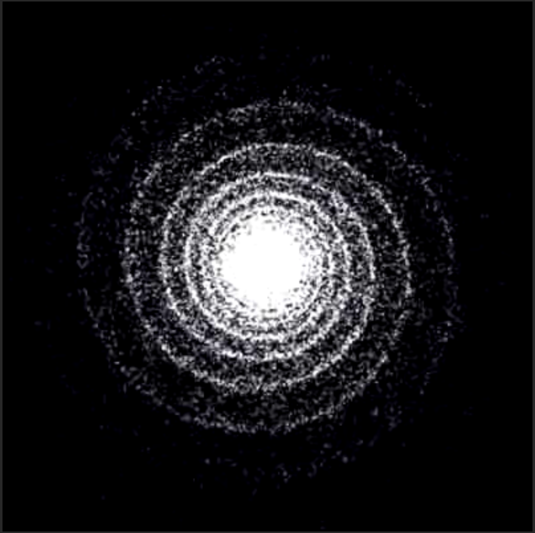
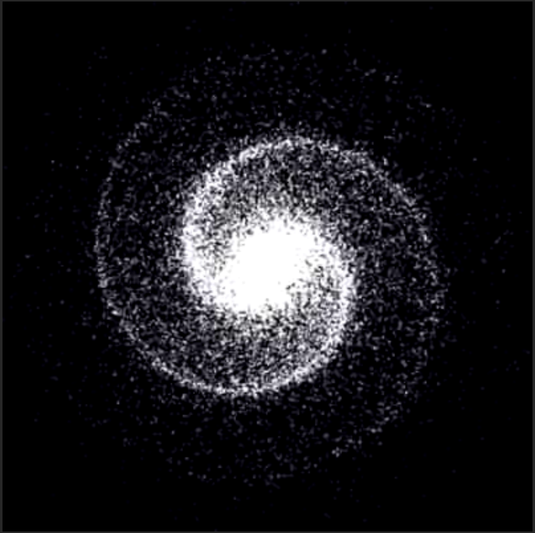
Announcements

- Webwork due on Wednesday
- Last week of lab for Group B!
- Final one week from Wednesday
  - 8am in this room
  - Technically have 3 hours, but I write for 1.5x or 2x normal test length
  - Last study materials will be posted tomorrow
  - Cumulative, but about 1/3 will be focused on most recent content (galaxies and cosmology)
- Polling: `rembold-class.ddns.net`

Galaxy Spins





Review Question

How fast is a galaxy retreating from us if it is located 300 Mpc away?

A. 4.167 km/s
B. 4167 km/s
C. 21,600,000 m/s
D. 21,600,000 km/s

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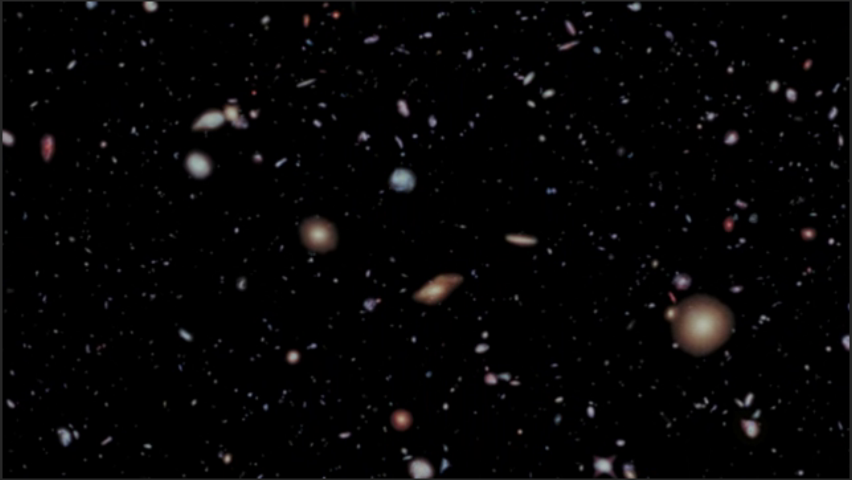
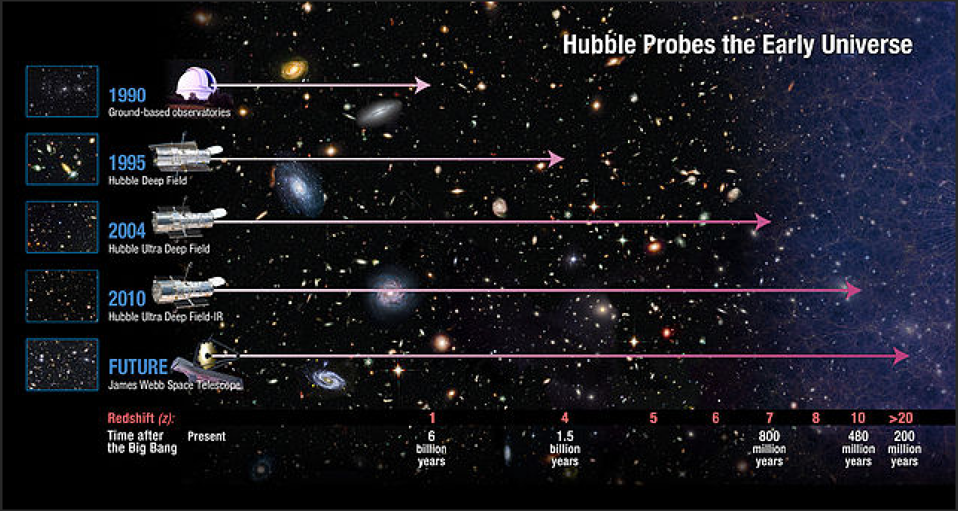
The Hubble Xtreme Deepspace 3D!



