Neutrino Detectors

(Part II)

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Lecture 2: Outline

- Lecture 2 (Detector Technologies)
    - Overview of Detector Technologies
    - How do they map to neutrino sources and physics goals
    - Three Technologies (emphasis on LArTPCs)
        - Cherenkov
        - Scintillator
        - LArTPCs
    - Others *(time permitting)*

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)*

Neutrino Detector Technologies

Physics Problem(s)	Neutrino Source(s)	Detector Classification
Absolute mass; Dirac or Majorana	Radioactive	Semiconductors, Crystals, gaseous and scintillator detectors
Oscillation/Sterile neutrinos	Accelerator, Reactor, Atmospheric, Solar, Astro/galactic	Liquid Scintillator, Liquid Argon, Emulsion, Sampling detectors, Water Cherenkov, Radiochemical
Astronomy/ Cosmology	Astro/galactic sources, Relic neutrinos, radioactive	Water Cherenkov, Liquid Argon, Liquid Scintillator
Earth	Geoneutrinos	Liquid scintillator

- Great synergy across experiments and technologies
- The beauty of this: Neutrino technologies are all multi-purpose and serve more than one physics goal and exploit more than one neutrino source
- More bang for the buck!

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Earth	Geoneutrinos	Liquid scintillator

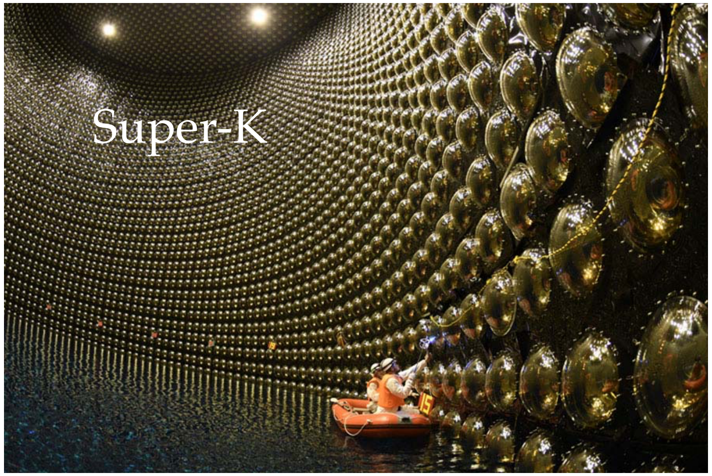
Lot to cover here but not enough time.
I will focus on the following:

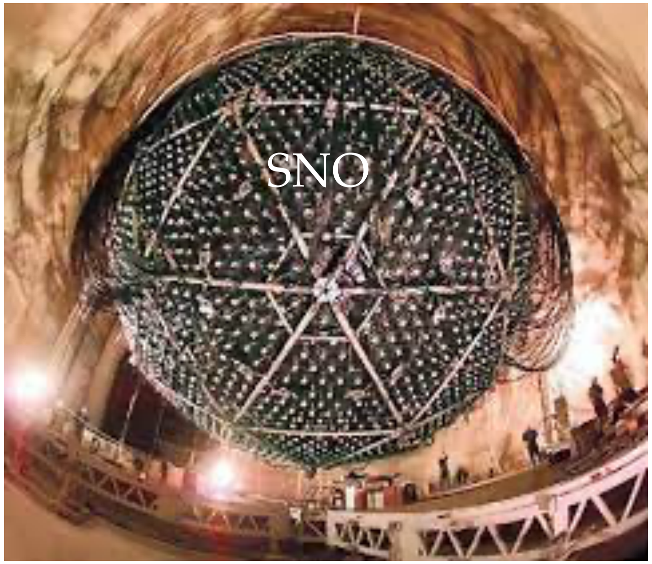
- Scintillator
- Cherenkov
- LArTPCs (more emphasis on this)
- Others *(time permitting)*

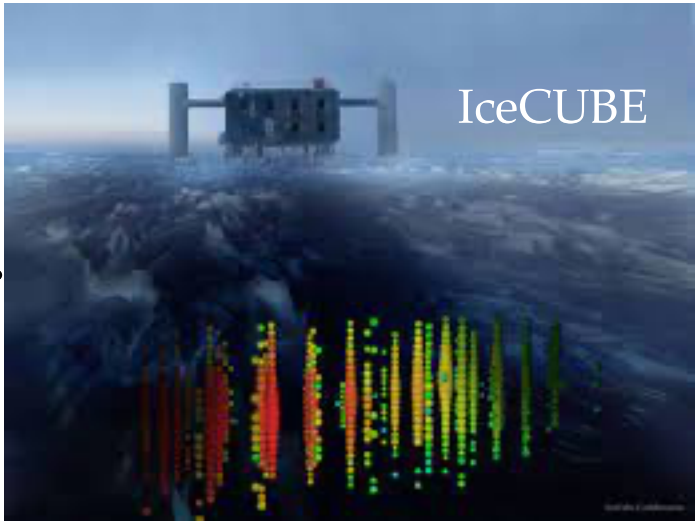
- Great synergy across experiments and technologies
- The beauty of this: Neutrino technologies are all multi-purpose and serve more than one physics goal and exploit more than one neutrino source
- More bang for the buck!

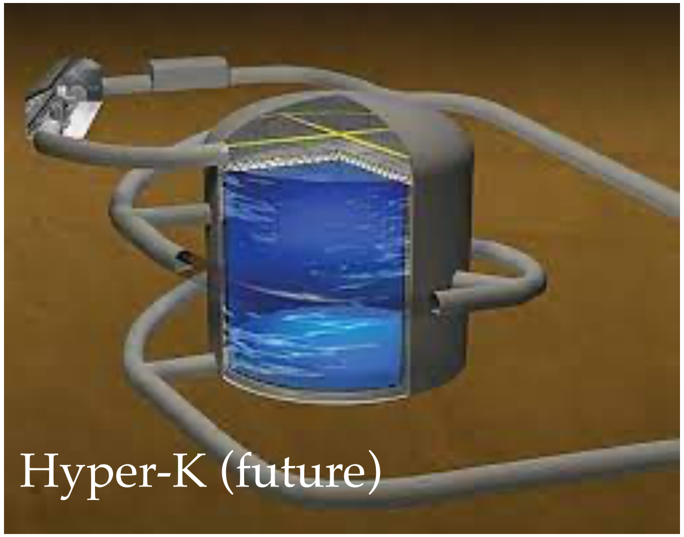
Water Cherenkov Detectors

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

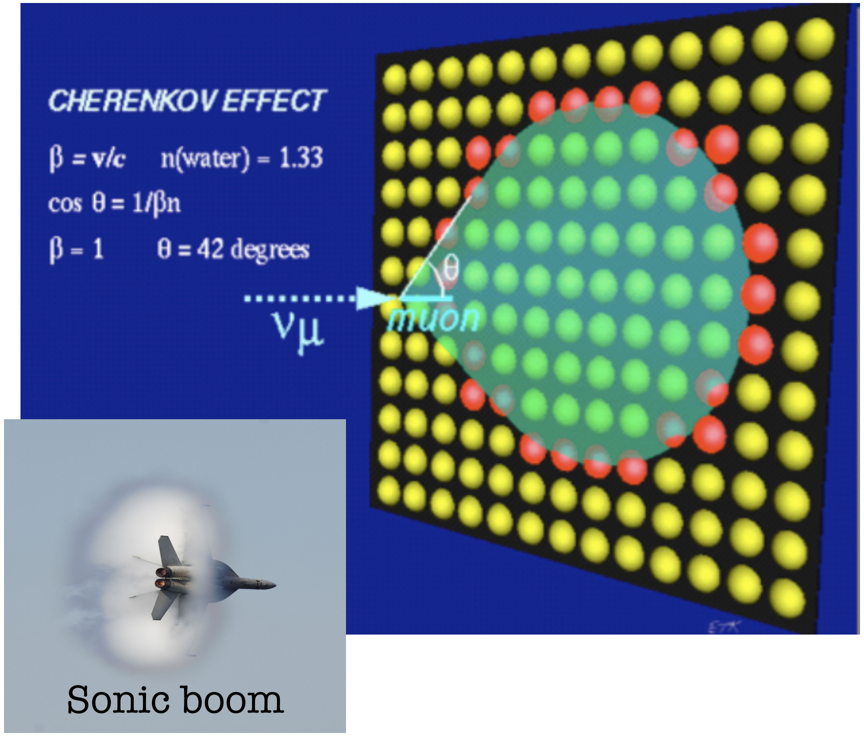








Cherenkov Light



- 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, $n = 1.33$

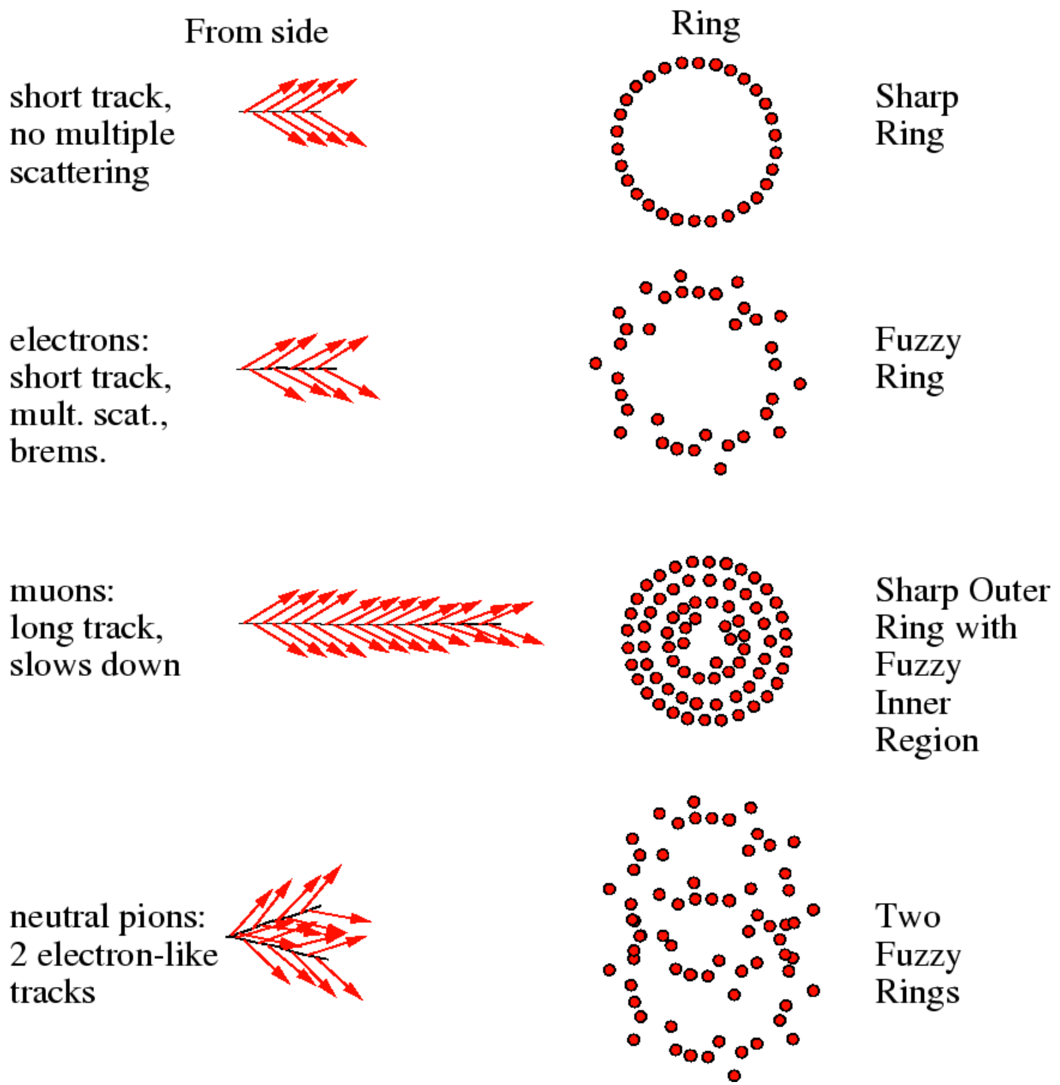
- Cherenkov thresholds

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

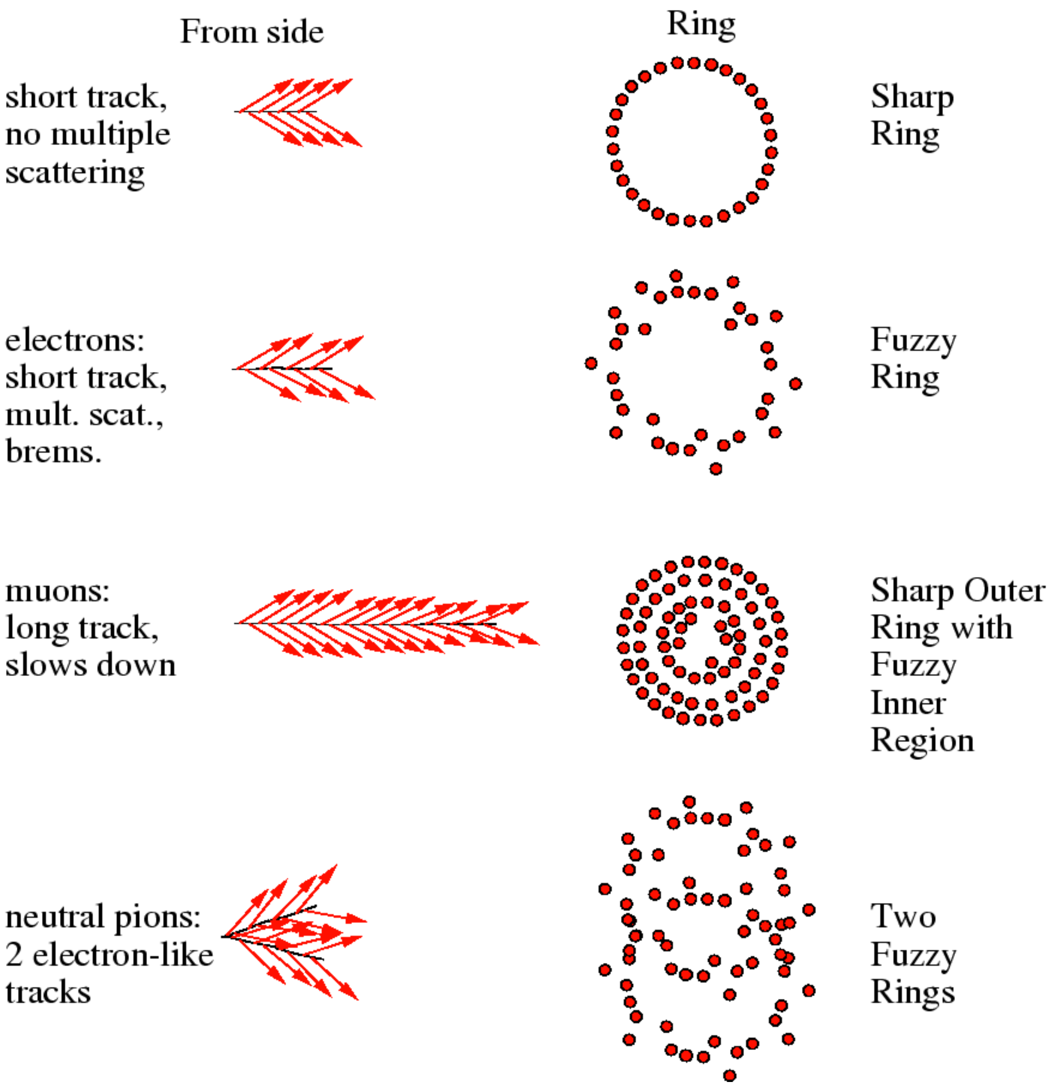
e	0.73 MeV
μ	150 MeV
π	200 MeV
P	1350 MeV
K	650 MeV

- 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



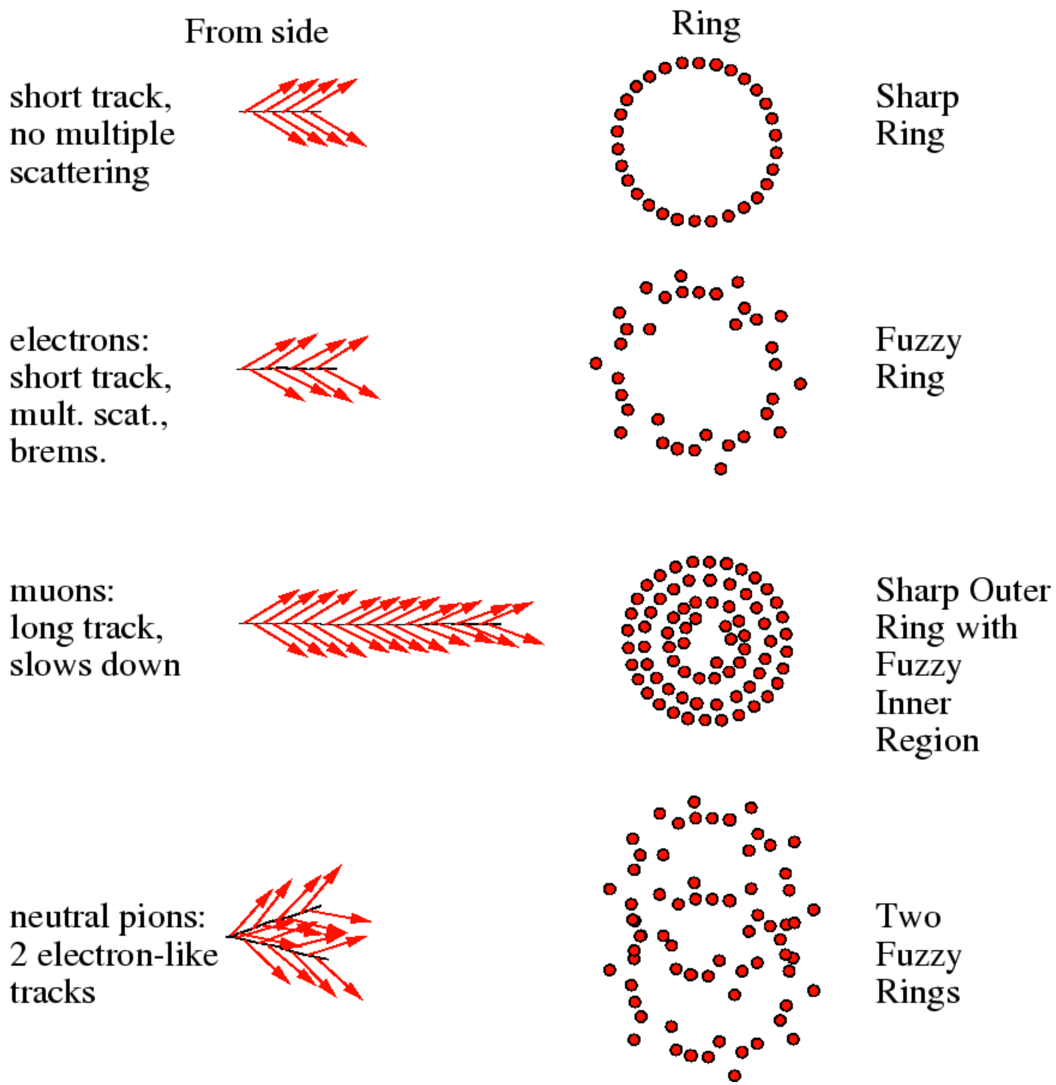
Particle ID in Cherenkov Detectors

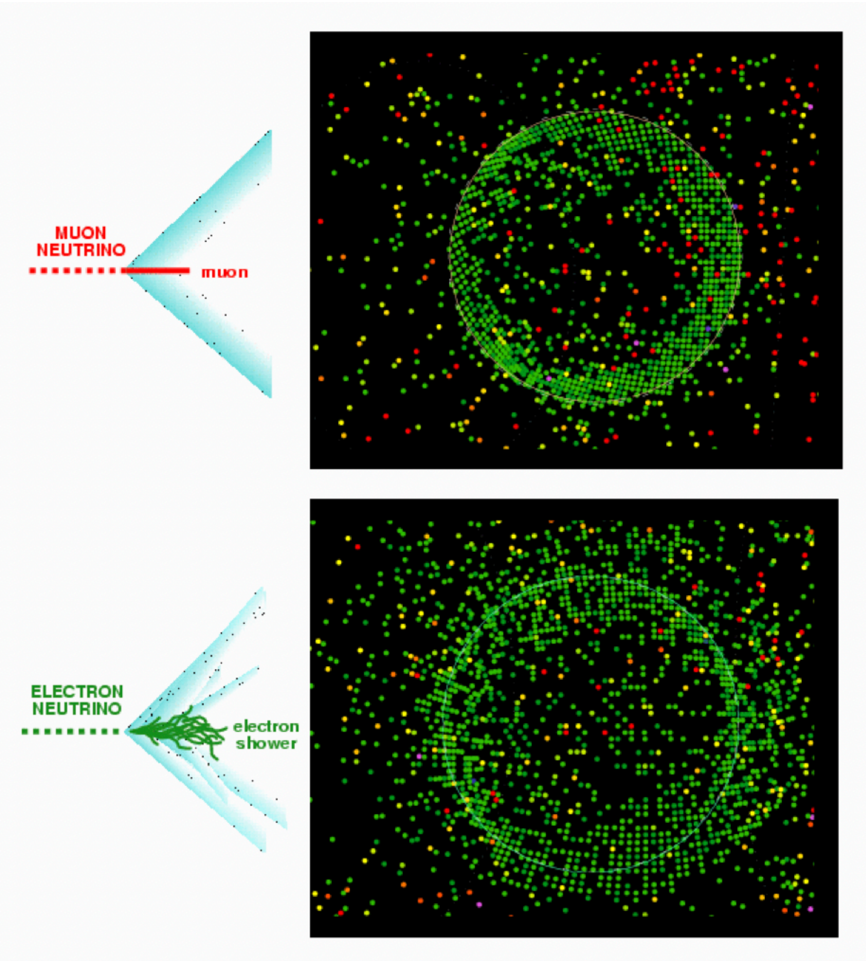


Some issues:

- 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

Particle ID in Cherenkov Detectors

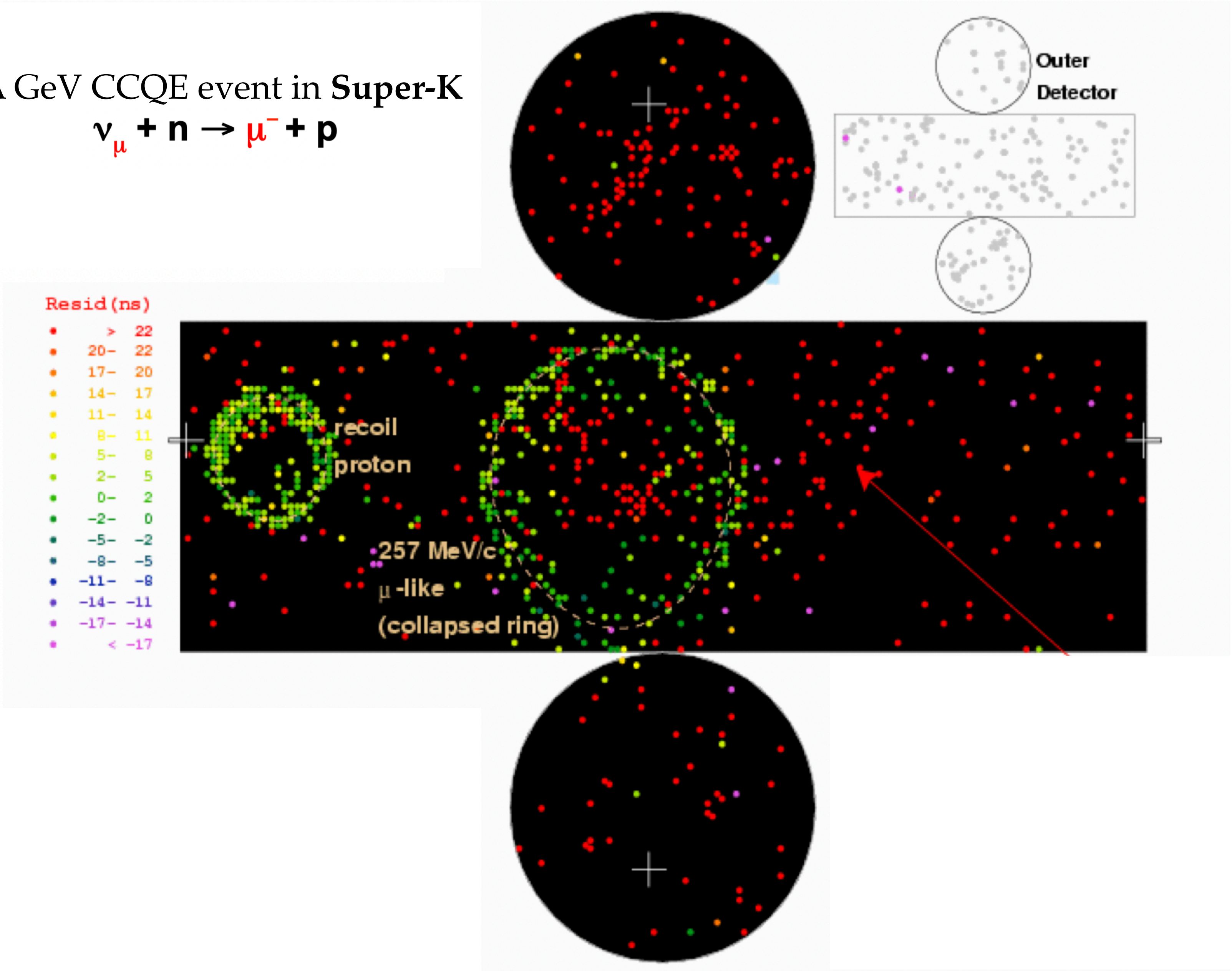




Super-K Water Cherenkov Detector

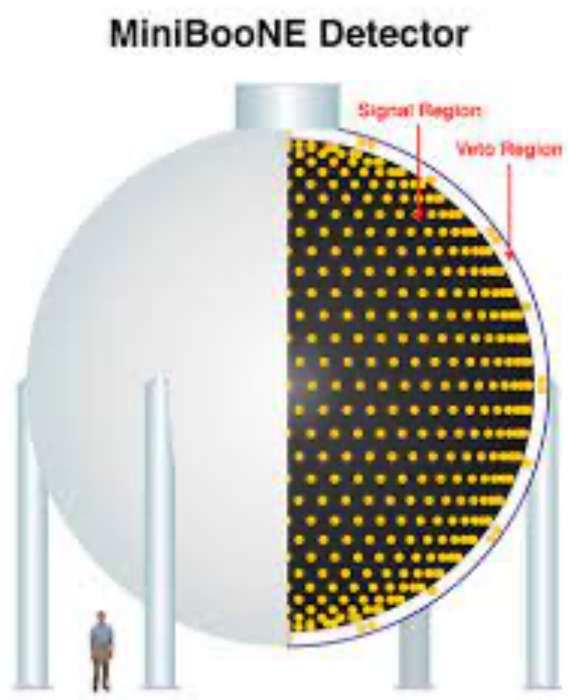
A GeV CCQE event in **Super-K**

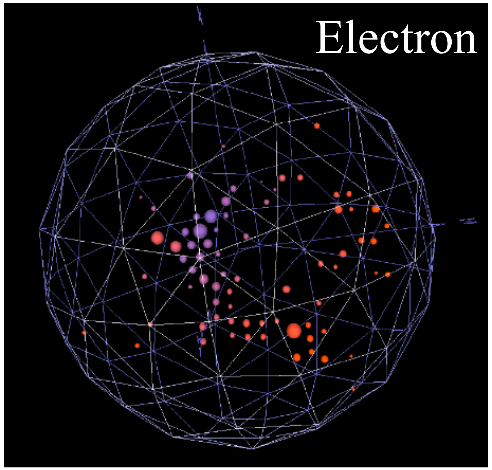
$\nu_\mu + n \rightarrow \mu^- + p$

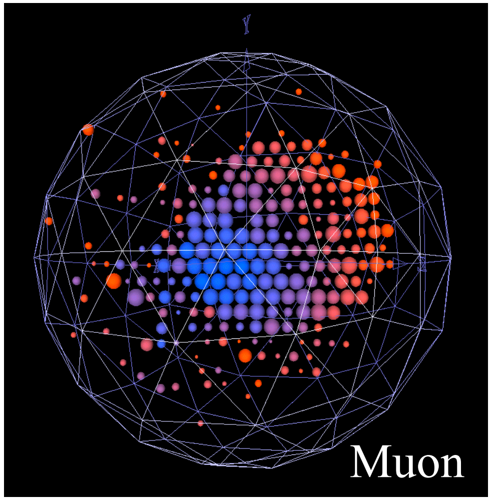


MiniBooNE Cherenkov Detector

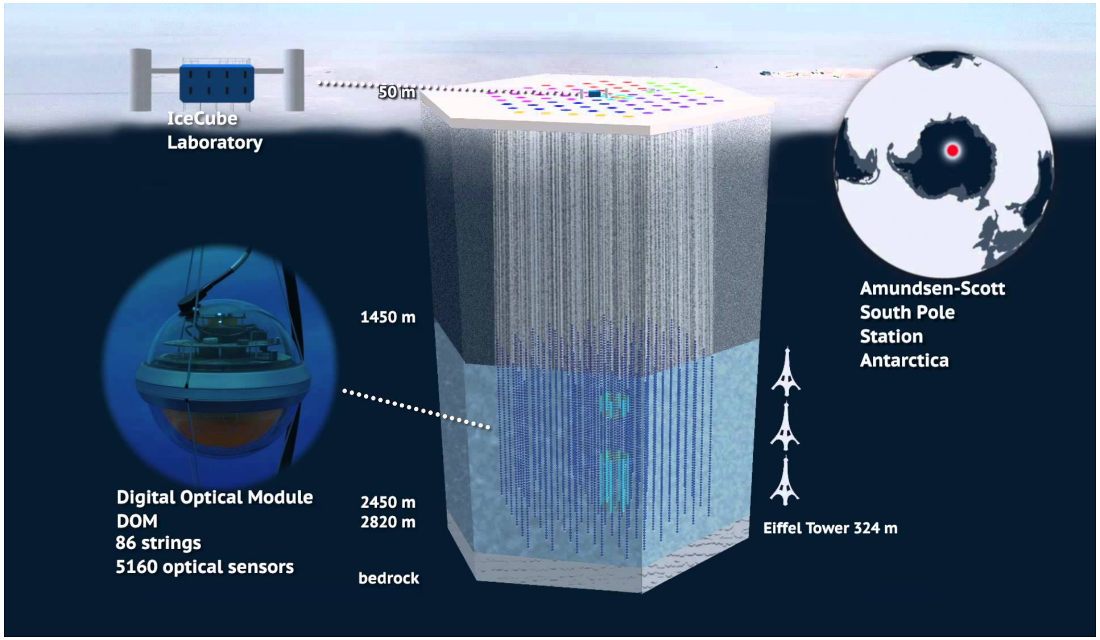
- Mineral Oil Cherenkov detector at Fermilab
- Aim was to address the LSND anomaly
- 6 m radius (800 tons total volume)
- 1280 PMTs
- Why Mineral oil?
    - Higher refractive index (1.47) than water (1.33)
    - Lower density than water
    - More Cherenkov light produced
    - Lower velocity
    - Lower 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

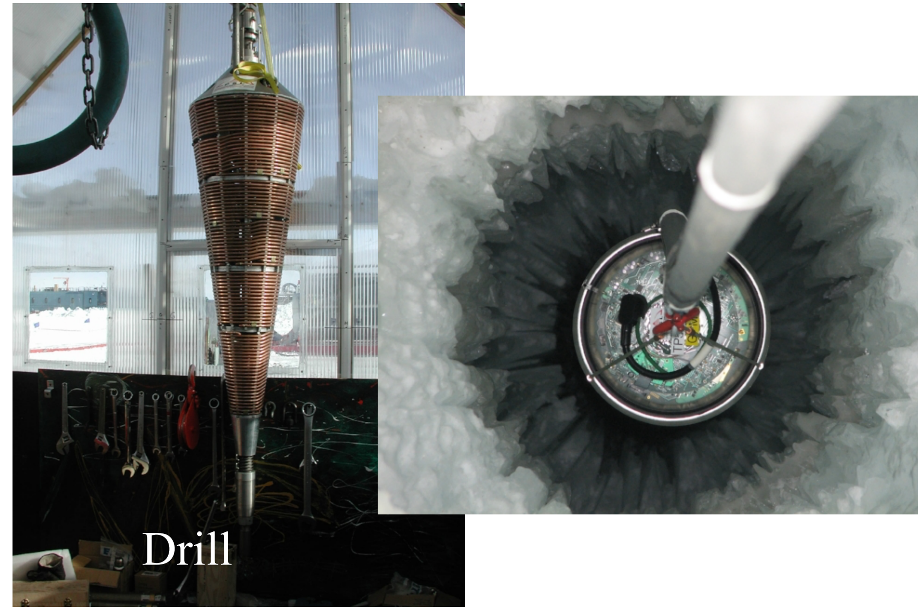




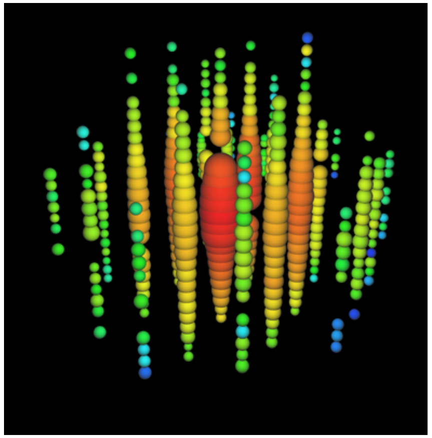


IceCUBE Cherenkov Detector

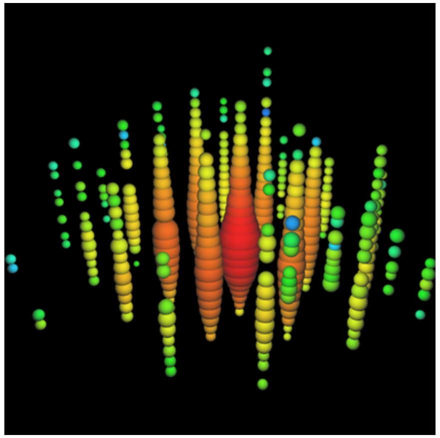




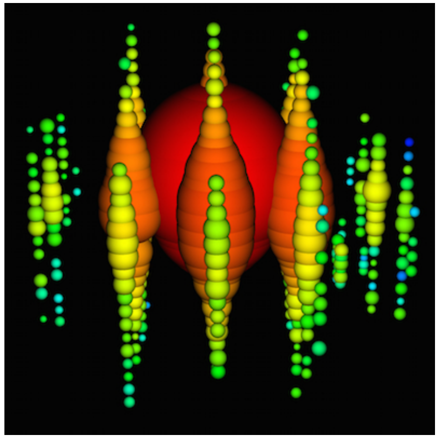
- Long-string s of PMTs in ice or water (domes spaced at ~10m)
- Particles from astrophysical sources produce Cherenkov light
- Other similar efforts: ANTARES, PINGU, Lake Baikal (KM3NET, IceCube-Gen2)



Bert



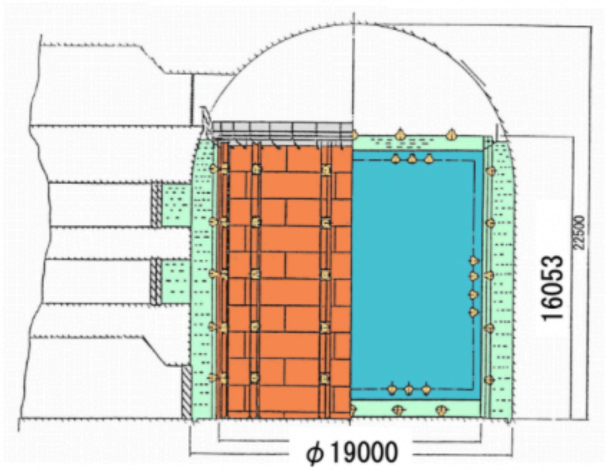
Ernie

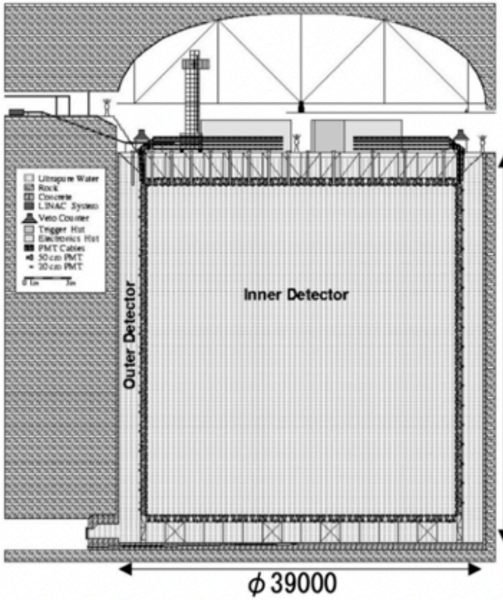


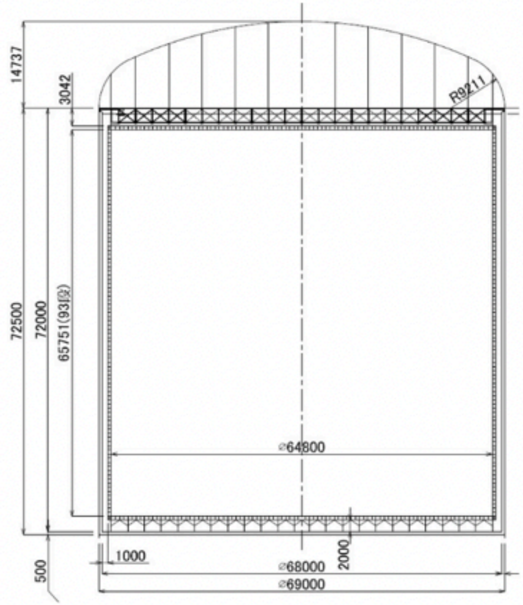
Big Bird

Water Cherenkov Detectors in Japan

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983〜1996	1996~Present	Aiming to start observation in 2027

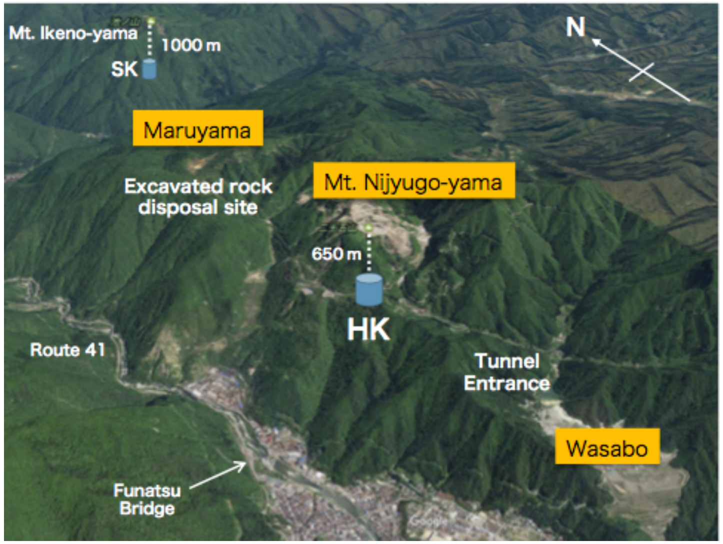


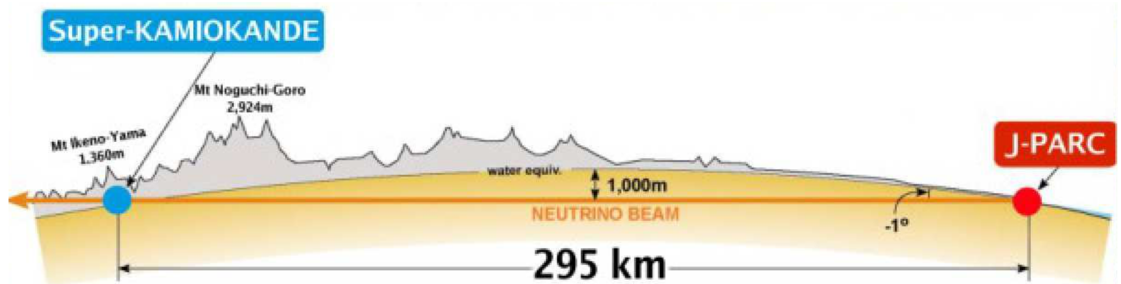




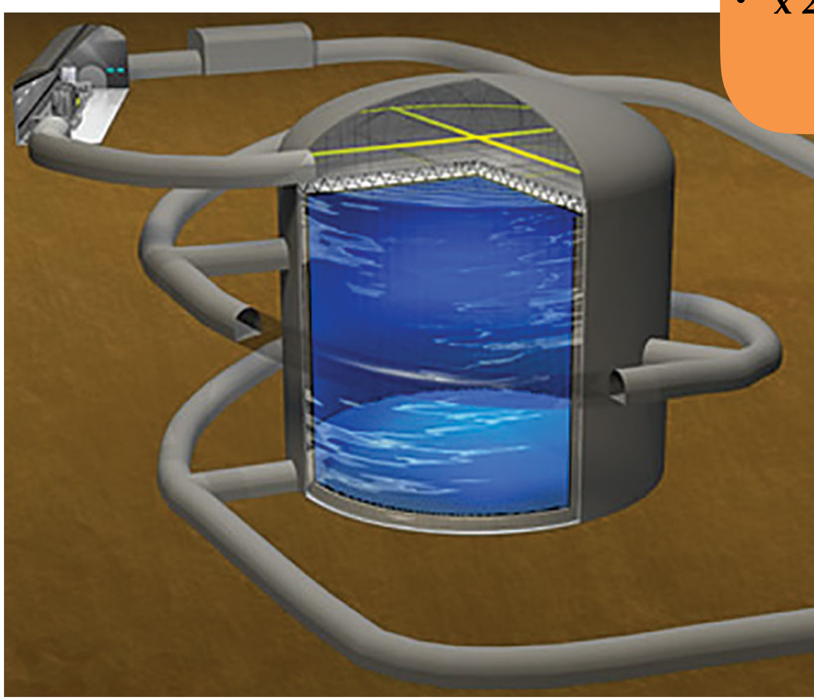
Kamiokande	Super-Kamiokande	Hyper-Kamiokande
19m diameter x 16m hight	39m diameter x 42m hight	68m diameter x 71m hight
4500 ton *Total mass*	50000 ton	260000 ton
(680~1040 ton) *Fiducial mass*	(22500 ton)	(190000 ton)
50 cm diameter / 948 *PMTs*	50cm diameter / 11146	50cm diameter / about 40000

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

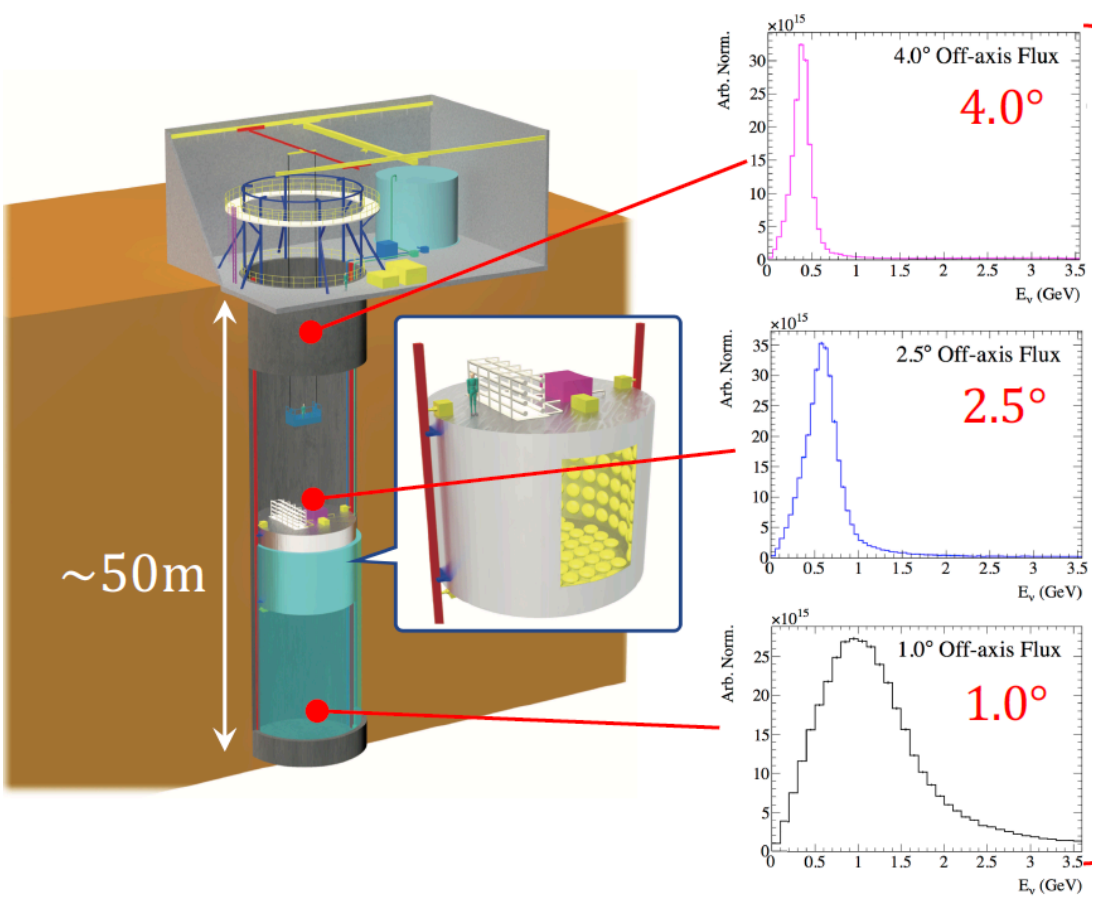
(..+ a lot of R&D towards near and far detectors underway; not covered here)

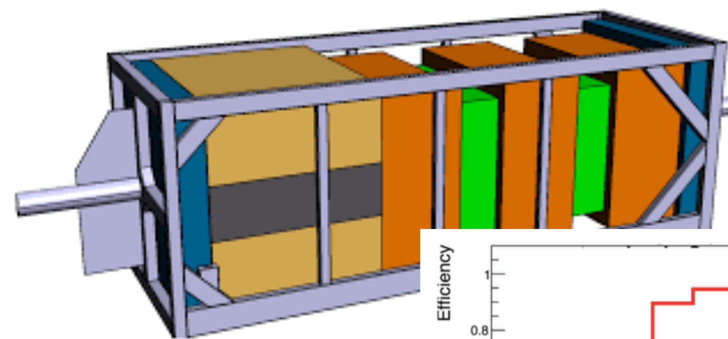
Intermediate Water Cherenkov Detector (IWCD)

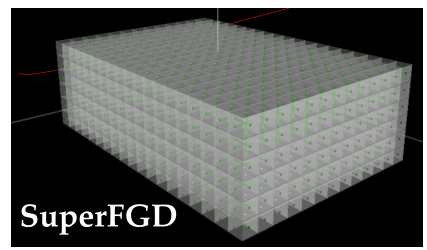
- 1 kton scale Water Cherenkov detector at ~1 km baseline
- Detector can vertically move for different off-axis angle measurements

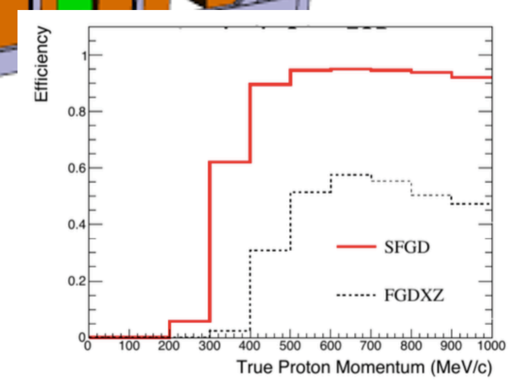
ND280 Upgrades

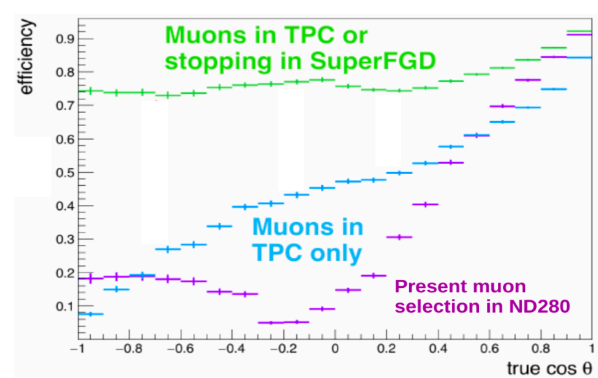
- T2K's near detector will be updated and used by Hyper-K
- Upgrade to SuperFGDs
- Improved short-track efficiency; high angle acceptance





