What do we know about the Universe?

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Just the facts....

- Structures in the Universe are arranged hierarchically
- Universe is expanding
- Age of the Universe is 13.7 billion years
- Universe is spatially flat
- Most of the stuff in the Universe is in the form of things we cannot see and we don't understand

Structures in the Universe are arranged hierarchically

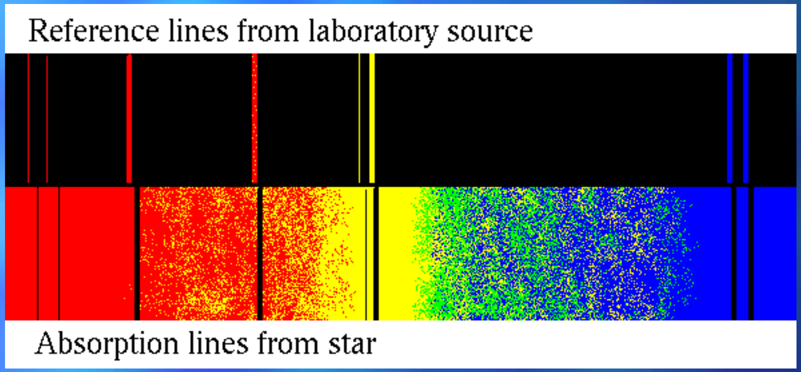
- We survey the types of objects in the Universe using bigger and bigger telescopes
- We measure the speeds at which objects move to find out if they are gravitationally bound to each other
- How do we measure the speed?

Measuring speed

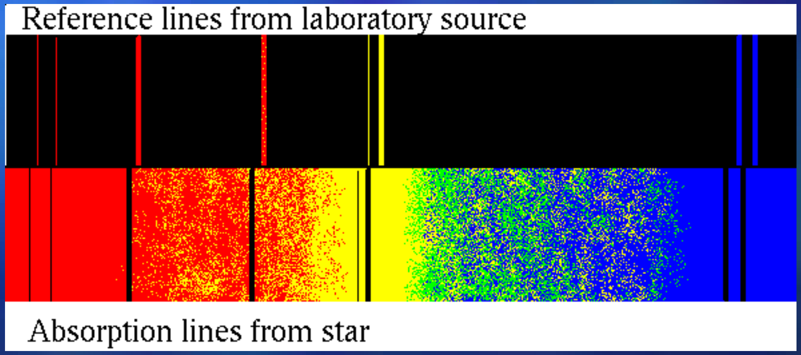
- Doppler shift works for both sound and light
- It is the change in pitch or color that is observed when the source or receiver is moving toward or away from an observer
- You may be familiar with the change in sound of a police siren as it passes you

Doppler Shift of light

Comparison of laboratory to blue-shifted object



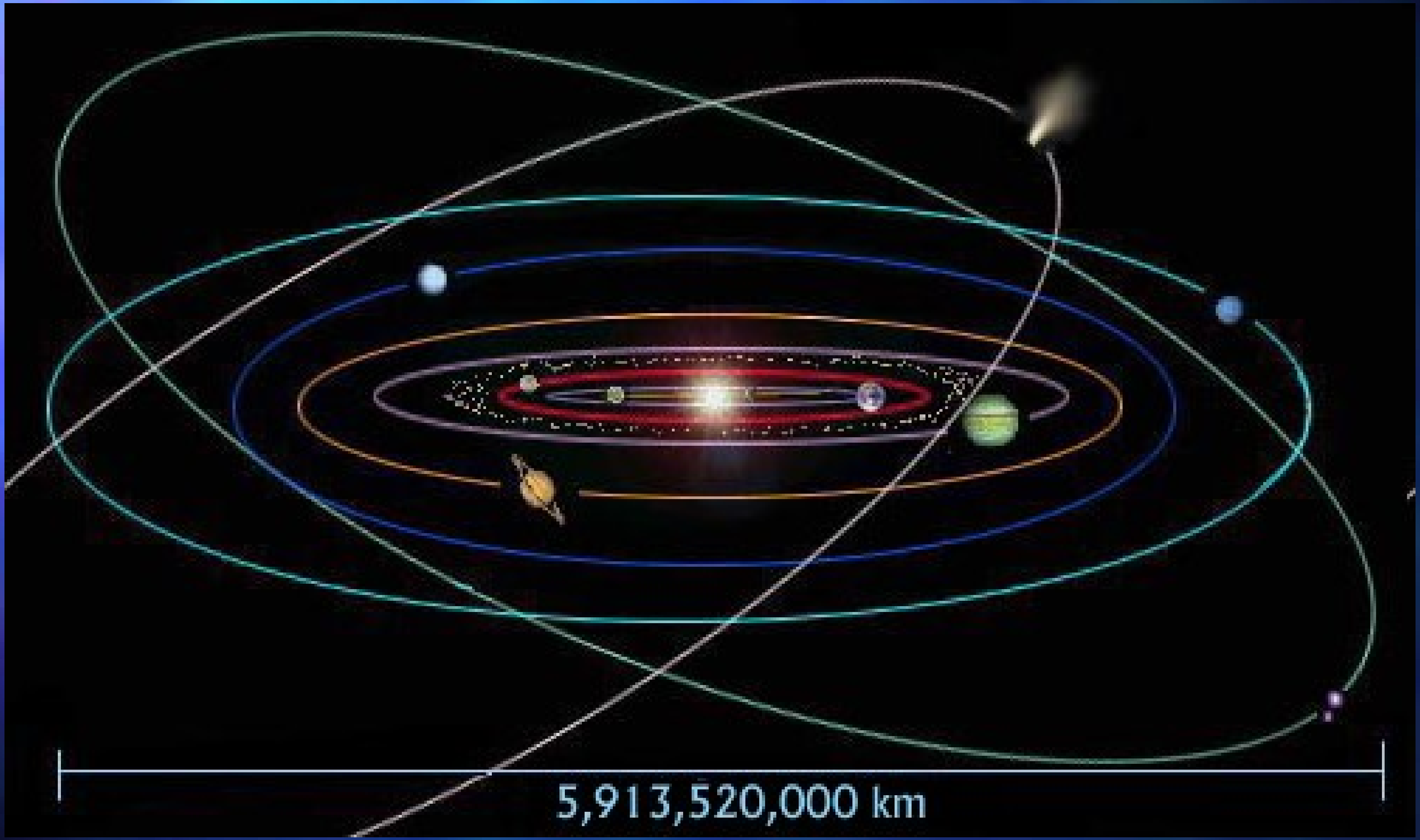
Comparison of laboratory to red-shifted object



Hierarchy of the Universe

- We live on a planet in a Solar System
- The Sun is the central object with most of the mass in our Solar System
- We use Kepler’s Laws to determine the mass of other objects orbiting the Sun
- Almost all the objects in our Solar System are gravitationally bound to the Sun (exception – some

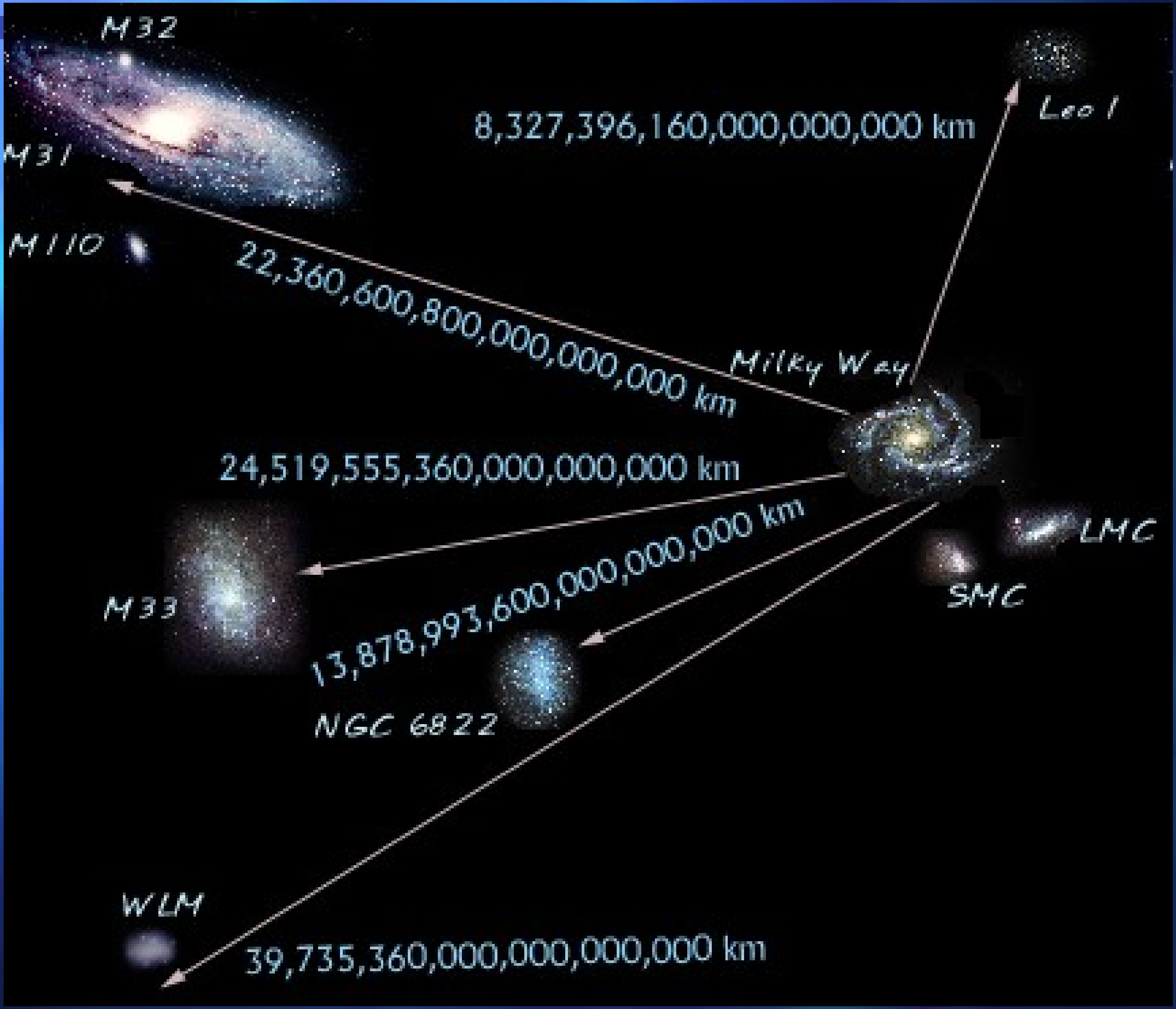
Solar System



Hierarchy of the Universe

- Our Sun is just one (rather boring) star in our Galaxy (out of about 100 billion)
- Our galaxy is part of the Local Group that includes M31 (Andromeda)
- The galaxies in our group are all gravitationally bound to each other
- None of the galaxies are moving fast enough to escape the group
- Some of the galaxies in the group are moving towards us (like M31) - blueshifted

Local group of galaxies



Hierarchy of the Universe

- Many galaxies are parts of larger groups called clusters of galaxies
- There are typically tens of thousands of galaxies in a cluster
- They are all gravitationally bound to each other
- Clusters of galaxies are moving away from each other as the Universe expands

