Logistical notes

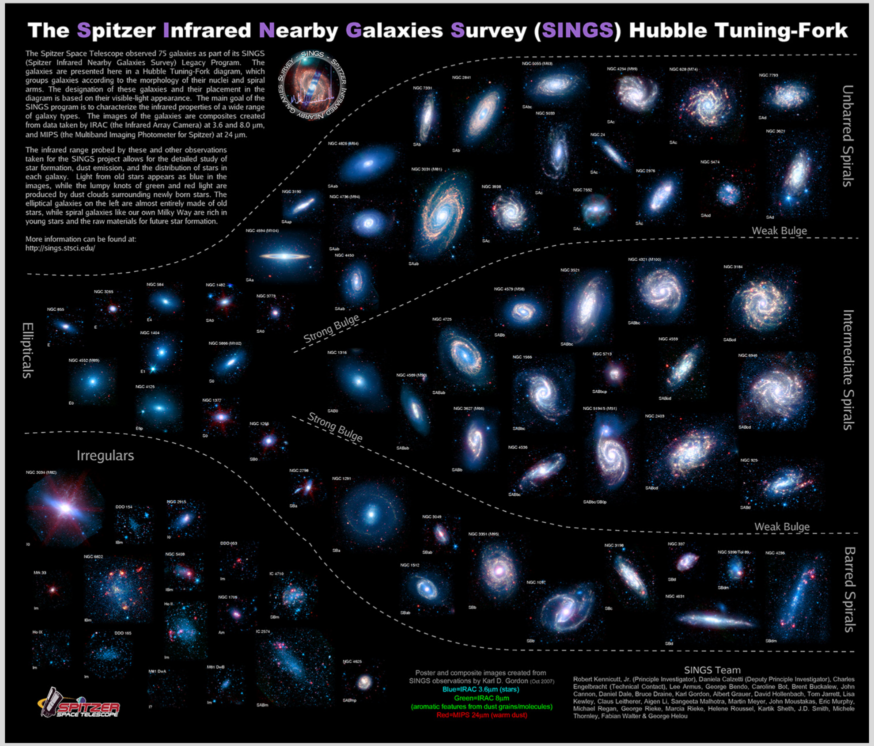
- Please pick up your midterm 1 if you haven't already!
- TCO trip tonight if weather clear! (Ugh the forecast looks bad)
  - I have added additional nights:
    - Tuesday 11/13
    - Wednesday 11/14

- If your clicker is broken or battery dead, please talk to one of the admins in the Physics department office, Petty 321
- On Canvas, there's now a grade tabulator excel file- enter homework/lab scores, clicker scores, midterm 1 grade, guesses for midterm 2 and final, yes/no for planetarium or if you plan to do extra credits, grade will appear!

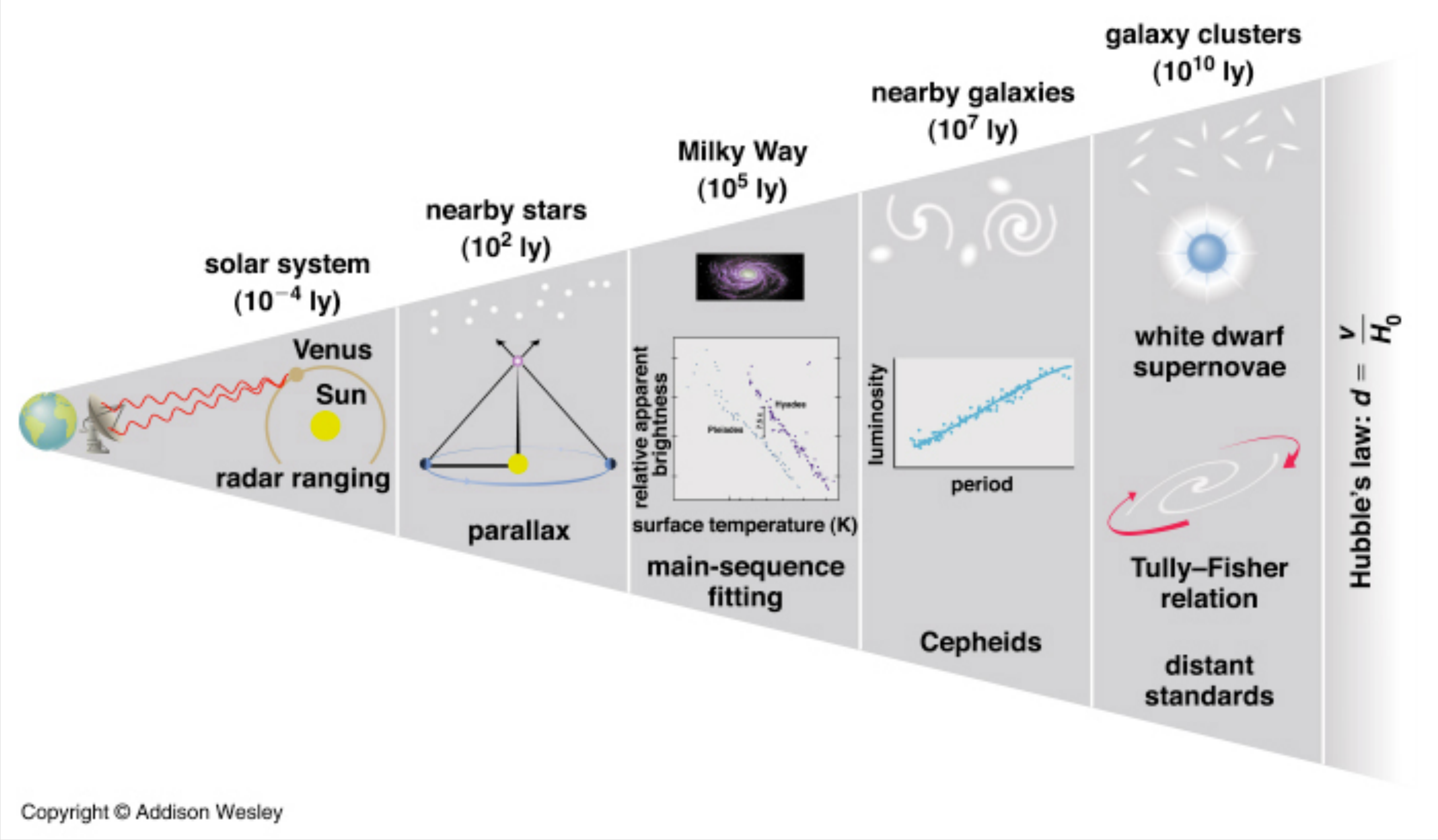
Announcement!

Recap of last time:

- We talked about…
  - where stars form (in galaxies' spiral arms: density waves)
  - morphological types of galaxies (spirals, lenticulars, ellipticals, irregular)
  - colors of galaxies, depending on their star formation rates
  - the cosmic distance ladder: rungs that build upon each other
    - We know how far away things are
    - We measure how fast they're moving
    - We know how far back in time things are

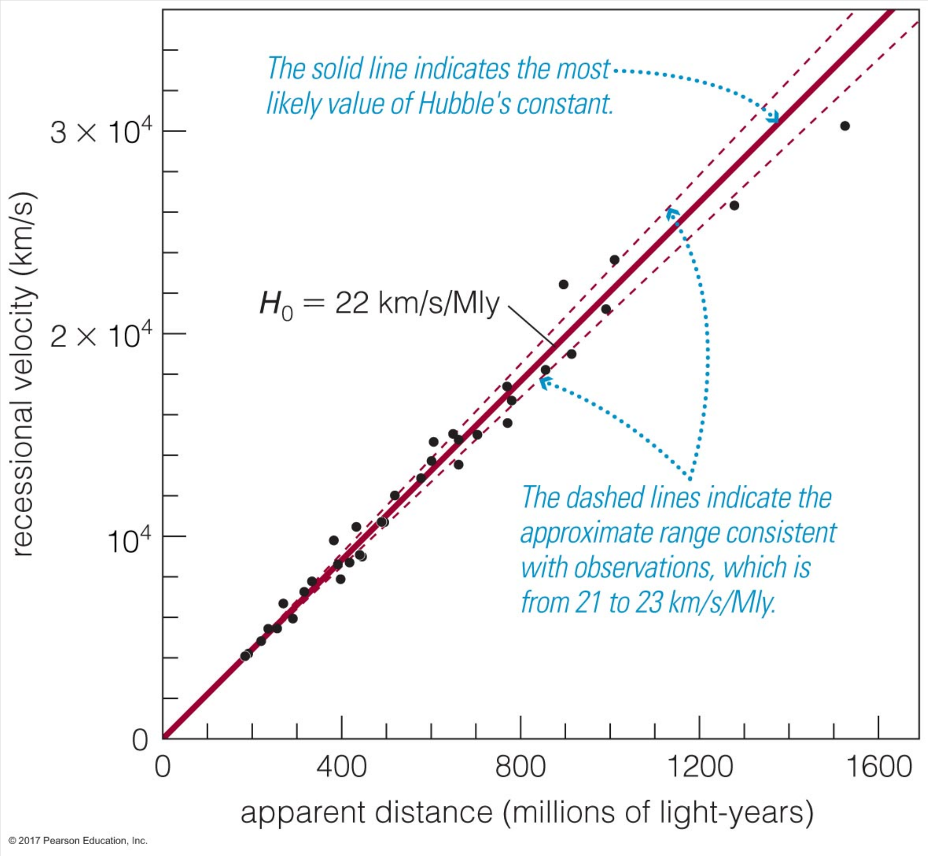


Distance scales in the universe



Expansion of the universe

- It was already known that spectra of distant galaxies showed redshifted spectral lines
- Hubble combined velocities measured from the redshifts with distances, found farthest galaxies are moving the fastest
- So... If they're moving away from us now…
  - Were closer together at some point in the past
  - Forget the raisin cake, try points on a balloon!



