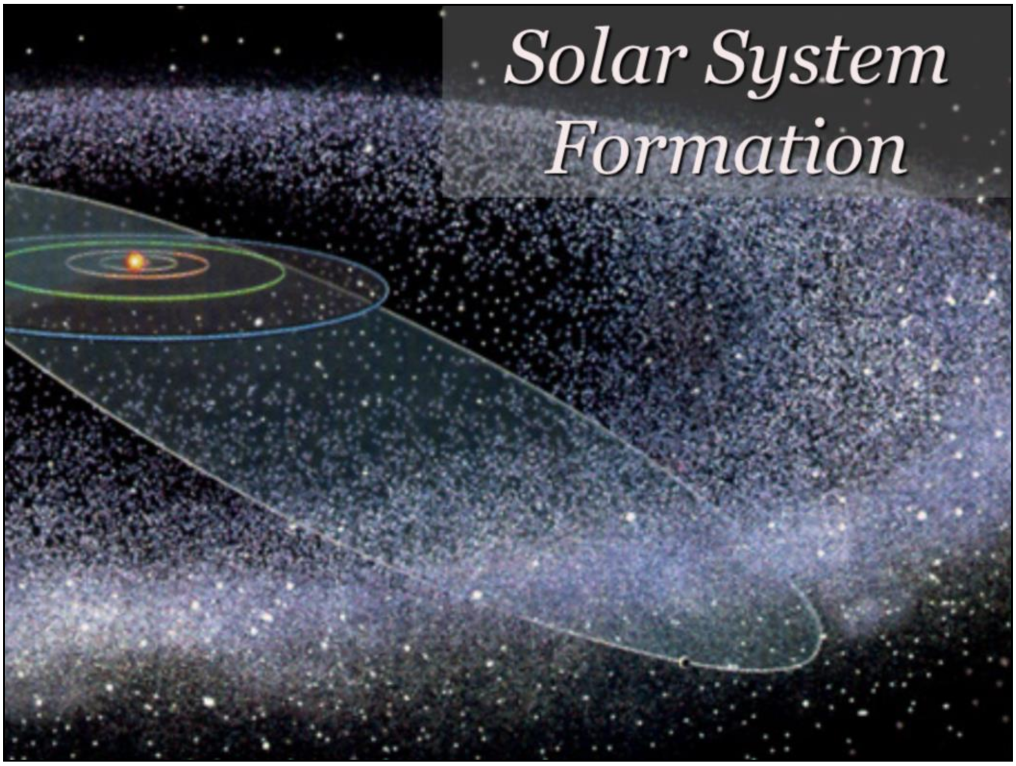
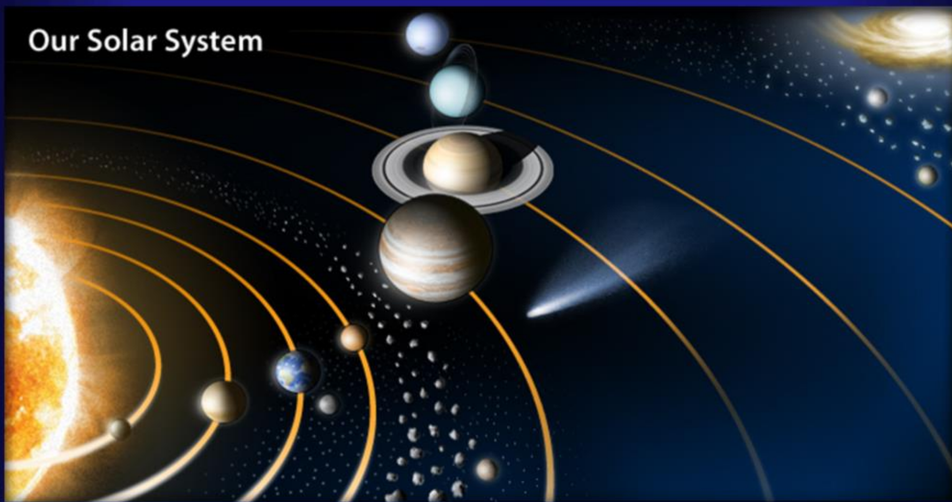

Solar System
Formation

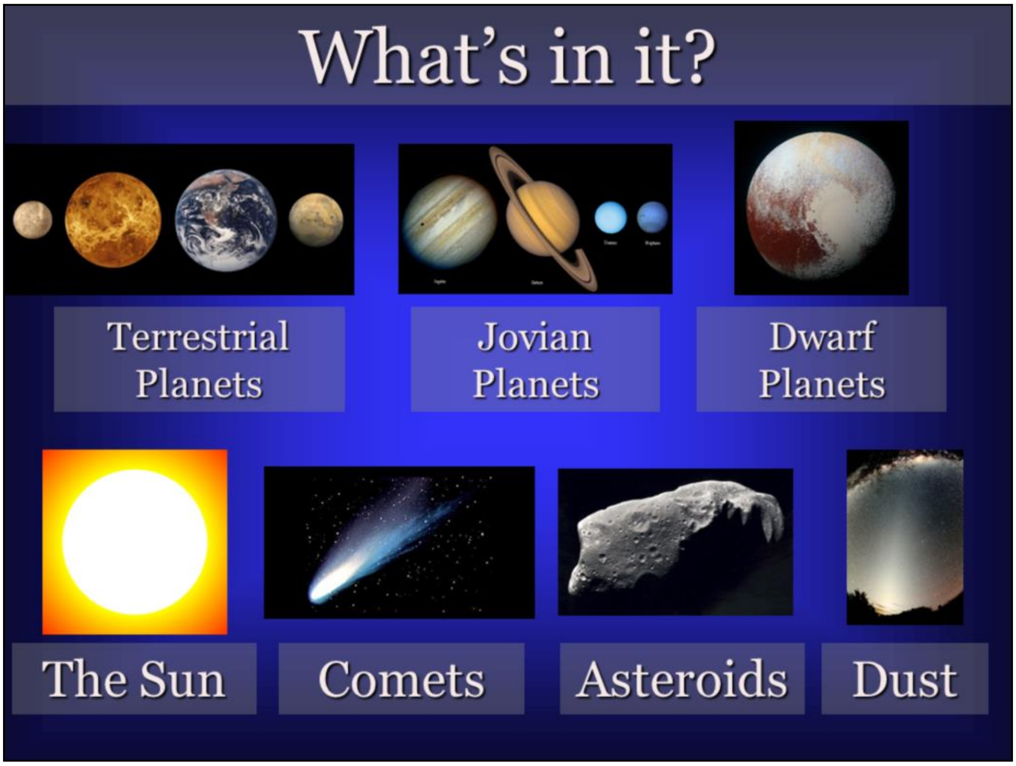
Planetary Formation



What do we need to know?

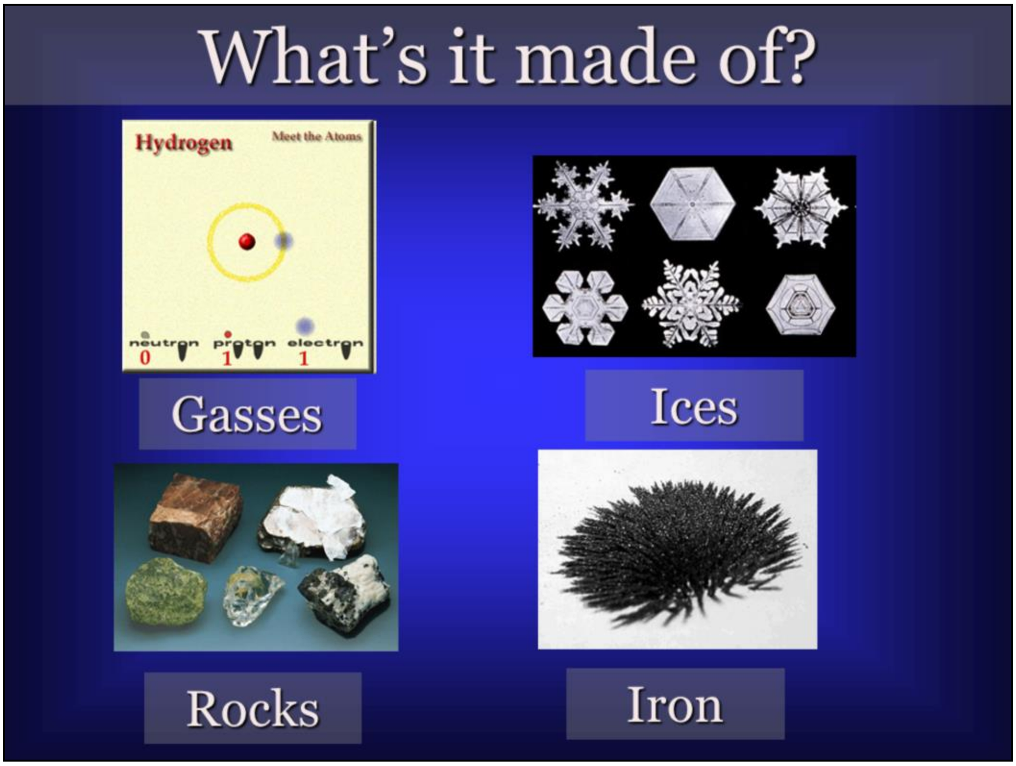
Planetary Formation

1. Basic characteristics
2. How does it start forming?
3. How do I make the planets (& stuff)?



What are the components of the solar system?

Sun, terrestrial planets, jovian planets, asteroids, comets, moons, dust



Terrestrial Planets: Primarily Rocks and Iron

Jovian Planets: Mostly Hydrogen but, in the core, rocks, iron, and ices

The Sun: Gasses (Mostly Hydrogen)

Asteroids: Rocks and Iron

Comets: Rocks, Iron, and Ices

Dust: Rocks, Iron, Ices

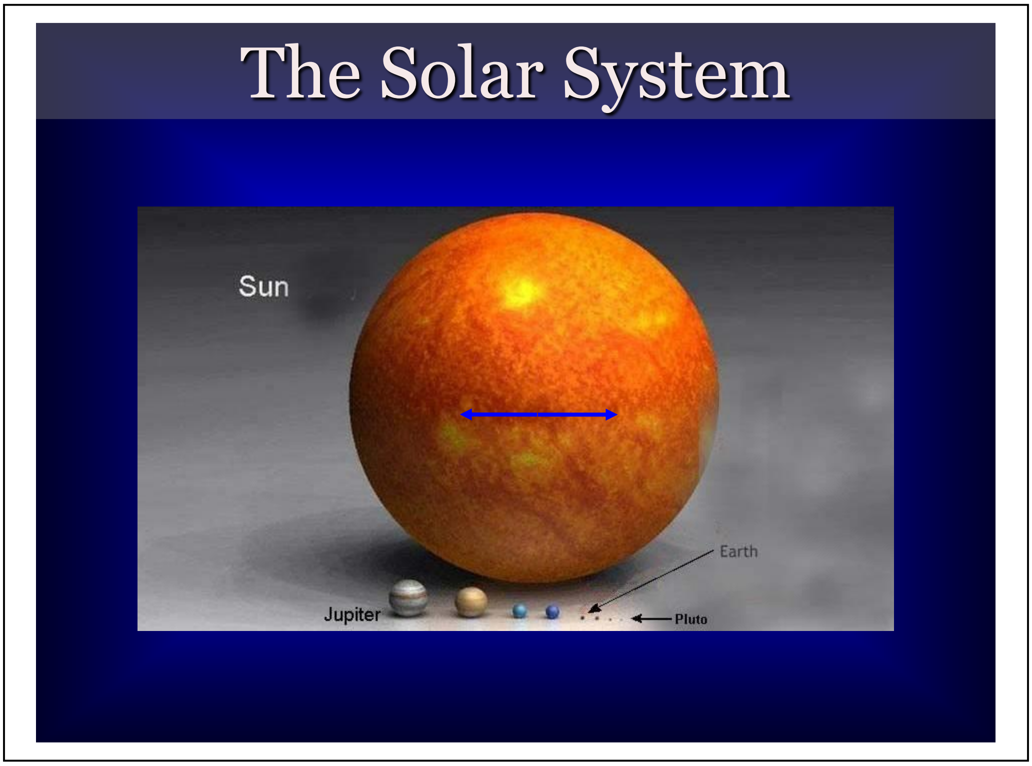
Dwarf Planets: Rocks, Iron, Ices.

From inside out:

Terrestrial planets, asteroid belt, Gas giants, Kuiper Belt objects, Oort cloud

There is a high degree of order in the solar system that must be explained.

- The planets all lie in a plane.
- They all orbit in the same direction.
- Most of them rotate in the same direction.
- Most rotation axis are roughly perpendicular to the ecliptic
- Rocky planets are in the interior, Gassy planets in the exterior, and icy planets waaay out there.



We Must Explain:

1. All orbits are in the same plane

2. Everything orbits in the same d

3. (Almost) Everything spins in th

4. (Almost) All of the spin axes are approximately aligned

The orbit of objects in the asteroid belt tend to be more elliptical

The orbits of objects in the Kuiper belt tend to be more elliptical and their orbital planes are at greater angles.

