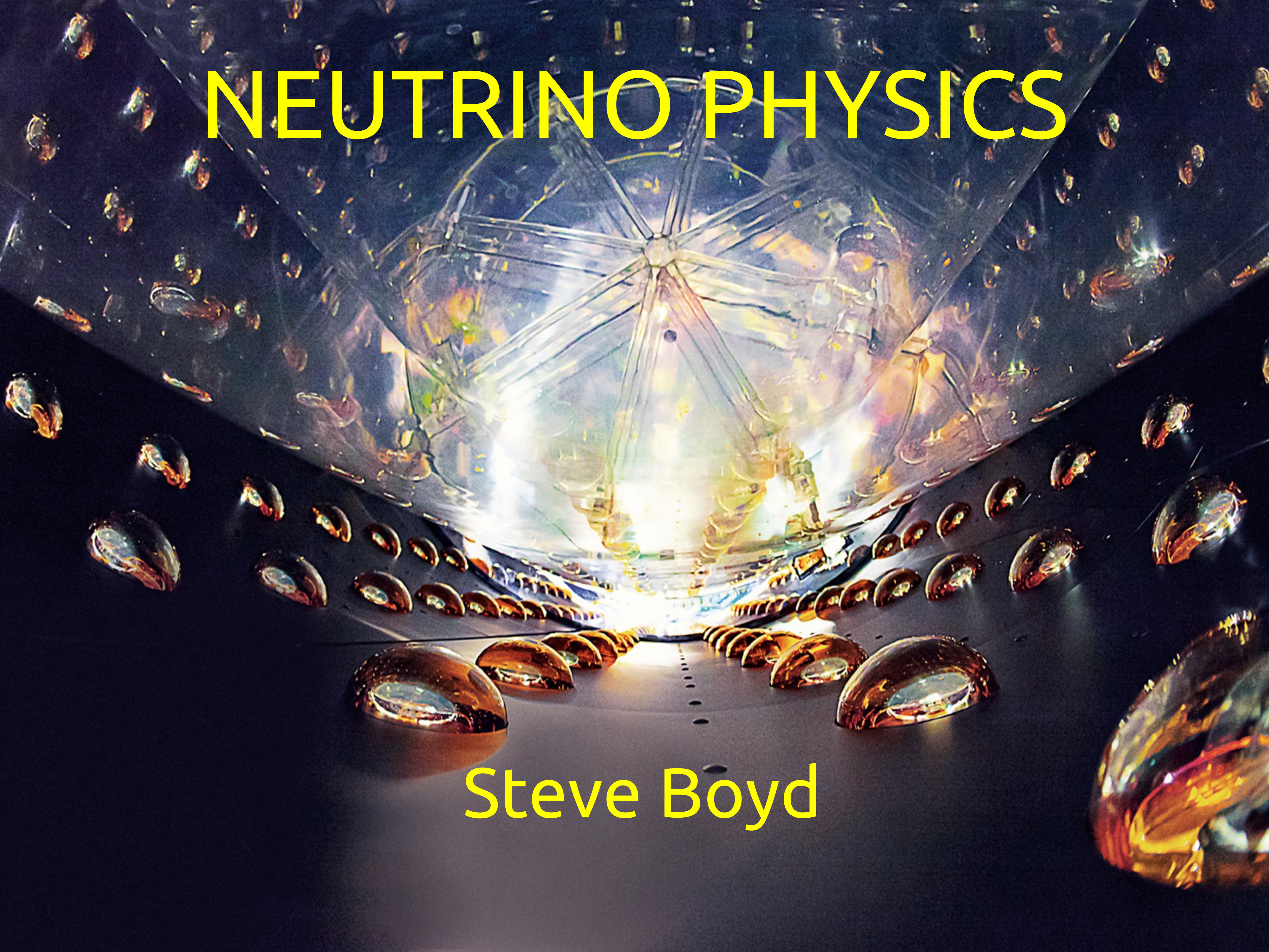
NEUTRINO PHYSICS



Steve Boyd

What's in the lectures

1. History and properties of the neutrino, neutrino interactions, beams and detectors

2. Neutrino mass, direct mass measurements, double beta decay, flavour oscillations

3. Unravelling neutrino oscillations experimentally

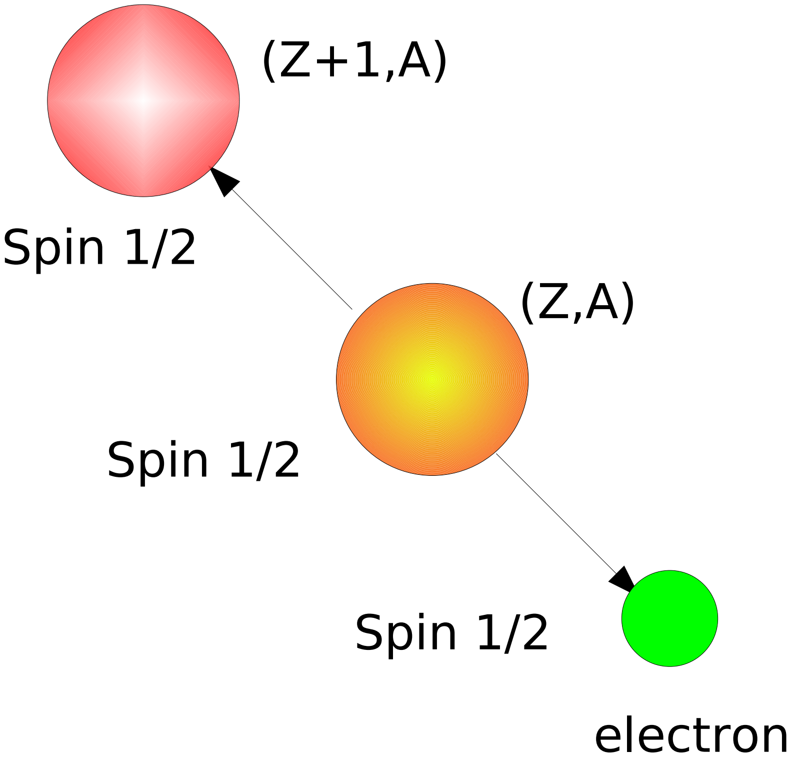
4. Where we are and where we're going

Lecture 1

In which history is unravelled, desperation is answered, and the art of neutrino generation and detection explained

Crisis

It is 1914 – the new field of atomic physics is in trouble



(Z+1,A)

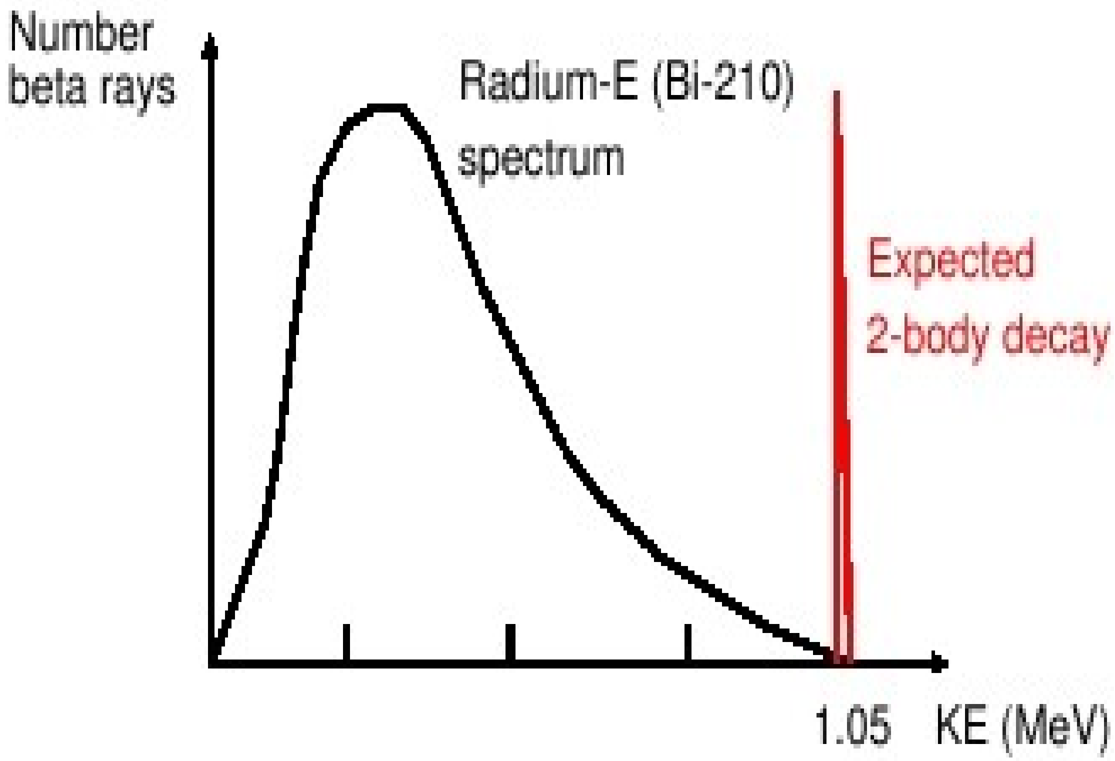
Spin 1/2

(Z,A)

Spin 1/2

Spin 1/2

electron



Spin ½ ≠ spin ½ + spin ½

$$E_{Ra} \neq E_{Bi}+e$$

“At the present stage of atomic theory we have no arguments for upholding the concept of energy balance in the case of β-ray disintegrations.”

“Desperate remedy.....”
“I do not dare publish this idea....”
“I admit my way out may look improbable....”
“Weigh it and pass sentence....”

“You tell them. I'm off to a party”

4th December 1930

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the ”wrong” statistics of the N and ^{6}*Li nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the ”exchange theorem” of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call* ***neutrons****, which have spin and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass (and in any event not larger than 0.01 proton masses). The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...*

From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensible here due to a ball which will take place in Zurich during the night from December 6 to 7...

Your humble servant,
W. Pauli

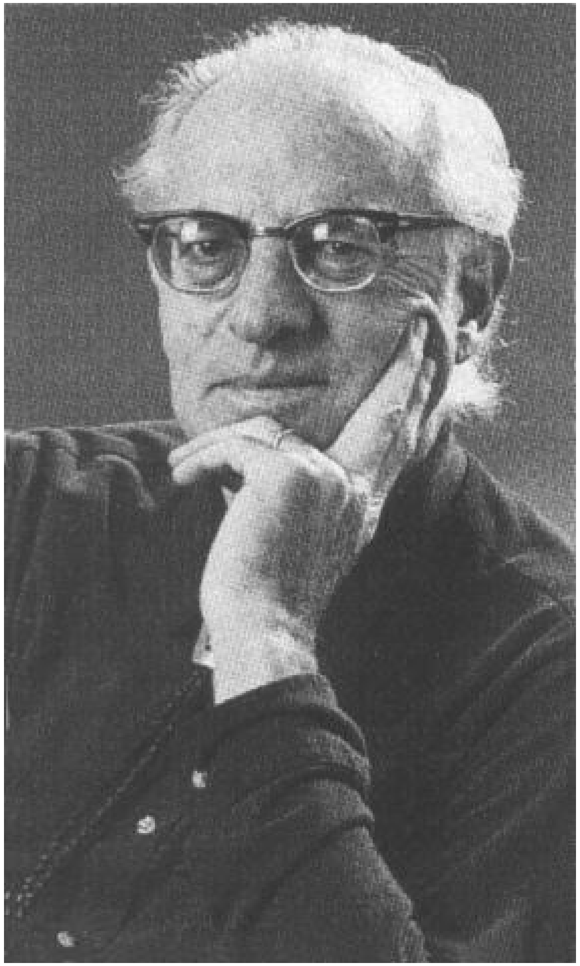
Oh the pain

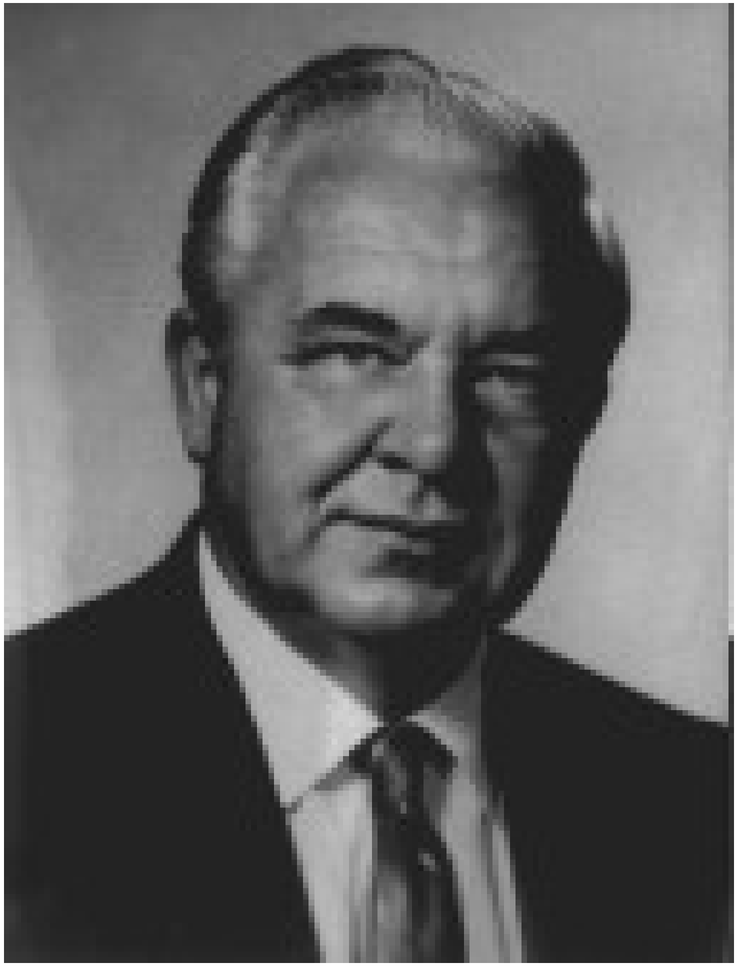
“I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do.”

Pauli, 1930

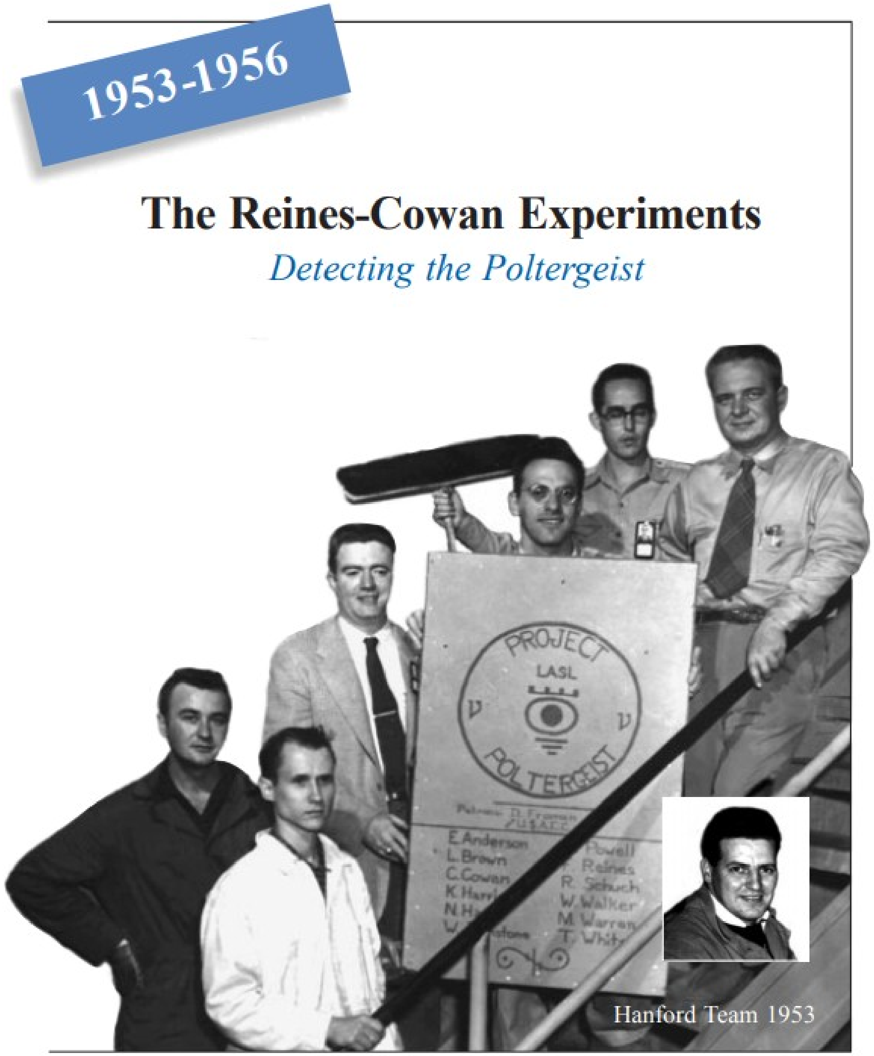
Detection of the Neutrino

1950 – Reines and Cowan set out to detect ν





Detection of the Neutrino

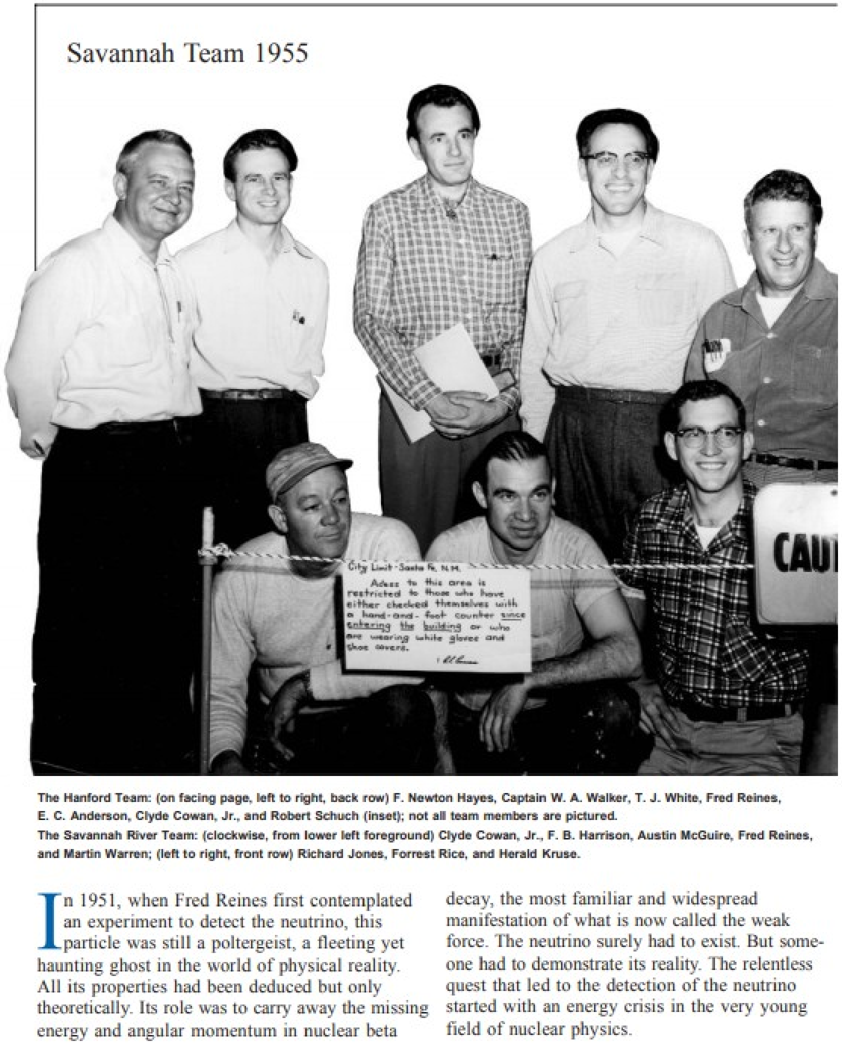


1953-1956

The Reines-Cowan Experiments

Detecting the Poltergeist

Hanford Team 1953



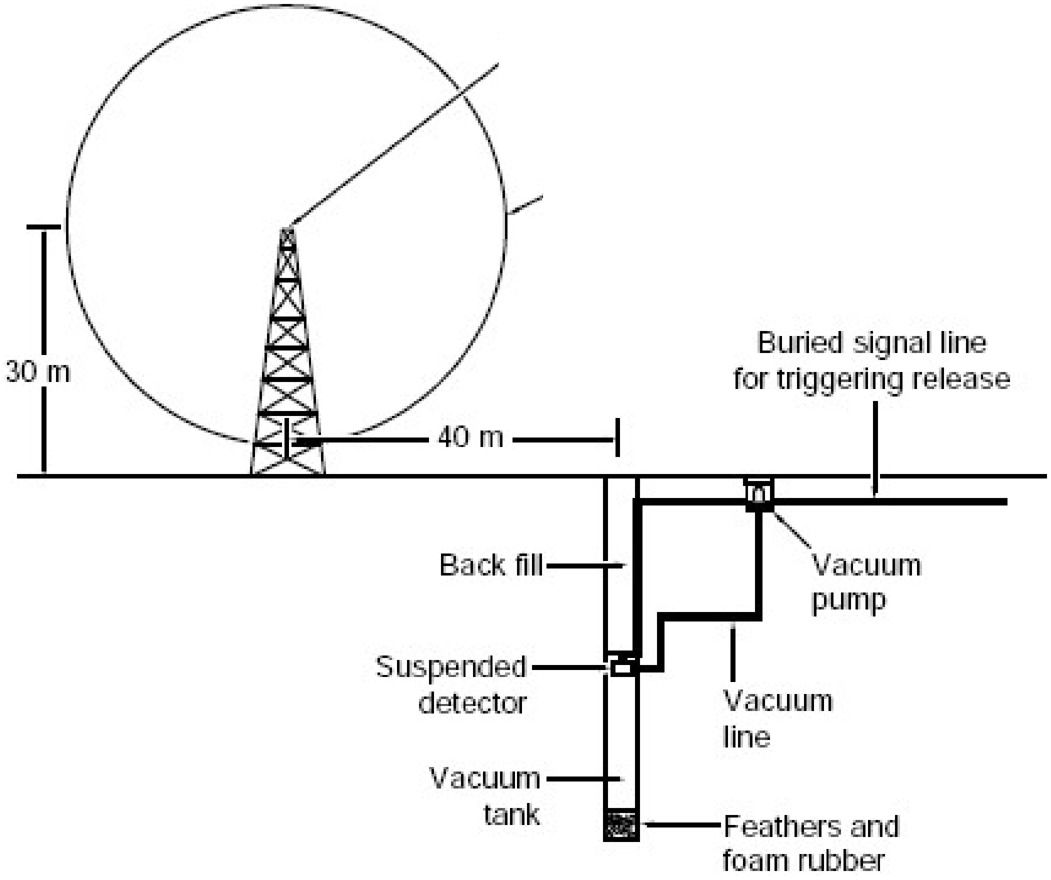
Savannah Team 1955

The Hanford Team: (on facing page, left to right, back row) F. Newton Hayes, Captain W. A. Walker, T. J. White, Fred Reines, E. C. Anderson, Clyde Cowan, Jr., and Robert Schuch (inset); not all team members are pictured.

