

Nature and Origin of Planetary Systems

f_p

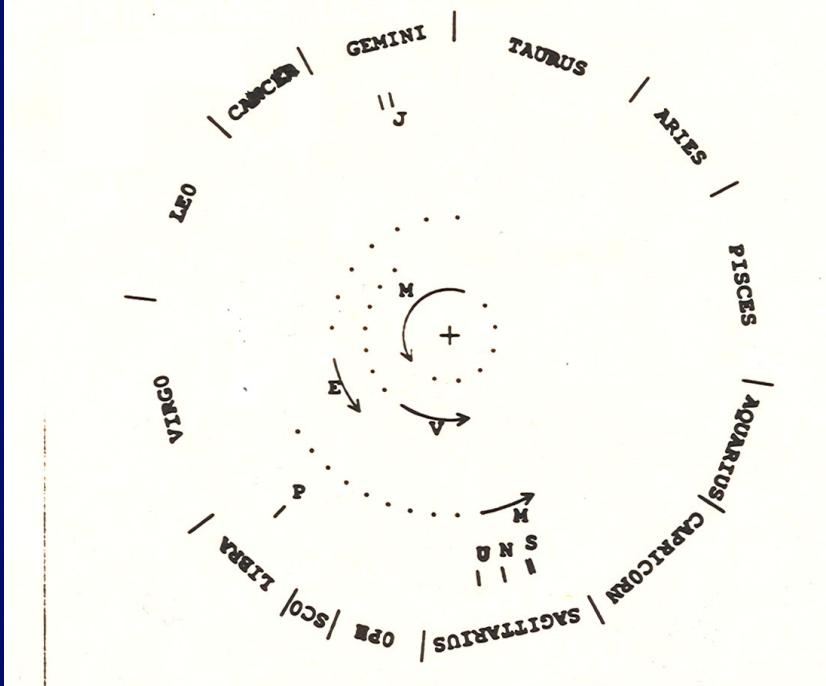
Our Solar System as Example

- 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
- Compare predictions to facts about ours
- Complete our estimate of f_p , prepare for n_e

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



Heliocentric Charts by Richard Binzel



Mercury
Venus - Neptune

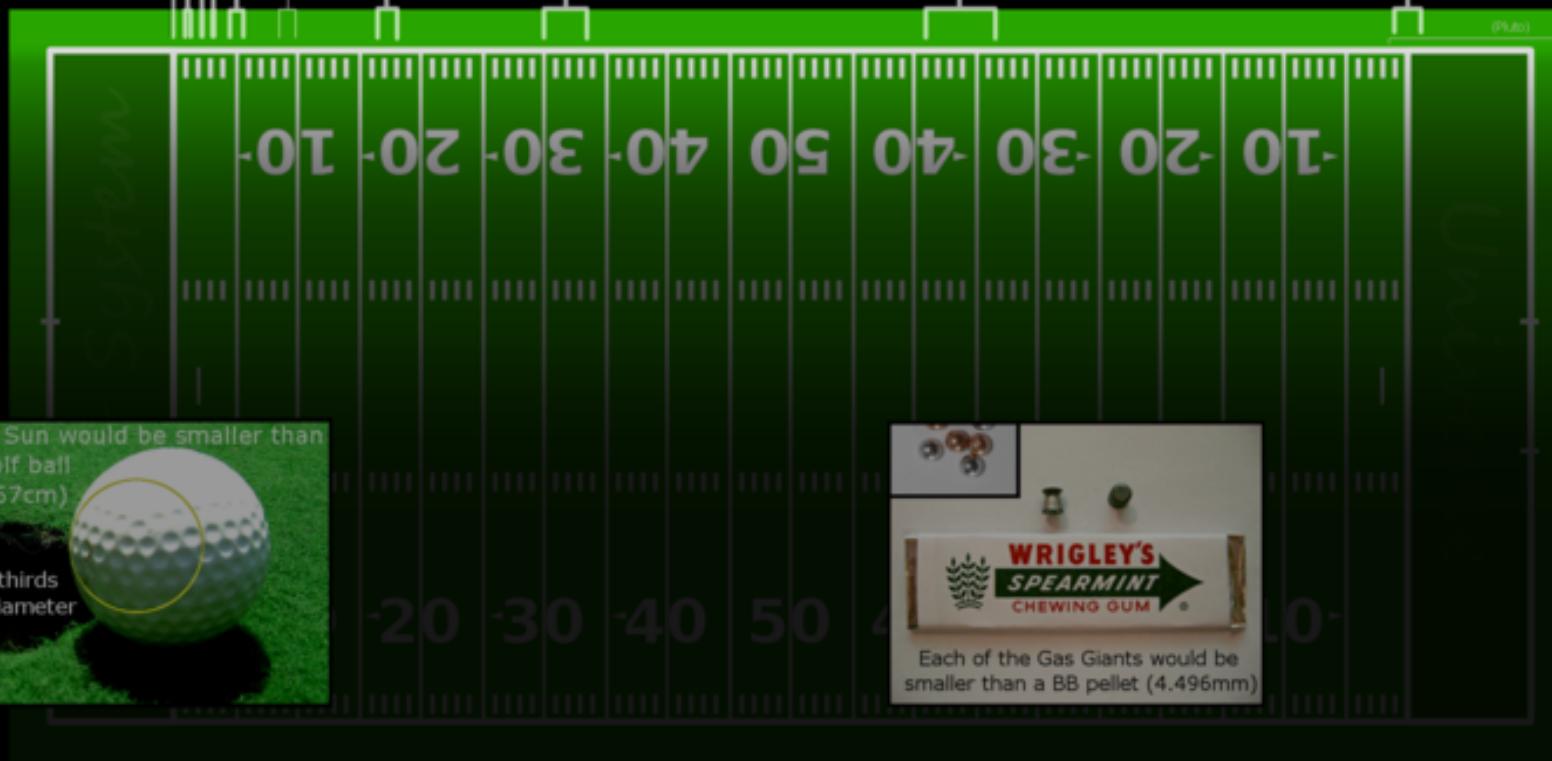
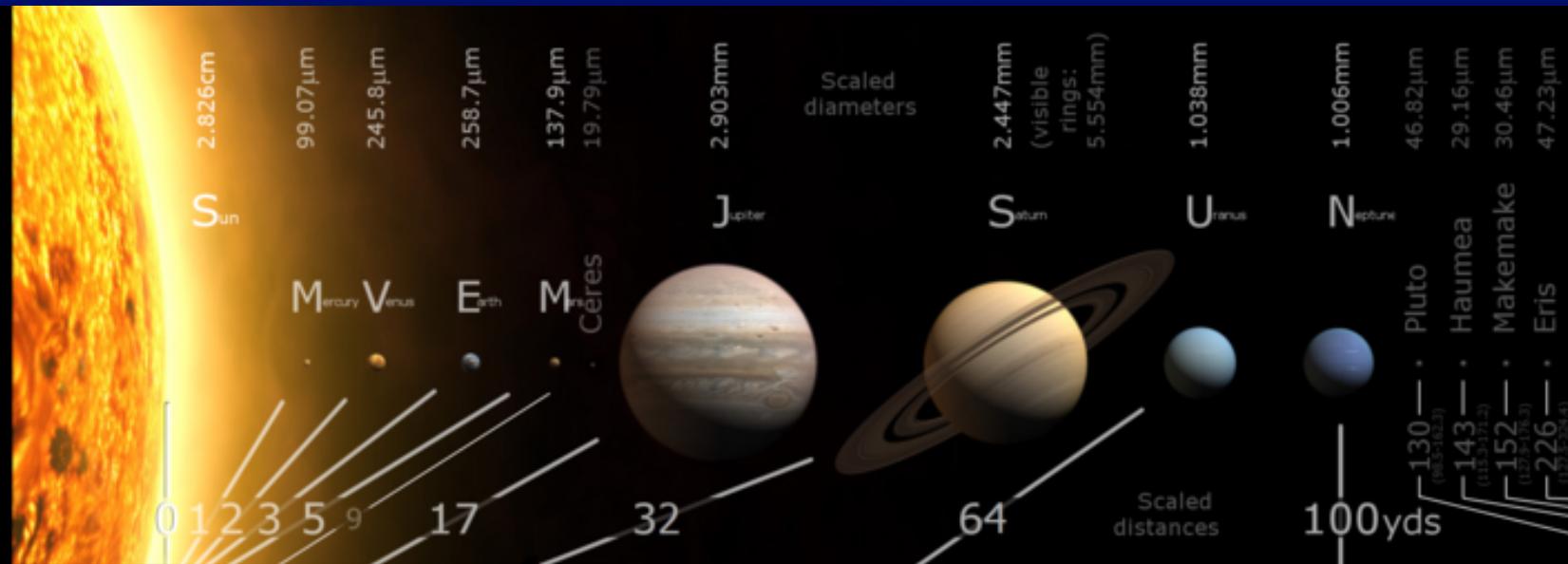
Side View

