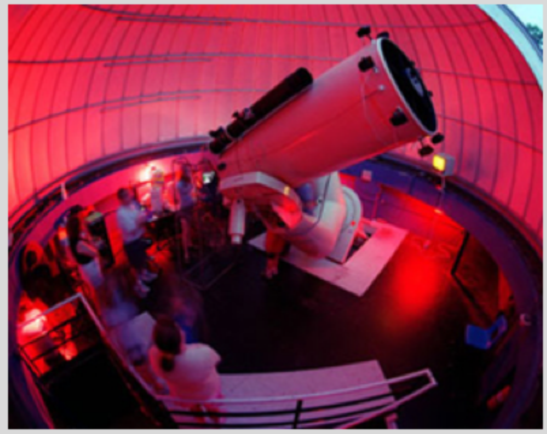
What… was that about

- Midterm 2: why am I doing it this way
  - Reduce stress when studying
  - De-emphasize memorization
    - It's not how astronomy is done. We learn fundamental principles, apply to problems. A lot of test questions have a memorization approach
    - Focus on concepts
    - Take-home tests whether you can locate needed information and apply it
  - See where you feel confident, or not
  - Going through test in class, you could ask me questions
    - (still can! Office hours today, 3-4, or by appointment)

Reminders

- Extra credit trip to Three College Observatory- pick a date (contingent on weather):
  - Today! But probably not because clouds
  - Sunday, 11/4
  - Monday, 11/5
  - Next Thursday, 11/8
- I will call on/off by 5:30pm, we'll meet up at 6 in Petty foyer (by bridge door) and carpool



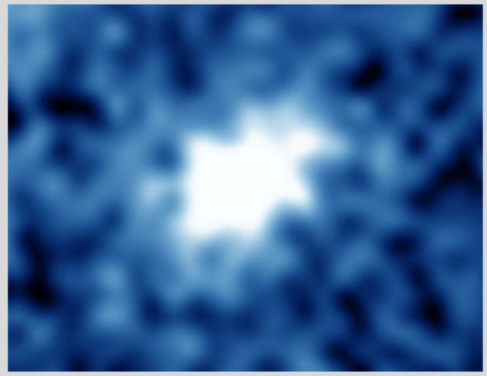
Today in science…

- Looking for the first stars!
- 12.9 billion year light travel time (12.9 billion ly away)
- 800 million years after the Big Bang
- Originally only seen to have H, He
- Recently discovered: C

…is this surprising?

Has a mix of ”Population II” and “Population III” stars

Drat. Will have to keep looking!

