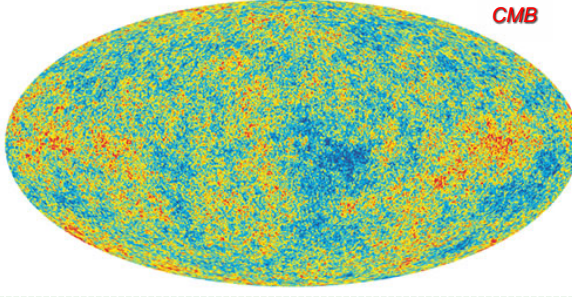


**ASTR 1040: Stars & Galaxies**



**CMB**

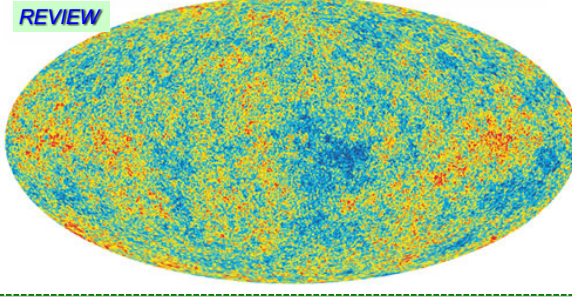
Prof. Juri Toomre TAs: Piyush Agrawal, Connor Bice  
Lecture 29 Tues 2 May 2017  
zeus.colorado.edu/astr1040-toomre

**Our Schedule**

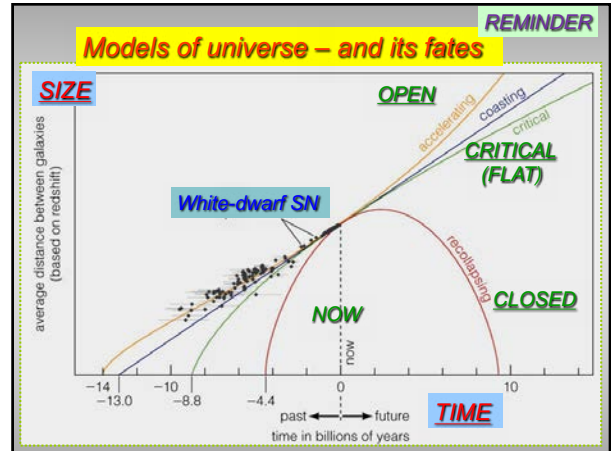
- **Final Exam on Wed May 10**, 1:30pm-4:00pm, here, closed book, 2 crib sheets allowed (4 sides), bring pencils
- **Review #4** tomorrow (Wed) 5pm-7pm by Conner Bice, here
- All **observatory reports**, "virtual" or actual project A, due **D2L dropbox** by Mon May 8
- Finish reading **23.4 Dark Energy and Fate of Universe**
- Today: **First few minutes of our Universe**

**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 ~1000** → **3 K!** (microwaves)



**White-dwarf SN → accelerating universe**

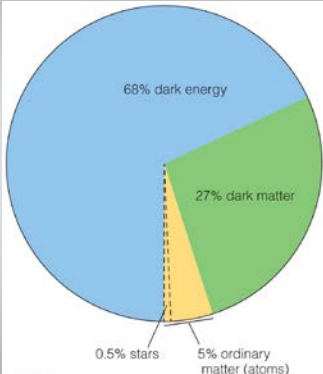
Conjecture: An unknown force at large scales begins to counteract pull of gravity

