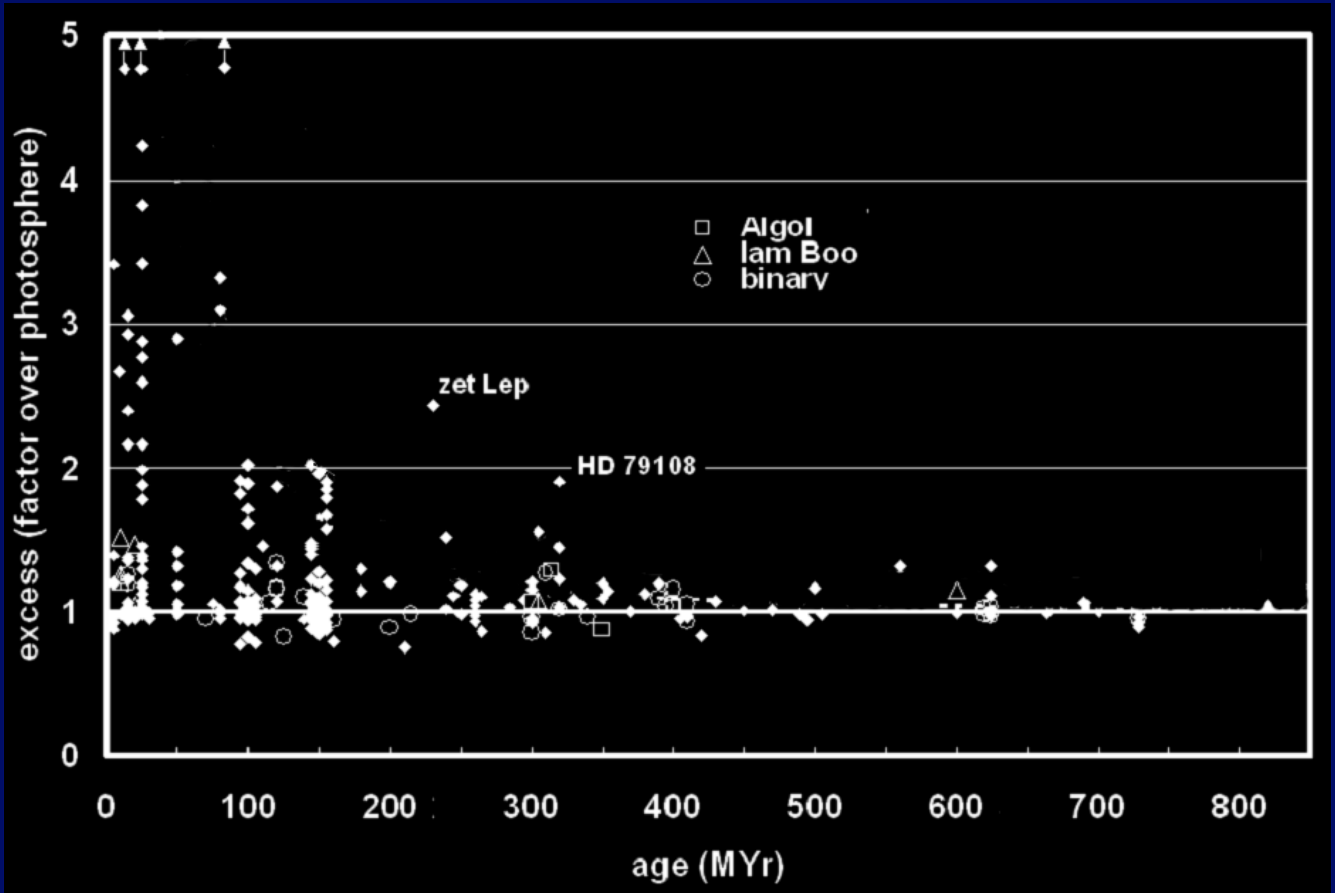
Issues for Planet Formation

- The time to build up the giant planets from dust is long in core accretion theories
  - Gas has to last that long to make gas giants
- How long do dust disks last?
  - How long does the gas last?
- Are there faster ways to make planets?
- What about planet building for binary stars?

