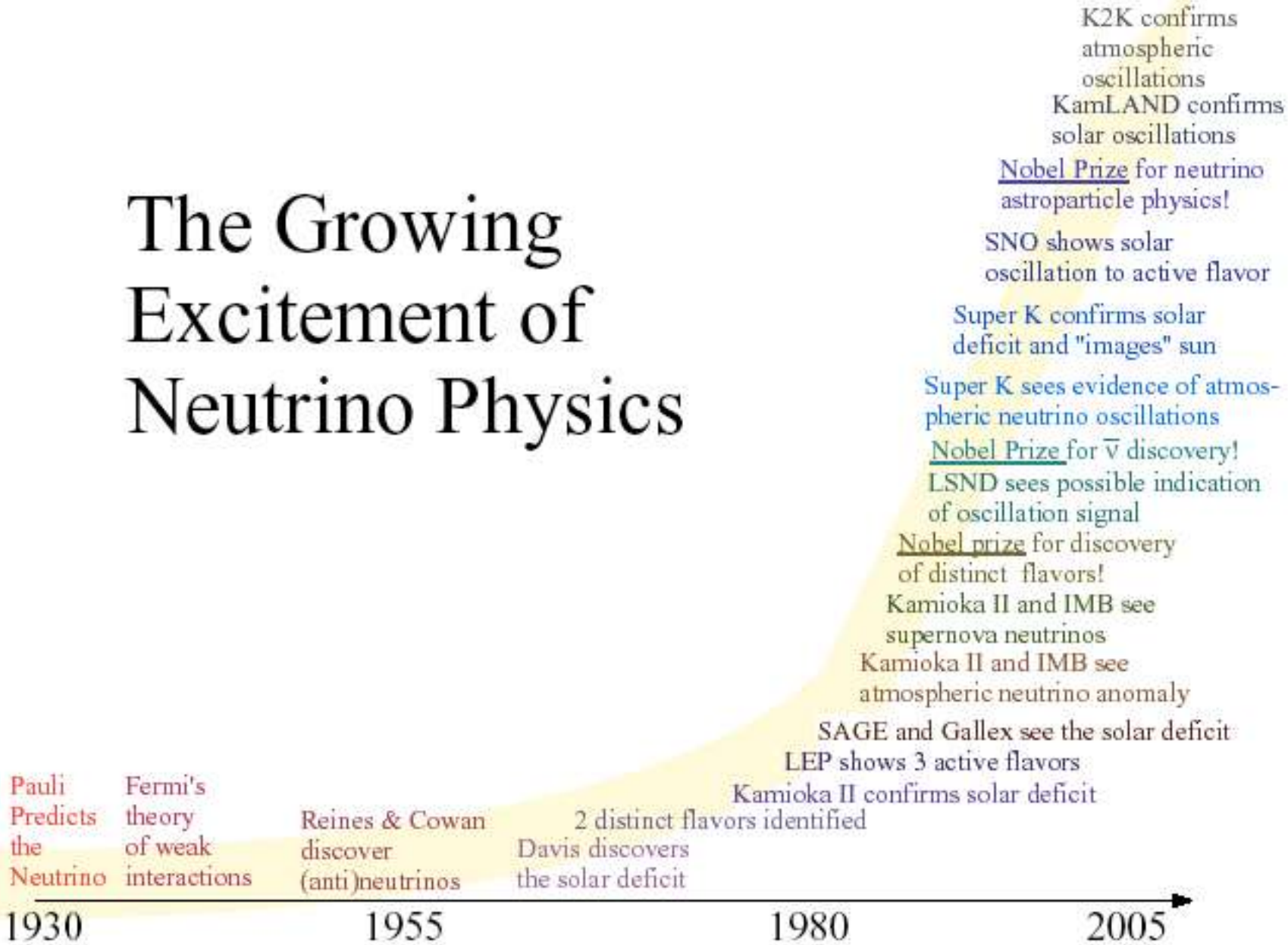
Bonnie Fleming
Argonne HEP Seminar
December 7th, 2005

Liquid Argon Detectors for Long Baseline Neutrino Physics

The Growing Excitement of Neutrino Physics



We've learned a lot ⇒ many open questions...

Big unknowns in neutrino physics:
$\sin^2 2\theta_{13}$, sign(Δm_{23}^2), δ, **and LSND**?

The CP Violation Parameter

Three Neutrino Mixing Matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

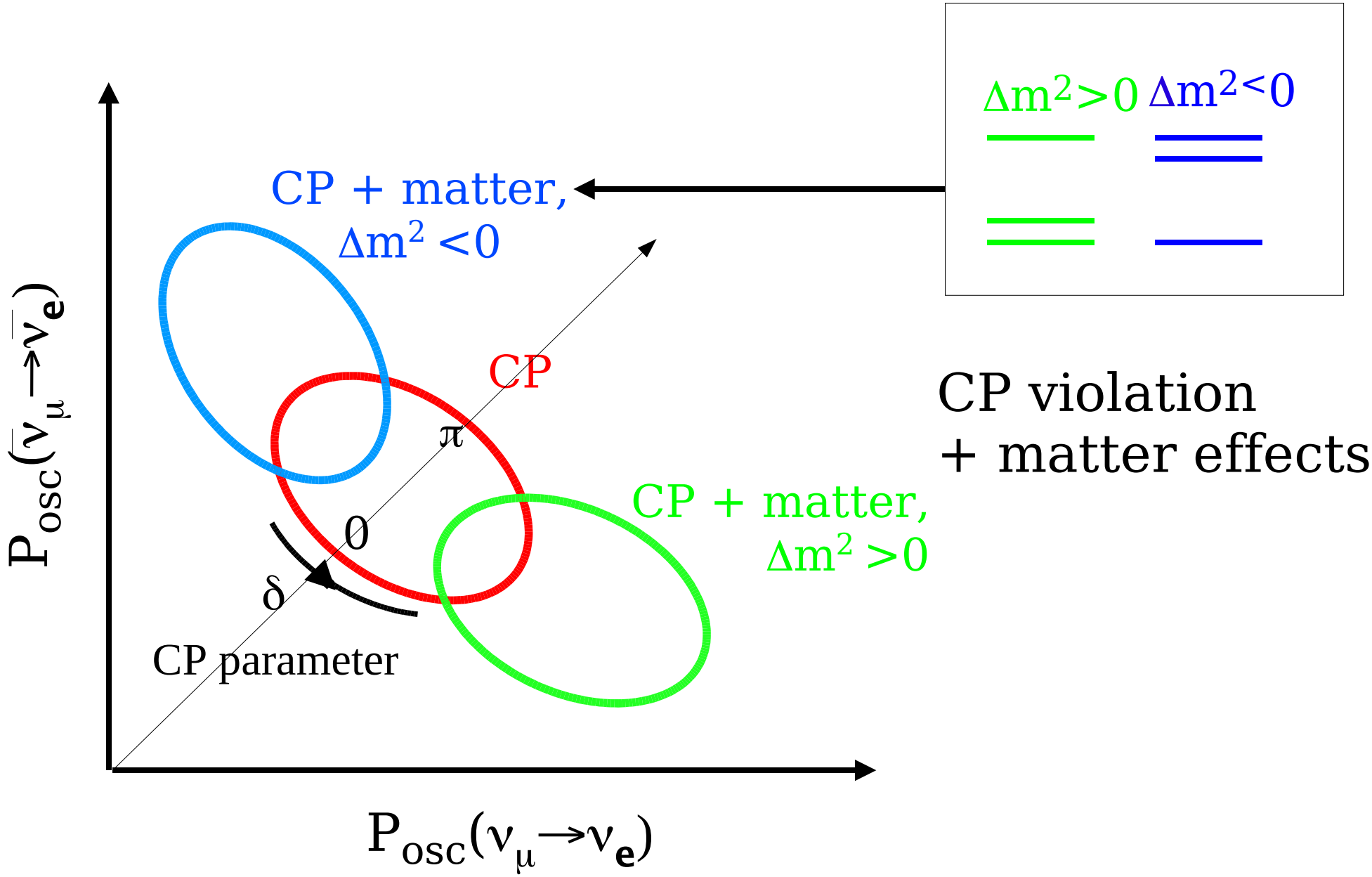
From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Chooz limit is
$\sin^2 2\theta_{13} \sim 0.1$

Long Baseline measurements probe δ and θ_{13}

As well as the mass hierarchy....



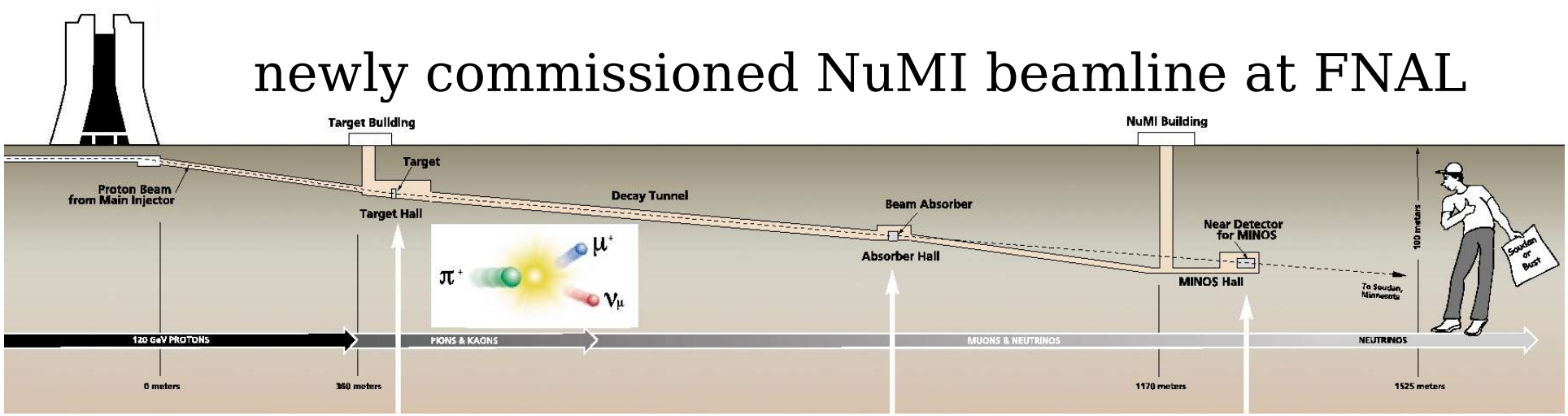
CP violation
+ matter effects

Long-baseline, off-axis, $\nu_\mu \Rightarrow \nu_e$ neutrino oscillation physics:

structure of the mixing matrix, CP Violation in the neutrino sector,hierarchy of the neutrino masses

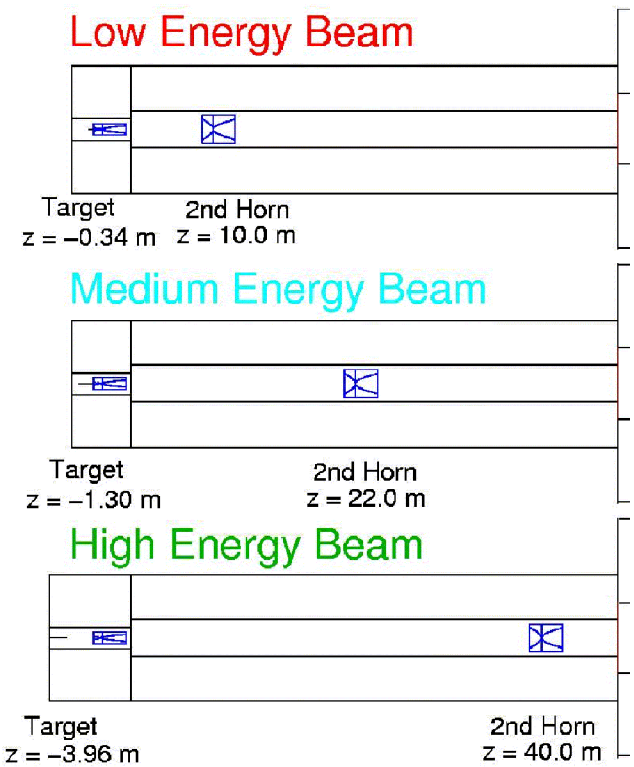
New high intensity sources available for these programs.....

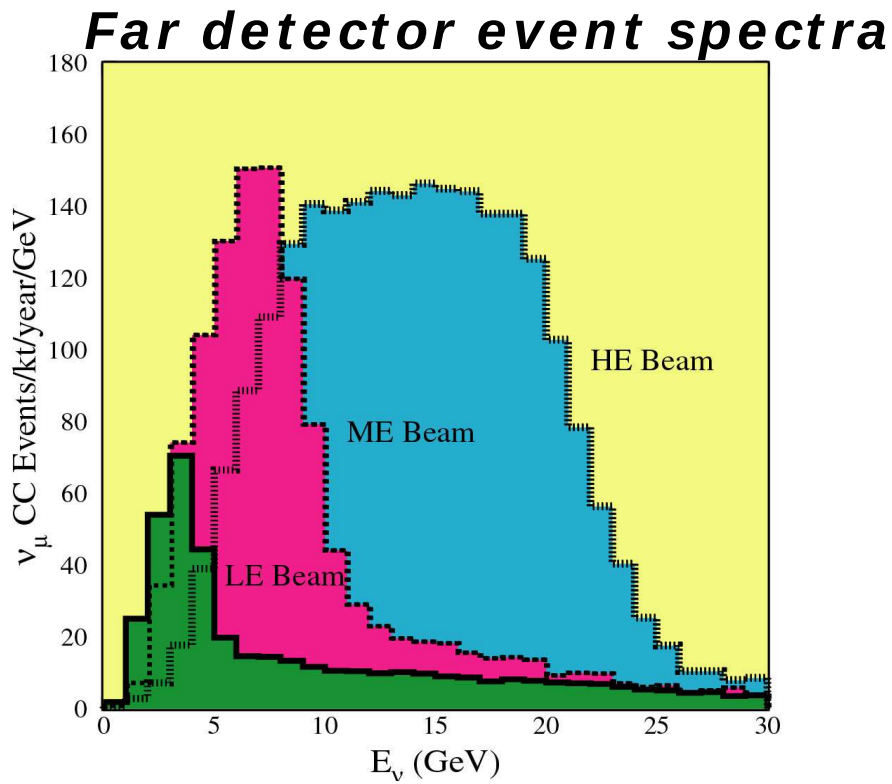
newly commissioned NuMI beamline at FNAL



Limiting factor in sensitivity for long-baseline neutrino physics is ν_e event rate and background rejection

Intense “adjustable” beam

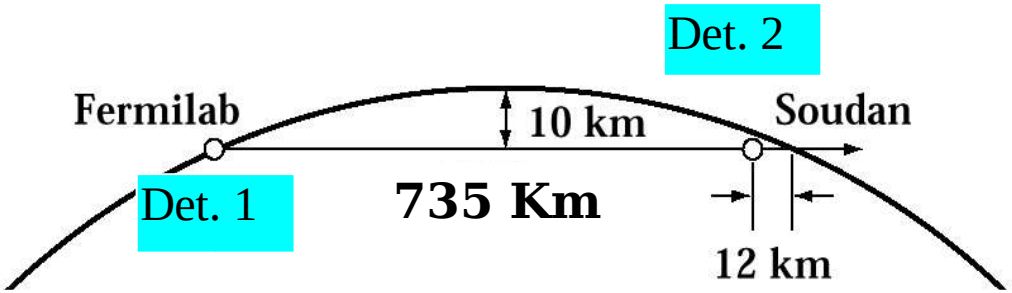




High power neutrino beam

- 120 GeV protons from main injector
- facility designed for up to 0.4MW (4E13 ppp)
- ~2E20 protons/year now
- 3.4E20 protons/year 2008-2009
- 6.5E10 protons/year in post collider era
- 25E20 protons/year with a Proton Driver

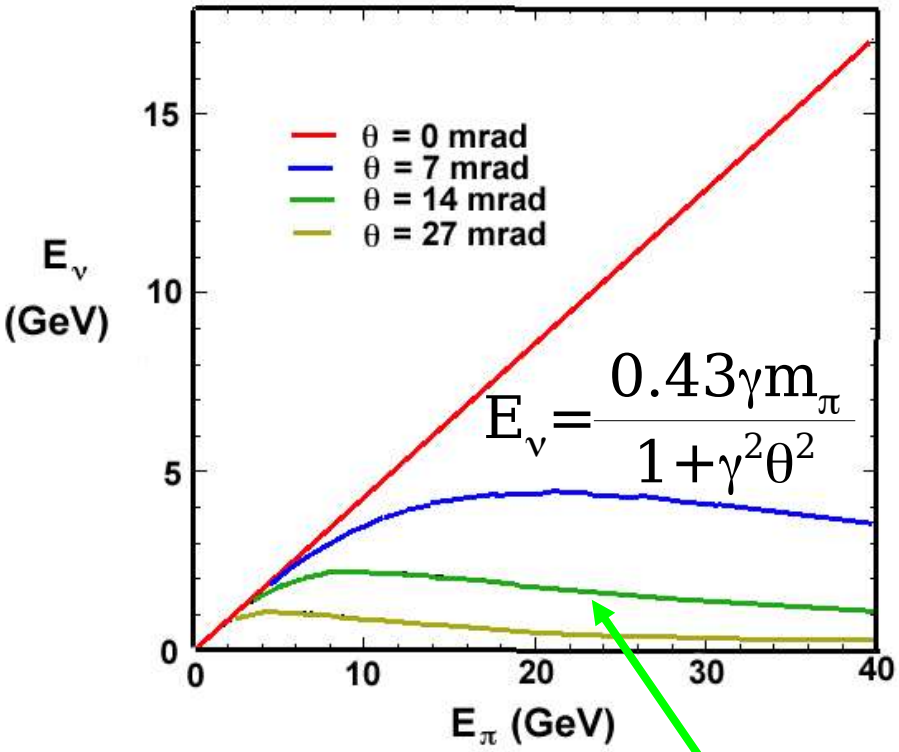
Delivering beam to MINOS



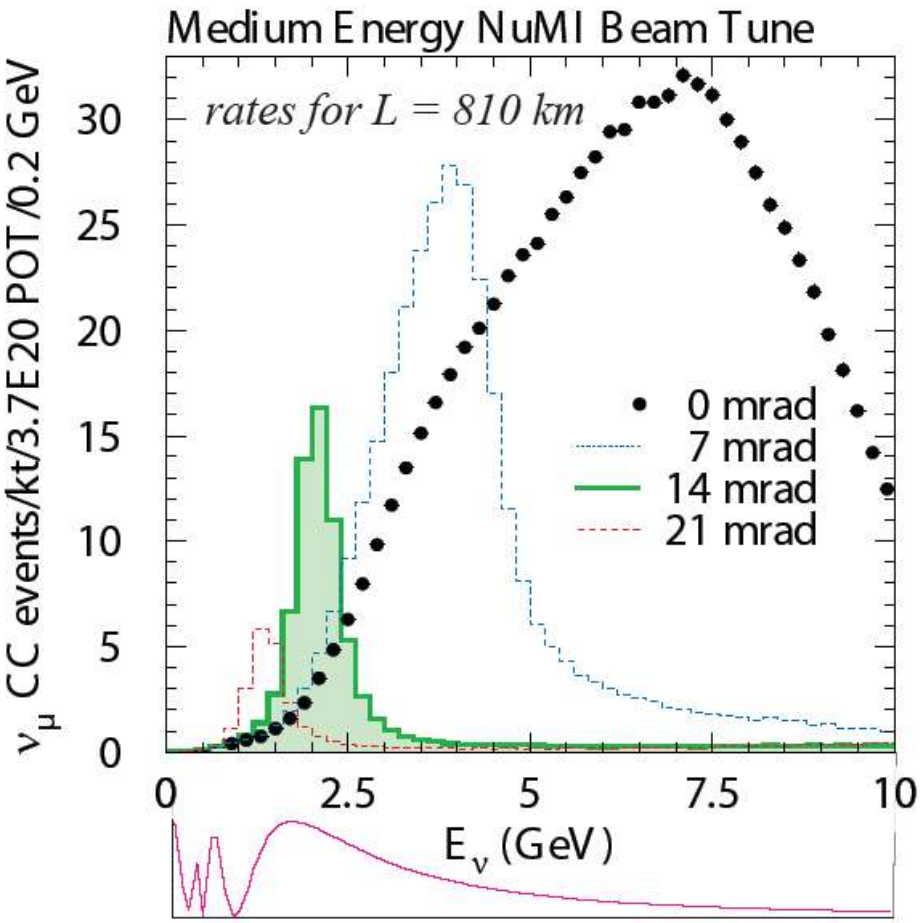
MINOS experiment:

- neutrinos travel ~735km to Soudan Mine
- large near hall ~1km from target
- to far detector at Soudan

NuMI off-axis beam: clean, low energy, high intensity needed for ν_e appearance searchs



