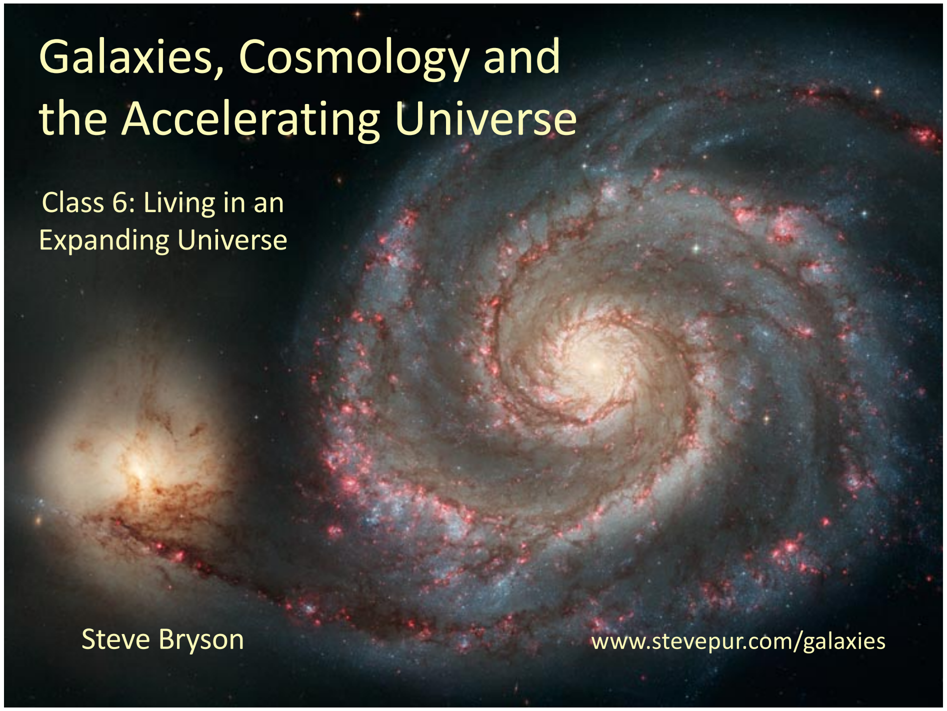
Galaxies, Cosmology and the Accelerating Universe

Class 6: Living in an Expanding Universe



Steve Bryson

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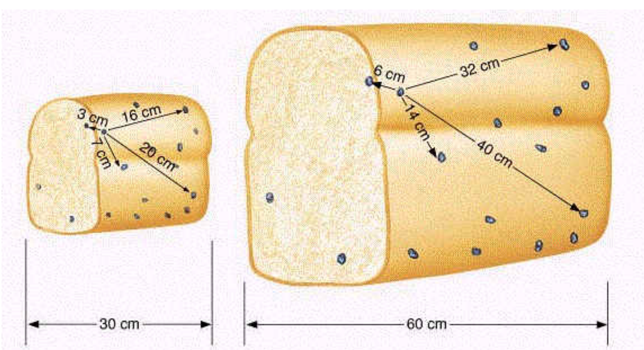
Questions?

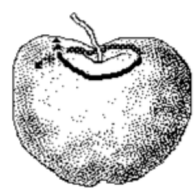
Remember the Raisin Bread

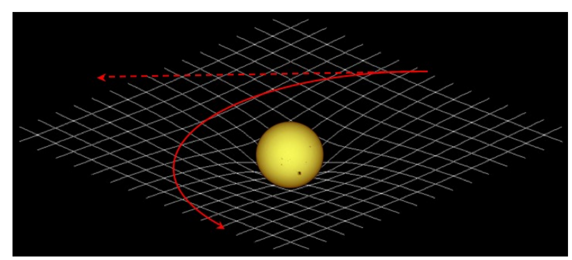
- This is a very good model for the expansion of the universe, so long as the raisin bread is infinitely large



Gravity = Curving of Space and Time

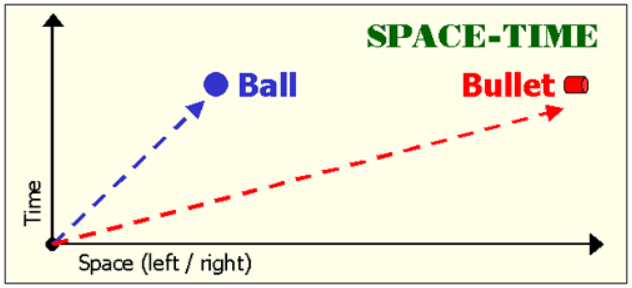
- What is curving?
  - Space and time
- What corresponds to the path of the ants?
  - Our paths in space and time





