Origin of the Solar System

Current Properties of the Solar System

Look for General Properties

Dynamical Regularities

Orbits in plane, nearly circular

Orbit sun in same direction (CCW from North pole)

Rotation Axes perpendicular to orbit plane

(Sun & most planets; Uranus exception)

Planets contain 98% of angular momentum

Spacing and Composition

Spacing increases with distance

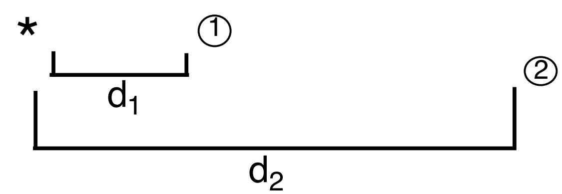
(roughly logarithmic)

Composition varies with distance

inner 4: rocky, small, thin atmospheres

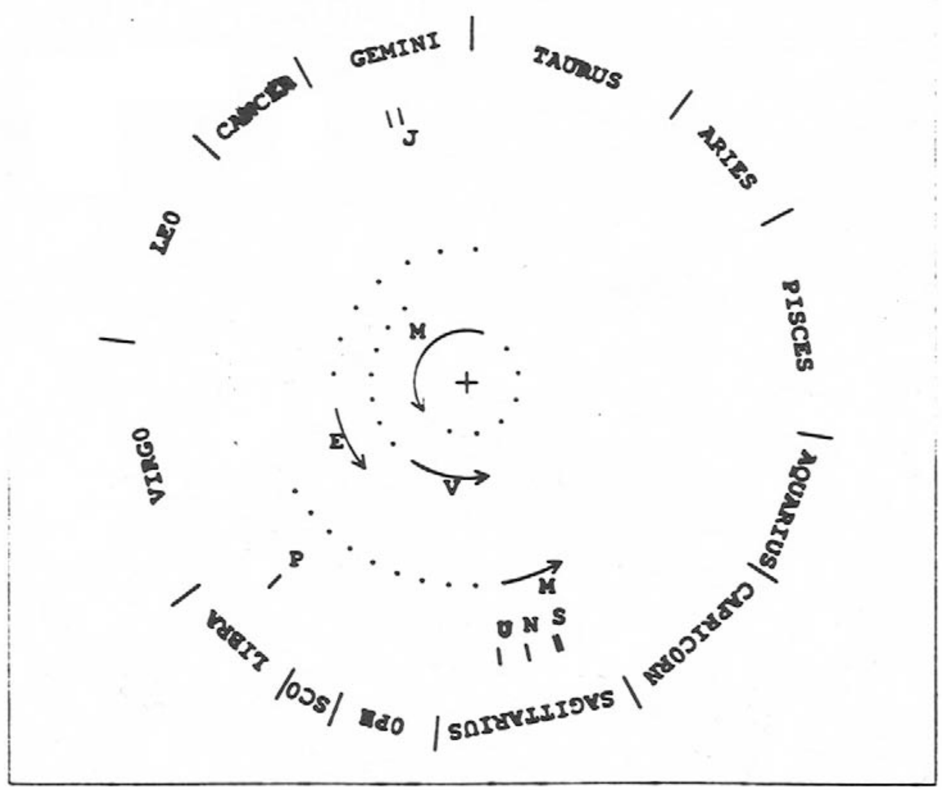
outer 4: gaseous, large, mostly atmosphere

Sun contains 99.9% of mass

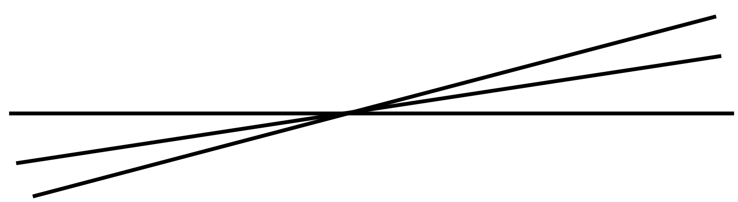


$$\frac{d_2}{d_1} \simeq 1.5 - 2$$

April Heliocentric View



Heliocentric Charts by Richard Binzel



Side View

The Solar System

Distance from Sun .1 | 1 | 10 | 100 AU (Log scale)

M V E M J S U N P

M ($M_\oplus$) 0.06 .82 1 .11 < .001 318 95 15 17 0.002

Terrestrial ← Asteroids → Gas Giants

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 larger than Pluto (Xena)
- IAU voted in 2006
  - 1. Create a new category of dwarf planet
  - 2. Demote Pluto to a dwarf planet

