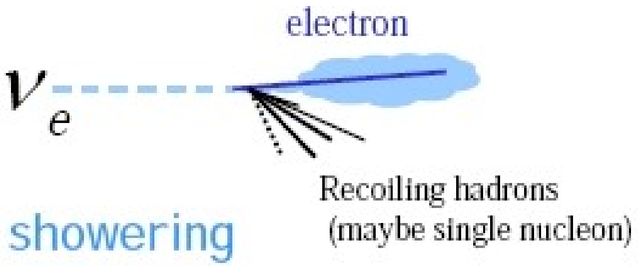
Neutrino Detectors

So, you want to build a neutrino detector?

- How many events do you need to do the physics?
  - Determines detector mass
  - Determines the target type
- What kind of interaction? ν_e, ν_μ, CC, NC?
- What do you want to measure?
  - Energy? Final state particles? This influences detector technology
- What sort of backgrounds do have to deal with?
  - More influence on technology – usually conflicting with signal requirements.
- How much cash do you have? (most important)

Neutrino Flavour Identification



showering

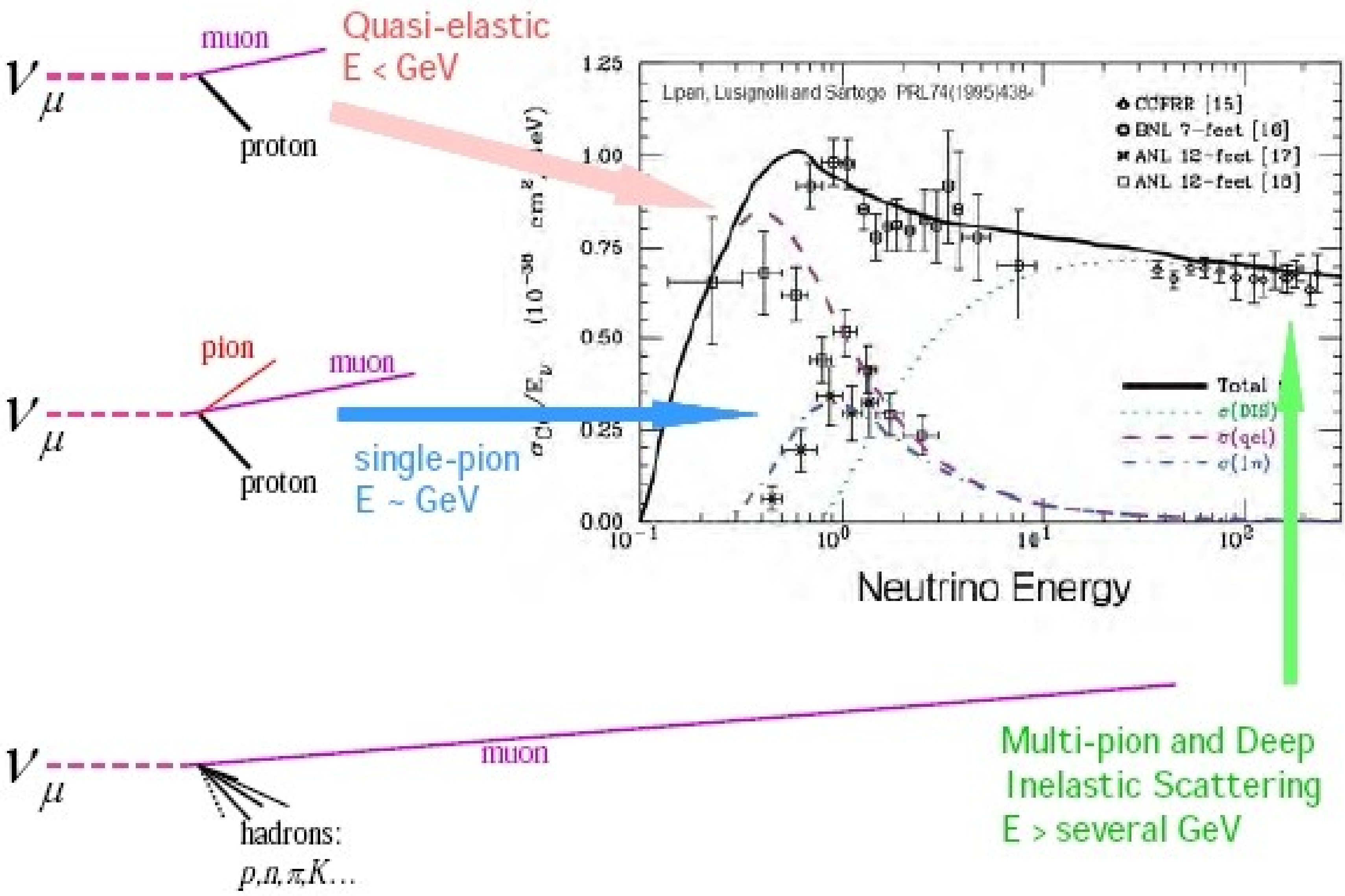
penetrating

challenging

τ	$\rightarrow e\nu\nu$	18%
	$\rightarrow \mu\nu\nu$	18%
	$\rightarrow 3\pi\nu$	14%
	$\rightarrow \pi\nu$	11%

annoying (frequently background)

Types of Interactions

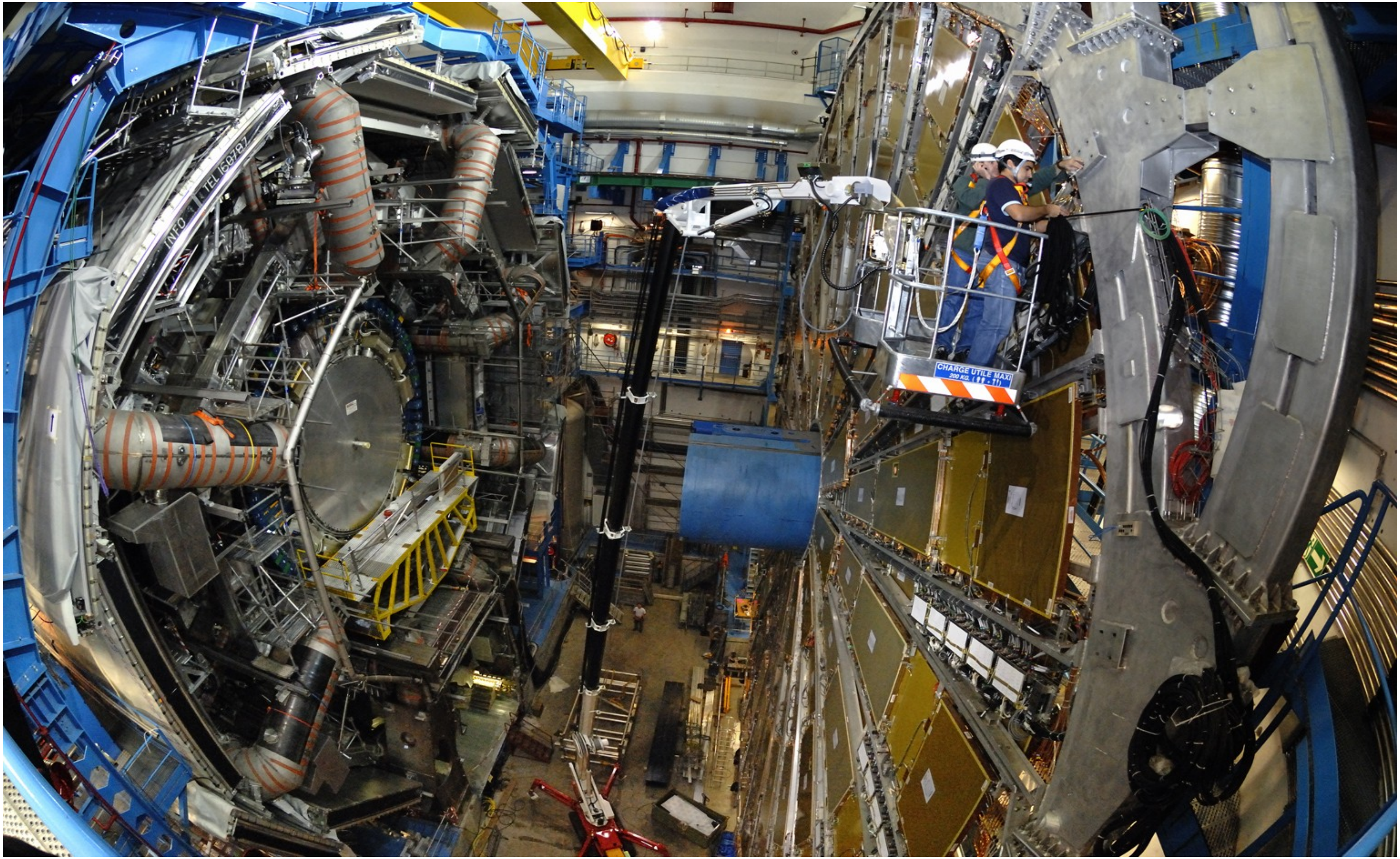


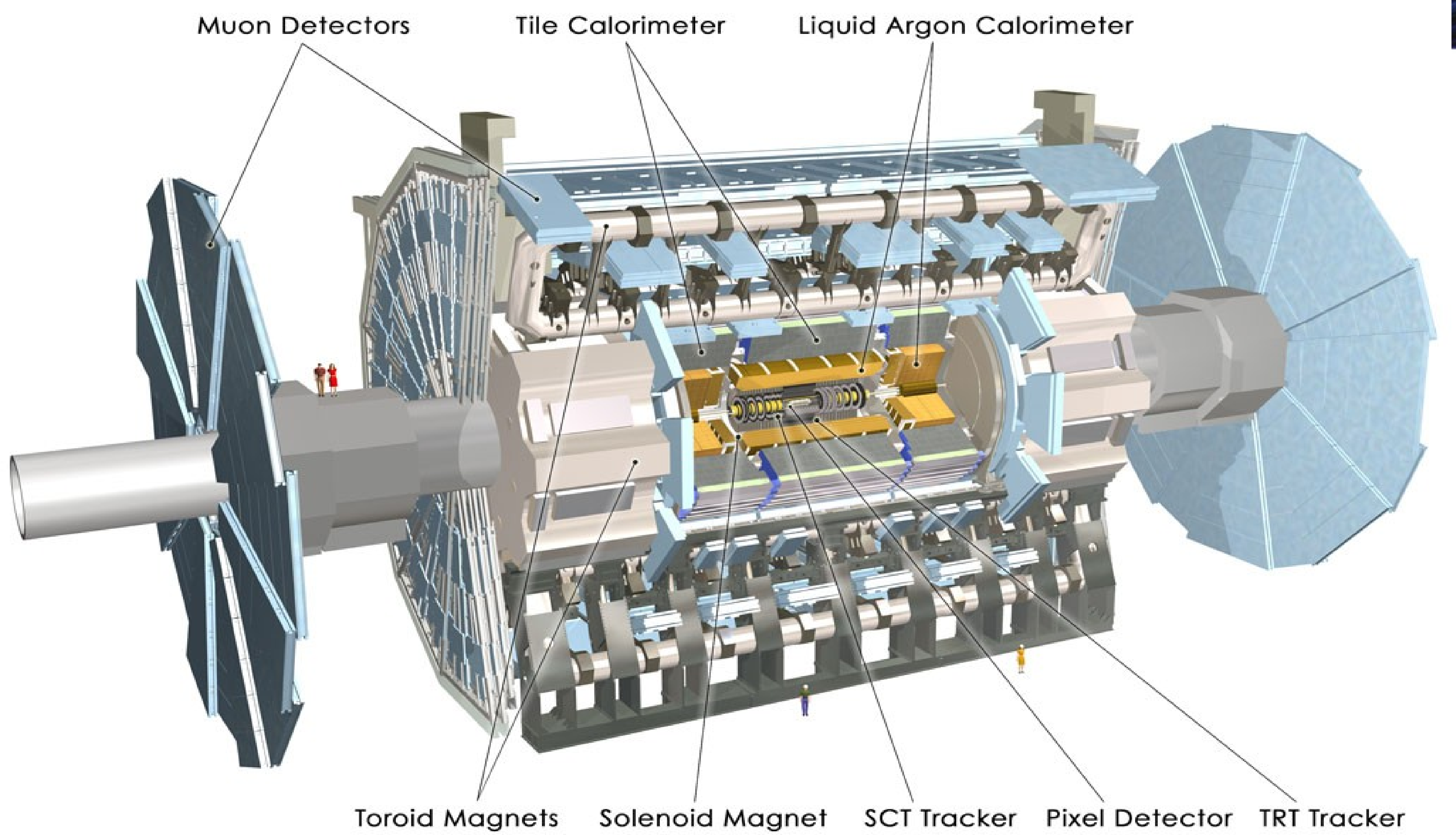
Quasi-elastic
E < GeV

single-pion
E ~ GeV

Multi-pion and Deep
Inelastic Scattering
E > several GeV

Usual collider detector



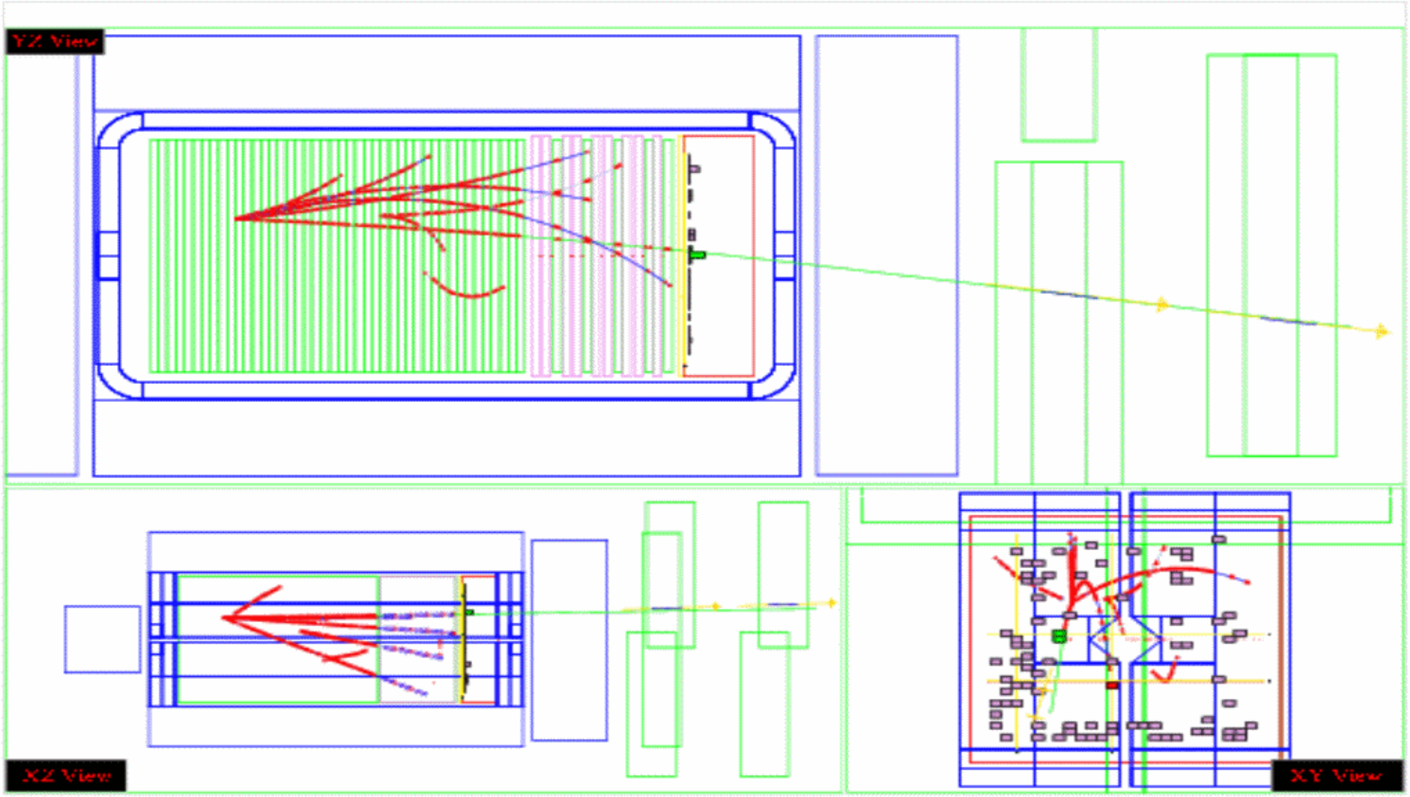


- Know when and where the interaction will occur. So can design a detector around that point

Neutrinos will interact *anywhere*

Detector Techniques

You can never detect the neutrinos themselves – you have to detect the products of their interactions and work back.



