H. A. TANAKA

ACCELERATOR-BASED NEUTRINO EXPERIMENTS

RECALL: NEUTRINO ECONOMICS

- The ability to precisely study neutrino interactions depends heavily on statistics
  - i.e. how many neutrino interactions you observe

$$N = \boxed{\varphi} \times \boxed{\sigma} \times \boxed{V \times n \times \varepsilon}$$

- N = number of neutrino interactions
- φ = flux of neutrinos (neutrinos/cm^2)
- σ = neutrino interaction cross section on target (e.g. electron, nucleon, nucleus)
- V = volume of detector (cm^3)
- n = number of density of targets
- ε = detection efficiency

Lecture 1: how do we produce large number of neutrinos with accelerators

Thanks, Minerba!

Lecture 2: How do we make massive detectors that can efficiently detect neutrino interactions

Thanks, David!

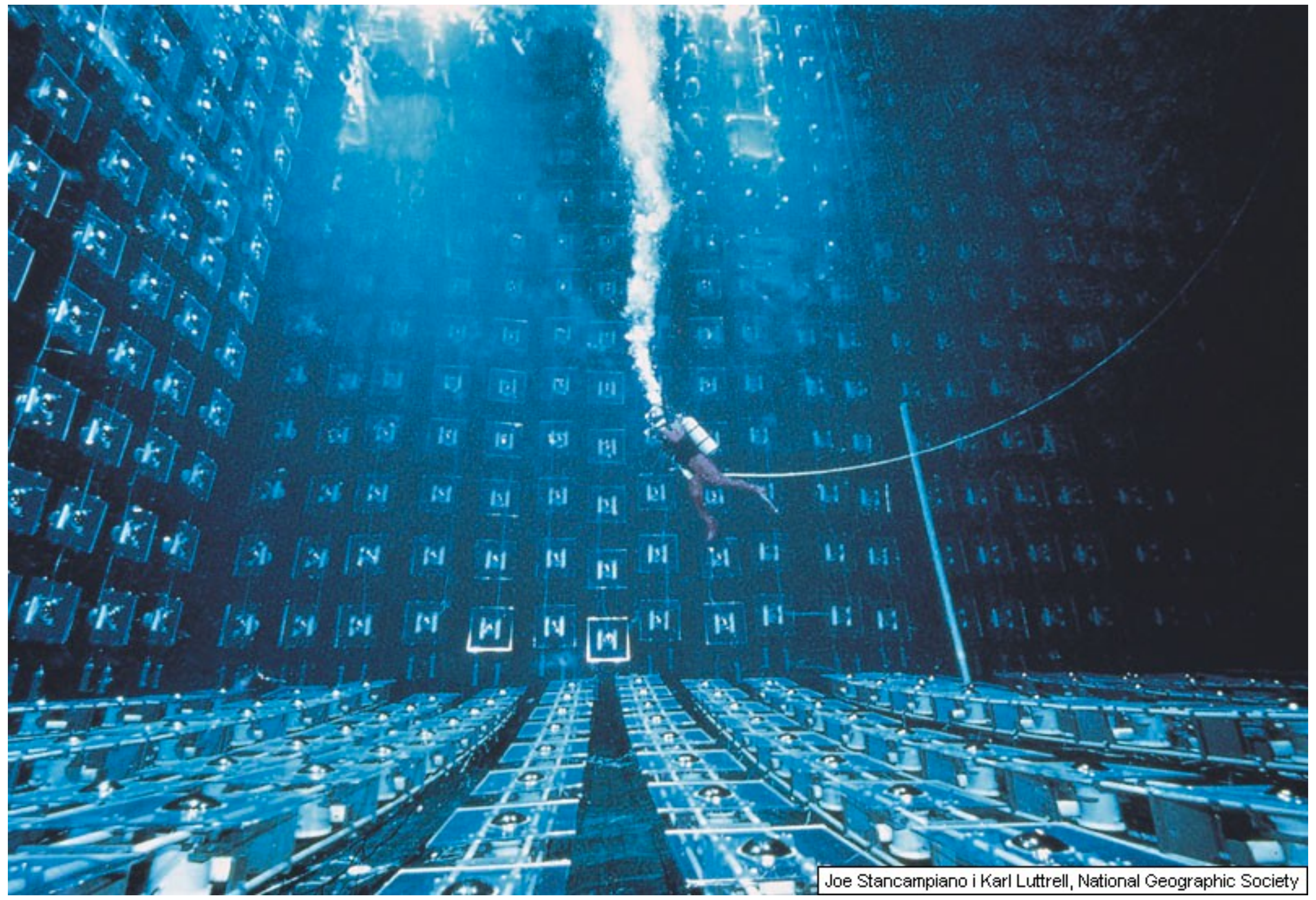
LECTURE 2:
DETECTORS FOR ACCELERATOR-BASED NEUTRINO EXPERIMENTS

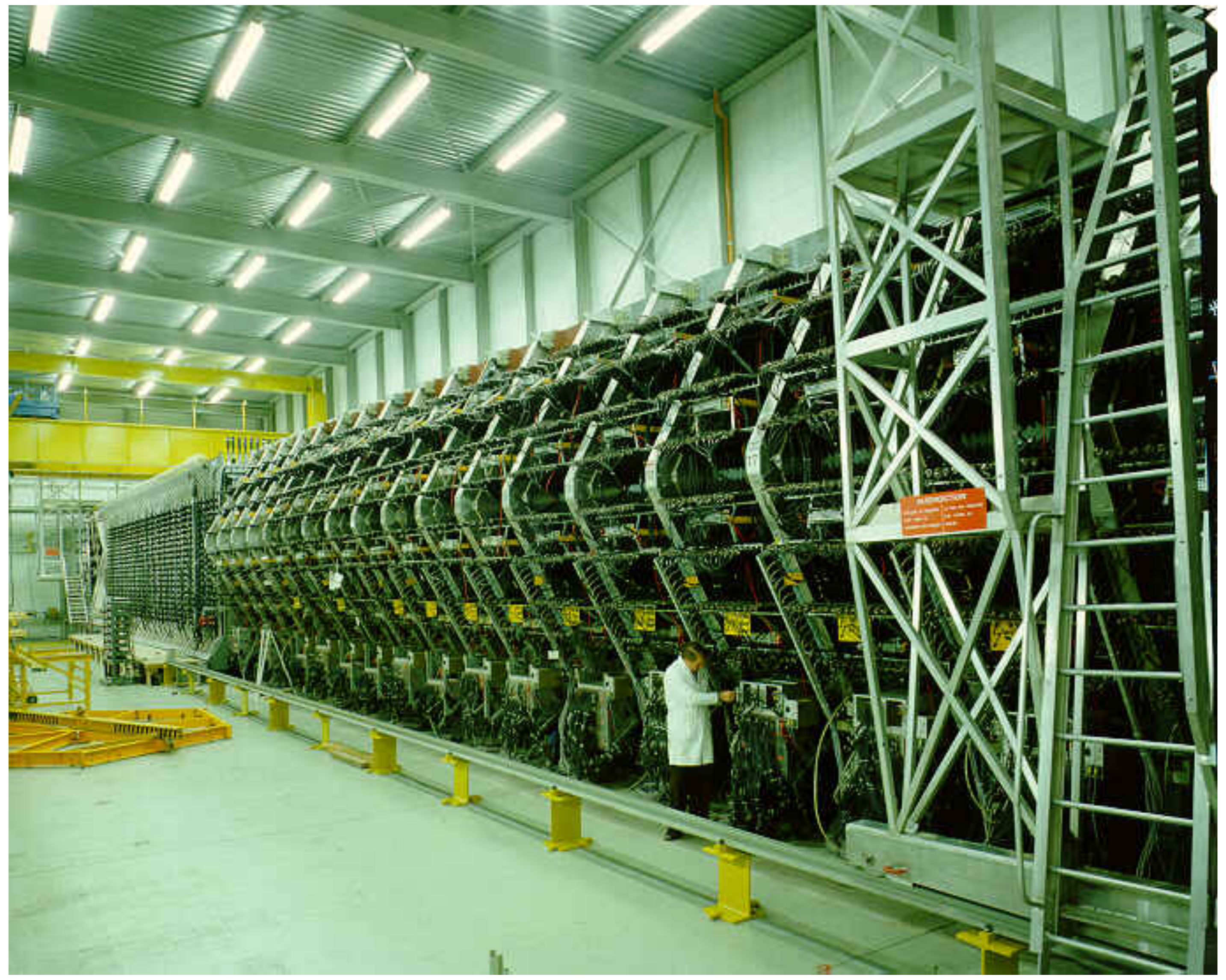
WHAT DO WE WANT FROM A DETECTOR:

- We need to have "enough" neutrino interactions
  - sufficient mass, especially for long baseline experiments!
- Looking at neutrino oscillations = flavour change of neutrinos that depend on energy and baseline
  - we want to be able to identify the neutrino flavour and energy
    - lepton identification (e, μ, τ), energy reconstruction
- Relevant performance metrics:
  - Efficiency and purity: for a sample of ν_l charged current interactions identified by the detector
    - separate $\nu_k \neq \nu_l$ charged current interactions
    - separate neutral current interactions
  - Resolution on neutrino energy: two strategies
    - calorimetric: add up energy of all final state particles
      - issues: threshold, resolution, particle identification, modelling
    - kinematic: if underlying interaction mechanism is known, infer with subset of particles (e.g. lepton)
      - issues: purity in selecting targeted interaction mechanism, modelling
    - Practically, containment is an important consideration for both strategies

LARGE DETECTORS

"miserable old technology"





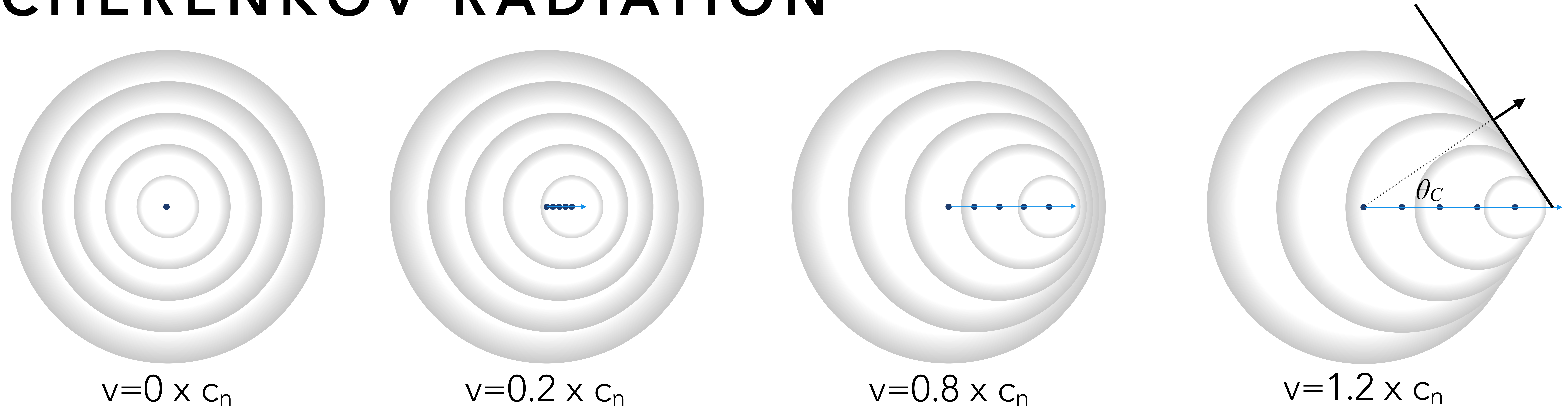
- Neutrinos interact with anything!
    - water, cleaning fluid, mineral oil
    - Lakes, oceans, antarctic ice
    - Steel from decommissioned battleships
    - Roman lead, Marble
- Other ideas
    - the moon
    - corn flakes
    - .....
- Detecting the interaction is the next step

FOCUS ON THREE TECHONOLOGIES

- ACT 1: WATER CHERENKOV DETECTOR
- ACT 2: SCINTILLATING TRACKER DETECTOR
- ACT 3: LIQUID ARGON TIME PROJECTION CHAMBER

ACT 1: WATER CHERENKOV DETECTORS

CHERENKOV RADIATION



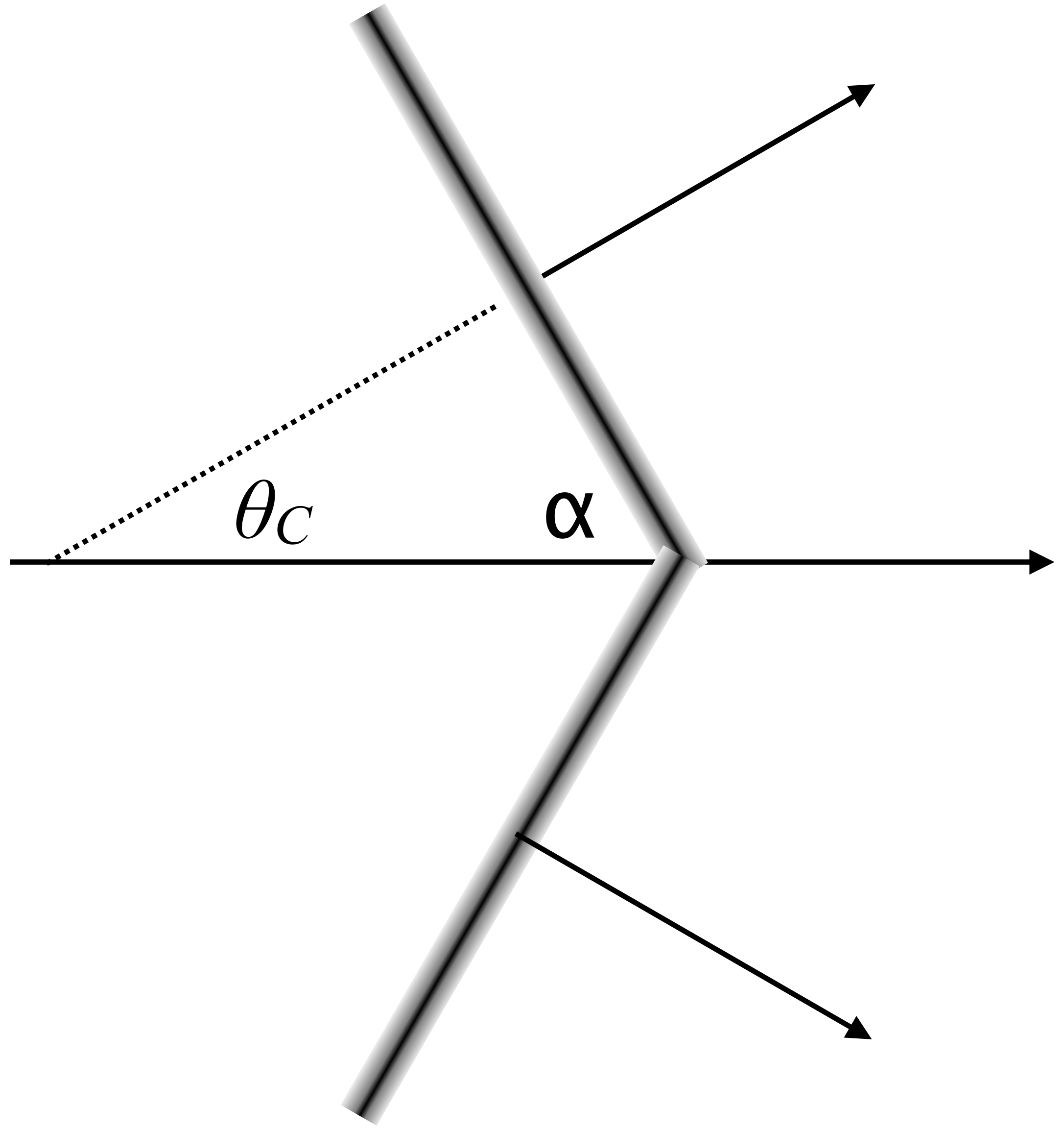
- Charged particle passing through a dielectric medium ($n > 1$) induces a EM disturbance that propagates at speed $c_n=c/n$
- If $v > c_n$, the disturbance piles up
  - electromagnetic "shock wave" emitted with angle θ_C

$$\cos\theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$

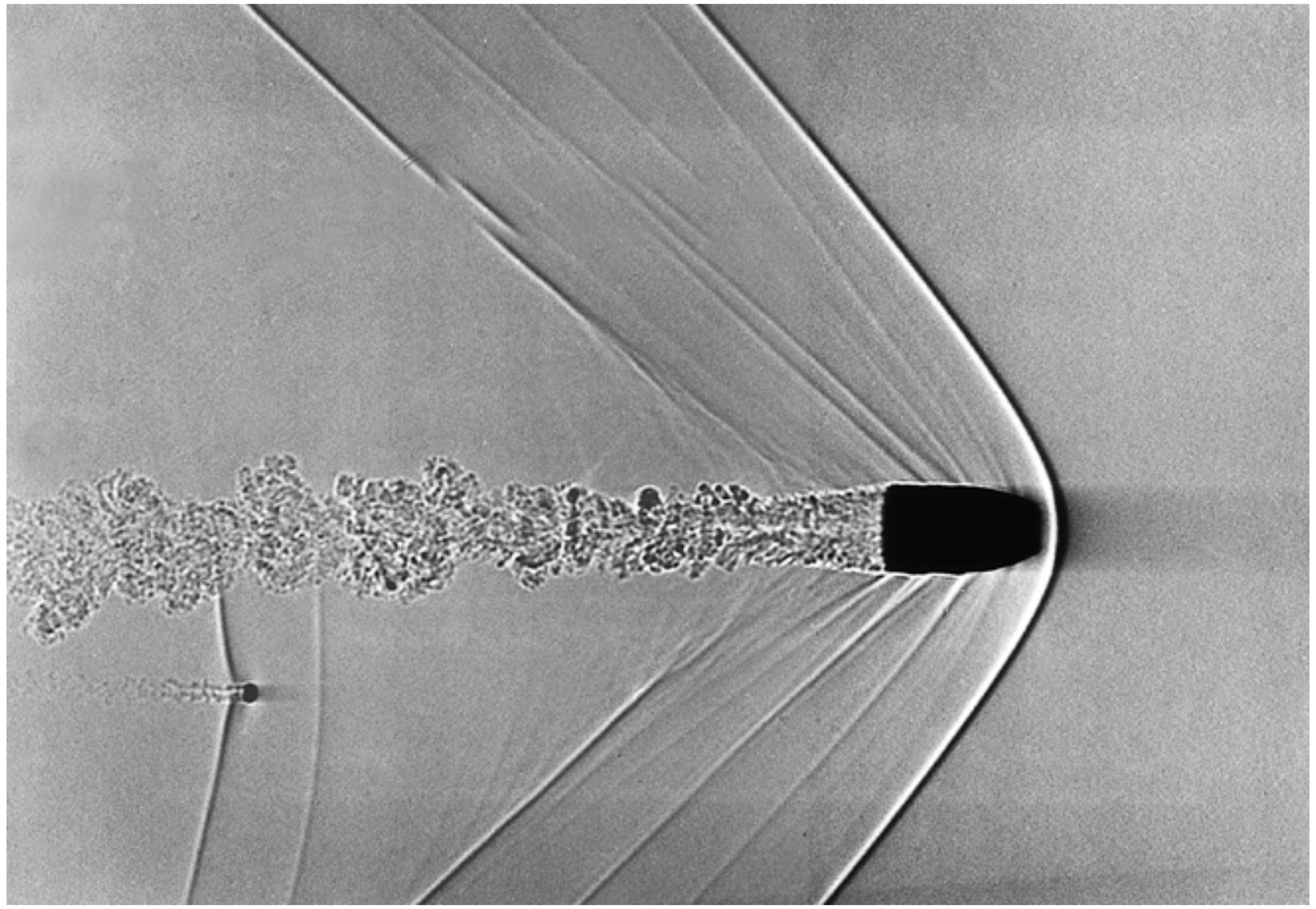
- This is Cherenkov (Č) radiation

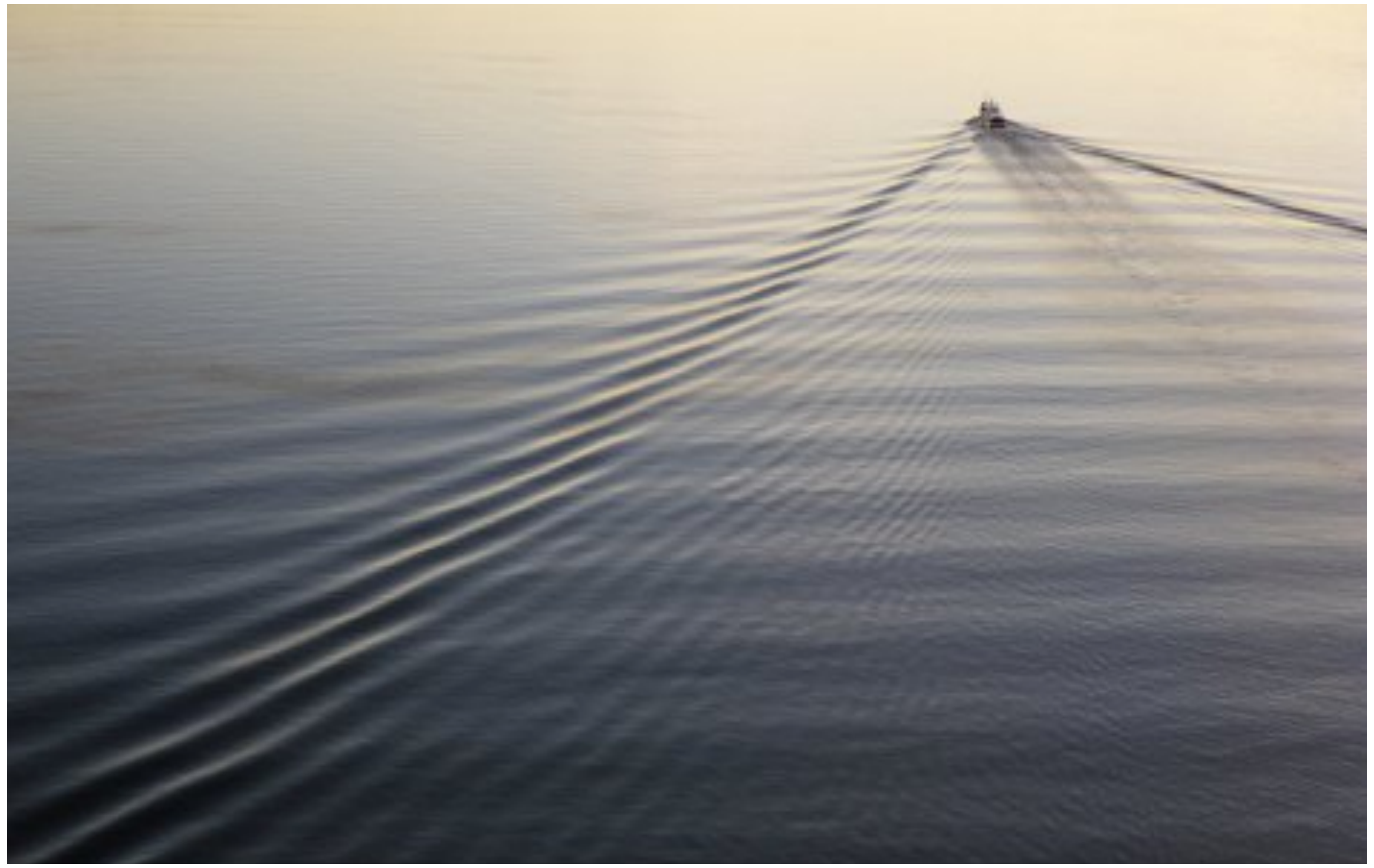
SHOCK WAVES

courtesy findagrave.com



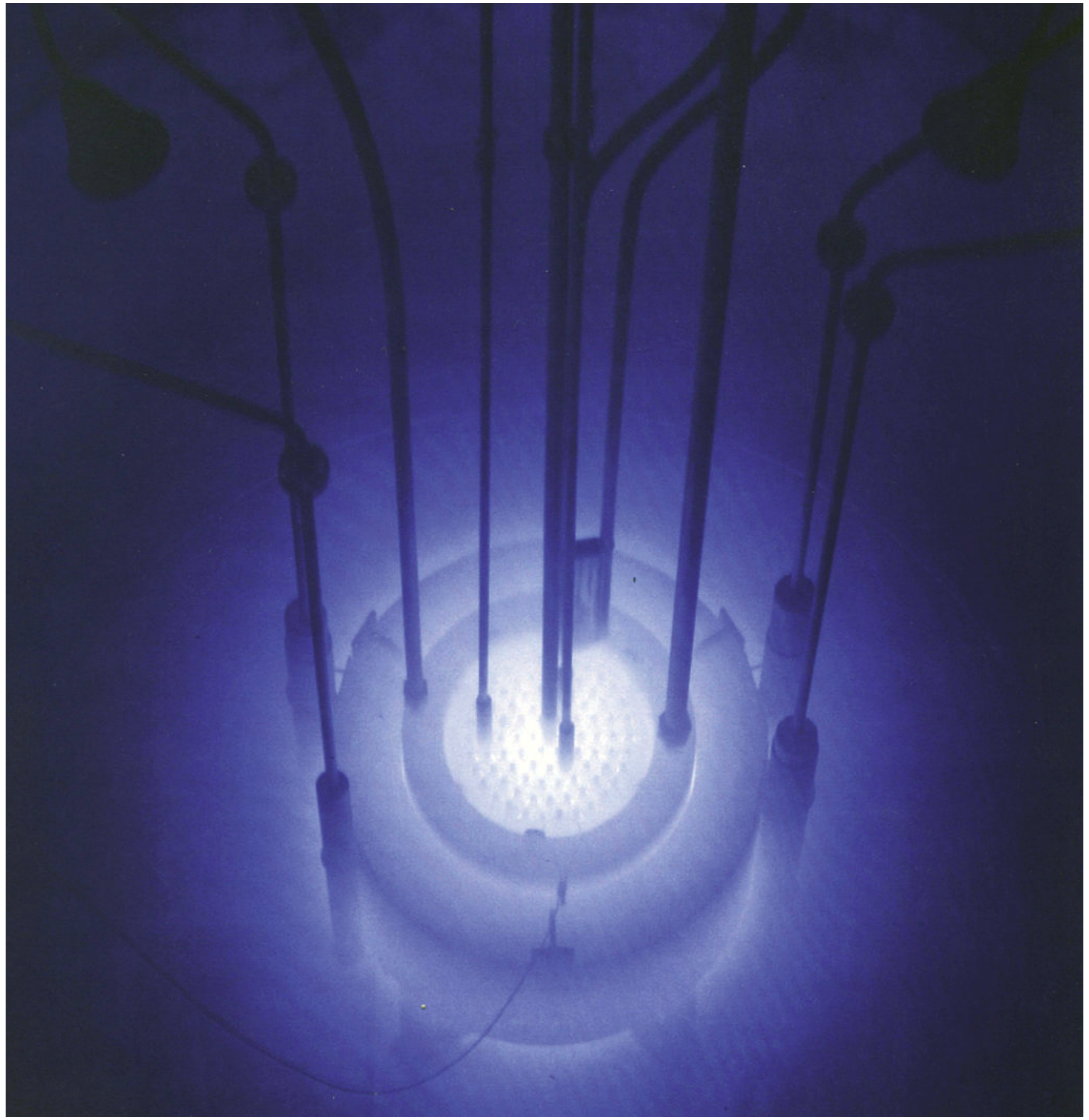
$$\sin\alpha = \frac{v_s}{v} \qquad \alpha = \frac{\pi}{2} - \theta_C$$





- Analogous to other (mechanical) systems where a disturbance exceeds the propagation velocity
    - e.g. “sonic boom” from supersonic object

CHERENKOV RADIATION



- Considerations of "spatial singularity":
  - k = wavenumber, so that p=ħk
  - light is emitted "flat" in k

$$k = \frac{2\pi}{\lambda} \qquad\qquad dk = -\frac{2\pi}{\lambda^2}d\lambda$$

  - wavelength spectrum is $1/\lambda^2$

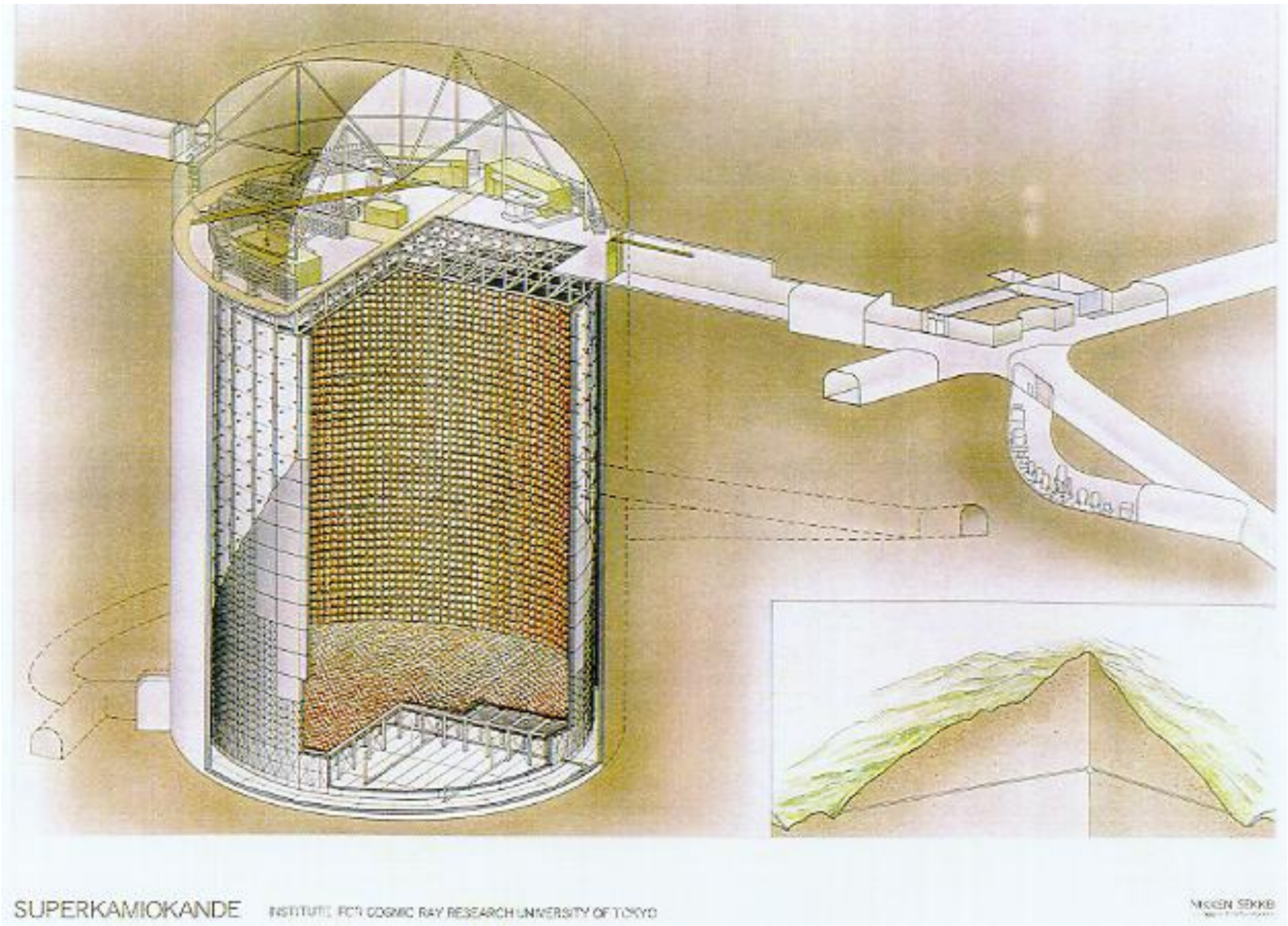
- Frank-Tamm Equation

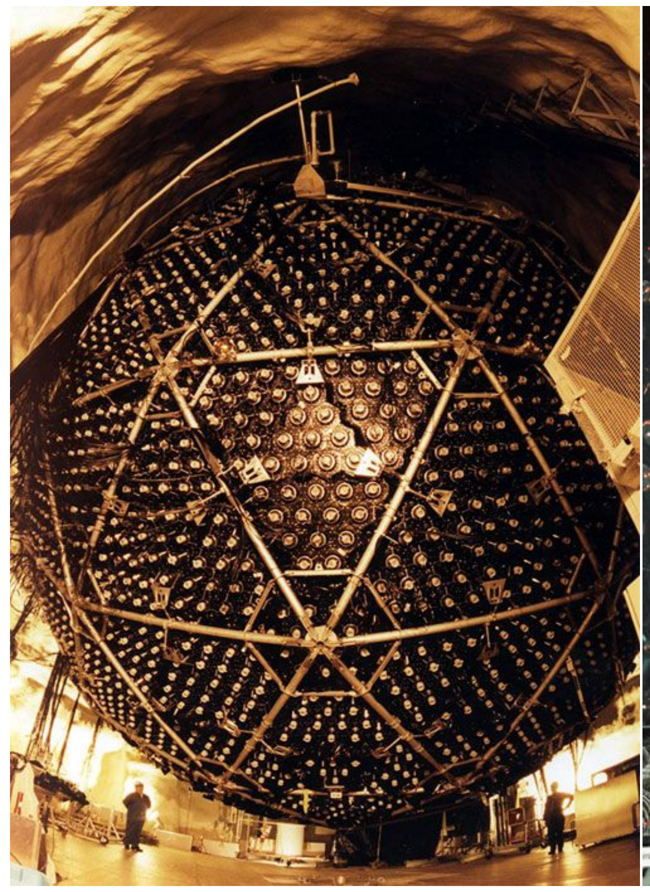
$$\frac{d^2N}{dE\,dx} = \frac{\alpha z^2}{\hbar c}\sin^2\theta_C \sim 370\sin^2\theta_C \text{ eV}^{-1}\text{cm}^{-1}$$

