The Cosmos

Planets & Life

PHYS 214

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Please start all class related emails with "214:"

Today's Lecture

- Pop Quiz 1
- Cosmology
  - Expansion of the Universe

What is Cosmology?

- (Wikipedia):
  - **Cosmology**, from the Greek: κοσμολογία (cosmologia, κόσμος (cosmos) order + λογια (logia) discourse) is the study of the Universe in its totality, and by extension, humanity's place in it.
- Note, study of the creation of the Universe is called *Cosmogony*
- The distinction between the two can become blurred and I will not bother to use "cosmogony"

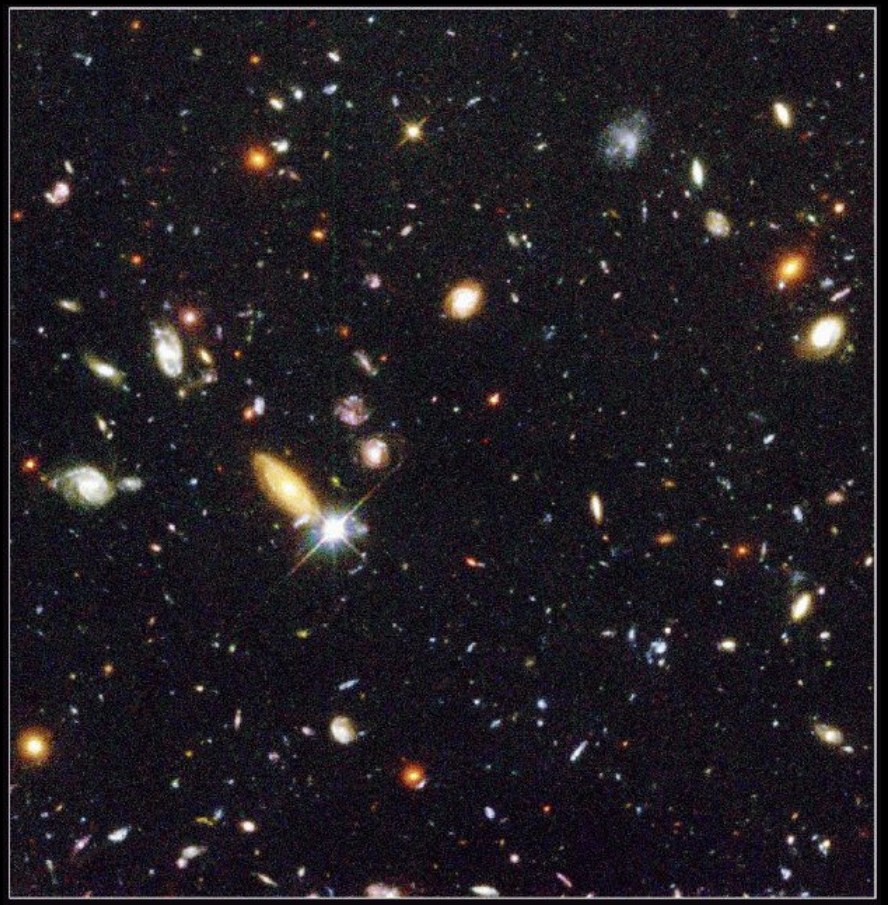
Humour: "Oh, you're a *cosmologist*?"

- I was once hiking with my wife and we met some school teachers at a cabin…
- We got chatting and they asked us what we did…
- When I said I was doing a PhD in Cosmology one of the lady teachers replied:
  - "Wow! It is wonderful that in this day and age a guy can spend five years studying *make-up*!"
- (Wikipedia)

  A ***cosmetologist***, sometimes called a **beautician**, a **beauty specialist**, or an **esthetician** or **aesthetician**, is a worker who specializes in giving beauty treatments.

Galaxies provide cosmic "milestones"

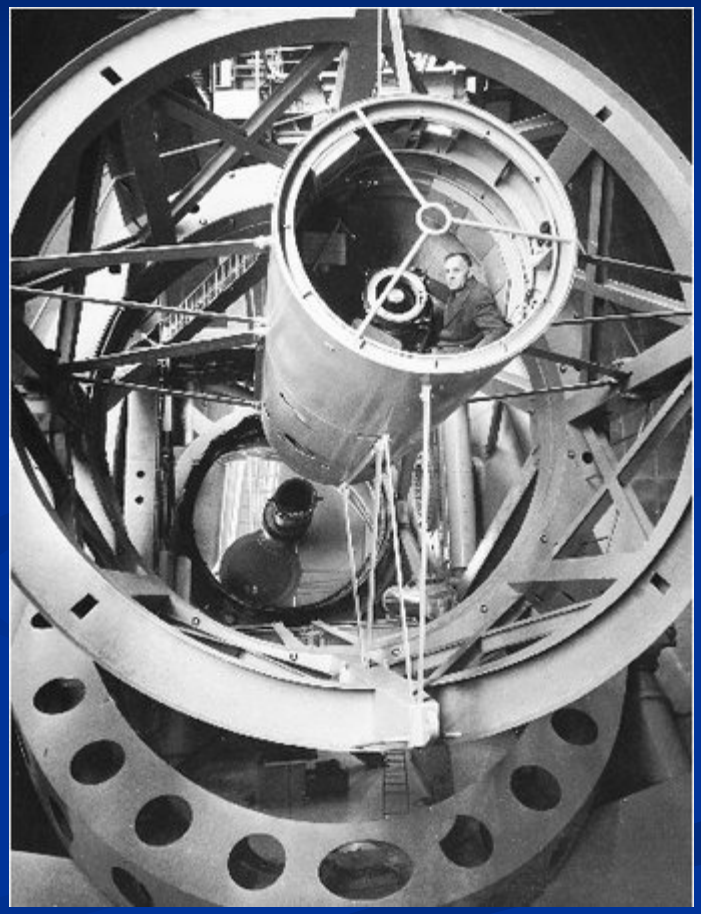
- Beyond a few thousand light years stars are very hard to see
- Fortunately, since galaxies are made of tens/hundreds of billions of stars we can see them at enormous distances
- If the Universe didn't have galaxies it would be extremely hard for us to judge how big it is