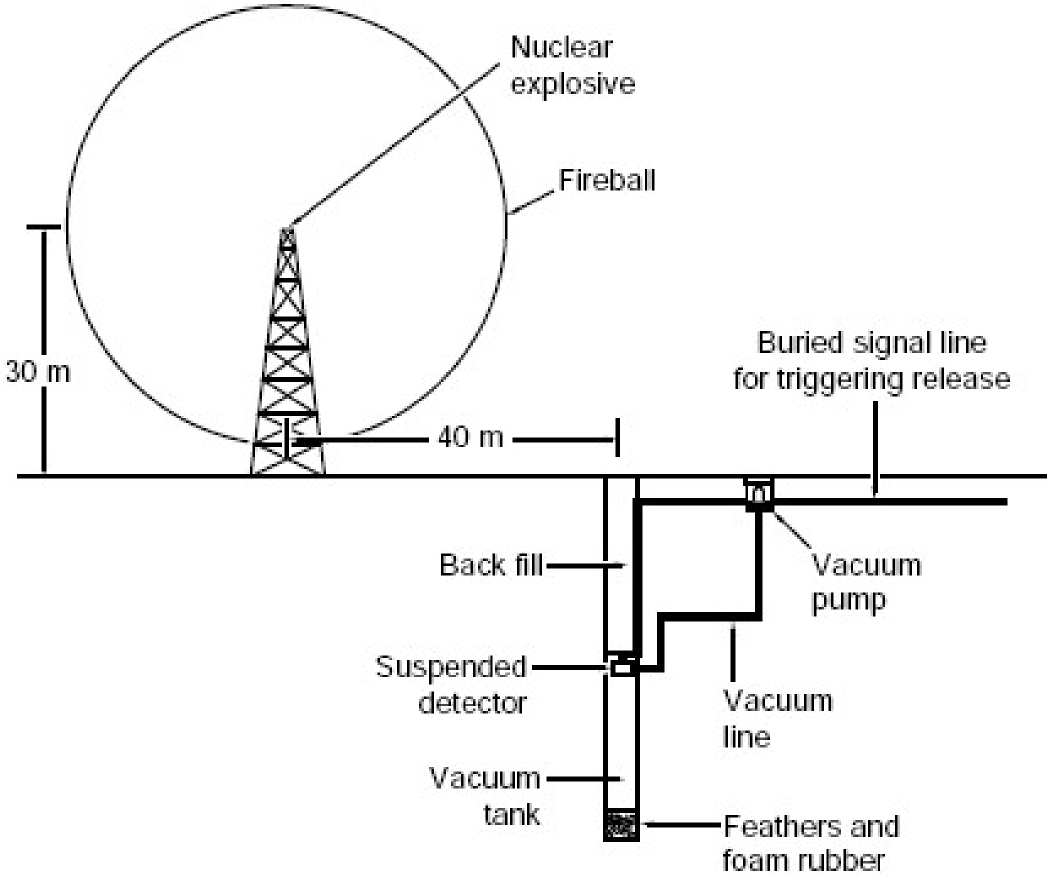
The Savannah River Team: (clockwise, from lower left foreground) Clyde Cowan, Jr., F. B. Harrison, Austin McGuire, Fred Reines, and Martin Warren; (left to right, front row) Richard Jones, Forrest Rice, and Herald Kruse.

In 1951, when Fred Reines first contemplated an experiment to detect the neutrino, this particle was still a poltergeist, a fleeting yet haunting ghost in the world of physical reality. All its properties had been deduced but only theoretically. Its role was to carry away the missing energy and angular momentum in nuclear beta decay, the most familiar and widespread manifestation of what is now called the weak force. The neutrino surely had to exist. But someone had to demonstrate its reality. The relentless quest that led to the detection of the neutrino started with an energy crisis in the very young field of nuclear physics.

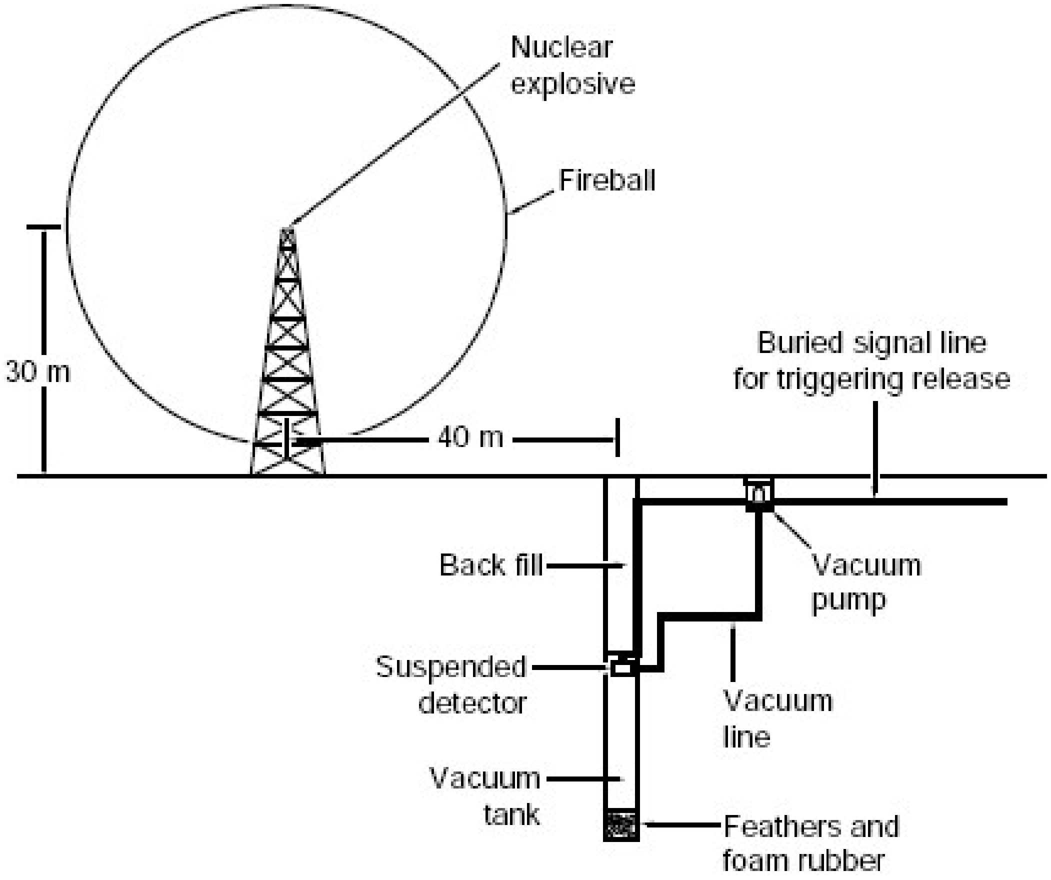
1951


30 m
40 m
Buried signal line for triggering release
Back fill
Vacuum pump
Suspended detector
Vacuum line
Vacuum tank
Feathers and foam rubber

1951


Nuclear explosive
Fireball
30 m
40 m
Buried signal line for triggering release
Back fill
Vacuum pump
Suspended detector
Vacuum line
Vacuum tank
Feathers and foam rubber

1951



I. Explode bomb
II.At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

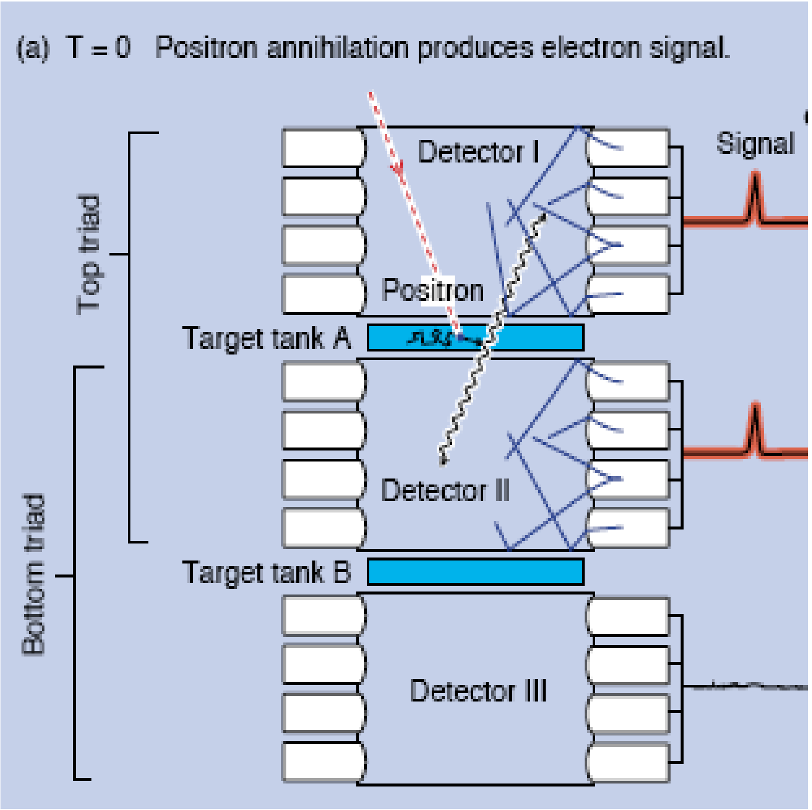
OK – but repeatability is a bit of a problem

Idea Number 2 - 1955

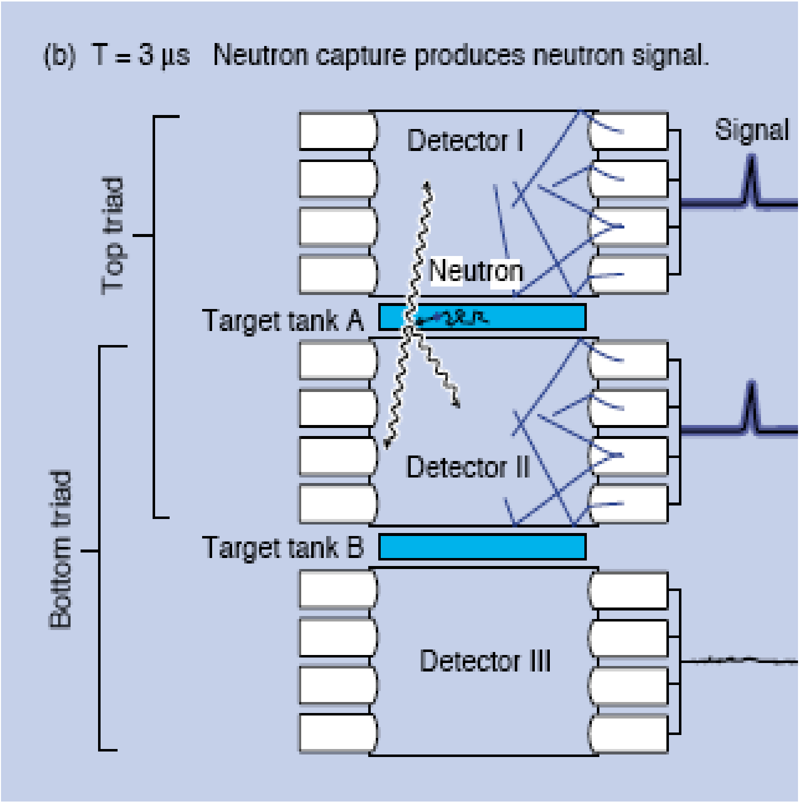
A nuclear reactor is the next best thing

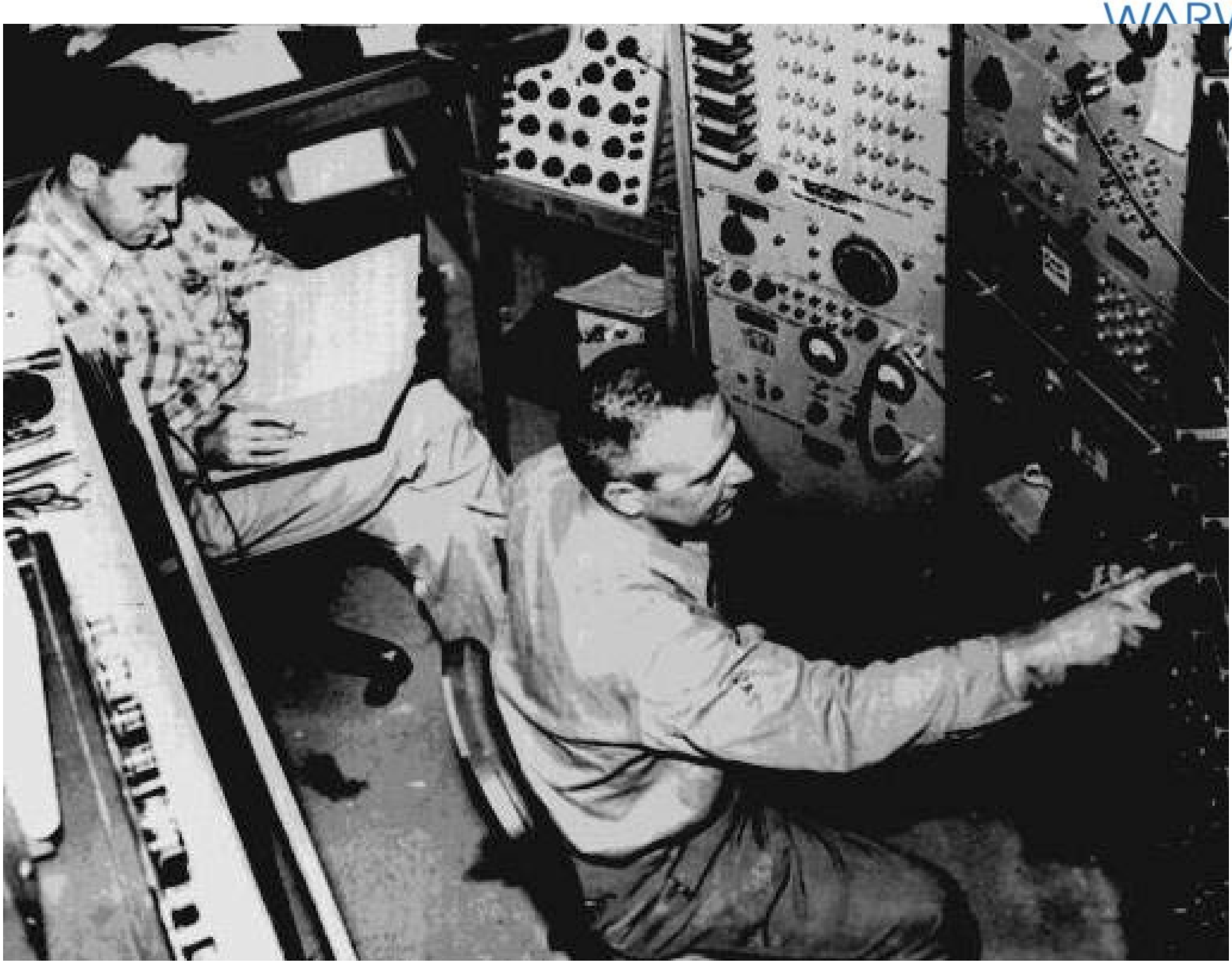
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

Positron Annihilation

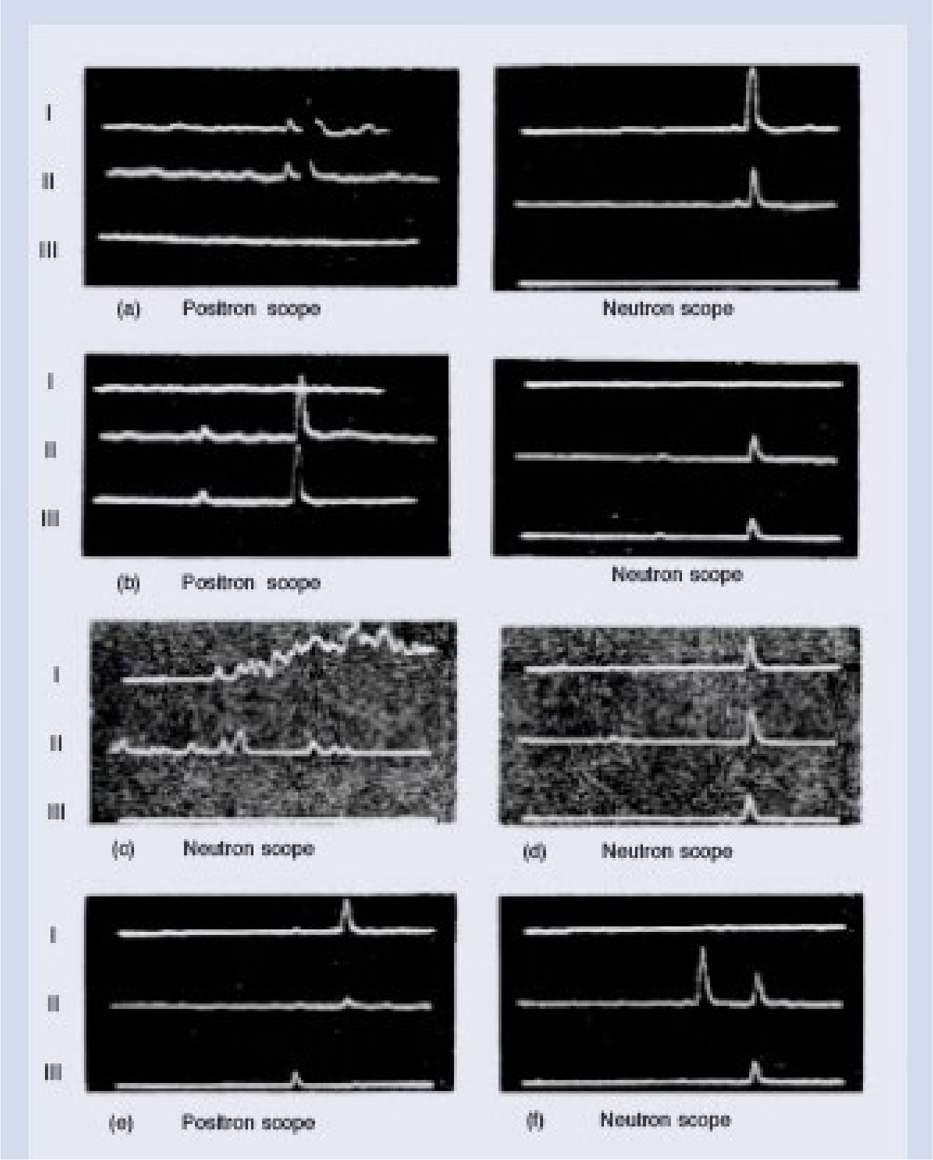


Neutron Capture





1959 – Savannah River Reactor



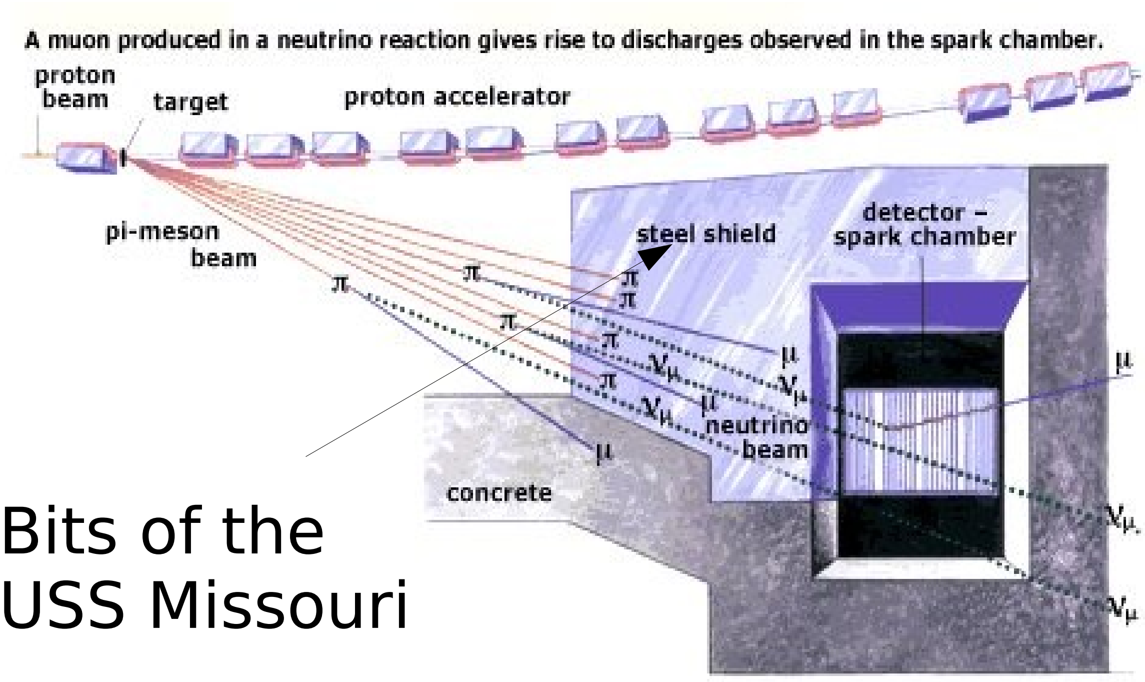
ON – OFF = 2.88 +/- 0.22 hr^{-1}

σ = (11 +/- 2.6) x 10^{-44} cm^2

σ (Pred) = (5 +/- 1) x 10^{-44} cm^2

Neutrinos come in flavours!

Up to 1962, only the electron neutrino had been detected – and hence only the “neutrino” existed.
Suspicions were strong that more were out there
In 1962, Schwartz, Steinberger and Lederman presented evidence for the muon neutrino and built the very first neutrino beam!



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

Bits of the USS Missouri

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$\nu_\mu + n \rightarrow \mu^- + p$ OK

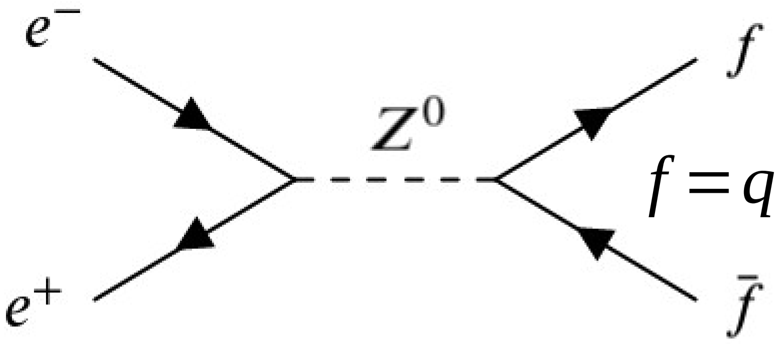
$\nu_\mu + n \rightarrow e^- + p$ ~~OK~~

The State of Play pre-2000

Flavour	Mass (GeV/$c^{2)}$	Electric Charge
ν_e	< 1 x 10-8	0
electron	0.000511	-1
ν_μ	< 0.0002	0
muon	0.106	-1
	?	
tau	1.7771	-1

How many neutrinos do we expect to find?

