COSMOLOGICAL PRINCIPLE

- Combine Homogeneity and Isotropy and you get:
  - On a large scale, the universe is pretty much the same everywhere
- A corollary:
  - Not only is the Earth not a special place (*we've known that for a while*) but there is no special place anywhere in the universe, since one place is pretty much like the next

THE BIG BANG

- If the universe is expanding now, let's put it in rewind and see what happened
  - Running backwards in time, it would be more and more compact
  - Compact things get hotter and hotter
  - Long ago, the whole universe would have been very compact and very hot
- Starting at this point and putting the tape in fast forward again
  - The hot compact universe comes busting out all over
  - "The Big Bang"

NOT AN EXPLOSION

- The first thing you think of is that there was this little compact blob of mass and that it exploded out
- This is <u>not</u> what happened
  - There was no “outside” to be in so you could look in at the blob
- The whole universe was compact and hot, and as space stretched, it expanded and cooled off

REWIND

- Back in time, universe is smaller, hotter, denser
- Will press "play" at 10^{-46}s old

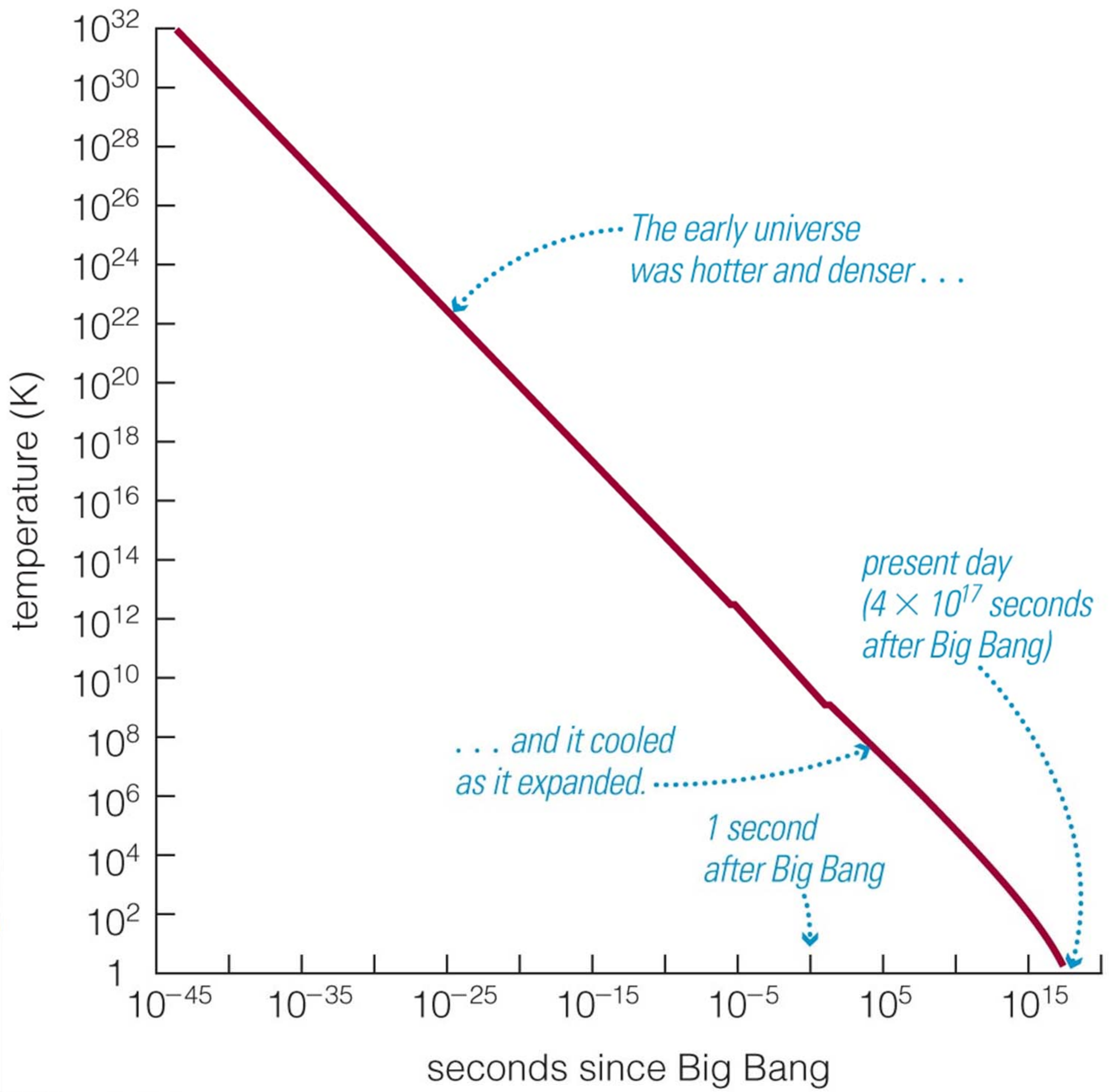
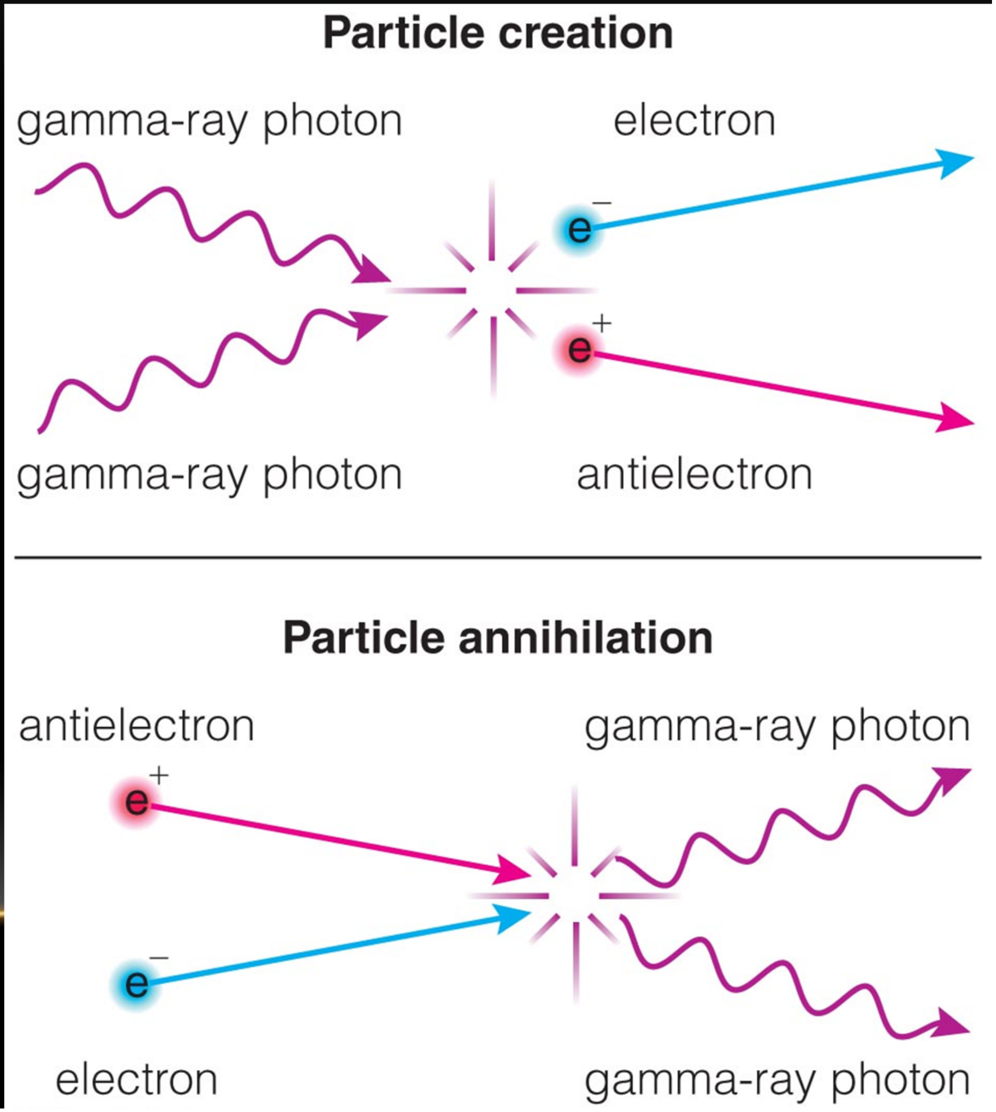


Fig.17.1

$E=MC^2$

- As we saw with fusion power, it's not just a slogan
- Works both ways: not only can mass turn into energy, but energy can turn into mass
- The early universe was so hot this happened all the time

Fig.17.3



WE ALSO DO THIS

- On a much smaller scale, at particle accelerators
- Get tiny volumes of very high energy content, make particles, watch them fly out and measure them

Fermilab near Chicago,
The accelerator I work with

FOUR FUNDAMENTAL FORCES

- We know of four forces in the universe. From strongest to weakest:
    1. The Strong Force
    2. The Electromagnetic force
    3. The Weak Force
    4. Gravity

