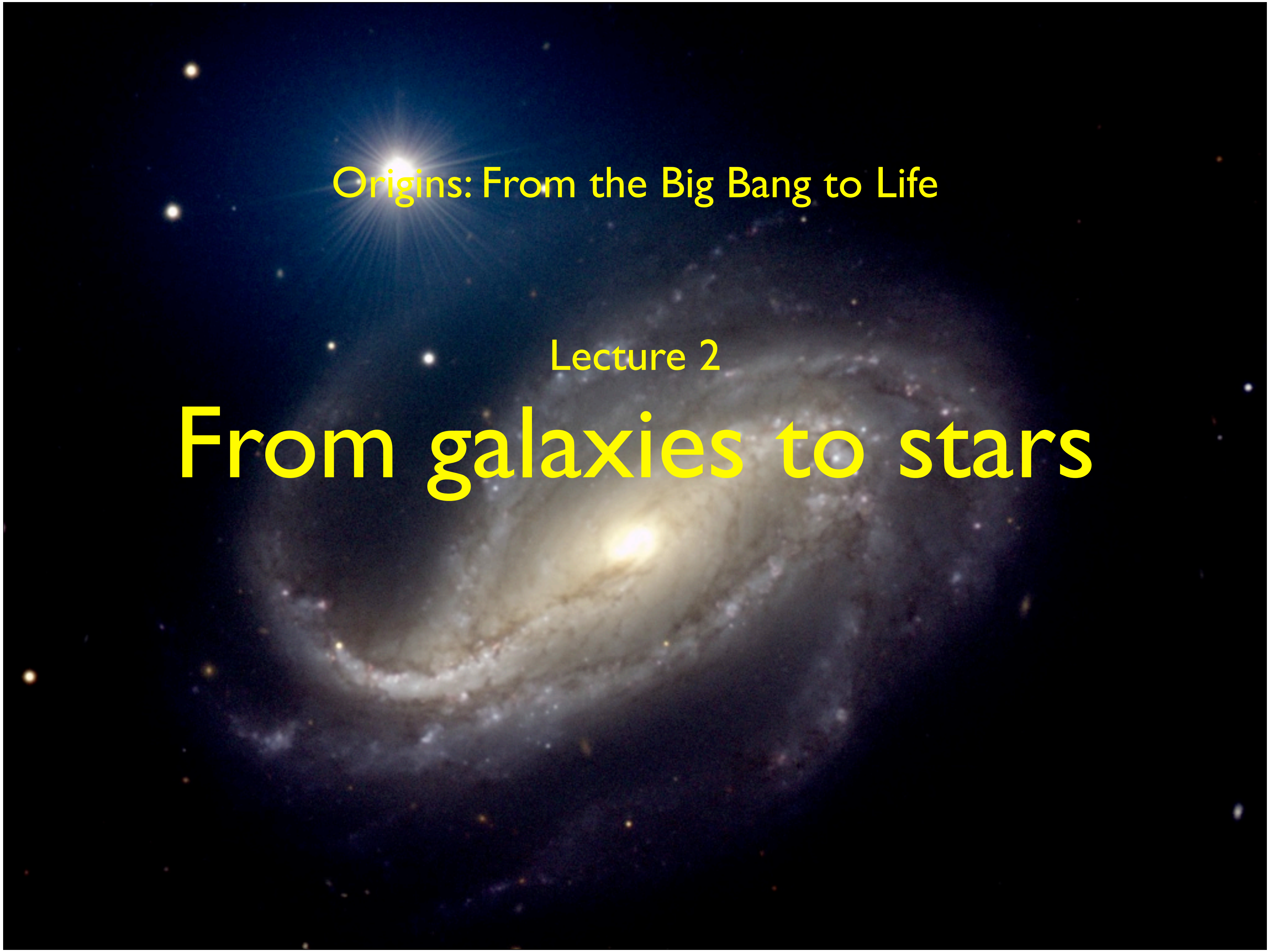

Origins: From the Big Bang to Life
Lecture 2
From galaxies to stars

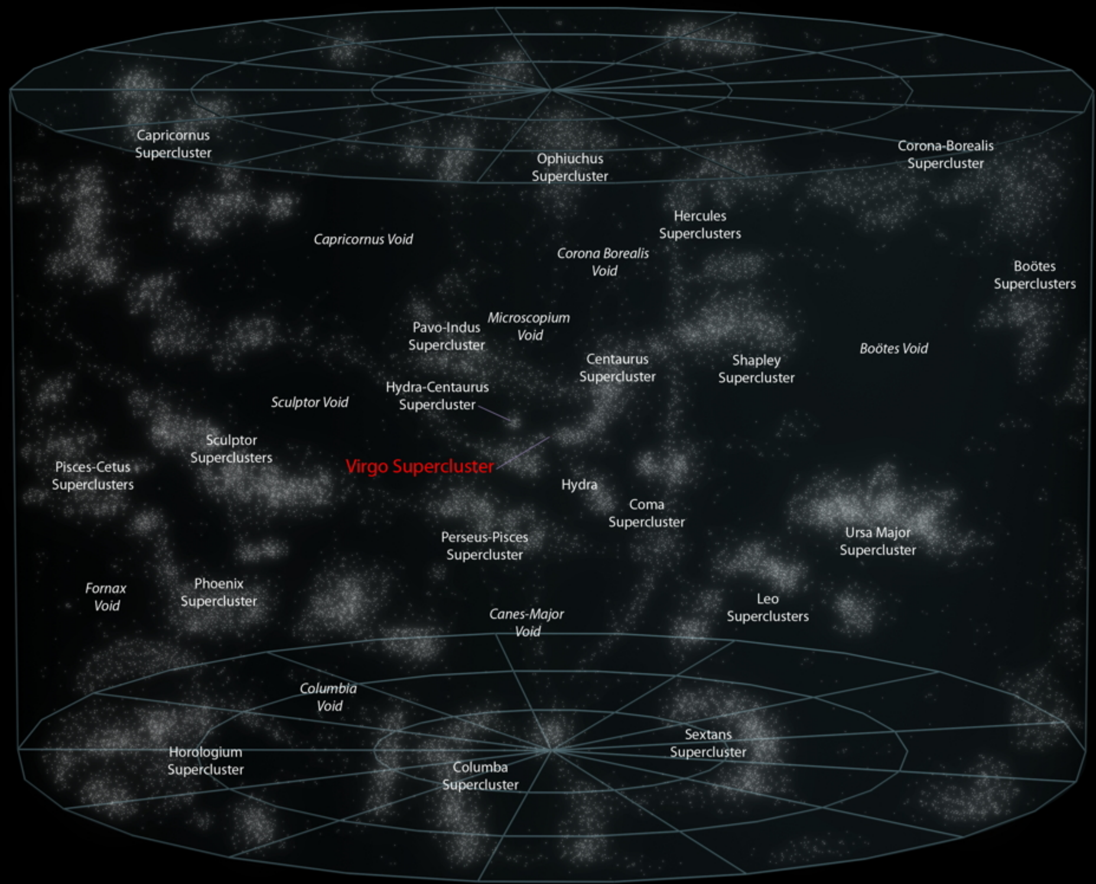
Last week, we talked about how galaxies formed via the merger of smaller galaxies, which both increased the mass of the galaxy and the mass of the black hole at its centre. This picture explains the elliptical galaxies very well.

The spiral galaxies, on the other hand, don't quite fit this picture.

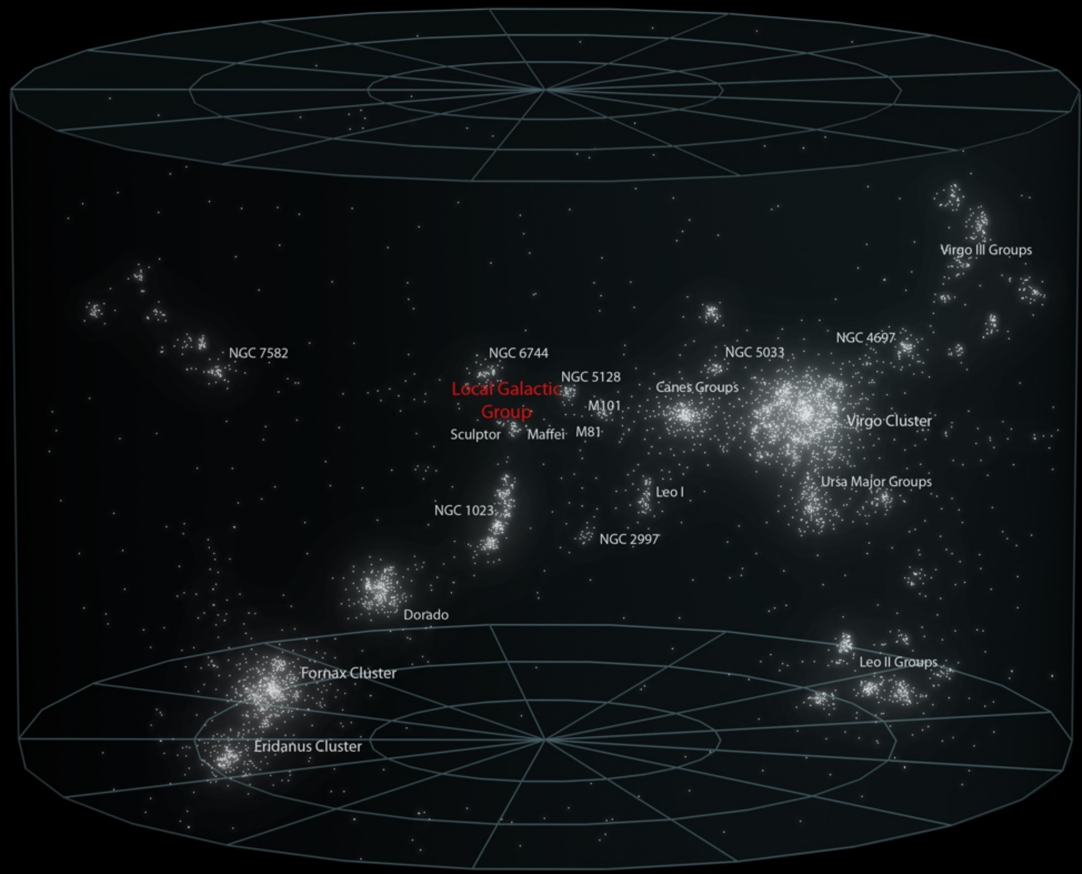
Tonight, we'll talk about how the Milky Way formed, and how stars began, how they live, and how in dying they enrich the Galaxy.

Our place in the universe

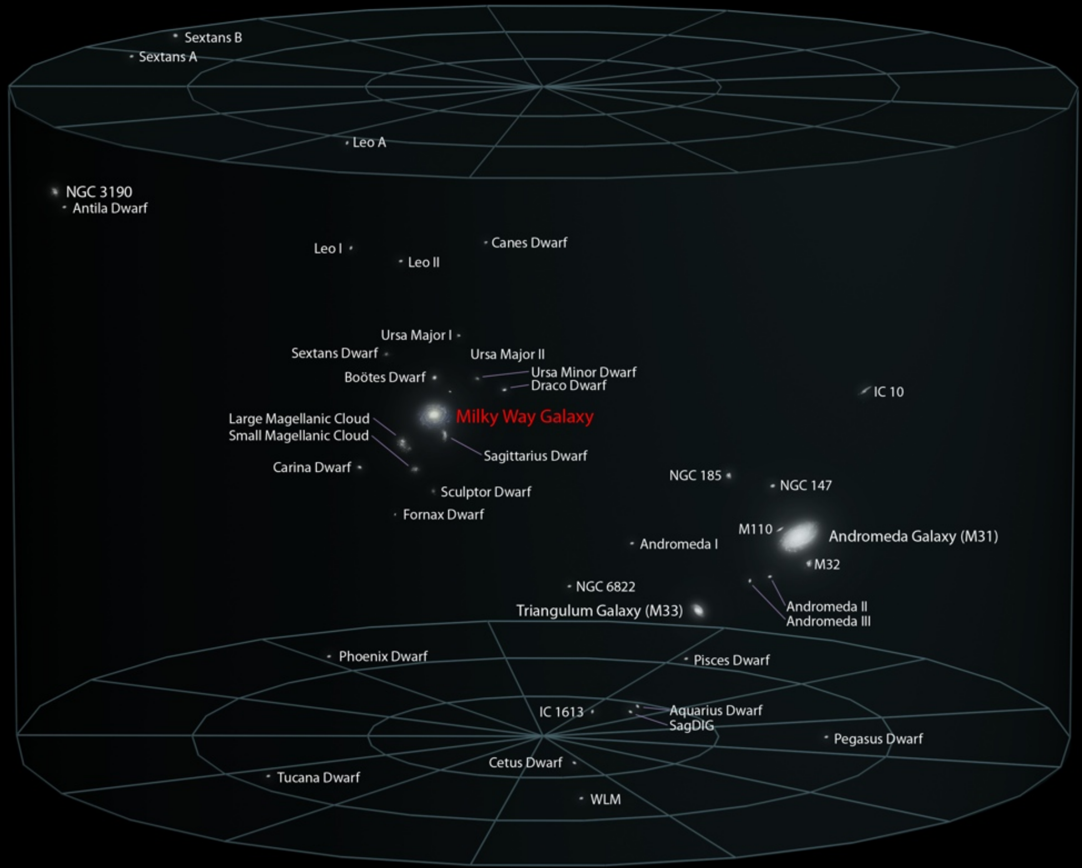
Amongst the hundreds of thousands of galaxy clusters in the Universe...



