FINAL EXAM SCHEME

- Friday 15 December, 12:00-13:55
  - Yes, Friday sucks. No, you can't take it early.
- There's been ~one midterm's worth of new stuff since last midterm (Ch.15-18)
  - So about half the final will look like a midterm on the recent chapters
- However, it is a final exam after all, and there are two hours to take it, so the other half the final will be comprehensive, reviewing older stuff

HOW TO REVIEW OLD STUFF?

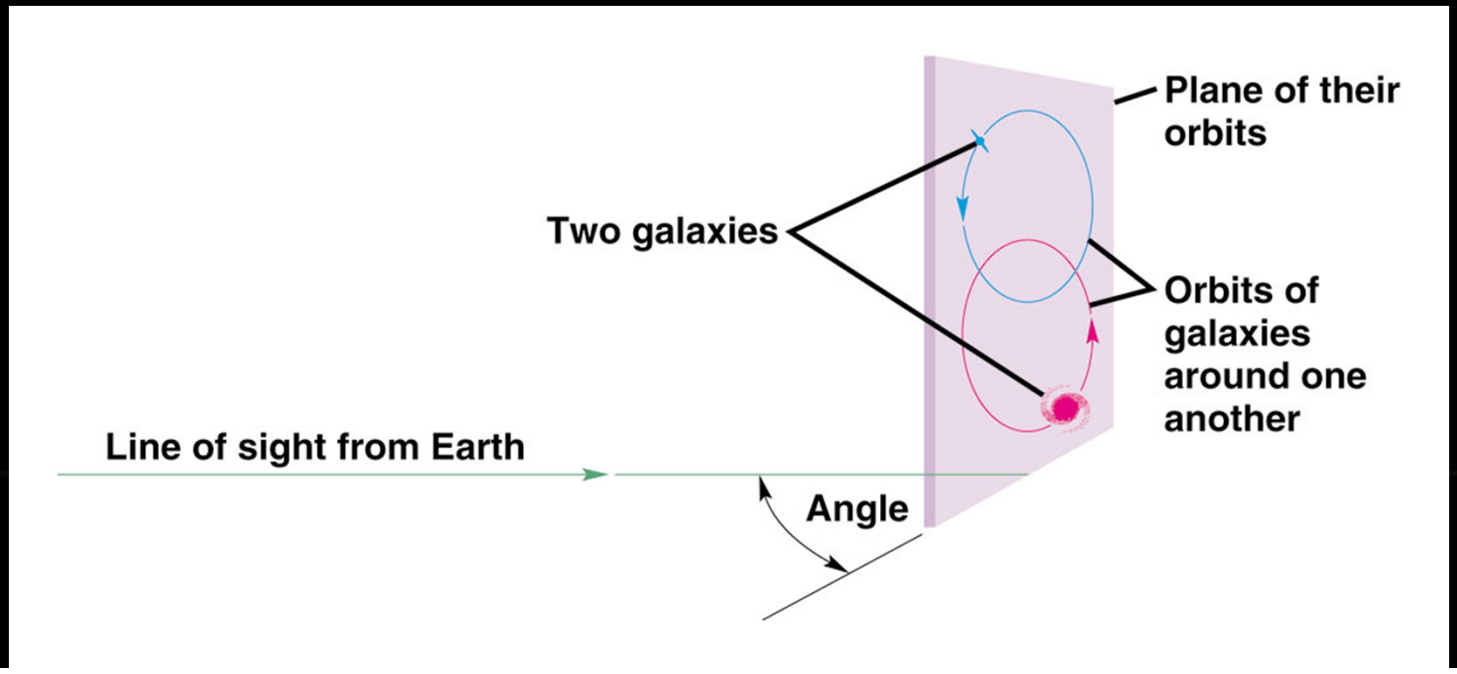
- Start with your old midterms. Can you work them out, starting fresh? You've got the practice midterms (and practice final) to work from too
  - For topics that give you trouble, then go work out problems from HW and concept quizes on Mastering
- The key to all this: Figure it out yourself! Don't look it up or google it till after you've tried hard to figure it out
  - Otherwise, you think you know it, which lasts for the next five minutes and then evaporates

PLANETARIUM

- If you didn’t go to the planetarium shows for this class at the start of the semester, you’ve got an “N” in that item in eGradebook
- You need to do the makeup assignment to change that to an “S”
- …. and there’s only a week left to do so

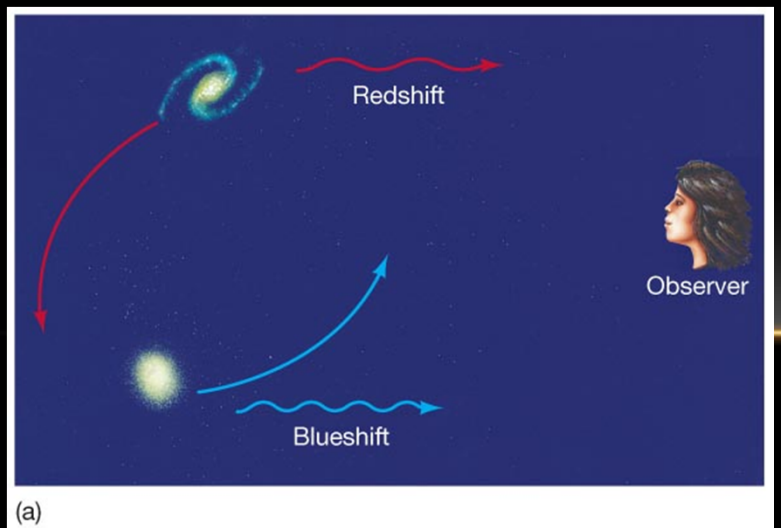
ORBITING GALAXIES

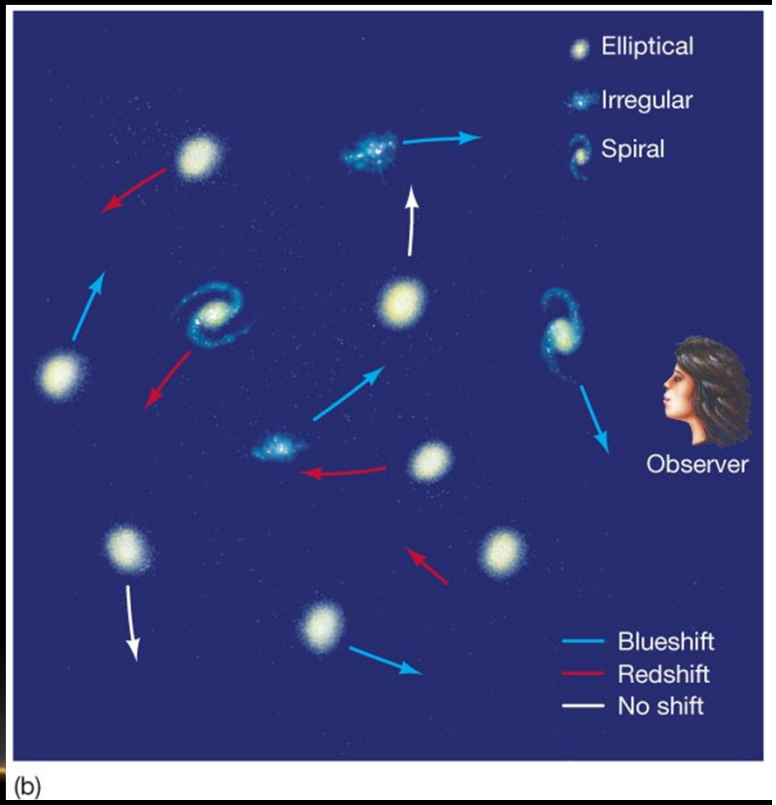
- Just like binary stars, two orbiting galaxies can give us a hint to the mass, still using Kepler's Laws and Doppler shifts



SHOWS UP IN CLUSTERS TOO

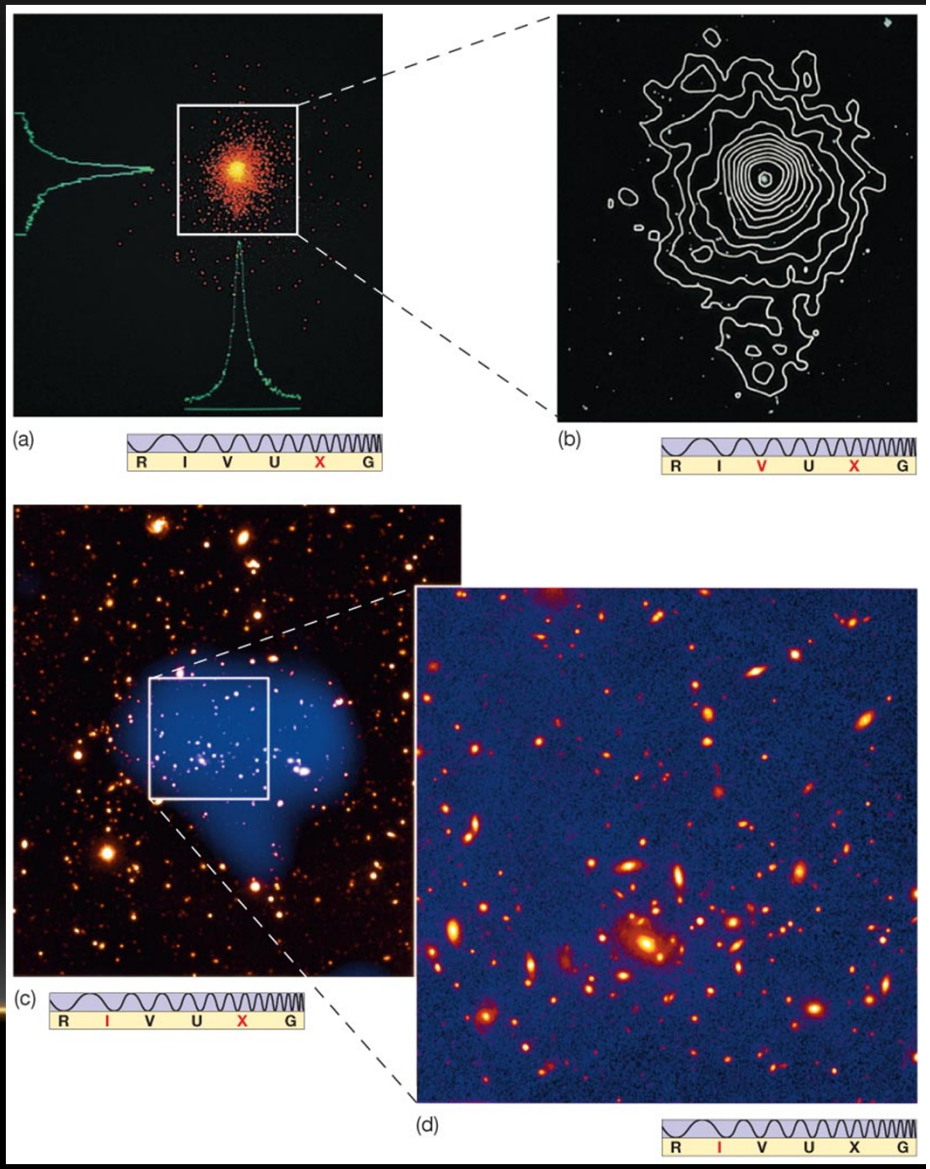
- Looking at the motion of galaxies in their clusters, more dark matter!
  - Calculate escape velocity of cluster needed to keep the cluster together, need a lot more gravity than visible stuff provides
  - Need 50x as much mass as we see





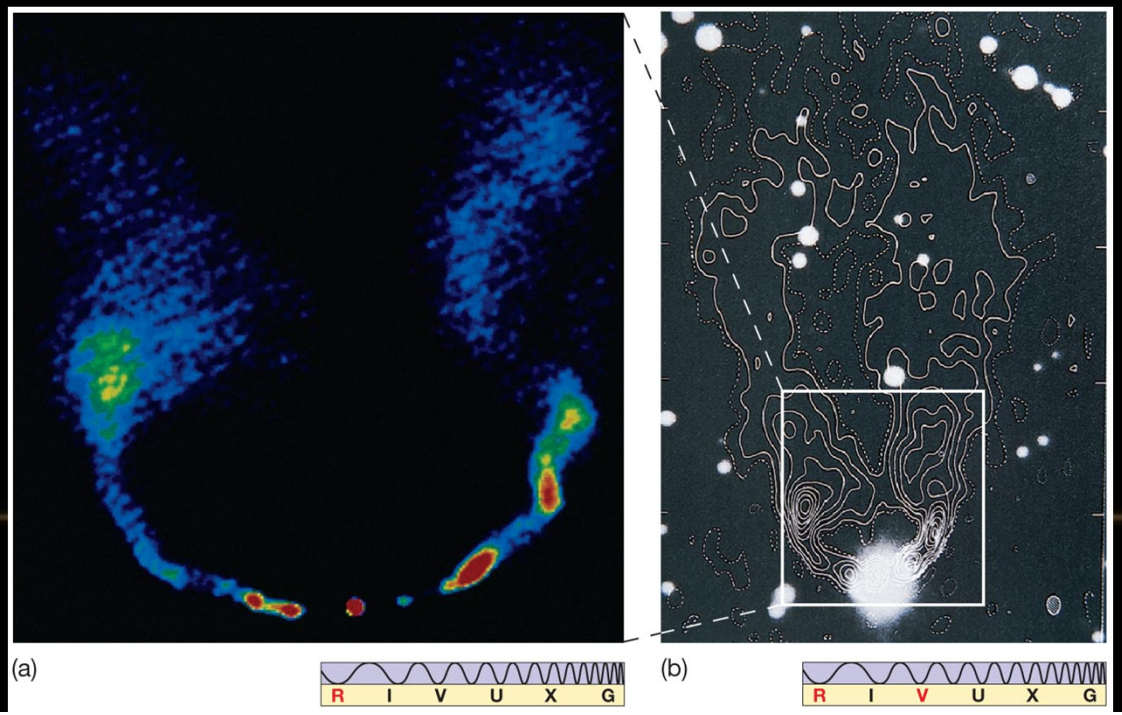
…AND IN X-RAYS

- Galaxy clusters have a thin haze of X-ray emission
  - From very diffuse, very hot gas
  - 10 million degrees
  - Denser near center
  - But not enough of it to be the dark matter



SEE THE EFFECTS OF THAT GAS

- It pushes around the jets of active galaxies in the clusters



MORE DARK MATTER EFFECTS?

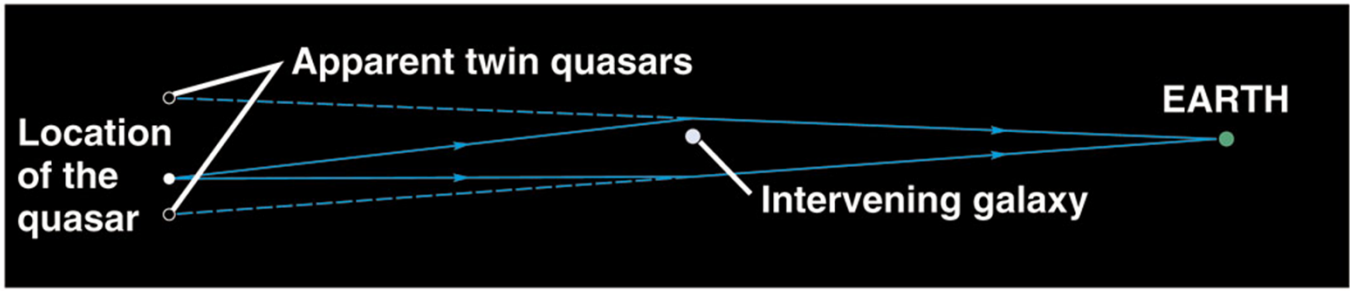
- Yes! Hot gas means gas atoms are really zipping around
- So fast, they'd leave the cluster
  - Unless there was a lot of gravity to keep them held in
- Cluster mass seems to be 85% dark matter, 13% hot gas, 2% stars

