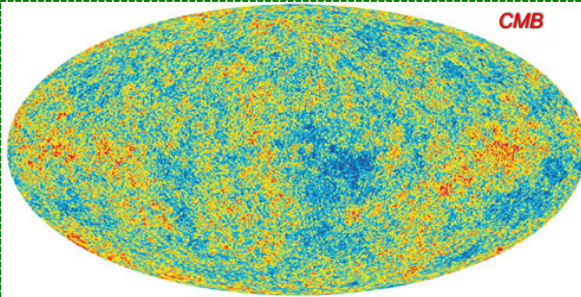


ASTR 1040: Stars & Galaxies



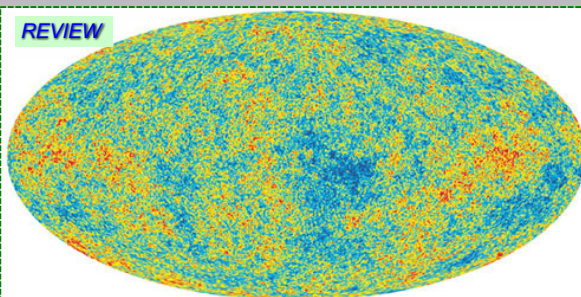
Prof. Juri Toomre TAs: Peri Johnson, Ryan Horton
Lecture 29 Tues 1 May 2018
zeus.colorado.edu/astr1040-toomre

Our Schedule

- **Final Exam on Wed May 9, 4:30pm-7:00pm**, here, closed book, 2 crib sheets allowed (4 sides), bring pencils
- **Review #4** tomorrow (Wed) 5pm-7pm by Ryan Horton, here
- All **observatory reports**, "virtual" or actual project, due **D2L dropbox** by Mon May 7
- **HW #13** being returned (+answers), and **all** prior graded **HWs** and **MT Ex 3**
- 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 $Z \sim 1000 \rightarrow 3\text{ K!}$ (microwaves)

Models of universe – and its fates **REMINDER**



SIZE **TIME**

average distance between galaxies (based on redshift)

past ← 0 (NOW) → future

time in billions of years

OPEN accelerating coasting

CRITICAL (FLAT) critical

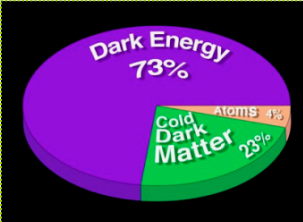
CLOSED decelerating recollapsing

White-dwarf SN

White-dwarf SN \rightarrow accelerating universe

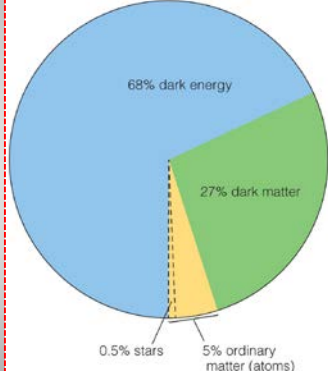
Conjecture: An unknown force at large scales begins to counteract pull of gravity