These are all due mostly to angular momentum arguments… Everything lines up along the original angular momentum axis

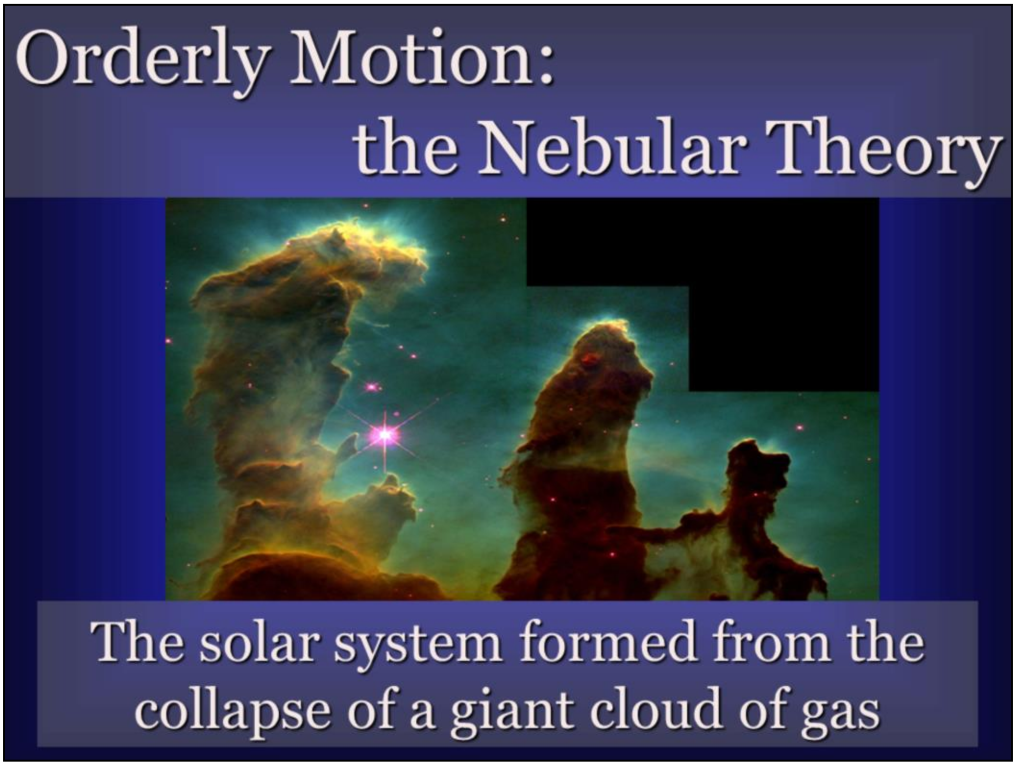
http://janus.astro.umd.edu/javadir/orbits/ssv.html

How did the solar system form so that the motion was very orderly?

Why are the inner planets (terrestrial planets) different from the outer planets (gas giants)?

What's the deal with asteroids, the Kuiper belt, and the Oort cloud?

Venus spins backward, Uranus is tipped on its side, the Earth has a ginormous moon….why?

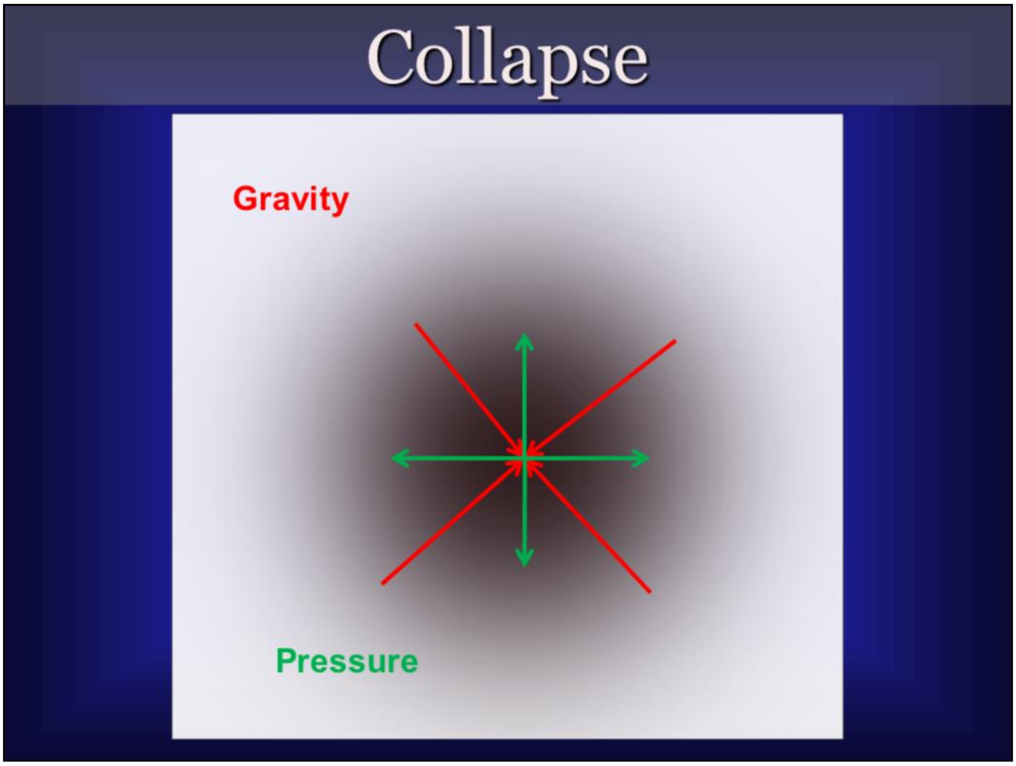


The Nebular Theory:

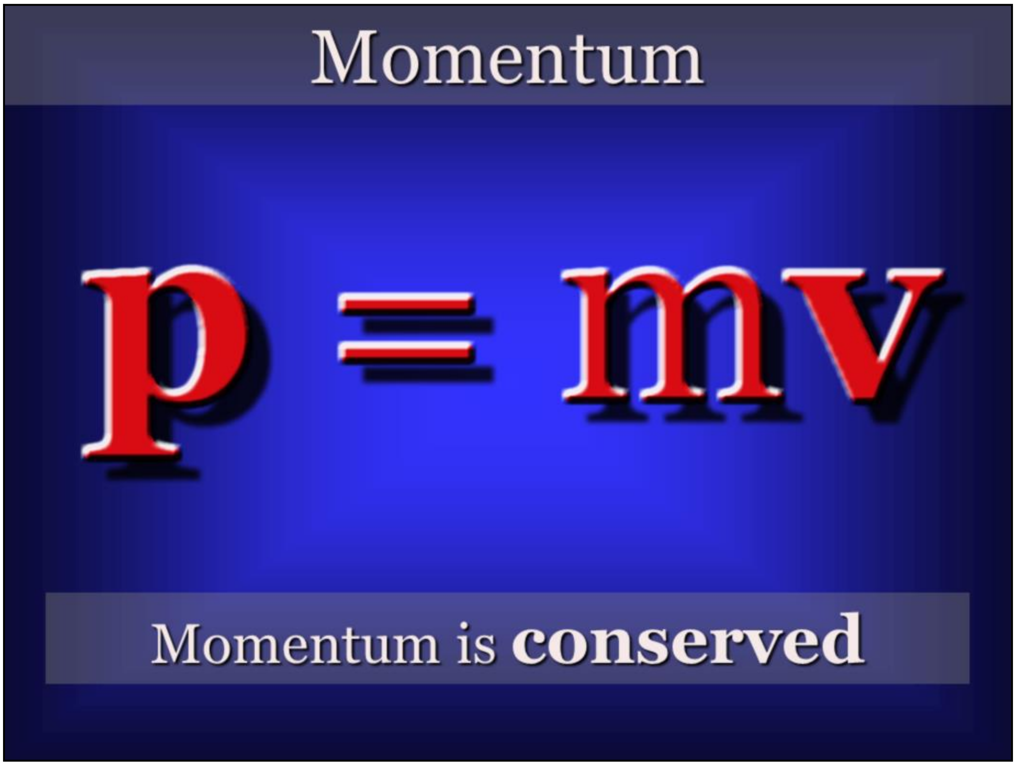
A cloud of interstellar gas began to collapse due to it’s own gravity.

As it collapses, it conserves angular momentum and spins faster

As it the density increases, collisions between particles cause it to flatten into a disk.



The collapse is a battle between GRAVITY and internal PRESSURE
If gravity wins, the cloud collapses.



Our first conservation law.

In a closed system MOMENTUM IS ALWAYS CONSERVED.
This includes situations where the gravitational force is involved.
It also includes situations where energy is transferred such as:

Friction robs kinetic energy
and explosion occurs (potential energy transfers into kinetic energy)

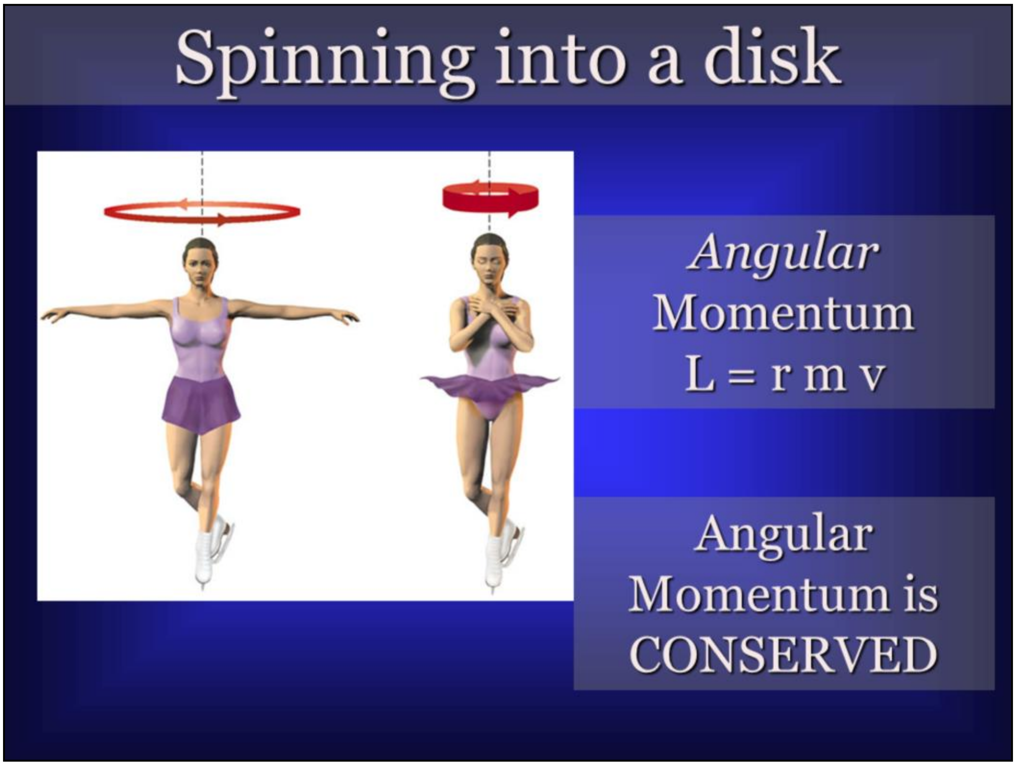
If we add up (M1 X V1) + (M2 X V2) + … and wait for some time
And add them up again, the answer will be the SAME.

As long as no external forces act on the system.

In the rocket, an EXPLOSION occurs that propels exhaust out the back of the rocket and propels the rocket forward.

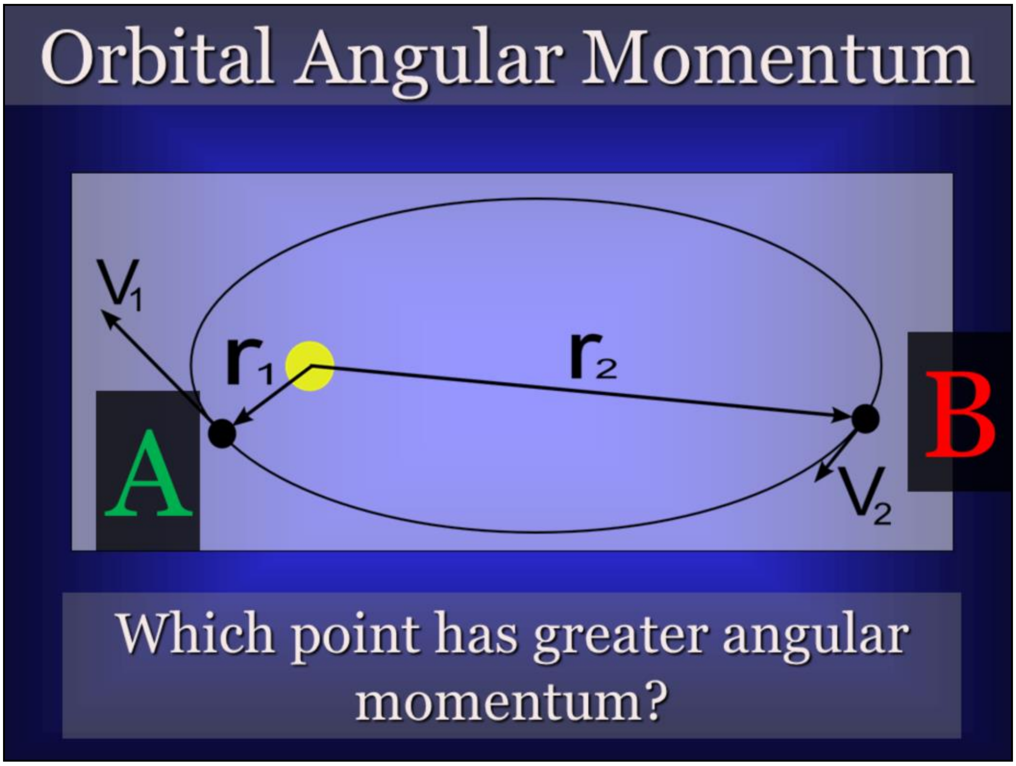
The system conserves momentum.

If the rocket fuel system has zero momentum initially, the momentum of the rocket plus the momentum of the exhaust will be zero afterward.