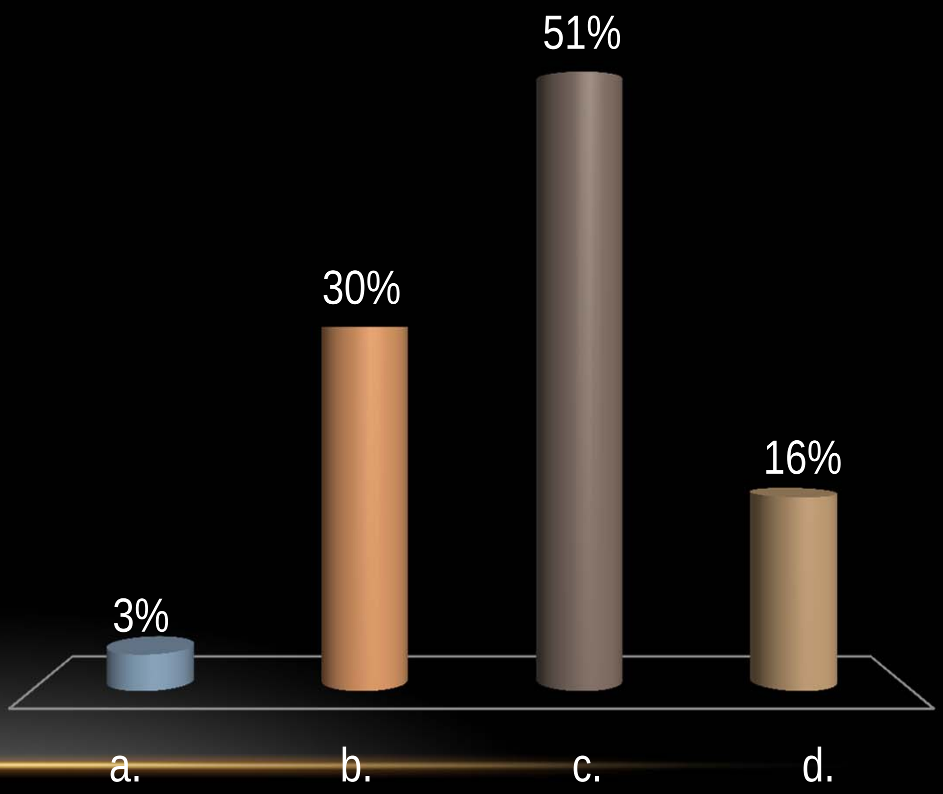
GRAVITY IS PULLING YOU DOWN. WHICH OF THE FOUR FORCES KEEPS YOU FROM SINKING TO THE CENTER OF EARTH?

a. Gravity

✓ b. Electromagnetism

c. Strong Force

d. Weak Force



FOUR FUNDAMENTAL FORCES

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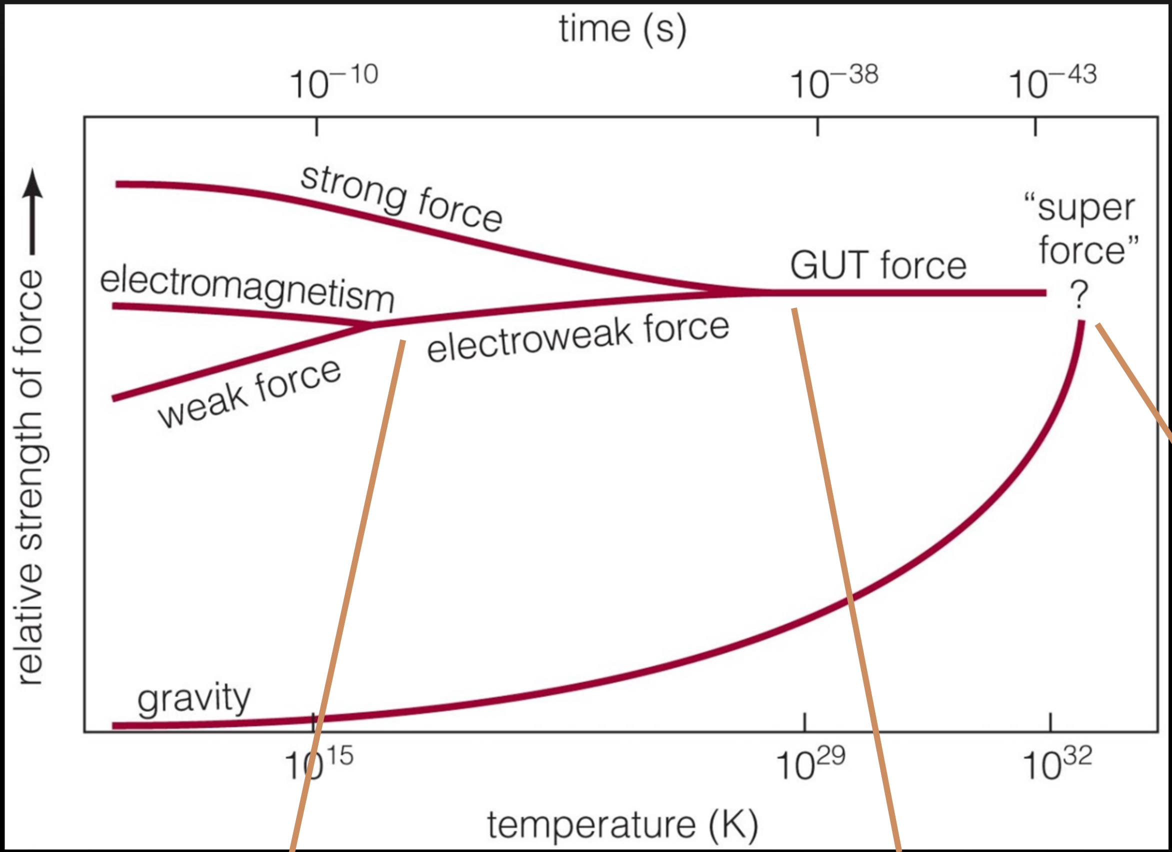
DO FORCES UNIFY AT HIGH TEMPERATURES?



Four known forces in universe:

Strong Force

Electromagnetism

Weak Force

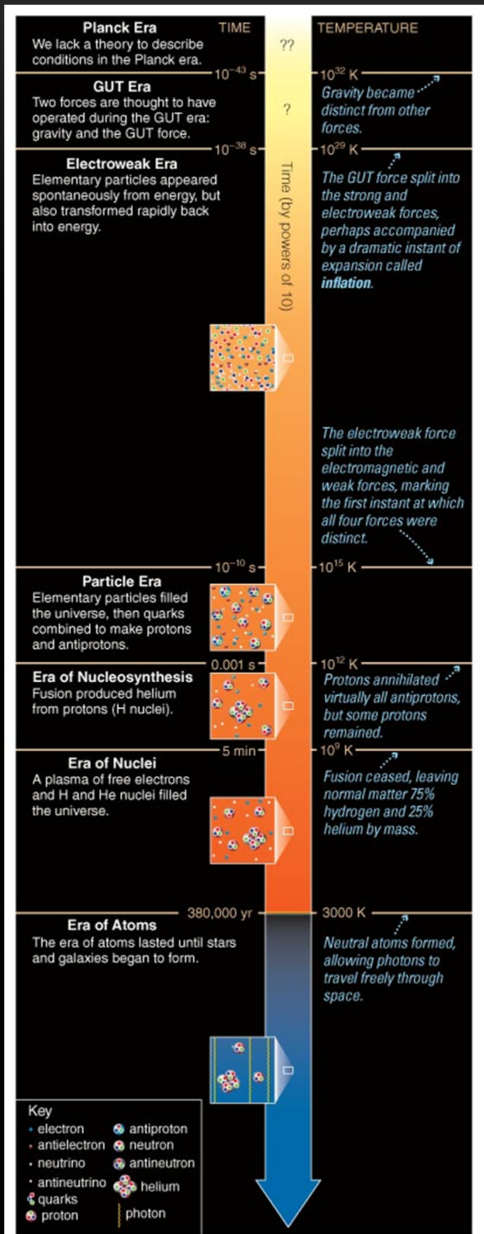
Gravity

Yes!
(Electroweak)
(seen in accelerators)

Maybe
(GUT)
(solid theories exist, but not yet observed)

Who knows?
(String Theory)
(speculative theories exist)

