After the Big Bang

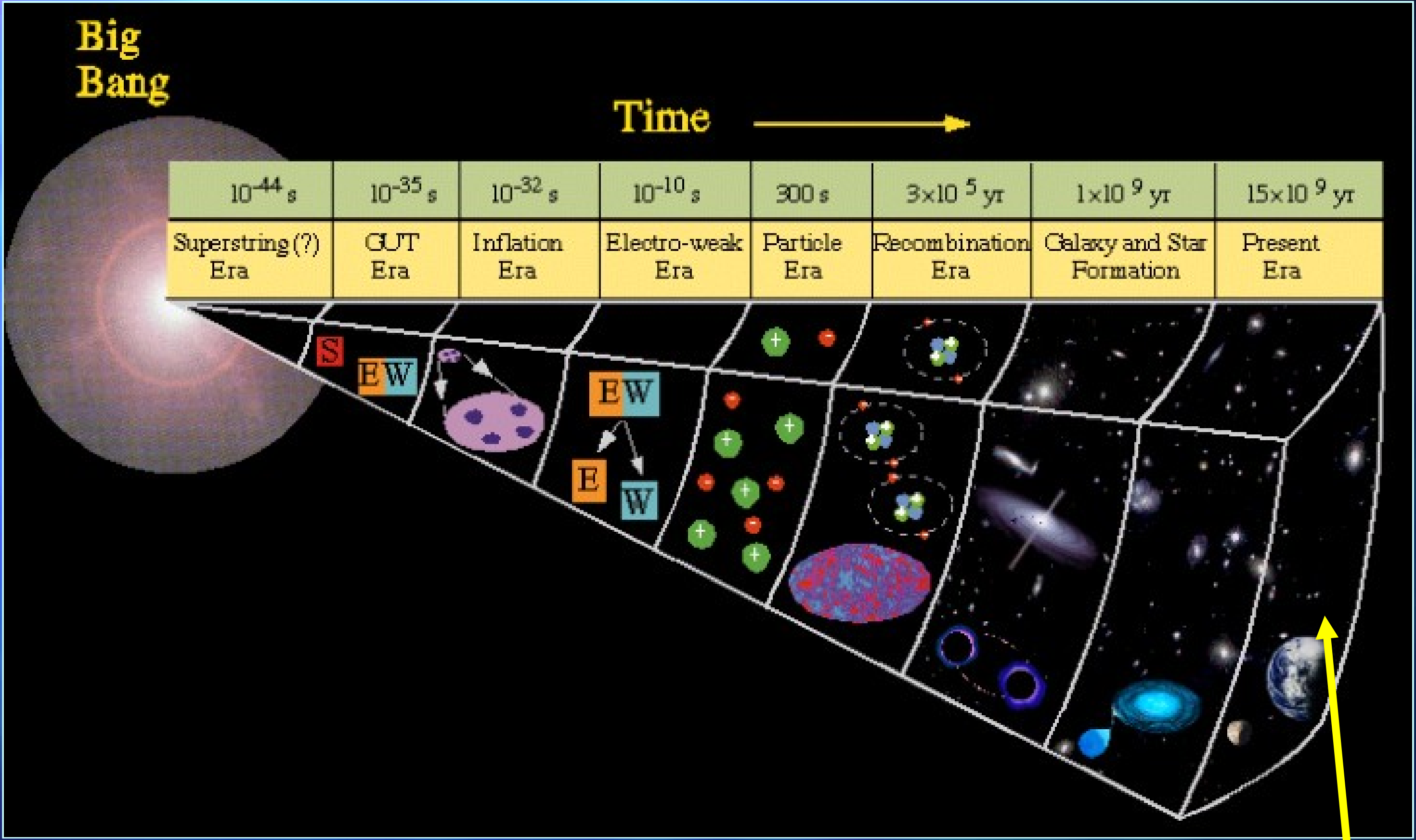
Prof. Lynn Cominsky, Dr. Phil Plait and Sarah Silva

NASA E/PO at SSU

Golden Age of Cosmology

- How did the Universe begin?
  - Standard Big Bang theory
  - Inflation
  - Hubble Expansion
- 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

Big Bang Timeline



We are here

Big Bang?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THE HUBBLE TELESCOPE FINALLY SEES THE BEGINNING OF THE 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

Standard Big Bang Cosmology

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

Big Bang by Physics Chanteuse Lynda Williams (SRJC)

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

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 is a modification of standard Big Bang cosmology
- It was originated by Alan Guth in 1979 and since modified by Andreas Albrecht, Paul Steinhardt and Andre Linde (among others)

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

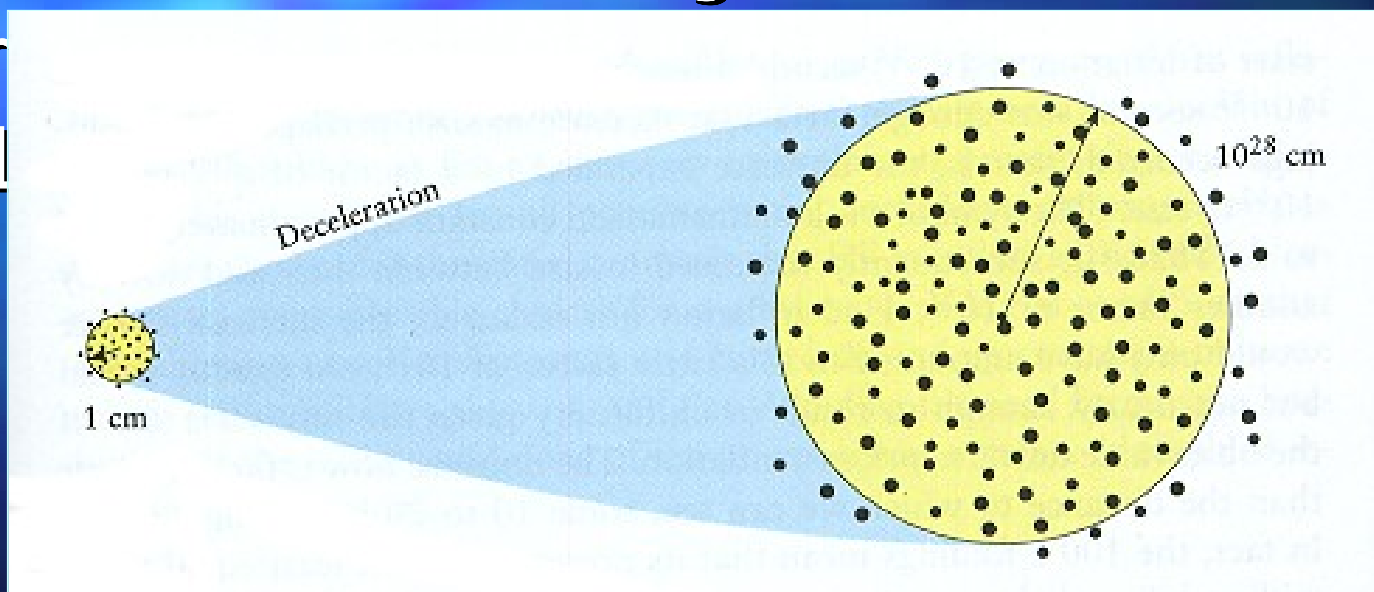
Alan Guth

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)?