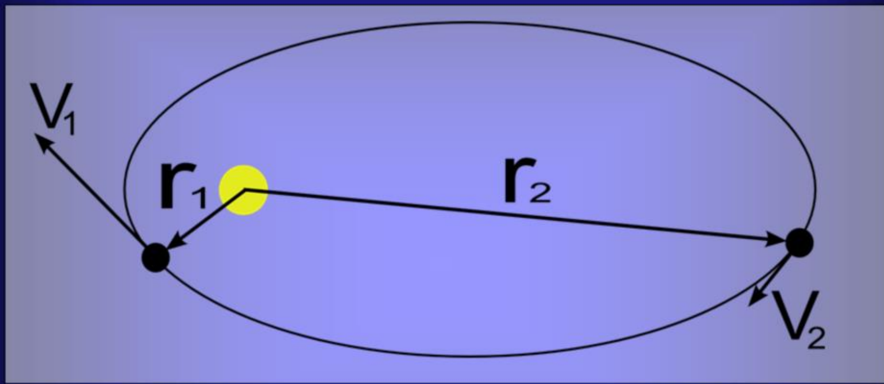
So everything is going in (roughly) the same direction. Motions vertical cancel out (same number of ups as down; collisions → neutral).

As it collapses what happens to the speed?

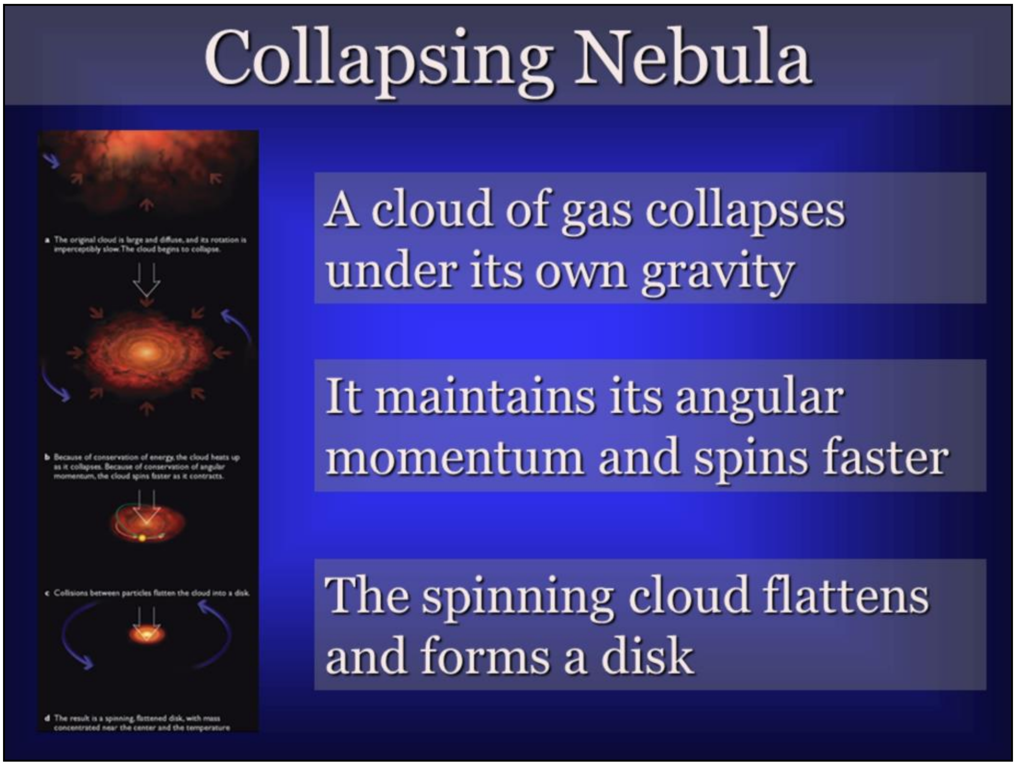


SAME! L = rmv. So when r goes up, v goes down proportionally

Orbital Angular Momentum



How does conservation of angular momentum explain Kepler's Second Law?



Disks form all the time. Galaxies, disks around black holes, forming stars…

(L = angular momentum = m v r)

Imagine filling a washing machine with balls and putting it on the spin cycle.

All the balls are whizzing around in a circle.

Now… throw a ball into the machine in any random direction.

Collisions between balls will drag the “oddball” along with the rest and soon it will be going in the preferential direction.

Close Encounter Theory:

The Sun encountered another star at some point in the distant past and great blobs of gas were ripped off.

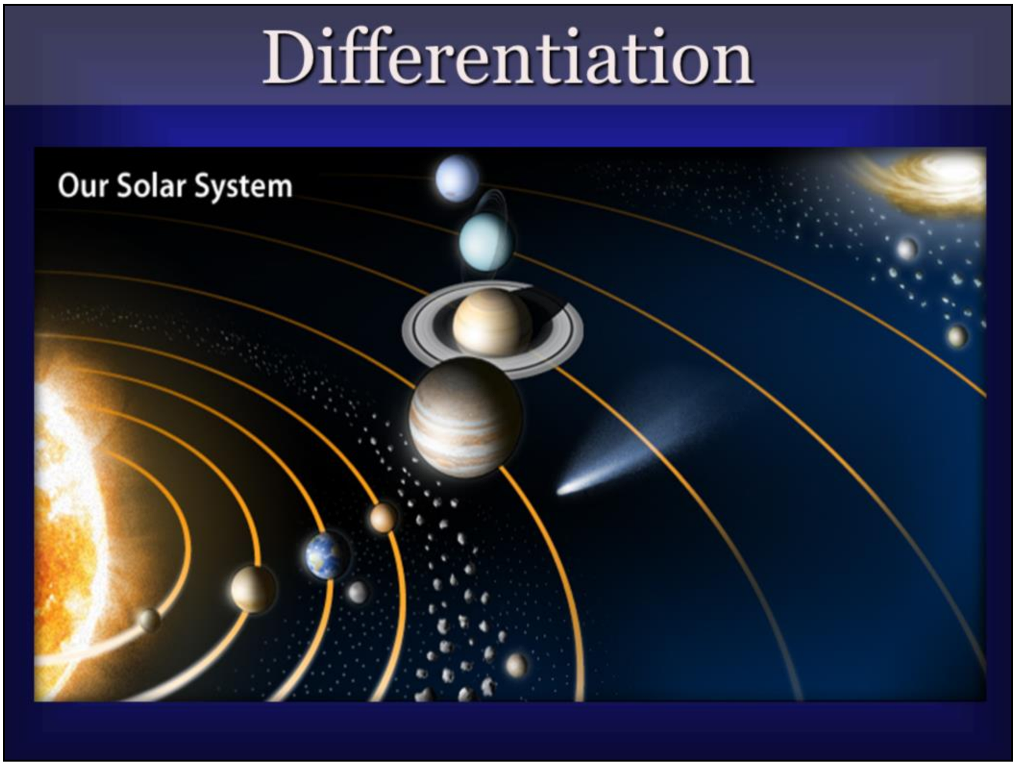
Those blobs eventually formed the planets.

Problems with this scenario the “Close encounter Theory”

Encounters are rare.

It’s hard to get stable orbits when we model this in the computer.

It’s nearly impossible to get a well ordered and differentiated solar system.



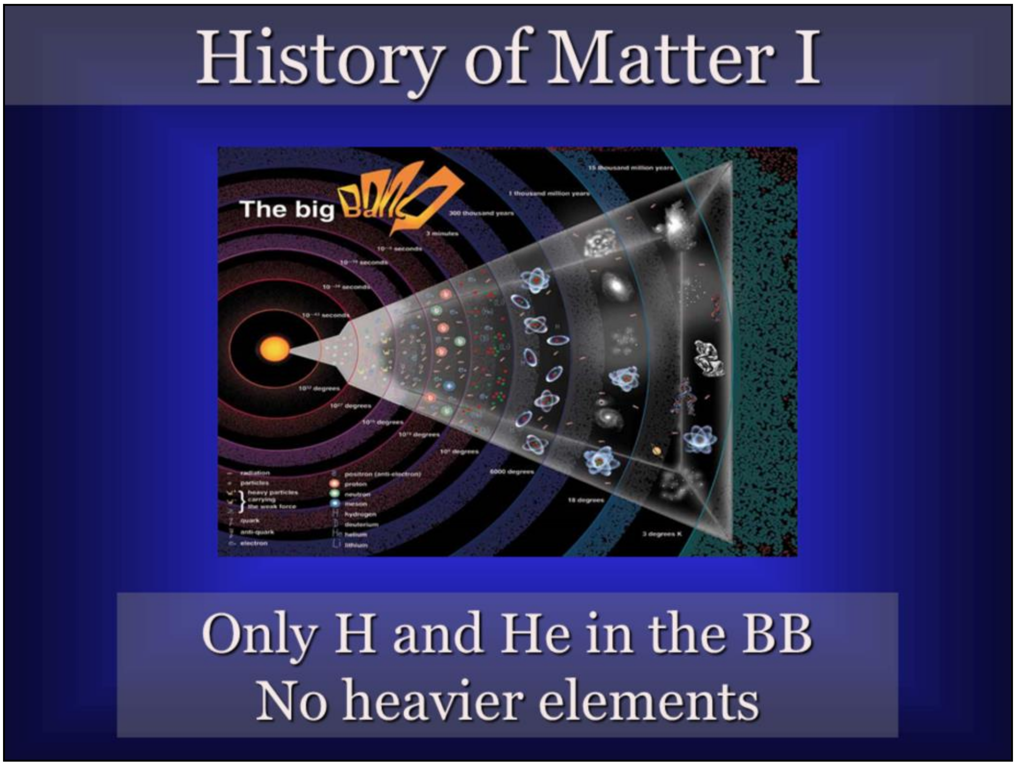
Why are the planets differentiated by composition?

Inner terrestrial planets are primarily rock and iron. They are small and dense. They have few moons and no rings.

Jovian planets, at middle distances, are primarily hydrogen (plus helium) gas with icy/rocky/iron cores. Low density but very large. They have lots of moons and all have rings.

Dwarfs, on the outskirts of the solar system, are an even mixture of rocks and ice. (except Ceres in the asteroid belt, which is more rock and not icy…probably)

Let’s look at the proto-Planetary disk and see if we can figure out the answer.

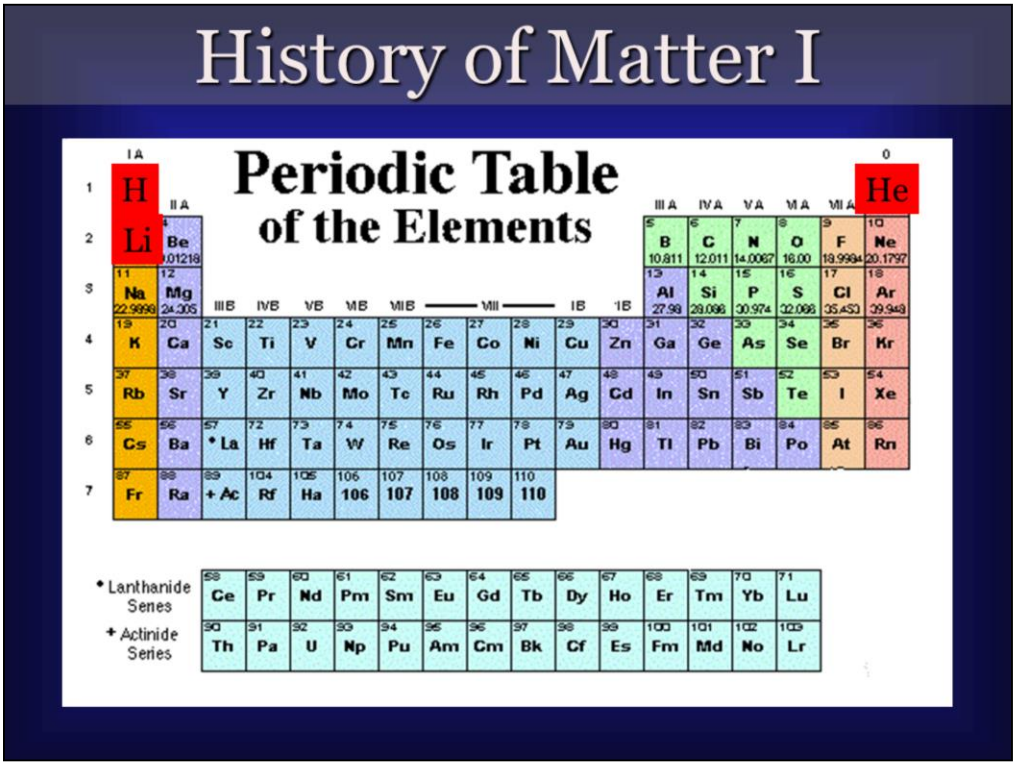


What elements are in the proto-solar system are another piece of what we need to figure out how the planets were formed. So where does the “stuff” come from?

The big bang created Hydrogen and Helium. 75% Hydrogen, 25% Helium

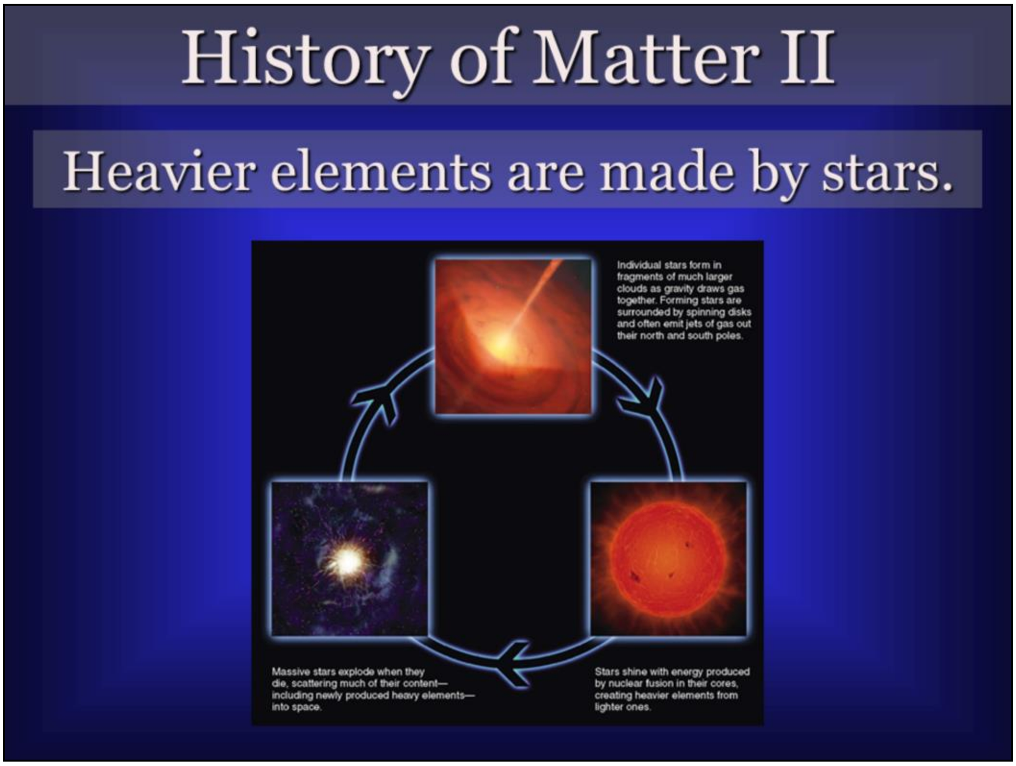
Stuff is made of more than Hydrogen and Helium.

