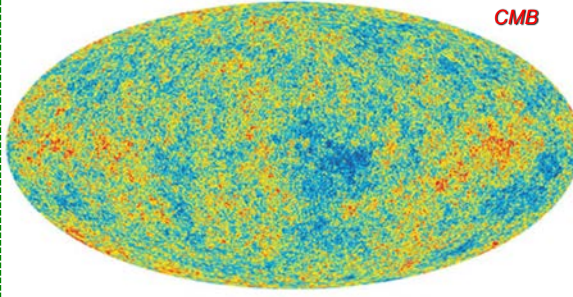


ASTR 1040: Stars & Galaxies



CMB

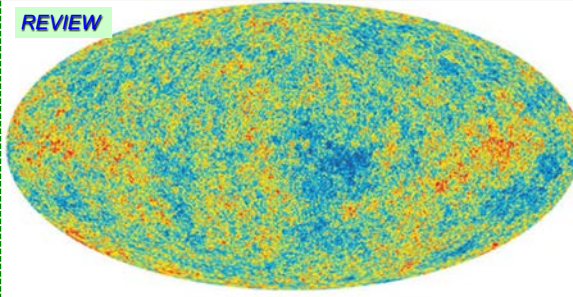
Prof. Juri Toomre TAs: Ryan Horton, Loren Matilsky
 Lecture 29 Tues 11 Dec 2018
zeus.colorado.edu/astr1040-toomre

Our Schedule

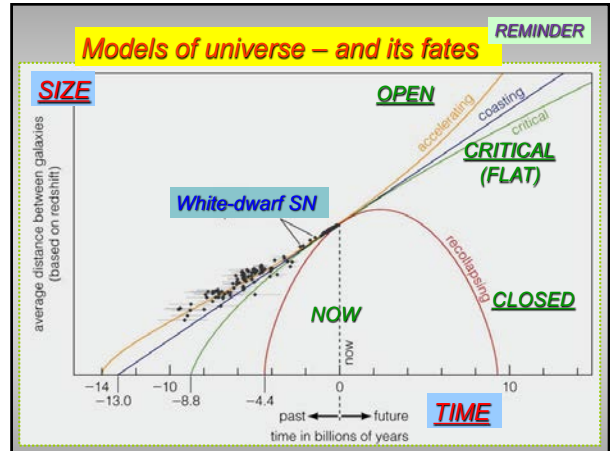
- **Final Exam on Sun Dec 16**, 4:30pm-7:00pm, here, closed book, 2 crib sheets allowed (4 sides), bring pencils
- **Review #4** tomorrow (Wed) 5pm-7pm by Loren Matilsky, here
- All **observatory reports**, projects 1 & 2, due **D2L dropbox (or paper)** by Thur 13 Dec 6pm
- **HW #13** being returned (+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 $Z=1000 \rightarrow 3\text{K}$** (microwaves)

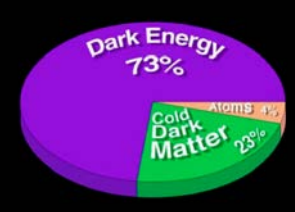


REVIEW

White-dwarf SN \rightarrow accelerating universe

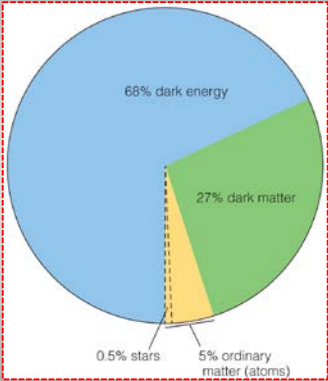
Conjecture: An unknown force at **large scales** begins to counteract pull of gravity