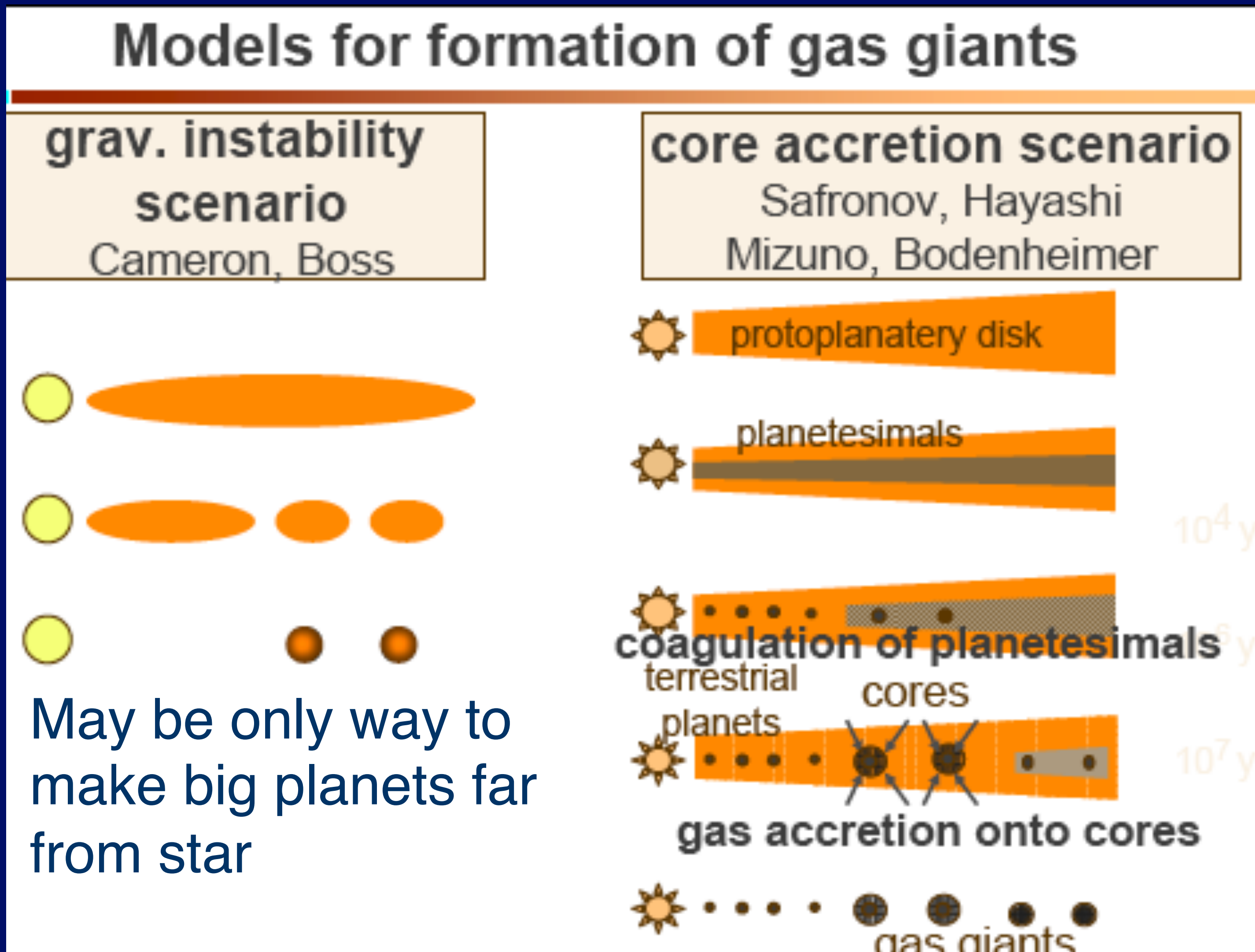
Time Available to form planets

- The disks around young stars can form planets
- How long do the disks last?
  - Sets limit on time to form planets
  - Half of disks have little dust left by 2 Myr
  - Most gone by 3 to 5 Myr
  - No evidence that gas stays longer
  - Some “debris” around older stars
  - May be evidence of planet building

Disks versus Age of Star
Evidence for Collisions



Formation of Gas Giants (Jupiter, Saturn)



May be only way to make big planets far from star

Brown Dwarfs

- Stars range from 0.07 to ~100 M_{sun}
- Jupiter is about 0.001 M_{sun}
- Brown dwarfs between stars and planets
  - Dividing line is somewhat arbitrary
  - Usual choice is 13 $M_{jupiter}$
  - Brown dwarfs rarely seen as companions to stars
  - But “free-floaters” as common as stars
  - Many young BDs have disks
    - Planets around BDs?