Where does Iron come from? Silicon? Krypton? All the stuff on the periodic table…



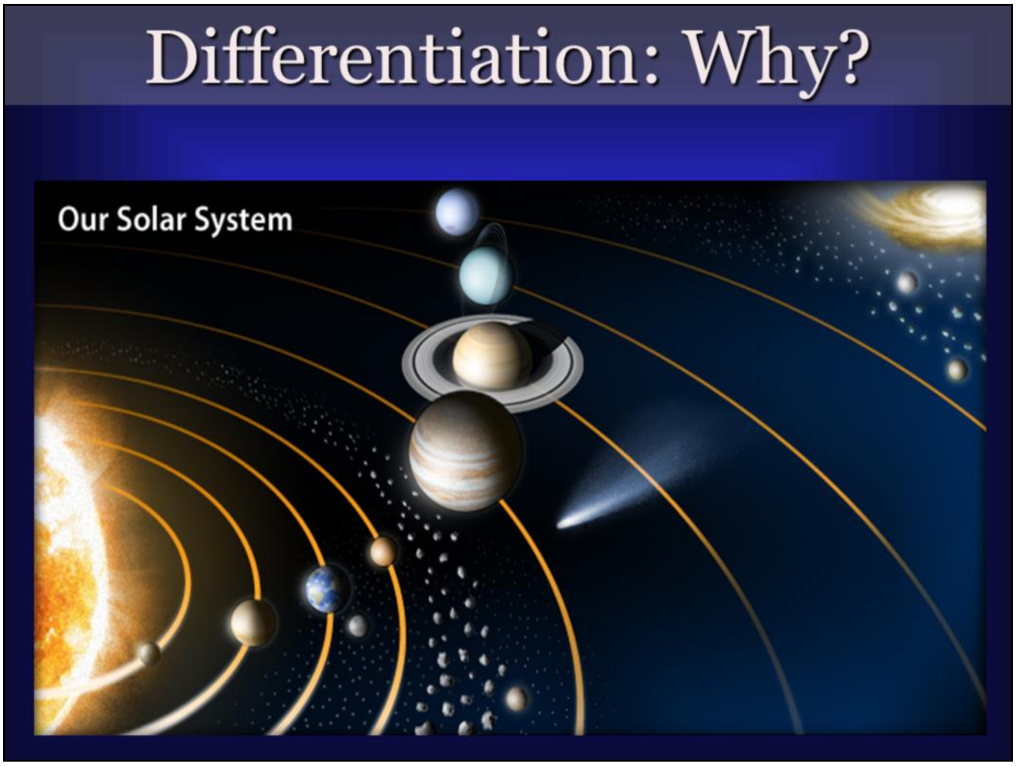
Stuff is made of more than Hydrogen and Helium.

Where does Iron come from? Silicon? Krypton? All the stuff on the periodic table… There are a lot of other elements (and *most* Lithium was not created in the Big Bang)



Fusion creates everything up to Iron (Fe)

The rest are created by processes when a very massive star dies. This stuff gets mixed into clouds in the interstellar medium (ISM), and can be used to make new stars (and after several generations, planets). We will talk about this process more in the future, but at least we know where the elements came from.



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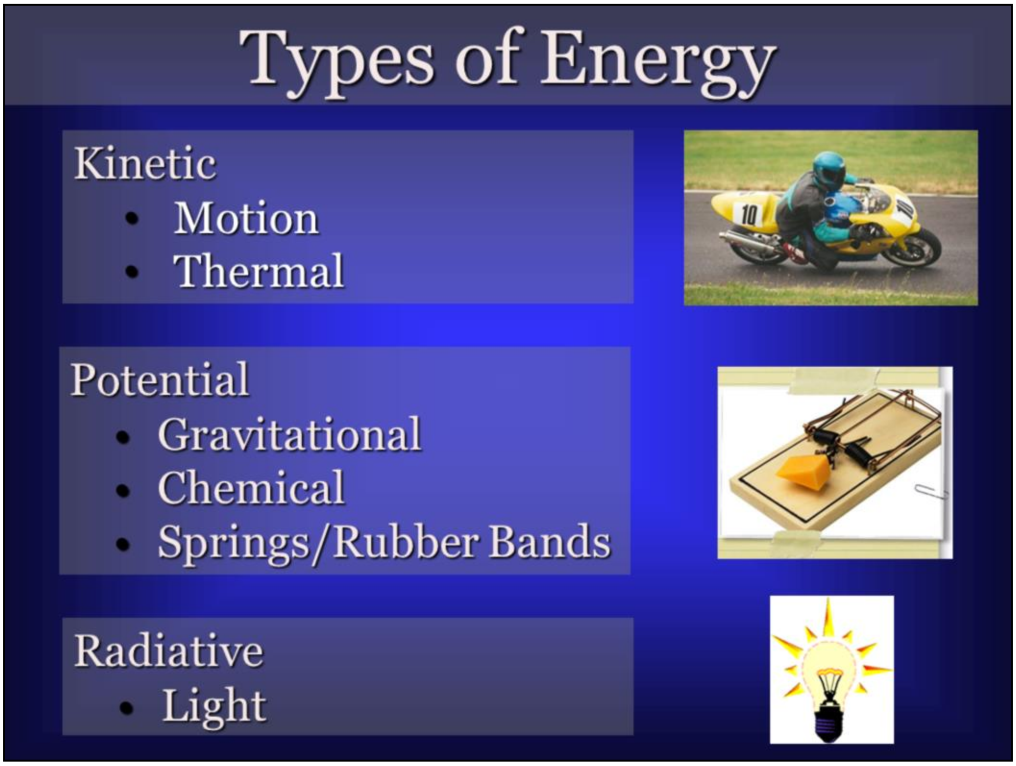


All of the energy forms that you can think of fit into one of these three types.

Energy that is stored. Potential energy can be converted into either kinetic or radiative (light) energy.

Sources of Potential Energy:

Chemical-

Gasoline, Hydrogen (both are forms of combustion, or combining with oxygen)

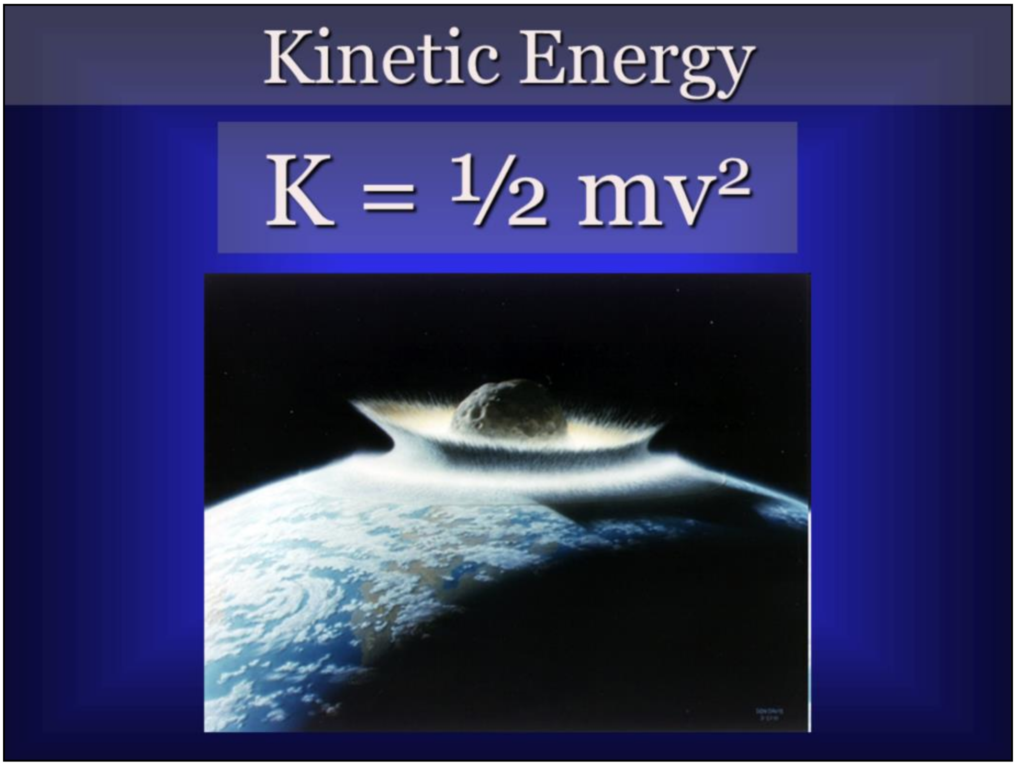
Gravitational-

Water flowing down a mountain.

A space rock falling towards the earth

Molecular bonds

Springs and rubber bands



Kinetic energy depends on

mass

A truck moving at 10 miles an hour has more energy than a bicycle moving at moving at 10 miles per hour

And the SQUARE of the velocity.

You saw this in the Impact lab.

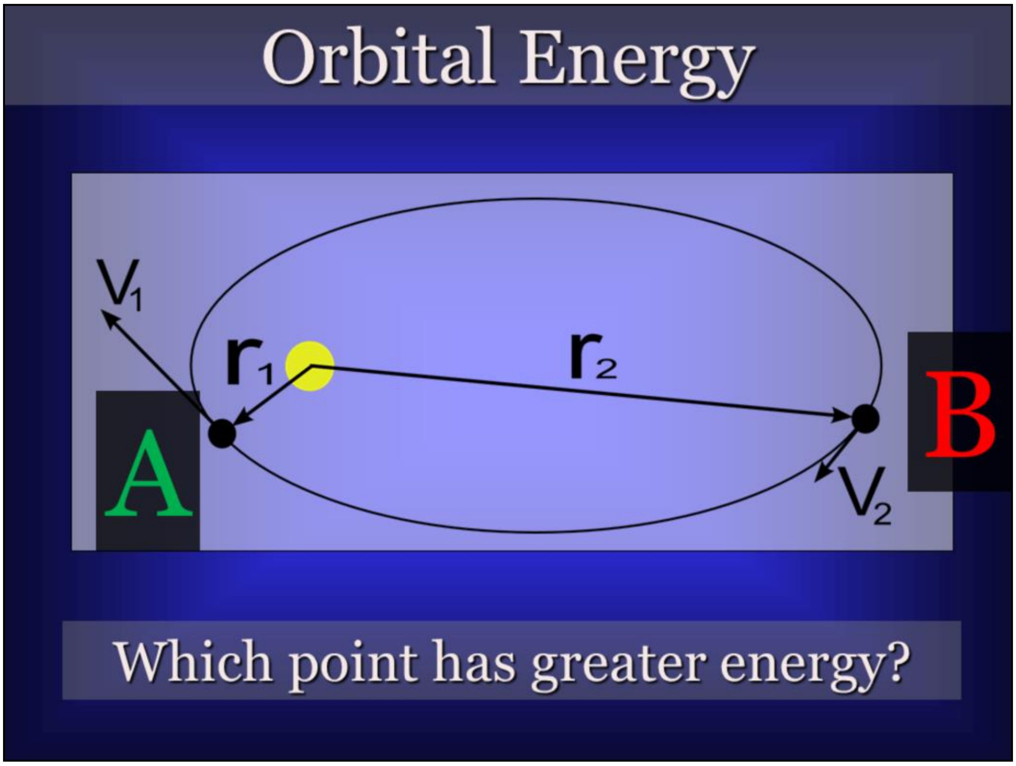
2 times the velocity is 4 times the energy

4 times the velocity is 16 times the energy

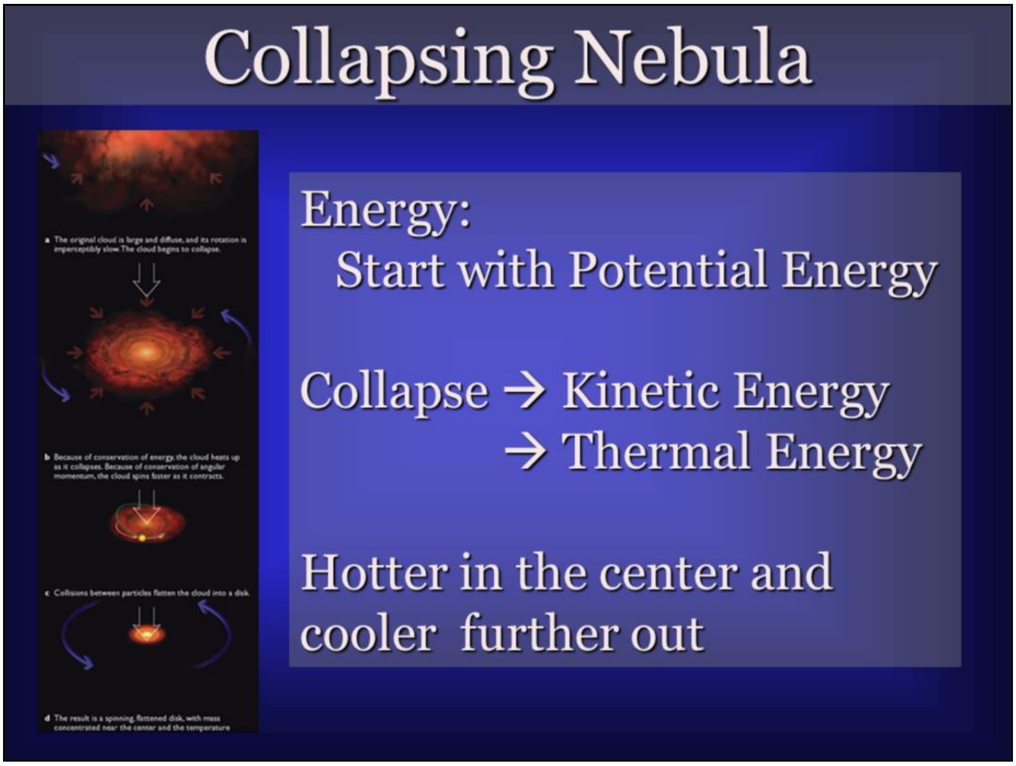
Fast moving asteroids carry ENORMOUS kinetic energy.

