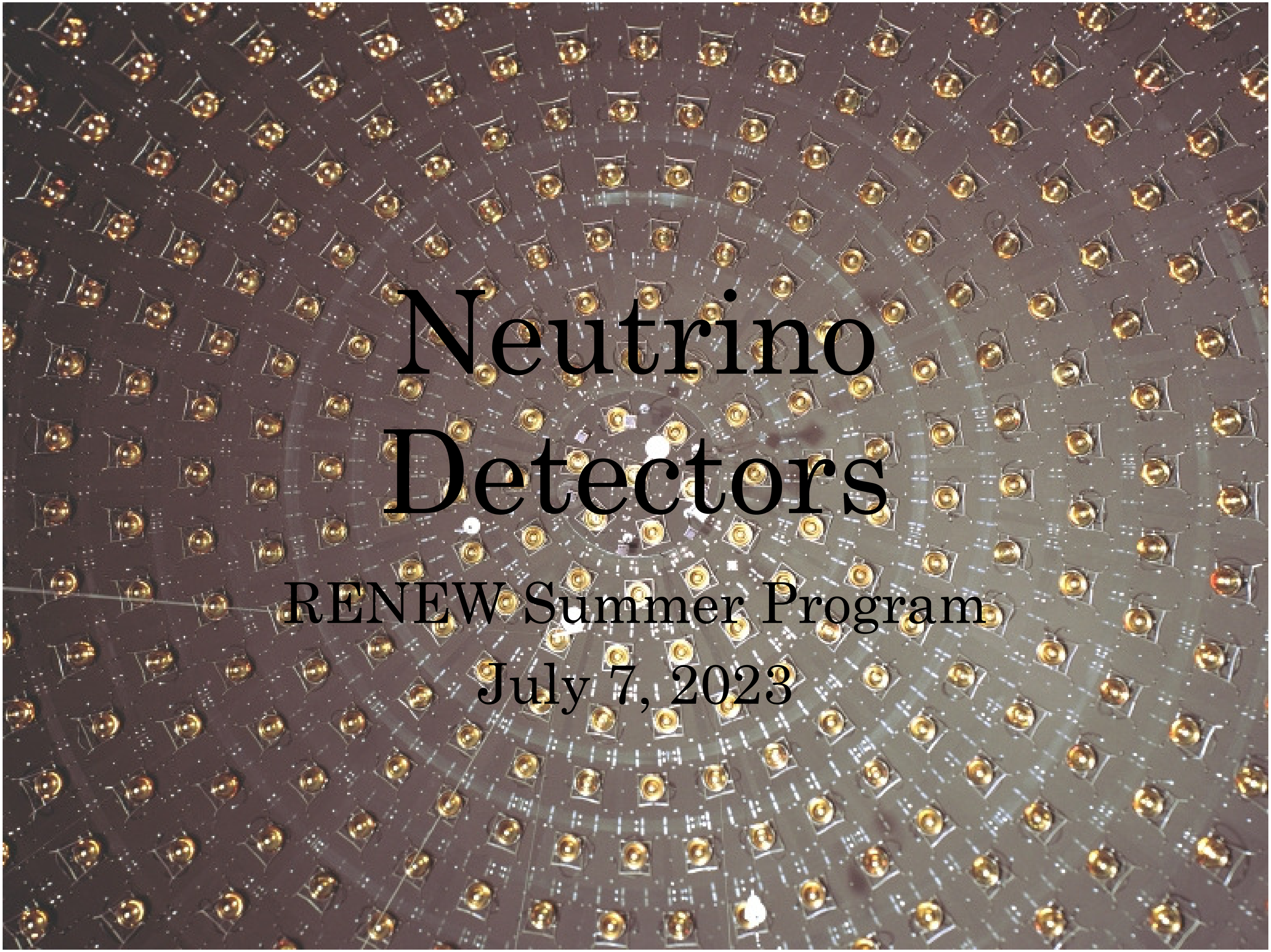
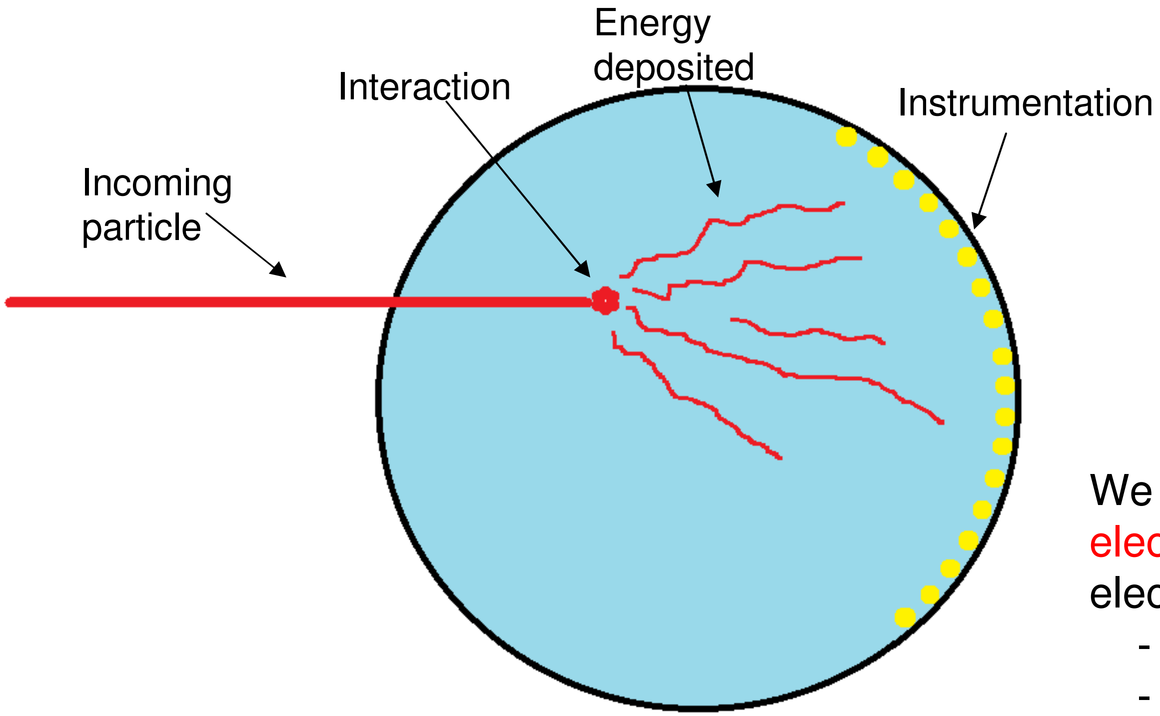


Neutrino Detectors

RENEW Summer Program

July 7, 2023

How do we detect particles?



We can only detect particles through their interactions.