Spacing and Composition

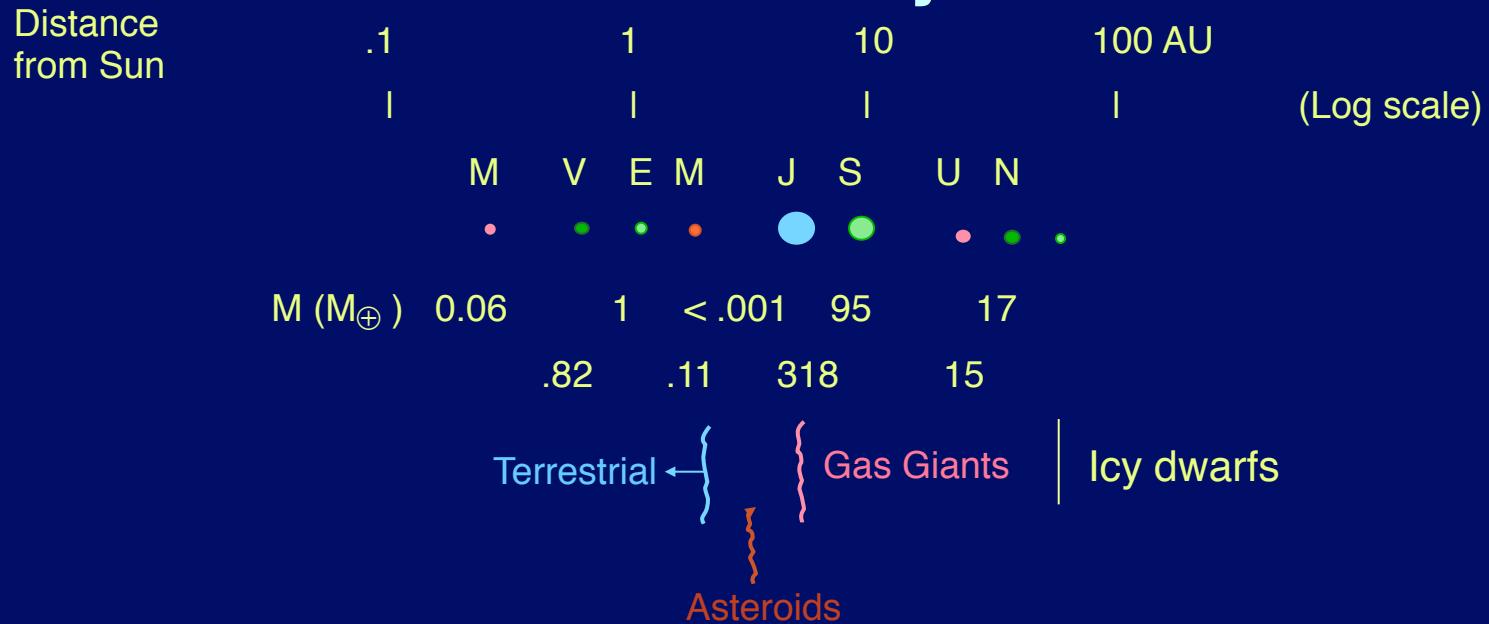
- Spacing increases with distance
 - Evenly spaced if plotted logarithmically
 - Missing planet in asteroid belt
- Composition varies with distance
 - Inner 4 are “terrestrial”
 - Small, rocky, thin atmospheres
 - Outer 4 are “gas giants”
 - Gaseous, large, mostly atmosphere



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



The Solar System



Composition (%)	Enhancement to get ⊕ abundance			
	Rocky	“Icy”	Gaseous	
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

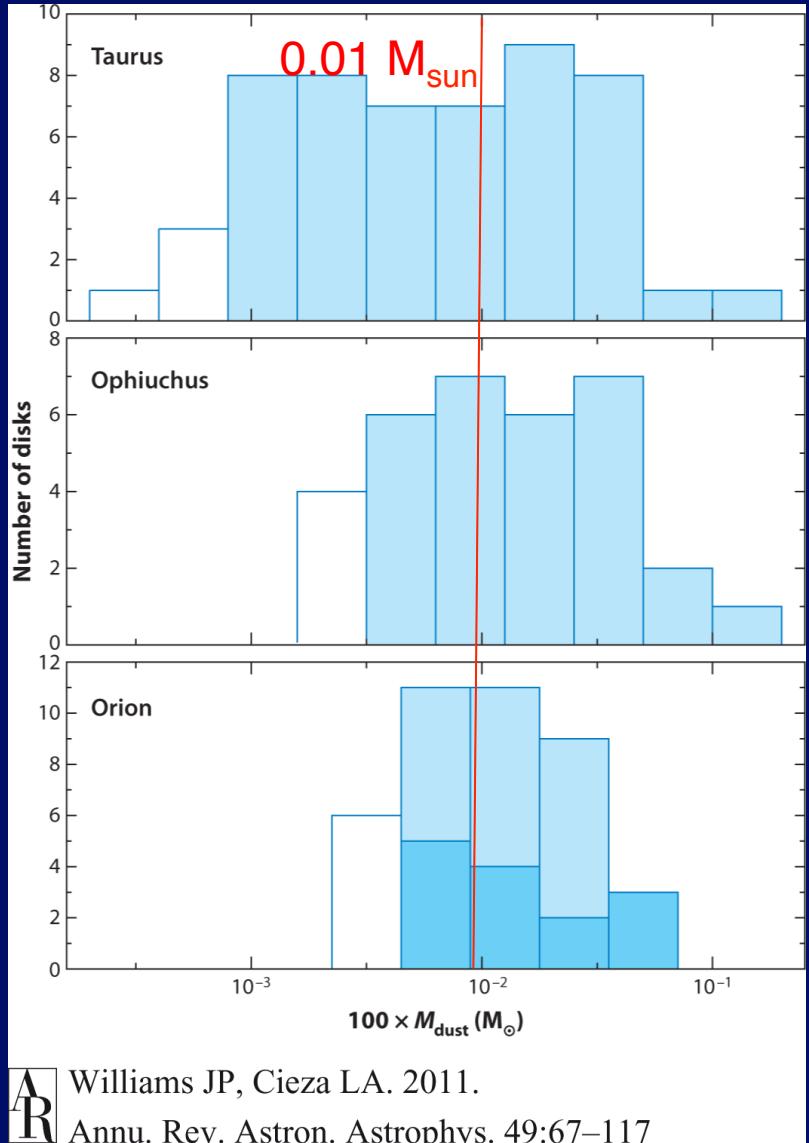
What is a Planet?