Can't always go backward though!

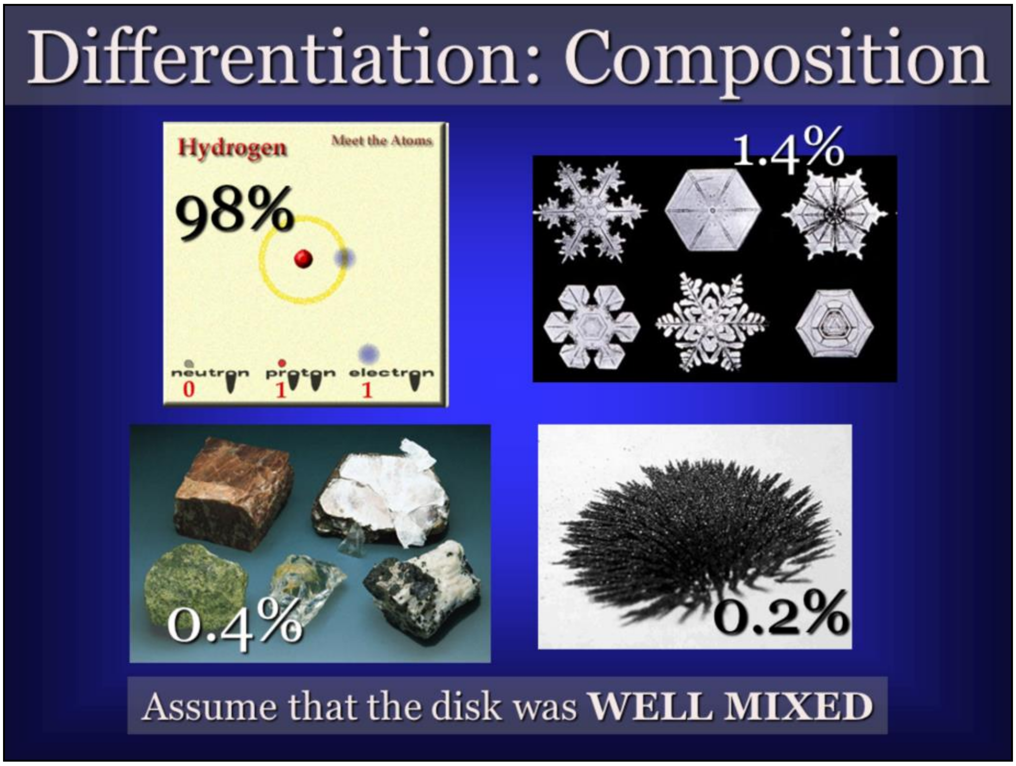
Where does the energy in the gasoline come from?



Same! *Conserved* quanitity!



Energy (and therefore temperature) will help us figure out why the planets formed the way they did. It’s one piece of the puzzle we will need.



Why are the planets differentiated by composition?

Let's start here: What are the various components?

The disk is made up of lots of different stuff. Some stuff is more abundant

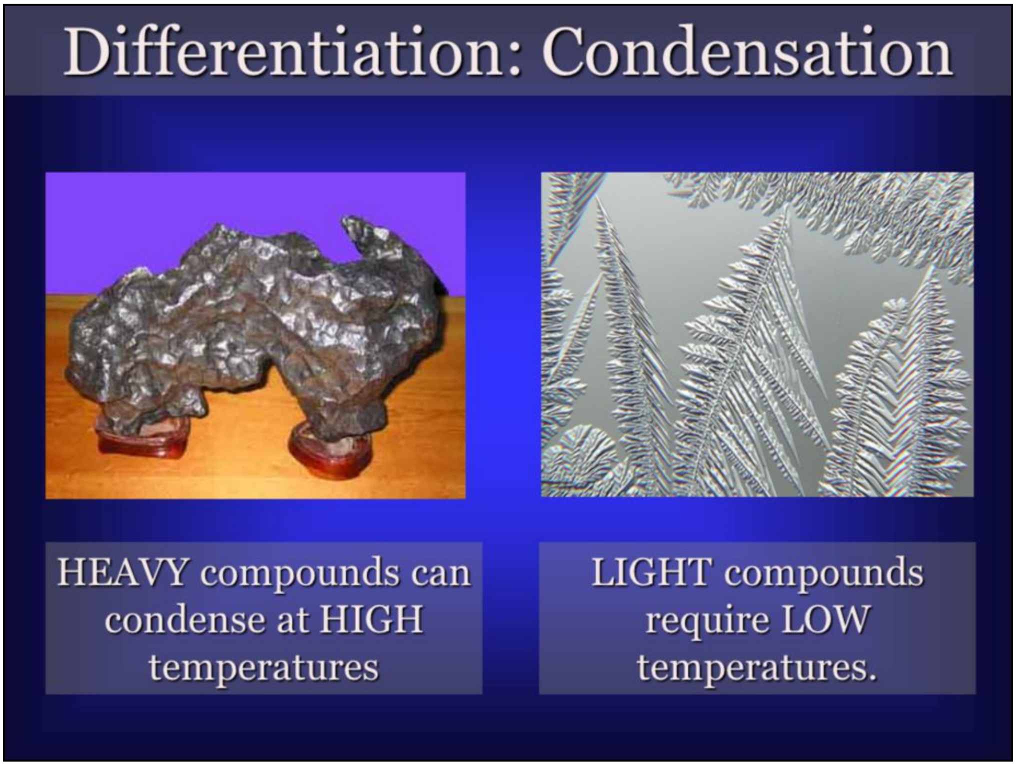
In order of abundance:

Hydrogen (gas), There is a LOT of hydrogen
Most of the mass of the solar system.

Ices (hydrogen compounds like water or methane) way more than the iron or rocks

Rocks (silicate compounds)
Not much, but more than Iron

Iron (and other trace heavy metals)
Very little

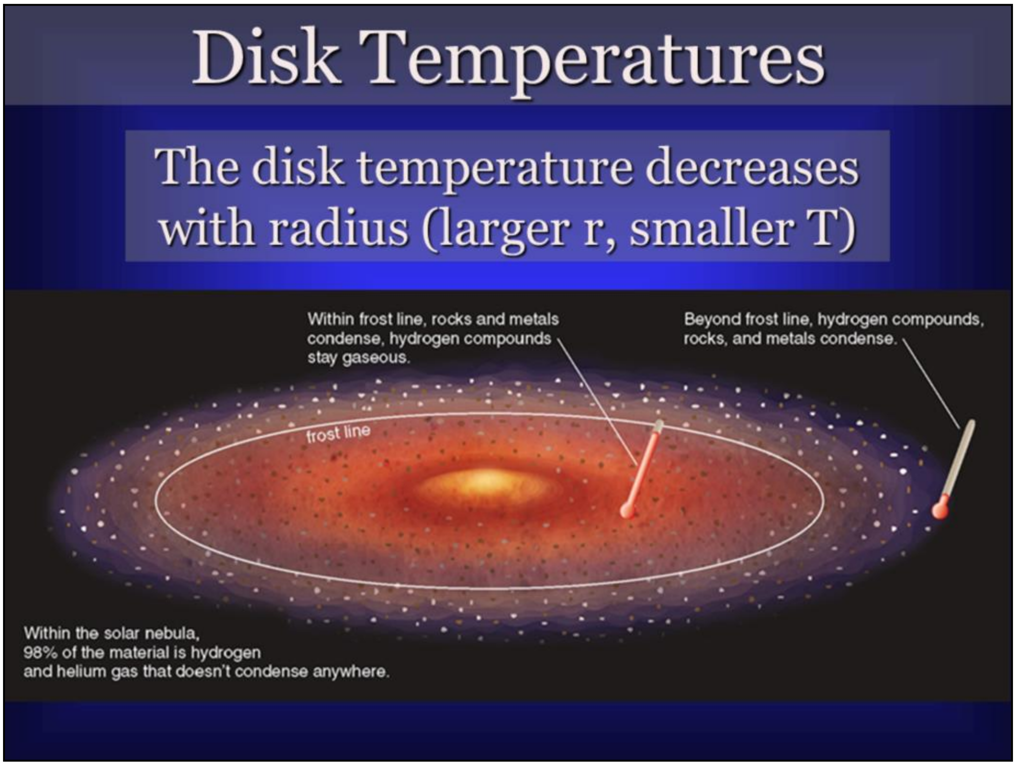


Condensation is changing from the gaseous state to the solid state.
In the summer, water from the air condenses on your glass of ice water.

In a proto-planetary disk, the gaseous compounds condense to form solids.

Hydrogen compounds (NOT to be confused with hydrogen GAS)
Require LOW temperatures to condense at low temperatures to form ices.

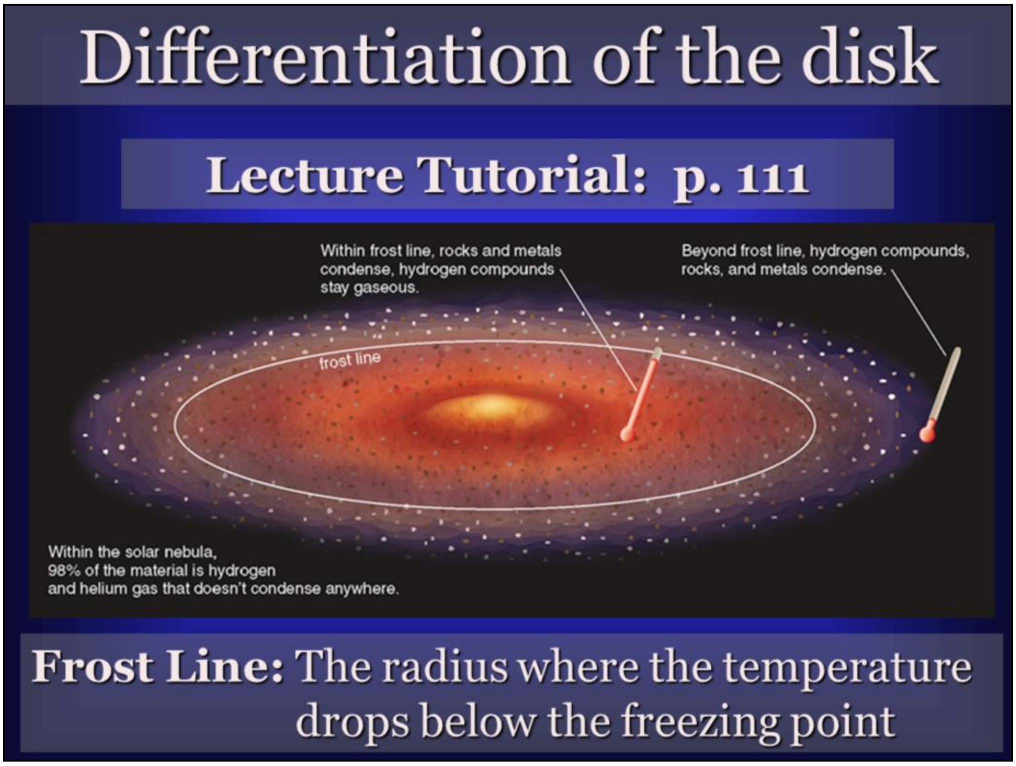
Rocks and Metals are able to condense at HIGH temperatures.



So let's go back to our proto-planetary disk. How do we make planets in this disk? Well, first let's talk about what elements we find where… and how that changes what planets will form.

Closer to the proto-sun (it hasn't started fusing yet!) it is hotter because it has given up more Potential Energy. Further out, it's colder. Moving out from the sun, it is too hot for things like water ice (or other ices like ammonia). So any water that's there is vapor and moving fast. As you move further from the sun, though, it gets colder and colder, until eventually you can form ice. Those ice particles don't zip around like a gas zips around, and can condense onto rocks and dust. This makes the rocks and dust particles *bigger* than the ones on the inner solar system.