Theory of Solar System Formation

All start with rotating disk

Minimum mass: 0.01 $M_\odot$

Sum of planets ~ 0.001 $M_\odot$ but most of H_2, He lost

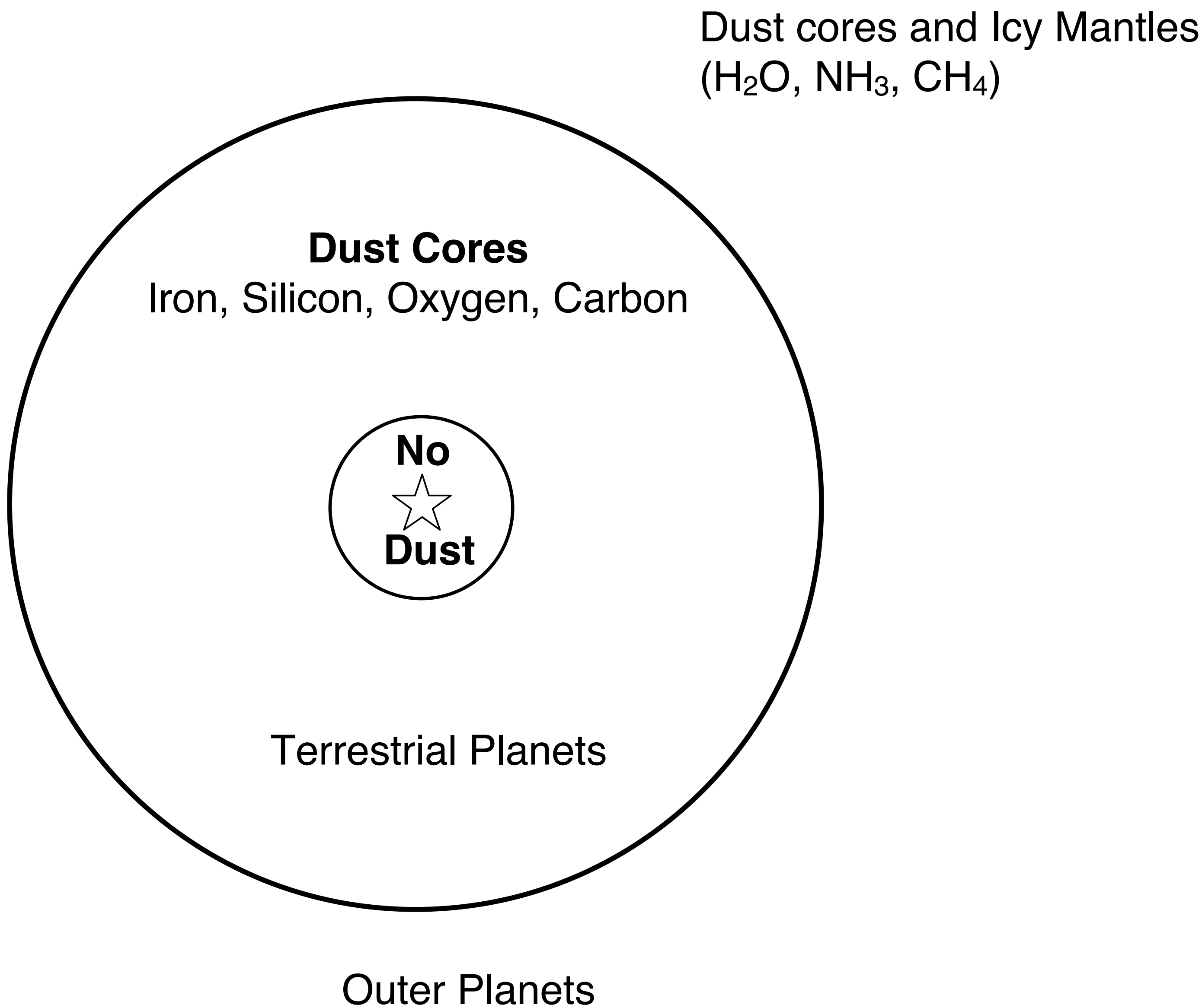
Note: Similar to typical masses of disks around forming stars

Some models assume more massive disks

Temperature, Density decrease with distance from forming star

(Observations suggest slower decrease than models usually assume)

DUST PLAYS A KEY ROLE


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

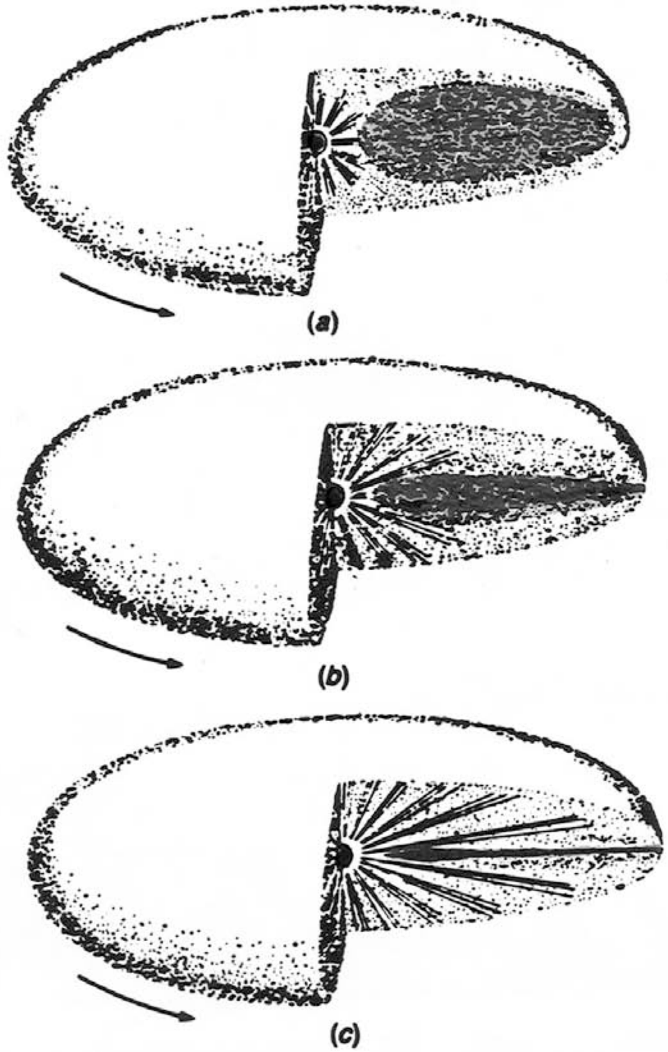


Fig.2.13. In the spinning preplanetary solar nebula the dust retreats to the equatorial plane due to the energy losses that occur in the collision process illustrated in Figure 2.12 (from Boris Levin, *The Origin of the Earth and the Planets*, Foreign Languages Publishing House, Moscow, 1956).