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

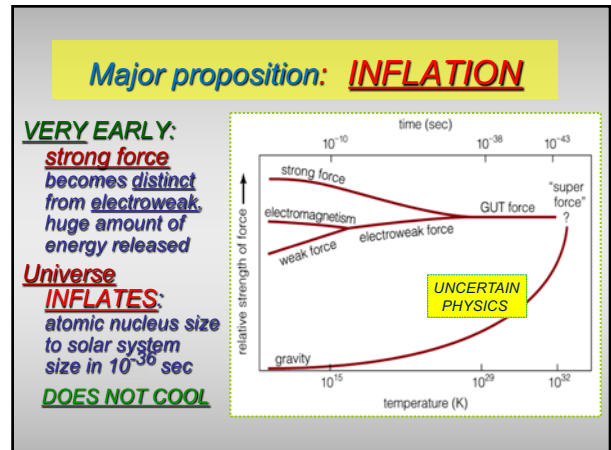
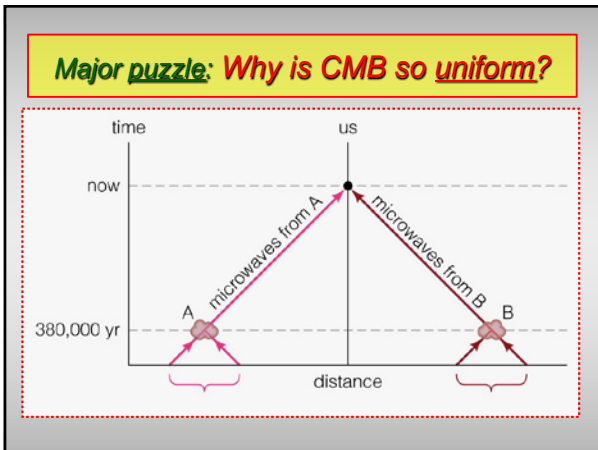
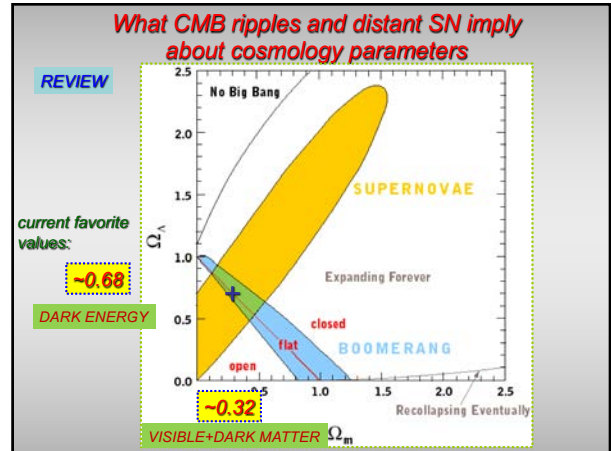
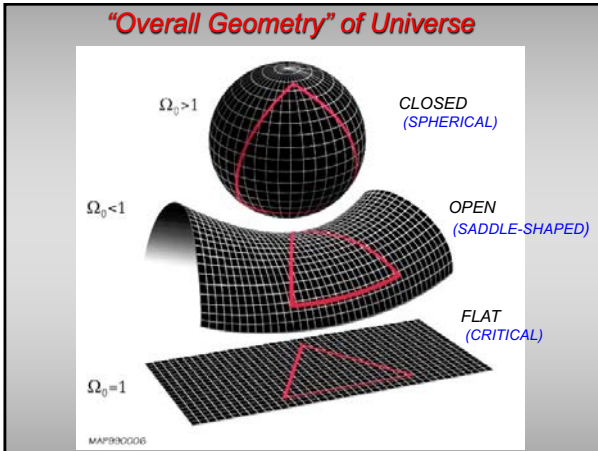
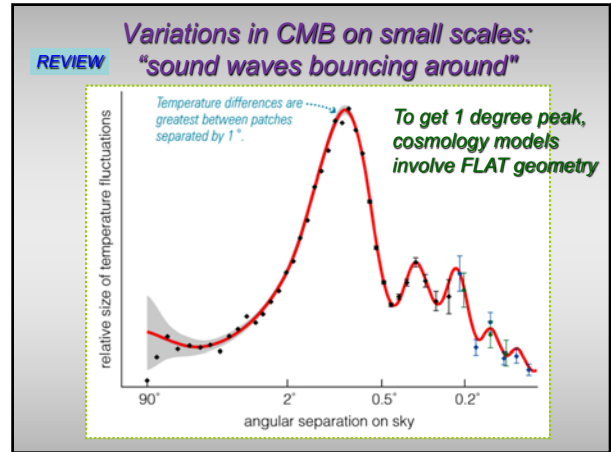
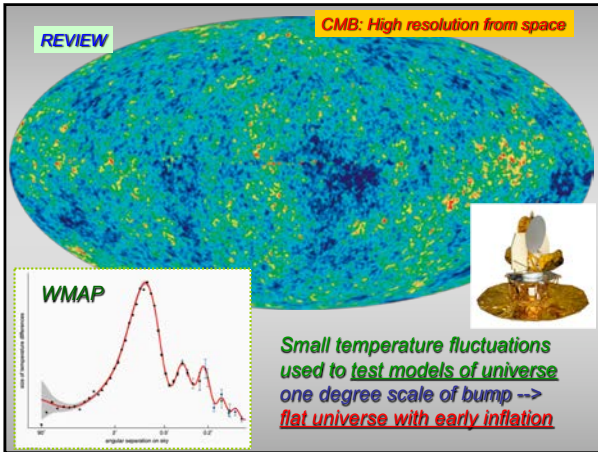


