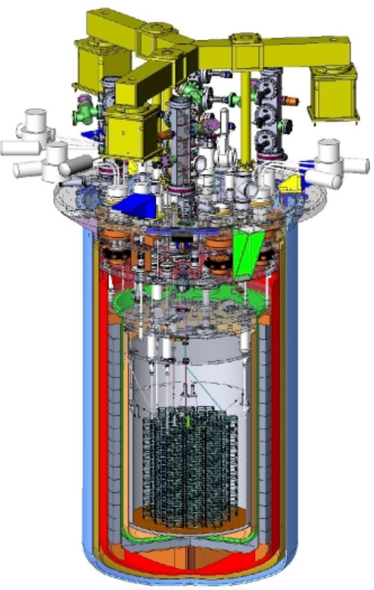
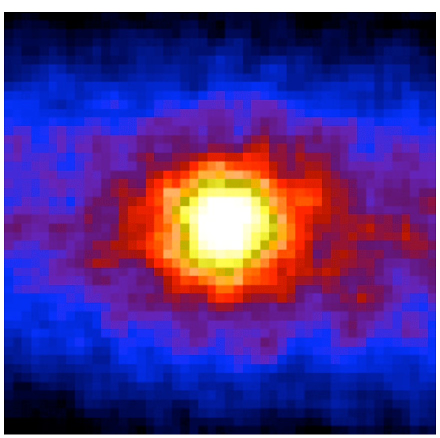
Neutrino Detectors

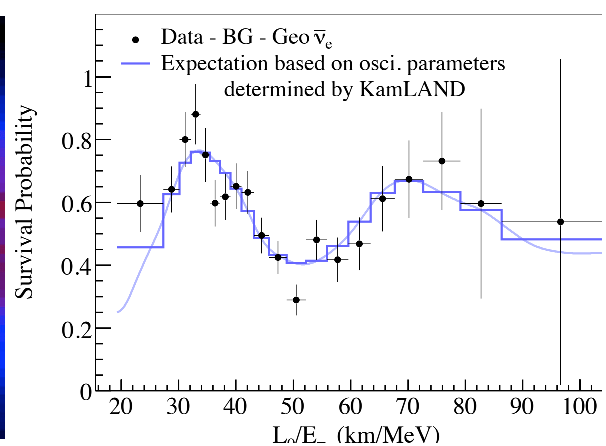
Physics 290E

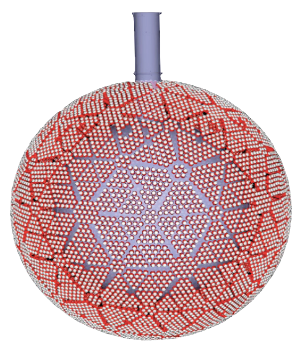
February 12, 2025

Slides adopted from Sowjanya Gollapinni, 2023 INSS Summer School
(many thanks)



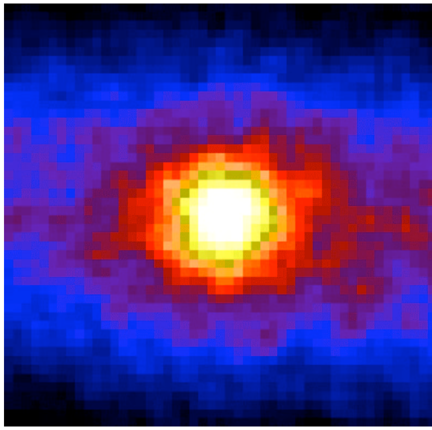






Mysterious Neutrinos

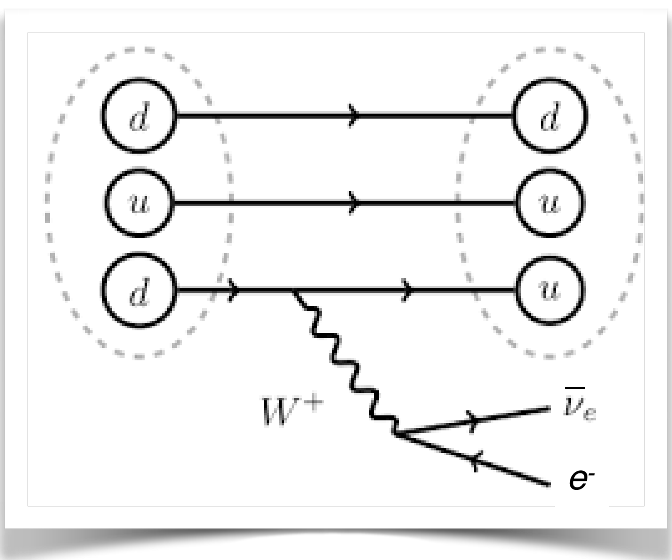
- Extremely abundant
  - ☞ 10^{11} $\nu/cm^2/s$ from the Sun @ Earth surface
  - But are *not* dark matter
- Weakly interacting, neutral particles
  - Massless in the Standard Model !
- Massive in real life, but much lighter than other elementary particles
  - Mass may not be from the Higgs mechanism
  - May be telling us something about Grand Unification
- May hold keys to the question of matter-antimatter asymmetry in the universe



Courtesy SNO Collaboration

History of Neutrinos

- Proposed by Pauli to explain the beta-decay spectrum
- Named by Fermi (*neutrino* = little neutron) and incorporated into the theory of weak interactions



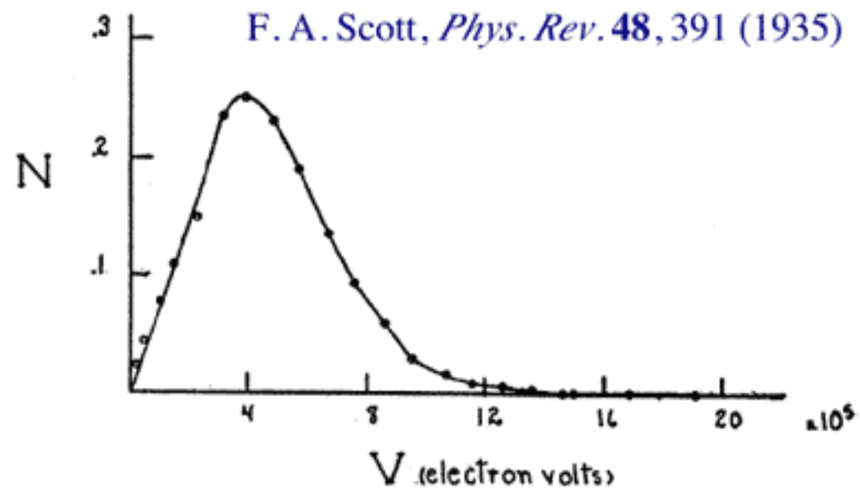


FIG. 5. Energy distribution curve of the beta-rays.

History of Neutrinos

original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the Gauverein meeting in Tübingen.

Copy

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

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, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that 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 mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}$ cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

[Translation: Kurt Riesselmann]

Neutrinos in the Standard Model

- Left-handed neutrinos: together with their charged lepton partners, form weak isospin doublets

$$\begin{pmatrix} \nu_e \\ e_L \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu_L \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau_L \end{pmatrix}$$

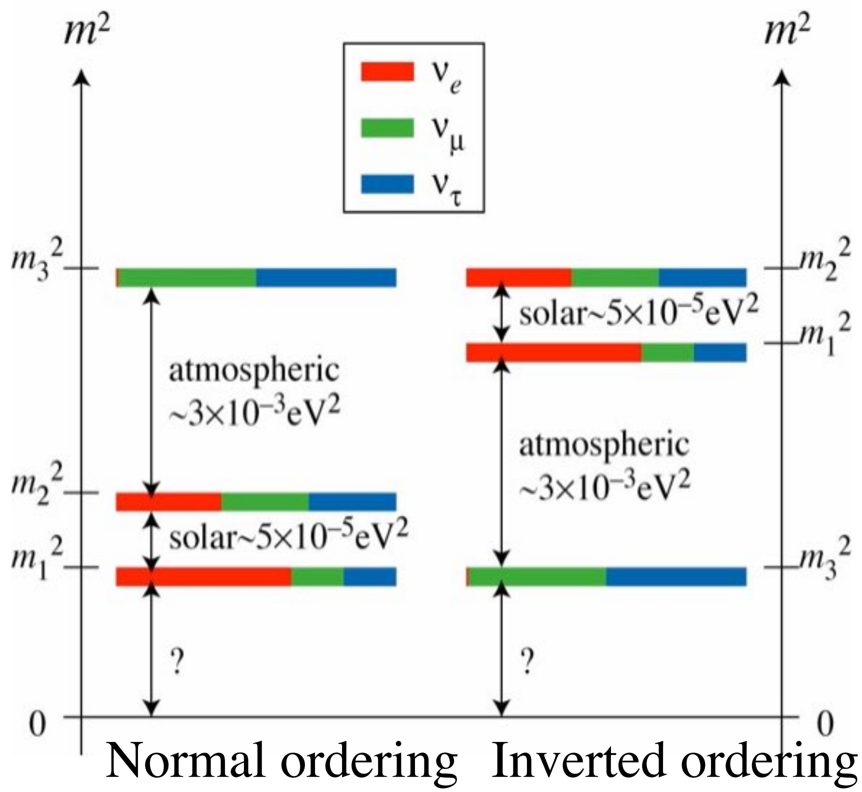
$$e_R \qquad \mu_R \qquad \tau_R$$

  - Left-handed neutrinos: zero charge, non-zero weak isospin and hypercharge
  - Right handed neutrinos have no charges in SM

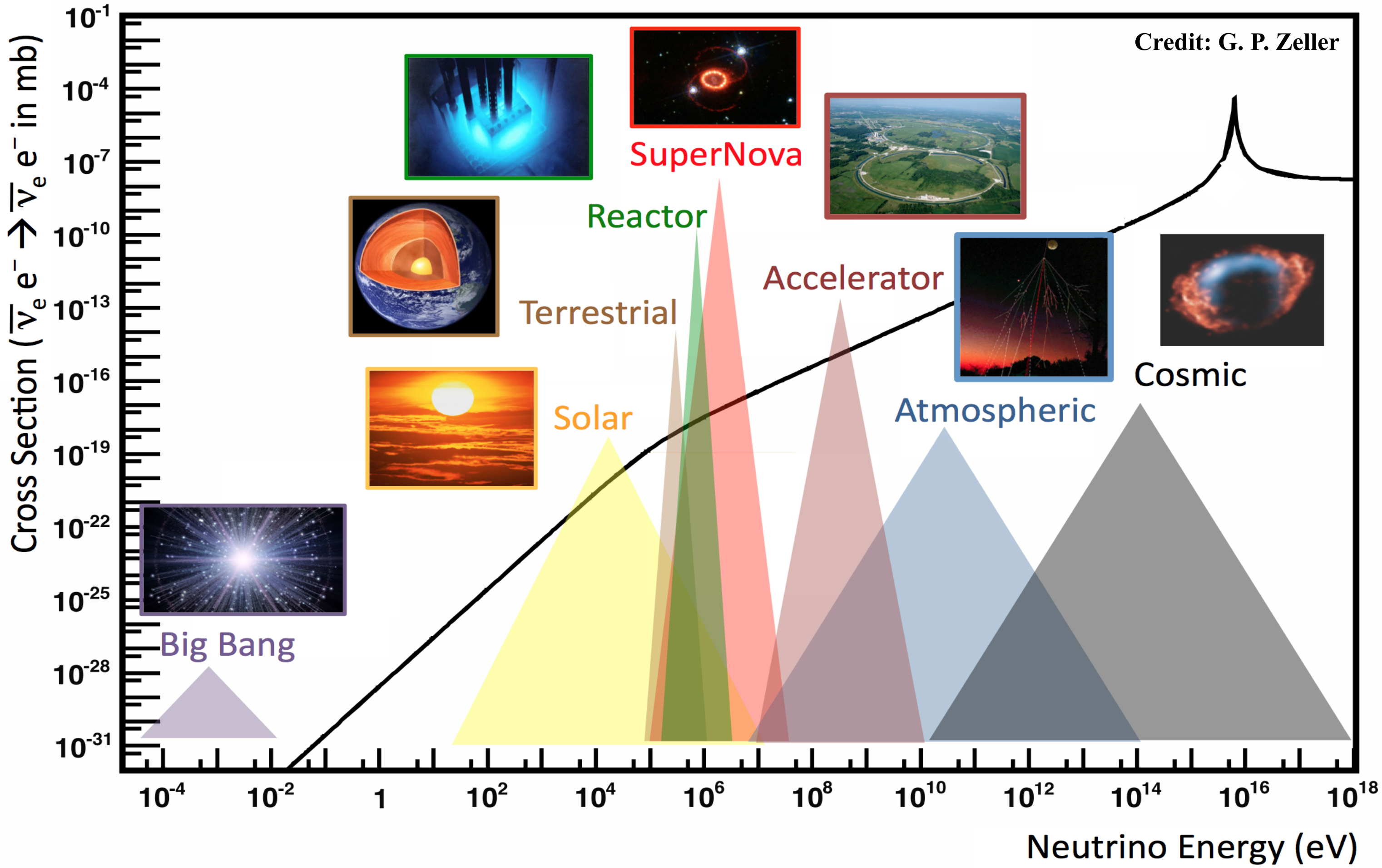
Neutrino Physics Landscape

- Compelling evidence for
  - ❑ Neutrino flavor-changing oscillations
  - ❑ (therefore) finite neutrino masses
  - ❑ Mixing angles are well measured
- Open questions in ν Physics:
  - ❑ How many neutrinos?
    - ☞ Sterile neutrinos ?
  - ❑ What is absolute scale of ν mass ?
  - ❑ How are masses arranged ?
  - ❑ Are neutrinos responsible for matter-antimatter asymmetry ?
  - ❑ Majorana or Dirac neutrinos ?
  - ❑ Is Lepton Number conserved ?
- Very active program worldwide

Neutrino mass hierarchy



Neutrino Sources



Neutrinos span multiple frontiers!

- Particle Physics
- AstroPhysics
- Cosmology
- High energy Astro-particle physics
- Nuclear physics

Neutrino Detectors

- Problem: neutrino interaction cross section is small

$$\sigma(\nu_\ell e^- \to \ell^- \nu_e) \approx \sigma(\nu_\ell n \to \ell^- p) \approx \sigma(\bar{\nu}_\ell p \to \ell^+ n)$$
$$= \frac{G_F s}{\pi} = \frac{G_F}{\pi} 2mE_\nu \approx 10^{-41} \frac{E_\nu}{\text{GeV}} \text{cm}^2 = 10^{-17} \frac{E_\nu}{\text{GeV}} \text{barn}$$

☞ Iff $2mE_\nu > m_l^2$, i.e. if charged current reaction is allowed kinematically

- E.g. for solar neutrinos ($E_\nu \approx 10$ MeV), interaction cross section is $9 \cdot 10^{-44}$ cm^2 ($9 \cdot 10^{-20}$ barn) !

Neutrino Detection Challenges

- They are invisible (no charge)
- They are *extremely weakly* interacting
- In other words, they have very small interaction cross sections
- MeV-scale neutrino (typical energy of a neutrino emitted from sun or a nuclear reactor) has a cross section, $\sigma \sim 10^{-44}$ cm^2 — tiny!
- GeV-scale neutrino (typical energy of a neutrino from a particle accelerator) has a cross section, $\sigma \sim 10^{-40}$ cm^2 — still tiny!
- Mean free path of a neutrino in lead
  - MeV-scale neutrino: $d_{lead} \sim 10^{16}$ *m* (over a light year of lead!)
  - GeV-scale neutrino: $d_{lead} \sim 10^{12}$ *m* (still almost a trillion miles of lead!)
- What about a GeV-scale proton? $\sigma \sim 10^{-25}$ cm^2
  - GeV-scale proton: $d_{lead} \sim 10$ *cm!*

atomic mass unit

$$d_{lead} = \frac{1.66\text{x}10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}$$

ν-N cross-section

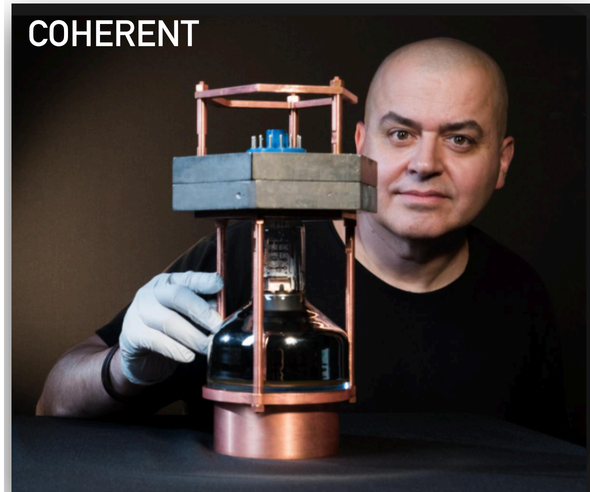
density of lead

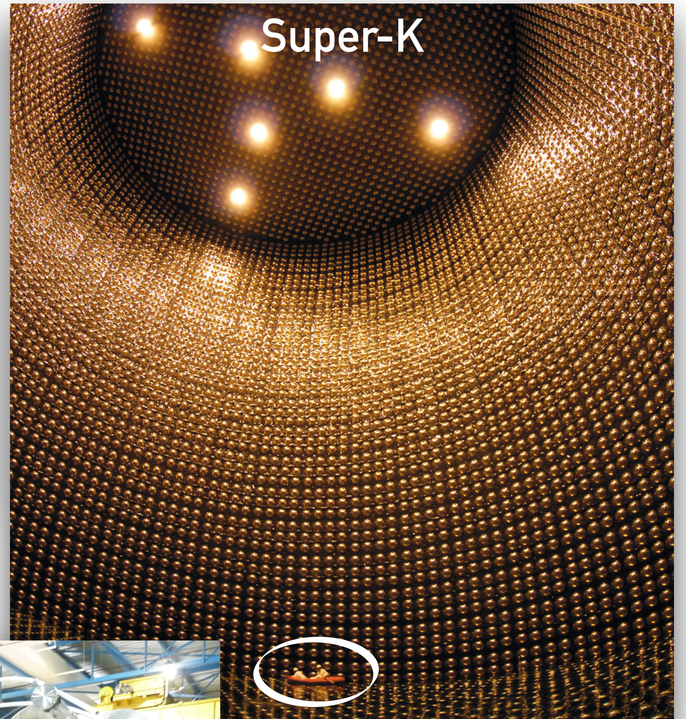
Detecting Neutrinos 101

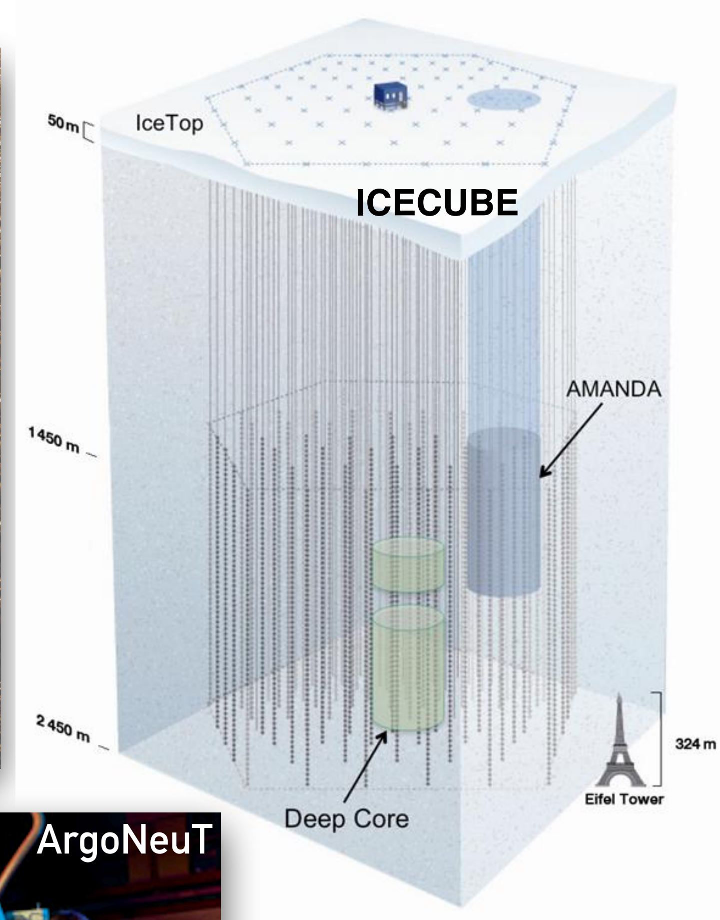
- *Basic Strategy*
  - Produce them in large quantities in a well defined area
  - Put something very **Dense**, very **BIG** and very **Sensitive** for neutrinos to interact

- *In other words*
  - High intense beams (typically kW beams, now moving to MW)
  - Large neutrino fluxes
  - Long exposure time
  - Dense targets (e.g. Argon)
  - Large target mass (tens of meters, hundreds to multi-kiloton-scale)
  - Low background (place them underground; design for maximum signal sensitivity; efficient background tagging etc.)

Neutrino Detectors

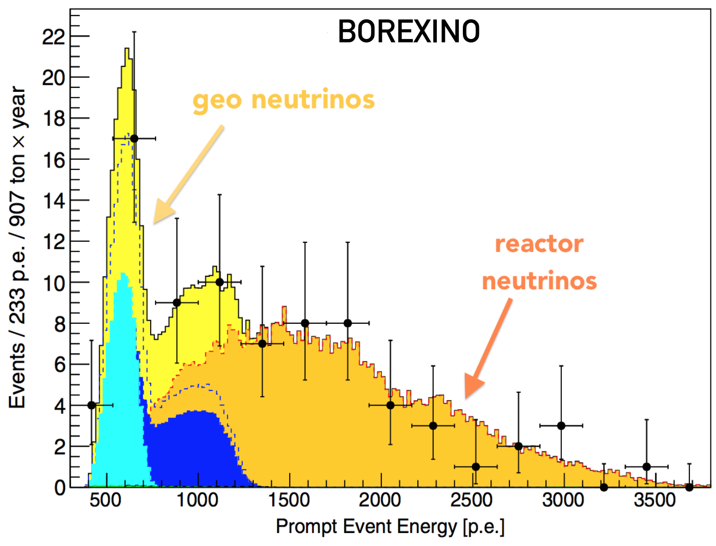




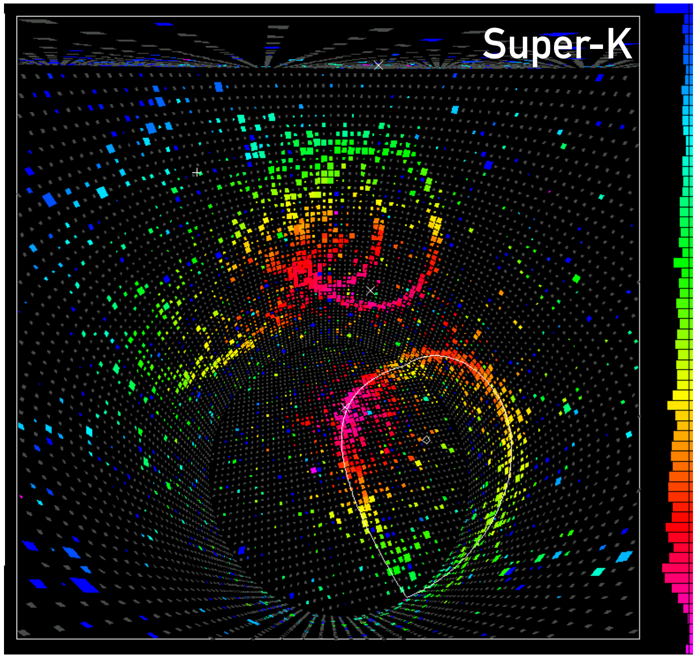


Technologies advances at every turn have enabled and continue to enable neutrino discoveries

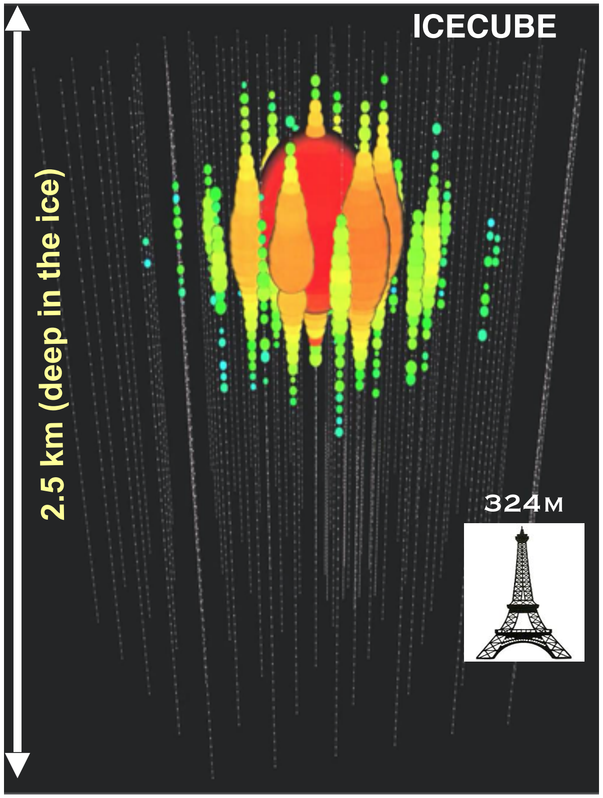
Visualizing Neutrinos



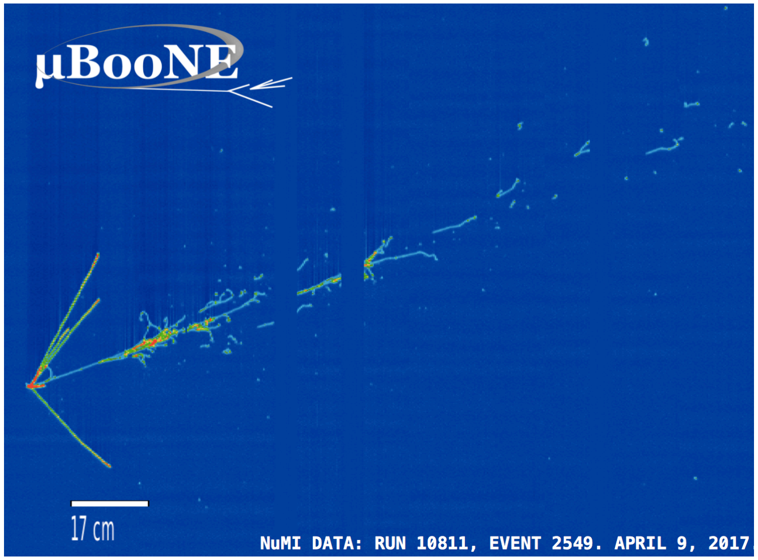
MeV-scale neutrino



A few-100 MeV neutrino



A 2 PeV scale astro physical event in the detector

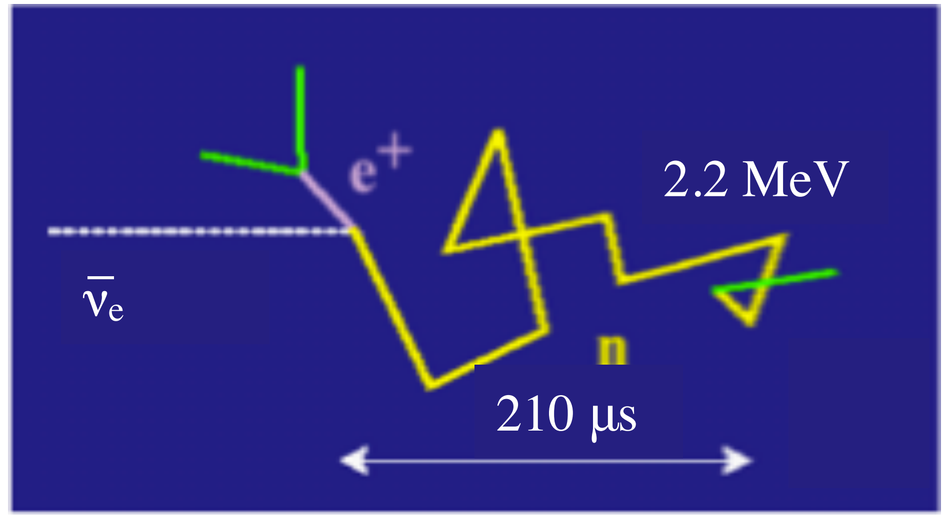


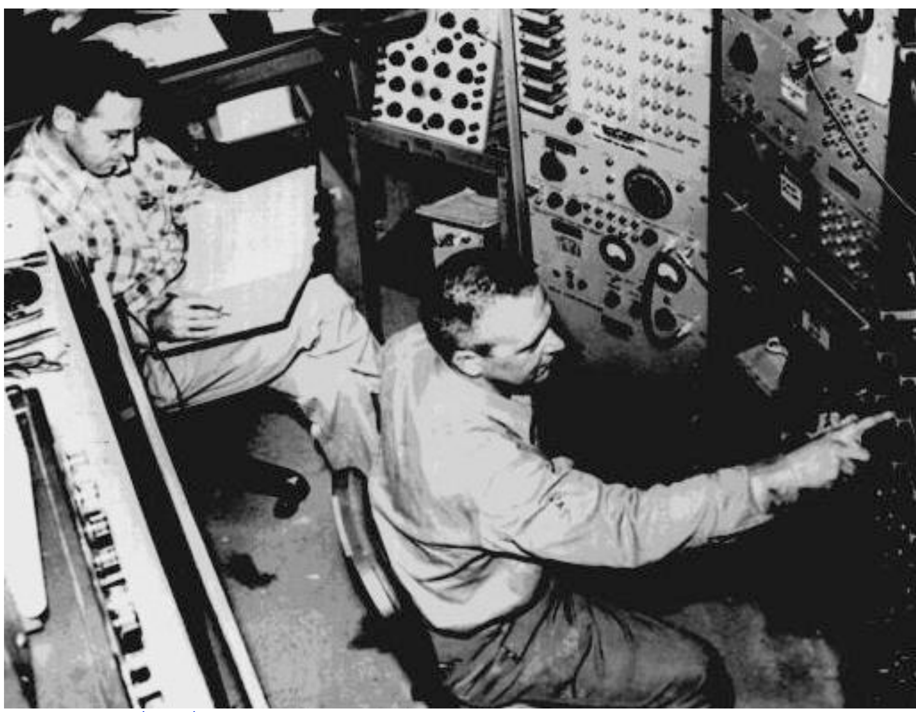
MeV → PeV

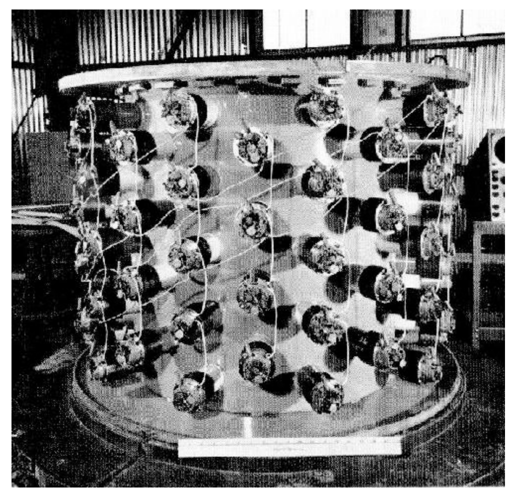
We have observed neutrinos at wide range of energies

First Direct Detection of Neutrinos

$$\bar{\nu}_e p \longrightarrow e^+ n$$

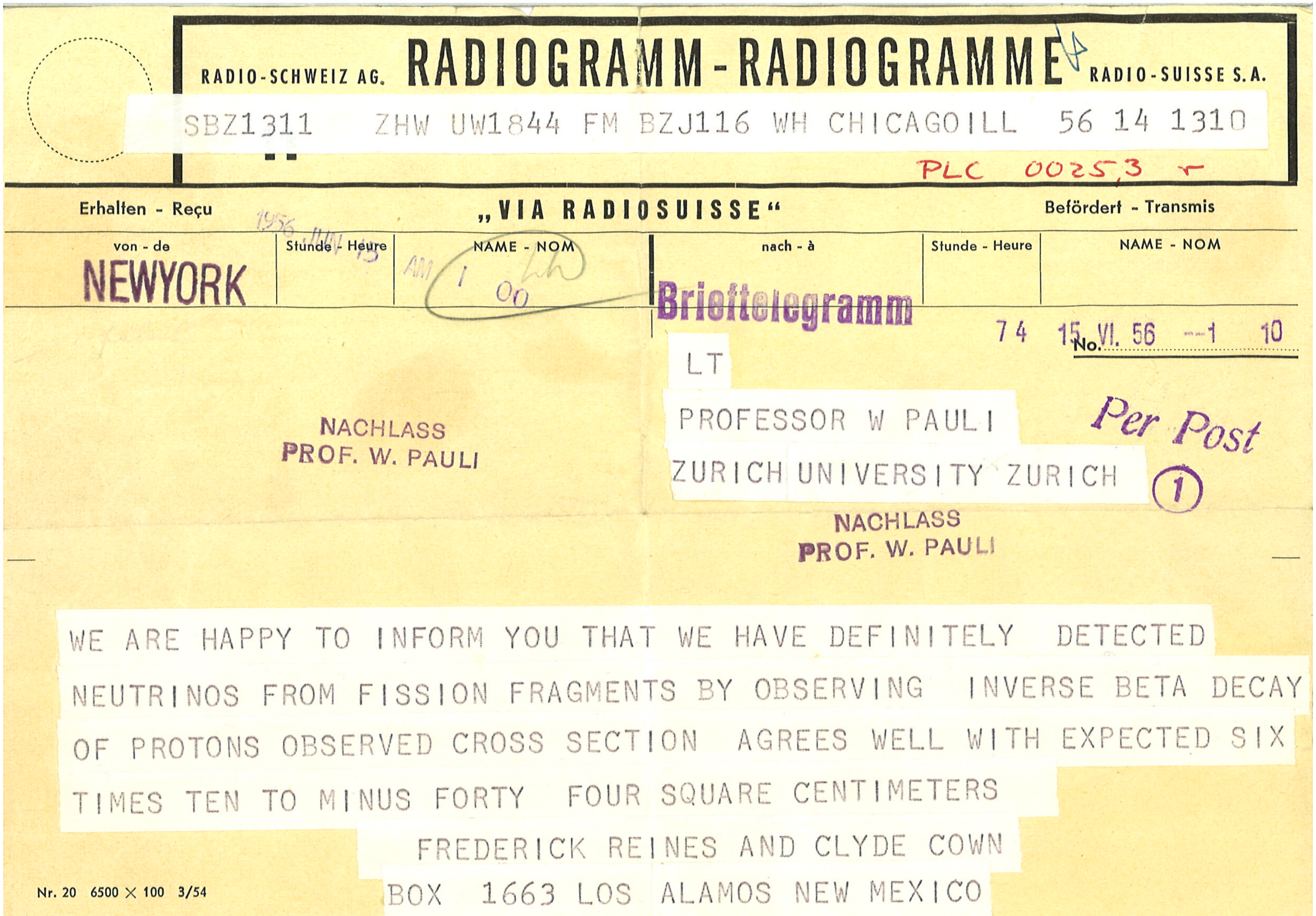






Reines and Cowan 1958

Direct Detection of Neutrinos



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

NACHLASS PROF. W. PAULI

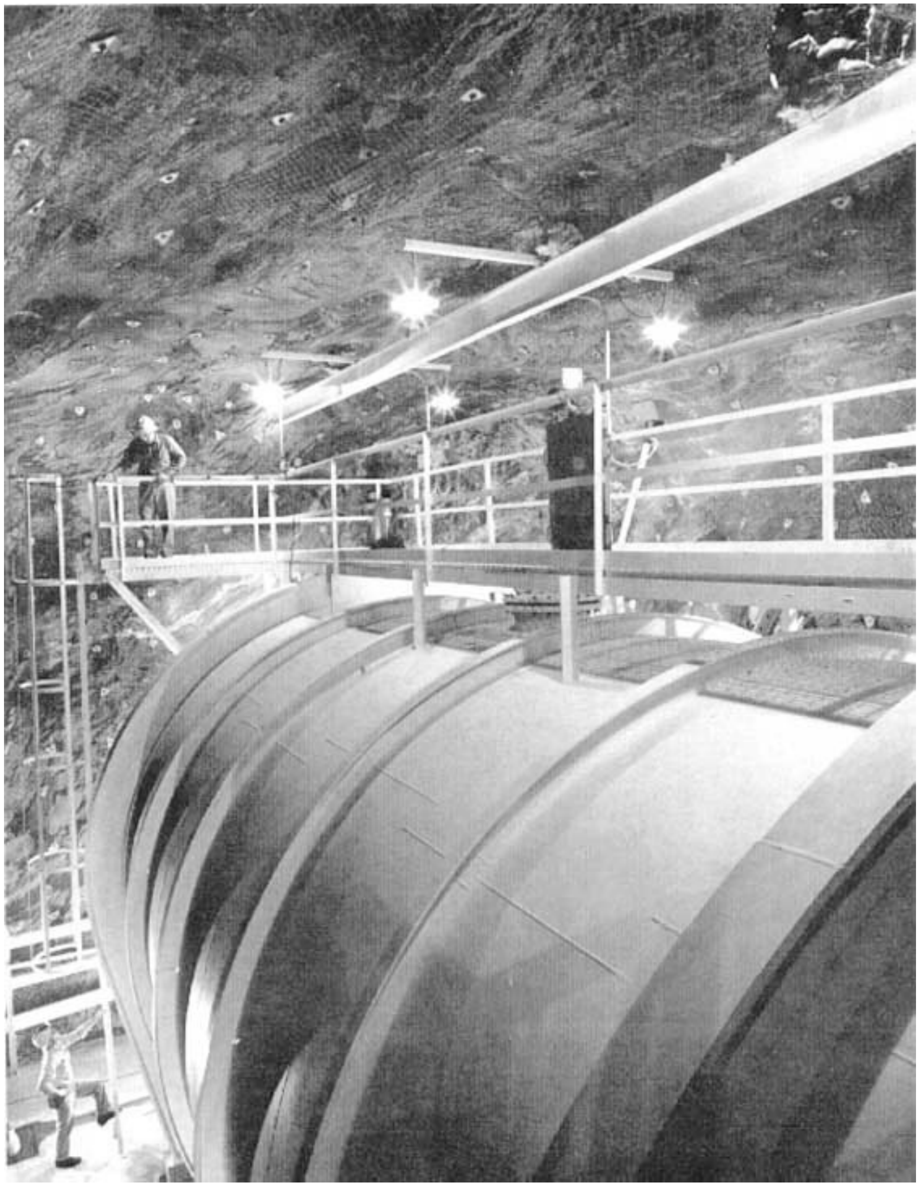
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

