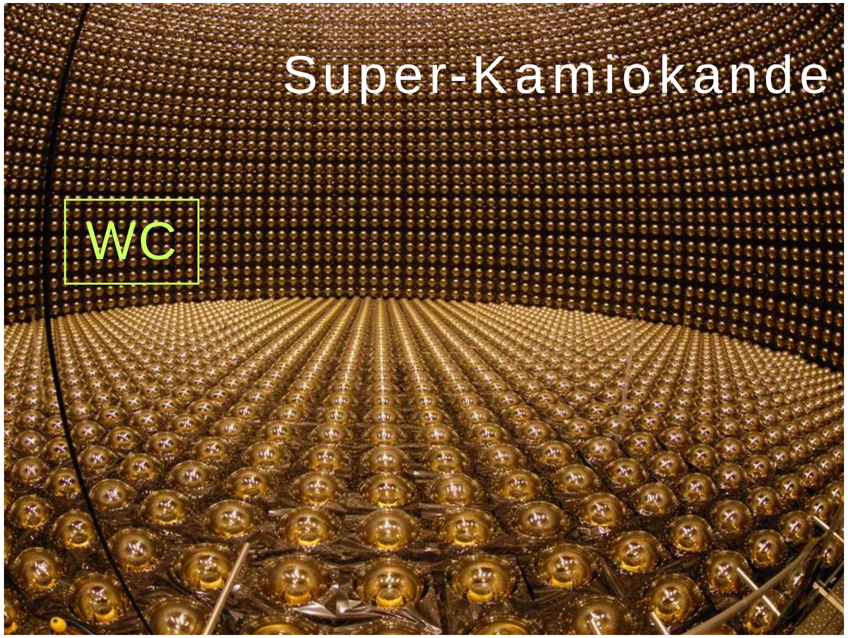
Detectors for the Next Generation of Neutrino Beams

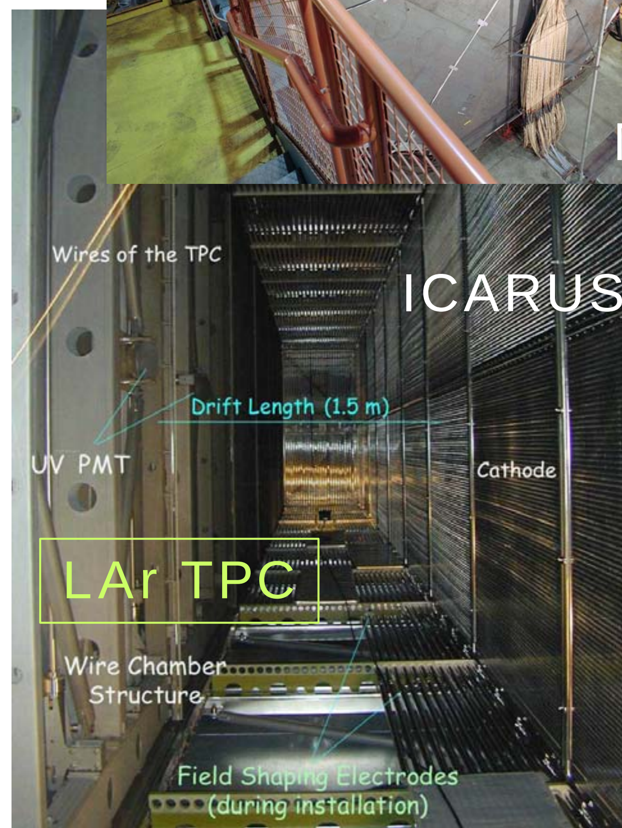
A. Marchionni, ETHZ

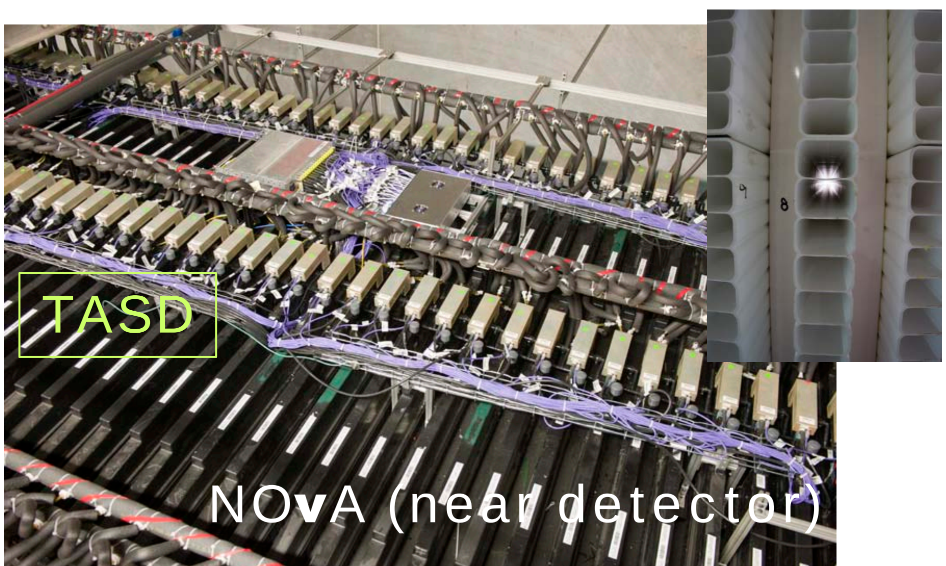
NuFact'11, Geneva, 1-6 August 2011

- **Detector technologies**
  - Magnetized Iron, Water Cherenkov, Totally Active Scintillator, LAr TPC
- **Accelerator neutrino beams**
  - SuperBeams, Beta Beams, Neutrino Factory
- **Additional fundamental physics?**
  - Astrophysical neutrino sources, rare processes
- **Extrapolation from present detectors**
  - just 'the bigger than the past the better'? New approaches, more segmentation, more fine-grained, magnetization?
- **Detector R&D**
  - photodetectors, LAr technology
- **Some concluding thoughts**

