The Connection Between the Periodic Table and Astronomy

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For the Naperville Astronomical Association

7/7/20

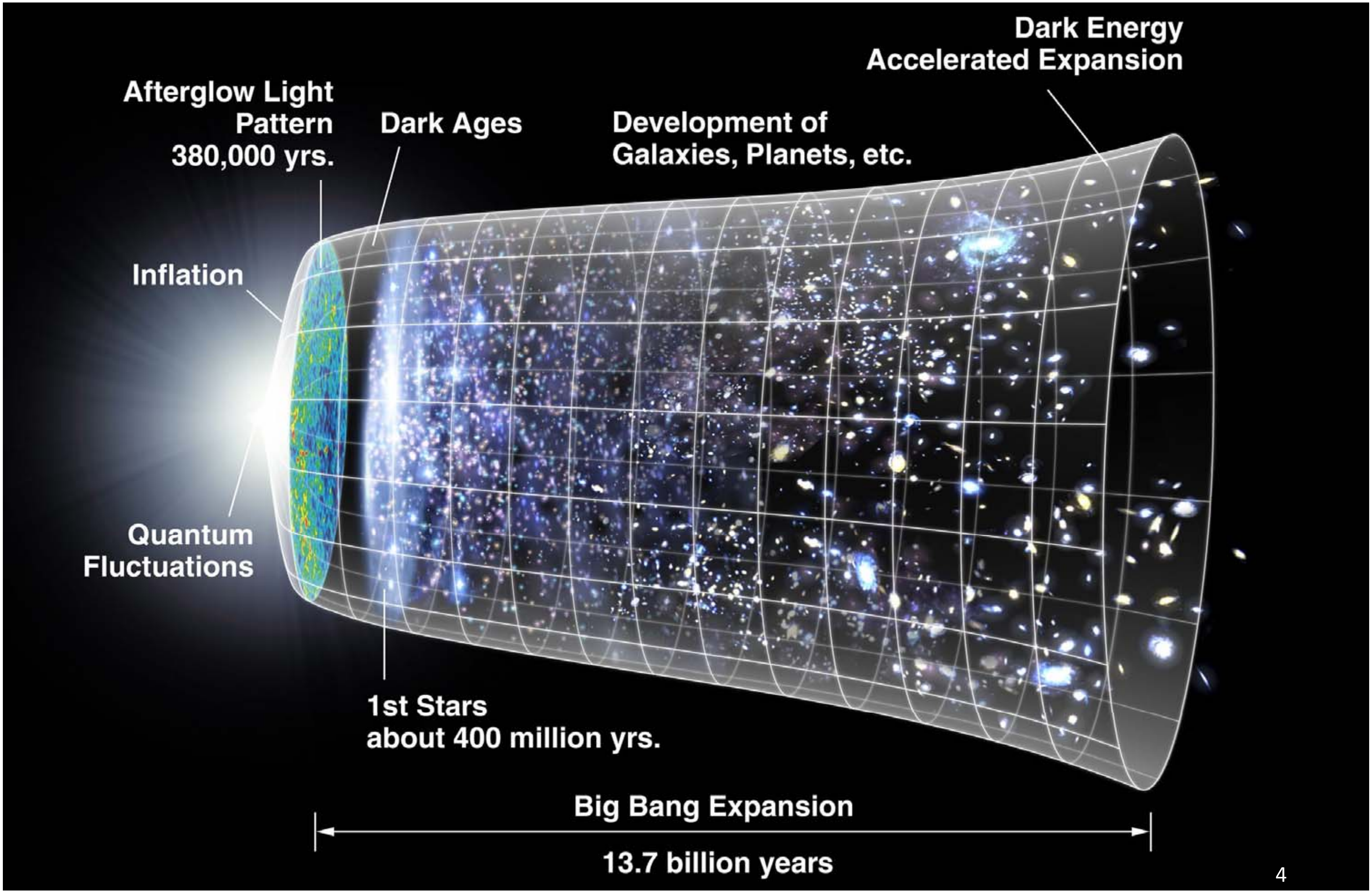
Things to be covered

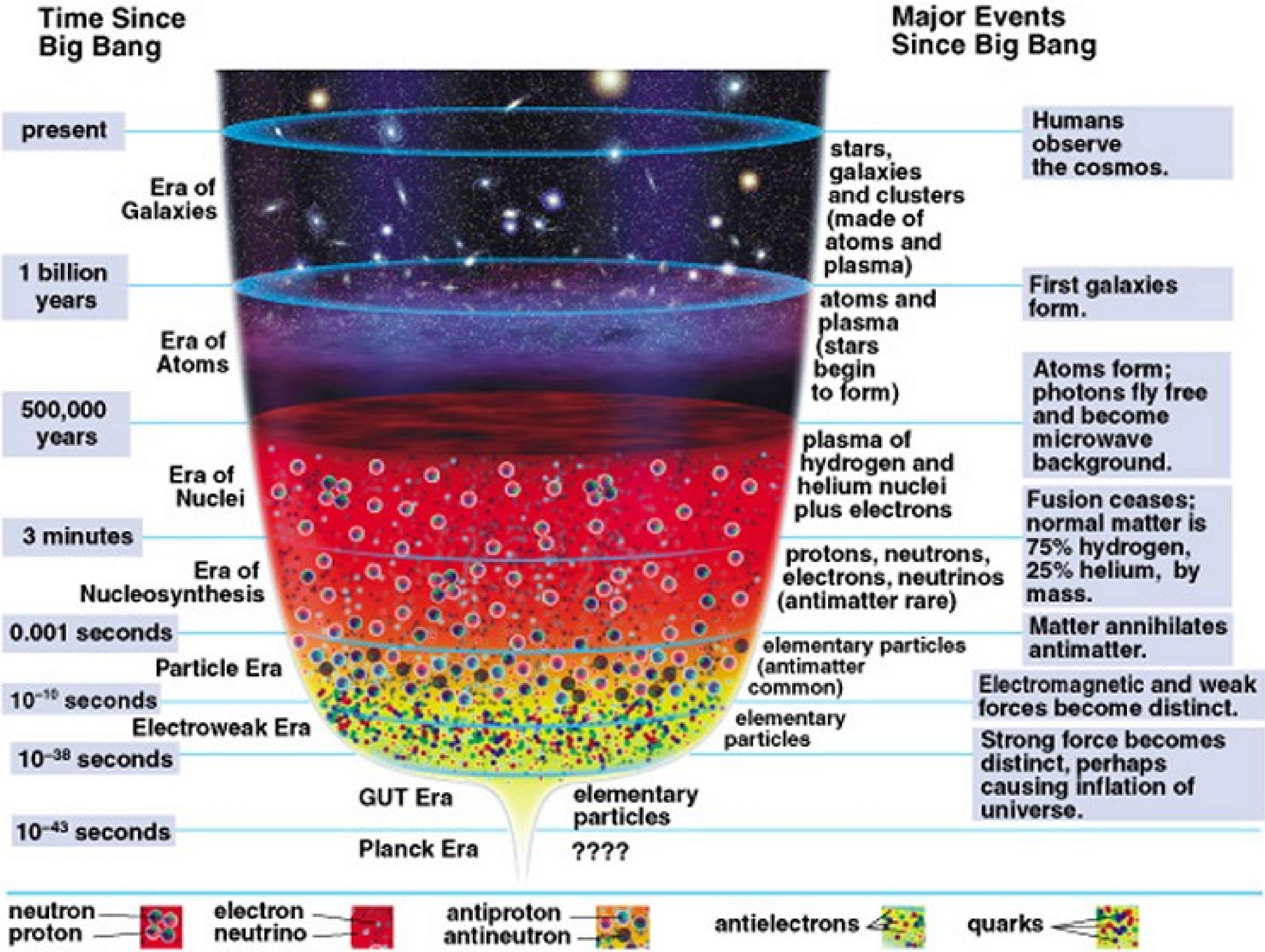
- What is the relationship between astronomy and the Periodic Table?
  - A brief history of the Universe
- How does looking at atoms on earth tell us anything about things we see in our telescopes?
  - Spectroscopy and redshift
- Where do the elements come from?
- How do the elements affect the life cycle of a star?

The Basics

- Everything we've ever learned about anything in the sky has come to us through the photons reaching the Earth from space
- We can probe our Solar System with machines and even return samples to understand the chemistry of other objects in the Solar System, but we cannot touch the stars beyond our Sun
- We had to learn how to interpret the wealth of data in starlight
  - That begins with understanding the relationship between matter and light

What we think the history of the Universe looks like





Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
500,000 years
Atoms form; photons fly free and become microwave background.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Era of Nucleosynthesis
protons, neutrons, electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10^{-10} seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10^{-38} seconds
Strong force becomes distinct, perhaps causing inflation of universe.
GUT Era
elementary particles
10^{-43} seconds
Planck Era
????
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks

Three major eras of the Universe

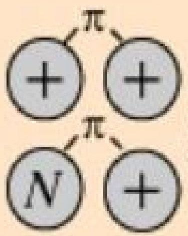
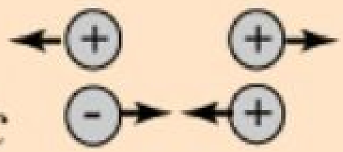
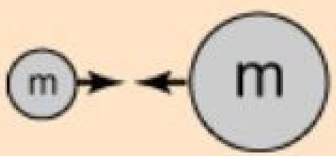
1. The Radiation Era—up to 380,000 years after the Big Bang (ABB)
   - Planck Era (All four known forces are unified.)
   - GUT (Grand Unified Theory) Era (Gravity "freezes out" and becomes distinct.)
   - Electroweak Era (The nuclear strong force "freezes out" and becomes distinct.)
   - Particle Era (particles begin to form)
   - Era of Nucleosynthesis (nuclear fusion creates Helium, and tiny amount of heavier elements—finished ~3 minutes ABB!)
   - Era of Nuclei (electrons are not yet bound to nuclei)
   - Photons dominate the Universe
2. The Matter Era—380,000 years to 8.8 billion years ABB
   - Era of Atoms (electrons recombine to form neutral atoms, and the first stars are born)
   - Photons escape the plasma and the CMB flashes across the Universe
   - Era of Galaxies (Galaxies begin to form ~1 billion years ABB)
3. The Dark Energy Era—8.8 billion years ABB to the present
   - Dark Energy dominates the expansion of the Universe

How do we know anything about the first moments after the Big Bang?

- All the work on particle physics for the last century informs our understanding of the earliest moments of the Big Bang
- Fermilab's Tevatron (used to,) and now the Large Hadron Collider at CERN recreate conditions inside their detectors within 10^{-12} seconds after the Big Bang (13 TeV collisions)
  - Temperature of the Universe was 10^{16} Celsius
  - Size of the Universe was ~10 million kilometers (fits inside the orbit of Mercury)
  - The energy of the collision point makes the Sun look cold
- We can't build a powerful enough accelerator on Earth to go much before this time
- The key thing to remember is that the early Universe was much simpler than it is today. Much easier to understand.

The only four forces we know about in some detail in modern physics:

Fundamental Forces

		Strength	Range (m)	Particle	
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)	Force that holds nuclei together
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1	All of chemistry
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1	Force involved in radioactive decay
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2	Force that holds the Universe together

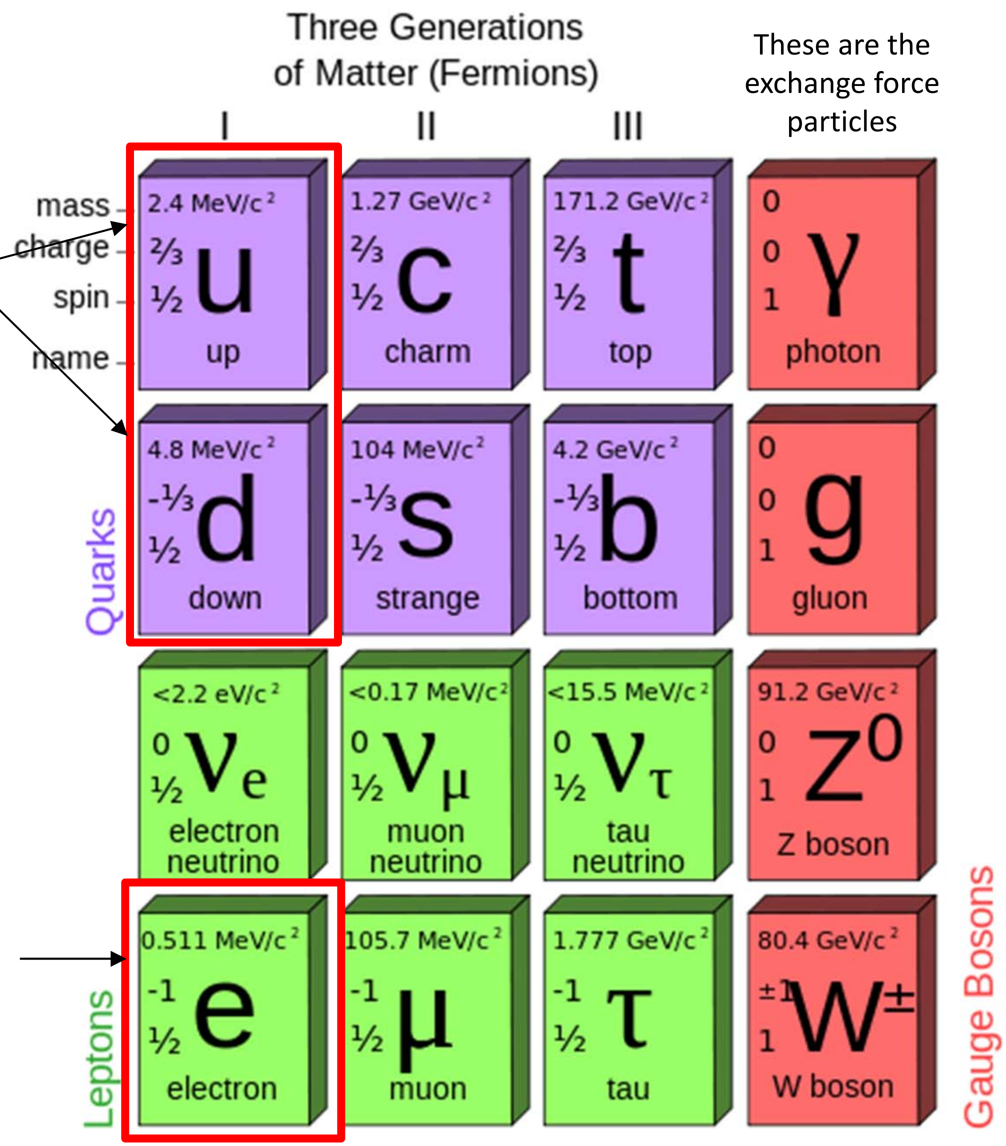
See how much smaller this number is than all the others? Why?