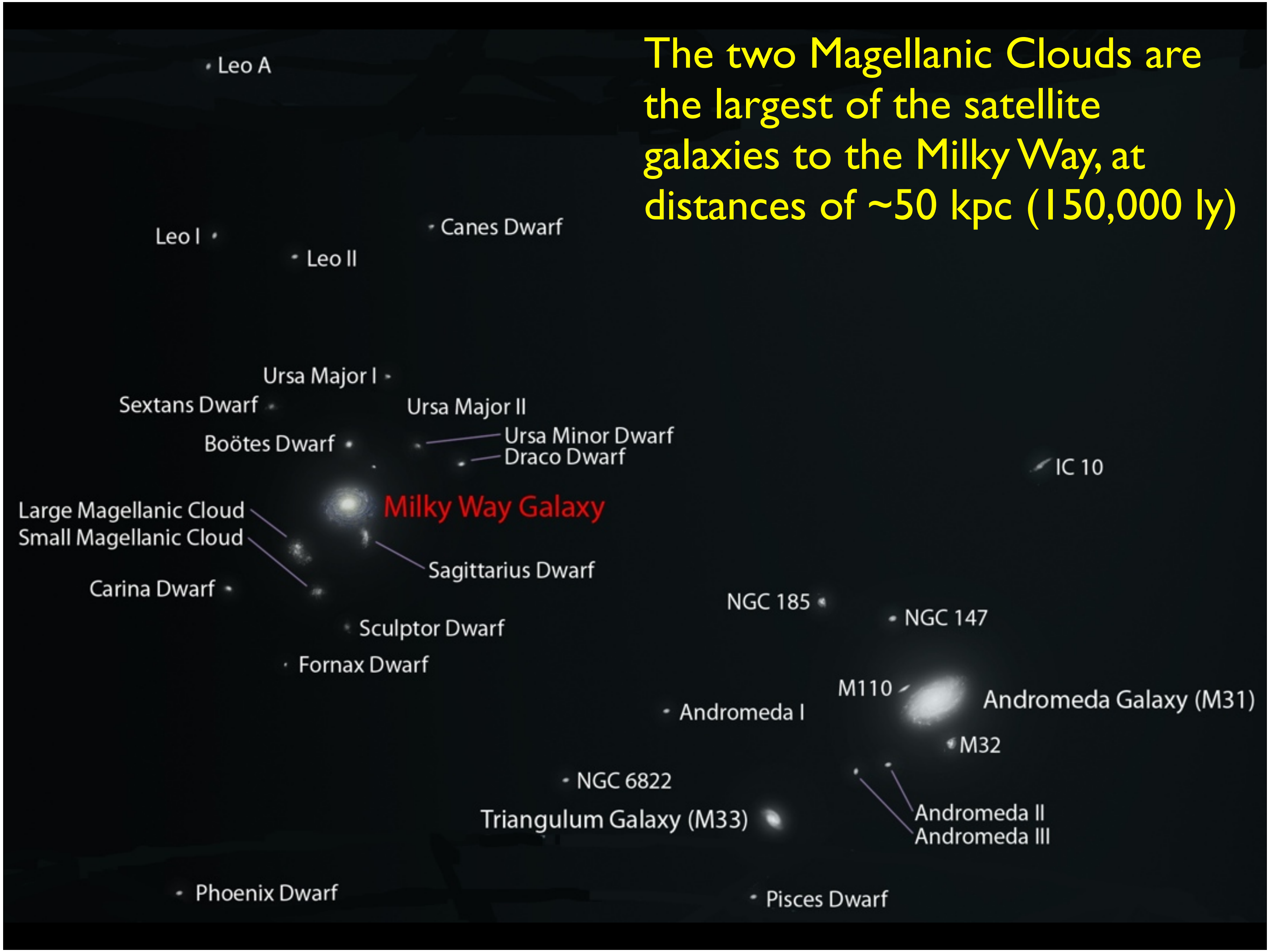
... we live at the outskirts of the *Virgo supercluster*, in one of many small groups of galaxies.



Our group of galaxies, the *Local Group*, contains two large spirals – Andromeda (M31) and our own Milky Way – with a few dozen smaller galaxies in two subgroups around them.



The two Magellanic Clouds are the largest of the satellite galaxies to the Milky Way, at distances of ~50 kpc (150,000 ly)



We cannot see the shape of our own Galaxy, but we have a good idea of what it looks like from looking at other nearby spirals. From face-on, we can clearly see the spiral arms, and the fact that the colours of the stars are very different in the disk and the bulge.

The spiral galaxy NGC 891

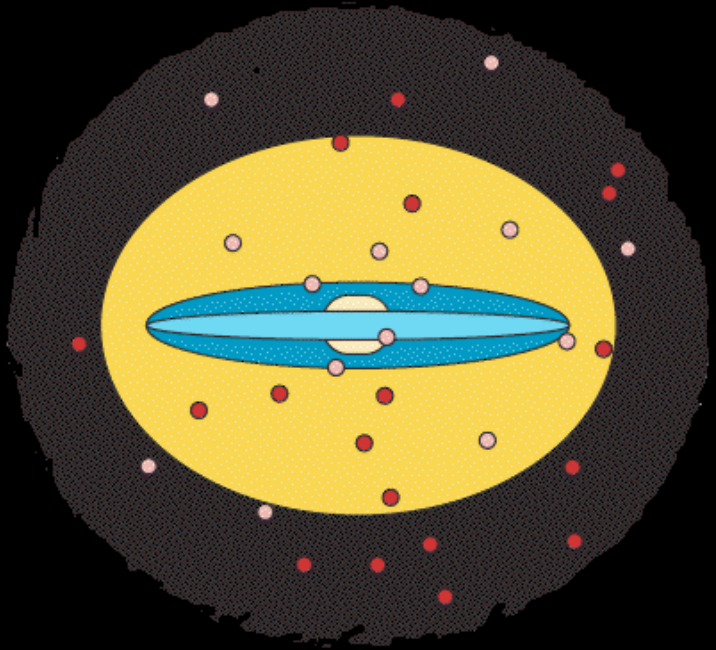
The edge-on spiral galaxy NGC 1232

Spirals viewed from the side show the characteristic "flying saucer" shape, with an extremely flat disk (cut by dark dust lanes) and a central bulge.

The Milky Way has several different regions which are quite distinct:

• the *bulge*: consists of old stars

• the *halo*: contains very few stars: most of the halo is made up of dark matter. Lying within the halo are the *globular clusters*, roughly spherical collections of up to a million stars, which appear to be the oldest objects in the Galaxy.



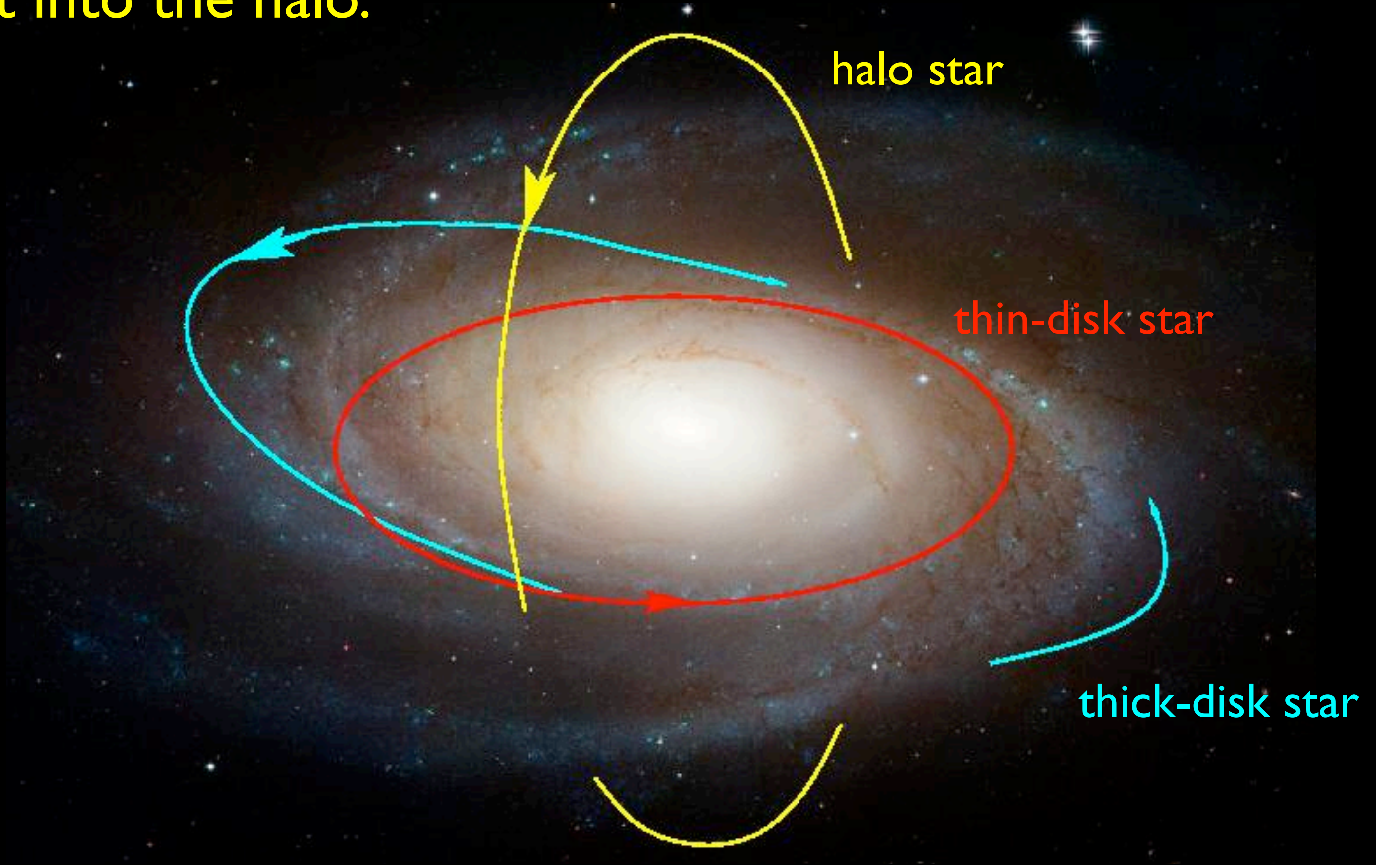
•the *spiral disk*, which can be separated into the *thin disk* and the *thick disk*

Schematic of Milky Way showing the stellar disk (light blue), the thick disk (dark blue), stellar bulge (yellow), stellar halo (mustard yellow), dark halo (black), and globular cluster system (filled circles). From Bland-Hawthorn & Freeman 2005.