Hubble Deep Field
Hubble Space Telescope · WFPC2

Origin of modern cosmology

- Observations by Edwin Hubble (1889-1953) in 1923-24 allowed us to establish the distance to nearby galaxies
  - Measured the brightness of stars in these galaxies
- It was also known at the time that galaxies exhibited a Doppler shift – they tend to "redshifted" – and are thus moving away from us
- Hubble put these two pieces of information together to derive Hubble's Law
  - A relation between distance and the speed at which galaxies move away from us



Hubble sitting in the 200 inch reflecting telescope at Mount Palomar

Cosmological Redshift

- The Doppler shift(s) towards longer wavelengths (red) Hubble measured are viewed as being down to the *overall expansion of the Universe*
  - Remember the Doppler shifts are measured using atomic lines
- Using the Doppler shift equation (see last lecture)

$$\frac{\lambda_{\text{observed}} - \lambda_{\text{in lab}}}{\lambda_{\text{in lab}}} = \frac{\Delta\lambda}{\lambda} = \frac{v}{c}, \text{ rearranged to give } v = c\frac{\Delta\lambda}{\lambda}$$

where $\Delta\lambda$ is the change in wavelength measured, c is the speed of light and v is the velocity Hubble found results similar to the following

$$v = c\frac{\Delta\lambda}{\lambda} = 3.0\times10^{5}\,\text{km s}^{-1} \times \frac{(486-483)\text{nm}}{483\text{nm}} = 1860\,\text{km s}^{-1}$$

Hubble's Law

The original graph from Hubble's 1929 paper

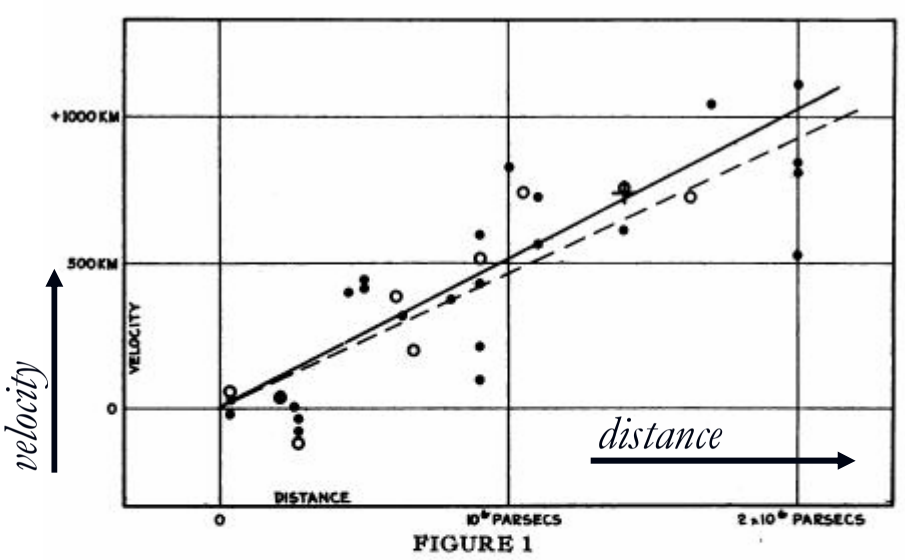


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

- Hubble, in collaboration with Humason, showed that the relationship with velocity, v, and distance, d, is linear:

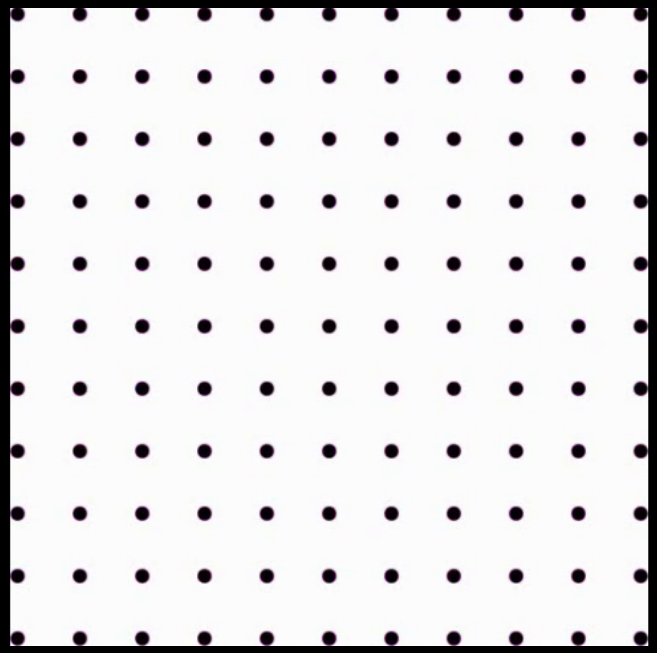
$$v = H_0 d$$

  where H_0 is called Hubble's constant
- Galaxies are millions of parsec's distant!
- Moving at speeds of hundreds of kilometers per second away from us!

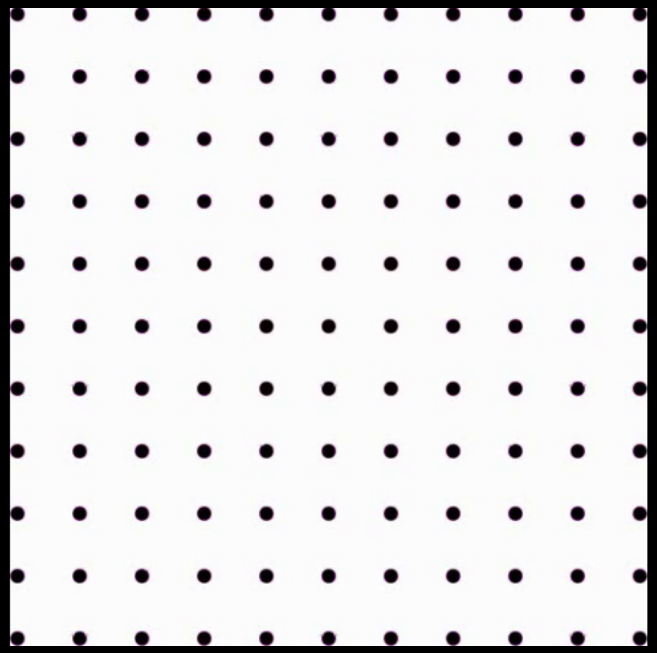
Conclusion: Universe is expanding

Is there a center of the expansion?

Blue dots = initial position of galaxies
Red dots = final position after expansion



Choosing "centre" to be middle of panel



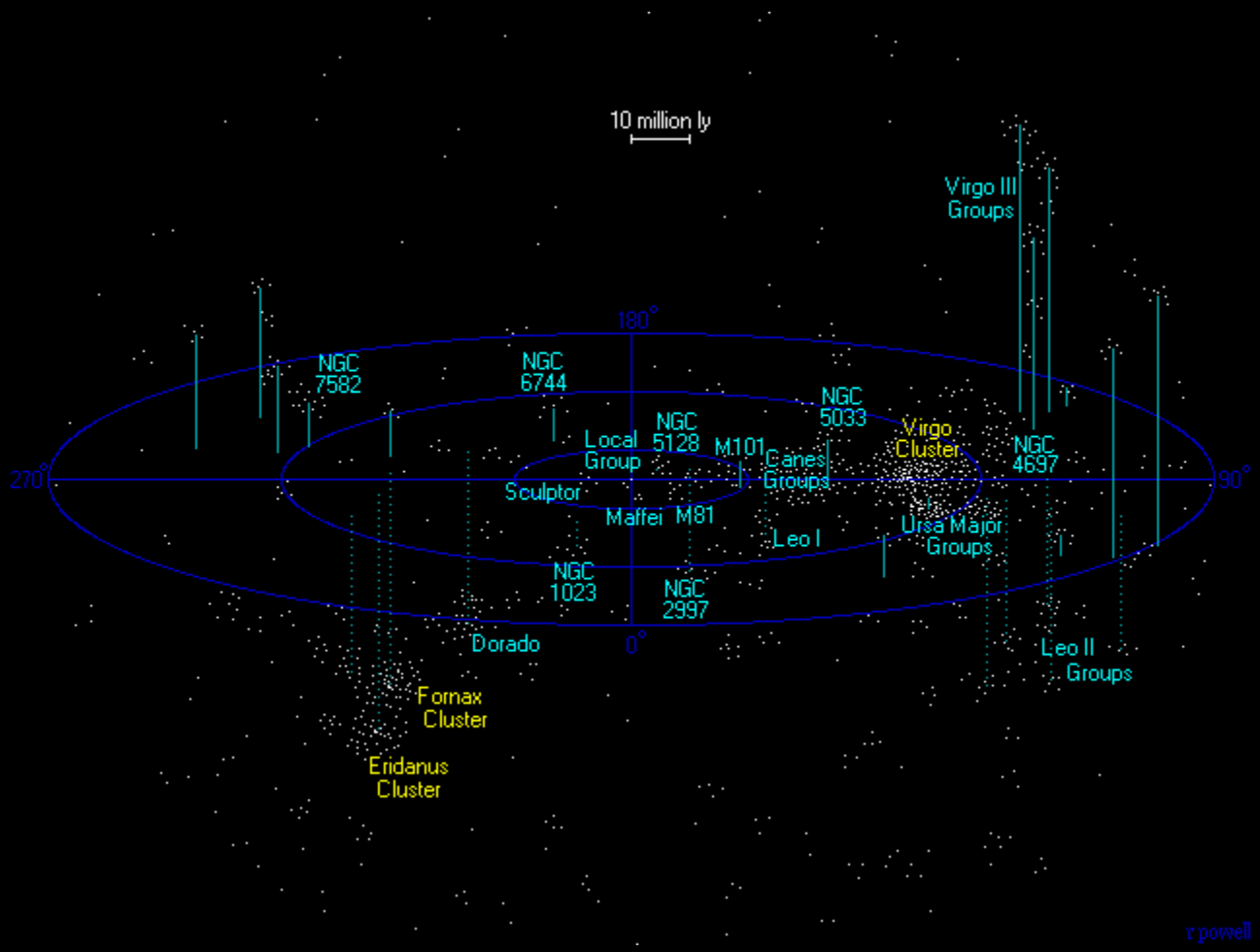
Choosing "centre" to be offset lower right

