Neutrino Experiment II

2nd JENNIFER Summer School 2018
ICTP, Trieste

T. Wongjirad (Tufts University)

Outline

Day 1: Detecting Neutrinos: the physics of detectors

Day 2: Principles behind different commonly used detectors

Day 3: Current neutrino experiments: Physics!

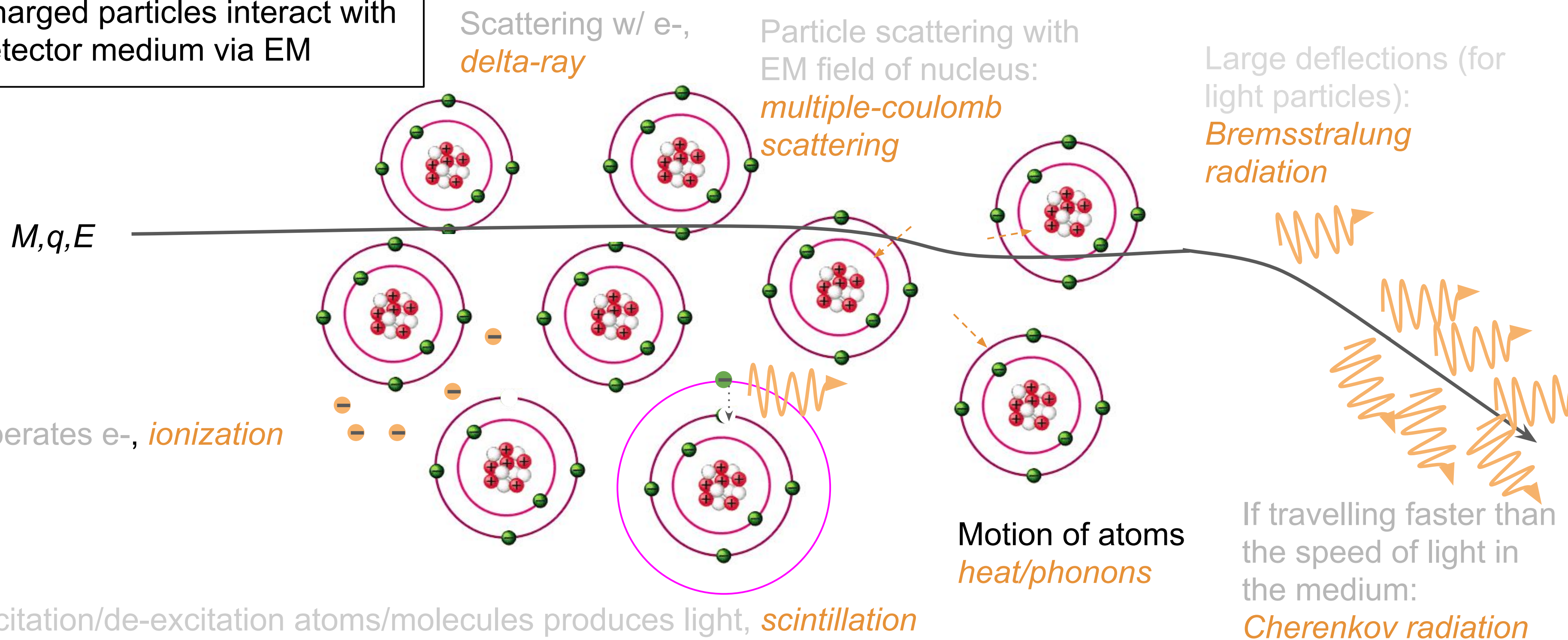
Please send me experiments or topics you might want to hear about -- especially if there are neutrino-related topics you might be interested to work on in graduate school

Provide questions/feedback at: https://tinyurl.com/jen2-nu-exp

Thank you to the person who provided a request!

Yesterday: detector signals

Charged particles interact with detector medium via EM



Classes of Detectors

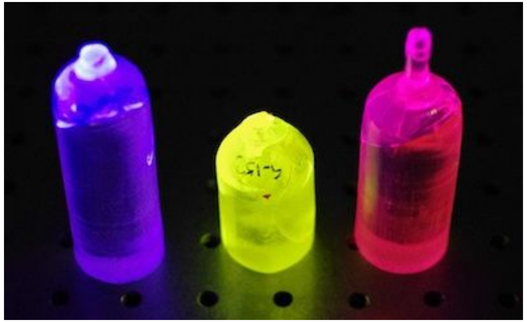
- Today we'll go through several classes of detectors and discuss how each use the various signals we talked about yesterday

Classes of Detectors

- **Scintillator detectors**
- Cherenkov detectors
- Tracking calorimeters
- Time Projection Chambers

Scintillator Detectors

- Basic principle is to instrument some scintillating medium with photodetectors
- Common media
    - Organic liquid scintillators
    - Inorganic crystal scintillators (e.g. NaI)
    - Plastic Scintillators

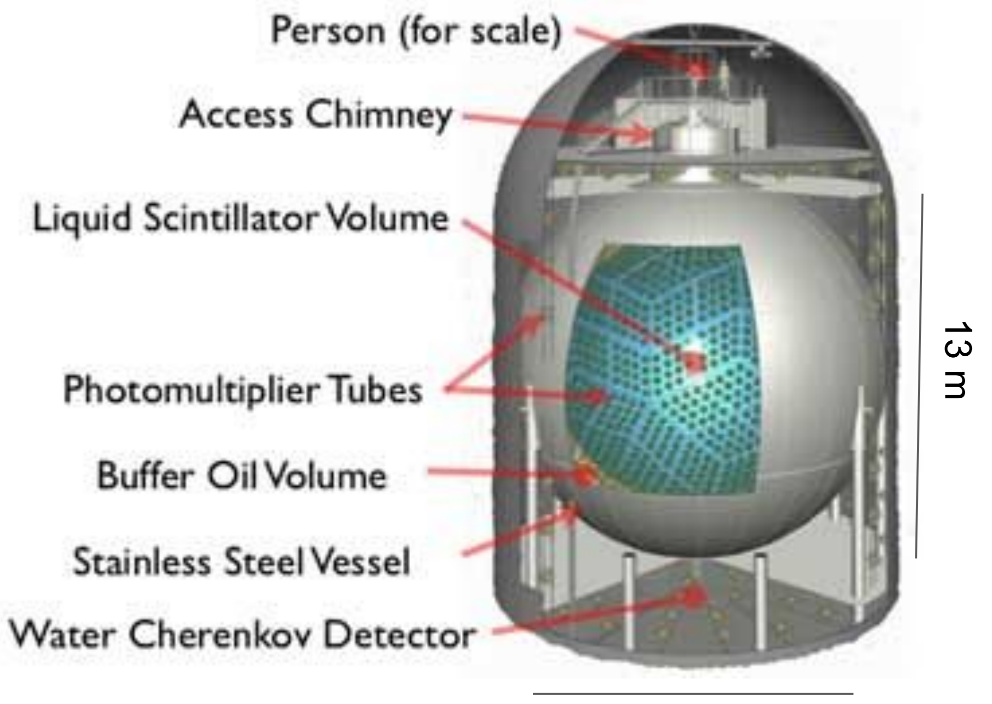


Liquid Scintillator Detectors

Example:
KAMLAND

- A giant tank, lined with photosensors and filled with liquid scintillator

The view from inside, looking up



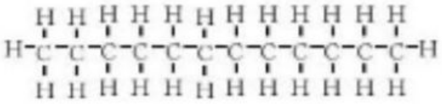
Liquid Scintillator Detectors

Example:
KAMLAND

Liquid Scintillator Detectors

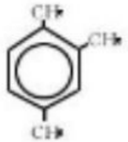
Example:
KAMLAND

- Filled with:



normal dodecane

80% by volume

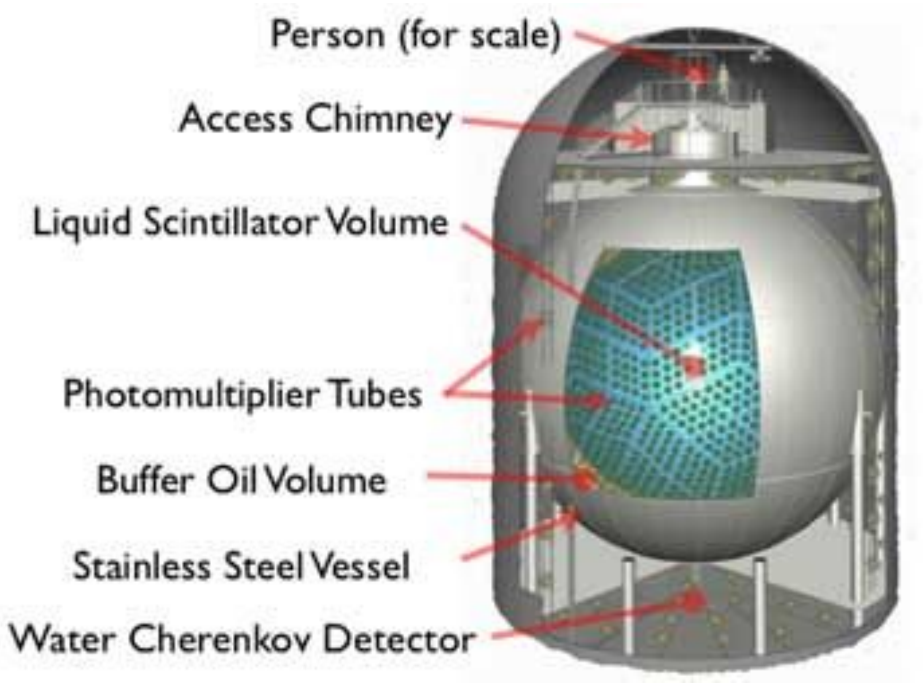


pseudocumene

20% by volume

PPO

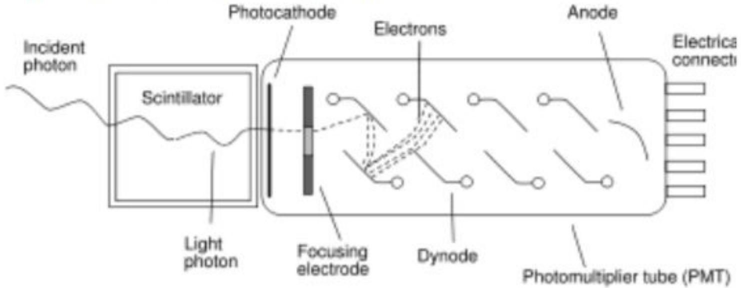
1.52 g/L



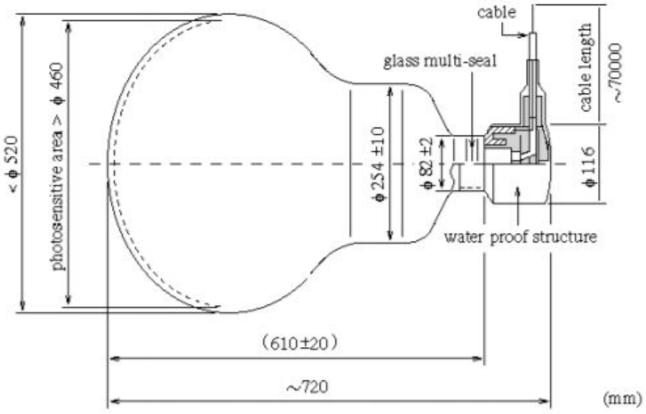
Photomultiplier tubes

Photon incident on the *photocathode* produces a *photo-electron* via the photoelectric effect. Probability to produce a photoelectron is called the *quantum efficiency* of the PMT.

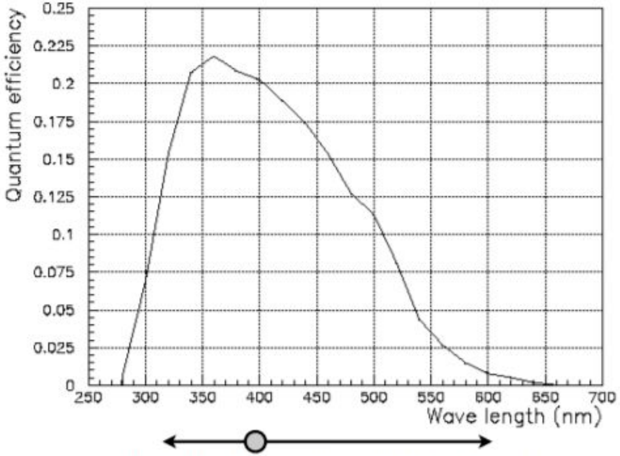
Output signal is seen as a current delivered to the *anode*. Typical *gains* are 10^6 yielding pC-scale currents



A series of plates called *dynodes* are held at high voltage by the *base* such that electrons are accelerated from one dynode to the next. At each stage the number of electrons increases. Probability to get first electron from the photocathode to the first dynode is called the *collection efficiency.*



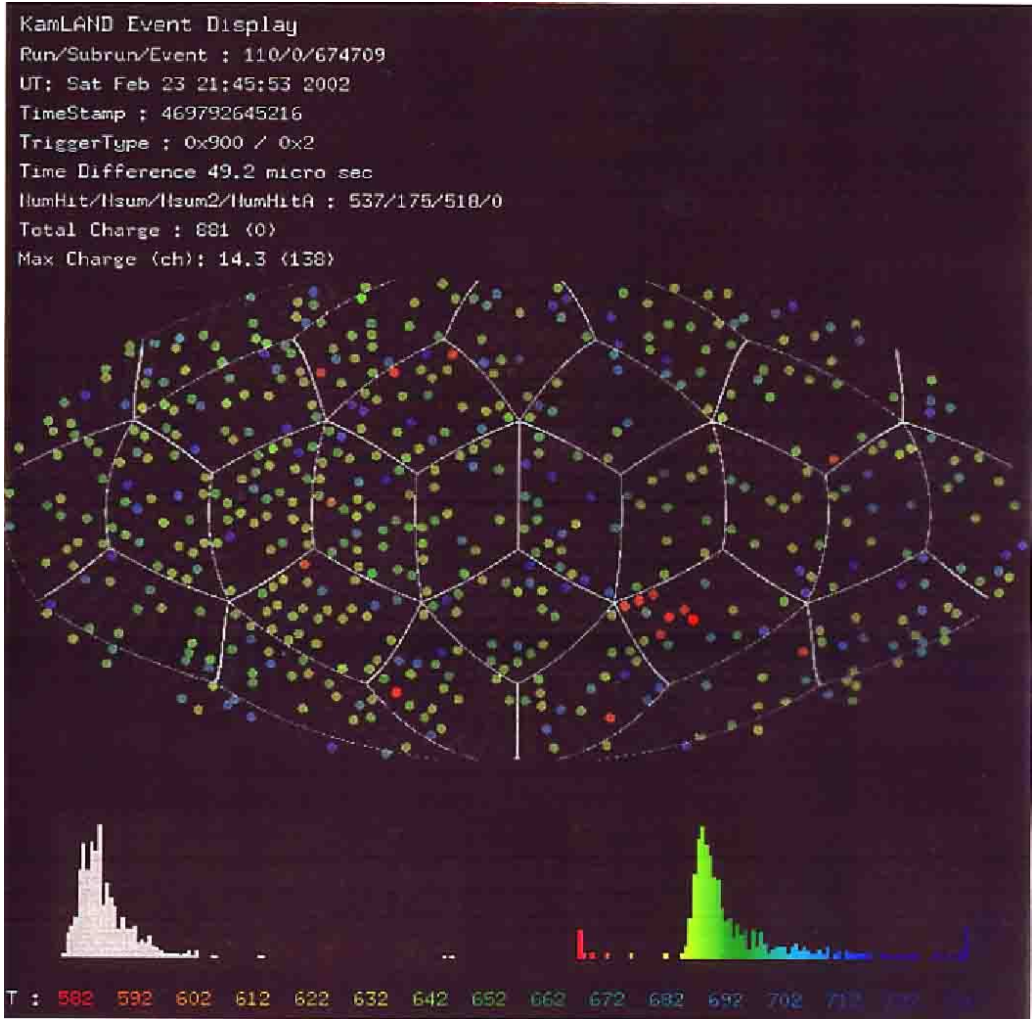
100 ns transit time, 2.2 ns time resolution



wavelength of Cherenkov photons in water

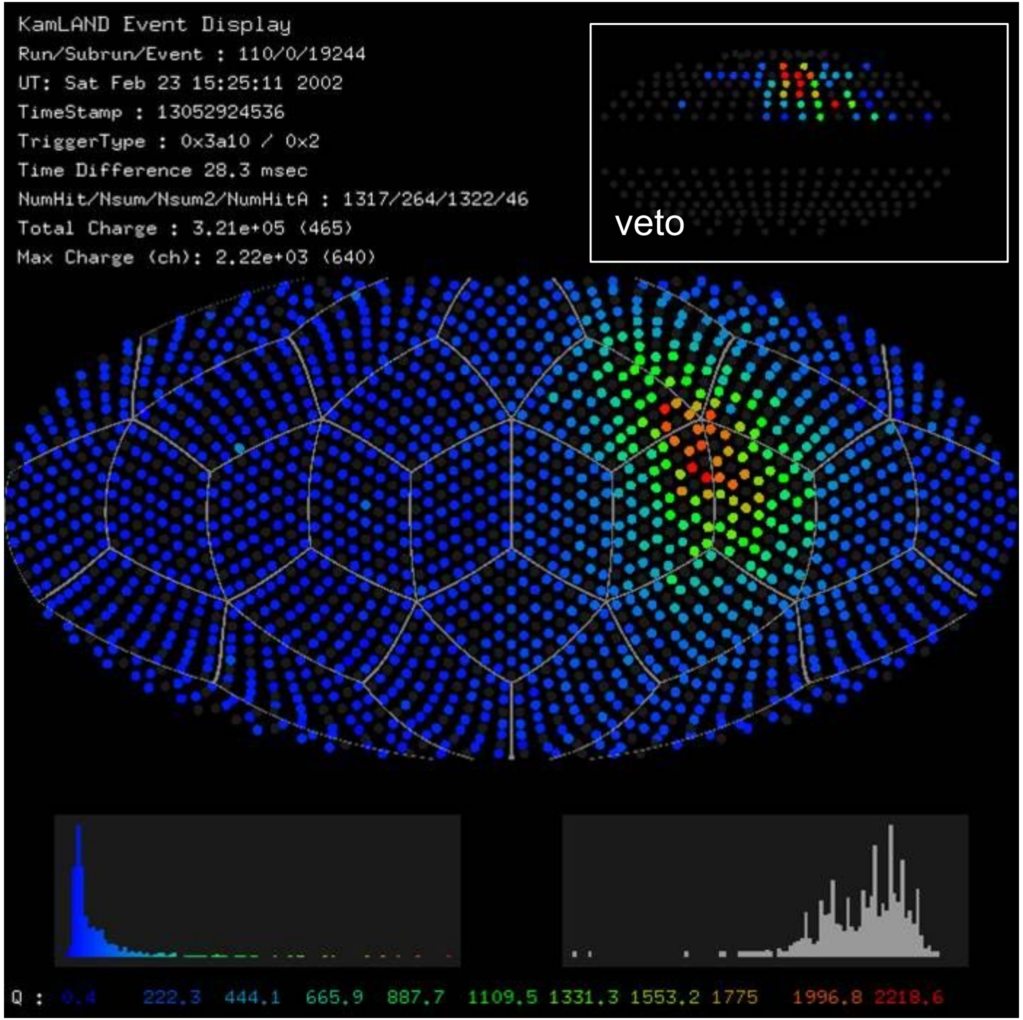
Efficiency approximately between 20-40%

Experiments quote number of photoelectrons seen, i.e. photons that this the PMT ***and*** make a detected signal



