Universe appears to be ~100% matter, no antimatter

How do we know this?

(1) Within Milky Way: cosmic rays arriving from all regions ~~of~~ it are matter

(2) Beyond Milky Way: collisions between matter + antimatter regions would emit γ-rays; no known γ-ray sources have right characteristics

(3) What if there are matter galaxies + antimatter galaxies, but separated by large voids?

... how the universe could evolve into such a state from a pointlike Bang would be a NEW BIG QUESTION

3 ingredients are necessary to produce a matter/antimatter asymmetry:

#1 A natural process that does not conserve "$\underbrace{\text{matter-ness}}_{\text{baryon number ?}}$";

i.e, allows quarks to become $\underbrace{\text{non-quarks}}_{e,\gamma,\text{ etc.}}$

This process is called Baryon Number (B) Violation

#2 CP Violation

... to be explained ...

#3 A period in the history of the universe when it is out of thermal equilibrium

... also to be explained ...

Explain the 3 ingredients:

#1 Baryon Number Violation

An example of a process that violates $\mathbb{B}$ is

$$q \rightarrow e^- e^-$$

(The same process, for antiquarks, would be

$$\bar{q} \rightarrow e^+ e^+$$)

* no known process that violates $\mathbb{B}$ appears to be active in nature today

BUT... there is a class of theories called

Grand Unified Theories ("GUTs")

which attempt to $\underbrace{\text{unify the forces}}_{\text{describe them all as different aspects of 1 single force}}$

and all of these naturally include $\mathbb{B}$ violation.

GUT's say:

Early universe had same total energy as now, but was smaller,

$\Downarrow$

so it had higher energy density (energy/volume)

$\Downarrow$

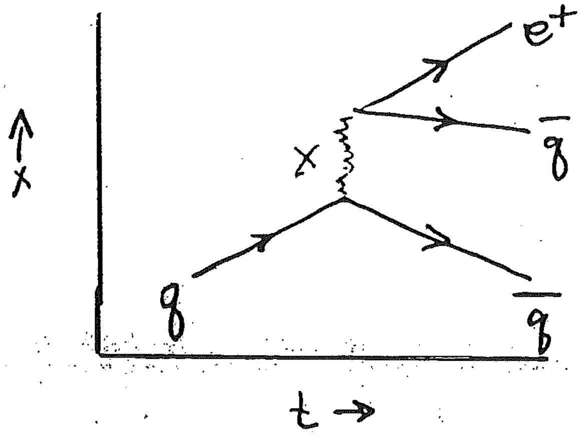
very massive particles could be created in collisions there via $E=mc^2$

$\Downarrow$

Call those particles X's + Y's

$\Downarrow$

They mediate B violation à la:



LOOKS PROMISING but ...

$\mathbb{B}$ violation alone CANNOT create a matter/antimatter asymmetry since, if $\mathbb{CP}$ is conserved, the rate of $\underbrace{q \to \bar{q}\bar{q}e^{+}}_{\text{matter loss}}$ will always BALANCE the rate of $\underbrace{\bar{q} \to qqe^{-}}_{\text{antimatter loss}}$

So, in addition to $\not{\mathbb{B}}$ we need a process that treats matter + antimatter differently ...

So the combination of $\not{B}$ violation + $\not{CP}$ violation looks promising to explain the matter/antimatter asymmetry BUT! a third ingredient is required. Why:

Suppose that in the early universe,

(1) There are X's converting q's $\to$ $\bar{q}$'s

(2) There are $\bar{X}$'s converting $\bar{q}$'s $\to$ q's

(3) There is CP violation enhancing the $\bar{q} \to q$ rate

... we <u>still</u> won't get the asymmetry if the universe is in thermal equilibrium:

In thermal equilibrium, every process AND ITS REVERSE PROCESS have the SAME RATE,

So the processes that <u>create</u> X's and $\bar{X}$'s will operate as fast as the processes that <u>decay</u> them.

So an enhanced $\bar{q} \to q$ rate will just make $\underbrace{\text{extra } q\text{'s}}$.

⇓

make extra X's

⇓

make extra $\bar{q}$'s

⇓

cancel any enhancement

The only way to "lock-in" a matter/antimatter asymmetry is for the universe to reach a $\underbrace{\text{state of coolness}}$ beyond which no more X's or $\bar{X}$'s can be produced

i.e., universe volume expands until energy density is too low to get $2m_X$ from E=mc

Then the remaining X's, $\bar{X}$'s decay away + leave a residual matter/antimatter asymmetry

This moment in the history of the universe when X and $\bar{X}$ can decay but not be created provides

Ingredient #3: Thermal non-equilibrium

How to check this theory: Need to prove

(1) That B violation can happen. (Look for proton decay.)