Off-axis beam from ME configuration

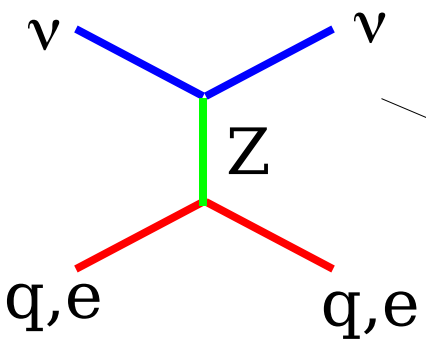


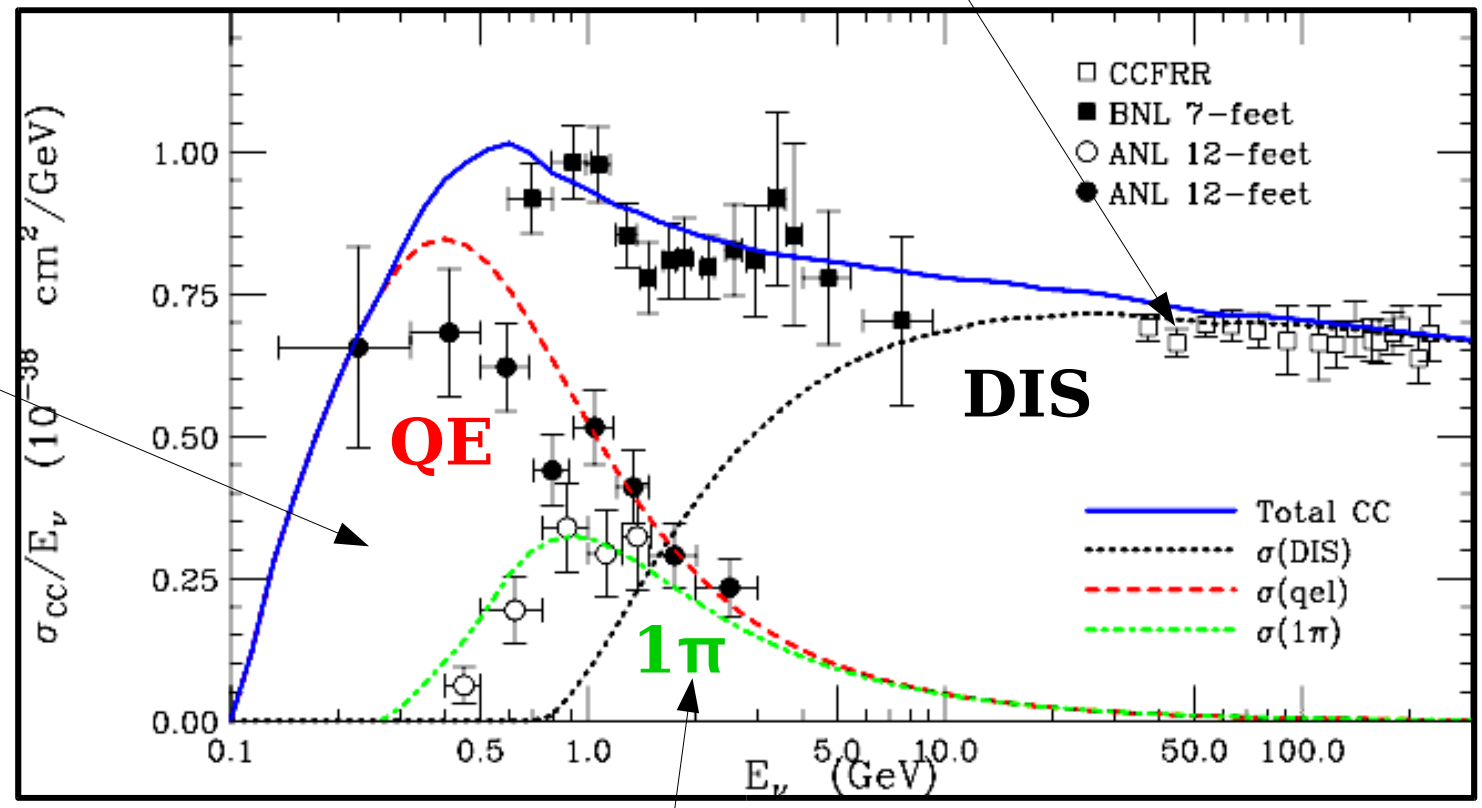
For a given θ≠0, a large range of pion energies contributes to a small range of neutrino energies

Neutrino Scattering

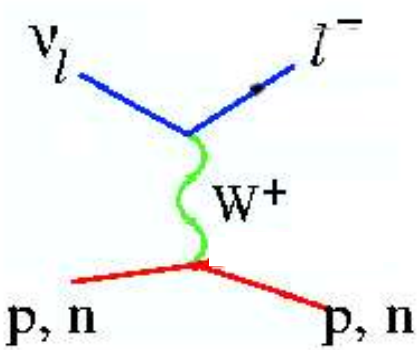
Deep Inelastic Scattering: break apart the nucleon all together

Elastic Scattering

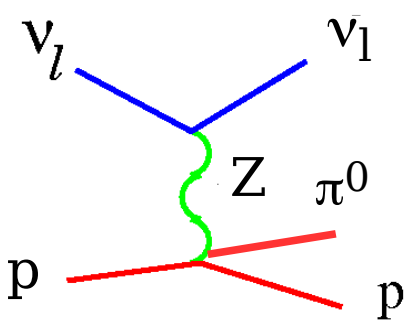


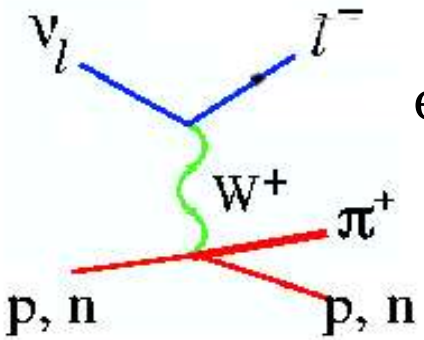


Quasi-Elastic



Single Pion Production : Resonance...





or off entire nucleus

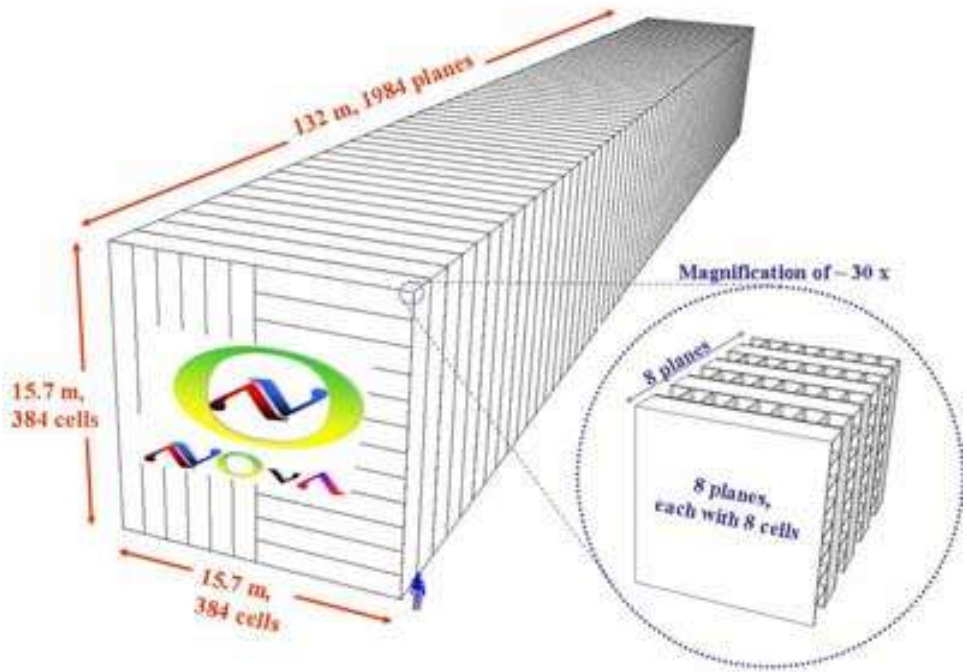
Coherent Scattering

Looking for just a handful of oscillated ν_es
Need a detector
to well identify signal and background!

Physics Requirements:

- optimized for 1-3 GeV neutrinos
- very large mass (~10's ktons)
- identify with high efficiency ν_e charged current interactions
- good energy resolution for background rejection
  - ν_e intrinsic background has a broader energy spectrum than oscillation signal
- good event topology for background rejection
  - e/π^0 separation
  - e/μ,h separation
- for surface detector: handle data rates from cosmics and background

NOvA



30 kton tracking calorimeter

- alternating xy cells of liquid scintillator
- cells: 15.7m x 3.87cm x 6.0 cm
- 0.8mm looped WLS fiber in each cell for light collection
- WLS fibers read-out by APDs
- 80% active material

- Longitudinal granularity ~ 0.13 X_0
- Efficiency for ~2 GeV ν_e events ~24%
- Backgrounds from intrinsic ν_es and ν_μ NCπ^0 production
- known technology

How does this technology compare to massive Liqiud Argon TPCs?

Massive LArTPCs provide excellent means to do this physics

- Improved efficiencies and background rejection ameliorate statistics limitations of long-baseline neutrino physics
- Success of the ICARUS T600 proves technical feasibility for “small” detectors

  - How much better are they?
  - Can we build these detectors?

LArTPC's report to NuSAG*

www-lartpc.fnal.gov

Fermilab Note: **FN-0776-E**

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam

Submission to NuSAG

September 15, 2005

D. Finley, D. Jensen, H. Jostlein, A. Marchionni, S. Pordes, P. A. Rapidis
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Princeton University
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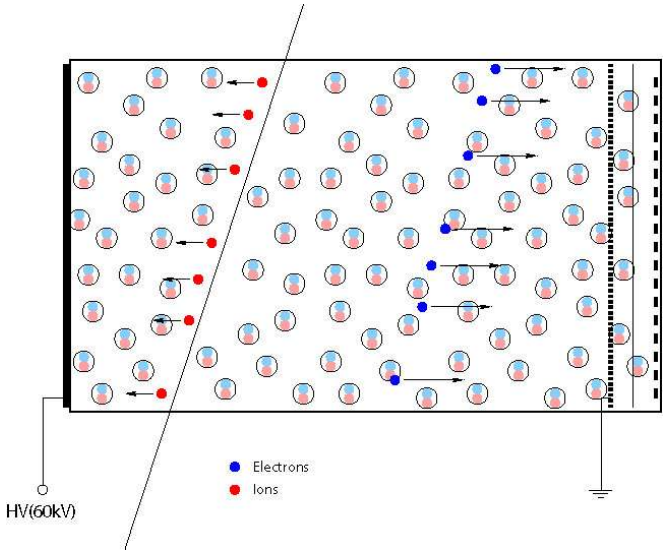
S. Menary
York University

Contact Persons: B. T. Fleming and P. A. Rapidis

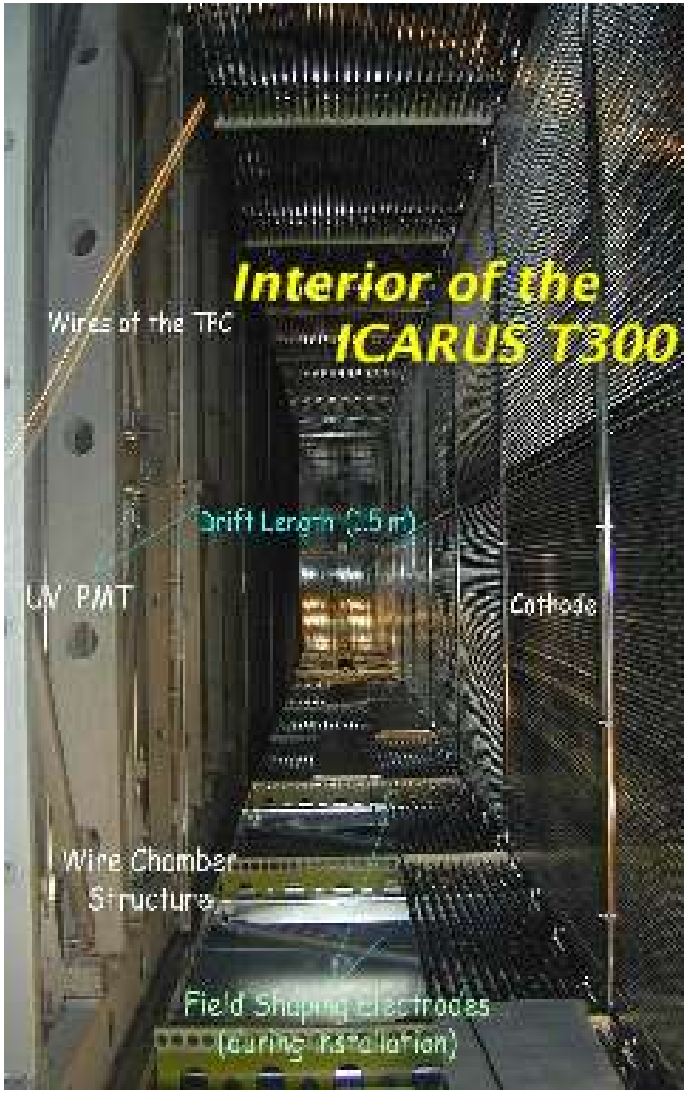
* The ***Neu***trino ***S***cientific ***A***ssessment ***G***roup for the DOE/NSF

Liquid Argon TPCs:
Fine-grained tracking, total absorption calorimeter

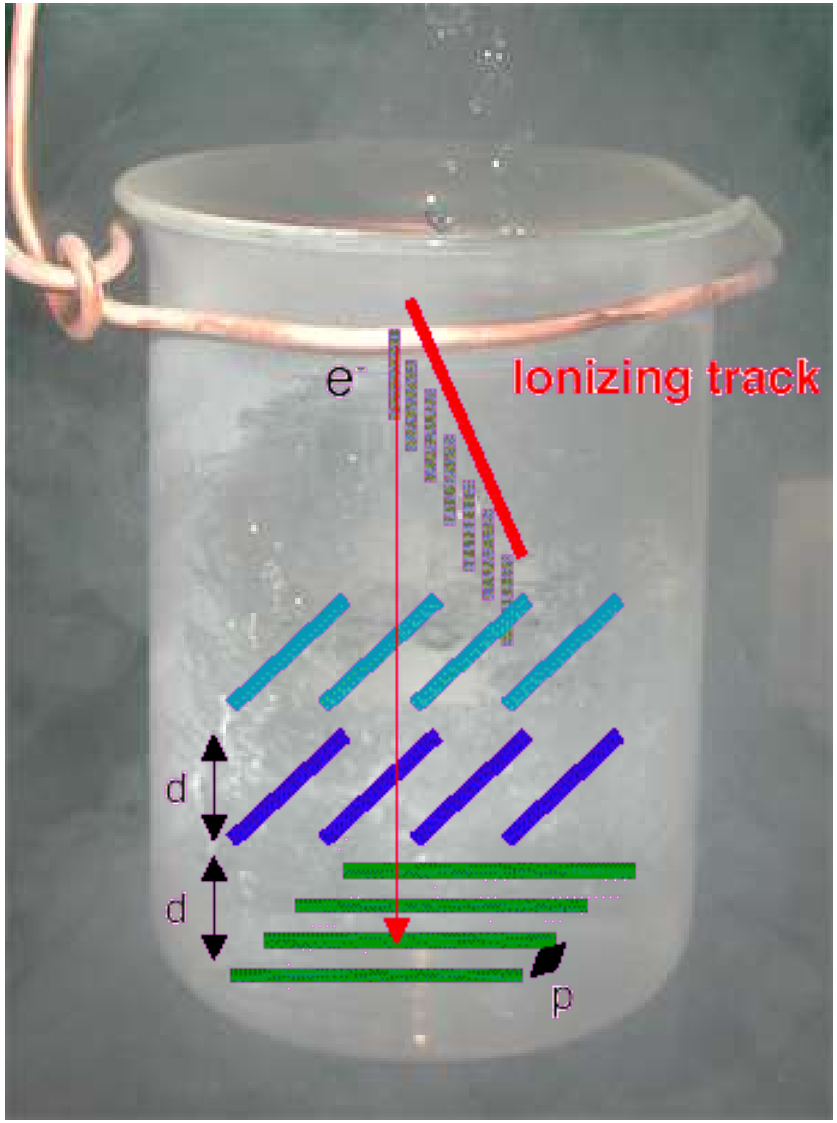
55,000 electrons/cm

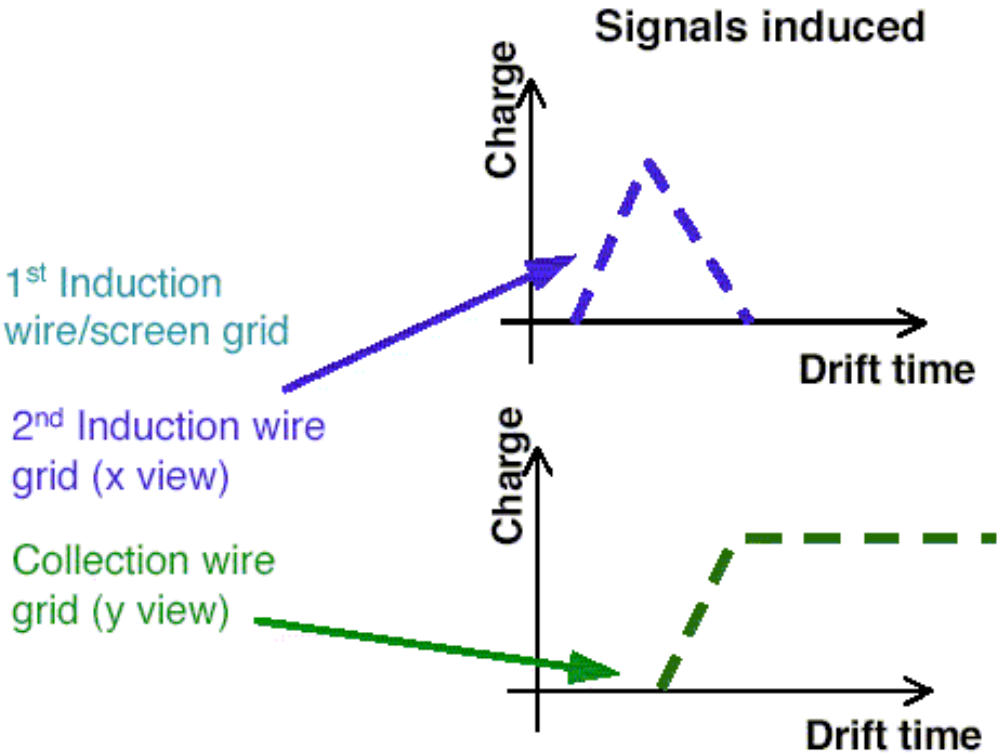


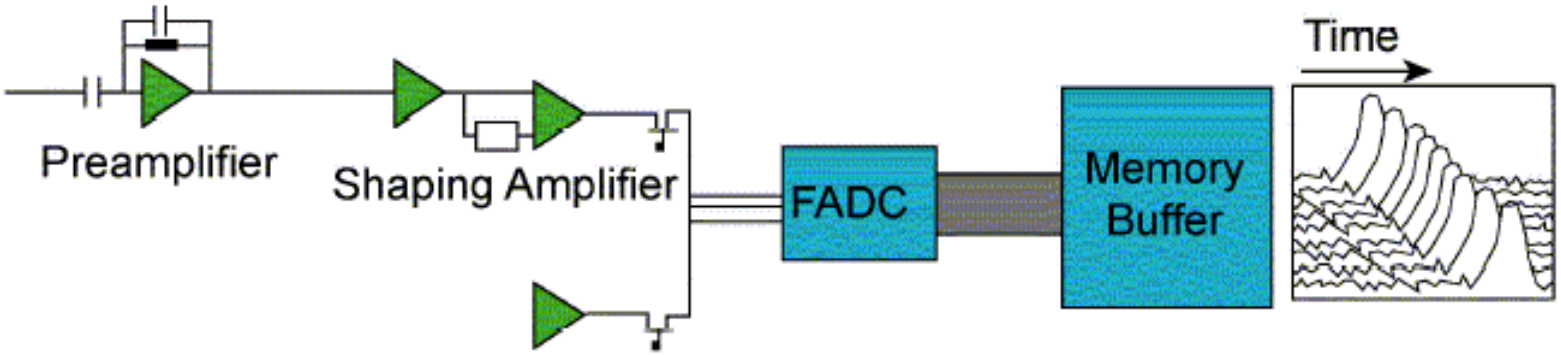
Drift ionization electrons over meters of pure liquid argon to collection planes to image track



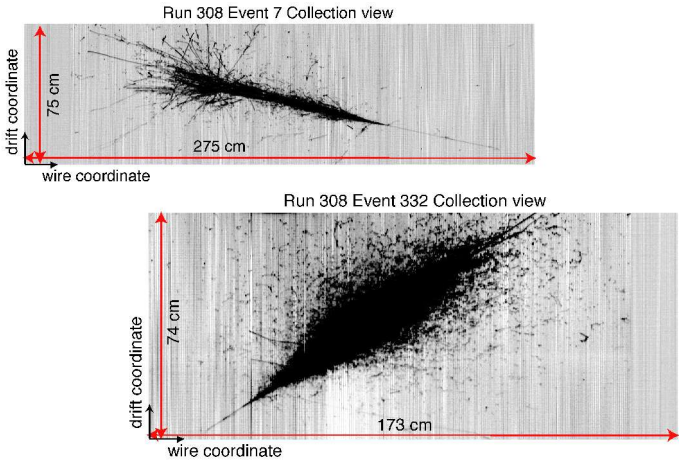
Liquid Argon TPC

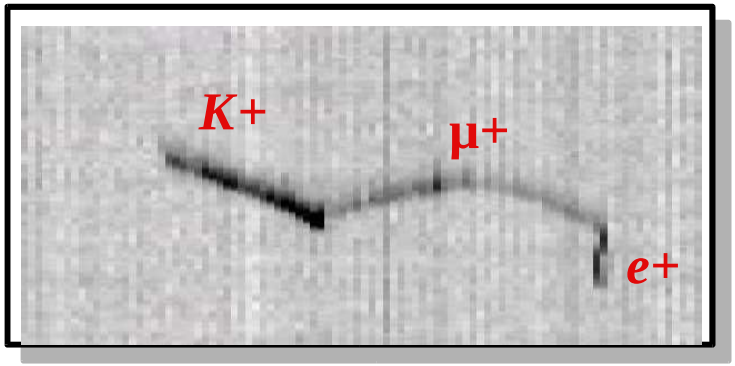






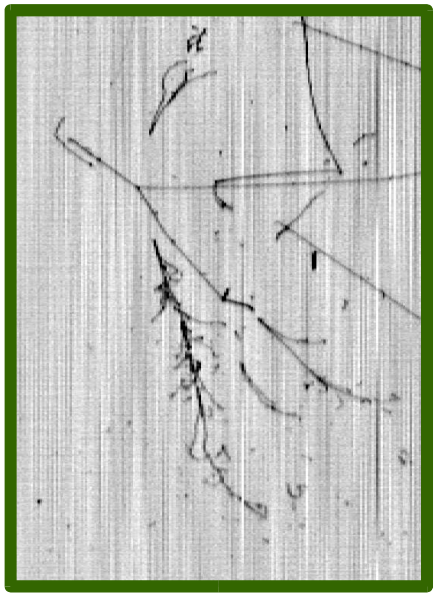
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)

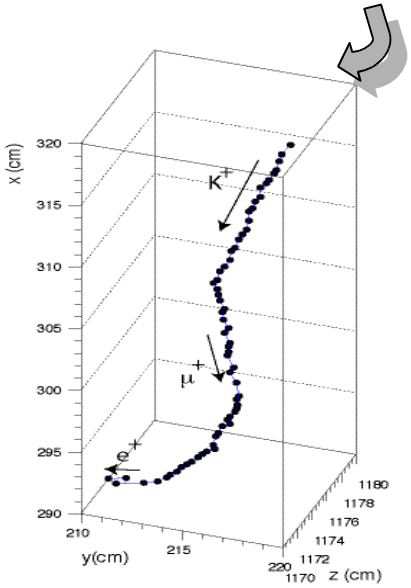




data

data





3D representation of data event

ICARUS images

How good are these detectors at identifying ν_e interactions

and

rejecting NC interactions?