Dots show PMTs hit

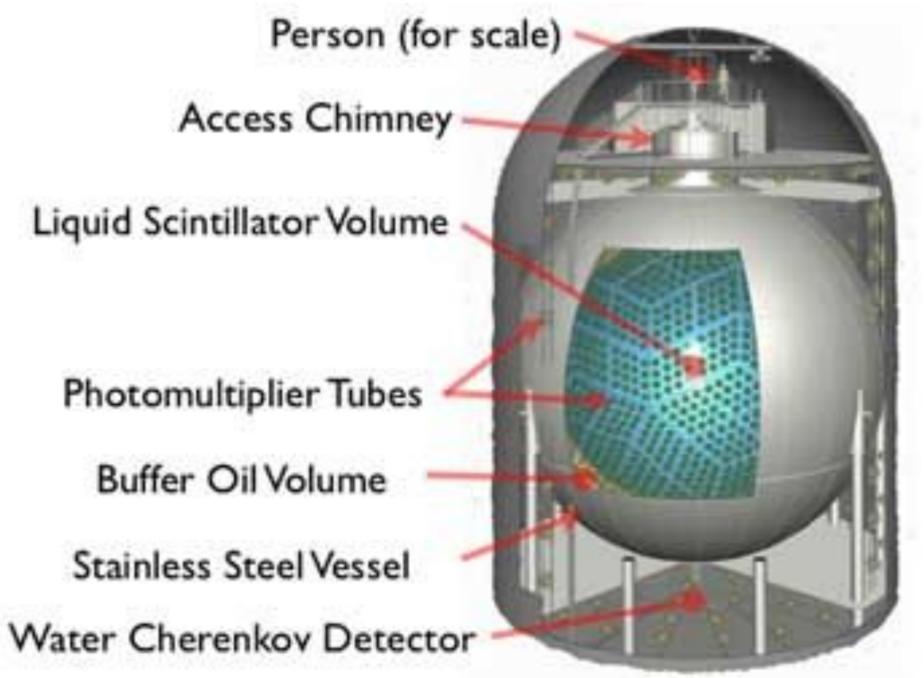
Color tells you time


KamLAND Event Display
Run/Subrun/Event : 110/0/19244
UT: Sat Feb 23 15:25:11 2002
TimeStamp : 13052924536
TriggerType : 0x3a10 / 0x2
Time Difference 28.3 msec
NumHit/Nsum/Nsum2/NumHitA : 1317/264/1322/46
Total Charge : 3.21e+05 (465)
Max Charge (ch): 2.22e+03 (640)
veto
Q : 0.4 222.3 444.1 665.9 887.7 1109.5 1331.3 1553.2 1775 1996.8 2218.6

Liquid Scintillator Detectors

Example:
KAMLAND

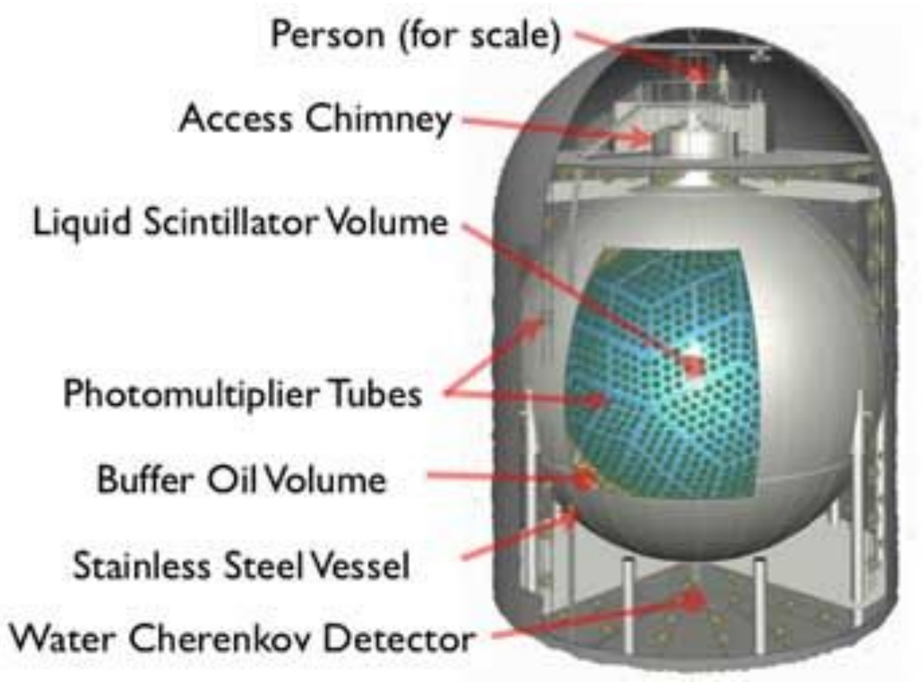
- (liquid) scintillators produce a lot of photons per MeV and are well suited to detector low-energy (~1-10 MeV) neutrino interactions
- At those energies, what kind of neutrinos can we see?



Liquid Scintillator Detectors

Example: KAMLAND

- Signal is flash of light with number of photons indicating energy of interaction
- Backgrounds come from
  - impurities that produce radioactive decays in the detector (0.1-10 MeV particles)
  - Low energy Cosmic ray particles
  - Neutrons produced by cosmic rays interacting in the walls around the detector
- Therefore, you want to shield the detector -- common is water veto
- Also, there is a buffer volume around PMTs



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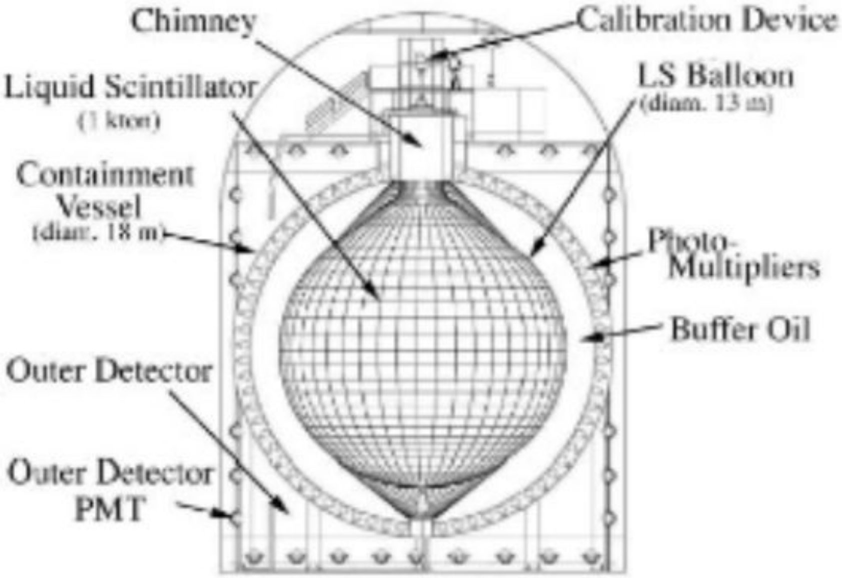
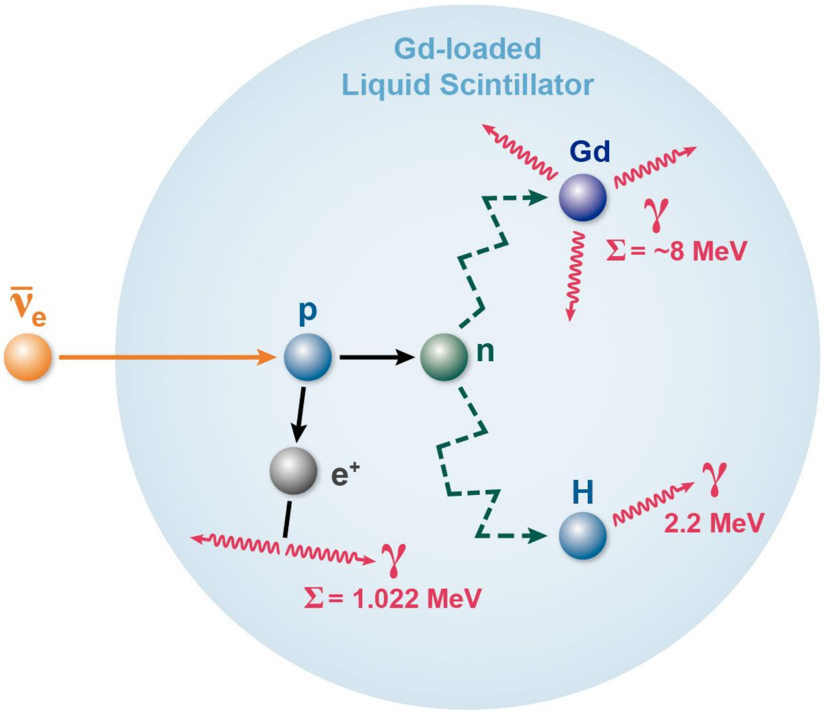


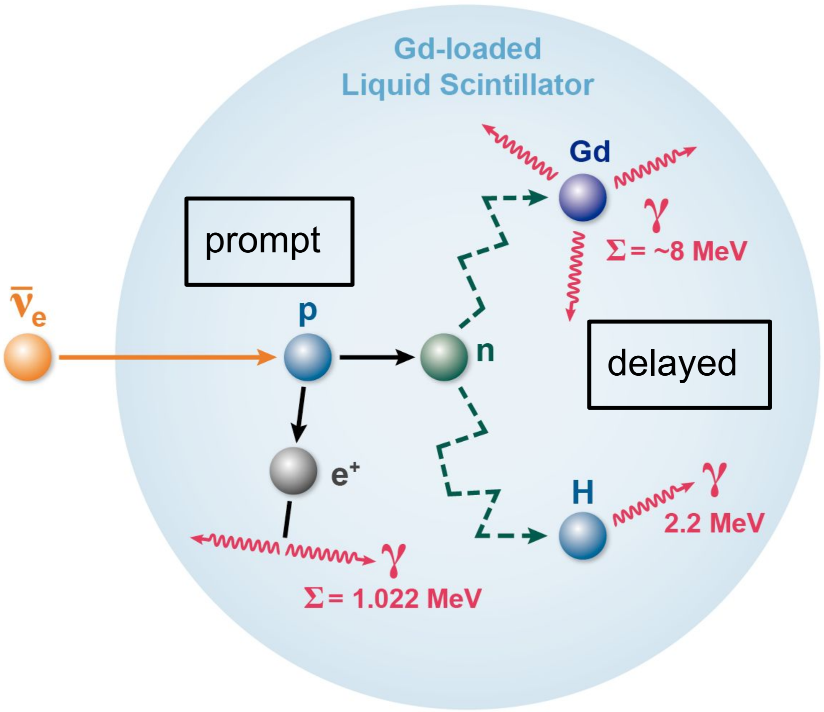
Liquid Scintillator Detectors

- Even with a veto and shielding, a single flash of light is an easy signal to mimic. What can we do to reduce backgrounds?
- *Look for interactions that produce multiple flashes of light within a short time*



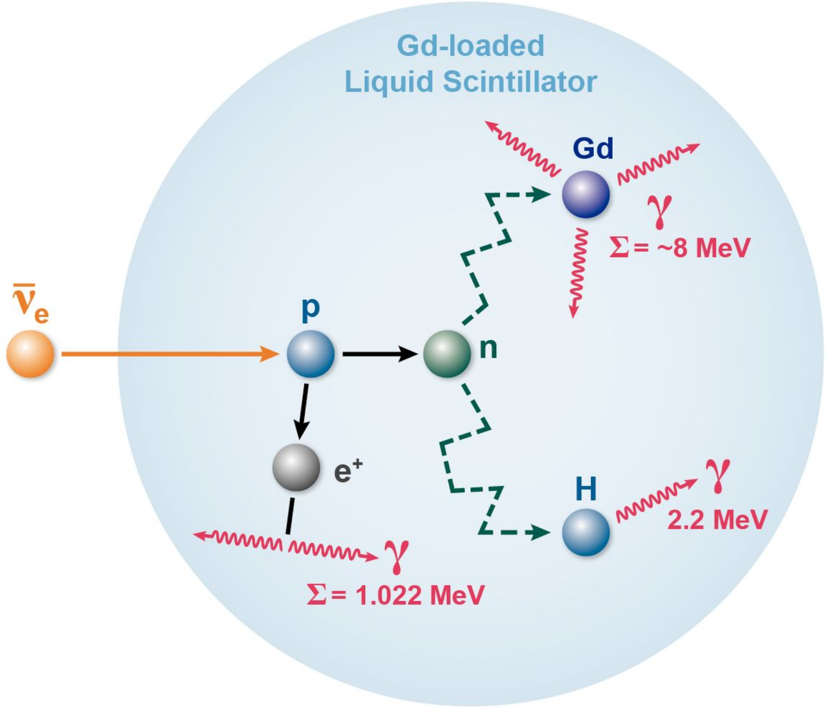
Liquid Scintillator Detectors

- Interaction is ***inverse beta decay***
- Anti-electron neutrino + proton produces a positron and neutron
- Position quickly annihilates with electron, producing photons with a total energy of 1.022 MeV + Energy of neutrino (few MeV) -- **prompt signal**
- Neutron bounces around -- about 200 microseconds -- but can eventually capture on H to make a deuteron + 2.2 MeV photon -- **delayed signal**
- Can dope with metals like Gadolinium (Gd) which have a large capture cross section AND produce photons with a higher total energy



Liquid Scintillator Detectors

- Time-coincidence is a powerful technique
- KAMLand had a single flash rate of 30 Hz
- Expected to detect only a few anti-neutrino interactions per day
- Starting with
  30 Hz x (86,400 sec/day)
  = 2.59 million background flashes !!!
- What's the fake-coincident rate for a background of 30 Hz with a time window of 600 microseconds?



