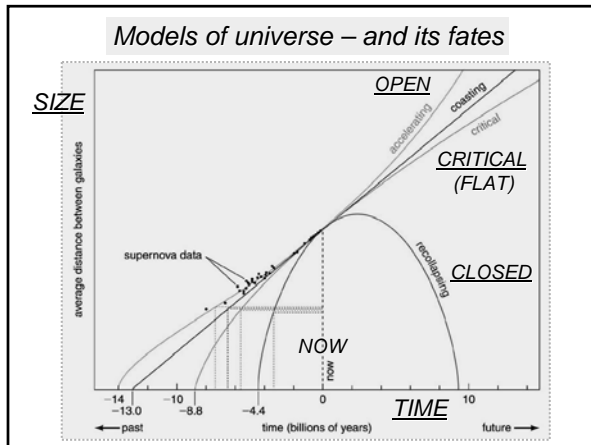


- Cosmological Events**
- Today look at "BEGINNING OF TIME"
 - Final Exam Review this Wed 27 Apr by Ben Brown, here, 7-9pm. Final review sheet available in class Wed. All extra-credit observing projects due by this Wed.
 - Course evaluation on Wed – please bring your favorite #2 pencil!
 - On Wed discuss extra-solar planets and possibilities of life elsewhere (Chap 24)



- Clicker on our universe**
- Which events had profound effects on our modern views of universe?
- D.**
- A. Einstein devising General Theory of Relativity
 - B. Penzias & Wilson detecting uniform CMB radiation from all directions
 - C. Hubble finding that most galaxies are receding – “the Hubble law”
 - D. All of the above

REMINDER Which is it ?

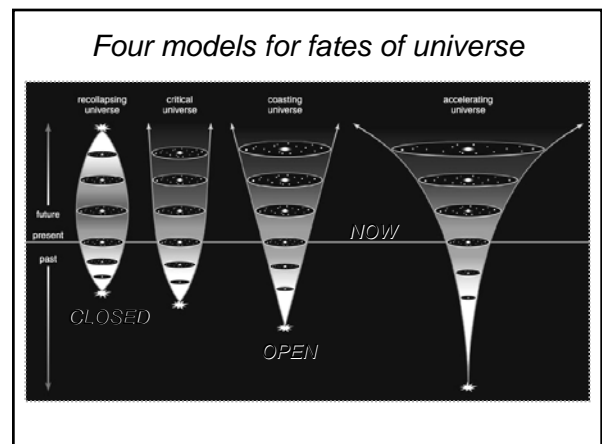
Is there enough dark matter to recollapse the universe?

Baryonic matter: only few % of critical density

Dark matter: only about 25 % of what is needed

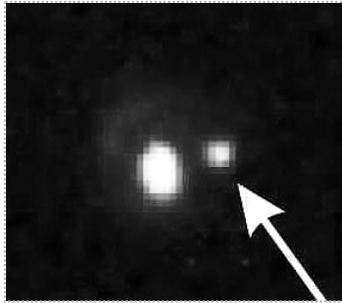
Universe is between the “coasting” and “critical” models

Universe will expand forever (or so it seems)



New twist in the new millenium

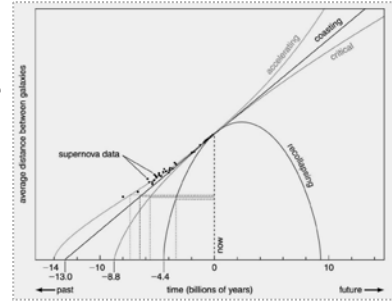
- White dwarf supernovae: standard candles at $Z \sim 1$
- Explosions bright enough to be seen very far away (back in time)



Made especially possible by HST

Redshifts of the supernova plot their vertical position

- $Z = 1$ means about halfway down from the "NOW" level
- Expansion factor = $1 + Z = 2$

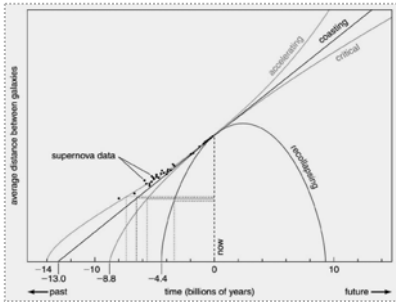


Brightness plots their horizontal position

Dimmer

= more distant
= longer ago

- Supernovae are DIMMER than expected for a coasting universe
- Universe is accelerating ??

