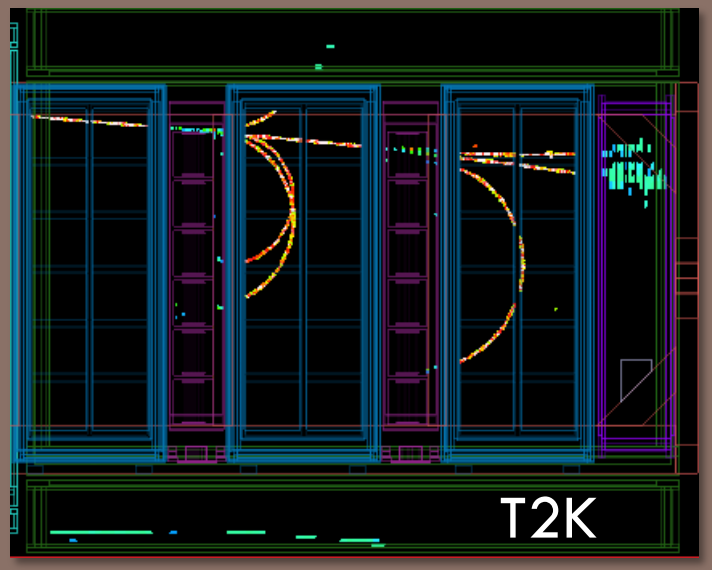
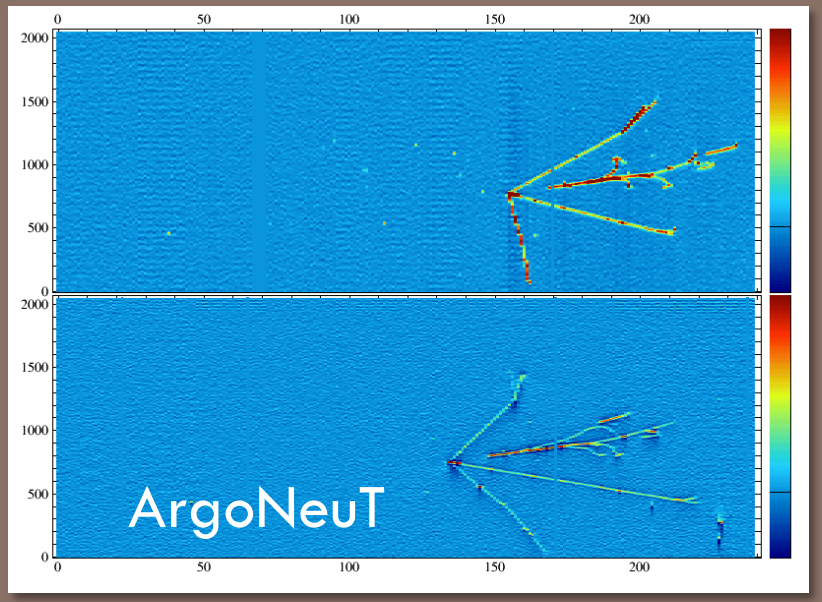
TIME PROJECTION CHAMBERS IN NEUTRINO PHYSICS



Sam Zeller
Fermilab

NygrenFest

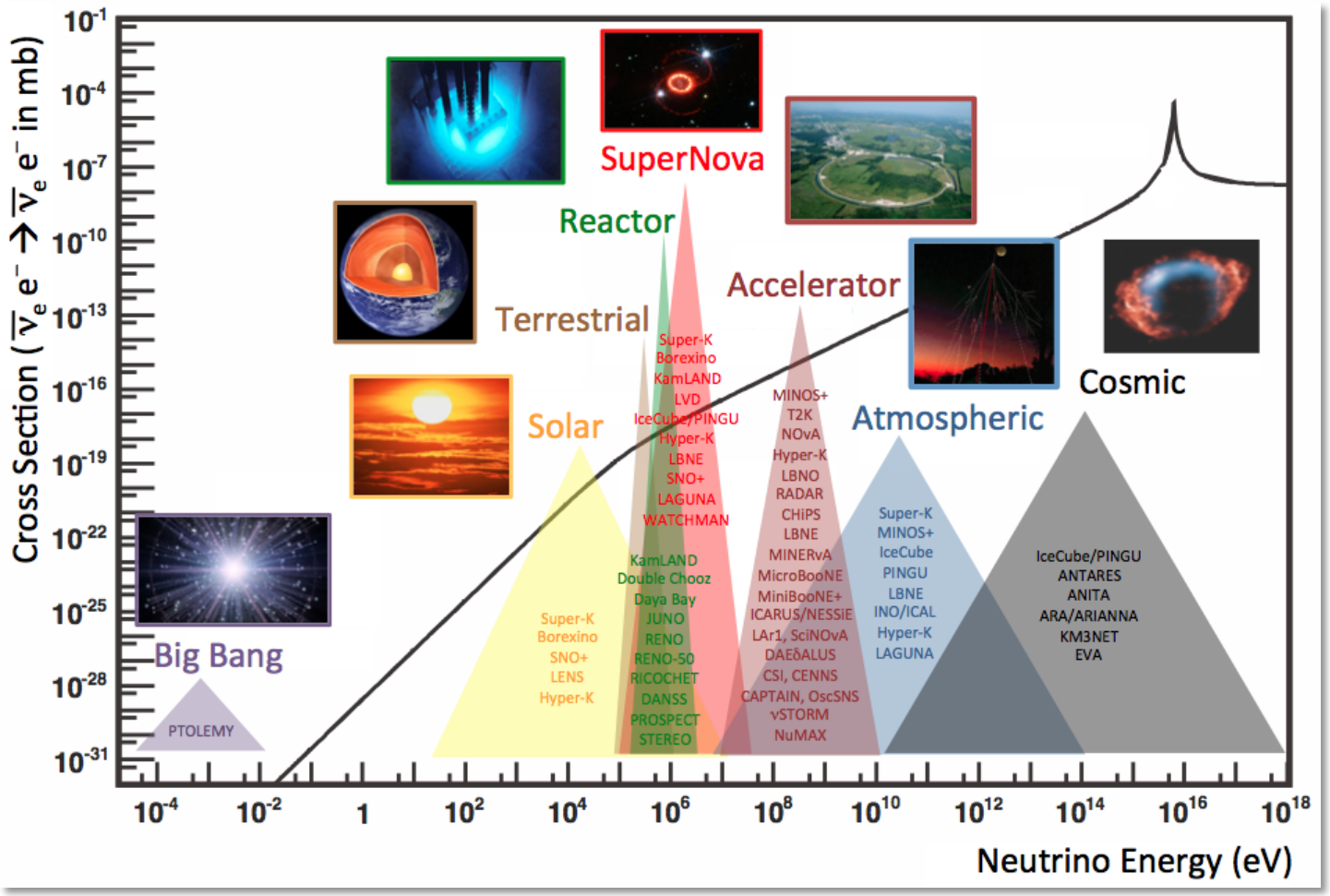
May 2, 2014



- LAr TPCs play a big part of our future in neutrino physics

Many Sources of Neutrinos

- span an enormous energy range (eV to PeV)



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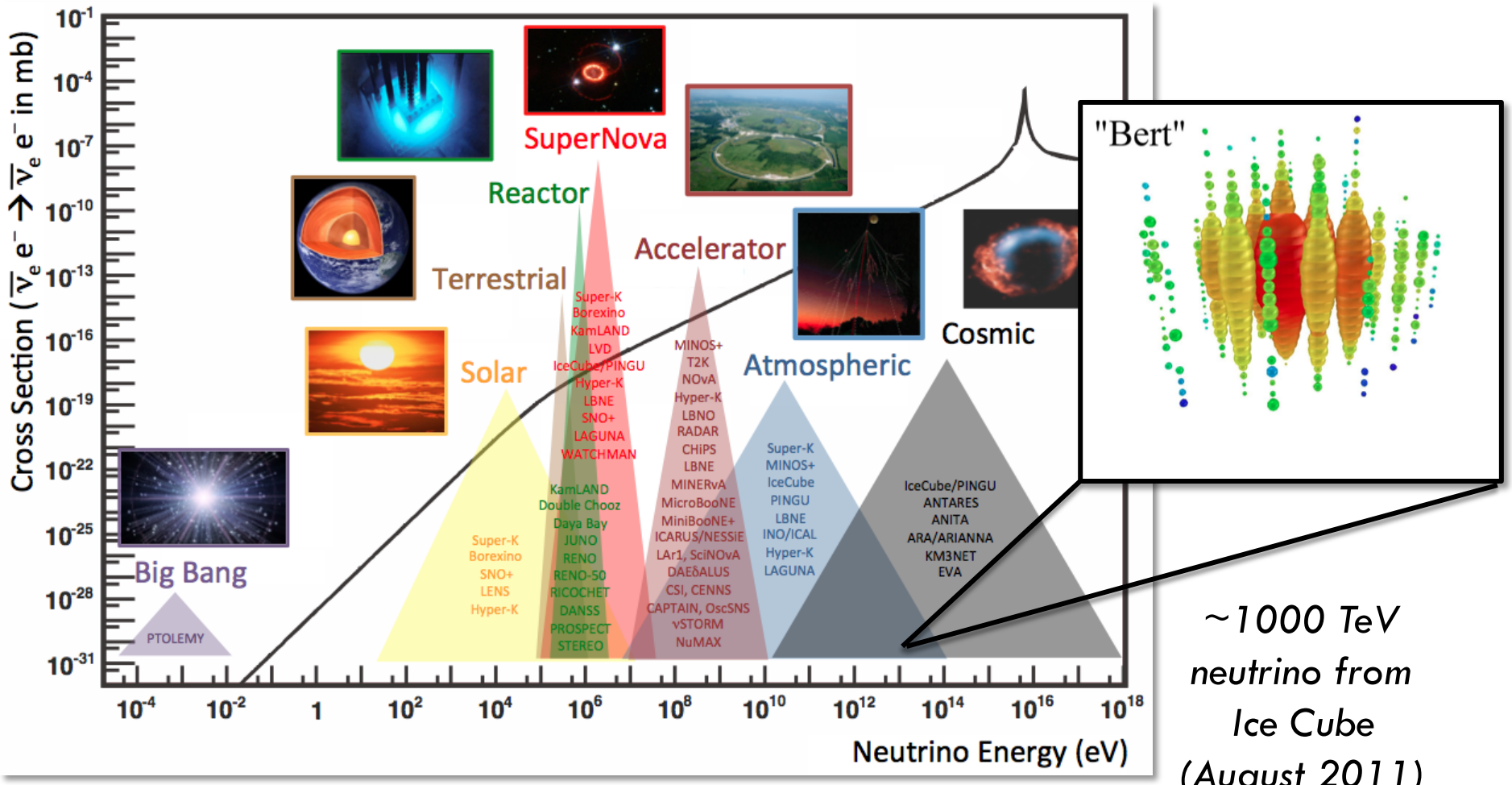

~1000 TeV neutrino from Ice Cube (August 2011)

Many Sources of Neutrinos

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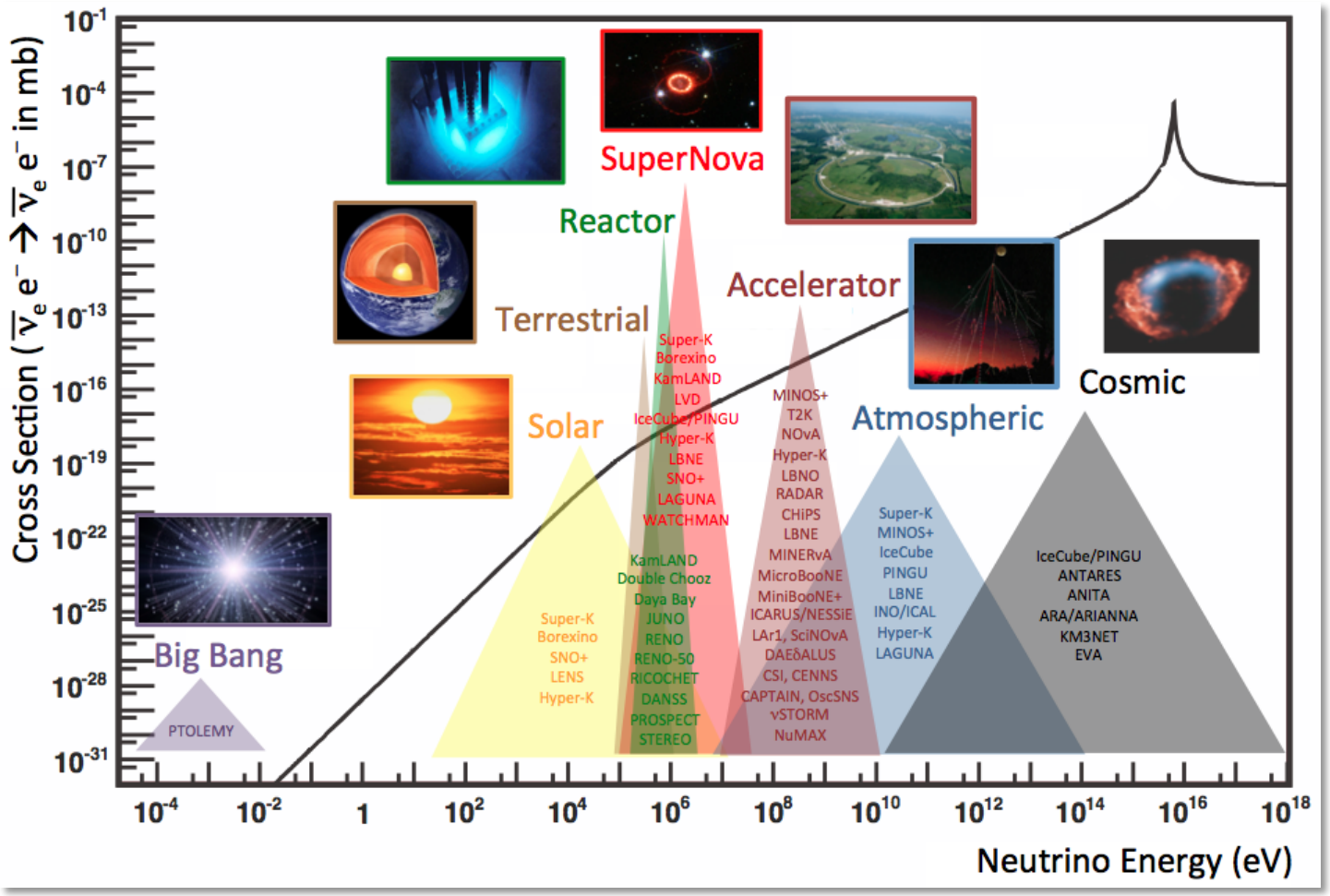
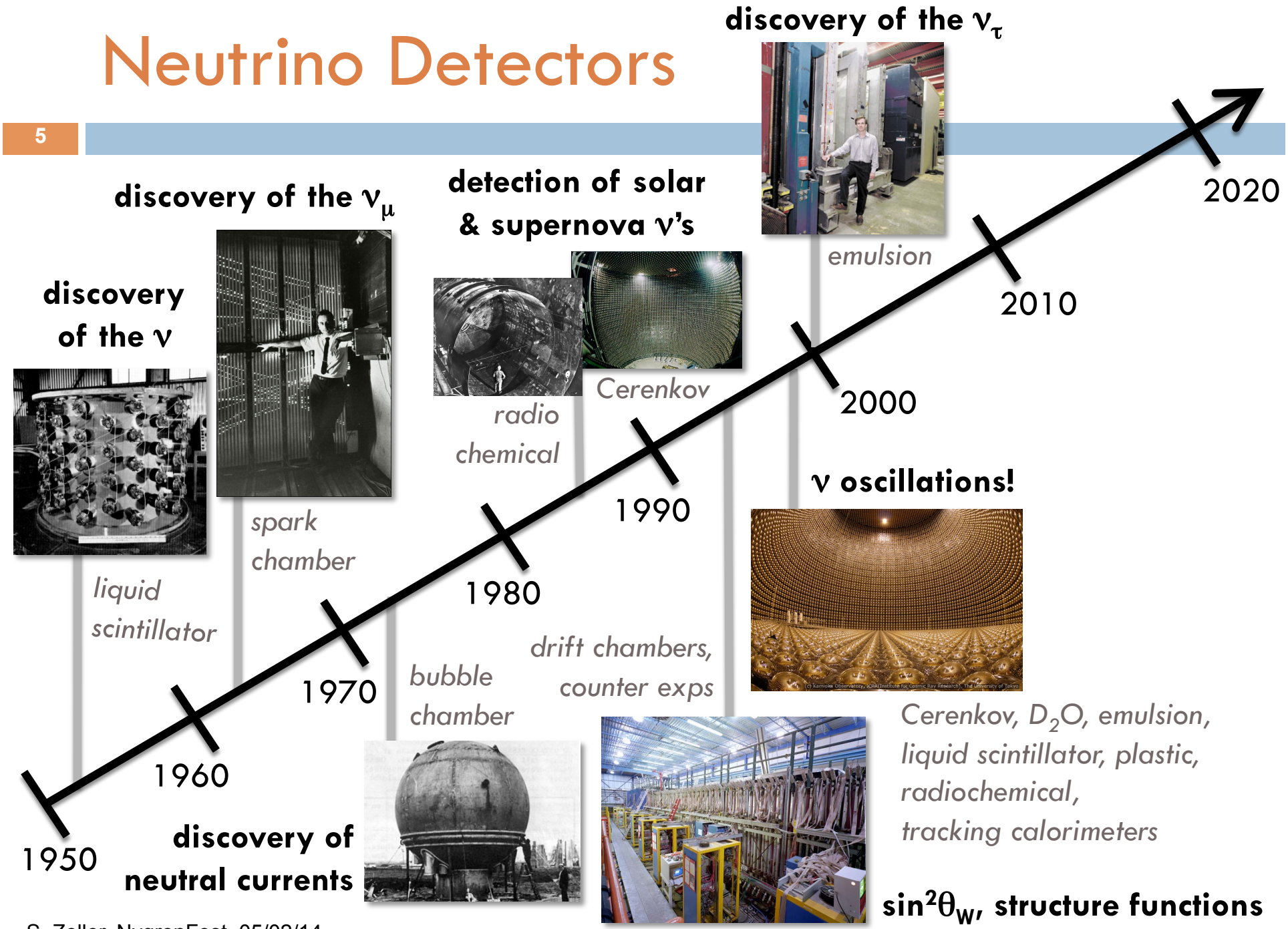
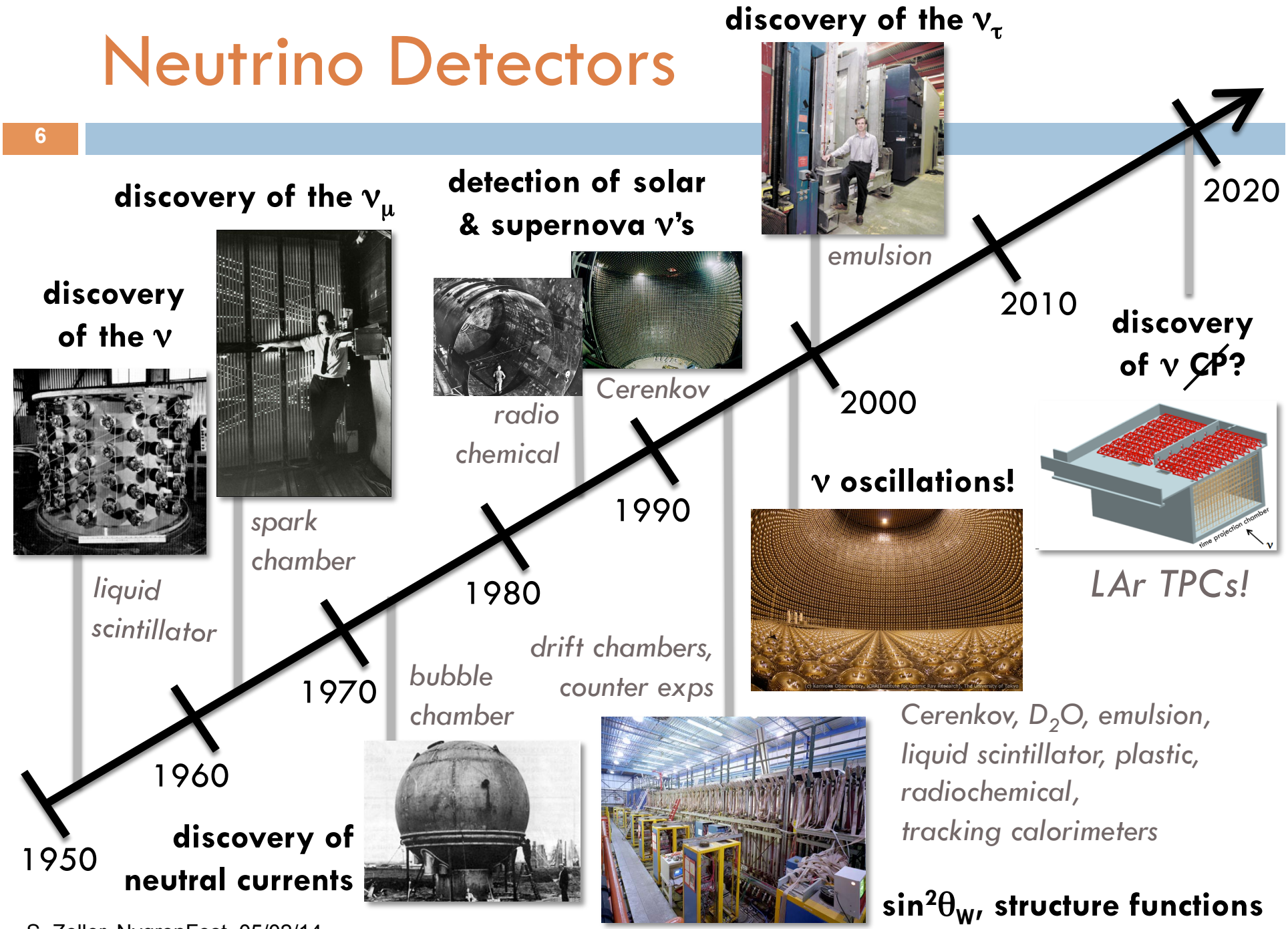