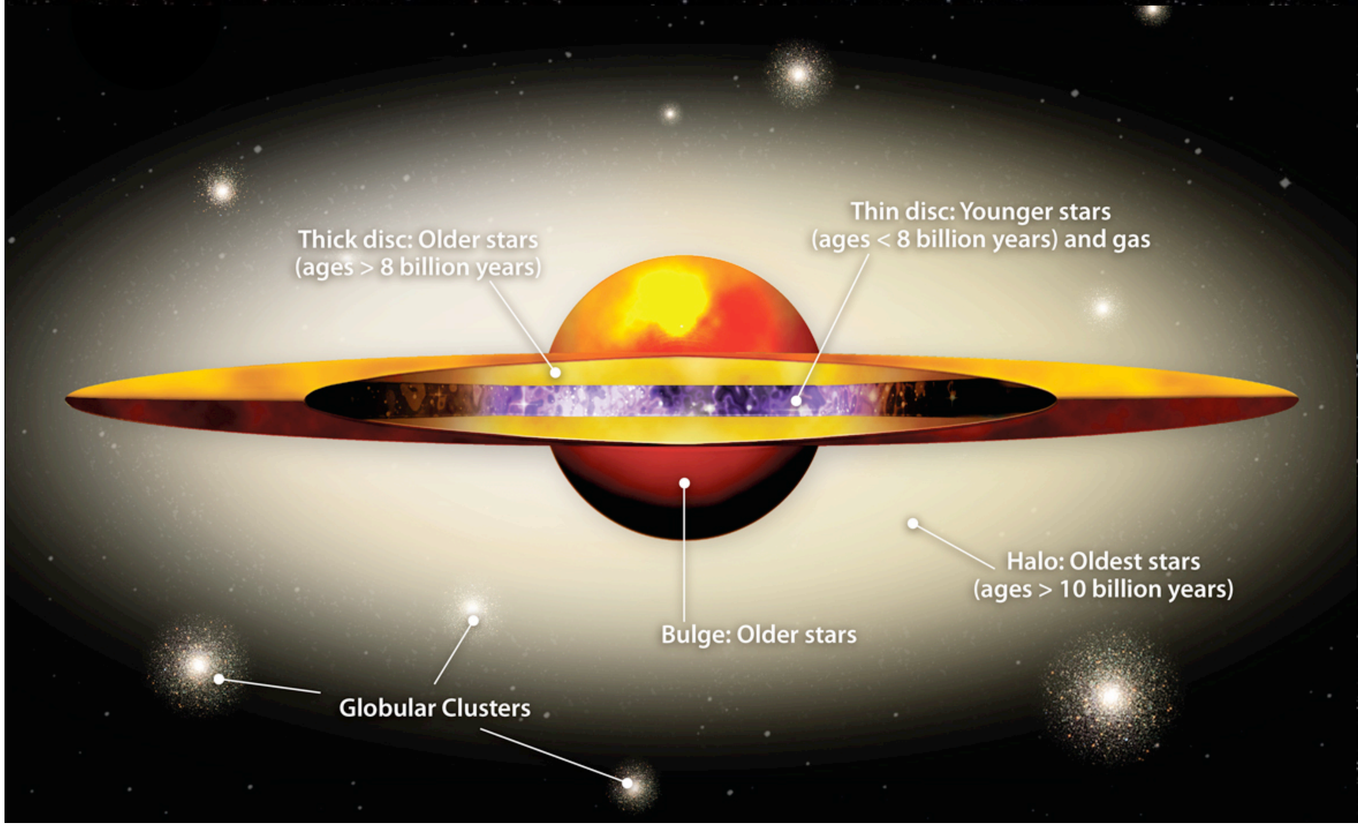
The thin disk extends about 1000 light years above and below the Galactic plane, and is responsible for about 90% of the light of the Galaxy. The thick disk is about 3.5 times as thick, but contains much older, fainter stars so contributes much less light.

It was not until the orbits of large numbers of stars were determined that these two components could be properly distinguished.

The orbits of stars in these different regions are very different. *Thin-disk stars* have circular orbits almost completely in the plane. *Thick-disk stars* have orbits that take them up to 1 kpc (3000 ly) above and below the plane. *Halo stars* are on highly eccentric orbits that take them plunging through the disk and out into the halo.

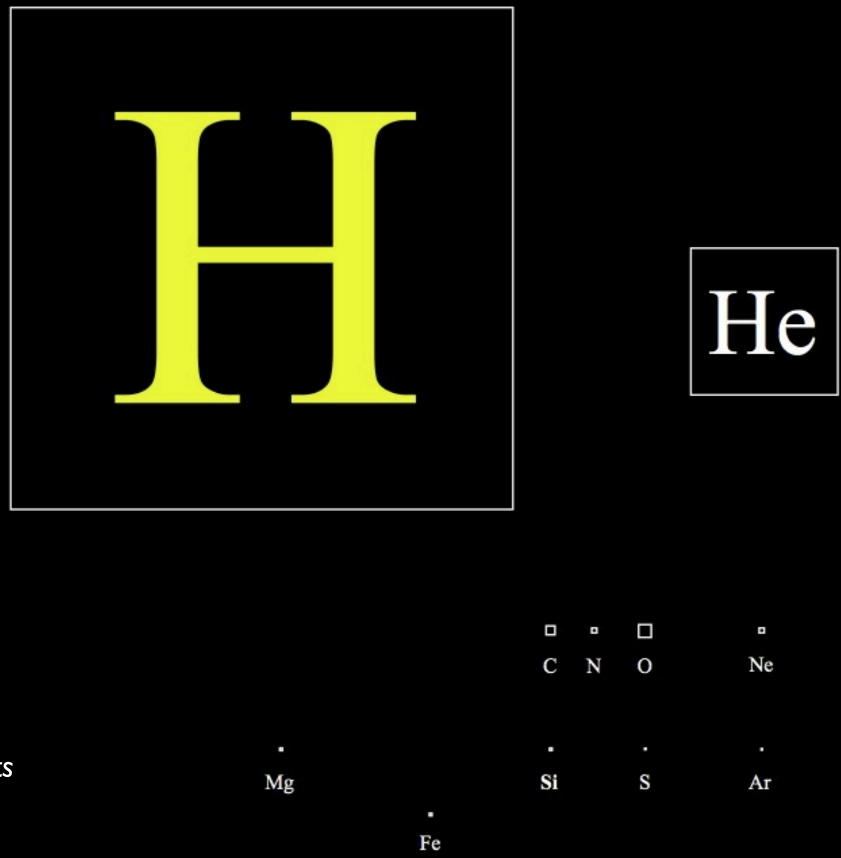


The composition of stars in the different populations are also different from each other. The stars of the halo are very metal-poor, those of the thin disk metal-rich and young, while the stars of the thick-disk have intermediate metallicity and age.



Aside: To an astronomer, every element other than hydrogen and helium is called a *metal*, so oxygen and carbon are described as metals. We saw last week how only hydrogen and helium were made in the Big Bang, so the first generation of stars, made from the primordial gas of hydrogen and helium, was metal-free.

These two elements are still by far the dominant components of the Universe: other elements are less than one-thousandth as abundant as hydrogen.

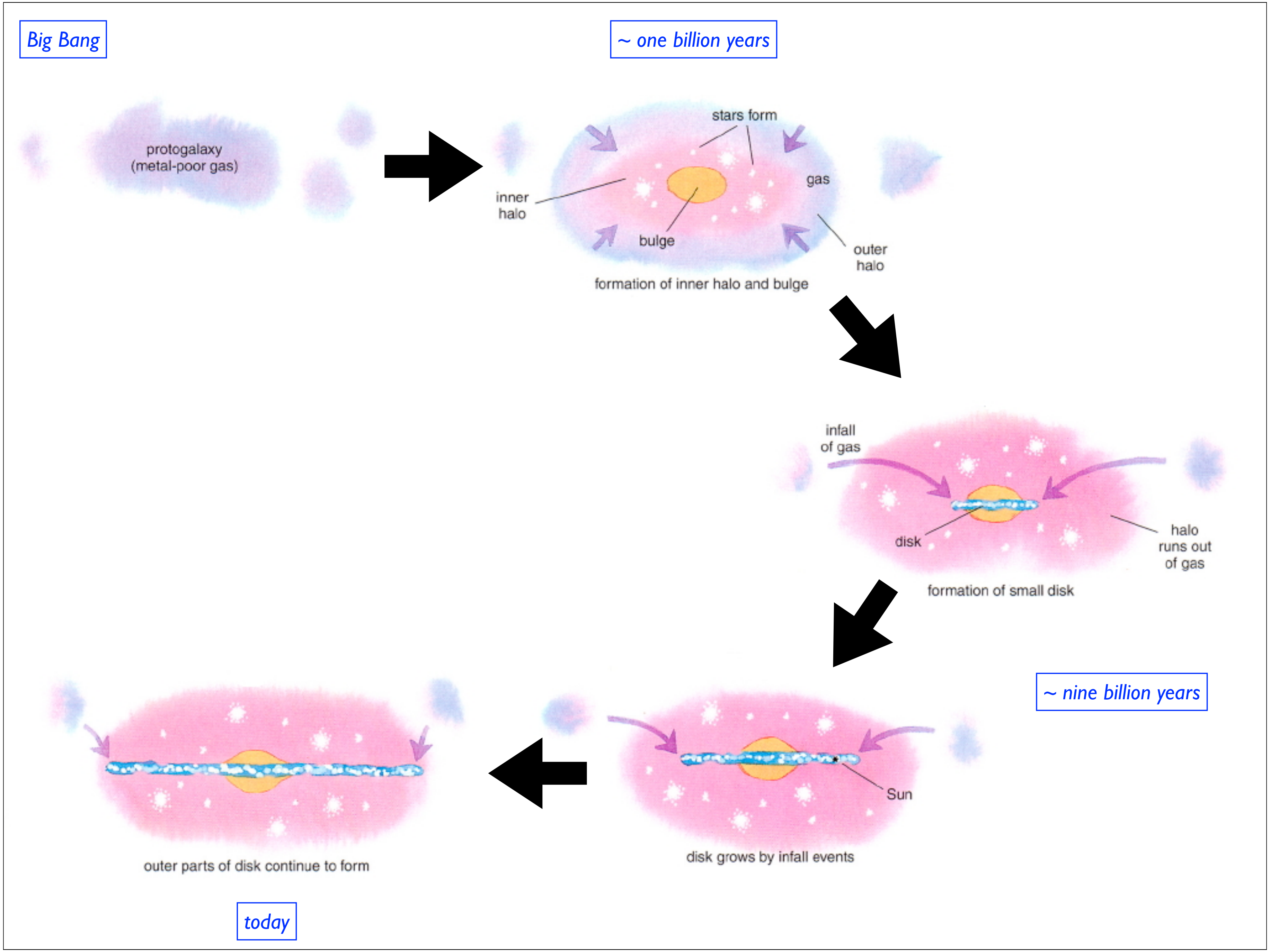


The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight. (Figure by Ben McCall)

However, as we will see, each generation of stars polluted the interstellar gas with materials made during its lifetime, so later generations of stars contained more and more heavy elements. By measuring the *metallicity* of a star – the relative abundance of (say) carbon or iron – we can have a good idea of how pristine the gas from which it formed was.

Since we think that galaxies were assembled by the merging of different clumps, it seems likely that these different populations of stars came from different events.

One model suggests that the halo and bulge formed from the collapse of the initial cloud. Later, about 10 billion years ago, there was another accretion event – the collision of a satellite galaxy – which formed the thin disk. The disk has been growing ever since as gas is accreted at the edges.