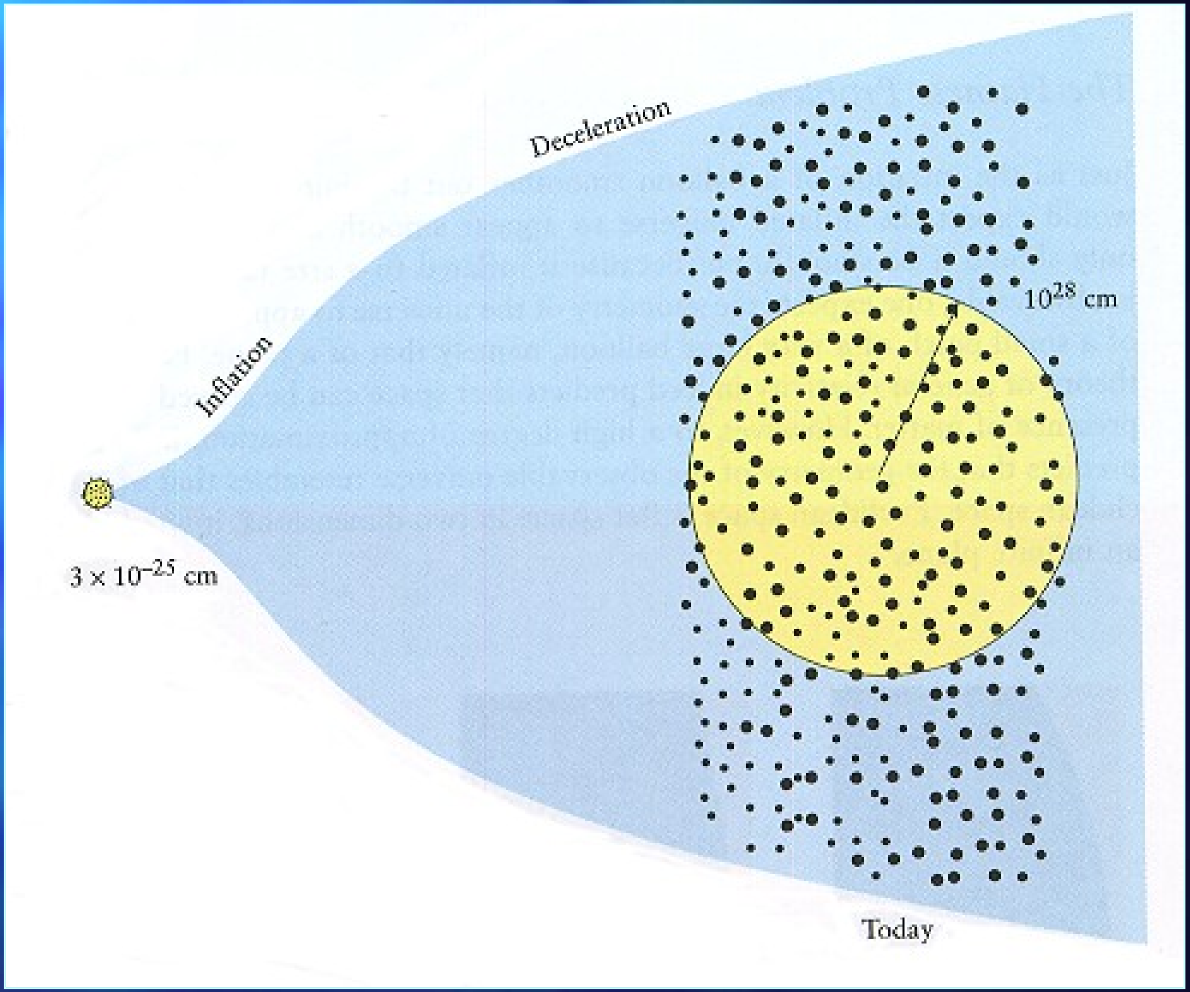
No inflation

- 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 … 3 x 1



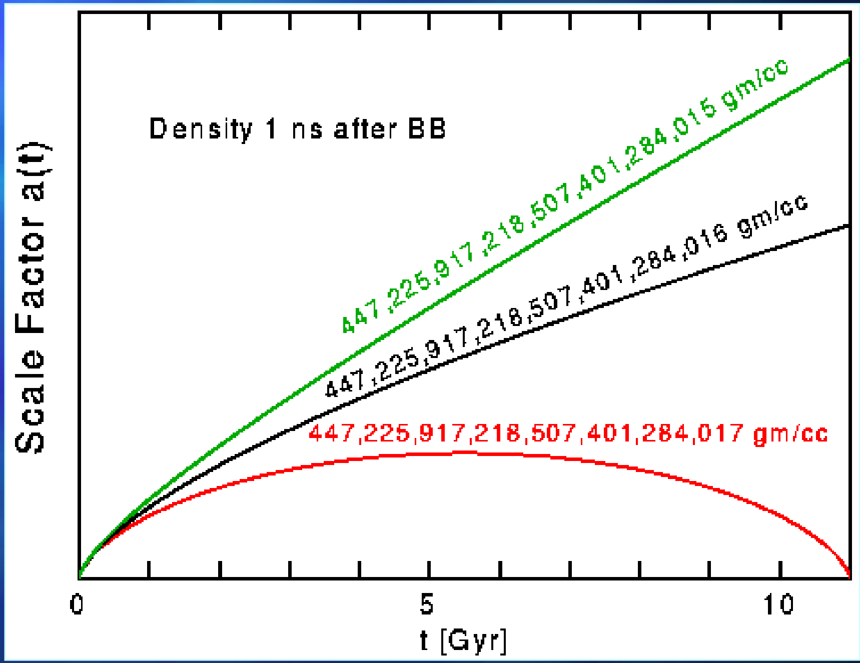
With inflation

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



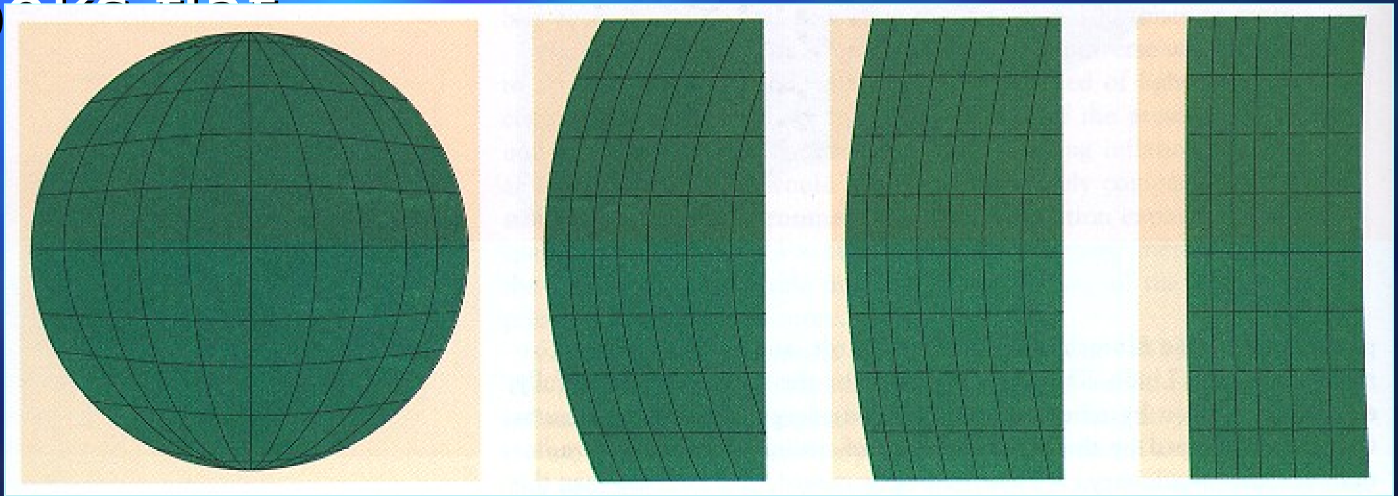
Flatness Problem

- 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



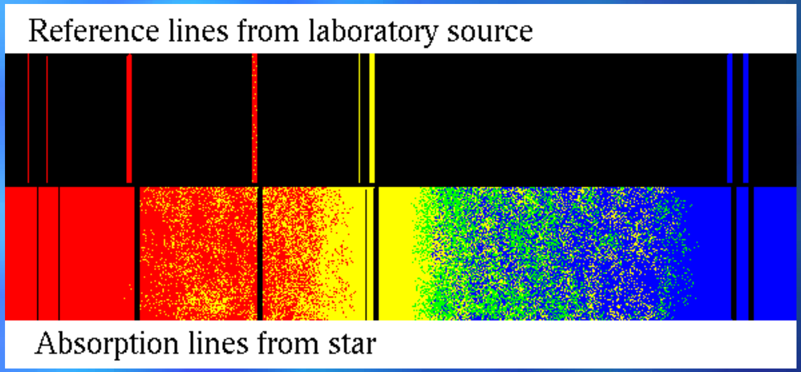
Redshift and Doppler Shift

- Redshift z is determined by comparing laboratory wavelength λ_o to observed wavelength λ
- If objects are moving away from observer, light will be redshifted
- Velocity of object can be determined from z

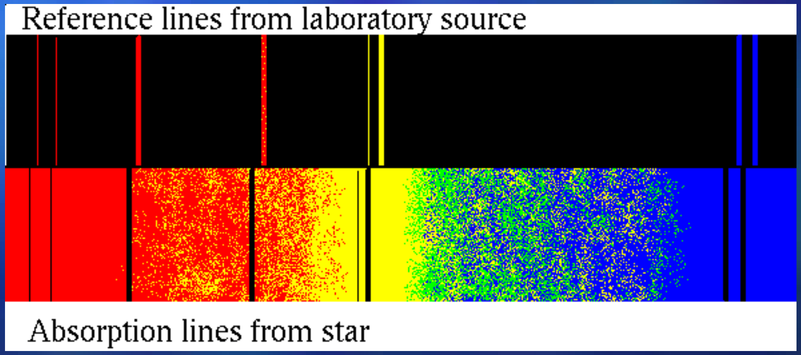
$$z = \frac{\Delta\lambda}{\lambda_o} = \frac{\lambda - \lambda_o}{\lambda_o} = \frac{v}{c}$$

