Astronomy 230

TR 1300-1420

134 Astronomy Building

Leslie Looney

Phone: 244-3615

Email: lwl @ uiuc . edu

Office: Astro Building #218

Office Hours:

T: 10:30-11:30 a.m.

W: 3:00-4:30 p.m.

or by appointment

This class (Lecture 4):

Cosmology and the Origin of Elements

Next Class:

From Atoms to Molecules to Clouds

Presentation Synopsis due Thursday.

Music: *We Are All Made of Stars* – Moby

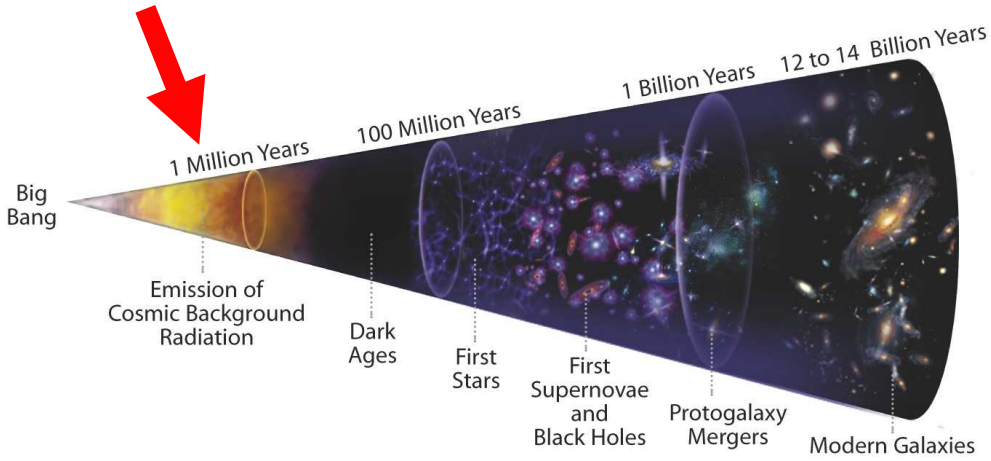
Outline

- The probable fate of the Universe
- The Universe is mostly Dark Energy
- As the Universe cools….
- The seeds of galaxies
- Hydrostatic equilibrium

The Universe

- Began with a Big Bang
  - 13.7 billion years ago
- Still expanding and cooling
  - The rate of expansion is known
- It is BIG
  - As far as we are concerned, it is infinite in any direction
- The universe is homogeneous and isotropic
  - **Homogeneous** - The same "stuff" everywhere
  - **Isotropic** - The same in all directions
- Our place in the Universe is not special
  - Extension of the Copernican revolution
- The center of the Universe is everywhere or nowhere!

Origin of the CMB

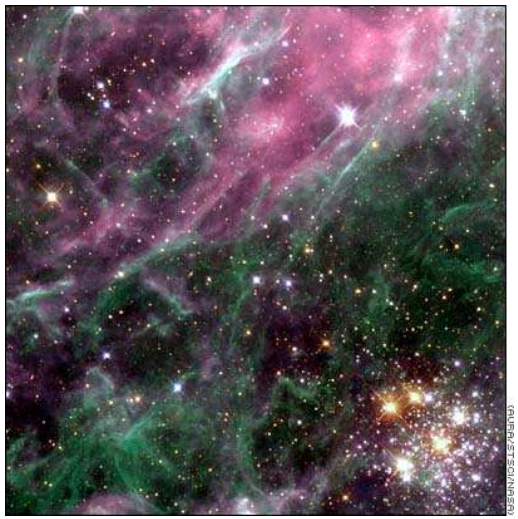


- After recombination came a period known as the Dark Ages
  - 500,000 to 100 million years
  - No star light comes to us from this period
- Matter consists of warm clouds of hydrogen and helium
  - Too hot for star formation to occur
  - Gravity slowing drawing clouds together into bigger and bigger clumps

http://www.darkages.com/

The First Stars

- We think the first stars began to form after about 200 million years
- Proto-galactic clouds are slowly collapsing – no galaxies yet

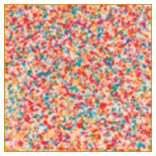


"Thinking Cap"

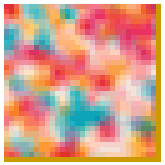
What if our solar system formed with the first generation of stars? How would our solar system be different? Would the Earth exist as a habitable planet?

The Beginnings of Galaxies

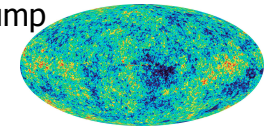
Quantum fluctuations during GUT era (before 10^{-35} s)



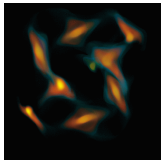
Inflation stretches fluctuations to galaxy size (before 10^{-32} s)