Expansion appears the same at both viewpoints – you can either think there is *no centre*, or *every position is effectively the centre*

The Cosmological Principle

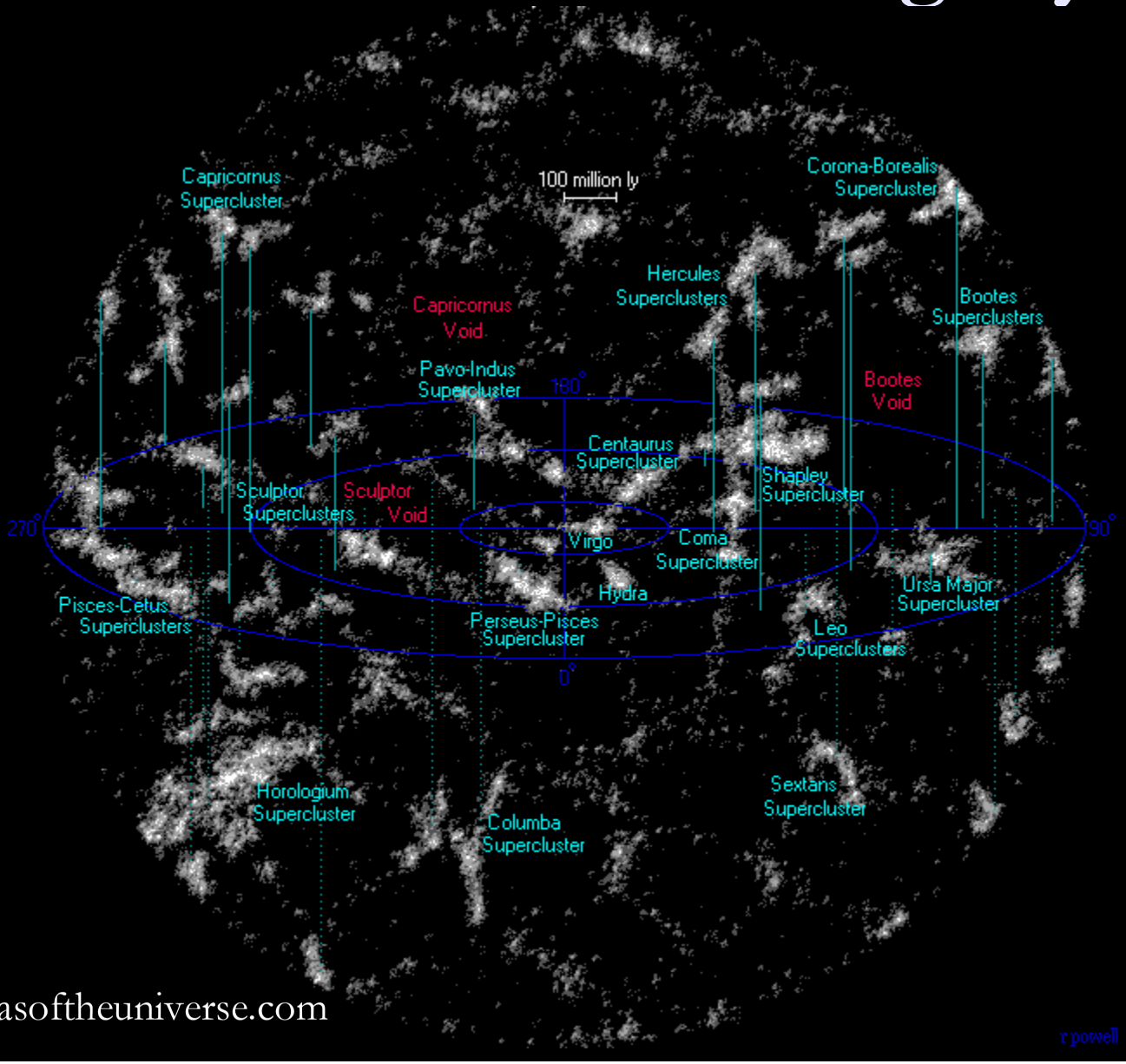
- Although we've looked at a 2-d sheet, the real Universe has the same properties in all directions
  - **The Universe *Isotropic***
- The Universe also exhibits the same properties all places too
  - **The Universe is *Homogeneous***
- These two well supported *assumptions* (we cannot test them) form the *Cosmological Principle*
- *This idea is only valid on very large scales though!*
  - *Definitely not true on small scales*

