Announcements

- Webwork due on Monday
- I'll have study materials for the final posted early next week.
- Physics Tea today at 3pm!
- Physics Talks by Seniors all afternoon, starting from 2 until 5
  - Catch me afterwards if you have questions or need help on anything!
- Blood Drive today! Donate your precious life-essence!
- Polling: `rembold-class.ddns.net`

Spiral Galaxies

- Many of the characteristics of the Milky Way
  - Spiral disk, bulge, halo, etc
- Can come in normal or barred varieties

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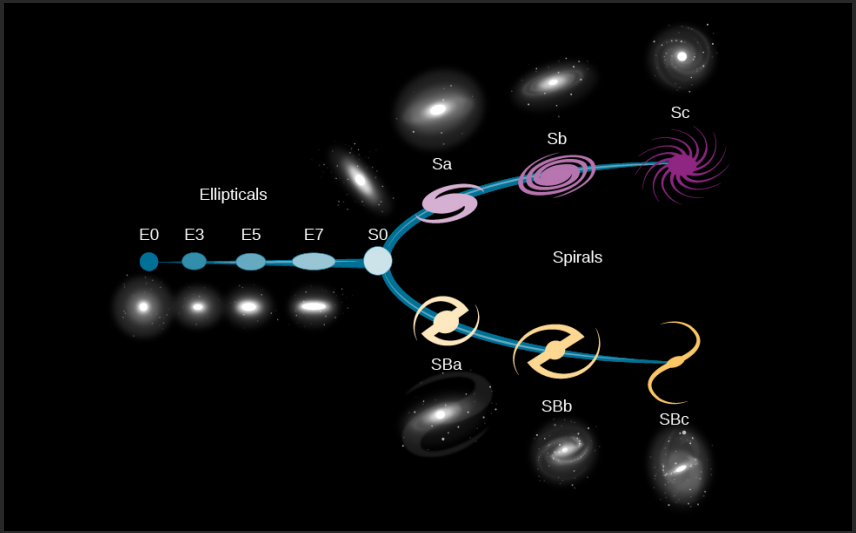
Elliptical Galaxies

- Differ from spirals is important ways:
  - Have no disk
  - Rotate more slowly
  - Contain very little gas or dust
  - Contain mainly old stars
  - Huge range of sizes
    - 0.0001–100 times the Milky Way

Irregular Galaxies

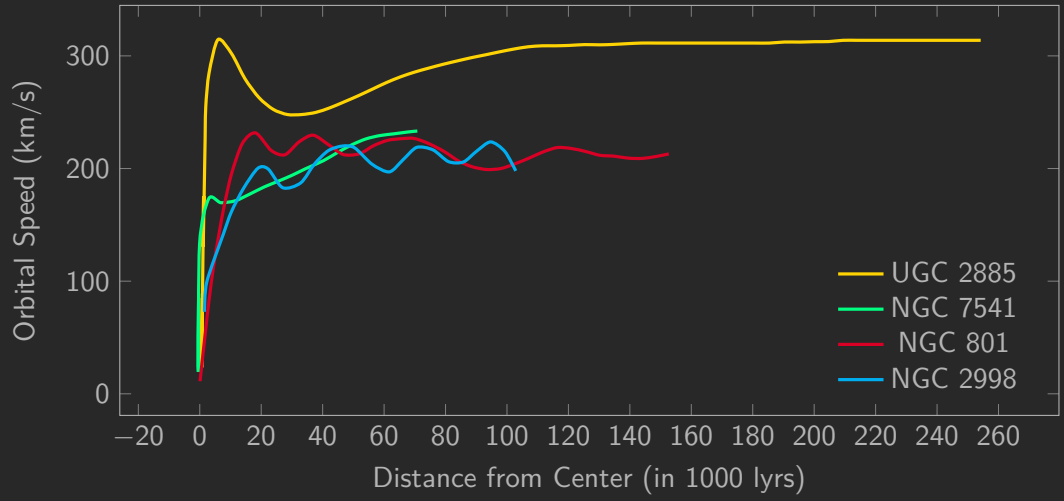
- The misfits
- Often times harbor very active star forming regions
- Can sometimes be the result of galaxy collisions

Hubble's Fork



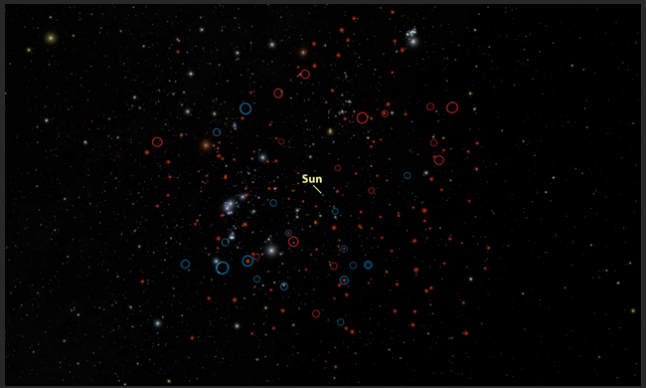
Back to the Darkness

The Milky Way is not unique with its rotation curve!