A table of the particles that go into making atoms, the ones in the quark-gluon plasma of the Big Bang

Up and Down quarks make up the protons and neutrons of the nucleus of the atom

No one knows why there are heavy cousins to the basic particles inside atoms. The cousins are unstable and decay in very short times.

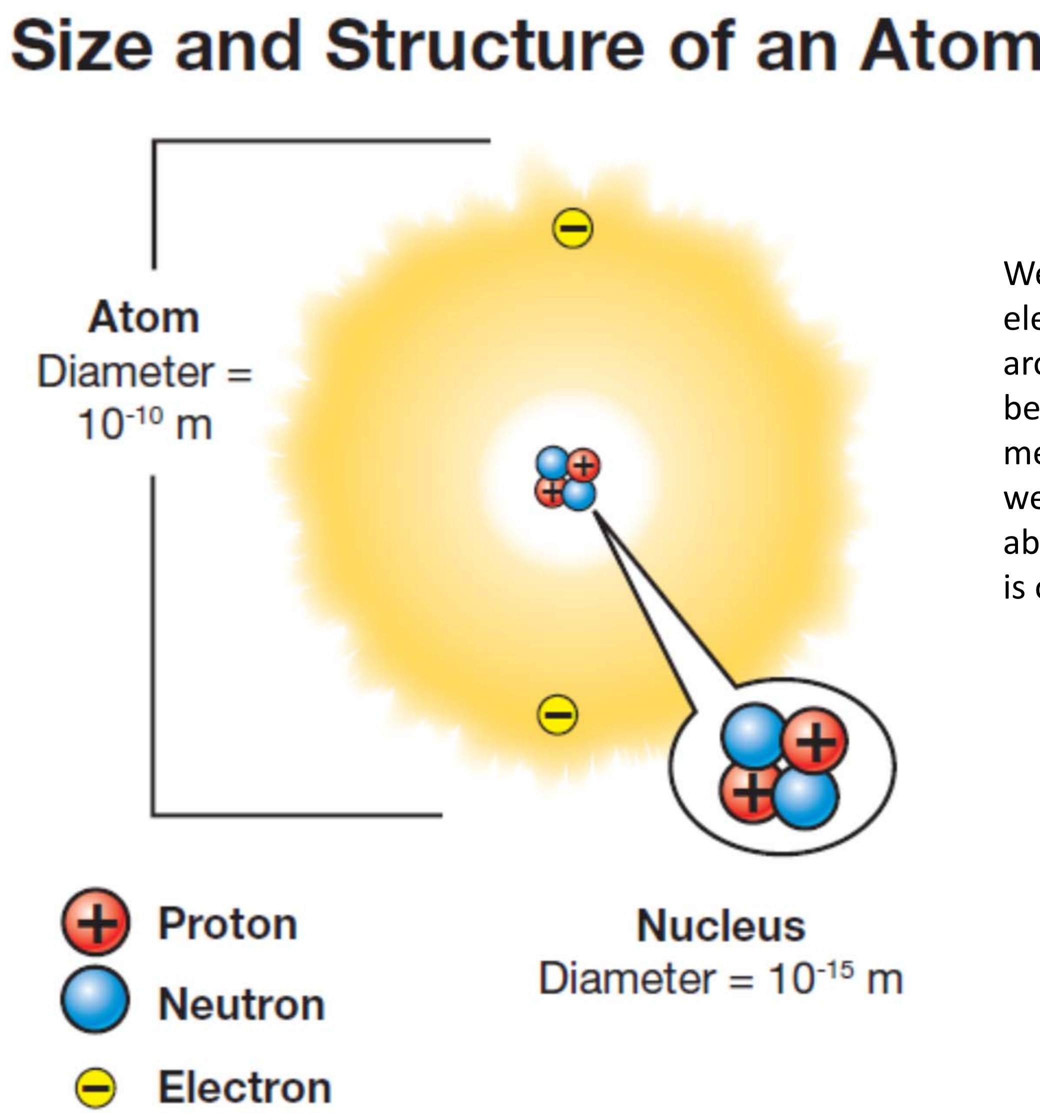
The electrons swarm around the nucleus in shells far away from the center (by atomic standards)



What is an atom?

- An atom is the smallest thing you can cut a material into that keeps the chemistry of the material the same.
- Atoms are made from three fundamental particles:
  - Protons—heavy particle with a positive electric charge
  - Electrons—light particle with a negative electric charge
  - Neutrons—almost same mass as the proton but no electric charge

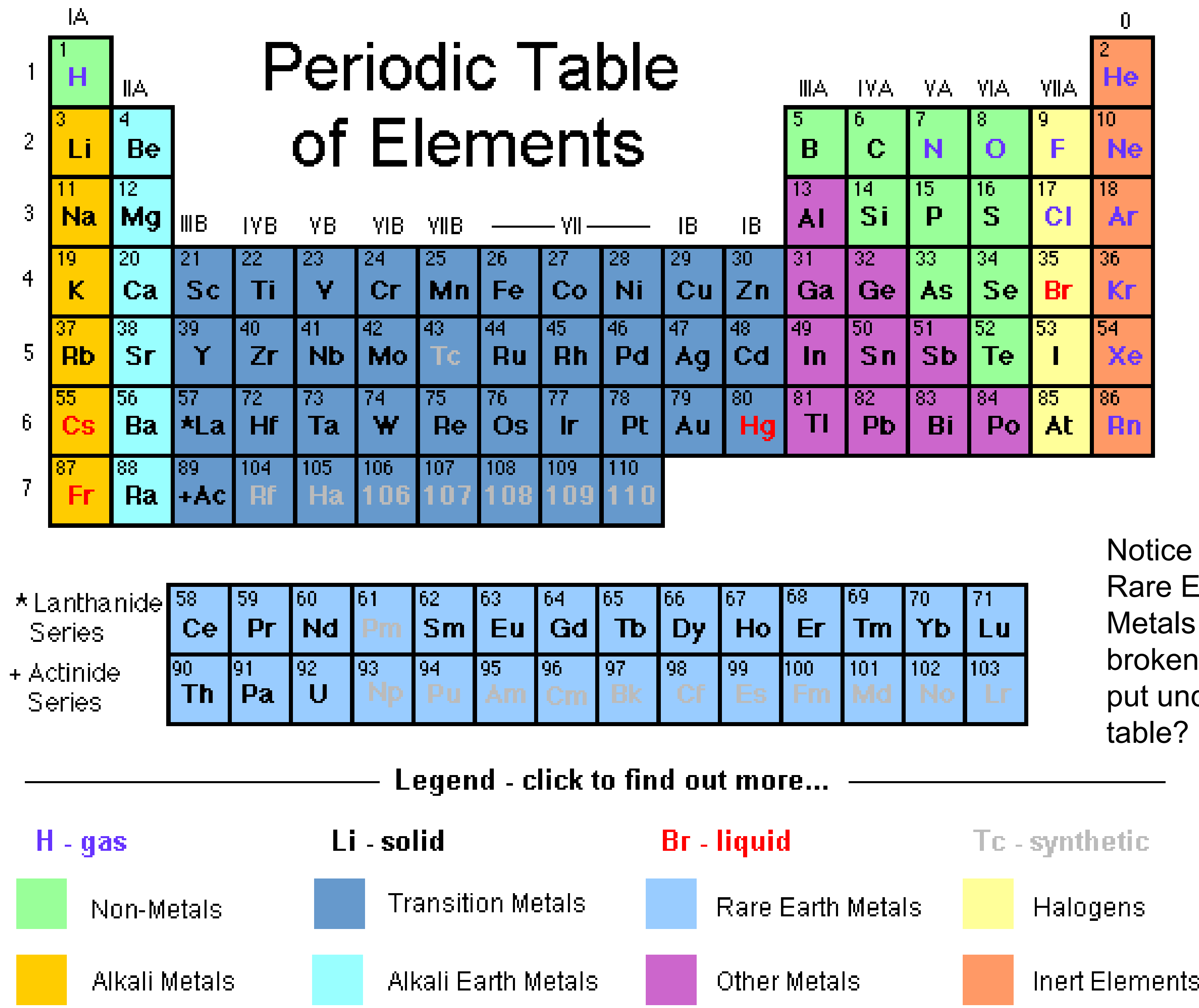
A conceptual picture:



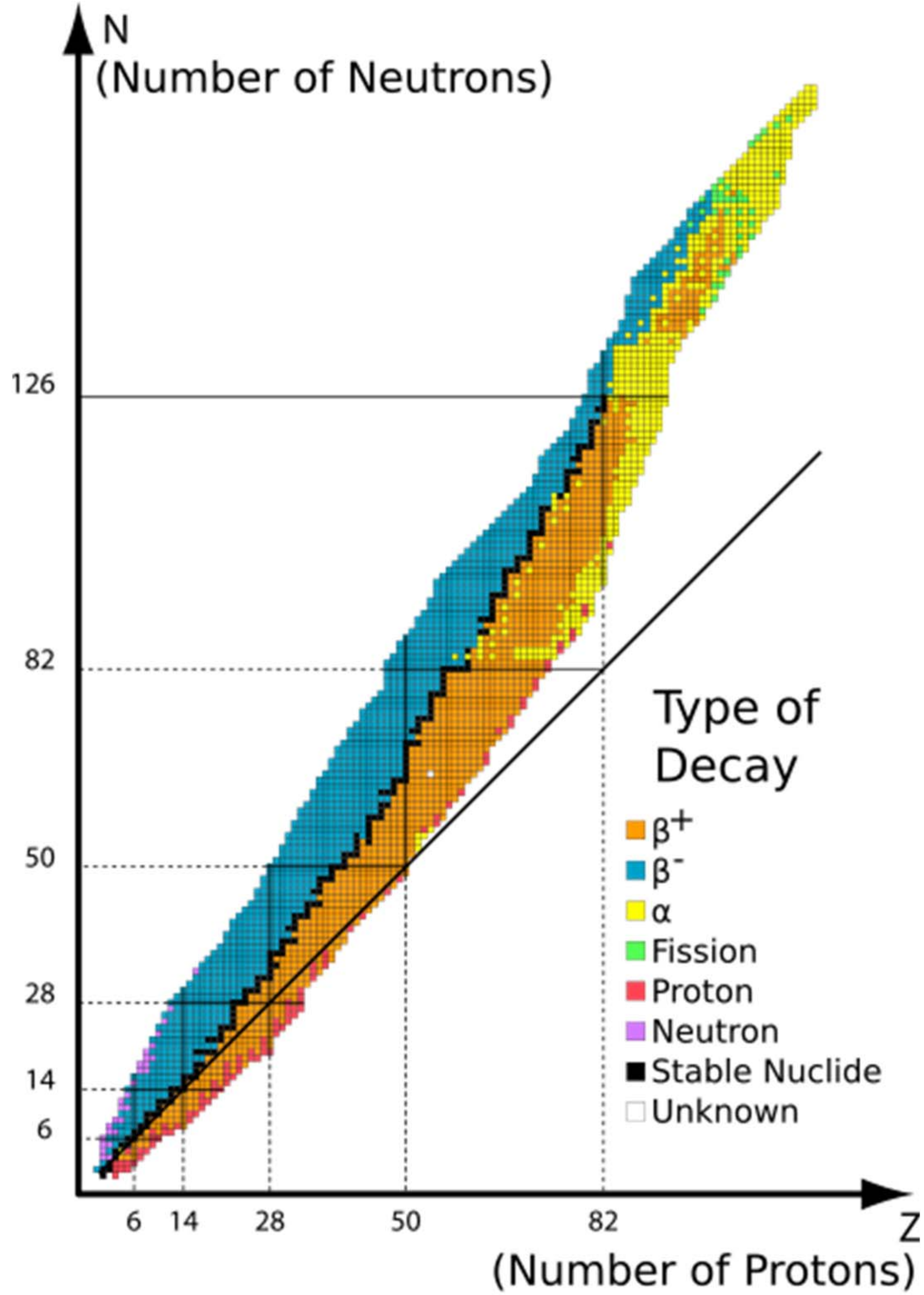
We always draw the electrons as a cloud around the nucleus because quantum mechanics tells us that we can't know too much about where an electron is or how fast it is going.

The Periodic Table you have seen…

(from http://www.corrosionsource.com/handbook/)



Notice how the Rare Earth Metals are broken out and put under the table?



The Table of Radionuclides

This graph includes all of the isotopes of the elements in the Periodic Table.

There are 3,339 nuclides known. Of all of them, there are only 253 that have never been observed to decay.

The colors tell you that the black boxes are the stable elements.

Above element 83, Bismuth, there are no stable elements. Heavier atoms than bismuth all fall apart eventually.

If an isotope is radioactive, the color tells you what kind of radiation the atom gives off when it decays.

Lighter elements decay by beta decay, giving off either an electron or a positron (sometimes a proton or neutron).

