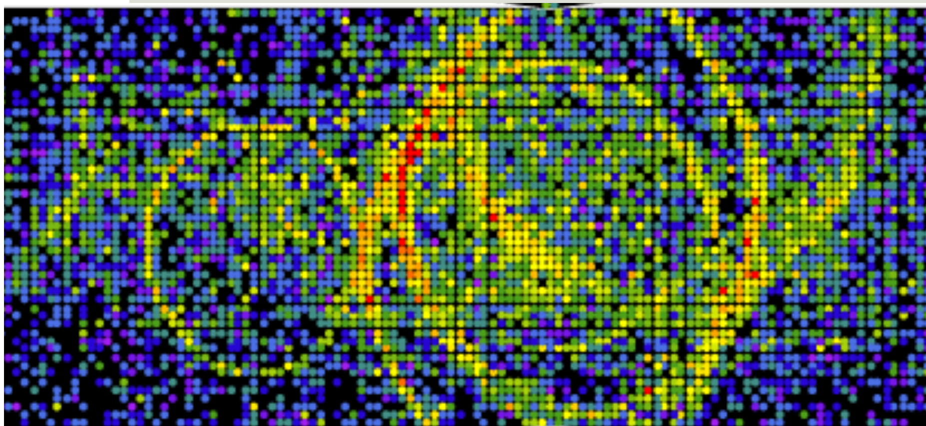
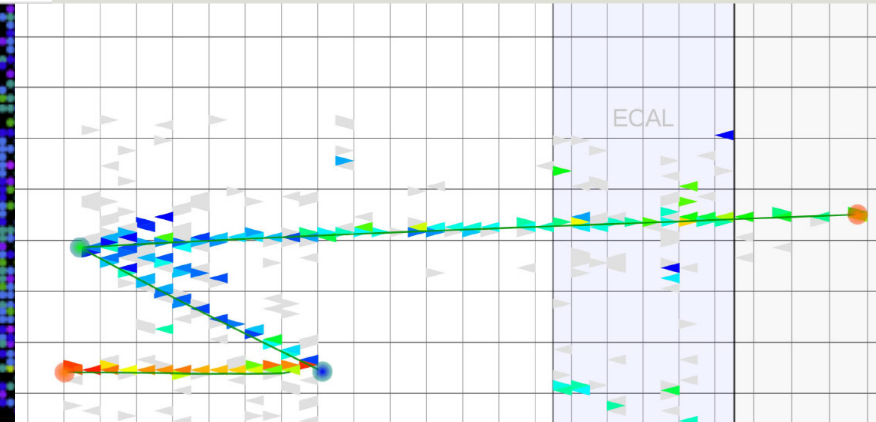


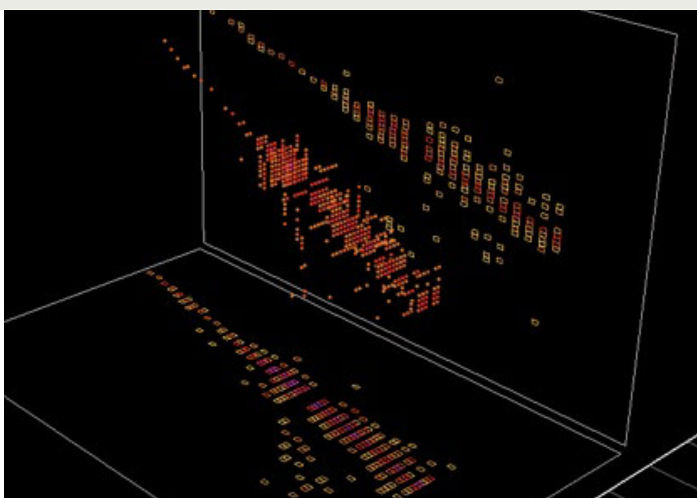


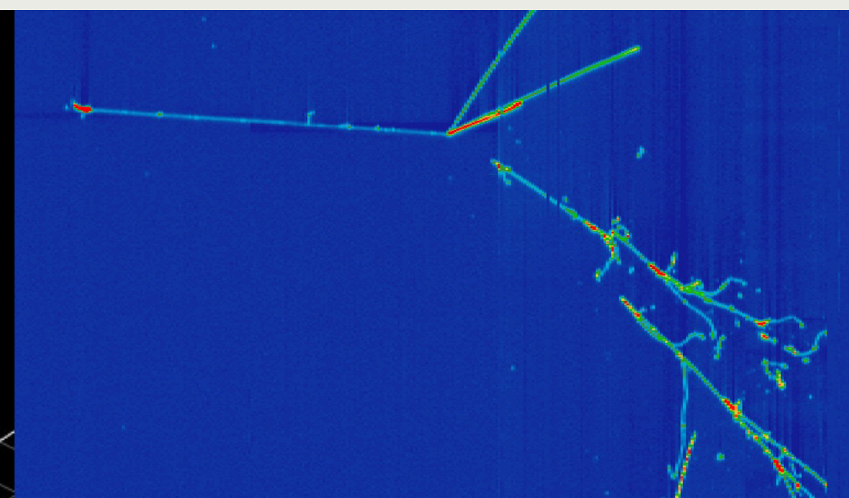
Neutrino Detection Techniques

"Neutrino University" 2018 Summer Undergraduate Lecture Series

Jen Raaf – Fermilab

2018 June 28





Caveats

- I have not attempted to call out every neutrino experiment by name – apologies if your favorite experiment is not mentioned
- I have not attempted to discuss every detail of detection techniques, but instead to give you an overview of general techniques which are applied in many different types of experiments

Quick reminder from Boris' talk

All the constituents of matter are $\sim 10^{-16}$ cm in diameter.

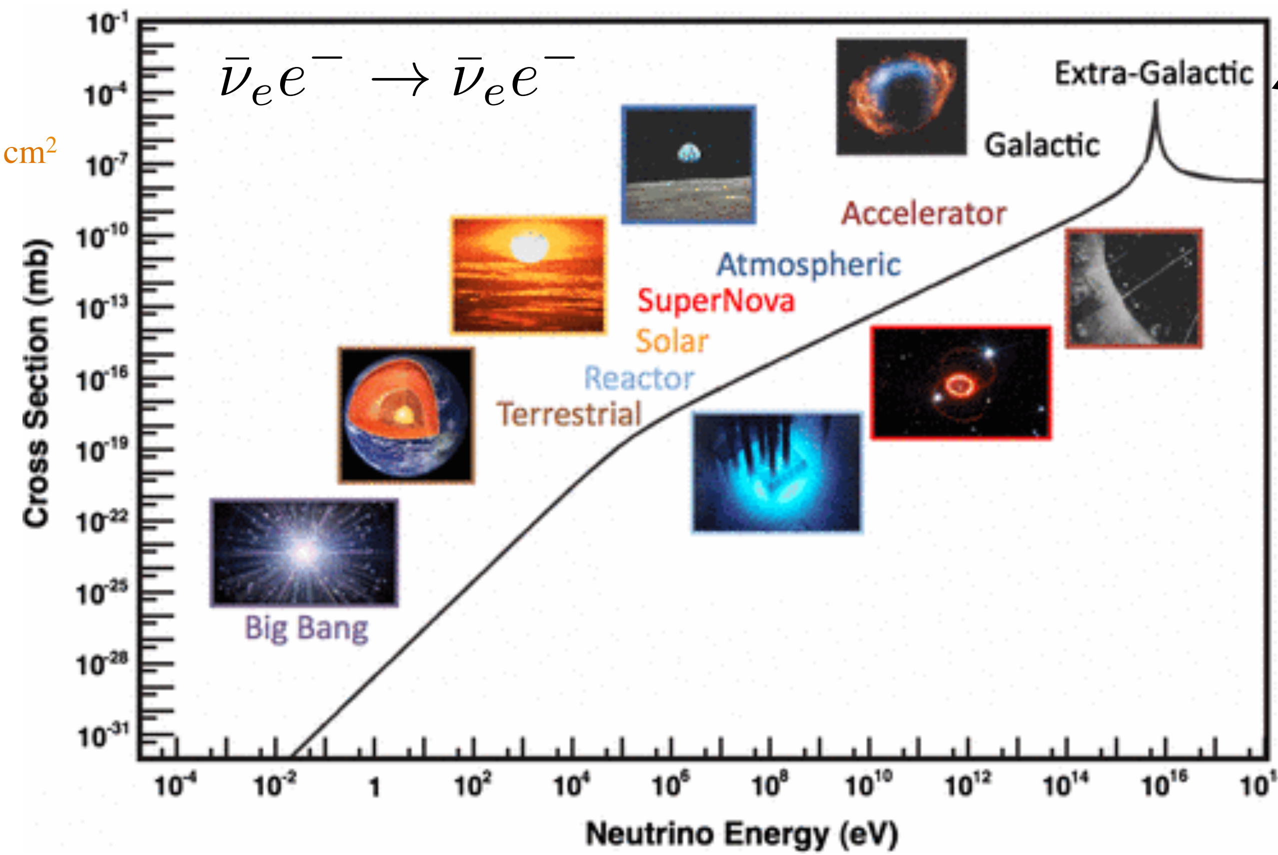
A neutrino does not interact appreciably with another constituent of matter unless it is within $\sim 10^{-16}$ cm of it.

In other words, it must make a direct hit, or it will just pass by. That is why neutrinos pass so easily through matter.

Neutrinos' probability of interacting

- General trend: cross section increases with increasing energy (also true for neutrino-nucleon cross sections, not shown here)

1 millibarn = 10^{-27} cm^2

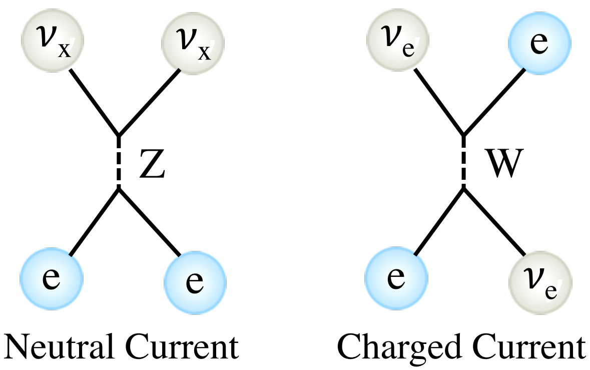


Rev.Mod.Phys. 84 (2012) 1307-1341

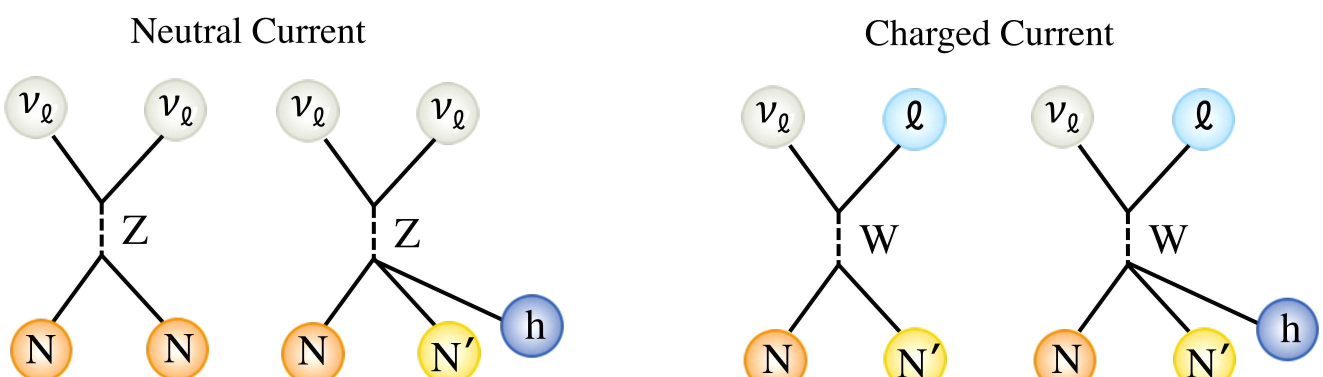
These sources and more were the subject of Stephen's talk earlier this week

Neutrino interactions

Neutrino-electron elastic scattering



Neutrino-nucleon scattering



N = neutron or proton
h = hadron(s) [π, K…]

- At low energies, neutrinos interact with atomic electrons and nuclei as a whole
- At higher energies, they interact with nucleons (n or p) inside a nucleus
- At the highest energies, the neutrino will transfer enough energy to the nucleus to break it apart

Camilo Mariani's lecture on July 12 will cover neutrino interactions in more detail

Observing neutrino interactions

Flux of neutrinos (#/cm²/s)

Cross section (cm²)

Total detector mass

Exposure time

Detection efficiency

$$N_{obs} \propto MT \int \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

- Since the probability for interaction is very small (~10^{-38} cm²), increase your chances of seeing a neutrino event by:
  - Making the detector mass large (and with high efficiency)
  - Sending a lot of neutrinos through it!

Interactions of particles with matter

- In neutrino interactions we only see the (charged) particles exiting the interaction, but actually we don't even see those directly – we only see them by the energy they leave behind
  - Need to identify particle type, and measure the energy and direction, and charge too (if detector is magnetized), then add up all the energies to work backwards and get the neutrino energy
  - Neutral particles can only be detected if/when they interact to produce charged particle(s).

    ⇒ Understanding/recovering energy lost from undetected neutral particles is a big deal for precision neutrino experiments; not covered in this talk.

- Particles lose energy <u>primarily</u> by two processes:
  - **Inelastic collisions with atomic electrons** of atoms in a material

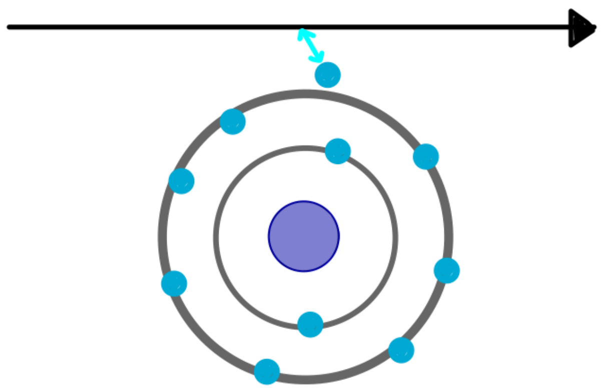
    ⇒ Causes excitation of atom ("soft" collisions) or ionization ("hard" collisions)
  - **Elastic scattering from nuclei** (less frequent than electron collisions)

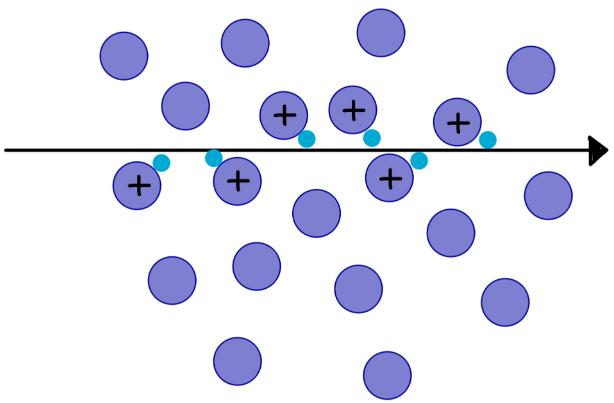
    ⇒ Known as multiple Coulomb scattering; changes particle trajectory

- Additional processes for energy loss (not complete):
  - Emission of Cherenkov radiation
  - Bremsstrahlung

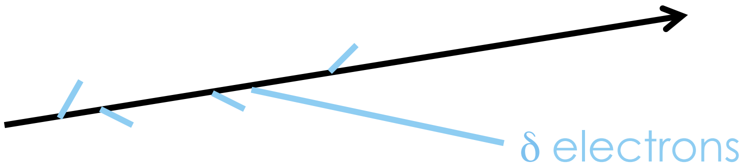
Inelastic collisions with atomic electrons

- Charged particles with energy larger than the binding energy of electrons in an atom lose energy by ionizing the atoms, kicking an electron loose from the atom





- Sometimes a freed electron has enough kinetic energy to cause other ionization events → these are called delta rays

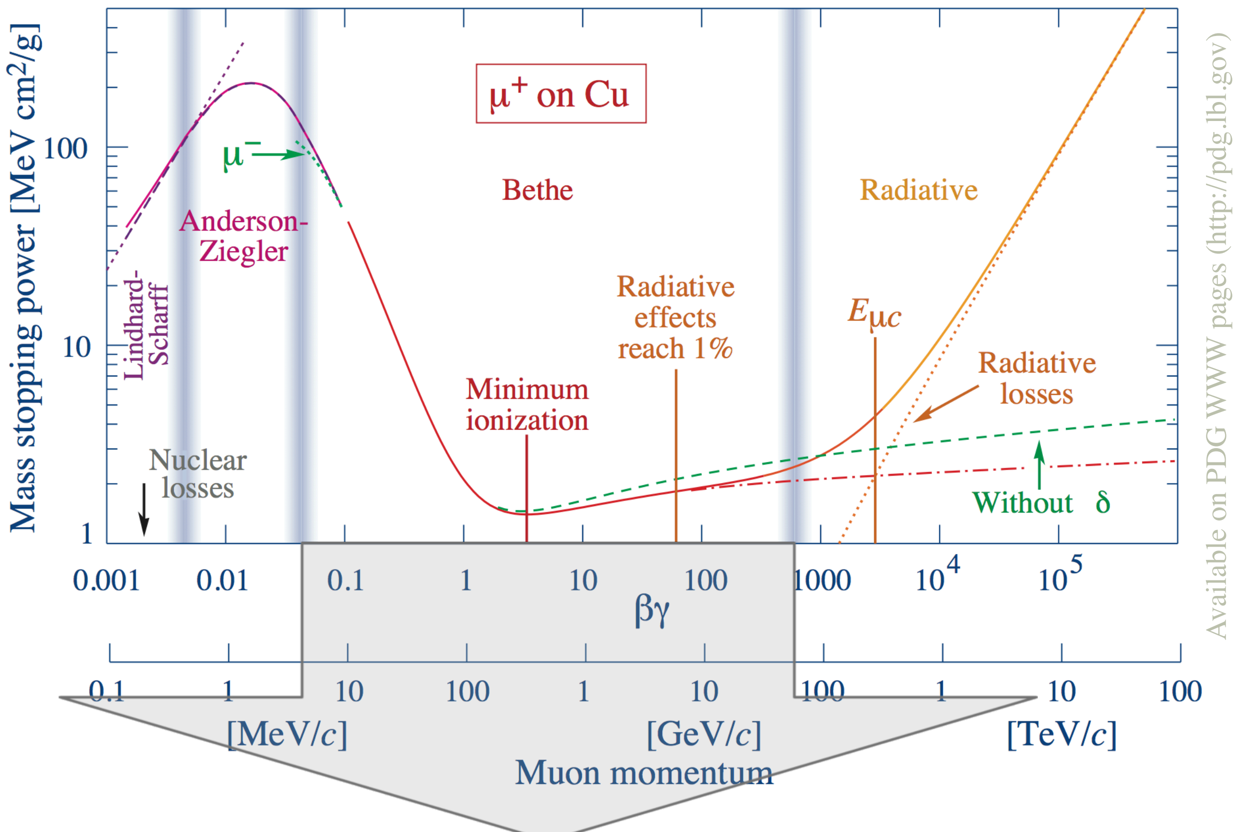


- Not all collisions cause ionization; some just cause excitation of the atom. De-excitation produces low energy photons (scintillation light)
  - The number of photons is proportional to the amount of energy deposited by the ionizing particle

“Heavy” charged particles (i.e., not electrons)

- Particles in the range of $\beta\gamma$ ~ 0.1-1000 lose energy primarily by ionization
  - Bethe-Bloch equation (below) describes mean energy loss in that range
  - Most particles in accelerator-based neutrino experiments are in this range

To get mean energy loss (MeV/cm), must multiply by density of material

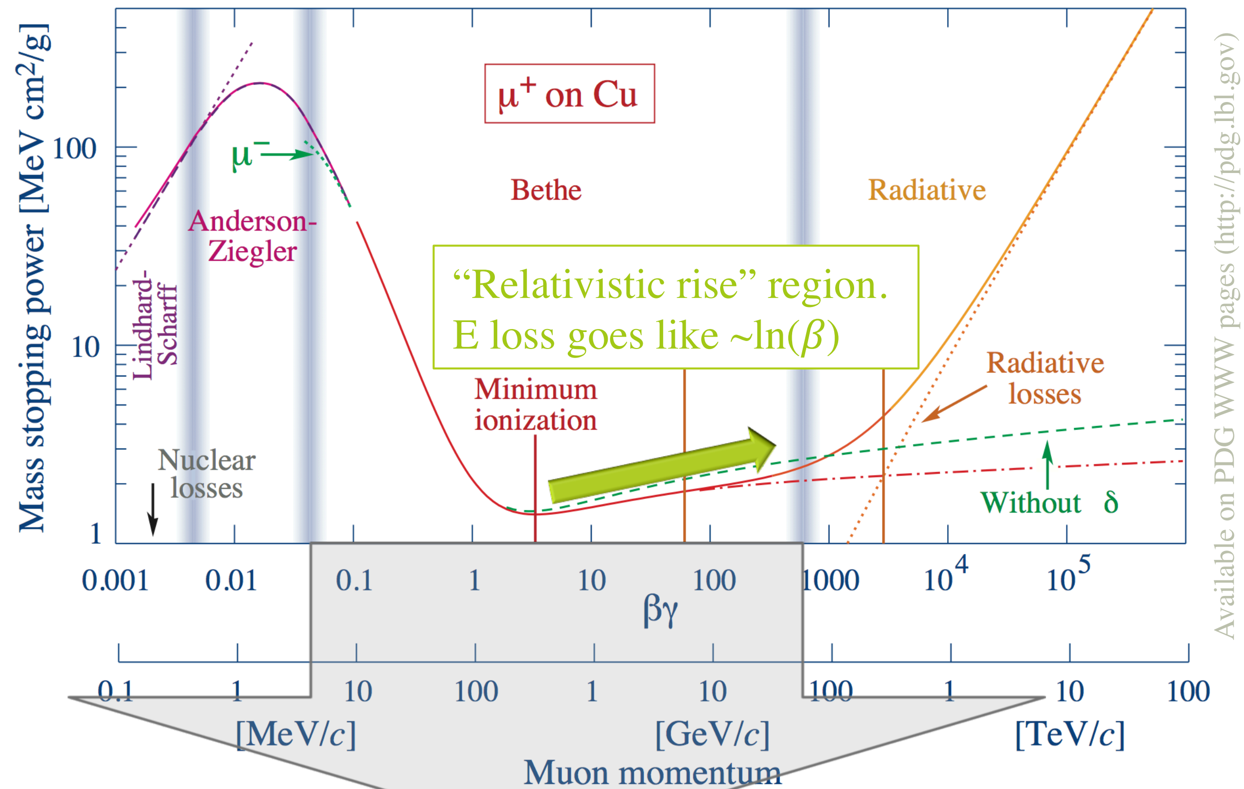


$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

"Heavy" charged particles (i.e., not electrons)

- Region just above minimum ionization is known as the "relativistic rise" where dE/dx roughly plateaus, but is very near minimum
  - Particles near the mimimum are often called MIPs (minimum ionizing particles)