Detector Techniques

Neutrinos interaction anywhere there is mass. More mass, more interactions. Combined with small cross-sections this means that detection mass must be large (and therefore cheap) and usually you need to go underground for shielding

Usually large containers of matter surrounded by detection elements

- Radiochemical experiments
- Water (H_20 or D_20) experiments
- Scintillator detectors
- Tracking calorimeters

Radiochemical Experiments

This technique uses the production of radioactive isotopes.

Davis-Pontecorvo experiment was the first attempt to use this to look at solar neutrinos

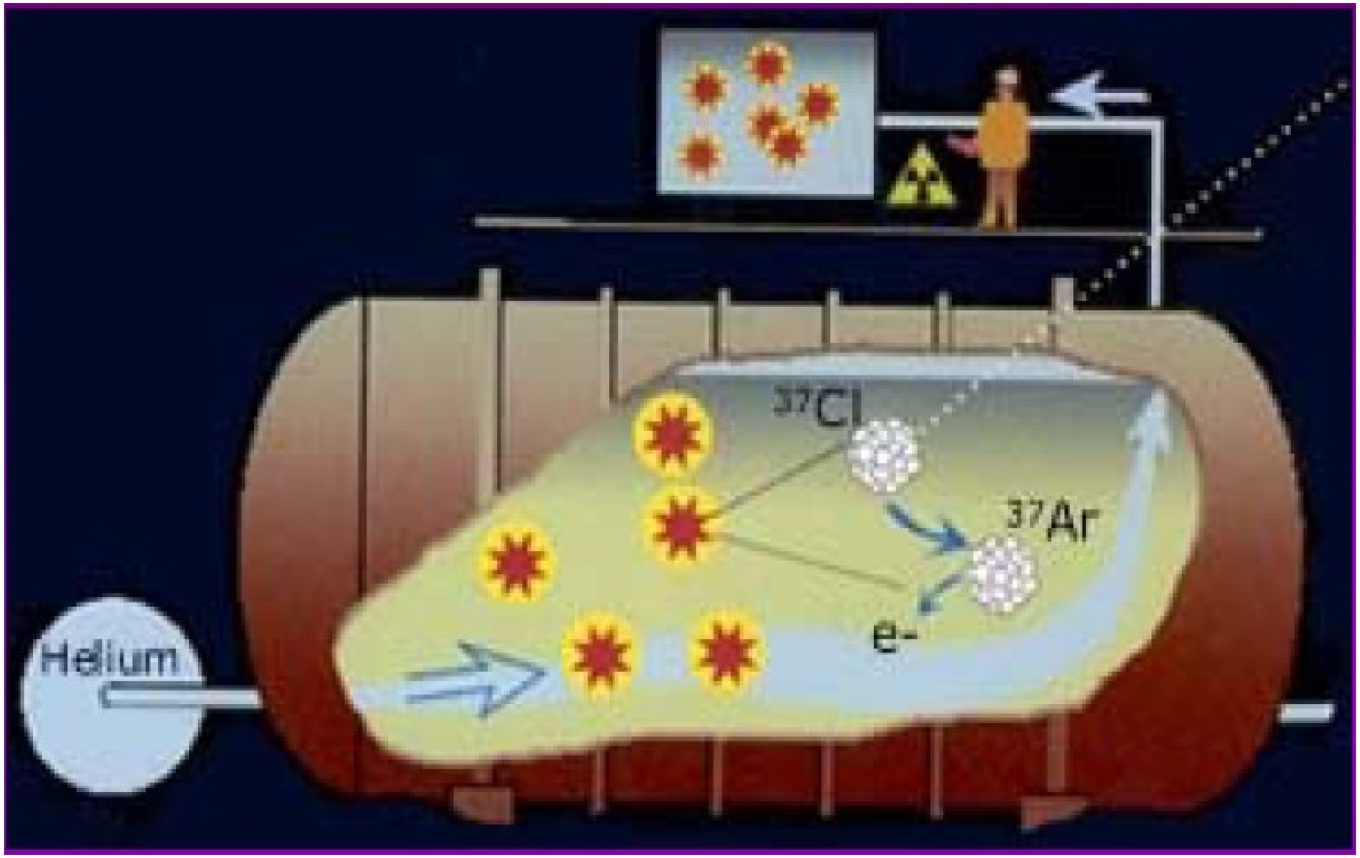
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^- \qquad \nu_e + Ga^{71} \rightarrow \mathrm{Ge}^{37} + e^-$$

The isotopes Ar or Ge are radioactive. In this type of experiment the isotopes are chemically extracted and counted using their decay

Disadvantage is that there is no information on interaction time, neutrino direction or flavours other than ν_e

The Davis Experiment

The very first solar neutrino experiment in the Homestake mine in South Dakota



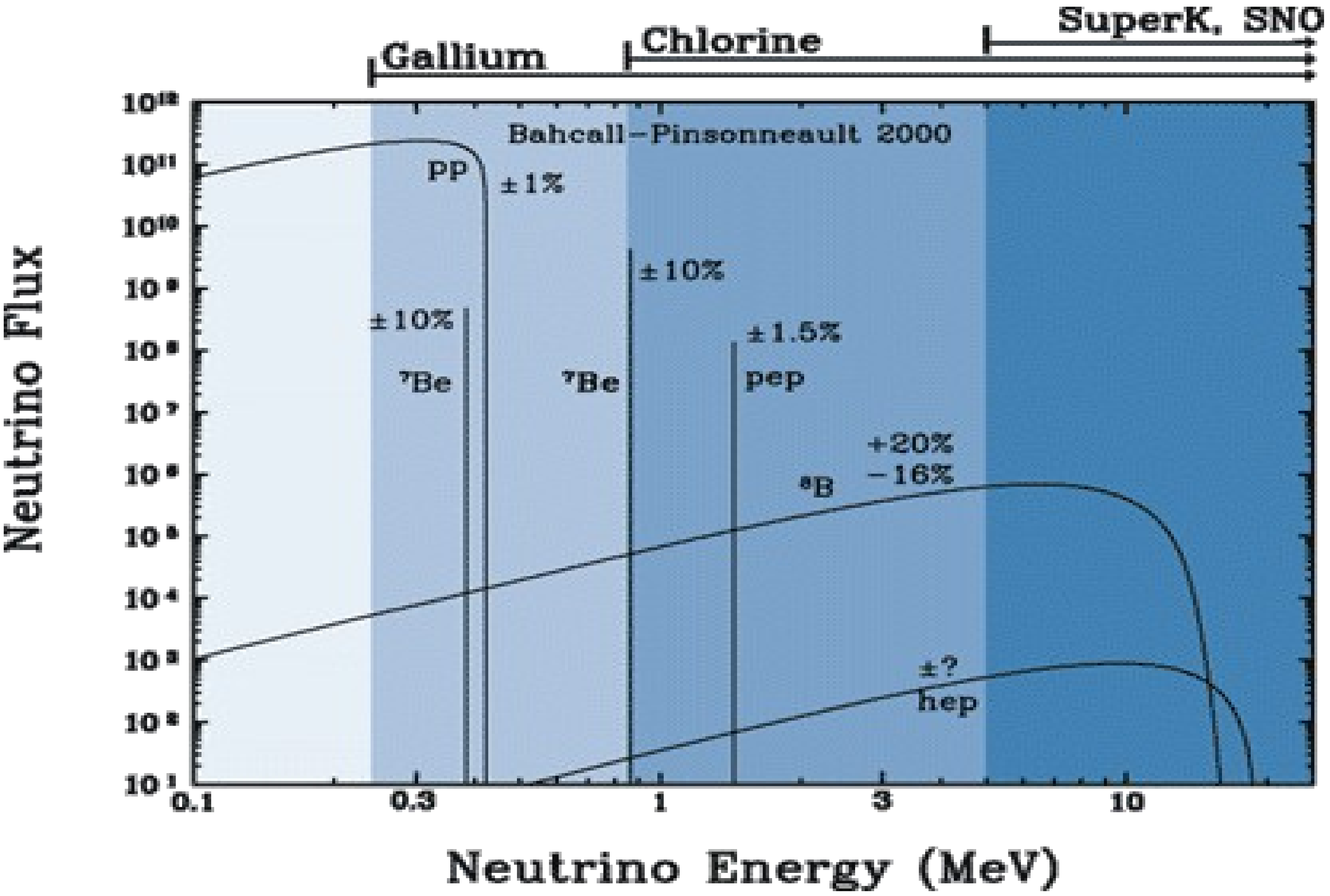
615 tonnes of CCl4
Ran from 1968
to 1994

Individual argon atoms are captured and counted.

1 atom per 2 days.

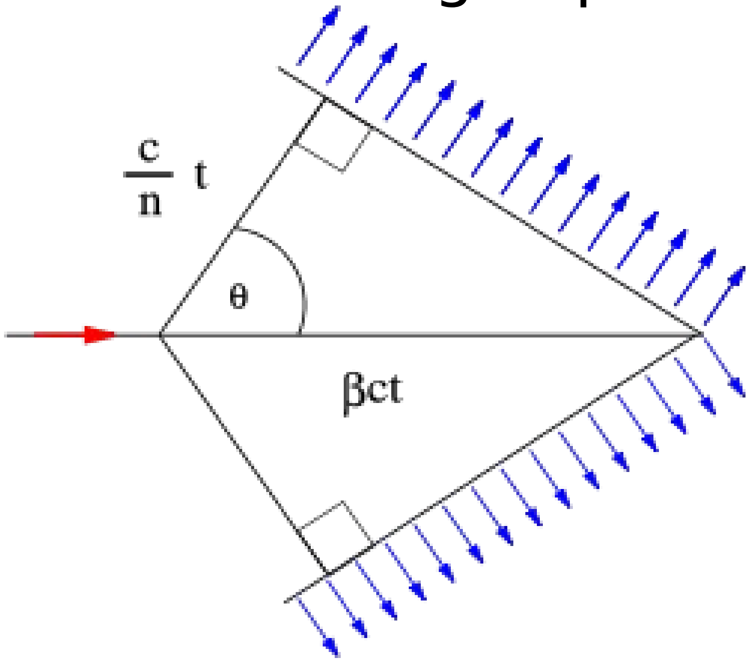
Threshold : 814 keV

Standard Solar Model



Water Experiments

Water is a very cheap target material – these experiments detect charged particles using Cerenkov radiation.

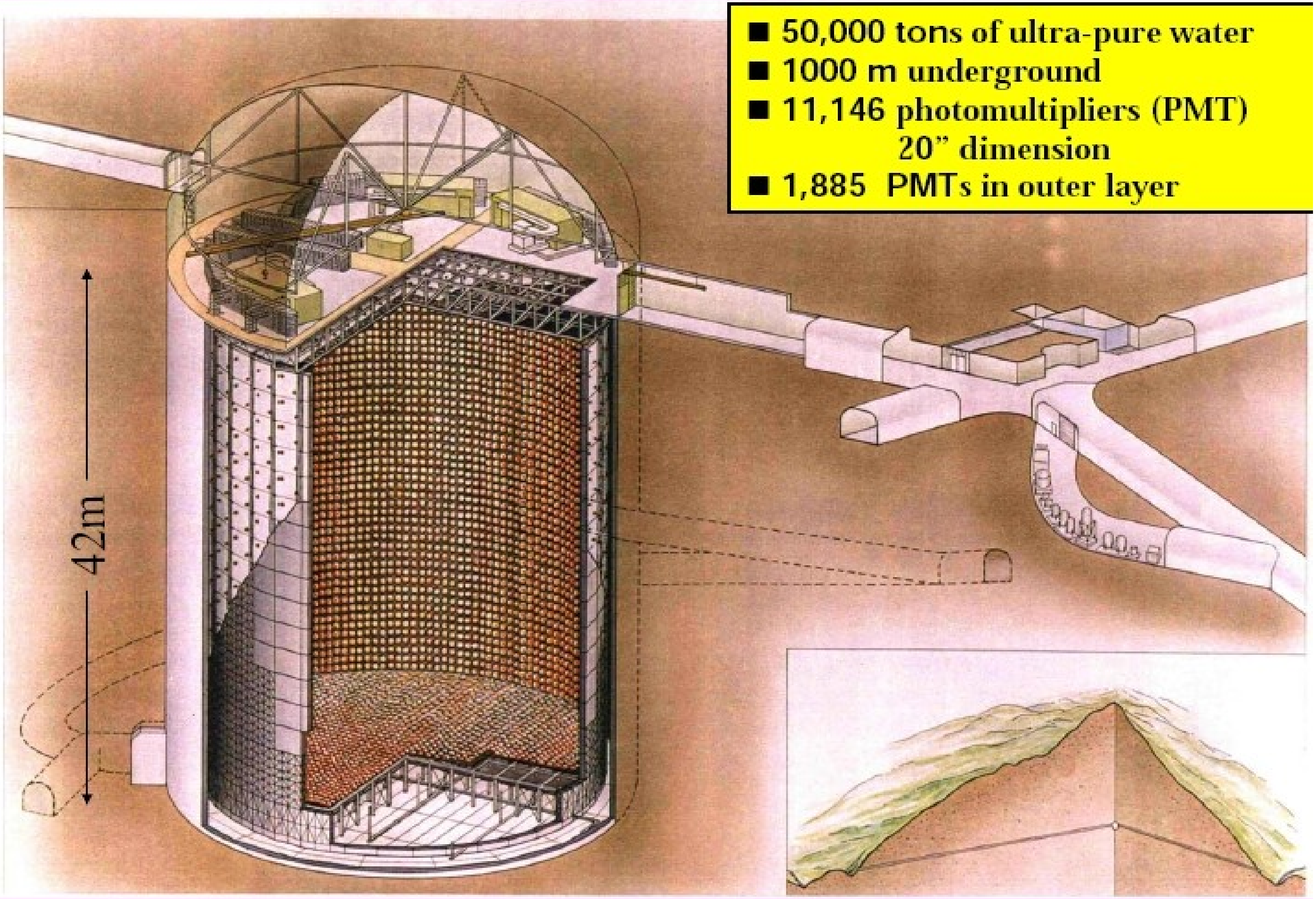


If a charged particle moves through a material with β > 1/n it produces an EM shockwave at a particular angle.