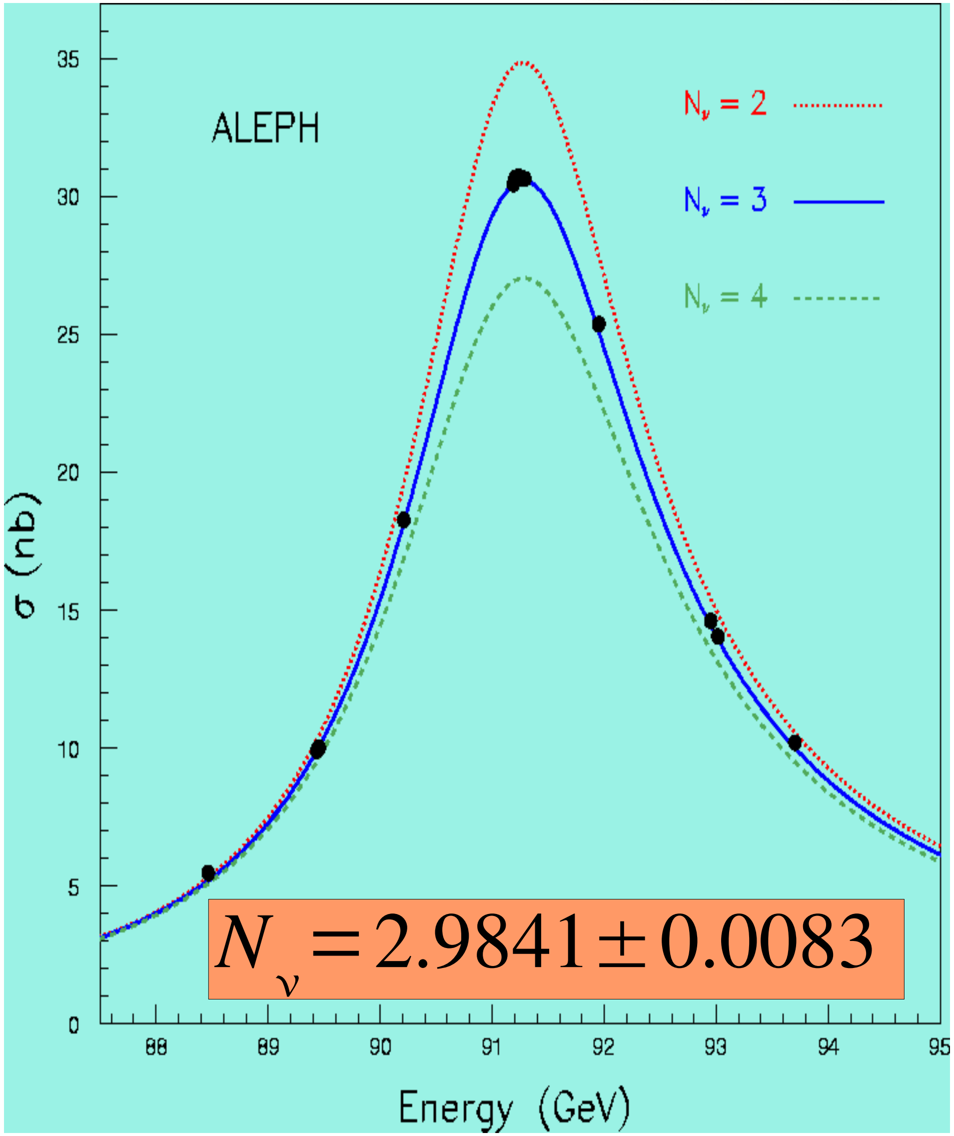
The Number of light neutrinos



$f = q, l, \nu$

$$\Gamma_Z = \sum \Gamma_{q\bar{q}} + 3\Gamma_{l\bar{l}} + N_\nu \Gamma_{\nu\bar{\nu}}$$

Discovery of Z^0 allowed a measurement of the number of light neutrinos since the Z^0 can decay to a neutrino and antineutrino



$N_\nu = 2.9841 \pm 0.0083$

NB Mass of ν < $m_Z/2$ ~ 46 GeV

The Tau Neutrino

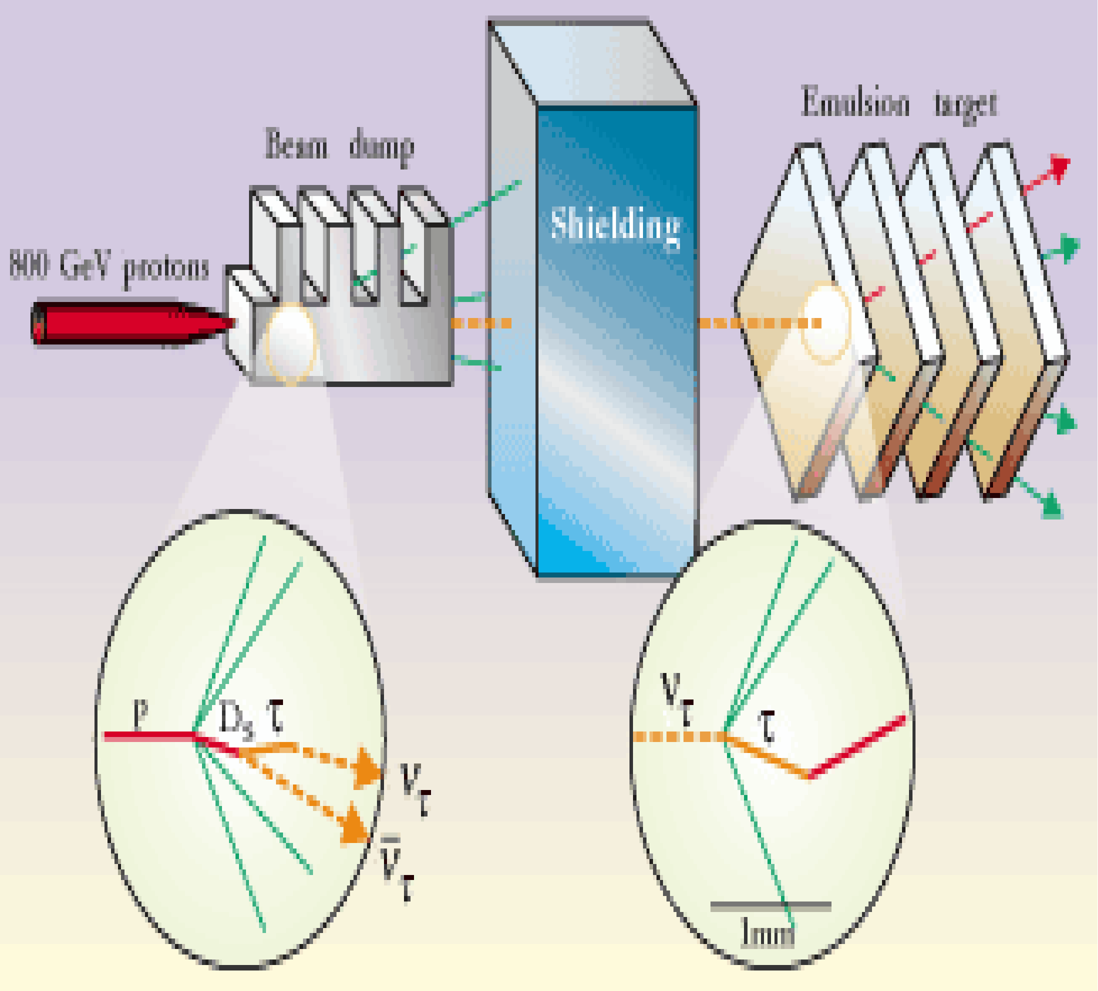
ν_τ was finally discovered by DONUT in 2000.

800 GeV protons on Tungsten produce D_s (=$c\bar{s}$) mesons

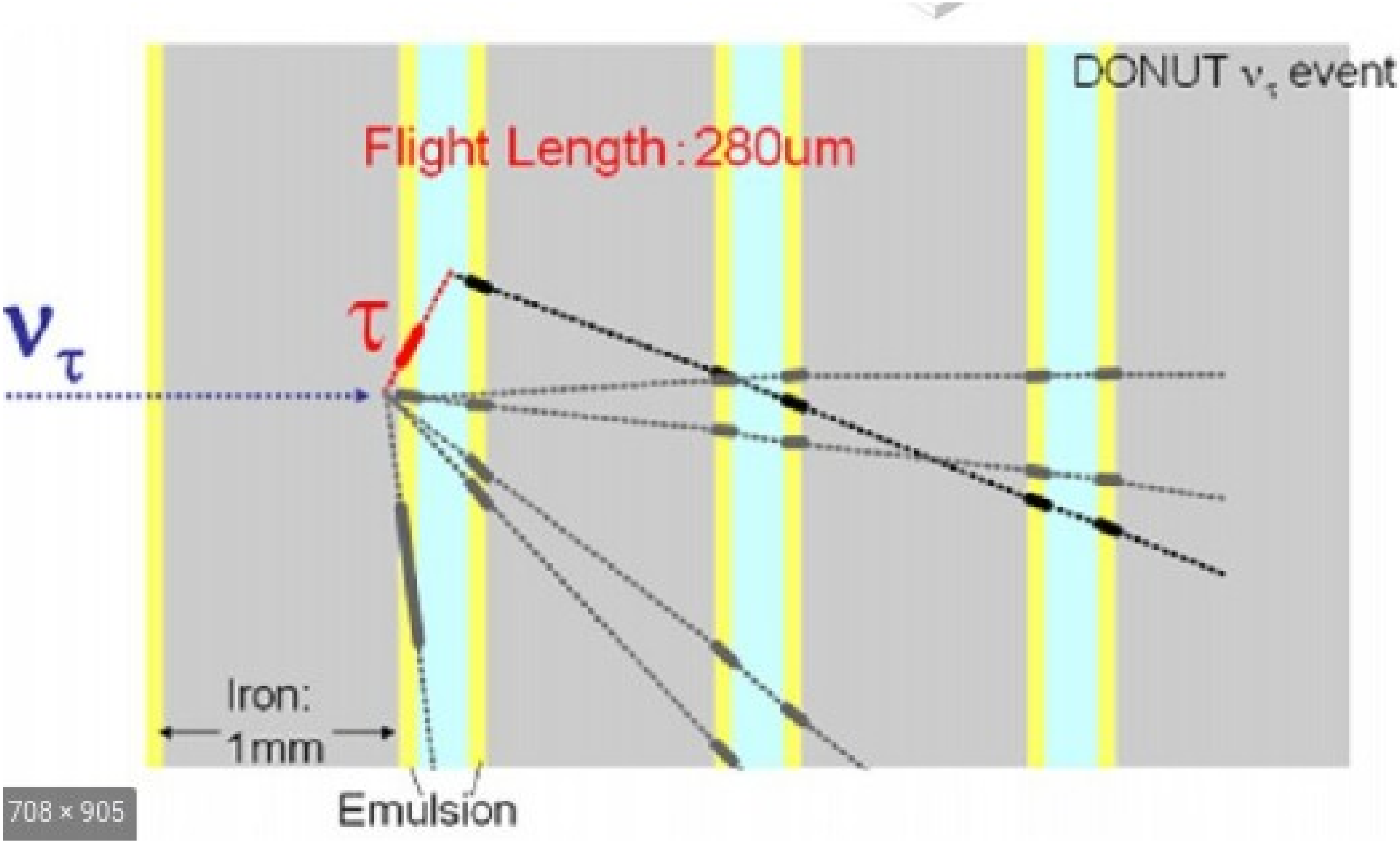
$$D_s \to \tau + \nu_\tau$$

$$\nu_\tau + N \to \tau + X$$

$$\tau \to \mu + \nu_\tau + \overline{\nu_\mu}$$



Discovery of the ν_τ



Neutrino Properties

- Electrically neutral and interact only via the weak interaction.
- spin 1/2
- (anti)neutrinos are chirally left(right)-handed (but can be helically right(left)-handed if massive)
- Exist in (at least) 3 active flavours
- Are almost massless
- Are the most common fermions in the universe

- Is a neutrino it's own anti-particle (Majorana particle)?
- Are there sterile neutrinos?
- What is the absolute neutrino mass?
- Is there CP violation in the neutrino sector?
- Does the neutrino have a magnetic moment?
- Are they stable?

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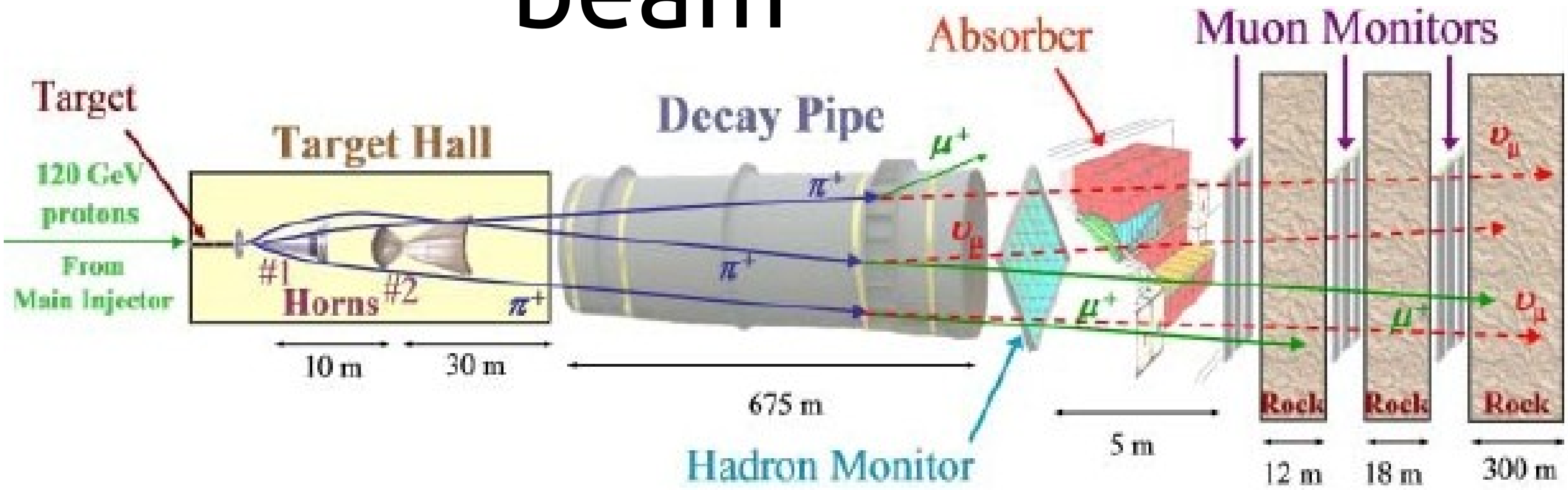
Making Neutrinos

Neutrino experiments are hard!

“..in an ordinary way I might say that I do not believe in neutrinos. Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos”

Sir Arthur Eddington

How to make a neutrino beam



protons π/K μ,π,K,ν_e,ν_μ ν_μ,ν_e

- Each part of the beamline must be designed with many tradeoffs in mind
- Major uncertainty in beam is the production of π/K in p-target interactions
- Total flux uncertainties ~ 20%

Proton Beam

- Number of pions ∝ total number of protons on target (POT) times proton energy

- The higher energy neutrino beam you want, the higher energy proton beam you need.

Source	p Energy (GeV)	p/year	Power (MW)	Neutrino Energy
FNAL Booster	8	5.0E+20	0.05	1
FNAL Main Injector	120	2.5E+20	0.25	3.0-17.0
CNGS (CERN)	400	4.5E+19	0.12	0.0-40.0
J-PARC (Japan)	30	1.1E+21	0.48	0.8
*LBNF (Fermilab)***	*60 / 120*	*1.90E+21*	*1.2*	*0.5 – 10.0*
*J-PARC Upgrade***	*30*	*1.60E+22*	*1.5*	*0.6*

**Design parameters – beams still under construction

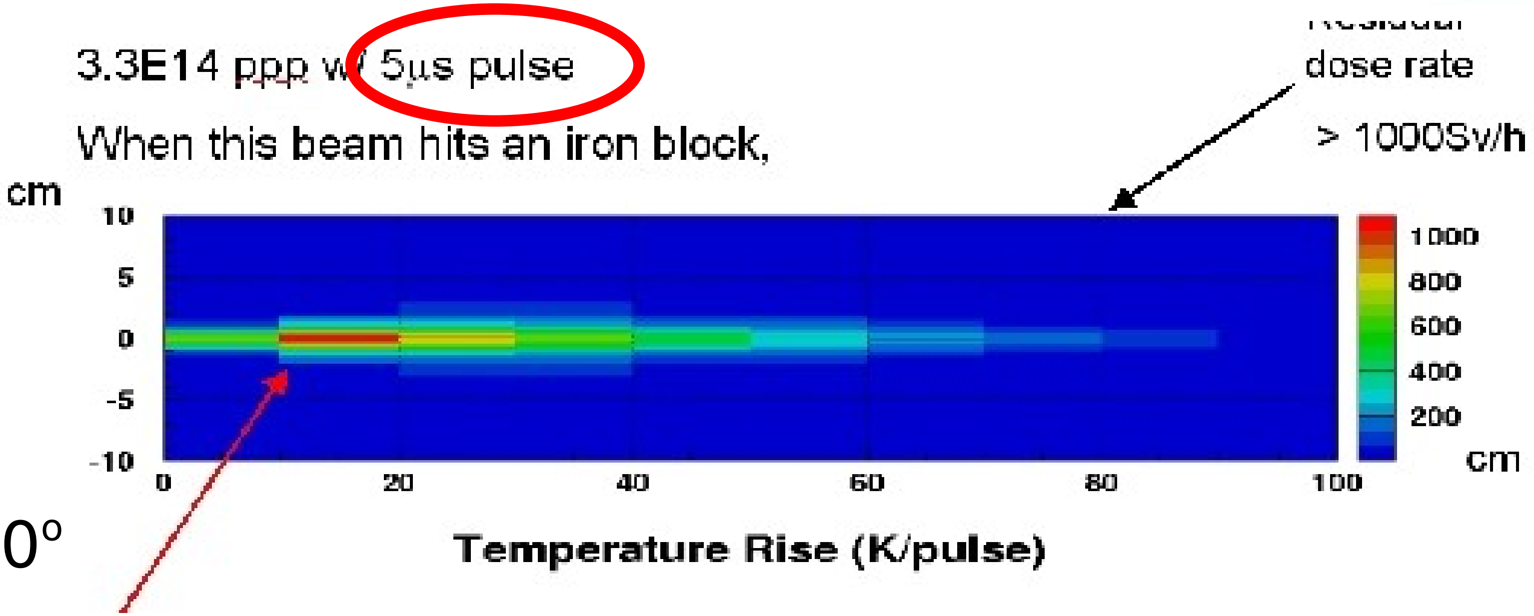
Targetry

Have to balance competing needs

- The longer the target, the higher the probability that a proton will interact (☺)
- But more secondary particles will scatter (☹)
- The more protons interact the hotter the target will get (☹)
- The wider the target the cooler it is (☺) but more material to scatter secondaries (☹)

Low Z material (C, Be, Al) for heat properties
Usually around 50 cm to 1 m long
In small segments so that heating won't break the entire thing
Cooling systems needed (air, water, liquid helium)