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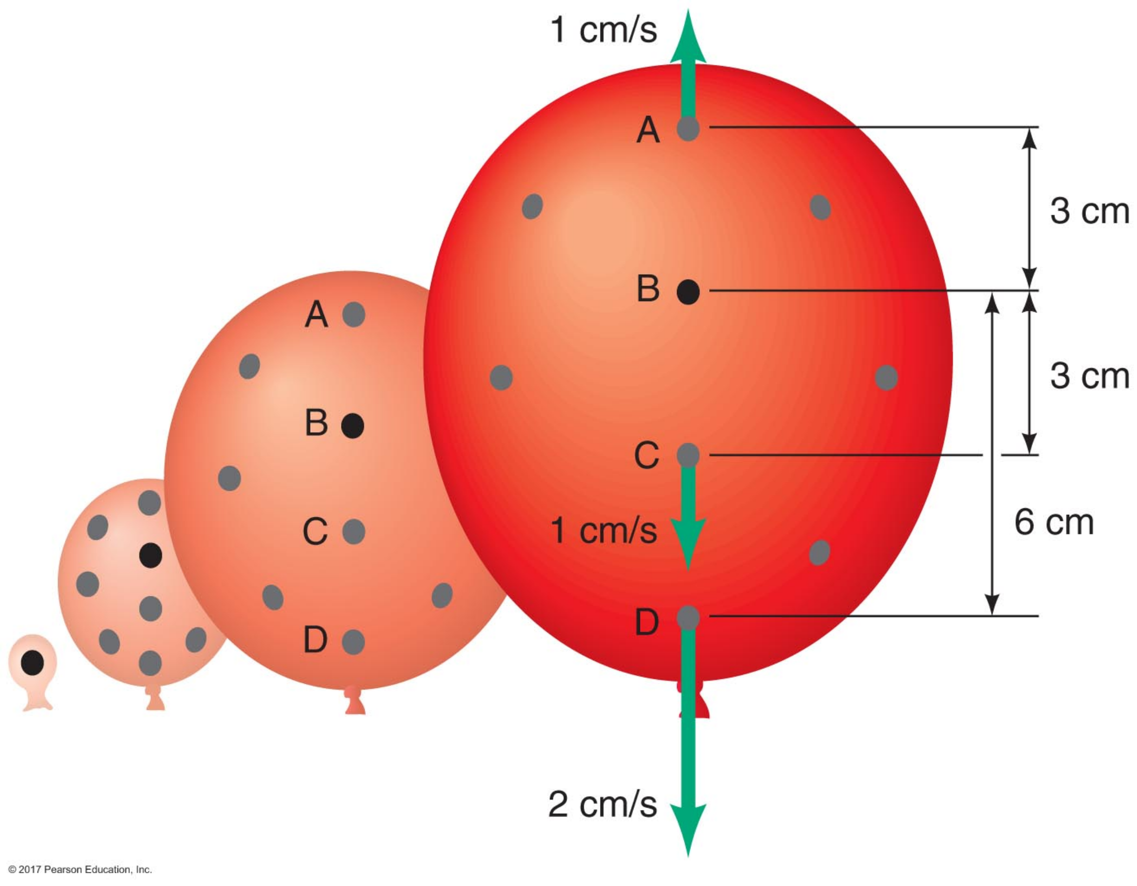


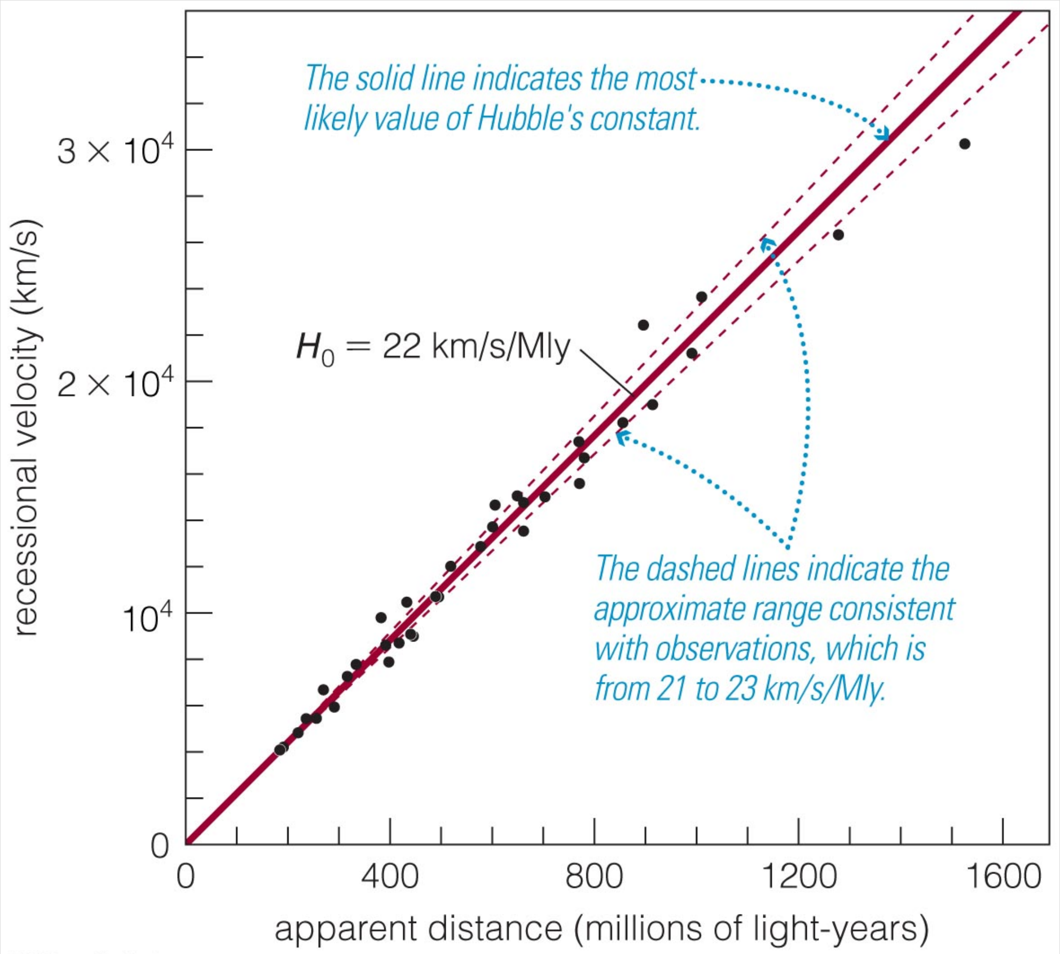
Shifts on the biggest distance scales

- Remember this midterm 1 question? Let's dig into it a little deeper…

17. In the blanks on the left, write the letter of the motion in the column on the right that is responsible for that phenomenon. Some letters may not be used at all, some may be used multiple times.

_______ In the year A.D. 15,000, Vega will be a better north star than Polaris.	A. Earth rotates once each day.
_______ The Big Dipper will look different 100,000 years from now than it does today.	B. Earth revolves around the Sun once each year.
_______ The Moon, Sun, and stars rise in the east and set in the west.	C. The direction of Earth's axis in space precesses with a period of 26,000 years.
_______ A million years from now, Alpha Centauri will no longer be the nearest star system to our own.	D. Stars are moving relative to each other as they orbit in the Milky Way
_______ We see different constellations at different times of the year	E. The universe is expanding.