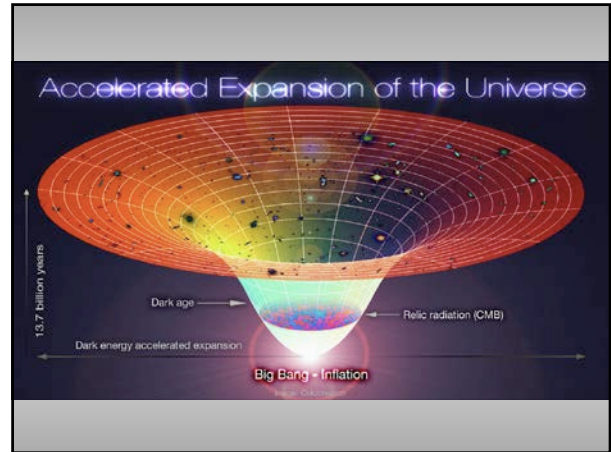
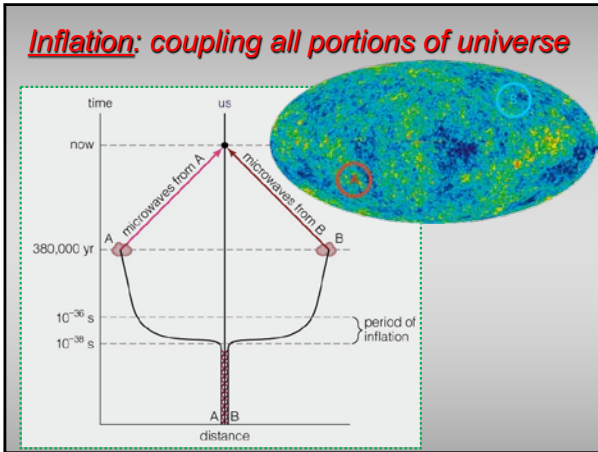
Baryons: 4.4% (5%) **Dark Matter:** ~23% (27%)
 with a **FLAT** universe and early inflation

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

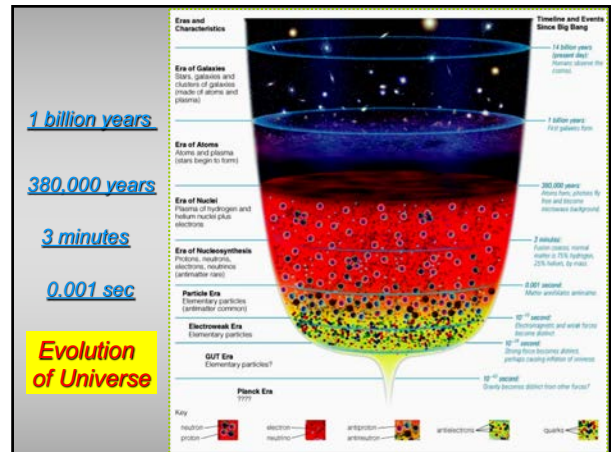
- 1) infinite
- 2) unchanging
- 3) everywhere the same

Then stars would cover the night sky

SO WHY NOT?