Targetry



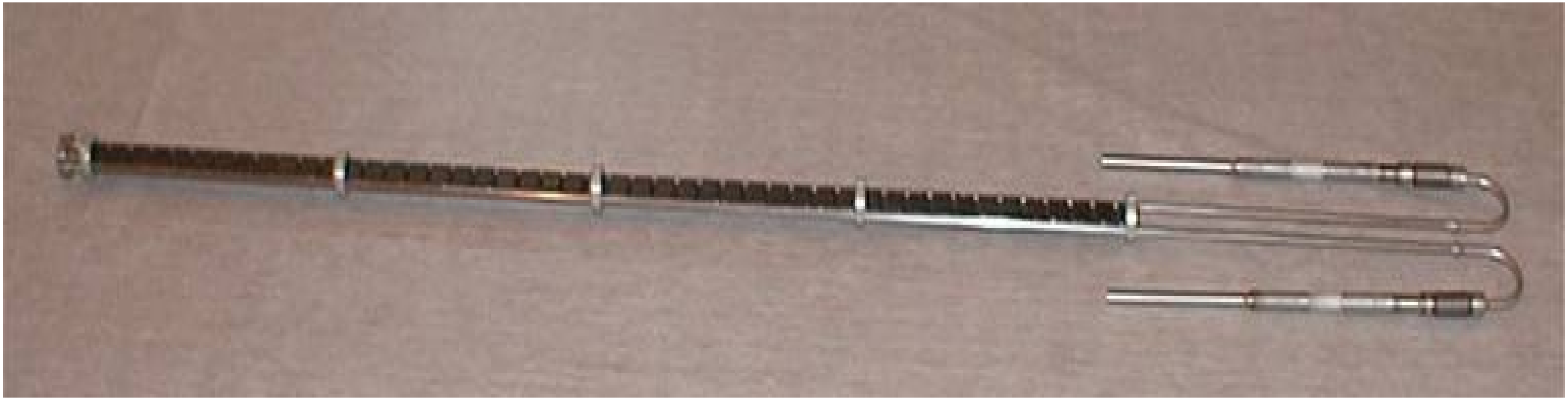
3.3E14 ppp w/ 5µs pulse

When this beam hits an iron block,

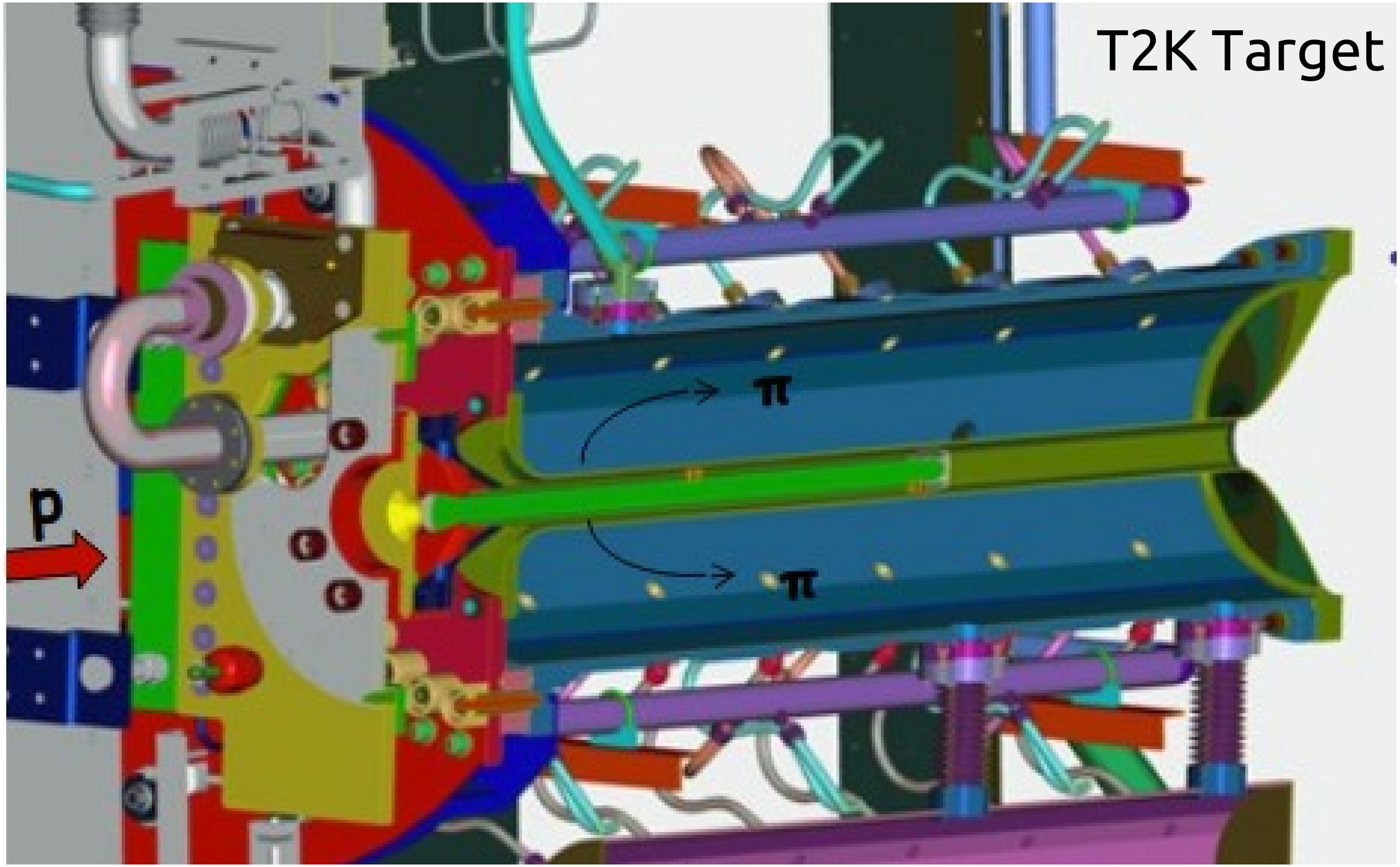
Residual dose rate

> 1000Sv/h

1100°

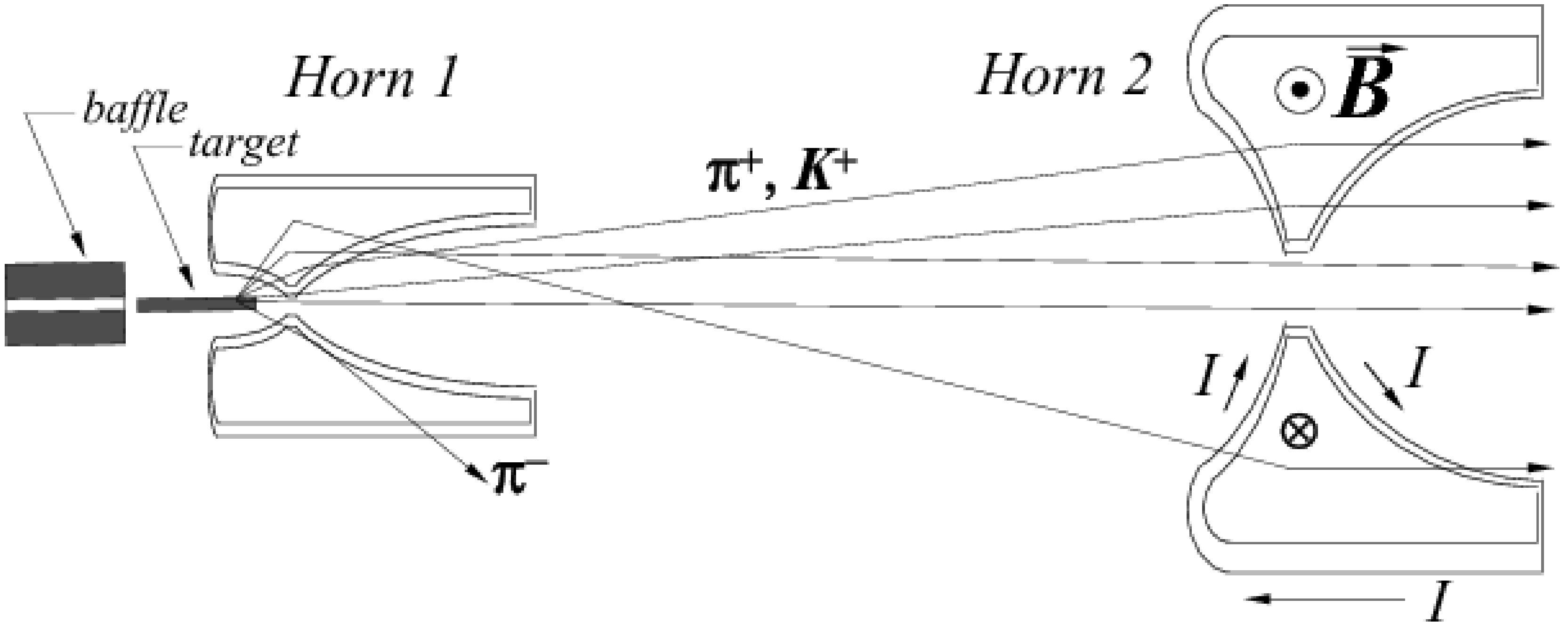


Target Infrastructure



T2K Target

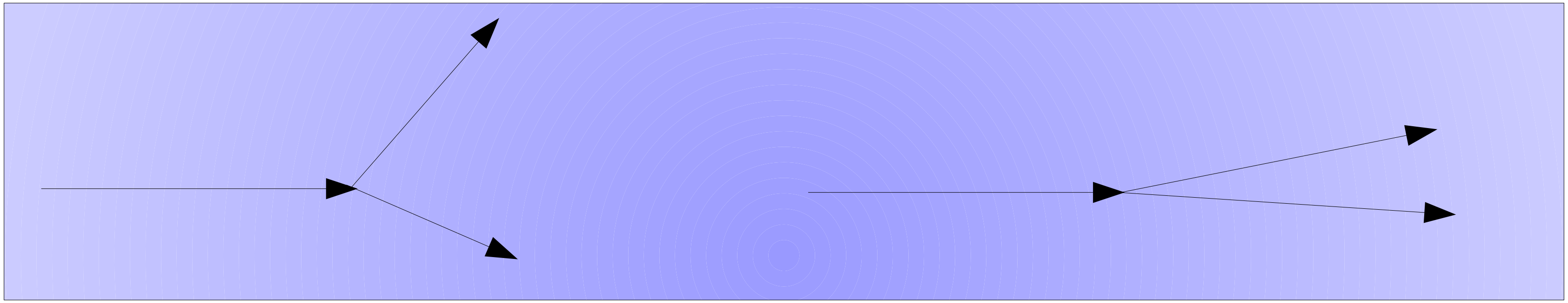
Basics of Horn Focussing



To give a 200 MeV transverse momentum kick to a pion requires a pulsed current of about 180 kA

Magnetic Horns

Decay Tunnel



Low Energy decays

High Energy decays

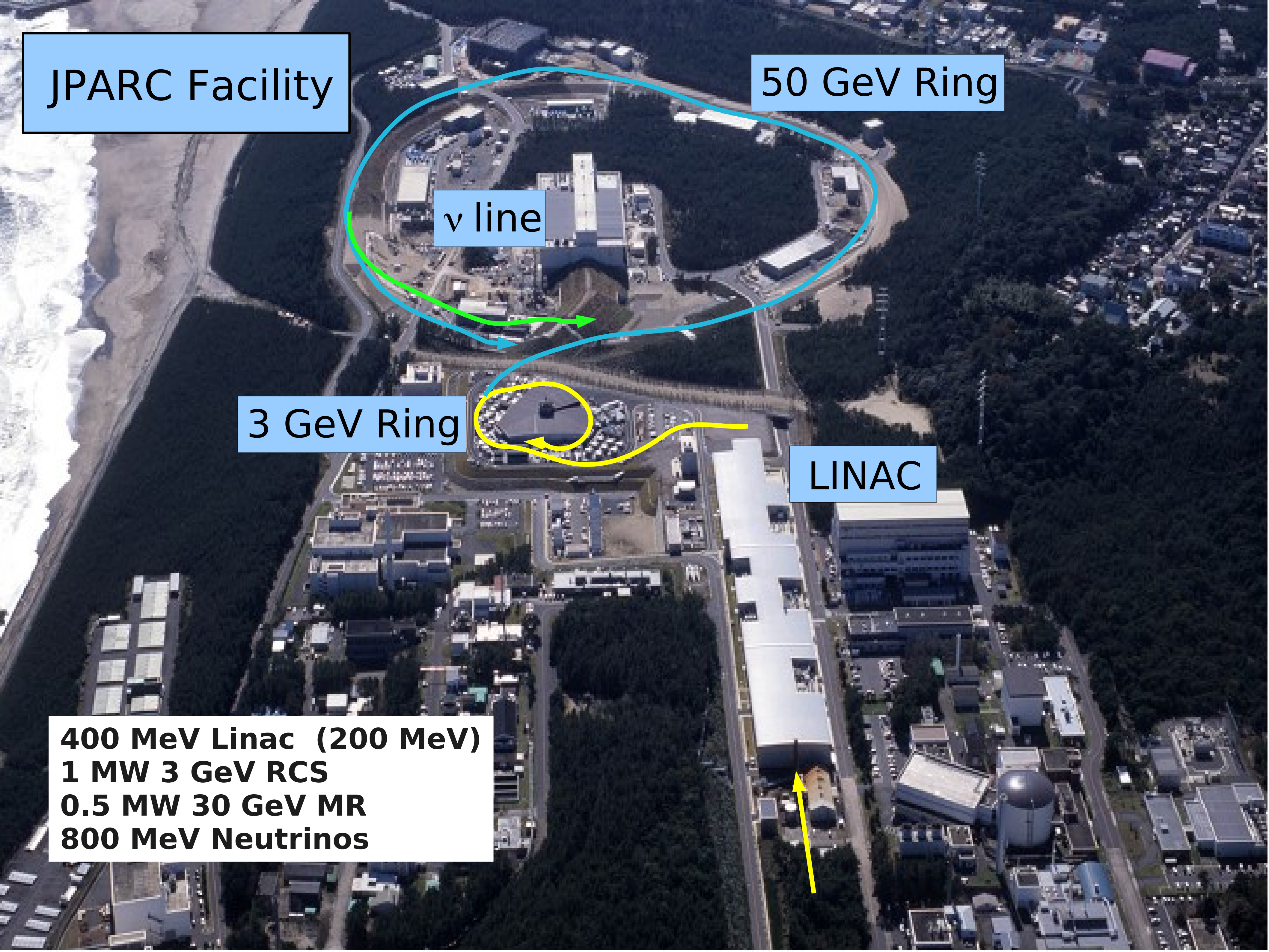
$$P(\pi \rightarrow \nu\,\mu) = 1 - e^{-t/\gamma\tau} = 1 - e^{-L m_{\pi}/E_{\pi}\tau}$$

Shorter tunnel, less pion decays

Longer tunnel, more pion decays, but muons decay to ν_e as well

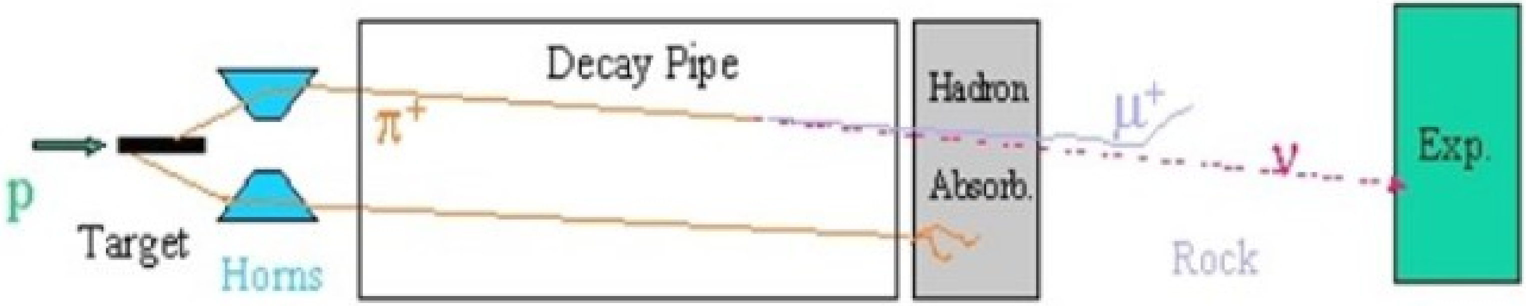
Vacuum? Then more material is needed to hold it. Air? Less material but interactions in decay pipe.

JPARC Facility

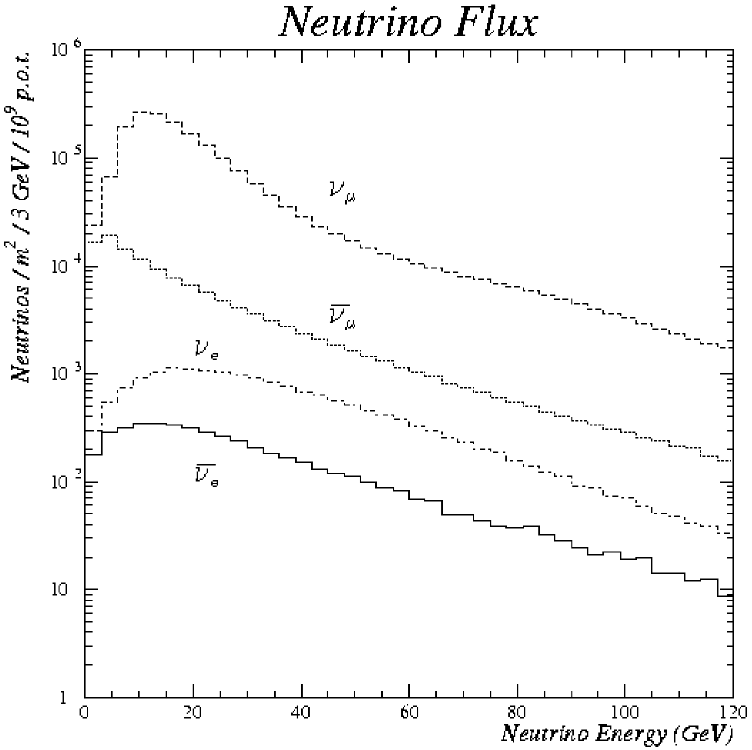


400 MeV Linac (200 MeV)
1 MW 3 GeV RCS
0.5 MW 30 GeV MR
800 MeV Neutrinos

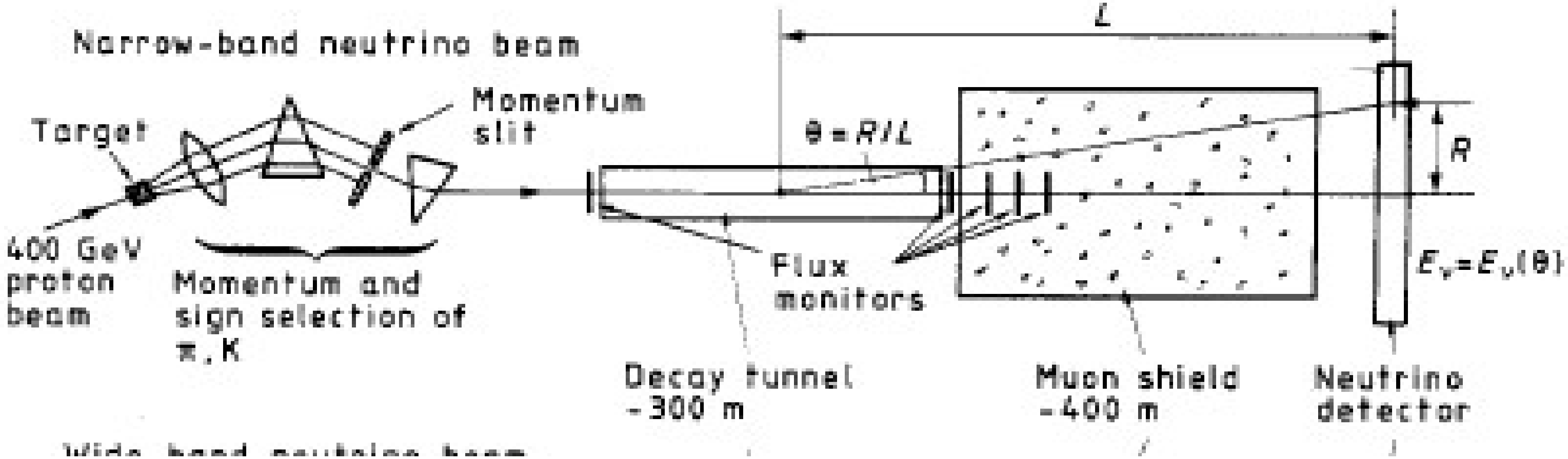
Wide band beams



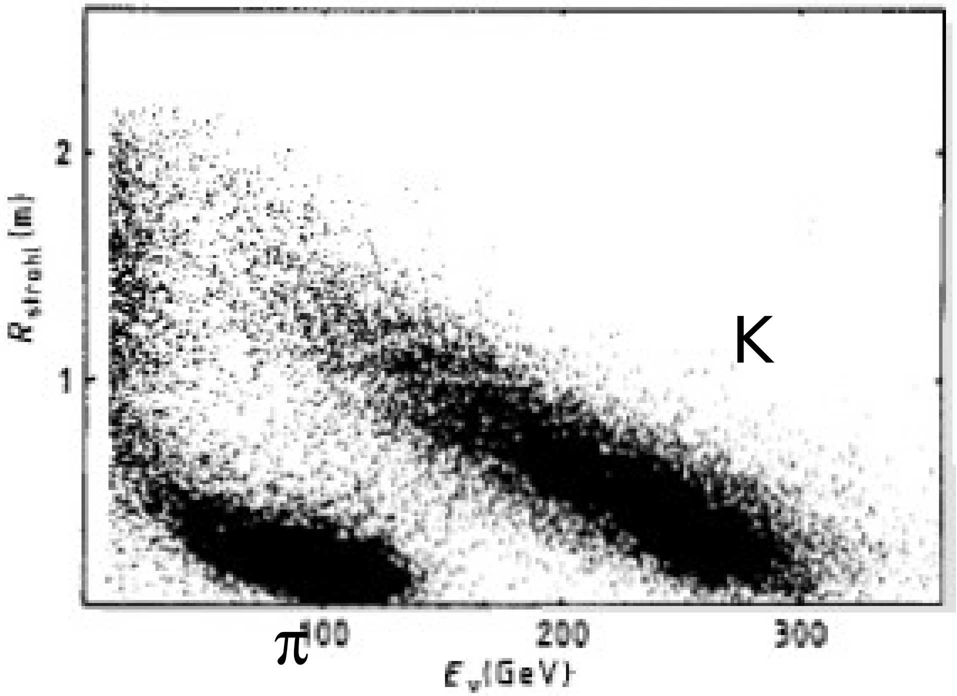
- Large flux of neutrinos.
- Wide range of energies.
- Complex mix of flavours.
- Hard to predict (and measure) neutrino flux.
- Spectrum is a function of radius and decay point



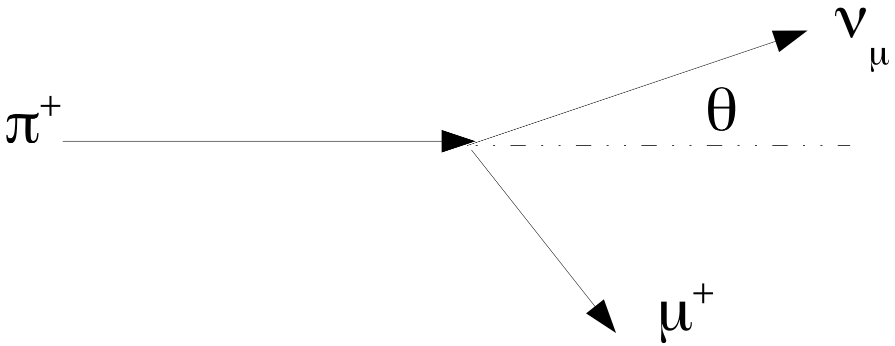
Narrow Band Beams



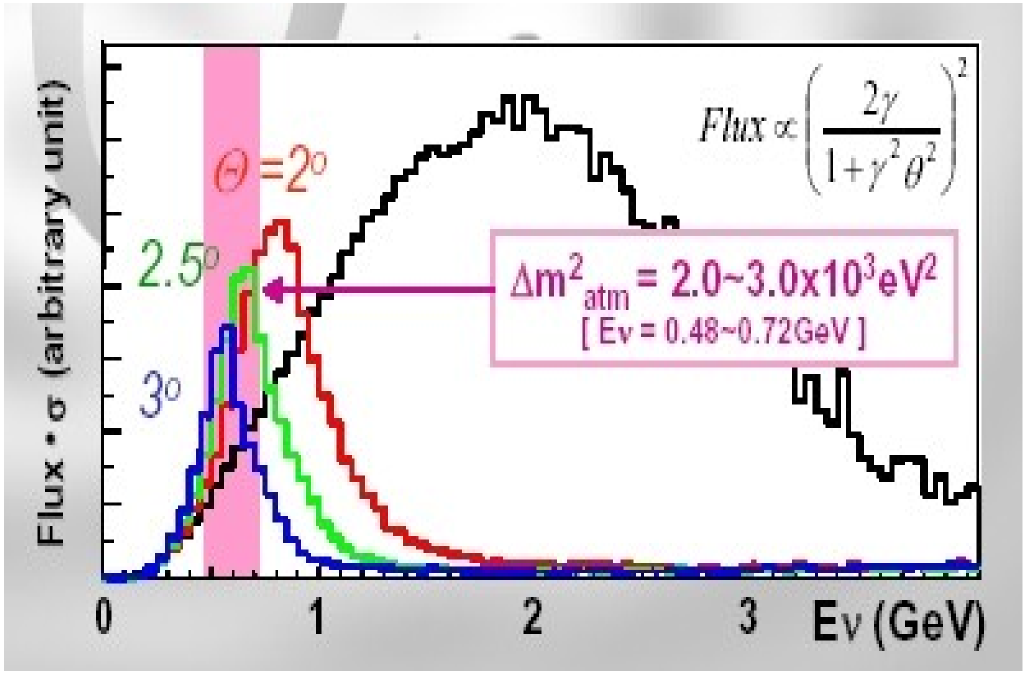
- Flat flux (easy to predict)
- Beam can be tuned to different energies
- flux is 100 times lower than WBB

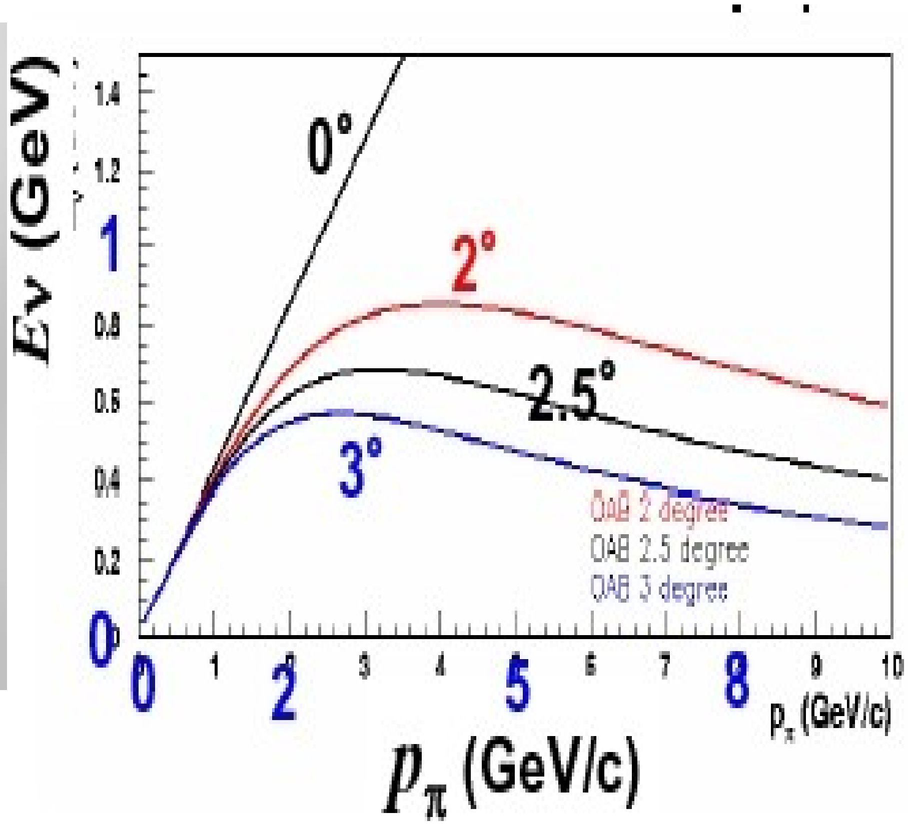


Off-axis beams



$$E_\nu = \frac{0.43\, E_\pi}{1+\gamma^2\theta^2} \qquad \gamma = \frac{E_\pi}{m_\pi}$$





Neutrino Detection

So, you want to build a neutrino detector?