Present neutrino detectors

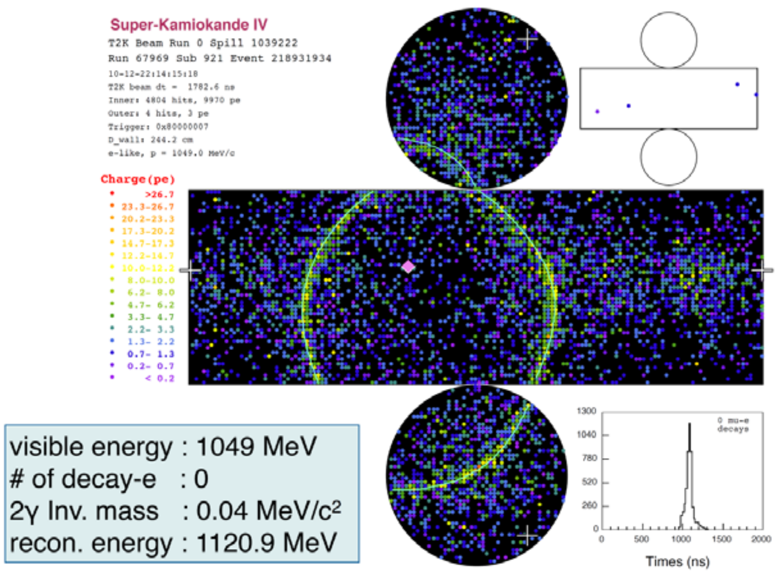


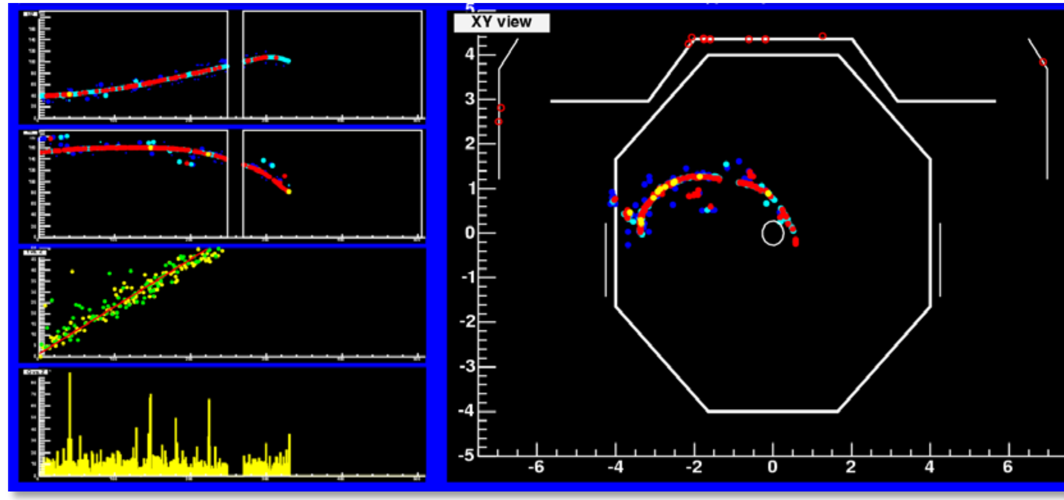


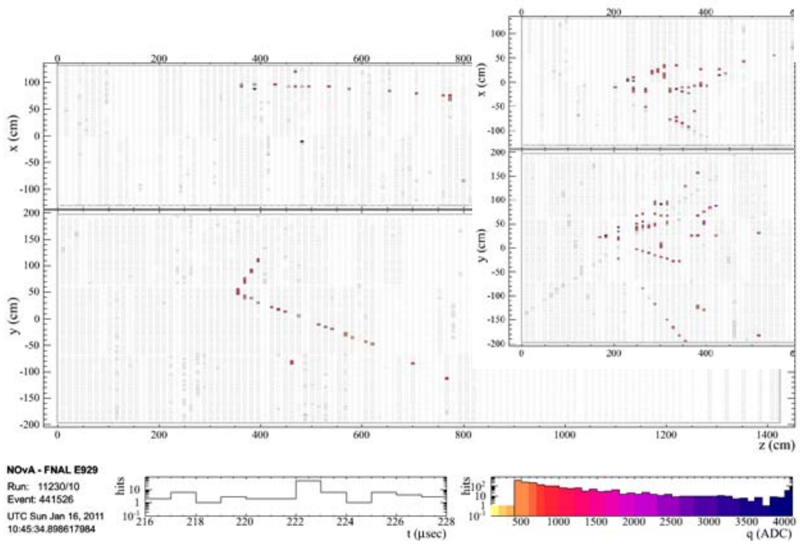


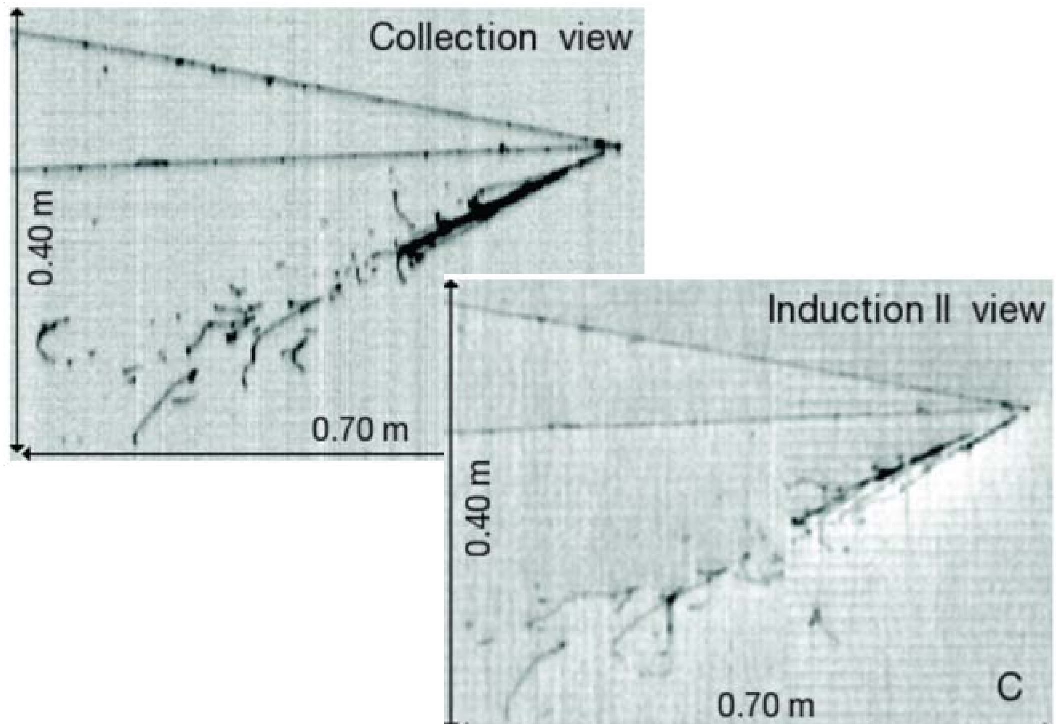
...and their events

ν_e candidate event









Next generation of neutrino beams

- **SuperBeams (MWatt scale proton beam power)**
  - mainly $\pi^+ \to \mu^+ \nu_\mu$, with ν_e contaminatiom from μ and K (~0.5-1%)
  - from wide-band to off-axis beams: tuning of ν beam peak energy and width
  - main channels: $\boldsymbol{\nu_\mu \to \nu_\mu}$, $\boldsymbol{\nu_\mu \to \nu_e}$, $\boldsymbol{\nu_\mu \to \nu_\tau}$
- **or strict selection and acceleration of neutrino parent**
- **Beta Beams**
  - pure ν_e / $\bar{\nu}_e$ from radioactive beta decays

	^{6}He	^{18}Ne	^{8}Li	^{8}B
Decay	β^-	β^+	β^-	β^+
Q (MeV)	3.5	3.0	13.0	13.9

$$E_\nu \leq 2\gamma(Q - m_e)$$

γ ~ 100-400

main channels:

$\boldsymbol{\nu_e \to \nu_e}$, $\boldsymbol{\nu_e \to \nu_\mu}$

- **Neutrino factory Beams**
  - ν beams from μ decays in a storage ring $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
  - Baseline option: E_μ = 25 GeV
  - Low Energy NF: E_μ = 4-5 GeV

channels

- golden $\boldsymbol{\nu_e \to \nu_\mu}$
- silver $\boldsymbol{\nu_e \to \nu_\tau}$
- platinum $\boldsymbol{\bar{\nu}_\mu \to \bar{\nu}_e}$

Additional fundamental physics with a large neutrino detector?