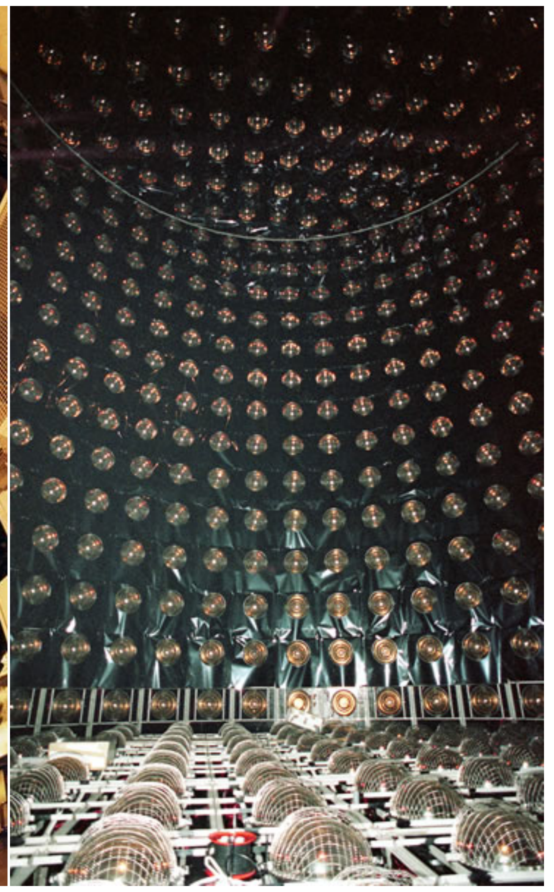
- For water, n ~1.34, $\sin^2\theta_C = 0.44$
  - "~160 photons per cm traversed by β=1 particle in 1 eV interval of photon energy"
  - ~250 photons emitted/cm in the visible light region
  - "Collapse" of Č cone: as v~c_n (threshold), θ_C and $\sin^2\theta_C$ goes to zero

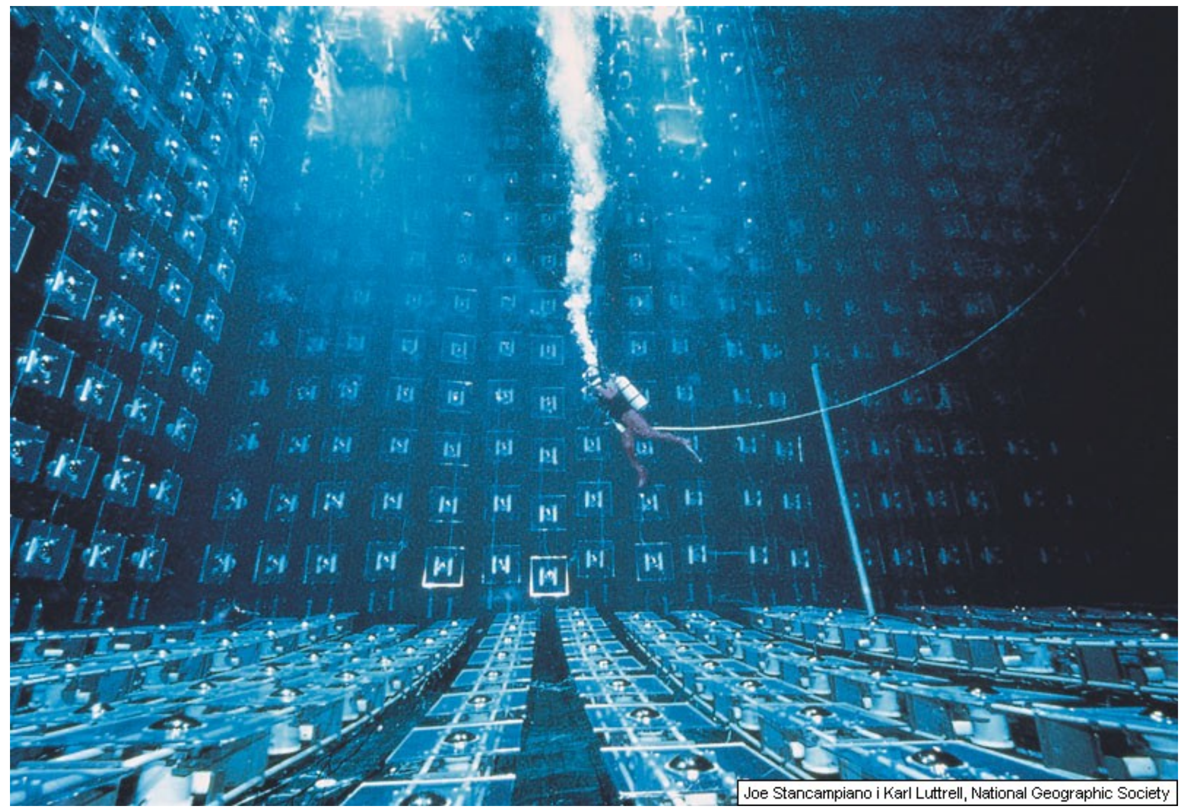
WATER CHERENKOV DETECTORS:

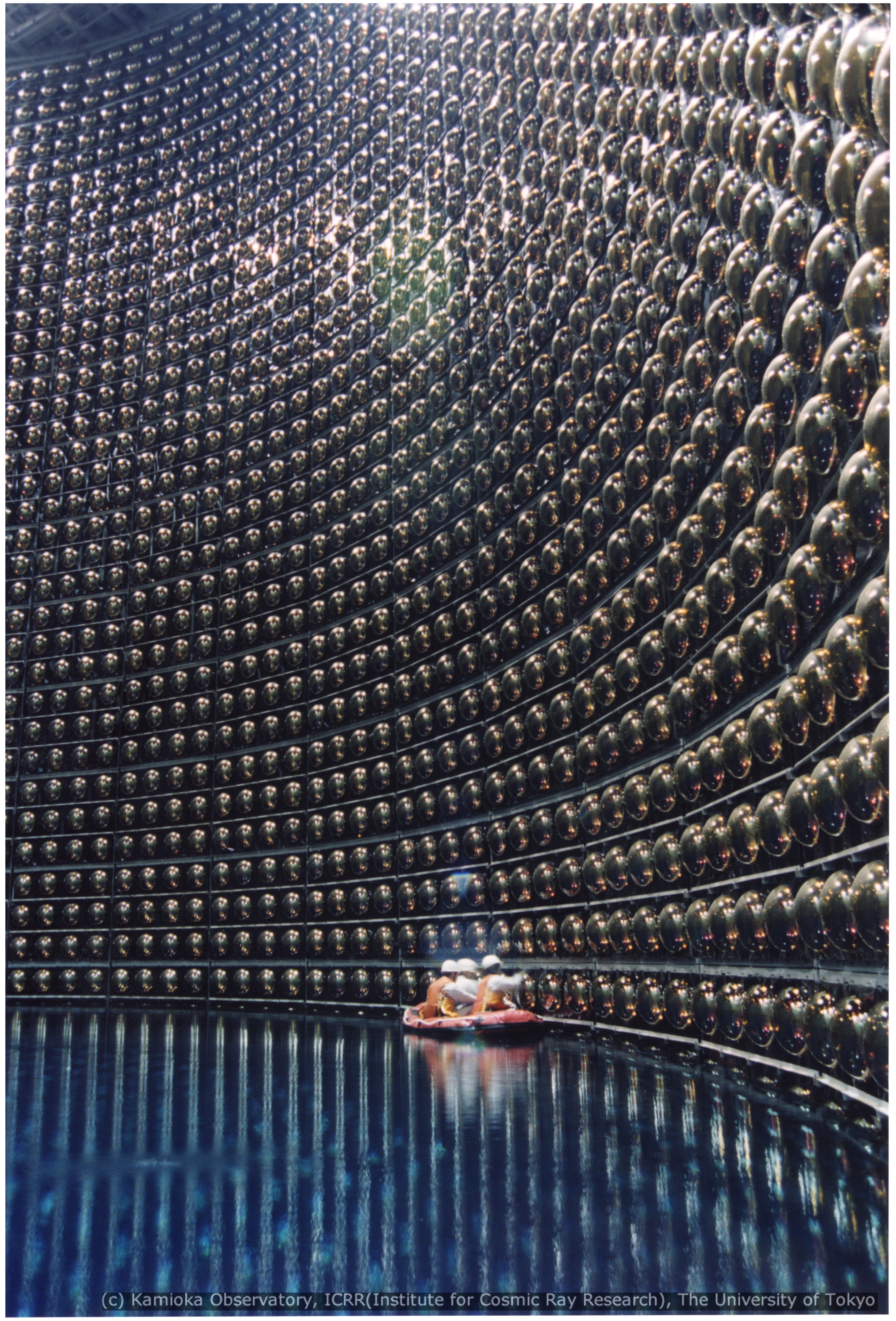
- Large tank of water surrounded by photosensors
- Cherenkov light produced by particles in water are detected on wall
- Examples:
  - IMB, Kamiokande, SNO, K2K 1 kT, Super-Kamiokande . . . . .





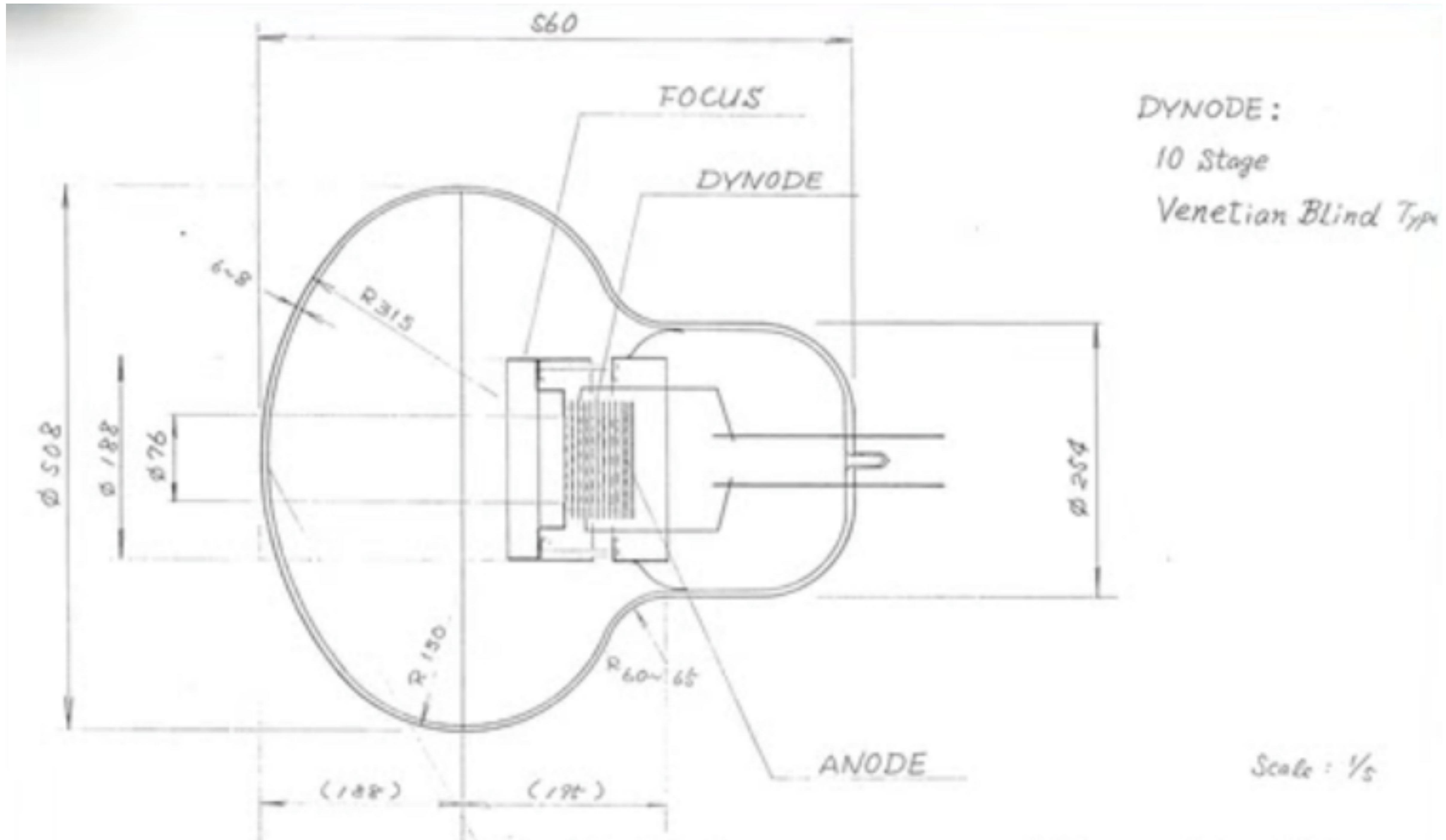






CHALLENGES:

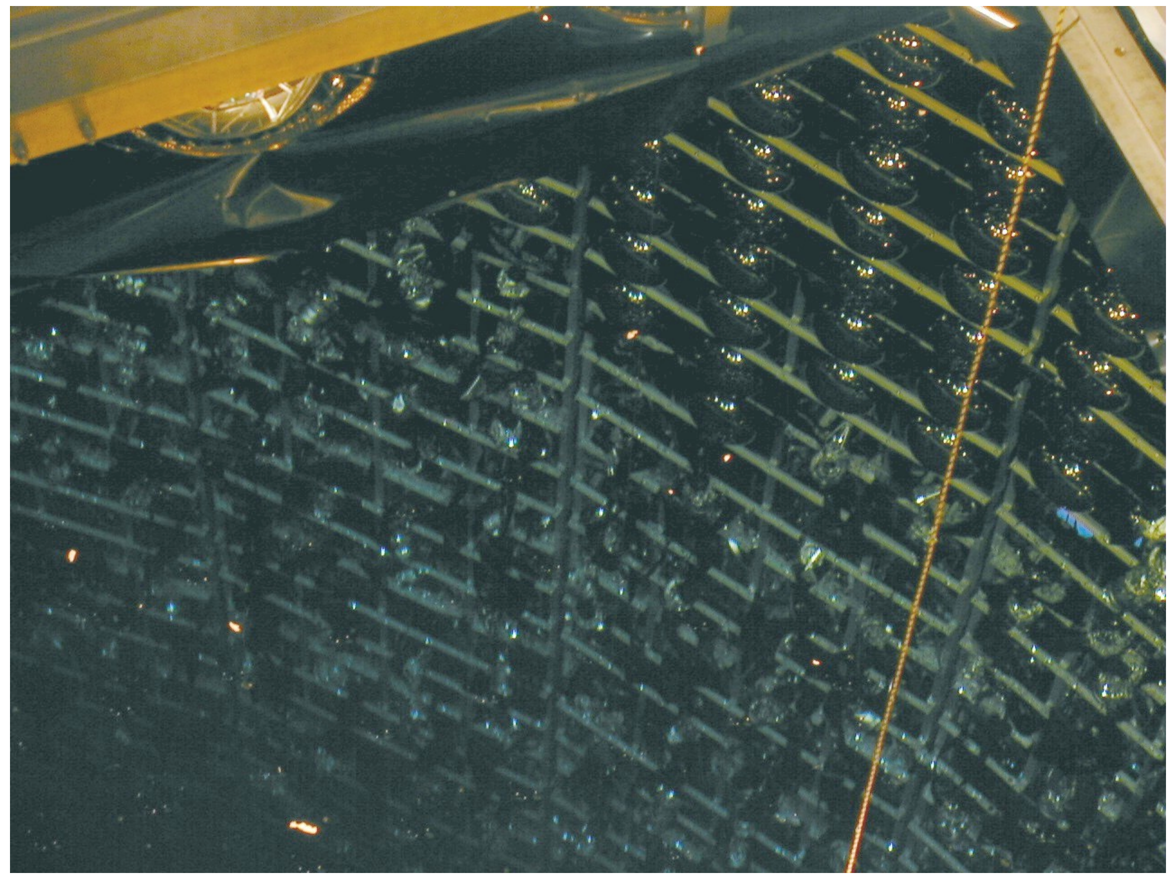
- The Super-Kamiokande active region
  - cylinder ~34 m in diameter, 37 m high
  - nearly 6000 m^2 of surface area
- For a ~500 MeV muon
  - ~200 cm of path length
  - 50,000 photons produced
  - typical efficiency for detection is 10%
    - 5000 photons detectable on the wall
  - Reconstruction requires high detection efficiency
    - provide kinematic/vertex reconstruction
    - particle identification.



20” PMT developed by Hamamatsu

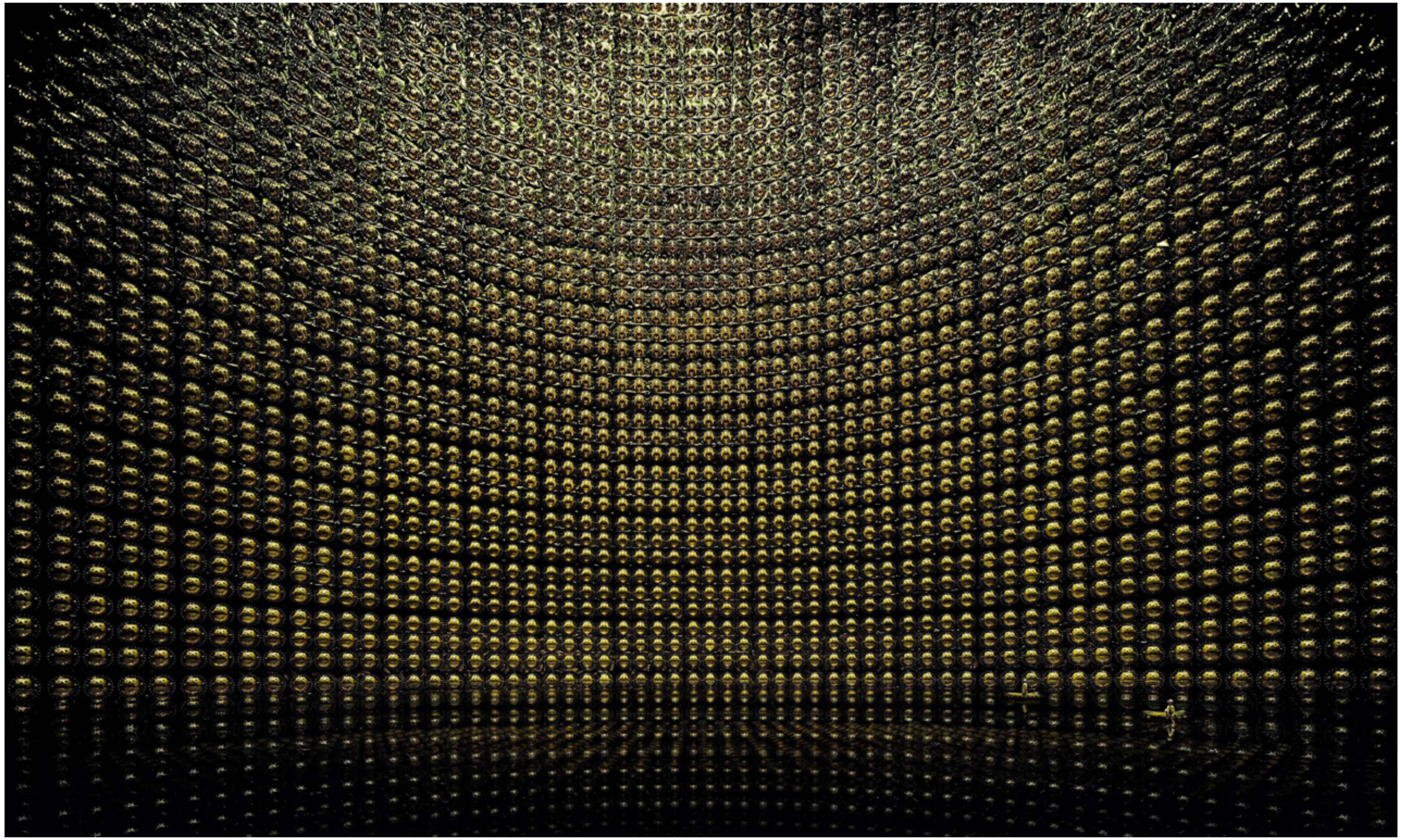
PMT IMPLOSION

courtesy: smartereveryday



- "Prince Rupert's drop"
  - cooled molten glass is extraordinarily strong
  - enormous stresses are pent up from the cooling process
- Implosion of single PMT under enormous pressures from deep underwater deployment release shockwave in water
  - induces implosion of adjacent PMTs
  - chain reaction destroys all PMTs in water

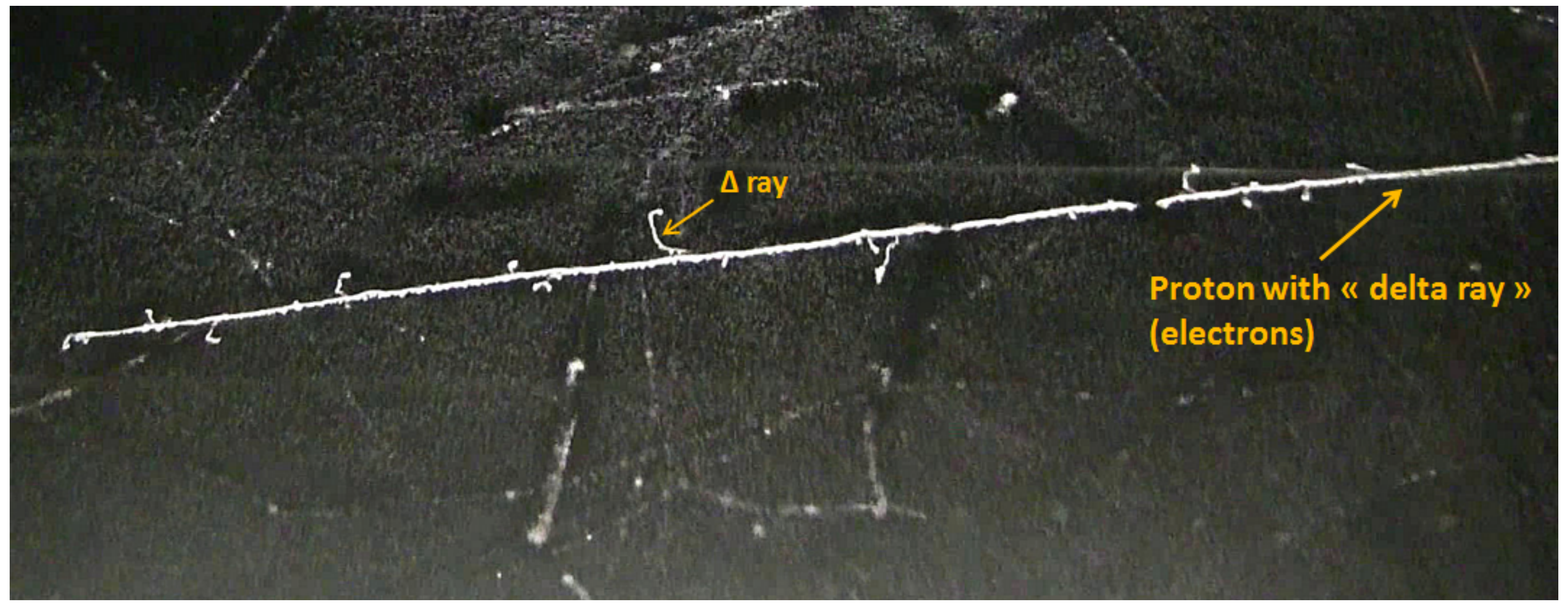
SUPER-KAMIOKANDE

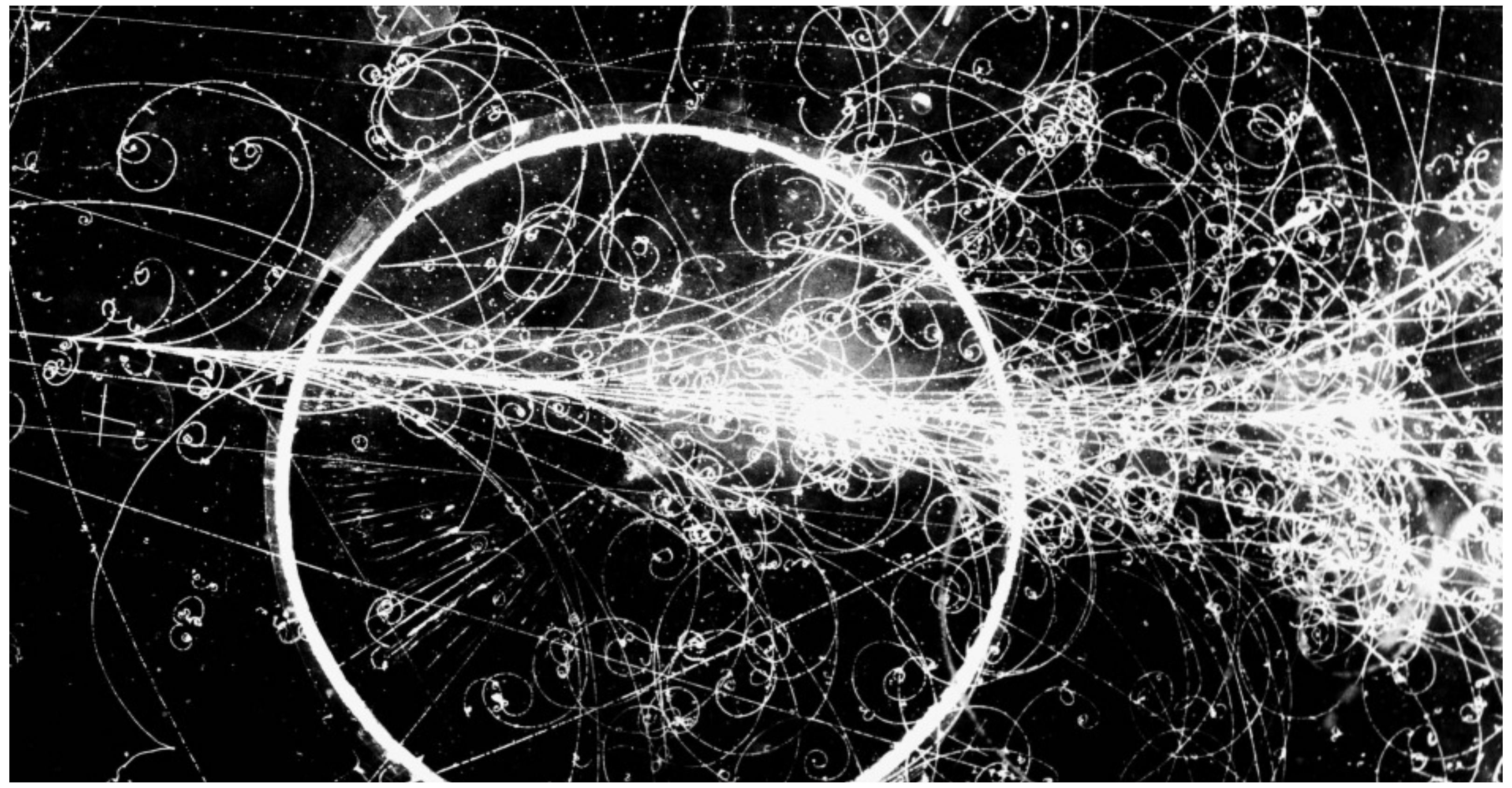


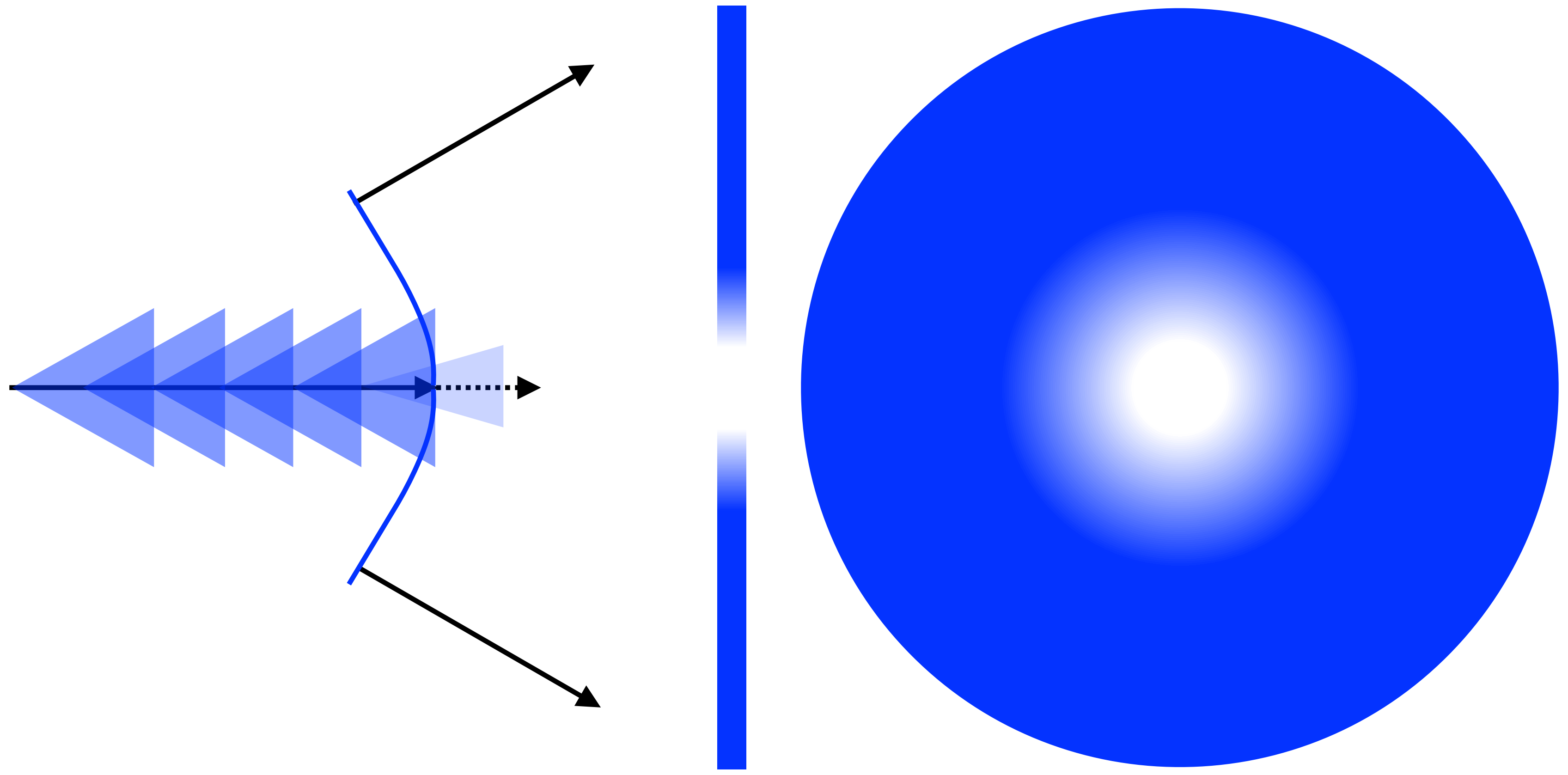
- 11200 20" PMTs deployed in inner detector
  - 40% coverage of detector surface
  - Successful operation over 20 years!
  - solar neutrinos, atmospheric neutrinos, beam neutrinos (K2K, T2K), neutrino astrophysics, etc.