LArTPCs

- Total absorption calorimeter
- 5mm sampling
  -> 28 samples/rad length
- energy resolution

→ ν_e efficiency
NC rejection

First pass studies using hit level MC show
~80 ± 7 % ν_e efficiency and
NC rejection factor ~70 (99 ± 1% eff.)

(only need NC rejection factor of 20 to knock background down to ½ the intrinsic ν_e rate)

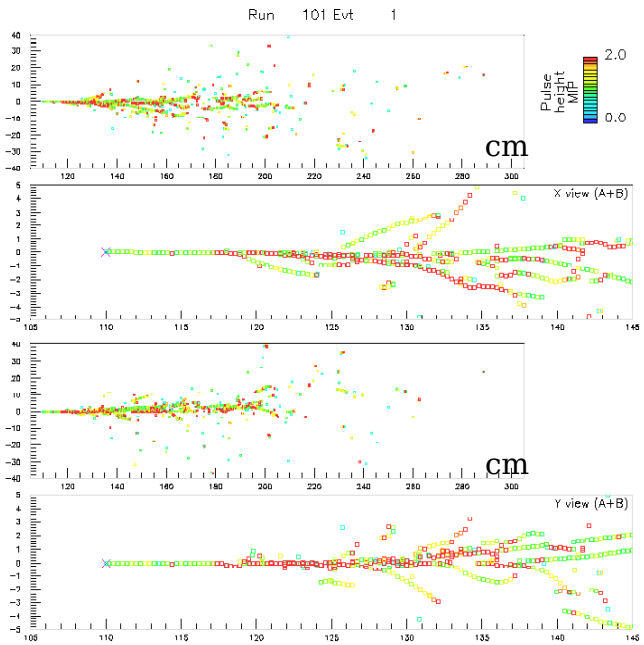
Studies from groups
working on T2K LAr indicate 85-95% ν_e efficiency

in documents submitted to NuSAG

Electrons versus π^0's at 1.5 GeV

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

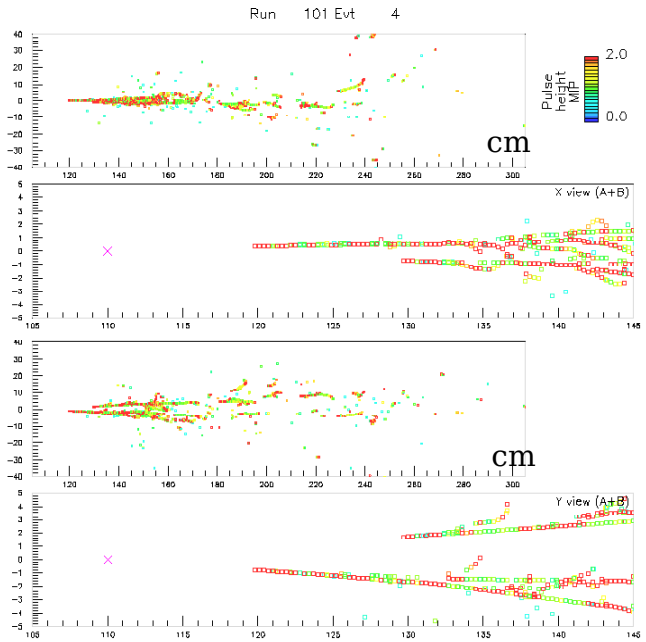
X plane
zoom in
Y plane
zoom in



Electrons

Single track (mip scale) starting from a single vertex

X plane
zoom in
Y plane
zoom in



π^0

Multiple secondary tracks can be traced back to the same primary vertex

Each track is two electrons – 2 mip scale per hit

Use both topology and dE/dx to identify interactions

Neutral current event with 1 GeV π^0

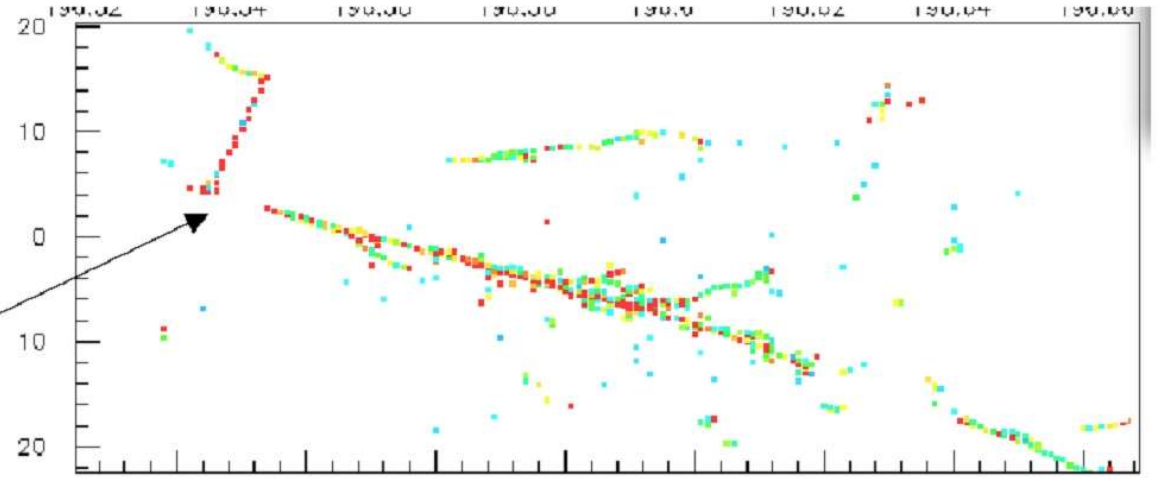
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

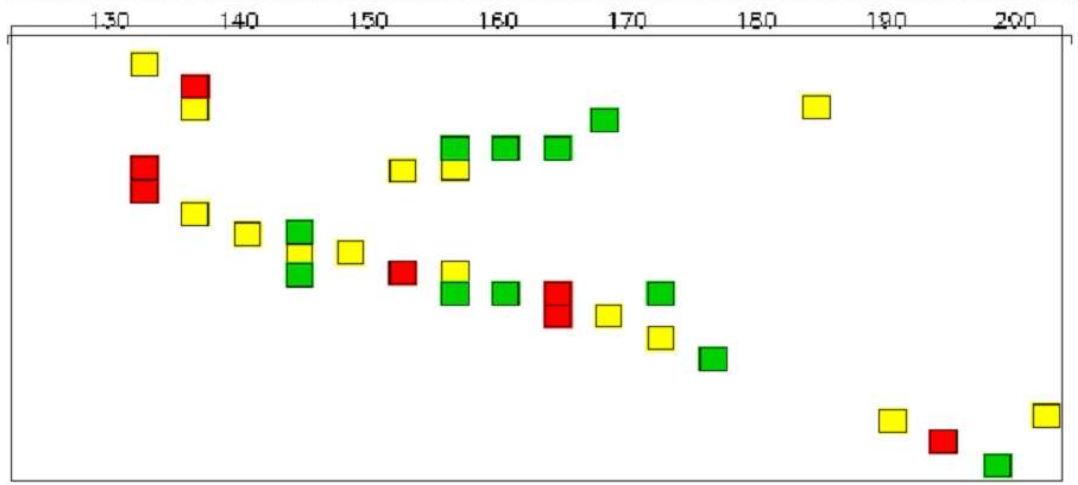
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



Efficiency and Rejection study

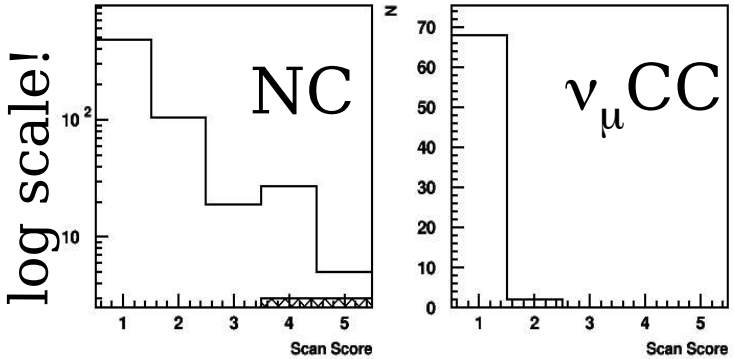
Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of "signal" events by experts.

- Neutrino event generator: NEUGEN3. Used by MINOS/NOvA collaboration. Hugh Gallagher (Tufts) is the principal author.
- GEANT 3 detector simulation: trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:

50 events each of ν_eCC, ν_μCC and NC

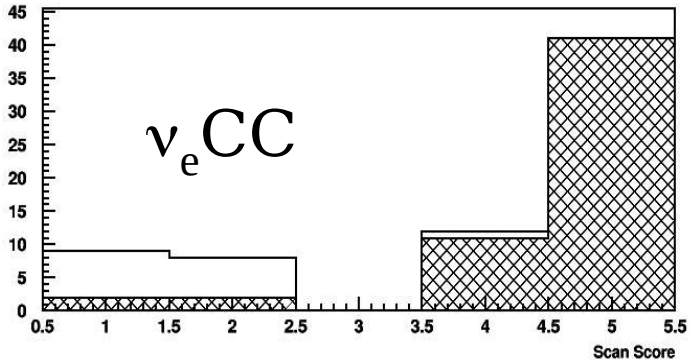
- individual samples to train
- mixed samples to test training



Blind scan of 450 events scored from 1-5 with

- signal=5
- background=1

plain region: students
Hatched region: experts

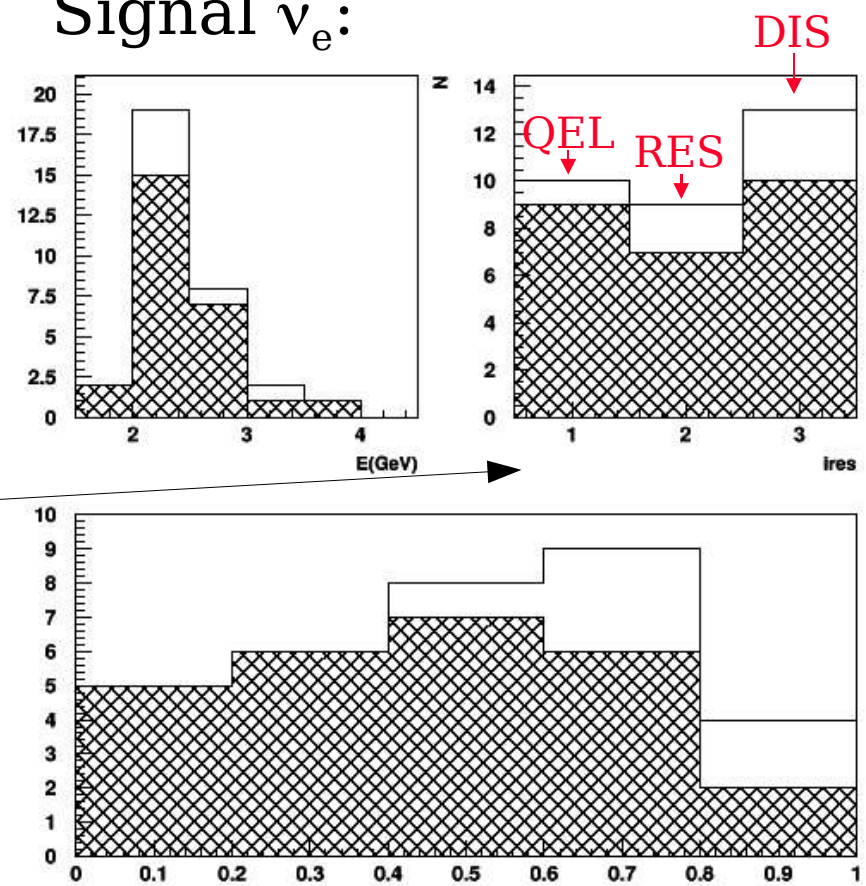


Tufts University Group

Overall efficiencies

	N	pass	ε	η
NC	290	4	-	99
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	

Signal ν_e:



Efficiency is substantial even for high multiplicity events

Efficiency is ~100% for y<0.5, and ~50% above this

$y = E_{had}/E_{\nu}$

Given very high ν_e efficiency and NC background rejection well below ½ of the intrinsic ν_e beam backgrounds, how sensitive are these detectors?

↓

Sensitivity =
detector mass x
detector efficiency x
protons on target/yr x
# of years

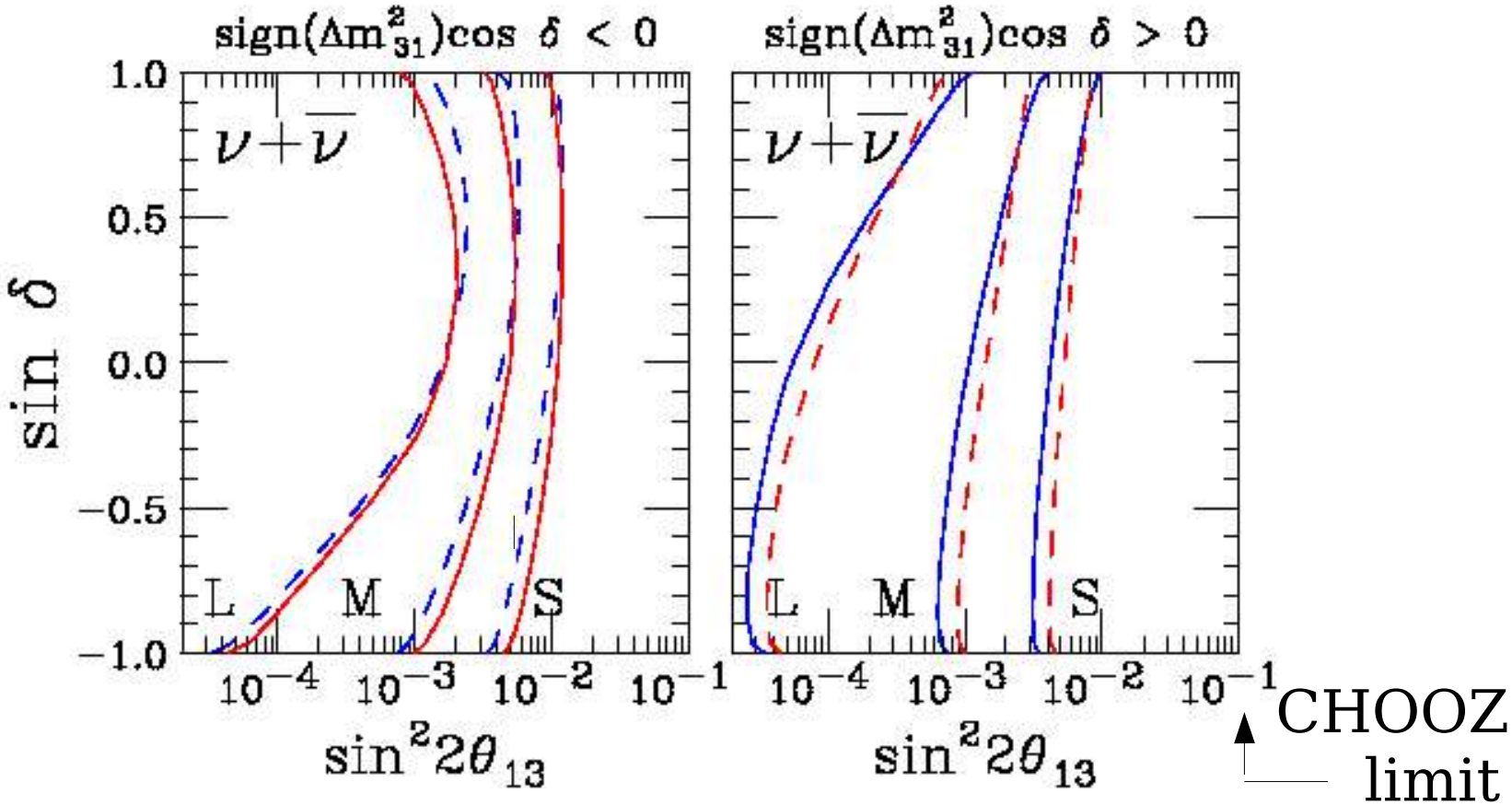
As an example: focus on recent paper by Mena and Parke

hep-ph/0505202

	Small	Medium	Large
NOvA	30kTon	30kton + PD or x5 mass or exposure	30kton + PD + x5 mass or exp.
LArTPC (90% ν_e eff.)	8kton	40kton	40kton + PD or exposure

All sensitivities assume 3 years running each in ν and $\bar{\nu}$ mode

Sensitivity to CP phase(sin δ) vs $\sin^2 2\theta_{13}$ for



most restrictive:

cos δ <0, normal hierarchy

cos δ >0, inverted hierarchy

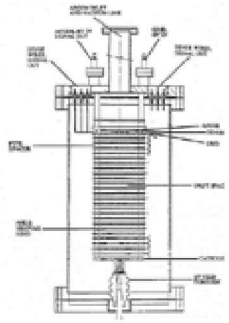
least restrictive:

cos δ >0, normal hierarchy

cos δ <0, inverted hierarchy

Can we build these detectors?

Technical Feasibility:
History of prototype work on ICARUS

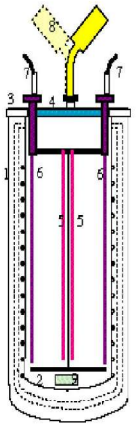


24 cm drift wires chamber

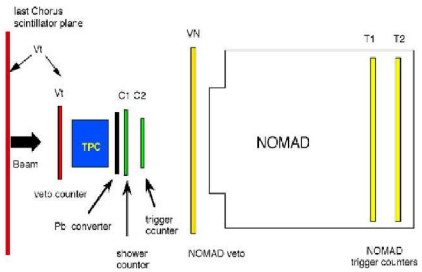
1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

3 ton prototype

1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.



50 litres prototype
1.4 m drift chamber

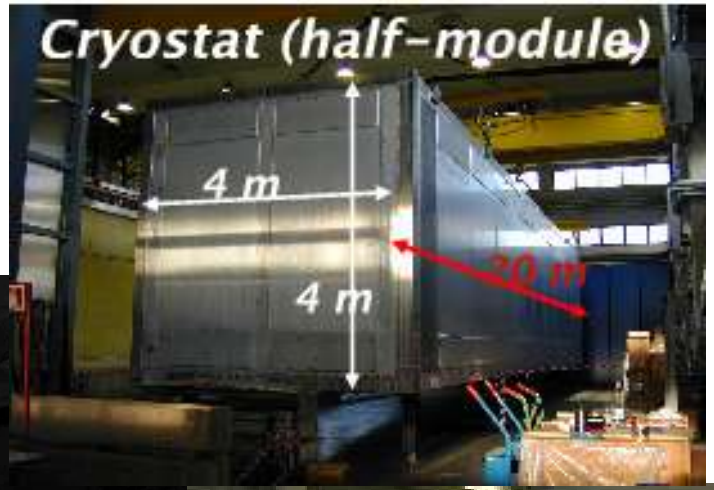


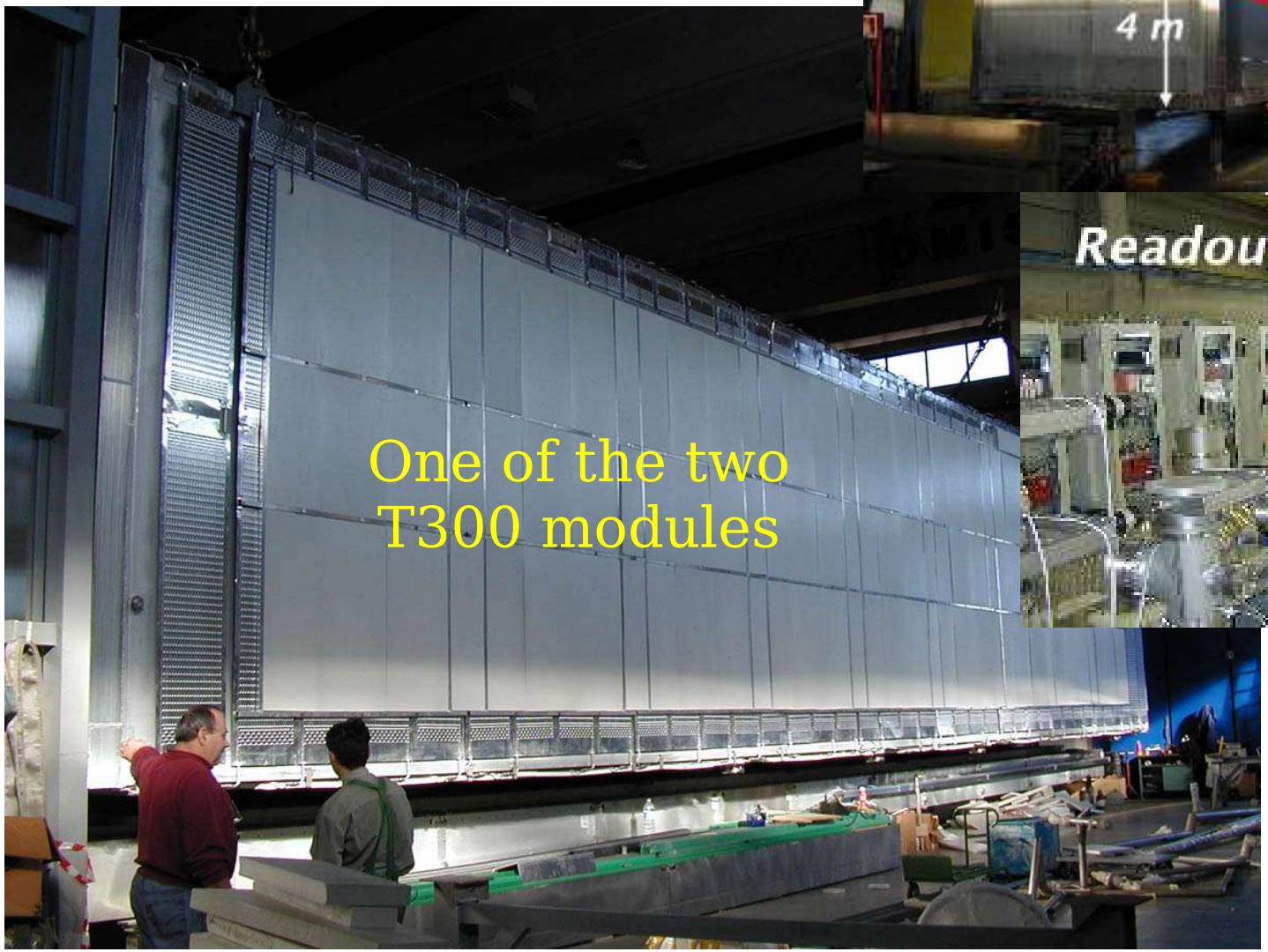
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