$$\cos\theta = 1/\beta n$$

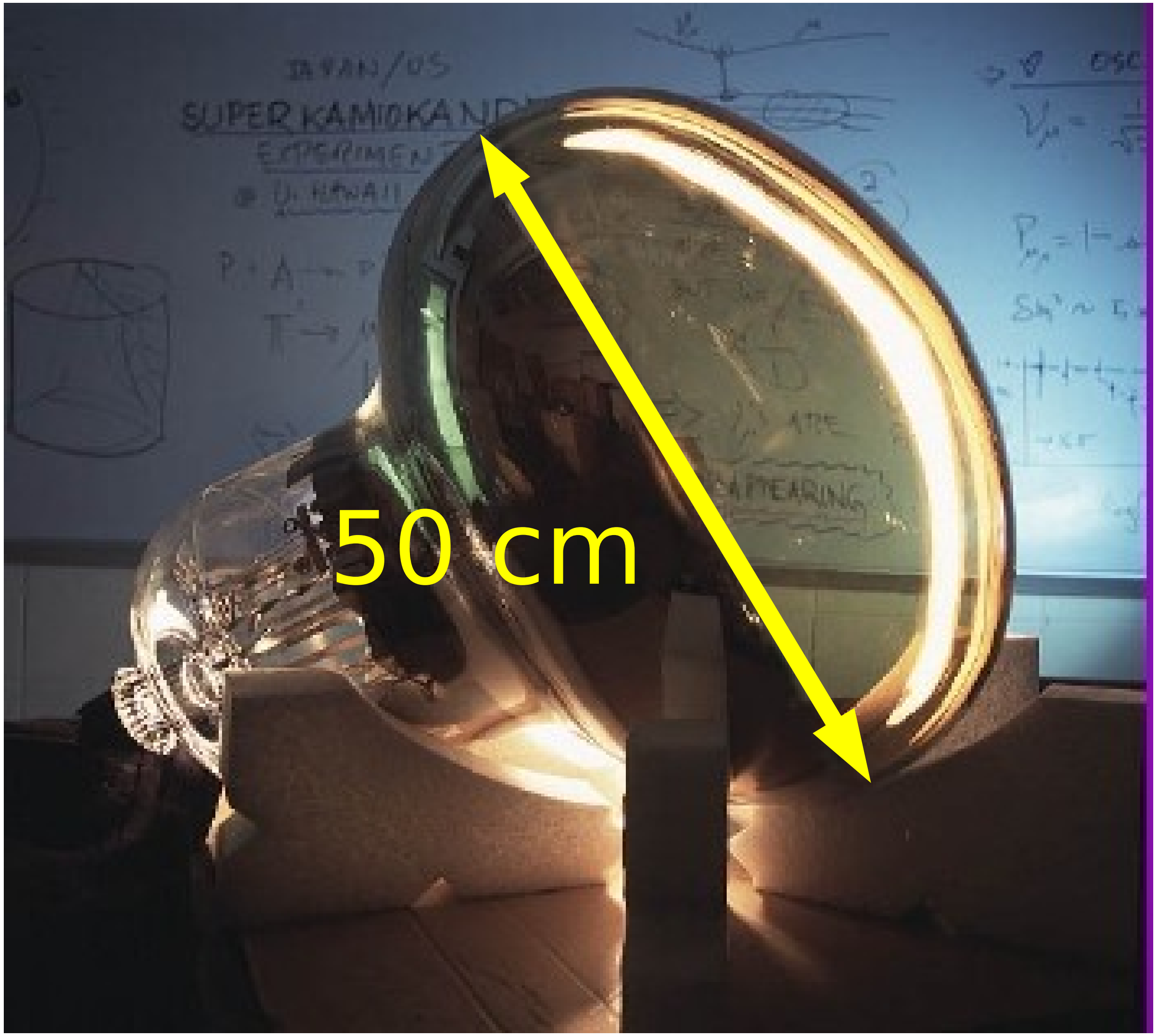
The shockwave can be detected and used to measure the particle direction and vertex.
Particles below threshold and neutral particles are not detected

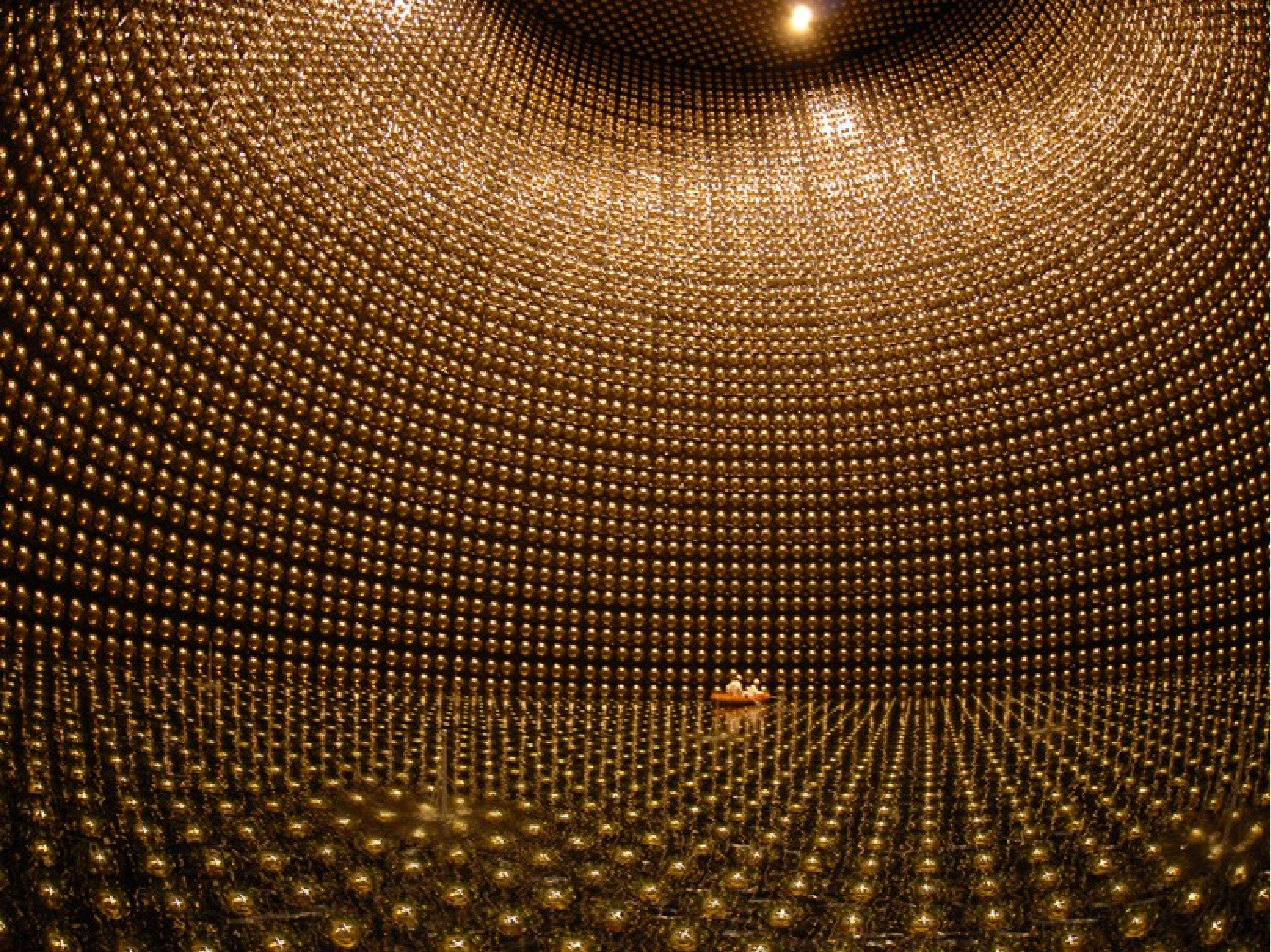
Super-Kamiokande



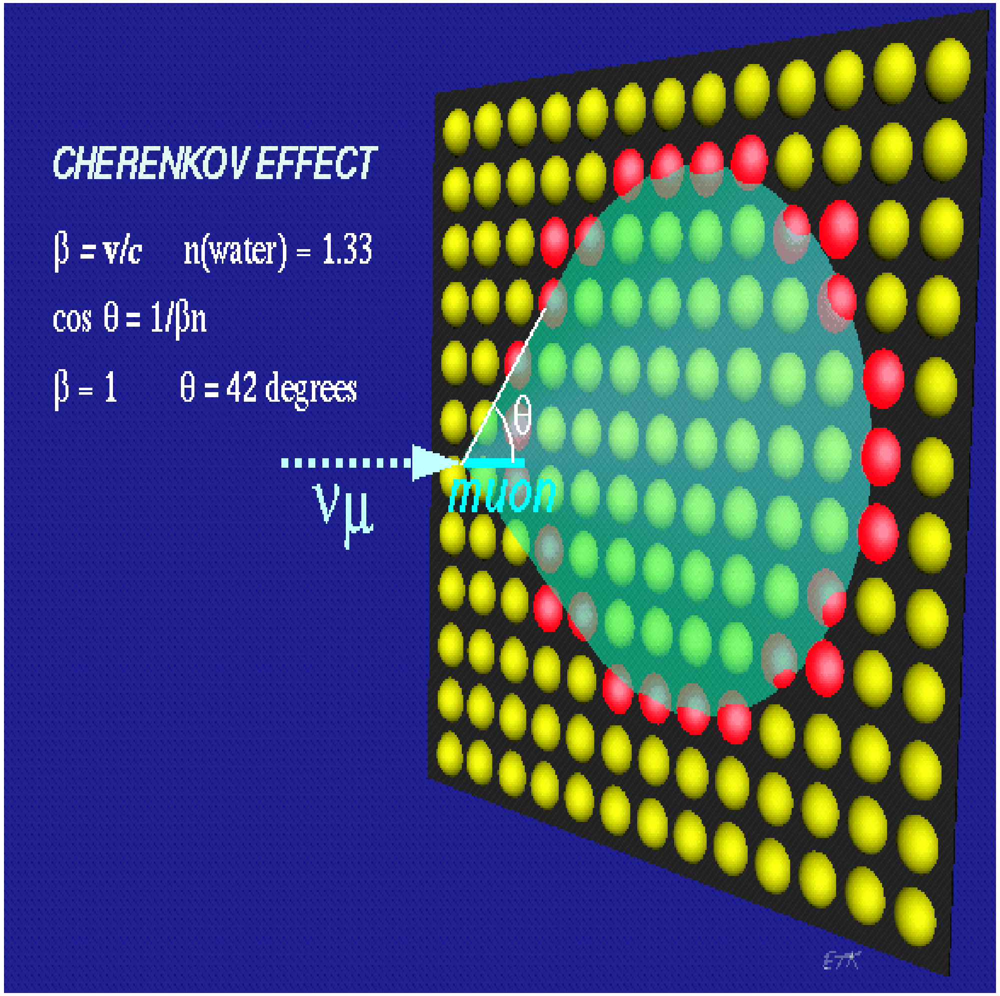
- 50,000 tons of ultra-pure water
- 1000 m underground
- 11,146 photomultipliers (PMT) 20” dimension
- 1,885 PMTs in outer layer