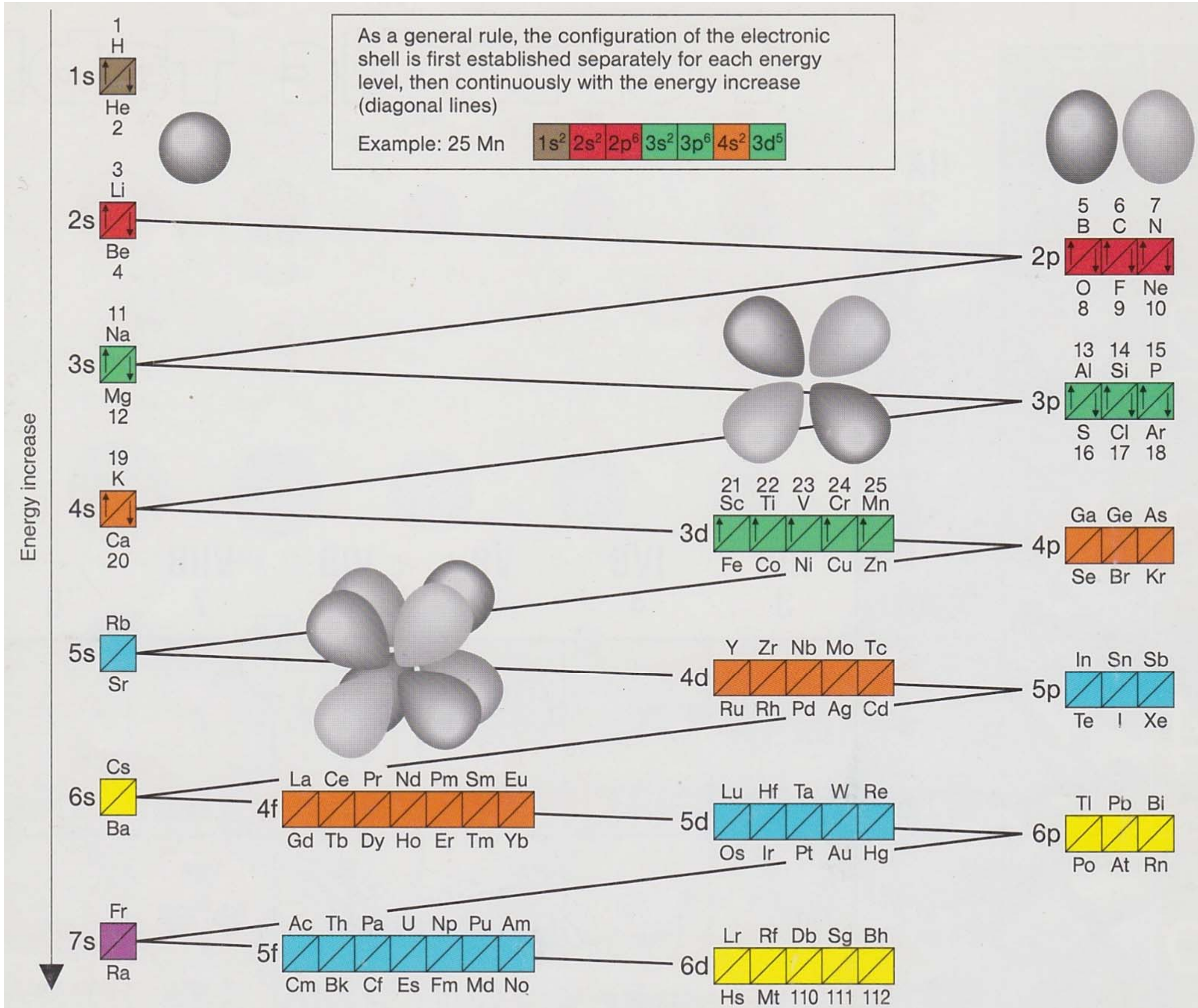
Let’s talk about electron shells for a moment

This diagram shows how the electrons fill the “shells” around atoms.

It explains all of chemistry and spectroscopy!

It explains the grouping of elements and the periodicity of the periodic table.

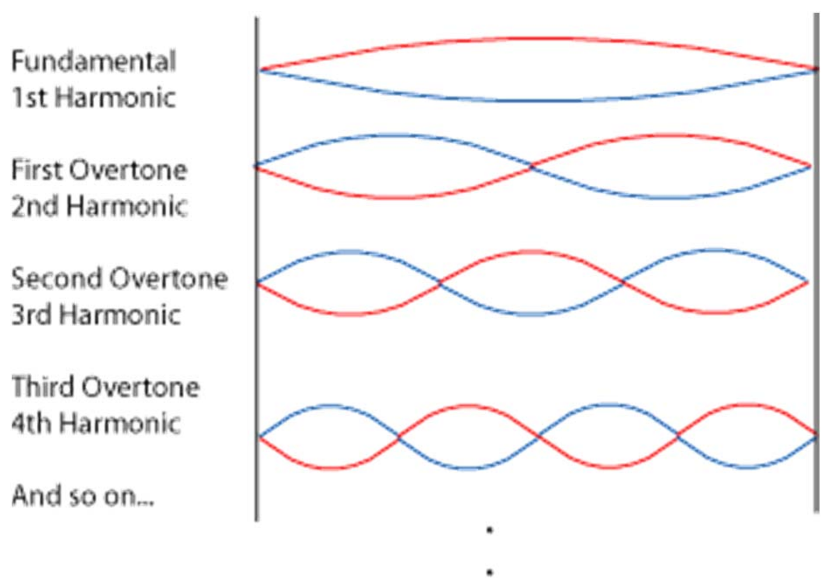
(It can be almost incomprehensible.)



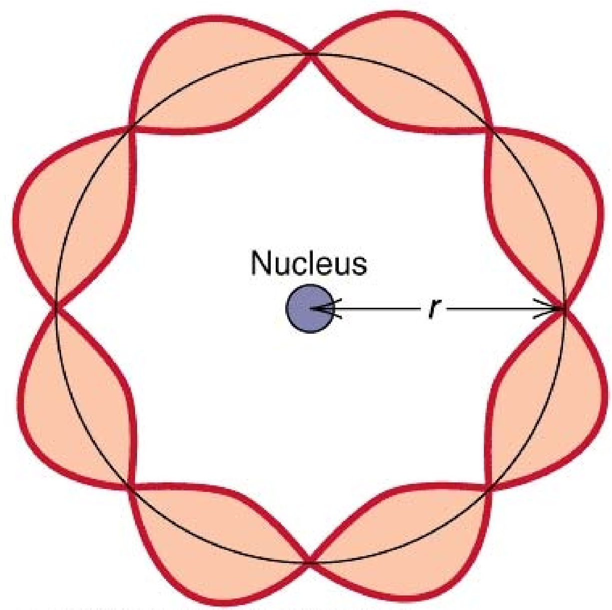
This comes from a really handy sheet available at American Science and Surplus.

How to think about the shells

- Quantum Mechanics shows us that particles have a wave nature
- The energy levels around the atom are the standing waves of electrons
  - Standing waves always represent whole numbers of waves—that's why there are discrete shells
  - Electrons cannot occupy just any level because the in-between ones are not standing waves
  - More wavelengths represent higher energy particles

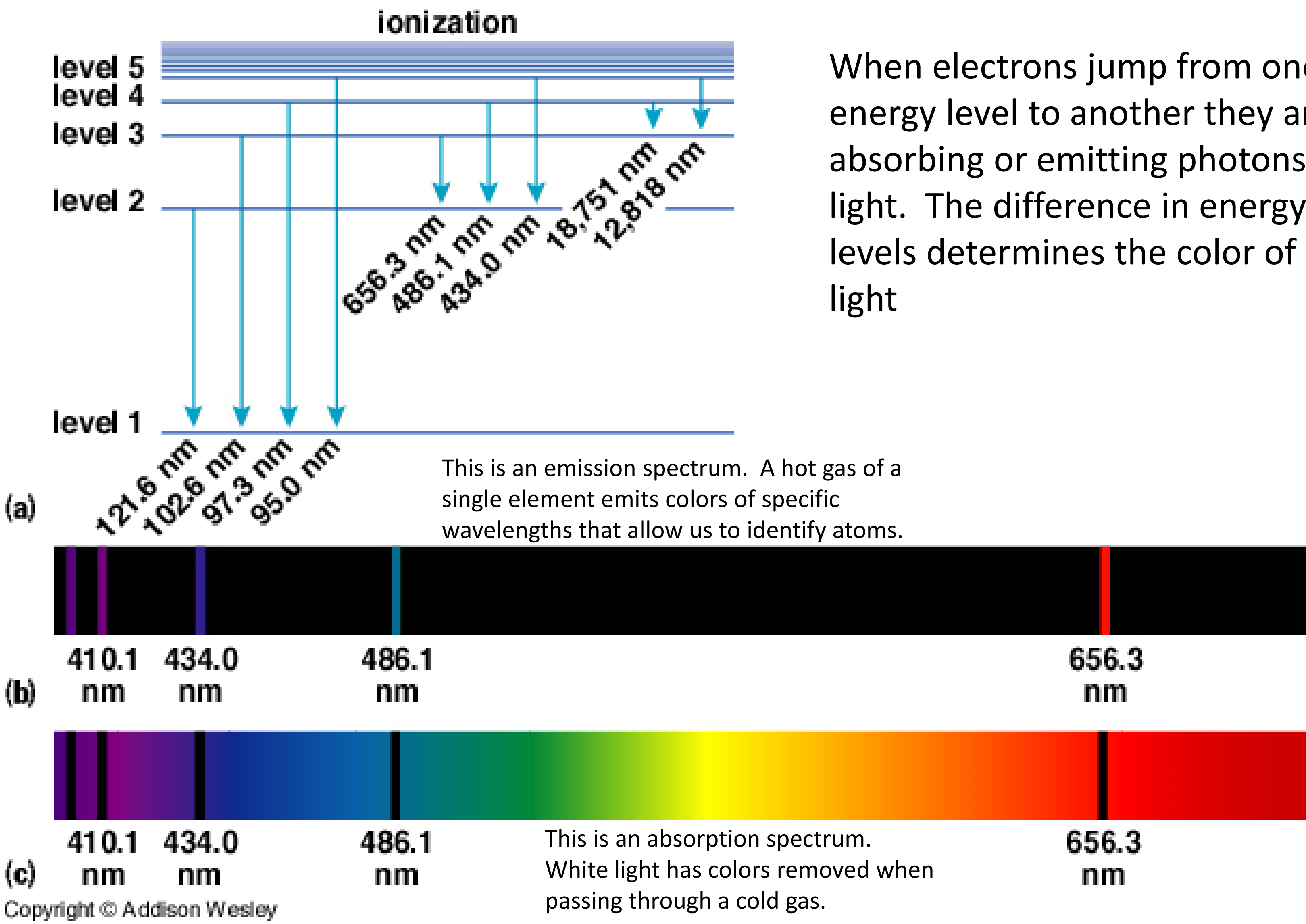


These are the discrete energy levels



How atoms give off light when electrons jump shells

When electrons jump from one energy level to another they are absorbing or emitting photons of light. The difference in energy levels determines the color of the light

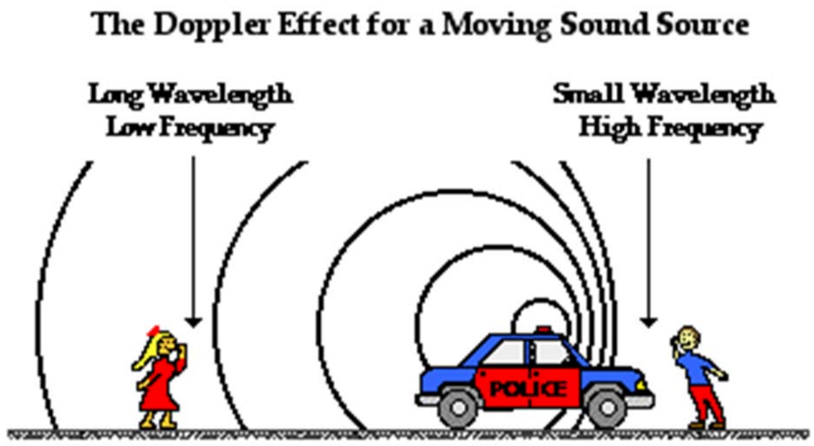


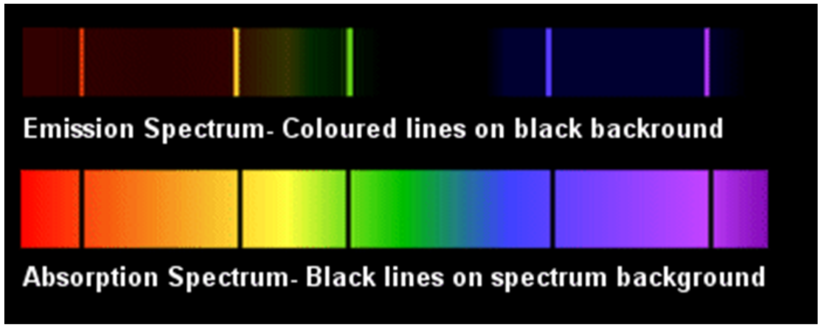
This is an emission spectrum. A hot gas of a single element emits colors of specific wavelengths that allow us to identify atoms.

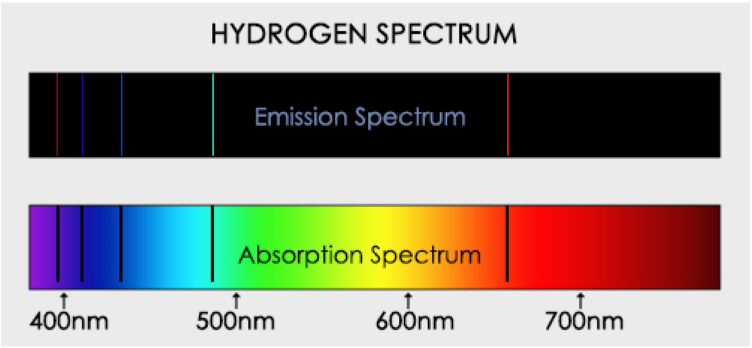
This is an absorption spectrum. White light has colors removed when passing through a cold gas.

