# Lecture 17 : The Cosmic Microwave Background

- Discovery of the Cosmic Microwave Background
- The Hot Big Bang
- Cosmic radiation and matter densities
- Stages of evolution in the early Universe



*This week: read Chapter 12 in textbook*

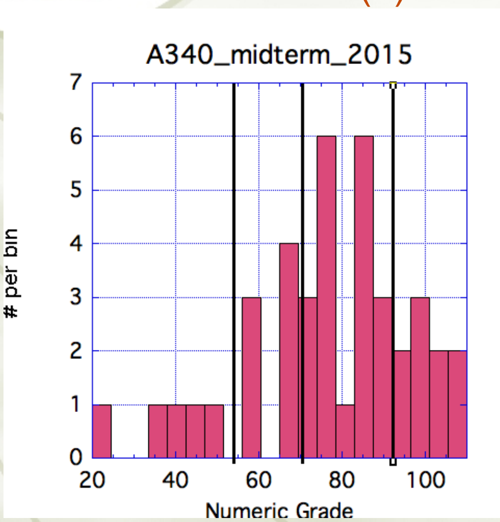
## Let's think about the early Universe…

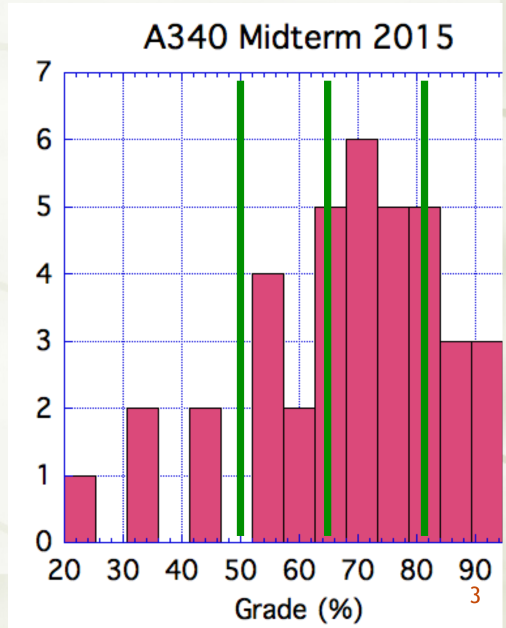
- From Hubble's observations, we know the Universe is expanding
  - This can be understood theoretically in terms of solutions of GR equations
- Earlier in time, all the matter must have been squeezed more tightly together
  - If crushed together at high enough density, the galaxies, stars, etc could not exist as we see them now -- everything must have been different!
- What was the Universe like long, long ago?
  - What were the original contents?
  - What were the early conditions like?
  - What physical processes occurred under those conditions?
  - How did changes over time result in the contents and structure we see today?

mean=70% (e.g. 77pts)
on the test

| | | |
|---|---|---|
| A=>85% | 93pts | (7 students) |
| B= 65-85% | 71pts | (19) |
| C=50-65% | 55pts | (9) |
| D=30-50 | | (4) |
| F<30 | | (1) |

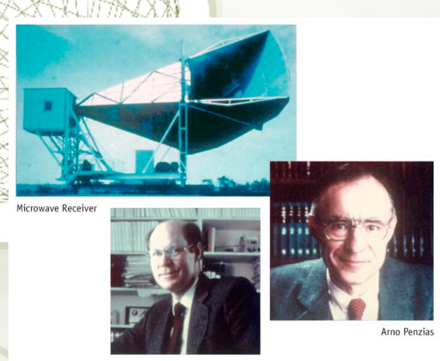
# Mid-Term

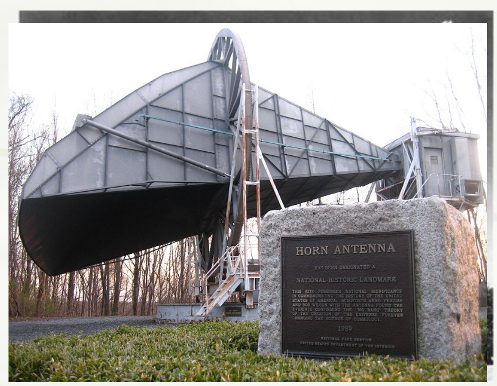





# I : The Cosmic Microwave Background




- Arno Penzias & Robert Wilson (1964)- Noble Prize 1978
  - Attempted to study radio emissions from our Galaxy using sensitive antenna built at Bell-Labs
  - Needed to characterize and eliminate all sources of noise- bird droppings
  - They never could get rid of a certain noise source… noise had a characteristic temperature of about 3 K (3 degrees above absolute ZERO) .
  - They figured out that the noise was coming from the sky, and was approximately the same in all directions…
  - Discovered the *cosmic background radiation*, or *CBR (or CMB, for Cosmic Microwave Background, since there are other backgrounds)*

## At the same time in a nearby university

- Robert Dicke (Princeton Univ) and collaborators Dicke and his colleagues reasoned that the Big Bang must have created not only the matter that condensed into galaxies but also must have released a tremendous blast of radiation (this had been predicted 20 years before by G.Gamow, Alpher and Herman but had been forgotten)
- **With the proper instrumentation, this radiation should be detectable.** The characteristics of the radiation detected by Penzias and Wilson fit exactly the radiation predicted by Dicke
- see astro.berkeley.edu/~mwhite/rosetta/node1.html

A bit of history- Dicke first experiment was in 1946 but his equipment was not sensitive enough to detect the CMB (but he was not looking for it since in the same issue of Physical Review letters Gamow first predicted its existence )
However there was a mysterious result in 1940 that showed that the CN molecule in interstellar space (!) appeared to be stimulated by radiation of temperature 2.3k

## From Penzias and Wilson to COBE

- While Penzias and Wilson detected the CMB and showed that it was more or less uniform
- more information and more precise measurements were necessary
- This was very difficult using the technology of the 1960's

The first detection of 'anistropy' was in 1971

major advances used rockets and balloons to get above the atmosphere see
“The cosmic background radiation and the new aether drift,” Scientific American 238, 64 (1978). R. Muller for the early history

# *Why Microwaves??*

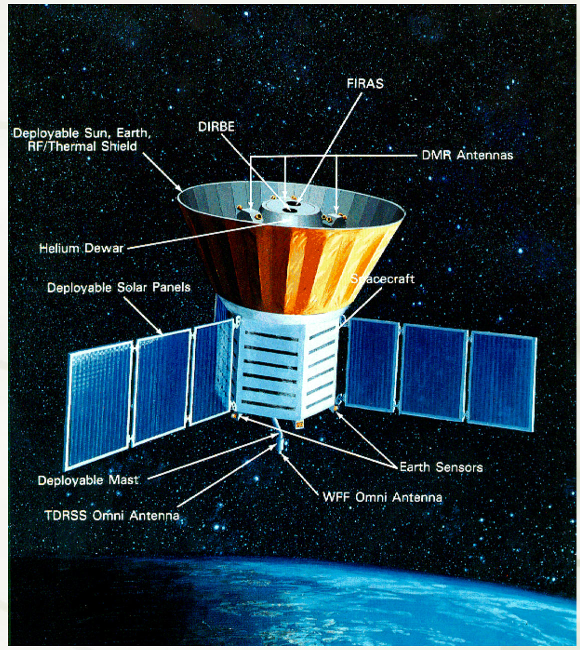
- When the CMB was initially emitted it was not in the form of microwaves at all, but mostly visible and ultraviolet light.
- Over the past few billion years, the expansion of the universe has redshifted this radiation toward longer and longer wavelengths, until today it appears in the microwave band.



