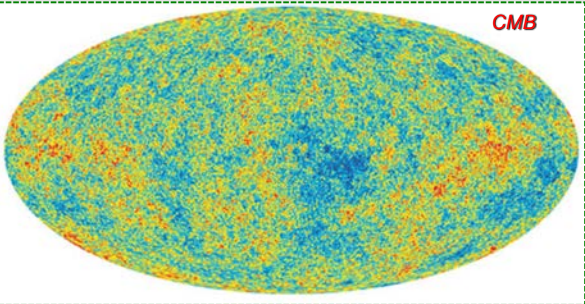


ASTR 1040: Stars & Galaxies



CMB

*Prof. Juri Toomre TAs: Daniel Segal, Max Weiner
Lecture 29 Tues 28 Apr 20
zeus.colorado.edu/astr1040-toomre*

Our Schedule

- **Final Exam on Wed May 6, 4:30pm-7:00pm**, comprehensive, on Canvas/Quizzes, closed book, 2 crib sheets allowed (4 sides)
- **Review #4** next Mon May 4, 4:30pm-6:30pm by Max Weiner, on zoom
- **Review Set #4** posted on Modules
- All **observatory night reports**, extra-credit, due by Thur (Apr 30) latest
- **Overall course grade estimate** to date posted
- Finish reading 23.4 **Dark Energy and Fate of Universe**
- Today: **First few minutes of our Universe**

THIRD MID-TERM EXAM

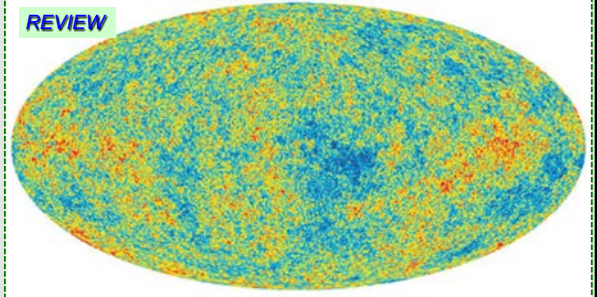
- **Grade boundaries**, based on 120 points (graded on a "curve"):
- If 108/120 (90%) or over, **A's [41%]**
- 96/120 (80%) or over, **B's [40%]**
- 84/120 (70%) or over, **C's [19%]**

Also +, plain, and - within these ranges

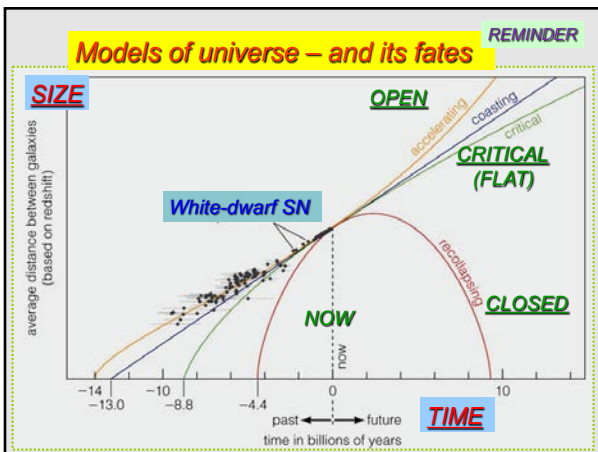
Go through answers – and talk to us if do not understand our choices.

CMB: Light from beginning of time

REVIEW



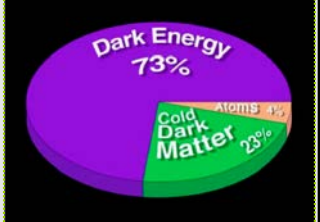
- This faint light looks like a solid glowing wall
- **Thermal spectrum at 3000 K (visible)**, if redshifted by factor $Z \sim 1000 \rightarrow 3 K!$ (microwaves)



White-dwarf SN → accelerating universe

Conjecture: An unknown force at large scales begins to counteract pull of gravity

