H. A. TANAKA

PARTICLE DETECTORS AND ACCELERATORS

ANNOUNCEMENTS

- Typo in problem set 1

Problem 2 (5 pts): Draw Feynman diagrams for the dominant contributions to the following processes:

- $B^+ \to \boxed{\bar{D}^0} + e^+ + \nu_e$

    - thanks to Eric Yeung for pointing this out
- Office hours:
    - 1500-1600 on Thursdays

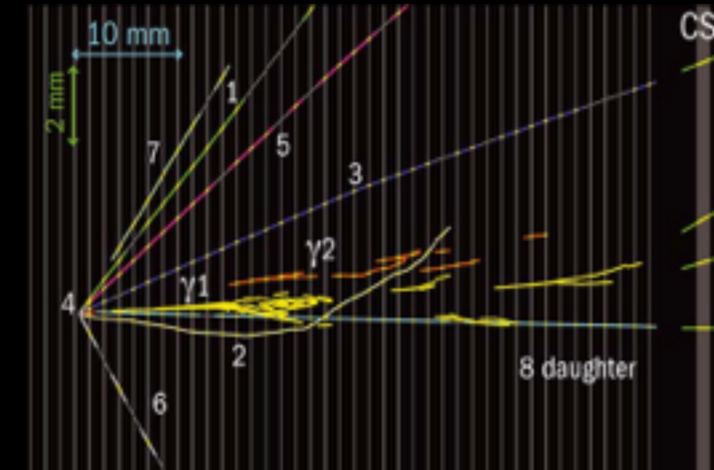
"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT <u>NOW</u> I <u>CAN</u> <u>SEE</u> THEM!"

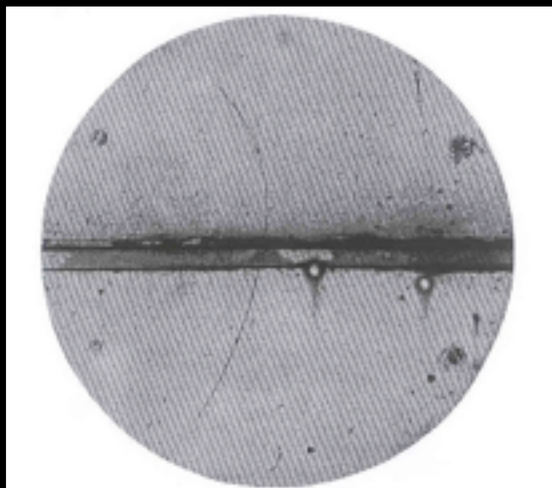
BASIC DETECTION PRINCIPLES

- Ionization
  - electrons unbounded from their atoms by electromagnetic disturbance of charged particle passing nearby.
- Cherenkov radiation
  - light emitted by charged particle exceeding the speed of light
- Scintillation:
  - molecular excitations leading to light emission
- Thermal
  - heat deposited/phonons generated by particle
- Other . . . . . (maybe your idea!)
- The primary detection mechanism is usually accompanied by amplification to make the signal (usually electric) macroscopic
  - semiconductor (electron/hole pair)
  - vacuum/electrostatic
  - gas avalanche
  - . . . .

IONIZATION:

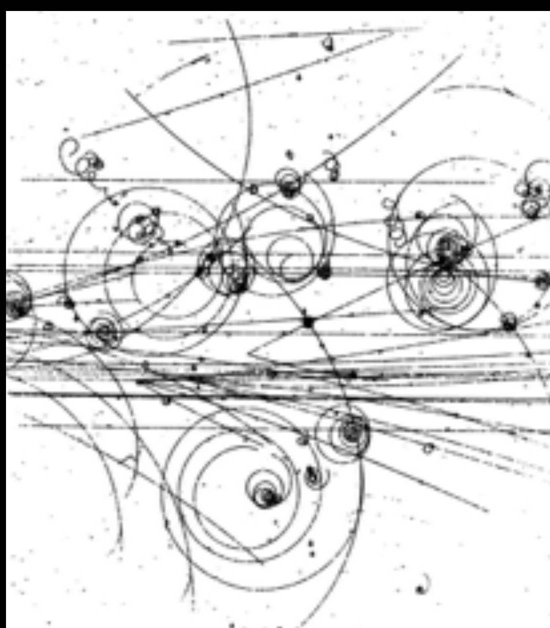
Emulsion in the OPERA experiment



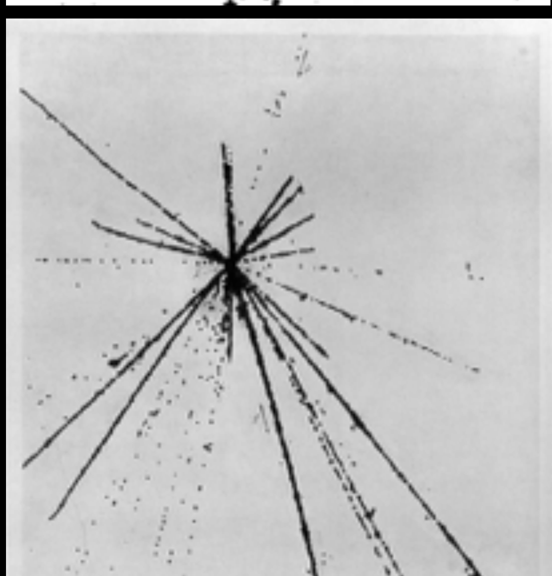


from CERN

- Cloud chamber:
  - ionization induces droplet formation in super-saturated gas.
  - Particle trajectory “recorded” by trail of droplets which are then photographed.



- Bubble chamber:
  - ionization induces bubble formation in superheated liquid
  - provides much more “target mass” when considering scattering of particles

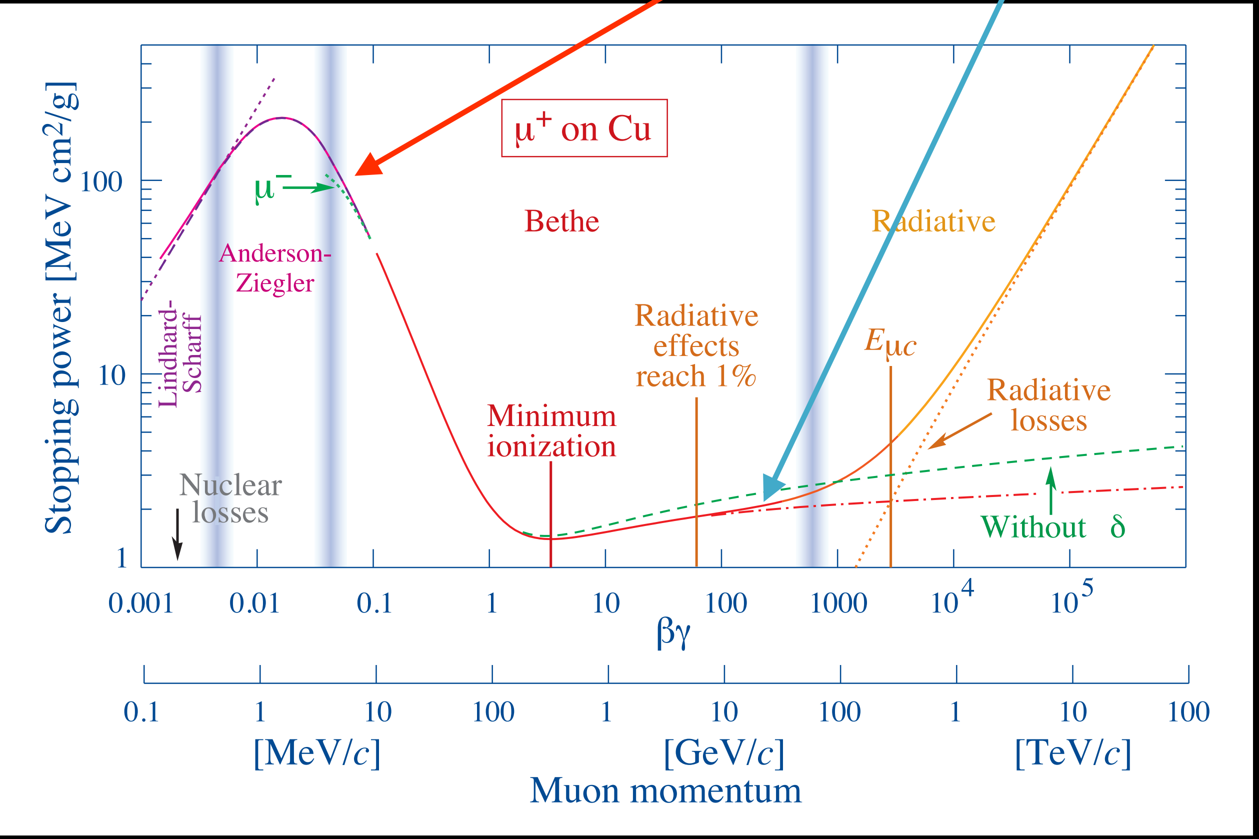


- Emulsion:
  - chemical transformation induced by ionization

From pdg.lbl.gov

BETHE FORMULA

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \boxed{\frac{1}{\beta^2}} \left[\boxed{\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2}} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

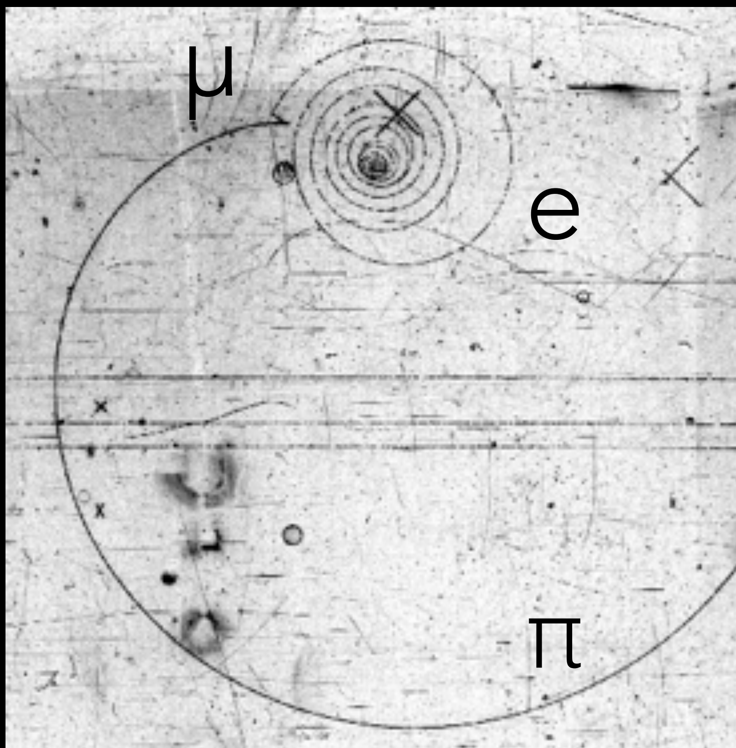


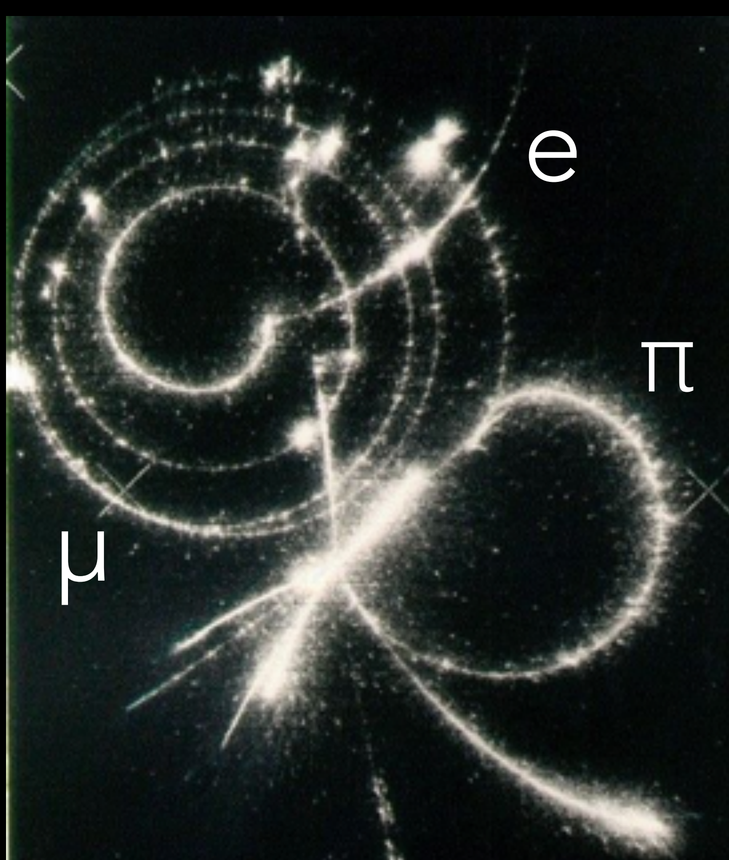
- Valid for "heavy" particles with M>> m_e
- β= v/c, γ= $(1-\beta^2)^{-1/2}$
- W_{max}: maximum energy transfer of particle to atomic electron
- I: mean excitation energy of electron
- δ: "density effect" correction