Photomultiplier Tubes

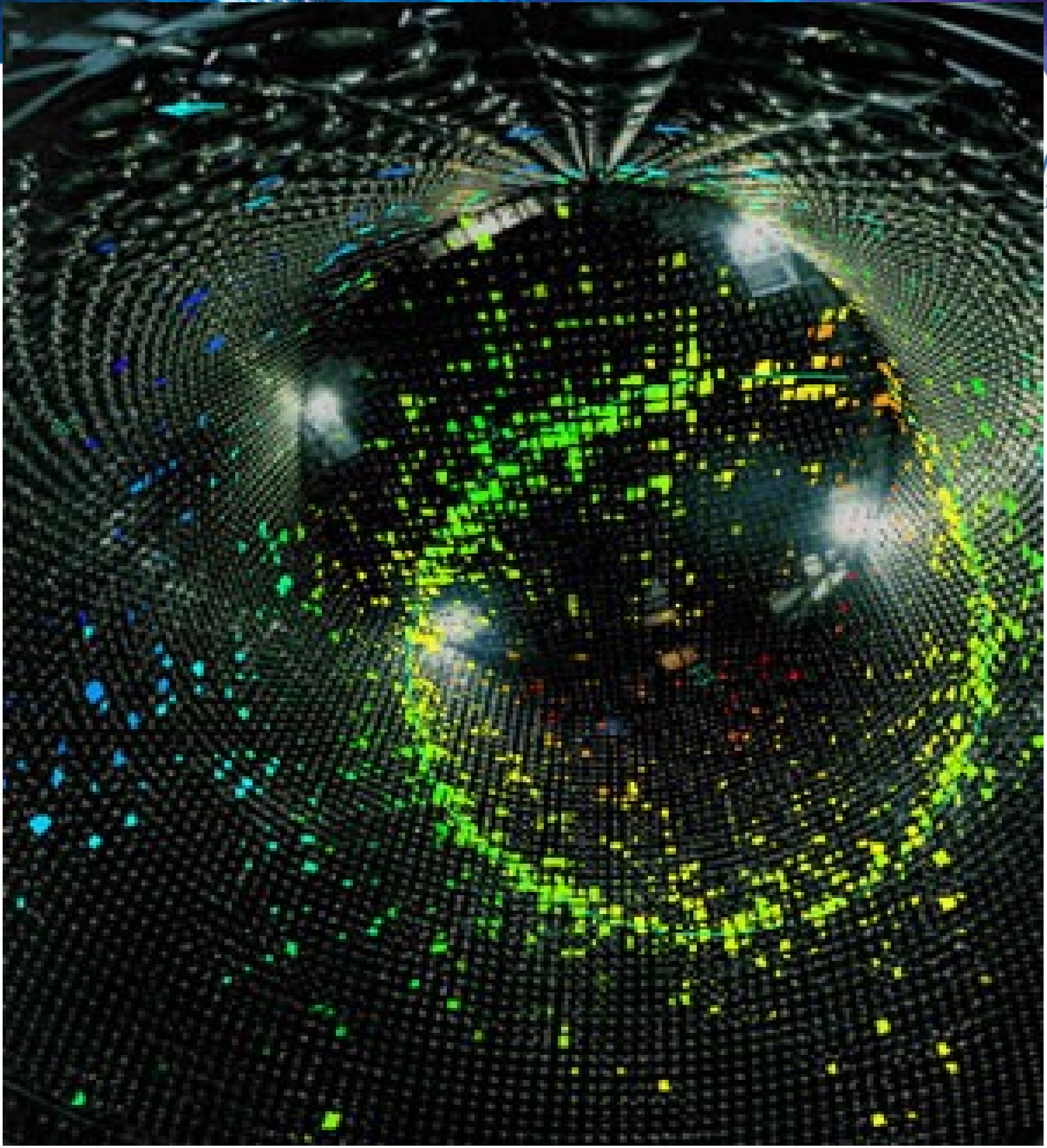




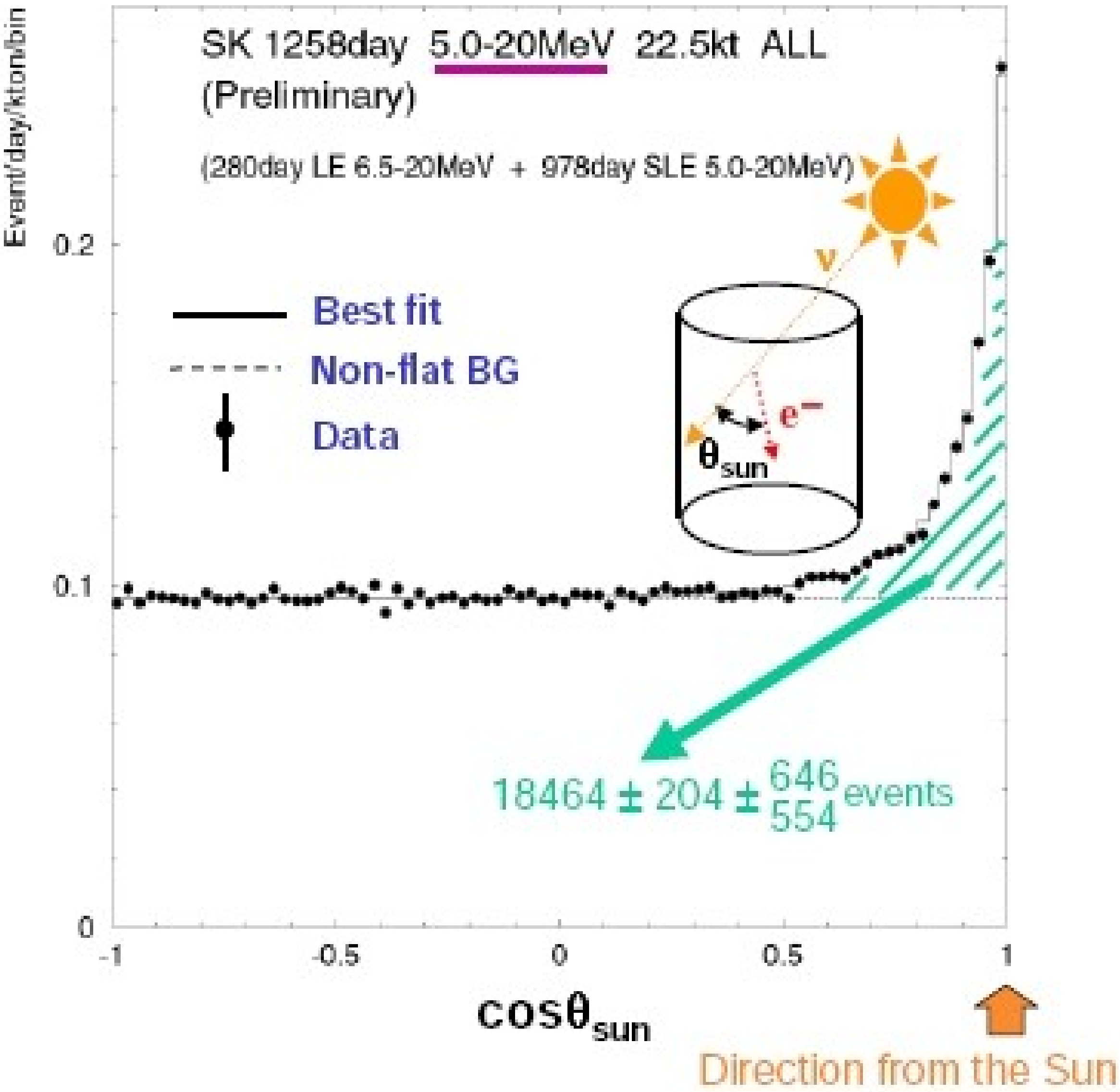
Principle of operation



- Cerenkov light detected as a ring or circle by PMTs
- Vertex from timing
- Direction from cone
- Energy from summed light
- No neutrals or charged particles under Cerenkov threshold
- Low multiplicity events

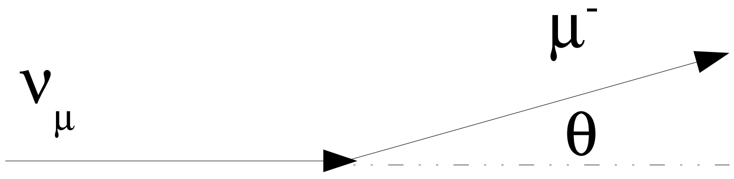


Directionality



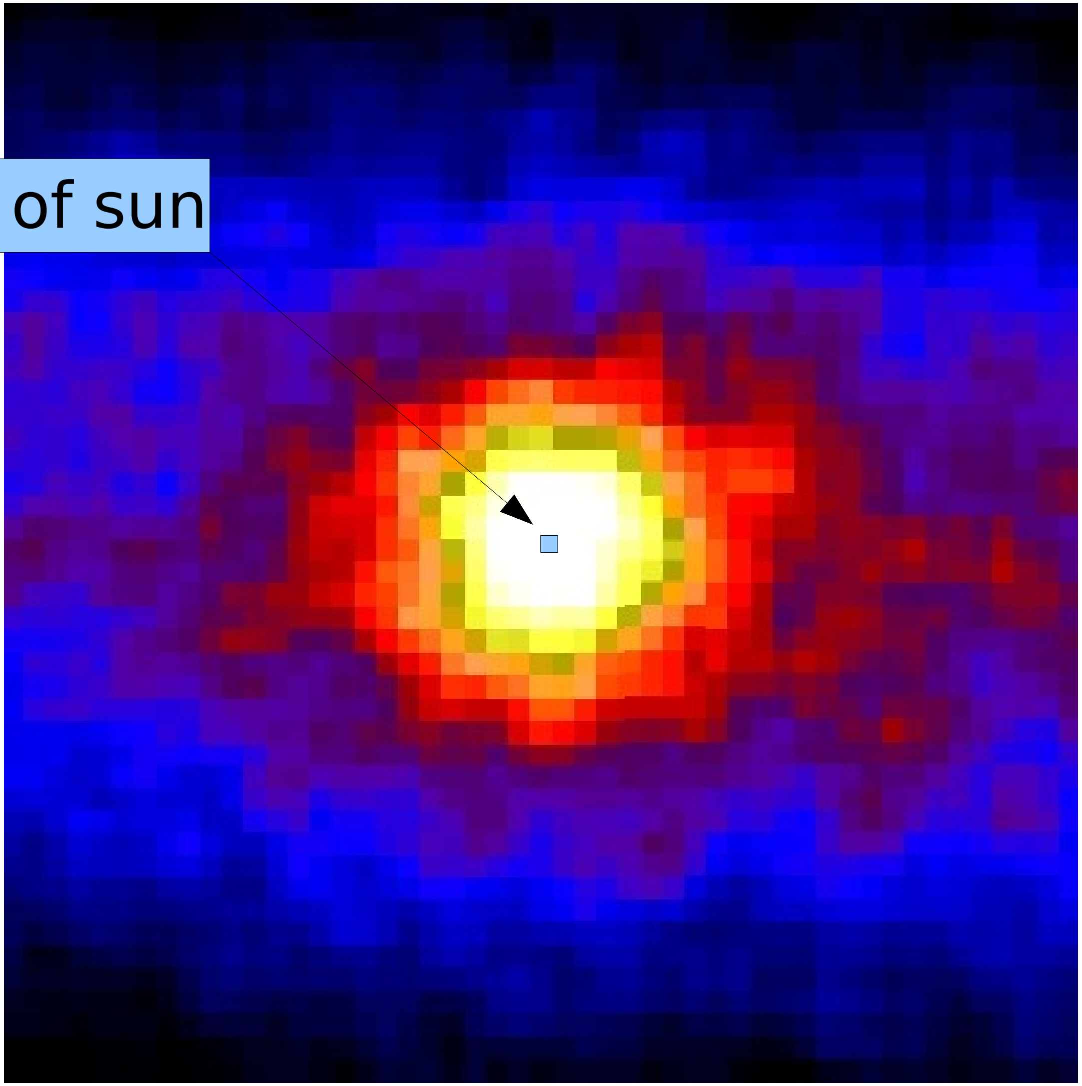
For simple events , the direction of the ring can be used to point back to the neutrino source

Proof that these neutrinos were coming from the sun



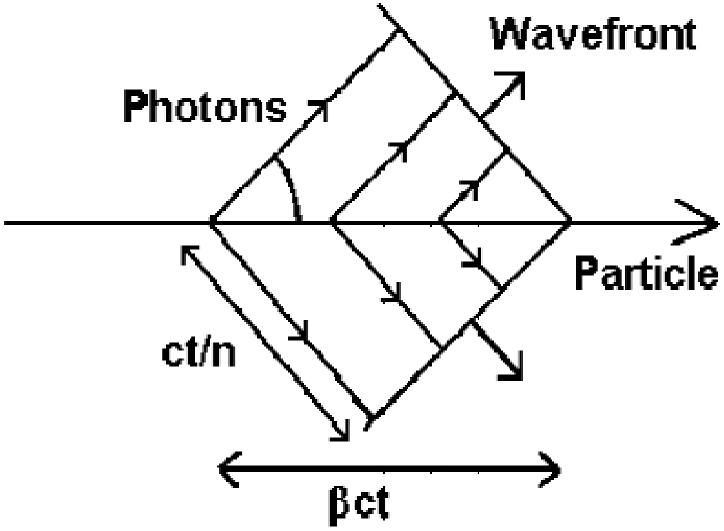
Neutrino-Gram

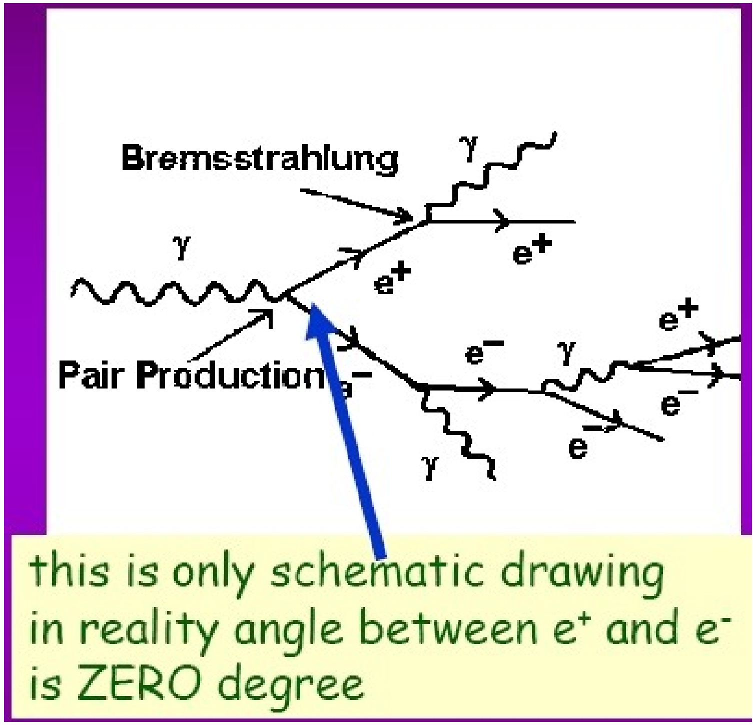
Image of the sun 1 kilometer underground



Actual size of sun

Muons vs Photons

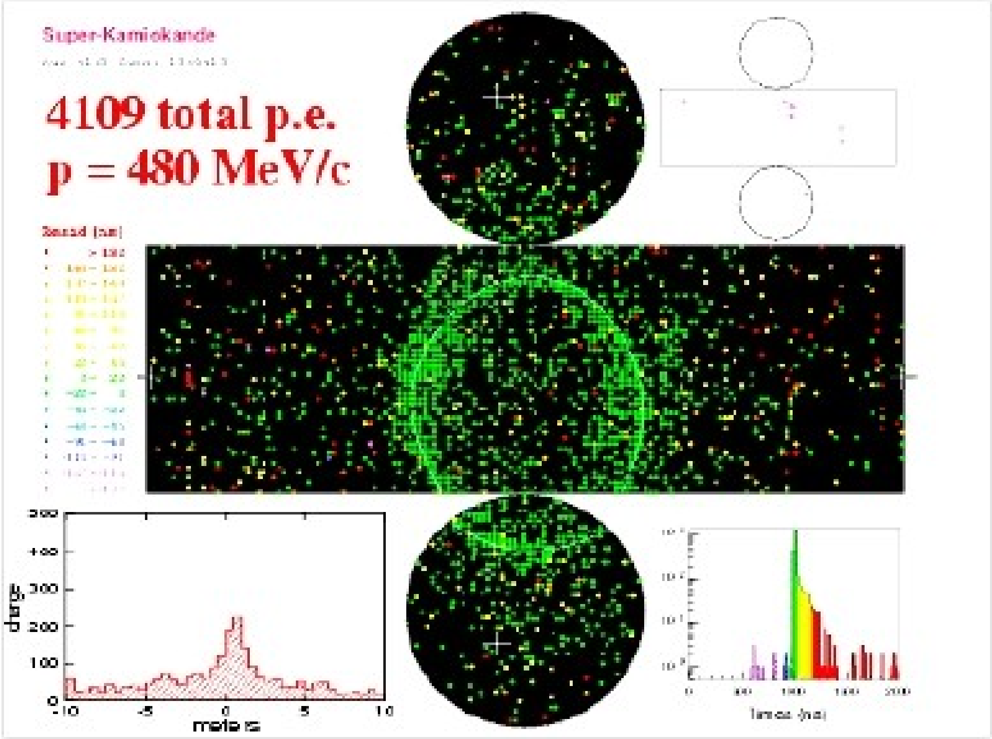




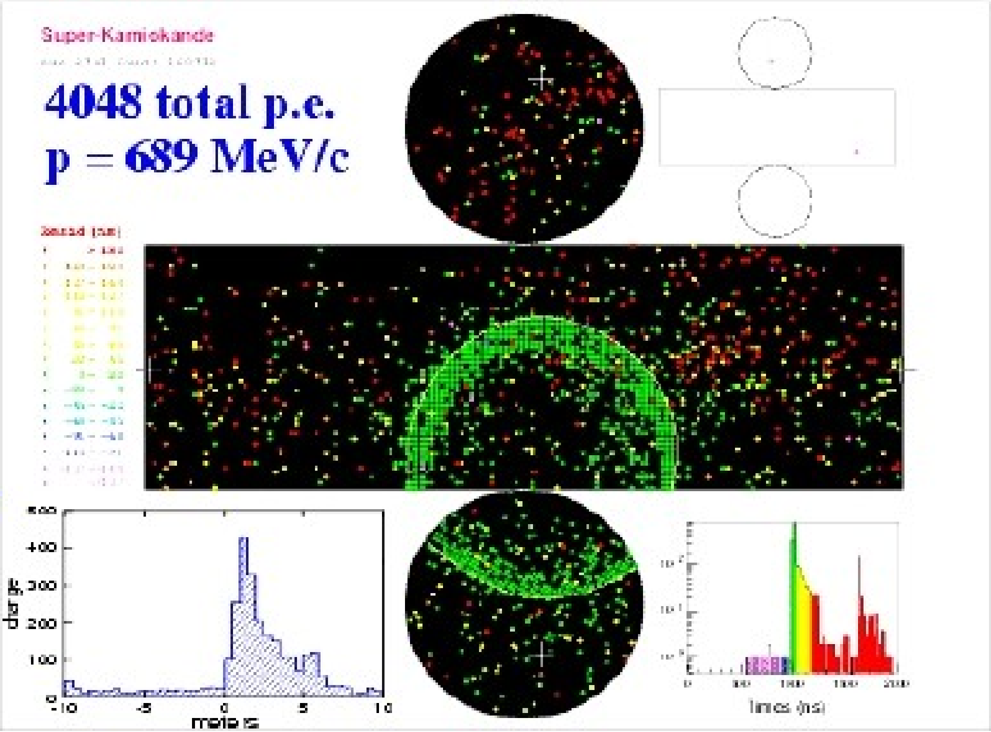
this is only schematic drawing
in reality angle between e^+ and e^-
is ZERO degree