- both natural and manmade
- we have detected neutrinos from almost all of these sources

Neutrino Detectors



Neutrino Detectors

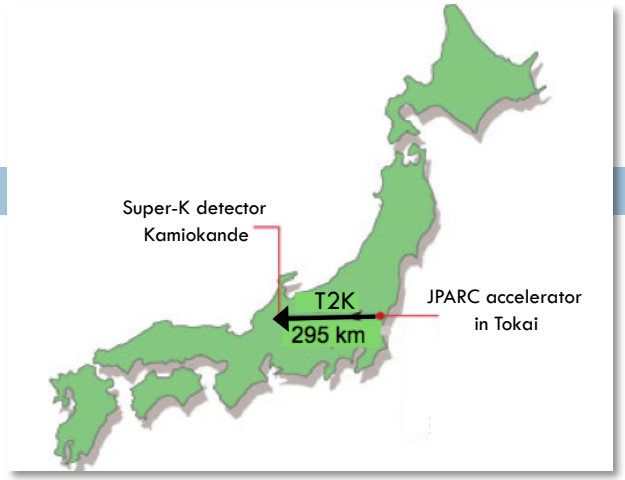


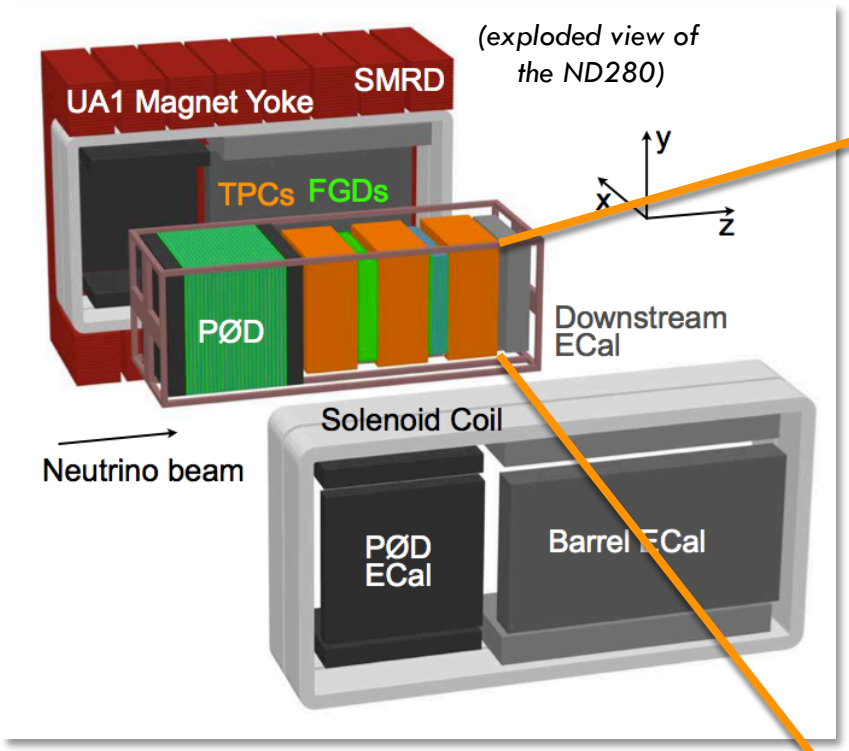
TPCs for Neutrino Physics

- while the concept of TPCs has been around for a long time, they have really only been recently employed in ν physics …

Recent Example …

- T2K: ν oscillation experiment in Japan



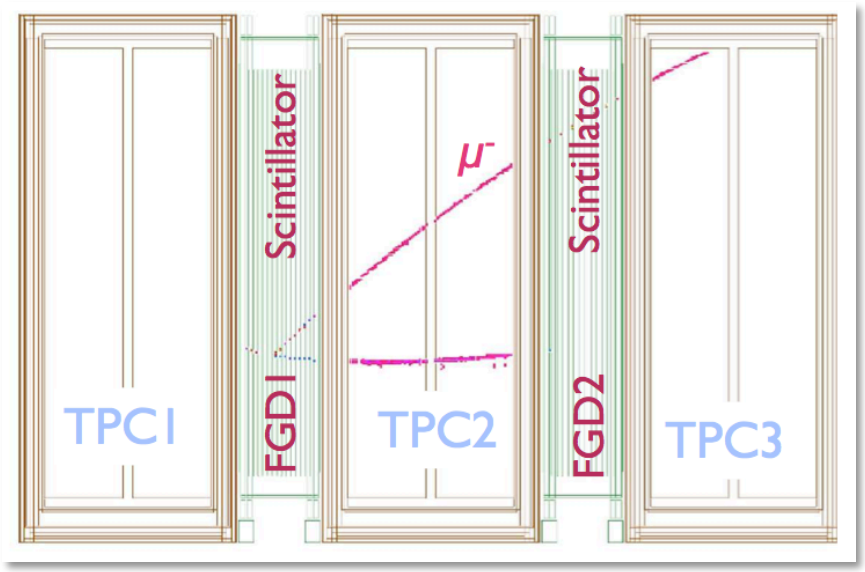


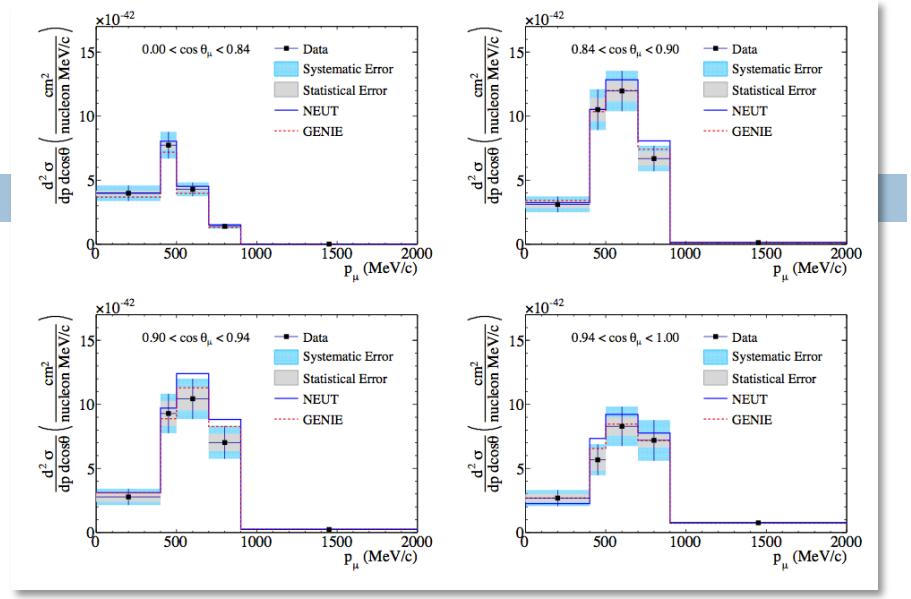
- suite of tracking calorimeters form the T2K ND including 3 gas-filled TPCs

T2K Near Detector

- CC ν_μ interaction in the T2K ND

(TPCs were the main detector used in this analysis)



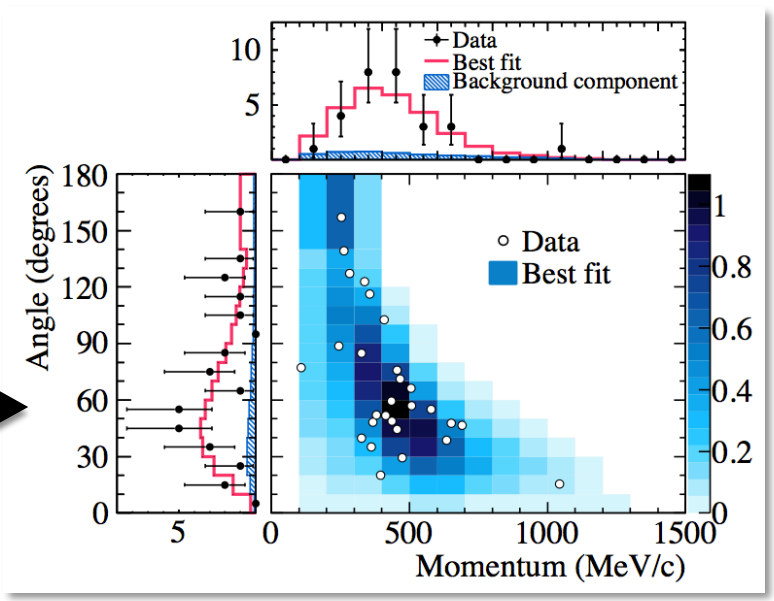


- world leading ν cross sections

Abe et al., PRD 87, 092003 (2013)

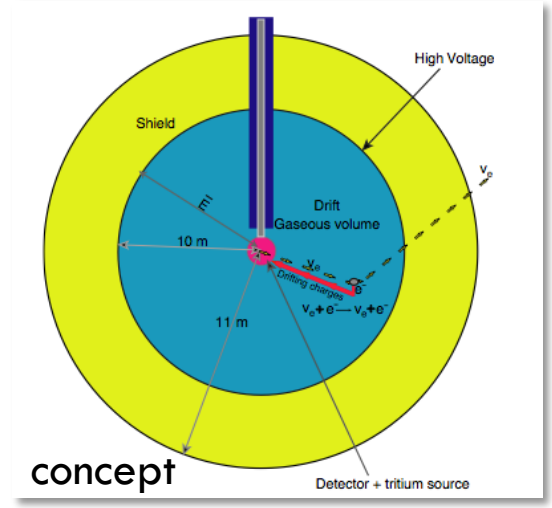
- first definitive (7σ) observation of the appearance of ν_e in a ν_μ beam

Abe et al., PRL 112, 061802 (2014)

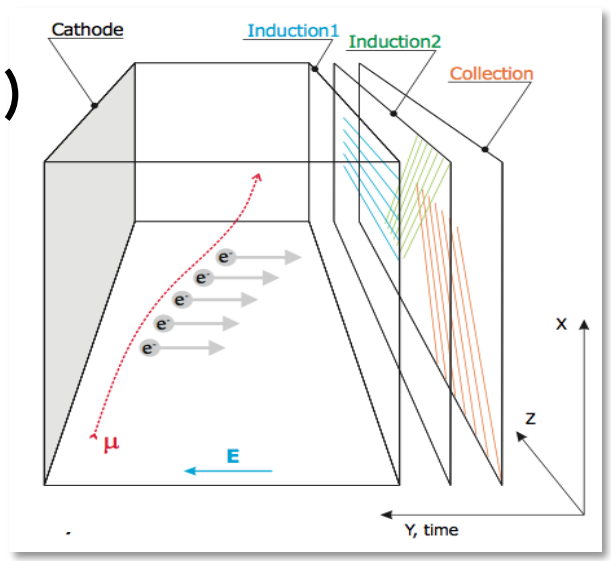


TPCs for Neutrino Physics

- **<u>gaseous TPCs</u>**
  - T2K
  - hadro-production exps used to constrain ν fluxes (HARP, NA61, MIPP)
  - spherical TPCs
    (for very low energy ν physics)



- **<u>liquid argon TPCs</u> (new generation)**
  (denser so more ν interactions!)
  - ICARUS
  - ArgoNeuT, MicroBooNE
  - future short and long-baseline ν oscillation experiments



both massive and extremely high resolution

LAr TPC Concept

- starting with **Nygren**'s invention of the TPC …

EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

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

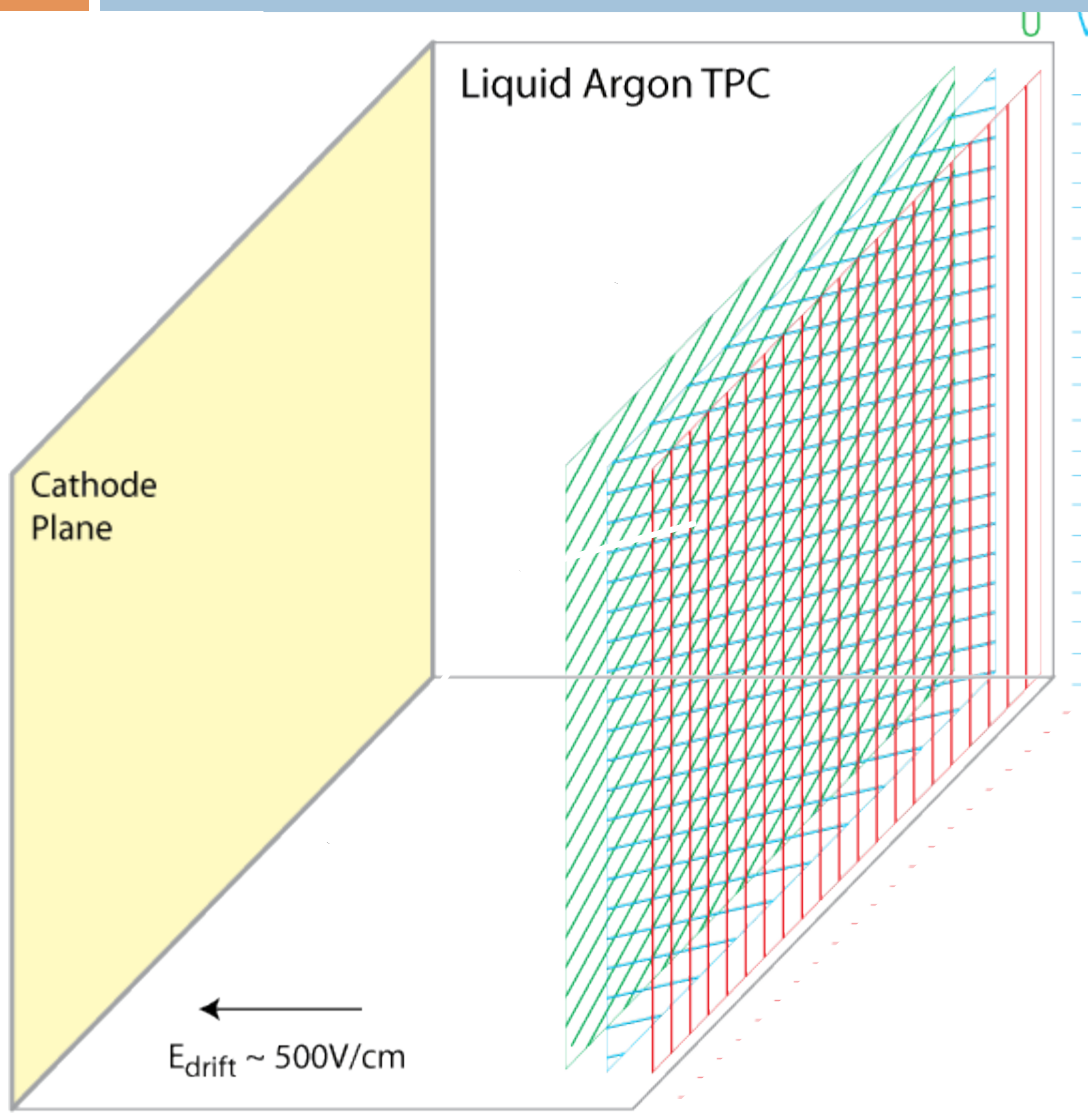
- **Willis, Radeka**
  LAr for calorimetry
  NIM, 120, 221 (1974)

- **Carlo Rubbia**
  LAr TPC first proposed
  CERN-EP/77-08 (1977)

- **Chen, Lathrop, Learned**
  drifting ionization electrons
  IEEE Trans.N.Sci. 25, 358 (1978)