- Features:
  - rapid rise towards low energy/momenta
  - slow rise in high momentum region ("relativistic rise")
  - minimum in between: "minimum ionization particle" or "MIP"

IONIZATION LOSS:

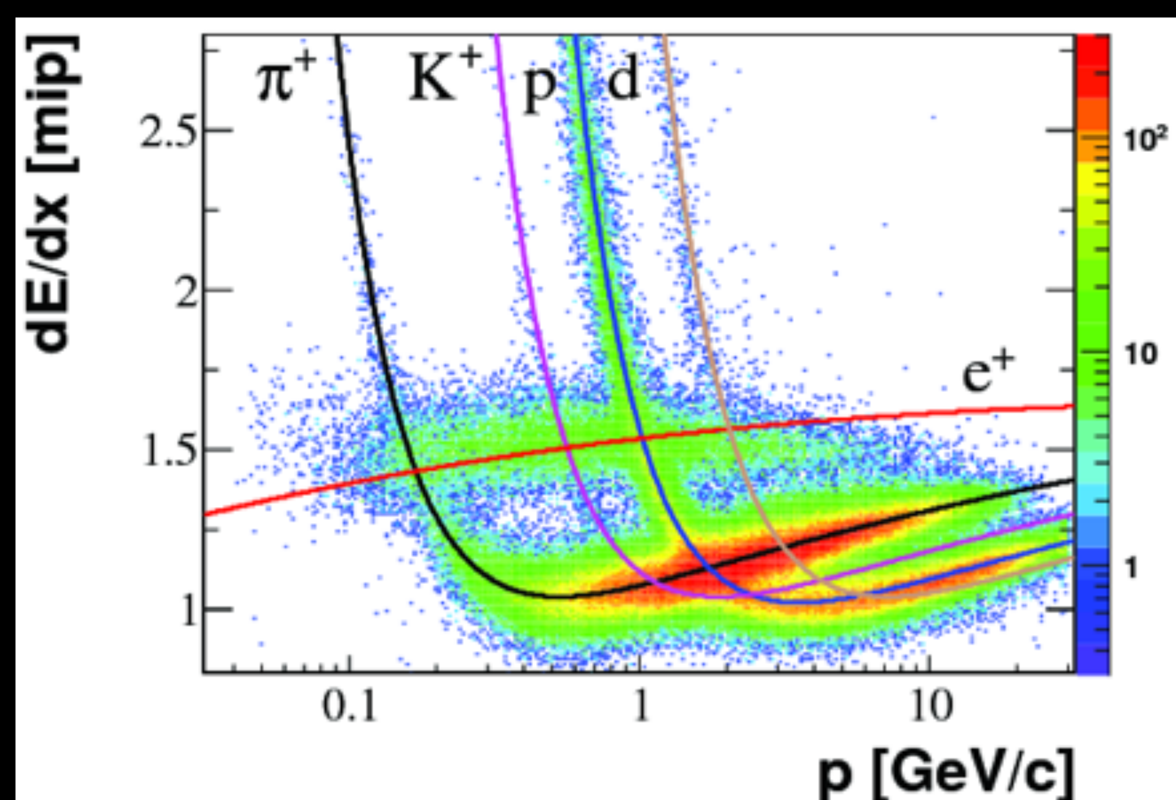
CERN





- Two examples of $\pi \rightarrow \mu \rightarrow e$ decay. Note:
  - magnetic field
  - "darkness" and "thickness" of the track
- From the curvature we have an independent measurement of the momentum
- Together with the velocity estimated from the ionization loss, we can estimate the mass of the particle.

$$p = \gamma m v \quad \Rightarrow \quad m = \frac{p}{\gamma v}$$



"particle identification"

from NA61/SHINE collaboration

TOWARDS THE ELECTRONIC ERA

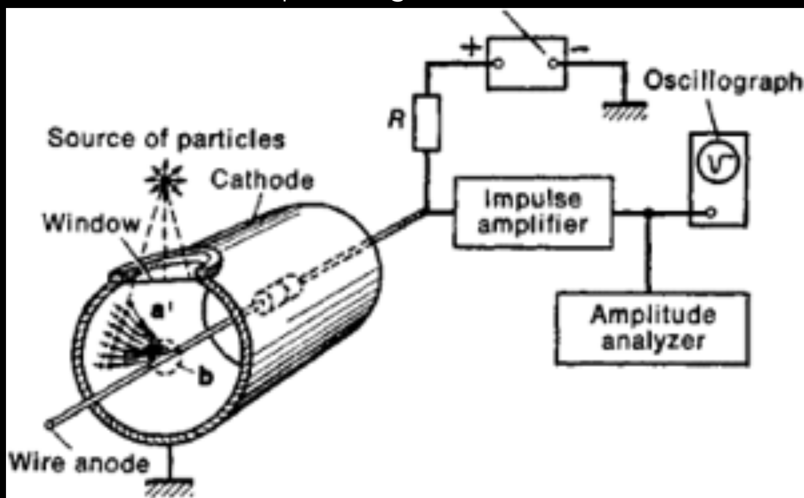
BNL

- Spark Chamber:
  - Adjacent wires/planes at relatively relatively high voltages
  - Ionization from passing particle results in "break down"and a spark
  - Visible, but can also be detected by pulse current on the wires which can be recorded electronically

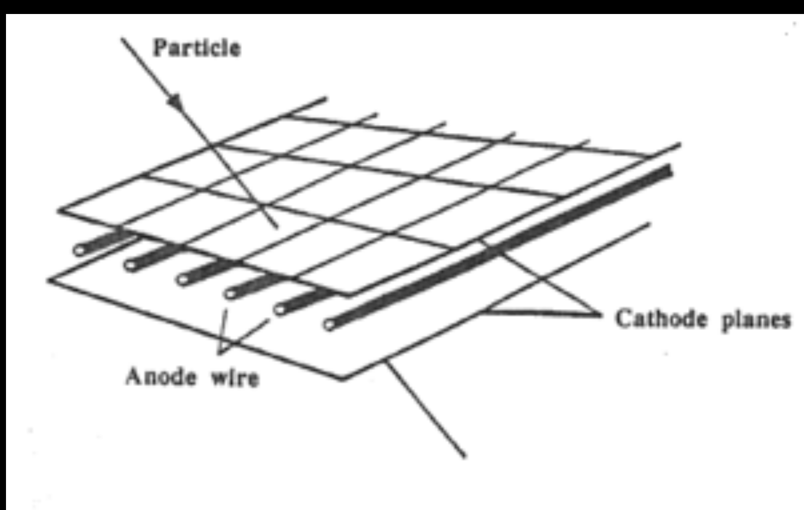
- With increasing statistics critical to:
  - faster detector response/less dead time
  - automation of data analysis

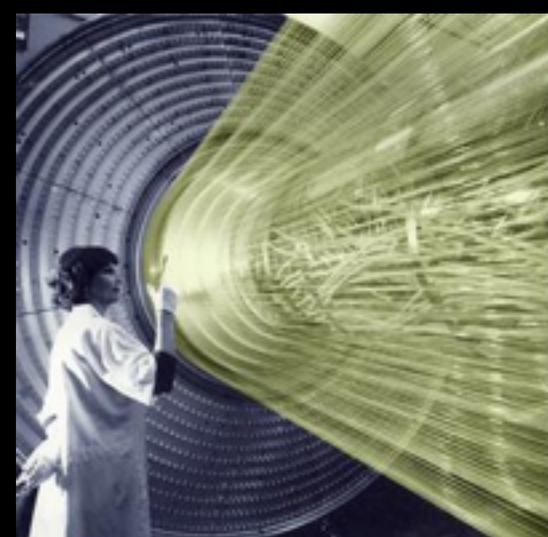
MULTI WIRE PROPORTIONAL COUNTER

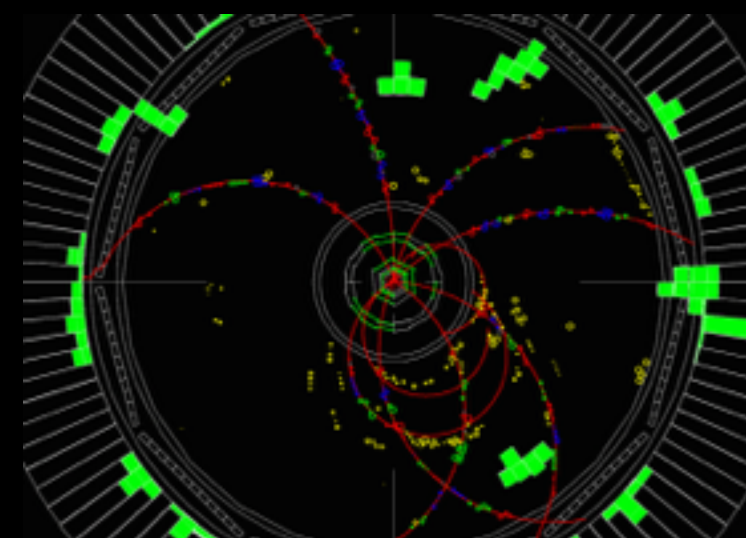
from nobelprize.org



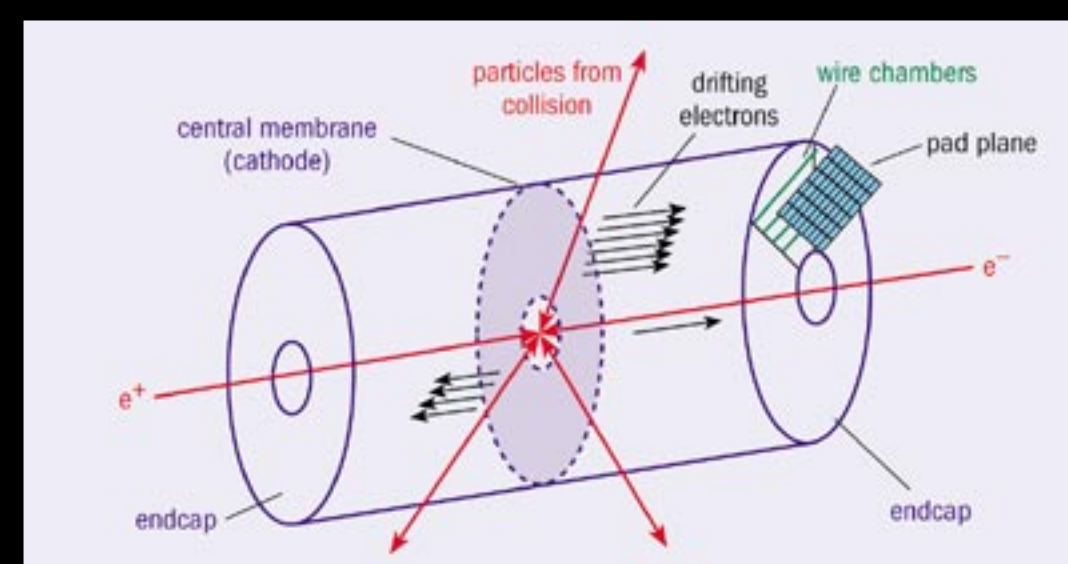
- Ionization from charged particle eels electrons + ions
- anode wires attract electrons, cathode plane attracts ions
    - acceleration of electrons results in more ionization, etc. an "avalanche" that results in "gain/ amplification" of signal .







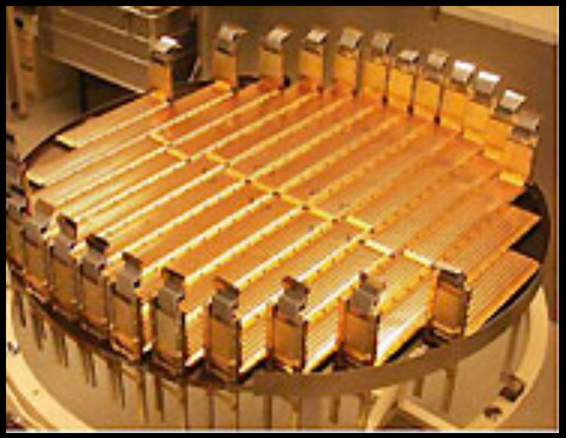
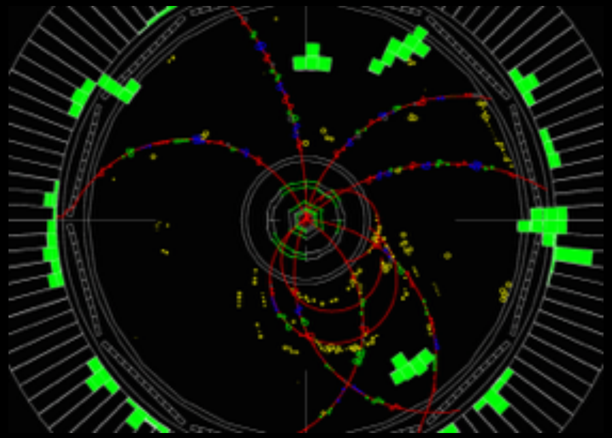
- "Drift chamber"
    - Use time between primary ionization and detection ("drift") to refine measurement
- Time Projection Chamber:
    - "drift" the electrons all the way to one side of the detector and read it out there
    - use drift time to infer coordinate along the drift direction
        - 3D tracking!



