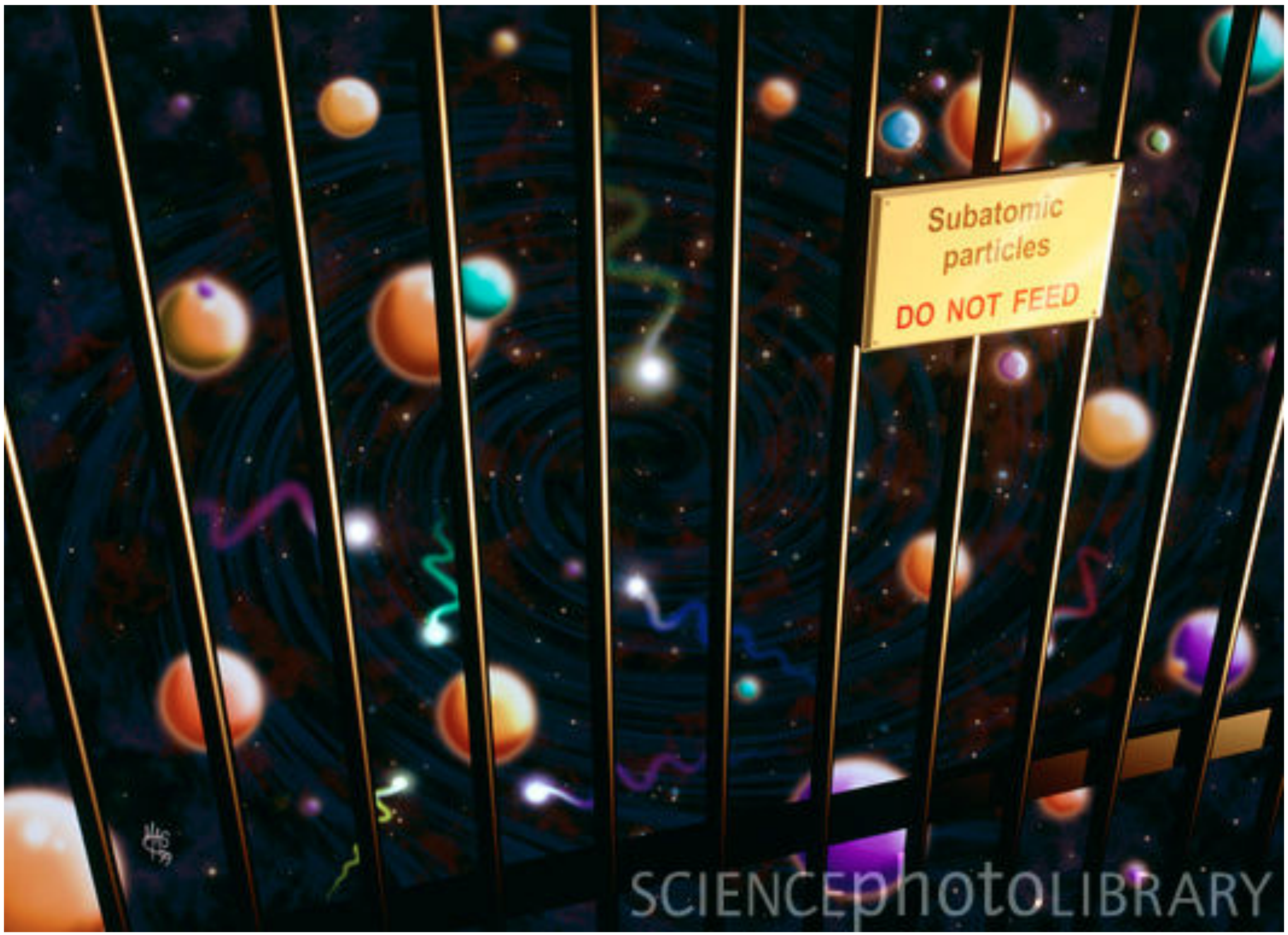
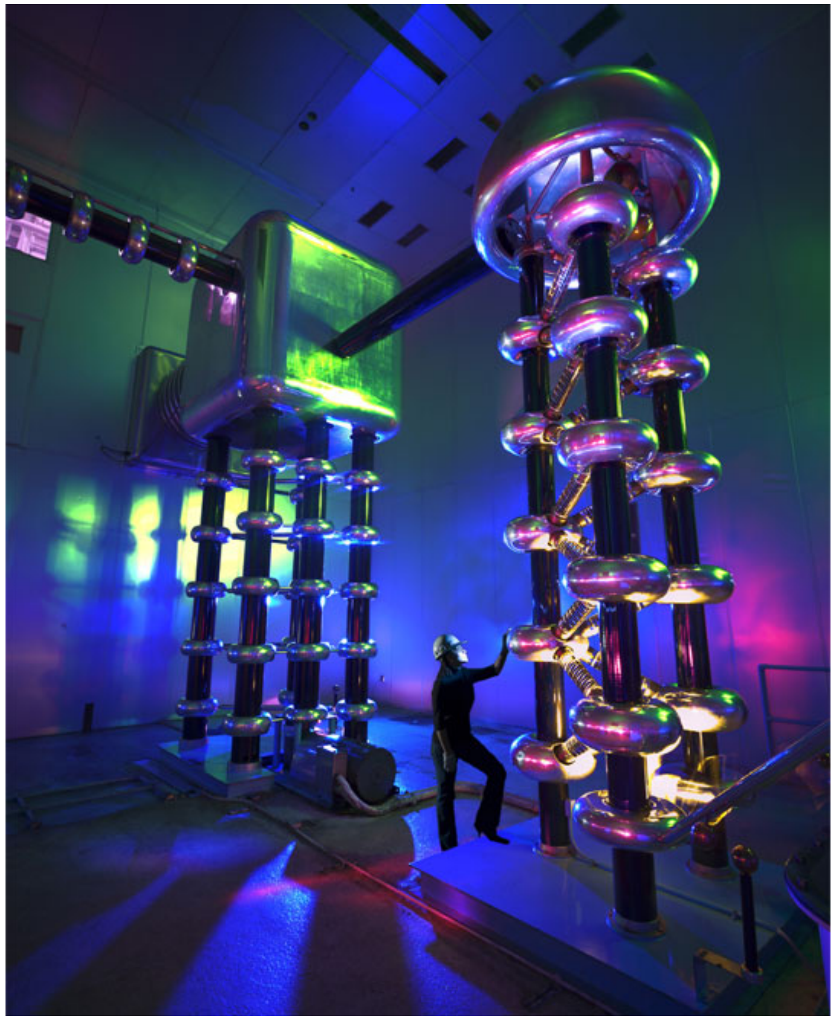
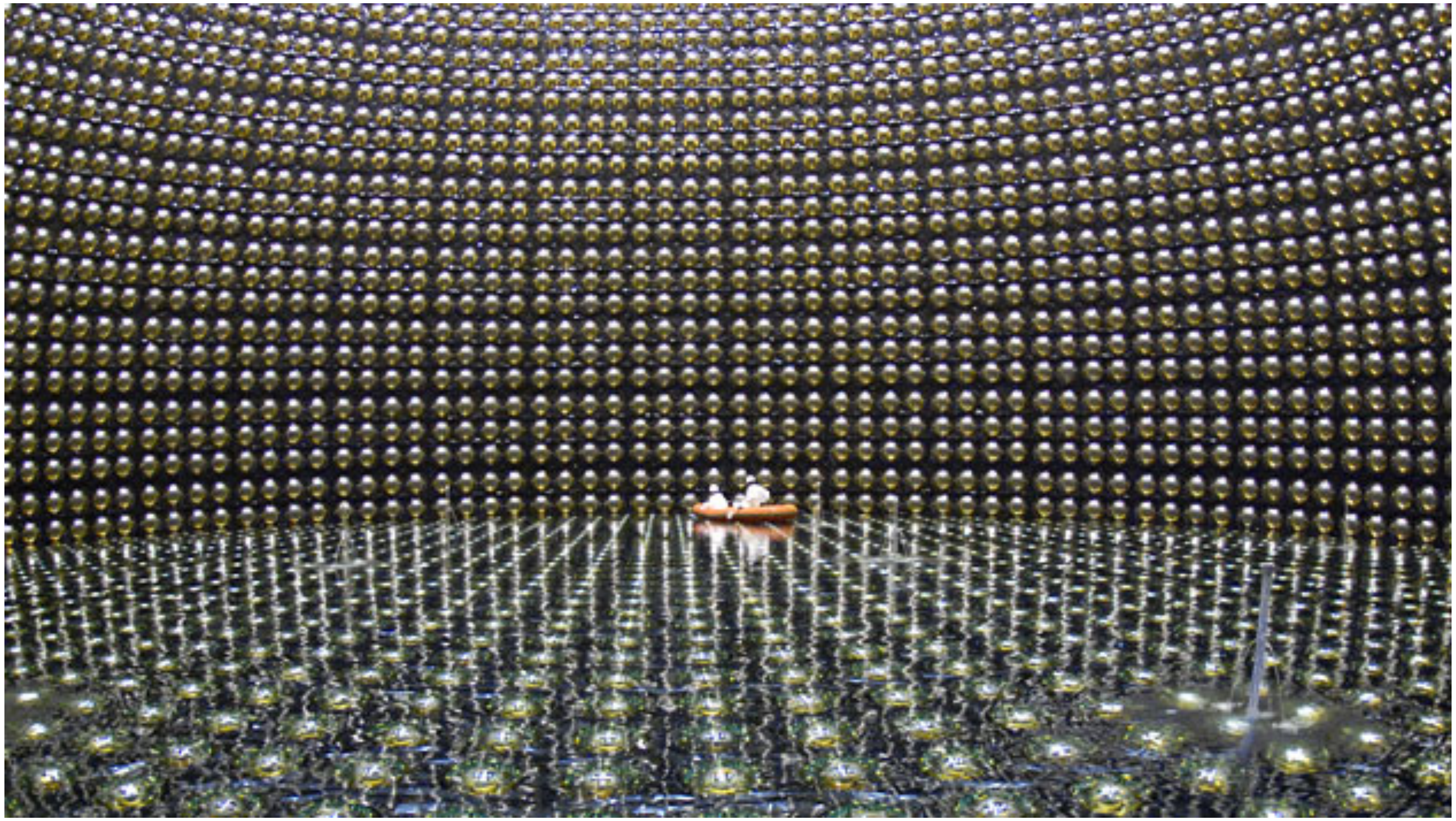
Particle Detectors and Accelerators for High Energy Physics: QuarkNet Lecture

How do you study objects invisible to the naked eye, that span a vast range of masses, energies, lifetimes?

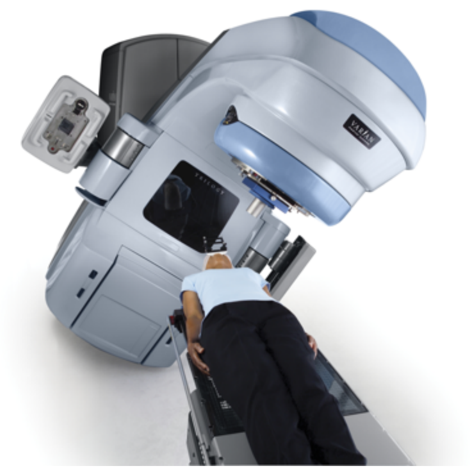



Accelerator


Detector

Accelerators: A particle accelerator is a device that uses electric and magnetic fields to propel charged particles to high speeds and to contain them in well-defined beams.
Detectors: Device(s) for recording the behavior of particles traveling through matter.

- Development/ Applications of detectors and accelerators is a HUGE topic. We'll barely scratch the surface here.
- This subject is full of examples of how particle physics leads to applications that are important in the real world, in addition to all the fun physics we are primarily interested in studying.