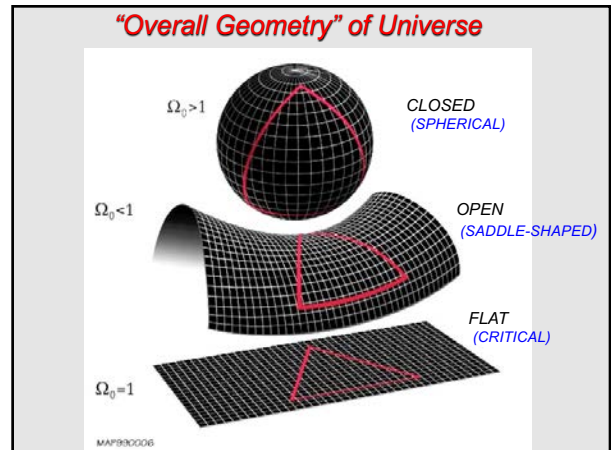
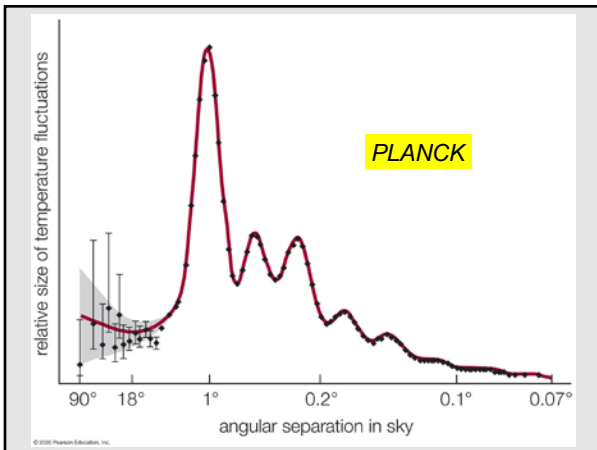
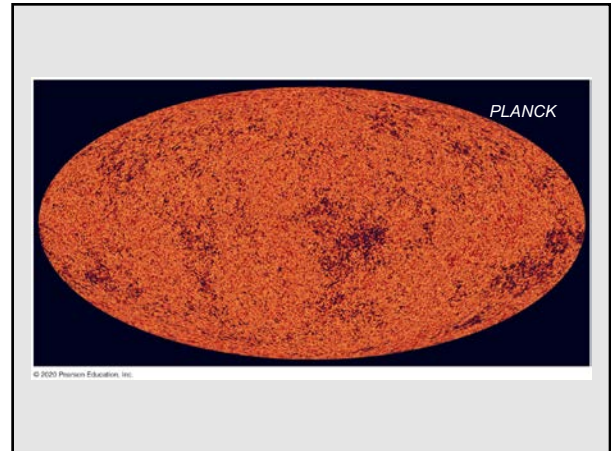
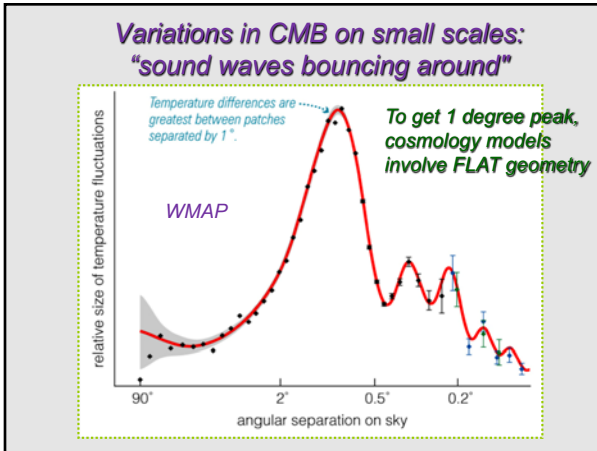
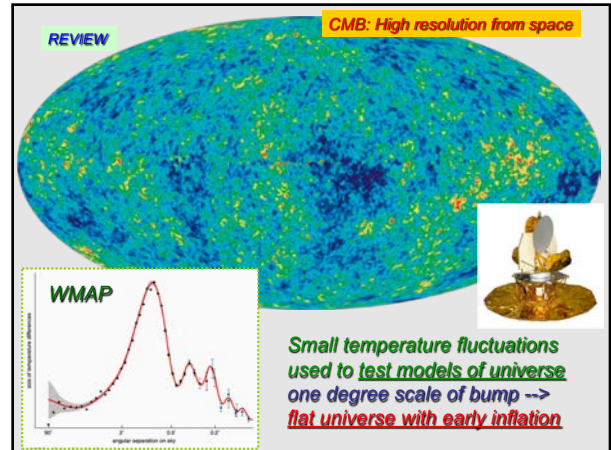
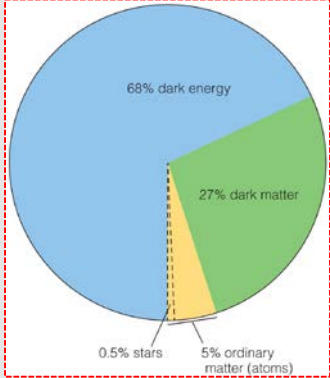
"Dark energy" – outweighs every other form of mass/energy ~73% (maybe 68%)