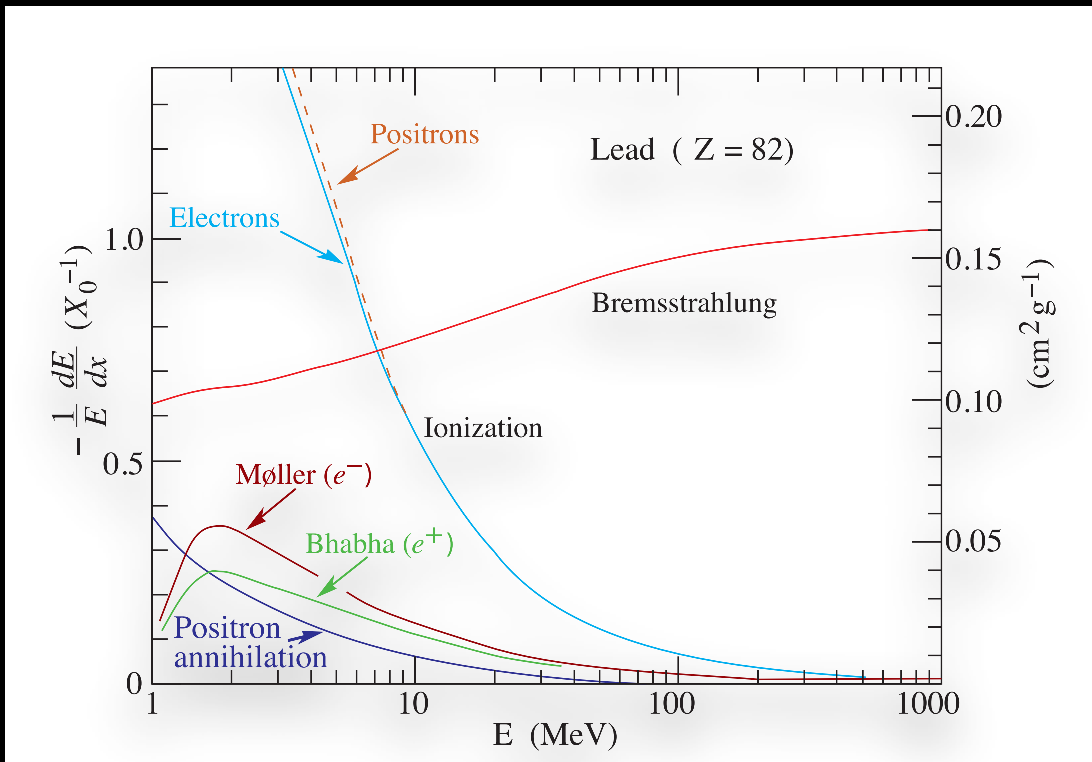
SILICON

- Typically: reversed biased pn junction collects electron-hole pairs produced by ionizing particles passing through
- Miniaturization allows extreme precision:
  - devices laid out in strips or pixels
- Ubiquitous now as first layer of tracking in collider experiments
  - detached vertices, etc. arising from decays of short lived particles.
  - vertex displacement for time-dependent studies, etc.



ELECTRONS AND PHOTONS

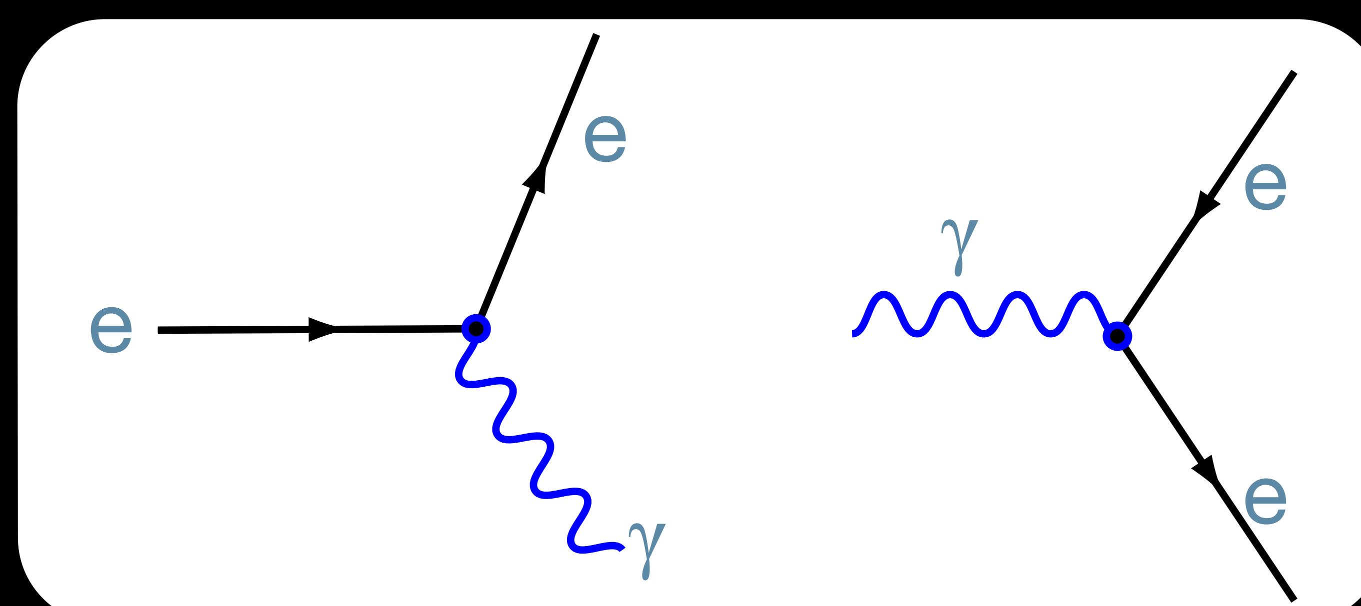


from PDG

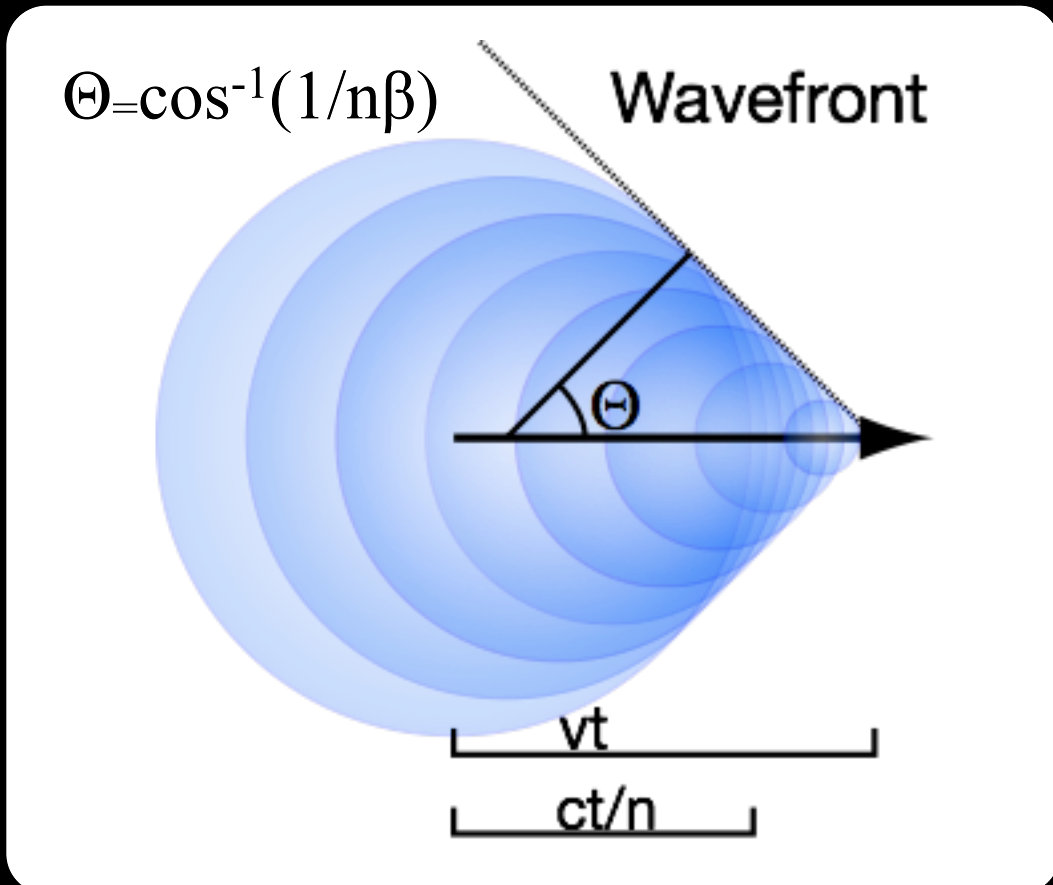
$$\frac{1}{X_0} = 4\alpha r_e^2 \frac{N_A}{A}\left\{Z^2\left[L_{\rm rad} - f(Z)\right] + Z\,L'_{\rm rad}\right\}$$

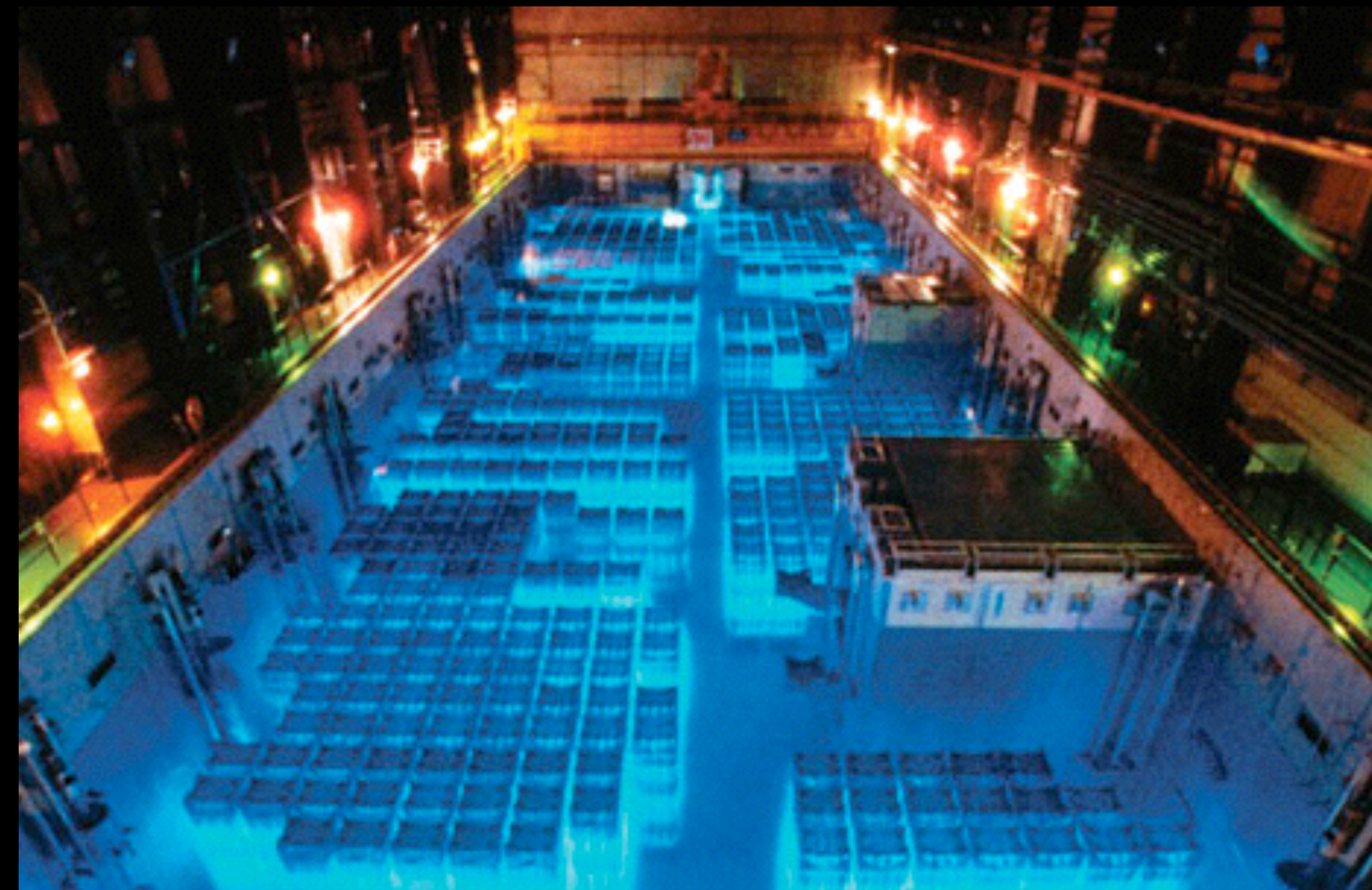
	Z	ρ (g/cm³)	X_0 (cm)
C	6	2.0	21.0
Al	13	2.7	8.9
Cu	29	9.0	1.4
Pb	82	11.4	0.6

