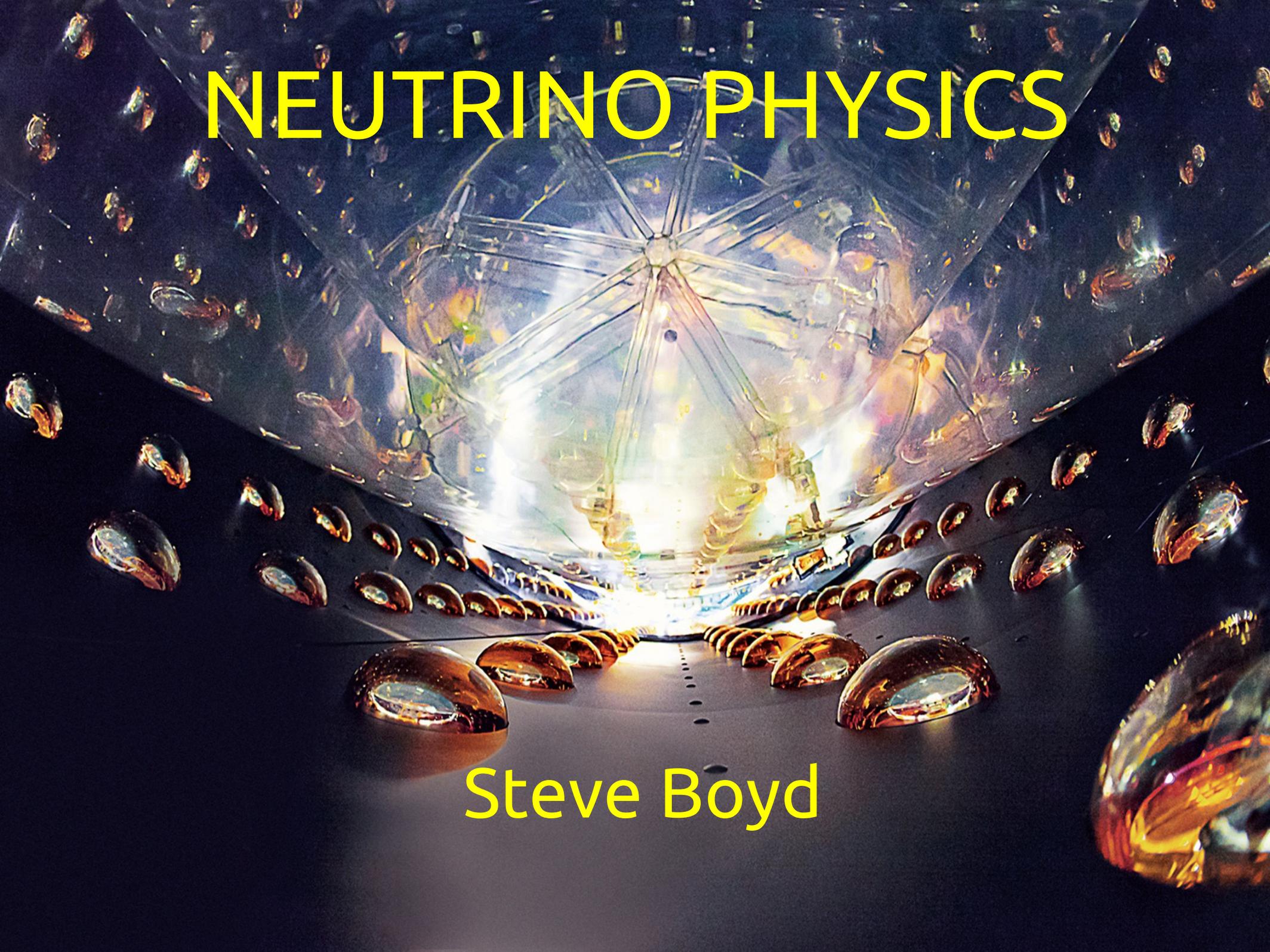


NEUTRINO PHYSICS

The image shows a large, complex detector structure, likely a neutrino detector. It features a central glowing core with a complex, multi-faceted structure. The core is surrounded by a dense array of smaller, glowing components, possibly photomultiplier tubes or scintillators, arranged in a circular pattern. The overall appearance is that of a highly sophisticated and intricate scientific instrument.

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

References

- K. Zuber, “Neutrino Physics”, IoP Publishing 2004
- **C. Giunti and C.W.Kim, “Fundamentals of Neutrino Physics and Astrophysics”, Oxford University Press, 2007.**
- V. Barger and D. Marfatia, “The Physics of Neutrinos”, Princeton University Press, 2012
- H.V. Klapdor-Kleingrothaus & K. Zuber, “Particle Astrophysics”, IoP Publishing, 1997.

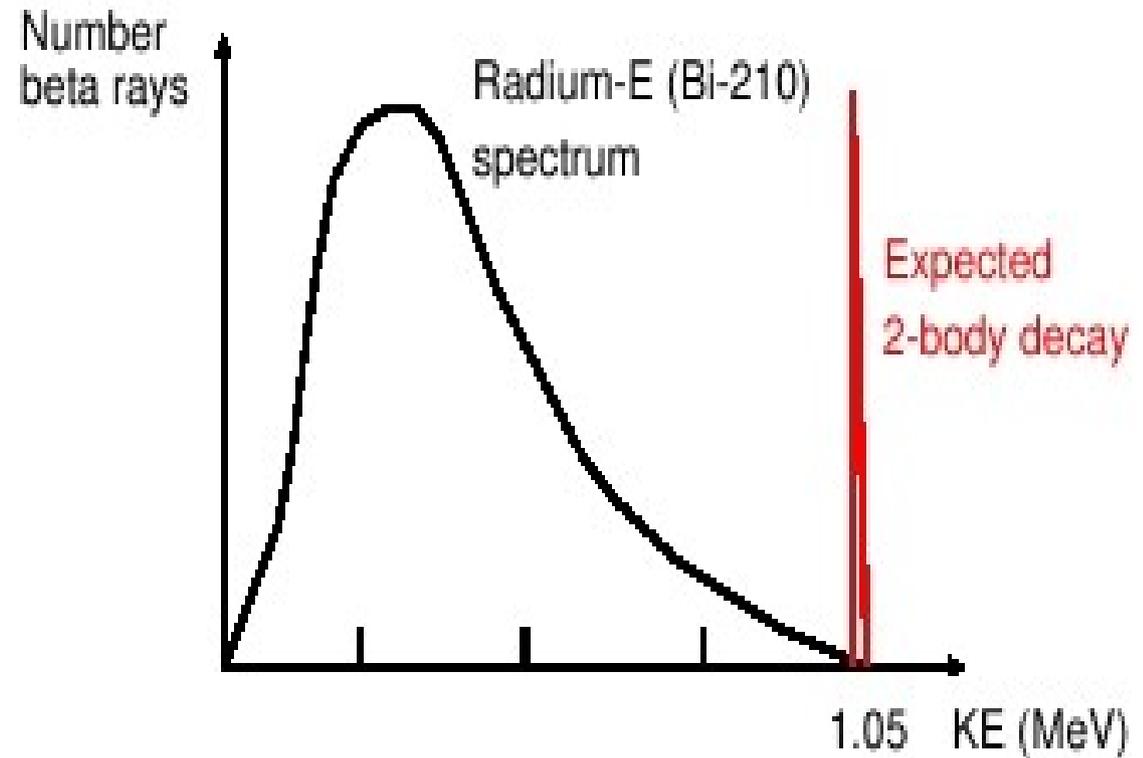
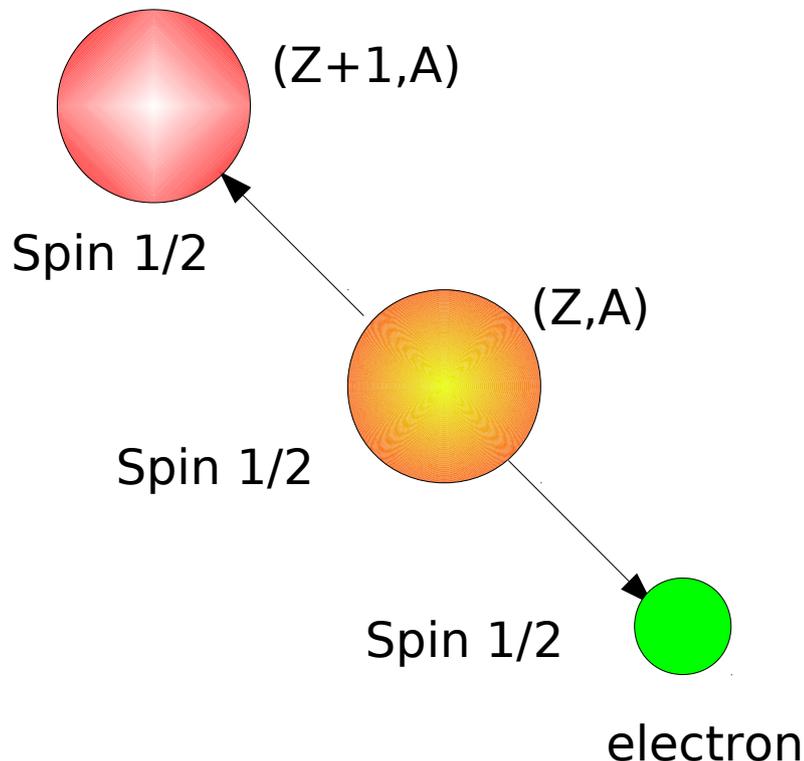
- F. Close, “Neutrino”, 2012
- R. Jayawardhana, “The Neutrino Hunters”, 2014
- C. Sutton, “Spaceship Neutrino”, 2010

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 study of atomic physics is in trouble



$$\text{Spin } \frac{1}{2} \neq \text{spin } \frac{1}{2} + \text{spin } \frac{1}{2}$$

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



“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,

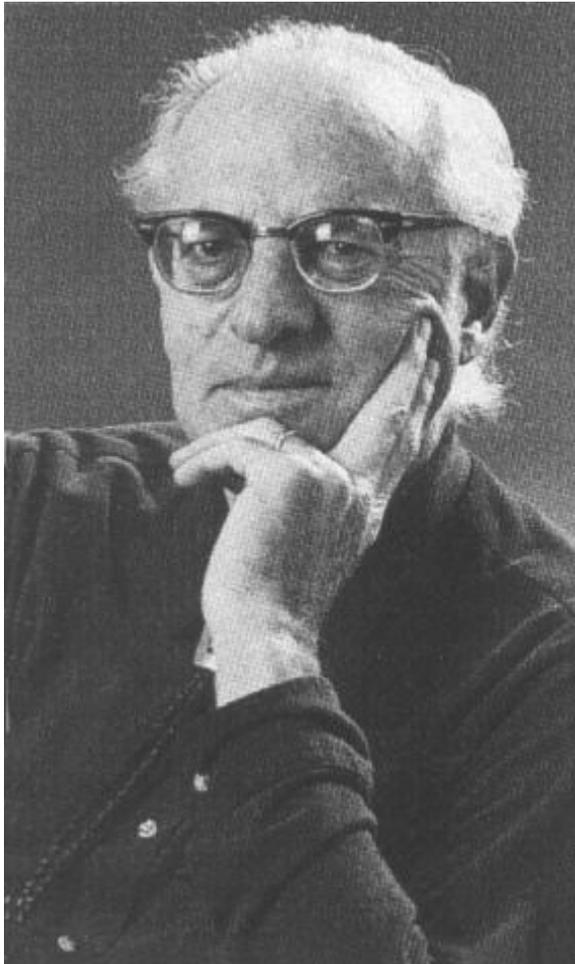
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ${}^6\text{Li}$ nuclei and the continuous beta spectrum, *I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the 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 Tübingen personally, because I am indispensable here due to a ball which will take place in Zurich during the night from December 6 to 7...*

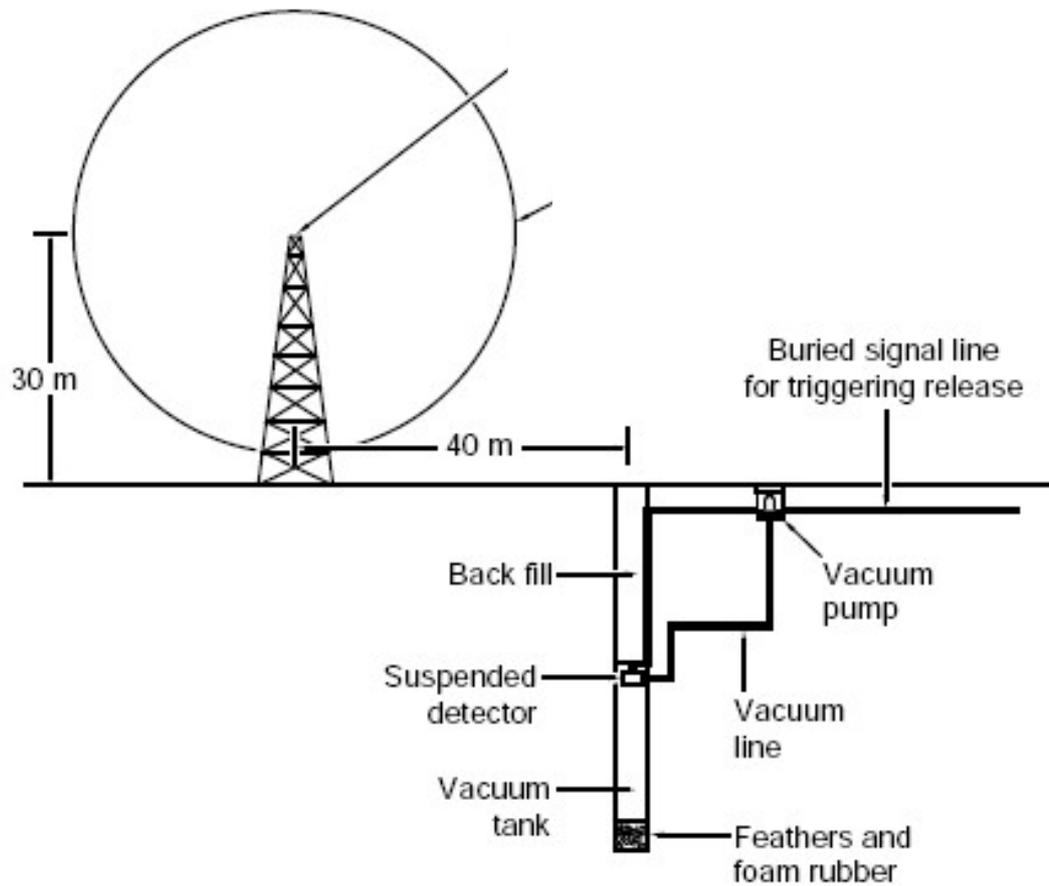
Your humble servant,
W. Pauli

Detection of the Neutrino

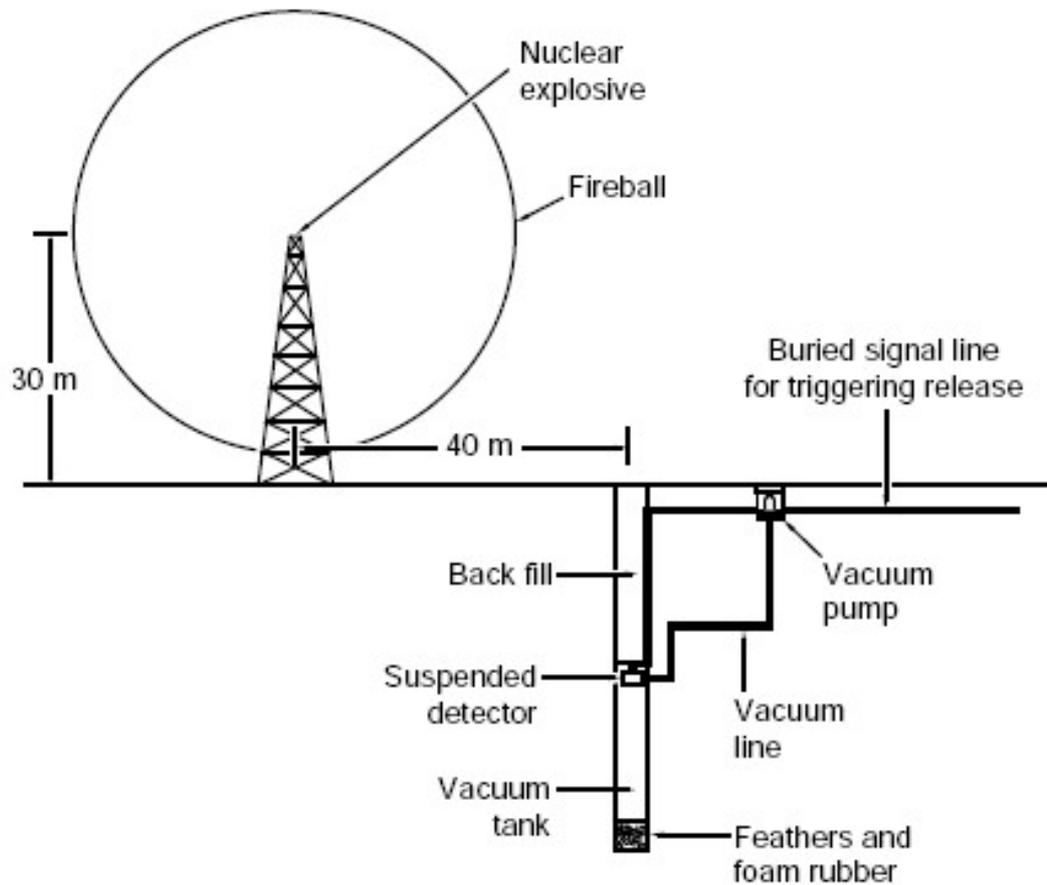
1950 – Reines and Cowan set out to detect ν