Particle interacts with matter in detector

Loses some of its energy

We convert that deposited energy to electrical charge to read it out in our electronics:

- collect ionized electrons
- convert light to electric signal
- convert motion of atoms to signal

Every detector must have two things:

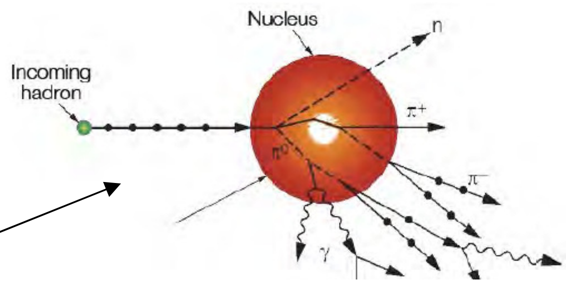
- TARGET (matter for the particle to interact with)
- INSTRUMENTATION (way to convert energy to electrical signals)

How do particles interact?

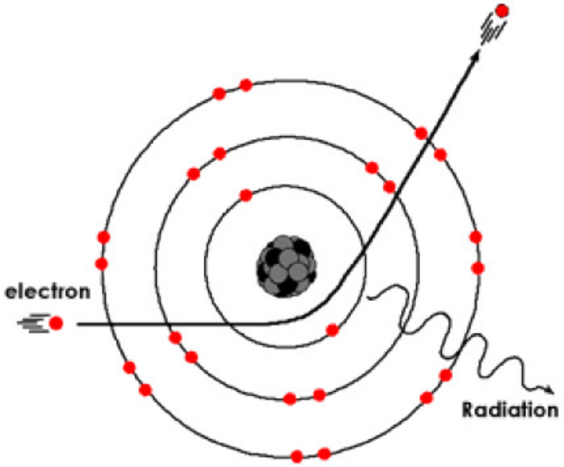
Interactions depend on particle type and energy

Four fundamental interactions (“forces”):

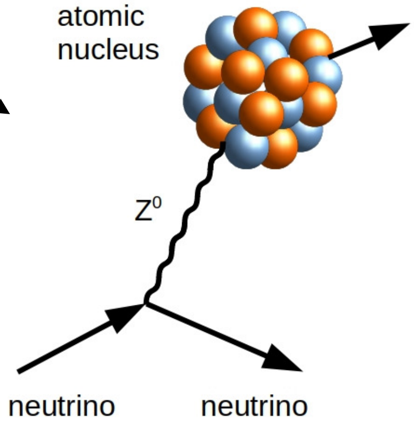
- Strong interactions – only affects hadrons (e.g. protons, neutrons), short-range



- Electromagnetic – affects all charged particles, most common interaction in detectors, only one that we directly detect



- Weak interactions – happen rarely, but only interaction of neutrinos



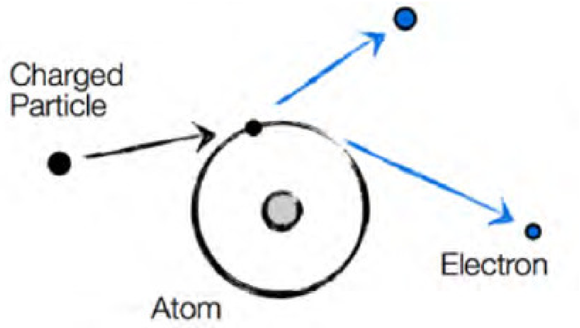
- Gravity – much too weak for particles

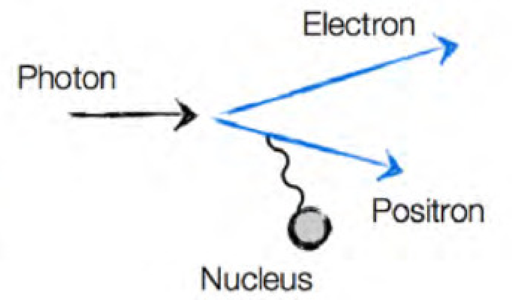
Charged Particles

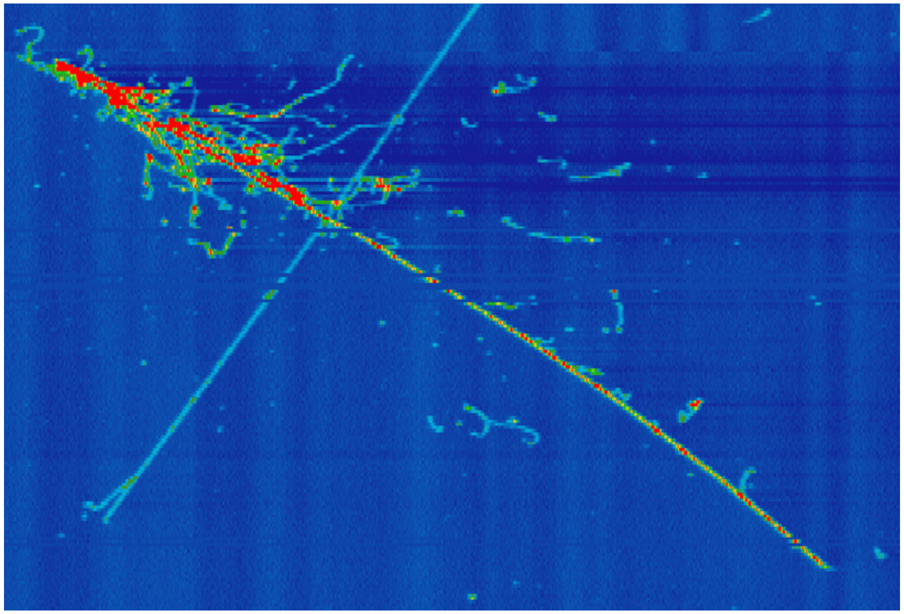
A charged particle passing through matter is almost constantly interacting

Charged particle interactions include:
Ionization: knocks electrons out of atoms
Scintillation: produces photons
Bremsstrahlung: produces photons

Photon interactions include:
Compton scattering: recoil with electron
Pair production: produces electron, positron
Photoelectric effect: knocks electrons out of atoms







MicroBooNE event

Rate and mode of energy loss depend on the particle’s mass and energy

Threshold = energy a particle needs to produce a signal in the detector

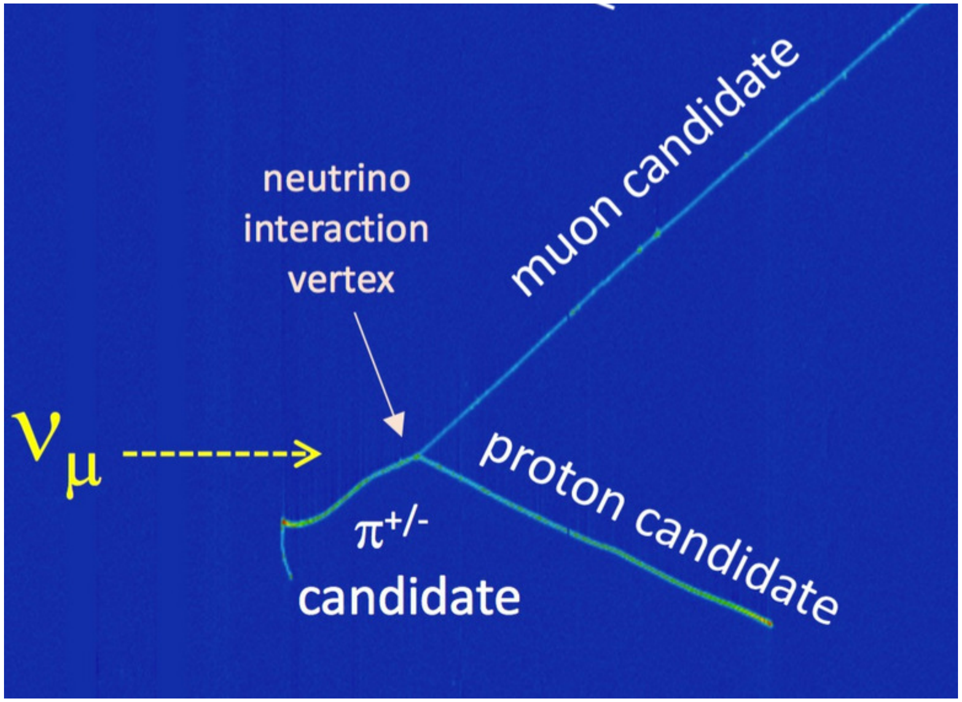
What about neutrinos?