Fig.17.5



Planck Era

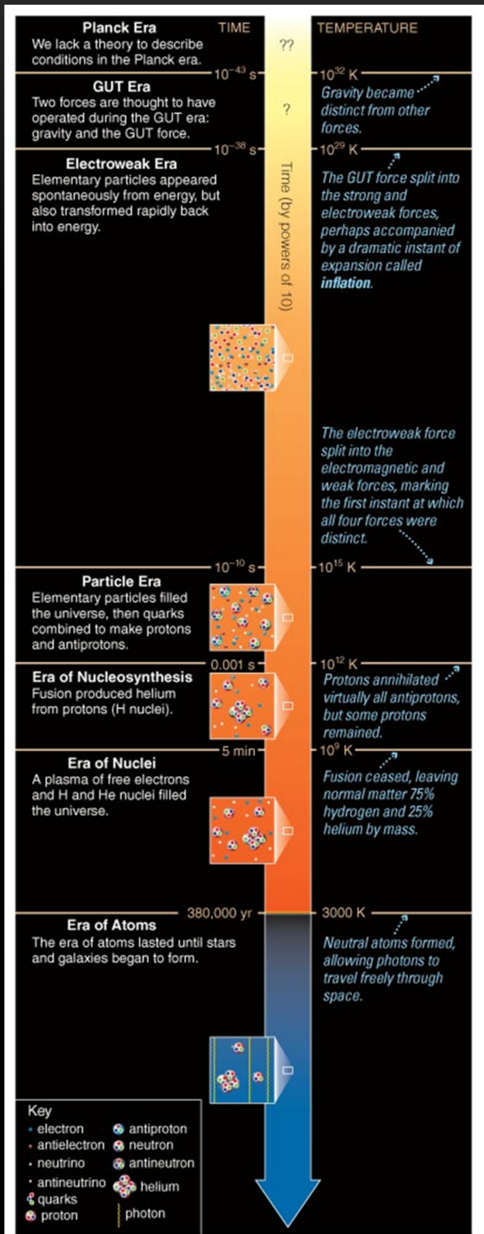
Time: < 10^{-43} s

Temp: > 10^{32} K

No theory of quantum gravity yet which could explain this

All forces may have been unified

Fig.17.5



GUT Era

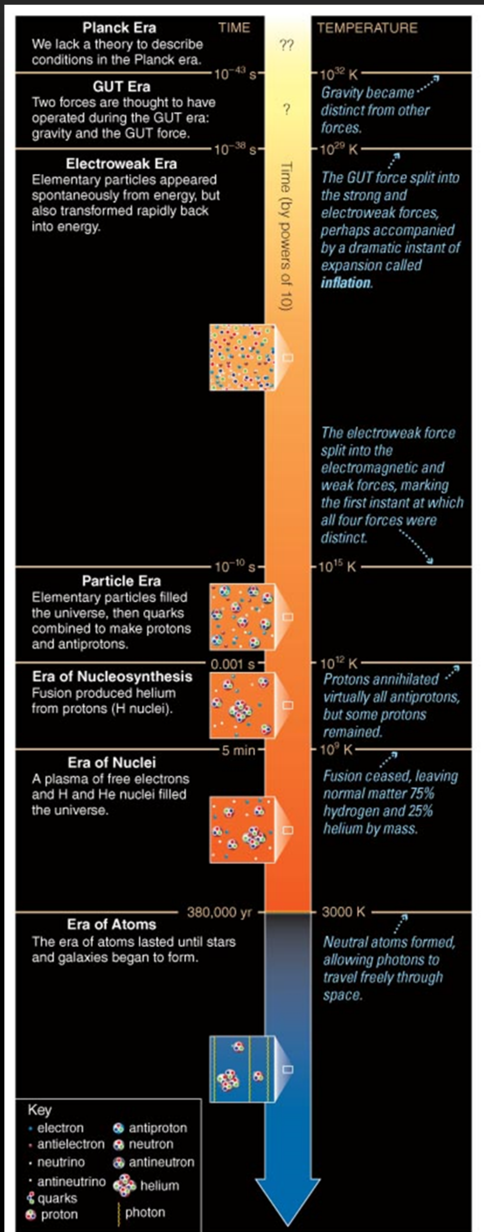
Time: 10^{-43}–10^{-38} s

Temp: 10^{32}–10^{29} K

GUT era began when gravity became distinct from other forces.

GUT era ended when strong force became distinct from electroweak force.

Fig.17.5



Electroweak Era

Time: 10^{-38}–10^{-10} s

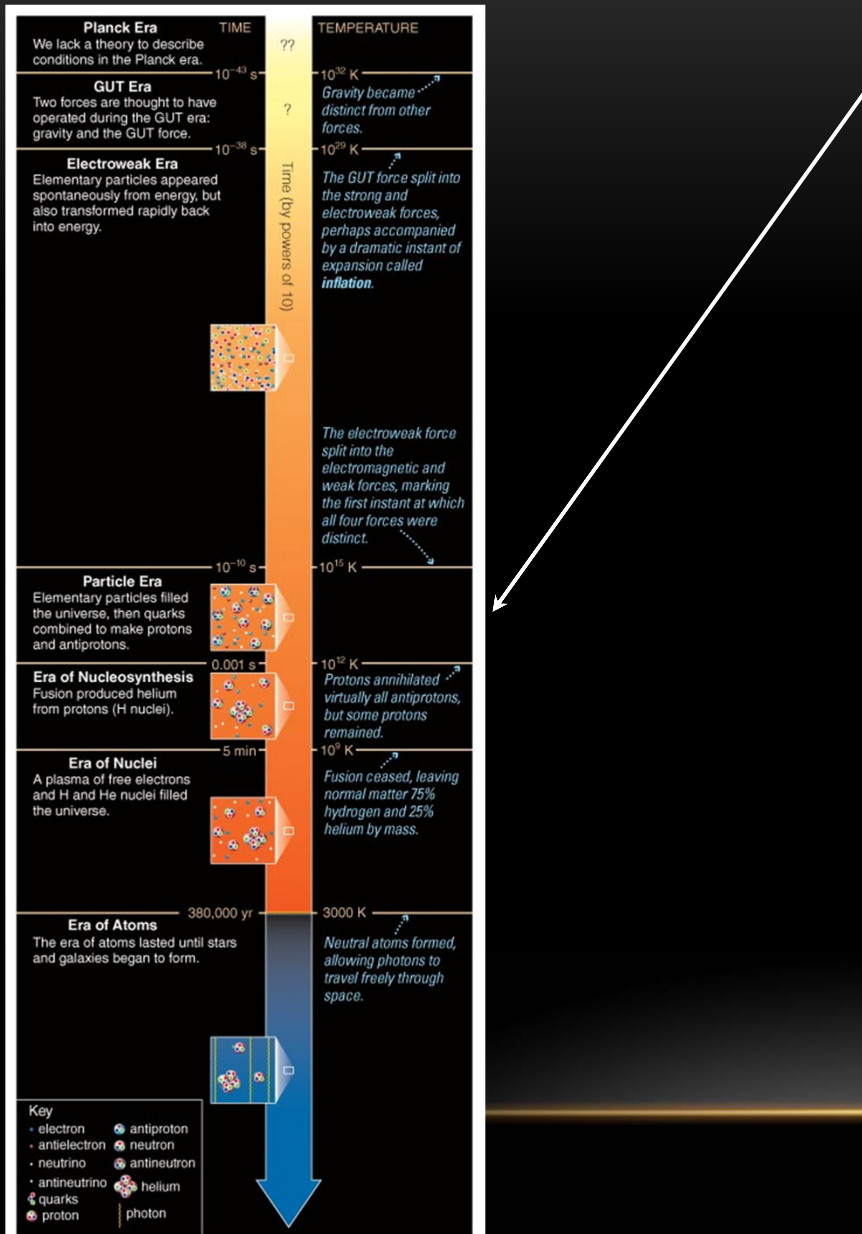
Temp: 10^{29}–10^{15} K

Begins when Strong force became distinct from the electroweak force.

We can replicate this era in particle accelerators!

Ends when the weak force separates from electromagnetism

Fig.17.5



Particle Era

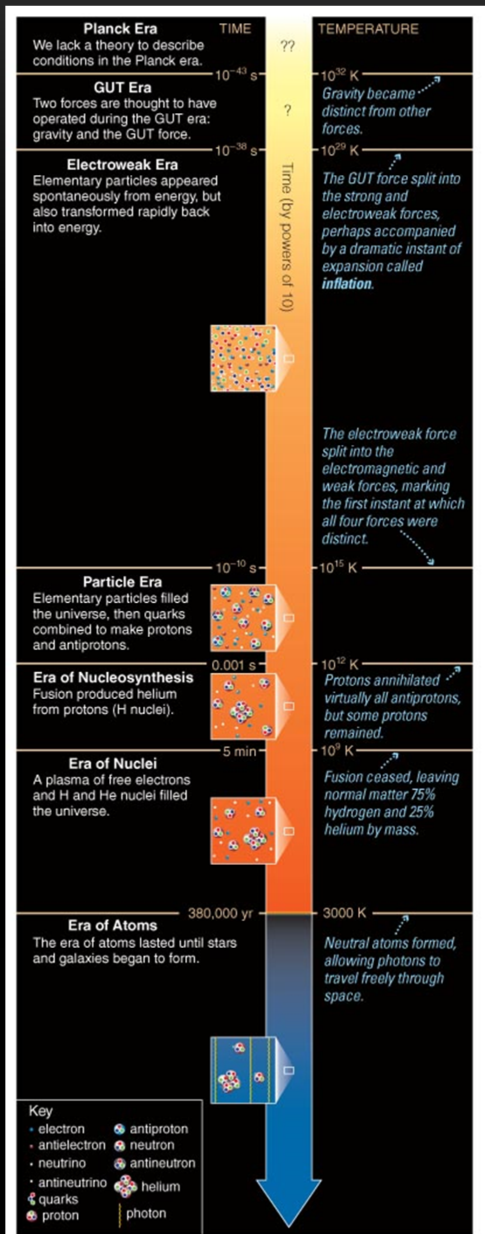
Time: 10^{-10}–0.001 s

Temp: 10^{15}–10^{12} K

Amounts of matter and antimatter are nearly equal.

(Roughly one extra proton for every 10^{9} proton–antiproton pairs!)