Doppler Shift

Comparison of laboratory to blue-shifted object



Comparison of laboratory to red-shifted object

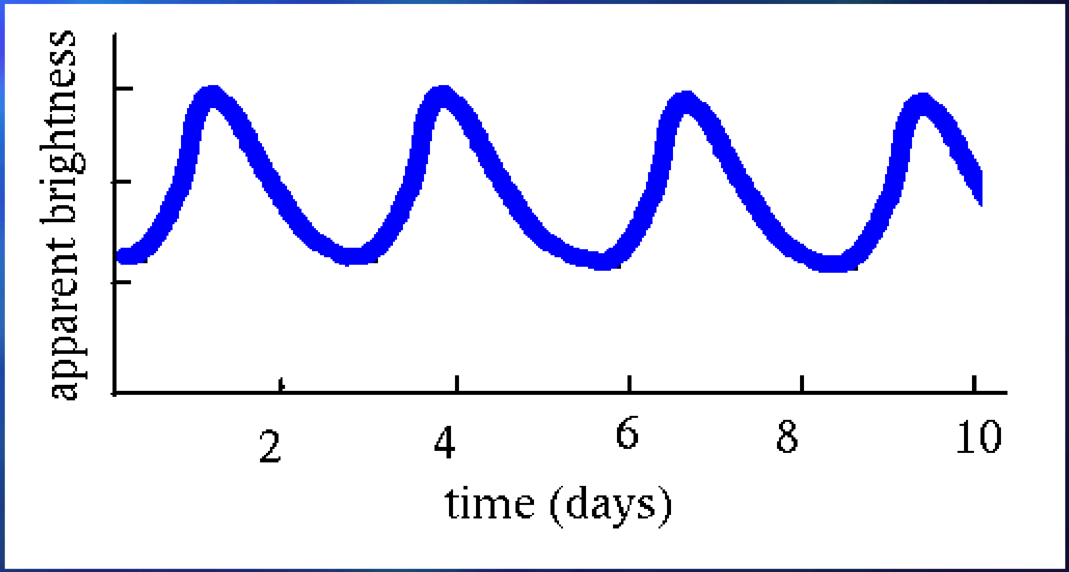


Cepheid variables and Nebulae

- In 1923, Edwin Hubble used new Mt. Wilson 100 inch telescope to observe Cepheid variables in the nearby “nebula” Andromeda.
- Cepheids vary periodically

$$L = K P^{1.3}$$

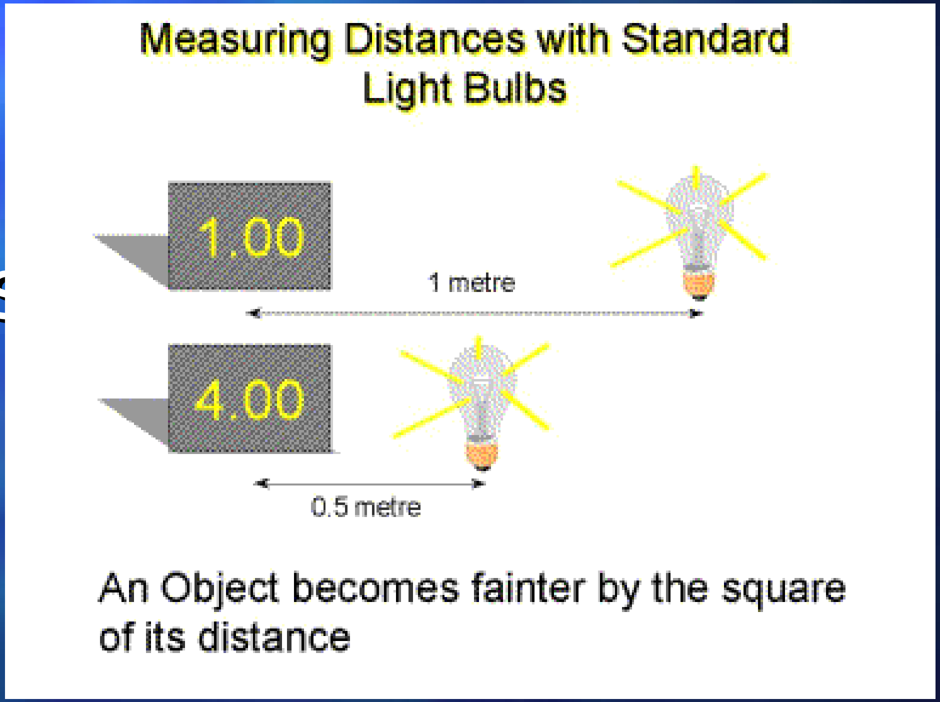
- Distance to Cepheids can be calculated from their luminosity



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

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



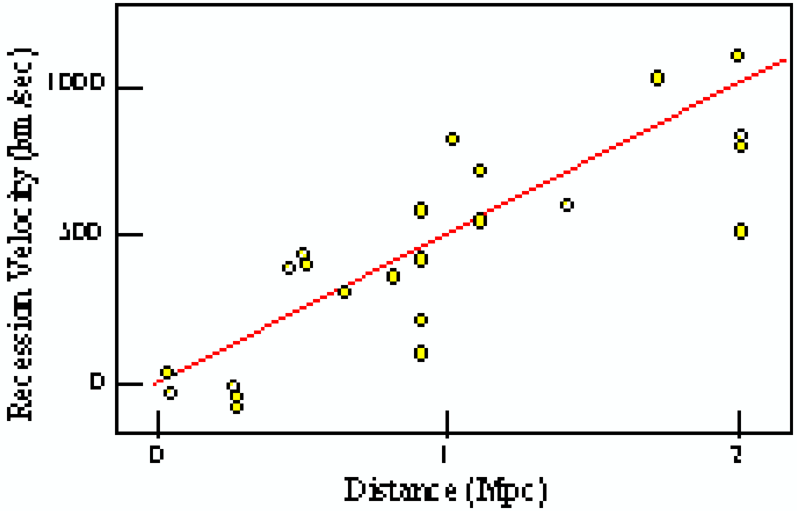
Hubble Expansion

The Hubble constant

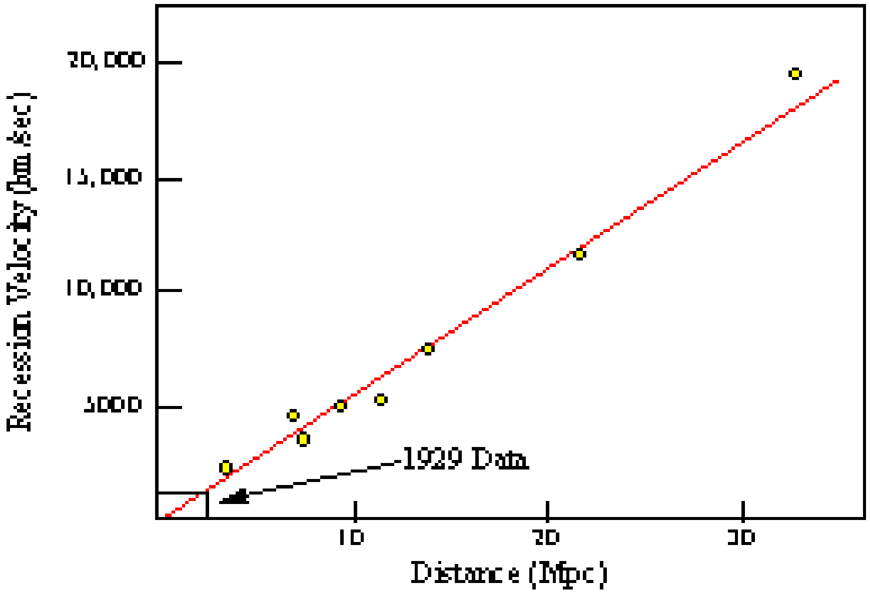
$H_o = 558 \text{ km s}^{-1} \text{ Mpc}^{-1}$

is the slope of these graphs

Hubble's Data (1929)



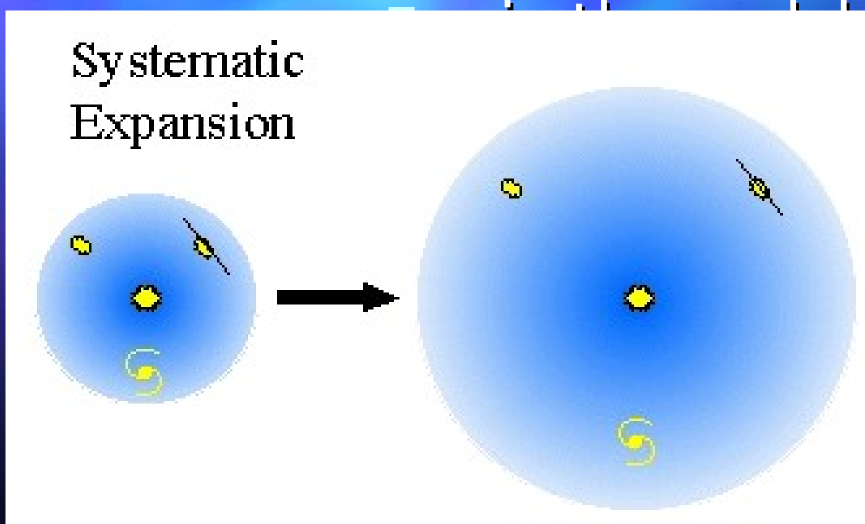
Hubble & Humason (1931)