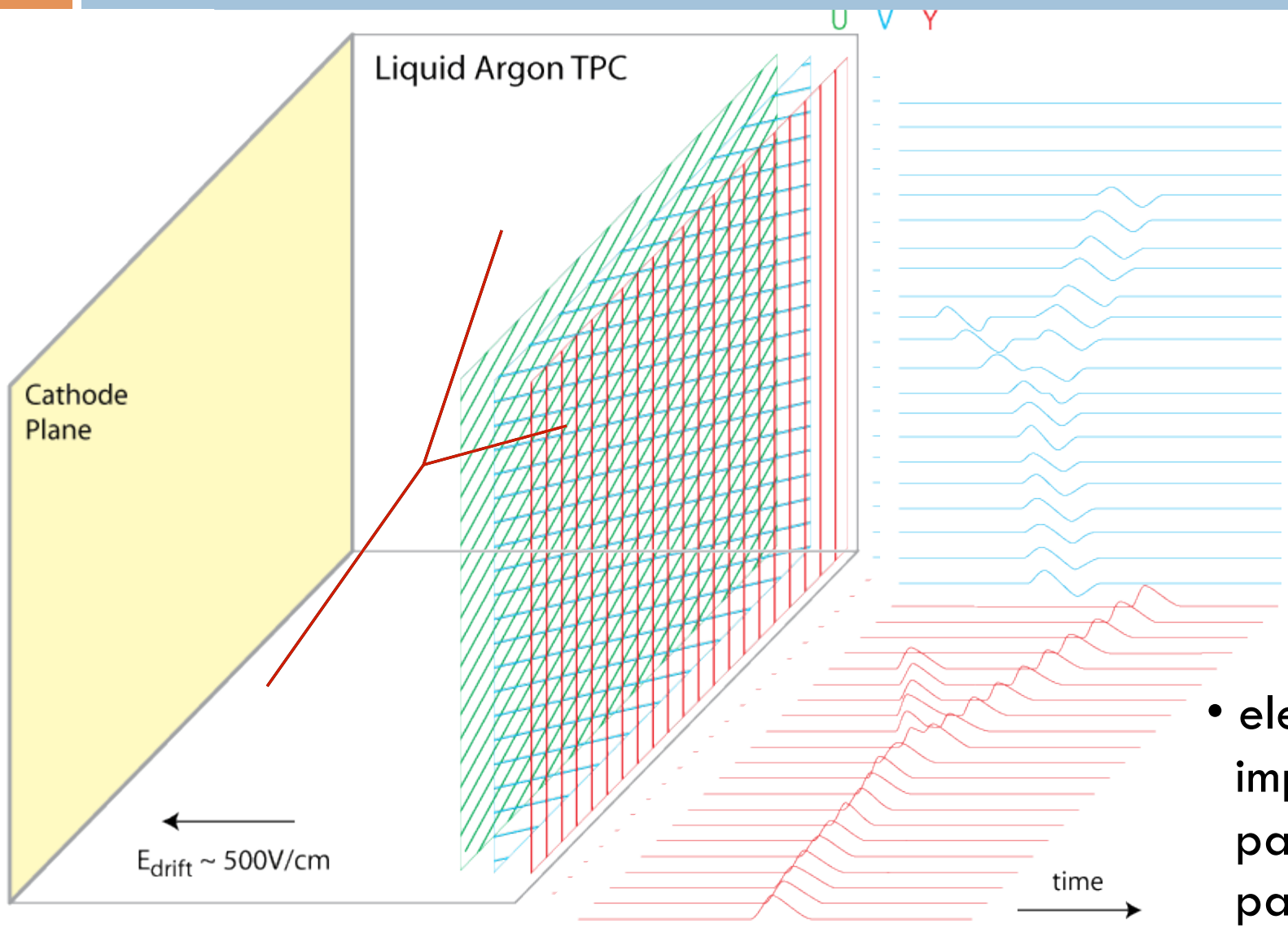
- **Gatti, Padovini, Quartapelle, Greenlaw, Radeka**
  signal, readout analysis
  IEEE Trans. N. Sci. 26, 2910 (1979)

How a LAr TPC Works



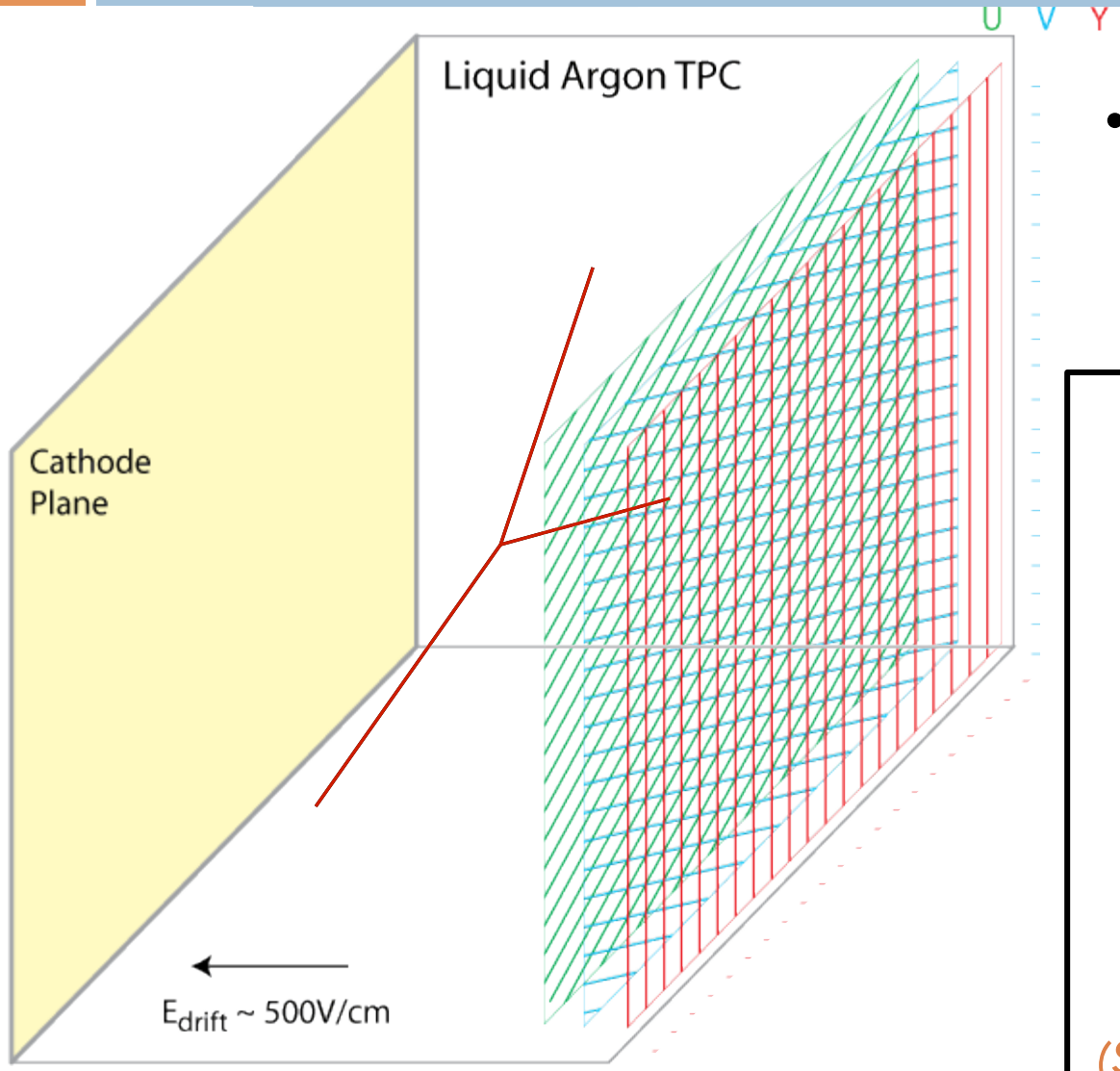
- large open volume filled with liquid argon
- noble liquids are dense so make good ν targets
- get a lot of ionization electrons in argon
- for these detectors to work, need high purity LAr so that these electrons can be drifted over large distances in $\vec{E}$ field

How a LAr TPC Works

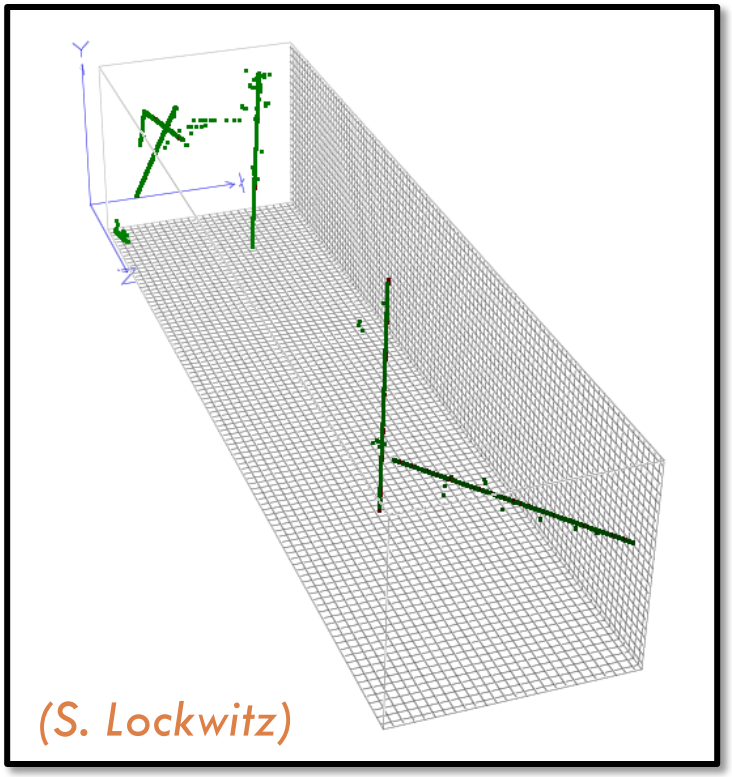


- the drift electrons preserve the details of the ionizing track
- electronic imprint of the particle track pattern

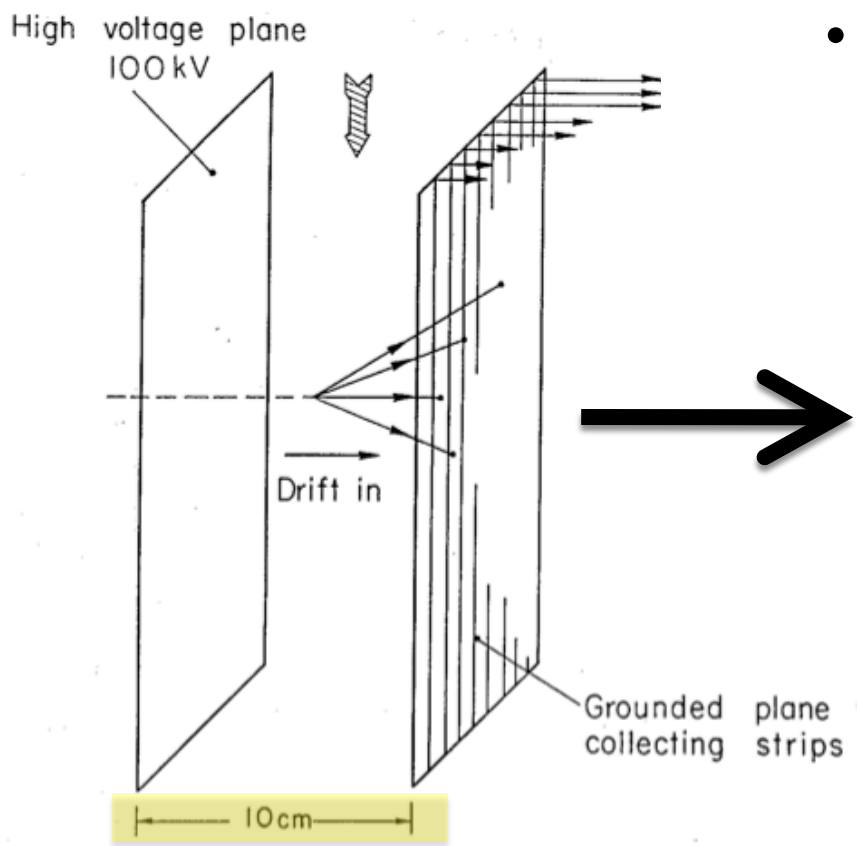
How a LAr TPC Works



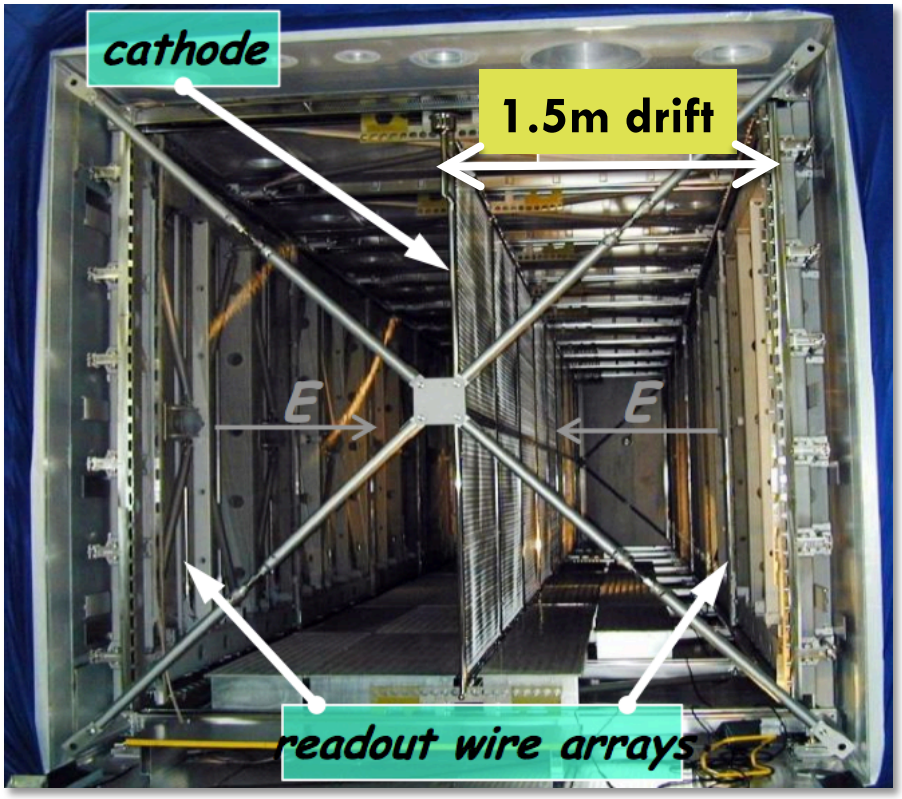
- 3D image from x,y of the wire chambers and arrival time



ICARUS T600 is Born



- largest LAr TPC in the world (600 tons)

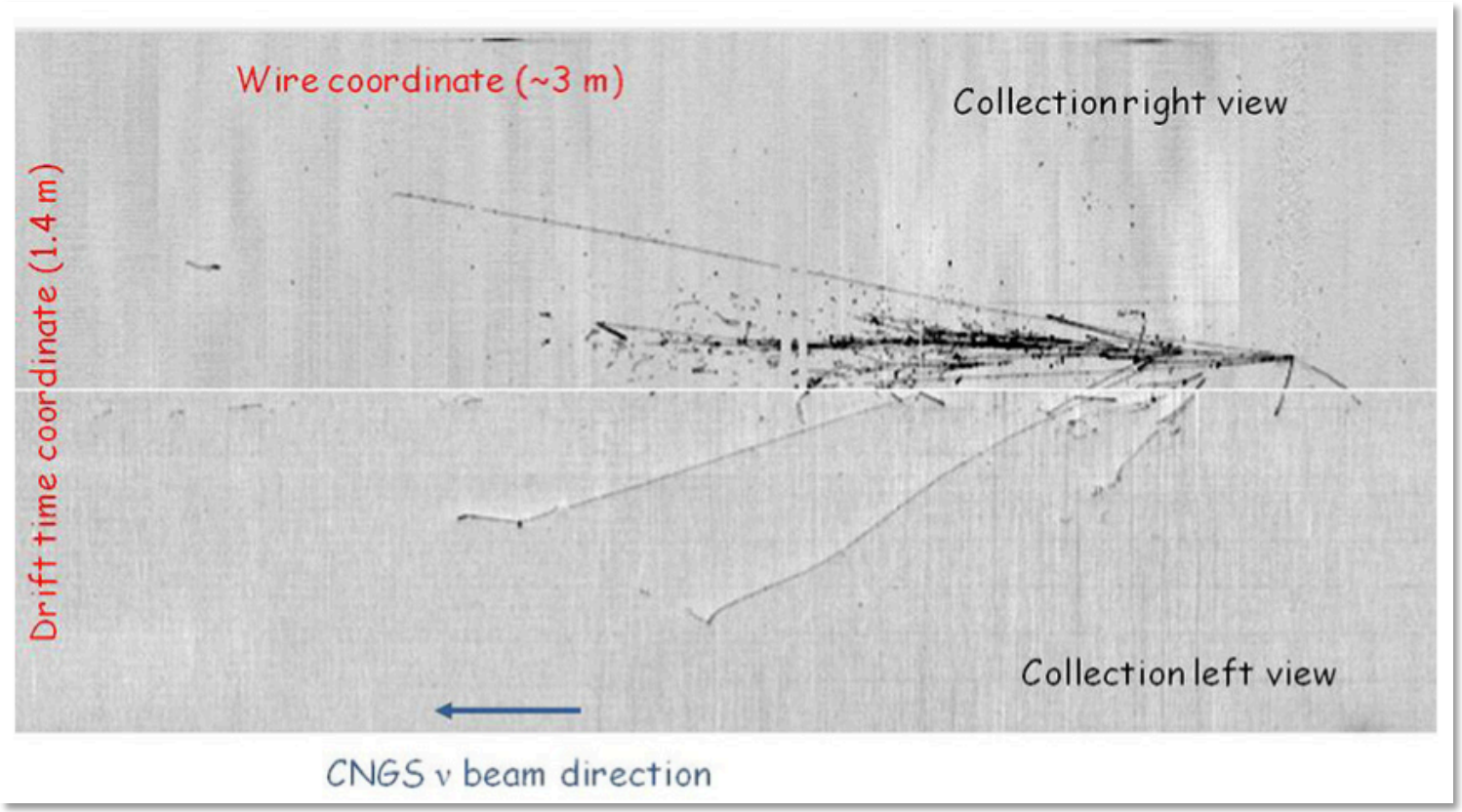


- **Carlo Rubbia**
  CERN-EP/77-08 (1977)

- two 300 ton modules, each with 2 TPCs
- 3.6 x 3.9 x 19.9 m^3
- 75 kV nominal voltage; 53,248 wires

ν events in the ICARUS LAr TPC

- ICARUS recorded ν's from the CNGS with >93% livetime (2010-2013) in parallel with studying cosmics from a prior run on the surfave in Pavia