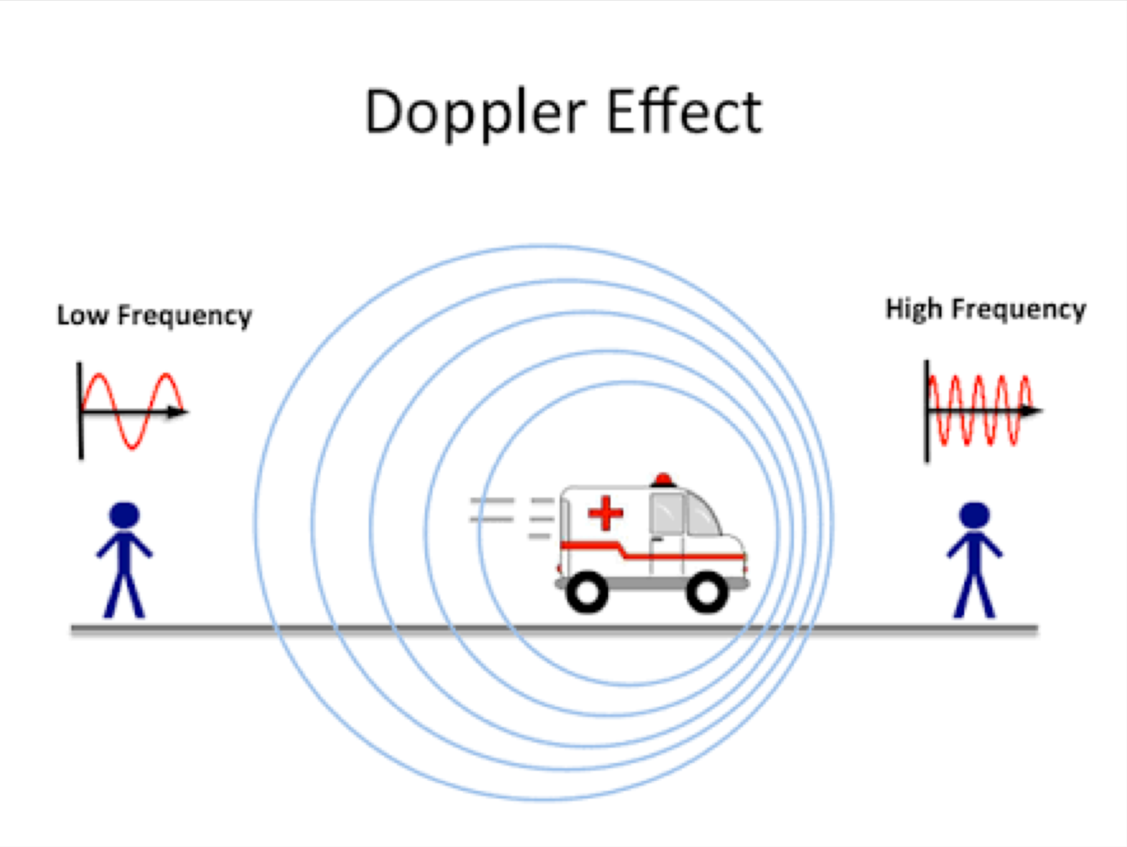
Shifts on the biggest distance scales



- Hubble's law tells us that for every million light years of distance, galaxies at that distance will be moving 22km/s faster

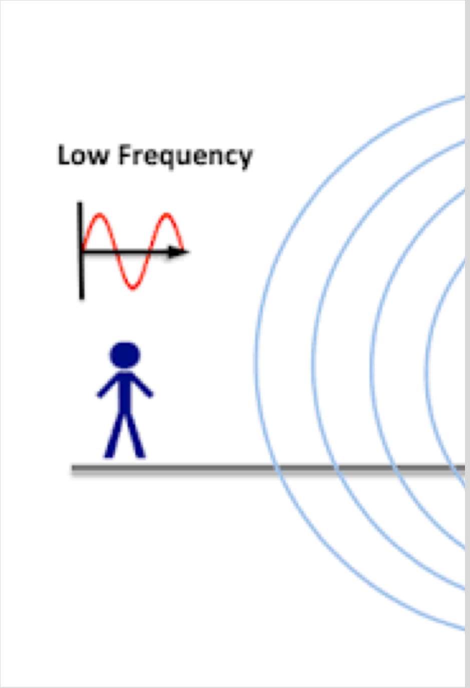
Redshift and cosmological redshift

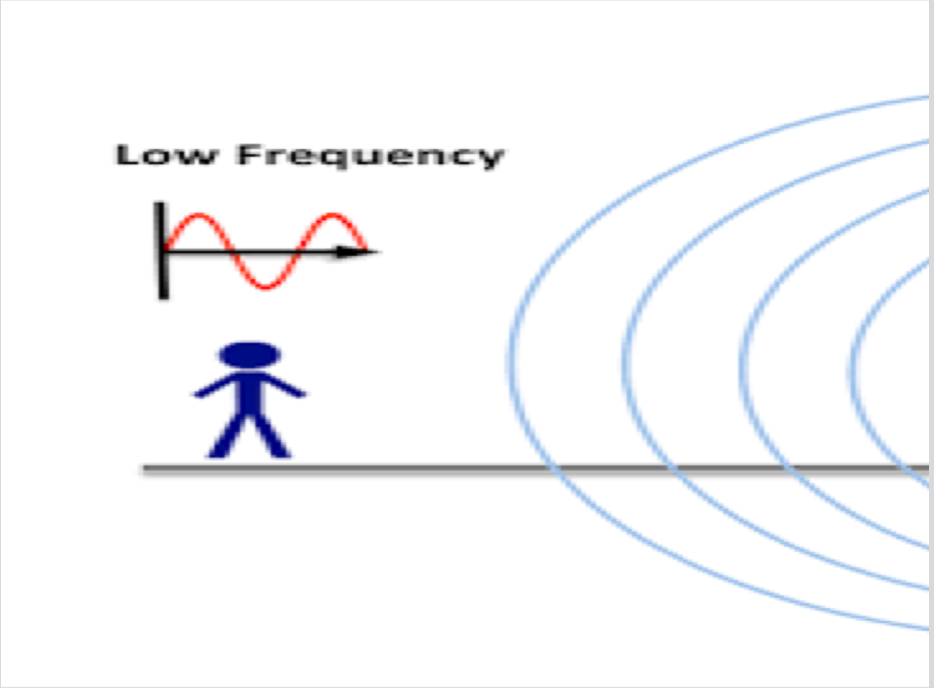
- Remember when we talked about Doppler shift, and how our *perception* of the wave's frequency, our observation of it, changes, but not its actual frequency?



Redshift and cosmological redshift

- Remember when we talked about Doppler shift, and how our *perception* of the wave's frequency changes, but not its actual frequency?
- What if I told you maybe the farthest galaxies' light isn't shifted because they're moving, but because space itself is growing between galaxies?





The age of the universe

- Hubble observed galaxies moving away from us, and the farthest galaxies moving faster than the nearest ones
- Hubble's law: for every million light years farther away, galaxies were moving 22km/s faster
- We can use this to calculate the age of the universe!