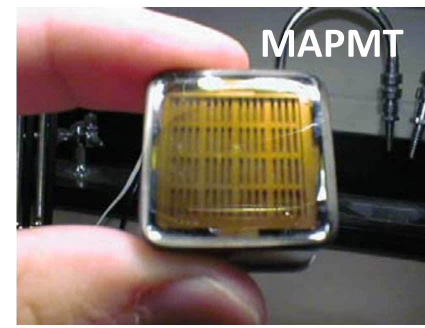
- **Baryonic number violation**
  - proton decay searches are a primary tool to address physics at the GUT scale (as well as ν masses and mixing)
- **An observatory for astrophysical neutrinos** (in order of decreasing energy)
  - atmospheric neutrinos
    - direct detection of ν_τ in atmospheric neutrinos
  - supernova core collapse neutrinos
  - diffuse supernova neutrino background
  - solar neutrinos
  - geo-neutrinos
- **Astrophysical neutrino sources could still be important for the determination of neutrino properties**

A neutrino detector sensitive to $\bar{\nu}_e$ down to ~10 MeV would also be capable of measuring $\bar{\nu}_\mu \to \bar{\nu}_e$ from a μ^+ decays at rest source generated by high intensity cyclotrons (Daedalus proposal)

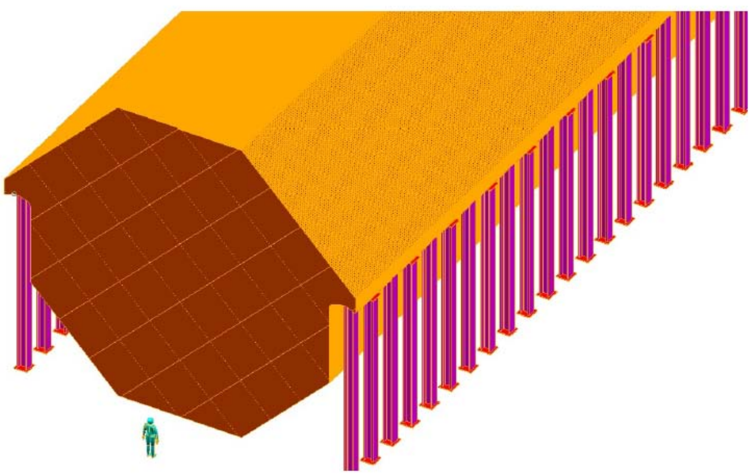
Magnetized Iron Neutrino Detector

MINOS

- 2 sections, each 15m long
- tracking calorimeter with interleaved planes of steel and solid scintillator
- total of 486 layers of 2.54 cm Fe planes, 8 m wide
- 1 cm thick and 4.1 cm wide solid scintillator strips with WLS fiber readout
- 25800 m^2 active detector planes
- ~1.5 T toroidal magnetic field
- longitudinal granularity 1.5 X_0
- 5.4 kton total mass



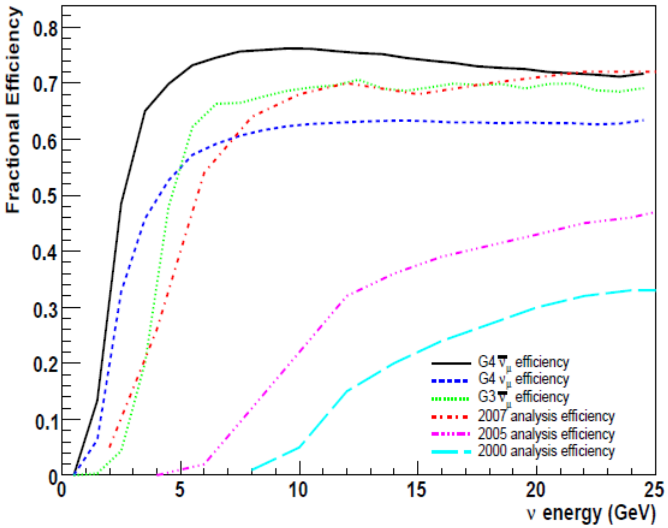
MIND



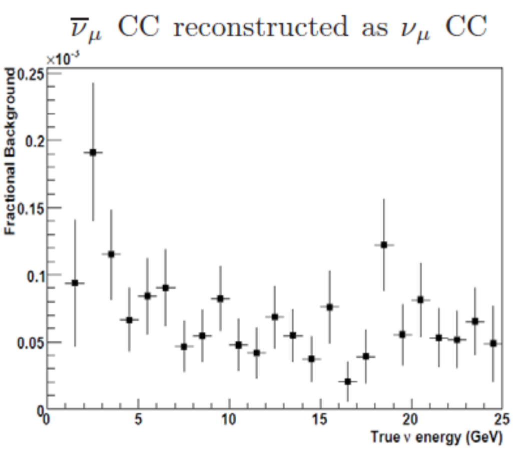
- 14 m x 14 m steel plates, 3.0 cm thick
- 100 kA-turn for magnetization using Superconducting Transmission Lines, providing a toroidal field between 1 T and 2.2 T
- Fe/Sci = 3 cm/2 cm (2 planes of scintillator, with 1 cm x 3.5 cm cross section)
- 50 m – 100 m length → 50 kton – 100 kton

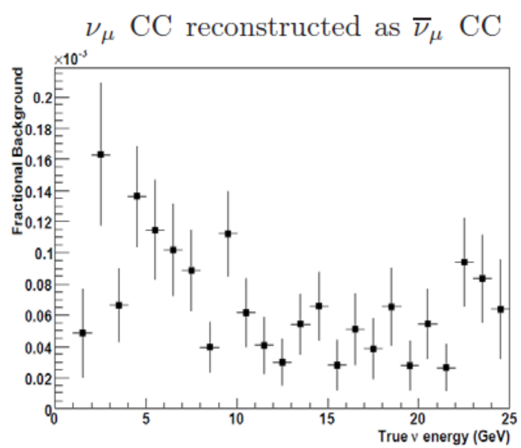
MIND efficiency and background rejection

Cervera, Laing,
Martin-Albo, Soler



MIND response to the golden channel (wrong sign muons)