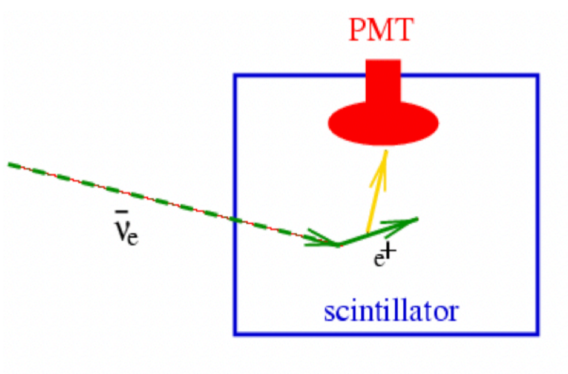






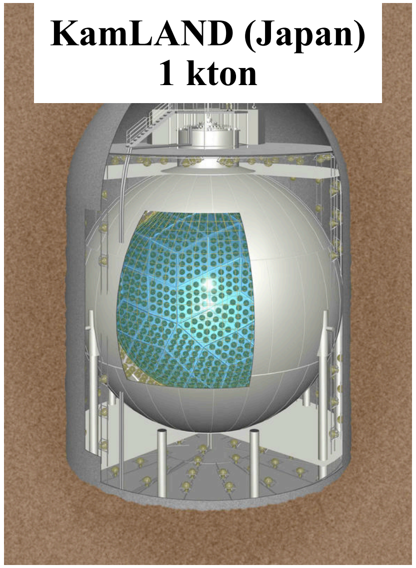
Scintillator Detectors

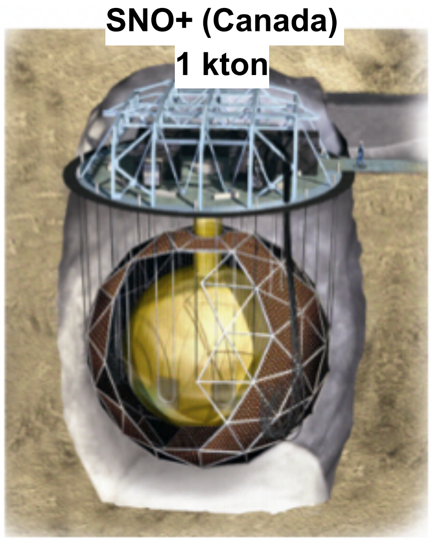
- Scintillators are materials that emit light when particles deposit energy
  - Light emission can be in visible spectrum or UV spectrum;
  - wave length shifting mechanisms typically used to shift light from e.g. VUV to visible
- Scintillators can be solid or liquid e.g. crystal, plastic, hydrocarbon
- 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

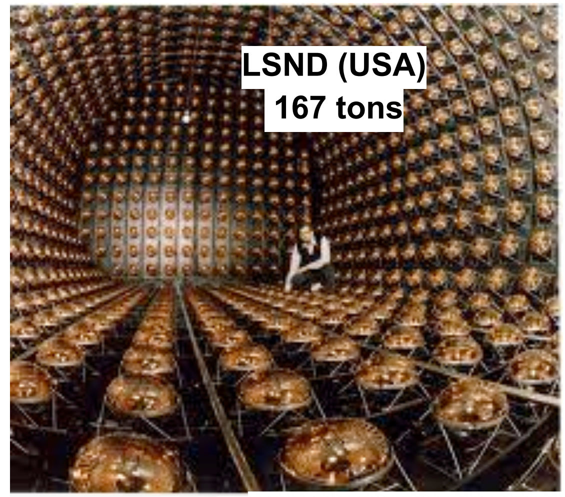


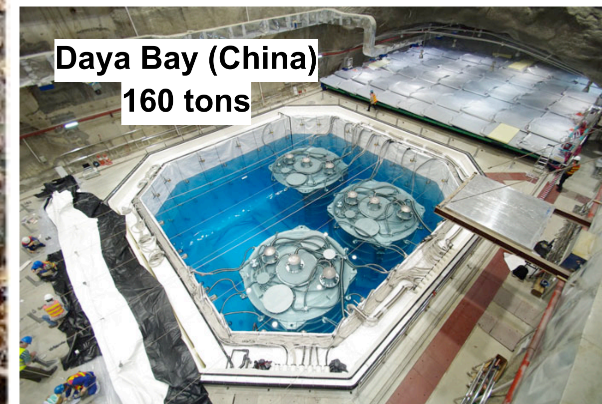
COHERENT-CAPTAIN Mills (CCM)
LANL; 10 tons of LAr
LAr Scintillation light detector;
no charge readout, only PMTs

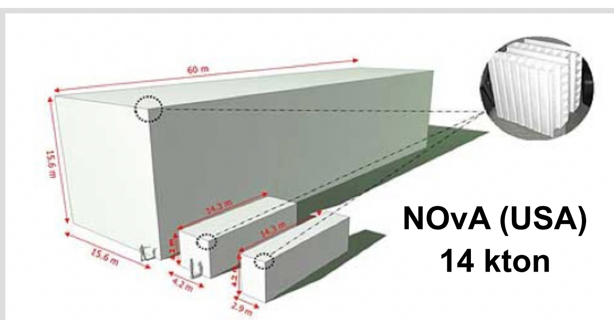
Scintillator Detectors: Past, Present & Future

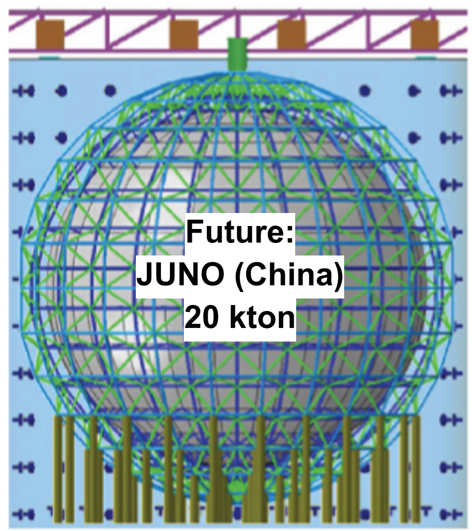


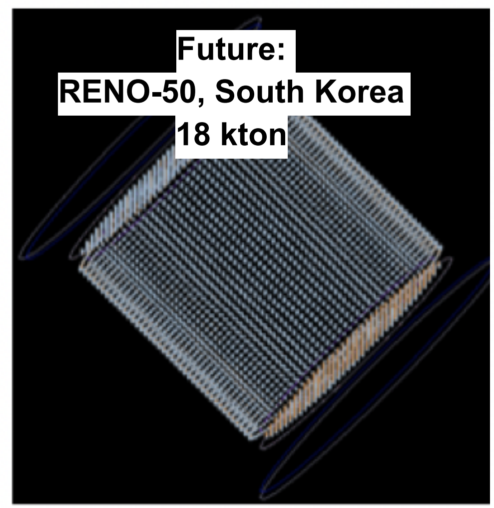


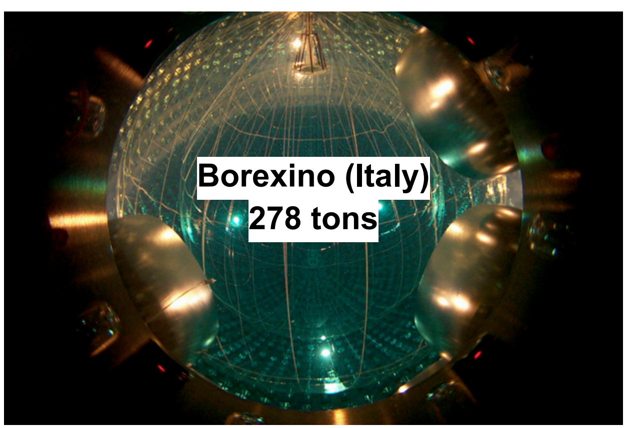






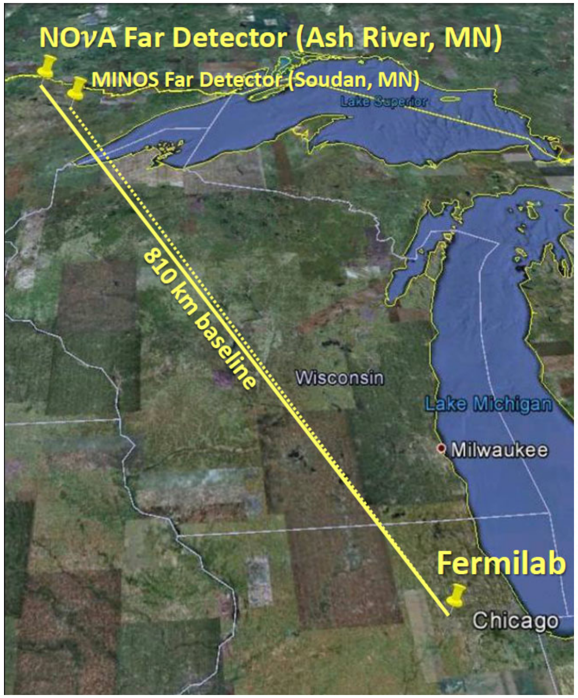


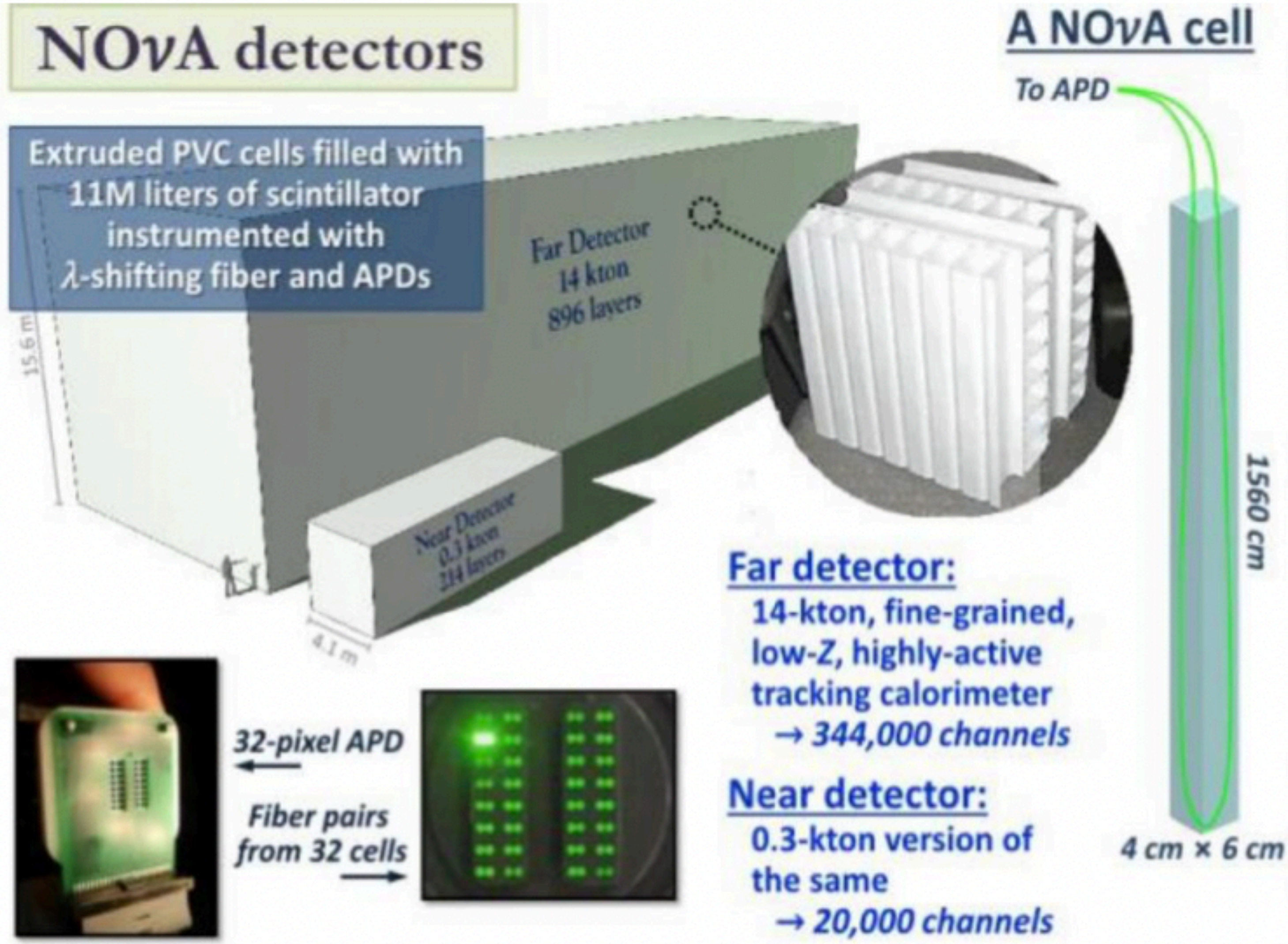




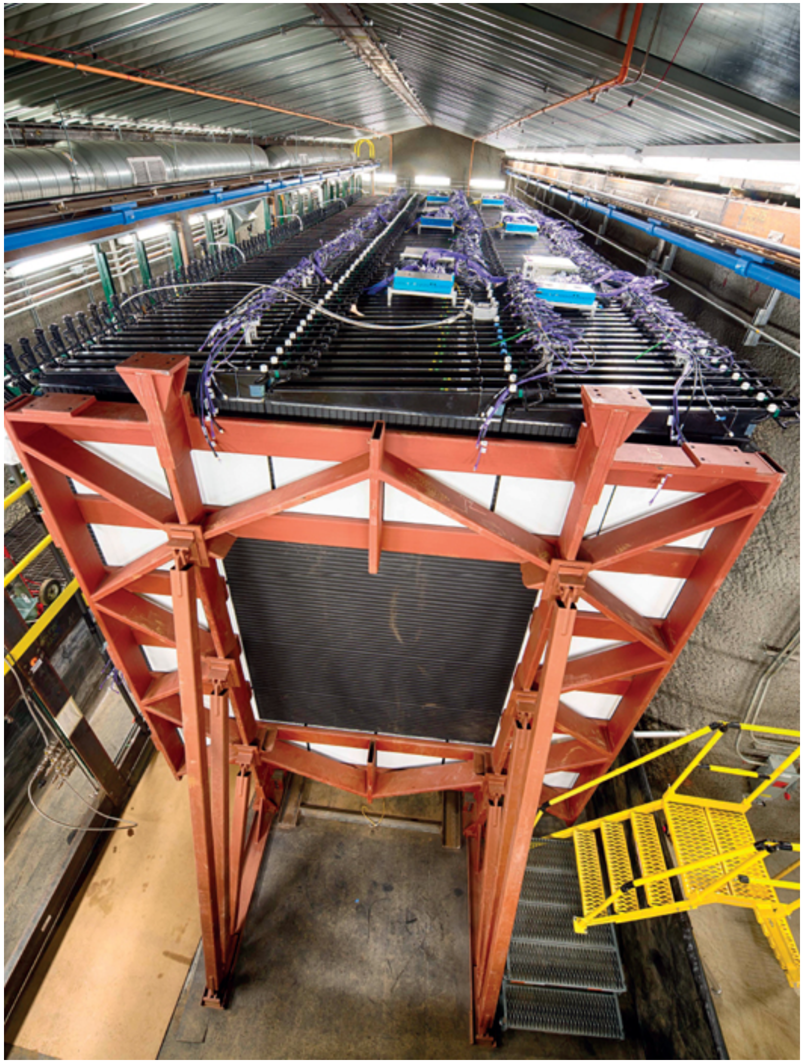
NOνA Detector

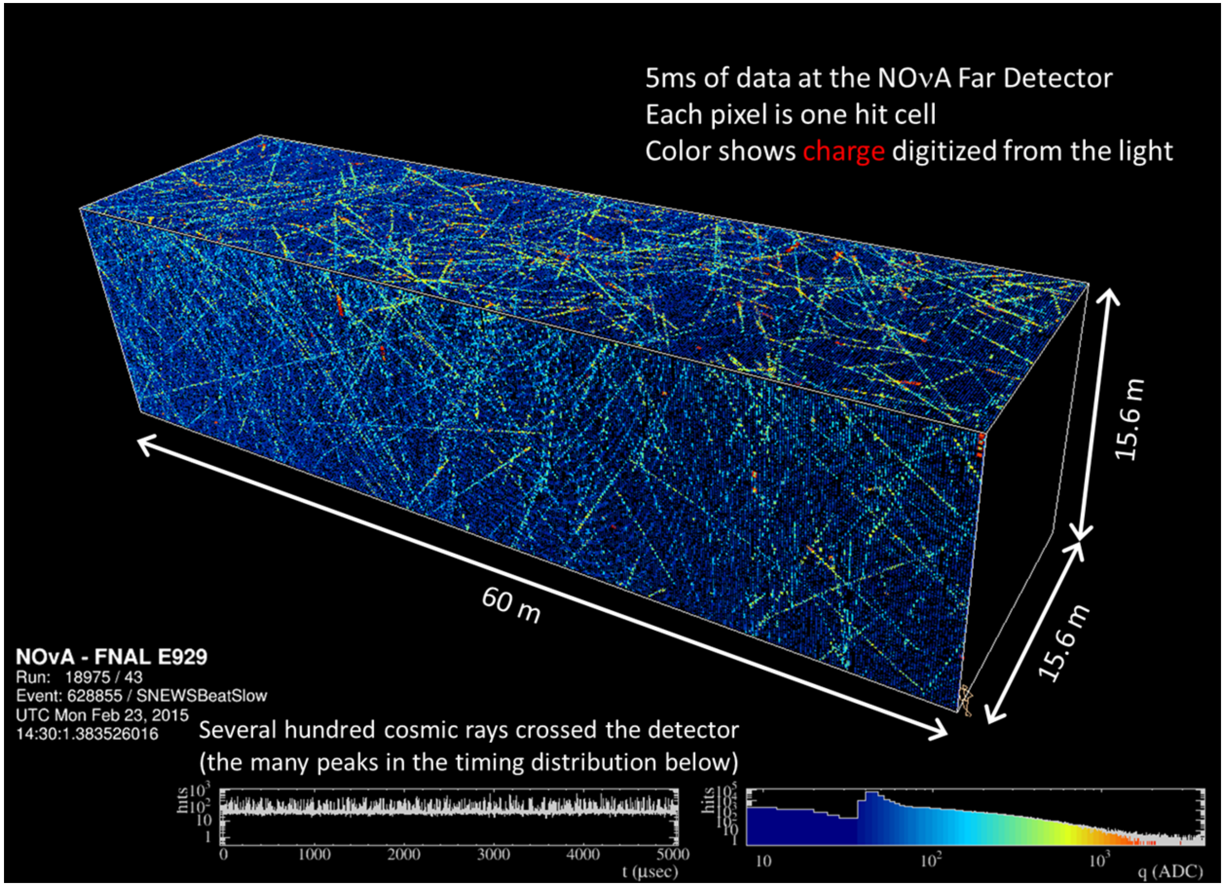
Long-Baseline Experiment





NOνA Detector





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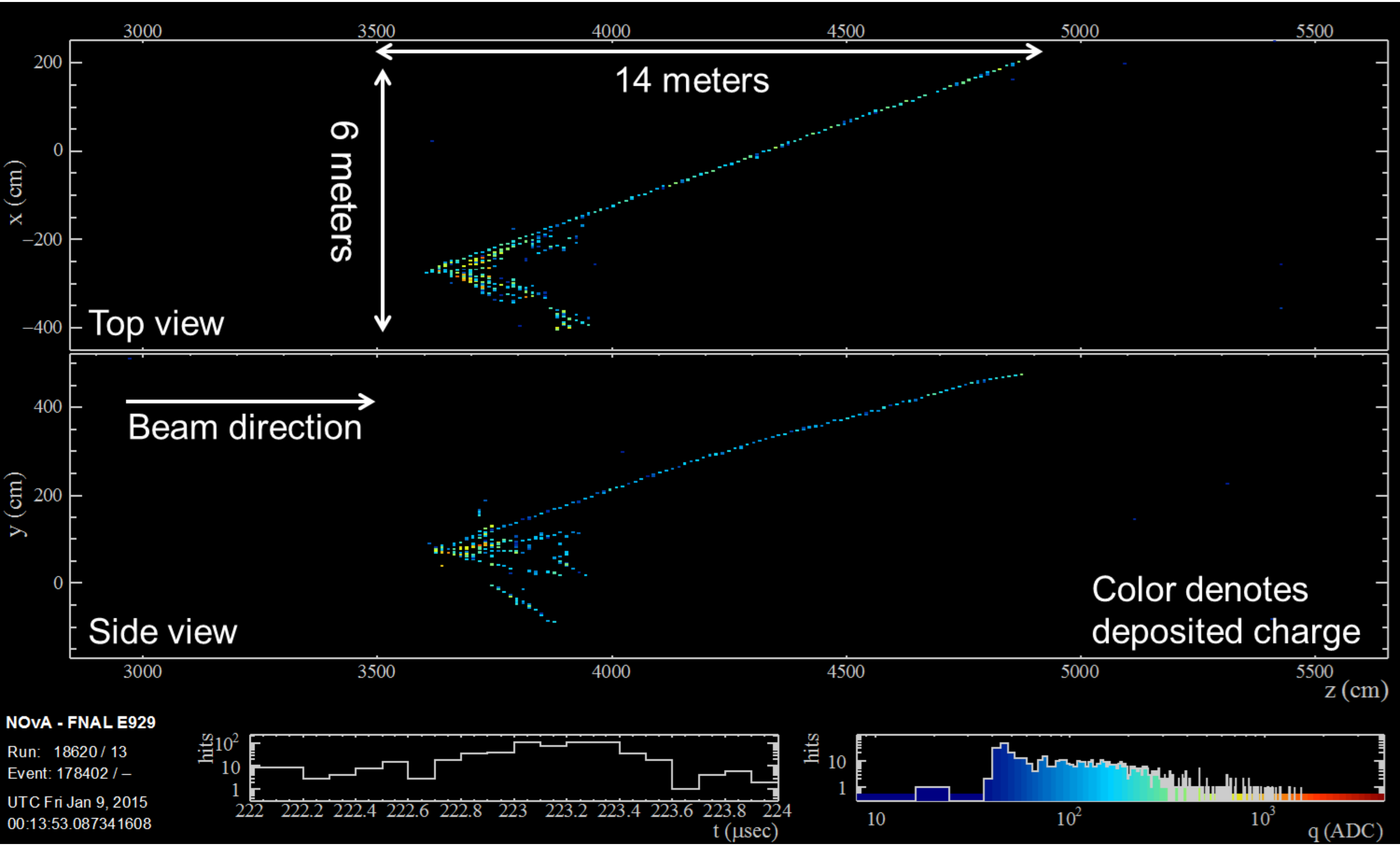

Noble Liquid Detectors

- 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*

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Focus on this

- **Neutrino Experiments**
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- Among other things, Noble liquid detectors provide precision signal detection (both charge and light), background rejection, and scalability

There is still a lot we don't know

Direct Mass Measurement Experi…

Short-Baseline Neutrino Experiments

New technology, high intensity beams, large volume detectors are needed for precision — this is where Liquid Argon Time Projection Chambers (LArTPCs) come in

LArTPCs are driving the future of neutrino physics!

Other BSM physics e.g. non-standard interactions

Short- and Long-Baseline…

…trino mass orderi…

- Is θ_{23} maximal mixing…
- CP violation in the ne… sector?