The age of the universe

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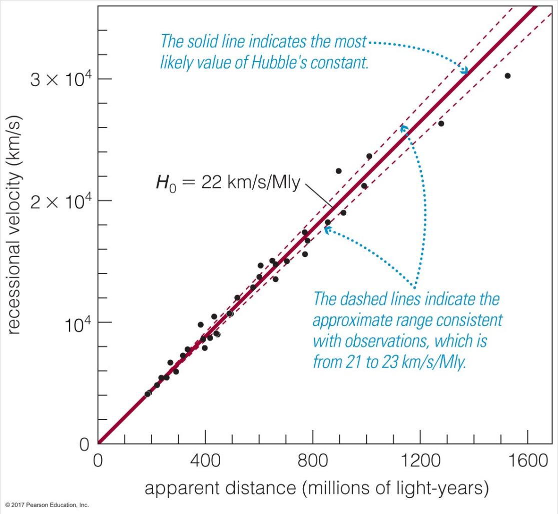
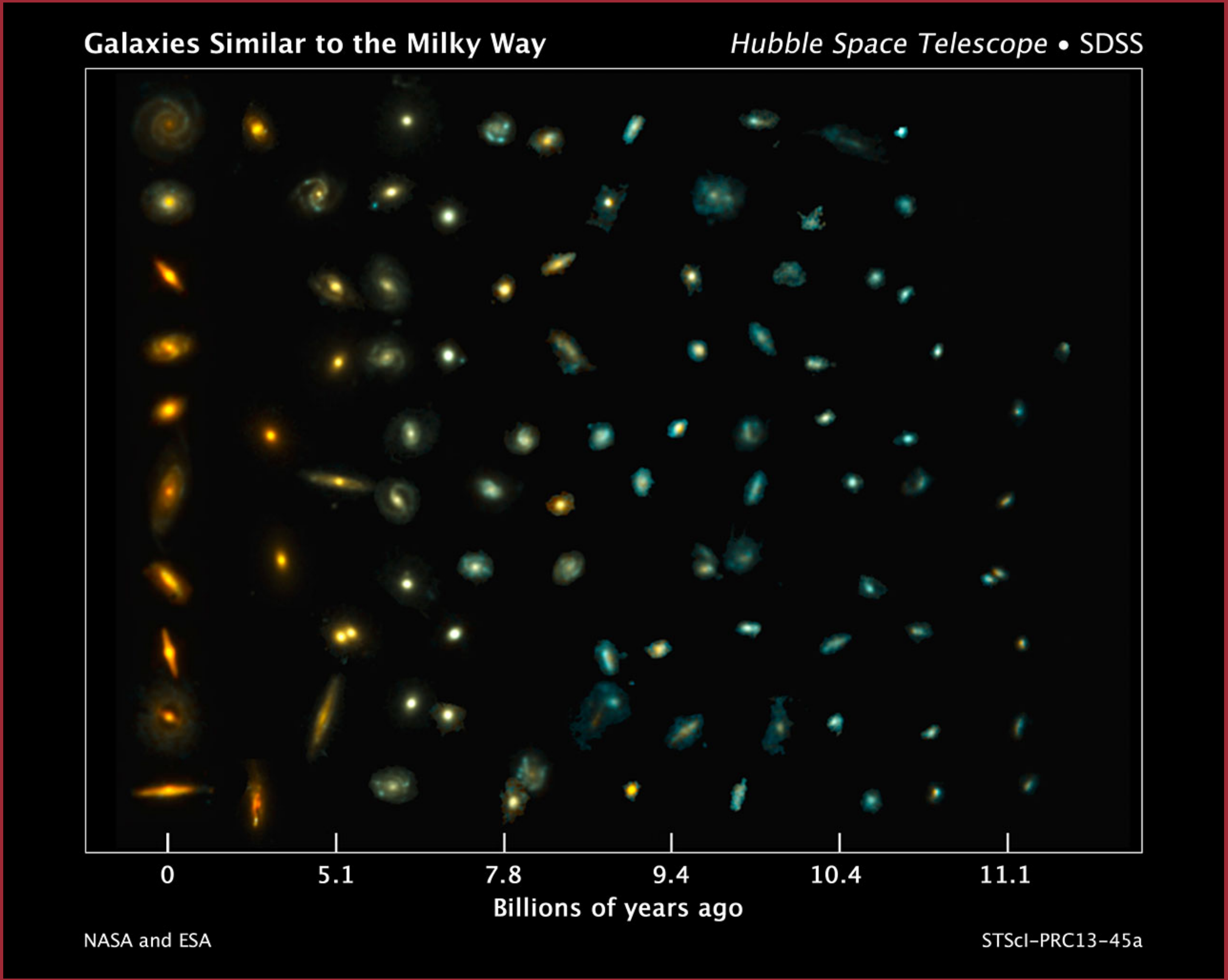
- We can use this to calculate the age of the universe!
  - Hubble's constant, $H_0 = 22\ \frac{km/s}{10^6 ly}$
  - Units are speed / distance 🤔 Hubble was observing speeds of galaxies and comparing them to their independently measured distances
  - We want to know how long they've been traveling if we assume they've been moving at that same speed the whole distance they've traveled
  - 🧐 time = distance/speed!
    - So if we calculate $1/H_0$, we'll get a time! 💯

The age of the universe (for now)

- $\frac{1}{H_0} = \frac{10^6 ly}{22km/s}$
- convert ly into km to cancel with denominator…
- $\frac{10^6 ly}{22\ km/s} * \frac{9.46\ x\ 10^{12} km}{1\ ly} = \frac{9.46\ x\ 10^{18} km}{22\frac{km}{s}} = 4.3\ x\ 10^{17}\ s$
- $4.3\ x\ 10^{17}\ s\ * \frac{1\ min}{60\ s} * \frac{1\ hr}{60\ min} * \frac{1\ d}{24\ hr} * \frac{1\ yr}{365.25\ d} = 13.6\ x\ 10^9 years$