Fig.18.6

GRAVITATIONAL LENSING

- In a few cases;
  - A galaxy lies in front of something really distant
  - Makes a “gravitational lens” by bending space (from general relativity)
  - Can be used to calculate the mass of the bending object

microsoft and apple not playing nicely together…



LENSING AROUND A CLUSTER

- … can tell us how much mass must be there to bend light to that degree

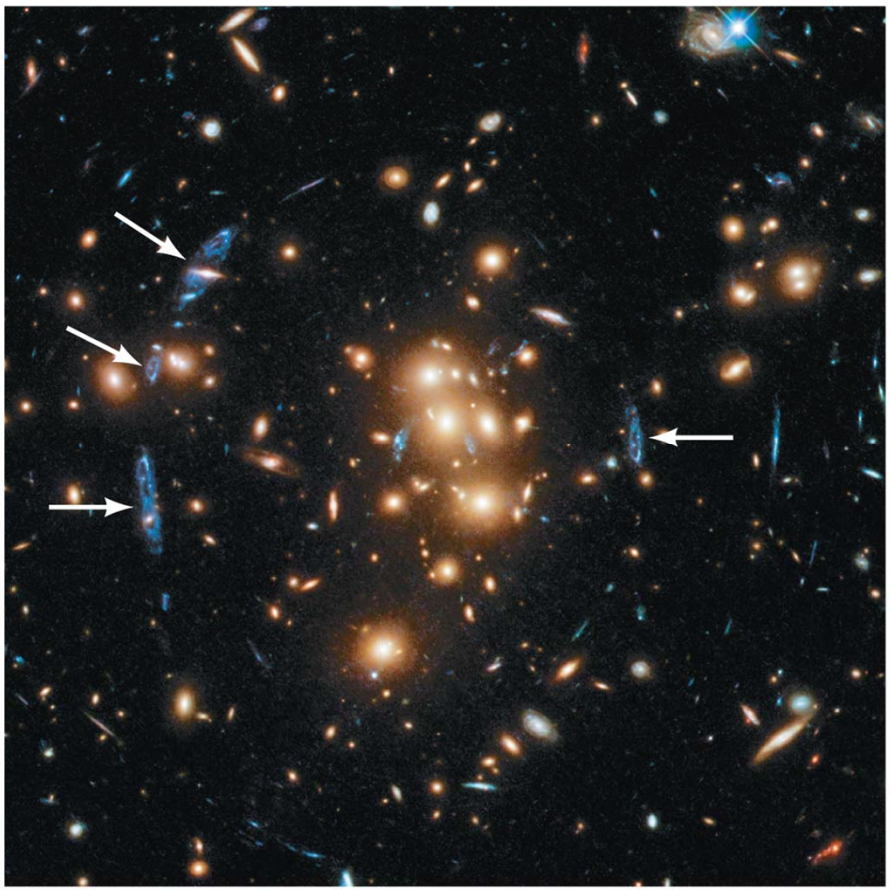


Fig.18.7

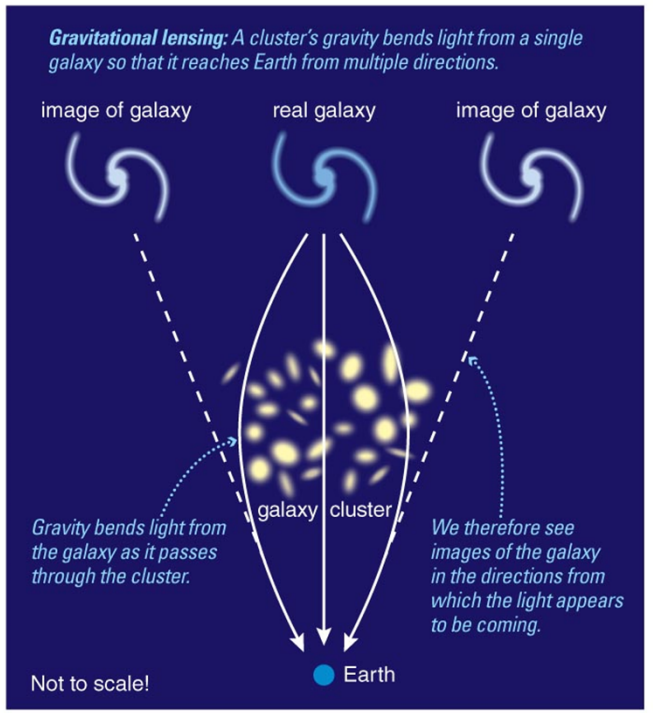


Fig.18.8

DARK MATTER GALORE

Fig.18.9

- Galaxy Orbits
- Hot x-ray gas
- Gravitational Lensing
  - All need about the same amount of Dark Matter to explain stuff

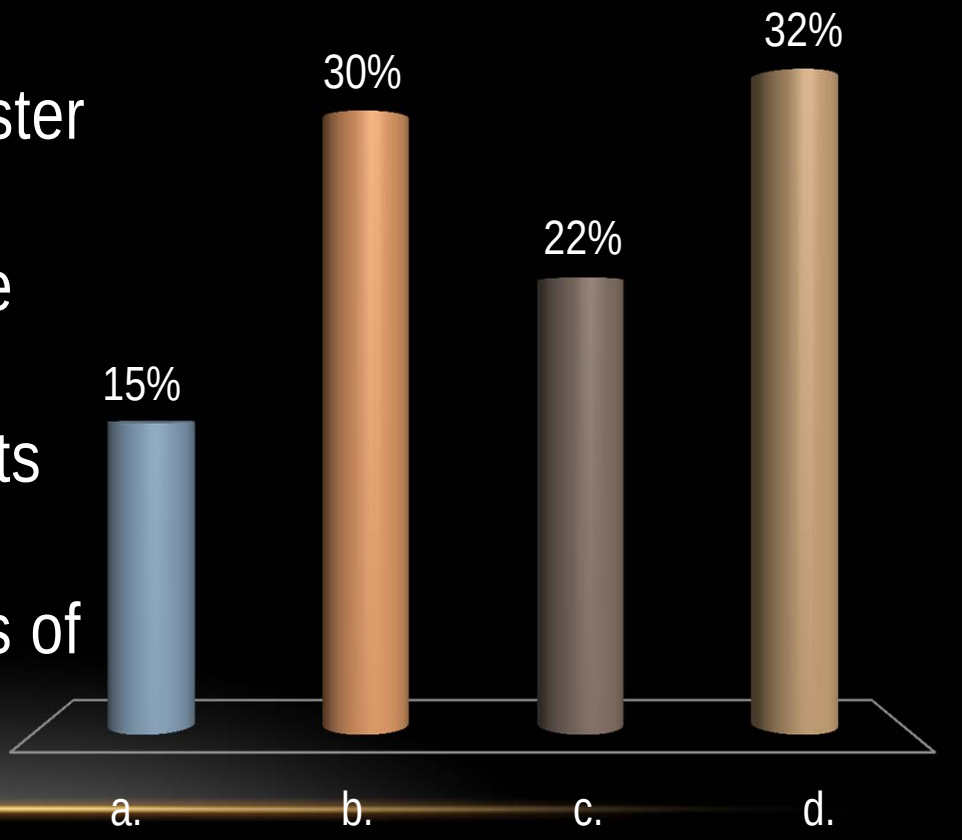
WHAT KIND OF MEASUREMENT DOES NOT TELL US THE MASS OF A CLUSTER OF GALAXIES?

a. Measuring velocity of a cluster galaxy

✓ b. Measuring total mass of the cluster's stars

c. Measuring temperature of its hot gas

d. Measuring distorted images of background galaxies



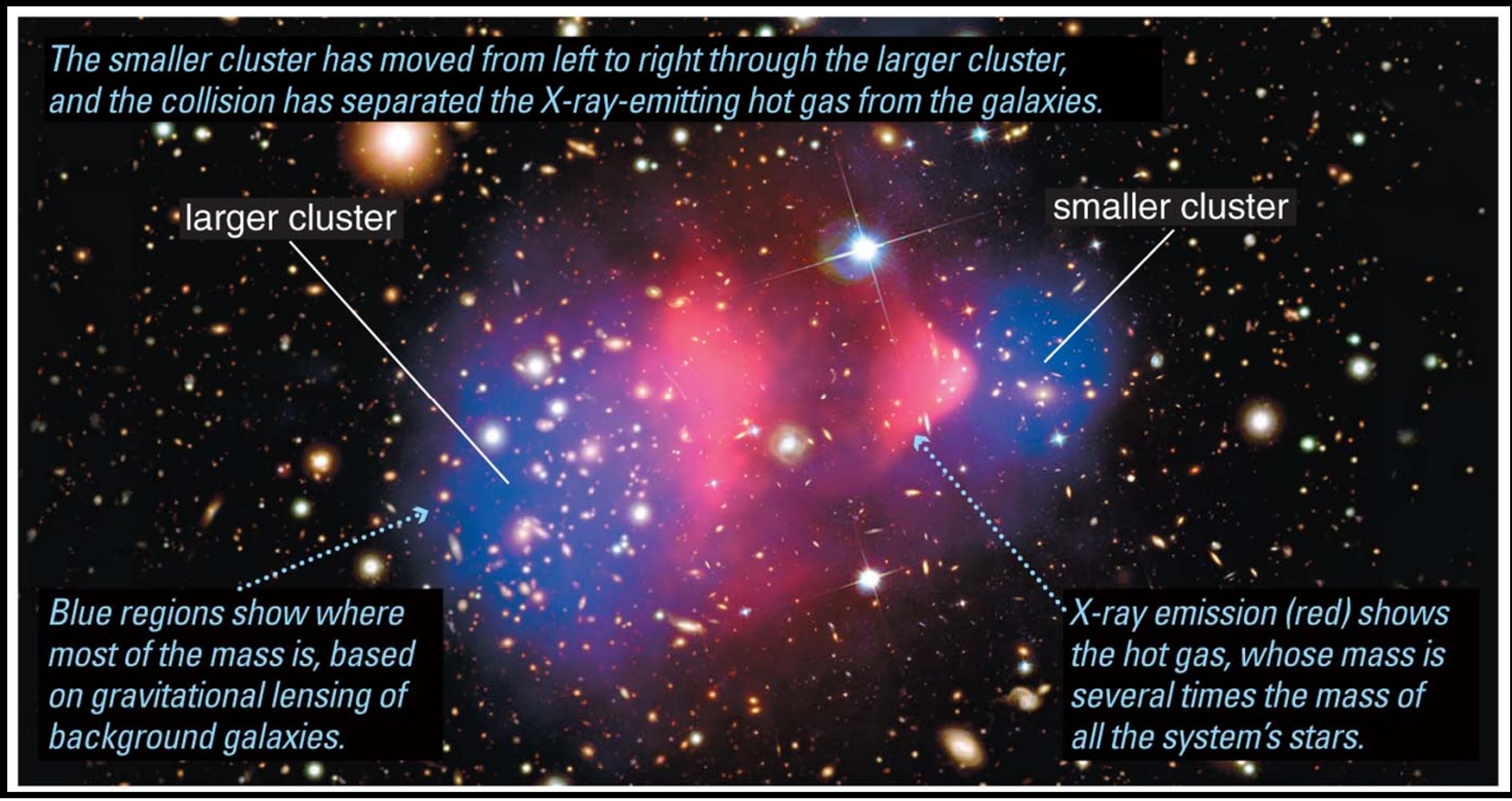
ANOTHER OPTION

- We infer the existence of this Dark Matter stuff by watching what gravity is doing to the bits we can see
- But what if how we think gravity works is wrong?
  - Say, maybe it doesn't go as $1/r^2$ on really big scales
  - This works… but differently in different places on different things
  - But there should be the same law of gravity everywhere

THE BULLET CLUSTER

- For example: in this one cluster collision, you'd need different gravity laws to explain both the lensing and the distribution of hot gas
- Or, only one set of Dark Matter

Fig.18.10



SIMULATIONS AGREE

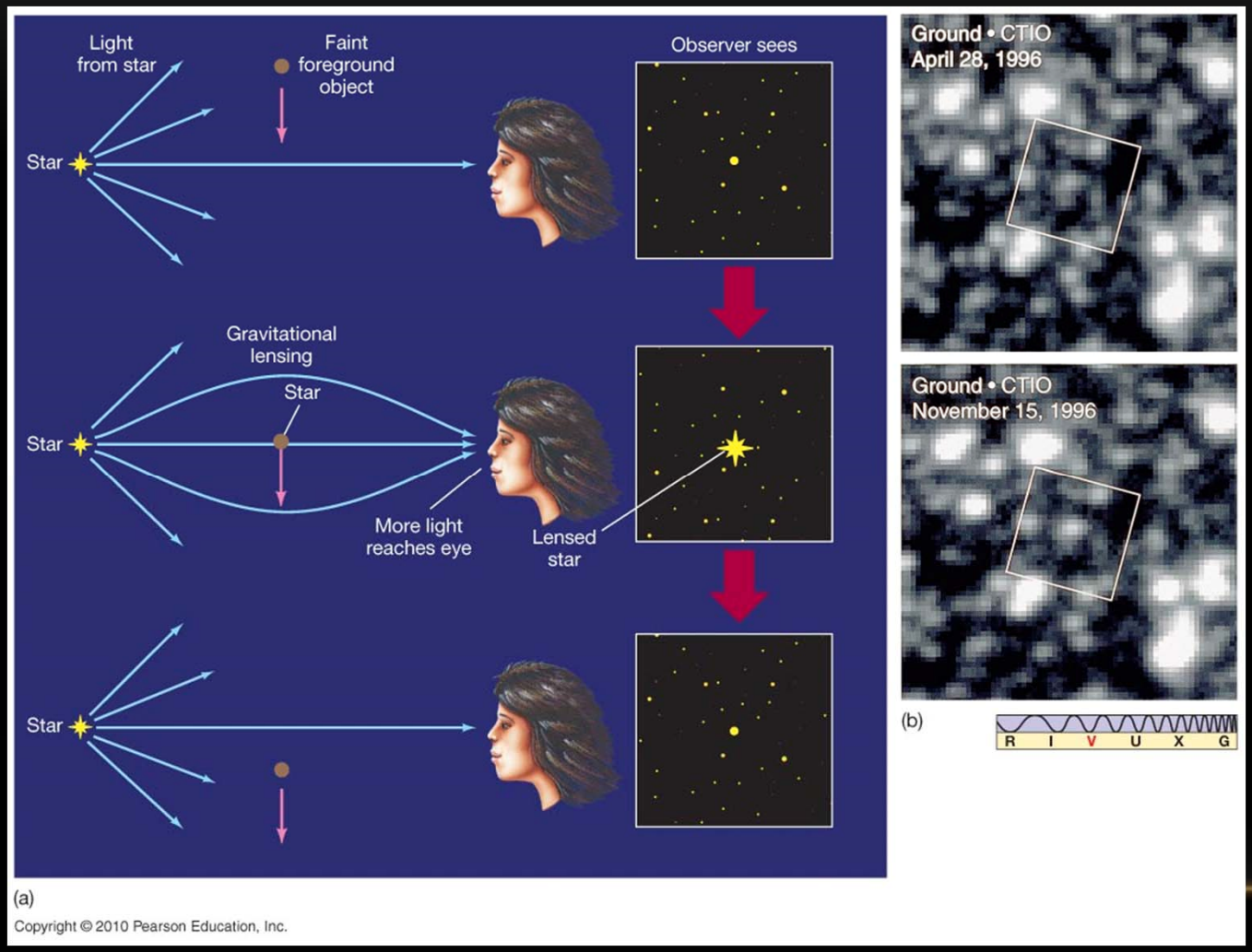
- Put galaxies, gravity, Dark Matter, and Newton's Laws into a computer and turn it loose, can replicated observed clusters
  - Diffuse gas in clusters collides, and we see it glow in X-rays

Another .mov which doesn't embed in the ppt

MACHOS

- Massive, Compact, Halo Objects
  - Brown/black dwarfs, black holes, etc
  - Could these be the Dark Matter in the Milky Way?
  - Heavy, hard to see!
- Would be part of the “normal” baryonic mass that’s not in stars

LOOK VIA GRAVITATIONAL LENSING



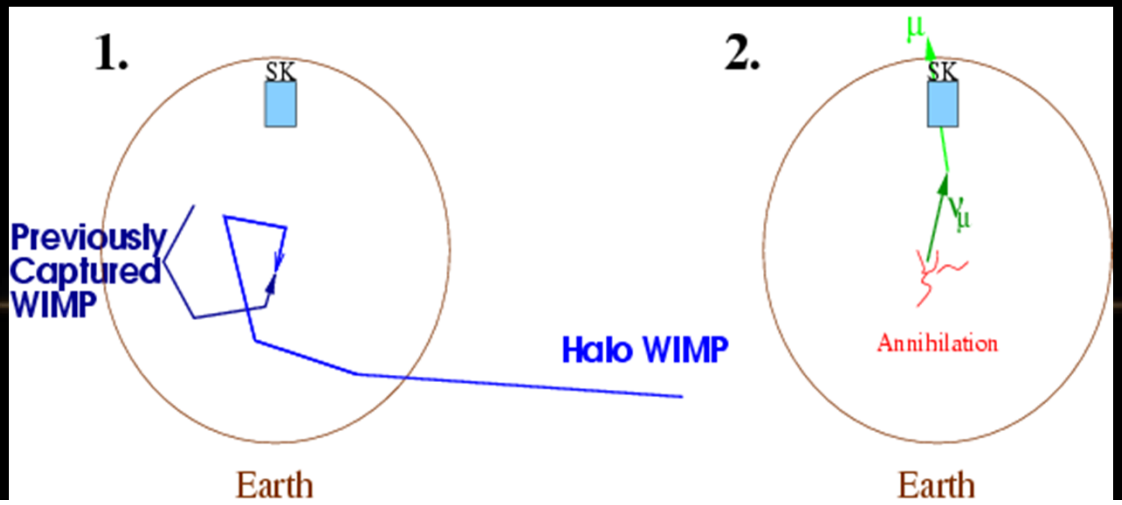
- And see some
  - So we know the technique works
- But not nearly enough