What is a Planet? II. High end…

- Brown dwarfs now found to very low masses
  – Some clearly less than 13 $M_{jupiter}$
    - Can’t even fuse deuterium
    - Some people call these rogue planets
    - Some are less massive than known planets
    - Sites for life??
  – Usual definition: planets orbit stars
    - Some brown dwarfs may have “planets”
- Nature does not respect our human desire for neat categories!

Binary Stars

- About 2/3 of all stars are in binaries
  – Most common separation is 10-100 AU
- Can binary stars have disks?
  – Yes, but binary tends to clear a gap
  – Disks well inside binary orbit
  – Or well outside binary orbit

Other Active Issues

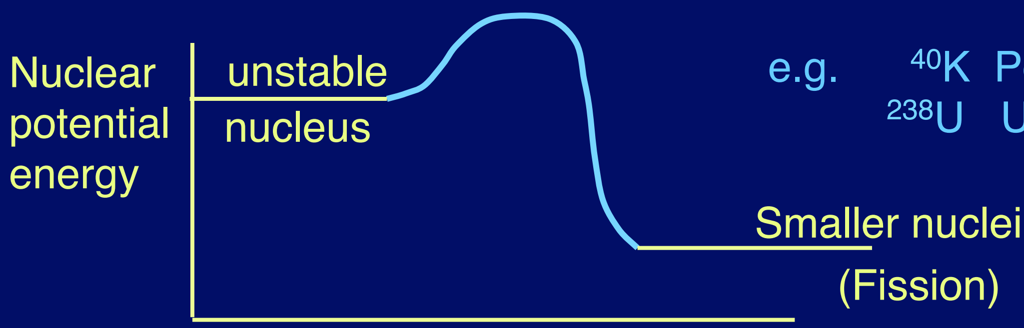
- Some planetary systems are quite different
  - First found were big planets in close
  - But this is probably due to selection effect
- Locations may differ with mass of star
  - Ices survive closer to lower mass star
  - May get ice giants in close
  - Also planets may migrate inwards
  - May prevent formation of terrestrial planets

Formation of Earth

- Almost entirely rocky material (iron, silicates)
- Radioactive elements heat interior
  - Were produced in supernovae explosions
- Interior becomes molten, iron sinks to core
  - Releases gravitational potential energy
  - Interior even hotter
  - Differentiated planet
- Collision forms Earth-Moon system
- Earth acquires atmosphere
  - Outgassing and delivery by comets

Radioactive Heating

Radioactive nuclei decay (release of nuclear potential energy)

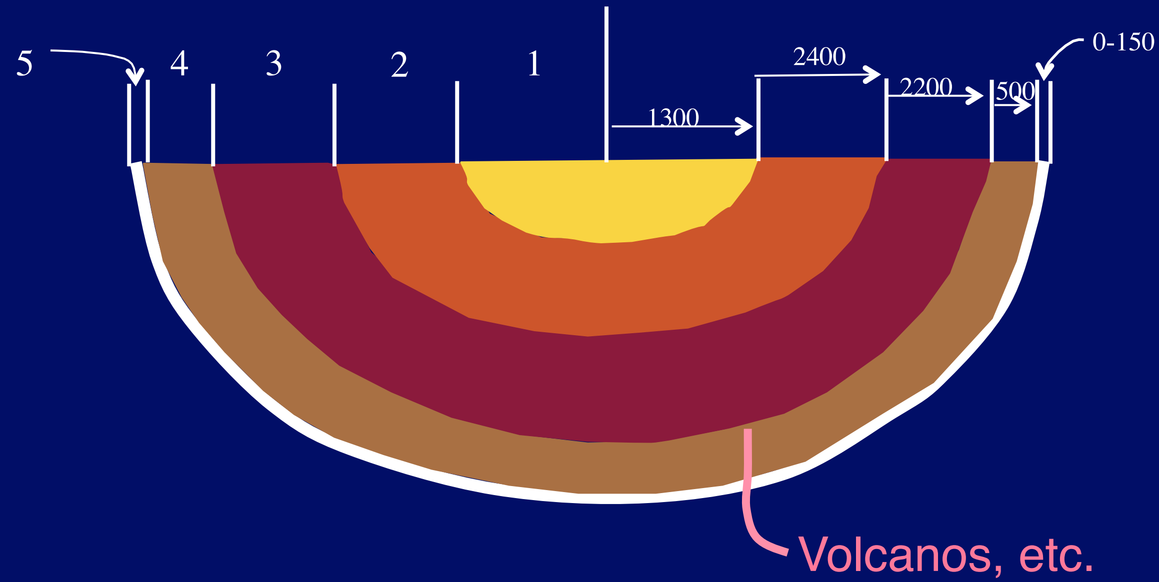


e.g. ^{40}K Potassium
^{238}U Uranium

Also emit α particles (He)
electrons, gamma-rays

→ Kinetic energy → heat

Results in layered Earth (like a soft-boiled egg)