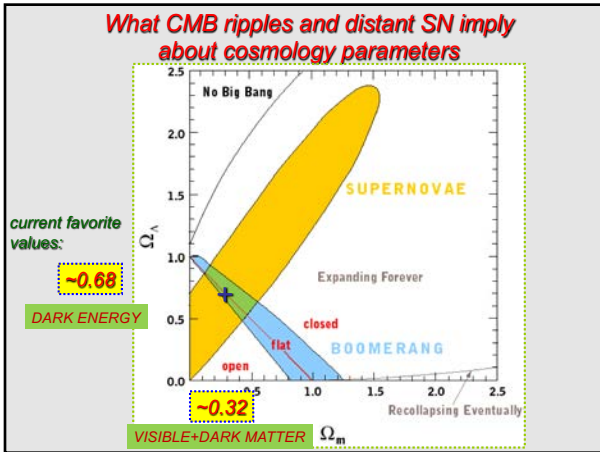


Baryons: 4.4% (5%) Dark Matter: ~23% (27%) with a **FLAT** universe and early inflation

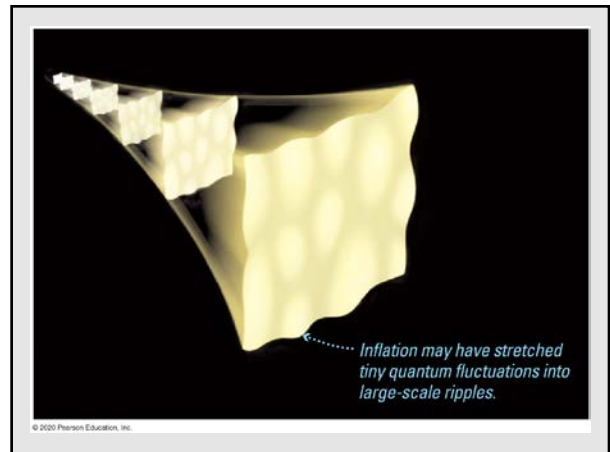
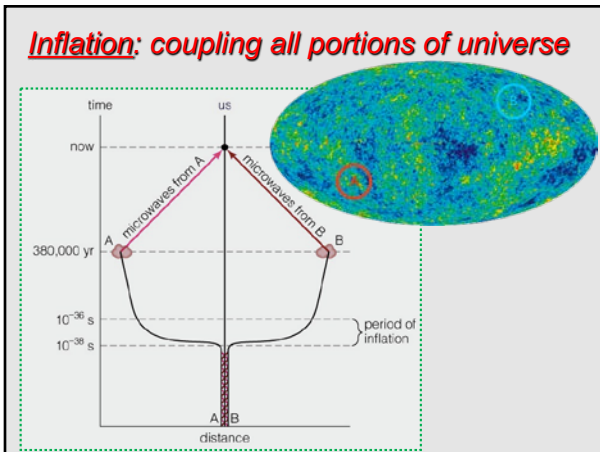
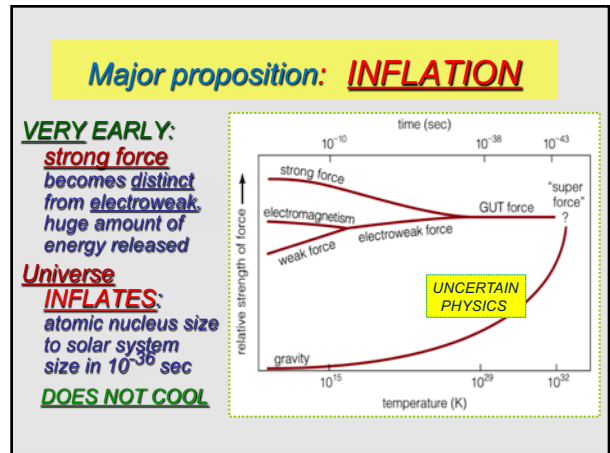
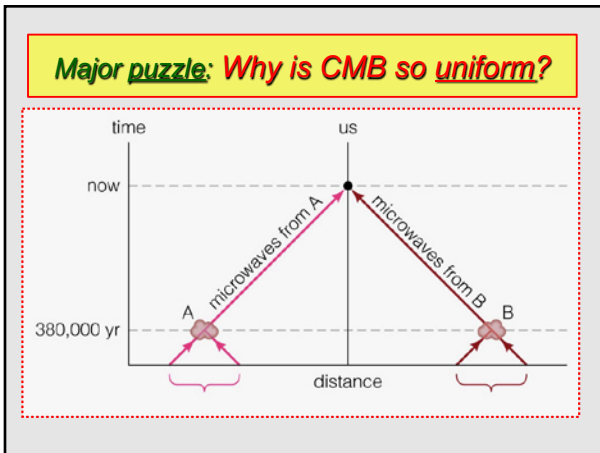
Accelerating Universe: Mass-Energy Pie Chart