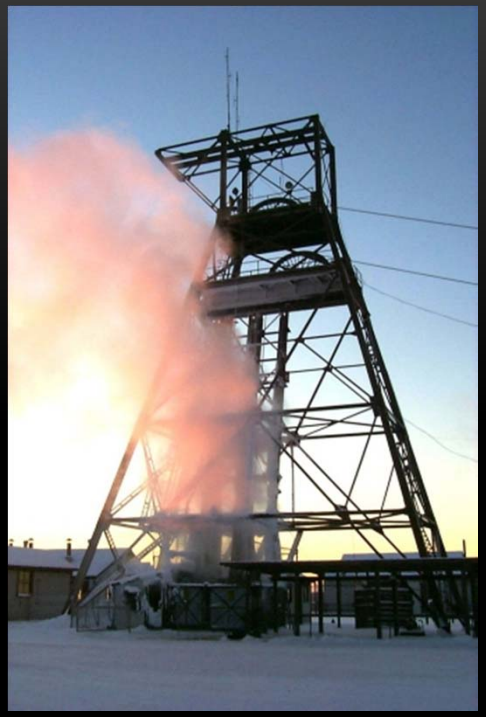
NEUTRINOS

- We talked about in the context of solar fusion
  - Weakly interacting (ie, very slippery) subatomic particles which are produced as a byproduct of the Sun's fusion
- "Hot Dark Matter"
  - Move around fast, because each neutrino is very light
  - So don't stick around in galaxies, can't be all of the dark matter we see doing galaxy stuff.
- More on UMD's contributions later (if time)
  - I am a neutrino astronomer, odd as that is

WIMPS

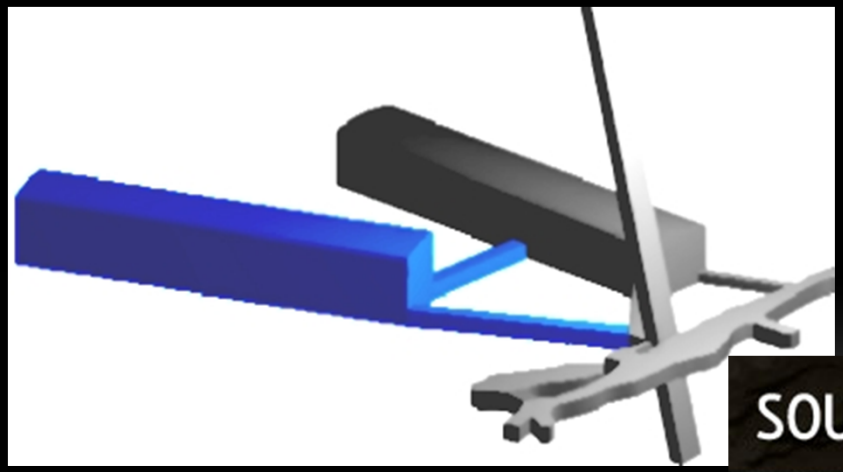
- Weakly Interacting Massive Particles
  - Predicted by many grand unified theories
  - Have much mass, slowly moving (“Cold Dark Matter”)
  - Interact only via the weak force
    - Like neutrinos
  - At UMD we look for them indirectly via neutrinos





ON THE IRON RANGE

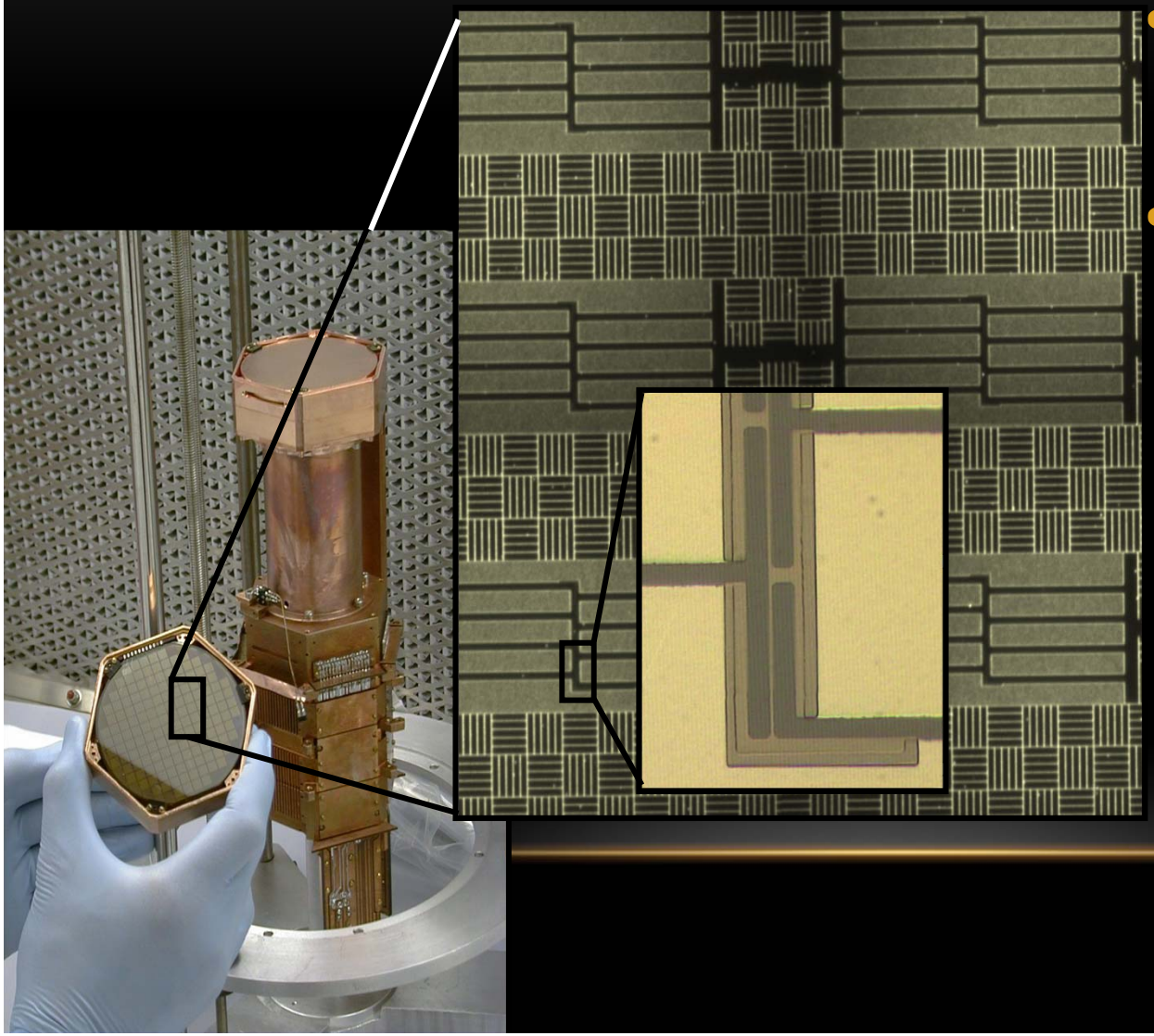
- Soudan Iron mine has been a state historical park since the 1960's
- A new cavern was excavated at the bottom of the mine
- Adjacent to Soudan2 expt. and Historical Tour – Closed now.
- Cryogenic Dark Matter Search (CDMS) in Soudan2 hall



DIRECT WIMP SEARCHES

- Cryogenic Dark Matter Search (CDMS) in the Soudan Mine was one such experiment
- It looks for the soft “thump” as a WIMP bounces off a nucleus in its detector

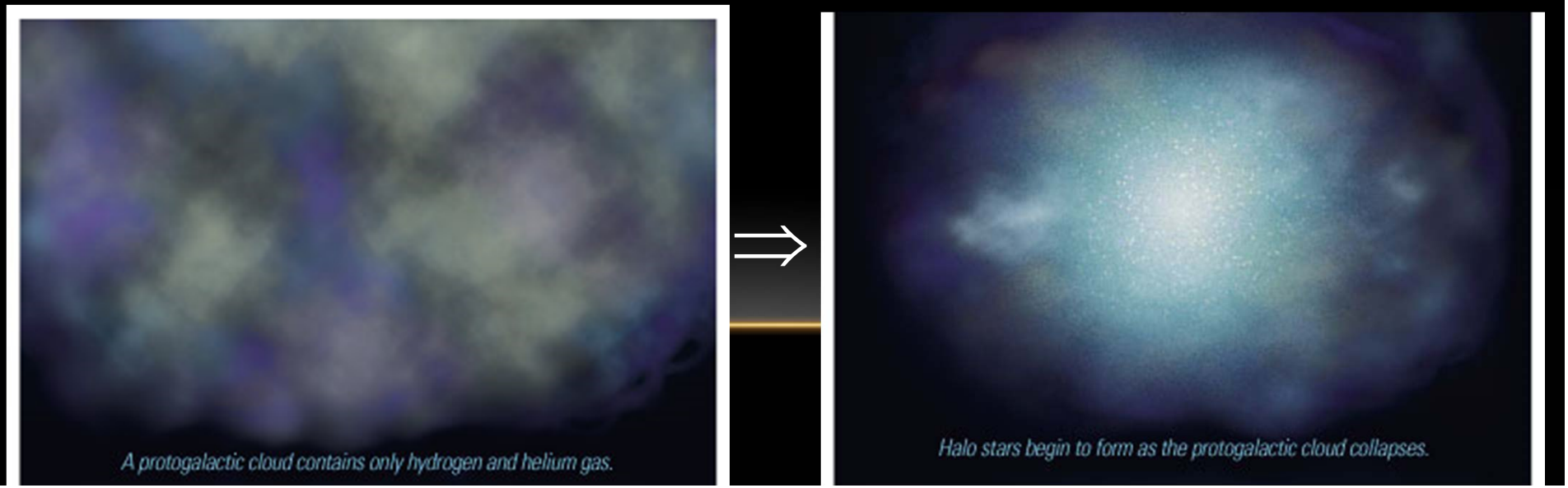
WIMP DETECTOR



- 100g Si chunks or 250g Ge chunks
- Chilled to 0.02 K
  - This lets them see the tiny vibration caused by a WIMP
  - Otherwise normal thermal vibrations dominate

DARK MATTER AND GALAXY FORMATION

- Galaxies formed quickly *(we see them already formed very far away*)
  - All that extra mass available as Dark Matter is needed to make them form quickly enough



WHY SHAPED LIKE THIS?

- Dark matter rarely bumps into things, stays in wide orbits
- Ordinary matter loses orbital energy to friction, settles down towards the middle of things

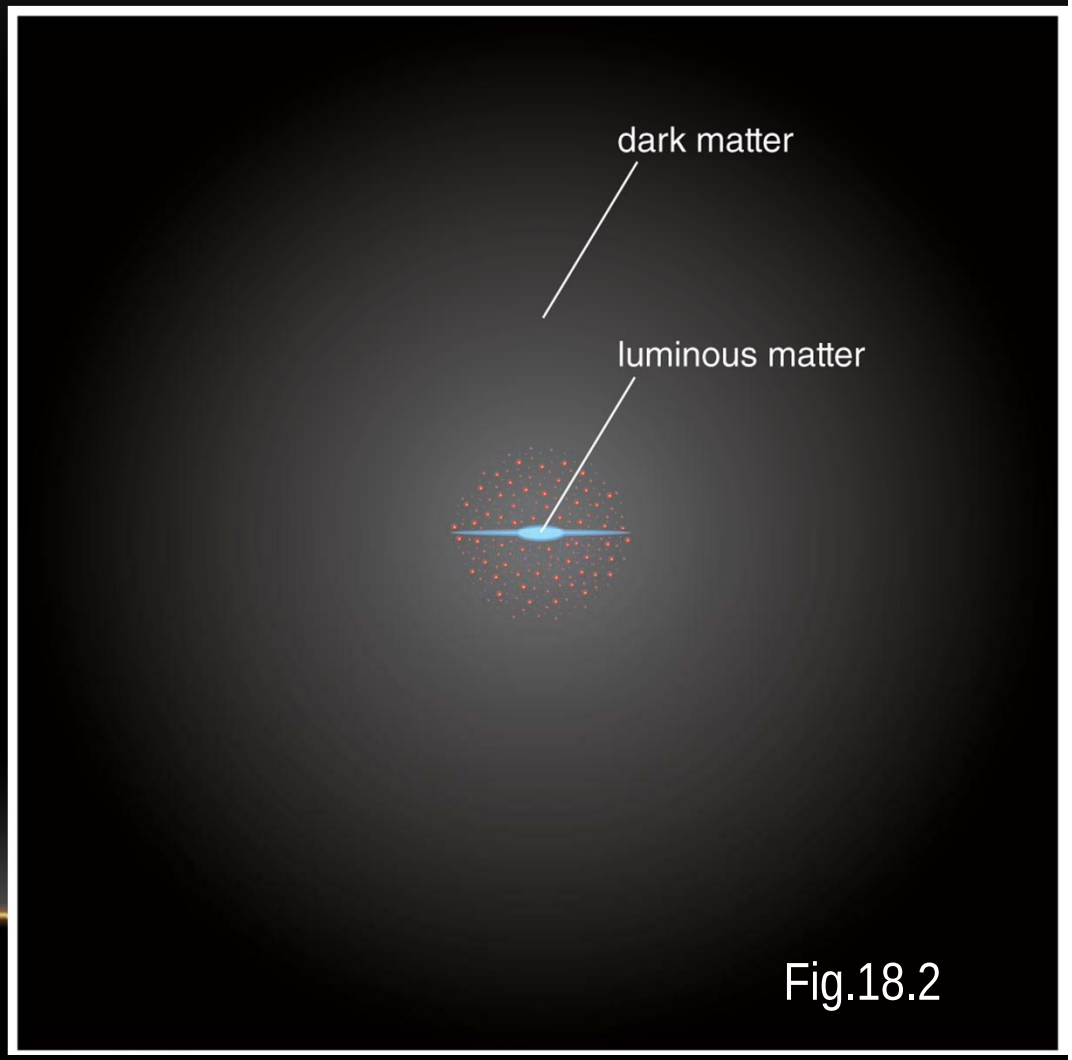
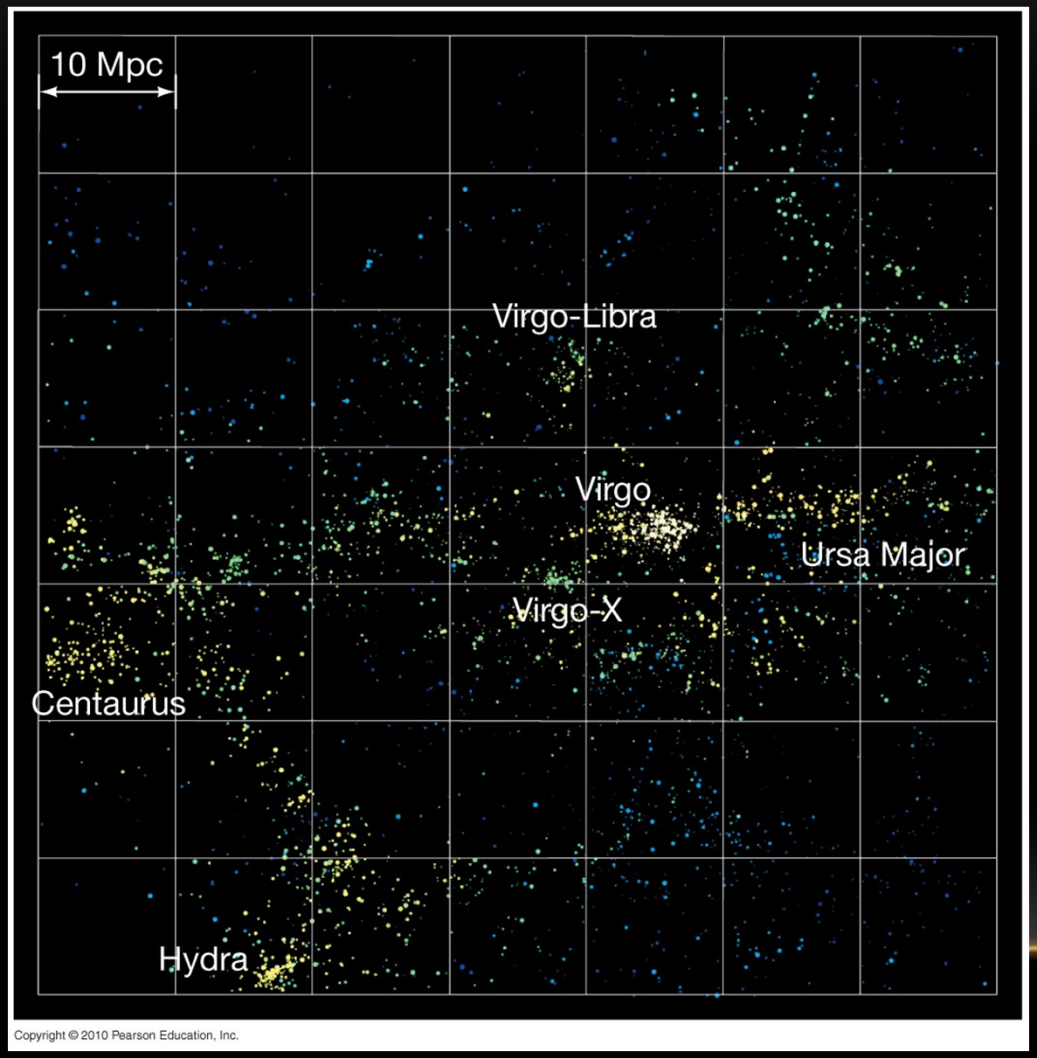