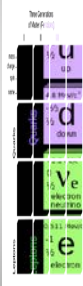
"Observational Pillars" of Big Bang Theory

- 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

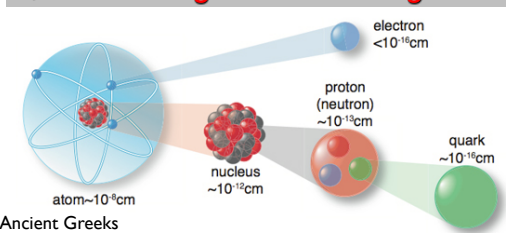


Briefly recall physics in our realm now: "Standard Model"

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



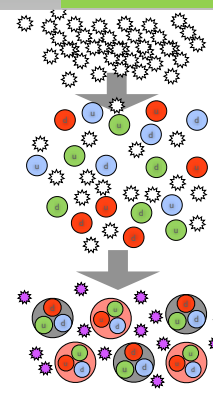
Quarks and gluons: building blocks



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

First Big Bang Idea
"COSMIC FIREBALL"
George GAMOW (1948)
Oops! Pure HELIUM

THE COSMIC FIREBALL

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

INFERS FROM 1 THAT UNIVERSE MUST HAVE BEEN COMPRESSED AT ITS BEGINNING

ALPHE, BERTHE, GEORGE GAMOW (1948) [10^{10} K]

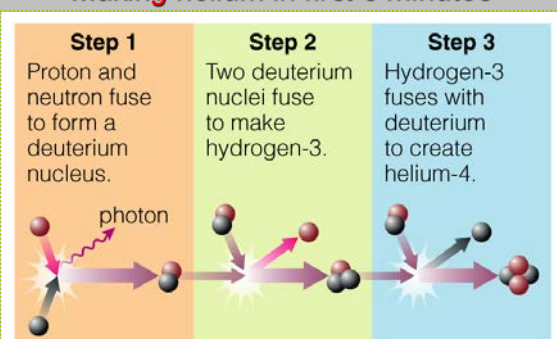
ASSUMES UNIVERSE BEGAN AS PURE NEUTRONS:
'YLEM'
NEUTRON DECAY $n \rightarrow p + e + \bar{\nu}$ HALF-LIFE 10.6 MIN

TABLE:
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 RECON. 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.
Step 2 Two deuterium nuclei fuse to make hydrogen-3.
Step 3 Hydrogen-3 fuses with deuterium to create helium-4.



photon

JUST DO NOT MAKE EVERYTHING INTO HELIUM!

HOT Big Bang (1950)

did the trick!

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

ANSWER: HAYASHI (1950, 1951)

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

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

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

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

ONE GAMMA-RAY MUST HAVE ENERGY $E \geq 2m_{\text{proton}}c^2$

COULD OCCUR: $\gamma + \gamma \rightarrow e^- + e^+$

PROTON MASS: $\gamma + \gamma \rightarrow p + \bar{p}$ (EXTERNAL NUMBER) (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 NEUTRONS THIS THE LESS HELIUM PRODUCED AT REEMANING

Matter, Anti-matter and Energy

Particle creation

Particle annihilation

- 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)

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 $\Rightarrow \Omega \approx 0.05$ NEEDS TO CLOSE UNIVERSE)
 THIS ORDINARY MATTER IS NOT SUFFICIENT TO STOP EXPANSION OF UNIVERSE (OPEN)

Sensitivity in making the light elements

The graph shows that as the density of ordinary matter increases, the predicted abundance of deuterium and helium-3 decreases, while the predicted abundance of lithium-7 increases. Measured values are shown as horizontal lines, and a vertical line at approximately 4% critical density indicates the observed universe's density.

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

- INCLUDE 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

Timeline

- Big Bang
- Gravity freezes out
- Strong Force freezes out
- Matter consists largely of quarks, electrons, positrons, & neutrinos
- Weak Force freezes out
- Quarks combine into protons, neutrons, & their antiparticles
- Virtually all anti-matter is annihilated.
- Fusion creates Helium
- Neutral atoms form, light decouples from matter (Cosmic Microwave Background)

Very good but complex: Fig 22.4 + 22.5

Quantum Fluctuations

Inflation

Afterglow Light Pattern 400,000 yrs.

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