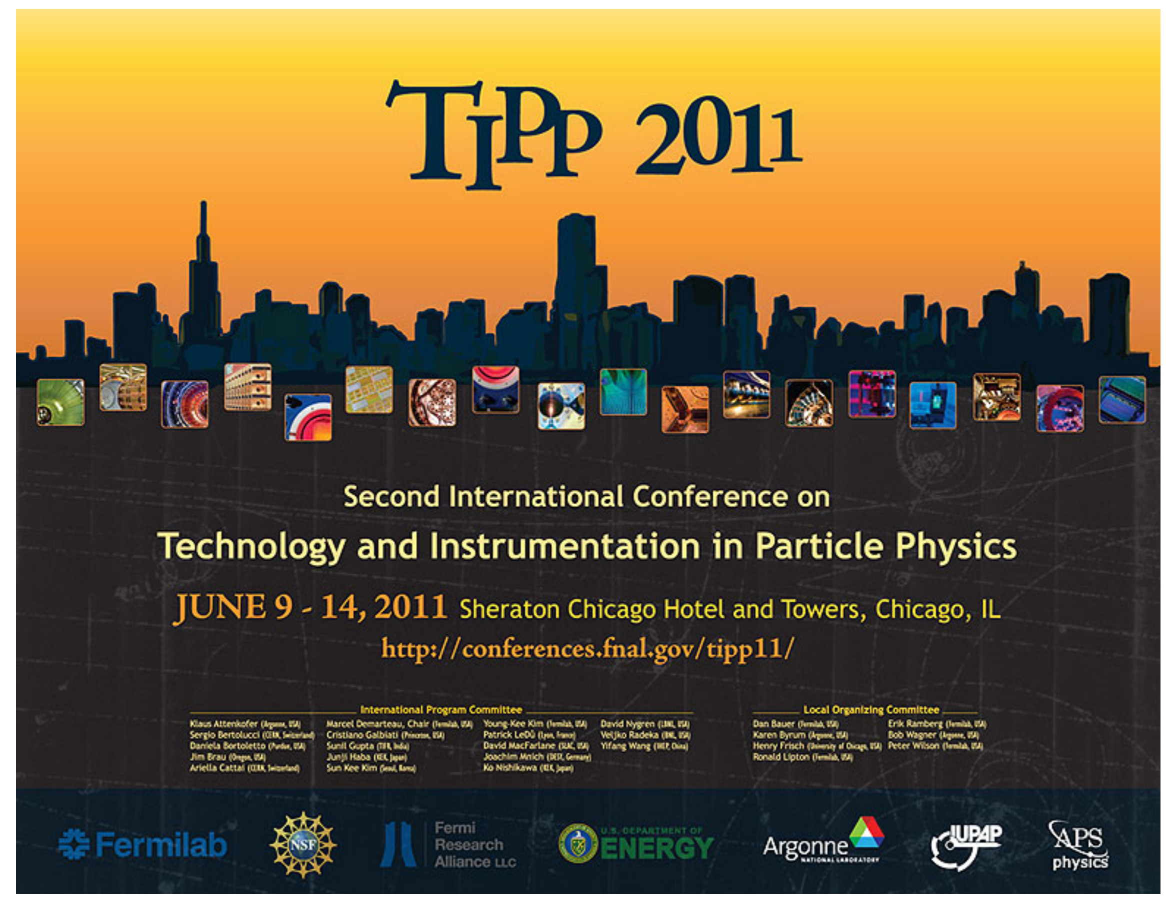


Medical Treatment

Diagnostic Scans

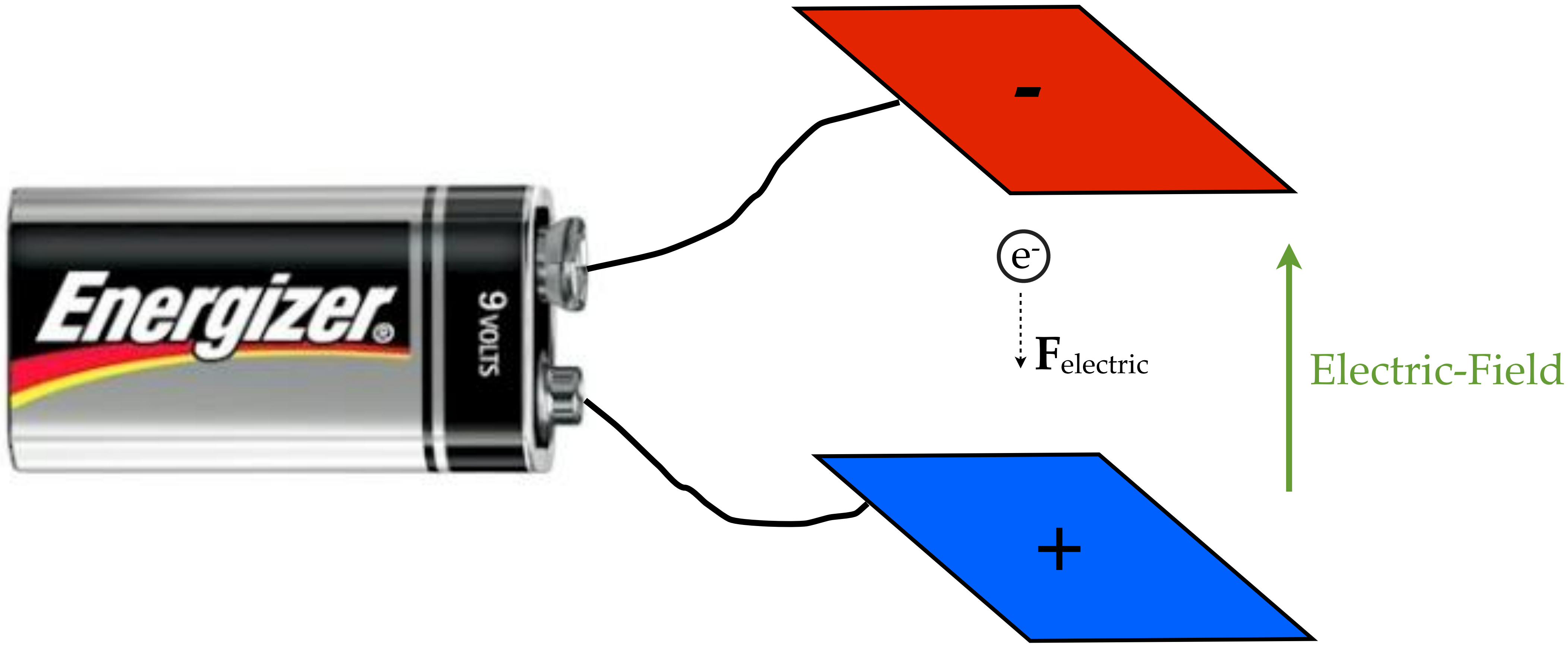
Security

Computing

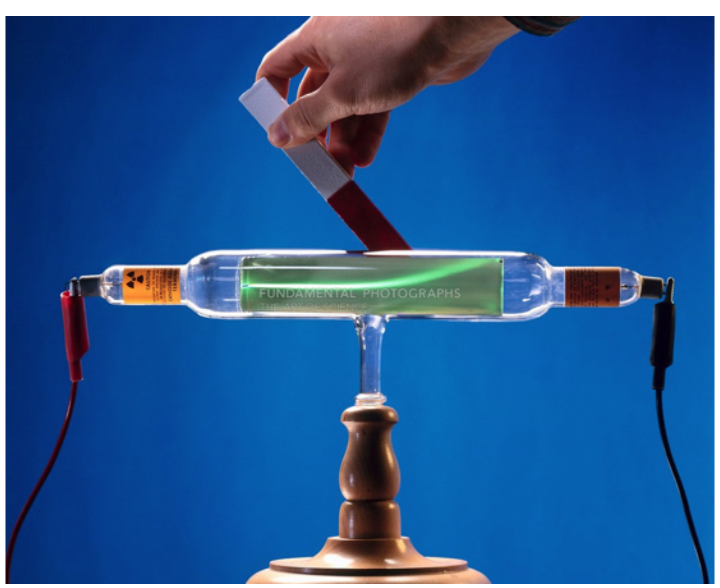


Entire conferences are dedicated to this subject.

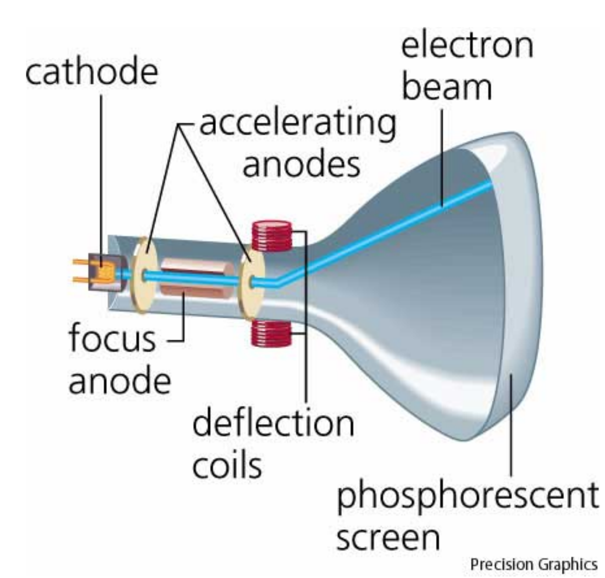
A simple particle accelerator



- Charged particles in an electric field experience force / acceleration.
- Energy acquired accelerating across an electric potential gap is = $q \times \Delta V$
- Example: An electron traversing a 1V gap: $q \times \Delta V$ = **1 eV = 1.6×10^{-19} J**

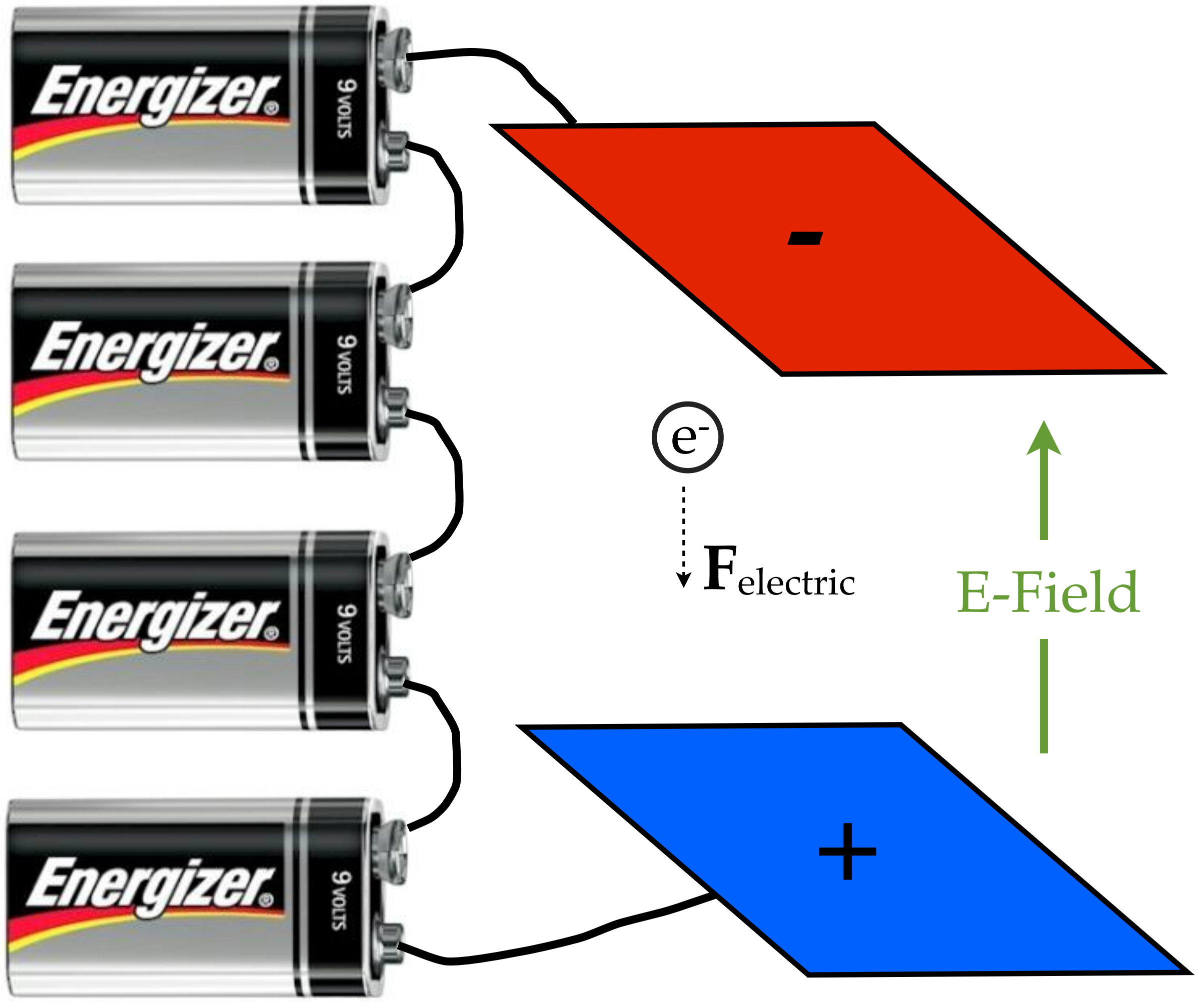

Cathode Ray Tube

Magnetic Fields can be used to steer the direction of the charged particles (example: old TVs).



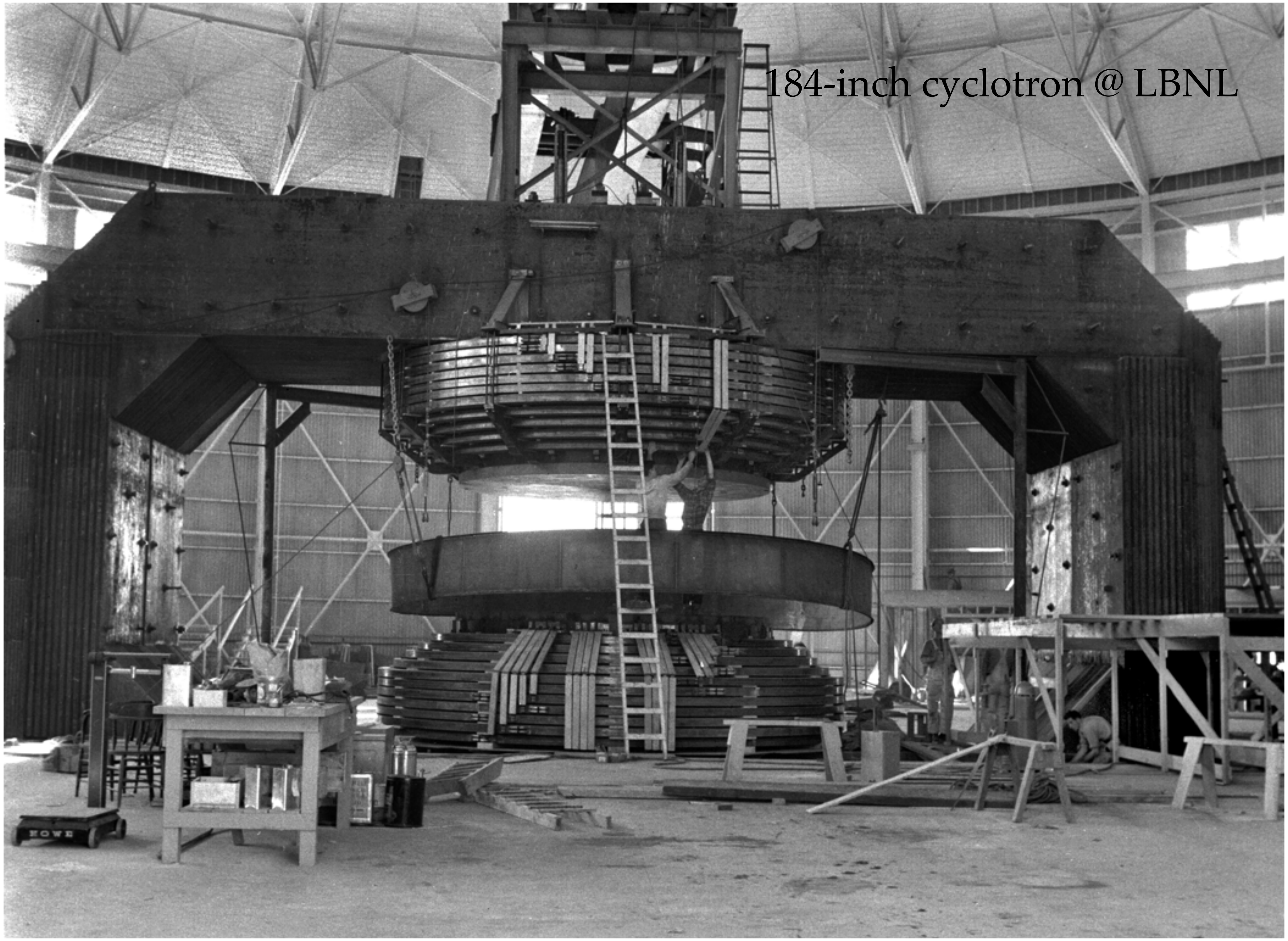
Cathode Ray Tube

More Power!



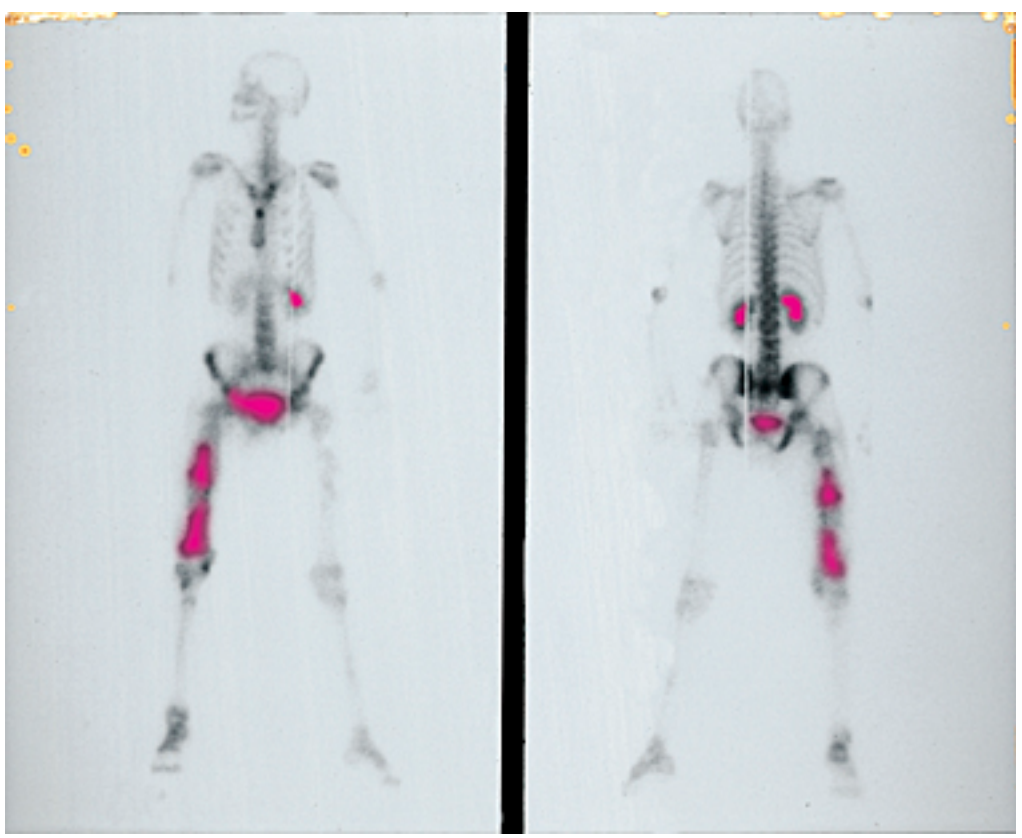
- Can't just keep adding additional batteries if we want to accelerate to higher energies.
- Materials have breakdown voltage, and discharge will occur if the potential difference is too large.