Fig.17.5



Era of Nucleosynthesis

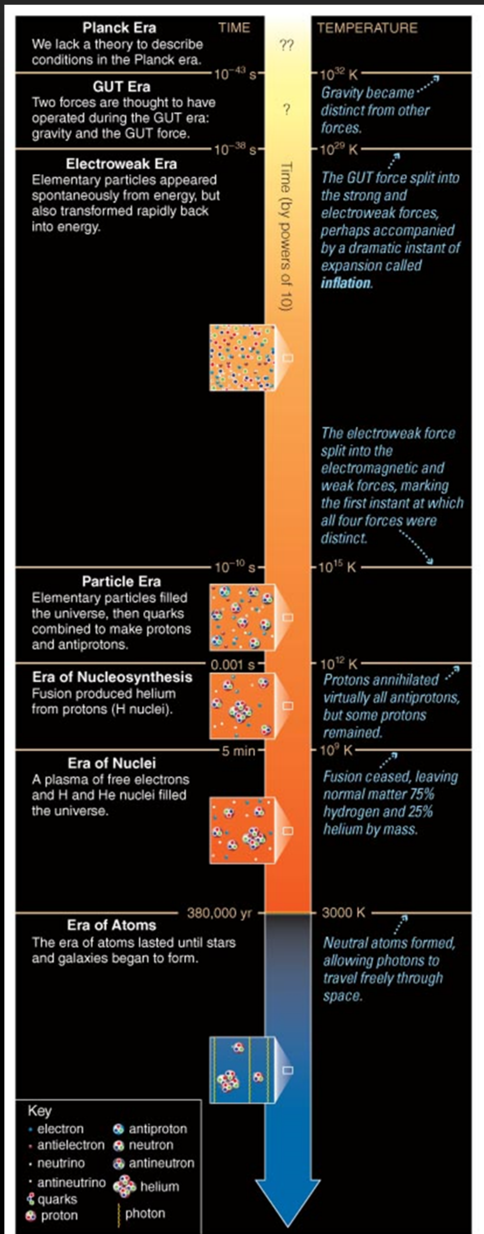
Time: 0.001 s–5 min

Temp: 10^{12}–10^{9} K

Began when matter annihilates remaining antimatter at ~ 0.001 s.

Nuclei began to fuse.

Fig.17.5



Era of Nuclei

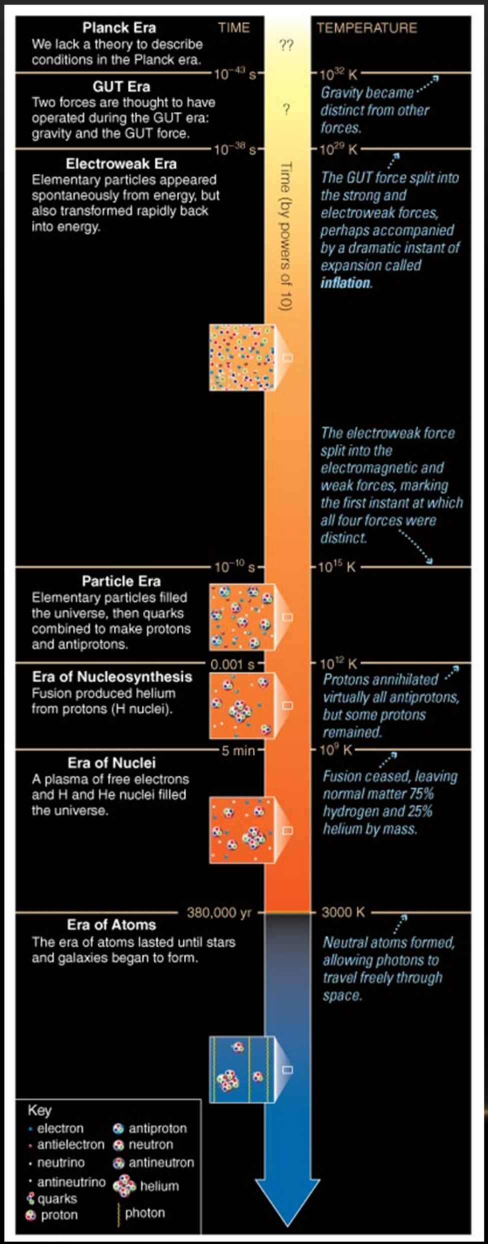
Time: 5 min–380,000 yrs

Temp: 10^{9}–3000 K

Helium nuclei formed at age ~3 minutes when the universe became too cool to blast helium nuclei apart.

Era ends when universe is too cool to blast atoms apart.

Fig.17.5



Era of Atoms

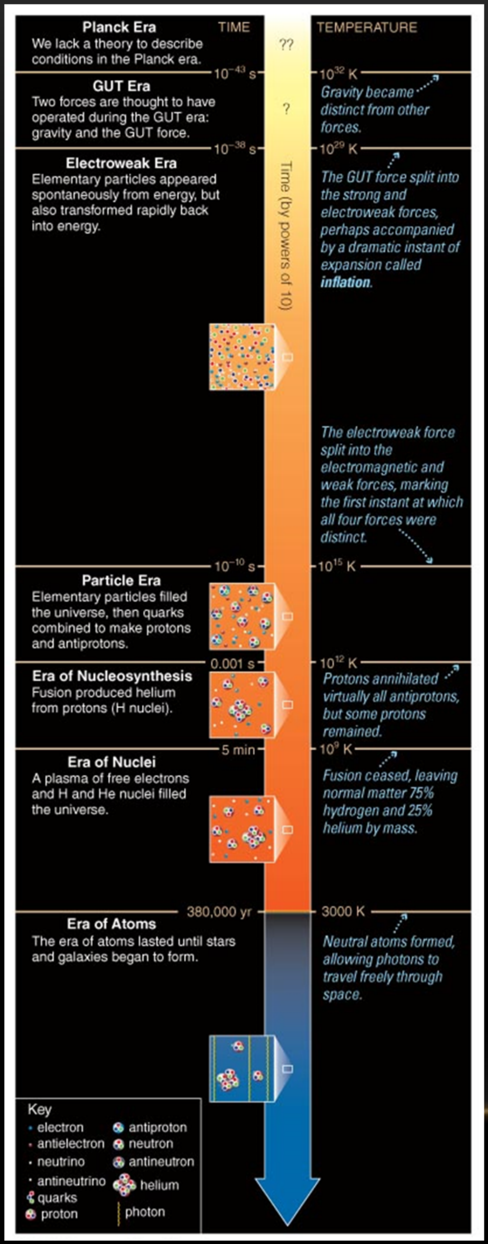
Time: 380,000 years–
1 billion years

Temp: 3000–20 K

Atoms formed at age ~380,000 years, when it is cool enough not to immediately ionize them.

Background radiation is released.

Fig.17.5



Era of Galaxies

Time: ~1 billion years–present

Temp: 20–3 K

The first stars and galaxies formed by
~1 billion years after the Big Bang.

OH COME ON NOW…

- How do we know this stuff?
- Primary evidence for this "Big Bang" theory:
  - We have detected the leftover radiation from the Big Bang.
  - The Big Bang theory correctly predicts the abundance of helium and other light elements in the universe.

NUCLEOSYNTHESIS

- Starting at t=(*really small*), the universe is very compact (the laws of physics stop working at $t=10^{-43}$ s)
- Compact things are very hot
  - So hot that if H were to fuse into He, the He would be broken up right away by the heat!
- The universe is expanding, cooling off
  - After t=1 minute, cools enough for the He to stick together
  - Still hot enough for fusion, like in a star
  - Light elements created from H

A COUPLE MINUTES LATER…

- After t=3 minutes, the universe has expanded and cooled enough that fusion stops
  - Leaves 75% of the H unburnt
  - But does produce ~25% He
  - …plus very low levels of other light elements like D, ^{3}He, Li, Be
- Calculations of the abundances created in the Big Bang in this fashion ("Big Bang Nucleosynthesis") match very well with the abundances we measure in the universe!

WHAT'S GOING ON?

- Before this time, it was hot enough to immediately zap apart conglomerations of particles
- When it cools enough for this not to happen, loose neutrons start to stick to protons