- Pluto much smaller than others ($0.002 M_{\text{earth}}$)
- 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

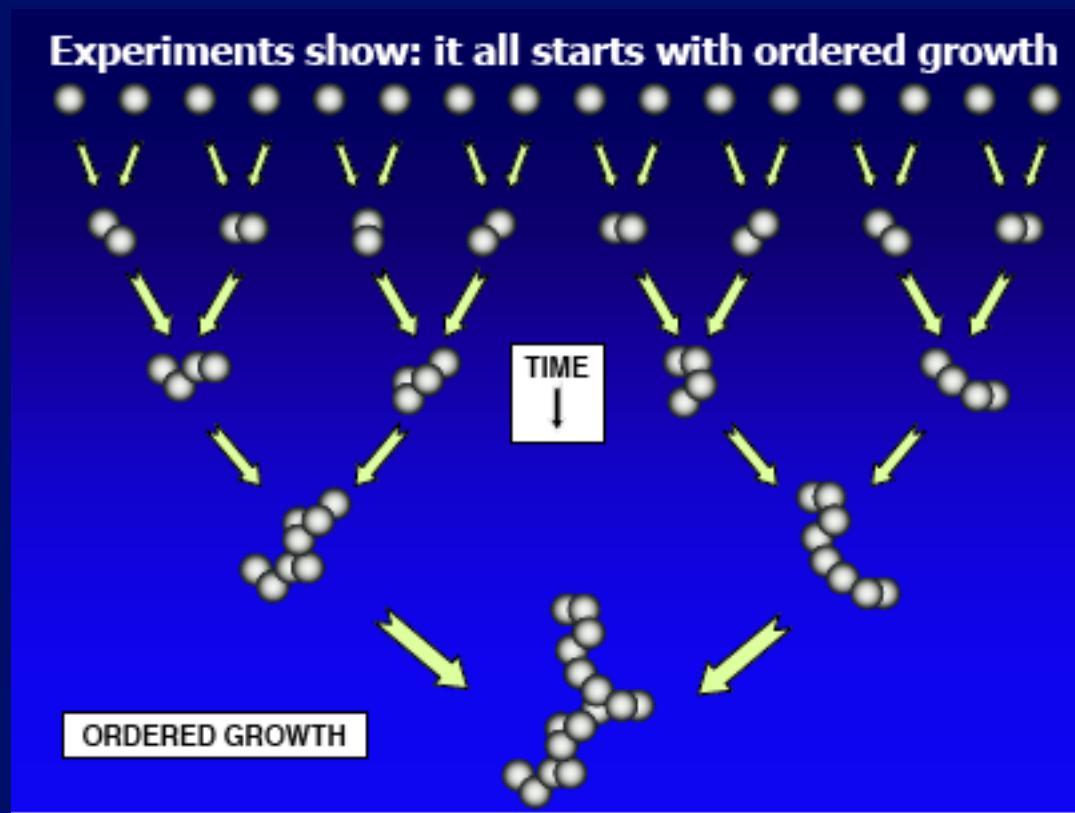
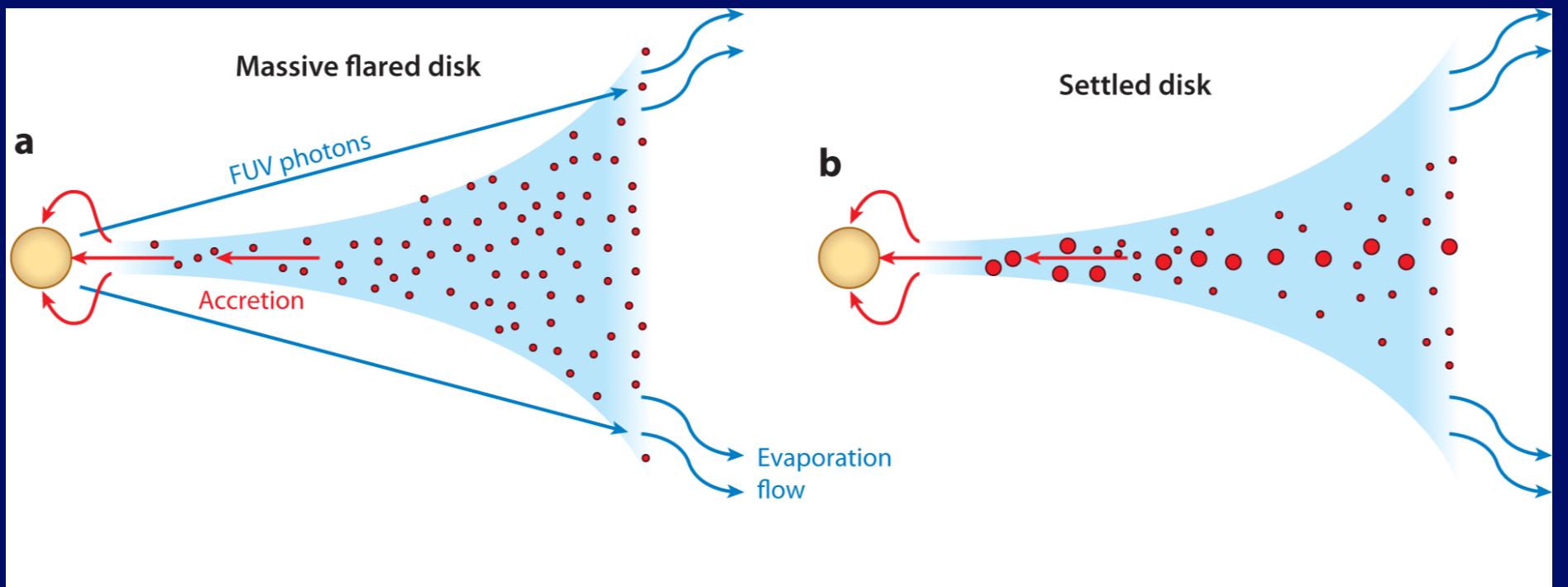


Fig. From talk by Jurgen Blum

Second Step: Dust settles to midplane



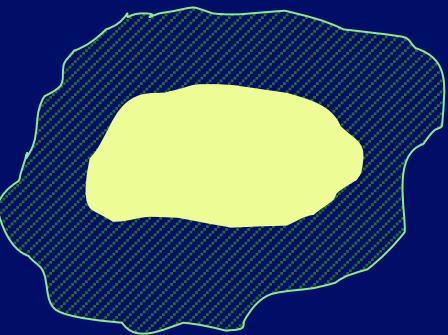
Step 3: Dust in midplane grows to rocks,
boulders, ...