Big Banger #13.7 Gyr



Galaxy Evolution

Chapter 21. The Cosmic Perspective

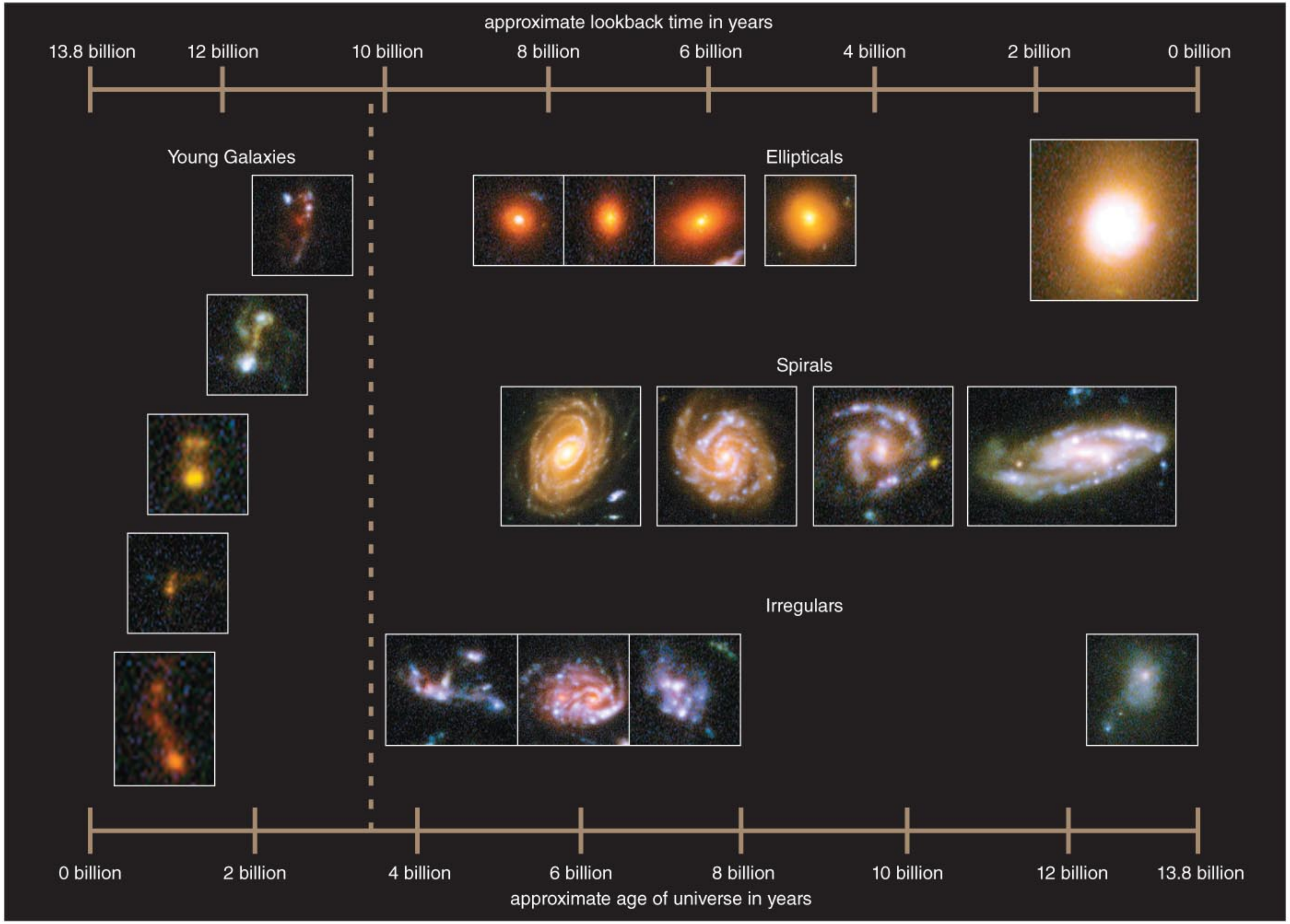
Surveying galaxies

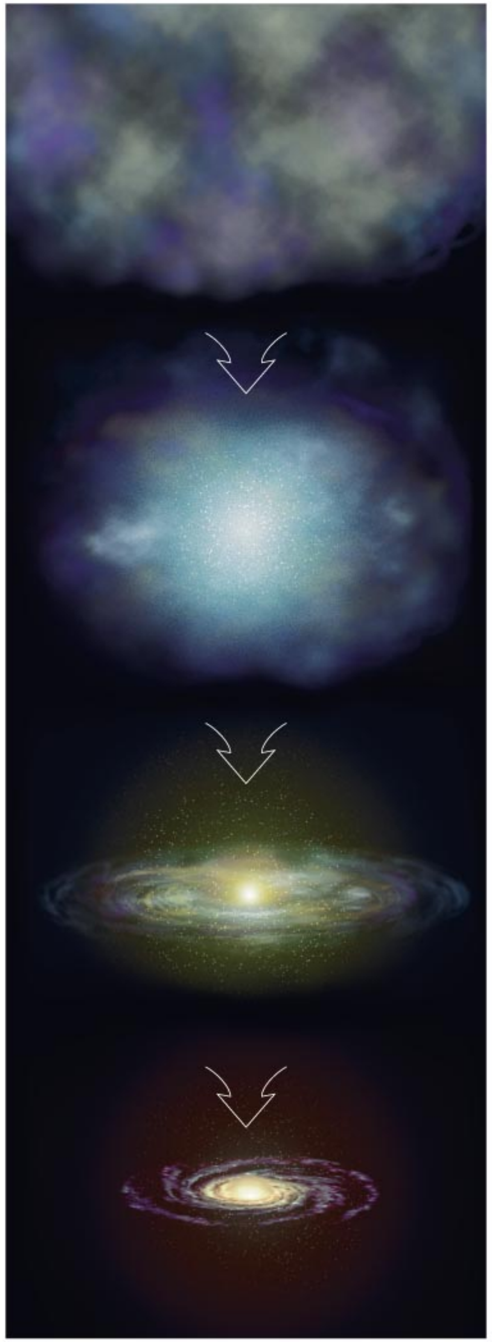
- Recall “surveying stars” chapter
- How did we put together how stars evolve?
  - Observing stars of different ages
  - We do the same for galaxies!
    - …how?

Surveying galaxies

- The nearest galaxies are the youngest, the farthest are the oldest
- *Lookback time* as a proxy for age!
- If we see light from a galaxy that is 13 billion light years away,
  - right now in that galaxy, it is about the same age as the Milky Way, but
  - we are seeing it as it was that long ago
  - if the universe is 13.something billion years old, the light we're seeing is from when that galaxy was no more than a few hundred million years old.

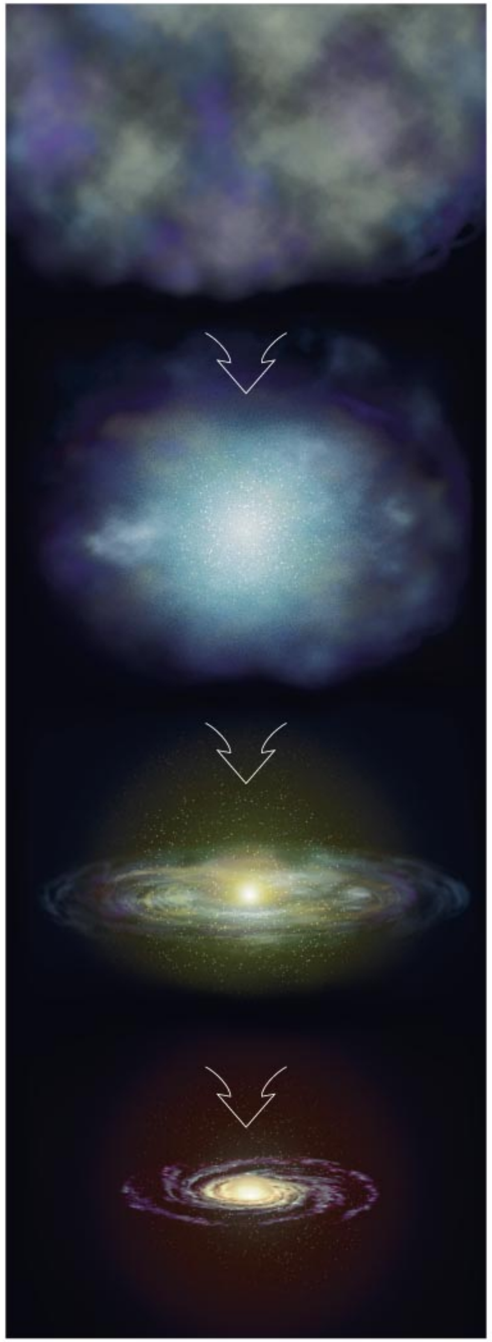
Snapshots of galaxies in time





Galaxy formation

- So after the Big Bang, we start with a universe full of not entirely uniform H and He
- Like in molecular clouds, over-dense regions start to collapse
- Energy conservation, angular momentum conservation, etc…
  - Some stars form, go supernova
  - Collapse is slowed by energy from supernovae
  - More stars form
  - Disk forms, star formation concentrated in disk where most material settles
  - Halo stars are from before rotation became ordered, have random-ish orbits
  - Disk stars have orbits in the disk, maintained from their being born in the disk



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Ok, great- if you're the Milky Way, this all fits. Why elliptical galaxies, then? Why irregular galaxies?

Galaxy evolution

- Ok, let's assume gravitational collapse part is ok and most galaxies are born the same way. What happens to change their course?
- Nature: different conditions at formation.

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    - You need some initial amount of angular momentum for any rotational speed or change in rotational speed at all
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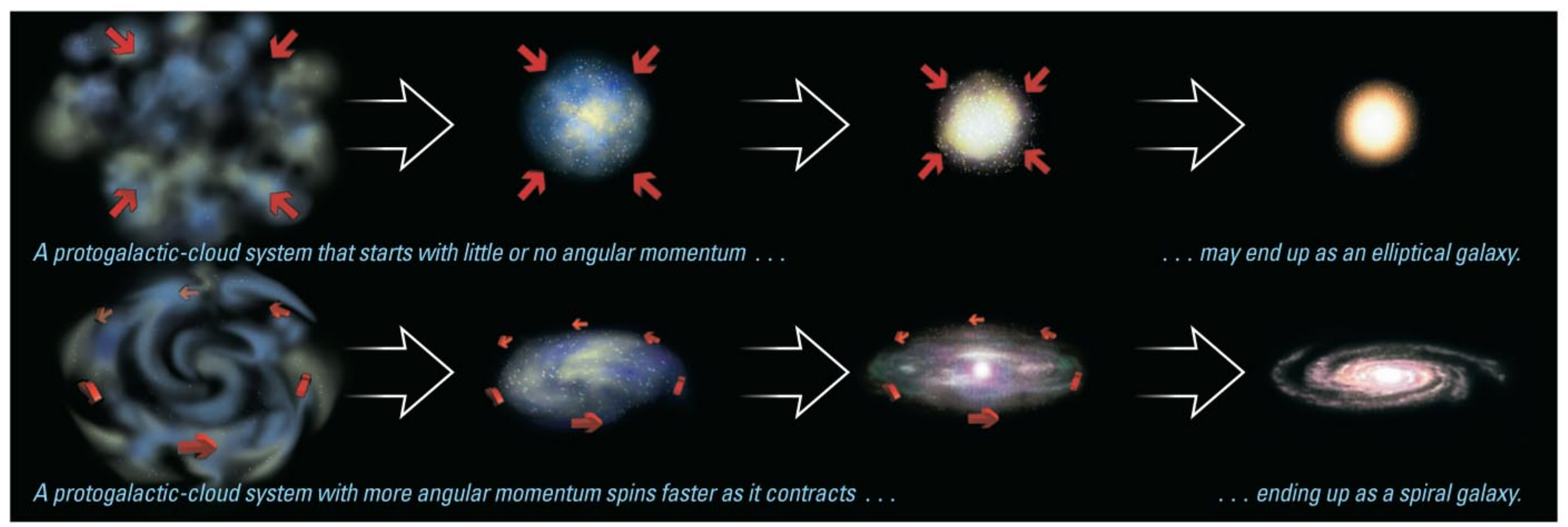

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  - Density of proto-galactic material
    - High density→ more rapid star formation, adios to all the gas for forming stars! Gone before galaxy disk has formed
    - Low density→ slow star formation, some gas left over to hang out in the disk of the galaxy

Galaxy evolution

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Size scales

- In the solar system…
  - Sun as a grapefruit, nearest also grapefruit-sized star ~1000km away
  - Milky Way galaxy as a grapefruit, Andromeda grapefruit galaxy ~3m away! Dwarf satellite galaxies (Magellanic Clouds) even closer