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



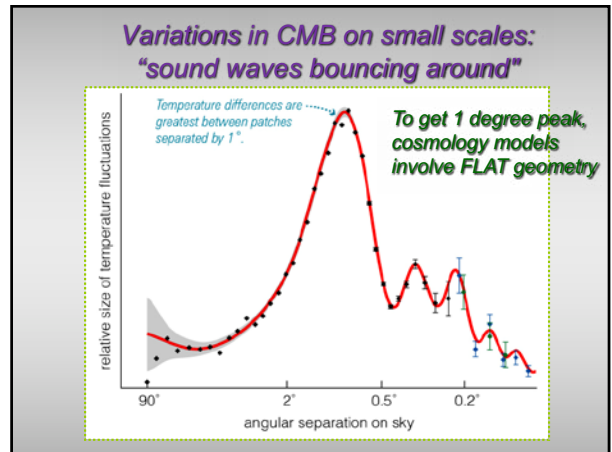
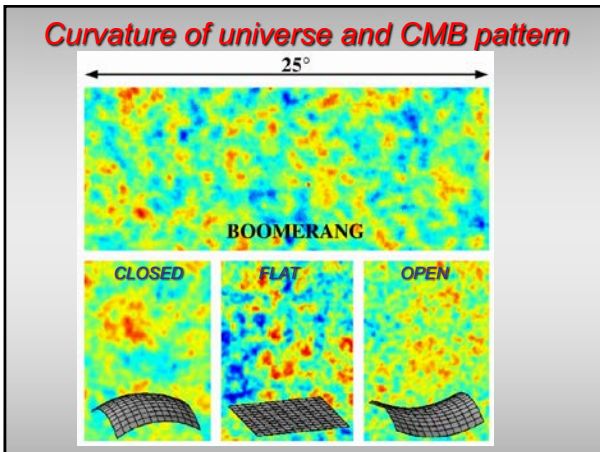
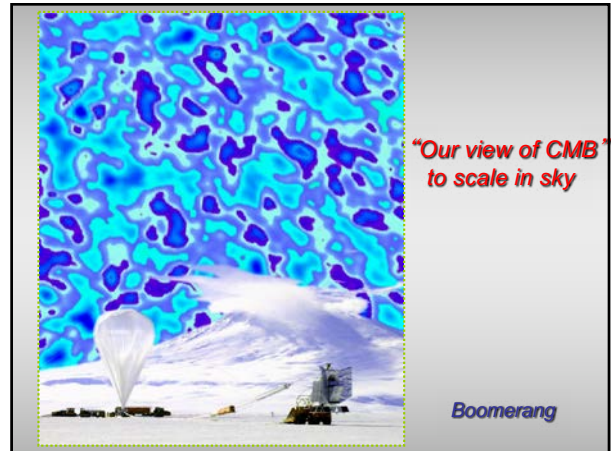
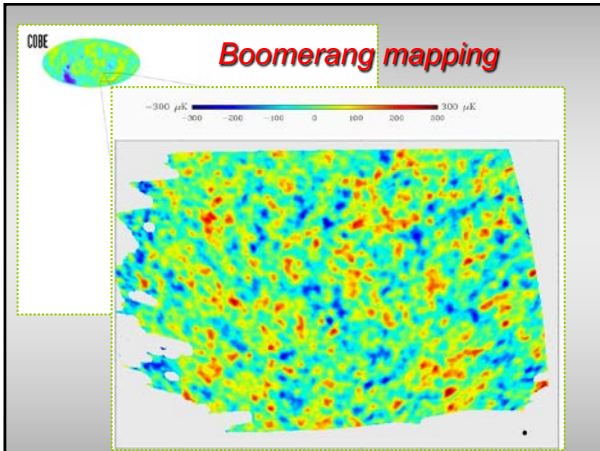
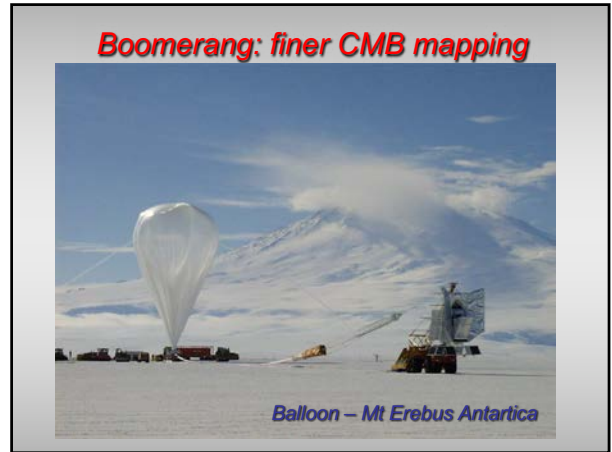
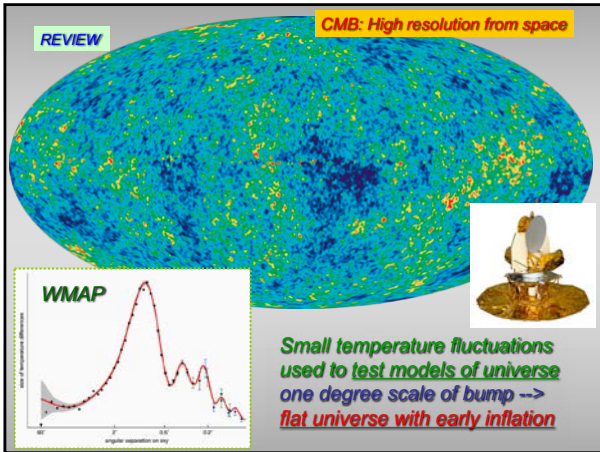
**Baryons: 4.4% (5%) Dark Matter: ~23% (27%) with a FLAT universe and early inflation**