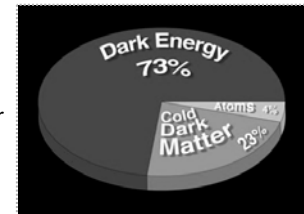


How can universe be accelerating??

A force that counteracts gravity?

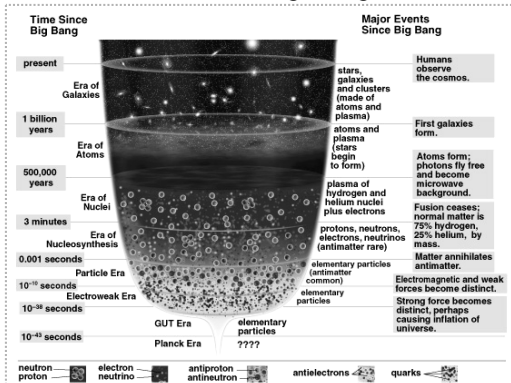
"Dark energy" – outweighs every other form of mass/energy!

Truly an unknown force in all of physics!



(Read "Einstein's Biggest Blunder" Cosmological Constant - p 695)

In the VERY Beginning



Big bang idea

COSMIC FIREBALL

George GAMOW (1948)

Oops! Pure HELIUM

THE COSMIC FIREBALL

- OBSERVE THAT
1. UNIVERSE IS EXPANDING
 2. "PRIMITIVE" MATTER COMPOSITION (BY MASS)
HYDROGEN 75% HELIUM 25% OTHER (METALS) 2%
- INFER FROM 1 THAT UNIVERSE WAS HIGHLY COMPRESSED AT ITS BEGINNING

ALPHEE, BEHNE, GEORGE GAMOW (1948) [N.R.S.]

ASSUMING UNIVERSE BEGAN AS PURE NEUTRONIC "YLEM"

NEUTRON DECAY: $n \rightarrow p + e + \bar{\nu}$ (NEUTRONS FROM ORIGINAL UNIVERSE HAD HALF-LIFE 10.6 MIN)

PROTON CAPTURE: $n + p \rightarrow d + \gamma$ (DEUTERIUM)

TRIAL 1) $n + p \rightarrow 2H + \gamma$

TRIAL 2) $2H + p \rightarrow 3He + \gamma$

TRIAL 3) $3He + n \rightarrow 4He + \gamma$

RESULT: A PURE HELIUM UNIVERSE

IN RECON. CONTACT WITH OBSERVATION THAT ABOUT 75% IS HYDROGEN!

HOT Big Bang

did the trick!

WHAT WAS MISSING IN "OLD" MODEL WAS SOMETHING TO SUPPLEMENT HELIUM FORMATION

ANSWER: HAWKING (1975, 1976)

VERY INTENSE RADIATION DEVIATES & CREATES MATTER
PRESENT IN THE VERY EARLY STAGES OF EXPANSION,
AT TEMPERATURES $T > 10^{10}$ (TEN BILLION) K

REACTIONS: MATTER (PROTON) + ANTI-MATTER (ANTI-PROTON) → GAMMA-RAY PHOTON
ANALOGOUS: $P + P^- \rightarrow \gamma$
CREATES: $\gamma + \gamma \rightarrow P^+ + P^-$
ONE QUANTA-RAY MUST HAVE ENERGY $E \geq 2 m_{\text{PROTON}} c^2$

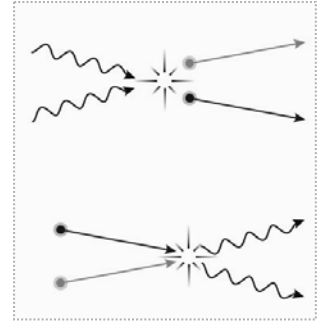
LOWER ENERGY PARTICLES MAKE: $\gamma + \gamma \rightarrow e^- + e^+$
ELECTRON PAIR (MATTER) + POSITRON (ANTI-MATTER)