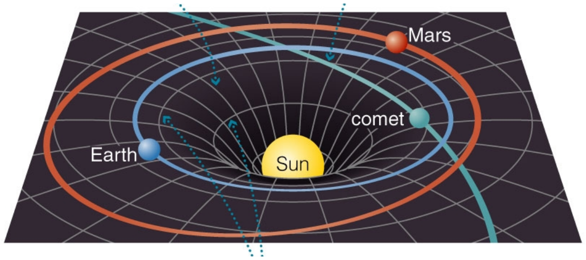
Paths in Space and Time

- You are always moving forward in time
- When you move in space you are combining motion in space and time
  – This determines your direction in space and time



Paths in Curved Space and Time

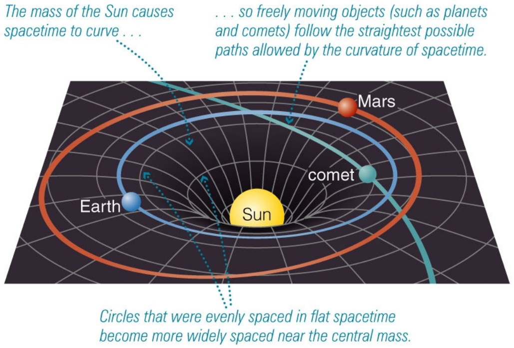
- Things move in the *straightest possible* line in the curved space and time
  – In curved space and time the straightest possible line will not be straight
  – When there are no other forces
  – Remember, all things always move forward in time



Summary of Gravity

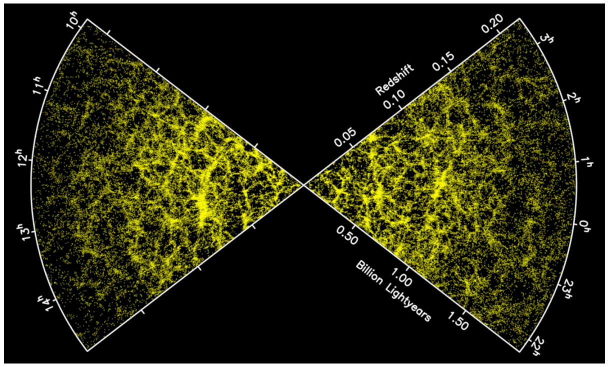
"Spacetime tells matter how to move; matter tells spacetime how to curve"

- John Archibald Wheeler



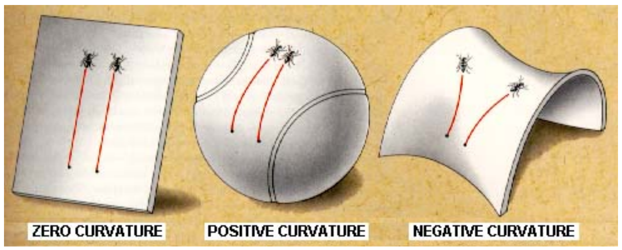
Large-Scale Galaxy Survey

- At each distance, galaxies look approximately evenly distributed
  – Remember, distances are views into the past, so at each time in the past matter is evenly distributed



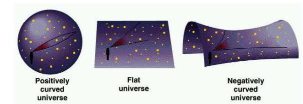
The Curvature of the Universe

- Because matter is evenly distributed at any particular time, there are the only three possibilities
  - Positive curved 3D sphere
  - Flat 3D space
  - Negatively curved 3D sphere
  - These are the spatial parts of the curvature of space and time