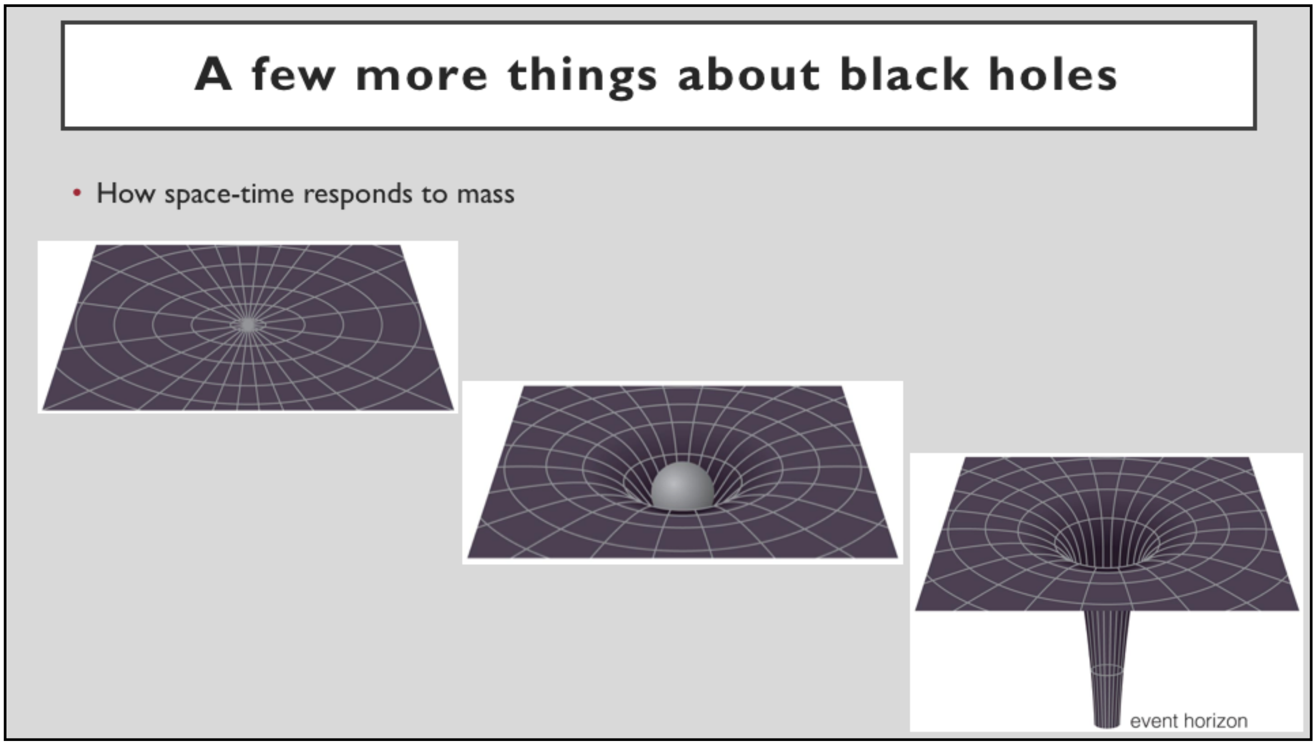


https://medium.com/starts-with-a-bang/astronomers-hopes-for-pristine-stars-dashed-they-re-polluted-after-all-e9ee9f216a3f

One more thing about supernovae!

- How does that whole "bouncing back" thing happen?
  - Let's watch a video…

https://www.youtube.com/watch?v=2UHS883_P60



What do these figures even tell you? If you're a mass traveling near these other bodies that are distorting and deforming space-time, your path will be affected if you're close enough. Information traveling to you around these things will also be impacted

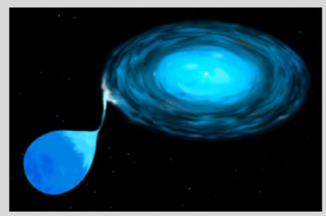
Where to find black holes?

Galaxy Centers

- Millions of solar masses (“supermassive” black holes)
- Generally 1 per galaxy
- We don’t know how they form

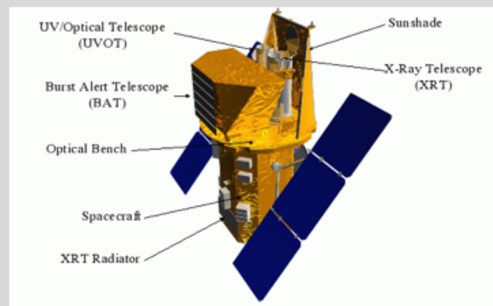
Binaries

- Likely millions of black holes per galaxy of ~10 $M_{\odot}$ or more
- Formed via massive star collapse
- One example: Cygnus X-1: 18 $M_{\odot}$ + unseen ~10 $M_{\odot}$ object



Detecting black holes

- Supermassive black holes: using Newton's laws on stars' orbits in galaxies
- Stellar mass black holes:
  - X-ray binaries
  - Gamma ray bursts (10^{-12}m wavelengths! 1000x shorter than visible light)
    - Originally discovered by military, thought to be residual from nuclear bomb tests
    - Produced by incredibly energetic explosions
      - Likely associated with supernovae that form black holes
    - Astronomers have used Neil Gherels *Swift* Observatory telescope to associate with supernovae
    - Other origins could be merging neutron stars
- Merging black holes



Why do we even think these things are real?

Continuing logic from how we think white dwarfs and neutron stars are formed, you can keep going to figure what happens when neutron degeneracy pressure is overcome