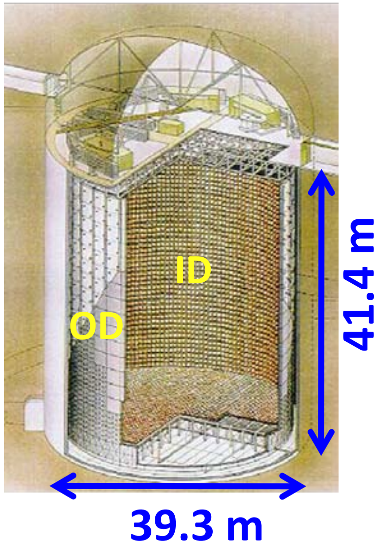




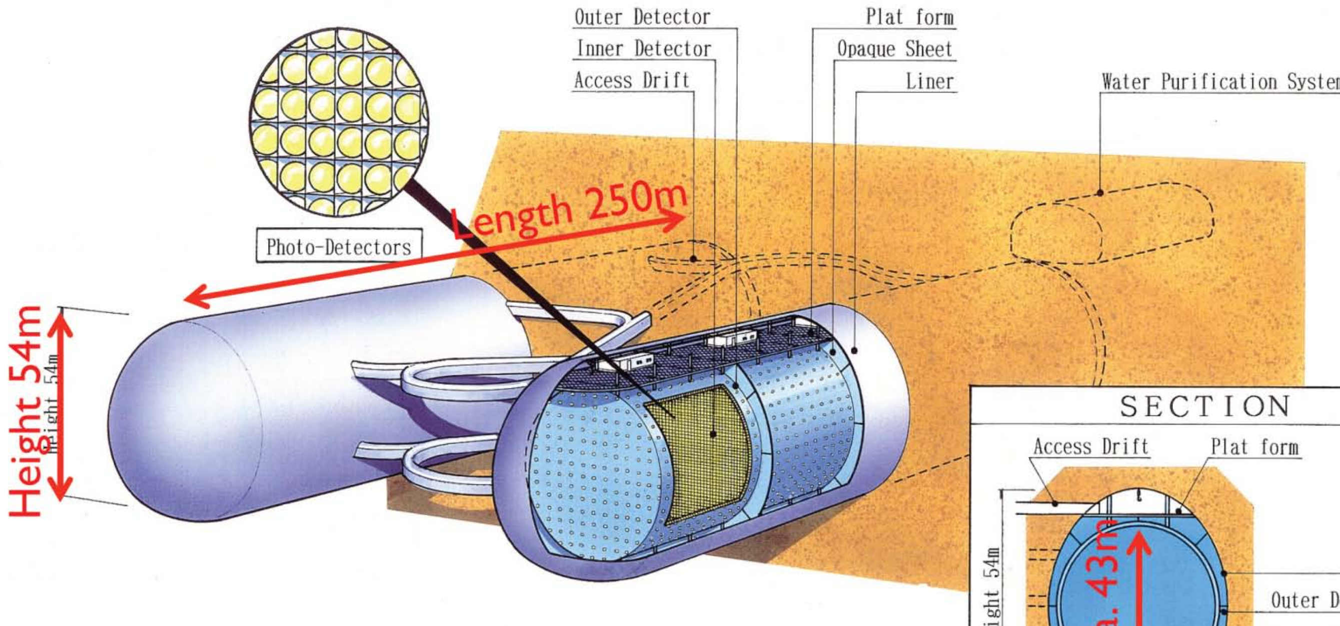
Main background from mis-identification of ν_μ ($\overline{\nu}_\mu$) CC interactions as the opposite polarity

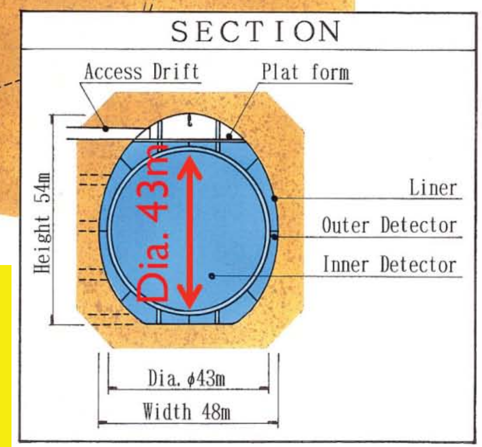
$\sim 10^{-4}$

Water Cherenkov



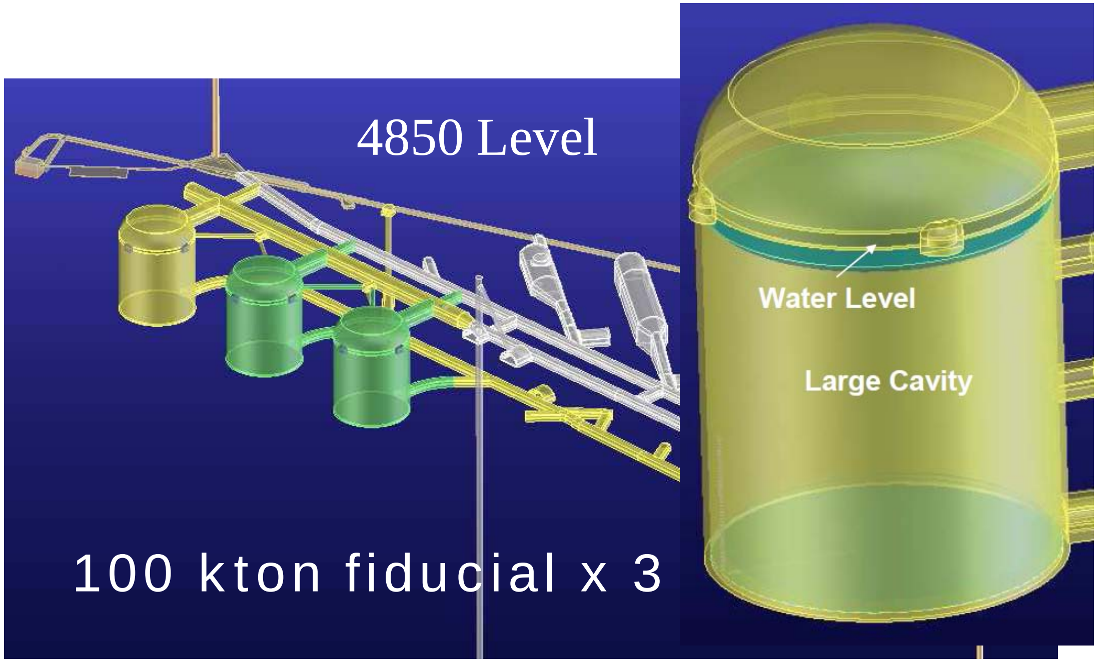
Super-K
Total volume 50 kton
Fiducial 22.5 kton
11129 20" ID PMTs
40% coverage
1885 8" OD PMTs