So, you want to build a neutrino detector?

Ha ha. Good one. 😂

So, you want to build a neutrino detector?

~~Ha ha. Good one. 😂~~

Oh you were being serious!? 😬

Alrighty then, riddle me this…

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

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- What sort of backgrounds do have to deal with?
  - More influence on technology – usually conflicting with signal requirements.

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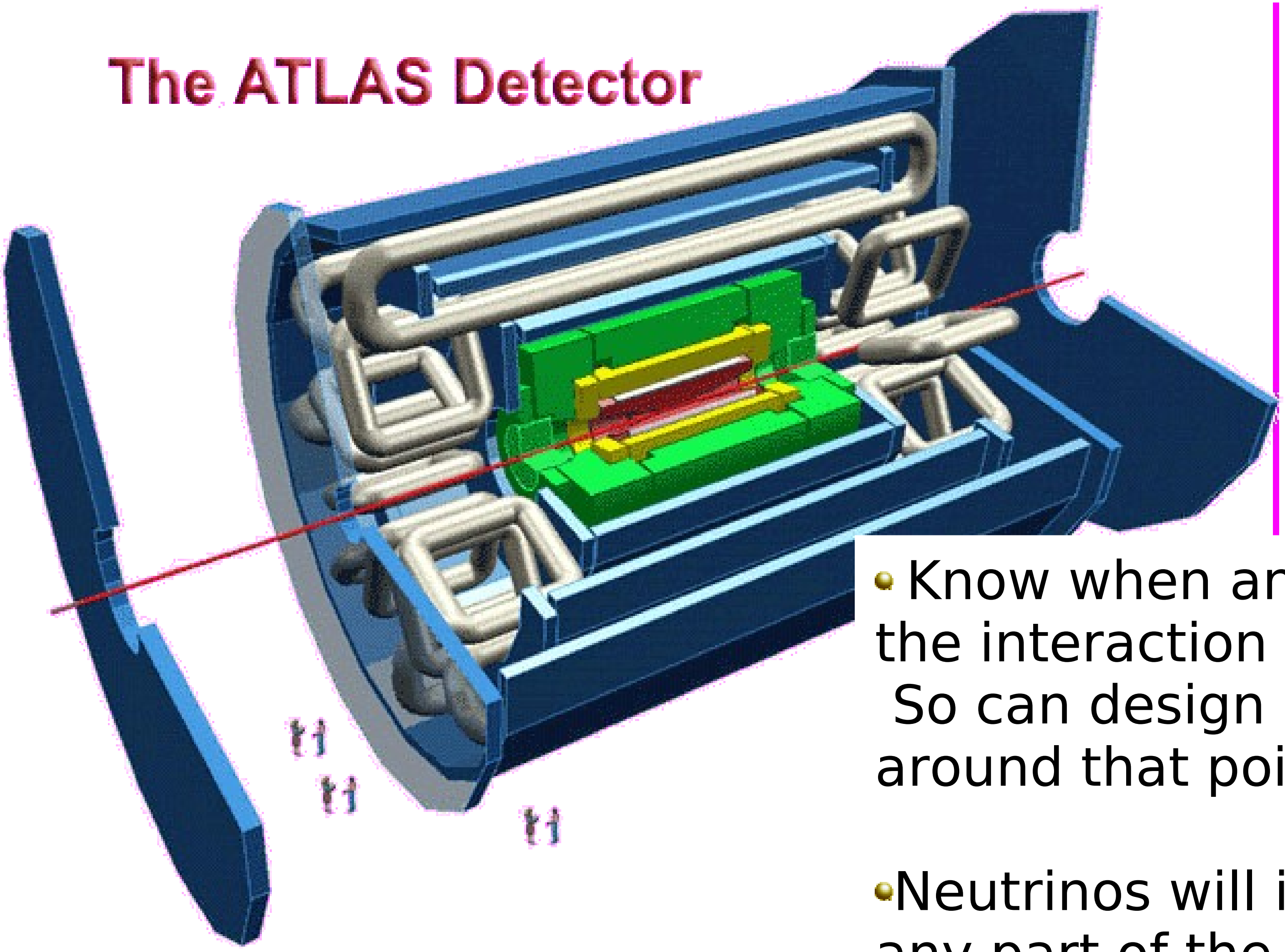
- How much  do you have?

Usual collider detector



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

- Neutrinos will interact in any part of the detector

Neutrino Detectors

- No neutrino colliders – detector IS the target
- Low cross section implies large mass and hence cheap material
- Neutrinos interact everywhere – vertex can be anywhere
- Neutrinos interact in matter - so final state is subject to nuclear potentials
- Need to identify charged lepton to separate NC and CC and neutrino flavour
- Measurement of energy and scattering angle of charged lepton
- Measurement of total hadronic energy
- Identification of single hadrons for hadronic studies

No experiment can satisfy all these requirements
Most experiments fall into one of a few types

Types of detectors

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

Radiochemical Experiments

This techniques uses the production of radioactive isotopes.

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

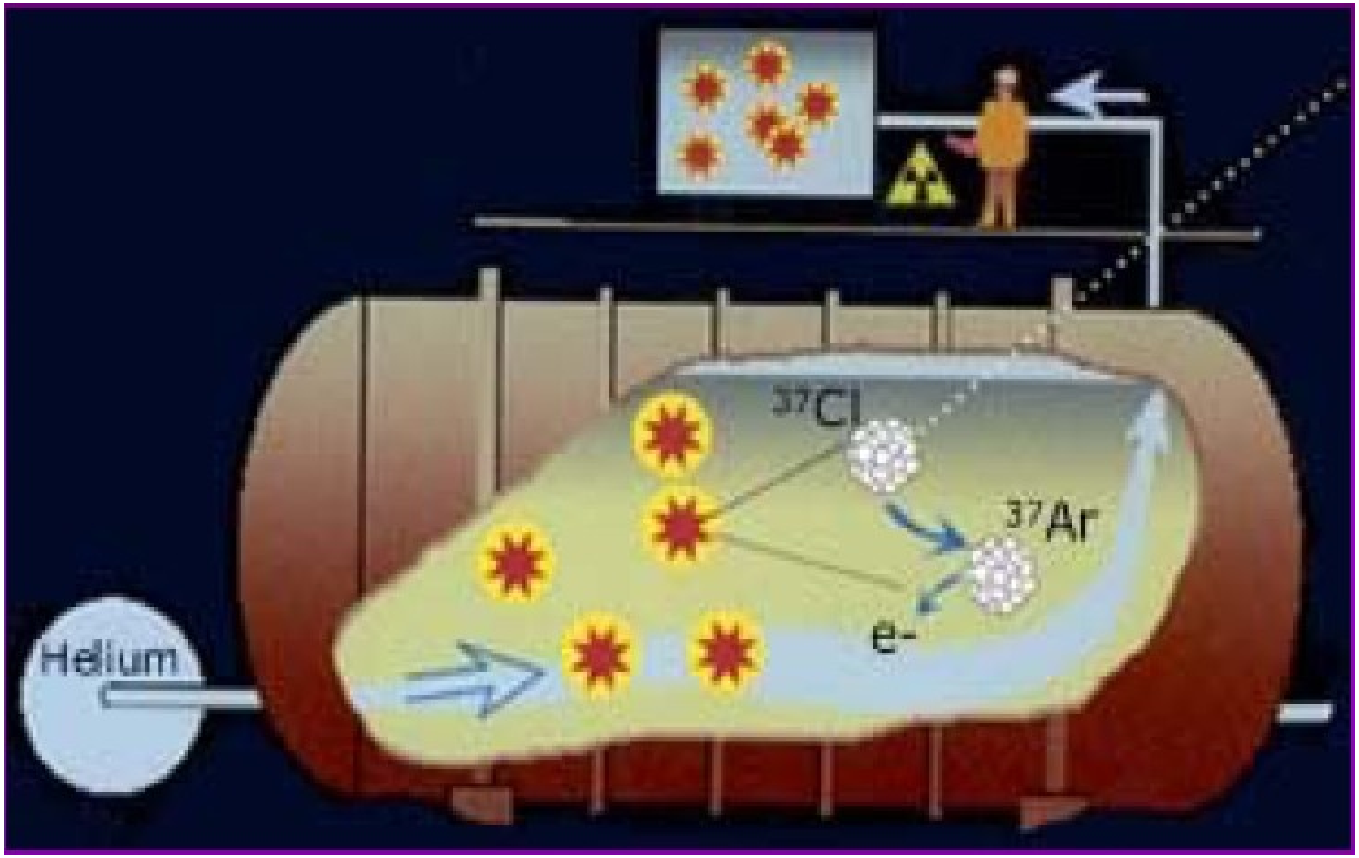
$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^- \qquad \nu_e + Ga^{71} \rightarrow \mathrm{Ge}^{37} + e^-$$

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 or neutrino direction, and only really generates “large” counte rates for low energy neutrinos (in the MeV range)

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

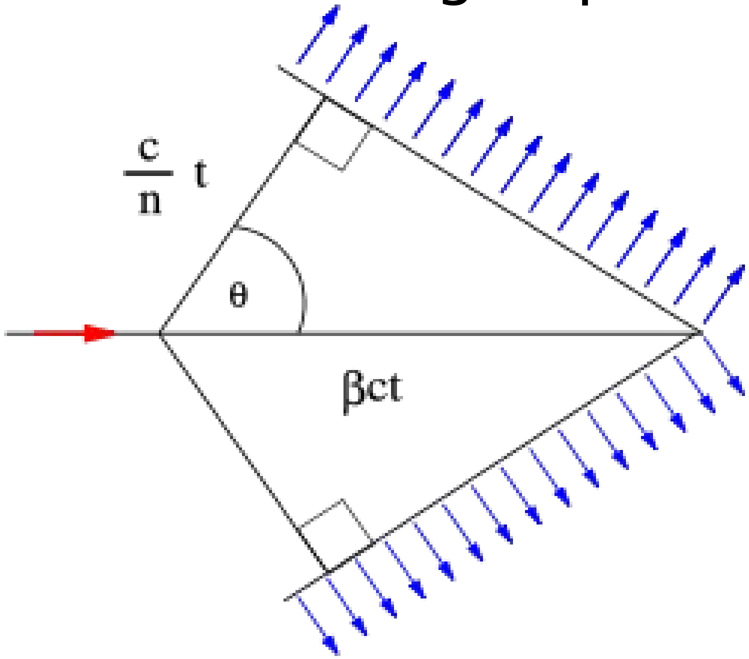
Individual argon atoms are captured and counted.

1 atom per 2 days.

Threshold : 814 keV

Water Experiments

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



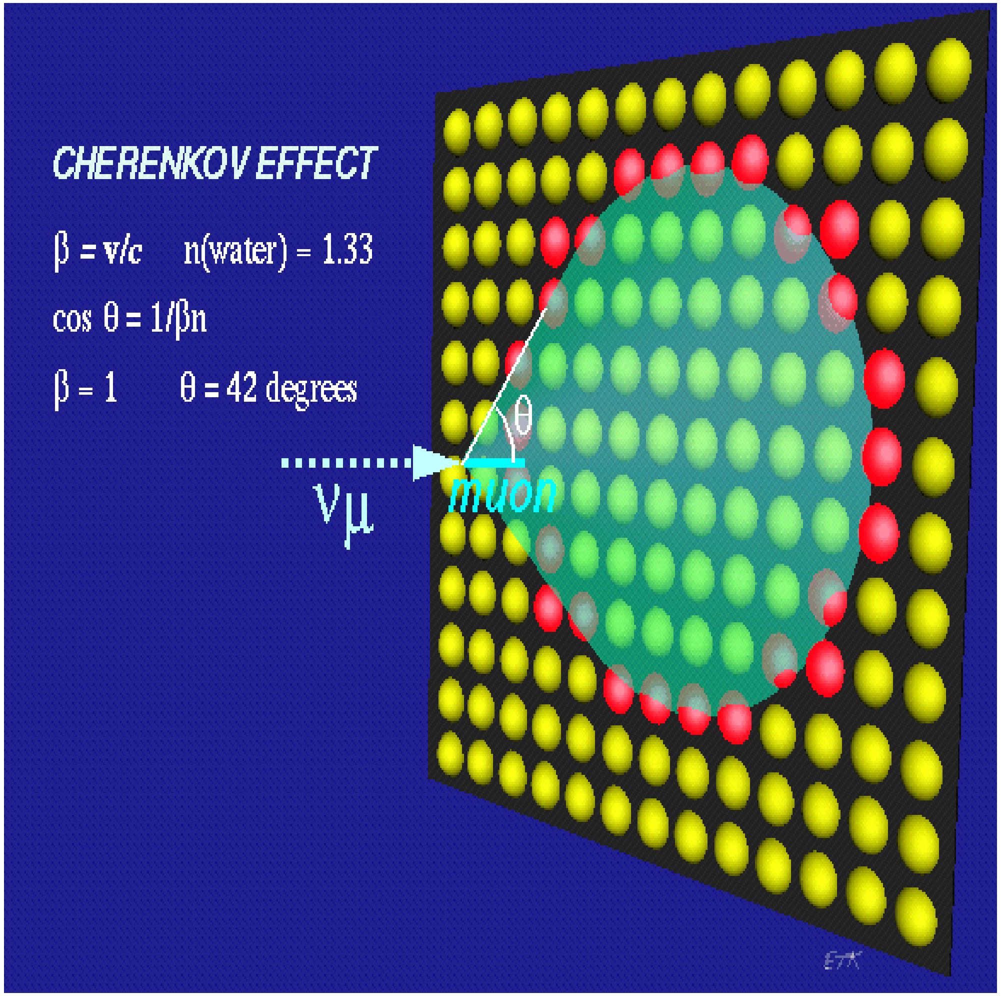
If a charged particle moves through a material with $\beta > 1/n$ it produces an EM shockwave at a particular angle.

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

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

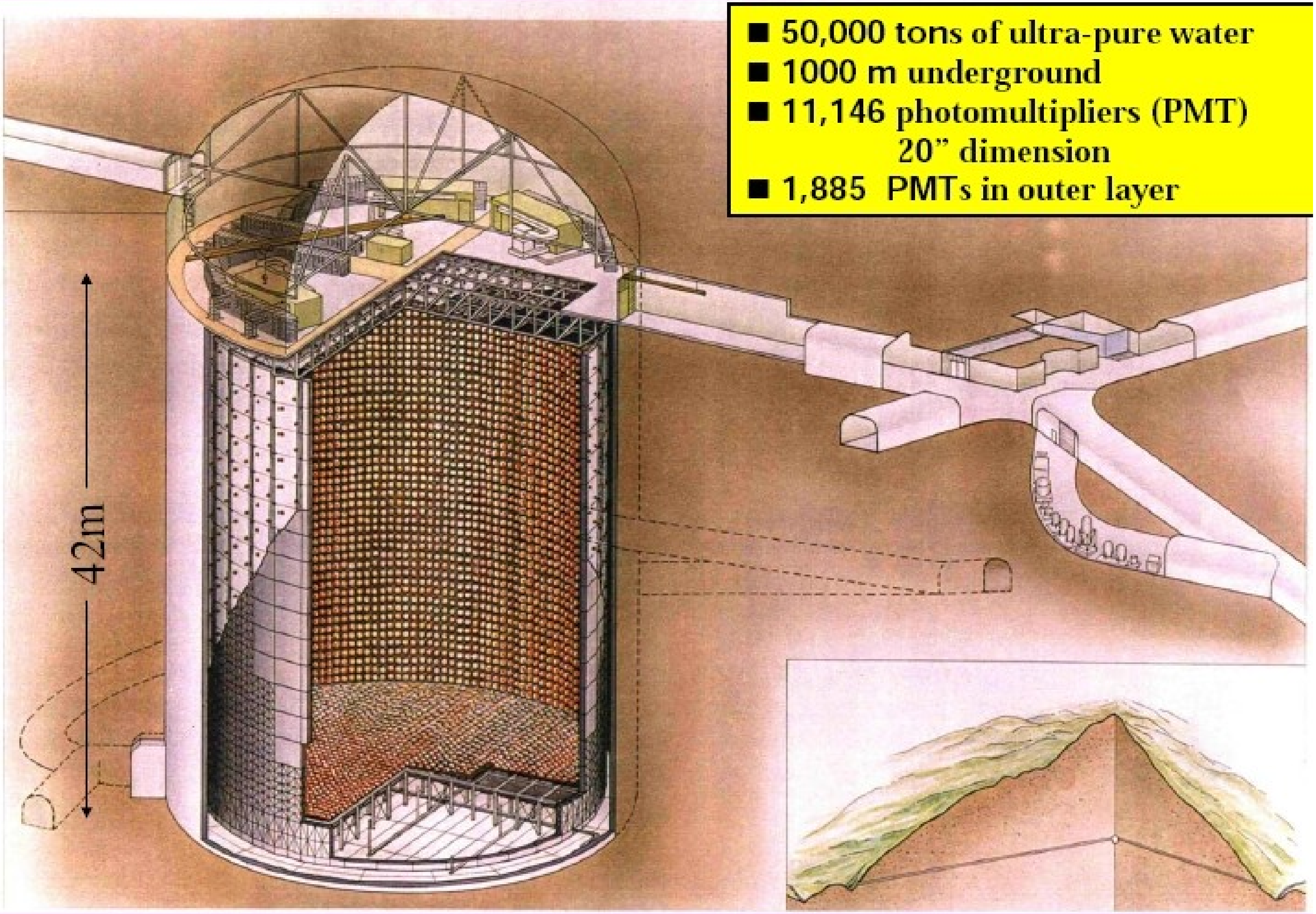
*See Antonis' lecture on Friday for more uses of the Cerenkov technique