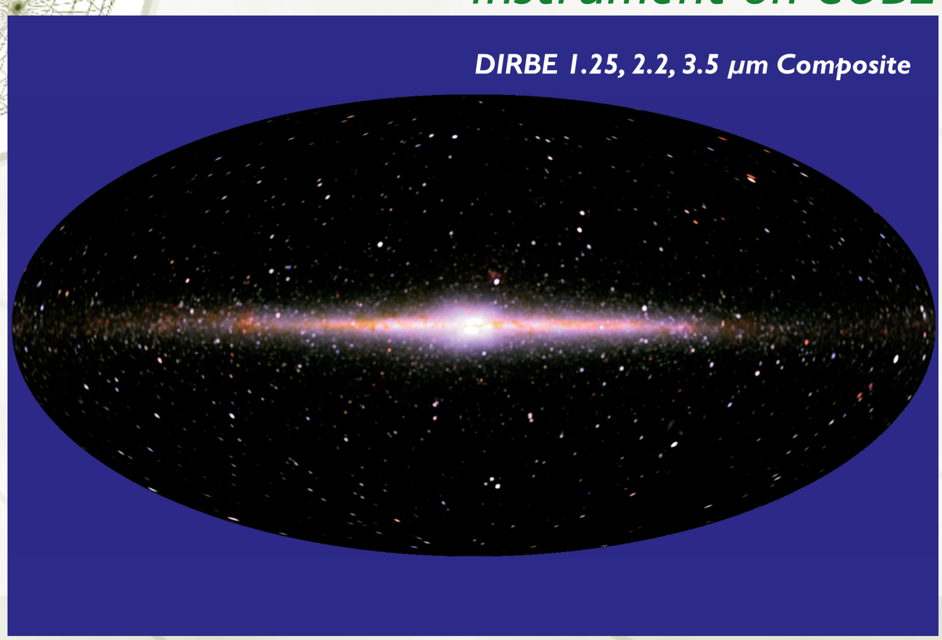
- Mueller 1978 said:
- The radiation is a few millidegrees hotter in the direction of Leo, and cooler in the direction of Aquarius. The spread around the mean describes a cosine curve.
- Such observations have far reaching implications for both the history of the early universe and in predictions of its future development.
- Based on the measurements of anisotropy, <u>the entire Milky Way is calculated to move through the intergalactic medium at approximately 600 kms</u>
- Furthermore, if the universe were perfectly homogeneous and isotropic, we would observe a homogeneous universe today. This is not the case ! -
  - the cosmos is filled with irregularities, from galactic clusters to moons and planets. Thus, the background radiation should also exhibit irregularities, which, to some extent, it does.

# 20 years of Ground Based Experiments Later

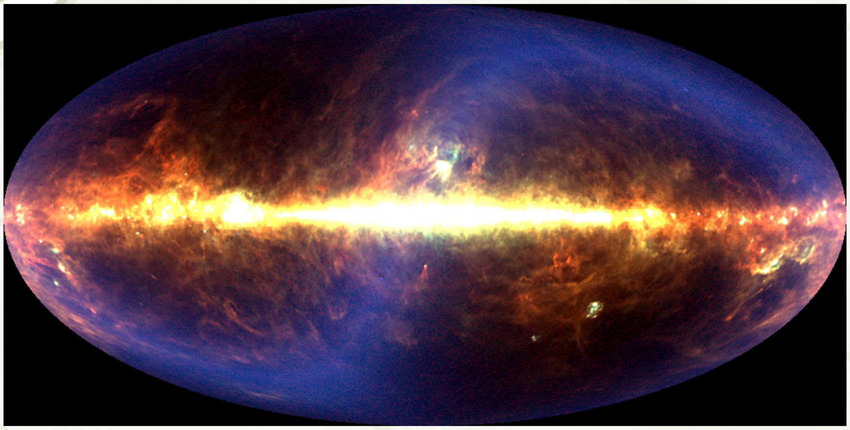
- The COBE mission
  - Built by NASA-Goddard Space Flight Center
  - Launched Nov. 1989
  - Purpose was to survey infra-red and microwave emission across the whole sky.
  - Primary purpose – to characterize the CMB.
- Had a number of instruments on it:
  - FIRAS (Far infra-red absolute spectrophotometer)-Precision spectrum of the CMB
  - DMR (Differential Microwave Radiometer)-fluctuations in the brightness
  - DIRBE (Diffuse Infrared background Experiment)- Infrared spectrum of the sky (dominated by the MilkyWay)



