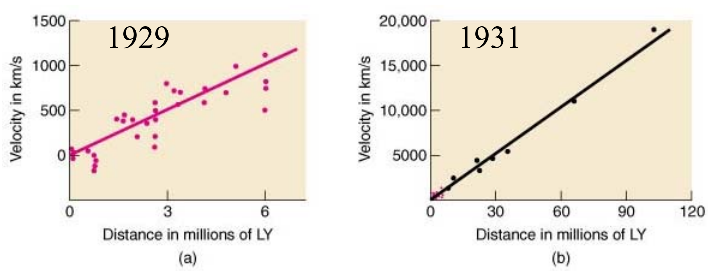
Final Exam

Thursday, June 26, 2:30-3:30PM
BPS 1410 (the regular classroom)

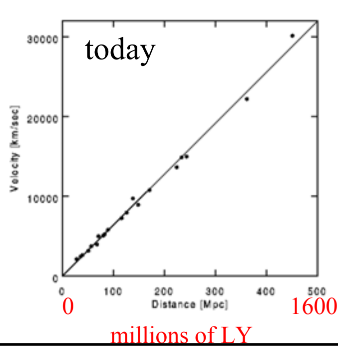
- 40 Questions
  - Roughly 10 covering material presented on June 24.
  - Roughly 25 based on questions you have already seen on quizzes.
    - But about half of those will be *variations* of the question that was on the quiz.
  - Roughly 5 new, general questions about whole course.

- Review session before the final
  - Will cover viewgraphs that will be available in advance on web.
  - Starts at 12:40 in regular classroom (BPS 1410)
  - Will go for about one hour.
  - Then I will be in the classroom until the start of the final, available to answer questions.

Hubble's Law (1929)



[Fig 25.18]

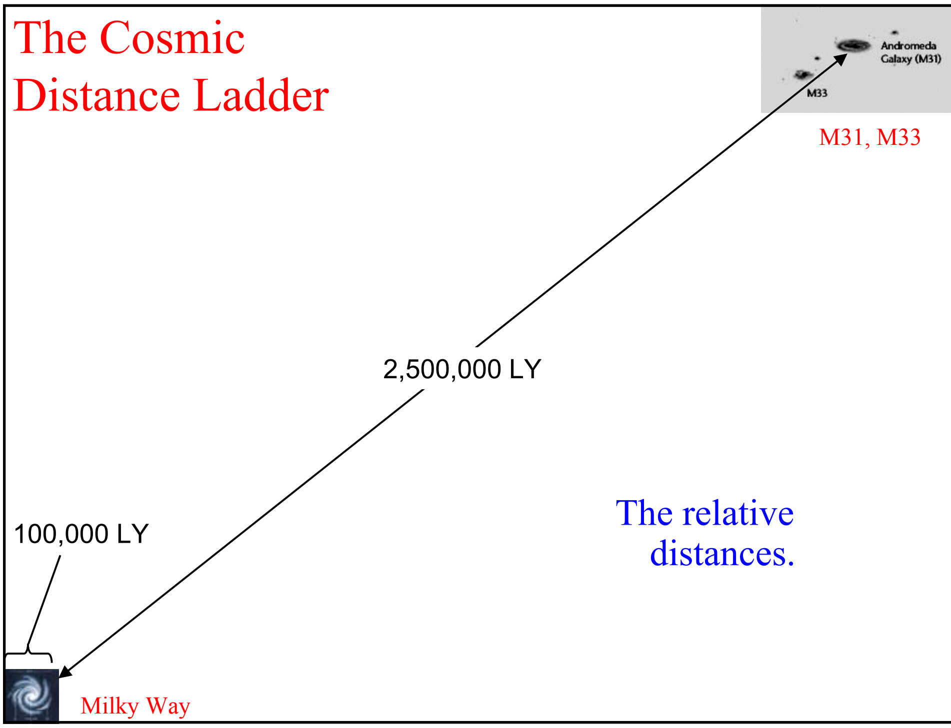


- Measure radial velocity v from Doppler shift.
- Hubble's Law:

  $v = H_o d$

- Proportionality constant H_o is called "Hubble constant"
- Note huge change in measured value of H_o between 1931 and today
  - Constant refinement of distance scale

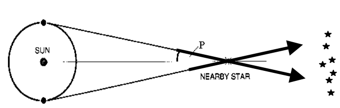
The Cosmic Distance Ladder



The relative distances.

The Cosmic Distance Ladder

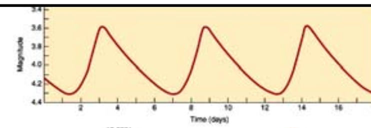
- Parallax
  - 20 pc = 65 LY

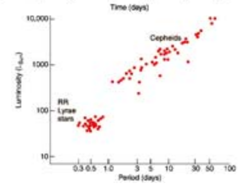


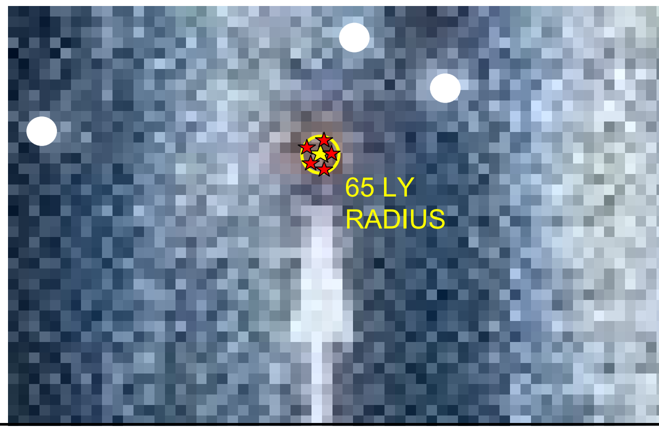
The Cosmic Distance Ladder

- Parallax
  - 20 pc = 65 LY

65 LY Radius
includes some pulsating variables

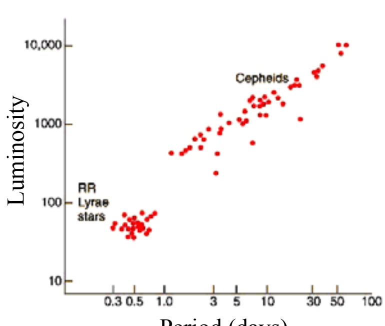


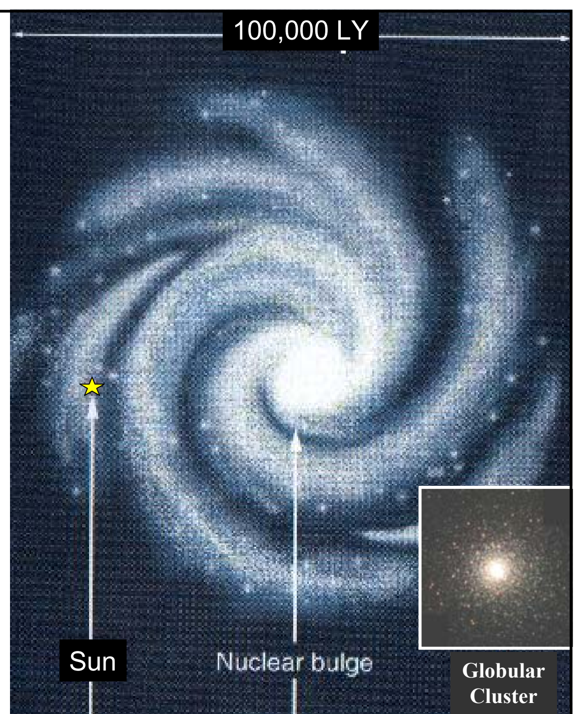




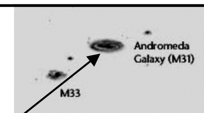
The Cosmic Distance Ladder

- Parallax
  - 20 pc = 65 LY
  - Calibrate luminosities of Pulsating Variables
- Map rest of Milky Way





The Cosmic Distance Ladder



M31, M33

- Parallax
  - 20 pc = 65 LY
  - Calibrate luminosities of Pulsating Variables
- Map rest of Milky Way and out to M31

2,500,000 LY

Measure luminosities of
- Brightest stars 10,000 $L_\odot$
- Brightest globular clusters 100,000 $L_\odot$
- Brightest H II regions 100,000 $L_\odot$
- Etc.
- ➔ can now measure distances to more distant galaxies

100,000 LY

Milky Way

Modern methods of determining distances

[Table 25.2]

Method	Distance Range (millions of LY)
Pulsating variable stars (Cepheids)	0-65
Brightest star in galaxy	0-150
Planetary Nebulae	0-70
Globular clusters	0-100
Rotation velocities	0-300
Supernovae	0-8000
Brightest galaxy in cluster	70-13,000
Redshifts (Hubble Law)	300 – 13,000

But these are still calibrated with parallaxes!