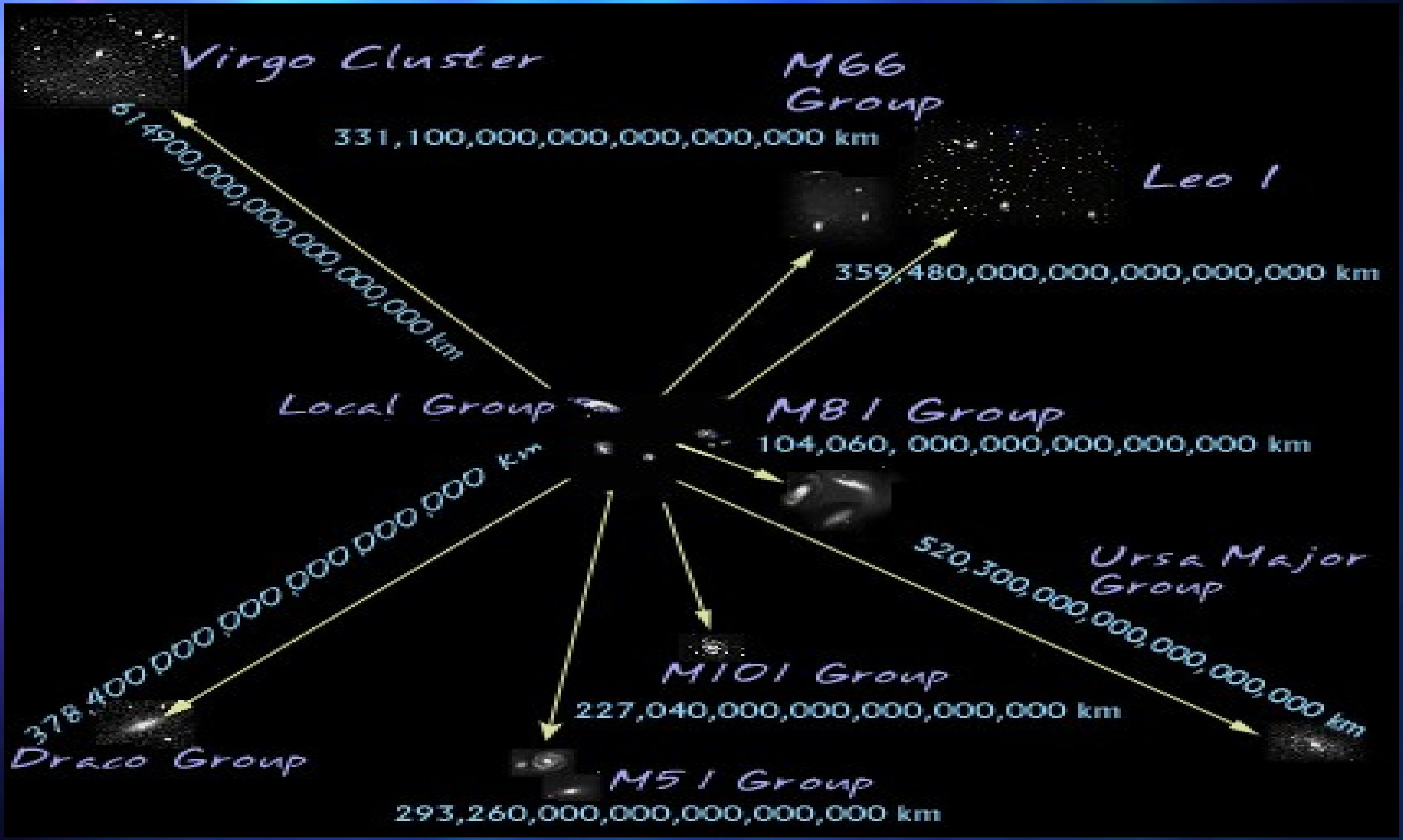
Virgo cluster of galaxies

- The closest cluster to our Local Group
- About 1000 galaxies

Hierarchy of the Universe

- The Virgo cluster and our local group are both parts of a supercluster
- However, superclusters are not gravitationally bound
- They are the largest structures in the Universe
- The hierarchy ends here
- We have measured the positions and velocities of millions of galaxies

Our local supercluster



Velocities → Distances ?

- All of the distances in the previous slides were derived from the measured velocities (which were derived from the Doppler shifts of the spectral lines)
- It was Edwin Hubble that figured out that the velocities represented the distances to the objects
- So how did Hubble figure this out?

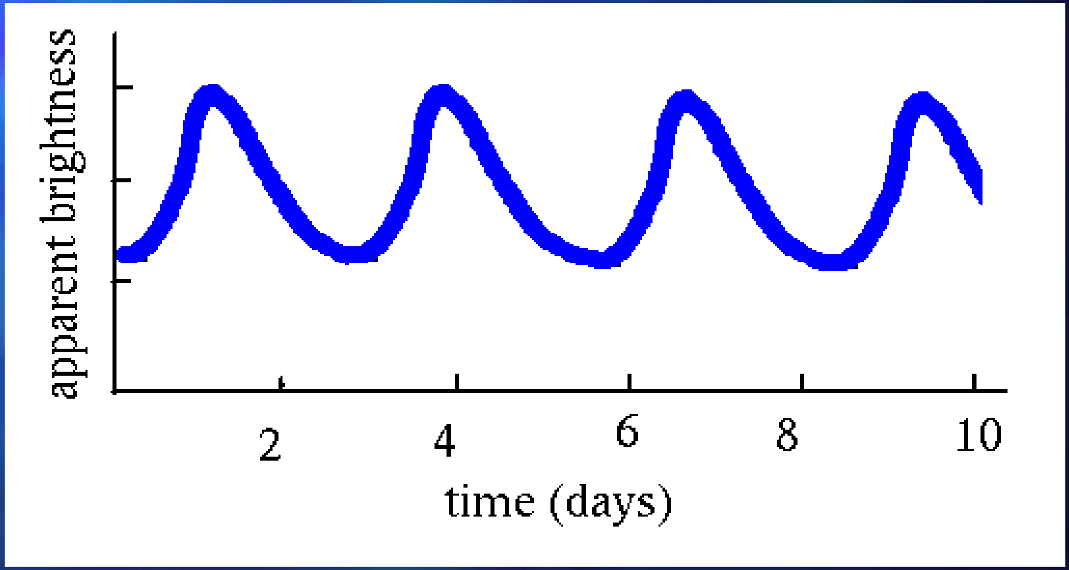
What Hubble saw?

What Hubble really saw

- Edwin Hubble studied "the realm of the nebulae" – fuzzy blobs – to try to figure out if they were in our galaxy or not
- He discovered individual stars which varied periodically in brightness
- Some of these stars were in our own galaxy, and he could use parallax to figure out how far away they were
- But others seemed to be much

Cepheid variables and Nebulae

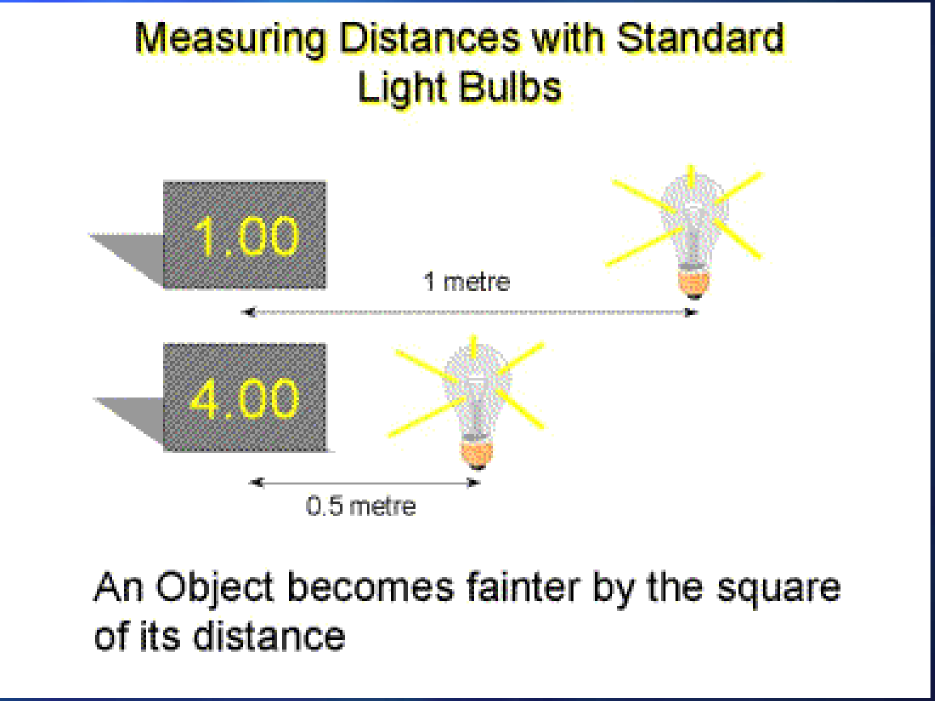
- In 1923, Edwin Hubble used new Mt. Wilson 100 inch telescope to observe Cepheid variables in the nearby "nebula" Andromeda.
- Cepheids vary periodically $L = K P^{1.3}$
- Distance to Cepheids can be calculated from their luminosity



Standard Candles

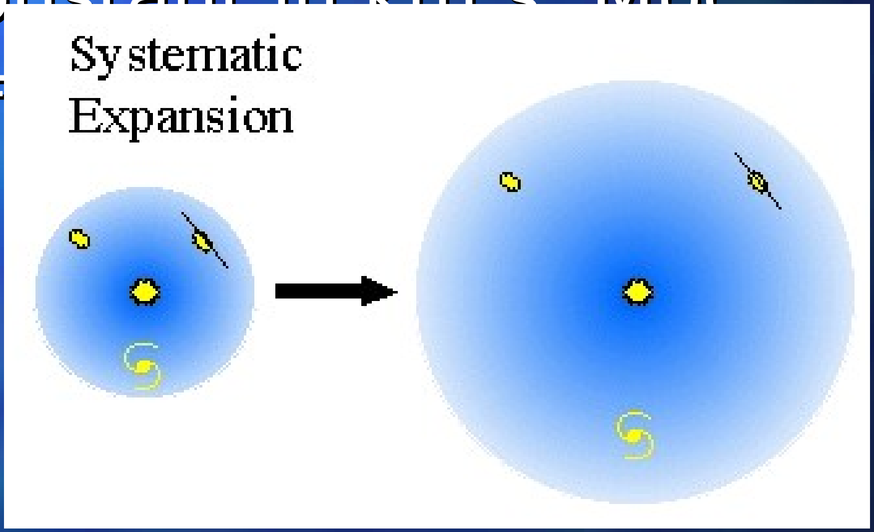
- If you know the absolute brightness of an object, you can measure its apparent brightness and then calcu
- Cepheids are standard candles
- So are some supernovae