Long-Baseline Neutrino Oscillation Experiments

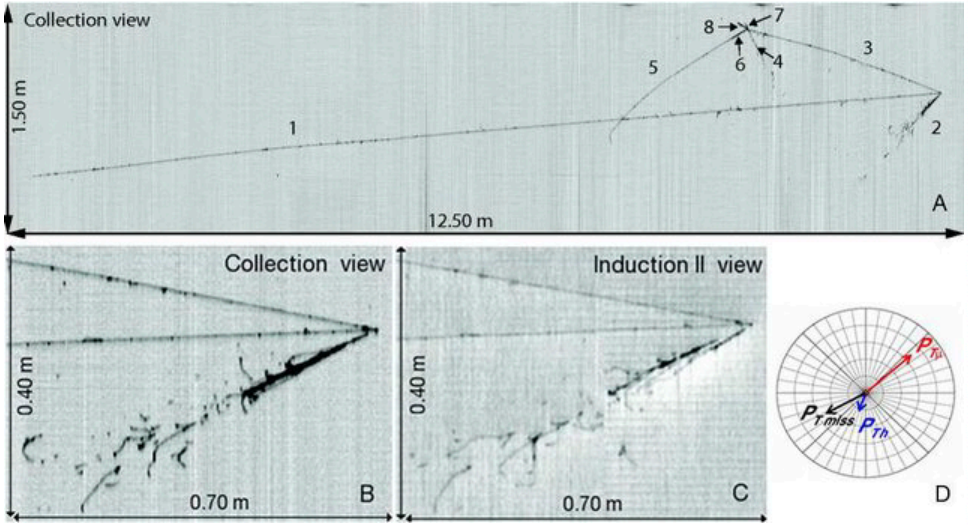
Benefits are enormous

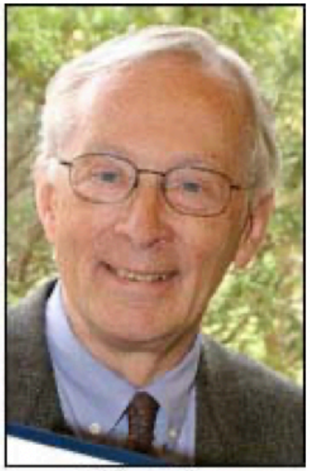
- Scalable to very large masses
- Bubble chamber quality images, only in HD! — presents interactions with unprecedented detail
- Full 3D reconstruction
- Full Calorimetry and particle ID
- Can operate on wide range of energies (MeV to GeV)

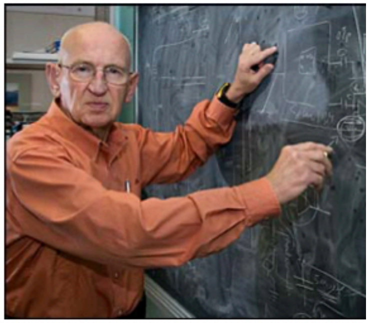
SM = Standard Model

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

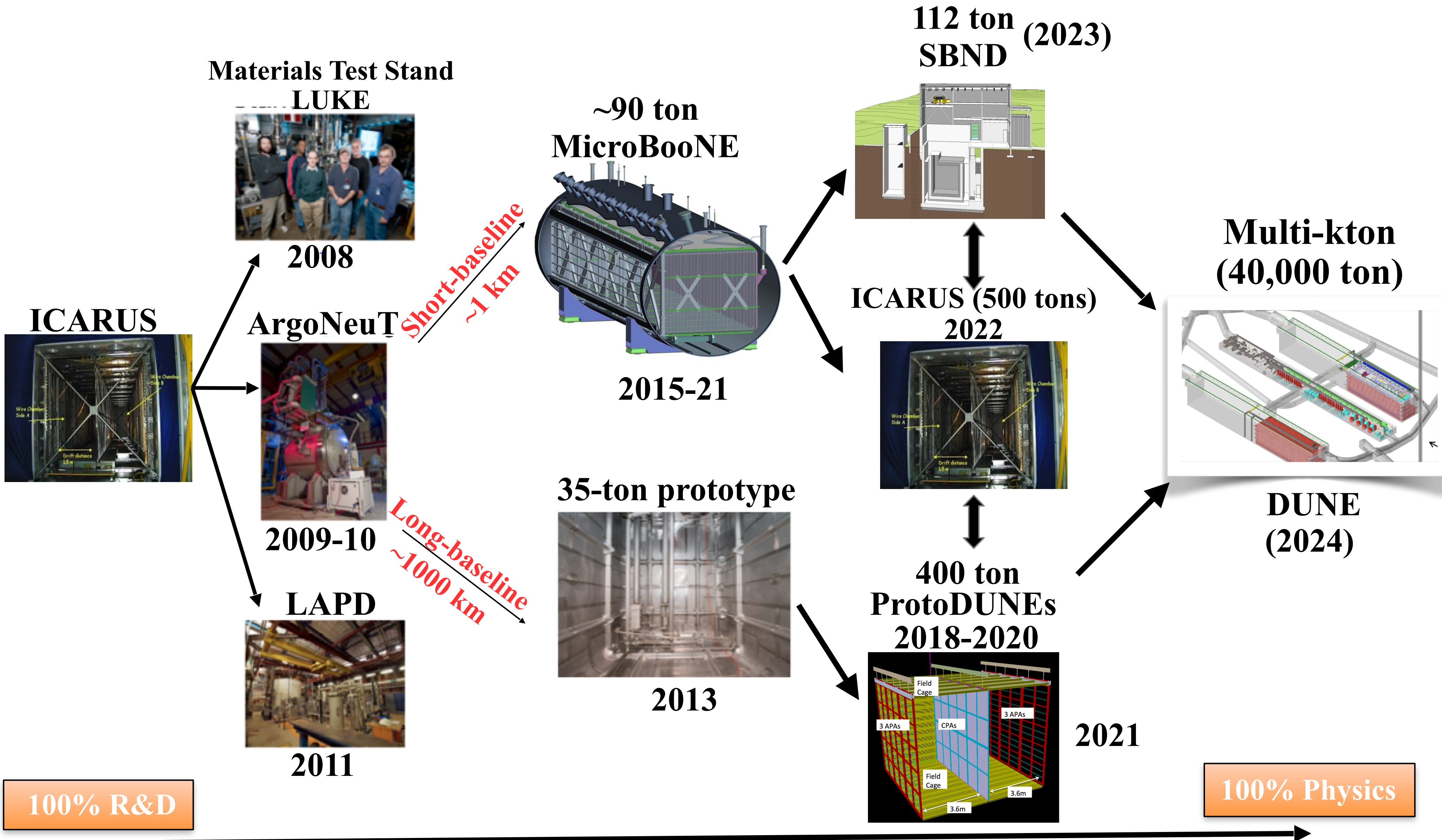

D. R. Nygren

H. H. Chen


C. Rubbia

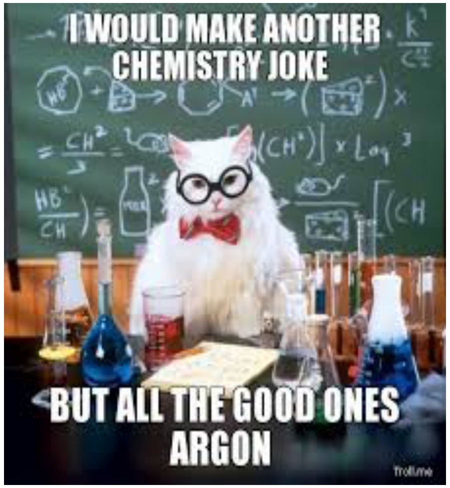
Tremendous progress in LArTPCs in the past few years

**active volumes listed*

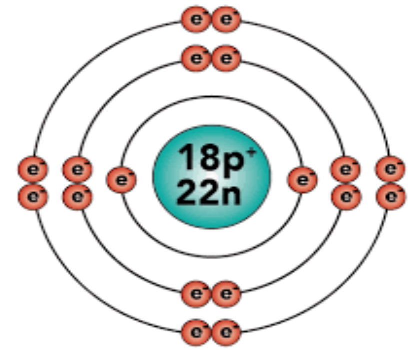


Other: *Yale TPC and Bo (2008-09), LArIAT (2015), (Mini) CAPTAIN, CCM (2019-now)*

Why Liquid Argon?



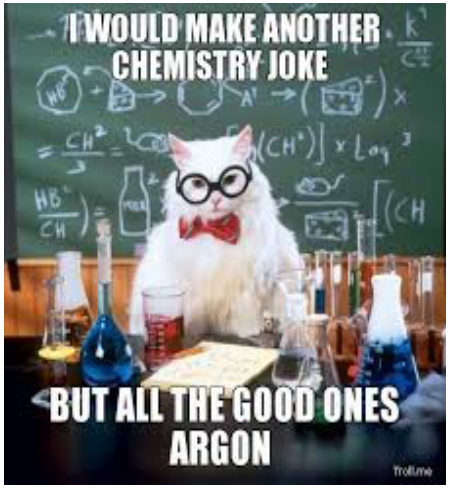
- dense
- abundant (1% of atmosphere)
- easily ionizable (55,000 electrons/cm)
- highly scintillating (transparent to light)
- pure argon results in high electron mobility implies long drift lengths



	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?



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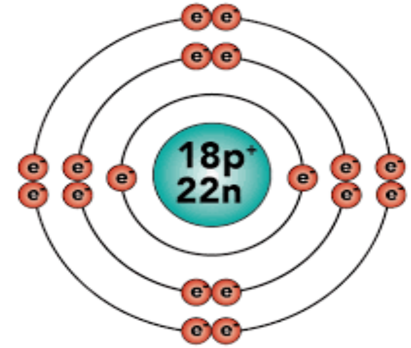


Cheap!

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	373
Density [g/cm³]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1
Radiation Length [cm]	755.2	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Scintillation [γ/MeV]	19,000	[illegible]	[illegible]	[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	

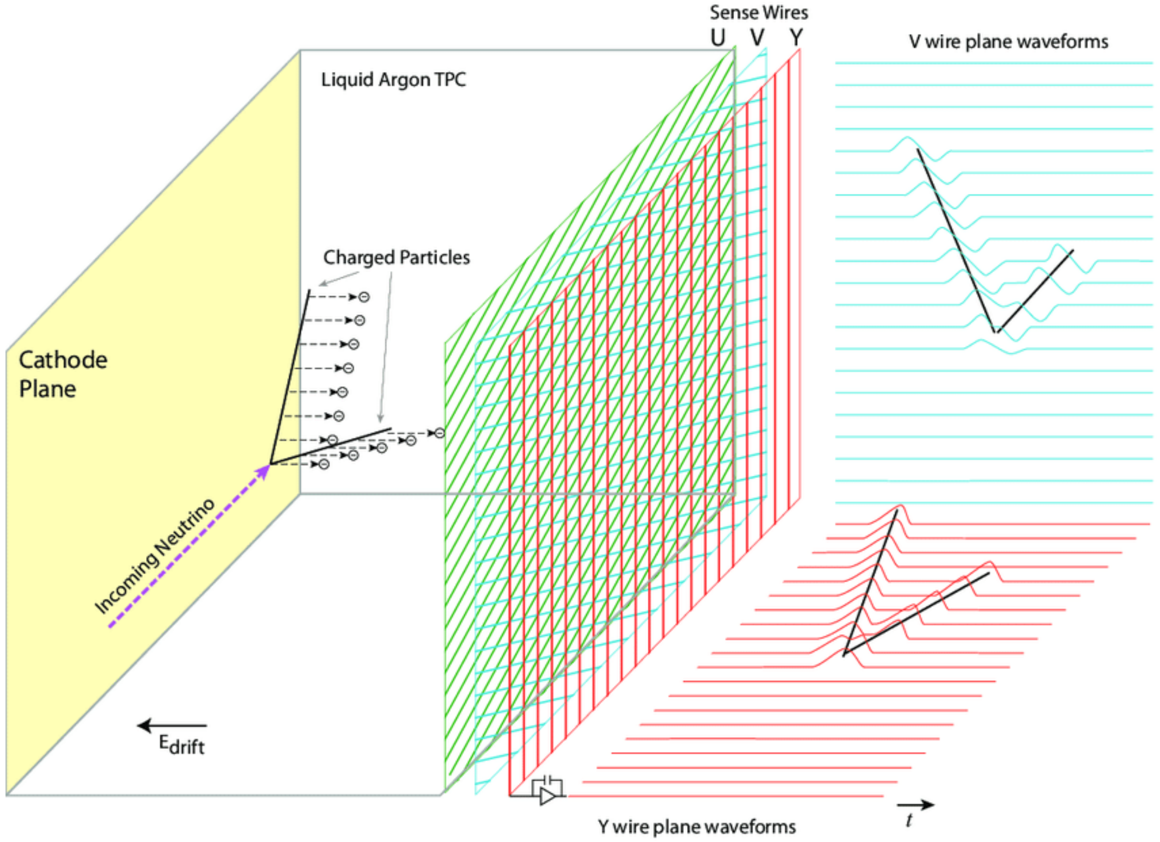
~$10/L (He) · ~$500/L (Ne) · ~$2/L (Ar) · ~$700/L (Kr) · ~$3000/L (Xe)

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

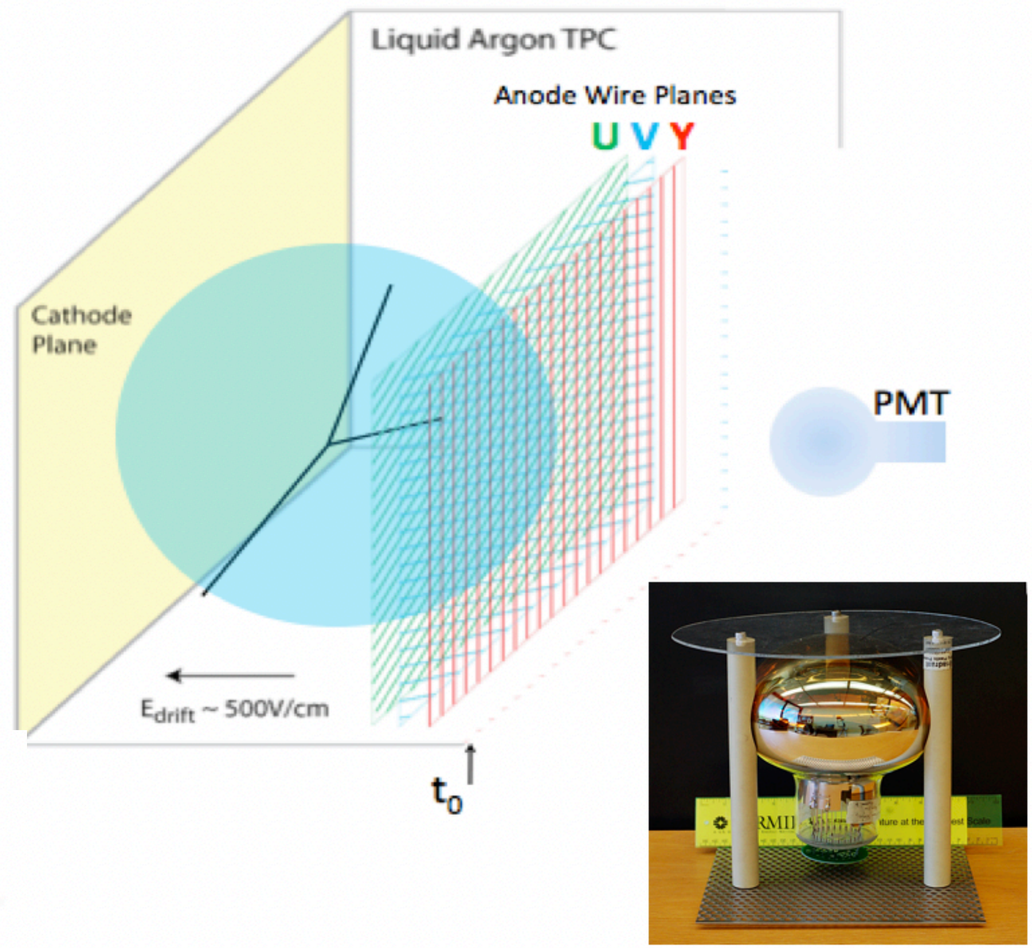


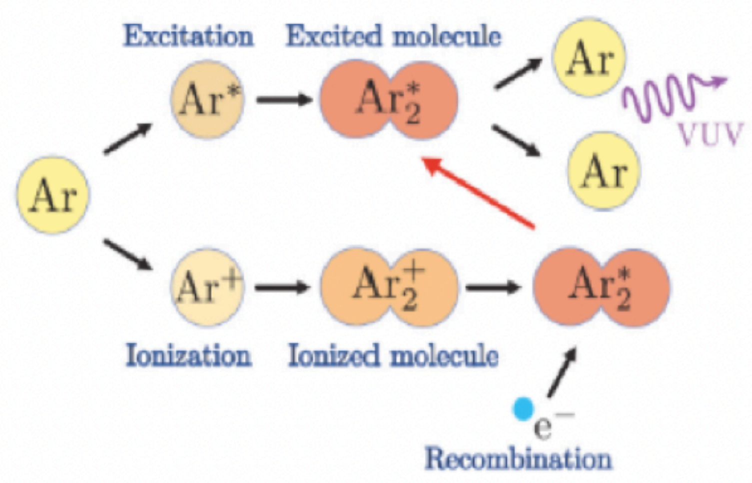
No need to instrument the entire detector volume = scalable to large sizes without increasing cost and complexity

How does a LArTPC work?

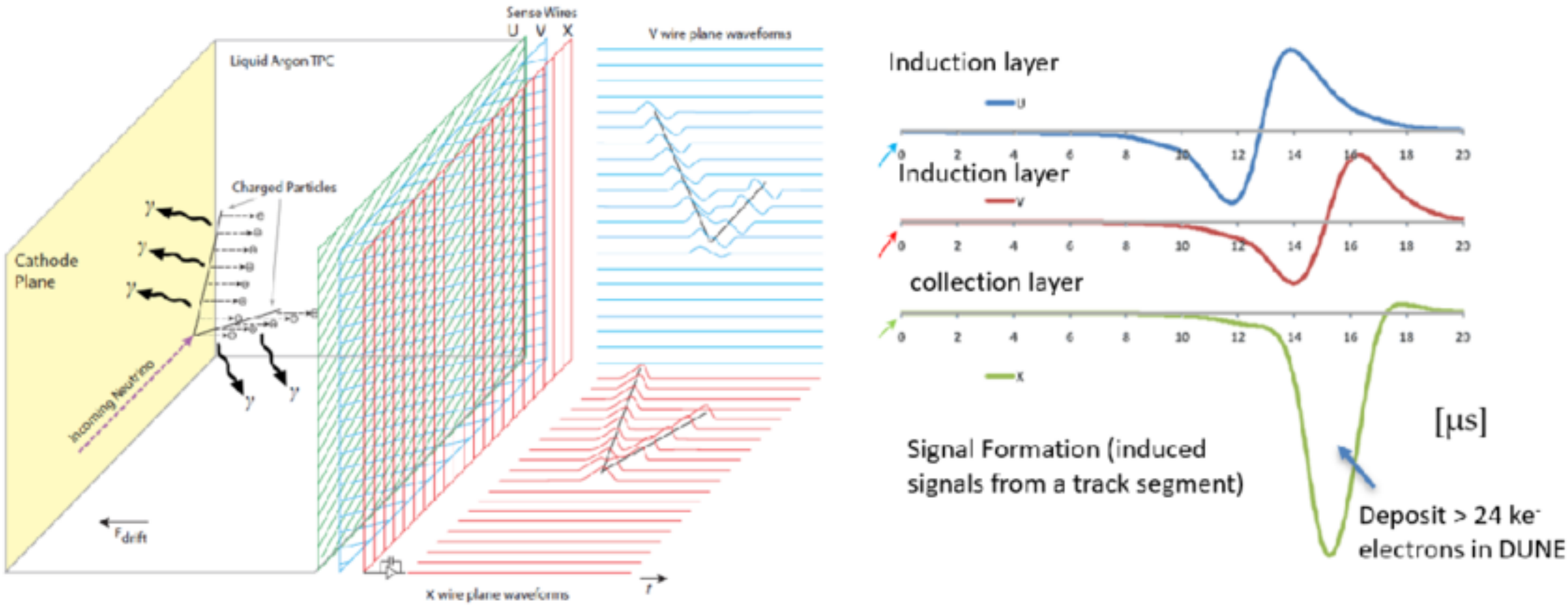
Light Signals

- 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



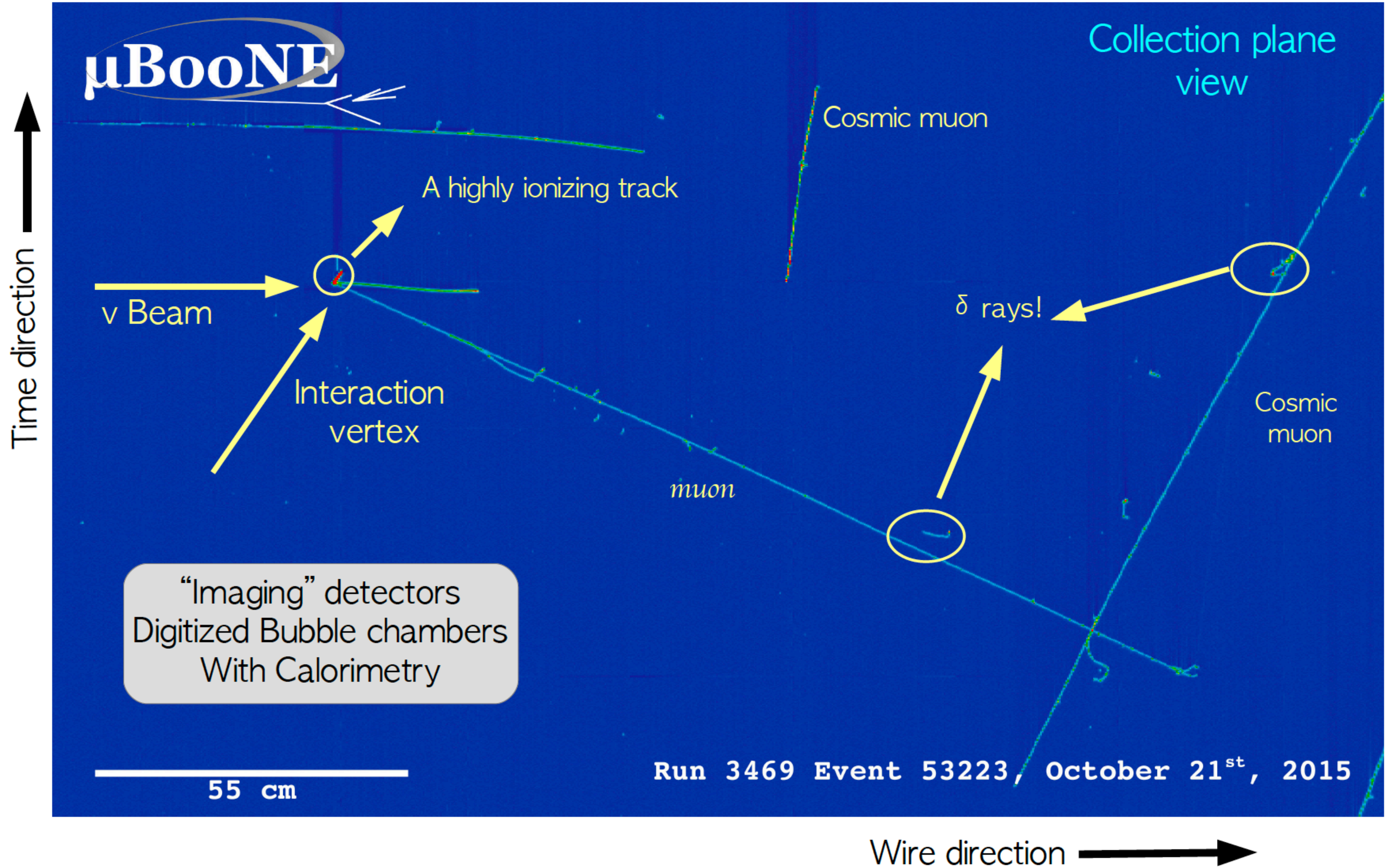


How does a LArTPC work?

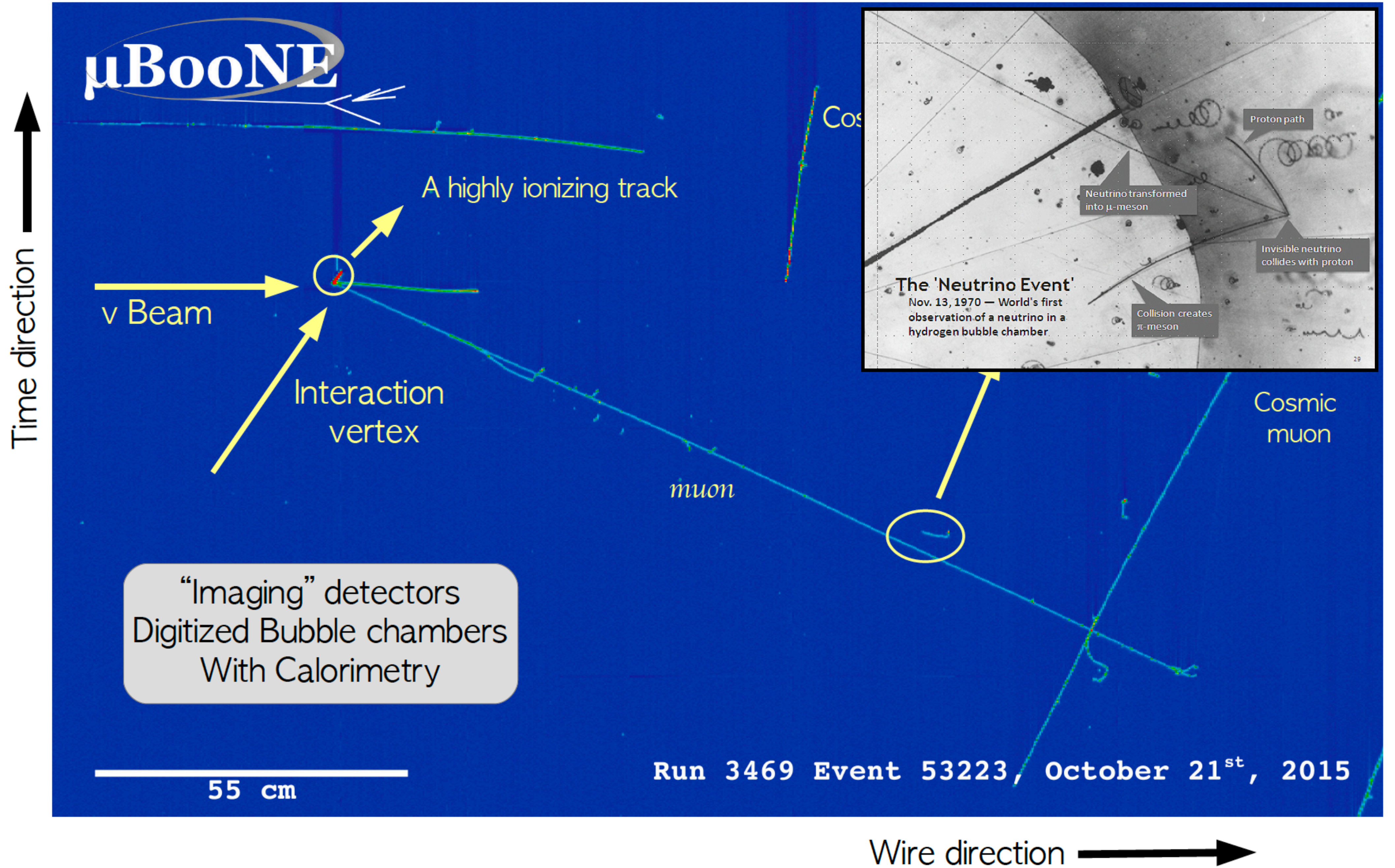


- Wire planes give 2D position information
- The third dimension is obtained by combining timing information with drift velocity (v_d): $x = v_d(t-t_0)$ hence the name "Time projection chamber"
- **Wire planes + signal arrival time = 3D image**