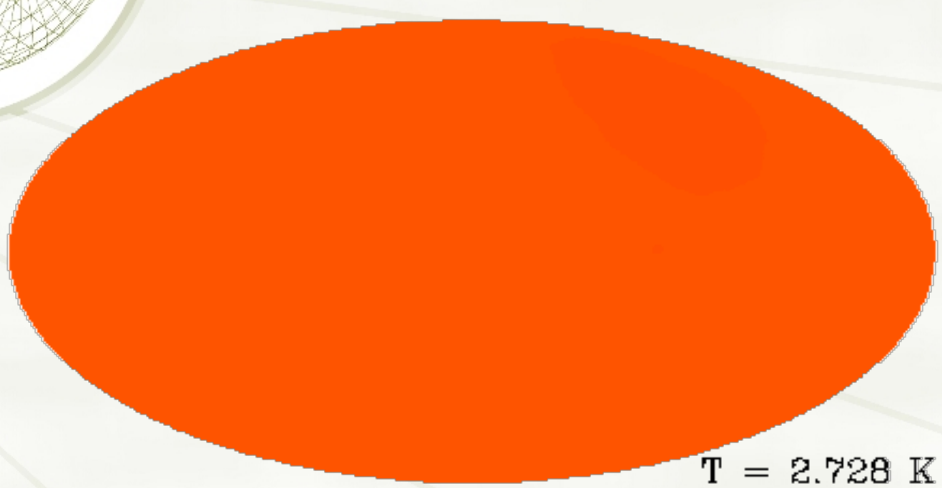

# Our Galaxy observed by the DIRBE instrument on COBE



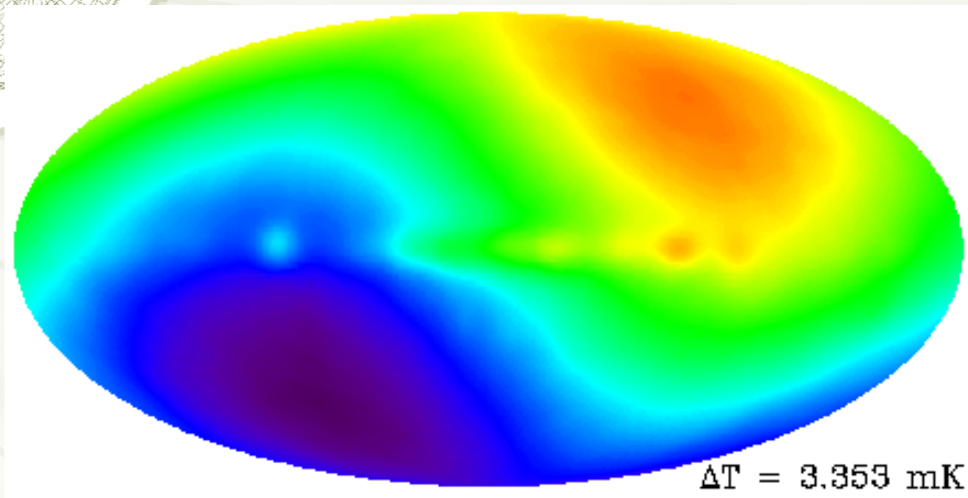
## The Whole Sky Observed by FIRAS



## Almost uniform intensity of microwaves in all directions (isotropic 2.7K black body radiation)

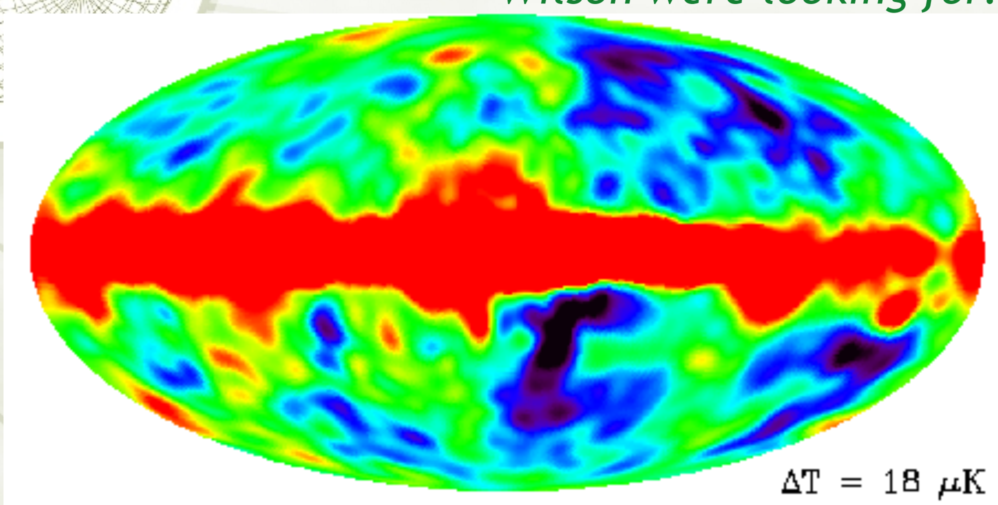


## *Subtracting off the **mean level** leaves with a "dipole" pattern... what is this??*

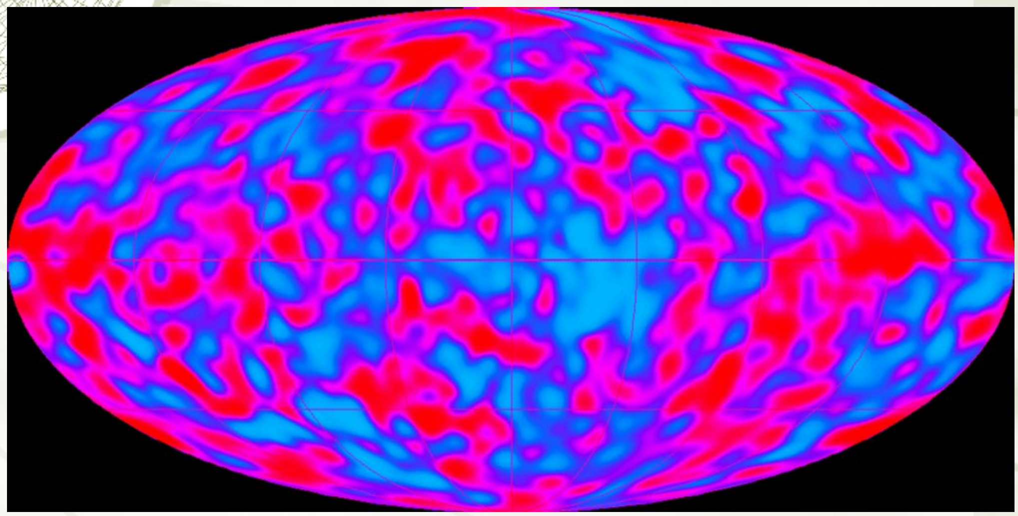


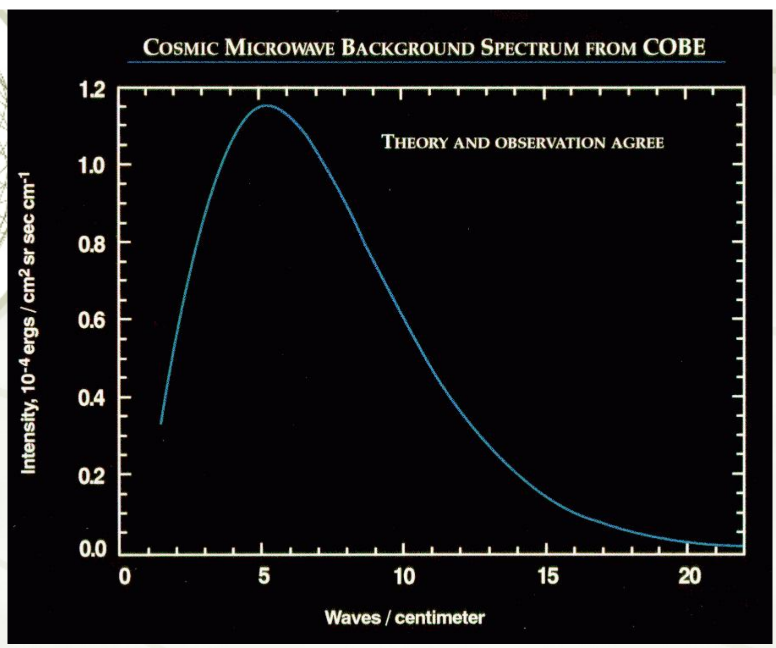

The motion of the earth with respect to the reference frame of the CMB-The Solar System is moving at 370 km/sec relative to the Universe and we can measure this using the dipole anisotropy