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

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}
  - ift



Space between the galaxies expands while galaxies stay the same size

Cosmic Microwave Background

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

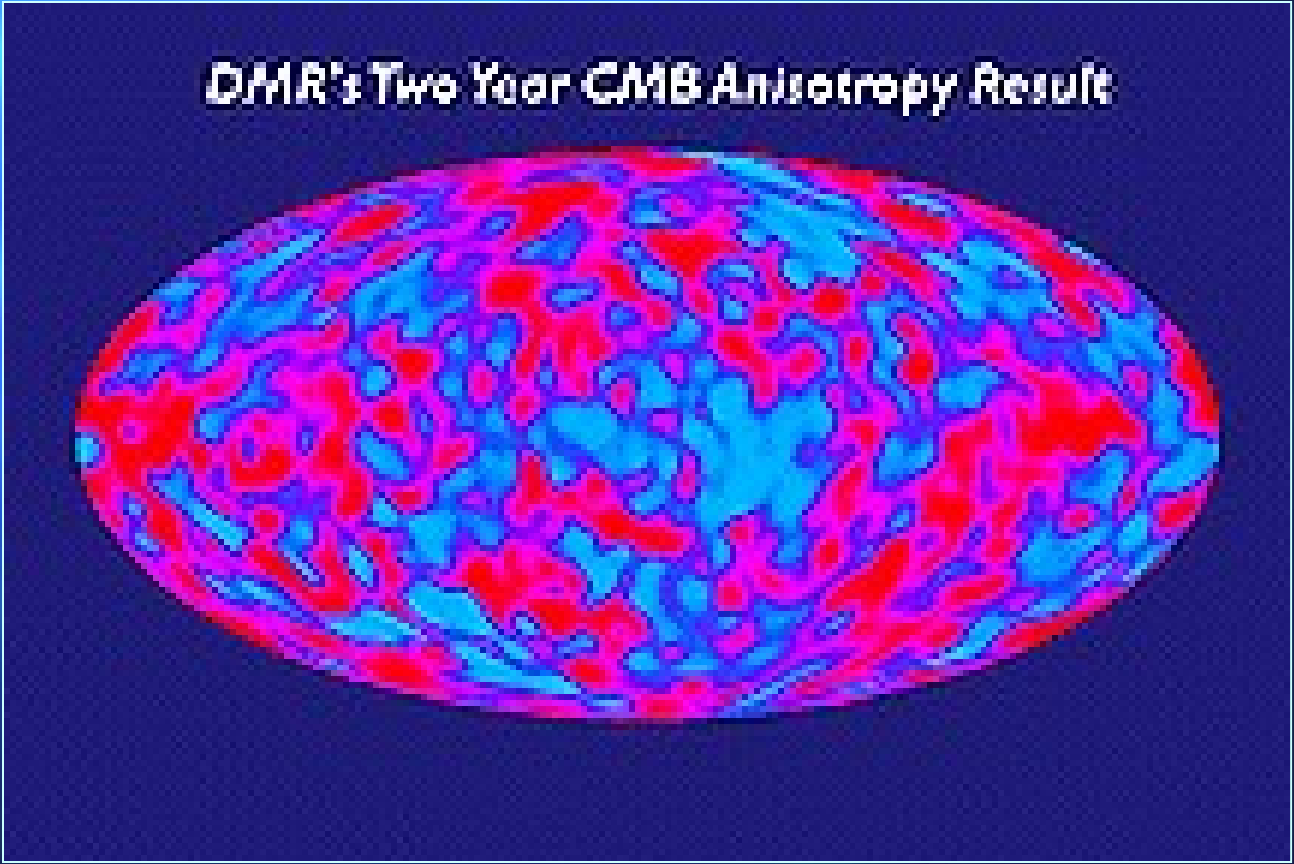
Excess noise in horned antennae was not due to pigeon dung!

Cosmic Background Explorer (1989-1993)

- Differential Microwave Radiometer
- PI George Smoot
- Discovered fluctuations in the CMBR
- These fluctuations are predicted by inflationary BB cosmology and are the seeds of the structure we now see