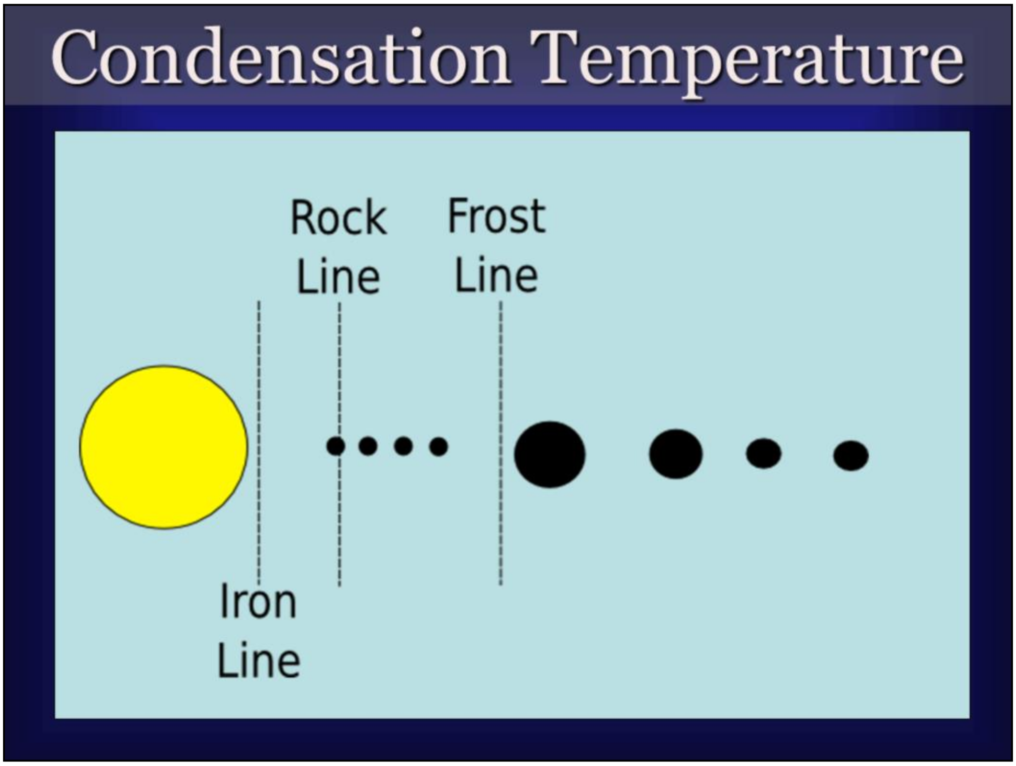
The dividing line between where it's too hot and where it is cold enough to have ice is what we call the *Frost Line*



Metals and rocks (silicon based stuff) condenses at higher temperatures than hydrogen compounds (in other words, you can form rocks at a higher temperature than you can form ices)

So… Inside the frost line, you get rocks and metals. Beyond the frost line, you get rocks, metals AND hydrogen compounds condense. Things like hydrogen (by itself) and helium don't ever condense to form solids.

So what does that mean?



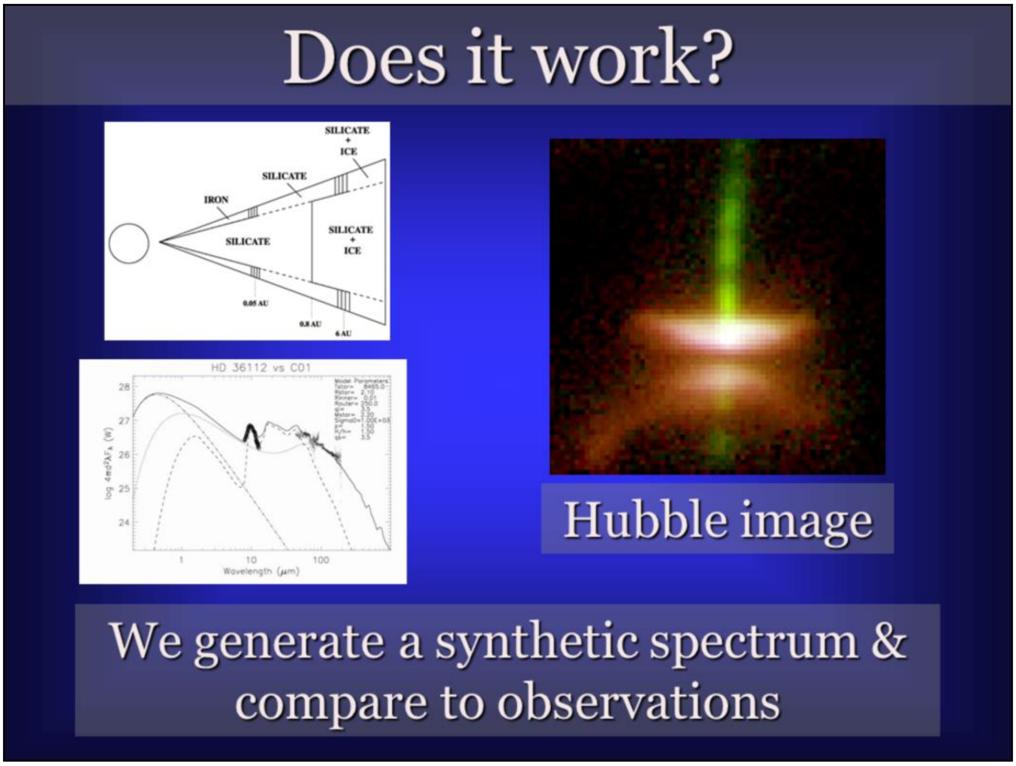
Inside the frost line, ices do not condense, so only rocks and iron are available for construction of planets.

So, near the sun, planets made of rocks and iron form. These are called Terrestrial planets.

The terrestrial planets are small because the abundance of rocks and heavy metals is small

Compared to the compounds that form ices.

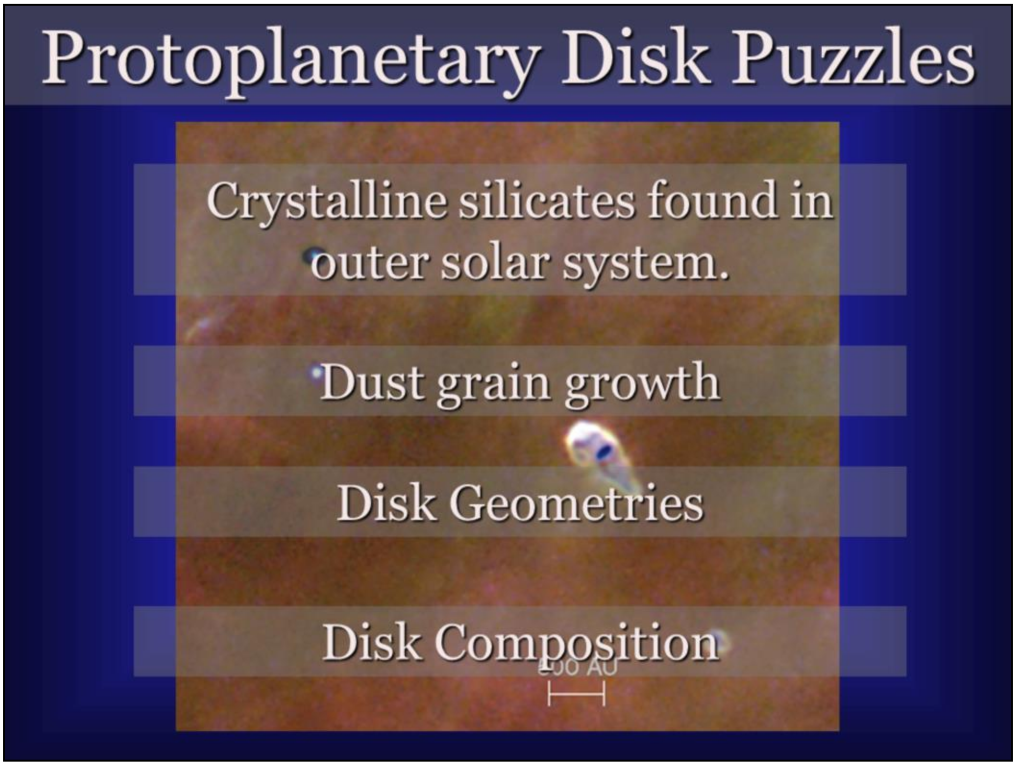
They are too small and hot to capture a hydrogen atmosphere.



Modeling: You think of what the disk looks like (shape, temperature, energy) and what it's made out of (H, He, rock, metals, ices) and use a computer to generate the spectrum.

Compare the output spectrum with real observations to see if the beast in the computer looks like what we see in space.

Why? This way we try to answer the questions on the next slide.

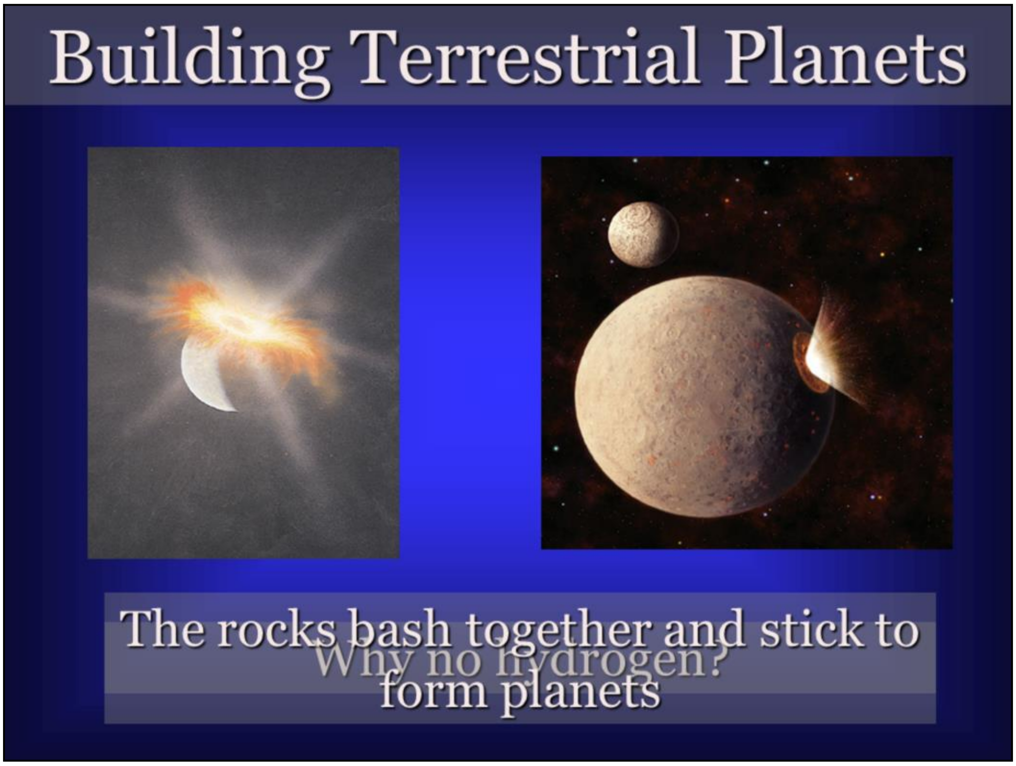


Certain crystals require high temperatures to form, yet we find them in comets which come from the outer solar system. How did they get there?

We don't completely understand grain formation and growth in a proto planetary disk

The geometry of the disk is a matter being hotly debated.

The composition of the disk is not completely characterized.



The components of rocky stuff are less abundant than the components of icy stuff.

Inner planets are therefore too small (and hot) to capture hydrogen (hydrogen is light and reaches escape velocity if the temperature is even slightly warm)

Things are violent in the early solar system… smaller planetesimals are easily shattered… only the largest ones survive the impacts so a few planets get the mass.

In the outer solar system, it's cold enough to form ices.

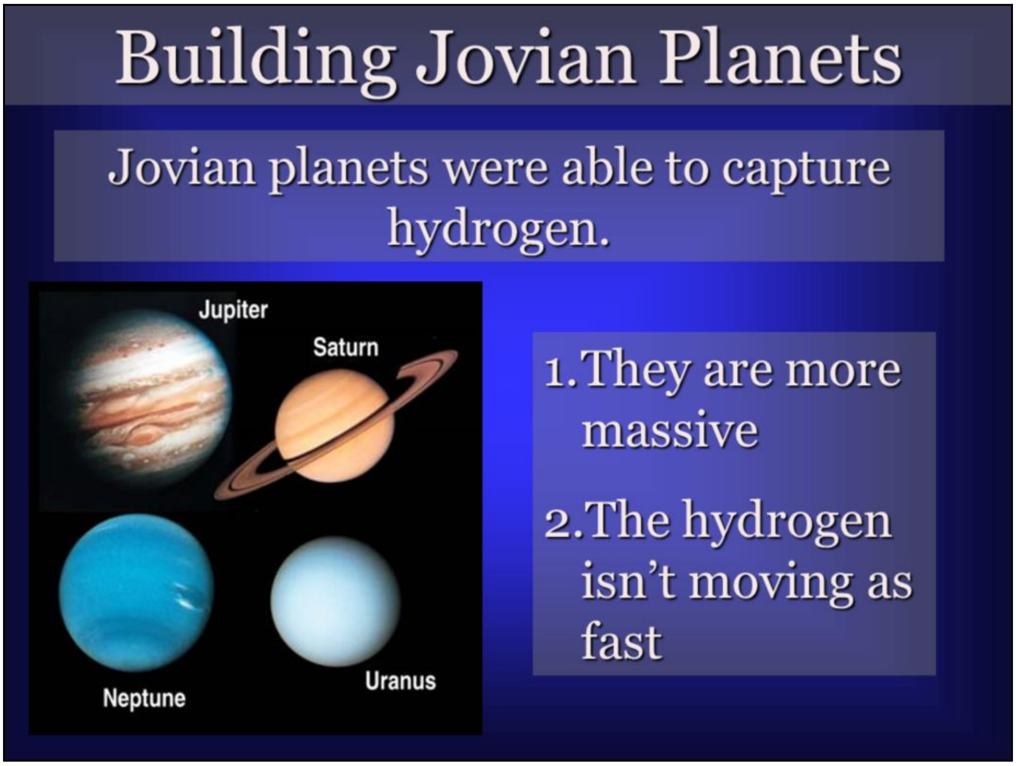
There is a LOT more icy stuff than rocky stuff so BIG dirty snowballs are built.

Ices as well as rocks can condense beyond the frost line so there is more stuff available to accrete

Hydrogen is moving slow AND the planetary cores are BIG so hydrogen does not achieve escape velocity.