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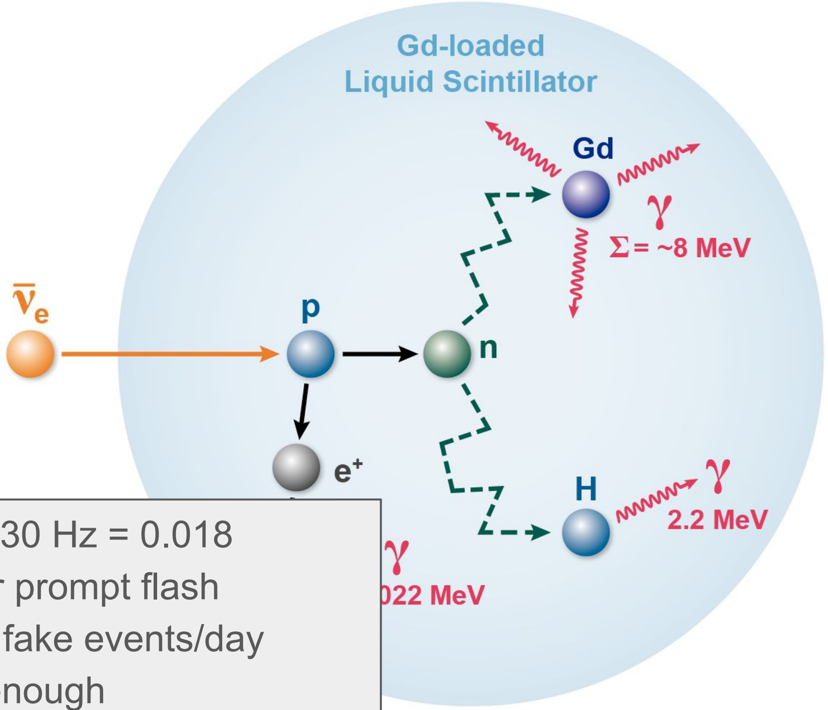
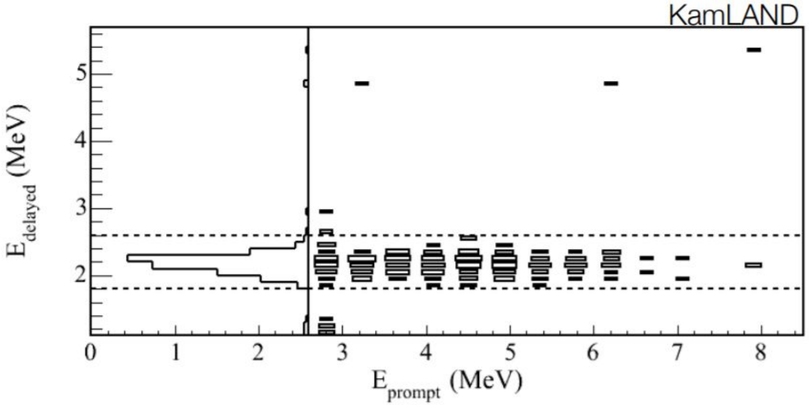


- 0.0006 sec window x 30 Hz = 0.018 fake coincidences per prompt flash
- 2.59 M x 0.018 ~ 46k fake events/day
- Better, but not good enough

Liquid Scintillator Detectors

- What else can we use to cut?
  - The veto
  - The energy we are interested in
- We are looking for flashes that correspond to 1 MeV -- 8 MeV
- Can make a cut on energy for ***both*** flashes
- This means measuring energy precisely is important to set a narrow box
- What's the approx. energy resolution?



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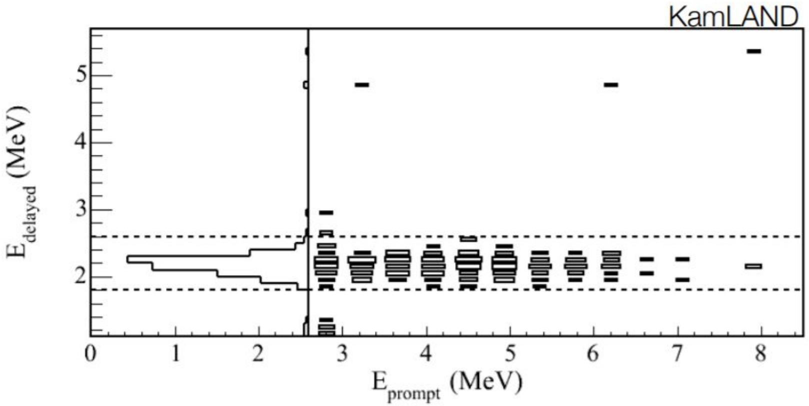

- Our resolution is going to be 1/sqrt(N), the mean number of photons we expect for an event
- So we need to know the light yield of KAMLAND: ~12k photo-electrons per MeV
- 12k/MeV x 1 MeV x 54% coverage x 0.2 QE = 1300
- 1/sqrt(1300) ~ 3% (paper cites 7%)
- So cuts in energy probably eliminates much of the background

Liquid Scintillator Detectors Recap

- Signal are isotropic flashes of light
- Not a lot of topological information there typically -- maybe can get position of event
- So we to avoid backgrounds
  - Shield w/ buffer volume/go underground
  - Veto
  - Use events with timing structure
  - Look in a certain energy window -- so need good energy resolution
  - How can I tell what neutrino I am looking at? Keep to low energy neutrinos, so we can only see electron (anti-)neutrinos

Classes of Detectors

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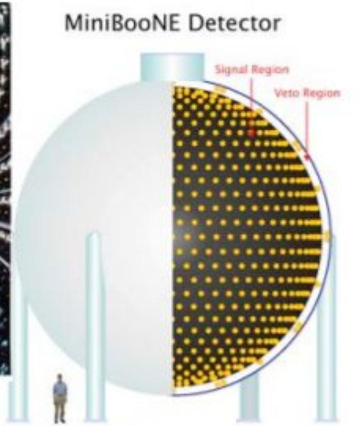
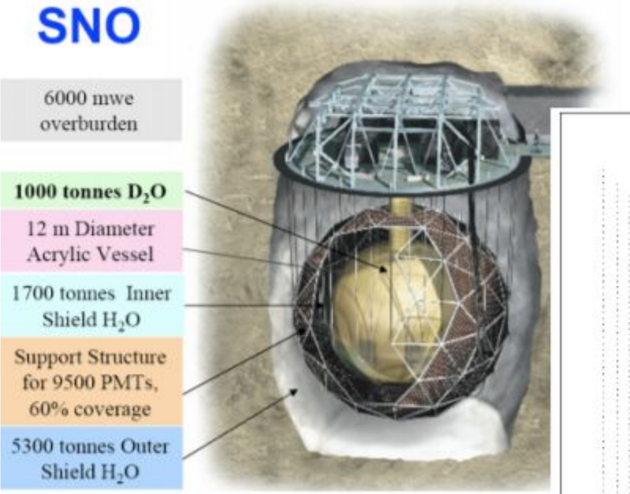
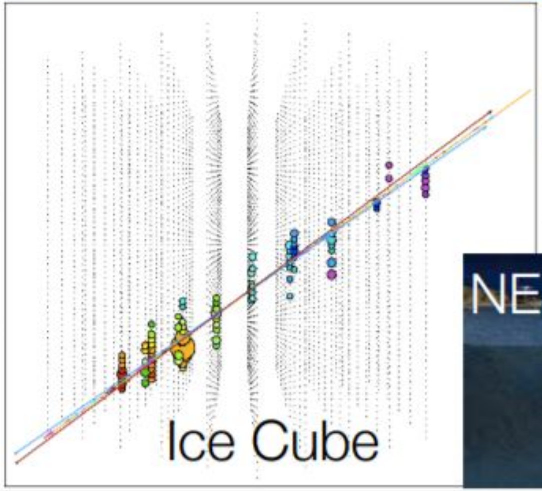
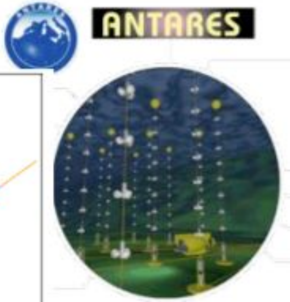
- **Cherenkov detectors**
- Tracking calorimeters
- Time Projection Chambers

Cherenkov detectors

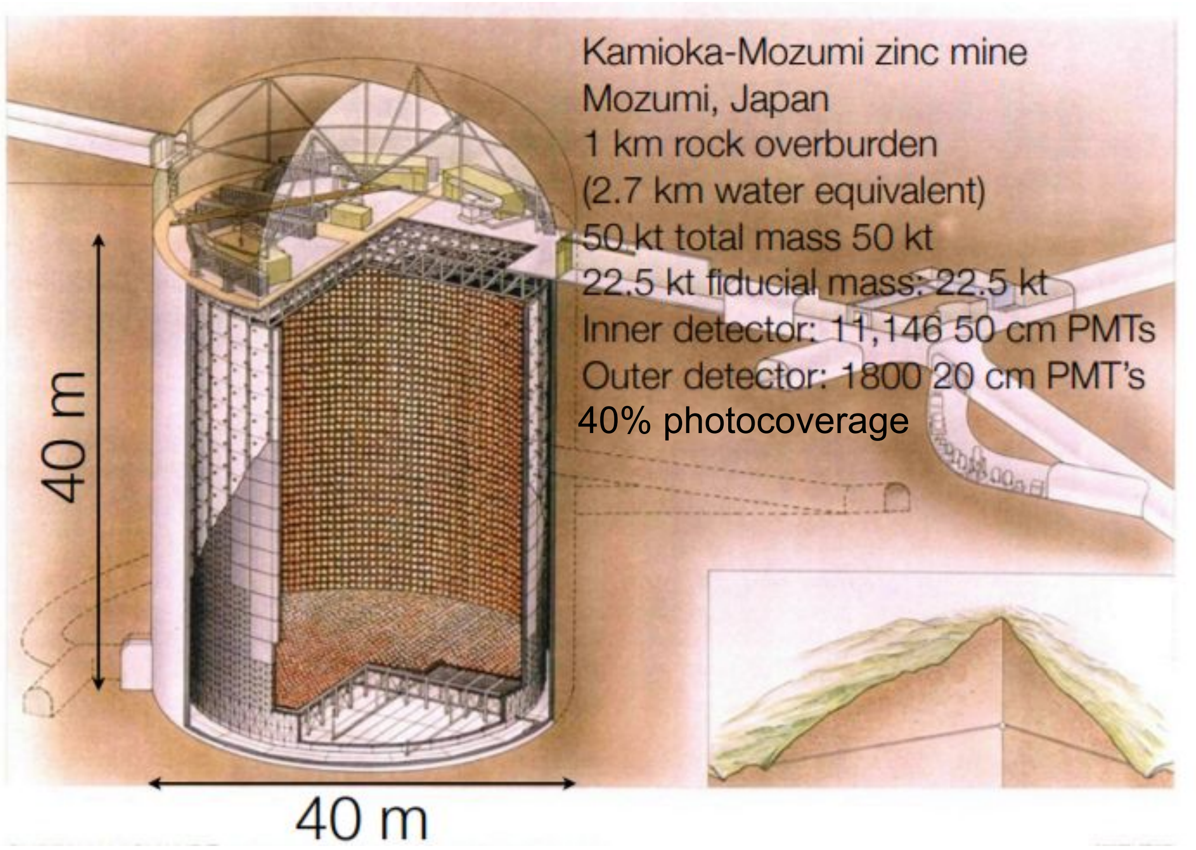








Example:Super-Kamiokande



Example:Super-Kamiokande

- For sense of scale
- Piazza Unità d'Italia
- Rough estimates
- 60 m wide
- 150 m long
- The tower of the municipal building around 40 m

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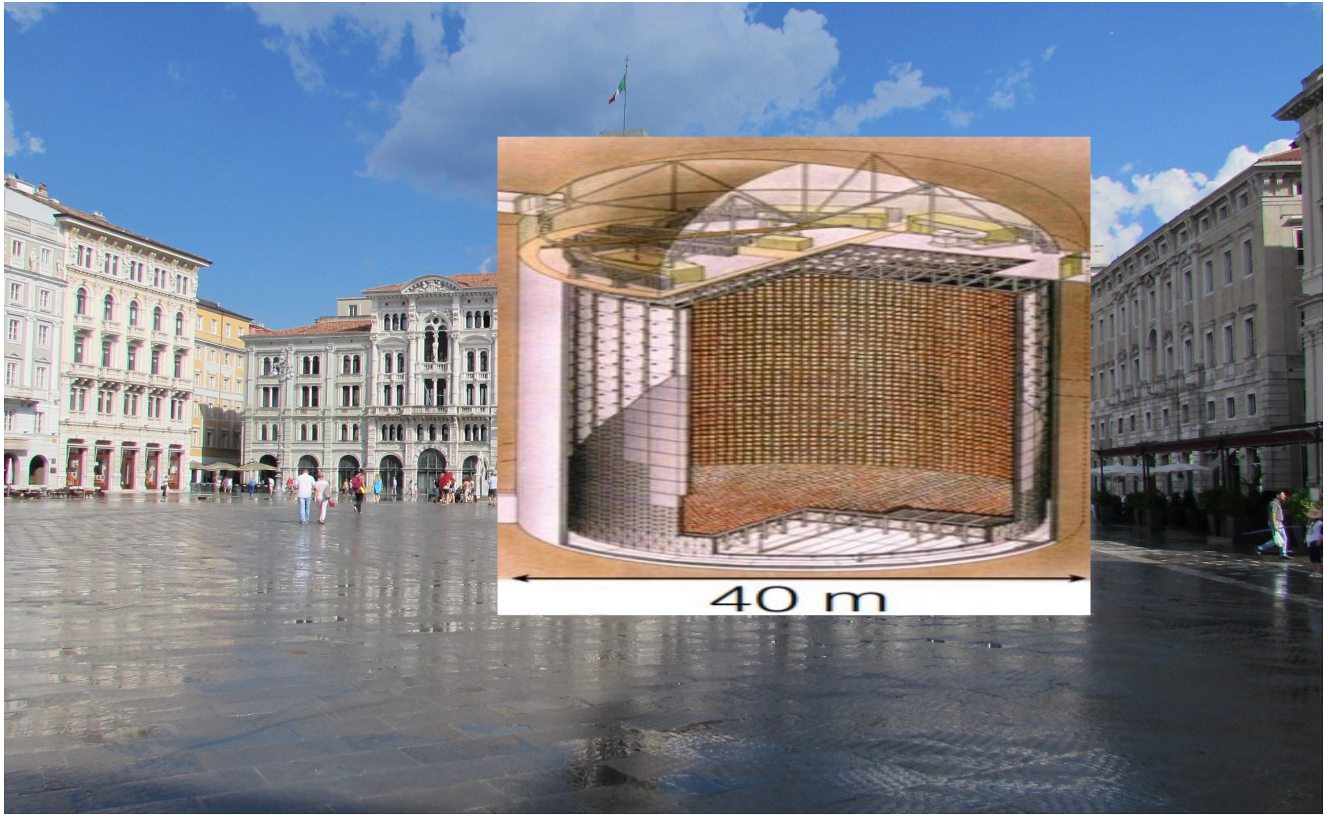
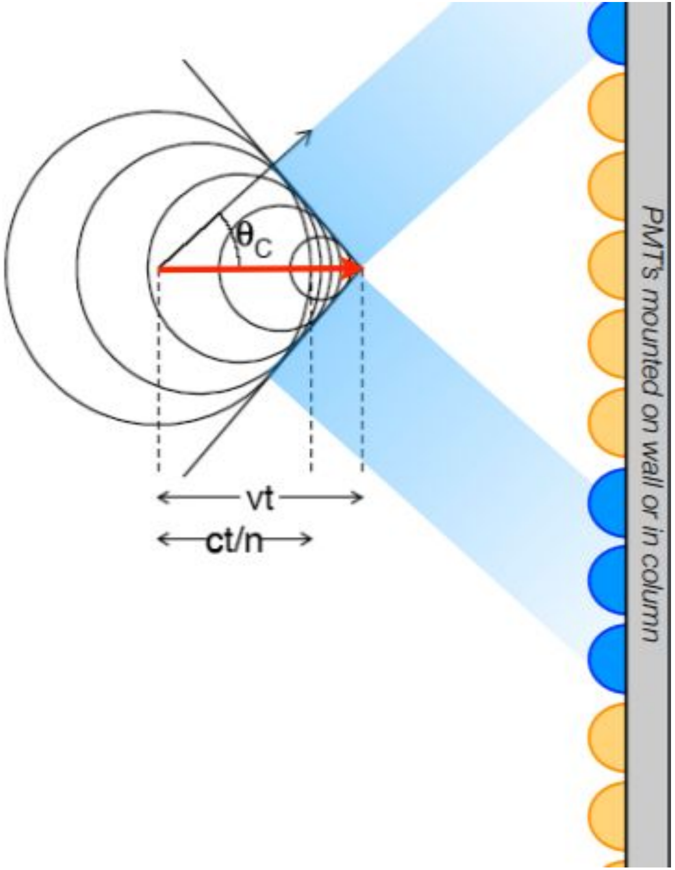


Cherenkov Light

- If speed of charged particle exceeds speed of light in a dielectric medium of index of refraction *n*, a "shock wave" of radiation develops at a critical angle:
  $$\cos\theta_C = \frac{1}{\beta n}, \beta > \frac{1}{n}$$
- PMTs record time and charge which provide unique solution for track position and direction. For Nhit PMTs measuring light arrival time t, minimize:

$$\chi^2 = \sum_{i=1}^{N_{\text{hit}}} \frac{(t_i - TOF_i)^2}{\sigma_t^2}$$

where TOF is the time of flight for photons to go from the track to the PMT



Cherenkov Light

- Threshold means that slow particles produce no light. As particles come to a stop their rings collapse. Useful for particle ID near threshold.