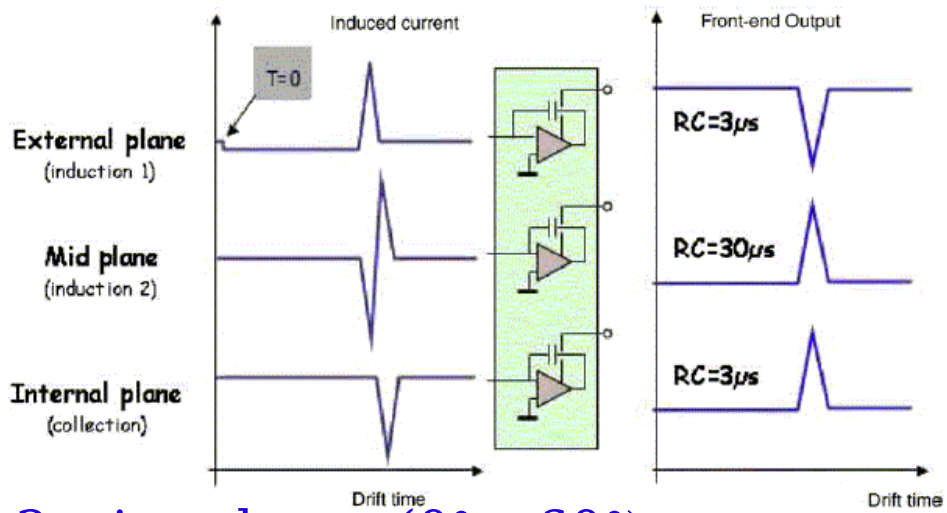
The success of the ICARUS T600

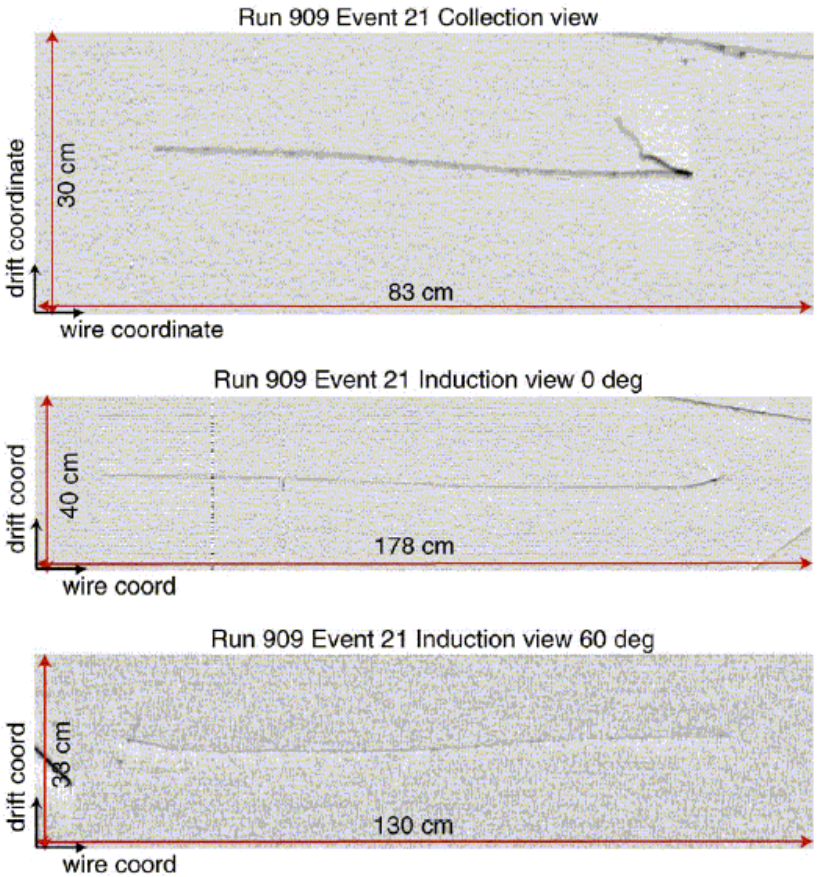




tested above ground in Pavia in 2001
now below ground in Gran Sasso

Signals and event reconstruction from T300

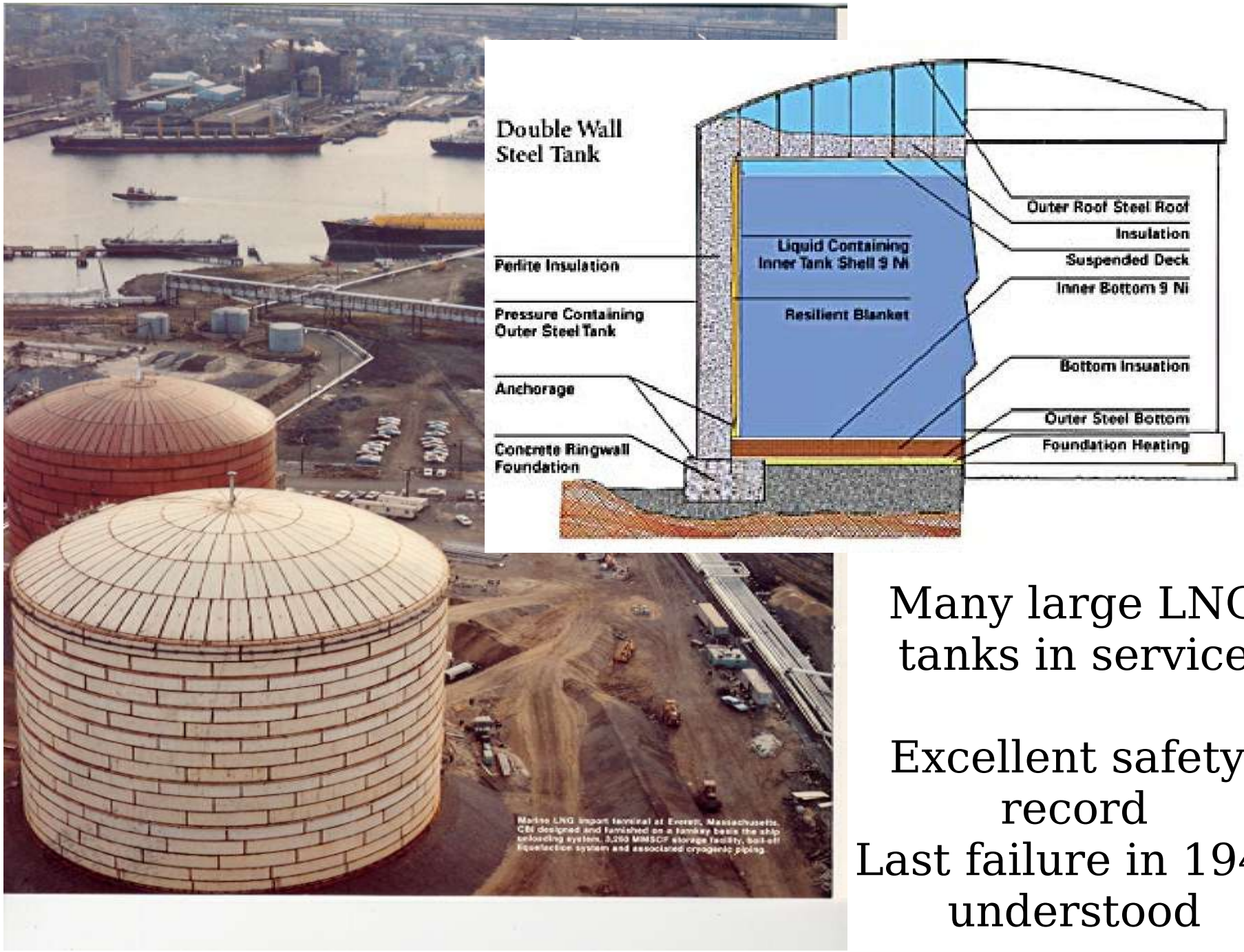




- 3 wire planes (0°, ±60°)
- 3mm wire pitch, 3mm distance b/t wire planes
- 0° **wires**: 9.4 m long, ±60° wires: 3.8m long
- Input capacitance (wire+cable)
  0° **wires**: ~400 pF, ±60° wires: ~200 pF

- Ionization signal: 55,000 e/cm @ 500 V/cm (before atten.)
- Signal/Noise ratio ~10
- each wire digitized at 2.5 MHz by a 10 bit flash ADC

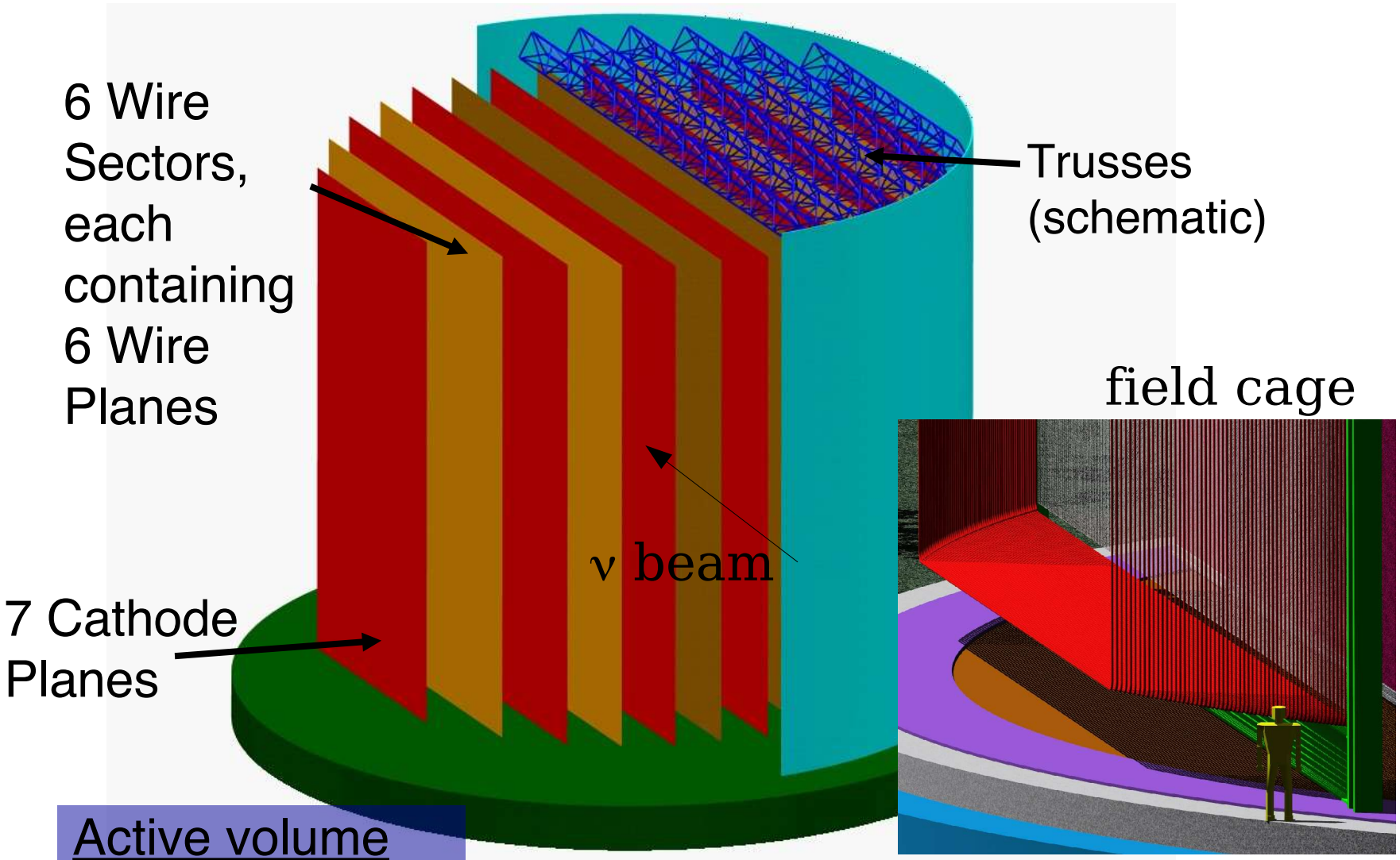
Can we scale up to more
massive detectors?
15-50ktons?



Many large LNG tanks in service

Excellent safety record
Last failure in 1940 understood

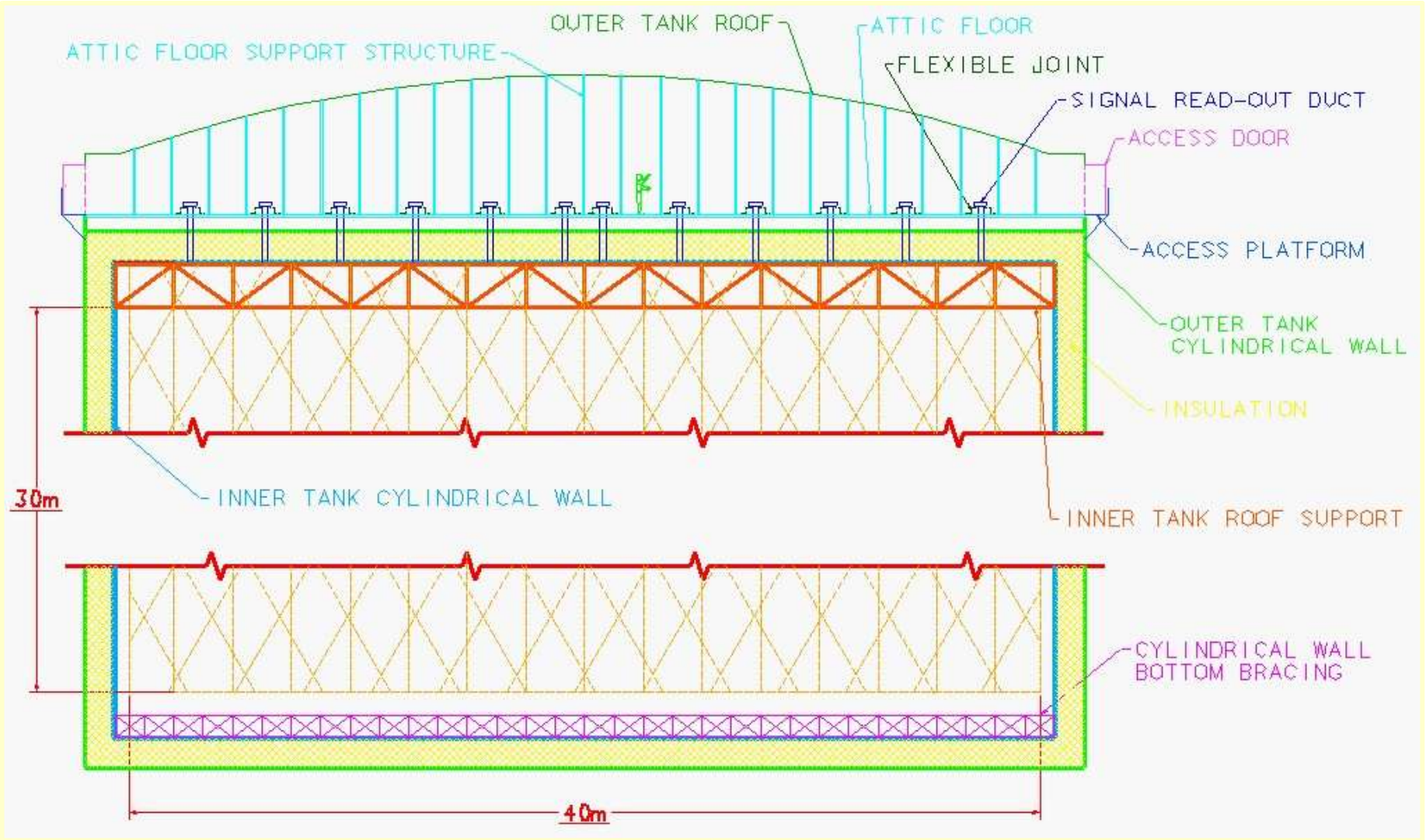
Modularized drift regions inside tank



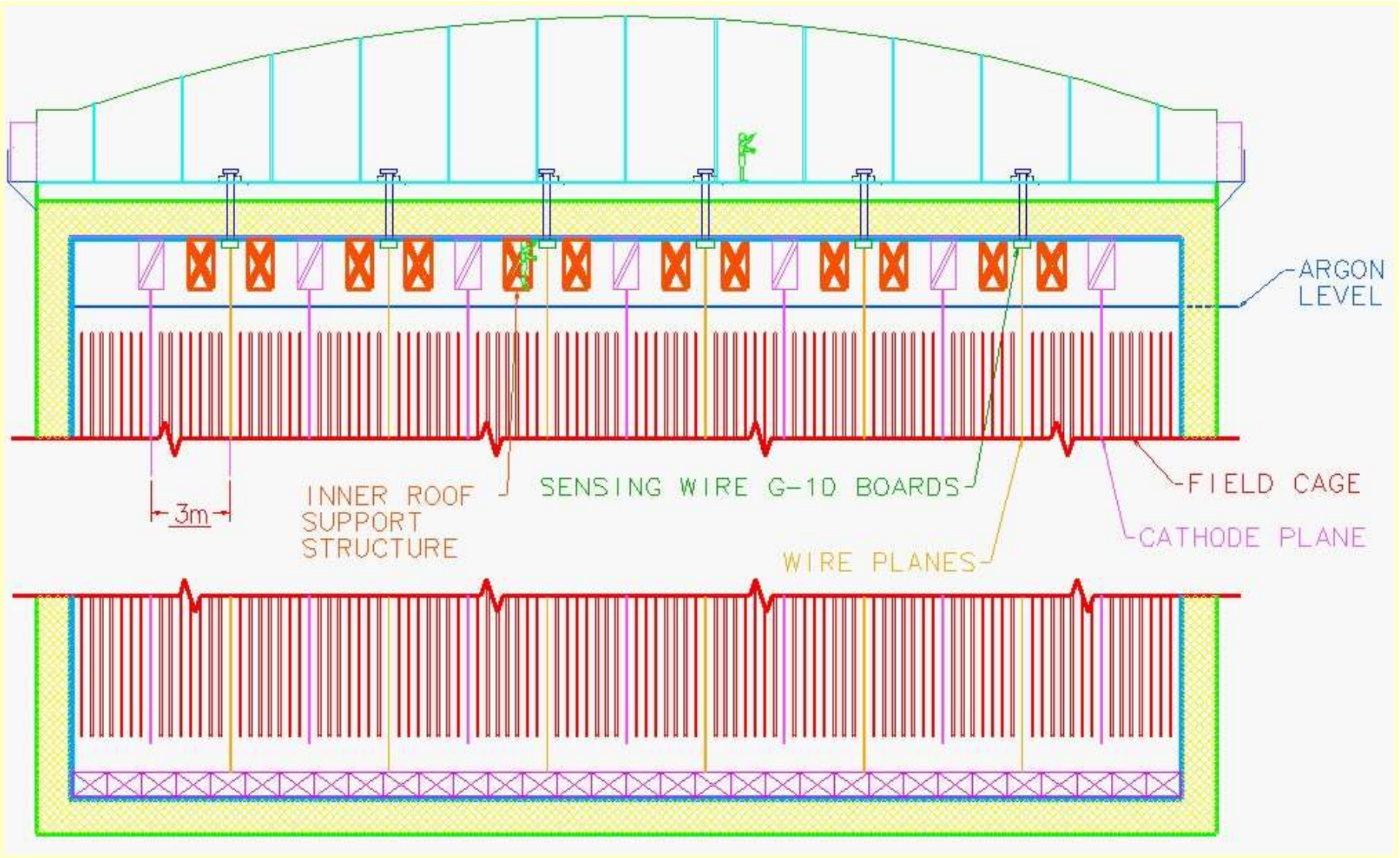
Active volume
Diameter: 40m
Height: 30m

Scalable → 15-50 kTons
4 - 6 wire planes

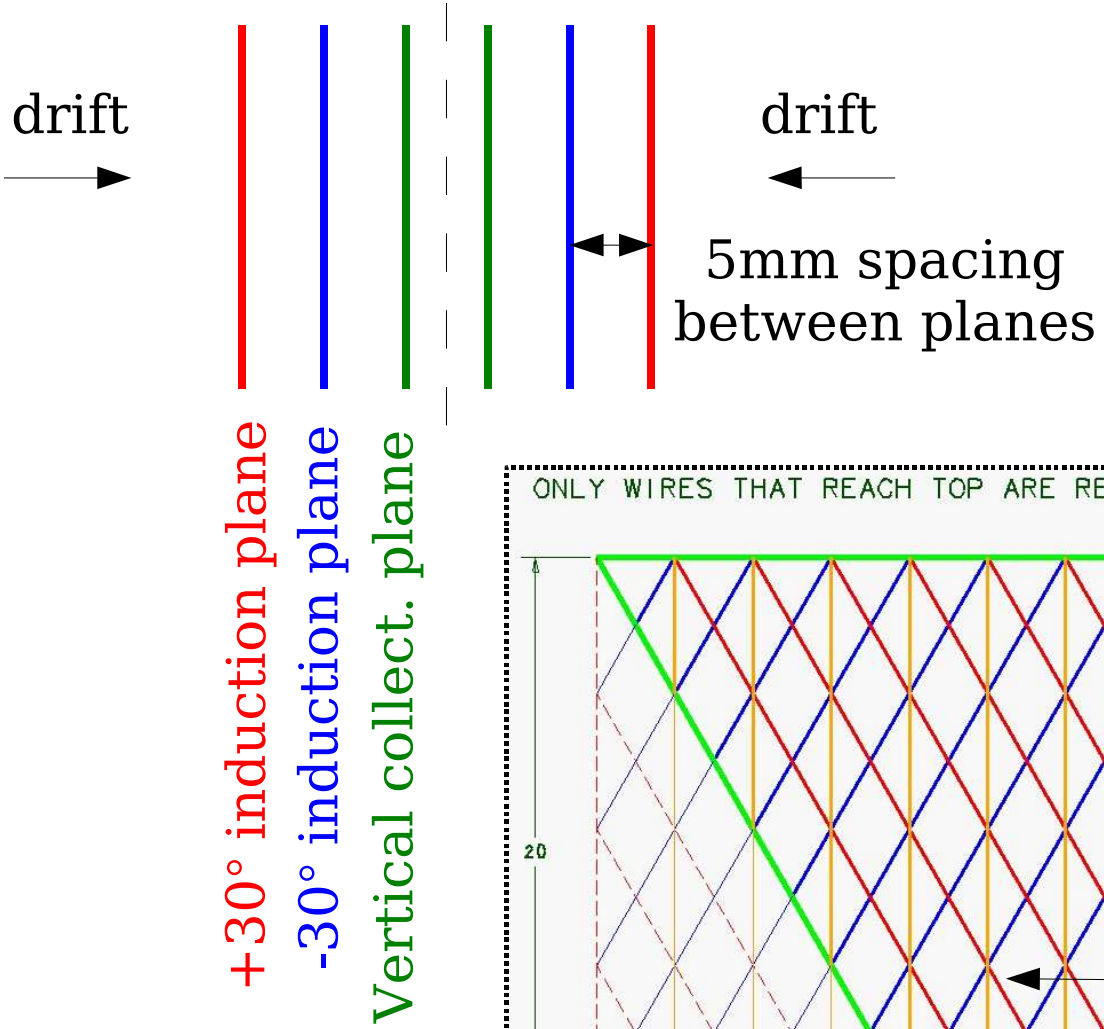
Front View


OUTER TANK ROOF
ATTIC FLOOR
ATTIC FLOOR SUPPORT STRUCTURE
FLEXIBLE JOINT
SIGNAL READ-OUT DUCT
ACCESS DOOR
ACCESS PLATFORM
OUTER TANK CYLINDRICAL WALL
INSULATION
INNER TANK CYLINDRICAL WALL
INNER TANK ROOF SUPPORT
30m
CYLINDRICAL WALL BOTTOM BRACING
40m