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

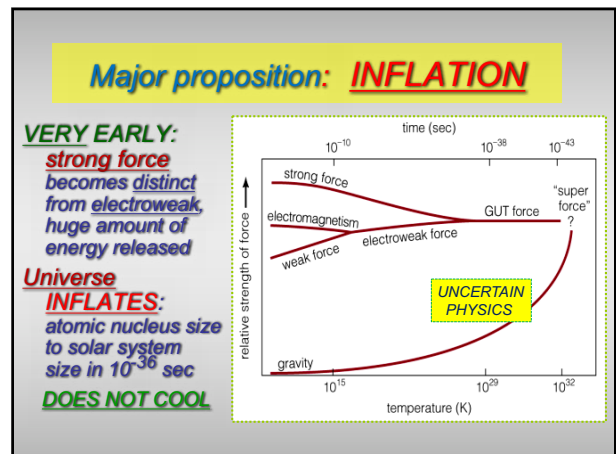
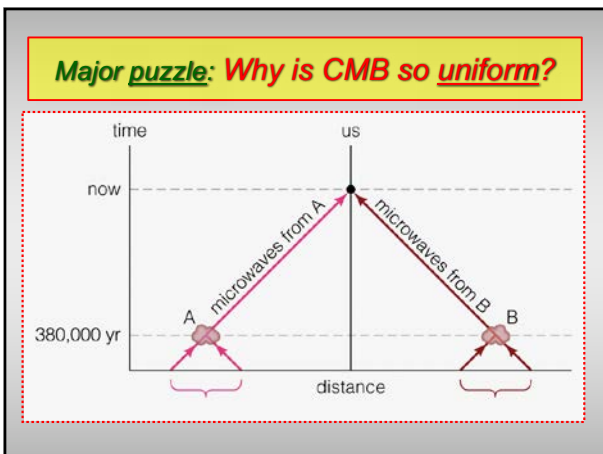
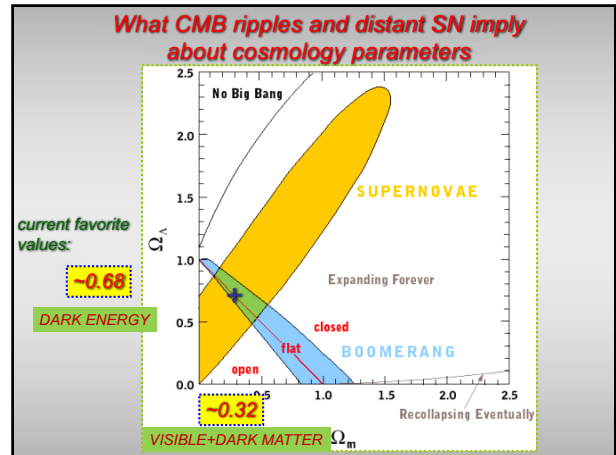
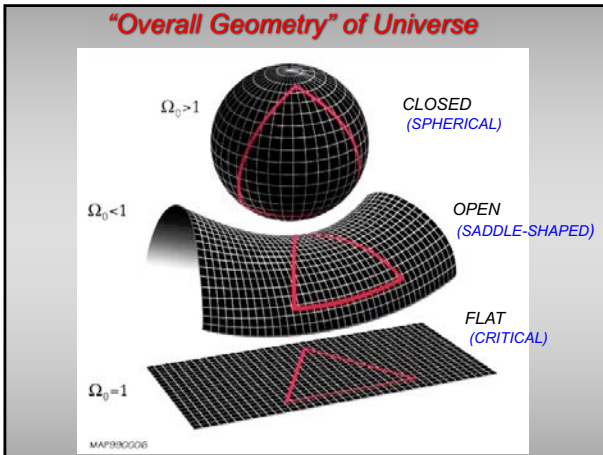
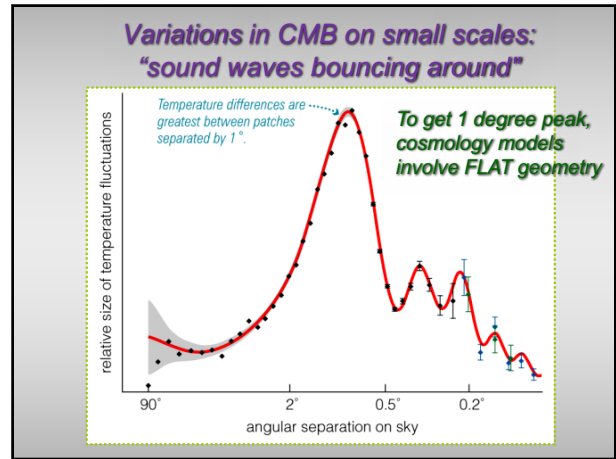
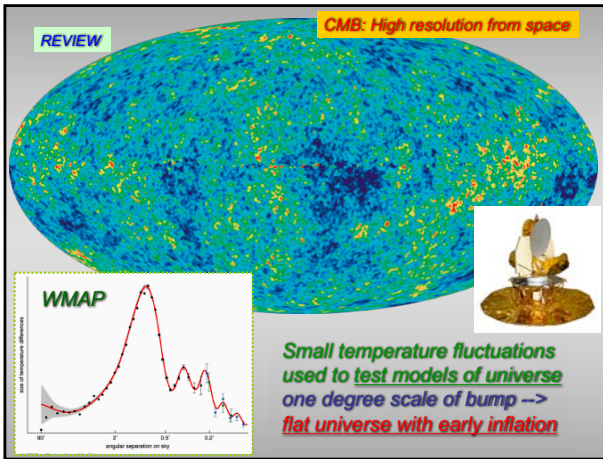