Fig.18.2

LARGE-SCALE STRUCTURE

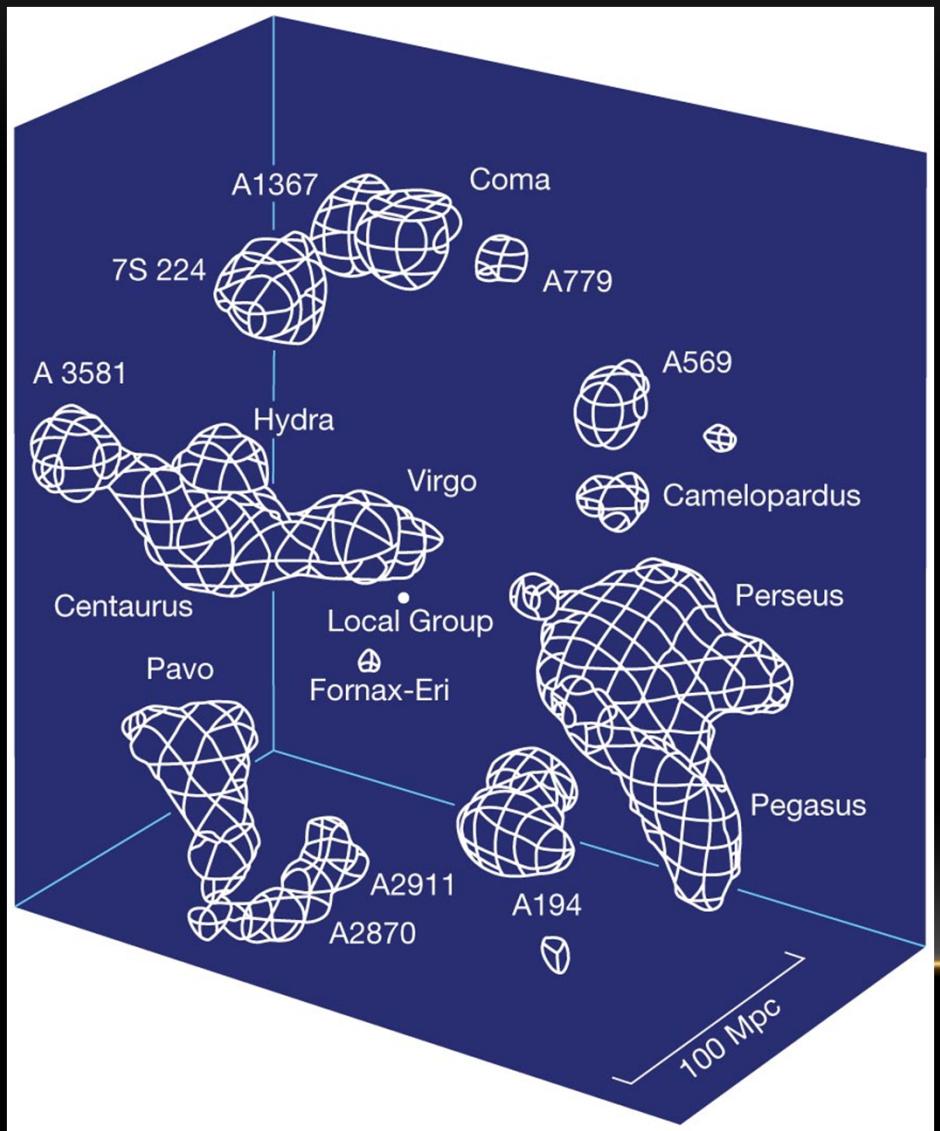
Ch. 18.3

MAKE A GALAXY MAP



- Nearby galaxies on the sky look like this

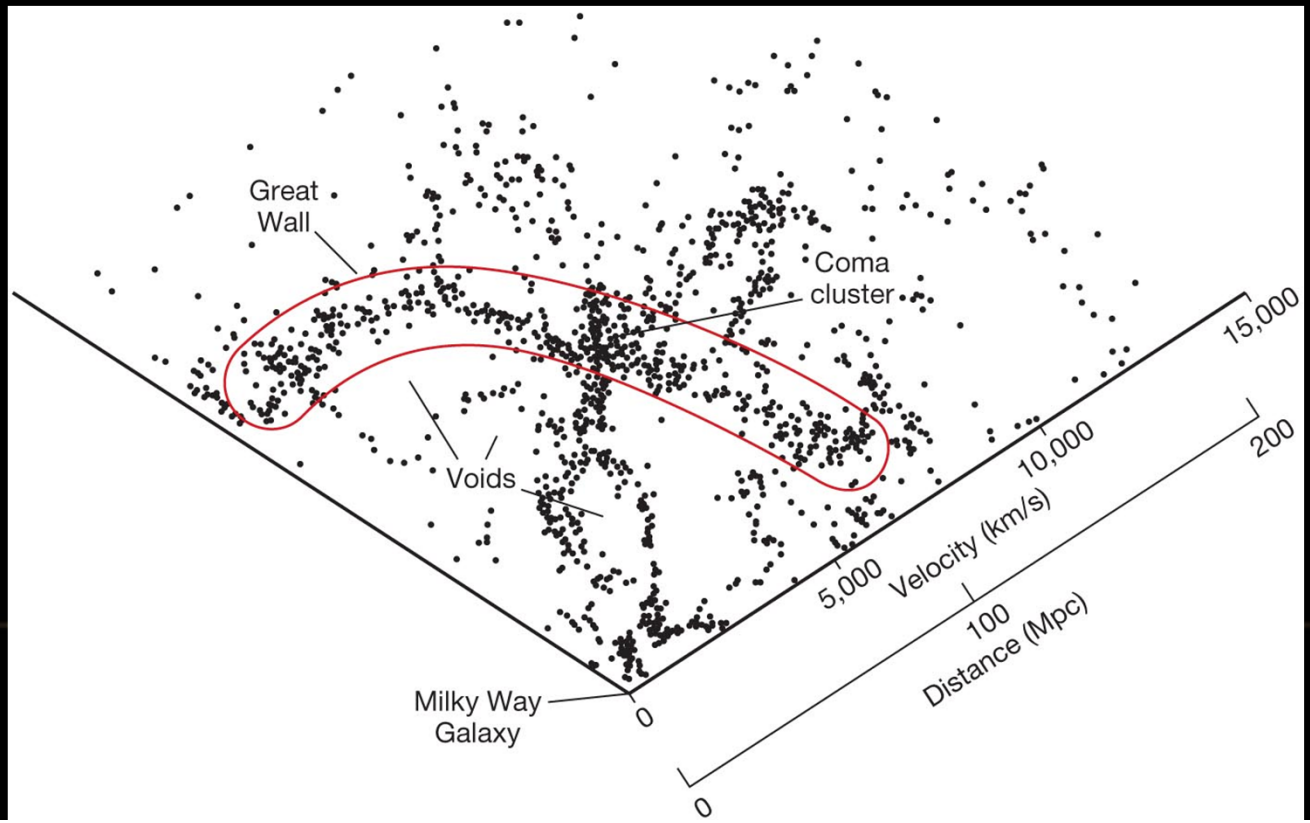
MAKE A GALAXY MAP



- In 3-D
- See "Superclusters" of galaxies
  - We are on the edges of the Virgo Supercluster

REALLY LARGE SCALE STRUCTURE

- Surveys of all the galaxies we see show “bubbles”, “voids”, “The Great Wall”, etc.



WHY SUCH A SHAPE?

- Make a map of which way the galaxies are moving
  - They're headed towards the denser areas, because there's more gravity that way
  - Again, need to account for the dark matter to get enough gravity to do this

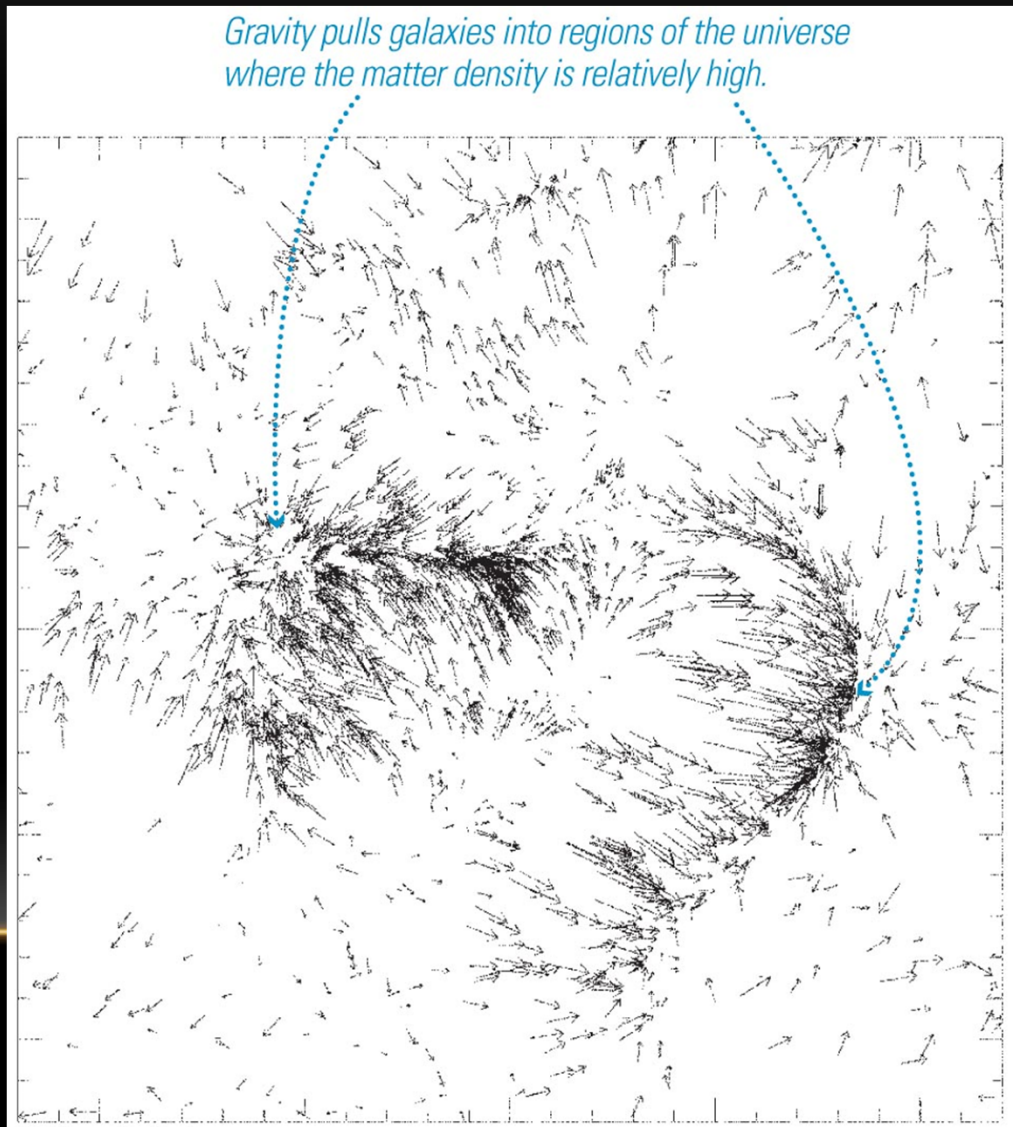
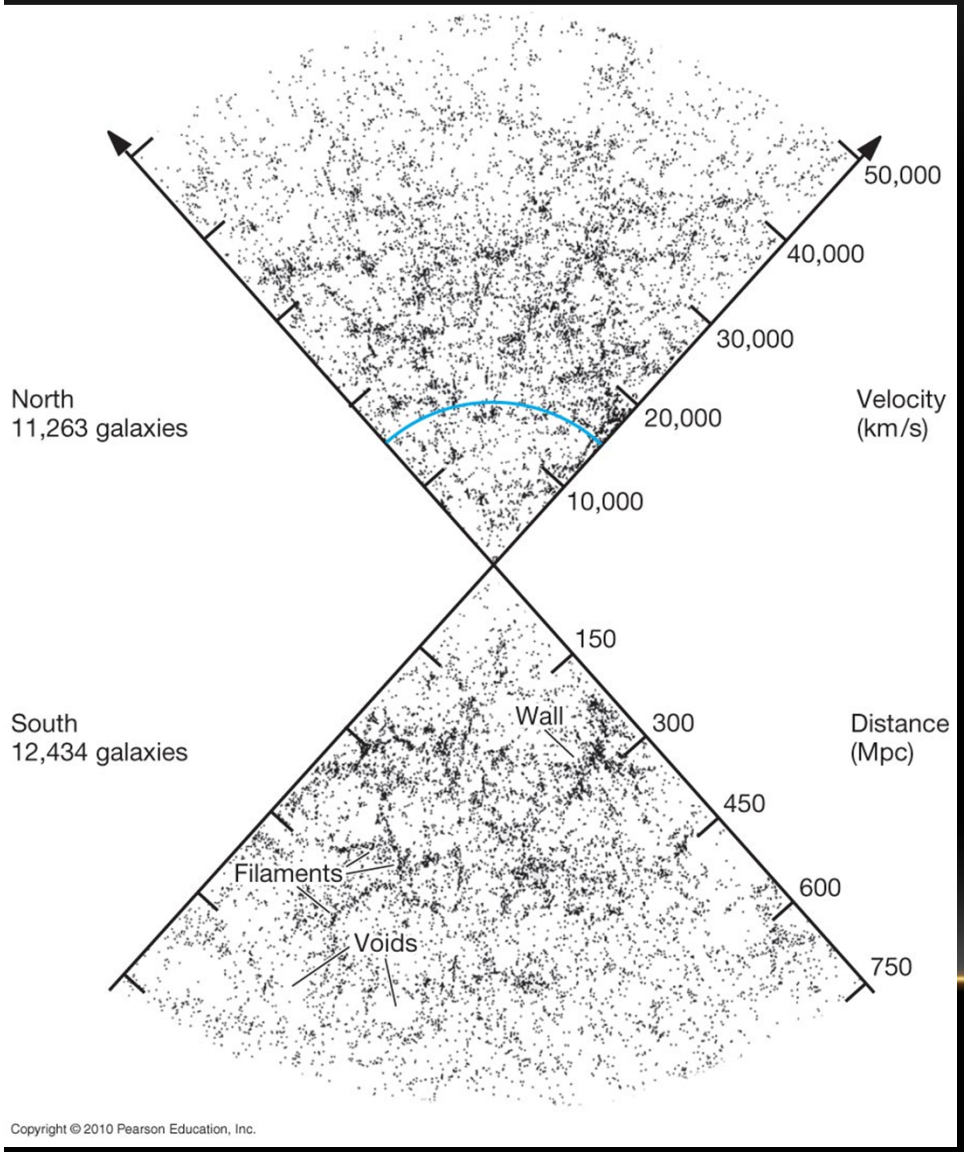


Fig.18.12

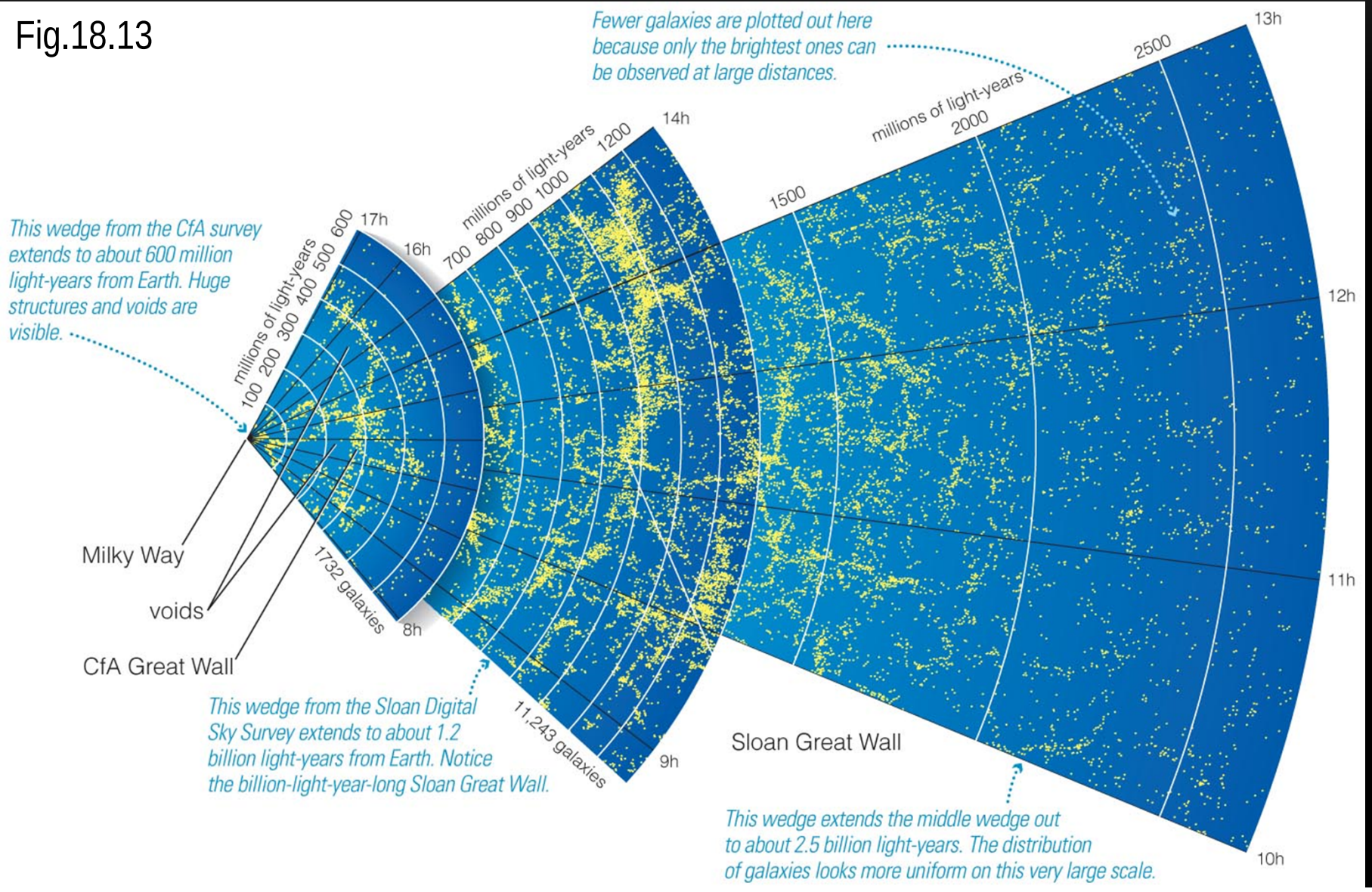
EVEN FURTHER OUT



- Starts to look the same on a large scale – “bubbles”, “voids”
- Combining gravity plus the Big Bang model, computer simulations can more or less understand this structure

COMBINING EVEN MORE SURVEYS…

Fig.18.13



OVER TIME?