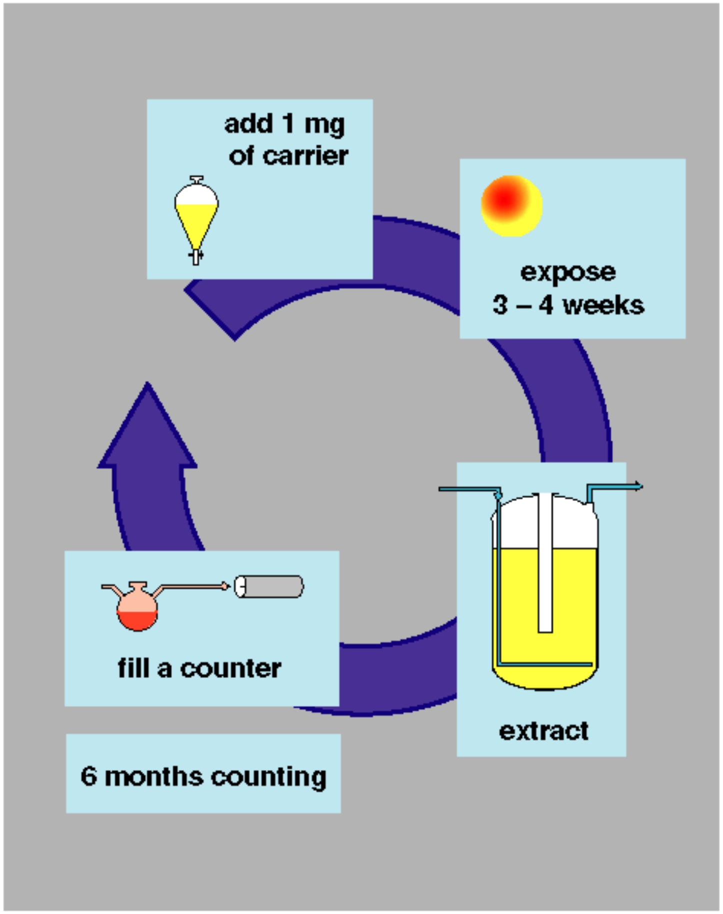
Pioneers in Solar Neutrino Physics



$$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e$$

1968 First Solar Neutrino Experiment (Homestake)

Homestake Ga Experiment



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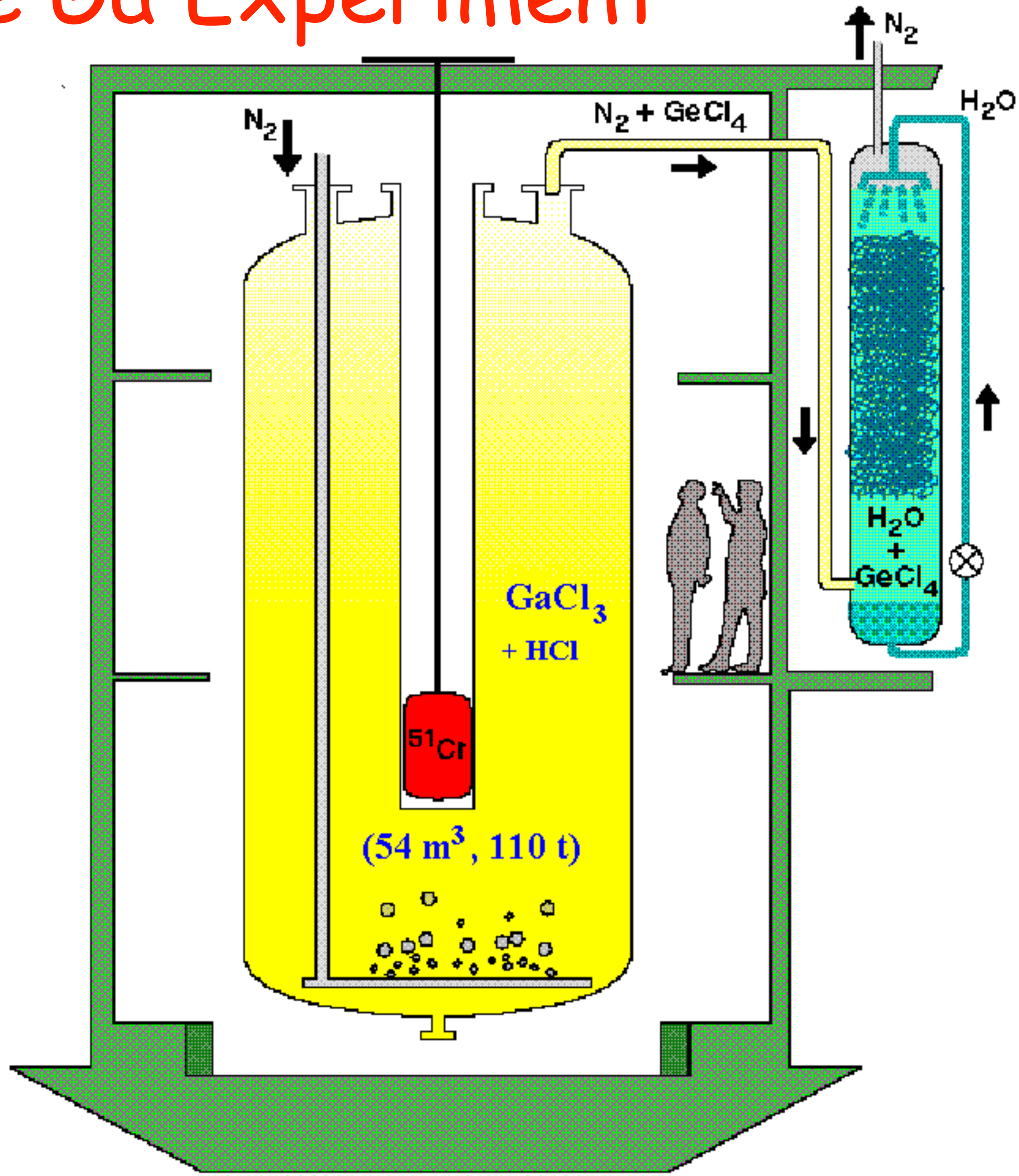
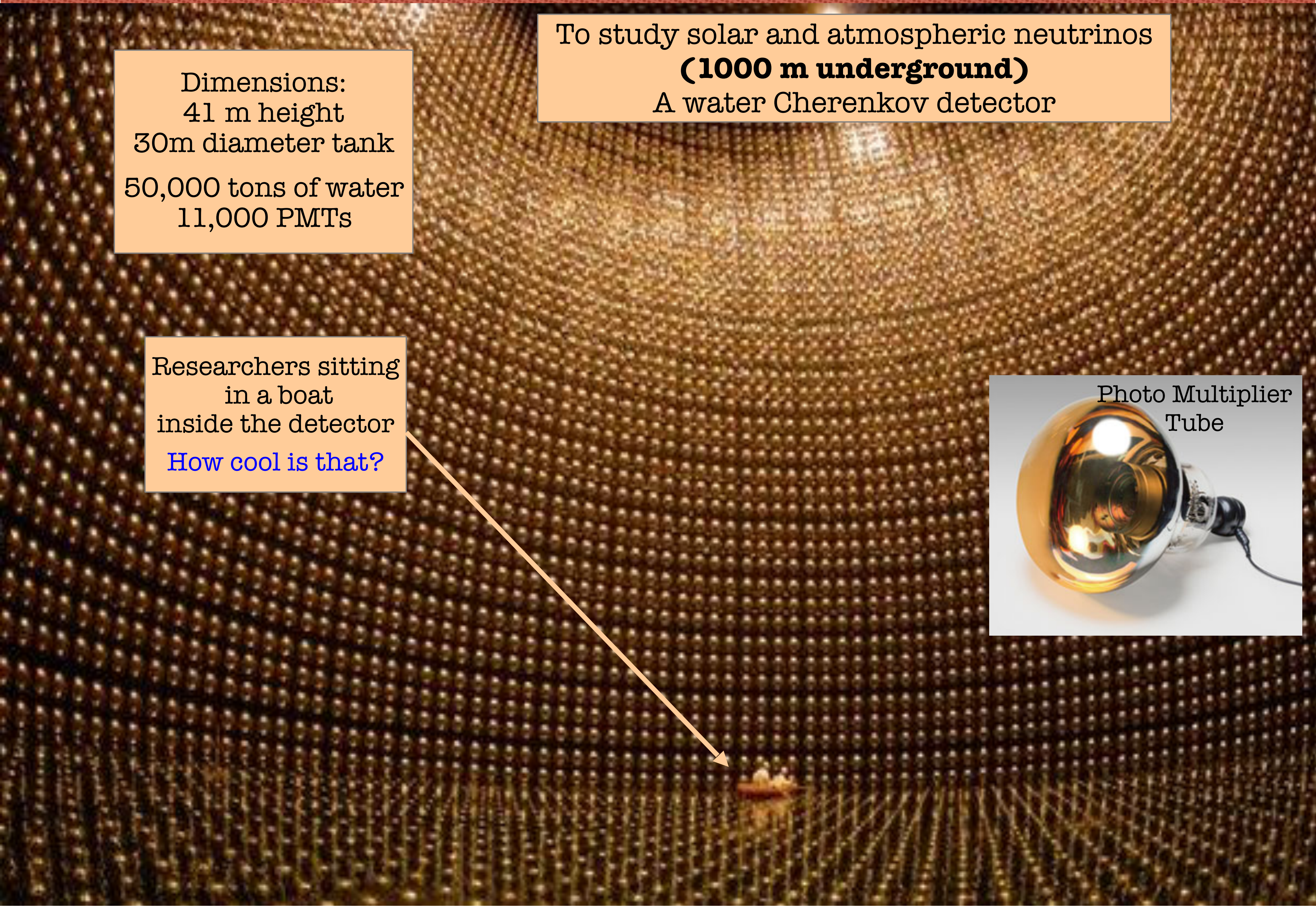


Gallium Experiment-Gallium Neutrino Observatory

The Super Kamiokande Experiment (Japan)



To study solar and atmospheric neutrinos
(1000 m underground)
A water Cherenkov detector

Dimensions:
41 m height
30m diameter tank

50,000 tons of water
11,000 PMTs

Researchers sitting in a boat inside the detector

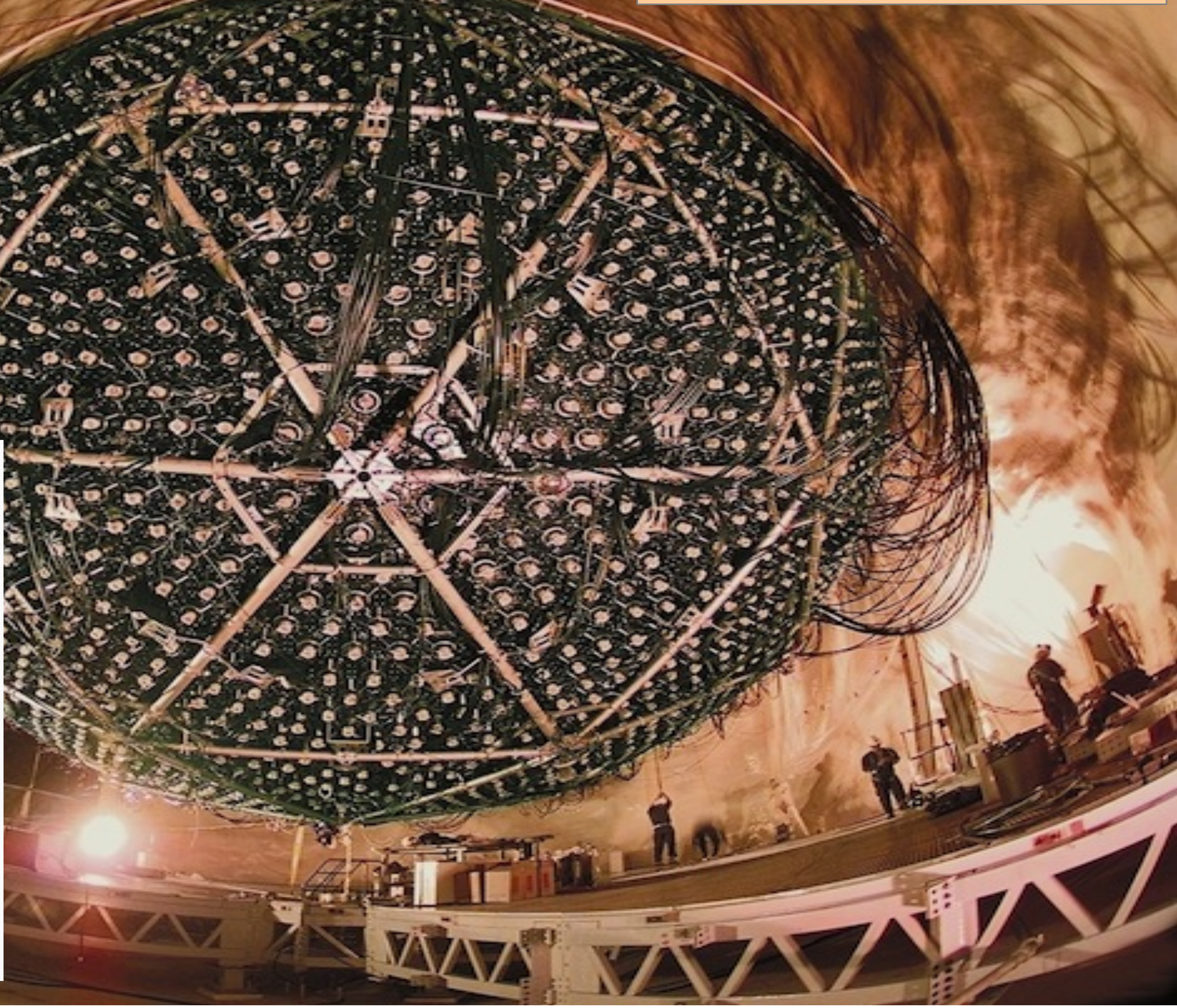
How cool is that?

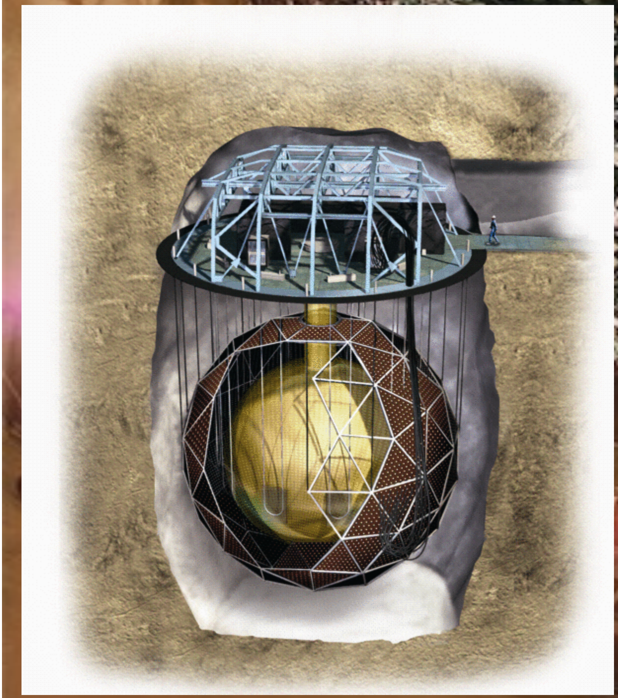
The Sudbury Neutrino Observatory (Canada)

Dimensions:
12m diameter tank

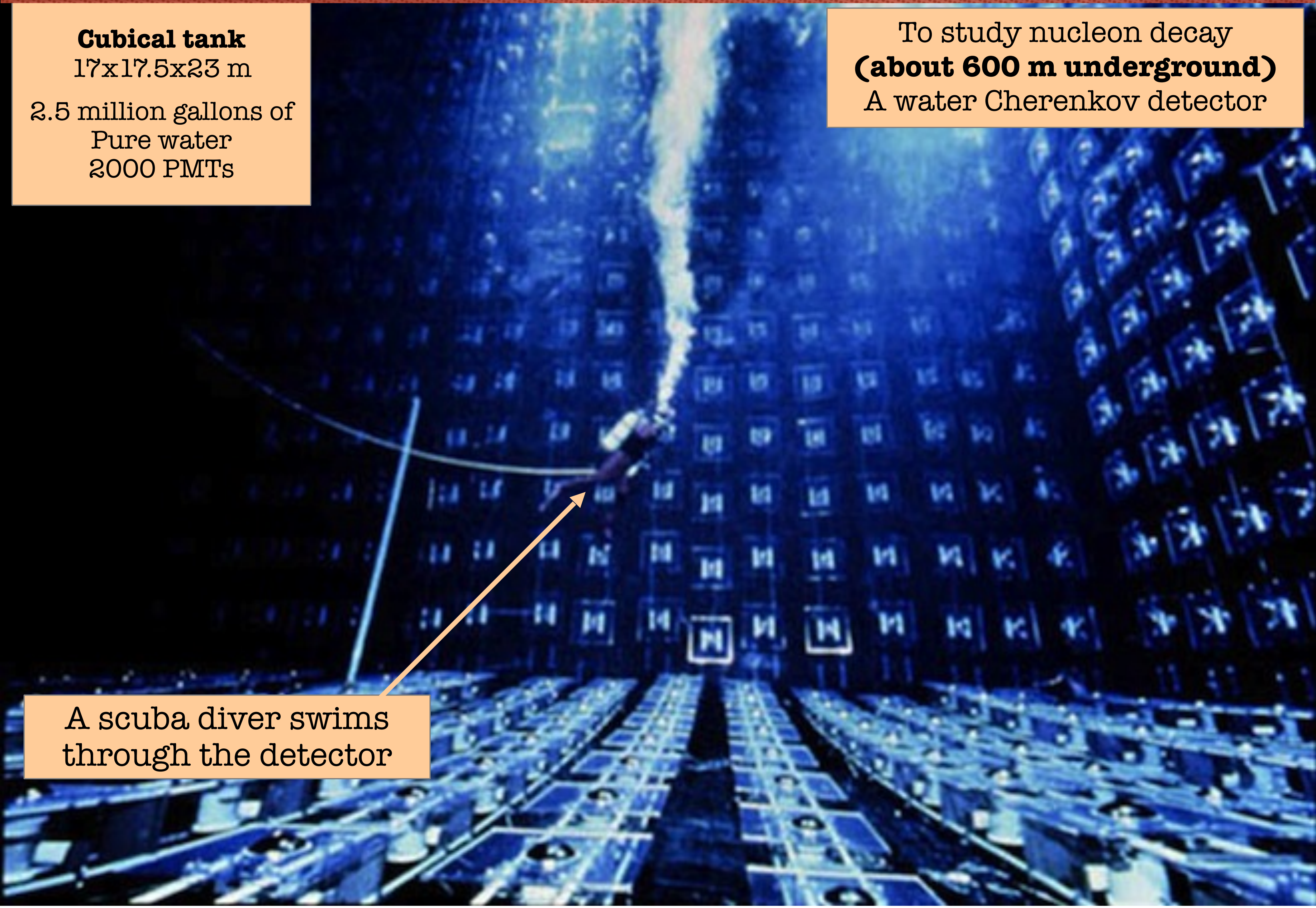
1000 tons of heavy water
9000 PMTs

To study solar neutrinos
(about 2 km underground)
A water Cherenkov detector

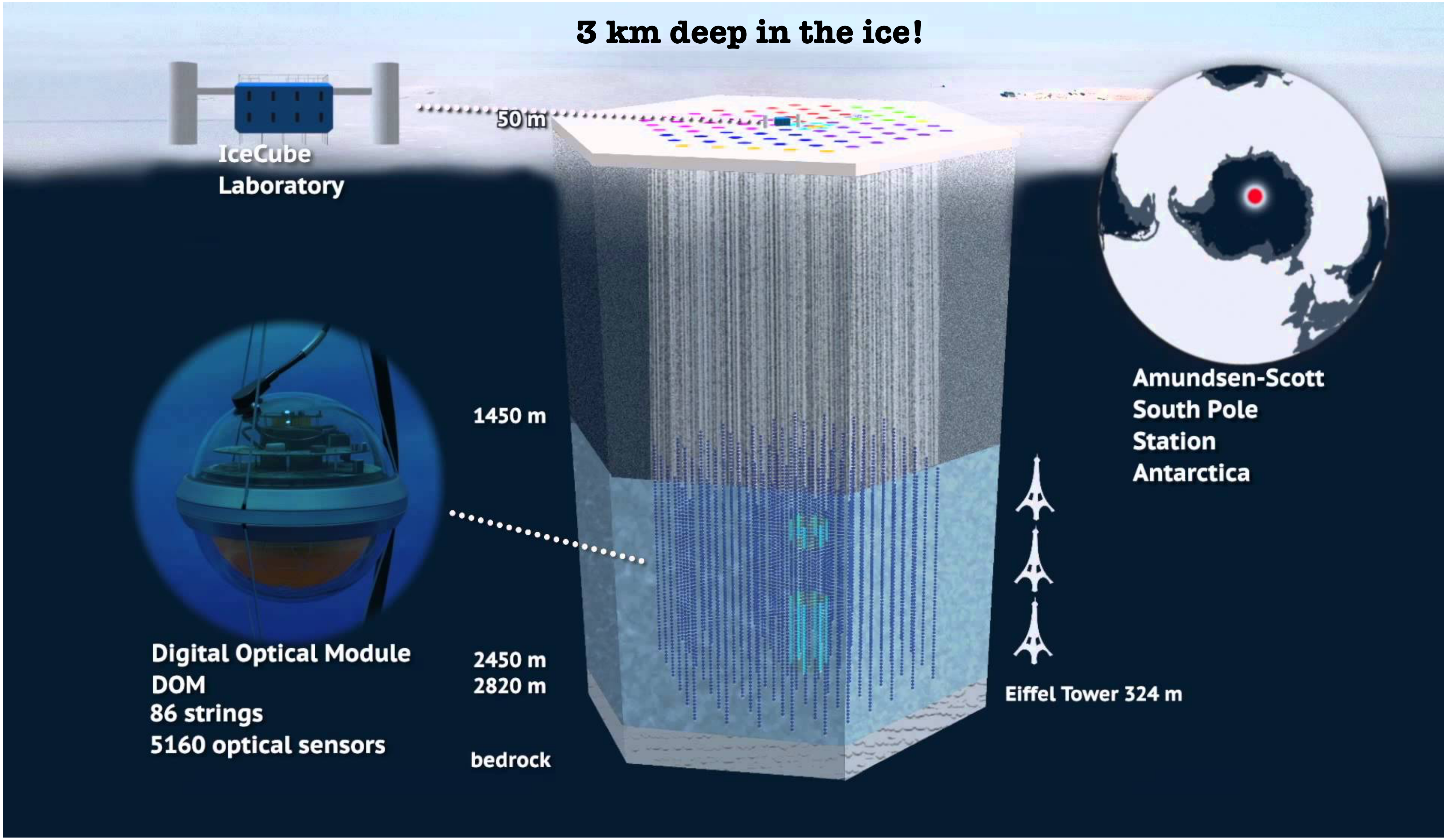




The Irvine-Michigan-Brookhaven Detector

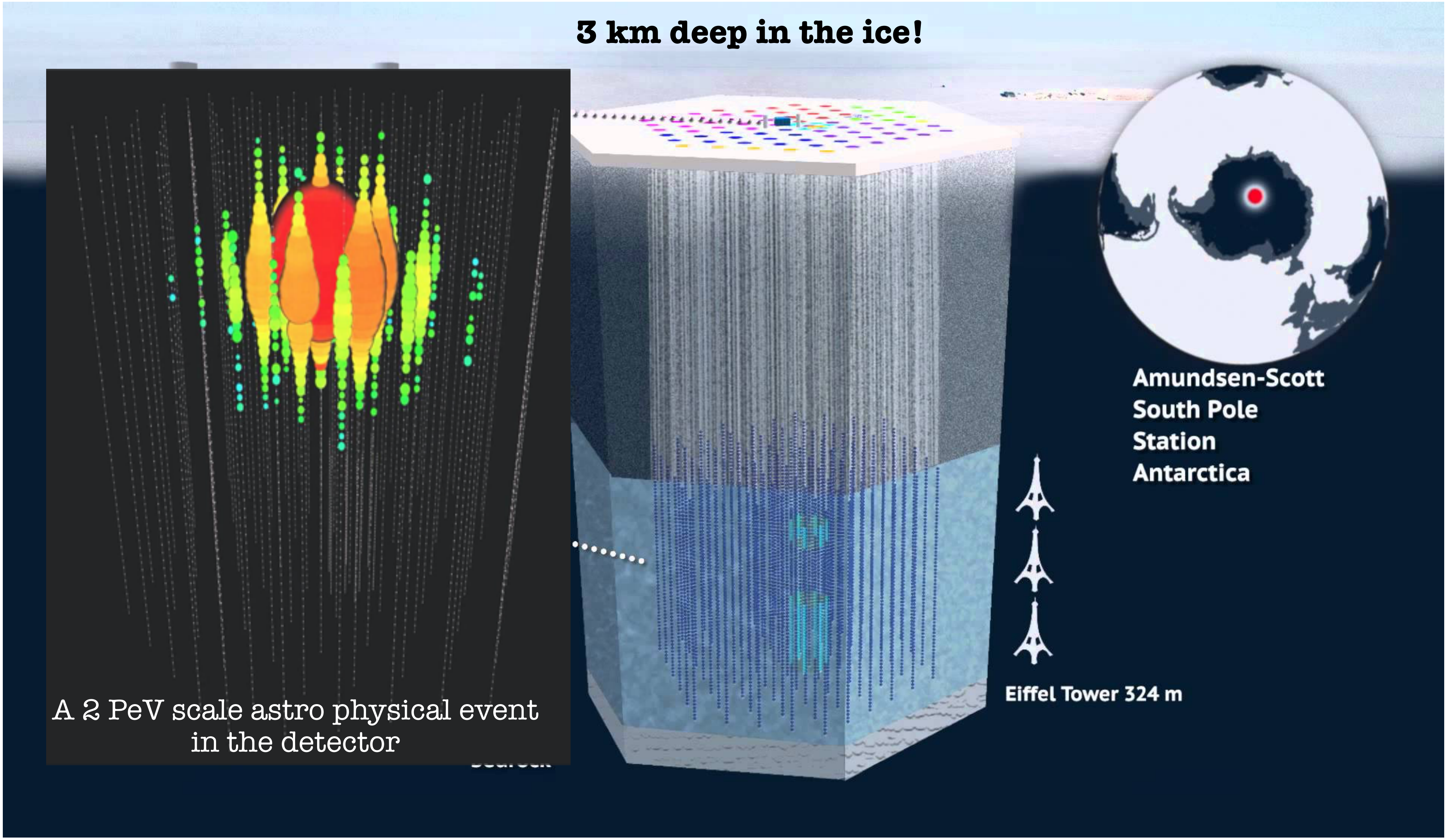


The IceCUBE Experiment (South Pole)



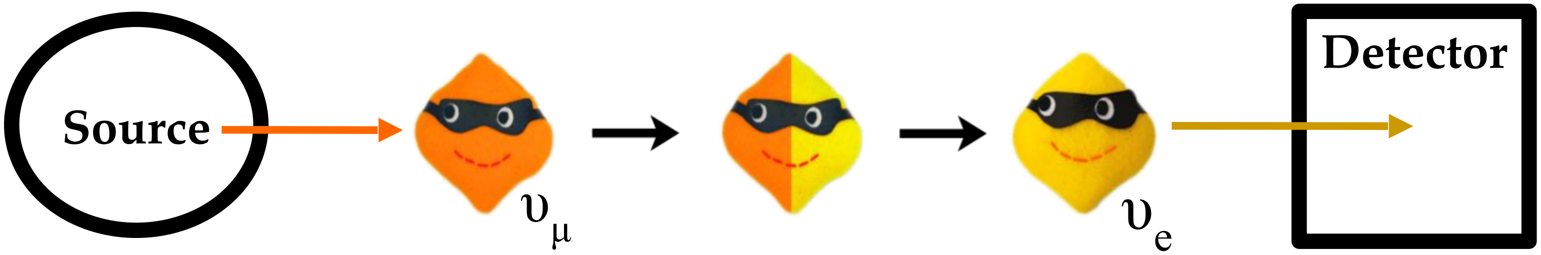
searches for neutrinos from the most violent astrophysical sources: exploding stars, gamma-ray bursts, black holes and neutron stars.

The IceCUBE Experiment (South Pole)



searches for neutrinos from the most violent astrophysical sources: exploding stars, gamma-ray bursts, black holes and neutron stars.