Principle of operation

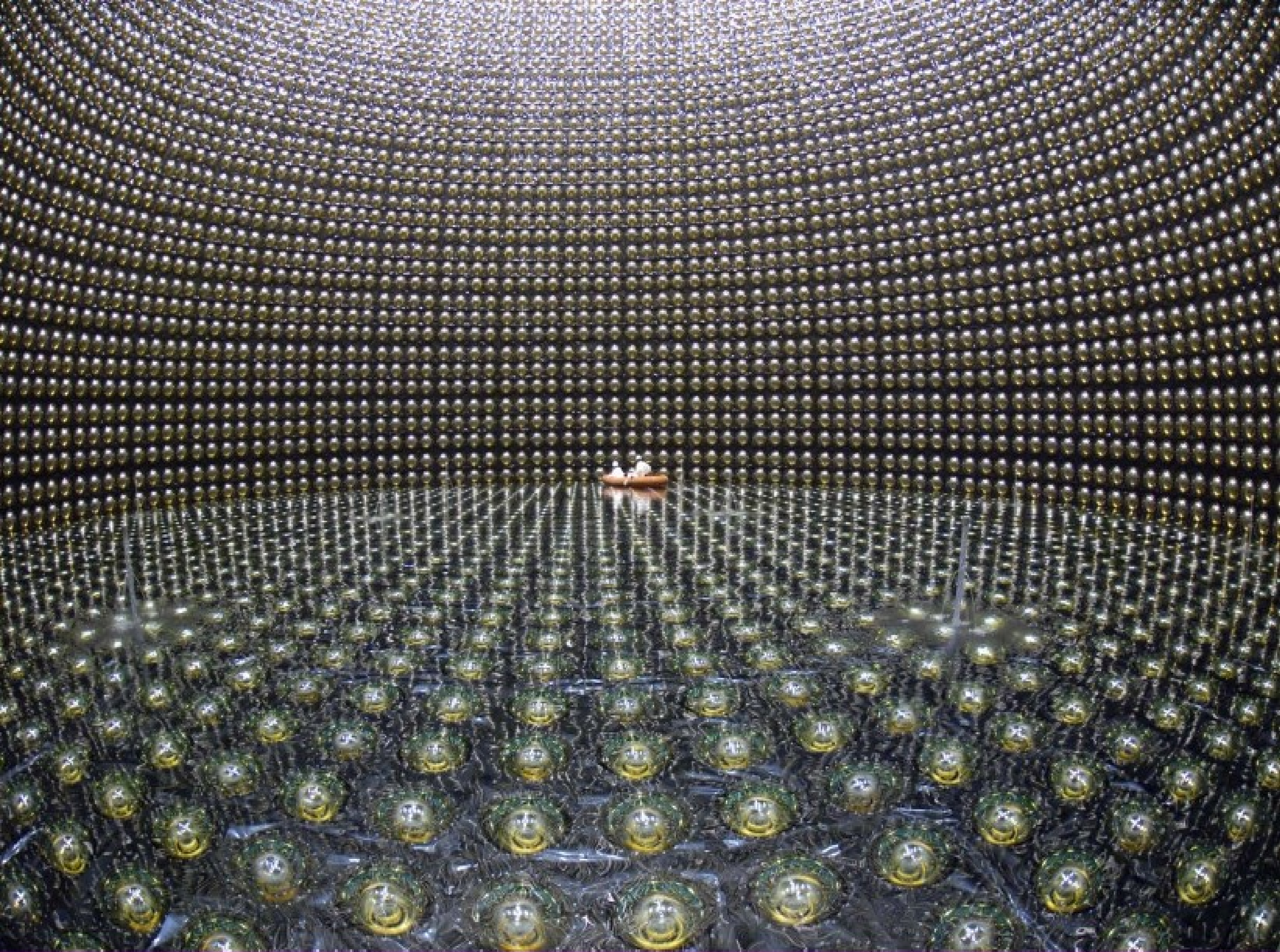


- Cerenkov light detected as a ring or circle by PMTs
- Vertex from timing
- Direction from cone
- Energy from summed light
- No neutrals or charged particles under Cerenkov threshold
- Low multiplicity events

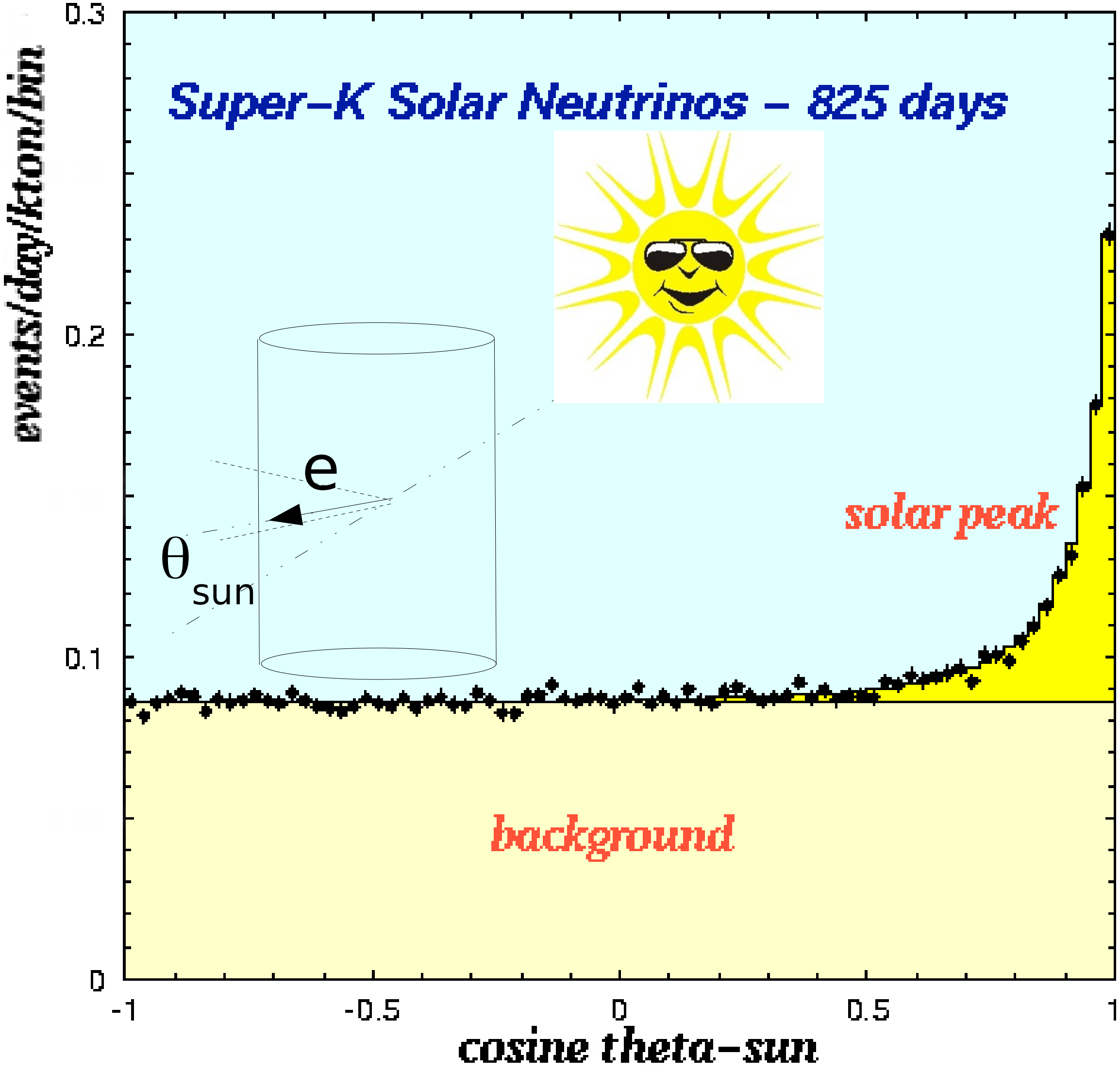
Super-Kamiokande



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

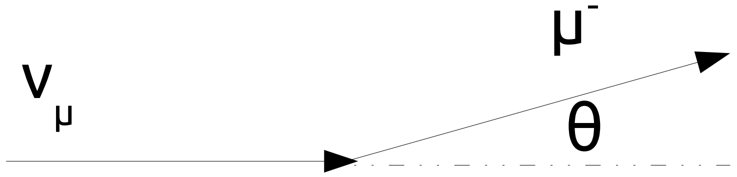


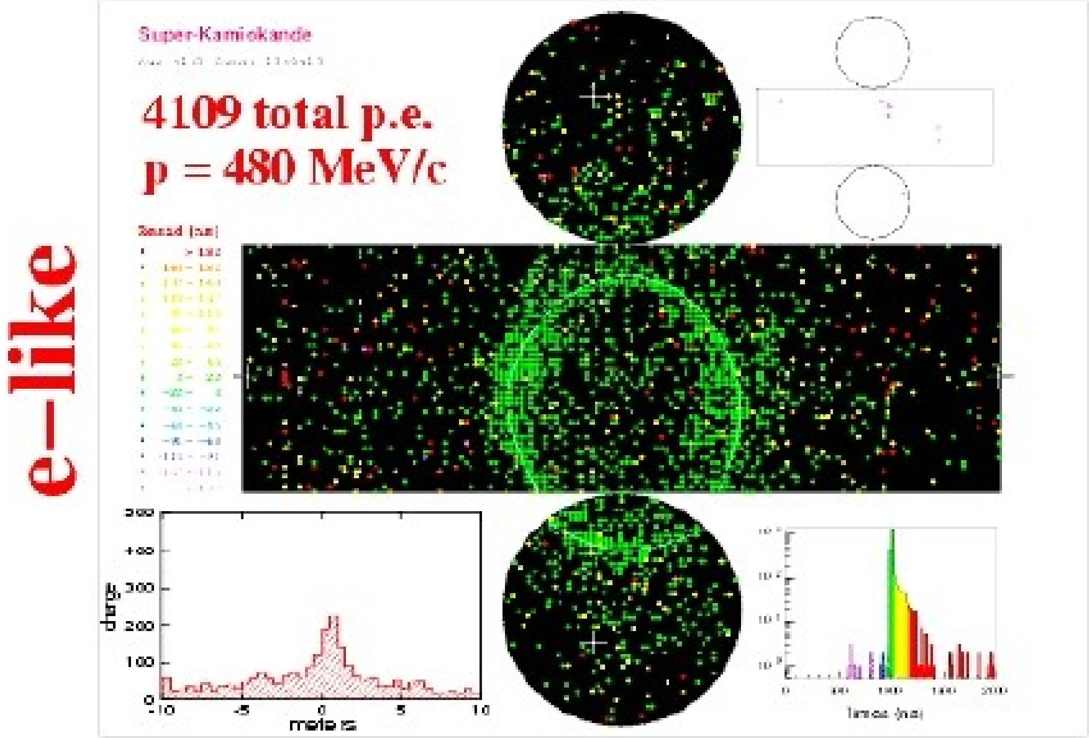
Directionality

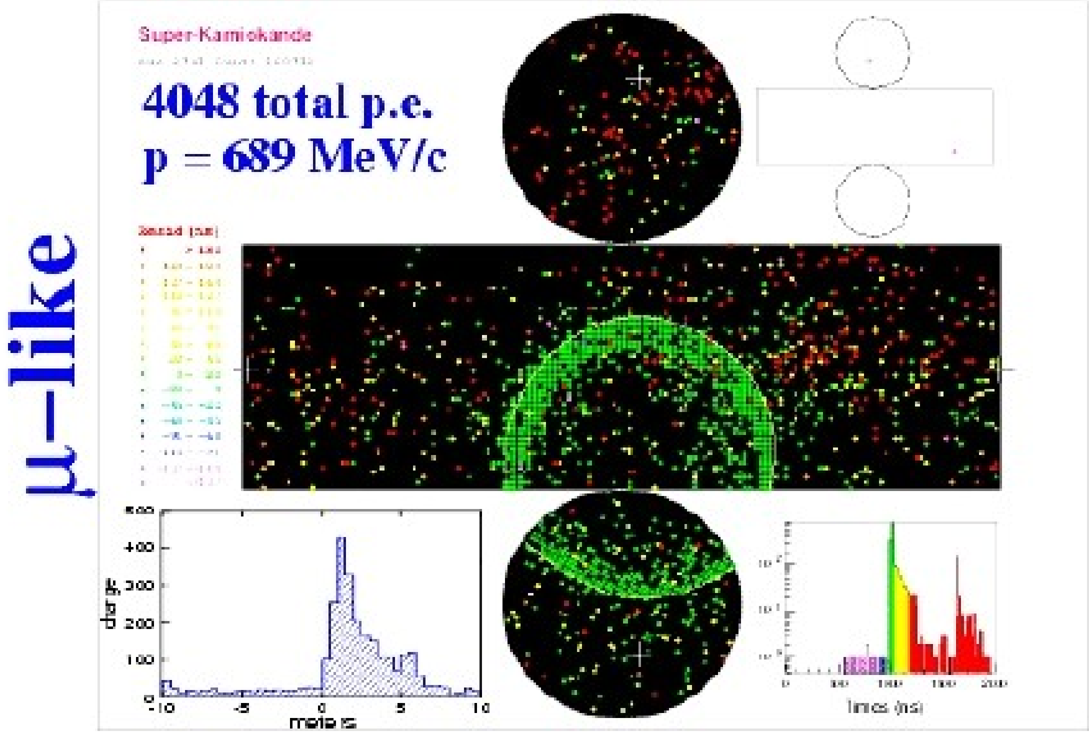


For simple events , the direction of the ring can be used to point back to the neutrino source

Proof that these neutrinos were coming from the sun







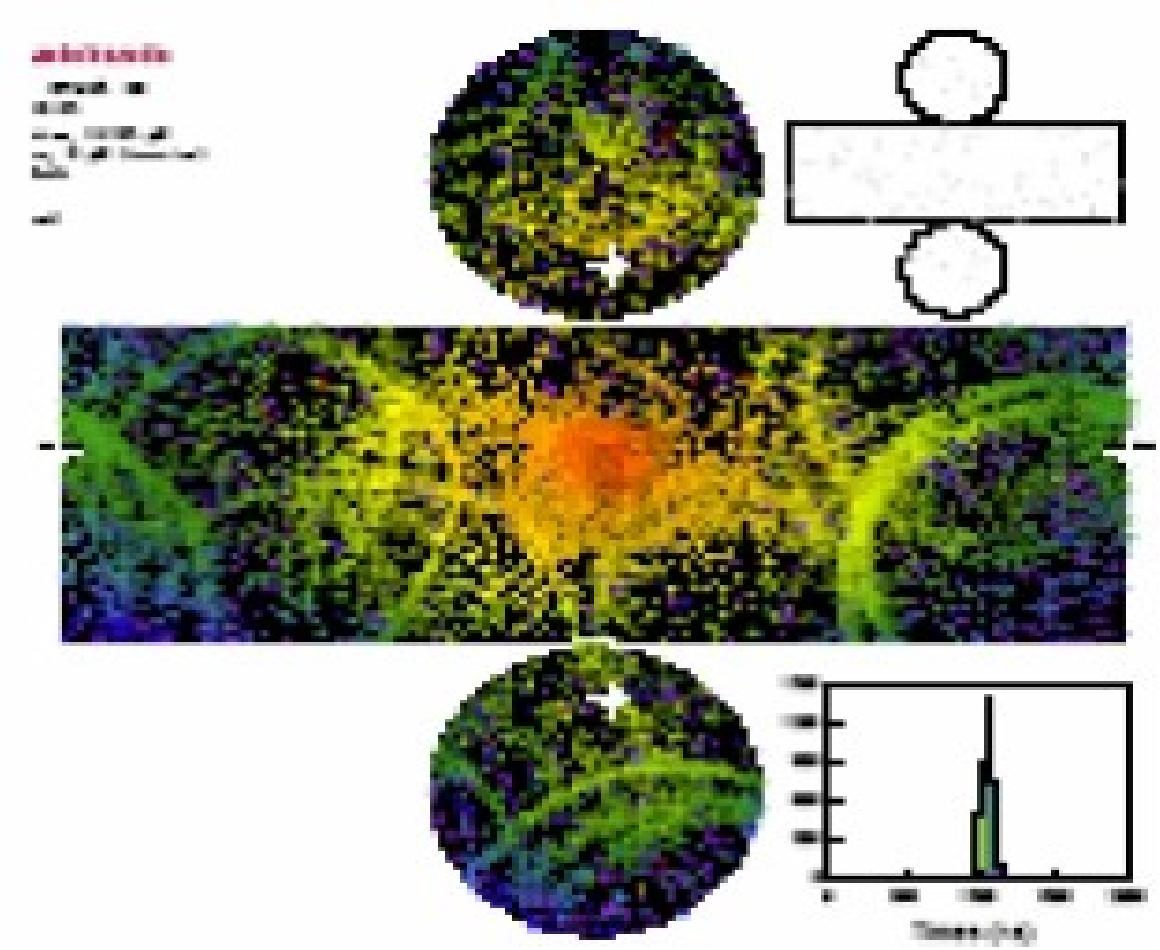
Electron-like : has a fuzzy ring

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

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

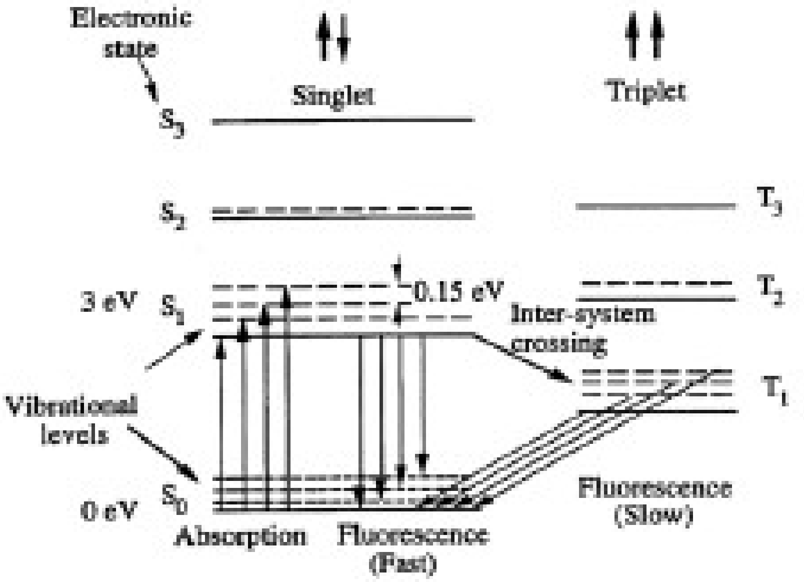
Problems

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



Scintillator Detectors

Light emission following ionisation



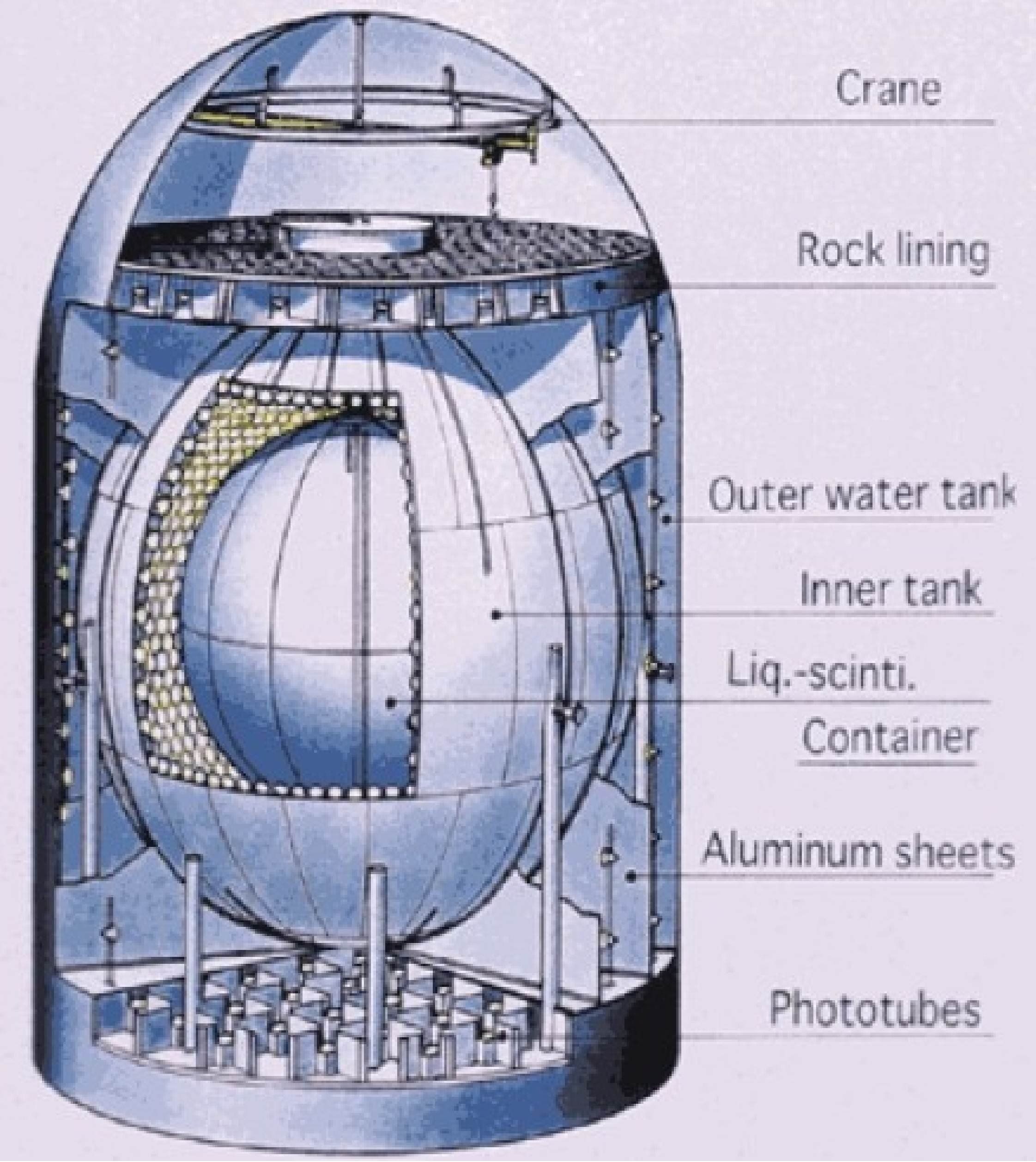
Organic liquids and plastics

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.
- But no information on directionality,the emission wavelength depends on the scintillator material, and the scintillator is usually highly toxic.

KamLAND



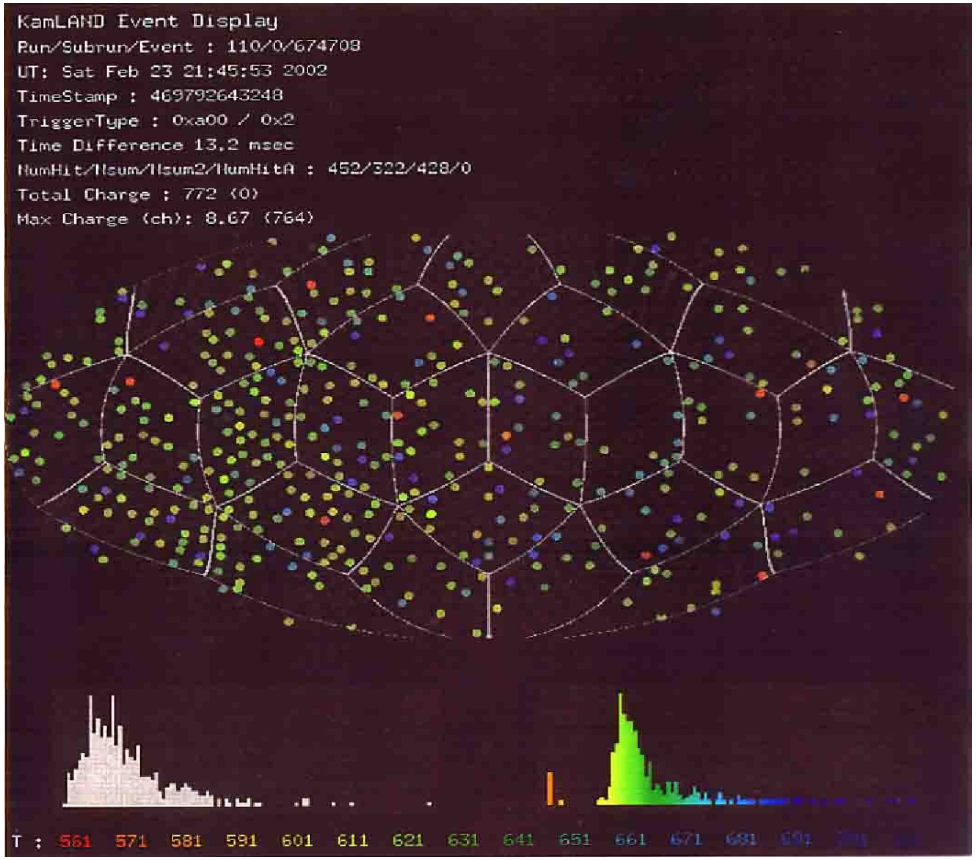
- External container filled with 3.2 kton H_2O
- Inner sphere filled with 2 kton of mineral oil
- Inside transparent balloon filled with 1 kton of liquid scintillator
- Located 1km deep in the Kamioka mine, just up the street from Super-Kamiokande
- Very pure – background is a major problem.