Galaxy evolution

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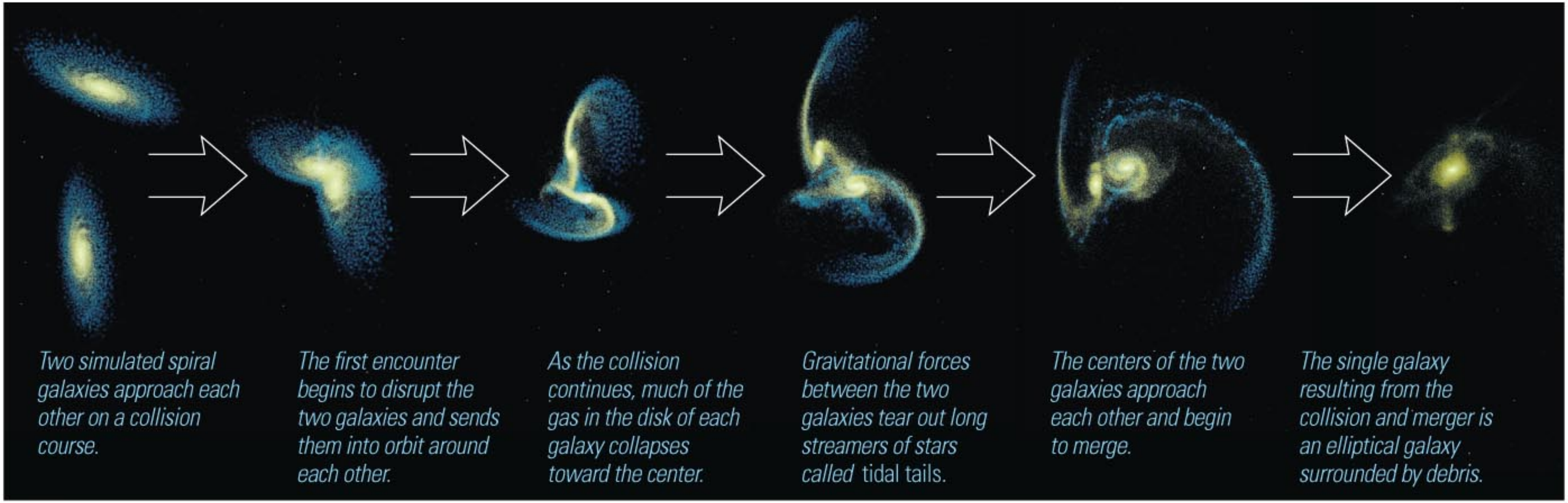
- Nurture: interactions important in determining galaxy's evolutionary path! Galaxies don't form/evolve in isolation, like many stars don't
  - Average distances between galaxies aren't much bigger than the galaxies themselves: they interact
  - Lots of evidence for galactic collisions
  - Collision timescales ~100s of millions of years: we observe some galaxies mid- or post-merger, use computer simulations to fill in the blanks
    - Two spirals colliding could create an elliptical galaxy

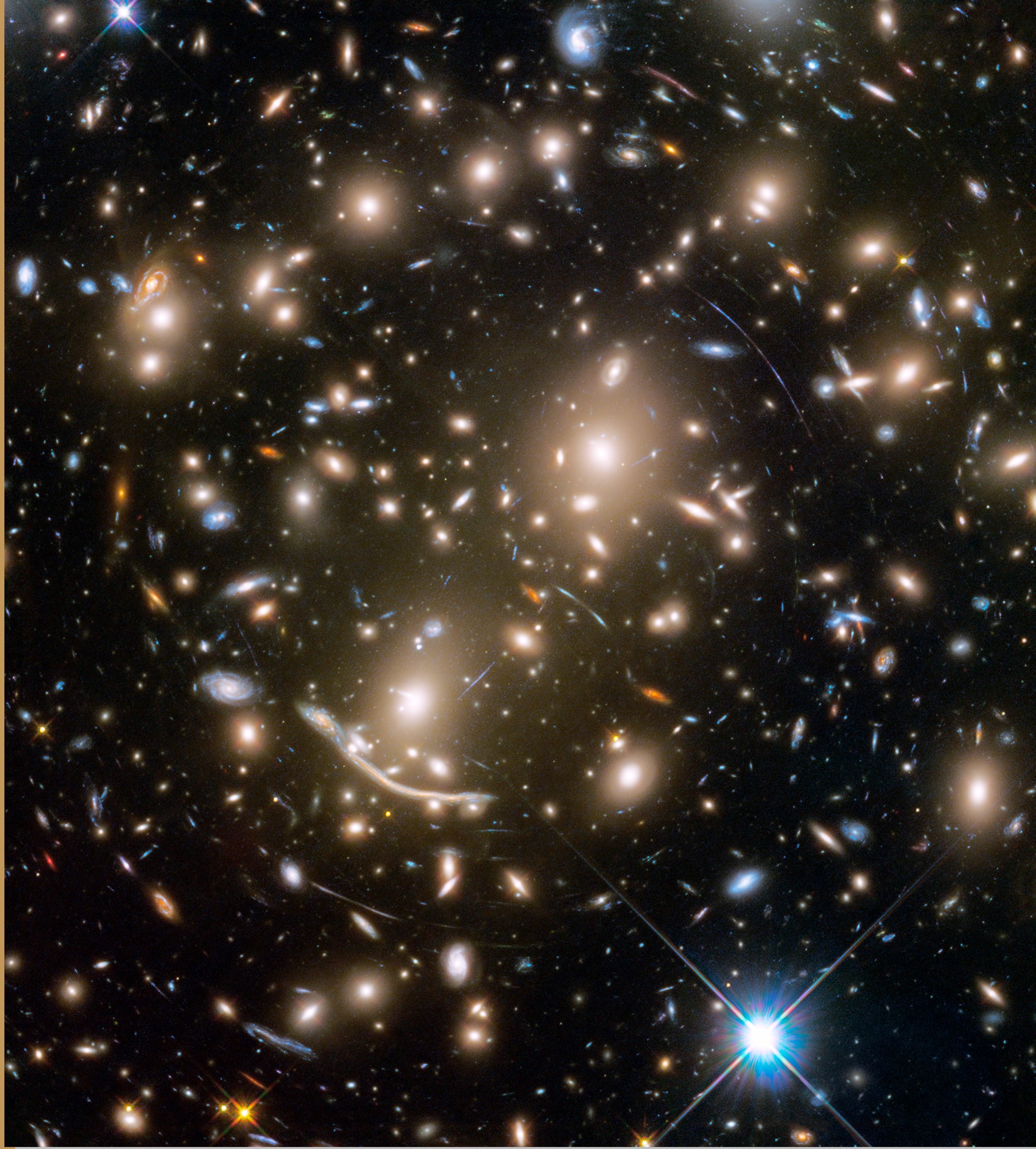
Colliding spiral galaxies—the antennae

Galaxies crash



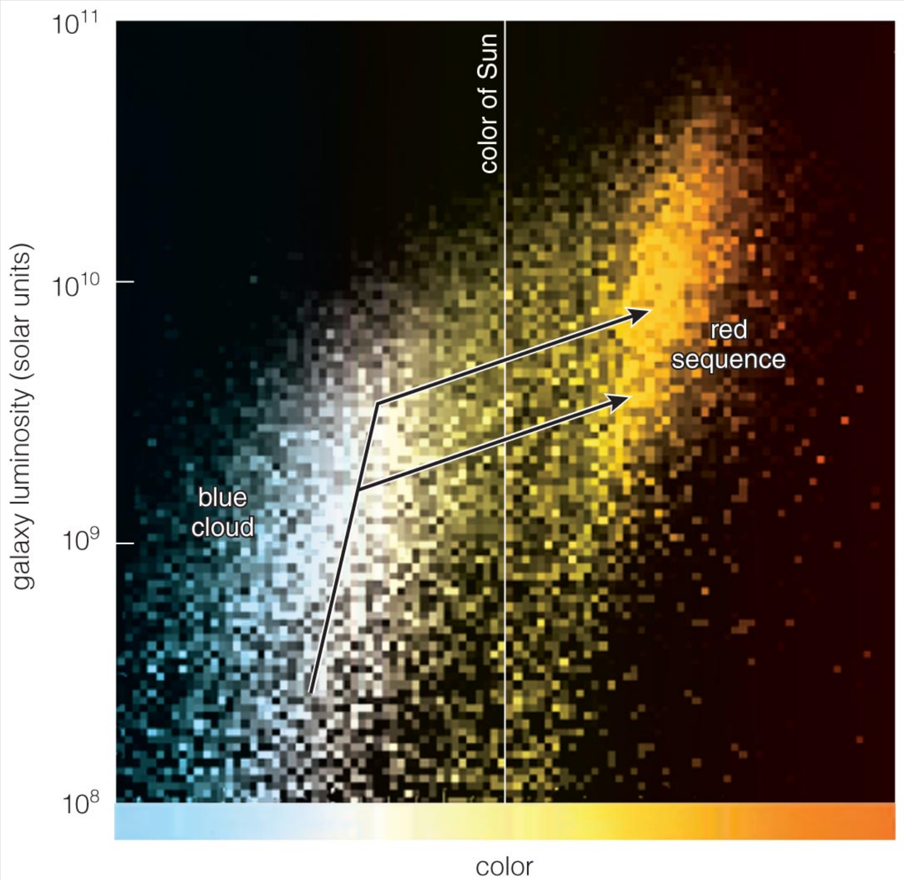
Extragalactic CSI: investigating crashes