Jovian planets capture an ENORMOUS hydrogen atmosphere

So, the jovian planets are very large compared to the terrestrial planets. Jupiter is 318 Earth masses.



Jovian planets could capture hydrogen because it's cold out there.

Ices as well as rocks can condense beyond the frost line so there is more stuff available to accrete

Lower temperatures mean lower thermal velocity of hydrogen and helium atoms.

These two facts combined mean that hydrogen doesn't achieve escape velocity

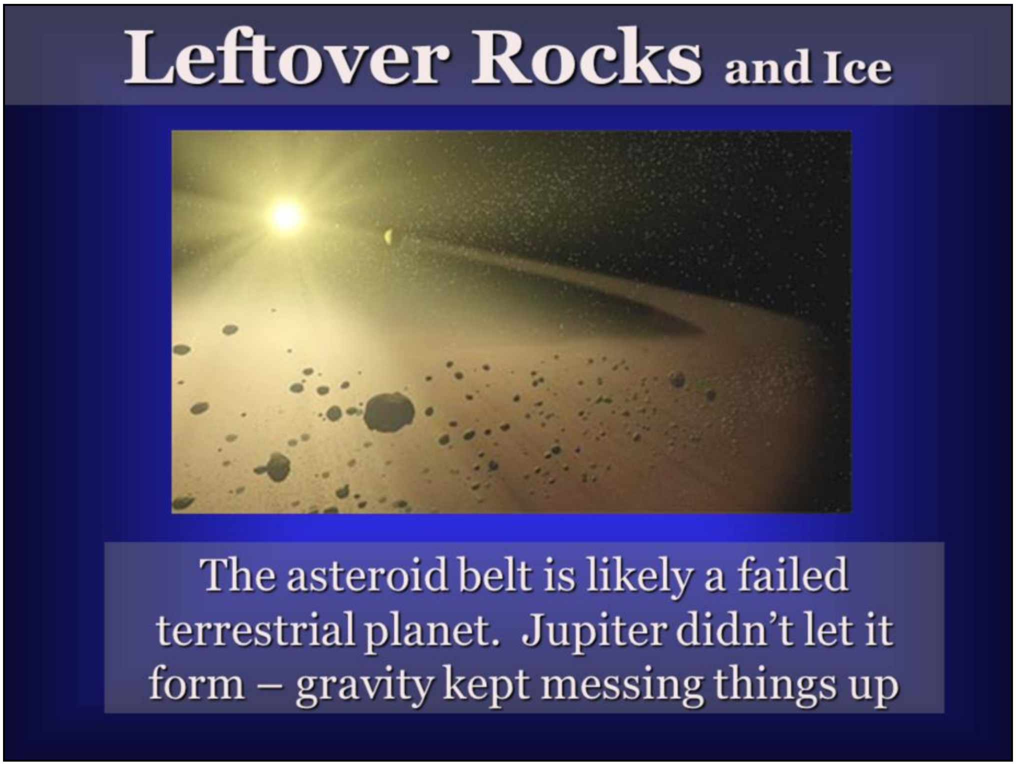
Planetary Formation

A Formation Scenario must answer

1. Origins of the orderly motion. ✓
2. Differentiation of material ✓
3. Rubble
4. Exceptions

This is not what the asteroid belt looks like.

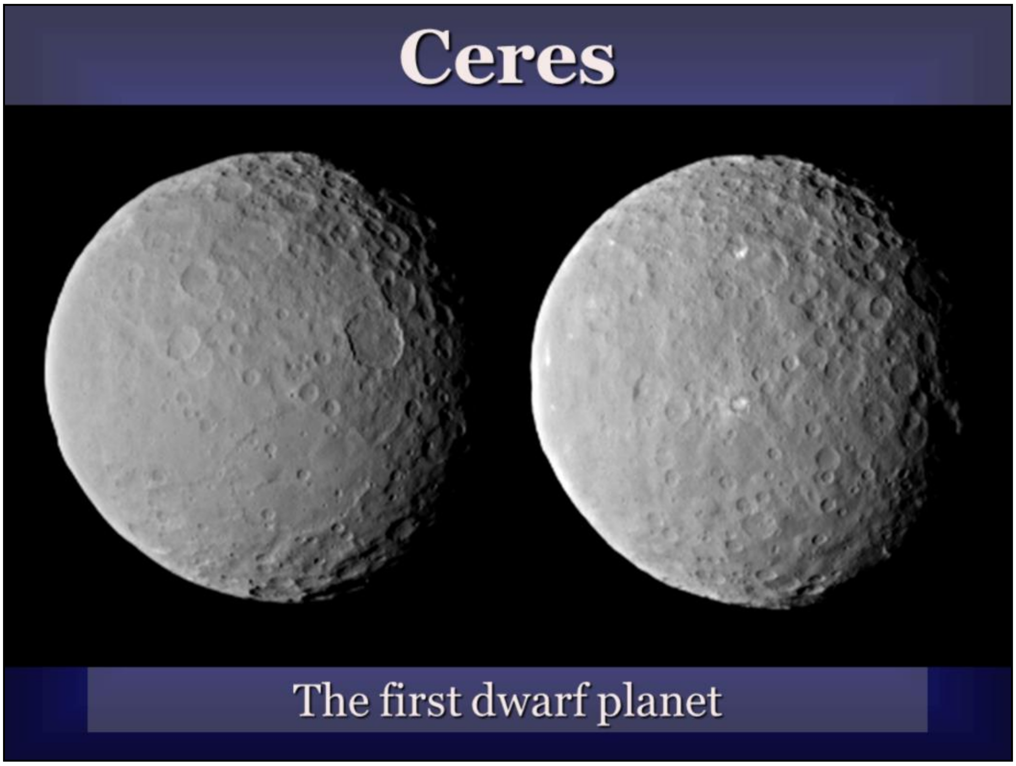
This is more like it…. Lots of empty space



The asteroid belt appears to be a terrestrial planet that didn't form… lots of chunks of rock.

Perhaps a planet tried to form but was too close to Jupiter's gravitational influence.

The asteroid belt is not very dense, and has a mass of ~one thousandth of a terrestrial planet



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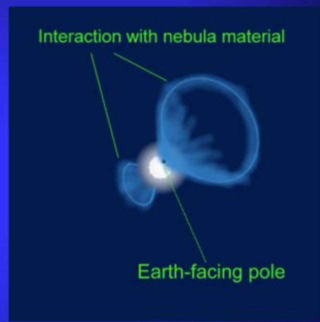
Sweeeet: http://www.nytimes.com/interactive/2015/01/13/science/space/photos-of-ceres-from-nasa-dawn.html?smid=pl-share

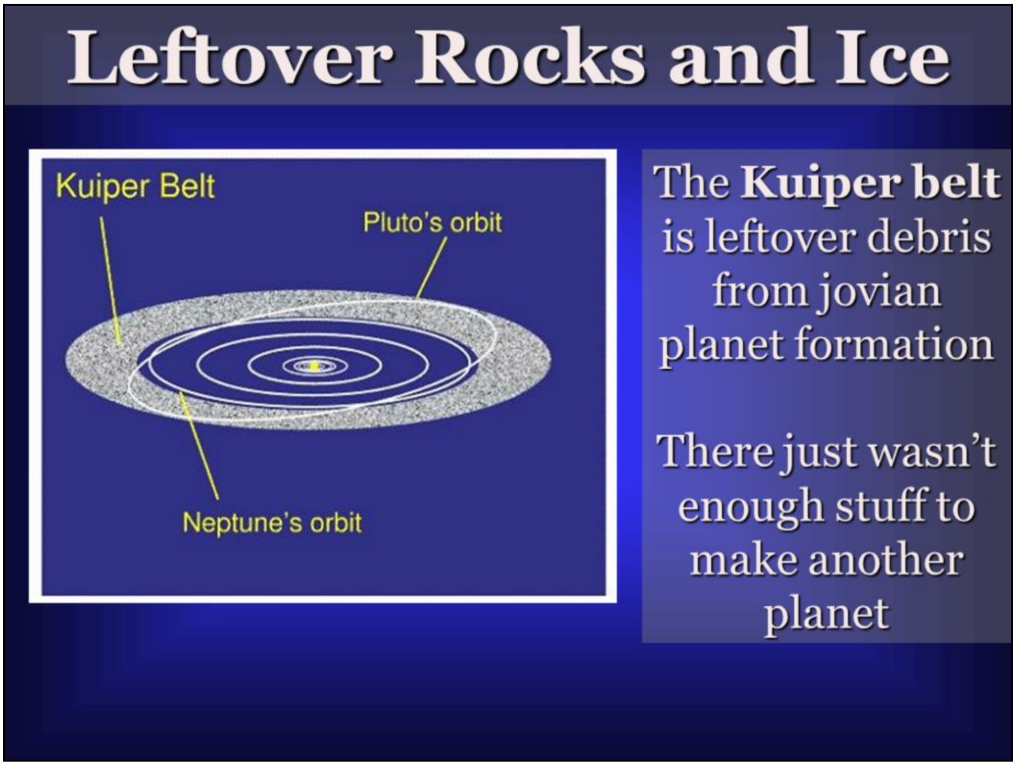
Where's the Hydrogen?

Young stars have strong winds

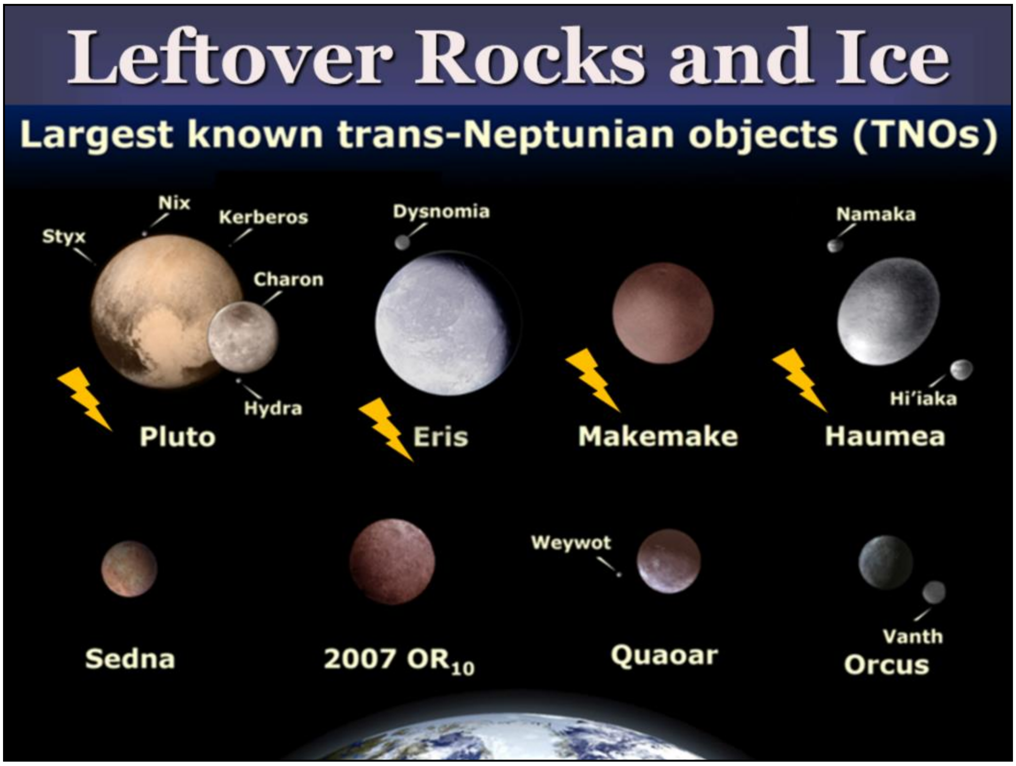


The light elements were blown out of the system over time. *You have to form planets before this happens!*

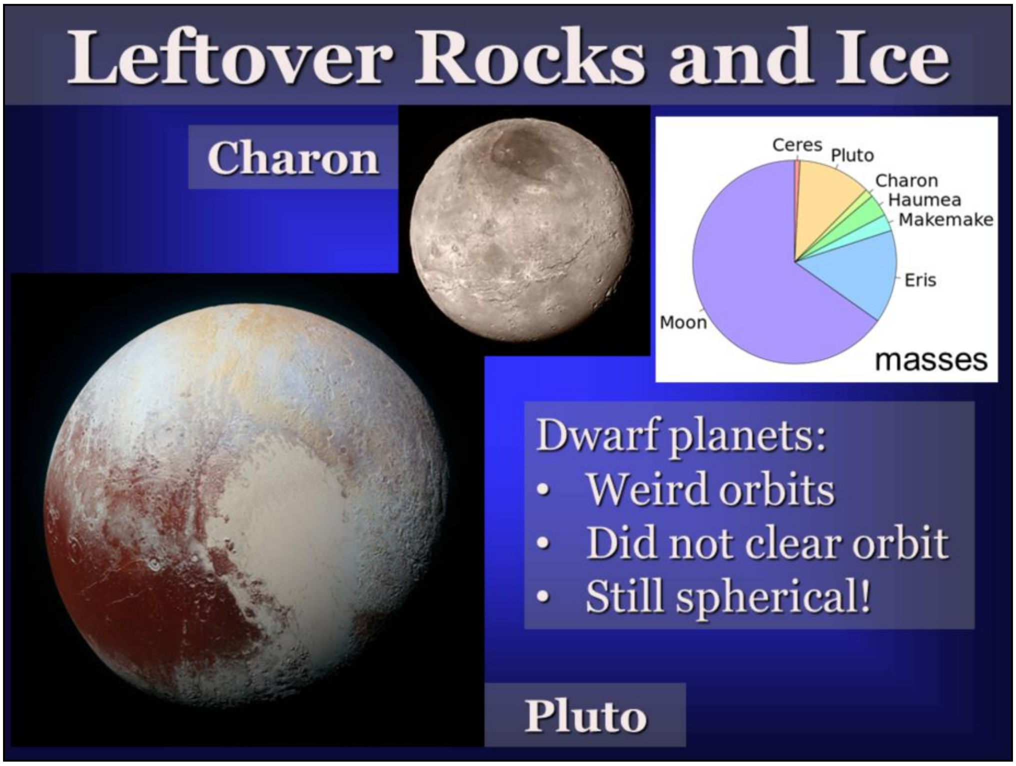
Since things with mass will orbit the sun, and Hydrogen and Helium have mass… Shouldn't they still be in orbit?