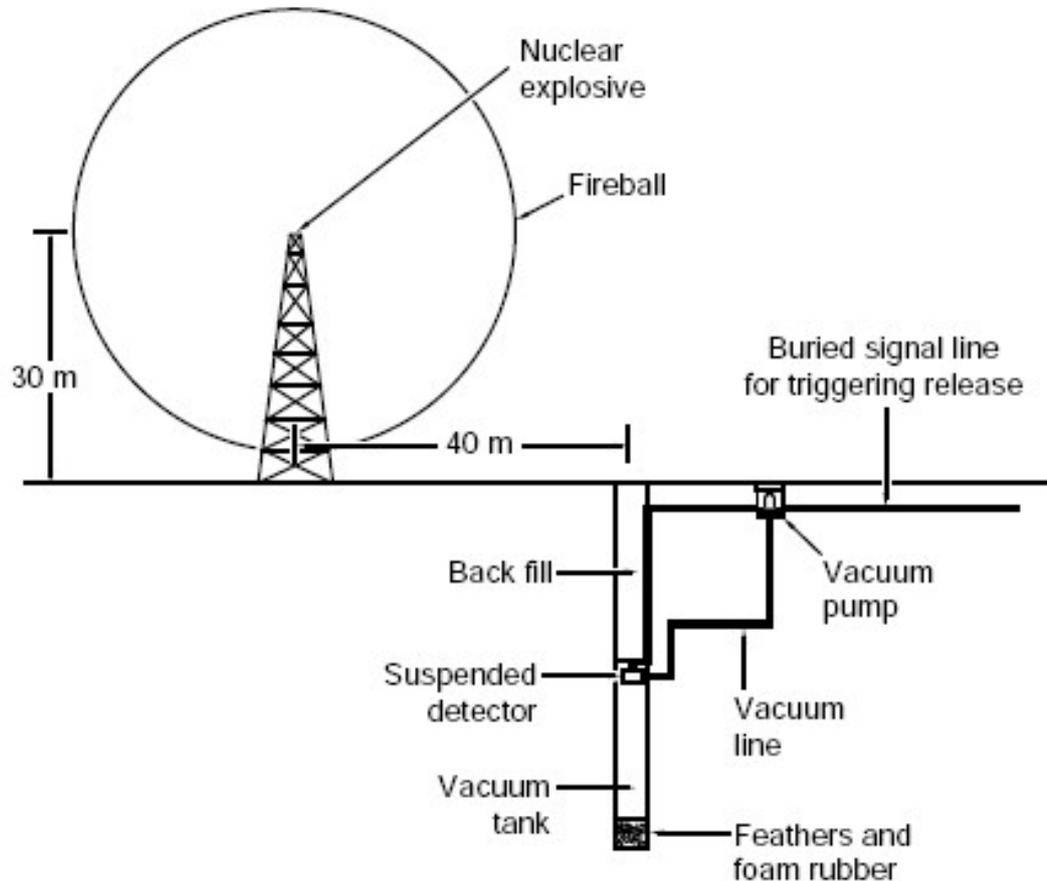
1951



1951



1951

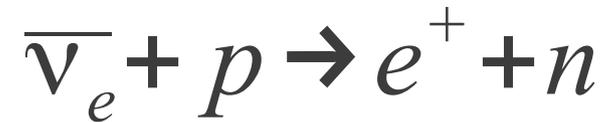


- I. Explode bomb
- II. At same time let detector fall in vacuum tank
- III. Detect neutrinos
- IV. Collect Nobel prize

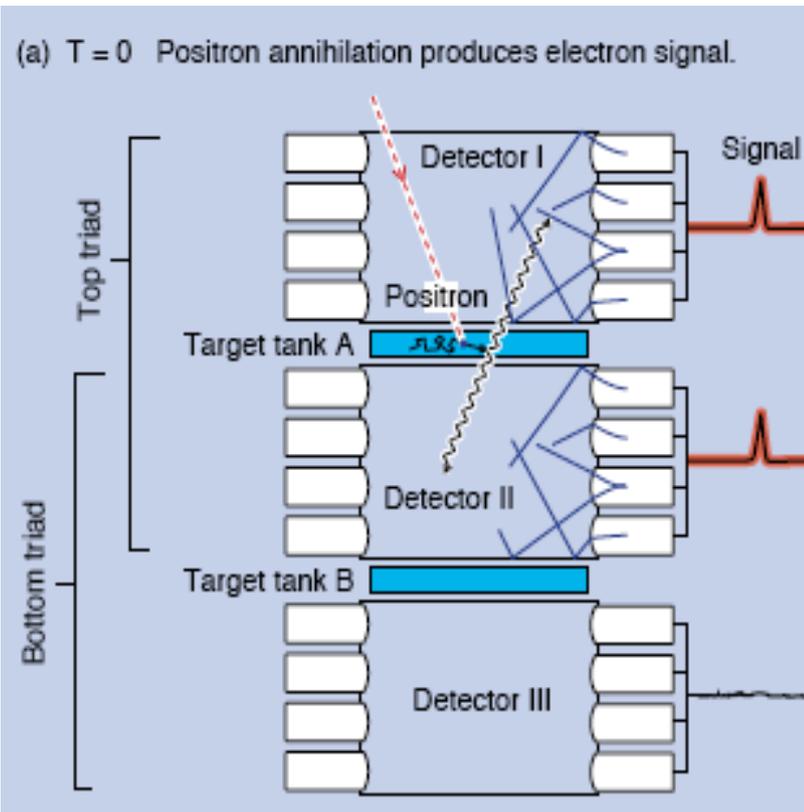
OK - but repeatability is a bit of a problem

Idea Number 2 - 1956

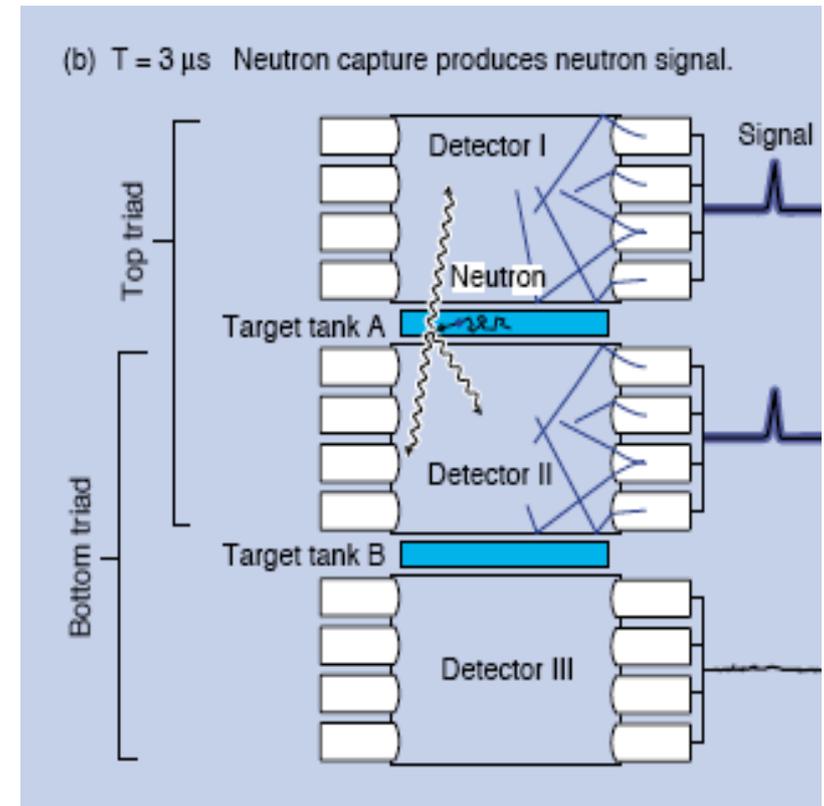
A nuclear reactor is the next best thing



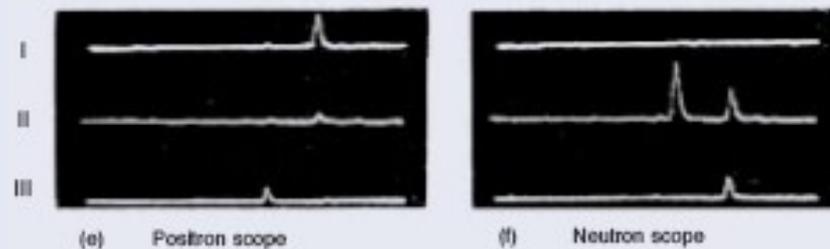
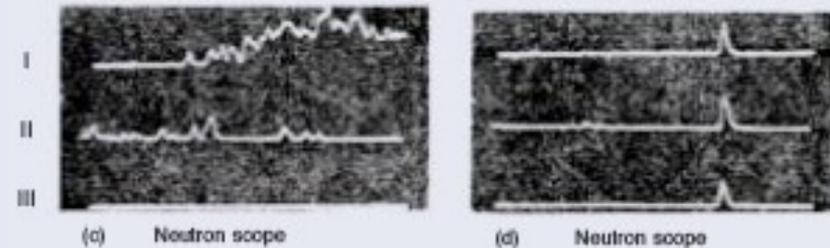
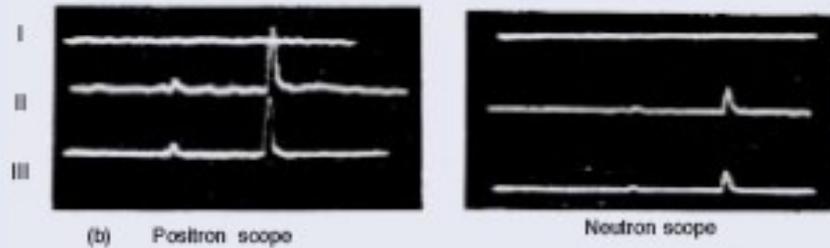
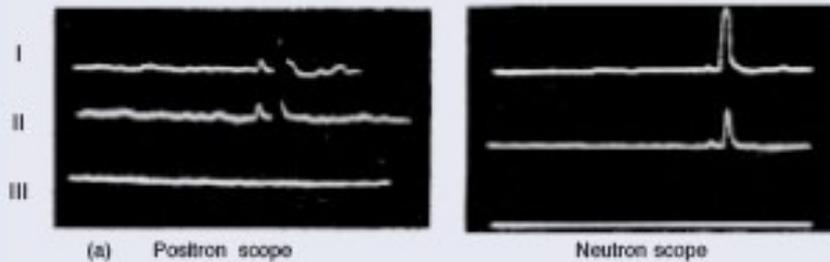
Positron Annihilation



Neutron Capture



1959 – Savannah River Reactor



$$\text{ON} - \text{OFF} = 2.88 \pm 0.22 \text{ hr}^{-1}$$

$$\sigma = (11 \pm 2.6) \times 10^{-44} \text{ cm}^2$$

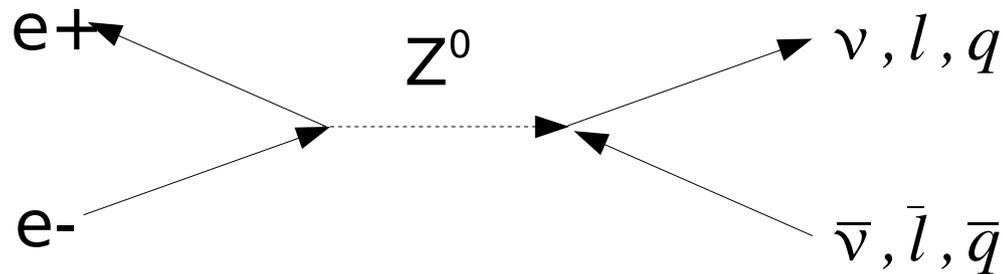
$$\sigma (\text{Pred}) = (5 \pm 1) \times 10^{-44} \text{ cm}^2$$

The State of Play pre-2000

Flavour	Mass (GeV/c ²)	Electric Charge
ν_e	$< 1 \times 10^{-8}$	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?