Artist's conception of dust in disk

Accretion of Dust Grains

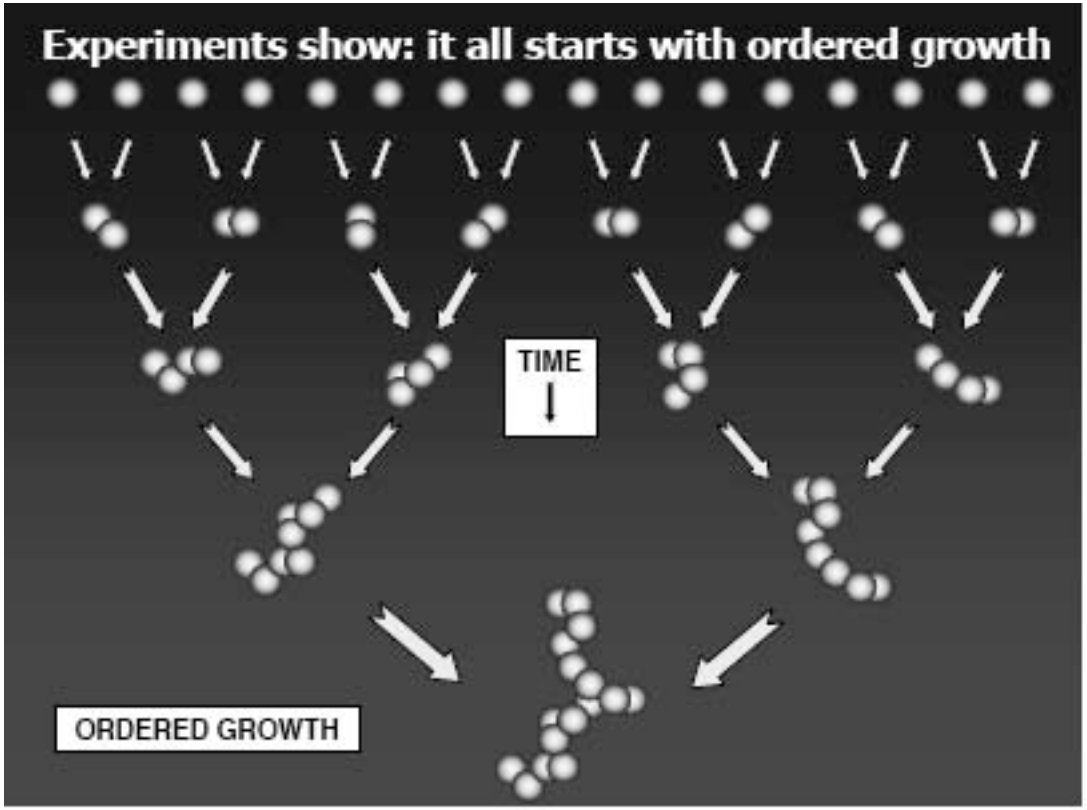


Fig. From talk by Jurgen Blum

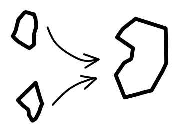
Core Accretion Model

Dust sinks to midplane

~10^4yr { Gravitational instability → planetesimals (~ 1 km in size)

and/or

Accretion of dust grains → planetesimals }



10^6 - 10^8 yr (problem) Collisions between planetesimals builds rocky planet cores

<u>Gas Processes</u> <u>(Outer Planets)</u>

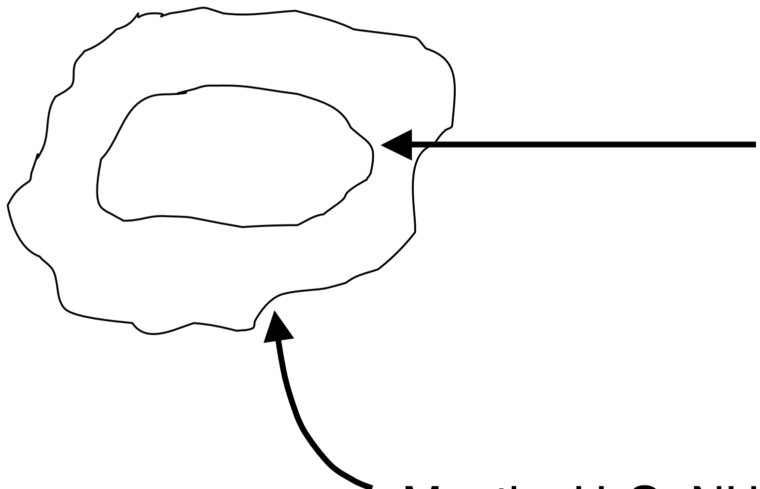
Accretion of gas/gravitational collapse onto rocky cores

Leads to H, He in atmosphere

Rings, moons (minature solar system)