Neutrino Interactions in HD

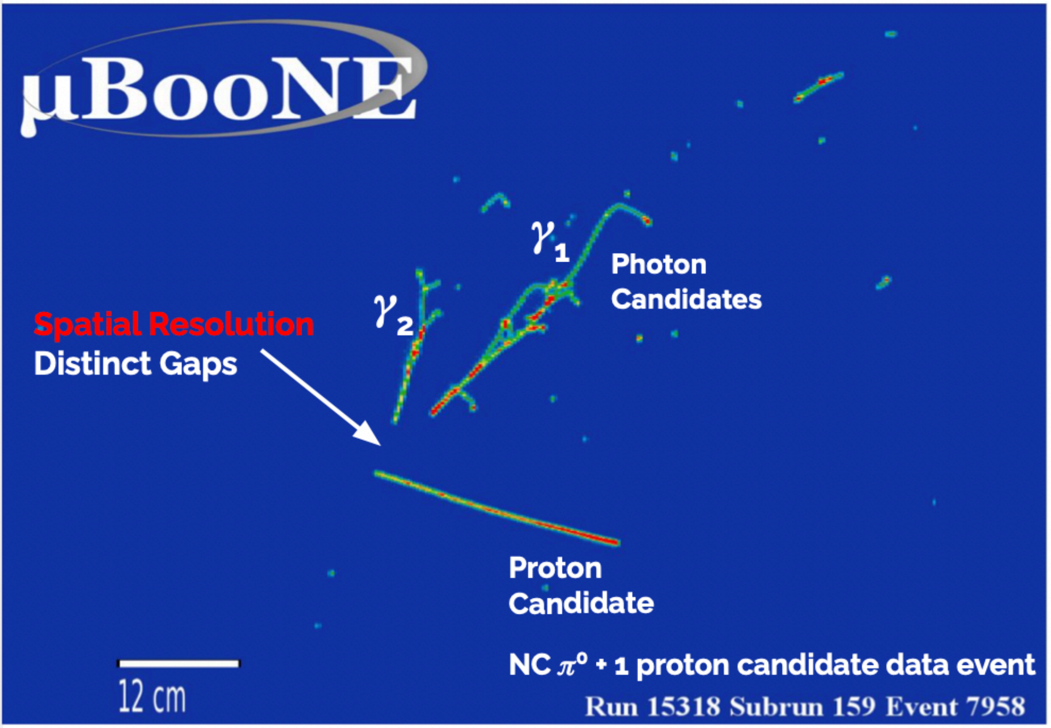


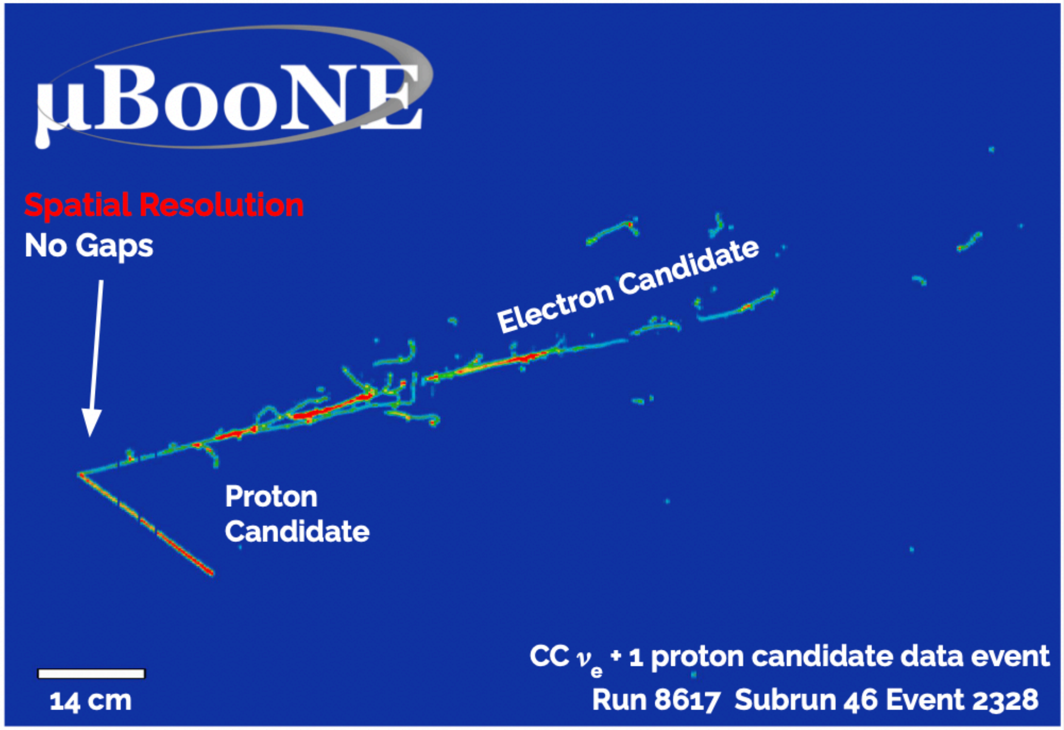
Neutrino Interactions in HD

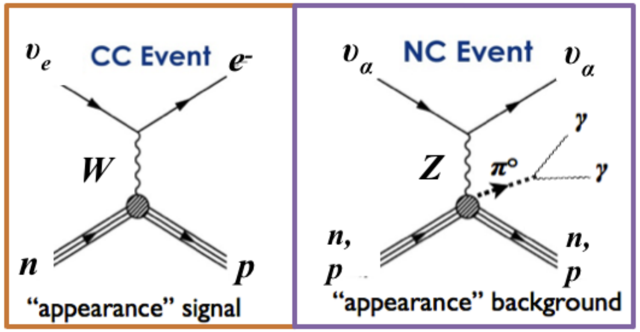


e/γ separation: Benefits of a LArTPC

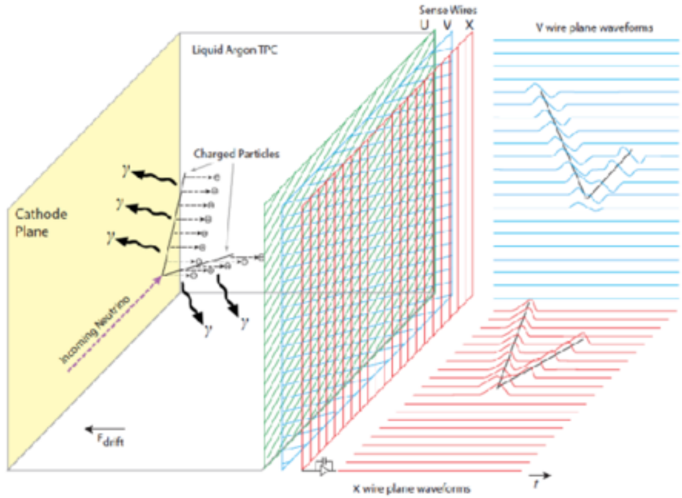
- For ongoing and future oscillation experiments , e/γ separation is critical
- Combining topology and charge information gives excellent separation

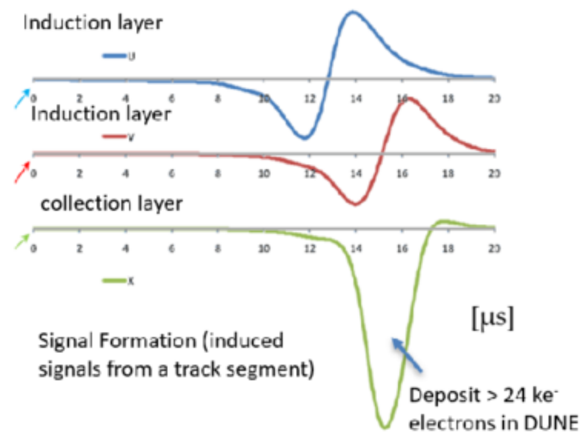




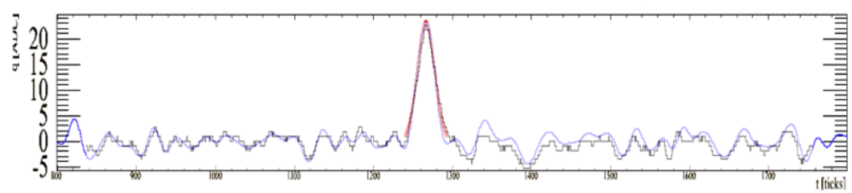


Energy Reconstruction in a LArTPC





TPC wire signal: “Hit”



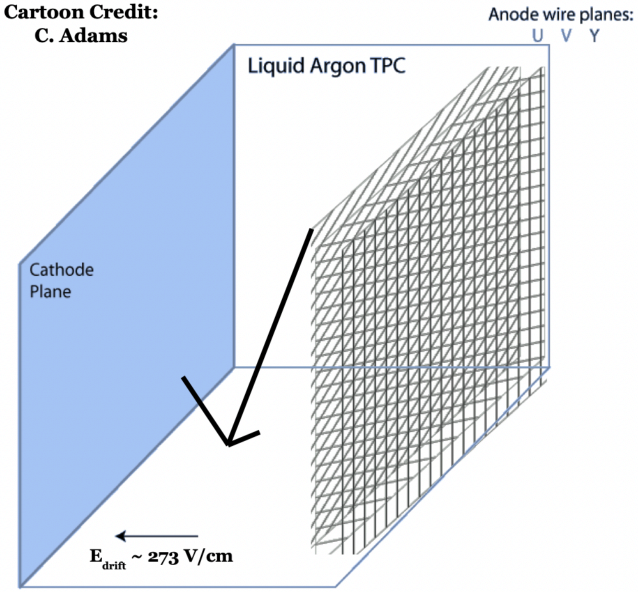
- Hit coordinates (*wire#* and t_{hit}) ⇒ **3D image**
- Hit Amplitude ⇒ **dQ (**Ionization Charge Deposited)
- Distance in space between hits ⇒ **dx** (track pitch)
- dQ/dx ⇒ dE/dx ⇒ **Particle Id**
- **Calorimetry**

$$\int_l \frac{dE}{dx}\, dx = E_{Tot}$$

Not as Easy as it Sounds

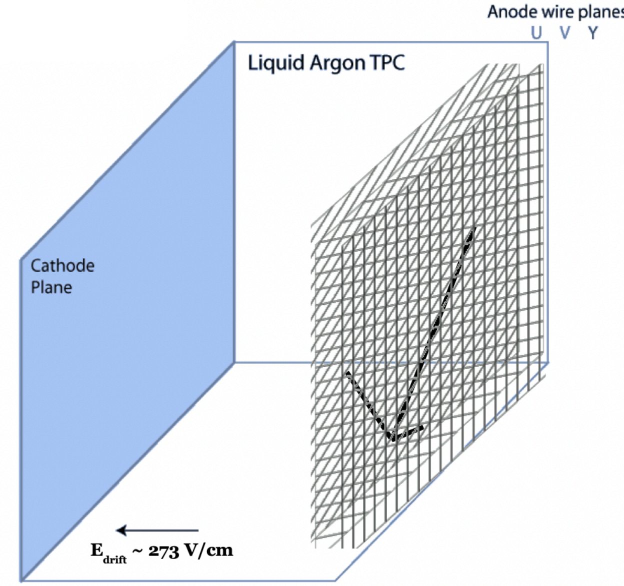
Point of Formation

Cartoon Credit: C. Adams



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

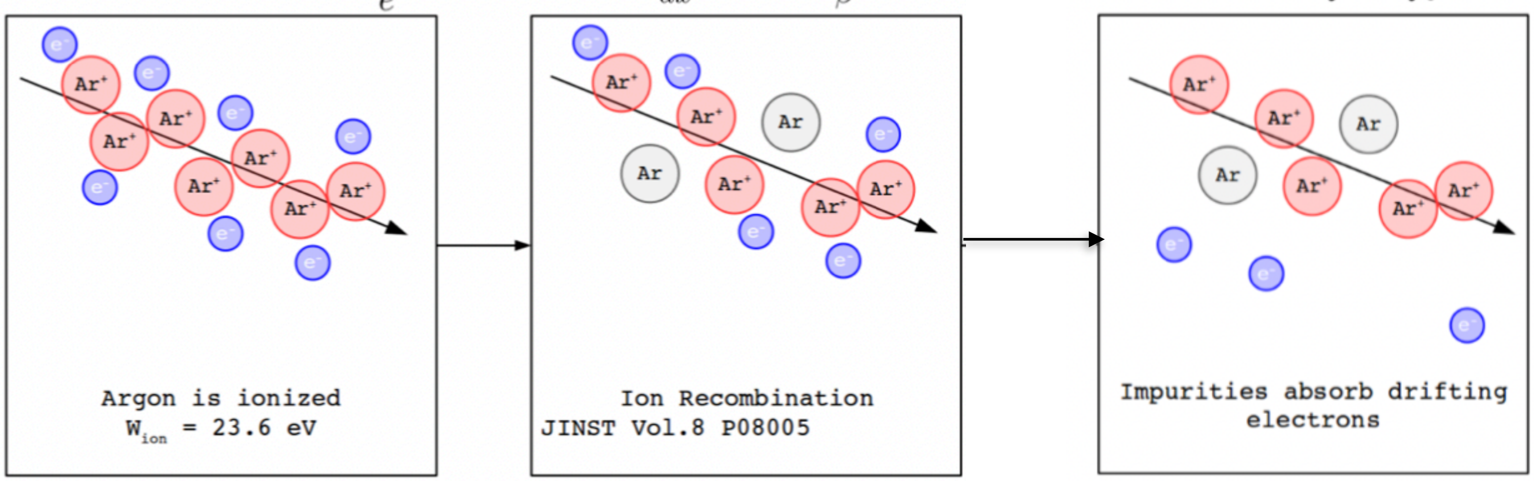
Point of Collection



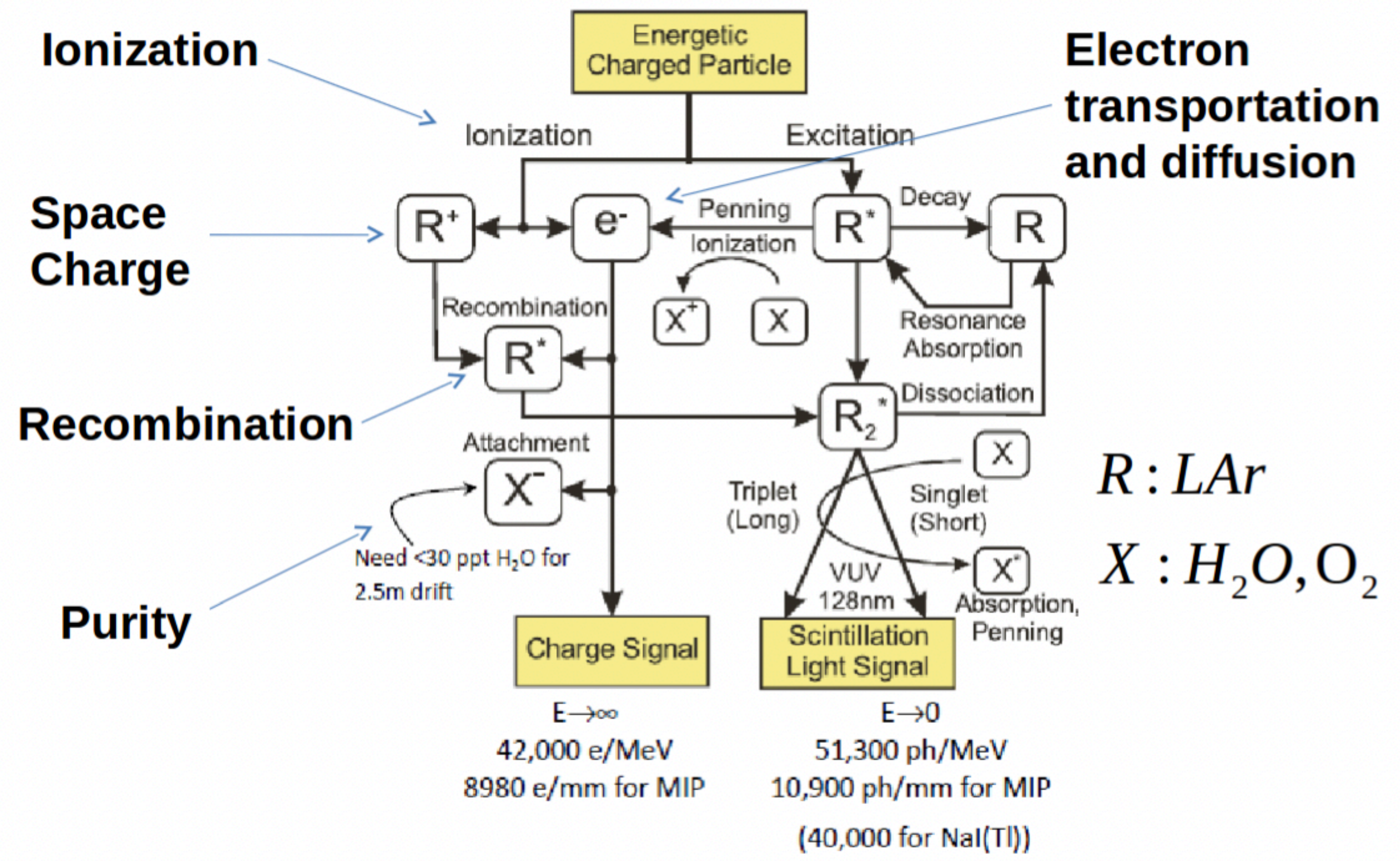
$$dQ = dE \times \frac{W_{ion}}{e^-}$$

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

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



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

How to Achieve Purity?

- Nitrogen to less than 1 **ppm** level for light collection (provided by the manufacturer) — so scintillation light is not quenched
- Water and Oxygen contaminants to $<$ 50 **ppt** for a 2.5 m drift

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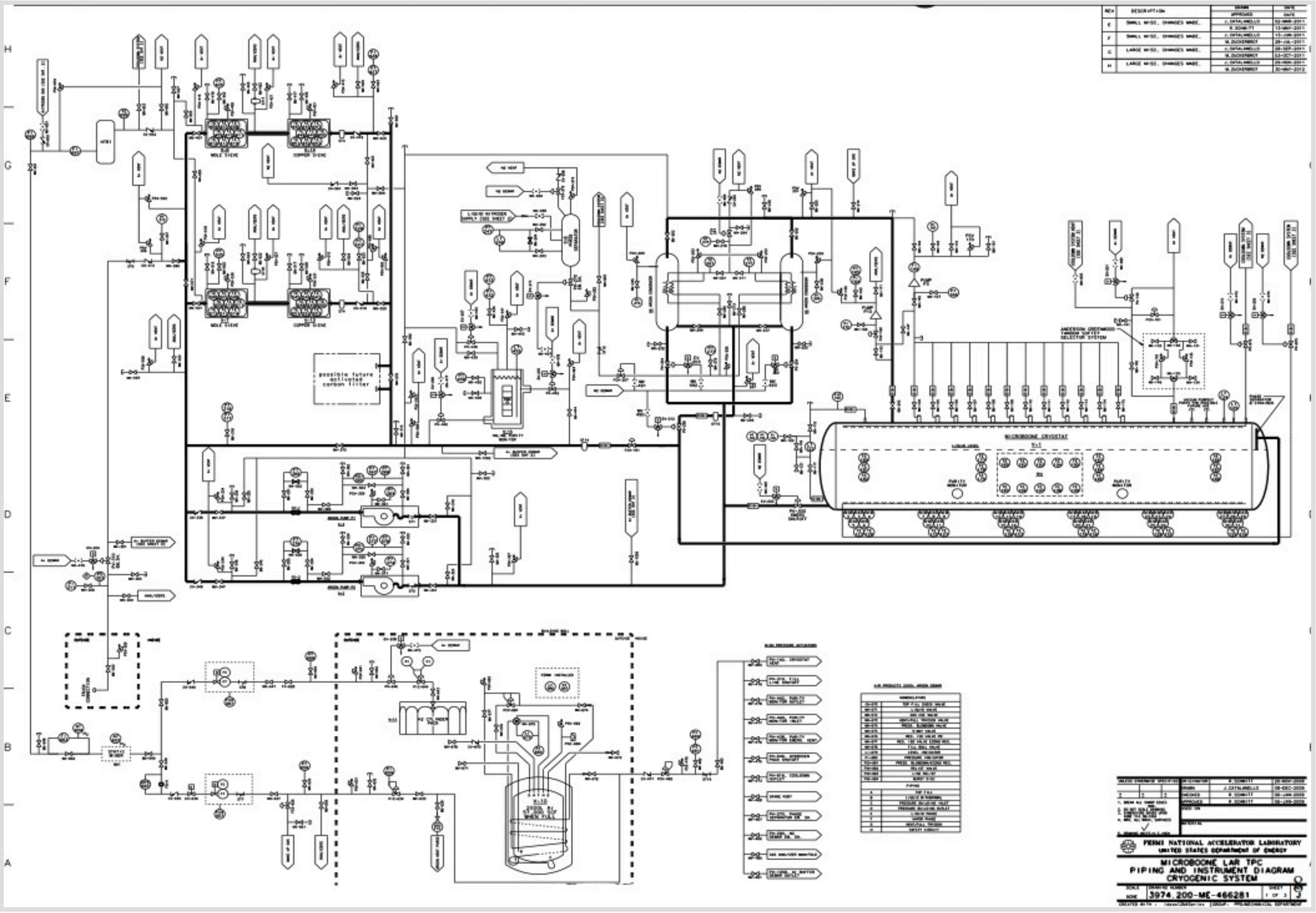

MicroBooNE Purification & Recirculation system

How to Achieve Purity?

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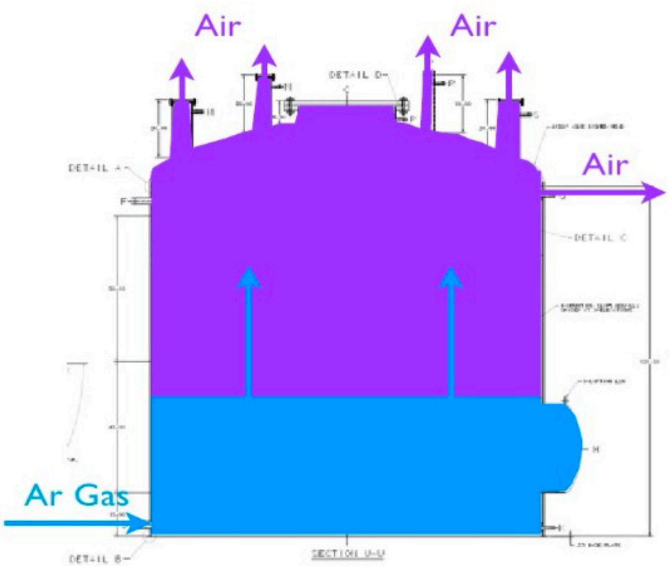
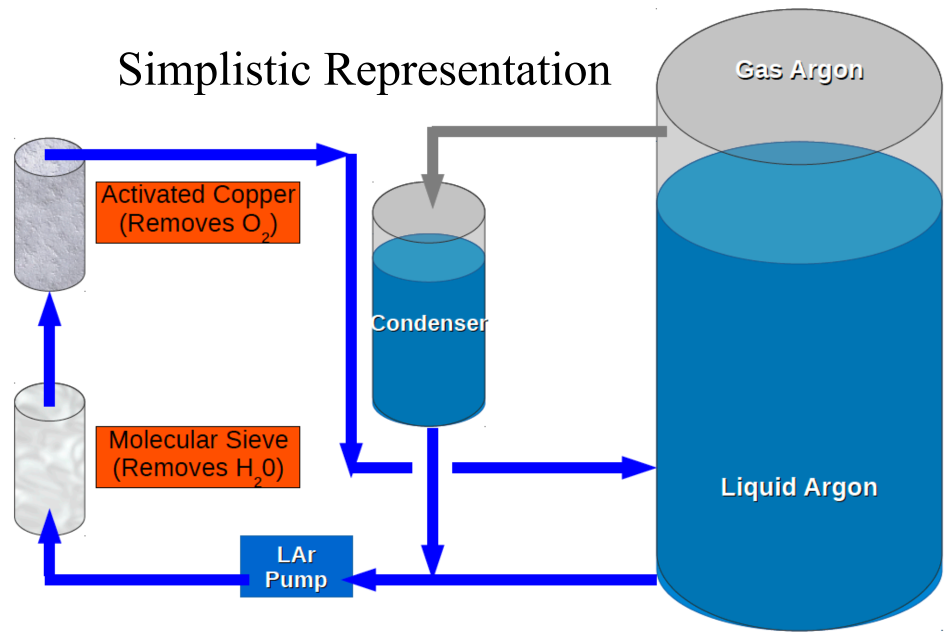
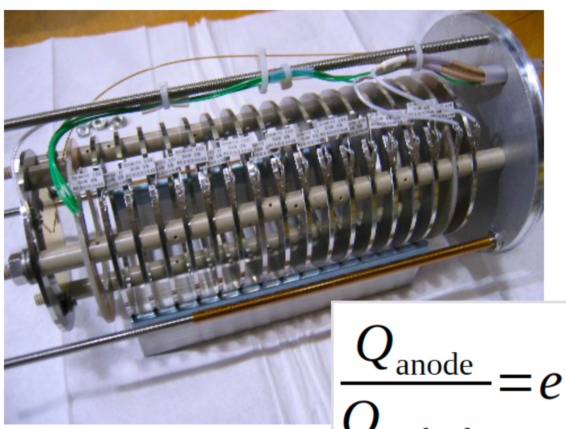