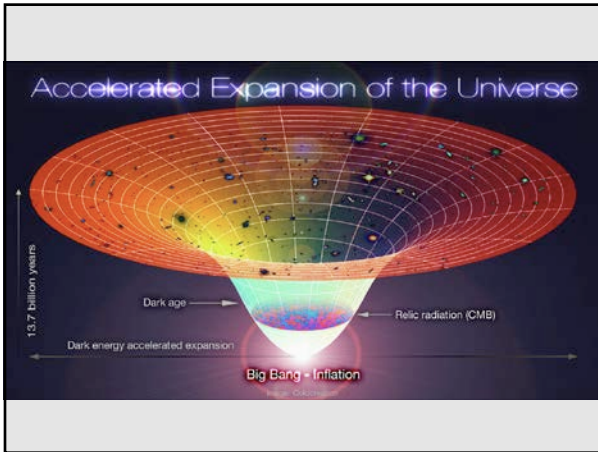
- **Dark energy**—more prevalent than every other form of mass/energy!
- A repulsive force that counteracts gravity?





Questions or Comments





Poll 1: What is Olber's paradox?

- A. If the universe was infinite, any direction you looked you would eventually see a star
- B. If the universe was infinitely old, the starlight would have time to get here
- C. The sky should look bright at night—because all directions would have starlight
- D. All of the above

Darkness of the night sky

Olbers' Paradox

If universe were

- 1) infinite
- 2) unchanging
- 3) everywhere the same

Then stars would cover the night sky

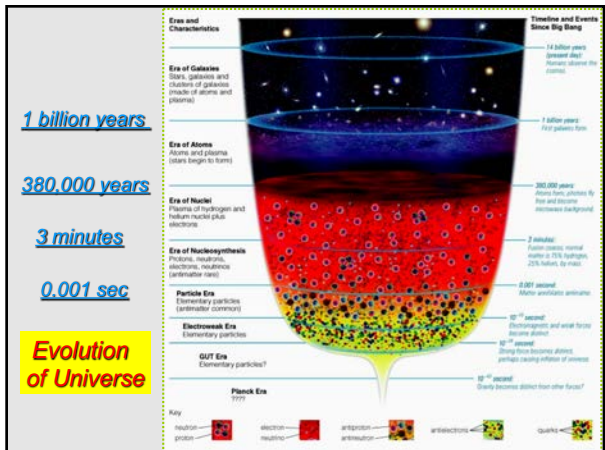
SO WHY NOT?

Questions or Comments

22

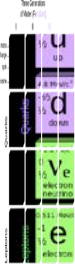
"Observational Pillars" of Big Bang Theory

1. The universe is aglow with thermal radiation, the Cosmic Microwave Background (CMB)
2. The observed abundances of light elements agree with Big Bang predictions
3. The universe is expanding
4. The night sky is dark

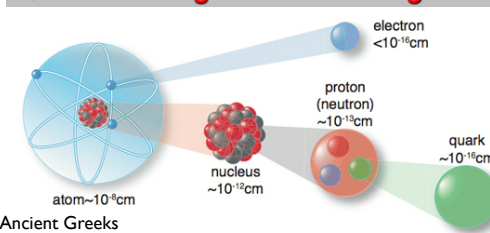


Briefly recall physics in our realm now: "Standard Model"

particle	properties	habits
up quark	+ or - charge large mass	always in groups of 3, form nucleons: proton = u+u+d neutron = u+d+d
down quark		
neutrino	no charge tiny mass	barely interacts
electron	- charge small mass	orbits nucleus