Hyper-K (current baseline)
1Mton total vol.
540kton fiducial vol.
Inner Detector {D43m x L(5x50m)} x 2
PMT ~100,000 (20inch)
(Photo-coverage 20%)

...or with vertical tanks

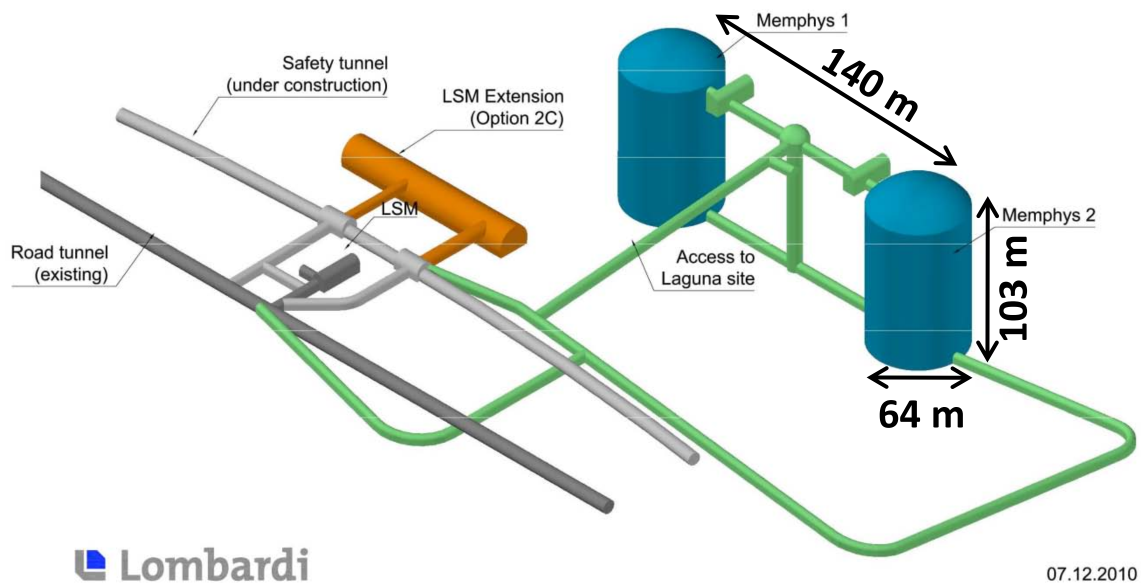


LBNE DUSEL

- **Water Tank**
  - **53m Dia. x 54m vertical**
- **Fiducial Volume**
  - **50m Dia. x 51m vertical**

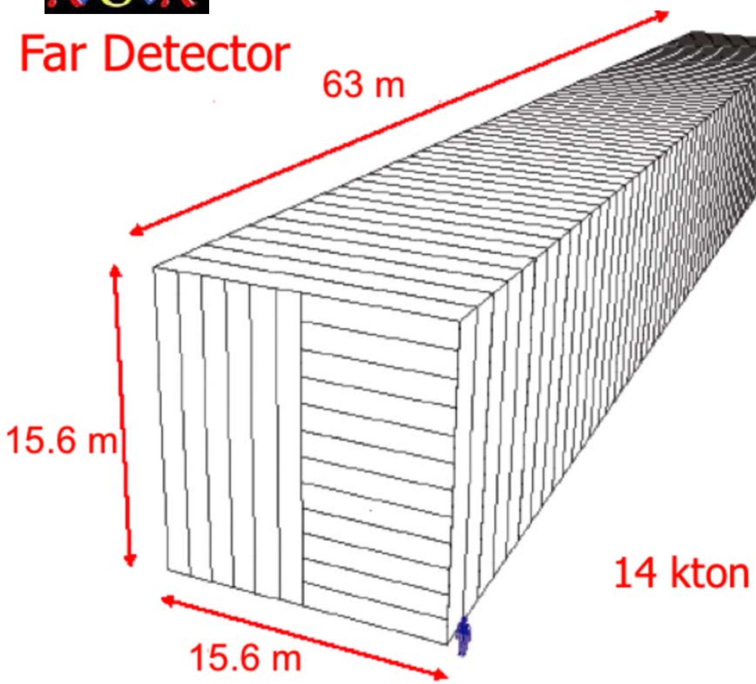
LAGUNA – Frejus MEMPHYS

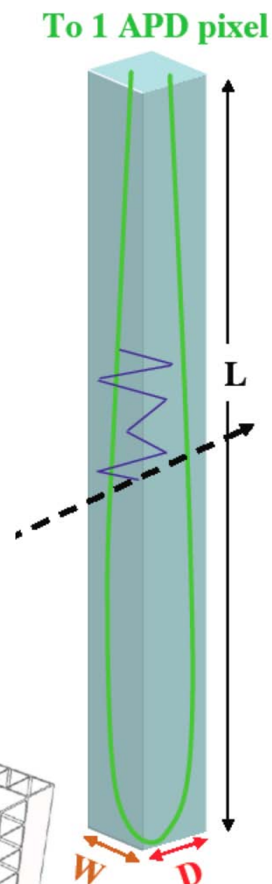
2 independent modules,
330000 m³ each
220000 8-10" PMTs
≈ 500 kton fiducial mass

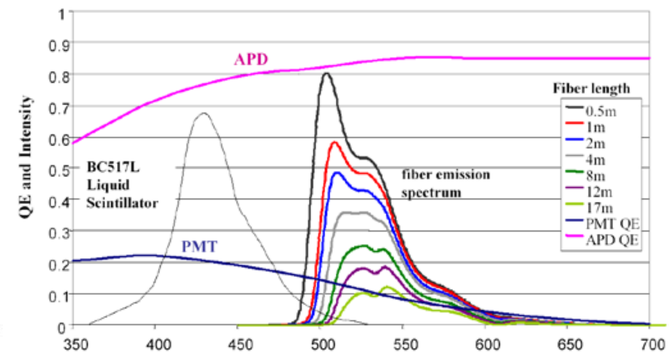


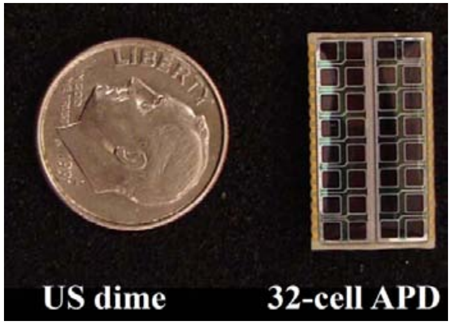
Totally Active Scintillator Detector (segmented) I