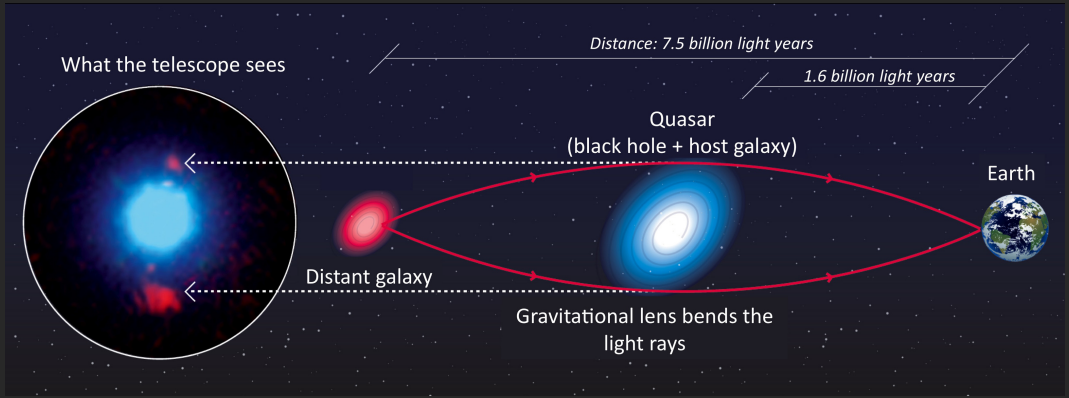
Macho Man!

- How else could we get invisible mass?
- Could the halo be filled with faint, dead stars?
  - Massive Compact Halo Objects
  - Brown Dwarfs
  - Neutron Stars
  - Black Holes
- How does one find an invisible object?



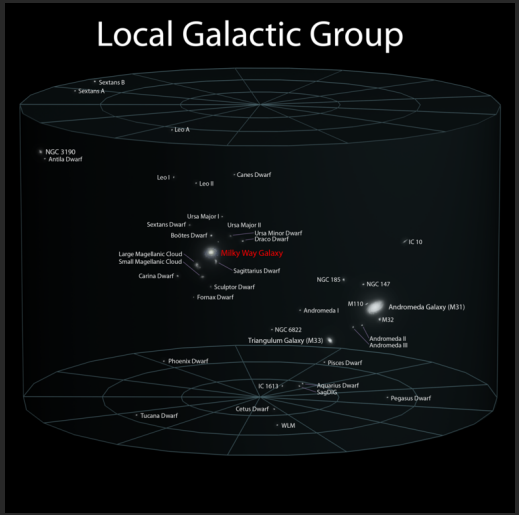
Gravitational (Micro)lensing

- We look for their mass's effect on nearby light
- Find that MACHOs account for 20% of the missing halo mass at most
- So dark matter definitely still on the table...



Social Galaxies

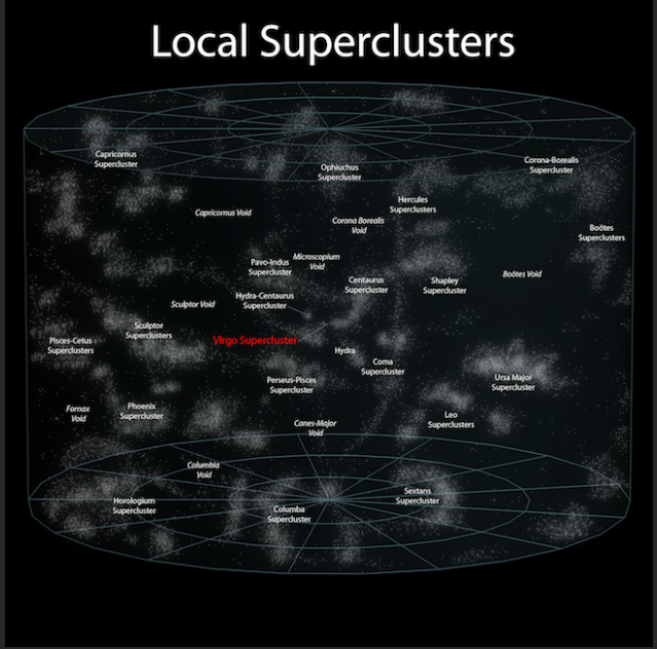
- Galaxies tend to group up
  - Compared to their size, distances between galaxies much smaller than distances between stars
- Milky Way is part of the aptly named Local Group



Clusters also want friends

- Clusters and Groups also tend to group up, forming superclusters!