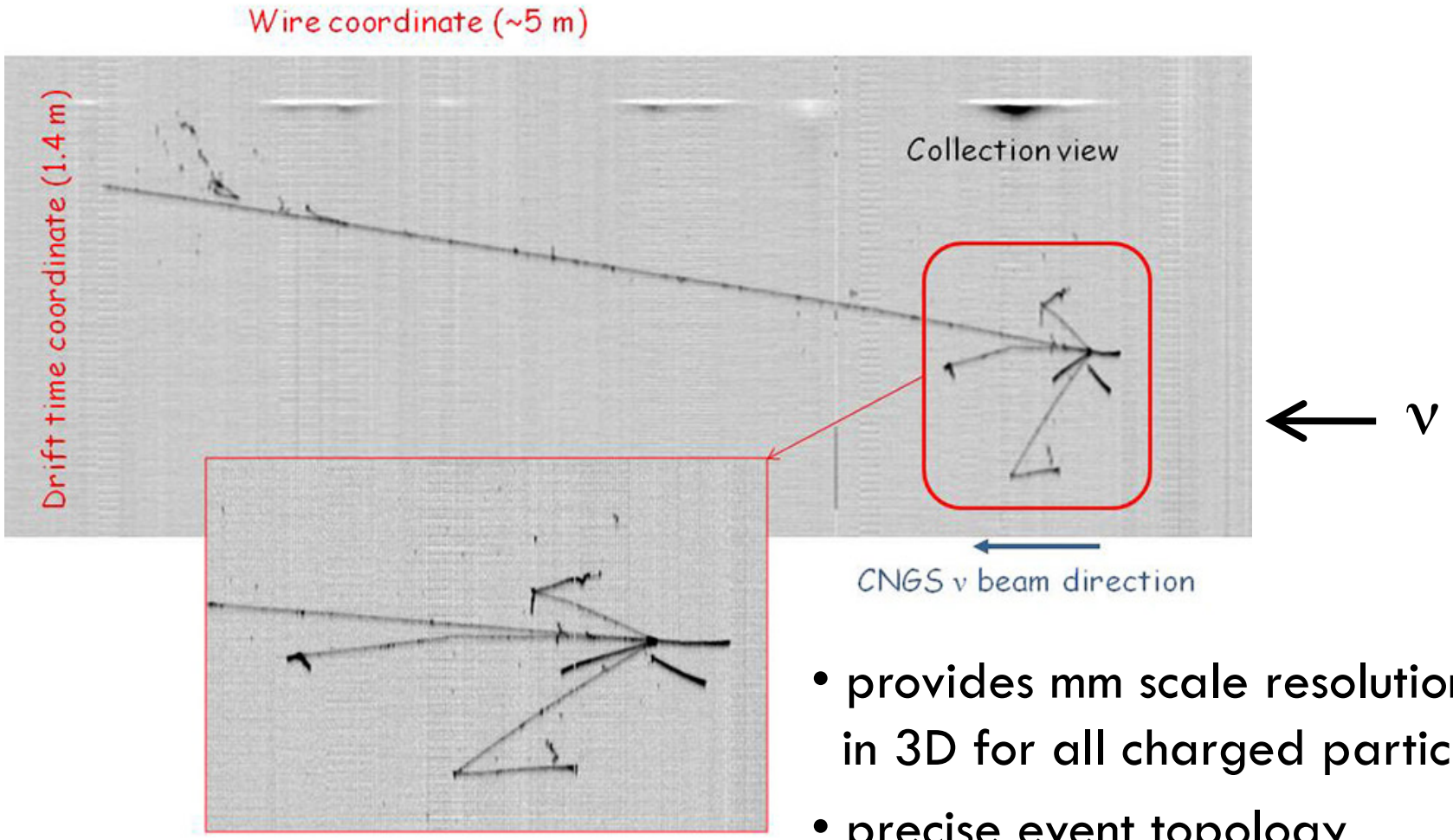


can see the precise tracks of particles produced by ν interactions in LAr

← ν

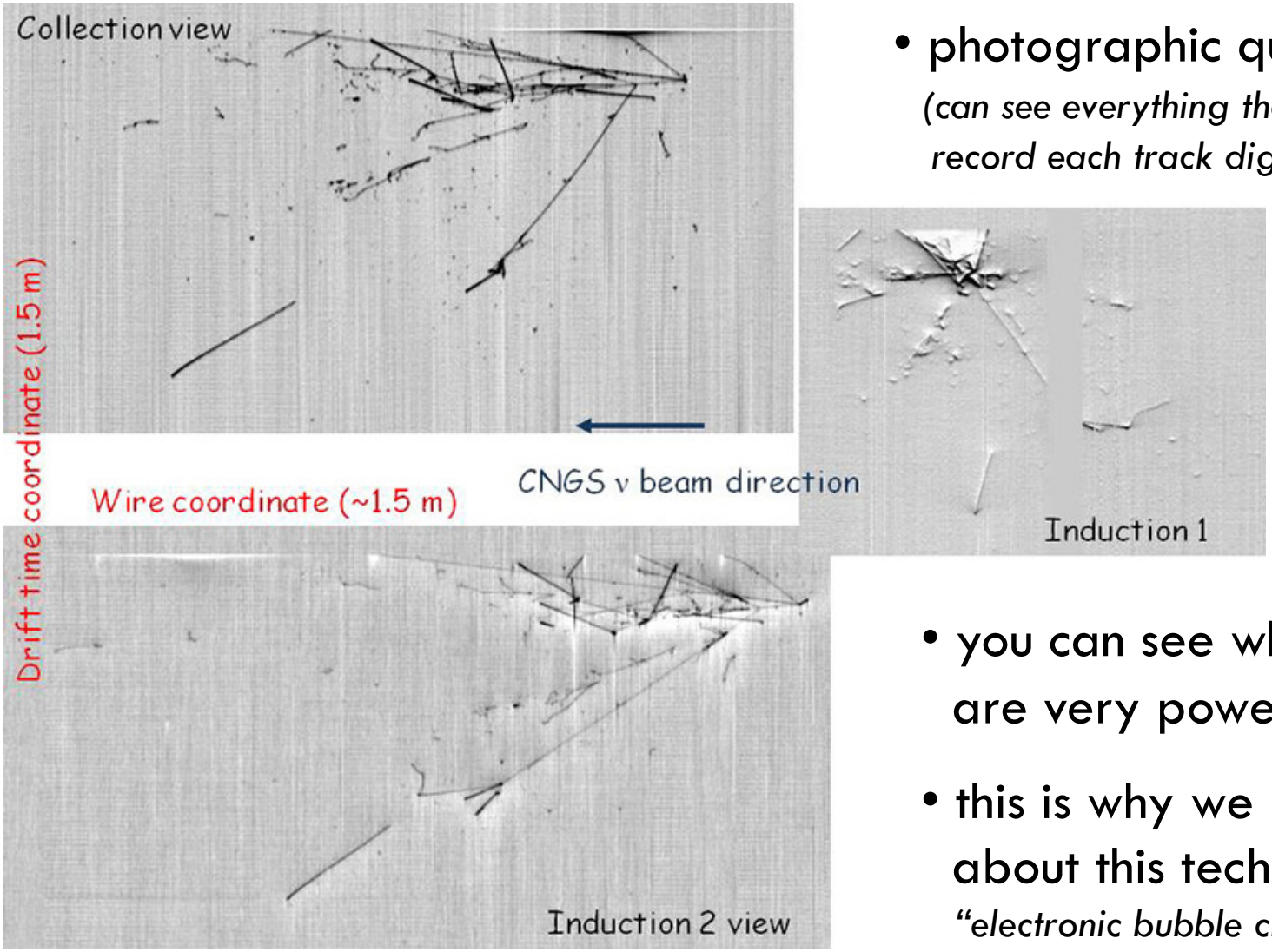
- great success! ν_S, ν_ν

ν events in the ICARUS LAr TPC



- provides mm scale resolution in 3D for all charged particles
- precise event topology
- excellent calorimetry & PID

ν events in the ICARUS LAr TPC



- photographic quality images
  (can see everything that happens and record each track digitally)

- you can see why LAr TPCs are very powerful tool

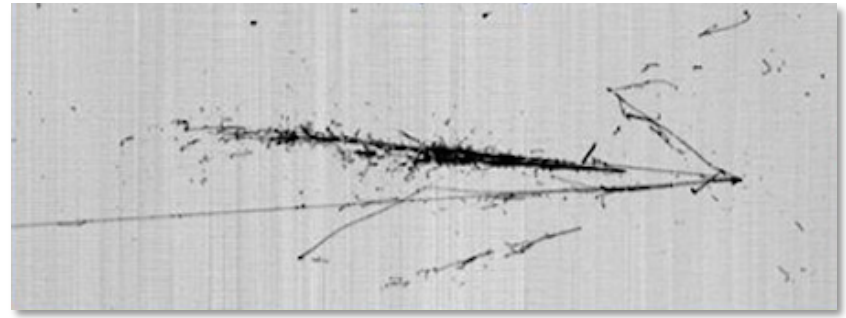
- this is why we are excited about this technology
  "electronic bubble chambers"

LAr TPCs vs. Bubble Chambers

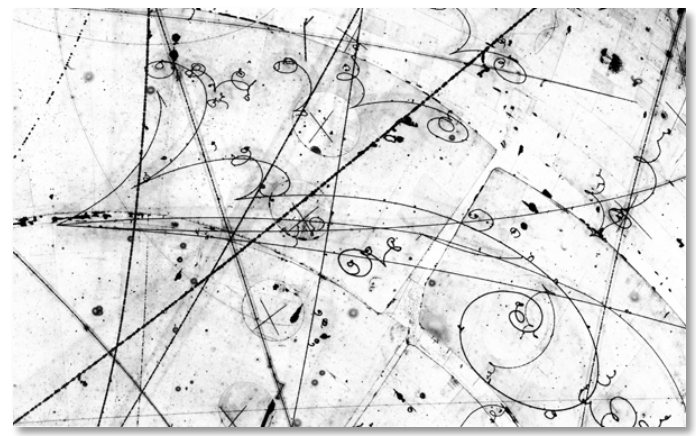
C. Rubbia CERN-EP/77-08 (1977)

	Argon	CF_3Br
Nuclear collision length	53.2	49.5 cm
Absorption length	80.9	73.5 cm
dE/dx, minimum	2.11	2.3 MeV/cm
Radiation length	14	11 cm
Density	1.40	1.50 g/cm^3

CF_3Br was used in bubble chamber Gargamelle for neutrino detection 1970-1978



(LAr TPC)



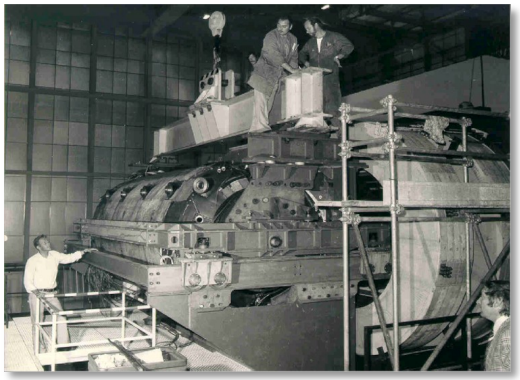
(bubble chamber)

- unlike bubble chambers, LAr TPCs provide a digital image of the event & can handle the high event rate delivered by modern particle accels

LAr TPCs

(ICARUS LAr TPC)

- advantages:
  - *faster response time; record events in real time*
  - *continuously sensitive and self-triggering*
  - *argon has high electron mobility and is also relatively inexpensive*
  - *can fill large volumes → more ν interactions!*

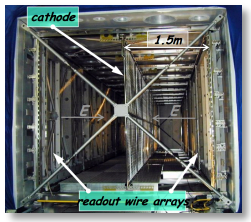


(Gargamelle bubble chamber)

- some challenges:
  - *more difficult to build & maintain than gas TPCs*
  - *LAr → cryogenic system*
  - *stringent purity requirements → purification facilities*
  - *long drift distances → high voltage*
    (important complication: breakdown voltage of LAr is a strong fcn of purity)

LAr TPC R&D in the U.S. *(+ many contributions worldwide)*

ICARUS
600 ton
2001(2010)



short
baseline
ν physics

long
baseline
ν physics

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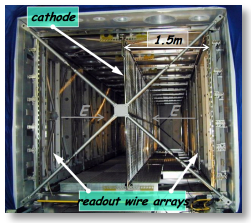
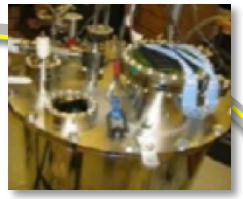
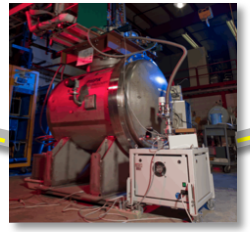


Yale TPC
0.002 ton
2007



Bo
0.02 ton
2008

ArgoNeuT
0.03 ton
2009-2010



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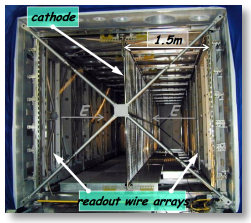

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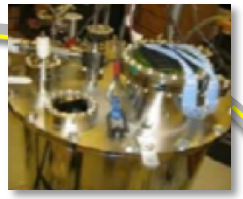

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Material Test Stand
2008+

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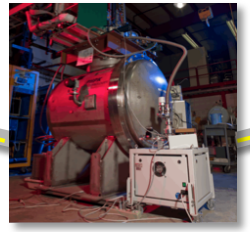

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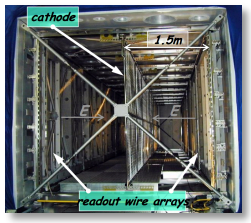

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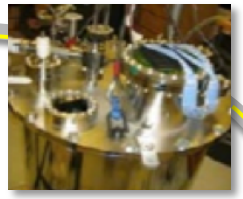

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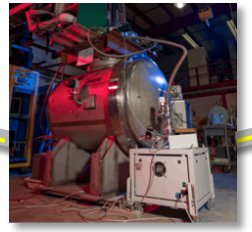
Material Test Stand
2008+

LAPD purity demonstrator
2008-2013

ArgoNeuT
0.03 ton
2009-2010



short *baseline* ν *physics*

long *baseline* ν *physics*

LAr TPC R&D in the U.S. *(+ many contributions worldwide)*

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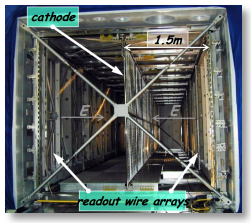

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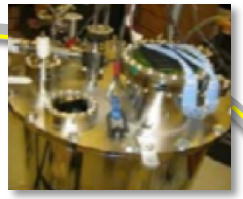

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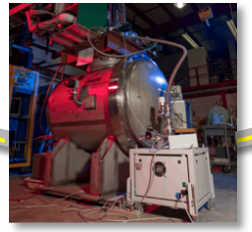

LArIAT, CAPTAIN
testbeams
2014

short
baseline
ν physics

long
baseline
ν physics

LAr TPC R&D in the U.S. *(+ many contributions worldwide)*

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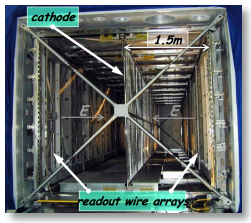
600 ton
2001(2010)



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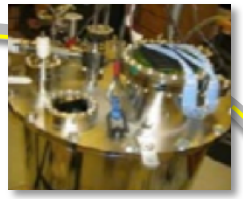

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2008-2013

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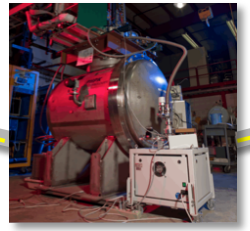
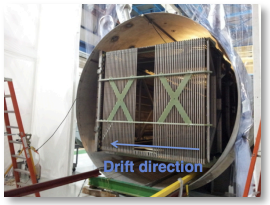
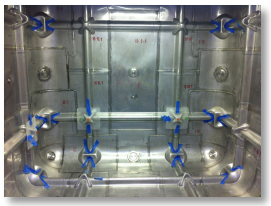


LArIAT, CAPTAIN
testbeams
2014

MicroBooNE
170 ton
2014



LBNE prototype
35 ton
2013-2014



short *baseline* *ν physics*

long *baseline* *ν physics*

LAr TPC R&D in the U.S. *(+ many contributions worldwide)*

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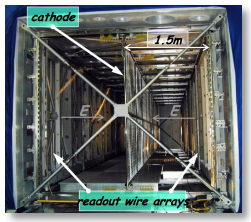
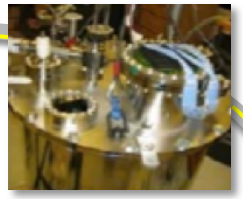
600 ton
2001(2010)