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
(H₂O, NH₃, CH₄)



Outer Planets

Dust Cores
Iron, Silicon, Oxygen, Carbon



Terrestrial Planets

“Snow” line

- Van der Marel

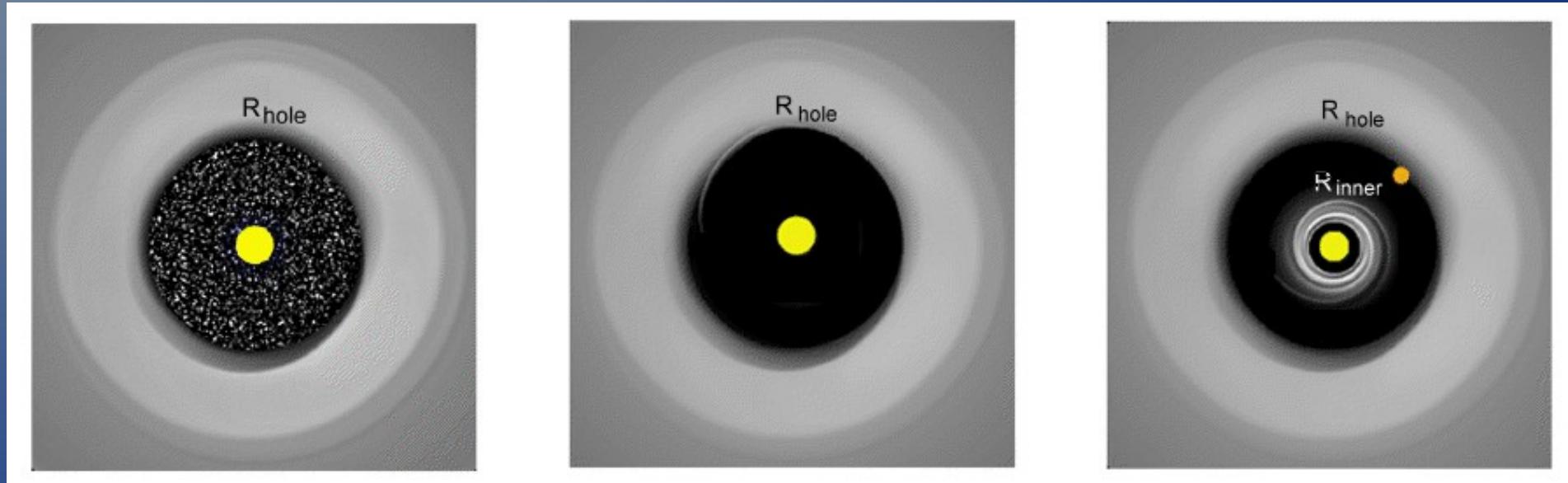
Transitional disks

- Dust hole: mechanisms

Grain growth

Photoevaporation

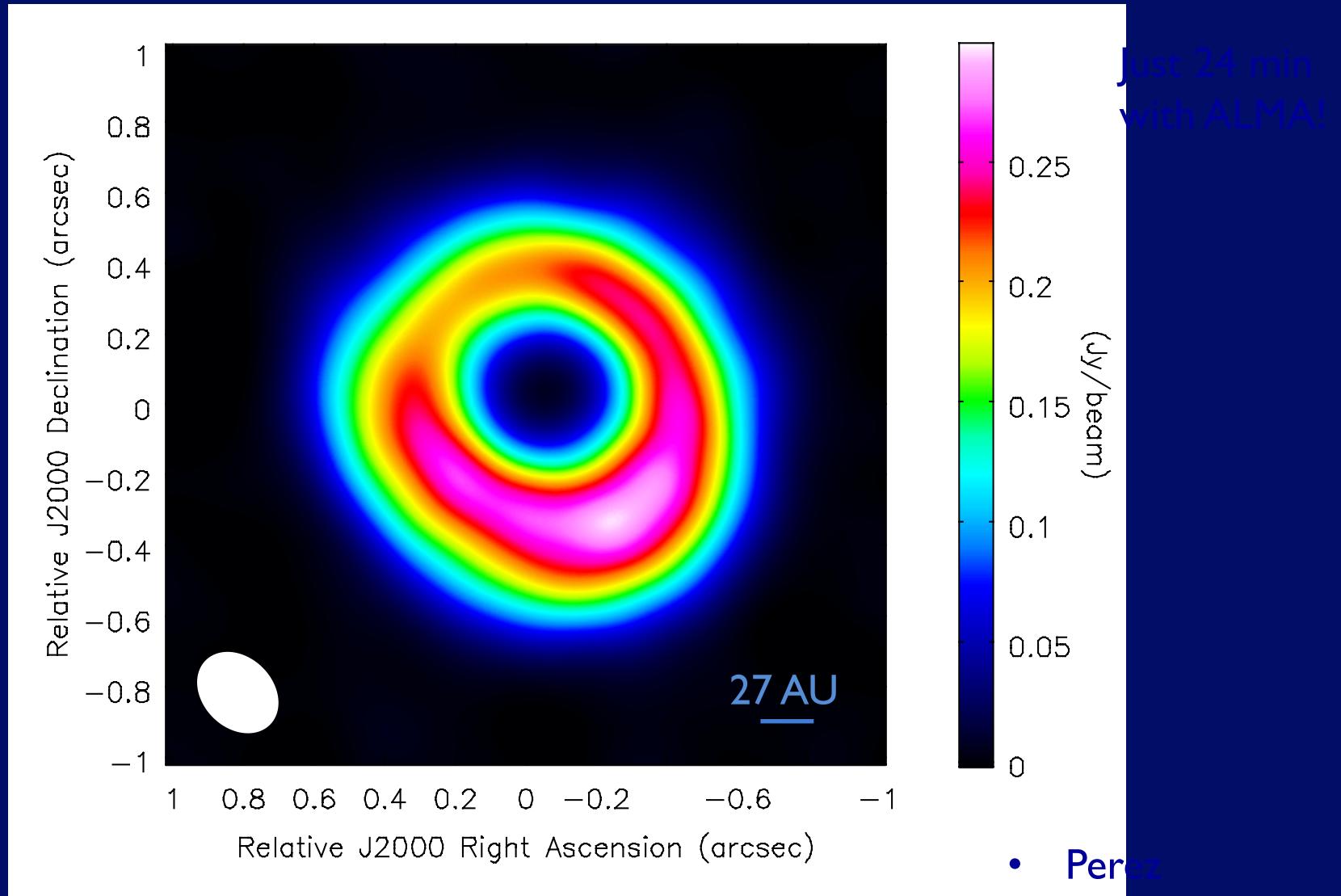
Stellar companion
Forming planet?