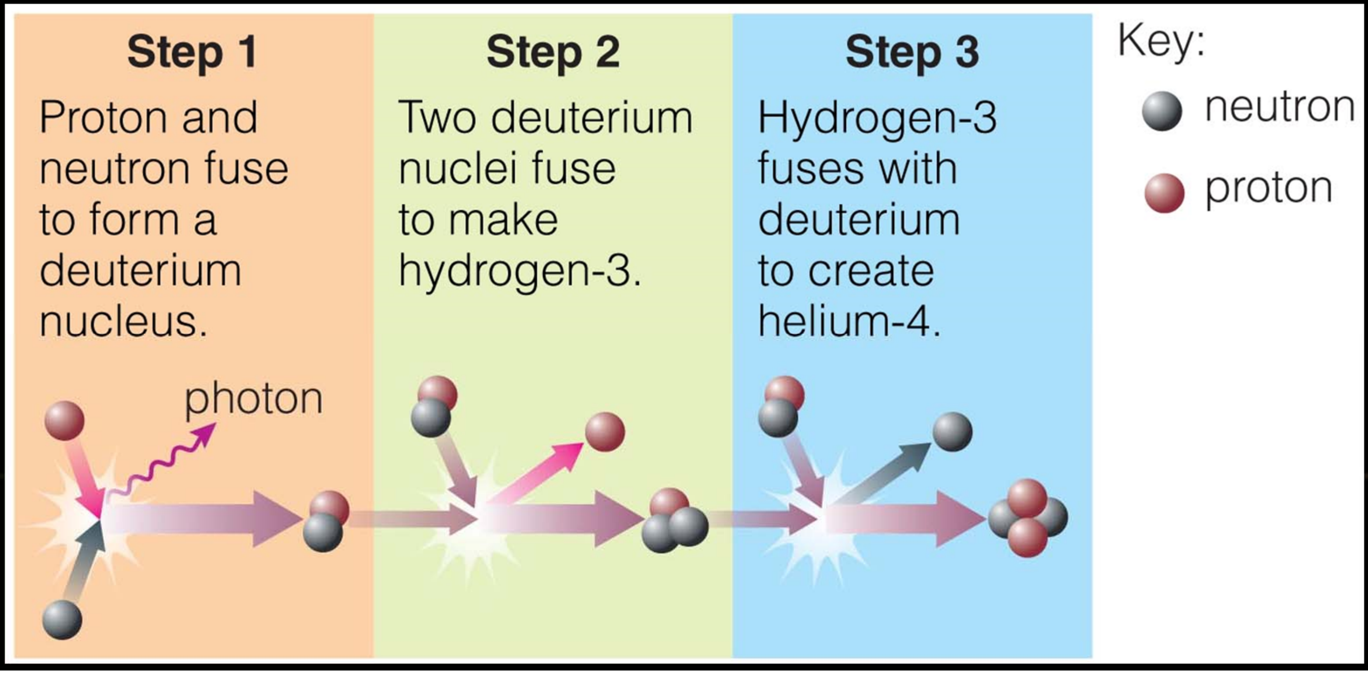


Fig.17.11

WHAT GETS MADE?

- At point when this starts, calculations show there were 7 protons for each neutron
  - Slightly heavier neutrons are harder to make, gets you 5-1
  - Some time elapses after making them, some neutrons decay, end up with 7-1

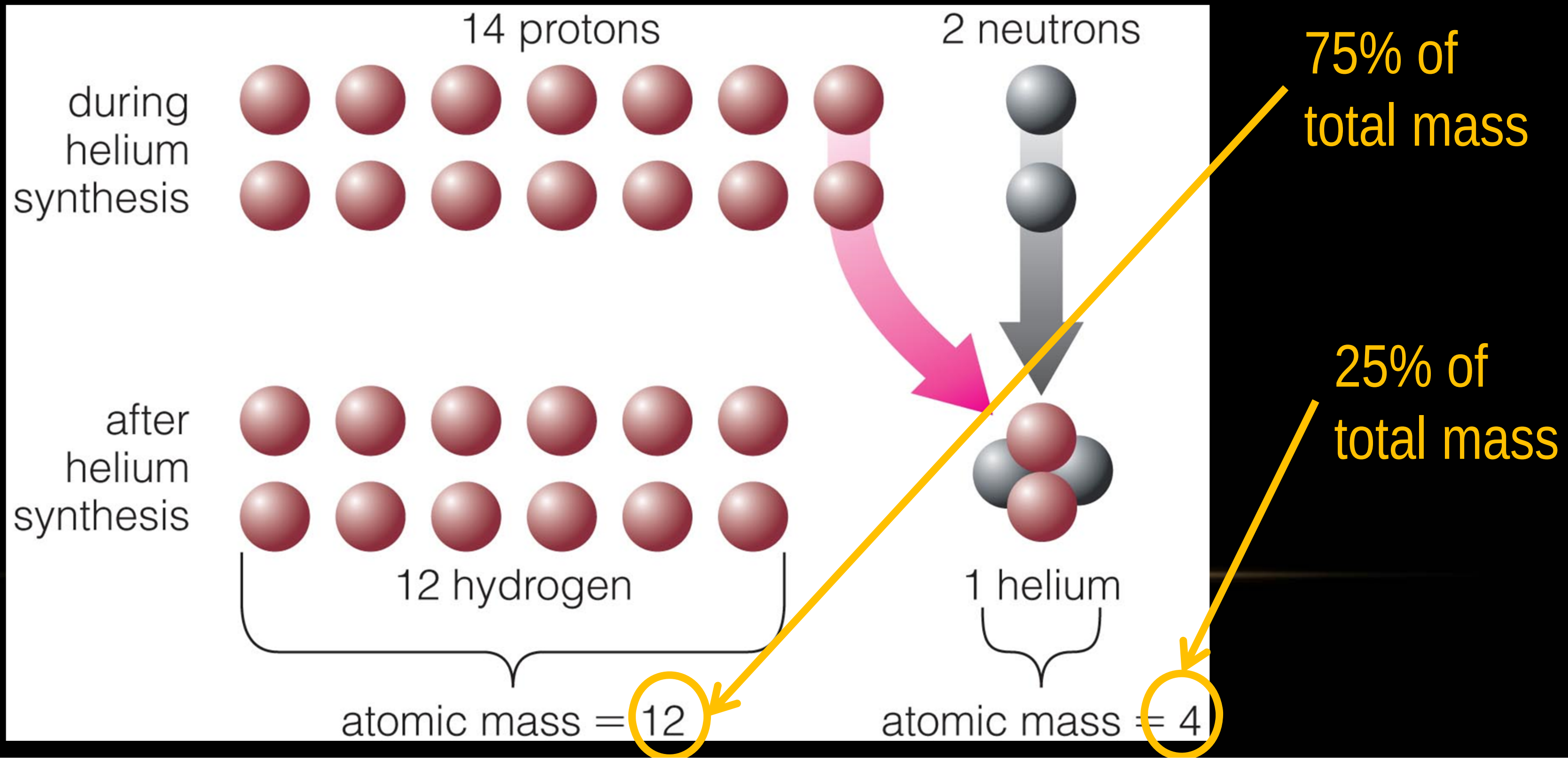


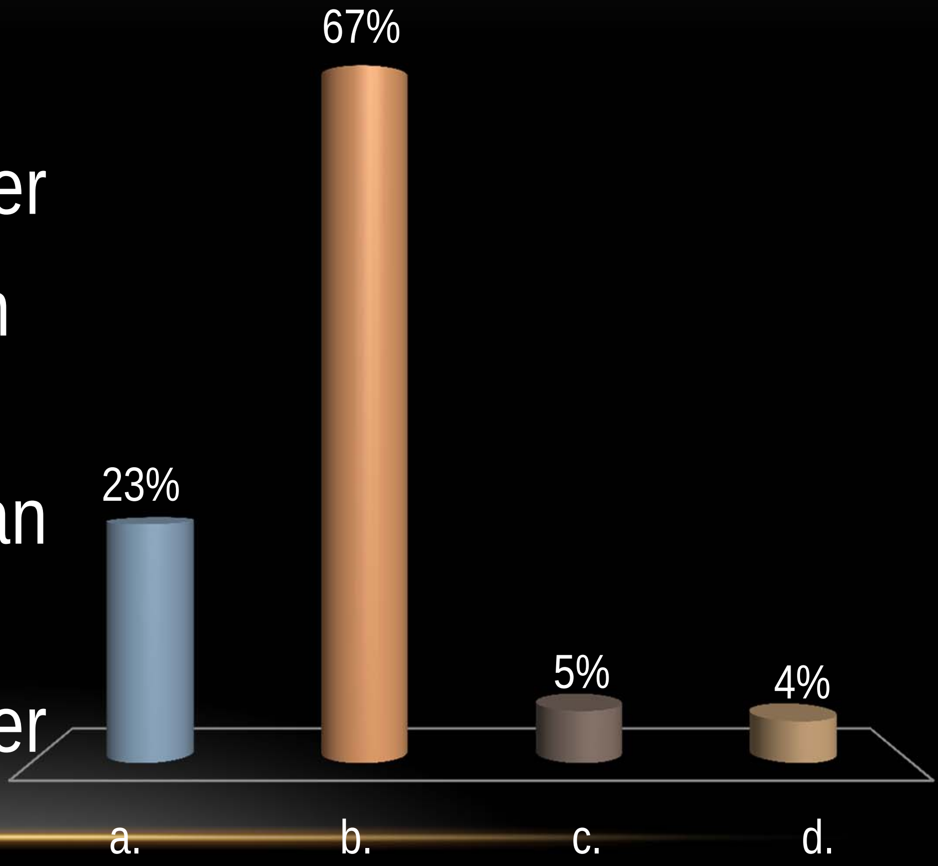
Fig.17.12

OTHER LIGHT ELEMENTS TOO

- Similar calculations show:
  - Deuterium (^{2}H): 0.003%
  - Helium-3 (^{3}He): 0.001%
  - Lithium-7 (^{7}Li): 0.00002%
- And spectral observations of very old things agree with this
  - Old as in before stellar recycling makes more heavy stuff, like it had when our solar system formed

WHICH OF THESE ABUNDANCE PATTERNS IS AN UNREALISTIC CHEMICAL COMPOSITION FOR A STAR?

a. 70% H, 28% He, 2% other
b. 95% H, 5% He, less than 0.02% other ✓
c. 75% H, 25% He, less than 0.02% other
d. 72% H, 27% He, 1% other



AFTER 380,000 YEARS

- A while later, with the universe still expanding and cooling, the temperature is about 3000 K
  - About the temperature of the surface of a cool red star
- This is cool enough to become transparent to light
  - Electrons can stick to atoms without getting zapped apart right away
- The hot stuff radiates
  - Glowing “red hot”, acts like a 3000 K blackbody

CAN'T SEE THROUGH PLASMA

- Light smacks into free electrons really well
- This is the same reason we call the "surface" of a star the photosphere