$$F_{obs} = L_{abs}/4\pi d^2$$

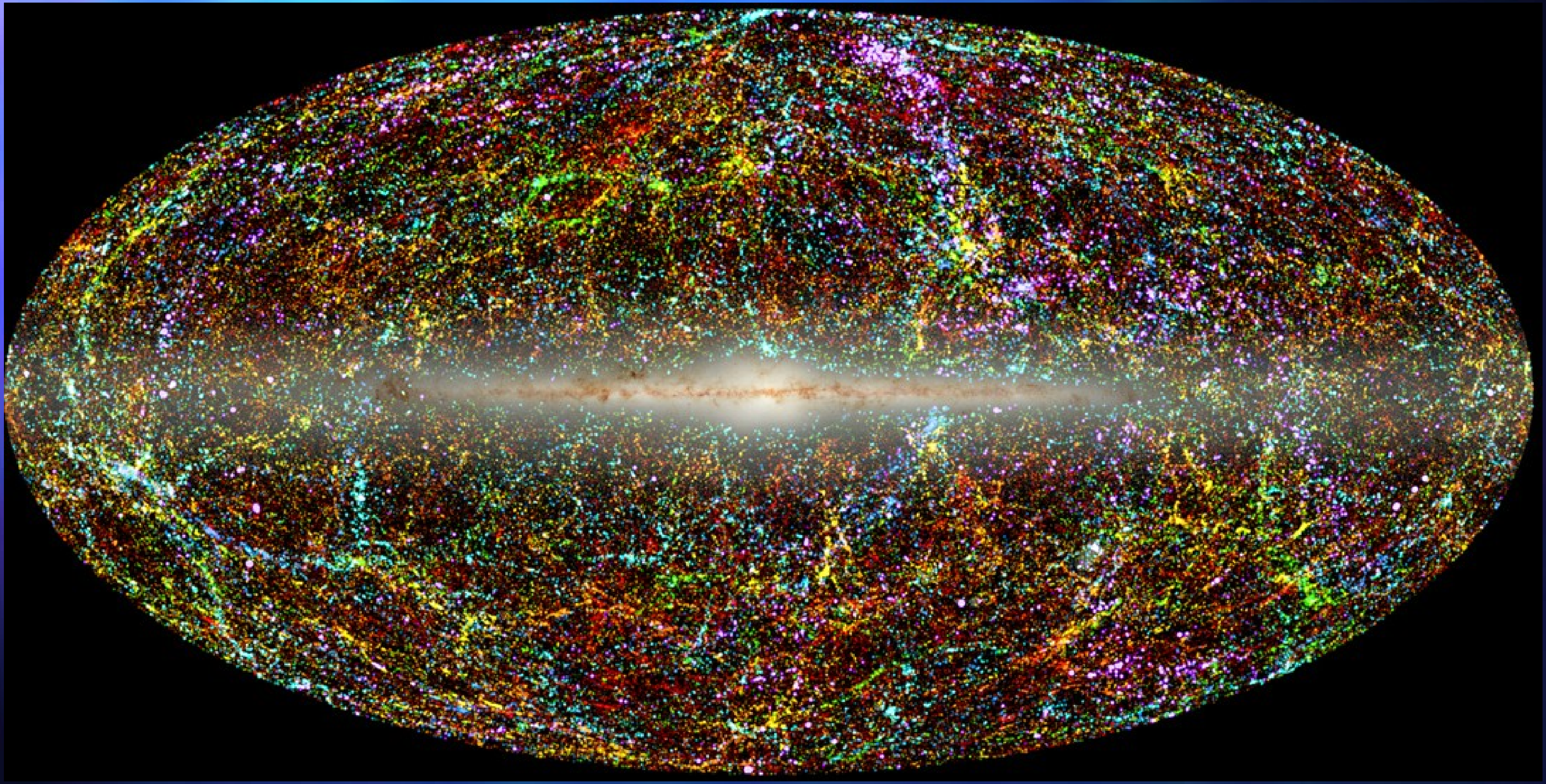


Hubble Law

- $v = H_0 d = cz$ where
  - v = velocity from spectral line measurements
  - d = distance to object
  - H_0 = Hubble constant in km s^{-1} Mpc^{-1}
  - z is the redshif



Galaxy map in infrared (Jarrett)



Universe is Expanding

- Using Hubble's Law, we can measure the recession velocities → distances
- Beyond our local group, all galaxies are moving away from us → Universe is expanding
- Galaxies are not changing size → space between them is expanding
- We are NOT at the center of the Universe (despite what we might think)

Universe is 13.7 billion years old

- *Simple version:* Using Hubble's Law, we can run the clock backwards, to see how long it has taken for it to have expanded to its current observable size
- H_0 = Hubble constant in km s^{-1} Mpc^{-1}
- $1/H_0$ = Hubble time → 14 billion years
- But this all assumes that Hubble's constant is really constant – is it?

Universe is 13.7 billion years old

- *Next steps:* Need to understand the detailed expansion history of the Universe
- Has Universe been expanding at a constant rate throughout?
- No! (Hubble's constant is not really constant, it is just the value we measure today.)
- *But how do we measure the expansion history of the Universe?*

History of the Universe

- What is the most distant light we can see?
- It is called the “Cosmic Microwave Background” and this light dates to a time about 300,000 years after the Big Bang which started the initial expansion
- The CMB light comes from all the photons left over when atoms (mostly Hydrogen) first formed

Cosmic Microwave Background

- Discovered in 1965 by Arno Penzias and Robert Wilson who were working at Bell Labs
- Clinched the hot big bang theory

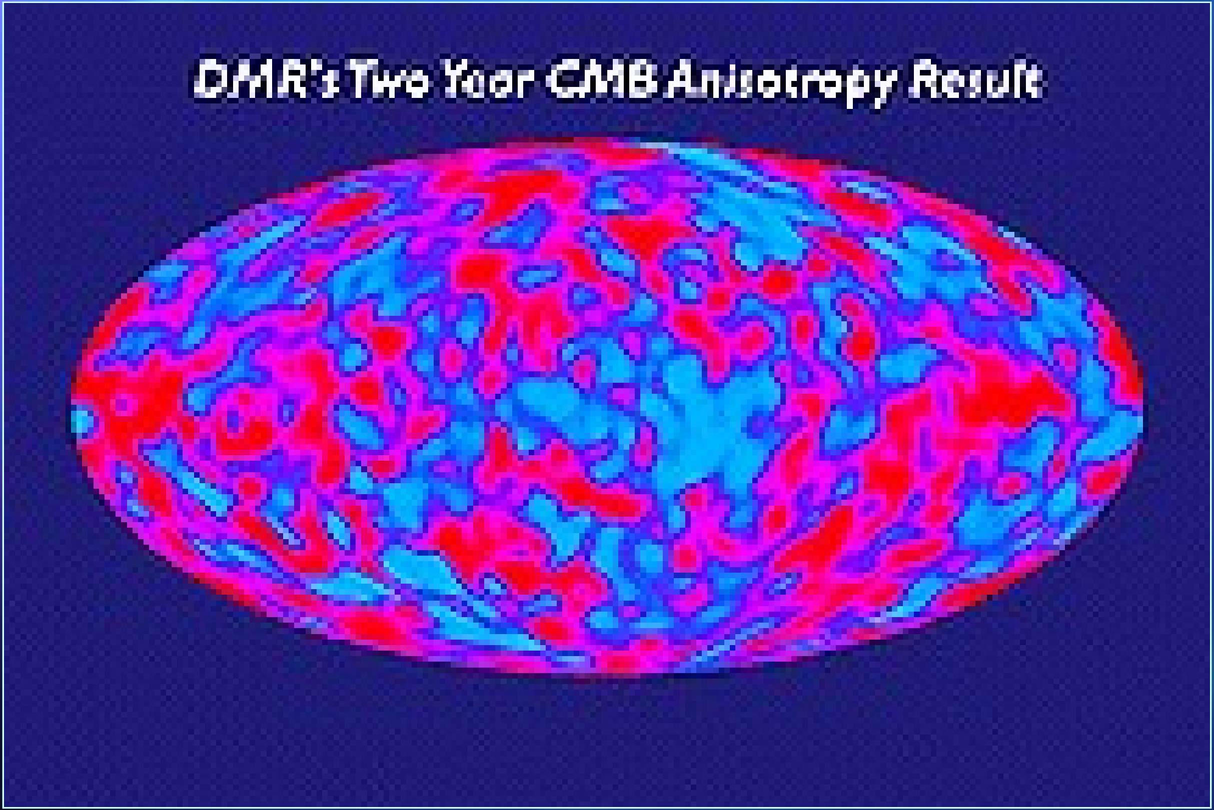
Excess noise in horned antennae was not due to pigeon dung!

Cosmic Background Explorer
(1989-1993)

- Differential Microwave Radiometer
- PI George Smoot
- Discovered fluctuations in the CMB
- These fluctuations are the seeds of the structure we now see

COBE data/DMR

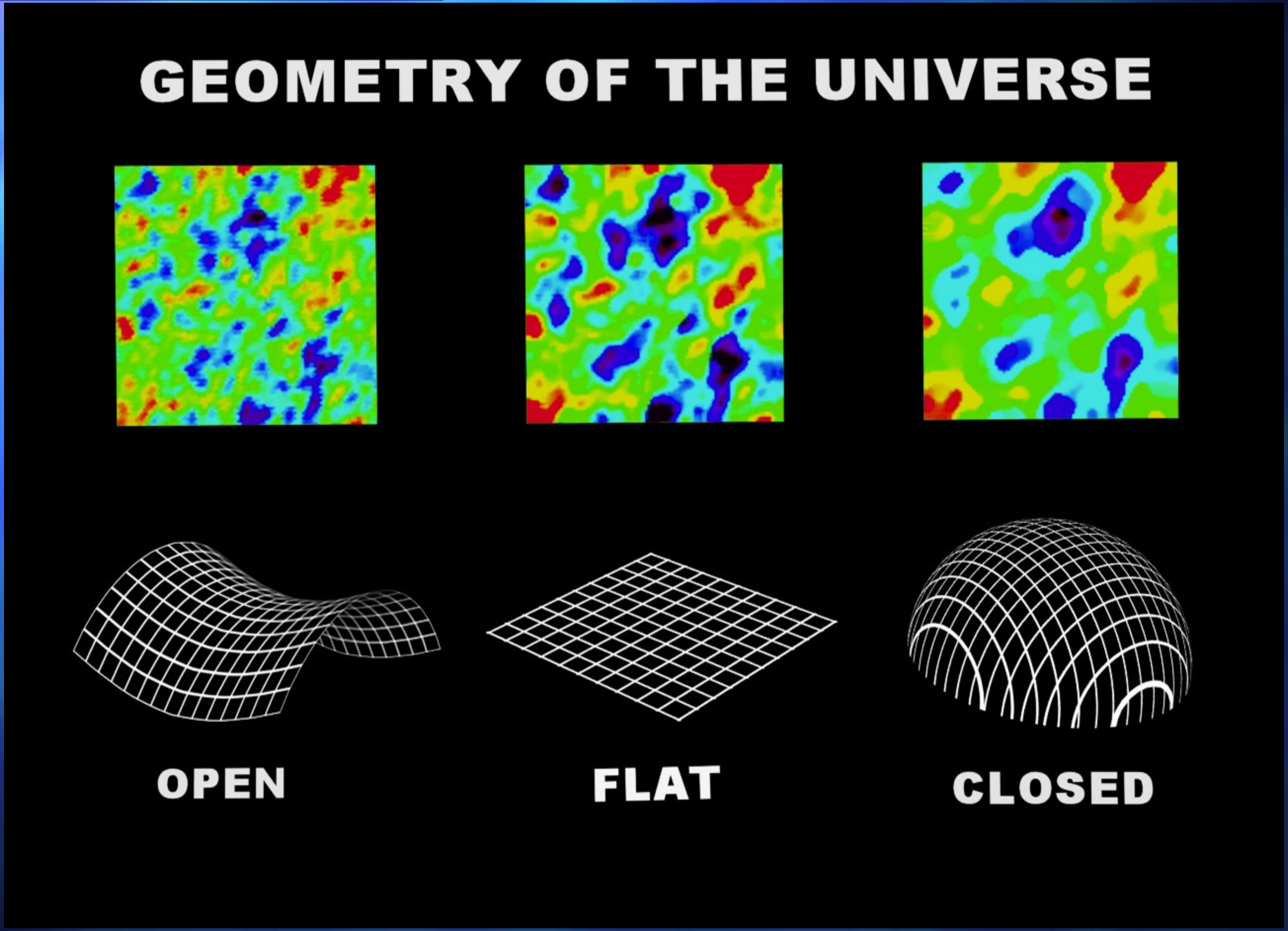
- These fluctuations have been called the "wrinkles on the face of God"