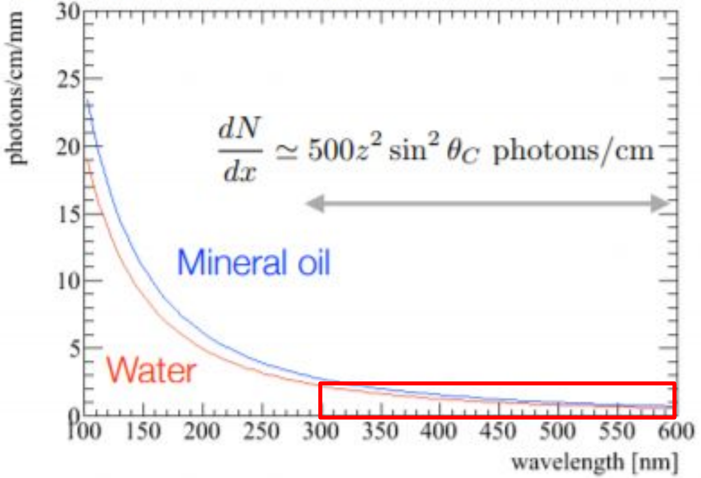
$$p_{\text{thresh}} = m\sqrt{\frac{1}{n^2 - 1}}$$

		p_{thresh} [MeV/c]					θ_C	
		e	μ	π	K	p	$\beta = 1$	$\beta = 0.9$
Water	n = 1.33	0.58	120	159	563	1070	42	33
Mineral Oil	n = 1.46	0.47	98	130	458	817	47	41

- Number of photons produced per unit path length:

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

- In both oil and water the useful part of this spectrum is between 300 and 600 nm bracketed by Rayleigh scattering on the low end and absorption on the high end



~200-300 photons/cm

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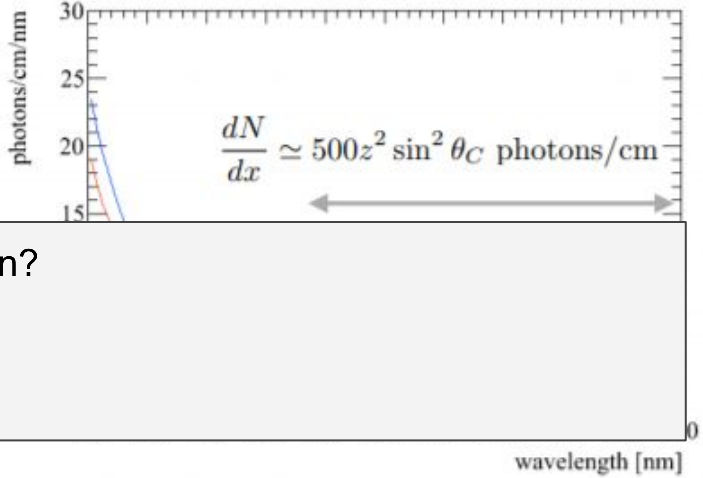

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end

What's the resolution of a 1 GeV muon?

~200-300 photons/cm

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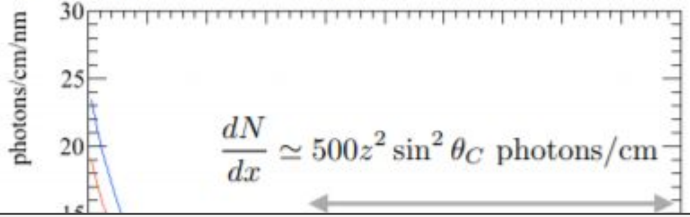

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What's the resolution of a 1 GeV muon?

- Number of photons:
  1000 MeV/(2 Mev/cm) x 300 ph/cm x 40% coverage x 20% QE = 12k p.e.
- 1/sqrt(12k) ~ 1% (the number I put into my thesis analysis)

~200-300 photons/cm

Cherenkov Light

- That’s the muon resolution (electron at the few perent resolution)
- We are interested in the neutrino properties
- (We can tag flavor by ring pattern)
- How about neutrino energy? What will we do to measure energy?

Cherenkov Light

- That's the muon resolution (electron at the few perent resolution)
- We are interested in the neutrino properties
- (We can tag flavor by ring pattern)
- How about neutrino energy? What will we do to measure energy?
  - Count energy of particles
  - What kind of particles we expect?
  - To know what kind of products, need to know energy of neutrinos we're dealing with and the kinds of reactions we get

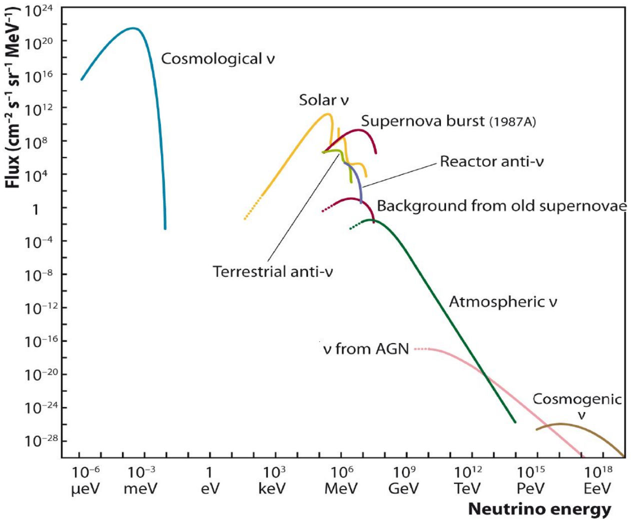
Cherenkov Light

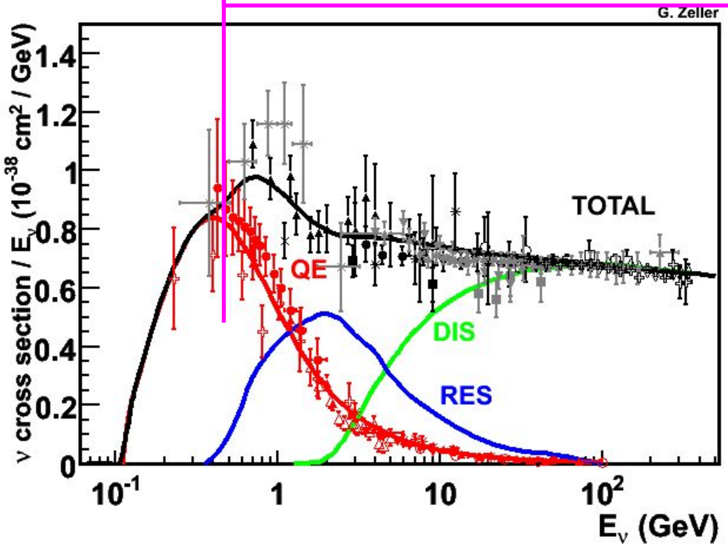
- That's the muon resolution (electron at the few parent resolution)
- We are interested in the neutrino properties
- (We can tag flavor by ring pattern)
- How about neutrino energy?

Get a sizable portion of quasi-elastic

Nu_mu + n -> muon + proton

Will we see both?





Cherenkov Light

- We're beginning to outline our analysis strategy
- We can only see the muon
- If CCQE, then we can assume elastic collision and use formula to measure energy
- This means we have to pick out CCQE -- we will plan to look for 1-ring muon events
- We can also do the same to electron-like events

$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l cos\theta_l}$$

From 2 body kinematics

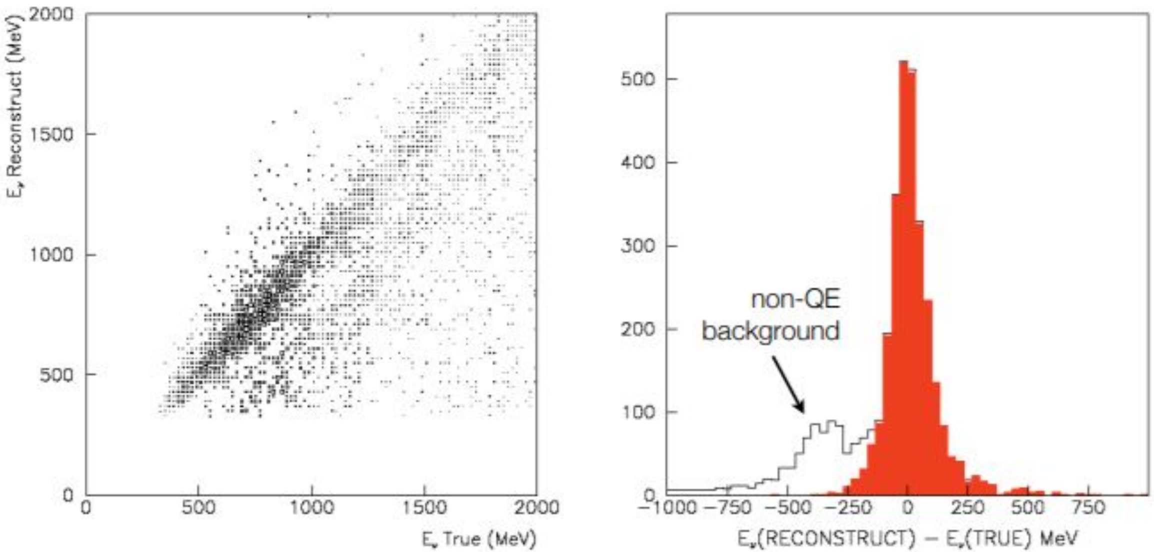
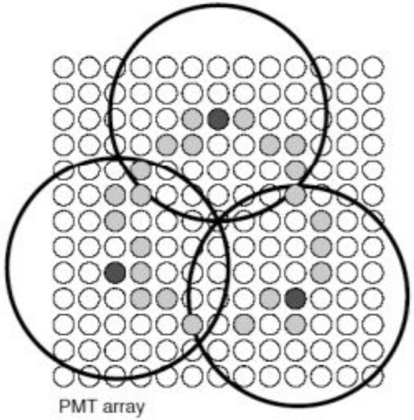


Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for ν_μ events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of ν_μ events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.

Water Cherenkov: Ring Counting

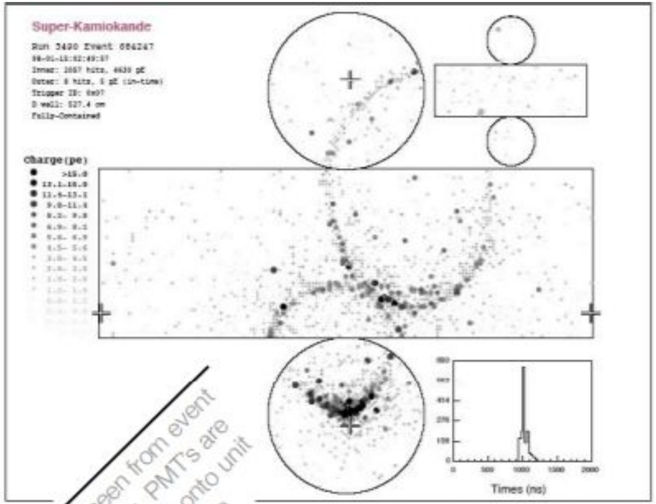


Not-hit PMT

Hit PMT

PMT corresponding to circle

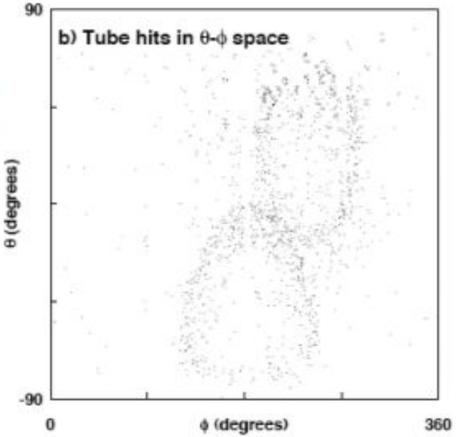
Circles overlap in center of ring corresponding to direction of particle

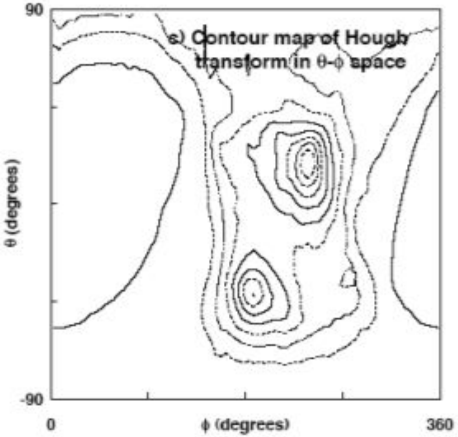


Figures from M. Earl's PhD Thesis

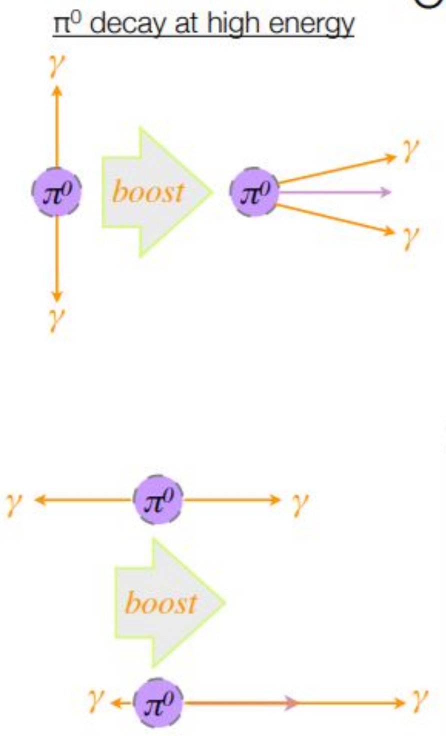
As seen from event vertex, PMT's are mapped onto unit sphere

If you know the pattern you are looking for (line, circle, oval, etc.) the Hough transform is a method for converting a pattern recognition problem to a peak finding problem

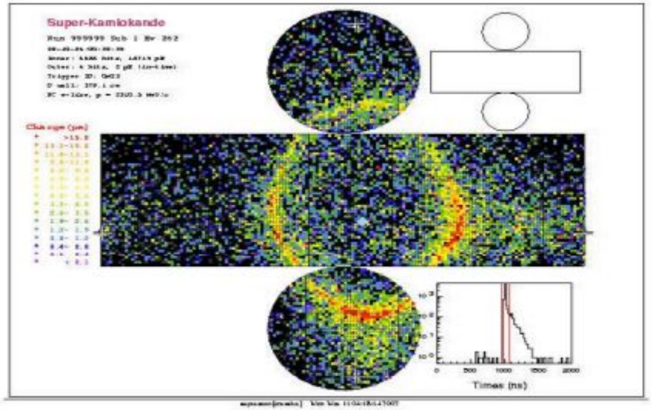


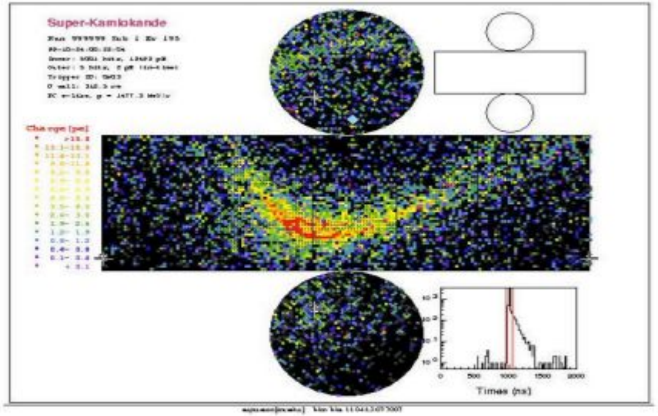


- What about backgrounds?
- Cosmics easily removed by veto
- If our analysis requires a certain type of neutrino event -- our background are the wrong kind of neutrino events
- This is an example of an important background to electrons



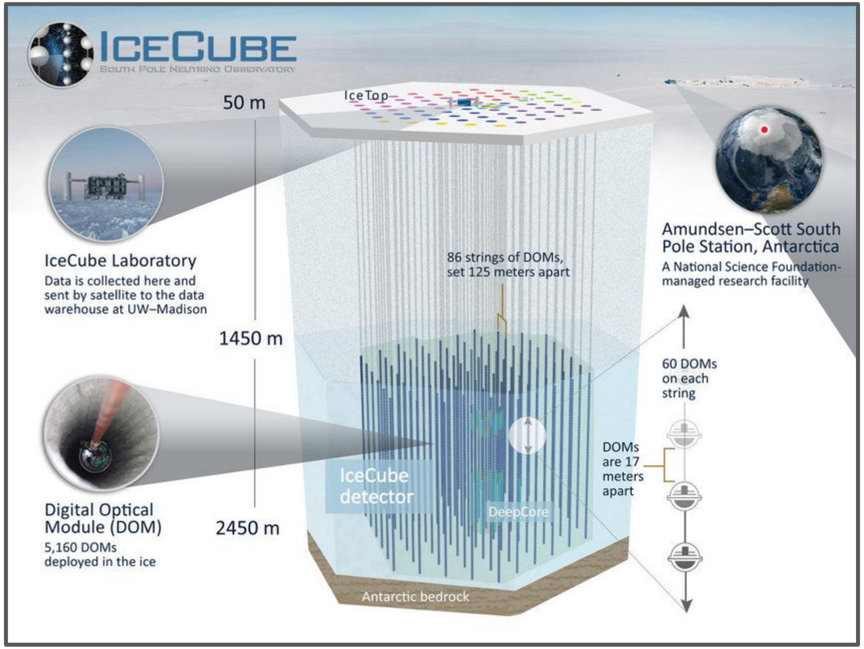
2 GeV visible energy
One is signal, the other background