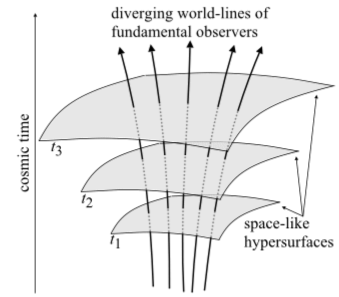


Predicting the Expanding Universe

- These three shapes are just the spatial curvature at any one time

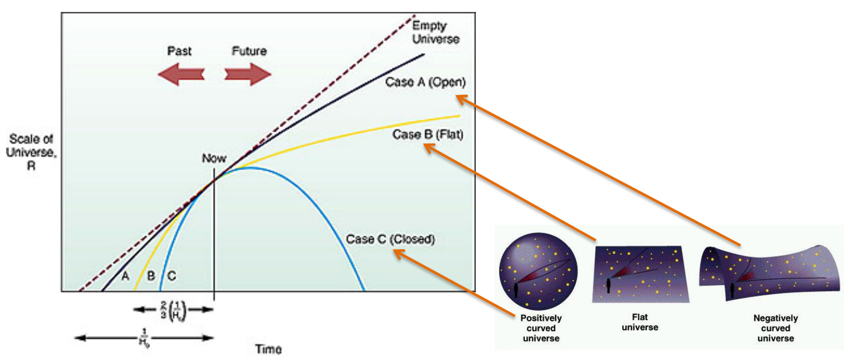


- The time direction is also curved, which causes the expansion of the universe



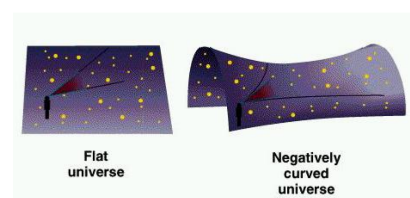
The Future of the Universe

- General Relativity predicts that the ultimate future depends on the spatial curvature
  - The flat and negatively curved universes expand forever
  - The positively curved universe reaches a maximum size then contracts

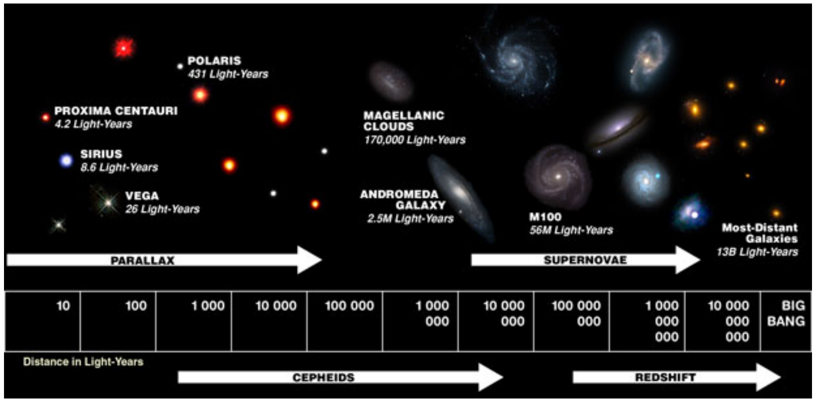


So Which Shape is Our Universe?

- When we measure the large-scale density of matter, we find we have just enough to make the universe very flat, probably slightly negative
  - This is surprising: why so close to flat?
  - So the universe will expand forever

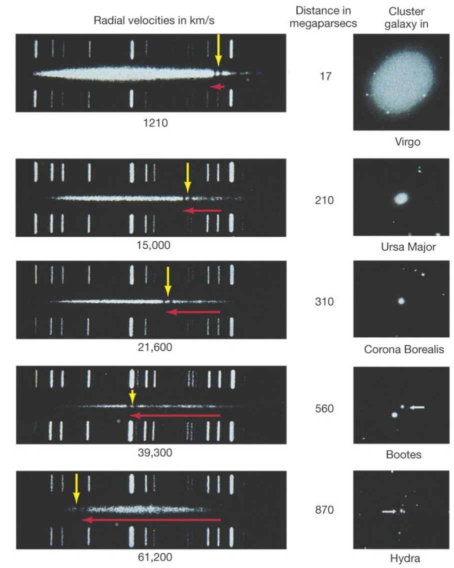


The Cosmic Distance Ladder



The Spectra of Galaxies

- Most surprising of all: most galaxies have a red shift
  - Indicating that they are moving away from us
- The more distant the galaxy the larger the red shift
  - In all directions!
- What could be going on?