A Trip Down Memory Lane



Galaxy Evolution Detour

- Build up a sort of yearbook of galaxy ages
  - Looking at more distance objects means we are looking at younger objects
- Do we see a trend between spiral, elliptical and irregular galaxies over time?
  - Not really, they all follow their own path
- So why the different types?

A Product of their Time

- Two main ideas though to determine galaxy type:
  - Initial rotation rate: Perhaps with a small enough angular momentum, galactic disks never form and they stay elliptical
  - Initial density: Clouds with a high gas density would have formed stars much faster, and maybe used up all the gas before it had a chance to collapse into a disk
- Observations of a few massively redshift elliptical galaxies:
  - Lack blue and white stars
  - Even though universe still quite young
  - Supports fast star formation theory?
- Collisions and gravitational tugs likely played major roles in subsequent shaping

Back to the Universe: A Slowing Expansion?

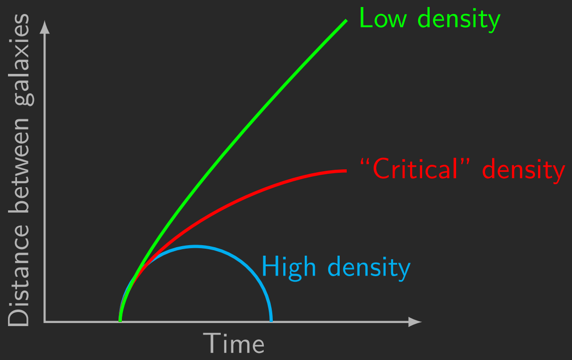
- We've been assuming that space expands at a constant rate
- But gravity is attractive, and should be slowing that expansion?
- Are we overestimating the lifetime of the universe?

Ultimate Questions of the Universe

- Is it infinite?
- Is it curved or flat?
- Is it growing or shrinking?
- What is the whole deal with this Big Bang thing?

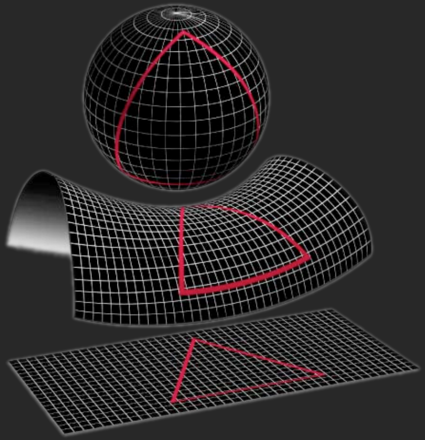
Mass: Forever the Answer

- The simplest GR models predict that expansion will slow
  - Gravity will slowly win, at a rate dependent on the mass density (Ω) of the universe



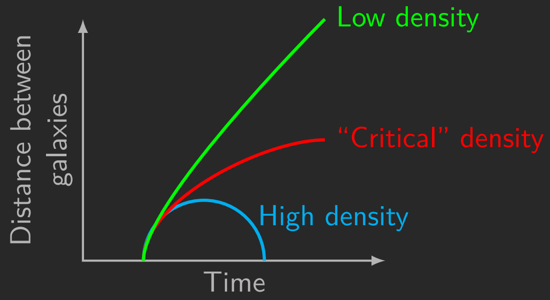
Curved Geometry

- The mass density also determines the shape of the universe:
  - $\Omega > 1$ implies a positive curvature
  - $\Omega < 1$ implies a negative curvature
  - $\Omega = 1$ implies no curvature (flat)



