Announcements

Homework.

- Set 8 now open.
  - due late at night Friday, Dec 10 (3AM Saturday Nov. 11)
- Set 7 answers on course web site.

Review for Final.

- In class on Thursday.

Course Evaluation.

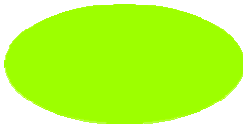
https://rateyourclass.msu.edu

Final Exam.

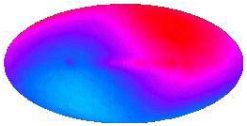
- Monday December 13.
- 8-10 PM. (PM = in the *evening*!!!).
- In the usual classroom (Natural Resources 158).
- Counts as 1.5 midterms.
- 70 questions.
- 2/3 over material since Midterm 3.
- 1/3 over earlier material.
  - reworded midterm questions.
  - + a few new general questions.
  - + a few about *telescopes.*

Isotropy of the CMB

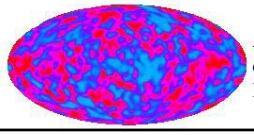
- COBE satellite.



Blue = 0°K
Red = 4°K



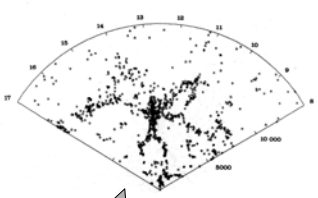
Blue = 2.724°K
Red = 2.732°K
Dipole Anistropy
➔motion of Sun through Universe.



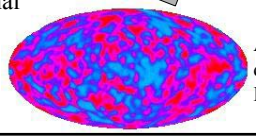
After removing dipole
Red – blue = 0.0002°K

Formation of Structure

- Cosmic Microwave Background is nearly smooth
  - < 0.5% density variations when universe was 300,000 yrs old.
- Present universe is very clumpy
  - ~100% density variations.
- But not enough time since CMB for these gravitational perturbations to have grown.



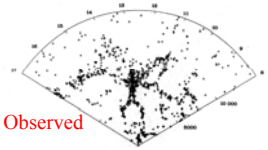
So where did galaxies and clusters come from?



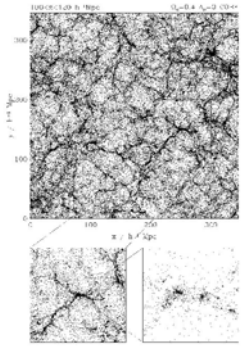
After removing dipole
Red – blue = 0.0002°K

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.



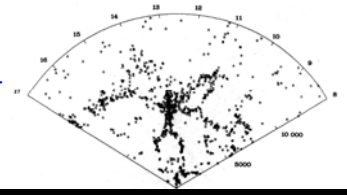
Observed



Computer models with Dark Matter can reproduce observed type of structure

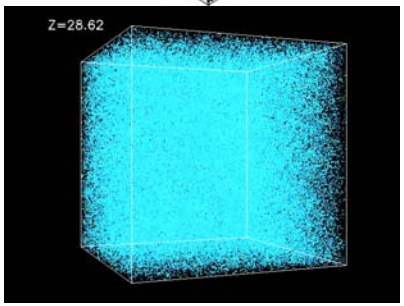
The Observed Distribution of Galaxies

- Like giant soap bubbles.



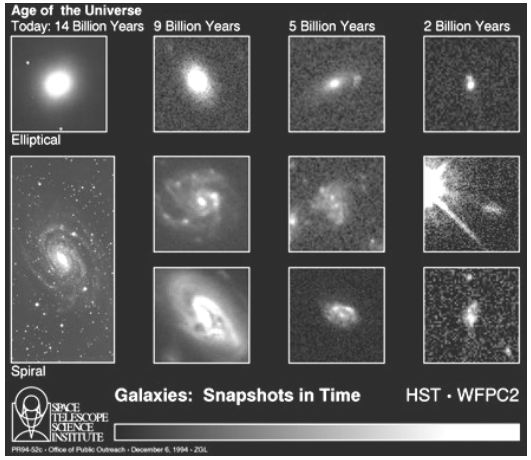
➔ The Structure of the Universe

- The "Cosmic Web".
- Structures formed due to gravitational attraction of "dark matter".