To get mean energy loss (MeV/cm), must multiply by density of material



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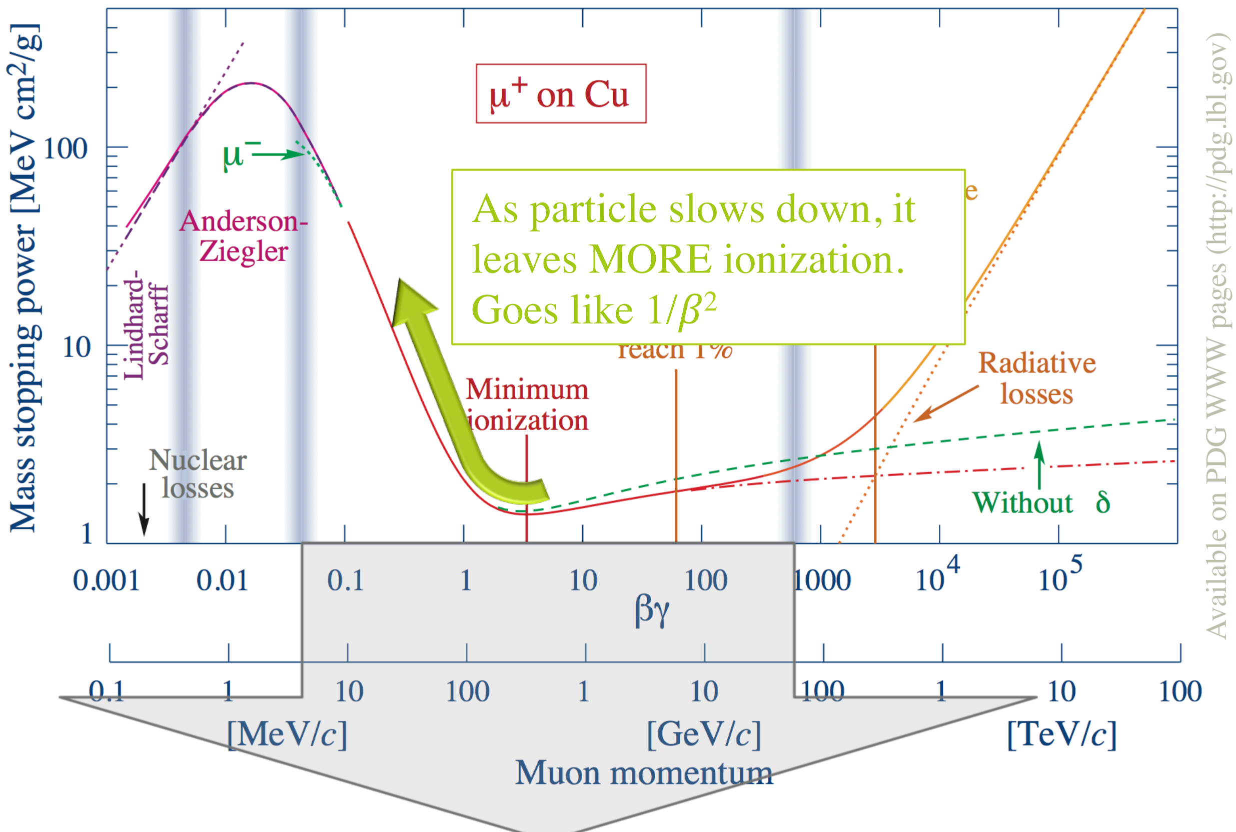
"Heavy" charged particles (i.e., not electrons)

- Particles below the minimum ionization point start to lose more energy as they slow down
  - Can be used to identify which type of particle you have detected

To get mean energy loss (MeV/cm), must multiply by density of material



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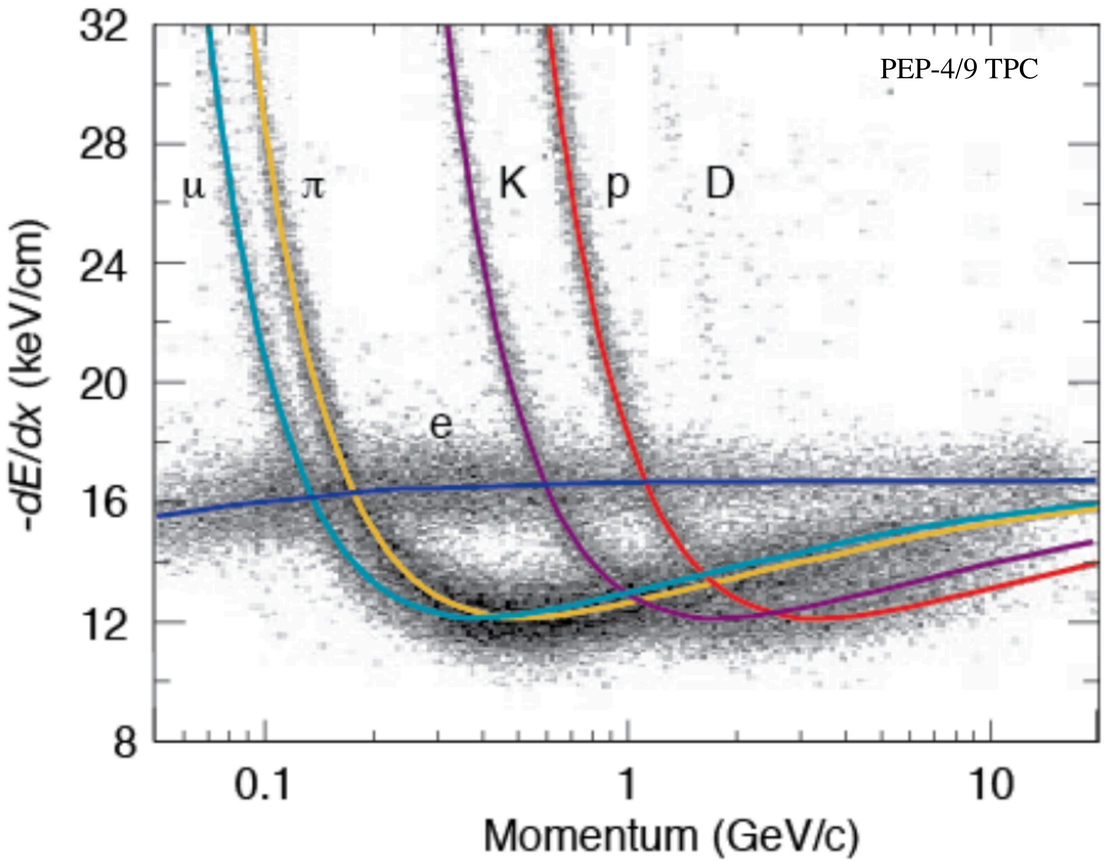
Particle Identification with dE/dx

- For a given momentum, dE/dx is different for particles with different masses
  Measure both momentum and dE/dx ⇒ particle ID (for a certain range of momenta)

$$\frac{dE}{dx} \propto \frac{1}{\beta^2}$$

$$\beta = \frac{p}{mc}$$

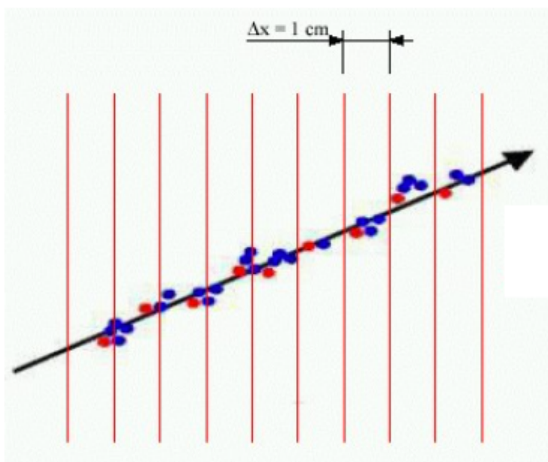
$$\frac{dE}{dx} \propto \frac{m^2}{p^2}$$

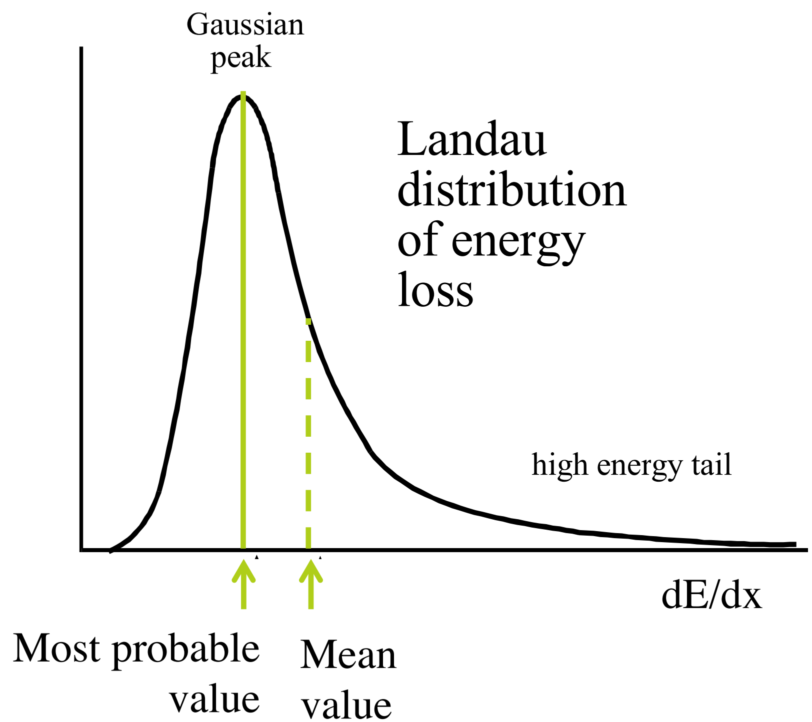


A stopping particle deposits most of its energy at the end of its track ⇒ Bragg peak

Mean energy loss <dE/dx>

- Problem: Bethe-Bloch formula only gives the *mean* energy loss
  - Single measurements have large fluctuations (Landau distribution)
  - Need multiple measurements of dE/dx to get an accurate estimate of energy loss (sampling)



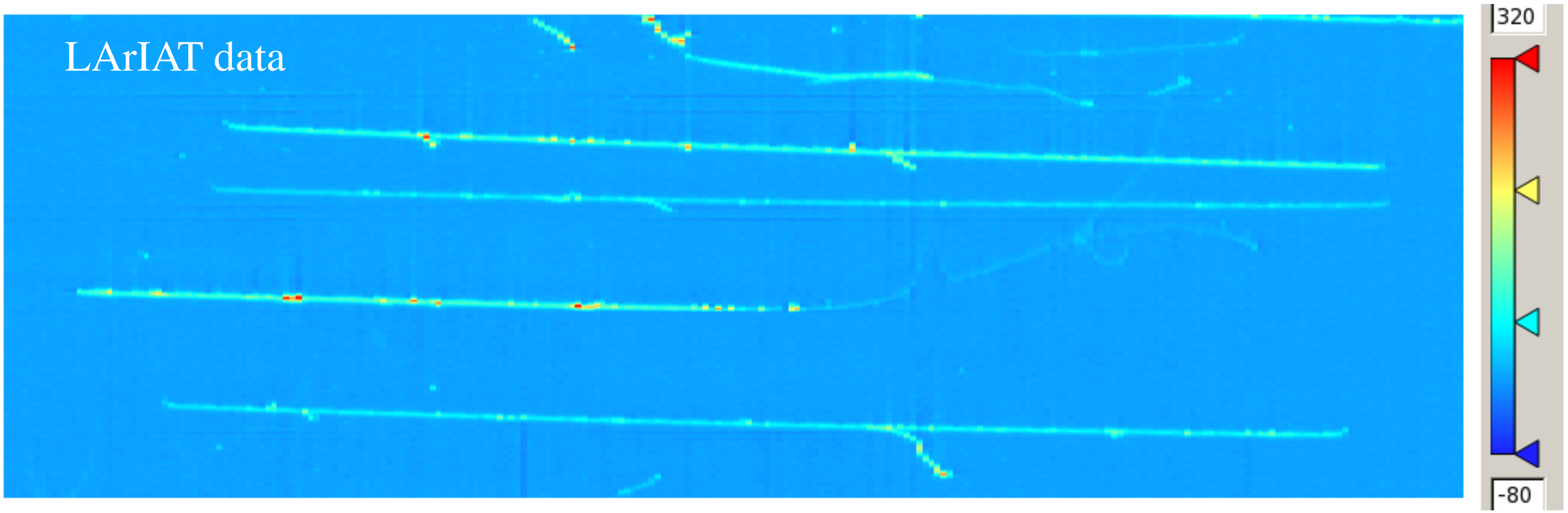


Methods to deal with the fluctuations:

- Measure dE/dx many times along a track and fit a Landau distribution
- Neglect x% of measurements with highest dE/dx (typically 20-30%), restrict dE/dx ("truncated mean")

Mean energy loss <dE/dx>

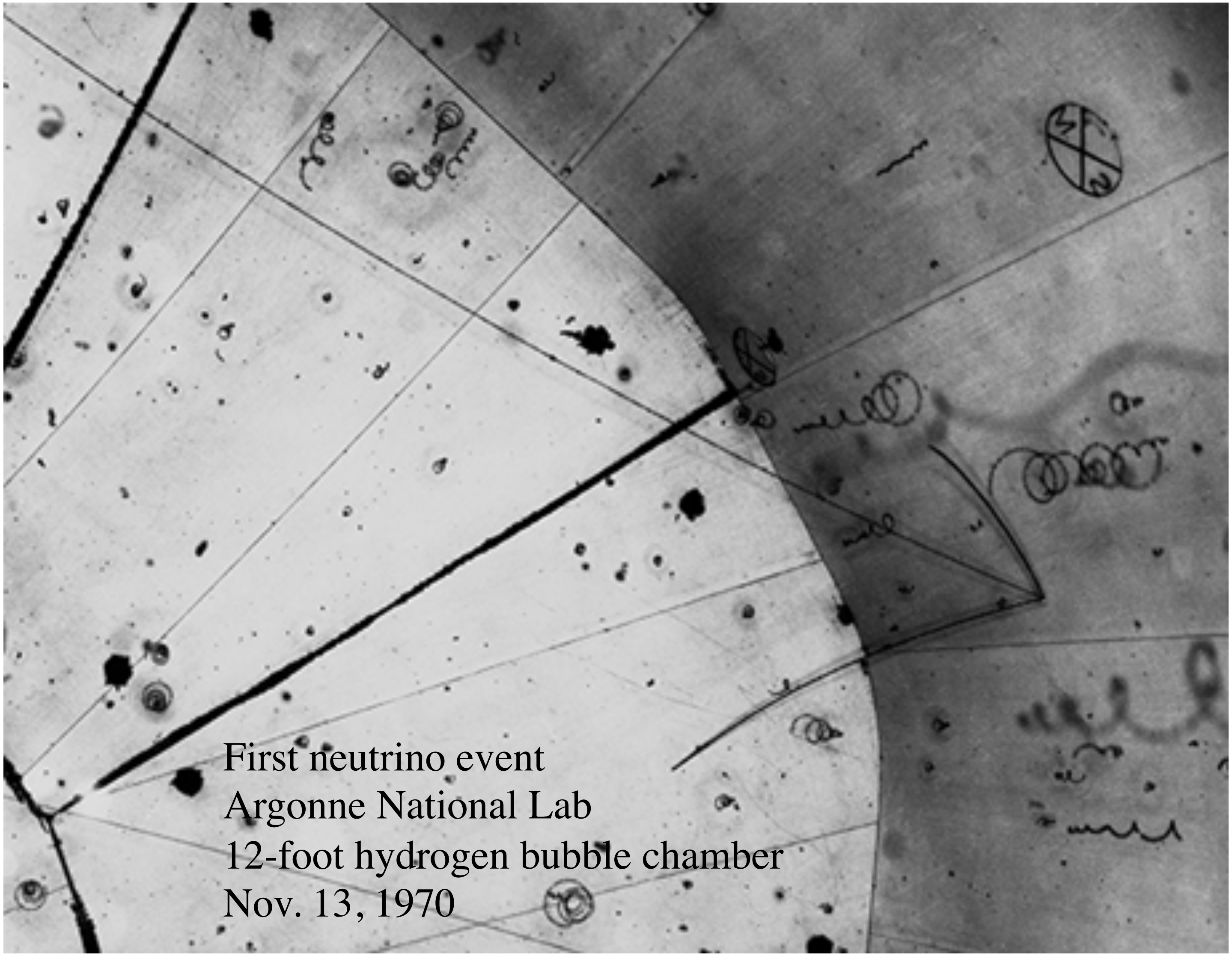
- Problem: Bethe-Bloch formula only gives the *mean* energy loss
  - Single measurements have large fluctuations (Landau distribution)
    - Fluctuations in energy result in fluctuations of particle range
  - Need multiple measurements of dE/dx to get an accurate estimate of energy loss (sampling)



Charged pions and muons traveling through the LArIAT TPC

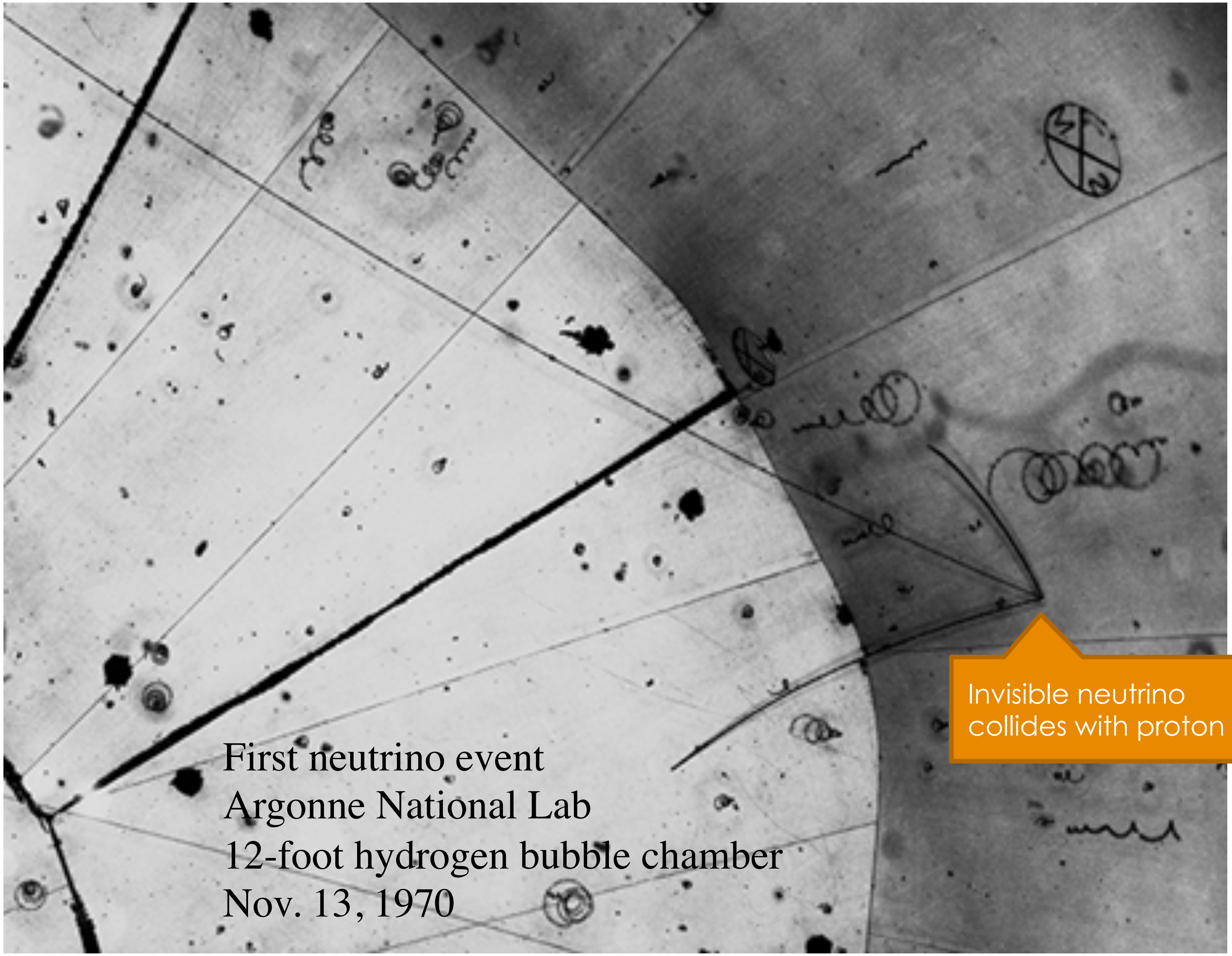
Particle challenge! Bubble chamber data

- Can you find the neutrino interaction? Is it CC or NC?



Particle challenge! Bubble chamber data

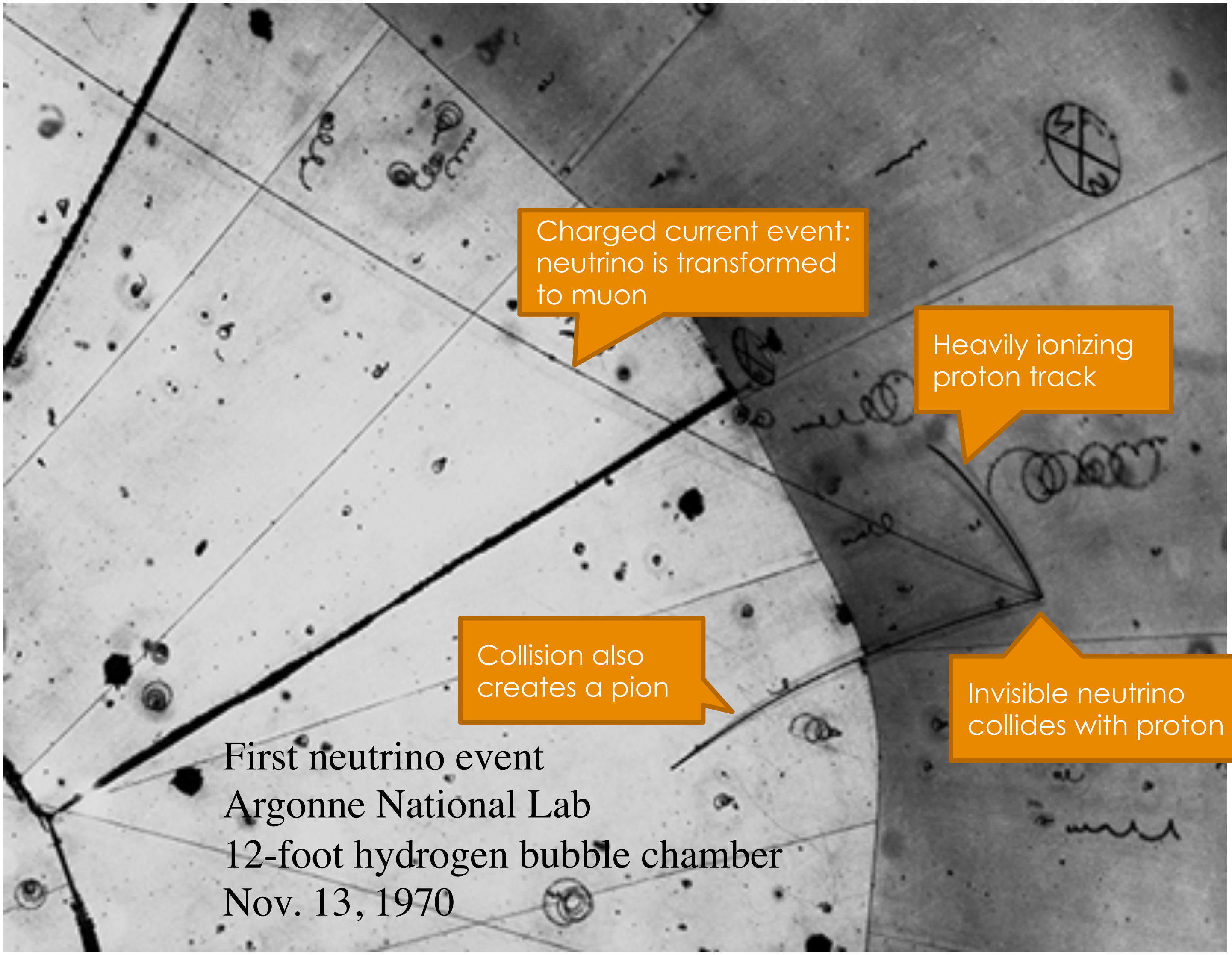
- What can you tell me about the particles exiting the interaction?