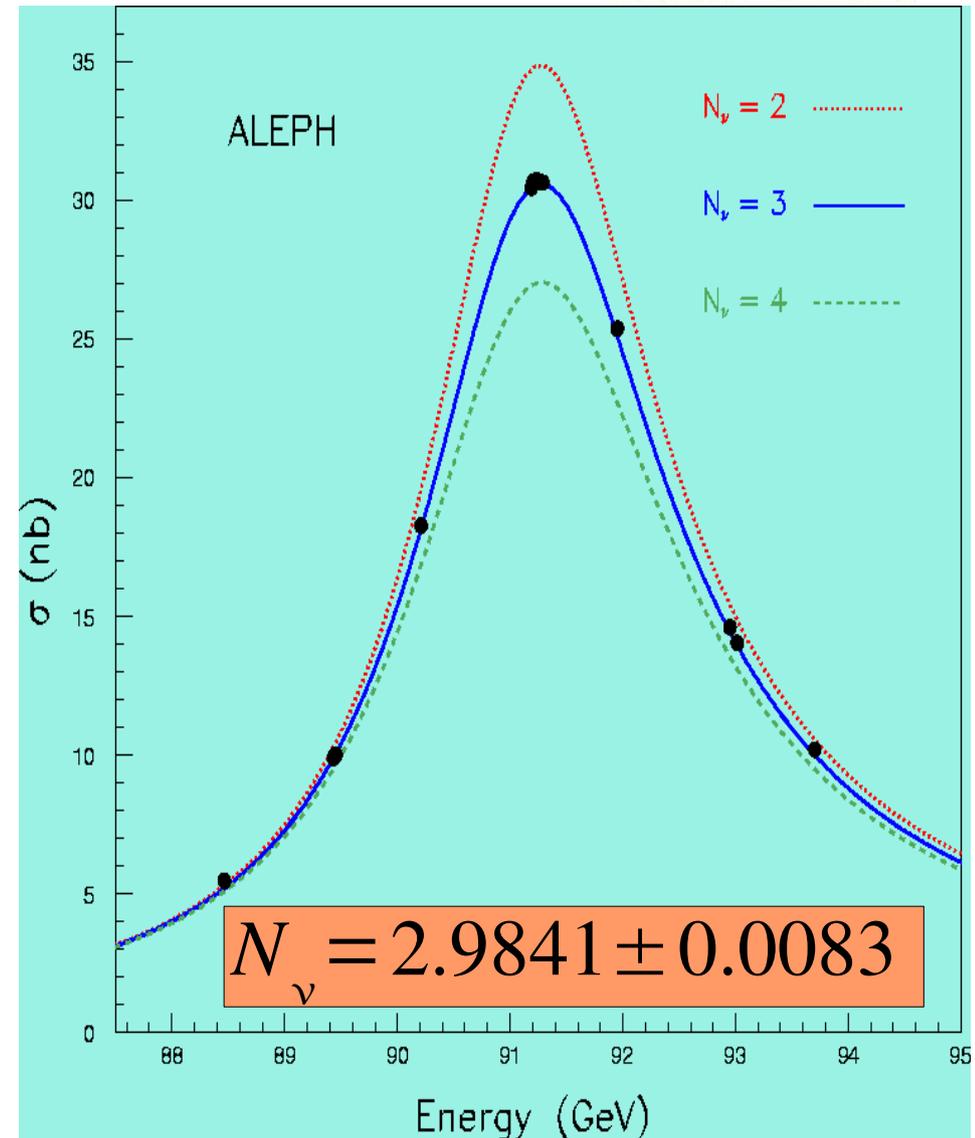
The Number of light neutrinos



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

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

NB Mass of $\nu < m_Z/2 \sim 46$ GeV



The Tau Neutrino

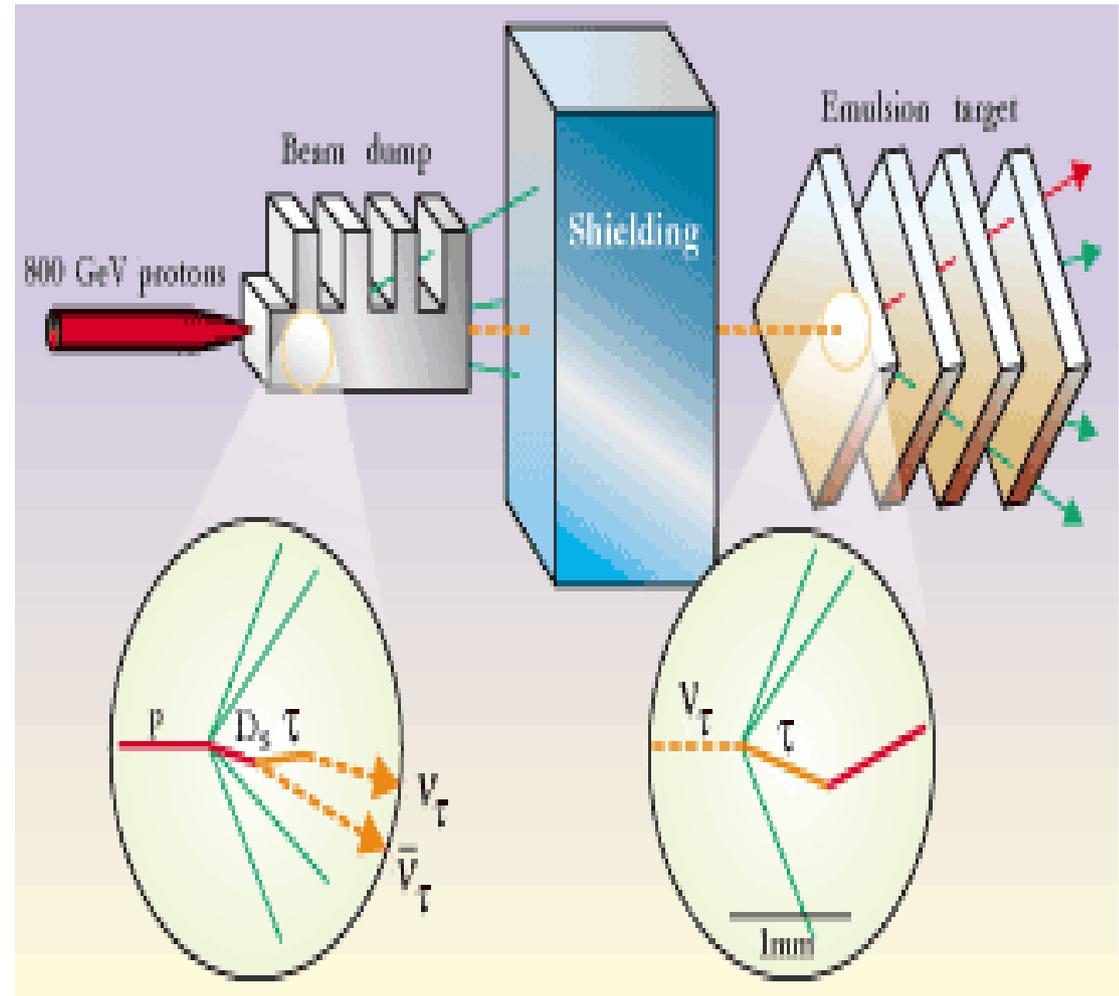
ν_τ was finally discovered by DONUT in 2000.

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

$$D_s \rightarrow \tau + \nu_\tau$$

$$\nu_\tau + N \rightarrow \tau + X$$

$$\tau \rightarrow \mu + \nu_\tau + \bar{\nu}_\mu$$



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 its 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?

Neutrino Properties

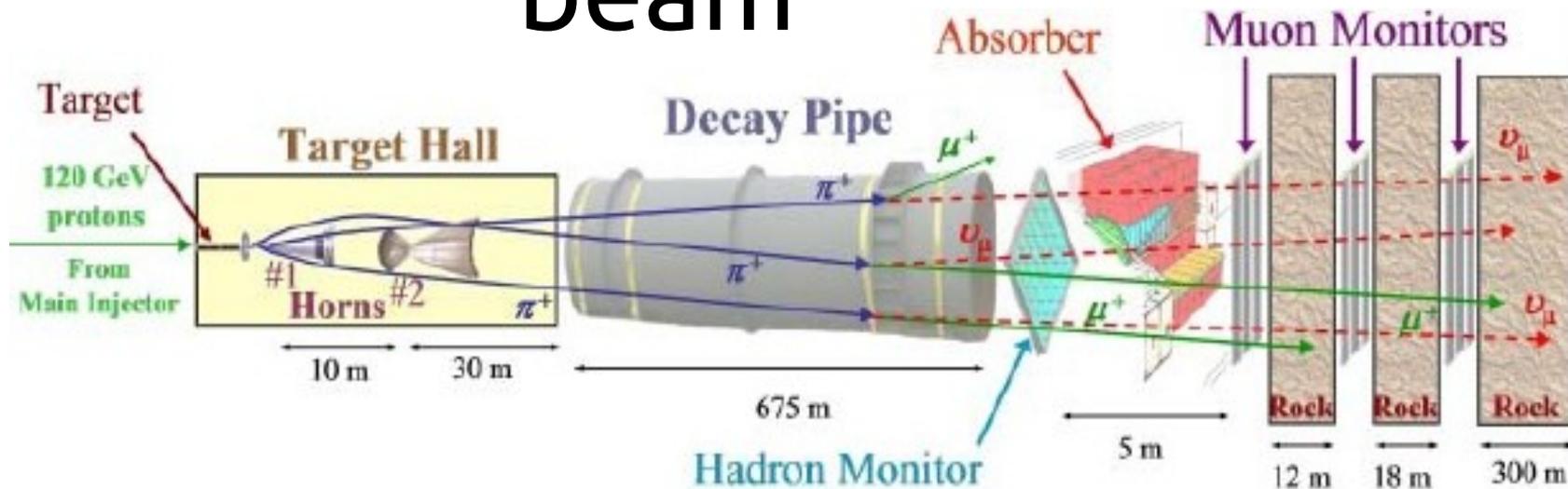
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- Are they stable?

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 p/K $\mu, p, K, \nu_e, \nu_\mu$ 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 p/K in p-target interactions
- Total flux uncertainties $\sim 20\%$

Proton Beam

- Number of pions \propto 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
<i>LBNF (Fermilab)**</i>	<i>60 / 120</i>	<i>1.90E+21</i>	<i>1.2</i>	<i>0.5 – 10.0</i>
<i>J-PARC Upgrade**</i>	<i>30</i>	<i>1.60E+22</i>	<i>1.5</i>	<i>0.6</i>

**Design parameters – beams still under development

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)

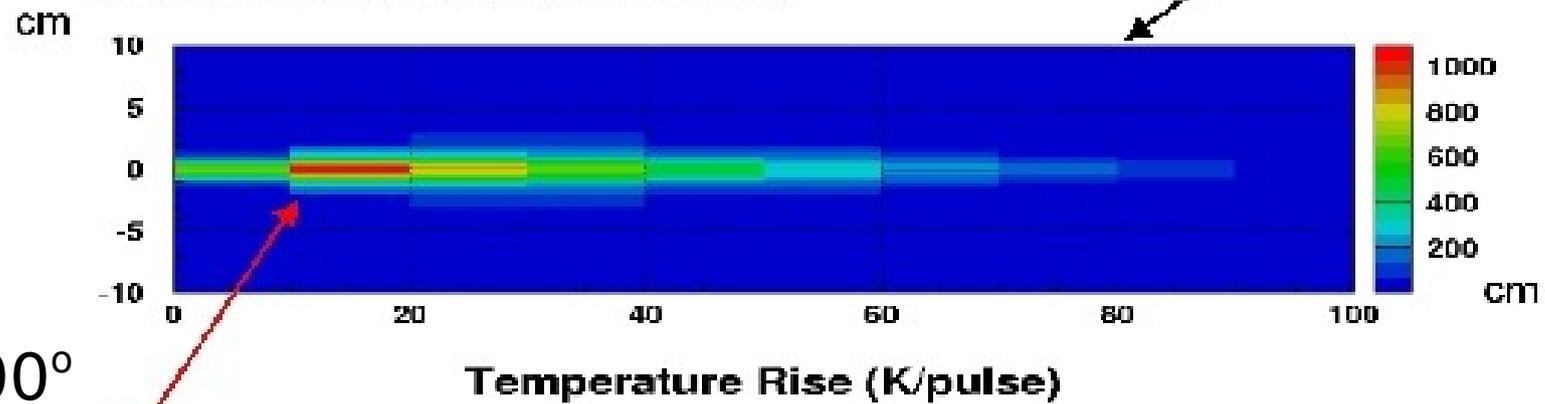
Targetry

3.3E14 ppp w/ 5 μ s pulse

When this beam hits an iron block,

radiation
dose rate

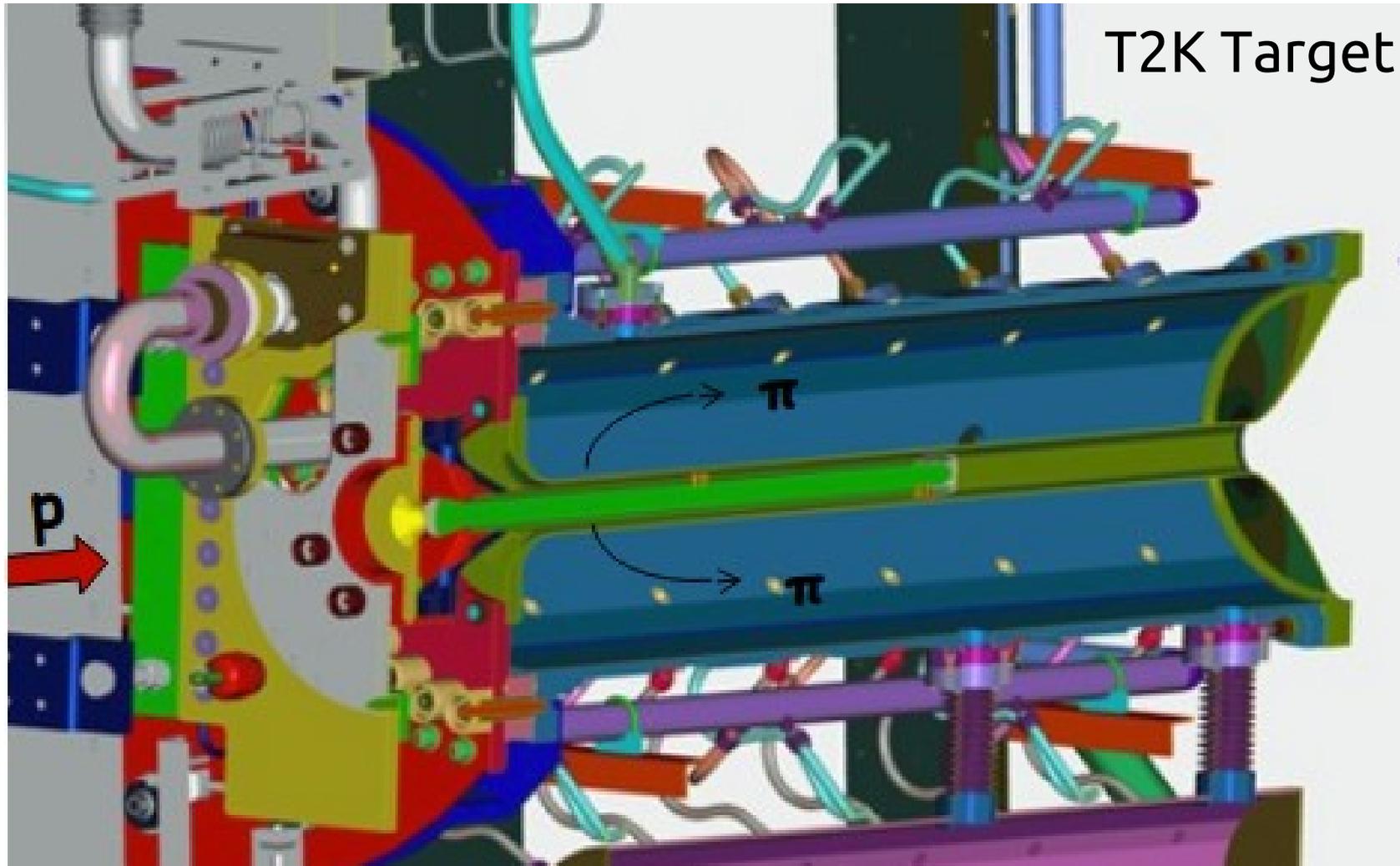
> 1000Sv/h



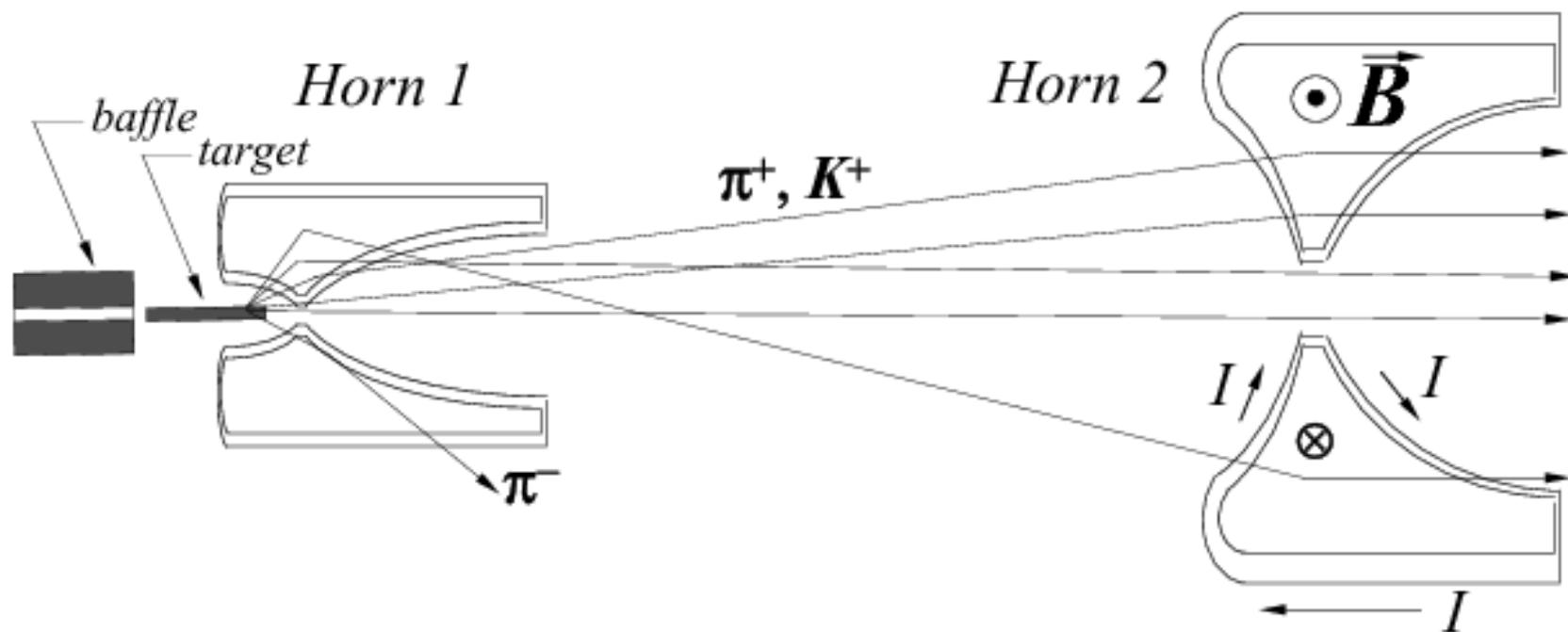
1100°



Target Infrastructure



Basics of Horn Focussing

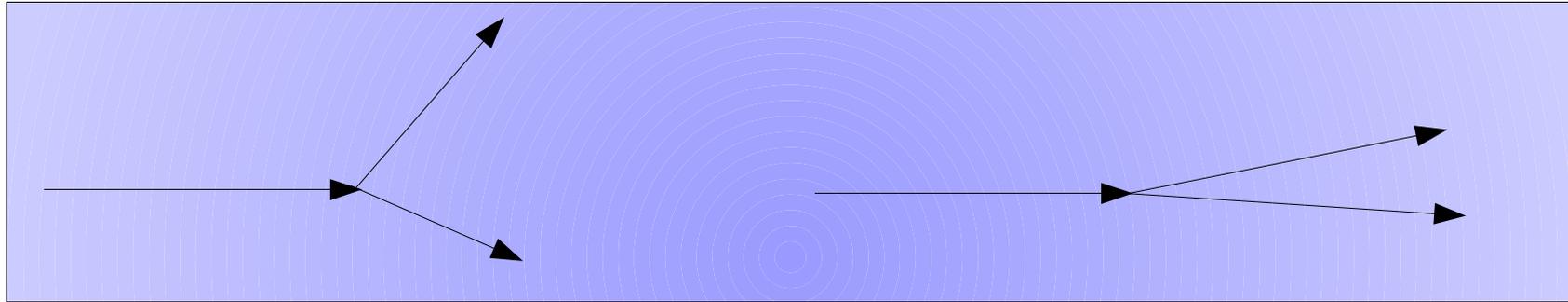


To give a 200 MeV transverse momentum kick to a pion requires a pulsed current of about 180 kA