Black holes: concluding thoughts

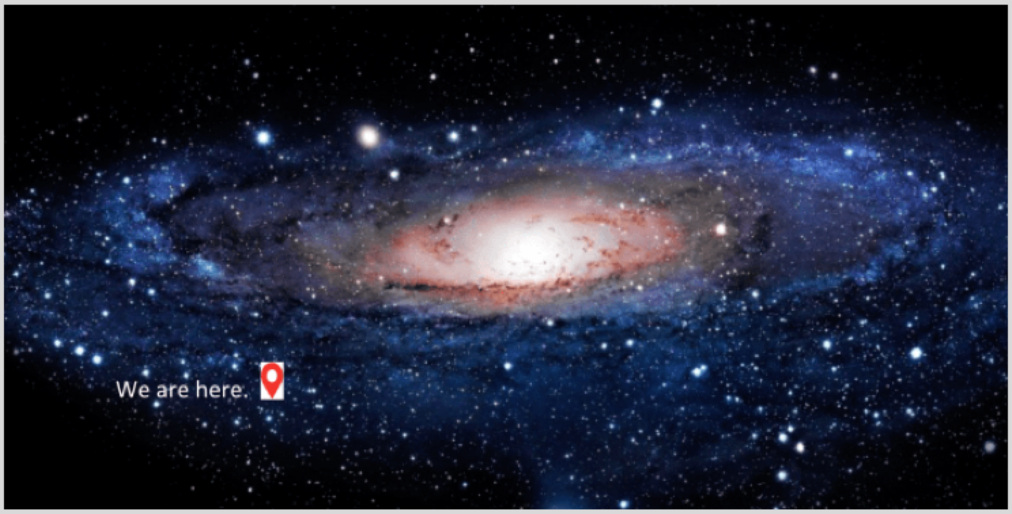
- The theory of relativity predicts that time should run more slowly as the force of gravity grows stronger
- The light coming out of a strong gravitational field should show a gravitational redshift (recall: neutron stars do this, too)
- A body falling through the event horizon will be stretched and squeezed
- Black holes produce among the most dramatic and energetic phenomena in the universe
  - Gamma ray bursts
  - Black hole-black hole mergers
  - Galactic center black holes accrete, drive energetic outflows

Gravitational redshift is distinct from Doppler shift… in gravitational redshift, the photons are actually losing energy while trying to escape the pull of the neutron star. It's like trying to launch a rocket- it takes more energy to escape a more massive body.

Chapter 18 concluding thoughts

- This chapter was very morbid. So was Ch17 a little, and the homeworks. I apologize for that.
- Think of it not as "stellar death," but life after the main sequence. They may not be stars (fusing H, in gravitational equilibrium) any more, but they live on in some form or another:
  - White dwarfs
  - Neutron stars
  - Black holes
  - Chemical enrichment of the universe
  - Dust creation
  - Triggered star formation
- Energy is neither created nor destroyed; it just changes forms

You probably don’t want to hear about candy after yesterday, but … here we are


We are here.

Why do you think galaxies can look like this?

(this is M81, all visible light filters
http://www.imagingdeepsky.com/Galaxies/M81/M81.htm)

Why are the outer edges blue? Scattering! Remember how blue is scattered more efficiently than red? (i.e. why the sky is blue on earth)

Notes on M81 (Messier 81)

- A galaxy is the biggest grouping of stars, gas, dust, star clusters, molecular clouds, etc. we've studied yet
- Vast majority of the stars in the image on the right are in our Milky Way, not M81
  - What look like stars in M81 are mostly clumps of star formation
  - There are a few supergiants we might be able to distinguish, but most individual stars are smaller than 1 pixel and we can't resolve them

M81 and M82

- We can see galaxies from different angles: more face-on like M81, or more edge-on like M82

This is just like protostars with their disks- how we perceive them depends on the inclination we view them at

Size scales, revisited

- We can't go outside of the Milky Way to observe it…
  - 40 AU to Pluto
  - https://voyager.jpl.nasa.gov/mission/status/
- Milky way is about
  - 925,000,000,000,000,000 km across
  - 6,200,000,000 AU
  - 100,000 ly
  - 30 kpc (see why we use parsecs?)
- We live in the outskirts: 8 kpc from center of galaxy