Far Detector

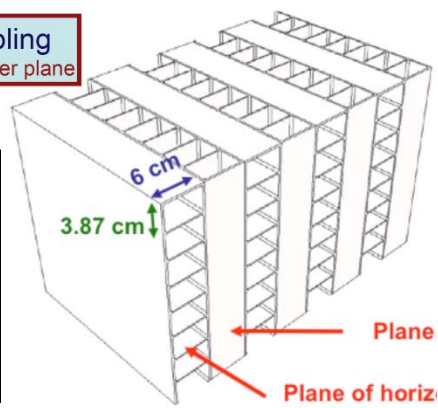








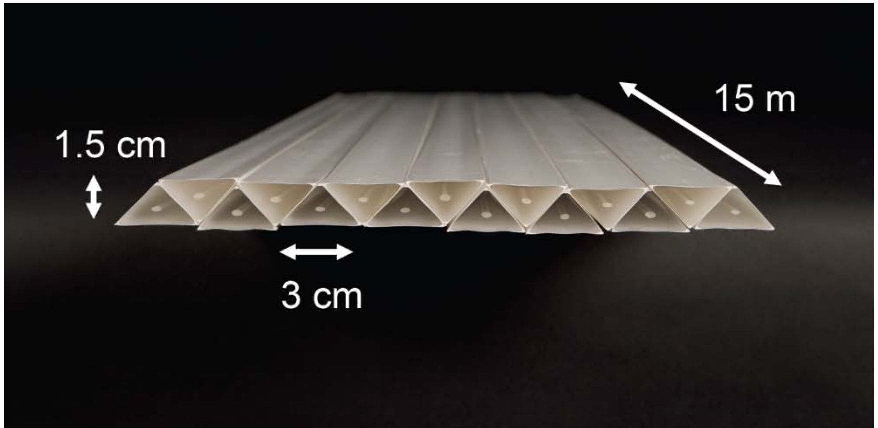
Sampling
$0.15\ X_0$ per plane

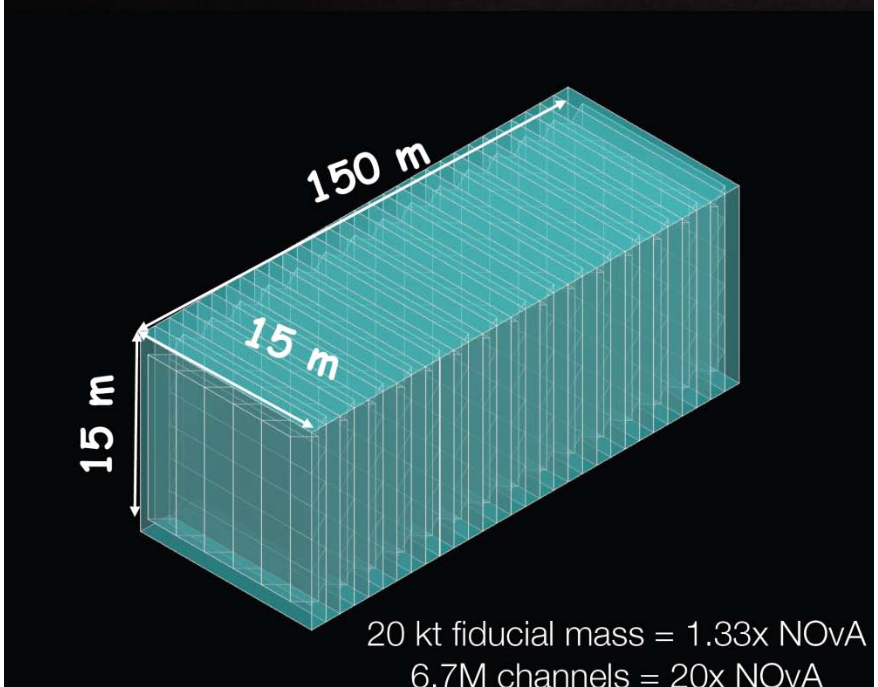


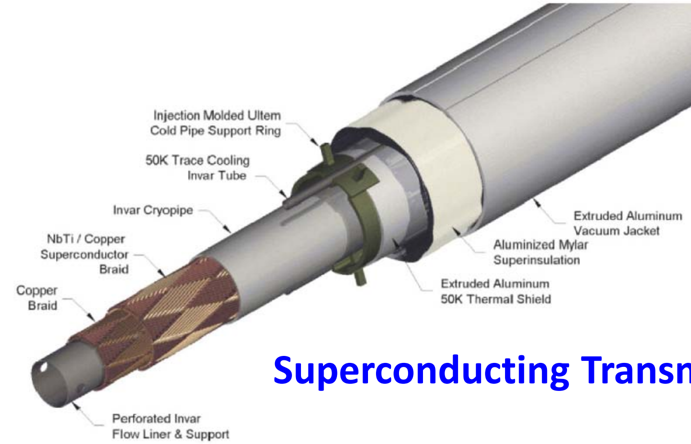
NOvA achieves 35% efficiency for ν_e CC while limiting NC$\rightarrow\nu_e$ CC fake rate to 0.1%

Totally Active Scintillator Detector (segmented) II

A. Bross et al., Phys. Rev. D 77 (2008) 093012

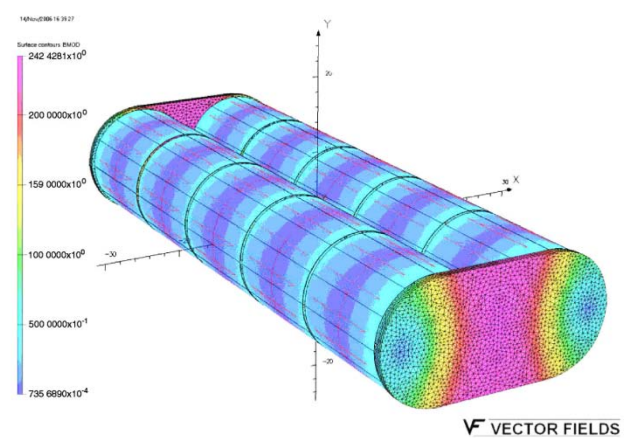






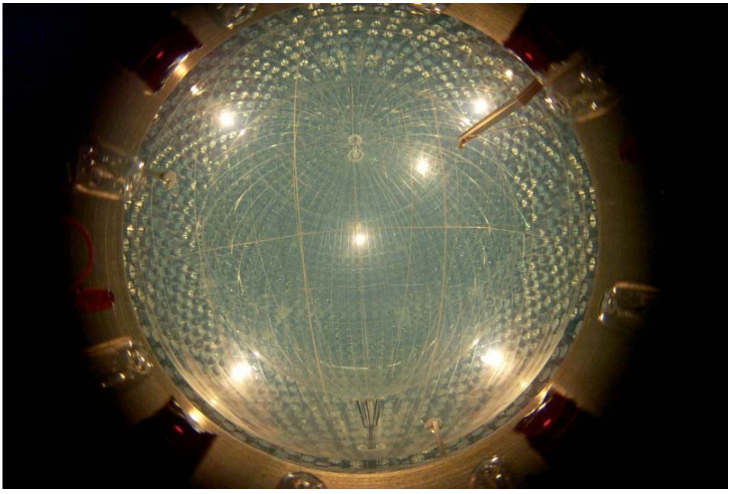
Superconducting Transmissison Line

could be used to construct large solenoids (15 m ϕ, 75 m long) capable of producing 0.5 T field



Totally Active Scintillator Detector (non-segmented)

Borexino



active mass of 278 tons of pseudocumene, doped with PPO

Low Energy Neutrino Astronomy

Target volume
- height 100 m
- diameter 26 m
- **50 kton liquid scintillator**

Shielding from cosmics: 4000 m.w.e.