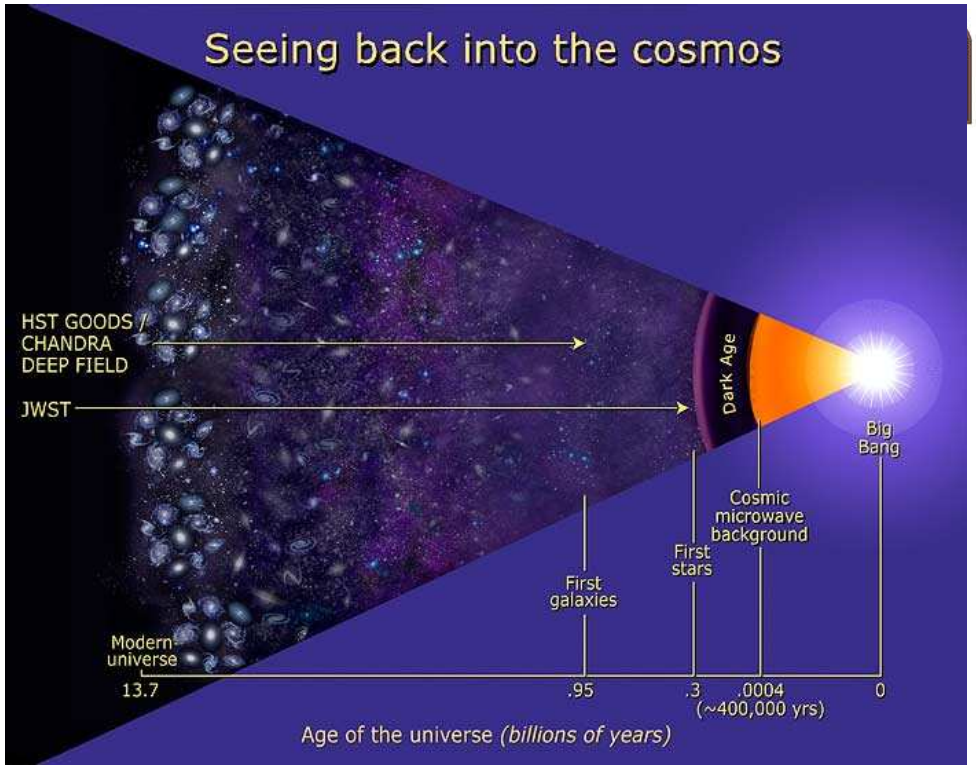


Before recombination, particles moving too fast to clump



After recombination, gravity of denser regions draws particles together





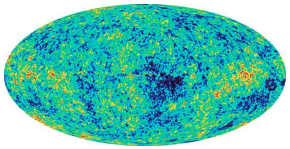
From the Home Office in Urbana, IL

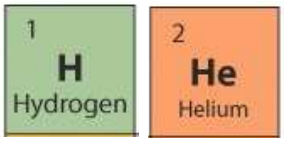
Top 3 Reasons We Believe in the Big Bang

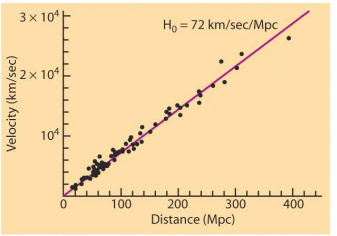
1. Cosmic Microwave Background
   - Big Bang working at about 500,000 yrs
   - Tiny fluctuations: "seeds" of galaxies
2. Big Bang Nucleosynthesis
   - H and (almost all) He comes from the Big Bang
   - Big Bang working at 1 sec
3. The Hubble Law: $v=H_0 d$

   + Einstein's General Relativity

   = Expanding Universe with an age of 13.7 billion yrs







What is the fate of the Universe?

Fire and Ice

Some say the world will end in fire,
Some say in ice.
From what I've tasted of desire
I hold with those who favor fire.
But if it had to perish twice,
I think I know enough of hate
To say that for destruction ice
Is also great
And would suffice.

-- Robert Frost

What is the Universe's Fate?

Today: Universe is expanding. What do you expect to happen next?

Competition: gravity vs inertia

Compare: Pop fly and rocket!
- Quantitative question
- Launch speed vs speed to escape Earth

or

?

What is the Universe's Fate?

For Universe it is still gravity vs speed.
- Gravity acts on mass of galaxies (pulling back)
- The speed is the speed of expansion

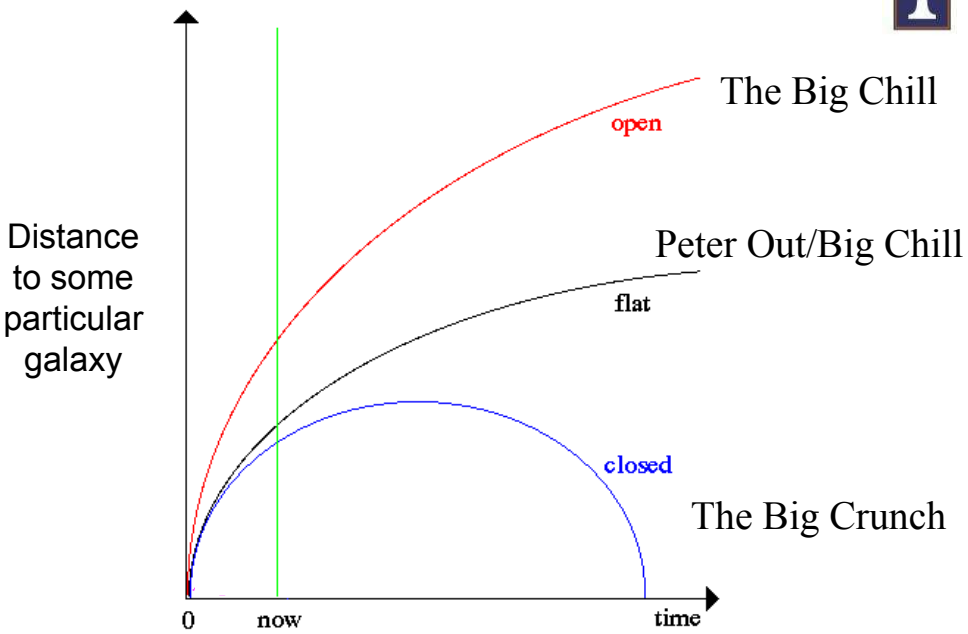
Both are observable!

or

Our fate is a **quantitative** question :

- **If our mass is small enough we expand forever.**
- **If our mass is large enough expansion halts, and we collapse.**

What kind of Universe do we live in?



Think-Pair-Share

- What kind of a Universe would you want to live in? Open? Closed? Flat?

Big Chill/Big Crunch

- **Less mass:**
  An open or flat Universe will end in a **Big Chill**:
  - Galaxies exhaust their gas supply
  - No more new stars
  - Old stars eventually die, leaving only dust and stellar corpses
- **More mass:**
  A closed Universe will end in a **Big Crunch**:
  - Expansion will stop, and the Universe will re-collapse
  - Ends as it began, incredibly hot and dense

How Much Do We Weigh?