Event Displays

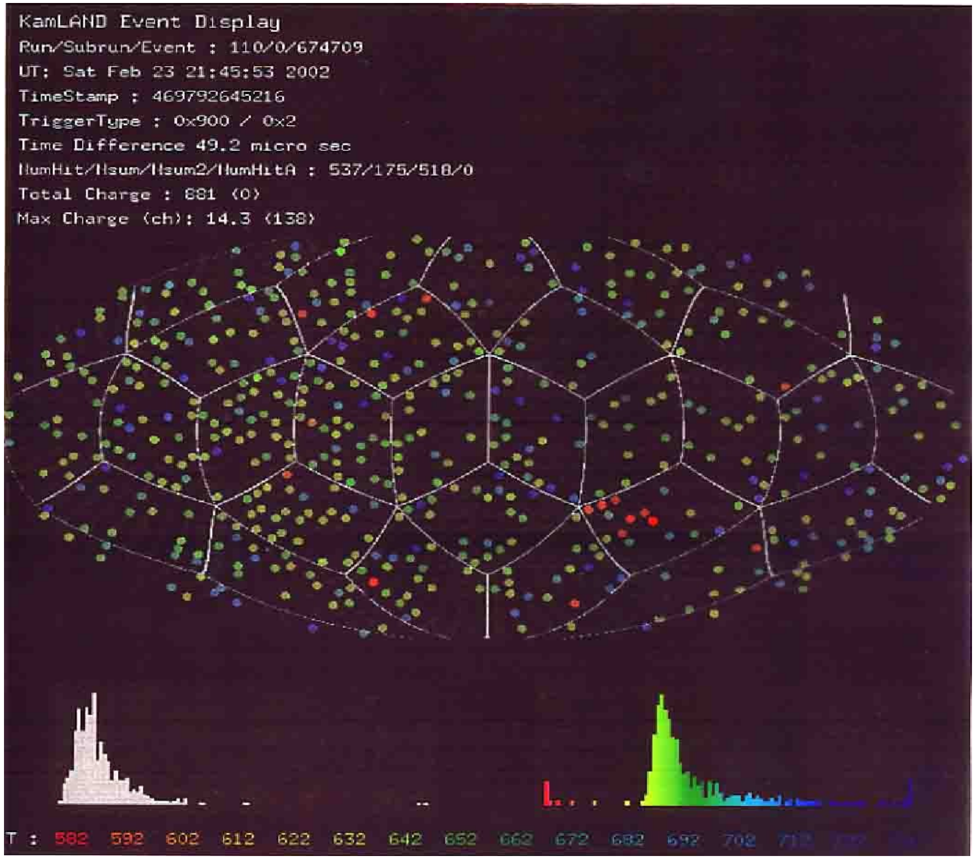
$\overline{\nu}_e + p \rightarrow e^+ + n$