“Virgo Supercluster”



http://www.atlasoftheuniverse.com

Universe within 1 billion light years



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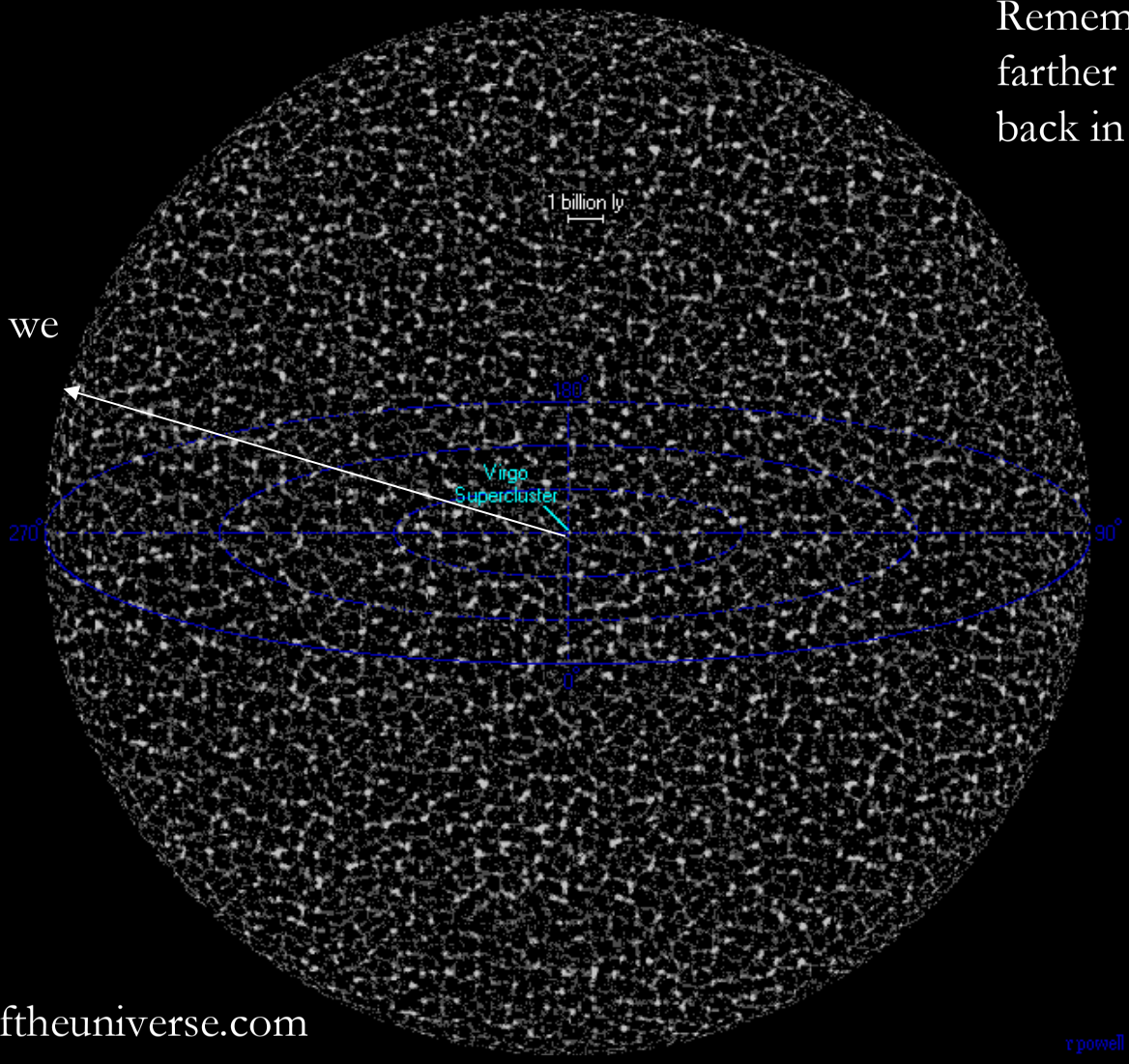
Universe within 14 billion light years (approximate)