- Bremsstrahlung:
  - "braking radiation"
  - radiation of photons from acceleration of electron in the intense field near an atomic nucleus
  - "Radiation length" X_0
    - characteristic distance over which electrons will emit a Bremsstrahlung photon
- Photon pair production/conversion:
  - Process where photon "converts" to e^+e^- pair
  - at high energies "conversion length" = 9/7 X_0



CHERENKOV RADIATION





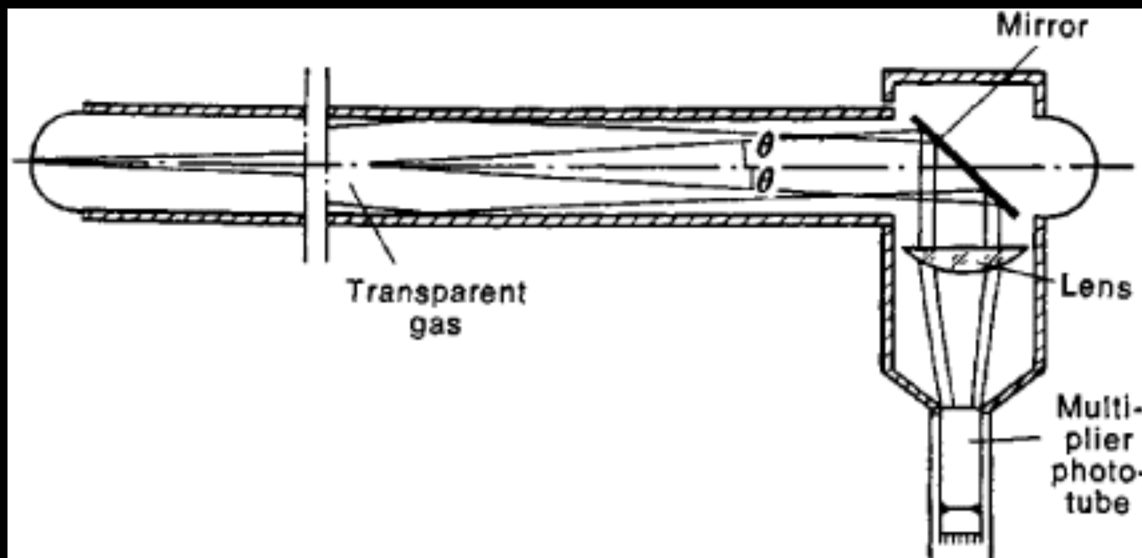
EM radiation emitted in when a charged particle exceeds velocity of light in a dielectric medium

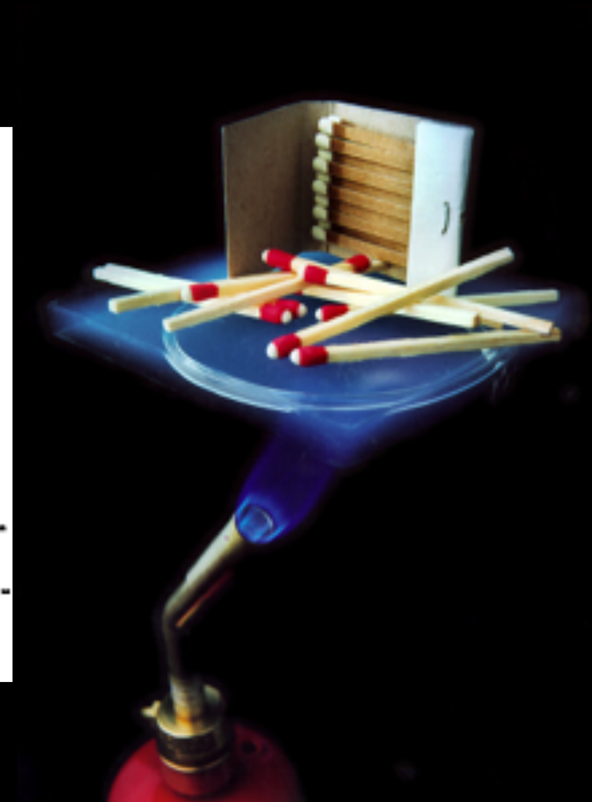
- optical analog of "sonic boom"
  - blue-shifted optical light ($1/\lambda^2$)
- For water, n ~ 1.33
  - "threshold" for Č radiation is 0.75 c
  - Θ ~ 42° for v ~ c

from findagrave.com

APPLICATIONS;

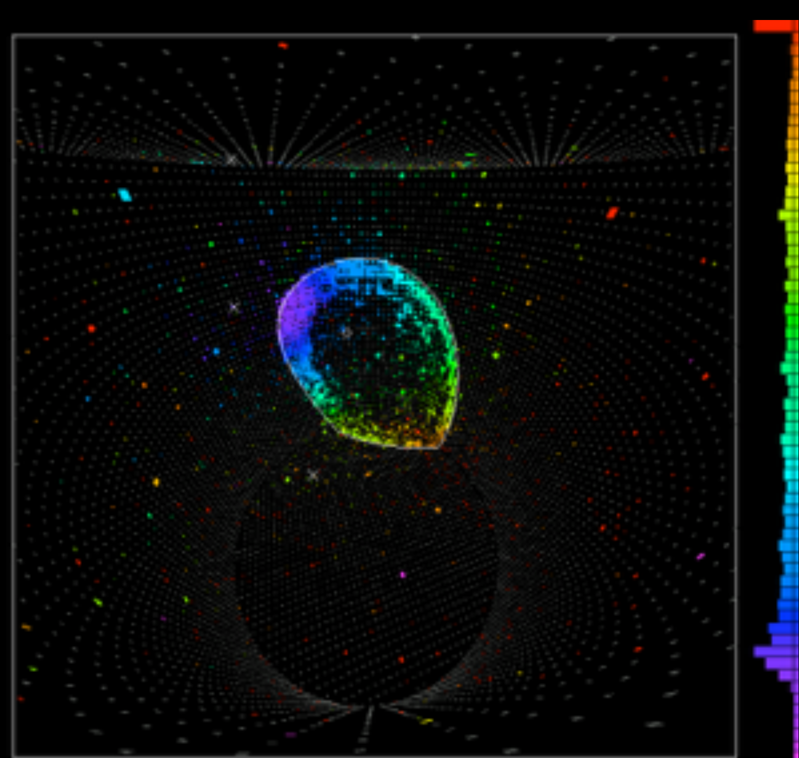
- Threshold counter:



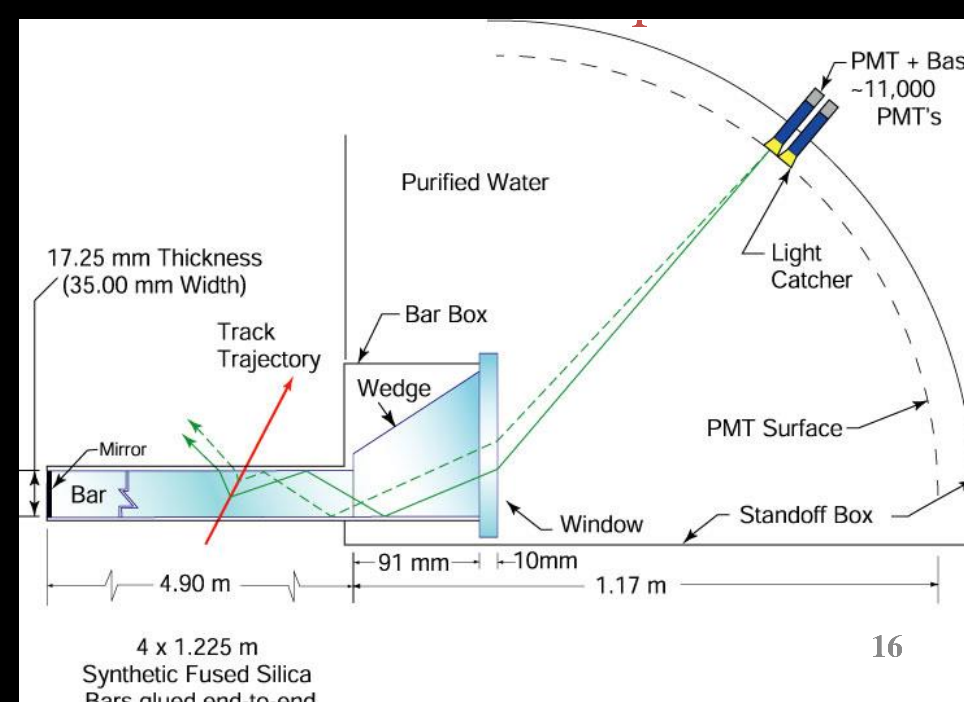


Use gas or other transparent material to set a velocity threshold with appropriate refractive index

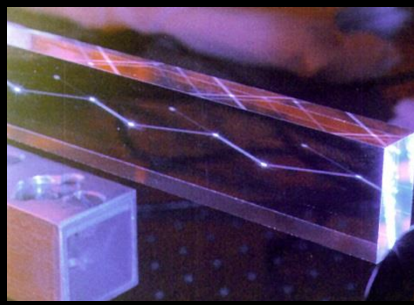
- Ring imaging:

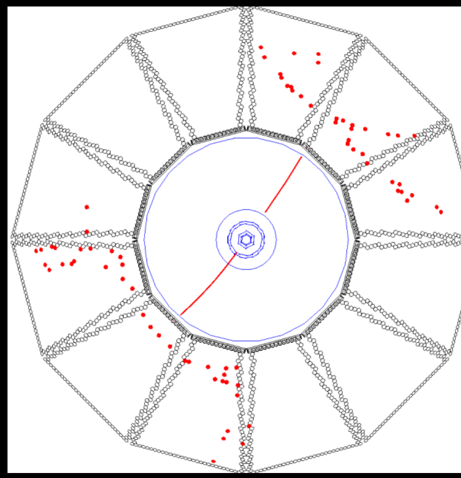


from Super-Kamiokande collaboration

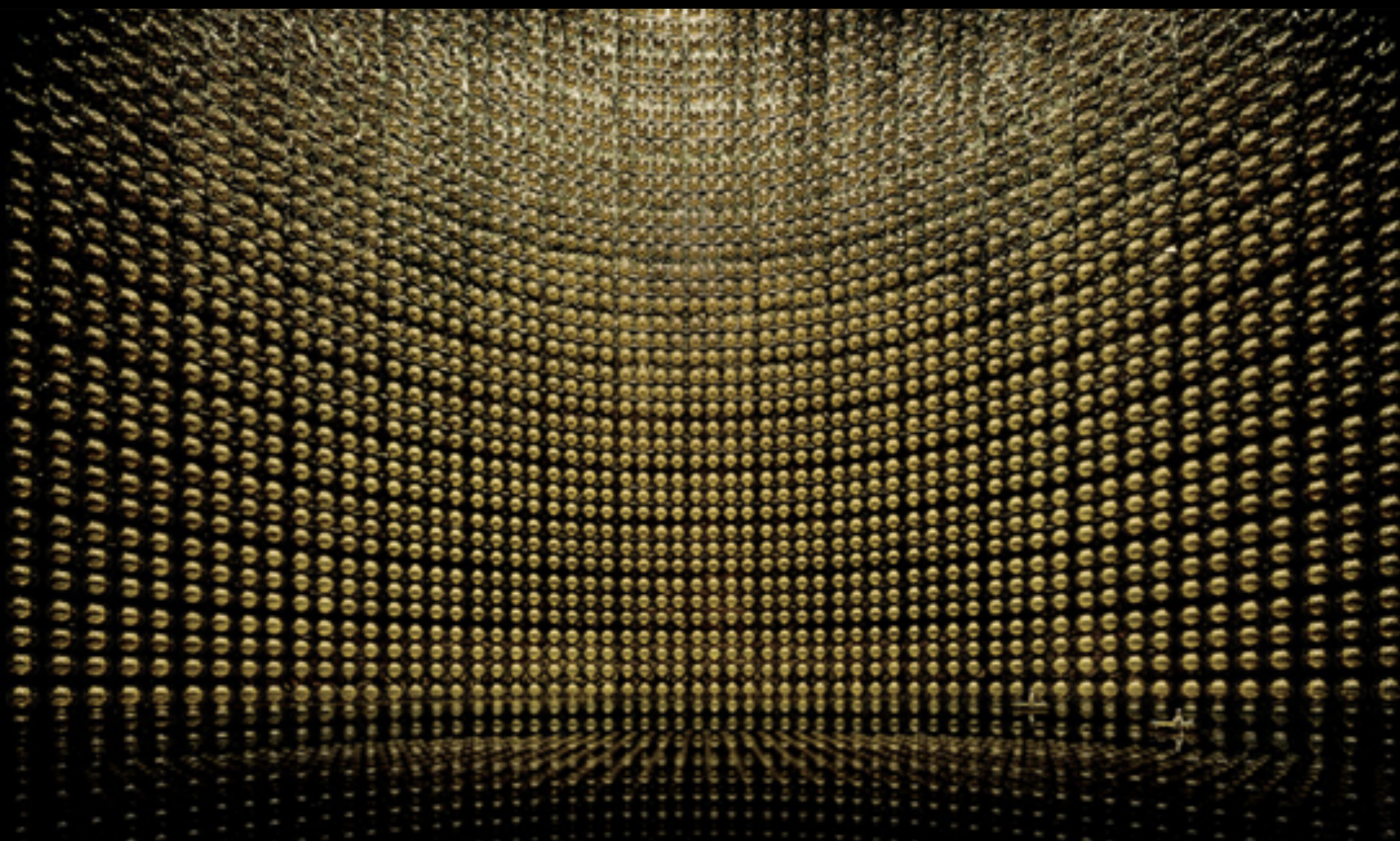


from BaBar collaboration





EXAMPLES:



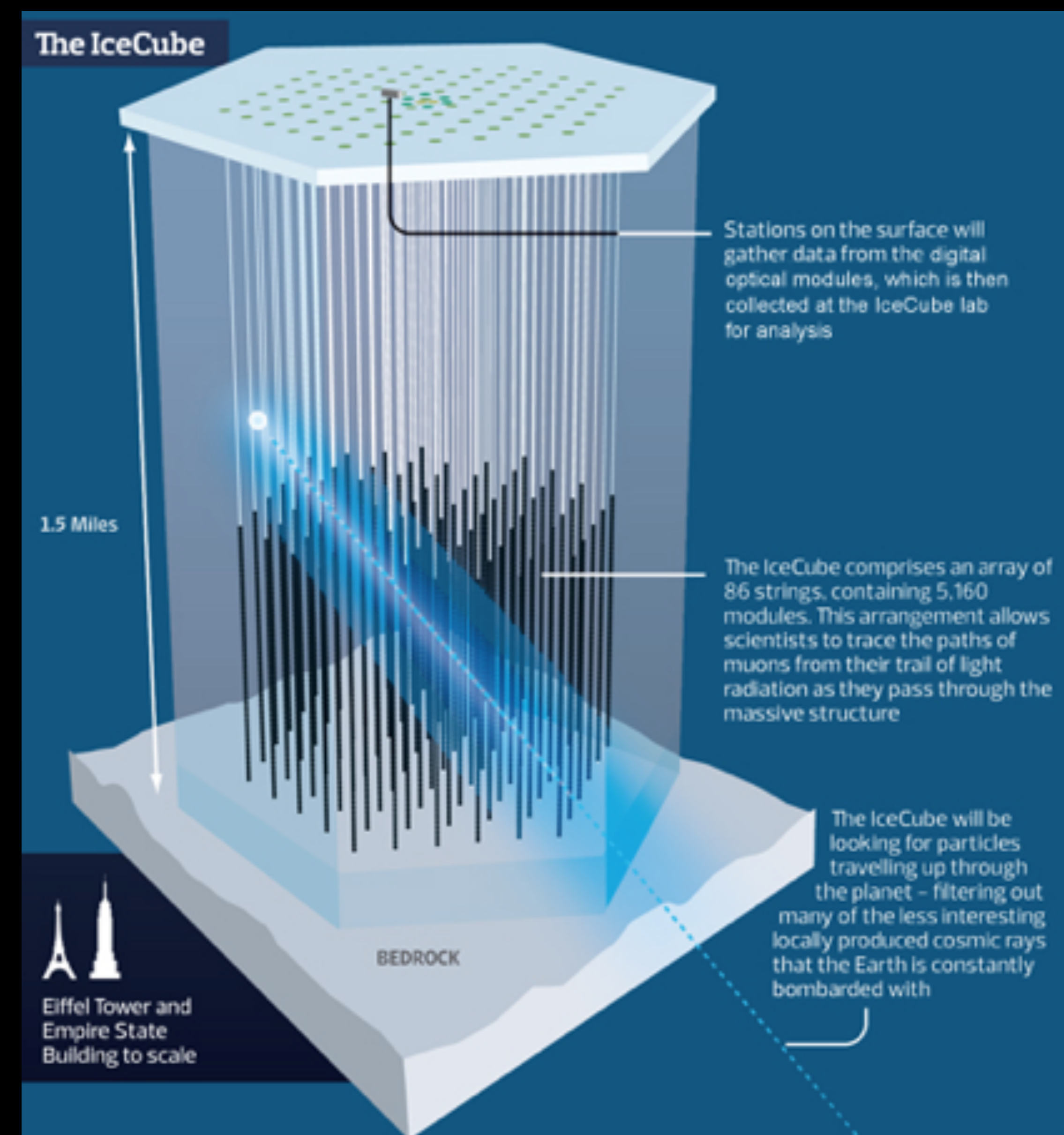
from Super-Kamiokande

Super-Kamiokande:

50 kT water Cherenkov detector instrumented with 11,000 photosensors

IceCube:

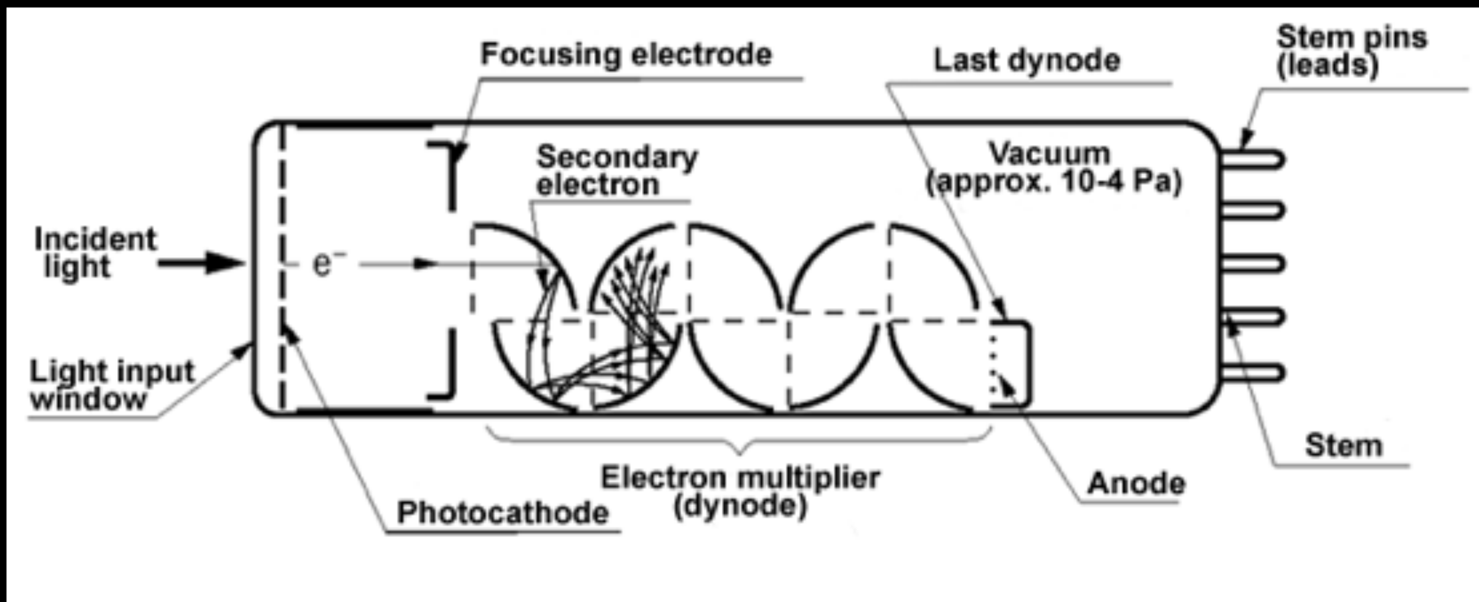
1 km^3 array of photosensors embedded in antarctic ice



from IceCube collaboration

PHOTOMULTIPIER

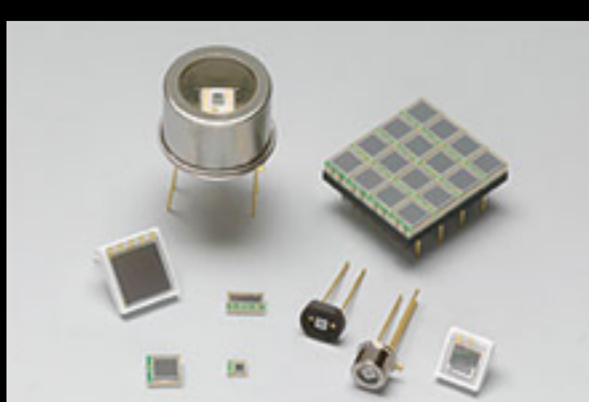
From hamamatsu.com



- How to detect light?
  - photon on photocathode can eject an electron
  - electron is accelerated to a "dynode" with high voltage (~1 kV)
  - dynode releases more electrons which continue to the next dynode, amplifying the signal
- photon is "covered" to an electric pulse.
- Latest innovations include silicon based detection and amplification

from Super-Kamiokande

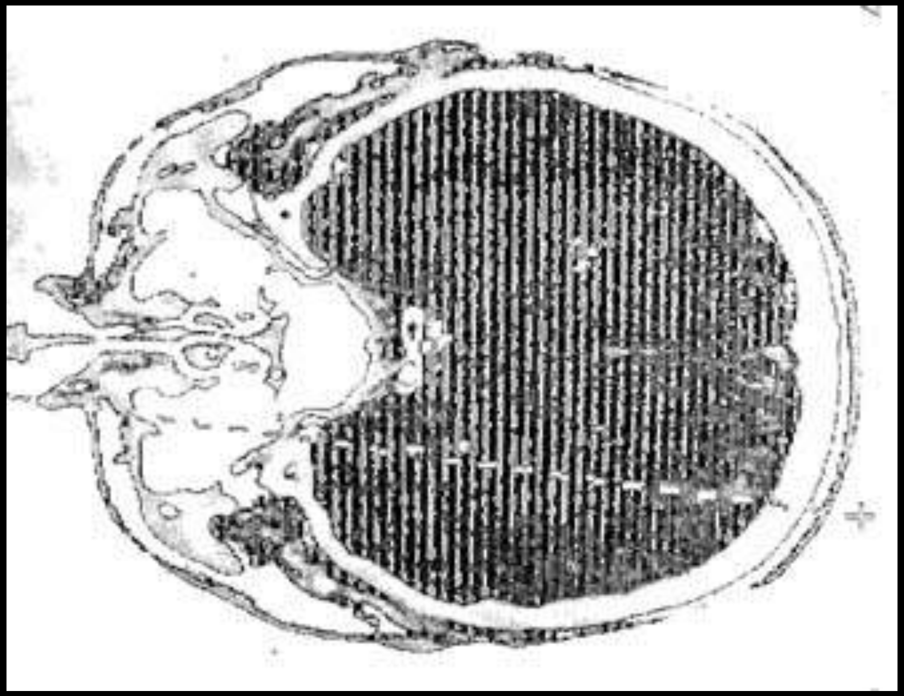
From hamamatsu.com



from BABAR

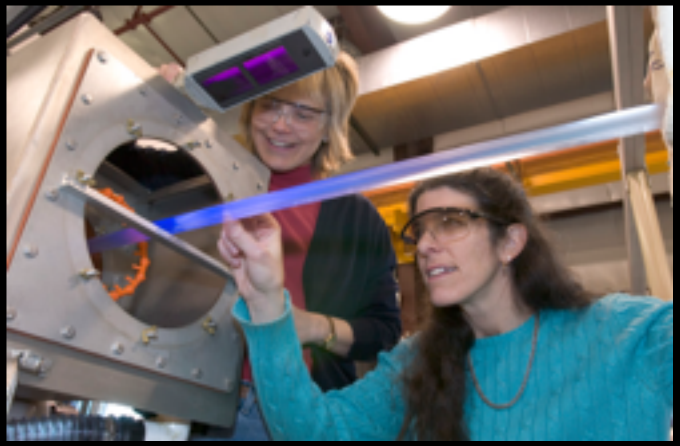
UNINTENTIONAL CHERENKOV DETECTOR?