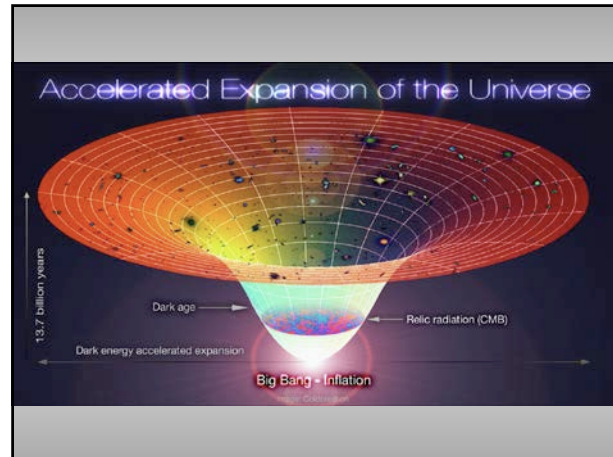
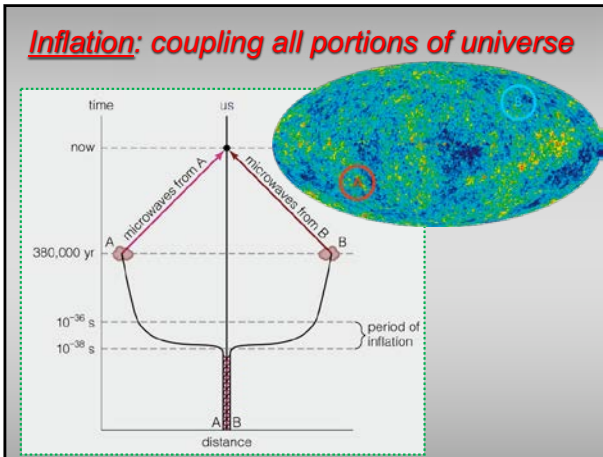
Baryons: 4.4% (5%) Dark Matter: ~23% (27%) with a FLAT universe and early inflation

Accelerating Universe: Mass-Energy Pie Chart



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





- ### 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

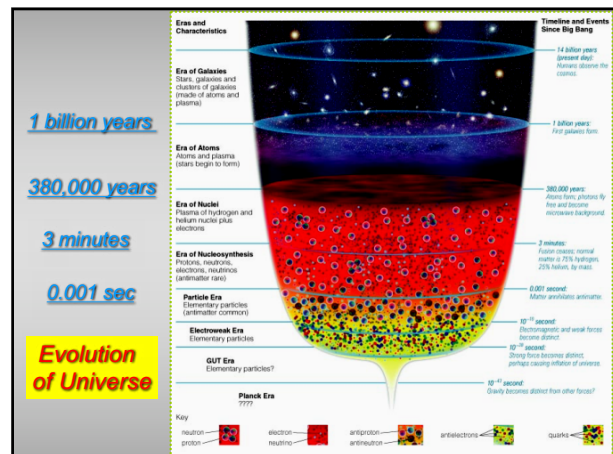
If universe were

- infinite
- unchanging
- everywhere the same

Then stars would cover the night sky

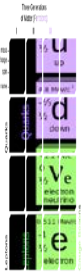
SO WHY NOT?