This is where most of our dwarf planets live (Pluto, Eris, Sedna, others which haven't been confirmed yet).



This is where most of our dwarf planets live (Pluto, Eris, Makemake, Haumea. The others haven't been confirmed as dwarf planets yet). Remember Ceres is also a dwarf planet!! So we have five.



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http://www.slate.com/blogs/bad_astronomy/2015/10/02/charon_new_closeup_color_photos.html

Planetary Formation

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2. Differentiation of material ✓
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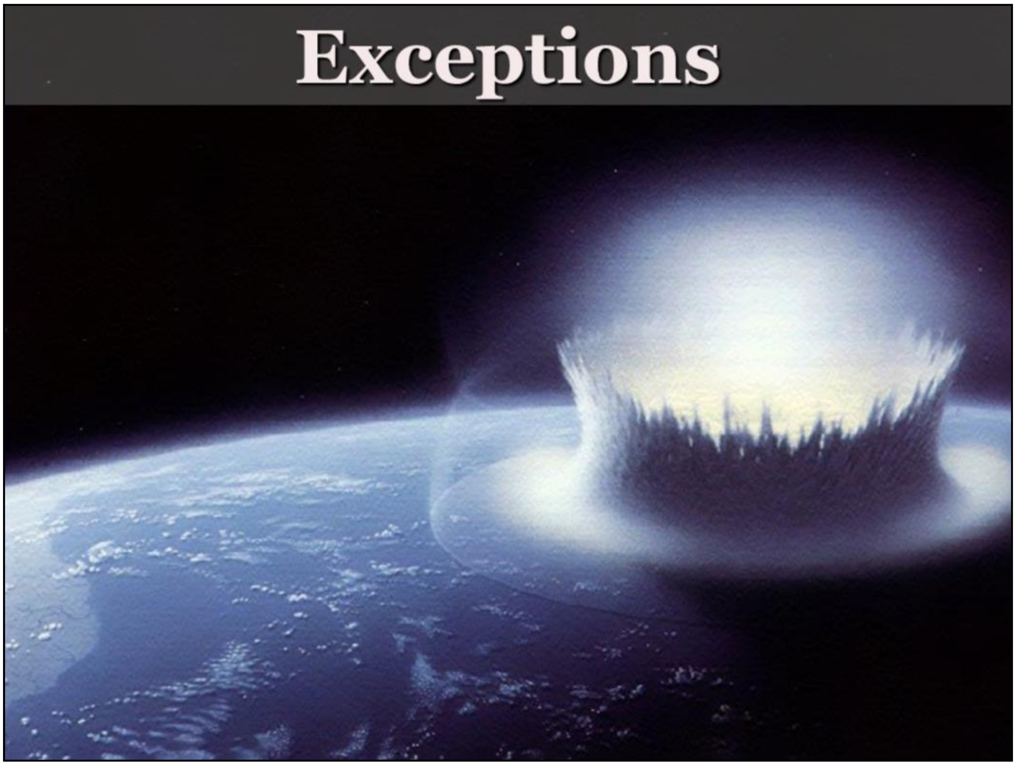
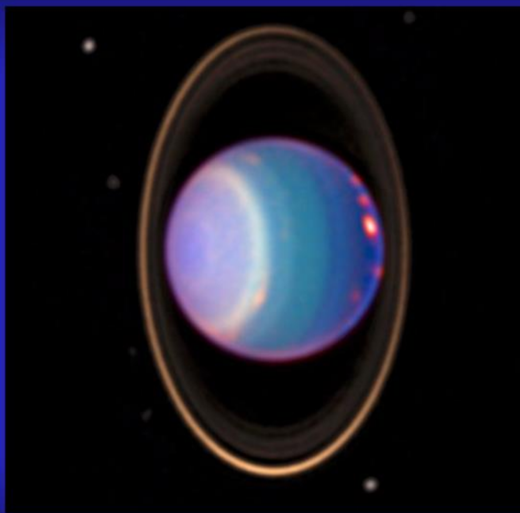


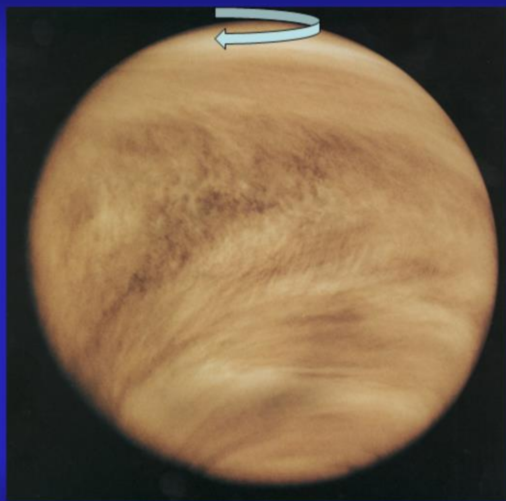
KABOOM!

Uranus' Tilt



A big collision is the leading hypothesis

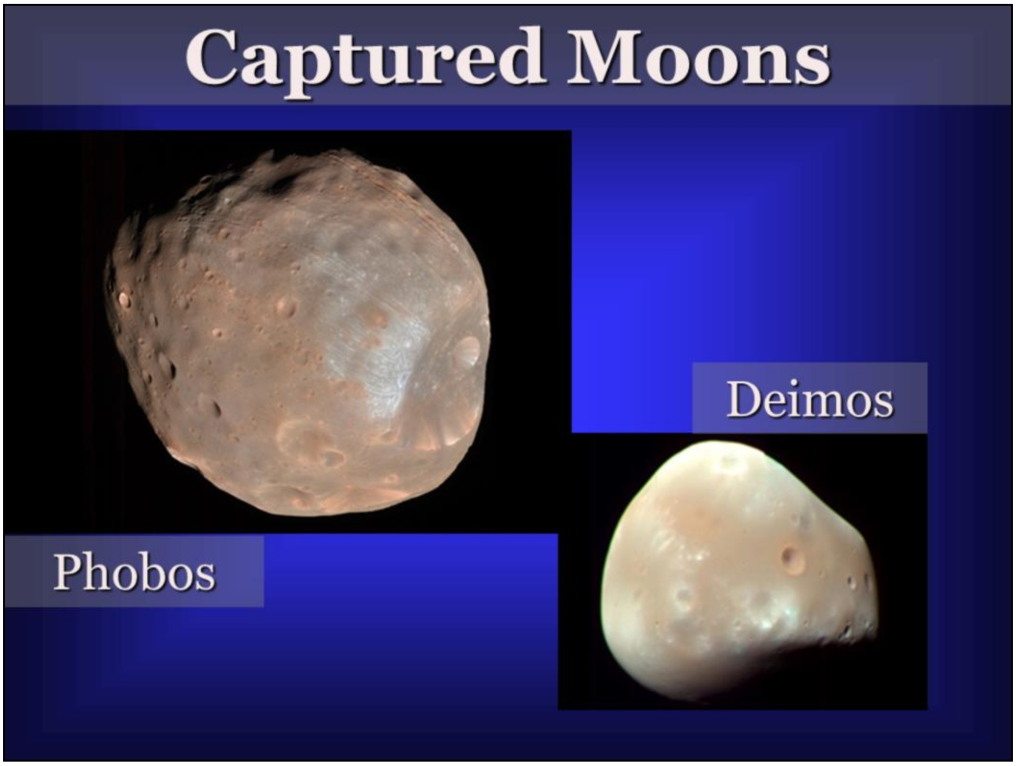
Venus' Spin



A big collision is the leading hypothesis

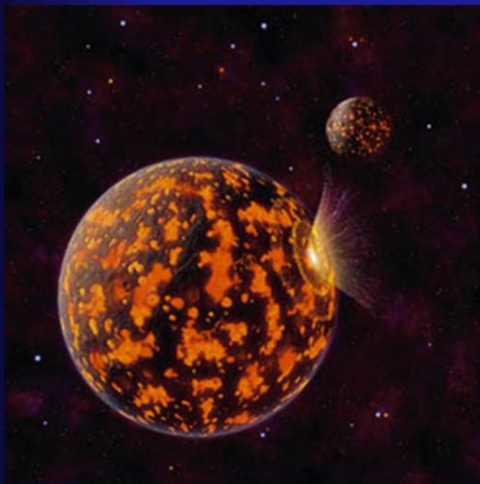
Origin of the Moon

A big collision is the leading hypothesis



Mostly angular momentum arguments… Everything lines up along the original angular momentum axis

Heavy Bombardment

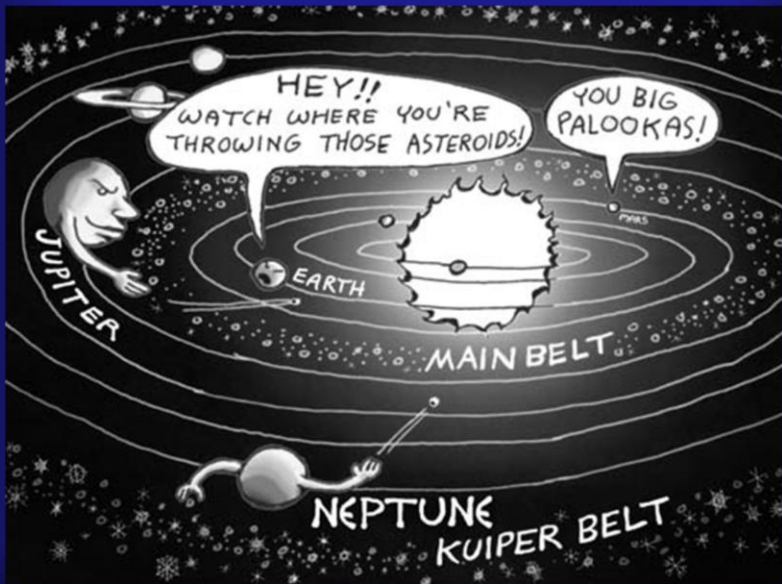


There were lots of big rocks flying around the early solar system!

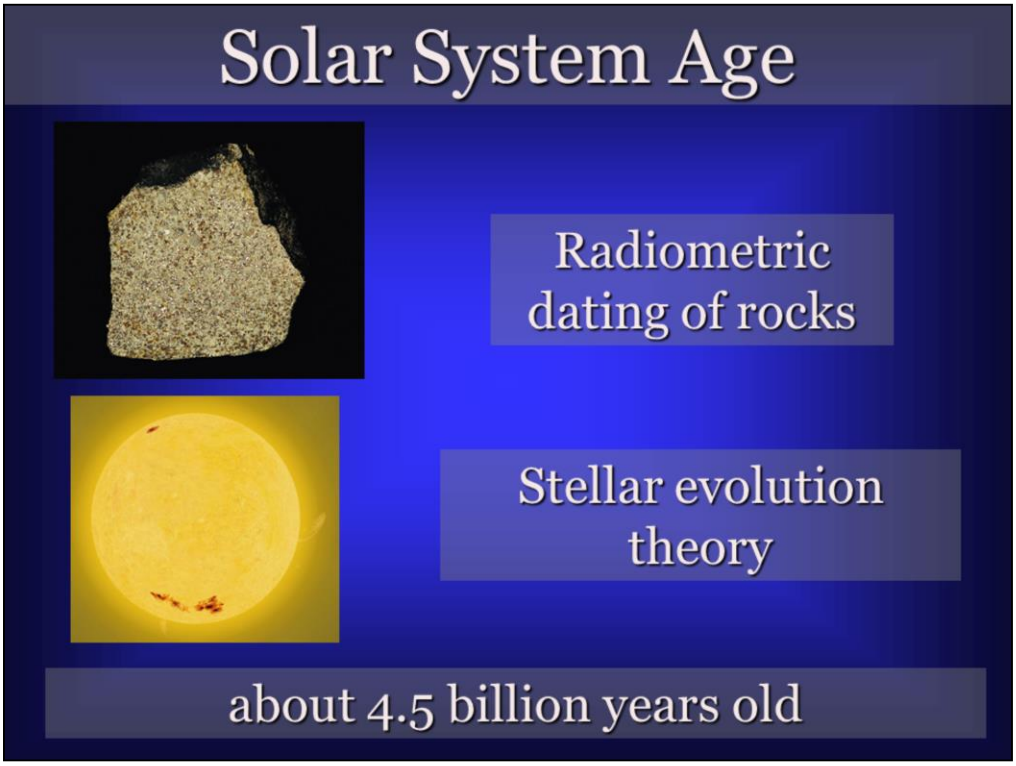
Some of them hit things! BOOM!

until about 3.8 billion years ago

Why?



Jupiter is the one throwing its mass around the most, but the other Jovian planets got into the act as well. Even now, (mostly) Jupiter perturbs things out even in the Kuiper belt or further out in the Oort cloud, which is how we get new comets…



1) Things decay at a fixed rate. Some of the decay products are gases.

By looking at the ratio of the radioactive element to the decay product, the formation date can be calculated.

2) We understand how stars work and can date the sun based on our knowledge

They agree to within 100 million years.

What can impacts explain?

1. Venus' spin
2. Captured moons
3. Axis tilts
4. Mercury's high density*
5. AND our moon!

*bonus!

Planetary Formation

A Formation Scenario must answer

1. Origins of the orderly motion. ✓
2. Differentiation of material ✓
3. Rubble ✓
4. Exceptions ✓