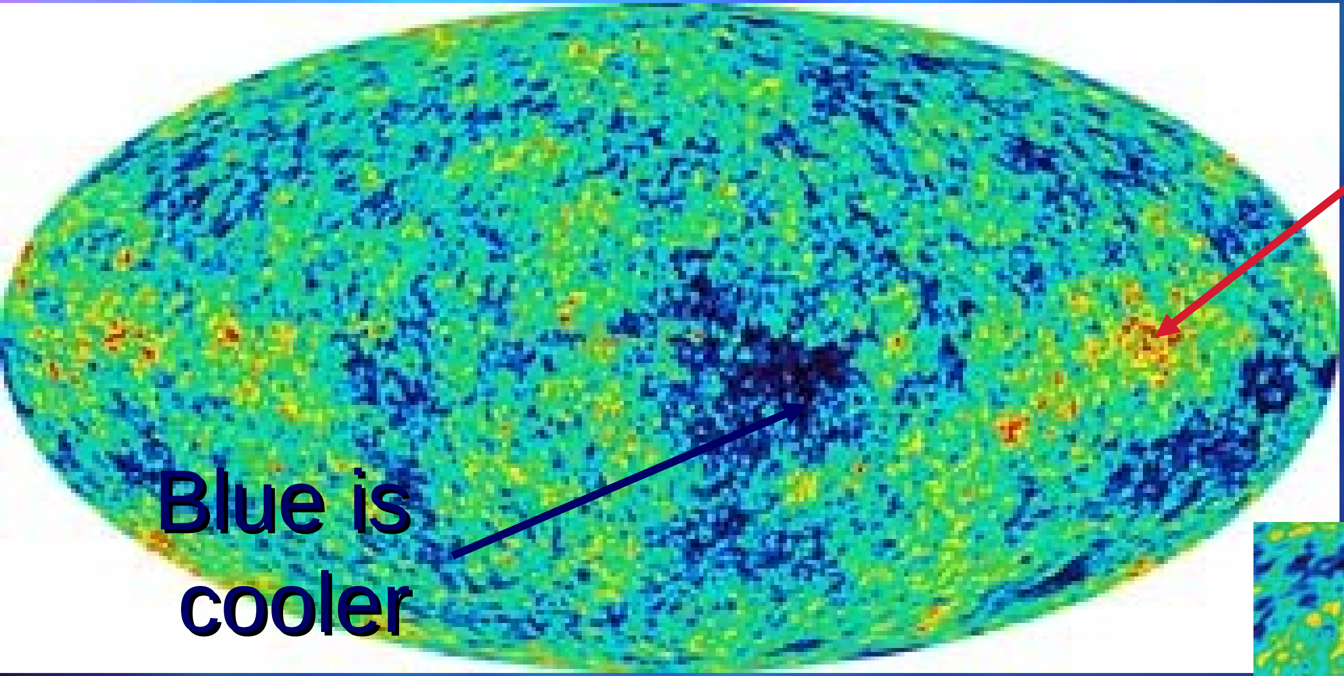
2006 Nobel prize in physics awarded to George Smoot!

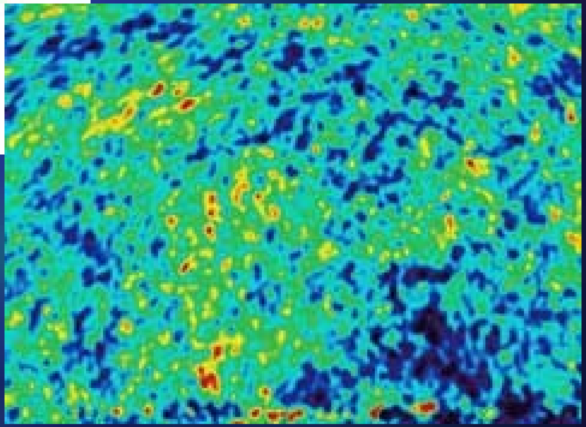
(Also John Mather for measuring temperature of CMBR precisely at 2.7 K with FIRAS on COBE.)

Fluctuations and geometry



Flat



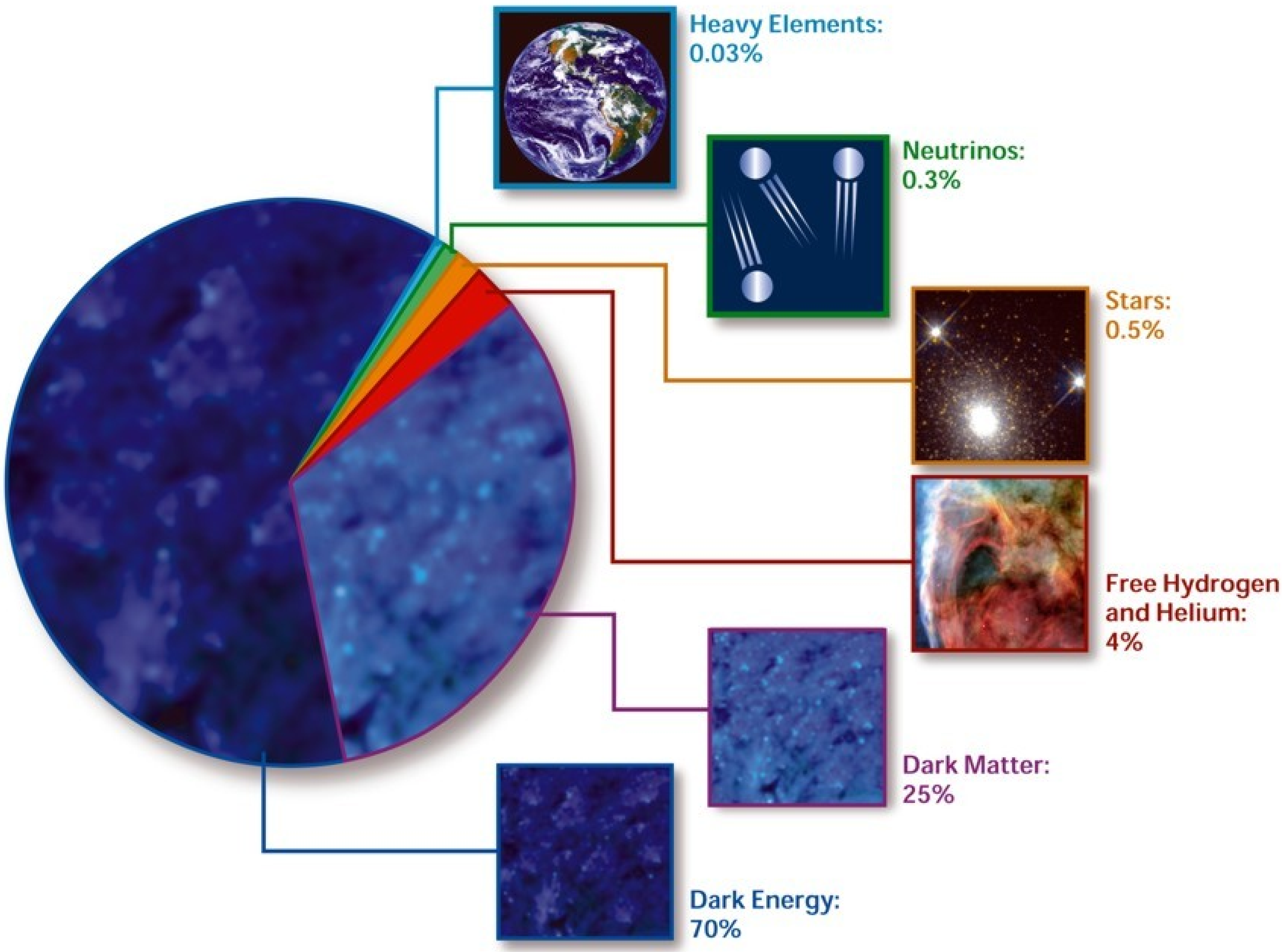


Credit: NASA/WMAP

Universe is 13.7 billion years old

- *Final answer:* Detailed calculations using data from WMAP have more accurately determined the age of the Universe, including the effects of inflation (ask me later)
- These calculations (in combination with other data) also lead to the "Cosmic Composition" pie chart which illustrates the types of matter and energy in the Universe

COMPOSITION OF THE COSMOS



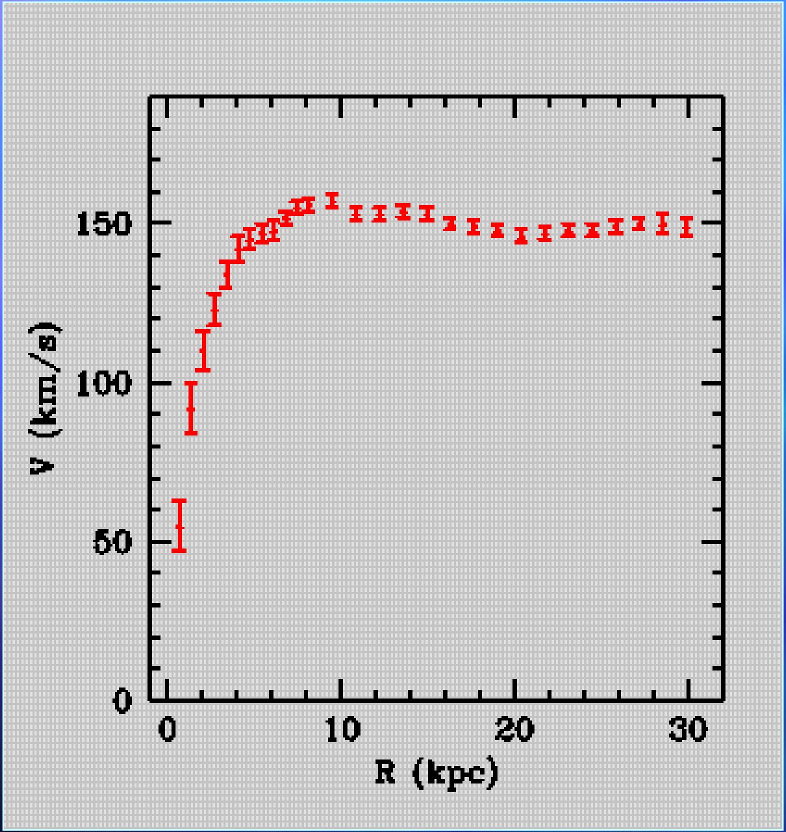
Most of the stuff in the Universe is in the form of things we cannot see and we don’t understand

- Dark Matter – you can feel it but you can’t see it
- Dark Energy – the mysterious force which is causing the expansion of the Universe to accelerate

Dark Matter

- In 1930, Fritz Zwicky discovered that the galaxies in the Coma cluster were moving too fast to remain bound in the cluster
- Something else that cannot be seen must be holding the galaxies in the cluster!