## *Subtracting off the dipole finally reveals the emission from the Galaxy that Penzias and Wilson were looking for!*



## *Subtracting contribution from Galaxy reveals fluctuations in the CMB*



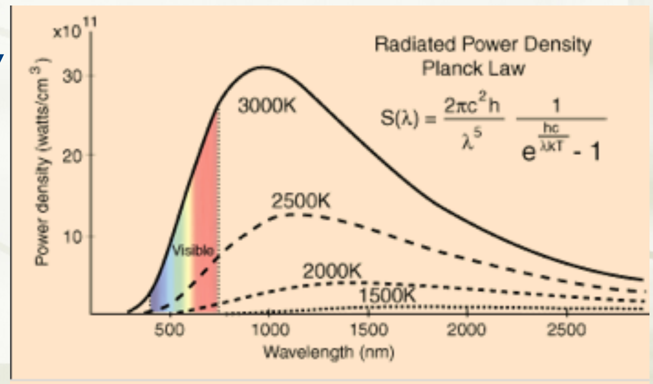



Spectrum of the CMB:
This is the actual data- the error bars are tiny !
when this was shown at an AAS meeting people applauded - Noble prize to John Mather at Goddard

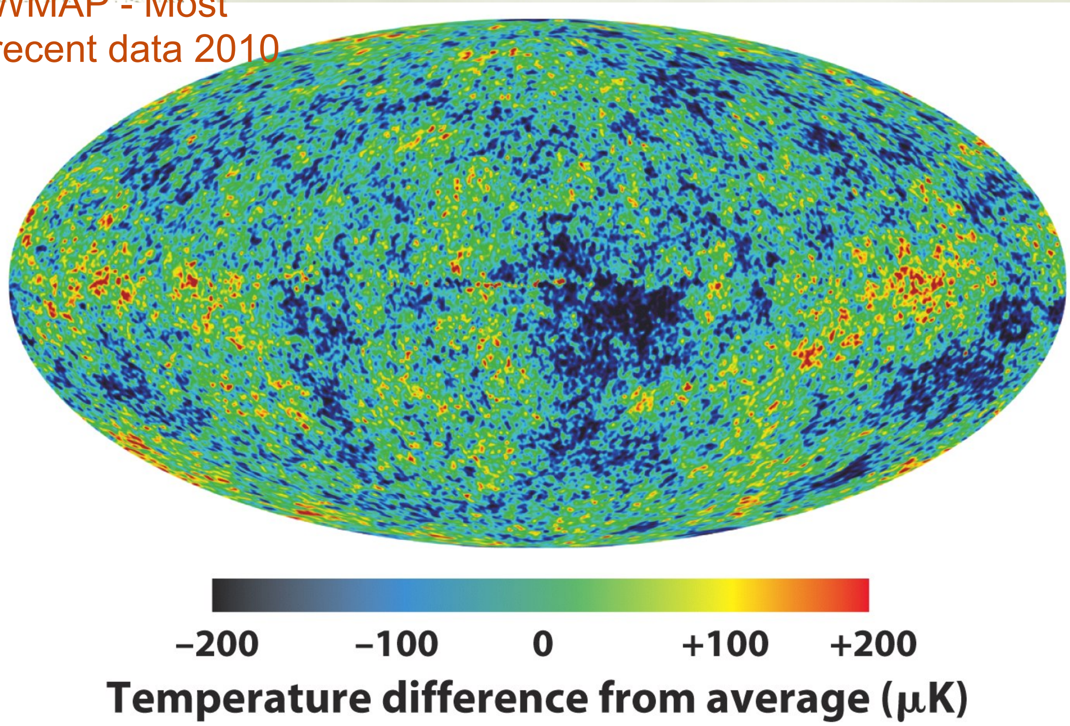
# Properties of the CMB

- Pervasive throughout Universe
- Range of wavelengths, with peak in microwave range
- Present density is 411 photons/cubic centimeter
- ***Spectrum perfectly consistent with a black body- shape of a black body spectrum only depends on the temperature***

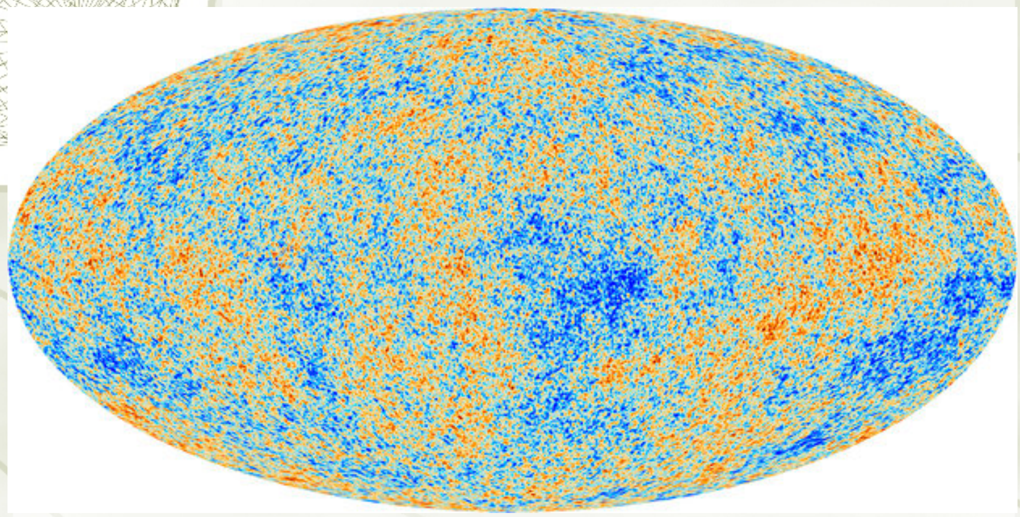
For the non-physical scientists Blackbody radiation" refers to an object or system which absorbs all radiation incident upon it and re-radiates the energy with a  characteristic spectrum which depends only on temperature and size of object-not dependent upon the type of radiation which is incident upon it.