Dust and Ice

Interstellar dust - core + mantle



$\xrightarrow{?}$ Planet types

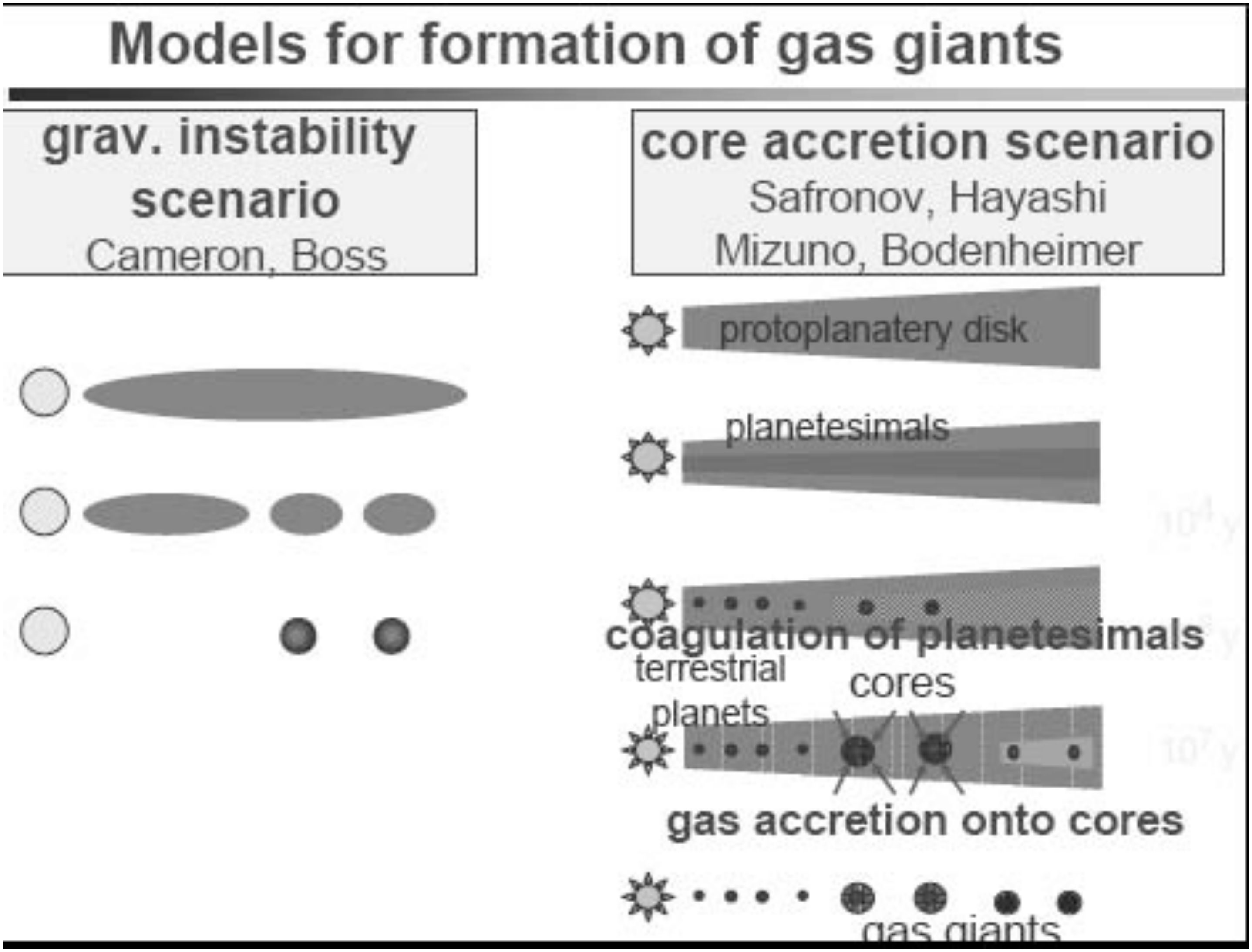
Inner: Only rocky cores, little or no ice survives $\longrightarrow$ rocky planets

Outer: Ice survives $\longrightarrow$ comets, icy moons of outer planets

Outgassing

Planet heats internally, so ice turns to gas (atmosphere)
Uranus and Neptune (thick atmospheres, formerly icy materials)
If pressure, T suitable, may form liquid and get ocean (Earth)

Formation of Gas Giants (Jupiter, Saturn)



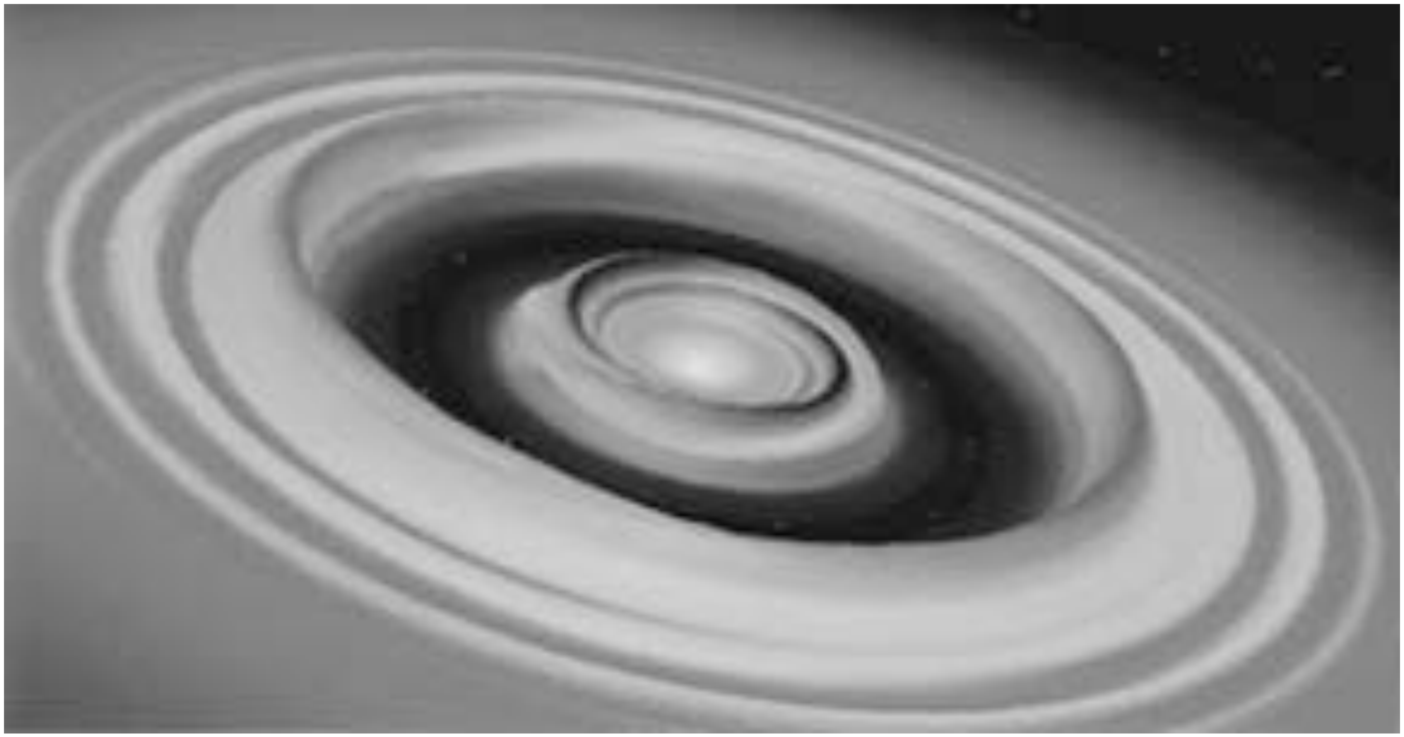
General Expectations about Planetary Systems