Invisible neutrino collides with proton

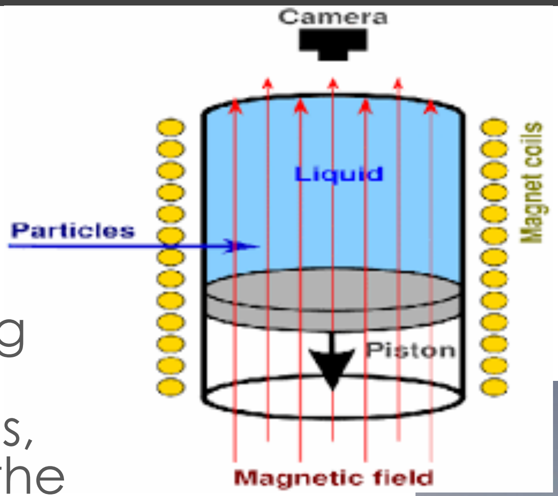
Particle challenge! Bubble chamber data

- What can you tell me about the particles exiting the interaction?



Bubble chambers

- Super-heated liquid (e.g. hydrogen) kept just below boiling point and under pressure
- Charged particles traveling through liquid ionize the hydrogen along their paths, tiny bubbles form around the ions
- Pressure in the tank is reduced to allow the bubbles to grow larger in size
- Take photos from several angles
- Repressurize the liquid to collapse the bubbles, in preparation for the next event

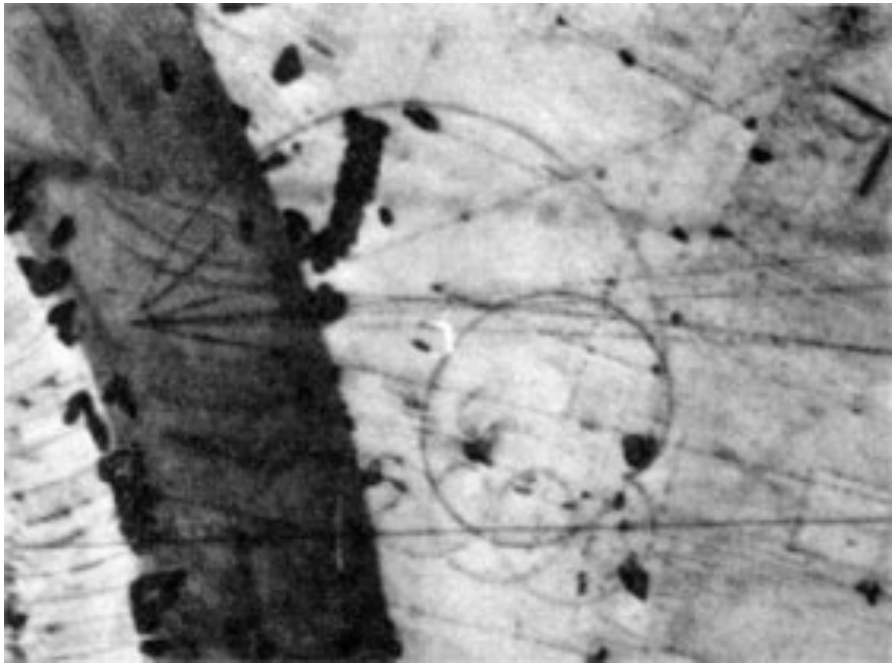


Fermilab 15-ft bubble chamber

Bubble Chamber Data Analysis

- Hired scanners carefully examine every photo...

- Looking for things like this
  - Measure track curvature
  - Identify particle types and energies



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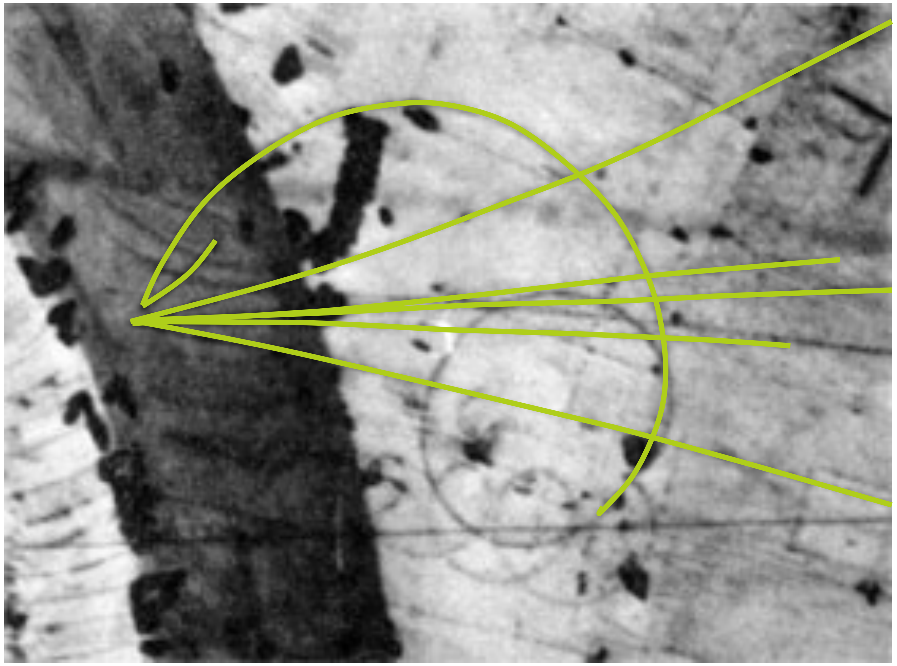
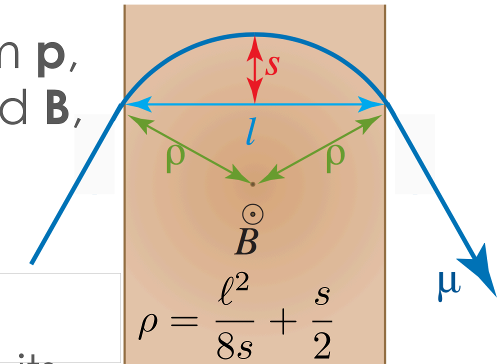


Momentum measurements



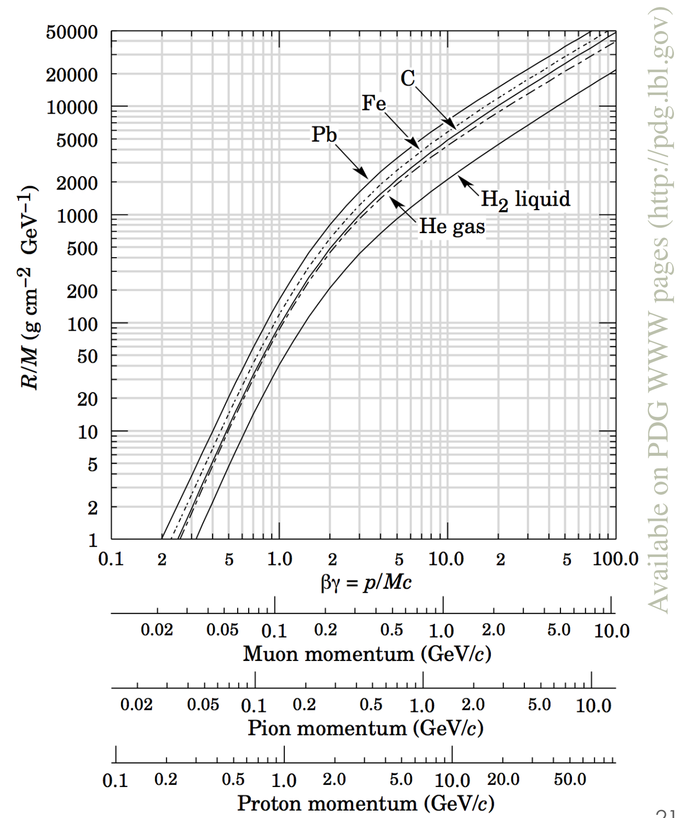
- **Momentum by curvature**: A particle with momentum **p**, traveling through a uniform transverse magnetic field **B**, will travel on a circle of radius ρ:

$$p[GeV/c] = 0.3B[T]\rho[m]$$

  - Measure the sagitta and chord of a track to determine its momentum:

$$p \simeq 0.3\frac{b\ell^2}{8s}$$

- **Momentum by range**: If the detector is long enough to stop a particle, you can determine the momentum by measuring its range
  - How far (on average) will a 1 GeV/c muon travel in iron (density = 7.86 g/cm^3)?



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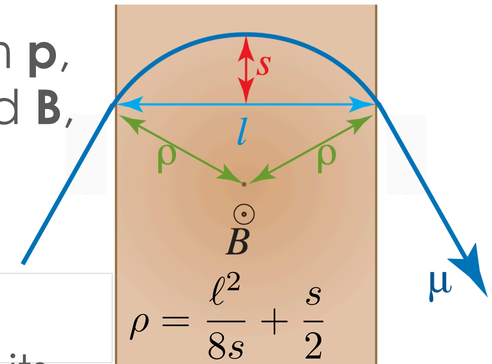

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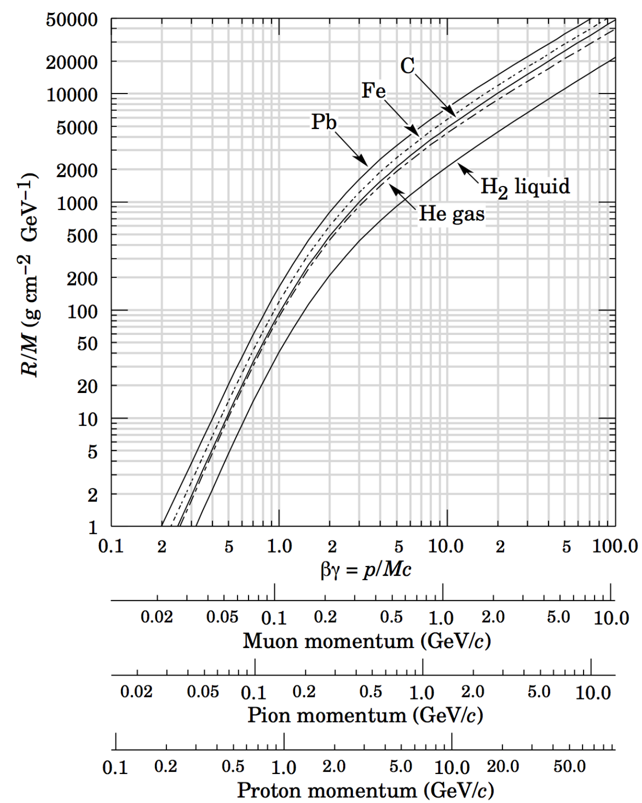
  - How far (on average) will a 1 GeV/c muon travel in iron (density = 7.86 g/cm^3)?

$$\frac{R}{M} \simeq 6000\ [g/cm^2/GeV]$$

$$R \simeq 6000\ [g/cm^2/GeV] \cdot m_\mu = 639\ [g/cm^2]$$

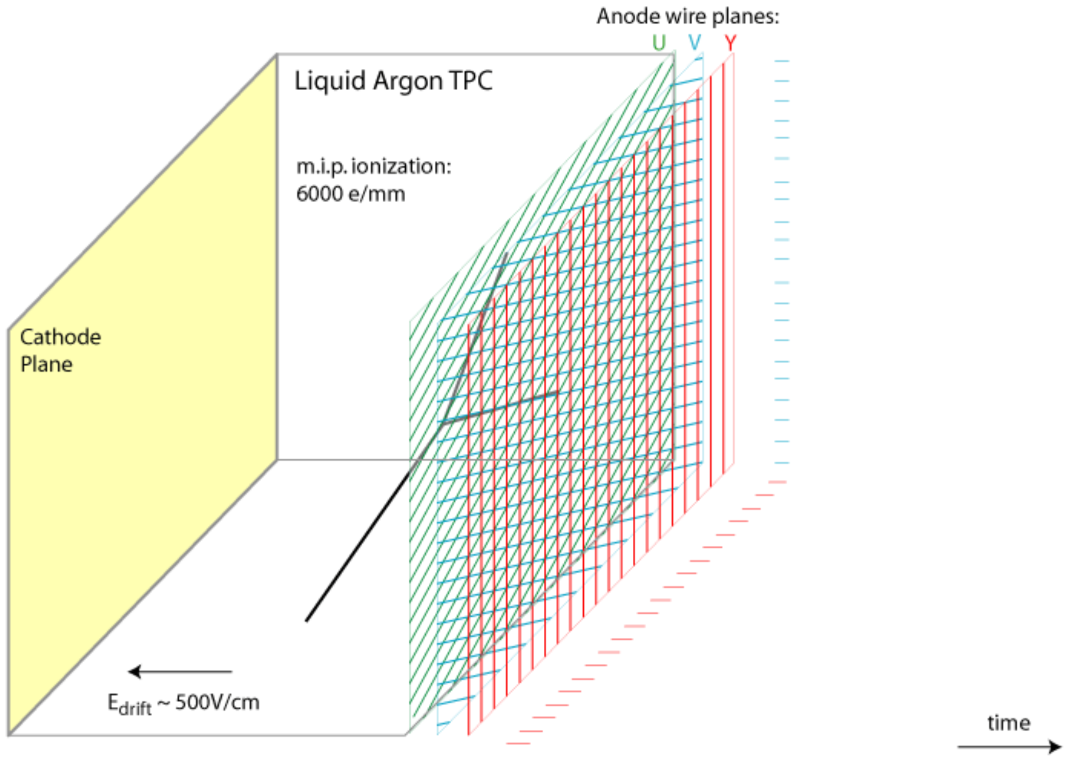
$$\frac{639\ [g/cm^2]}{7.86\ [g/cm^3]} = 81\ cm$$



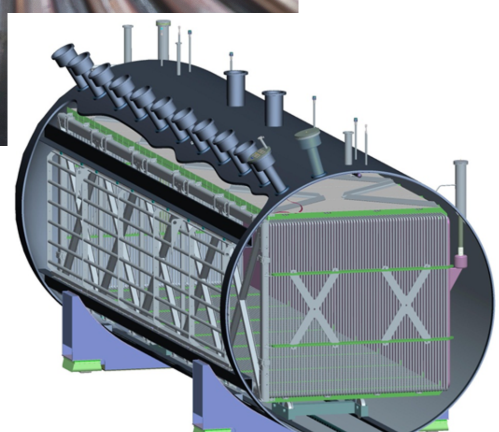
Available on PDG WWW pages (http://pdg.lbl.gov)

Modern-day bubble chambers: Time Projection Chambers

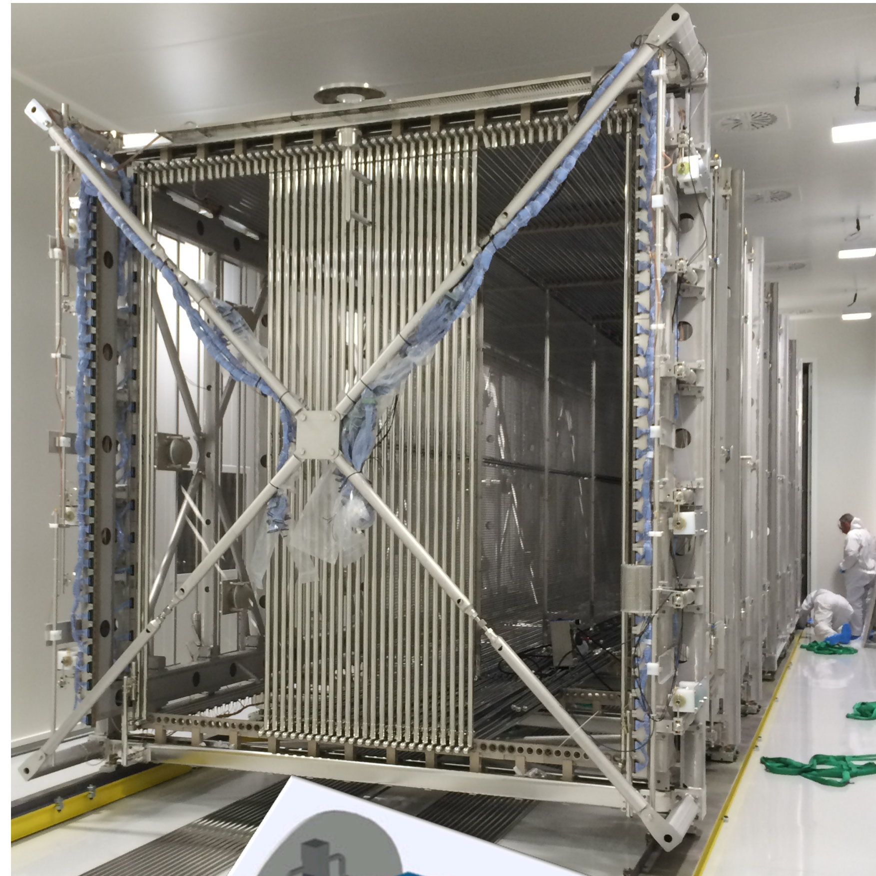
- Can collect energy lost both by ionization and by light production
  - Several different types of TPCs: liquid single-phase, liquid dual-phase, gas
- Ionized atoms are kept from recombining with their stripped off electrons by an electric field in the detector active volume