Side View

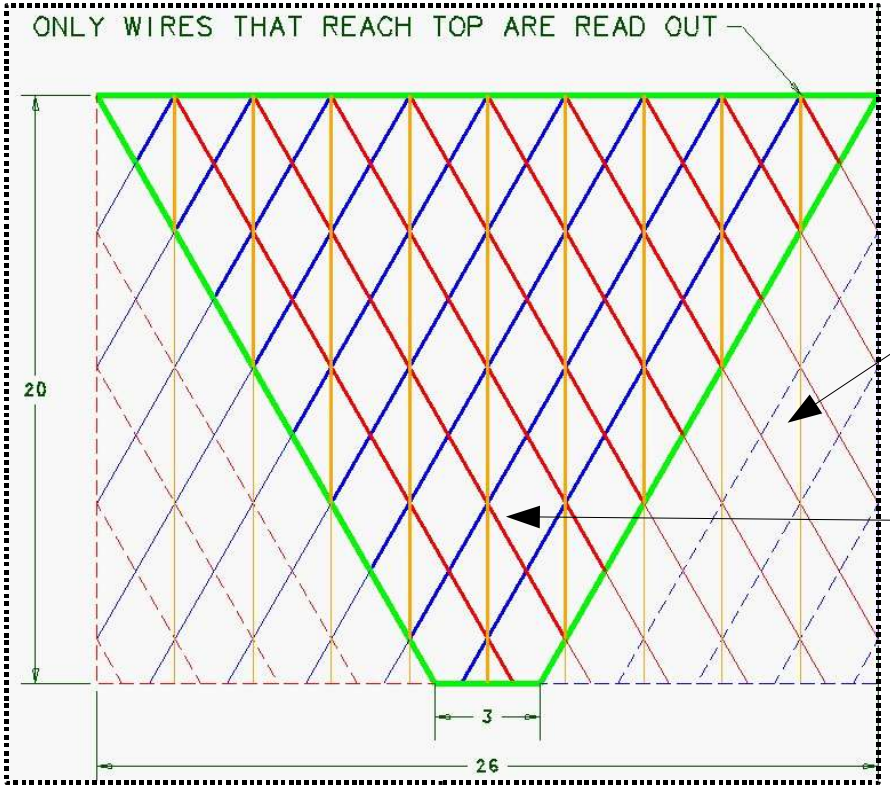

ARGON LEVEL
3m
INNER ROOF SUPPORT STRUCTURE
SENSING WIRE G-10 BOARDS
FIELD CAGE
CATHODE PLANE
WIRE PLANES

Each wire plane:



Wires are
- 150 μm stainless steel
- 5mm pitch
- 23m long (15kton)
  35m (50kton)
- 100K total (15kton)
  220K (50kton)

Wire planes
head on

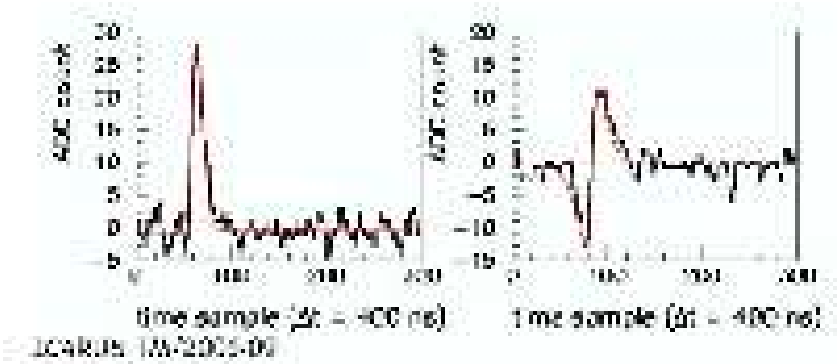


2 wire readout

3 wire readout
(overconstrained)

Electrons drift 1.5m/ms (150kV field) over 3m drift region

Electronics and Data Acquisition



Electronics:

ICARUS scheme: an intelligent waveform recorder on each wire: (S/N = 8.5/1)

- digitize with commercial ADCs: adequate performance, resonable cost
- intelligence from commercial FPGAs: adequate performance, resonable cost.

Data acquisition

- Use commercial switches and multiplexors
- Have a design to achieve 5 Gbytes/sec

Challenges for massive detector

Purity:

3 m drift in LAr

purification - starting from atmosphere (cannot evacuate detector tank)

- effect of tank walls & non-clean-room assembly process

Wire-planes:

long wires *- mechanical robustness, tensioning, assembly, breakage/failure*

Signal processing:

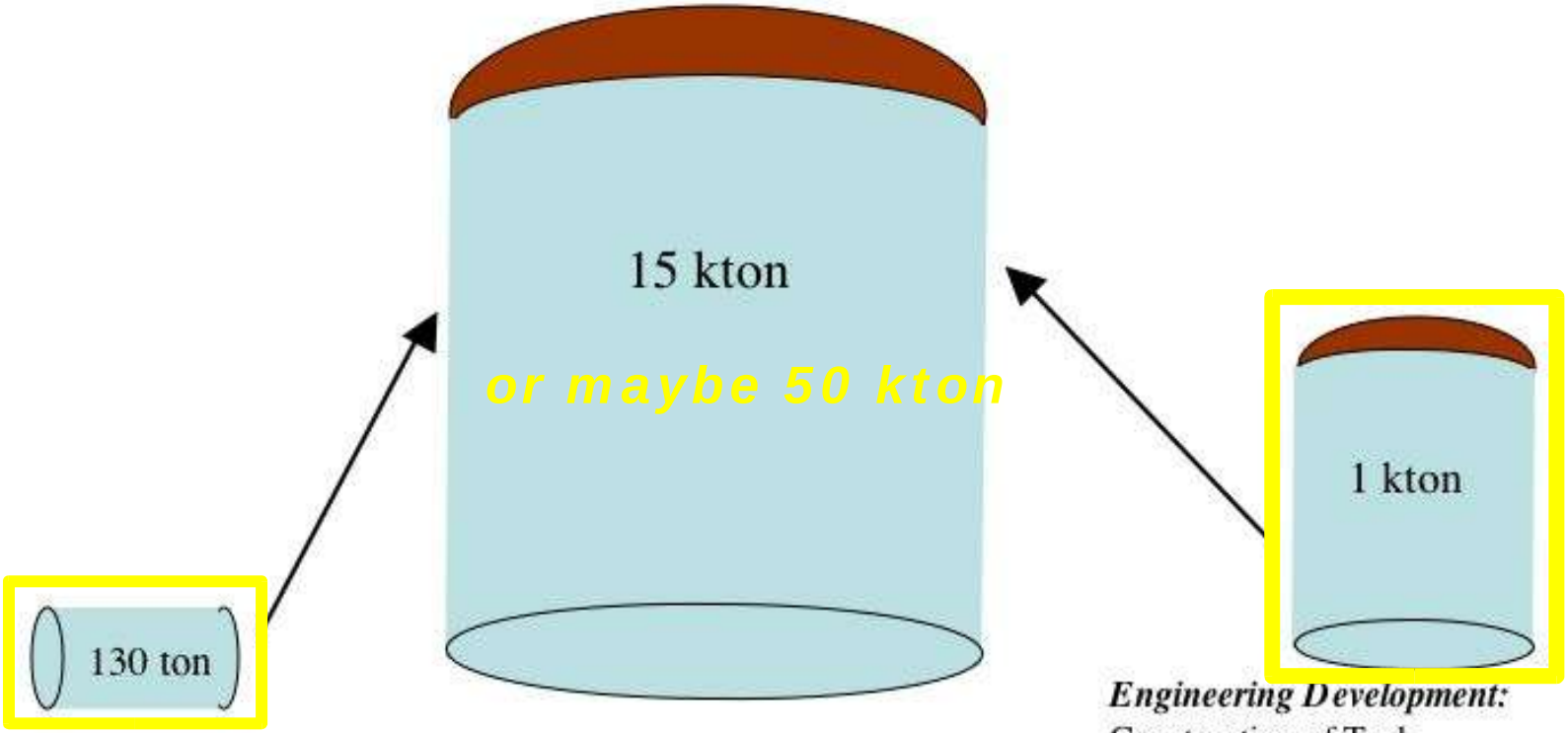
electronics *- noise due to long wire and connection cables (large capacitance)*

surface detector - data-rates,

- automated cosmic ray rejection

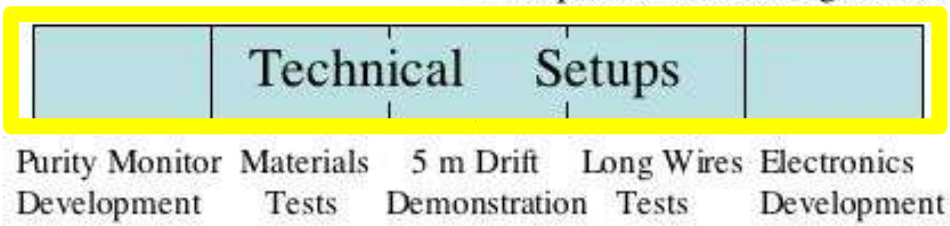
- automated event recognition and reconstruction

Addressing the challenges: The R&D path

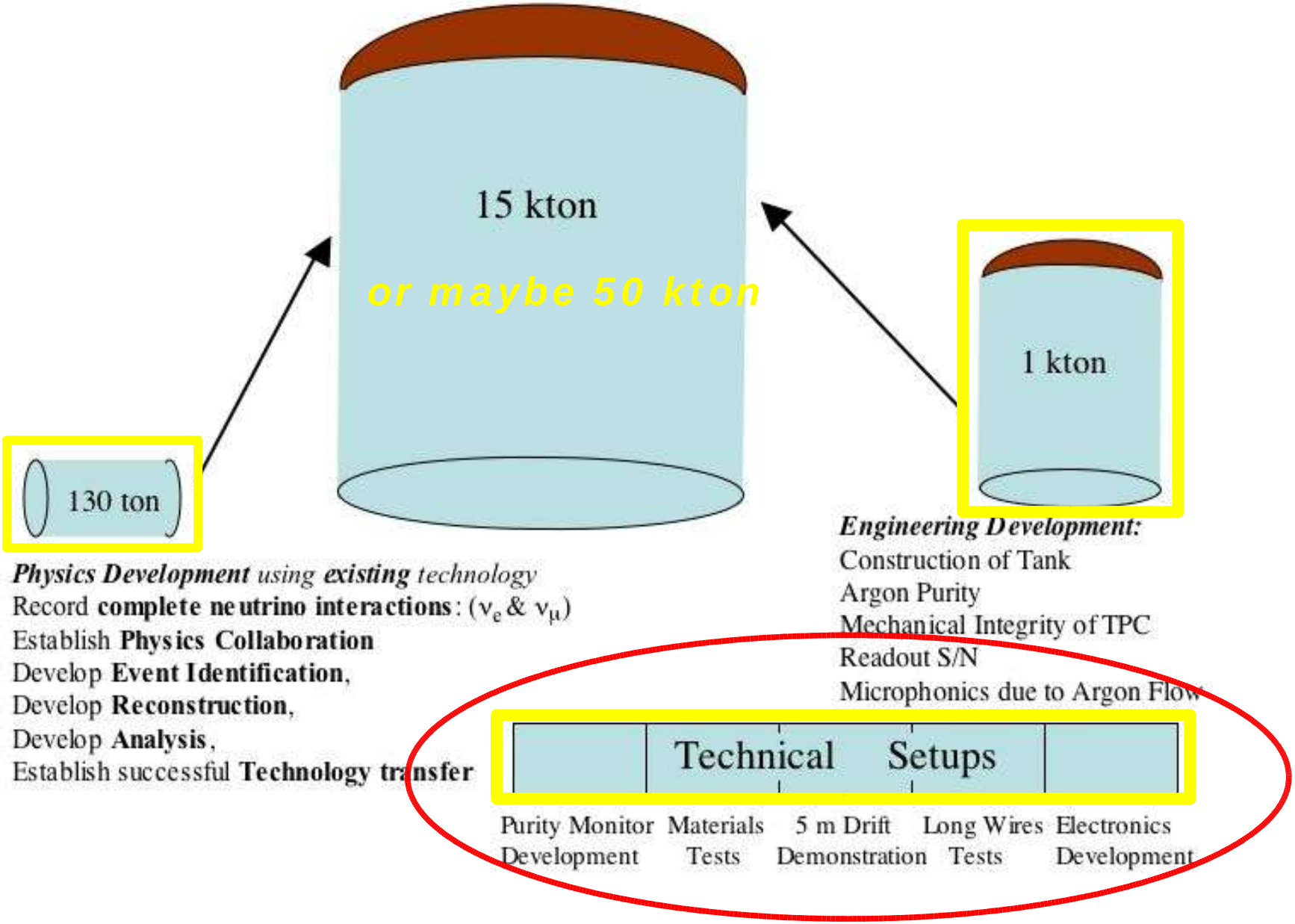


Physics Development *using* ***existing*** *technology*
Record **complete neutrino interactions**: (ν_e & ν_μ)
Establish **Physics Collaboration**
Develop **Event Identification**,
Develop **Reconstruction**,
Develop **Analysis**,
Establish successful **Technology transfer**

Engineering Development:
Construction of Tank
Argon Purity
Mechanical Integrity of TPC
Readout S/N
Microphonics due to Argon Flow

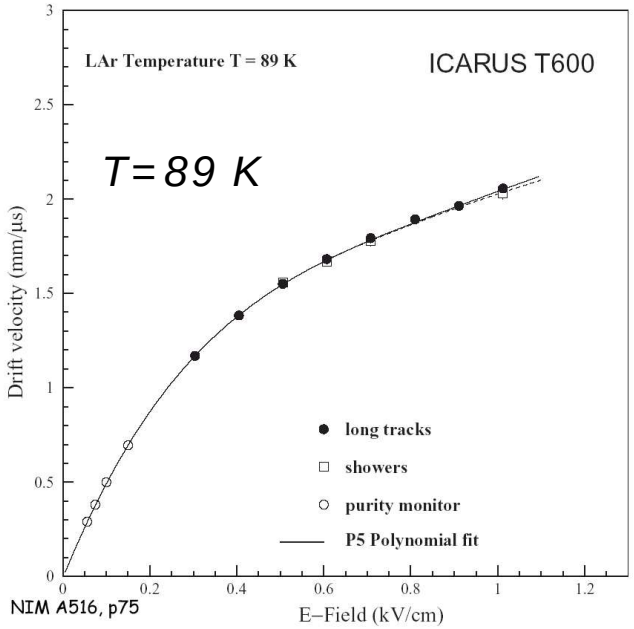


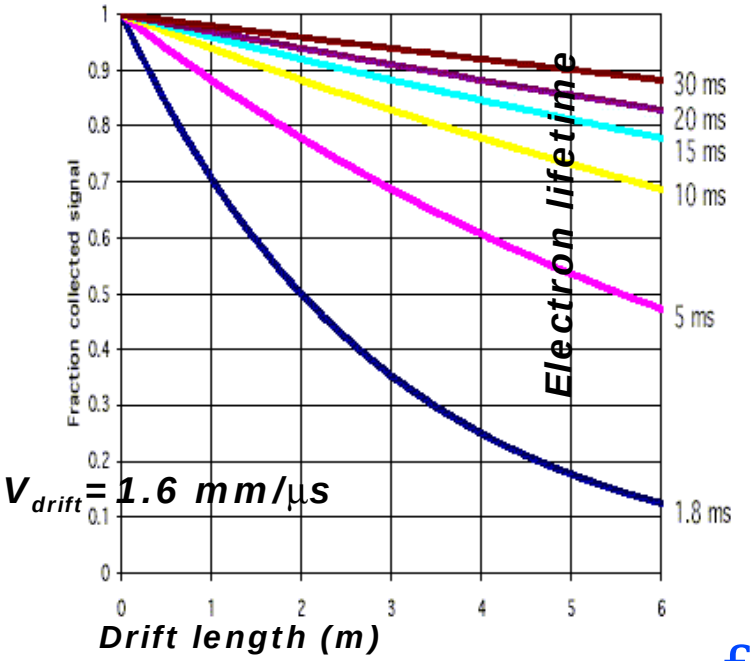
Addressing the challenges: The R&D path



Can we drift over over long distances (3m) ?

Experience from ICARUS:
Max HV: 150kV
(E=1kV/cm in T600)
v_{drift} = 1.55±0.02 mm/μs
@ 500 V/cm



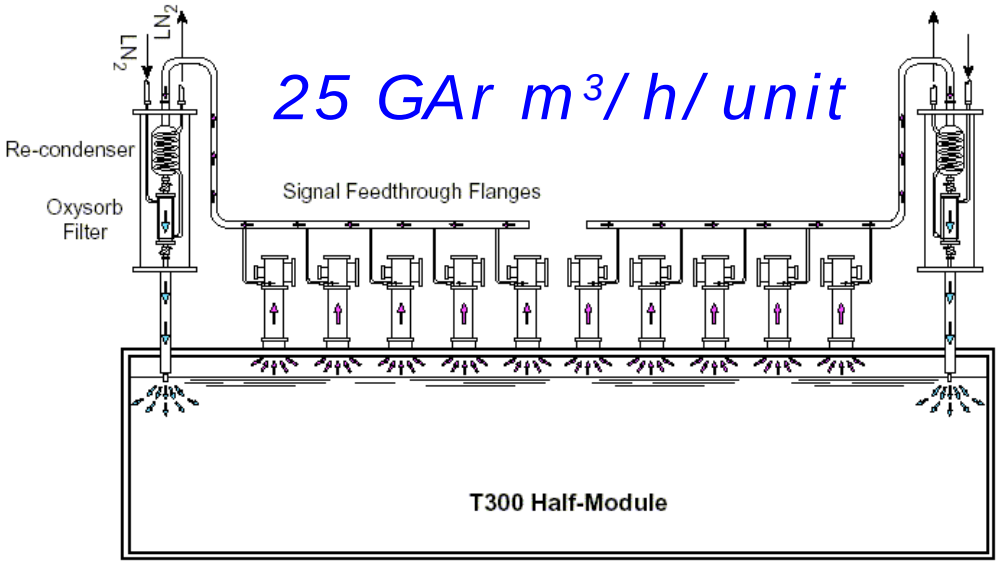


To drift over macroscopic distances -> very pure LAr

- a concentration of 0.1 ppb Oxygen equivalent gives an electron lifetime of 3ms

for 3m drift and <20% signal loss -> electron lifetime of 10ms

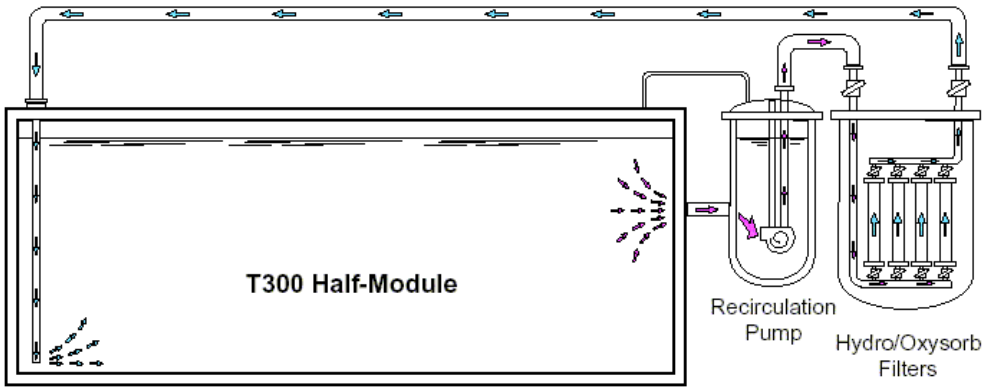
Argon purification in ICARUS



25 GAr m³/h/unit

Recirculate gaseous and liquid Argon through standard Oxysorb/Hydrosorb filters

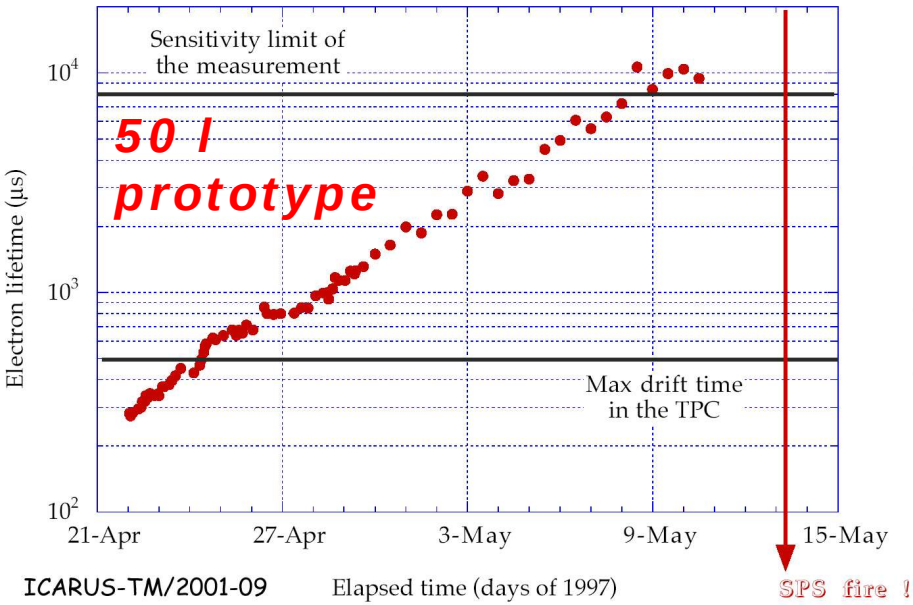
during operation....