Magnetic Horns



Decay Tunnel



Low Energy decays

High Energy decays

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

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

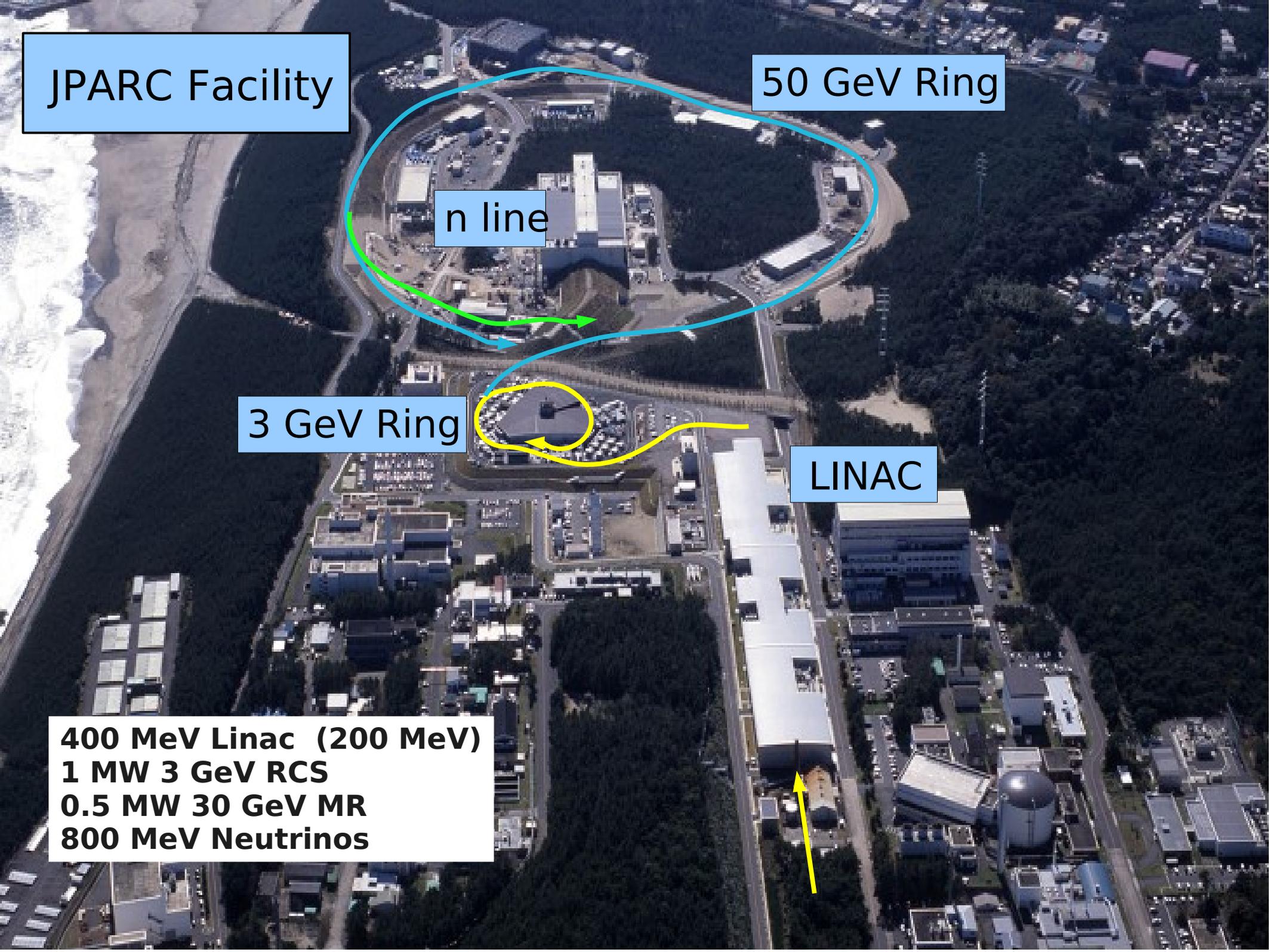
50 GeV Ring

n line

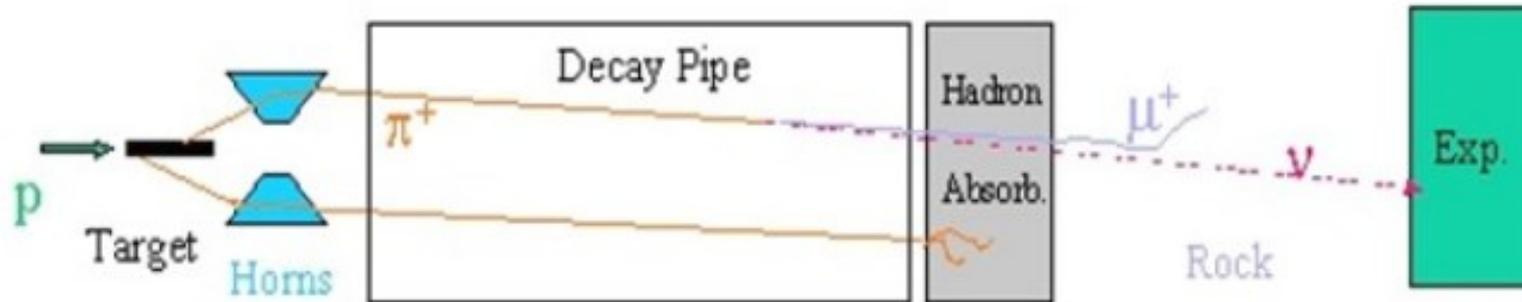
3 GeV Ring

LINAC

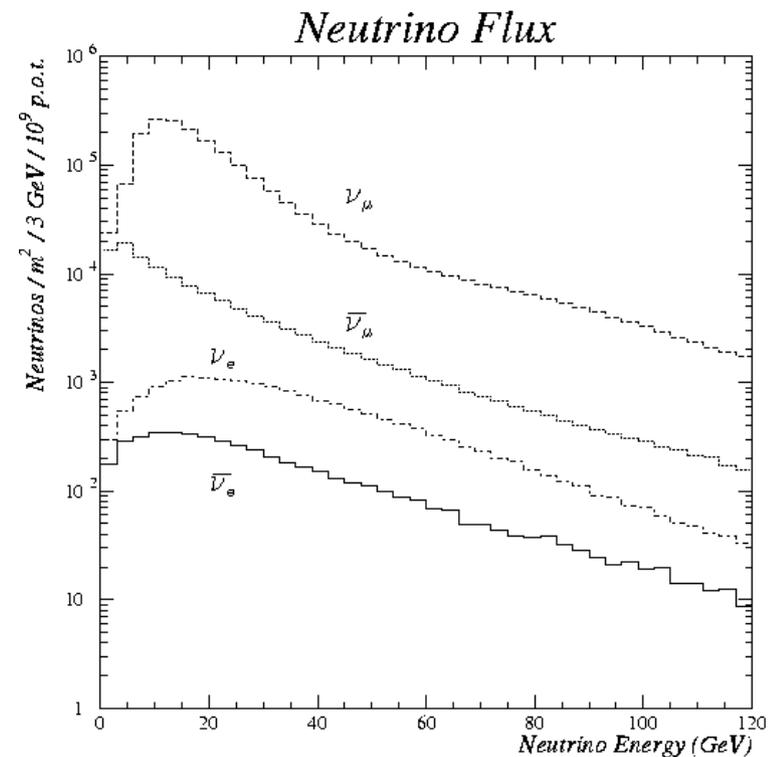
400 MeV Linac (200 MeV)
1 MW 3 GeV RCS
0.5 MW 30 GeV MR
800 MeV Neutrinos



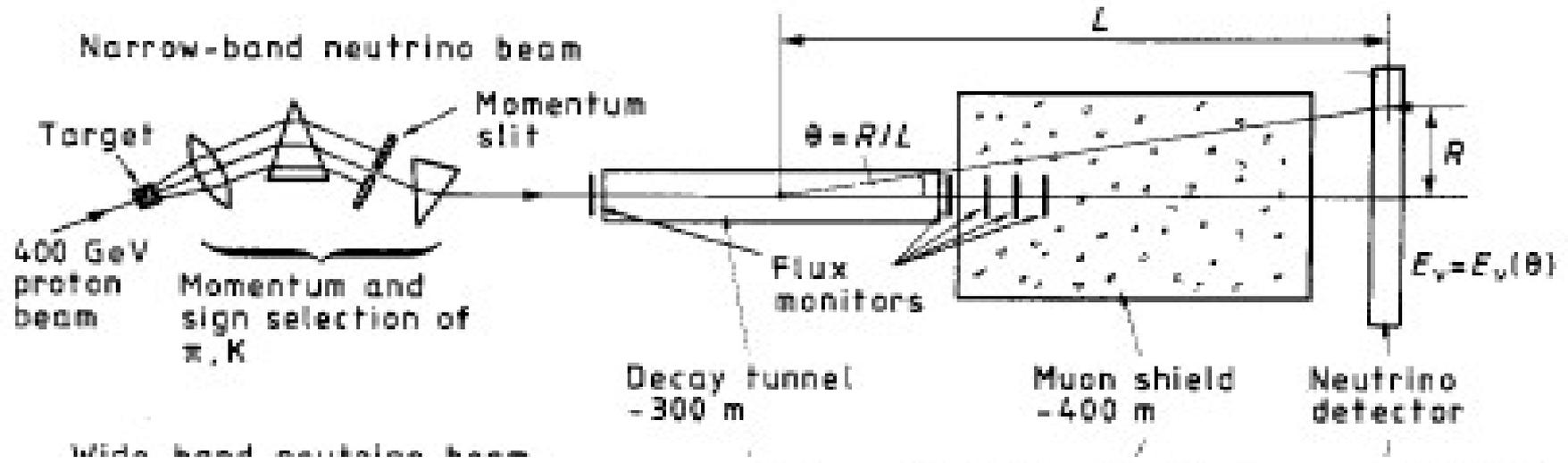
Wide band beams



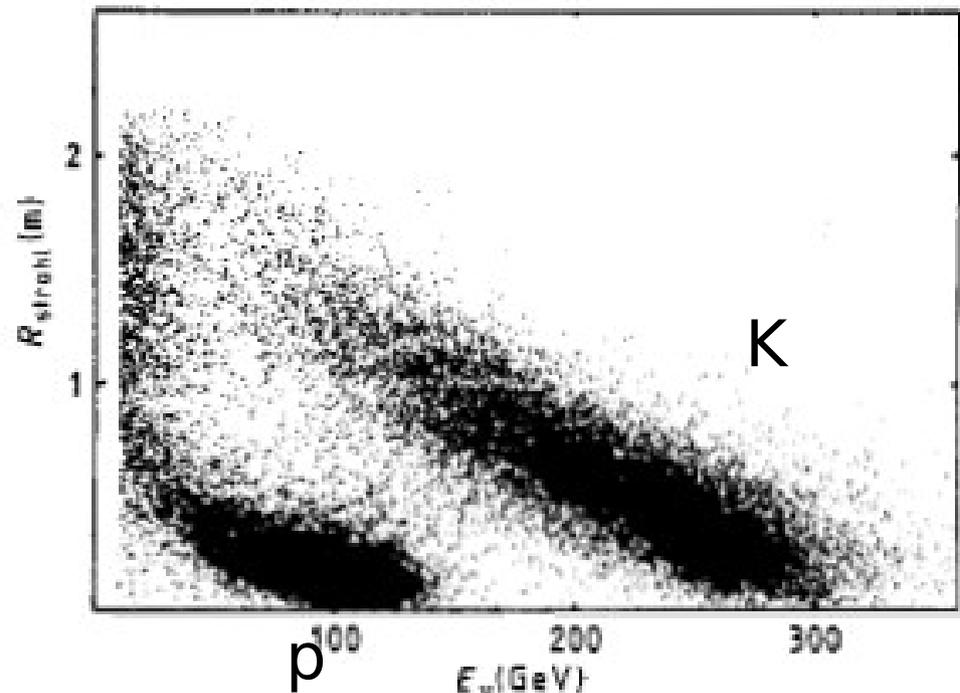
- Large flux of neutrinos.
- Wide range of energies.
- Complex mix of flavours.
- Hard to predict (and measure) neutrino flux.
- Spectrum is a function of radius and decay point



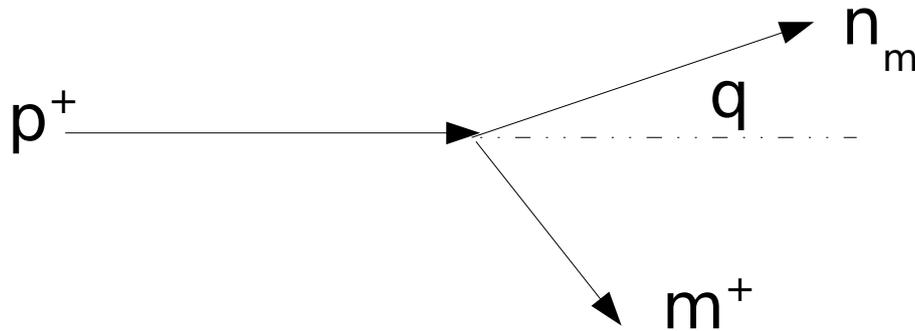
Narrow Band Beams



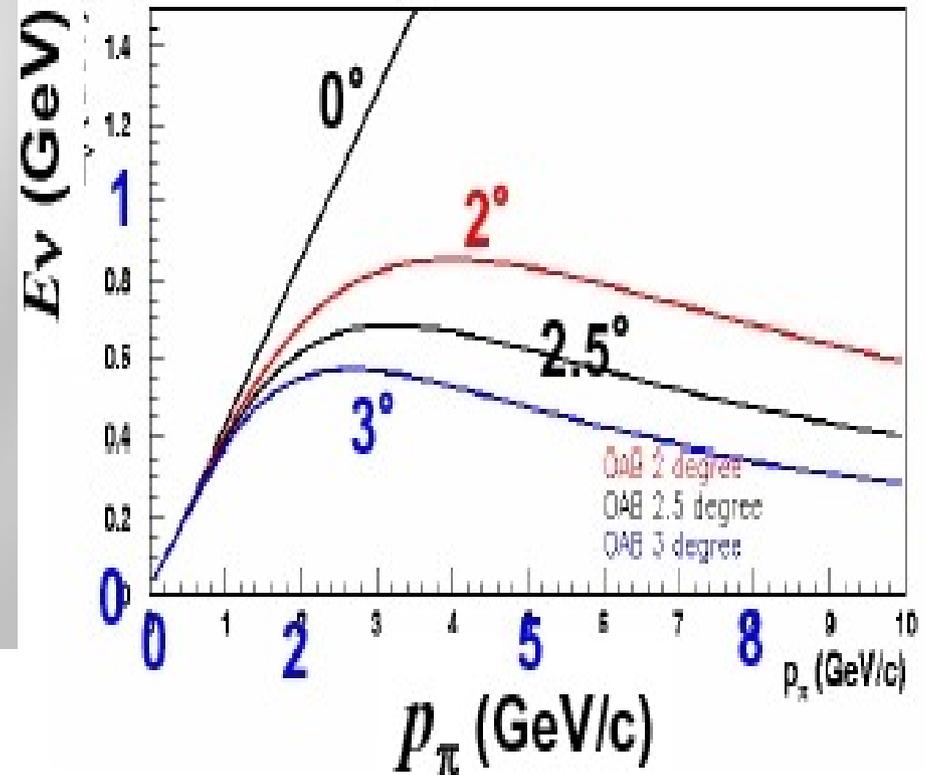
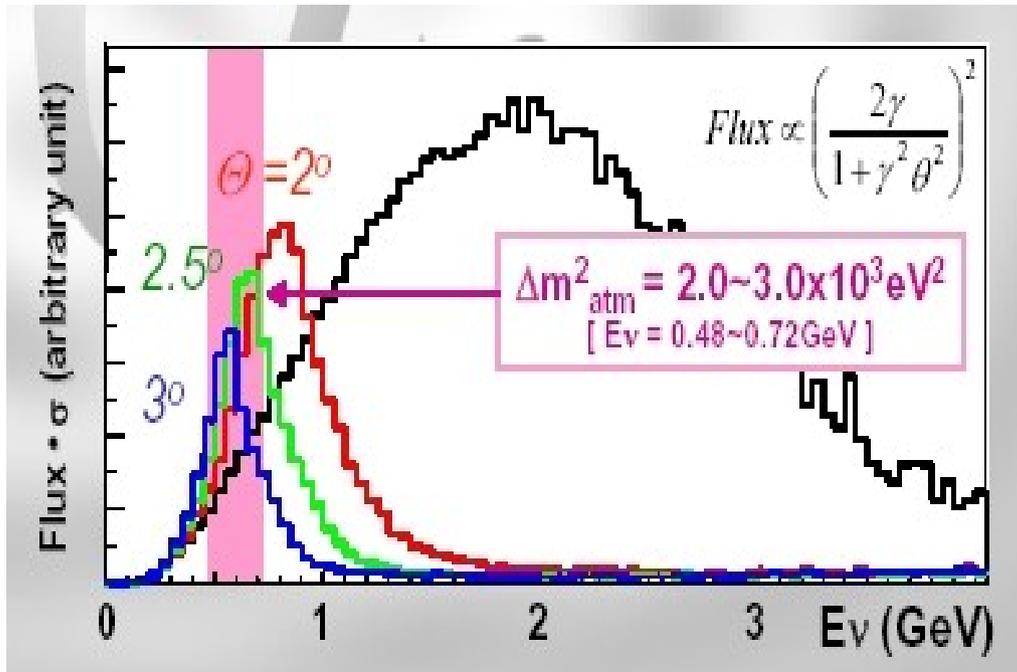
- Flat flux (easy to predict)
- Beam can be tuned to different energies
- flux is 100 times lower than WBB