What about neutrinos?

Neutrinos only interact weakly – most pass through detector without interacting

A small fraction of them will “collide” with an electron or nucleus and deposit some or all of their energy in the detector.

Neutrinos can only be detected by the products of their interactions



MicroBooNE event

Total energy is conserved

If we can record *all* of the deposited energy, we can reconstruct the energy of the neutrino.

Cross Sections and Event Rates

How many neutrino events will we get in our detector?

Depends on: target volume and density, number of neutrinos passing through, and "cross-section" for the interaction

events = flux * cross-section * number of targets * time
= flux * cross-section * volume * density * time
= 1/(s * cm^2) * cm^2 * cm^3 * 1/(cm^3) * s = number

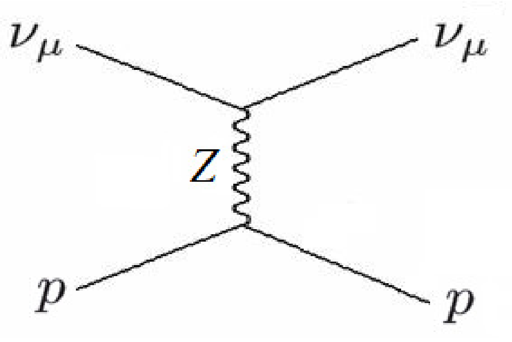
Cross-section is a measure of how likely an interaction is. If the particles were solid balls, the cross-section really is the physical cross-section.

For particles, cross-section depends on the types of particles involved and the energy of the incoming particle.

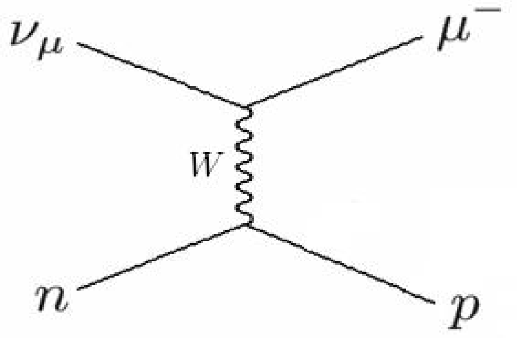
To detect as many events as possible, want maximize volume of target, density of the target, and length of time the detector is running.

Neutrino interactions: charged current vs. neutral current

Unlike electromagnetism, the weak interaction is mediated by both charged (W) and uncharged (Z) bosons.



Neutral current: neutrino exchanges a Z (uncharged) with another particle, gives that particle some of its energy



Charged current: neutrino exchanges a W (charged) with another particle, converts neutrino into charged lepton and changes charge of other particle correspondingly

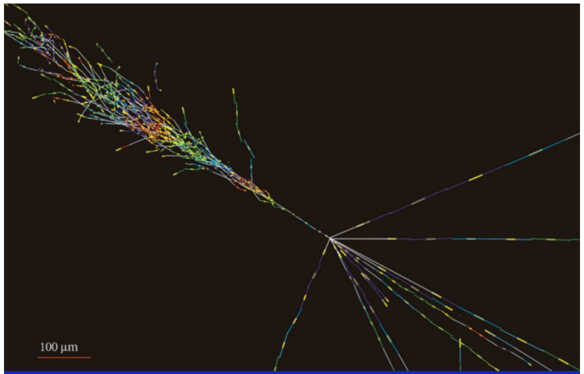
Electrons, muons, and taus

Three flavors of charged lepton: electron (e), muon (μ), tau lepton (τ)

All have charge -1, but different masses, lifetimes → different signatures

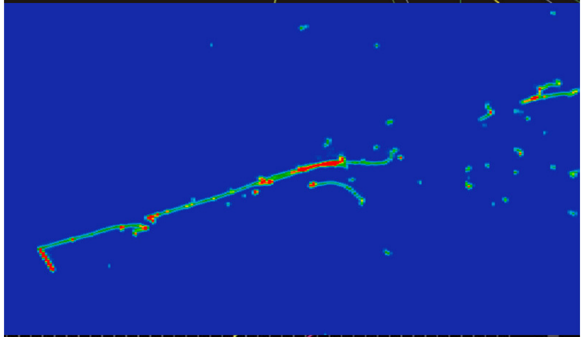
Electron: mass ~ 500 keV
stable

Produce photons through bremsstrahlung → photons produce electrons/positrons through pair production → . . .



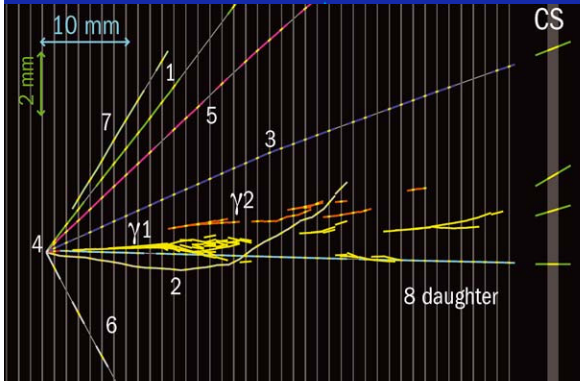
Muon: mass ~ 100 MeV,
lifetime ~ 10^-6 s.

More massive, so harder to deflect → less bremsstrahlung, long straight track



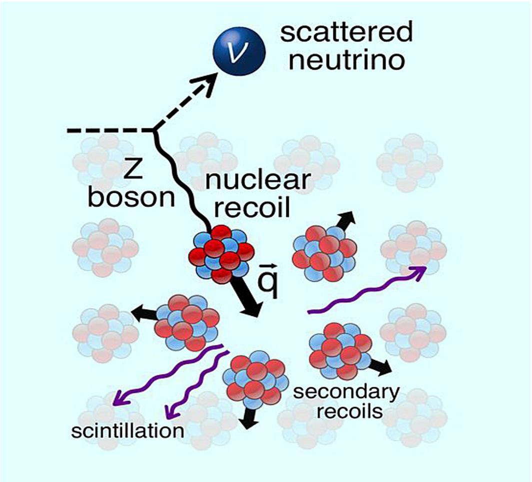
Tau: mass ~ 1 GeV
lifetime ~10^-13 s.