(2) That CP violation can be explained by The Standard Model.

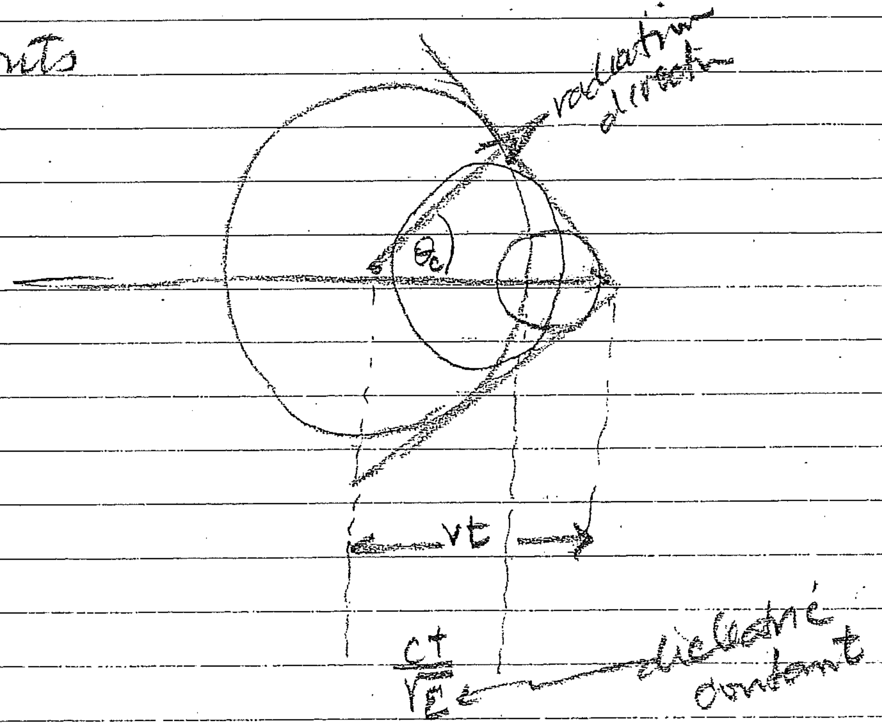
(3) The fact of $\underbrace{\text{thermal non-equilibrium}}_{\text{The Big Bang}}$ is not in dispute, although details of the universe's evolution still are

IV Particle IDentification (Measure the mass)

(1) Cherenkov detectors

When a charged particle passes through a medium, the adjacent atoms polarize, then depolarize, and this produces a weak EM wave.

If the particle travels with v > c in that medium, a shock wave forms as constructive interference of the wavefronts



This Cherenkov Radiation is emitted in a cone at an angle θ_c relative to the particle's path. θ_c depends on v and ε; ε depends on λ. If one filters for a specific λ, one can measure v precisely by imaging the ring and measuring its radius.

Typically the ring is imaged by photomultiplier tubes (i.e light detectors) with or without focussing by mirrors The radiator can be liquid or gas.

For "small-scale" (accelerator-based) experiments, Cherenkov detectors are used primarily to measure velocity which is then compared with momentum to infer mass → particle ID.

For "large-scale" (non-accelerator) experiments the rings may be used to reconstruct the track direction.

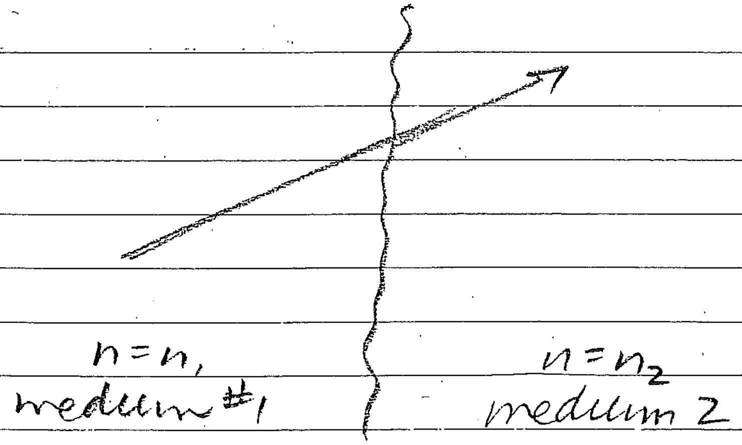
$\theta_c = \cos^{-1}\left(\frac{1}{\beta n}\right)$. For $\beta \approx 1$ (ultrarelativistic particles),

$\theta_c = \cos^{-1}\left(\frac{1}{n}\right)$ $n = 1.0003$ air, so $\theta_c \to 0$

When $v \approx c$ (some electrons emitted by high energy collisions) Cherenkov rings cannot effectively resolve velocity, need another technique: Transition Radiation Detection:

(2) TRD:

Consider a relativistic particle traversing a boundary between 2 media



As with Č radiation, it polarizes + depolarizes the medium as it passes by. So within each medium there is an EM radiation field appropriate to that medium. At the point where the particle crosses the interface the field must reorganize. The reorganization process results in radiation of X-rays oriented strongly in direction of particle track:

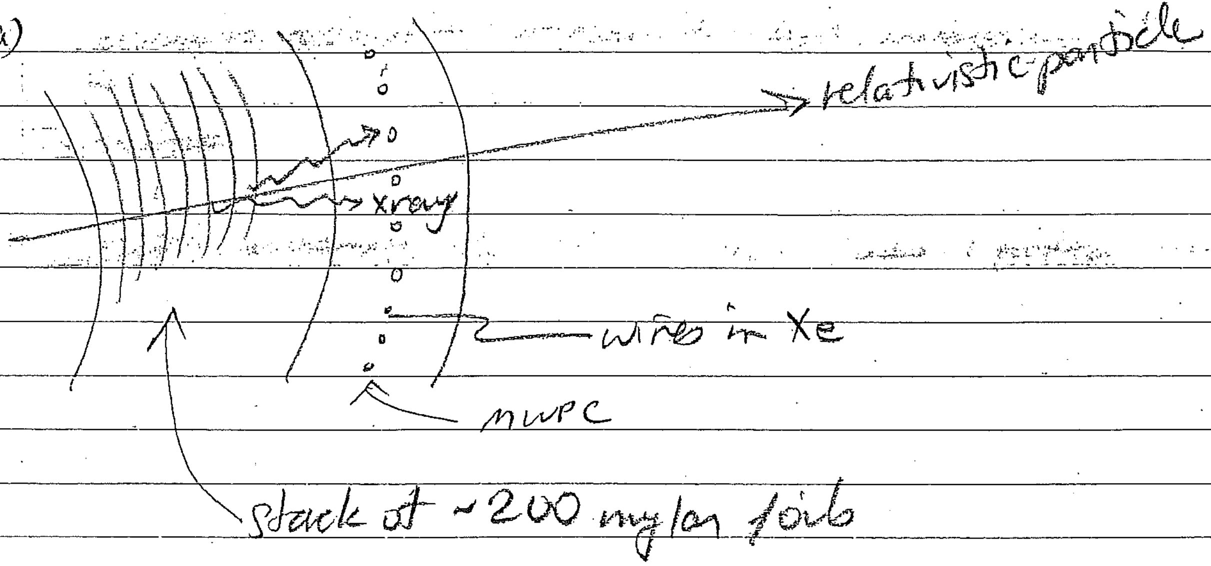
$$\Theta_{tr} = \frac{1}{\gamma} = \sqrt{1-\frac{v^2}{c^2}}$$

These x-rays are called Transition Radiation.

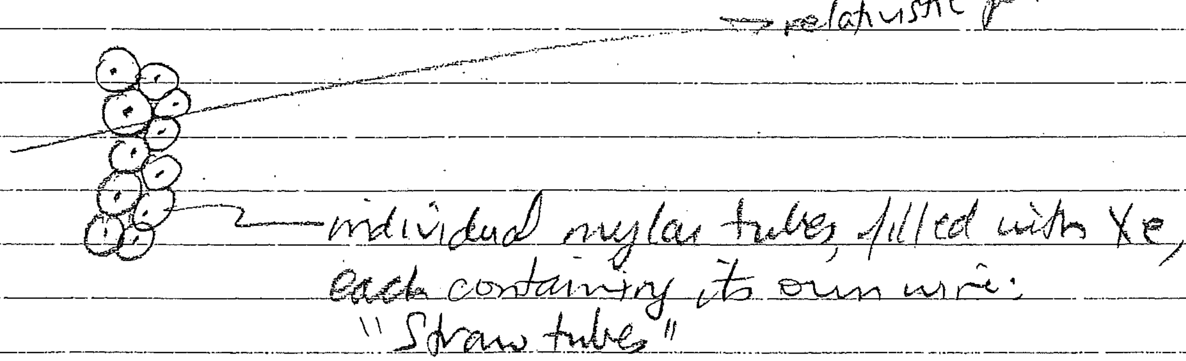
Detect these x-rays with MWPC filled with Xenon.