Simplistic Representation



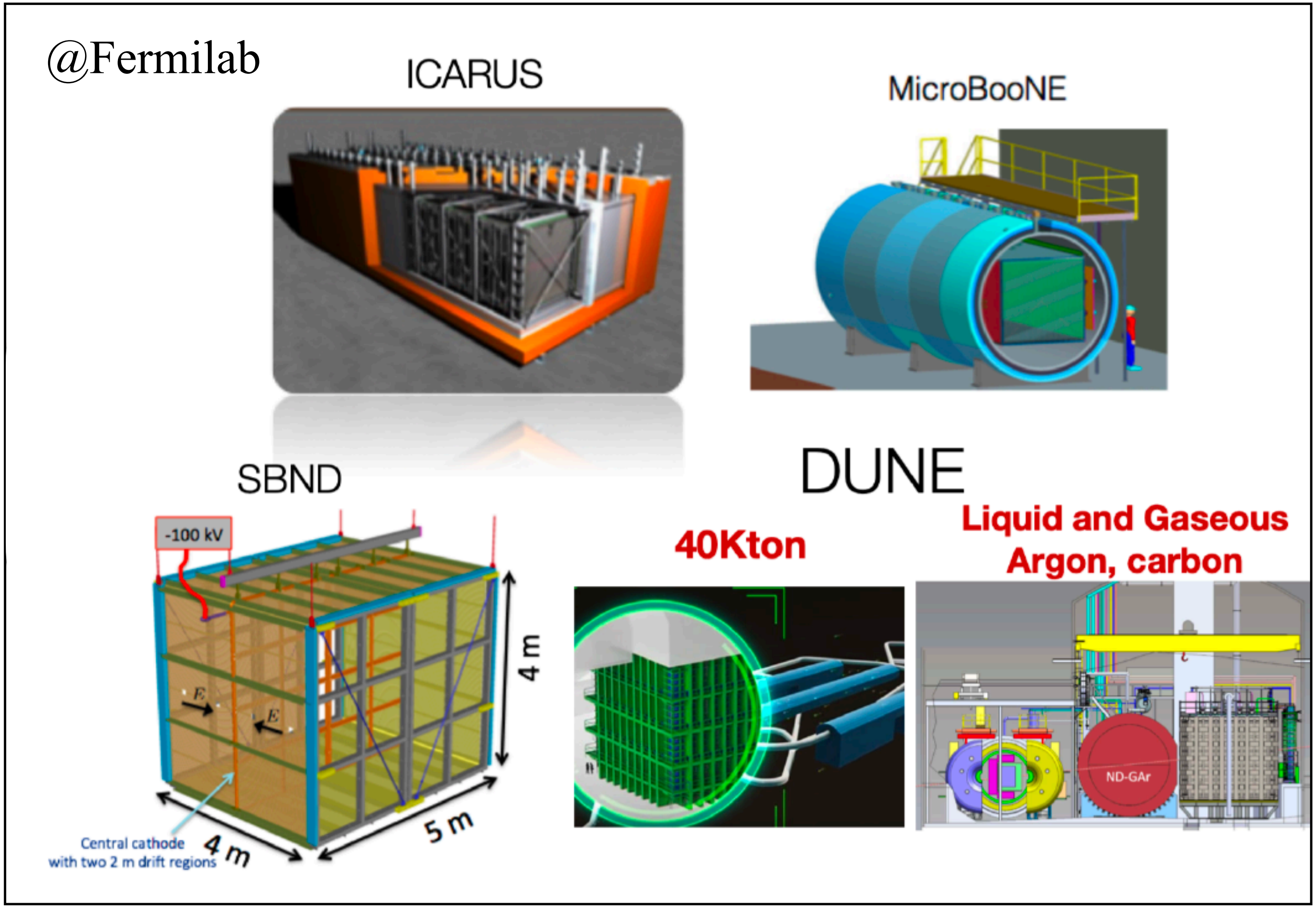
- Argon Purge for large cryostats — pioneered by MicroBooNE
- Vacuum evacuation for small cryostats



$$\frac{Q_{\text{anode}}}{Q_{\text{cathode}}} = e^{\frac{-t_{\text{drift}}}{\tau_e}}$$

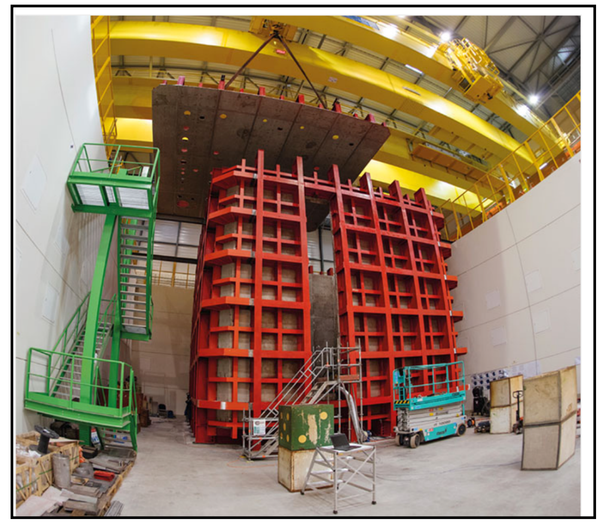
- Monitor purity via various ways
  - Purity Monitors (mini TPCs)
  - Cosmic ray muons

Liquid Argon Detectors (Current & Future)



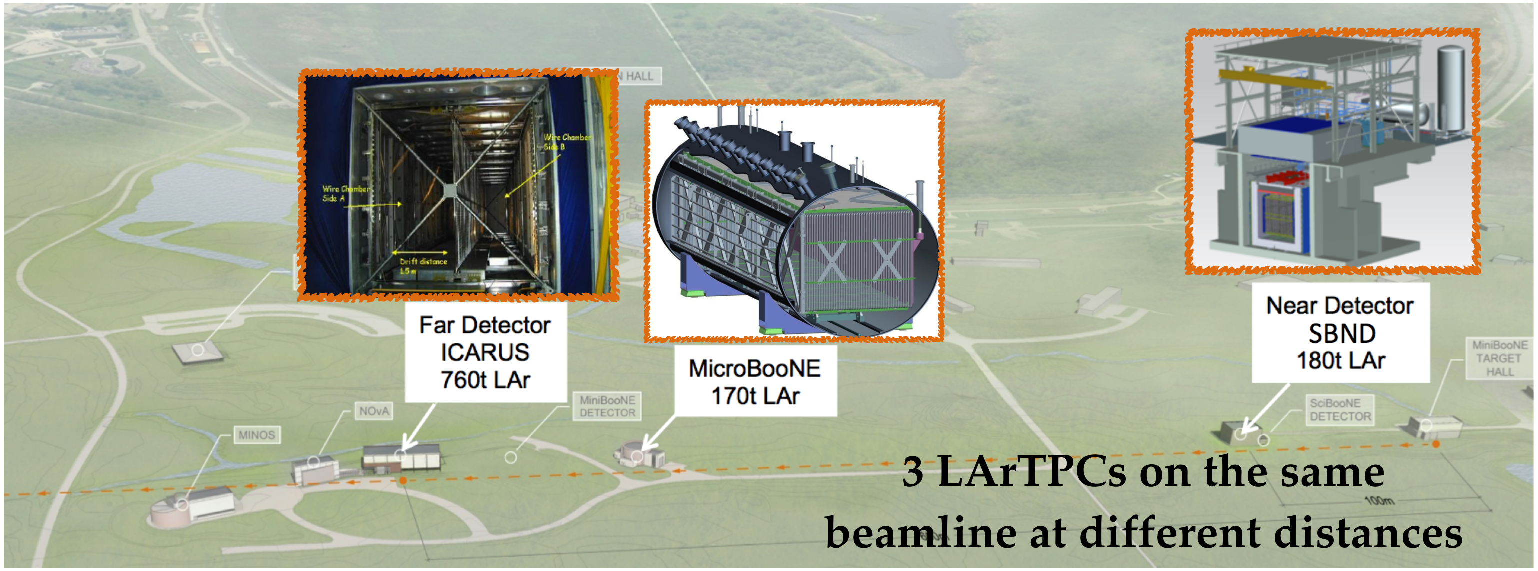
CCM@LANL

ProtoDUNE@CERN



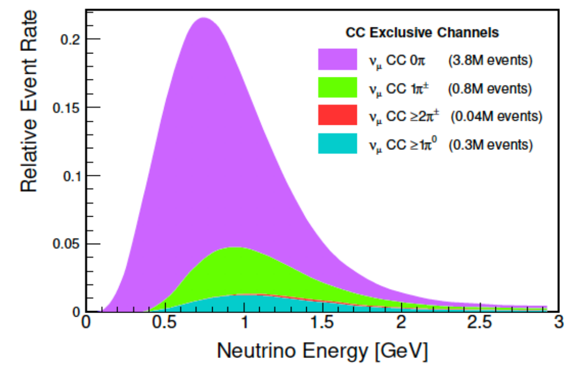
- CCM is both a Dark Matter and Neutrino Experiment at the Los Alamos Neutron Science Center and is a 10-ton light-only detector
- **I will highlight the DUNE experiment**

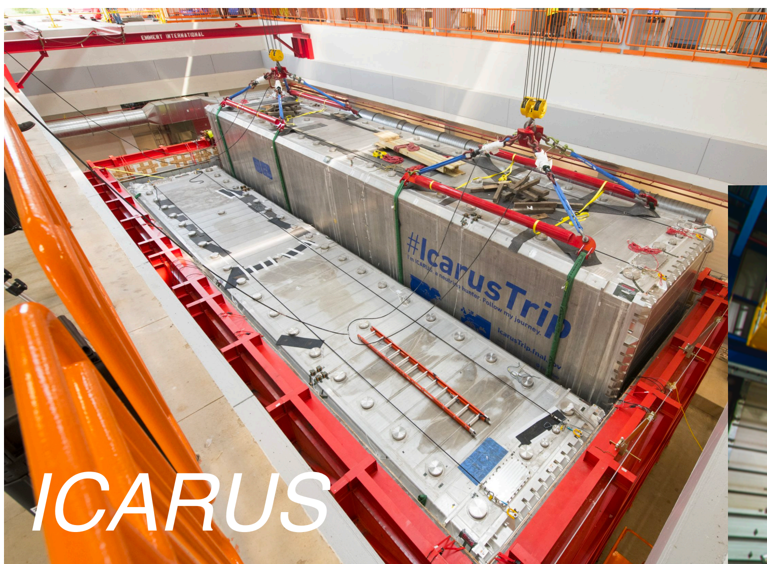
Fermilab Short-Baseline Program

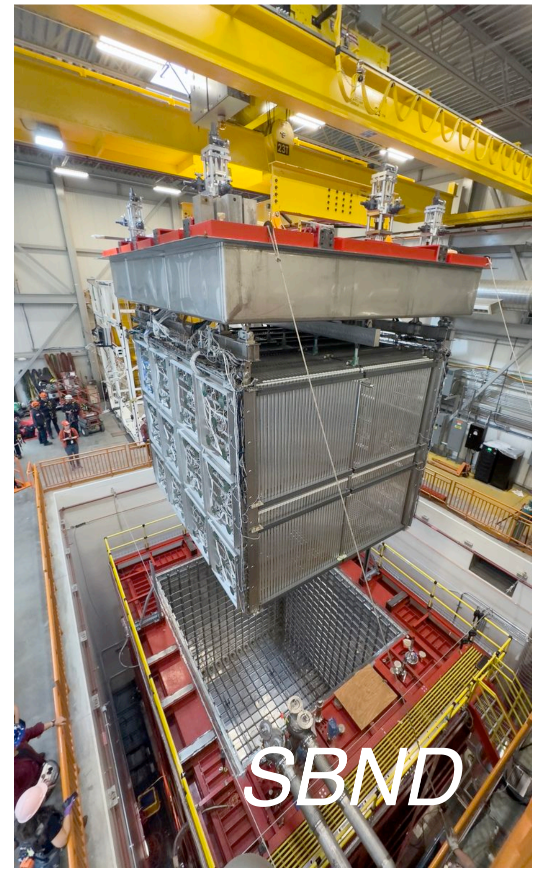


3 LArTPCs on the same beamline at different distances

SBND will have world's highest statistics on argon

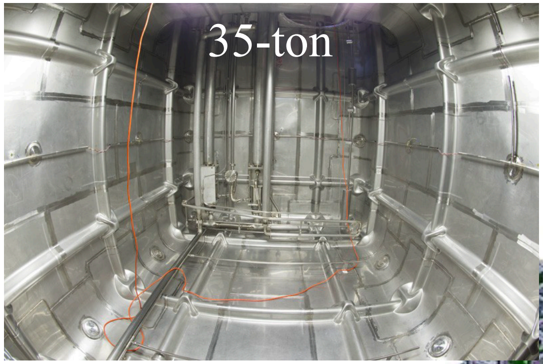


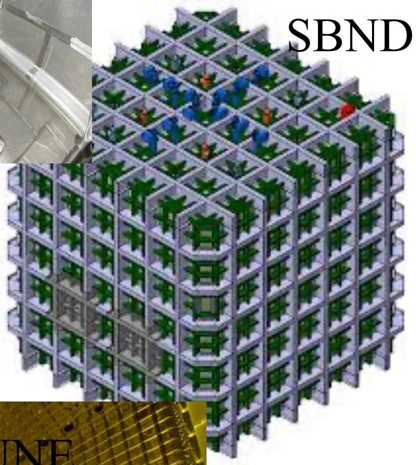


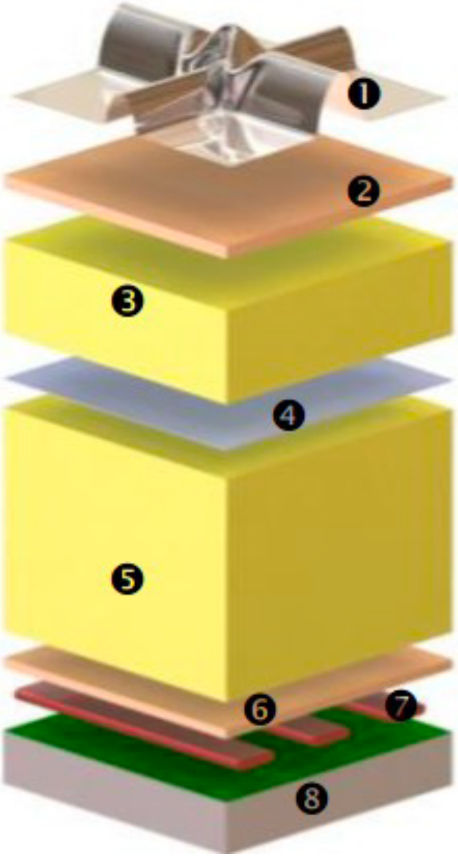


LArTPC Cryostat Technologies

- **MicroBooNE, ICARUS:** steel vessels
- **35-ton, SBND, ProtoDUNE/DUNE:** membrane cryostats





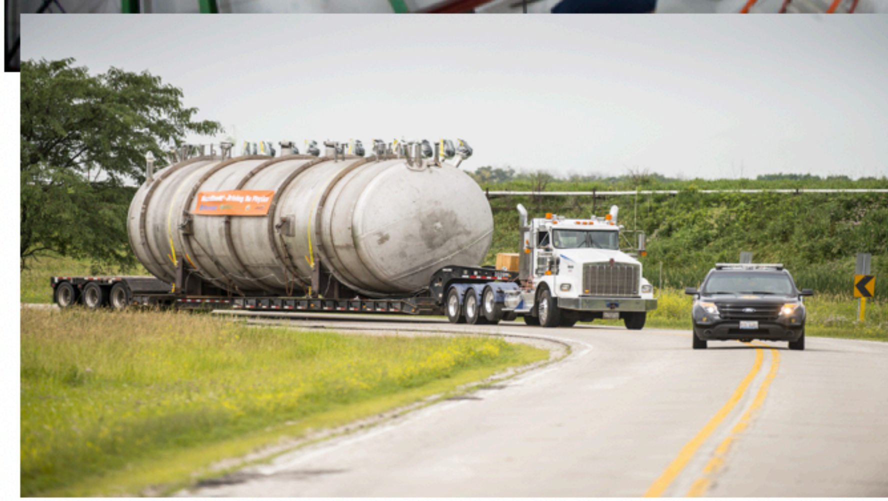


Membrane Cryostat:
Technology borrowed from industry used for liquid natural gas (LNG) shipping

1) Stainless steel primary membrane (LAr inside here)
2) Plywood board
3) Polyurethane foam
4) Secondary barrier
5) Polyurethane foam
6) Plywood board
7) Bearing mastic
8) Concrete

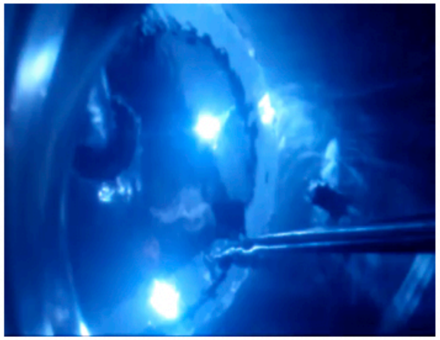
MicroBooNE

- Goals: Address MiniBooNE anomaly; measure neutrino-Ar cross sections; LArTPC R&D
- Took data from 2015 to 2021 — first 100-ton scale LArTPC in the US & longest-running

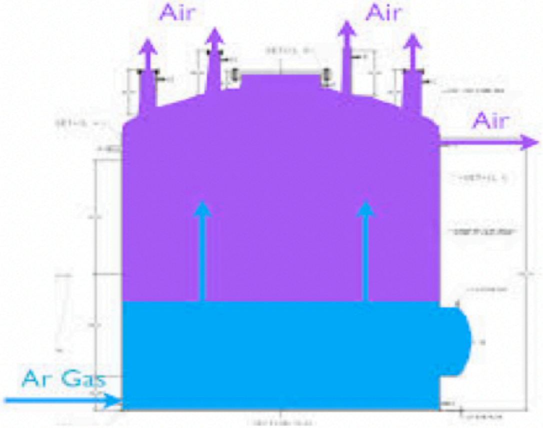


MicroBooNE pioneered the LArTPC R&D

HV BREAKDOWN IN LAR
SURGE PROTECTION DEVICES

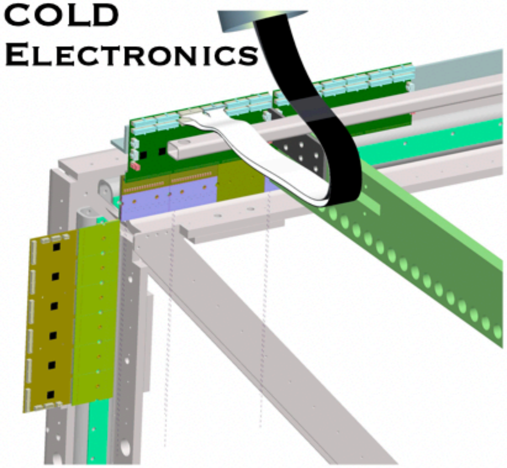


PURITY WITHOUT EVACUATION



SUCCESSFUL DESIGN & INSTALLATION OF THE 1ST 100-TON SCALE TPC IN THE U.S.

COLD ELECTRONICS

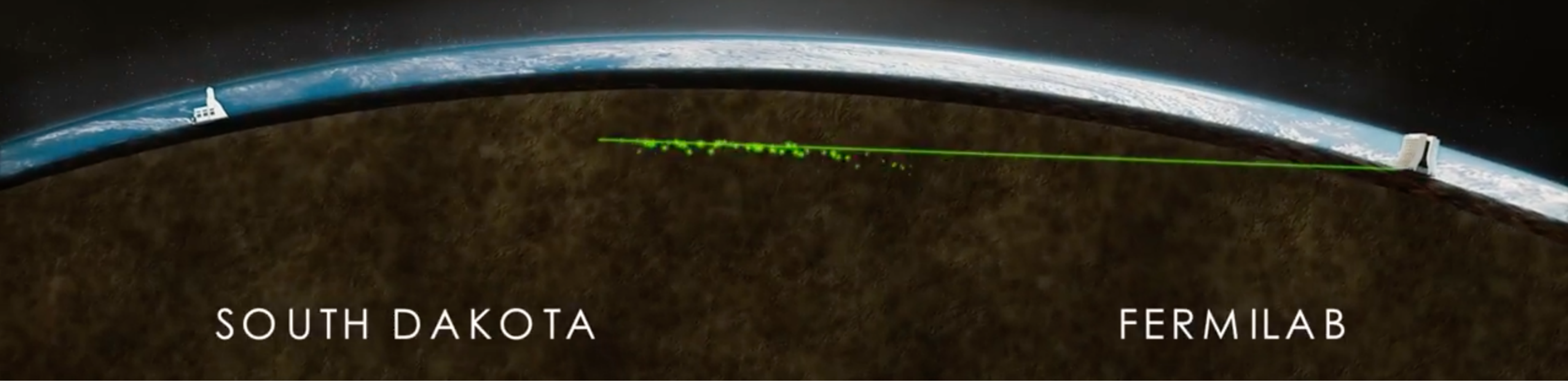


CRYOGENICS

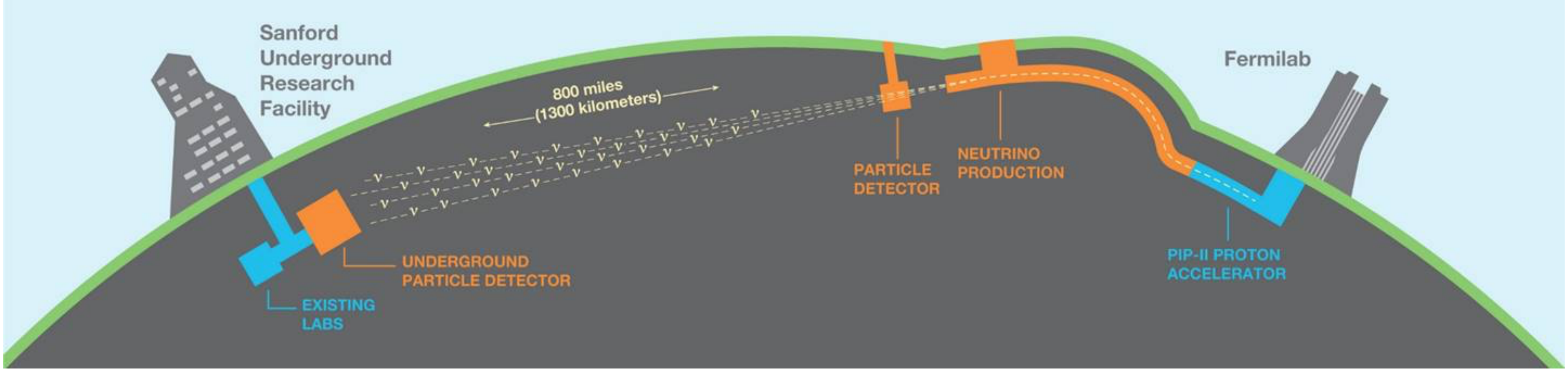
- Other: LArTPC software and reconstruction techniques; calibration methods; signal processing; several first neutrino cross section measurements on argon at ~1 GeV scale