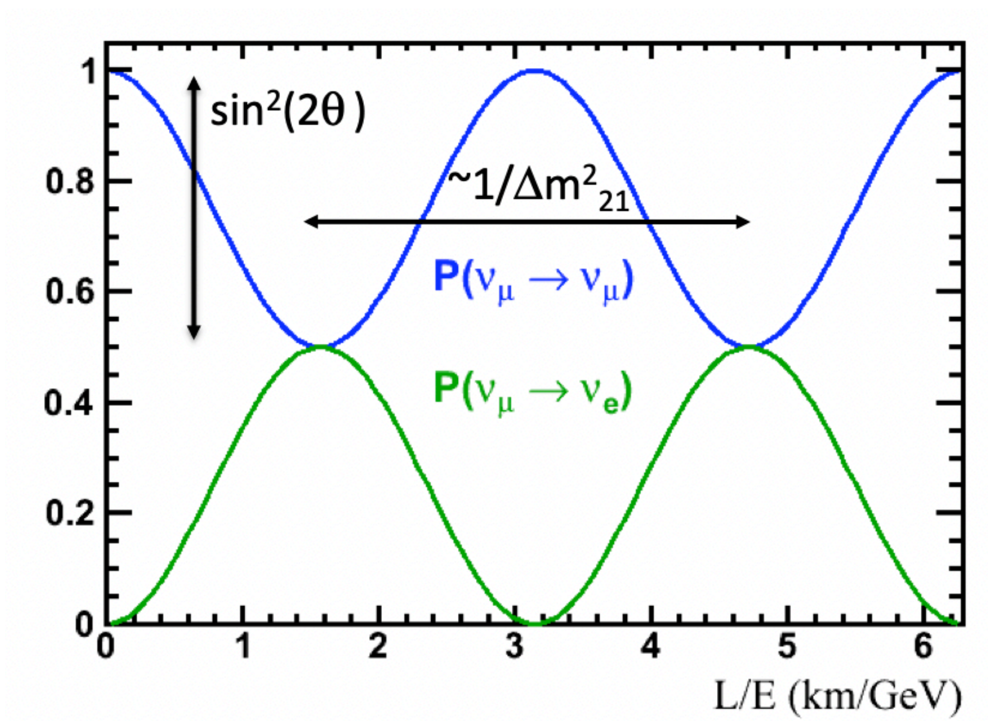
2-Flavor Oscillations



Oscillation Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = sin^2(2\theta) sin^2(1.27 \Delta m^2 \frac{L(km)}{E(GeV)})$$

$$\Delta m^2_{21} = m^2_2 - m^2_1$$



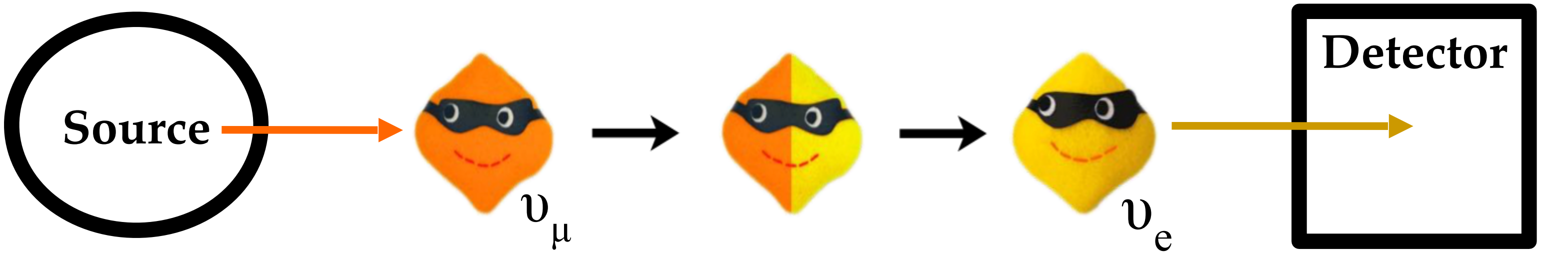
Experimental parameters: **L, E**

Parameter of nature: **Δm^2, $Sin^2 2\theta$**

Long-baseline: L ~ 1000 km

Short-baseline: L ~ 1 km

2-Flavor Oscillations



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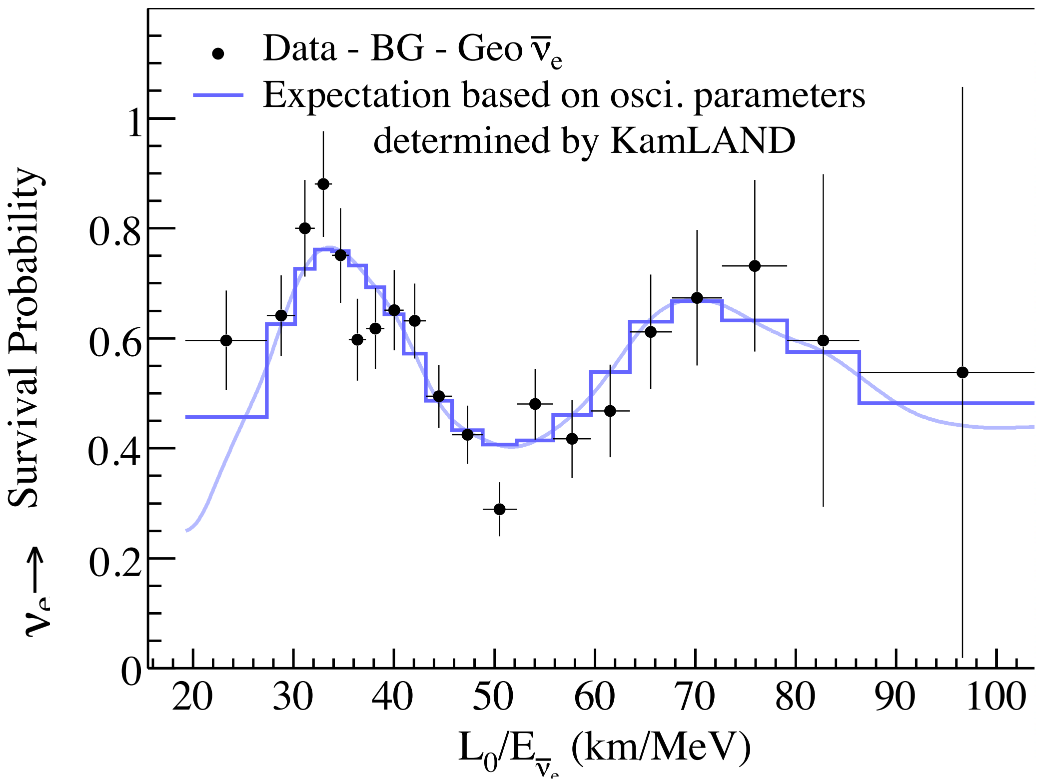


Experimental parameters: **L, E**

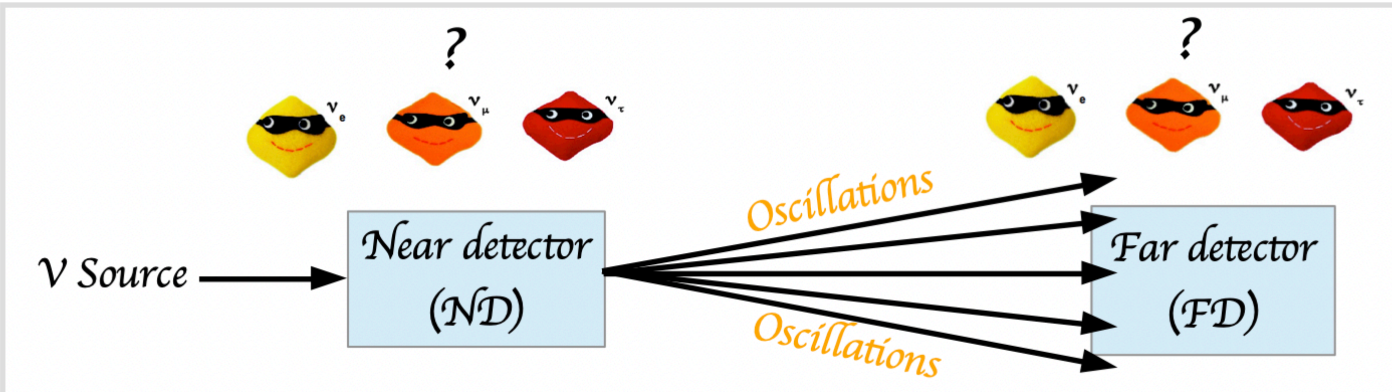
Parameter of nature: **Δm^2, $Sin^2 2\theta$**

Long-baseline: L ~ 1000 km

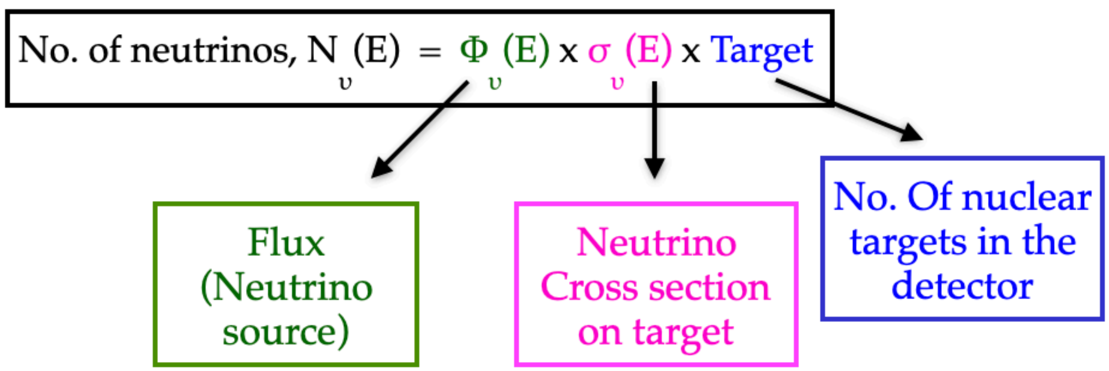
Short-baseline: L ~ 1 km

A Typical Oscillation Experiment

A Typical Oscillation Experiment *Oscillation experiments are basically counting experiments*

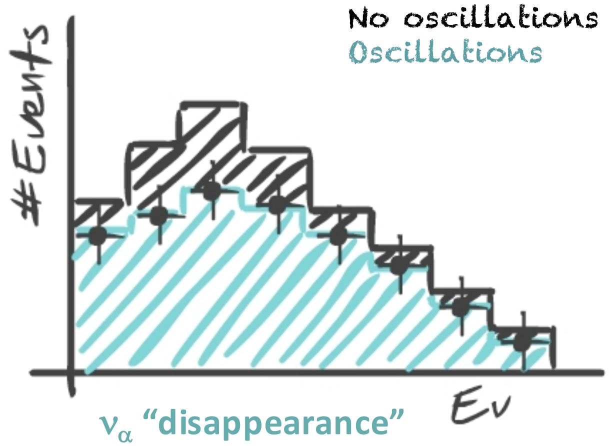


- Start with an intense source of neutrinos (e.g. υ_{μ})
- Build a near detector and a far detector with distance optimized for oscillations to occur
- Measure unoscillated flavor and energy spectrum at L~0 (near detector)
- Measure oscillated flavor and energy spectrum again at L~oscillation maximum (far detector)
- Compare



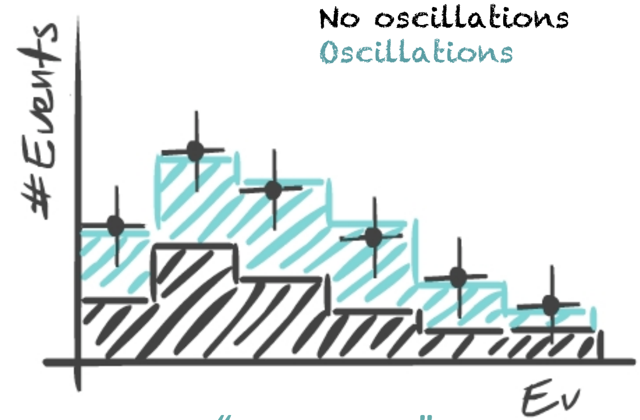
A Typical Oscillation Experiment

Image credit: G. Karagiorgi



ν_α **"disappearance"**

(look for <u>deficit</u> of ν_α events)



ν_β **"appearance"**

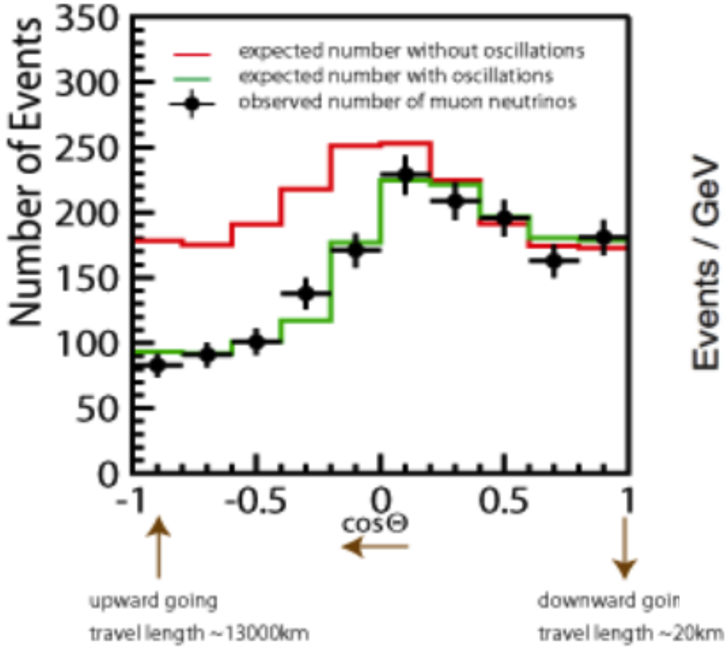
(look for <u>excess</u> of ν_β events)

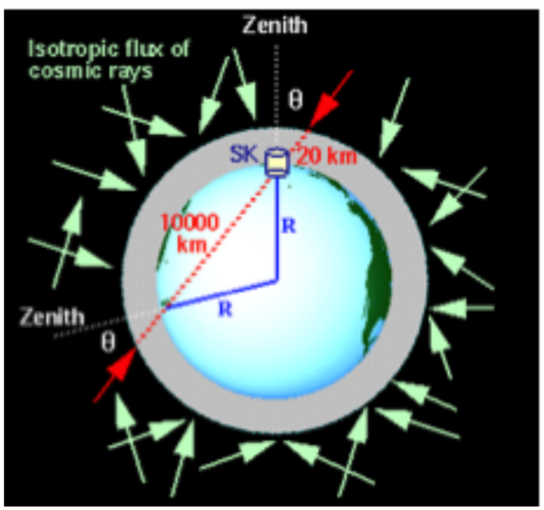
Can perform **"Appearance"** or **"Disappearance"** measurements

Oscillation Experiments

SUPER-K

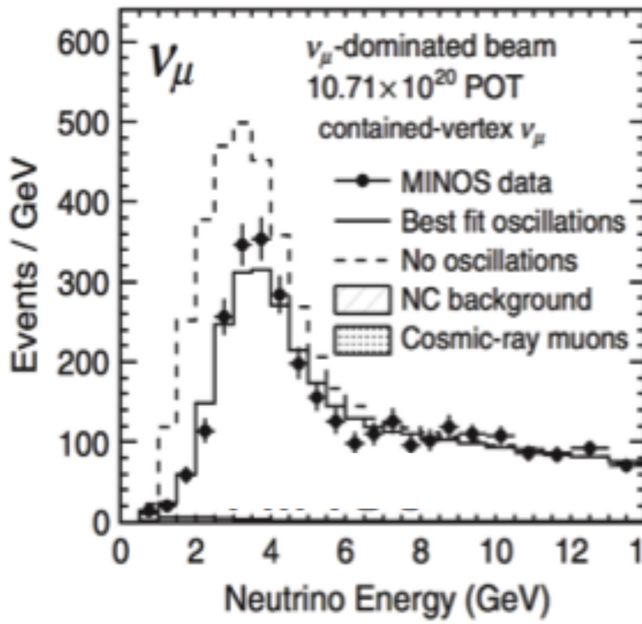
Atmospheric

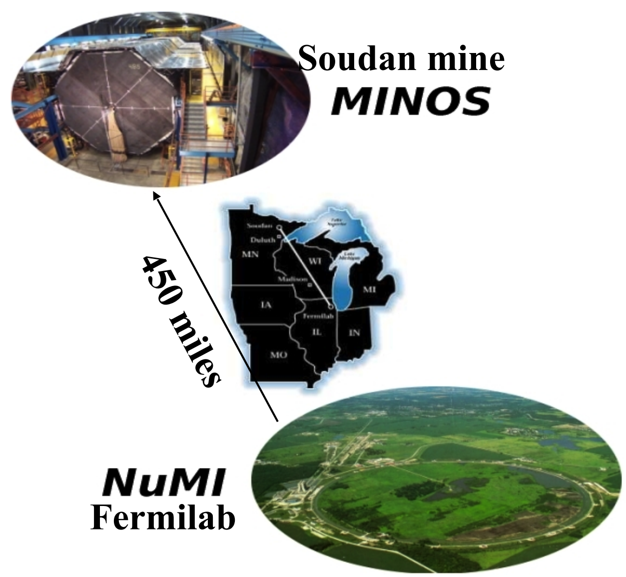




MINOS

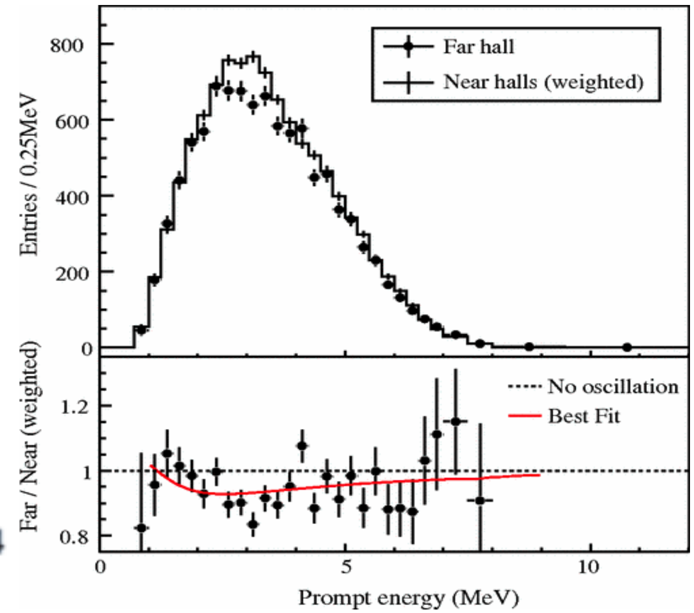
Accelerator

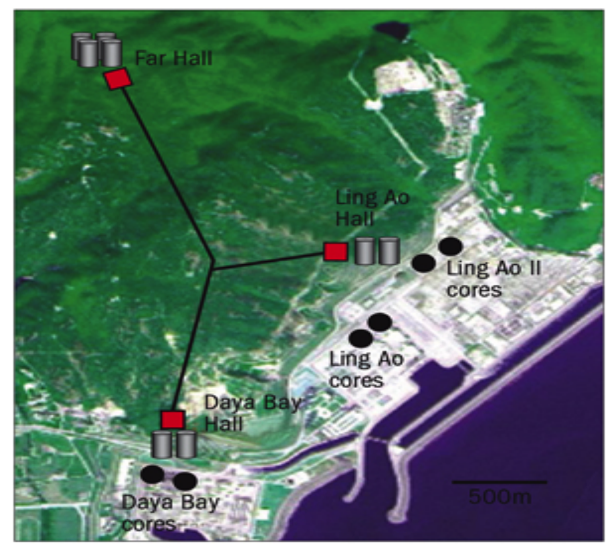




DAYABAY

Reactor source

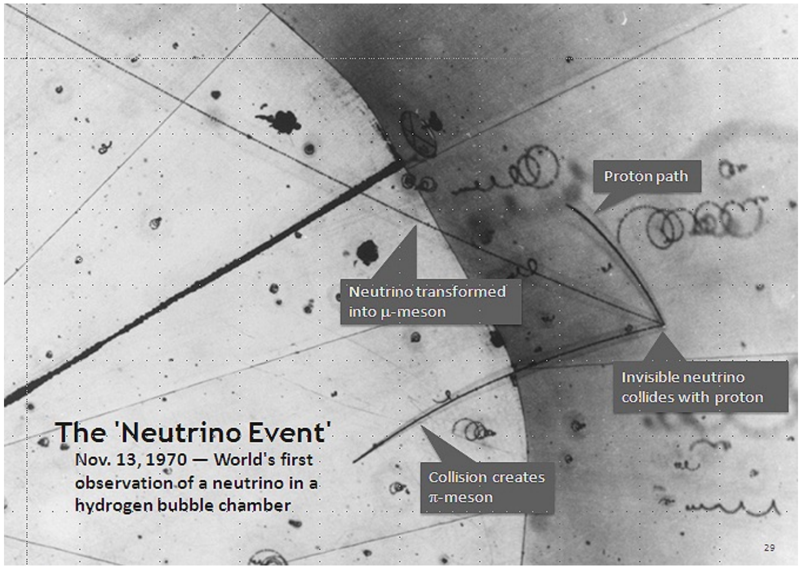




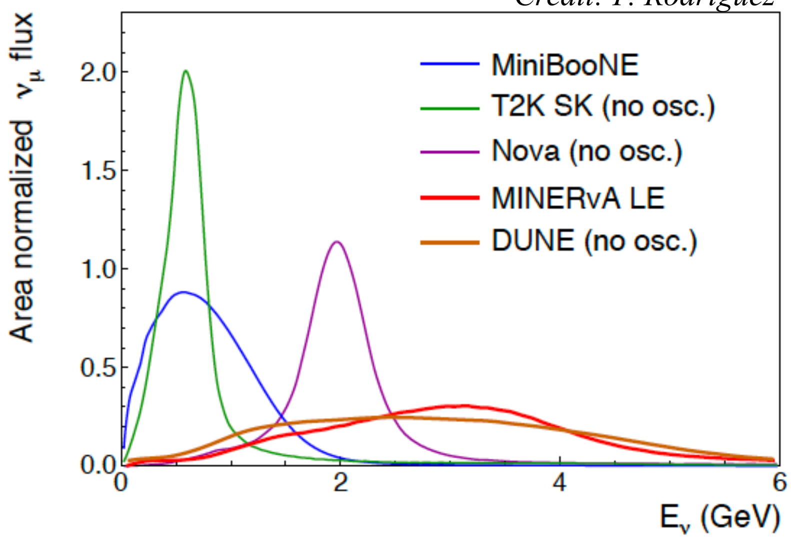
Neutrino Detection Goals

This depends on the experiment but typically

- **Identify the flavor of the neutrino**
  - Only indirect detection *via* particles produced in neutrino interactions
  - Need to know the reaction channel
    - Charged Current vs Neutral Current
    - Various interaction modes within each reaction channel
- **Measure the E_{ν} as accurately as possible**
  - Not easy since neutrino sources are not always monochromatic
- **Neutrino or Anti-neutrino?**
  - differentiate this e.g. oscillation experiments aiming to measure Charge-Parity Violation
  - Charged Current interactions can provide handles



Credit: P. Rodriguez

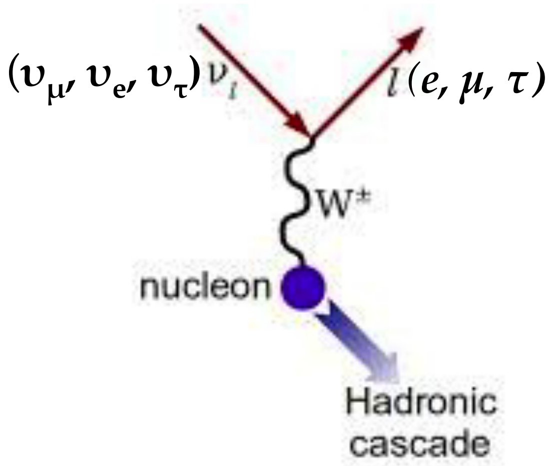


Neutrino Flavor Tagging

Neutrino-nucleon scattering

Charged Current (CC)

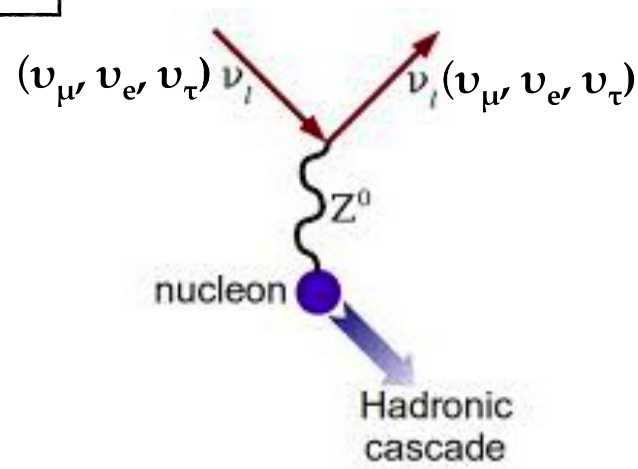
(W+/- exchange)



- Outgoing lepton determines the υ flavor
- Outgoing hadrons: protons, neutrons, pions
- Typically, your signal event
- Production of a lepton requires minimum energy. Thresholds
  - E_υ ~ 500 keV (for an electron)
  - E_υ ~120 MeV (for a muon)
  - E_υ ~3.5 GeV (for a tau)

Neutral Current (NC)

(Z exchange)

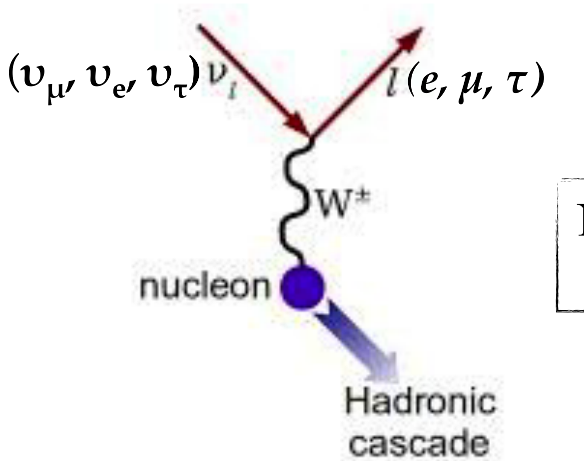


- No outgoing lepton to tag the υ type
- Can only see hadrons in the final state
- Typically, your background event (e.g. in "appearance oscillation" measurements)

Neutrino Flavor Tagging

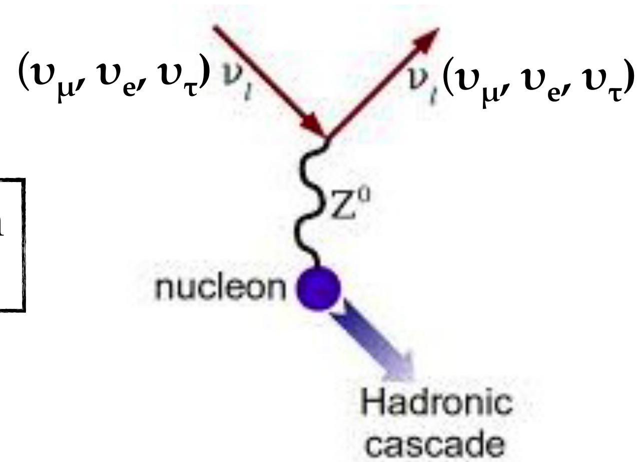
Charged Current (CC)

($W^{+/-}$ exchange)

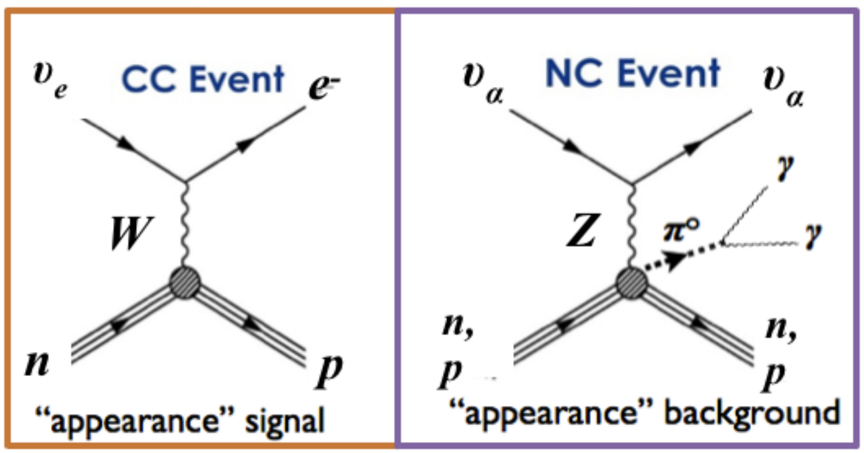


Neutral Current (NC)

(Z exchange)



Neutrino-nucleon scattering



- No outgoing lepton to tag the υ type
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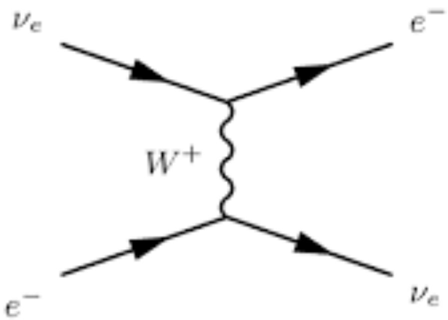
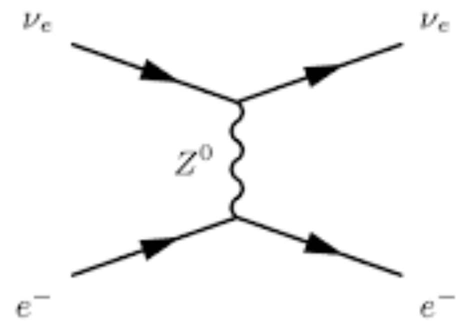
Neutrino Flavor Tagging

Charged Current (CC)
($W^{+/-}$ exchange)



Neutral Current (NC)
(Z exchange)



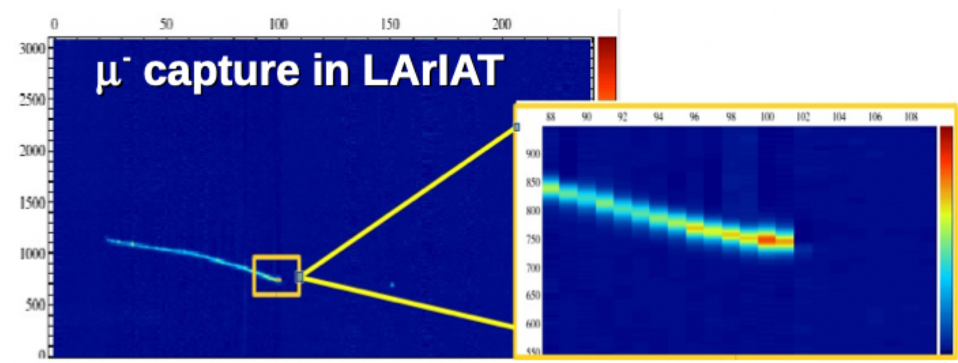
Neutrino-electron scattering

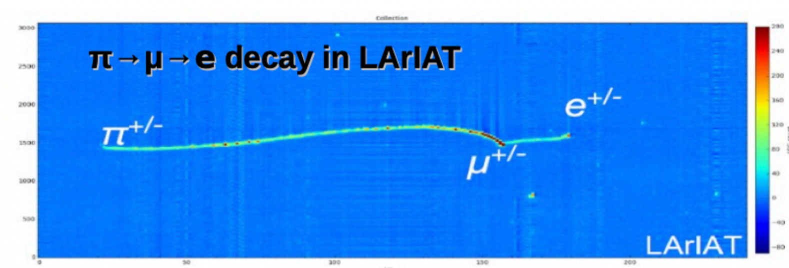
- Neutrino scattering off of an electron
- Signal is a single final state electron

Neutrino vs Anti-Neutrino Tagging

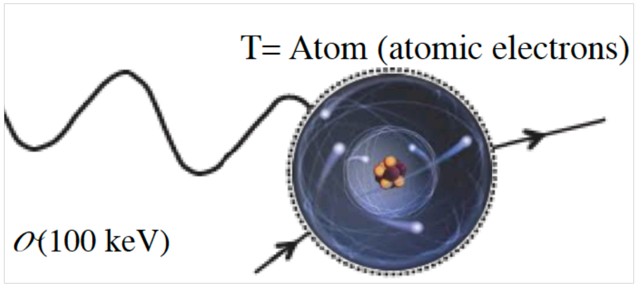
- Key for many experimental searches such as oscillation experiments looking to measure charge-parity violation in the neutrino sector
- Magnetic field is ideal for charge sign determination, however,
  - Neutrino detectors are typically huge
  - High volume magnetic field is hard
  - Expensive
  - Impacts other detector elements e.g. electronics

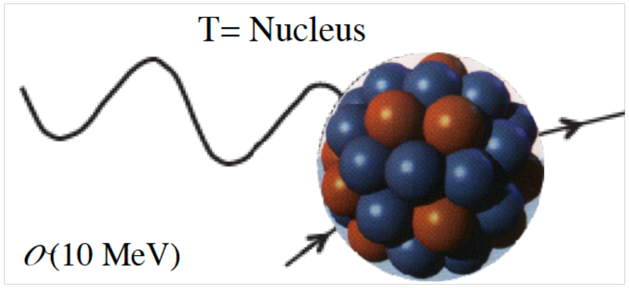
- One can use topology (e.g. decay vs capture) for particle sign identification in the absence of a magnetic field
- NC interactions cannot distinguish
- But, CC can distinguish b/n υ and anti-υ using
  - opposite lepton charge
  - different final state hadrons
  - Muons from hadron decays
  - Requires good final state reconstruction



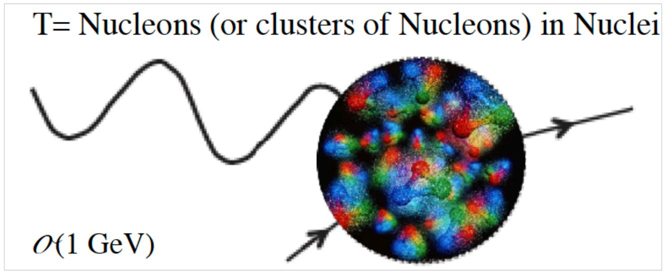


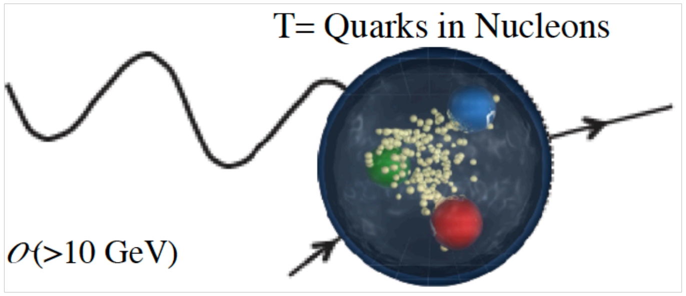
Neutrino Interactions are Complex





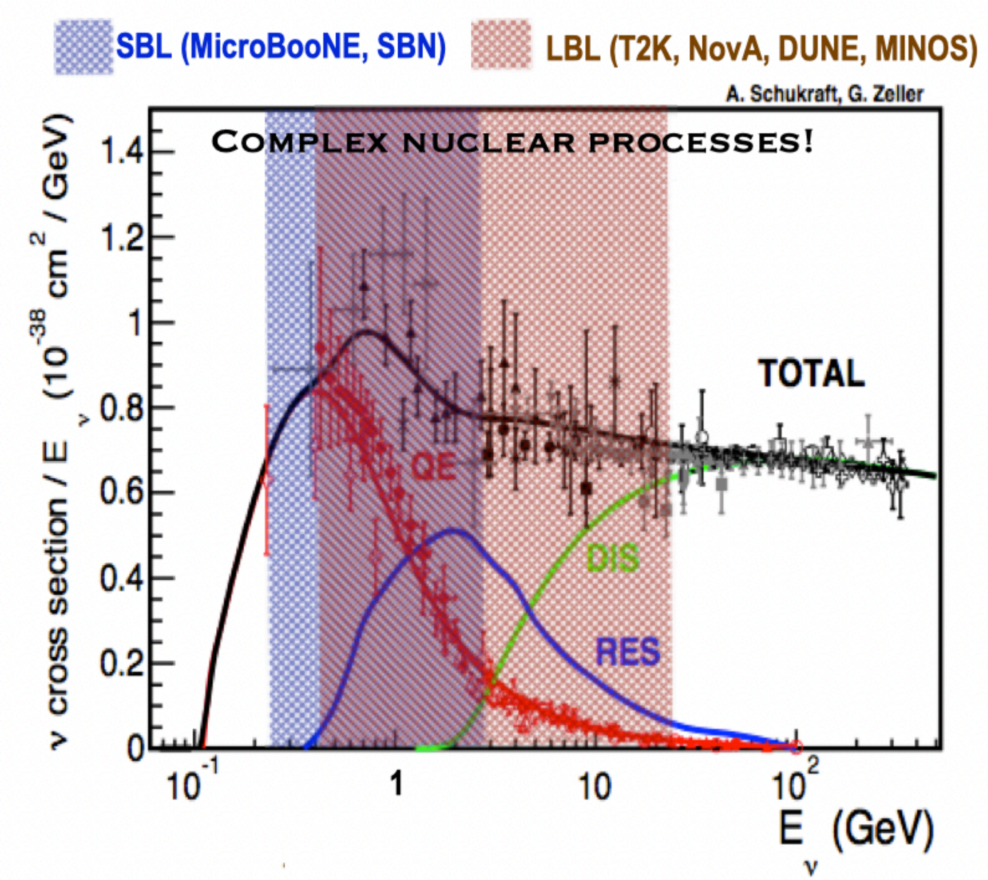
Neutrinos probe matter from its Atomic structure to quark structure depending on the energy of the incoming neutrino

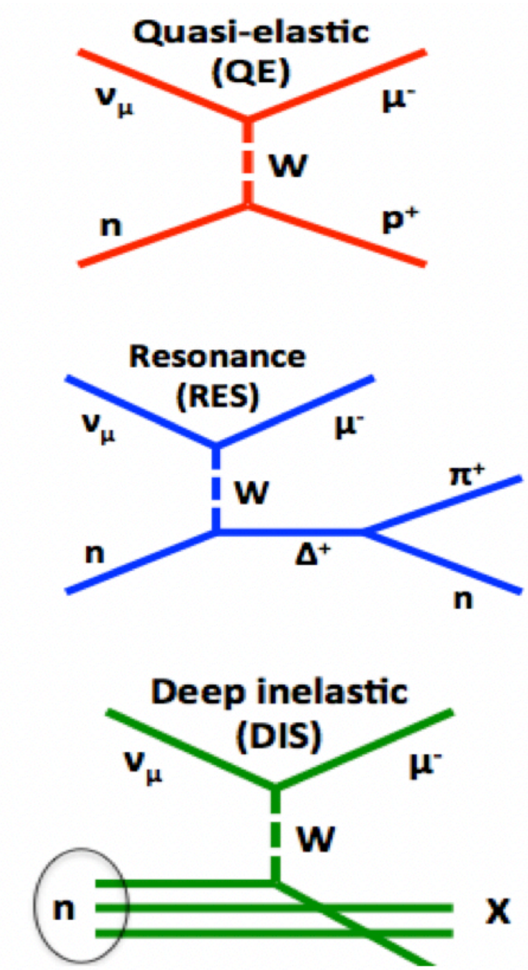




Neutrino Interactions are Complex

Current and future neutrino oscillation experiments focus in the few GeV range





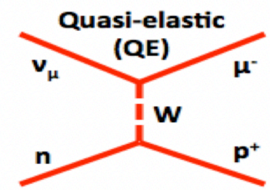
- Higher energies are more messy due to superposition of different channels

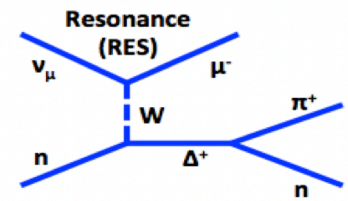
Neutrino Energy Reconstruction

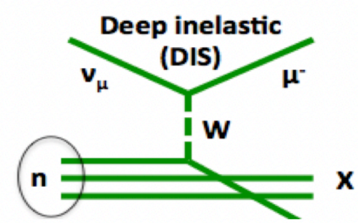
- Neutrino energy from charged lepton kinematics for CCQE

$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}^2 E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos\theta_{\text{beam}})}$$

(2 body kinematics; assumes the target nucleon is at rest)