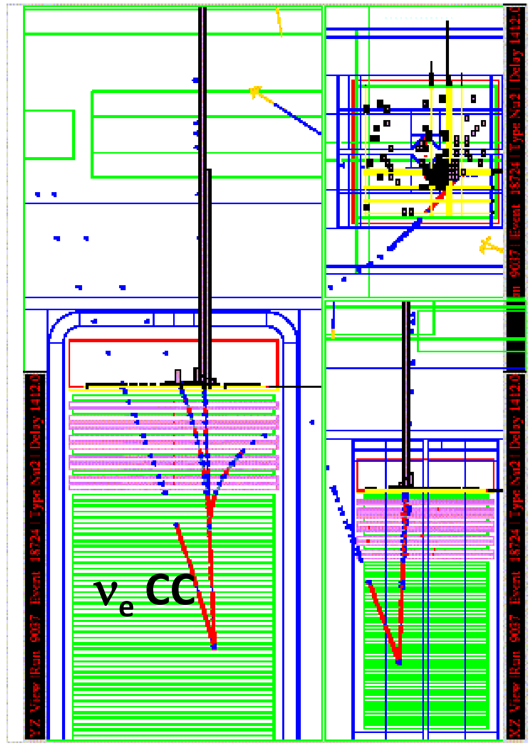
LENA

- Geoneutrinos
- Solar neutrinos
- Supernova burst neutrinos, diffuse supernova neutrinos
- Proton Decay
- Tracking capability being investigated for use with ν beams

From bubble chamber to LAr TPC

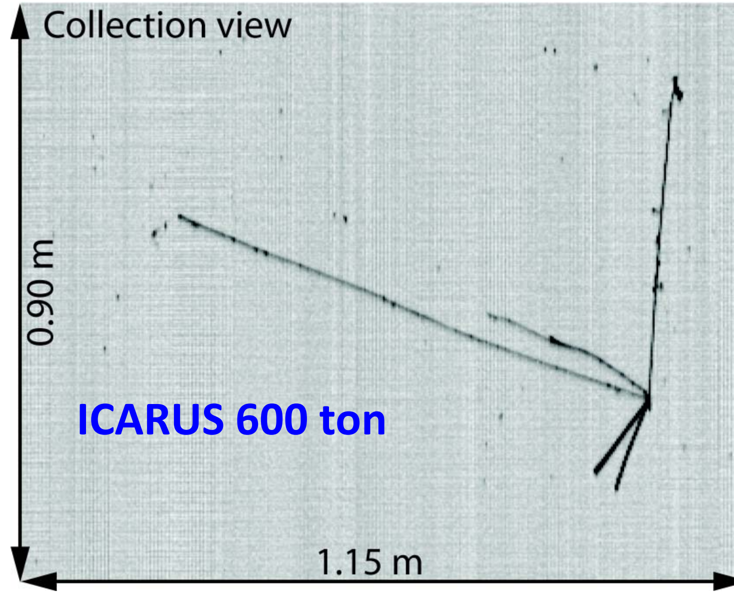
Bubble ∅ (mm)	3
Density (g/cm^3)	1.5
X_0 (cm)	11.0
λ_T (cm)	49.5
dE/dx (MeV/cm)	2.3

NOMAD



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

TRD detector
Lead glass calorimeter



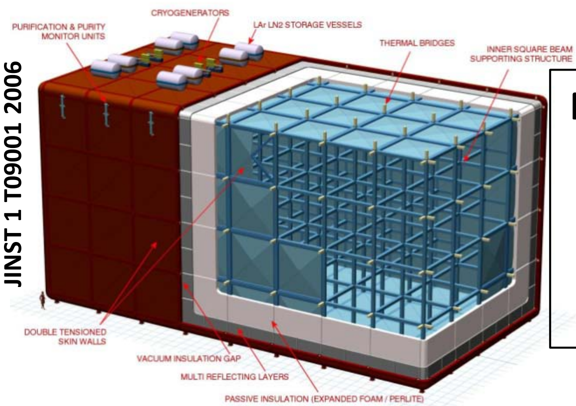
Resolution (mm^3)	3×3×3
Density (g/cm^3)	1.4
X_0 (cm)	14.0
λ_T (cm)	54.8
dE/dx (MeV/cm)	2.1

C. Rubbia,
CERN Report 77-8,
May 1977

Concepts for large LAr TPC

LBNE-LANND

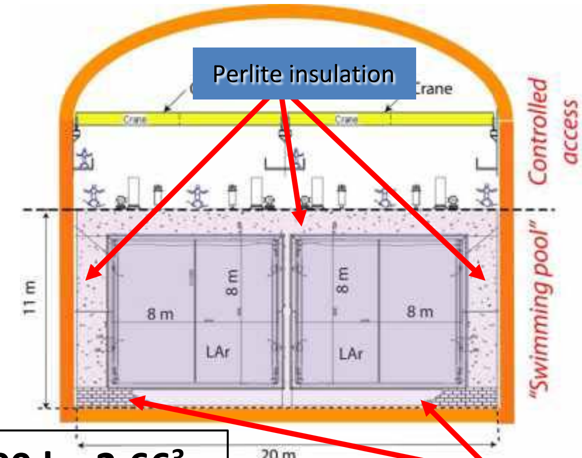
D.B. Cline, F. Raffaelli, F. Sergiampietri JINST 1 T09001 2006



Modular structure of
5^3 m^3 cubes
Evacuable
Charge readout in single-phase LAr

10 kton

MODULAR



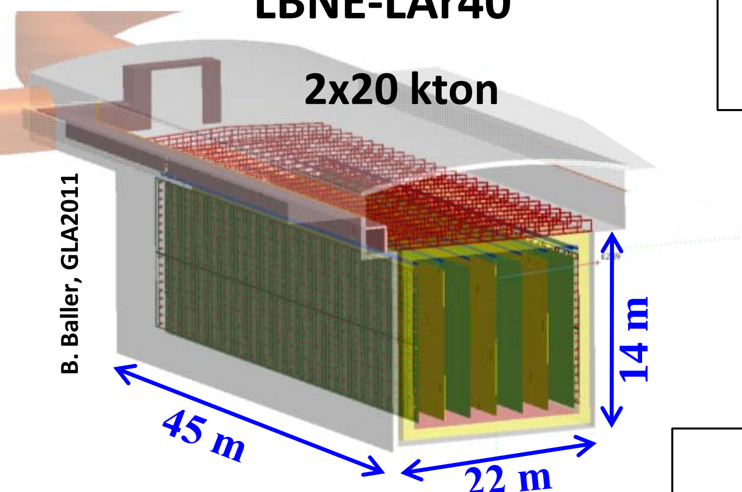
B. Baibussinov et al., Astr. Phys. 29 (2008) 174
D. Angeli et al., JINST 4 (2009) P02003