9.25x10^17 km

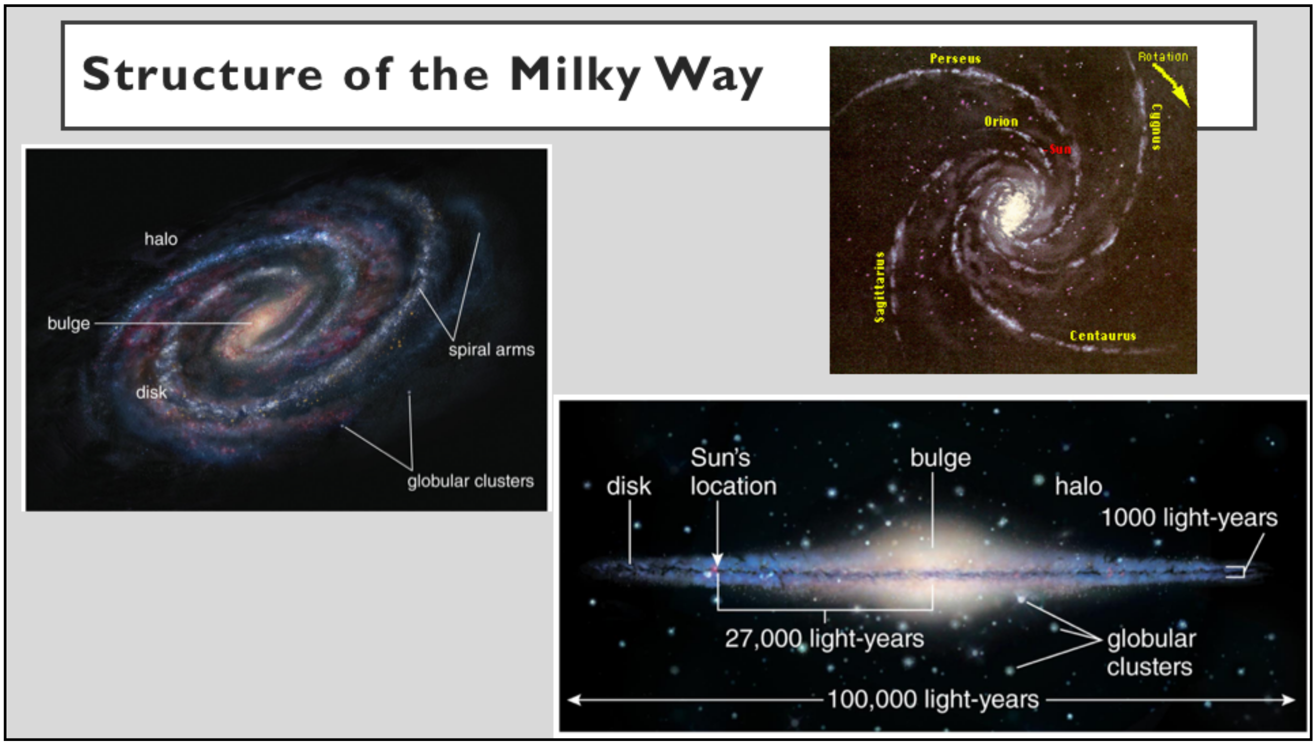
Can't see it from the outside… remember Voyager is our farthest explorer, and it's just barely left the solar system (and came back, and left again, and came back, and left again..). Solar system is 40AU.. Voyager is around 144 AU (as of 10/31/18, 8pm)

Structure of the Milky Way

- We think the Milky Way is a spiral galaxy made up of gas, dust, stars
  - Structure on our sky
  - Interstellar medium
- Contains >100 billion stars
- Is one of >100 billion galaxies in the Universe
- Milky Way has satellite galaxies: called the Magellanic Clouds
- Of our local group of galaxies, Milky Way and Andromeda are two largest
- Until 1920, we thought we were at/near the center of the Milky Way

‘trying to figure out the size/shape of the milky way from our position in it is like trying to draw a picture of your house from inside one of the bedrooms’

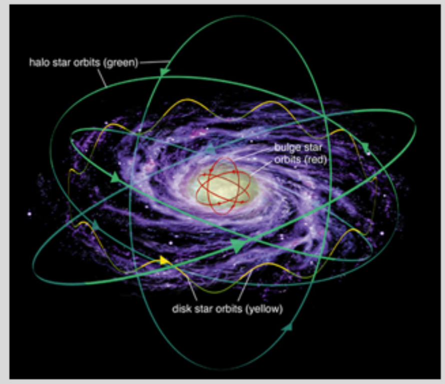
I wonder how amazing the milky way looks to some civilization in Andromeda



A lot of how we define galaxy structure is from observations of other galaxies, rather than what we know of our own

Stars orbiting the galaxy

- Have different orbit patterns if in the disk vs the halo
- How long does it take for us to orbit the Milky Way? We're in the disk- let's do a rough estimate, assuming the orbit is circular:
  - Circumference at Sun's orbit:
    - 2*pi*8 kpc = 50.3 kpc = 1.6×10^{18} km
  - Our (solar system) speed in the Milky Way:
    - 828,000 km/hr
  - Speed = distance/time ; time = distance/speed
    - 1.6×10^{18} km / 828,000 km/hr = 1.8×10^{12} hr
    - 1.8×10^{12} hr * (1d / 24 hr) * (1 year/365.25 d) =
      - At least 2.1×10^{8}, or 210 million years!