Local Superclusters



Understanding Check

Which of the following is NOT one of the ways that elliptical galaxies differ from spiral galaxies?

A. They have no galactic disk
B. They have mainly younger type stars
C. They rotated more slowly
D. They contain little gas or dust

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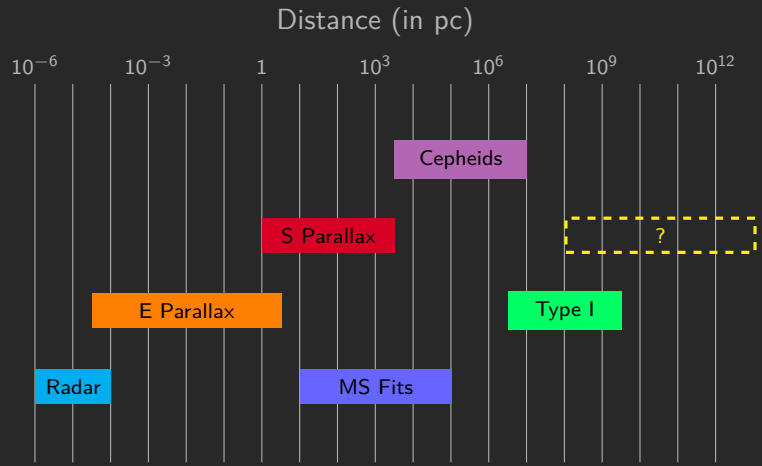
The Distance Ladder



A Red Tale

- Vesto Melvin Slipher - 1912
  - While observing spiral galaxies found that they all seemed to be redshifted by various amount
  - This would imply that all the distant galaxies were moving away from us!
- Edwin Hubble - 1929
  - Used Type Ia supernova to estimate distances to distant galaxies
  - Found that the more distant galaxies were more redshifted

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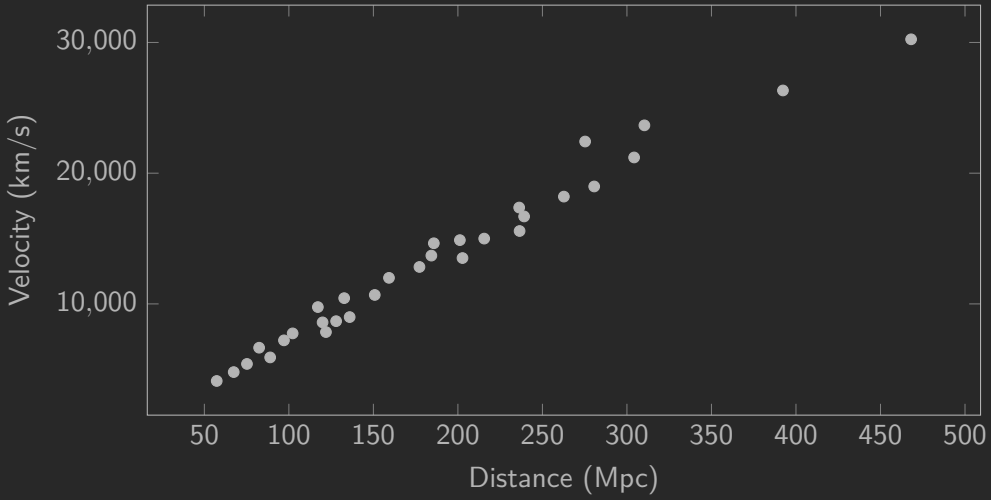
The Hubble Relation

The more distant an object is, the faster it is moving away from us!