Hubble's Original Redshift-Distance Graph (1929)

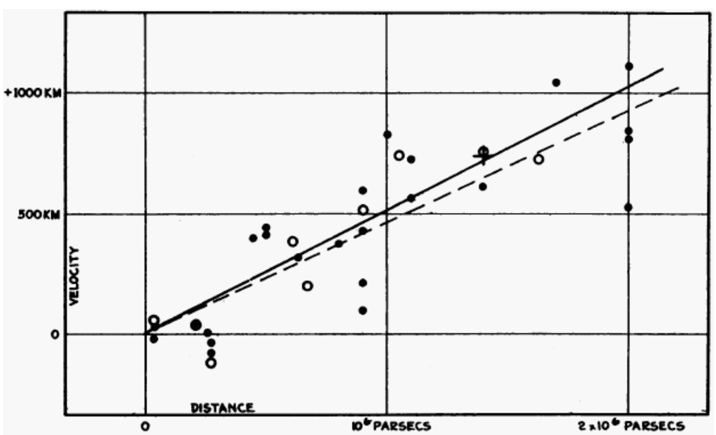


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Interpreting the Graph: Hubble's Constant

- The points fall close to a straight line
  - This means the speed is proportional to the distance
- Constant of proportionality is called Hubble's Constant
  - Defined as the speed of a galaxy, moving away from us due to the expansion of the universe, at a distance of 1 million parsecs
  - Early measurements were difficult

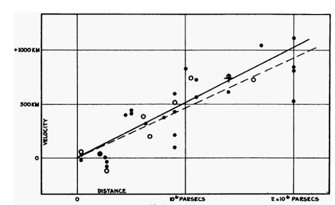
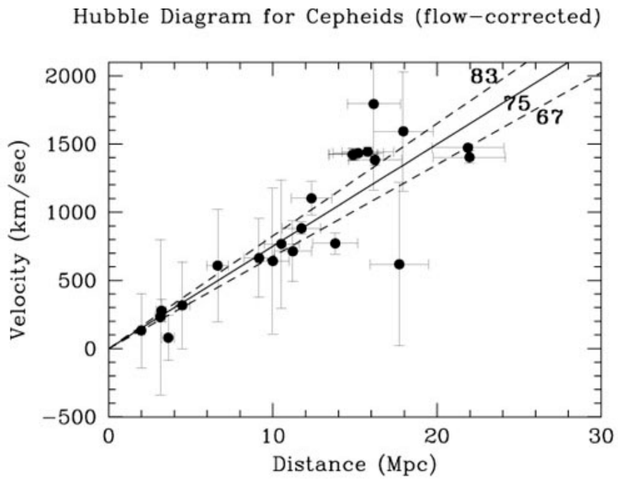
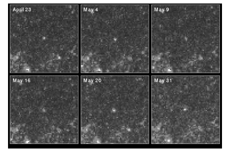
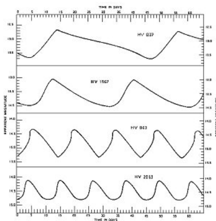


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

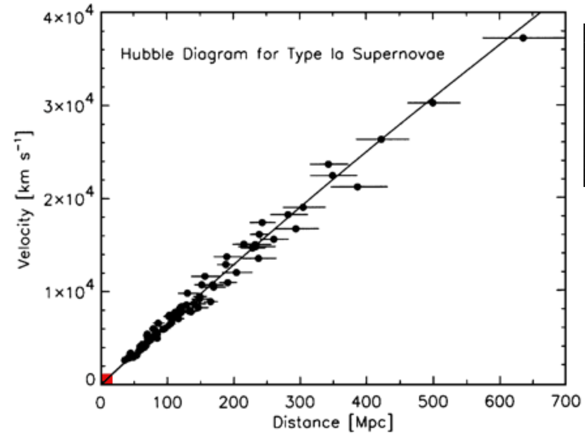
Modern Version Based on Variable Star Distances