Calibrated with pulsating variables

H_o calibrated with supernovae, rotation velocities, etc

Measuring Distances using Redshifts

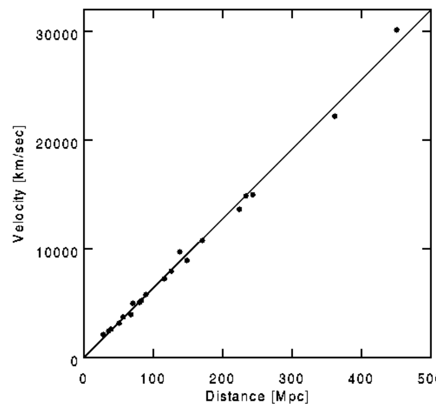
- Measure Doppler shift from emission or absorption lines:

  Redshift $z = \Delta\lambda/\lambda = v/c$

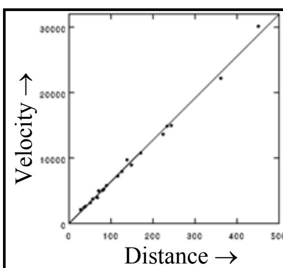
- Plug v into Hubble's Law:

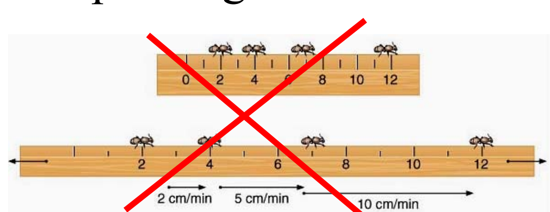
  $v = H_o d$

  $d = v/H_o$



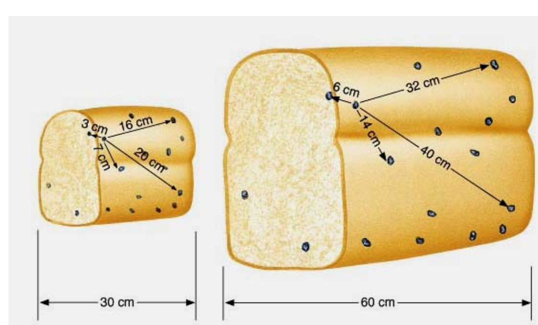
The Expanding Universe





[Fig 25.19]

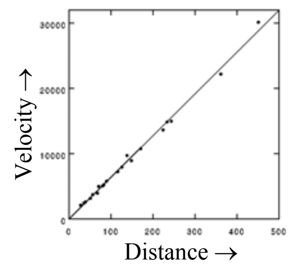
- We are unlikely to be at exact center.
- ➔ Scale of the whole universe is expanding.
- Galaxies all recede from each other
  - Except for small random motions.
- But galaxies do *not* expand internally
  - Held together by internal gravitational forces

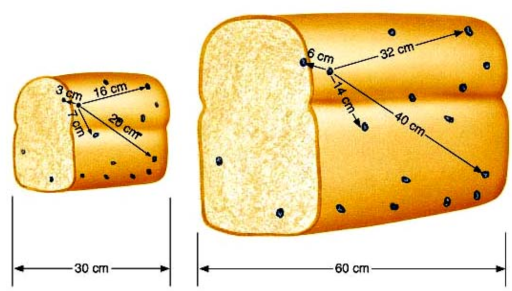


[Fig 25.20]

The Shape of the Universe

- Cosmological principle
  - Universe looks the same from any point.
- Expanding Universe
  - Hubble's Law
- Scale Factor = R(time) = R(t)
  - Distance = R(t) x (co-moving distance).





R(t) increased by factor 2

General relativity

- Worked out in 1907 - 1915
- Consistent with (incorporates) special relativity
- Describes motions of objects in presence of gravity
- Gravity = distortion into extra space-like dimensions.

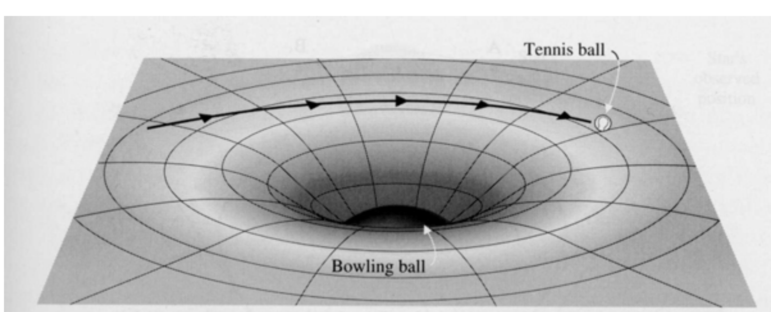
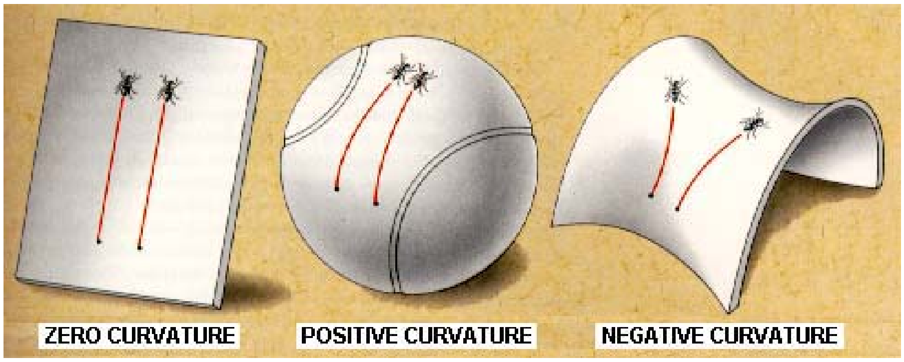


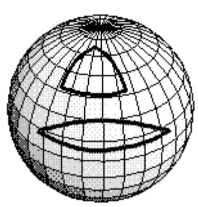
Figure 16.2 Rubber sheet analogy for curved space around the Sun.

Some possible geometries

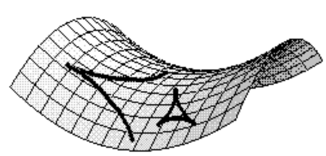


- For the particular case of positive curvature:
  - A particularly large Black Hole
  - So solutions *do* exist for uniform matter distributions.

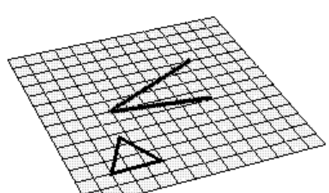
Geometrical Tests



Positive
Curvature

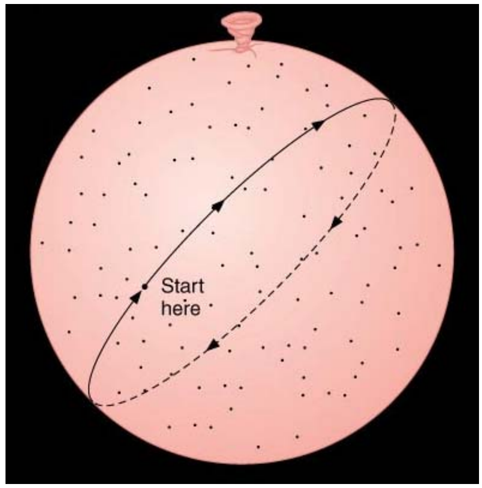


Negative
Curvature



Flat
(zero curvature)

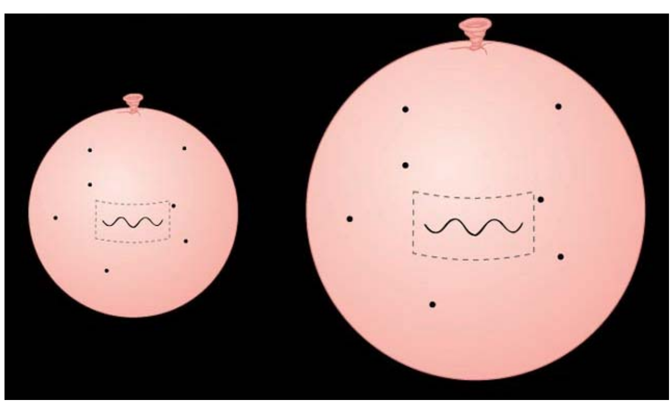
Positive curvature:
light follows closed path



[Fig 28.5]

The Expanding Universe

- Light waves get stretched ➔ redshift.
- Individual galaxies do not get stretched.



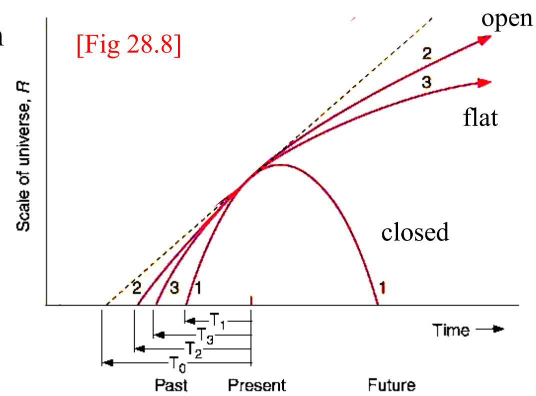
[Fig 28.6]

- This example has positive curvature.
- But same true for other curvatures.

In spite of these examples, positive curvature is *not* the preferred model.

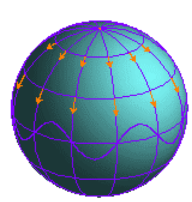
The Evolving Universe

- Formerly concentrated in a tiny volume
- Kinetic energy vs. gravitational attraction
  - ➔ Curvature of space
  - ➔ Evolution
- The search for (until recently) two numbers
  - H_0
    - rate of expansion
  - Ω_0 (q_0)
    - Change of rate of expansion



Energy balance	Ω_0	Curvature	Future
kinetic > gravitational	< 1	negative	open
kinetic = gravitational	1	flat	critical
kinetic < gravitational	> 1	positive	closed

Expansion causes redshift

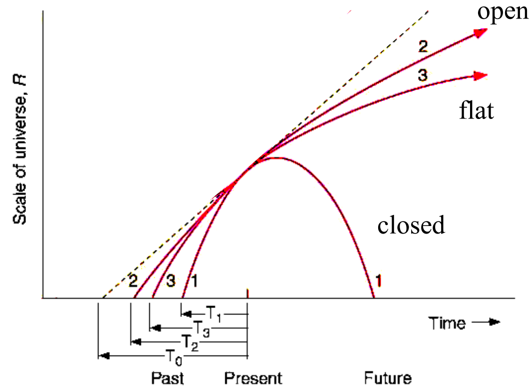


Lookback time

- Looking back in time ➔ test theories of evolution
  - Stars
  - Galaxies
  - Larger structures
- But models are in units of years.
- We measure redshift (z)
- Redshift ➔ scale factor

$$R(t) = \frac{1}{1+z}$$

- Must use cosmological model to find how R depends on t.

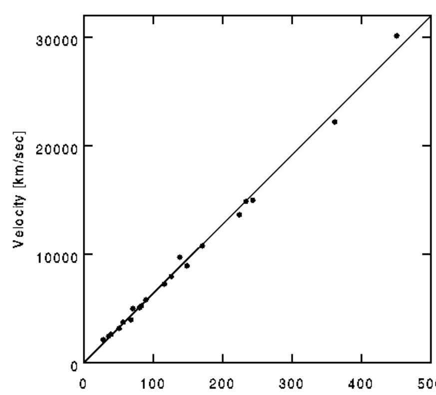


But is the universe *really* expanding?