So.. If dinosaurs went extinct 65 million years ago, we've completed about 1/3 of a trip around the galaxy

But Earth is about 4.54 billion years old, Sun is 4.57 billion years old. So the Sun has made around 20 orbits around the Milky Way

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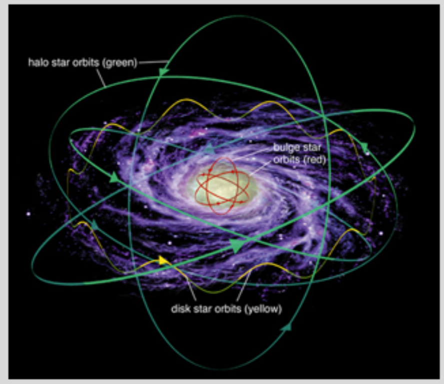
- How long does it take for us to orbit the Milky Way? We're in the disk- let's do a rough estimate, assuming the orbit is circular:
    - At least 2.1×10^8, or 210 million years!
  - Orbit isn't circular, but this is close; it's over 200 million years, and the up/down weaving in/out of the disk is ~10 Myr
- Halo stars' orbits fairly random; pass through disk at high speeds
- Bulge stars have a mix of disk-like orbits and halo-like orbits



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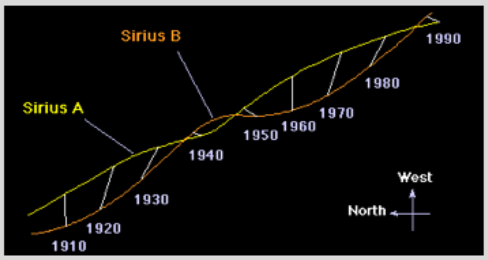
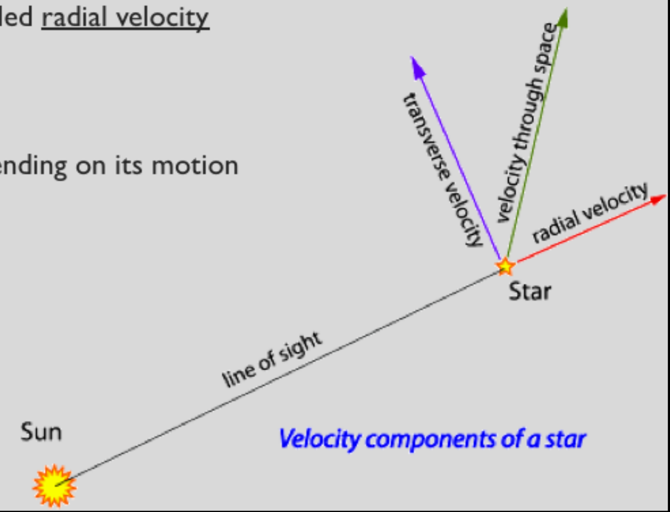
Measuring stars' motions

- You already know about Doppler shift
  - Measures velocity *along our line of sight*. Called radial velocity
- Also measure proper motion
  - Movement across the sky
  - Takes a while to see a star shift much, depending on its motion relative to us

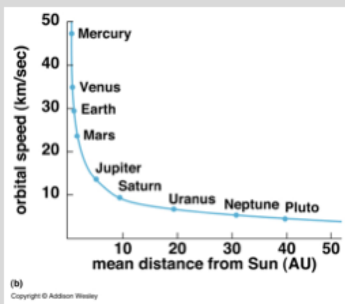


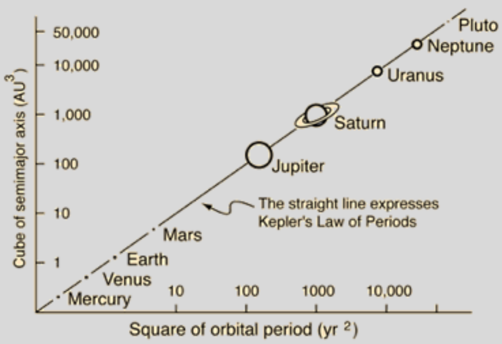


http://www.atnf.csiro.au/outreach/education/senior/astrophysics/proper_motion.html
http://www.atnf.csiro.au/outreach/education/senior/astrophysics/binary_types.html

Mass of a galaxy, and mystery!