Yale TPC
0.002 ton
2007

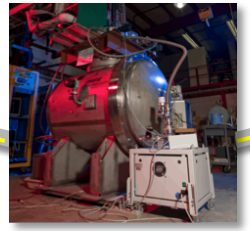


Bo
0.02 ton
2008

Material Test Stand
2008+

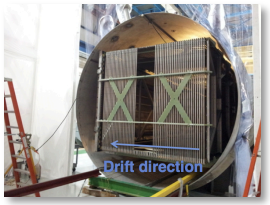
LAPD purity demonstrator
2008-2013

ArgoNeuT
0.03 ton
2009-2010

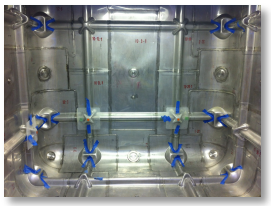


LArIAT, CAPTAIN
testbeams
2014

MicroBooNE
170 ton
2014



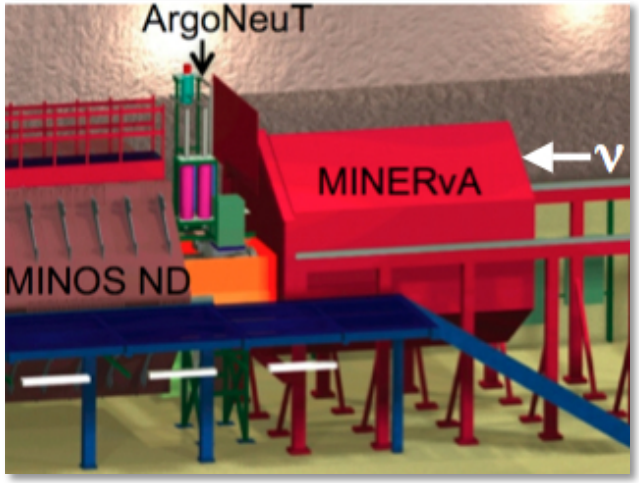
LBNE prototype
35 ton
2013-2014

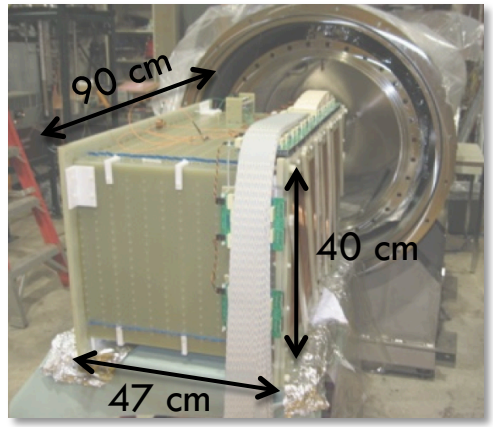


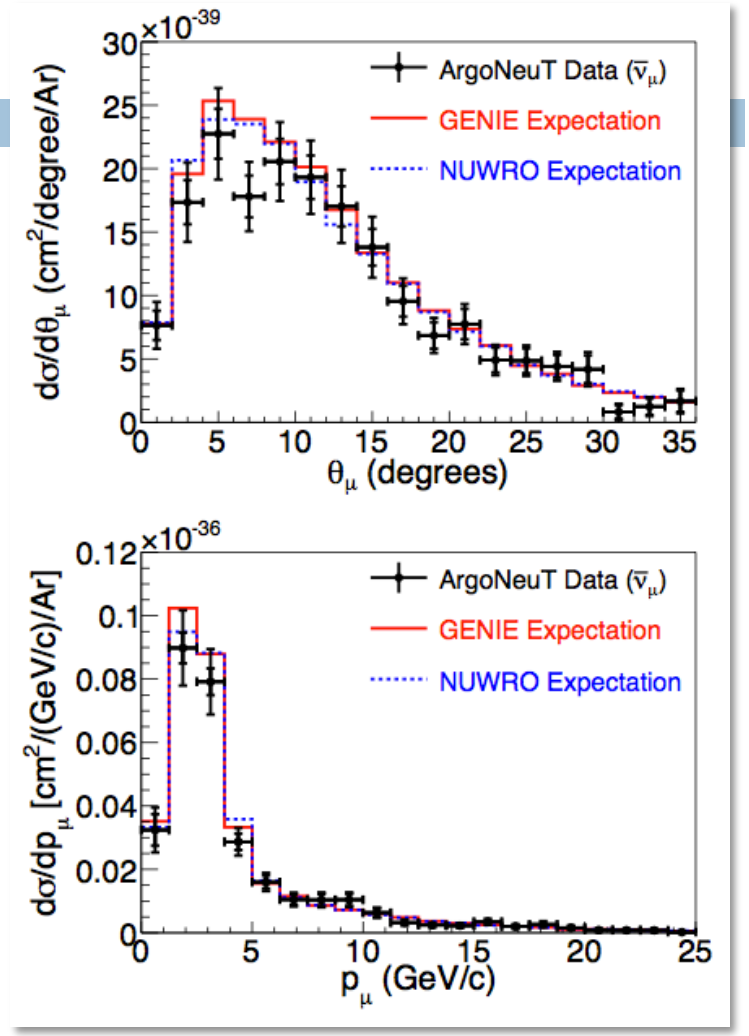
short *baseline* ν *physics*

long *baseline* ν *physics*

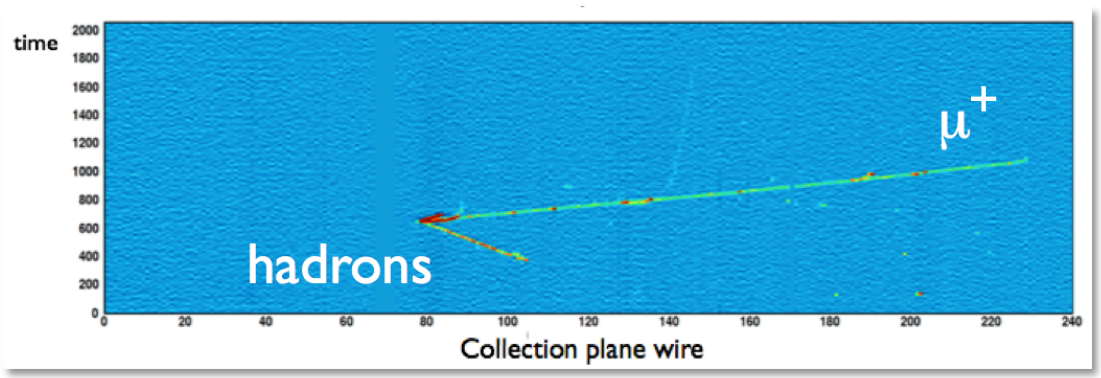
ArgoNeuT







- 170 liter LAr TPC (table top), first LAr TPC in the U.S. to ever record neutrino data
  - *NuMI beam at Fermilab (2009-2010), >8k ν and $\bar{\nu}$*

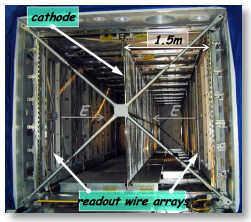


- first measurement of $\bar{\nu}_\mu$ cross section on argon

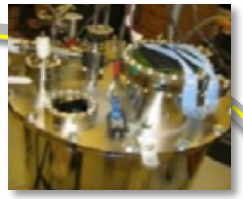
arXiv:1404.4809

LAr TPC R&D in the U.S. *(+ many contributions worldwide)*

ICARUS
600 ton
2001(2010)



Yale TPC
0.002 ton
2007



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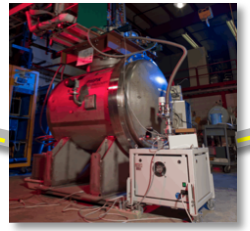
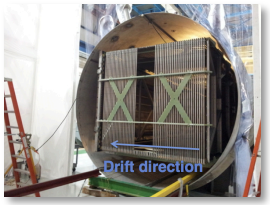
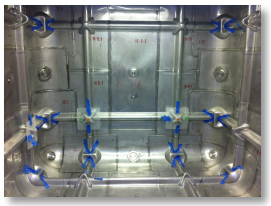


LArIAT, CAPTAIN
testbeams
2014

MicroBooNE
170 ton
2014



LBNE prototype
35 ton
2013-2014

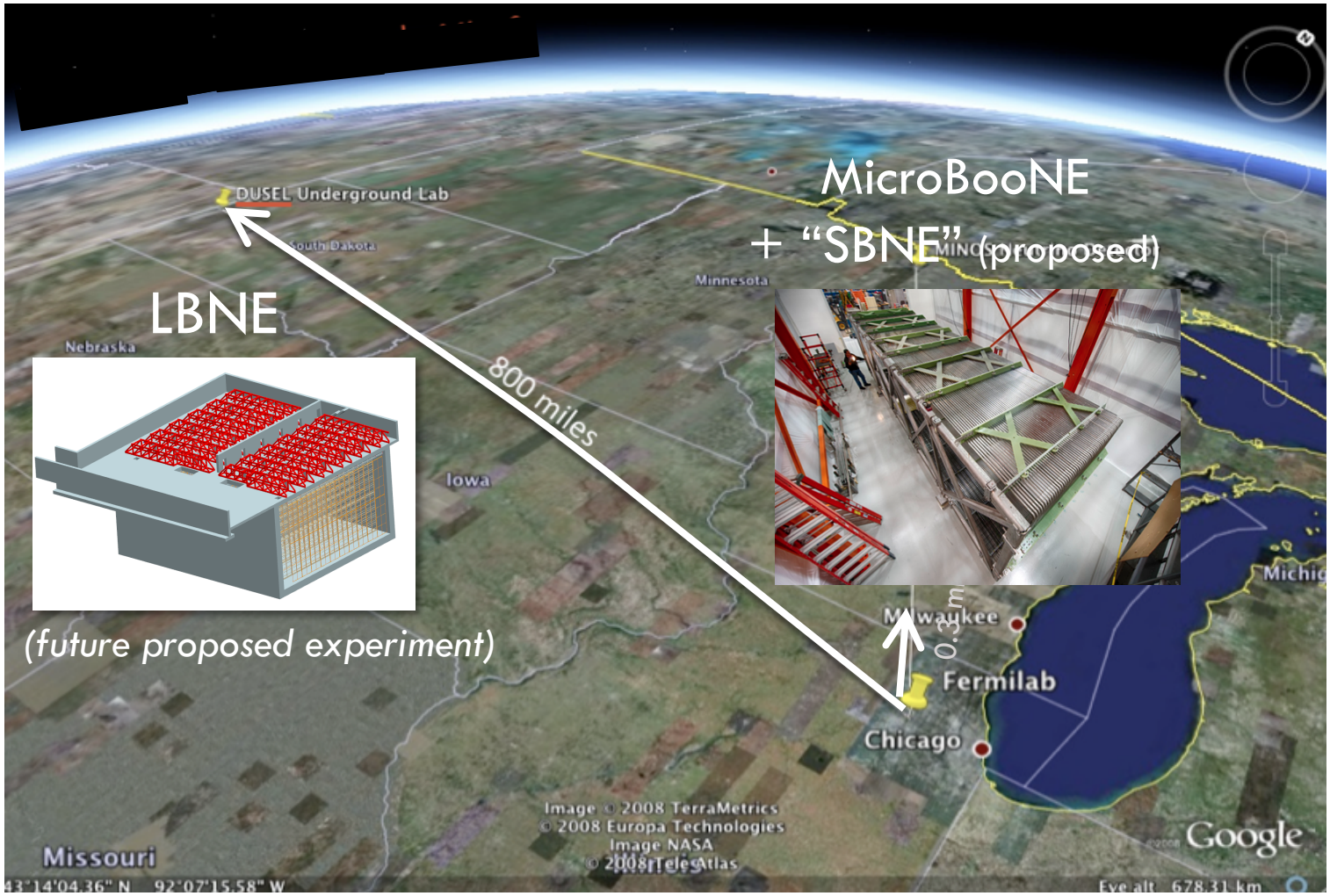


short *baseline* *ν physics*

long *baseline* *ν physics*

Future LAr TPC Program at Fermilab

- Fermilab is the only facility in the world that simultaneously operates



both a **low** and a **high** energy ν beam

this enables both **short** and **long** baseline ν oscillation experiments

currently delivering beam to MiniBooNE & NOvA, MINERvA, MINOS+

Big Questions

- these are the questions that will be driving the experimental program in neutrino physics for the next decade and beyond …

- how much do neutrinos weigh?

- what is the nature of the ν?

β decay
and $0\nu\beta\beta$ decay

Big Questions

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- how much do neutrinos weigh?

- what is the nature of the ν?

β decay
and 0νββ decay

- which neutrino is the heaviest and which is the lightest (MH)?

- do neutrinos violate CP?

- is our picture correct?

long-baseline
neutrinos

Big Questions

- these are the questions that will be driving the experimental program in neutrino physics for the next decade and beyond …

- how much do neutrinos weigh? ***- what is the nature of the ν?***	β decay and $0\nu\beta\beta$ decay
- which neutrino is the heaviest and which is the lightest (MH)? ***- do neutrinos violate CP?***	long-baseline neutrinos
- is our picture correct?	
- are there more than 3 kinds of neutrinos?	short-baseline neutrinos

Big Questions

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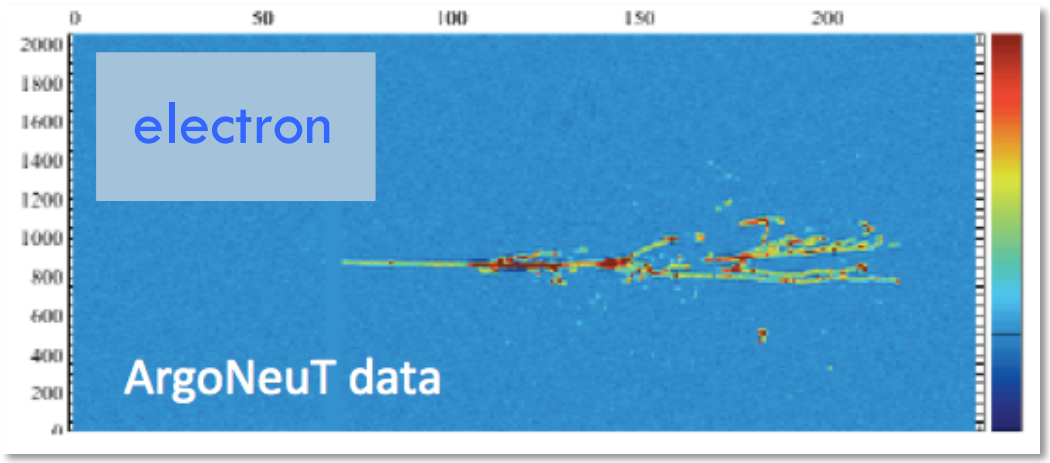
- how much do neutrinos weigh? ***- what is the nature of the ν?***	β decay and $0\nu\beta\beta$ decay
- which neutrino is the heaviest and which is the lightest (MH)? ***- do neutrinos violate CP?***	long-baseline neutrinos
- is our picture correct?	
- are there more than 3 kinds of neutrinos?	short-baseline neutrinos

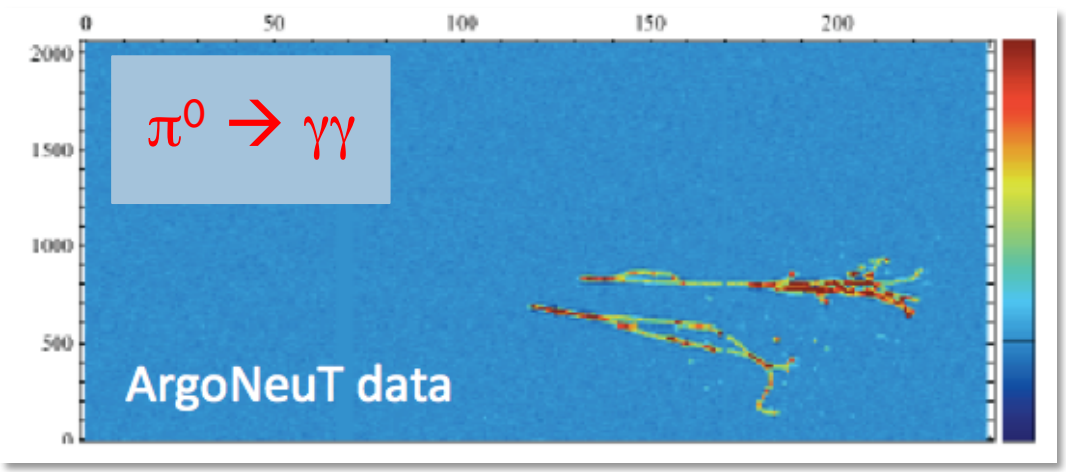
liquid argon TPCs!

$\nu_\mu \rightarrow \nu_e$

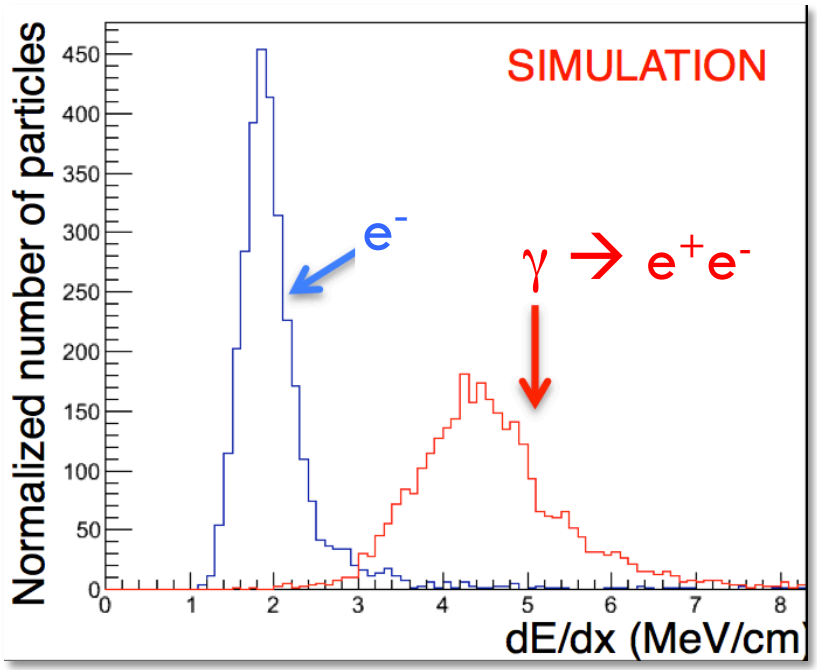
e/γ Separation

- both short and long baseline oscillation experiments will probe $\nu_\mu \rightarrow \nu_e$





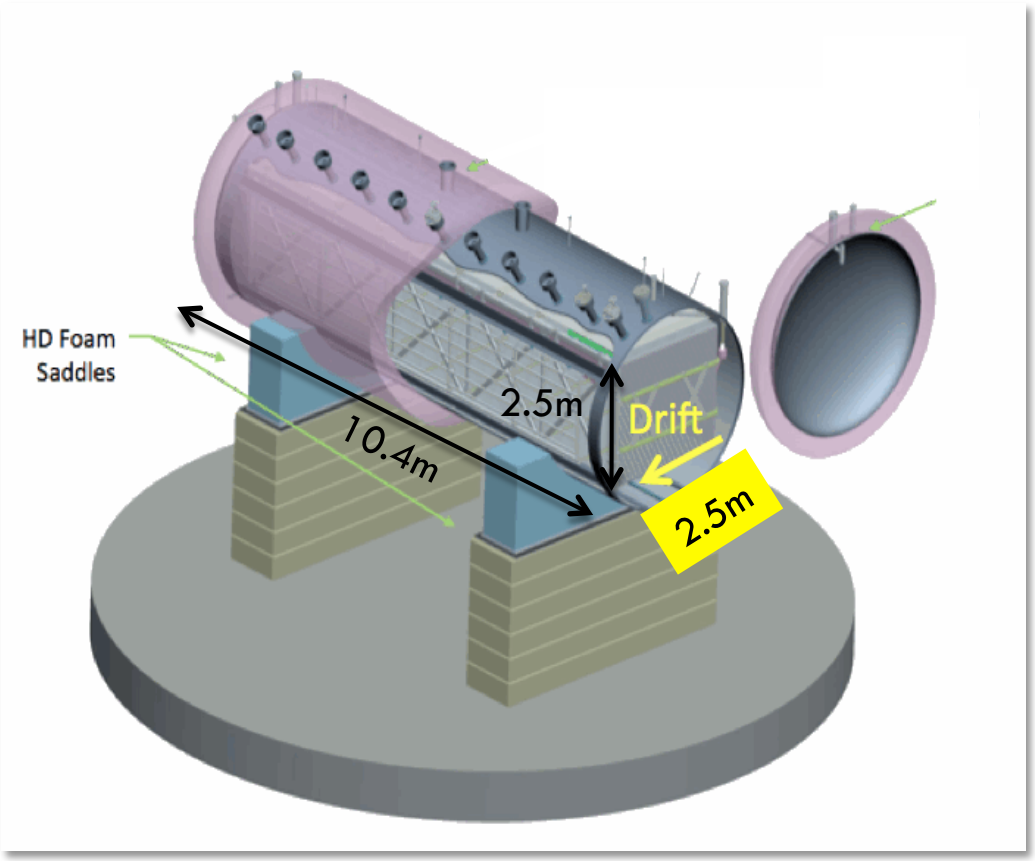
- LAr TPCs are a game-changer for ν_e appearance physics



>90% e^- efficiency, >90% γ rejection

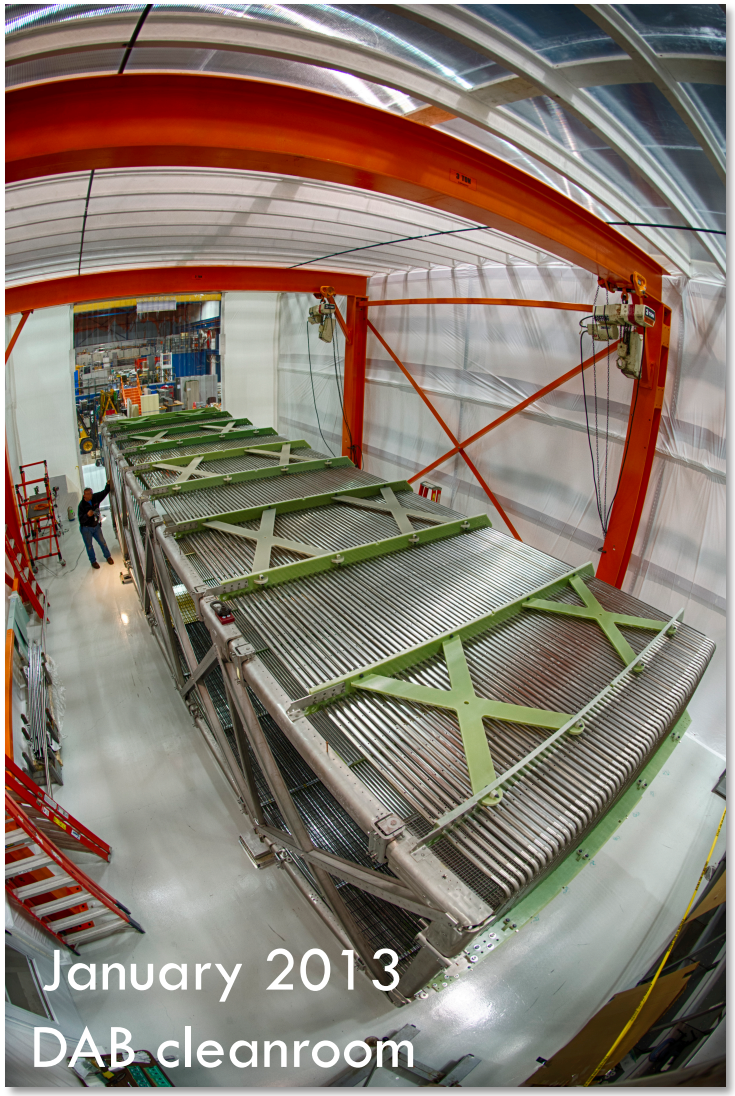
MicroBooNE

- we are currently building MicroBooNE
- 170 ton liquid argon TPC, the largest ever built in the U.S.