- Everything definitely is moving away from everything else.

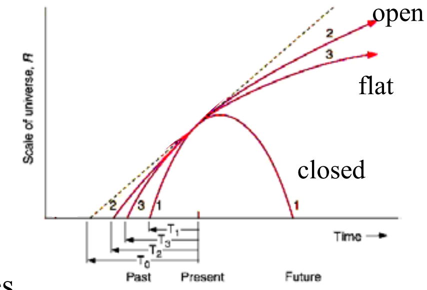
- But maybe matter (H atoms) is constantly being created throughout the universe.

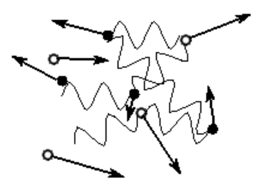
  - Steady State Theory
    - Fred Hoyle, 1950's.



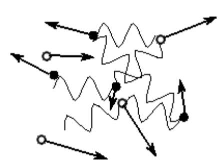
The Cosmic Microwave Background (CMB)

- Proof of expanding Universe.
- Universe used to be smaller ➔
  - Denser
  - Hotter
- Most normal matter is hydrogen
  - Was fully ionized at earlier times
  - Photons could not travel far
    - Absorption by free electrons
- Matter and photons intimately linked together.





Cosmic Microwave Background



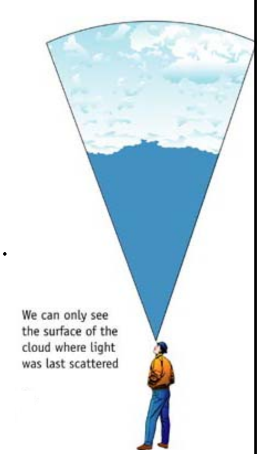
Hotter

- Hydrogen ionized.
  - Universe opaque.
    - Photons travel only short distances.
    - Absorbed, re-emitted by free electrons.

Decoupling
- T = 3000°K
- 14 billion yrs ago
- Universe 300,000 yrs old.

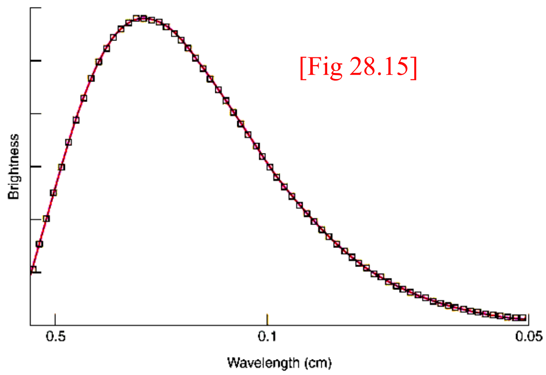
- Hydrogen becomes neutral (p + e^- ➔ H).
  - Universe becomes transparent.
  - Photons decouple from matter, continue in whatever direction they were moving.

Cooler



Expansion of universe ➔ redshift

- Photons formed in blackbody with T ~ 3000° K
- Redshifting ➔ lower energy per photon
  - E = hν = hc/λ
  - So we see T = 3° K blackbody spectrum



[Fig 28.15]

Discovered in 1965

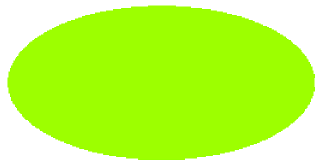
Penzias, Wilson, and their radio telescope.

Summary:
How do we know the universe is expanding from a very much smaller size?

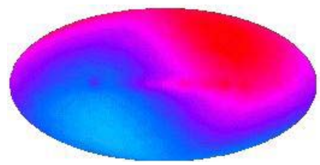
- Hubble's Law
- Cosmic Microwave Background (CMB)

Isotropy of the Cosmic Microwave Background

- COBE satellite.



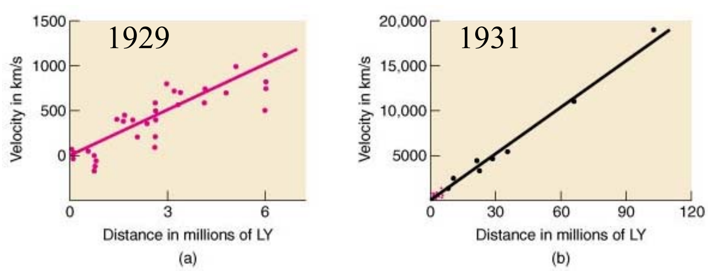
Blue = 0°K
Red = 4°K



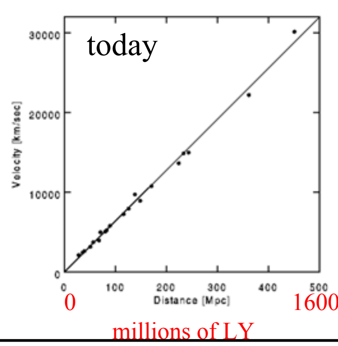
Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
➔motion of Sun through Universe.

Whole-Sky Maps

Hubble's Law (1929)



[Fig 25.18]



- Measure radial velocity v from Doppler shift.
- Hubble's Law:

  $v = H_o d$

- Proportionality constant H_o is called "Hubble constant"
- Note huge change in measured value of H_o between 1931 and today
  - Constant refinement of distance scale

The Horizon

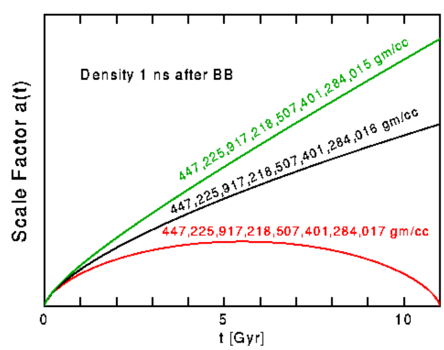
- At any time, we can only see as far as light can have traveled within age of Universe.
  - Present age of U = 14 billion yrs.
- Universe presumably is much bigger than this.
- At earlier times, we could have seen only a smaller fraction of the Universe.

- The Horizon Problem:

  Causality.

  How can parts of Universe that *never before* communicated know how to have almost *exactly* the same conditions?

What happened back at the Big Bang?



- The Flatness Problem:

  Ω_0 close to 1 at present time.

  - But this requires incredible precision at start (t = 0).
  - ➔ Ω_0 *exactly* = 1

The solution: Inflation

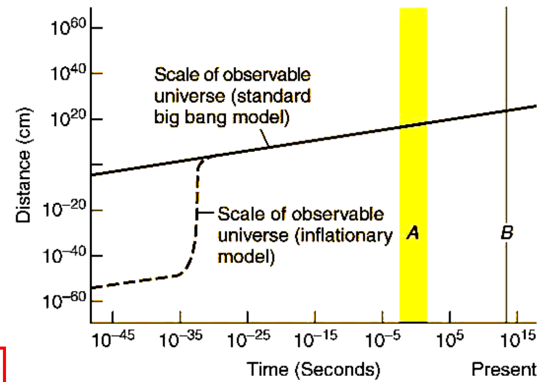
(probably)

(maybe)

Extremely rapid expansion of universe

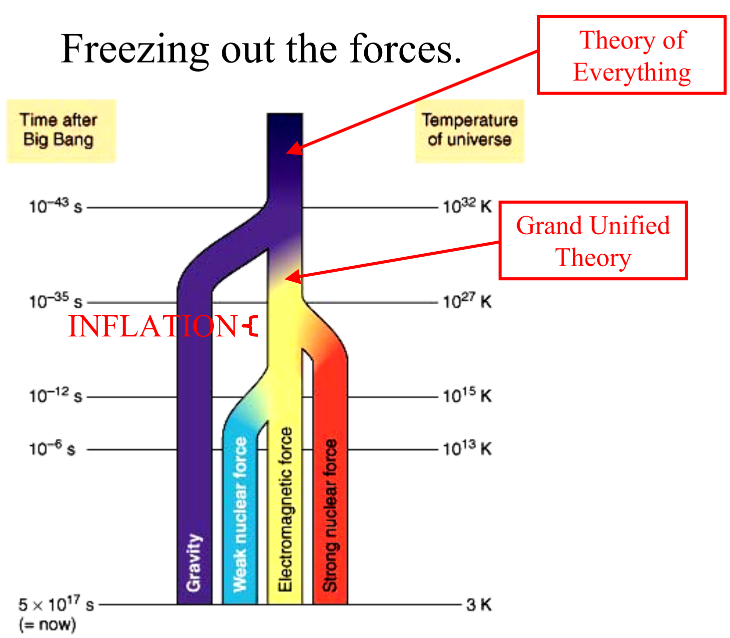
- due to release of energy in "phase change".
- like ice to water.

Universe became 10^{43} times larger within 10^{-32} seconds.



[Fig 28.17]

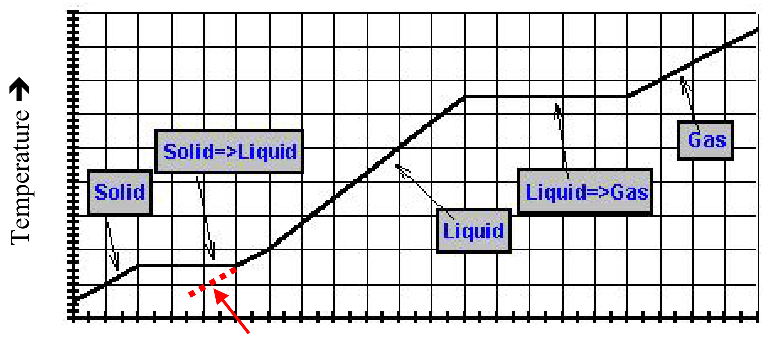
Freezing out the forces.



[Fig 28.16]

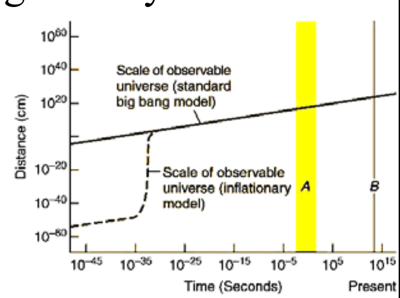
Phase changes and latent heat

- Apply heat energy at a steady rate to a fixed quantity of H_2O
- How does the temperature change?