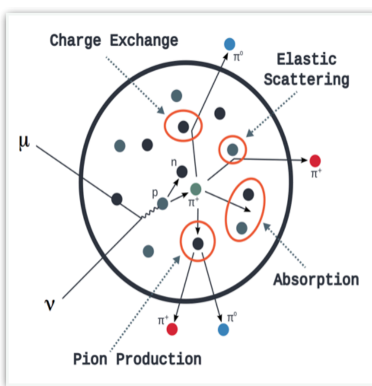




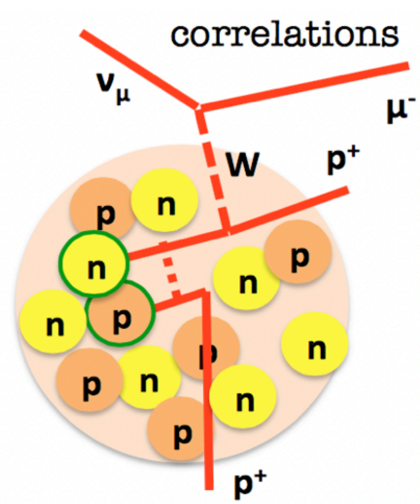


- More complicated final states for RES and DIS channels
- Both lepton and hadron kinematics important for an accurate measurement for all reaction channels
- Modern experiments use denser targets (e.g. Argon) making this picture even more complex — thorough understanding of neutrino-nucleus interaction theory is key

Final State Interactions

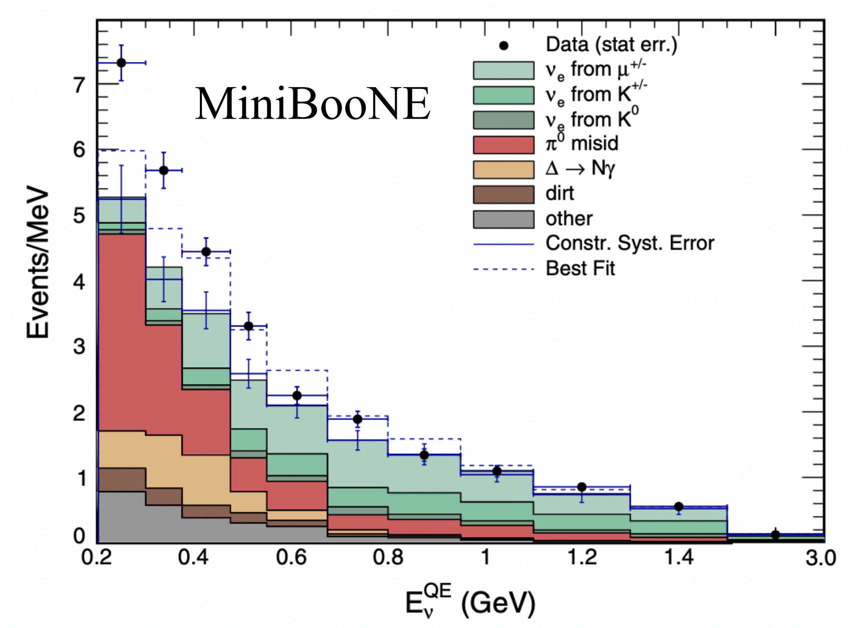


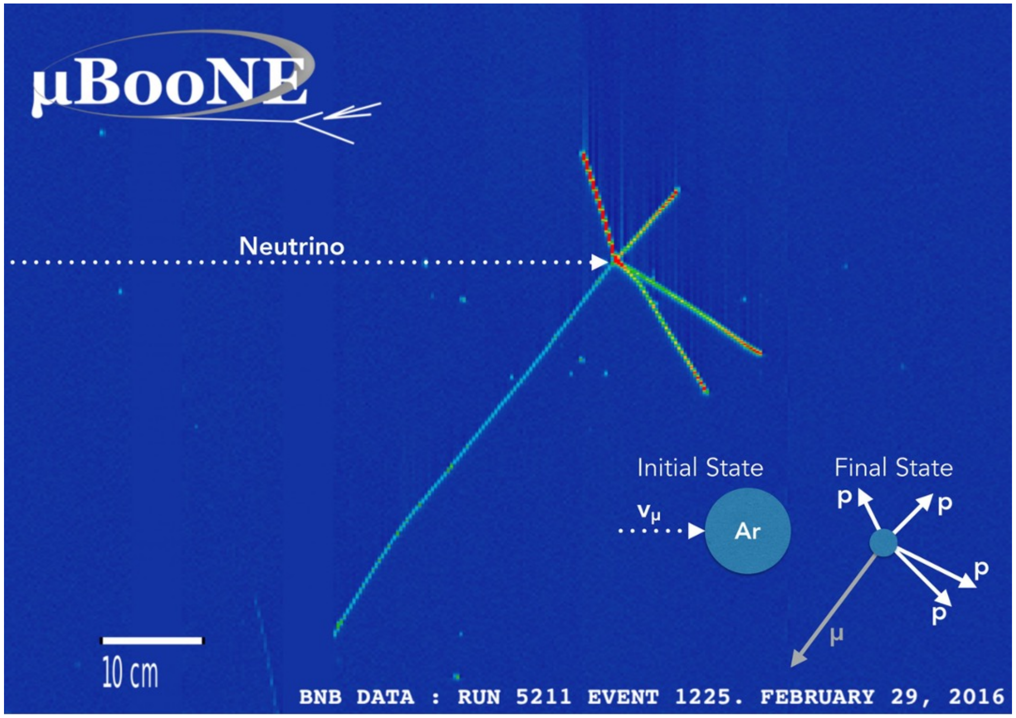
Nucleon-nucleon correlations



Neutrino Detector Goals

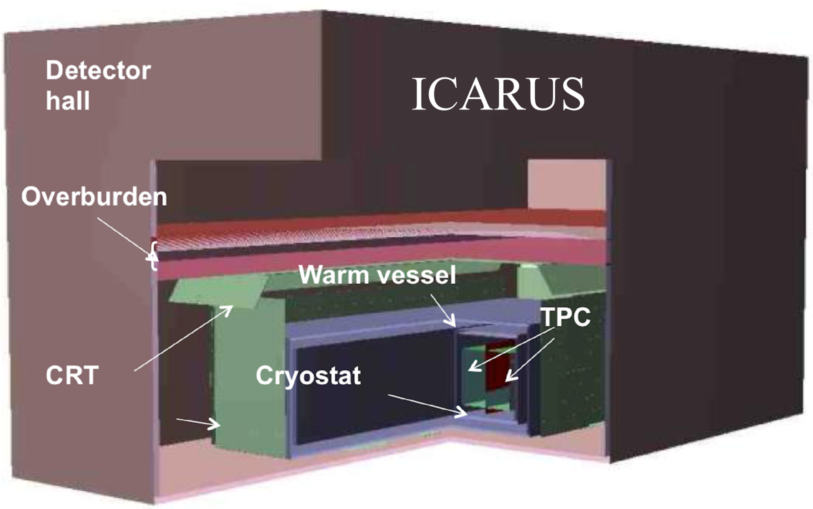
- Neutrino detectors need to work over a broad energy range (from MeV to PeV)
- They should
  - detect leptons and hadrons (protons, pions etc.)
  - distinguish electrons from photons (key for $\upsilon_\mu \rightarrow \upsilon_e$ Appearance experiments)
  - reduce backgrounds and measure them when necessary

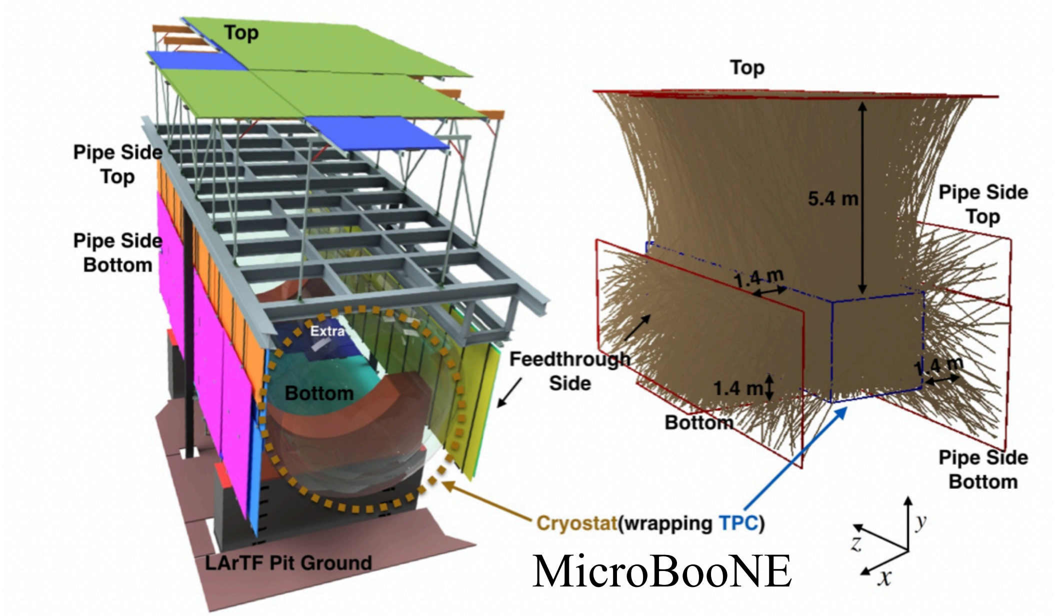




About Backgrounds

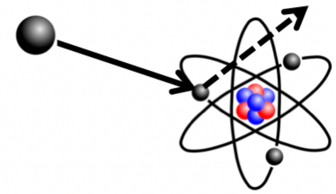
- Backgrounds vary with neutrino energy
  - backgrounds for MeV-scale are not the same as GeV-scale neutrinos)
- Cosmic rays are a worrisome background, many ways to handle this
  - place your detector underground when possible
  - Take beam-off runs to measure cosmic ray background
  - If on surface, implement a cosmic veto/tagger system and/or shielding/overburden
- Reactors produce copious amounts of low-energy (< 10 MeV) neutrinos
  - place your detectors far away from reactors
- Low-energy backgrounds are a concern for many experiments (e.g. reactor, solar/atmospheric, geo-neutrino etc.)



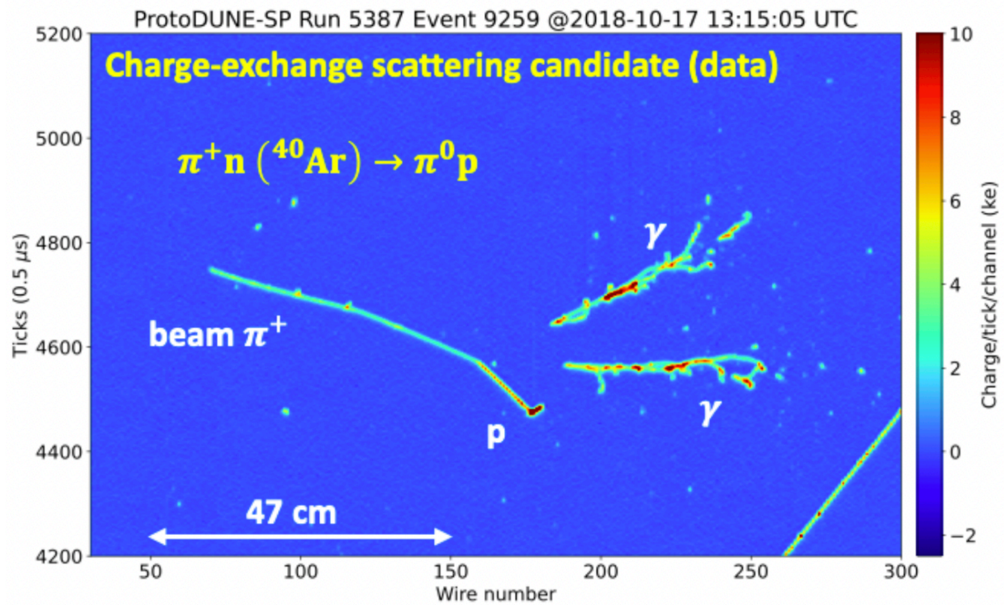


Particle Interactions in Matter

- As particles move through matter, many things can happen
  - Ionization: strip electrons off of atoms in the medium
  - Scintillation: excite atoms and produce scintillation light
  - Cherenkov radiation
  - Decay into other particles
  - Produce new particles



- Many processes can occur that can result in energy loss of the particle
  - Common energy loss process is inelastic collisions with atomic electrons (Ionization)
  - Elastic scattering from nuclei
  - Atomic excitations
  - Hadronic interactions
  - Compton scattering
  - Bremsstrahlung
  - Pari production
  - Photoelectric effect…and so on



Neutrino Detector Technologies

- Cherenkov light Detectors
- Scintillation light Detectors
- Noble element detectors e.g. LArTPCs
- Scintillator Detectors
- Sampling detectors
- Emulsion detectors
- Semiconductor/Crystal detectors
- Gaseous detectors

Caveat: Not a complete survey!

- Many sub-detector technologies employed within these categories

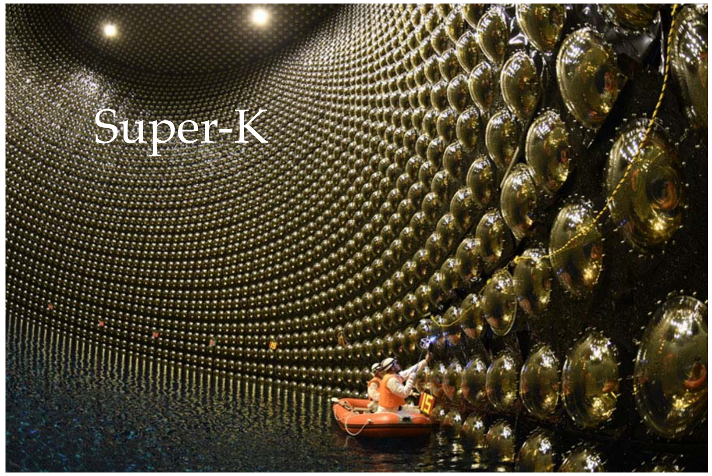
  e.g. Muon spectrometers, Resistive Plate Chambers (RPCs), photon sensors etc.

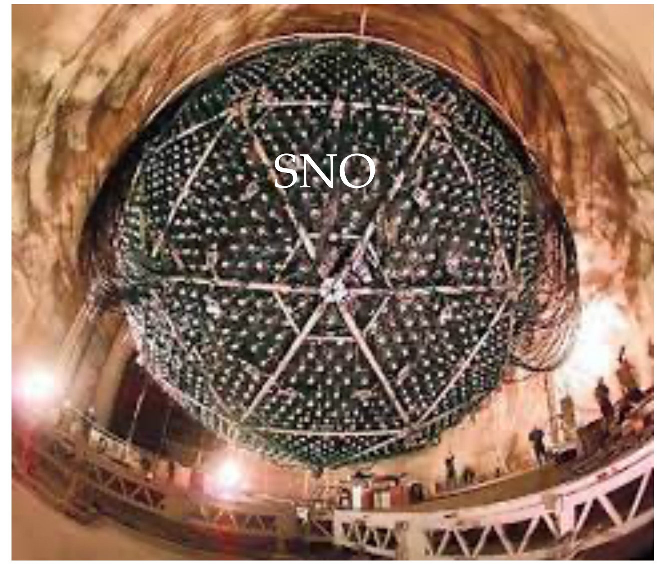
Neutrino Detector Technologies

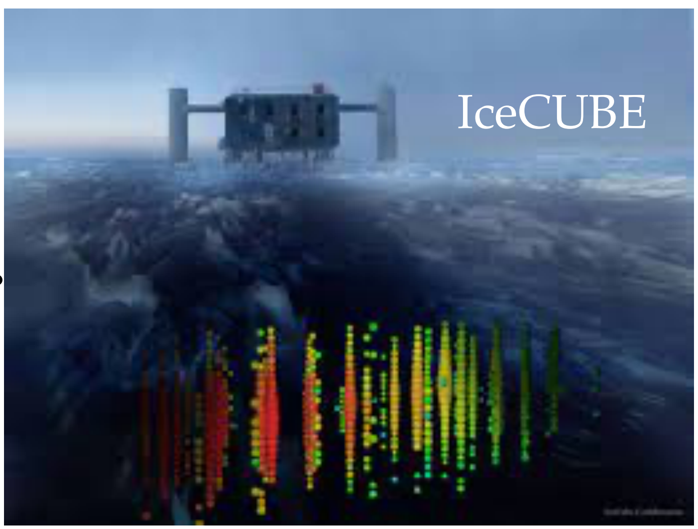
- Cherenkov light Detectors
  - *e.g. water, ice, oil)*
- Noble element detectors e.g. LArTPCs
  - *Mainly ionization drift chambers*
  - *LAr, LXe (both dark Matter & neutrino experiments)*
- Scintillator Detectors
  - *liquid e.g. hydrocarbon; or, solid e.g. plastic, crystal, steel*
  - *Noble element detectors also scintillate e.g. LArTPC*
  - *Coherent-CAPTAIN Mills (CCM) is a LAr Scintillation light detector*
- Sampling detectors
  - *Tracking or Tracking Calorimeters*
  - *Typical design: alternative layers of passive (lead, iron) and active (scintillators, emulsion, RPCs) materials*
- Emulsion detectors *(e.g. lead, Silver Halide)*
- Semiconductor/Crystal detectors *(e.g. Ge detectors, Crystal Bolometers)*
- Gaseous detectors *(e.g. GArTPCs)*

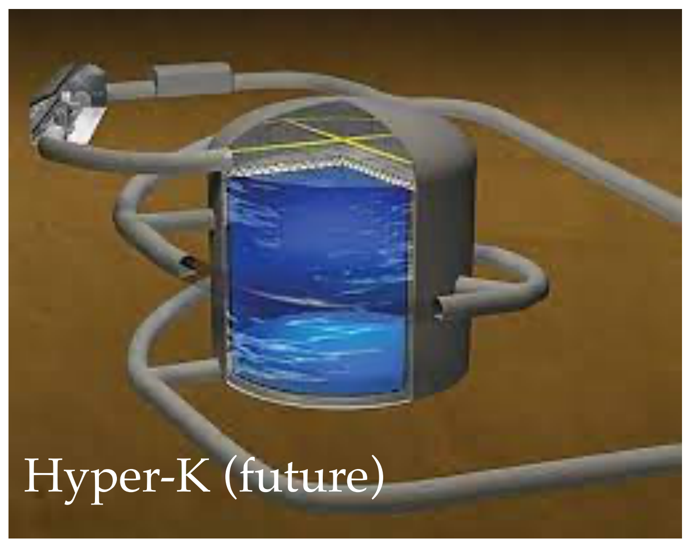
Water Cherenkov Detectors

- Water Cherenkov technology proven for large-scale (multi-kiloton) detectors
- Cost is also cheap!

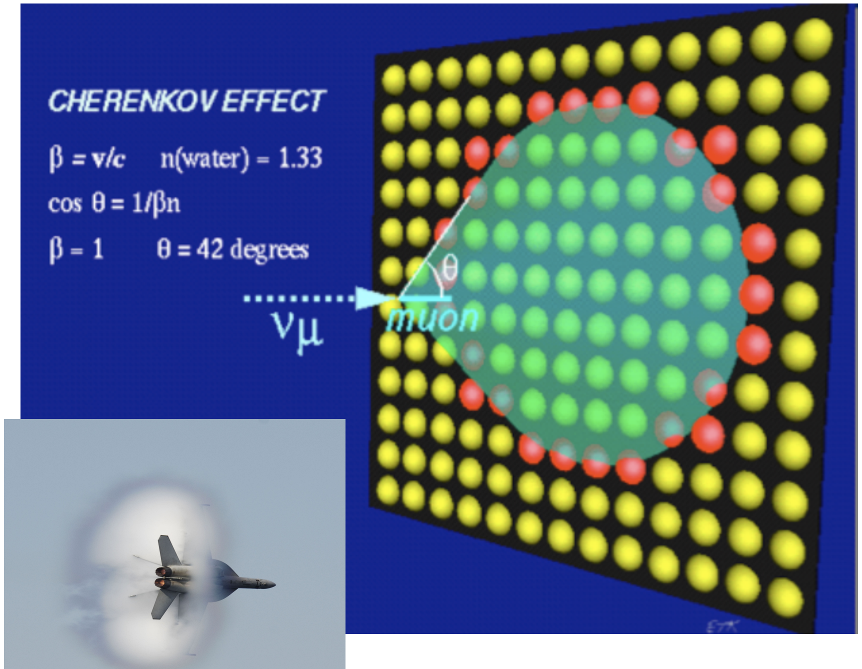








Cherenkov Light



Sonic boom

- When a particle moves faster than speed of light in a given medium, they emit Cherenkov light

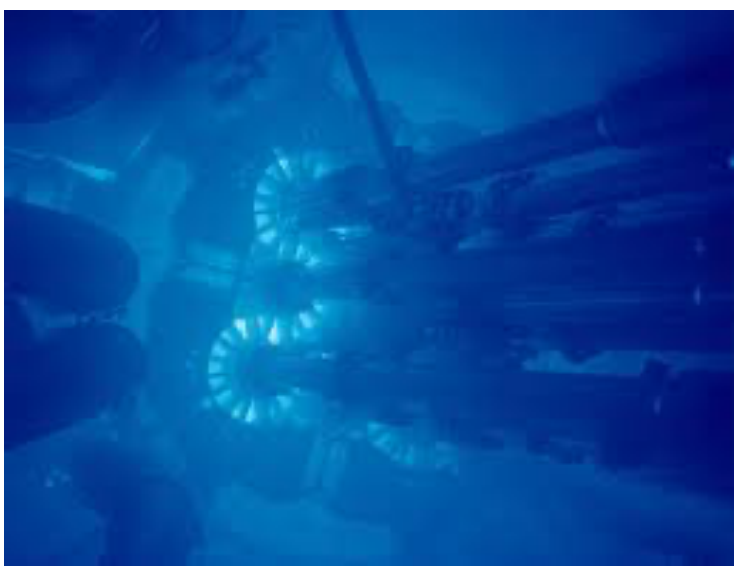
  $\beta = v/c \qquad \beta > 1/n$

  β = ratio of speed of particle to speed of light
  n = refractive index of the medium
  For water, $n = 1.33$

- Cherenkov thresholds

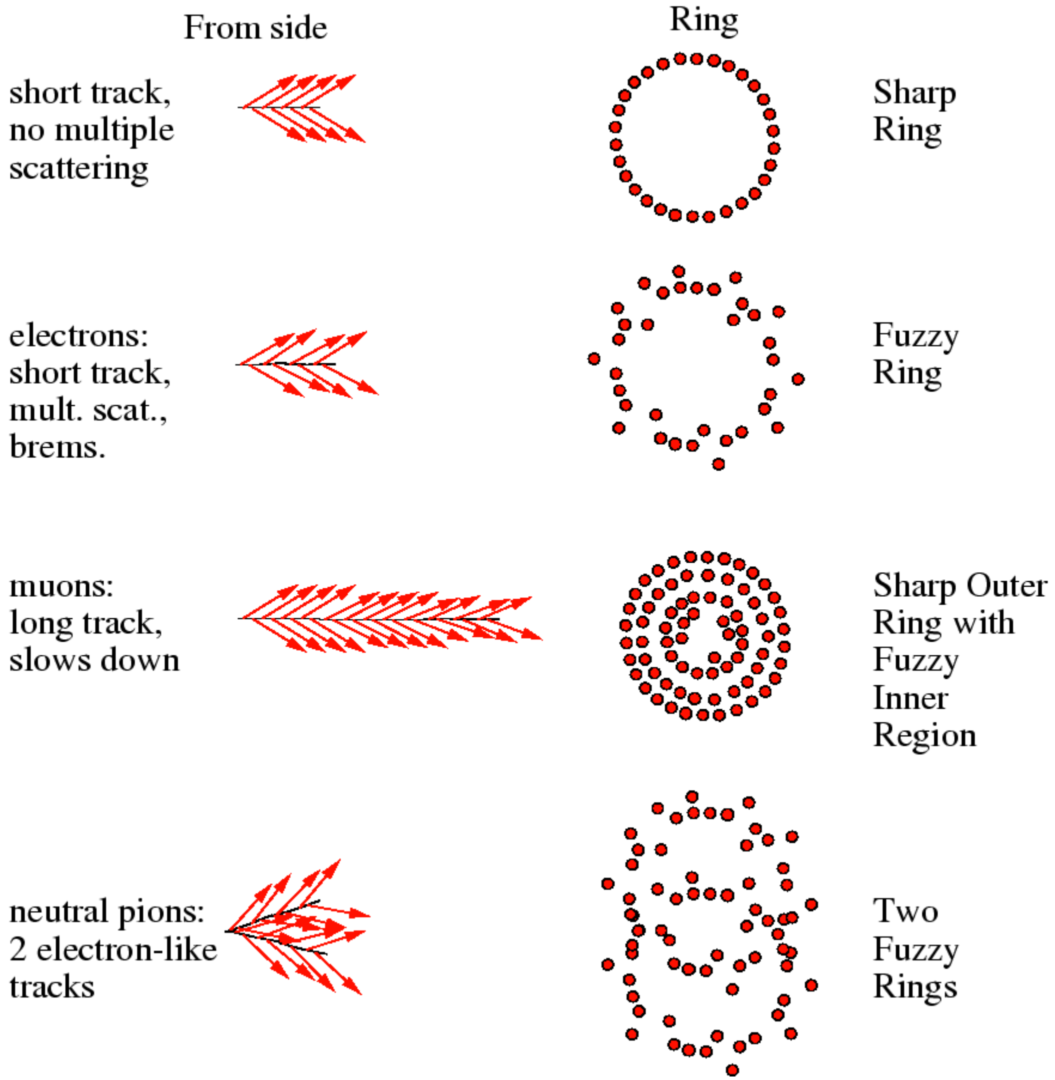
$$E_{th} = \frac{m}{\sqrt{1 - 1/n^2}}$$

e	0.73 MeV
μ	150 MeV
π	200 MeV
P	1350 MeV
K	650 MeV



- Light patterns, light collected, and the directionality of light signal help reconstruction
- Cons: low light yield, loss of low/heavy energy particles due to Cherenkov thresholds
- Requires a segmented detector
- Light signals typically measured by PMTs

Particle ID in Cherenkov Detectors



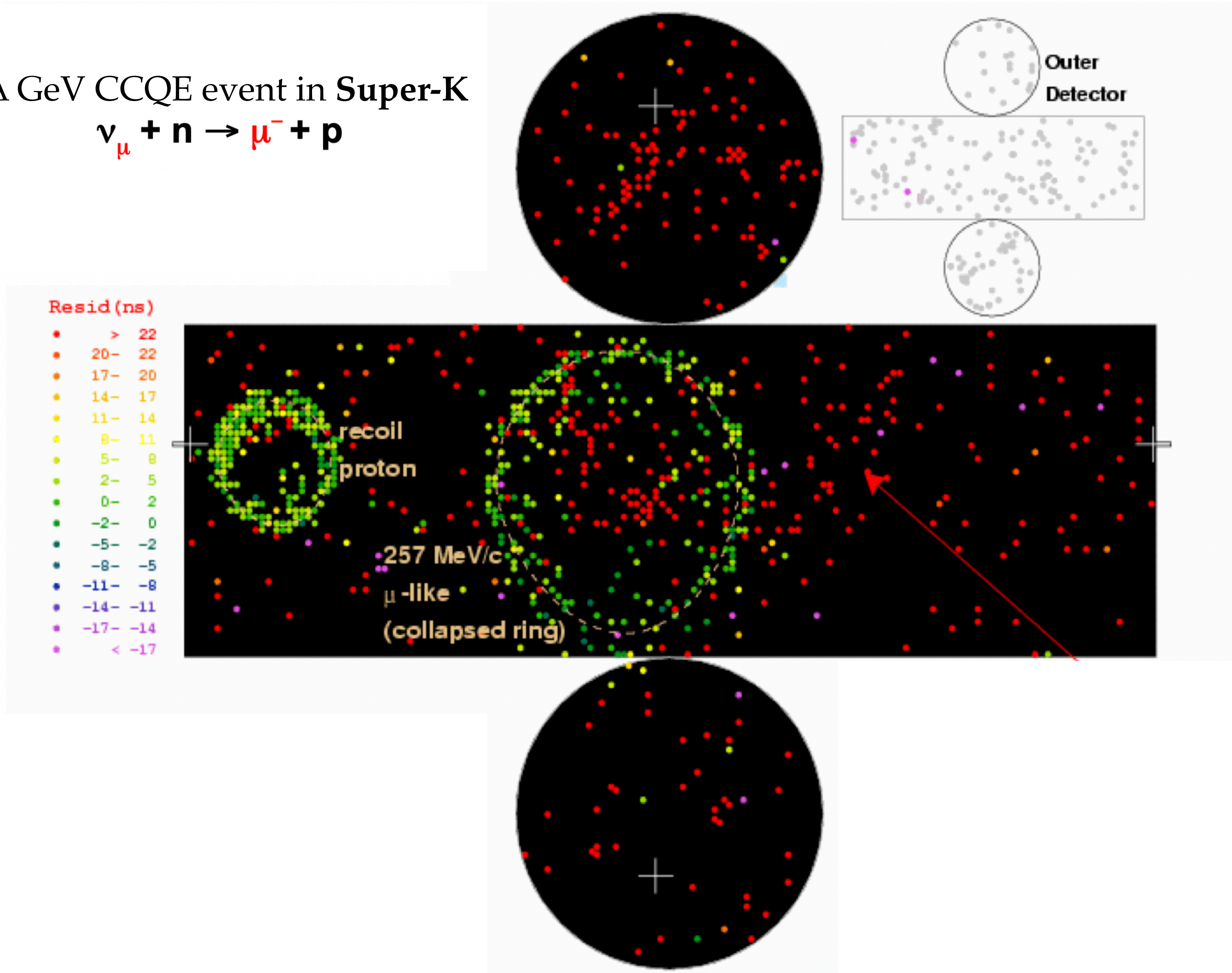
Some issues:

- Both electrons and photons shower and create fuzzy rings
- e/γ separation gets tricky
- In the case of π^0 (which decays to two gammas, hence two fuzzy rings), if the two rings overlap or one ring is missing, it mimics an electron signal
- Take away: signal to background discrimination is difficult or not possible in certain cases

Super-K Water Cherenkov Detector

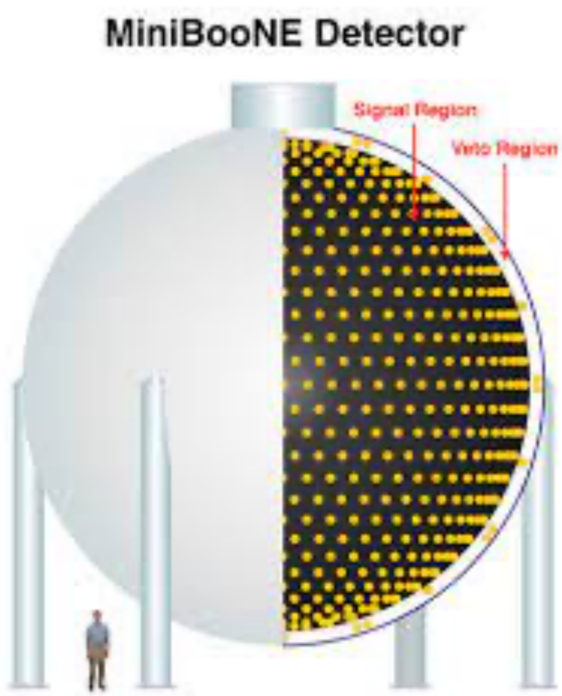
A GeV CCQE event in **Super-K**

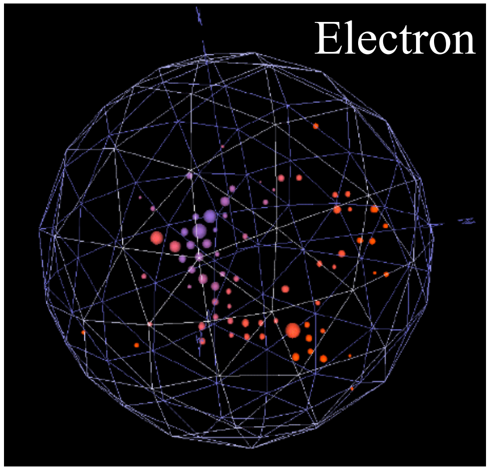
$\nu_\mu + n \rightarrow \mu^- + p$

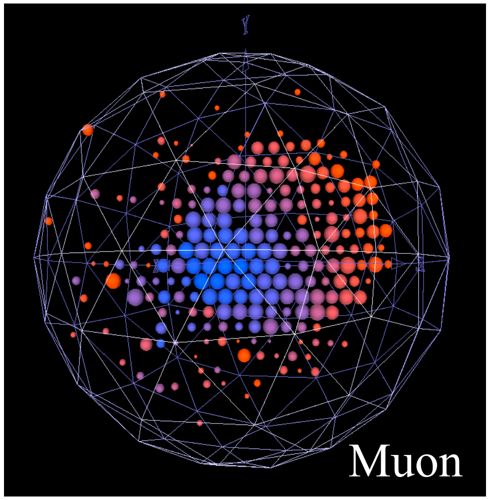


MiniBooNE Cherenkov Detector

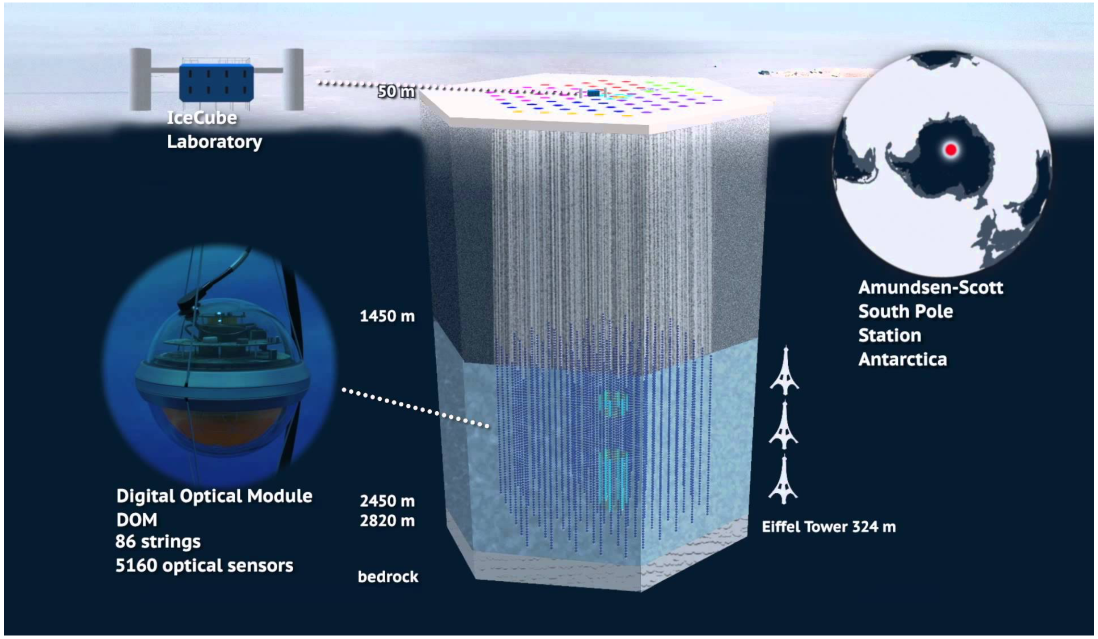
- Mineral Oil Cherenkov detector at Fermilab
- Aim was to address the LSND anomaly
- 6 m radius (800 tons total volume)
- 1280 PMTs
- Why Mineral oil?
  - Higher refractive index (1.47) than water (1.33)
  - Lower density than water
  - More Cherenkov light produced
  - Lower velocity
  - Lower Cherenkov threshold helps in production of low energy muons, pions, protons etc.
- Challenge: requires a much more complicated optical model to describe the generation and transmission of light in oil