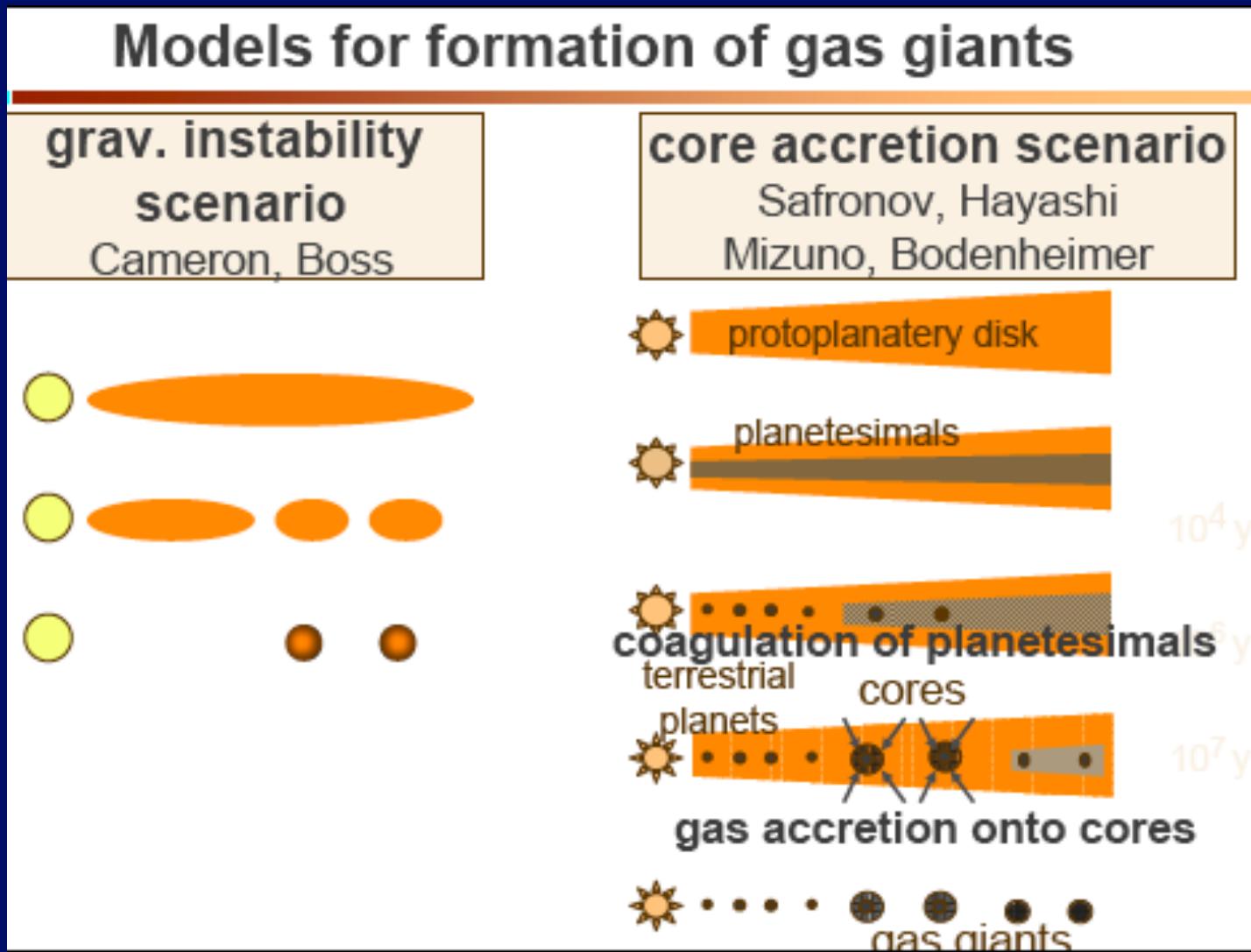
⇒ What about the gas?

Strom & Najita

A “dust trap” observed last year: Planet forming?



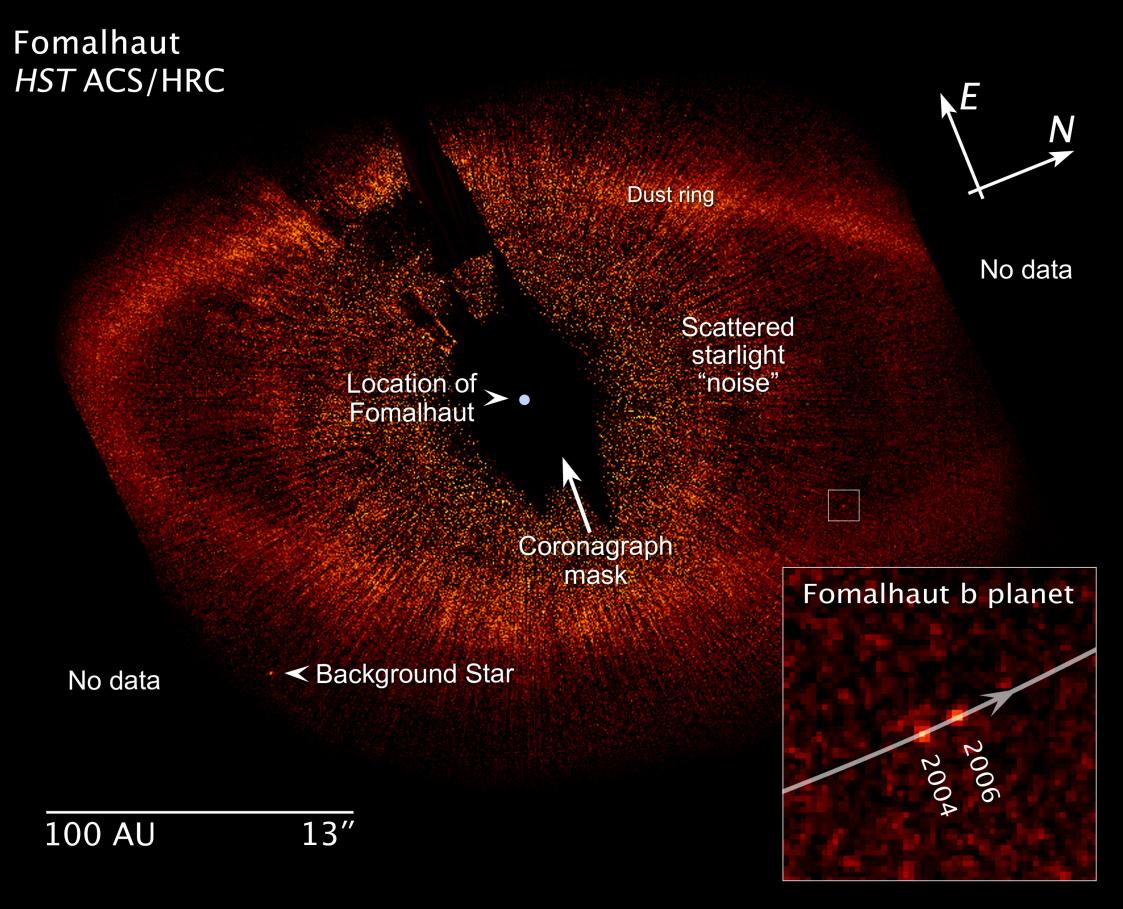
Formation of Gas Giants (Jupiter, Saturn)