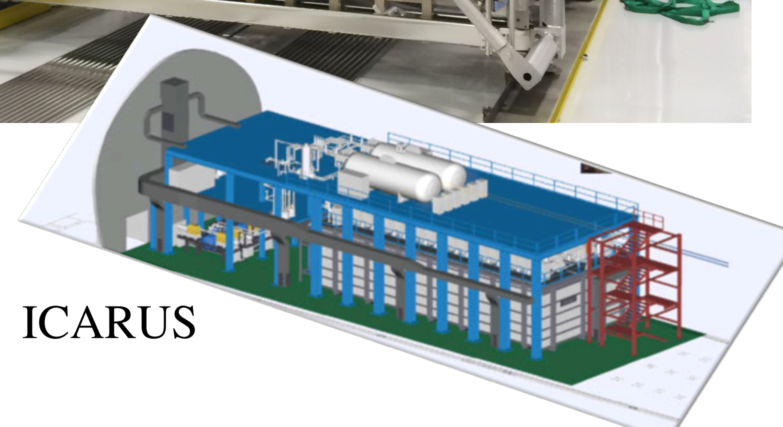


Typical Time Projection Chambers



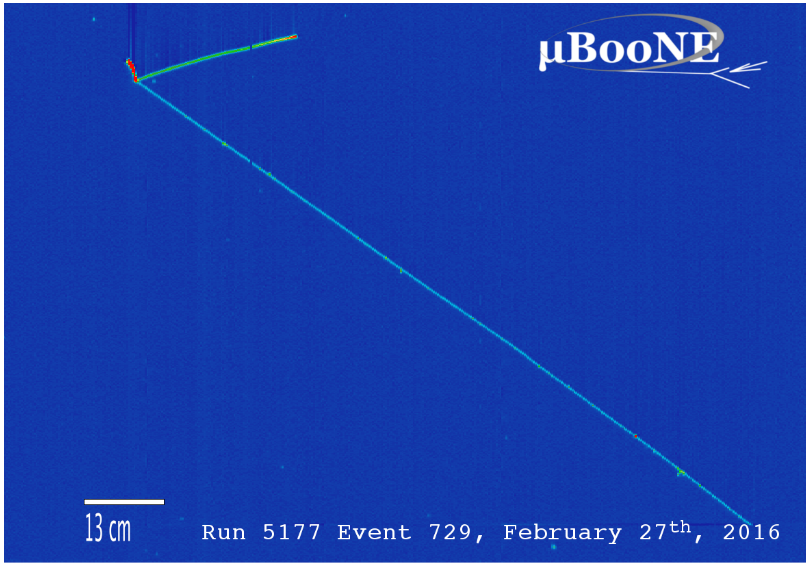
MicroBooNE

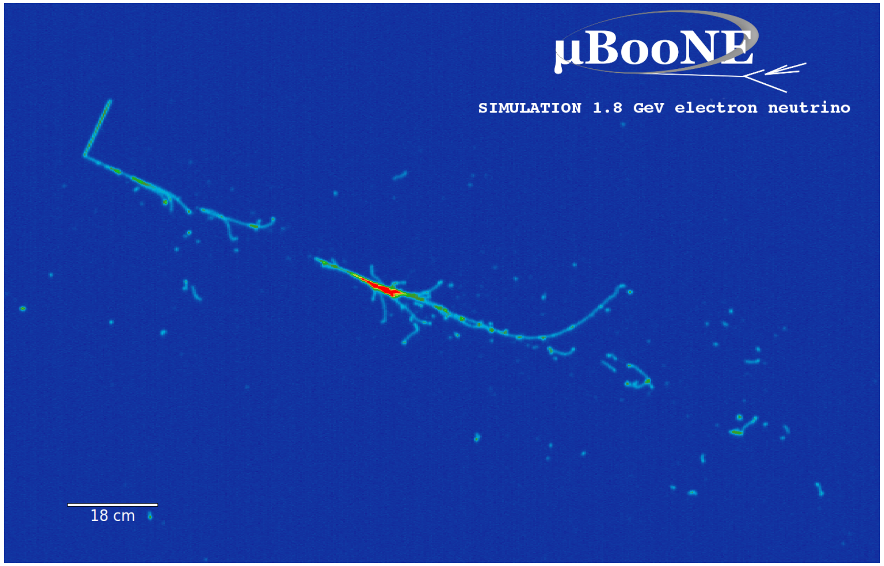


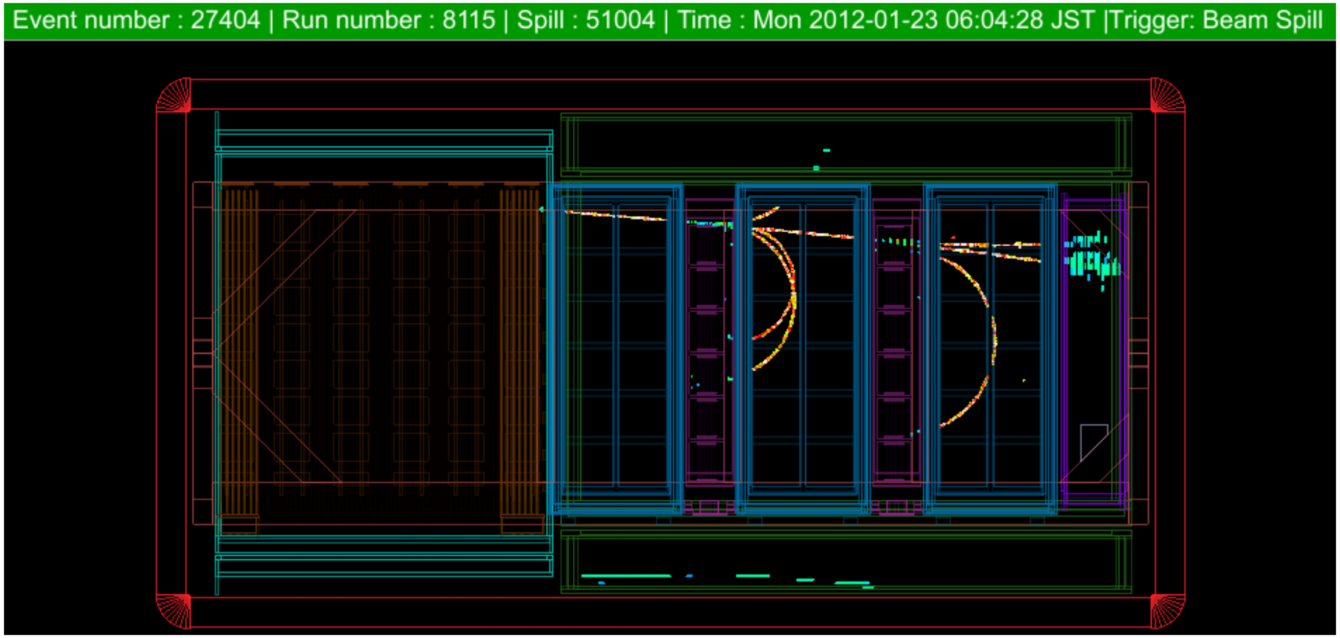


ICARUS

Time Projection Chamber Data



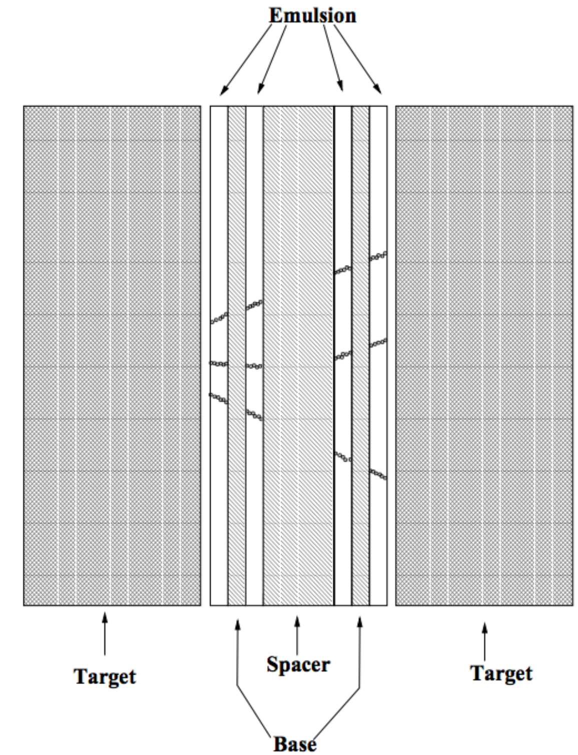


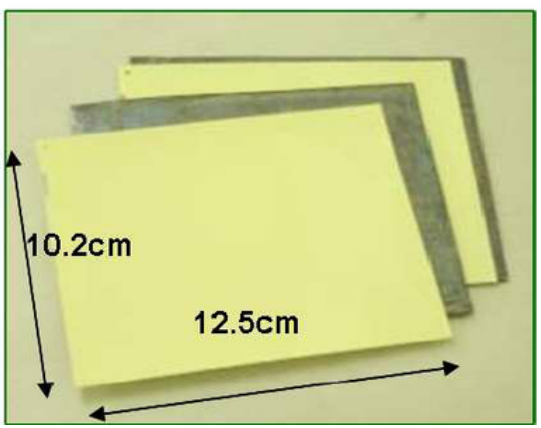


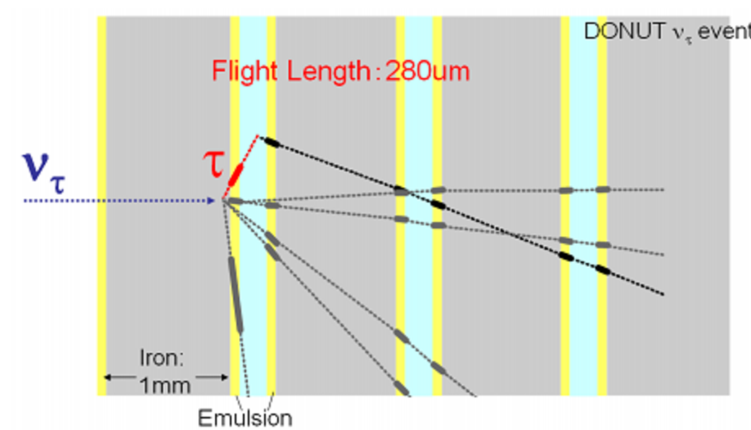
T2K ND280

Emulsion Detectors

- Use photographic films (emulsions) layered with passive absorbers (target material for interactions) to track ionizing particles
- Build detector from modules of interleaved film/target layers

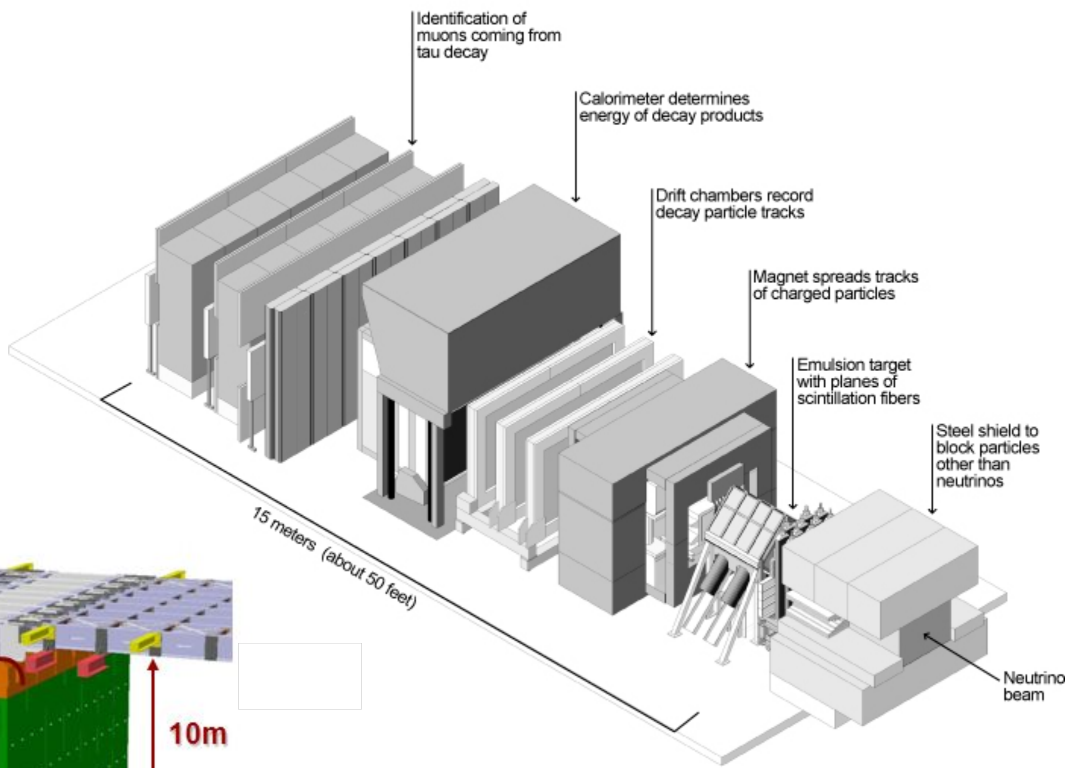






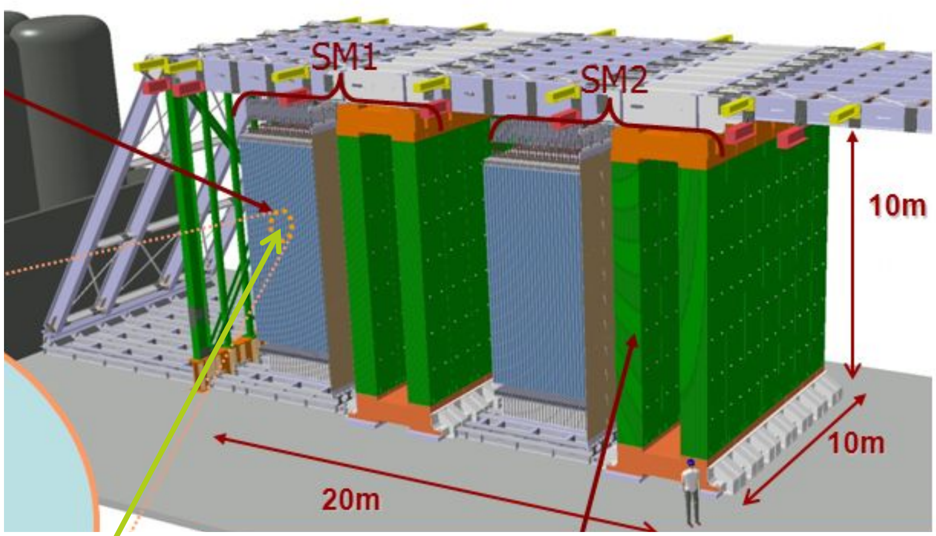
Typical Emulsion Detectors

DONUT Detector



First direct evidence of tau neutrino!

OPERA Detector



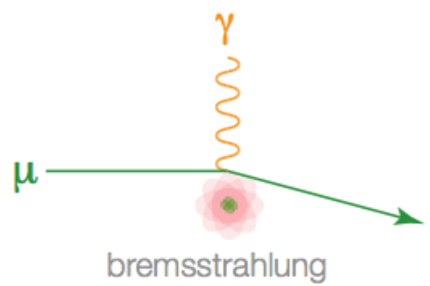
Lead/emulsion bricks

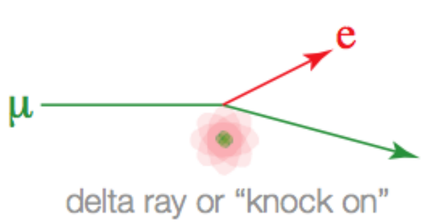
Muon spectrometers

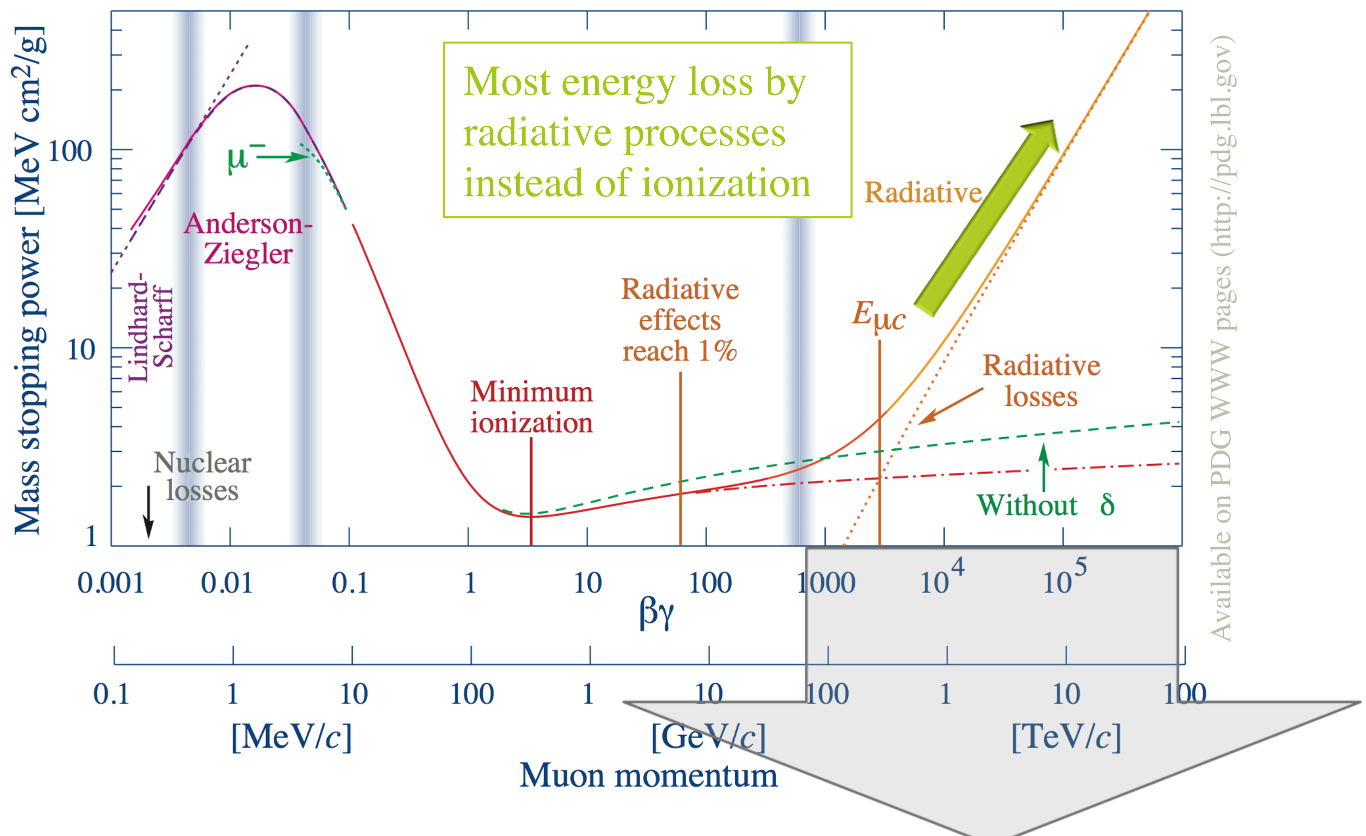
"Heavy" charged particles (i.e., not electrons)

- For particles with $\beta\gamma \gtrsim 1000$, radiative energy losses dominate
  - Bethe-Bloch not valid here (dE/dx in this region is not simply a function of β).

To get mean energy loss (MeV/cm), must multiply by density of material





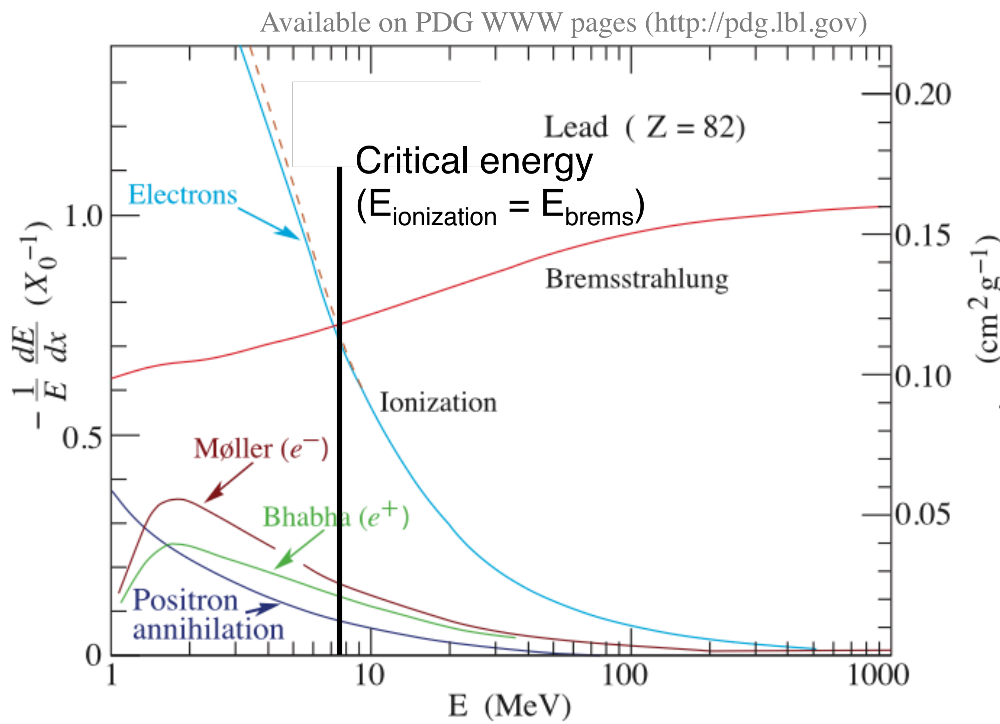


Energy losses due to things like bremsstrahlung and knock-on electrons (delta rays)

Bremsstrahlung (braking radiation)

- Emission of EM radiation (photons) arising from a charged particle scattering in the electric field of a nucleus
- For heavy particles, this starts to dominate the energy loss when they are ultra-relativistic (above $\beta\gamma$~1000)
- It is much more important for electrons, as it is the dominant energy loss mechanism above electron energies of ~10-100 MeV (depends on material)

Fractional energy loss per radiation length



Radiation length (X_0)

Radiation Length & EM showers

- The radiation length, X_0, of a material is defined as the distance over which an electron loses all but 1/e of its energy (~63%) via bremsstrahlung radiation:

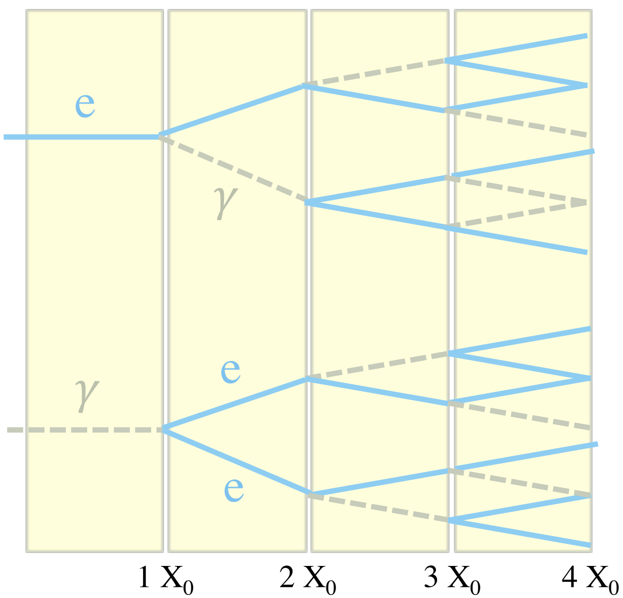
$$X_0 \simeq 180 \frac{A}{Z^2} \; g/cm^2$$

  - Measured in cm or in g/cm^2
  - Roughly, an electron emits one brem photon for every 1 X_0 of material traversed

- Radiation length also describes the distance over which photons pair produce (interact with a nucleus to convert to an electron-positron pair):

$$\lambda_{pair} = \frac{9}{7} X_0$$

Simple model of EM shower development



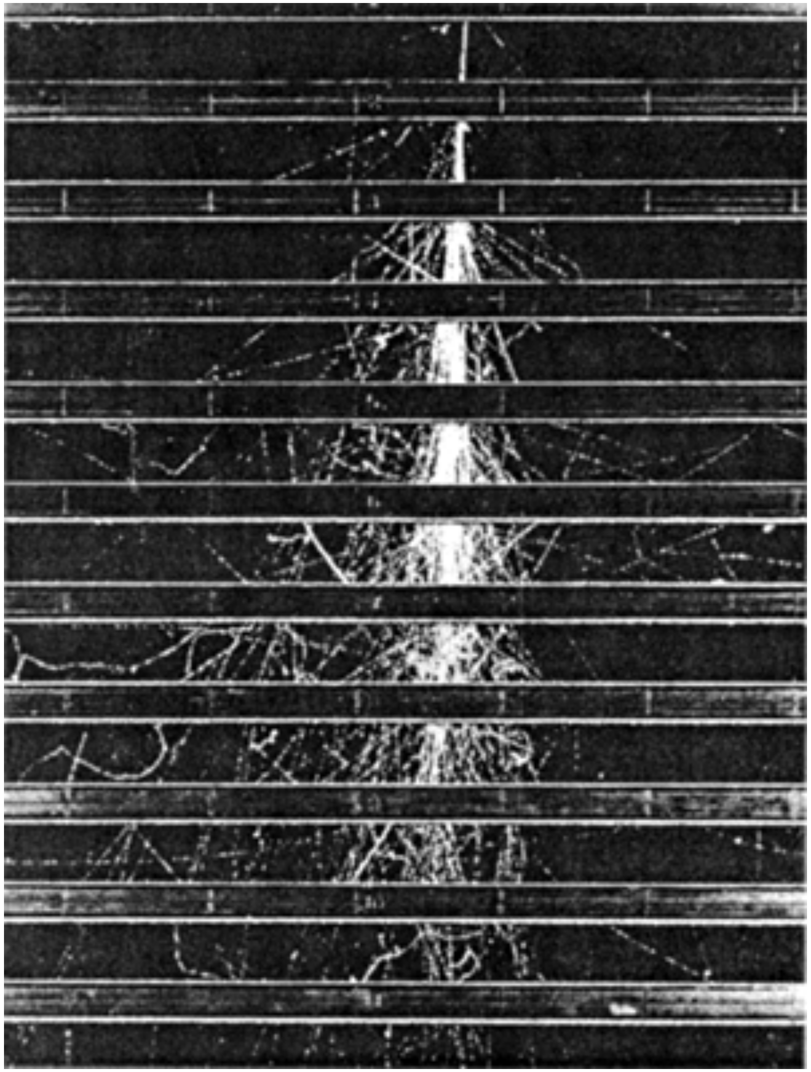
Shower continues until all electrons fall below the critical energy (i.e., no more brems).

EM Showers

- The length of an EM shower is typically measured in units of X_0
- The "width" (transverse to initial particle direction) is measured in units of Moliere radius (R_M):

$$R_M = \frac{21.2\ MeV}{E_C} X_0$$

Roughly speaking, all EM showers look similar, independent of material and energy

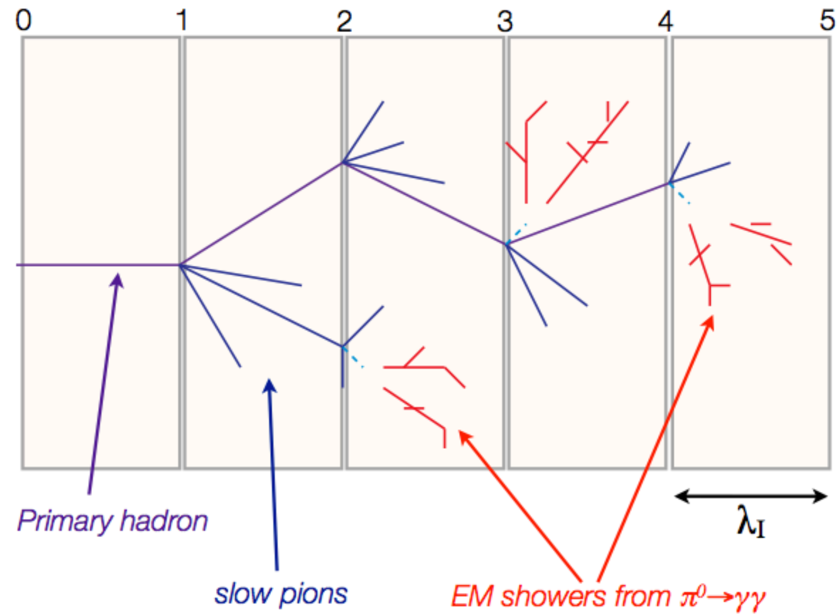


Cloud chamber photo of EM shower traversing brass plates

Hadron Showers

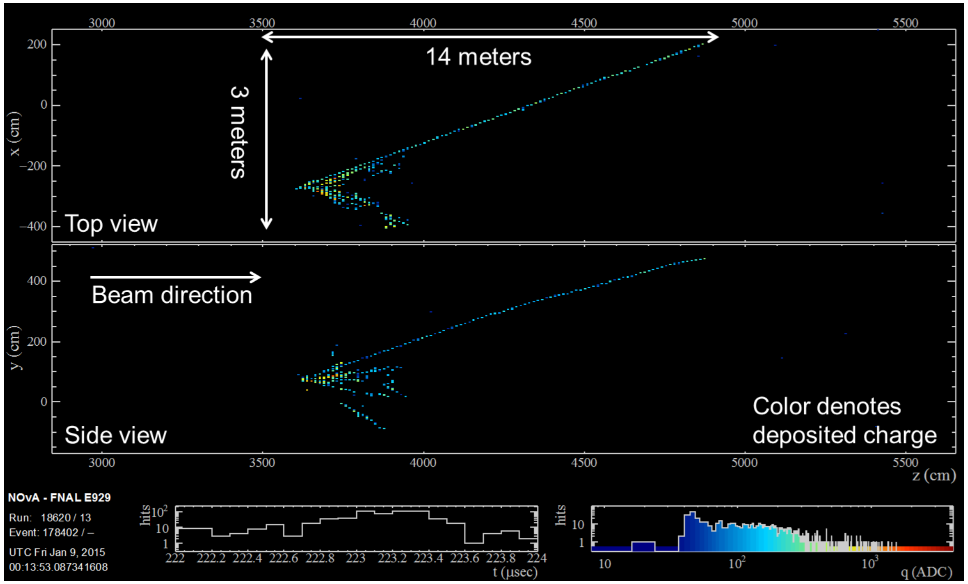
- Hadrons (particles that interact via the strong force, like baryons and mesons) are likely to interact within one "interaction length" (λ_I)
- Can produce tracks and/or showers
  - If the initial hadron only has enough energy to travel less than one interaction length (losing energy via ionization only) → track
  - If it has enough energy to travel longer than one interaction length, you'll probably get a shower
  - Hadron showers are complicated, and can have some EM showers embedded within them!