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



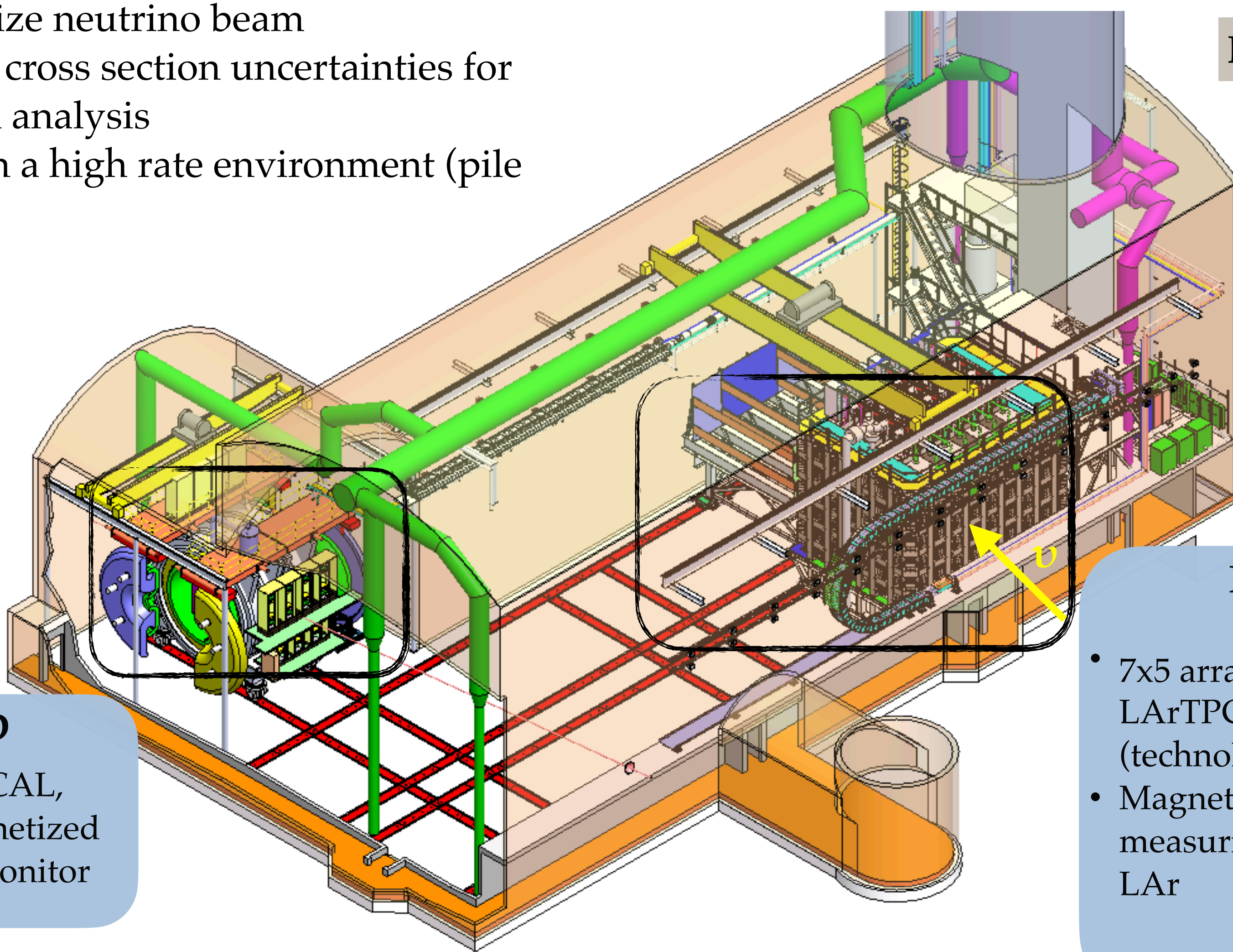
The DUNE Near Detector Complex

- 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

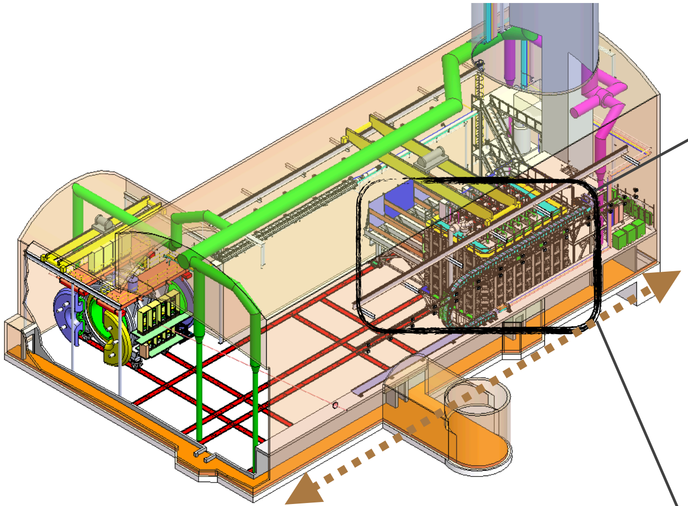
Tracker, ECAL,
On axis magnetized
beam flux monitor

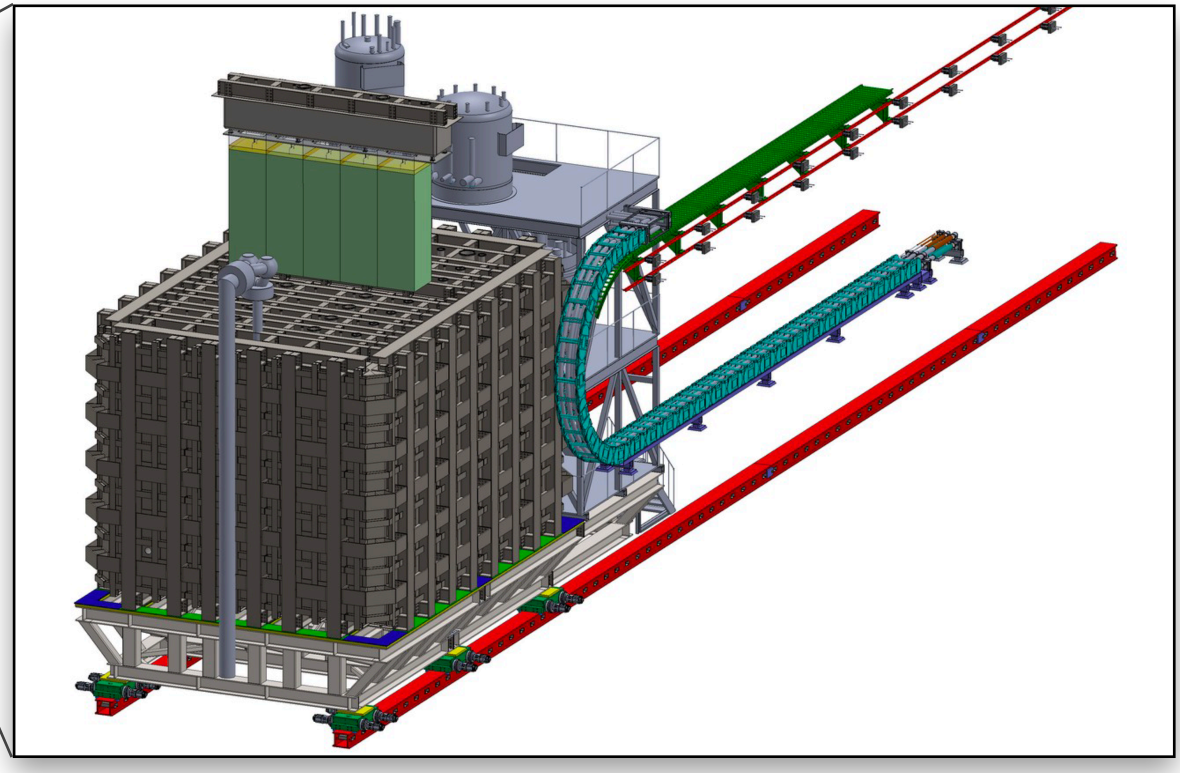
ND-LAr + TMS

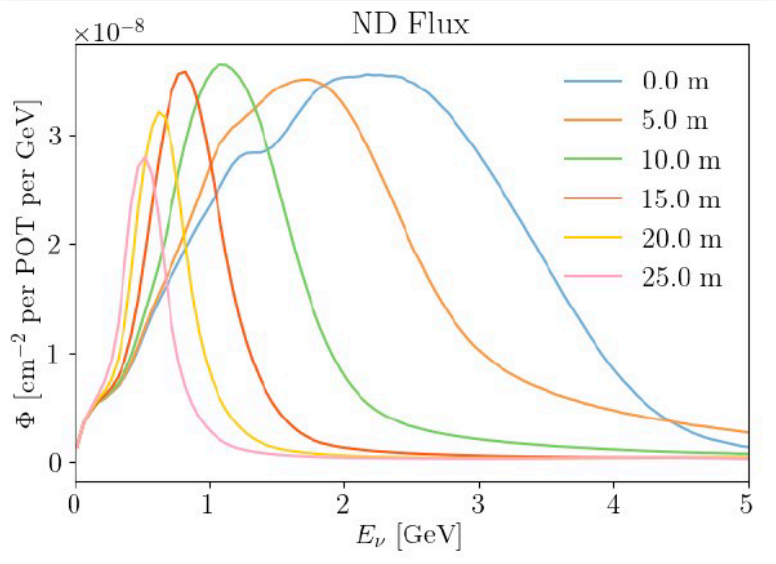
- 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout (technology closest to far detector)
- Magnetized steel range stack for measuring muons that exit ND-LAr

CDR: arXiv:2103.13910

The DUNE-PRISM



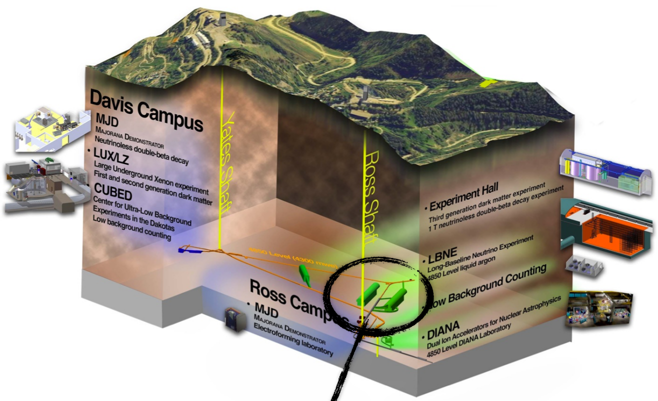


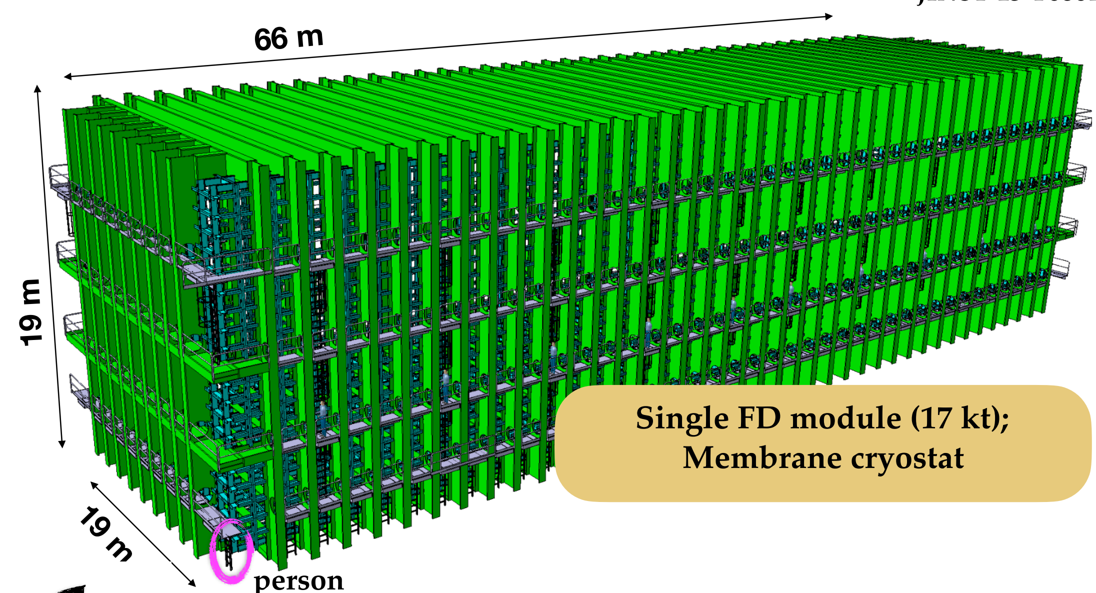


- ND flux changes with angle due to pion decay kinematics
- ND-LAr and TMS systems can move off-axis up to 28.5 m to observe varied beam spectra
- Will help address uncertainties in ND to FD extrapolation

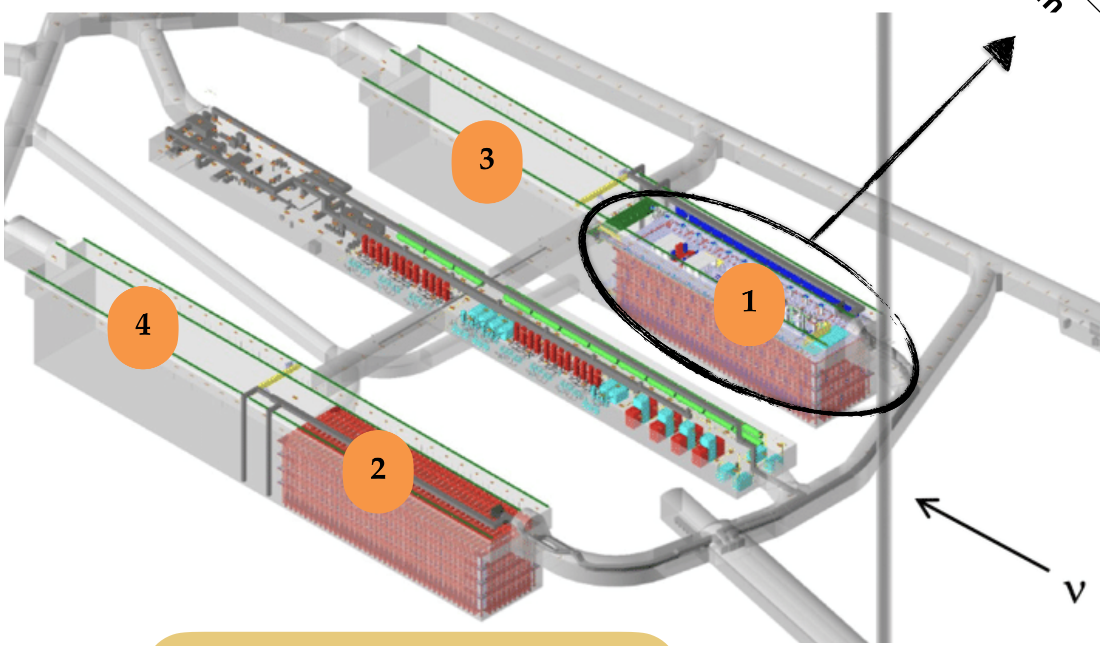
The DUNE Far Detector: *Largest LArTPC ever to be built*

JINST 15 T08010





Single FD module (17 kt); Membrane cryostat

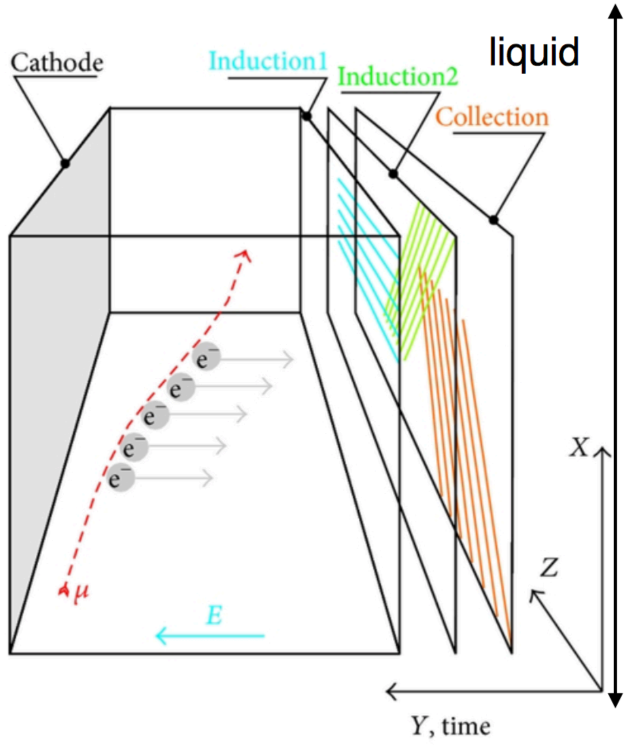


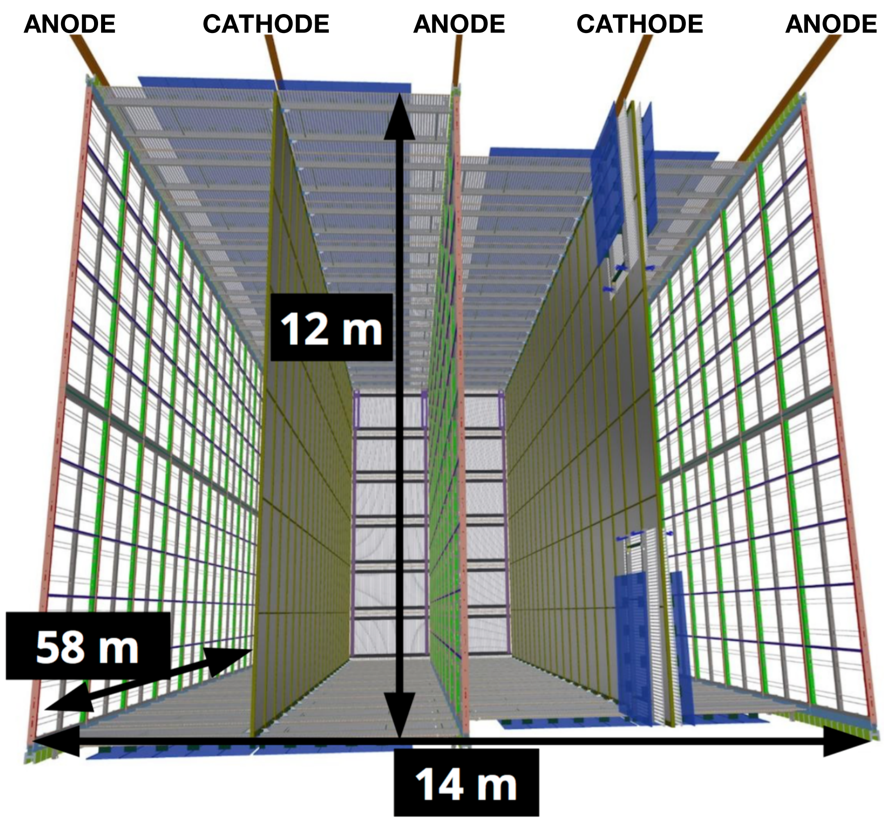
2 caverns, 4 detectors, **flexibility in design**

- 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

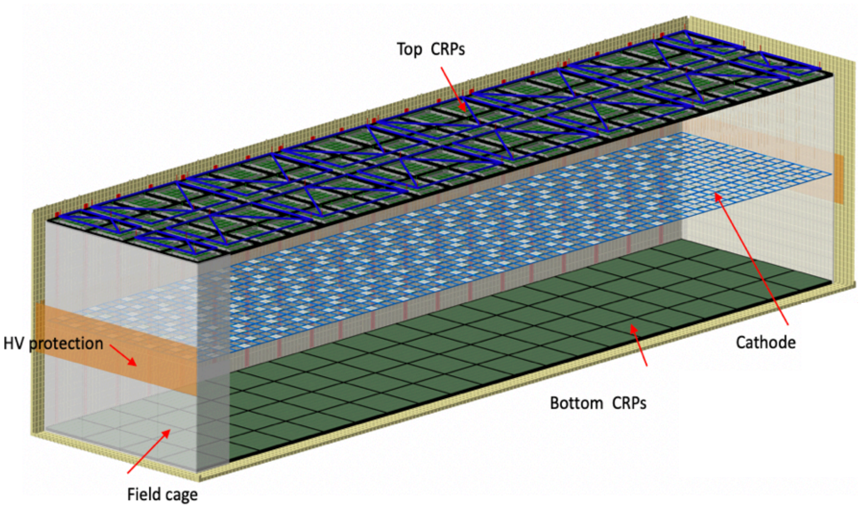




JINST 15 T08010 (2020)

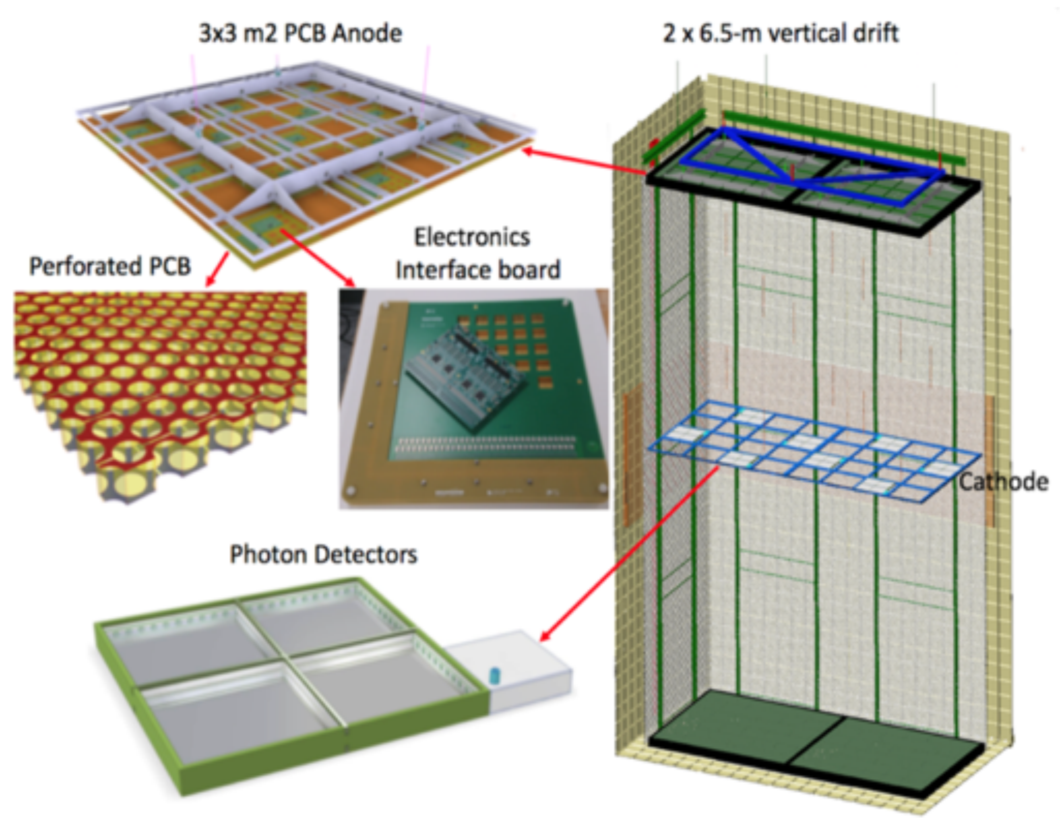
- 12 m x 14 m x 58 m active volume
- Each Anode-Cathode chamber has 3.5 m drift
- Cathode at -180 kV
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- Anode planes have wrapped wires (readout on both sides)
- 6000 photon detection system (PDS) channels for light readout

FD#2: Vertical Drift LArTPC

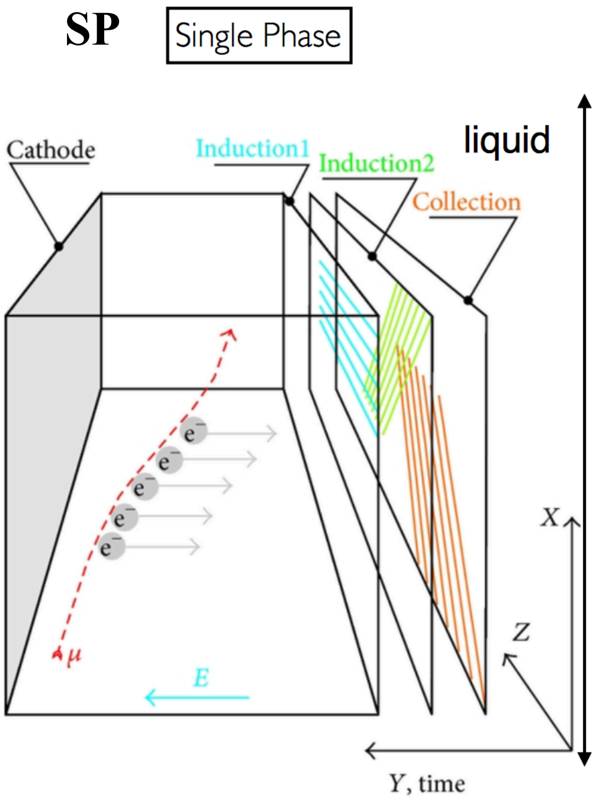


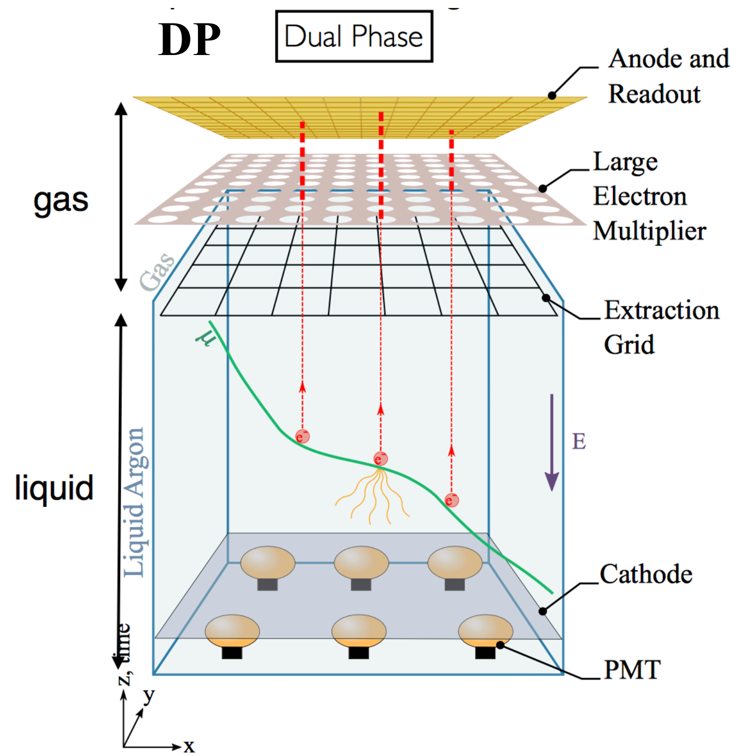
- VD technology evolved from extensive R&D from single and dual phase LArTPCs
- Designed to maximize active volume
- Perforated PCBs with segmented electrodes (strips) as readout units