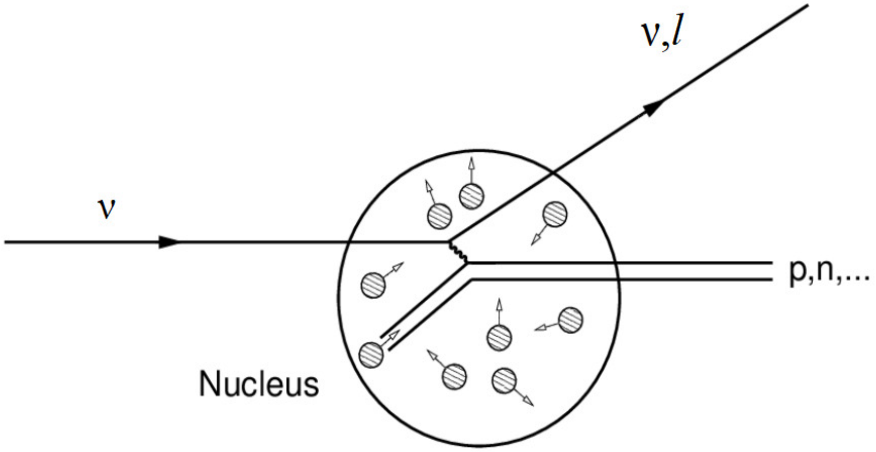
Decays before travelling very far – have to identify by products it decays to



Neutrino interactions at different energies

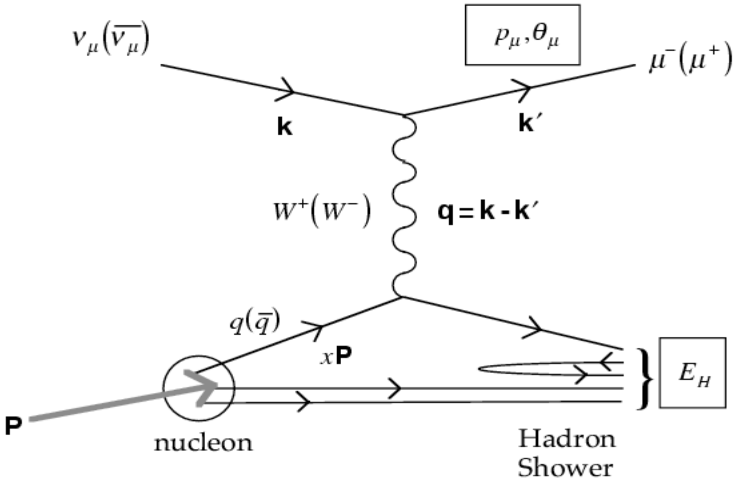
Low energies (~MeV): interaction with nucleus. Nuclear recoil or excitation of nucleus





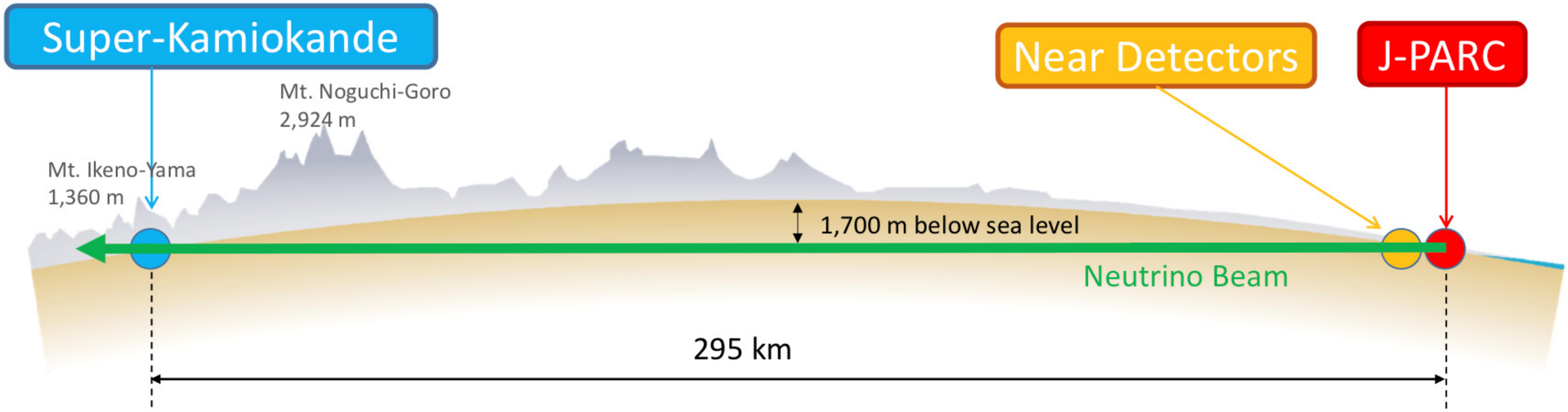
Intermediate energies (~GeV): interaction with a proton or neutron. Enough energy to kick a proton or neutron out of the nucleus and maybe produce a few additional particles.

High energies (many GeV): interaction with a proton or neutron. Enough energy to create many new particles (deep inelastic scattering).



Example: Looking for ν_e in a ν_μ beam

Typical oscillation experiment: Start with beam of ν_μ and look for ν_e at detector



Identify electron neutrino charged current quasi-elastic events, $\nu_e + n \rightarrow e + p$, as events with one electron shower, one proton

Efficiency: # of ν_e CCQE events in sample / total # of ν_e CCQE events

Purity: # of ν_e CCQE events in sample / total # of events in sample

Backgrounds

Other things can deposit energy in our detector!

- cosmic rays
- radioactive emissions from materials in detector
- radioactive emissions from materials outside detector
- interactions outside detector, with products that enter detector
- . . .

Sometimes these will have similar signature to signal events

Strategy:

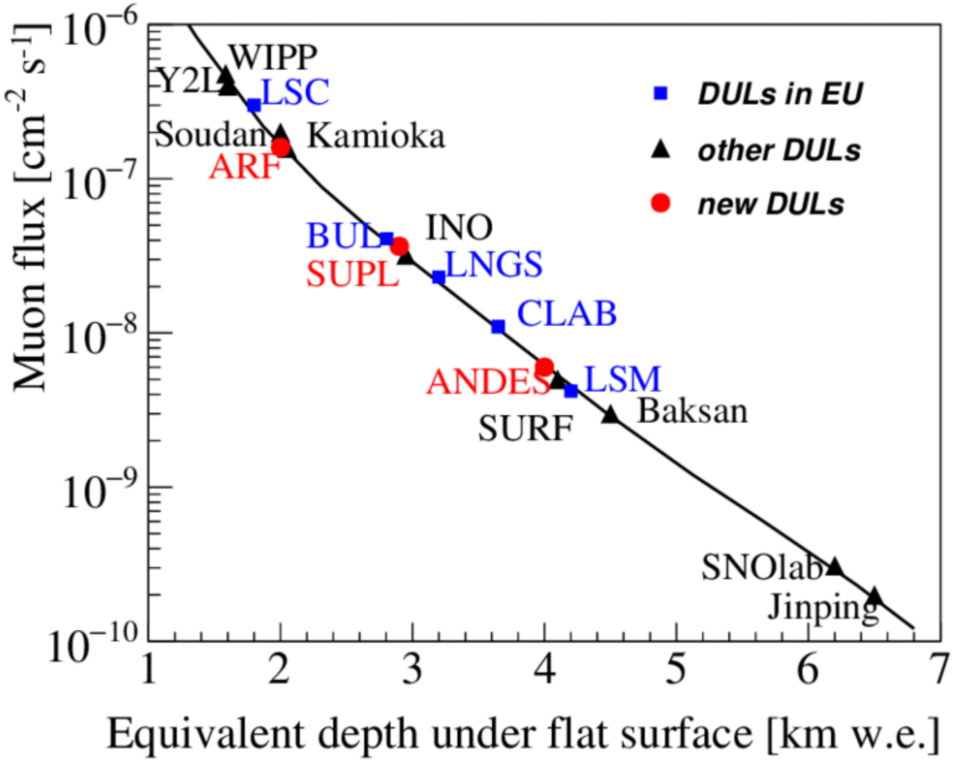
1. Prevent backgrounds
   - Use radiopure materials
   - Shield detector
   - Go deep underground
2. Identify background events
   - Apply cuts to data to remove backgrounds.
   - Need to know what backgrounds look like, what signal looks like
   - Cuts are never perfect – characterize with efficiency and purity
3. Model backgrounds
   - Determine how many background events will make it past cuts (simulation)
   - Look for statistically significant excess of events above expected background

Cosmic Ray Backgrounds

Cosmic rays are high energy particles (mostly protons and atomic nuclei) produced by supernovae, the sun, and other sources

Produce showers of high energy particles in atmosphere, including neutrinos and muons

Muons travel far and can penetrate deep into the ground



Reduce muon flux with overburden or by going underground.

About 1 muon per cm^2 per minute at surface, average energy ~few MeV

This is a lot if you’re looking for a rare process!

Underground, this can be reduced by many orders of magnitude

Some neutrino detector technologies

Type	**Target**	**Density (g/cm^3)**	**Signal**	**Comments**
Water Čerenkov	H_20	1.0	Čerenkov light	Can be huge
Liquid Scintillator	$\sim CH_2$	~0.9	Scintillation light	Low energy threshold
Plastic scintillator	$\sim CH_2$	~0.9	Scintillation light	Segmented
Steel planes	Fe	~7.8	Scintillation / Calorimeter	Magnetized
Liquid Nobles	Ar, Xe, Ne	1.4, 3.1, 0.9	Charge / scintillation	Very fine-grained
Radiochemical	Ga, C_2Cl_4, In	Varies	Induced radioactivity	Extremely low threshold
Water-based scintillator	H_20 (+ CH_2)	1.0	Čerenkov and scintillation	Can be huge, low threshold

Čerenkov radiation

Produced when a charged particle travels faster than the speed of light in a material

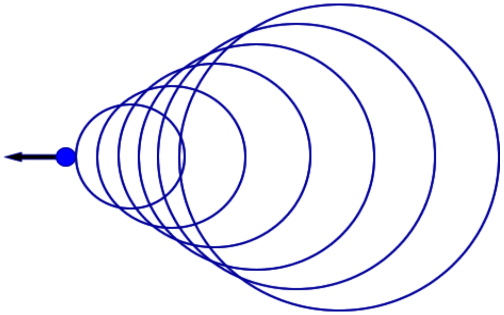
Question: What happens when something travels faster than the speed of sound?

Čerenkov radiation

Produced when a charged particle travels faster than the speed of light in a material

Question: What happens when something travels faster than the speed of sound?

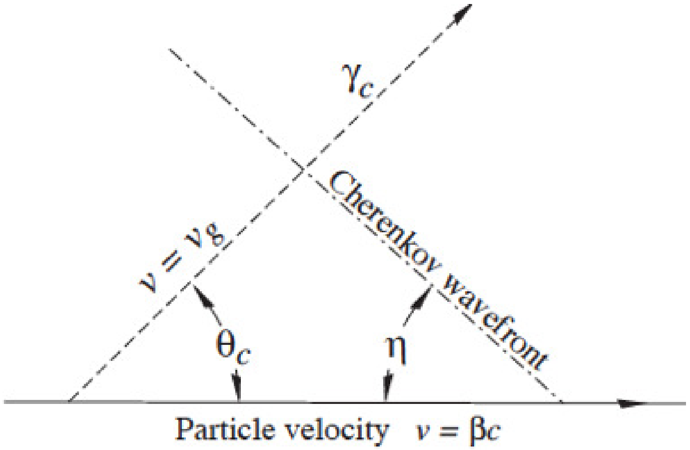
A sonic boom! Čerenkov radiation is the equivalent for light.



Critical energy depends on particle mass:

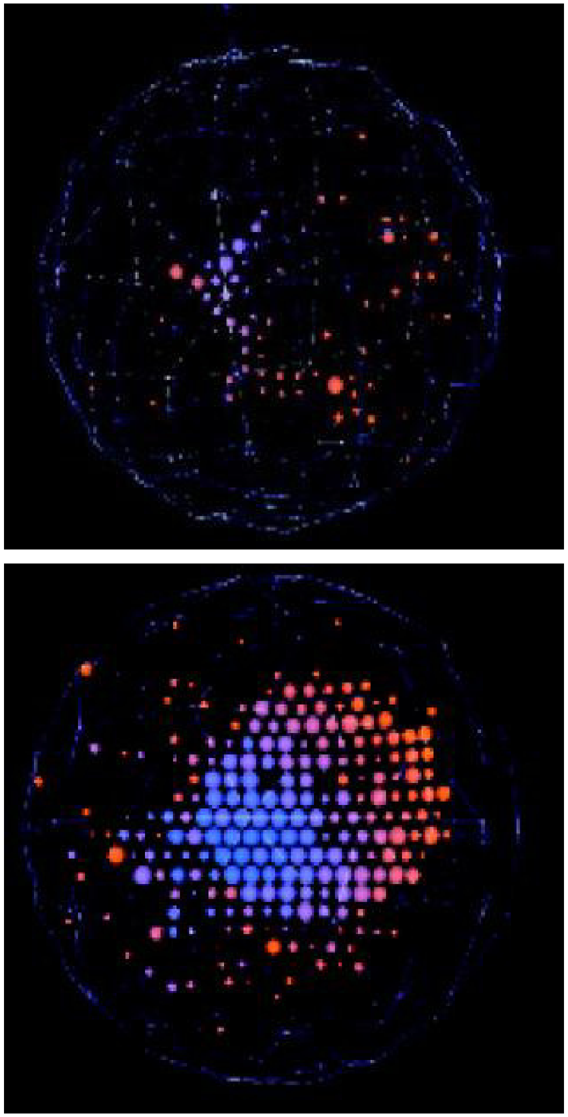
In water:
Electron: 0.58 MeV/c
Muon: 120.5 MeV/c
Pion: 159.2 MeV/c
Proton: 1070.0 MeV/c