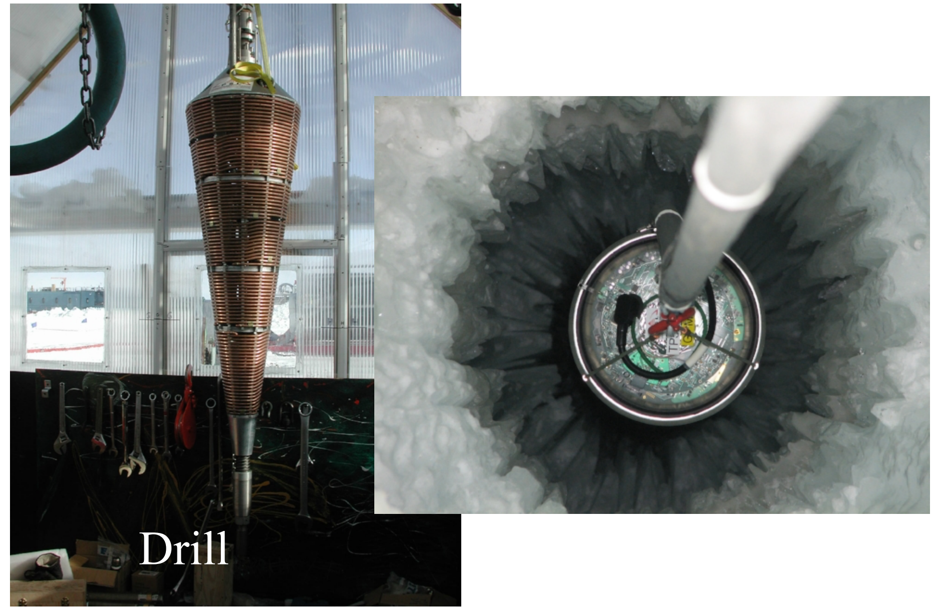




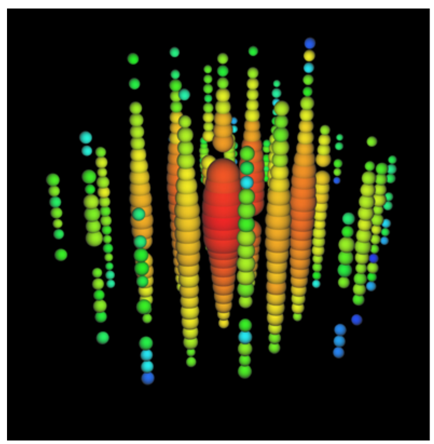


IceCUBE Cherenkov Detector

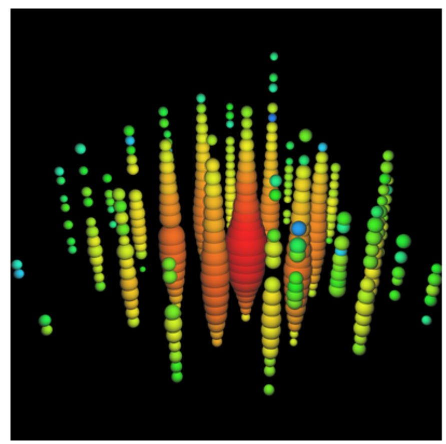




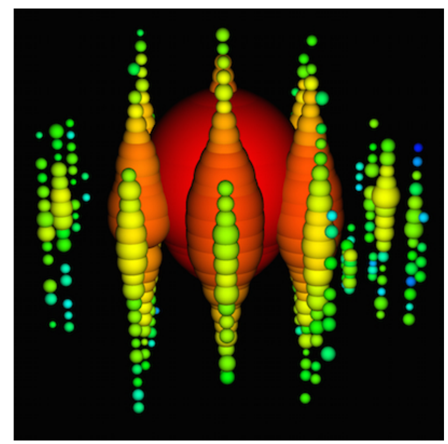
- Long-string s of PMTs in ice or water (domes spaced at ~10m)
- Particles from astrophysical sources produce Cherenkov light
- Other similar efforts: ANTARES, PINGU, Lake Baikal (KM3NET, IceCube-Gen2)



Bert



Ernie

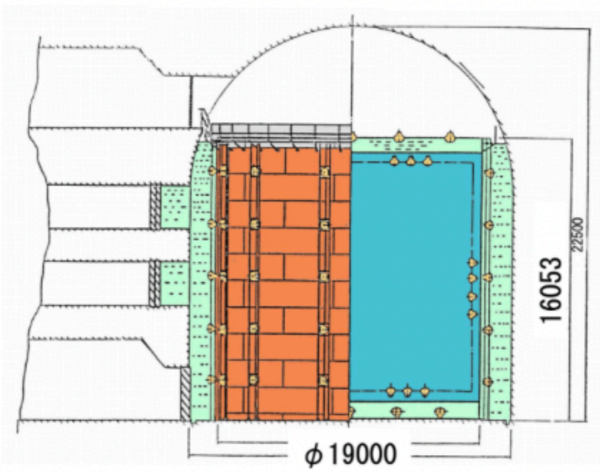


Big Bird

Water Cherenkov Detectors in Japan

Kamiokande

1983〜1996



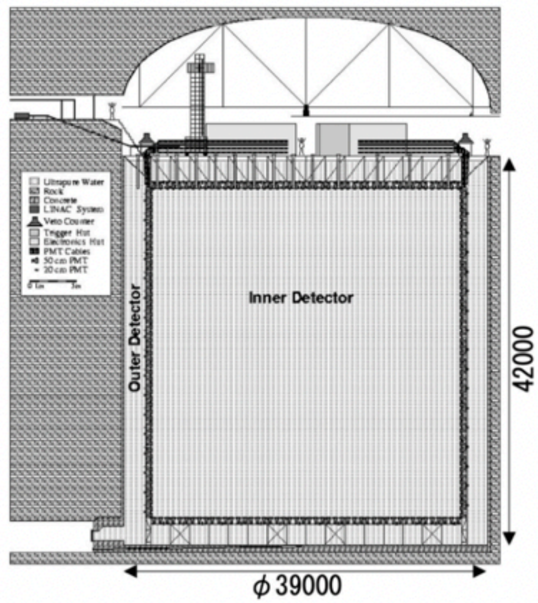
19m diameter x 16m hight

4500 ton *Total mass*
(680~1040 ton) *Fiducial mass*

50 cm diameter / 948 *PMTs*

Super-Kamiokande

1996~Present



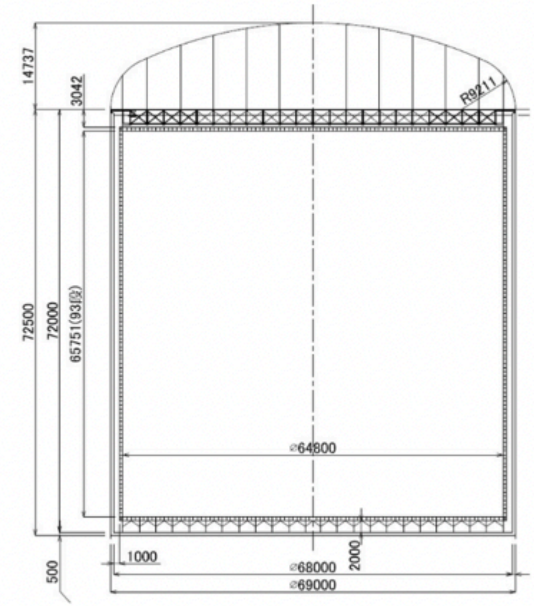
39m diameter x 42m hight

50000 ton
（22500 ton）

50cm diameter / 11146

Hyper-Kamiokande

Aiming to start observation in 2027

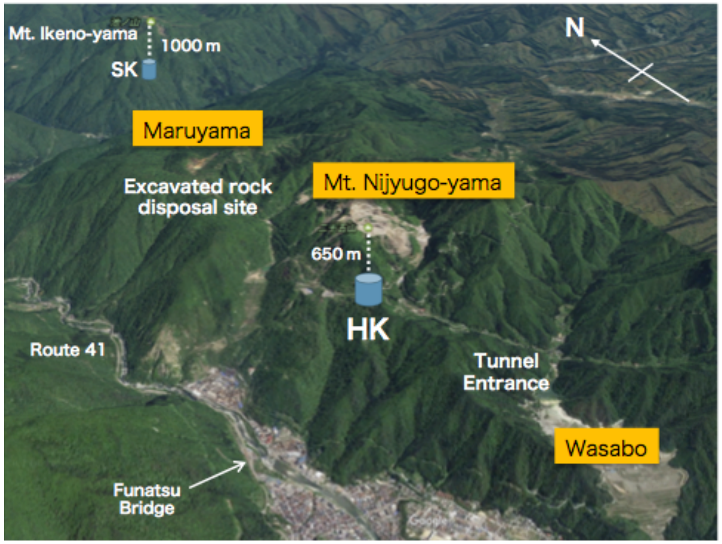


68m diameter x 71m hight

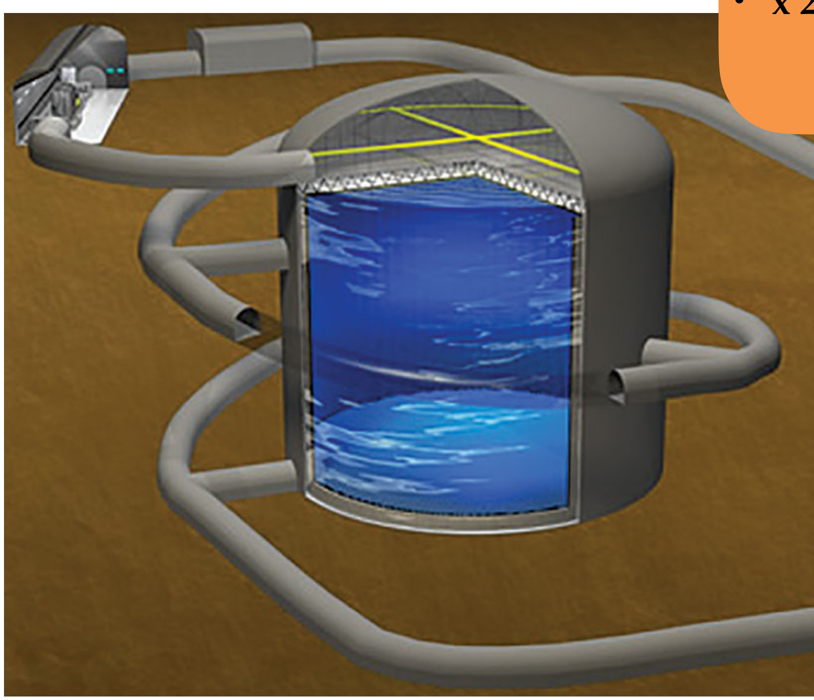
260000 ton
（190000 ton）

50cm diameter / about 40000

The Hyper-K Water Cherenkov Detector



- x 8.4 fiducial volume (SK → HK)
- x 2.6 beam power
- J-PARC upgrade: 500 kW → 1.3 MW
- x 20 Statistics



- Very Rich Physics Program like DUNE
- Future detector, complementary to DUNE
- Hyper-K under construction
- Operation to start in 2027
- Two Near Detectors: upgraded T2K ND280 and IWCD

Hyper-K Near Detectors

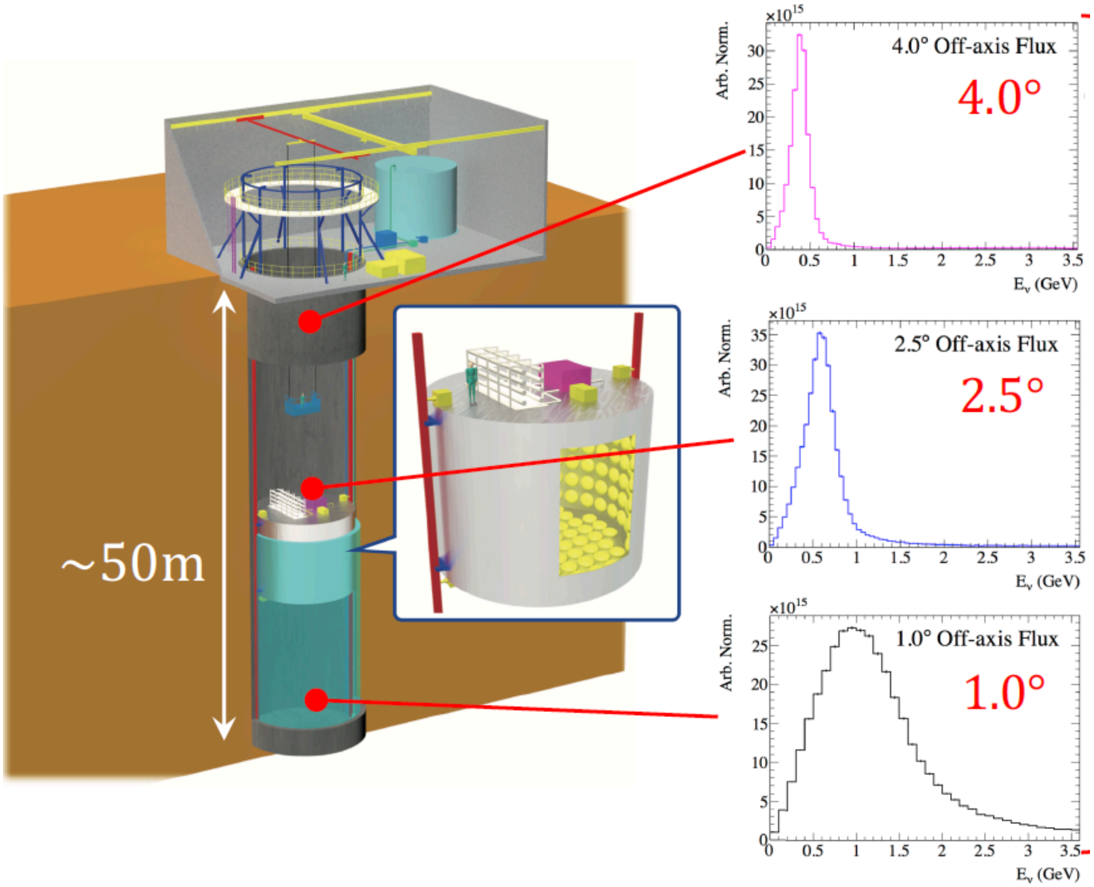
(..+ a lot of R&D towards near and far detectors underway; not covered here)

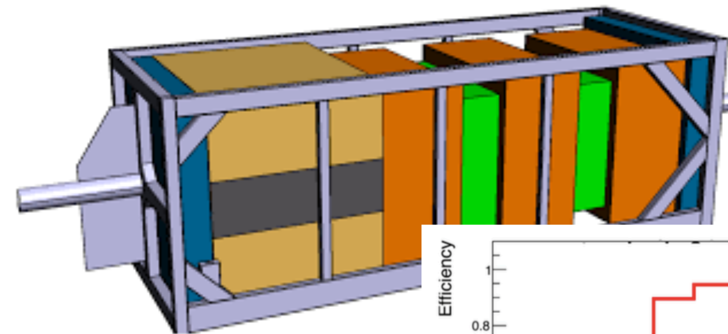
Intermediate Water Cherenkov Detector (IWCD)

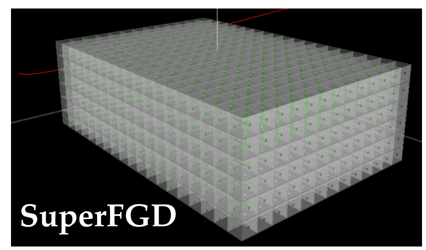
- 1 kton scale Water Cherenkov detector at ~1 km baseline
- Detector can vertically move for different off-axis angle measurements

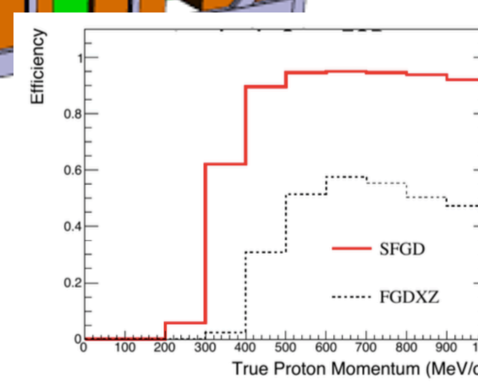
ND280 Upgrades

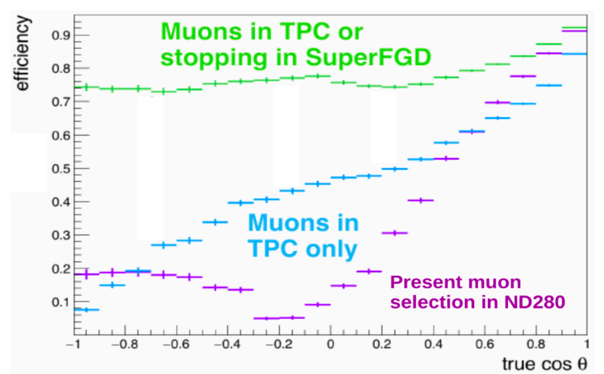
- T2K's near detector will be updated and used by Hyper-K
- Upgrade to SuperFGDs
- Improved short-track efficiency; high angle acceptance





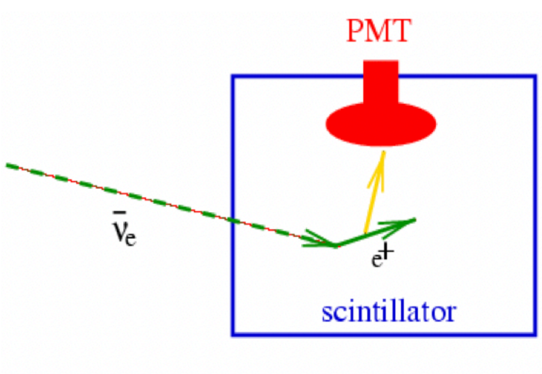






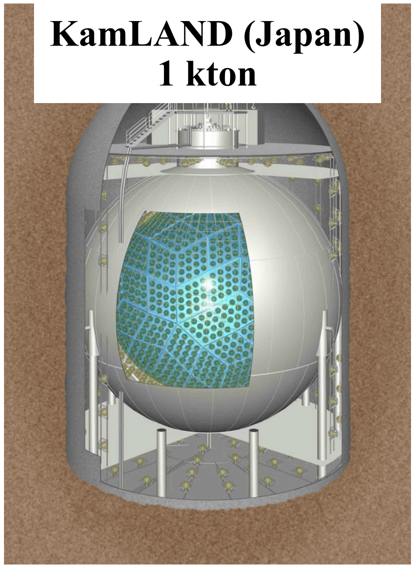
Scintillator Detectors

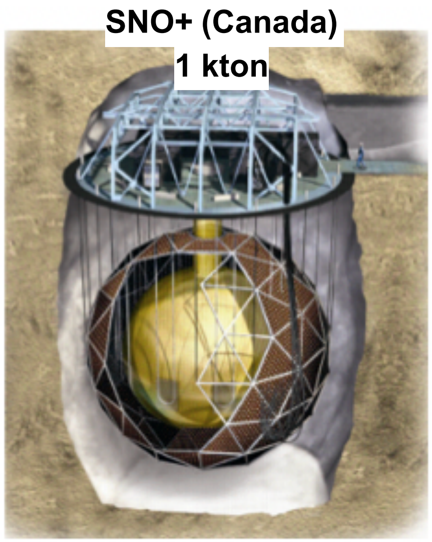
- Scintillators are materials that emit light when particles deposit energy
  - Light emission can be in visible spectrum or UV spectrum;
  - wave length shifting mechanisms typically used to shift light from e.g. VUV to visible
- Scintillators can be solid or liquid e.g. crystal, plastic, hydrocarbon
- Typical design involves surrounding the volume of the liquid scintillator with light sensors e.g. PMTs, SiPMs, APDs etc.
- Need through understanding of the chemistry involved and transmission of light in that medium
- Pros: High light yield (few hundreds photoelectrons per MeV), low thresholds, good energy resolution
- Con: little directionality as light is emitted isotropically
- Noble liquid detectors also produce scintillation light

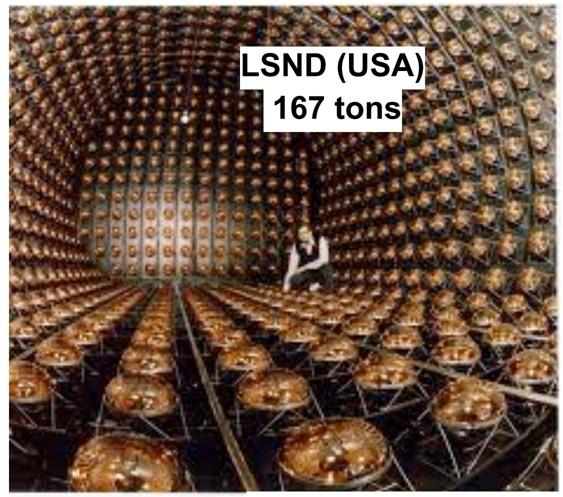


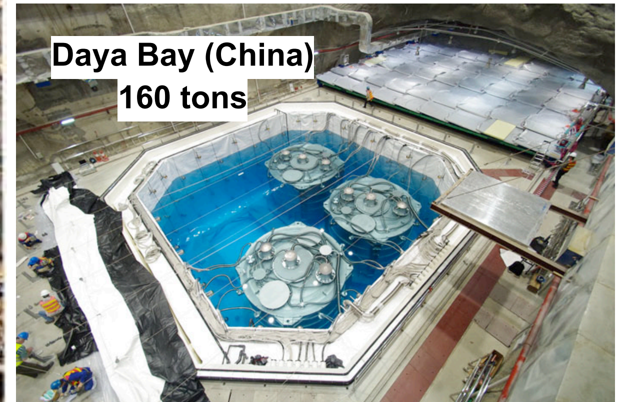
COHERENT-CAPTAIN Mills (CCM)
LANL; 10 tons of LAr
LAr Scintillation light detector;
no charge readout, only PMTs

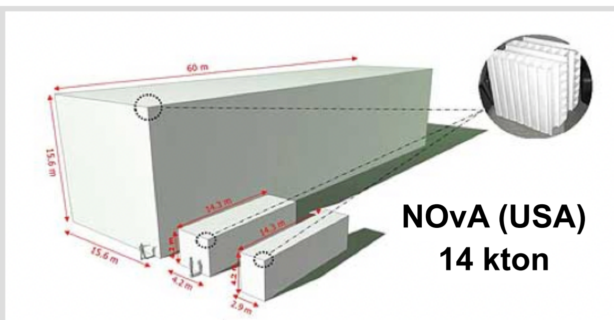
Scintillator Detectors: Past, Present & Future