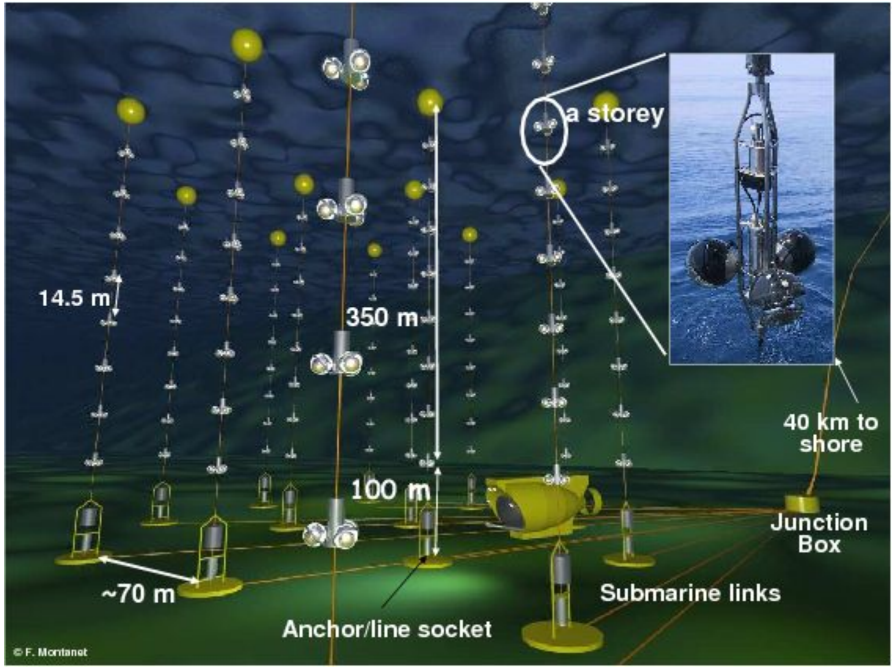




Cherenkov Neutrino Telescopes: ICE-CUBE/ANTARES

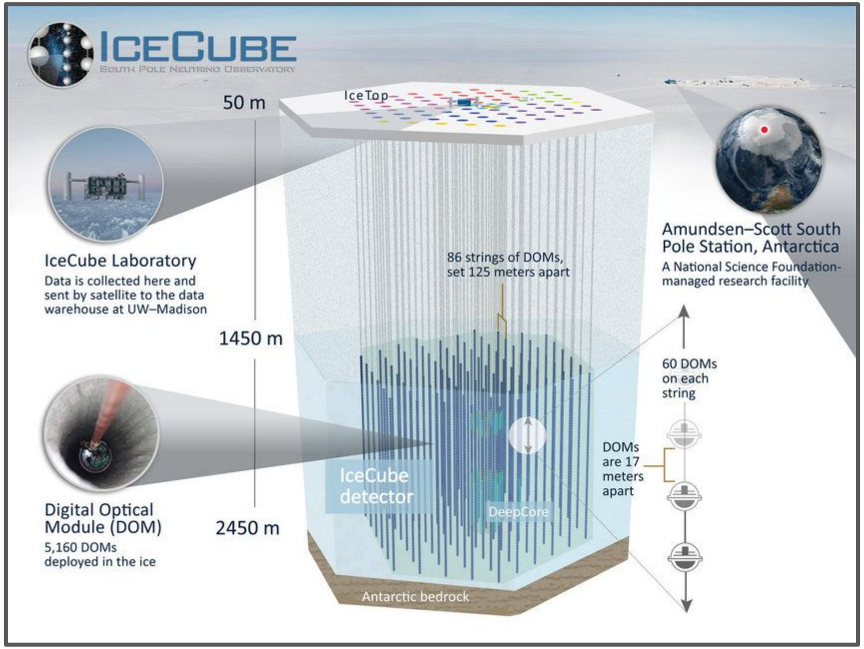
- Array of photodetector strings placed 10s of meters apart
- Cubic kilometer arrays

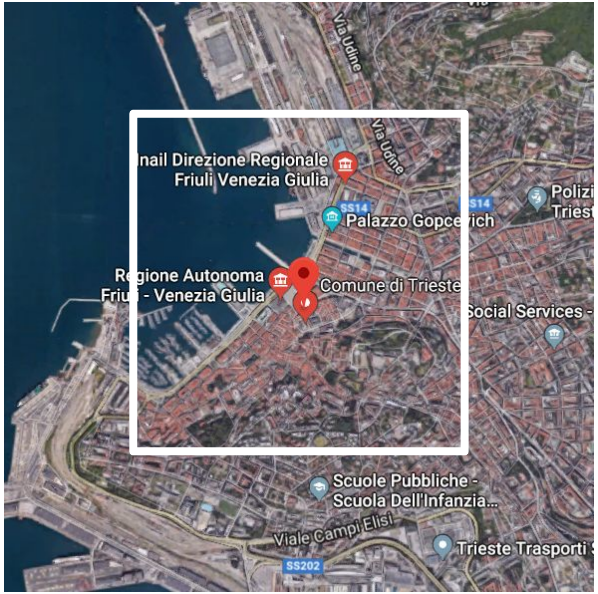




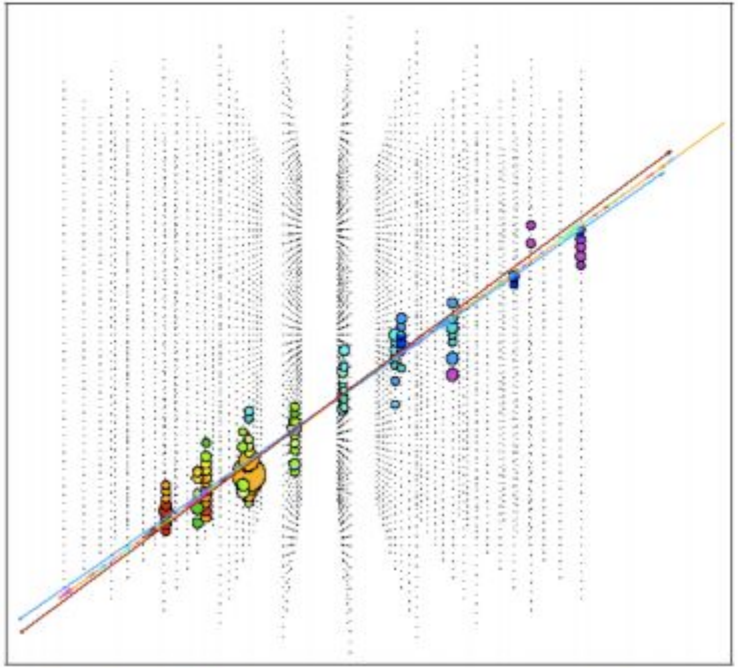
Cherenkov Neutrino Telescopes: ICE-CUBE/ANTARES

- Array of photodetector strings placed 10s of meters apart
- Cubic kilometer arrays

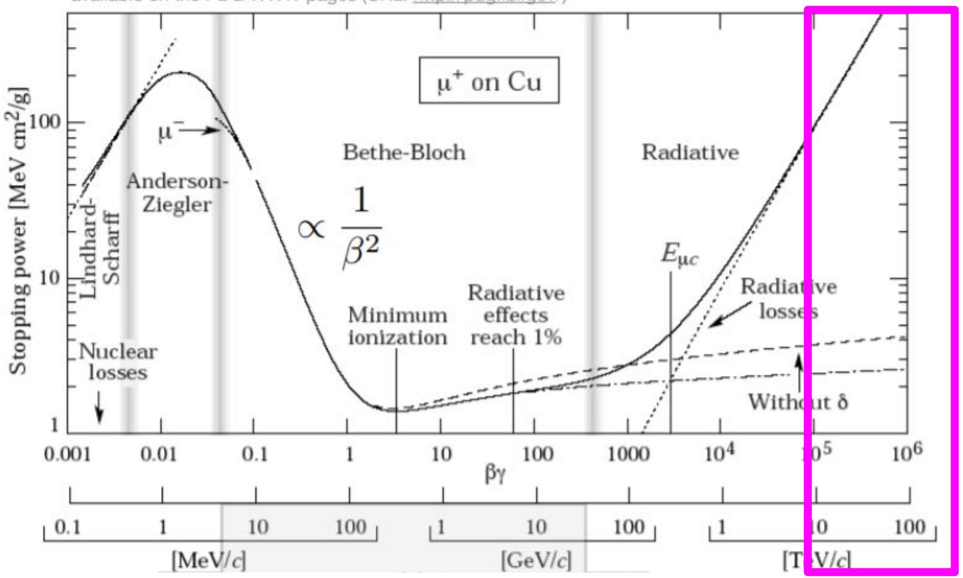




ICE-CUBE

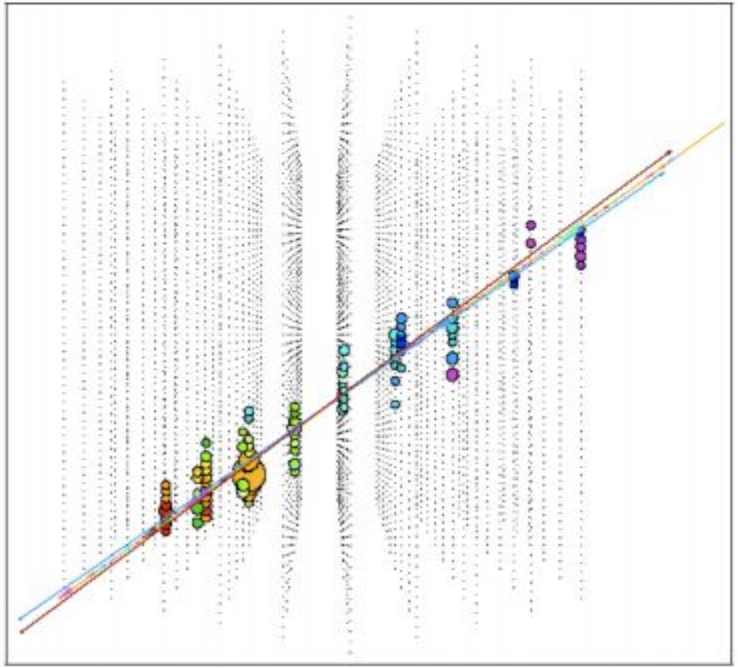


10 TeV muon neutrino induced upward muon



At these energies -- muons are showering objects too

ICE-CUBE



10 TeV muon neutrino induced upward muon

375 TeV electron neutrino

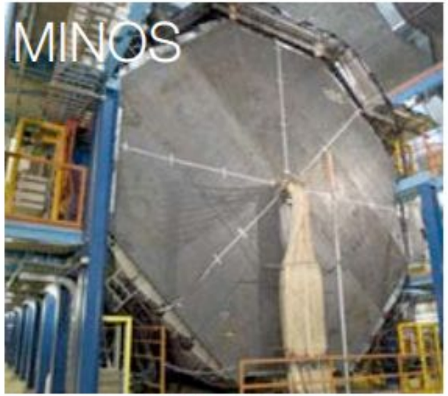
Cherenkov Detector Recap

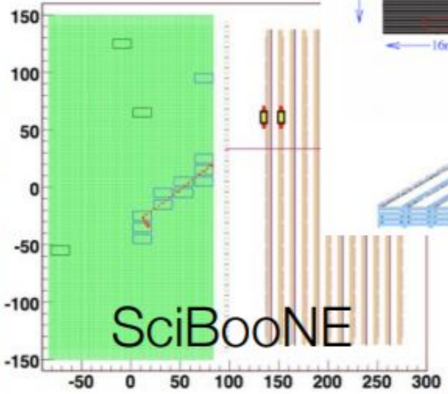
- Signal are rings of PMT hits
- Can ID particle using ring pattern -- fuzzy for electron/photon. Sharp for muon, proton, pion. For latter can use opening angle and energy loss per distance to try and distinguish (not easy)
- Avoid backgrounds w/ veto
- Signal requires relatively high energy particles (exception the electron)
- Often focus on “golden” sample of CC-quasielastic events -- best chance at neutrino energy
- This means that other neutrino interactions are our backgrounds

Classes of Detectors

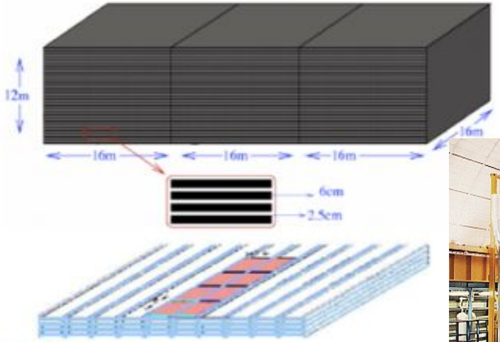
- Scintillator detectors
- Cherenkov detectors
- **Tracking calorimeters**
- Time Projection Chambers

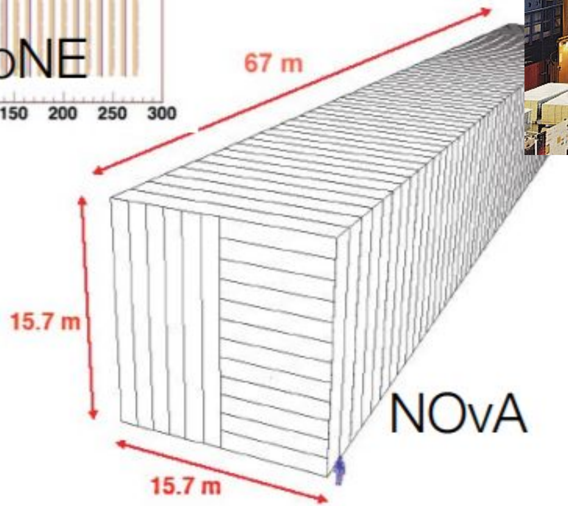
Tracking calorimeters





INO





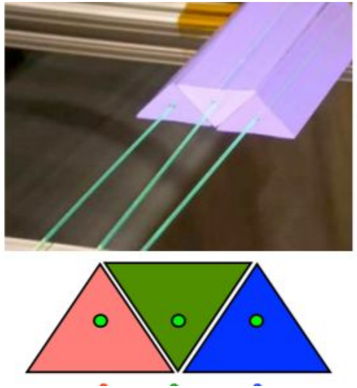
MACRO

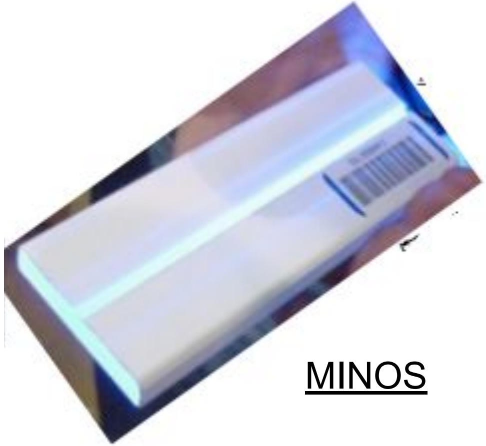
Example:Nova

Tracking Calorimeters

- Opposed to what we saw before, which were unsegmented detectors, tracking detectors are segmented
- Goal is to measure energy position pattern
- Build a detector out of "cells" that measure some signal -- usually collect light

Minerva





MINOS

Plastic scintillator read out by light-guiding fibers

Nova

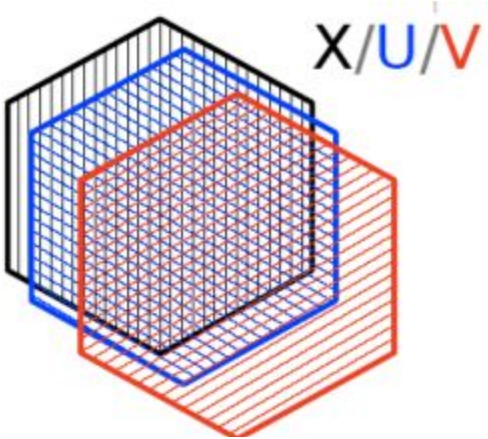
Cells of plastic filled with liquid scintillator

Photodetectors at end read out the bars and fibers

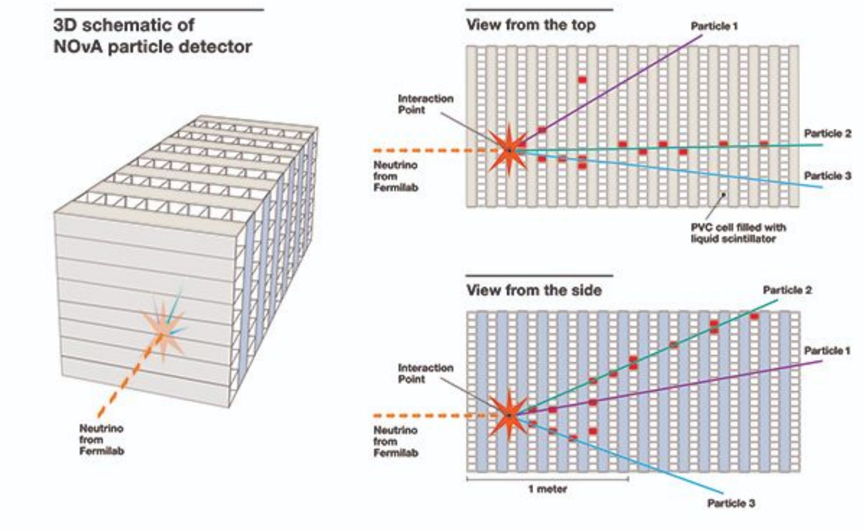
Tracking Calorimeters

- Make sure you orient your cells so you can get 3D information about particle track