WMAP - Most recent data 2010



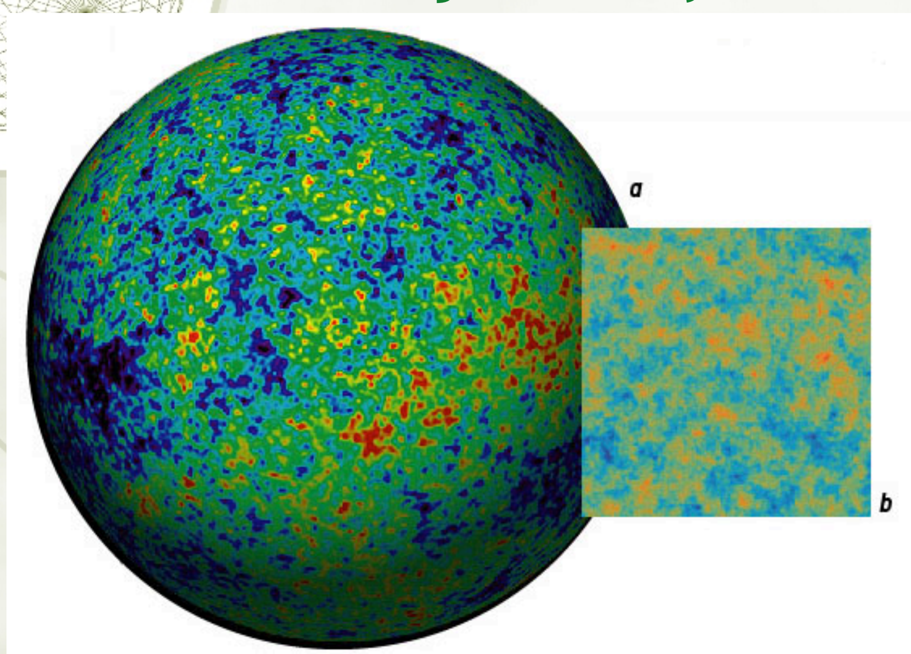
# Planck Map 2014



http://www.esa.int/Our_Activities/Space_Science/Planck/Planck_and_the_cosmic_microwave_background

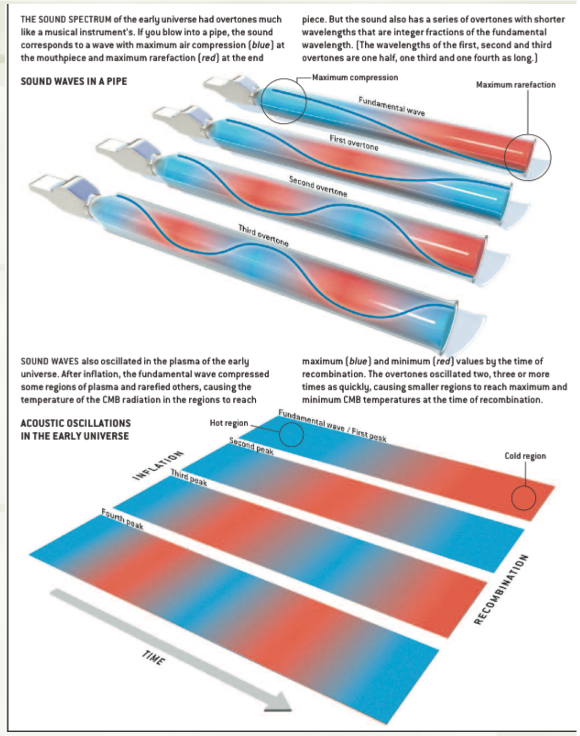


# *Intensity MAP of the CMB*



# Universe is like A Flue

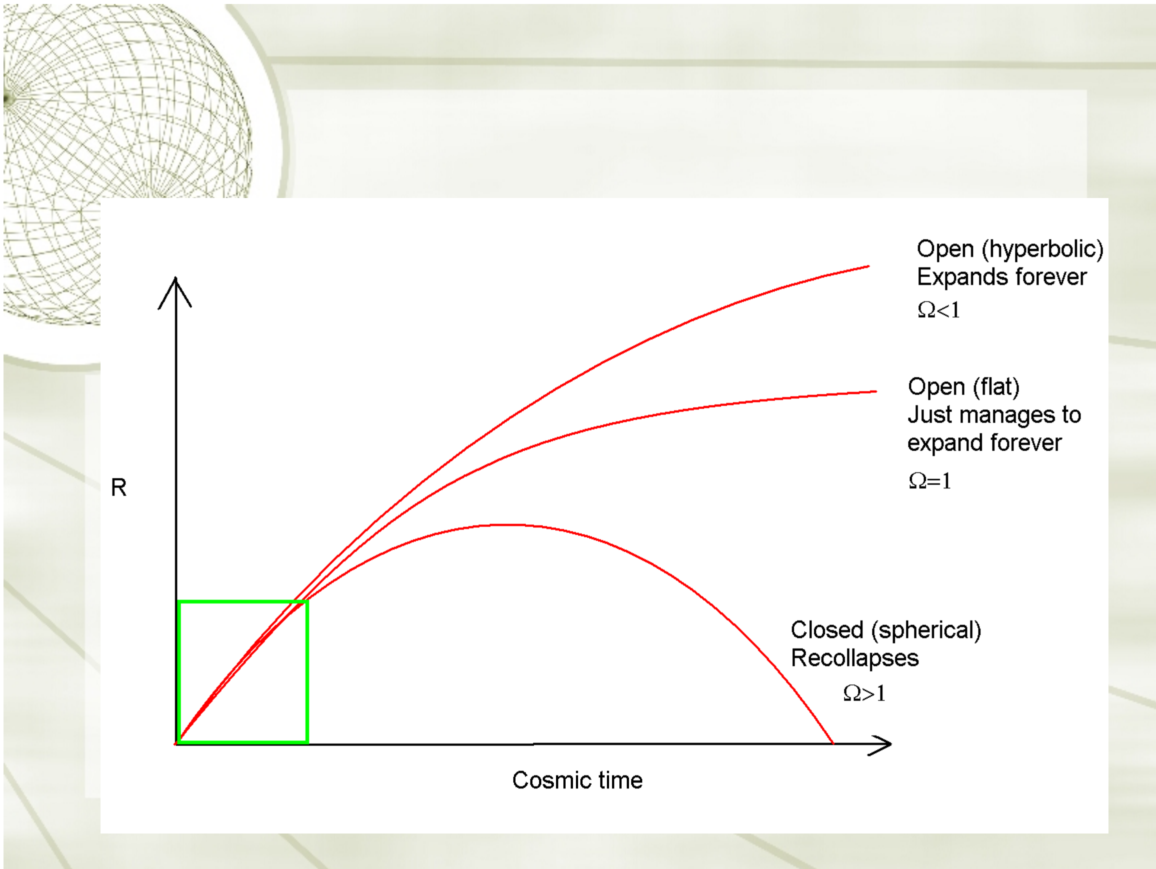
- The BIG BANG , wave compressed some regions of plasma and rarefied others, causing the temperature of the CMB radiation in the regions to reach maximum (blue) and minimum (red) values .
- The overtones oscillated two, three or more times as quickly, causing smaller regions to reach maximum and minimum CMB temperatures at the time of recombination.
- The regions with the greatest variations subtend about one degree across the sky, or nearly twice the size of the full moon