200 ms later

$n + p \rightarrow d + \gamma$



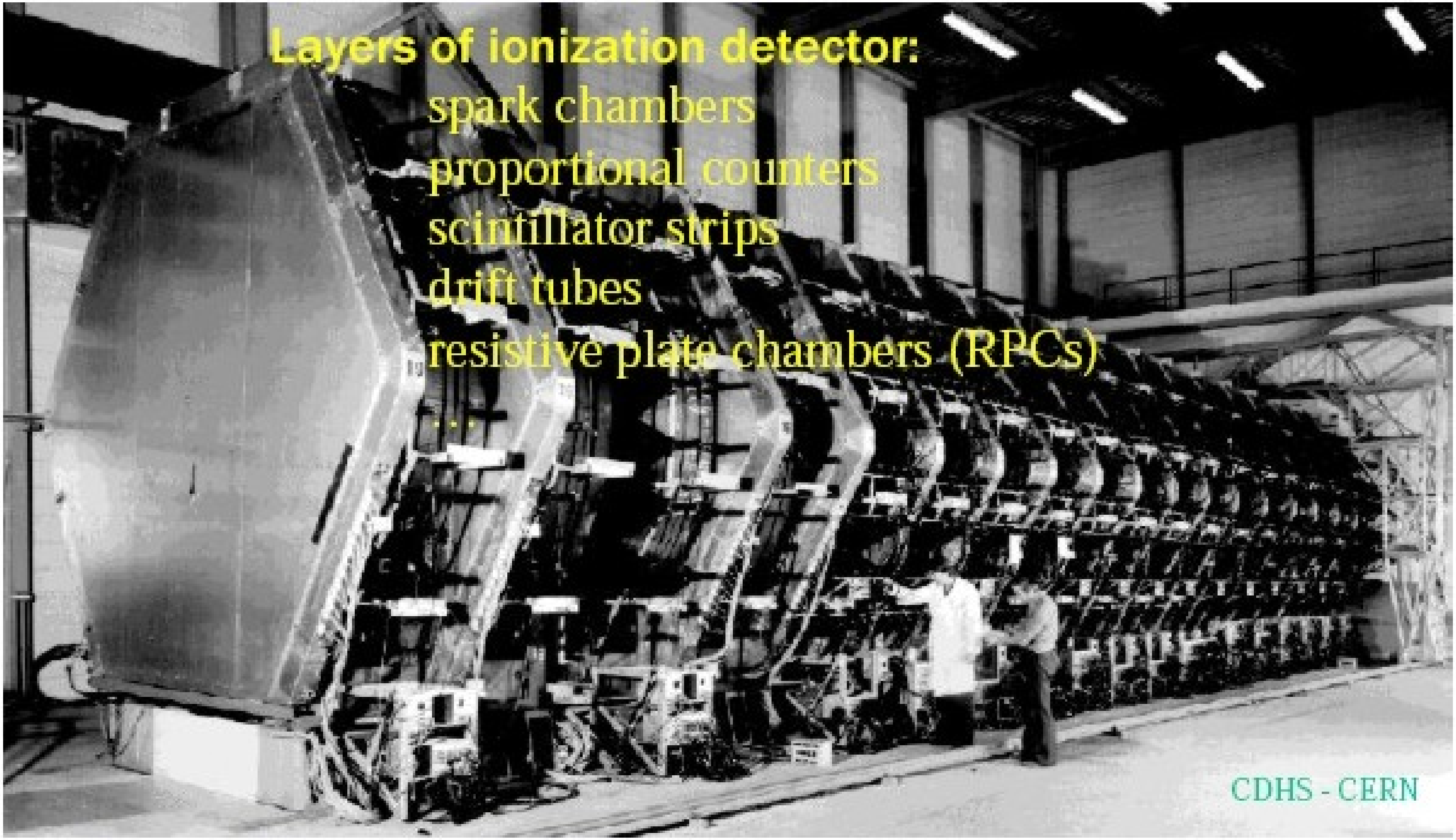
```
KamLAND Event Display
Run/Subrun/Event : 110/0/674708
UT: Sat Feb 23 21:45:53 2002
TimeStamp : 469792643248
TriggerType : 0xa00 / 0x2
Time Difference 13.2 msec
NumHit/Nsum/Nsum2/NumHitA : 452/322/428/0
Total Charge : 772 (0)
Max Charge (ch): 8.67 (764)
```



```
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 Calorimeters

Layers of target: eg. steel, marble, glass



Layers of ionization detector:

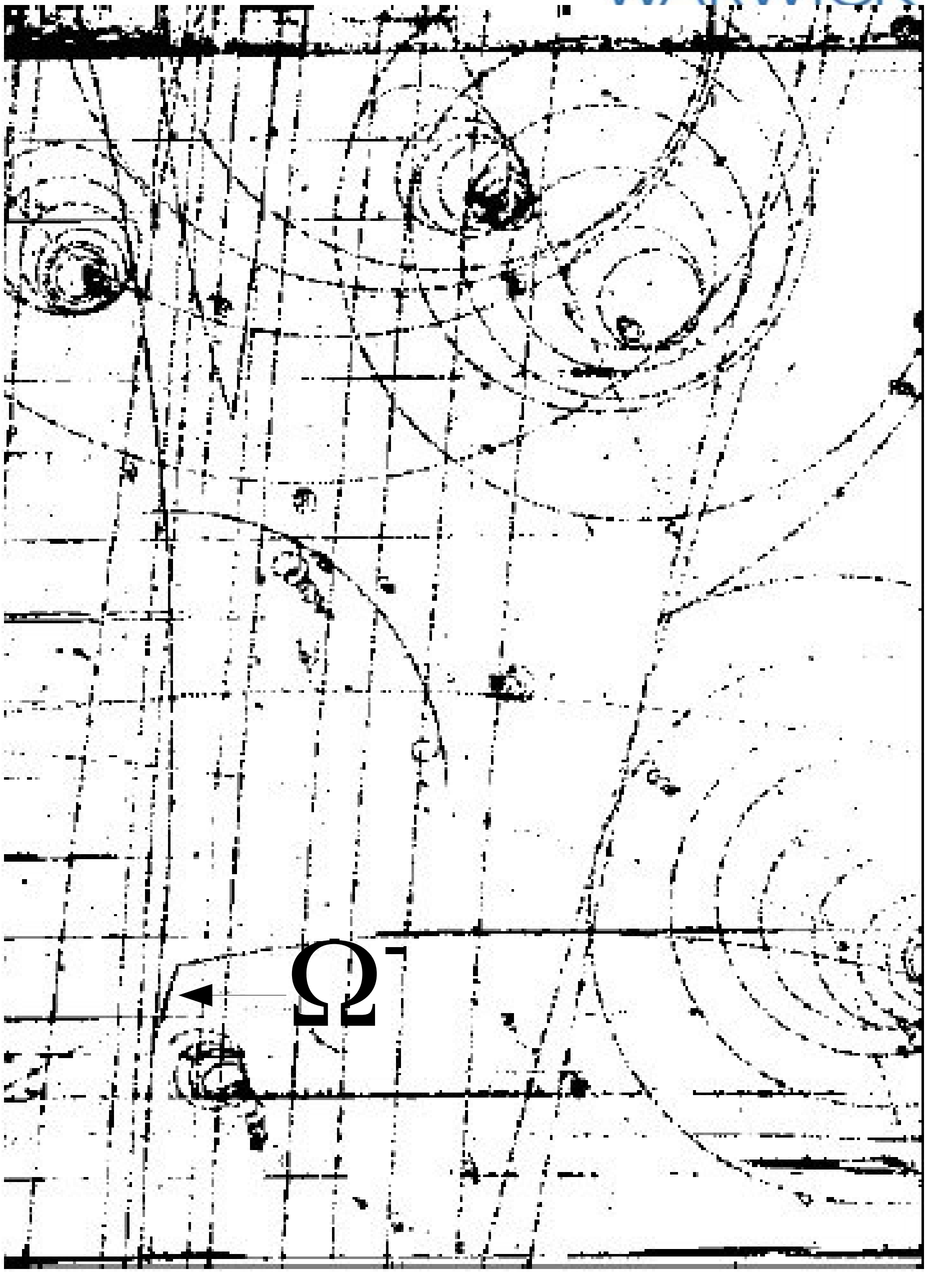
- spark chambers
- proportional counters
- scintillator strips
- drift tubes
- resistive plate chambers (RPCs)
- ...

CDHS - CERN

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

Tracking Chambers

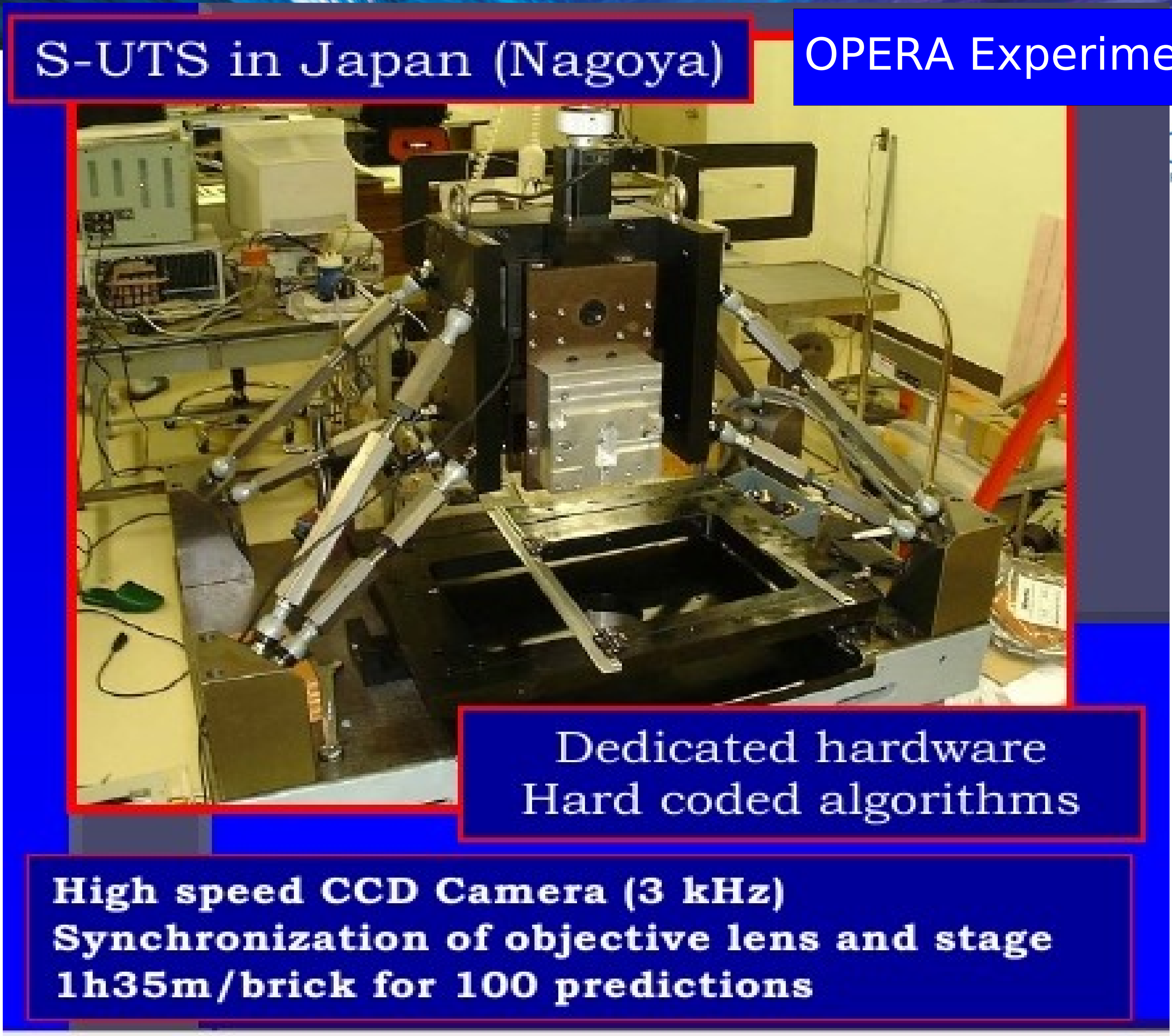
BEBC Chamber



The LBL Frankenstein

Scan 24,000 events per year and required 5 people to keep operating

OPERA Experiment



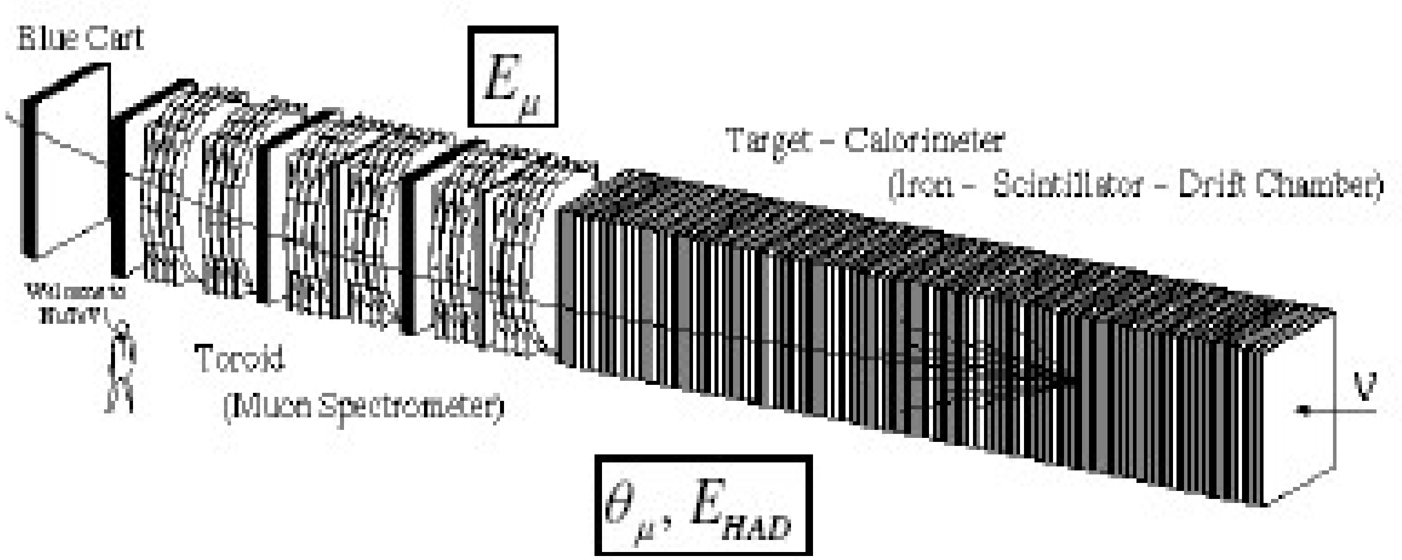
S-UTS in Japan (Nagoya)

Dedicated hardware
Hard coded algorithms

High speed CCD Camera (3 kHz)
Synchronization of objective lens and stage
1h35m/brick for 100 predictions

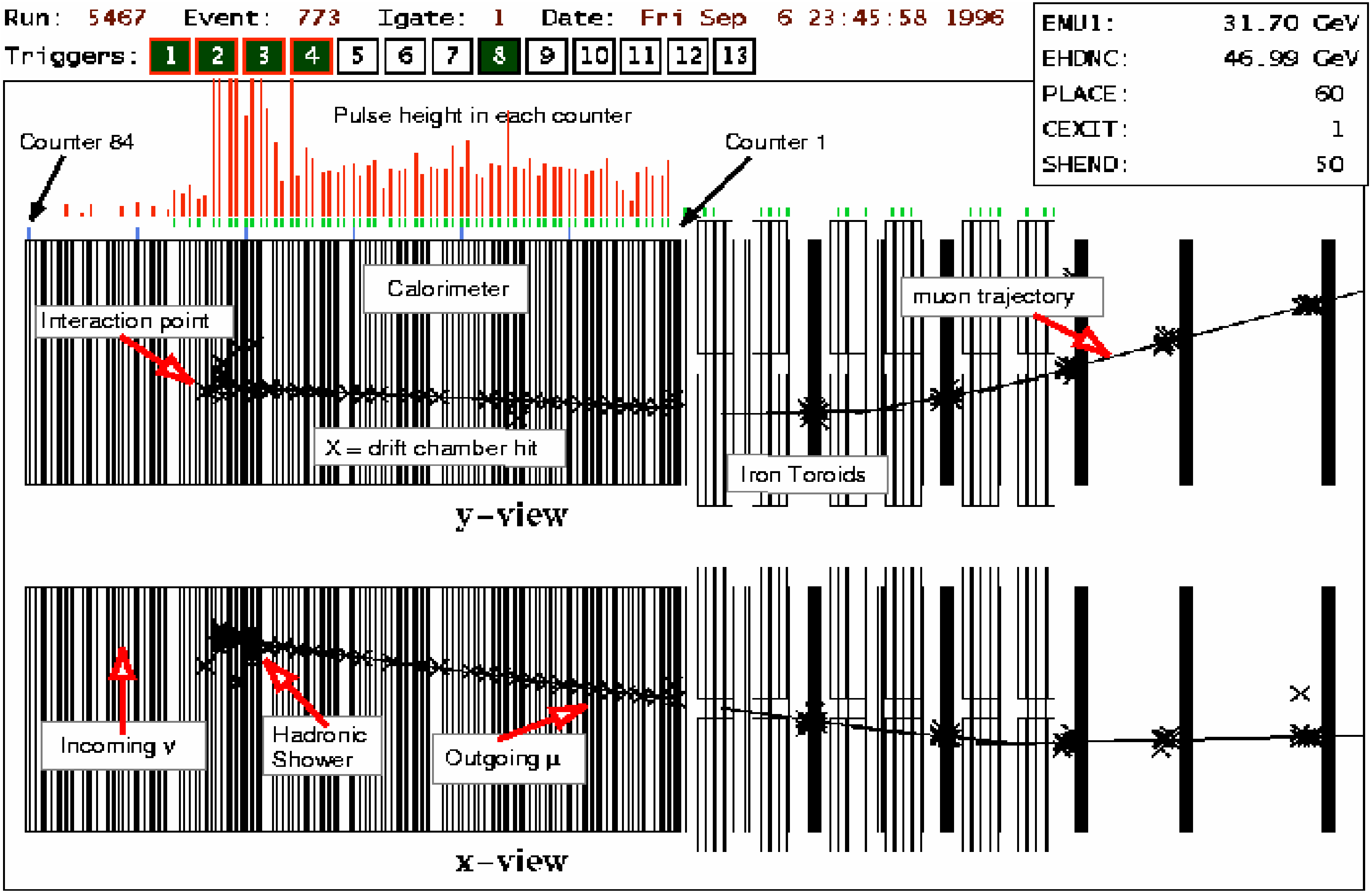
NUTEV

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



- 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 Event Display

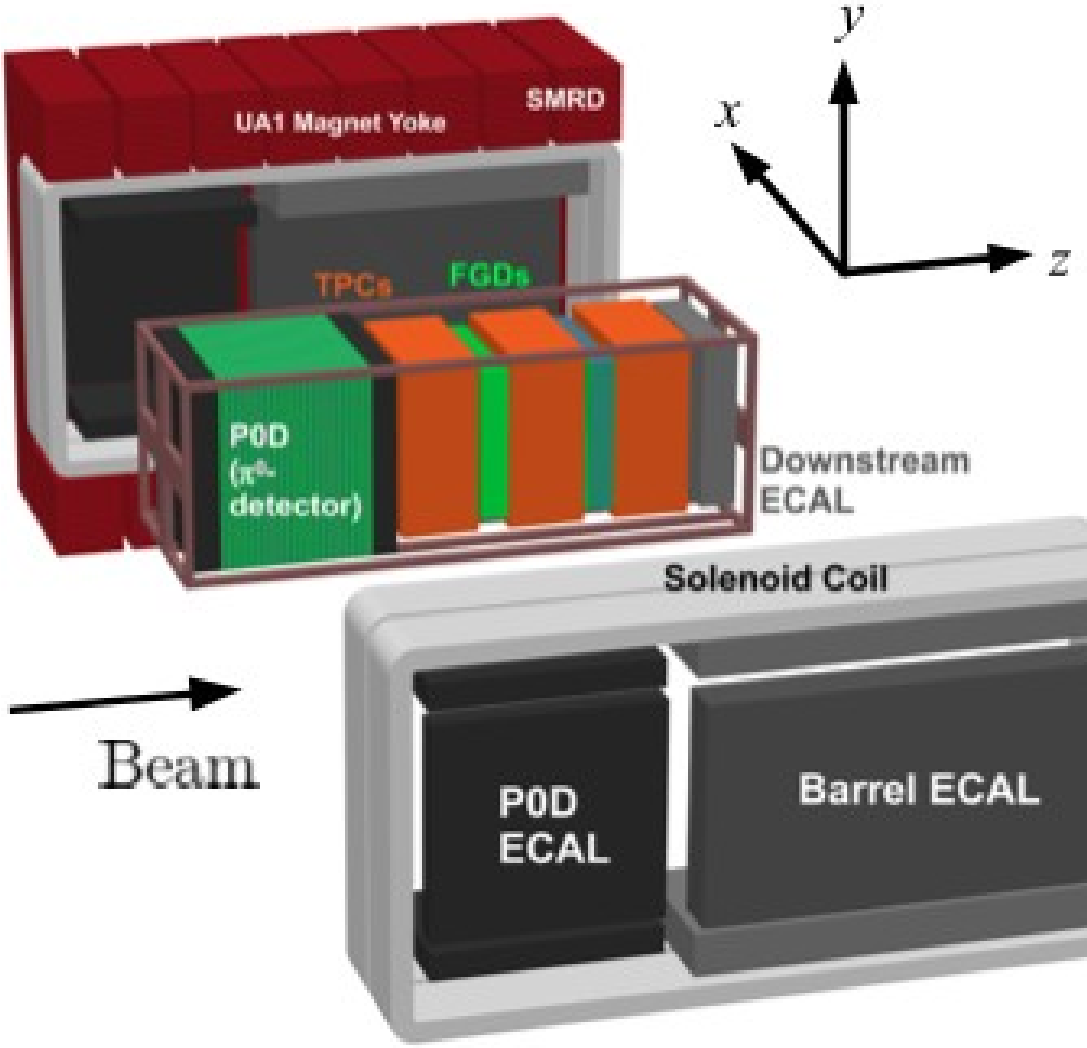


Run: 5467 Event: 773 Igate: 1 Date: Fri Sep 6 23:45:58 1996

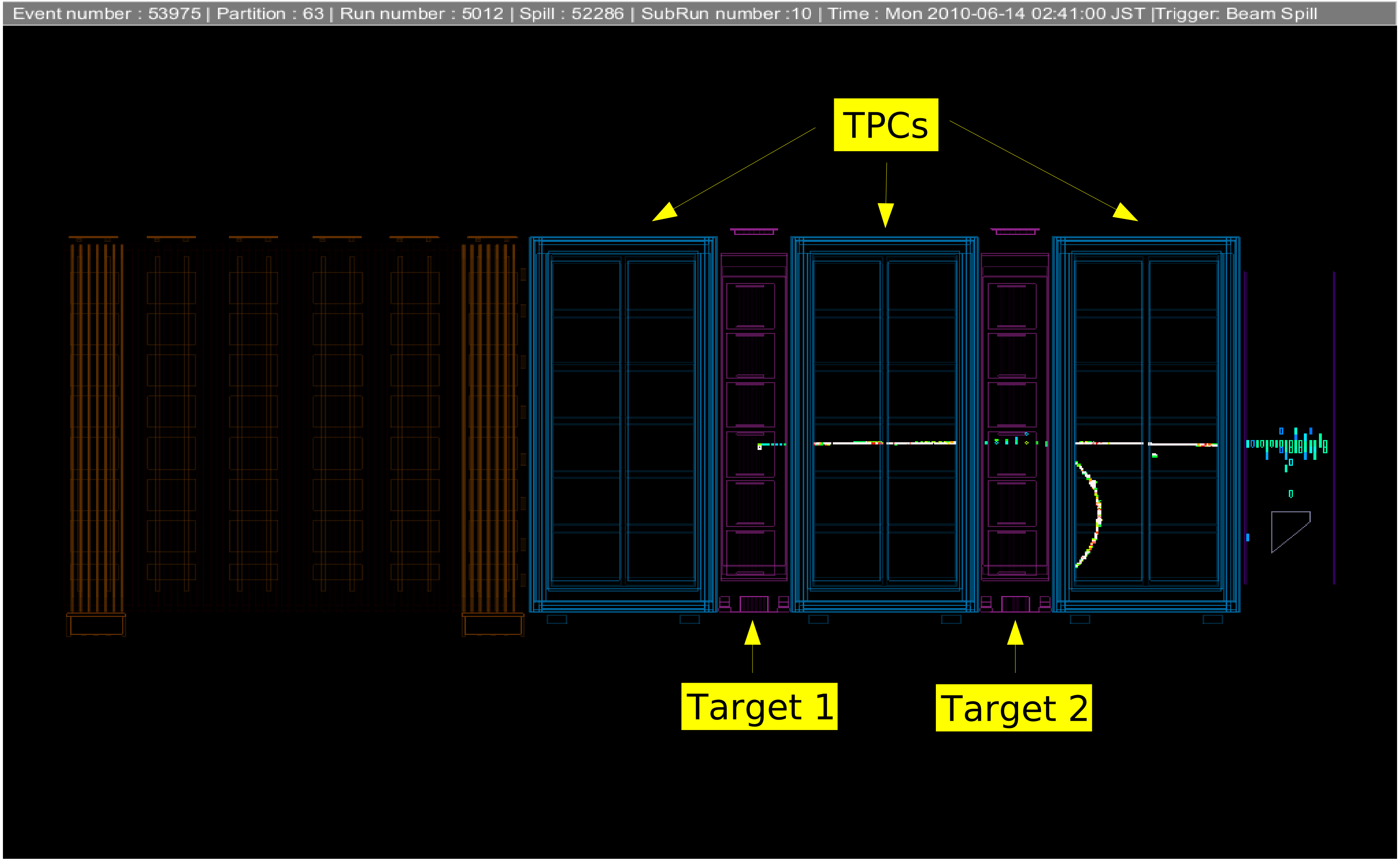
Triggers: 1 2 3 4 5 6 7 8 9 10 11 12 13

EMU1: 31.70 GeV
EHDNC: 46.99 GeV
PLACE: 60
CEXIT: 1
SHEND: 50

T2K ND280


UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π^0-
detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL
Beam
y
x
z

T2K



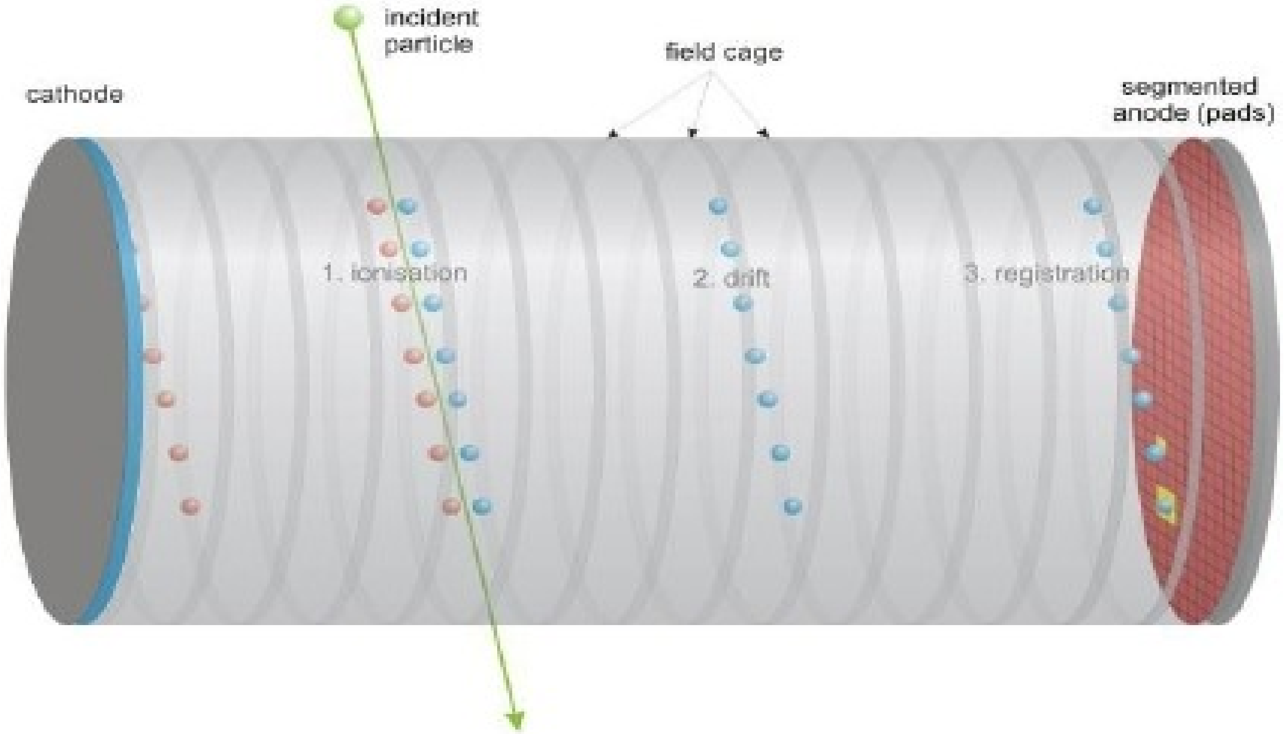
Event number : 53975 | Partition : 63 | Run number : 5012 | Spill : 52286 | SubRun number :10 | Time : Mon 2010-06-14 02:41:00 JST |Trigger: Beam Spill

TPCs

Target 1

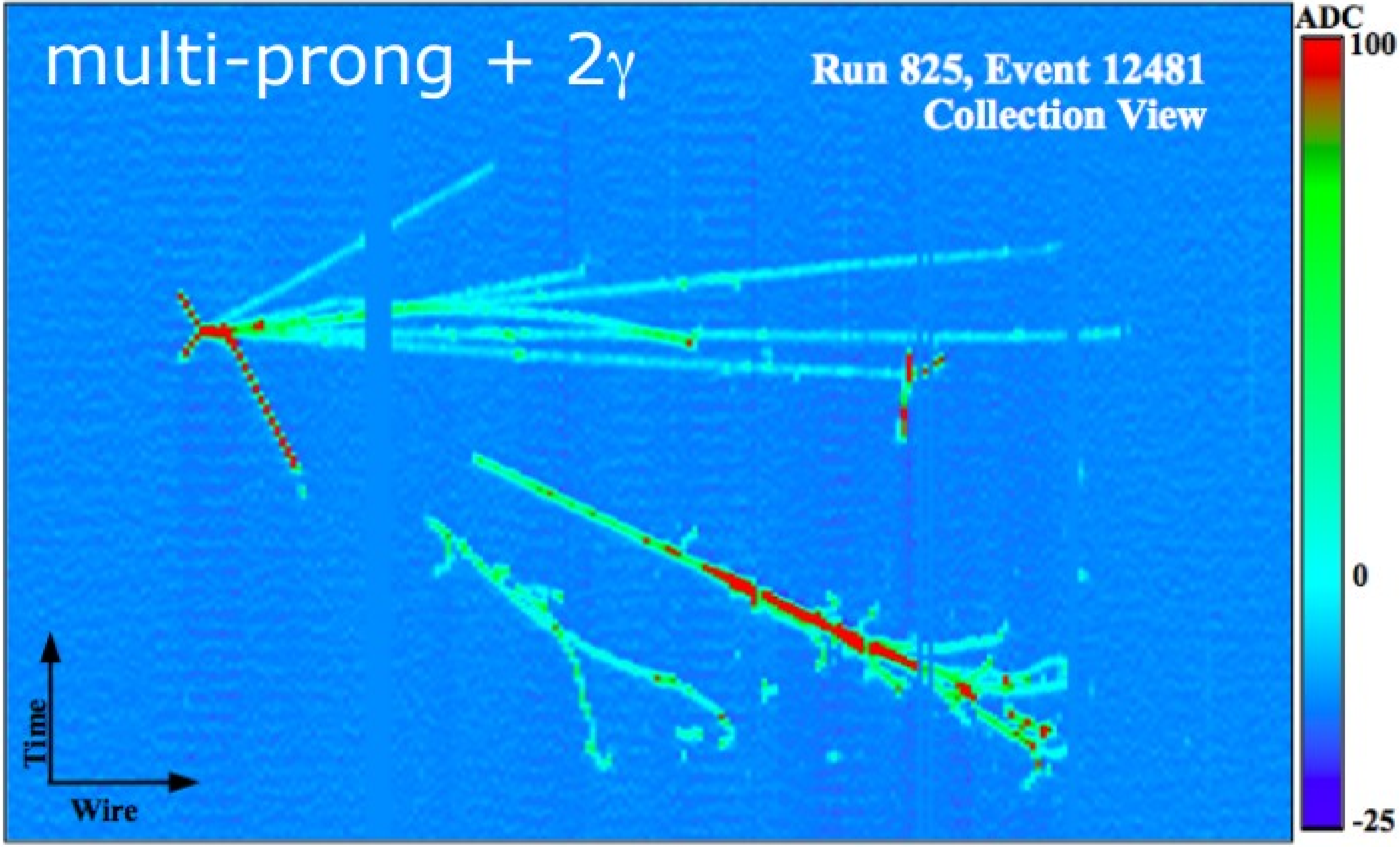
Target 2

Liquid Argon TPCs

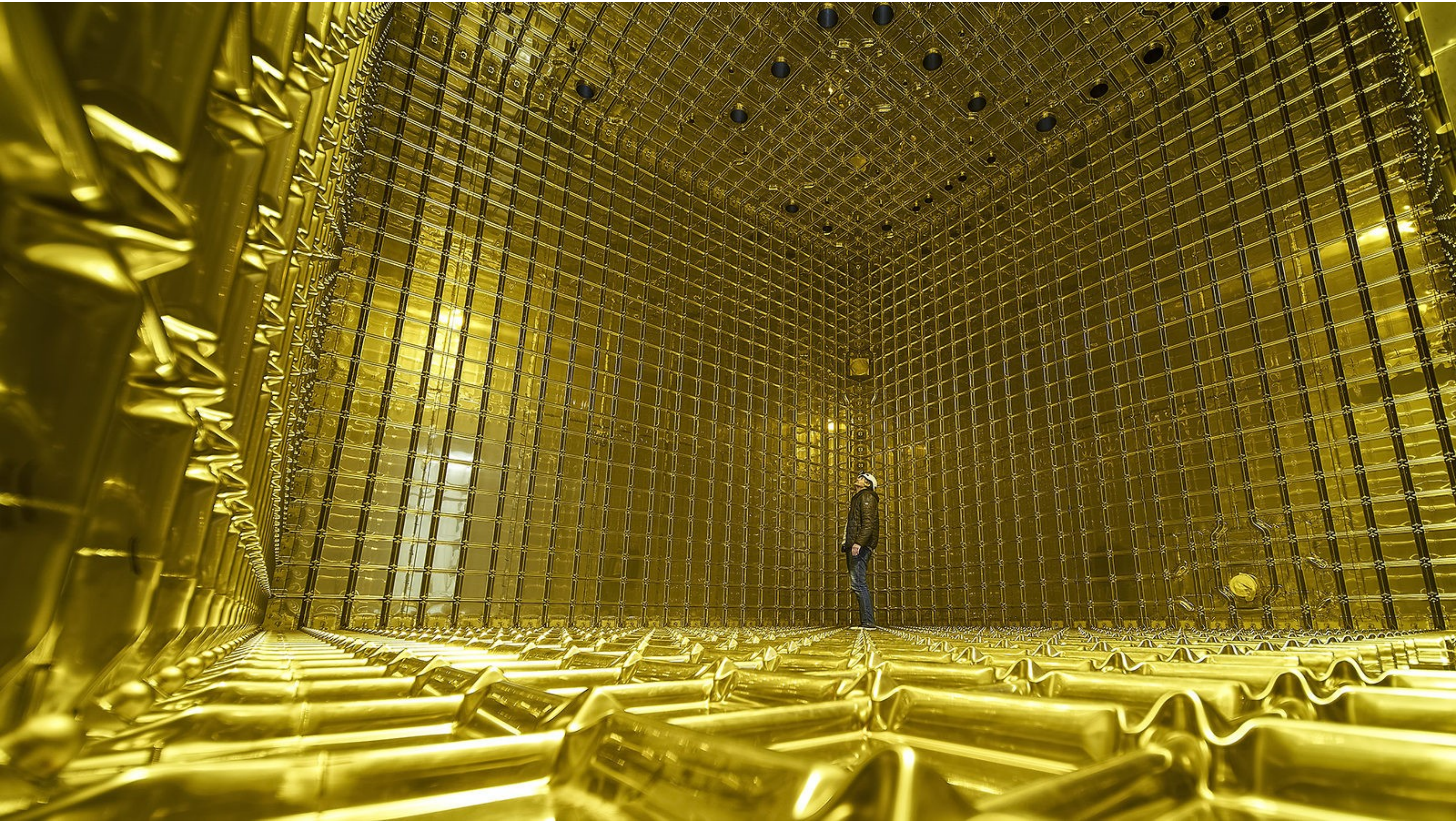


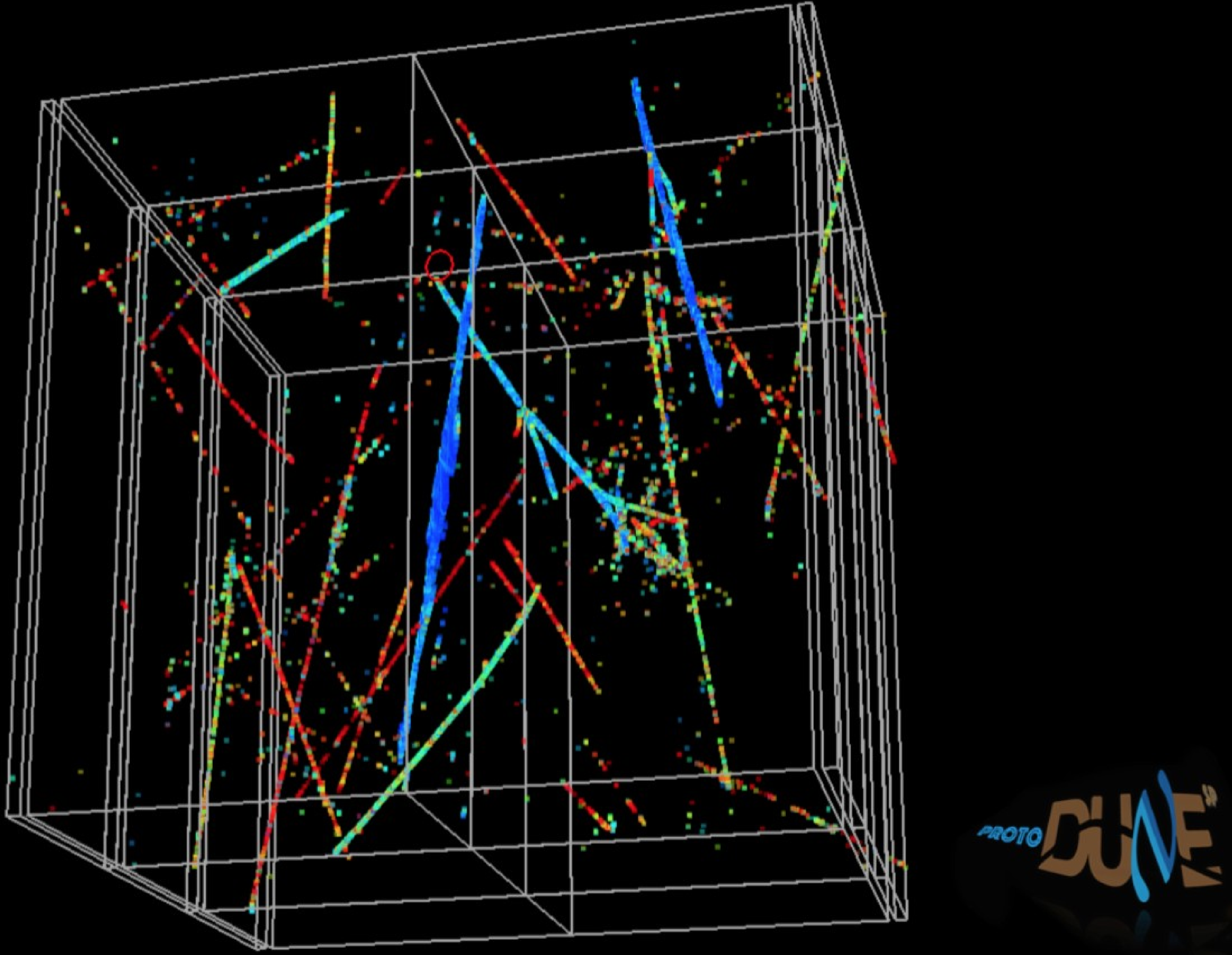
3D tracking with excellent resolution
Calorimetry from energy deposition in filler material
Filler can be gas or liquid.
Neutrino Physics looking at liquid argon TPCs

LAr event


multi-prong + 2γ
Run 825, Event 12481
Collection View
ADC
100
0
-25
Time
Wire

protoDUNE




PROTO
DUNE
SP

Summary

- Type of neutrino detectors depend on target, event rate, and interaction type and cost
- 4 “main” techniques
  - radiochemical (low threshold but no direction or timing information - sub-MeV neutrinos)
  - water cerenkov (high threshold, cheap target mass, direction and timing but only low multiplicity events - 100 MeV up to a few GeV)
  - scintillator (no threshold but no directionality unless enhanced by water cerenkov - few MeV)
  - tracking calorimeters (high energy events - full reconstruction of events - 1 GeV and up)