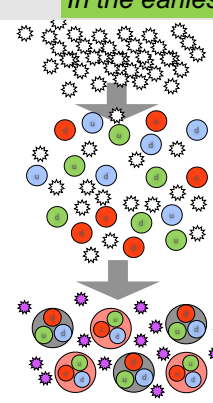
Quarks and gluons: building blocks



electron 10^{-16}cm
proton (neutron) $\sim 10^{-13}$ cm
nucleus $\sim 10^{-12}$ cm
atom $\sim 10^{-8}$ cm

Ancient Greeks hypothesize "atoms" or indivisible particles
1700s-1800s many different kinds of atoms discovered (elements)
early 1900s - atoms composed of nucleus and electrons
nucleus composed of protons, neutrons
1960s - protons and neutrons composed of quarks

In the earliest stages after inflation



High-energy photons create quarks, anti-quarks
Quark-gluon plasma - at very high temperatures ($T > 10^{12}$ K), strong force not strong enough to hold quarks together.
Once photon energy drops below 10^{12} K, strong force overcomes kinetic energy.
Quarks are immediately confined \rightarrow protons, neutrons

From quarks to atoms

everything held together by Strong force

proton = u+u+d
neutron = u+d+d

hydrogen = proton
deuteron = p + n (isotope of hydrogen)
tritium = p + 2n (isotope of hydrogen)

^3He ^4He
helium isotopes
2 protons + 1,2 neutrons

Questions or Comments

First Big Bang Idea

"COSMIC FIREBALL"

George GAMOW (1948)

Oops! Pure HELIUM

THE COSMIC FIREBALL

OBSERVE THAT 1. UNIVERSE IS EXPANDING
2. "PRIMITIVE" NUCLEAR COMPOSITION (BY MASS)
HYDROGEN HELIUM OTHER (METALS)
75% 25% 2%
X Y Z

INFOS FROM 1 THAT UNIVERSE WAS HEAVY COMPRESSED AT ITS BEGINNING

ALPHE, BETHE, GEORGE GAMOW (1948) [M.P. 8]

ASSUMED UNIVERSE BEGAN AS PURE NEUTRONS:
'YLEM'
NEUTRON DECAY $n \rightarrow p + e + \bar{\nu}$ HALF-LIFE 10.6 MIN

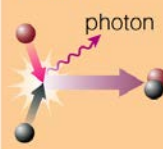
THEY:
a) $n + p \rightarrow ^2\text{H} + \gamma$
b) $^2\text{H} + p \rightarrow ^3\text{He} + \gamma$
c) $^3\text{He} + n \rightarrow ^4\text{He} + \gamma$

RESULT: A PURE HELIUM UNIVERSE IN BOLD CONTRAST WITH OBSERVATIONS THAT ABOUT 75% IS HYDROGEN!

Making helium in first 3 minutes

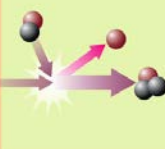
Step 1

Proton and neutron fuse to form a deuterium nucleus.



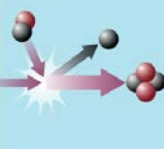
Step 2

Two deuterium nuclei fuse to make hydrogen-3.



Step 3

Hydrogen-3 fuses with deuterium to create helium-4.



JUST DO NOT MAKE EVERYTHING INTO HELIUM!

HOT Big Bang (1950)

did the trick!

WENT WAS MISTAKE IN "SAFE" MODEL WAS SOMETIMES TO SUPPRESS HELIUM FORMATION

REASON: HAYASHI (1950, 1951)

VERY INTENSE RADIATION DESTROYED CIRCULAR MATTER

PRESENT IN THE VERY EARLY STAGES OF FORMATION, AT TEMPERATURES $T > 10^{10}$ (100 BILLION) K

REACTIONS: MATTER (PROTON) + ANTIMATTER (ANTIPROTON) → GAMMA-RAY PHOTON

ANALOGOUS: $P + P^- \rightarrow \gamma$

CREATES: $\gamma + \gamma \rightarrow P^+ + P^-$ (MATTER ANTIMATTER)

LOWER ENERGY PRODUCTS MORE: $\gamma + \gamma \rightarrow e^- + e^+$ (ELECTRON POSITRON) (MATTER ANTIMATTER)