% of mass for closed Universe

22% Dark matter
Needed to explain:
galaxy rotation curves
clusters of galaxies

4.5% Ordinary matter
Made of protons, neutrons, and electrons

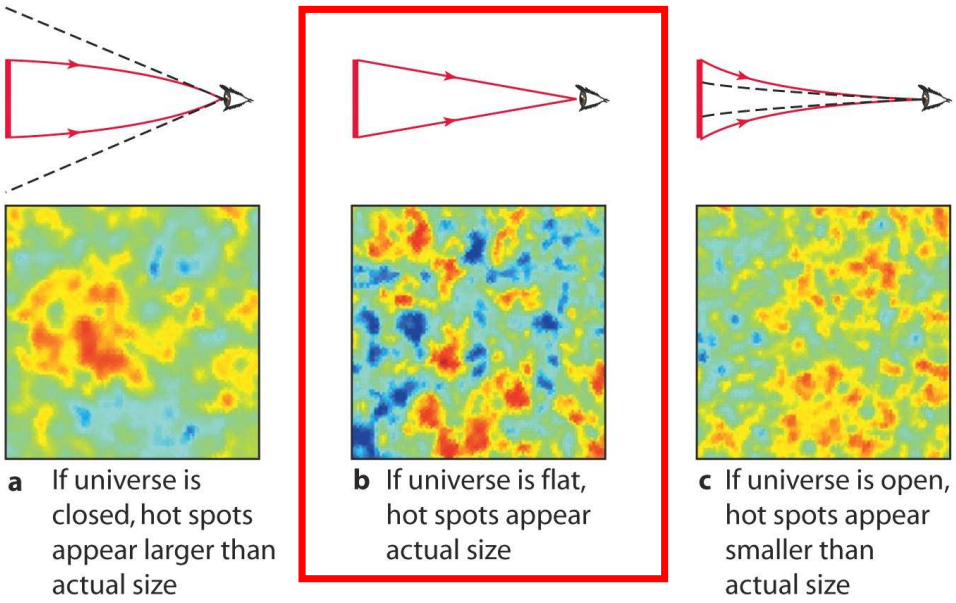
<1.5% Neutrinos

28% Total Not enough to close the Universe

So we live in an open Universe?

CMB Measurements

Universe is Flat!!!!



a If universe is closed, hot spots appear larger than actual size

b If universe is flat, hot spots appear actual size

c If universe is open, hot spots appear smaller than actual size

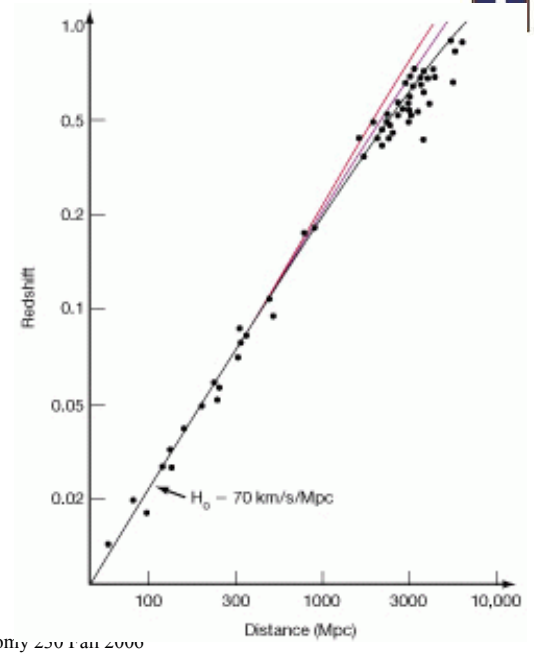
Peter Out/ Big Chill

- The Universe will just barely expand forever, getting cooler and cooler.
- If all of the mass, dark+regular, isn't enough, **then what's up**?
- The fate of the Universe is really dependent on the amount of matter and energy in the Universe → $E = mc^2$

The Accelerating Universe!!!

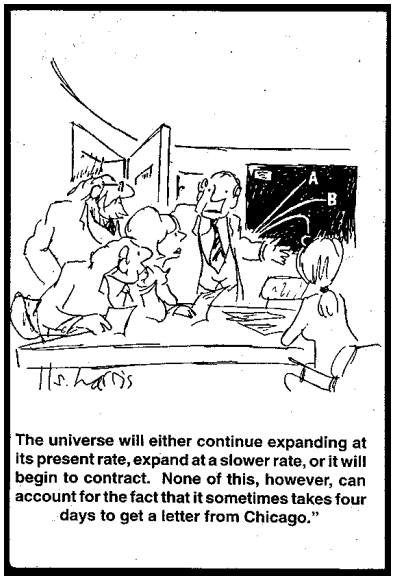
The universe is not slowing down at all. In fact, it's speeding up!!! We live in an accelerating universe!

It's as if there's another force pushing the universe apart – a Cosmological Constant!!!

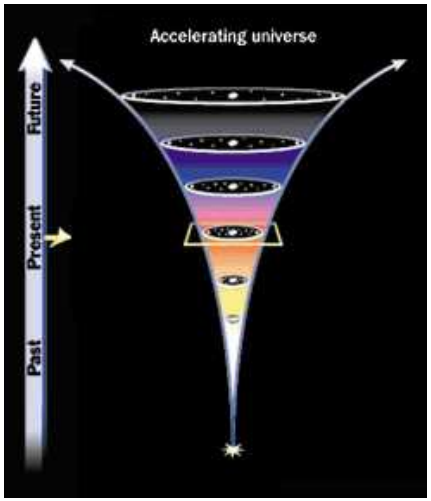


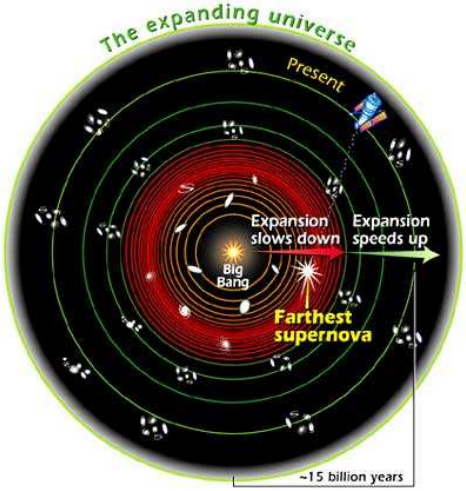
Dark Energy

- The matter census isn't enough to be flat and the expansion is accelerating!
- So, a new type of energy called ***dark energy*** exists
  - Not related to dark matter
  - Acts as repulsive gravity
- Dark energy is actually *accelerating* the expansion of the Universe!