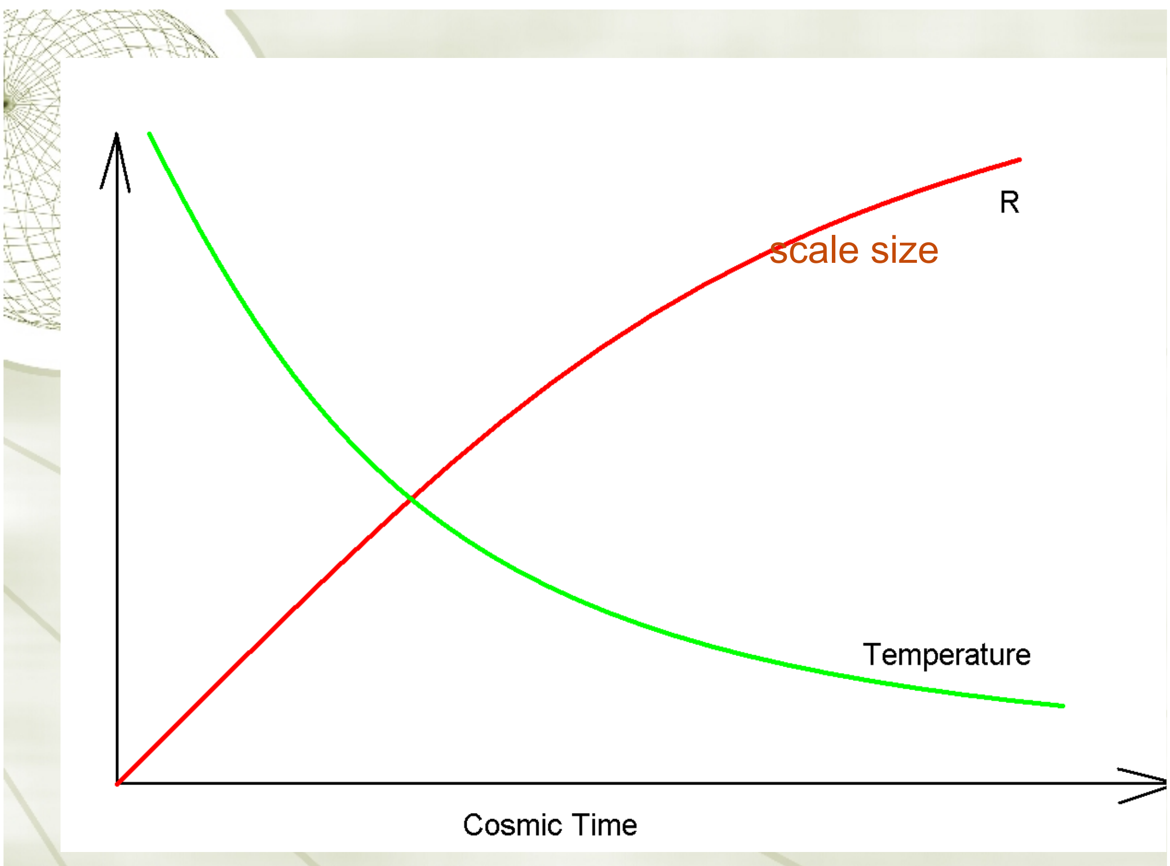



http://astro.berkeley.edu/~mwhite/sciam03_short.pdf

# II : THE HOT BIG BANG MODEL

- Penzias & Wilson had discovered radiation left over from the early universe…
- The hot big bang model…
  - Independently developed by James Peebles and George Gamov
  - They suggested that the universe started off in an extremely hot state.
  - As the Universe expands, the energy within the universe is spread over an increasing volume of space…
  - **Thus the Universe cools down as it expands**


Open (hyperbolic)
Expands forever
Ω<1
Open (flat)
Just manages to
expand forever
Ω=1
R
Closed (spherical)
Recollapses
Ω>1
Cosmic time


R
scale size
Temperature
Cosmic Time

# Cosmic radiation

- How does the radiation change with time?
  - The total number of photons per "co-moving volume" remains constant
  - So… number of photons per unit (normal) volume proportional to $(R_0/R(t))^3$
  - Photons get stretched by expanding space (- the redshift..Sort of like the Doppler effect)… so energy of photon is proportional to $R_0/R(t)$
  - So, energy density of radiation is $(R_0/R(t))^4$
- The CMB has a "blackbody" spectrum characterized by a temperature T
  - The energy density of blackbody radiation is proportional to $T^4$.
  - So… $T \alpha\ R_0/R(t)=1+z$ ($\alpha$ *means proportional to)*

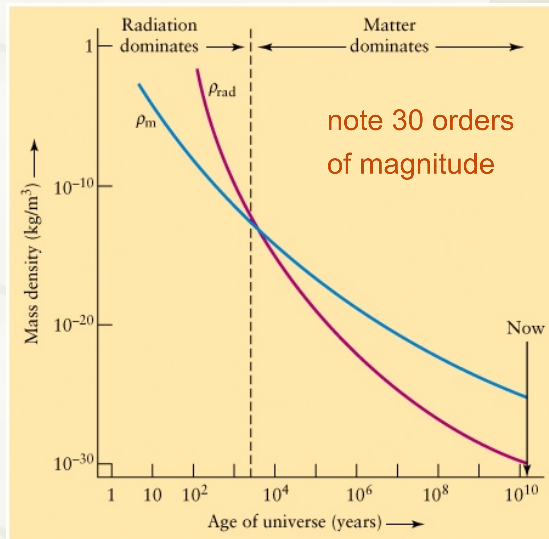


# Cosmic radiation

- At earlier times, this radiation field must have been *more intense*
- Energy density of background radiation *increases* as cosmic scale factor $R(t)$ *decreases* at earlier time $t$:
  - Multiply current number of photons/volume by $(R_0/R(t))^3=(1+z)^3$
  - Multiply current energy per photon by $(R_0/R(t))=(1+z)$
    - Why? Because photon energy is inversely proportional to wavelength, and wavelength at earlier time = present wavelength × $(R(t)/R_0)$
  - Overall, radiation energy density must vary as $(1+z)^4$
  - The spatial structure of the CMB (lumps and bumps in it) contain information about universe (Hubble constant, how much matter (both normal and dark), cosmological constant etc)

# *Matter and radiation densities compared*

- Already know matter density varies inversely with volume
- Thus:
  - $\rho_{matter} \propto (R_0/R(t))^3=(1+z)^3$
  - $\rho_{radiation} \propto (R_0/R(t))^4=(1+z)^4$
- At early times, energy density of CBR must have exceeded energy density of matter!
- When radiation field is strong, matter is heated up
- Therefore earlier and earlier in the Universe, it must have been hotter and hotter
- This suggests that origin of the Universe was a ***hot*** *Big Bang*!




note 30 orders of magnitude

Remember its the sum of matter energy that is conserved



- Why did Gamov and Peebles suggest this model?
- If the early Universe was hot (full of energy), a lot of features of the current universe could be explained…
  - Could explain where the matter that we see around us came from (**baryogenesis** occurred well within first second)- Gamow first calculated that this could be important in 1948
  - Could explain the observed ratio of H,He Li *
  
  (**nucleosynthesis** occurred within first few minutes)
  - This scenario predicted that there should be left over radiation in the present Universe…
  - This radiation redshifts as the Universe expands… nowadays should be redshifted to microwave/radio wave frequencies.