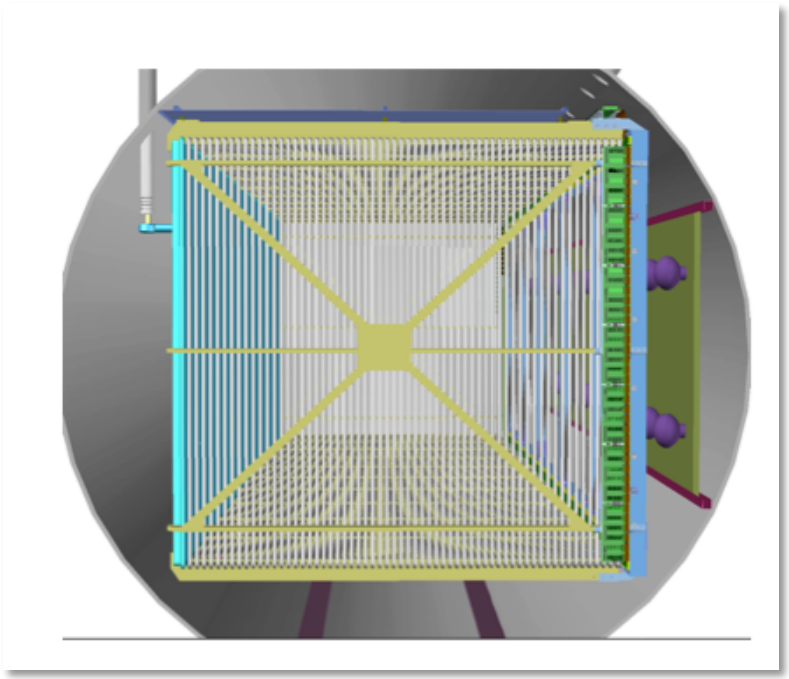
- several advances:
  - *argon fill without evacuation*
  - *cold front-end electronics*
  - *long drift (2.5m)*
  - *near surface operation*
  - *automated ν reconstruction*
- this is key R&D for future large scale LAr TPCs

MicroBooNE Cryostat and TPC

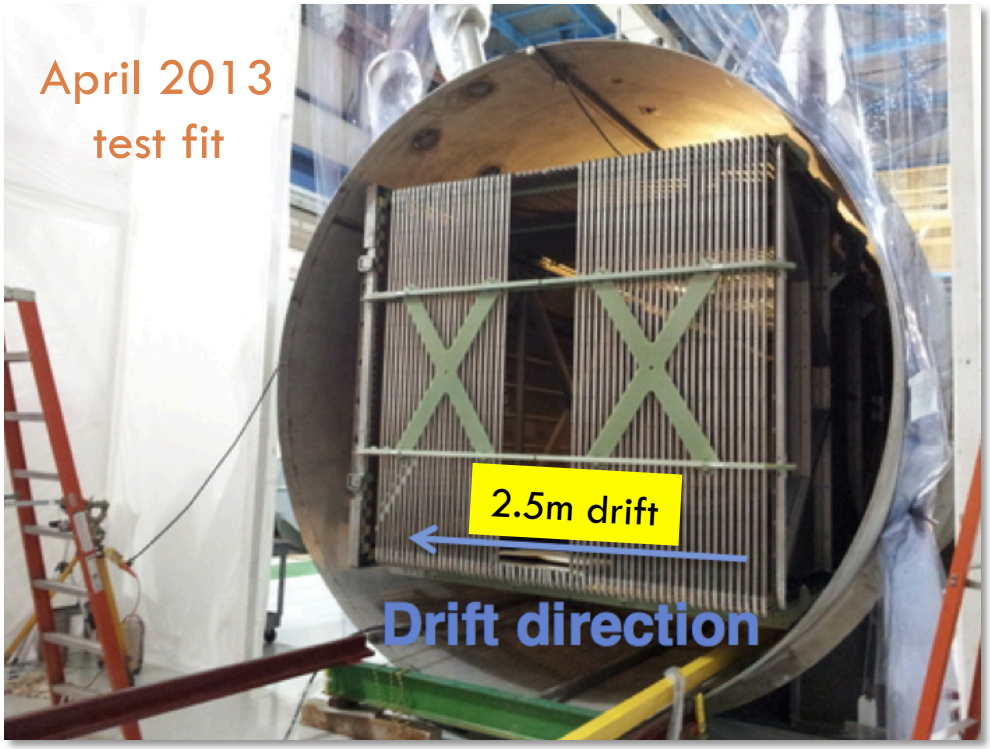


MicroBooNE TPC

- stainless steel tubes maintain a constant electric field gradient along the drift length supported by insulating G10 braces; 2.5m drift

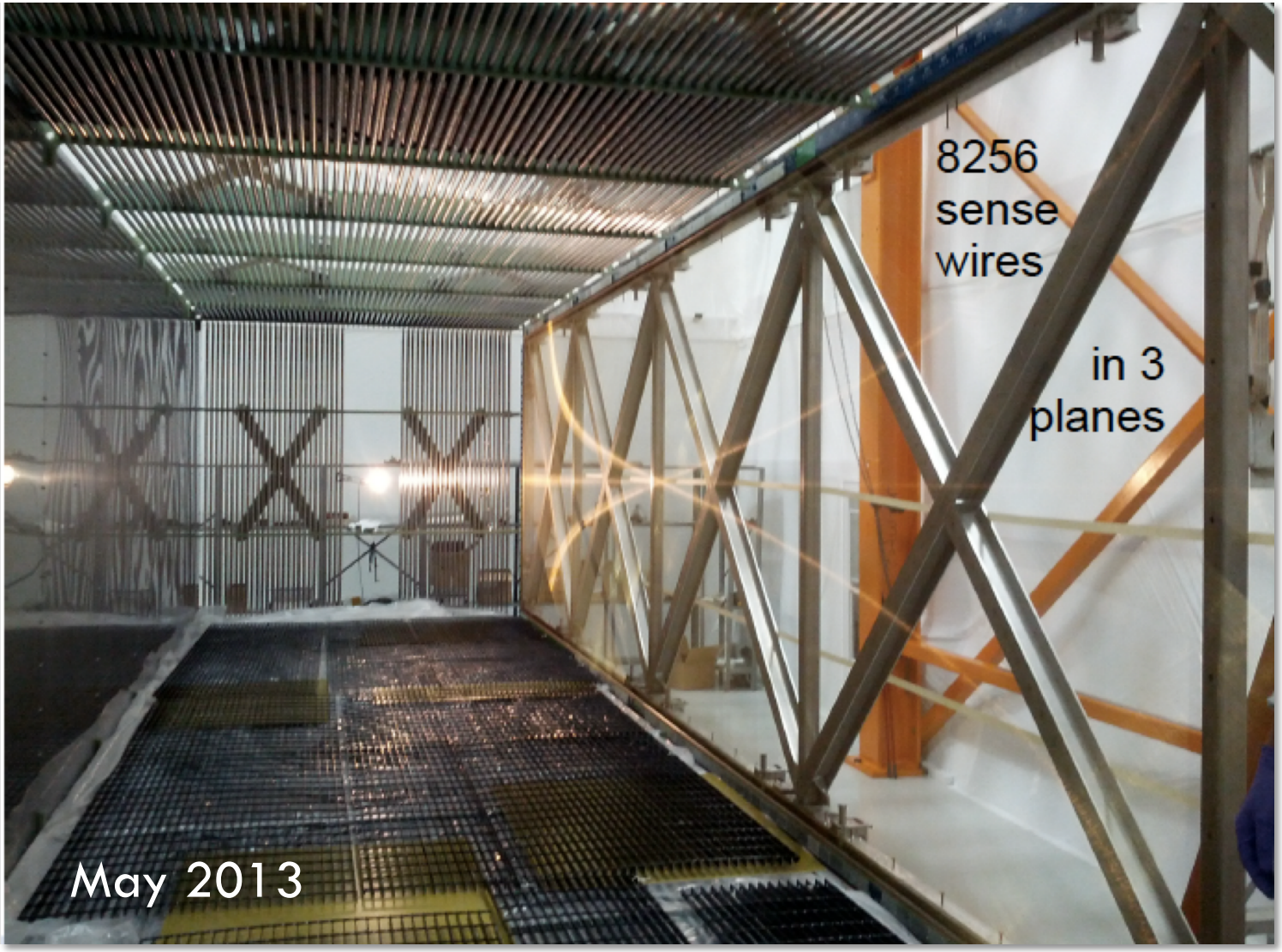


(uni-directional)



(ideally, we would like this drift distance as long as possible)

MicroBooNE TPC



- ionization electrons drifted through the wire planes are then readout by custom cold CMOS ASIC electronics

(designed & built by BNL)

MicroBooNE Photo Detection System

Final Insertion in the Cryostat

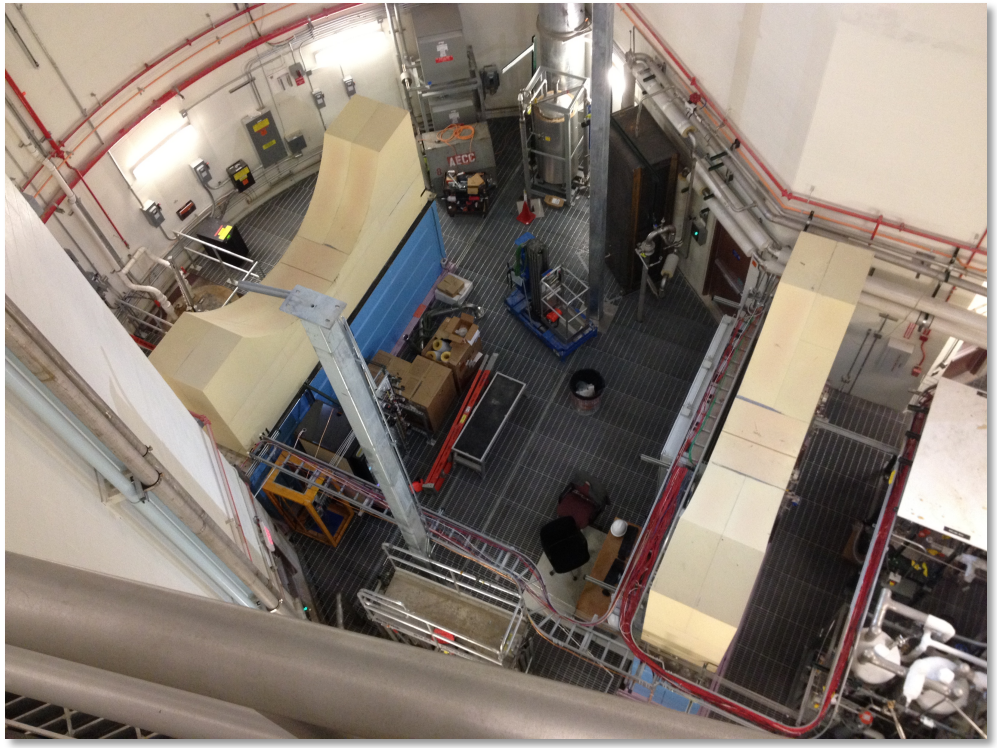
MicroBooNE Detector Building

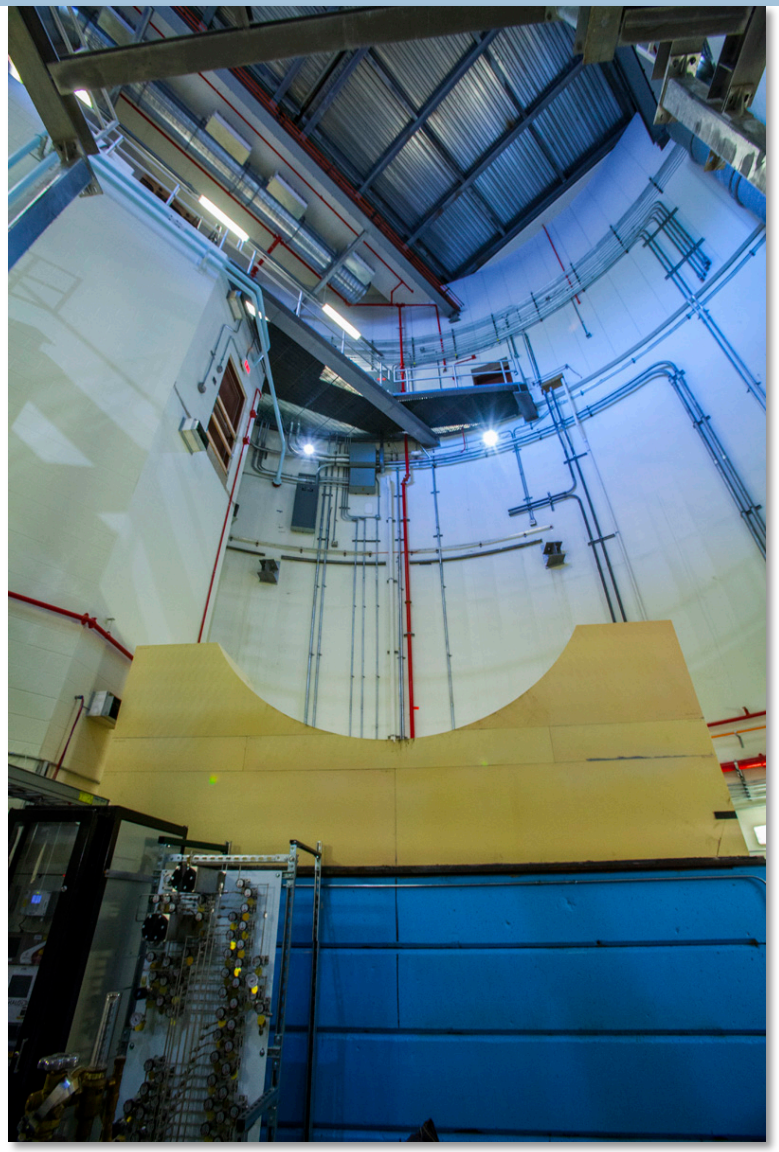
- new building where the detector will eventually be housed on the Fermilab Booster neutrino beam is ready and is being outfitted
  (detector will be 25 feet below grade, on beam axis)

- LArTF = Liquid Argon Test Facility

MicroBooNE Detector Building

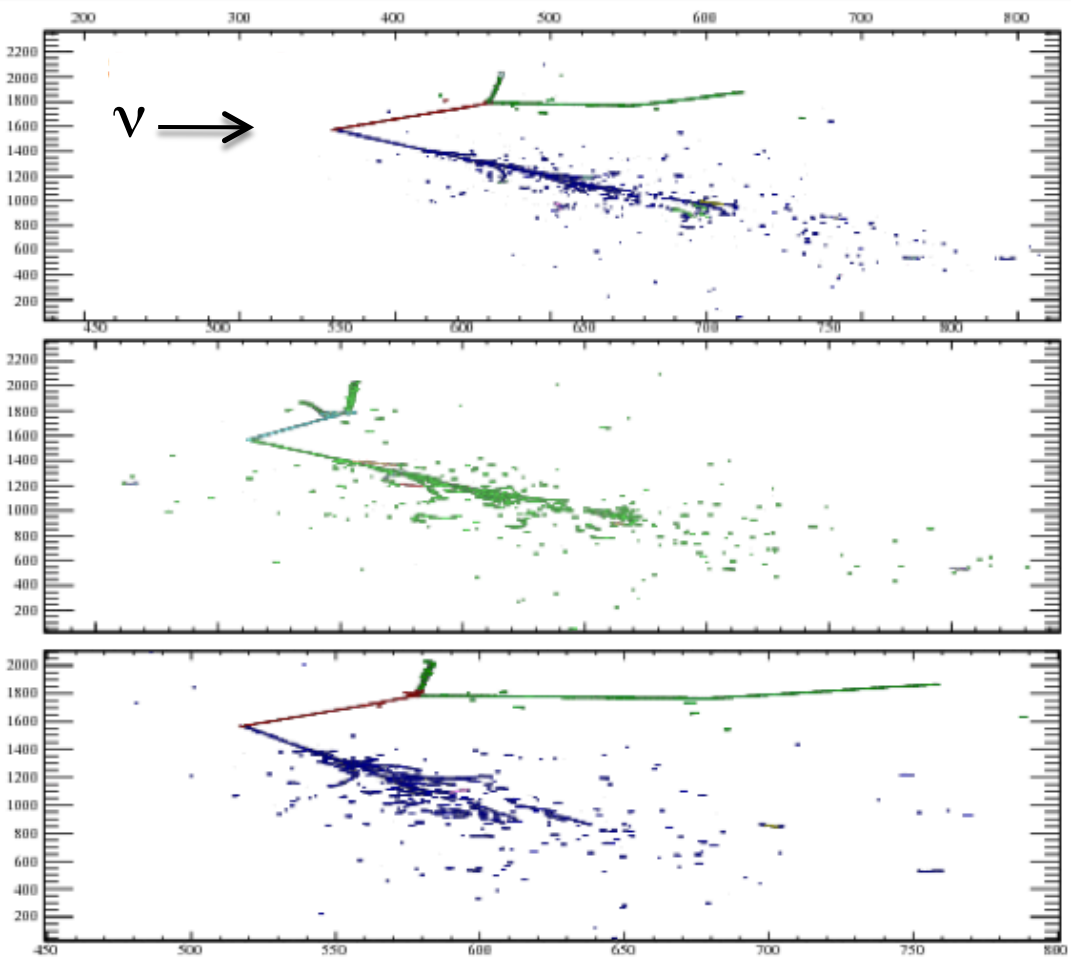
- last month, we started circulating and purifying liquid argon





- building is ready for the detector!

MicroBooNE



(simulated ν interaction in MicroBooNE and output of clustering algorithm)

- commissioning this new detector this year and will embark on a multi-yr run
- <u>MicroBooNE's goals</u>:
  - *determine the source of the low energy event excess seen in MiniBooNE*
  - *measure neutrinos interactions in argon*
  - *provide an important test of the LAr TPC technology*

Short-Baseline ν Oscillations

Existing enclosure vacated by SciBooNE detector

Phase 0: MicroBooNE
86 t active volume TPC
L = 470 m
start in 2014

Phase 1: LAr1-ND
82 t active volume TPC
L = 100 m
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

- proposal to stage multiple LAr TPCs along FNAL BNB
- sterile neutrinos!