Flythrough NSCA
Growth of structure NCSA

Bottom-Up Structure Formation



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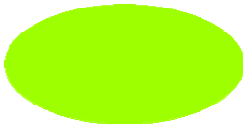

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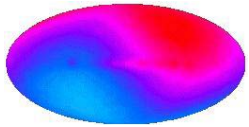

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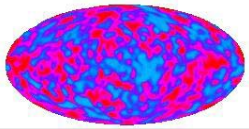
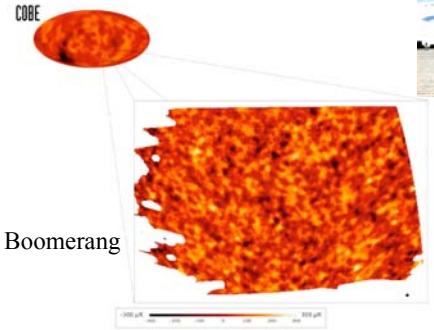


After removing dipole
Red – blue = 0.0002°K

Structure in the CMB

- Boomerang balloon flight. 1998

Launch near Mt. Erebus in Antarctica

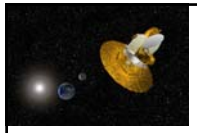


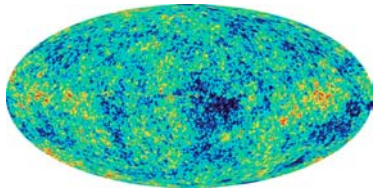
Boomerang

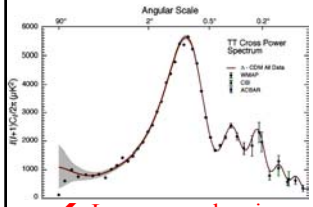
Mapped Cosmic Microwave Background with far higher angular resolution than previously available.

WMAP

Wilkinson Microwave Anistropy Probe
Launched 2001

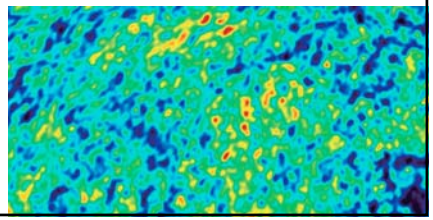






← Larger angular size

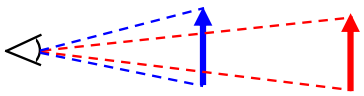
Measure "power" in fluctuations on different angular scales.

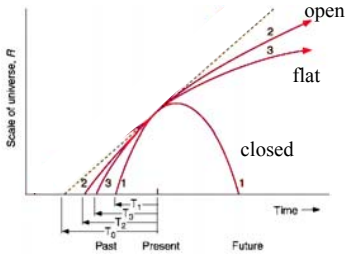


Structure in the CMB

What does it tell us?

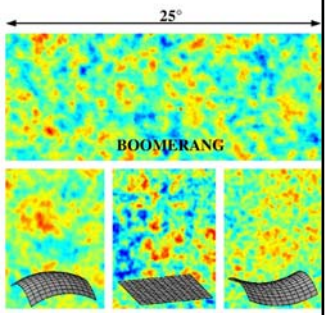
- Sound waves permeated universe just before decoupling of CMB.
- Linear size of largest structure
  = (speed of sound) x (age of universe at that time)
- Distance to surface emitting CMB depends strongly on cosmological model.
- ➔ Angular size depends on cosmological model.





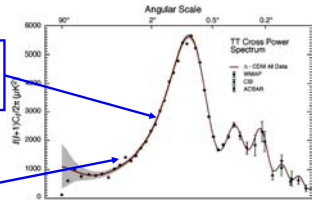
Structure in the CMB

- The result:
  - The universe is FLAT.



Line shows predicted result for flat universe

Points show measured values



But there is not enough matter.