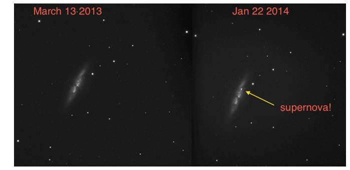






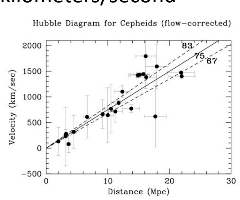
Based on Type 1a Supernovae

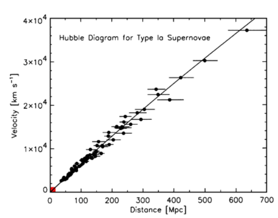




Measuring Hubble's Constant

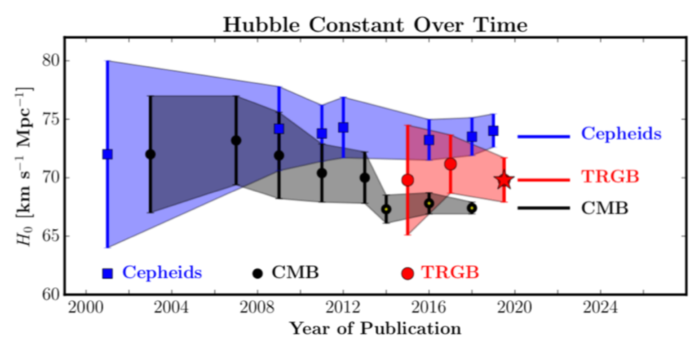
- Until the 1990's there was big disagreement about the value of Hubble's constant
  - One group says 50, another says 90
- Until Recently, Hubble, Planck and WMAP space telescopes all agreed: 65 to 80 kilometers per second per megaparsec, with ~72 most likely
  - So a galaxy 1 million parsecs away will be moving away from us at 68 kilometers/second





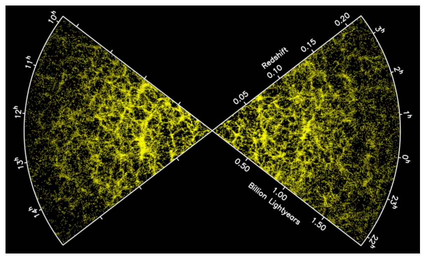
Measuring Hubble's Constant

- But as the measurement gets more precise, different measurements methods have stopped agreeing
  - 67 or 70 or 72 km per second per megaparsec



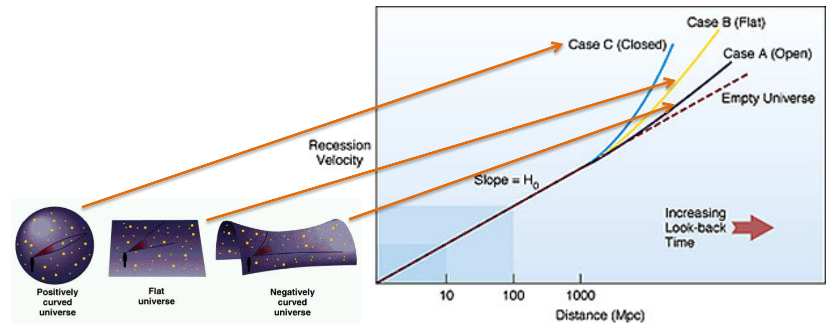
Redshift as a Distance Measurement

- Once we accept the expansion of the universe, we can trust large redshifts as measurements of distance
  - Another rung on the distance ladder
  - Based on the best measurement of Hubble's constant
- This is how the distances to most galaxies is measured
  - Measure speed from redshift
  - Divide by Hubble's Constant
    - So long as redshift is not too large



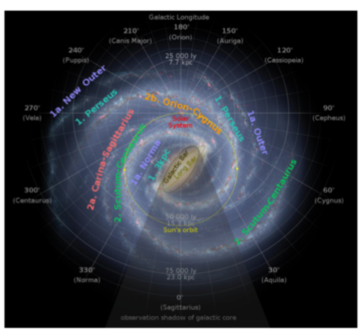
Hubble's Constant is Not Really Constant

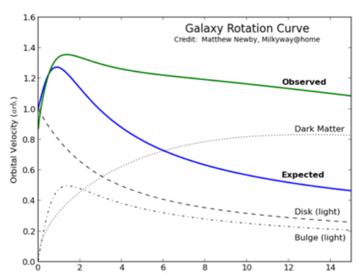
- Gravity from matter slows the expansion
- When we look out to a billion parsecs we expect to see a small departure from the straight line
  - But distances this far away are very difficult to measure



To Predict the Expansion We Have to Know How Much Matter There Is

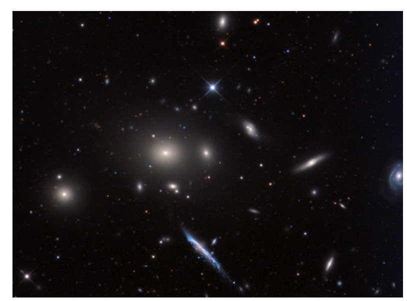
- Remember the orbits of stars in the Milky Way?
  - Stars far from the center are moving faster than they should
  - Indicates that there is a lot of mass not in the stars, gas or dust: "Dark Matter"