Egg

Yolk {
1. Inner solid core
2. Outer liquid core
} T up to 7000 K, iron, nickel, …

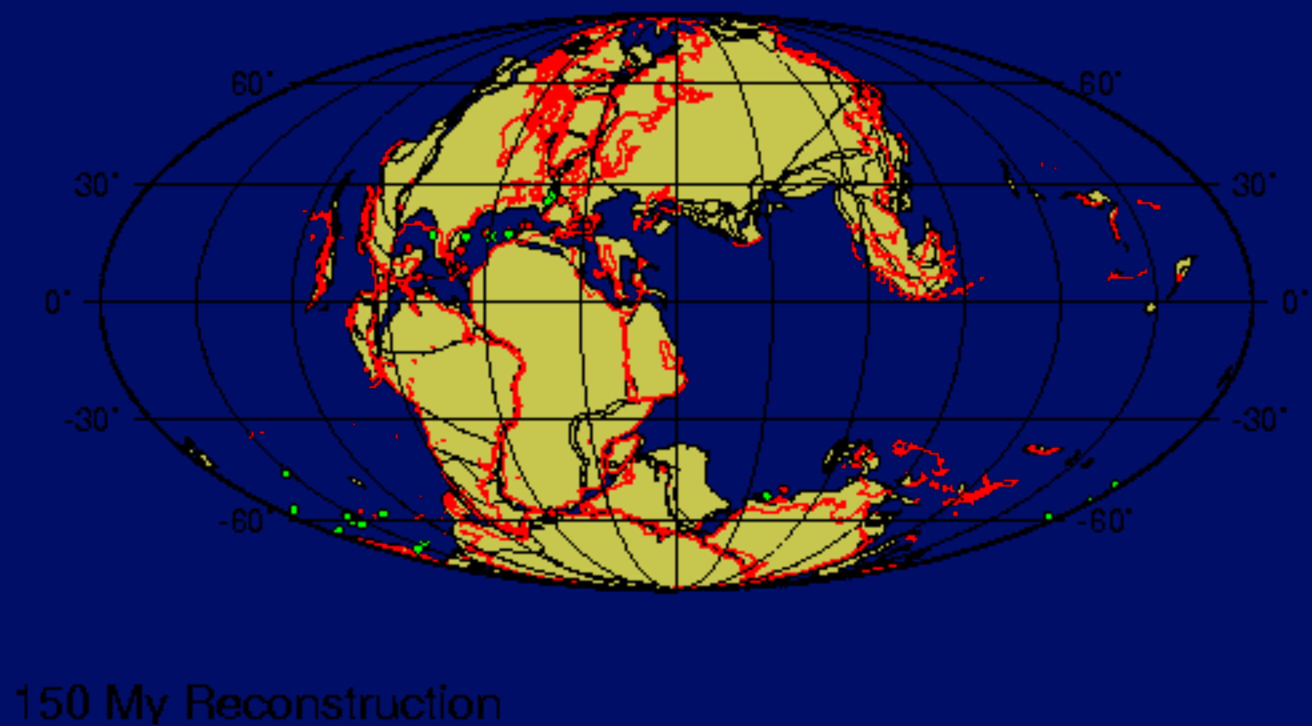
White {
3. Lower mantle - iron rich silicates, solid
4. Asthenosphere (upper mantle) pliable
}

Shell
5. Lithosphere - rigid silicates (crust)

Lithosphere can "float" on asthenosphere

Leads to Continental Drift, Earthquakes, Volcanos

Continental Drift Reconstructed



Shows motion of continental plates over last 150 Myr.
Red and green dots show locations of ocean drilling.