Minerva

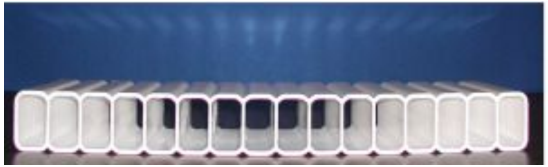


Nova



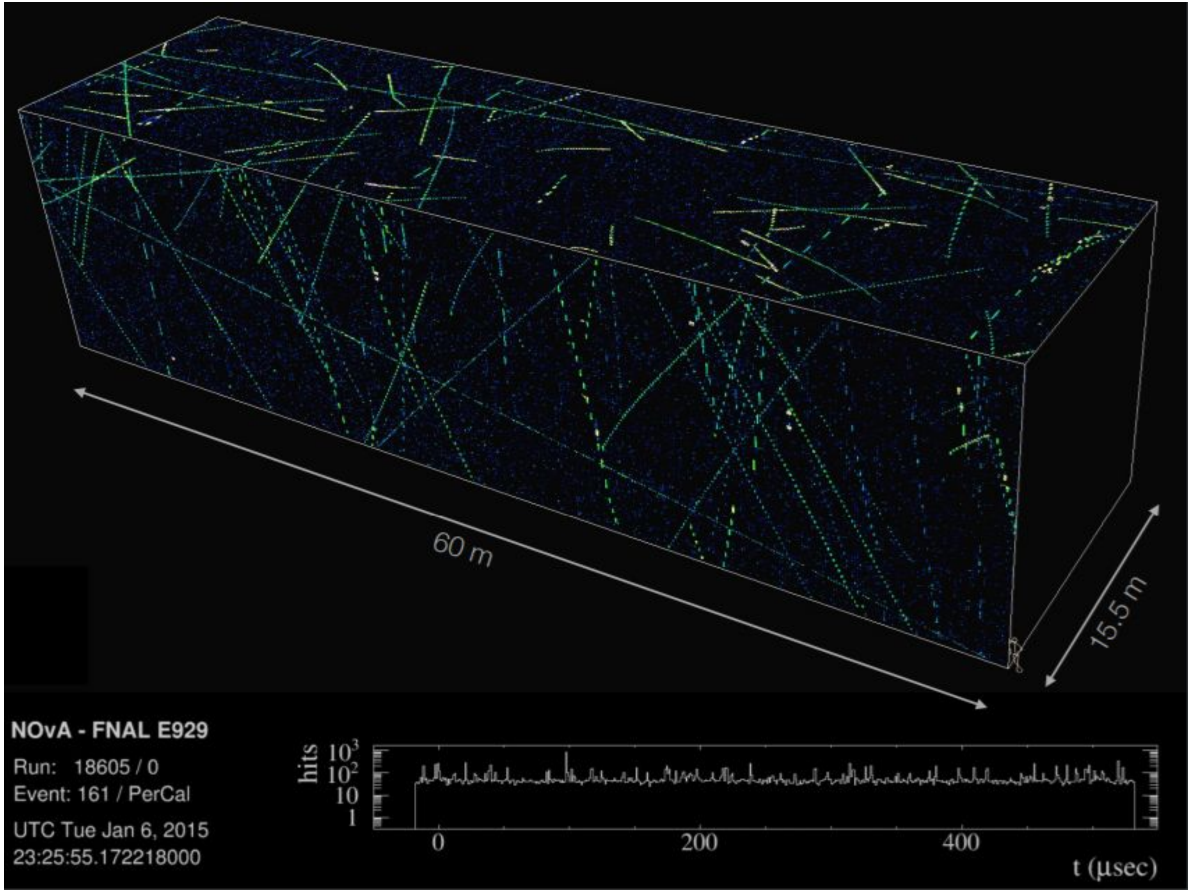
Nova Event Display

3x3x1500 cm cells

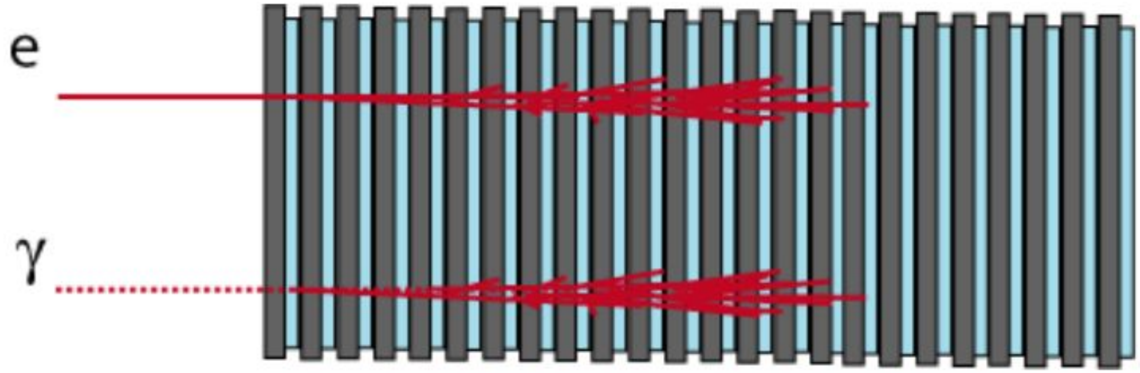


What's the lowest energy muon track that we can 3D locate?

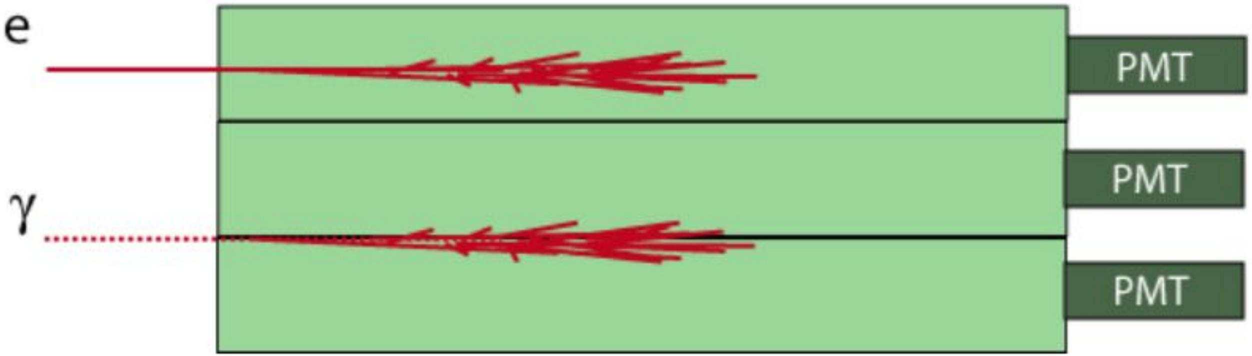
These have been long rectangles -- what kind of neutrinos are they looking at?



Types of Calorimeters

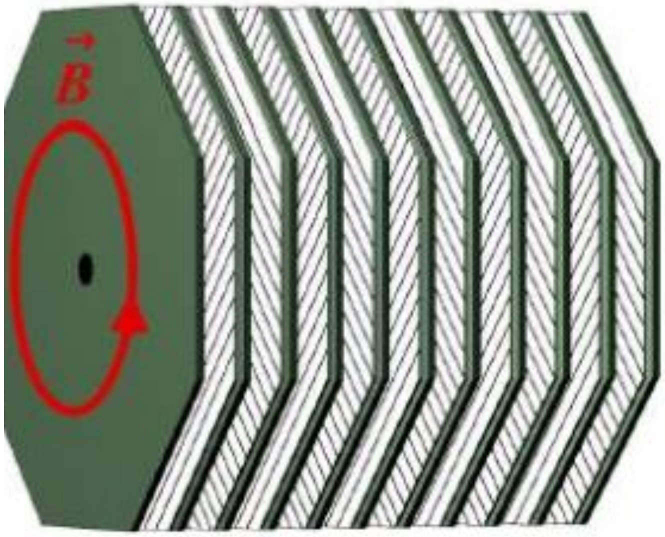


Sampling calorimeter
Alternating layers of absorber and active material



Homogeneous calorimeter
The active material y the absorber itself

Tracking Calorimeters

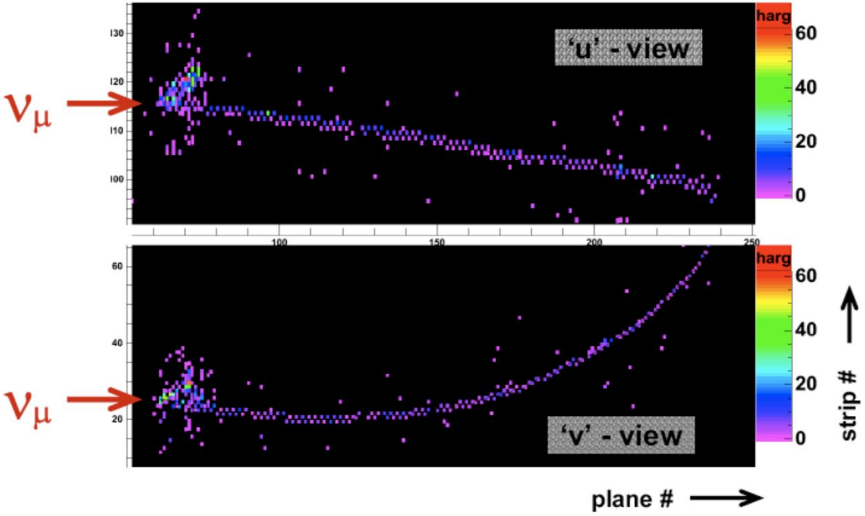


- MINOS and Minerva were Sampling calorimeters
- Iron sandwiched between the plastic
- Why?

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}\left[\frac{\text{g}}{\text{cm}^2}\right]$$

Tracking Calorimeters

- Iron can also be magnetized
- Tracks will be bent and you can get momentum from curvature



A particle with momentum p, traveling through a constant transverse magnetic field B will travel on a circle of radius ϱ

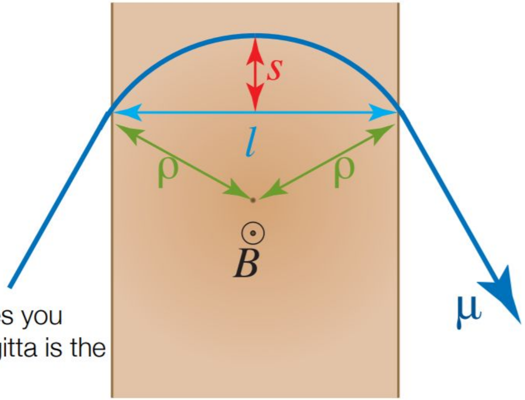
$$p[\mathrm{GeV}/c] = 0.2998 B[\mathrm{T}] \rho[\mathrm{m}]$$

$$\rho = \frac{l^2}{8s} + \frac{s}{2}$$

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

Measurement of sagitta and chord gives you momentum. Detector resolution on sagitta is the same as the momentum resolution:

$$\left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$



More common to talk about the track curvature

$$k = \frac{1}{\rho}$$

which has roughly Gaussian errors.

Classes of Detectors

- Scintillator detectors
- Cherenkov detectors
- Tracking calorimeters
- **Time Projection Chambers**

Example:MicroBooNE

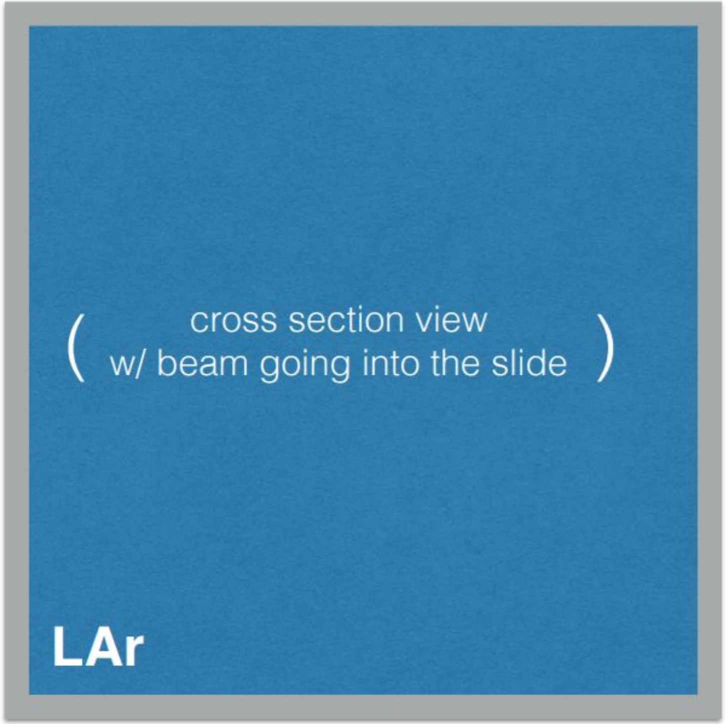
- This detector is about the size of a school bus
- ICARUS, mentioned yesterday, about the size of a tractor-trailer

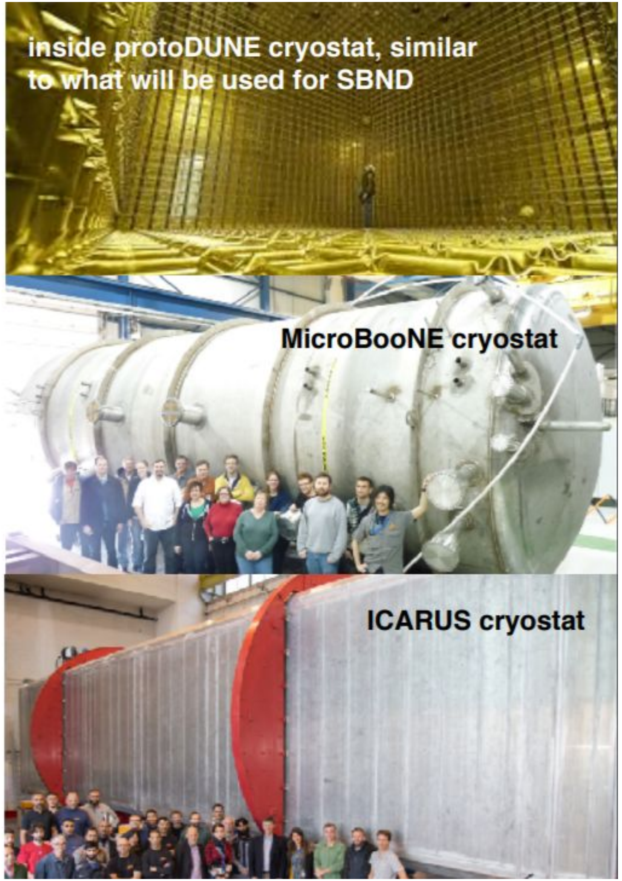
DUNE

- Many in the field, in particular the US, are working towards the DUNE experiment, which will use 1-4 17 kton LArTPCs

TPCs (liquid argon)

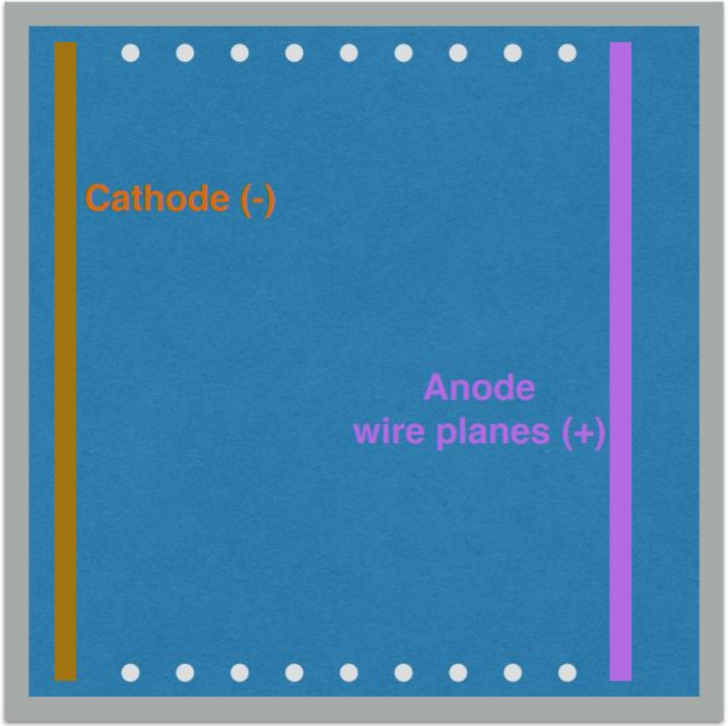
Start with cryostat filled w/ LAr

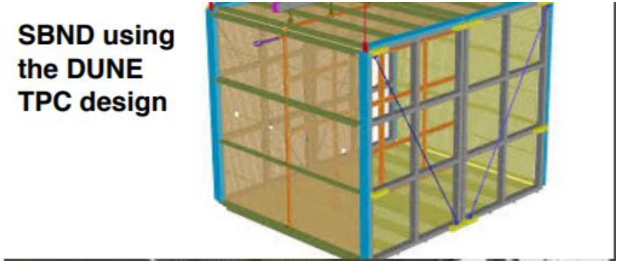


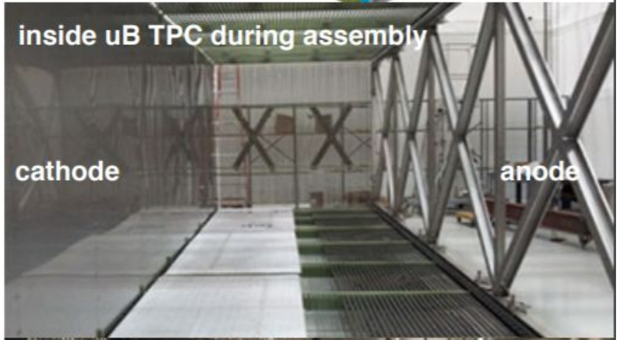


TPCs (liquid argon)

Create a region with a uniform electric field
(with a giant capacitor)