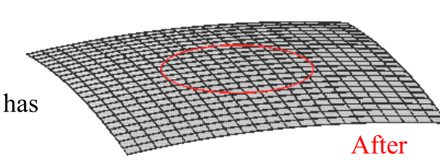
What does inflation predict for geometry of present universe?

Universe became 10^{43} times larger within 10^{-32} seconds.



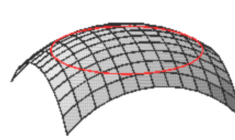
- Predicts a flat universe
  - $\Omega_0 = 1.000000....$
  - As far out as we can see
    - red circle = horizon

    = most distant place from which light has had time to travel.



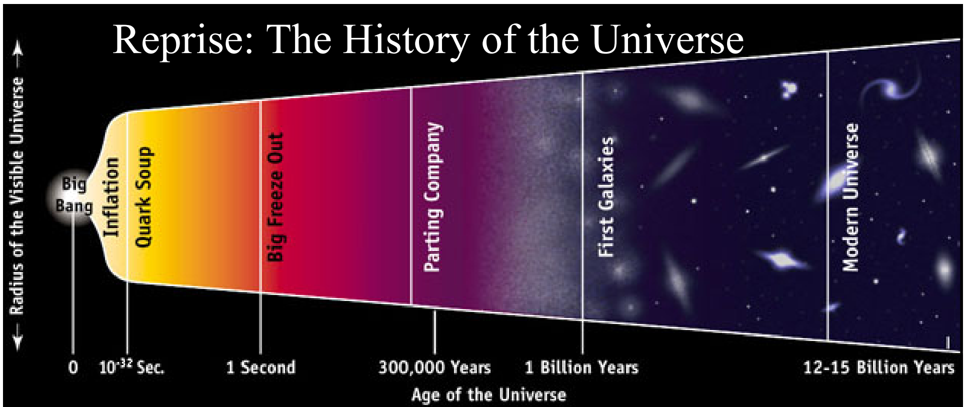
After Inflation

- Solves flatness and horizon problems.
- But there is insufficient normal matter to presently maintain a flat universe.



Before Inflation

Reprise: The History of the Universe

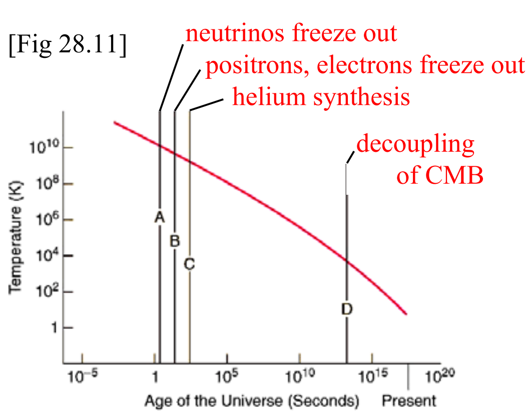


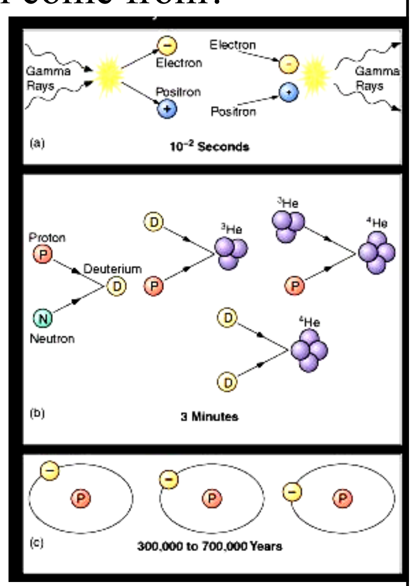
Planck time; Gravity separated out	10^{-43} sec	10^{32} °K
Strong nuclear force separated out	10^{-35} sec	10^{27}
Inflation	10^{-32} sec	
Electromagentic, Weak nuclear forces	10^{-12} sec	10^{15}
Nucleosynthesis of H, He, Li	1 sec - 3 min	10^{9}
Decoupling of CMB	300,000 yrs	3000
Now	14 billion yrs	3

Where did H, He and Li come from?

- Nucleosynthesis in the big bang.
- First 3 minutes.

[Fig 28.11]



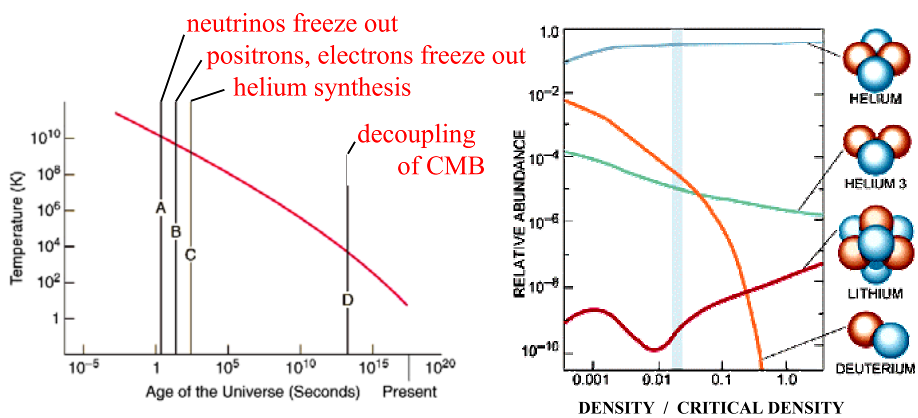


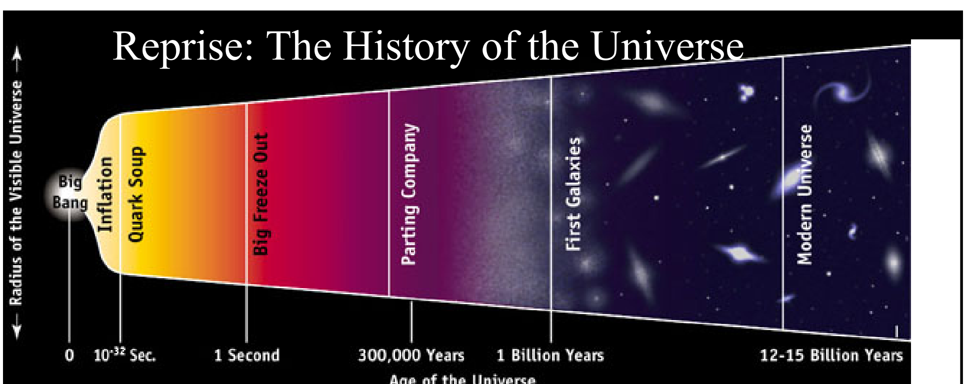
[Fig 28.12]

Where did H, He and Li come from?

- Exact mix of H, He, Li is sensitive to exact density at time when T dropped below 900 million ºK.
  - Ratios of H/He, D/H tell us density of ordinary matter = 0.03 x critical density.

deuterium = ^2H





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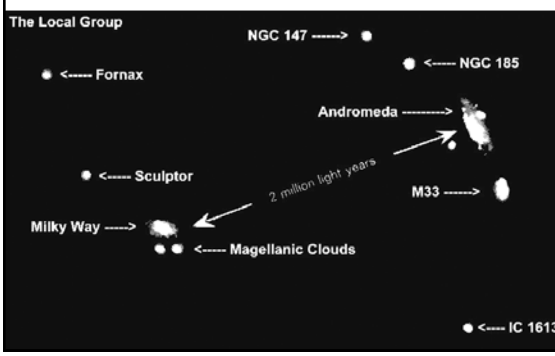
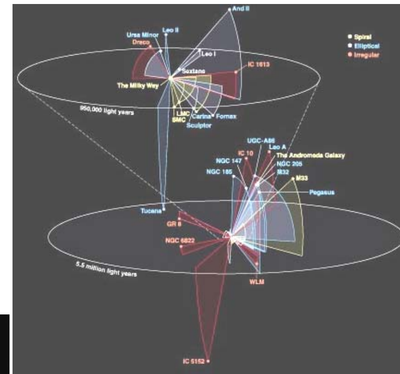
Nucleosynthesis of H, He, Li	1 sec - 3 min	10^{9}
Decoupling of CMB	300,000 yrs	3000
Galaxy Formation	1 billion years	
Now	14 billion yrs	3

Structure within the Universe

- The Local Group
  - Our Galaxy and its satellites.
  - Andromeda galaxy (M31) and its satellites.



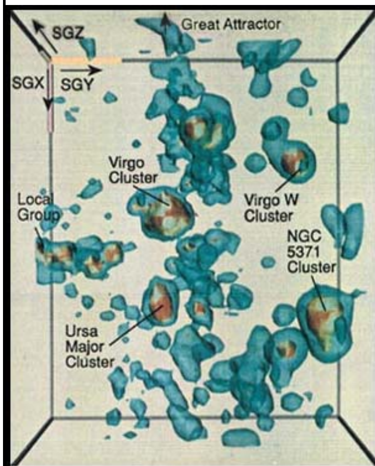


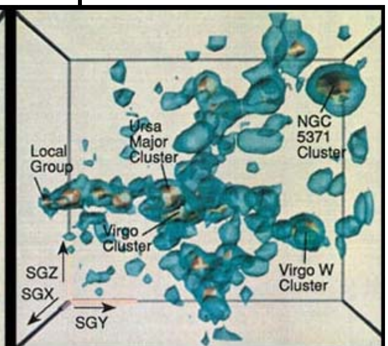
[Fig 27.3]

Galaxy Clusters

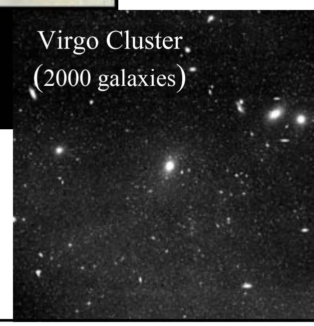
1000's of galaxies

Structure upon structure



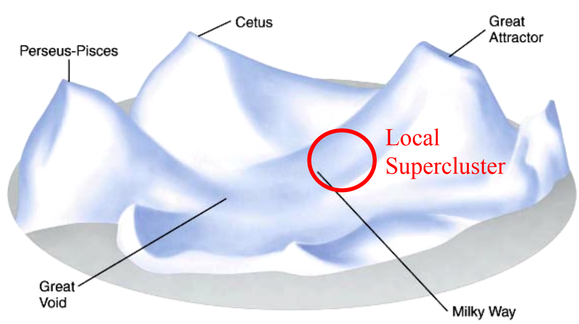


[Fig 27.7]