"Bugorski, a 36-year-old researcher at the Institute for High Energy Physics in Protvino, was checking a piece of accelerator equipment that had malfunctioned - as had, apparently, the several safety mechanisms. Leaning over the piece of equipment, Bugorski stuck his head in the space through which the beam passes on its way from one part of the accelerator tube to the next and saw a flash brighter than a thousand suns. He felt no pain." (WIRED magazine)



- Several other reports of observing Cherenkov radiation with the human eye:
  - astronauts report observing "flashes" in space (debated)
  - criticality accidents at nuclear reactors

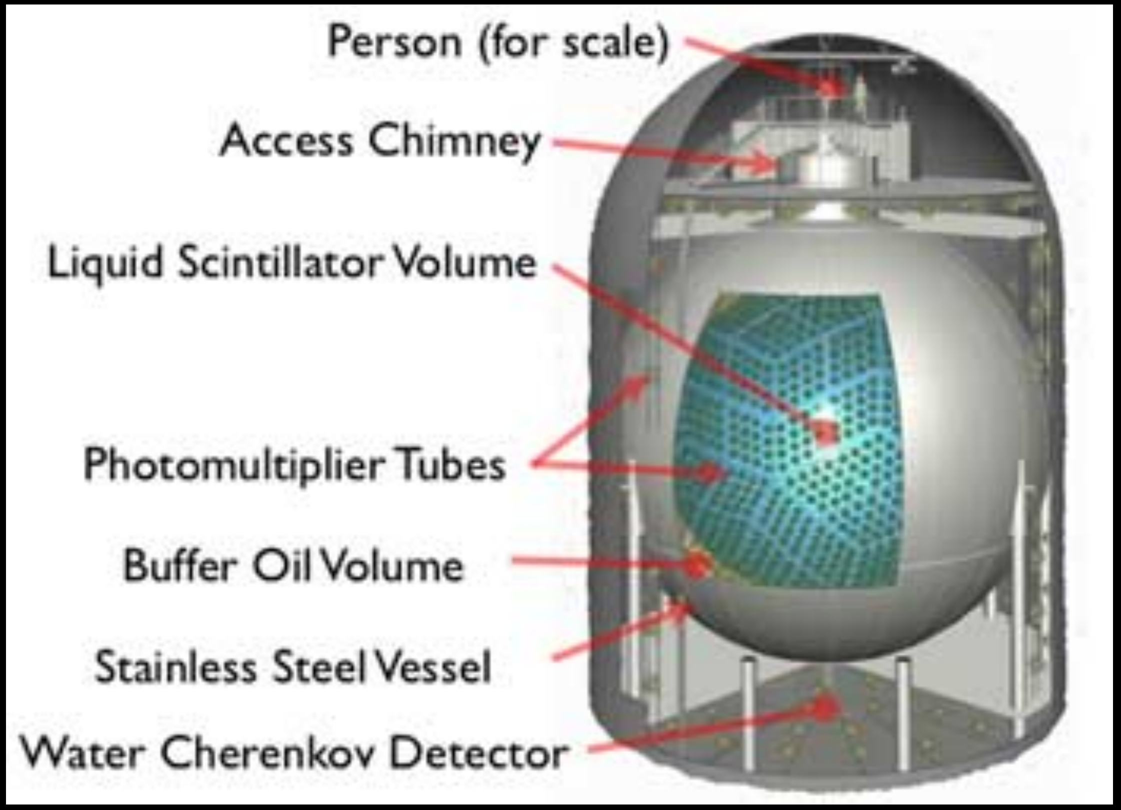
SCINTILLATION



from Fermilab

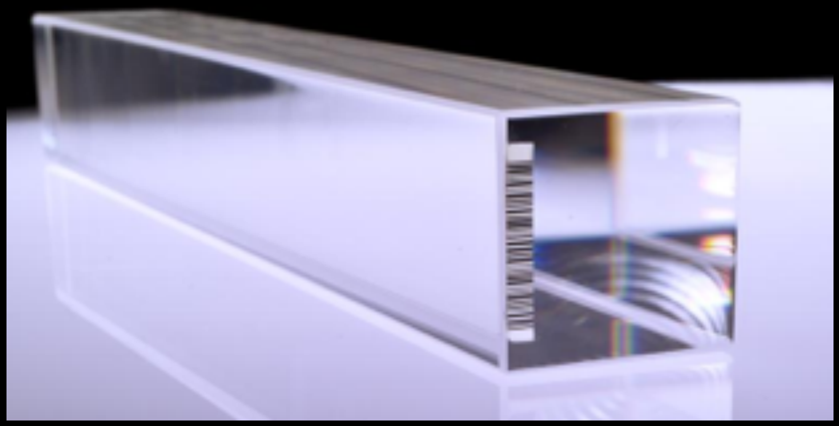
- General idea:
  - band gap between ground and excited states
  - ionization induces excitations with decay to ground state, emitting photons
- examples:
  - organic scintillators: usually hydrocarbons in both solid and liquid form
    - polystyrene
    - linear alkylbenzene
  - inorganic crystals (NaI, CsI, $PbWO_4$)
  - Noble gases/liquids (Ar, Xe, etc.)

from KamLAND collaboration



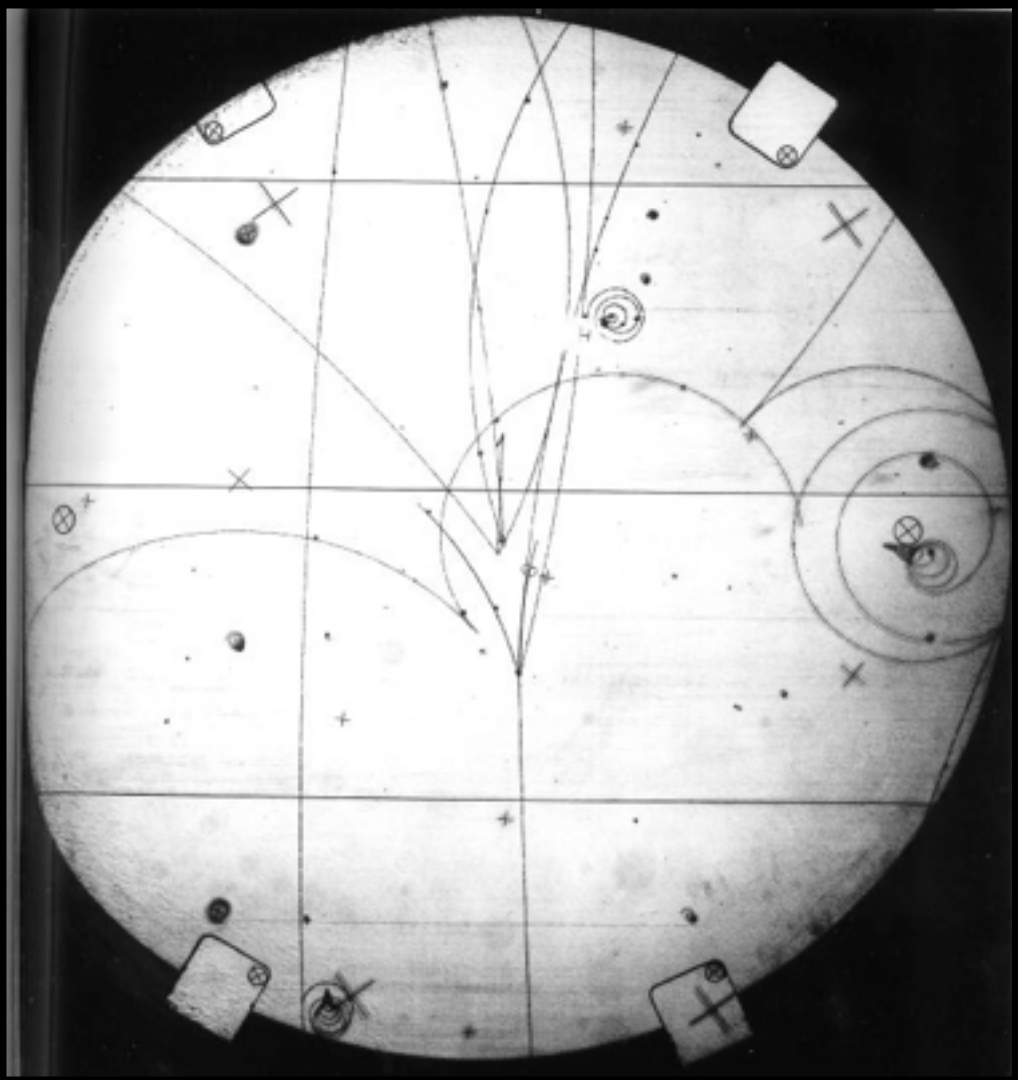
from LUX collaboration

from CMS collaboration



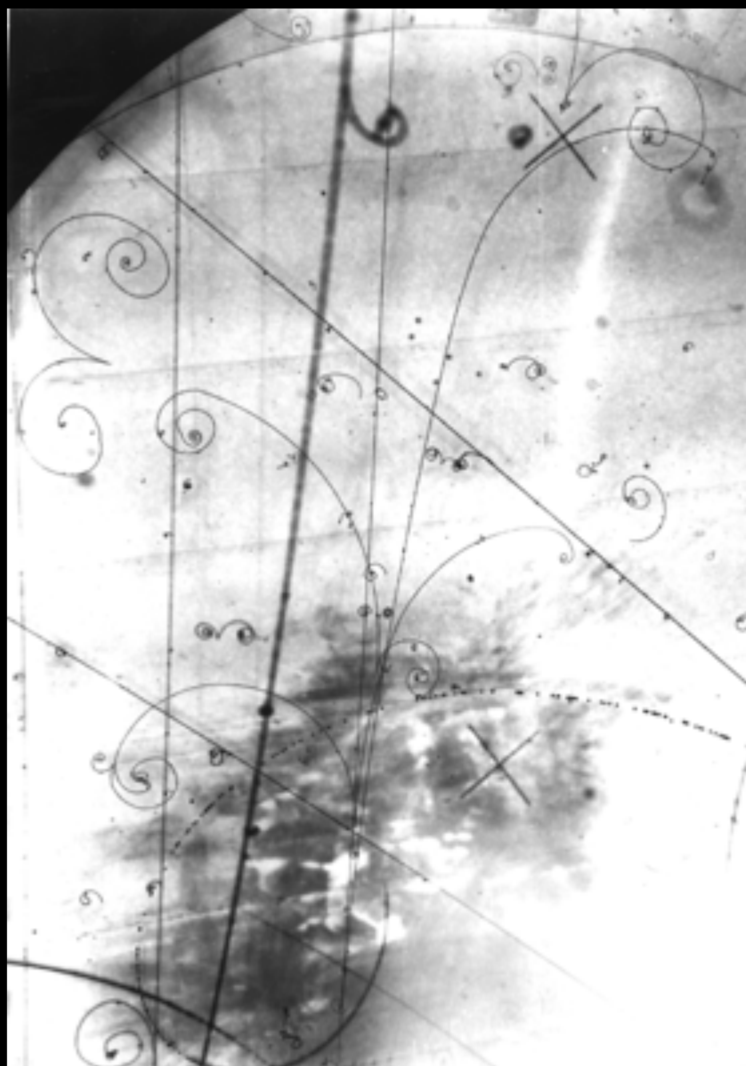
NEUTRAL PARTICLES

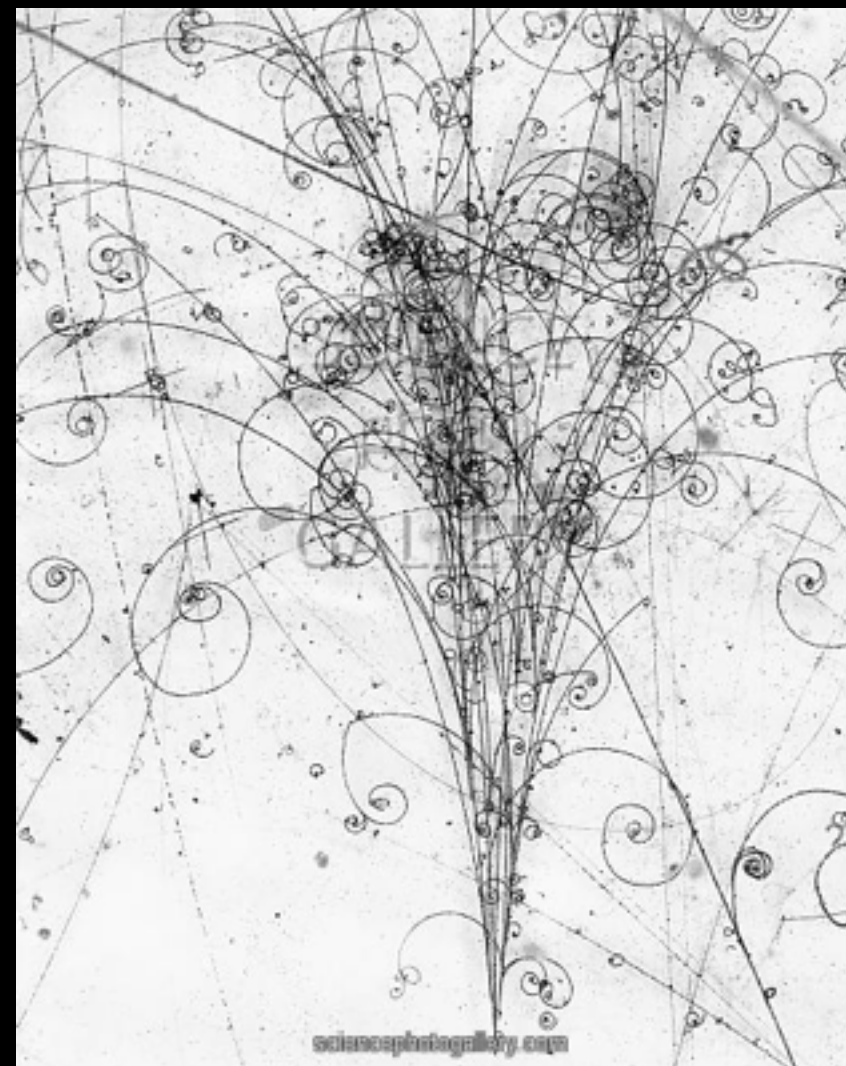
- To first order:
  - make it interact to produce/eject charged particles and observe those
  - wait for it to decay (if it does decay) into charge particles
    - if "daughter" particles are neutral, may need to have those decay.