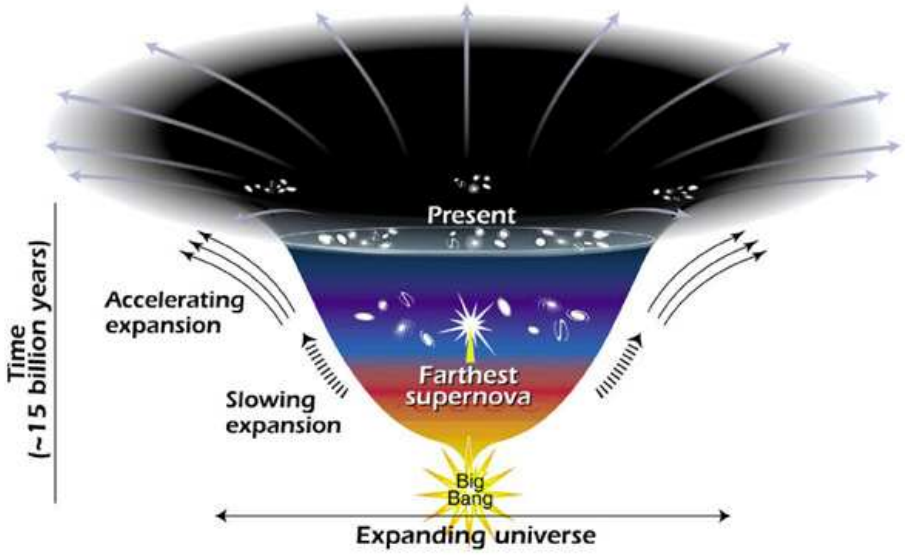
The Accelerating Universe!!!





Whatever this force is, we *think* that it is growing stronger as the universe evolves. The more empty space in the universe, the greater the acceleration – as if the vacuum of space has energy.

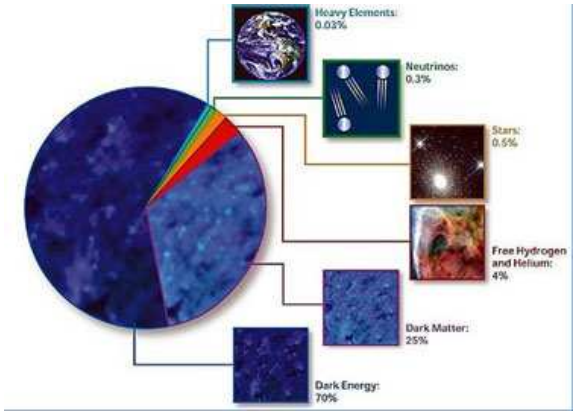
Effects of Dark Energy



http://www.lbl.gov/Publications/Currents/Archive/Apr-06-2001.html

The Accelerating Universe!!!

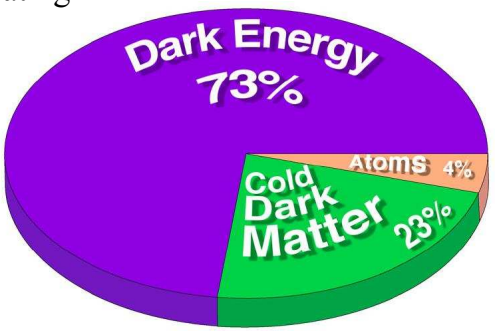
We appear to live in a universe with a flat shape, but which will go on accelerating forever. The universe is 13.7 billion years old, and is now dominated by dark energy. And it will only get worse – the more empty space, the more dark energy.



The Dark Energy even dwarfs dark matter! Regular matter is really insignificant. We *really* don't know anything about what's going on!!

The Distant Future

- Now – the Universe is (nearly) flat
- But the expansion is accelerating
  - An open Universe?
- The future depends on the nature of dark energy



The Early Universe?

- So, in the early Universe, the first elements formed were mostly Hydrogen (75%) and Helium (25%) by mass. What does that mean for life in the early Universe?
- Globular clusters contain the oldest stars in the Milky Way– about 10 to 13 billion years old. Should we look for life around these stars?

http://www.shef.ac.uk/physics/research/pa/DM-introduction-0397.html

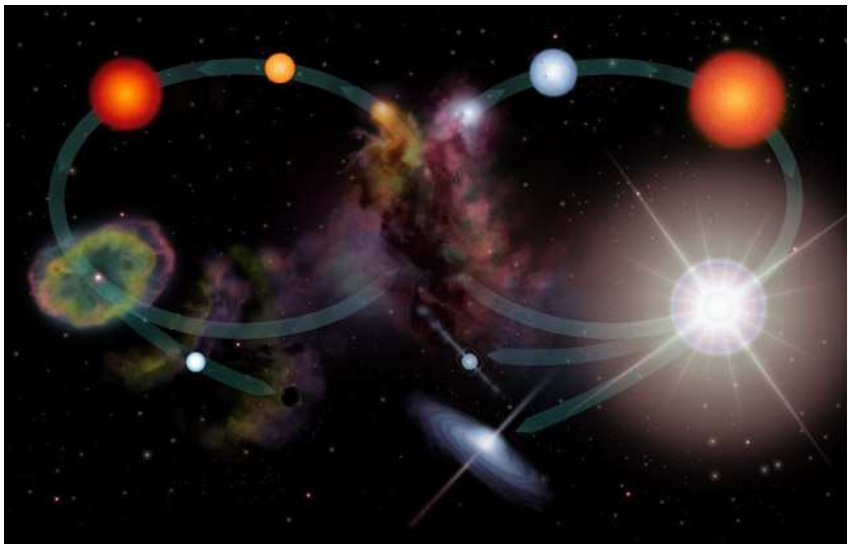
What is the Earth made of?