- We can use Newton's laws to calculate how much mass lies between us and the center of the galaxy (see mathematical insight 19.1)
- When you do this for our orbit and then compare to stars farther away from galaxy's center, a weird thing happens
  - Remember Kepler's laws? And how orbital speed drops off the farther away from the center of the solar system you get?





http://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/darkmatter.htm

http://hyperphysics.phy-astr.gsu.edu/hbase/kepler.html

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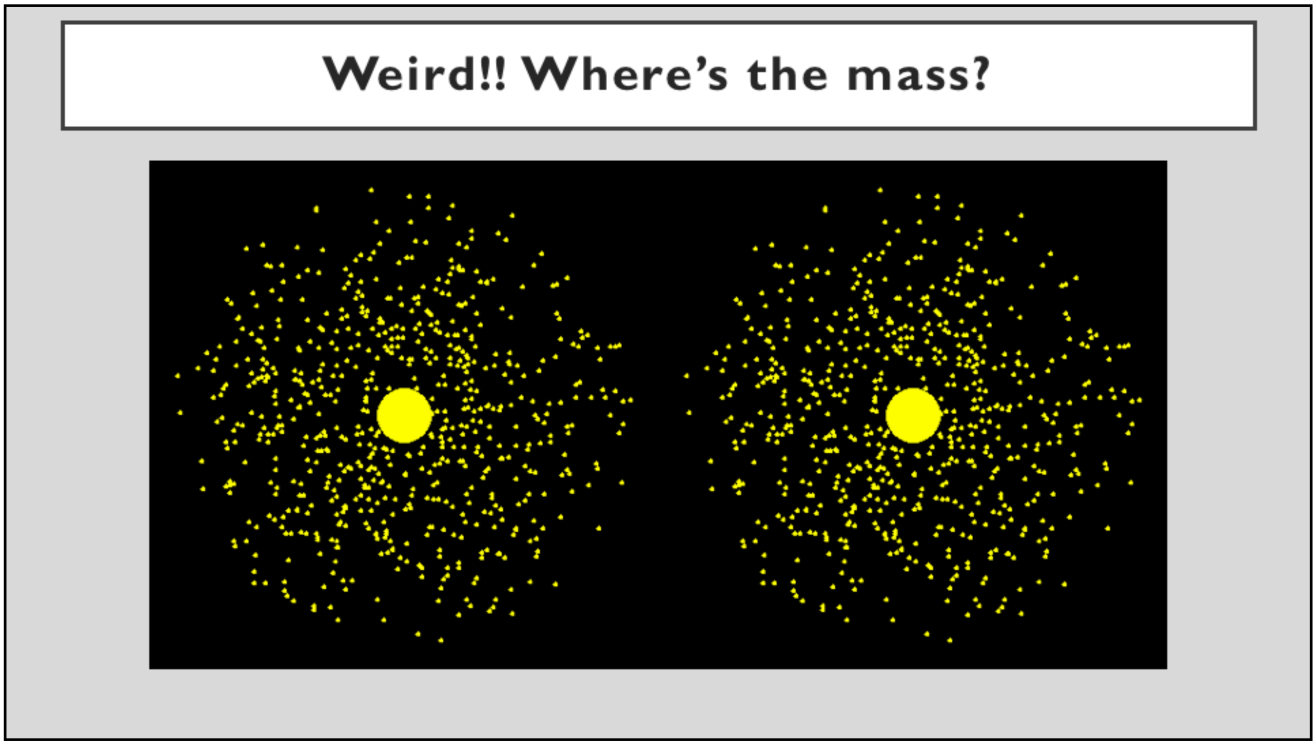
- When you do this for our orbit and then compare to stars farther away from galaxy's center, a weird thing happens
  - Remember Kepler's laws? And how orbital speed drops off the farther away from the center of the solar system you get?
    - In galaxies, this is not so! So … most of the mass isn't in the center of the galaxy? But that's where all the light is coming from…



Left: if stars obeyed Kepler's laws and orbits got longer/slower the farther out you go

Right: what we actually observe…

More on this later.

http://ircamera.as.arizona.edu/NatSci102/NatSci/lectures/darkmatter.htm

Reduce, reuse, recycle!

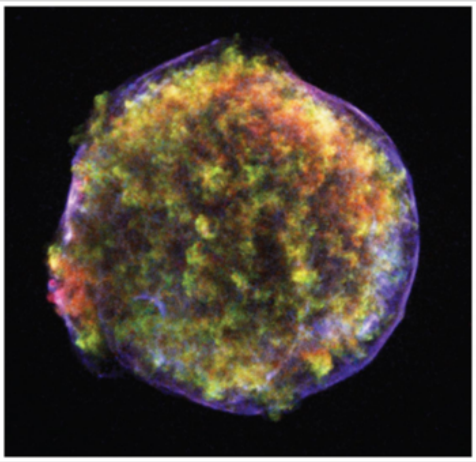
- Generations of stars have enriched the galaxy through winds, planetary nebulae, supernovae
- Disk ~2% elements heavier than H, He
- Without these elements, star formation and life as we know it wouldn't happen
- Star formation happens in the disk; younger than other parts of galaxy, more metal rich
  - Ejected metal-rich material can impact other gas and dust in the galaxy, trigger star formation:
    - Produces density non-uniformity
    - Provides energy
    - Lives out star-gas-star cycle

Reduce, reuse, recycle!