The secondary photon interactions smear out the edge of Cerenkov cone and provide particle identification as well.

e–like



μ–like



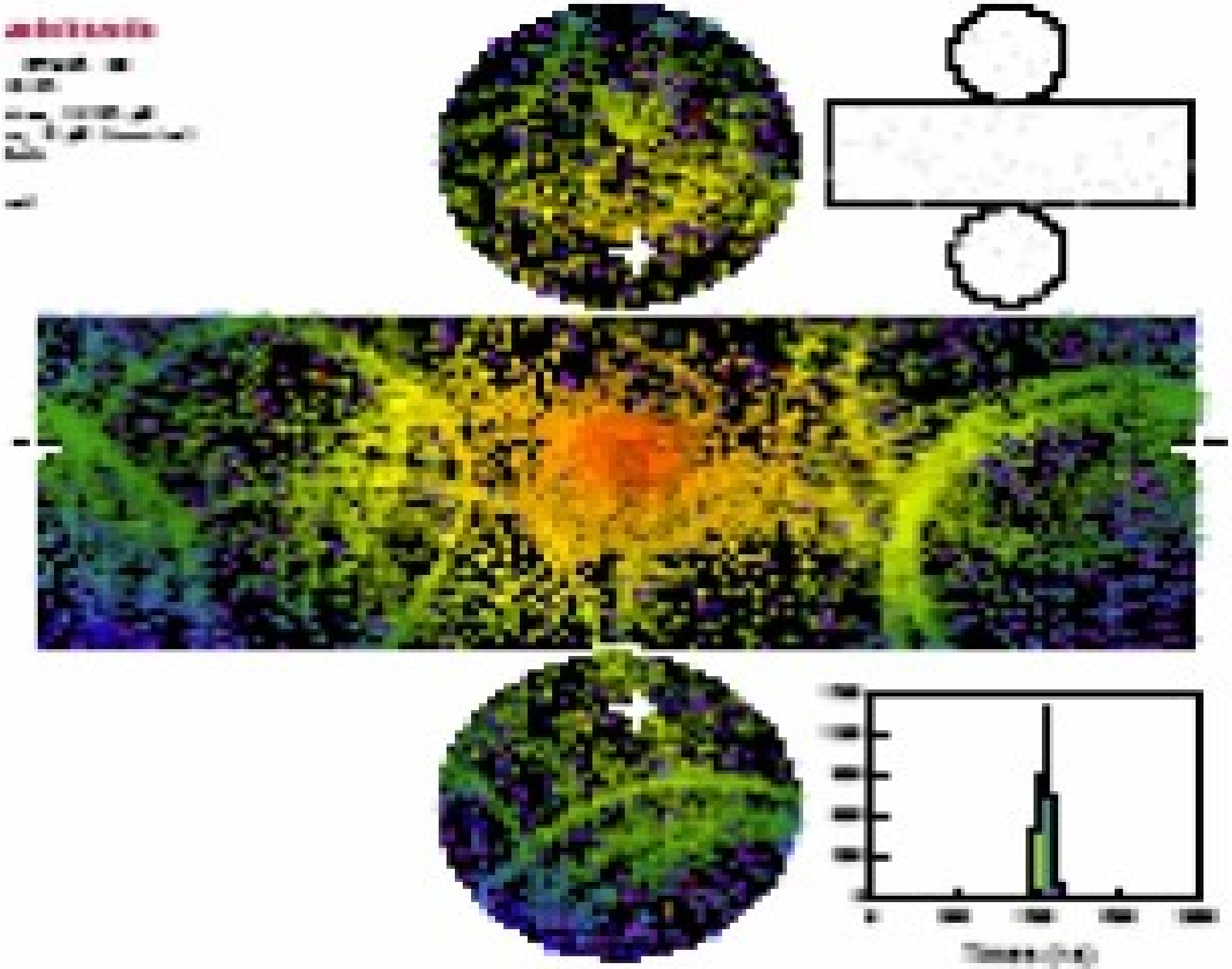
Electron-like : has a fuzzy ring

Colours = time of hit
Event energy = sum of PMT signals

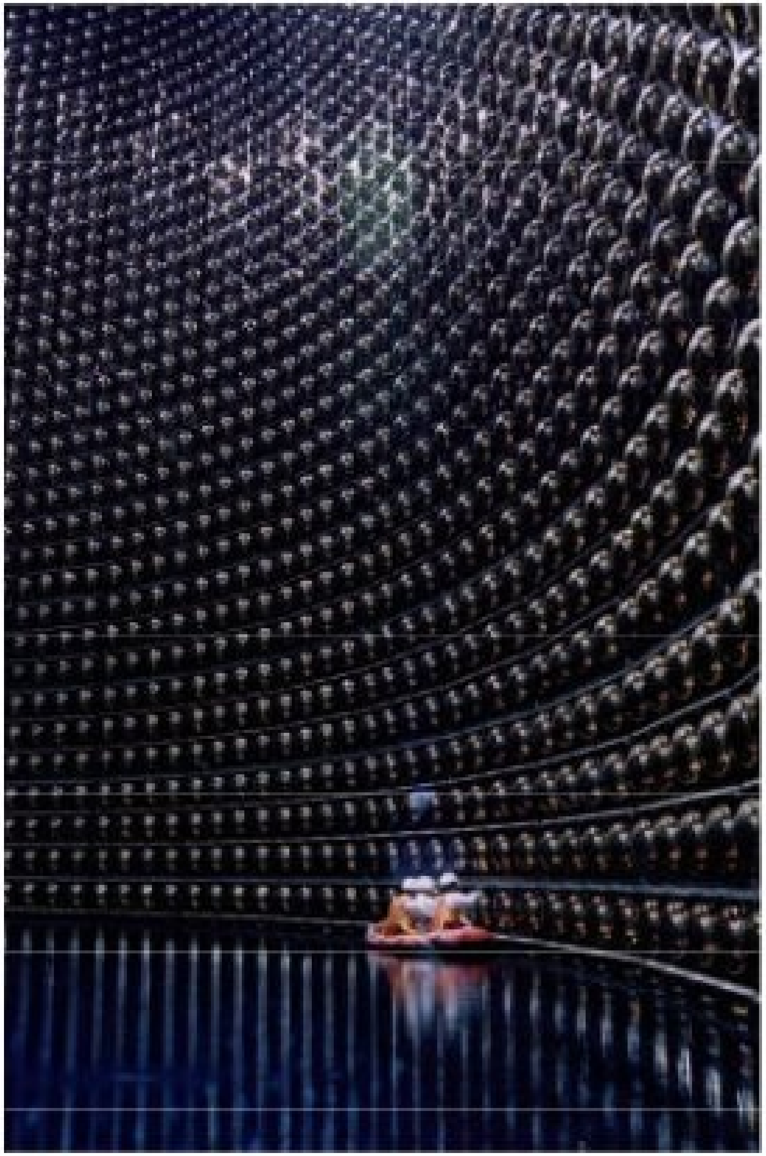
Muon-like : has a sharp edged ring and particle stopped in detector.

Problems

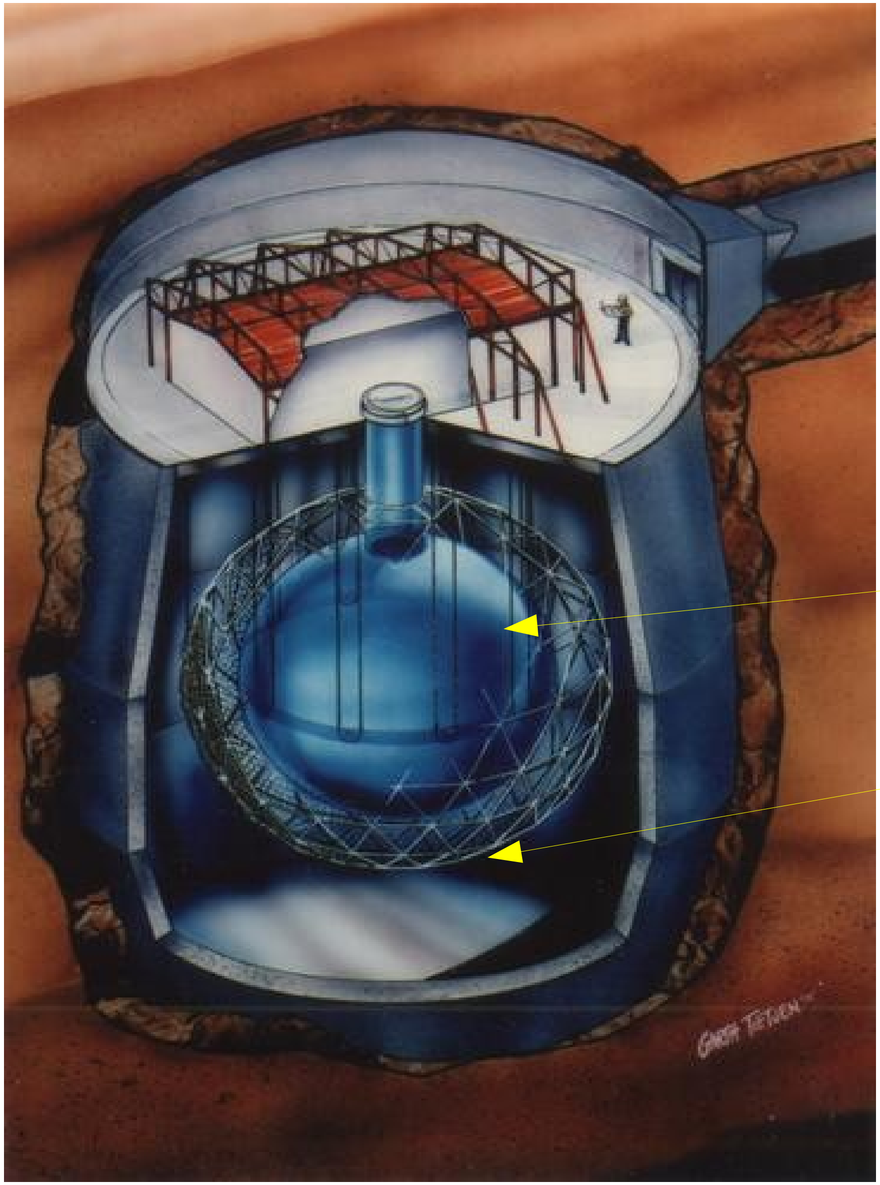
- Any particle below threshold is not seen
- Neutral particles are not observed
- Multi-ring events are extremely hard to reconstruct

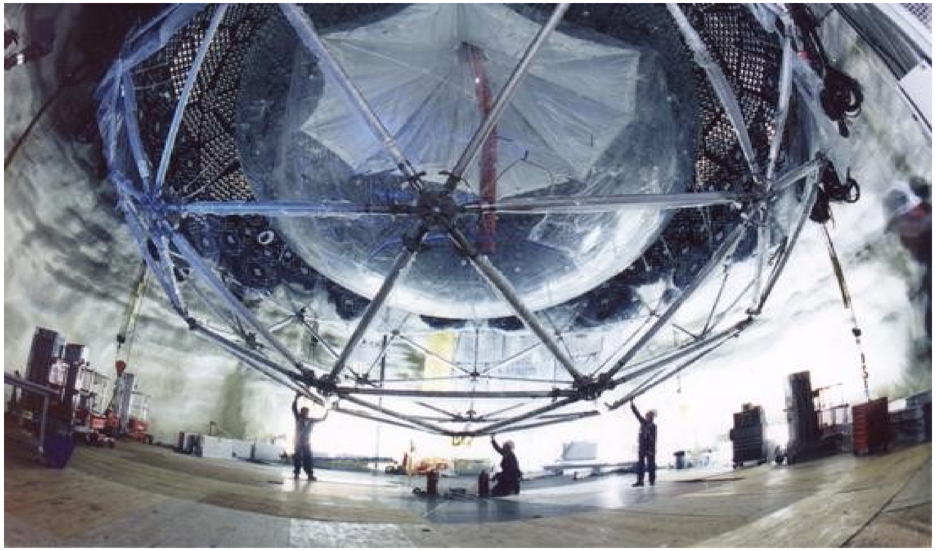


Oops



SNO – A twist





1000 tonnes of D_20

6500 tons of H_20

Viewed by 10,000 PMTS

In a salt mine 2km underground in Sudbury, Canada

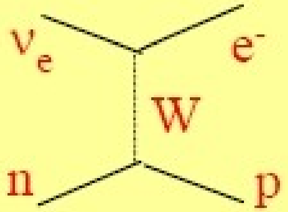
ν Reactions in SNO

Charged Current Reaction:

$\nu_e + d \rightarrow p + p + e^-$ $E_{thres} = 1.4$ MeV

CC

- 6-9 events per day
- n_e flux and energy spectrum
- Some directional sensitivity $(1 - 1/3\cos\theta_e)$

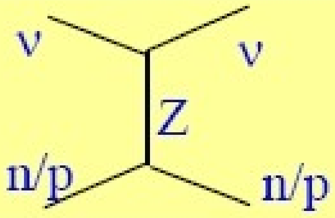


Neutral Current Reaction:

$\nu_x + d \rightarrow \nu_x + p + n$ $E_{thres} = 2.2$ MeV

NC

- 1-2 or 6-8 events per day
  (different detection mechanisms)
- Total solar ^8B active neutrino flux

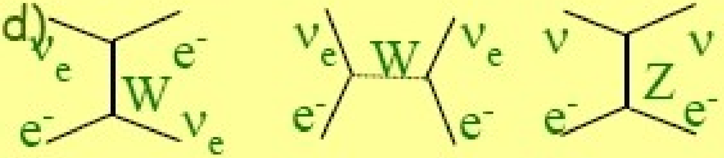


Elastic Scattering Reaction:

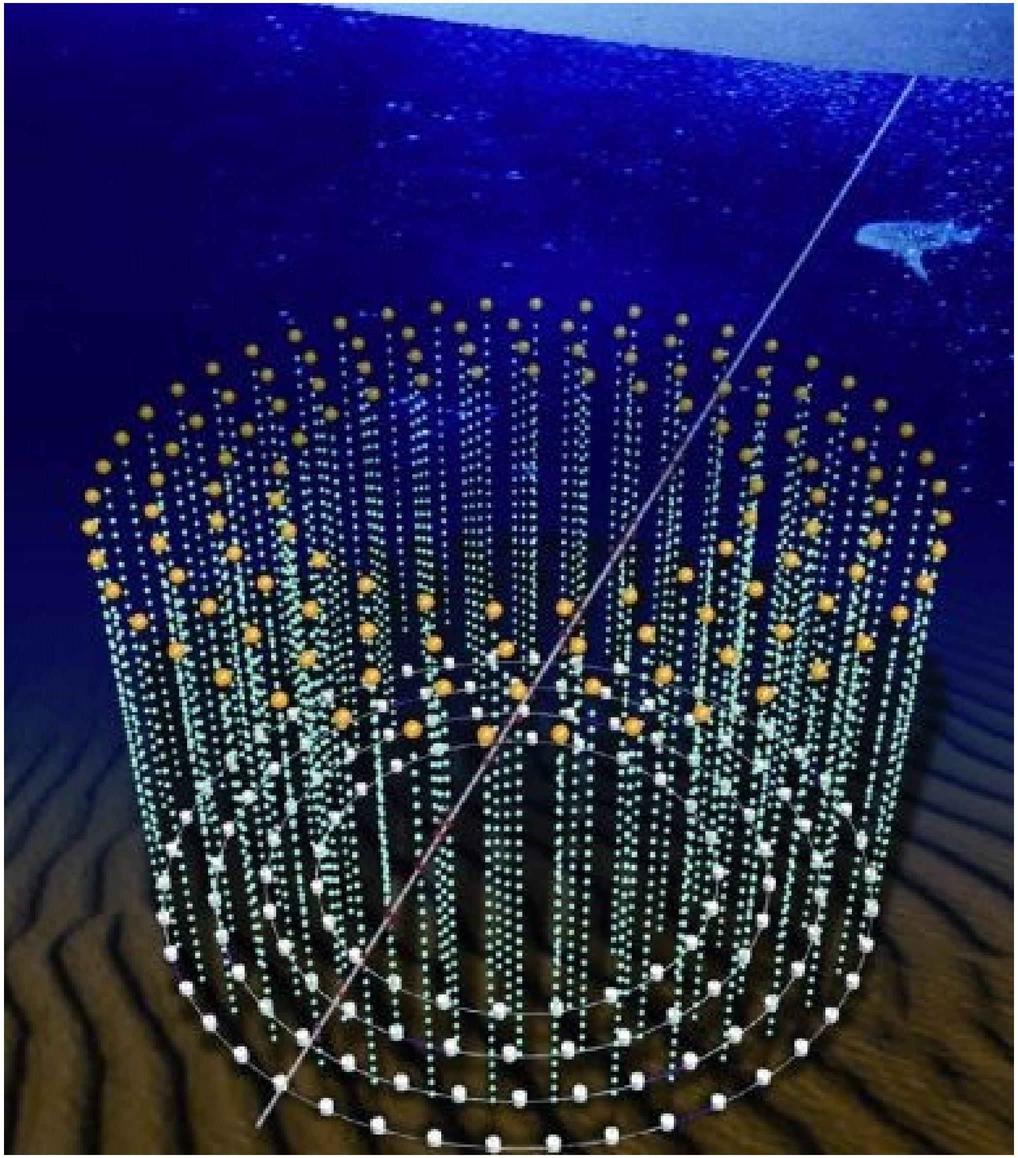
$\nu_x + e^- \rightarrow \nu_x + e^-$ $E_{thres} = 0$ MeV

ES

- 1-2.5 events per day
- Directional sensitivity (very forward peaked)



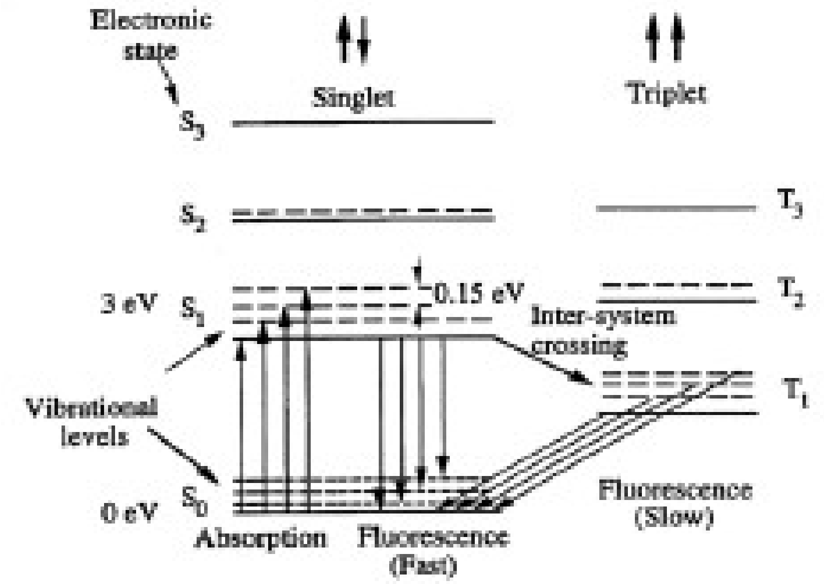
Deep Water Detectors -KM3Net



Sited off Toulon in the Mediterranean
@2400m depth

Scintillator Detectors

Emission of a pulse light following ionisation



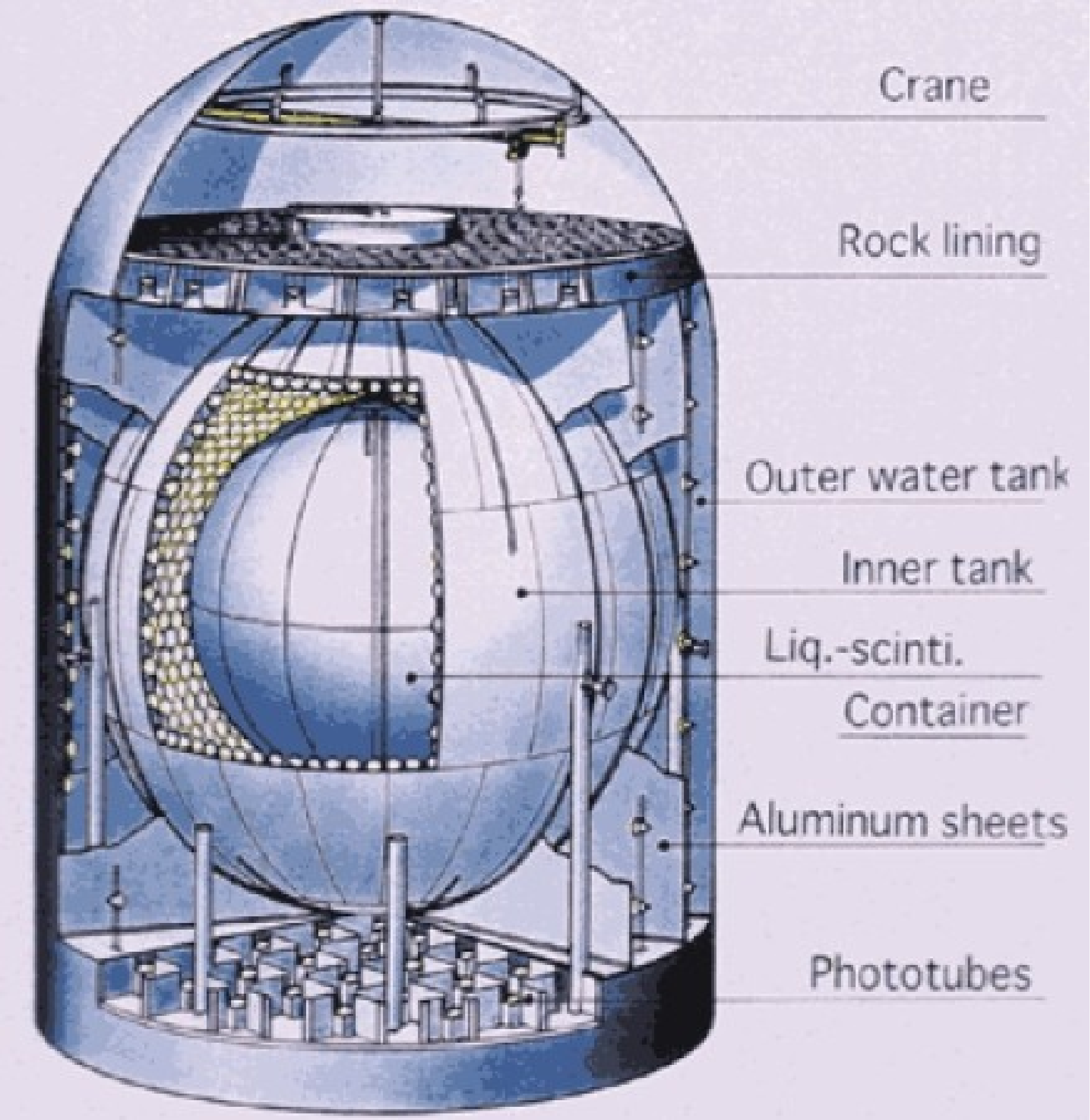
Organic liquids and plastics

Inorganic crystals

Nobel liquids

- In a good scintillator, much more light is emitted by scintillation than by the Cerenkov process.
- Scintillation light is isotropic and there is no threshold.
- No information on directionality,the emission wavelength depends on the scintillator material, and the scintillator is usually highly toxic.

KamLAND



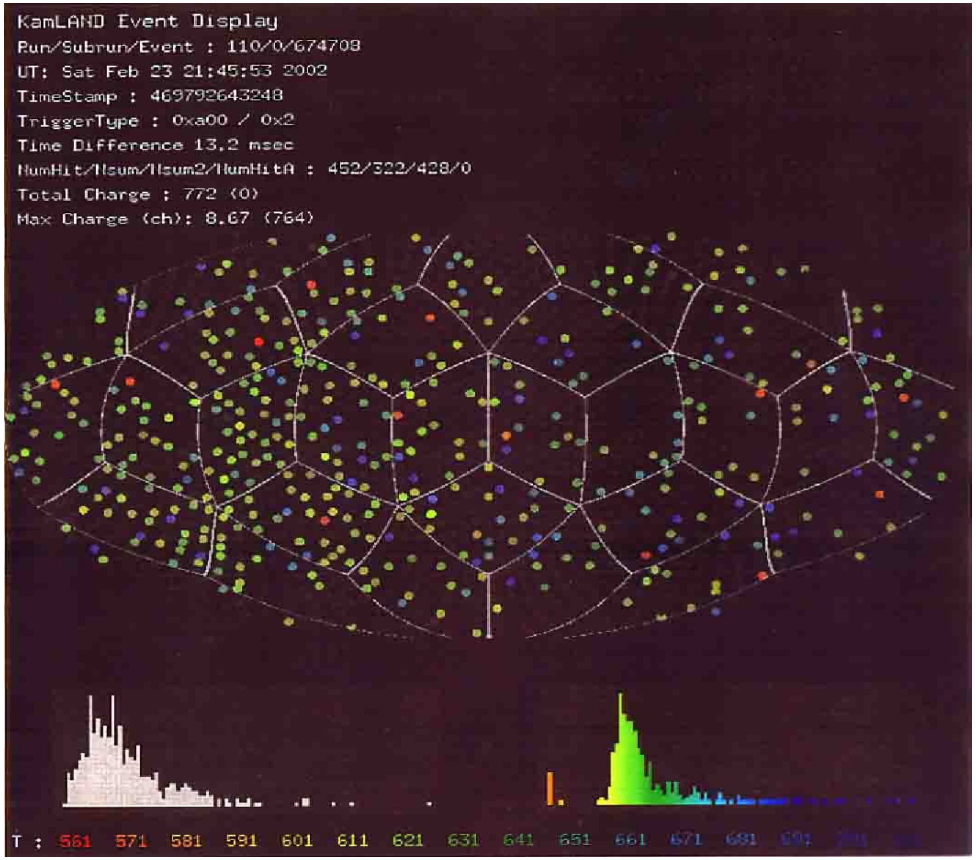
- External container filled with 3.2 kton H_2O
- Inner sphere filled with 2 kton of mineral oil
- Inside transparent balloon filled with 1 kton of liquid scintillator
- Located 1km deep in the Kamioka mine, just up the street from Super-Kamiokande
- Very pure – background is a major problem.

Event Displays

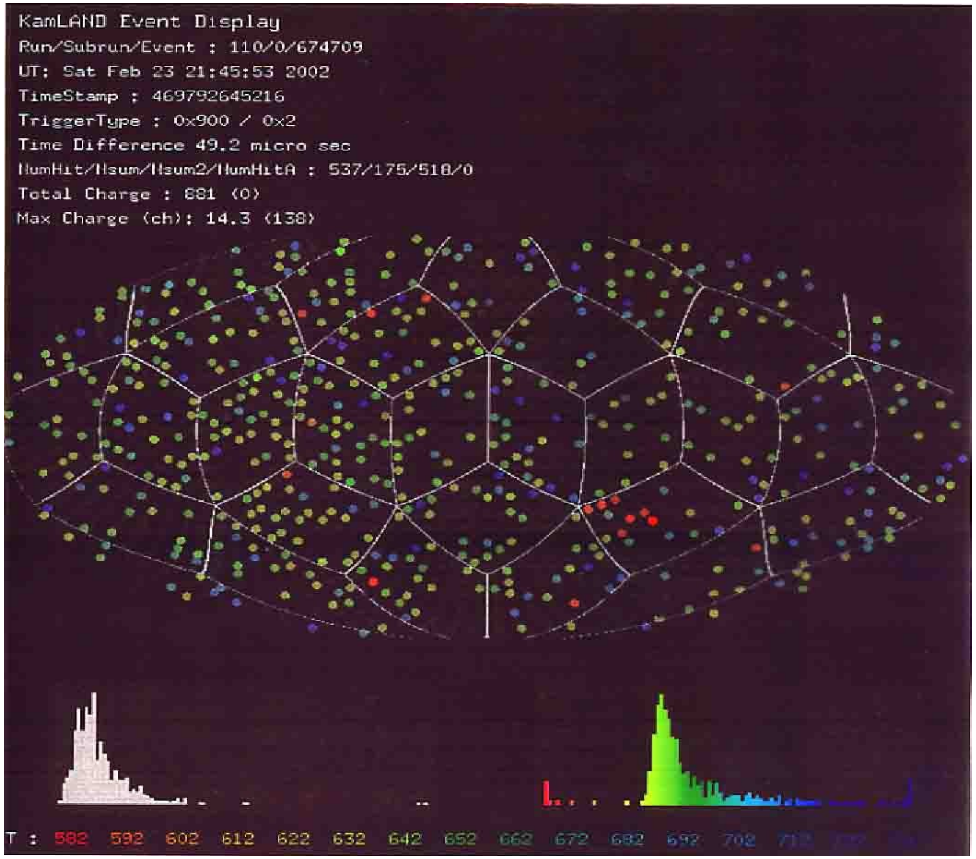
$\overline{\nu_e} + p \rightarrow e^+ + n$