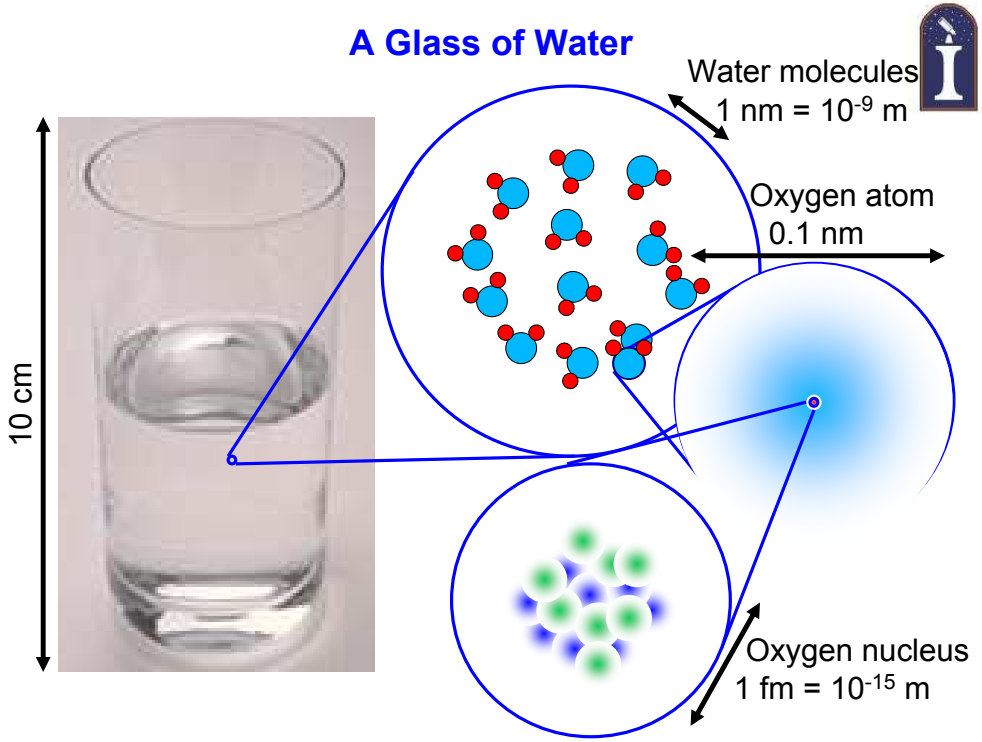
- Very little hydrogen and helium. They make up less than 0.1% of the mass of the Earth.
- Life on Earth does not require any helium and only small amounts of non-H_2O hydrogen.
- All of these elements must be formed in stars. That means 2nd or 3rd or nth generation of stars are required before life can really get going. These elements were not originally formed in the Big Bang.
- **"We are star stuff!"**
- How did that come about?

What are Galaxies?

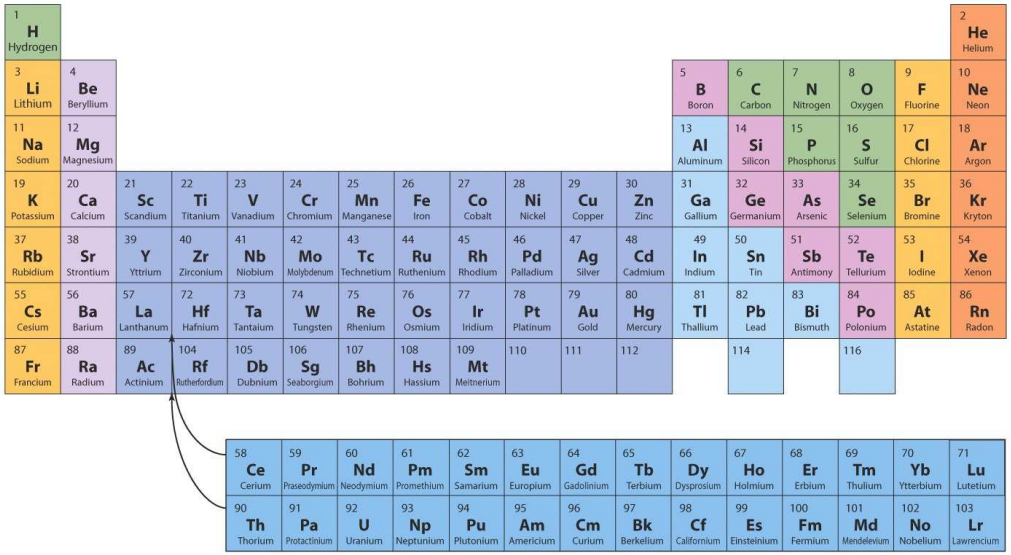
- They are really giant re-cycling plants separated by **large** distances.
- Stars are born in galaxies out of dust and gas.
- Stars turn hydrogen into helium, then into heavier elements through fusion for millions or billions of years.
- Stars die and eject material back into the galaxy.
- New stars are formed.
- And so on.
- Crucial to the development of life!

