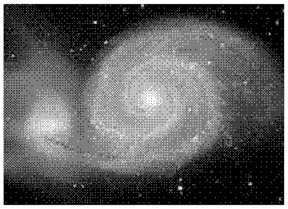
Why is the Universe So Lumpy?

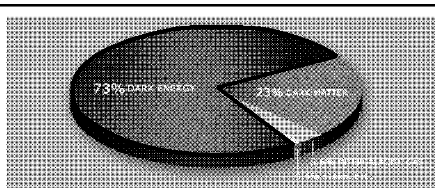


Monday, November 23

The average density of the universe is 10^{-26} kg/m^3.

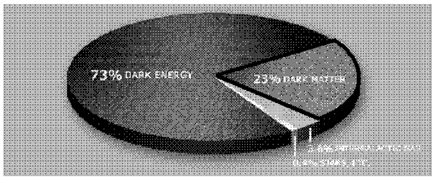
However, most of the universe is slightly **less dense** than average (voids).

Some of the universe is **much denser** than average (stars, white dwarfs, black holes…)



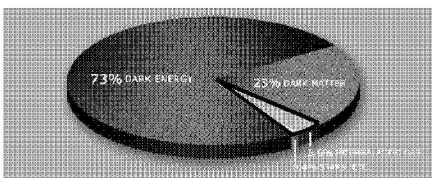
Dark energy: apparently uniform density, with no lumps.

Evidence: speeding up of expansion seems to be the same everywhere.



Dark matter: large lumps, about 1 million parsecs across.

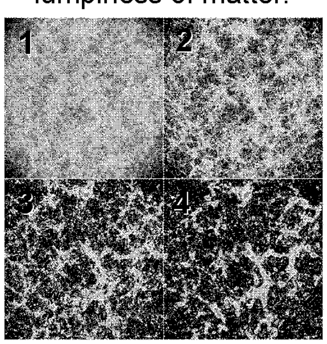
Evidence: “dark halos” around galaxies and clusters of galaxies.



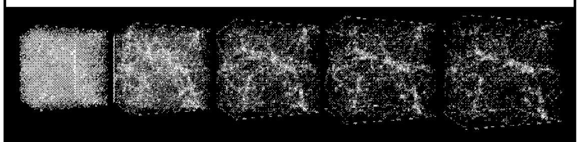
Ordinary matter (protons, neutrons, electrons): small, but very dense, lumps.

Evidence: Some of these lumps (that is, **stars**) glow in the dark!

Gravity tends to increase the lumpiness of matter.



Dense regions at the time the universe became transparent have evolved to become clusters & superclusters today.



However, **gravity alone** can’t account for the **extreme** lumpiness of ordinary matter.

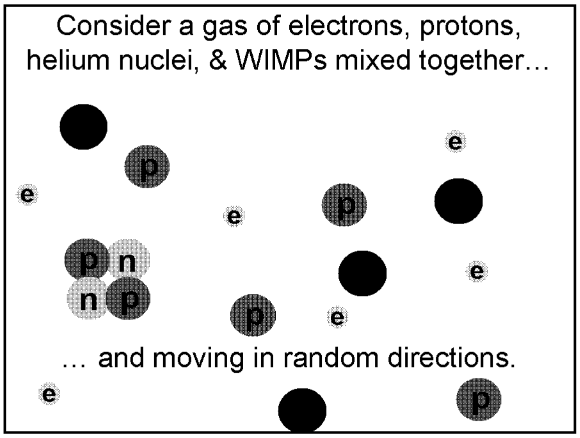
Luminous part of a galaxy (electrons, protons, & neutrons) is smaller than the **dark** part (**W**eakly **I**nteracting **M**assive **P**articles).

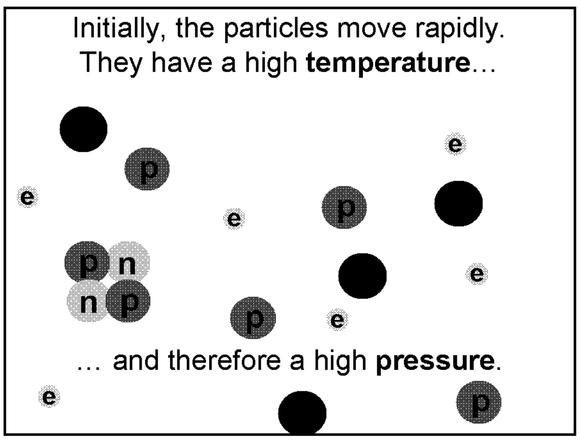
What’s special about **electrons, protons, & neutrons** that concentrates them at the center of dark halos?