Measuring Curvature

- There are several approaches to measuring Ω:
  - Look at all the mass, and figure out a density directly
    - From visible mass $\Omega \approx 0.02$
    - Including dark mass $\Omega \approx 0.3$
  - Try to measure very precise triangles to look for angles $>$ or $<$ $180°$
  - Look for changes in the expansion rate: the "deceleration parameter" q_0

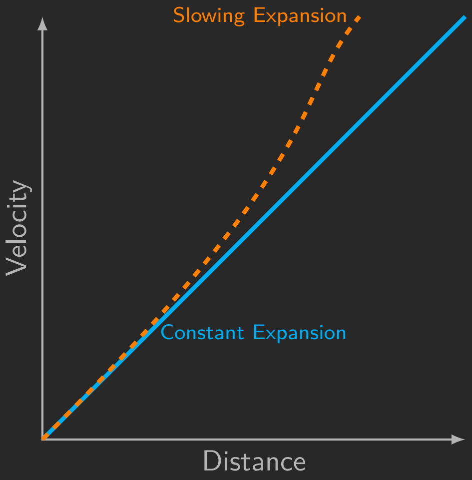


A Geometrical Conundrum!

- Based off all our adding up of the masses, including dark matter we have a density of $\Omega \approx 0.3$
  - This would imply an open, negative curvature universe
- Very recent results from Baryon Acoustic Oscillation (BAO) work though has the universe being flat to within 0.4% probability
- Are we missing something? Or is some physical law flawed?

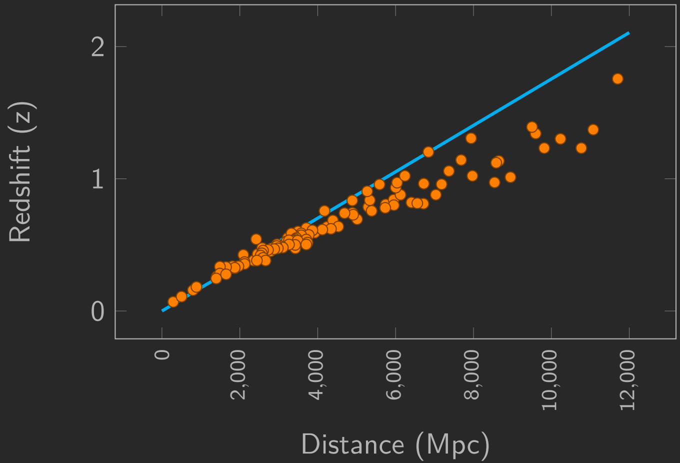
Return of the Hubble

- GR predicts gravity should slow expansion
- Looking at the Hubble Relation out to very large distances then, we don't expect a straight line
- Measuring that deviation from straight has been a long-standing goal of observational cosmology!



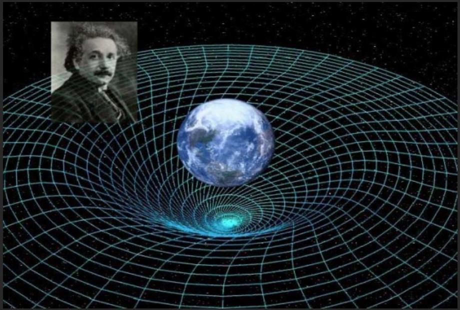
And the results are in!

- So what did astronomers finally see?



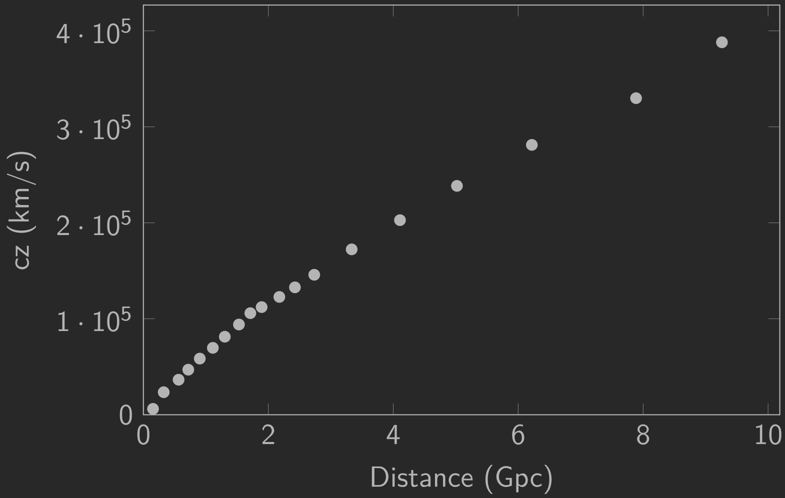
Oh #@*$! What?!