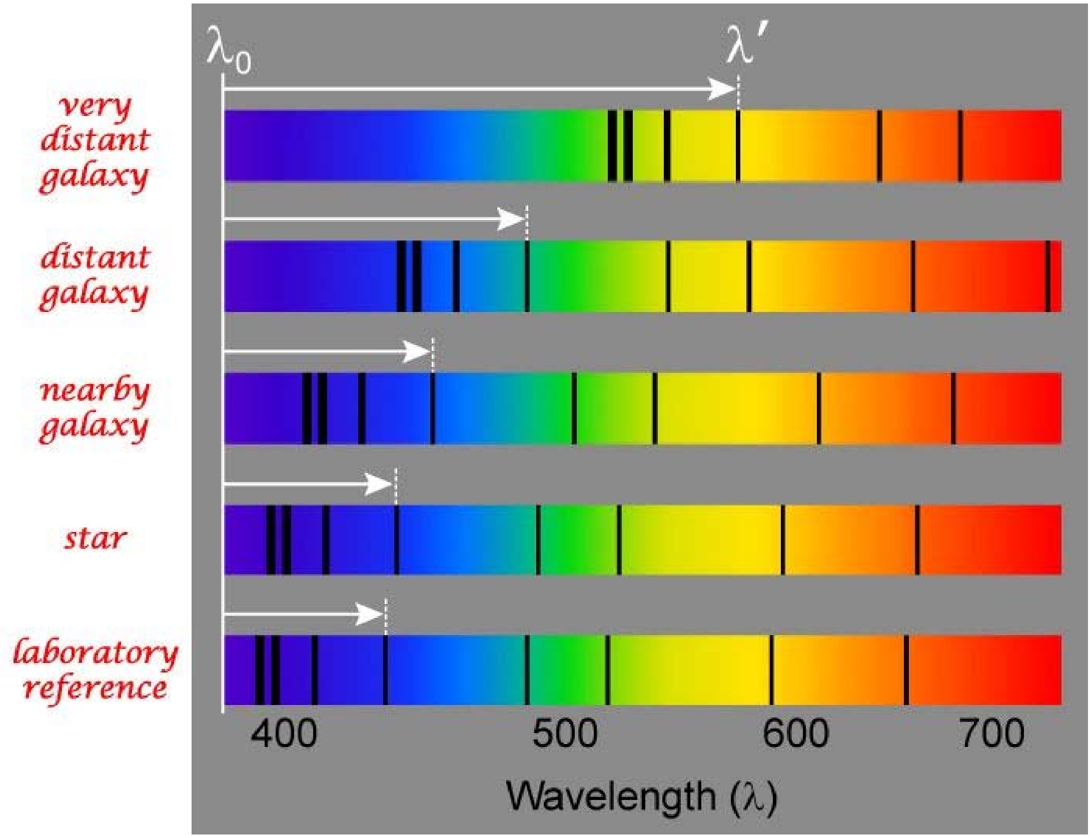
How does the Doppler shift work?

- If you just look at a spectrum of pure white light (the rainbow,) you won't see the Doppler shift
- You need markers in the colors of the rainbow that are fixed at different colors
- Every atom in the Periodic Table absorbs or gives off light at specific wavelengths
  - We get the same color pattern measured in labs all over the world
- The Doppler shift is observed when we see colors of light coming from atoms in distant stars and galaxies at different wavelengths than we measure on Earth
  - On Earth, the atoms are not moving with respect to us
- **The change in wavelength is caused by the source of the light moving either toward or away from us**





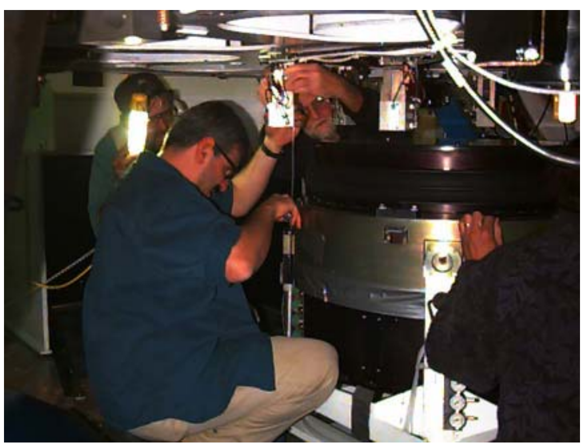


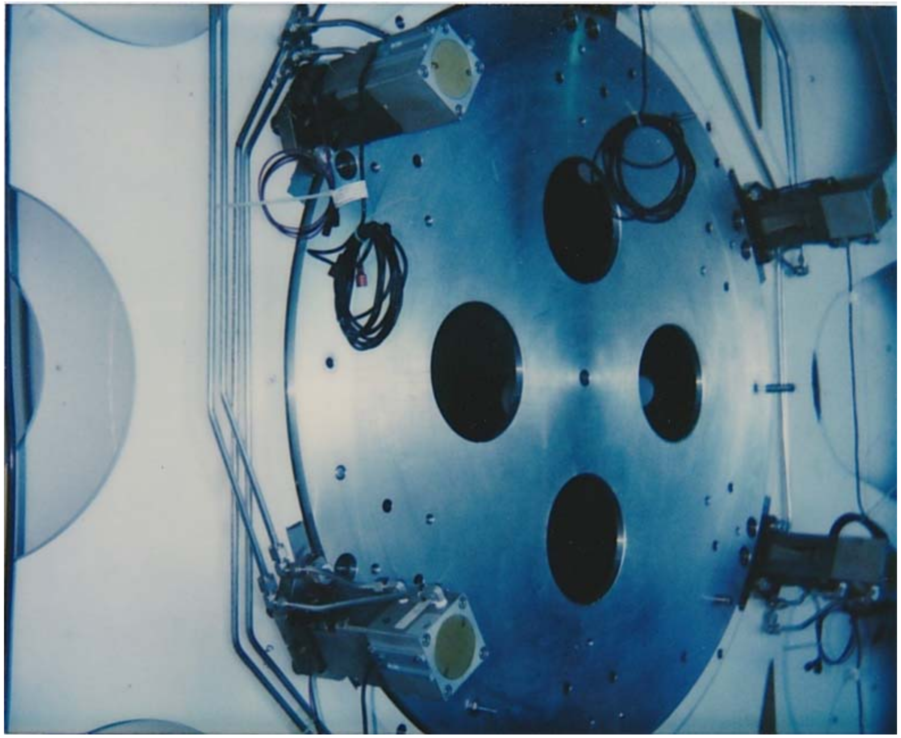


Atomic spectral lines provide the markers in the rainbow that allow us to measure the speed and direction of galaxies around us.

Each atom's spectrum is a fingerprint that can be recognized even if the lines are shifted by the Doppler effect.

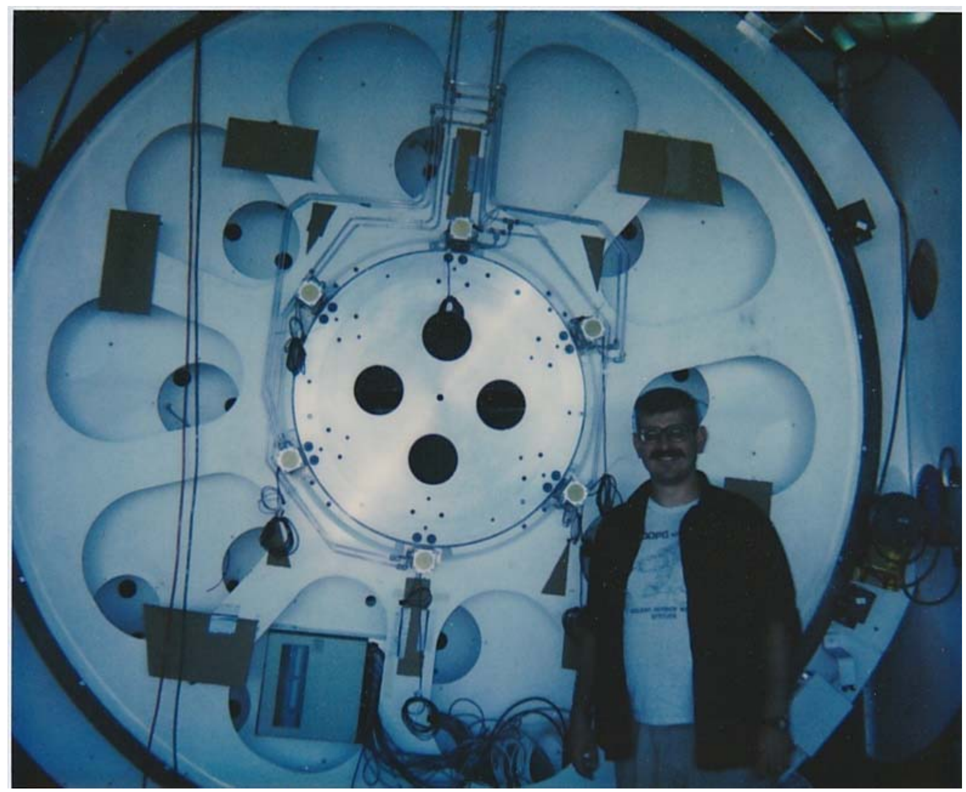
The telescope I helped build:
The 2.5m Sloan Digital Sky Survey Telescope
Apache Point Observatory, NM





←Closer view of the pneumatic latches I installed to hold the camera and spectroscope on the telescope. They could not ever fail or we would drop a $4 million camera.

I had just spent several days at Apache Point Observatory attaching and installing the pneumatic piping for the latches →



The Sloan Telescope Process

1. One night the telescope would scan across the sky recording the images with a large optical CCD camera
2. Astronomers would look at the images and select objects for spectroscopic analysis
3. A "plug plate" was made with individual holes for each object selected
4. The camera was taken off and a spectroscope was mounted with optical fibers to each hole in the plug plate (so each individual object's light could be separately analyzed)
5. On a following night, the telescope looked at the same patch of sky with the spectroscope and the light of each object was separated into its spectrum to observe the redshift of the object
   – Farther objects are whole galaxies, not single stars

Attaching the optical fibers between the plug plate and the spectroscope

SDSS accomplishments

- The Sloan Digital Sky Survey has created the most detailed three-dimensional maps of the Universe ever made, with deep multi-color images of one third of the sky, and spectra for more than three million astronomical objects.
- SDSS helped create the first map of the Dark Matter in the Universe
- The data are all available to the public

Where do atoms come from?

- There are four main mechanisms to create atoms:
  1. Big Bang Nucleosynthesis

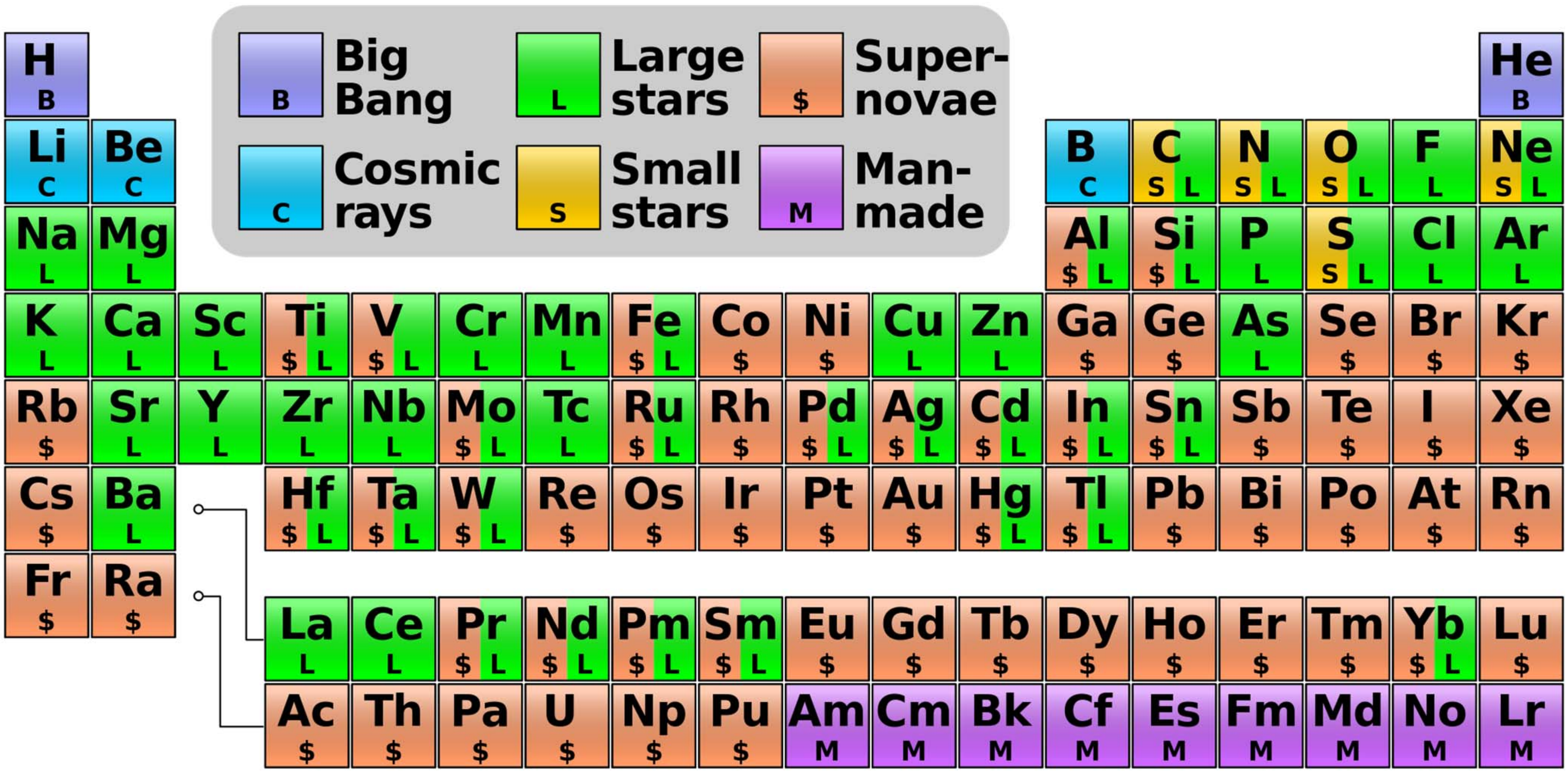
     Elements up to Boron were created during the Big Bang
  2. Stellar Nucleosynthesis