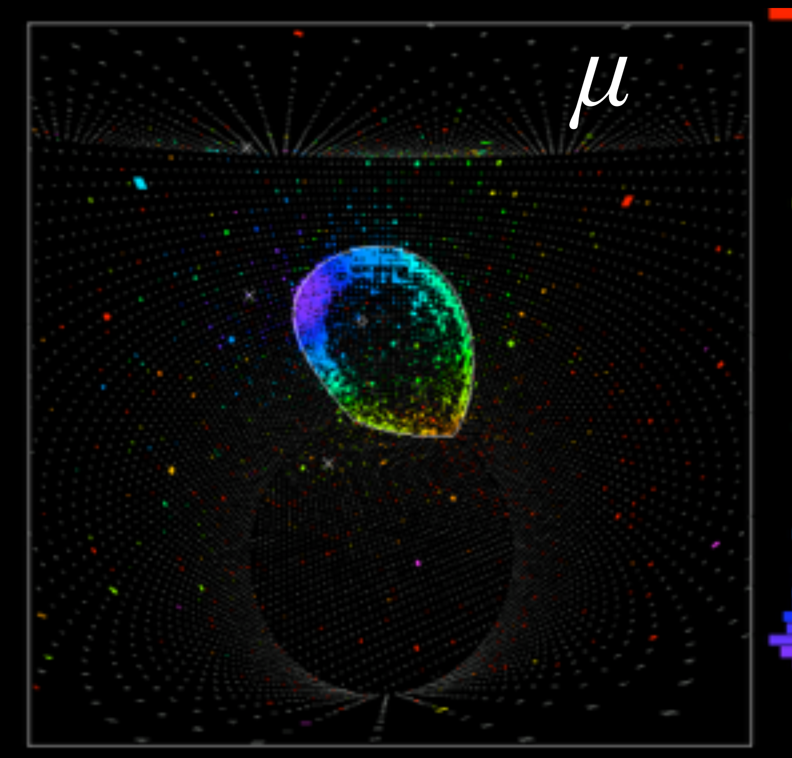


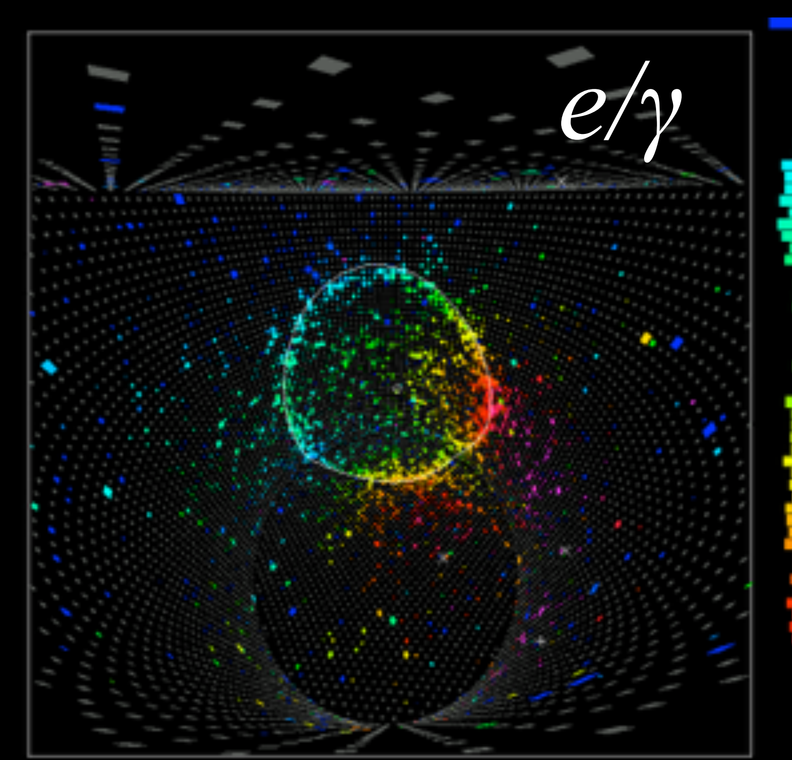
- Three examples in this picture:
  - $\pi^0 \rightarrow \gamma + \gamma$ decay
    - γ then "converts" to $e^+ + e^-$
  - $K^0_s \rightarrow \pi^+ + \pi^-$ decay
  - antineutron annihilates on a proton
- Other examples:
  - neutrons can capture to produce photons:
    - $n + p \rightarrow d + \gamma$ (2.2 MeV)
  - neutrino interactions:
    - $\nu_\mu + n \rightarrow \mu^- + p$
    - $\nu_\mu + p \rightarrow \nu_\mu + p$
    - $\nu_\mu + e \rightarrow \nu_\mu + e$

ELECTROMAGNETIC SHOWERS



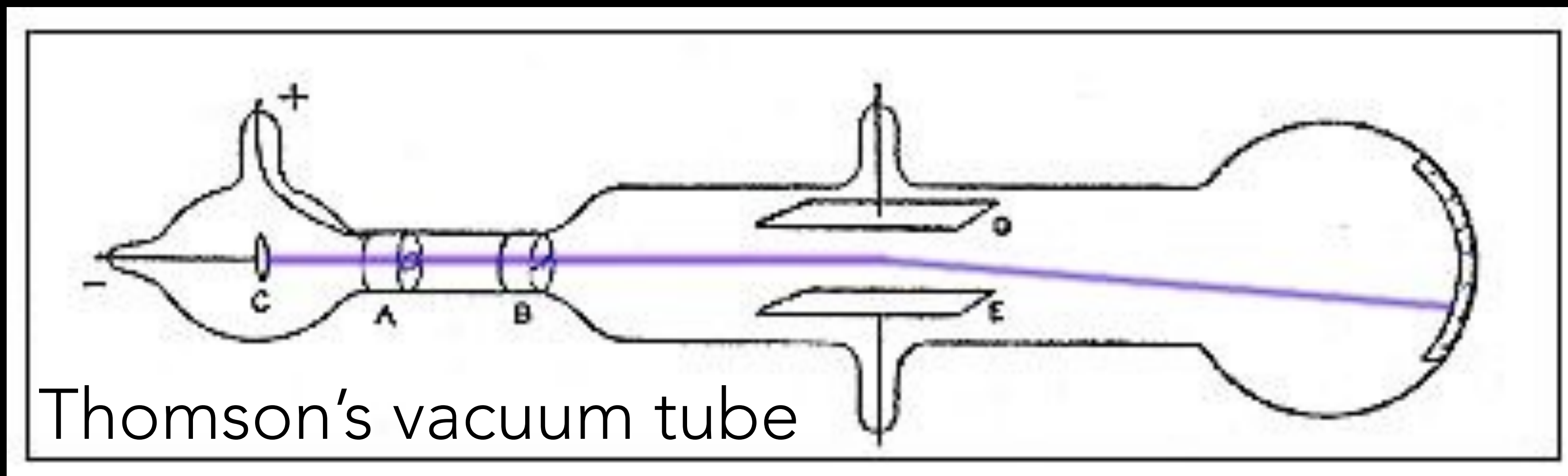






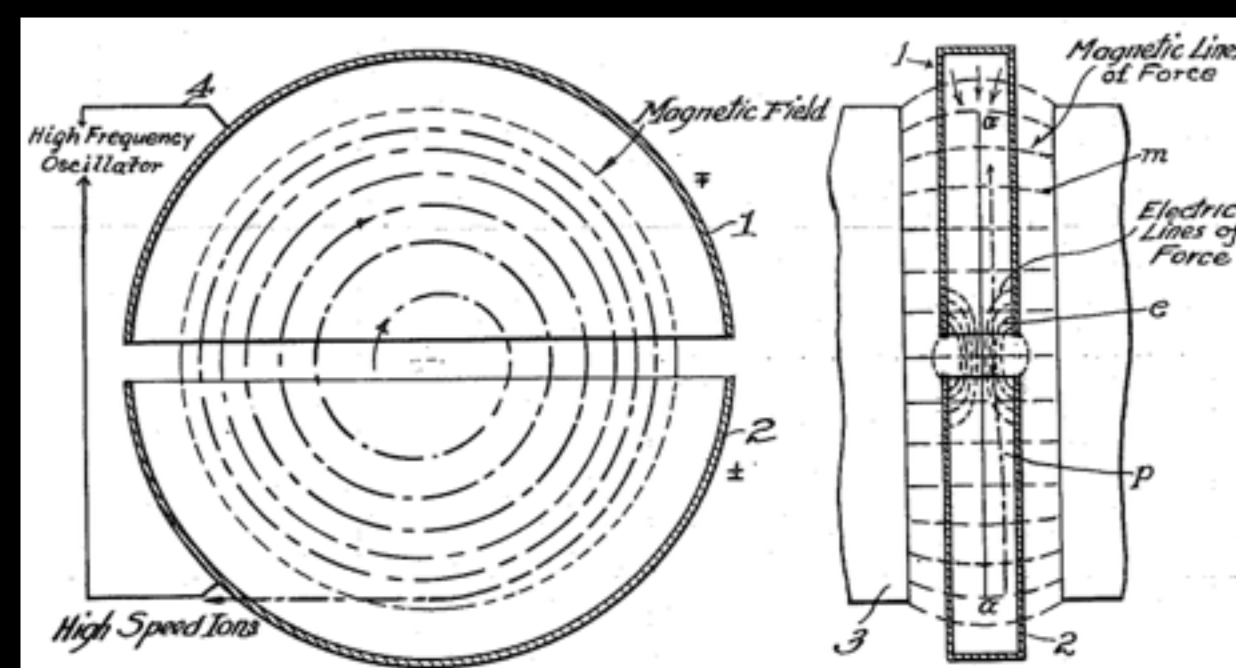
- Cascade of electromagnetic interactions from bremsstrahlung and photon conversion
  - allows particle identification of e/γ from more massive particles that exhibit “mip” behaviour
- Similar processes can happen hadronically (via hadronic interactions)