- Most of a star's mass returns to the galaxy eventually
  - High mass stars' winds
  - Planetary nebulae
  - supernovae

- Why doesn't something blown off in a supernova escape the galaxy?
  - Interaction with the interstellar medium!

Gas’ journey in the galaxy

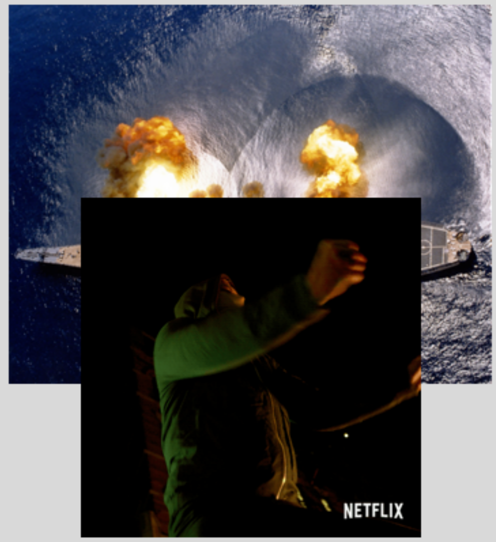


Left: x-ray emitting supernova remnant

Right: planetary nebula

Gas' *bubbly* journey in the galaxy

- Young supernova remnants expand outward quickly, and are very hot
  - Create shocks when they encounter interstellar medium
  - A shock is a high-pressure wave that is moving faster than the speed of sound where it's propagating
  - Sound speed ~ sqrt 1/density
    - Sound travels faster in solids than in air
    - This makes sense: molecules run into each other, passing momentum along: more molecules, faster relay



Iron fist danny rand's hand was moving faster than the local speed of sound in the asphalt, driving a wave that propagated through the pavement to knock the bad guys over.

So.. It really should have buckled the pavement, and this makes it look like the wave went more through air than through the ground, so it's not super accurate. He probably can't punch at 767 mph. But you get the idea: a fast-moving wave creates a high pressure edge that fells all enemies in its path

We live in a bubble

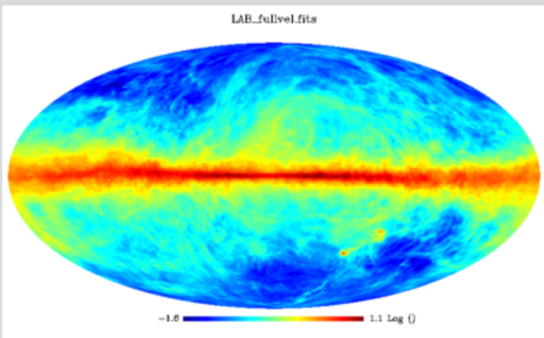
- Supernova shocks move outward, creating a bubble in space
- We see X-ray emission from all around us
  - We're living inside at least one recent supernova's bubble
- Since stars are far apart, it can take hundreds of thousands of years before a bubble's edge hits something else
  - When multiple supernova bubbles combine, it's a … you guessed it. Superbubble.
  - Stars tend to form in clusters, so it isn't all that odd that multiple supernovae may occur in a small enough area that their bubbles merge together
- If superbubbles merge and expand enough, they may go outside the galactic disk: no more interstellar medium to slow them down!

Galactic fountains

- Gas blown out into halo of galaxy
- Slows, cools, condenses, gravitationally attracted back toward galactic disk
  - It's like the water cycle on earth, but with hot, fast-moving gas
- Overall we think its effect is to disperse heavy elements far and wide throughout the galaxy

Cooling, completing star-gas-star cycle

- Gas in bubbles relatively hot: most gas in the galaxy is cool
  - Cool enough to be neutral H, hanging on to its electron. Called atomic hydrogen
  - Atomic hydrogen has a distinct spectral feature in radio wavelengths: 21cm line
  - We see the 21cm line all around us; a huge fraction of gas in the galaxy is atomic hydrogen



Isotopes of hydrogen:

Light hydrogen, or protium: proton and electron. 99.985% of all hydrogen in this form