2.5 LAr m³/h

It was verified that LAr recirculation system does not induce any microphonic noise to the wires, so it can be active during the operation of the detector

Argon purity, electron lifetime in ICARUS



The concentration of impuritites, N, is determined by

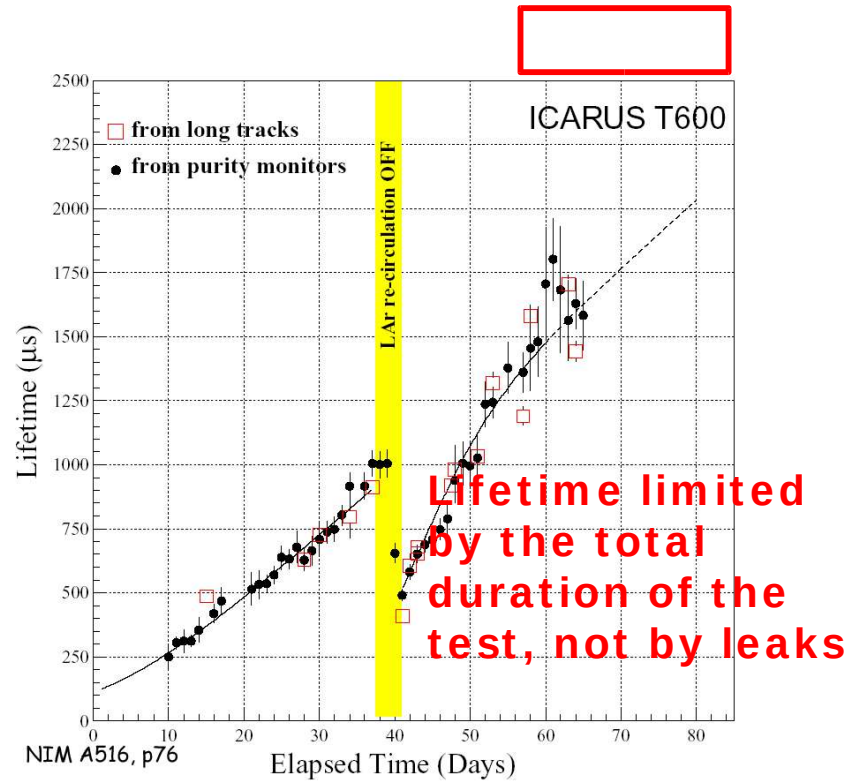
- constant input rate of impurities (leaks) $\mathbf{F}_{in}$
- outgassing of material A, B
- purification time tc (4.5 days to circulate whole LAr volume)

$$\frac{dN}{dt} = -\mathbf{F}_{out}(t) + \mathbf{F}_{in}(t) = -\frac{N(t)}{t_c} + \mathbf{F}_{in}^{0} + \frac{A}{(1+t/t_0)^B}$$

$\Phi_{in}^{0} = (5\pm5)\times10^{-3}$ ppb/day oxygen

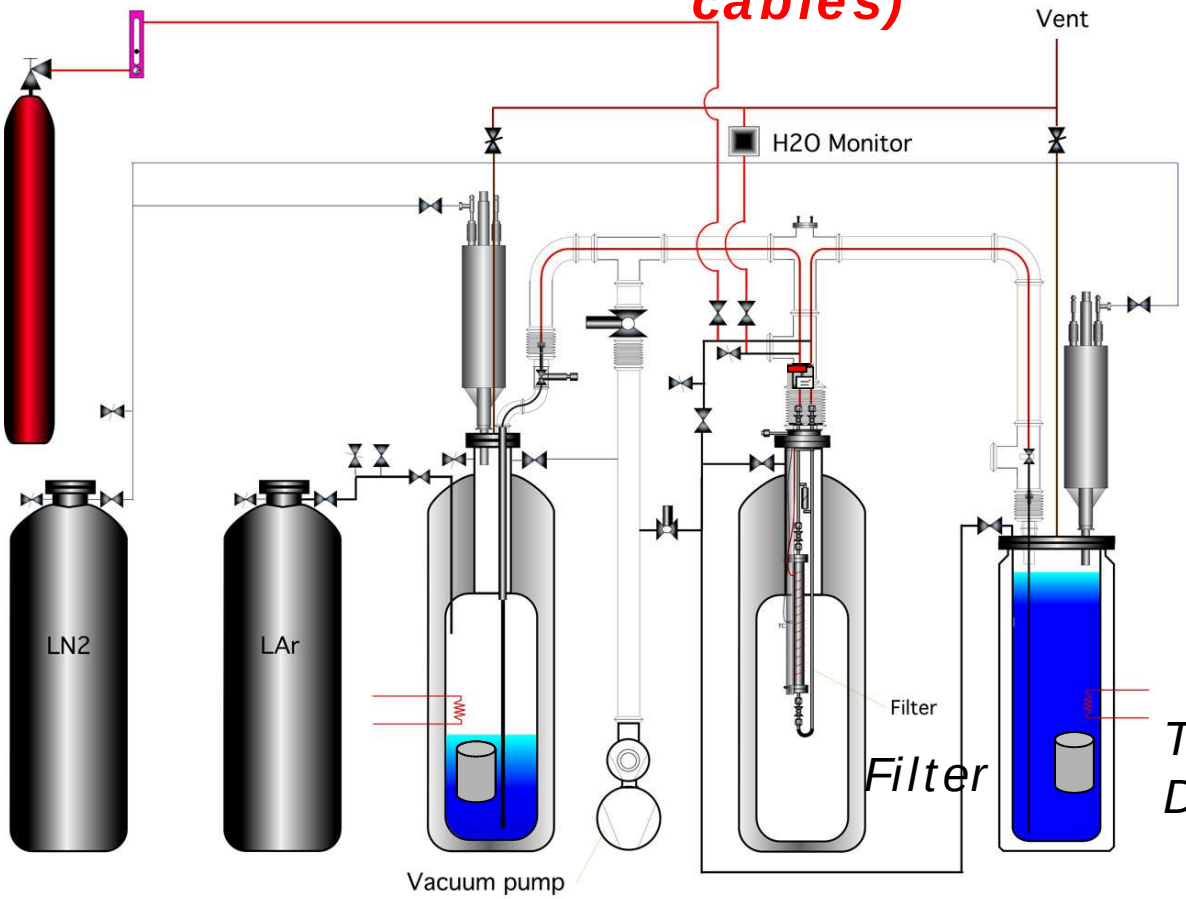
$A = 0.33\pm0.07$ ppb/day

$B = 1.39\pm0.05$



Material tests

System at Fermilab for testing filter materials and the contaminating effects of detector materials (e.g. tank-walls, cables)



ICARUS purity monitor

G. Carugno et al., NIM. A292 (1990

Filter

Test Samples Dewar

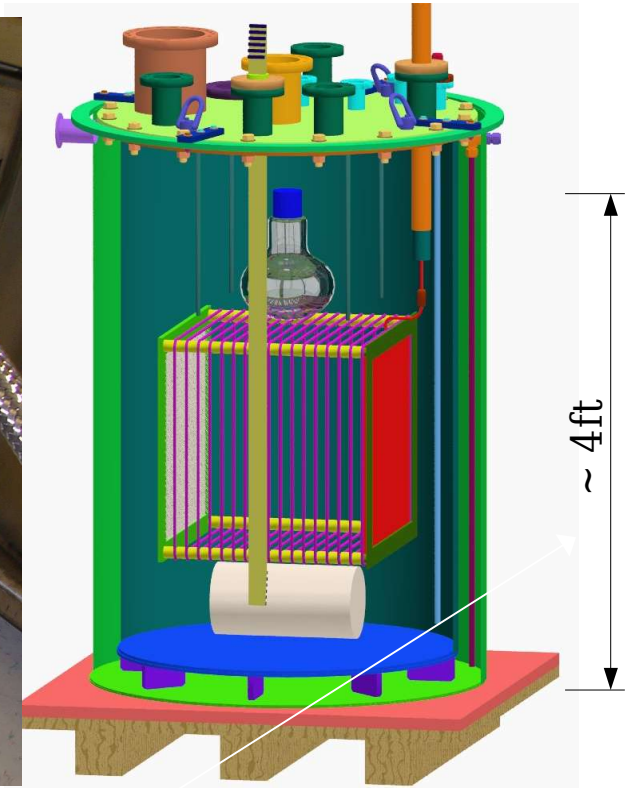
C.Kendziora6.13.05

Material tests

setup for lifetime measurements (effect of materials and effectiveness of different filters) under assembly at Fermilab

LAr TPC Test Setup @ Yale

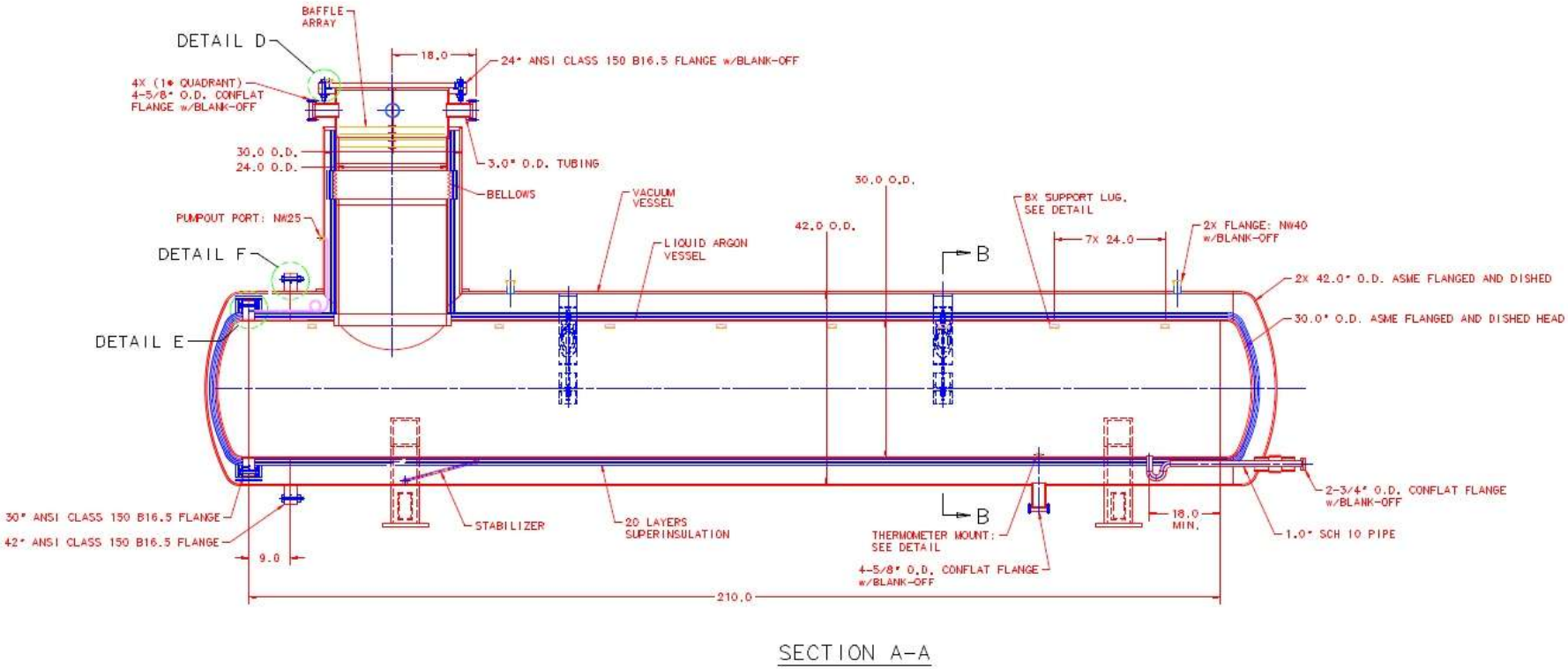
Purity monitor in liquid argon



Purity and light collection

5 m Drift Demonstration at Fermilab

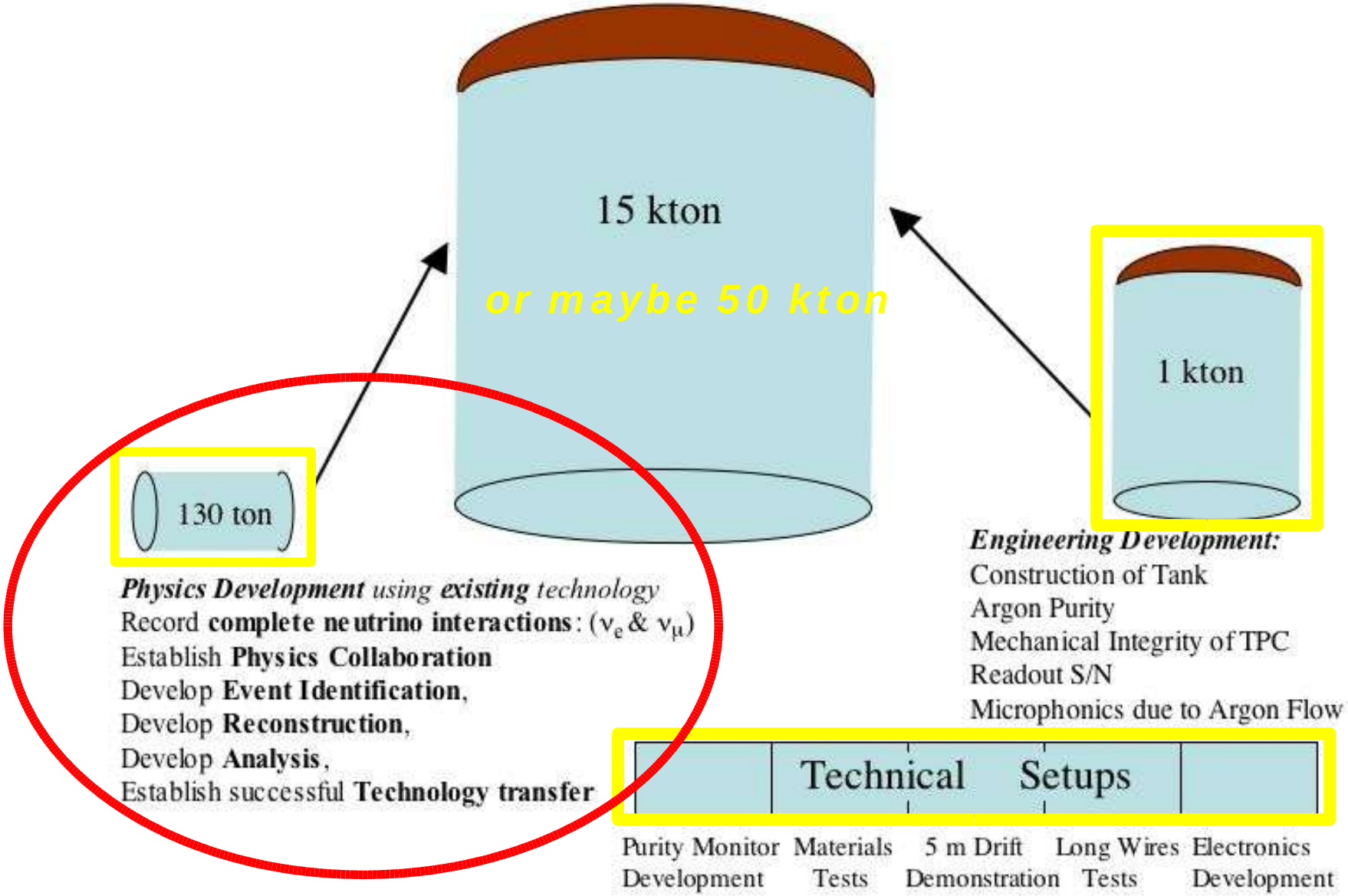
Cryostat drawing for purchasing department



Long wires tests

- ***measurements of the mechanical properties of the wires both at room temperature and in LAr***
  - *100 μ and 150 μ Stainless Steel 304V*
- ***develop wire holders that work at cryogenic temperature and do not pollute LAr***
- ***determination of wire tension***
  - *electrostatic stability*
  - *wire supports*
- ***study of noise on long wires***
  - *mechanical vibrations (i.e. induced by LAr flow)*
  - *measure damping effect of LAr on wire oscillations*
  - *study of electronics coupled to long wires (large input capacitance !)*

Addressing the challenges: The R&D path



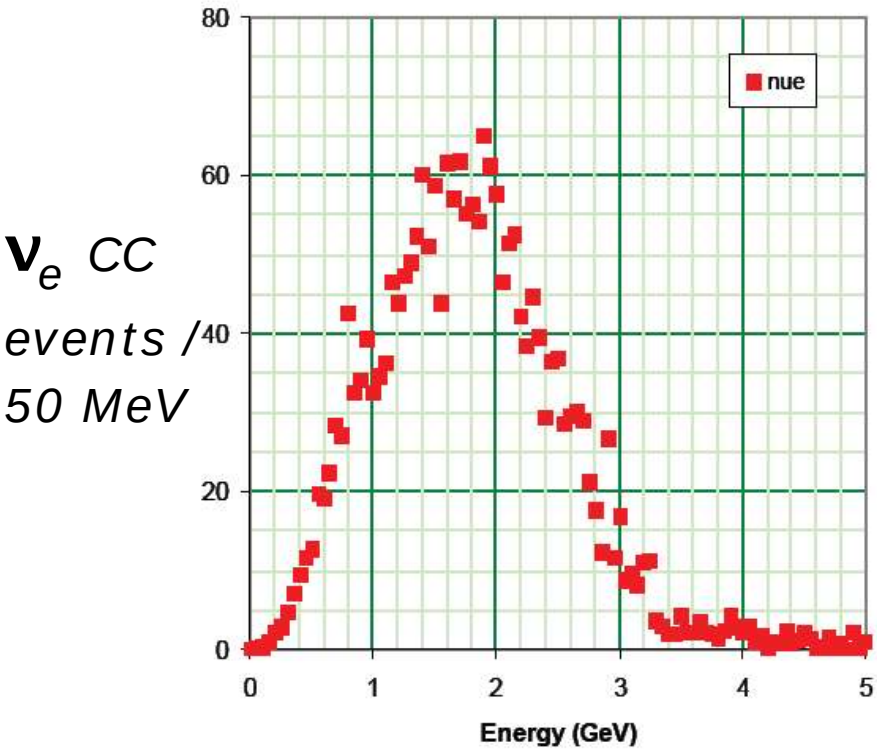
The “130 ton” detector (50 ton fiducial)

- ***Physics development using existing technology***
  - ***Establish successful technology transfer***
  - ***Record and reconstruct complete neutrino interactions (ν_μ and ν_e NC and CC) on the surface in the presence of cosmic rays***
  - *Establish physics collaboration by:*
    - *Developing event identification*
    - *Developing reconstruction*
    - *Developing analysis*
  - ***Measure ν interactions in the quasi-elastic and resonance region***

Where to find 2 GeV electron neutrinos ?

Electron Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005



- *The charged current ν_e event spectrum in the MINOS surface building.*
- *The ν_e event spectrum peaks just below 2 GeV.*
- *There are ~2,000 ν_e events shown here for 6.5E20 POT and the 20.4 ton fiducial mass NOvA near detector.*

NuMI is presently providing ~2E20 POT per year.

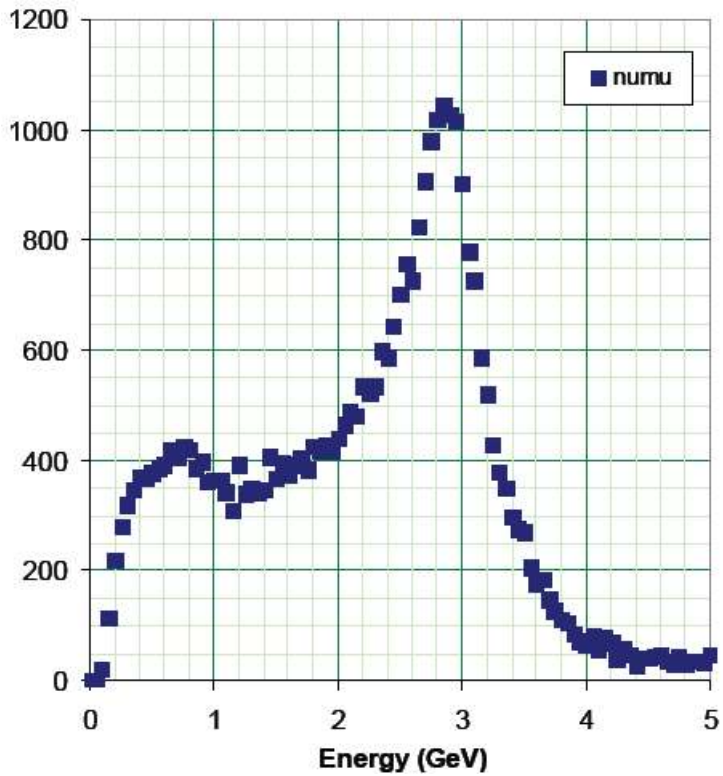
The 130 ton LArTPC has a 50 ton fiducial mass.