Stellar Evolution Re-Cycle





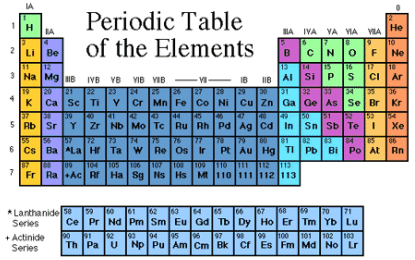
The Periodic Table of the Elements



The number of protons in an atom determines the type of element, and the number of protons and neutrons determine the atomic weight.

Chemical Basis for Life

- The average human has:
  - 6×10^{27} atoms (some stable some radioactive)
  - During our life, 10^{12} atoms of Carbon 14 (^{14}C) in our bodies decay.
  - Of the 90 stable elements, about 27 are essential for life. (The elements from the Big Bang are not enough!)



http://www.genesismission.org/science/mod2_aei/

Chemical Basis for Life

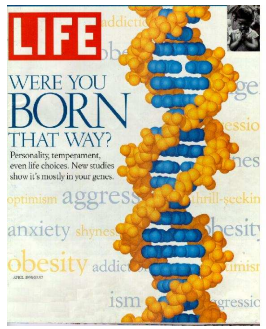
By Number…

- Life on Earth is mostly:
  - 60% hydrogen
  - 25% oxygen
  - 10% carbon
  - 2% nitrogen
  - With some trace amounts of calcium, phosphorous, and sulfur.
- The Earth's crust is mostly:
  - 47% oxygen
  - 28% silicon

- The Universe and Solar System are mostly:
  - 93% hydrogen
  - 6% helium
  - 0.06% oxygen
  - 0.03% carbon
  - 0.01% nitrogen

Little Pink Galaxies for you and me

- Life as we know it, needs more elements than the Big Bang could provide.
- Composition of life is unique.
- Does the environment of the Galaxy nourish life?
- At the vary least we need galaxies to process the material from the Big Bang into materials that life can use.
- How did galaxies form?

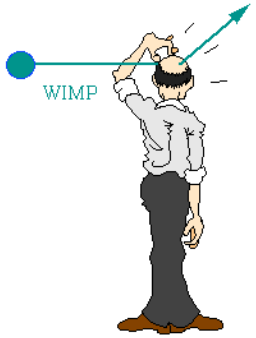


http://www.chromosome.com/lifeDNA.html

The Early Galaxies

- The Universe is dominated by Dark Matter, probably some heavy exotic particle created during the Big Bang. (Weakly Interacting Massive Particle– WIMPs?).
- One way that we know this comes from the rotation curves of Galaxies. We can't see dark matter, but we can see the influence of it.
- The normal matter flocks to the dark matter due to gravity. These initial seeds of galaxies and galaxy clusters are the original mix of elements– 75% hydrogen and 25% helium (by mass).

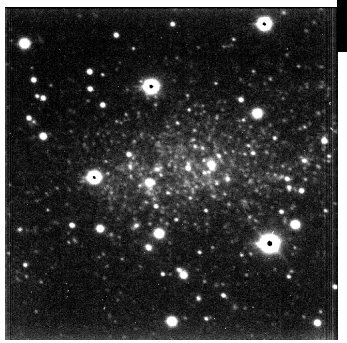
How to search for WIMPs?



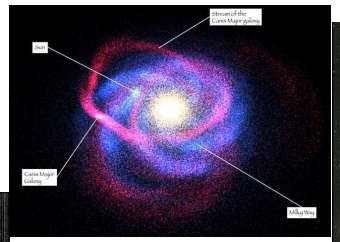
http://www.shef.ac.uk/physics/research/pa/DM-introduction-0397.html

Remember that the Milky Way is Not Alone?

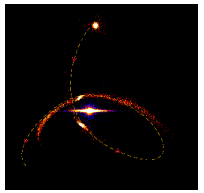
We have a few orbiting galaxies that are gravitationally bound to the Milky Way.



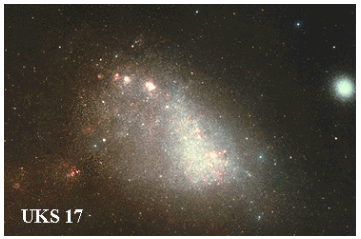
Sagittarius Dwarf Elliptical (80,000 ly away)



Canis Major (42,000 ly away)

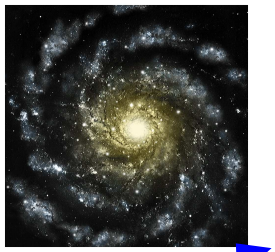


Large Magellanic Cloud (180,000 ly away)



Small Magellanic Cloud (250,000 ly away)

And Many Galaxies in the Local Group



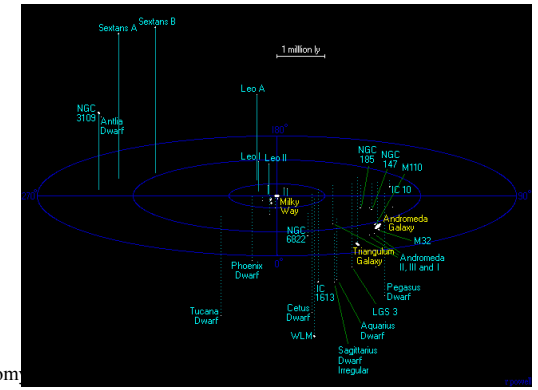
Milky Way

2 MLyrs

Andromeda (M31)

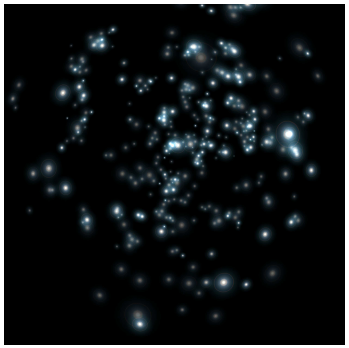
Triangulum (M33)

Local Group Dwarf galaxies



The First Stars

- From the initial seeds of the Big Bang, our local group of galaxies probably broke into clumps of hydrogen and helium.
- We'll look at star formation in detail latter, but let's think of the first star to form in our proto-Milky Way
- May have formed as early as 200 million years after the Big Bang.
- Probably more massive than stars today, so lived quickly and died quickly.
- What happened? Why did this "raw" gas form anything?



http://www.blackshoals.net/ImageBank/gallery/gallery/huge/The-first-stars-clustering.jpg

Water Power?