     Stars make elements up to iron throughout their lives
  3. Explosive Nucleosynthesis

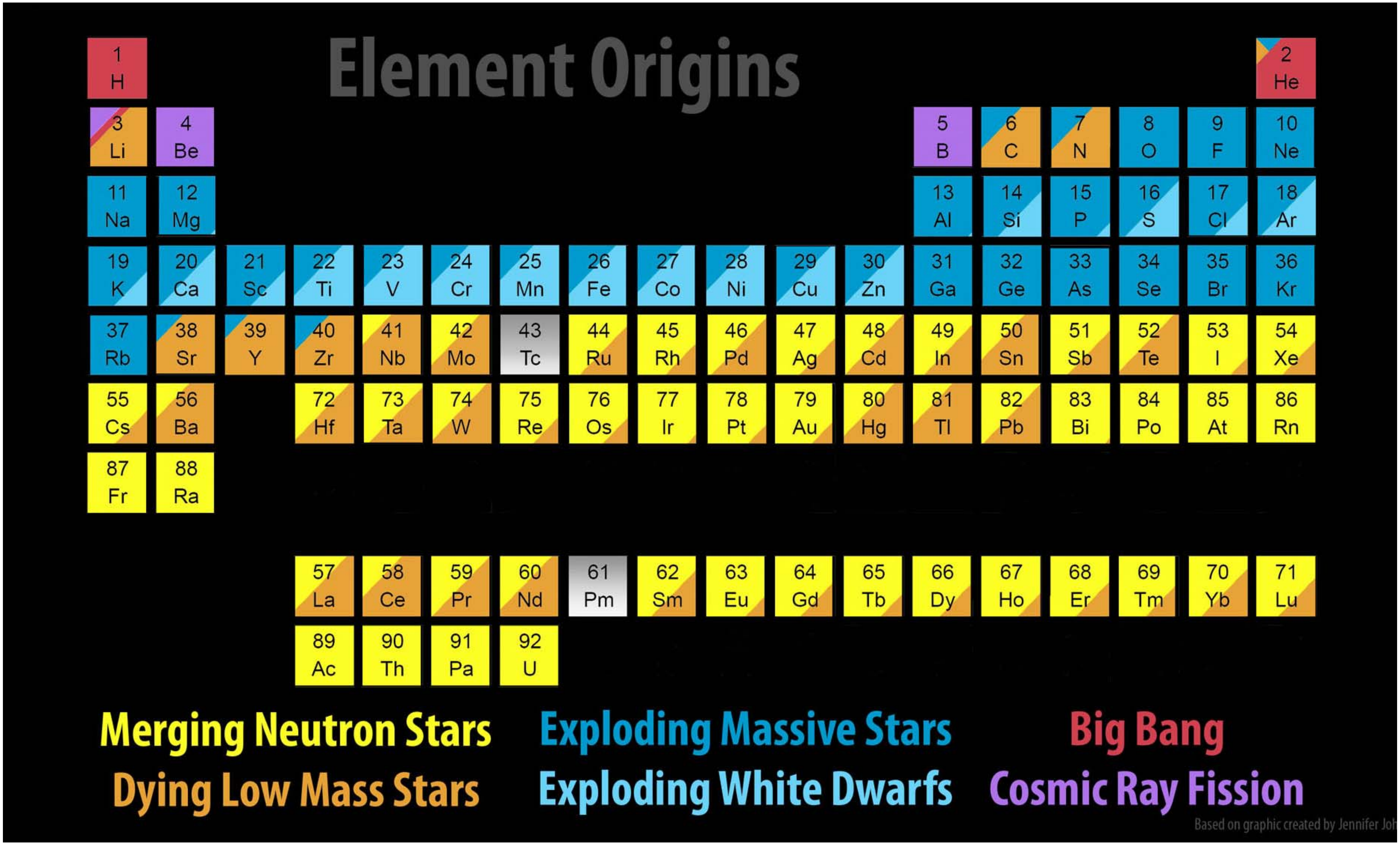
     Supernovae make all the natural elements up to Plutonium and spread them through the universe *(Old thinking! See next slides.)*
  4. Cosmic Ray Spallation

     Cosmic rays (fast protons) break up C, N and O in the interstellar medium and increase the amount of Be, B and Li

An Older Periodic Table that shows where we thought each of the elements is made in the universe



A New Periodic Table that shows where each of the elements is made in the universe



https://caltech.app.box.com/s/258ahpdnvjc8h23eucb1ywvtkkzf9arq This image via Jennifer Johnson of SDSS

How the universe creates gold

By **EarthSky Voices** *in* **SPACE** | October 25, 2017

Finally, scientists know how the universe makes gold. They've seen it created in the cosmic fire of 2 colliding stars via the gravitational wave they emitted.

Sharing is caring!

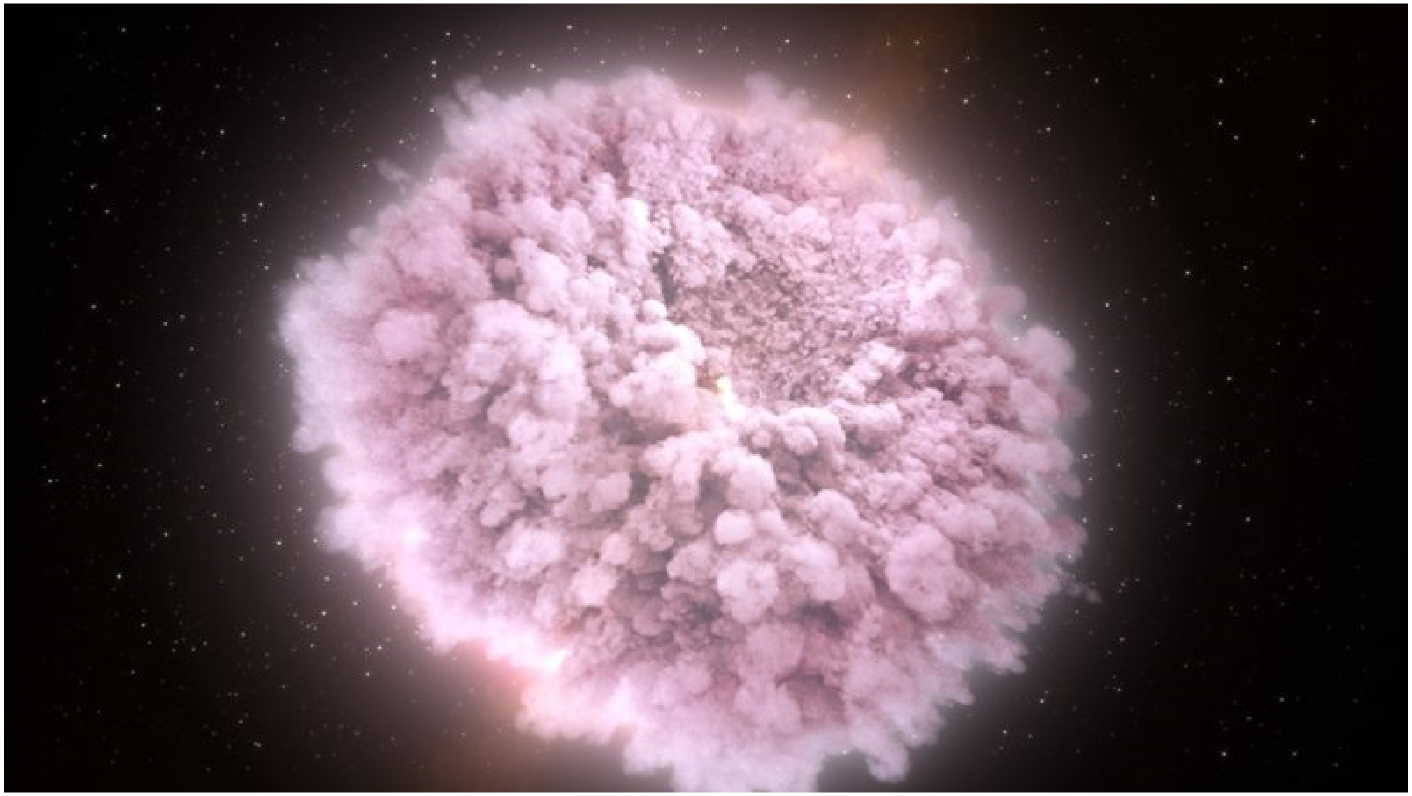


Illustration of hot, dense, expanding cloud of debris stripped from the neutron stars just before they collided. Image via NASA's Goddard Space Flight Center/CI Lab.

https://earthsky.org/space/how-the-universe-creates-gold

Duncan Brown, *Syracuse University* and Edo Berger, *Harvard University*

"On the morning of August 17, 2017, a ripple in space passed through our planet. It was detected by the LIGO and Virgo gravitational wave detectors. This cosmic disturbance came from a pair of city-sized neutron stars colliding at one third the speed of light. The energy of this collision surpassed any atom-smashing laboratory on Earth.

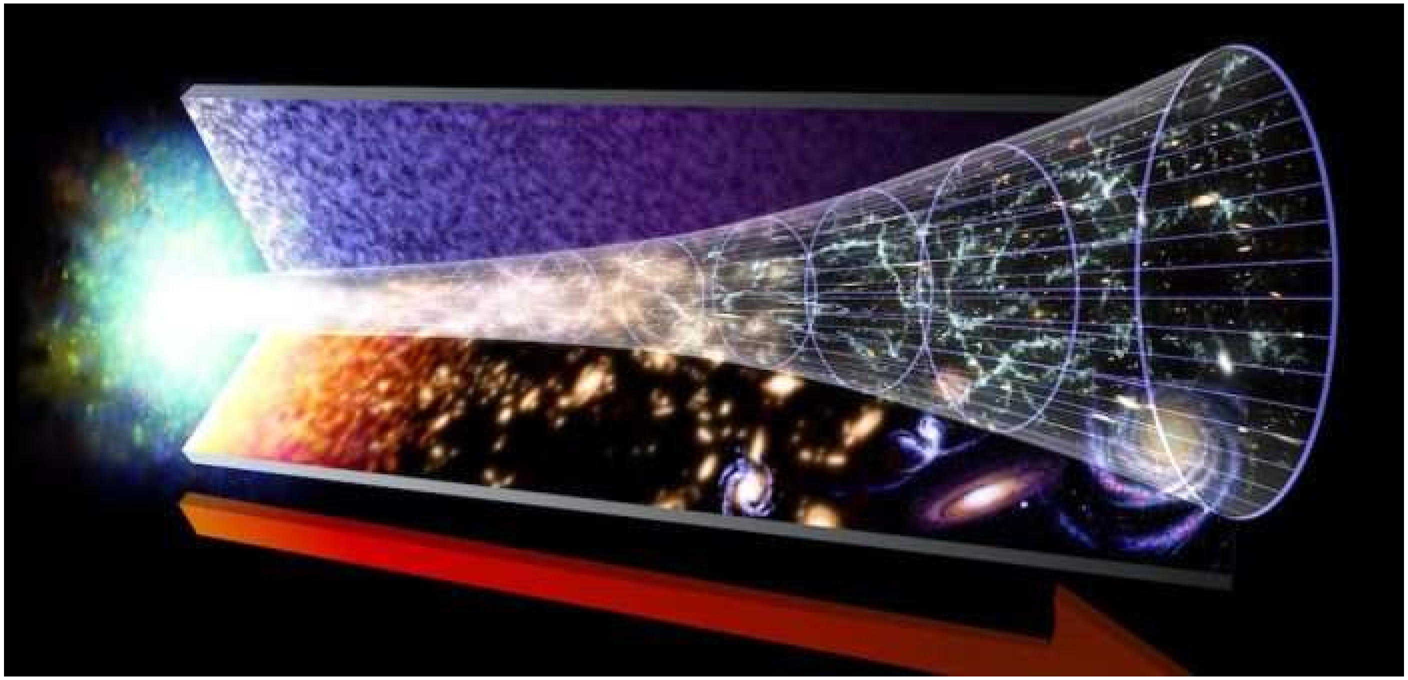
The spectrum of the kilonova contained the fingerprints of the heaviest elements in the universe. Its light carried the telltale signature of the neutron-star material decaying into platinum, gold and other so-called "r-process" elements.

For the first time, humans had seen alchemy in action, the universe turning matter into gold. **And not just a small amount: This one collision created at least 10 Earths' worth of gold."**

Chinese scientists may have solved the mystery of the missing lithium in the early universe by assuming that the primordial plasma deviated from an ideal gas.

The universe has a lithium problem

February 20, 2017 by Evan Gough, Universe Today



This illustration shows the evolution of the Universe, from the Big Bang on the left, to modern times on the right. Credit: NASA

Over the past decades, scientists have wrestled with a problem involving the Big Bang Theory. The Big Bang Theory suggests that there should be three times as much lithium as we can observe. Why is there such a discrepancy between prediction and observation?