Remember: as we look farther out we are looking back in time



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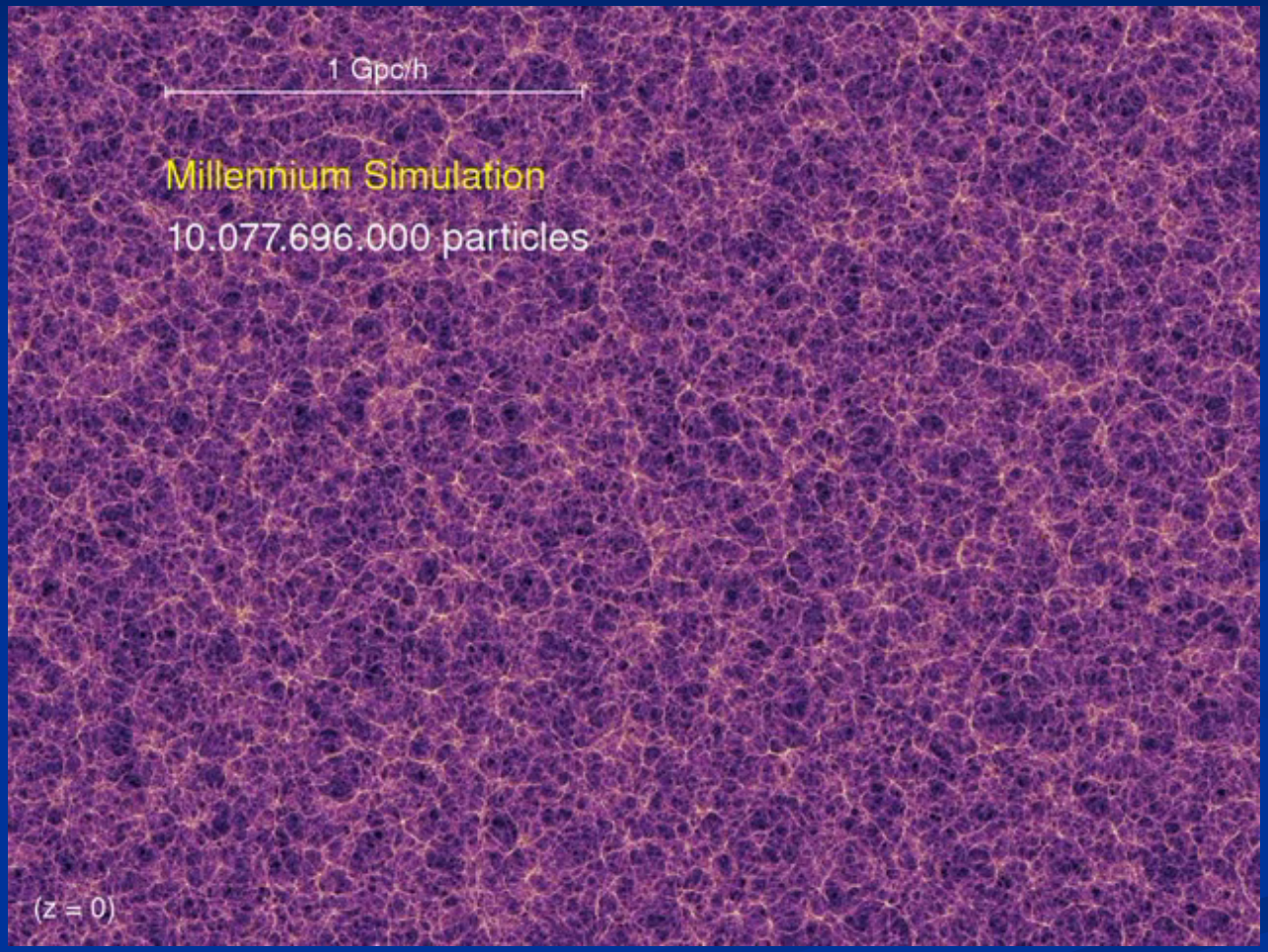
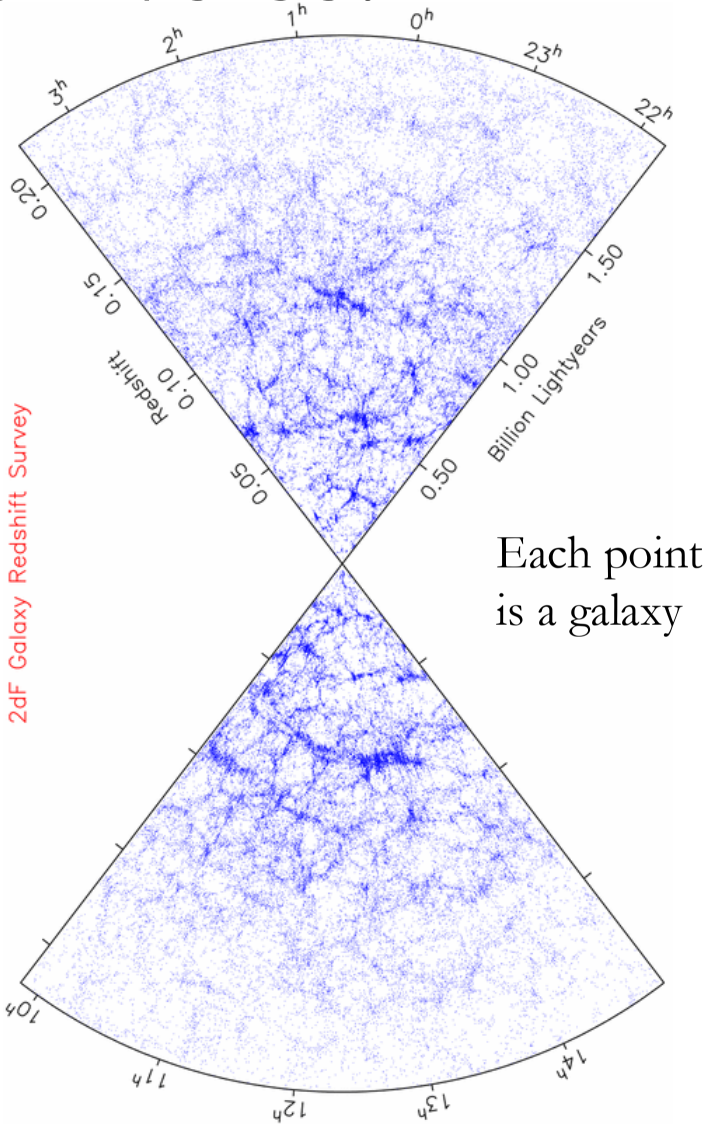
A simulation of cosmic structure