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

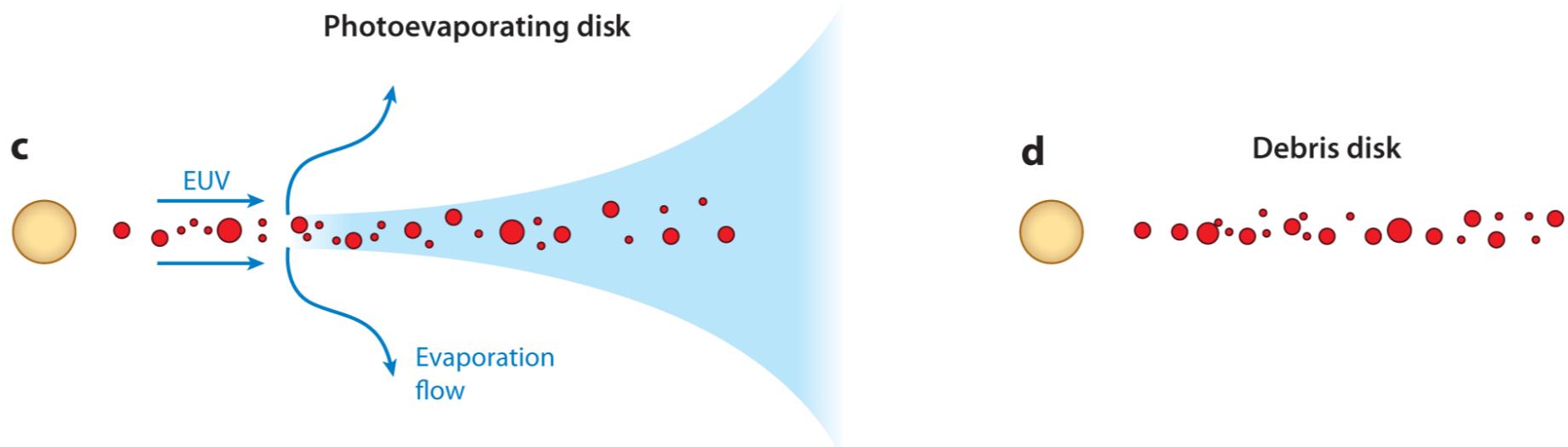
Detection of planet within disk



A planet just inside the dust ring around the star Fomalhaut. A coronagraph was used to block the star light. 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 $3 M_{\text{Jupiter}}$ 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



AR Williams JP, Cieza LA. 2011.
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Annual
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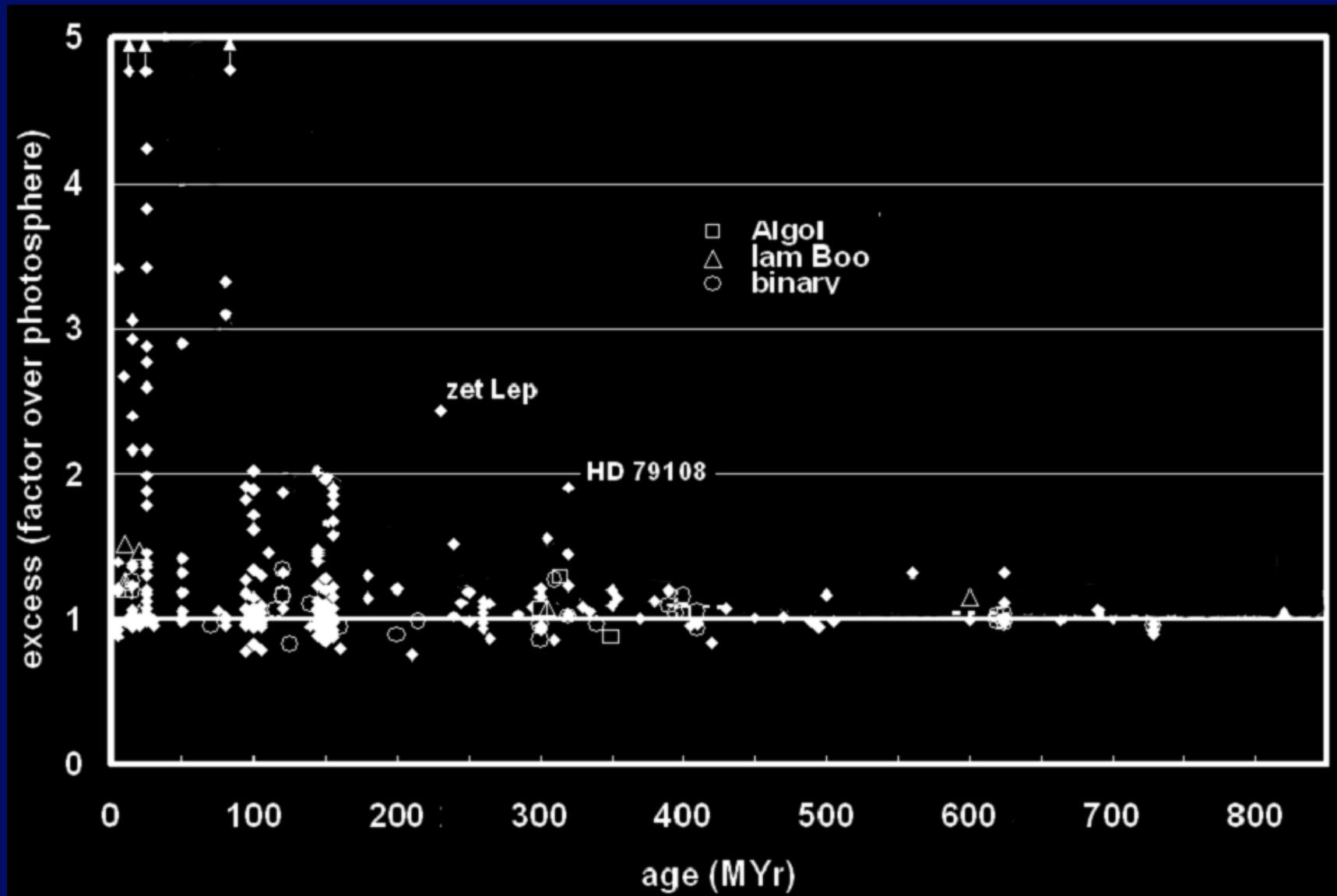
Issues for Planet Formation