Galaxy Rotation Curves



NGC 3198

- In 1970, Vera Rubin discovered that the gas and stars in the outer parts of galaxies were moving too fast
- This implies that most of the mass in the galaxy is outside the region where we see the stars
- Since we do not see light from this matter, it is called
Dark Matter

Hubble Expansion revisited

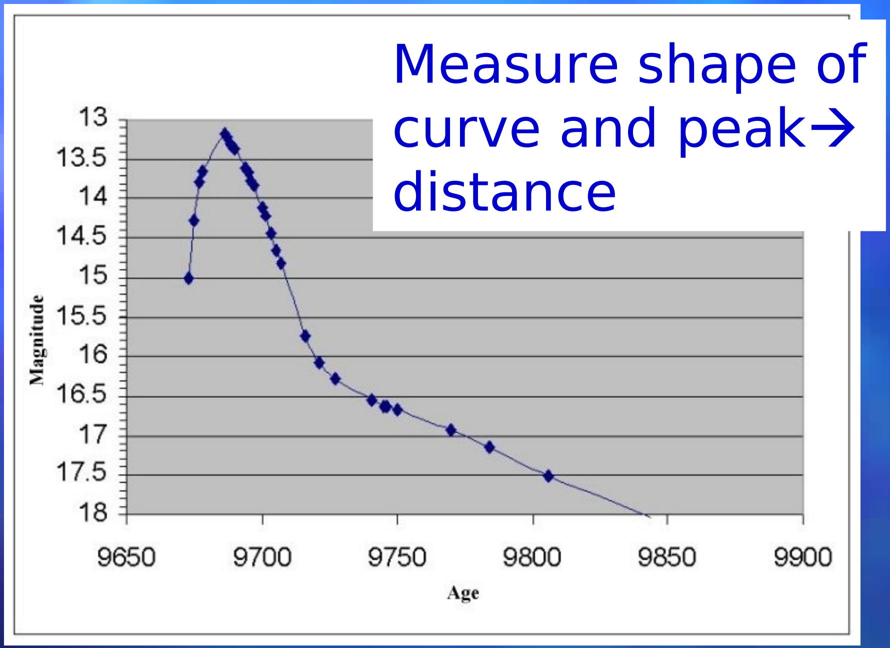
- We have already seen how the galaxies move away faster at further distances
- We measured the slope of the velocity of the galaxies vs. their distances → Hubble constant, which tells us the expansion rate at the present time
- But what will the future expansion rate be?

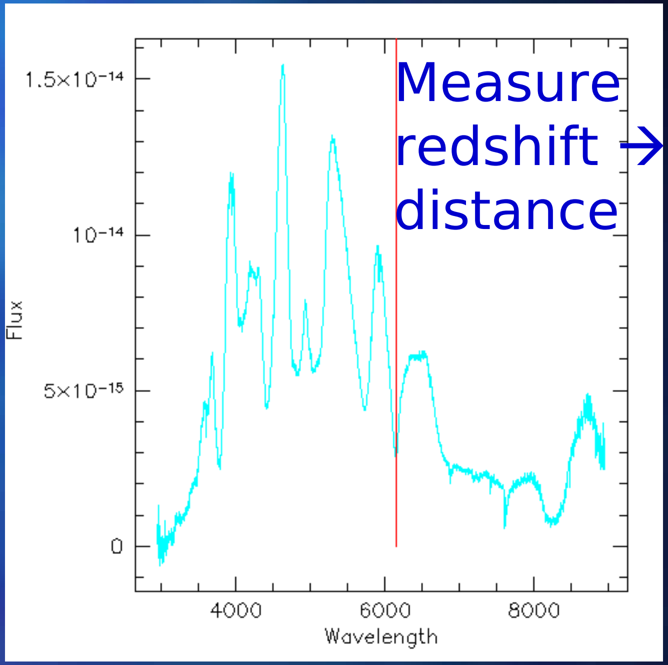
Distances to Supernovae

- Type Ia supernovae are “standard candles” just like Hubble’s Cepheid variables
- Some Type Ia supernovae are in galaxies with Cepheid variables but most are much farther away
- Decay time of light curve is correlated to absolute luminosity
- Good to 20% as a distance measure

Supernovae as Standard Candles

- Here is a typical supernova lightcurve and its spectrum





- Compare two distances to see if expansion rate has changed

Supernovae and Cosmology

- Analyze lightcurves vs. redshifts for many Type 1a supernovae at redshifts z <2
- Observations of over 100 SN (over 7 years) by Perlmutter et al. and Schmidt et al. have showed that they are dimmer than would be expected if the Universe was expanding at a constant rate or slowing down (as was previously thought)
- This is evidence that some unknown “dark energy” is causing the Universe to fly apart at ever-increasing speeds

Today's Cosmology

- We live in a flat Universe (WMAP)
- Universe is expanding at a rate of 70 km/sec/Mpc (HST and others)
- Age of Universe is around 13.7 billion years (WMAP and others)
- Dark matter makes up about 25% of the Universe (many sources)
- Dark energy makes up about 70% → causes the expansion to accelerate (Type 1a SNe + WMAP)

Web Resources

- Bell Labs Cosmology Archives

http://www.bell-labs.com/project/feature/archives/cosmology/

- Big Bang Cosmology Primer

http://cosmology.berkeley.edu/Education/IUP/Big_Bang_Primer.html

- Martin White's Cosmology Pages

http://astron.berkeley.edu/~mwhite/darkmatter/bbn.html

- Cosmic Background Explorer

http://space.gsfc.nasa.gov/astro/cobe/cobe_home.html

- Hyperspace by Michio Kaku (Anchor Books)

Web Resources

- Ned Wright's CMBR pages
http://www.astro.ucla.edu/~wright/CMB-DT.html
- Ned Wright's Cosmology Tutorial
http://www.astro.ucla.edu/~wright/cosmolog.htm
- WMAP mission http://wmap.gsfc.nasa.gov
- Universe Adventure
http://www.universeadventure.org

Backups Follow

Hot gas in Galaxy Clusters

- Measure the mass of stars in galaxies in the cluster
- Measure mass of hot gas → 3-5 times greater than the mass in stars
- Calculate the mass the cluster needs to hold in the hot gas - it is 5 - 10 times more than the mass of the gas plus the mass of the stars!

Dark Matter Halo

- The rotating disks of the spiral galaxies that we see are not stable
- Dark matter halos provide enough gravitational force to hold the galaxies together
- The halos also maintain the rapid velocities of the outermost stars in the galaxies

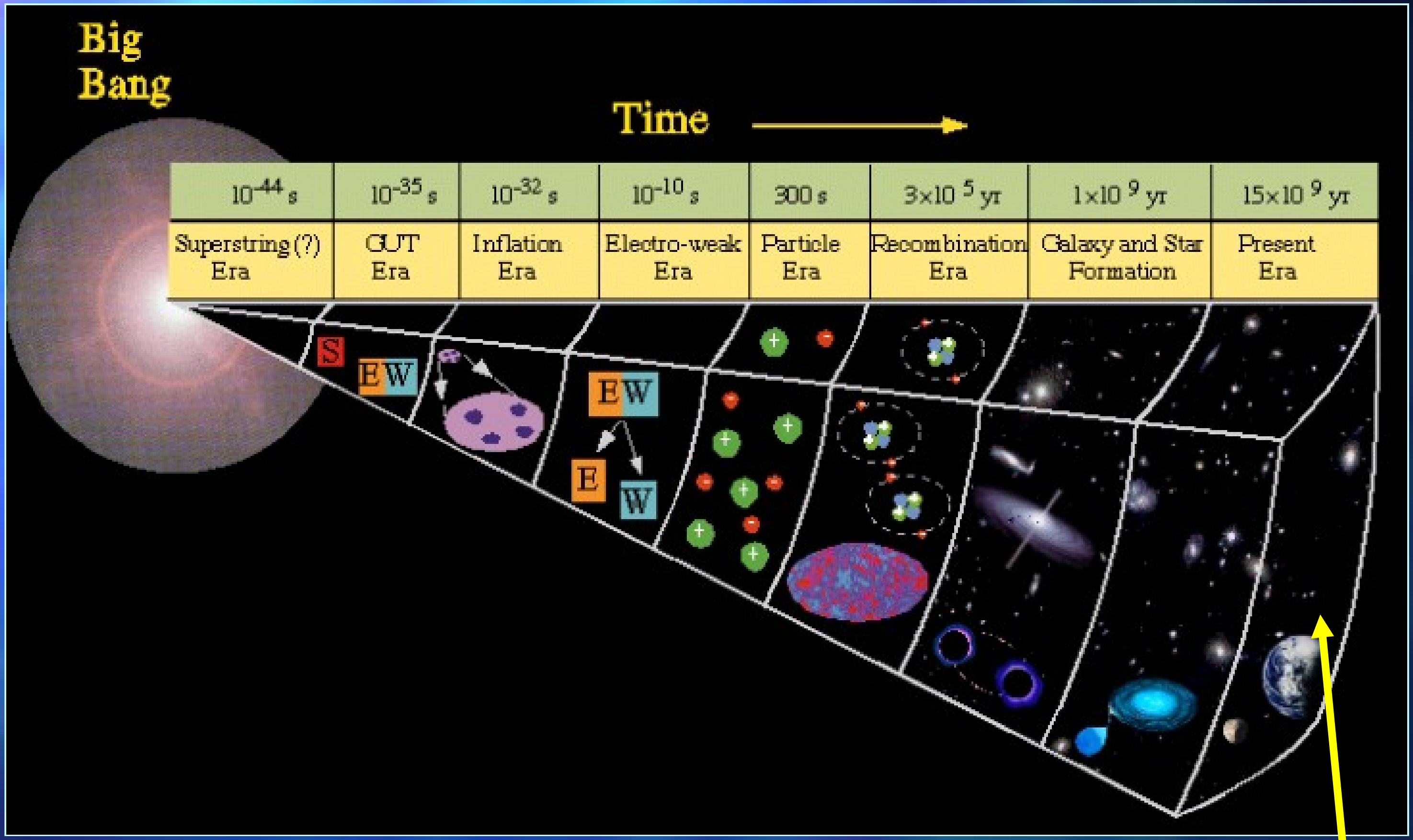
Golden Age of Cosmology

- How did the Universe begin?
  - Standard Big Bang theory
  - Hubble Expansion
  - Inflation
- What is the fate of the Universe?
  - Observations of CMBR
  - Dark Matter
  - Distances to Supernovae
- Today's Cosmology
  - Einstein and the Cosmological Constant
  - Dark Energy and the Accelerating Universe

Standard Big Bang Cosmology

- Sometime in the distant past there was nothing – space and time did not exist
- Vacuum fluctuations created a singularity that was very hot and dense
- The Universe expanded from this singularity
- As it expanded, it cooled
  - Photons became quarks
  - Quarks became neutrons and protons
  - Neutrons and protons made atoms
  - Atoms clumped together to make stars and galaxies