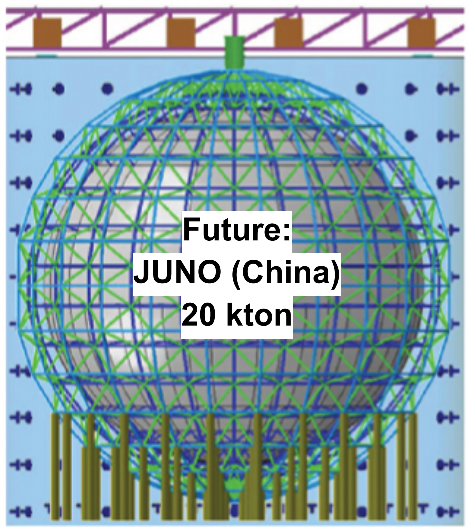


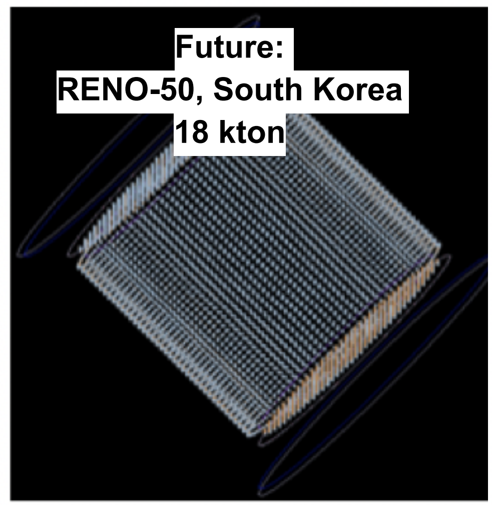


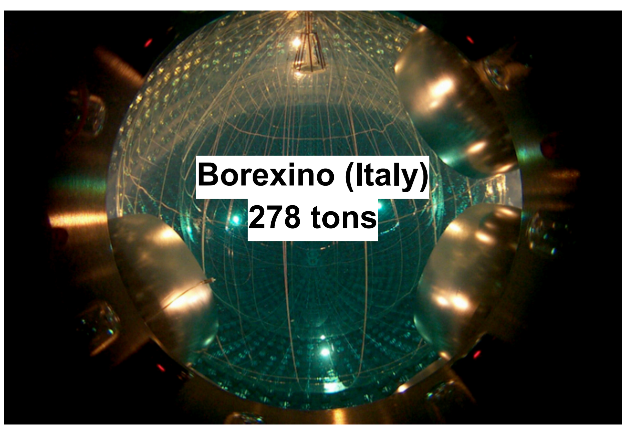






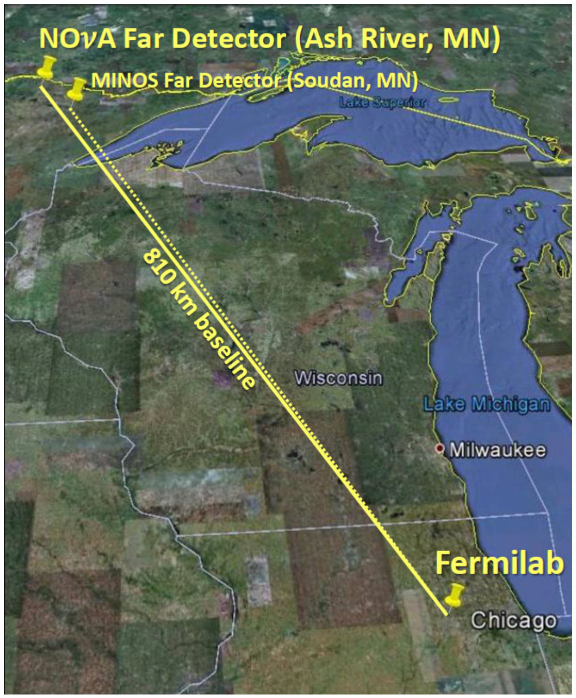


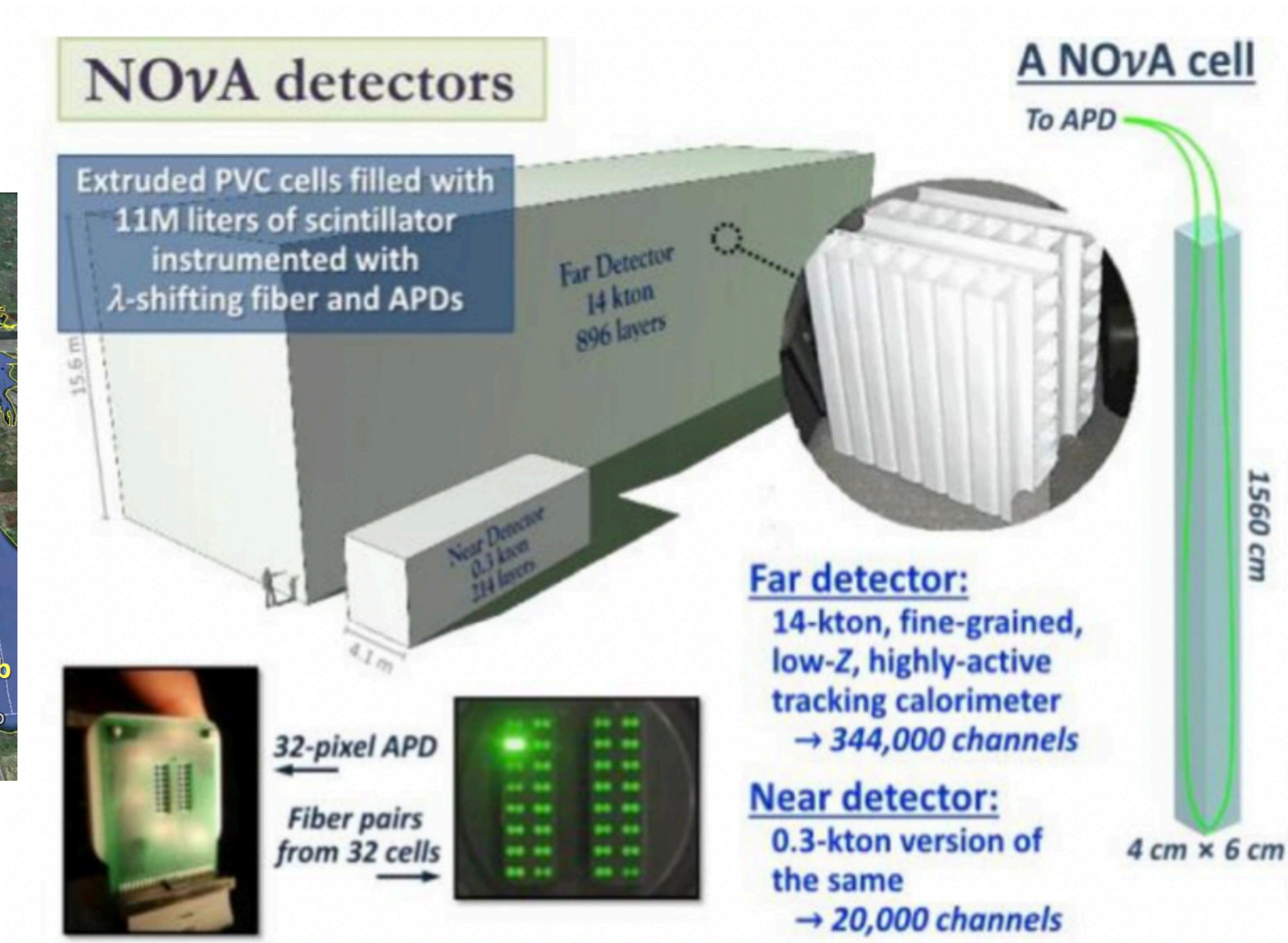




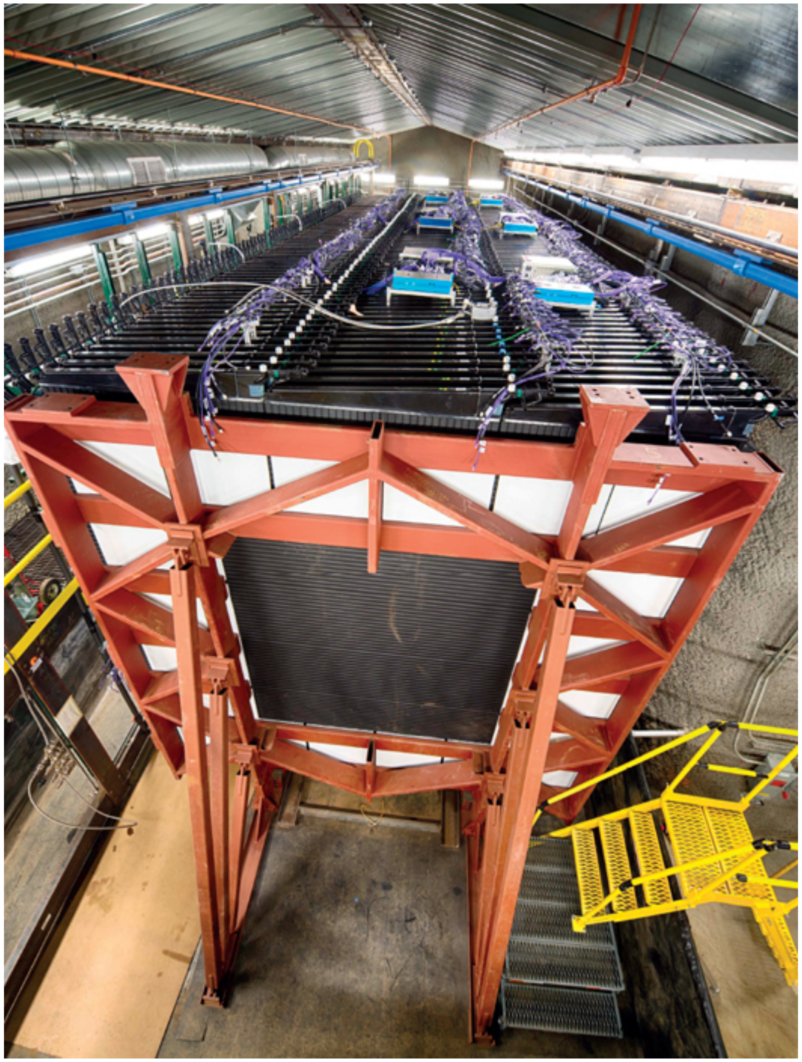
NOνA Detector

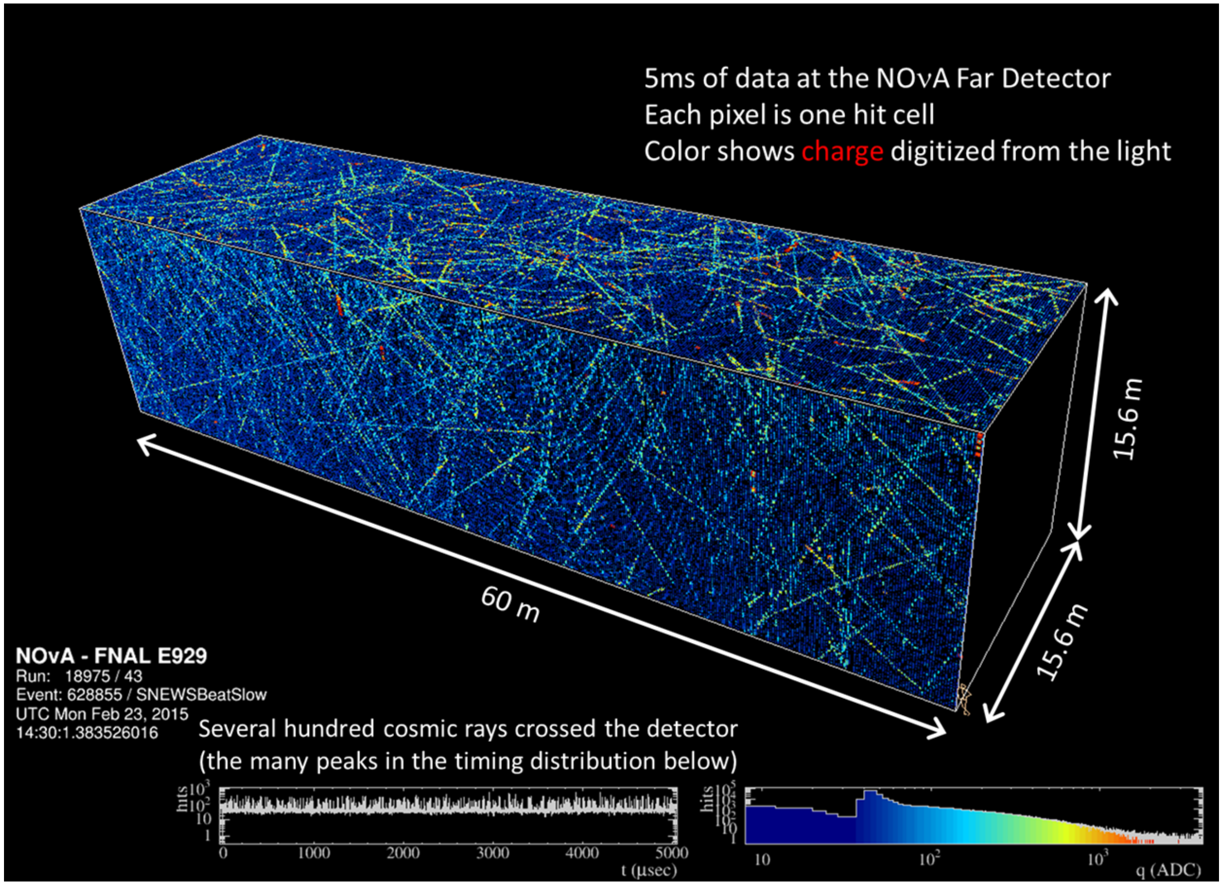
Long-Baseline Experiment



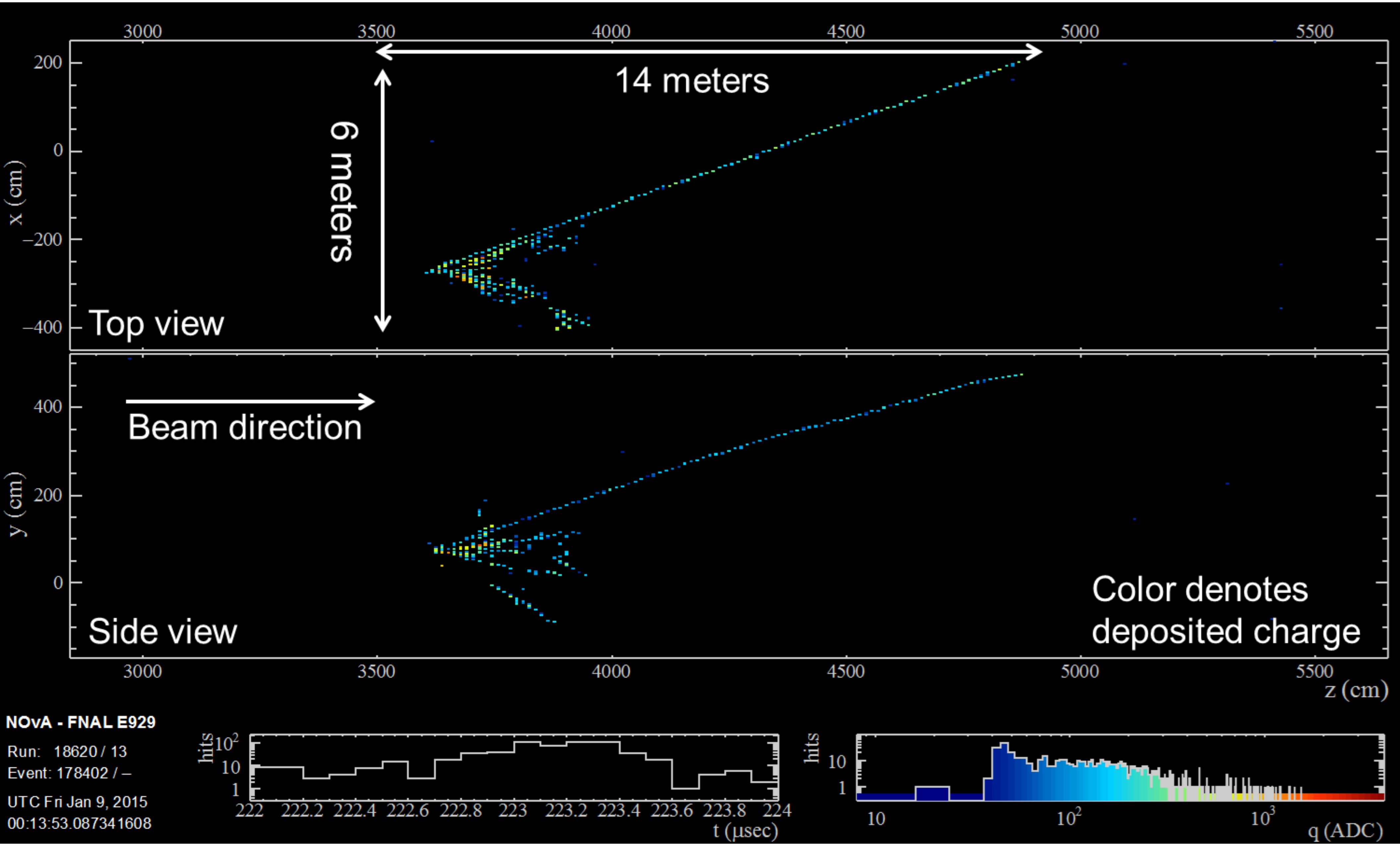


NOνA Detector



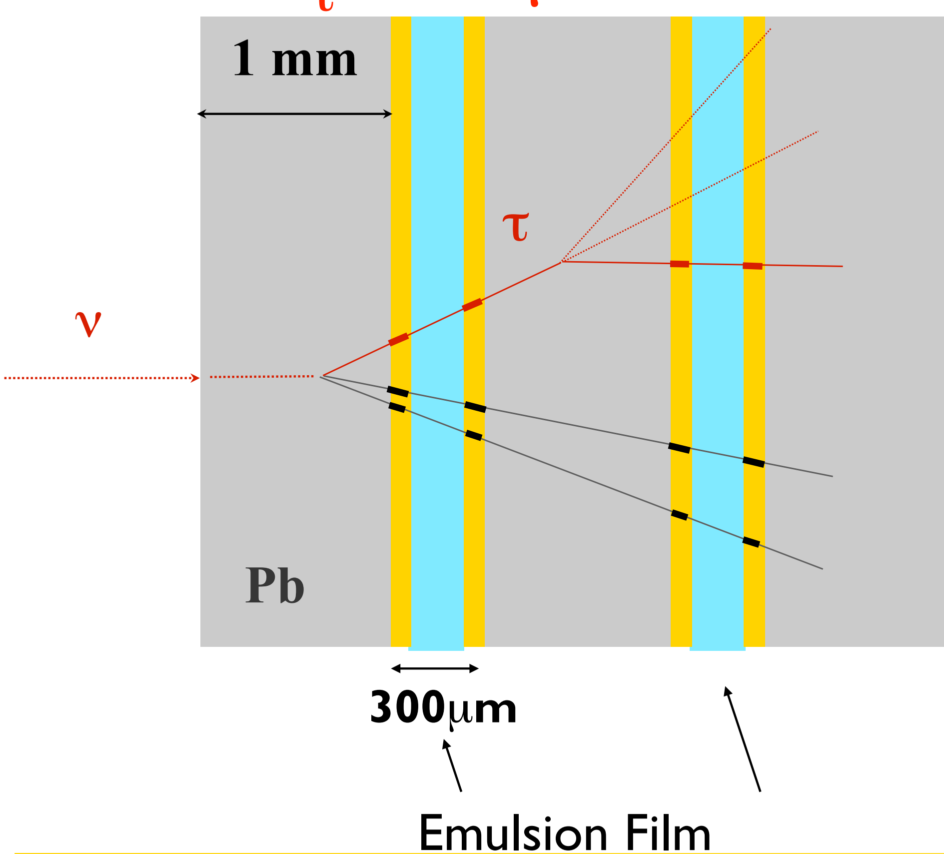


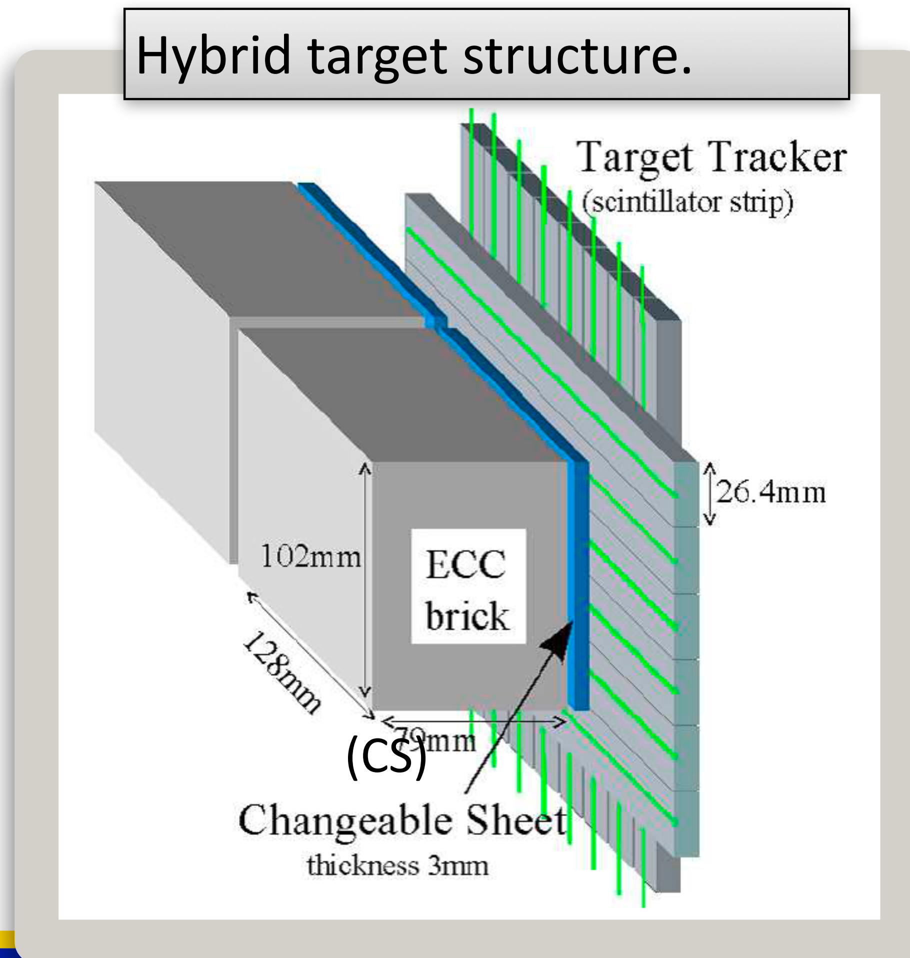
NOvA Detector



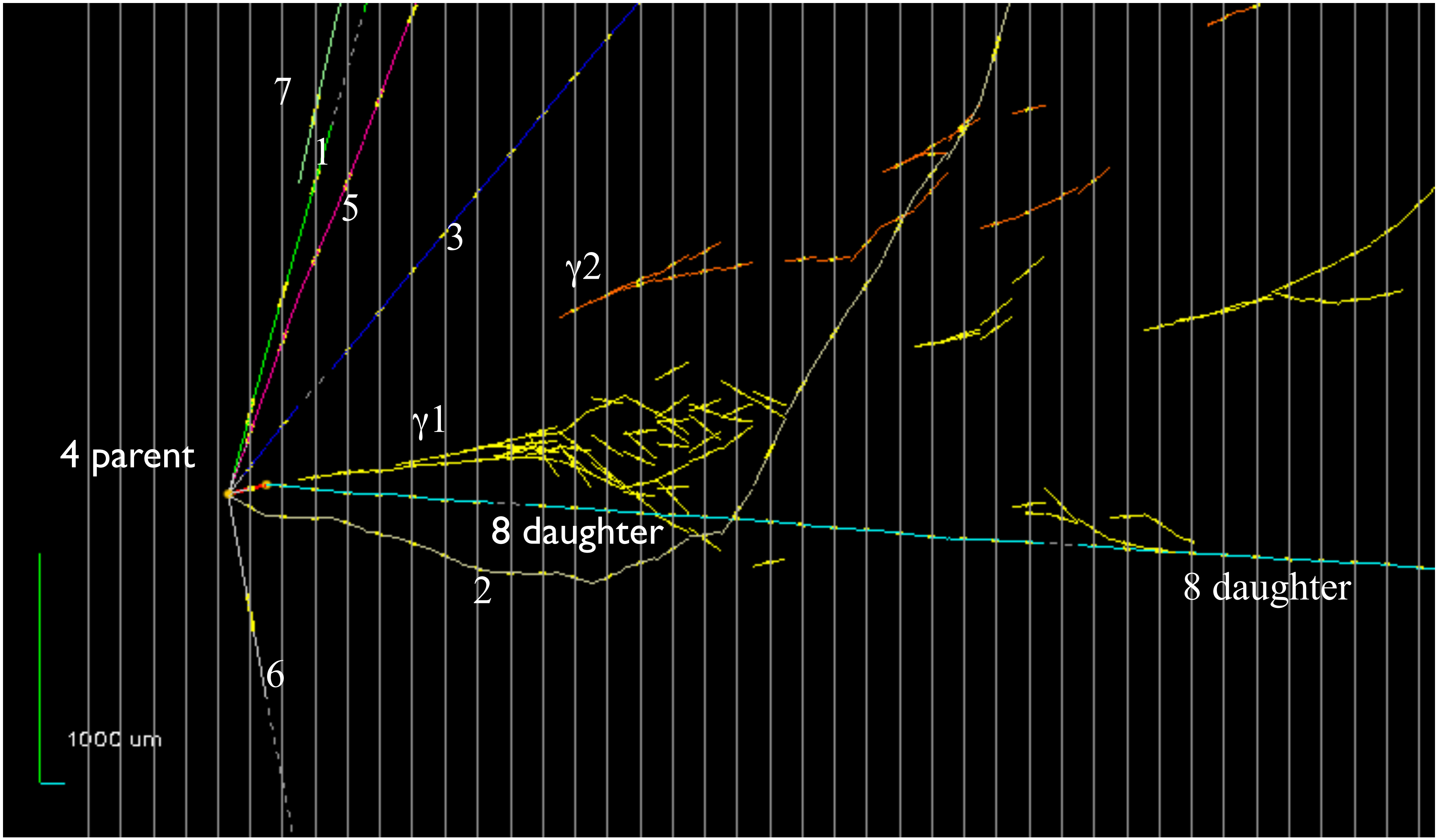
OPERA: Emulsion Cloud Chamber

- The micron-resolution with one kilo-ton mass scale.
  - $c\tau_{\tau} = 87\mu m$

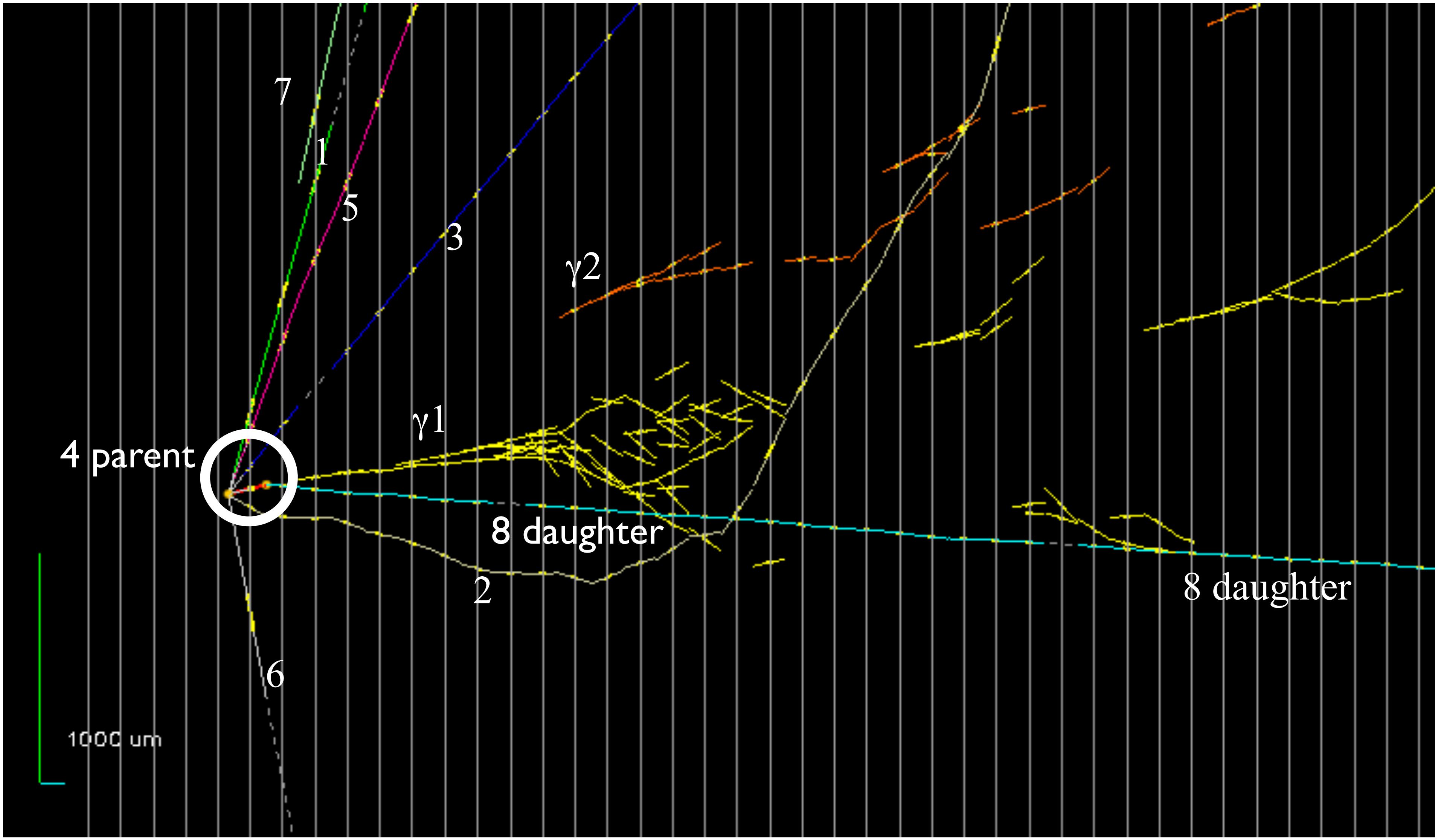




Tau Appearance Observation: OPERA



Tau Appearance Observation: OPERA



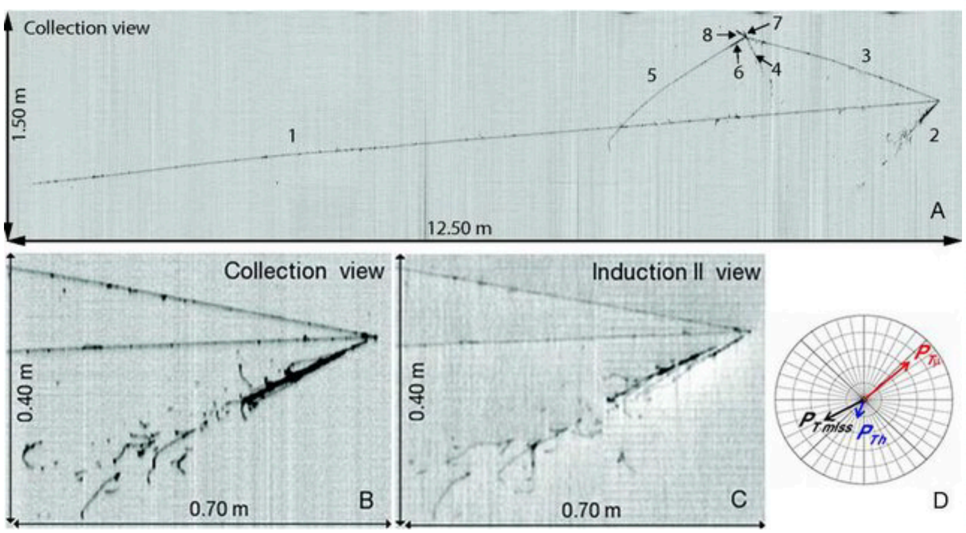
Noble Liquid Detectors

- Noble liquid detectors have emerged as technology of choice for many Dark Matter and Neutrino Physics experiments
- **Dark Matter**
  - Liquid Xenon: e.g. *LUX, Xenon*
  - Liquid Argon: e.g. *ArDM, DEAP, DarkSide, MiniCLEAN (also Liquid Neon)*
- **Neutrino Experiments**
  - Liquid Argon is the chosen nuclear target for many ongoing and future neutrino experiments including the U.S. flagship DUNE experiment
  - *E.g. ICARUS, ArgoNEUT, MicroBooNE, SBND, ProtoDUNE, DUNE*
- LAr technology has also been employed in other particle physics experiments
  - R806, Helios, D0, NA48, ATLAS and so on

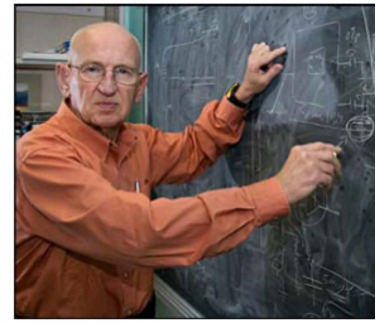
- Among other things, noble liquid detectors provide *precision signal detection*, *background rejection*, and *scalability*

Early History of LArTPCs

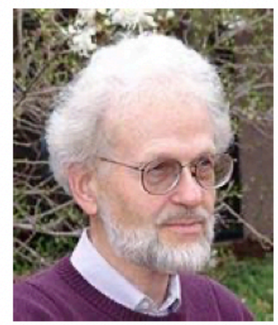
- W. Willis and V. Radeka, Liquid argon ionization chambers as total absorption detector, NIMA 120:221 (1974)
- D. R. Nygren, The Time Projection Chamber: A New 4π Detector for Charged Particles. eConf. C740805:58 (1974)
- H. H. Chen et al. A Neutrino detector sensitive to rare process. I. A study of neutrino electron reactions. FNAL-Proposal-0496 (1976)
- C. Rubbia, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)
- 1986: Proposal for a Massive LArTPC ICARUS T600
- ICARUS at Gransasso lab ran in the CERN CNGS beam from 2010-13



William Willis



V. Radeka

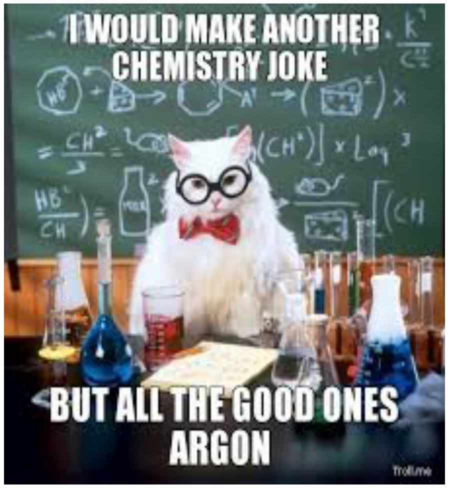


D. R. Nygren

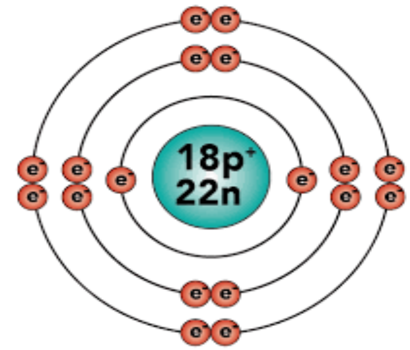
H. H. Chen

C. Rubbia

Why Liquid Argon?



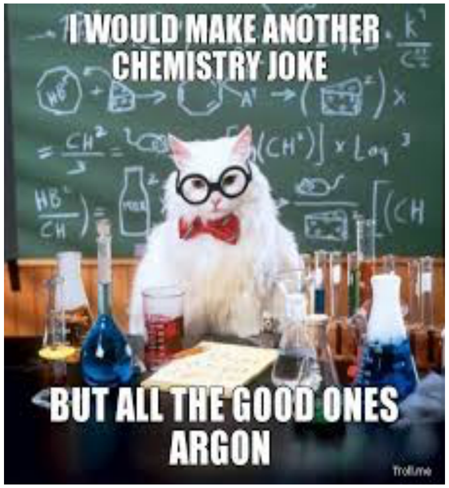
- dense
- abundant (1% of atmosphere)
- easily ionizable (55,000 electrons/cm)
- highly scintillating (transparent to light)
- pure argon results in high electron mobility implies long drift lengths



	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	

Table credit: M. Soderberg

Why Liquid Argon?



- dense
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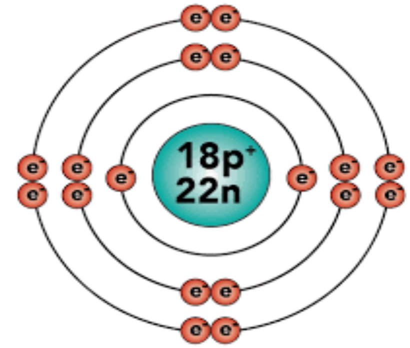


Cheap!

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.[illegible]	2[illegible].1	87.[illegible]	1[illegible]0.0	16[illegible].0	373
Density [g/cm³]	[illegible]	[illegible]	[illegible]	[illegible]4	3[illegible]	1
Radiation Length [cm]	755.2	[illegible]	14.0	[illegible]9	[illegible]	
Scintillation [γ/MeV]	19,000	[illegible]	[illegible]0,000	[illegible]	42,000	
MIP dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150	175	

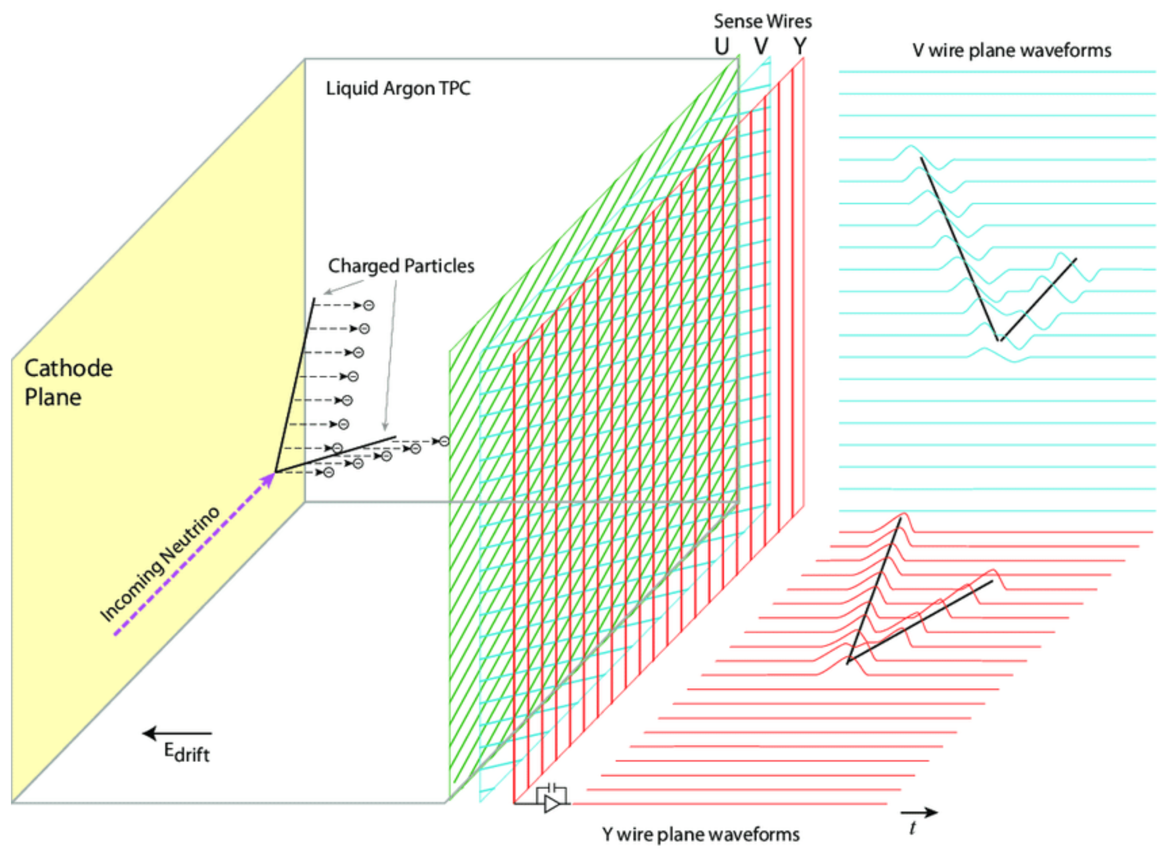
~$10/L (He) · ~$500/L (Ne) · ~$2/L (Ar) · ~$700/L (Kr) · ~$3000/L (Xe)

Table credit: M. Soderberg

How does a LArTPC work?

Charge Signals

- Neutrino interactions with LAr in the TPC produces charged particles that cause Ionization
- A high Electric field (e.g. 500V / cm) drifts ionization electrons towards finely segmented anode wire planes *(typically 150µ thick; 3-5 mm apart — allows for very fine spatial resolution)*
- Moving electrons induce currents on wires and are collected

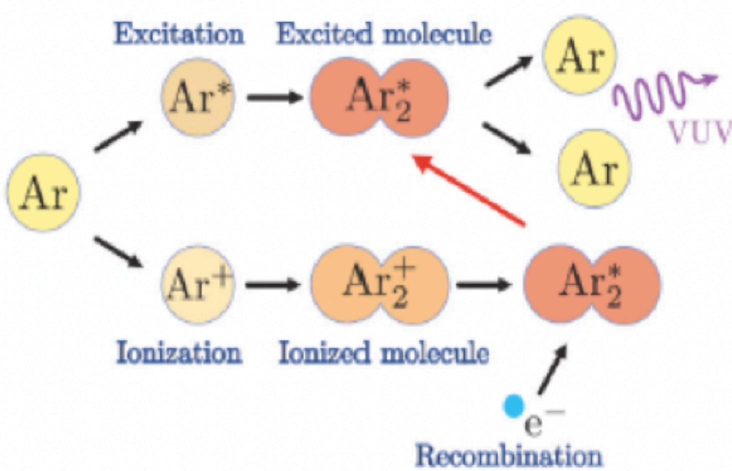


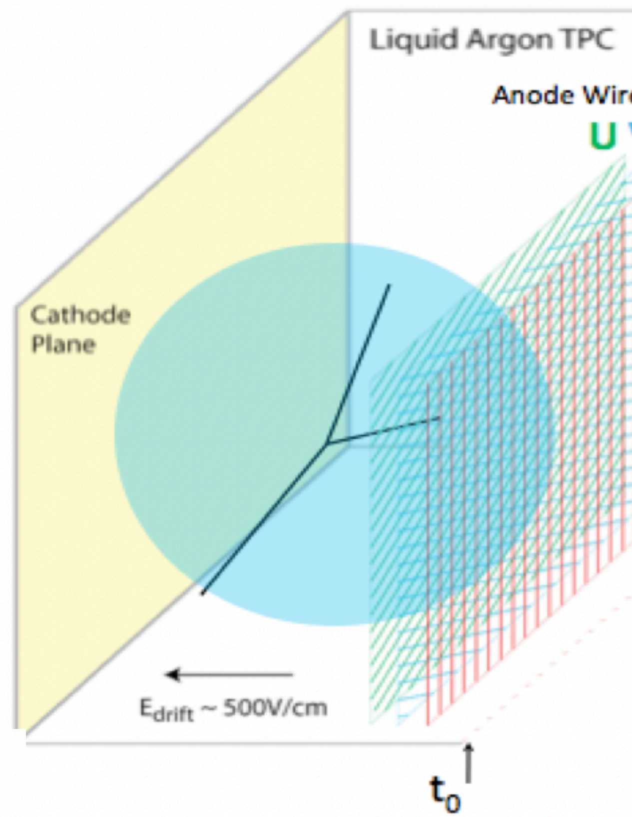
No need to instrument the entire detector volume = scalable to large sizes without increasing cost and complexity

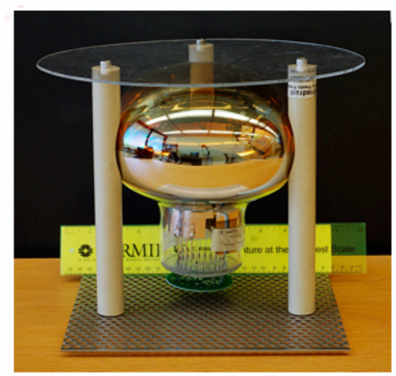
How does a LArTPC work?

Light Signals

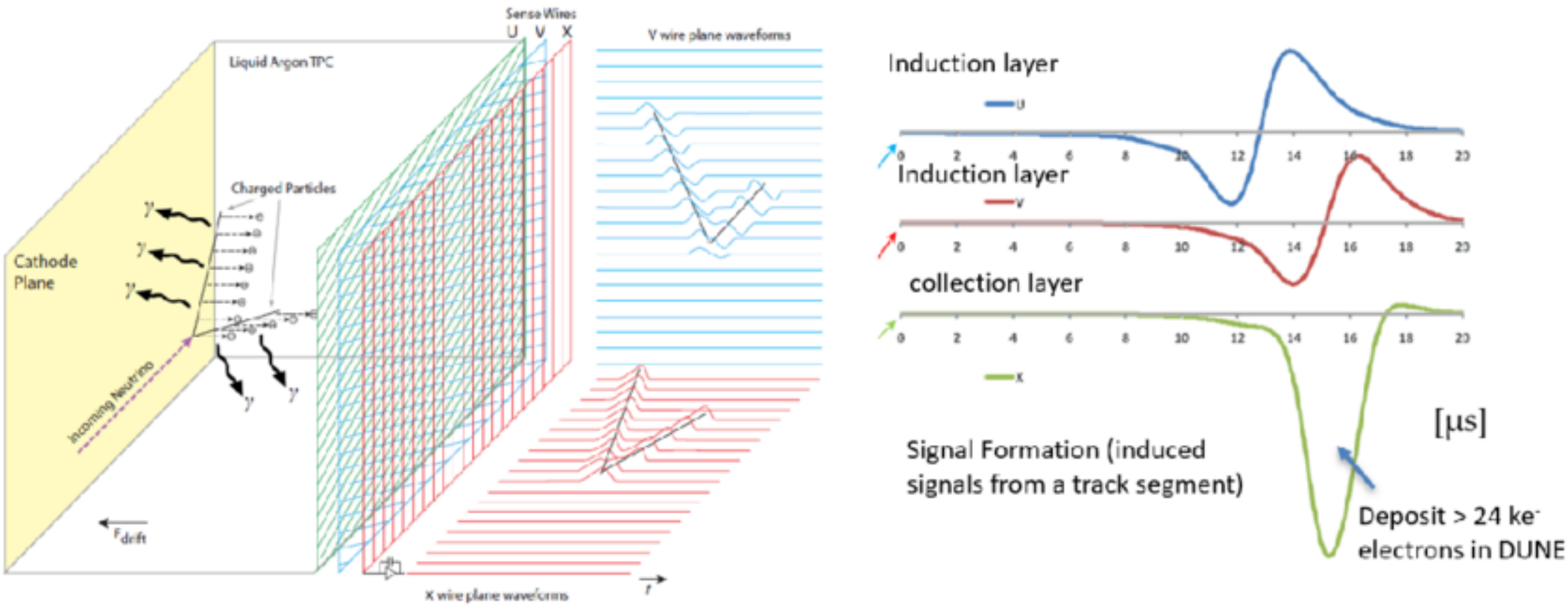
- Neutrino interactions with LAr in the TPC produces charged particles that cause excitation of Argon
- Excitation of Ar produces prompt scintillation light giving "t_0" of the interaction
- Ar emits light at 128 nm at VUV range – a wavelength shifting mechanism neede to make it visible





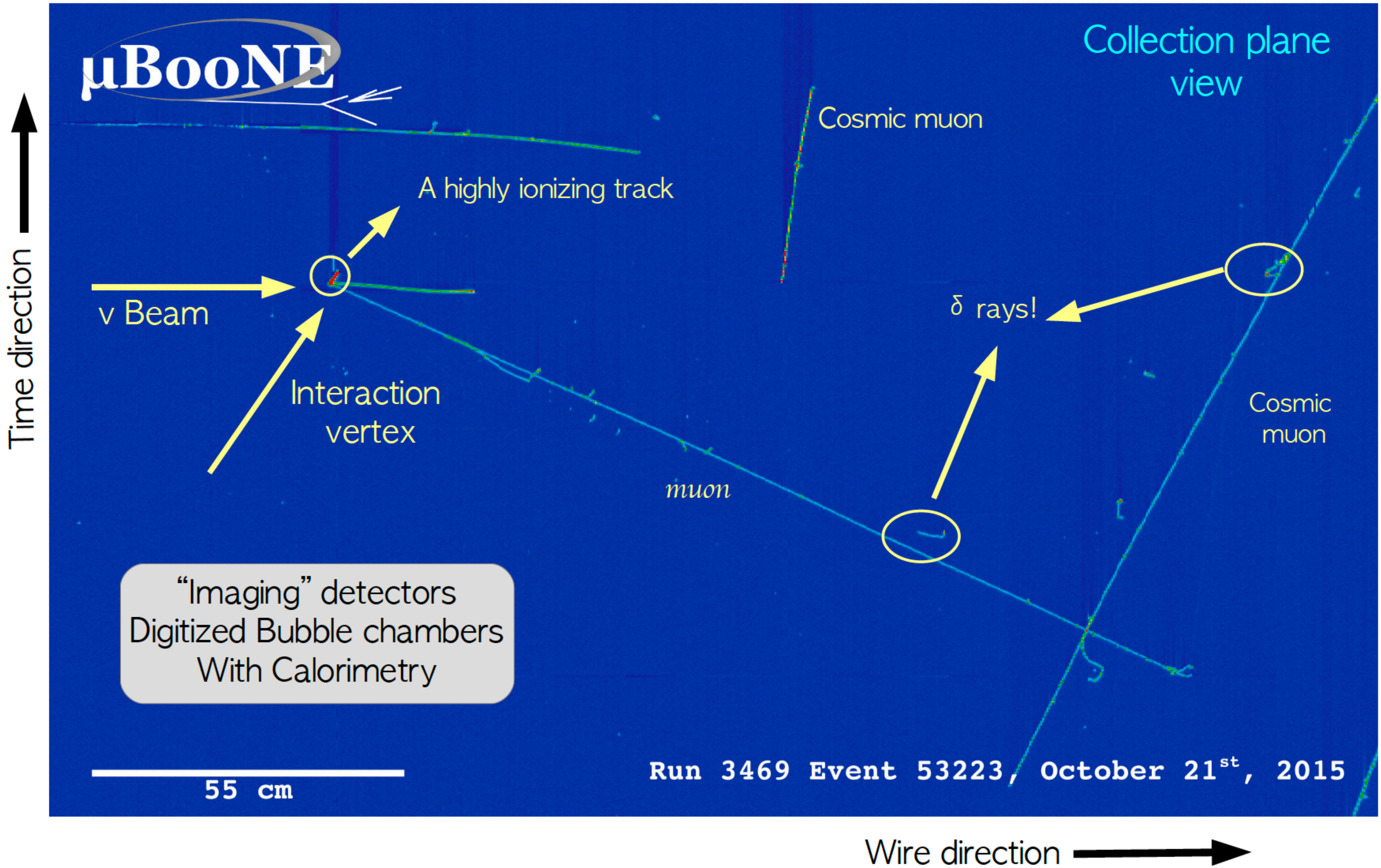


How does a LArTPC work?