- ***the LAr TPC detector would get ~1600 ν_e events/year.***

Muon Neutrinos in MINOS Surface Building

From the NOvA Proposal March 15, 2005

ν_μ *CC events / 50 MeV*



- *Same assumptions as previous slide, except this shows ~15,000 muon neutrinos.*
- *The* ν_μ *peak at ~2.8 GeV is from Kaon decay.*

- ***the LAr TPC detector would get ~34000 νCC events/year***

  ~10000 ν_μ ***CC events/year in the peak between 2.4 and 3.2 GeV***

Test data rate capabilites for surface detector

50 kt data rates

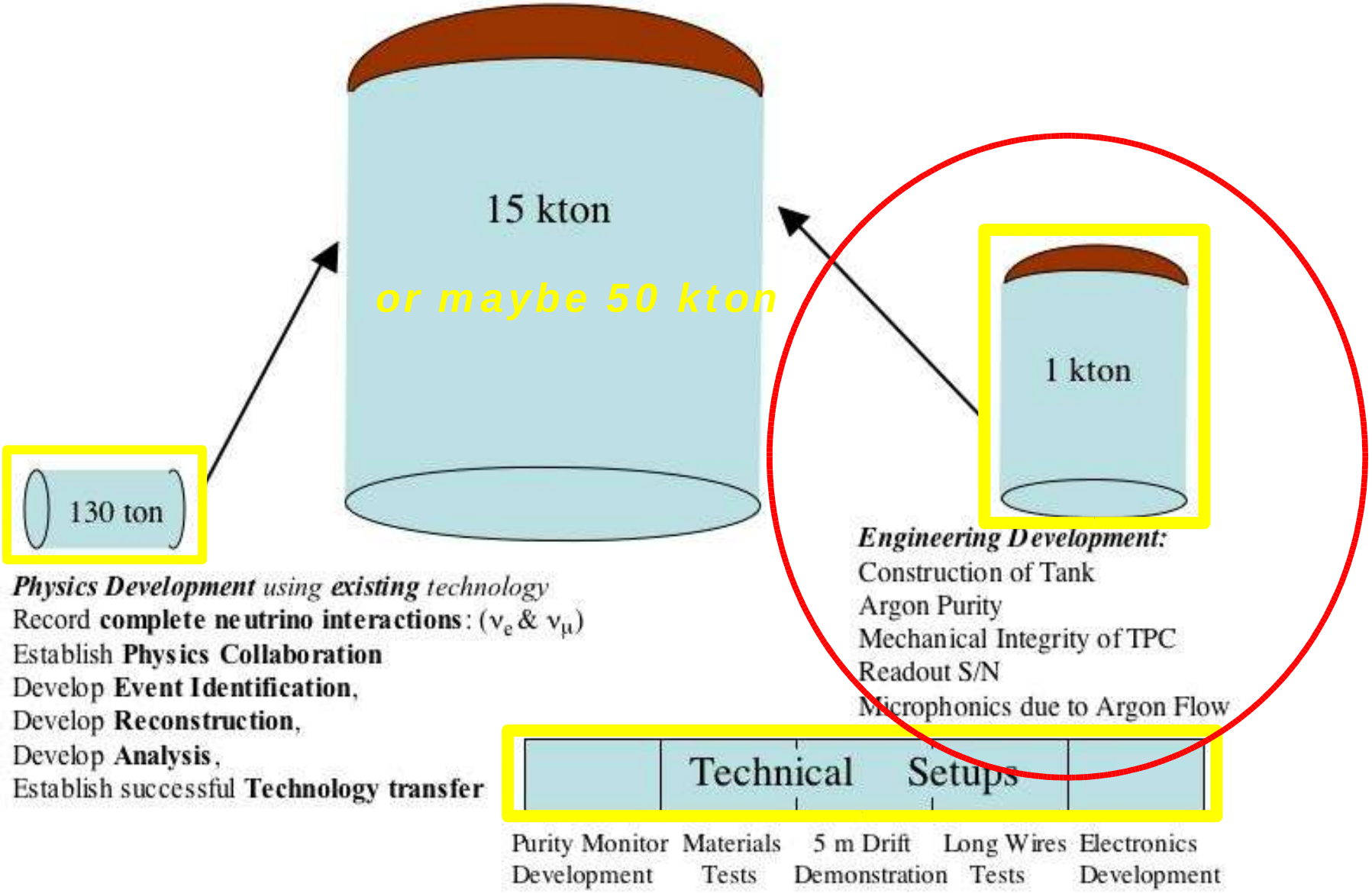
Data Type & Data Rates	Spill Only* (bytes/sec)	Always Live (bytes/sec)
Wave Train	2×10^9	10^{12}
Data above threshold	8×10^7	4×10^{10}
Full hit processing	8×10^6	4×10^9

exceeds bandwidth of 5 GB/sec

Note: Full hit processing allows for Always Live running

* Spill Only looks at 4 milliseconds (to see events plus any early cosmic rays) each spill (every 2 seconds)

Addressing the challenges: The R&D path



The “1 kton” tank

- ***Engineering Development to demonstrate scalability to large tank***

  - ***Construction of tank with the same techniques to be used with the large tank***
  - ***Demonstrate argon purity with the same techniques to be used with the large tank***
  -
  - ***Mechanical integrity of TPC***
  - ***Readout signal / noise***
  - ***Microphonics due to argon flow***

  - ***Uncover whatever surprises there may be***

LArTPC's report to NuSAG*

www-lartpc.fnal.gov

Fermilab Note: **FN-0776-E**

A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam

Submission to NuSAG

September 15, 2005

D. Finley, D. Jensen, H. Jostlein, A. Marchionni, S. Pordes, P. A. Rapidis
Fermi National Accelerator Laboratory, Batavia, Illinois
C. Bromberg
Michigan State University
C. Lu, K. T. McDonald
Princeton University
H. Gallagher, A. Mann, J. Schneps
Tufts University
D. Cline, F. Sergiampietri, H. Wang
University of California at Los Angeles
A. Curioni, B. T. Fleming
Yale University
S. Menary
York University

Interest in the community as per NuSAG's charge

* The ***N****eu*trino ***S***cientific ***A***ssessment ***G***roup for the DOE/NSF

Contact Persons: B. T. Fleming and P. A. Rapidis

This is a great, scalable technology that can enhance growing NuMI long baseline program!

Support from the community in pursing new technologies:

2005 APS neutrino study

"The development of new technologies will be essential for further advances in neutrino physics"

Support from incoming director Pier Oddone ....

Neutrino Initiative: NOvA

- In addition to Beam power: detector mass and detector sensitivity: NOvA is 30 ktons, totally active
- NOvA is the only experiment sensitive to matter effects (hence the mass hierarchy).
  - We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.
  - Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

P. Oddone September 12, 2005

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growing support from university groups as well.....

Conclusions

Liquid Argon TPC detectors are great tools for low energy neutrino oscillation physics

~1kton scale detectors have been successfully built by ICARUS

There is a path towards adressing R&D questions for realizing massive LArTPCs.

We have great new neutrino sources -- we should couple these with great detectors!

Backup Slides

Capability depends on δ and θ_{13}

The CP Violation Parameter

Three Neutrino Mixing Matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

From Atmospheric and Long Baseline Disappearance Measurements

From Reactor Disappearance Measurements

From Long Baseline Appearance Measurements

From Solar Neutrino Measurements

Chooz limit is $\sin^2 2\theta_{13} \sim 0.1$

Given very high ν_e efficiency and NC background rejection well below ½ of the intrinsic ν_e beam backgrounds, how sensitive are these detectors?

↓

Sensitivity =
detector mass x
detector efficiency x
protons on target/yr x
# of years

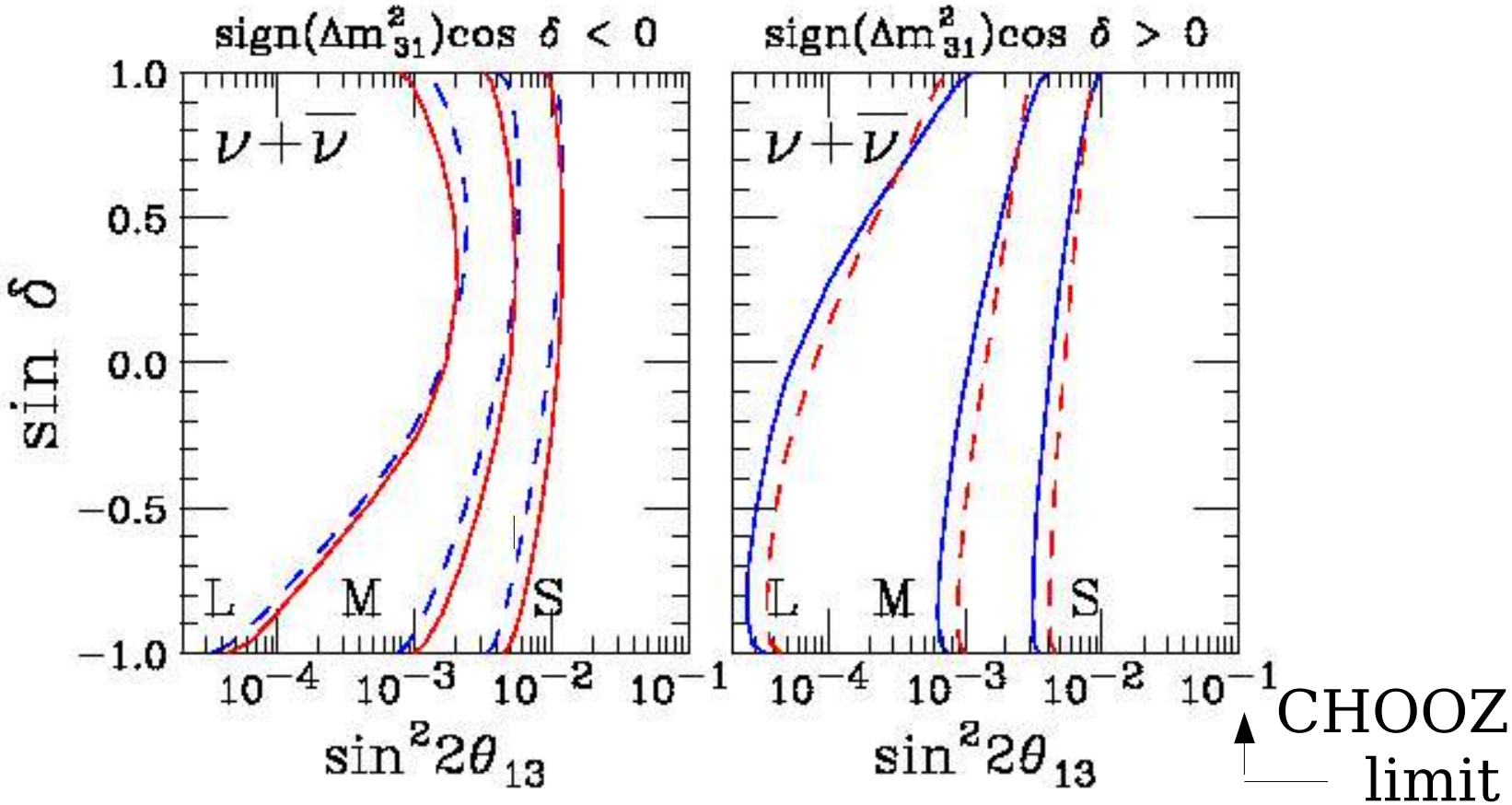
As an example: focus on recent paper by Mena and Parke

hep-ph/0505202

	Small	Medium	Large
NOvA	30kTon	30kton + PD or x5 mass or exposure	30kton + PD + x5 mass or exp.
LArTPC (90% ν_e eff.)	8kton	40kton	40kton + PD or exposure

All sensitivities assume 3 years running each in ν and $\bar{\nu}$ mode

Sensitivity to CP phase(sin δ) vs $\sin^2 2\theta_{13}$ for



most restrictive:

cos δ <0, normal hierarchy

cos δ >0, inverted hierarchy

least restrictive:

cos δ >0, normal hierarchy

cos δ <0, inverted hierarchy

Efficiency and Rejection study

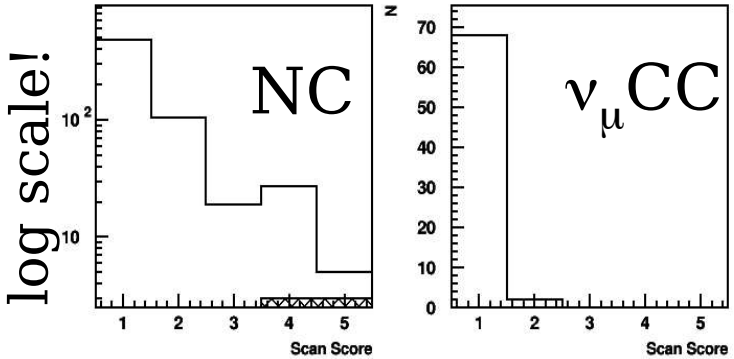
Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of "signal" events by experts.

- Neutrino event generator: NEUGEN3. Used by MINOS/NOvA collaboration. Hugh Gallagher (Tufts) is the principal author.
- GEANT 3 detector simulation: trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

Training samples:

50 events each of ν_eCC, ν_μCC and NC

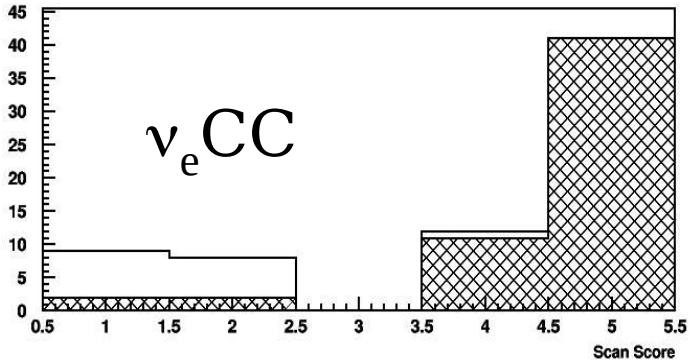
- individual samples to train
- mixed samples to test training



Blind scan of 450 events scored from 1-5 with

- signal=5
- background=1

plain region: students
Hatched region: experts

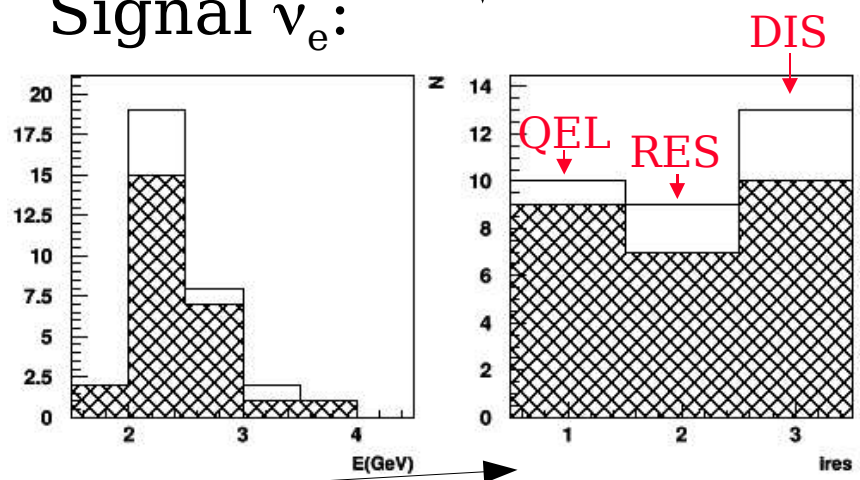


Tufts University Group

Overall efficiencies, rejection factors, and dependencies

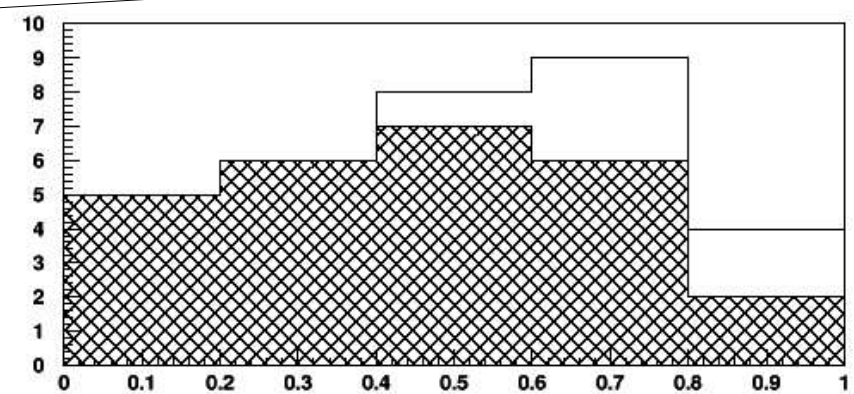
	N	pass	ε	η
NC	290	4	-	72.5
signal ν_e	32	26	0.81	-
Beam ν_e: CC	24	14	0.58	-
NC	8	0	-	

Signal ν_e:



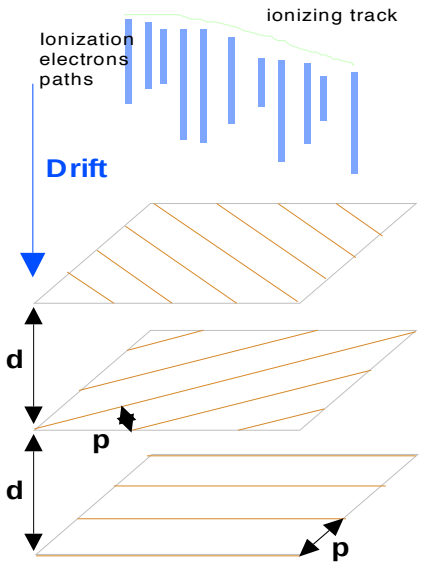
Efficiency is substantial even for high multiplicity events

Efficiency is ~100% for y<0.5, and ~50% above this

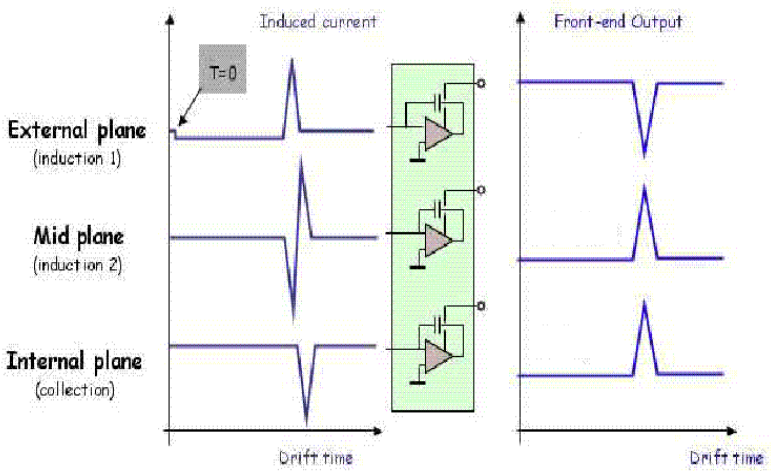


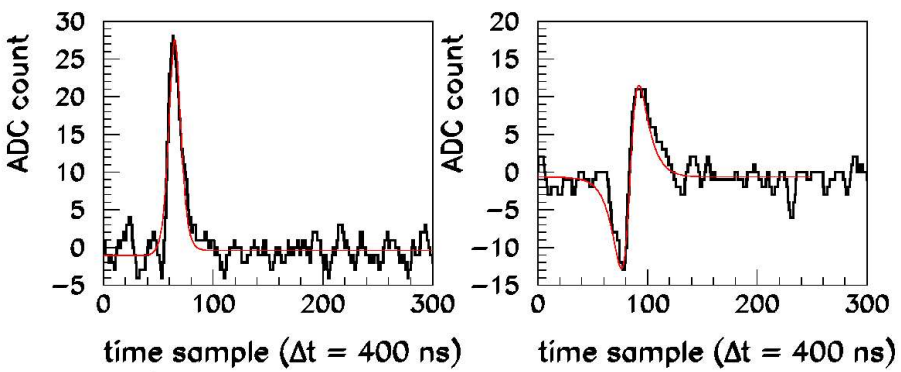
$y=E_{had}/E_{\nu}$

Signals on wire chamber planes



Arrange E fields and wire spacing for total transparency for induction planes. Final plane collects charge

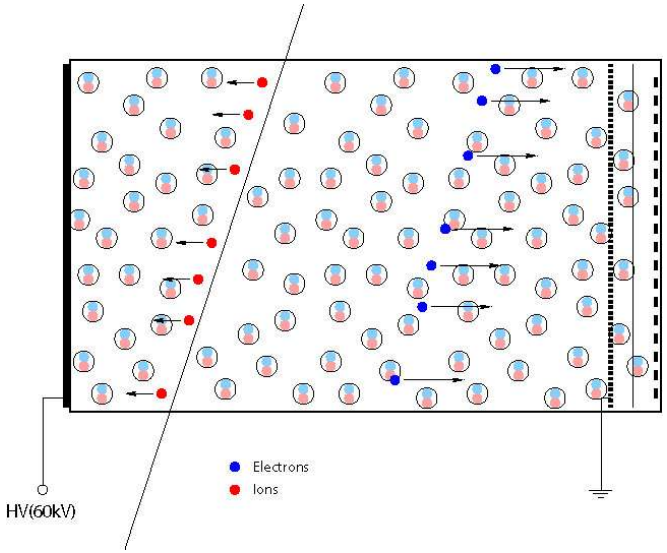




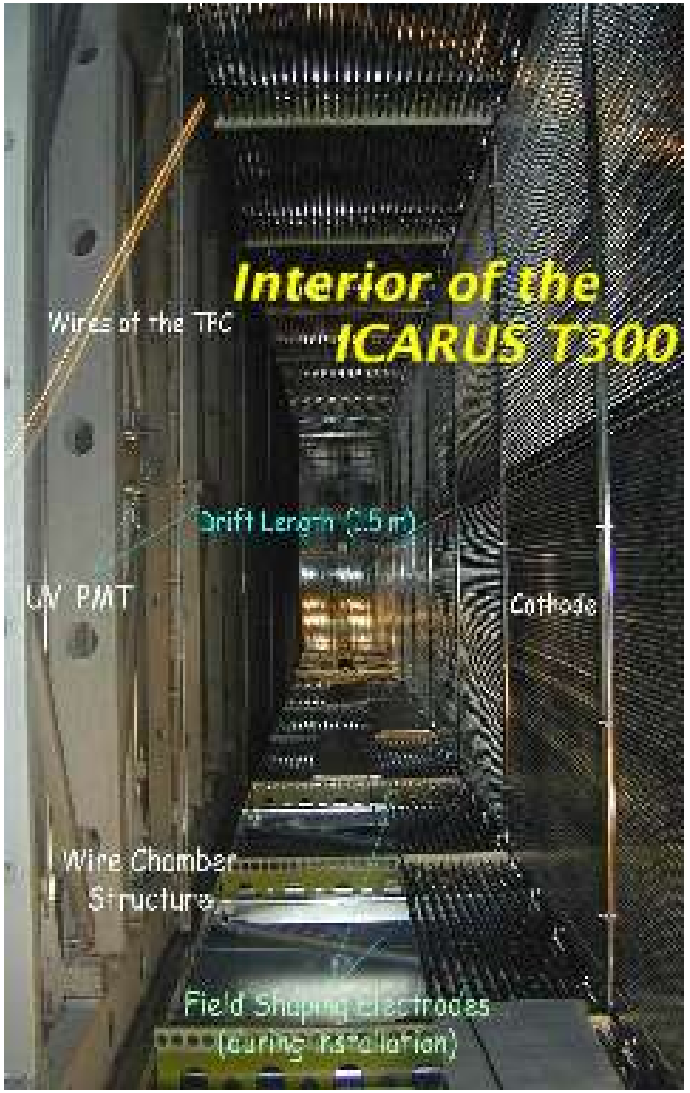
ICARUS TM/2001-09

Liquid Argon TPCs:
Fine-grained tracking, total absorption calorimeter

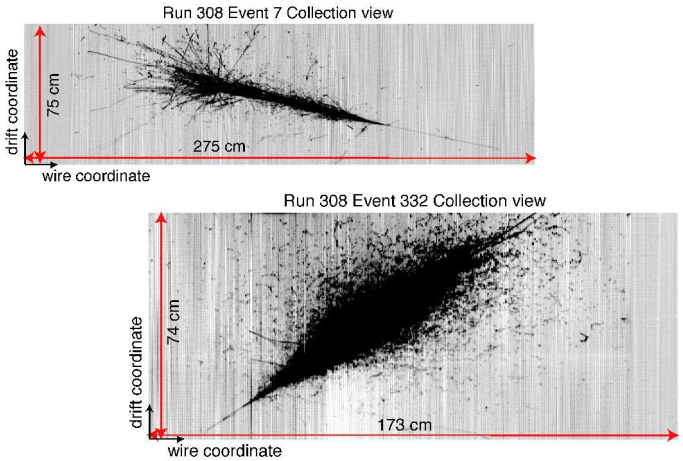
55,000 electrons/cm

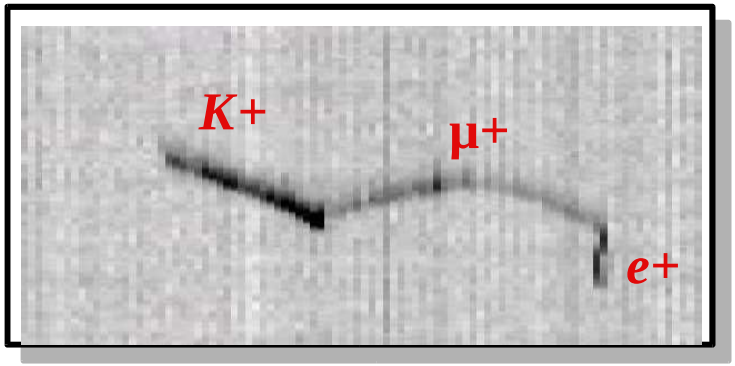


Drift ionization electrons over meters of pure liquid argon to collection planes to image track