THEN: $n + e^+ \rightarrow p + \bar{\nu}$
 $p + e^- \rightarrow n + \nu$

NEUTRONS SWITCH BACK AND FORTH TO PROTONS!
SO CANNOT STAY WITH PURE NEUTRONIC
THIS FOR LESS HELIUM PRODUCED AT BEGINNING

Matter and Anti-matter

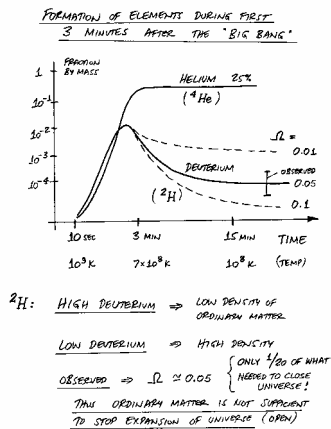
- Protons slightly outnumber anti-protons
- At end of particle era, universe contains some matter!
- Universe ratio today:
1 billion photons (light)
1 leftover proton (matter)



During first 3 minutes

Making the elements

How much DEUTERIUM made depends on density of ordinary matter (baryons)



After first 3 minutes

RADIATION ERA

--> 380,000 yr

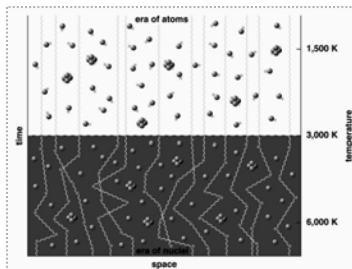
MATTER ERA

AFTER THE FIRST 3 MINUTES :

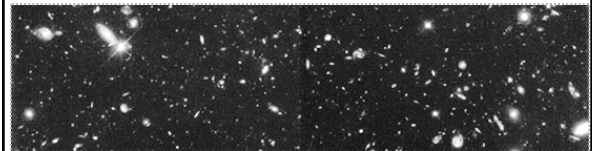
- RADIATION ERA : 1 SEC \rightarrow 1 MILLION YR
 10^{10} K \rightarrow 3000 K
- INCLUDES EPOCH OF ELEMENT FORMATION
 - MOST ENERGY IN UNIVERSE IN FORM OF RADIATION
 - RADIATION PRESSURE PREVENTS STRUCTURE FROM FORMING
- ENDS WITH RECOMBINATION H AND He BECOME NEUTRAL, RADIATION UNCOUPLES FROM MATTER
- MATTER ERA : 1 MILLION YR \rightarrow NOW (15 BILLION YR)
3000 K \rightarrow 2.7 K
- CLUMPING OF MATTER (MATTER NOW NOT AFFECTED BY RADIATION PRESSURE)
 - QUASARS FORM, THEN GALAXIES AND CLUSTERING OF GALAXIES