1. Planet formation in a rotating disk with icy dust can explain most of the general facts about our solar system
2. Planetary systems are likely to be common since disks with $M \gtrsim M_{min}$ are common around forming stars.

   If we are typical,

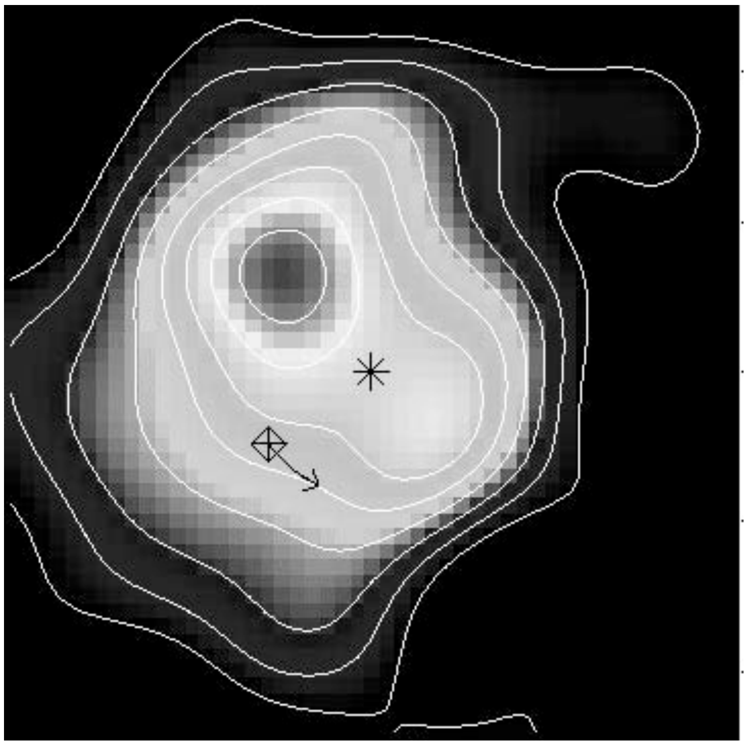
3. Expect other planetary systems will have ~10 planets, logarithmic spacing, different planet types

Theory Predicts Forming Planets Clear a Gap



Can we observe such gaps?

Possible Evidence for Planet Formation



SMM image of Vega shows dust peaks off center from star (*). Fits a model with a Neptune like planet clearing a gap. Can test by looking for motion of clumps in debris disk.

SMM image of Vega
JACH, Holland et al.