**Acceleratic Universe: Mass-Energy Pie Chart**

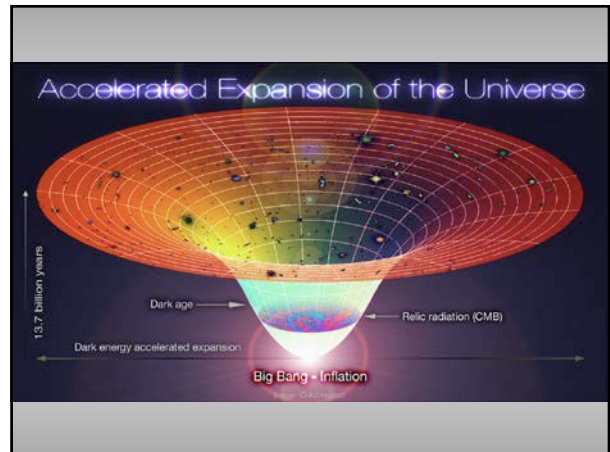
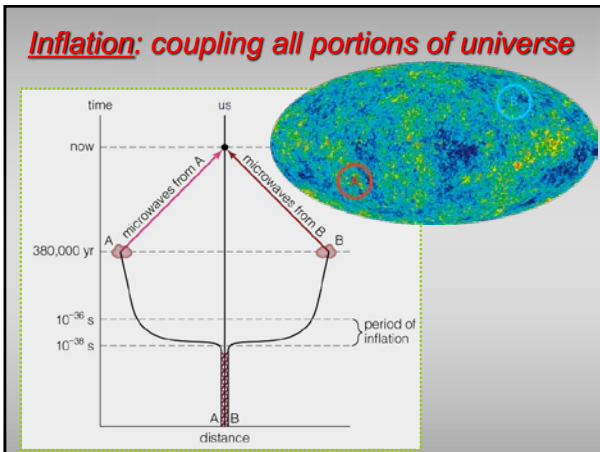
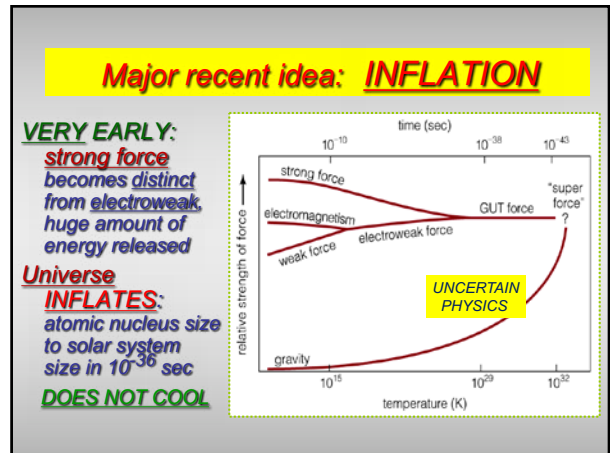
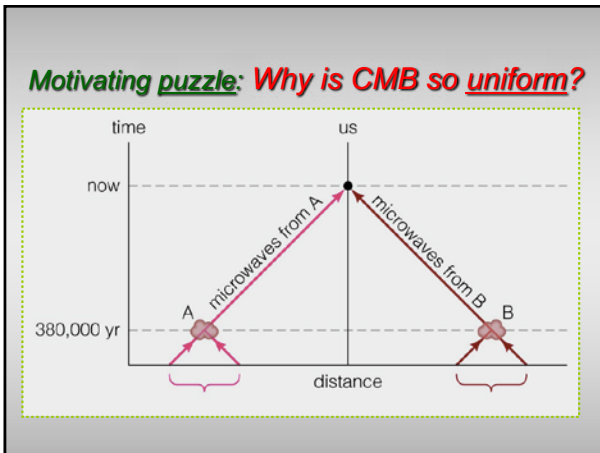
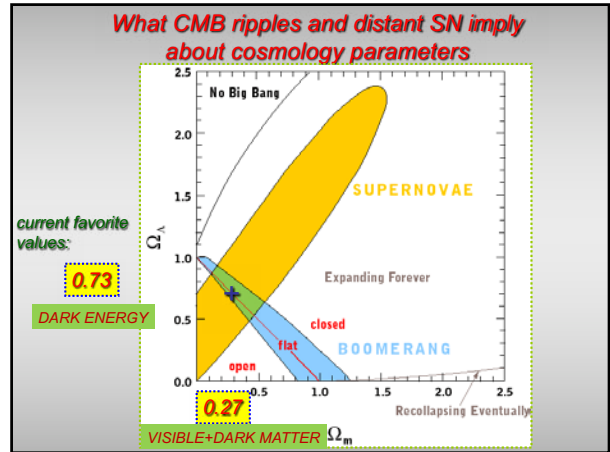
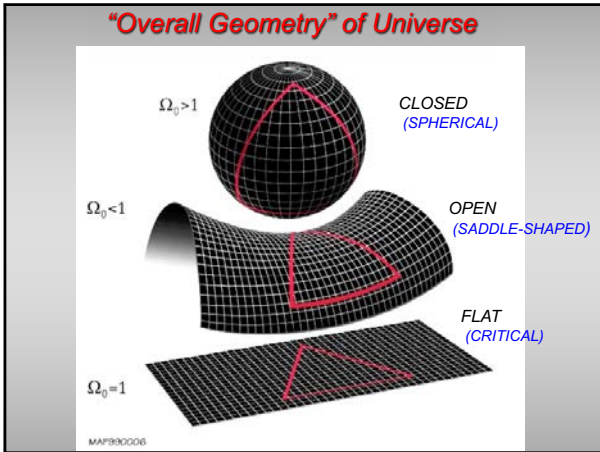