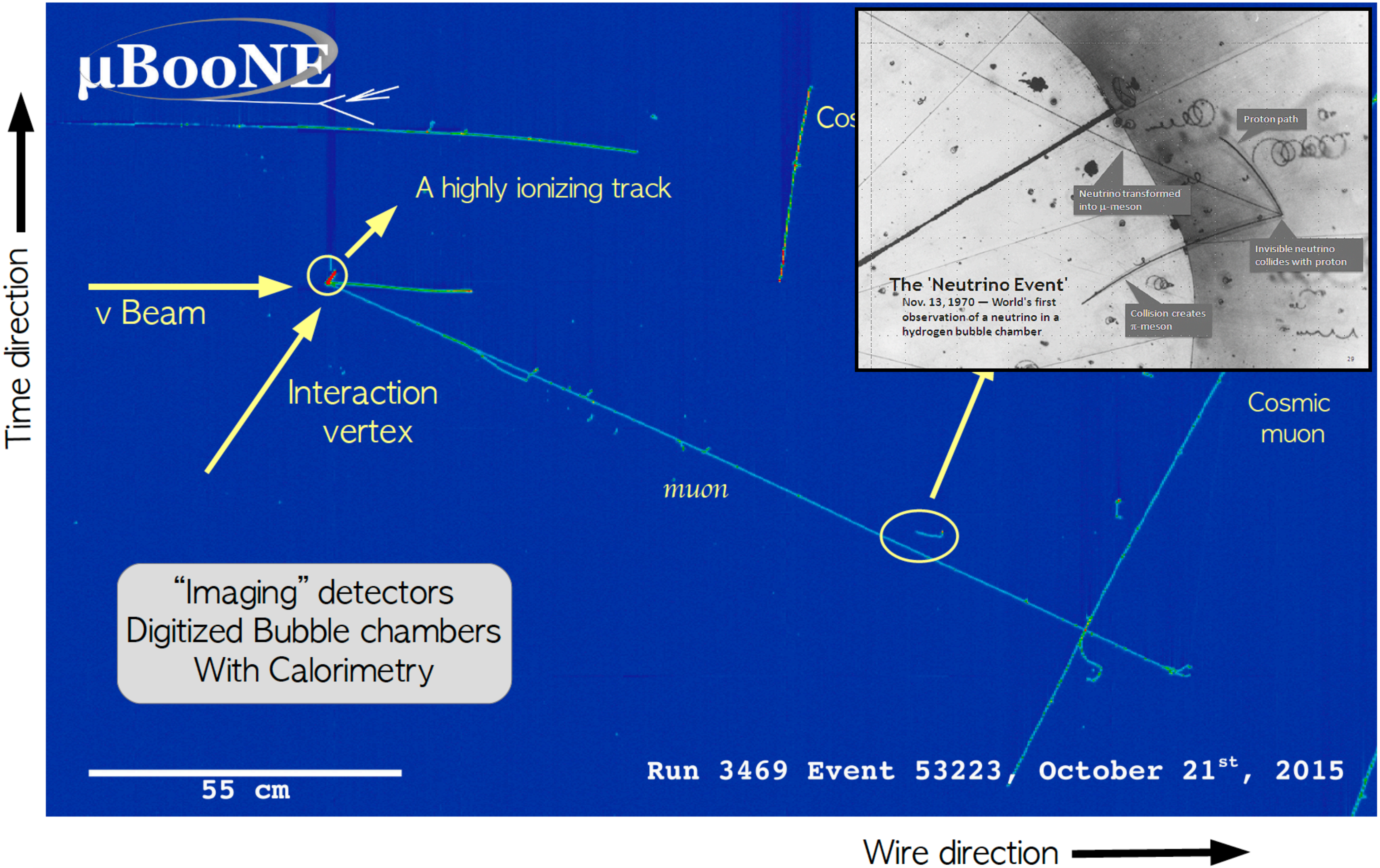


- Wire planes give 2D position information
- The third dimension is obtained by combining timing information with drift velocity (v_d): $x = v_d(t-t_0)$ hence the name "Time projection chamber"
- **Wire planes + signal arrival time = 3D image**

Neutrino Interactions in HD

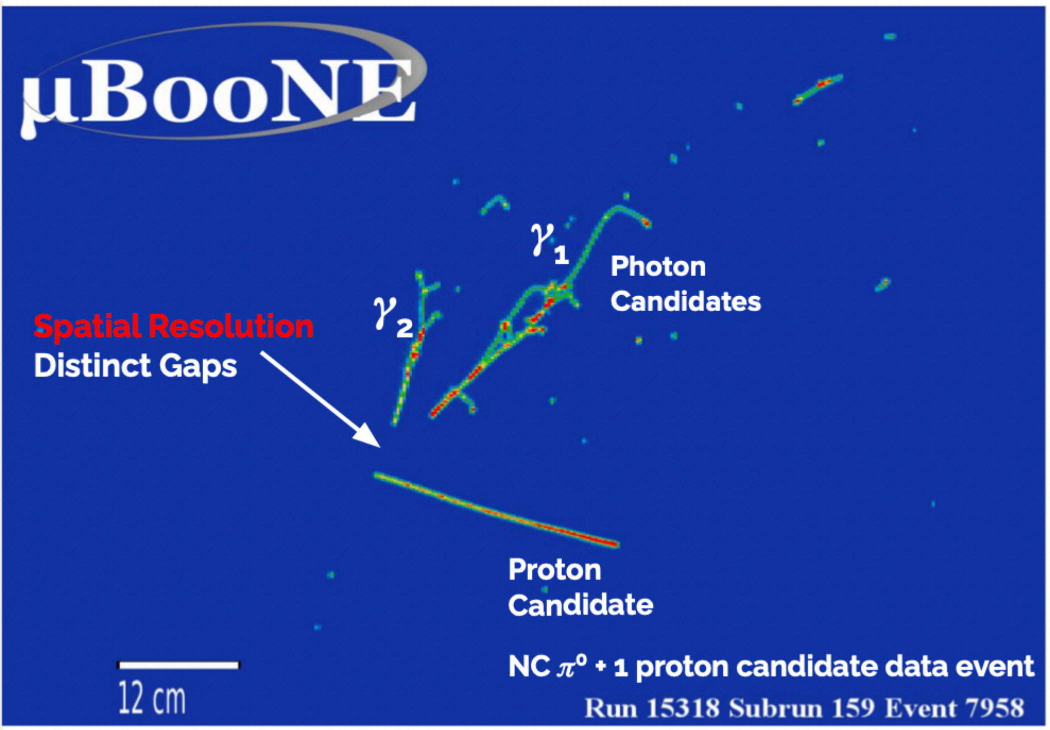


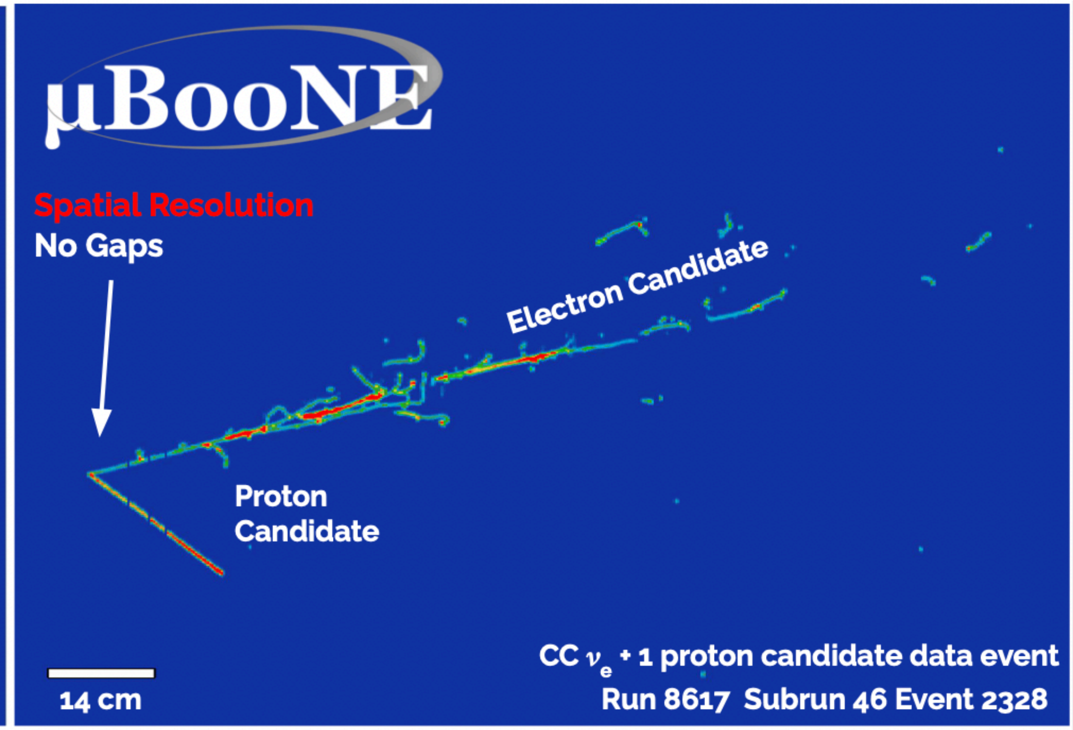
Neutrino Interactions in HD

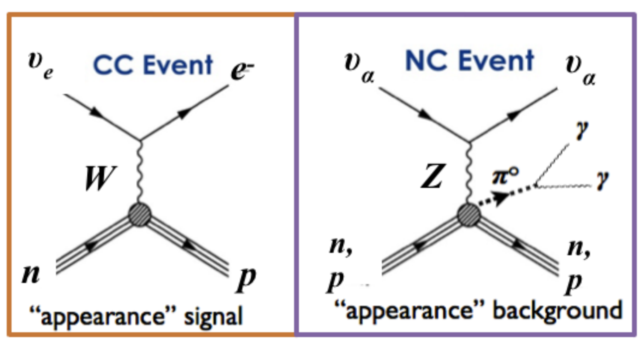


e/γ separation: Benefits of a LArTPC

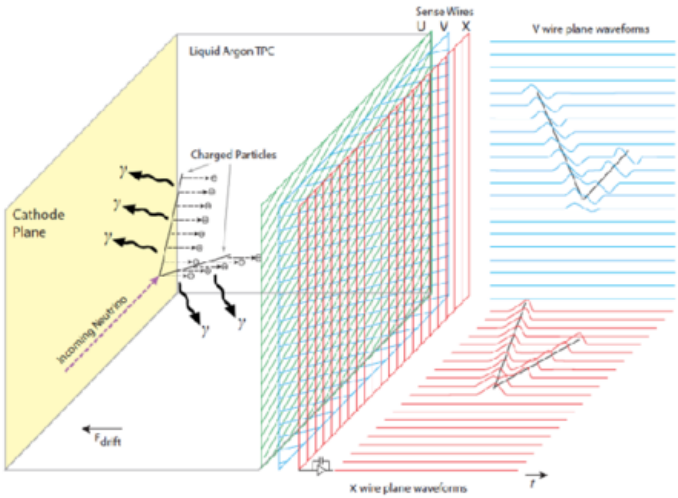
- For ongoing and future oscillation experiments , e / γ separation is critical
- Combining topology and charge information gives excellent separation

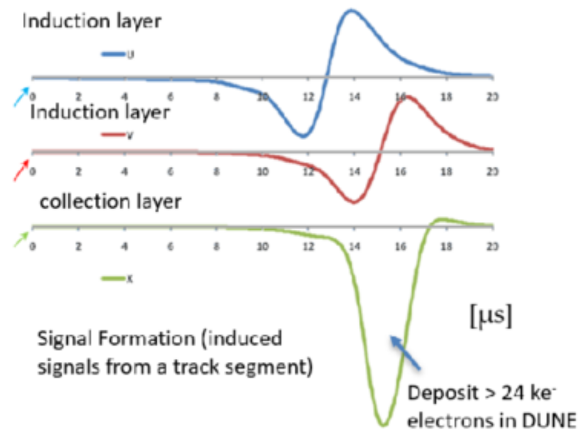




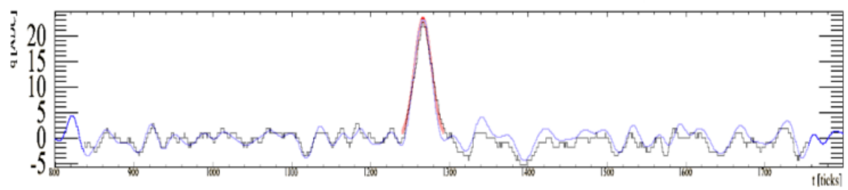


Energy Reconstruction in a LArTPC





TPC wire signal: "Hit"

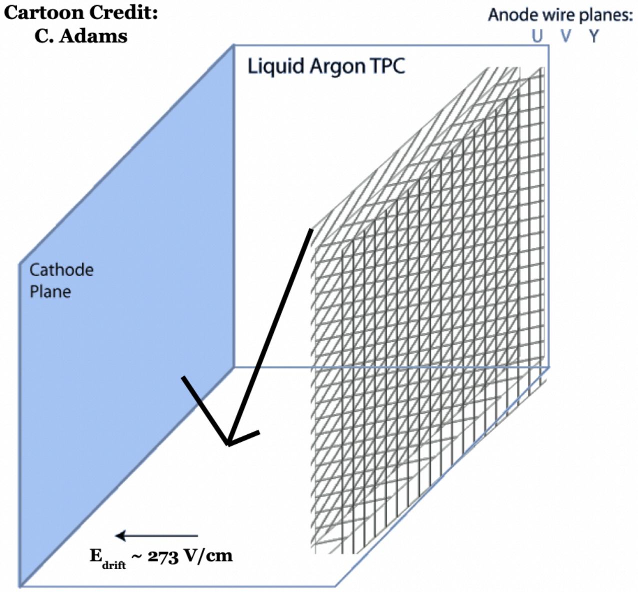


- Hit coordinates (*wire#* and t_{hit}) ⇒ **3D image**
- Hit Amplitude ⇒ **dQ (**Ionization Charge Deposited)
- Distance in space between hits ⇒ **dx** (track pitch)
- dQ/dx ⇒ dE/dx ⇒ **Particle Id**
- **Calorimetry** $$\int_l \frac{dE}{dx}\, dx = E_{Tot}$$

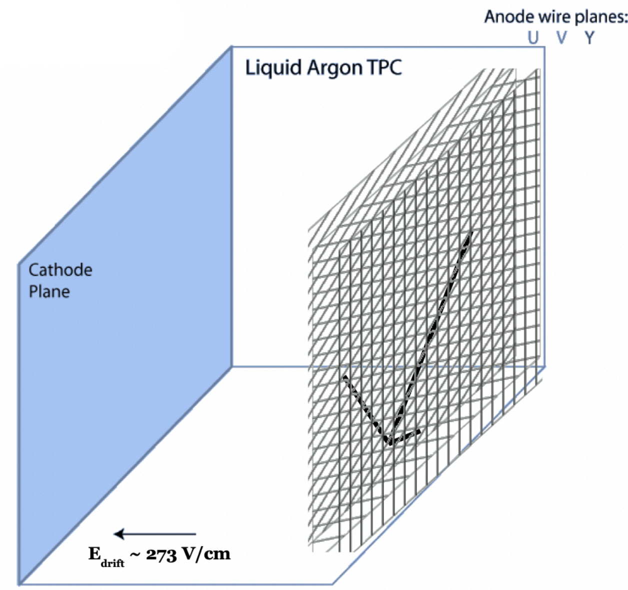
Not as Easy as it Sounds

Point of Formation

Cartoon Credit:
C. Adams



Point of Collection

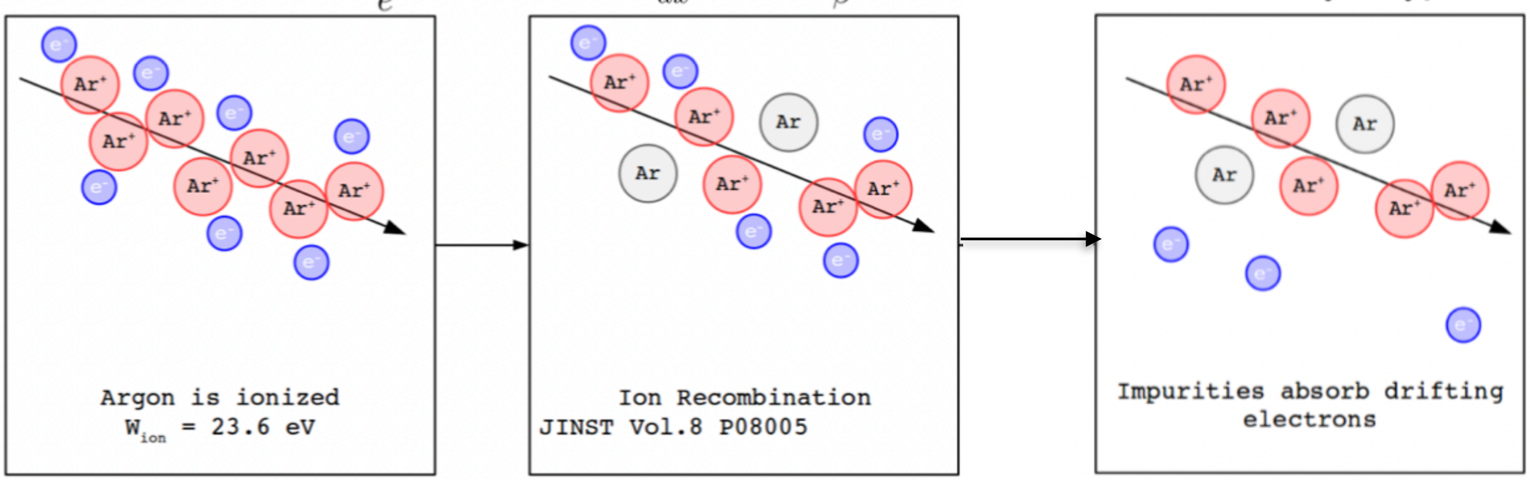


Many Effects impact the drifting charges impacting the spatial and energy resolution

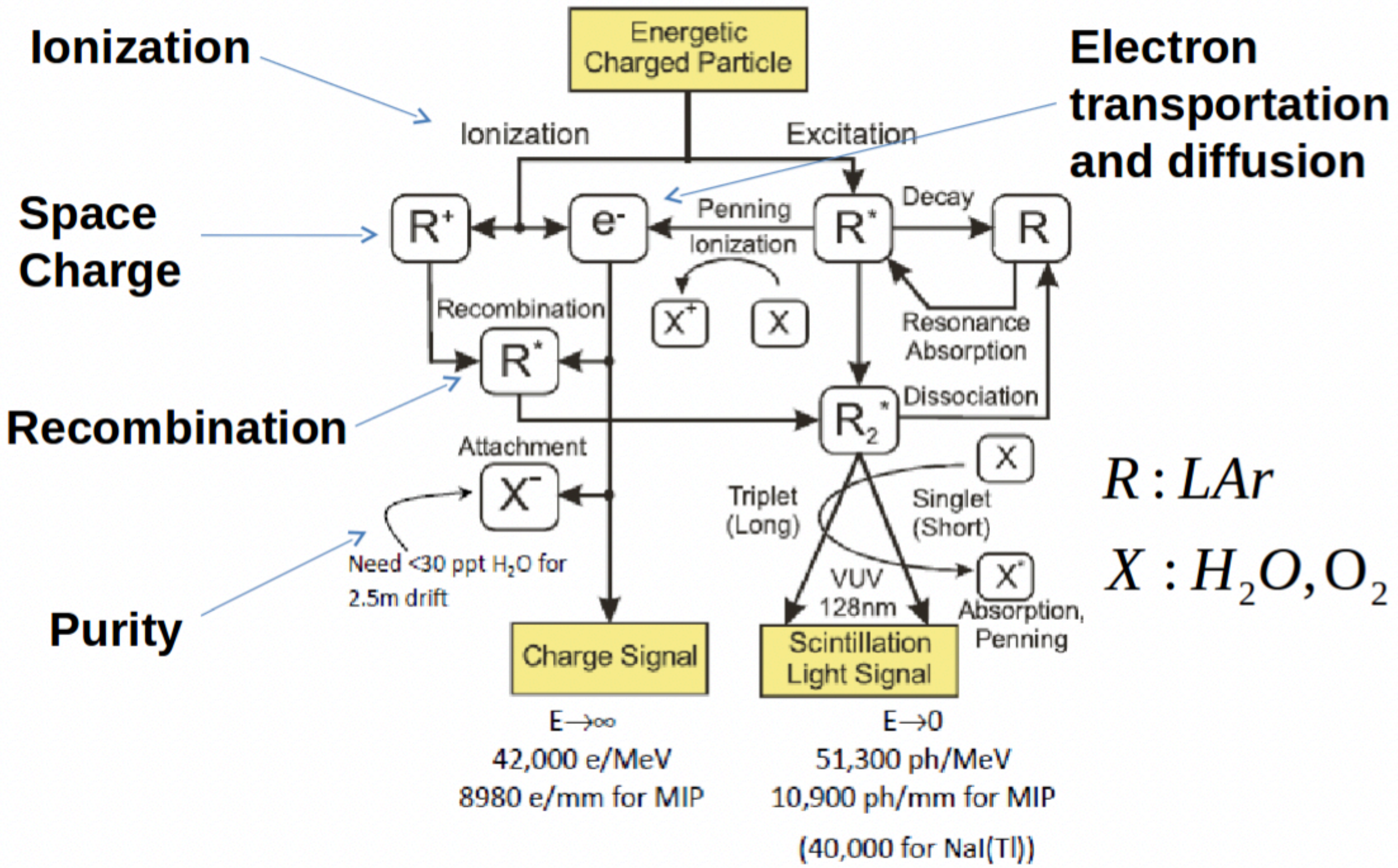
$$dQ = dE \times \frac{W_{ion}}{e^-}$$

$$\frac{dE}{dx} = \frac{e^{\beta \times \frac{W_{ion}}{e^-} \frac{dQ}{dx}} - \alpha}{\beta}$$

$$Q = Q_0 e^{-t/\tau}$$

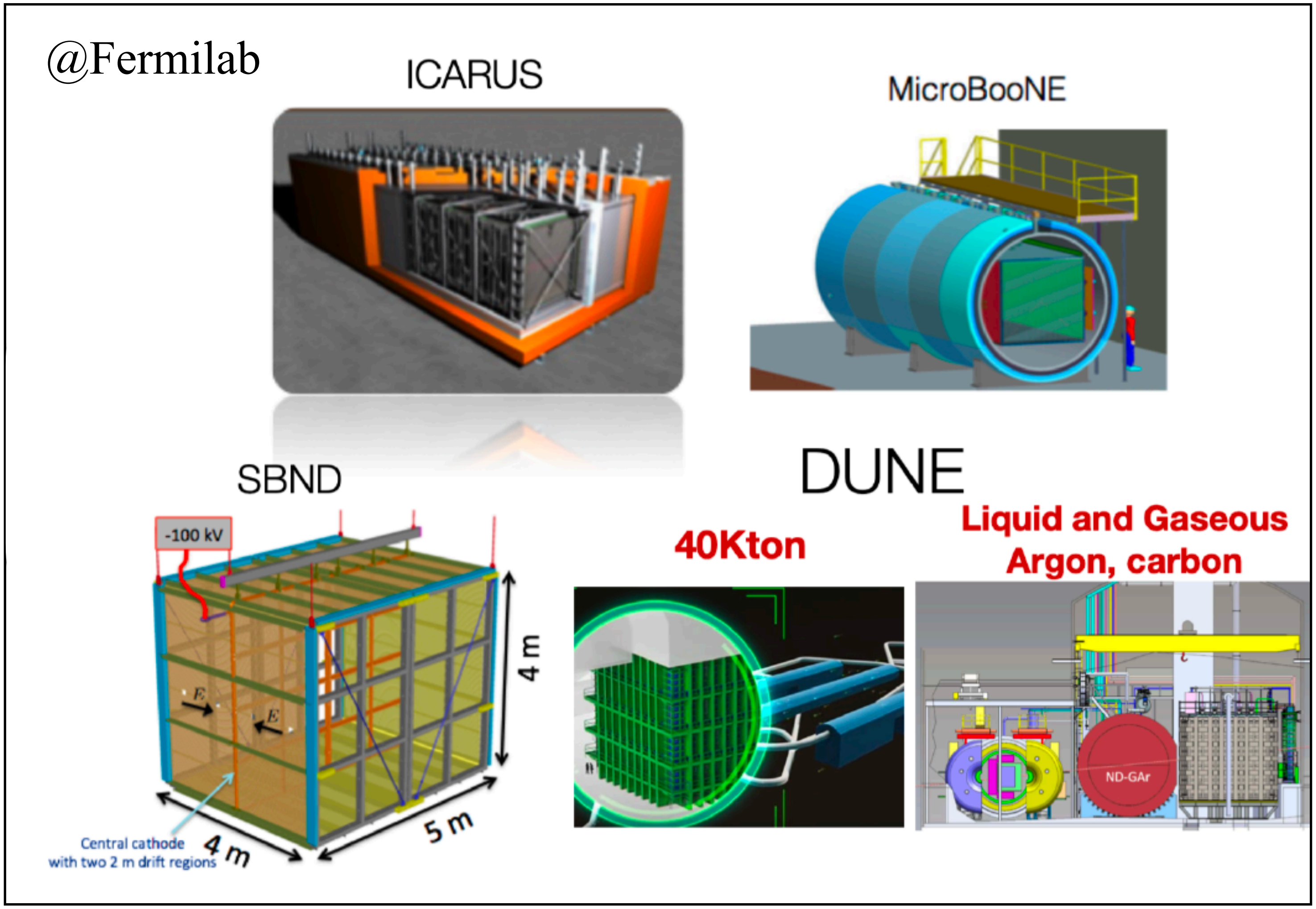


The picture is even more complex



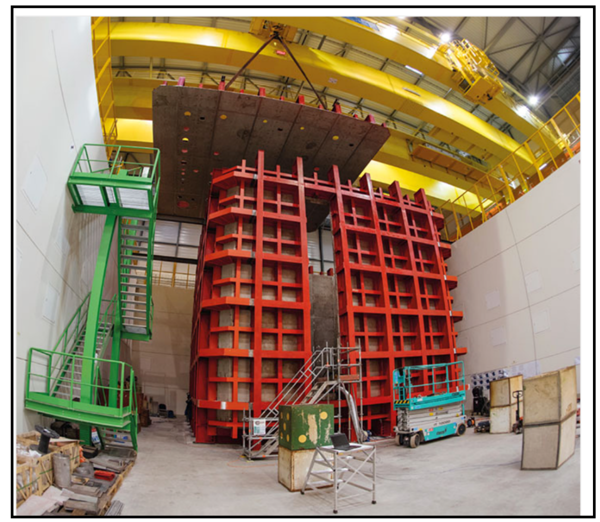
- Purity of Argon is key for successful LArTPC operation
- Calibration is crucial to ensure uniform detector response and eliminate biases in the signal

Liquid Argon Detectors (Current & Future)



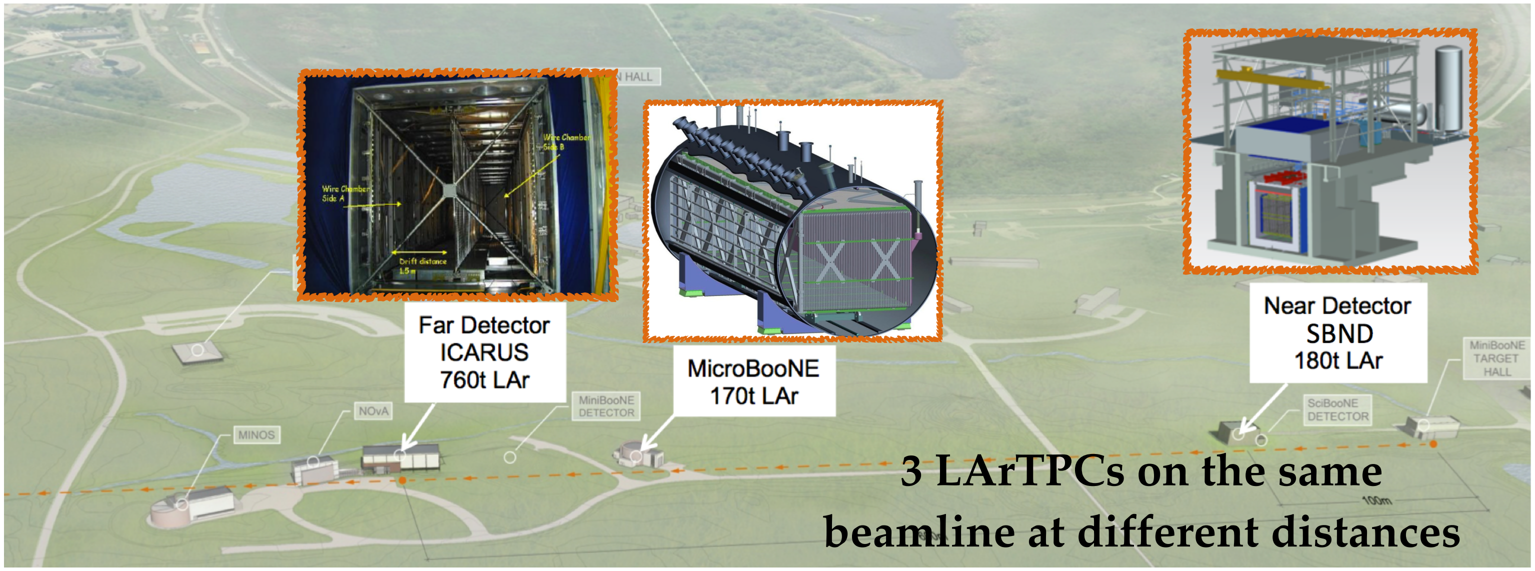
CCM@LANL

ProtoDUNE@CERN

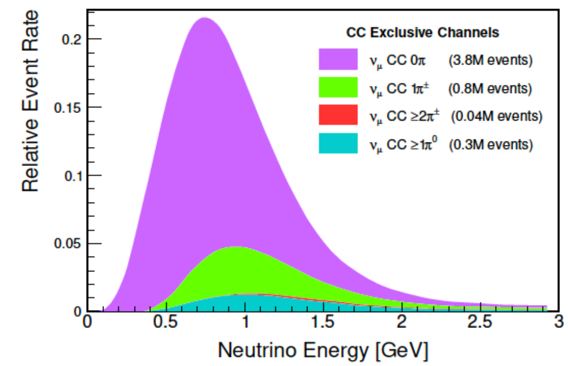


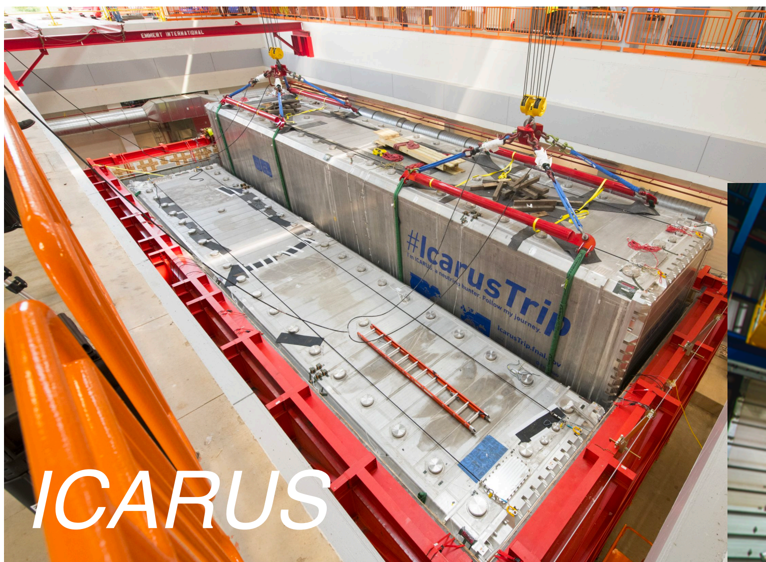
- CCM is both a Dark Matter and Neutrino Experiment at the Los Alamos Neutron Science Center and is a 10-ton light-only detector
- **I will highlight the DUNE experiment**