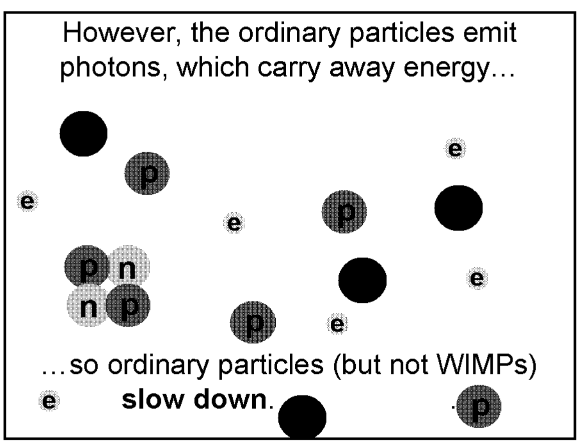
At first, dark matter (WIMPs) and ordinary matter (electrons, protons, neutrons) were mixed together.

What can ordinary matter do that dark matter cannot?

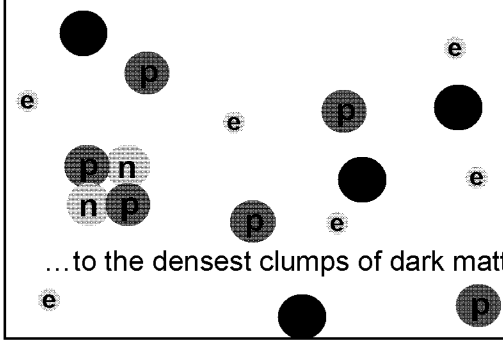
Emit light!


Consider a gas of electrons, protons, helium nuclei, & WIMPs mixed together…
… and moving in random directions.

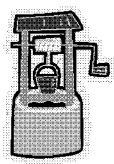

Initially, the particles move rapidly. They have a high **temperature**…
… and therefore a high **pressure**.


However, the ordinary particles emit photons, which carry away energy…
…so ordinary particles (but not WIMPs) **slow down**.

The cold ordinary particles now go where gravity pulls them…



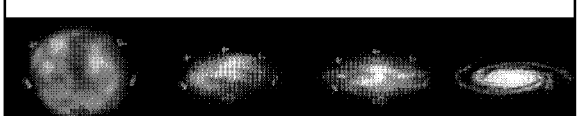
…to the densest clumps of dark matter



Astronomy jargon:
"falling down the gravity well."

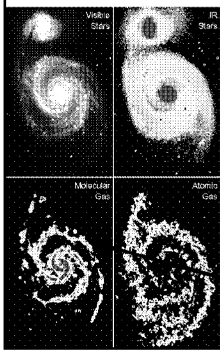
Since ordinary stuff,
made of electrons, protons, & neutrons,
can easily dump its excess energy,
it falls toward dense regions.

Galaxies form because ordinary matter cools down (by emitting photons) and falls to the center of dark halos.



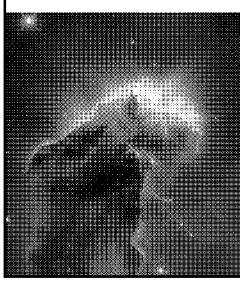
Why do galaxies curdle into tiny stars, instead of remaining as gas clouds?

Look at where stars are forming **now**.



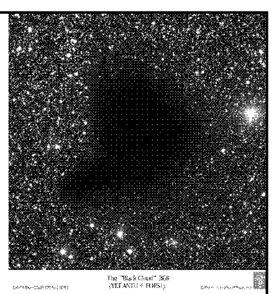
In the Whirlpool Galaxy, we see newly formed stars in dense, cold molecular clouds.

In regions where the gas is cooler and denser than elsewhere, hydrogen forms molecules (H_2).



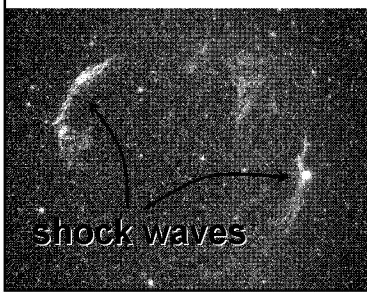
These cool, dense regions are thus called "**molecular clouds**".

Consider a small, dense molecular cloud.