Short-Baseline ν Oscillations

Existing enclosure vacated by SciBooNE detector

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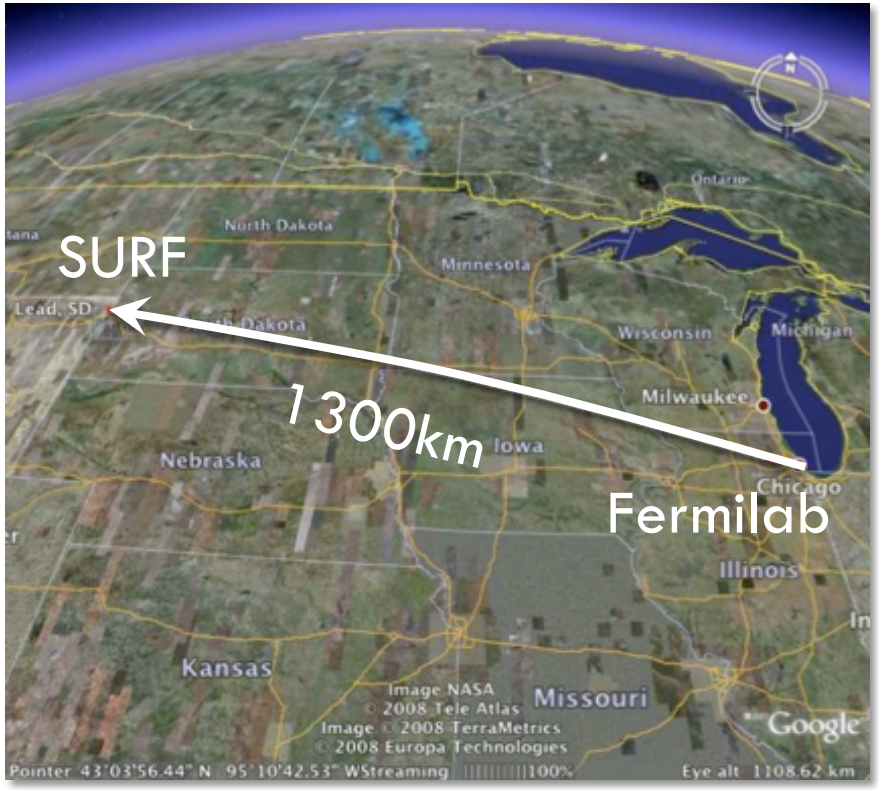
2017-2018

Phase 2: LAr1-FD
1000 t active volume TPC
L = 700 m
2020+

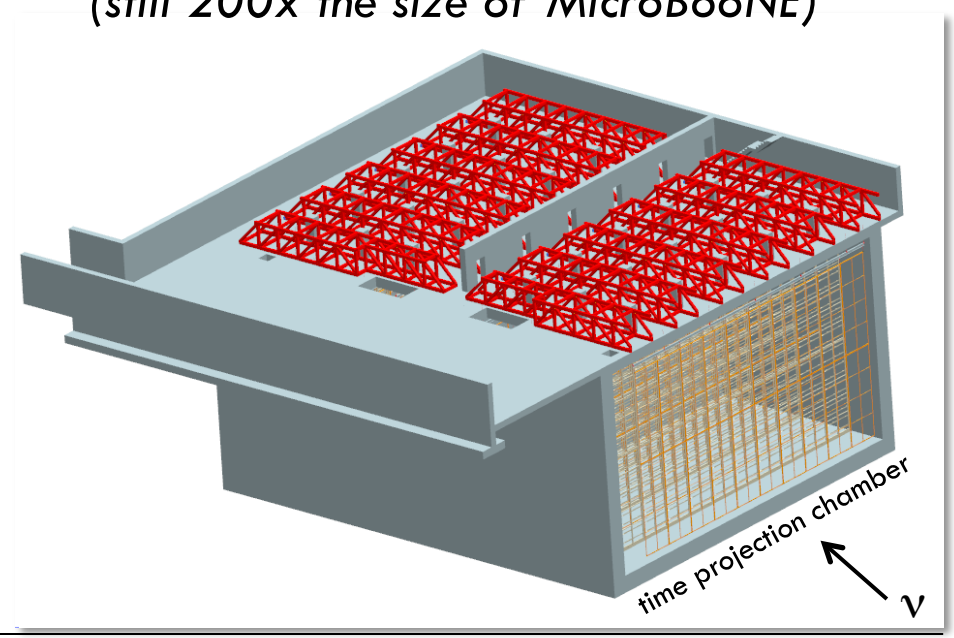
- *working with ICARUS team to explore bringing refurbished T600 to FNAL*

- sterile neutrinos!

Long-Baseline Neutrino Experiment (LBNE)



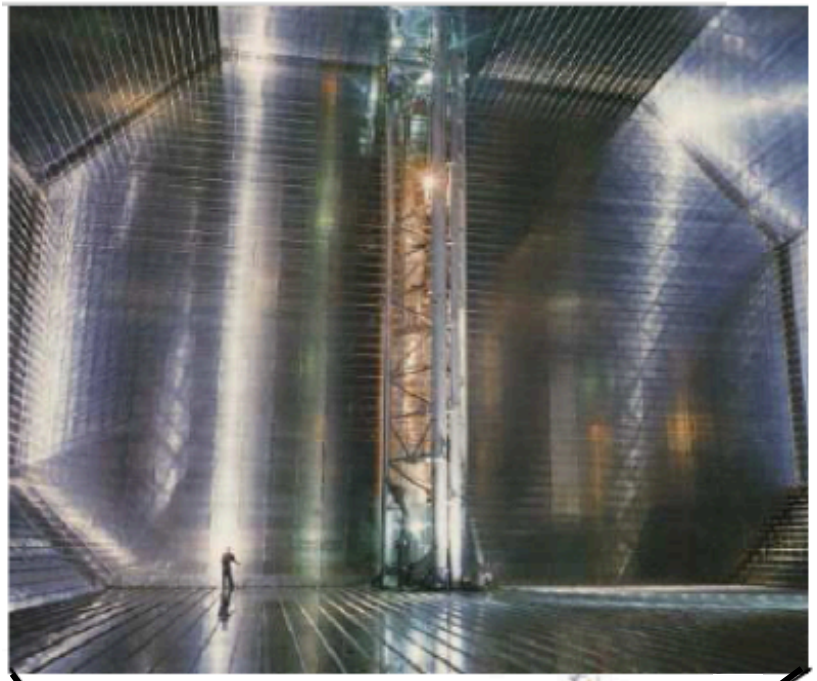
- three ingredients:
- <u>1300 km baseline</u>
  - *optimized for joint $\not{C}\not{P}$, MH determination*
- <u>Liquid Argon TPC</u>
  - *massive 34 kton detector underground*
  - *high ε, so need less detector mass (still 200x the size of MicroBooNE)*

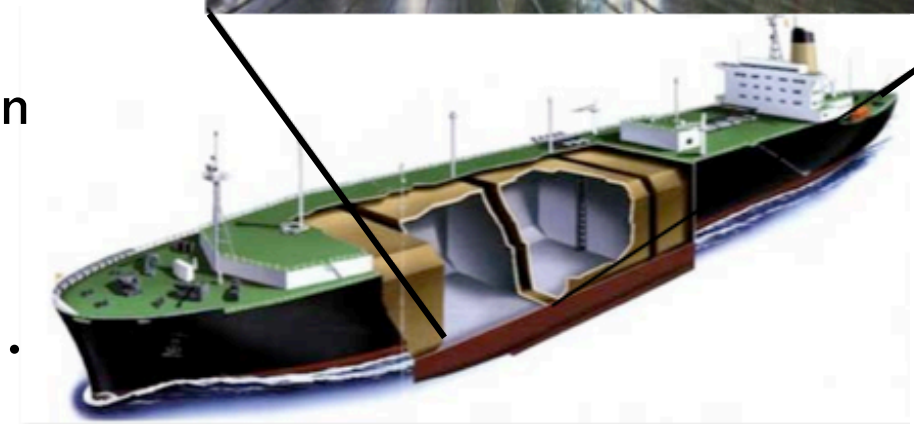


- <u>on-axis, wide band beam</u> (ν, $\bar{\nu}$)
  - *want to measure the spectrum of ν's across largest possible dynamic range*

LBNE Far Detector

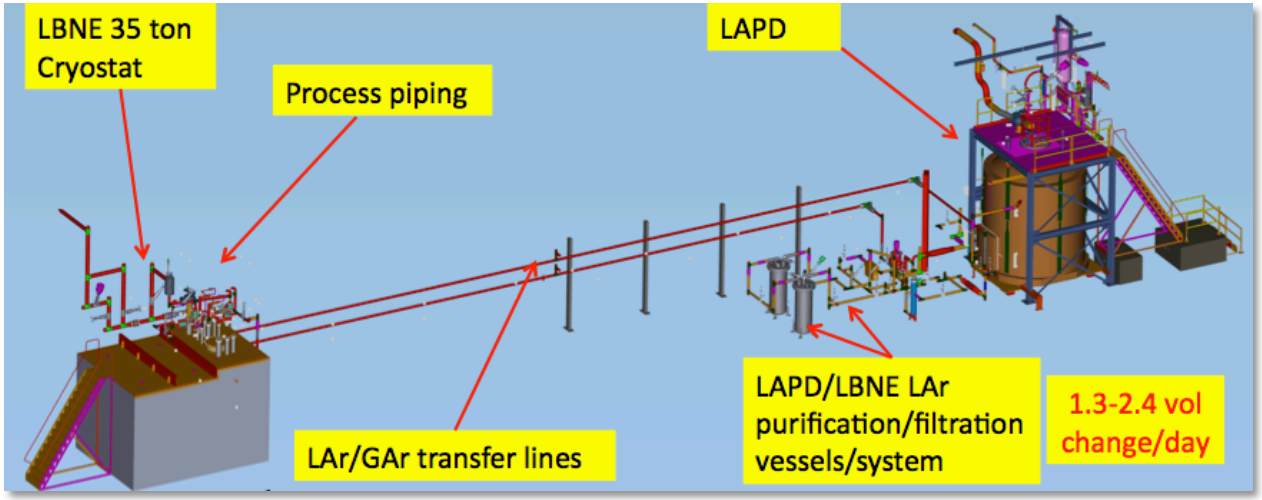
- detector vessel will be constructed using the same membrane cryostat technology that has been used in the liquified natural gas industry
  - *thin polished stainless steel membrane surrounded by thick foam insulation*
- the main difference is that the argon (in our case) must remain ultra pure in such a vessel
- so you would like to test this …





LBNE 35 ton Prototype

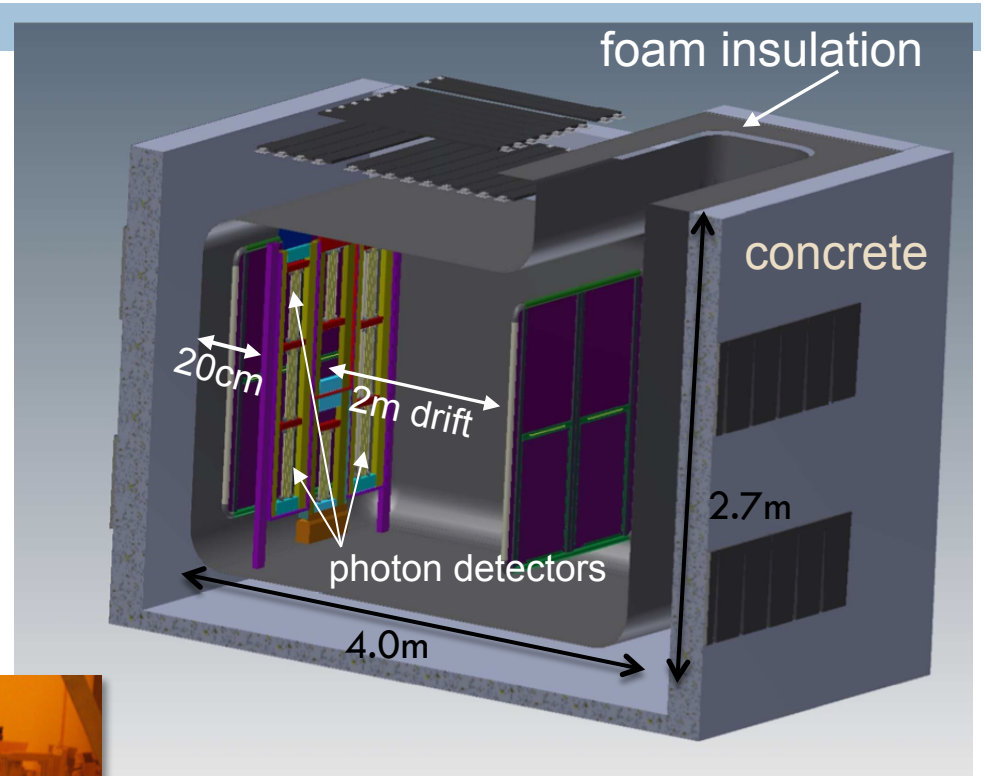
- first and only membrane cryostat built for scientific purposes
- view inside of the 35 ton prototype before filled with LAr



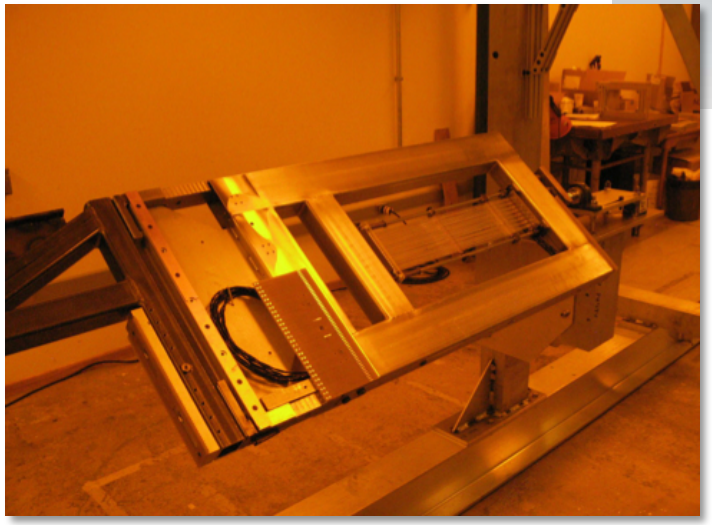
- plumbed into the existing cryogenic & purification infrastructure from LAPD

LBNE 35 ton Prototype

- earlier this year, demonstrated that high purity operation is achievable in membrane cryostat
  (3.0 ms e^- lifetime, 100 ppt O_2 achieved)

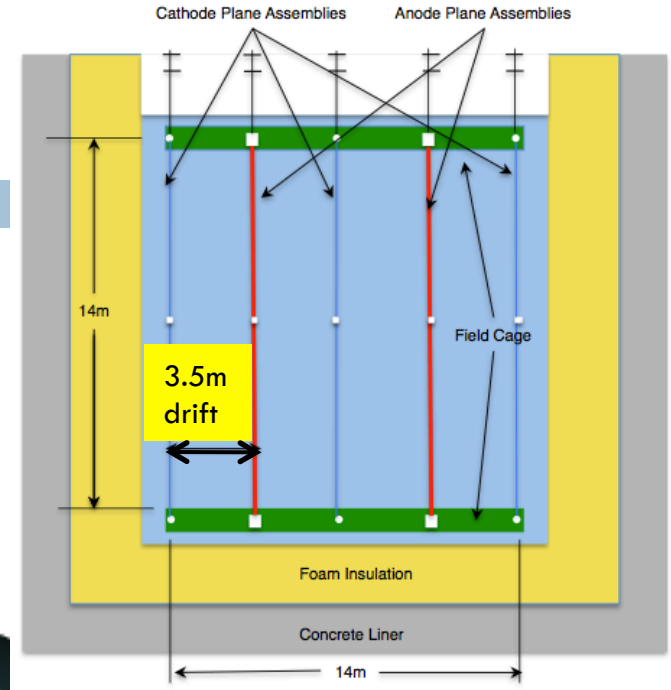


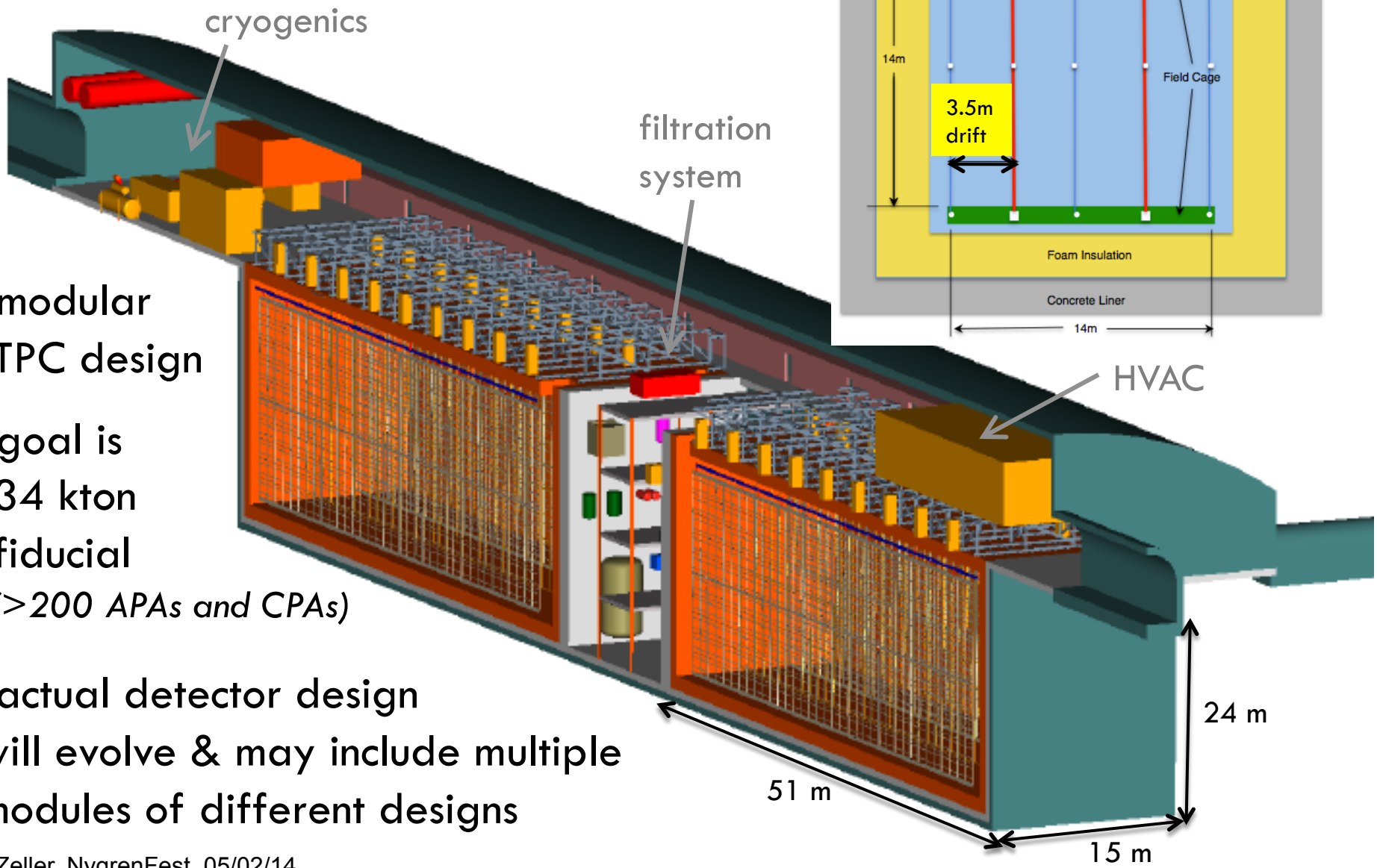
- next step, will install a small-scale TPC inside for cosmic ray data taking in 2015