- 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)

Models for formation of gas giants

grav. instability scenario

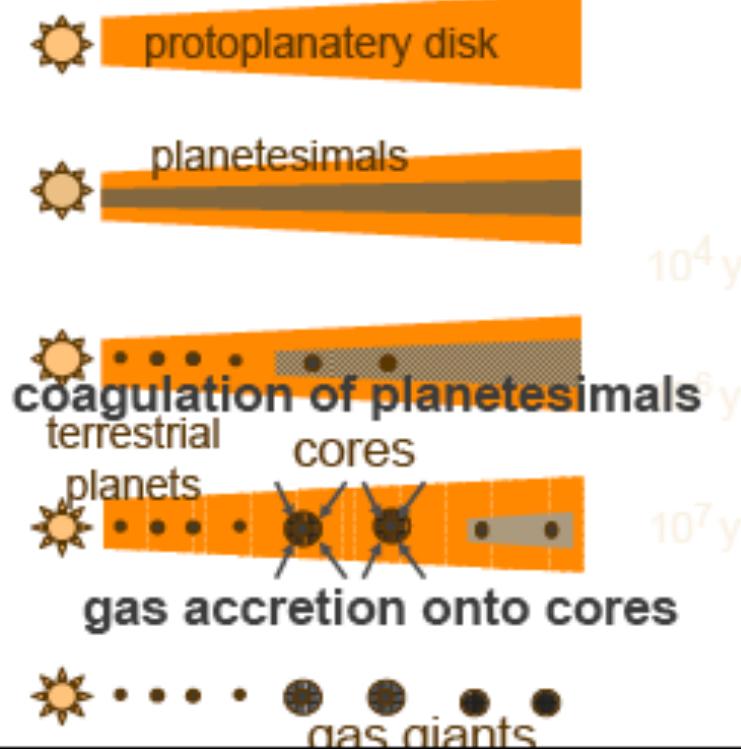
Cameron, Boss



May be only way to make big planets far from star

core accretion scenario

Safronov, Hayashi
Mizuno, Bodenheimer



Other Active Issues

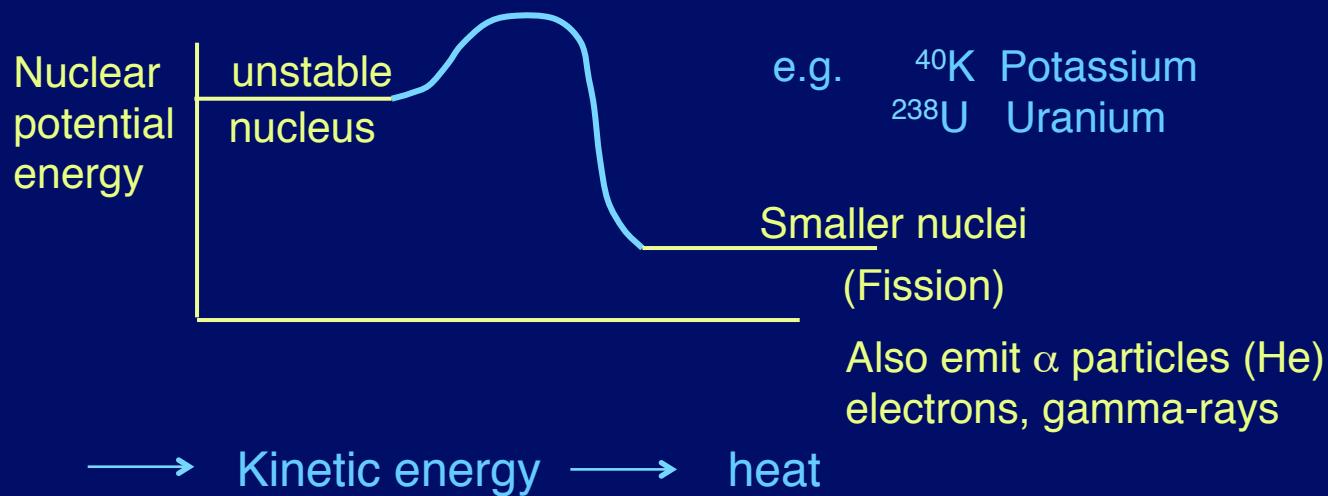
- Some planetary systems are quite different
 - First found were big planets in close
 - But this is probably due to selection effect
- Locations may differ with mass of star
 - Ices survive closer to lower mass star
 - May get ice giants in close
 - Also planets may migrate inwards
 - May prevent formation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