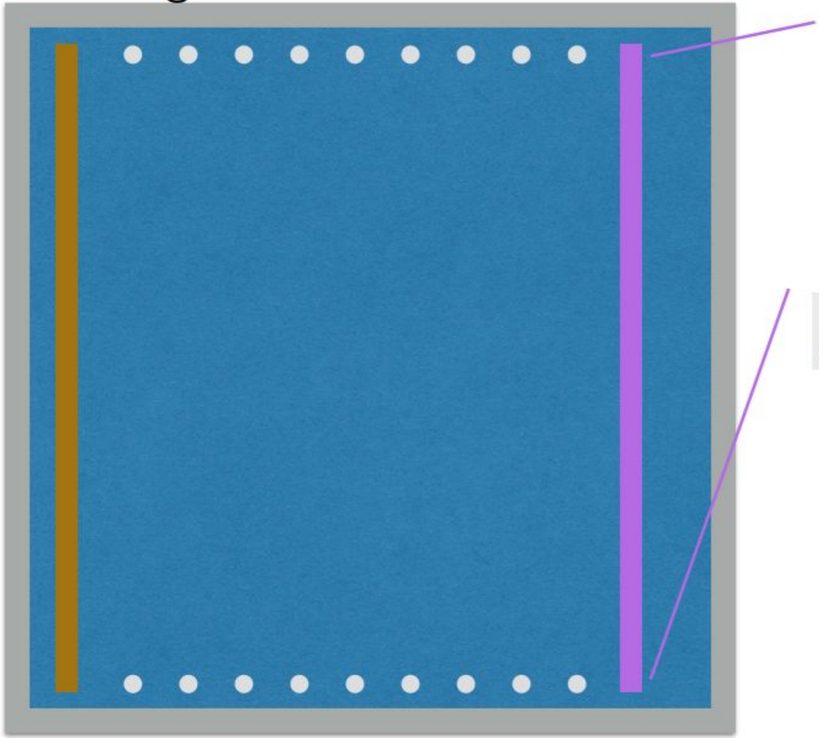


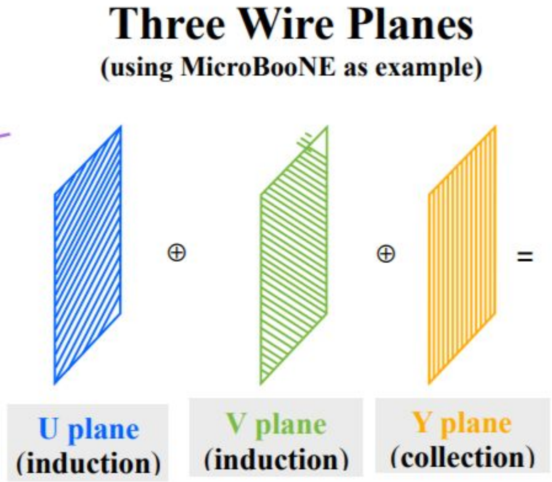


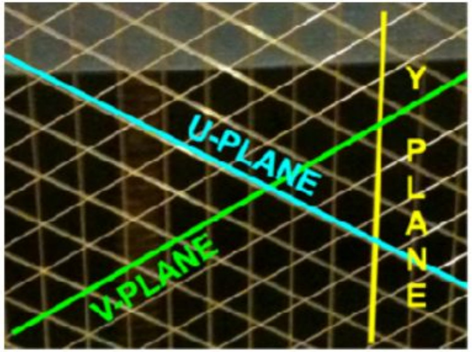
MicroBooNE: 270 V/cm, 250 cm dright region, **70 kV**

TPCs (liquid argon)

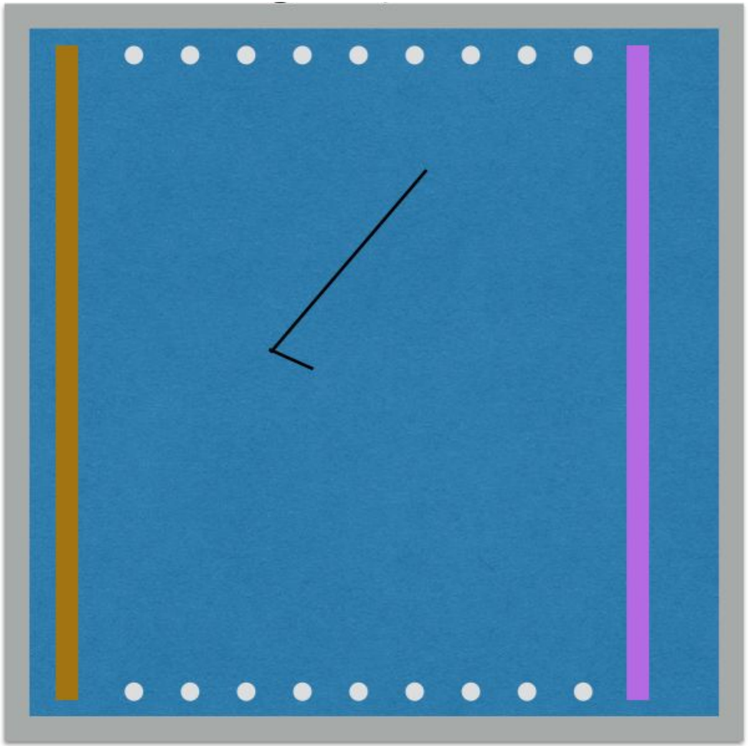
Anode consists of several charge-sensitive wirelines

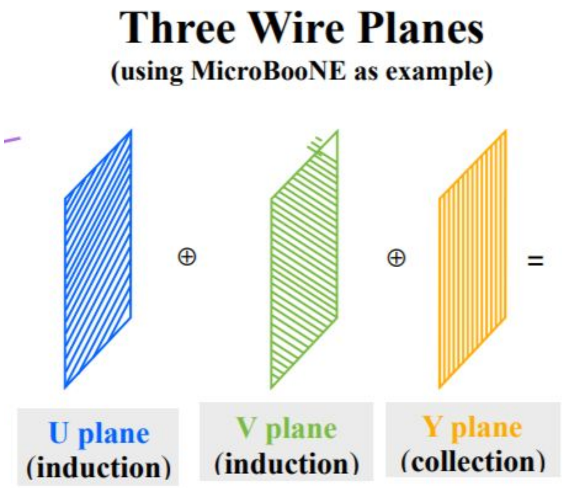






TPCs (liquid argon)





Wire planes at different angles?

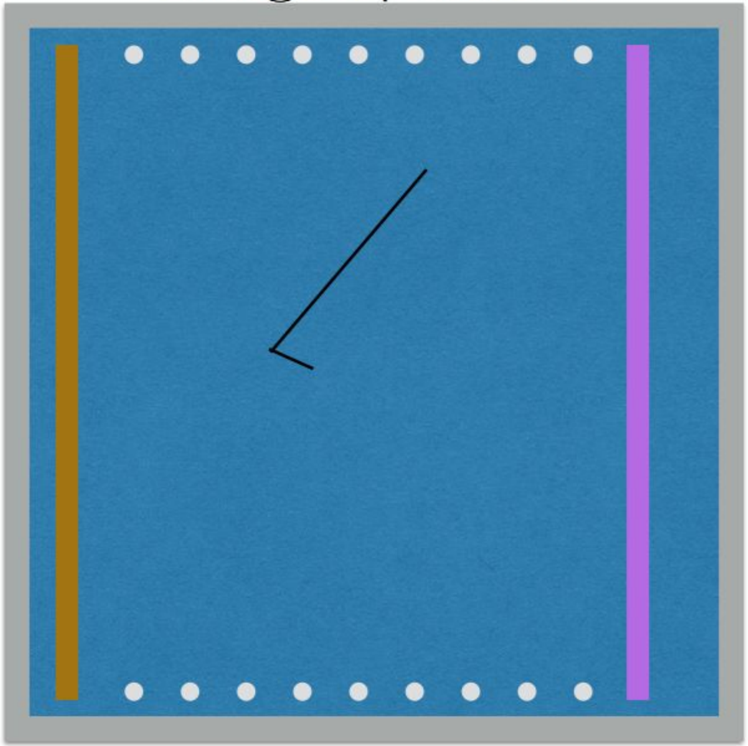
Would it be easier to have an 2D array of charge-sensitive electrons?

Reading out wireplanes scales linearly with size (length) of detector

2D readout goes as N^2

TPCs (liquid argon)

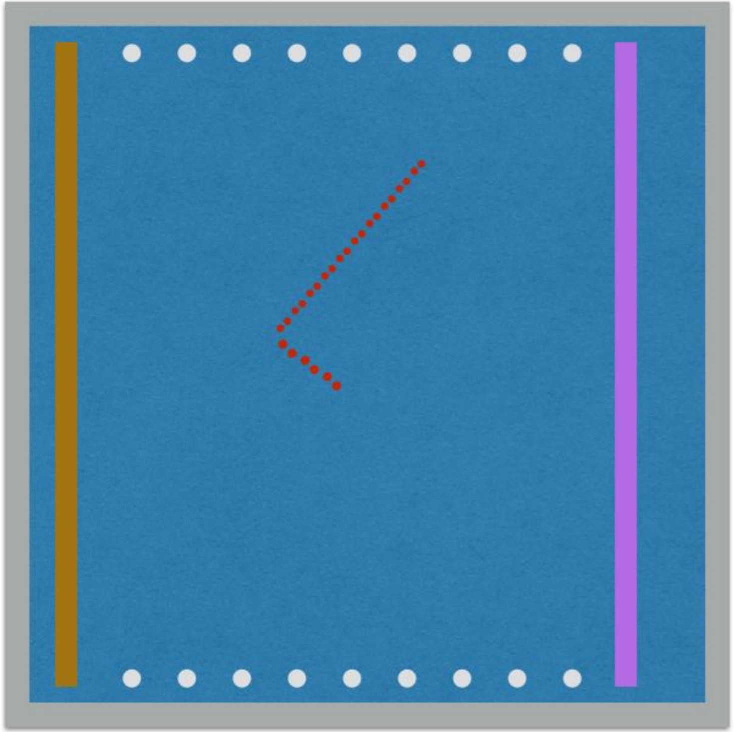
interaction produces
charged particles



TPCs (liquid argon)

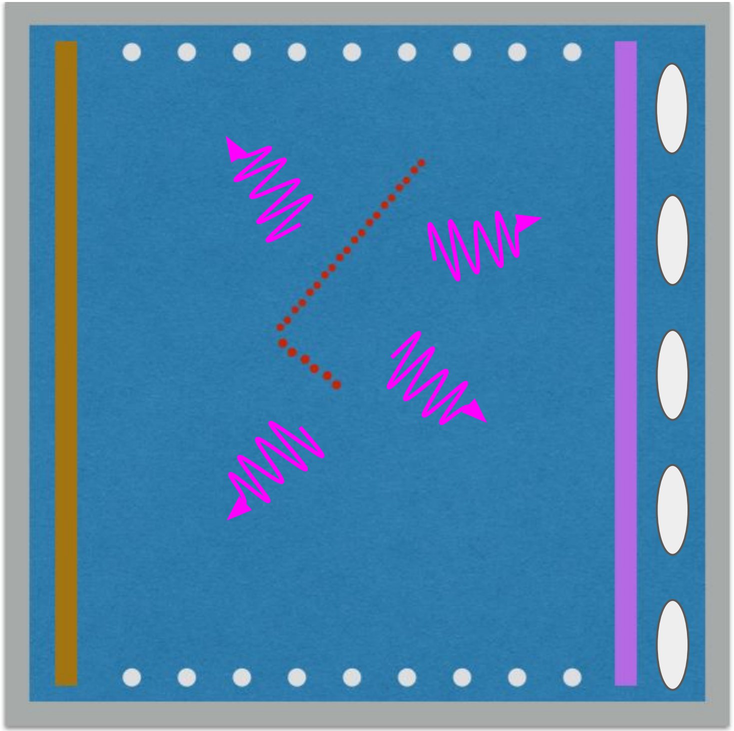
liberates ionization electrons

(and argon ions, not shown)



TPCs (liquid argon)

Charged particle also creates scintillation light

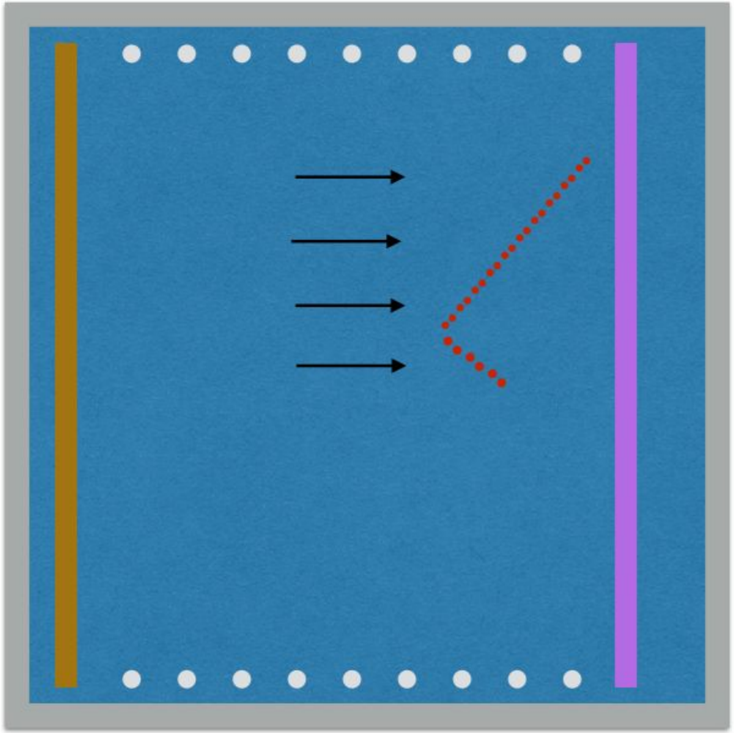


within nanoseconds photons collected by detectors placed behind the anode wires

light signal important for timing

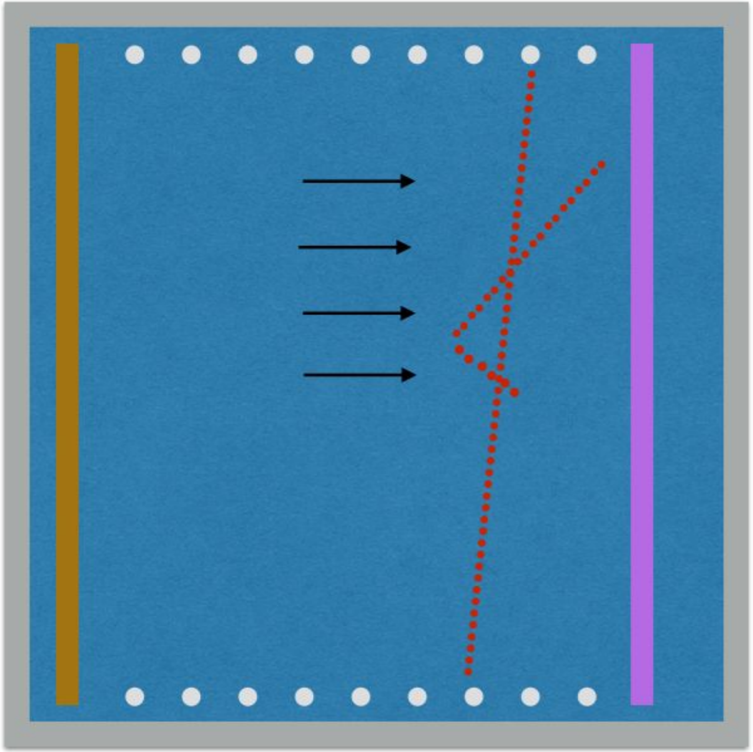
TPCs (liquid argon)

ionization follows field to anode



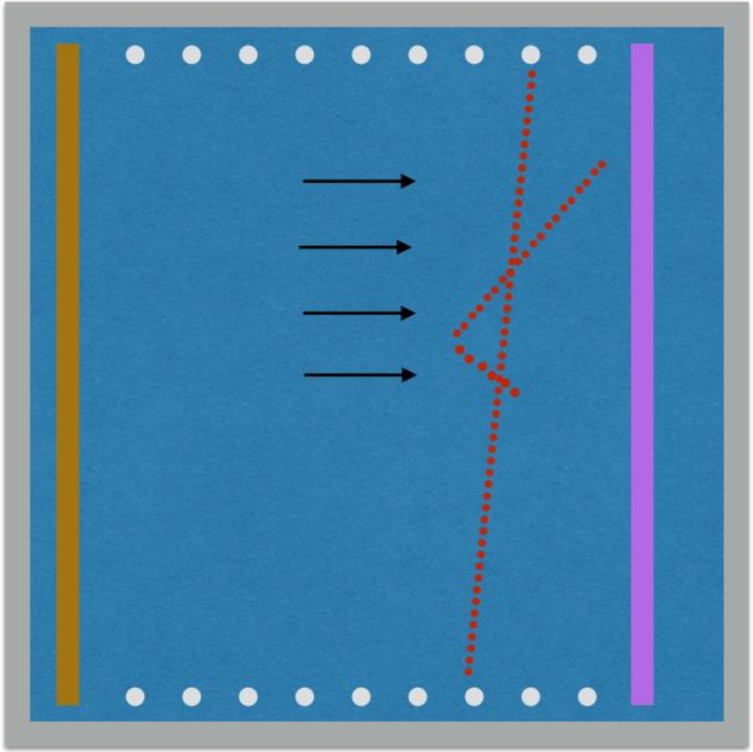
TPCs (liquid argon)