200 ms later

$n + p \rightarrow d + \gamma$



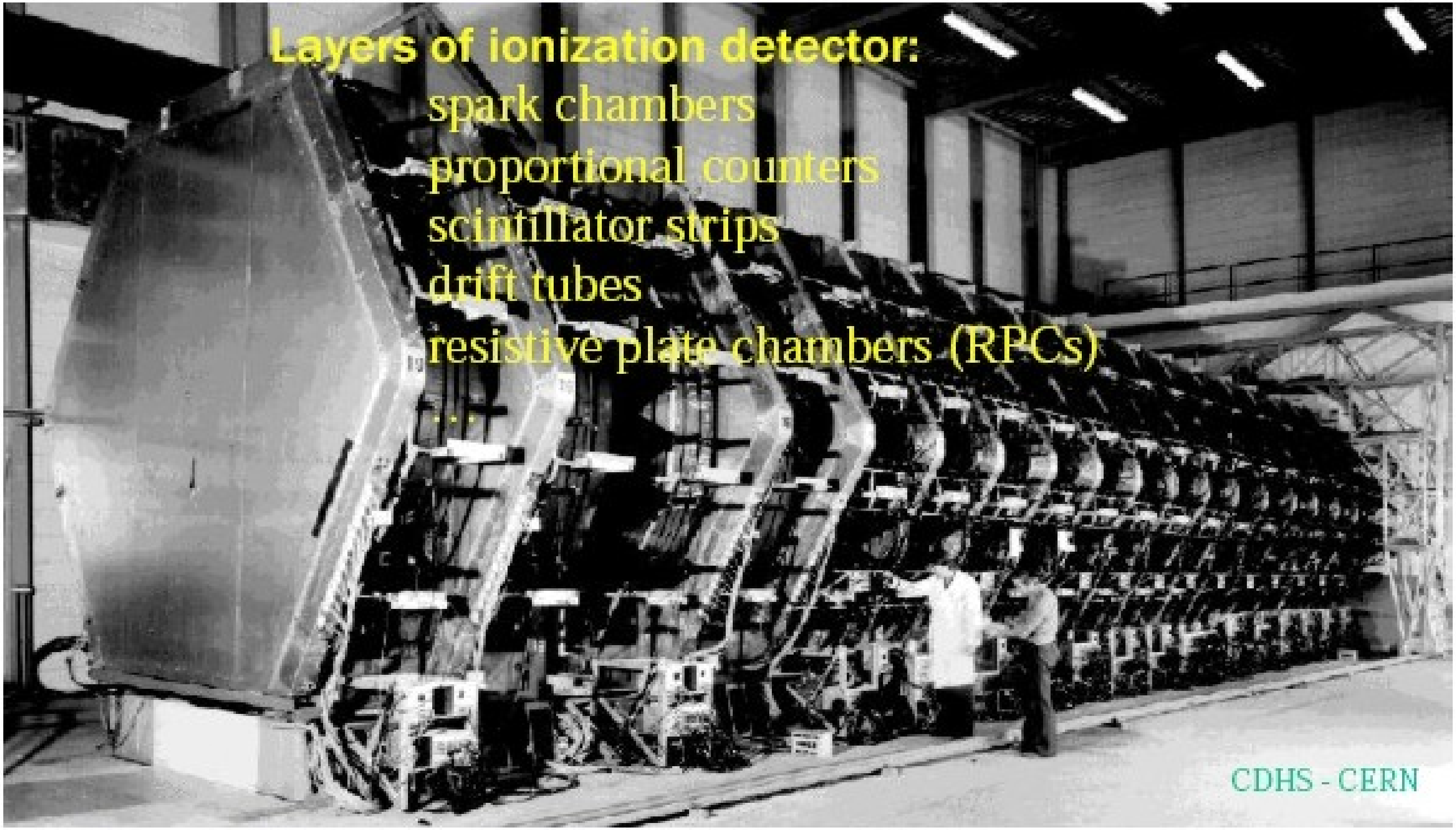
```
KamLAND Event Display
Run/Subrun/Event : 110/0/674708
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792643248
TriggerType : 0xa00 / 0x2
Time Difference 13.2 msec
NumHit/Nsum/Nsum2/NumHitA : 452/322/428/0
Total Charge : 772 (0)
Max Charge (ch): 8.67 (764)
```



```
KamLAND Event Display
Run/Subrun/Event : 110/0/674709
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792645216
TriggerType : 0x900 / 0x2
Time Difference 49.2 micro sec
NumHit/Nsum/Nsum2/NumHitA : 537/175/518/0
Total Charge : 881 (0)
Max Charge (ch): 14.3 (138)
```

Tracking Detectors and Calorimeters

Layers of target: eg. steel, marble, glass



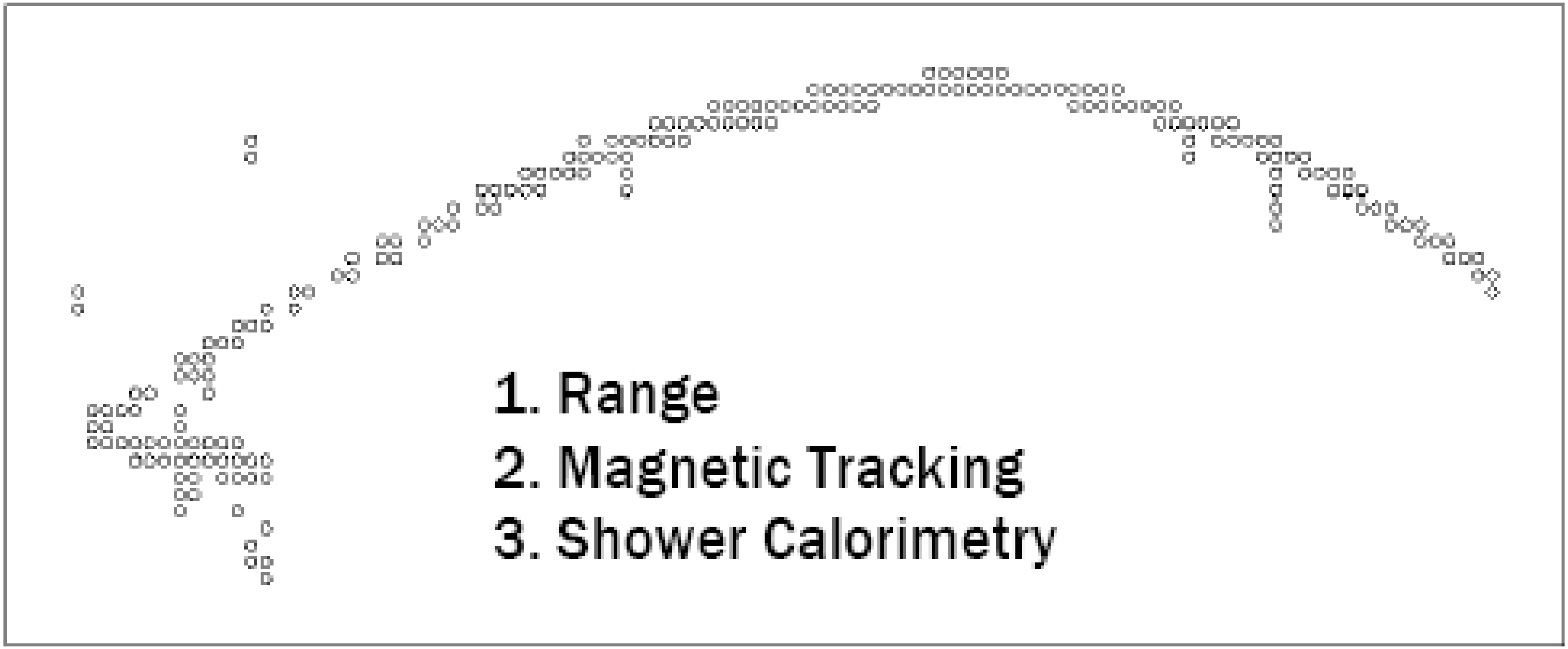
Layers of ionization detector:

- spark chambers
- proportional counters
- scintillator strips
- drift tubes
- resistive plate chambers (RPCs)
- . . .

CDHS - CERN

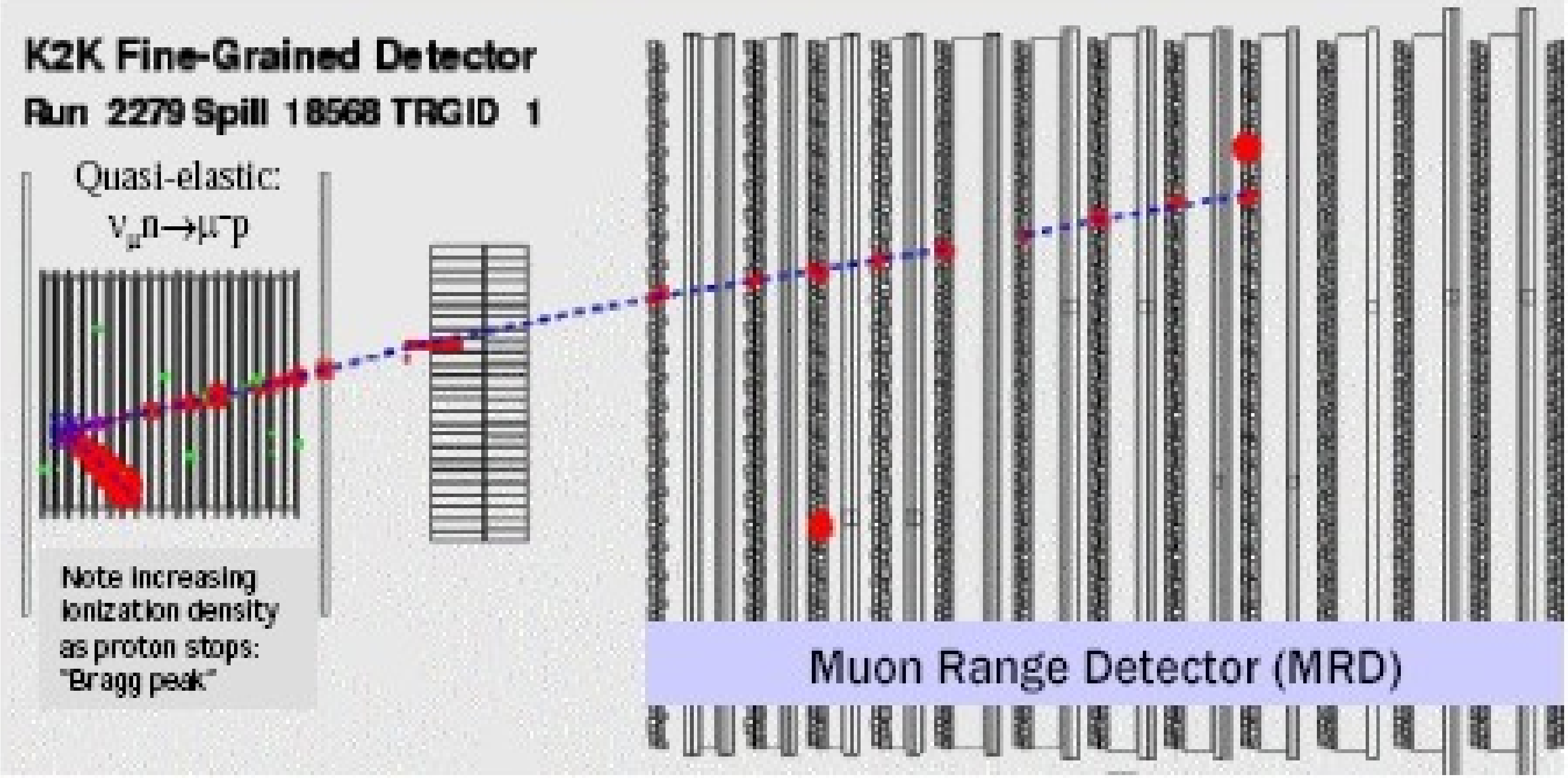
Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007

Energy Determination



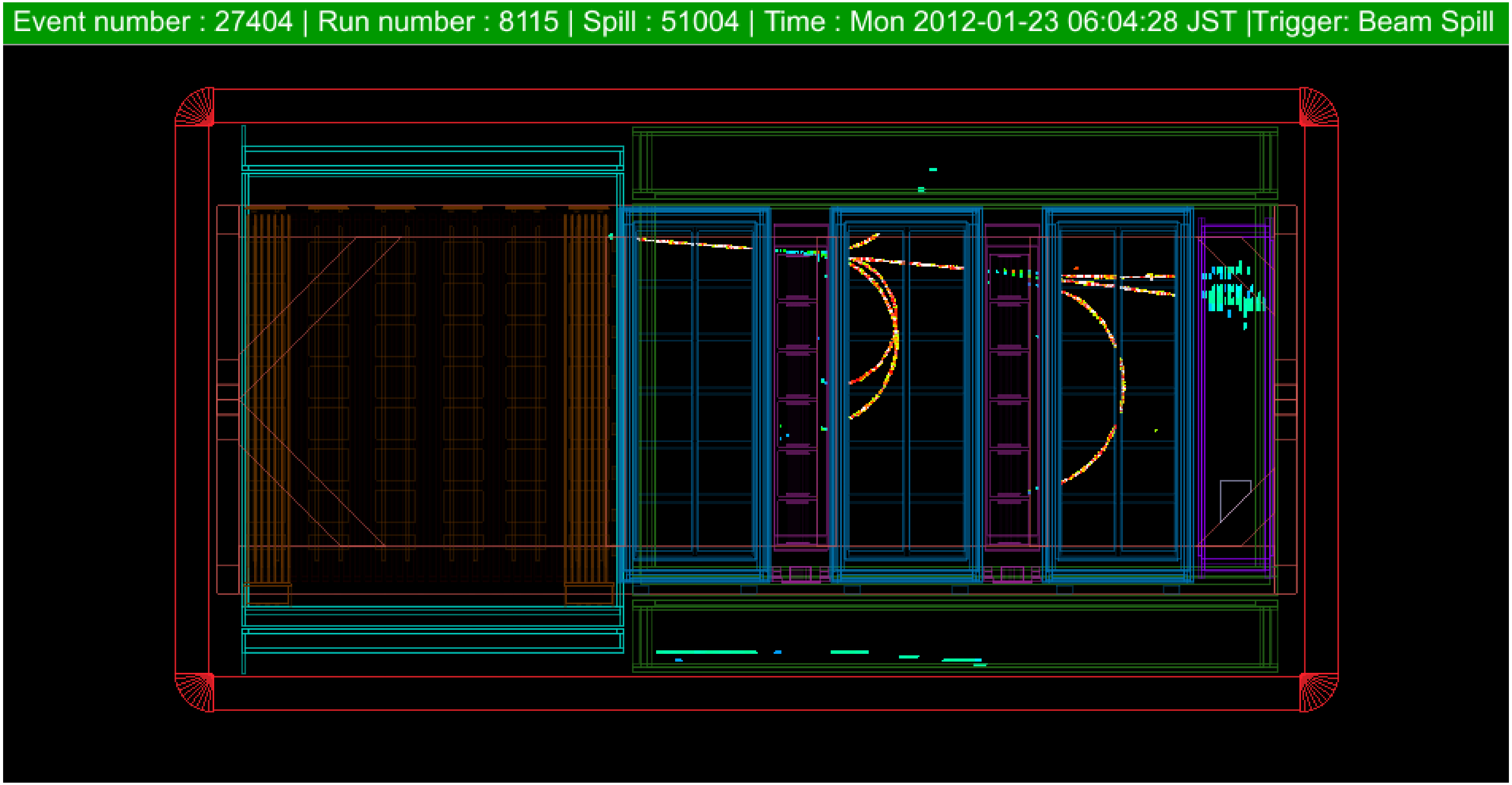
1. Range
2. Magnetic Tracking
3. Shower Calorimetry