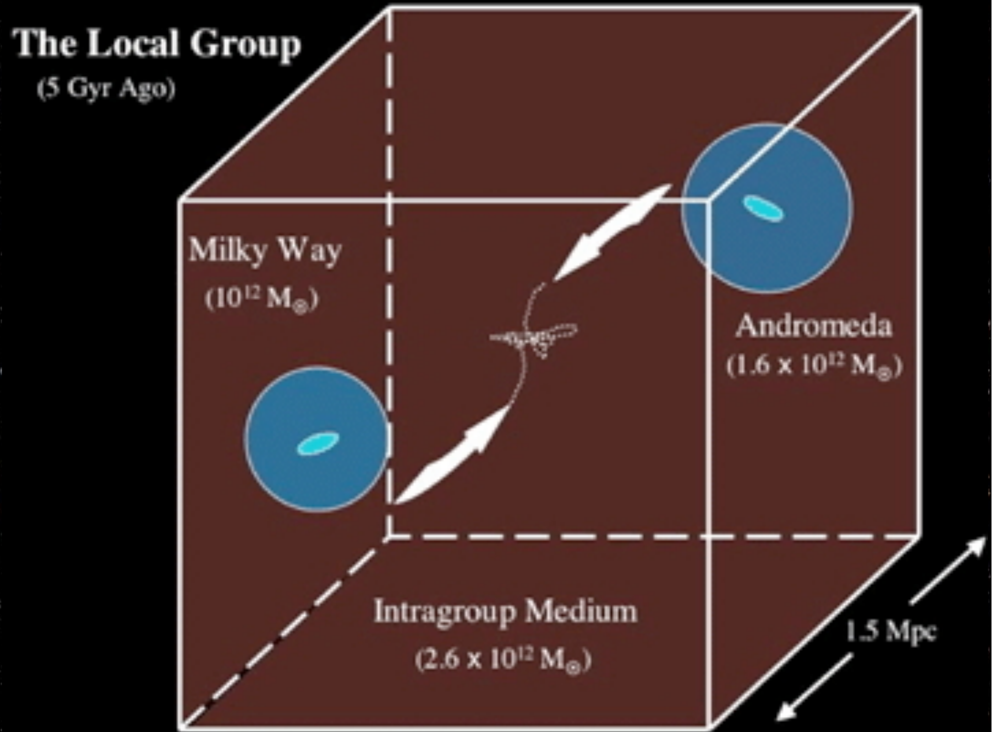
Big Bang
~ one billion years
protogalaxy
(metal-poor gas)
stars form
gas
inner halo
bulge
outer halo
formation of inner halo and bulge
infall of gas
disk
halo runs out of gas
formation of small disk
~ nine billion years
Sun
disk grows by infall events
outer parts of disk continue to form
today

The globular clusters may be the intact remnants of smaller galaxies which merged with the Milky Way very early in its life.

The globular cluster Omega Centauri, the most massive cluster in the Galaxy.

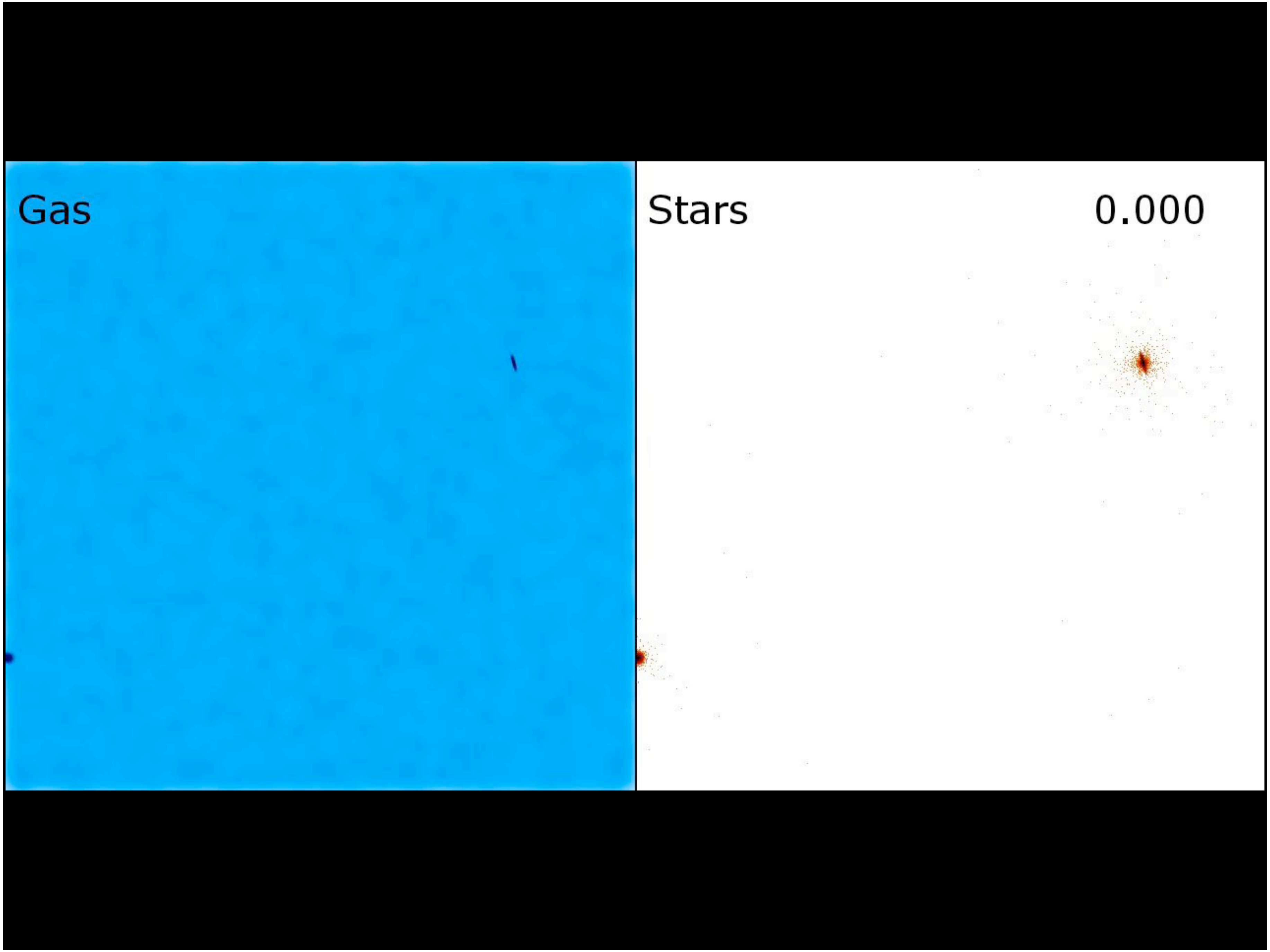
So the Milky Way hasn't had a major merger with another galaxy for about 10 billion years. Perhaps this is why it has a relatively small black hole at its centre.

On the other hand, we now know that the Milky Way and Andromeda will collide and merge in about 3 billion years.



Sketch of the merging of the Milky Way and Andromeda (from Cox & Loeb 2008)

Colliding spiral galaxies NGC 2207 and IC 2163.

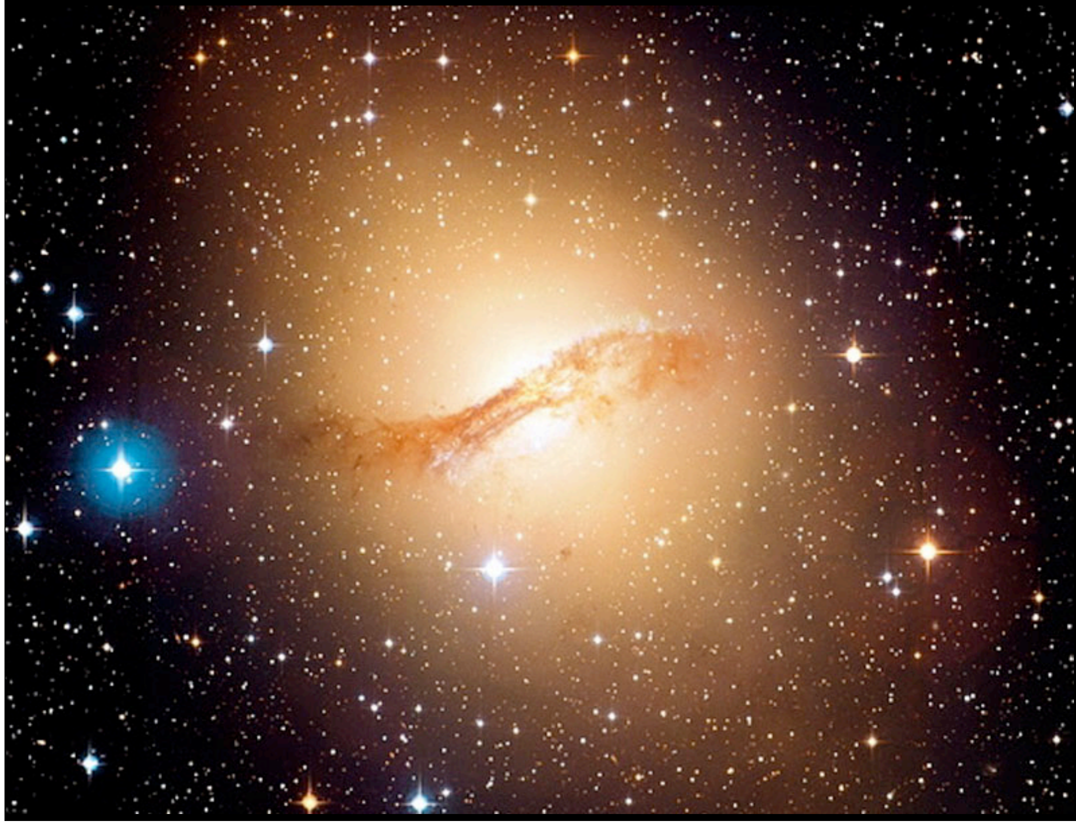

Gas
Stars
0.000

During the interaction, the likelihood that any stars will collide is vanishingly small. However, the gas clouds will collide and the galaxies will merge. Some stars will be thrown out of the galaxy in long tidal streams: this could well be the fate of the Sun.

The pair of merging galaxies known as the "Mice", NGC 4676

After several diminishing orbits, the remains of the two galaxies will coalesce into a giant elliptical galaxy, with all spiral structure destroyed: this has been called *Milkomeda*.

Possibly it will also have a dust lane running through it as a reminder of its merger past...

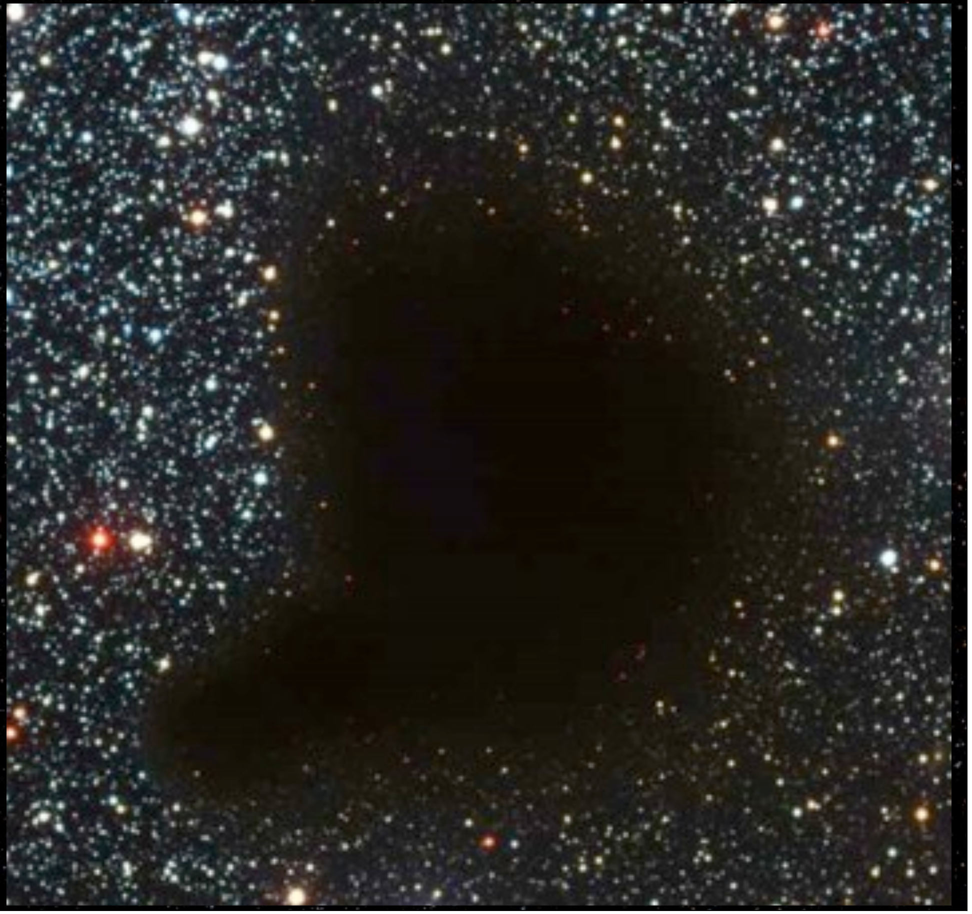


The elliptical galaxy Centaurus A (NGC 5128); the dark dust lane across its middle is all that remains of a spiral galaxy devoured less than a billion years ago.