- Put gravity, dark and luminous matter, universe expansion into a computer model, let it run
- Initially much more smooth distribution lumps out over time

PLAY

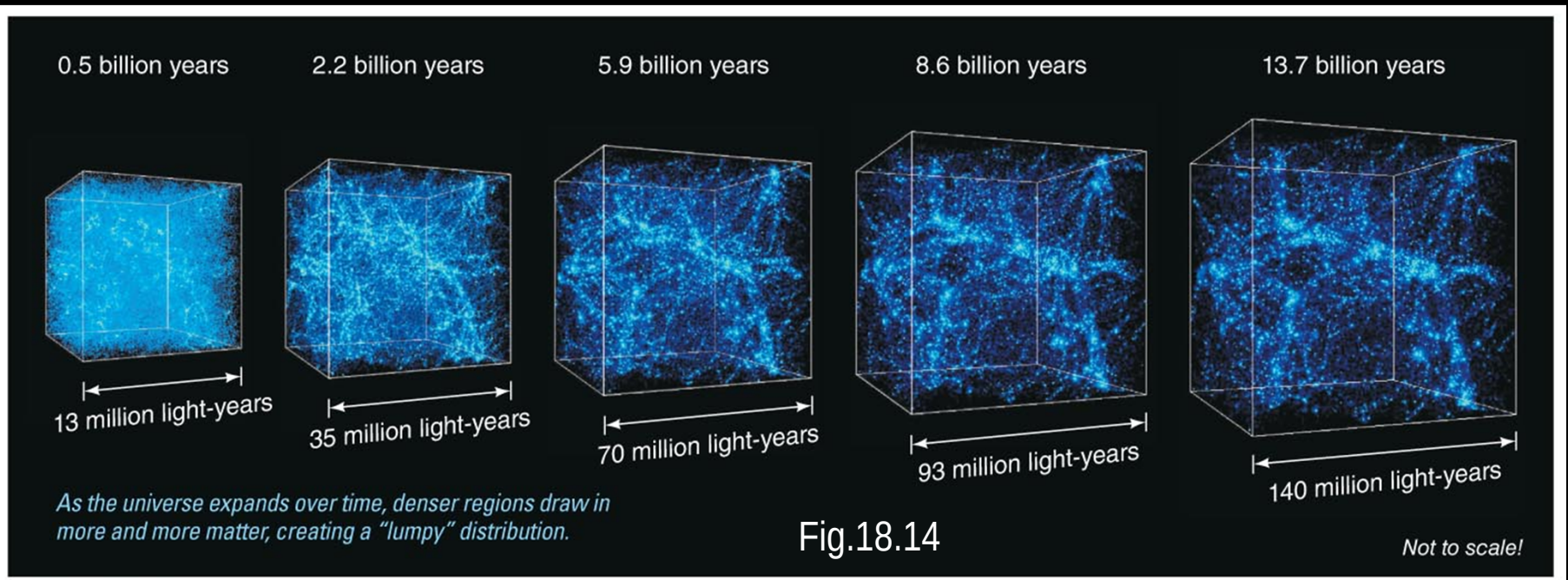
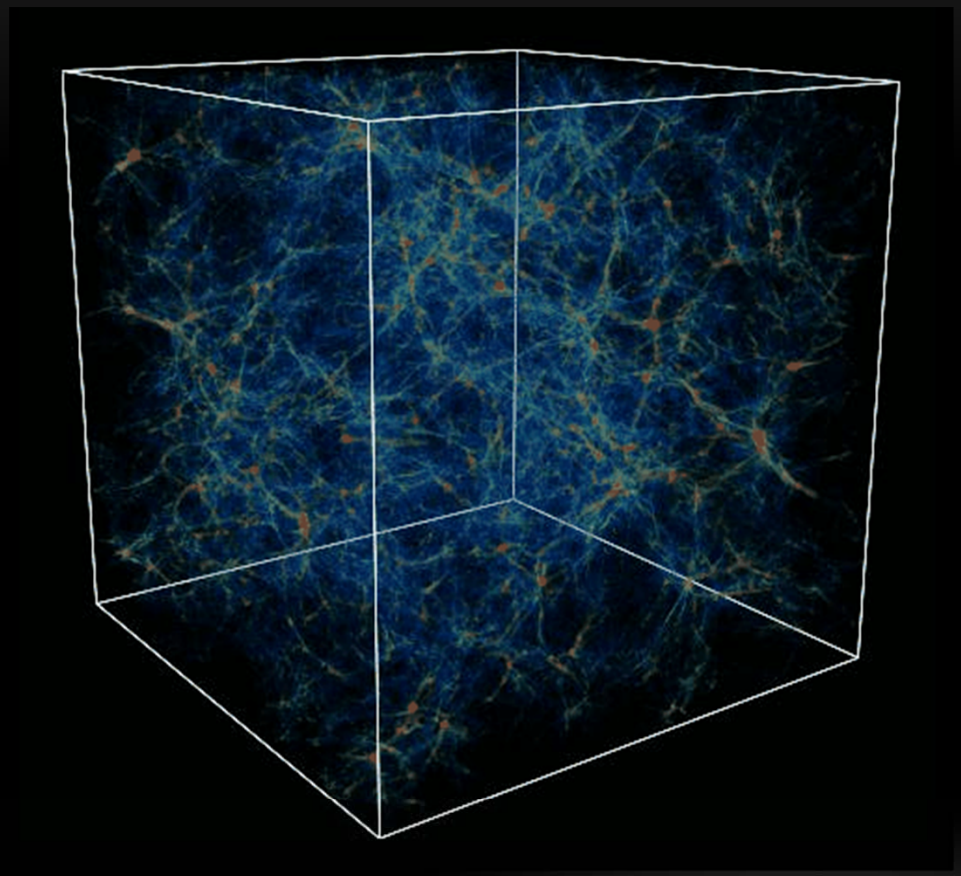


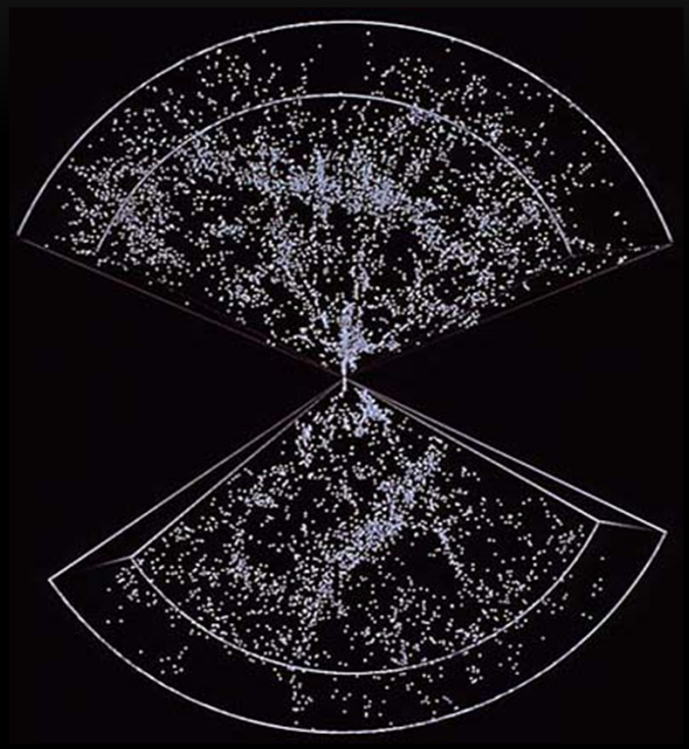
Fig.18.14

Simulated Universe,
Cold+Hot Dark Matter



Courtesy of Greg Bryan and Mike Norman, UIUC

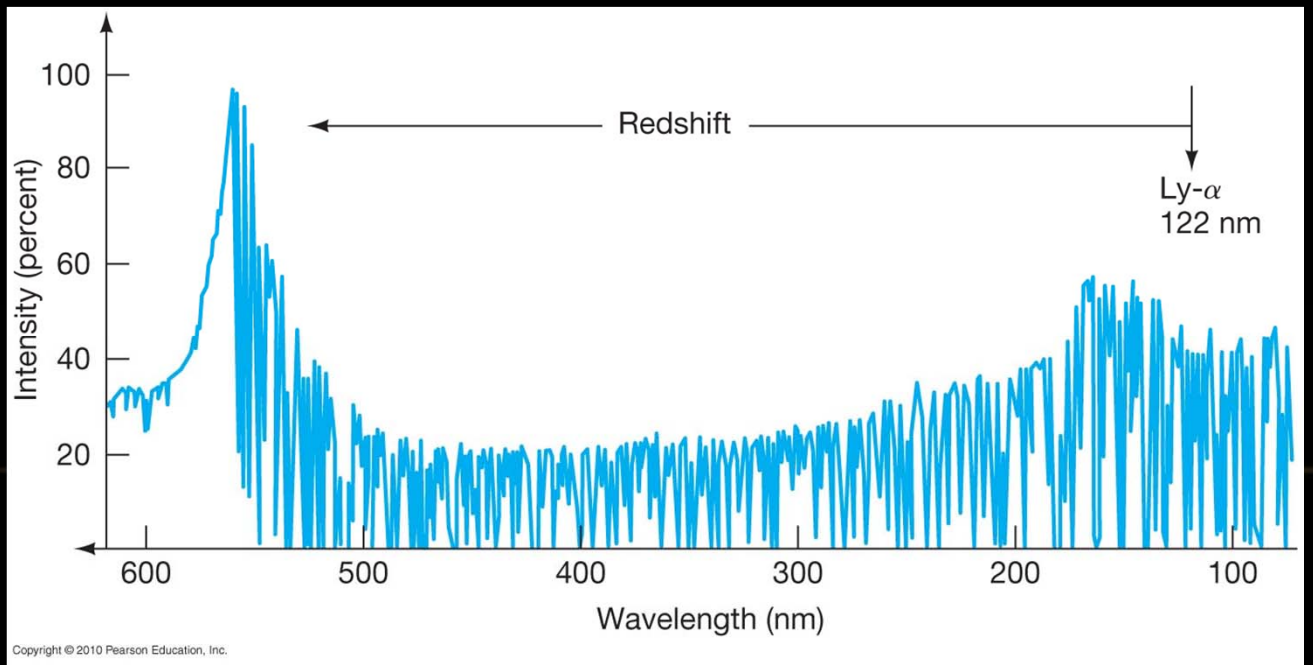
Real Galaxy
Survey



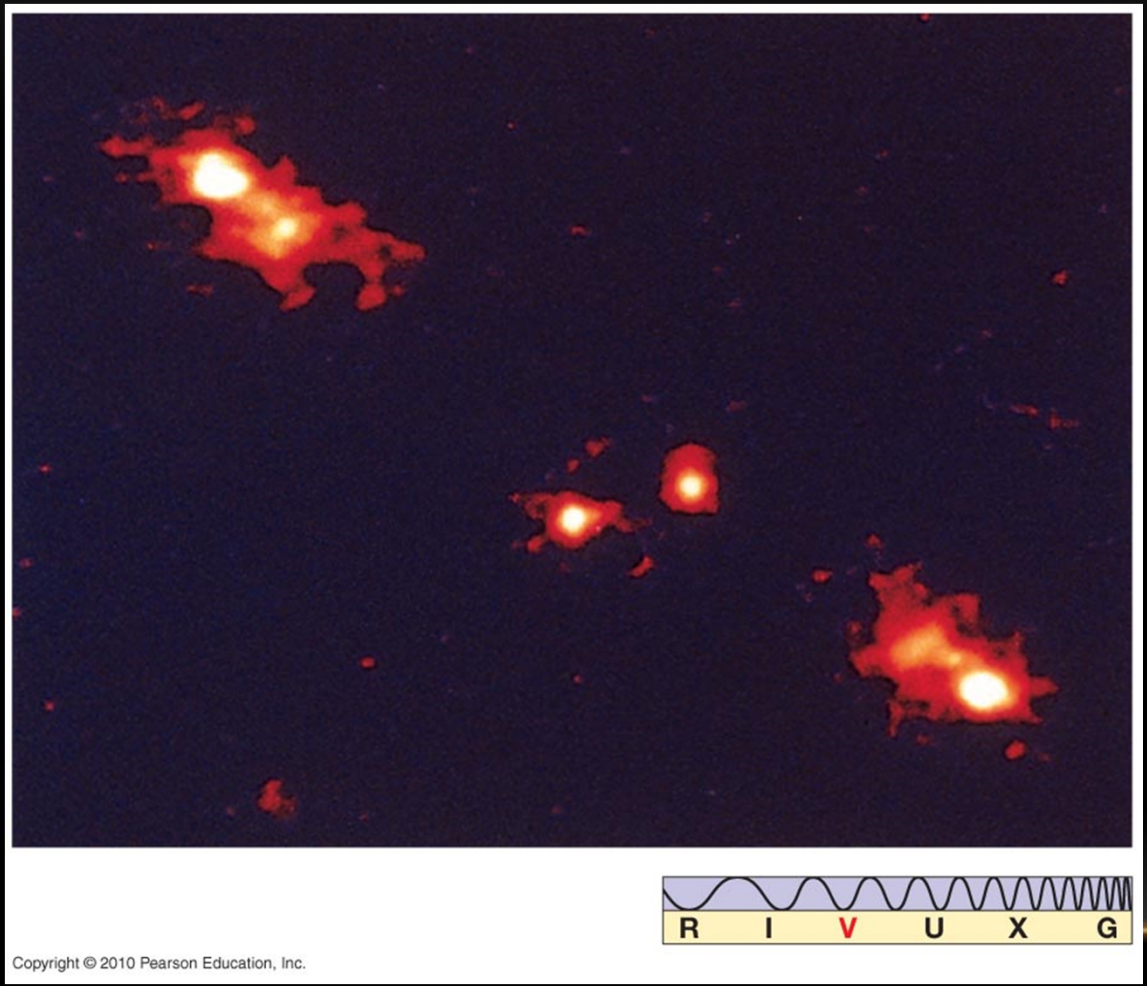
Courtesy of Margaret Geller and Emilio Falco,
Harvard-Smithsonian Center for Astrophysics

“LYMAN ALPHA FOREST”

- Light from distant quasars is absorbed by gas at different redshift
  - Each leaves the primary fingerprint of hydrogen on the light
  - A view <u>through</u> all that structure!