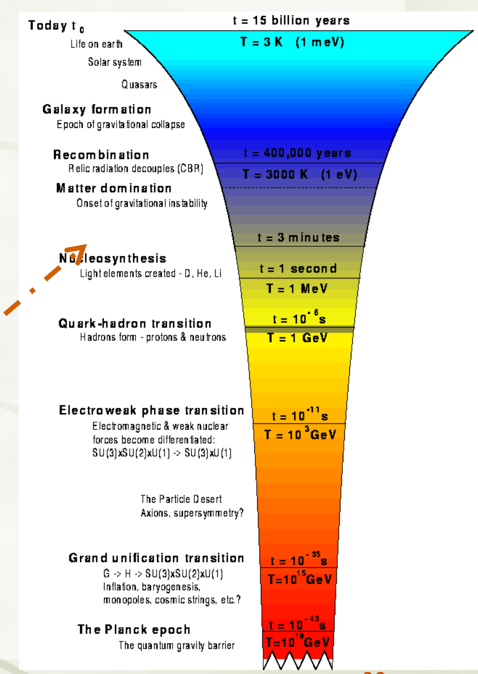
* cannot explain the existence and amount of 'heavier'elements (e.g. C,N, O, ...Fe) which are created in stars and supernova (later lecture)

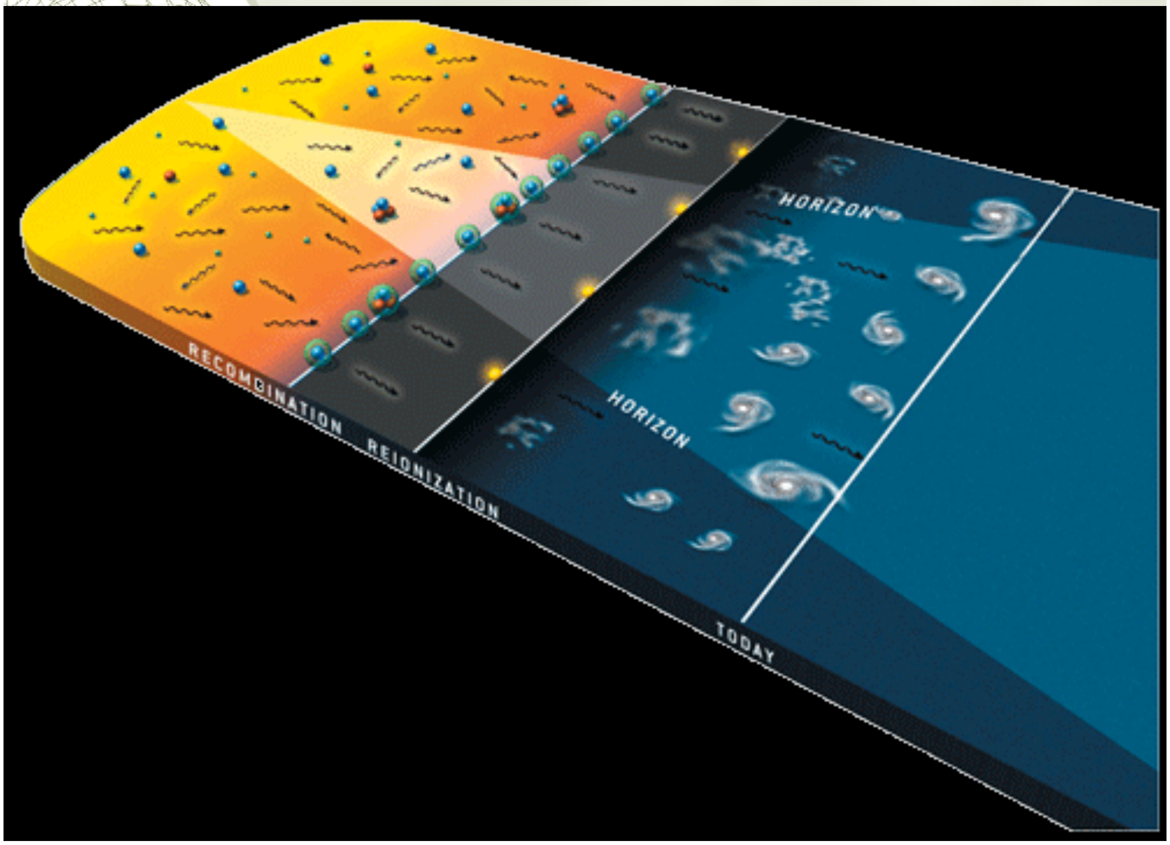
# The Early Universe and Nucleosynthesis and the structure of matter

- ch 12 of book

# A brief look at the stages of the Universe's life…

- We will discuss this diagram in detail in future classes…
- Crude overview:
  - t=0: The Big Bang
  - For first 400,000 yrs, an expanding "soup" of tightly coupled radiation and matter
    - Earliest epochs were "extreme" physics
    - Then more "normal" physics: protons & neutrons form
    - Then came nucleosynthesis
  - After 400,000 yrs, atoms form ("recombination") and radiation and matter "decouple"
  - Following decoupling, matter and radiation evolve independently
  - Galaxies, stars, planets, etc can then form and evolve






## *SOME TERMINOLOGY*

- Our terminology…
  - **Very** Early Universe: from BB to $t=10^{-35}$ s
  - Early Universe: from $t=10^{-35}$ s to t=3 mins
- The study of the early universe:
  - No direct observations to constrain theories…
  - .. but, the basic physics governing the universe is well understood and tested in laboratories on Earth (particle accelerators).
- The study of the **very** early universe:
  - Still no observations to constrain theories…
  - … and the basic physics gets less and less certain as one considers times closer and closer to the big bang.