“New” idea : Off-axis beams



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



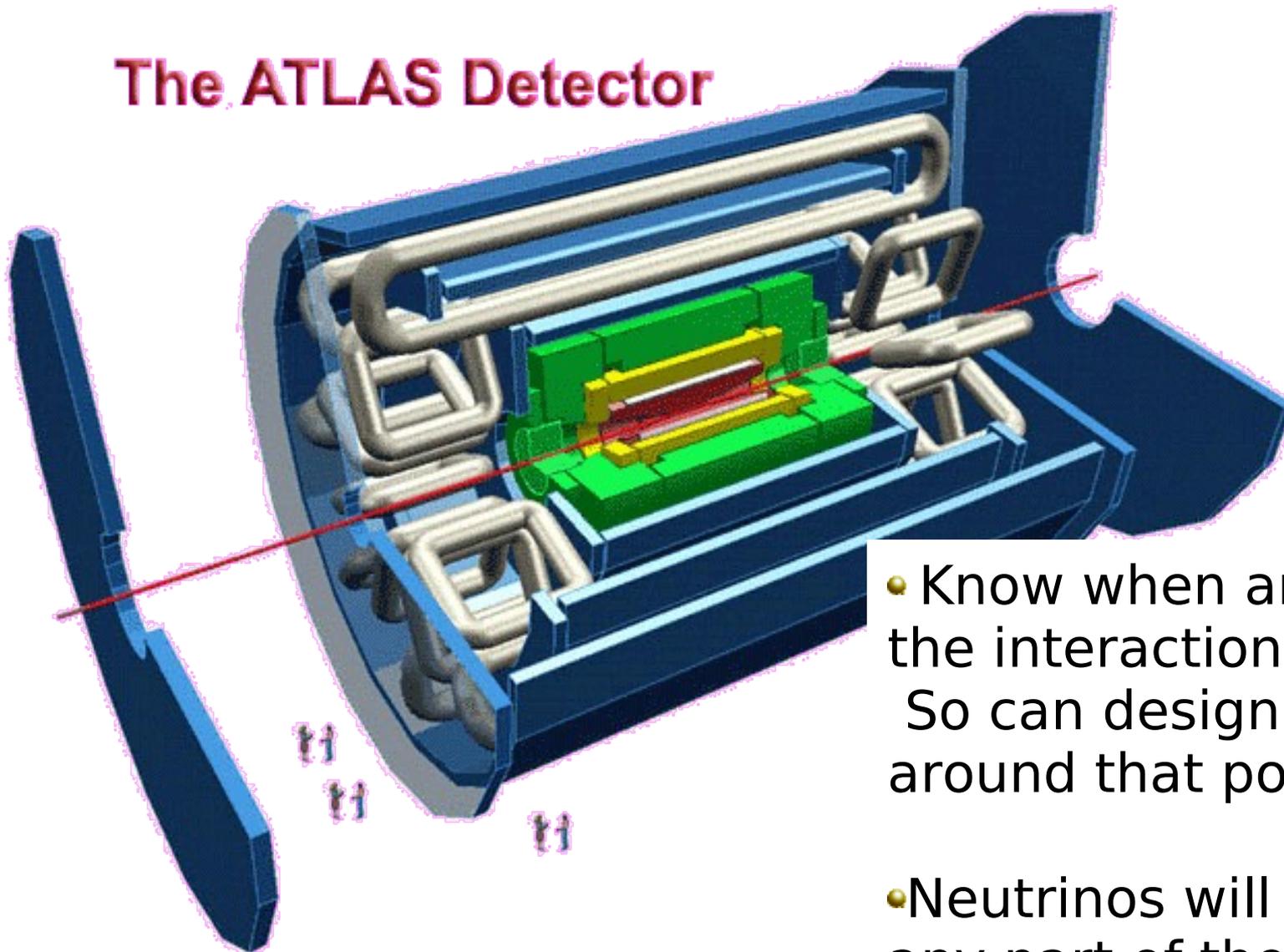
Neutrino Detectors

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 ca\$h do you have?

Usual collider detector

The ATLAS 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_2O or D_2O) 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

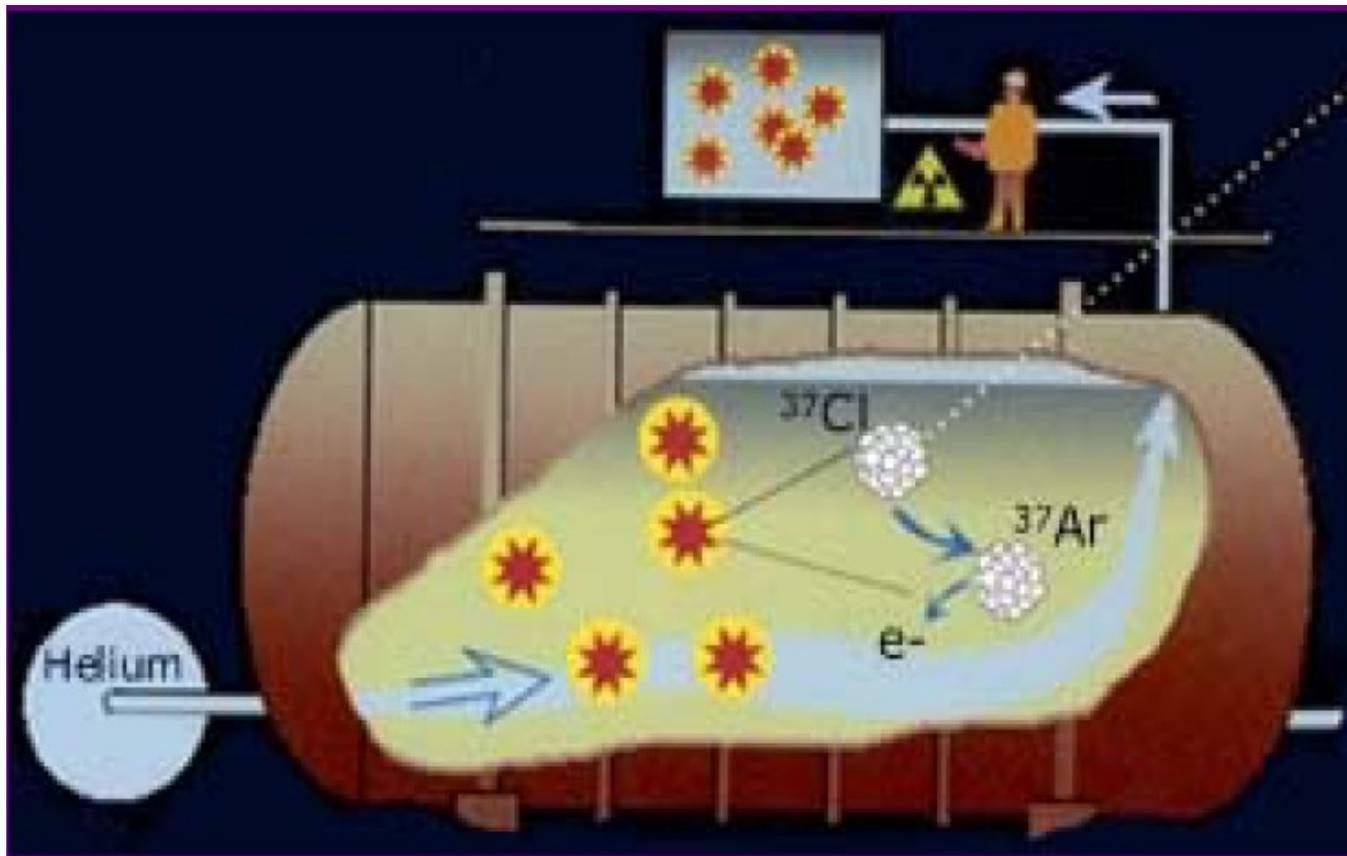


The isotopes Ar or Ge are radioactive. In this type of experiment the isotopes are chemically extracted and counted using their decay

Disadvantage is that there is no information on interaction time or neutrino direction, and only really generates “large” count 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 Ccl_4
Ran from 1968
Still running!

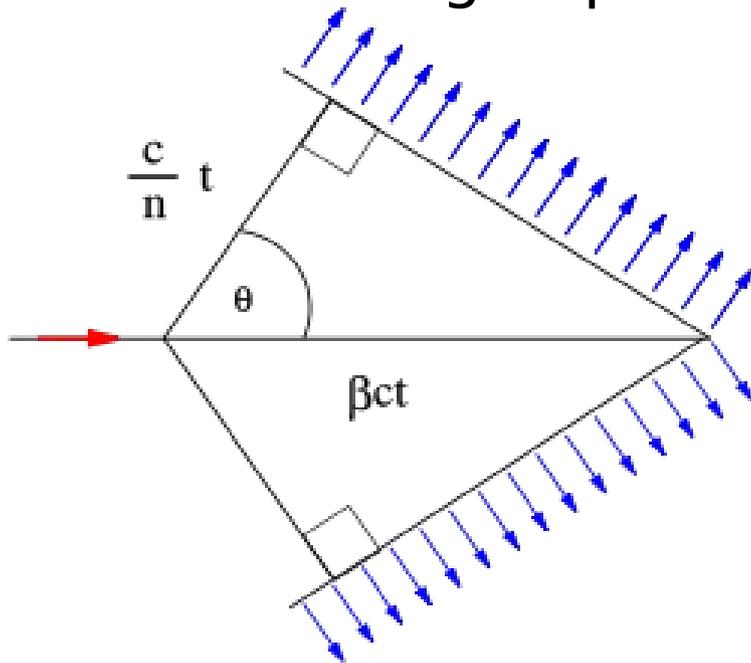
Individual argon atoms are captured and counted.

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.



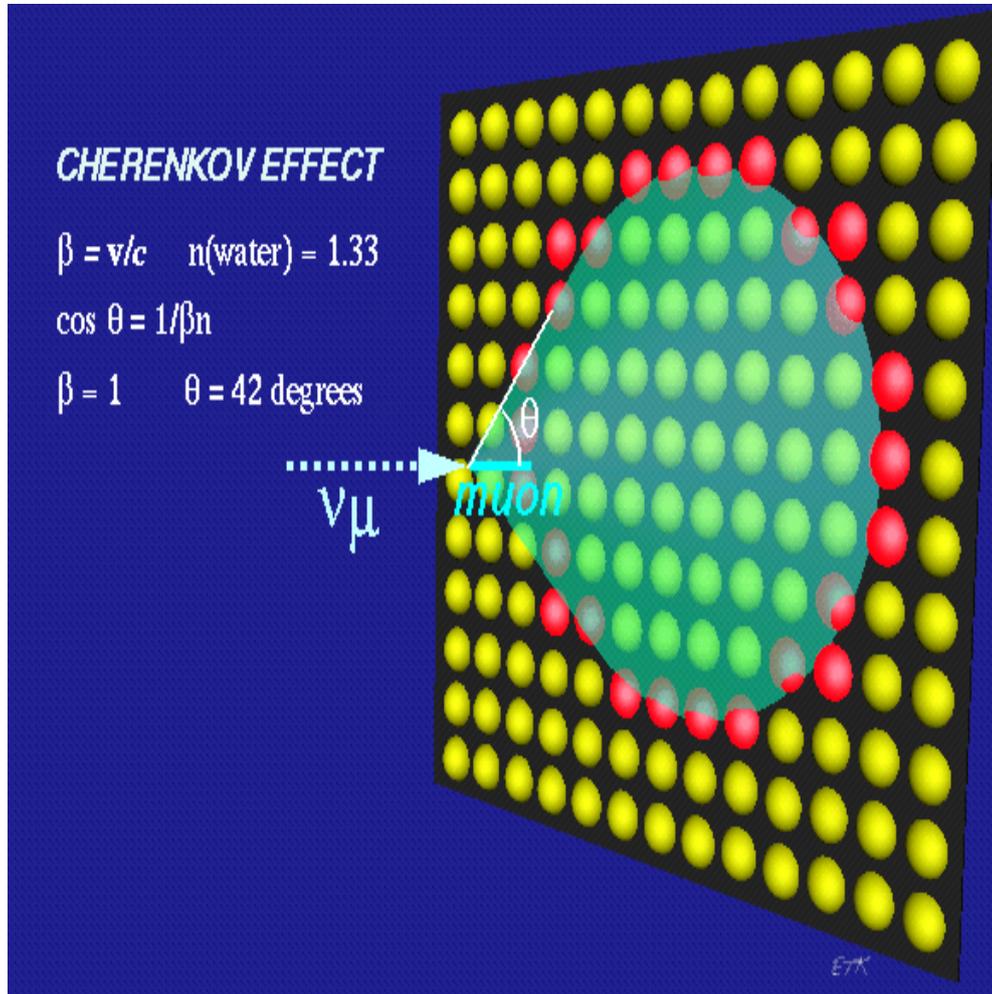
If a charged particle moves through a material with $b > 1/n$ it produces an EM shockwave at a particular angle.

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

The shockwave can be detected and used to measure the particle direction and vertex.

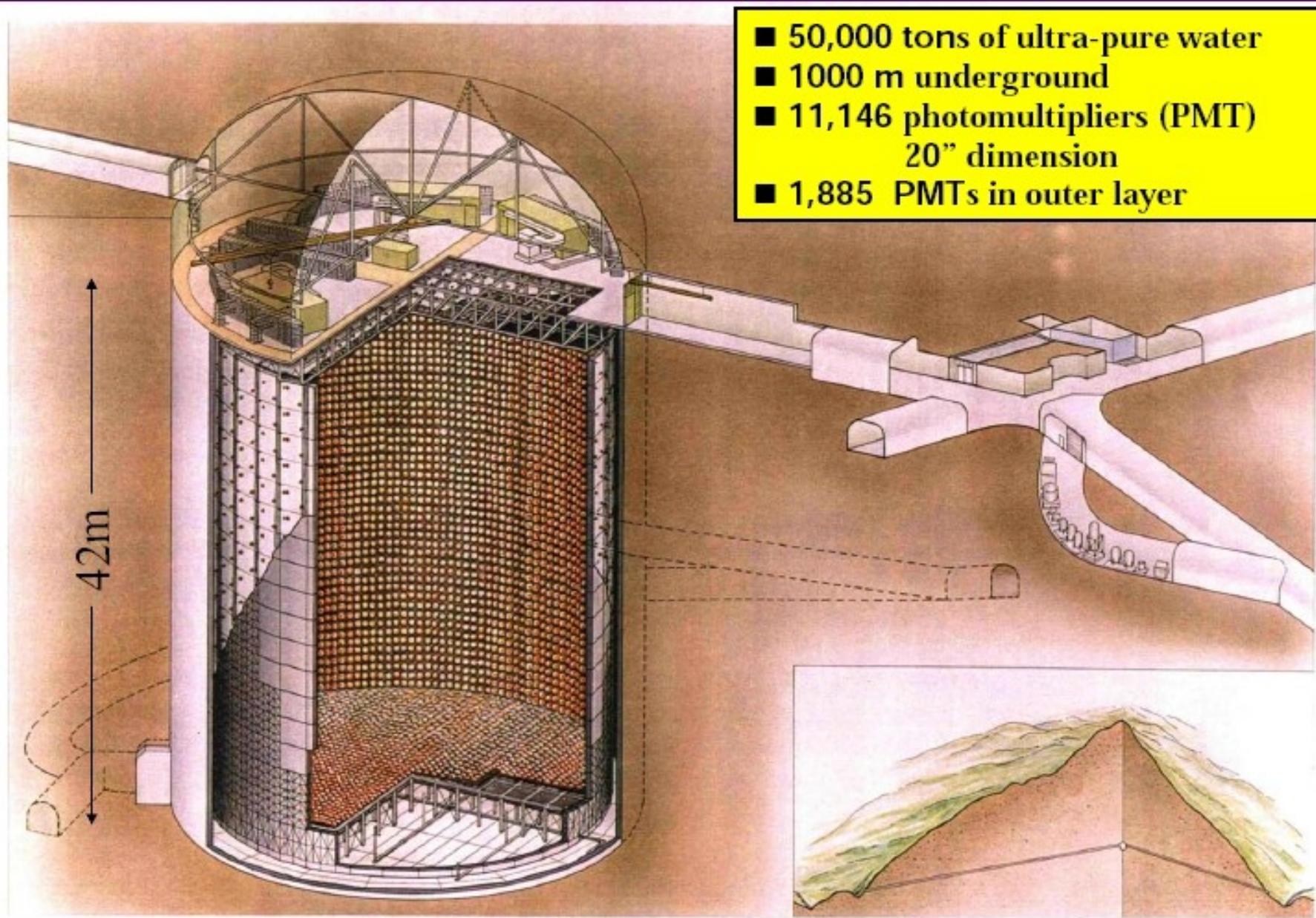
Particles below threshold and neutral particles are not detected