Big Bang Timeline



We are here

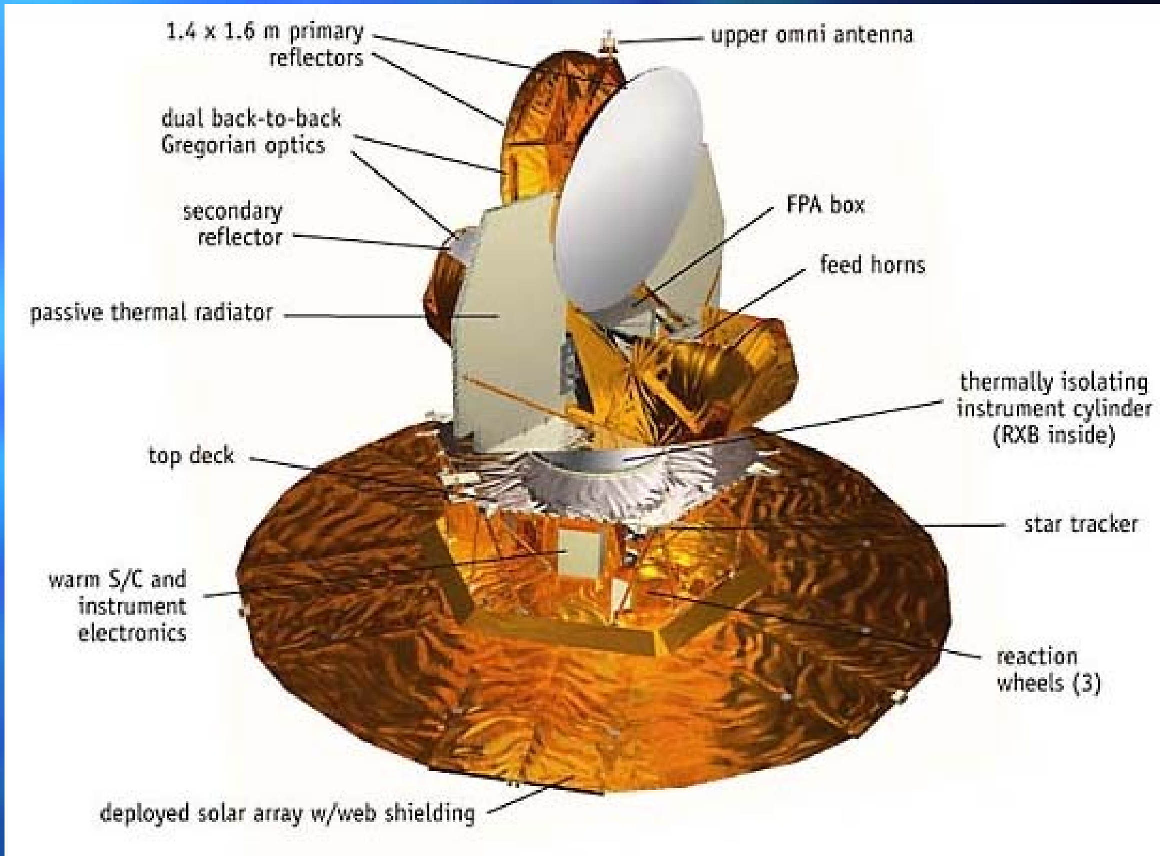
Standard Big Bang Cosmology

- Top three reasons to believe big bang cosmology
  1. Big Bang Nucleosynthesis
  2. Hubble Expansion
  3. Cosmic Microwave Background (CMB)

Wilkinson Microwave Anisotropy Probe (2001-present)

- PI Charles Bennett (JHU)
- Improves on COBE's angular resolution → sharper pictures of CMBR fluctuations
- Measures past

l = 200



CMB vs. Inflation

- The fluctuations measured by WMAP indicate that the Universe is flat (Typical size is about 1 degree.)
- Finding fluctuations of this size also supports a non-uniform expansion history for the early Universe called “inflation”
- Inflation also explains some other problems with the simple Big Bang (uniform expansion) model (Ask me later)

What is inflation?

- Inflation refers to a class of cosmological models in which the Universe exponentially increased in size by about 10^{43} between about 10^{-35} and 10^{-32} s after the Big Bang (It has since expanded by another 10^{26})
- Inflation was originated by Alan Guth in 1979 (and has been modified since)
- Inflation is an example of non-uniform expansion

Big Bang Nucleosynthesis

- Light elements (namely deuterium, helium, and lithium) were produced in the first few minutes of the Big Bang
- Elements heavier than ^{4}He are produced in the stars and through supernovae
- However, enough helium and deuterium cannot be produced in stars to match what is observed because stars destroy deuterium in their cores
- So all the deuterium we see must have been made around three minutes after the big bang, when $T \sim 10^9$ K
- BBN predicts that 25% of the matter in the Universe should be helium, and about 0.001% should be deterium, which is what we see

Why believe in inflation?

- Inflation is a prediction of grand unified theories in particle physics that was applied to cosmology – it was not just invented to solve problems in cosmology
- It provides the solution to two long standing problems with standard Big Bang theory
  - Horizon problem
  - Flatness problem

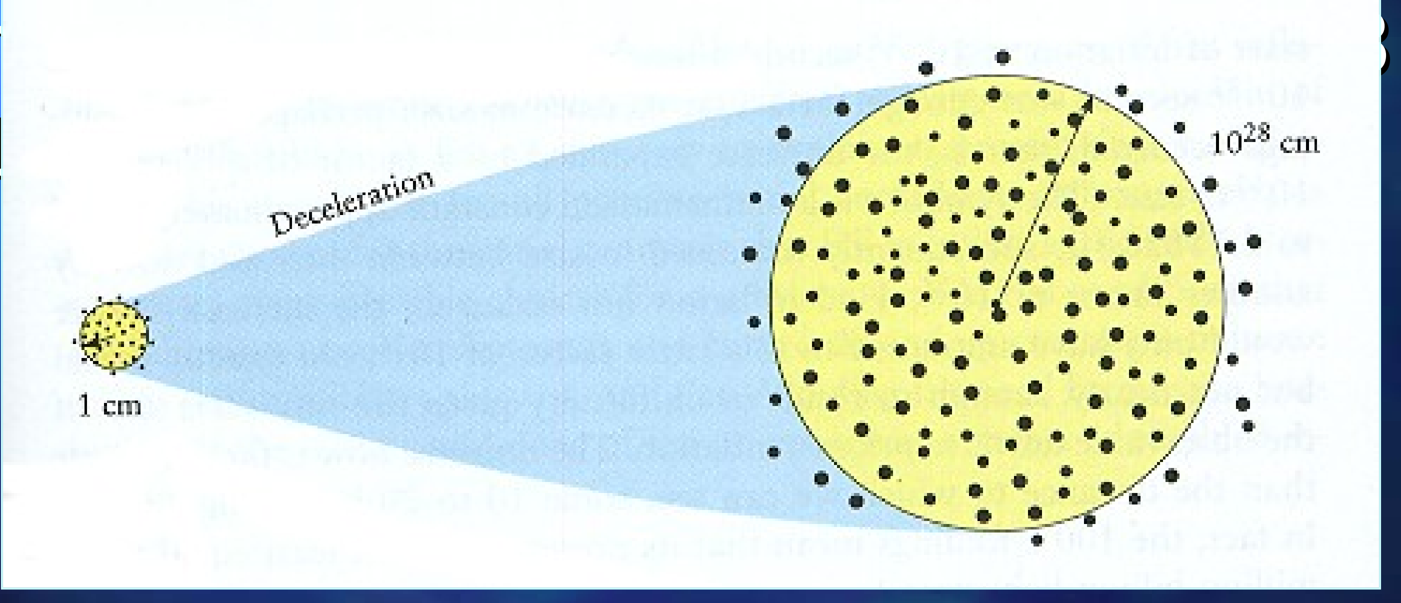
Alan Guth

Horizon Problem

- The Universe looks the same everywhere in the sky that we look, yet there has not been enough time since the Big Bang for light to travel between two points on opposite horizons
- This remains true even if we extrapolate the traditional big bang expansion back to the very beginning
- So, how did the opposite horizons turn out the same (e.g., the CMBR temperature)?

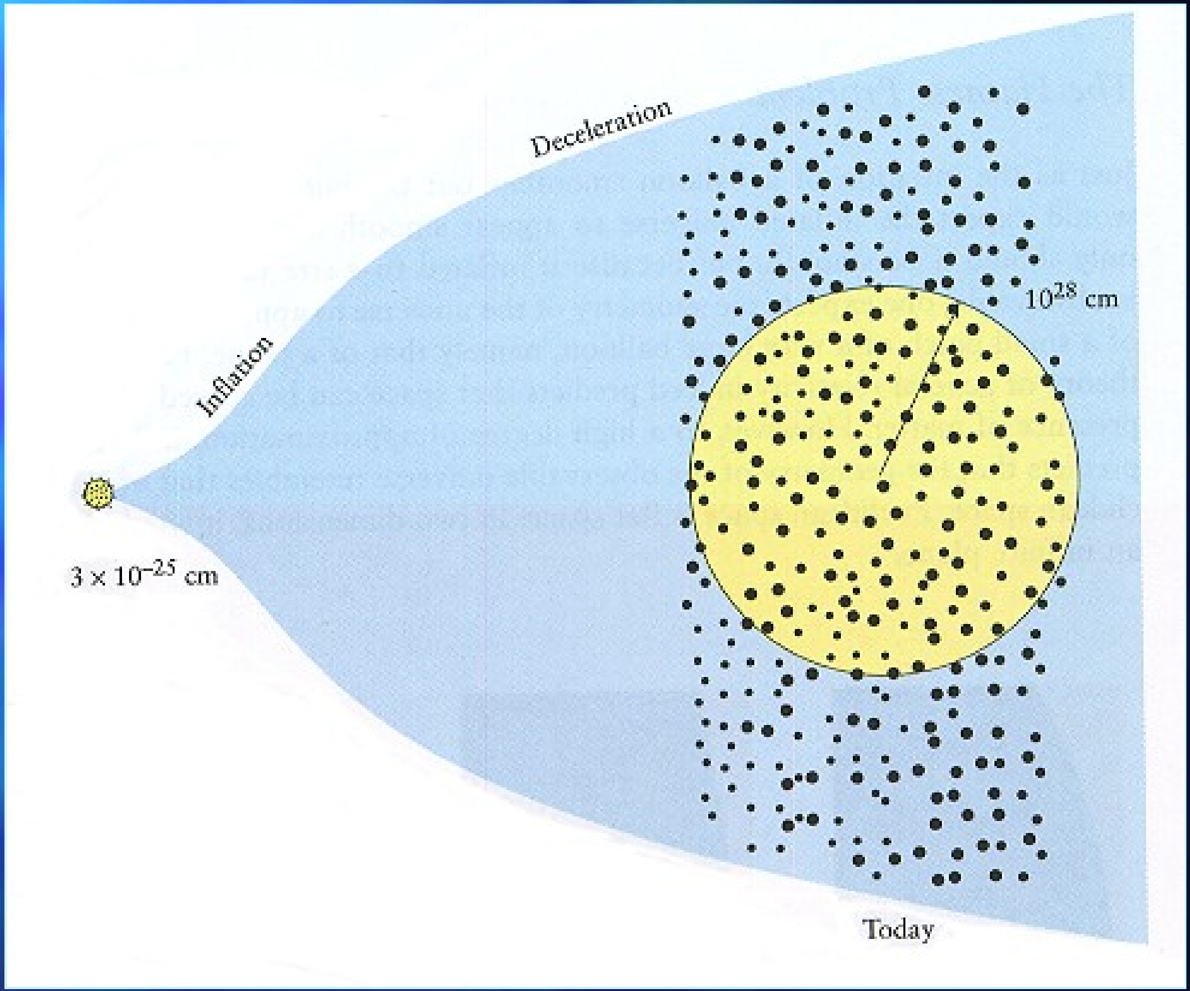
No inflation

- At $t=10^{-35}$ s, the Universe expands from about 1 cm to what we see today
- 1 cm is much larger than the h … 8 x 1 …