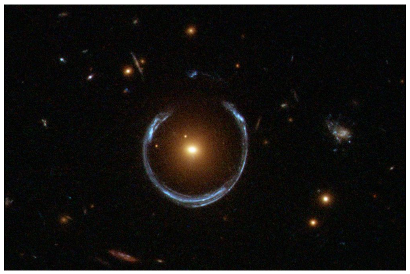
Galaxies Moving in Clusters

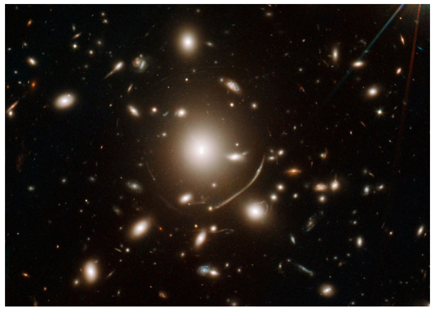
- When we watch galaxies orbiting each other in clusters we see the same thing
  - The galaxies are moving too fast: if stars and gas in the galaxies is all the mass there is, then there would not be enough gravity in the cluster and the galaxies would escape



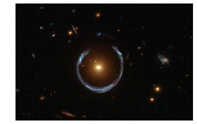
We Can Use Light to Measure Mass

- Mass causes space and time to curve
- This curves the light passing by the masses
  - "Gravitational Lensing"
- The amount of lensing measures the mass





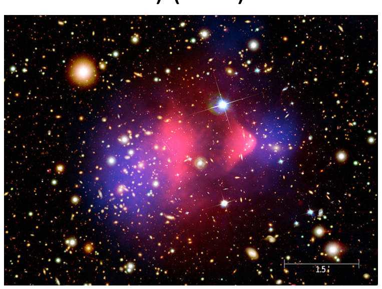
Dark Matter



- Based on watching orbits and gravitational lensing, we believe that there is about 5.5 times as much dark matter as ordinary matter
  - So dark matter makes up about 84.5% of all matter, ordinary matter 15.5%
- We don't know what dark matter is, but we're pretty sure it's not protons, neutrons and electrons
  - Probably means a new, undiscovered particle
    - Would interact with ordinary matter very weakly and only through gravity
  - Dark matter probably moves like the stars
    - Is "cold", otherwise it's difficult for galaxies to form
      - More next week

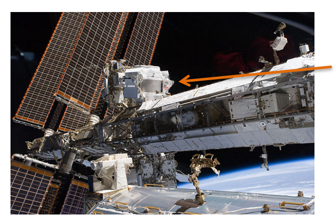
(Almost) Direct Observation of Dark Matter

- The Bullet Cluster: a collision between two galaxy clusters
  - The ordinary gas (red) stays in the location of the collision while the stars in the galaxies move on
  - Gravitational lensing shows that the mass of the two clusters (mostly dark matter) (blue) also moved on with the galaxies



Should We Feel Dark Matter Here?

- There is lots of dark matter passing through this room right now
  - If dark matter is even spread through the disk of the Galaxy, then our Solar System is surrounded by it, so its gravity cancels out and does not effect orbits of the planets
- Attempts to detect dark matter particles have not been successful
  - Past tantalizing hints have come up empty

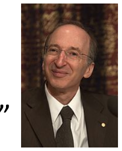


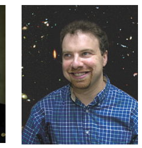
Alternatives to Dark Matter?

- Our theory of gravity could be wrong for very large distances
  - But this is difficult to reconcile with the gravitational lensing measurements
- How we think matter responds to gravity may be wrong
  - Proposed to explain dark matter with no evidence
- But without compelling evidence otherwise, we take dark matter to be an unknown type of matter