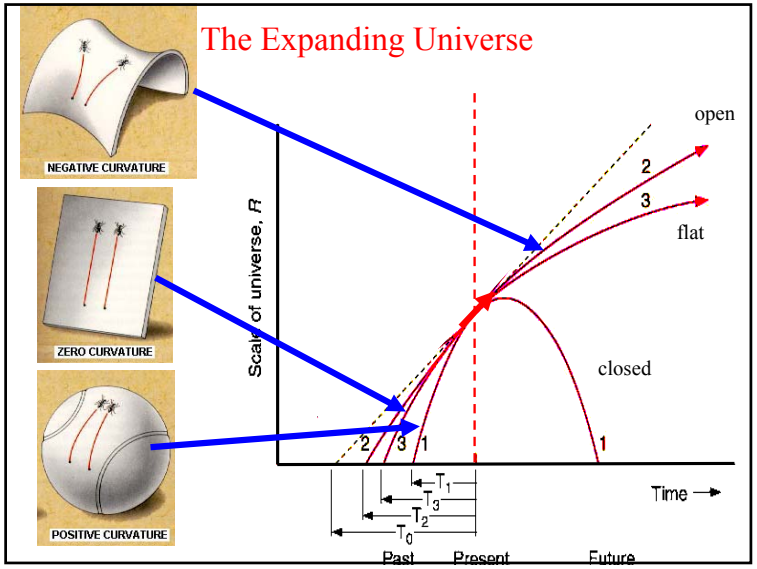
Location	Fraction of critical density
Gas within galaxies	0.001
Gas in galaxy clusters	0.003
Stars within galaxies	0.004
Gas between galaxy clusters	0.014
Dark Matter	0.3

Total normal matter = **0.022**

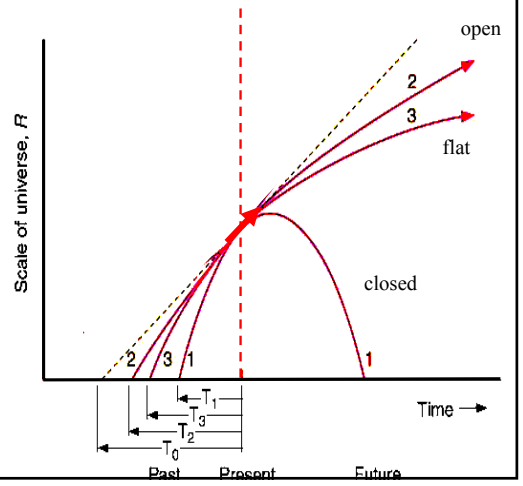
Big Bang Nucleosynthesis predicts **0.03**

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

The Expanding Universe



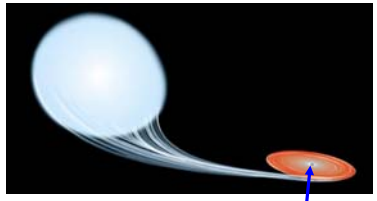
Which Universe Do We Live in?



Which Universe Do We Live In?

- Type Ia Supernovae
  - Neighbor star dumps too much mass onto a white dwarf.
  - Collapse to neutron star.
  - Supernova explosion.
- Type Ia Supernovae as "standard candles".
  - Always happens when mass goes just past limit for white dwarfs.

  ➔ Supernova always has same luminosity.
  - Get distance from $\text{Flux} = \frac{L}{4\pi r^2}$



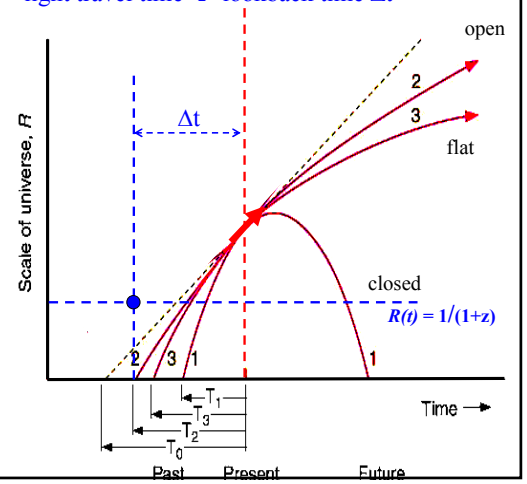
white dwarf at center of accretion disk

Which Universe Do We Live in?

Distance = light travel time ➔ lookback time Δt

What we can measure for supernovae:

- Redshift
- Distance

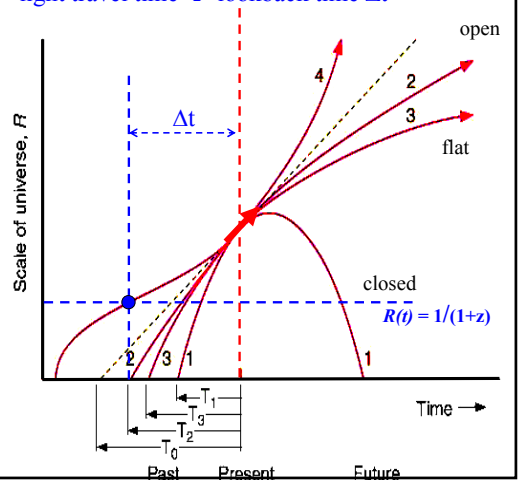


The Accelerating Universe

Distance = light travel time ➔ lookback time Δt

What we can measure for supernovae:

- Redshift
- Distance

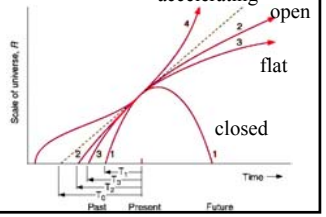


There is another force.