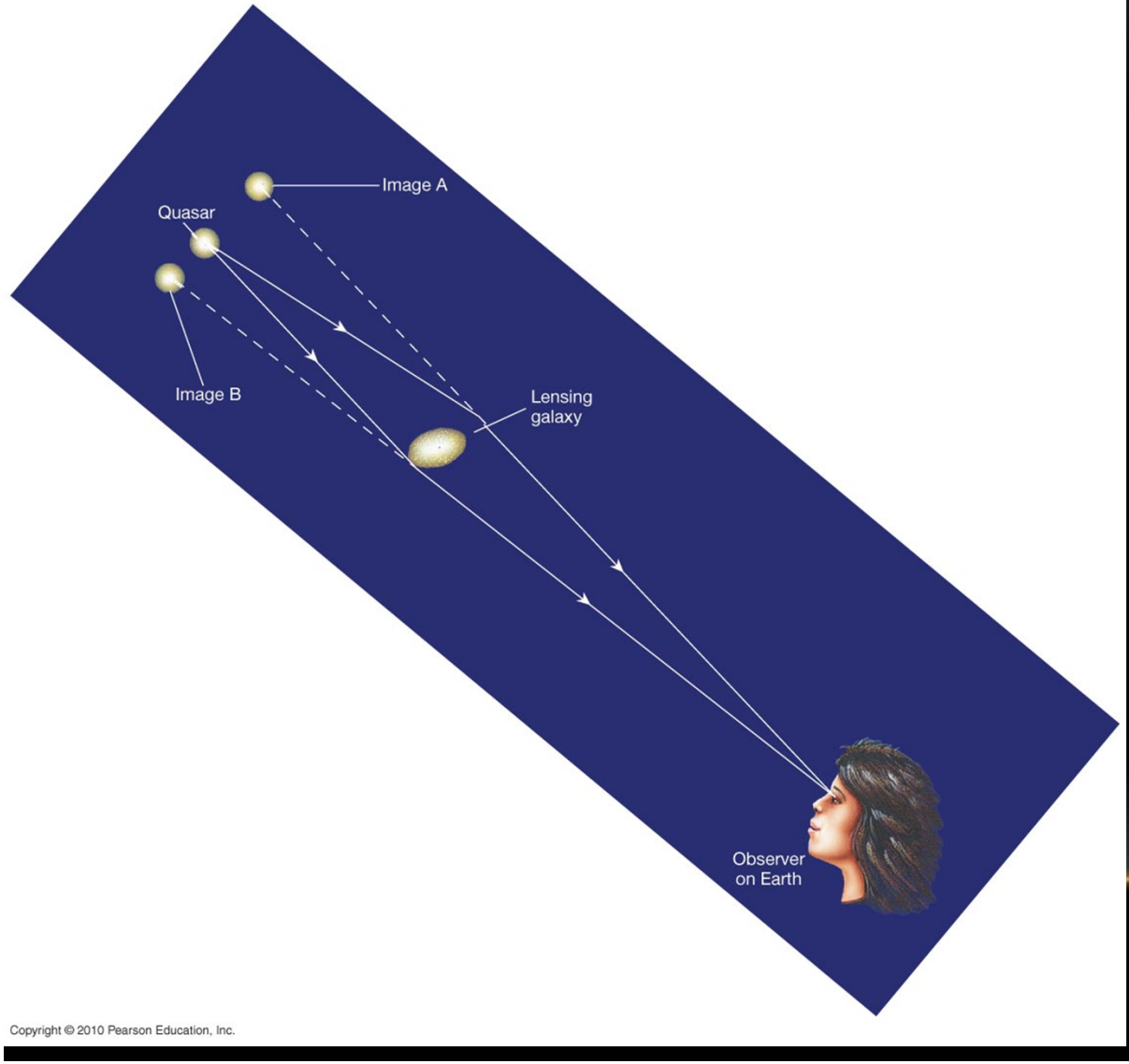


GRAVITATIONAL LENSING



- Two identical quasars were seen
  - Light varied in the same way

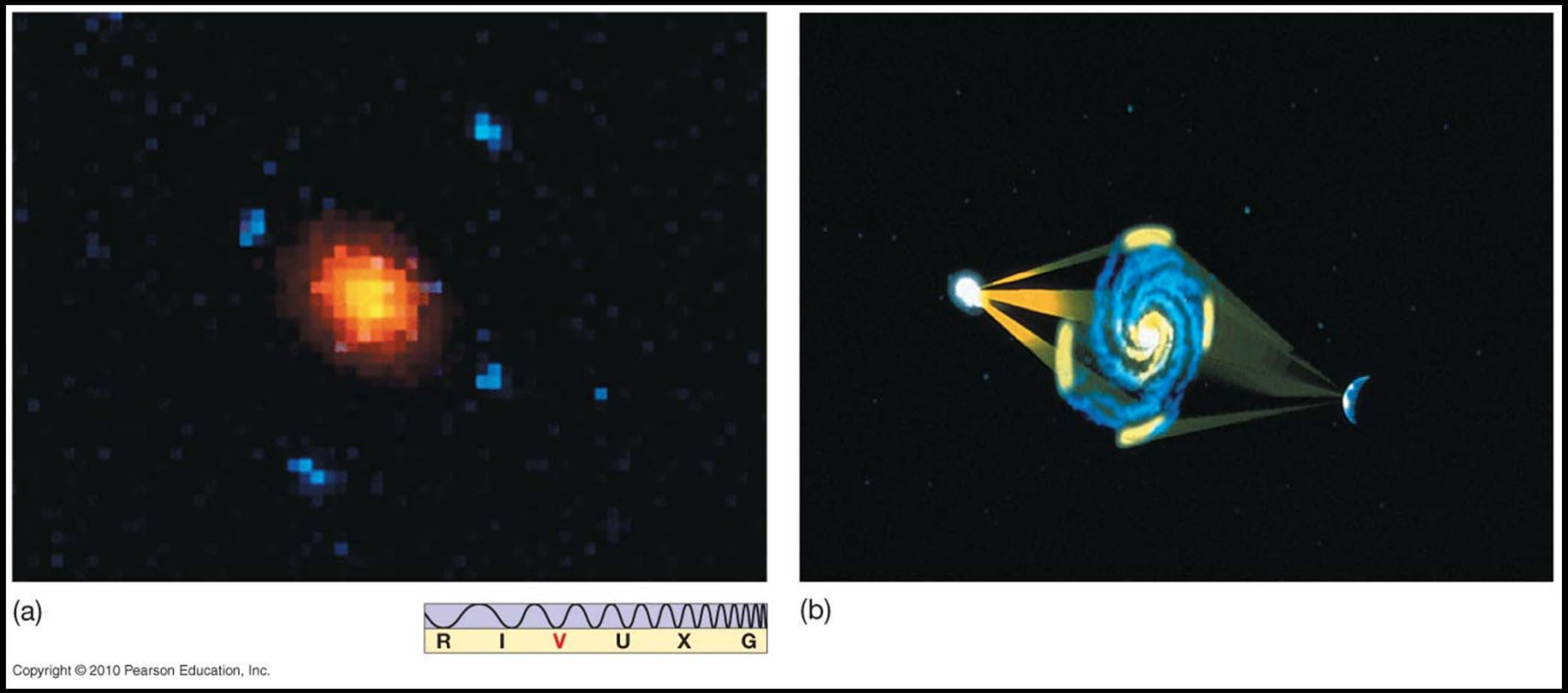
GRAVITATIONAL LENSING



- More nearby mass bends space
  - We see two copies

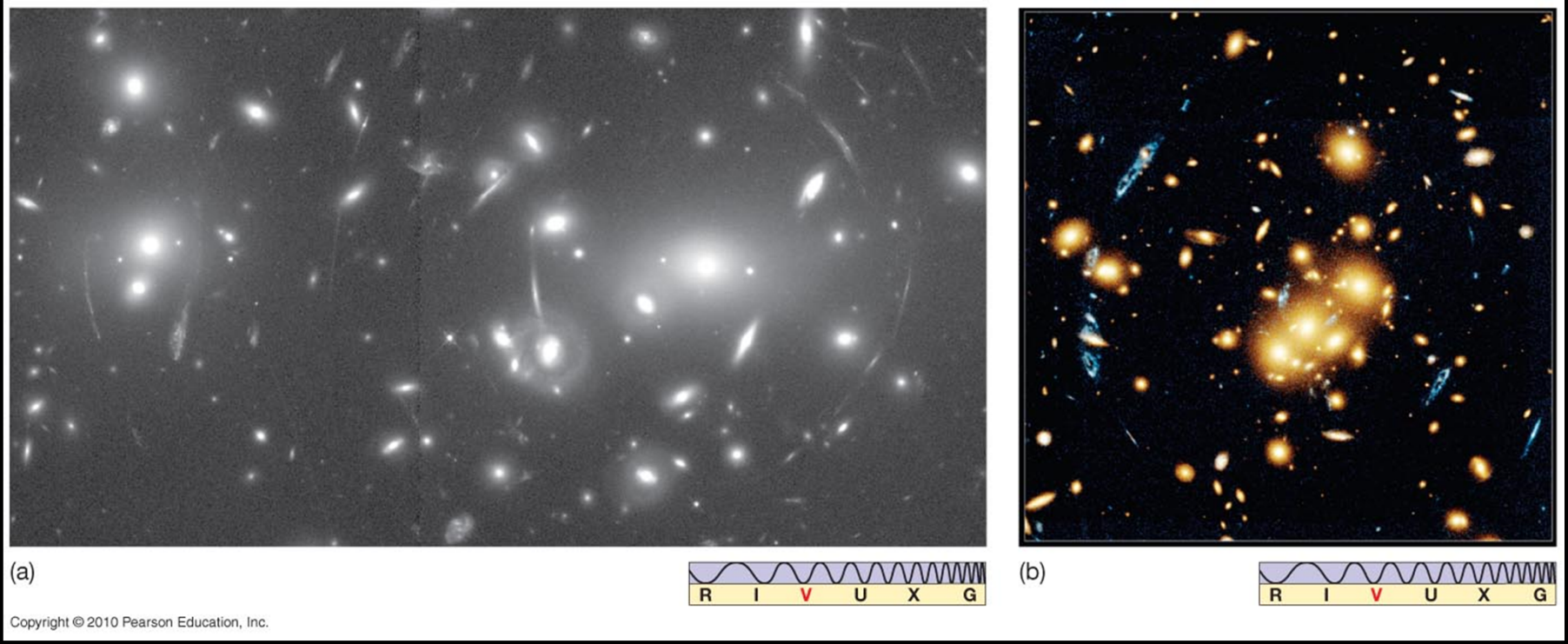
GRAVITATIONAL LENSING

- Or four…



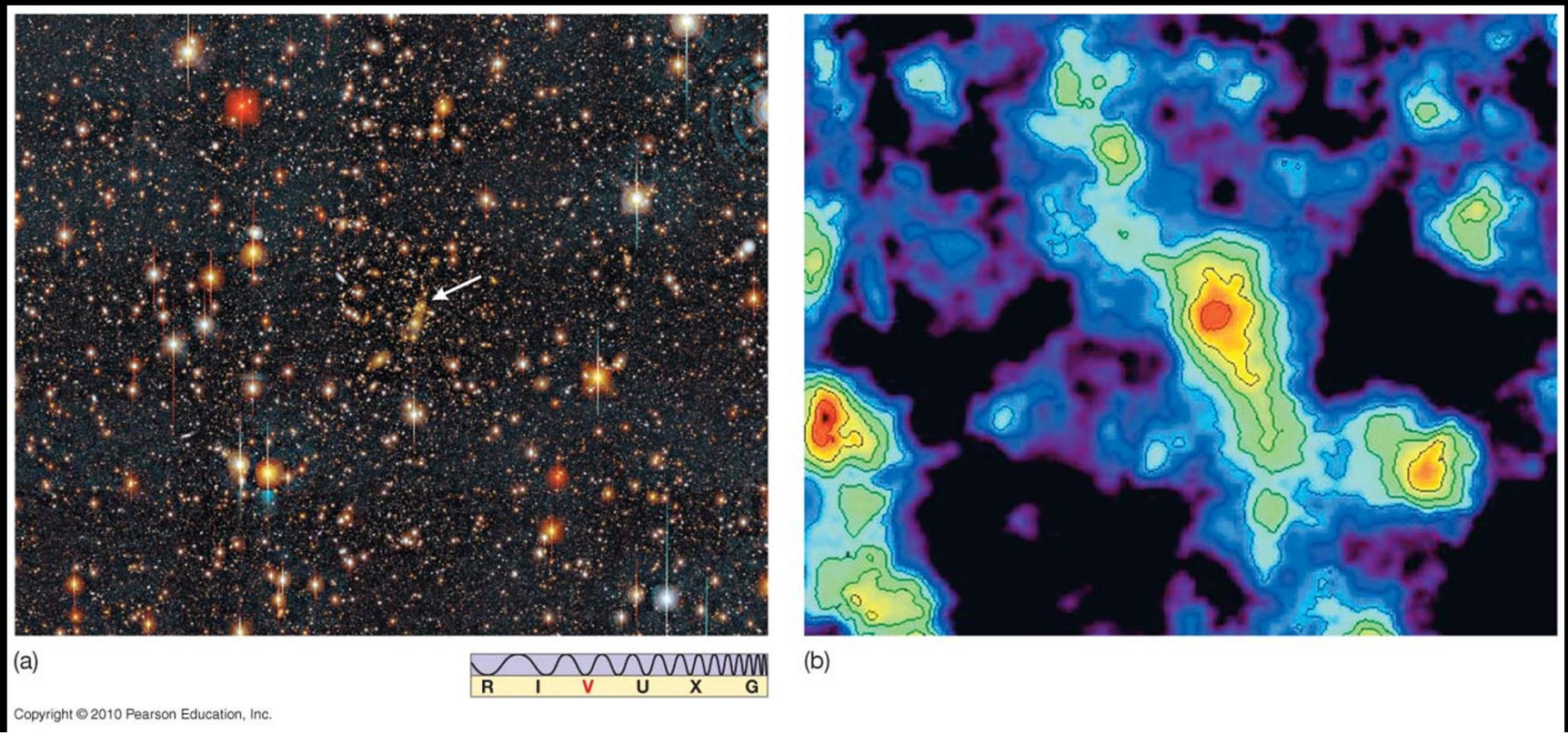
GRAVITATIONAL LENSING

- Or arcs…



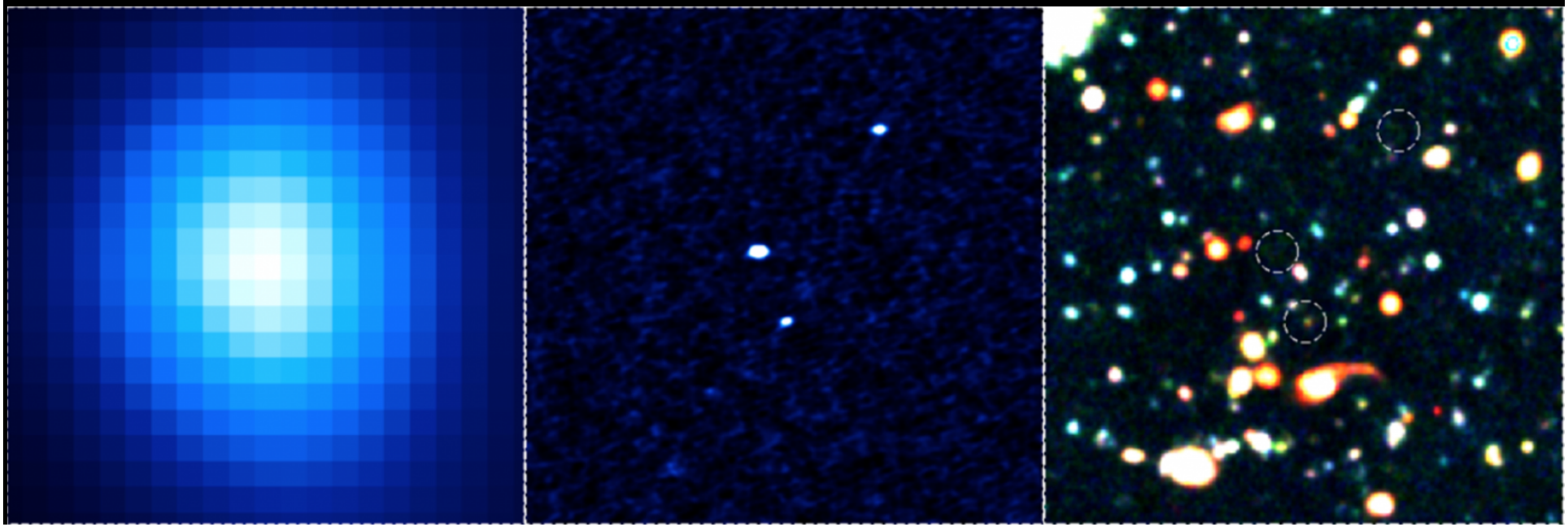
DARK MATTER MAPS

- Use this lensing to try and map the dark matter
- Doing this on an industrial scale now with automated surveys