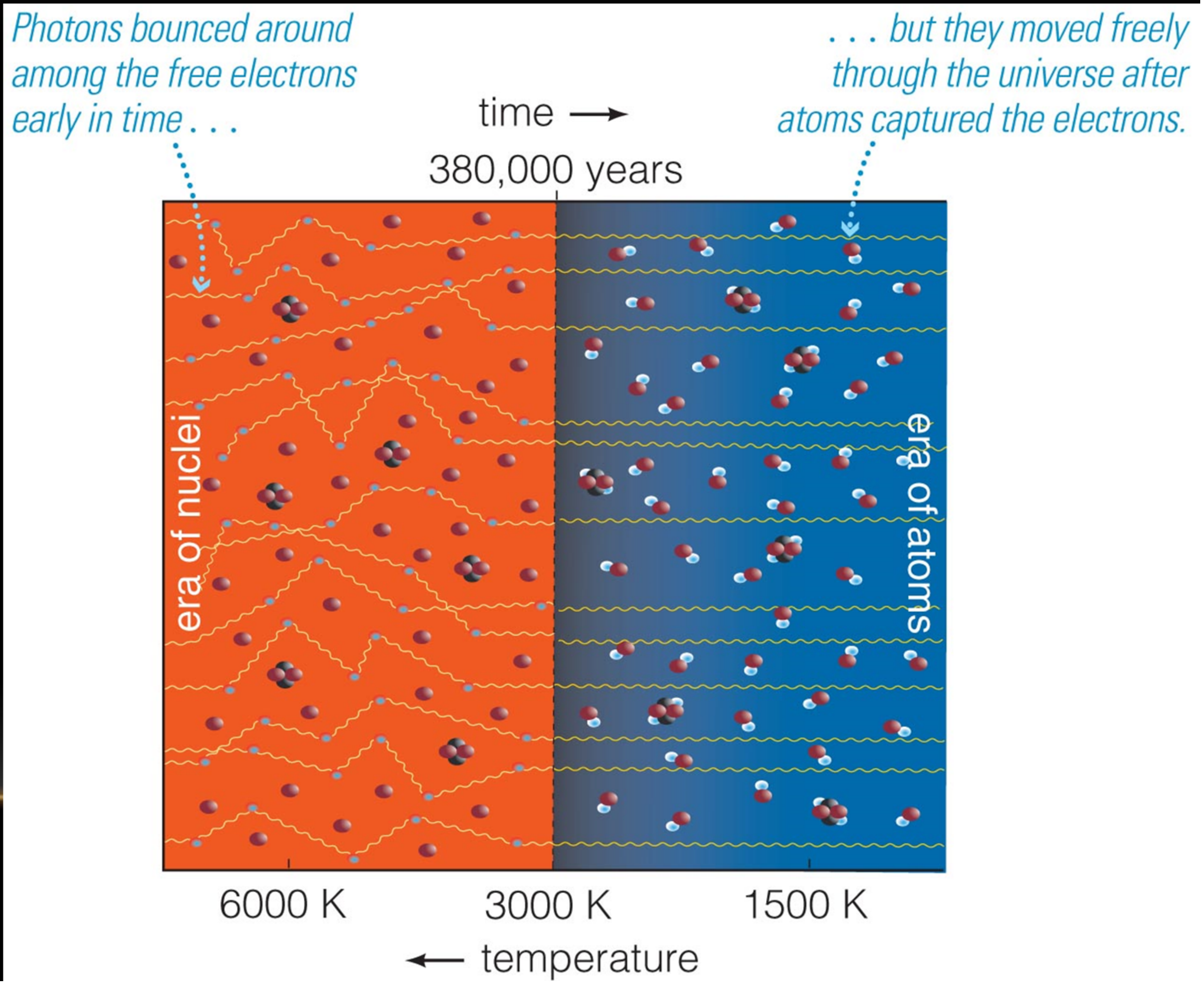


Fig.17.8

NOISY UNIVERSE…

- Two guys at Bell Labs were researching how to build microwave antennae
  - Why? Bell Labs was run by the phone company
  - Today, cell towers all talk to each other via microwave relays
  - They kept getting noise no matter where they pointed their antenna
  - Seagull poop?
    - Sometimes it takes dirty work to get a Nobel Prize…

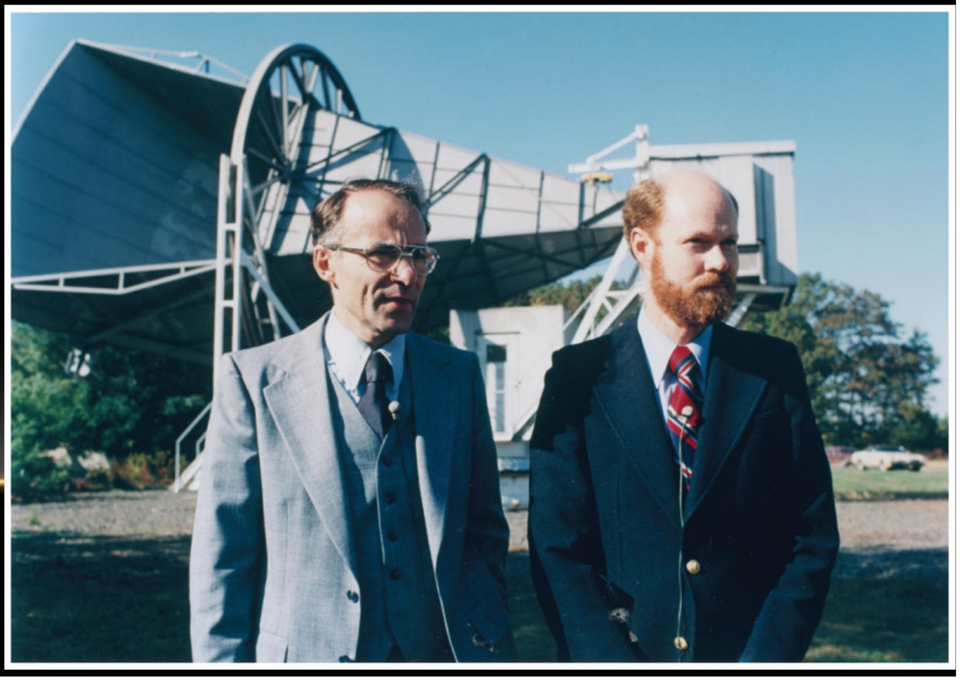


Fig.17.7, Penzias & Wilson

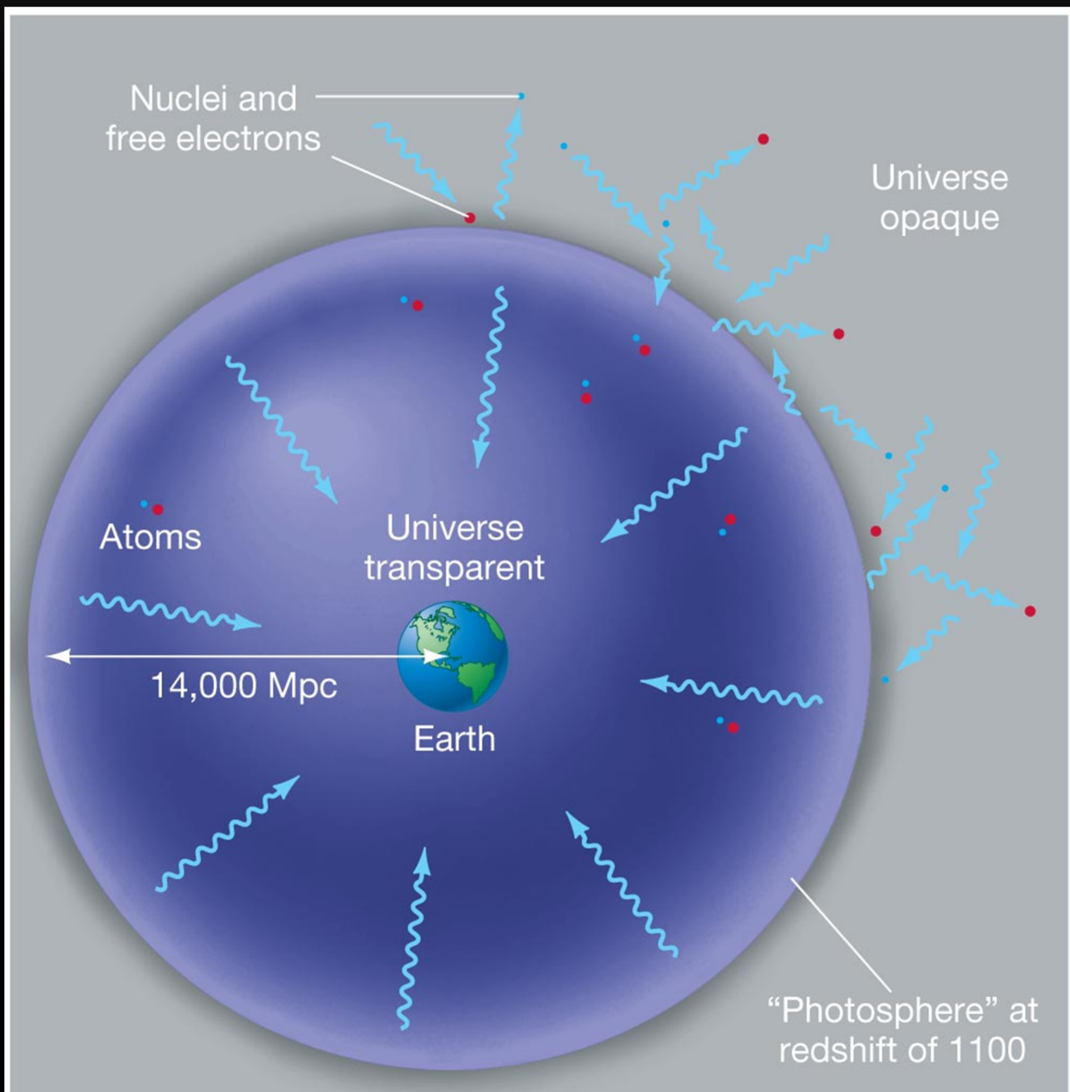
COSMIC MICROWAVE BACKGROUND

- Wherever we look in the sky, we see microwave radiation
  - Corresponds to a blackbody of 2.7 K (T=-270 ^{o}C)
- Today, we look back into the past when seeing things far away
  - The “look back time”
- The farther stuff is away (and thus the older it is), the more it is redshifted

SNAPSHOT OF THE YOUNG UNIVERSE!