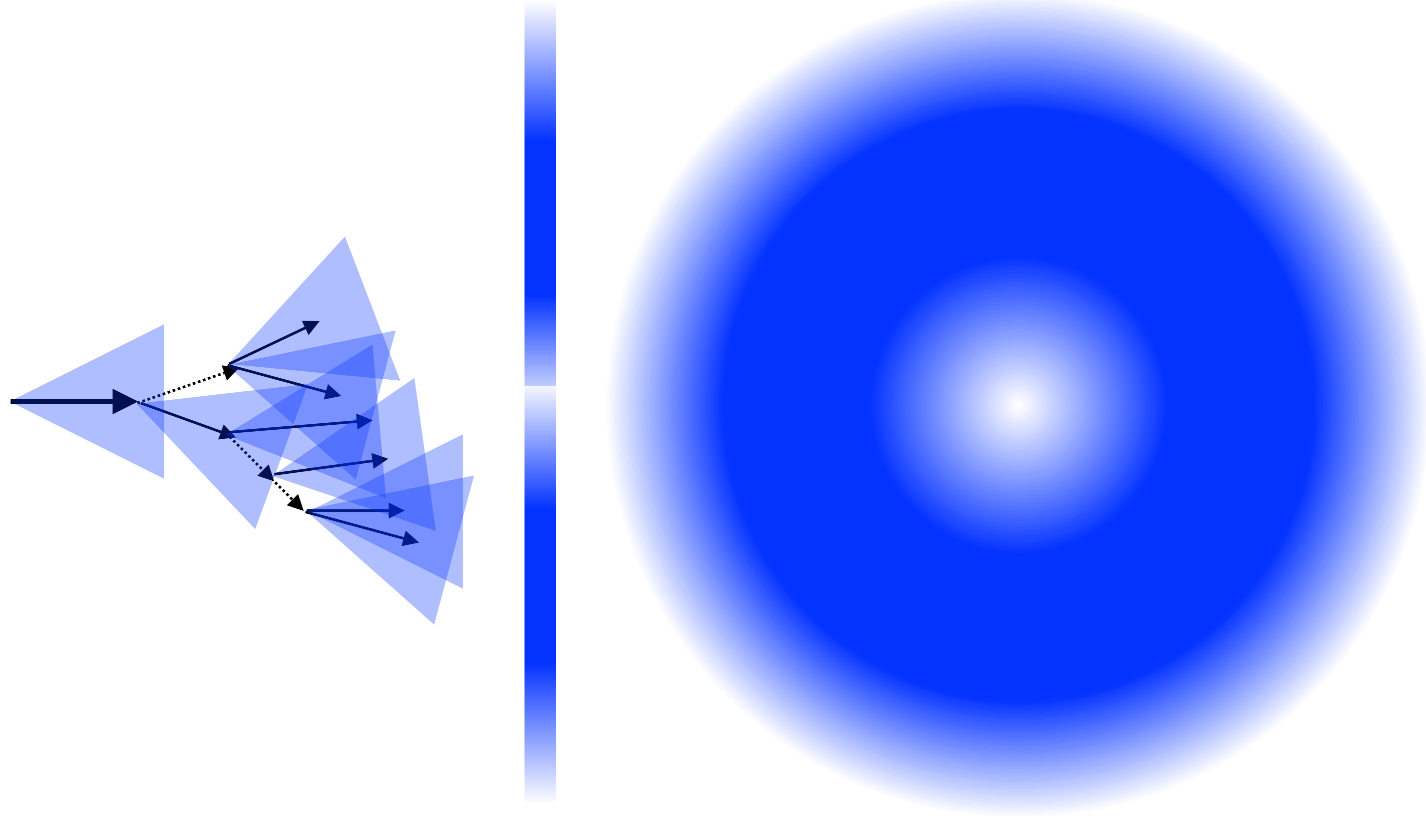
RING TOPOLOGIES

- Other processes as charged particles passes through media
- Ionization loss: steady energy transfer by ionizing atoms.
- Bremsstrahlung:
  - high energy photon emission from acceleration in field of atomic nucleus
    - Photon can then Compton scatter, pair produce, inducing cascade
    - “Electromagnetic shower”
- Č Ring can tell us:
  - position/direction/energy of the particle “track reconstruction”
  - identify the particle as non-showering (μ, π, p) vs. e/γ

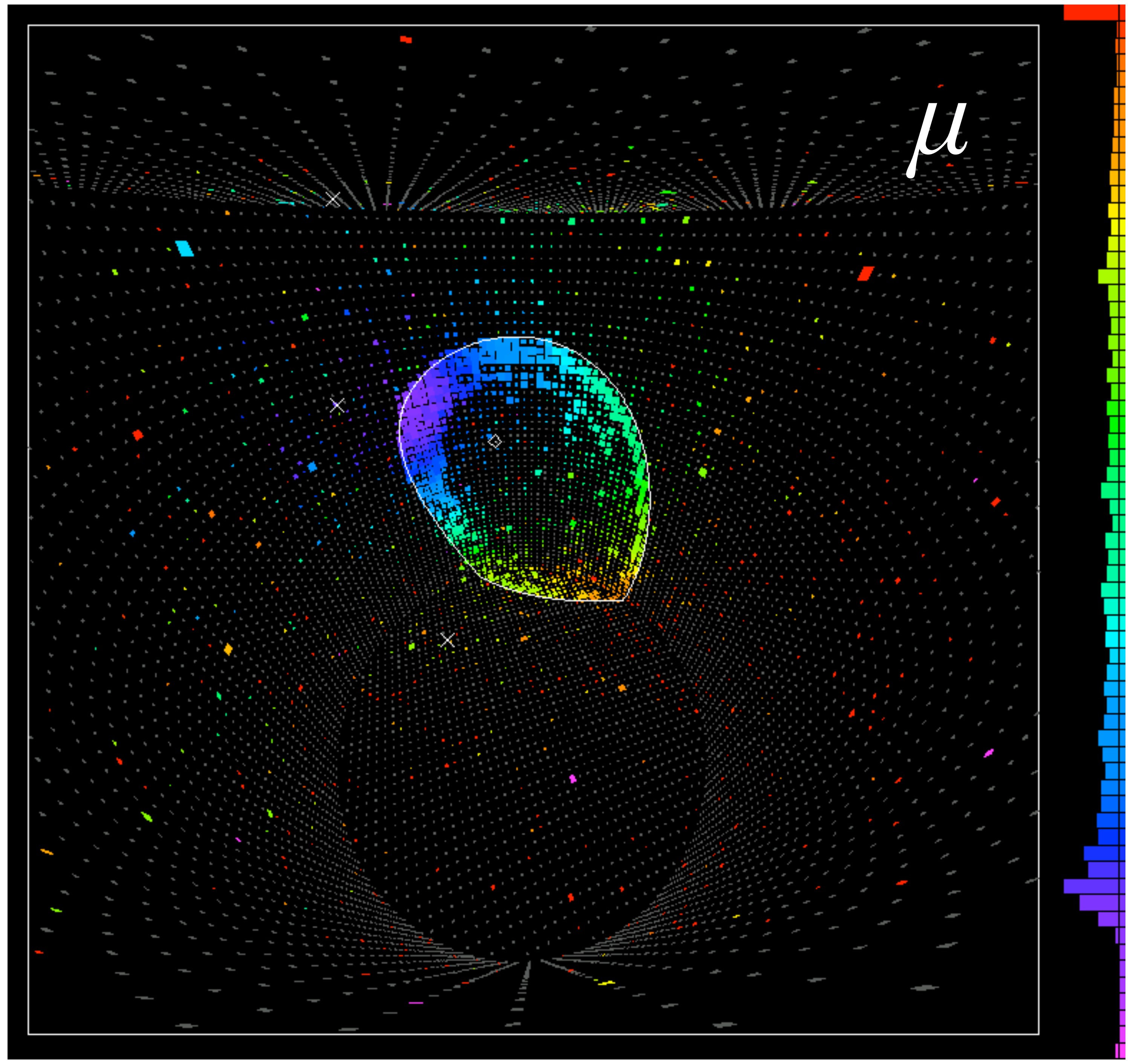


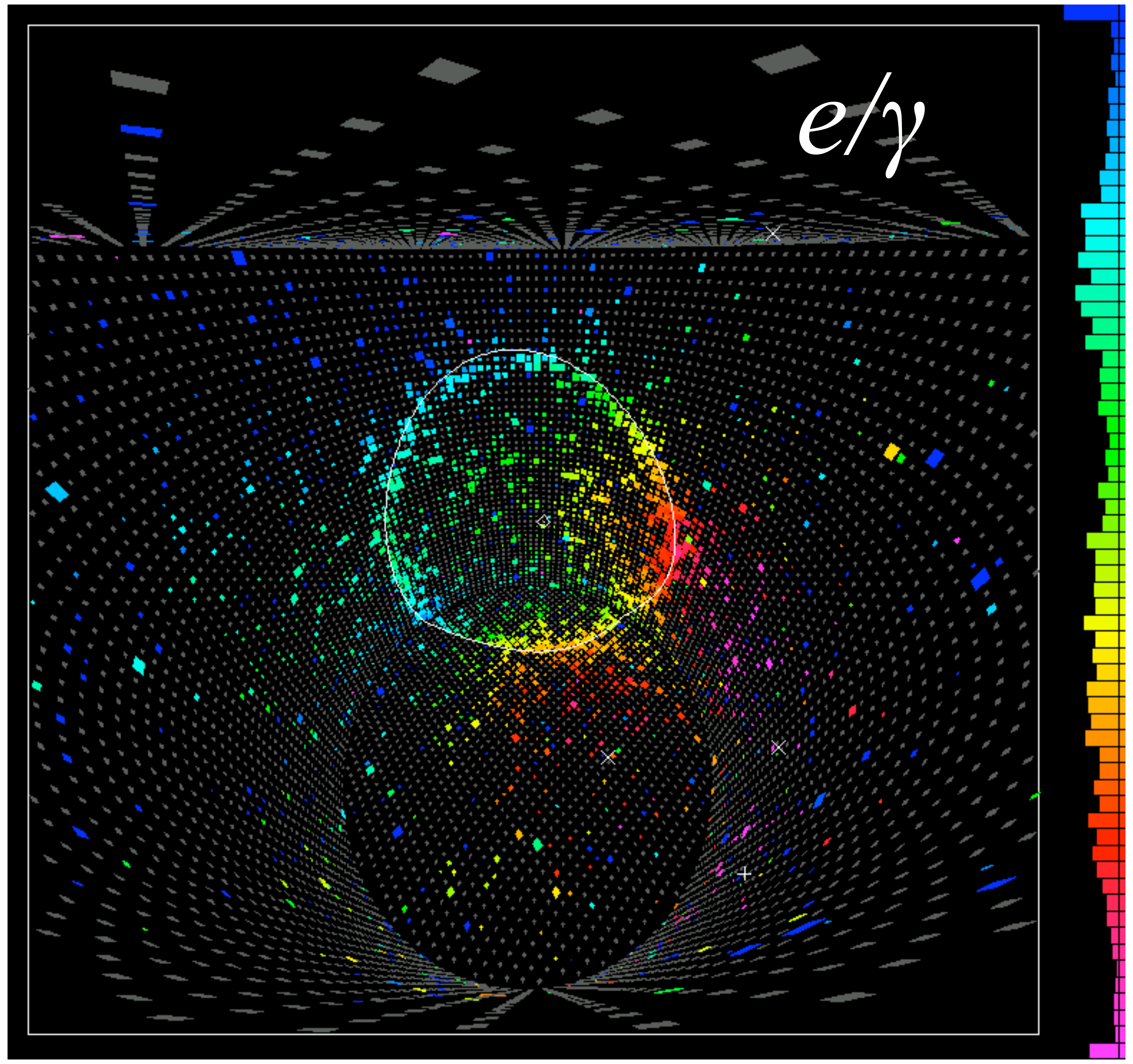


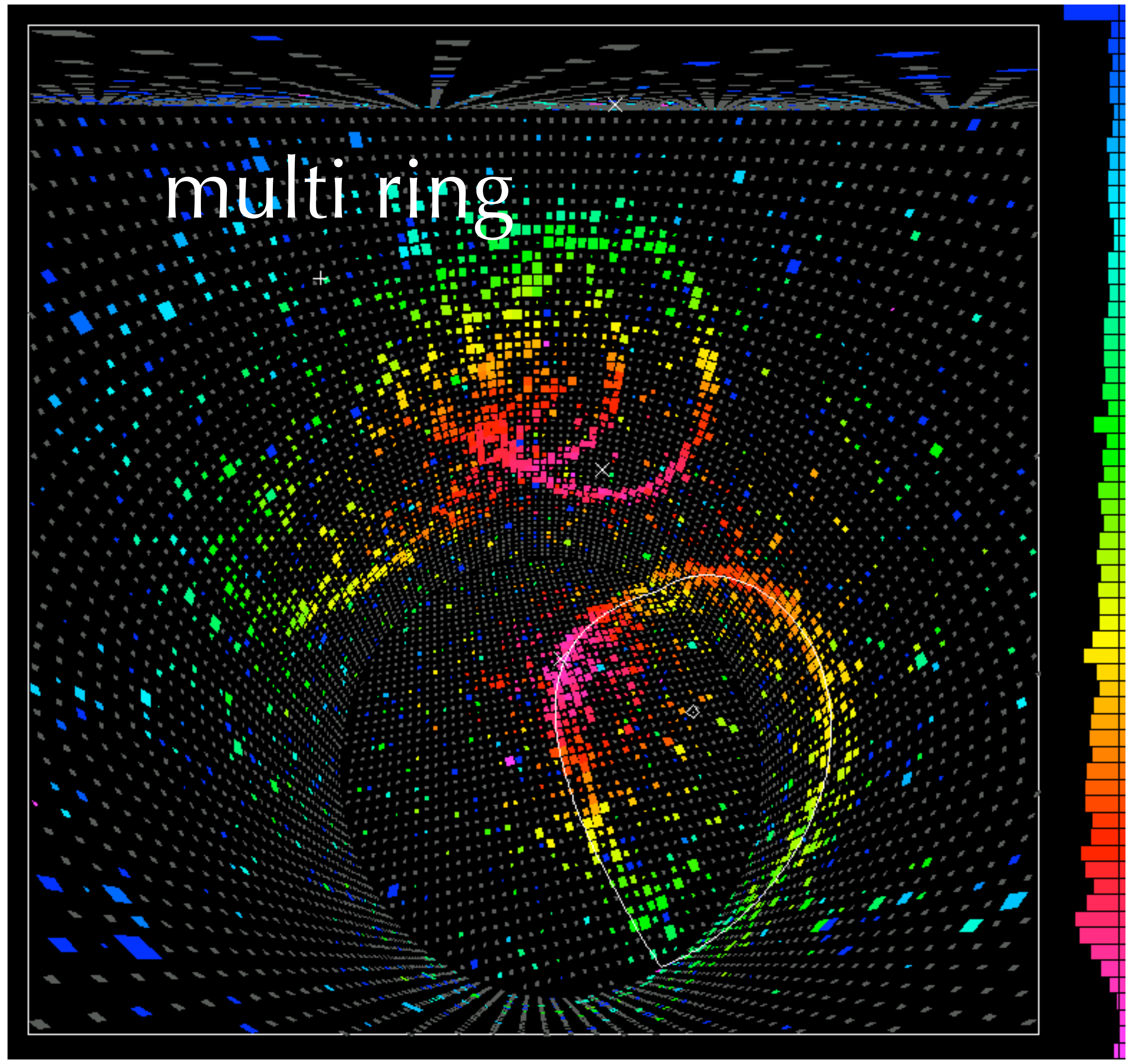


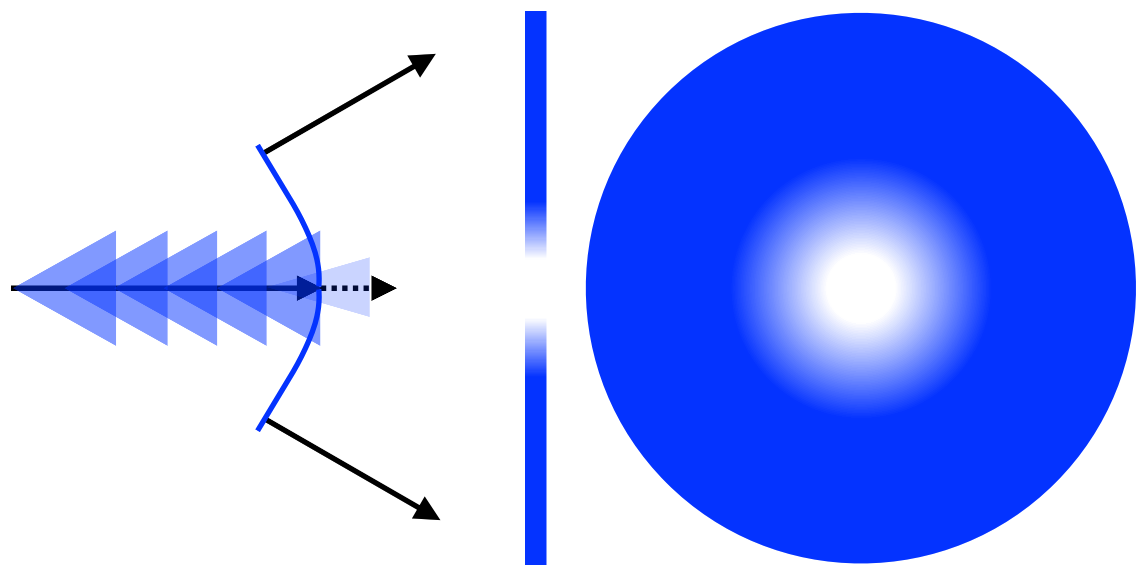


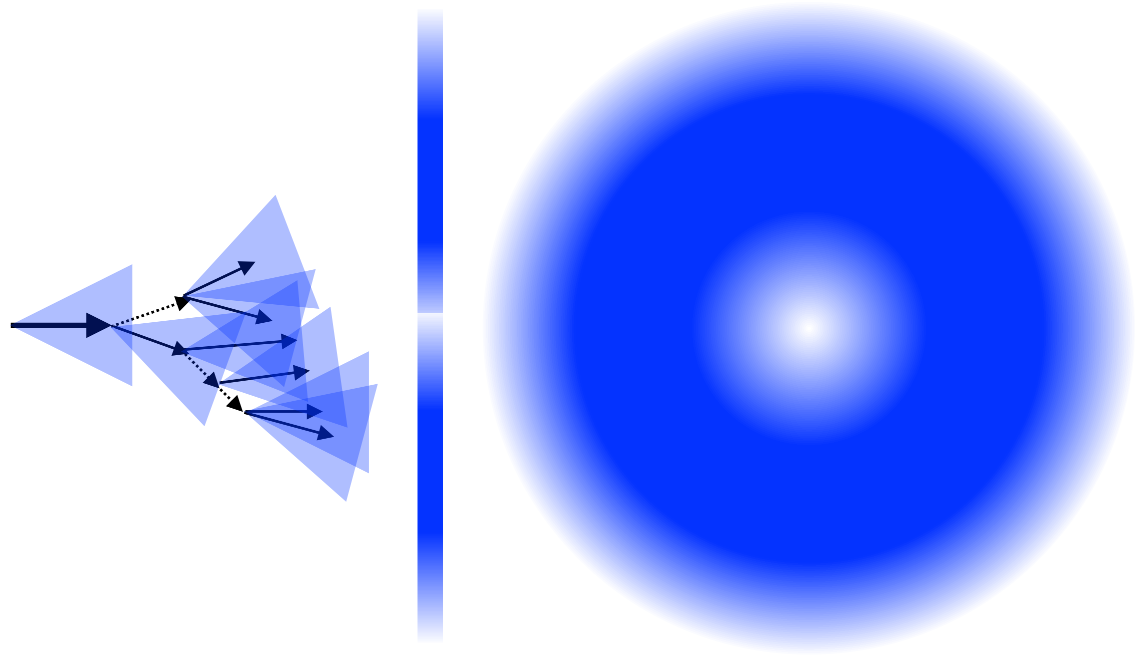
SUPER-KAMIOKANDE IN ACTION











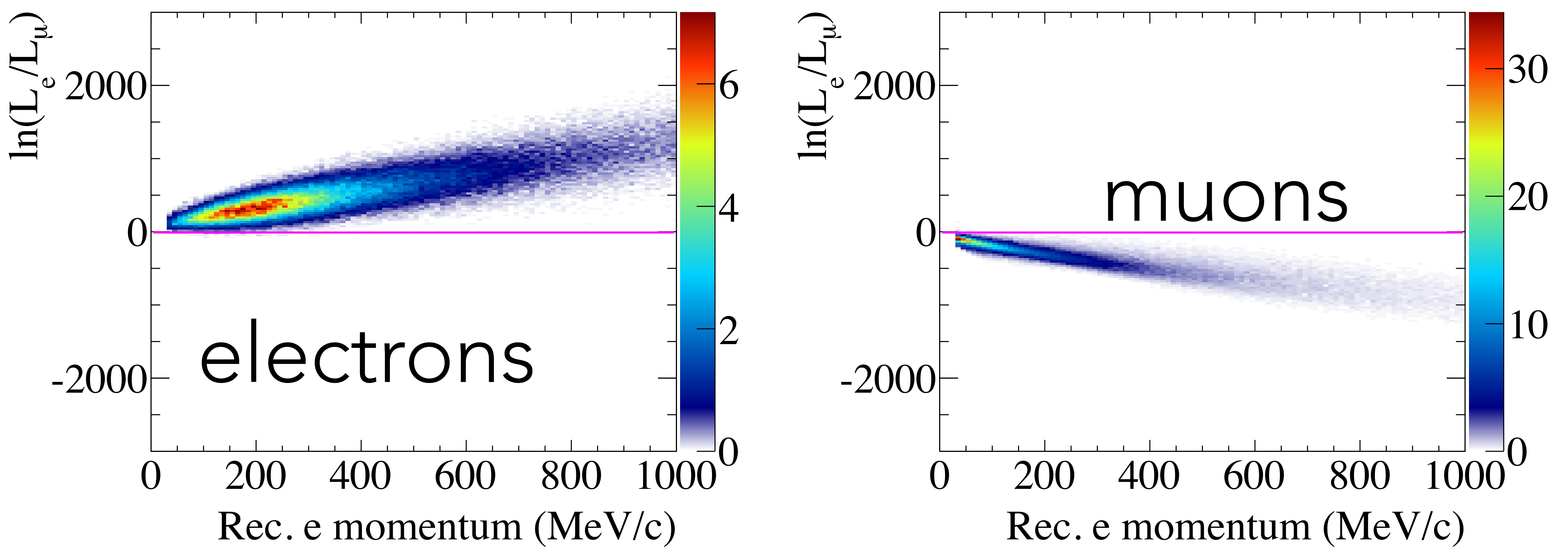
PERFORMANCE

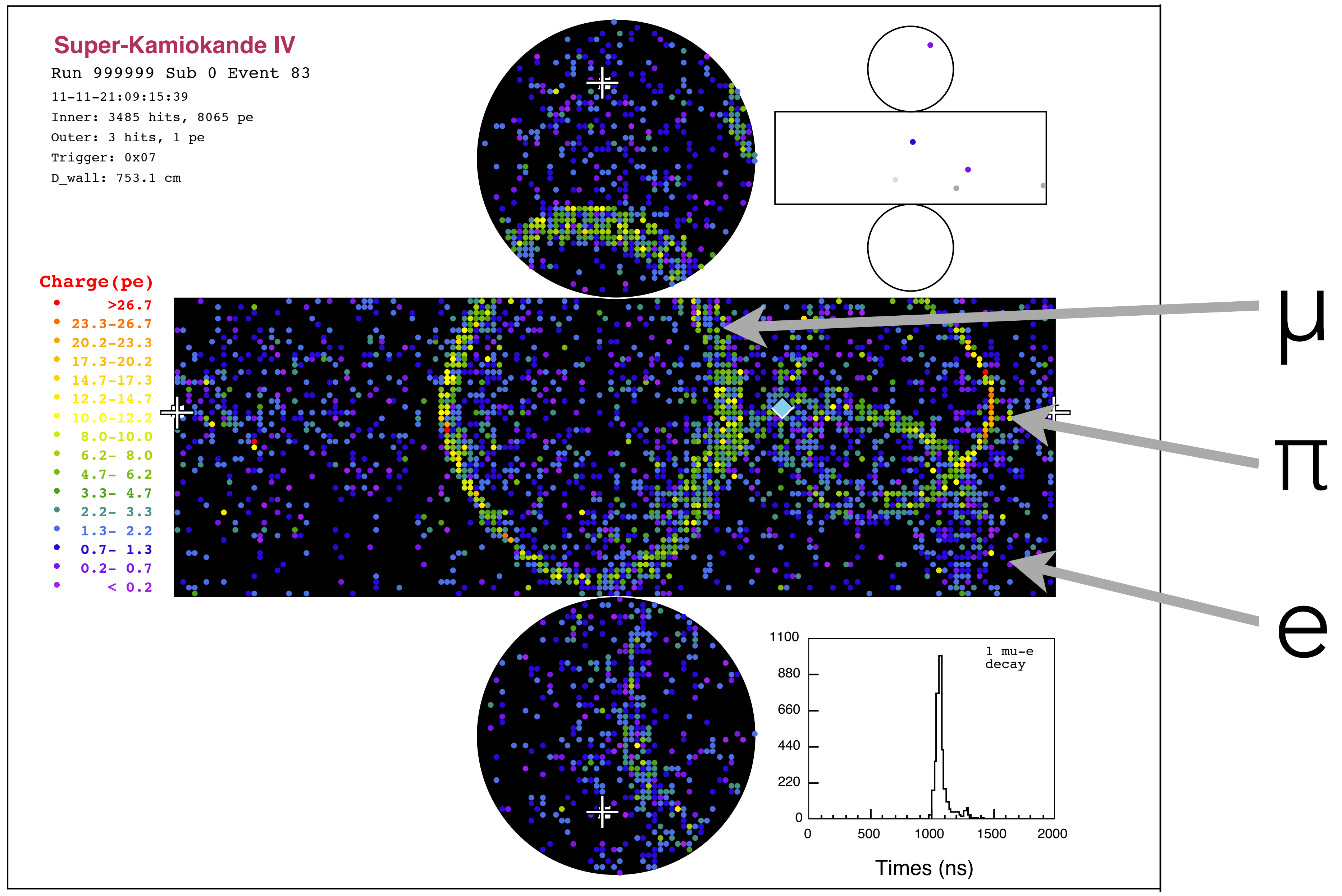
- Vertex resolution ~20 cm, angle ~few degrees
- For low multiplicity (1-2 rings)
  - <1% misidentification of e↔μ
  - few % misidentification of $\pi^0 \rightarrow e$
- Historically, focused on 1 ring topologies
  - overlapping rings pose reconstruction challenge
  - recent progress in multi-ring reconstruction
- Notes:
  - particles below Č threshold can't be directly detected. For water:

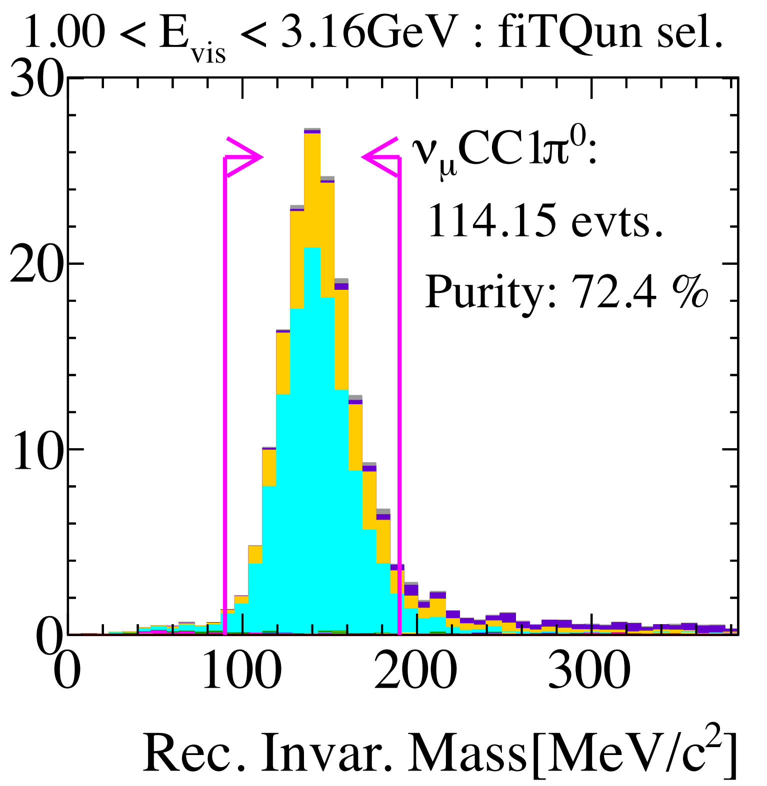
	$\mu^\pm$	$\pi^\pm$	$K^\pm$	p
p_{thr} (MeV/c)	120	160	550	1050