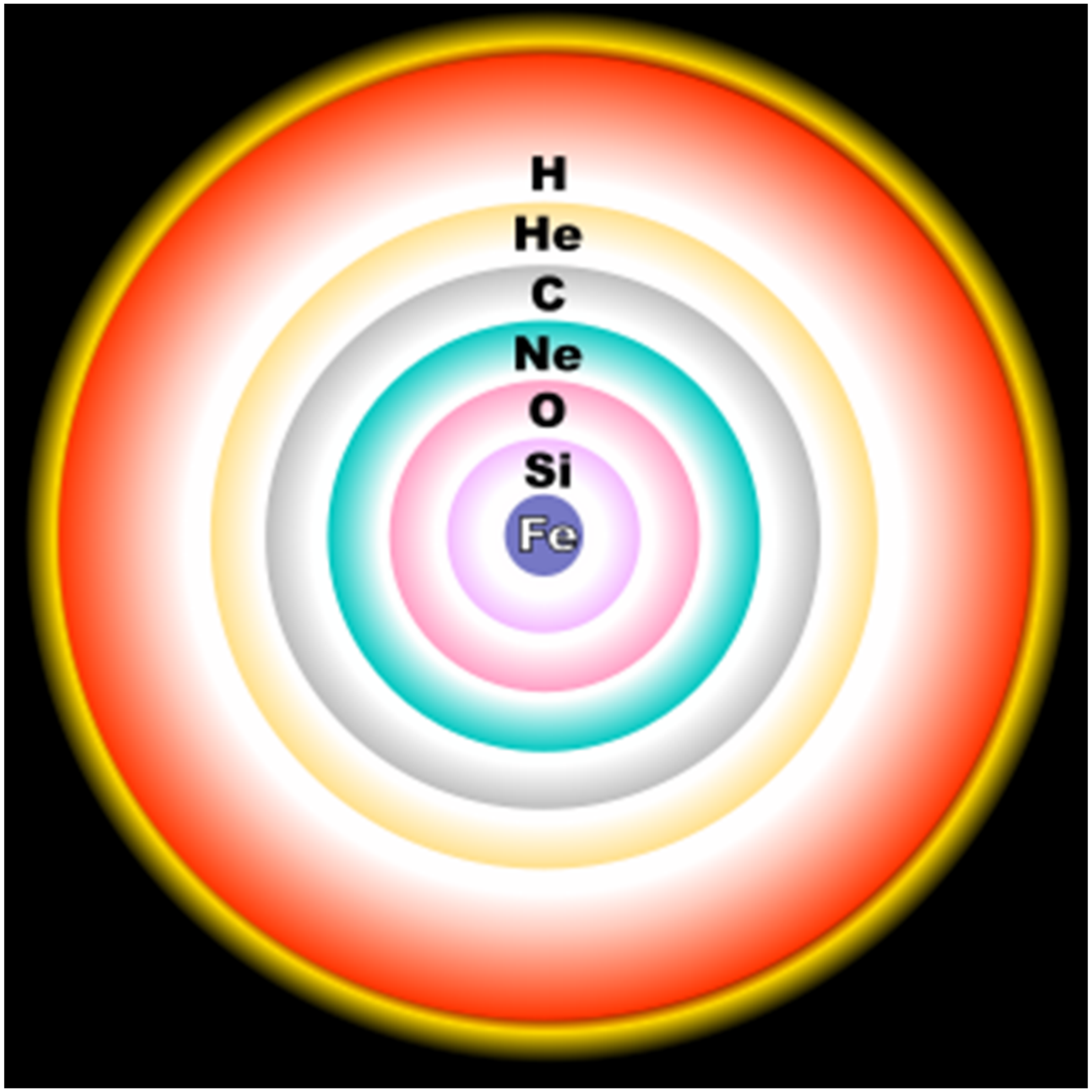
https://phys.org/news/2017-02-universe-lithium-problem.html

The connection between stars and elements

- A star first lights its nuclear fusion fire when gas in a nebula (mostly hydrogen) clumps together because of the force of gravity until it is so heavy that it squeezes the hydrogen atoms hard enough to cause them to fuse together into helium. A star is born!
- The star burns its hydrogen throughout its life, always making more helium.
  - Helium needs more pressure and heat to fuse into the next heavier elements.

As a star ages what it fuses changes…

- It burns up its available hydrogen until the core of the star is mostly helium.
- When the hydrogen is almost gone, a large star will begin to fuse the helium in its core.
  - Helium fuses at a higher temperature so the star gets hotter and changes color and size
- When the helium fuses it forms the next heavier elements, lithium and beryllium.
  - Li, Be and B are transitory steps to carbon
- As the lighter elements fuse, heavier elements form until you get to iron…



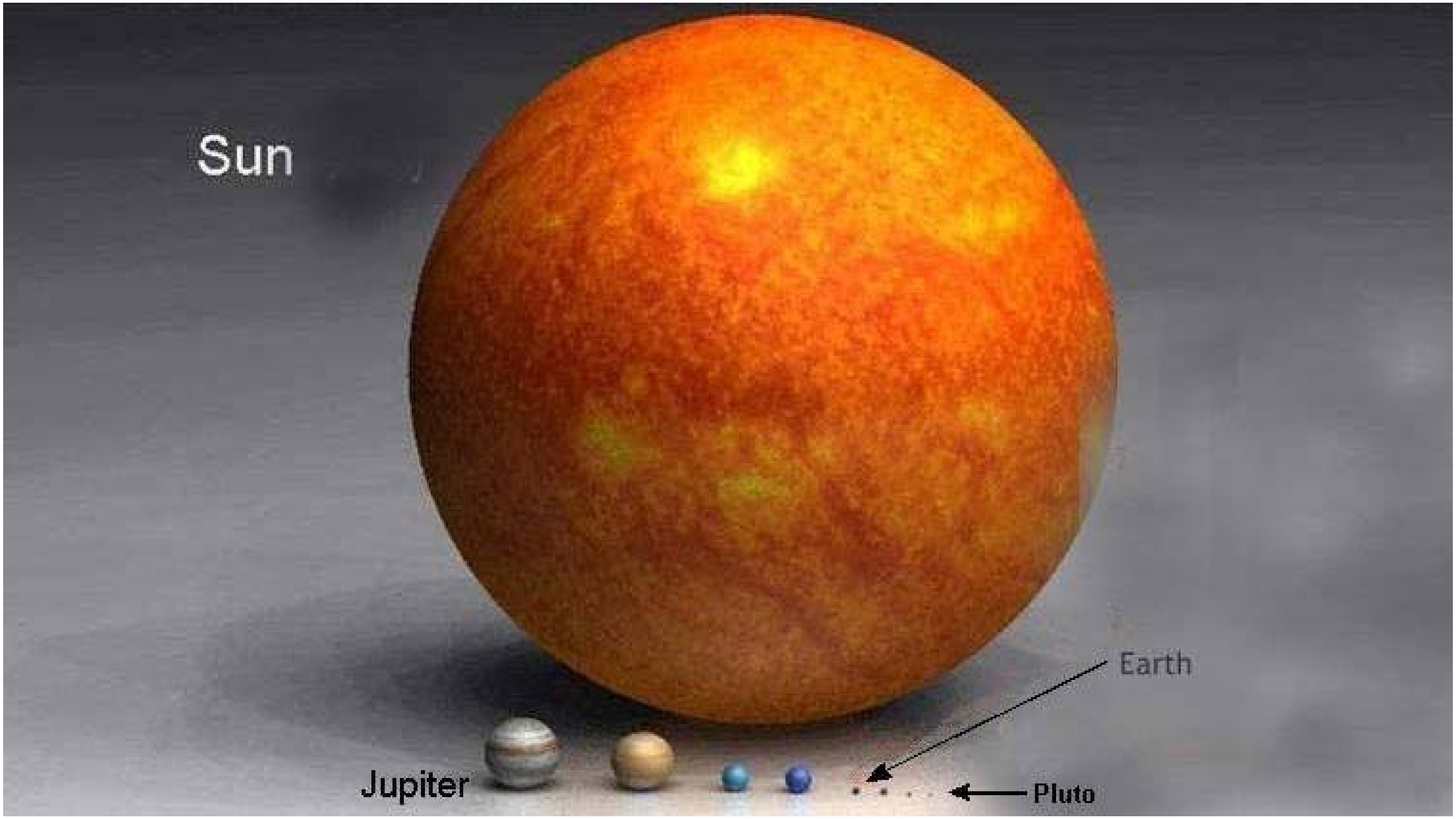
The onion-like layers of a massive, evolved star just prior to core collapse. (Not to scale.)

(From the Wikipedia article on stellar evolution)

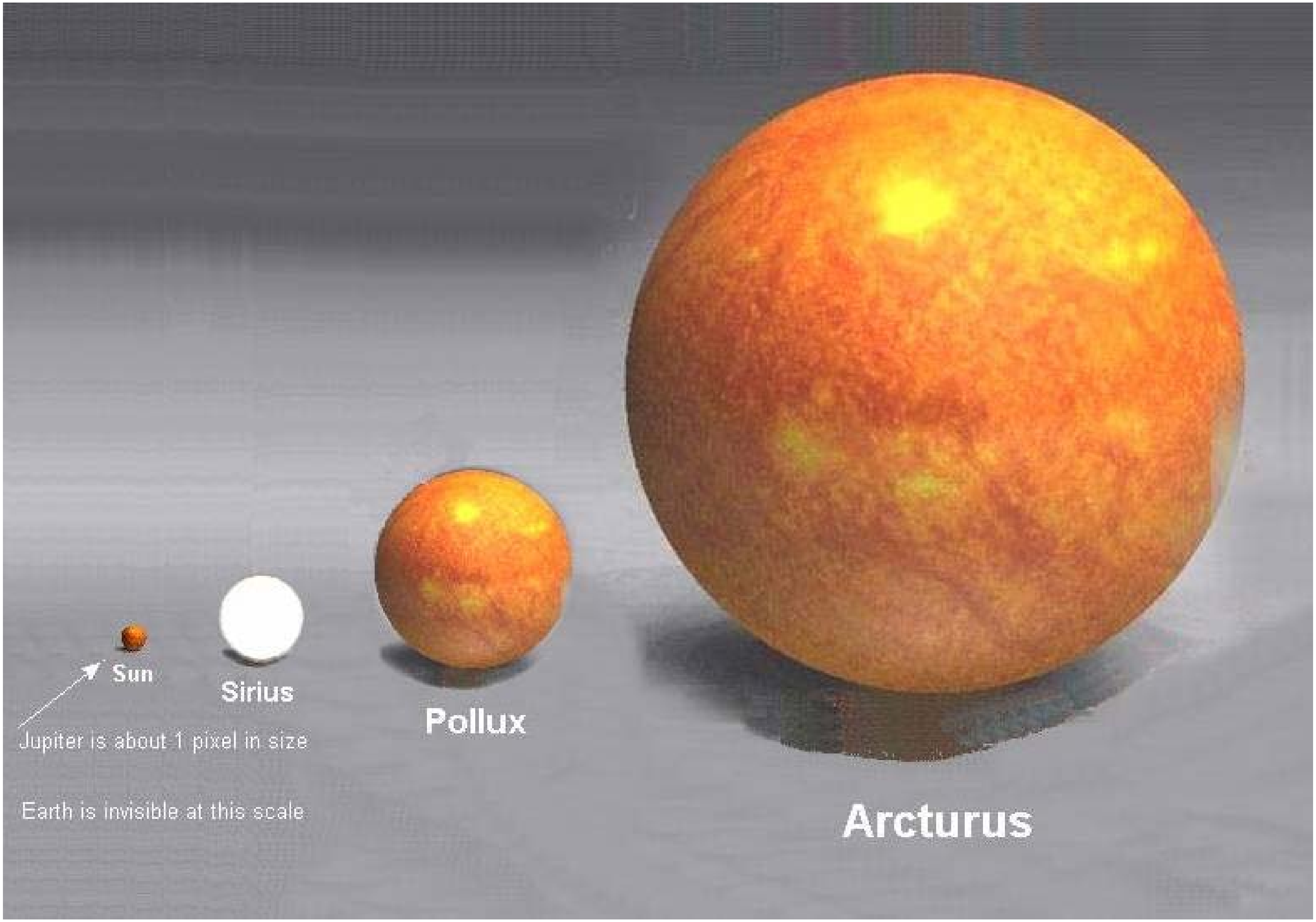
When iron nuclei fuse together to form heavier elements, the fusion reaction doesn't release energy, it takes energy. Fusing the heavier elements soaks up the energy released by the fusion of the light elements.

We don't completely understand the exact mechanisms that cause some stars to explode into supernovae, but we know that their cores collapse and the outer layers of the stars are blown off into beautiful planetary nebulae.