- Local Group is in orbit about Virgo Cluster (10^{14} $M_\odot$).
- All part of Local Supercluster (10^{15} $M_\odot$)

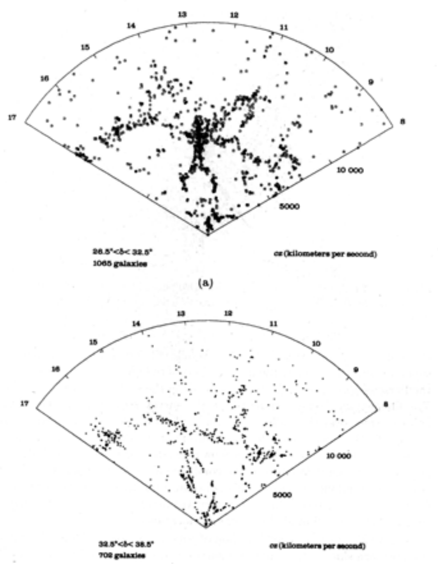
Structure upon structure

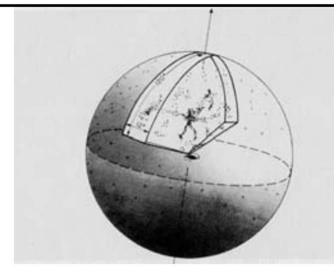


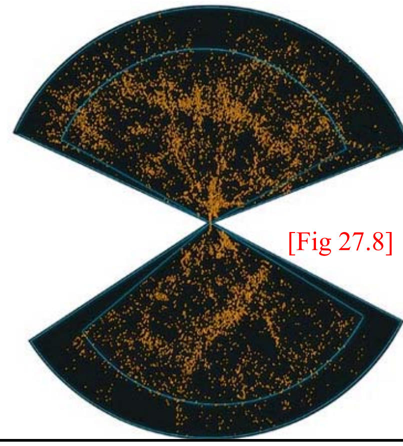
[Fig 27.20]

- Local Group is in orbit about Virgo Cluster (10^{14} $M_\odot$).
- All part of Local Supercluster (10^{15} $M_\odot$)
- Local Supercluster is part of streaming motion towards "Great Attractor"
  - $10^{16\text{-}17}$ $M_\odot$
  - located 45 Mpc away.
- Detected by extra motions superimposed on "Hubble Flow".

Bubbles and Voids



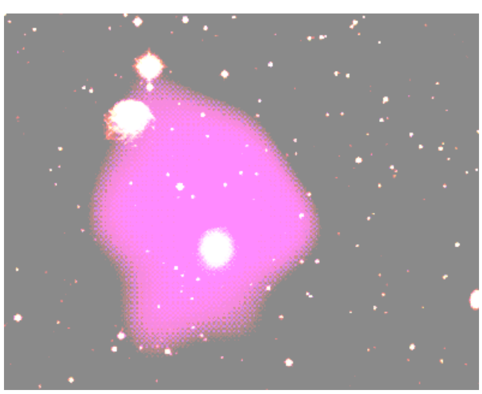




[Fig 27.8]

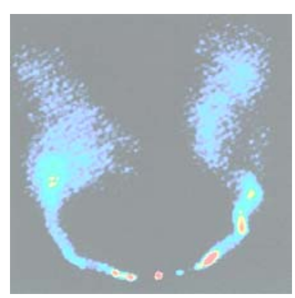
Gas within galaxy clusters

[Fig 27.10]



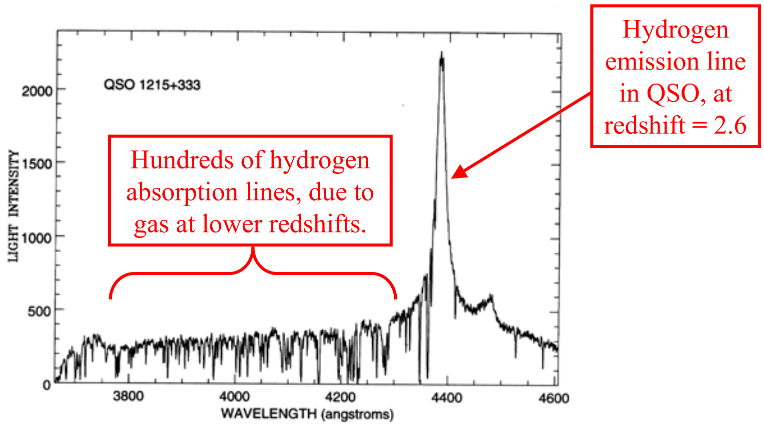
Measured from x-rays

see [Fig 27.9]

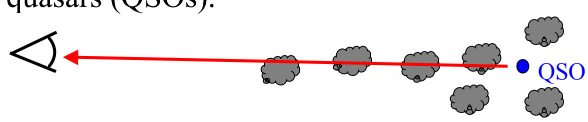


Occasionally causes trailing of radio jets

Gas between galaxy clusters.



- Detected by intervening gas clouds absorbing background light from distant quasars (QSOs).



The Distribution of Normal Matter

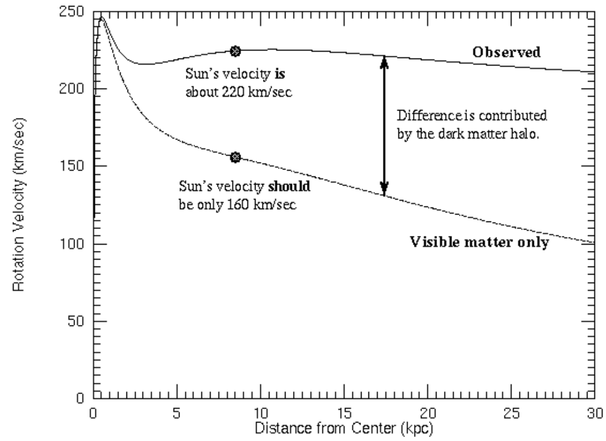
Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014

Total normal matter = **0.022**
Big Bang Nucleosynthesis predicts **0.03**

Dark Matter

- Motions in gravitational fields

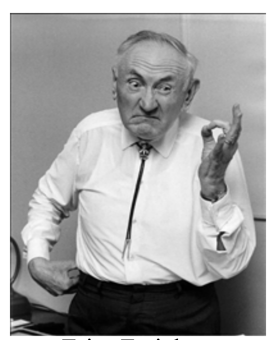
➔ ***much*** non-luminous matter.



- On scales of
  - Within galaxies
  - Galaxy clusters
  - Superclusters

Example: mass of Milky Way as determined from Sun's motion.

"Missing Matter" actually discovered in 1933



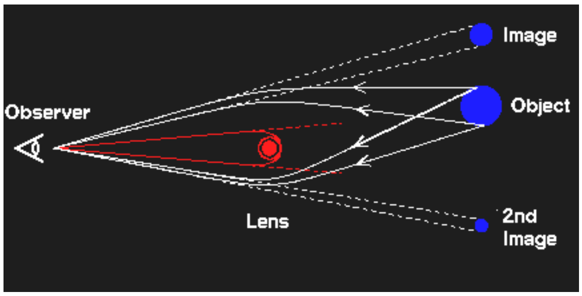
Fritz Zwicky

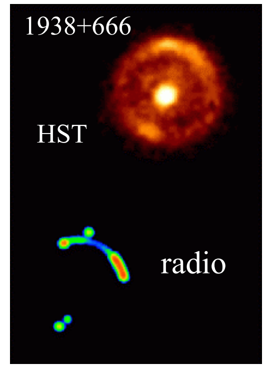
- Motions of galaxies within large clusters.
- Rapid motions ➔ larger cluster mass than suggested by luminosity of galaxies.

Gravitational Lenses

Another way to measure *total* mass in clusters

(see [26.4])

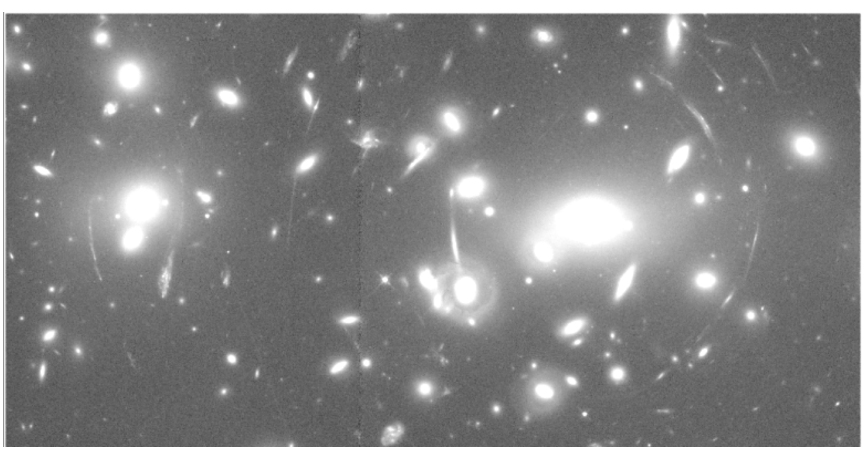




The “Einstein Cross”

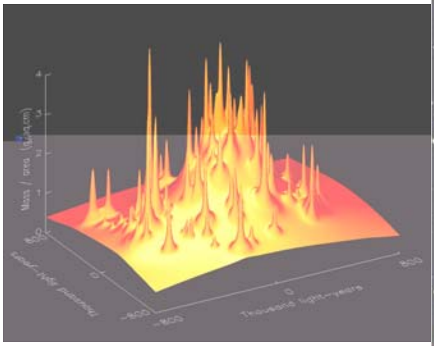
Galaxy at center causes 4 images of same quasar.