Looks homogeneous on large scales, and isotropic too
but as you zoom in you see this isn't true on small scales

So how many galaxies are there in the observable Universe?

- Well, we can do a rough estimate
- Based upon enormous "galaxy surveys" we can use the density of galaxies we find to estimate the total number
  - If you have the density you just multiply by the total volume
- It's about 100,000,000,000!
  - *i.e.* 100 billion
- So there roughly as many galaxies in the observable Universe as there are stars in the Milky Way



Does the Universe have an end or have an edge?

- Well we know the Universe is about 14 billion years old
  - So this sets a limit on the distance light can have travelled and what we can observe
  - So in some sense our *observable Universe* does have an edge
    - But it isn't a hard boundary like a provincial boundary
- What about things beyond the edge of the observable Universe?
  - We don't know – although we can try to estimate
    - Subject of ongoing research
  - Right now, the evidence cannot distinguish between an infinite or finite Universe

Olber's Paradox

- People have been thinking about the size & age of the Universe for hundreds of years
- Heinrich Wilhelm Olber(1758-1840) is famous for asking
  - *Why is the night sky dark?*
  - His reasoning: if the Universe is infinite in extent and has existed forever, then in every direction we should see a star
- We know the answer to this question now – the Universe has a *finite age*

Turning the clock back

- If space is becoming more and more empty due to expansion, running the clock backwards suggests things we much closer in the past
  - This is why the discovery of the expansion of the Universe is so important
- Very far back in the past things must have been incredibly close
  - At some point everything will have been compressed into a point with zero spatial extent – a "singularity"
    - We don't actually have the laws of physics to describe what happens here yet – this is viewed by many as the greatest challenge in physics
  - This point in evolution is more familiarly known as "***The Big Bang***"

How long ago?

- Although we know the age of the Universe quite accurately, we can estimate it very simply
- If we assume the Universe has been expanding at a roughly uniform speed *v*, over distance *d*, then for a time *t*,

$$v = \frac{d}{t} \Rightarrow t = \frac{d}{v}$$

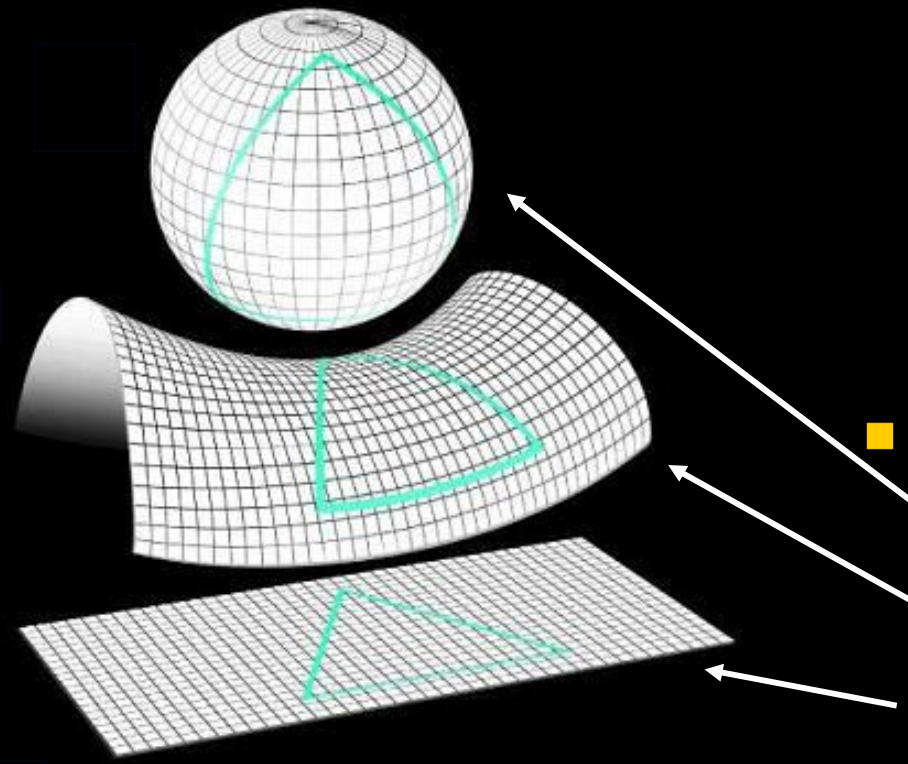
- Hubble's Law gives us $v=H_0 d$, substituting for v