- Does a bottle of water have any stored energy? Can it do work?

Gas powered

- Similar to my bottle of water, these initial gas clumps want to reach the center of their clump-ness.
- The center gets hotter and hotter. The gravitational energy potential turns into heat (same as velocity actually).
- It is a run-away feature (or snowballing), the more mass at the center, the more mass that wants to be at the center.
- The center of these clumps gets hotter and denser.

http://www.rob-clarkson.com/duff-brewery/snowball/04.jpg

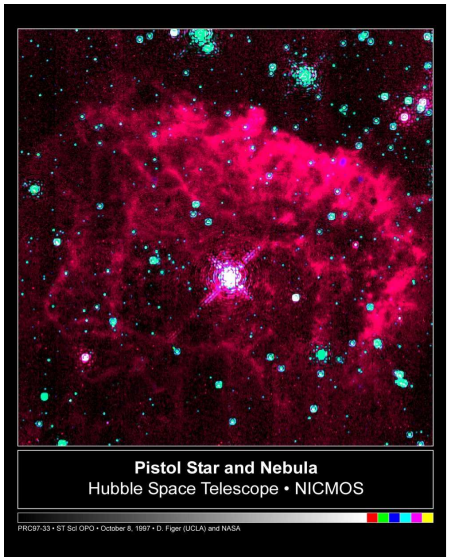
Cooking with Gas

- For the first time, since 1-month after the Big Bang, the centers of the clumps get above 10^7 K.
- That is hot enough for nuclear fusion to occur. If that had not happened, life would never have existed.
- But are things different than what we learned in Astro 100? These are the First Stars after all.

http://lgeku.energyunderground.com/images/images-deepearth/BURNERBL.jpg

The Most Massive Star in the Milky Way Today

- The Pistol star near the Galactic center started as massive as 200 solar masses.
- Releases as much energy in 6 seconds as the Sun in a year.
- But it blows off a significant fraction of its outer layers.
- How did the first stars stay so massive?
- Perhaps they are slightly different than this case?



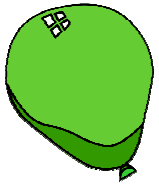
http://www.u.arizona.edu/~justin/images/hubblepics/full/PistolStarandNebula.jpg

Pressure

- What is pressure?
  - Pressure $= \frac{Force}{Area}$

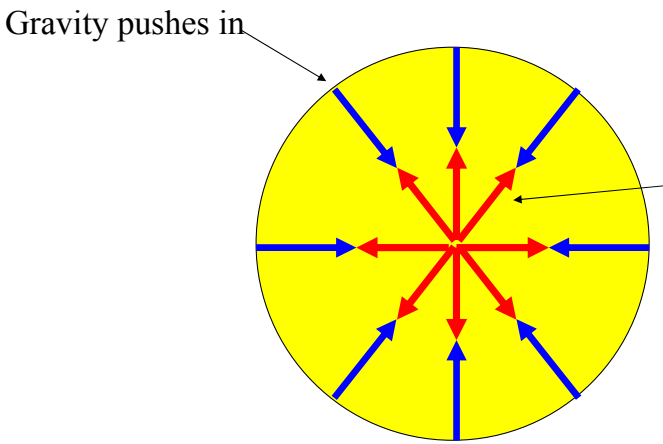
Pressure of Earth's atmosphere is 14.7 pounds per square inch

- Explain blowing up a balloon?



- http://www.phy.ntnu.edu.tw/java/idealGas/idealGas.html

The Battle between Gravity and Pressure



Hydrostatic equilibrium

The Sun's Energy Output

3.85 x 10^{26} Watts, but how much is that?

A 100W light bulb…

…the Sun could supply 4 x 10^{24} light bulbs!

U.S. electricity production in 2000: 3.8 trillion kWh…

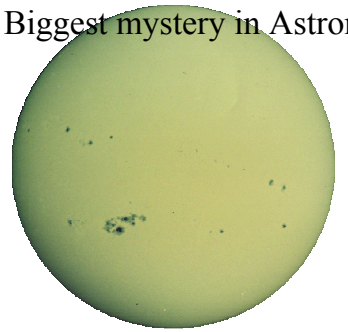
… Sun = 3 x 10^{7} times this *every second*

World's nuclear weapons: 3 x 10^{4} megatons…

… Sun = 4 million times this *every second*

So, What Powers the Sun?

- The Sun does collapse or even change it's radius.
- Gravity pushes in, but what pushes out?
- What is its power source?
- What keeps the Sun hot? It doesn't cool like a hot coffee cup.
- Biggest mystery in Astronomy up until 20th century.



How to Test?

- Without an energy source, the Sun would rapidly cool & contract
  - Darwin: evolution needs Sun & Earth to be > 10^8 years old
  - Lyell: geological changes also needs > 10^8 years
- Process must be able to power Sun for a long time! At least 4.5 Byrs.

- Gravity:
  - Seems like a good idea. Remember Jupiter gives off heat.
  - A contracting Sun releases gravitational energy.
  - But only enough for 20 million years
- Chemical:
  - If the Sun was made from TNT, something that burns very well, then it would last for 20,000 years

Radiograph of the hand of the anatomist Privy Councillor von Koelliker in Würzburg, taken by W.C. Röntgen in Würzburg on January 23, 1896

Eyes began to turn to the nuclear processes of the Atoms

What is Fusion?