http://www.odsn.de/odsn/index.html

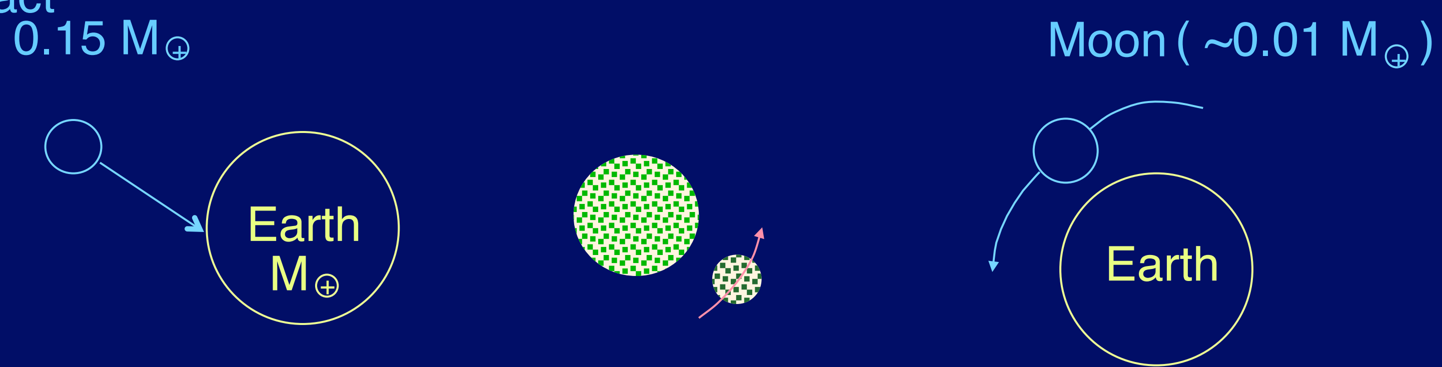
Formation of Earth and Moon

$\frac{M_{Moon}}{M_{Earth}}$ Larger than all other planets

Most terrestrial planets have no moons

(Martian moons are captured asteroids)

Moon most likely resulted from giant impact



Earth gets more iron $\rho_{\oplus} = 5.5\ g\ cm^{-3}$

Moon mostly silicate $\rho_{Moon} = 3.3\ g\ cm^{-3}$

Temperature was very high after impact (10,000 - 60,000 K)

Any icy material left?

Origin of Atmosphere

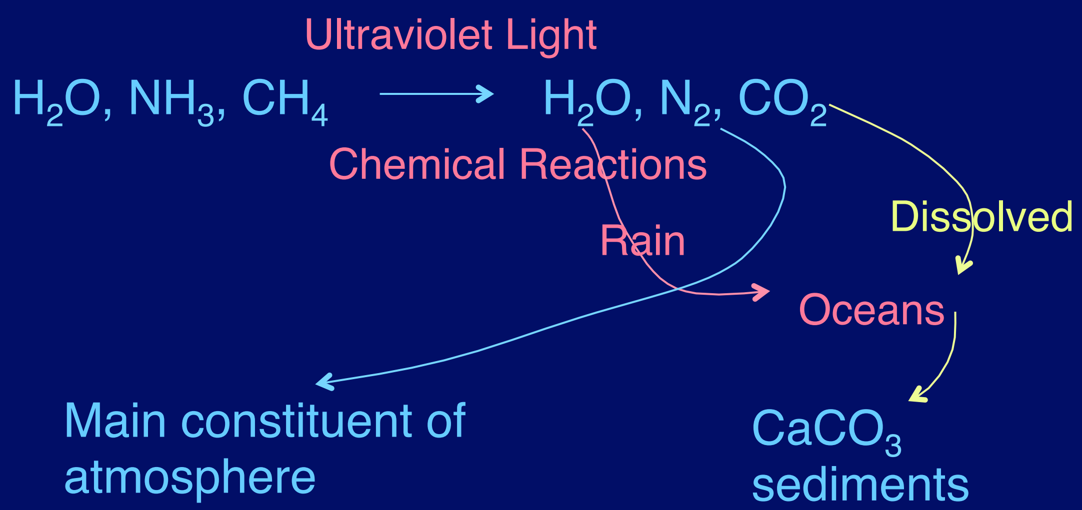
Certain “Noble” gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. ⇒ Atmosphere not collected from gas

Reason: Earth is small ⇒ gravity is weak

Temperature in solar nebula is high - atoms moving fast, harder to hold

Outgassing: “Icy” material vaporized by high temperatures

came out through vents, volcanos



No O_2 on early Earth; No ozone (O_3), so no protection from ultraviolet light

Alternative: Icy materials brought by comets.

Summary

- Planet formation theory suggests planetary systems should be common
- We see evidence of planet building in disks around young stars
- Binary stars with separations around 10 AU may prevent planet formation
- Consider these facts in estimating f_p
- Inner, terrestrial planets of sufficient size will differentiate, may get atmosphere, oceans
- Earth may be unusual (big Moon by collision)