- is providing important input to the design of the LBNE FD
- <u>now we just need ~1,000 of these a mile underground!</u>

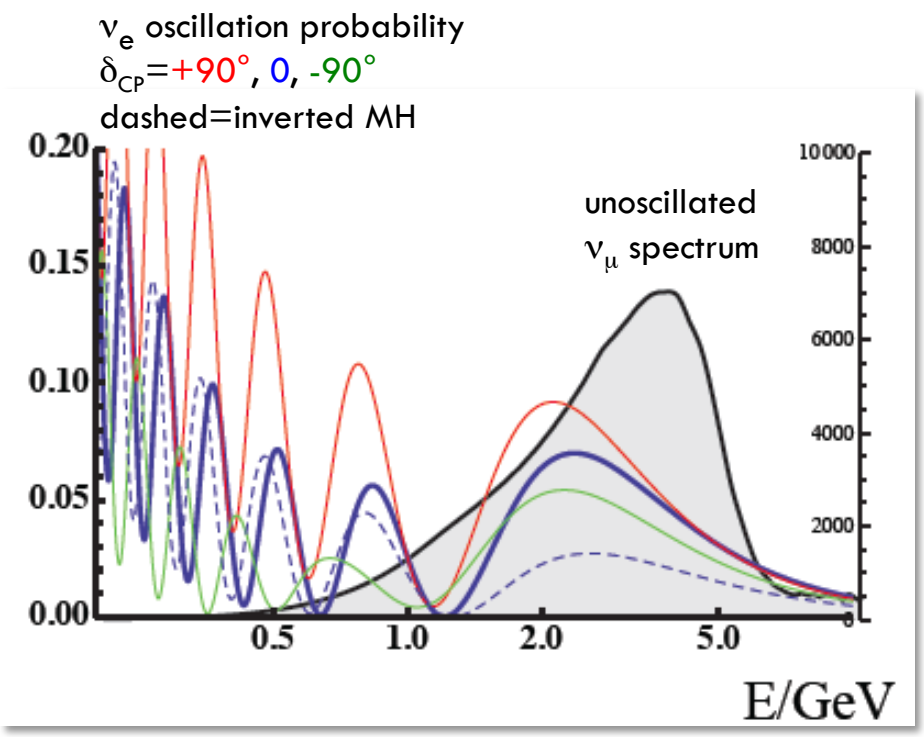
LBNE Far Detector





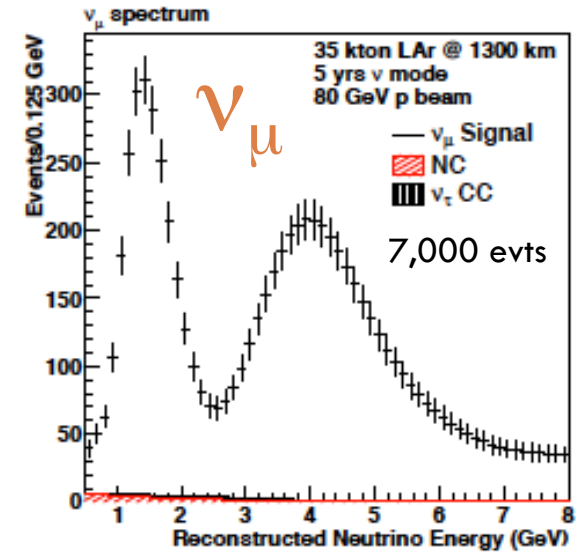
- modular TPC design
- goal is 34 kton fiducial
  (>200 APAs and CPAs)
- actual detector design will evolve & may include multiple modules of different designs

This is What LBNE Can Do



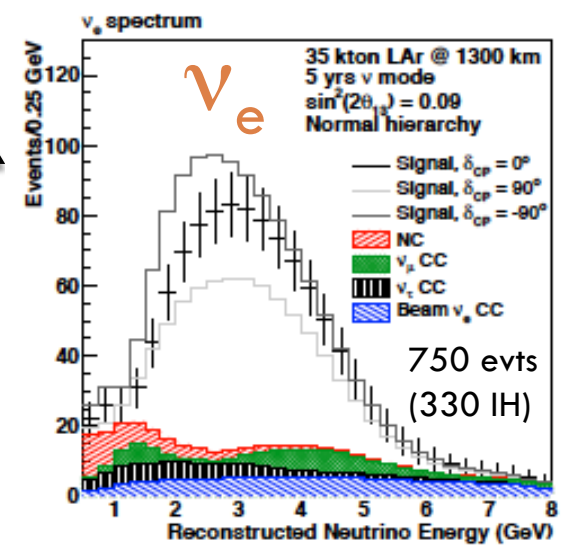
$\nu_\mu \not\rightarrow \nu_\mu$

disappearance



$\nu_\mu \rightarrow \nu_e$

appearance

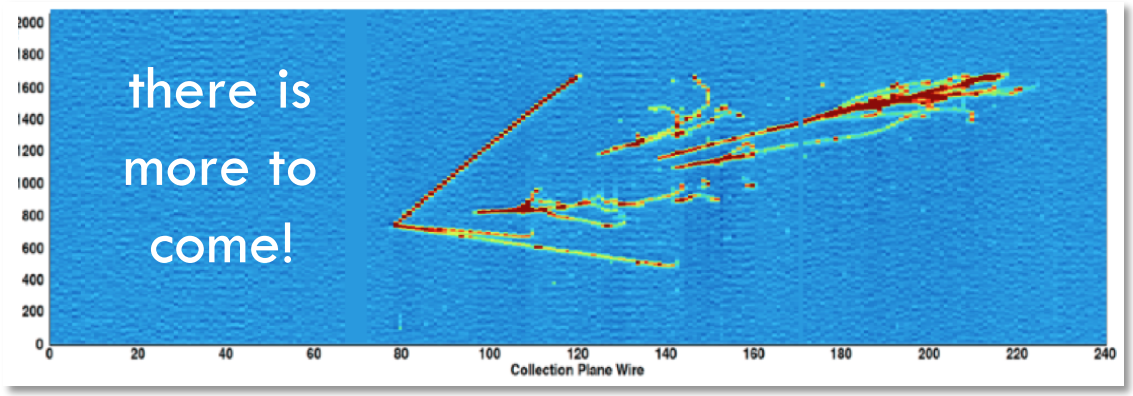


- plus, underground LBNE detector will be exquisitely sensitive to atmospheric ν's, supernova ν's, and proton decay

(arXiv:1307.7335)

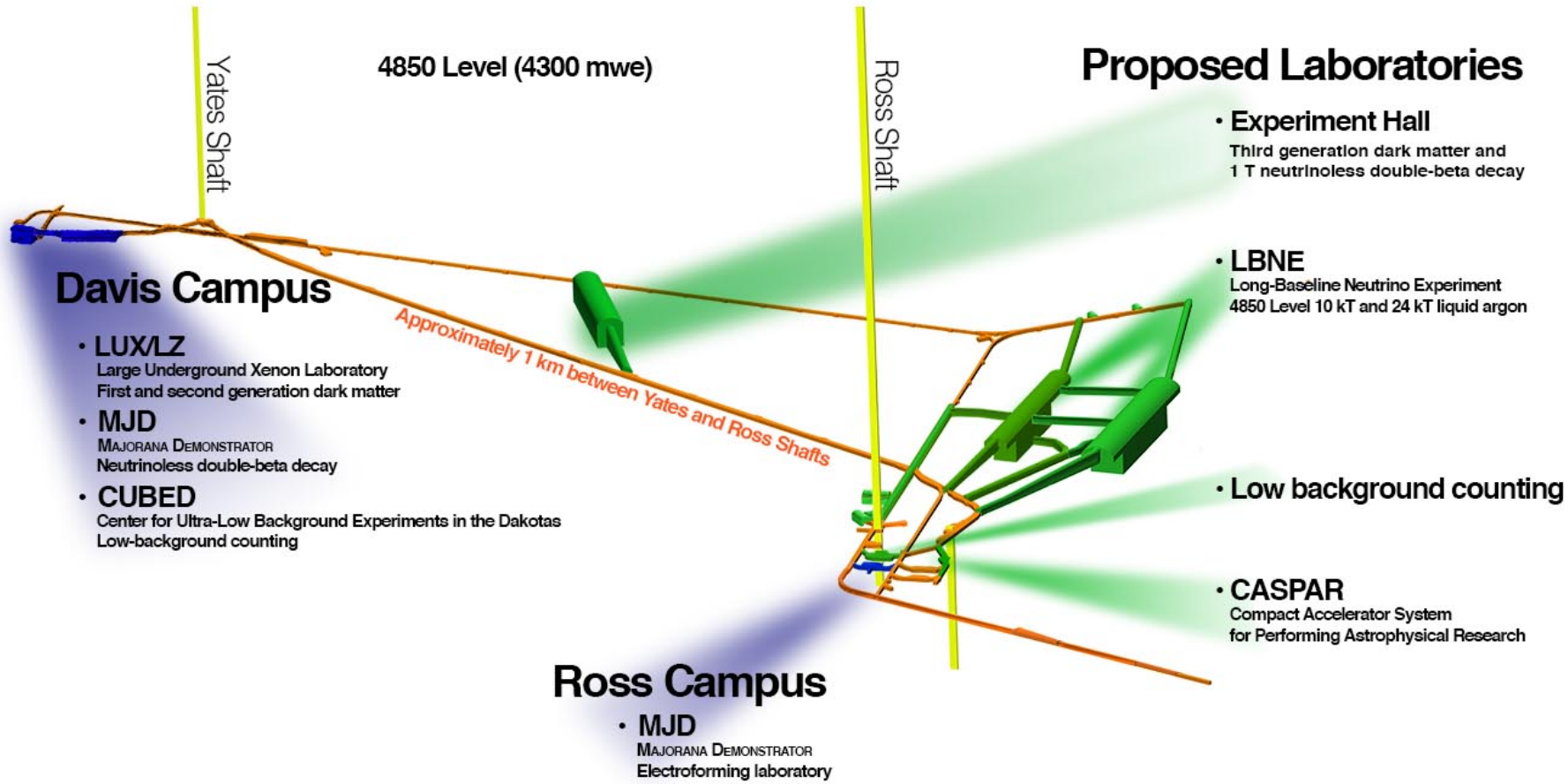
Conclusions

- LAr TPCs allow us to study ν properties in unprecedented detail
- these detectors are optimal for ν detection and are the technology of choice for future short & long baseline accelerator-based ν experiments that will answer major questions about ν's and their properties
- int'l community is working together to make this program a reality
- credit goes to Dave for the invention of a lasting concept (TPC) which has continued to evolve
  - for ν's we are really only getting started with our use of LAr TPCs
- this is an exciting time



Backups

Planned LBNE Caverns at SURF

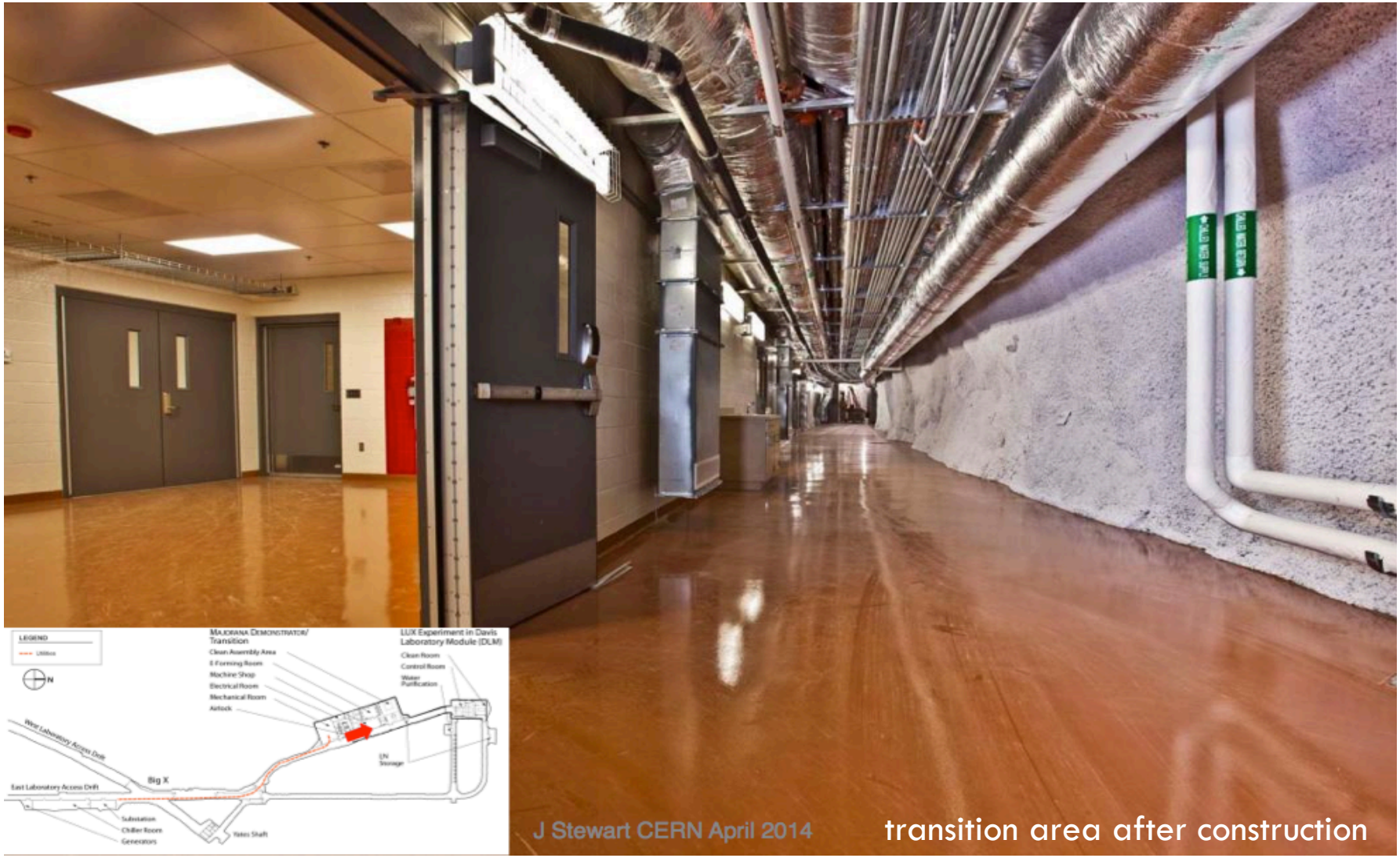


(actual layout will follow from detector design(s) agreed upon with international partners)

SURF

- Ross shaft at 800L before and after refurbishment

SURF



transition area after construction

Going Back to the Literature

The Influence of Cathode and Anode Surfaces on the Electric Strength of Liquid Argon

By D. W. Swan and T. J. Lewis
Electrical Engineering Department, Queen Mary College, Mile End Road, London, E.1

MS. received 13th March 1961

Abstract. The electric strength of liquefied argon is found to depend to a marked degree on the nature of both cathode and anode. This effect has been investigated systematically. The cathode is thought to influence the strength through the process of electron emission into the liquid, whilst the anode becomes important only if the rate of emission from the cathode exceeds that at which the anode can accept charge. In this case a high space charge field is set up near the anode which can lower the applied field necessary for breakdown. By measuring the electric strength of liquid argon containing various concentrations of oxygen, it has been shown that probably the anode space charge is formed only when part of the current before breakdown is carried by negative oxygen ions. The electric strength is found to be very sensitive to small concentrations of oxygen.

Table 1. Electric Strength of Liquid Argon with Anode and Cathode of Different Materials

Cathode material		Anode material		Electric strength (MV cm^{-1})
Aluminium	(15)	Aluminium	(15)	0·69
Aluminium	(15)	Stainless steel	(15)	1·44
Stainless steel	(15)	Aluminium	(15)	0·88
Stainless steel	(15)	Stainless steel	(15)	1·86
Stainless steel	(0)	Gold		1·22
Stainless steel	(17)	Gold		1·26

The period of oxidation in minutes is indicated in brackets.

Table 2. Electric Strength of Liquid Argon–Oxygen Mixtures with Aluminium and Stainless Steel Anodes and a Platinum Cathode

Liquid	Electric strength (MV cm^{-1}) Aluminium anode	Stainless steel anode	Difference in strength (MV cm^{-1})
Commercial A 20%	1·35	1·71	0·36
Commercial A 1%	1·33	1·68	0·35
Commercial A 0·002%	0·686	1·07	0·384
Spectroscopic A 0·0002%	0·764	0·888	0·124

The quantity of oxygen in the mixture is given as a percentage in each case.

It is clear from the foregoing results that the 'intrinsic strength' of liquid argon is not a meaningful quantity, but in order to obtain a reliable value for the electric strength of liquid argon a measurement was made using spectroscopically pure argon and gold electrodes. By using these electrodes contamination from oxygen absorbed on the electrode surfaces was reduced, and the percentage of oxygen in the argon itself was very small. The results of the measurement, shown in Fig. 4, are compared with the characteristic of breakdown voltage against the product of gap width and density for gaseous argon given by Kachikas and Fisher (1953) using brass electrodes. The strength of the liquid is found to be 750 kv cm^{-1}. It is seen that for a given value of density times gap-width the breakdown voltage of the liquid is considerably lower than that of the gas. The implications of this will be discussed in §3. Other measurements for spectroscopically pure argon have been given in Table 2 and in each case the strength is considerably less than 1 MV cm^{-1}.

- *but how much less, and what happens in argon with < ppb oxygen equivalent?*

Literature …

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ELECTRIC STRENGTH OF LIQUID DIELECTRICS

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9 November 1972

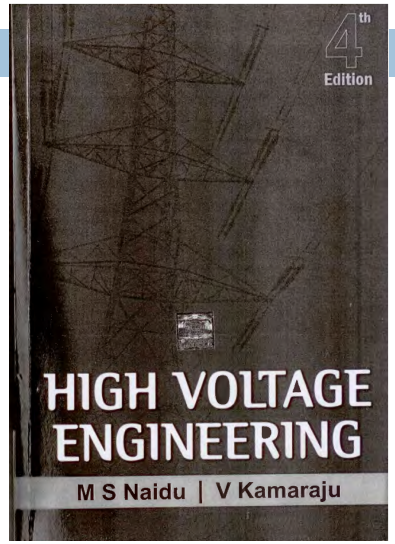

Table 3.3 *Maximum breakdown strengths of some liquids*

Liquid	*Maximum breakdown strength (MV/cm)*
Hexane	1.1–1.3
Benzene	1.1
Transformer oil	1.0
Silicone	1.0–1.2
Liquid Oxygen	2.4
Liquid Nitrogen	1.6–1.9
Liquid Hydrogen	1.0
Liquid Helium	0.7
Liquid Argon	1.10–1.42