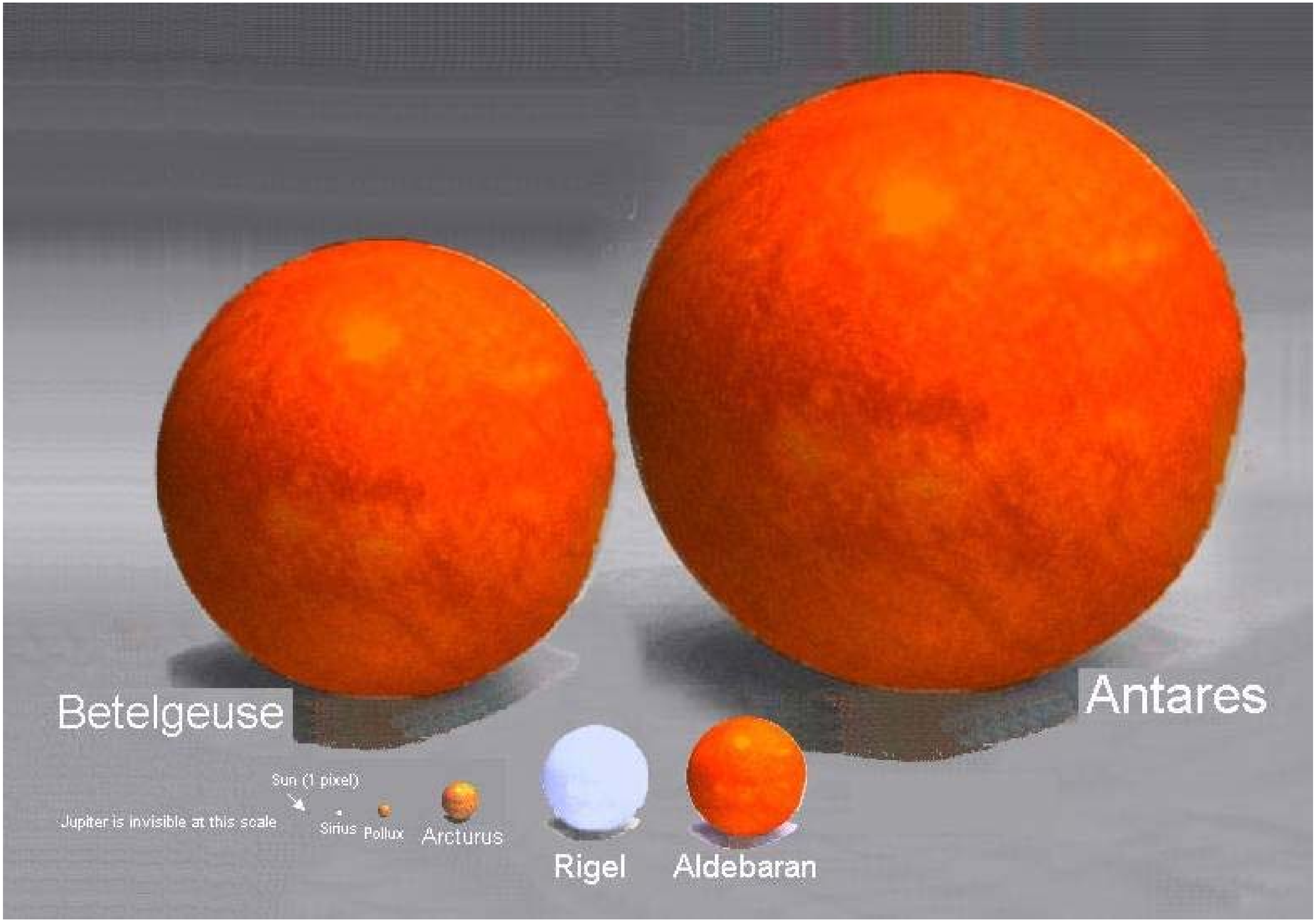
Large enough stars' cores must collapse into black holes—there is no force in the universe that can stop them!



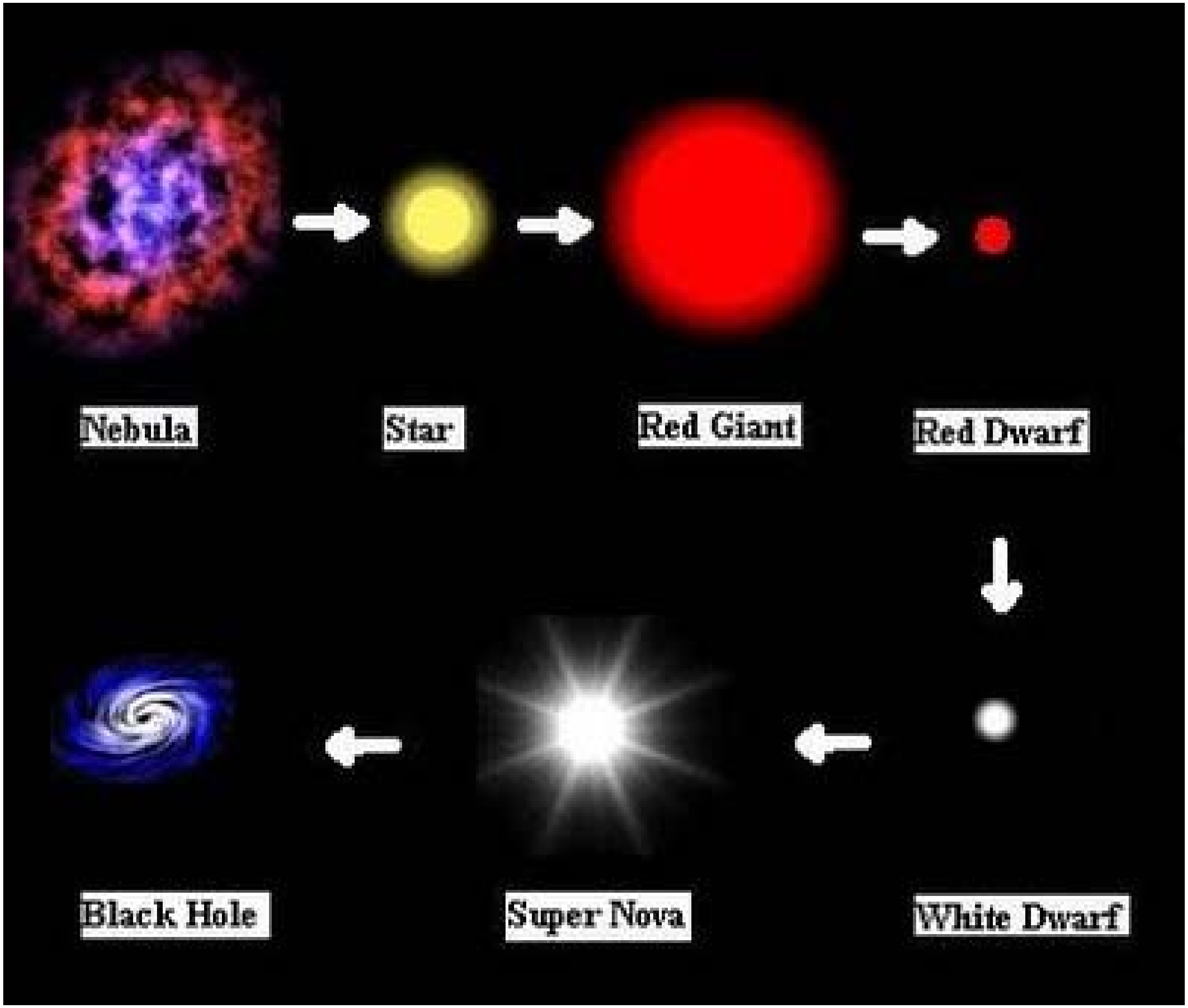
The next three slides give you an idea of what we mean when we talk about the difference between small and large stars. This picture shows how small the big planets look next to our Sun. **Our sun is a medium size star.**



Now see how small our Sun looks next to some other stars



Now do you see just how big stars can get?



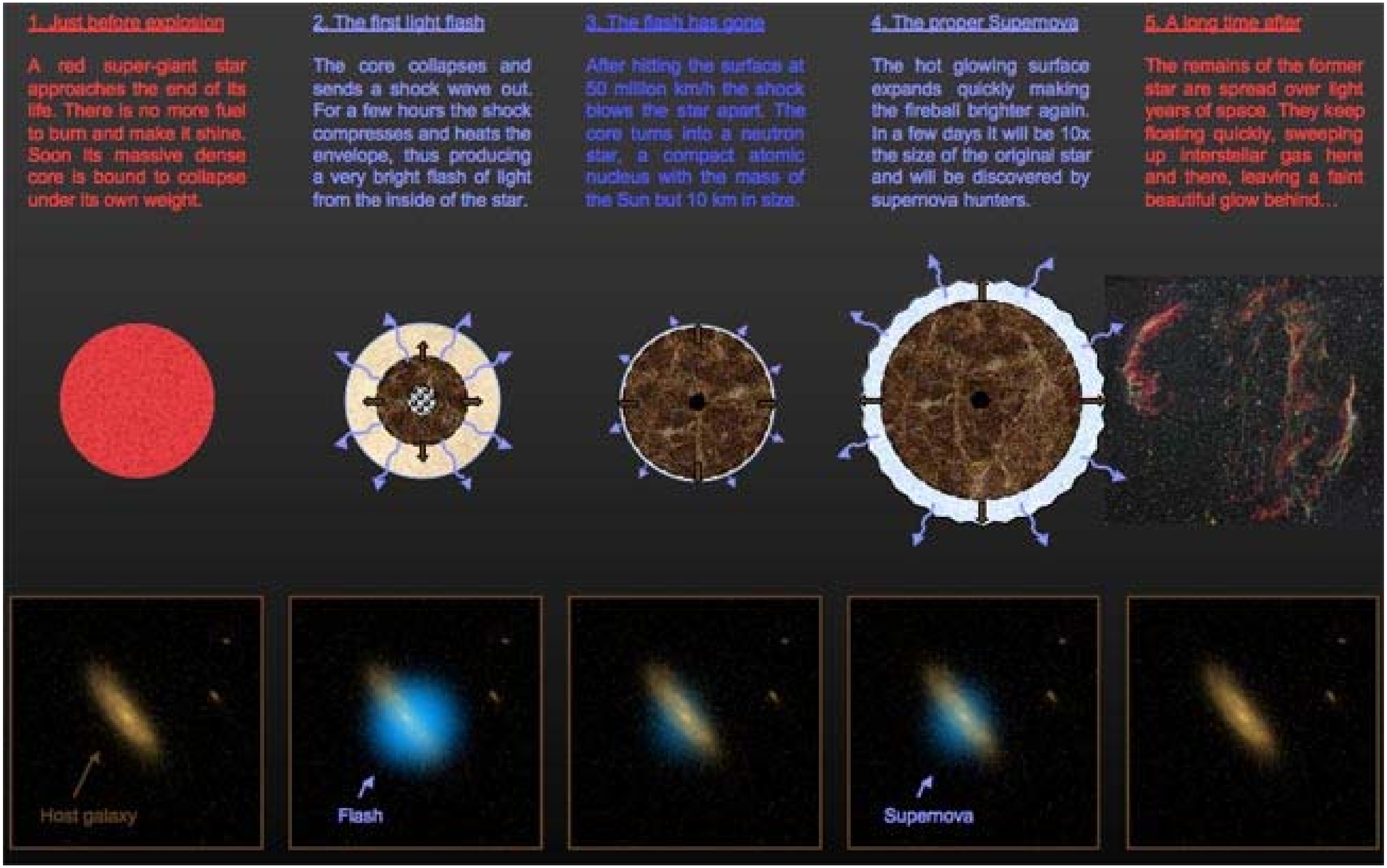
Picture from http://ram4blog.blogspot.com/2008/10/life-stages-of-star.html

Not every star follows the path shown here. A star's history depends on how large it was at its birth (and what it eats through out its life.)

Our sun is a medium mass star. It will live a very long time and never become a supernova. It will become a red giant, then a white dwarf.

Only bigger stars can go nova.

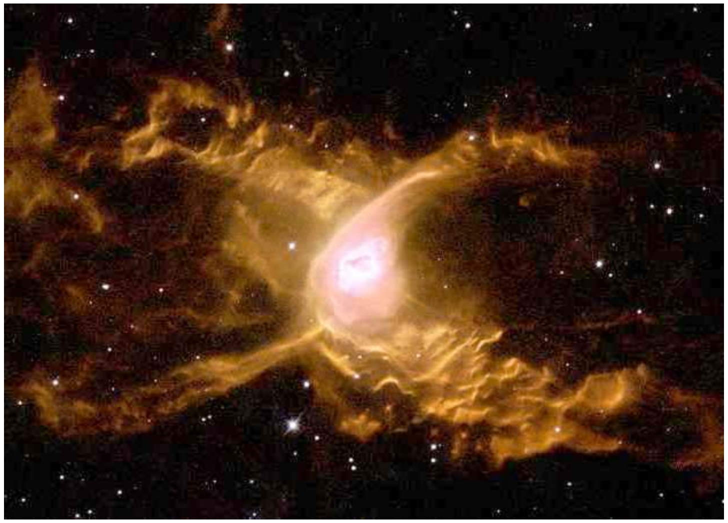
Stars a few times bigger than our Sun explode at the end of their lives in a **supernova**.

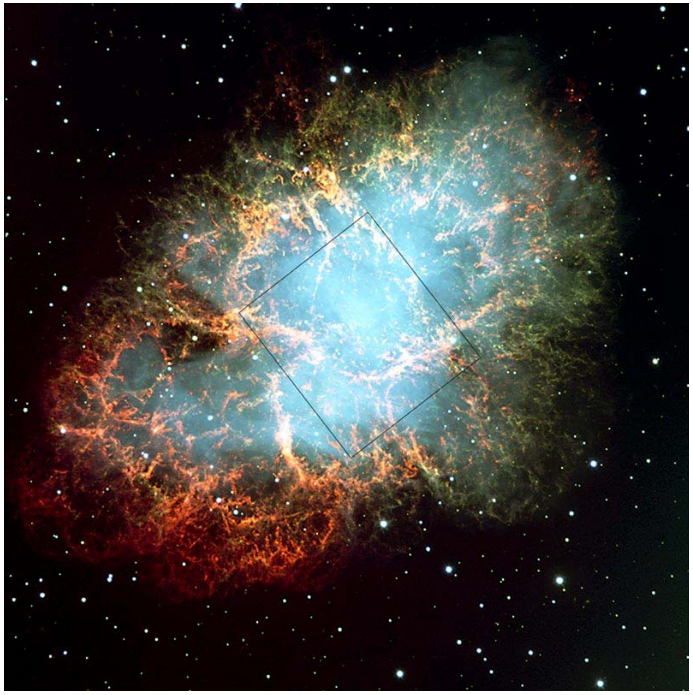


A supernova can outshine the whole galaxy it lives in—for a short time

A few example planetary nebulae blown off by dying stars

This is how the heavier elements get distributed throughout the universe.