- Recent observations (1998) suggest expansion is not slowing
  - The expansion rate is now higher than it was in the past!
  - $q_0 < 0$
  - Universe may actually be *older* than Hubble time?
- None of the basic GR models predicted this
- Was Einstein's "cosmological constant" correct after all?



$$R_{ab} - \frac{1}{2}Rg_{ab} = -8\pi T_{ab} + \Lambda g_{ab}$$

So how do we explain this?



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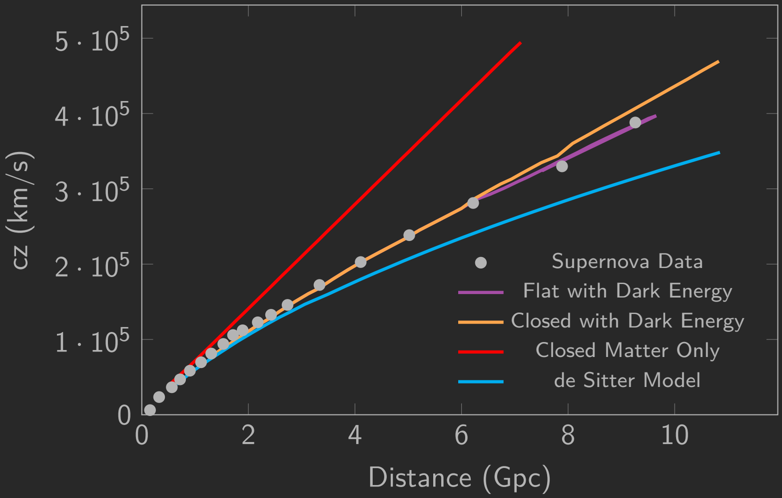
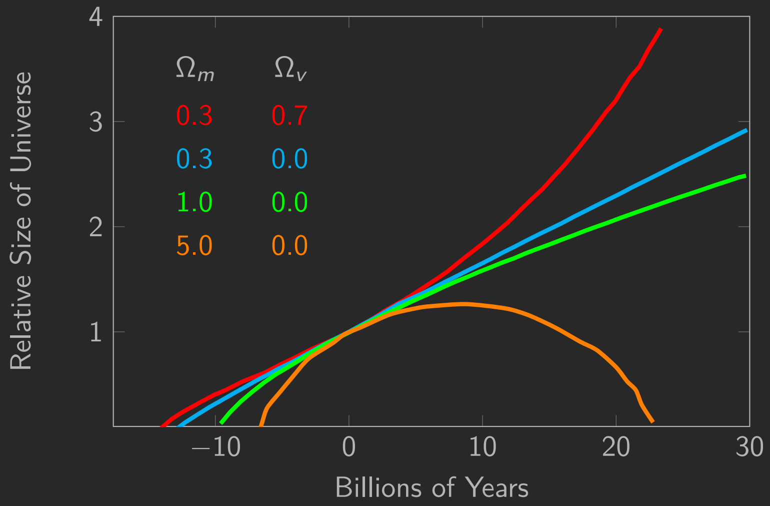


Dark Energy

- Of the many models so far put forth, adding dark energy to GR for a flat universe gives the greatest agreement with observations
- Dark energy is excess energy that is pushing the universe outward
  - Similar to how gas pressure pushes stars outward
- No idea yet of the source of this energy
  - Energies are tied to forces
  - No known forces would result in this invisible and excess energy!

The Galactic Timeline



Flat and Expanding

- Note that the sum of the two density factors now gives a value of 1
  - Supporting the findings that the universe seems to be flat!
- Dark energy provides the extra 70% of the mass/energy of the universe
- Results in an age of the universe very similar to the 14 billion years estimated from a constant expansion rate
- So, as far as we know, at the moment we think that our universe is:
  - Flat
  - Expanding increasingly quickly
  - About 14 billion years old
  - Infinite or Finite is not well determined yet