Cyclotrons

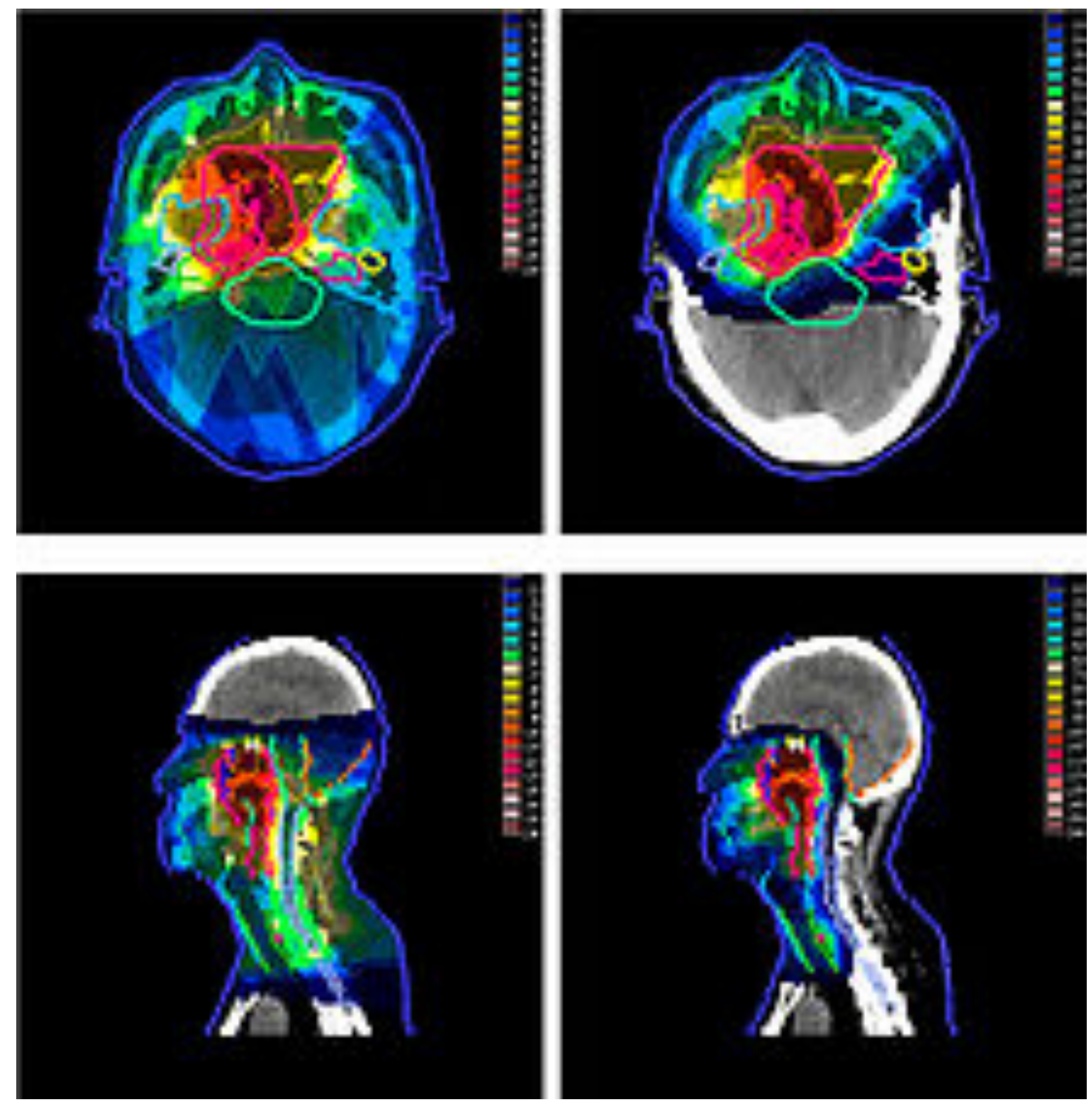


- Cyclotrons used alternating electric field, and large magnetic field, to gradually increase energy of charged particles (protons, electrons, ions).
- Huge breakthrough...allowed energies of **~10^6 eV (MeV)**
- Require very large magnets, vacuum....eventually have to confront relativistic effects.

- Modern cyclotrons can produce radioactive tracers used in medical applications, and can also be used directly to treat tumors.
- Technetium-99 is the most common isotope used in nuclear medicine.
- Technetium produced by radioactive decay of a rare isotope of Molybdenum (Mo-99...which comes from fission of U-235) or ~20 MeV proton bombardment of a more common isotope (Mo-100).

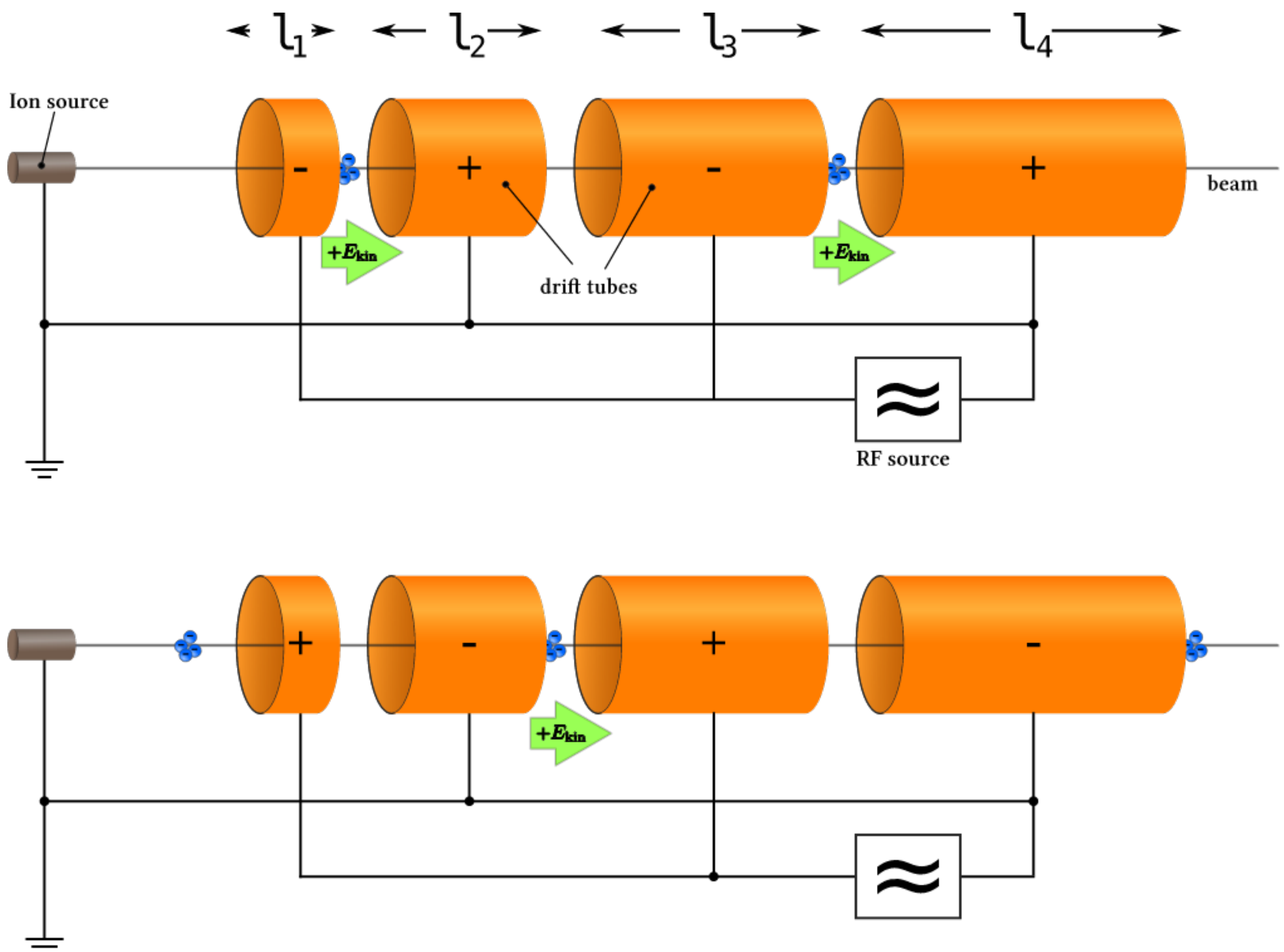


Technetium is radioactive and decays, producing easily detectable photons. Allows function of kidneys and other organs to be studied.

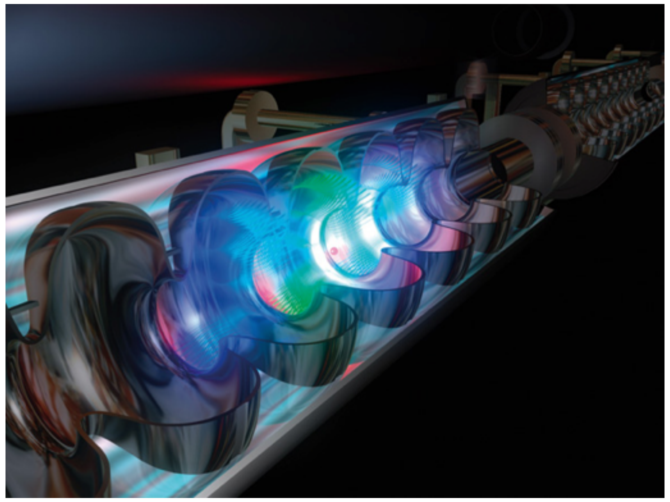


Protons accelerated in cyclotrons can be targeted at tumors within the body (right), causing less collateral damage than X-ray methods (left).

Even More Power!

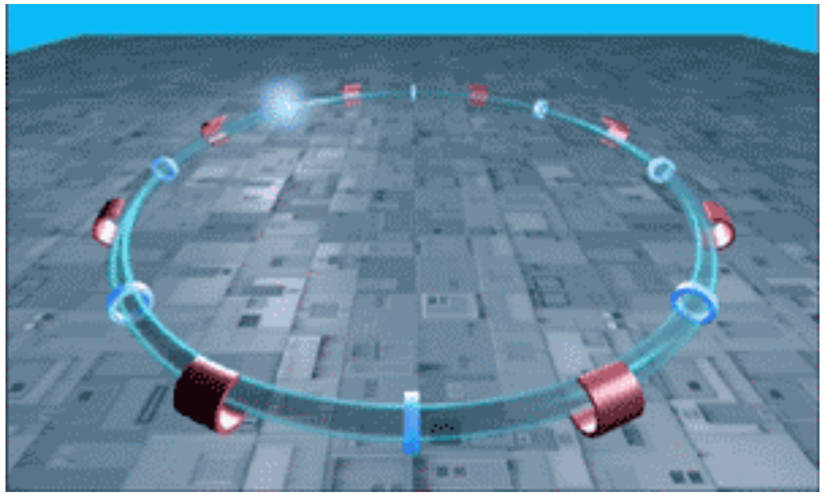


- Again we can use the idea of alternating RF electric fields to accelerate particles, but this time we'll use cavities arranged in a straight line.
- Stanford Linear Accelerator (SLAC) achieves electron energies of **50 GeV**.
- Not limited by needing bigger and bigger magnets to steer the beam.
- **Note: The use of alternating RF creates a bunch structure in the beam (i.e. - not a continuous beam)**

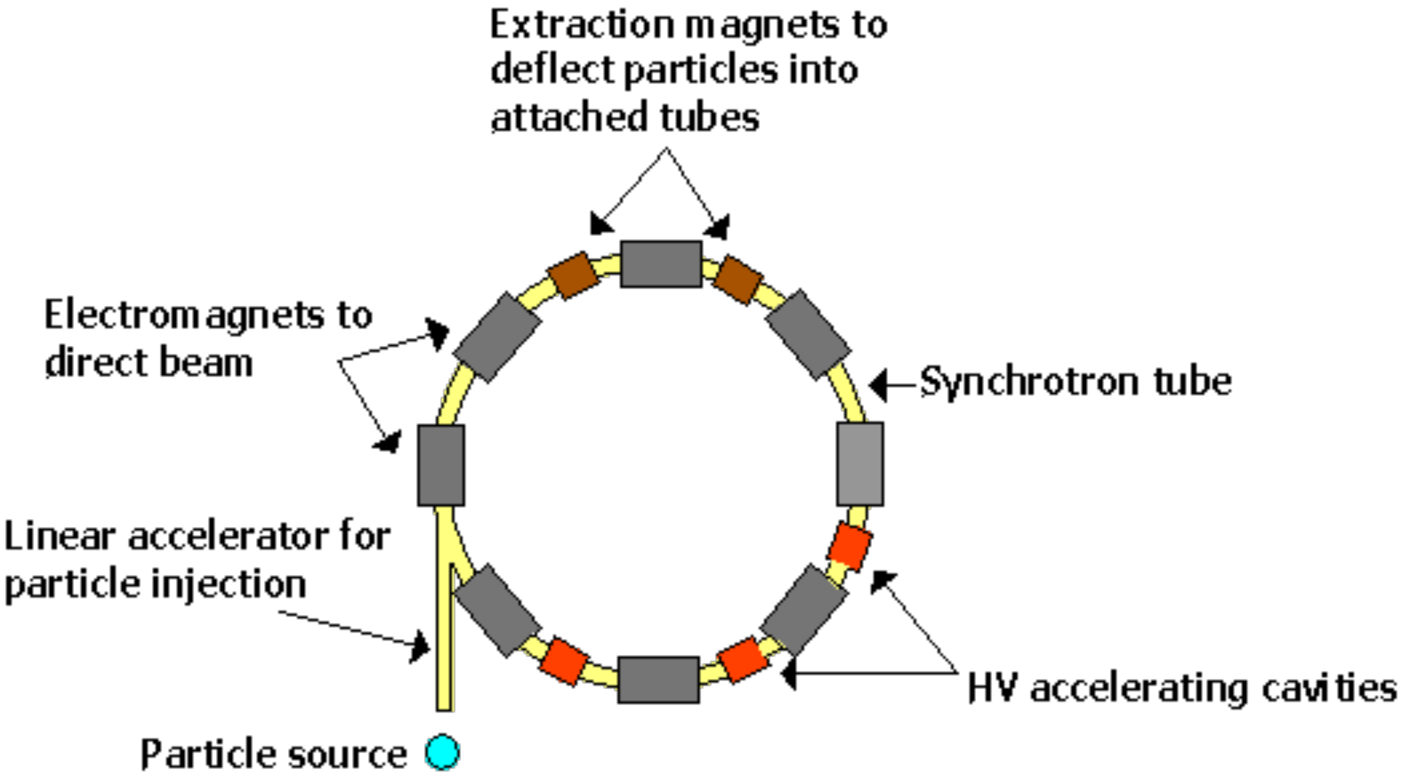


SLAC: 2 miles long, "World's Straightest Object"

Still Need More Power!