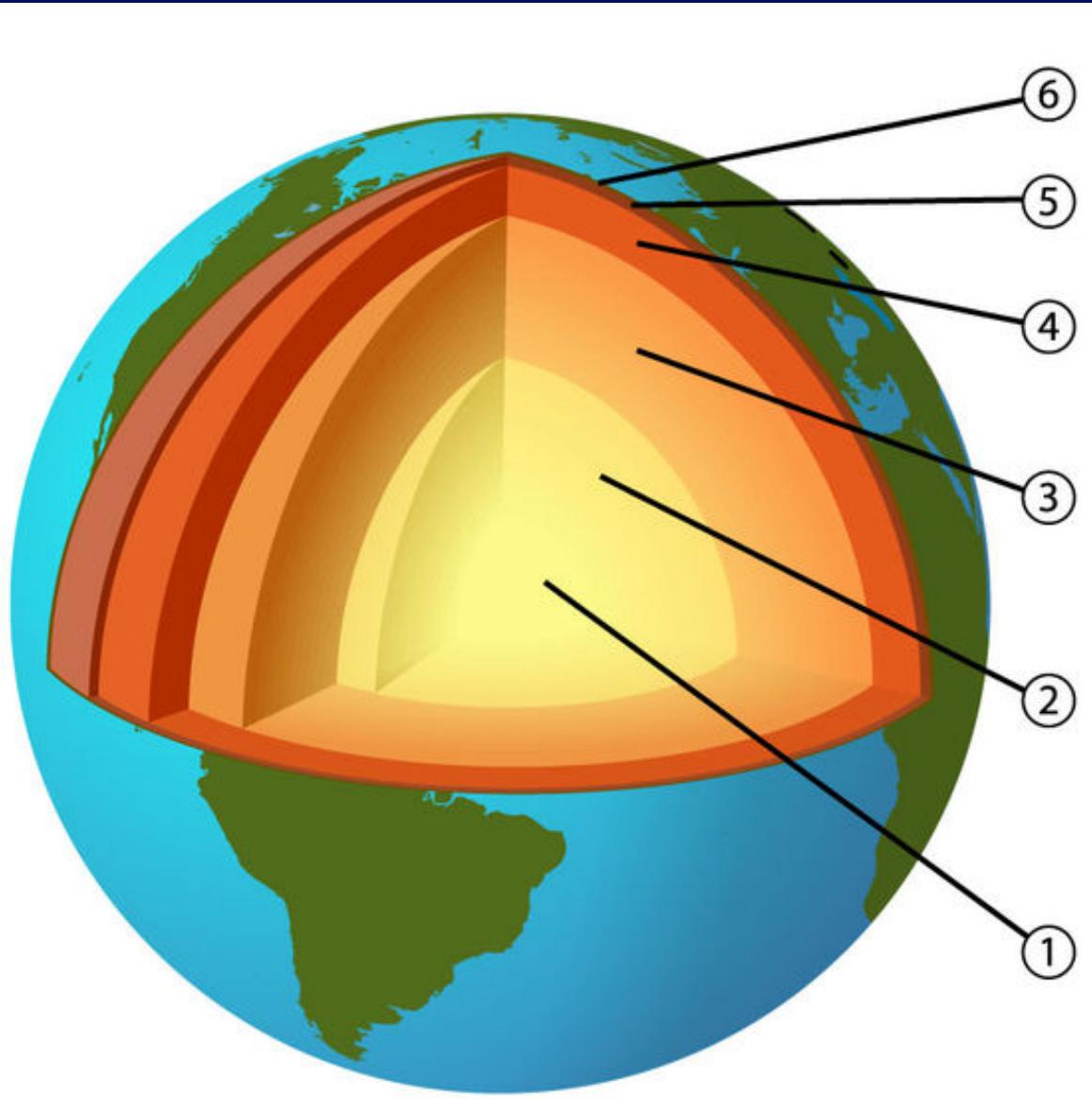
Formation of Earth

- 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)





Biosphere

Lithosphere (crust)
rigid

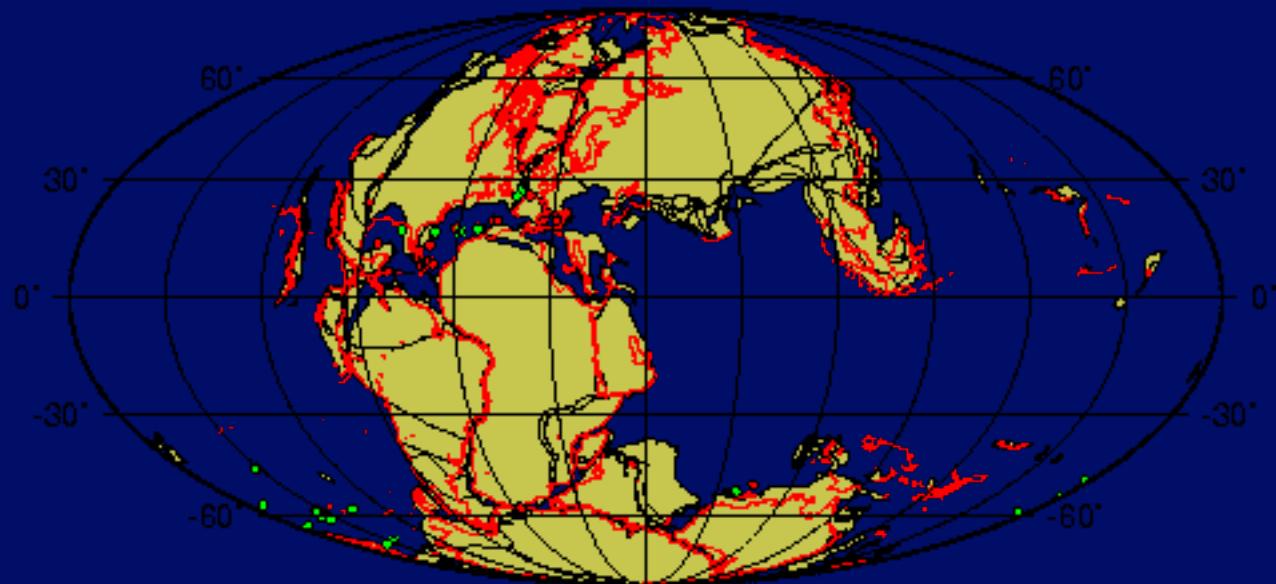
Asthenosphere
Upper mantle, pliable

Lower mantle, iron-rich
silicates, solid

Outer, liquid core
Iron, nickel

Inner, solid core
 $T \sim 7000$ K, iron, nickel

Continental Drift Reconstructed



150 My Reconstruction

Lithosphere floats on asthenosphere: volcanoes, continental drift
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

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

Most terrestrial planets have no moons

(Martian moons are captured asteroids)

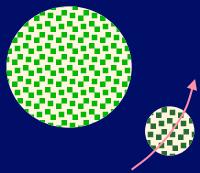
Moon most likely resulted from giant impact

$0.15 M_{\oplus}$



Earth gets more iron

$$\rho_{\oplus} = 5.5 \text{ g cm}^{-3}$$



Moon mostly silicate

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



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

Any icy material left?

Computer model of collision

movie of simulation

New model of collision (2012) requires fast-spinning (2 hour days) Earth to match detailed chemistry of Moon, which is very similar to that of Earth. Collision blasts a lot of Earth material into a disk around Earth, where Moon forms.

Origin of Atmosphere

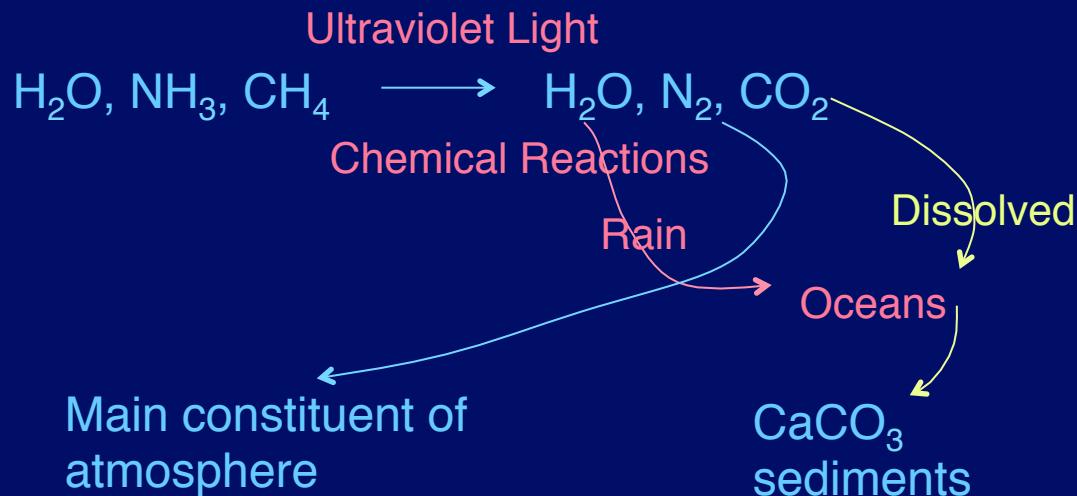
Certain “Noble” gases (e.g. Neon) are more rare in Earth atmosphere than in solar nebula. \Rightarrow Atmosphere not collected from gas

Reason: Earth is small \Rightarrow gravity is weak

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

“Icy” material vaporized by high temperatures, outgassed through vents, volcanoes

Alternative: Icy materials brought by comets, asteroids after Moon formation



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

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)