Simple, no magnetic field; limited by size.
Reconstructed energy: build range table, integrating Bethe-Bloch; incorporate each layer of differing material.(ask GEANT for help)



$dE/dx)_{Fe}$= 1.45 MeV $g^{-1}cm^2$ ×7.9 gm cm^{-3}=90 MeV/cm … 1 GeV muon travels ~ 1m
(careful use of range chart, eg. in PDG, gives 80 cm)

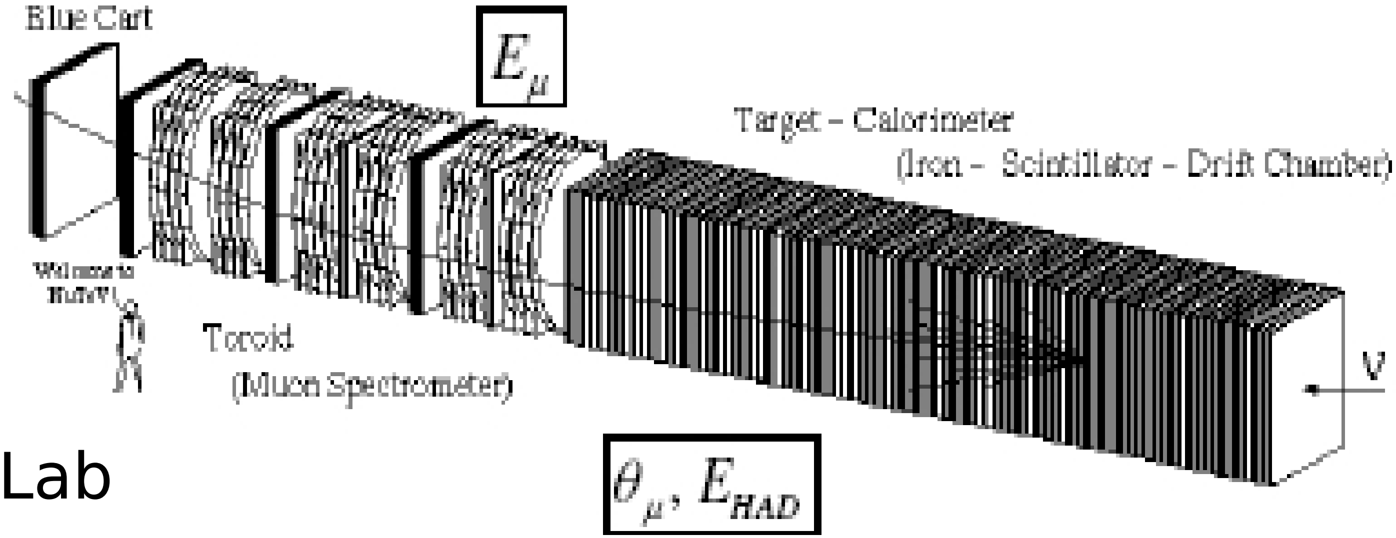
Magnetic Tracking


Event number : 27404 | Run number : 8115 | Spill : 51004 | Time : Mon 2012-01-23 06:04:28 JST |Trigger: Beam Spill

$$p_t = 0.3\,B[T]\,r[m]$$

NuTeV

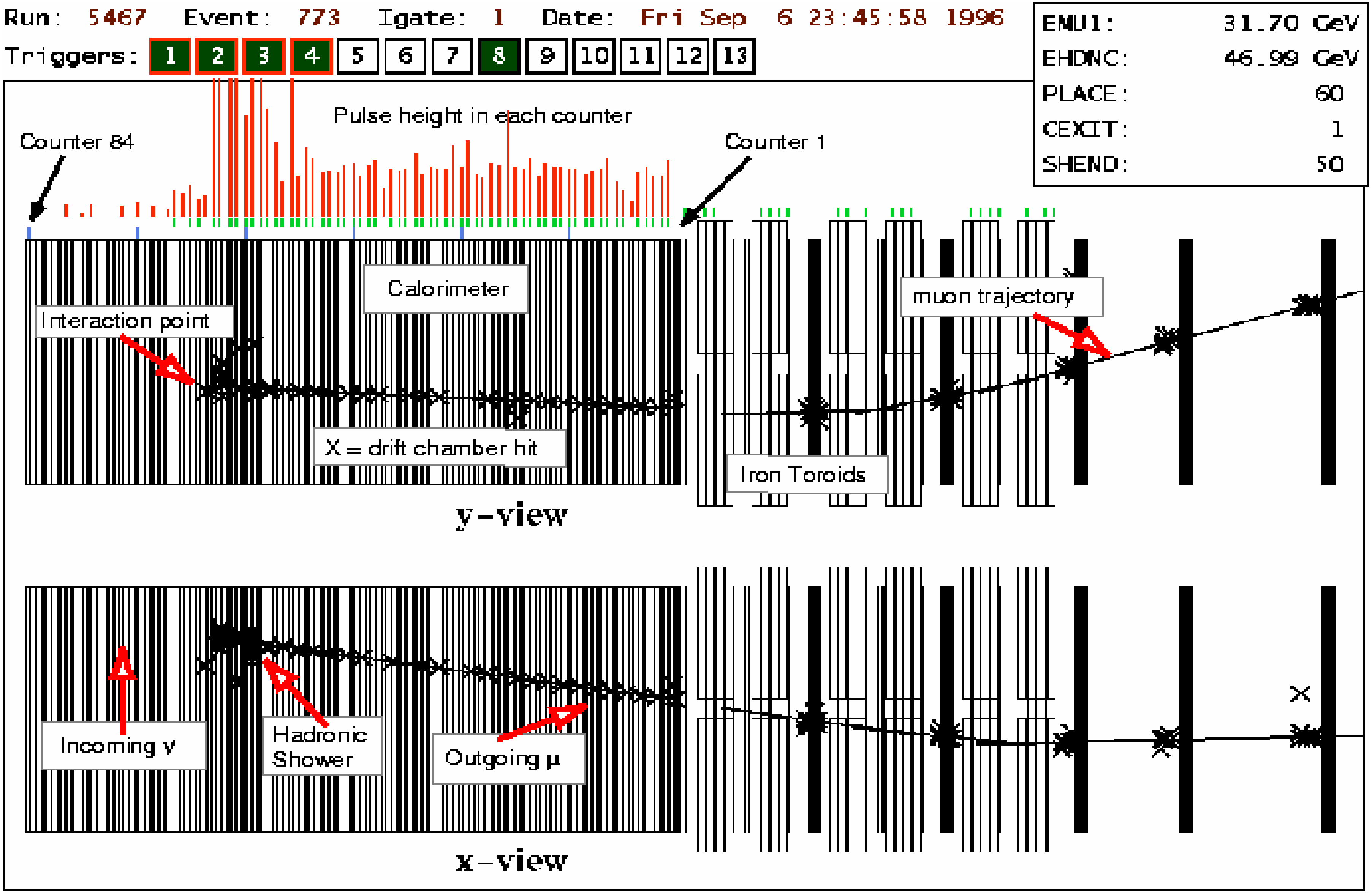
Iron Sampling calorimeter : CDHS,CHARM,CCFR,NUTEV,MINOS



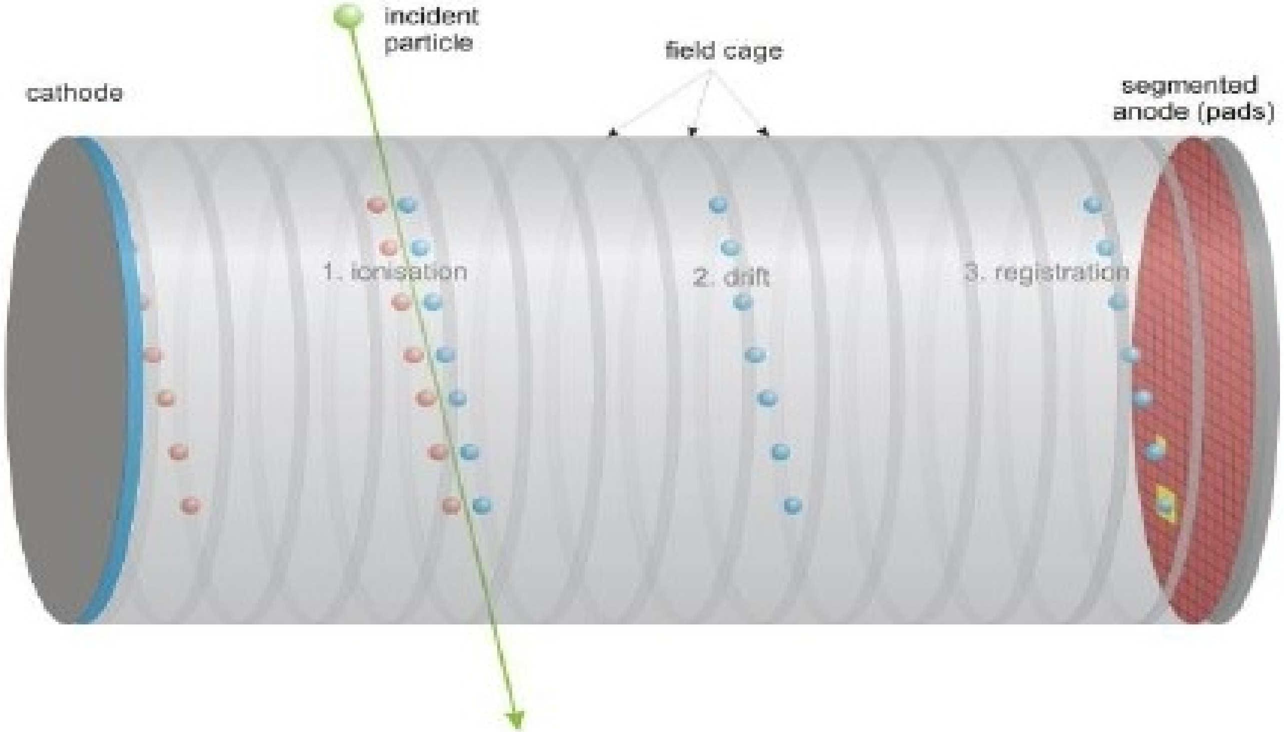
FermiLab

- Typically used for high energy (> a few GeV) beams
- Iron plates (target) interspersed by scintillator planes
- Muon tracked and radius of curvature measured in toroid
- Hadronic energy summed from active detector but single track resolution is not achievable

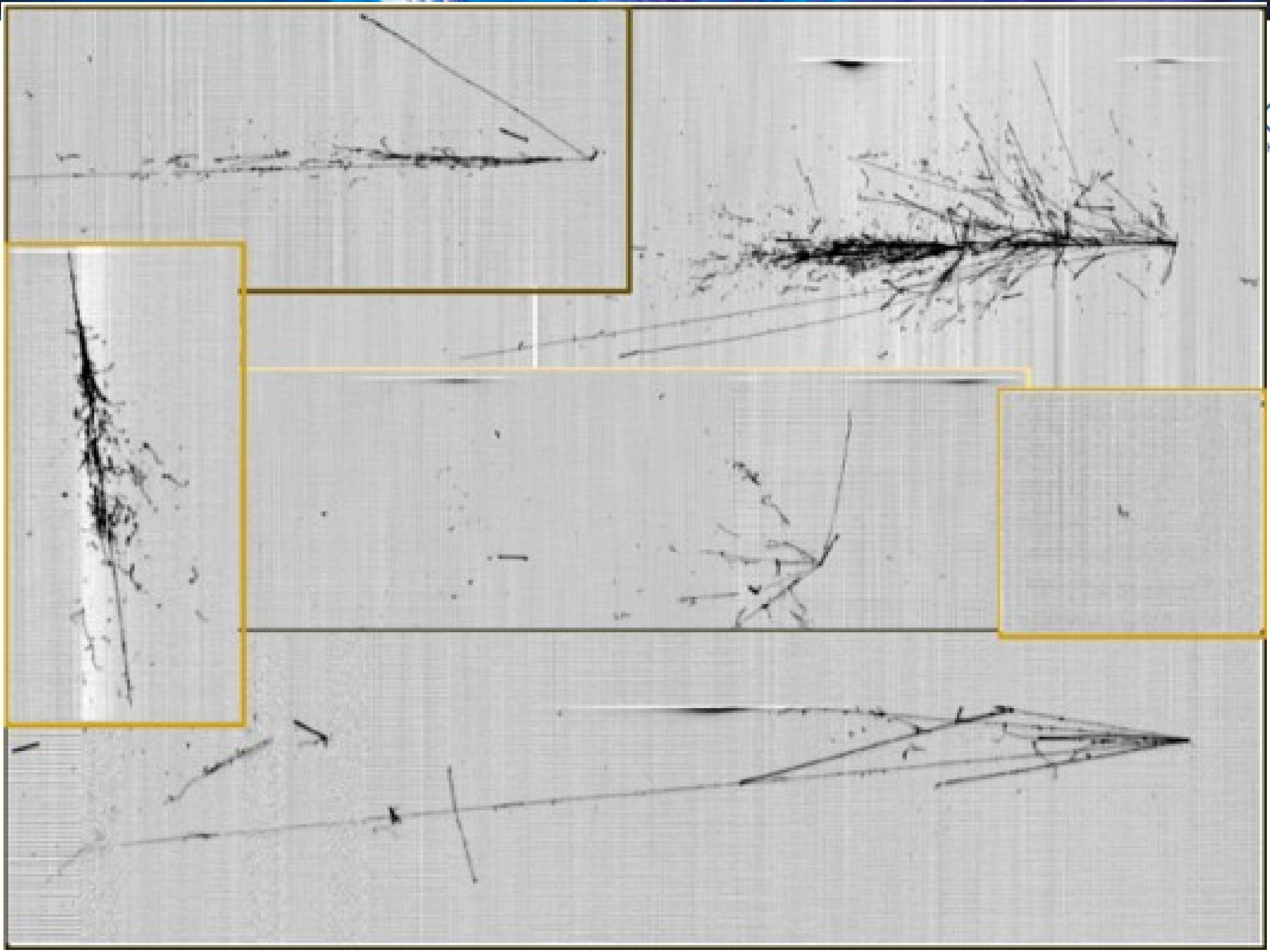
NuTeV


Run: 5467 Event: 773 Igate: 1 Date: Fri Sep 6 23:45:58 1996
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13
EMU1: 31.70 GeV
EHDNC: 46.99 GeV
PLACE: 60
CEXIT: 1
SHEND: 50
Pulse height in each counter
Counter 84
Counter 1
Calorimeter
Interaction point
X = drift chamber hit
muon trajectory
Iron Toroids
y-view
Incoming ν
Hadronic Shower
Outgoing μ
x-view

Liquid Argon TPCs



3D tracking with excellent resolution
Calorimetry from energy deposition in filler material
Filler can be gas or liquid.
Neutrino Physics looking at liquid argon TPCs



Summary

- Type of neutrino detectors depend on target, event rate, neutrino energies, interaction type and cost
- Four “main” techniques
  - radiochemical (low threshold but no direction or timing information)
  - water cerenkov (high threshold, cheap target mass, direction and timing but only low multiplicity events)
  - scintillator (no threshold but no directionality unless enhanced by water cerenkov)
  - tracking detectors and calorimeters (high energy events - full reconstruction of events)