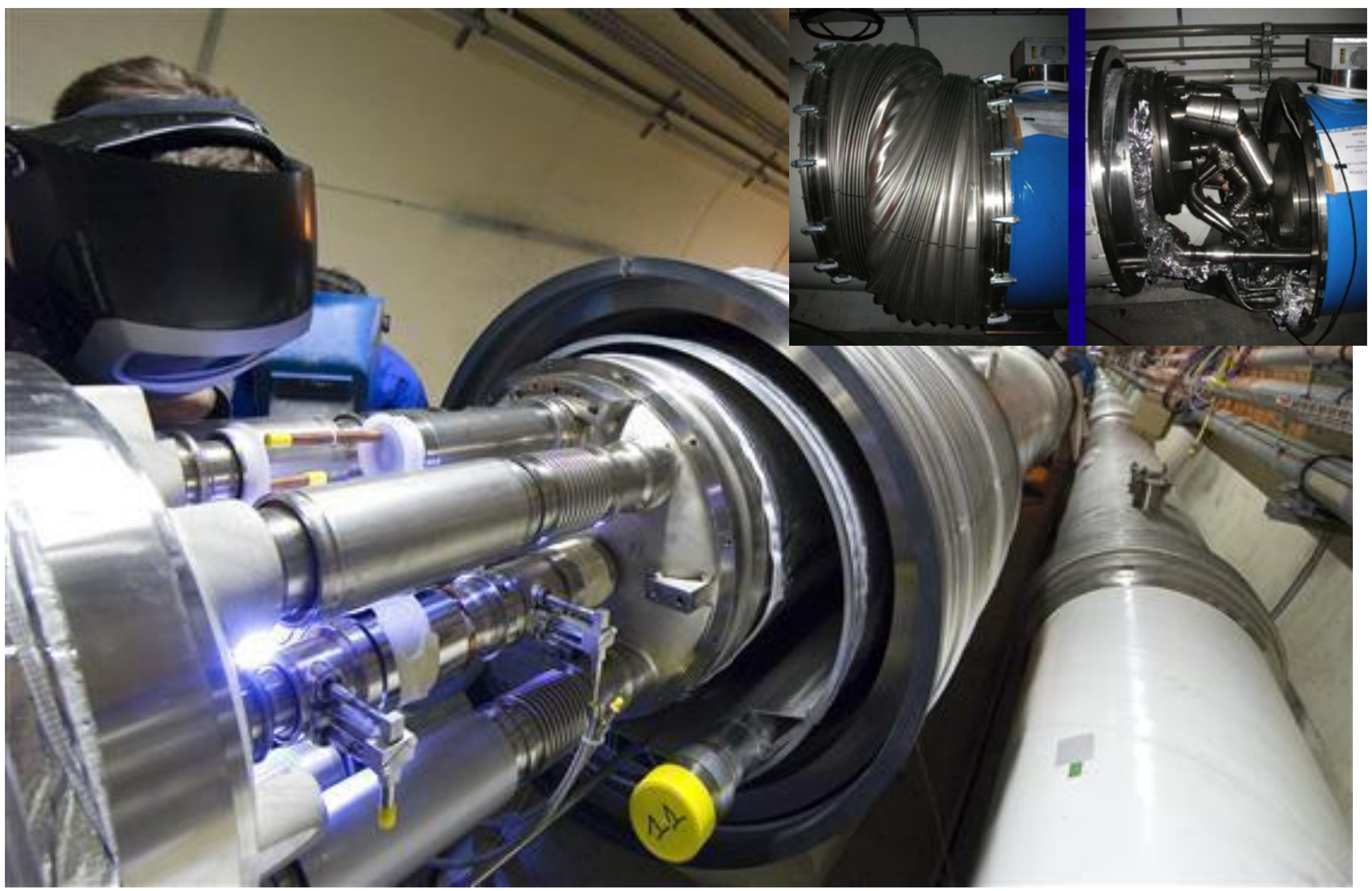
- Synchrotrons combine magnets and RF accelerating cavities.
- Magnets steer/focus the beam as it travels around accelerator path.
- RF cavities accelerate the particles as they pass.
- Magnetic field strength is increased as particles accelerate in order to keep them in a constant orbit.



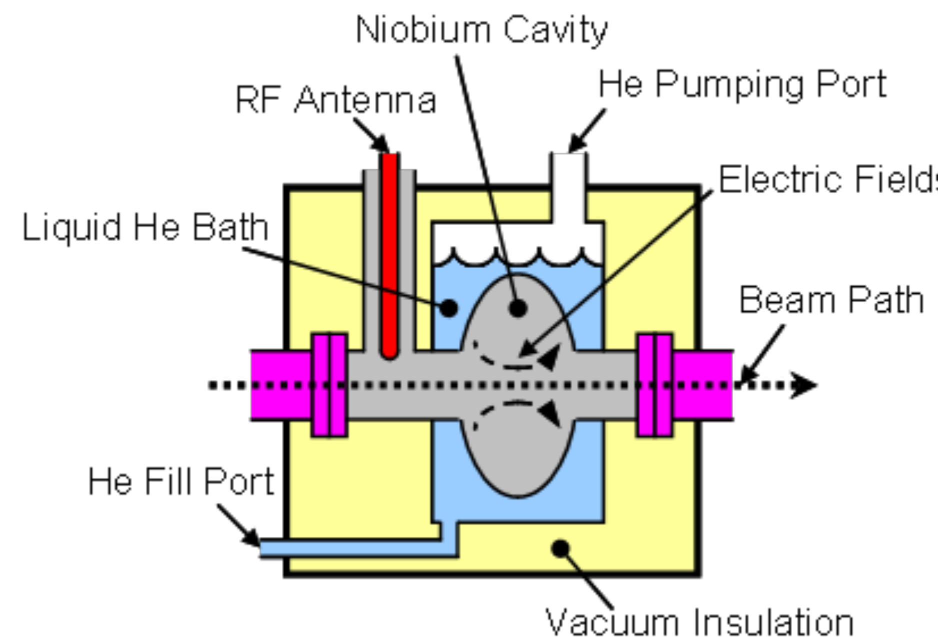
Synchrotron Accelerator

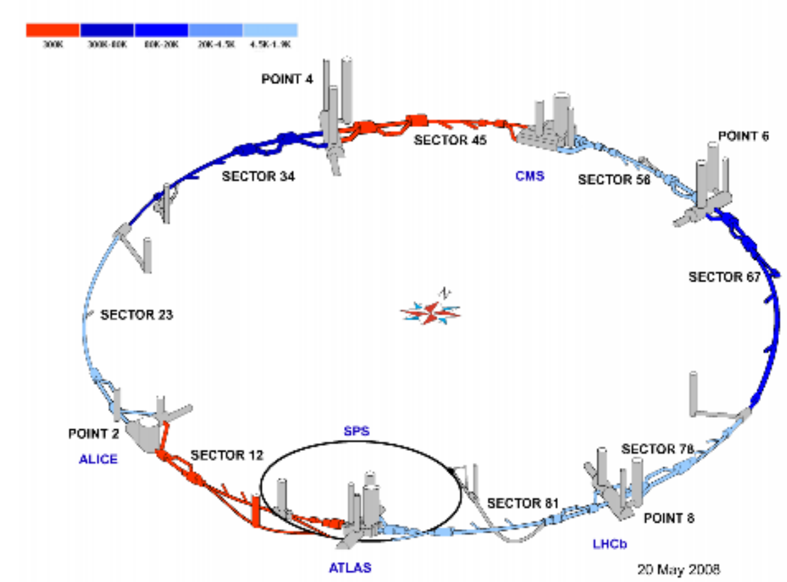
Steering Magnets at Fermilab

- Synchrotrons allow enormous energies to be reached (LHC will eventually reach **7 TeV** beam energy).
- Superconducting RF cavities allow more input energy to be used for acceleration, and less to be lost to the environment.
- This means the entire accelerator has to be cooled to cryogenic temperatures, which is not trivial for large accelerators (LHC circumference = 27km or 16.8 miles).



Accelerator Interconnects at the LHC





HW Problem:

What is the velocity of a 7 TeV proton, like those that will be in the LHC beam? (Hint: Need to use Special Relativity)

We’ve accelerated some particles and made a high-energy beam…now what?

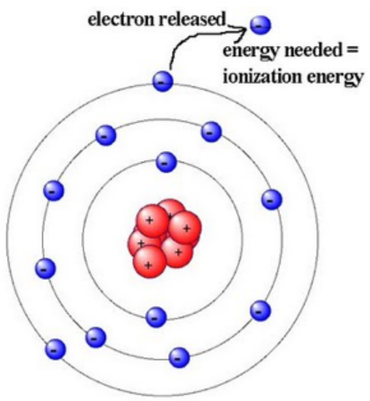
Take a picture of what happens when the particles do something!

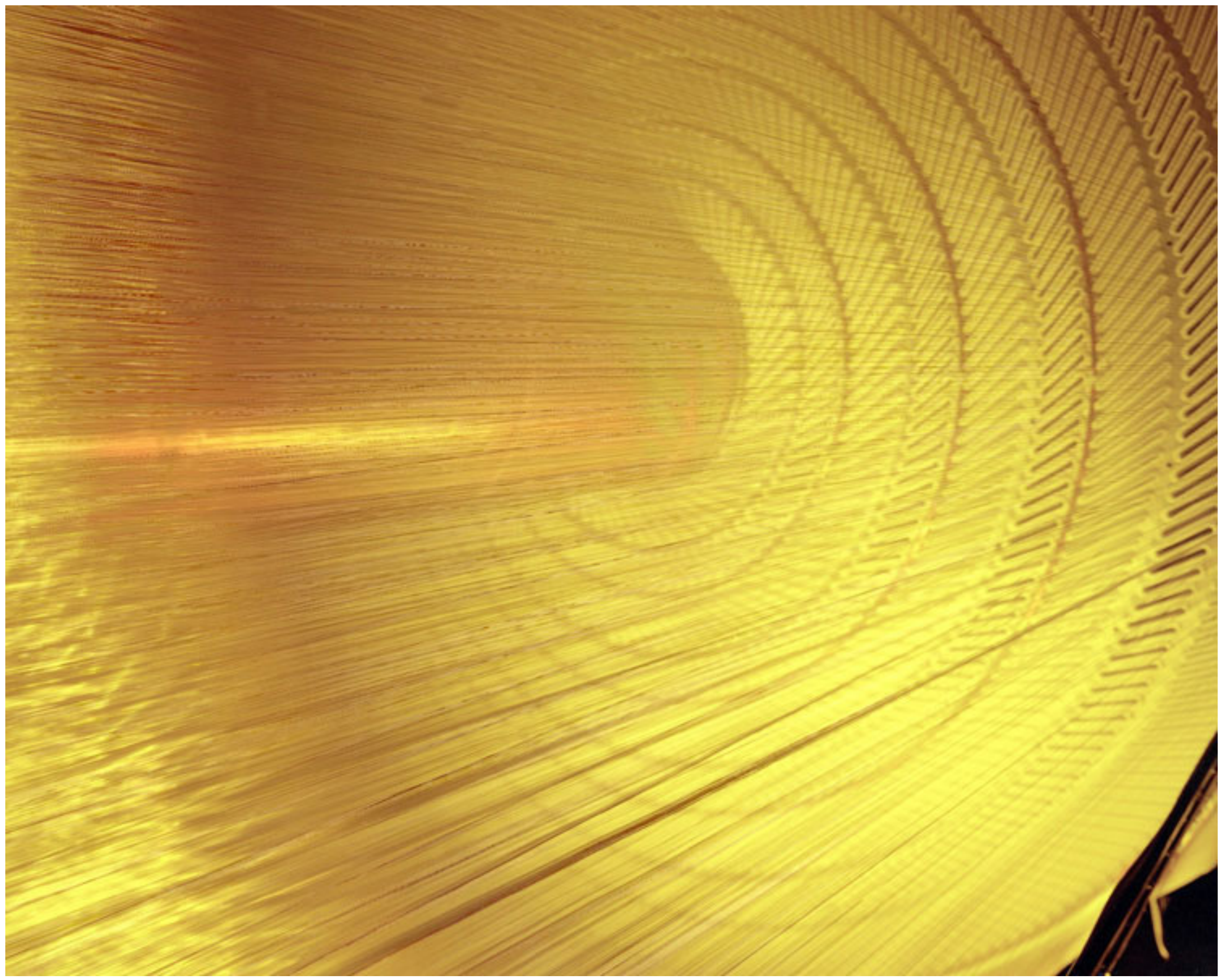
In the early days, people actually took a picture.
Not a scalable approach to modern accelerations (MHz collision rates).

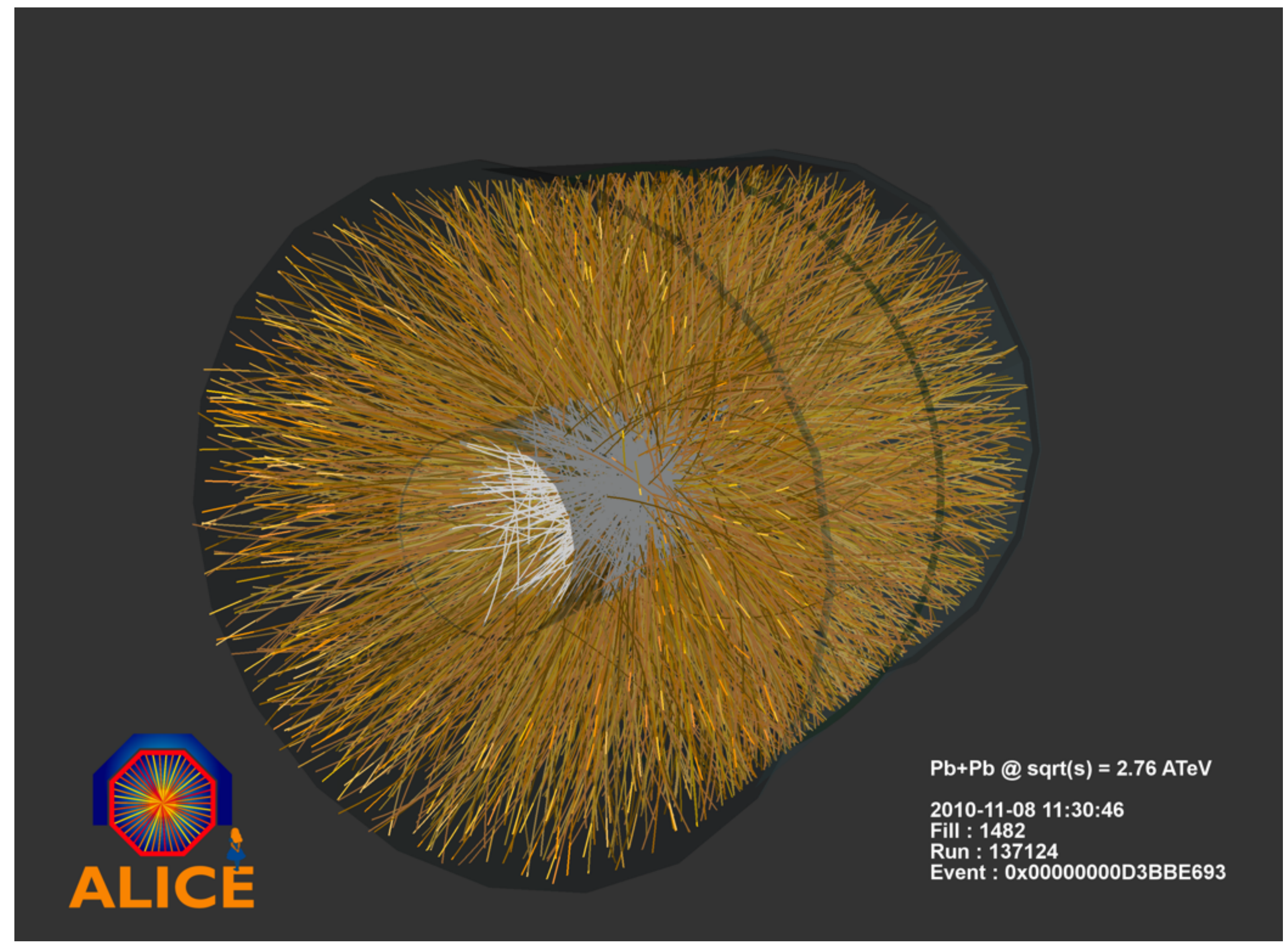
14-ft Bubble Chamber

Scanning an Image "By Hand"