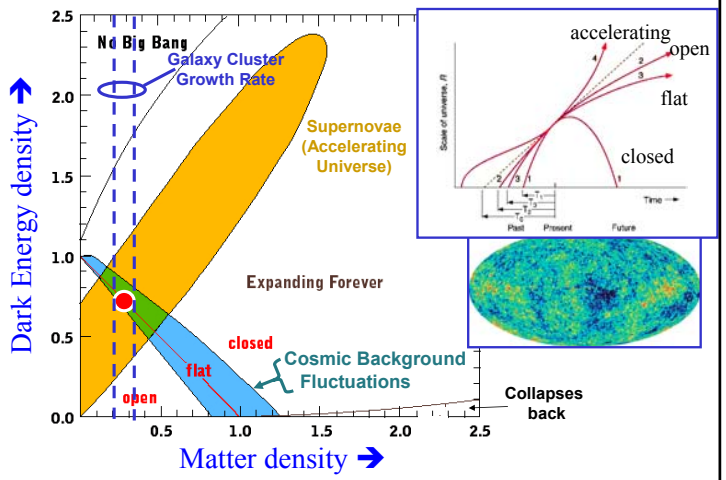
The Cosmological Constant. (Dark Energy)

- Einstein's static universe
  - Cosmological constant balanced gravity.
  - Einstein: "My greatest blunder"

- Acts as force pushing things apart.
- What is it?
  - Nobody knows.
- Is it really a constant?
  - Nobody knows.



What is the Universe Made Of ?



Both axes expressed as *fraction of Critical Density.*

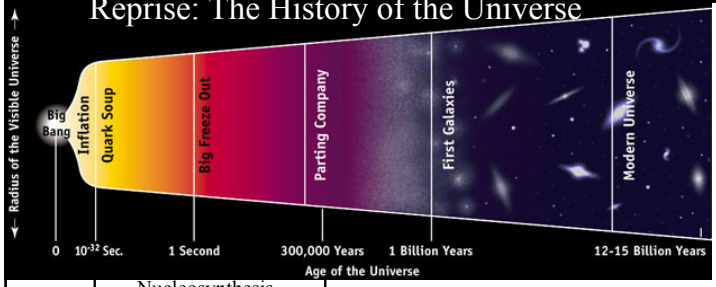
What is the Universe Made Of ?

We infer these are there, but we don't know what they are.

73% Dark Energy (using $E = mc^2$)
23% Dark Matter
4% Normal Matter

This is the only part we see.

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%
Accelerating universe.	Type Ia Supernovae measurements. Galaxy clusters.	75%
Inflation.	Grand Unified Theory. Flatness, horizon problems.	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
- Many little black holes:
  - Diameter $= \sqrt{\frac{\hbar G}{c^3}} =$ 10^{-33} cm
  - 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.

wild speculation

Causal connection across this distance

The End of the Universe

Continued expansion, forever… (we think).

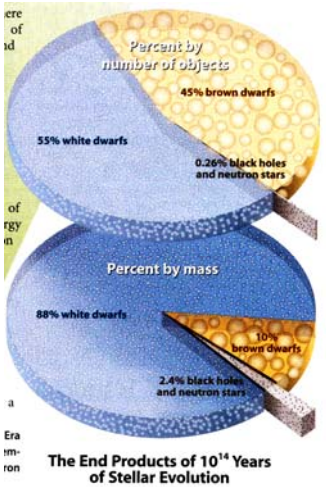
10^{-43} sec	Planck Time
10^{-38} – 10^{-32} sec	Inflation
10^{-32} sec – 10^{4} yrs	Radiation Era
10^{4} – 10^{14} yrs	Stellar Era
10^{14} – 10^{37} yrs	Degenerate Era
10^{37} – 10^{100} yrs	Black Hole Era
> 10^{100} yrs	Dark Era

Now = 1.4 x 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

- 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.

wild speculation

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