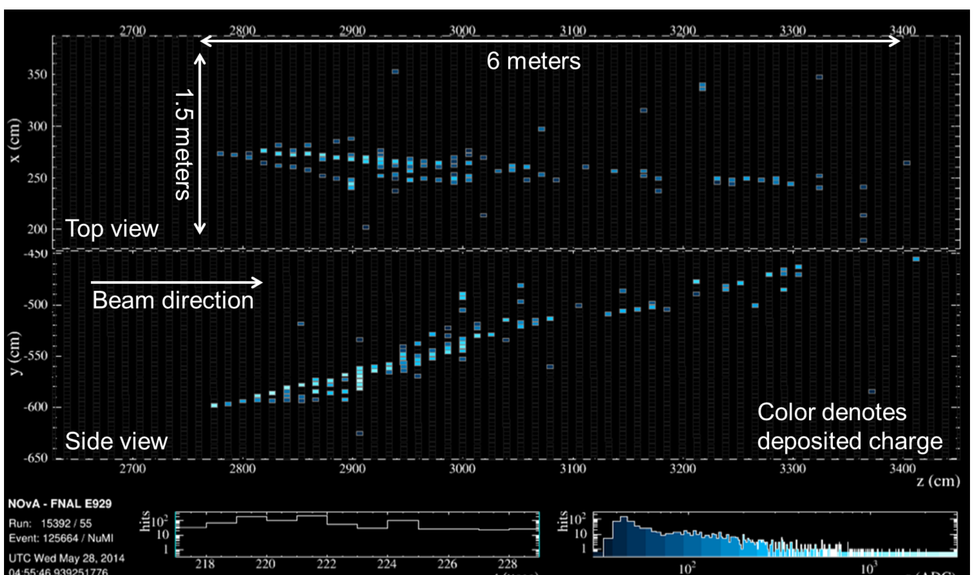
Hadron showers are typically "wider" than EM showers.



EM vs. Hadronic Showers

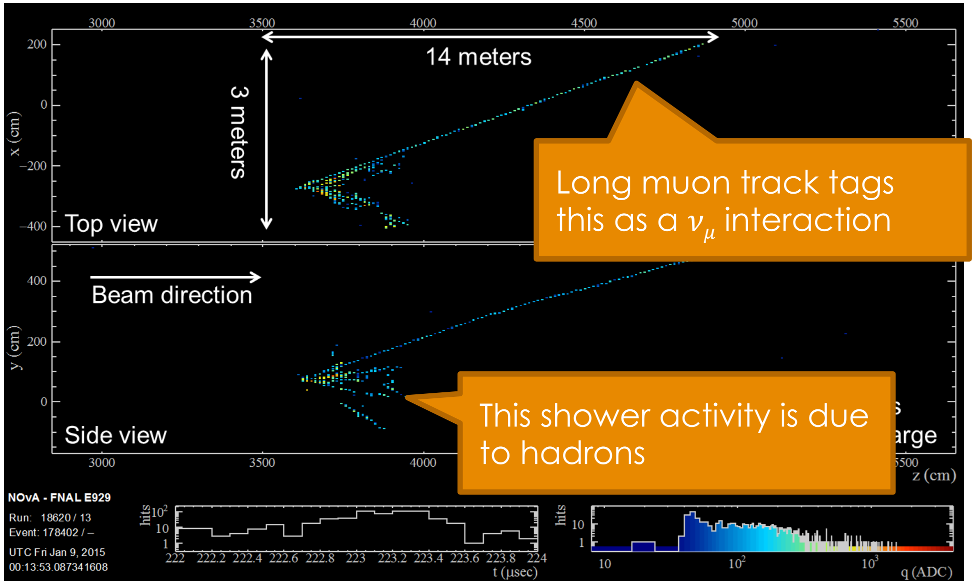
From http://novaexperiment.final.gov

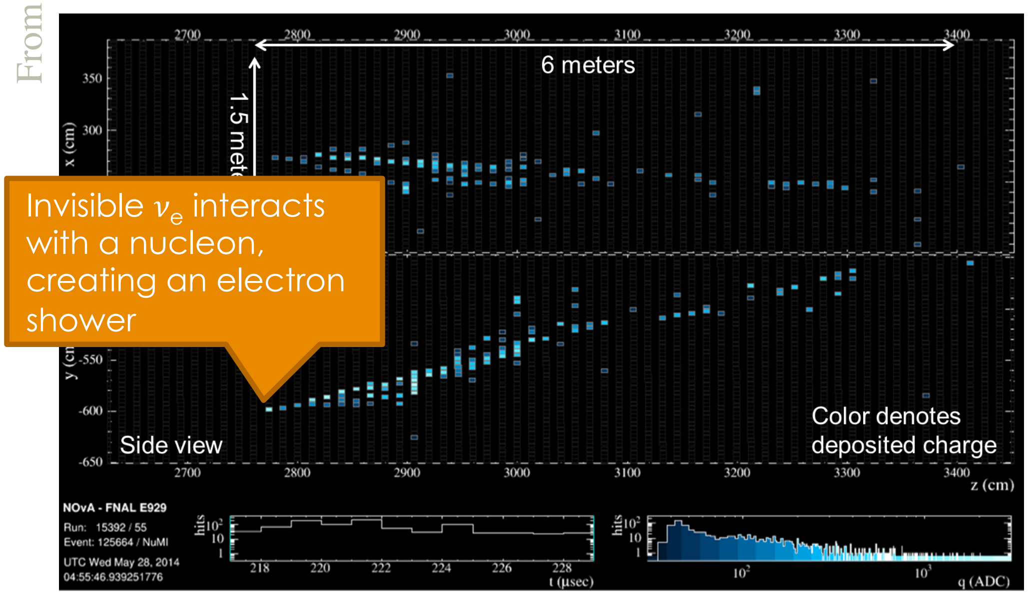




- Which is an EM shower?
- Are these CC or NC neutrino interactions are these?

EM vs. Hadronic Showers



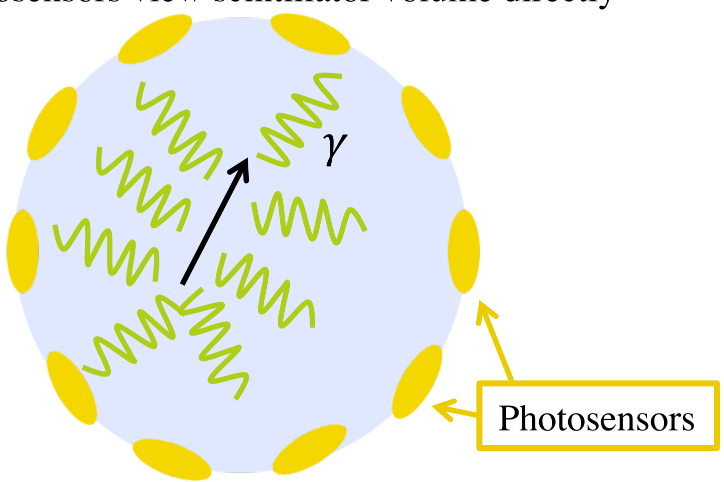


- Which is an EM shower?
- Are these CC or NC neutrino interactions are these?

Energy loss by atomic excitation (scintillation)

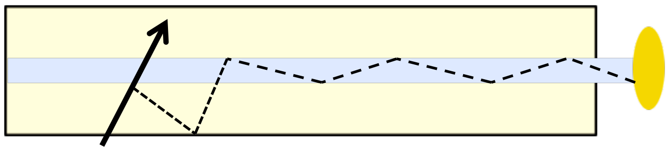
- Some of the energy deposited by a moving charged particle is in the form of atomic excitation
  - Atom decays to its ground state by emitting photons: scintillation light
  - Key property of scintillation mechanism: medium must be transparent to its own light over large enough distance for the light to be collected
  - Light output per unit length is proportional to the stopping power (dE/dx)
- Light can be collected in two ways:

Photosensors view scintillator volume directly



Borexino, KamLAND, Double Chooz, RENO, Daya Bay, and others use this technique

Photosensor is coupled to wavelength shifting fiber embedded in scintillator



NOvA, MINERvA, MINOS, SciBar, and others use this technique

First idea for a liquid scintillator neutrino detector

- Reines & Cowan (who were the first to detect antineutrinos) built a prototype liquid scintillator detector called "El Monstro"

GIANT LIQUID SCINTILLATION DETECTORS AND THEIR APPLICATIONS*

FREDERICK REINES

Los Alamos Scientific Laboratory, Los Alamos, New Mexico

I. GENERAL CONSIDERATIONS LEADING TO THE DEVELOPMENT OF LARGE DETECTORS

WHEN Clyde Cowan and I started in 1951 to pursue the free neutrino,[1] we knew that an essential ingredient in any successful scheme would be a solid or liquid target consisting largely of protons and measuring approximately a cubic meter. Furthermore, the events which occurred in this target had to

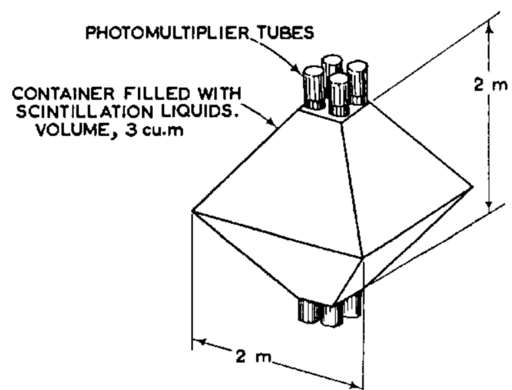
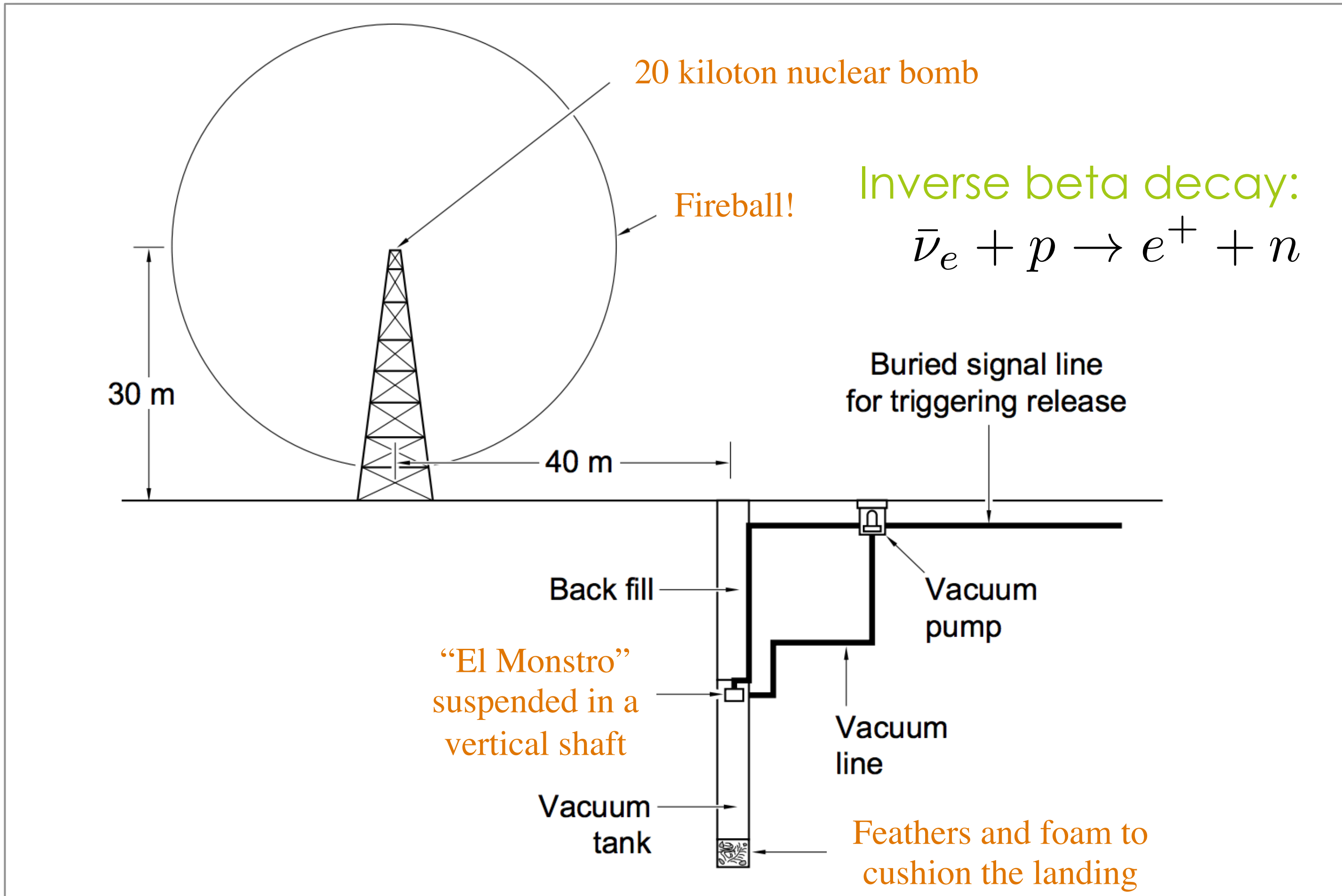


Fig. 1. Sketch of 'El Monstro', first Los Alamos attempt at a giant liquid scintillation detector (1952).

This was *actually approved* by the lab director…

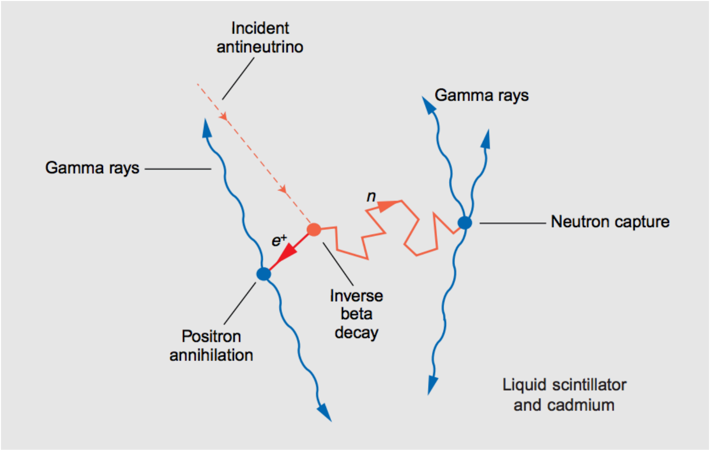
Los Alamos Science, Number 25 (1997)



- **Idea**: detect antineutrino interactions by recording scintillation light from positrons produced in interactions. Detector must be in free-fall to avoid shockwave from blast. Wait a few days, dig up detector. Analyze data!
- But then they had a better idea…

Savannah River Neutrino Detector

- A refined version of El Monstro (called the Savannah River Neutrino Detector) was used in the discovery of the antineutrino via the inverse beta decay reaction, using *delayed coincidences* of scintillation light
- Neutrino source: reactor (not nuclear explosion)



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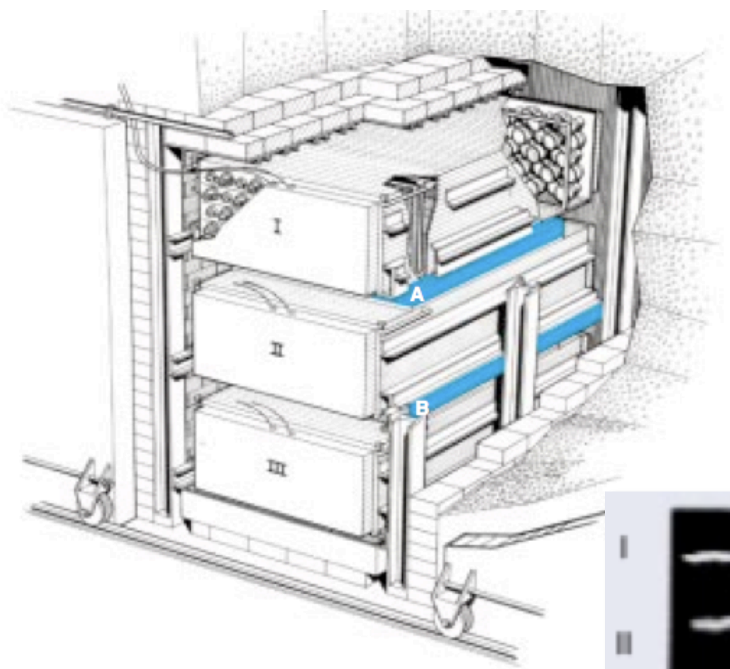
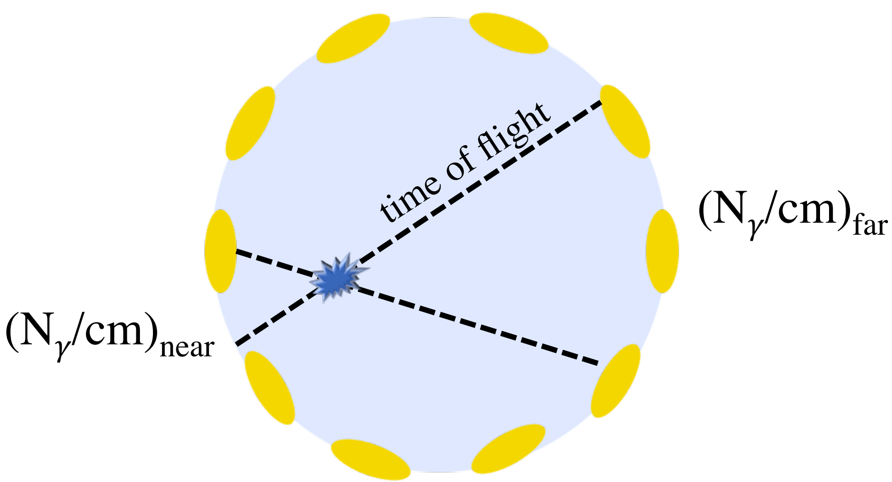
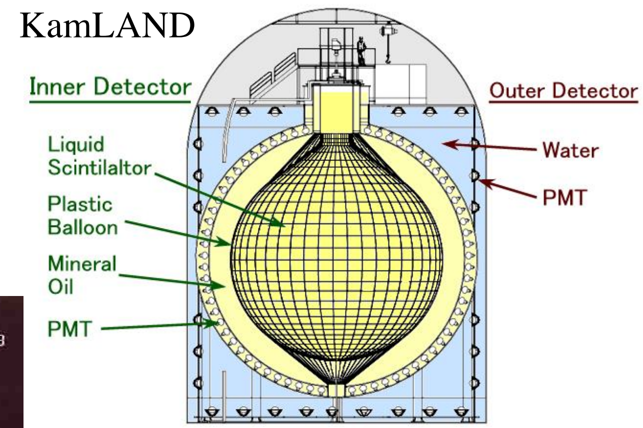


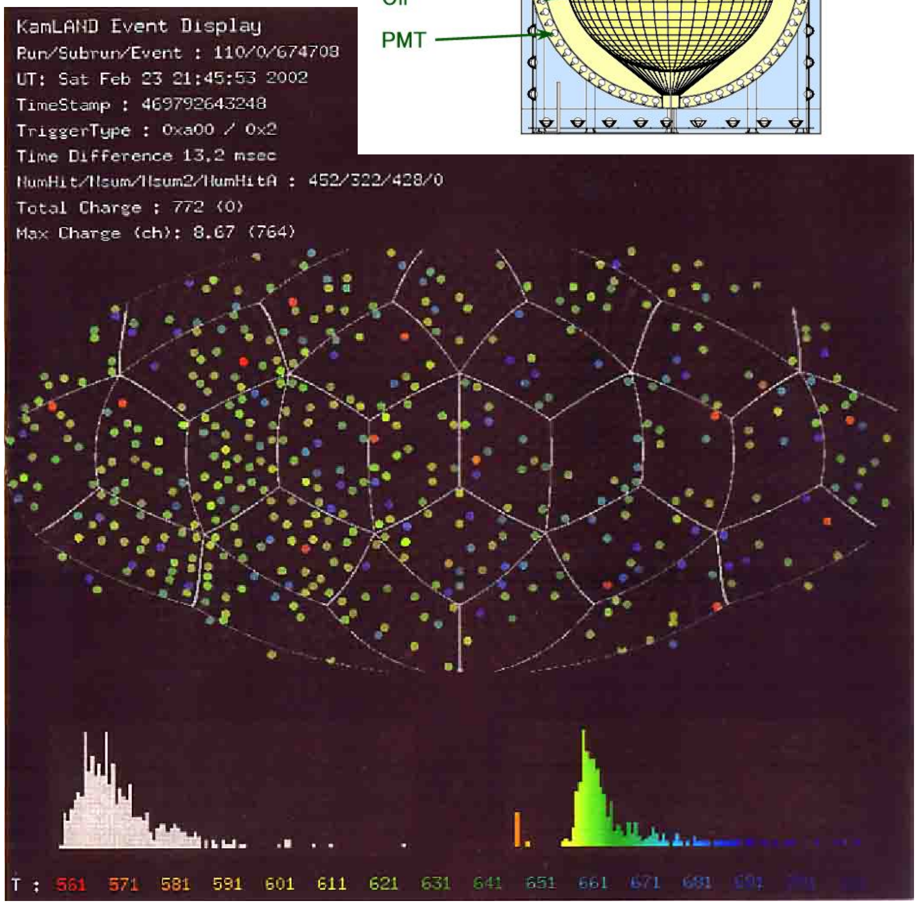
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Modern-day liquid scintillator detectors

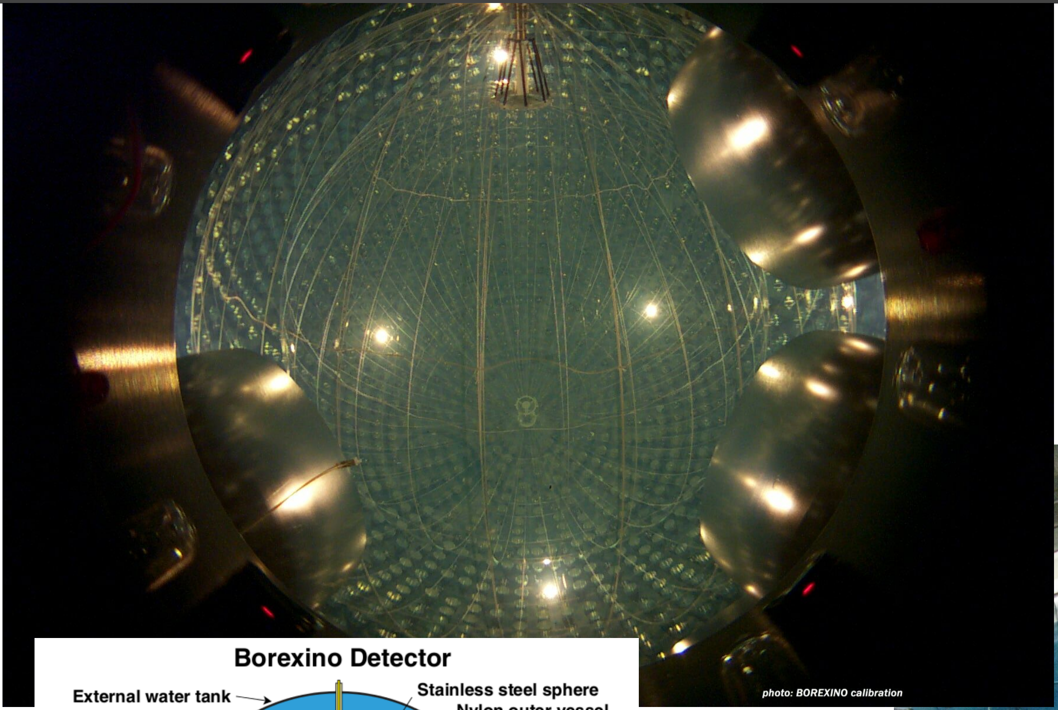
- Measure all of the energy a particle deposits in the detector using scintillation light
- Determine position of an interaction using timing and density of collected photons at each photodetector