Charge Production

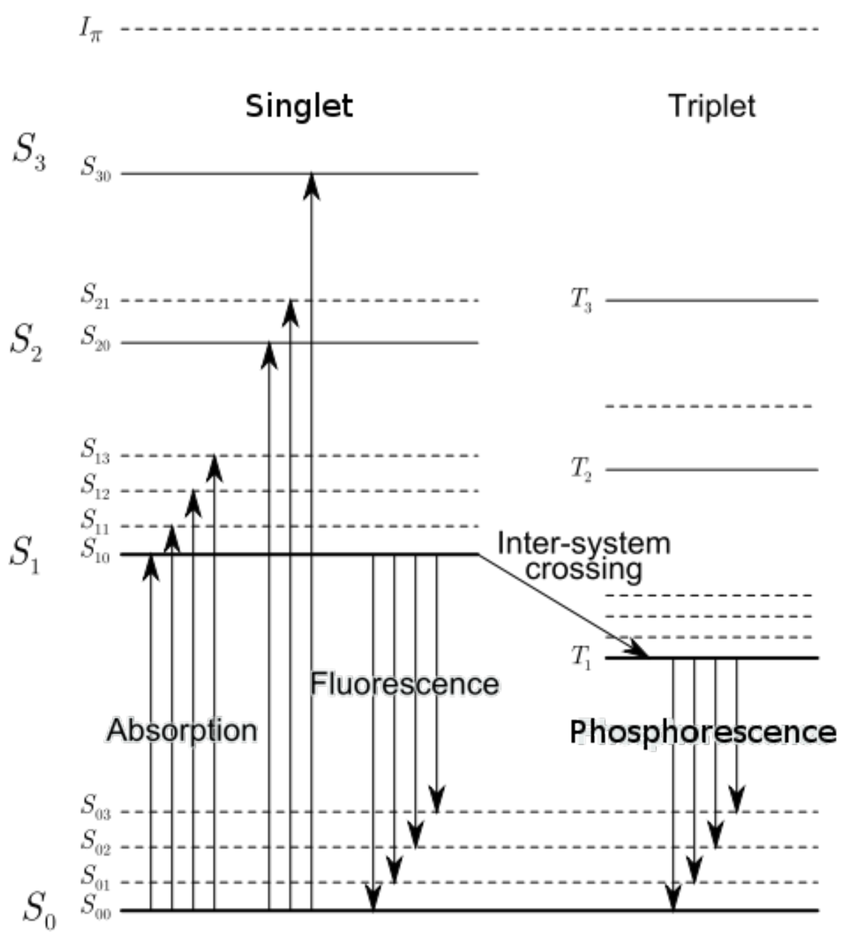


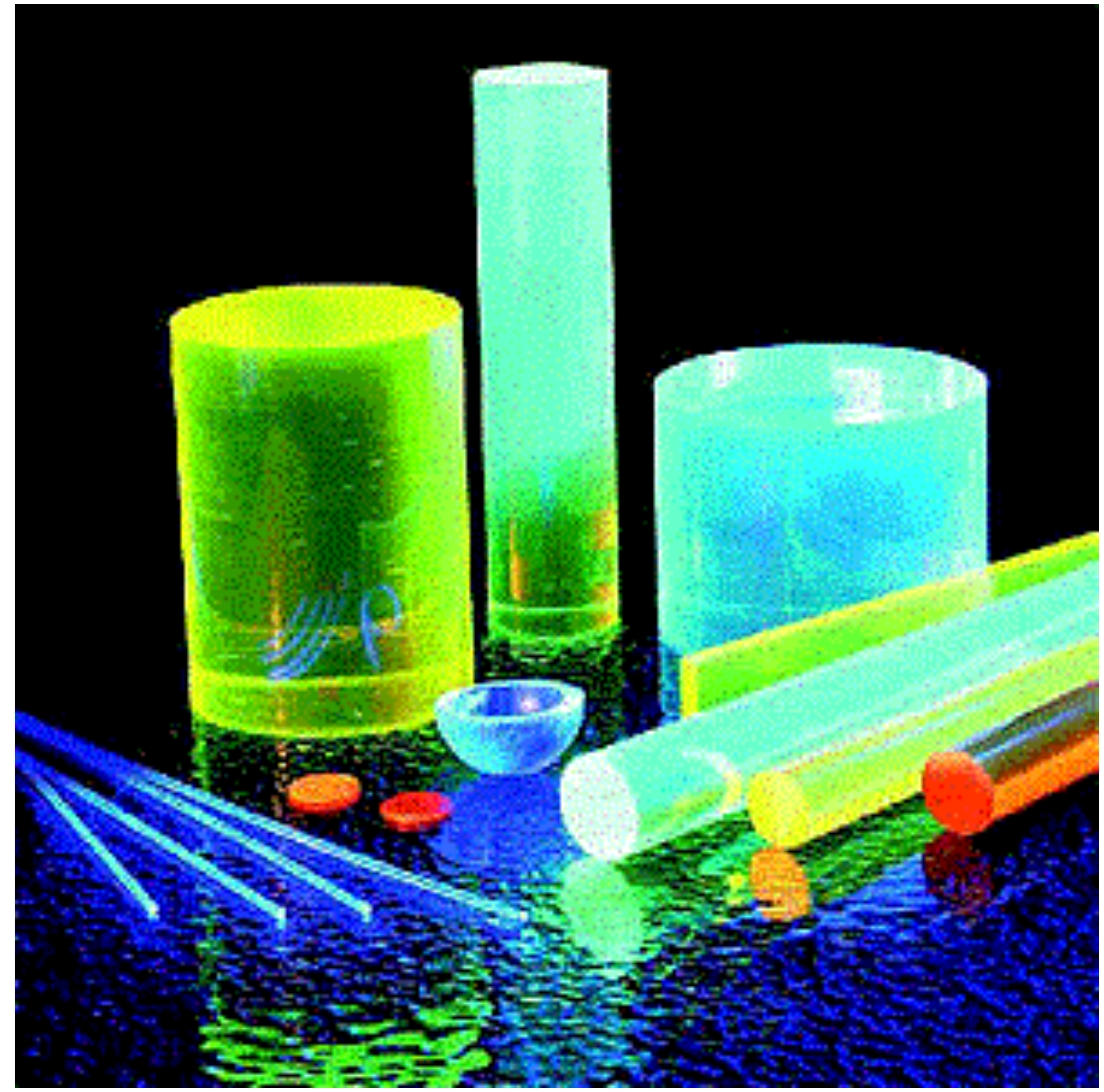




Charged Particles traversing a medium will produce charge (by ionization, for example), which remains behind in its wake. Collecting the charge on precisely placed electrodes gives us the trajectory of the particle.

Light Production: Scintillation Light

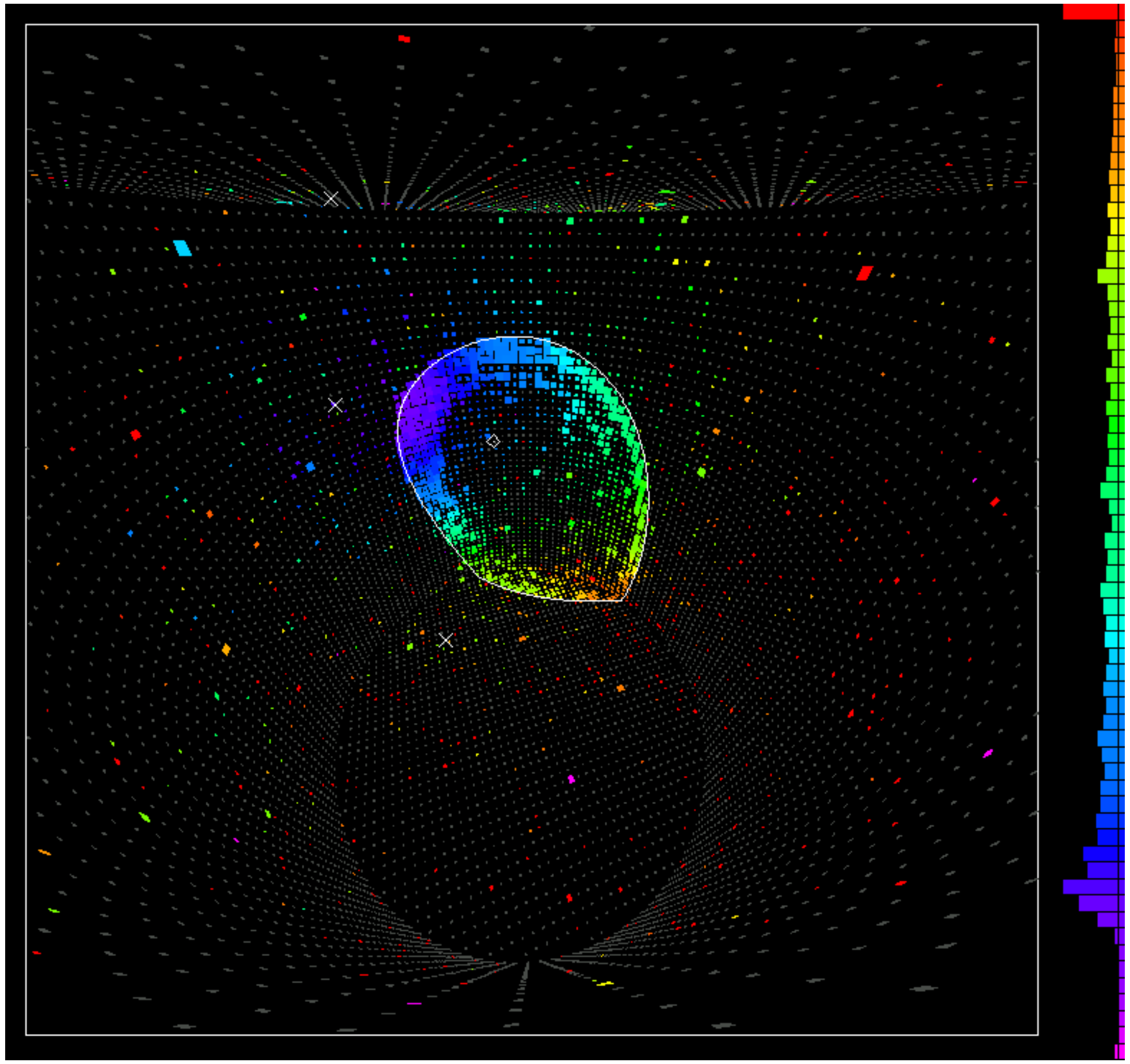




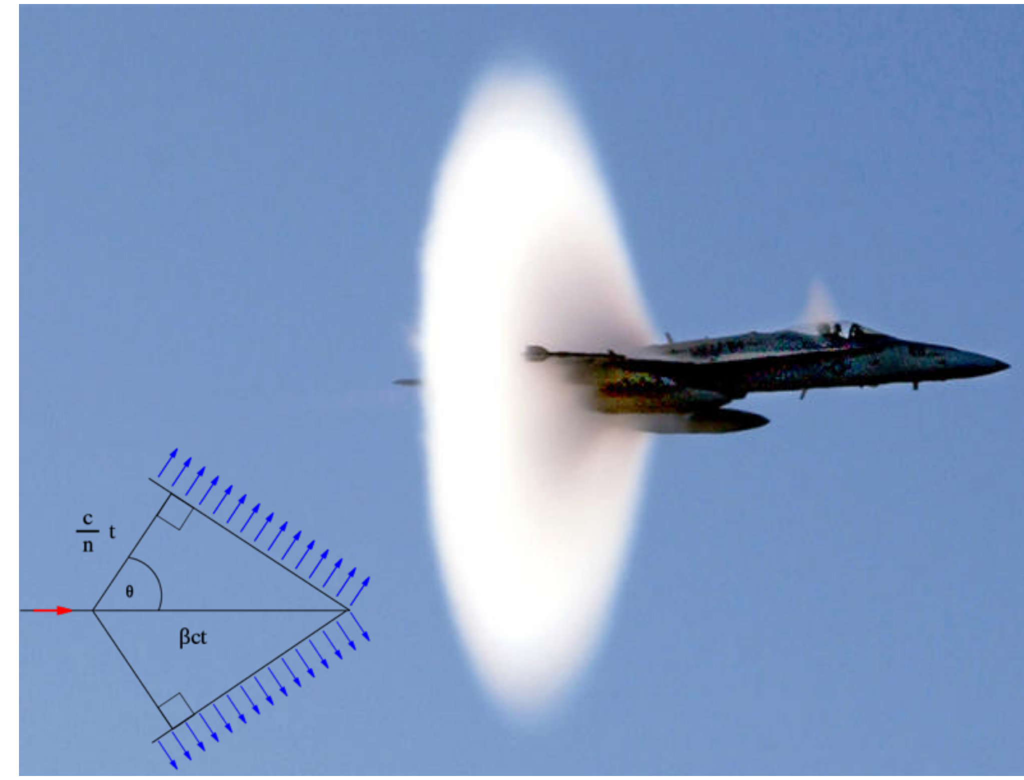
Organic Scintillators

- Atoms can be excited by passing particles, and then decay back to a ground state. In the decay, scintillation photons are emitted.
- Scintillator material can be engineered to give off specific frequencies.

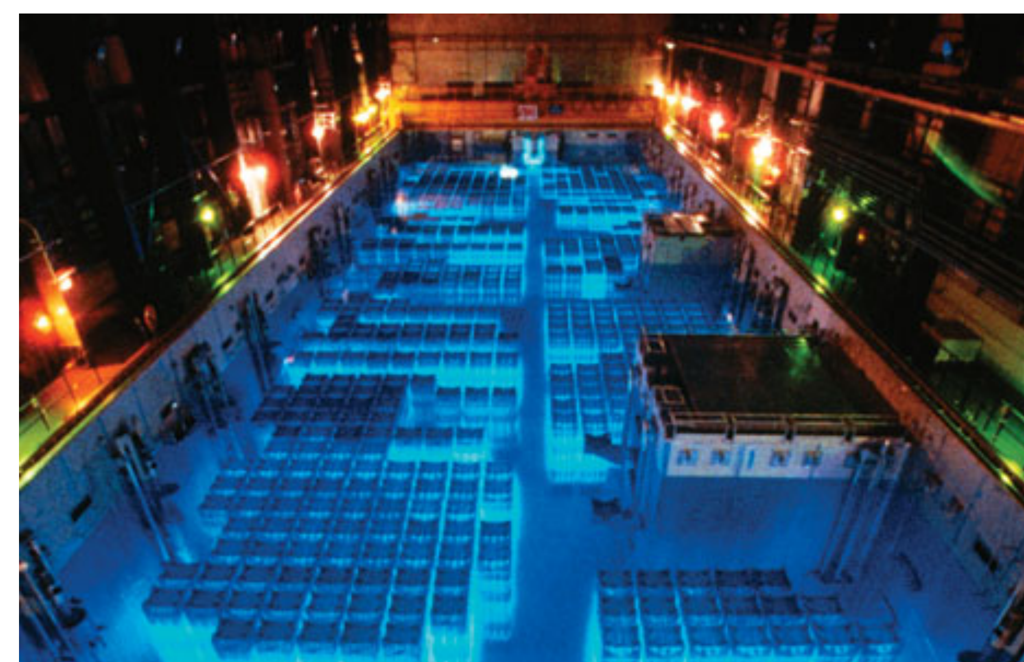
Light Production: Cerenkov Light



Muon Signature in Super-Kamiokande



- Particles traveling faster than light in a medium (**Note**: This doesn't violate relativity!) produce a "sonic boom" of light.
- Light is produced at a characteristic angle, **determined by velocity**, in a cone around the instigating particle.
- In a nuclear reactor pool, the intensity of this light can be used to measure the rate of fission.