Era of Atoms

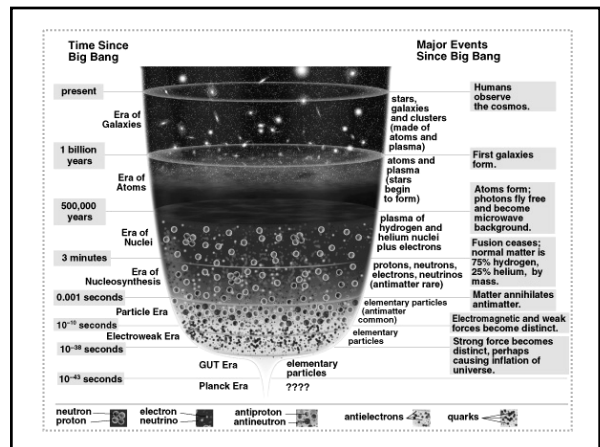
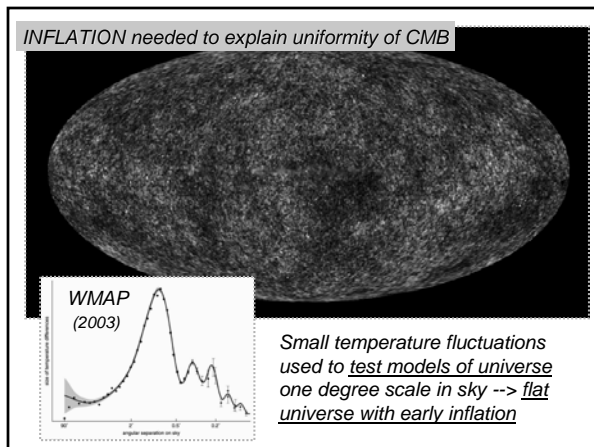
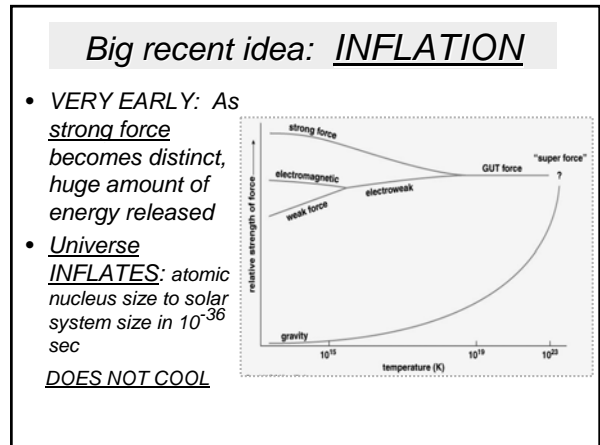
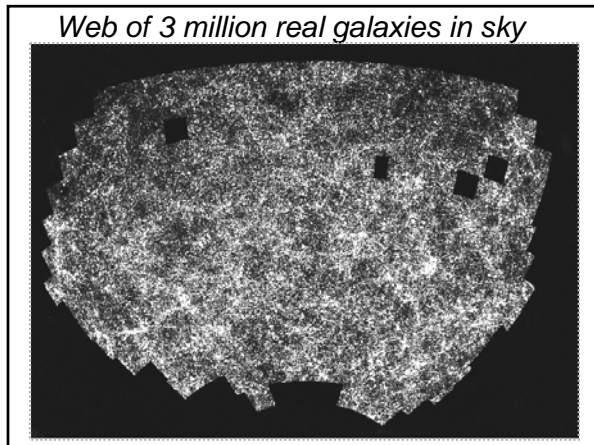
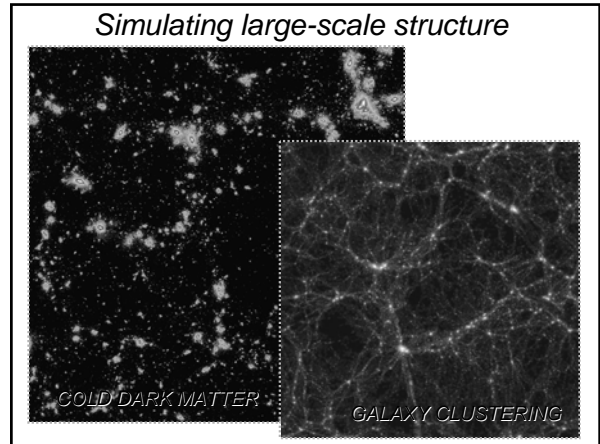
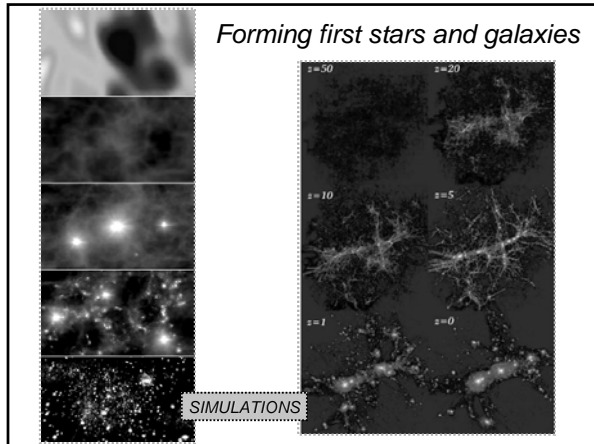
- Finally cool enough for electrons combine with nuclei to form atoms (380,000 yrs)
- Photons now "decoupled" = free to become CMB of future
- Universe becomes transparent to light



Era of Atoms and Galaxies



- About 1 billion years after Big Bang, first stars and galaxies start to form ($Z = 10$?)



- *With alarming new ideas like inflation and dark energy*
- *Einstein deserved to be concerned!*