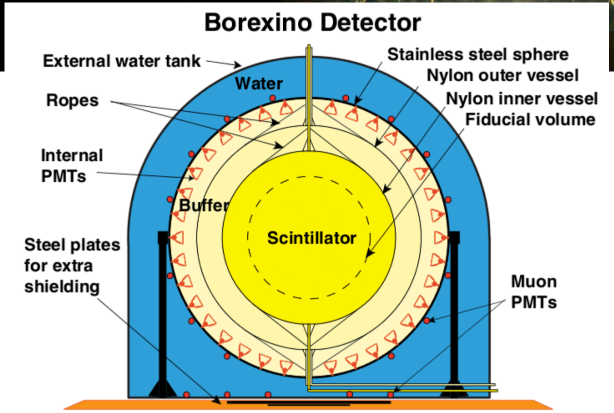




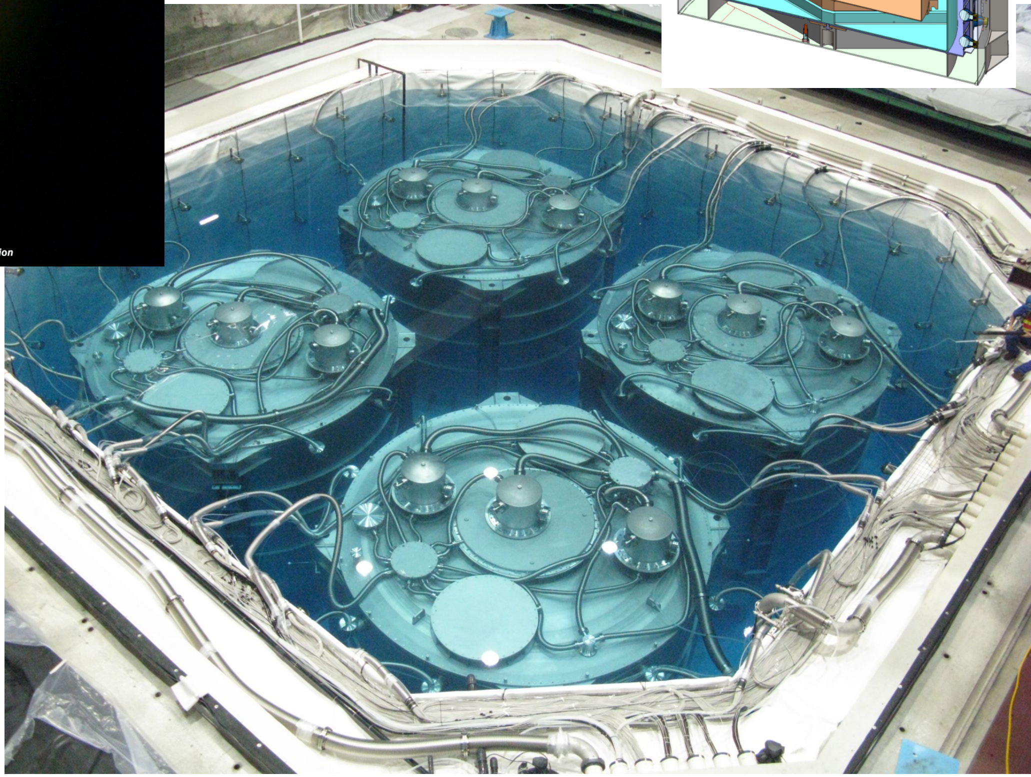


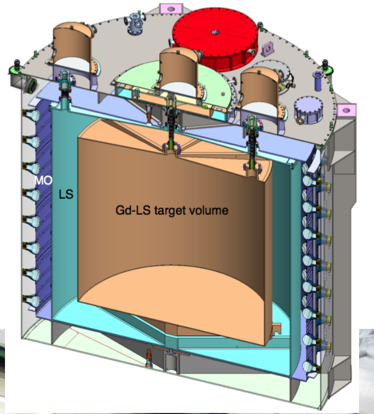
Typical Modern Liquid Scintillator Detectors



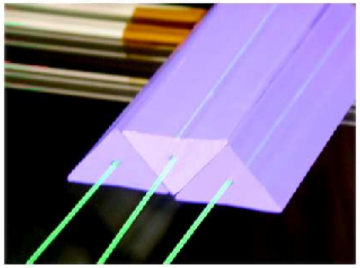


Daya Bay

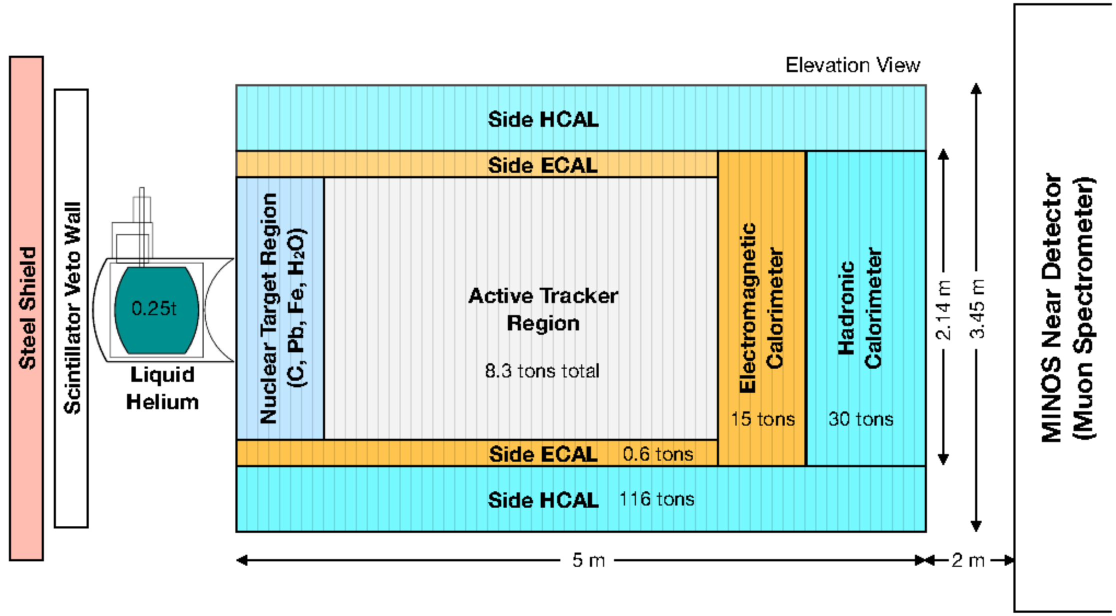


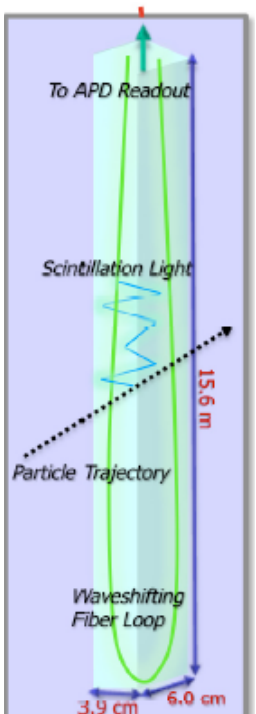


Segmented Scintillator Detectors

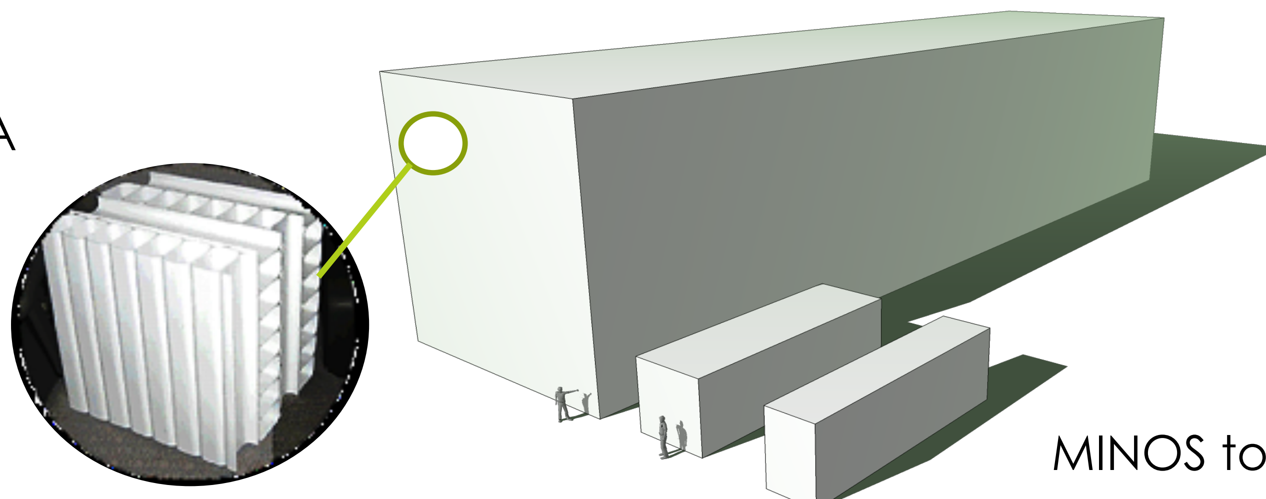


MINERvA





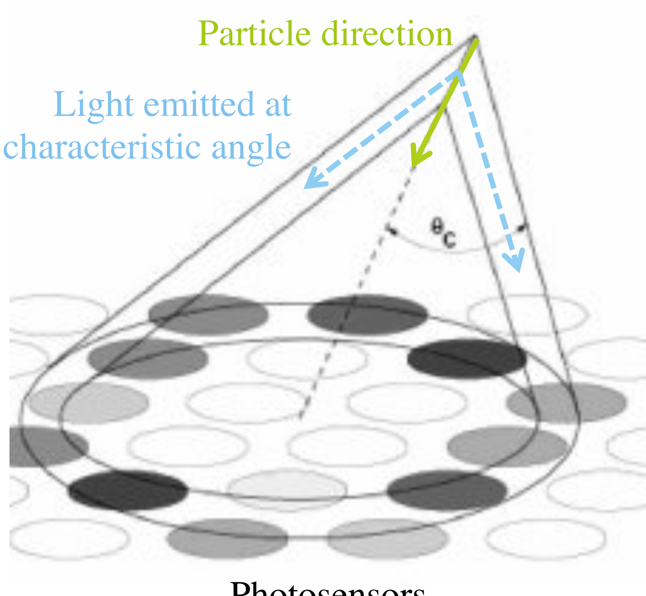
NOvA



MINOS too!

Cherenkov radiation

- The speed of light in a material depends on the index of refraction of that material: $$c_{material} = \frac{c_{vacuum}}{n}$$
- Cherenkov light will be emitted if a particle's velocity is above the speed of light in that material: $$v_{thresh} \geq \frac{c}{n} \Rightarrow \beta_{thresh} \geq \frac{1}{n}$$
- Light is emitted at an angle: $\cos\theta_C = \frac{1}{n\beta}$

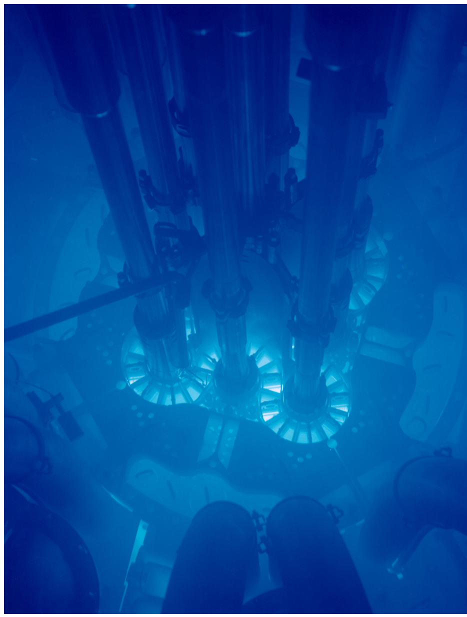


$$p_{thresh} \geq m\sqrt{\frac{1}{(n^2-1)}}$$

Particle type	Momentum threshold (MeV/c)	
	Water (n=1.33)	Oil (n=1.46)
Electron	0.58	0.48
Muon	121	99
Proton	1070	880

Cherenkov photons per unit length

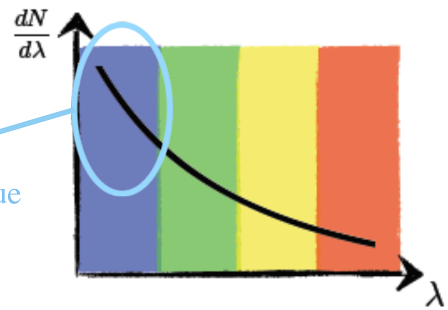
- Wavelength dependence ~ $1/\lambda^2$



Advanced Test Reactor

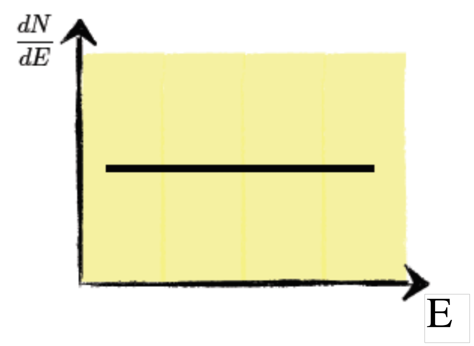
$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{2\pi\alpha z^2}{\lambda^2}\sin^2\theta_C$$

Wavelength dependence ~$1/\lambda^2$

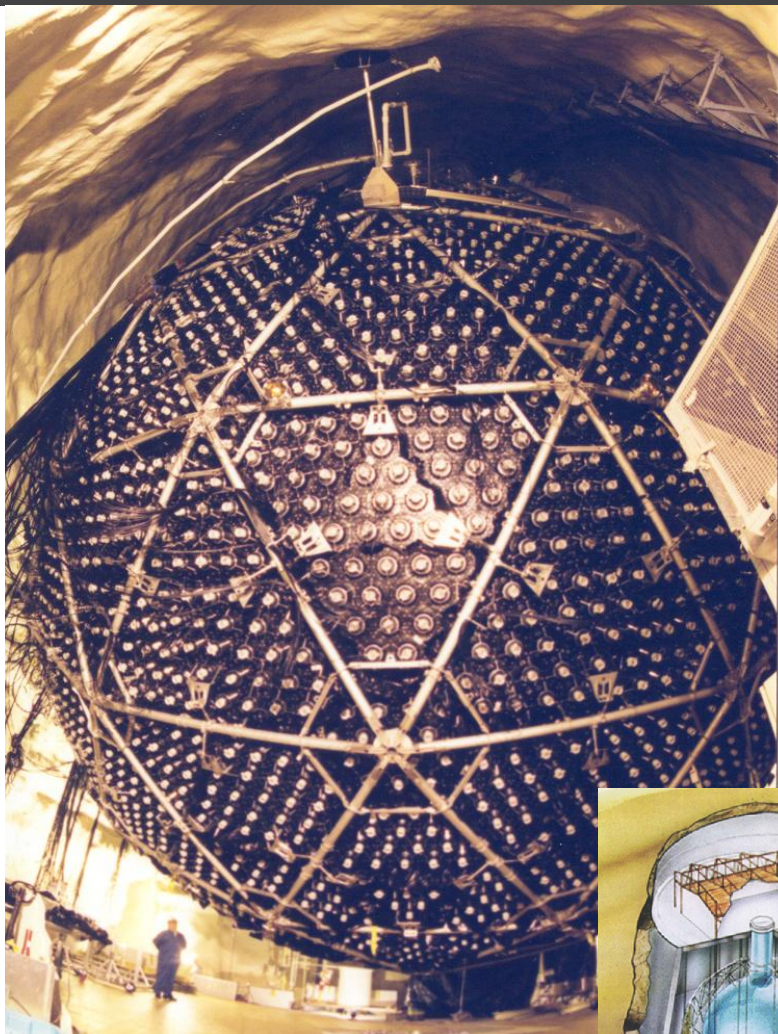


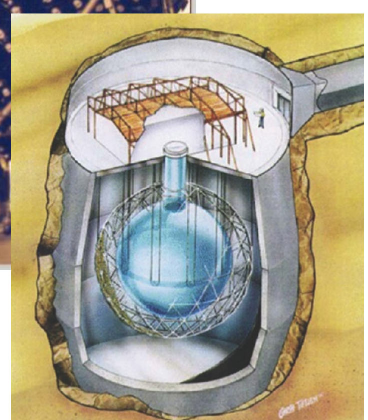
- Energy dependence ~ constant

$$\frac{d^2N}{dEdx} = \frac{\alpha z^2}{\hbar c}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right) = \frac{\alpha z^2}{\hbar c}\sin^2\theta_C$$



Typical Cherenkov Detectors





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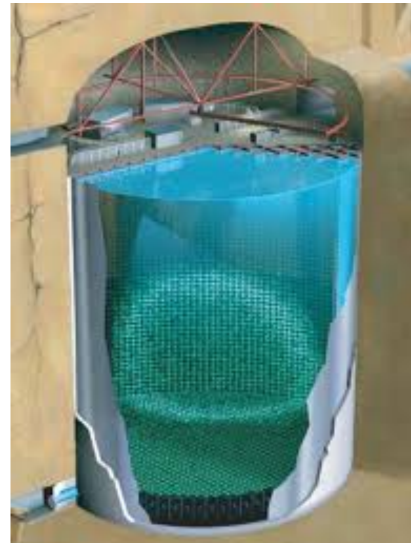
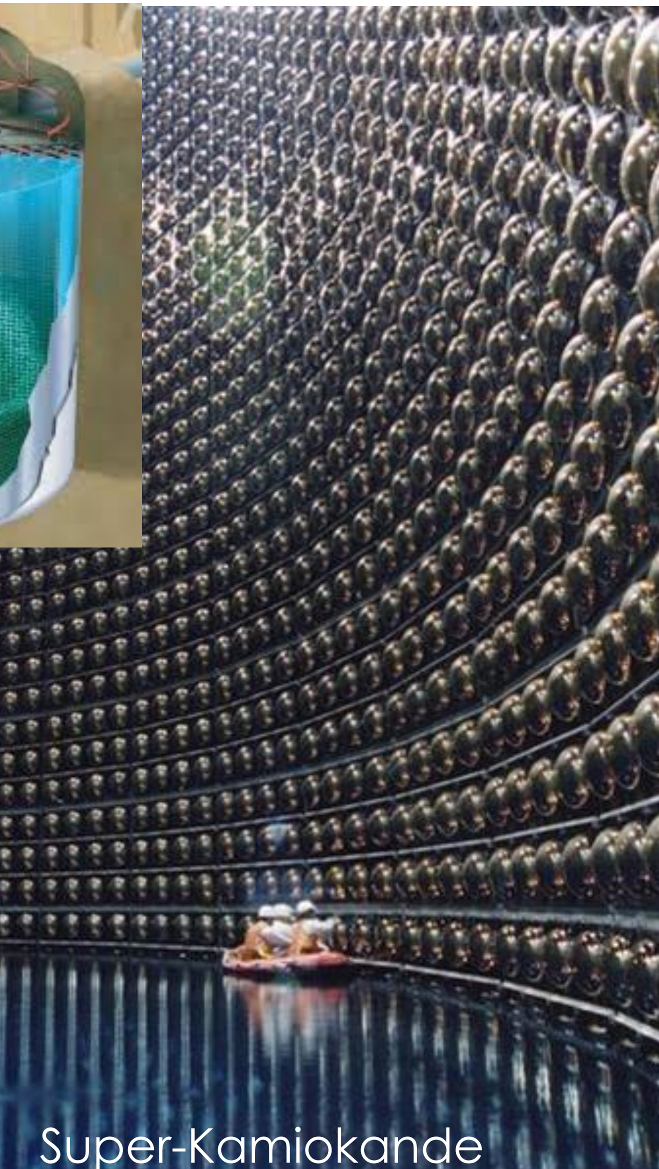
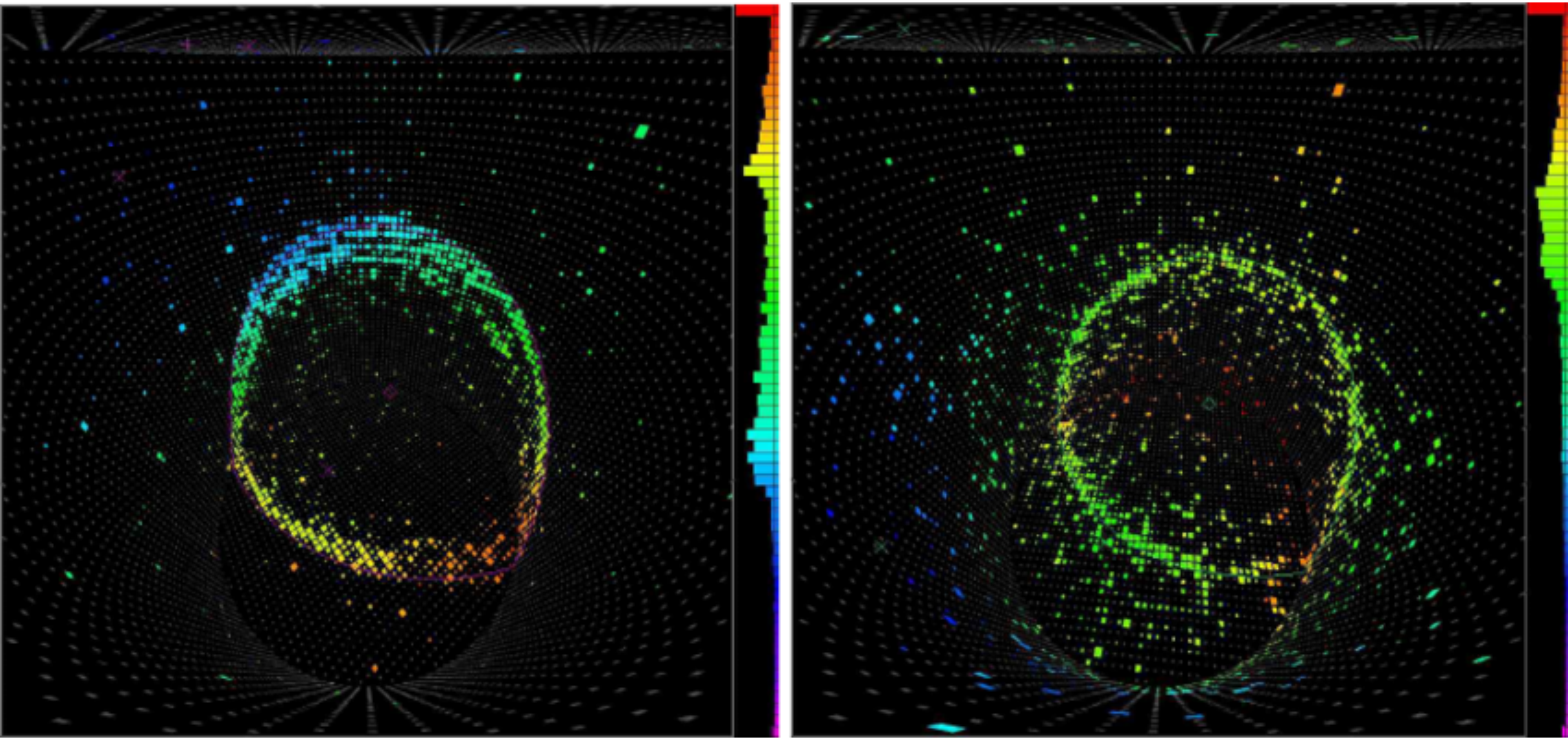