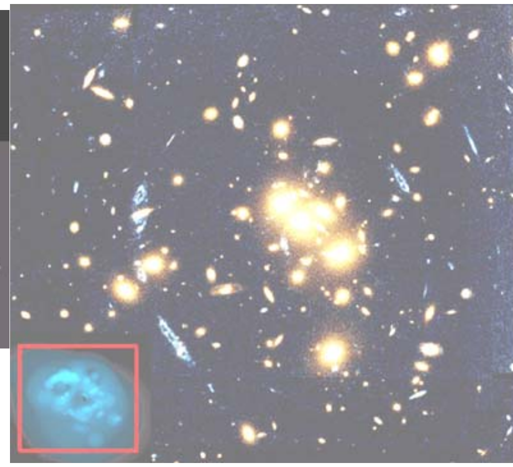
Gravitational Lens in Galaxy Cluster Abell 2218



- Foreground cluster distorts images of numerous background galaxies.
- Use to determine total mass of foreground cluster.
- Shows that 85% of mass is Dark Matter.

The Remarkable Case of CL0024+1654





- Single distant blue galaxy.
- Lensed by foreground cluster.
- 8 different images.

see [Fig 26.23]

- Allows detailed analysis of mass distribution in cluster.
- 83% of mass is non-luminous Dark Matter.

The distribution of *all* matter.

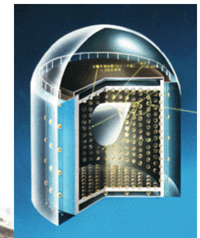
Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014
Dark Matter	0.3

Total normal matter = **0.022**
Big Bang Nucleosynthesis predicts **0.03**

90% of all matter is dark matter.

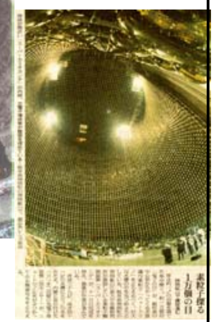
What *is* Dark Matter?

- Light, fast-moving particles?
  - Neutrinos recently discovered to have mass.
  - But only 1% of total mass.



see [Fig 15.14]

Super Kamiokande (Japan)

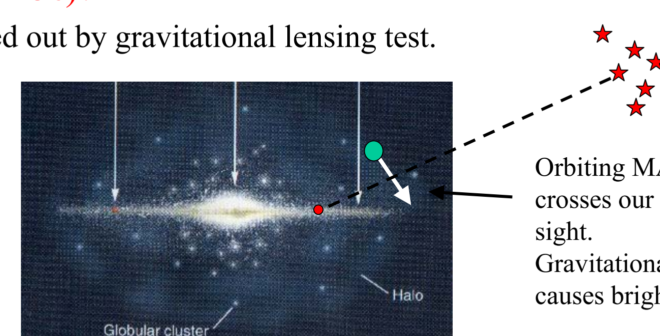


- Large chamber deep underground.
  - Neutrinos interact (weakly) with water.
  - 13,000 photocells detect resulting light.
- Found *neutrino oscillations*
  - Three types of neutrinos known.
  - Neutrinos change back and forth between types while in transit.
  - Can only happen if neutrinos have mass.

What *is* Dark Matter?

- Light, fast-moving particles?
  - Neutrinos recently discovered to have mass.
  - But only 1% of total mass.

- Massive Compact Halo Objects (MACHOs)?
  - Ruled out by gravitational lensing test.

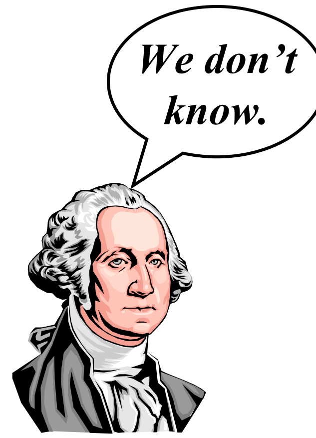


Large Magellanic Cloud

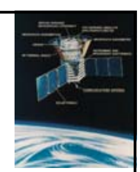
Orbiting MACHO crosses our line-of-sight.
Gravitational lensing causes brightening.

What *is* Dark Matter?

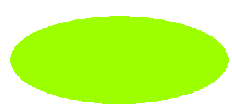
- Light, fast-moving particles?
  - Neutrinos recently discovered to have mass.
  - But only 1% of total mass.
- Massive Compact Halo Objects (MACHOs)?
  - Ruled out by gravitational lensing test.
- Weakly-Interacting Massive Particles (WIMPs)?
  - Current best bet.
  - Being searched for here on Earth.



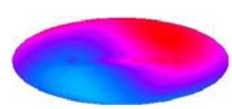
Formation of Structure



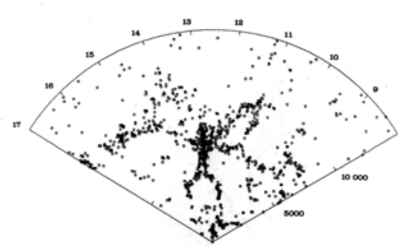
- Cosmic Microwave Background is extremely smooth
  - < 0.5% density variations when universe was 300,000 yrs old.
- Present universe is very clumpy
  - ~100% density variations.
- Insufficient time to go from one to the other through gravitational growth of density perturbations.



Blue = 0°K
Red = 4°K



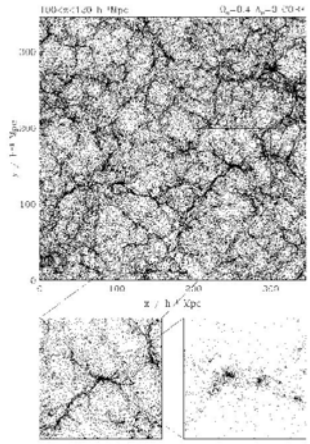
Blue = 2.724°K
Red = 2.732°K



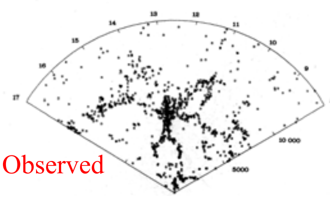
So where did galaxies and clusters come from?

Formation of structure

- Dark matter is necessary
- CMB only traces distribution of normal matter
  - Light does not interact with dark matter.
- Dark Matter must have already condensed into clumps by time of decoupling.



Computer models with Dark Matter can reproduce observed type of structure



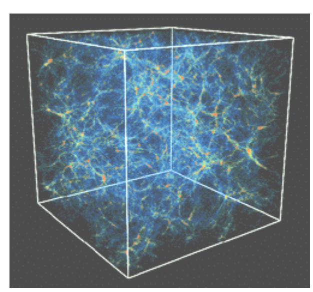
Observed

The Cosmic Web

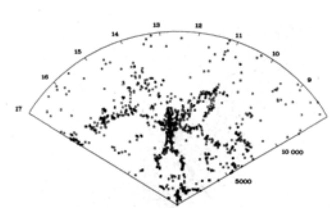
Recent calculations from the National Center for Supercomputing Applications.

Flythrough NSCA

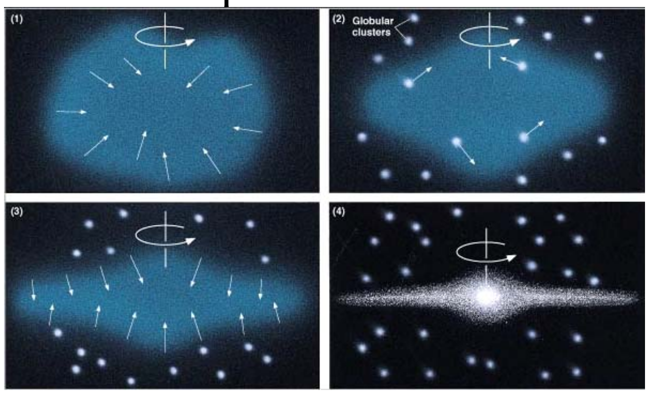
Growth of structure NCSA



Cannot get models to match observed structure unless 90% of matter is dark matter.



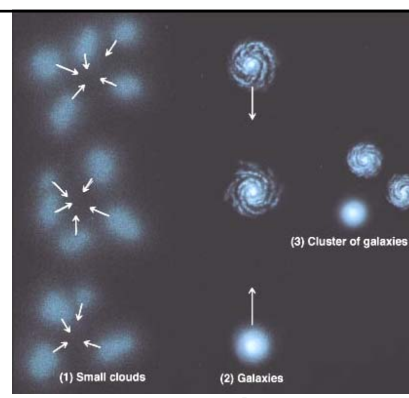
Formation of the Galaxy: Top-down model



- Collapse → rotating disk
- Halo (Globular clusters & halo stars) formed during collapse.
  - But many details are uncertain.

“Bottom Up” Galaxy Formation

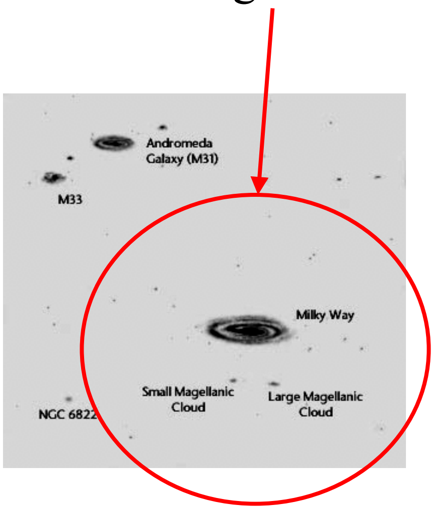
- Small structures form first
  - Dwarf galaxies
  - Globular Clusters
- Galaxies grow by cannibalism
- Ellipticals formed by mergers of spirals (?)
- Our current understanding is incomplete
  - Both “top-down” and “bottom-up” formation seem to play a role.