- Dark energy—more prevalent than every other form of mass/energy!
- A repulsive force that counteracts gravity?

68% dark energy  
27% dark matter  
5% ordinary matter (atoms)  
0.5% stars








**What is Olber's paradox?** **D.**

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

**Darkness of the night sky**



**Olbers' Paradox**

If universe were

- infinite
- unchanging
- everywhere the same

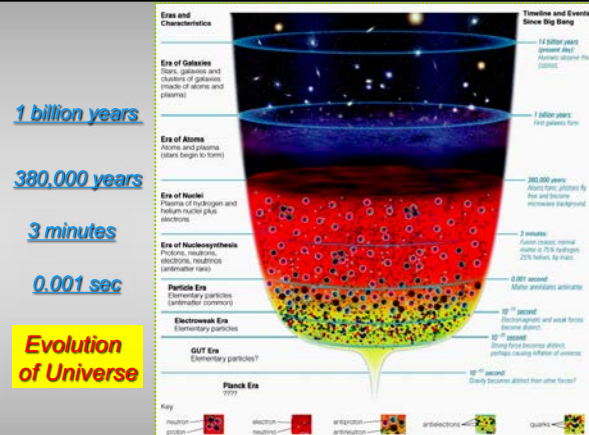
Then stars would cover the night sky

**SO WHY NOT?**

**"Observational Pillars" of Big Bang Theory**

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

**Evolution of Universe**



**Timeline and Events Since Big Bang**

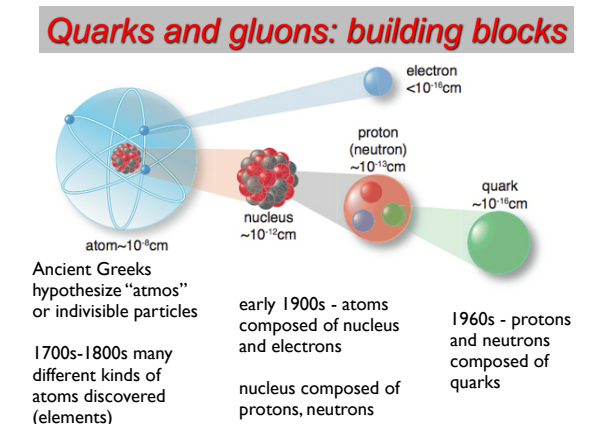
- 1.4 billion years (Present Day):** Present day (atoms and galaxies)
- 1 billion years:** First galaxies form
- 380,000 years:** Atoms and plasma (atoms begin to form)
- 3 minutes:** Era of Nucleosynthesis (nuclei, neutrons, electrons, neutrinos, neutrinos)
- 0.001 sec:** Particle Era (Elementary particles (quarks and leptons))
- Electroweak Era:** Elementary particles
- 10<sup>-12</sup> sec:** Quark-Hadron transition and weak force becomes gauge bosons
- 10<sup>-10</sup> sec:** Strong force becomes strong (perhaps leading inflation of universe)
- 10<sup>-35</sup> sec:** Gravity becomes distinct from other forces?
- Planck Era:** 10<sup>-43</sup> sec