Back to Redshift-Distance Measurements

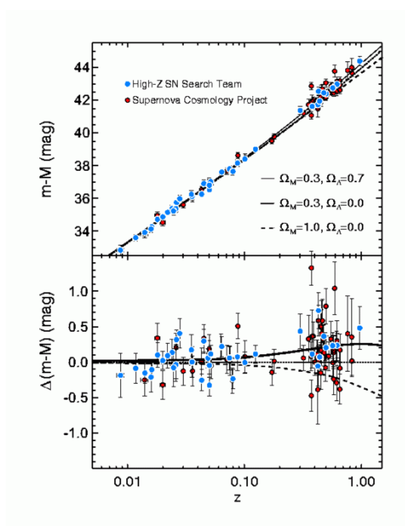
- In 1998 measurements of type 1a supernovae were pushed to even greater distances
- Two international teams:
  - "Supernova Cosmology Project"
    - Saul Perlmutter (Berkeley)
  - "High-Z Supernova Search Team"
    - Brian Schmidt (Australia) and Adam Riess (Space Telescope Sciences Institute)
      - And my Kepler collaborator Ron Gilliland



A Big Surprise

- The most distant galaxies are moving away faster than predicted from the measured speeds of the nearer galaxies
- The expansion of the universe is accelerating!
- 2011 Nobel Prize to Perlmutter, Schmidt and Riess



Why Would the Expansion Accelerate?

- Simple answer: we don't know
- But we have a name: "Dark Energy"
  - This has nothing to do with being dark
    - Doesn't really mean anything
  - It's called energy because everything is energy
    - So it's a safe name
  - "Dark Energy" is really just a catchy label
    - Unlike dark matter, we have absolutely no idea what is causing the accelerated expansion

Hints About Dark Energy

- Remember when Einstein predicted the universe would change size but changed General Relativity to prevent this?
  - "my greatest blunder"
- Actually, Einstein's problem was that if he started with all the galaxies standing still, original General Relativity said they would move together
  - The universe would contract due to gravity
- Einstein fixed this by introducing a "cosmological constant" that caused a negative pressure to counteract the gravity
  - It does fit naturally into the equations, it just doesn't have a reason
- Such a cosmological constant is just what we need to cause the universe to expand

Hints From Elementary Particle Physics

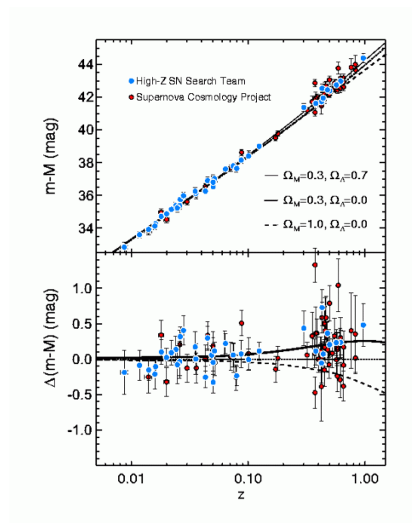
- The standard model of elementary particles (electrons etc.) and forces actually predicts something very much like a cosmological constant
  - But the predicted value is 10^{120} times too big (!!!)
    - Probably the most spectacularly wrong prediction in history
- There are other ideas from speculative theories of elementary particles
  - Supersymmetry, string theory and others
    - "quintessence"

But Dark Energy Acts Just Like the Cosmological Constant

- Quintessence theories often make measurable predictions, and when they do they have been ruled out
- Assuming dark energy is from a cosmological constant, we can say how much energy there is
  - 68.3% of the energy in the universe
    - The rest is in ordinary and dark matter
  - So the matter and energy composition of the universe is
    - 4.9% ordinary matter
    - 26.8% dark matter
    - 68.3% dark energy (negative pressure from a cosmological constant)

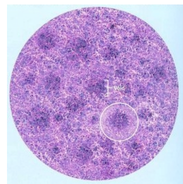
How Dark Energy is Measured

- By comparing the redshift-distance relationship to predictions with a cosmological constant
- Ω_M is the fraction of ordinary and dark matter
  - Fraction of amount needed to be exactly flat
- Ω_Λ is the fraction of dark energy



Alternatives to Dark Energy?