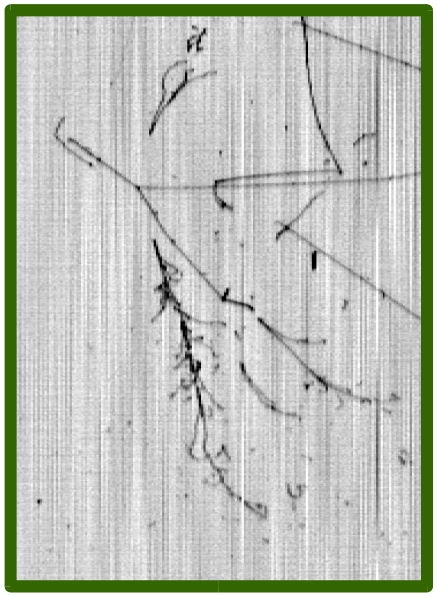
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime)

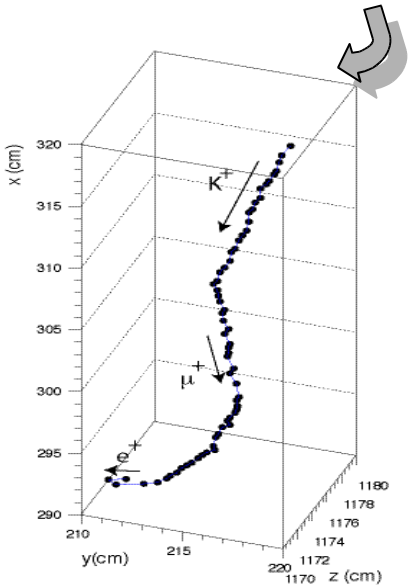




data

data





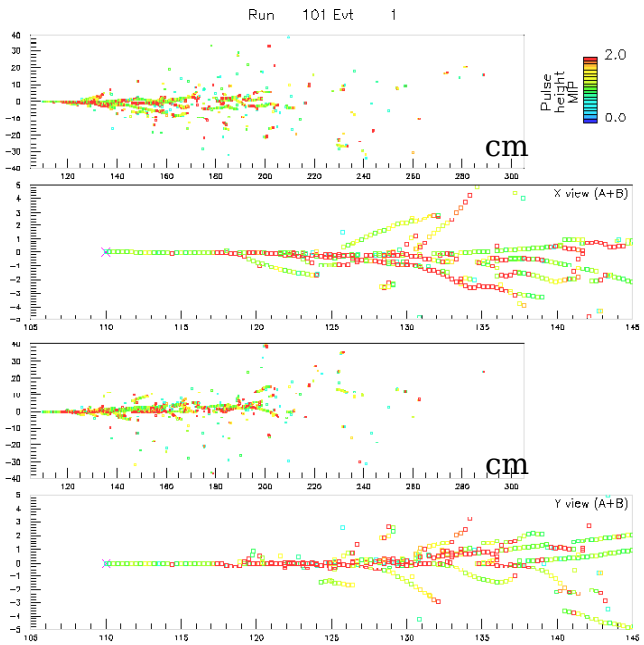
3D representation of data event

ICARUS images

Electrons versus π^0's at 1.5 GeV

Dot indicates hit
color indicates collected charge
green=1 mip, red=2 mips

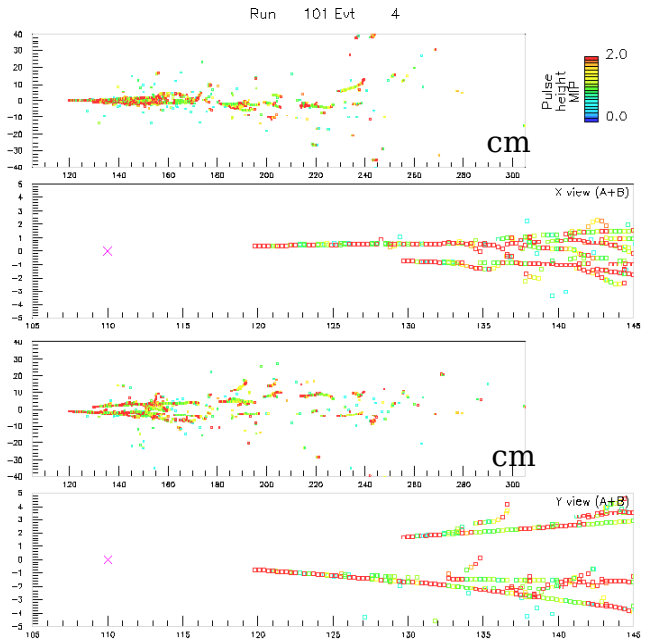
X plane
zoom in
Y plane
zoom in



Electrons

Single track (mip scale) starting from a single vertex

X plane
zoom in
Y plane
zoom in



π^0

Multiple secondary tracks can be traced back to the same primary vertex

Each track is two electrons – 2 mip scale per hit

Use both topology and dE/dx to identify interactions

Neutral current event with 1 GeV π^0

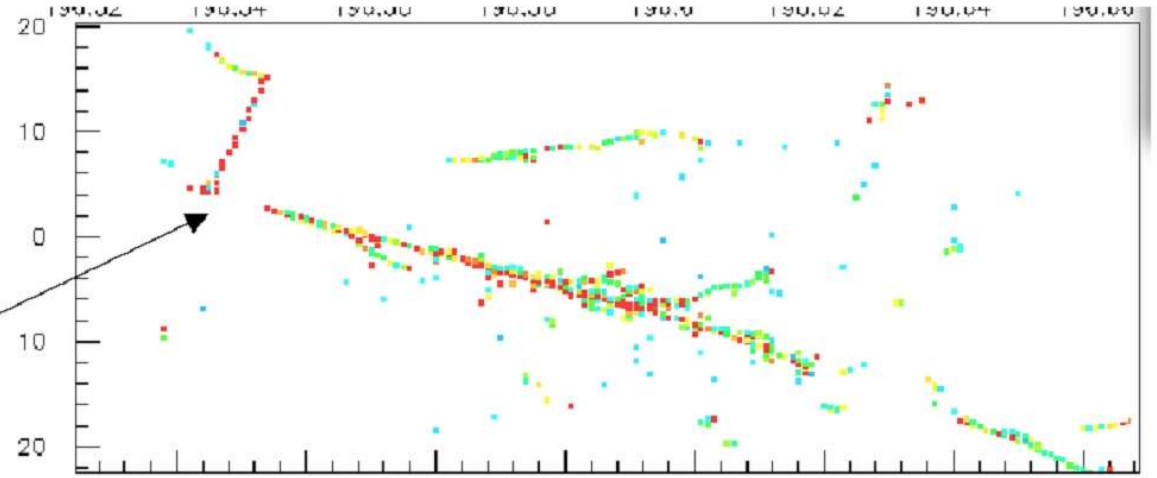
$$\nu_\mu + \mathrm{n} \rightarrow \nu_\mu + \pi^+ + \pi^- + \pi^0 + \mathrm{n}$$

$$(1\ \mathrm{GeV})\ \pi^0 \rightarrow \gamma + \gamma$$

3.5% X_0 samples

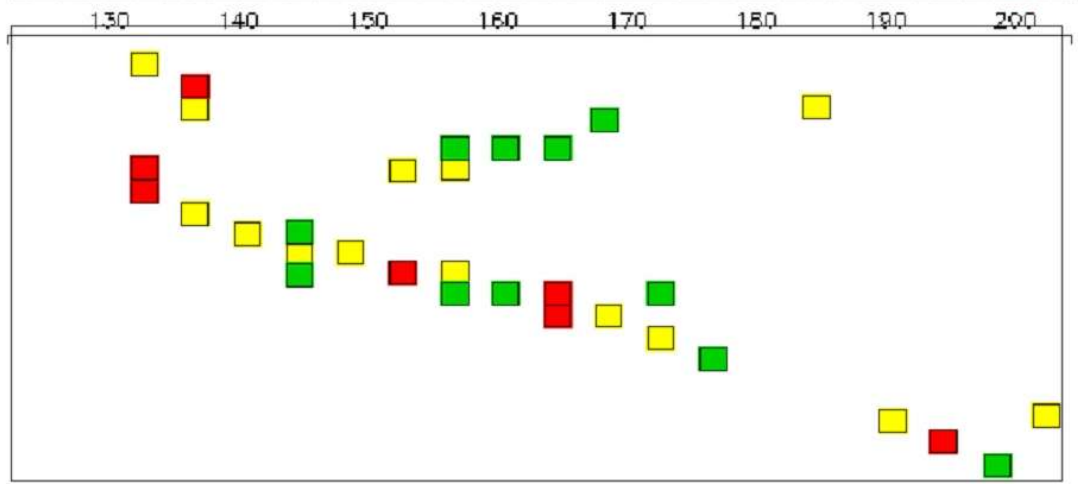
in all 3 views

4 cm gap



12% X_0 samples

alternating x-y



Efficiency and rejection study

Tufts University Group

Analysis was based on a blind scan of 450 events, carried out by 4 undergraduates with additional scanning of "signal" events by experts.

Neutrino event generator: NEUGEN3, used by MINOS/ NOvA collaboration (and others)
Hugh Gallagher (Tufts) is the principal author.

GEANT 3 detector simulation (Hatcher, Para): trace resulting particles through a homogeneous volume of liquid argon. Store energy deposits in thin slices.

signal efficiency ***background rejection***

Event Type		N	pass	ϵ	η
NC		290	4	-	0.99±0.01
signal ν_e	CC	32	26	0.81±0.07	-
Beam ν_e	CC	24	14	0.58±0.10	-
Beam ν_e	NC	8	0	-	/
Beam $\overline{\nu}_e$	CC	13	10	0.77 ± 0.09	-
Beam $\overline{\nu}_e$	NC	19	0	-	/
ν_μ	CC	32	0	-	/
$\overline{\nu}_\mu$	CC	32	1	-	/

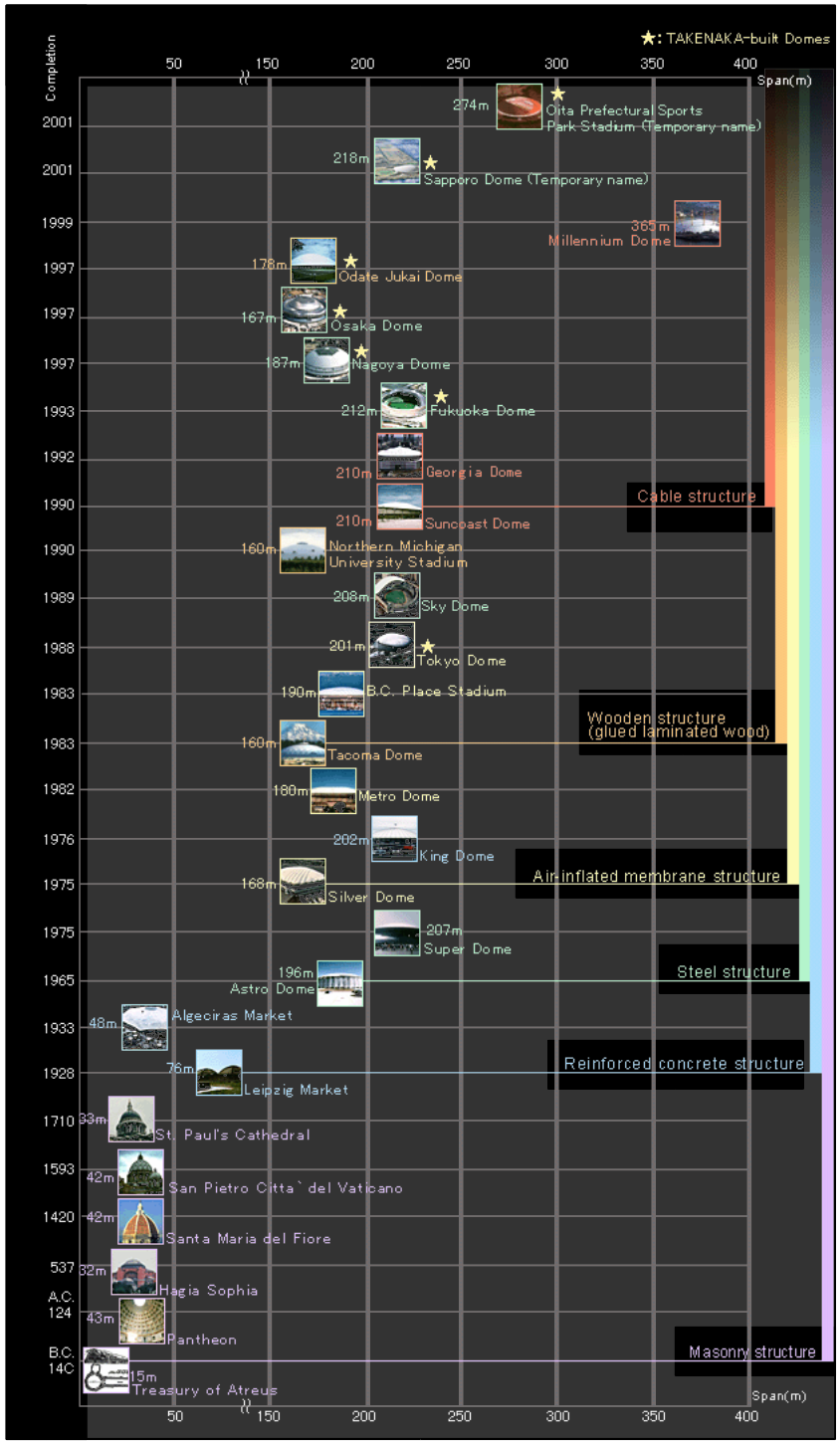
99.8% NC rejection efficiency

Good signal efficiency (81±7)%

Neutrino Initiative: NOvA

- In addition to Beam power: detector mass and detector sensitivity: NOvA is 30 ktons, totally active
- NOvA is the only experiment sensitive to matter effects (hence the mass hierarchy).
  - We want to start a long term R&D program towards massive totally active liquid Argon detectors for extensions of NOvA.
  - Improvement is proportional to (Beam power) x (detector mass) x (detector sensitivity)

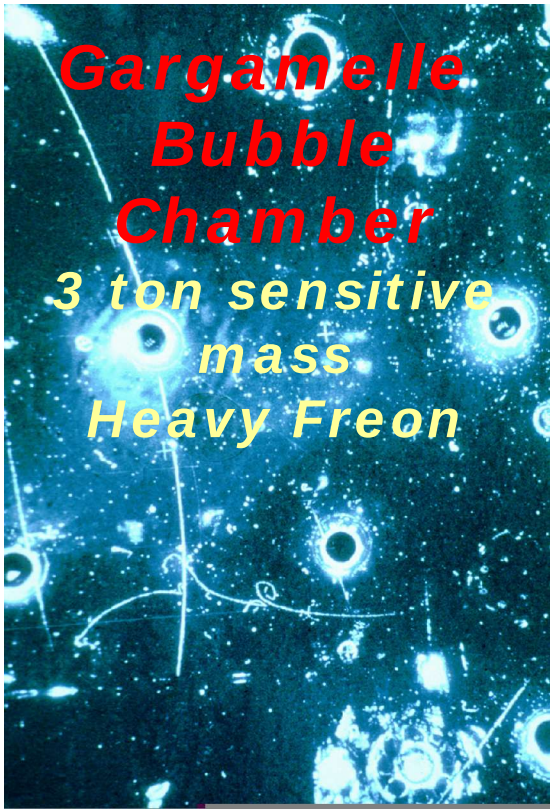
Scaling violations



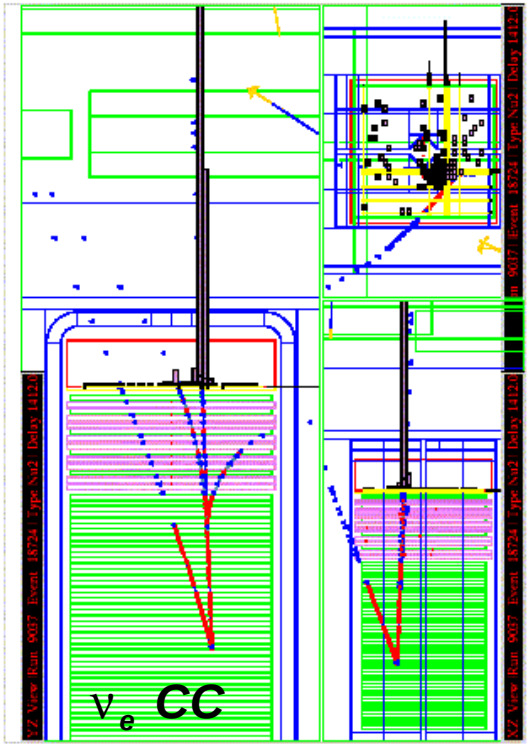
Florence Dome, span 42 m, masonry structure

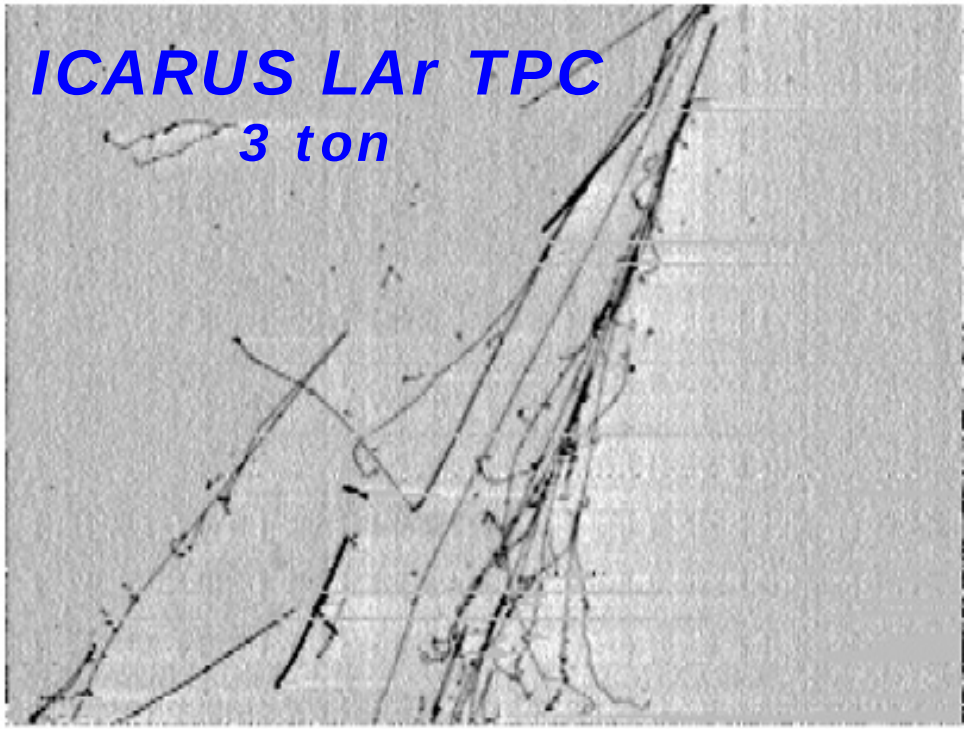
Oita sports park "Big Eye" dome, span 274 m, steel structure

Millennium Dome, Greenwich, London, span 365 m, cable structure



NOMAD





Bubble ∅ (mm)	3
Density (g/cm³)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3

2.7 tons drift chambers target
Density (g/cm³) 0.1
2% X_0/chamber
0.4 T magnetic field

TRD detector
Lead glass calorimeter

Resolution (mm³)	2×2×0.124
Density (g/cm³)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

A 15 –50 kton LAr Detector

Some Specific challenges:

3 m drift in LAr

purification - starting from atmosphere (cannot evacuate detector tank)

- effect of tank walls & non-clean-room assembly process

Wire-planes:

long wires *- mechanical robustness, tensioning, assembly, breakage/failure*

Signal processing:

electronics *- noise due to long wire and connection cables (large capacitance)*

surface detector - data-rates,

- automated cosmic ray rejection

- automated event recognition and reconstruction