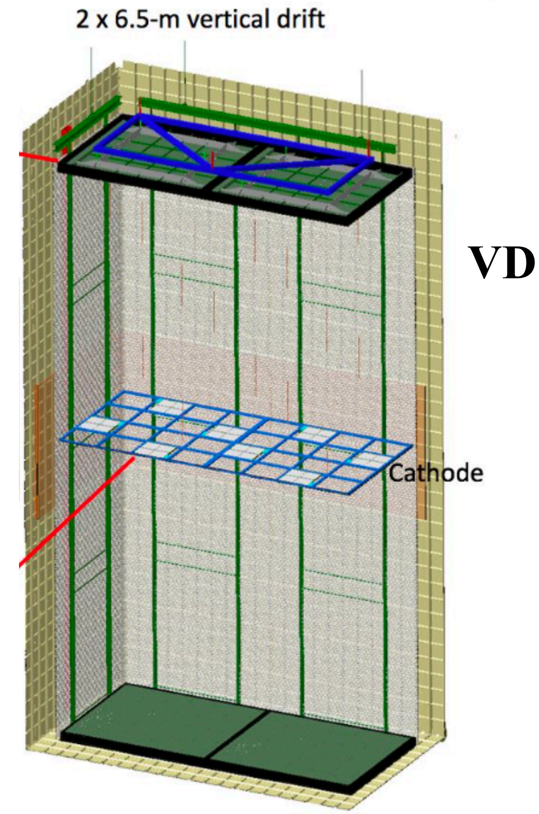
- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- -300kV on cathode; 450 V/cm field

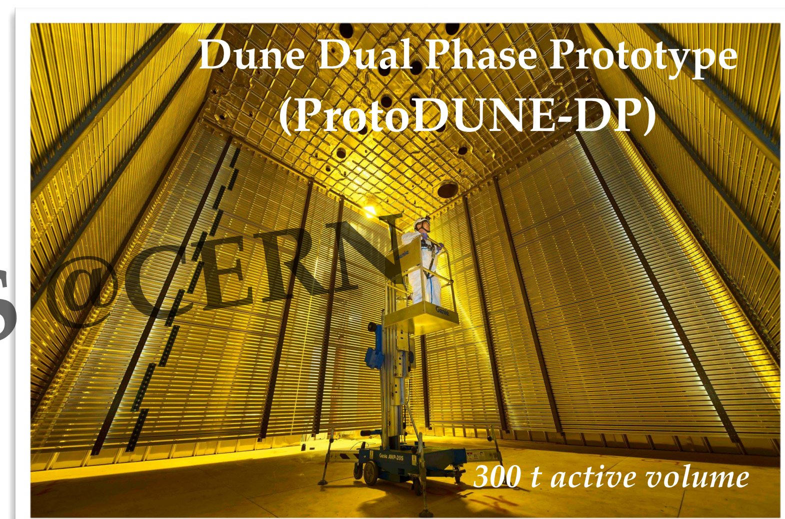


DUNE Prototype Technologies at CERN



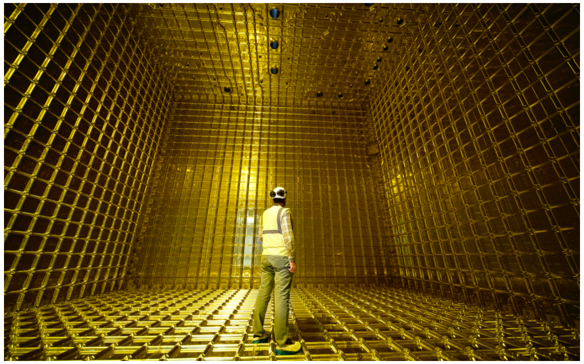






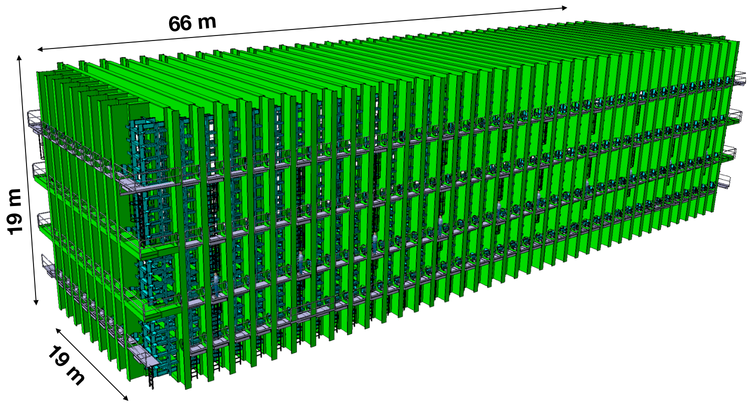
Many Challenges on the Path to DUNE

~400 ton (ProtoDUNE)



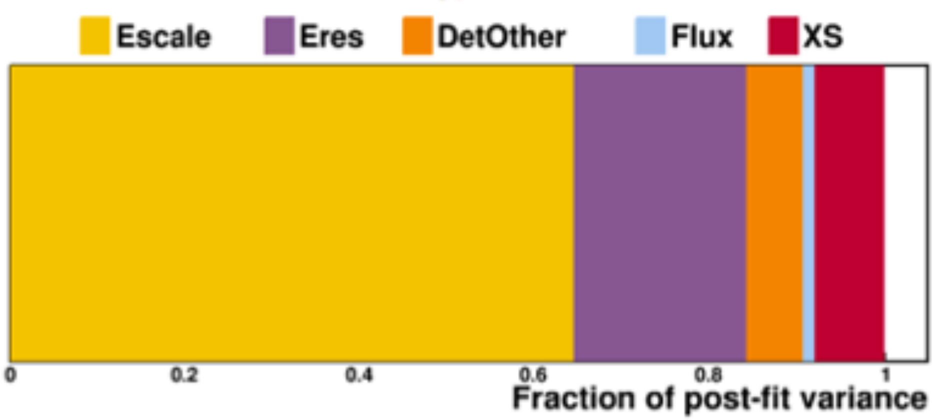
x 25

10,000 ton (1 DUNE module)



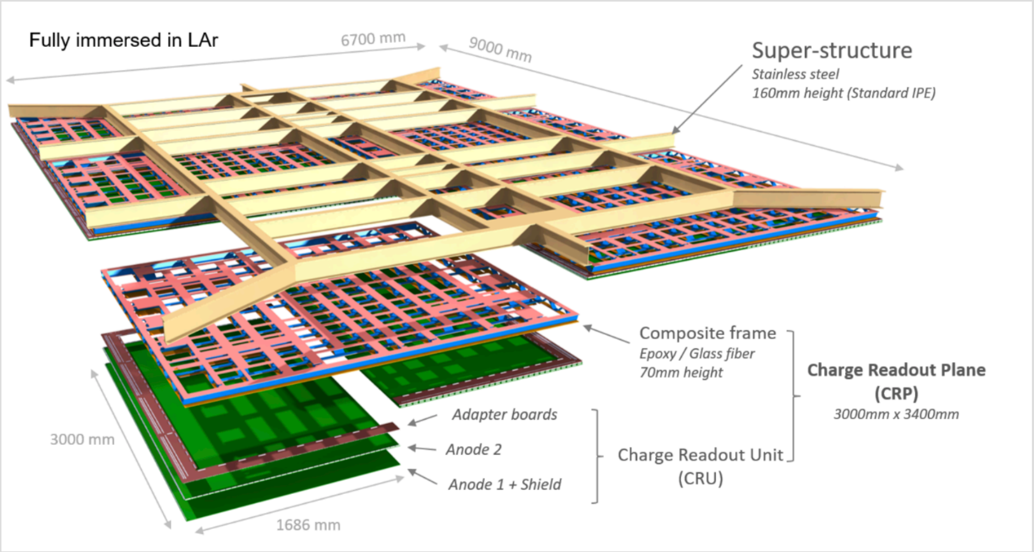
- *unprecedented* detector scale
- DAQ requirements never dealt before
- Neutrino-argon cross sections not well measured
- Neutrino energy reconstruction
- Unprecedented systematics requirements
- Calibrations most challenging!
- LArTPC R&D actively ongoing

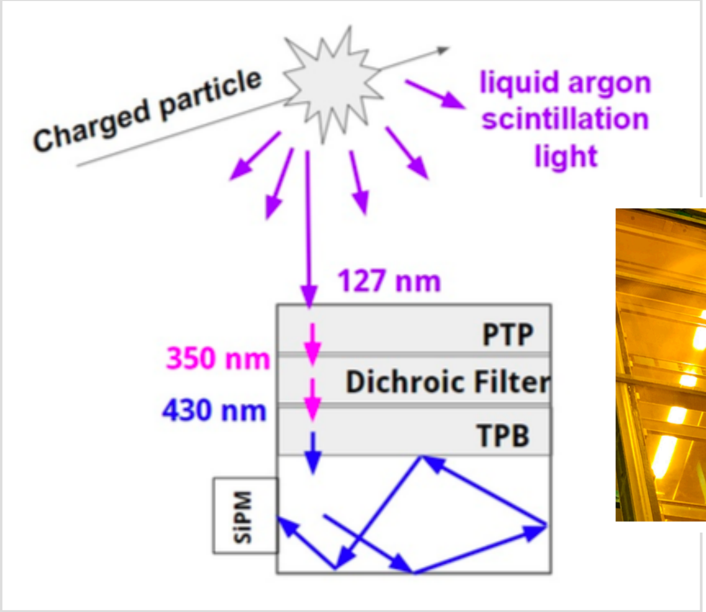
Contributions to δ_{CP} systematic:

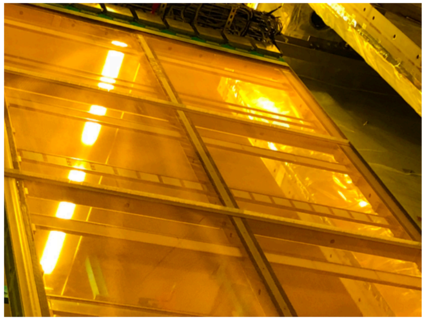


Further LArTPC R&D

- Charge Readout
  - Charge Readout Planes (CRPs): substitute wire planes with stacked PCB planes with readout strips; economical, easy to install, and more active area coverage
  - Pixelated readout: capture 3D images of trajectories
- Photon detection
  - ARAPUCA light traps
  - 4Pi optical coverage via power over fibres for high voltage surfaces like ProtoDUNE-VD
- Highly modular TPCs to address large pile up e.g. DUNE Near Detector LArTPC
- Magnetized LArTPCs for improved charge discrimination e.g. b/n e+ and e-





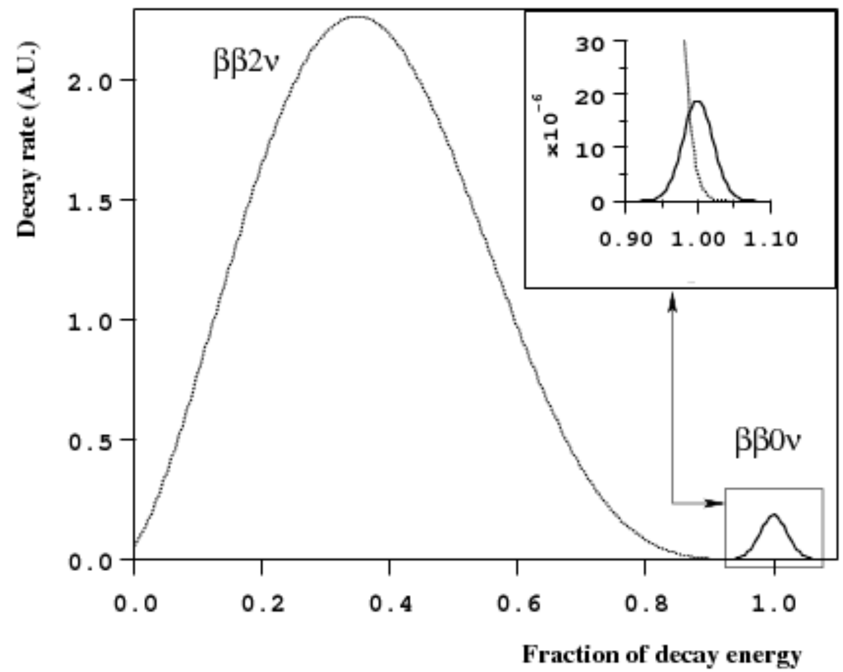


For more details, see A. Fava's talk here: https://zenodo.org/record/6717705

Double Beta Decay Experiments

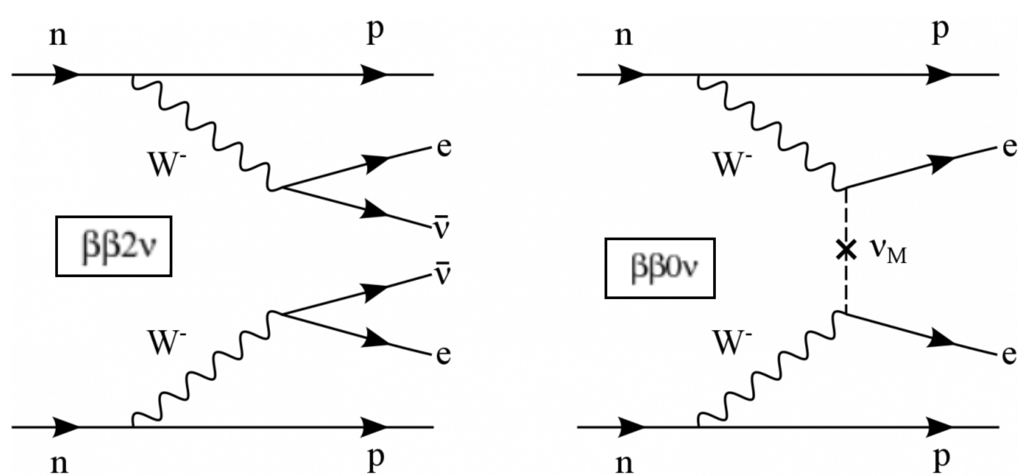
Is neutrino Majorana or Dirac?

Observation of neutrino less double beta decay (0νββ) provides evidence for "Majorana" nature of neutrinos



Recent Limits

^{136}Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
^{76}Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
^{130}Te (CUORE): $T_{1/2} > 3x10^{25}$ yrs



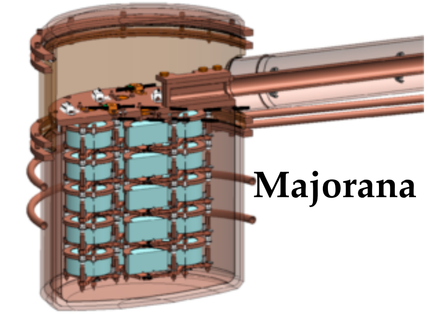
Experimental Landscape

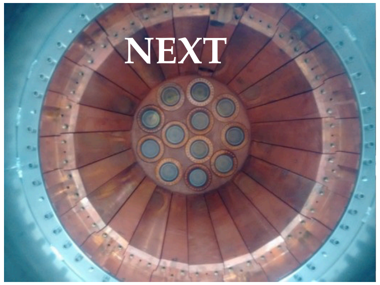
(J. Detwiler @ Neutrino 2020)

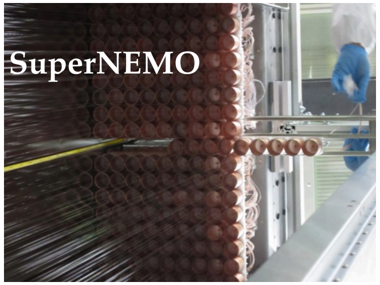
Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

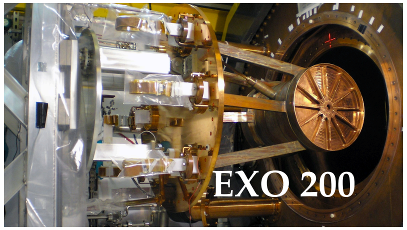
R&D | Construction | Operating | Complete

Very Active Program!



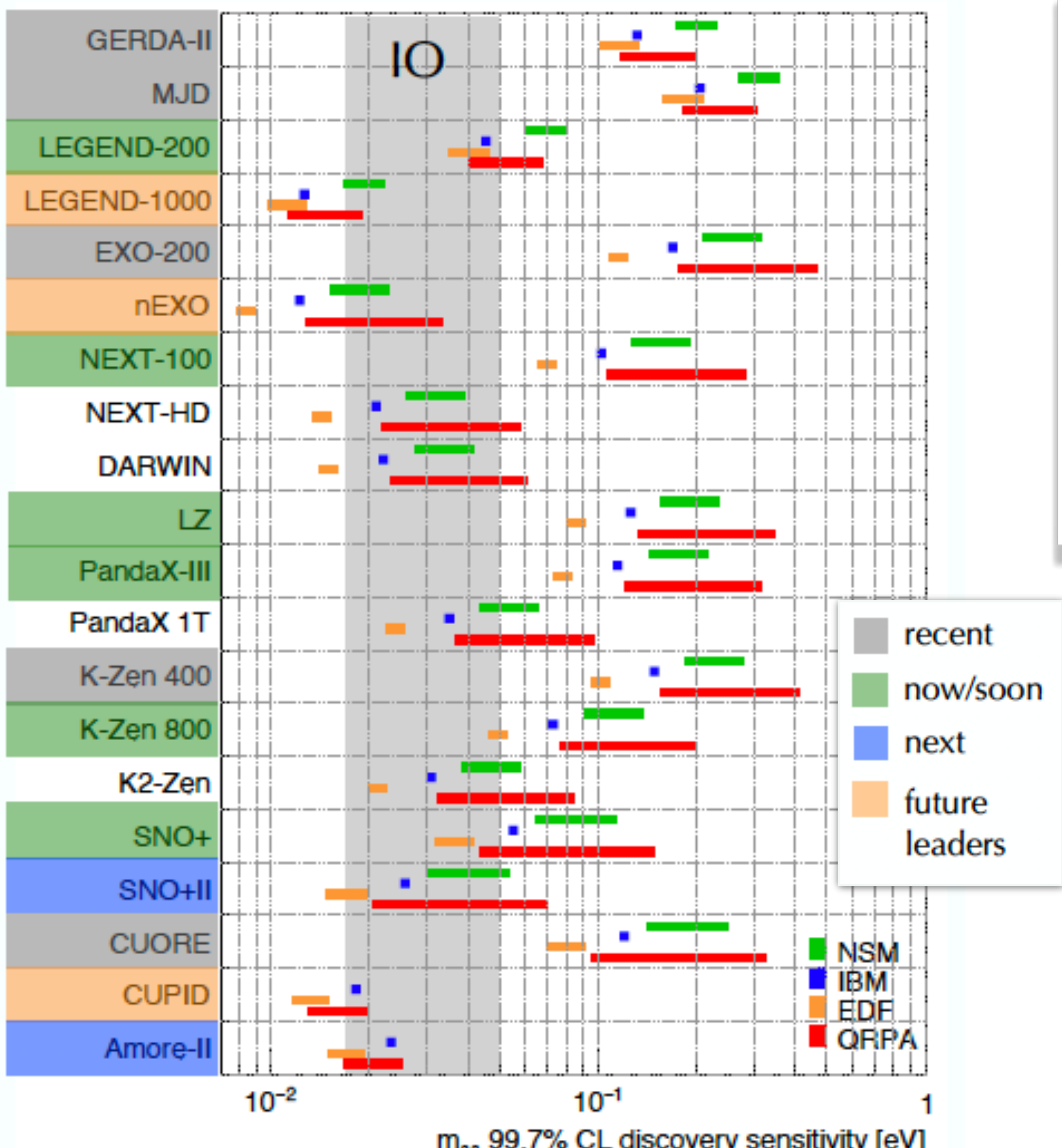




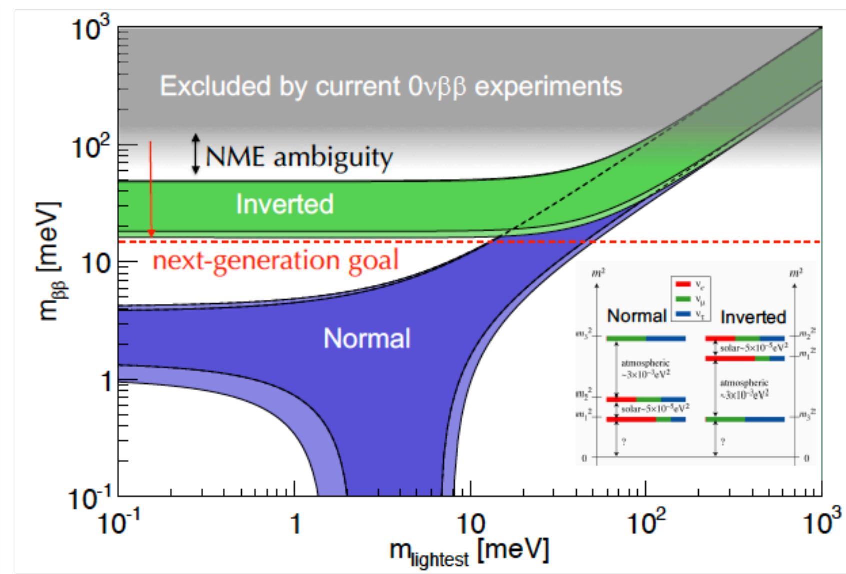


- **Challenges:** large mass to offset long 1/2 lifes; low backgrounds, excellent energy resolution/tracking
- **Multiple techniques:** Bolometers, Scintillators, Trackers, TPCs, Semiconductors
- Multiple Isotopes; larger sizes

Looking Towards Future



(J. Detwiler @ Neutrino2020)

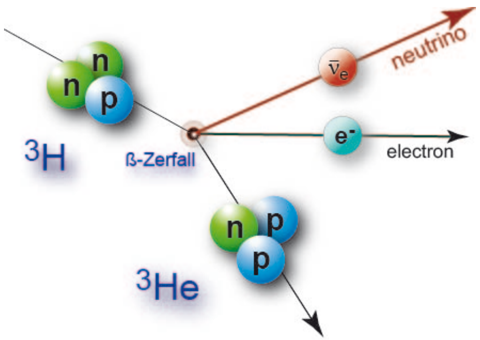


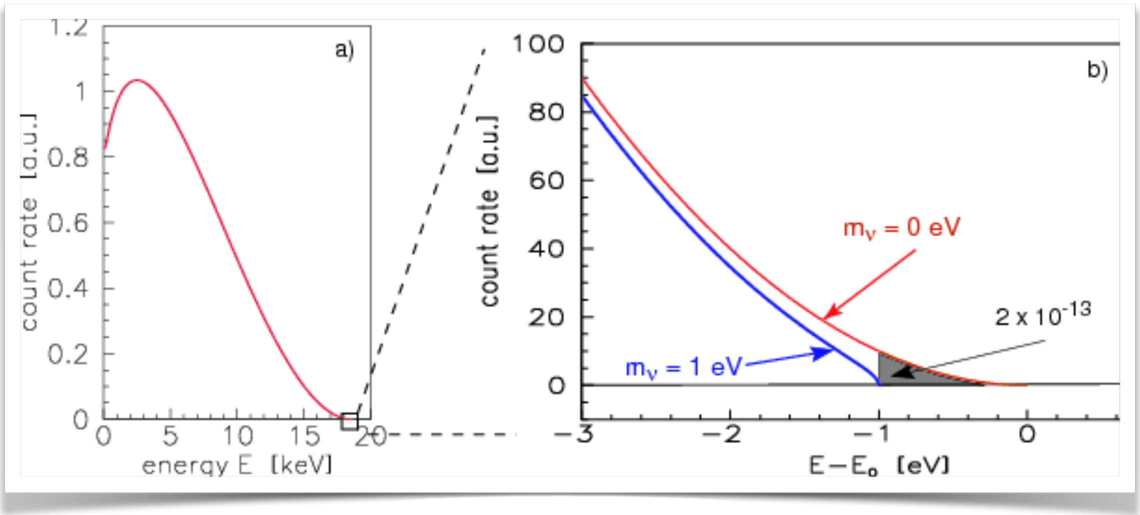
- **Future experiments** aiming for ~2 OoM improvement and cover "Inverted Ordering" region
- A lot to look forward to in the near to far future!

Direct Mass Measurement Experiments

Absolute mass of neutrinos?

- Constraints from cosmological and astrophysical data and precision measurements from β-decay experiments
- Experimental landscape
  - Tritium beta decay tagging: **KATRIN, Project 8**
  - Electron capture decay of ^{163}Ho: **ECHO, HOLMES**
  - Other: **Neutrino 4**





(KATRIN Experiment)

Mass $m <$ 1.1 eV, CL = 90% (tritium decay)

Nature Physics, volume 18, 160–166 (2022)

Closing Thoughts

- Neutrino Physics is a very active field of research
- We are striving towards a ***global picture*** of neutrinos
- Opportunities all around: physics, technology and data analyses
- We are boldly moving towards creative new technologies suitable for precision era
- Overlap b/n experiments is valuable: cross checks, improved constraints/precision, helps us move towards our global picture faster
- Next generation experiments are bigger/better and with broad physics programs; lot to look forward to in the next decade
- Already thinking about beyond the next generation!

Being in Neutrino Physics is like being on a Roller Coaster

It is adventurous, exciting and challenging, all at the same time — wouldn't have it any other way!