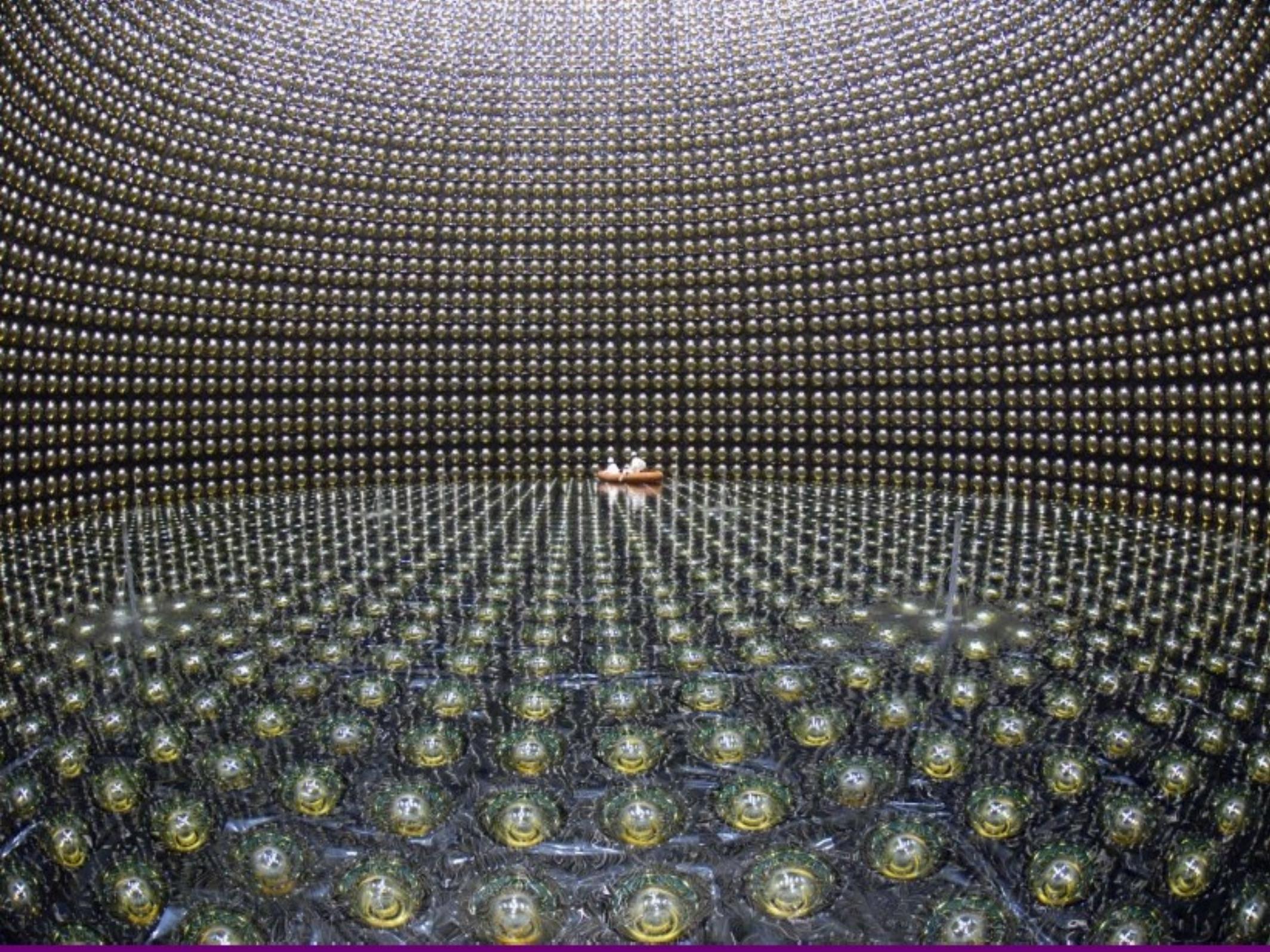
Principle of operation



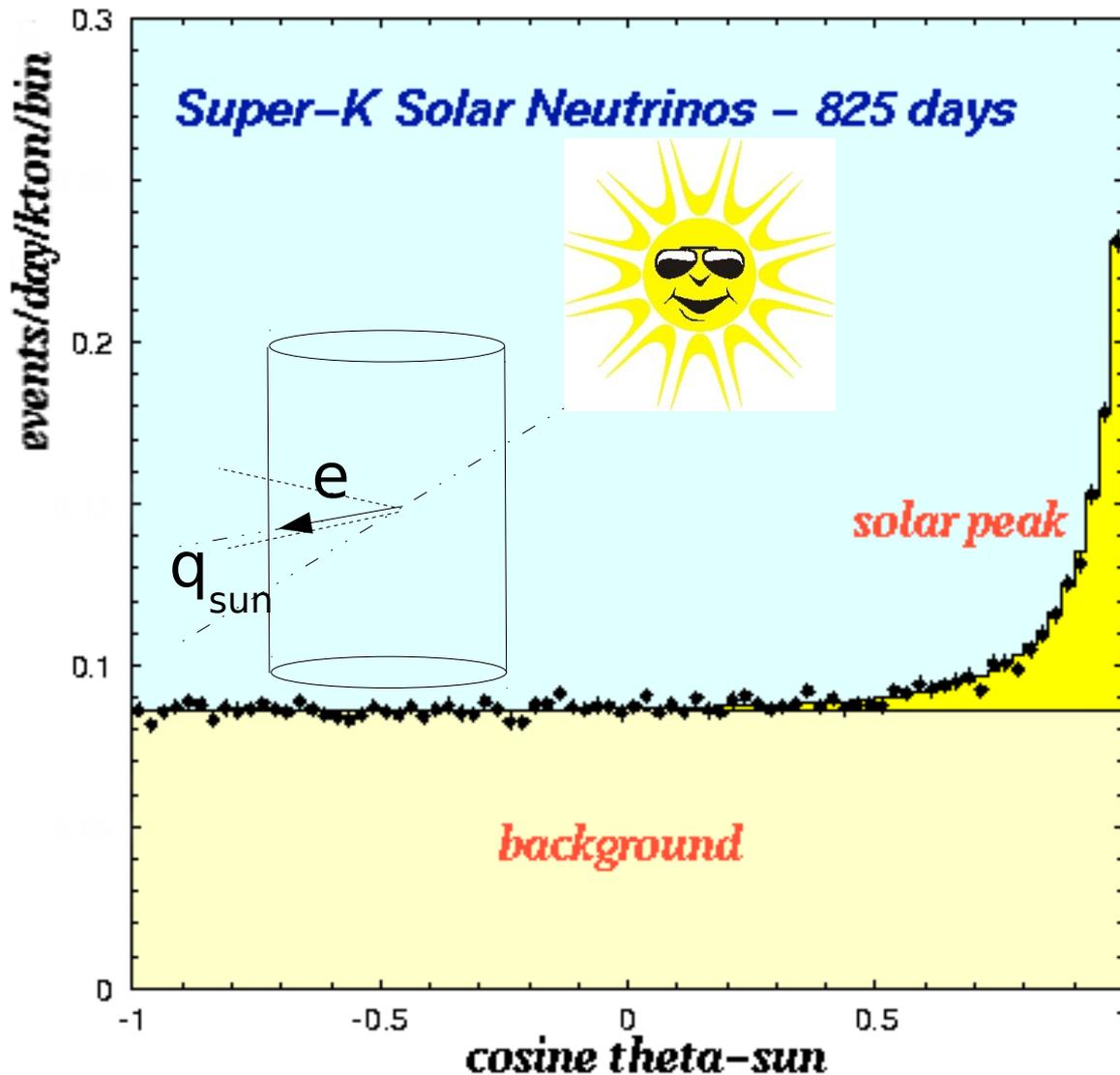
- Cerenkov light detected as a ring or circle by PMTs
- Vertex from timing
- Direction from cone
- Energy from summed light
- No neutrals or charged particles under Cerenkov threshold
- Low multiplicity events

Super-Kamiokande



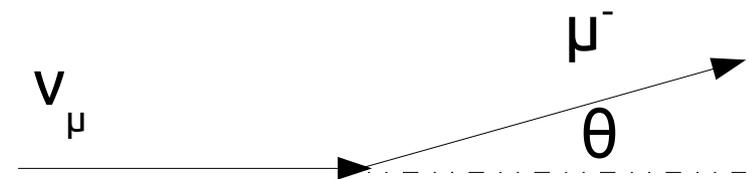


Directionality

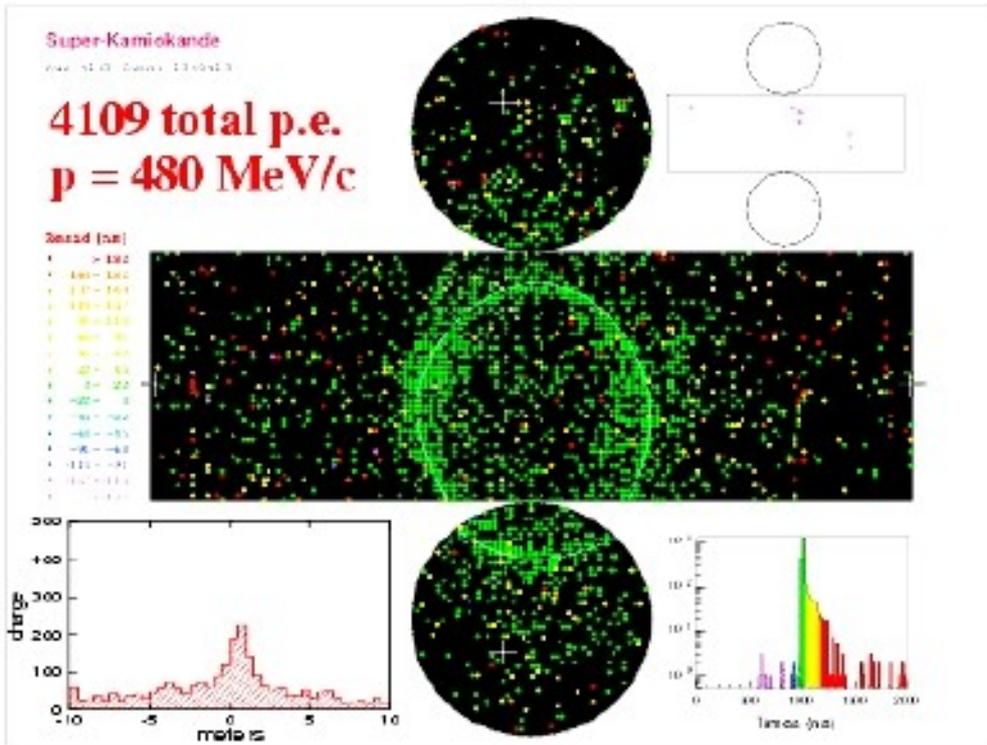


For simple events, the direction of the ring can be used to point back to the neutrino source

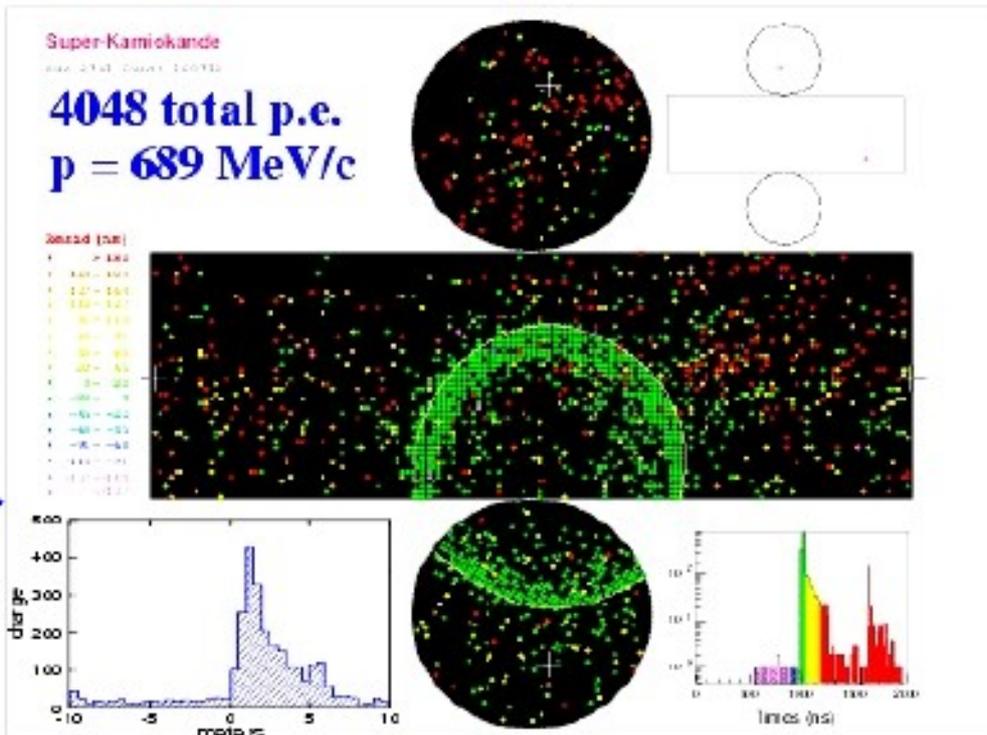
Proof that these neutrinos were coming from the sun