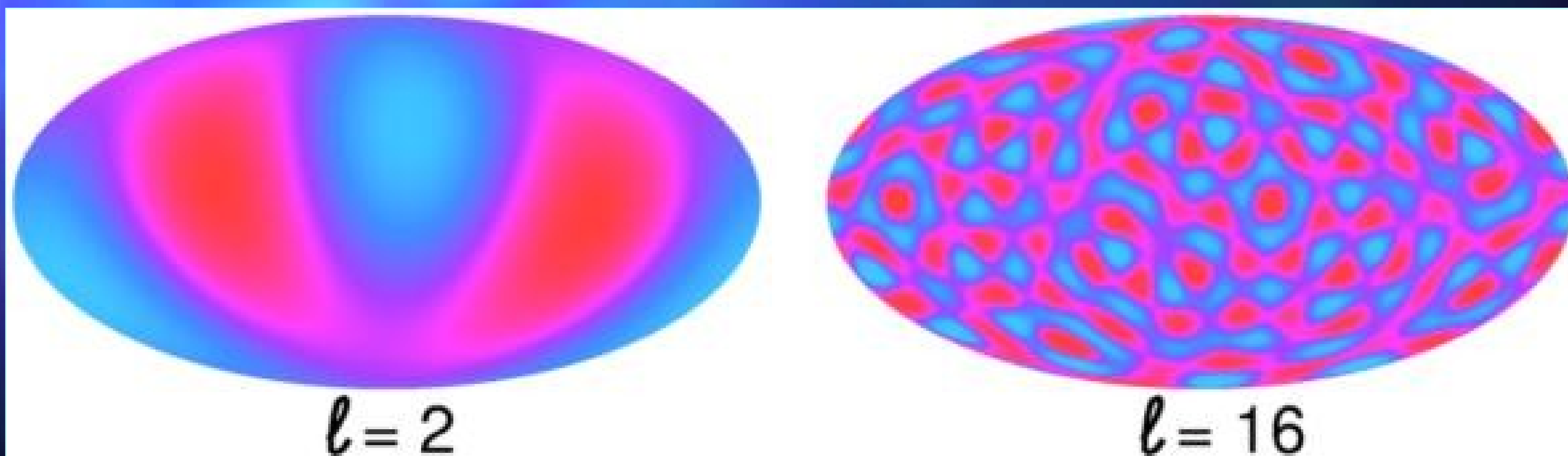
COBE data/DMR

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

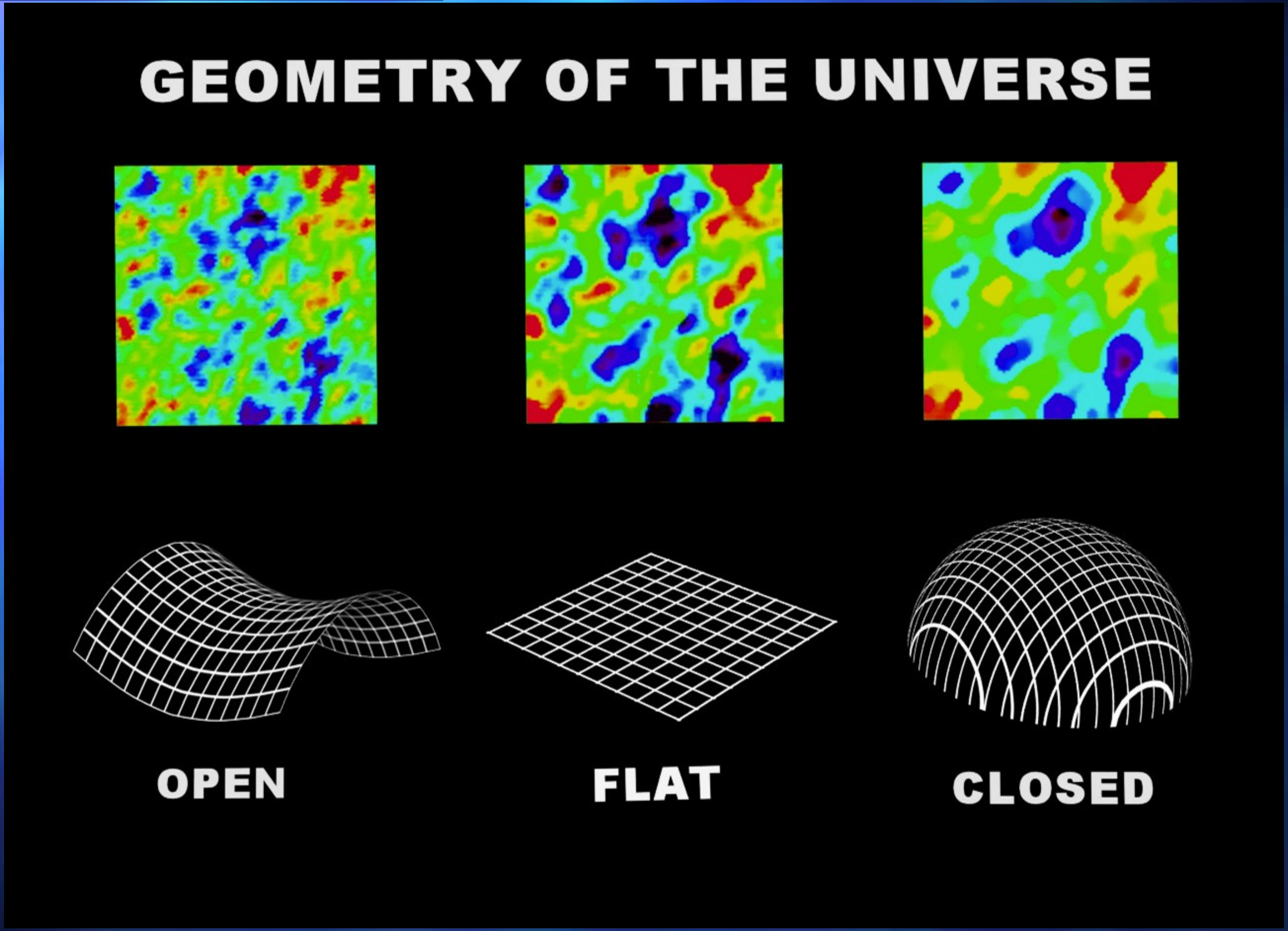


CMB Fluctuations

- COBE measures the angular fluctuations on large scales, down to about l=16



Fluctuations and geometry



Universe determines its destiny

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

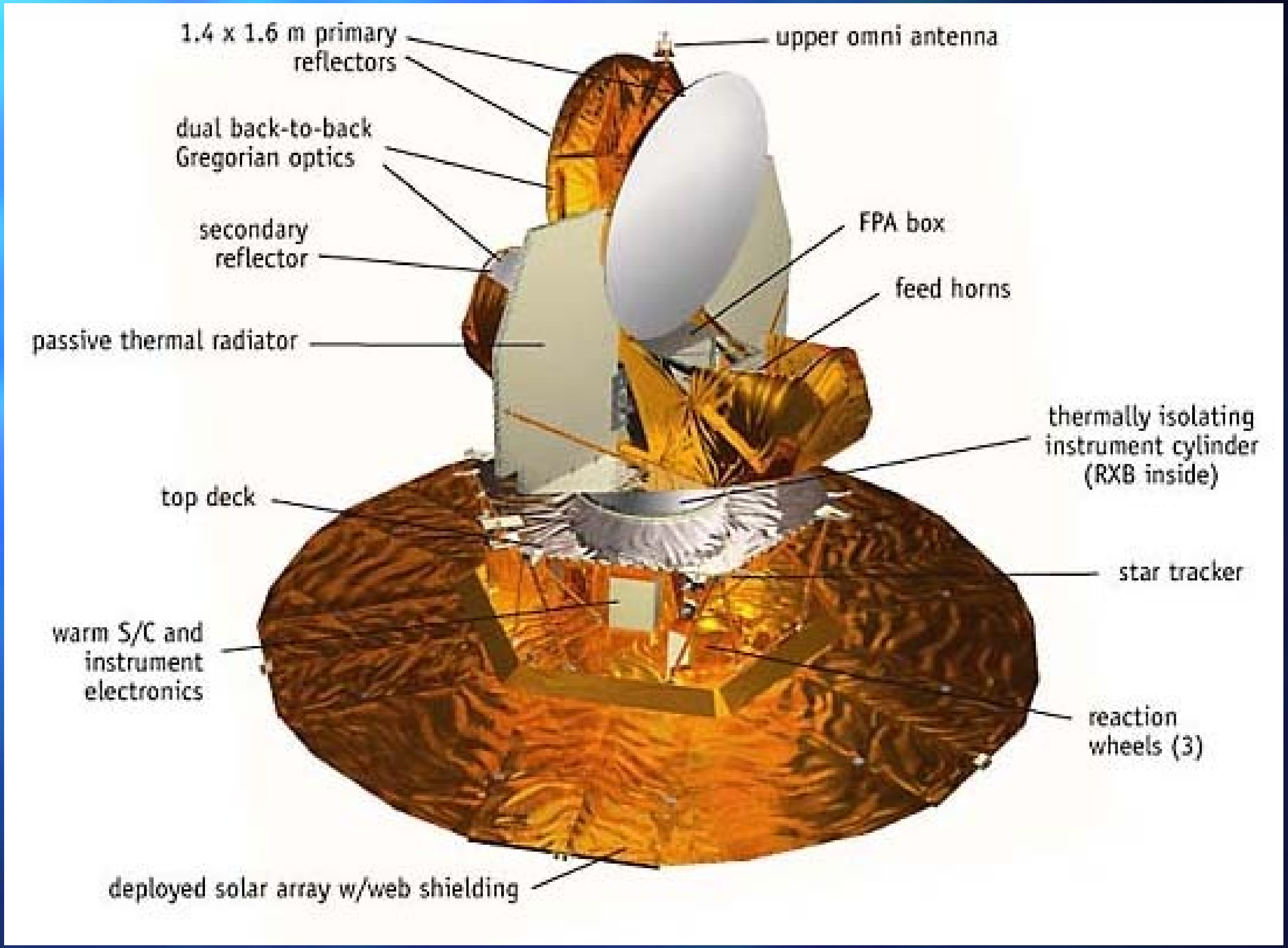
where

Ω_M = matter density (including regular and dark matter)

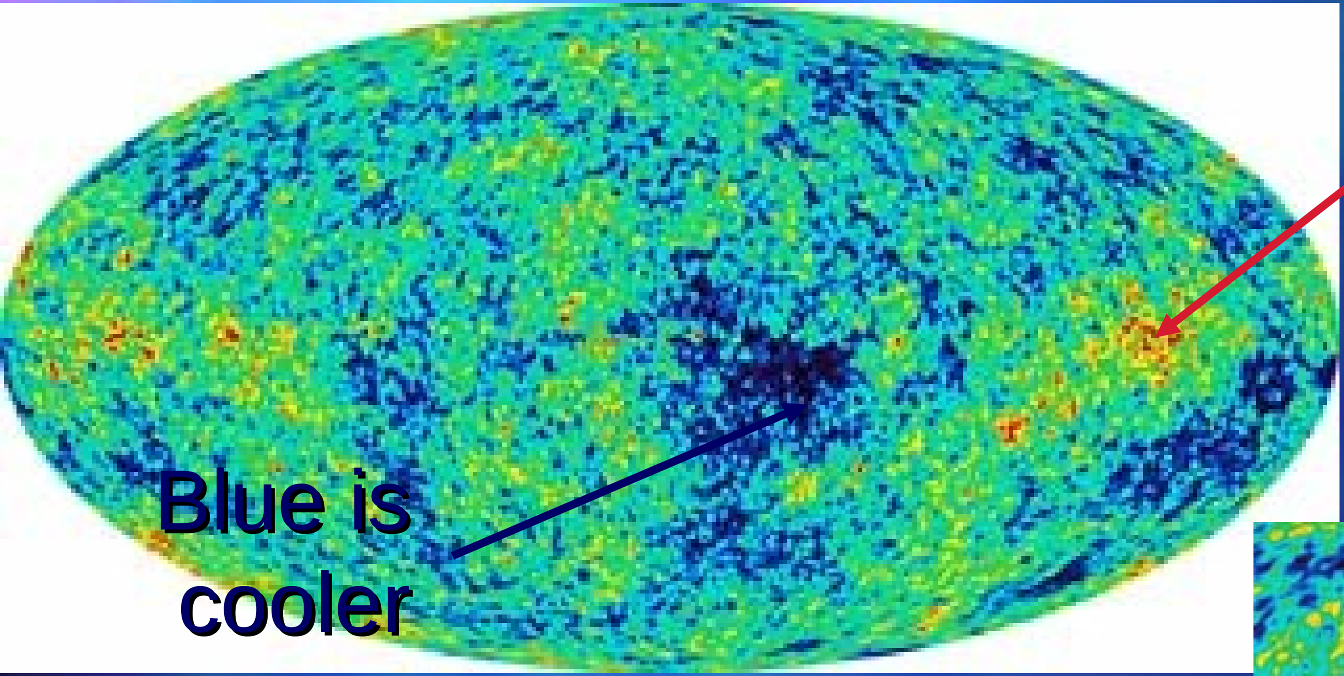
Ω_{tot} = density/critical density

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

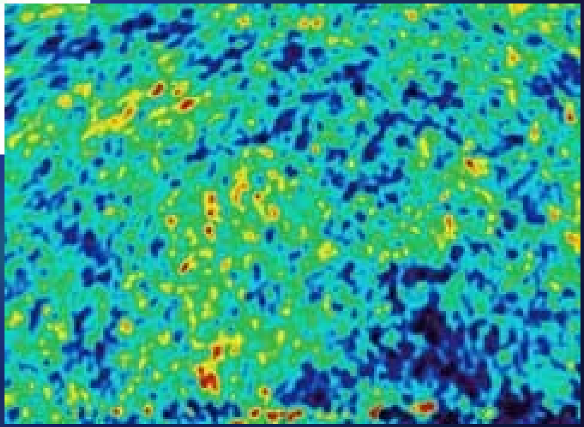
Wilkinson Microwave Anisotropy Probe (2001-present)