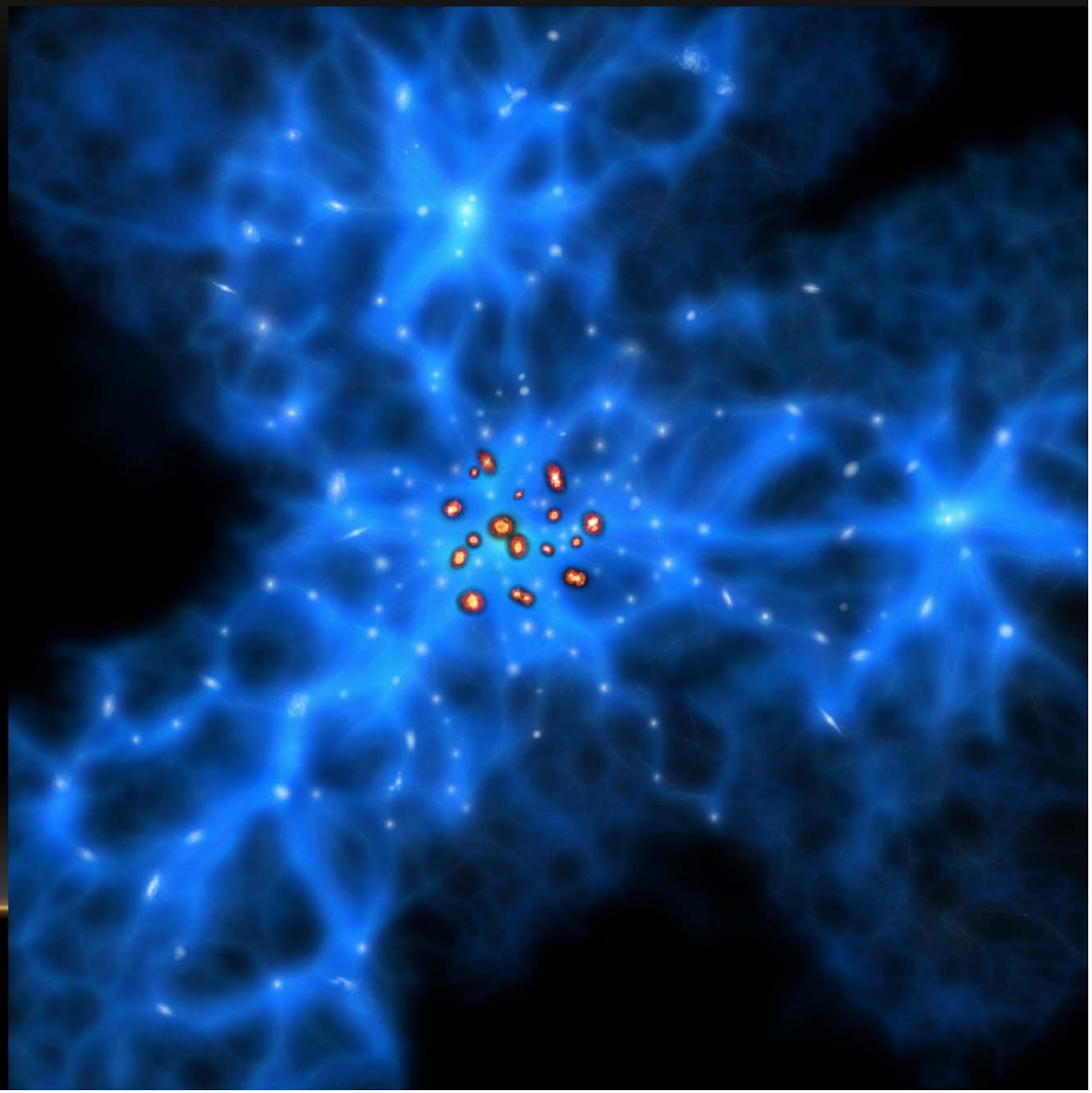
ALMA IS FINDING BABY GALAXIES

- Recently, the Atacama Large Millimeter/submillimeter Array resolved indistinct blobs in old observations into individual baby galaxies, glowing in the IR not visible light

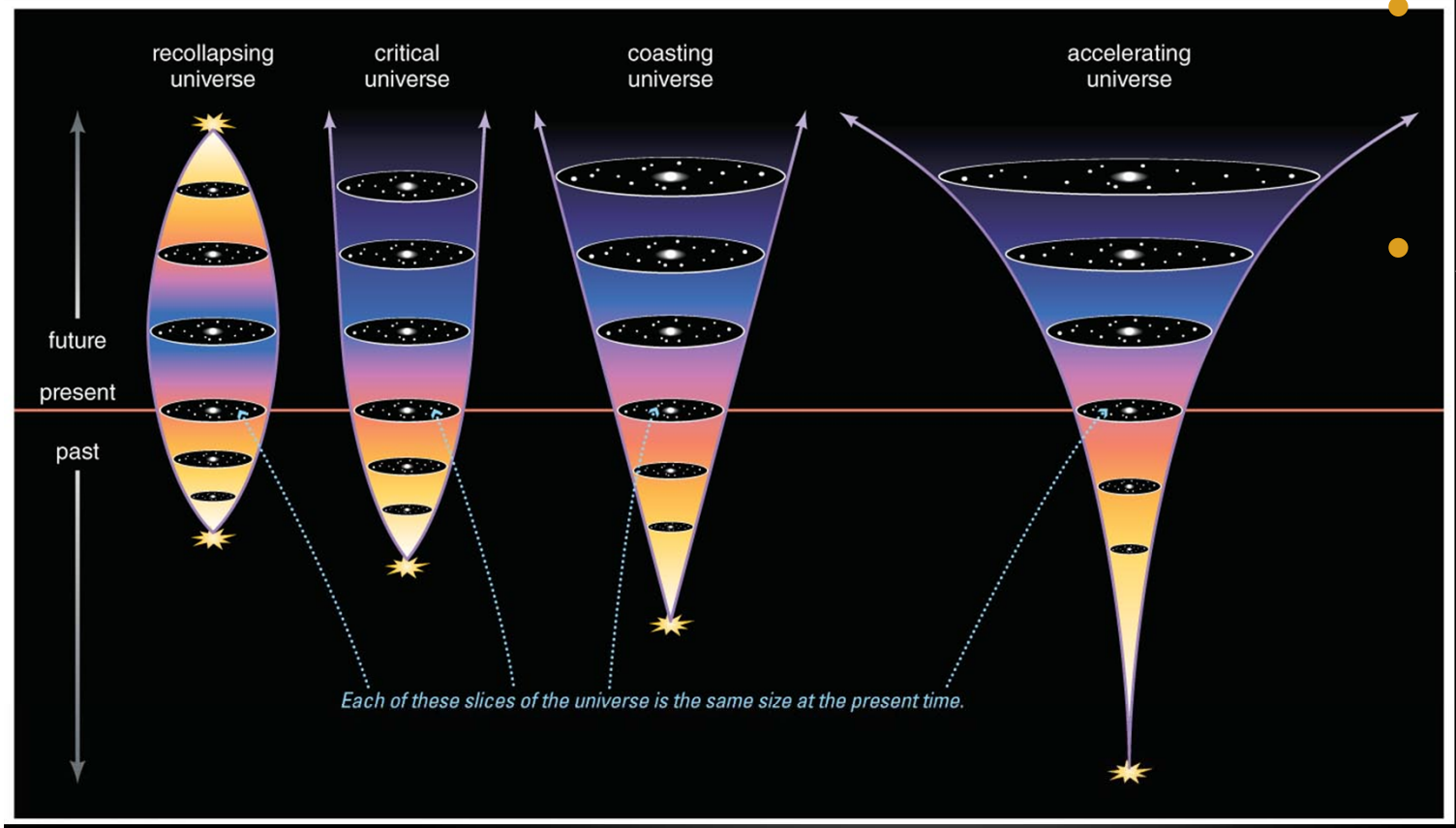


COMBINE WITH DARK MATTER MAPS

- The galaxies form at the intersections of the filaments of dark matter



THE FUTURE

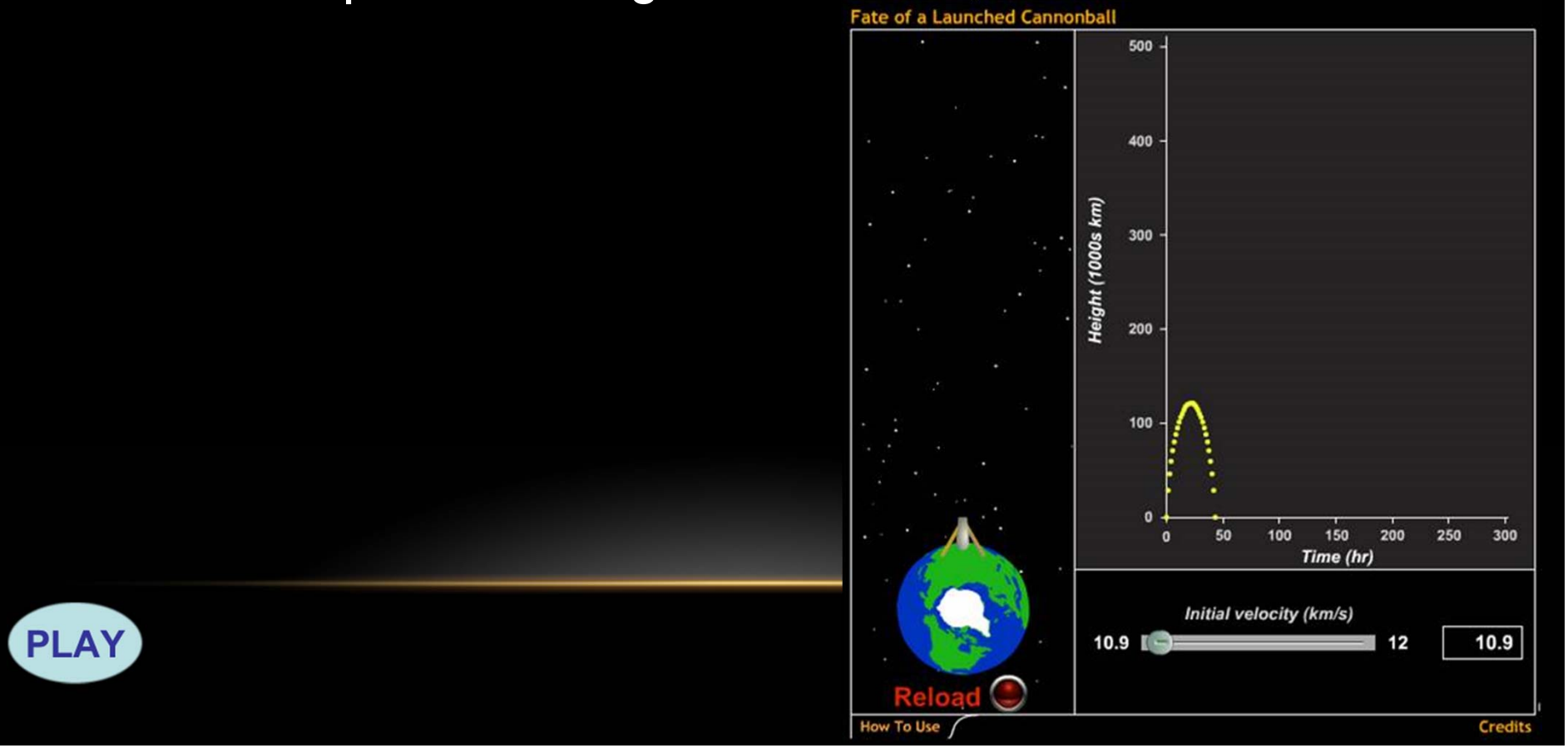


- Will the expansion stop?
- Another way of asking the same question:
  - Is the Universe open, closed, or flat?

Fig.18.15

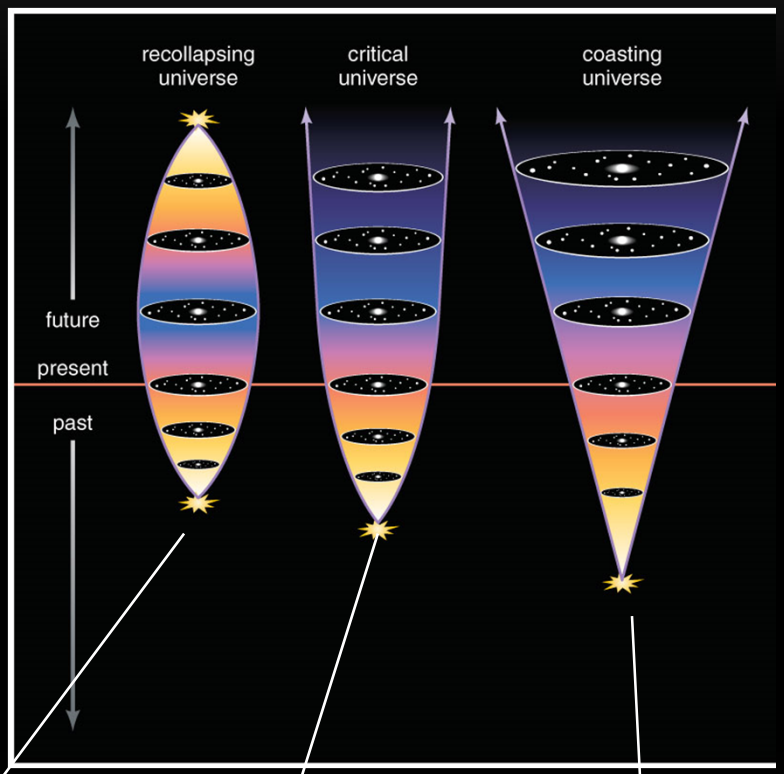
OR, AN ESCAPE VELOCITY QUESTION

- Does the universe have enough kinetic energy to escape its own gravitational pull?



THAT OMEGA THING

- Fate of the universe depends on the amount of matter (which, as we've seen, is mostly dark matter)
- We saw before that there was only "31%" of the needed matter