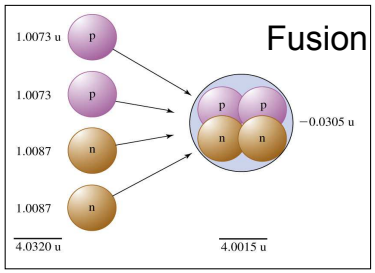
$$4\ p \rightarrow {}^{4}\mathrm{He}\quad (2\ p, 2\ n)$$

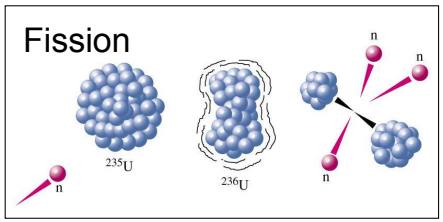
Basic idea is to take 4 protons (ionized hydrogen atoms) and slam them together to make an ionized helium atom.

Fusion vs. Fission

- Light nuclei: fusion
  - Happens in the Sun
  - H-Bomb

- Heavy nuclei: fission
  - Used in power plants
  - A-Bomb





Nuclear Fusion in the Sun's Interior

- Proton-Proton Chain
  - 4 Hydrogen atoms fuse to make 1 helium atom
  - Requires very high density and temperature (at least 7 million K)

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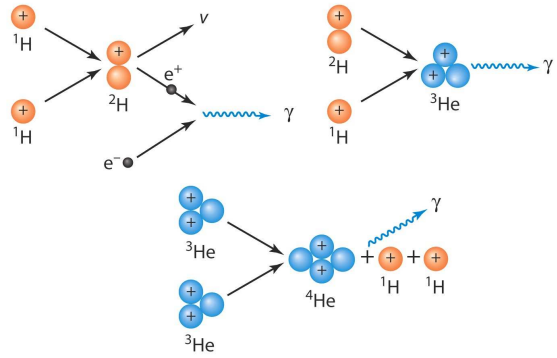
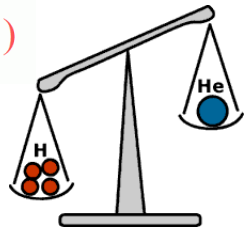


The Proton-Proton (p-p) Chain

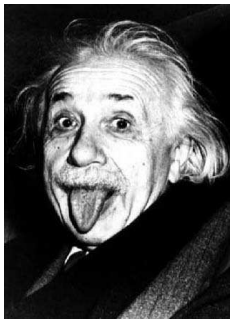
Why does fusion release energy?

Fusion: $4\ p \rightarrow {}^4\mathrm{He}\ \ (2\ p, 2\ n)$

Fact: **4m(*p*) > m(^{4}He)** !
mass of whole < mass of parts!



Einstein says ***E* = *mc*²**:
- Mass is a form of energy!
- Each ^{4}He liberates energy:



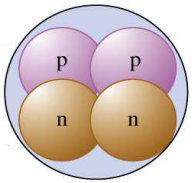
$$E_{\text{fusion}} = m_{\text{lost}}c^2 = 4m(p)c^2 - m(^4\text{He})c^2 > 0!$$

The Nucleus

- Okay, so we know that the nucleus can have numerous protons (+'s) very close.

Helium

- **Something is odd here!**
- **What is it?**

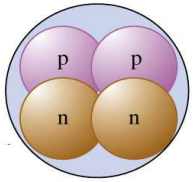


The Nucleus

- **Why doesn't the nucleus of the atom fly apart?**

Helium

- **Something is odd here!**
- **What is it?**



4 Fundamental Forces

- Gravity
- Electromagnetic
- **Strong Nuclear**
  - **The strongest of the 4 forces**
  - **The force which holds an atom's nucleus together, in spite of the repulsion between the protons.**
  - **Does not depend on charge**
  - **Not an inverse square law– very short range.**
- Weak Nuclear

Nuclear Reactions in the Sun

- Chain: 4 protons ⟹ helium
- First step in chain (2 protons combine):

$$p + p \rightarrow [np] + e^{+} + \nu$$

- Start with 2 particles (protons)
- End up with 4 particles (two of which are glued together)
- each of products is very interesting in its own right....

Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^{+} + \nu$$

$[np]$ = **deuterium**

- 1 proton + 1 neutron bound together into nucleus of element…
- Hydrogen, but has neutron, so 2 times mass of normal H
  - "Heavy Hydrogen"
- Simplest composite nucleus

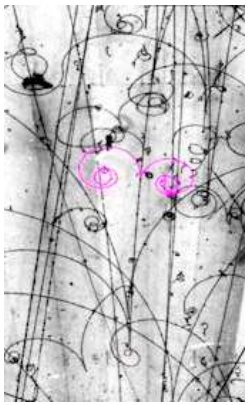
Discovery of D in lab: *Nobel Prize*
about 0.01% of all H on earth is D
✓ including in your body:
you contain about 10 kilos (20 lbs) of H, and about 2 grams of D
✓ Water (normally H_2O) with D is D_2O : "heavy water"

Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^+ + \nu$$

e^+ = **positron**

- Exactly the same as electron but charge **+1**
- **Antimatter**
- Combines with normal e^-
  - Both are gone, release of energy
  - ***Annihilation***



Discovery of positron in lab: *Nobel Prize*
Because of this reaction

➢ The Sun contains a small amount of antimatter!

Nuclear Reactions in the Sun

$$p + p \rightarrow [np] + e^+ + \nu$$

ν (Greek letter "nu") = **neutrino**

- Particle produced in nuclear reactions ***only***
- Tiny mass: $m(\nu) < 10^{-6} m(e)$!
- Moves at nearly the speed of light
- ***Very*** weakly interacting

Discovery of neutrino in lab: *Nobel Prize*

10 billion from Sun go through hand every sec

➢ Reach out!
➢ Go through your body, Earth, but almost never interact

Why Doesn't The Sun Shrink?

- Sun is currently stable
- Pressure from the radiation created by fusion balances the force of gravity.
- There has to be some pressure. The pressure is from fusion!