[redacted]

Let's step back a bit to where the initial clouds were starting to collect in the young galaxy. Just like the Cosmic Web, gravity pulls the gas into denser and denser clumps. By the time our Galaxy is forming, this gas has already been enriched by material from the first stars. The gas coalesces in giant clouds, many light years across.

Star formation takes place in the coldest, darkest regions called *dark nebulae*.



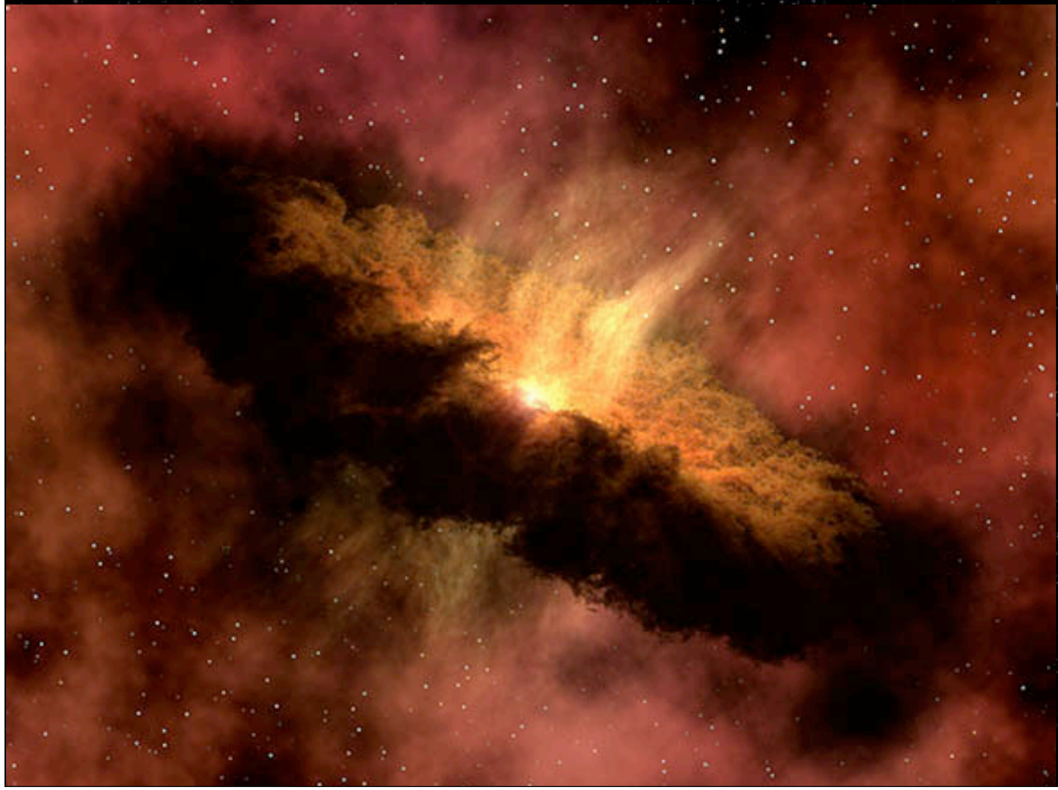
Molecular cloud Barnard 68.


The Coalsack Nebula

Orion and the Horsehead Nebula

The *Hubble* view of the nebula shows the intricate structure of the cloud, with a young star still embedded in the nebula at top left.

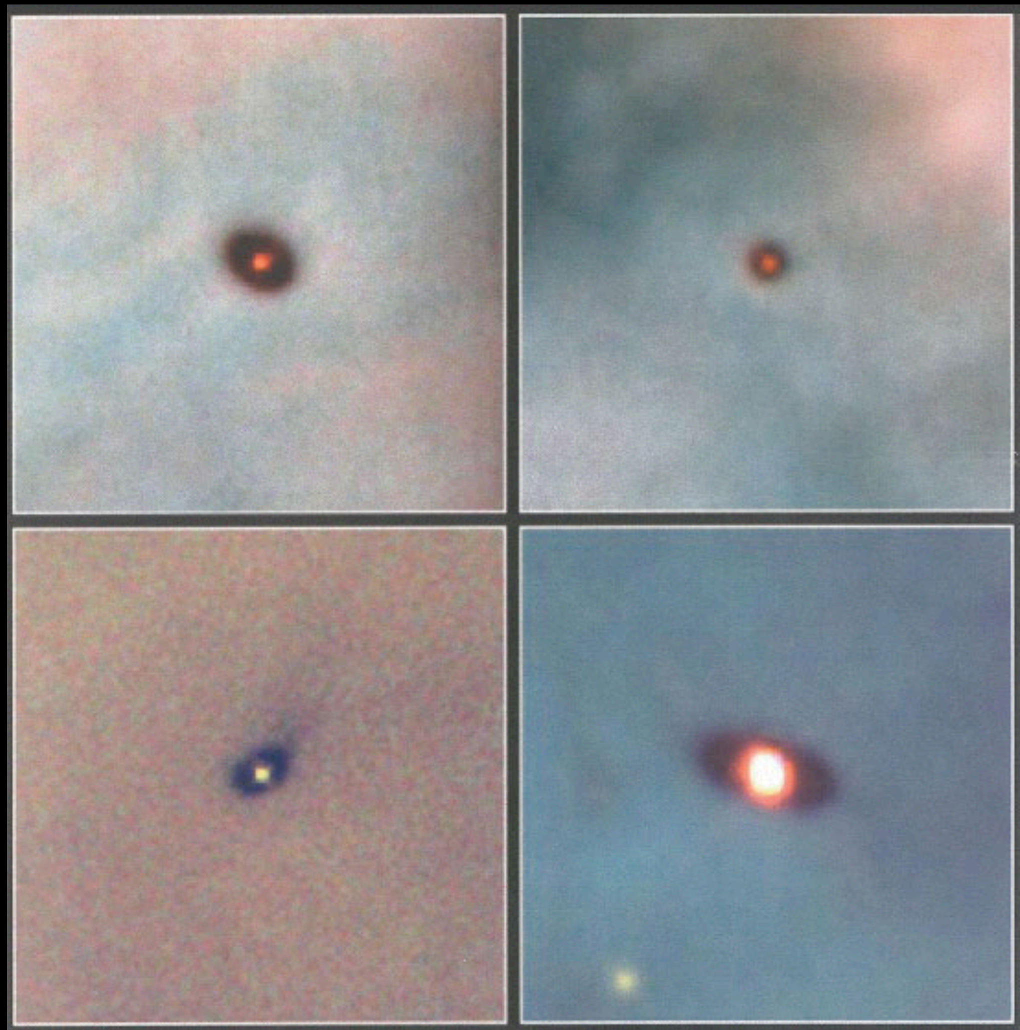
The collapsing cloud breaks into hundreds of fragments, each of which continues to collapse. As the fragment collapses, it tends to flatten into a disk. The central region collapses fastest, and begins to heat up: the cloud is collapsing from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud.



This then causes both the temperature and pressure to rise rapidly. The collapsing cloud is now a *protostar*, surrounded by a disk of gas.

Artist's impression of a young star surrounded by a dusty protoplanetary disk.

We can actually see these disks around newborn stars.



Hubble images of proto-planetary disks in the Orion nebula

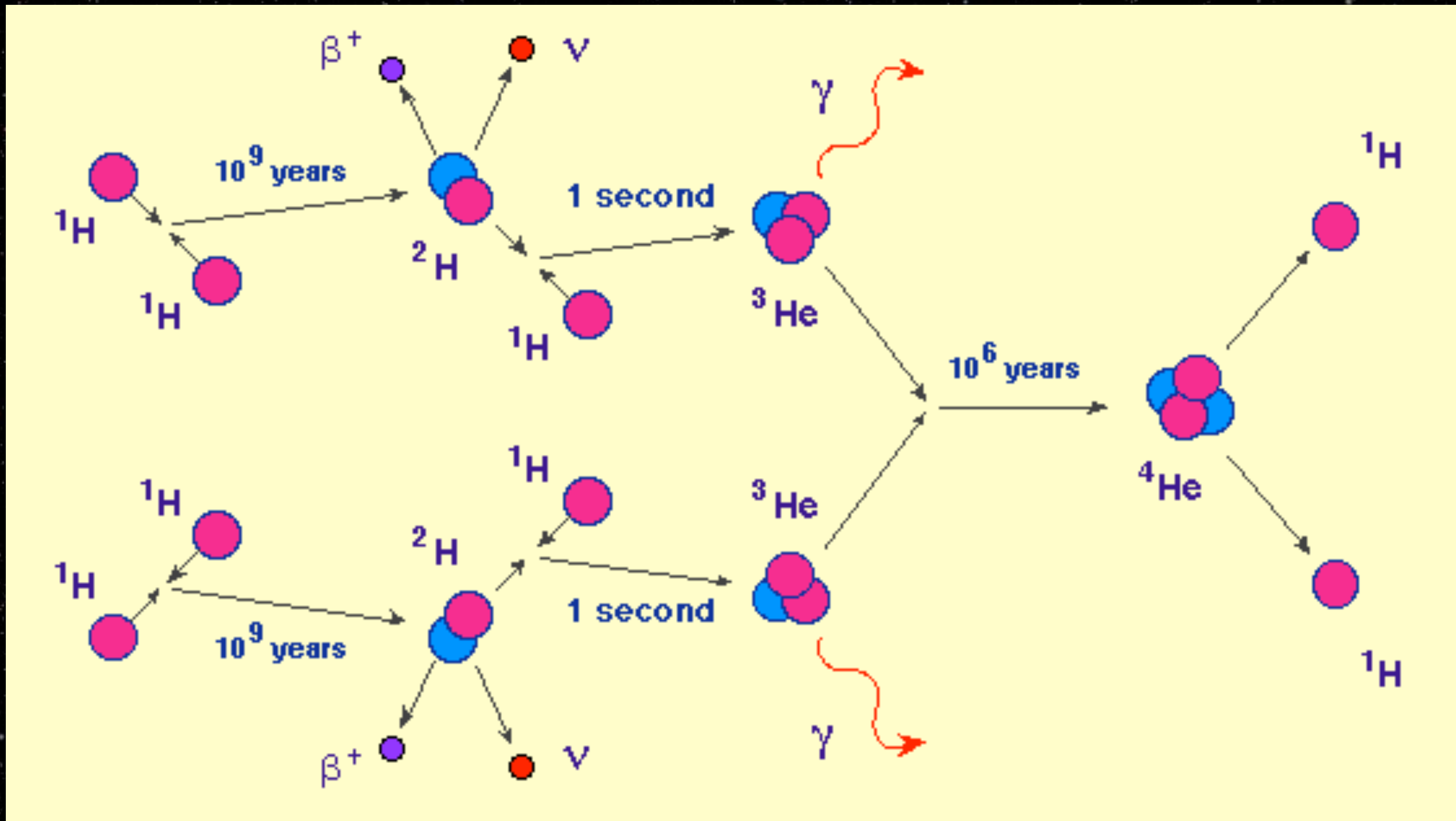
These disks will eventually be where planets form.

In the meantime, the protostar is continuing to contract and heat up. Eventually, the temperature in the core of the star becomes hot enough that hydrogen can fuse to form helium, just as it did in the first three minutes after the Big Bang. This fusion adds extra energy to the core, which halts the collapse. A star is born.

All around, the other cloud fragments are also collapsing and forming stars, so our newborn star is in a cluster of young stars.