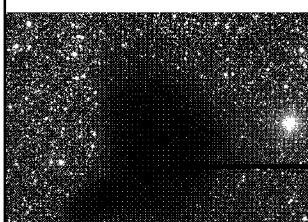
Mass = 1 M_{sun}
Radius = 0.1 pc = 4,000,000 R_{sun}
Temperature = 10 Kelvin = $T_{sun}/580$

Molecular clouds are usually stable; but if you hit them with a shock wave, they start to collapse gravitationally.

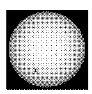


Once the collapse is triggered, it "snowballs".

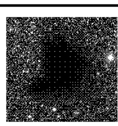
Once gravity has reduced the radius of the cloud by a factor of 4,000,000, it's the size of a star.



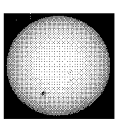
$\times \frac{1}{4{,}000{,}000}$



Why doesn't the molecular cloud collapse all the way to a black hole?



Escape velocity from molecular cloud ≈ 0.3 km/sec



Escape velocity from star ≈ 600 km/sec

Escape velocity from black hole = 300,000 km/sec

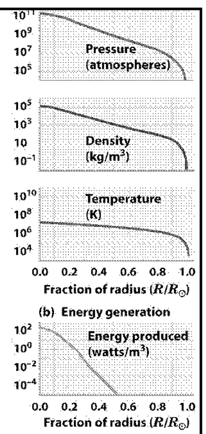
As the gas of the molecular cloud is compressed, it becomes denser.

As the gas is compressed, it also becomes hotter.

When the gas temperature is high enough (T ≈ 10 million Kelvin), nuclear fusion begins!

Nuclear fusion keeps the central **temperature** and **pressure** of the star at a constant level.

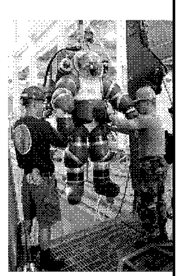
The star is static (not contracting or expanding) because it's in **hydrostatic equilibrium**.



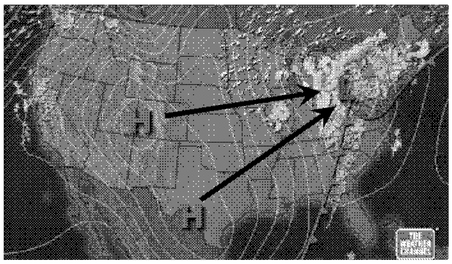
Hydrostatic equilibrium = a balance between gravity and pressure.

Pressure increases as you dive deeper into the ocean:

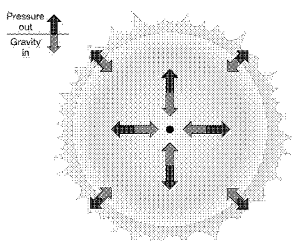
pressure increases as you dive deeper into the Sun.



Gas flows from regions of high pressure to regions of low pressure.

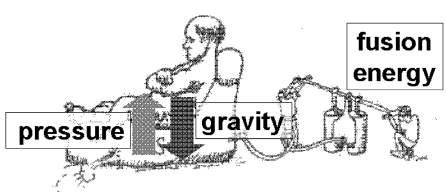


For gas in the Sun, pressure creates a net outward force, gravity creates a inward force.

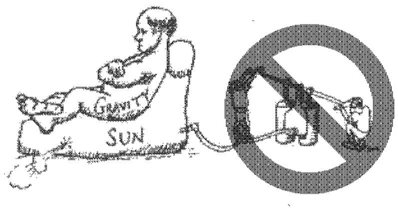


The Sun is in **hydrostatic equilibrium**.

The Sun is like a fat guy on an inflatable chair.

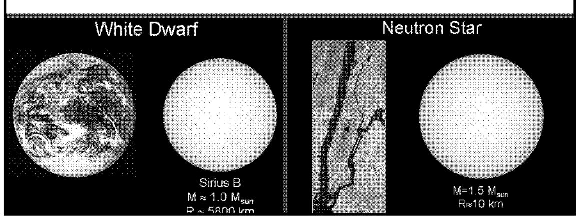


What happens when nuclear fusion ends inside a star?



Pressure drops: gravity compresses star to a denser object.

Small stars → white dwarf
(very dense)
Larger stars → neutron star
(very, very dense)
Largest stars → black hole
(ultimate in density)



Wednesday's Lecture:

The Inflationary Universe

Problem Set #7 due: make sure it's handed in by 5 p.m. Wednesday.

Reading:

Chapter 12