- ### "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

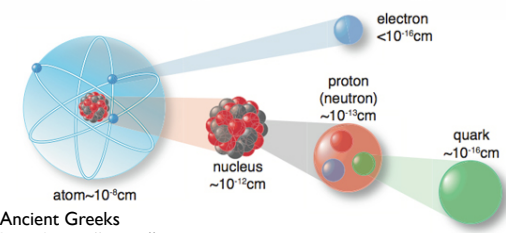


Briefly recall physics in our realm now: "Standard Model"

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



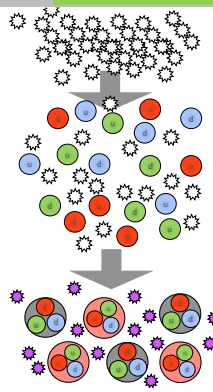
Quarks and gluons: building blocks



electron <math><10^{-16}\text{cm}</math>
 proton (neutron) $\sim 10^{-13}\text{cm}$
 nucleus $\sim 10^{-12}\text{cm}$
 atom $\sim 10^{-8}\text{cm}$
 quark $\sim 10^{-16}\text{cm}$

Ancient Greeks hypothesize "atomos" 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

First Big Bang Idea

"COSMIC FIREBALL"

George GAMOW (1948)

Oops! Pure HELIUM

THE COSMIC FIREBALL

CONCLUDE THAT
 1. UNIVERSE IS EXPANDING
 2. "PRIMITIVE" MATTER COMPOSITION (BY MASS)
 HYDROGEN HELIUM OTHER (METALS)
 75% 25% 2%

INFER FROM 1 THAT UNIVERSE WAS HEAVY COMPRESSED AT ITS BEGINNING

ALPHEE, BERTHE, GEORGE GAMOW (1948) [W.B.S.]
 ASSUMES UNIVERSE BEGAN AS PURE NEUTRONIUM:
 "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) $^3\text{He} + n \rightarrow ^4\text{He} + \gamma$

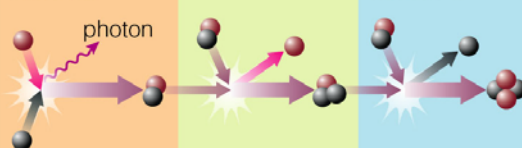
RESULT: A PURE HELIUM UNIVERSE
 IN REAL CONTACT WITH OBSERVATION THAT ABOUT 75% IS HYDROGEN!

Making helium in first 3 minutes

Step 1
 Proton and neutron fuse to form a deuterium nucleus.
 photon

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 "OLD" MODEL WAS STRONG TO SUPPRESS HELIUM FORMATION

ANSWER: HAYASHI (1950, 1951)

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

REACTIONS: MATTER (PROTON) ANTIMATTER (ANTI-PROTON) GAMMA-RAY PHOTON
 $P + P^{-} \rightarrow \gamma$

ANNIHILATE: $P + P^{-} \rightarrow \gamma$

CREATE: $\gamma + \gamma \rightarrow P^{+} + P^{-}$

ONE GAMMA-RAY MUST HAVE ENERGY $E \geq 2M_{\text{PROTON}} C^2$

LOWER ENERGY PAIRWISE MAKE: $\gamma + \gamma \rightarrow e^{-} + e^{+}$
 ELECTRON (MATTER) POSITRON (ANTI-MATTER)

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

NEUTRON SWITCH BACK AND FORTH TO PROTON!
 SO CANNOT STAY WITH PURE NEUTRON
 THIS PREVENTS 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

after helium synthesis

atomic mass = 12 atomic mass = 4

75% hydrogen, 25% helium, trace of deuterium

During first 3 minutes
 Making the elements

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 { ONLY 1/20 OF WHAT OBSERVED $\Rightarrow \Omega \approx 0.05$ NEEDED TO CLOSE UNIVERSE!
 THIS ORDINARY MATTER IS NOT SUFFICIENT TO STOP EXPANSION OF UNIVERSE (OPEN)

Sensitivity in making the light elements

After first 3 minutes

RADIATION ERA
 $\rightarrow 380,000$ 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