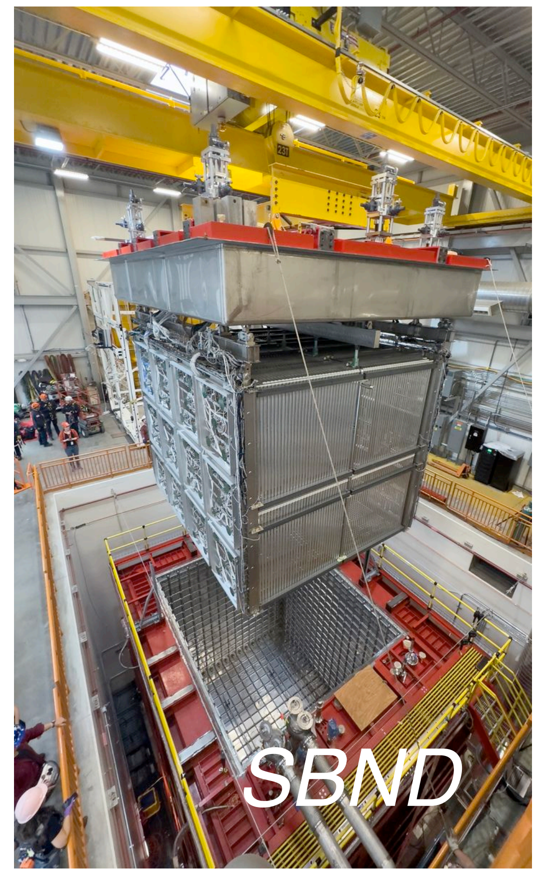
Fermilab Short-Baseline Program



SBND will have world's highest statistics on argon

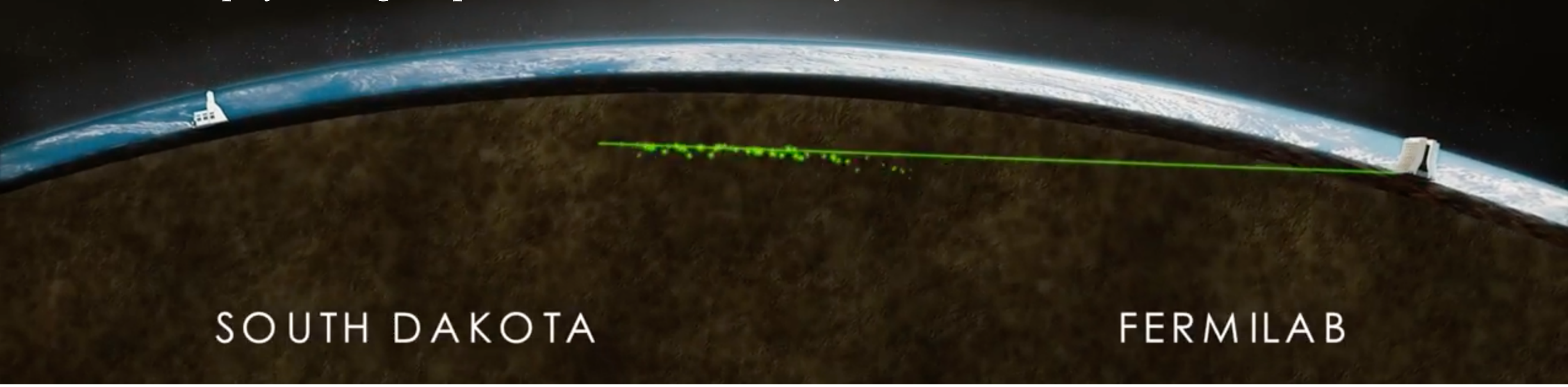




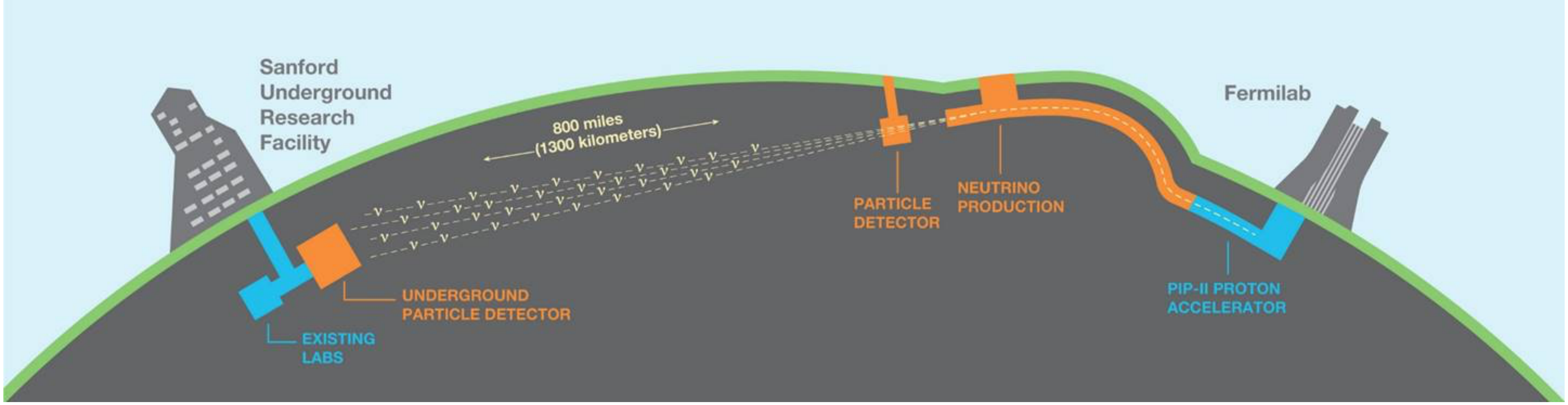


DUNE

Rich Physics program: Precision neutrino oscillation physics, CP-violation, MeV-scale physics e.g. Supernovae, Nucleon decay, and a suite of BSM Searches



DUNE will be built in 2 phases
1.2 MW beam by early 2030



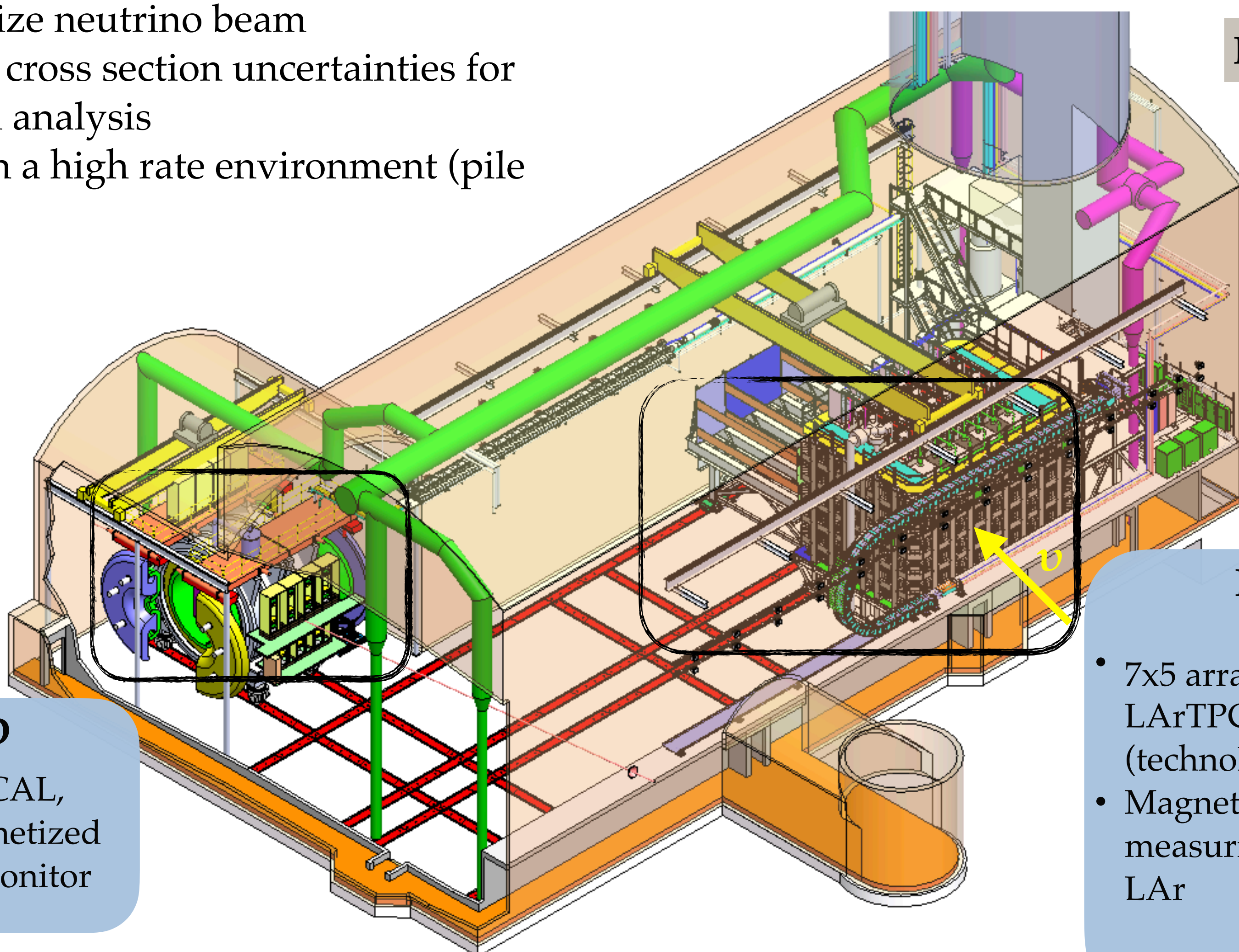
The DUNE Near Detector Complex

- Located **60 m** underground at Fermilab; **574 m** from neutrino beam target
- Comprises of multiple technologies; will be built in 2 phases

Primary Goals

- Characterize neutrino beam
- Constrain cross section uncertainties for oscillation analysis
- Perform in a high rate environment (pile up)

Phase 1 design



SAND

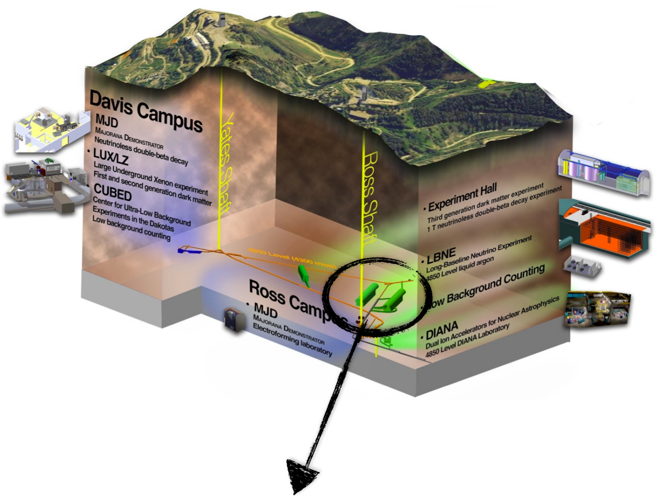
Tracker, ECAL,
On axis magnetized
beam flux monitor

ND-LAr + TMS

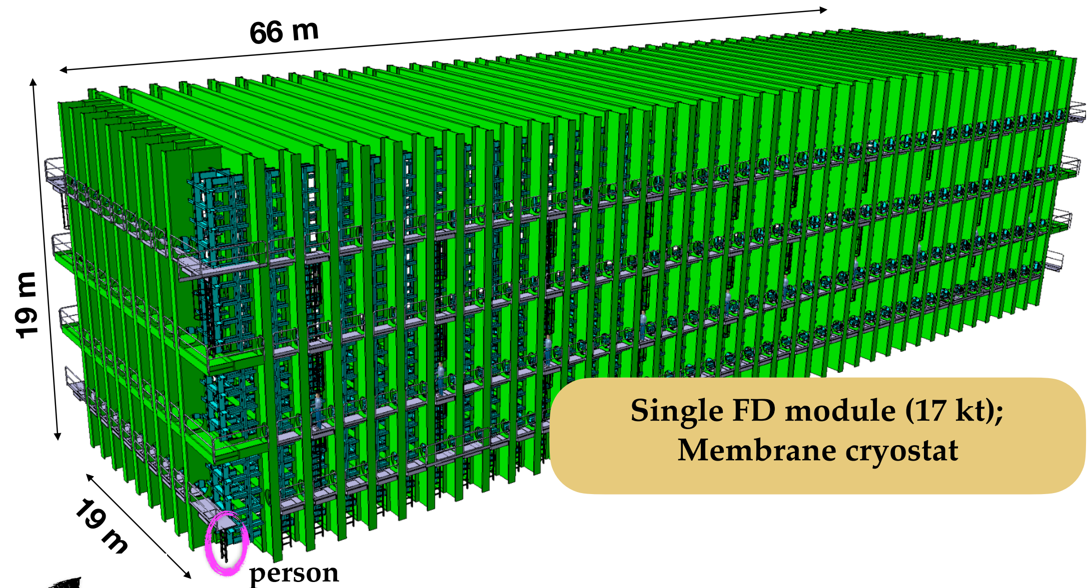
- 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout (technology closest to far detector)
- Magnetized steel range stack for measuring muons that exit ND-LAr

CDR: arXiv:2103.13910

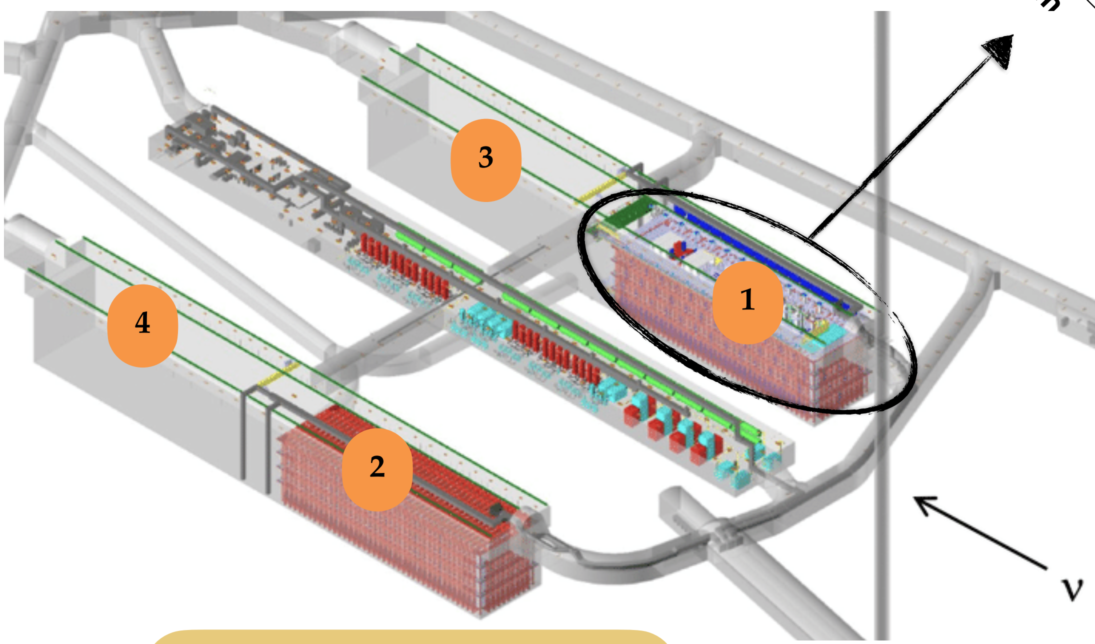
The DUNE Far Detector: *Largest LArTPC ever to be built*



JINST 15 T08010



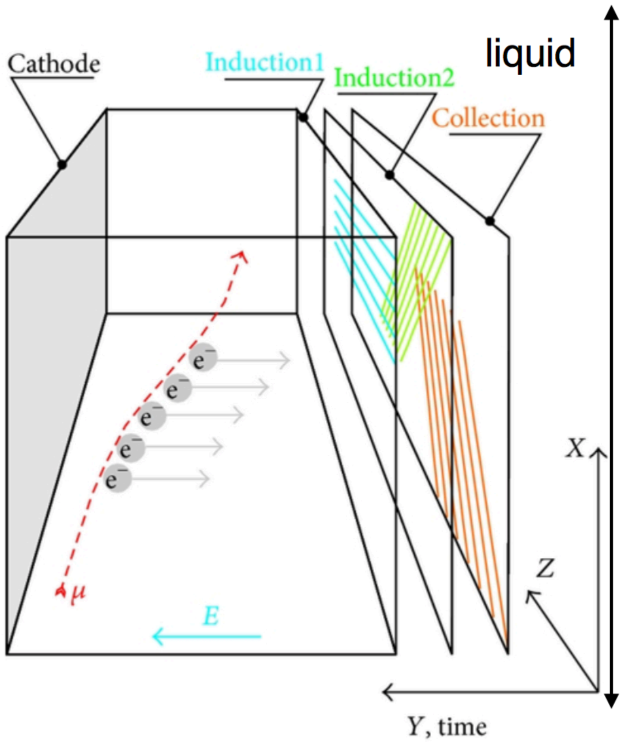
Single FD module (17 kt);
Membrane cryostat

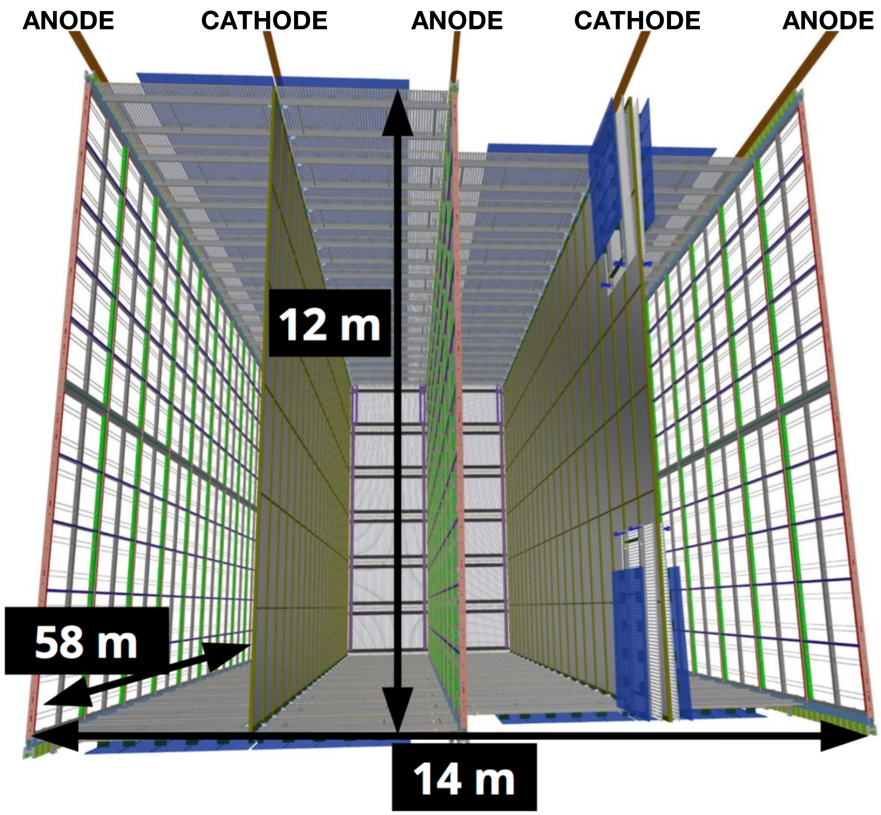


2 caverns, 4 detectors,
flexibility in design

- The first two DUNE FD modules will be **Liquid Argon Time Projection Chamber (LArTPC)** detectors with 17 kt mass each
- **FD#1:** Horizontal Drift (HD)
- **FD#2:** Vertical Drift (VD)
- **FD#3:** LAr technology TBD
- **FD#4:** Module of opportunity (R&D ongoing)

FD#1: Horizontal Drift LArTPC

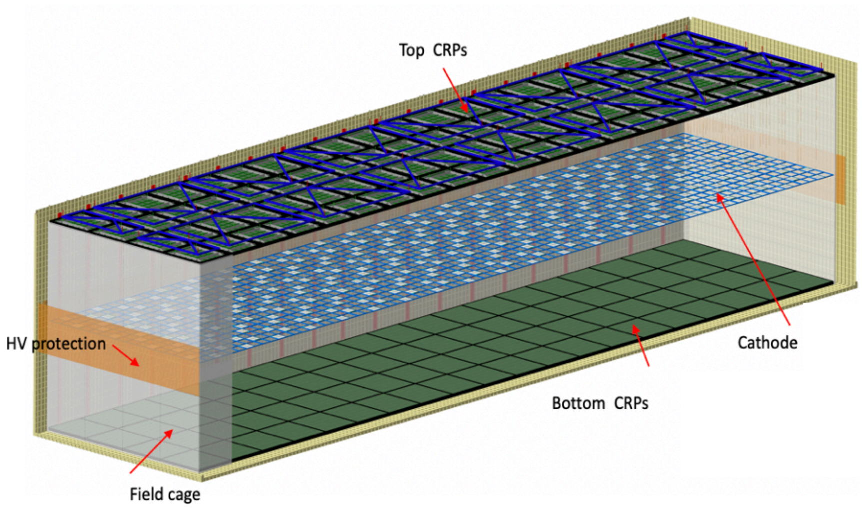




JINST 15 T08010 (2020)

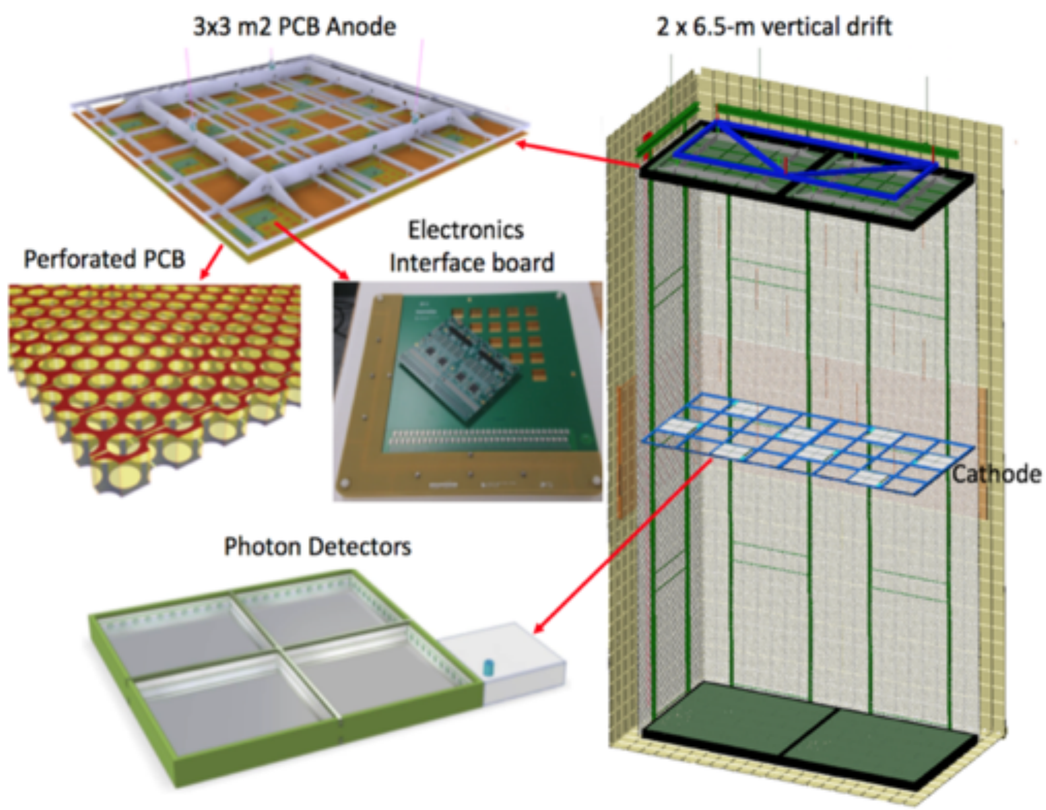
- 12 m x 14 m x 58 m active volume
- Each Anode-Cathode chamber has 3.5 m drift
- Cathode at -180 kV
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- Anode planes have wrapped wires (readout on both sides)
- 6000 photon detection system (PDS) channels for light readout

FD#2: Vertical Drift LArTPC



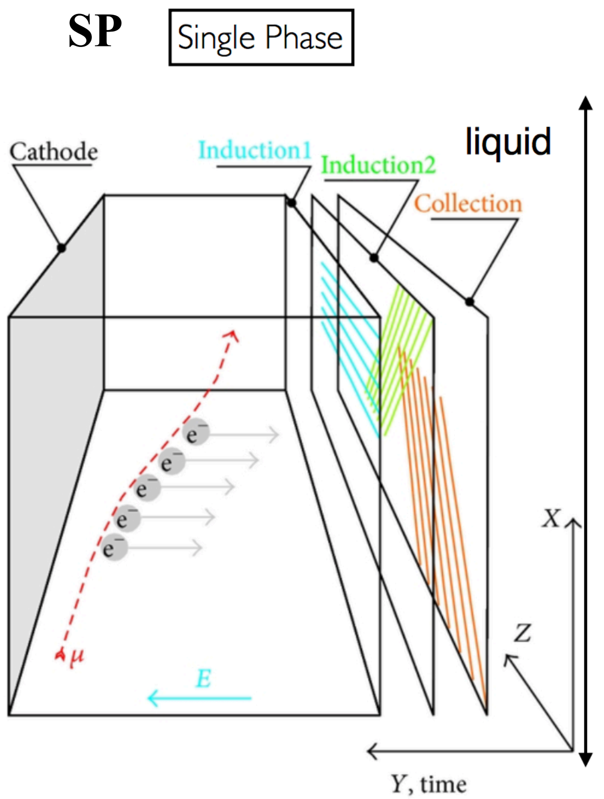
- VD technology evolved from extensive R&D from single and dual phase LArTPCs
- Designed to maximize active volume
- Perforated PCBs with segmented electrodes (strips) as readout units

- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- -300kV on cathode; 450 V/cm field

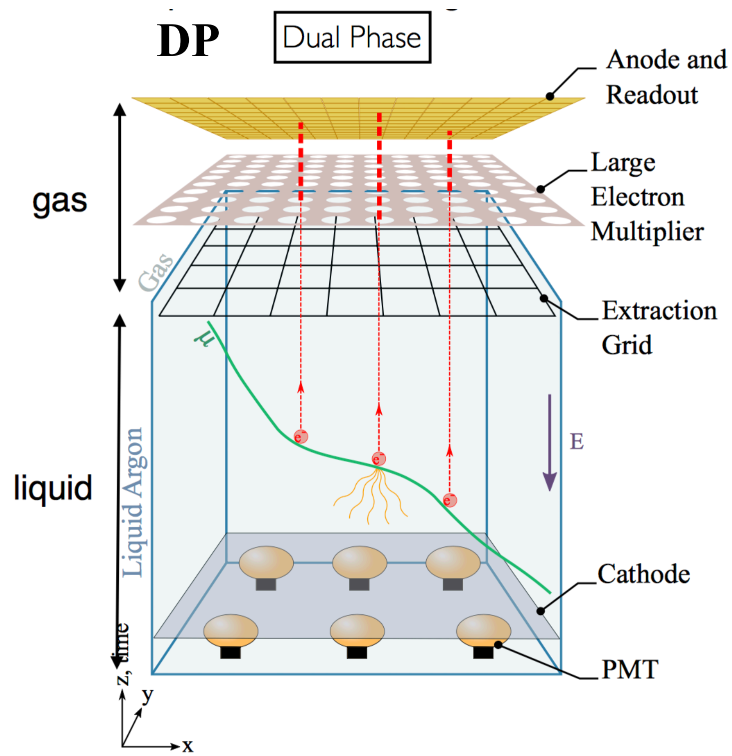


DUNE Prototype Technologies at CERN

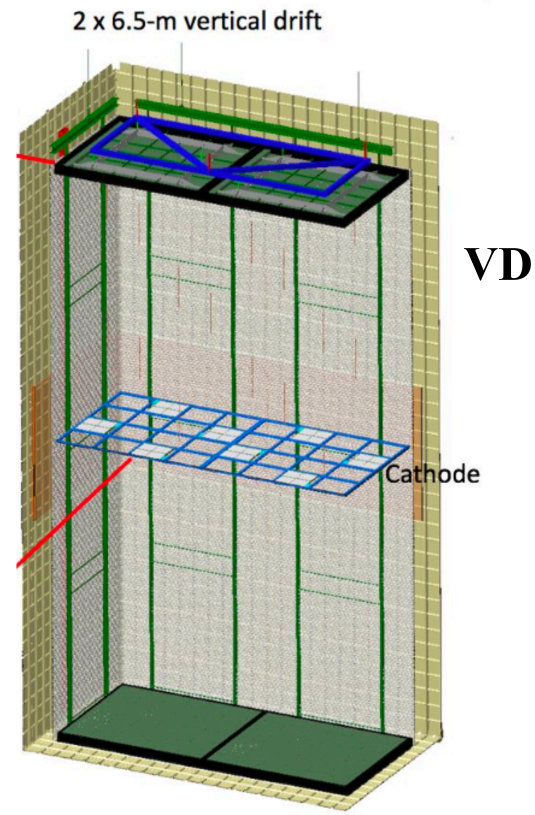
SP

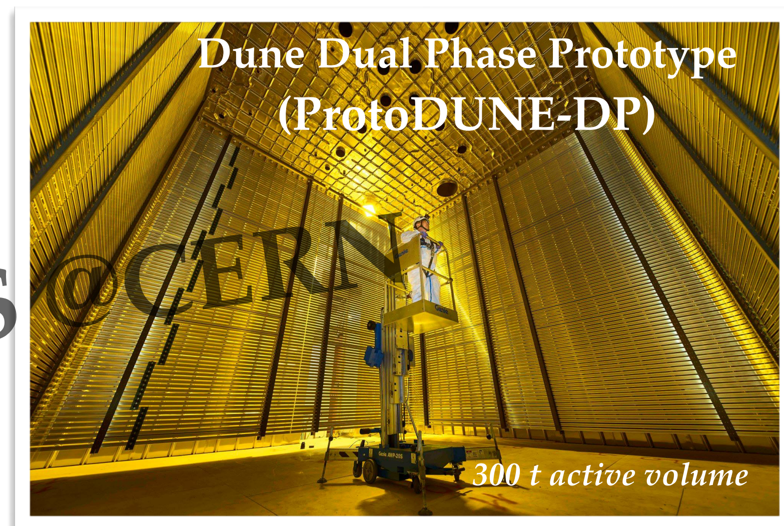


DP



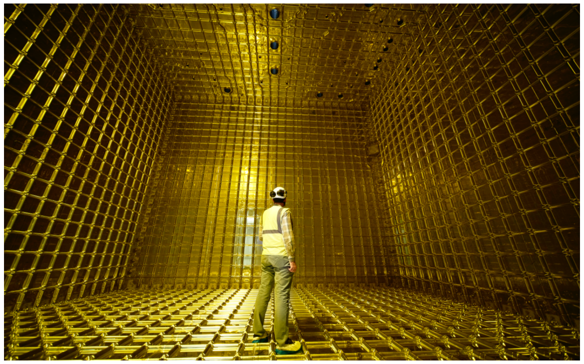
VD





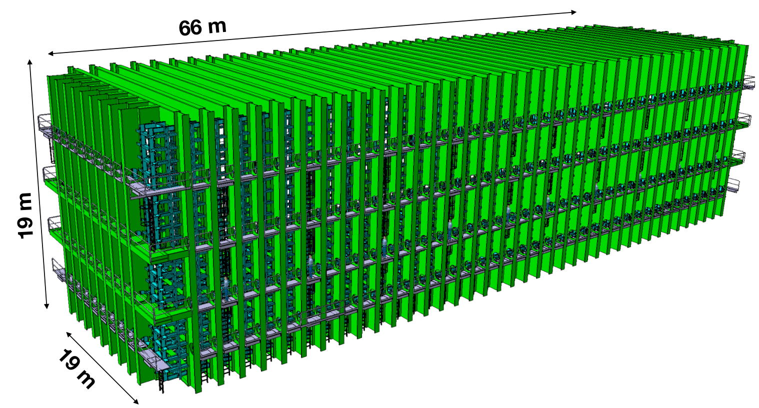
Many Challenges on the Path to DUNE

~400 ton
(ProtoDUNE)

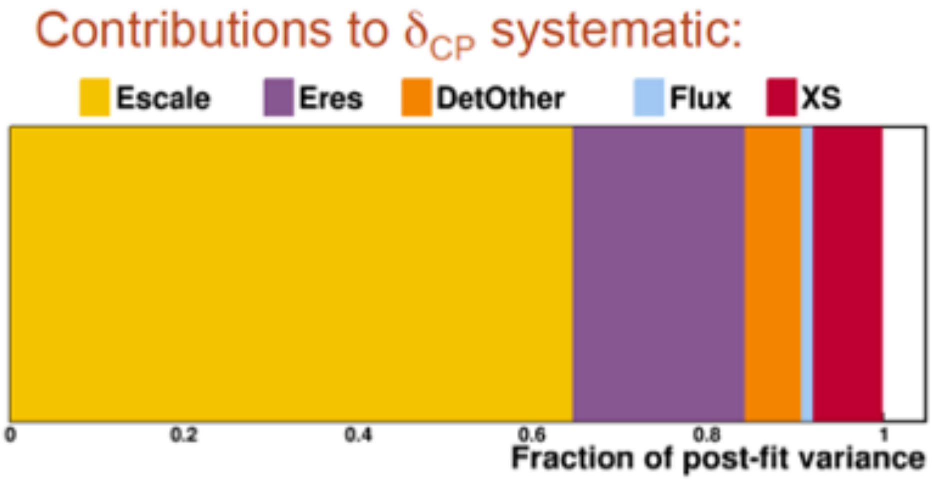


x 25

10,000 ton
(1 DUNE module)



- ***unprecedented*** detector scale
- DAQ requirements never dealt before
- Neutrino-argon cross sections not well measured
- Neutrino energy reconstruction
- Unprecedented systematics requirements
- Calibrations most challenging!
- LArTPC R&D actively ongoing



High-fidelity Neutrino Detectors

Neutrinos in the LBNL Physics Division

Current Activities:

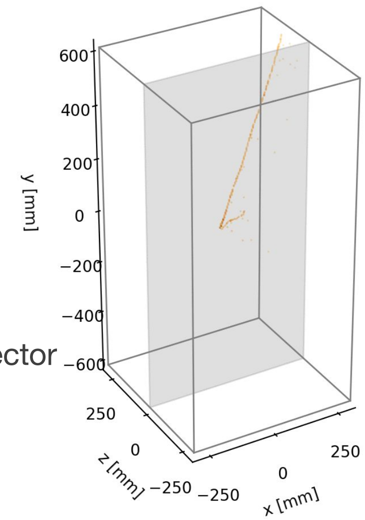
- Detector R&D
- Developing novel 3D pixel readout of large liquid argon detectors
- Design and testing of custom integrated circuits for particle detectors
- Exploring scalable pixelated photon detection

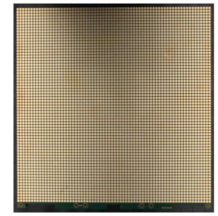
- DUNE Near Detector design and prototyping
- Design of the Liquid Argon Time-projection Chamber (LArTPC) Near Detector
- Small-scale prototyping of detector designs
- Construction and operation of a multi-ton prototype in a neutrino beam

- Far Detector electronics
- Production and testing of electronics for the DUNE Far Detectors

- Neutrino Oscillation physics
- Development of GPU-accelerated simulation techniques
- Exploration of native 3D signal analysis techniques
- Applications of Machine Learning in neutrino physics
- Studies of the physics potential of DUNE

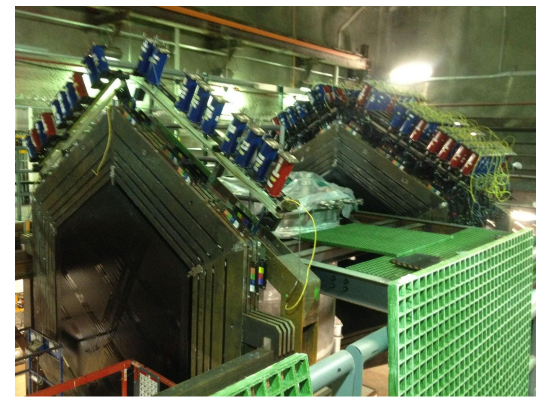
Cosmic rays imaged in 3D using recent prototype LArTPC

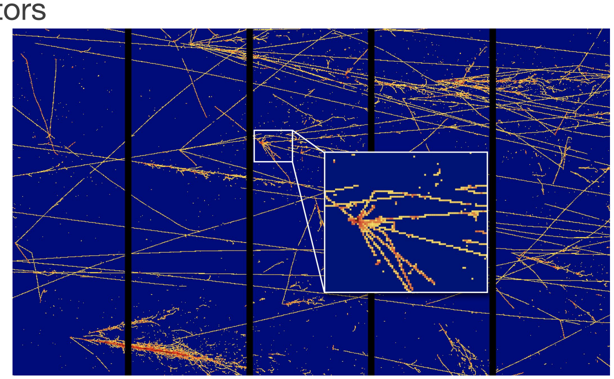




Prototype pixel tile with 6,400 channels

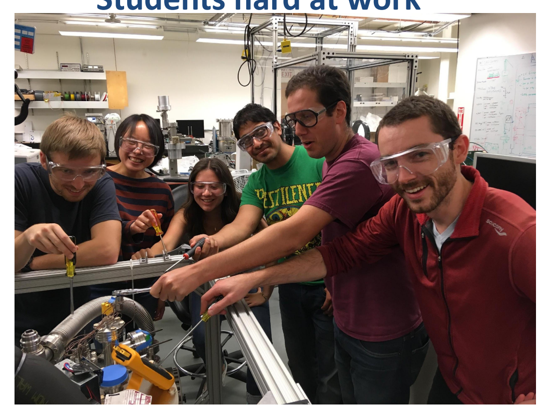
Multi-ton Detector in Neutrino Beam





GPU-accelerated neutrino detector simulation

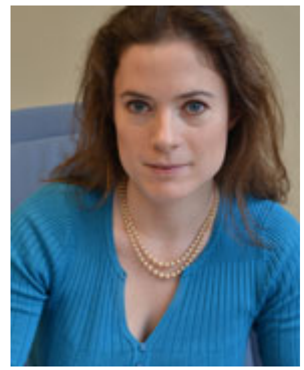
Students hard at work



Neutrino Physics @ Berkeley

Dan Dwyer
DUNE
LBNL PD

Yury Kolomensky
CUORE
Campus, NSD



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