Light cone with characteristic angle $\cos\theta_c = (1/n\beta)$



Particle signatures in Čerenkov detectors

Electron:	Scatters multiple times and stops after travelling a short distance.	→	Thin, fuzzy ring
Muon:	Little deflection; long, straight track	→	Sharp, possibly filled-in ring
Proton:	Čerenkov threshold is generally much higher	→	Usually can’t see



Electron (top) and muon (bottom) events in MiniBooNE

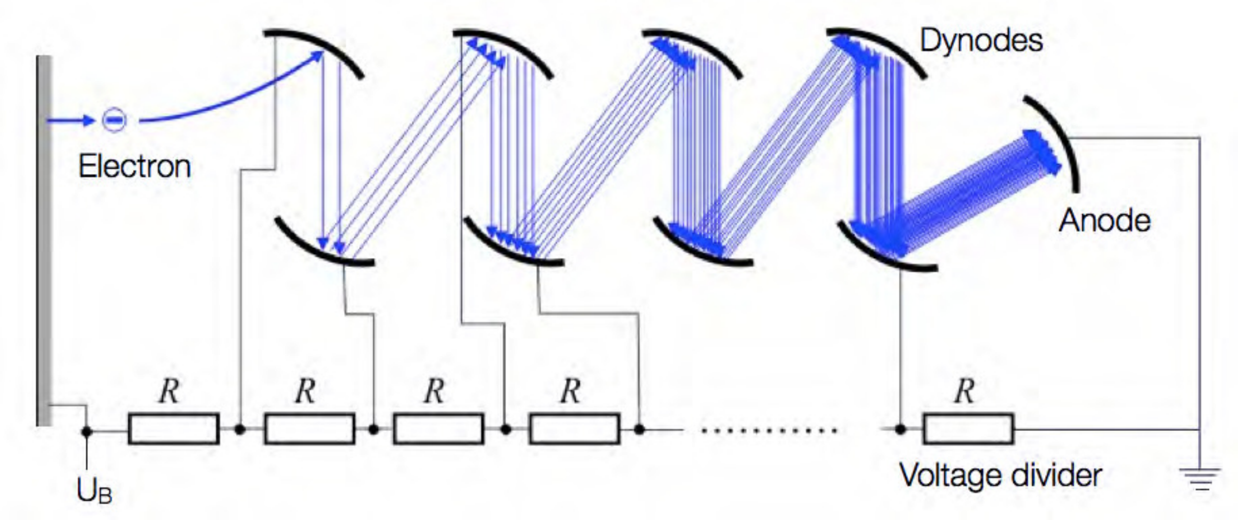
Light detection: Photomultiplier Tubes

Photoelectric effect: photon absorbed by photocathode and knocks an electron out

Electric field accelerates electron to first dynode, produces secondary electrons

Typical gain of $10^6 – 10^8$. Produces a signal proportional to the number of incoming photons

Requires voltage > 1000 V for amplification

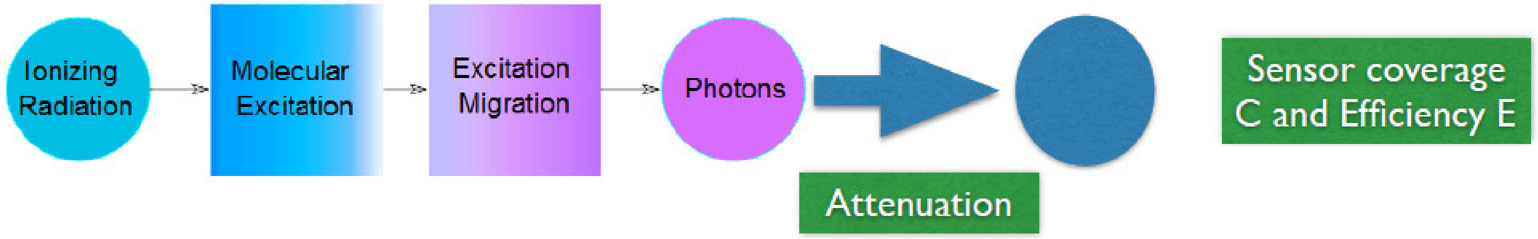


Limitations:

- Can be bulky
- Only sensitive to a range of wavelengths
- Efficiency of ~30%
- Efficiency lower in magnetic field