- Evidence of ellipticals formed by collisions: in galaxy clusters
  - Often have elliptical galaxies at their centers: ellipticals that appear to have grown large through mergers because their centers (central dominant galaxies) are full of star clusters that came from different galaxies
  - Ellipticals and lenticulars in clusters could be spirals that lose gas through mergers
    - Elliptical: gas loss before star-formation defined spiral arms
    - Lenticular: gas loss after star formation in spiral arms



Not entirely clear yet how galaxies evolve

- Could be a combination of "nature" vs "nurture" mechanisms
- What we do know for certain:
  - At some point, galaxies formed stars
  - Presence or absence of gas is very important
  - Observable signatures depend strongly on whether star formation is ongoing or has stopped
- Like H-R diagram, galaxy color-luminosity diagram could also be showing evolutionary paths

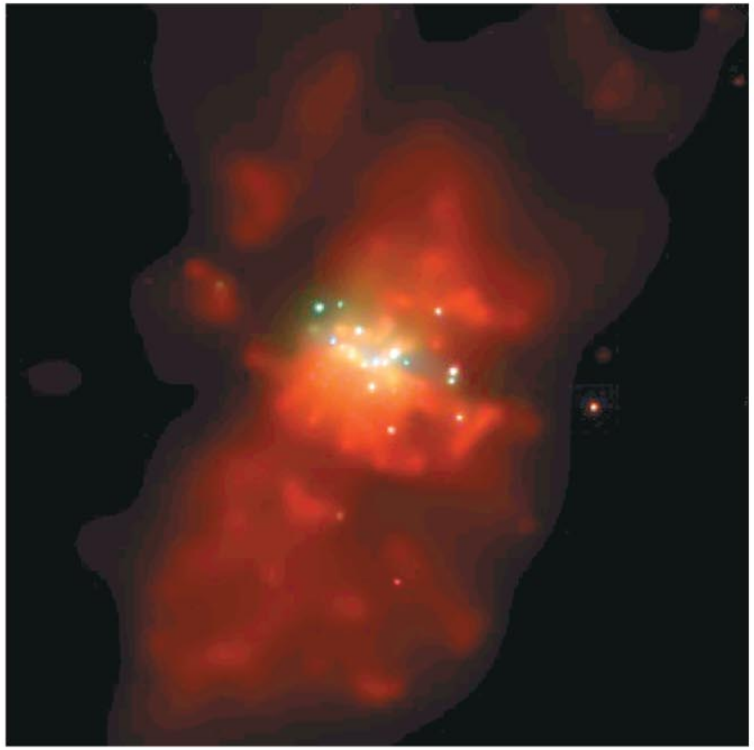


Star formation rate

- Star-gas-star cycle strongly depends on
  - How much gas is available for forming stars
  - How quickly stars are forming
    - Faster star formation, more frequent supernovae, faster star-gas-star cycle
- How to measure star formation in a distant galaxy?
  - Compare visible light output to infrared light
  - Dust, molecular gas absorb visible light; infrared light passes through
  - Lots of infrared: lots of young stars!

Star formation rate

- A star formation rate in a galaxy 100x the Milky Way's means 100x more frequent supernovae
- Bubbles, superbubbles, and … megabubbles?
  - No, they're called galactic winds, at that point

Ok, great, but what about those supermassive black holes?

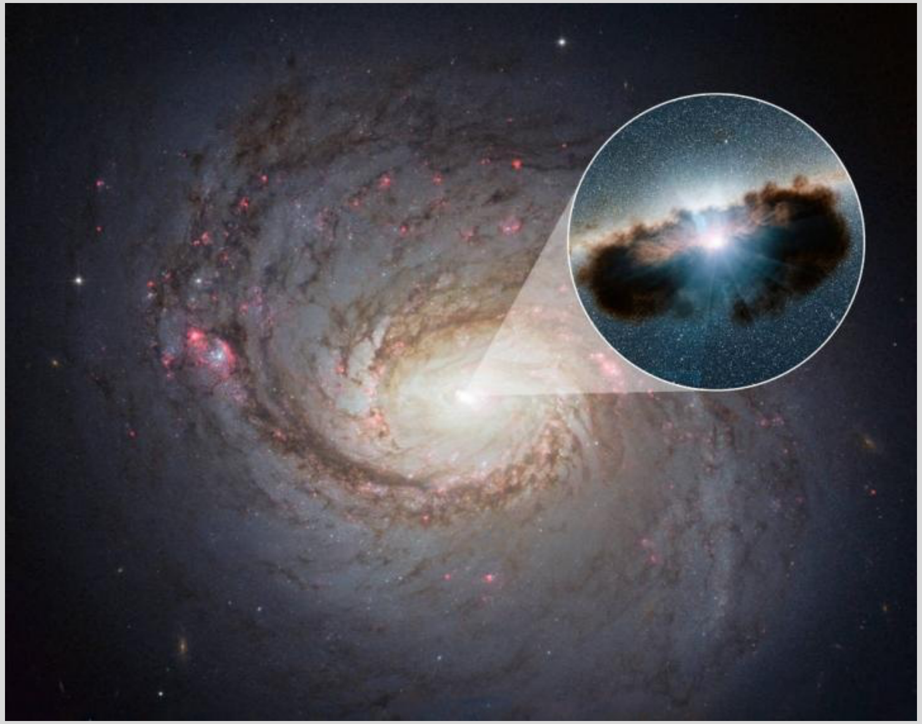
- Excellent question.
- When we look at galaxies, we notice for some…
  - Centers of other galaxies seem a lot brighter than maybe they should be if just stars 🤔
    - Can be up to trillions, 1,000 billions, of times the Sun's luminosity
  - Images (in radio wavelengths) confine sizes of brightest centers of galaxies (called galactic nuclei) to < 3 light-years across.
  - Hold up: we also observe galaxies to be variable at their centers.
    - If something is ~3 light-years across, we should notice it in the variability! 3 year time difference in the signal! But we don't see that.

Galaxy centers

- So if something is a light-year across, and it changes in luminosity, we'd see those changes happening over 1 year+ of time
- Period of variability limits how big the thing varying can be!
- We observe centers of galaxies varying over periods of *hours*.. Source must be small