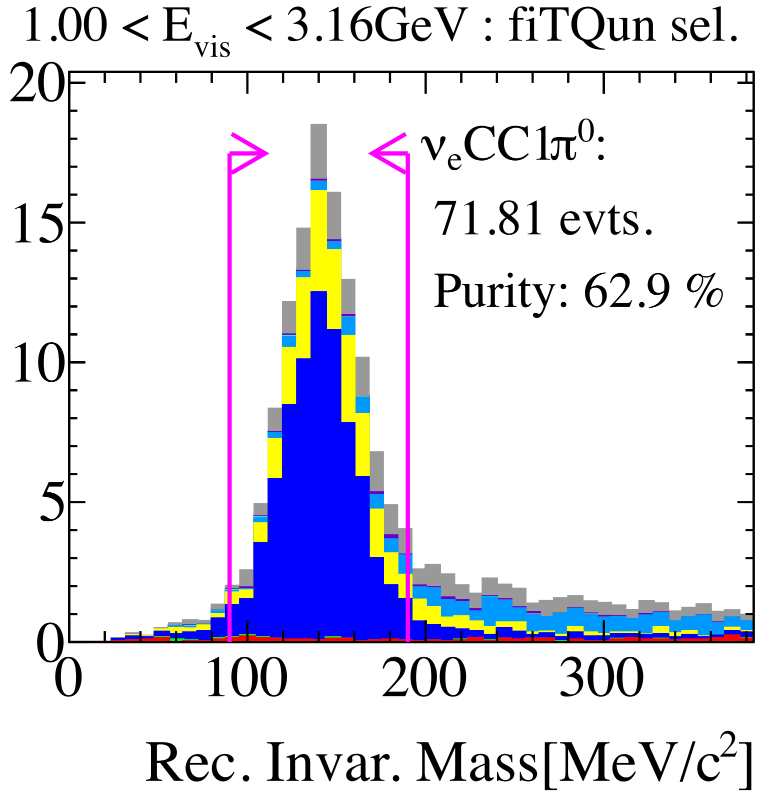
  - e/γ separation difficult/impossible
  - "Michel" electron ((π)→μ→e))
    - clean and independent tag of π, μ via timing
    - τ_μ > typical light transit times

e/μ identification at SK



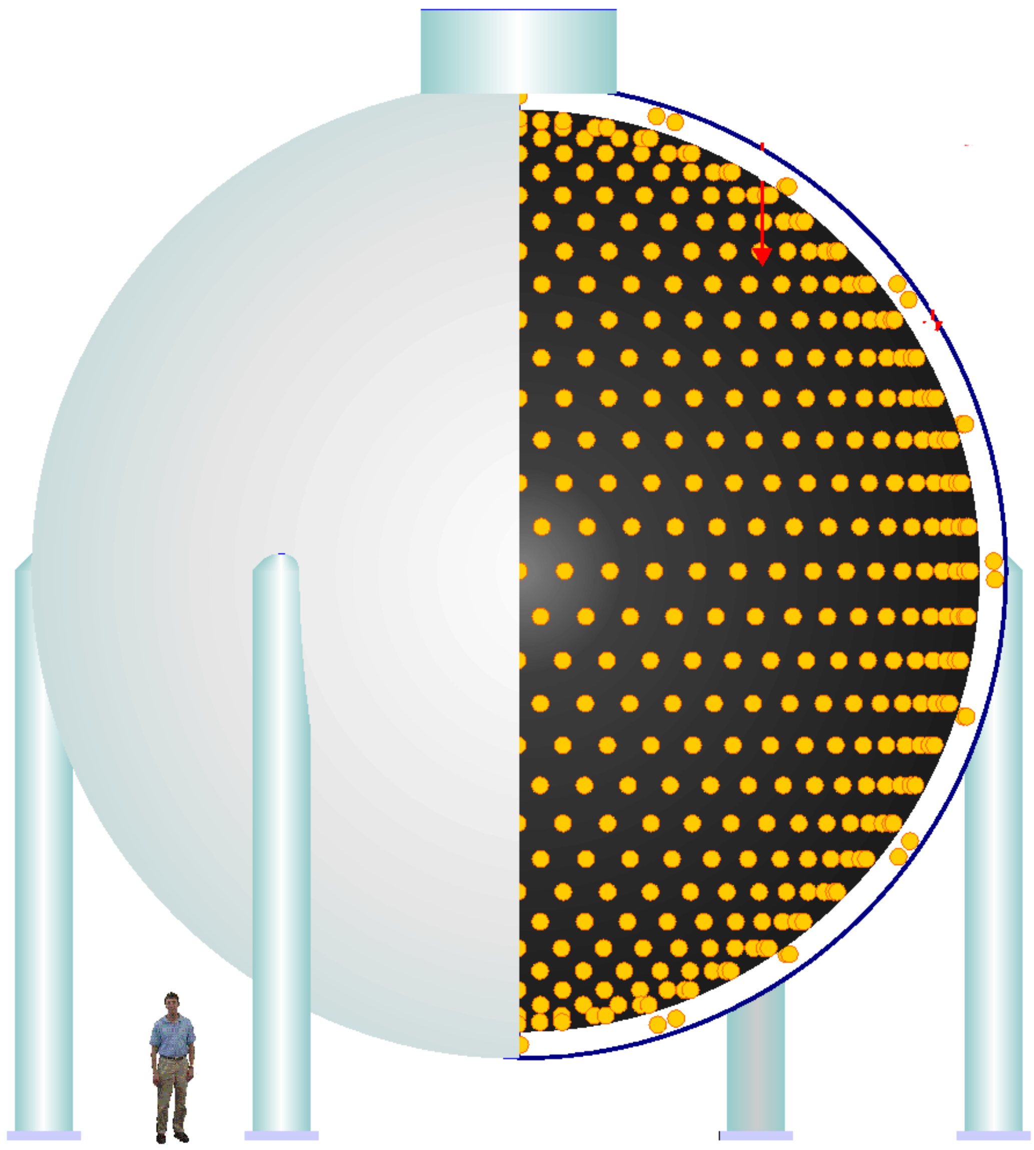


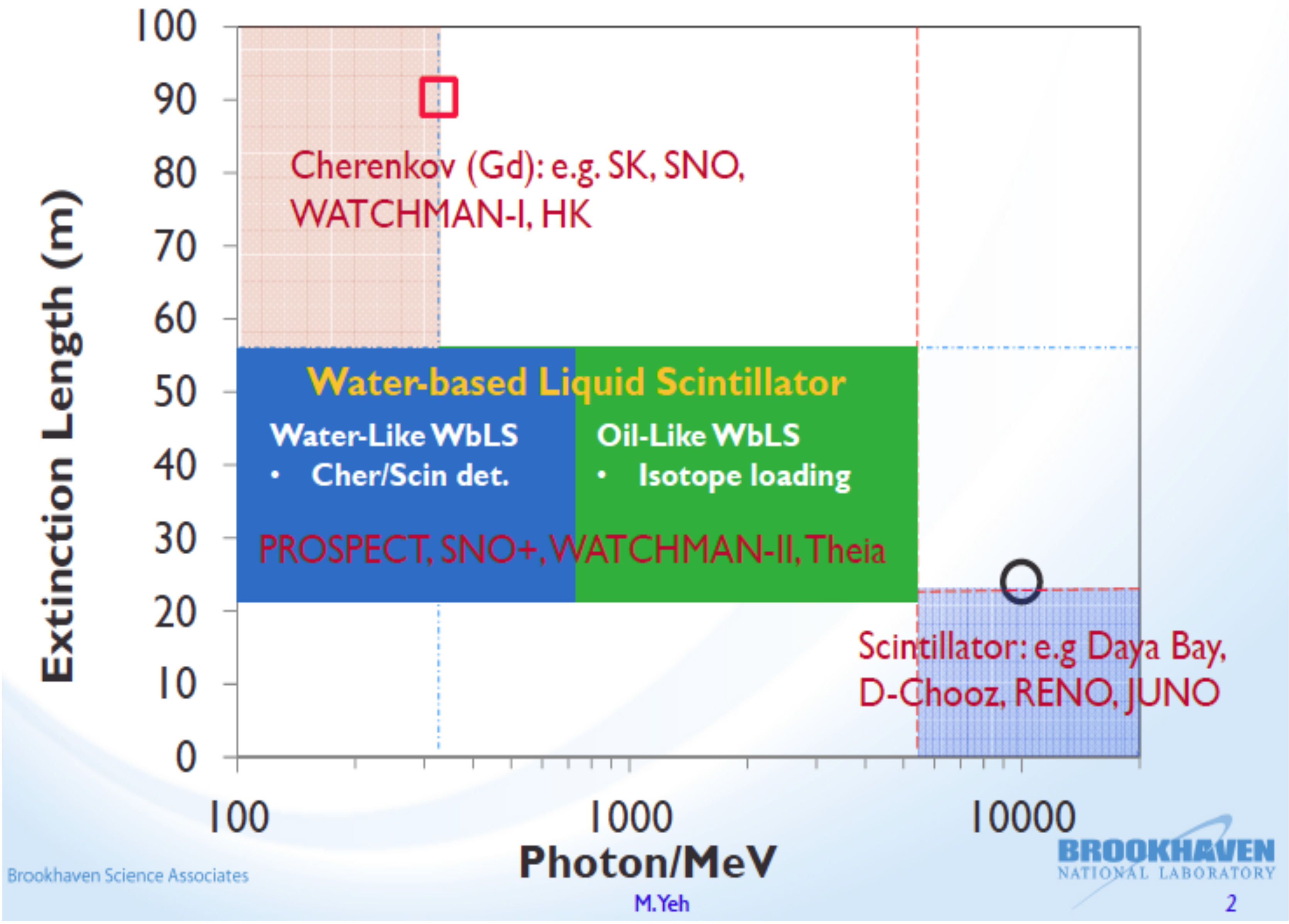


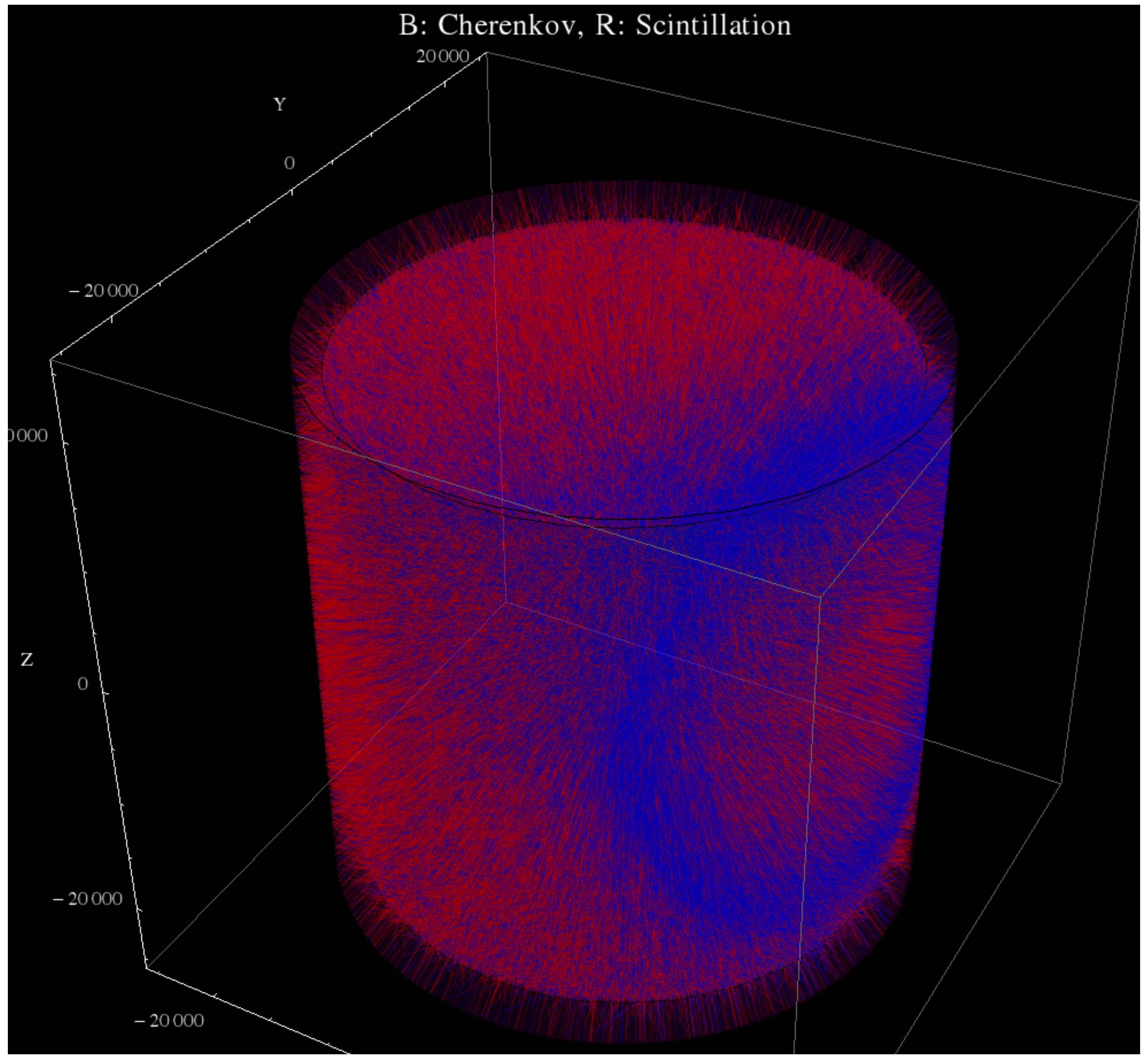


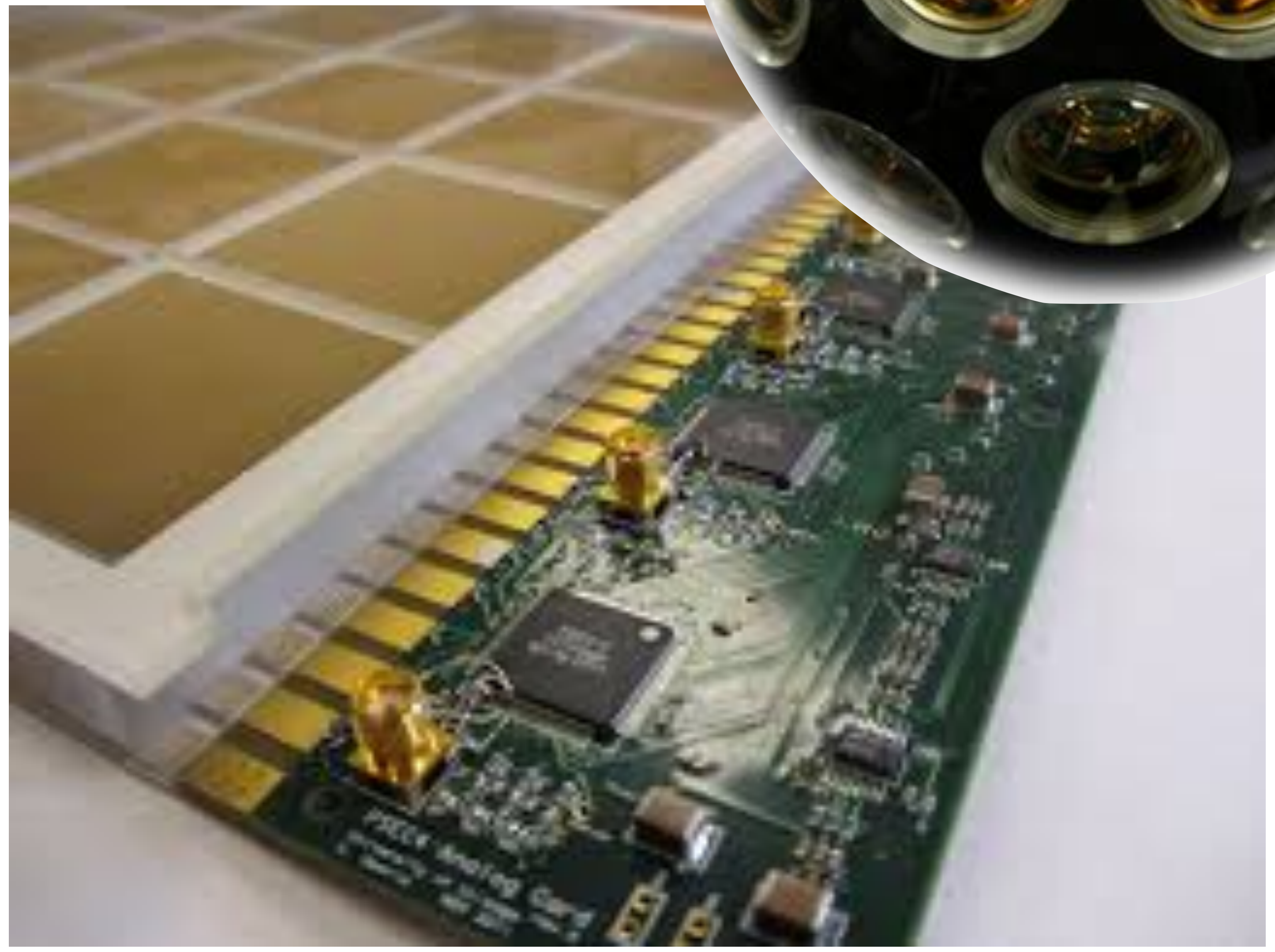
VARIATIONS

MiniBooNE Detector







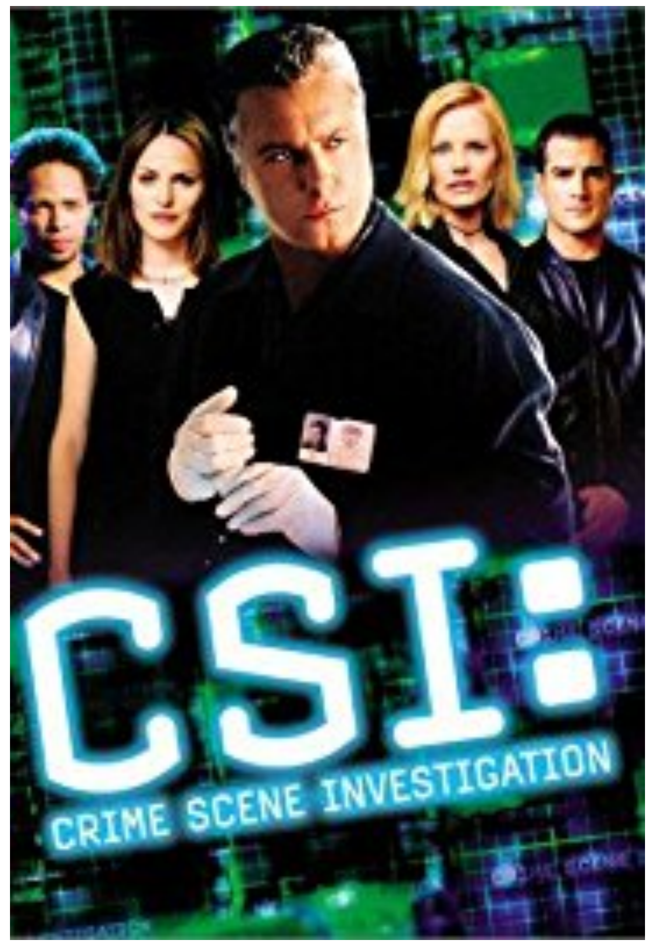


- Cherenkov + Scintillation medium
  - mineral oil, water-based liquid scintillator
- Photosensor technology/techniques
  - Large Area Picosecond Photon Detectors
  - Modular arrays of 3” PMTs

ACT 2: SCINTILLATING TRACKER DETECTORS

PRINCIPLE:

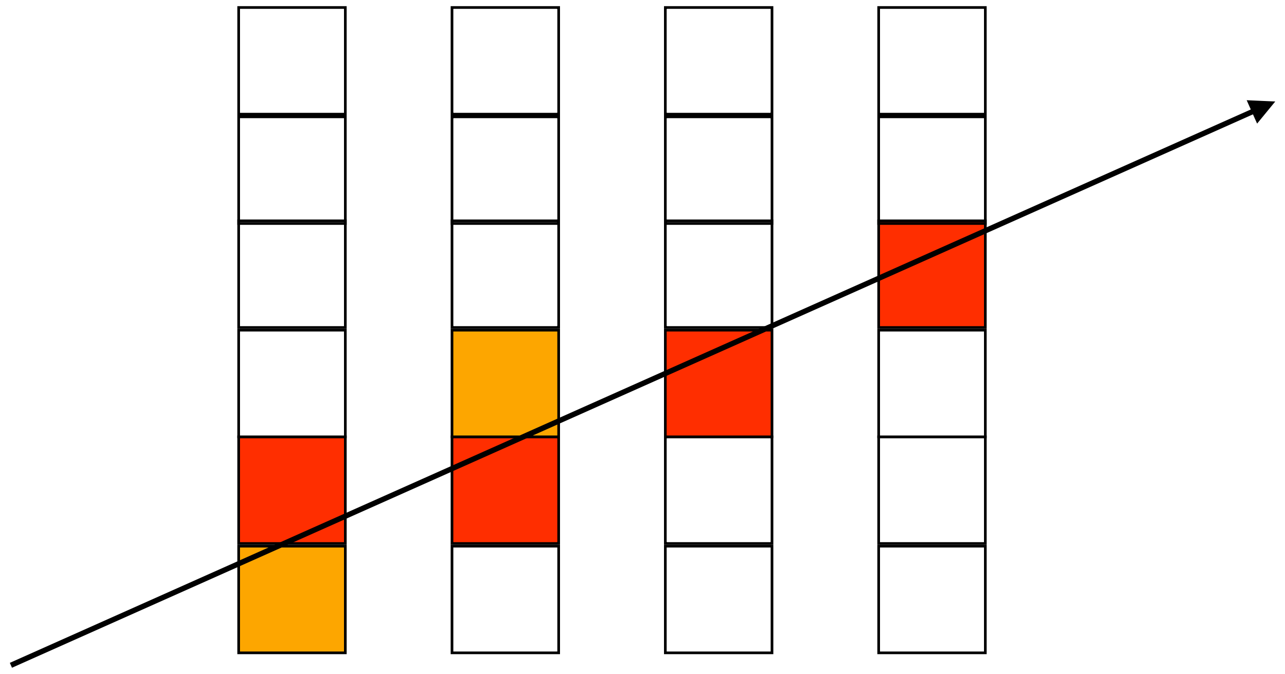
- Many hydrocarbons and organic compounds scintillate or fluoresce
  - your fingernail (keratin) under UV light
  - polystyrene
  - mineral oil
  - .many organic solvents
- A charged particle can be detected by the scintillation induced by its ionization through the material
- By segmenting, the particle can be localized



Catherine Willows: Okay, so... knives, screwdrivers, ice pick, letter opener. We're looking for a weapon with a splash of mineral oil. I'll grab the ALS.

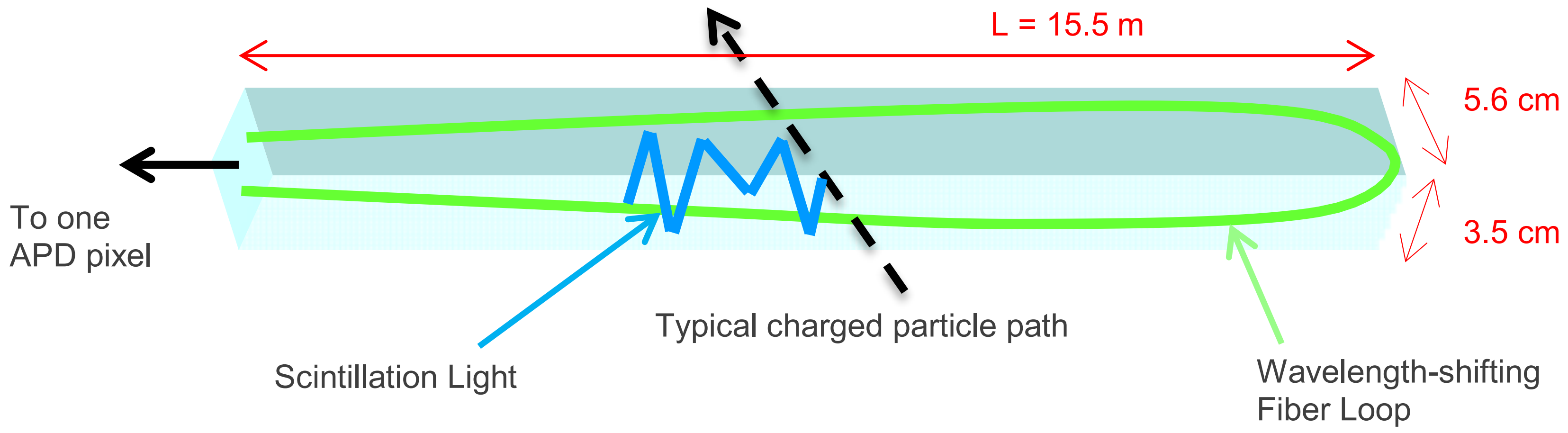
Greg Sanders: An ALS. For mineral oil?

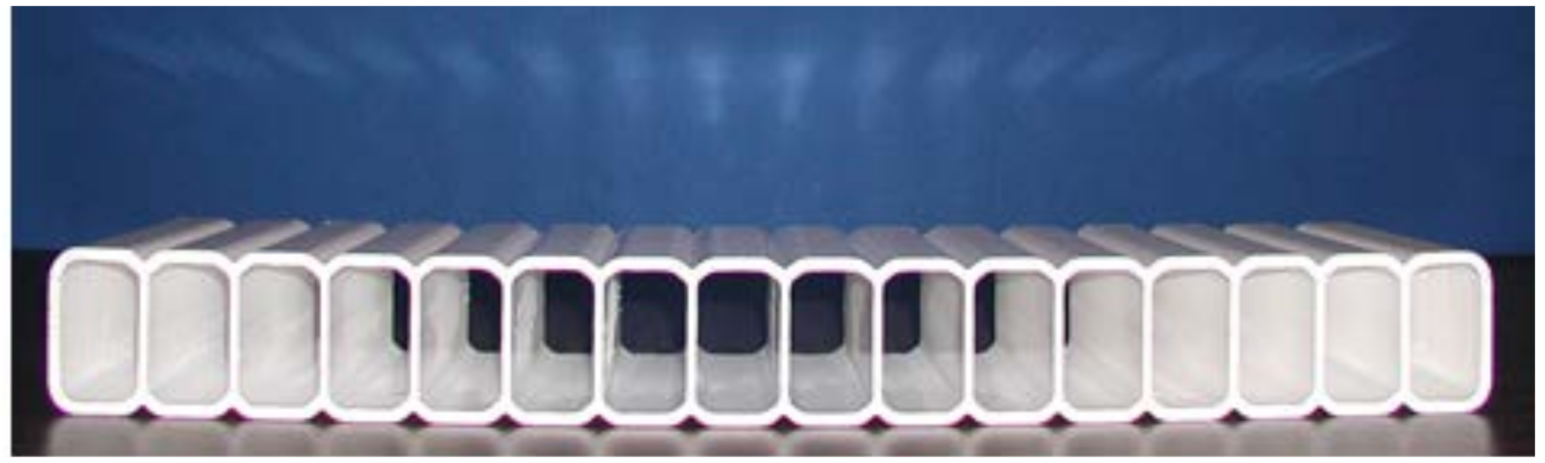
Gil Grissom: Mineral oil fluoresces at 525 nanometers when filtered through a kv590. A little more absorbing... a little less rock and roll.

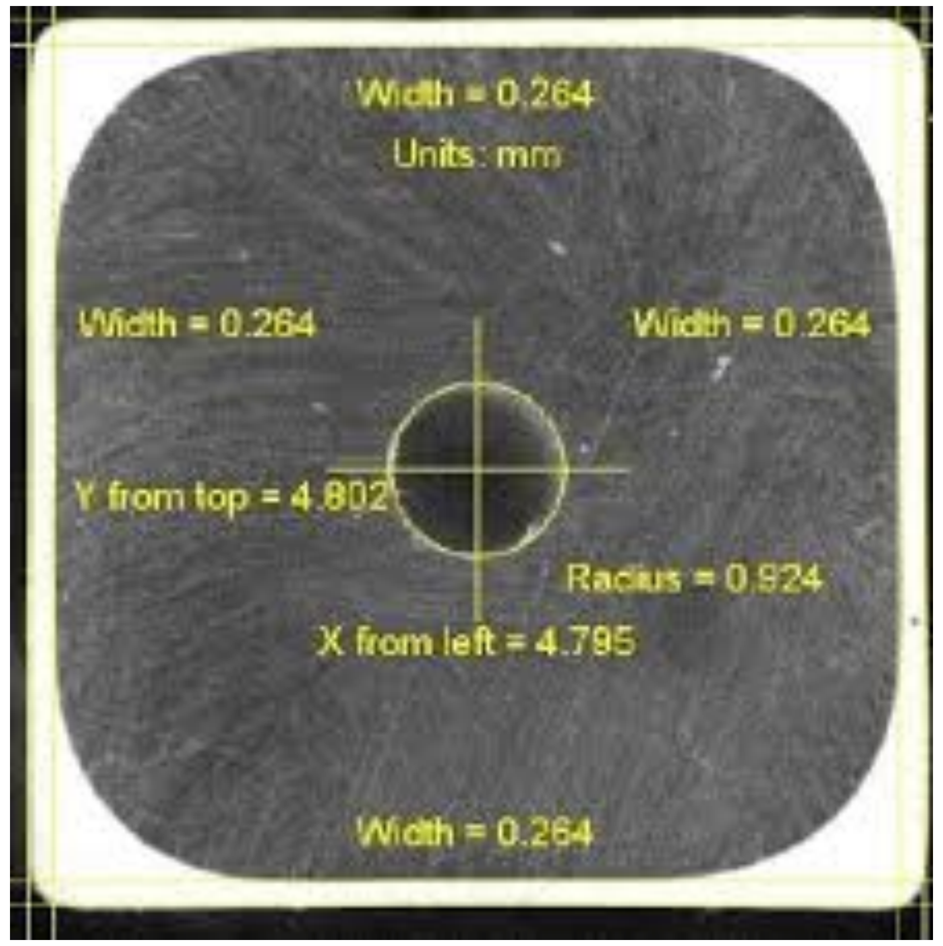


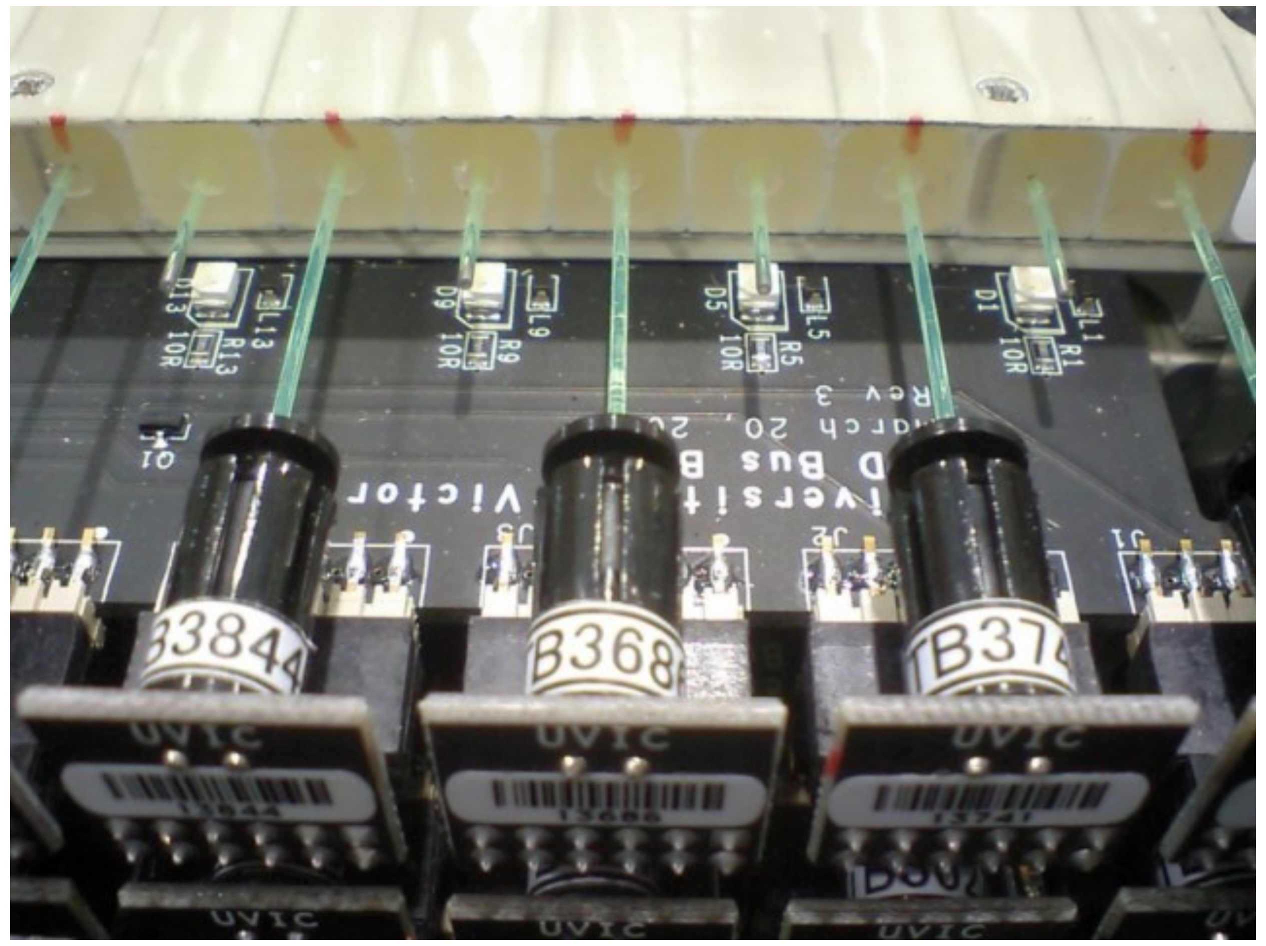
- Optical issues:
  - scintillating material may not transmit light efficiently
  - wavelength of emission may not match photosensor sensitivity
  - solution: wavelength shifting fiber
- Channel issues:
  - large number of channels from the segmentation (expensive, large?)
  - solution: cheap photosensors (SiPM, multimode PMTs)

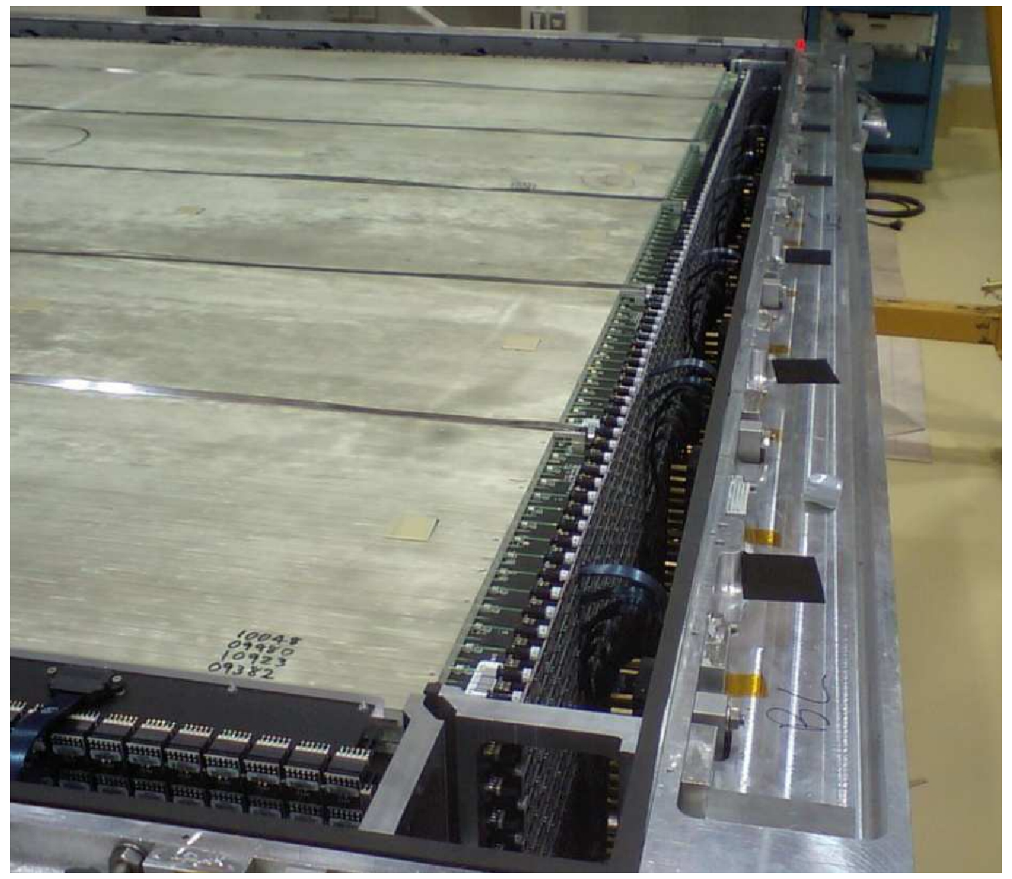
EXAMPLES:

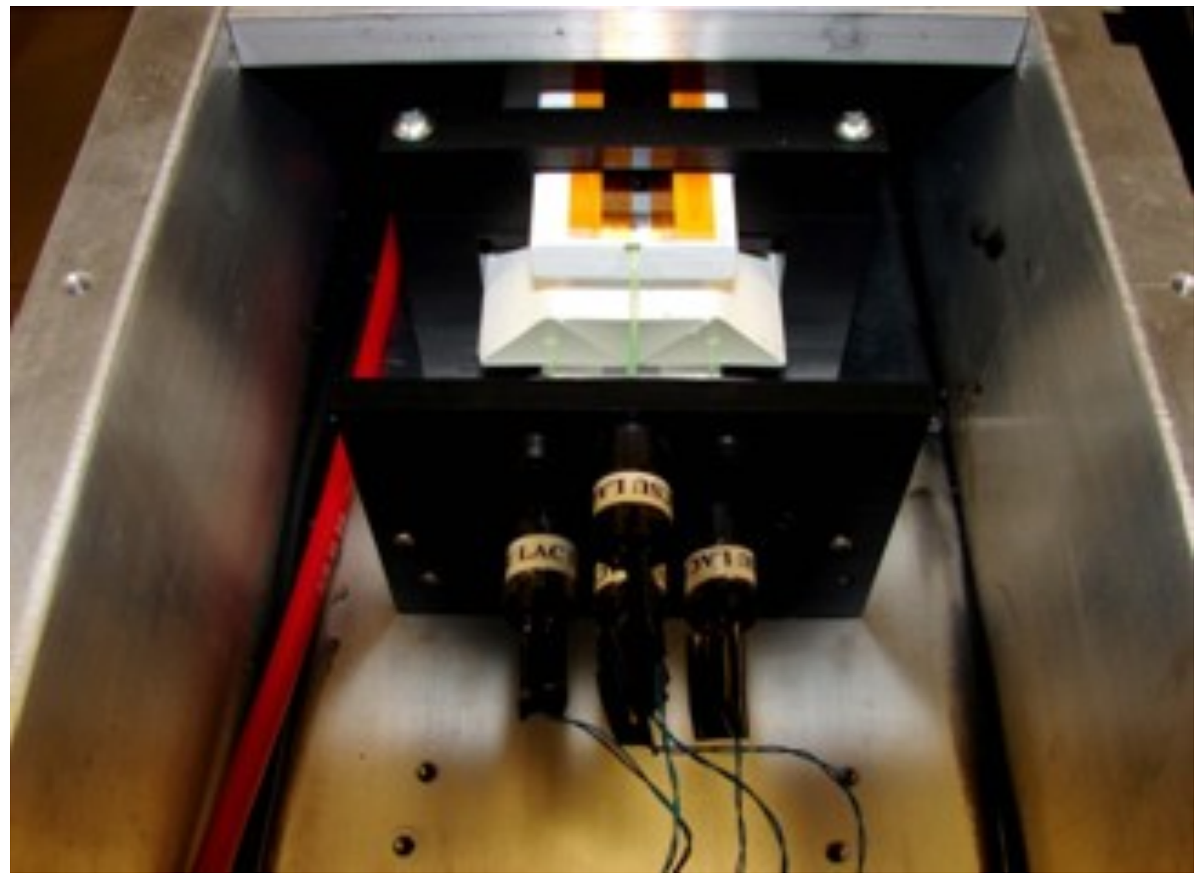












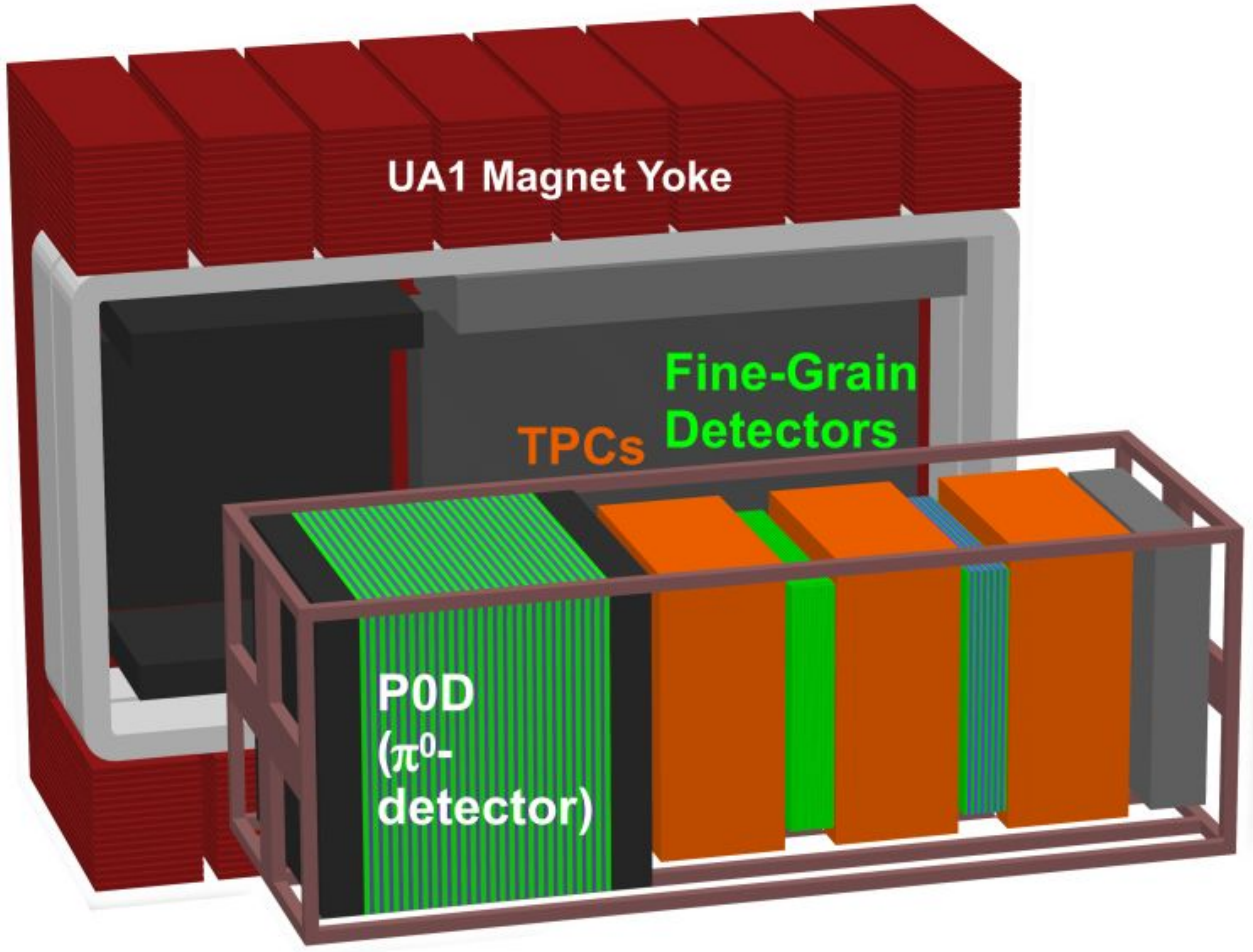
NOvA liquid scintillator cells

- (4 x 6 cm$^{2)}$ x15.6 m-long, 16 cell extruded PVC modules
- pseudocumene/mineral oil scintillator
- long fiber looped through cell coupled to APD
  - 13,000 km of fiber for detector!
  - 344,000 cells in total
  - 15 x 15 x 60 m^3 overall size

T2K ND280 Near Detectors

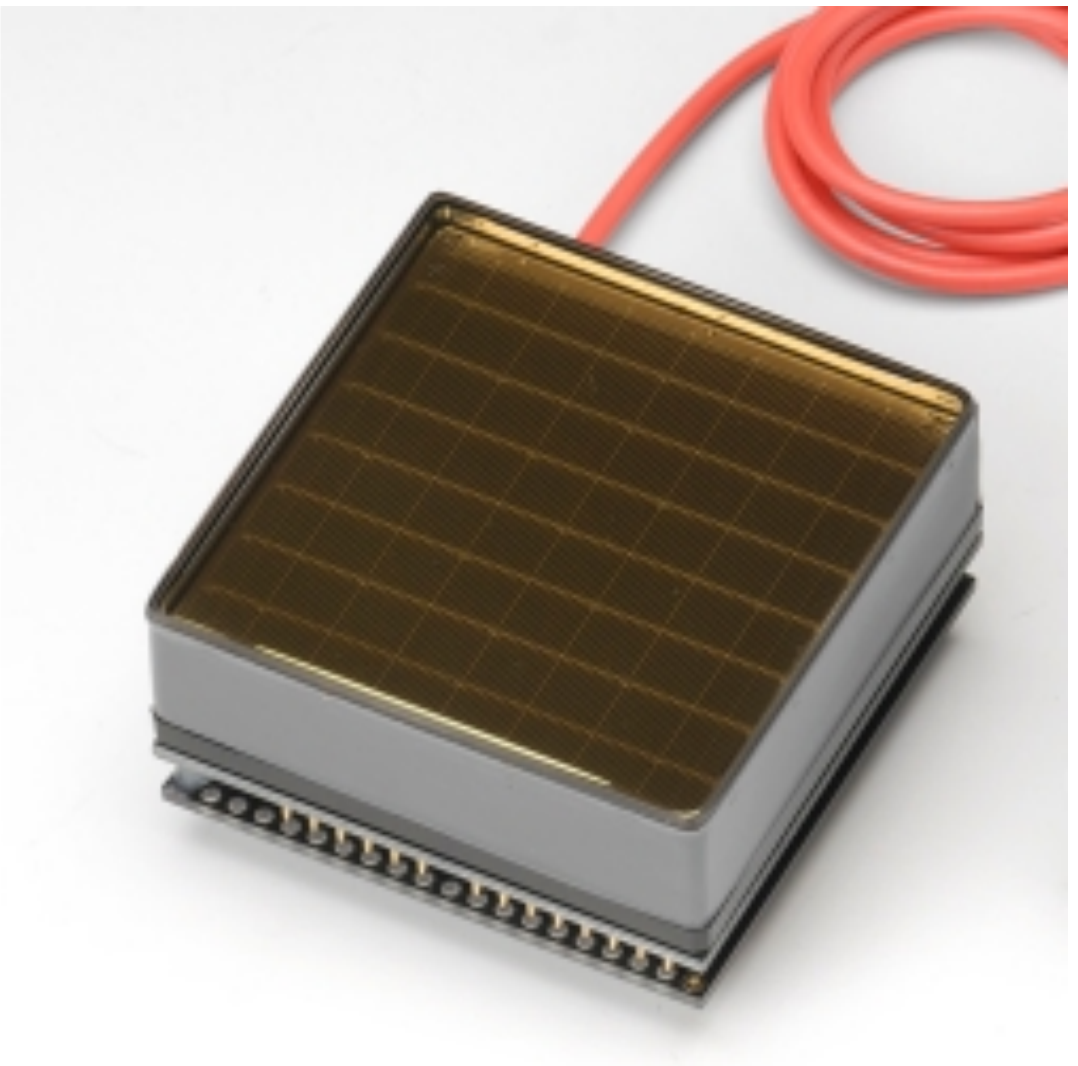
- Extruded polystyrene bars coated with TiO_2
  - 1 x 1 x 200 cm^3 extruded polystyrene bars coated with TiO_2
  - “triangular bars
- Bars are threaded with a wavelength shifting fiber coupled to SiPM

HYBRID



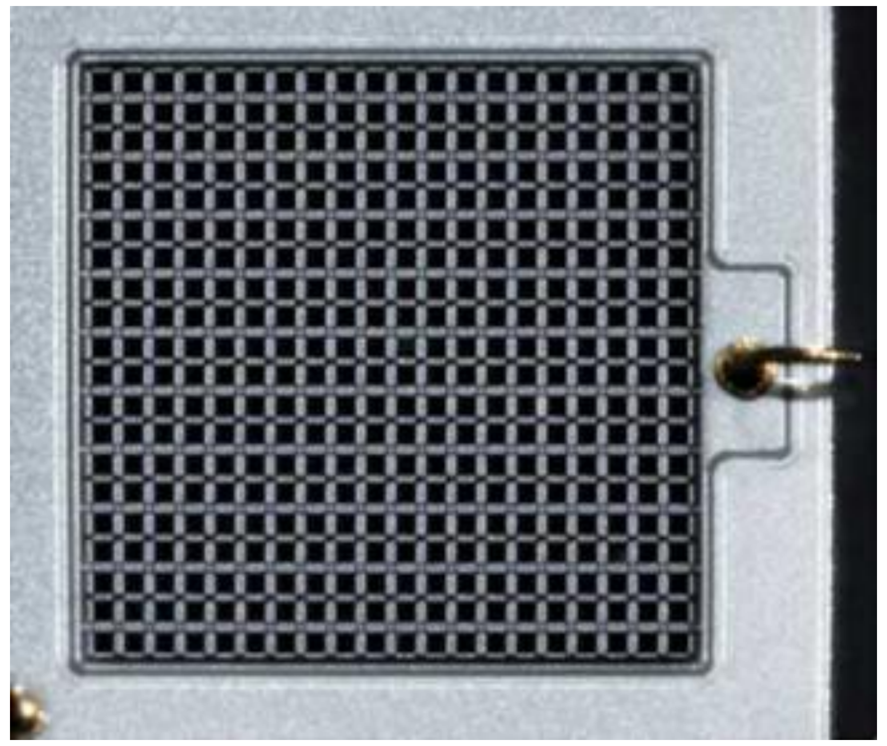
- Scintillator can be combined with other materials and detector technology
- Left: MINOS Iron/Scintillator tracking detector
  - scintillator is light, so we want more mass → add iron plates as extra (passive) target mass
  - works well for high energy (several GeV) neutrino energies
- Right: T2K ND280 detector
  - scintillator is the (active) target mass! one detector (FGD2) also intersperses water with scintillator
  - complemented by gaseous time projection chambers (with very little mass)

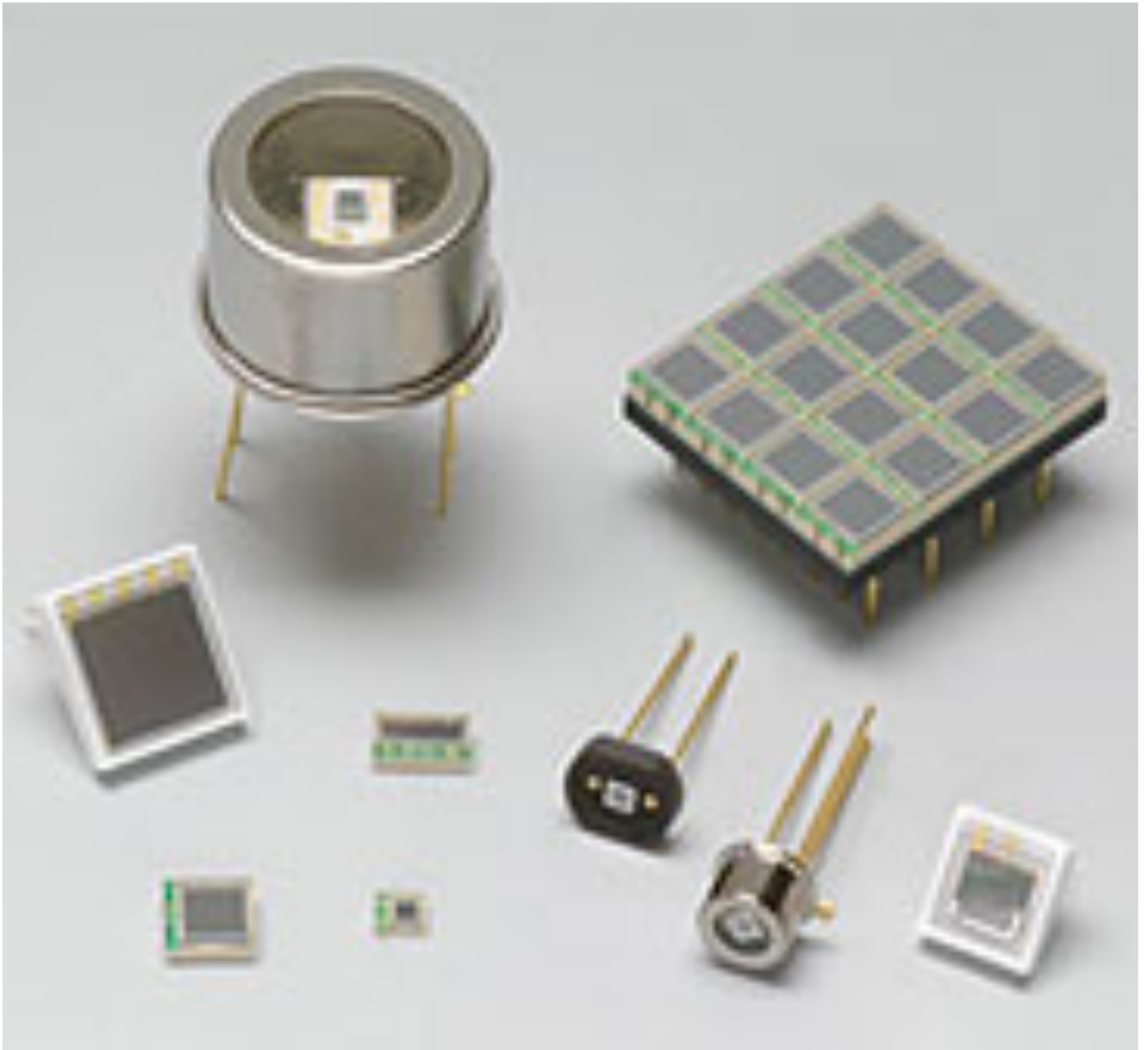
TECHNOLOGY:



- Multi-anode photomultiplier
  - PMT with one photocathode, but multiple anodes
  - readout as one unit
  - allows multiplexed readout of many fibres, but need strategy to demultiplex
  - all the nice properties of PMTs (high gain, relatively low noise, linearity)

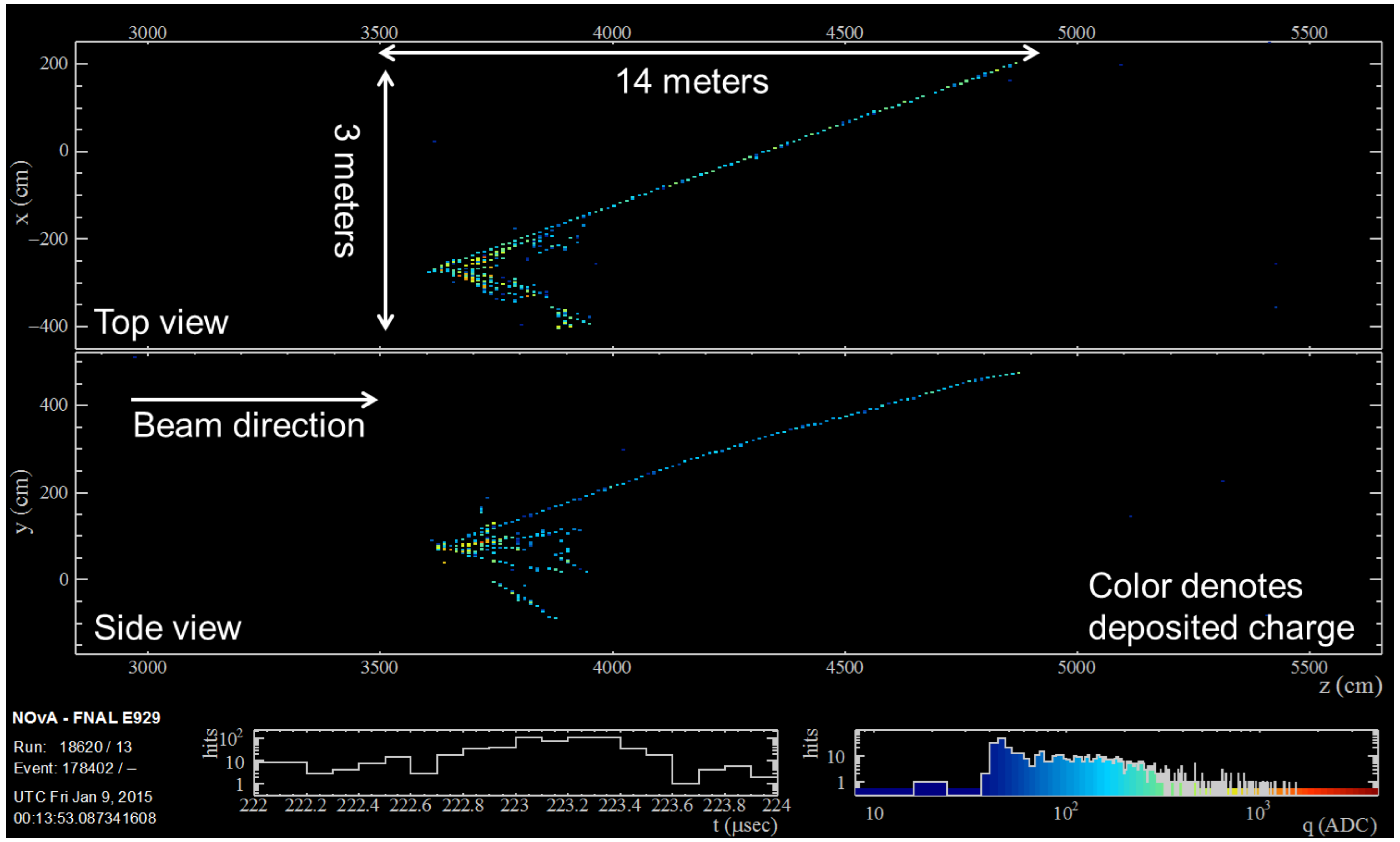
Reduction in cost/channel from O($\$10^{2\text{-}3}$) to O($\$10^{1}$)

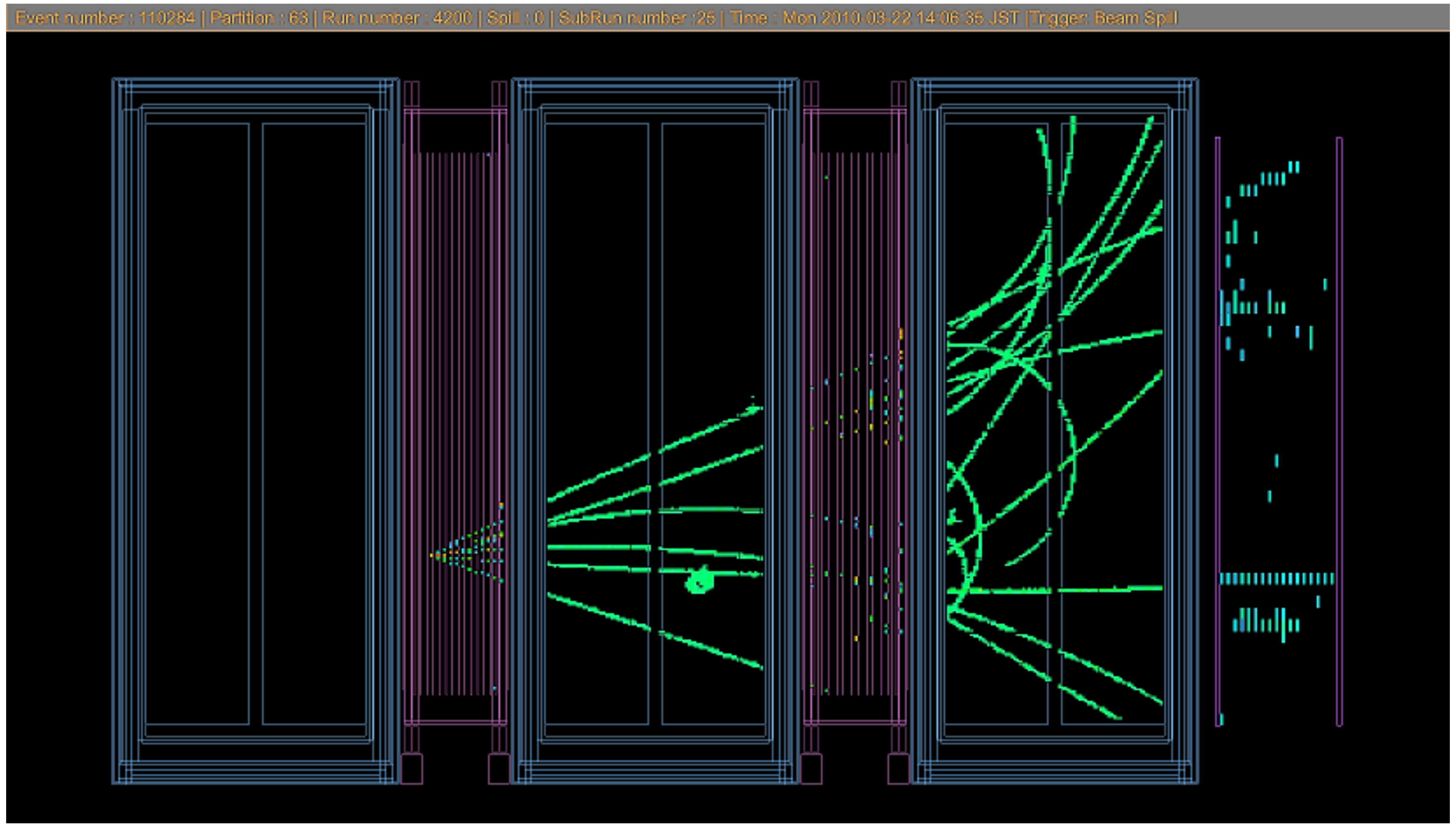




- Silicon photomultiplier
  - Array of several hundred pixels operated in avalanche mode
  - high photodetection efficiency, but lower gain than PMT
  - more noise, but dramatic recent improvements!
  - intrinsic non-linearity due to pixel counting
    - i.e. multiple photons on single pixel has same response as single photon
    - also after pulsing and cross talk across channels (greatly improved!)

EVENTS:

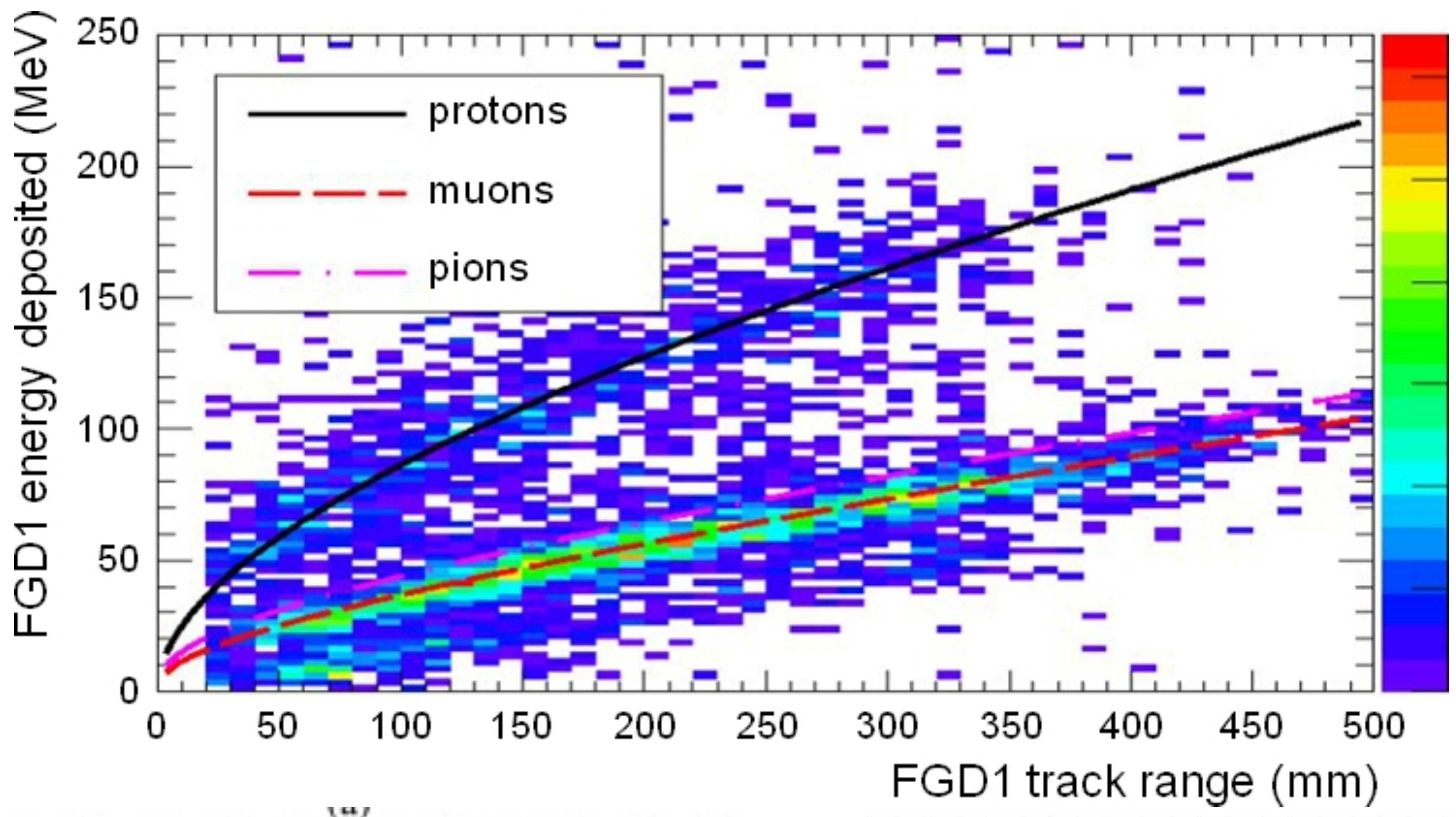


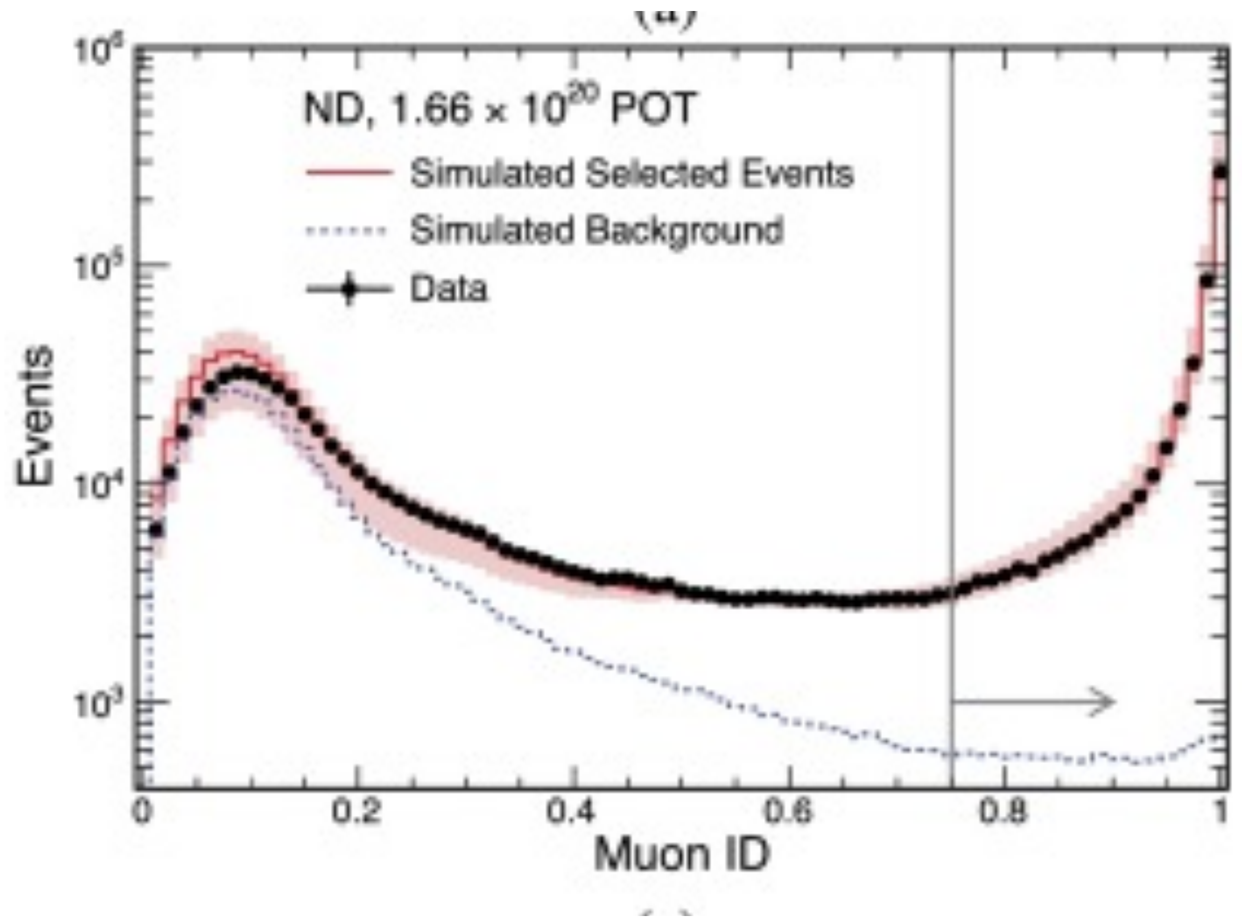


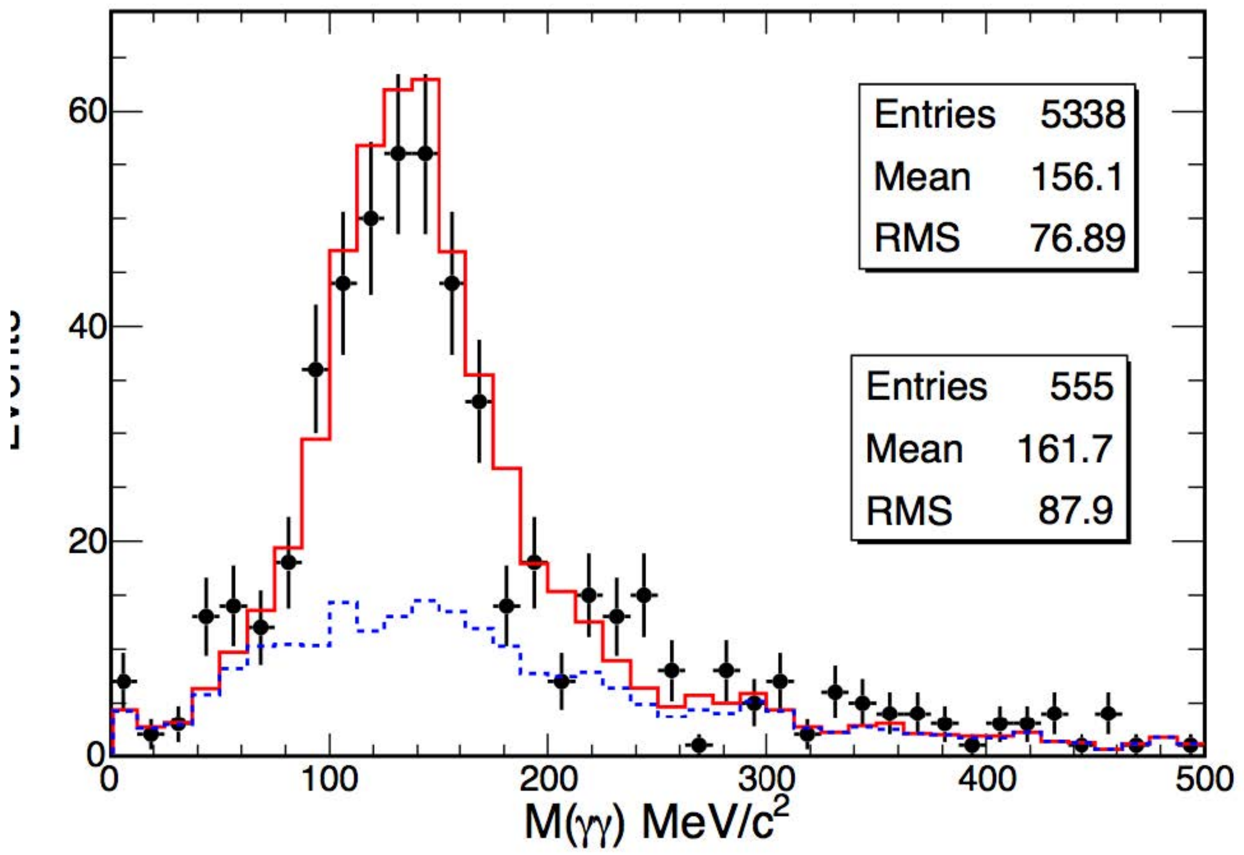
- NOvA ν_μ CC event
  - muon easily identified as long track
  - fine granularity on hadron shower, including resolution of individual tracks
  - timing allows large reduction of cosmic background at surface far detector
- T2K ND280 tracker
  - momentum and particle identification primarily in the time projection chambers (TPCs)
  - scintillator tracker proves precise tracking at vertex, matching to tracks in the TPC

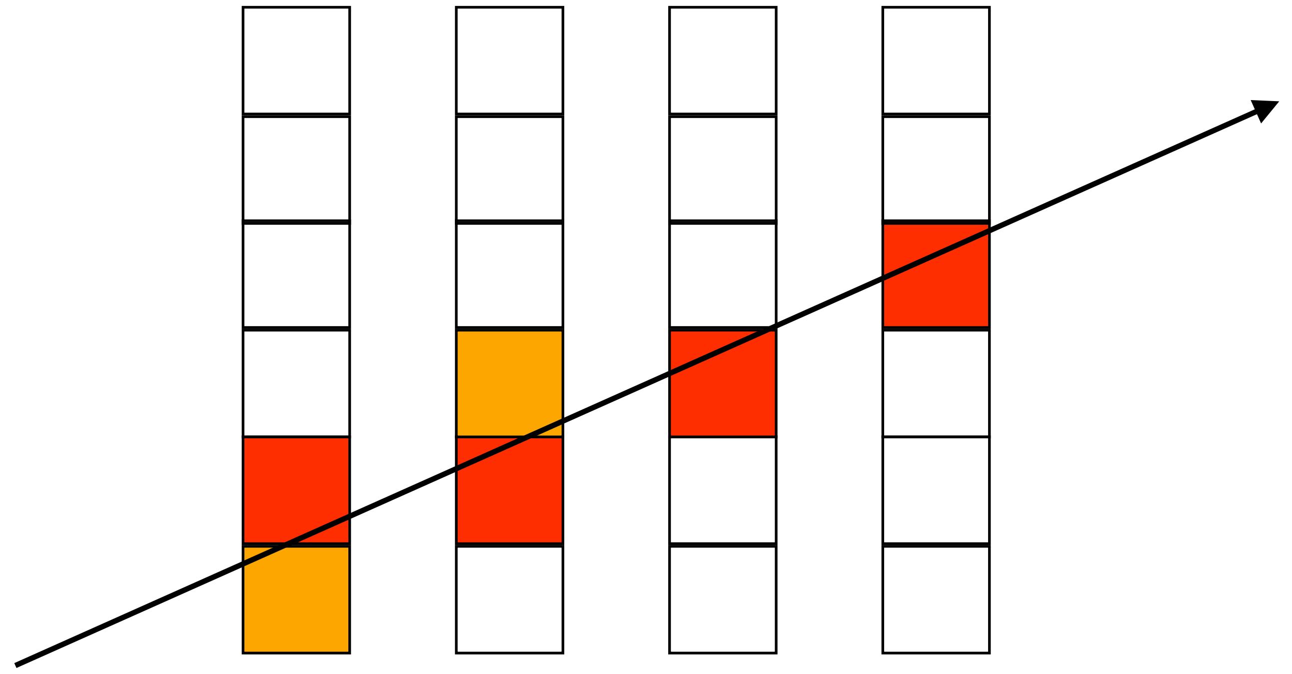
PERFORMANCE:

- Some performance depends on granularity
  - thresholds, vertex, etc.
  - granularity << X_0 achieves excellent particle identification
- Others (may) depend on containment of the event
  - muon fully ranges out in the detector?
  - hadronic/electromagnetic shower contained?
  - recover unconfined particles with another detector?
- Complications:
  - geometry has an “axis”
    - difficult to reconstruct at wide angles to the sampling
      - fewer hits, more distance between hits
      - worse at low energies→more isotropic
  - segmentation usually results in dead material
    - non-active material to isolate scintillator
    - reduces efficiency
    - detailed accounting needed for shower reconstruction



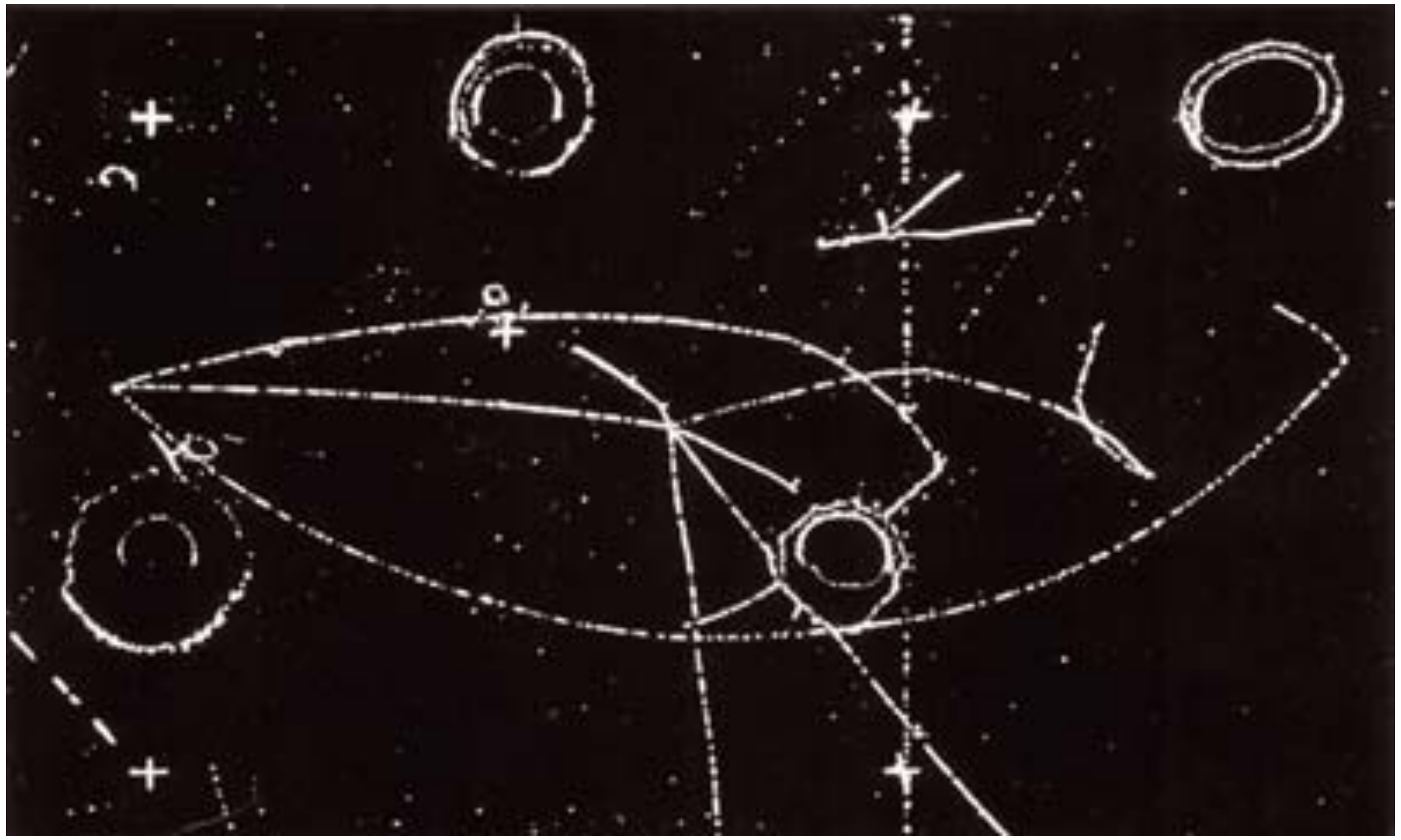






ACT 3: LIQUID ARGON TIME PROJECTION CHAMBER

ORIGINS



- C. Rubbia (1977):
  - bubble chambers give exquisite detail about events
  - allows searches for unexpected processes and topologies
  - "single event" discoveries
- Can we find a different way to achieve similar resolution with a simpler technology that can be realized on a massive scale for neutrino experiments?

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

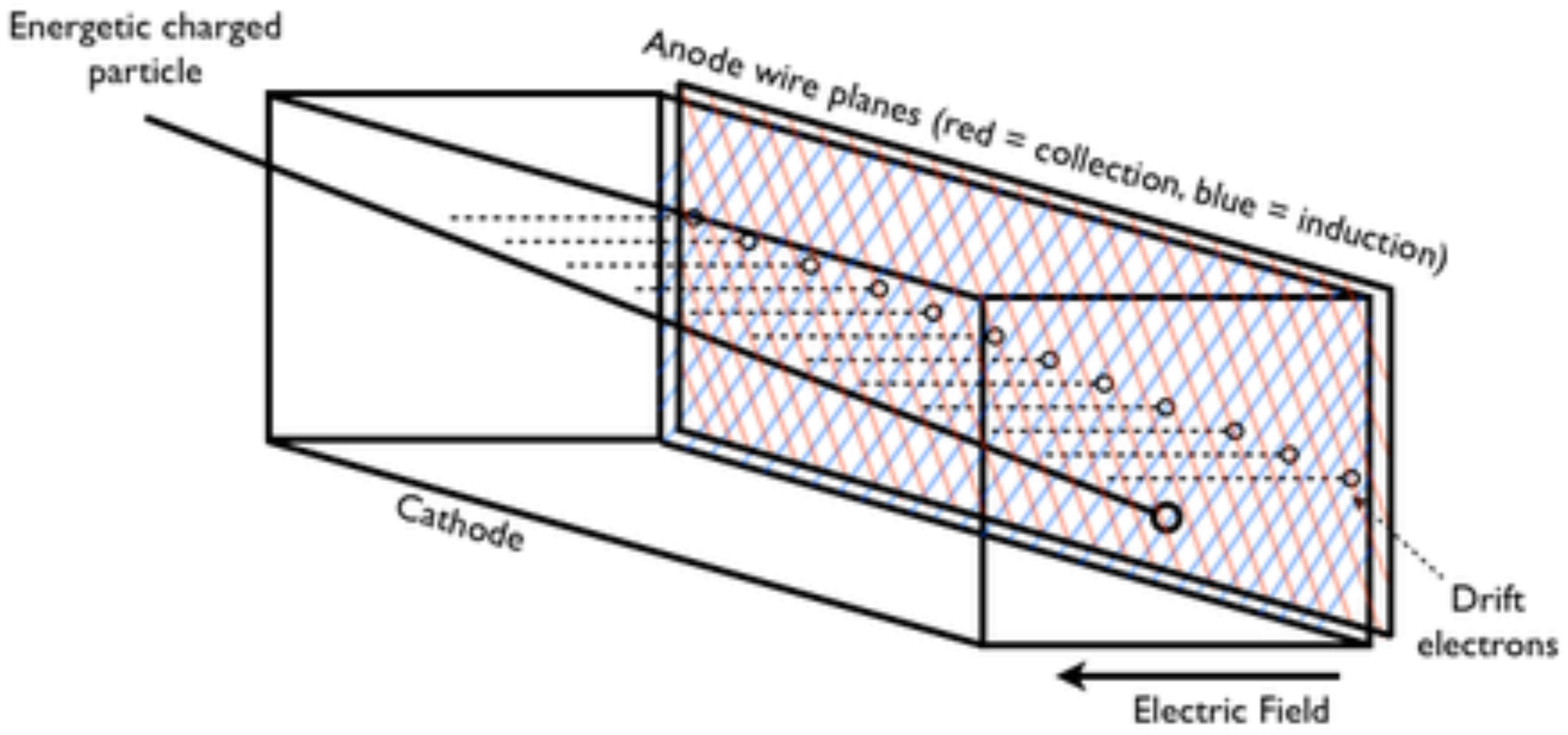
ABSTRACT

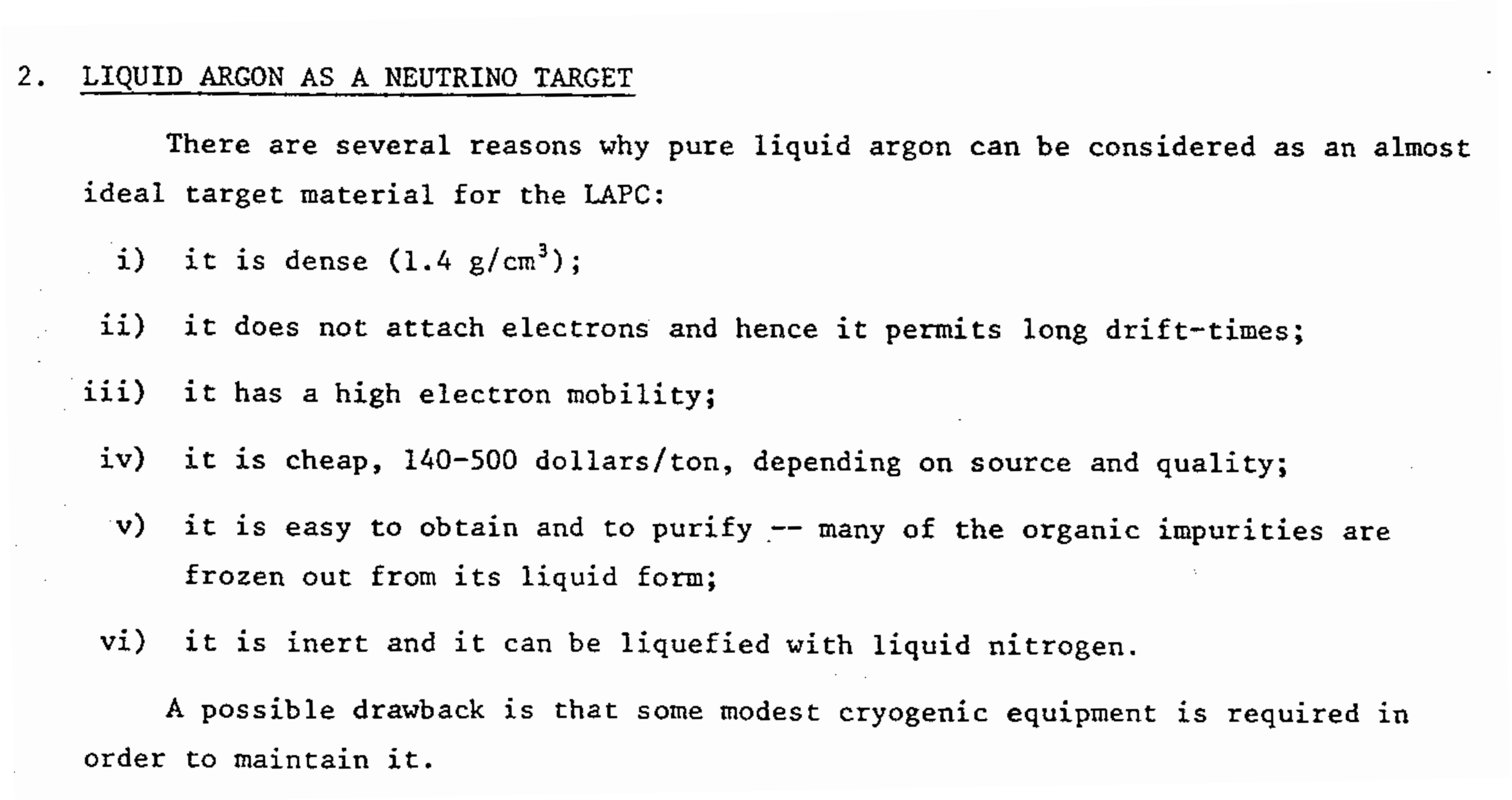
It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

G E N E V A

1977

WHY LIQUID ARGON?





2. LIQUID ARGON AS A NEUTRINO TARGET

There are several reasons why pure liquid argon can be considered as an almost ideal target material for the LAPC:

i) it is dense (1.4 g/cm^3);

ii) it does not attach electrons and hence it permits long drift-times;

iii) it has a high electron mobility;

iv) it is cheap, 140-500 dollars/ton, depending on source and quality;

v) it is easy to obtain and to purify -- many of the organic impurities are frozen out from its liquid form;

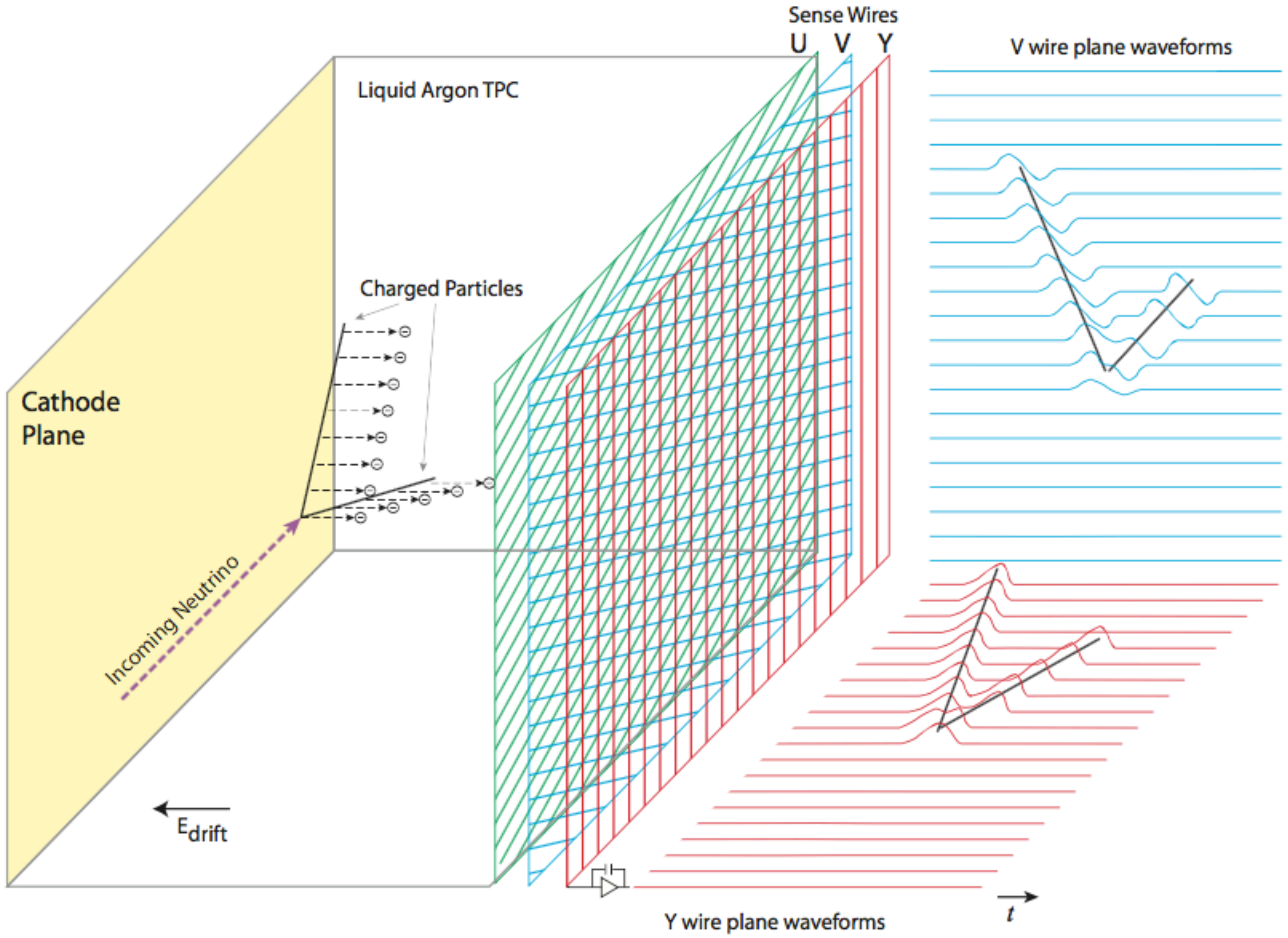
vi) it is inert and it can be liquefied with liquid nitrogen.

A possible drawback is that some modest cryogenic equipment is required in order to maintain it.

- The time projection chamber:
  - Charged particle leaves a trail of ionization
  - electrons "drifted" to readout plane by electric field
    - the pattern of ionization parallel to the plane will map directly onto the readout
    - the drift time provides the coordinate perpendicular to the plane

- Medium requirements:
  - **mobility**: the electrons drift in the electric field
  - **lifetime**: i.e. the electrons survive the drift and don't recombine or attach to atoms in its path
  - **diffusion**: the electrons should not spread out too much as they drift, else they obscure the track
  - ***density****: the medium can serve as the target for neutrino interactions and track outgoing particles "immediately"*

READOUT AND IMAGING:



- wire-based readout:
  - charge collection by wire plane gives 2 dimensional projection of the charge pattern
    - axis in the plane perpendicular to the wires
    - axis perpendicular to the plane (from drift time)

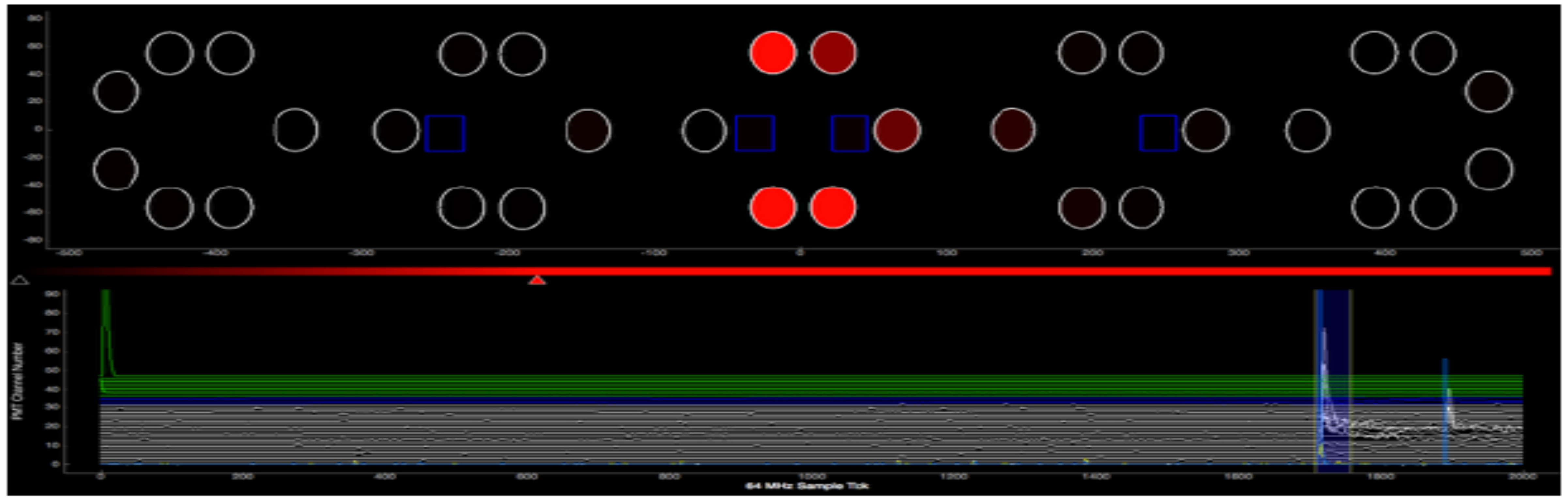
- Two detection modes:
  - **induction**: detect induced current on wires as electrons pass through wire plane
    - "non-destructive": additional wire planes can detect electrons afterwards
    - complicated bipolar signal
  - **collection**: collect electrons and detect charge
    - "destructive" (i.e. you can only collect once!)
  - wire planes oriented in different directions
    - get separate 2 dimensional projections
    - combine to obtain 3 dimensional representation
- Alternative: 2D pixel readout (native 3d image)

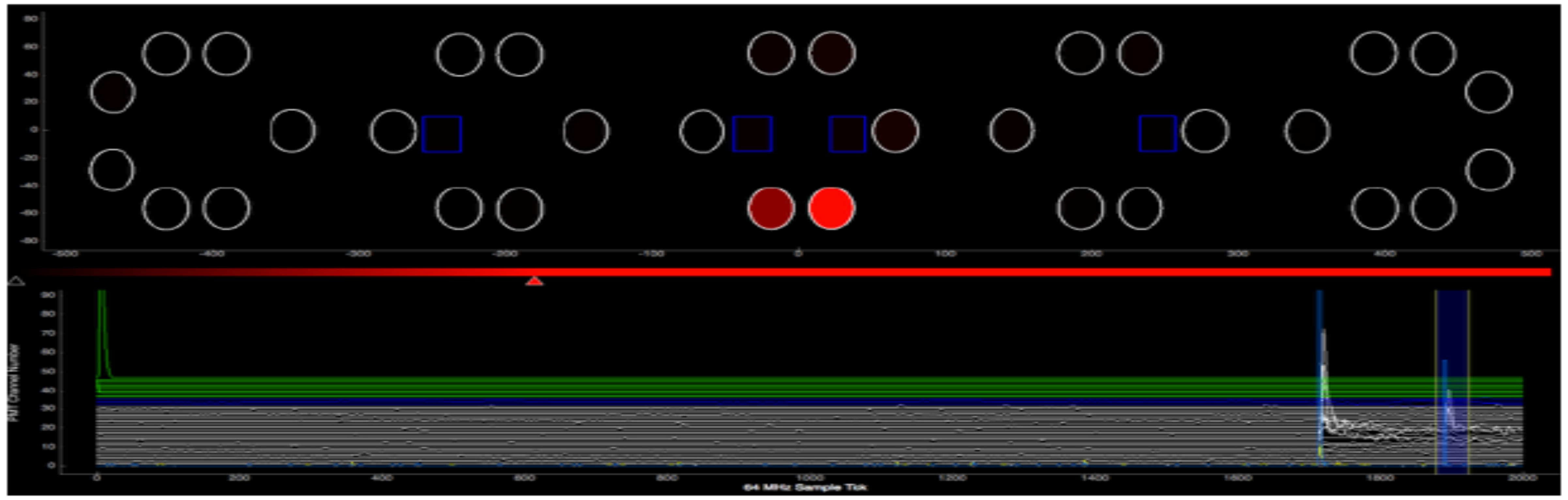
Drift parameters:
- Velocity: v_d ~1600 m/s
- Transverse diffusion: D_T ~ 13 cm^2/s
- Longitudinal diffusion: D_L ~ 5 cm^2/s