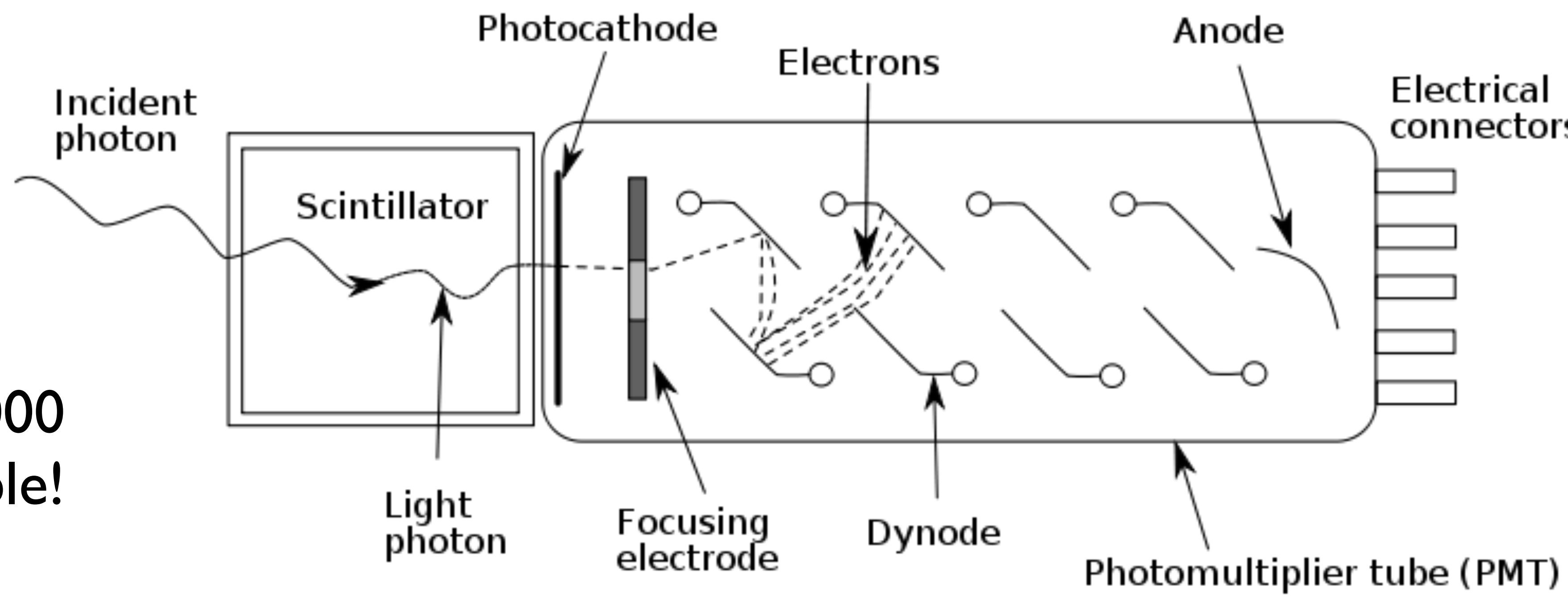


Reactor Pool

Photomultiplier Tubes: "Flashlights in Reverse"

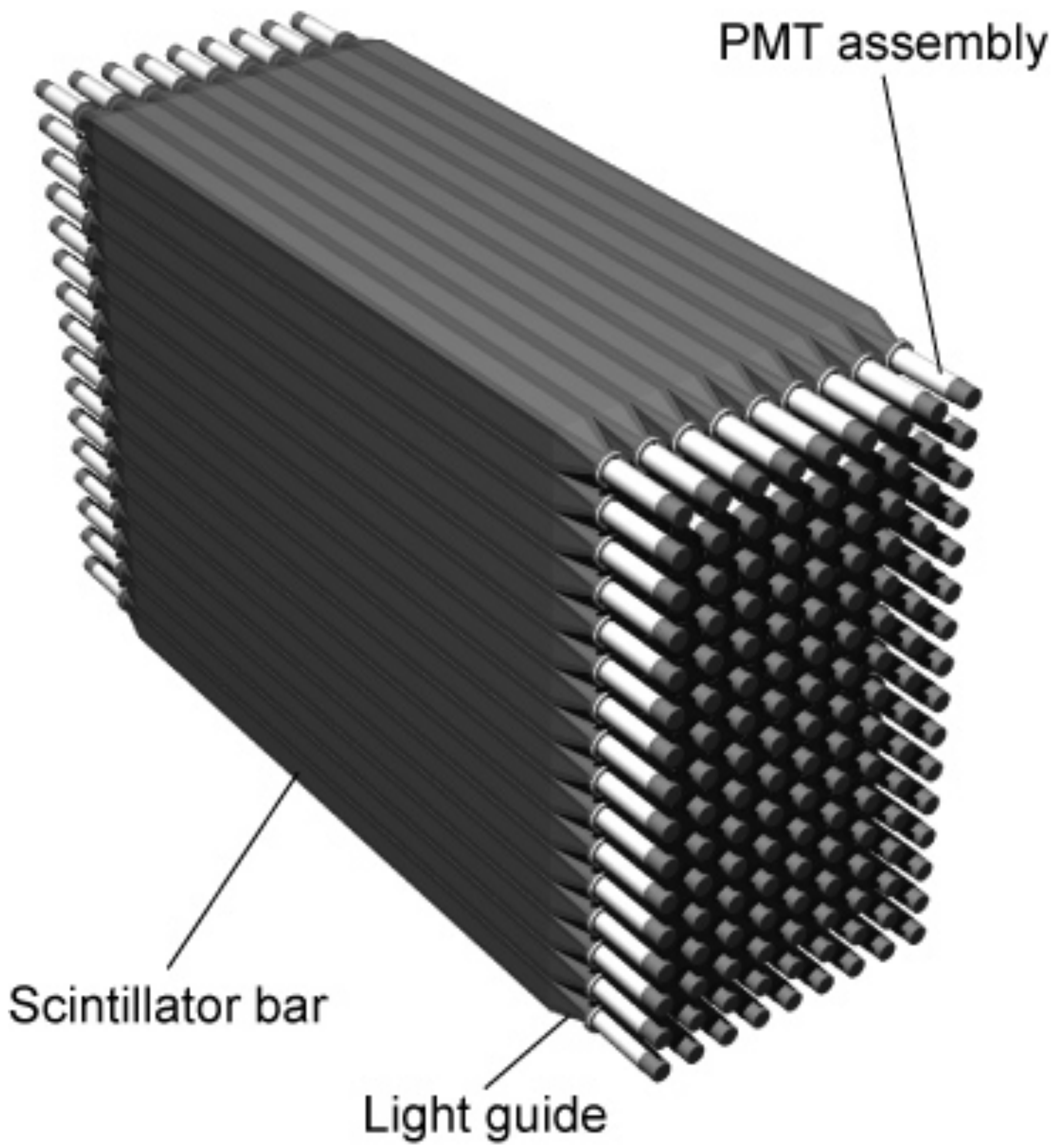
- Flashlight: Turn electrical current into light.
- PMT: Turn light into electrical current...using the Photoelectric Effect.

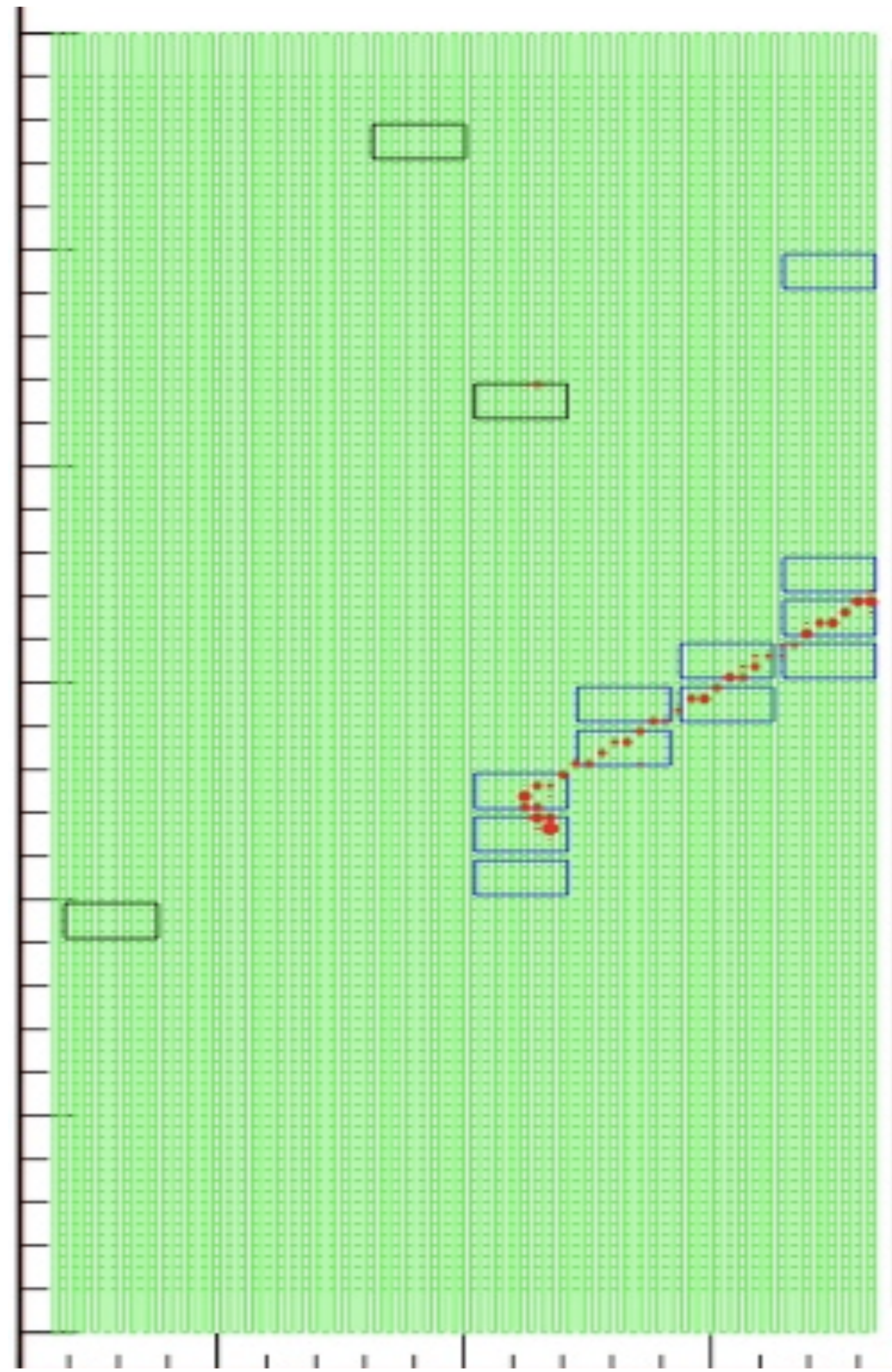
Gains of x100,000,0000 are achievable!



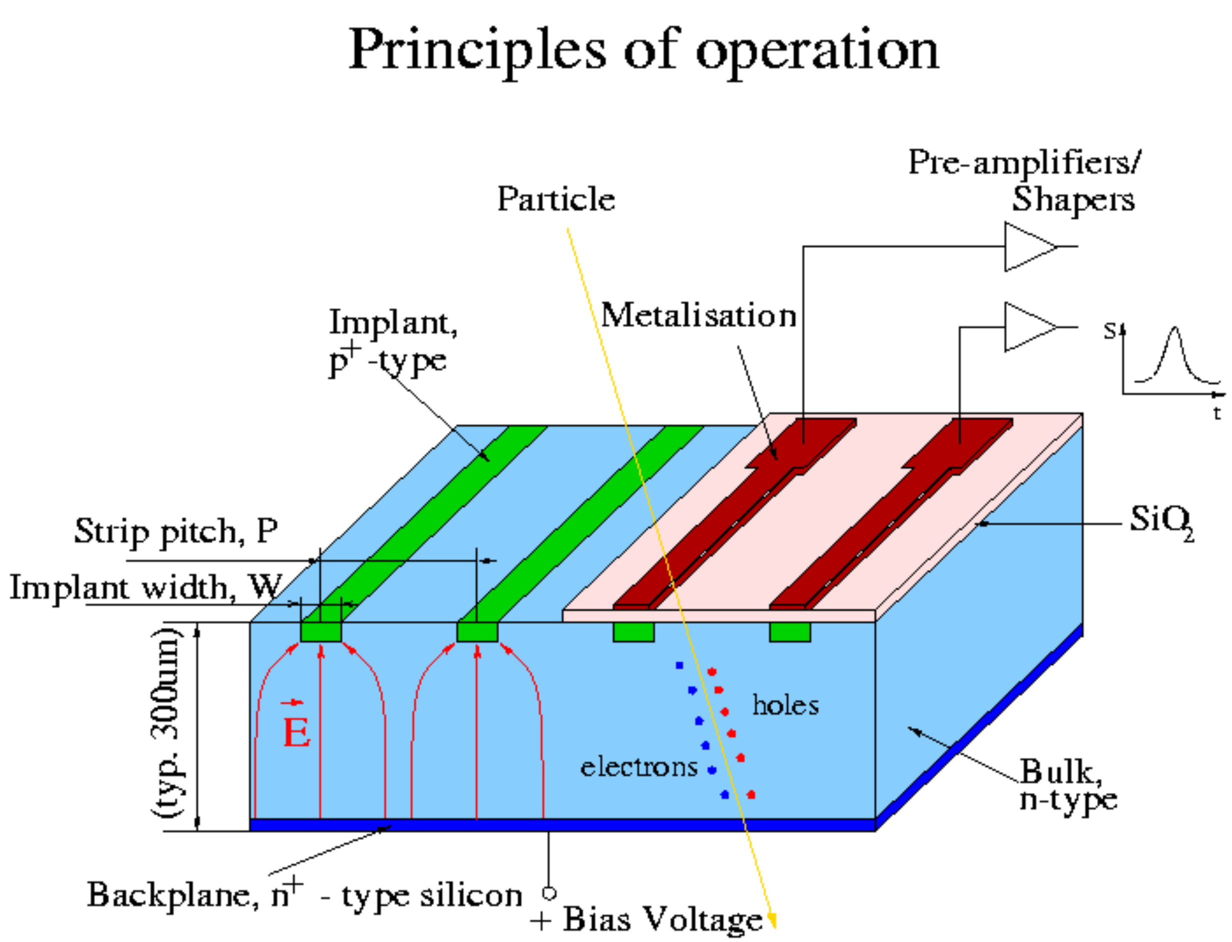
PMTs come in a wide variety of shapes/sizes.