**Key:** electron, proton, neutron, neutrino, antineutrino, photon, quark, gluon

**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**



atom ~10<sup>-8</sup>cm  
nucleus ~10<sup>-12</sup>cm  
proton (neutron) ~10<sup>-13</sup>cm  
quark ~10<sup>-16</sup>cm  
electron <10<sup>-16</sup>cm

Ancient Greeks hypothesize "atmos" 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 → protons, neutrons

### From quarks to atoms

proton =  $u+u+d$

neutron =  $u+d+d$

everything held together by Strong force

hydrogen = proton

deuteron =  $p + n$   
(isotope of hydrogen)

tritium =  $p + 2n$   
(isotope of hydrogen)

$^3\text{He}$        $^4\text{He}$

helium isotopes  
2 protons  
+ 1,2 neutrons

**First Big Bang Idea**

**"COSMIC FIREBALL"**

**George GAMOW (1948)**

**Oops! Pure HELIUM**

#### THE COSMIC FIREBALL

OBVIOUS THAT

- UNIVERSE IS EXPANDING
- "PROBLEMS" MATTER COMPOSITION (BY MASS)  
HYDROGEN    HELIUM    OTHER (METALS)  
75%          25%          2%  
X              Y              Z

INFOS FROM 1 THAT UNIVERSE MUST BEHEAVY COMPRESSED AT ITS BEGINNING

ALPHA, BETA, GAMMA RAY (1948) [ $10^{18}$ °K]

ASSUMED UNIVERSE BEGAN AS PURE NEUTRONS: 'YLEM'

NEUTRON DECAY     $n \rightarrow p + e + \bar{\nu}$   
NEUTRONS FROM COLLISIONS WITH ELECTRONS  
HALF-LIFE: 10.6 MIN

THEN:

- $n + p \rightarrow ^2\text{H} + \gamma$
- $^2\text{H} + p \rightarrow ^3\text{He} + \gamma$
- $^3\text{He} + n \rightarrow ^4\text{He} + \gamma$

RESULT: A PURE HELIUM UNIVERSE

IN RECON. CONFLICT 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!**

WHAT WAS MISSING IN "GAMOW" MODEL WAS SOMETHING TO SUPPRESS HELIUM FORMATION

ANSWER: HAYATZ (1950, 1951)

VERY INTENSE RADIATION    DETRIMENTAL TO COLD MATTER

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

REACTIONS: MATTER (PROTON)    ANTIMATTER (ANTI-PROTON)    GAMMA RAY PAIRS

ANNIHILATION:  $p + \bar{p} \rightarrow \gamma$

CREATION:  $\gamma + \gamma \rightarrow p^+ + p^-$   
ONLY GAMMA-RAY PAIRS HAVE ENERGY  $E \geq 2m_{\text{PROTON}}c^2$

COULD OCCUR FREQUENTLY:  $\gamma + \gamma \rightarrow e^- + e^+$   
ELECTRONS    POSITRONS (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 THE LESS HELIUM PRODUCED AT 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

during helium synthesis

14 protons  
2 neutrons

after helium synthesis

12 hydrogen  
1 helium

atomic mass = 12      atomic mass = 4

**75% hydrogen, 25% helium, trace of deuterium**

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

**During first 3 minutes**

**Making the elements**

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

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

### Sensitivity in making the light elements

abundance of light nuclei (relative to hydrogen)

density of ordinary matter (percentage of critical density)

### AFTER THE FIRST 3 MINUTES :

**After first 3 minutes**

**RADIATION ERA**

$\rightarrow$  380,000 yr

**MATTER ERA**

**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

### 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

time  $\uparrow$  380,000 years

era of atoms

1,500 K

3,000 K

6,000 K

temperature  $\downarrow$

era of nuclei

CMB

Big Bang Expansion  
13.7 billion years