## *THE TEMPERATURE OF THE UNIVERSE*

- The universe started off very hot and cooled as it expanded.
- In fact, the radiation temperature is inversely proportional to the scale factor

$$T \propto \frac{1}{R}$$

- Or if one is living at a time when the scale factor is $R_0$ $T(t)=T_0[R_0/R(t)]$

eq 12.2 in Text

- The evolving temperature is crucial in determining what goes on when in the early (and very early) universe



## How Does the Temperature Change with Redshift

Remember from eq 10.10 in the book that

$\mathbf{R_{now}/R_{then}=1+z}$

where z is the redshift of objects at observed when the universe had scale factor $R_{then}$

Putting this into eq 12.2 one gets

$T(z)=T_0(1+z)$

where the book has conveniently relabeled variables

$R_0=R_{now}$

- At a given temperature, each particle or photon has the same average energy:

$$E = \frac{3}{2} k_B T$$

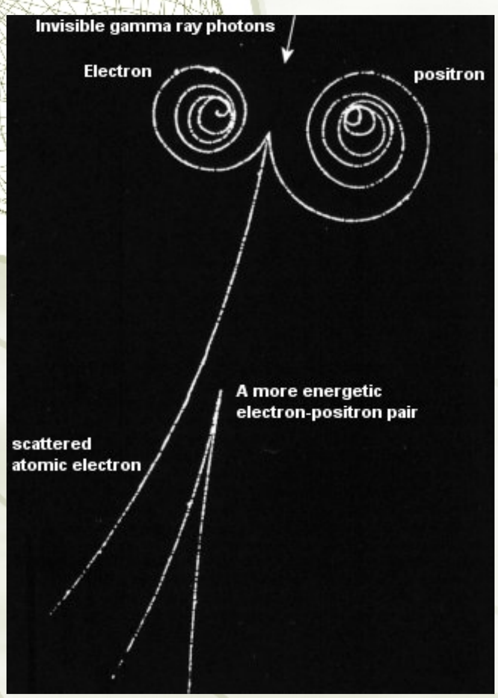
  - $k_B$ is called “Boltzmann’s constant” (has the value of $k_B = 1.38 \times 10^{-23}$ J/K)

---

- In early Universe, the average energy per particle or photon increases enormously
- *In early Universe, temperature was high enough that electrons had energies too high to remain bound in atoms*
- *In **very** early Universe, energies were too high for protons and neutrons to remain bound in nuclei*
- *In addition, photon energies were high enough that matter-anti matter particle pairs could be created*



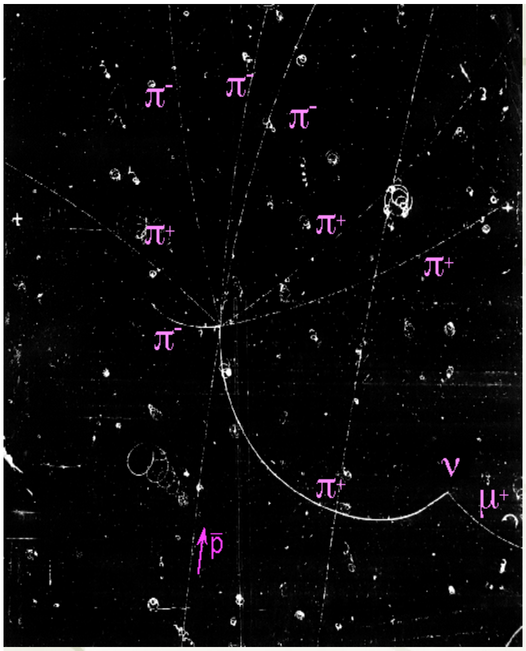
# Particle production




- Suppose two very early Universe photons collide
- If they have sufficient combined energy, a particle/anti-particle pair can be formed.
- So, we define ***Threshold Temperature***: the temperature above which particle and anti-particle pairs can be created.

$$T_{thres} = \frac{2mc^2}{3k_B}$$

- This comes from equating $E=mc^2$ to $E=3/2k_BT$




actual bubble chamber photograph of an antiproton (entering from the bottom of the picture), colliding with a proton and annihilating. 8 pions were produced. One decayed into μ+ and ν. The paths of positive and negative pions curve opposite ways in the magnetic field, and the neutral ν leaves no track

# *Particle production*

- Different particles with different masses have different threshold temperatures
  - Electrons : $T \approx 4\times10^{9}$K

lets calculate the temperature at which the univese is hot enough to create *protons*

$T=\{(2/3)*1.67\times10^{-27}\times(3\times10^{8})^{2}\}/1.38\times10^{-23}$

- $7\times10^{12}$ K
- so since T~1/R and T today is 2.7k the universe was $3.7\times10^{-13}$ its present size when it was this hot... the early universe.

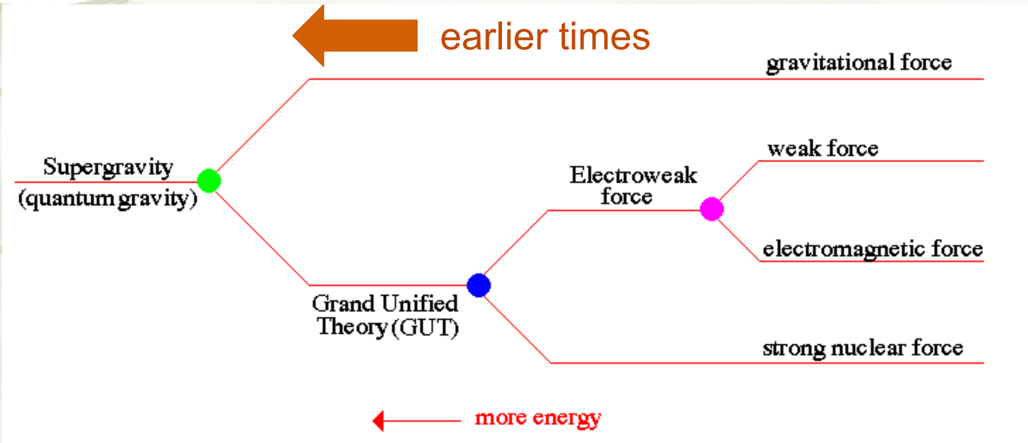


- Above the threshold temperature…(or alternatively at earlier times, smaller R)
  - Continual creation/destruction of particles and anti-particles (equilibrium)
- Below threshold temperature…
  - Can no longer create pairs
  - The particles and anti-particles that were created when the universe was hot annihilate each other
  - Small residual of particles (matter) left over ???-Since one needs an asymmetry between baryons and antibaryons in the very early universe, to produce the substantial amounts of matter that make up the universe today. this is a an unsolved problem called baryogenesis.

# Stages of the early Universe

- In the high-temperature very, very early universe, the 4 forces were all unified (in the same way that electricity and magnetism are unified today).
- As universe cooled down, they started to "decouple" from each other.-

*Complex quantum mechanics*






Graphics: University of Oregon Astronomy Dept