Time → Now

[Fig 27.18]

Satellite galaxies around the Milky Way



- In close orbits about our own Galaxy
- Irregulars and dwarf ellipticals

Galaxy	D (1000LY)	Lum. ($L_\odot$)
Milky Way	0	10^{11}
Large Magellanic Cloud	160	10^{10}
Small Magellanic Cloud	192	10^{10}
Fornax	450	10^{8}
Sagittarius Dwarf	80	10^{8}
Sculptor	285	10^{7}
+ 6 more known ones		

Satellite Galaxies

Large Magellanic Cloud

Small Magellanic Cloud

Milky Way

M31, M32, NGC 205

Life in the fastlane…

Colliding galaxies

Meanwhile, in a galaxy close, close to home…

The Milky Way Meets Andromeda

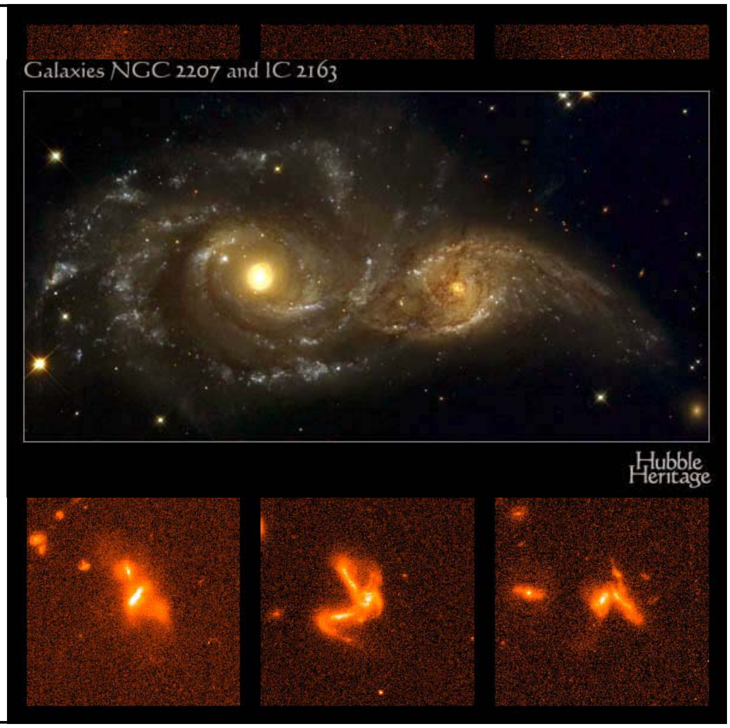
2.5 million ly away

Approaching at 500,000 km/hr

➔ Collision in 3 billion yrs

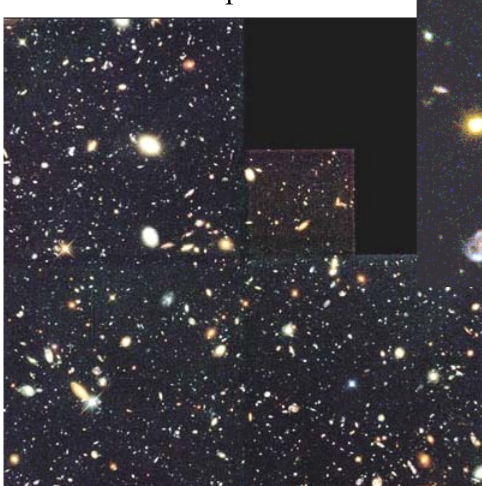
Movie lasts 1.3 billion yrs.

play

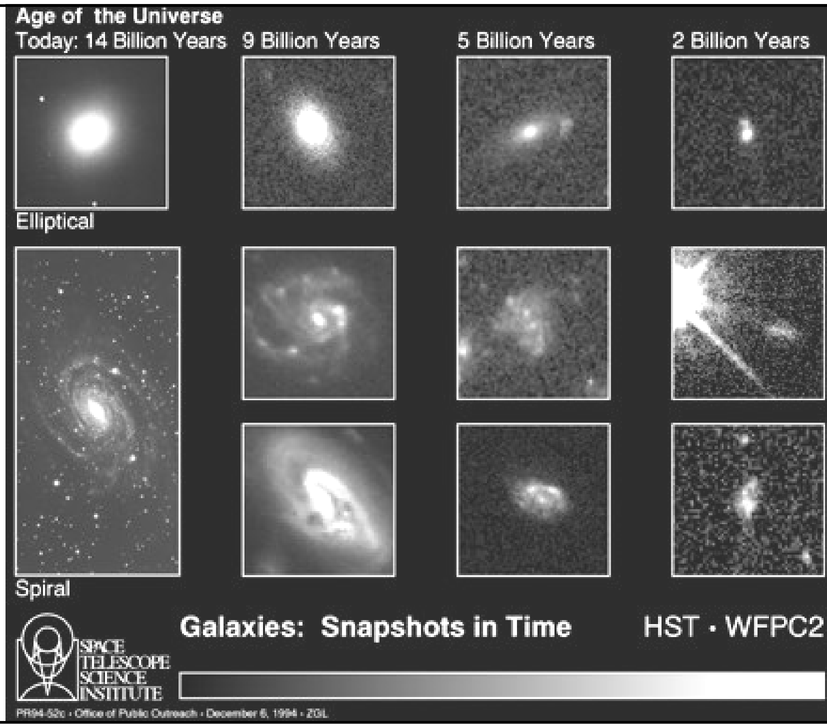


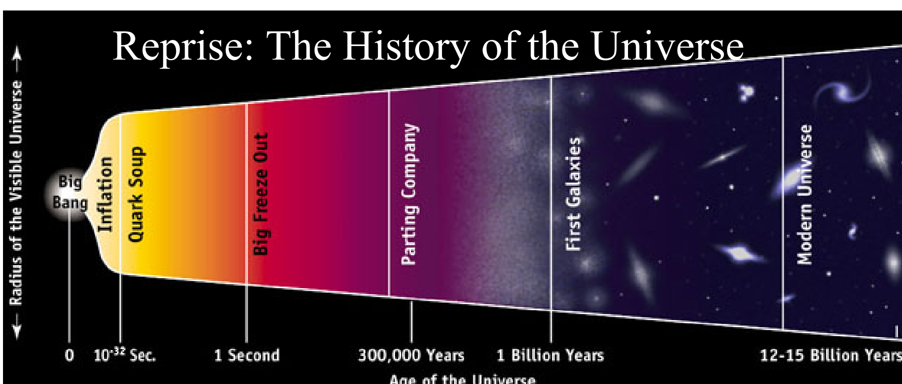
Looking back to the time of galaxy formation

The Hubble Deep Field



- Bottom-up structure formation.
  - We seem to see galaxies being assembled from smaller units.
- Large galaxy clusters are still forming.





Planck time

Inflation

Nucleosynthesis of H, He, Li

Decoupling of CMB

Galaxy Formation

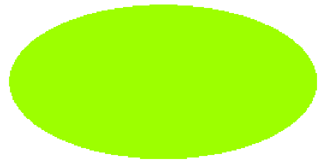
Now

Hot → Cool

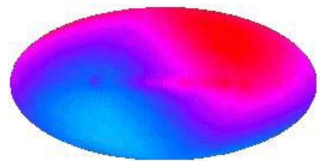
High density → Low density

Isotropy of the CMB

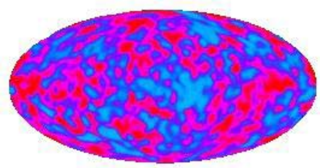
- COBE satellite.



Blue = 0^{o}K
Red = 4^{o}K



Blue = 2.724^{o}K
Red = 2.732^{o}K
Dipole Anistropy
→ motion of Sun through Universe.

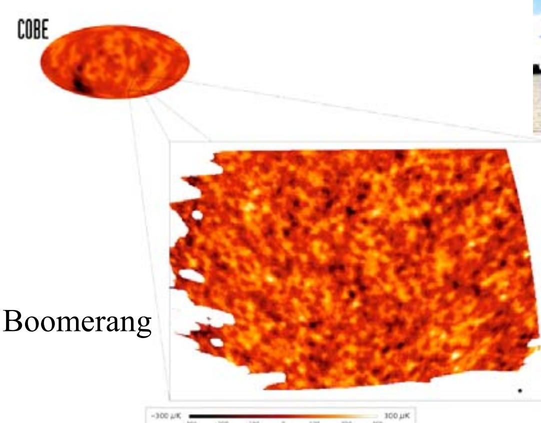


After removing dipole
Red – blue = 0.0002^{o}K

Structure in the CMB

- Boomerang balloon flight.

Launch near Mt. Erebus in Antarctica



Boomerang

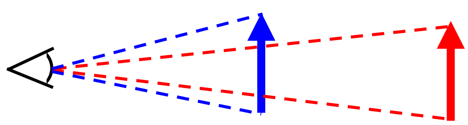
Mapped Cosmic Microwave Background with far higher angular resolution than previously available.

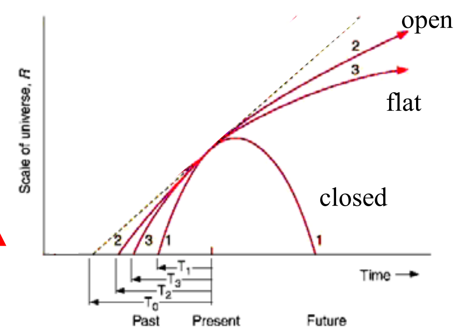
Structure in the CMB

What does it tell us?

- Sound waves permeated universe just before decoupling of CMB.
- Linear size of largest structure

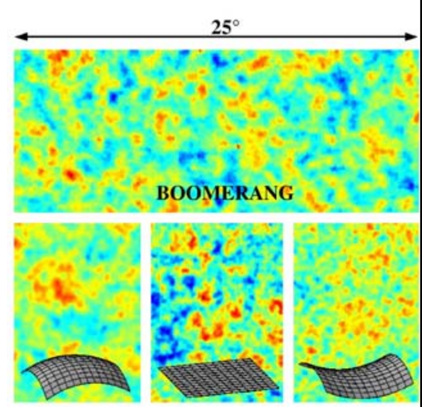
  = (speed of sound) x (age of universe at that time)
- Distance to surface emitting CMB depends strongly on cosmological model.
- ➔ Angular size depends on cosmological model.





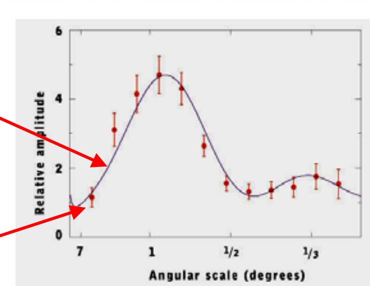
Structure in the CMB

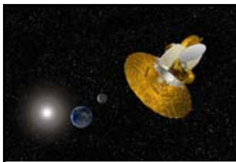
- The result so far
  - Universe is flat.
- Much better results coming soon
  - MAP satellite.
  - Planck satellite.