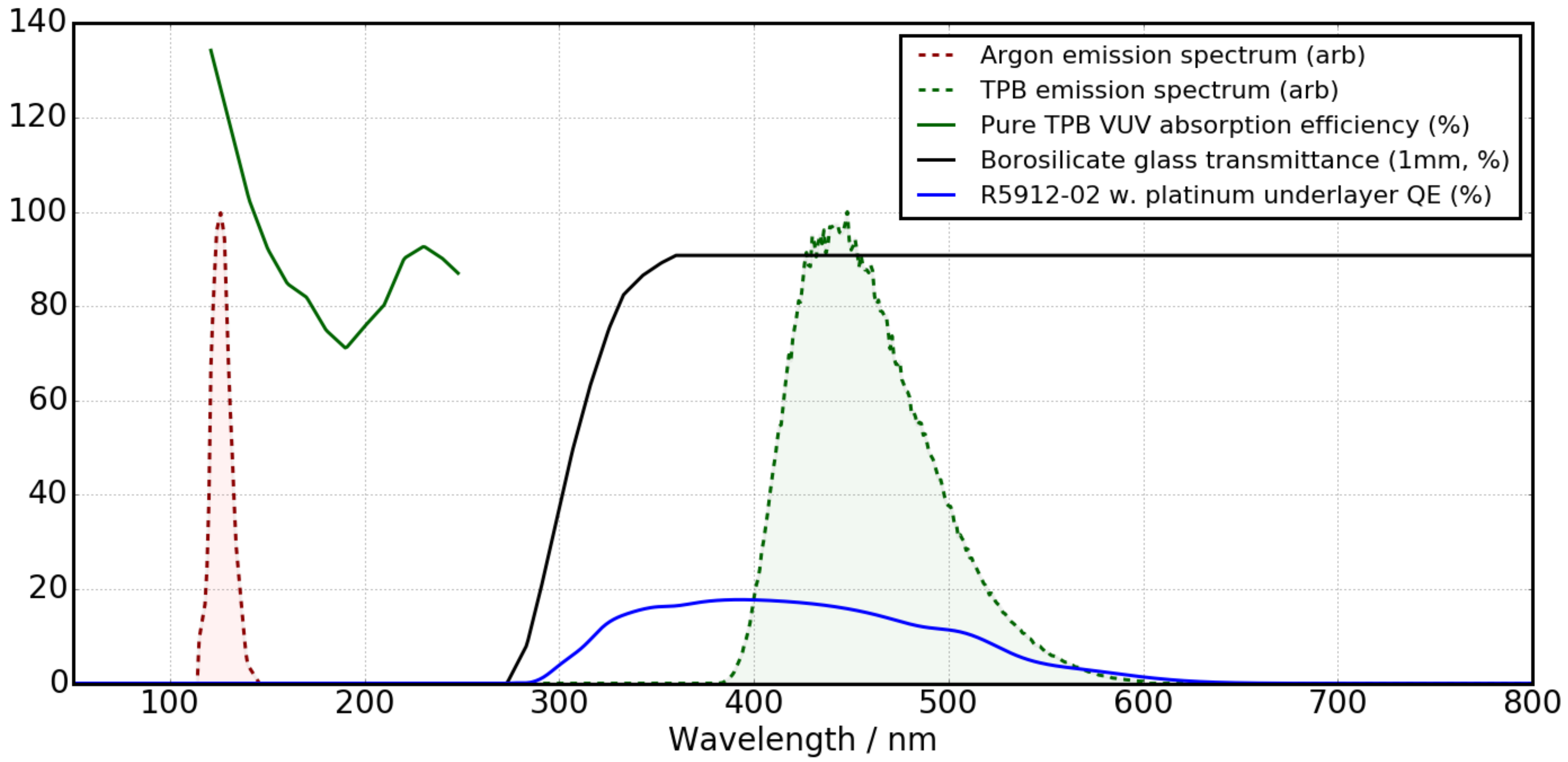
$$\sigma = \sqrt{\frac{2D_{L/T}x}{v_d}}$$

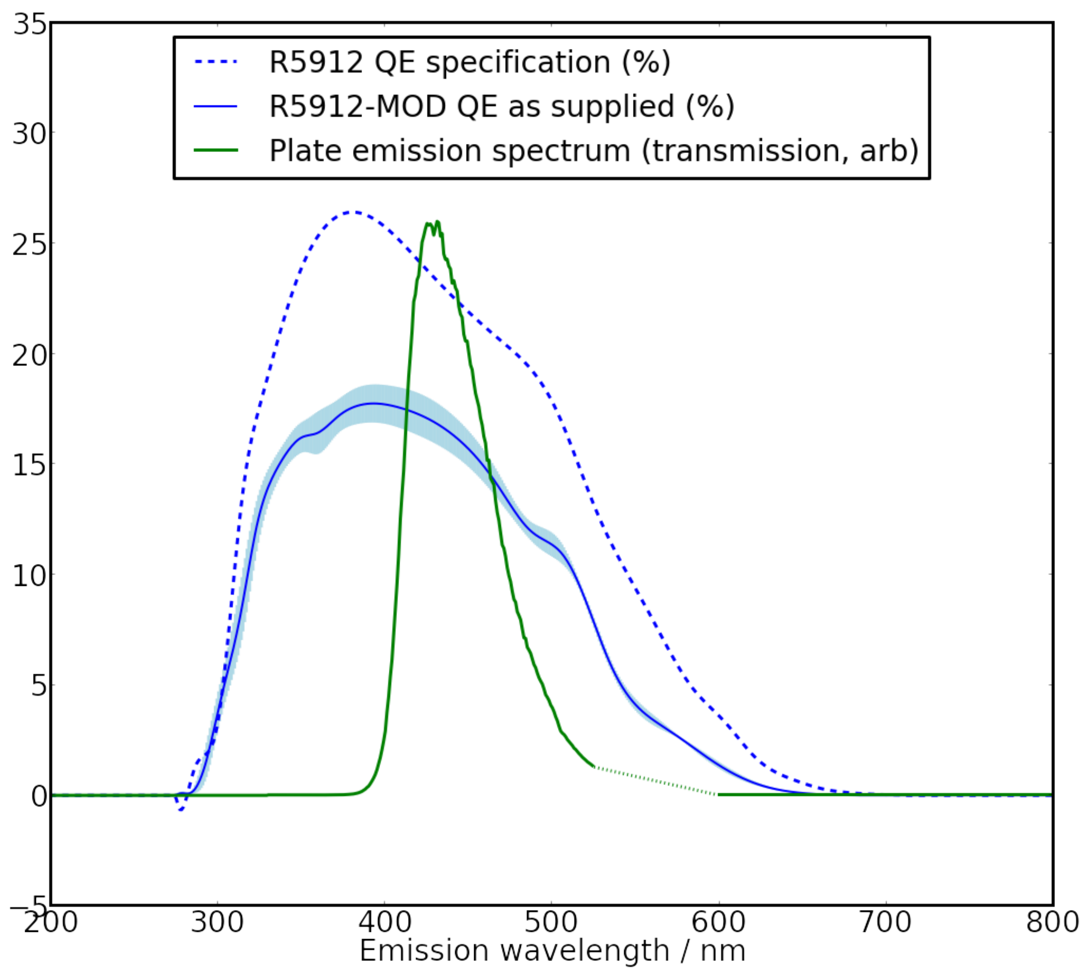
OPTICAL SIGNAL:

- Liquid Argon is a very good scintillator:
  - ~24,000 photons/MeV of deposited energy
  - 128 nm
  - 1.6 ns and 6 ns lifetime components
- Wavelength shifter needed to bring light into wavelength detectable by conventional photosensors (e.g. PMT)



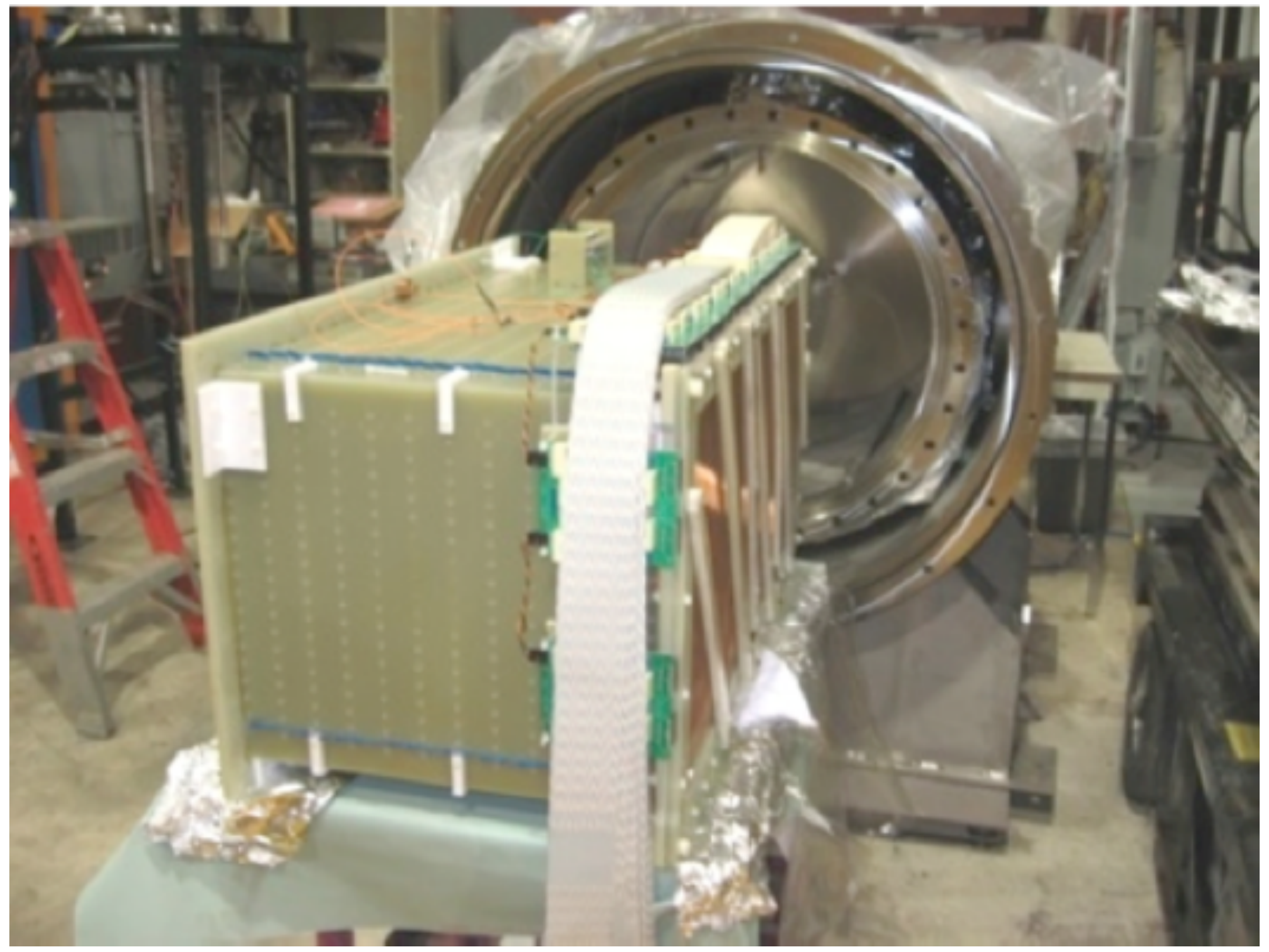


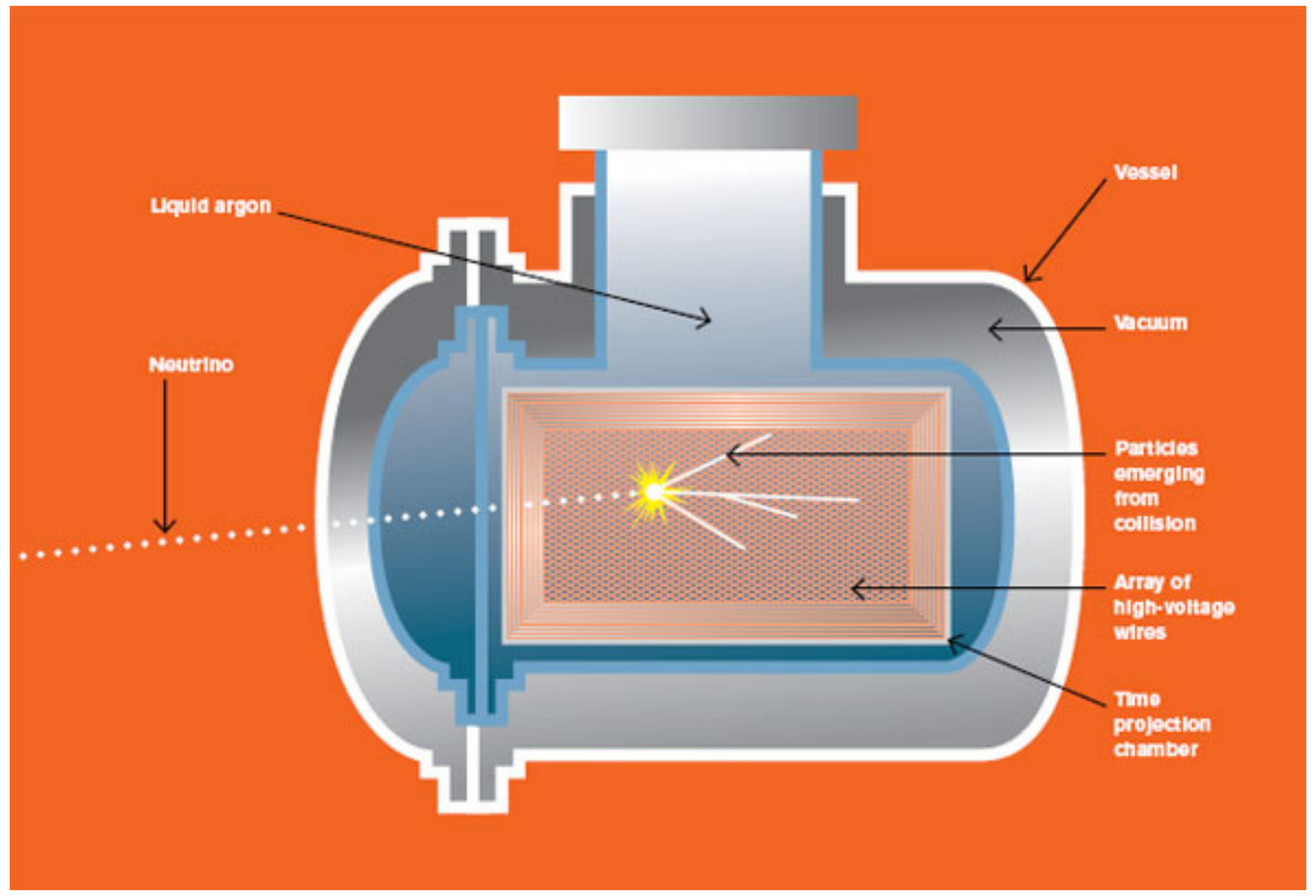




- Above:
  - muon/decay electron candidate in MicroBooNE
- Provides important "fast" complementary information
- Localization to match scintillation and ionization signals

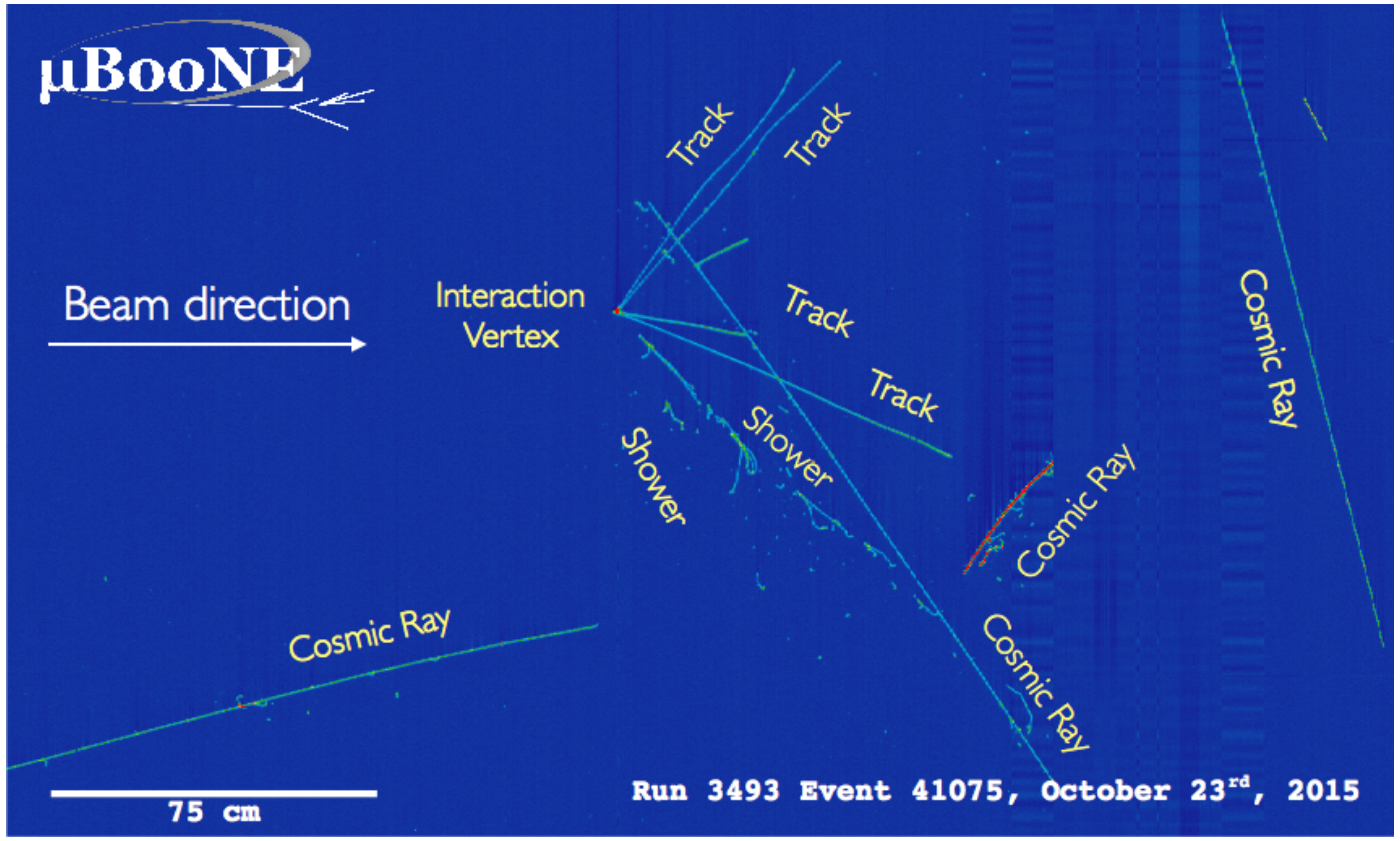
LAR-TPC DETECTORS:

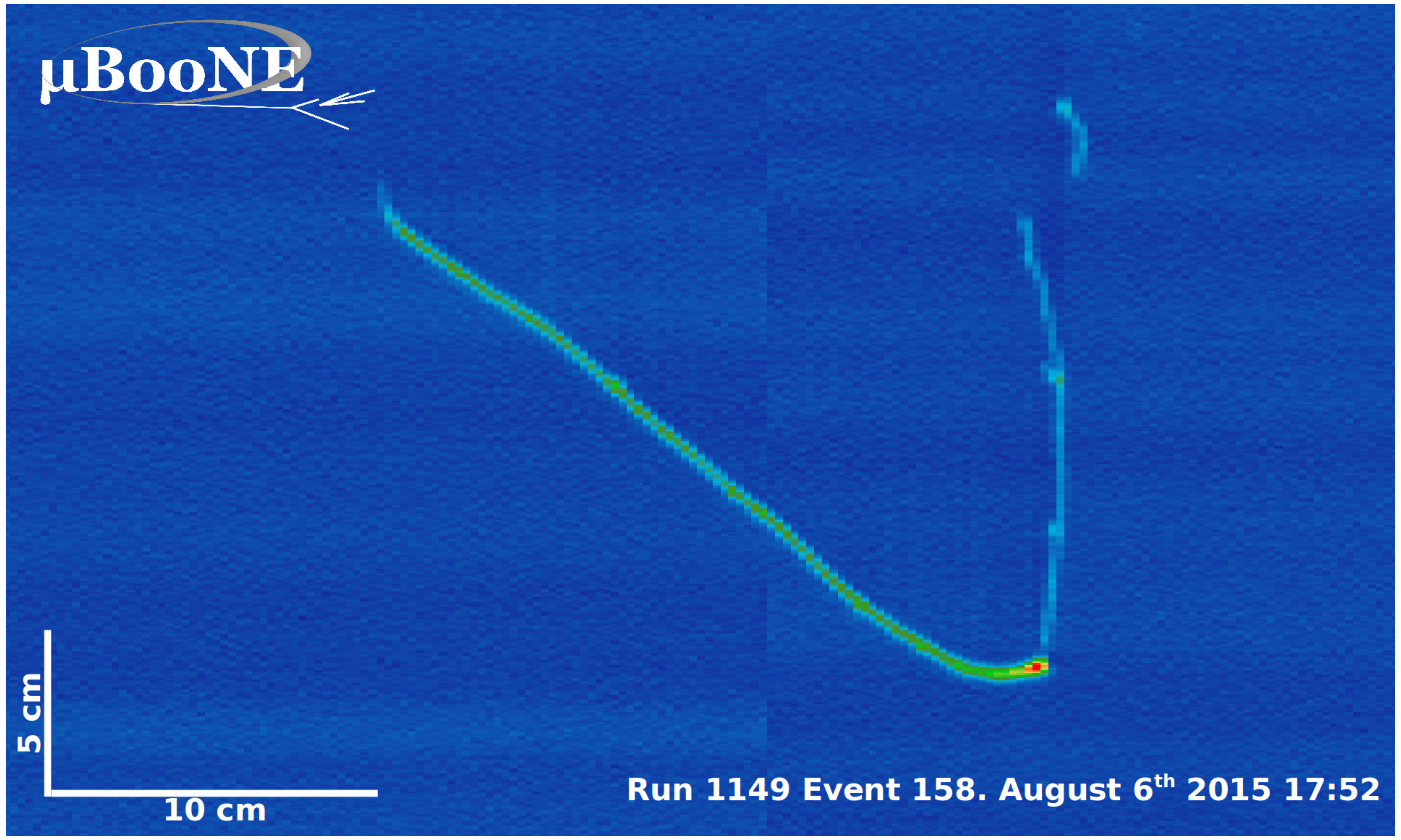




- Quest for ever larger detectors . . . . .

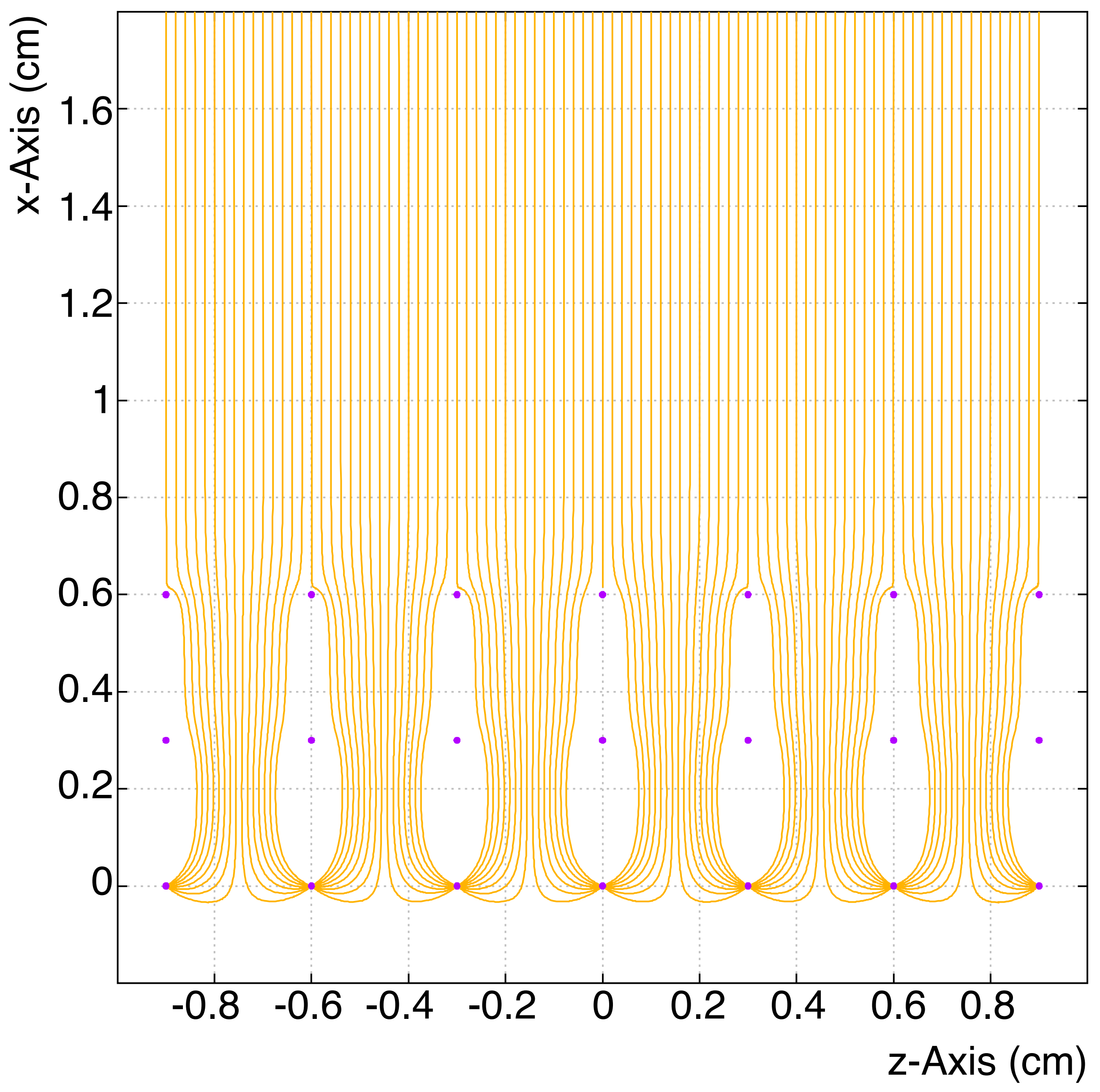
CAPABILITIES OF LAR-TPCS

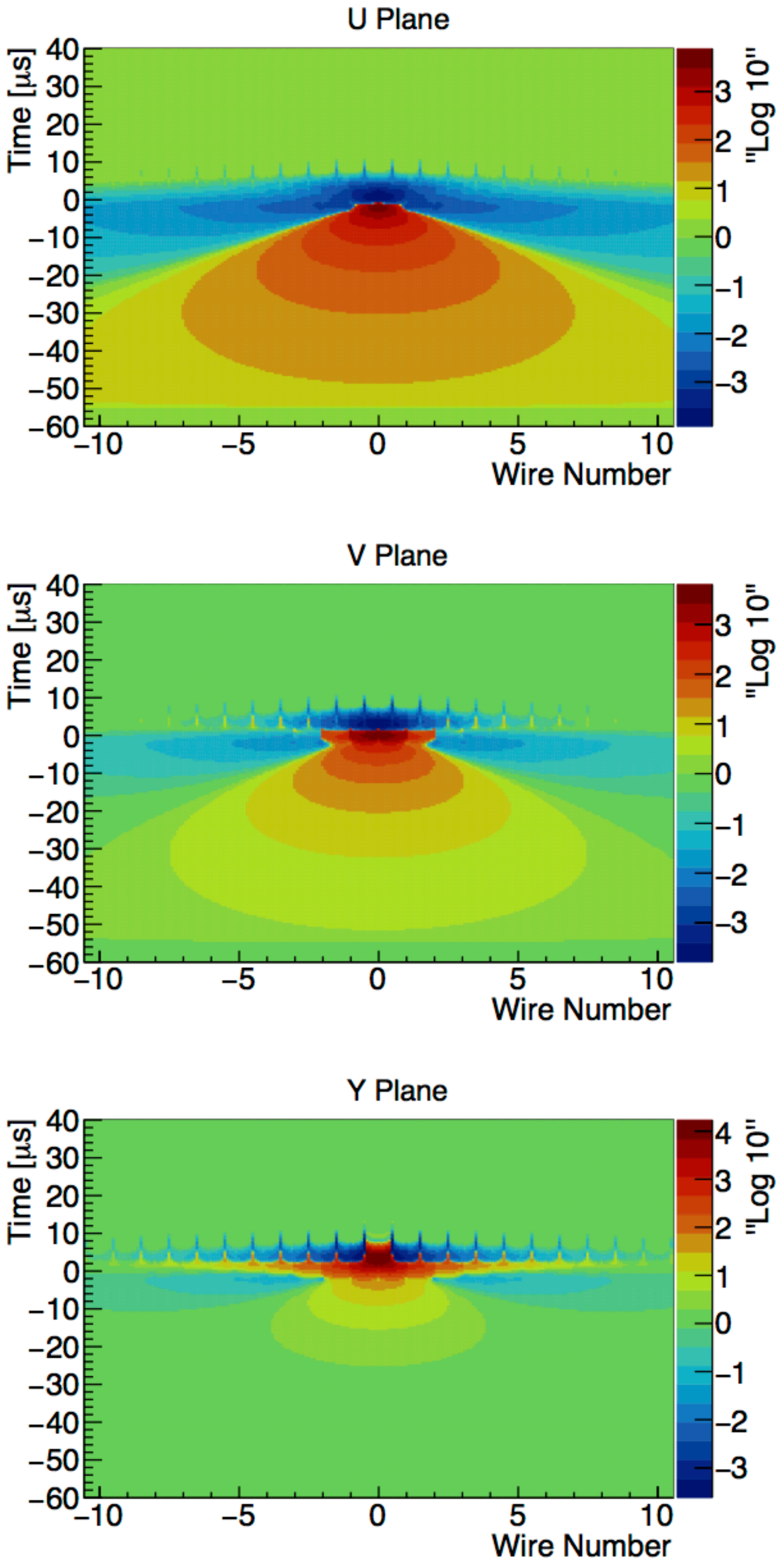




- Detailed and precise tracking information to relatively low thresholds
  - allows precise vertexing
  - matching/separation of distinct objects (e.g. cosmic ray overlaid on neutrino interaction)
- Topological information such as showering
  - track, electromagnetic shower, hadronic shower separation
  - delta rays from tracks
- Ionization pattern, such as Bragg peak from stopping track