Possible geometries:

(a)



(b)

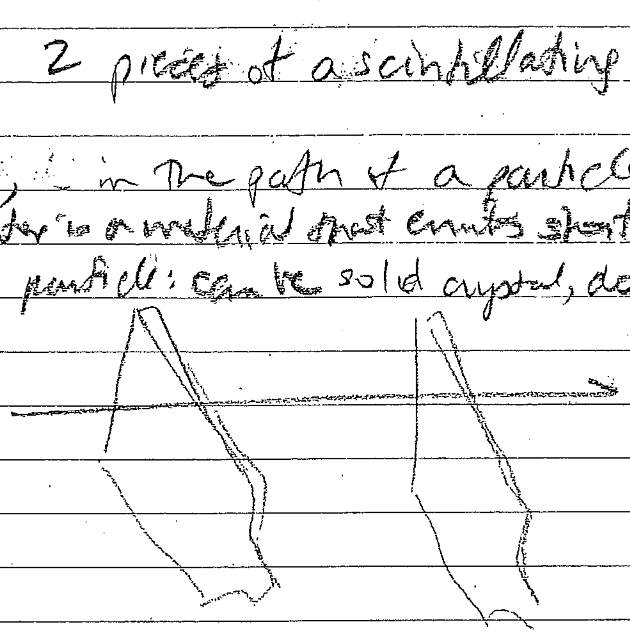


So find Θ_{tr} → infer v → combine with p to get m

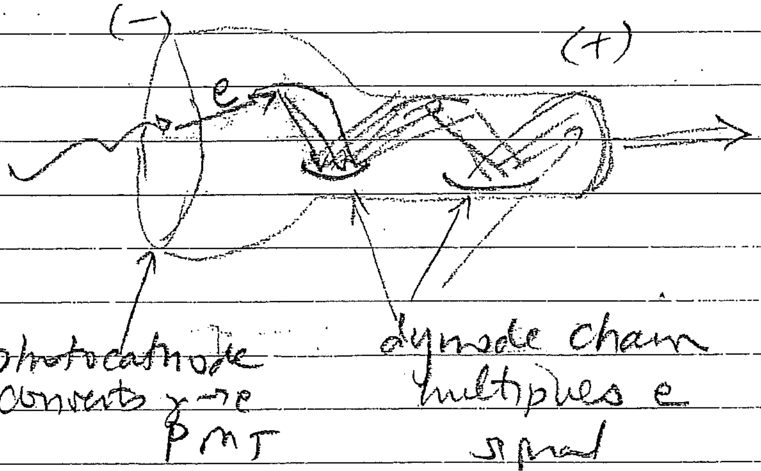
(3) Scintillator stack / Photomultiplier tubes

Place 2 pieces of a scintillating material, separated by a gap, in the path of a particle.

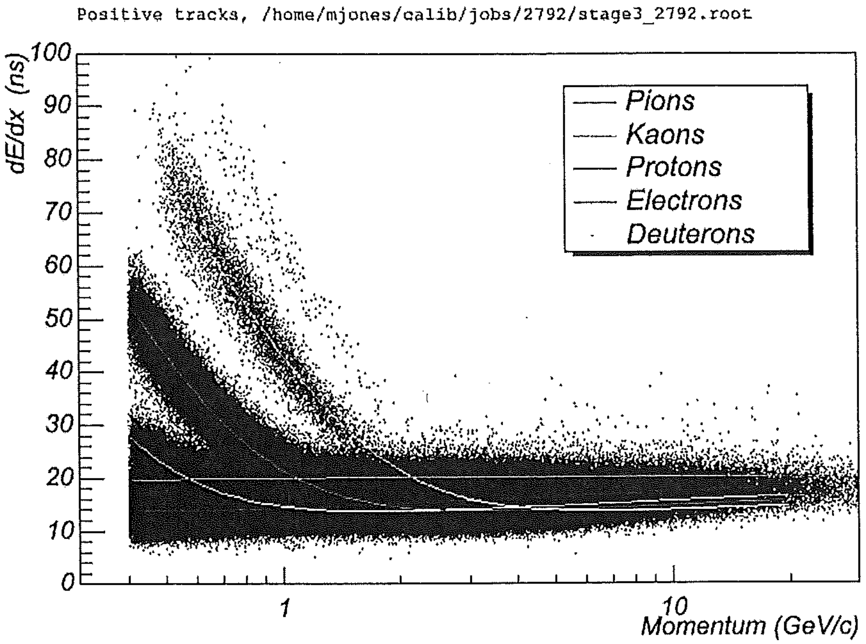
Scintillator is a material that emits short light pulses after excitation by charged particle: can be solid crystal, doped plastic, liquid, glass, gas



Particle stimulates light in material, light bounces around until it exits small end, interfaced to a photomultiplier tube (PMT)



Device is continuously active + time resolution is good (ns) → ("time of flight") high quality velocity measurements can be combined with $\vec{p}$ to get m.


Positive tracks, /home/mjones/calib/jobs/2792/stage3_2792.root
dE/dx (ns)
100
90
80
70
60
50
40
30
20
10
0
1
10
Momentum (GeV/c)
Pions
Kaons
Protons
Electrons
Deuterons