e-like



μ -like



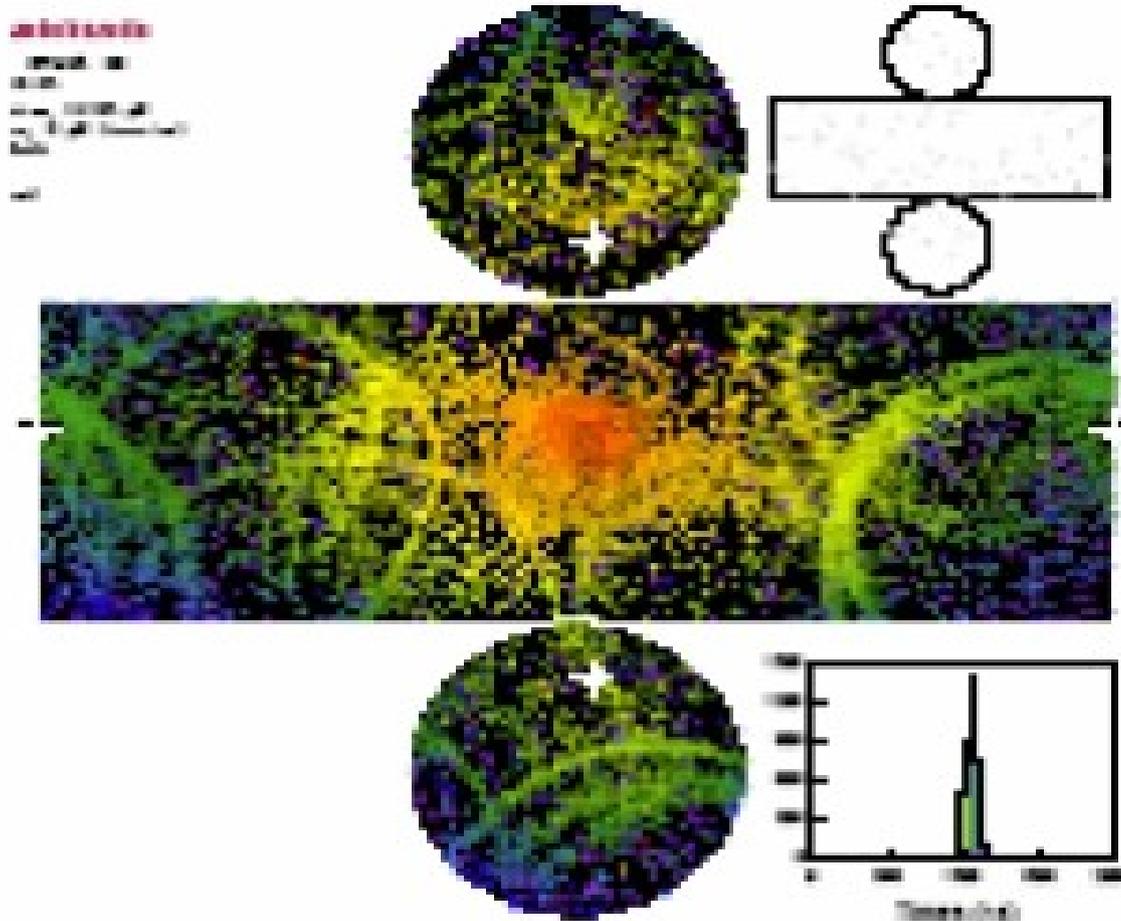
Electron-like : has a fuzzy ring

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

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

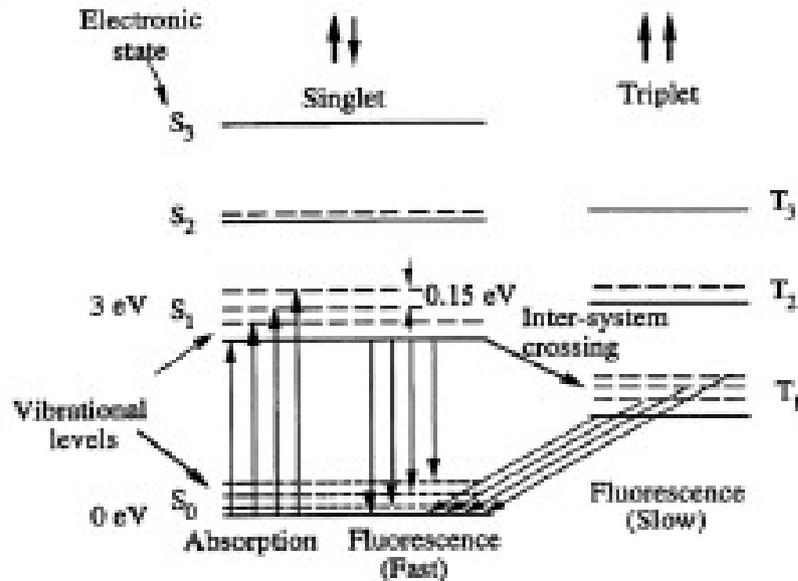
Problems

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



Scintillator Detectors

Light emission following ionisation



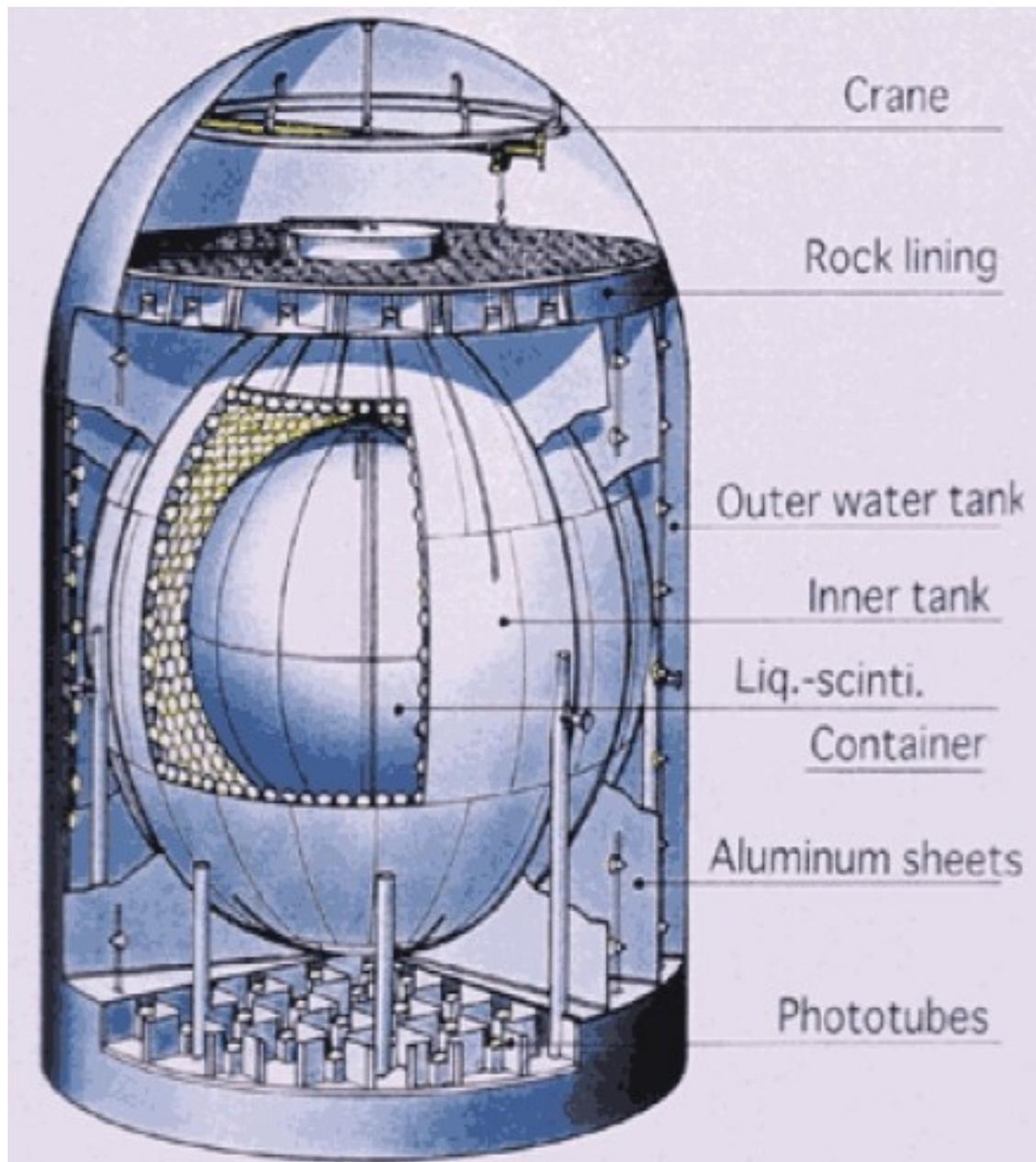
Organic liquids and plastics

Inorganic crystals

Nobel liquids

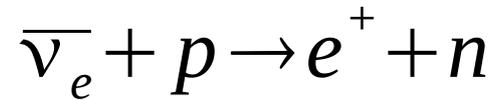
- In a good scintillator, much **more** light is emitted by scintillation than by the Cerenkov process.
- **Scintillation light is isotropic and there is no threshold.**
- But no information on directionality, the emission wavelength depends on the scintillator material, and the scintillator is usually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

KamLAND

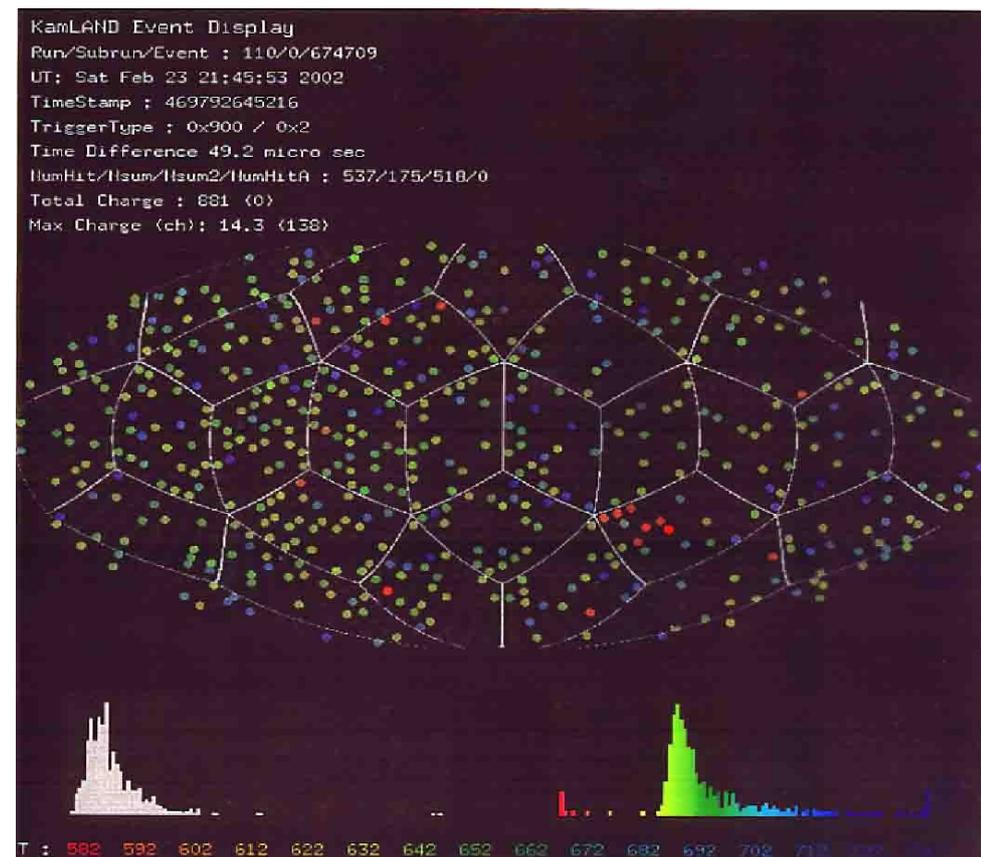
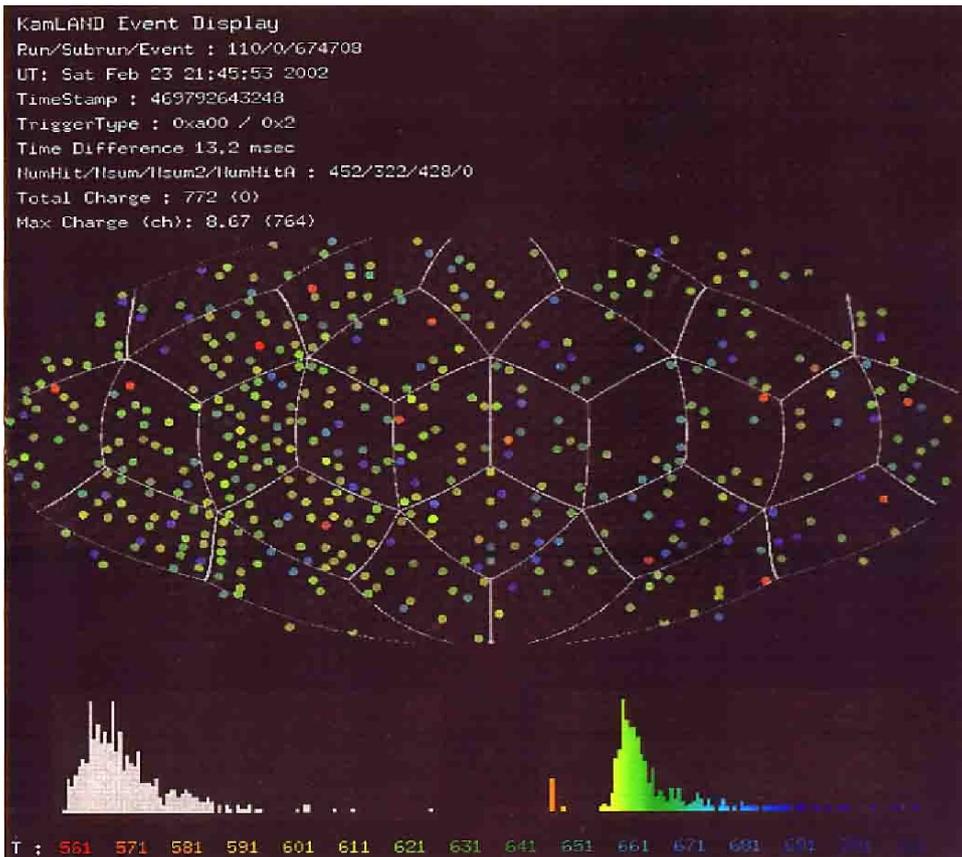
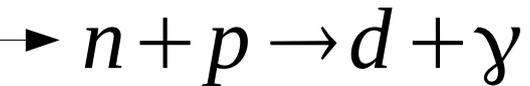


- External container filled with 3.2 kton H_2O
- Inner sphere filled with 2 kton of mineral oil
- Inside transparent balloon filled with 1 kton of liquid scintillator
- Located 1km deep in the Kamioka mine, just up the street from Super-Kamiokande
- Very pure – background is a major problem.

Event Displays



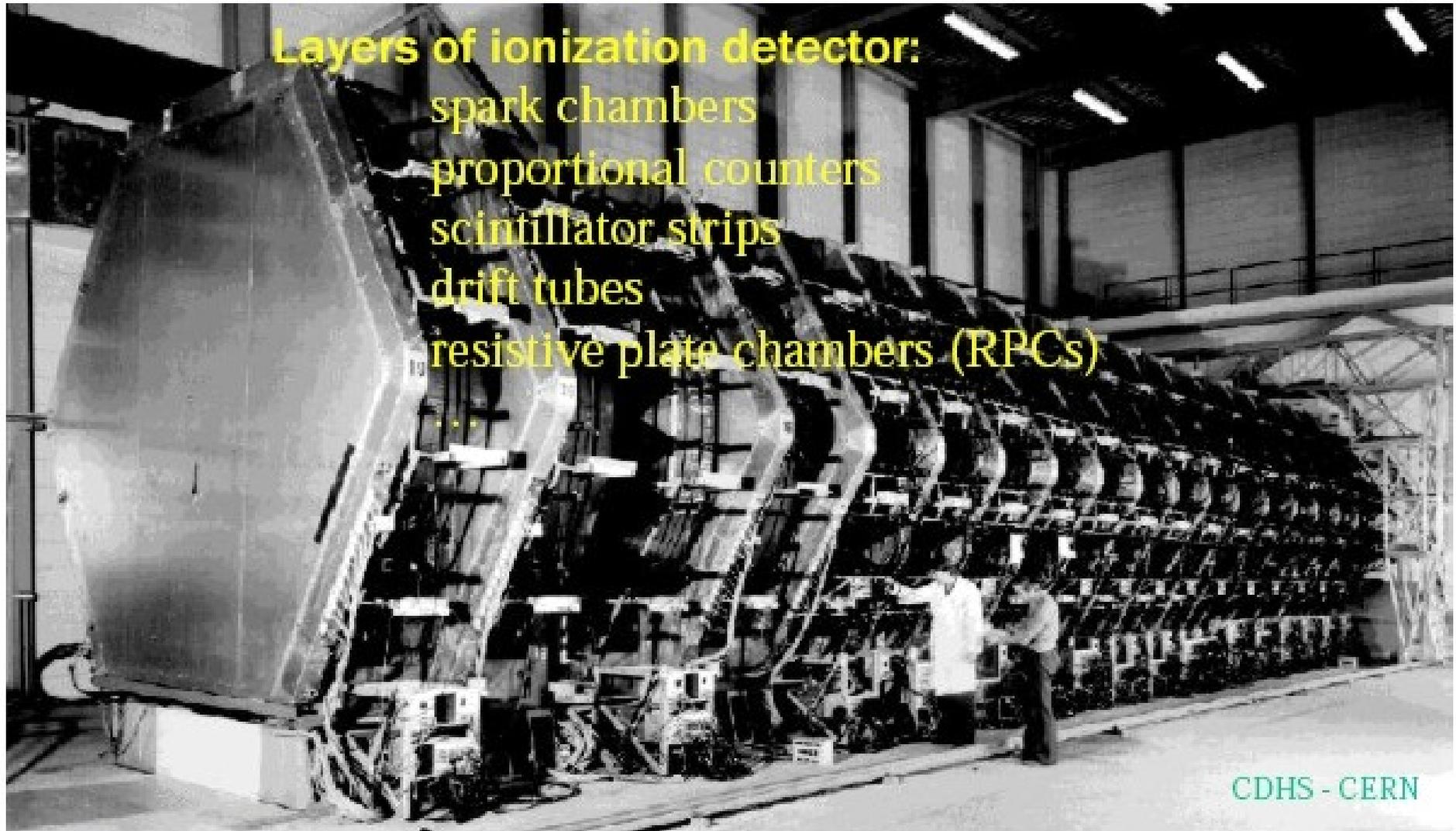
200 ms later



Tracking Calorimeters

Layers of target: eg. steel, marble, glass

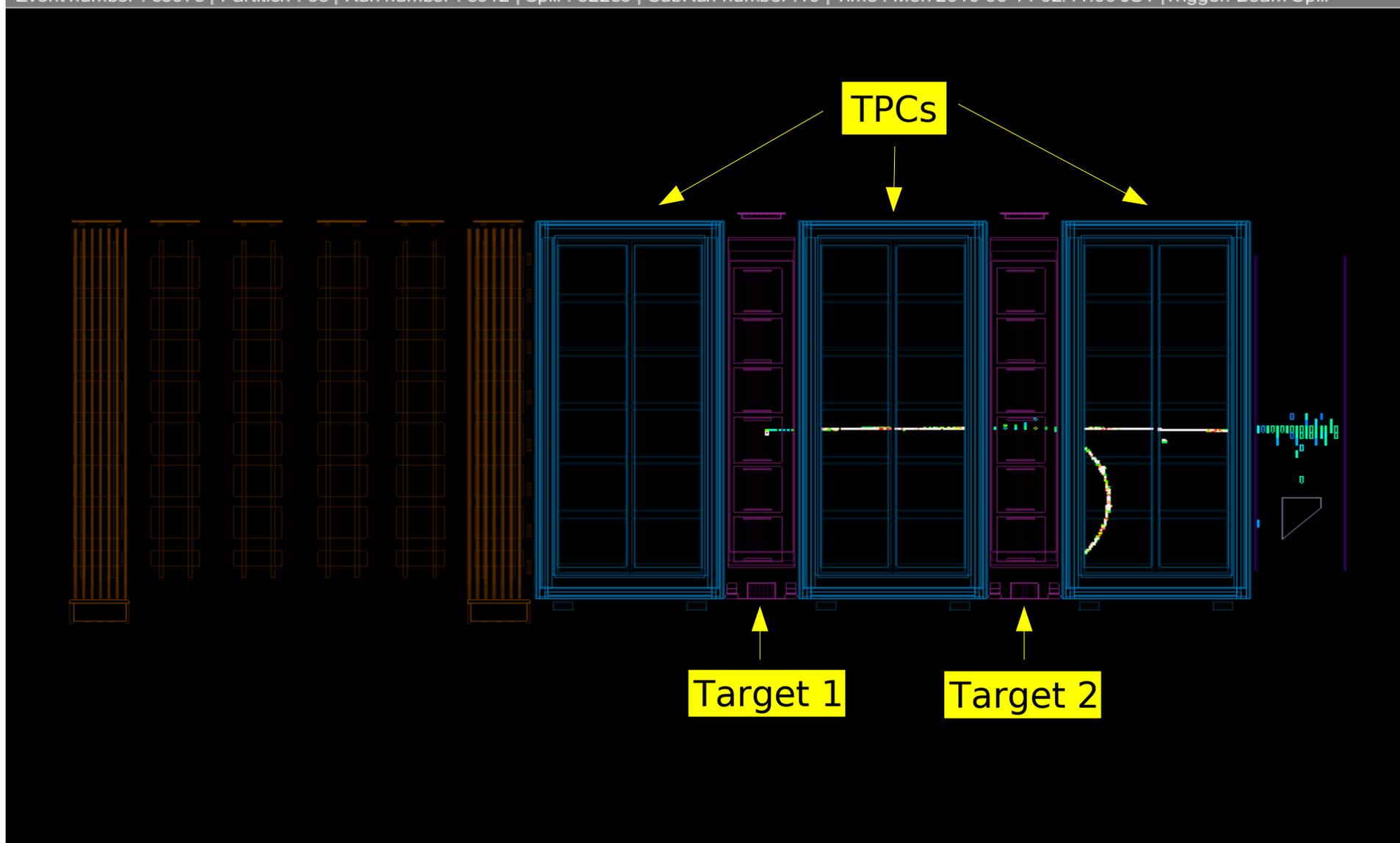
Layers of ionization detector:
spark chambers
proportional counters
scintillator strips
drift tubes
resistive plate chambers (RPCs)