Model by Wyatt (2003), ApJ, 598, 1321

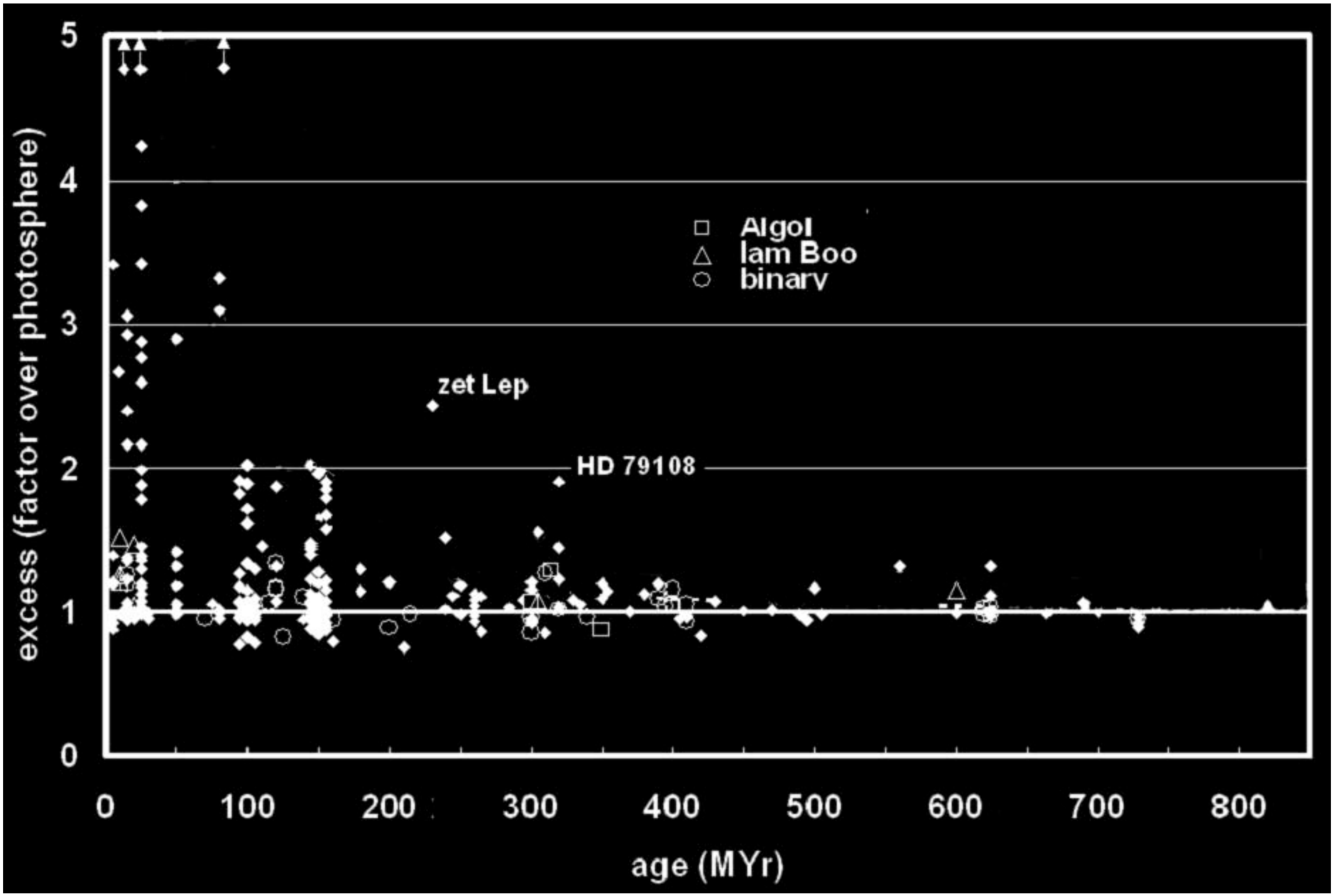
Issues for Planet Formation

- The time to build up the giant planets from dust particles is long in 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?

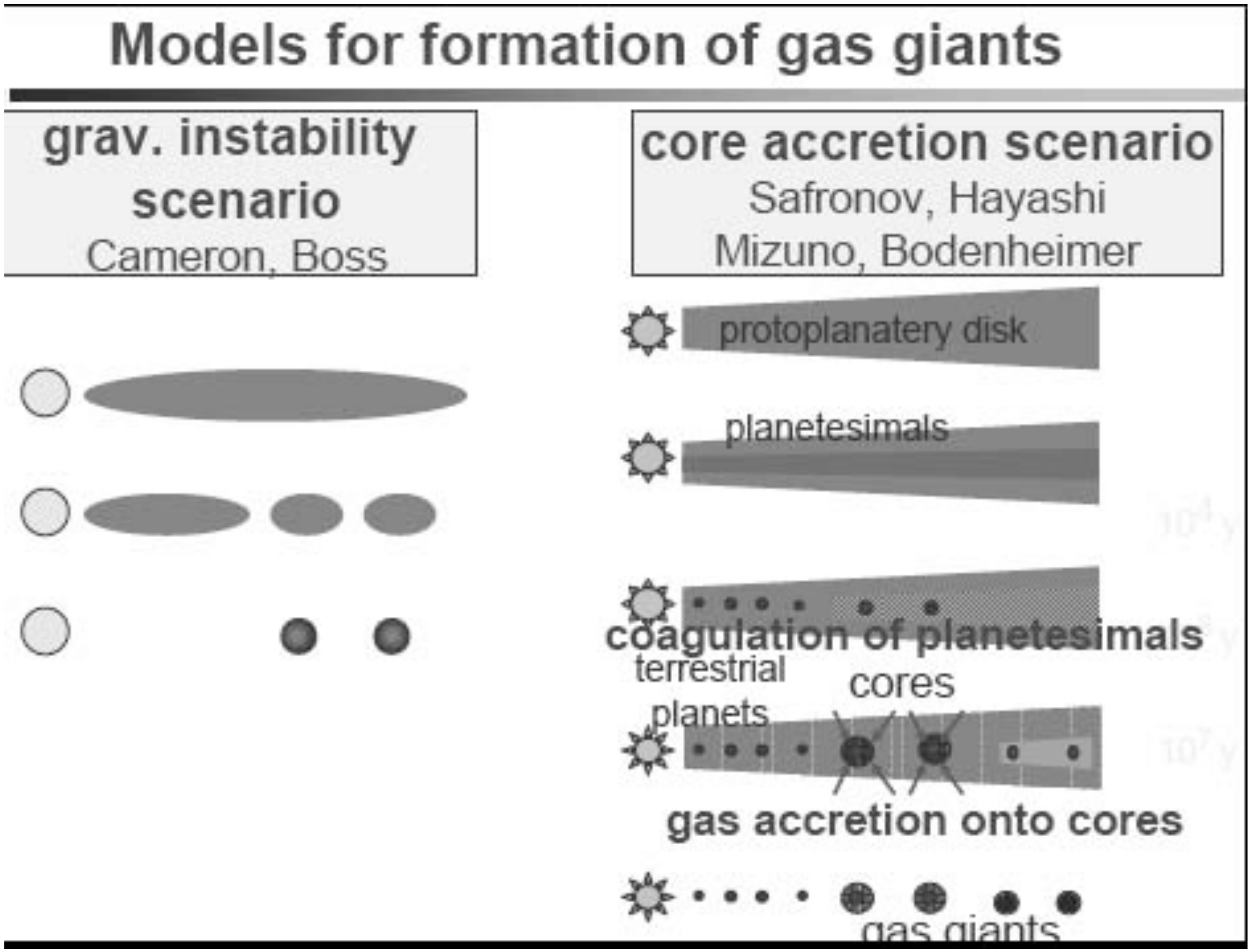
Time Available to form planets

- The disks around young stars can form planets
- How long do the disks last?
  - Sets limit on time to form planets
  - Most gone by 3 to 5 Myr
  - Little 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)



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

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 planets
    - Some less massive than known planets
  - Usual definition: planets orbit stars
    - Some brown dwarfs may have "planets"
- Nature does not respect our human desire for neat categories!