Universe's Baby Pictures



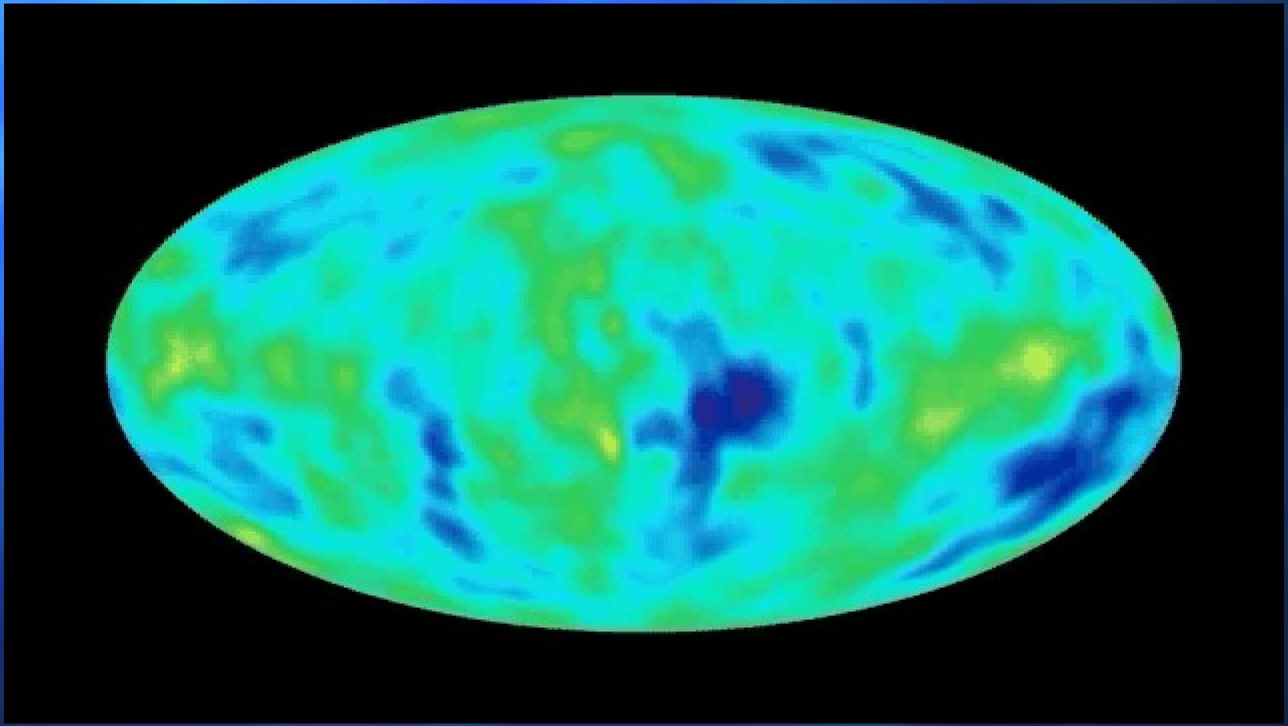
Red is
warmer



Credit:
NASA/WMAP

Compare to COBE

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

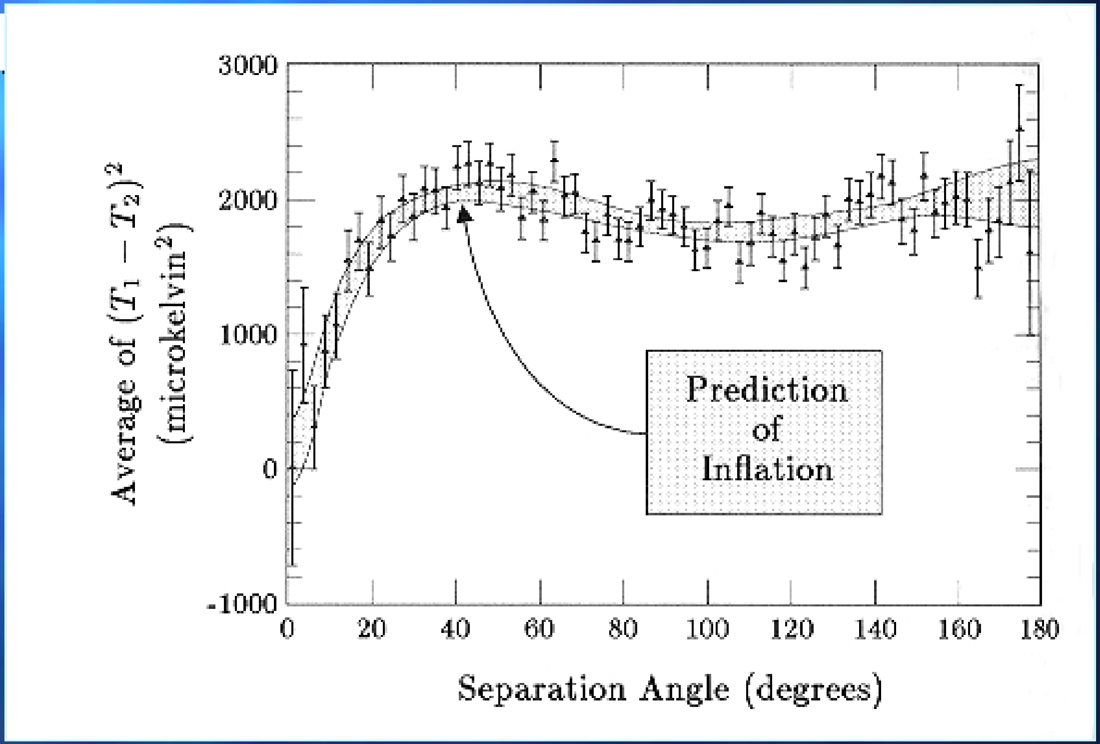


movie

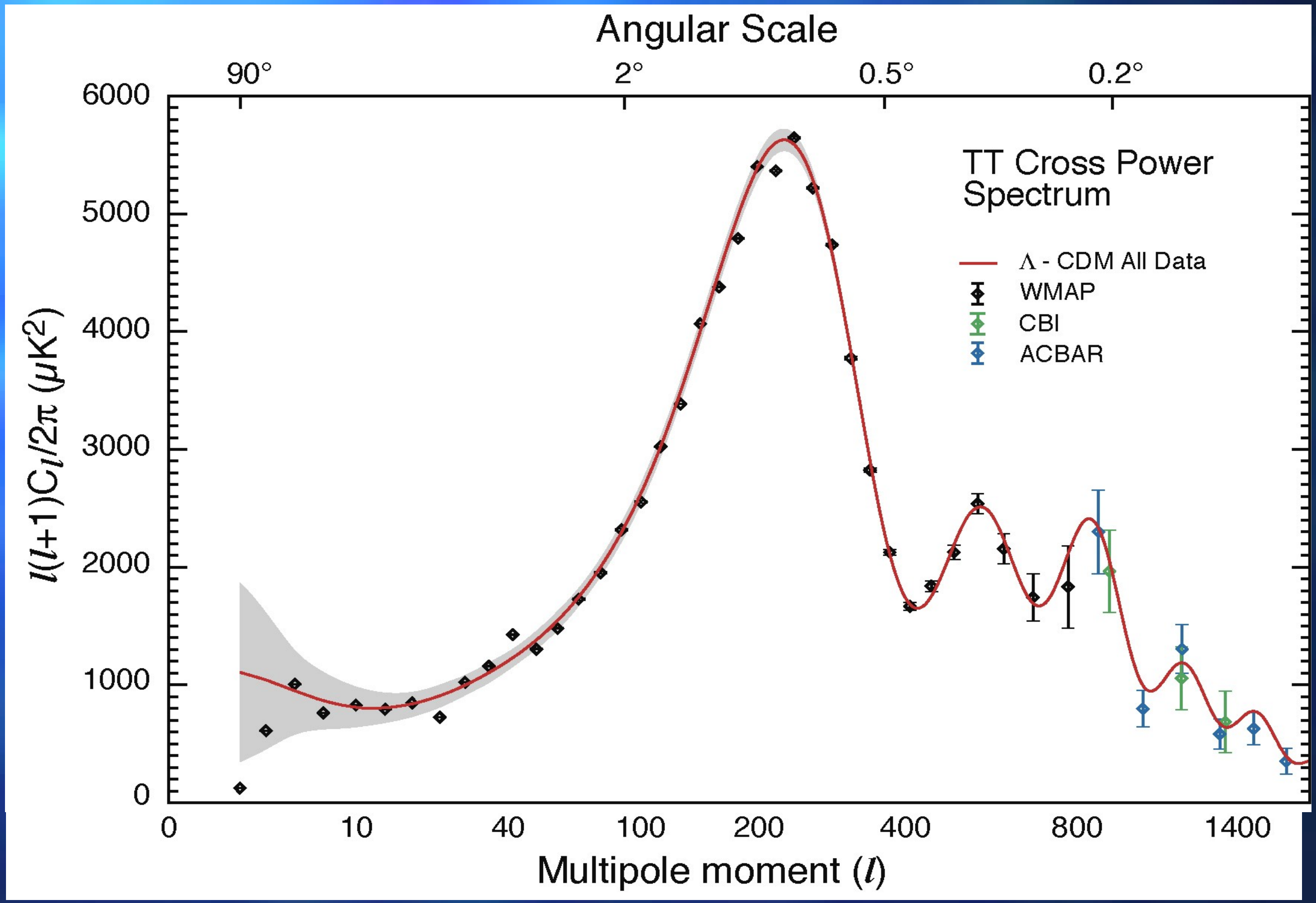
CMB vs. Inflation

- Inflation also predicts a distinct spectrum of fluctuations for the CMB which arise from the original quantum fluctuations in the pre-infl

Everything we see in the Universe started out as a quantum fluctuation!