$$t = \frac{d}{v} = \frac{d}{H_0 d} = \frac{1}{H_0} = \frac{1}{3\times10^{-18}\,s^{-1}} \approx 11\times10^{9}\,\mathrm{yr}$$

The Big Bang

- Marks the beginning of the Universe and the beginning of Time
- Two common misconceptions
  - *The Big Bang was an explosion expanding into the space around it…*
    - No! Space and time were created in the Big Bang - it happened *everywhere* at once
  - *Something must have been happening before the Big Bang*
    - The Theory of Relativity shows us Time is not an absolute concept – it depends how you are moving and where you are. As an analogy, consider the concept of "North": except for *one place* on the globe this is a well defined concept – once you stand at the North pole though you can't say what is North of the North Pole. The concept of time breaks down at the Big Bang in the same way.

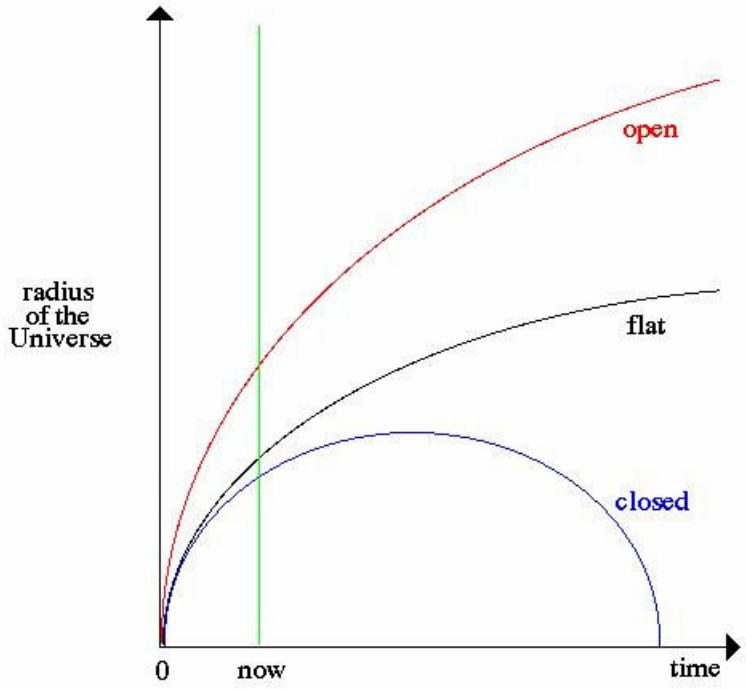
Geometry of the Universe



- We describe the shape (strictly speaking the geometry) of the observable Universe by two methods
  - What happens to parallel lines over very large distances
  - What value to the angles in a triangle add up to?
- There are three possibilities
  - Lines eventually cross, sum of angles is greater than 180°
  - Lines grow apart, sum of angles is less than 180°
  - Lines stay same width apart, sum of angle is 180°

The geometry-expansion connection

- The future evolution of the universe is determined by the total amount of matter contained within it
- Too much matter:
  - Universe is destined to collapse down into a "Big Crunch"
  - "Closed Universe" – parallel lines eventually cross
- Too little matter:
  - Universe will expand forever
  - "Open Universe" – parallel lines end up diverging
- "Just the right amount" of matter:
  - Universe expands forever but at a progressively slower rate
  - "Flat Universe" – parallel lines remain parallel



We appear to be living in a Universe that will expand faster and faster, but for which the geometry is flat!

This was not expected even 10-15 years ago.

Cosmic Inventory

- What makes up the mass of the Universe?
- About 4% is the "normal" matter that makes up stars, planets, you and I
- 26% is in a mysterious form called "dark matter"
  - We don't know exactly what it is (it's actually a sub-atomic particle of some kind), but we can describe what it does very well
- 70% is in the form of pure energy
  - This is called the Cosmological Constant
  - Einstein predicted this way back in 1916, but his first model was designed to prevent expansion and was thus wrong
  - Einstein called the Cosmological Constant his "greatest blunder"! When in fact he was absolutely correct to suggest it

Summary of lecture 3

- Galaxies are the reference points for measuring cosmic scales
- Hubble's Law parameterizes the speed of recession of a galaxy with distance
- The Cosmological Principle states that the Universe is homogeneous and isotropic
- The Big Bang created both space and time, and happened everywhere
- The final fate of the Universe and it's geometry are intimately connected

Next lecture

- Galaxies
- Start of life within the cosmos