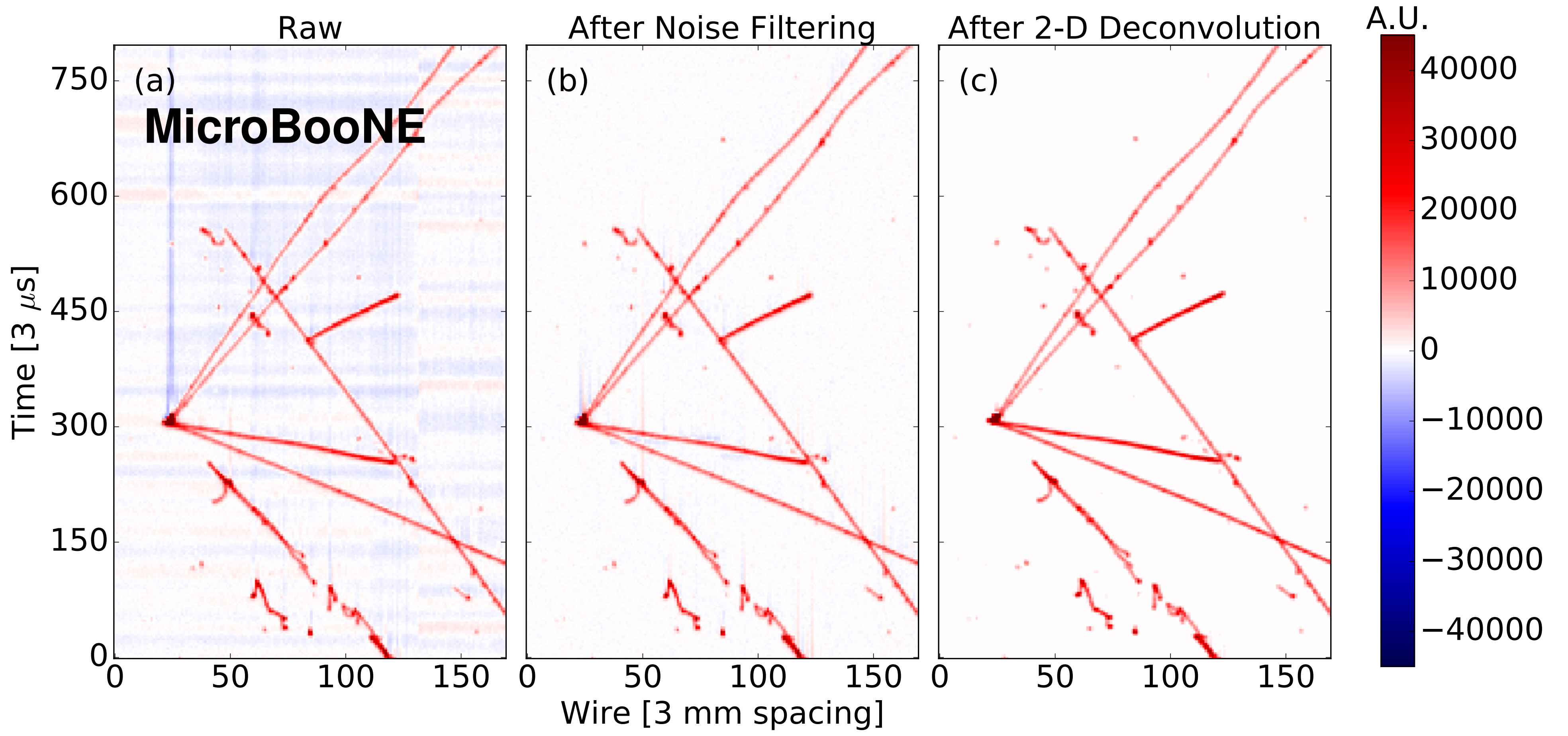
SIGNAL PROCESSING



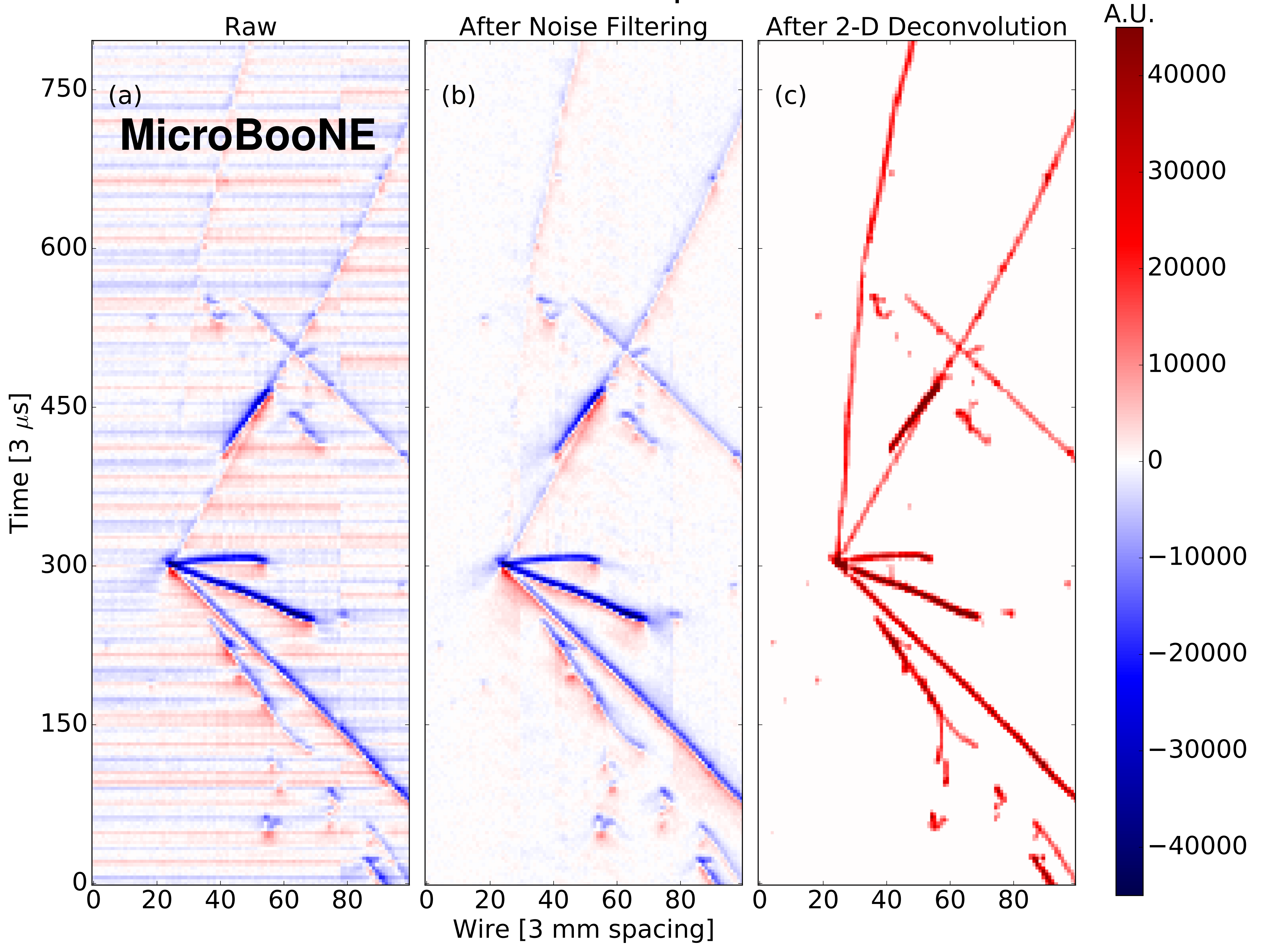


- Many complicated effects!
- Drift of electron is distorted by wires
- Induction signal from a single electron is observed over many wires
- “space charge” buildup distorts drift
- Noise from electronics, etc.
- signal processing necessary to recover “undistorted” image.

collection plane

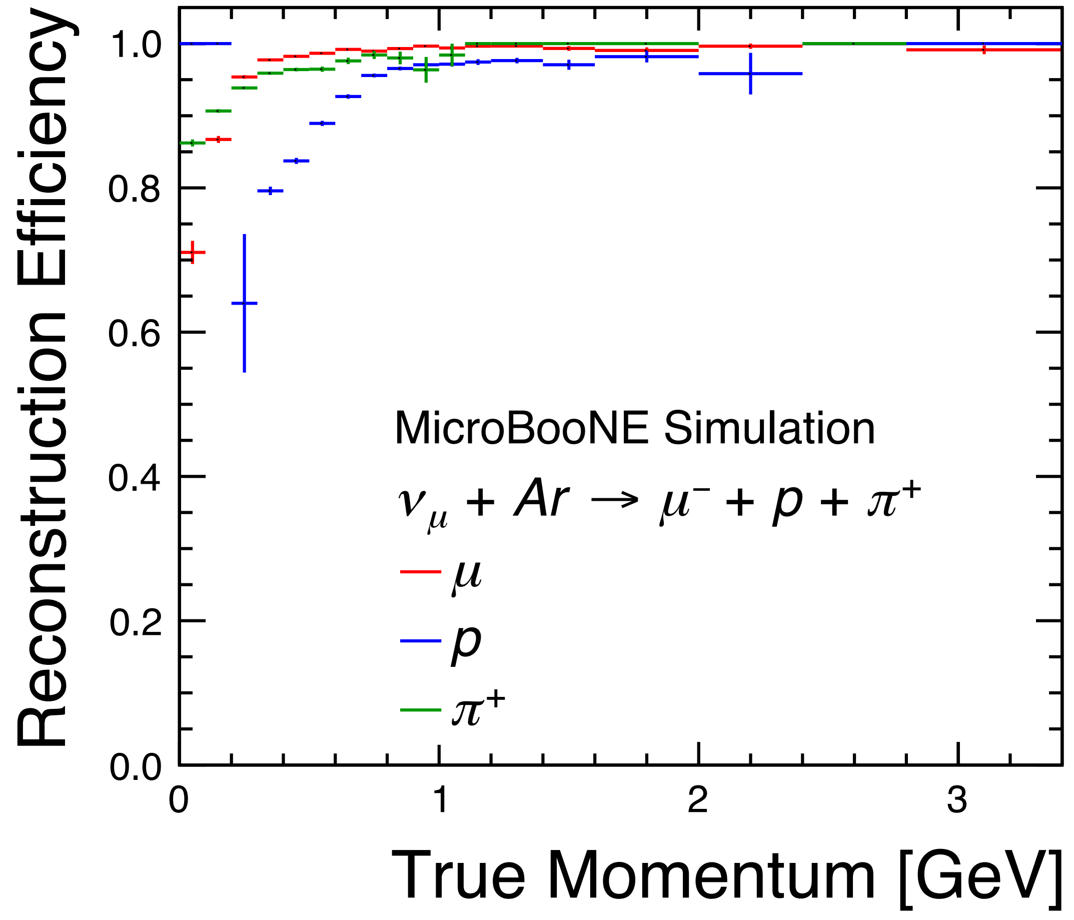


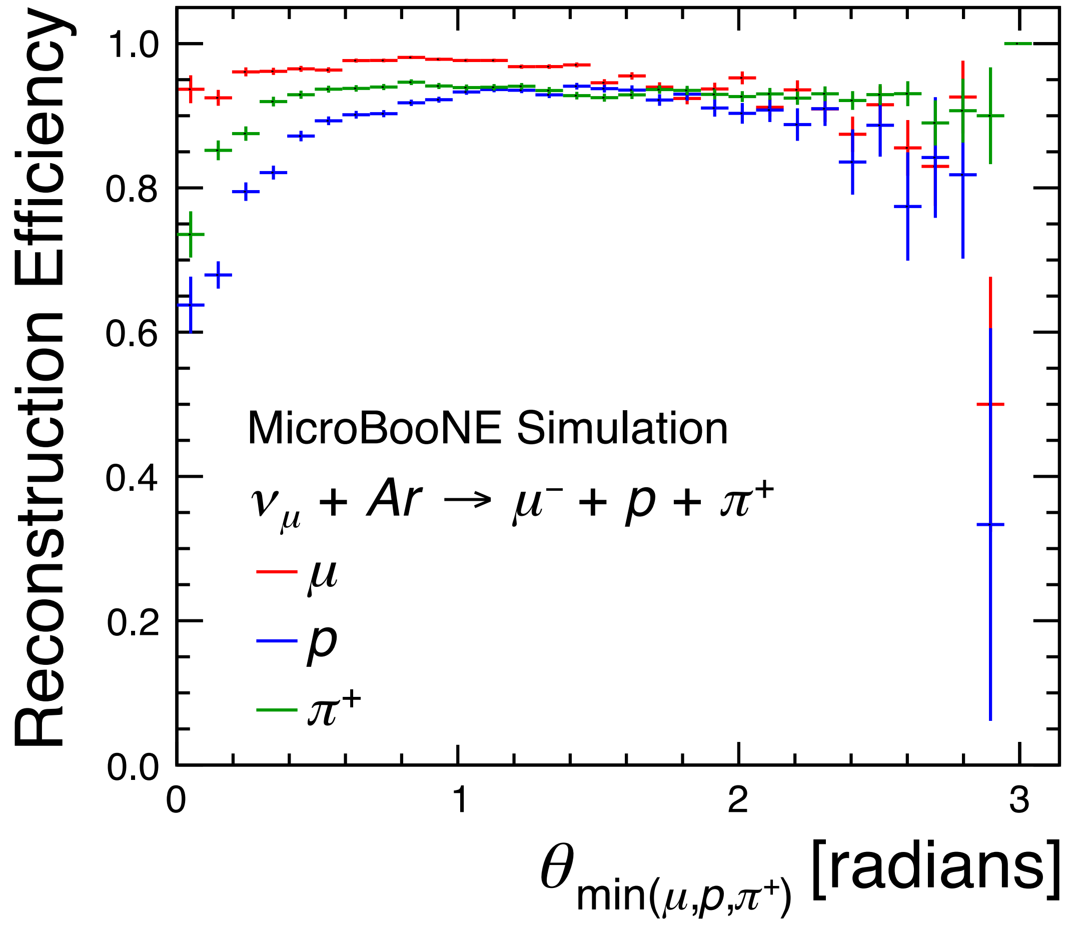
induction plane



PERFORMANCE:

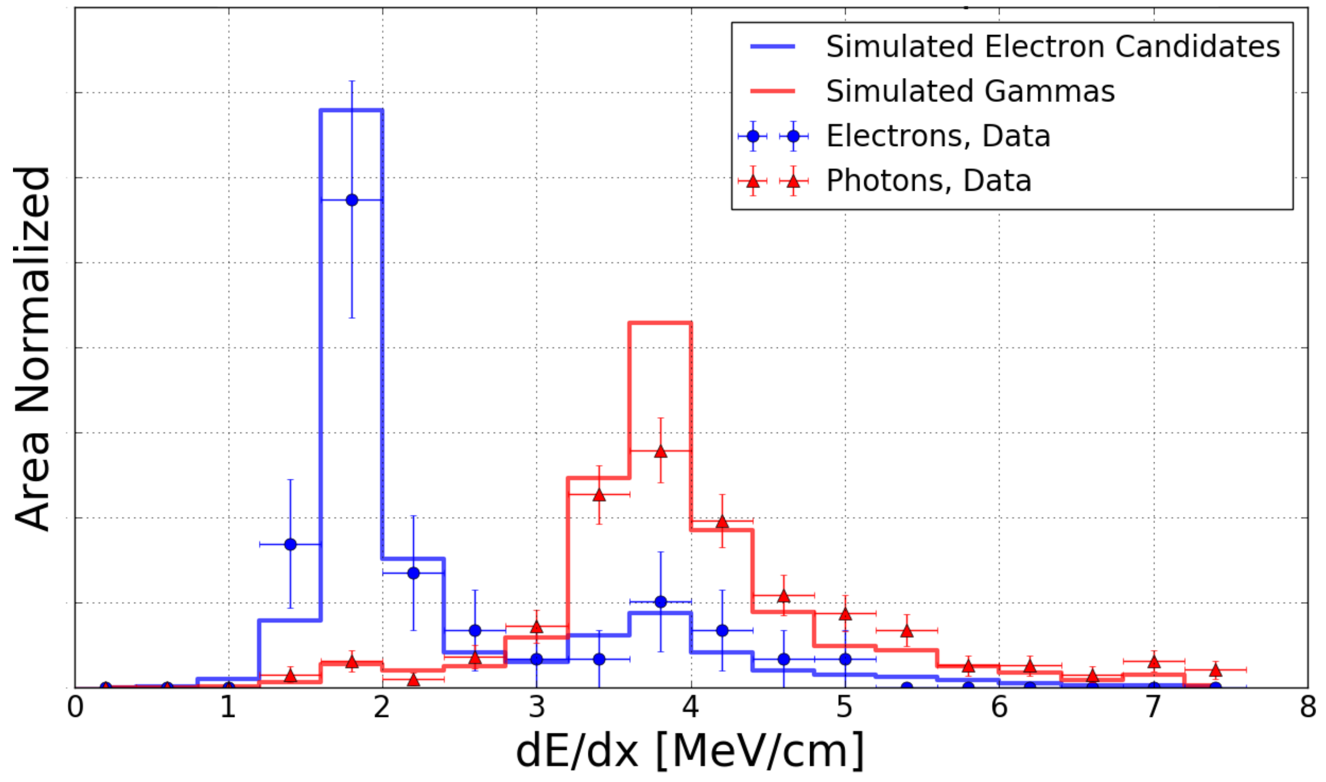
Reconstruction of
$\boldsymbol{\mu + p + \pi^{+}}$



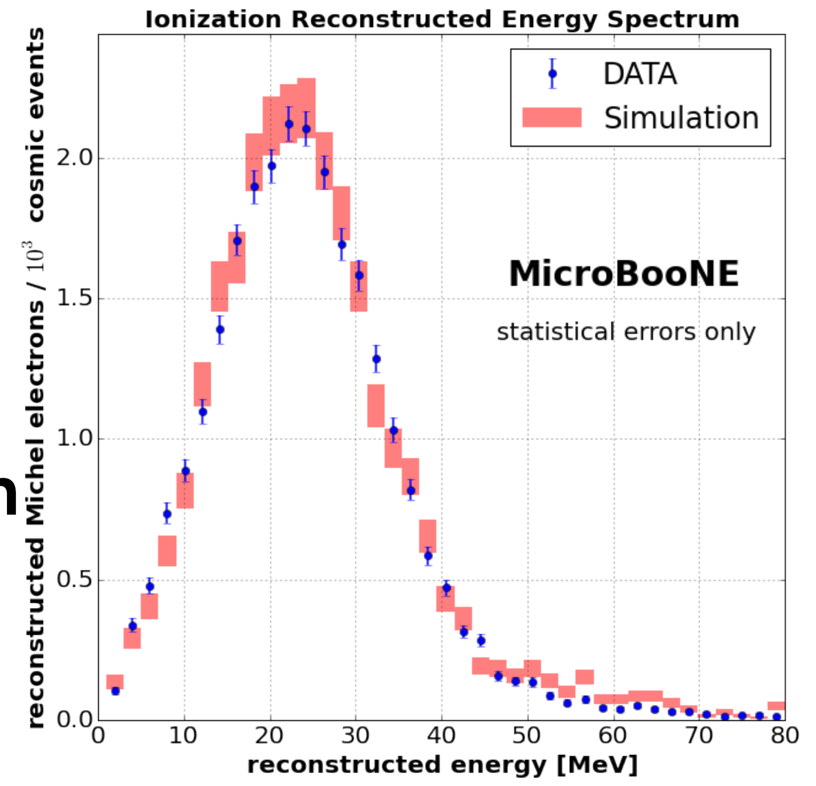


- Fine sampling allows tracking to very low thresholds
  - < 100 MeV/c for m/p
  - ~200 MeV/c for protons
  - detailed resolution of multiple track systems
- Powerful e/γ separation possibility
  - ionization at the start of the shower
  - separation from vertex
- Still many challenges and opportunities
  - shower reconstruction
  - momentum reconstruction by multiple scattering
  - machine learning techniques to sort/structure tremendous amount of information

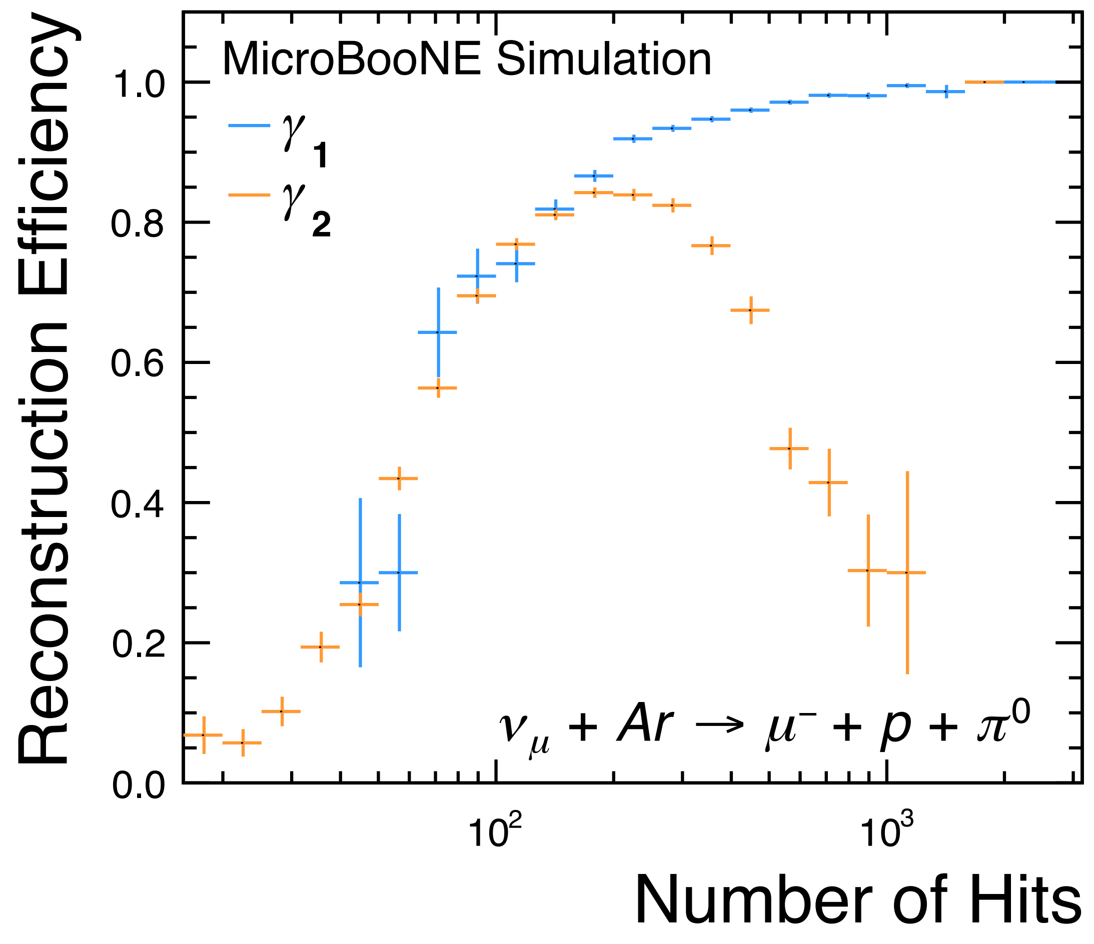
e/γ separation

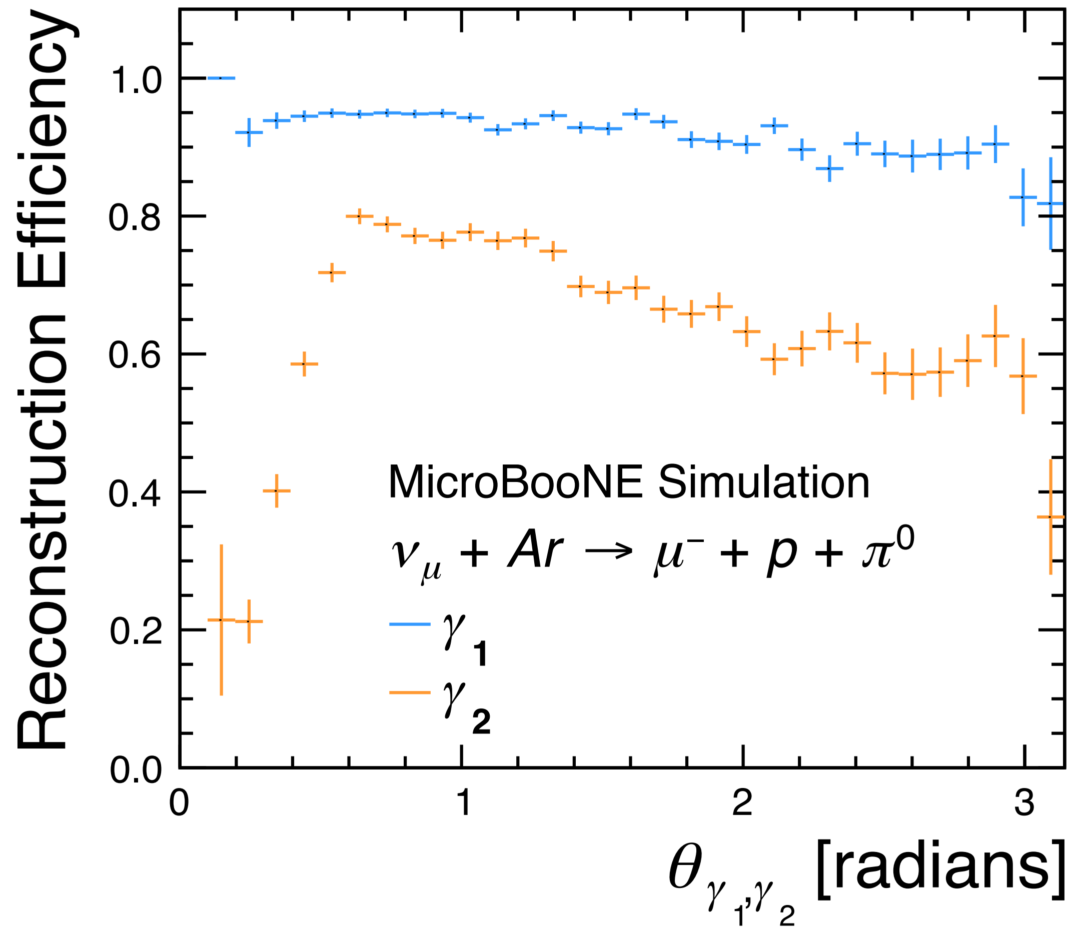


Michel electron spectrum



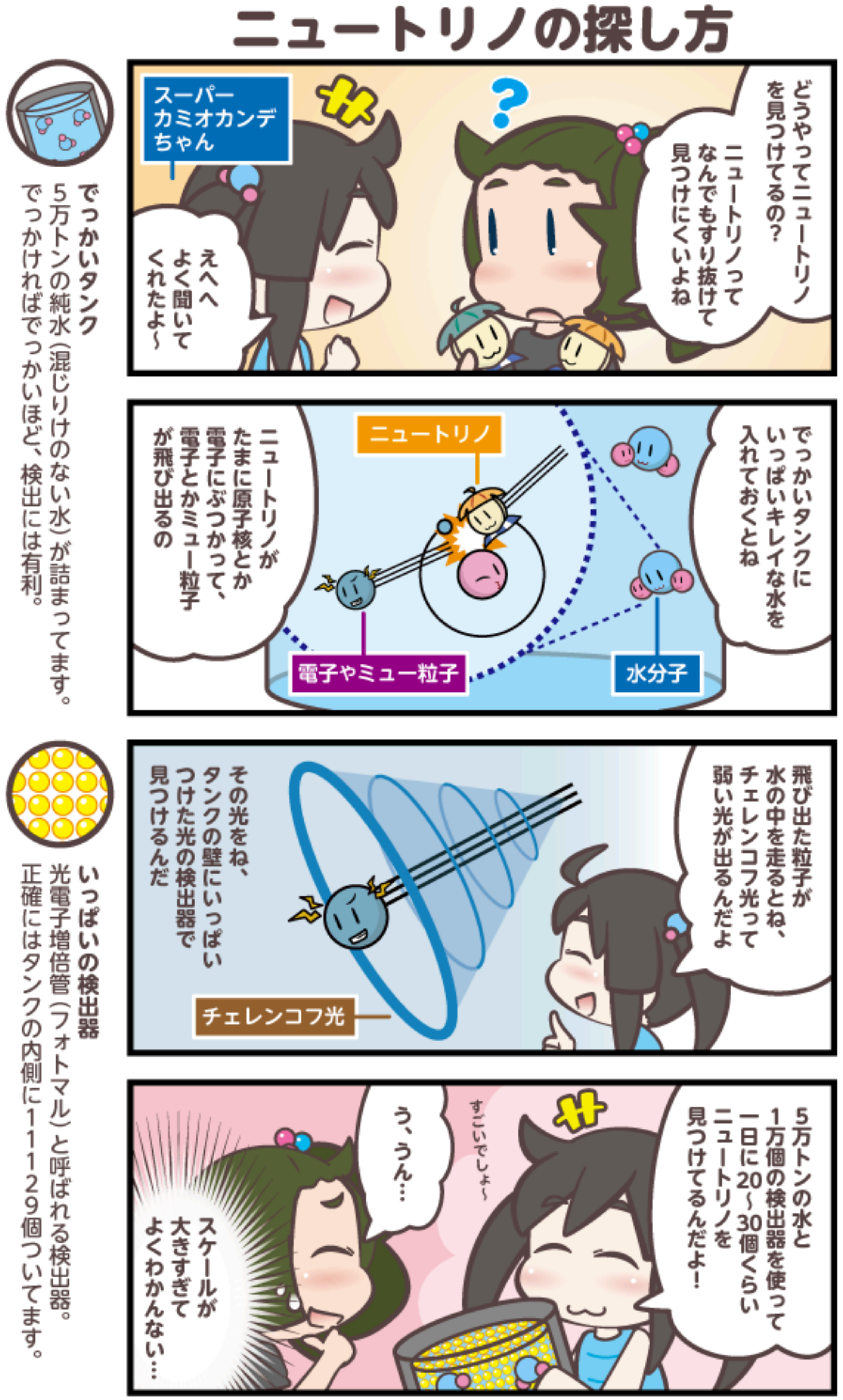
Reconstruction of
$\boldsymbol{\mu + p + \pi^{0}}$

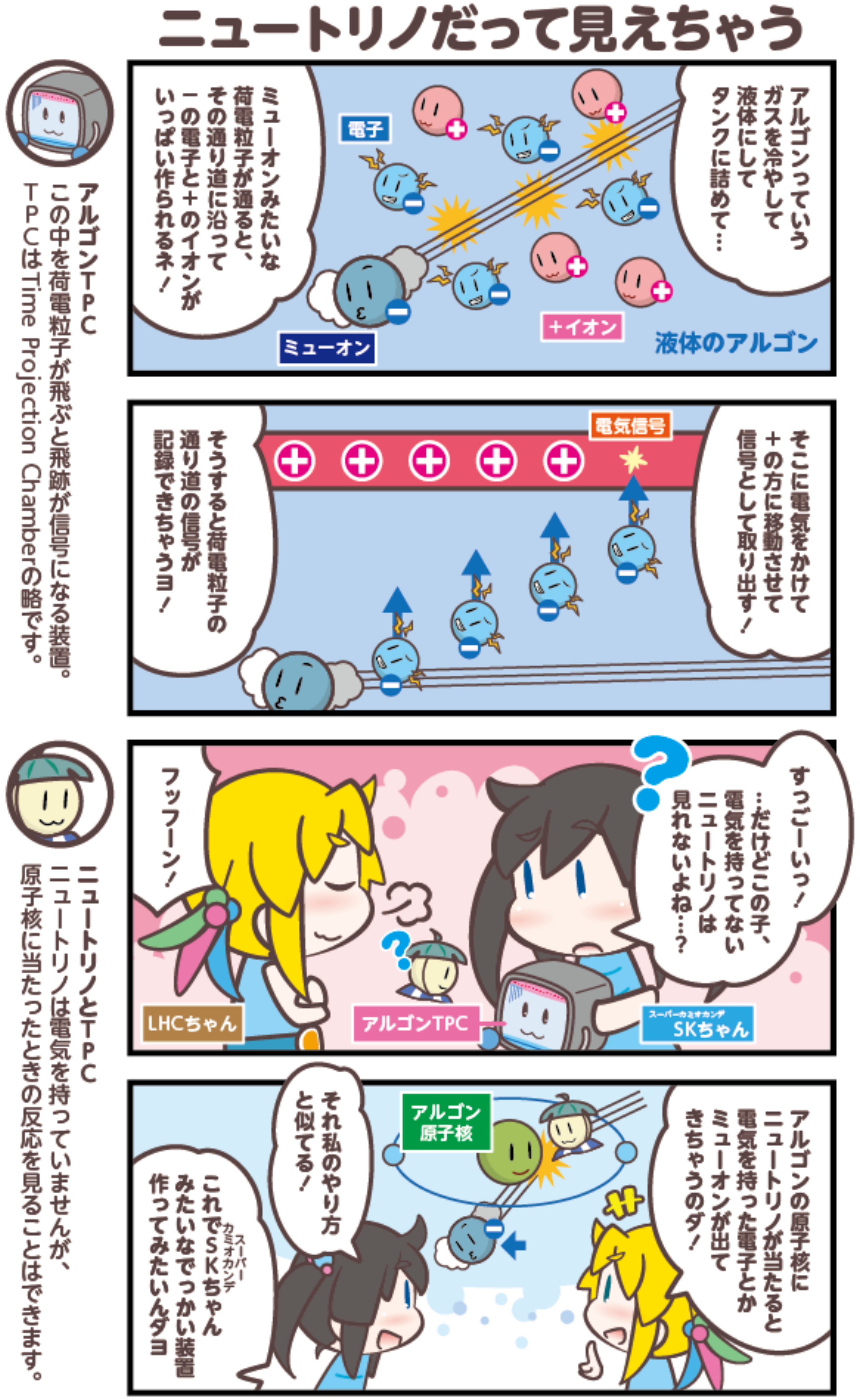




HIGGSTAN.COM

- Water Cherenkov detectors and LArTPCs explained in four frames.
- This and more on particle physics at higgstan.com





CONCLUSION:

- We need massive detectors to study neutrino detectors in detail
    - “massive” has evolved over time . . . by the turn of the millenia, multi-kiloton detectors are already in operation
    - technologies vary in what they can tell us about neutrino interactions
- Three technologies are dominant in current accelerator-based detectors
    - Water cherenkov detectors
    - Scintillating tracking detectors
    - Liquid argon time projection chambers
- Personally, I am amazed that we can build neutrino detectors with such basic ingredients
    - water, plastic, argon

DIVERSION

- All the detector technologies discussed rely (primarily) on neutrinos interaction on nuclei
  - Water Cherenkov: ^{16}O and ^{1}H
  - Scintillator: ^{12}C and ^{1}H (and other stuff)
  - LAr-TPC: ^{37}Ar
- We need to understand neutrino interactions on nuclei
- Particle physics bias/ignorance:
  - nuclei are collections of protons and nucleons
  - we can understand neutrino-nucleus interactions by understanding neutrino-nucleon interactions
  - **what could go wrong?**