Other Active Issues

- Other planetary systems are quite different
  - 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

Solid particles $\Rightarrow$ silicate + iron

No gas collected $\Rightarrow$ atmosphere outgassed

Radioactive heating $\Rightarrow$ molten core
$\hookrightarrow$ ice $\longrightarrow$ gas

H_2O $\longrightarrow$ gas $\longrightarrow$ liquid (oceans)

CO_2 $\longrightarrow$ dissolve in oceans $\longrightarrow$ carbonate rocks

N_2 $\longrightarrow$ gas

Early Earth Atmosphere

N_2, CO_2 , H_2O (CH_4, NH_3, H_2 ?)

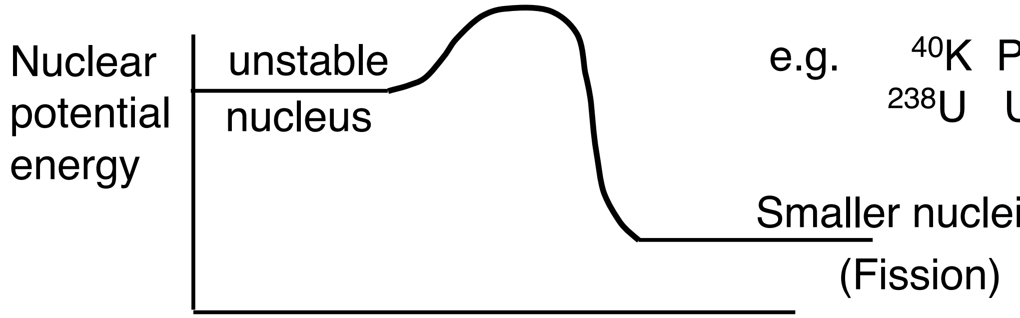
Reducing (No free O_2) Neutral ?

Energy Sources

Differentiation of the Earth

Impact heating by planetesimals (release of gravitational potential energy)

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

Result: molten Earth

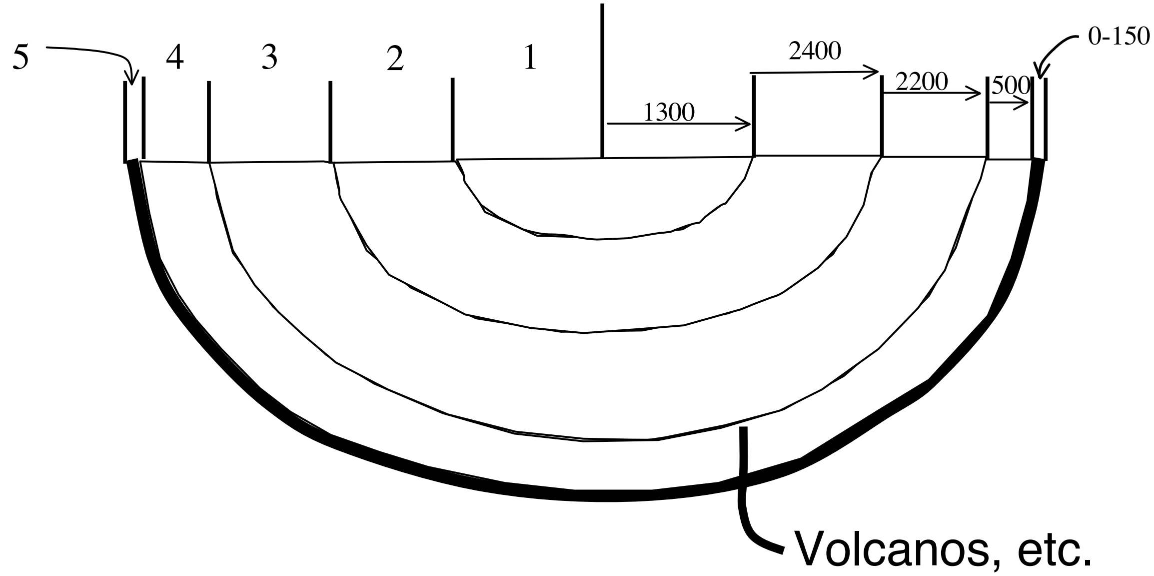
Iron-Nickel ⟶ center (core)

Silicates float ⟶ upper levels (mantle)

Differentiation released Grav. Potential energy ⟶ hot core

Radioactive heating continues

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



Egg

Yolk { 1. Inner solid core } T ~ 4500 K, iron, nickel, … (maybe 7200 K)