Predicted result for flat universe

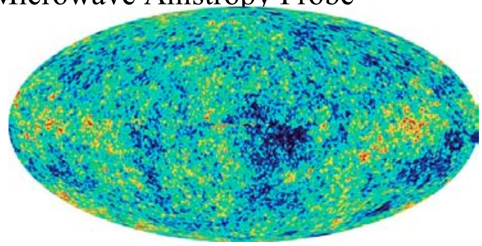
Points show measured values

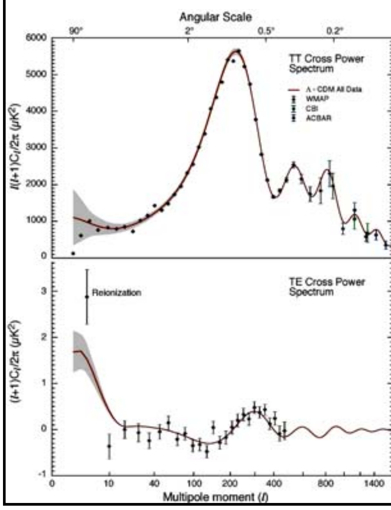


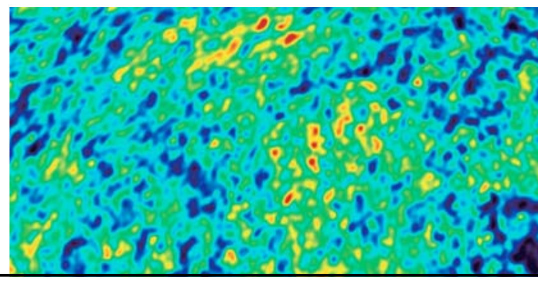


WMAP

Wilkinson Microwave Anistropy Probe







But there is not enough matter.

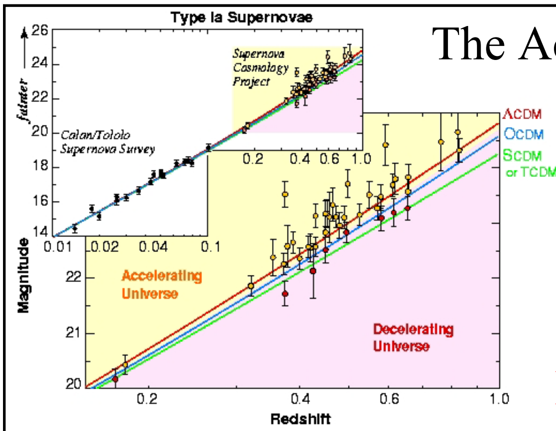
Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014
Dark Matter	0.3

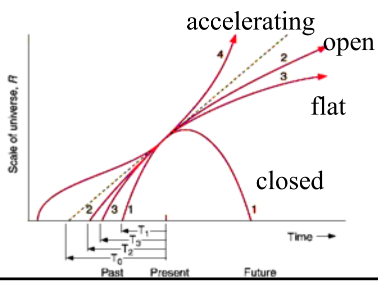
Total normal matter = **0.022**

Big Bang Nucleosynthesis predicts **0.03**

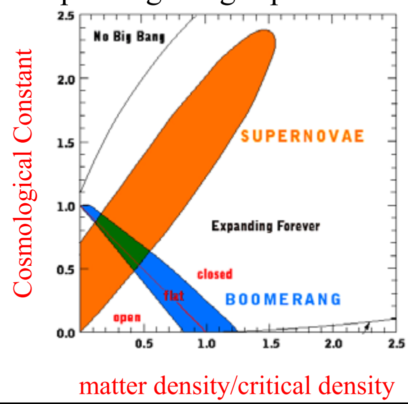
- Total detectable matter (luminous + dark) is only about 1/3 of "critical" density needed for flat universe.

The Accelerating Universe



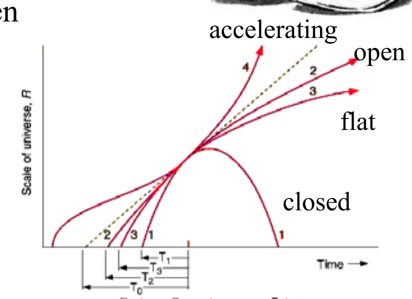


- Type Ia Supernovae as “standard candles”
  ➔ accelerating expansion.
- Two-parameter diagram
  ➔ mysterious extra “force” pushing things apart.

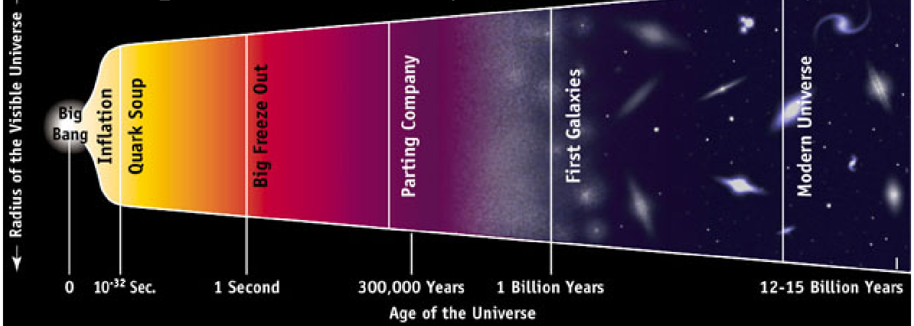


The cosmological constant.

- Einstein’s static universe
  - Cosmological constant balanced gravity.
  - Einstein: “My greatest blunder”
- Is it a constant?
  - If so, Universe hasn’t always been flat.
    - Density of mass and kinetic energy change with time.
  - “Rolling scalar fields” that relate this outward force to mass density???



Reprise: The History of the Universe



Planck time

Inflation

Nucleosynthesis of H, He, Li

Decoupling of CMB

Galaxy Formation

Now

Hot → Cool

High density → Low density

Event	Evidence	Odds
Big Bang followed by expansion.	Hubble's Law Cosmic Microwave Background	99.9%
Nucleosynthesis in Big Bang.	Lab measurements. Observed amount of helium.	99.9%
Essentially flat geometry.	Fluctuations in CMB. Flatness problem.	75%
Existence of Dark Matter	Lots of evidence. But wrong theory of gravity could explain it.	75%
Inflation.	Grand Unified Theory. Flatness, horizon problems.	50%
Accelerating universe.	Type Ia Supernovae measurements.	50%
What happened before inflation.	(slightly) informed speculation.	<10%

Where did the "Big Bang" Come From?

(dimensional analysis… no real theory exists)

- At earliest time about which we could hope to know anything:
  - Quantum fluctuations of energy, momentum

wild speculation

- Many little black holes:
  - Diameter $= \sqrt{\frac{\hbar G}{c^3}} = 10^{-33}$ cm

Causal connection across this distance

  - Light crossing time = **Planck Time**.

$$t_P = \sqrt{\frac{\hbar G}{c^5}} = 5.39 \times 10^{-44} \text{ seconds}$$

  - Temperature = 10^{32} °K

- One of these black holes blew up into our present universe.

The End of the Universe

Continued expansion, forever… (we think).

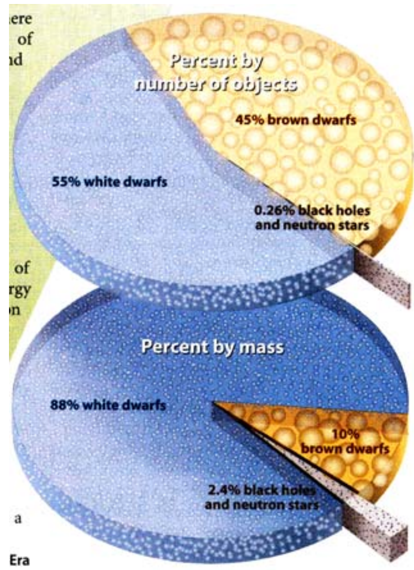
10^{-44} sec	Planck Time
$10^{-38} - 10^{-32}$ sec	Inflation
10^{-32} sec – 10^{4} yrs	Radiation Era
$10^{4} - 10^{14}$ yrs	Stellar Era
$10^{14} - 10^{37}$ yrs	Degenerate Era
$10^{37} - 10^{100}$ yrs	Black Hole Era
$> 10^{100}$ yrs	Dark Era

Now = 1.4×10^{10} yrs

(Extremely speculative: See *Sky & Telescope* magazine, August 1998)

Degenerate Era

- $10^{14} – 10^{37}$ yrs.
- Almost no further radiation from stars.
  - Cold, dark universe.
- But…
  - Occasional collisions between brown dwarfs ➔ new low-mass stars (10 to 100 in existence per galaxy at any given time).
  - Occasional collisions of degenerate stars ➔ supernova.



The End Products of 10^{14} Years of Stellar Evolution

Black Hole Era

wild speculation

- $10^{37} – 10^{100}$ yrs.
- Degenerate stars have all disappeared through proton decay (maybe)
  - p ➔ e^+ , neutrinos, gamma rays
  - No more atoms
- Dark matter previously swept into degenerate stars and annihilated (??????)
- Only black holes are left.
- But black holes also evaporate
  - *Hawking radiation*: very slow conversion of gravitational energy back to particles or photons.

Dark Era

- Essentially nothing left except hugely redshifted CMB photons.

What's outside the Universe?

- Other universes, not intersecting with our Universe??
- Some magic numbers:
  - At t = 1 second, our Universe defined by:
    - Ratios of
      - **Energy Density.** Matter:Kinetic-energy:Cosmolgical-constant-energy.
      - **Numbers of particles.** Photons:Normal-matter:Dark-matter
    - Amplitude of density fluctuations ~ 10^{-5}
  - Imprinted by Planck Time: ratios of physical constants.
    - Example: electrostatic force 10^{36} x stronger than gravitational force.
  - Different values in other universes?

- ***Anthropic Principle***: our particular universe is suitable for us to live in because otherwise we would not be alive to know about it.

Good book: ***Before the Beginning***, by Martin Rees