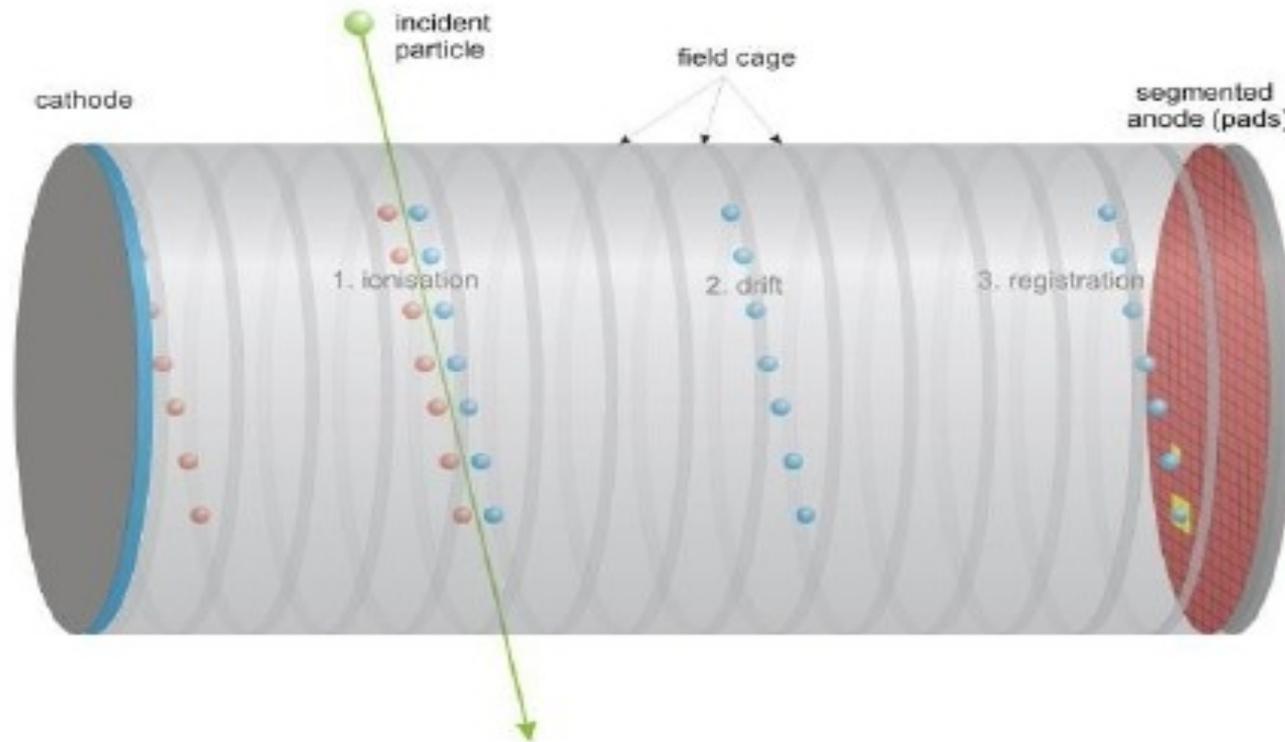
CDHS - CERN

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

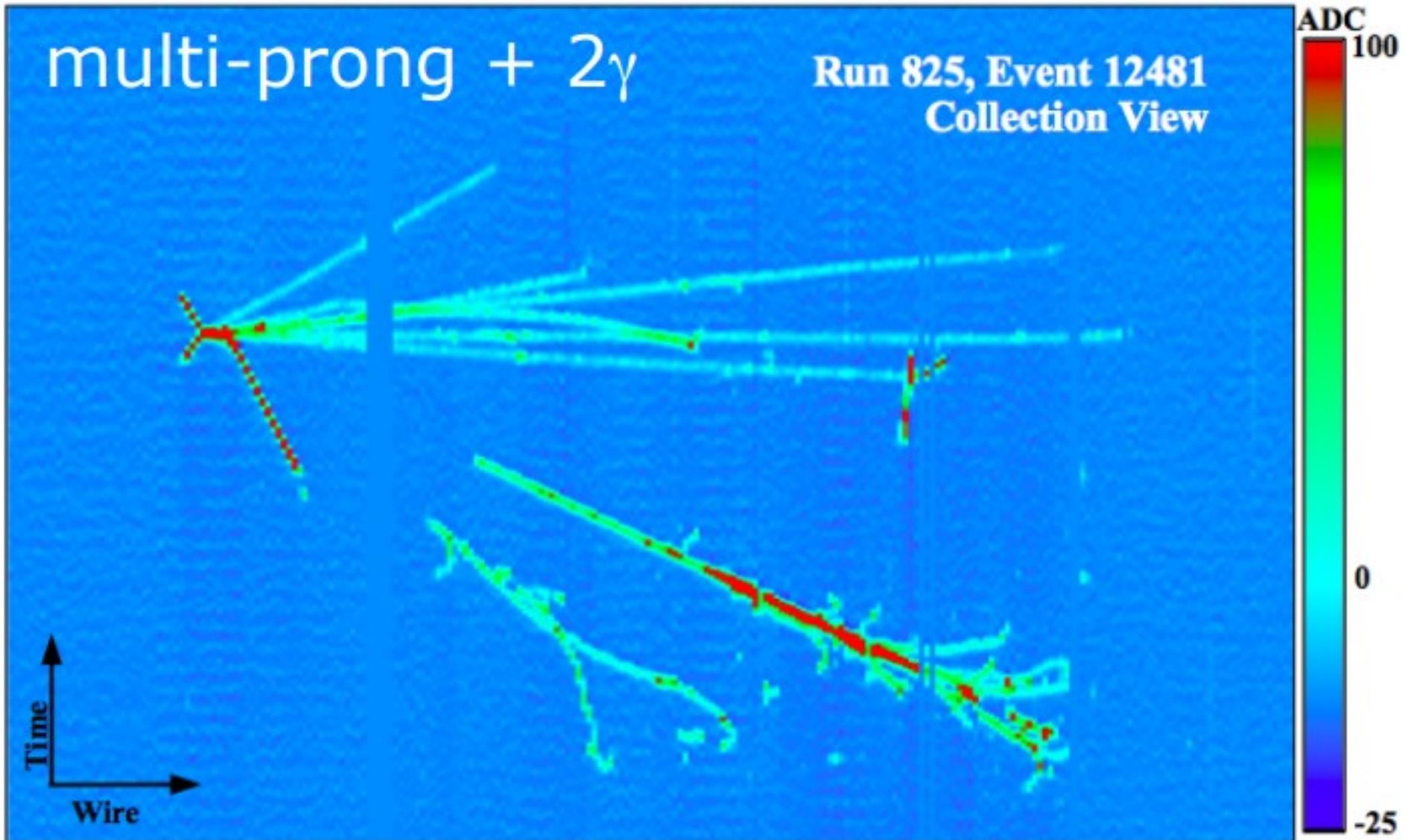


Liquid Argon TPCs



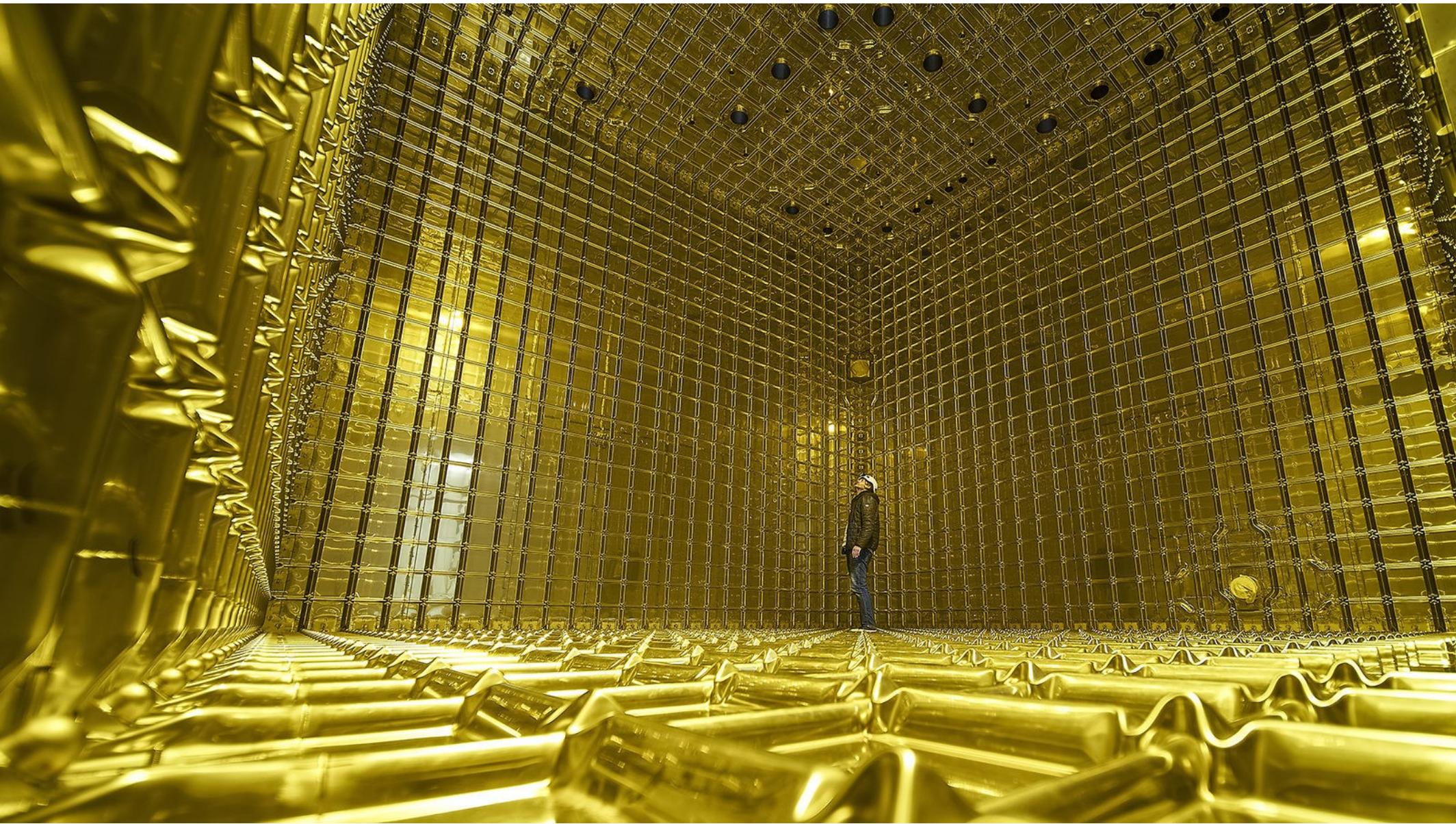
3D tracking with excellent resolution
Calorimetry from energy deposition in filler material
Filler can be gas or liquid.
Neutrino Physics looking at liquid argon TPCs

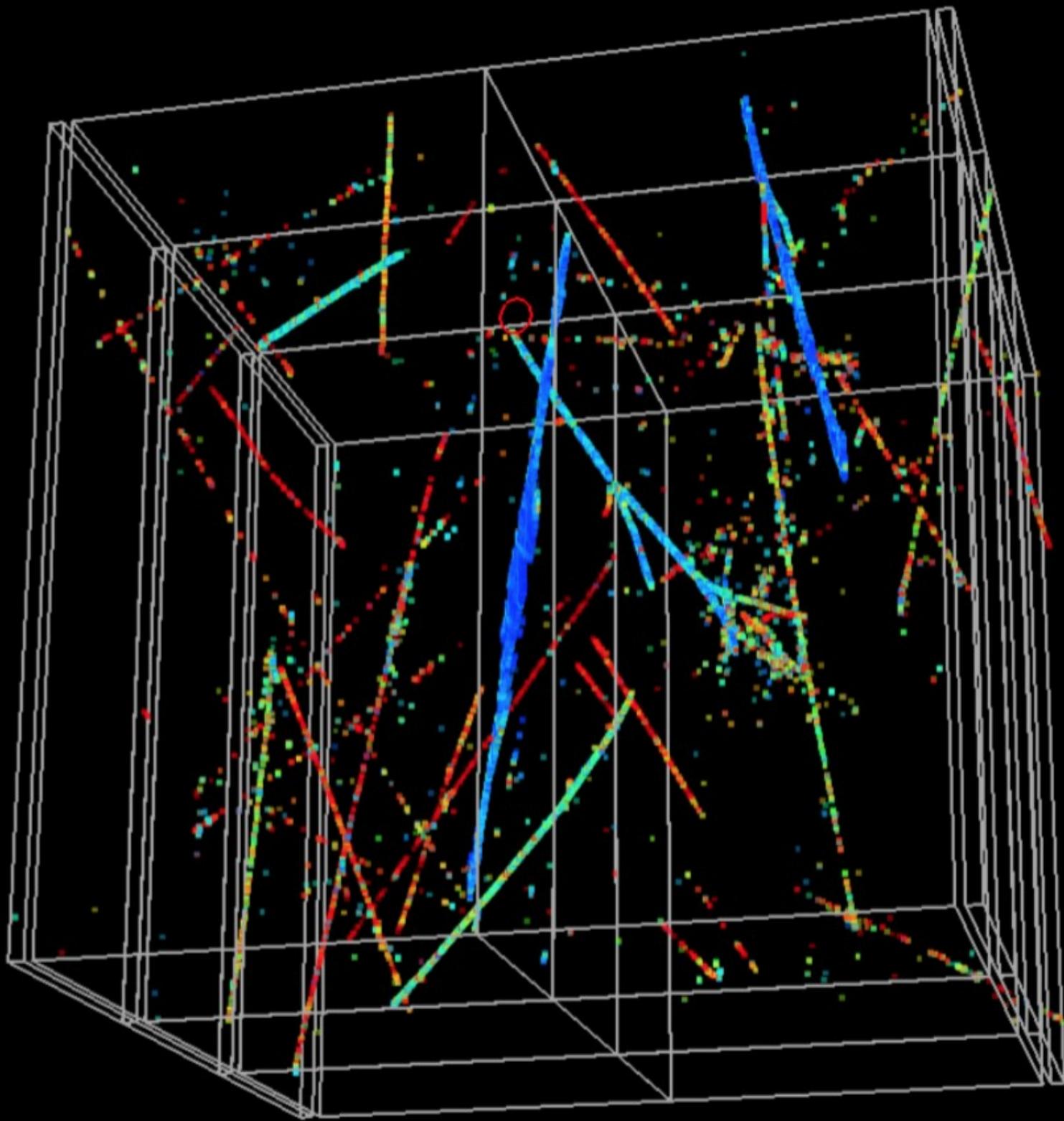
LAr event



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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)