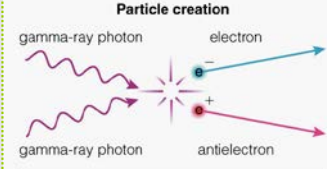
THEN: $n + e^+ \rightarrow p + \bar{\nu}$
 $p + e^- \rightarrow n + \nu$

NEUTRONS SWITCH BACK AND FORTH TO PROTONS!
SO CANNOT STAY WITH PURE NEUTRONS
THAT PREVENTS HELIUM PRODUCED BY BEGINNING

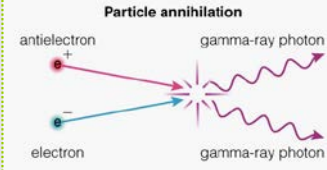
Matter, Anti-matter and Energy

- At **high temperatures**, photons convert into particle+antiparticle pairs, and vice-versa
- Matter & energy are the same: $E = mc^2$
- Early universe was full of particles and radiation
- Universe ratio today: **1 billion photons (light)** **1 leftover proton (matter)**

Particle creation




Particle annihilation




H and He ratio after ~3 minutes


14 protons




2 neutrons




during helium synthesis



after helium synthesis



12 hydrogen
atomic mass = 12



1 helium
atomic mass = 4

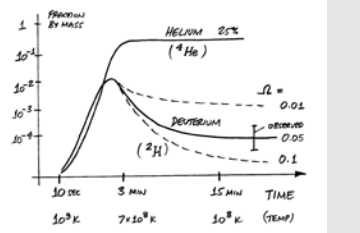
75% hydrogen, 25% helium, trace of deuterium

During first 3 minutes

Making the elements

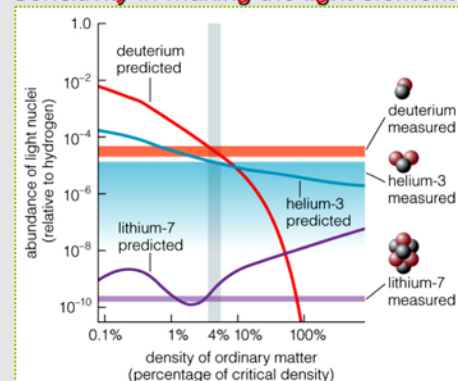
How much **DEUTERIUM** made depends on density of ordinary matter (baryons)

FORMATION OF ELEMENTS DURING FIRST 3 MINUTES AFTER THE "BIG BANG"



${}^2\text{H}$: HIGH DEUTERIUM \Rightarrow LOW DENSITY OF ORDINARY MATTER
 LOW DEUTERIUM \Rightarrow HIGH DENSITY
 OBSERVED $\Rightarrow \Omega \approx 0.05$ { ONLY 1/20 OF WHAT NEEDED TO CLOSE UNIVERSE!
 THIS ORDINARY MATTER IS NOT SUFFICIENT TO STOP EXPANSION OF UNIVERSE (ORIGIN)

Sensitivity in making the light elements



abundance of light nuclei (relative to hydrogen)
 density of ordinary matter (percentage of critical density)

After first 3 minutes

RADIATION ERA
--> 380,000 yr

MATTER ERA

AFTER THE FIRST 3 MINUTES :

RADIATION ERA : 1 sec → 1 MILLION YR
10¹⁰ K → 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 → NOW (15 BILLION YR)
3000K → 2.7 K

- CLUMPING OF MATTER (MATTER NOW NOT AFFECTED BY RADIATION PRESSURE)
- QUASARS FORM, THEN GALAXIES AND CLUSTERING OF GALAXIES

After "recombination": Era of Atoms

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

Photons bounced around among the free electrons early in time... but they moved freely through the universe after atoms captured the electrons.

time → 380,000 years

6000 K 3000 K 1500 K

← temperature

era of nuclei era of atoms

Timeline

- Big Bang
- Gravity freezes out
- Strong Force freezes out
- Weak Force freezes out
- Neutral atoms form, light decouples from matter (Cosmic Microwave Background)

Matter consists largely of quarks, electrons, positrons, & neutrinos

Quarks combine into protons, neutrons, & their antiparticles

Virtually all anti-matter is annihilated.

Fusion creates Helium

Very good but complex: Fig 22.4 + 22.5

Fig 22.5

Quantum Fluctuations

Inflation

Dark Ages

1st Stars about 400 million yrs.

Development of Galaxies, Planets, etc.

Dark Energy Accelerated Expansion

WMAP

Big Bang Expansion 13.7 billion years