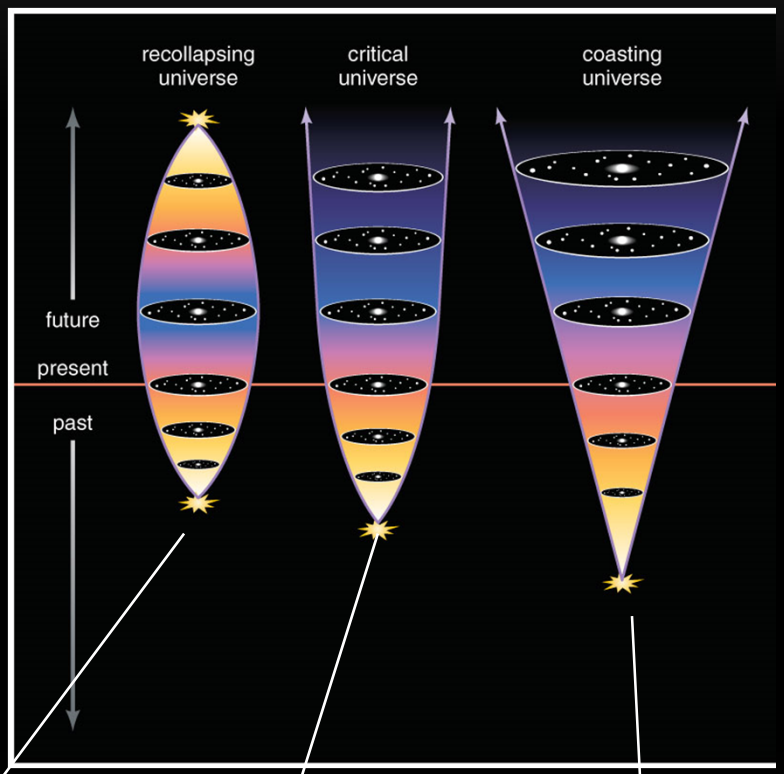
Lots of dark matter

Critical density of matter

Not enough dark matter

THAT OMEGA THING

- We saw before that there was only “31%” of the needed matter



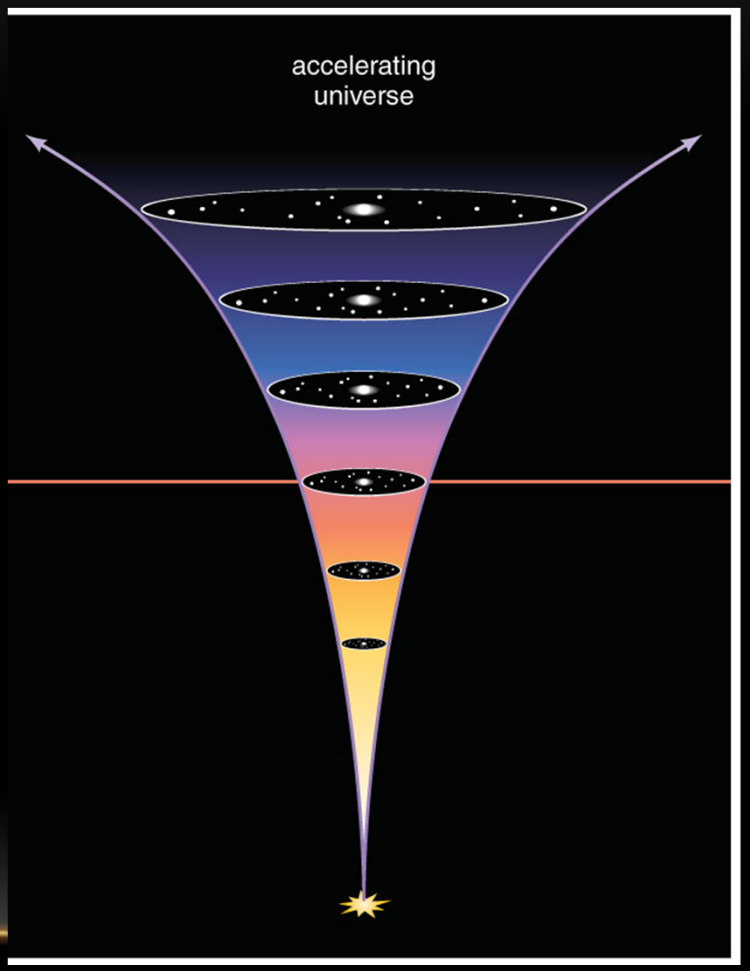
Lots of dark matter

Critical density of matter

Not enough dark matter

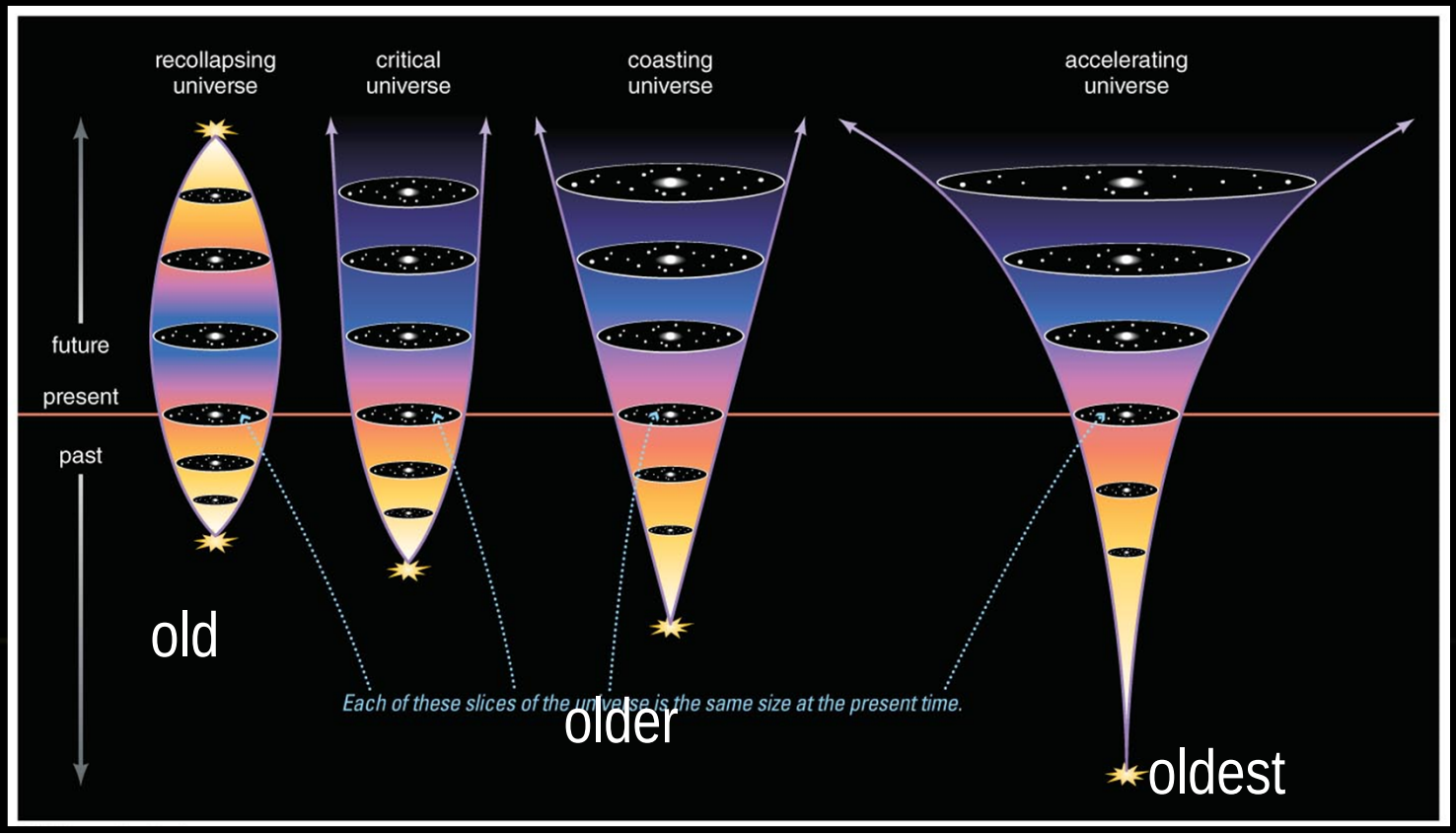
BUT IT GETS WEIRDER…

- Despite this, the universe seems to actually be expanding faster and faster!
- This is the Dark Energy stuff

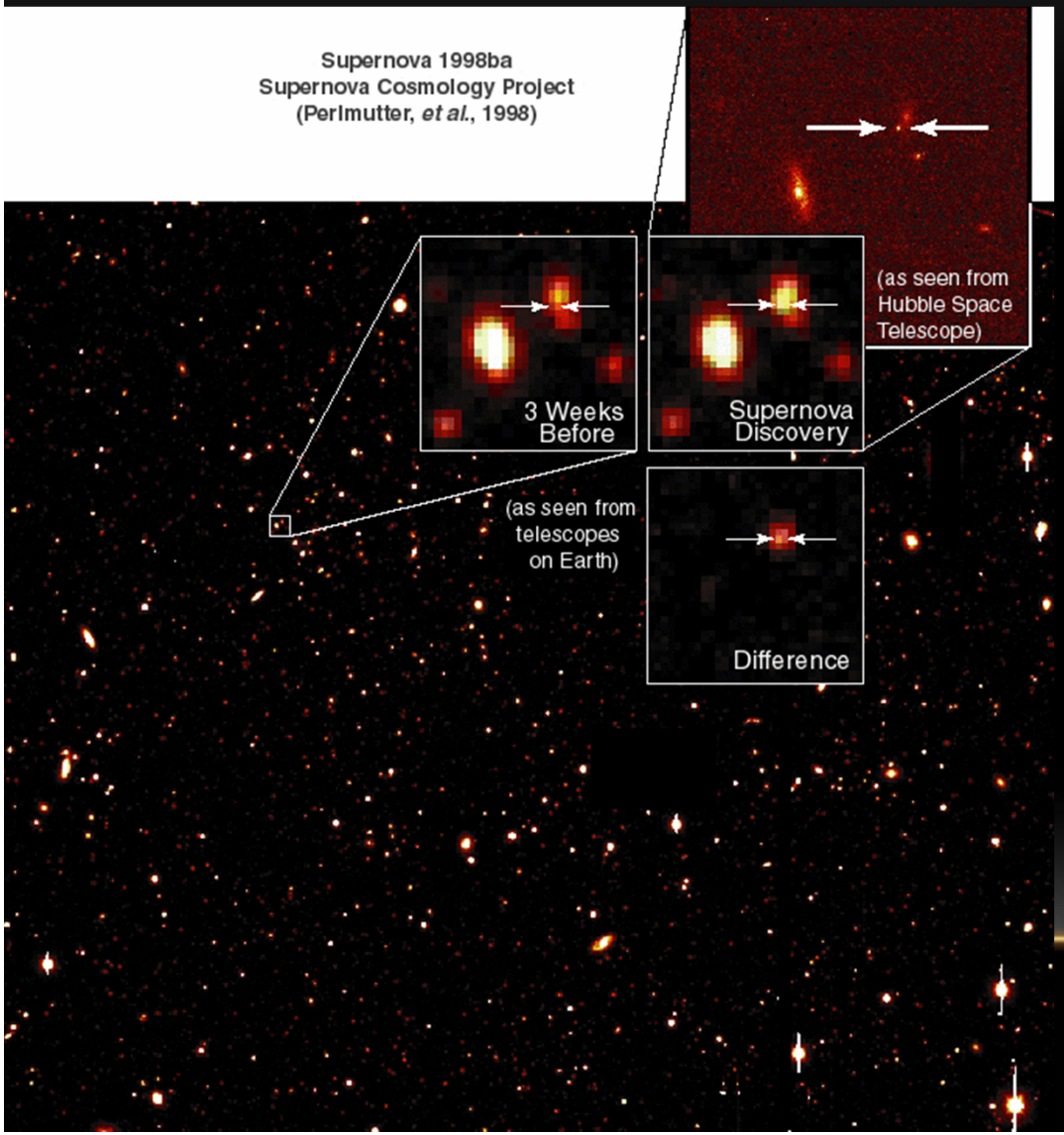


AGE OF THE UNIVERSE?

- When the “rewind the universe” gets back to “all in the same place” depends on the shape of this motion

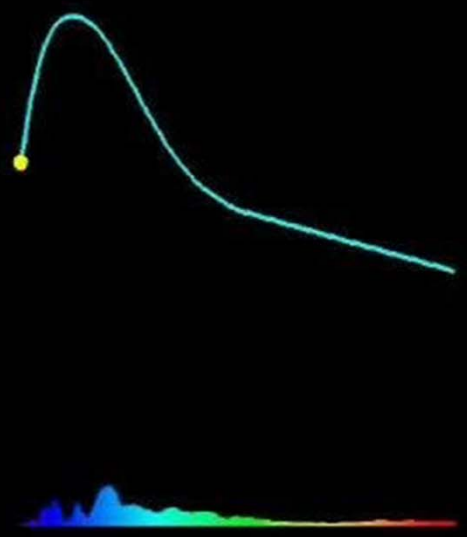


LOOKING FOR DISTANT SN



- Watch many galaxies for changes
- Zoom in with HST or Keck if you see one

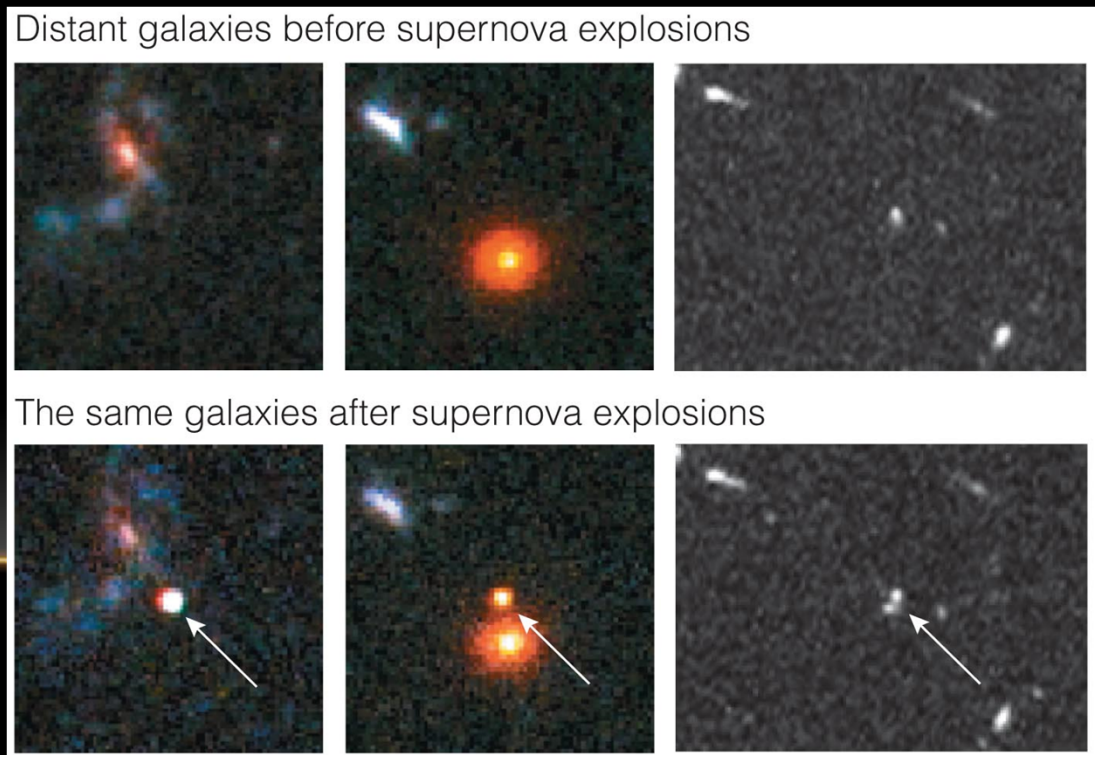
MEASURING THE EXPANSION



- Measure brightness of SNIa “standard bombs” far far away
- Measure their distance and redshift

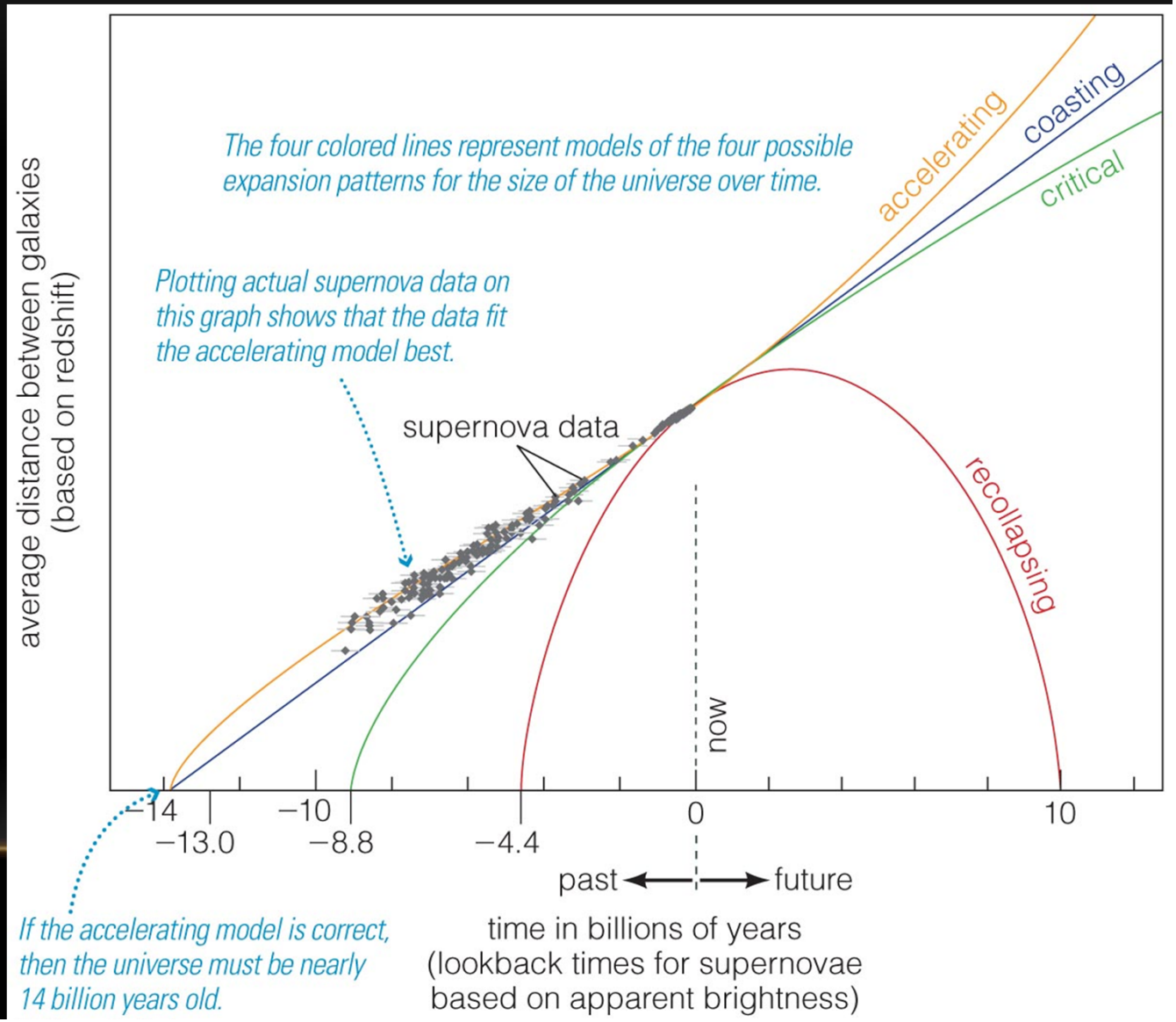
MEASURE DISTANCE, VELOCITY

- We know how luminous a white dwarf SN really is, so can figure out how far away it is
- We can measure the redshift of its galaxy, and see how fast the universe was expanding at that point long ago and far away



UNIVERSE SEEMS TO BE ACCELERATING

- Was expanding more slowly in the past than it is today
- As if that cannon ball had a rocket strapped to it



SUPPOSE THAT THE UNIVERSE HAS MORE DARK MATTER THAN WE THINK THERE IS TODAY. HOW WOULD THAT CHANGE THE AGE WE ESTIMATE FROM THE EXPANSION RATE?

a. Estimated age would be older
b. Estimated age would be the same
c. Estimated age would be younger ✓