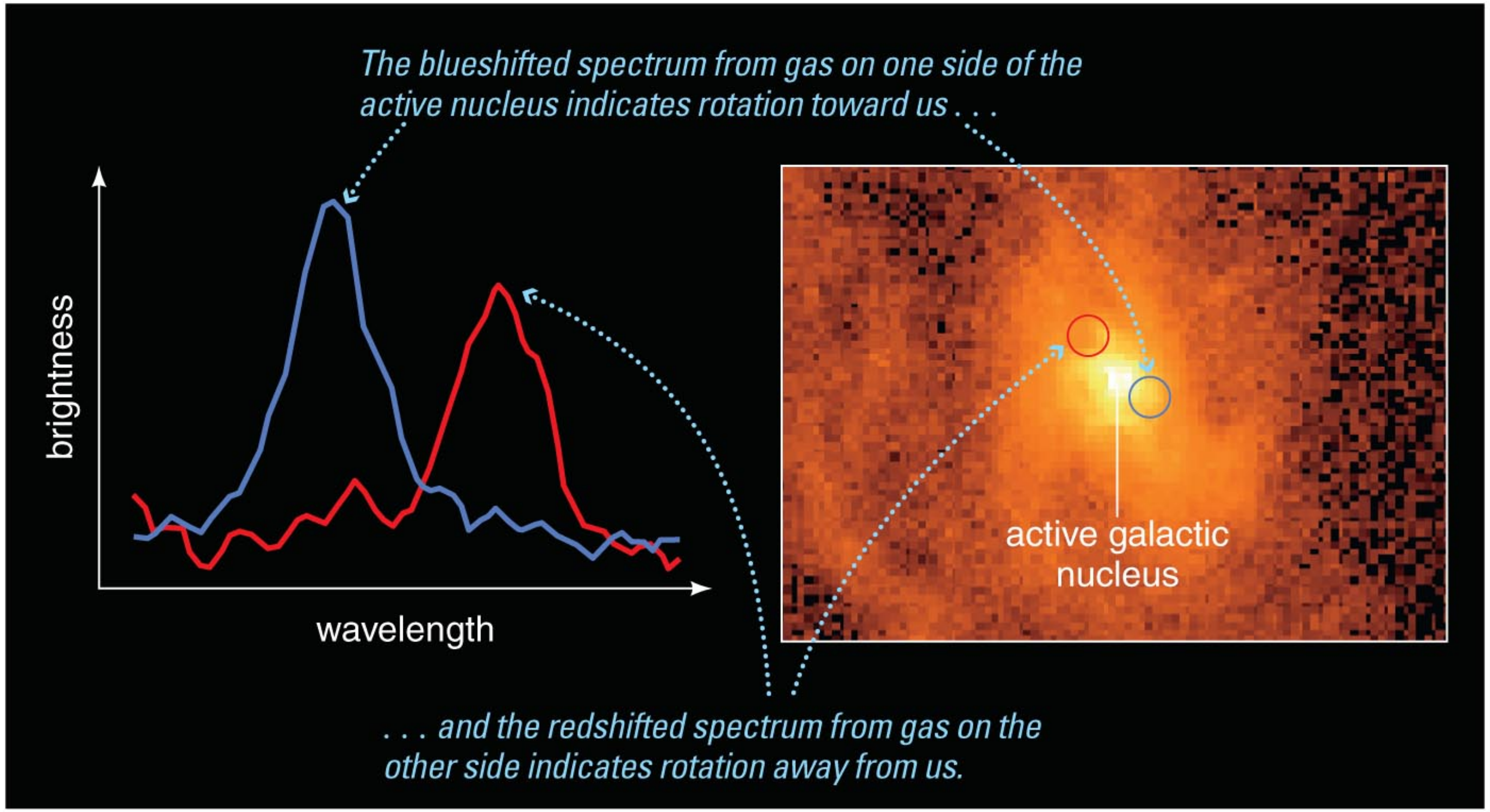
Active galactic nuclei

- Like in X-ray binary systems (black hole + star), material accreted by black hole forms a hot disk around the black hole
  - Gravitational potential energy → kinetic energy → thermal energy
  - Sizes agree: supermassive black hole would have event horizon of ~3 light-hours



Active galactic nuclei: supermassive black holes?

- Observing motion of gas in galaxies, we can estimate mass of central black holes
  - Orbital speeds, distance from center, indicate central mass is 2-3 billion solar masses!



Active galactic nuclei: supermassive black holes.

- Nearest galaxies allow for most precise measurements of how close material is orbiting galaxy centers
  - M106: emission of molecular gas (in the galaxy's disk!) resolved to ~1light-year from galaxy's center
  - Orbiting something small!
  - Something ~36 million solar masses

How do supermassive black holes form?

- We don’t know.
- Stellar-mass black holes, yes! Easy peasy, got it. Supermassive, hundreds to millions of times more than any progenitor star could possibly have been?
  - No idea.
  - But maybe mergers of smaller things, black holes, neutron stars.
  - Maybe youngest, highest-mass, earliest bursts of star formation formed a bunch of neutron stars at once, close enough to coalesce into supermassive black holes!
  - However these formed, it happened a long time ago because oldest galaxies (farthest ones away that we can see) already had them!

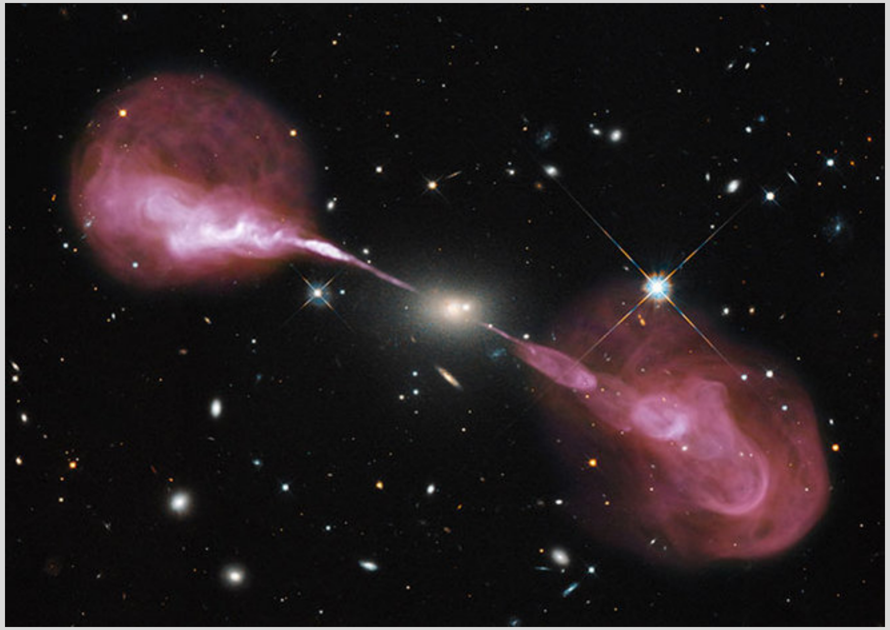
Galaxy feedback

- What role could a supermassive black hole play in galaxy formation and evolution?
  - We see relationship between mass of supermassive black hole, and mass of galaxy bulges (predicted by light from stars)

How well did I do today?

Galaxy feedback

- What role could a supermassive black hole play in galaxy formation and evolution?
  - We see relationship between mass of supermassive black hole, and mass of galaxy bulges (predicted by light from stars)
  - We also see jets being launched from centers of galaxies



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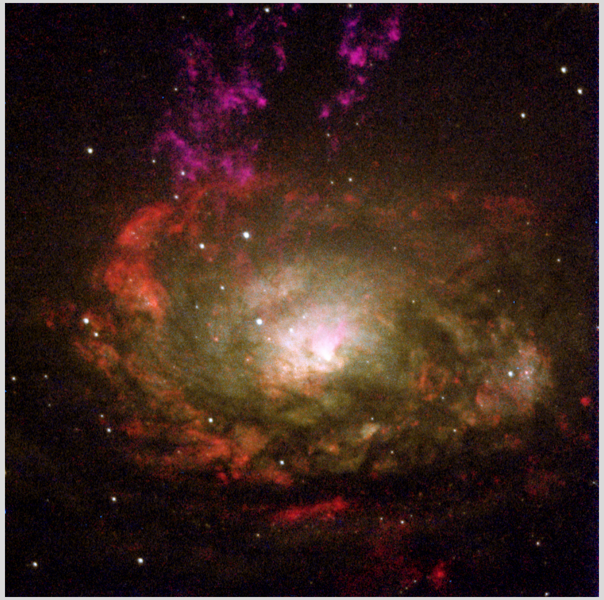
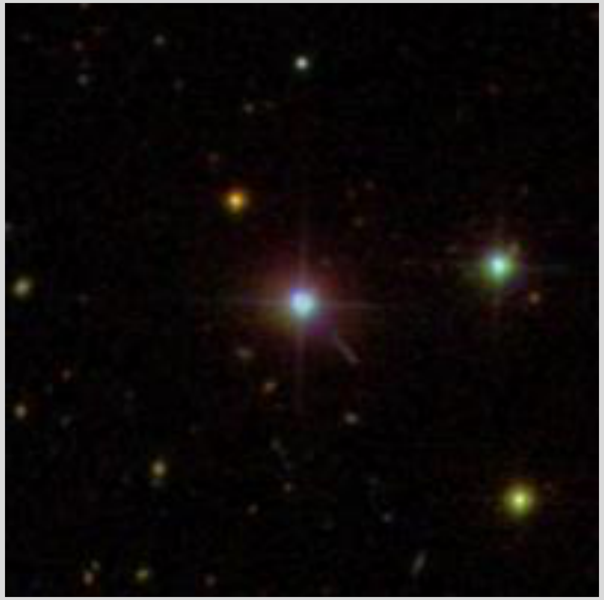
  - We see relationship between mass of supermassive black hole, and mass of galaxy bulges (predicted by light from stars)
  - We also see jets being launched from centers of galaxies
    - Jets can impact star-gas-star cycle, stopping bubble/superbubble/galactic wind gas from cooling and sinking back into disks
    - Activity of central supermassive black hole can allow or halt galactic star formation by affecting temperature of gas in galaxy

Now you see it, now you don’t

- Seyfert galaxies vs quasars
  - Two types of active galactic nuclei, probably the same thing but at very different distances
  - Quasar = quasi-stellar





Got gas? (probably not…)

- Distant quasars are active galactic nuclei (AGN) very, very far away: almost point-like sources of light
- Absorption of their light tells us about what is between us and the quasar
- We see absorption lines of gas at various redshifts
  - Gas is outside of galaxies
  - Implies much of universe's gas is outside of galaxies
  - … that is really odd. So galaxy formation is extremely inefficient!