Other options like silicon photomultipliers exist

Scintillators



Ionizing Radiation

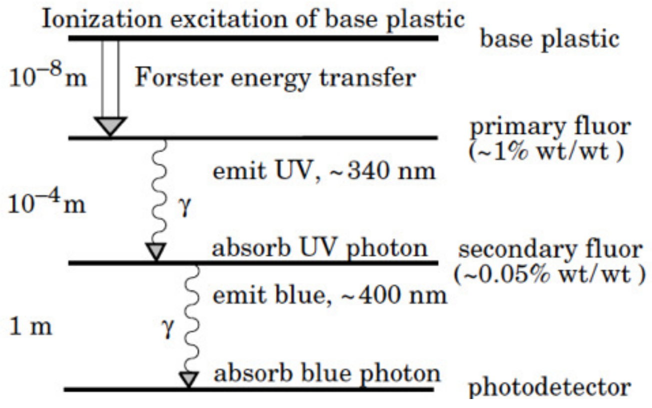
Molecular Excitation

Excitation Migration

Photons

Attenuation

Sensor coverage C and Efficiency E



Deposited energy ends up putting atoms / molecules in excited states

When they return to ground state, emit photons

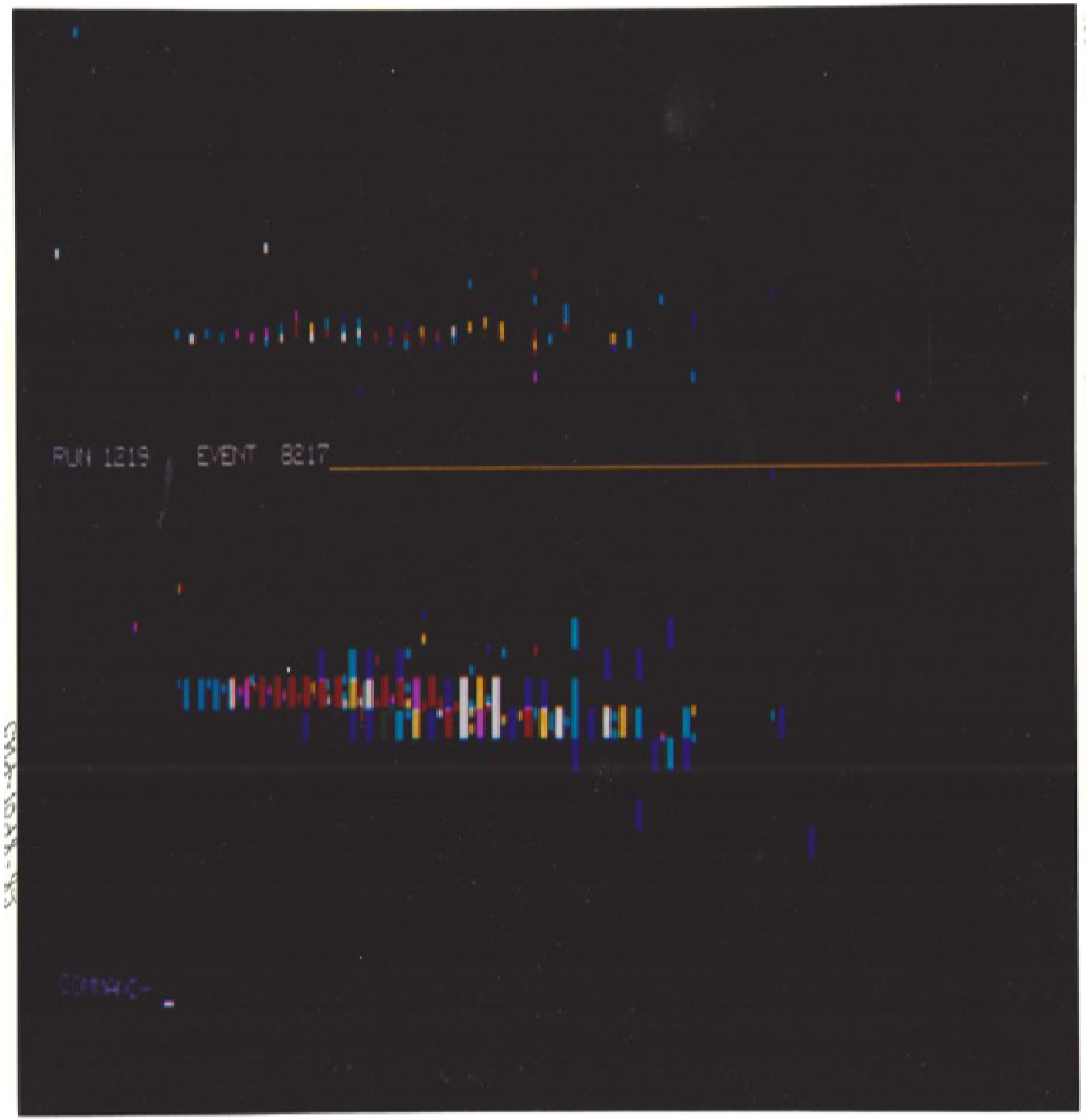
Amount of light produced, wavelengths, and time it takes for this to happen depend on material

Good scintillators: high light yield, detectable wavelengths, fast times

Organic scintillators and liquid nobles are used for neutrino physics.

Idea: Add some scintillator to a water-based detector – detect both Čerenkov and scintillation light!

Scintillators



Drawback to scintillator detectors: limited directional, positional information

If we want to see tracks, we can make a segmented detector

Many detector modules, each with its own instrumentation

Modules must be optically isolated

Left: Electromagnetic shower from E734 experiment in 1986.

Ionization detectors

Basic idea: ionization produces electrons. What if we could directly capture those electrons, creating an electrical signal?

One way of doing this is a time projection chamber (TPC)

Electric field is applied to the chamber

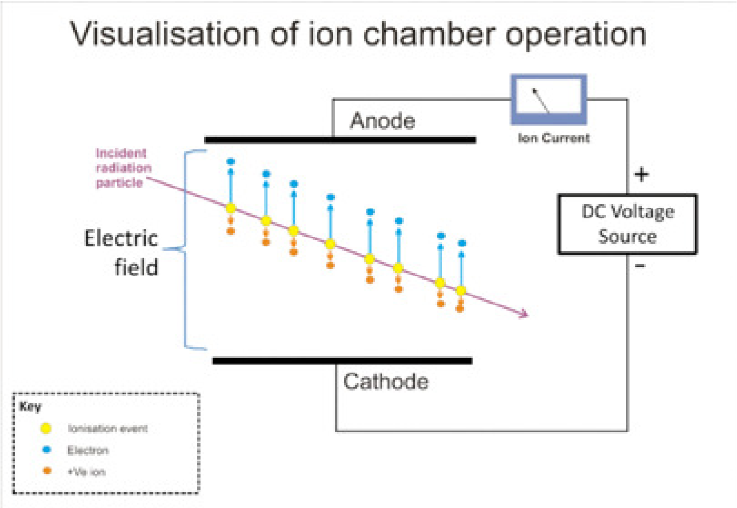
Field makes ionized electrons drift to the anode

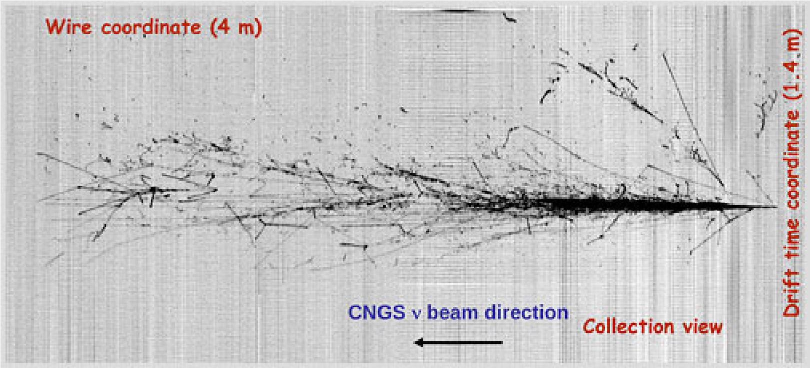
Wires or pixels of anode collect electrons → create electrical signal

x-y position determined from location on the anode

z position determined by timing of signal

Can produce very fine-grained track readouts





ICARUS event

Noble Liquid TPCs

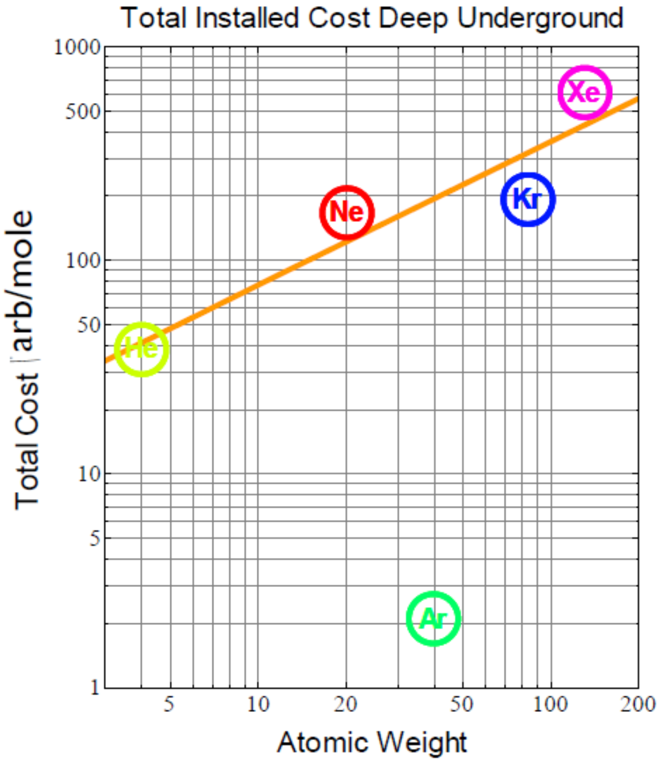
What target to use for TPCs?