ACCELERATORS

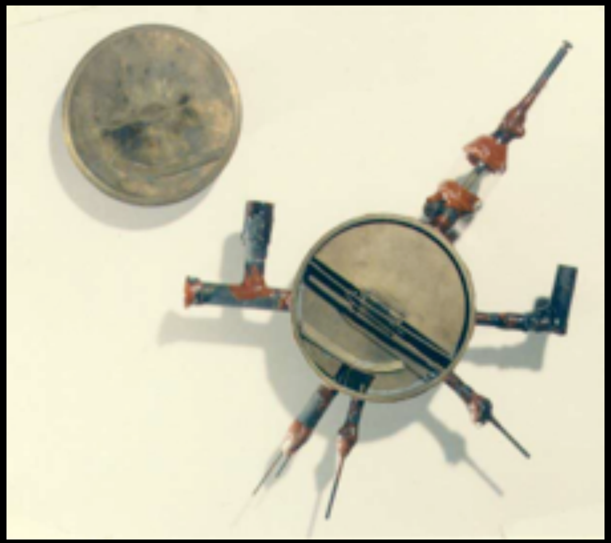


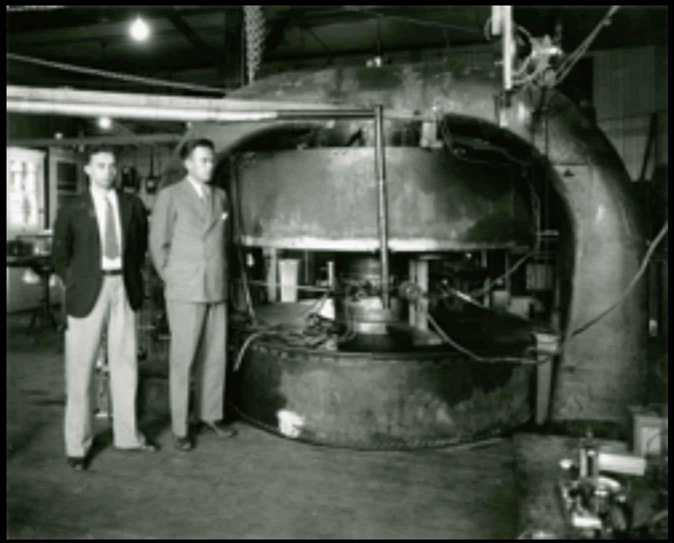
Thomson's vacuum tube

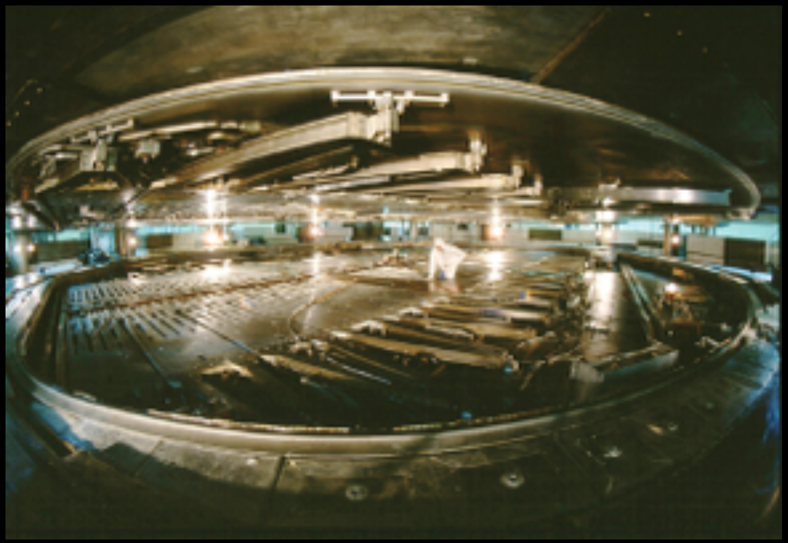
- Basic principle:
  - use electric fields to accelerate charged particles (usually $e^{\pm}$ or $p/\bar{p}$)
    - most acceleration is done by RF alternating currents to "pull" and "push" the particles
  - magnetic fields play an essential role in guiding and focussing particles.

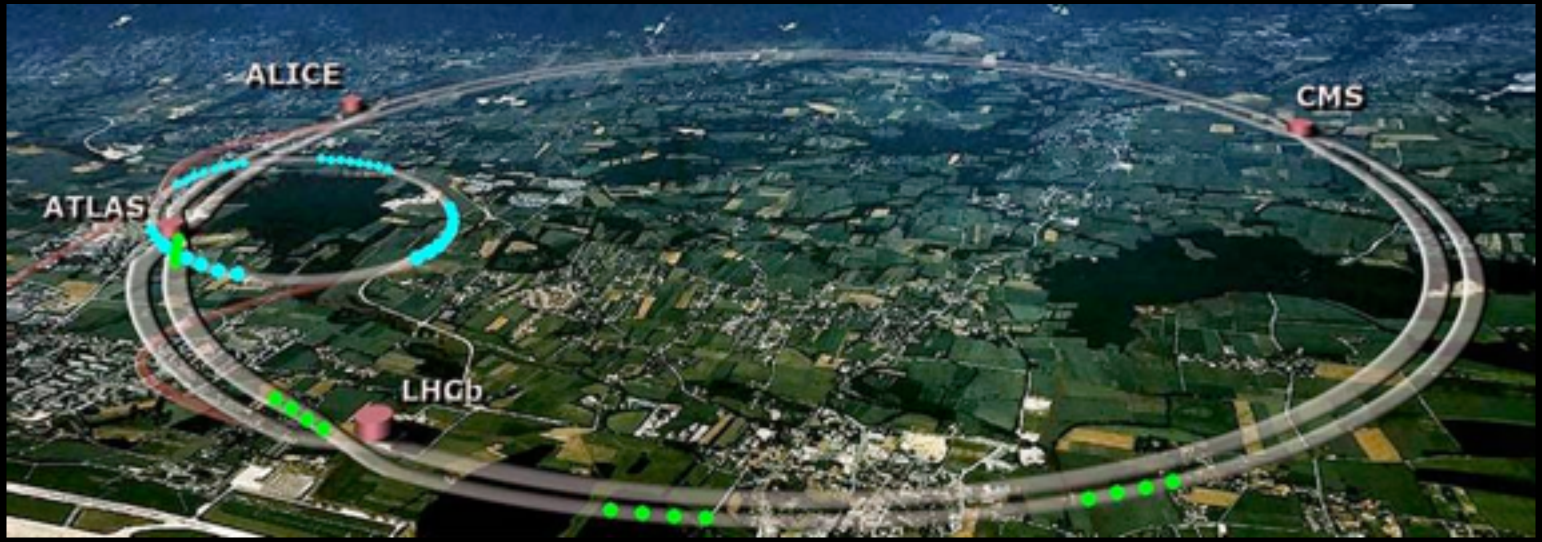


ACCELERATORS:

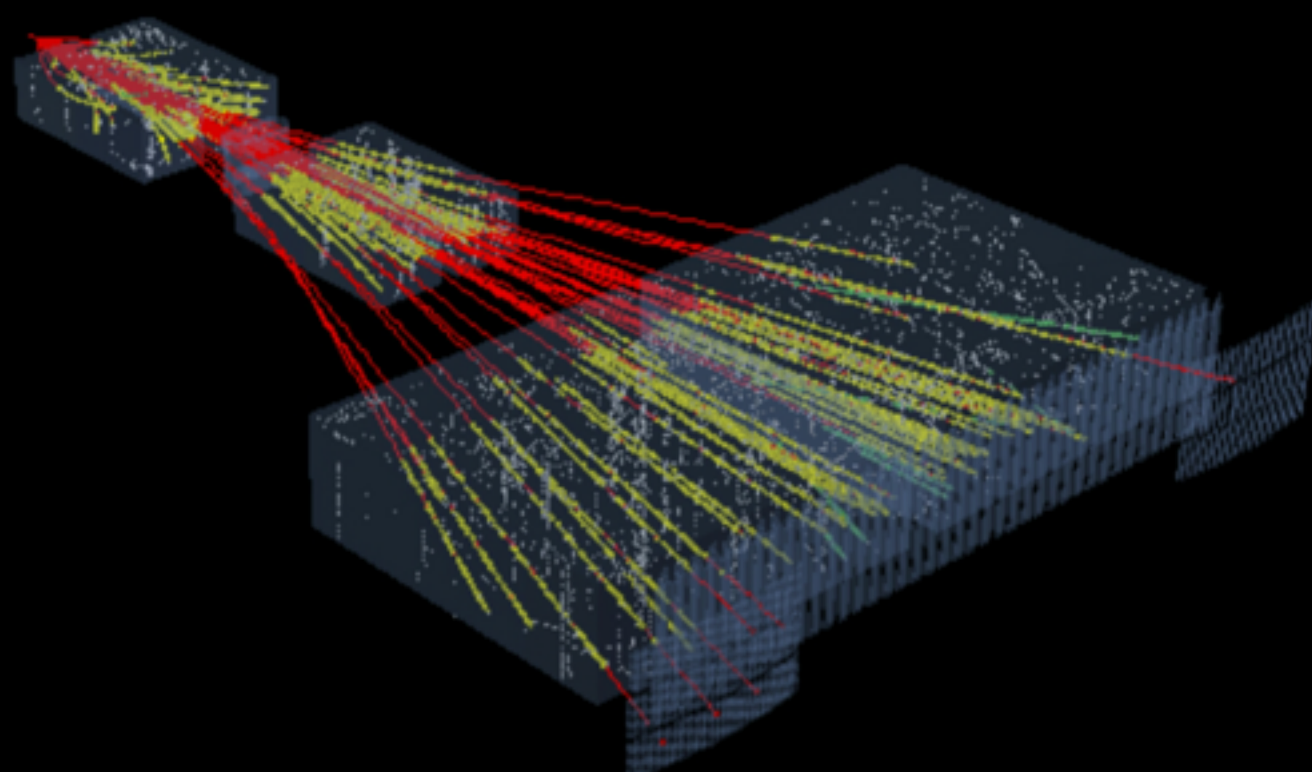








FIXED TARGET VS. COLLIDER



- Fixed target:
  - incident "beam" particle on stationary "target" particle

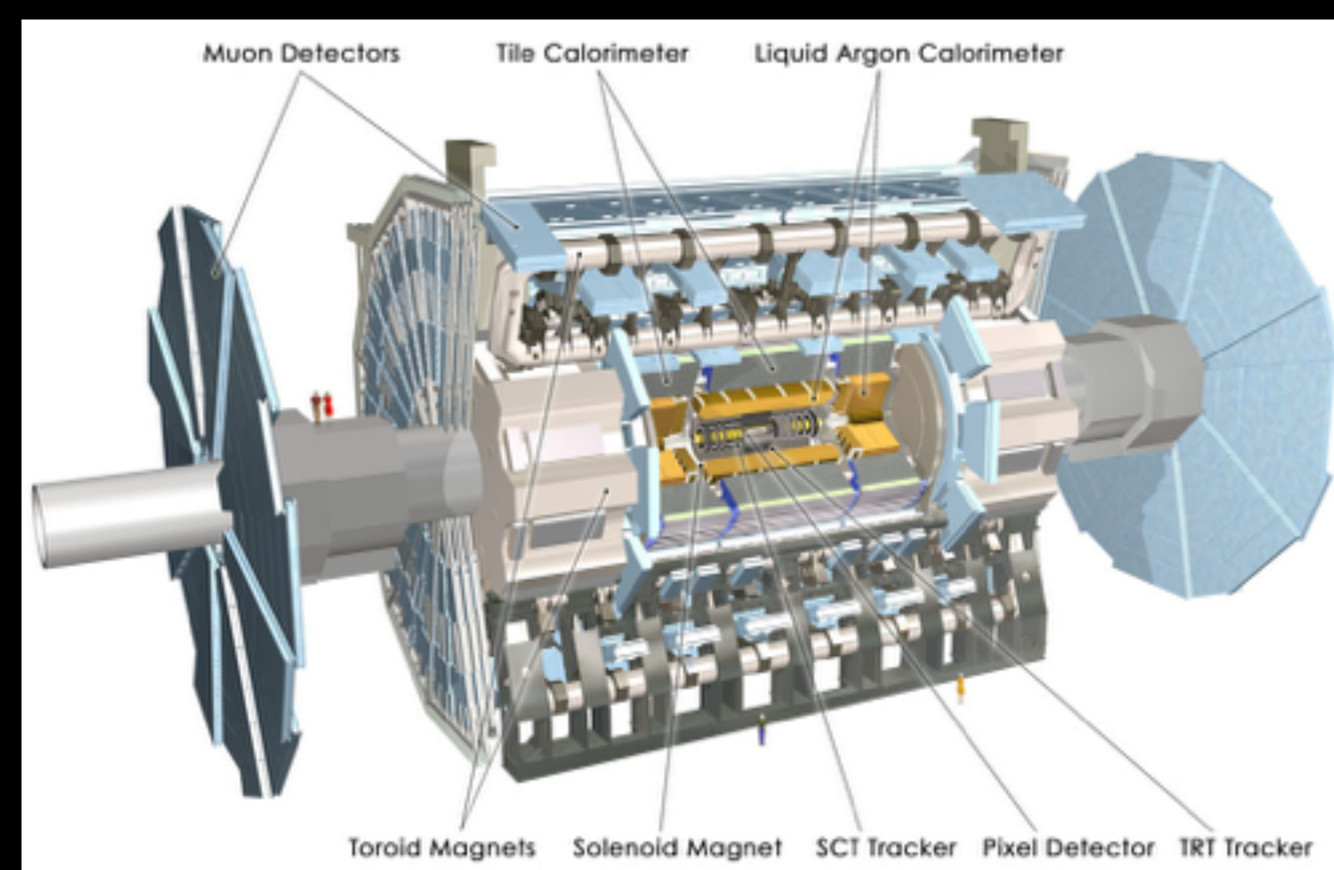
A B

$$E_{CM} \sim \sqrt{2E_A \times m_B c^2}$$

- Collider:
  - two beams of particles in opposite directions collide

A B

$$E_{CM} \sim 2 \times E_{beam}$$



SECONDARY BEAMS:

- Beams of "secondary" particles produced from other interactions.
- Typical arrangement:
  - "primary" proton beam strikes a target

NEXT TIME

- Move to more “quantitative" discussion about Special Relativity and relativistic kinematics.