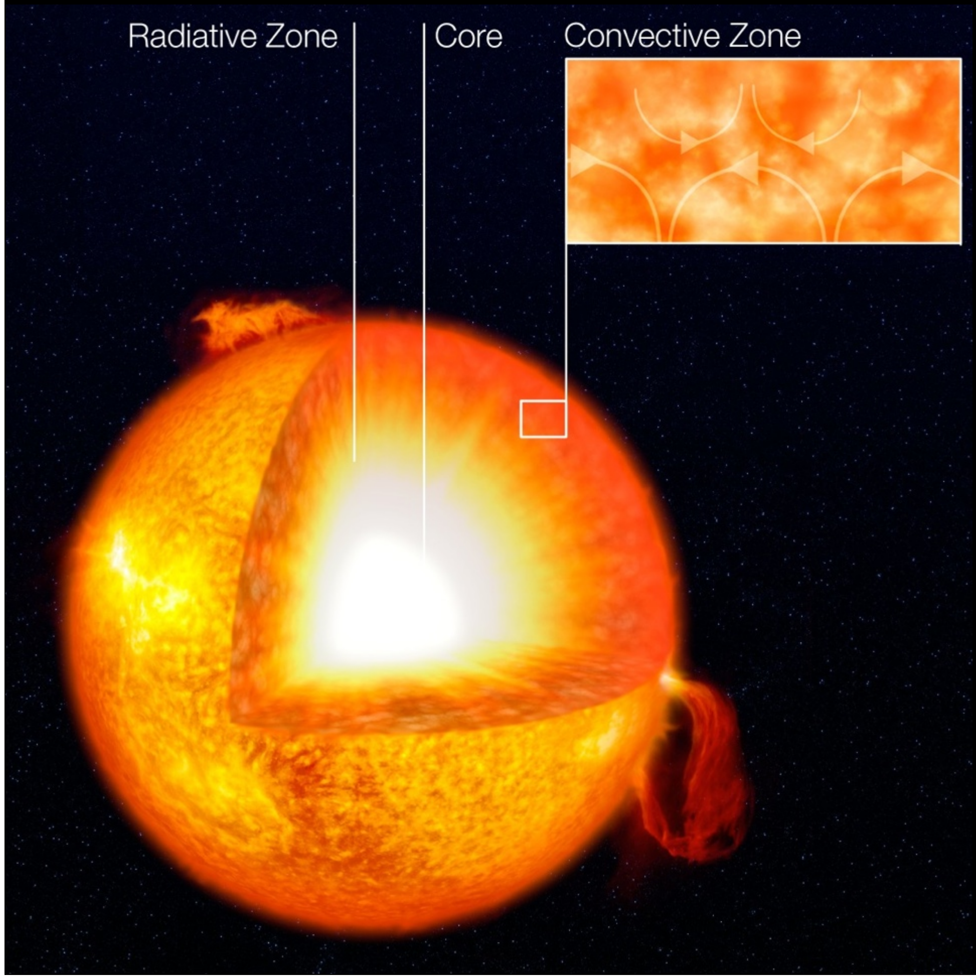
Star-forming region NGC 602

Now the star can settle down to life on the *main sequence*. Fusing hydrogen to helium in its interior, it can produce energy steadily for millions of years.

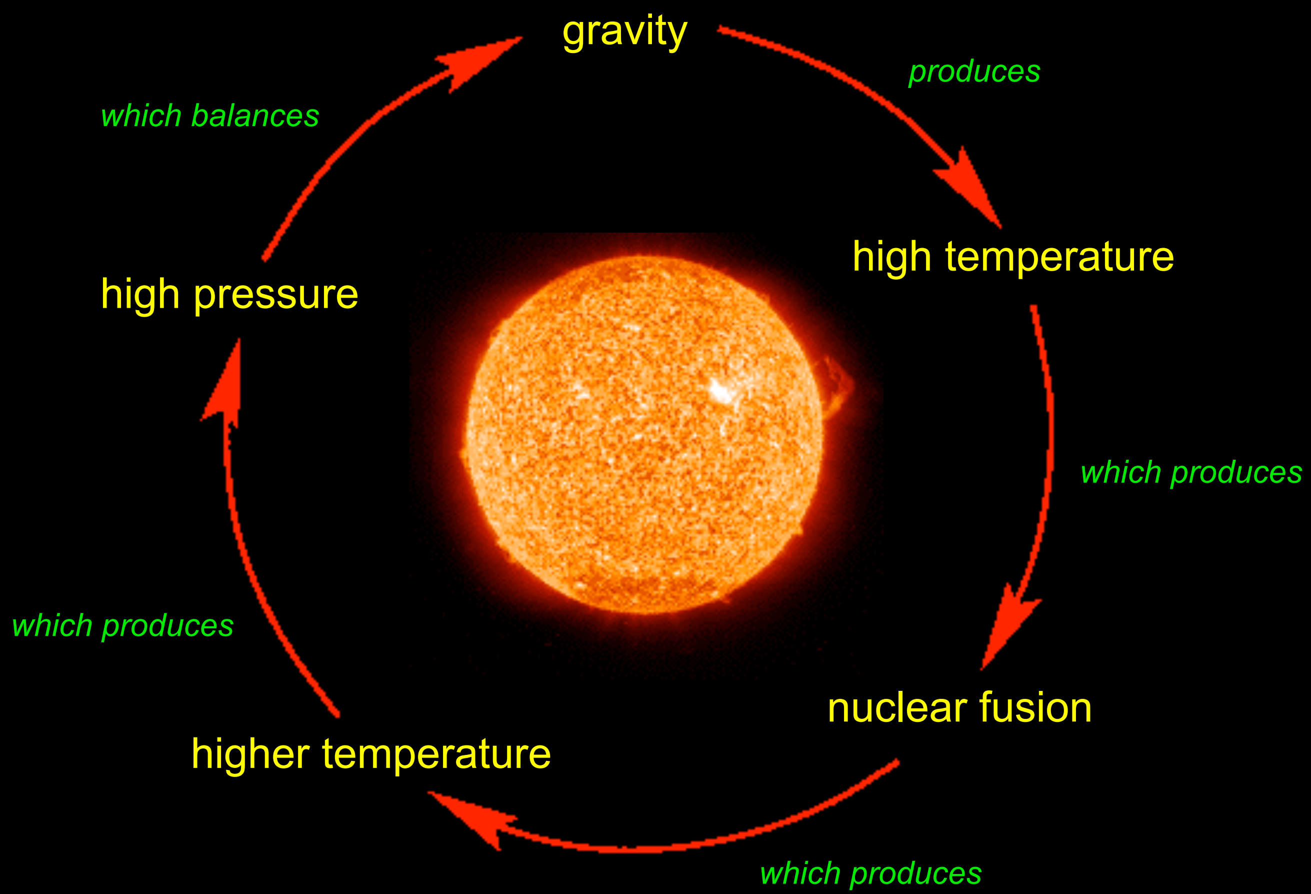


Four hydrogen atoms fuse to one atom of helium, and the reaction takes place in several steps.

Fusion only takes place at temperatures higher than a few million degrees. Only the core of the star is this hot – the surface of the Sun, for instance, is at a temperature of 5800 K, while even the hottest O-type stars are at ~100,000 K – so fusion only takes place in the core. Energy then leaks out to the surface via radiation and/or convection.



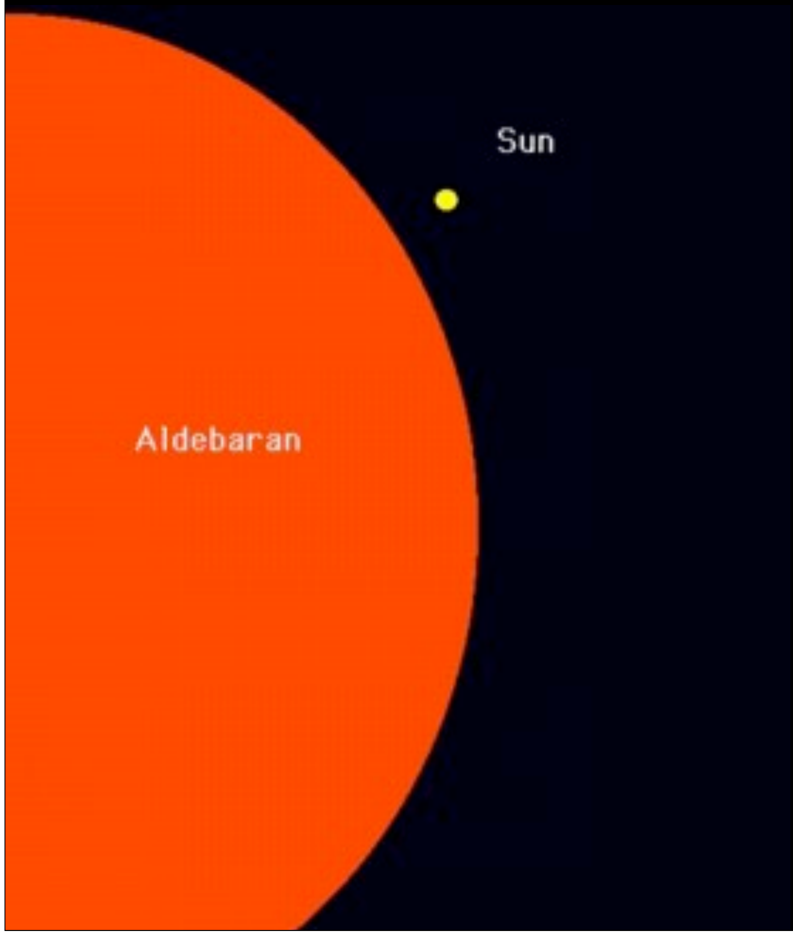
The energy produced in the star's core produces enough outward pressure to balance the inward pull of gravity.



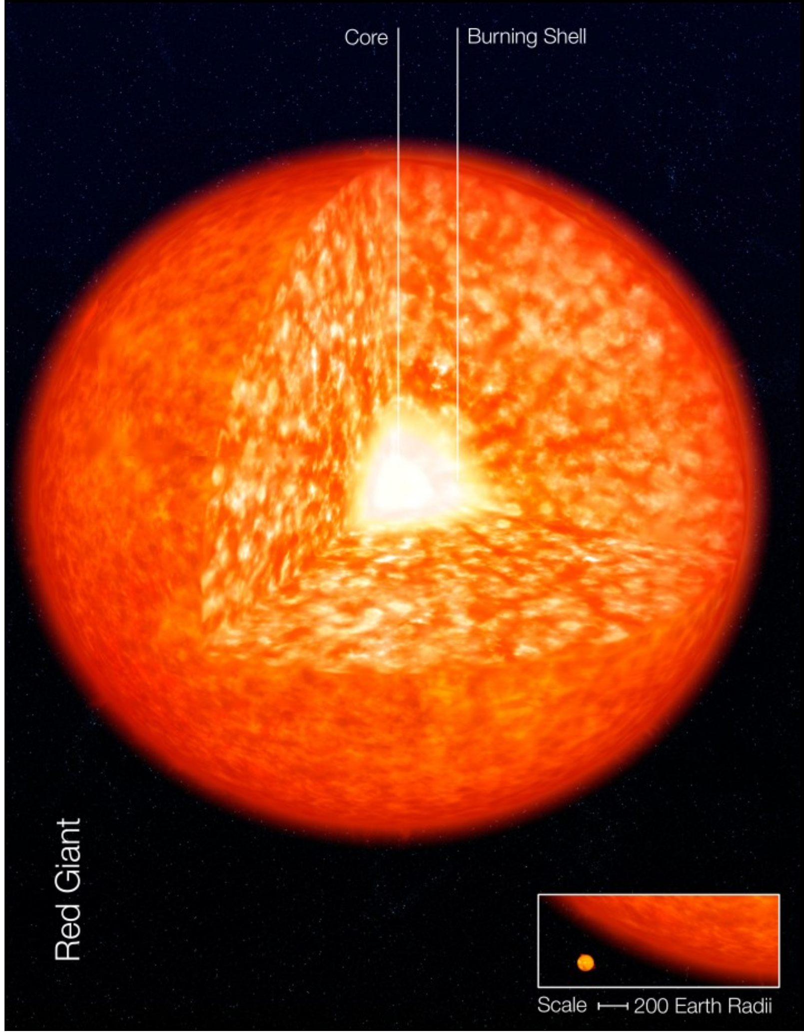
However, the star is only stable as long as it is producing energy in its interior. When the star runs out of hydrogen in its core, its life as a main sequence star is finished.

What happens next is a complicated dance as the star tries to hold off gravity, which is trying to make it collapse.

Once fusion stops, the core begins to collapse, and as it does so, it contracts and heats up. This extra heat forces the outer layers of the star to expand dramatically: it becomes a *red giant*. The star swells up to as much as 100 times its previous size, and as it expands the outside layers cool.



Down in the core, however, the temperature continues to rise. Eventually, the temperature reaches 100 million degrees, and helium begins to fuse to form carbon.