- Our predictions for the expansion of the universe assumed that at a large scale matter is evenly distributed
- What if this is wrong?
  - More matter in one direction than another, or really big clumps far away
    - Could explain accelerated galaxy motion in that direction
  - But we now see the acceleration in all directions
    - Would require us to be in the center of a low-density region
      - Possible, but there are no signs of this
- So for now we take the accelerated expansion as real



Looking Into the Past

- As we look at the furthest galaxies, we are looking into the deep past
  - As much as 13 billion years (picture at right)
- The most distant galaxies do look different from current galaxies
  - Bluer (after correcting for redshift), as we'd expect because there have been fewer generations of stars so we're looking at more young, bright stars
  - More active star formation
    - More gas not yet in stars

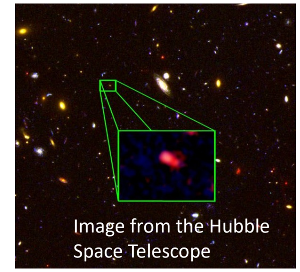
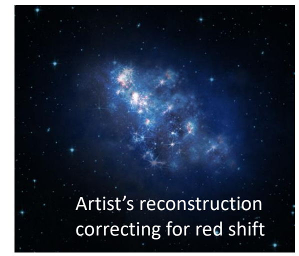


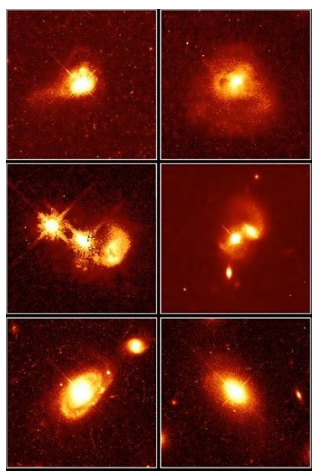
Image from the Hubble Space Telescope



Artist's reconstruction correcting for red shift

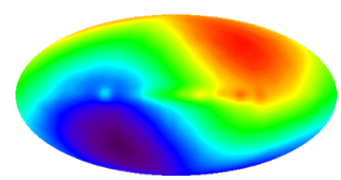
Quasars

- Some of the most distant objects do not look like nearby galaxies
- Objects much brighter and much smaller than a galaxy, called "quasi-stellar objects" or quasars
  - Looked like stars when discovered in the 60's
    - But with very large red shifts
    - 600 million to billions of light years away
  - Later observations revealed that these are the very bright cores of galaxies
  - Now believed to be an early stage of galaxy formation
    - As the central black hole was forming/growing



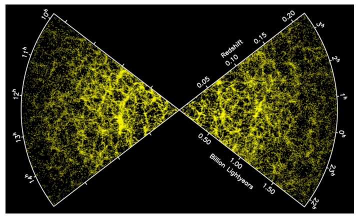
Cosmic Background Radiation

- Everywhere we look in the sky we see a constant microwave radiation
  - Has the same light as would be emitted by something at 2.7 Kelvins (= -454.81 degrees F)
- Almost exactly the same in all directions
  - We can see the red/blue shift due to the Earth's motion
- We believe this is the orange light from a hot gas of about 3000 Kelvins (= 4940 degrees F) redshifted by a very large amount
  - This gas completely filled the universe
  - We'll see why next week



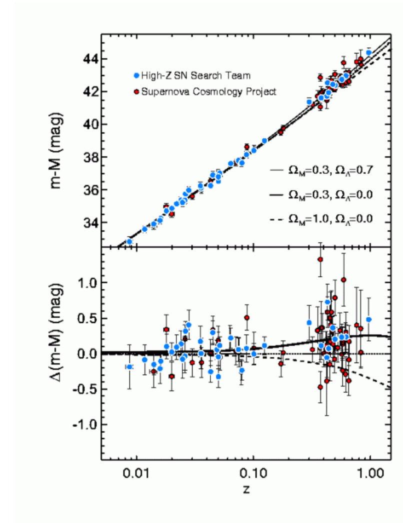
Subtle Mysteries

- Why is the universe so homogeneous?
  - When we look in opposite directions, we are looking at galaxies whose light just got to us
  - So galaxies on opposite sides of our sky cannot see each other
  - So they cannot effect each other (no signal can go faster than light)
  - So why do they look the same?
    - Same density on a large enough scale



Subtle Mysteries

- Why is the universe so flat?
  - The data says that we have just about the right amount of matter and (dark) energy to make the universe flat



The Universe Has a History

- It appears that the universe in the past looks different from the universe in the present
- This is not too surprising: if we back up the expansion of the universe, it gets a lot smaller and a lot more crowded
  - In early enough times the universe was so small all the galaxies we see now would overlap
  - Before that all the stars would overlap
  - At that time things must have been very very different!

The Universe Has a History (Preview of Next Week)