Cherenkov Challenge

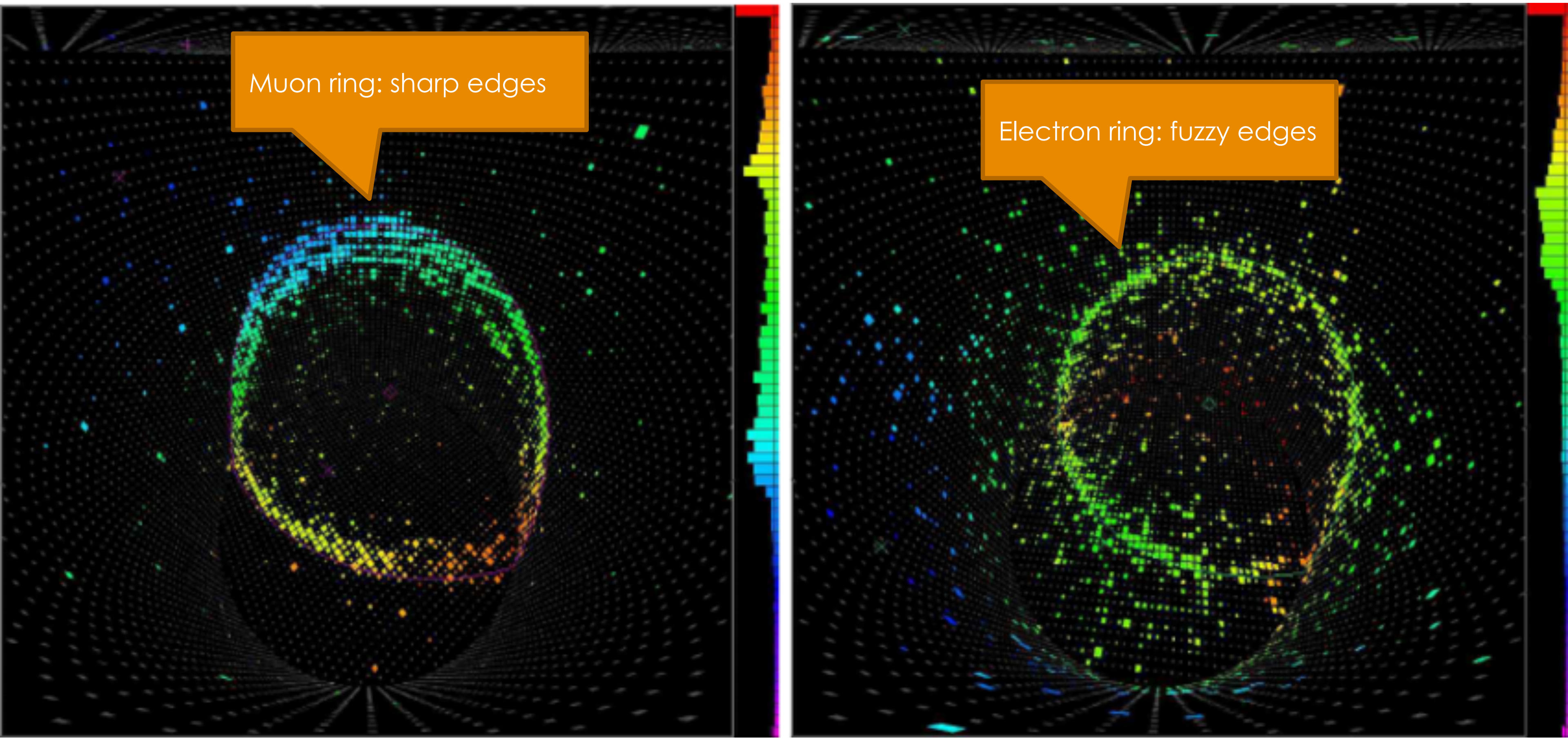
- Which ring is made by a muon?



Each "dot" is one PMT that saw light. Color indicates time (blue = early)

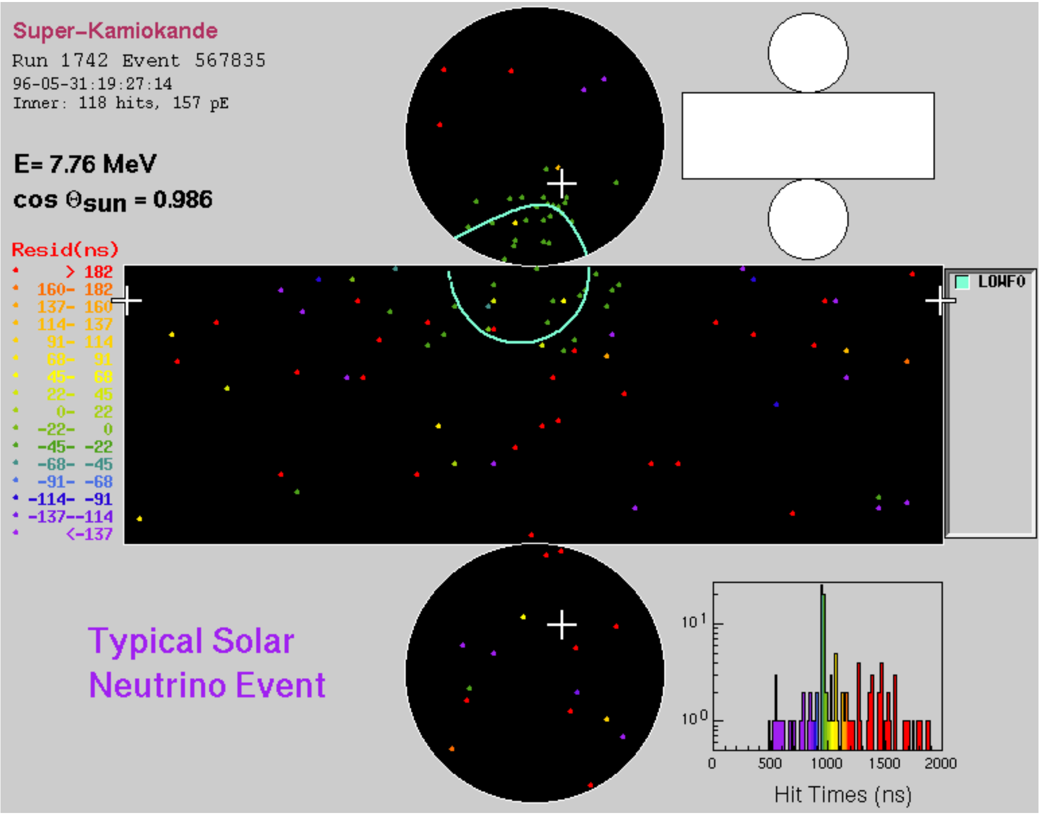
Cherenkov Challenge

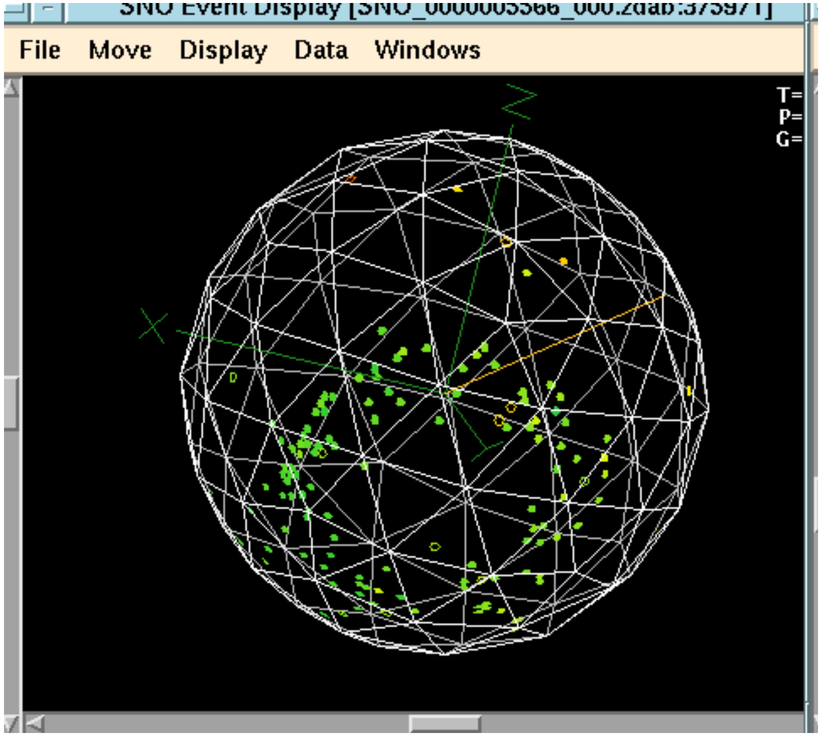
- Which ring is made by a muon?



Each "dot" is one PMT that saw light. Color indicates time (blue = early)

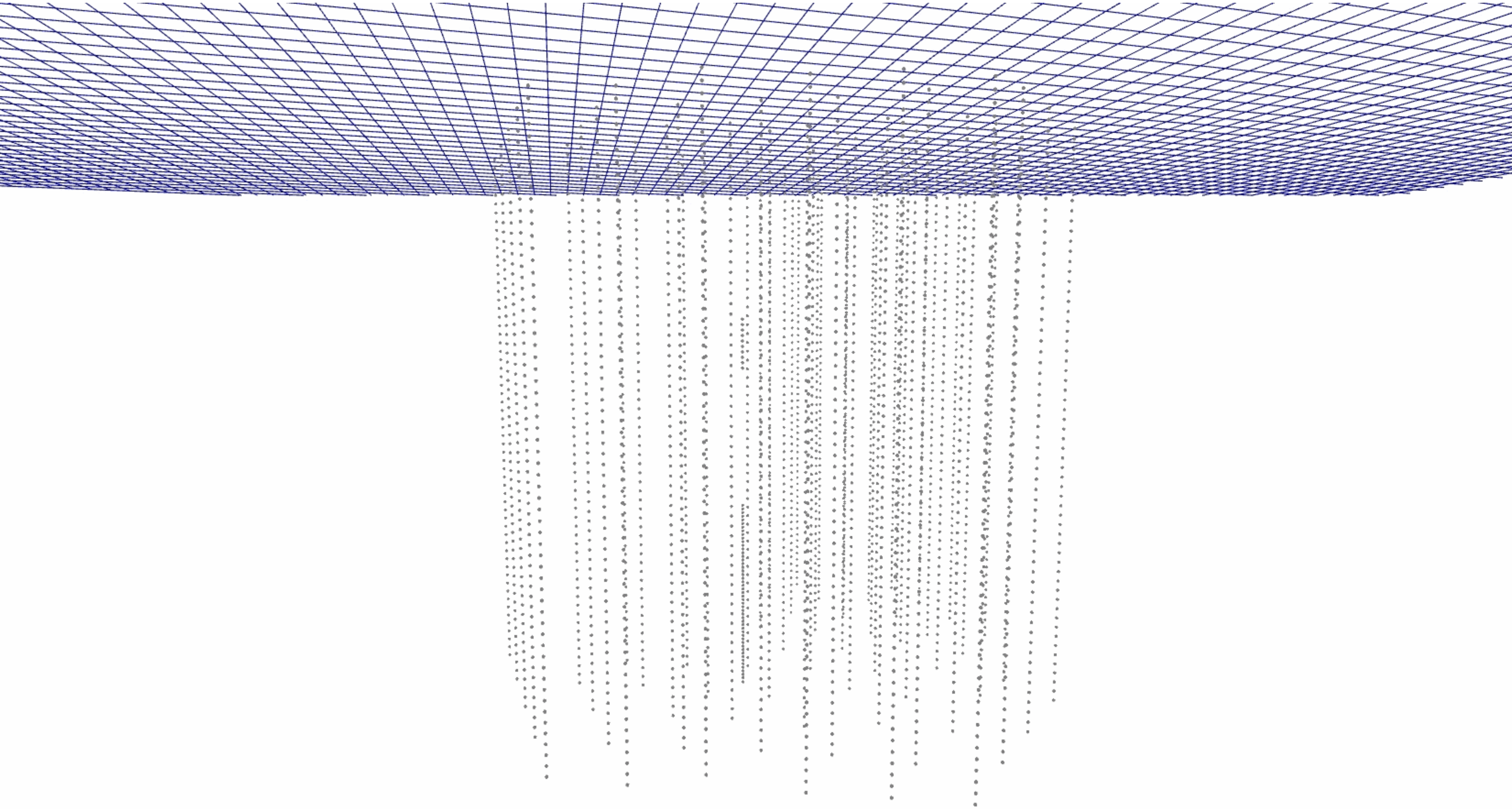
Solar Neutrino Cherenkov Rings





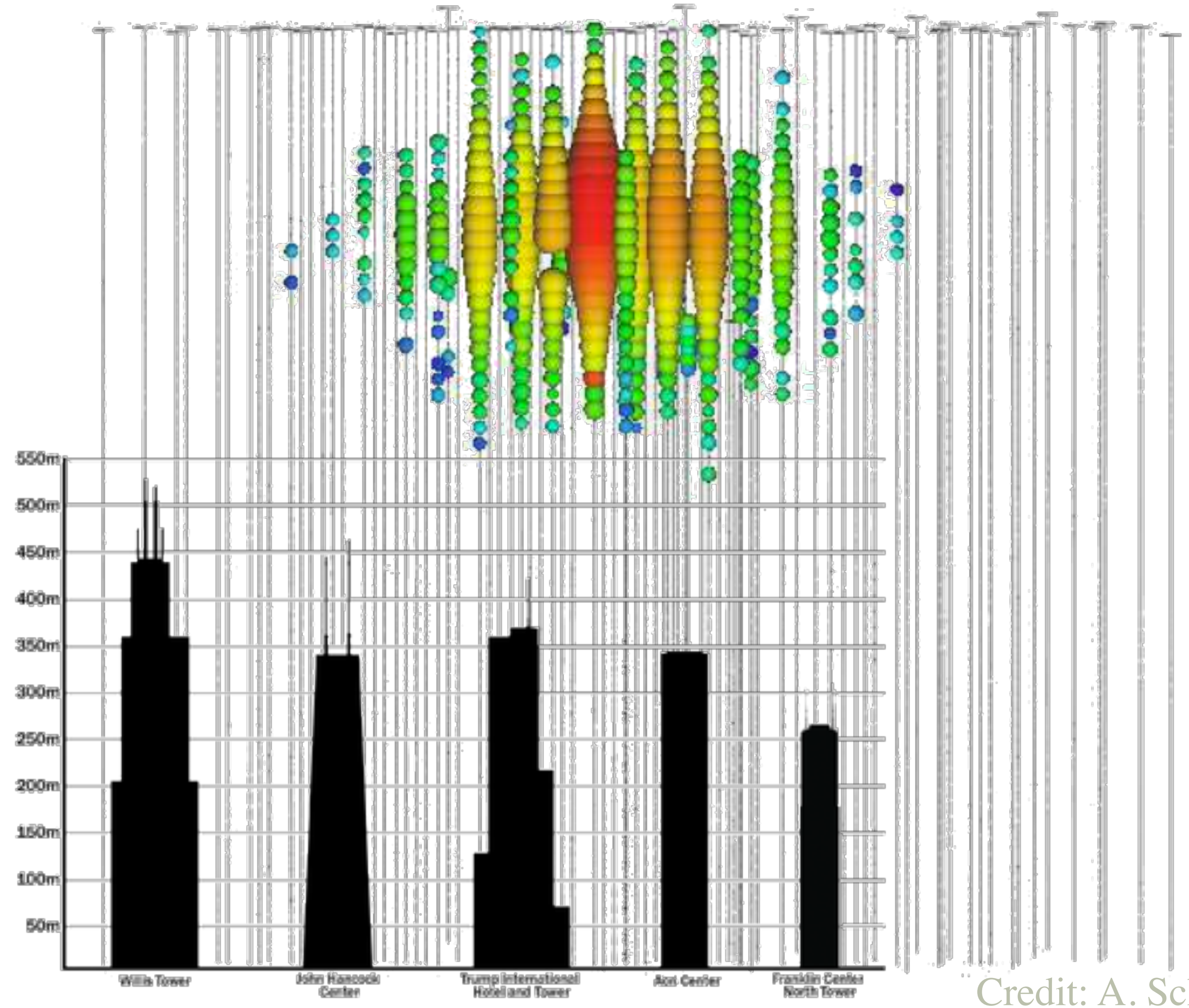
More difficult to see the ring (typical electron energy ~few MeV)

IceCube: 1 km^3 Cherenkov detector



Credit: A. Schukraft

IceCube: 1 km^3 Cherenkov detector

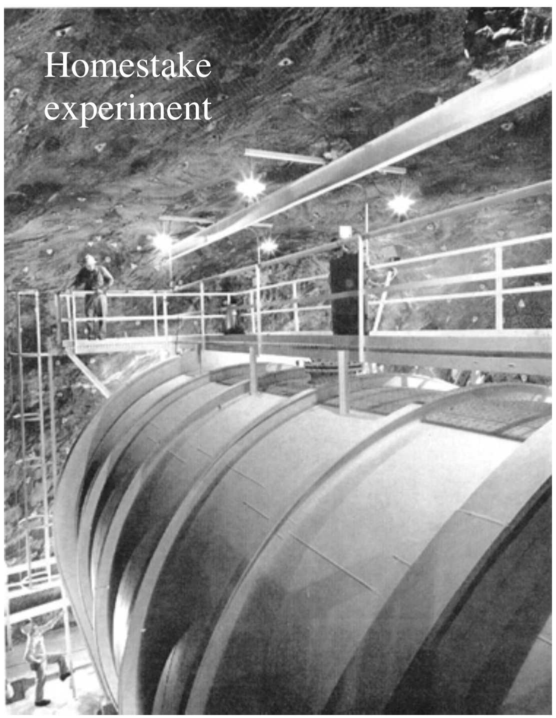


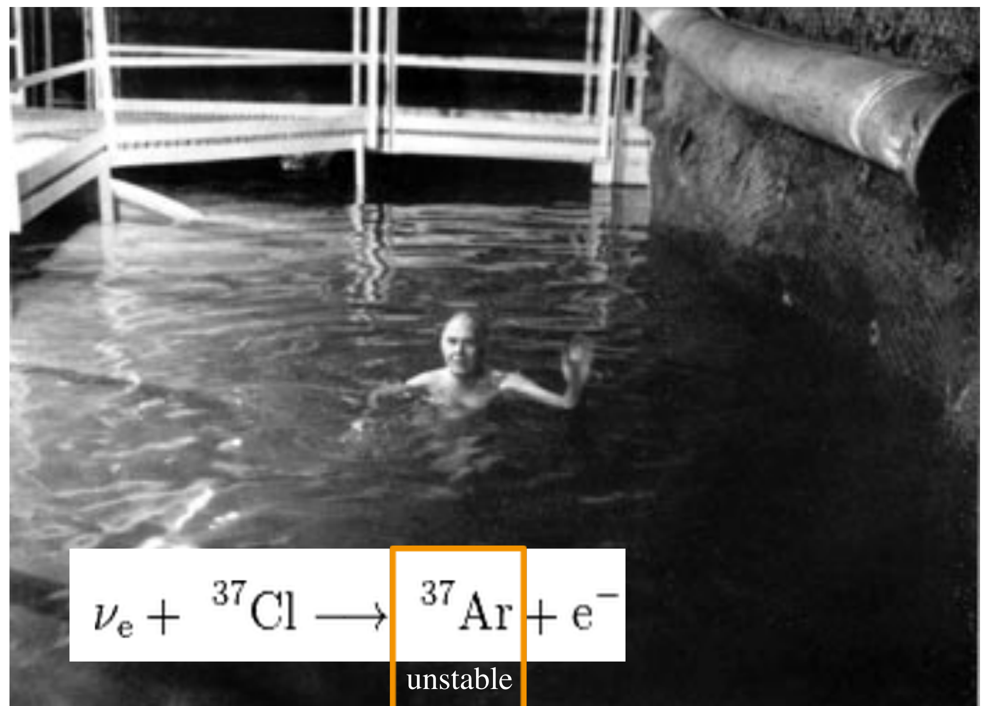
Credit: A. Schukraft

Radiochemical Experiments

- Neutrino absorbed by nucleus, converting neutron to proton
  - New nucleus is unstable
  - Chemically extract the unstable radioactive isotope from the detector and wait for its decay -- count # of decays

    Each detected decay = 1 neutrino interaction





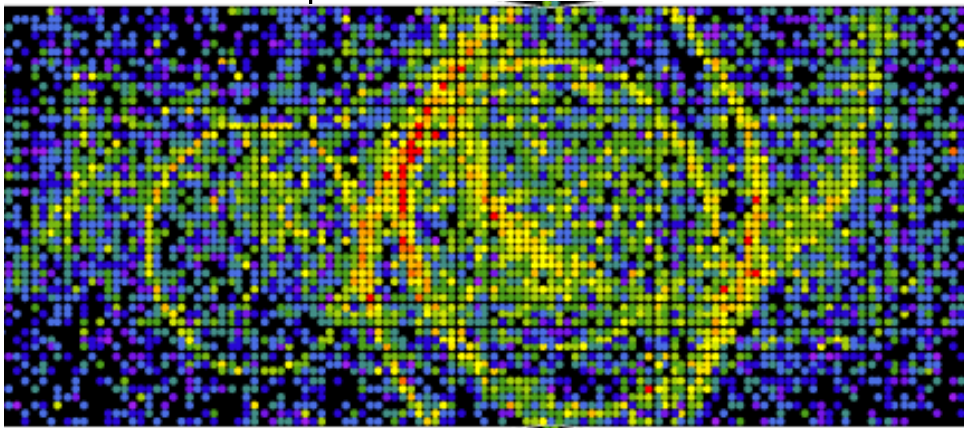
Summary/Things to Remember

- We don't see neutrinos directly; we only see the remnants of their interactions
  - Charged particles are "easily" detectable
  - Neutral particles must first interact to make a charged particle, and then we can detect them

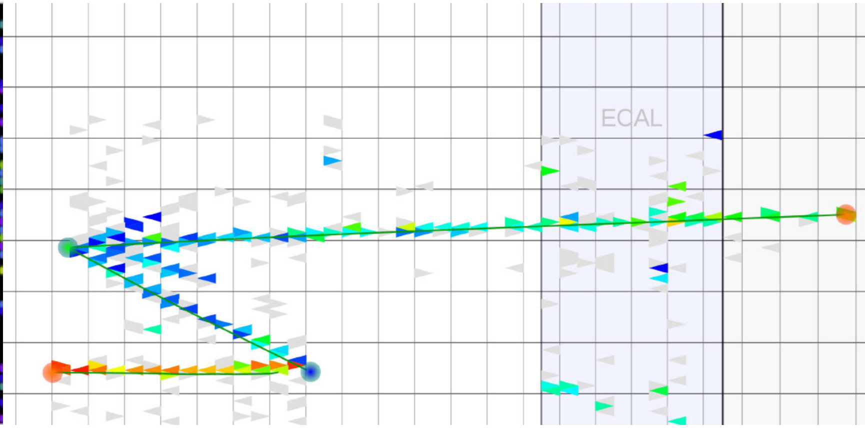
- Neutrino detectors (and all particle physics detectors) see particles by the energy they leave behind
  - Energy loss shows up mainly in the form of ionization, scintillation light, and Cherenkov light, and bremsstrahlung (at higher energies for heavy particles, even at low E for electrons)
  - We measure quantities like energy loss per unit length, particle range, and track curvature to understand the type of particle and its momentum (or energy)
  - In some sense (with caveats), the type of detector doesn't really matter, as long as you do a good job of collecting ionization and/or light...