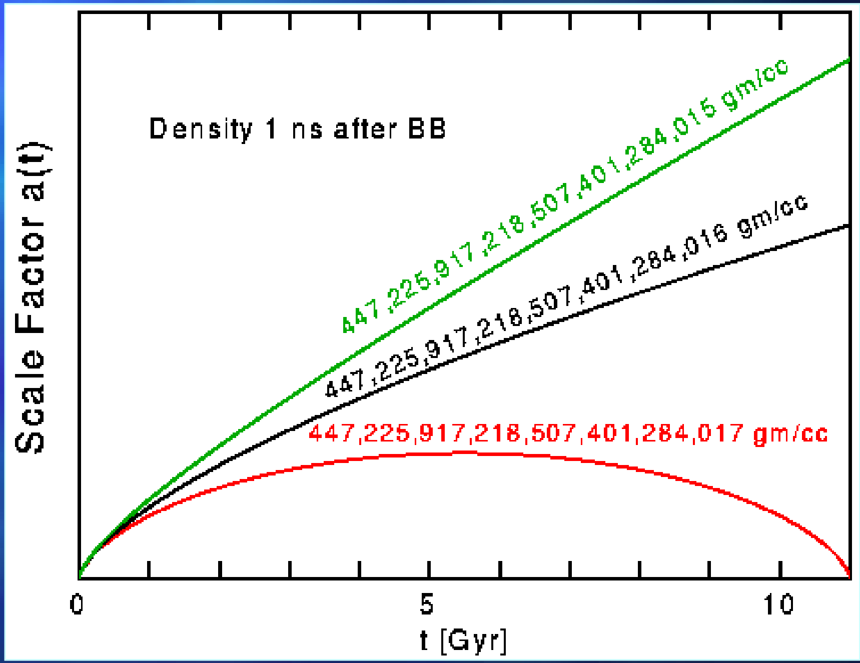
With inflation

- Space expands from 3 x 10^{-25} cm to much bigger than the Universe we see today



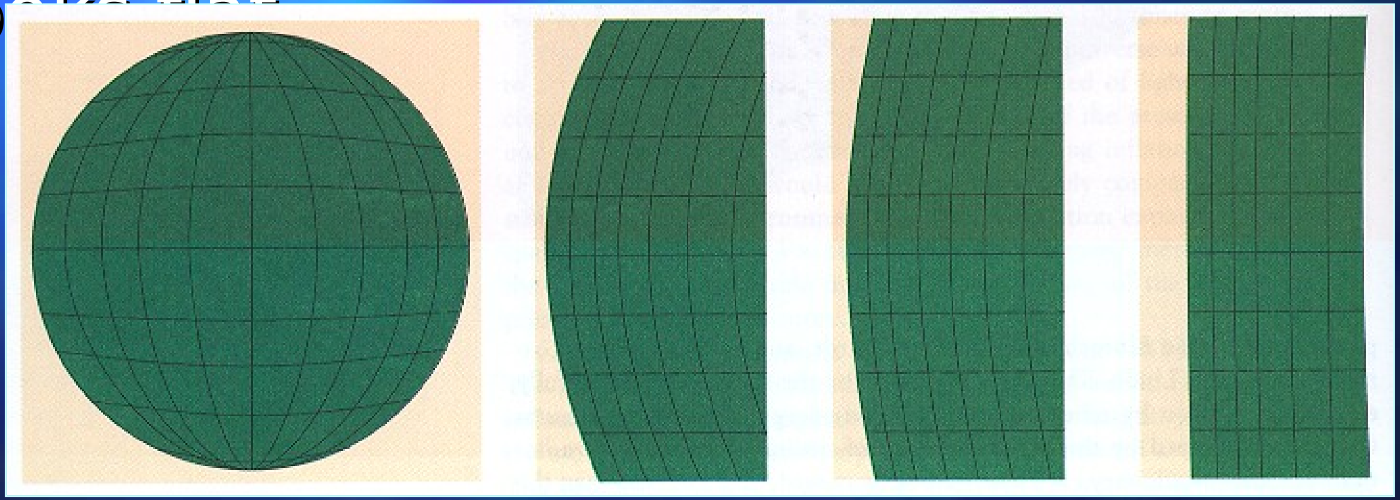
Flatness Problem

- Why does the Universe today appear to be near the critical dividing line between an open and closed Universe?
- Density of early Universe must be correct to 1 part in 10^{60} in order to achieve the balance that we see



Flatness Problem

- Inflation flattens out spacetime the same way that blowing up a balloon flattens the surface
- Since the Universe is far bigger than we can see, the part of it that we can see looks flat



Old view: Density of the Universe determines its destiny

$\Omega_{(total)} = \Omega_M$

where

Ω_M = matter density (including regular and dark matter)

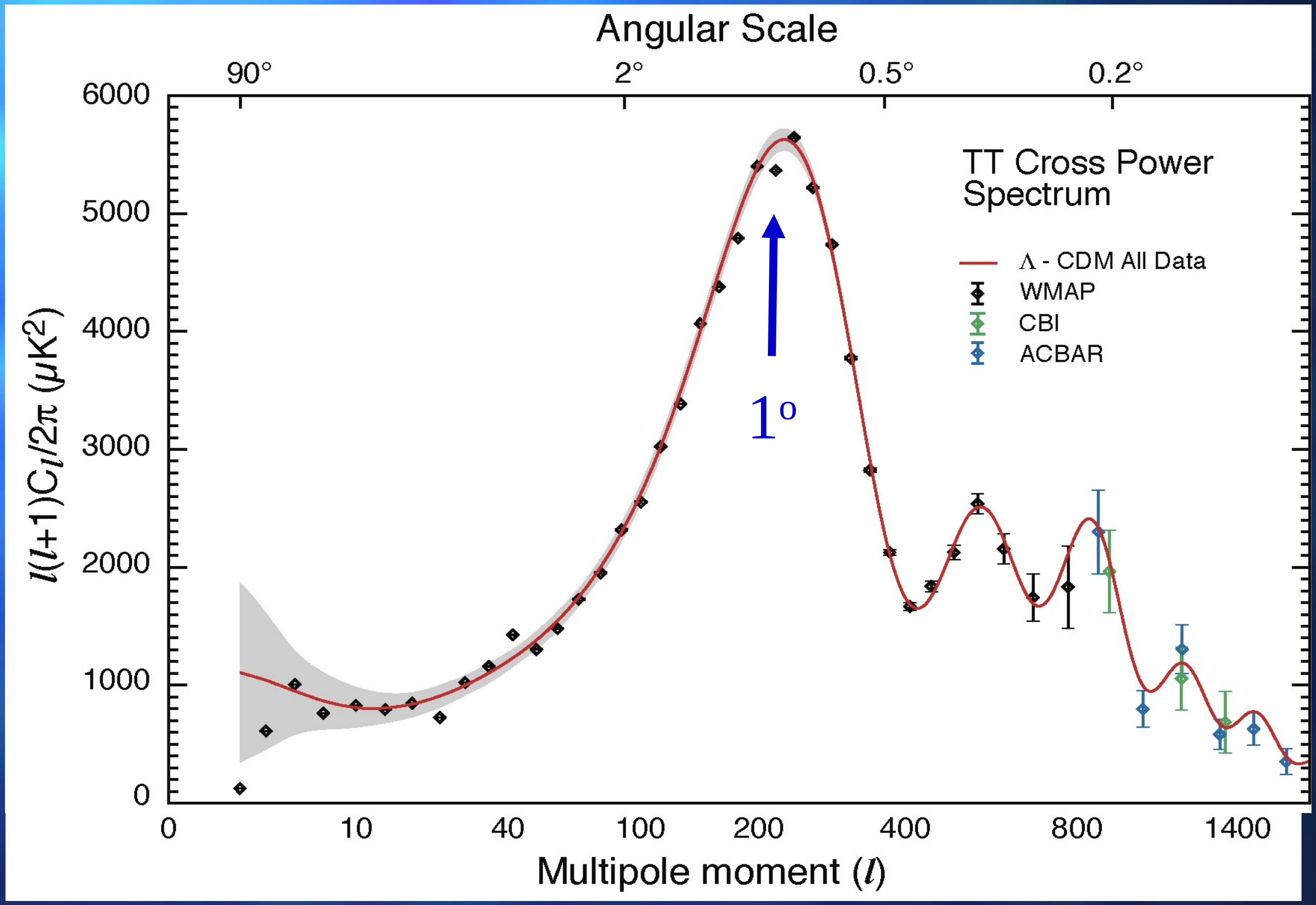
Ω_{tot} = density/critical density

If Ω_{tot} = 1,Universe is flat, expansion coasts to a halt as Universe is critically balanced.

If Ω_{tot} > 1, Universe is closed, collapses on itself.

If Ω_{tot} < 1, Universe is open, expands forever.

WMAP angular power spectrum



Cosmological Parameters revisited

- The strong first peak at l =200 confirms inflationary expansion – clumps are right size for flat Universe
- Recall that inflation also explains the apparent flatness of the Universe
- Flatness means that $\Omega_{TOT} = 1.0$
- So, in the old view, we live in a critically balanced Universe → asymptotic expansion
- However, to quote Rocky Kolb:

"Geometry is not destiny"

Einstein and the Cosmological Constant

- When Einstein first formulated his equations of General Relativity, he believed in a static Universe (or steady state Universe)
- Since the equations seemed to predict an unstable universe that would either expand or contract, he "fixed" his equations by inserting a "Cosmological Constant" called Λ
- When Hubble later found that the Universe was expanding, Einstein called the creation of the Cosmological Constant his "greatest blunder"

Einstein and Dark Energy

- However, now we see that there is indeed a cosmological constant term – but it acts in the opposite sense to Einstein's original idea
- The Dark Energy implied by the non-zero value of Λ pushes the Universe apart even faster, rather than adding stability to an unstable Universe, as Einstein originally intended.
- The dark energy density/critical density = Ω_Λ
- There are many theories for Dark Energy: vacuum fluctuations, extra dimensions, etc.