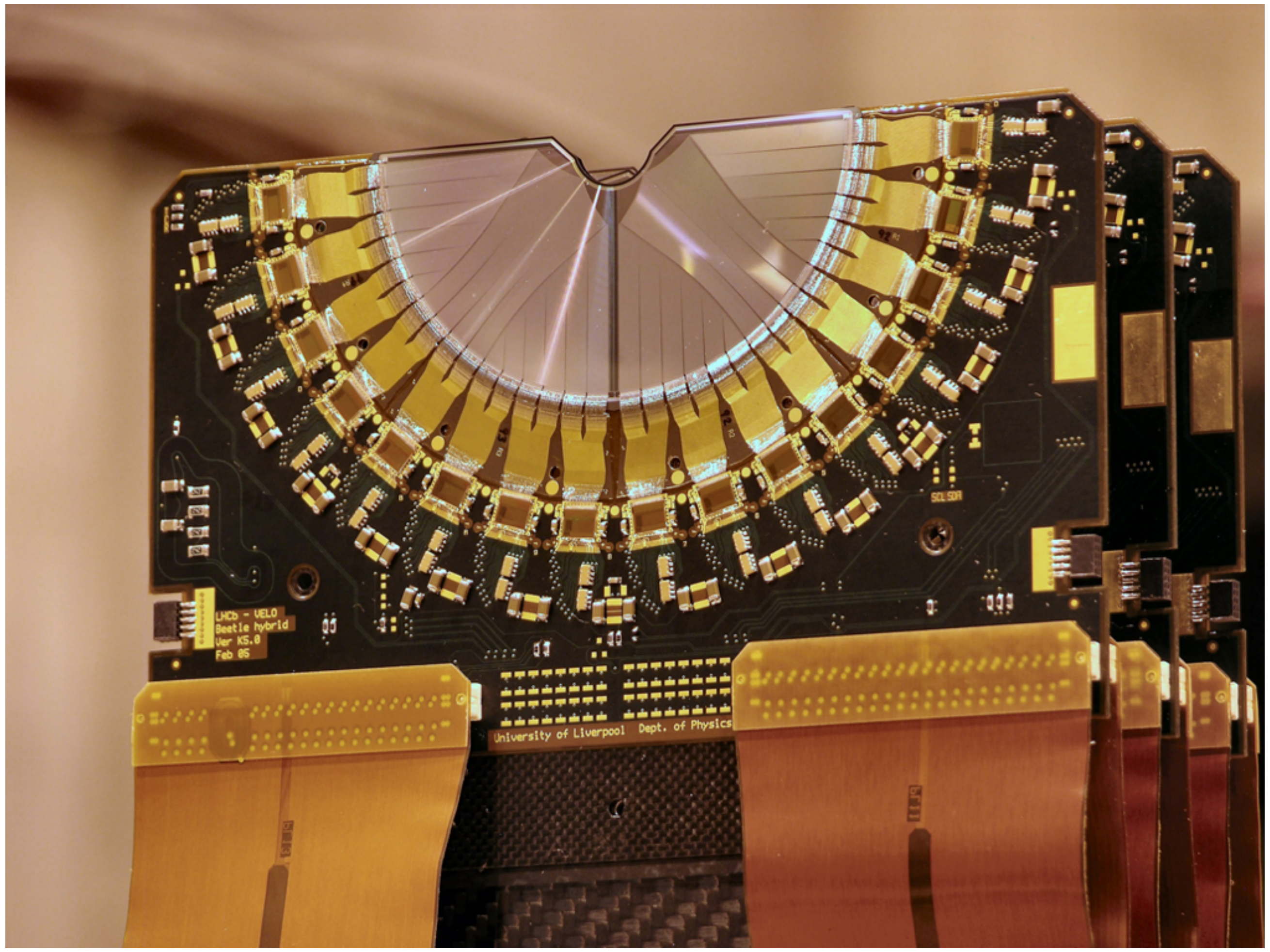
Example: Combine Scintillator and PMTs to make a Tracking Detector

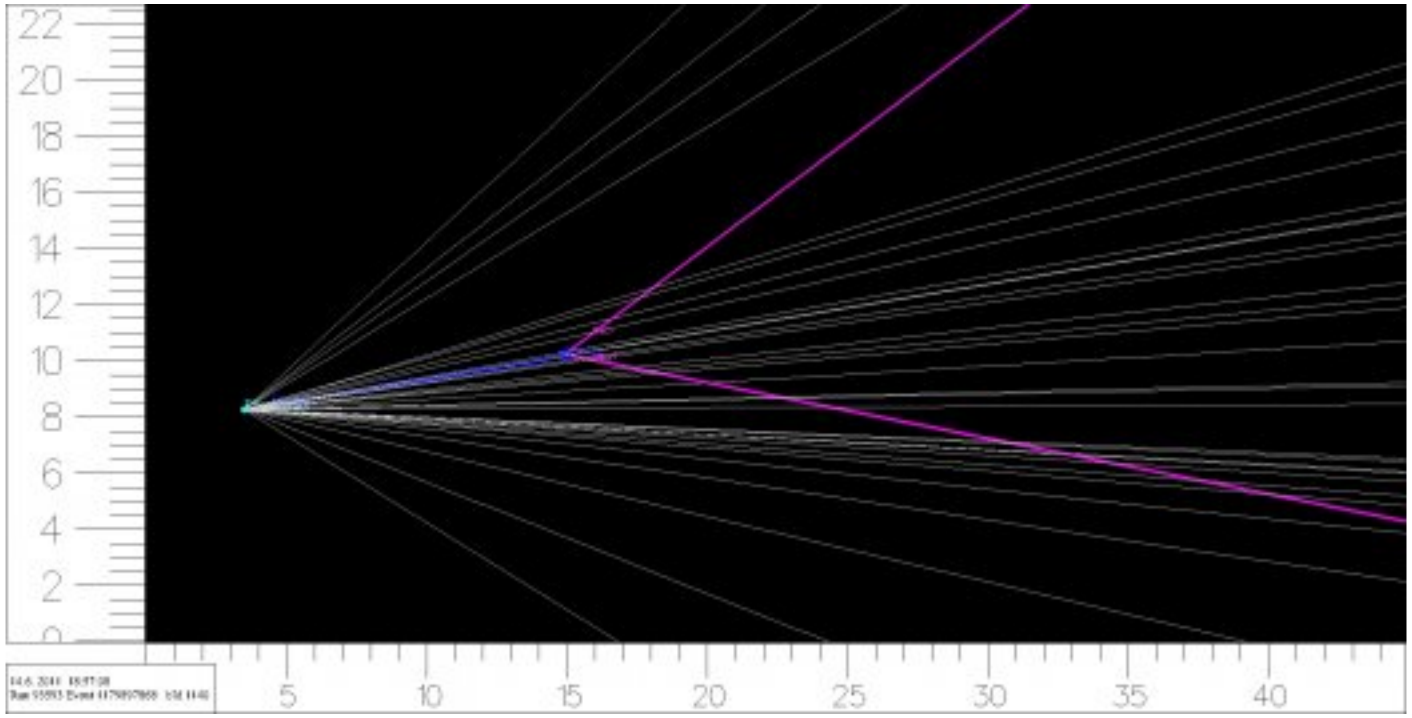




Semiconductor Detectors: Exquisite Precision

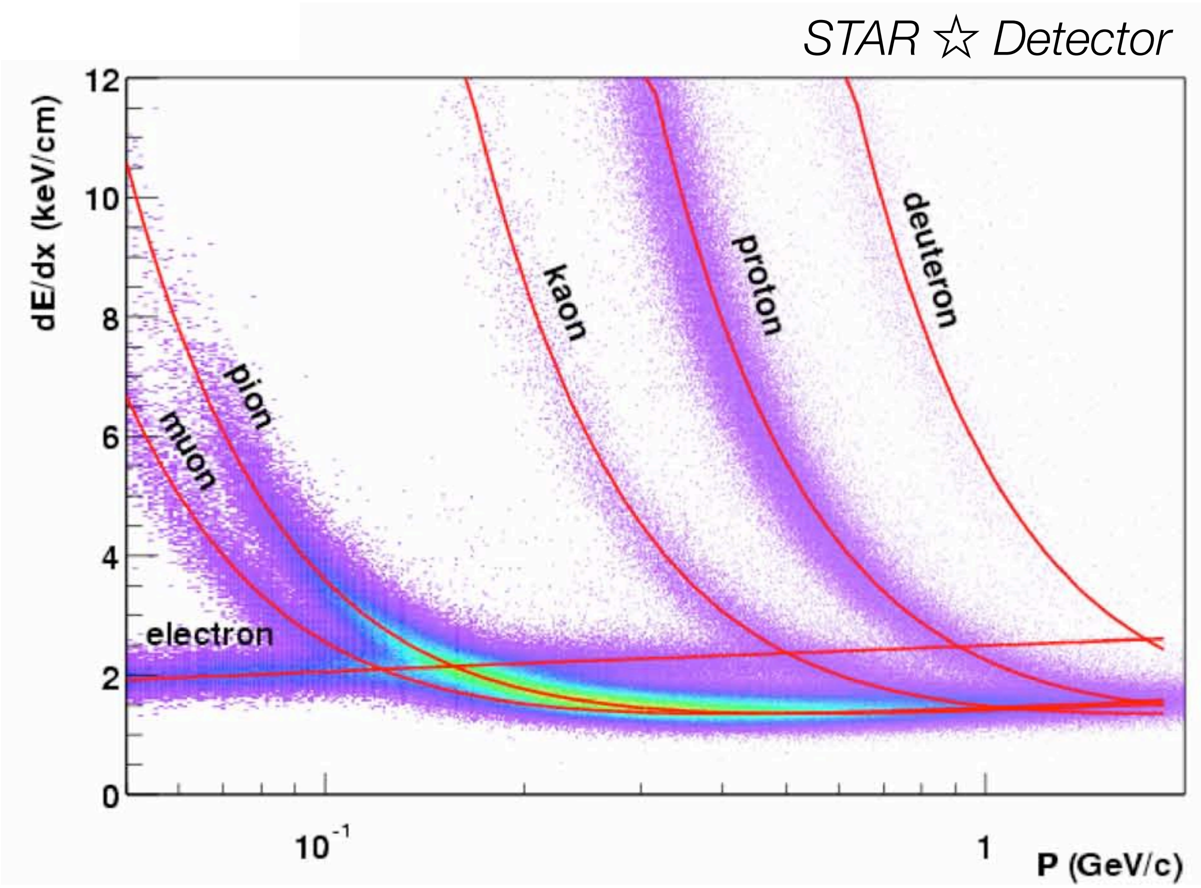




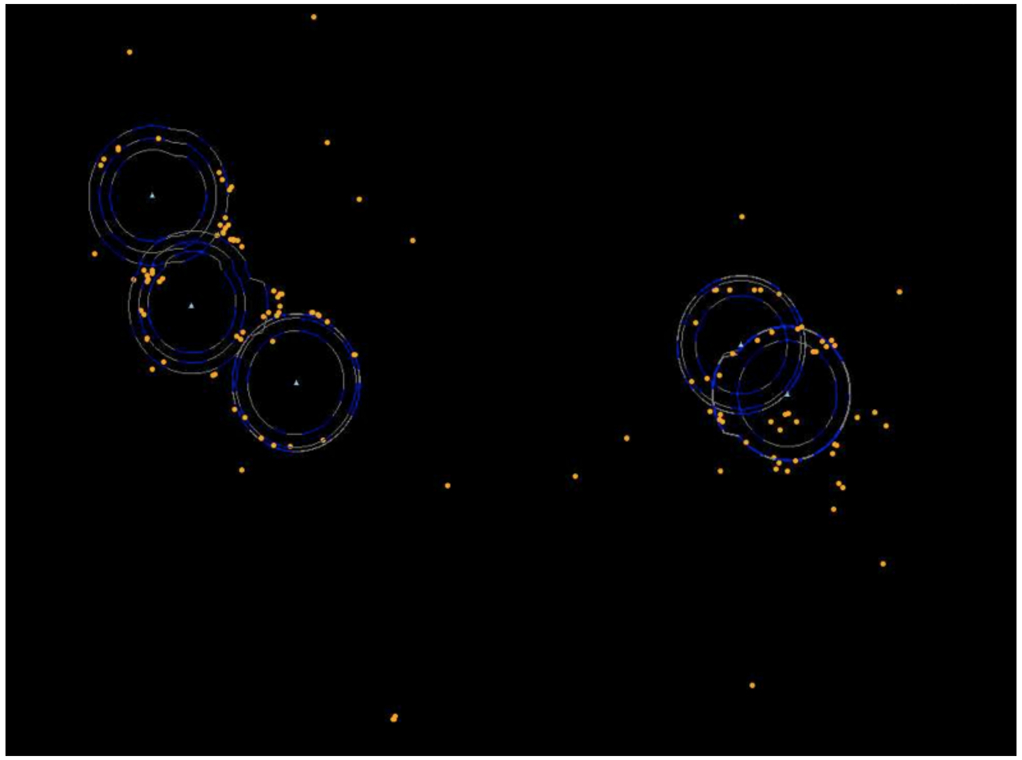


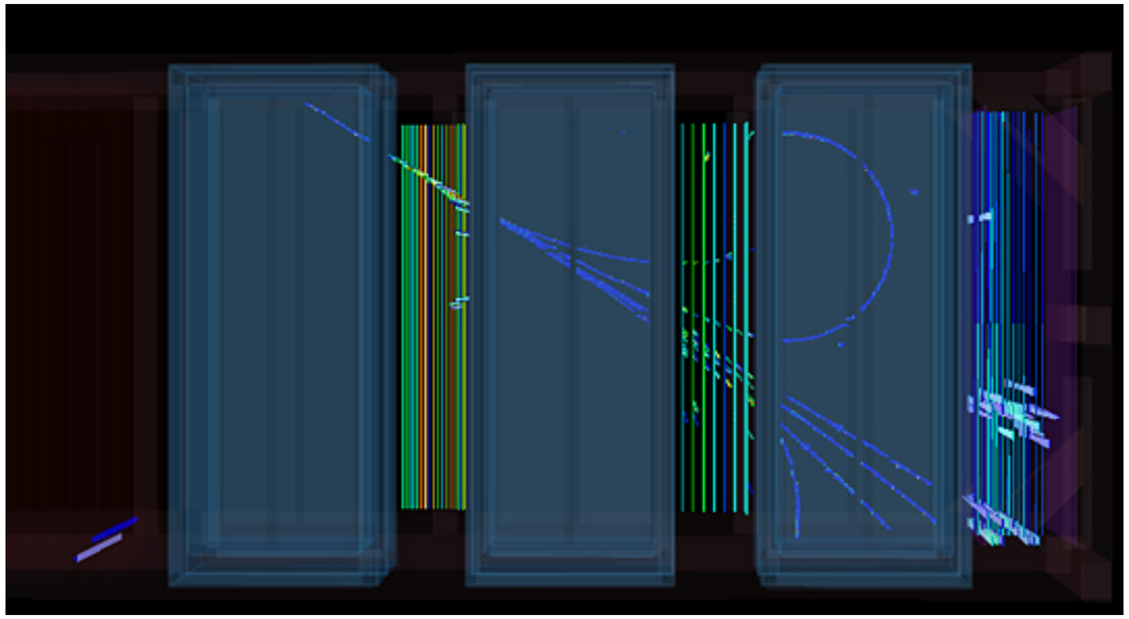
- Particles passing through a semiconductor create electron/hole pairs.
- The electrons or holes can be collected on electrodes that are connected to readout electronics.
- These detectors can provide much finer resolution than wire chambers due to the density of channels that are achievable with modern semiconductor fabrication.

Use all possible detector tools to identify the particle properties.

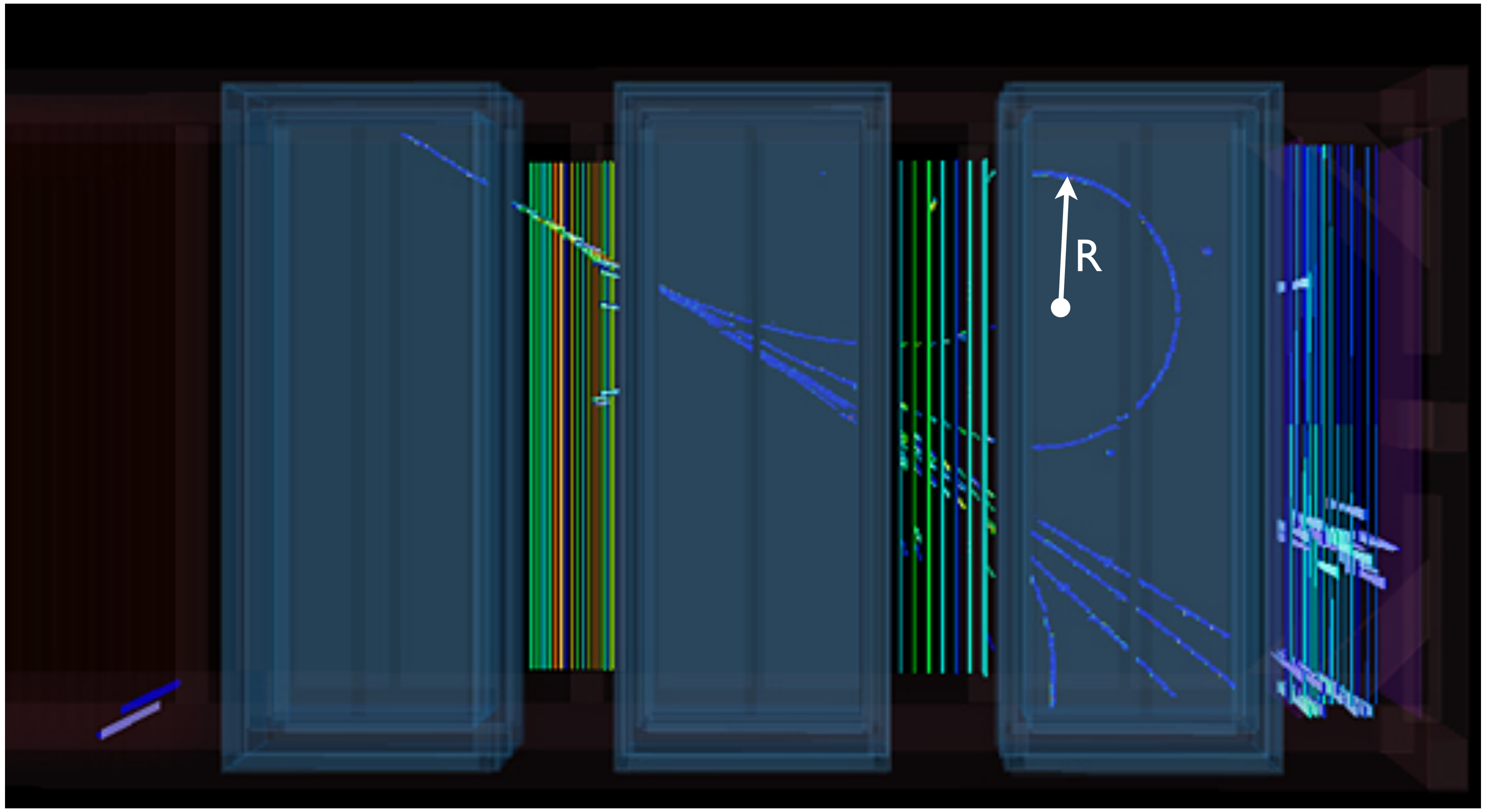


Particles often have a unique signature that lets us identify them.