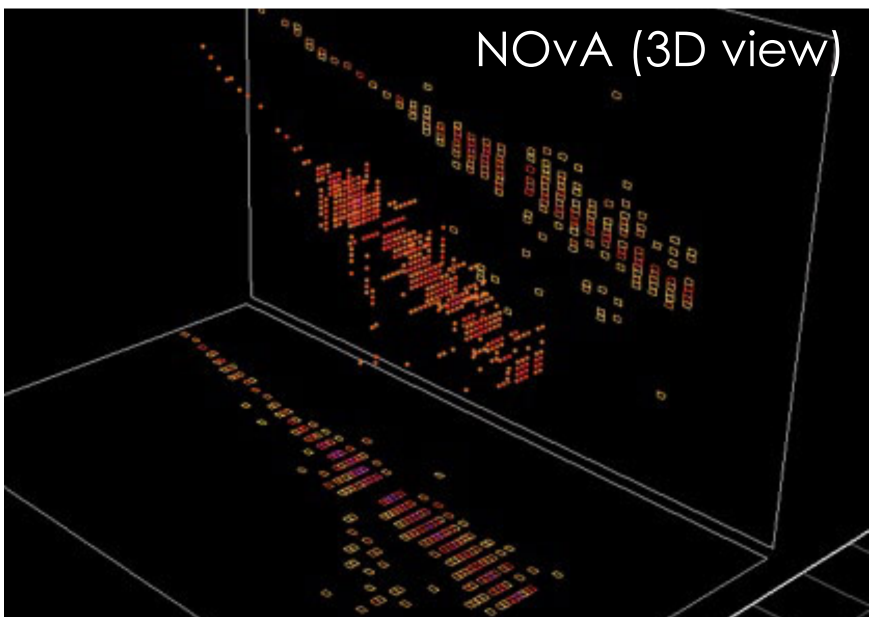
Thank you

Super-Kamiokande

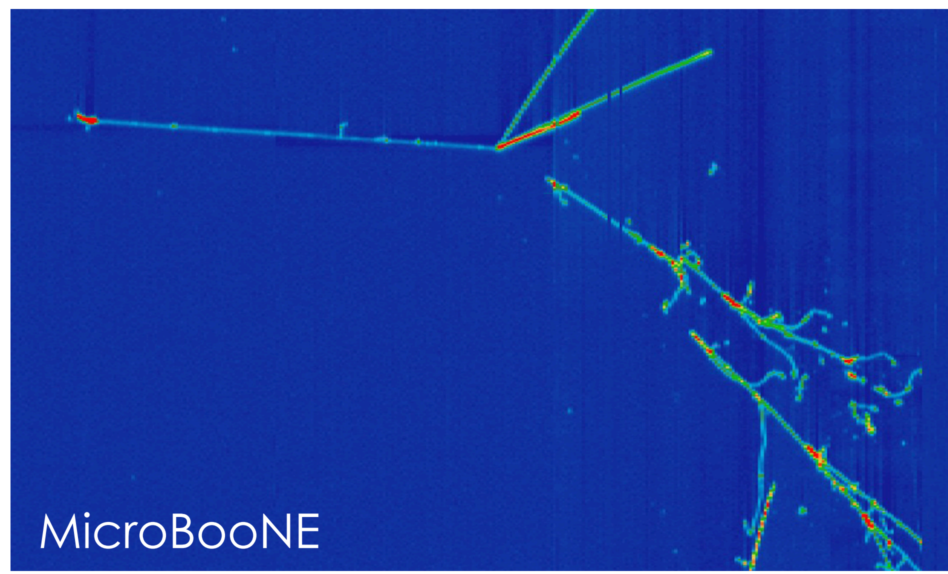


MINERvA





NOvA (3D view)



MicroBooNE

References

- M. Tanabashi *et al*. (Particle Data Group), Phys. Rev. D **98**, 030001 (2018), "Passage of particles through matter"
- W. R. Leo, "Techniques for Nuclear and Particle Physics Experiments: A How-to Approach"
- J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012), "From eV to EeV: Neutrino cross sections across energy scales"

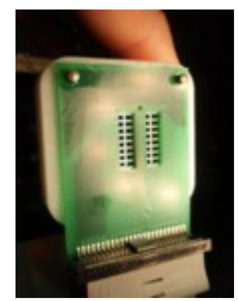
Additional slides

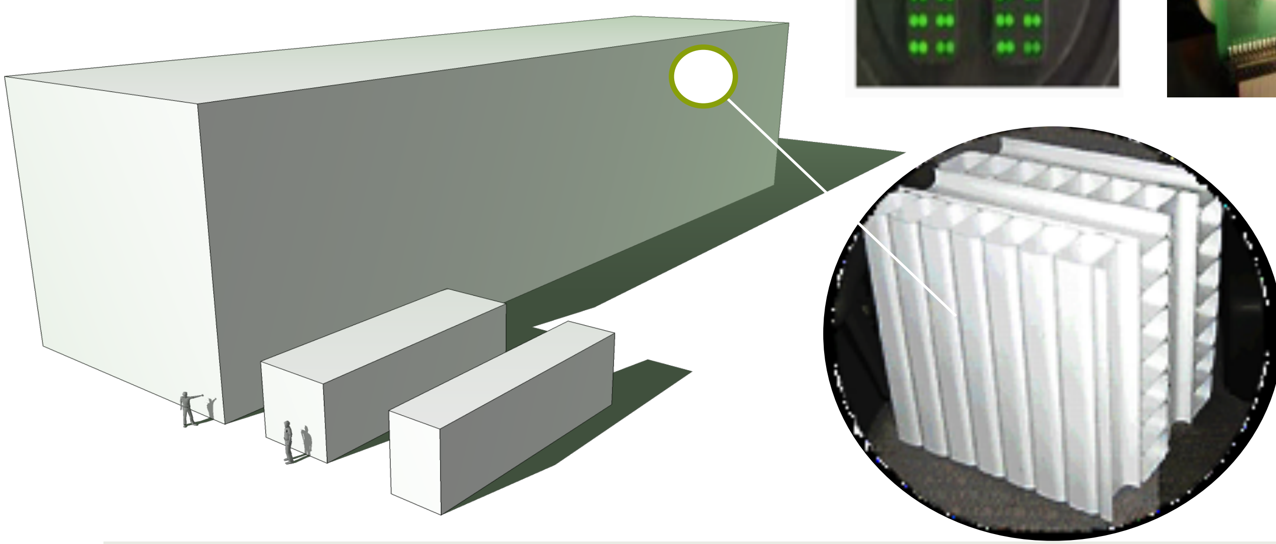
NOvA

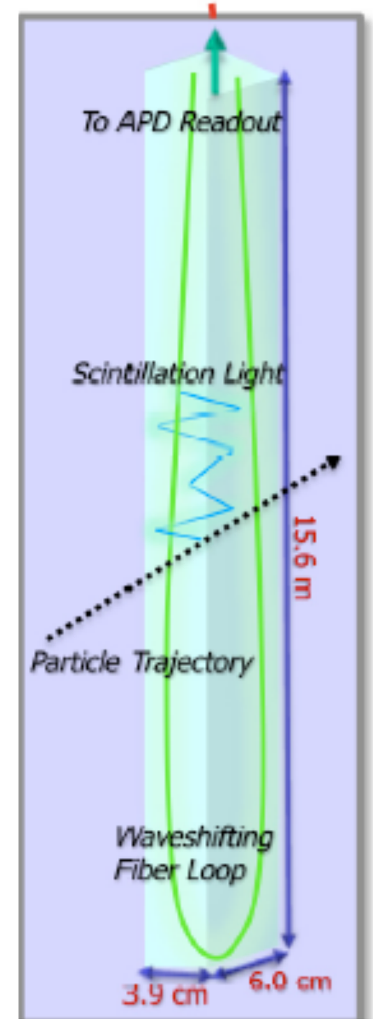
- Extruded PVC plastic tubes with a wavelength-shifting fiber inside, filled with liquid scintillator (mineral oil + pseudocumene)
  - Scintillation light deposited in each tube is proportional to the energy the particle lost in that tube
  - Wavelength-shifting fiber shifts the light to range in which the photodetector (APD) is sensitive, and transports it down the tube to the photodetector
- 14,000 ton Far Detector
  - 344,000 detector cells read by APDs
- 300 ton Near Detector
  - 18,000 cells (channels)

Both ends of fiber go to one pixel

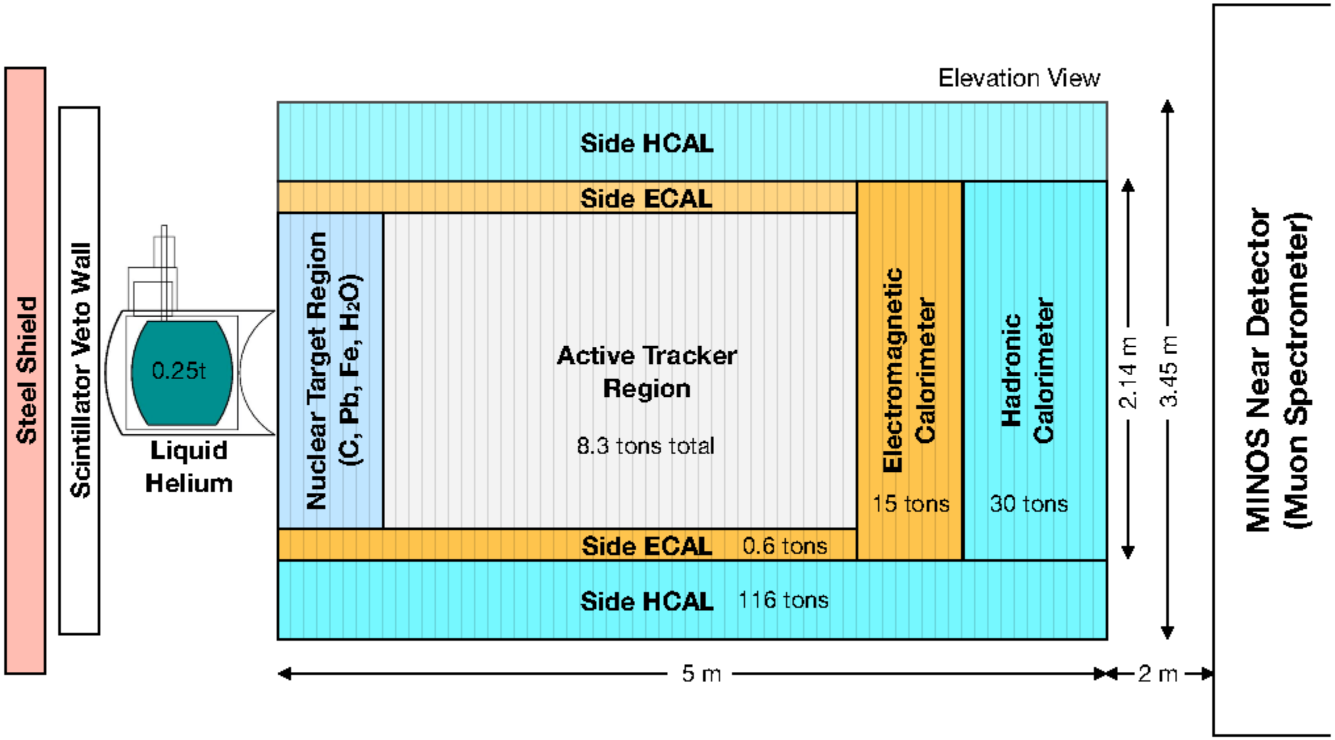
32-pixel APD



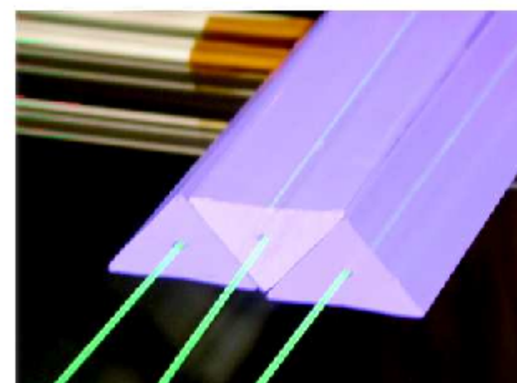




MINERvA



- MINERvA uses bars of plastic scintillator with a wavelength-shifting fiber running along length of bar. Fibers from 64 bars are attached to a 64-channel PMT
- Light collected in each bar is proportional to the energy deposited by the particle



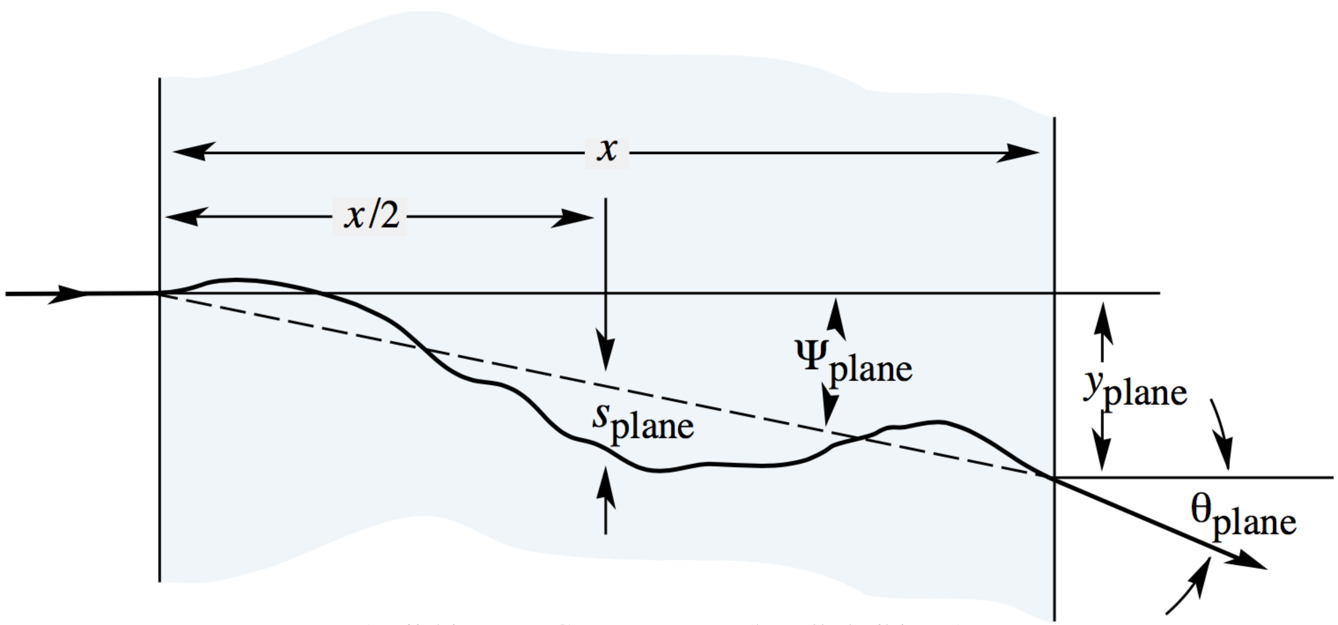
Energy loss by light production

- Charged particles can produce light in materials
  - **Scintillation** in some materials, due to excitation and ionization
  - **Transition radiation** when a charged particle crosses a boundary of two materials with different dielectric constants
    - Not typically used as main detection principle for neutrinos, so I won't cover it here aside from definition

      From Wikipedia: "…the electric field of the particle is different in each medium, [and] the particle has to 'shake off' the difference when it crosses the boundary"
  - **Cherenkov radiation** when the particle is traveling faster than light travels in that material
- Neutral particles (γ and n) must interact first, and the resulting electrons, protons, recoiling nuclei or other charged hadrons produce light

Multiple Coulomb Scattering

- A charged particle traversing a material is deflected by many small-angle scatters in the electric fields of nuclei, known as Coulomb scattering
  - Heavy particles aren't affected too badly, so a straight track assumption is not unreasonable
  - Electrons, due to their small mass, are more affected by Coulomb scattering
- Typically a large number of scatters, in the mostly-forward direction. No significant energy loss.

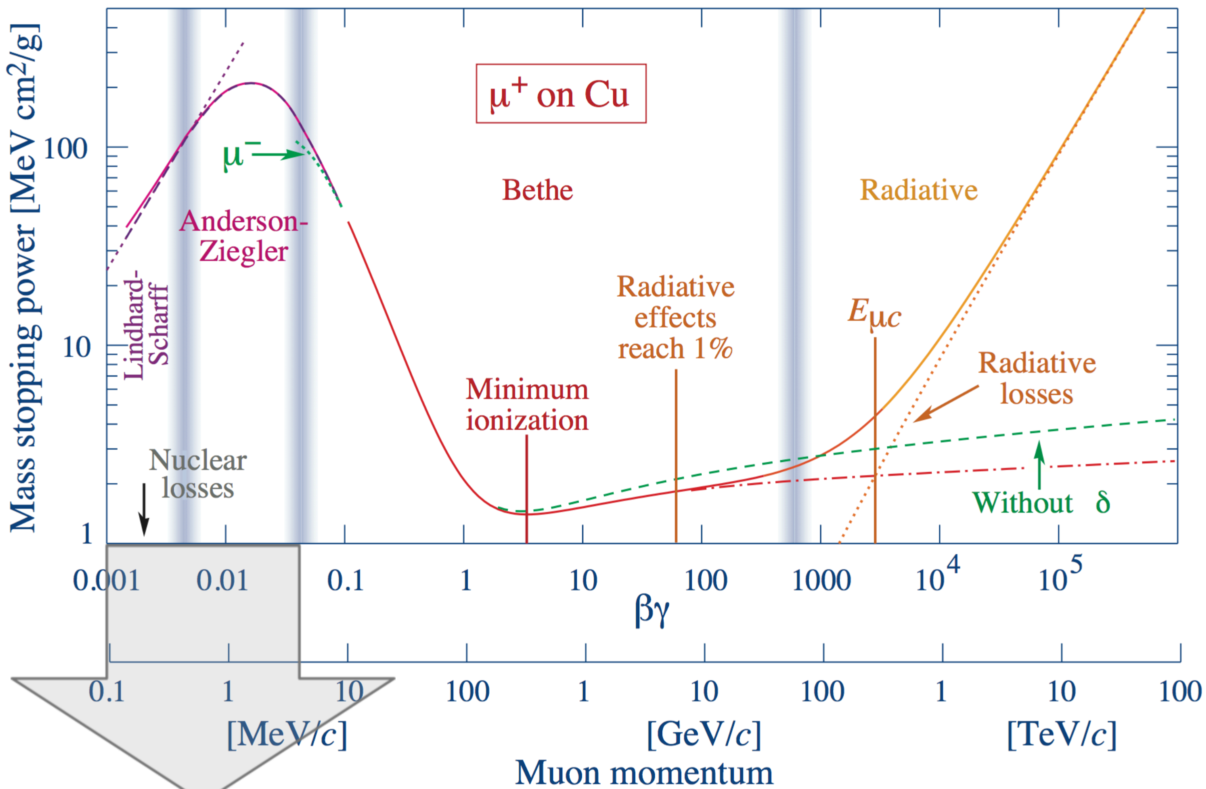


Available on PDG WWW pages (http://pdg.lbl.gov)

“Heavy” charged particles (i.e., not electrons)

- For particles with $\beta\gamma \lesssim 0.05$, non-ionizing energy loss
  - Bethe equation needs “shell corrections” added to correct for atomic binding. This works down to β~0.05; below that, the particles are moving at about the same speed as the outer shell atomic electrons, and stopping power is proportional to β

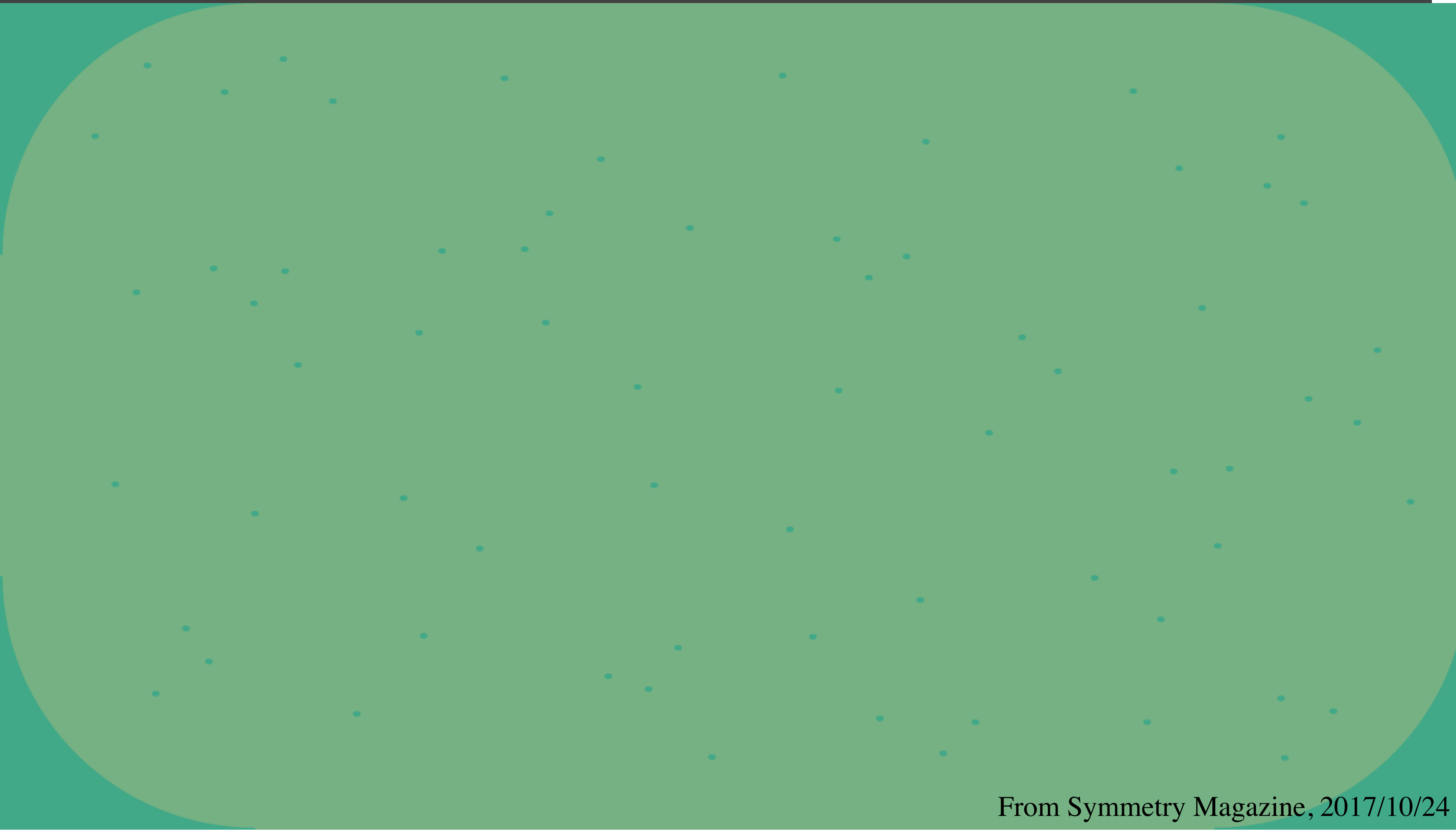
To get mean energy loss (MeV/cm), must multiply by density of material



For β~ 0.05-0.1, Bethe equation needs “shell corrections” added to account for atomic binding

Below β~0.05, particles are moving at about the same speed as the outer shell atomic electrons, and stopping power is proportional to β

Particle interactions ≠ billiards



From Symmetry Magazine, 2017/10/24

Probability of interaction for billiard balls depends on the sizes of both, and how well they're aimed at each other...

Particle interactions ≠ billiards

From Symmetry Magazine, 2017/10/24

Elementary particles don't behave like billiard balls -- they instead behave as waves of probability, so they might interact but not guaranteed. We talk about a particle's "interaction cross section," which is proportional to the probability of the particle interacting.