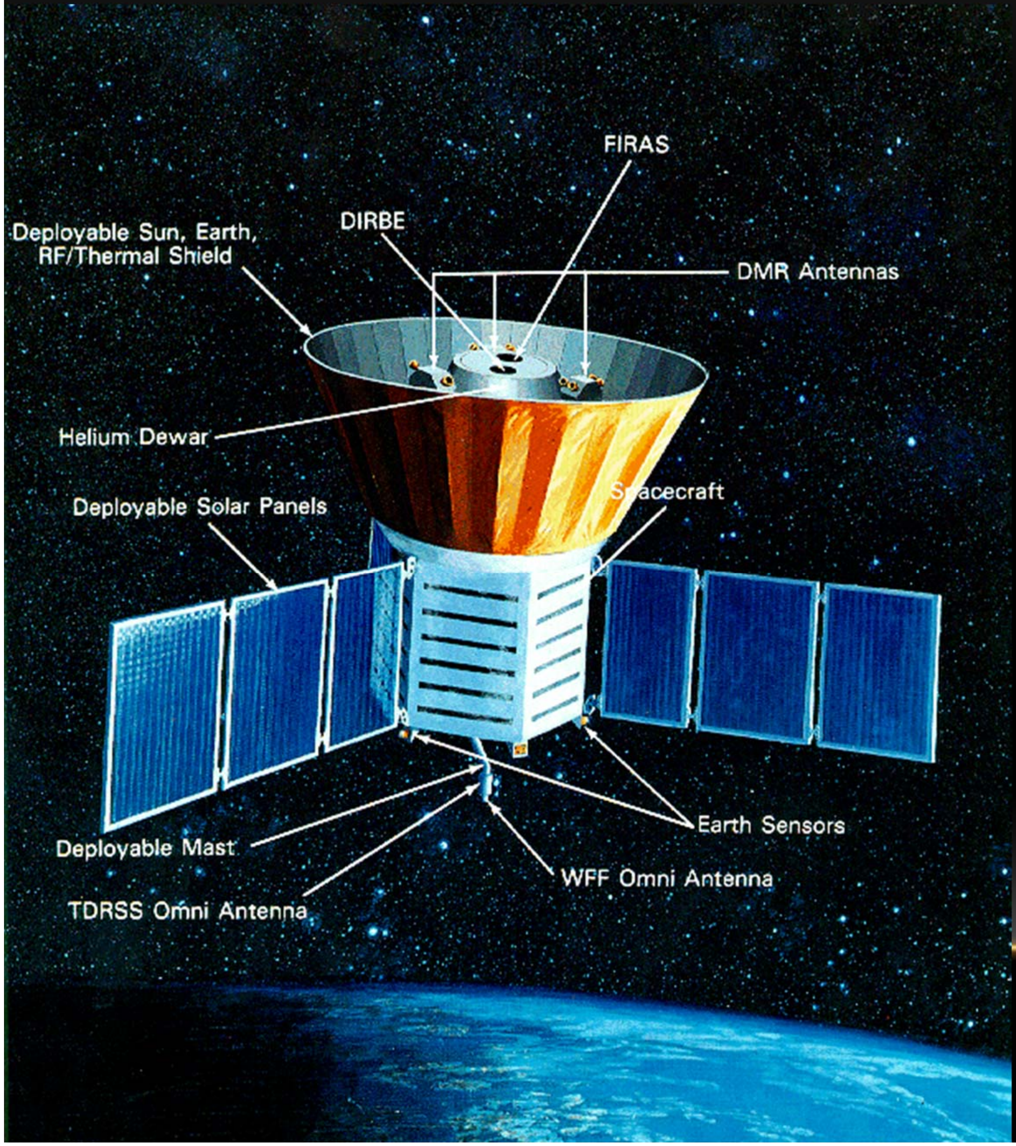
- Calculate the extreme redshift of something you could see if you looked back all the way to a 380,000 year old universe
- Apply that redshift to a 3000 K blackbody spectrum (which is red)
- The answer – the light is redshifted all the way to the microwave region
- The CMB is a picture of the universe just as it became cool enough to be transparent to light

FAR FAR AWAY…



- Remember, far, far away is also long, long ago

COBE

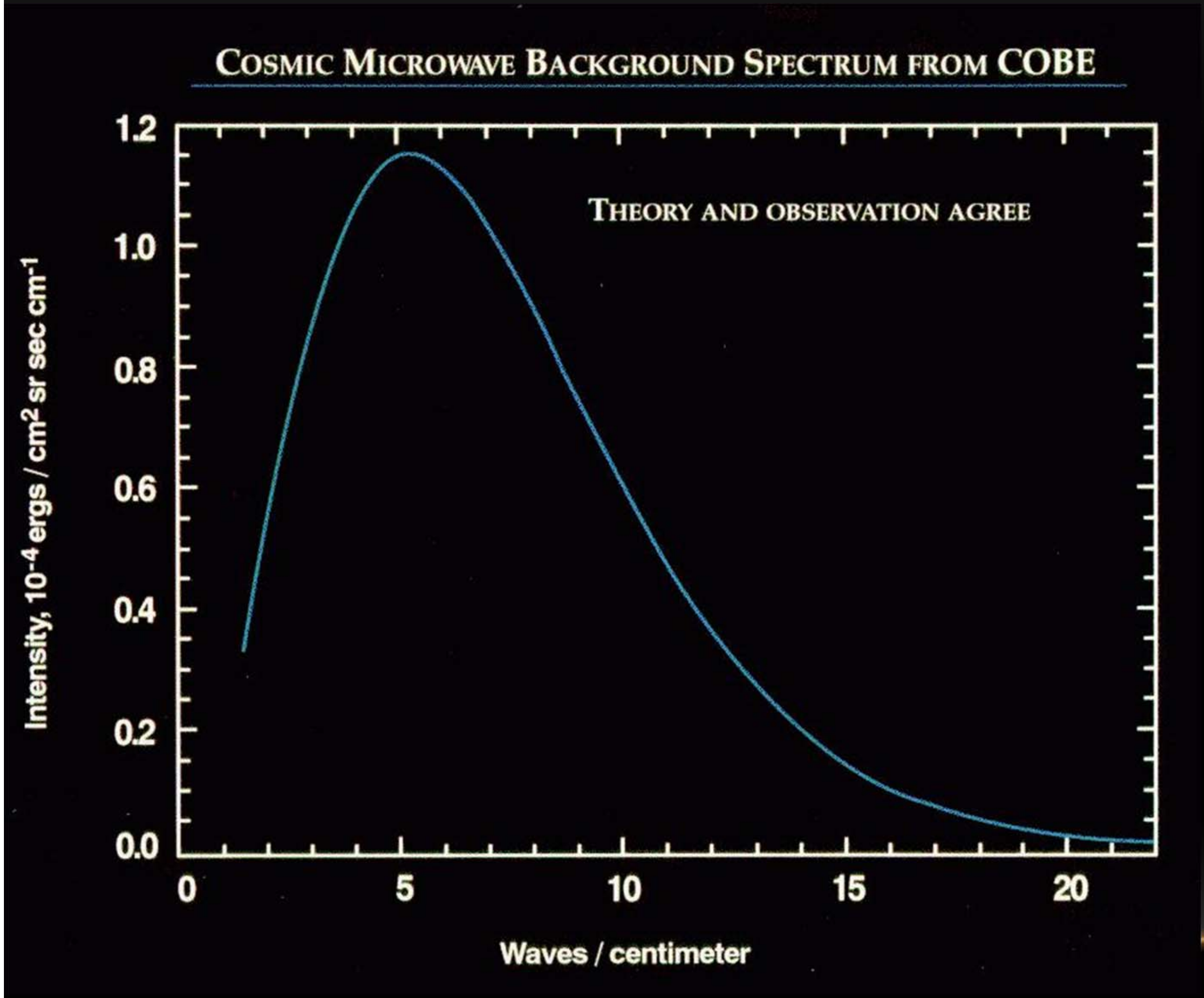


The Cosmic Background Explorer satellite was launched in 1989

- Need to get above atmosphere to see microwaves well, due to water in the atmosphere