We want: high density, low cost, transparent to electrons

Noble liquids are a good option!

Also produce scintillation light – can use both signals

Cryogenic – presents some challenges



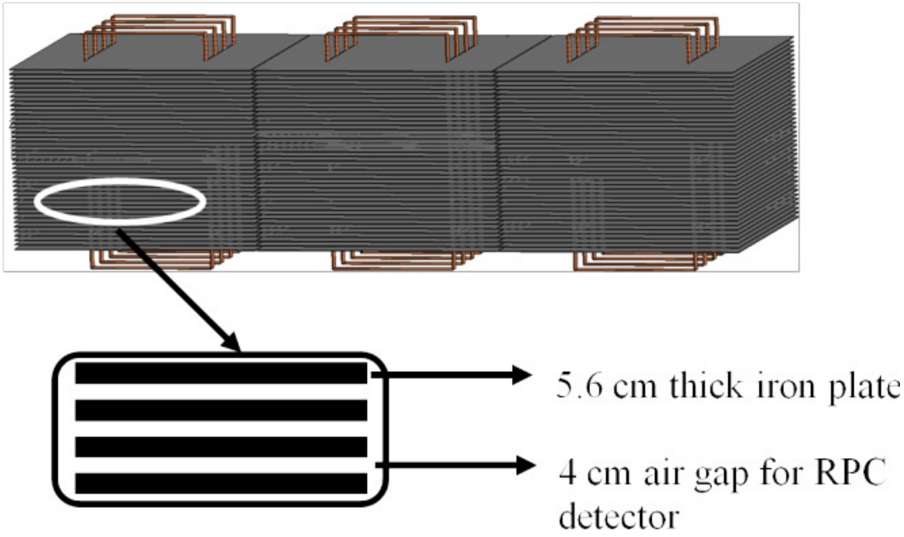
Element	In air (ppm)	Boiling point (K)	Atomic weight	Comments
He	5.2	4.2	4	Not practical
Ne	18	27	20	Could be used as “control” in Dark Matter searches
Ar	9300	87	40	Best option for most applications
Kr	1.14	120	84	Radioactive – problem with backgrounds
Xe	0.086	165	131	Used in some Dark Matter searches

Magnetized Steel Plates

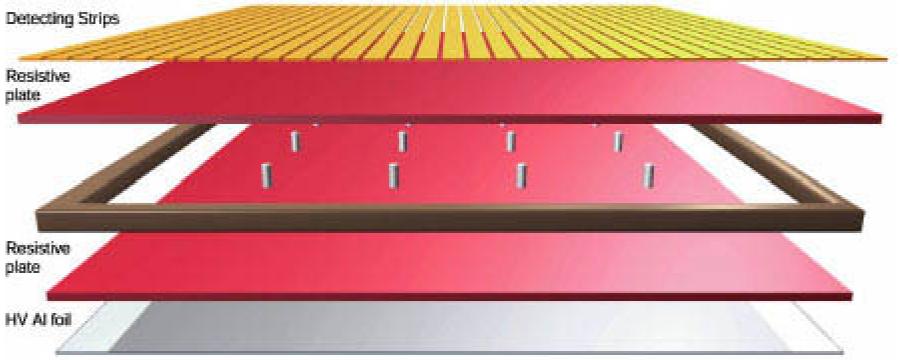
If we want a high target density, why not use some very dense material, like a metal?

Problem: metals are opaque to light, electrons. How do we collect the signal?

Solution: Use plates of steel with detectors between them.



INO detector



Example: Resistive Plate Chambers (RCPs)

Parallel resistive plates, cathode and anode, with thin layer of gas between

Ionized electrons collected on strips

Each RCP gives a snapshot of particle trajectories

Magnetic Spectrometers

Applying a magnetic field lets us: a) distinguish positive and negative particles, b) measure the momentum (and thus energy) of a particle

This can help us reconstruct the energy of the neutrino, even if the products are not fully contained – especially helpful for muons!

Magnetic force $F = qvB$

This is a centripetal force – recall:

$r = mv^2/F = mv/qB$

$r = s/\theta \approx L/\theta$

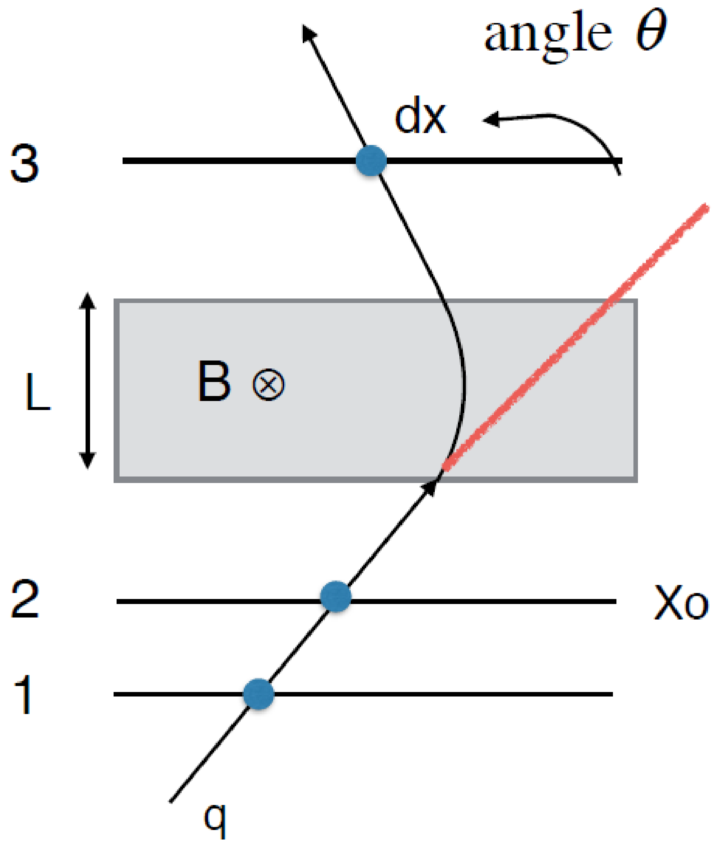
So $v \approx LqB/m\theta$

E.g. say a muon ($m = 106$ MeV/c^2) in a 1 T magnetic field with $L = 4$ cm is deflected by

$\theta = 10° \approx 0.175$ rad.

We get $v \approx 172{,}000{,}000$ m/s

$E = \gamma mc^2 \approx 128$ MeV → KE ≈ 22 MeV



Magnetic spectrometers are a useful addition to any detector!

Conclusion

- I’ve focused on neutrino detectors, but many of these techniques are common to all particle detectors.

- Neutrinos are detected by the products of their interactions.

- Detector = Target + Instrumentation

- All detectors fundamentally detect charge or light (by converting it to charge)

- Considerations must be made for each application:
    - Energy threshold
    - Position and time resolution
    - Size and target mass
    - Backgrounds