Hubble's Law


30,000
20,000
10,000
Velocity (km/s)
50
100
150
200
250
300
350
400
450
500
Distance (Mpc)

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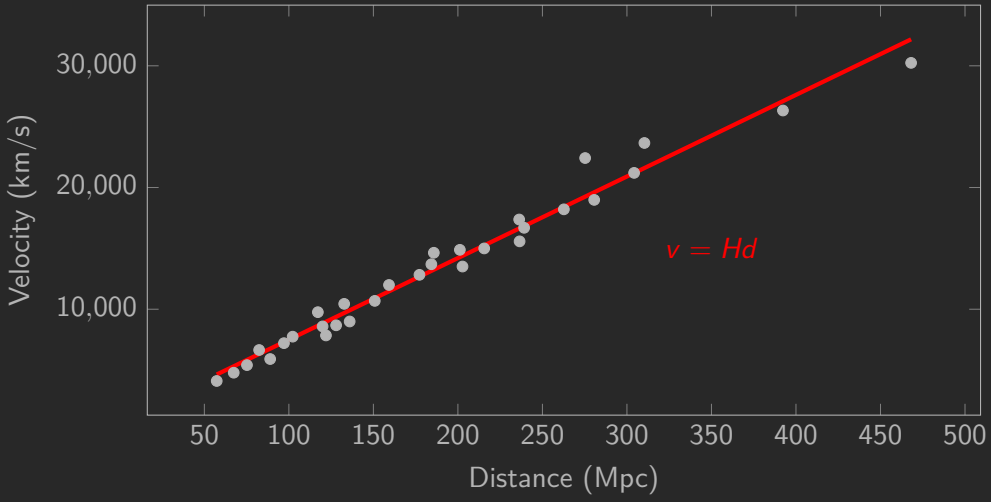
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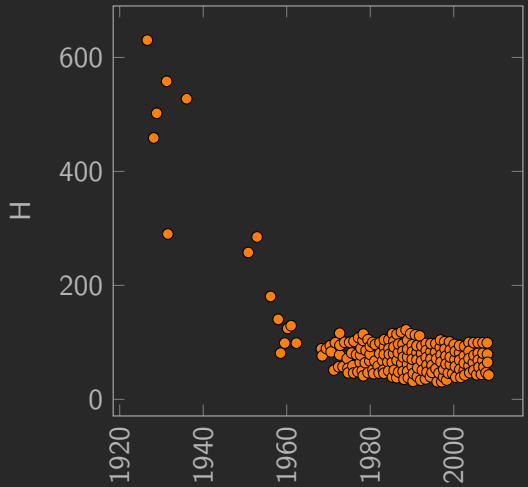
Distance (Mpc)
$v = Hd$

The Hubble Constant

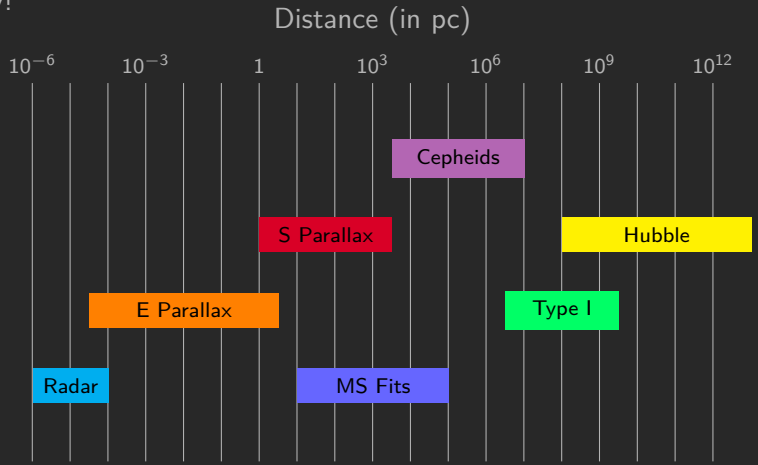
- Has varied greatly throughout its lifetime
  - Initially around 600 and took about 40 years to hone down to it near its current value
- Still empirically (experimentally) determined
- Current estimates range between 65–79
- Best value at the moment thought to be about

$$H = 72\,\mathrm{km/(s\,Mpc)}$$



The Ultimate Range Finder

- At extreme distances, Hubble's Law itself can be used to estimate the distance to a galaxy!



Puffing Up

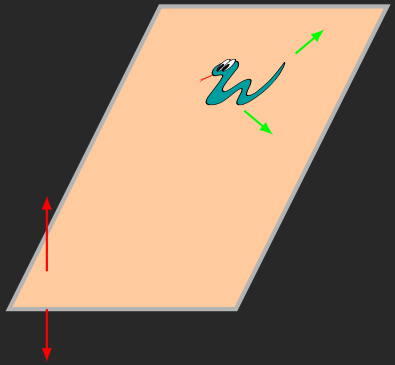
- So all galaxies are moving away from us, but surely we aren't in the center?
  - Nope!
  - But then again, neither is anyone else!
- The Cosmological Principle:
  - At a given cosmic time, the universe looks basically the same to all observers.
- Everyone sees everything moving away because the entire universe is actually expanding!