Example of Particle ID

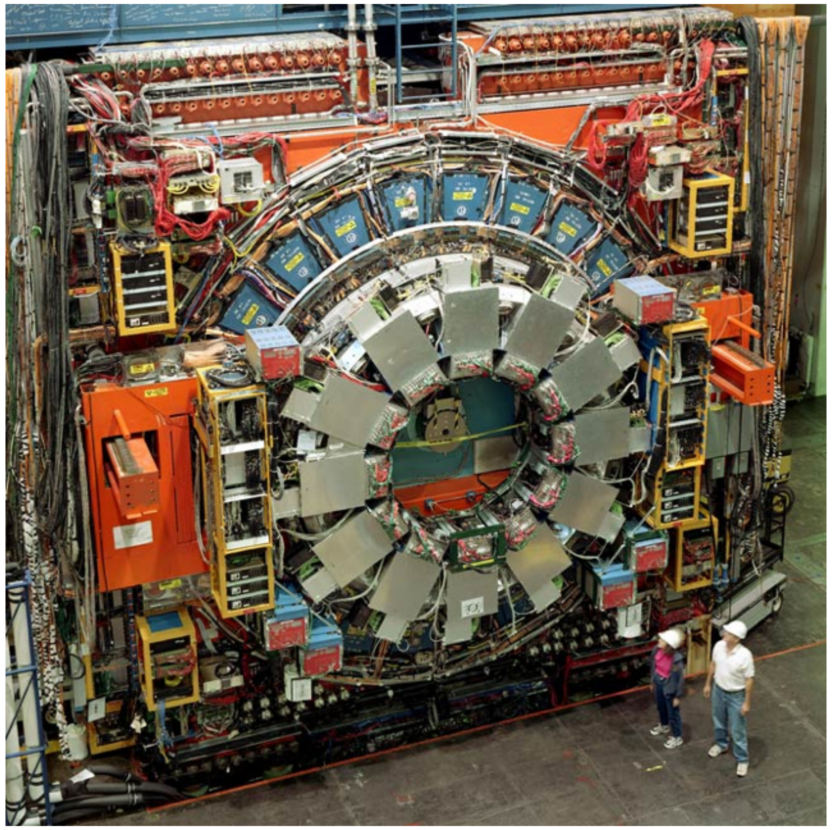


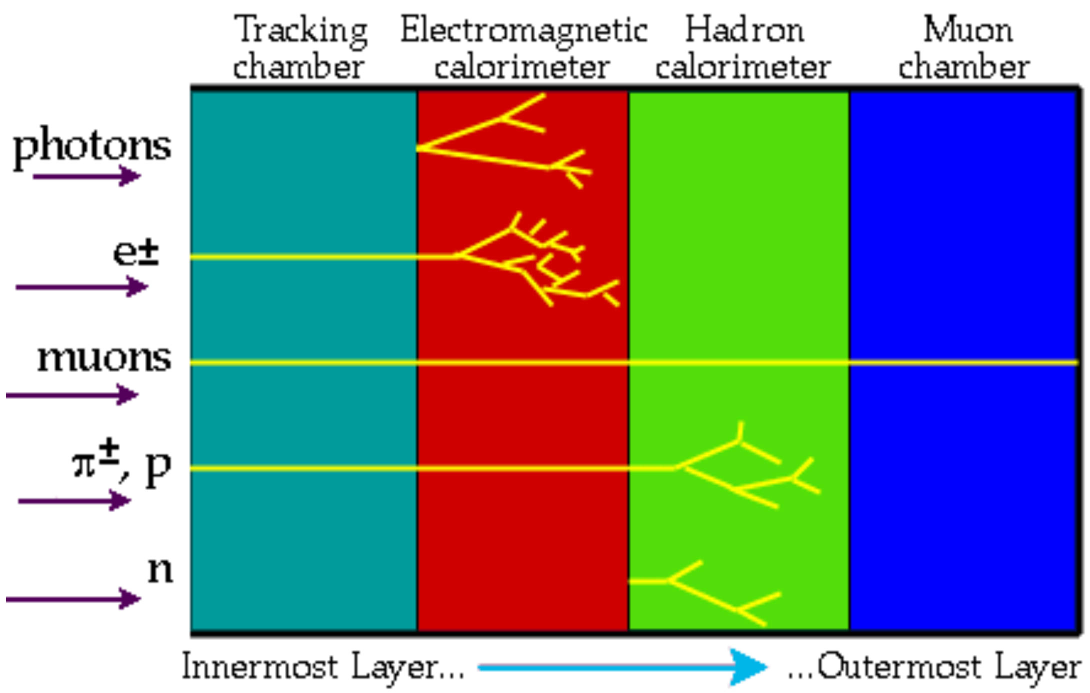
Bending in a Magnetic Field Gives Momentum:

$p=qBR$ ← Where from?

If we can combine magnetic-field tracker (to determine "p"), with Cherenkov detector (to determine "v"), we can ID particles unambiguously via $p=\gamma m_0 v$ relation.

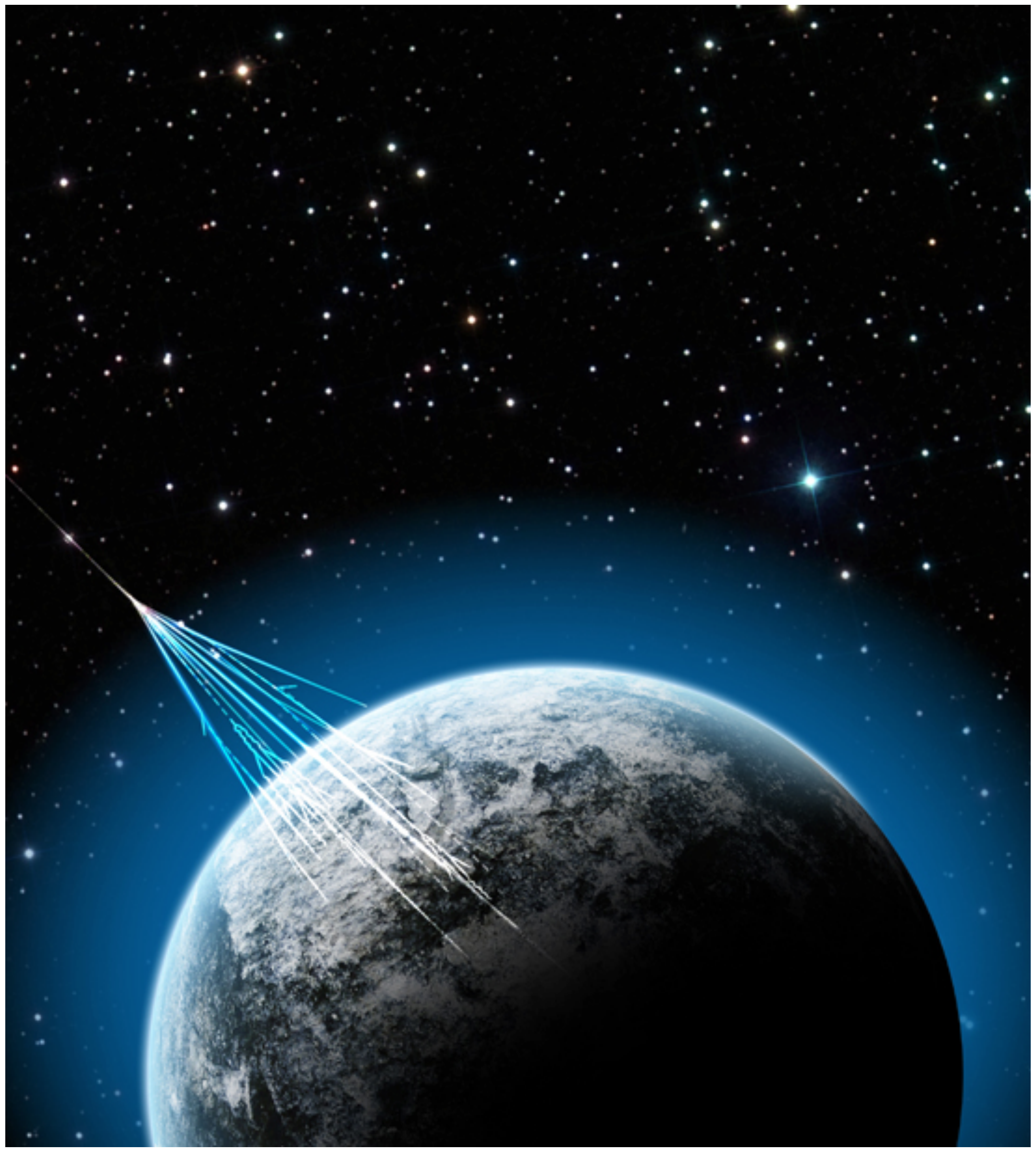
Use all possible detector tools to identify the particle properties.





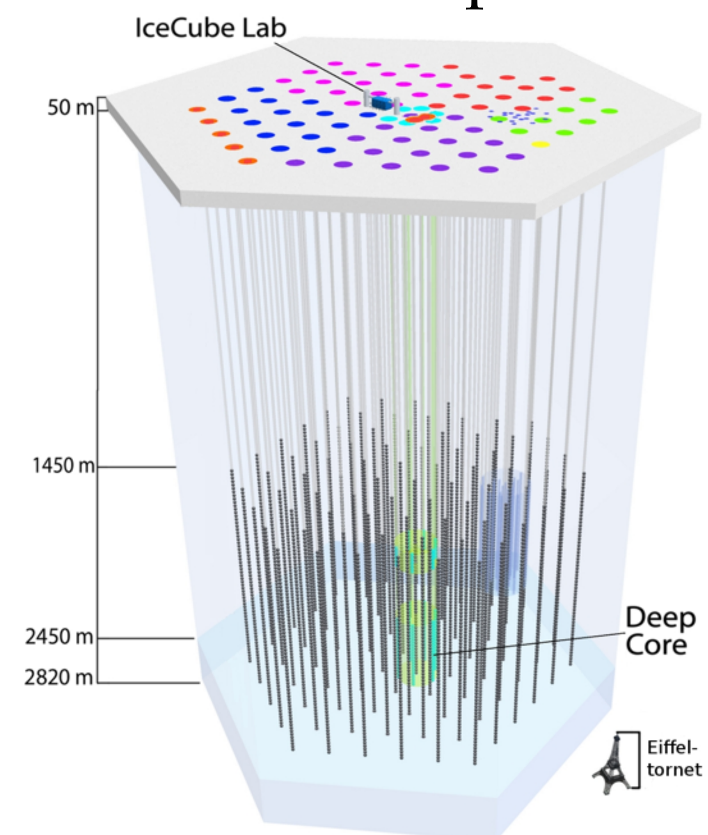
Modern Experiments are like Onions...lots of layers.

Try to find a nice quiet place to do your experiment!

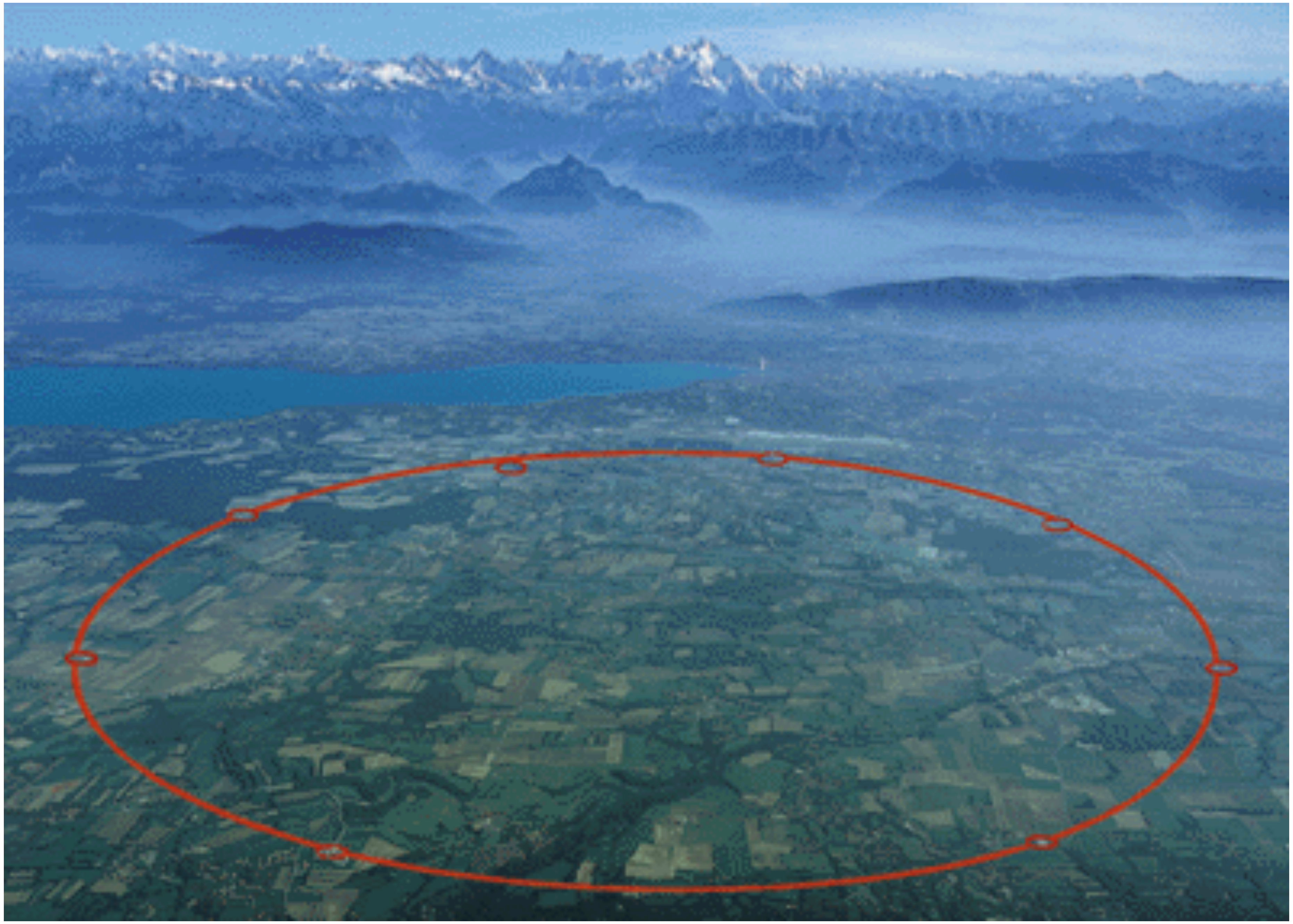


Cosmic-Rays

IceCube Experiment



South Pole



Questions?