Deuterium: one neutron, one proton, one electron. 0.0156% of all hydrogen

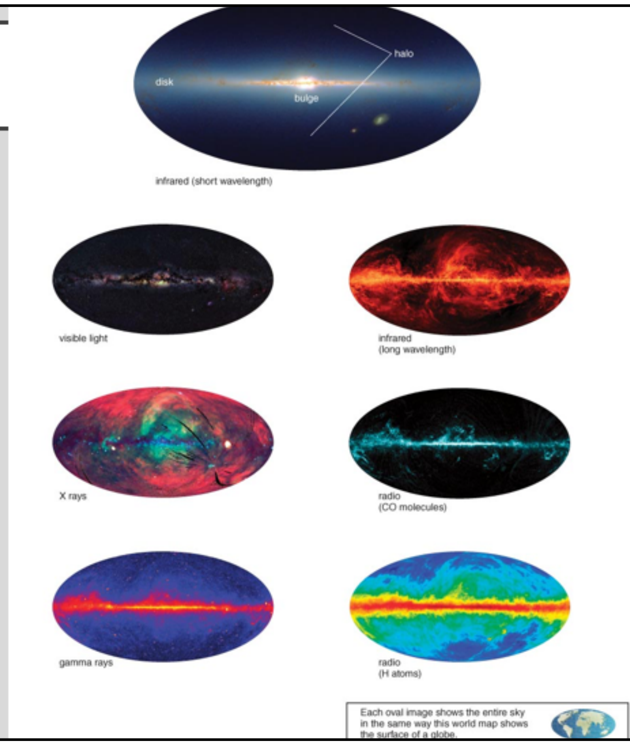
Tritium: two neutrons, one proton, one electron. Unstable. Half life of 12 years

Cooling, completing star-gas-star cycle

- Gas in the galaxy:
  - mostly warm (10,000K), tenuous clouds of atomic hydrogen
  - Some ionized bubbles
  - A few dense clouds of cool (100K) atomic hydrogen
- Cool clouds gradually start to condense and radiate energy away, becoming even cooler
- At low enough temperature (a few K), atomic hydrogen forms bonds with other hydrogen and becomes molecular hydrogen
  - Birthplace of stars!
  - Takes millions of years to form
  - Molecular clouds are dense, tend to settle toward middle of galactic disk

Star formation in a molecular cloud

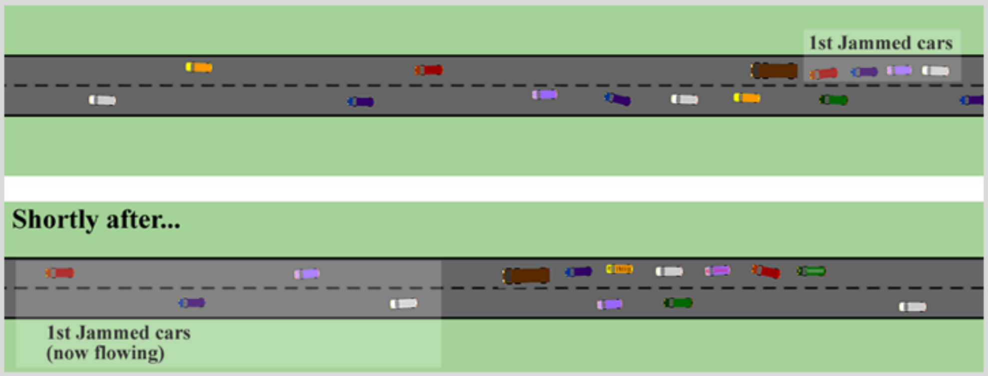
- Once the first set of stars forms, their radiation starts to evaporate cool molecular cloud material around them
  - Limits number of stars that can be formed in a given molecular cloud
  - Highest mass stars' supernovae enrich/send shocks into what's left
    - Can trigger new star formation
- Star-gas-star cycle can only continue as long as there is gas
  - Once you form enough brown dwarfs/low mass objects that won't go supernova, game over
  - With about 5 billion solar masses of atomic hydrogen, this will take about 50 billion years.


halo
disk
bulge
infrared (short wavelength)
visible light
infrared
(long wavelength)
X rays
radio
(CO molecules)
gamma rays
radio
(H atoms)
Each oval image shows the entire sky
in the same way this world map shows
the surface of a globe.

Where do stars form in the galaxy?

Density waves

- Spiral arms are created/maintained by *density waves*
  - Density waves drive star formation
  - For us, most common density wave we experience is a traffic jam



https://briankoberlein.com/2013/09/22/traffic-jam/

Spiral arms are created/maintained by *density waves*

For us, most common density wave is a traffic jam