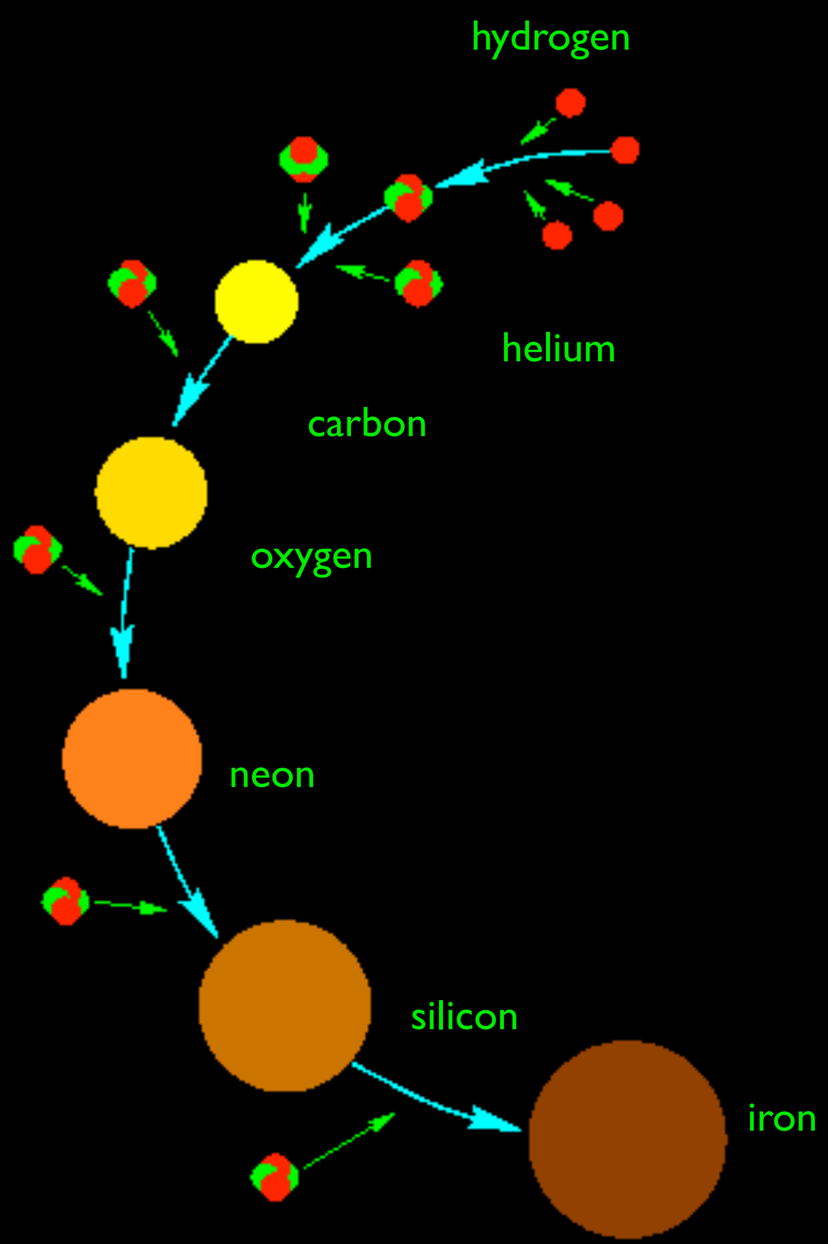
But this too cannot last forever. Eventually – and in less time – the core runs out of helium, and the star starts to collapse again.

If the star is a similar size to our Sun, then the core never gets hot enough for the next ignition stage. Instead, the star ejects its outer layers in a series of belches, and this gas expands into space. Lit by the central remnant, which is now a white dwarf, we see this glowing gas as a *planetary nebula*.

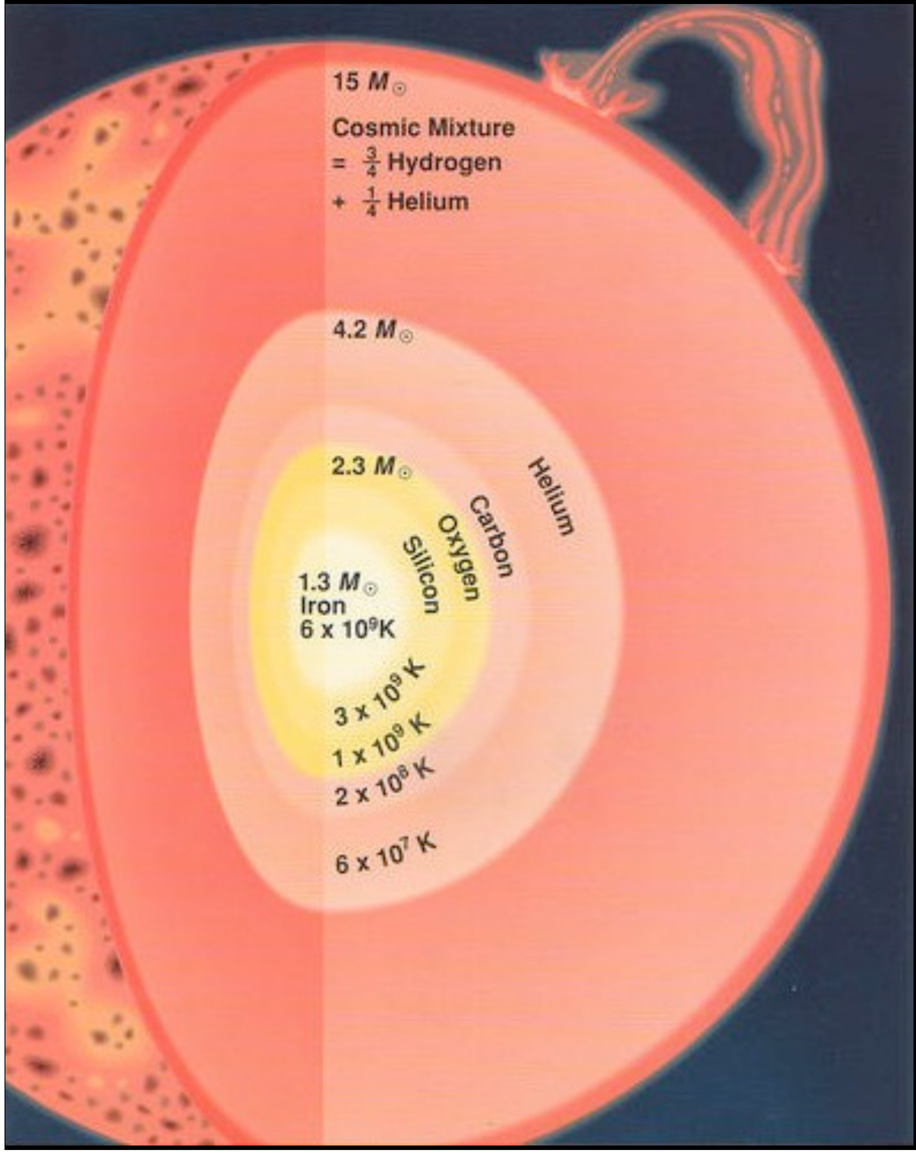
The Helix nebula

The Spirograph Nebula, IC 418

The Cat's Eye nebula,
NGC 6543



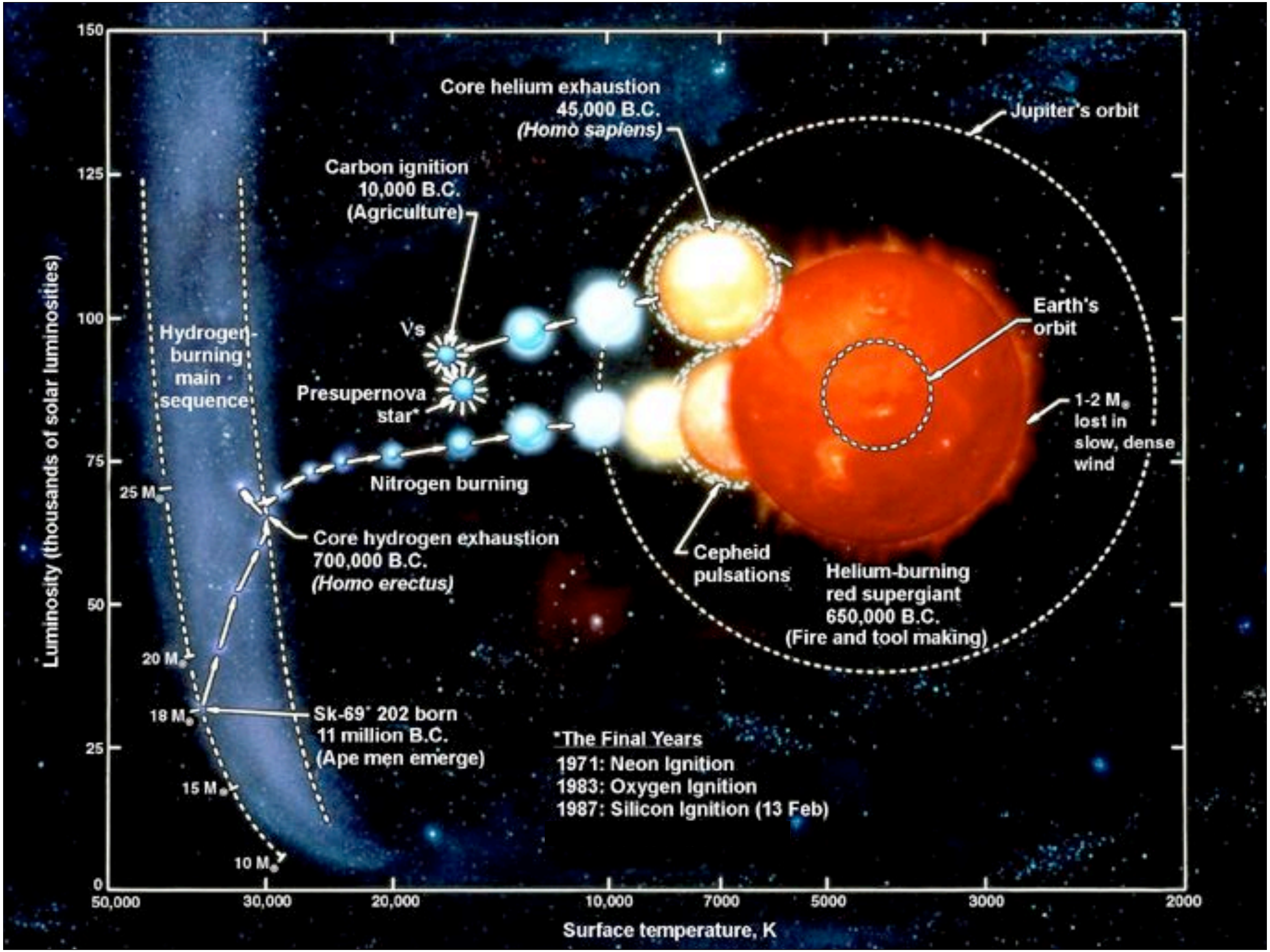
More massive stars, however, have strong enough gravity that their core can reach higher and higher temperatures. Element after element is ignited, then exhausted, until the chain reaches iron.



After iron, however, there is no more energy to extract from fusion.

Once the silicon in the core has fused to make iron, the star can no longer support itself against collapse.

The star is doomed: it begins to collapse for the last time.



Luminosity (thousands of solar luminosities)
150
125
100
75
50
25
0
Surface temperature, K
50,000
30,000
20,000
10,000
7000
5000
3000
2000
Core helium exhaustion
45,000 B.C.
(Homo sapiens)
Jupiter's orbit
Carbon ignition
10,000 B.C.
(Agriculture)
Vs
Hydrogen-burning main sequence
Presupernova star*
Earth's orbit
1-2 M lost in slow, dense wind
Nitrogen burning
25 M
Core hydrogen exhaustion
700,000 B.C.
(Homo erectus)
Cepheid pulsations
Helium-burning red supergiant
650,000 B.C.
(Fire and tool making)
20 M
18 M
Sk-69° 202 born
11 million B.C.
(Ape men emerge)
15 M
10 M
*The Final Years
1971: Neon Ignition
1983: Oxygen Ignition
1987: Silicon Ignition (13 Feb)

The core can no longer support itself. Electrons are forced to combine with protons to form neutrons, and the whole core compacts down to a ball of neutrons only 20 km across: a *neutron star*.