Measured the CMB carefully in all directions for 4 years

COBE RESULTS

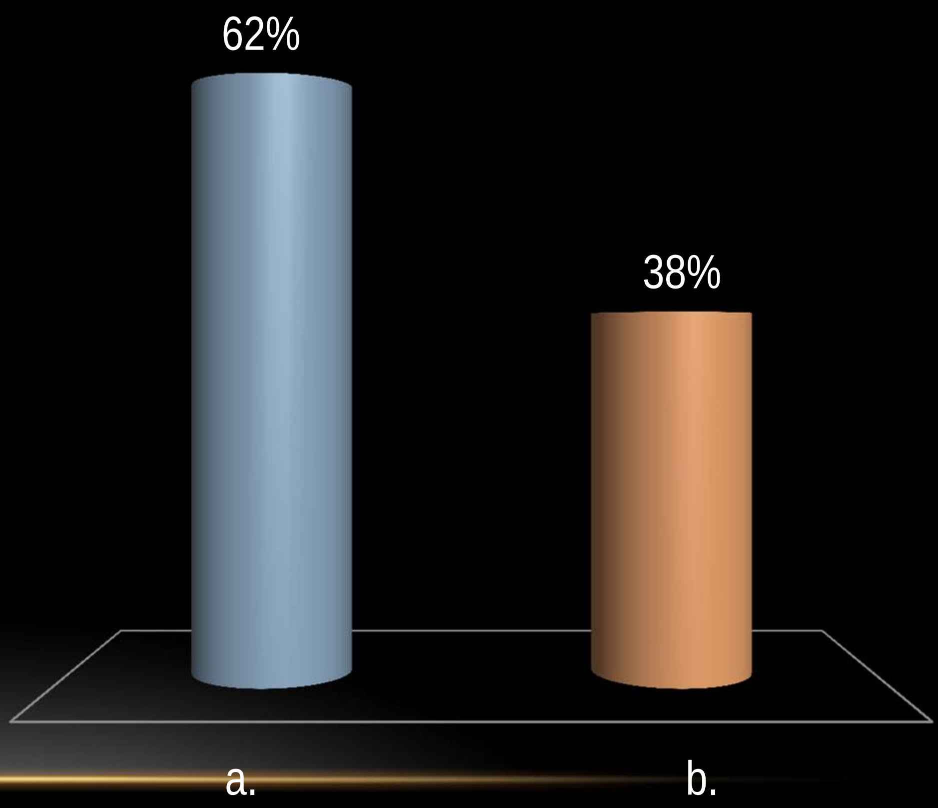


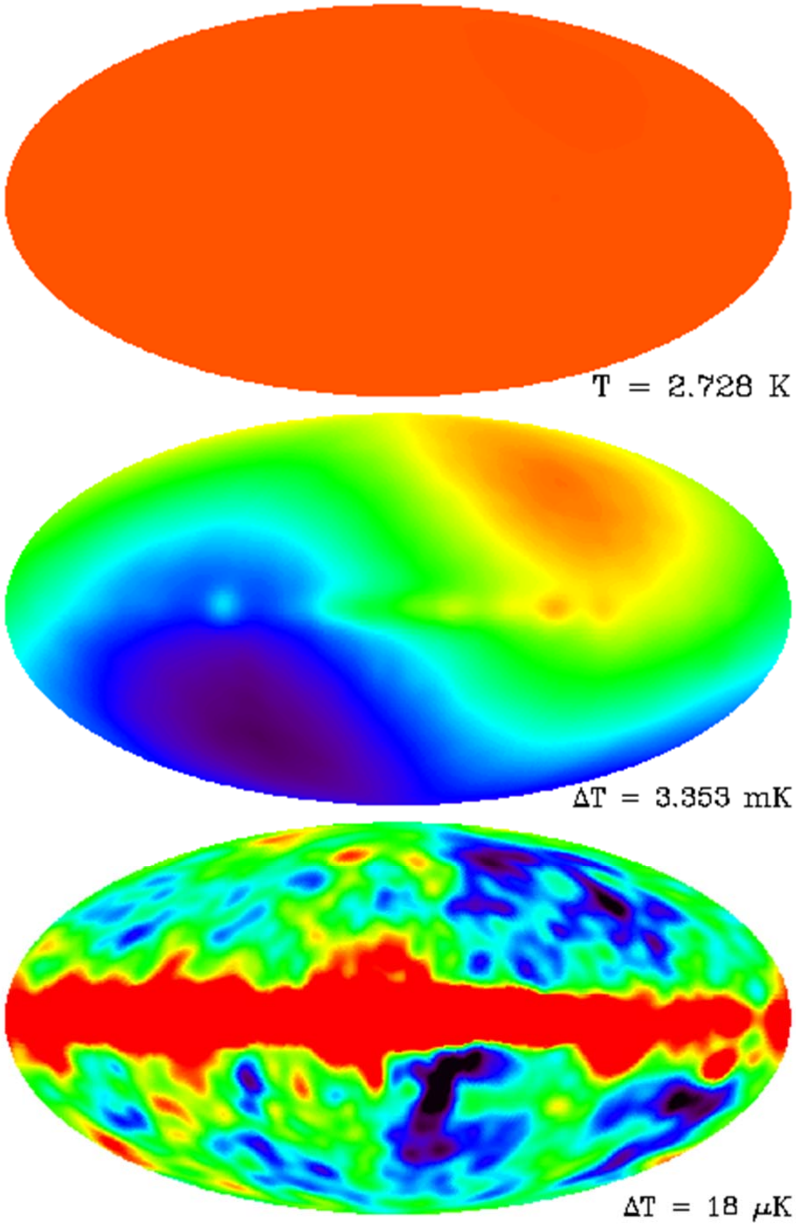
The data match a blackbody curve so well that their error bars are smaller than the width of that curve!

- T=2.728+/-0.004
- Uncertainty only 0.03%

SOME OF THE "SNOW" (RANDOM NOISE) YOU SEE ON A TV WHEN IT IS NOT TUNED TO A BROADCASTING CHANNEL, IS LEFTOVER RADIATION FROM THE BIG BANG.

a. True ✓
b. False





THE MOTION OF EARTH

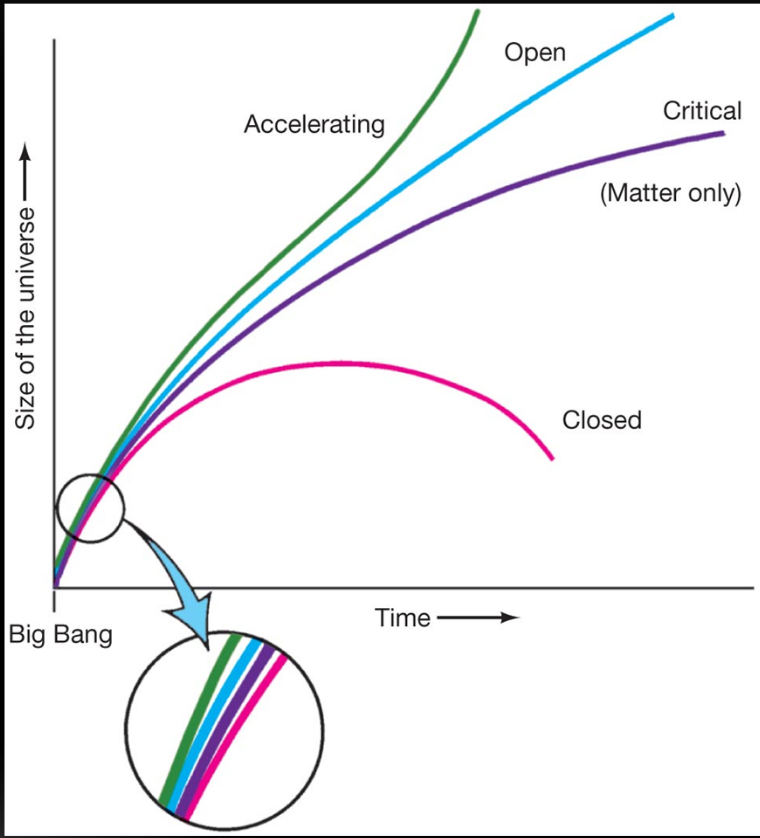
- The motions of
  - Earth about Sun
  - Sun about galaxy
  - Galaxy through space
- Slightly blueshifted where we are headed, redshifted where we are leaving

AGE OF THE UNIVERSE?

- How far away is that CMB
  - Thus, how old is the universe?
- If $v = H_0 d$ (Hubble Law) (H_0=20 km/s/Mly)
- $v=d/t$, so $d/t=H_0 d$ or $t=1/H_0$
  - Change units from km/s/Mly to years
  - Get ~13.4 billion years for age of universe (*after taking into account the shape of the universe*)
- Oldest globular clusters are about 12.7 billion years old, so that agrees (it hasn't always!)

GEOMETRICAL PROBLEMS

- Two problems with the Big Bang are:
- (1) The Flatness Problem
  - The universe is very close to flat
  - If it was a little bit different from flat early on, things wouldn't have lasted this long
- Why should it be so very close to perfectly balanced?
  - More than 1 part in 10^{15} wipes out, does not stay balanced



(2) THE HORIZON PROBLEM

- The CMB is very uniform
  - This means that the glowing stuff was all about the same temperature
  - This will happen via normal heat conduction, radiation
- But, at short times, how could the light travel far enough to equalize the temperature on both sides of the sky?