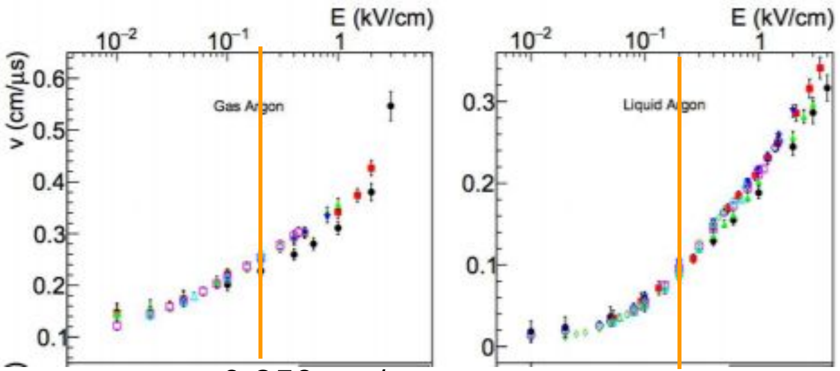
drift is relatively slow (e.g. ~2.3 ms from cathode to anode in uB)



during that time cosmic particles, mainly muons, will also create tracks of ionization

TPCs (liquid argon)





0.250 cm/usec

0.1 cm/usec

Drift velocity depends on density
Can see velocity in gas is higher

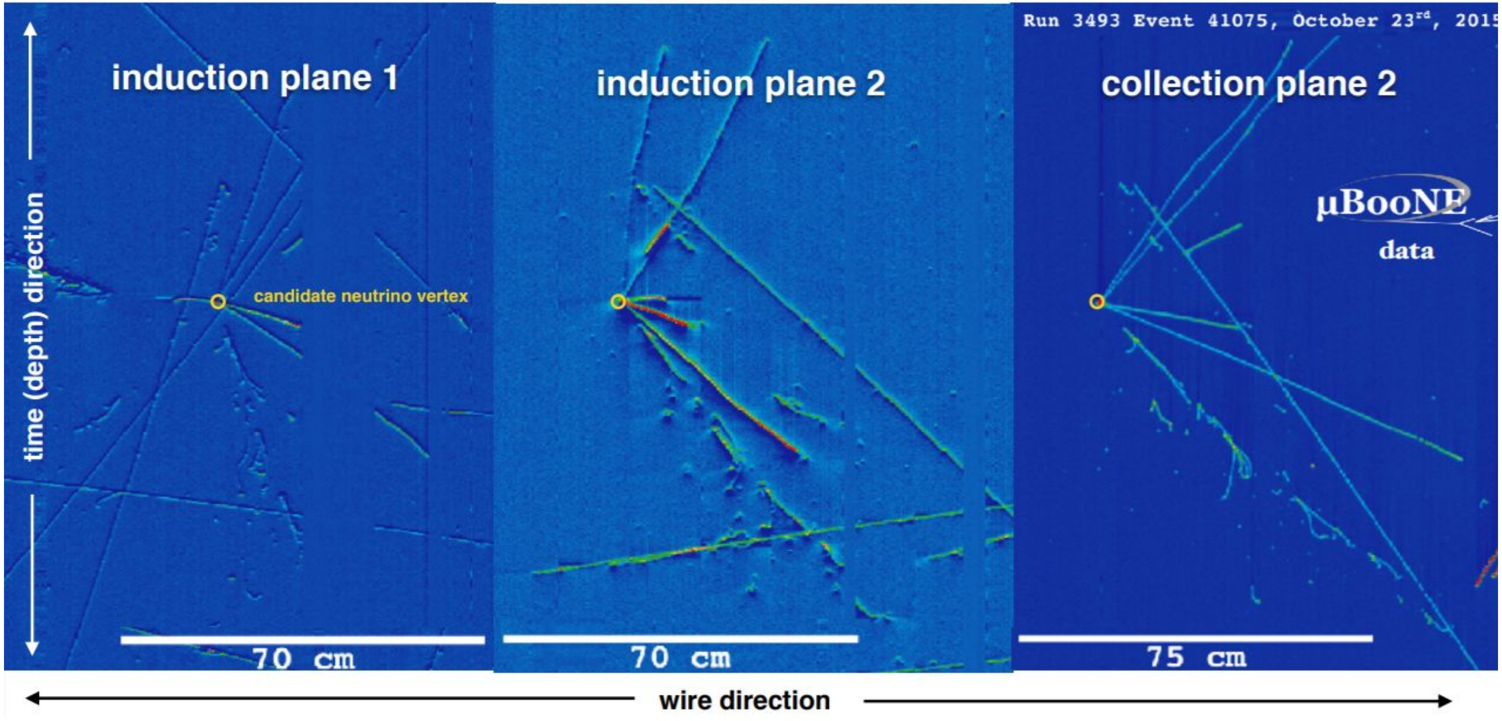
Velocity roughly linear with drift field

To avoid background pile up, would be good to drift *as fast as possible*

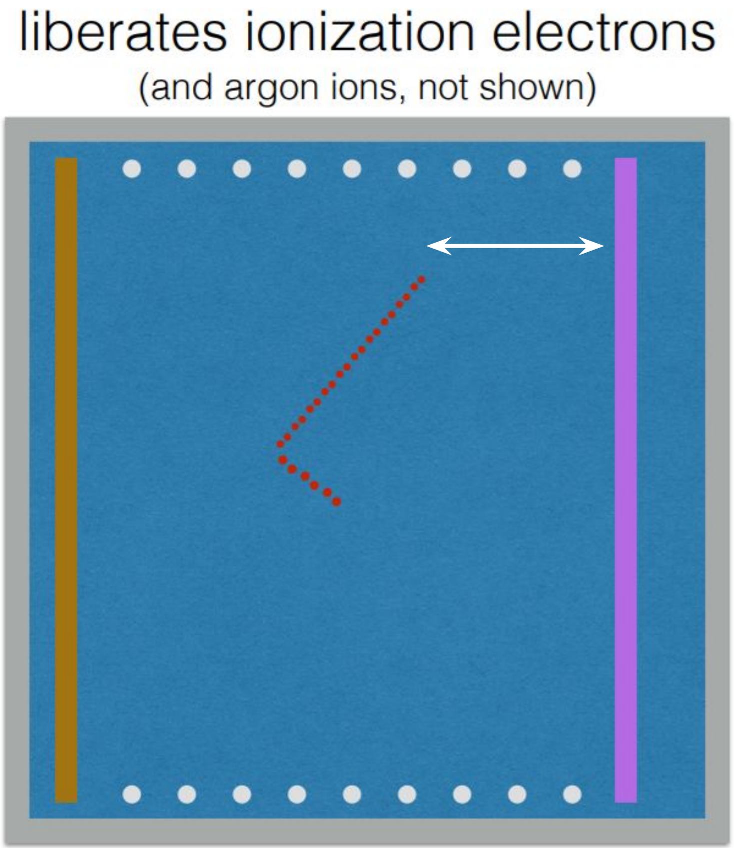
Then why not use gas and/or a really high drift field? When might you want to use gas?

TPCs (liquid argon)

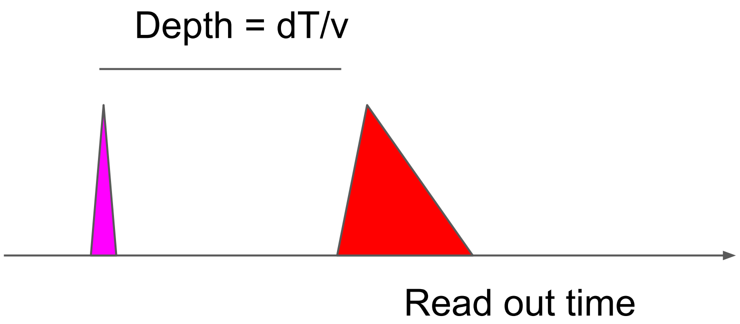
ionization drifts past (induction) or collects on (collection) wire planes. each provides 2D view of same event



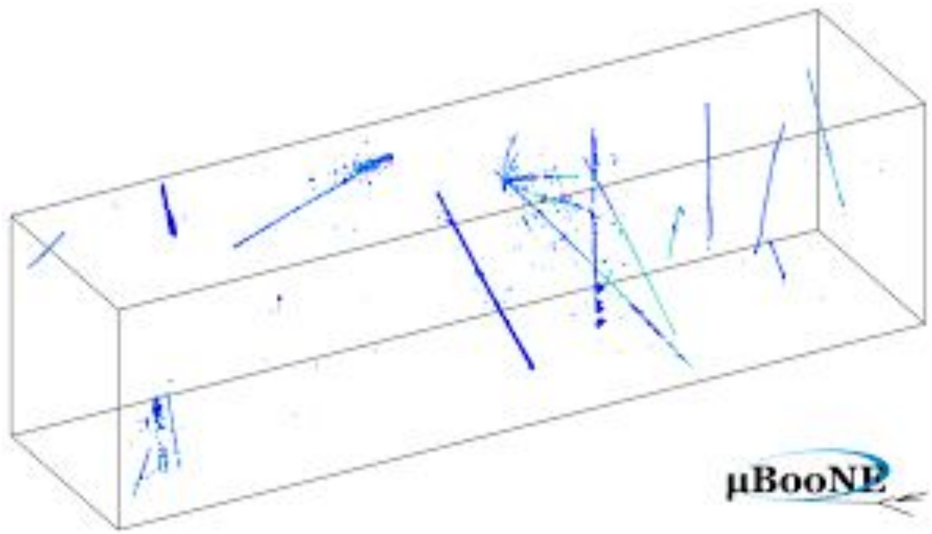
TPCs (liquid argon)



- Combining wire plane information gives us 2D position
- To get depth, we need the time it took the track to reach the wire planes divided by the drift velocity
- The time is the difference between when we see the charge and when we saw the flash



TPCs (liquid argon)



- Putting all the information together we can build a 3D reconstruction of the tracks through the detector
- Have to find the neutrino from cosmics
- And also identify the type of neutrino interaction
- Not a trivial problem
- But rewarded with high-resolution information on position and energy deposited with relatively low thresholds

TPC recap

- Define a charge-drift region, so that ionization electrons from charged particle tracks get collected and recorded by charge-sensitive electronics
- Can build a 3D view of an interaction
- But I could also do that with the tracking calorimeters -- so why the TPC?

Classes of Detectors

- Scintillator detectors
- Cherenkov detectors
- Tracking calorimeters
- Time Projection Chambers

Classes of Detectors

- Scintillator detectors
- Cherenkov detectors
- Tracking calorimeters
- Time Projection Chambers
- Will talk about other types tomorrow when going through the physics we can do with these neutrino detectors and the status of various neutrino experiments
  - Radiochemical
  - Bolometers

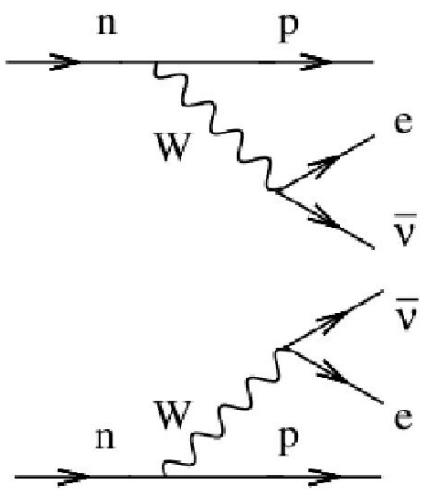
Activity

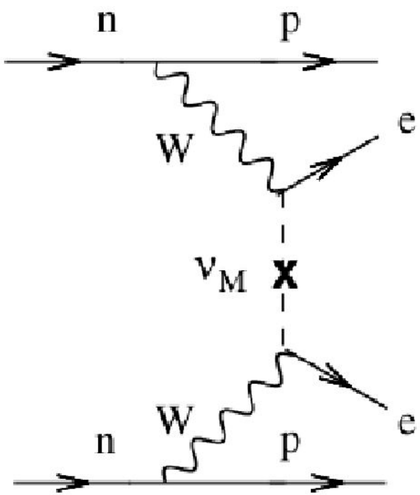
Activity

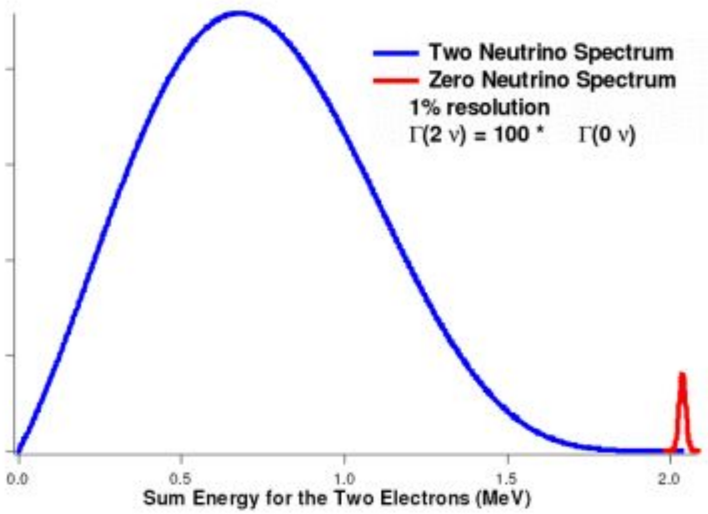
- Form into groups
- Pick a physics topic
  - Measuring neutrinoless double beta decay
  - Looking for sterile neutrinos
  - Measure delta-CP
  - Measuring one of the oscillation mixing angles
  - Looking for indirect signs of dark matter
- There are a couple of different strategies to make the measurement
- Come up with one or two ways to measure the signal and why it would work
  - This means, picking a ***source of neutrinos*** and a ***signal type***
- Also, think about one type of detector that won't work -- and why?
- We'll go around at the end and discuss. Volunteer someone in group to outline what kind of experiment you would build to look for your piece of physics. What were some reasons for your choice? Any drawbacks?

Neutrino-less double beta decay

- Neutrino-less double beta-decay
- A process that would indicate that the neutrino is it's own anti-particle
- Signal: two electrons back-to-back







CP-violation in the neutrino sector

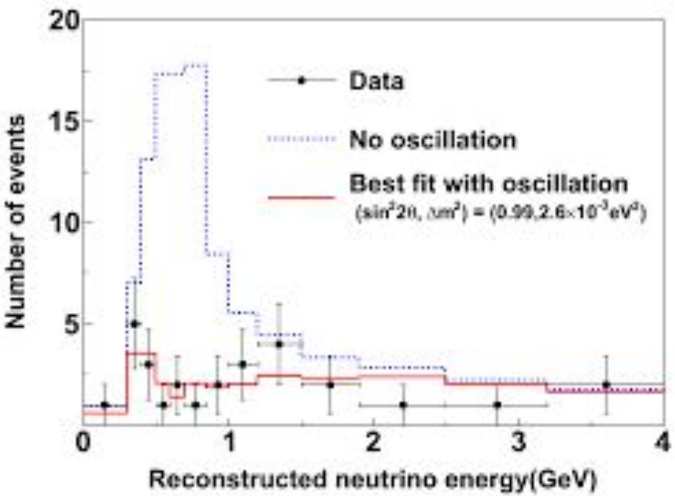
- Do neutrinos violate CP-symmetry?
- Compare rate of process called neutrino-oscillations for neutrino and anti-neutrinos
- Compare: numu turning into nue and numu-bar into nue-bar

Sterile Neutrinos?

- Is there an additional neutrino?
- Signal: neutrinos in one flavor can turn into another flavor (i.e. oscillate) for energies and over distances not consistent with the three standard model neutrinos
- Measurement: observe that the number of electron neutrinos in a majority muon neutrino beam (100:1) are more than expected
- Alternative: neutrinos coming from a source seem to disappear, i.e. they turn into a flavor where they cannot be seen

Measuring Neutrino Oscillations

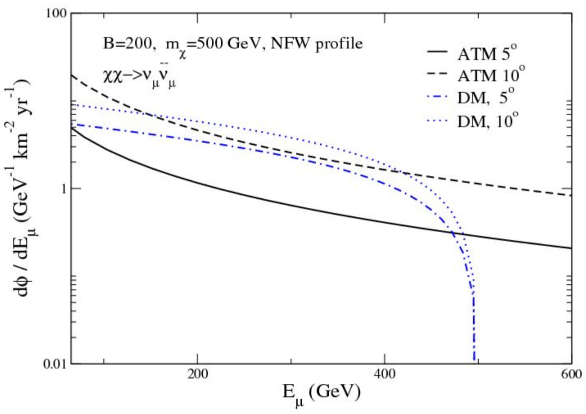
- Precision measurement of neutrino oscillation parameters
- Signal: neutrinos in one flavor can turn into another flavor (i.e. oscillate) with a very specific L/E depenence
- Measurement: observe the right pattern of oscillations for values of L and E



Numu spectrum with and without oscillations from an experiment called T2K

Neutrinos as evidence of dark matter

- Detect neutrinos coming from dark matter annihilation
- Signal: neutrinos coming from a region of relatively high gravitational mass such as the sun, the core of the earth, or the center of the milky way galaxy
- Dark matter masses of interest range from 1-10 GeV to 1-10 TeVs
- Start with a dark matter decay product is a pair of neutrinos



Things to consider when picking a source

-- energy
-- given energy, what products can I produce? (production threshold)
-- do I have the right flavor of neutrinos I need?