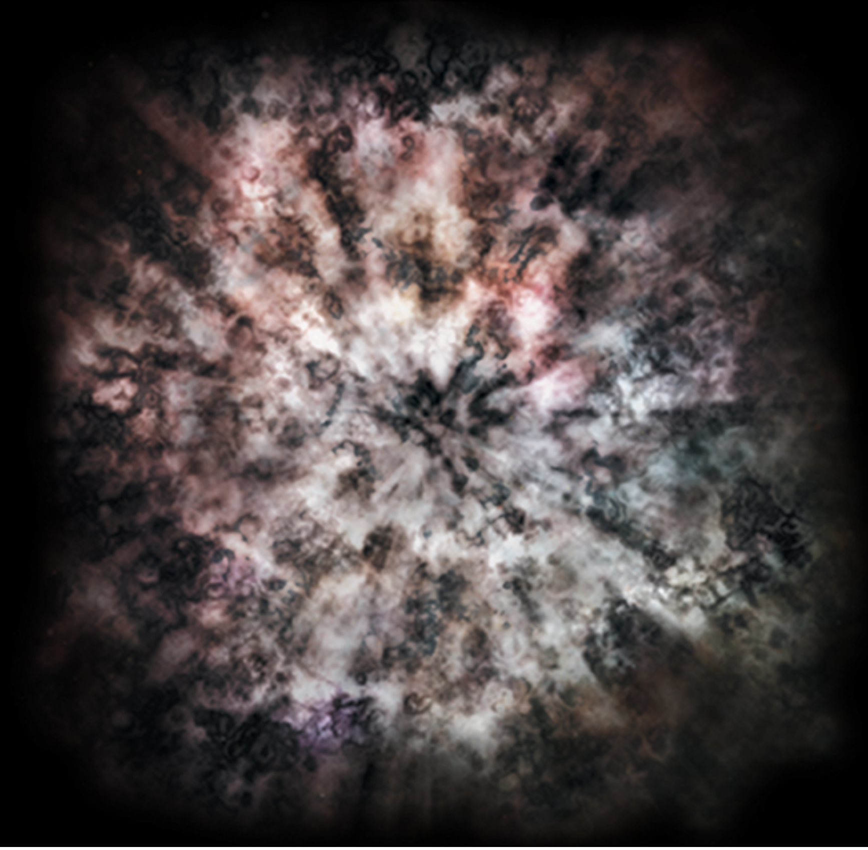
Meanwhile, the outer layers of the star fall inwards until they hit the newborn neutron star. When they meet the core they “bounce” off it so hard that they are ejected outwards in blast wave which explodes the rest of the star outwards.

When the blast wave reaches the surface of the star, we see a *supernova* explosion.

SN 1987A, 23 February 1987, the closest supernova to the Earth in more than 400 years.

Animation of a supernova explosion like that which formed the Cassiopeia A supernova remnant.

The supernova explosion expels into interstellar space not only the elements formed inside the star, but elements forged in the supernova blast wave itself. In the explosion, nuclei are bombarded with neutrons, until elements all the way up to uranium are formed within seconds.



All these heavier elements are then spread throughout the galaxy by the immense force of the supernova.

The Vela supernova remnant, image by Robert Gendler

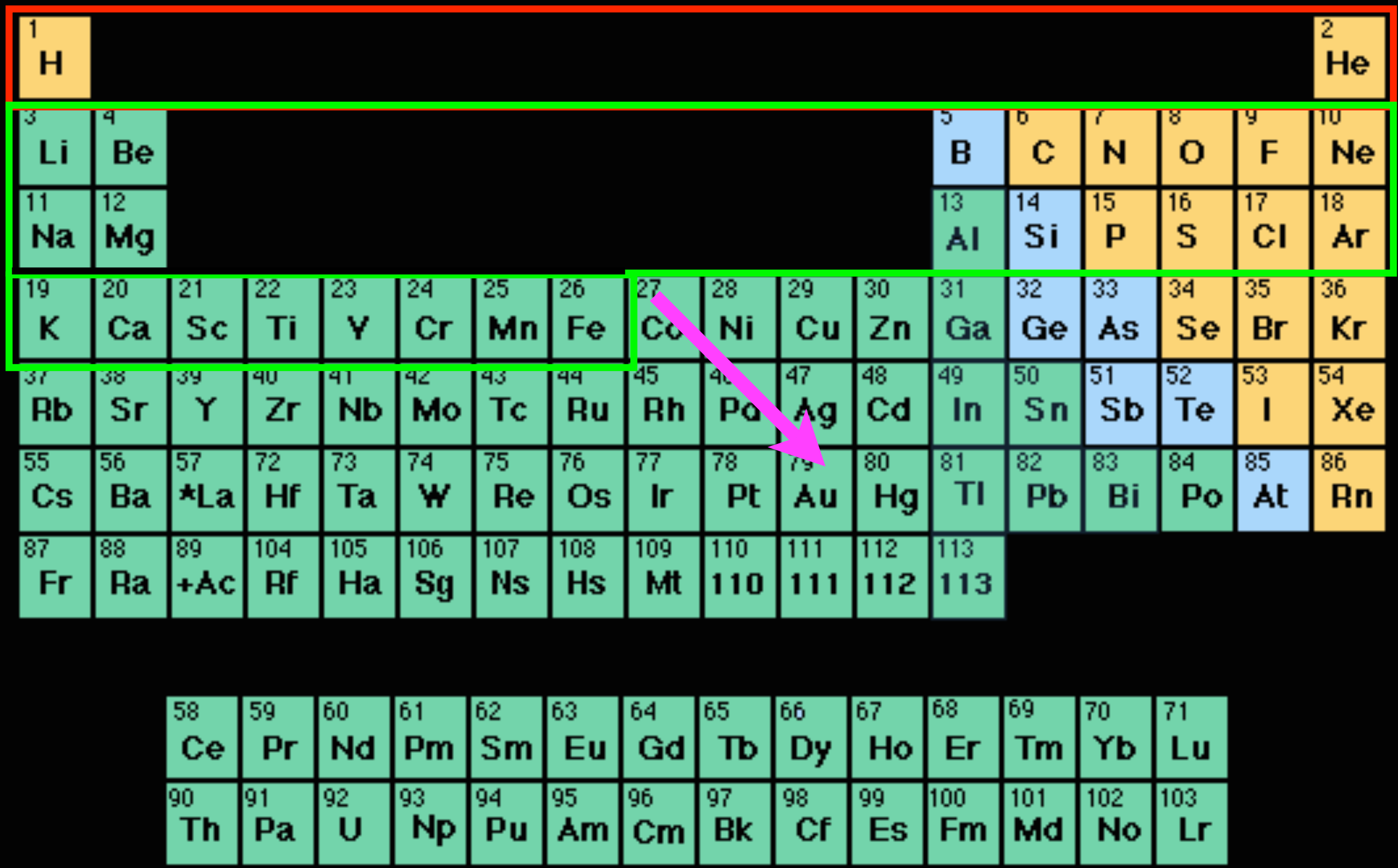
Supernovas are responsible for changing the composition of gas from which each generation of stars form.

Without supernova explosions, there would be no heavy elements in the interstellar gas. In particular, there would be no silicon to form rocky planets, no oxygen to form water, none of the elements we depend on here on Earth.

produced in the Big Bang

produced in stars

produced in supernova explosions



Next week...

... we'll talk about how planets form from these new heavy elements.

Further reading

Books:

- "**Galaxies and the cosmic frontier**" by William Waller and Paul Hodge (Harvard UP, 2003) is a bit dry (too much like a textbook for my taste) but is a very comprehensive description of galaxies and how they work

- Star birth is very well covered in **"The birth of stars and planets"** by John Bally and Bo Reipurth (Cambridge, 2006). It's written by two experts in the field, is entirely non-technical, and has fantastic illustrations all the way through.

- James Kaler has several books about how stars work.**"The Cambridge Encyclopedia of Stars"** (Cambridge UP, 2006) is the most comprehensive. It has a wealth of detail in it, possibly a bit too much for a casual read, but it certainly makes a fabulous reference.

- **"The Supernova Story"** by Laurence Marschall (Plenum Press, 1988) is a very nice book, including an excellent description of the excitement in the astronomical community generated by the explosion of SN 1987A, from someone who was right in the middle of it.

Websites:

- John Dubinski has an article on "The great Milky-Way – Andromeda collision" in *Sky and Telescope,* October 2006, available at http://www.galaxydynamics.org/papers/GreatMilkyWayAndromedaCollision.pdf

- NASA's **"Observatorium"** has a nice article called "Stellar Evolution and Death" at http://observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_intro.html

- The Australia Telescope has several very nice pages on their Outreach site. "**Post-Main Sequence Stars**", http://outreach.atnf.csiro.au/education/senior/astrophysics/stellarevolution_postmain.html is a good summary of the material of the later evolution of stars.

Sources for images used:

- Our place in the universe: from Wikimedia Commons, http://en.wikipedia.org/wiki/File:Earth%27s_Location_in_the_Universe_%28JPEG%29.jpg
- NGC 1232: VLT picture, from http://www.eso.org/public/images/eso9845d/
- NGC 891: from NOAO, APOD 1998 March 18 http://apod.nasa.gov/apod/ap980318.html
- M81: Hubble picture, http://hubblesite.org/newscenter/archive/releases/galaxy/2007/19/
- Ages of stars: from http://www.universetoday.com/83315/thick-stellar-disk-isolated-in-andromeda/
- Astronomer's periodic table: Ben McCall http://bjm.scs.uiuc.edu/pubs/BJMpres25.pdf
- Formation of the Milky Way: from "The formation and evolution of the Milky Way" by Cristina Chiappini, *American Scientist,* Nov/Dec 200, pp. 506-515. Downloaded from http://www.astro.caltech.edu/~george/ay20/Chiappini-MilkyWay.pdf
- Milky Way–Andromeda collision: from Cox & Loeb, "The collision between the Milky Way and Andromeda", MNRAS 386 461, http://adsabs.harvard.edu/abs/2008MNRAS.386..461C. Movie from https://www.cfa.harvard.edu/~loeb/Photos/localgroup.html
- Interacting spiral galaxies: http://hubblesite.org/newscenter/archive/releases/2004/45/
- The Mice: http://apod.nasa.gov/apod/ap090426.html
- Centaurus A: from APOD 2006 July 4 http://apod.nasa.gov/apod/ap060704.html
- Dark nebula Barnard 68: from APOD 2003 February 2, http://antwrp.gsfc.nasa.gov/apod/ap030202.html
- Coalsack nebula: image by Yuri Beletsky, from APOD 2007 May 17 http://apod.nasa.gov/apod/ap070517.html
- Orion in gas, dust and stars: image by Rogelio Bernal Andreo (Deep Sky Colors), from APOD 2009 Sep 29 http://antwrp.gsfc.nasa.gov/apod/ap090929.html
- Hubble view, from HubbleSite Press Release, 24 April 2001, http://hubblesite.org/newscenter/newsdesk/archive/releases/2001/12/ Disk around young star: http://www.spitzer.caltech.edu/images/1852-ssc2007-14d-Planet-Forming-Disk-Around-a-Baby-Star
- Disks in the Orion Nebula: from Herschel Space Observatory: Stars, http://hubble.hq.eso.org/images/opo9545b/
- Star-forming region NGC 602: from APOD 2008 October 25 http://apod.nasa.gov/apod/ap081025.html
- Nuclear fusion process: from Astronomy 162: Stars, Galaxies and Cosmology: The Proton-Proton Chain http://csep10.phys.utk.edu/astr162/lect/energy/ppchain.html
- Interior of a star: from http://www.eso.org/public/outreach/press-rel/pr-2007/phot-29-07.html

- Helix nebula: from HubbleSite http://hubblesite.org/gallery/album/pr2004032d/
- Structure of the core just prior to the supernova explosion: from "Geochemistry" by William White, http://www.geo.cornell.edu/geology/classes/geo455/Chapters.HTML
- The life cycle of SN 1987A: from http://jupiter.as.arizona.edu/~burrows/papers/rob/Stellar_Evolution.jpg
- SN 1987A before and after: images by David Malin, http://www.aao.gov.au/images/captions/aat050.html
- Supernova animation: from Chandra, Animation of a supernova explosion http://chandra.harvard.edu/resources/animations/snr.html?page=2
- Supernova illustration: from Chandra, Stellar evolution illustrations http://chandra.harvard.edu/resources/illustrations/stellar_evolution.html
- Vela remnant: by Robert Gendler, from APOD 2008 March 6 http://apod.nasa.gov/apod/ap080306.html