WMAP angular power spectrum



Cosmological Parameters - Ω_{TOT}

- The strong first peak at l =200 confirms inflationary expansion
- Recall that inflation 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
- However, to quote Rocky Kolb:

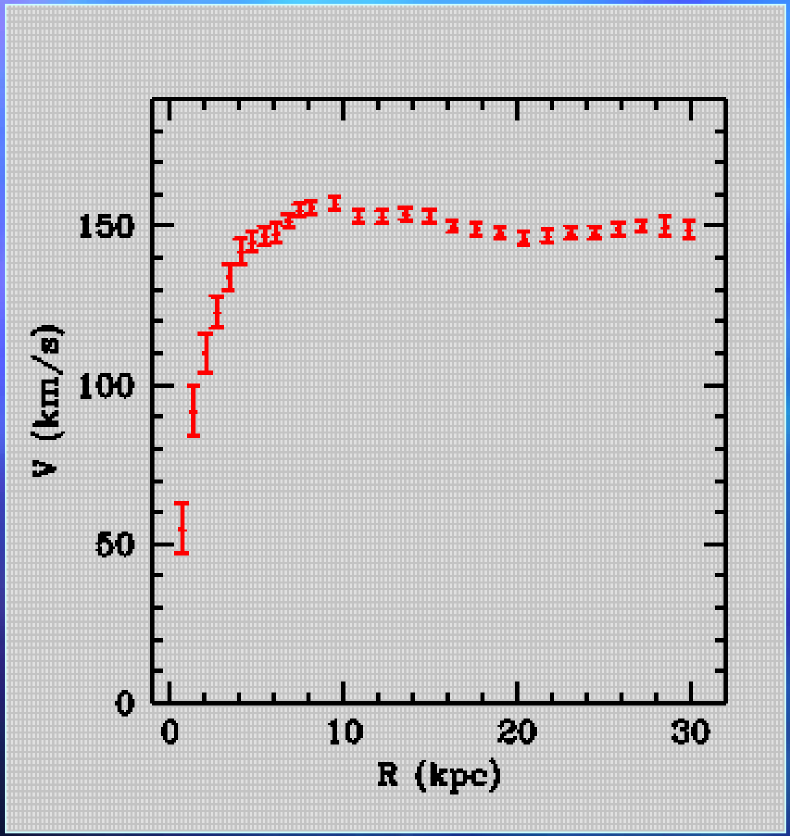
"Geometry is not destiny"

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

Hot gas in Galaxy Clusters

- Measure the mass of light emitting matter in galaxies in the cluster (stars)
- Measure mass of hot gas - it is 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

Hubble Expansion revisited

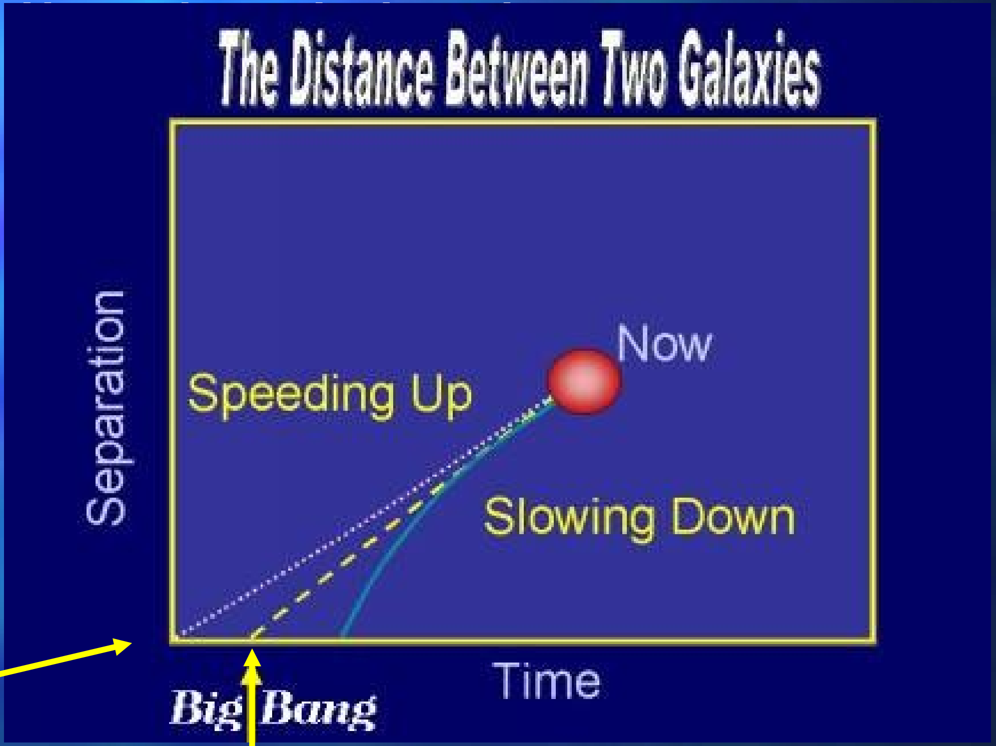
- We have already seen how the galaxies move away faster at further distances
- We measured the slope of the velocity of the galaxies vs. their distances → Hubble constant
- But is the Hubble constant really constant?
- In other words, has the expansion occurred at the same rate in the past as it is right now, and will the future expansion also be at this same rate?

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



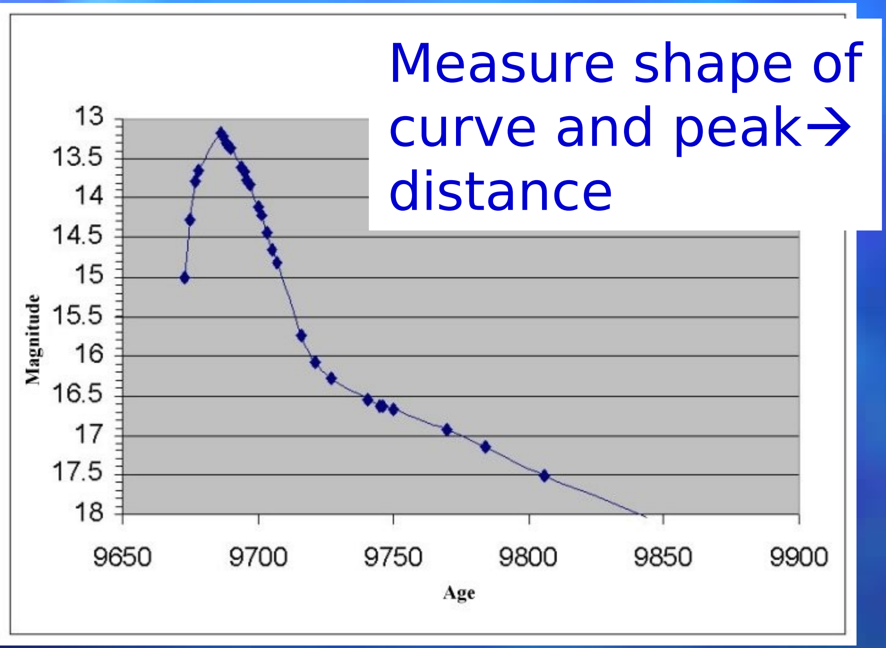
Derived from constant rate

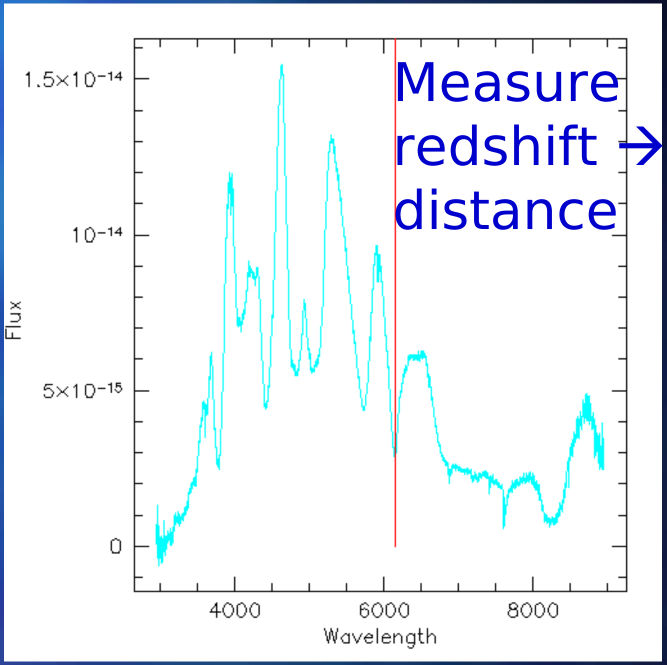
Distances to Supernovae

- Type Ia supernovae are “standard candles”
- Occur in a binary system in which a white dwarf star accretes beyond the 1.4 $M_{\odot}$ Chandrasekhar limit and collapses and explodes
- Decay time of light curve is correlated to absolute luminosity
- Luminosity comes from the radioactive decay of Cobalt and Nickel into Iron
- Some Type Ia supernovae are in galaxies with Cepheid variables
- 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 means that some unknown “dark energy” is causing the Universe to fly apart at ever-increasing speeds