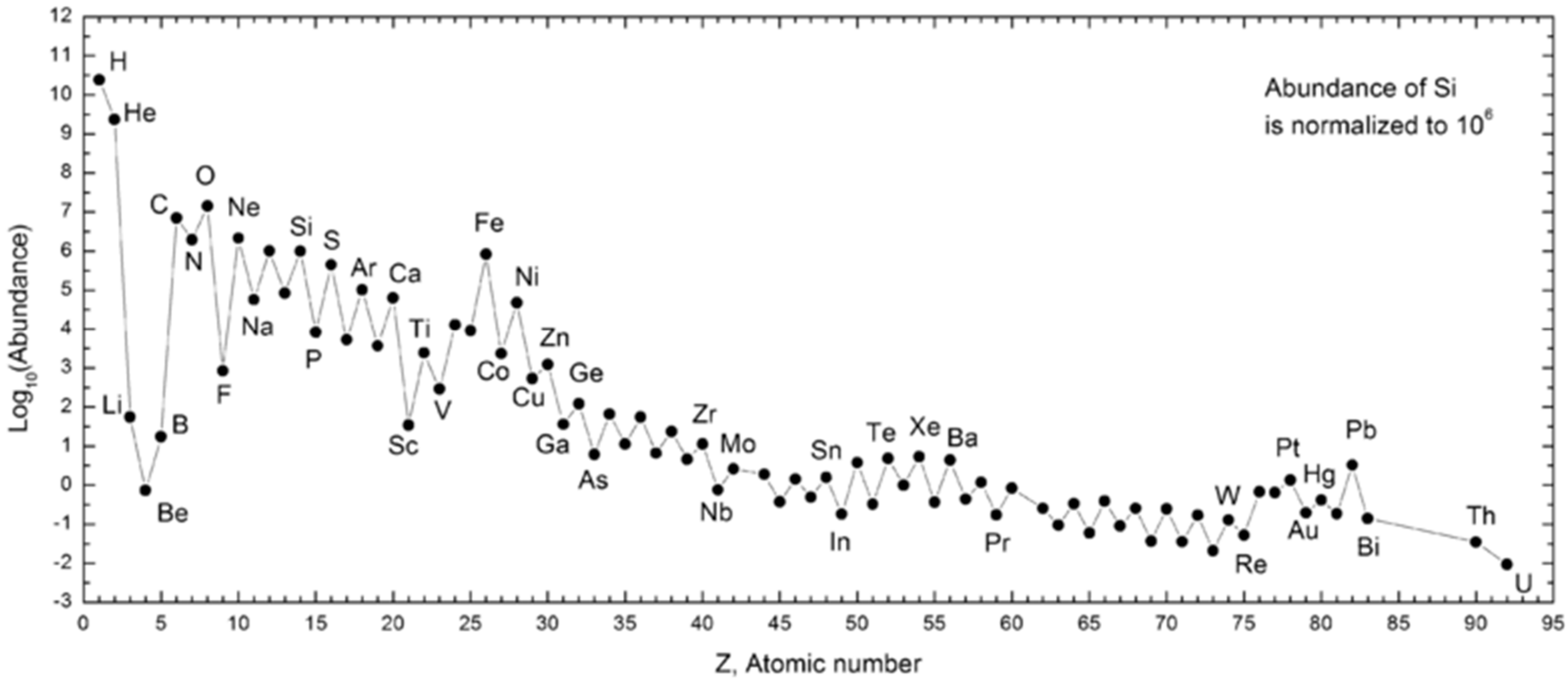




The Crab Nebula

Pictures from various sites through Google images

Abundances of the chemical elements in the Solar System today



Hydrogen and helium are most common. The next three elements (Li, Be, B) are rare because they are poorly synthesized in the Big Bang and also in stars. The two general trends in the remaining stellar-produced elements are: (1) an alternation of abundance of elements according to whether they have even or odd atomic numbers, and (2) a general decrease in abundance, as elements become heavier. Within this trend is a peak at abundances of iron and nickel.

-from the Wikipedia

How do we know the universe is expanding?

- Edwin Hubble discovered the expansion in 1931 by looking at the spectra of galaxies
- The light from almost every galaxy he looked at was “red shifted” by the Doppler effect, meaning that the galaxies were moving away from us
  - Further away showed faster recession
- Hubble calculated the rate of expansion of the Universe from the red shift
  - He thought it was constant because of the range of distances of objects he measured

Hubble's original graph of recession velocity vs distance from 1929

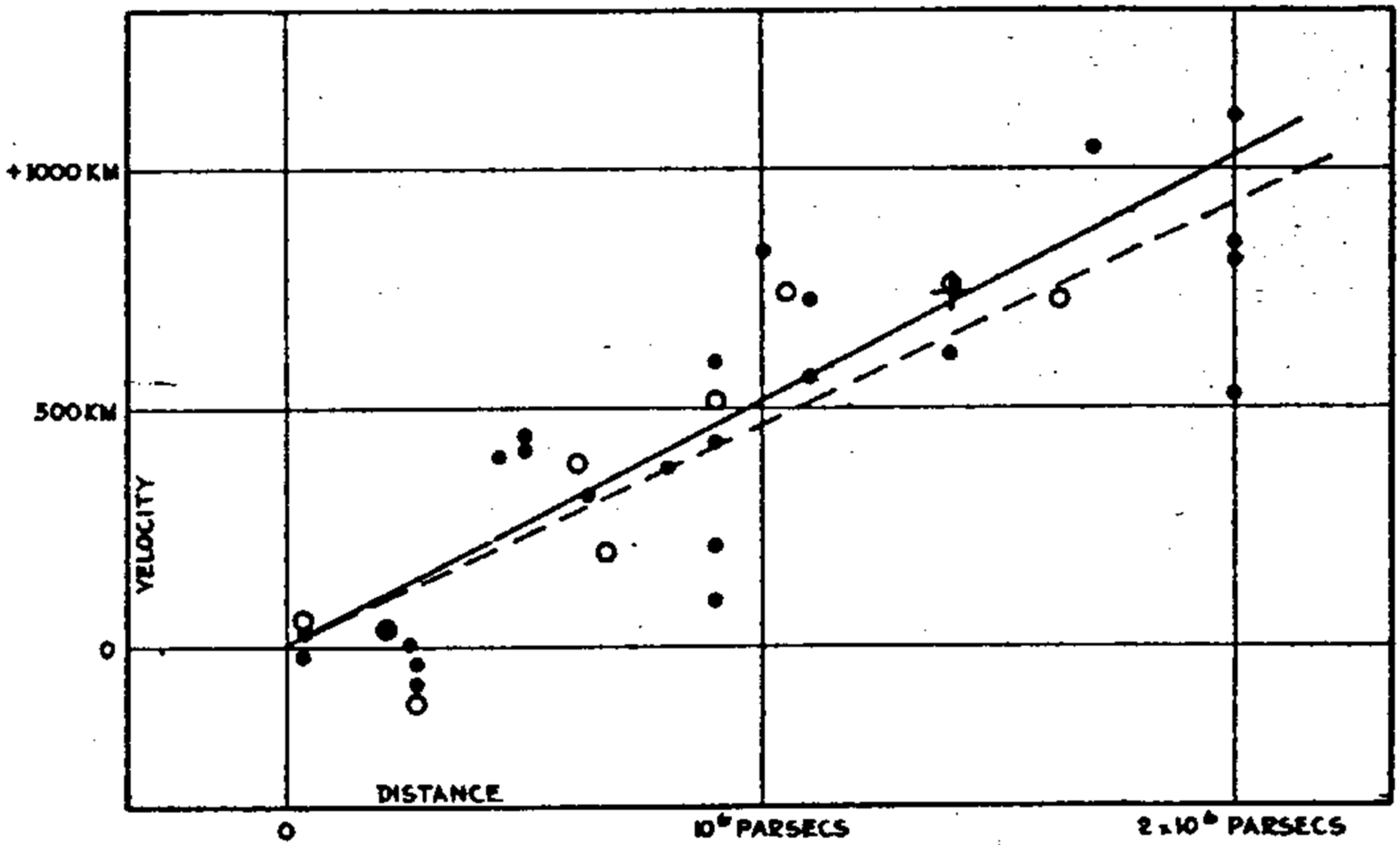


FIGURE 1

$v = H_0 D,$ H_0 = 68.3 ± 1 km/sec/Mpc (from DES)

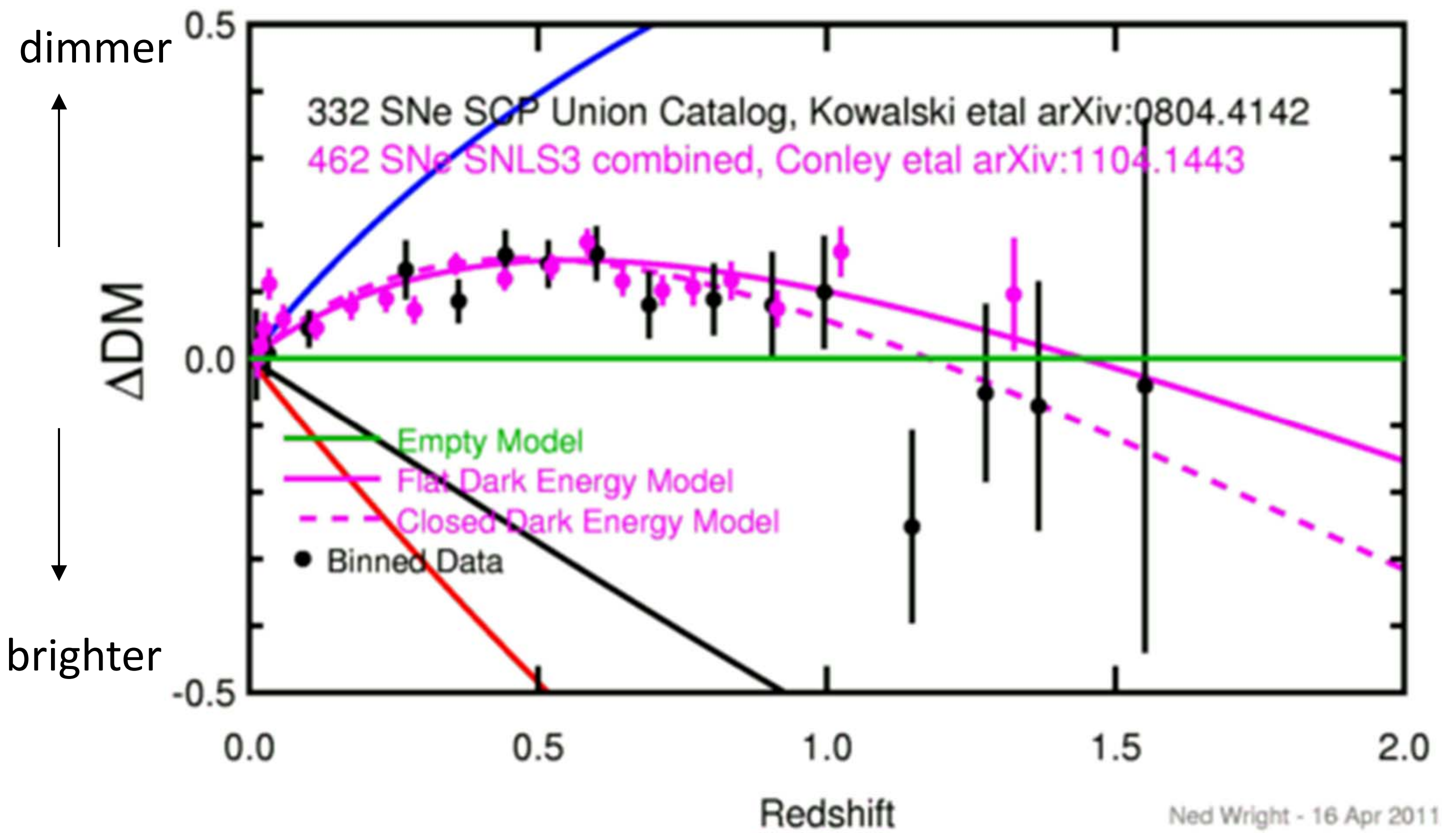
where v is the recession speed, D the distance to the object and H_0 the Hubble constant.

How do we know the expansion of the Universe is accelerating?

- The accelerated expansion was discovered in 1998, by two independent projects, the Supernova Cosmology Project and the High-Z Supernova Search Team
- Both used distant type Ia supernovae to measure the acceleration.
  - The idea was that these type 1a supernovae all have almost the same intrinsic brightness (a standard candle).
  - Since objects that are further away appear dimmer, we can use the observed brightness of these supernovae to measure the distance to them.
  - The distance can then be compared to the supernovae's cosmological redshift, which measures how fast the supernovae are receding from us.
- The unexpected result was that the universe seems to be expanding at an accelerating rate.
  - From the Wikipedia

Graph of relative brightness of Type 1A supernovae wrt redshift

Since type 1A supernovae all shine with the same brightness, the relative brightness is an indication of their distance to us. Dimmer means further away. Their redshift is an indication of the size of the Universe when they gave off the light. The dimmer SN above the green line mean that they are farther away than they would be if the Universe had not expanded an extra amount in the time it took the light to get to us. That is the acceleration of the expansion.



http://www.astro.ucla.edu/~wright/sne_cosmology.html

Caveats on Type 1A Supernovae

- Recent work from the Sloan Digital Sky Survey and others shows that there are several different mechanisms to produce Type 1A supernovae
- The downside of this is that the Type 1A supernova might lose its standing as a Standard Candle for measuring galactic distances
- This could change our view of Dark Energy
- There are new models that predict the expansion without invoking Dark Energy
  - Stay tuned!

So what do we know?

- We have an amazingly accurate model of the **~4.6%** of the Universe that we are made of: "normal" atoms
  - Quantum Electrodynamics (QED) is a fully relativistic theory of matter and electromagnetism
  - Theory tested out to 14 decimal places of accuracy!
- The whole model is called the "Standard Model" (We also know it is incomplete.)
- We don't know what dark matter or dark energy are

You're a ghost driving a meat coated skeleton made from stardust, what do you have to be scared of?