They are a crusty bunch. . .

- The Raisin Bread Analogy
  - Raisins are galaxies (or stars)
  - The dough is space
  - As it rises and cooks, all the raisins move away from each other
- Raisin bread fails the cosmological principle
  - The people of the crust

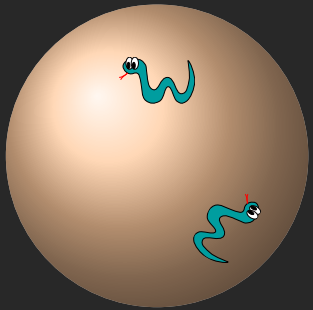
Snakes on a @#!$&%*&!*$ Plane!

- Imagine yourself a smooshed interstellar snake
- You live on a flat sheet of paper
- You can move around on the paper, but not up or down



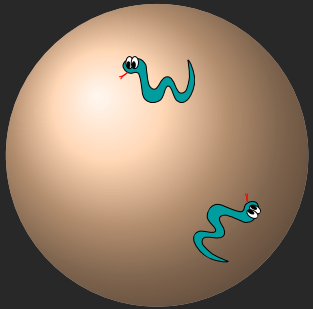
- This is basically just the raisin loaf so far

Snakes on a Sphere



- Suppose now we connected the ends of the paper to make it into a perfect sphere
- Now your "'universe" has:
  - No center
  - No edge!
- Looks the same regardless of where you are at
- Cosmological principle
- Inflating the sphere will increase all the distances
- The Hubble constant indicates how quickly the sphere inflates

Snakes on a Sphere



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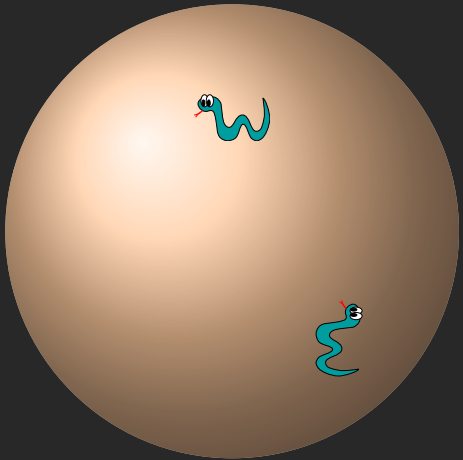

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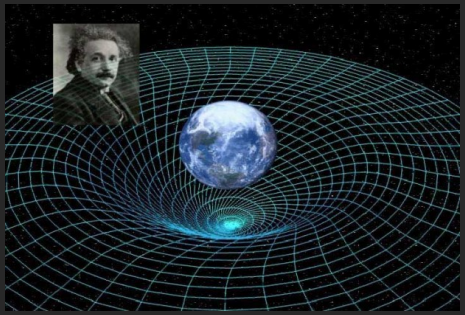
Einstein's Demon

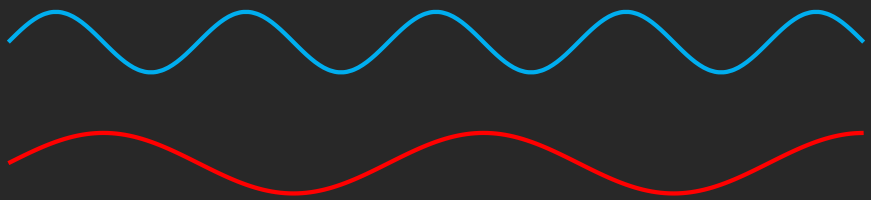
- Einstein's General Relativity + a homogeneous universe predicts either an expansion or contraction of space
- Einstein hated this and was convinced it couldn't be true
- Originally added an extra term, a "cosmological constant" to his equations to allow for a static, unchanging universe



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

Einstein's Expanding Space

- Galaxies appear to move only because space is expanding
  - Galaxies just conveniently mark points in space
- Space was expanding long before there were galaxies though
- Galaxies remain the same size
  - Gravity holds them together and determines the size
- Light is red-shifted because space expands so the wavelength is stretched



Expansion and Age

- If everything is expanding, we can reverse it to figure out how old the universe is
- "Hubble Time"

$$t_h \approx \frac{1}{H}$$

- Comes out to about 14 billion years
- Or at least that's when the universe would have been a tiny point
- Note that this assumes the rate of expansion is constant!

Evidence of Billion-Year Timescales

The Hubble Xtreme Deepspace 3D!