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 $= \Omega_\Lambda$
- Current measurements: $\Omega_{TOT} - \Omega_M = \Omega_\Lambda \sim 0.7$
- There are many theories for Dark Energy: vacuum fluctuations, extra

New View: Density of the Universe

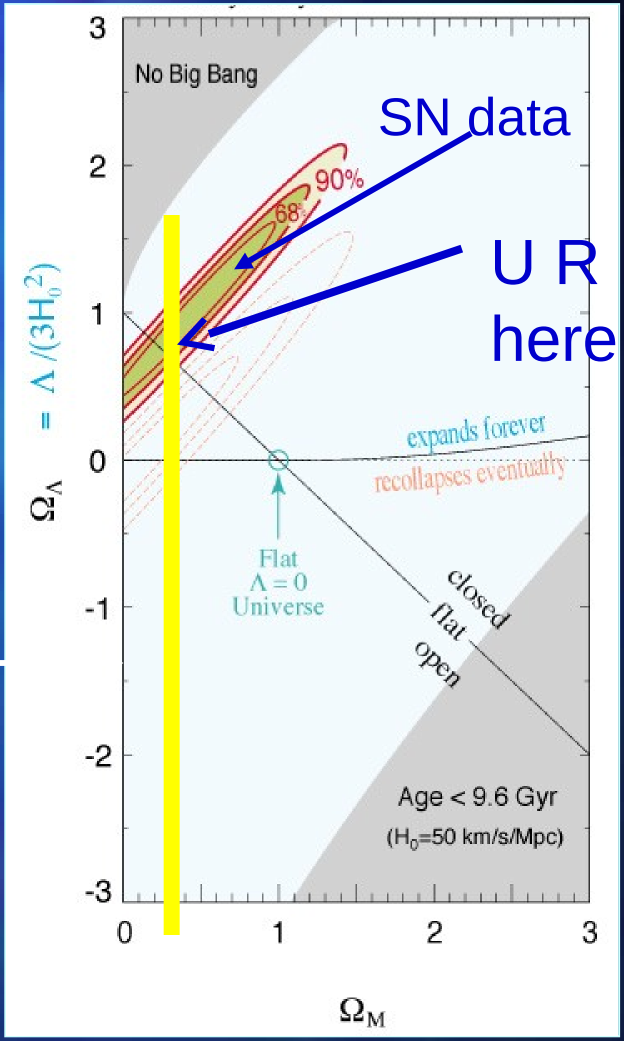
$$\Omega_{(total)} = \Omega_M + \Omega_\Lambda$$

where

Ω_M = matter density (including regular and dark matter)

Ω_Λ = cosmological constant or dark energy density

Ω_{tot} = density/critical density



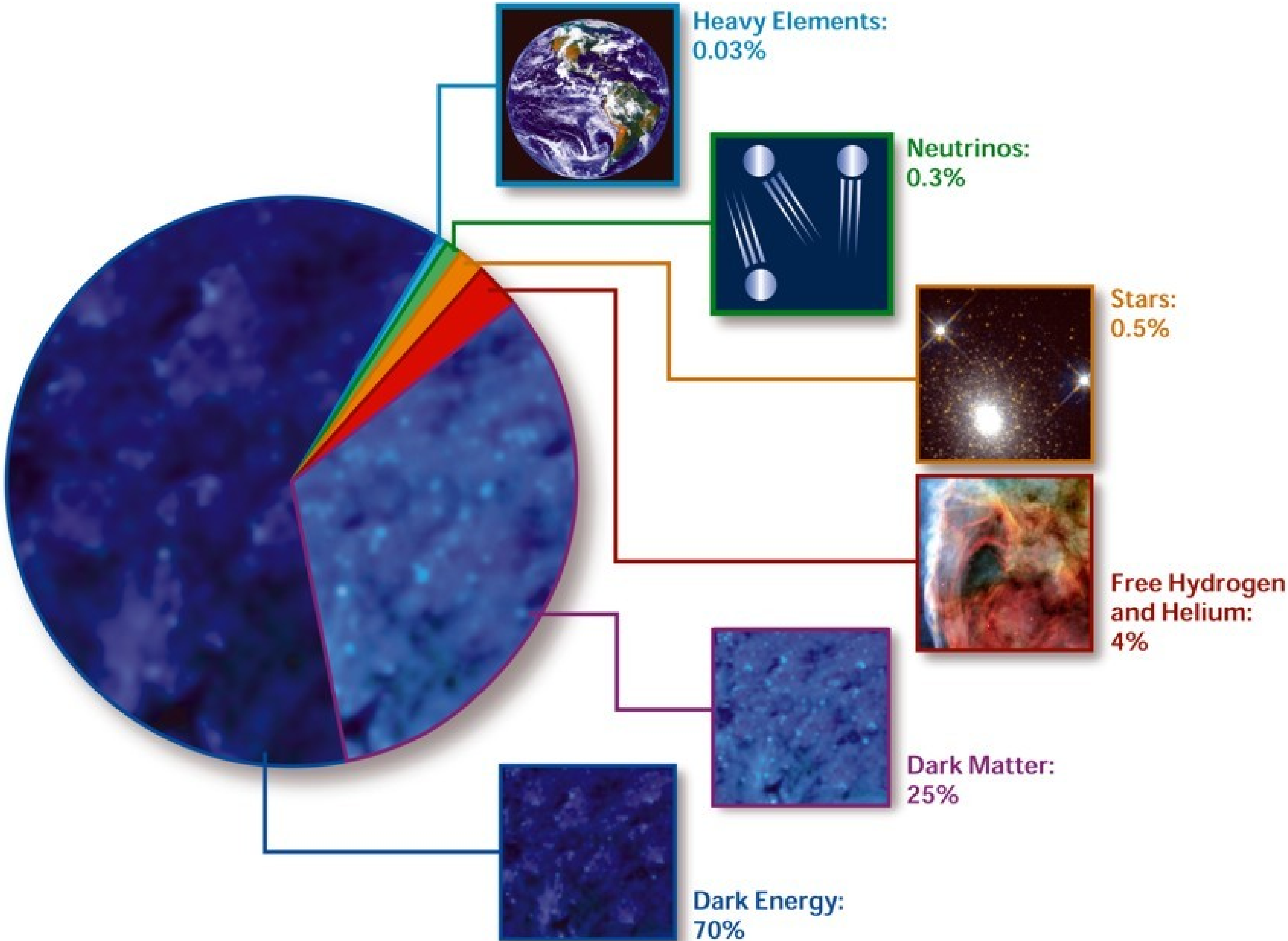
Perlmutter et al.

40 supernovae

Today's Cosmology

- $\Omega_{TOT} = 1.0$ from CMB measurements. We live in a flat Universe.
- $\Omega_{M} < 0.3$ from extensive observations at various wavelengths. Includes dark matter as well as normal matter and light.
- $\Omega_{\Lambda} \sim 0.7$ from Type 1a SN observations. Many different theories for "dark energy." Universe accelerates even though it is flat.
- Hubble constant = 70 km/sec/Mpc from HST observations. Age of Universe is around 13.7 billion years.

COMPOSITION OF THE COSMOS



Resources

- Inflationary Universe by Alan Guth (Perseus)
- A Short History of the Universe by Joseph Silk (Scientific American Library)
- Before the Beginning by Martin Rees (Perseus)
- Inflation for Beginners (John Gribbin) http://www.biols.susx.ac.uk/Home/John_Gribbin/cosmo.htm
- Ned Wright's Cosmology Tutorial http://www.astro.ucla.edu/~wright/cosmolog.htm
- James Schombert Lectures http://zebu.uoregon.edu/~js/21st_century_science/lectures/lec24.html

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
- MAP mission http://map.gsfc.nasa.gov
- SNAP mission http://snap.lbl.gov/

Web Resources

- Brian Schmidt's Supernova Pages
  http://msowww.anu.edu.au/~brian/PUBLIC/public.html
- Hubble Space Telescope sees Distant Supernova
  http://oposite.stsci.edu/pubinfo/pr/2001/09/pr.html
- MAP Teacher's Guide by Lindsay Clark
  http://www.astro.princeton.edu/~clark/teachersguide.html
- George Smoot's group pages
  http://aether.lbl.gov/