Yolk { 2. Outer liquid core

White { 3. Lower mantle - iron rich silicates, solid

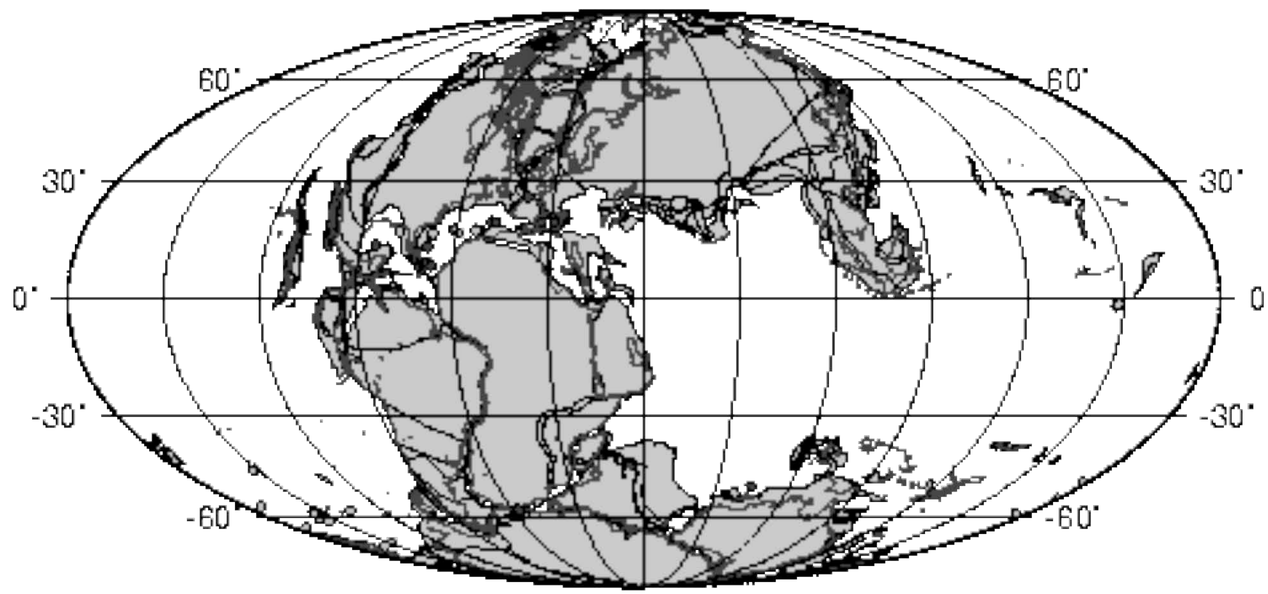
White { 4. Asthenosphere (upper mantle) pliable

Shell 5. Lithosphere - rigid silicates (crust)

Lithosphere can "float" on asthenosphere

⟶ Continental Drift, Earthquakes, Volcanos

Continental Drift Reconstructed



150 My Reconstruction

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

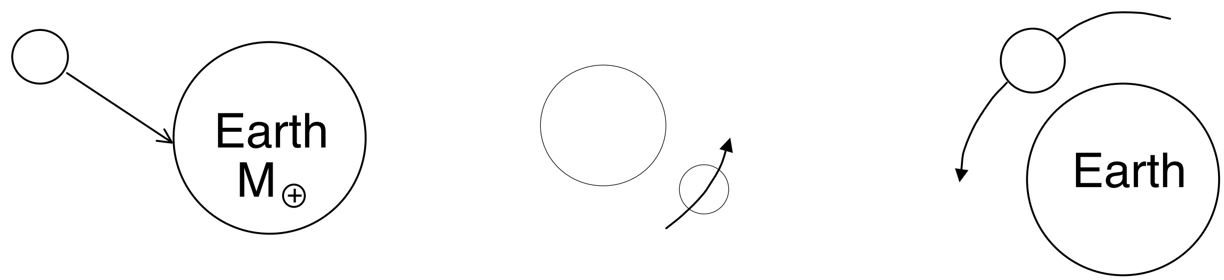
$\frac{M_{Moon}}{M_{Earth}}$ Larger than all other planets

Most terrestrial planets have no moons

(Martian moons are captured asteroids)

Moon most likely resulted from giant impact

$0.15\ M_{\oplus}$ Moon ($\sim 0.01\ M_{\oplus}$)



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

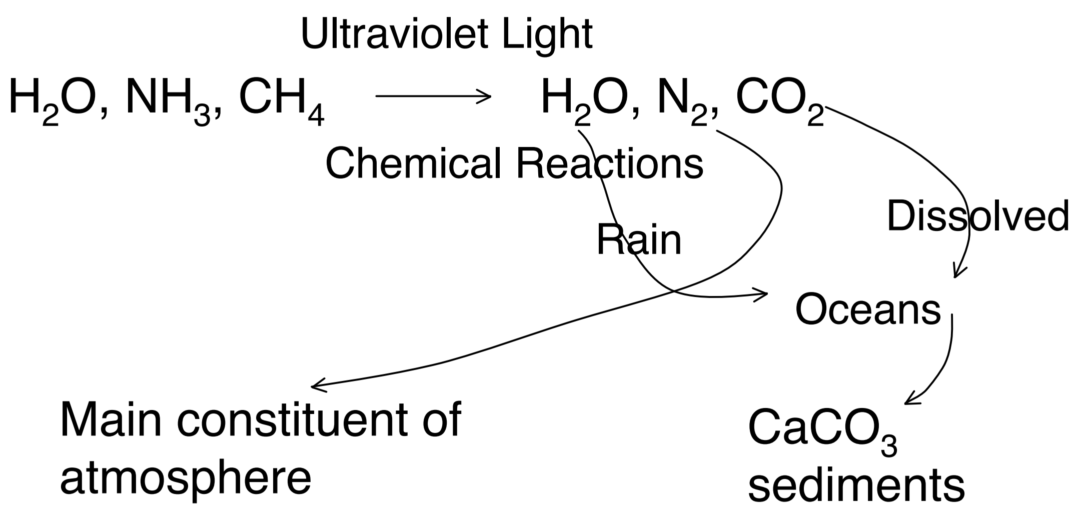
Certain "Noble" gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. ⇒ Atmosphere not collected from gas

Reason: Earth is small ⇒ gravity is weak

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

<u>Outgassing:</u> "Icy" material vaporized by high temperatures

→ vents, volcanos



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

Alternative: Icy materials brought by comets.