New View: Density of the Universe

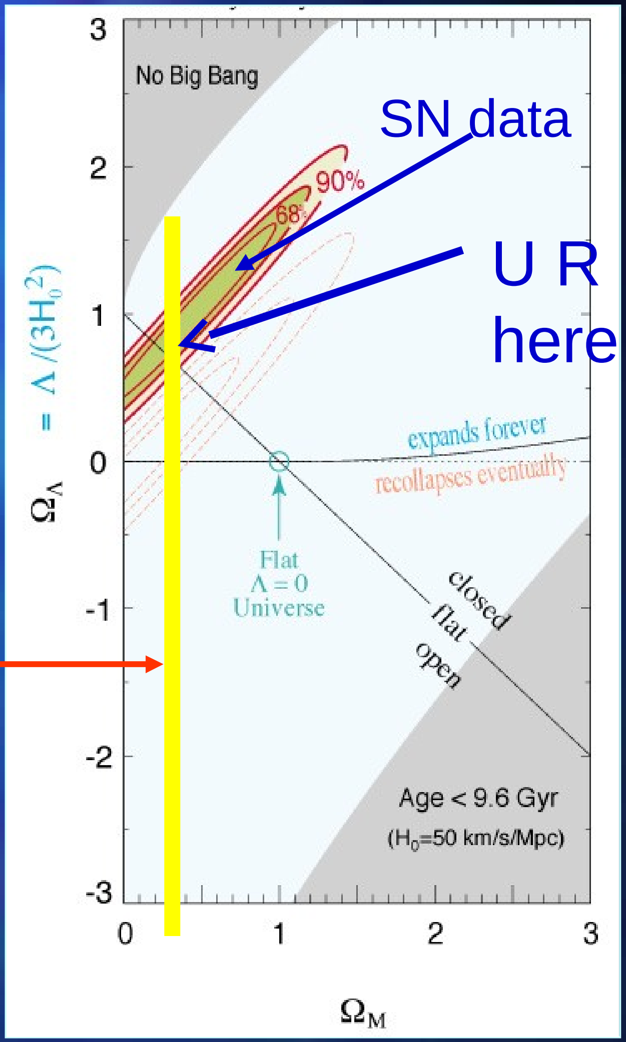
$\Omega_{(total)} = \Omega_M + \Omega_\Lambda$

where

Ω_M = matter density (including regular and dark matter)

Ω_Λ = cosmological constant or dark energy density

Ω_{tot} = density/critical density

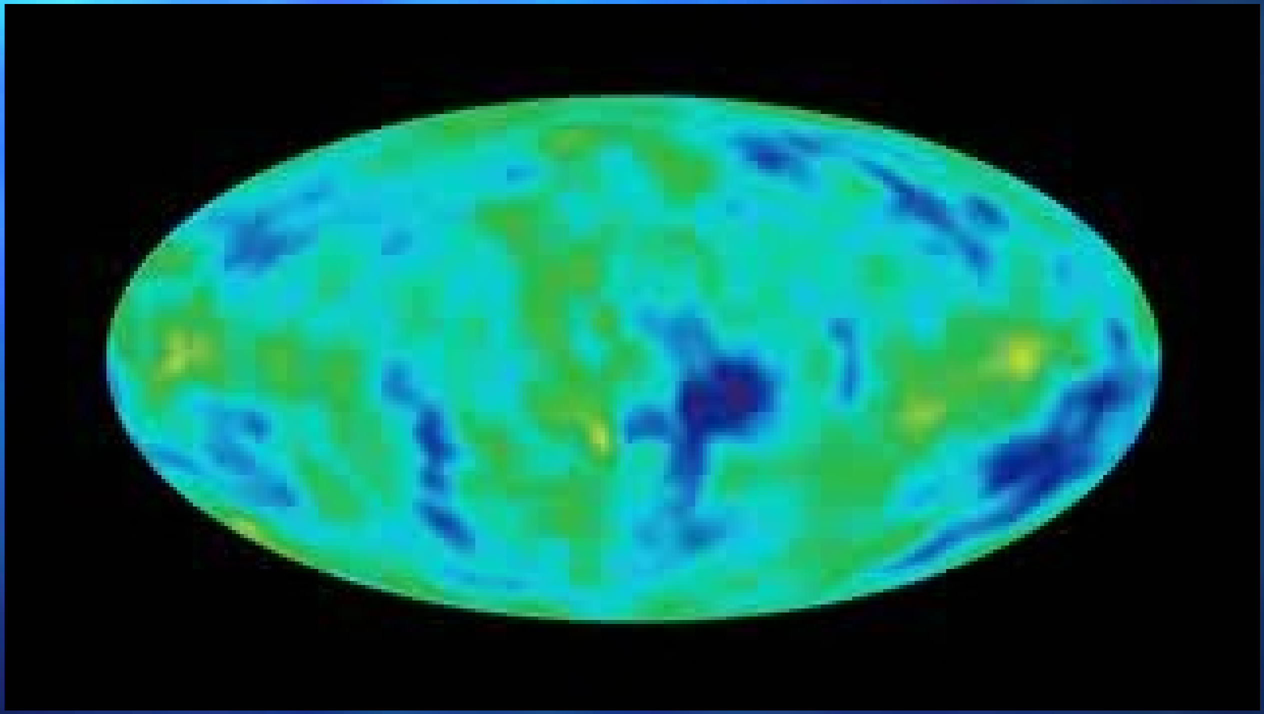


Perlmutter et al.

40 supernovae

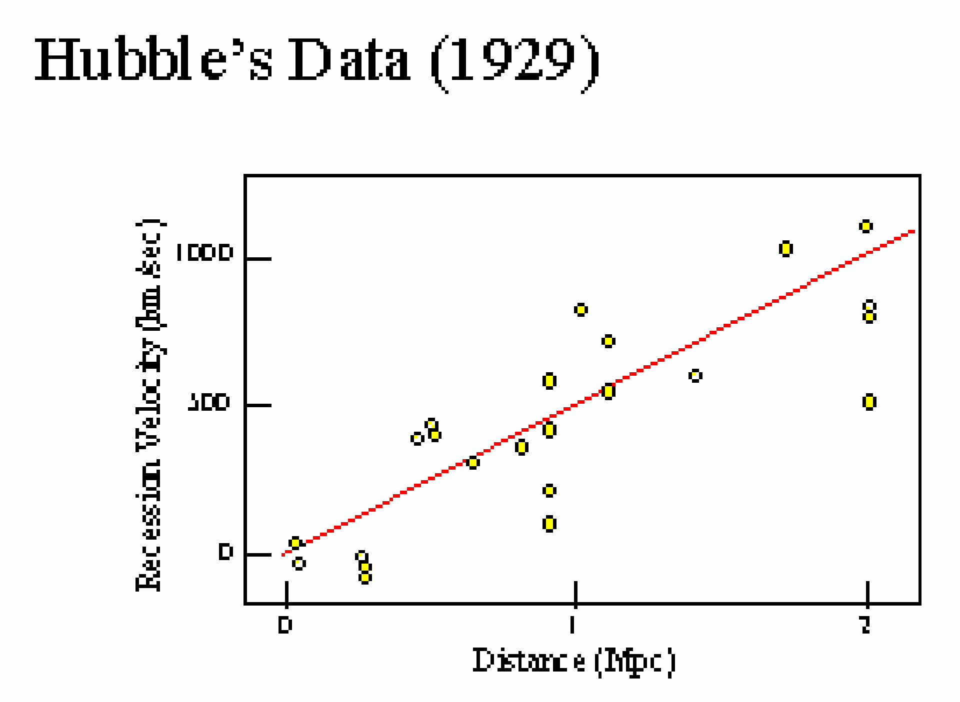
Compare to COBE

- The WMAP image brings the COBE picture into sharp focus.



movie

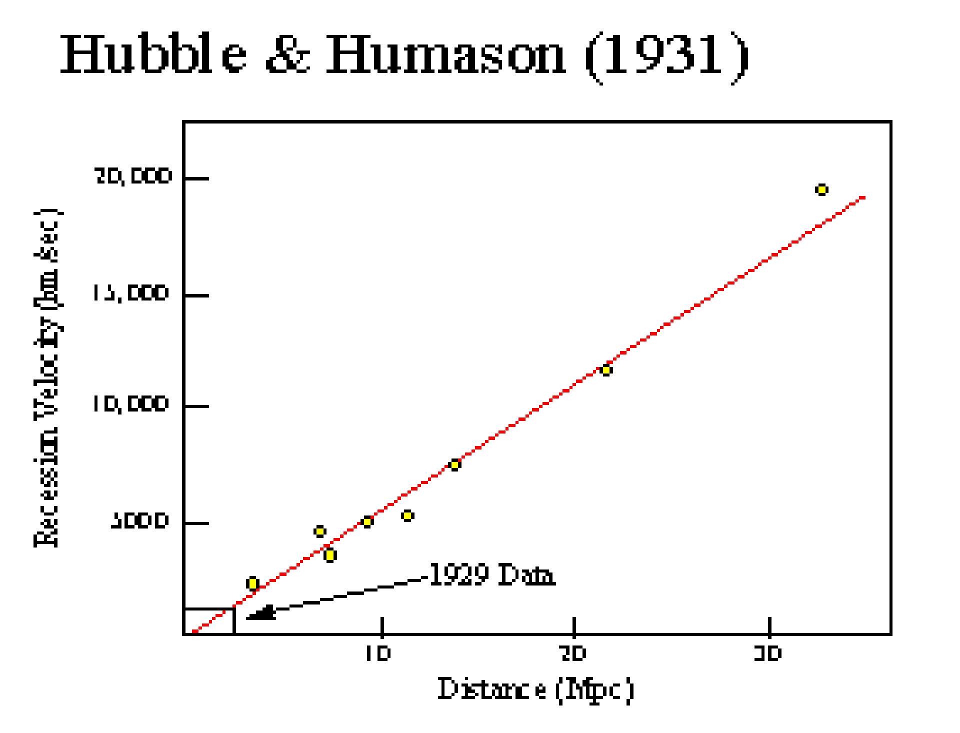
Hubble Expansion



The Hubble constant

H_o = 558 km s $^{-1}$ Mpc $^{-1}$

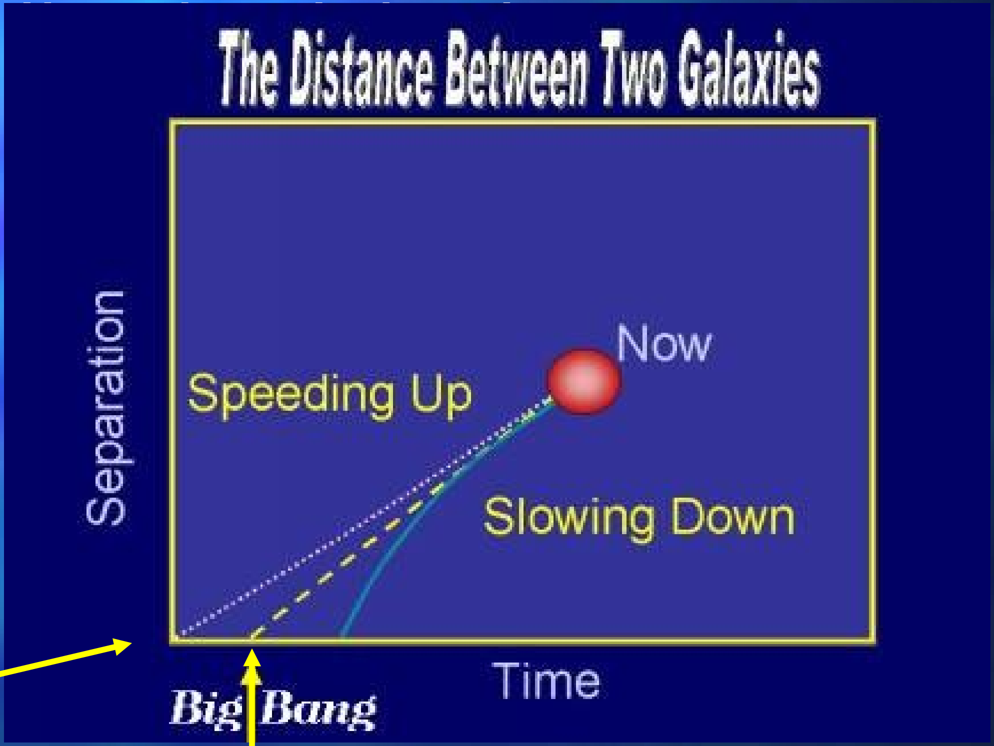
is the slope of these graphs



Compared to modern measurements, Hubble's results were off by a factor of ten!

Measuring the Hubble Expansion

- If the expansion rate is constant, distance between 2 galaxies follows yellow dotted



- If rate is speeding up, then the Universe is older than we think

Real Big Bang

Derived from constant rate