Scaled from Icarus-T600 by 2.66^3
Not evacuable
Charge readout in single-phase LAr

LBNE-LAr40

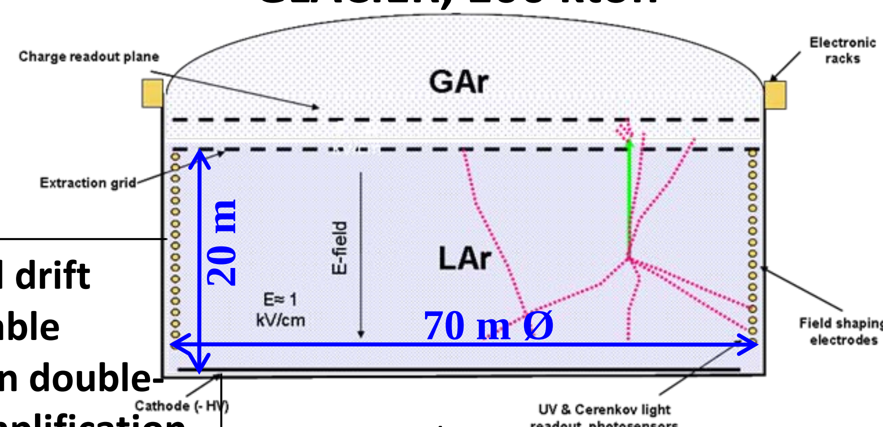
2x20 kton

B. Baller, GLA2011



3.7 m horizontal drift
Not evacuable, membrane tank
Charge readout in single-phase LAr

GLACIER, 100 kton



20 m vertical drift
Not evacuable
Charge readout in double-phase LAr with amplification

A. Rubbia hep-ph/0402110
Venice, Nov 2003

Comparison Water - liquid Argon

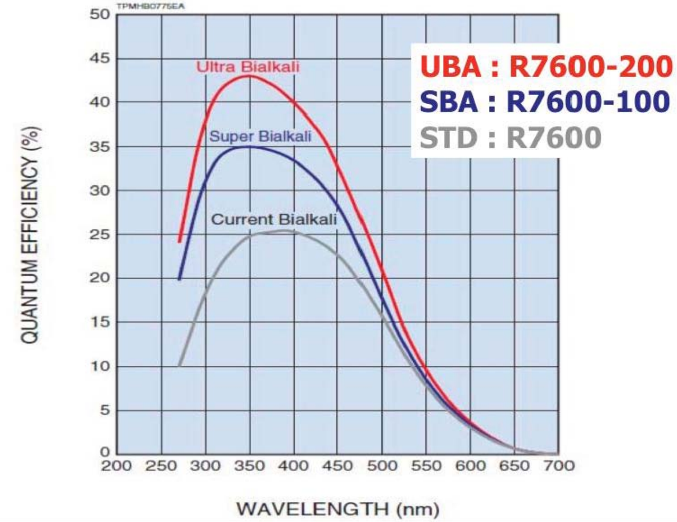
Particle	**Cerenkov Threshold in H_2O (MeV/c)**	**Corresponding Range in LAr (cm)**
e	0.6	0.07
μ	120	12
π	159	16
K	568	59
p	1070	105

- **LAr allows lower thresholds than Water Cerenkov for most particles**
- **Comparable performance for low energy electrons**

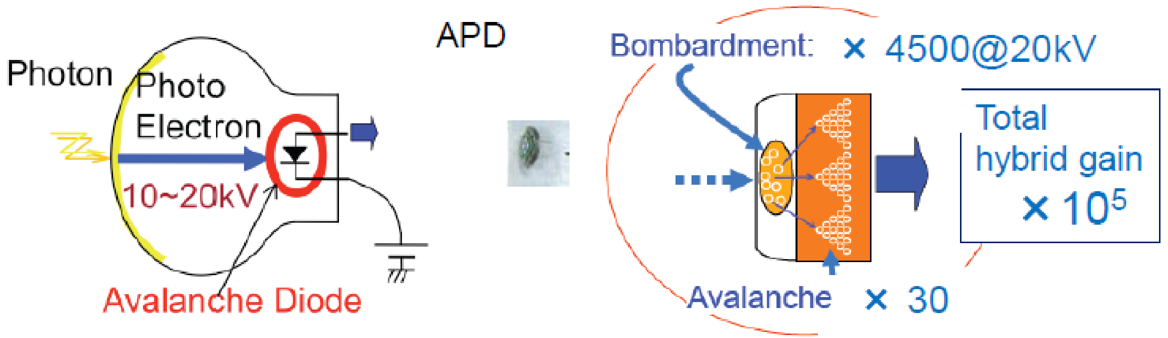
Photodetector R&D

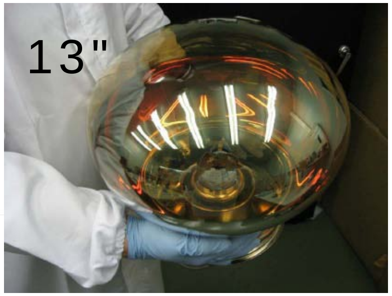
High QE PMTs

Super Bi-Alkali/Ultra Bi-Alkali

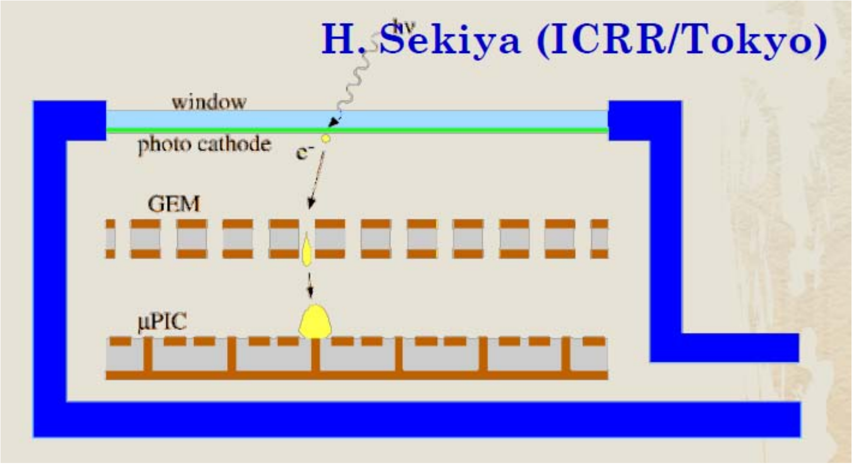


Hybrid Avalanche Photo-Detector(HPD)





Better single photon time, energy and collection efficiency than PMTs

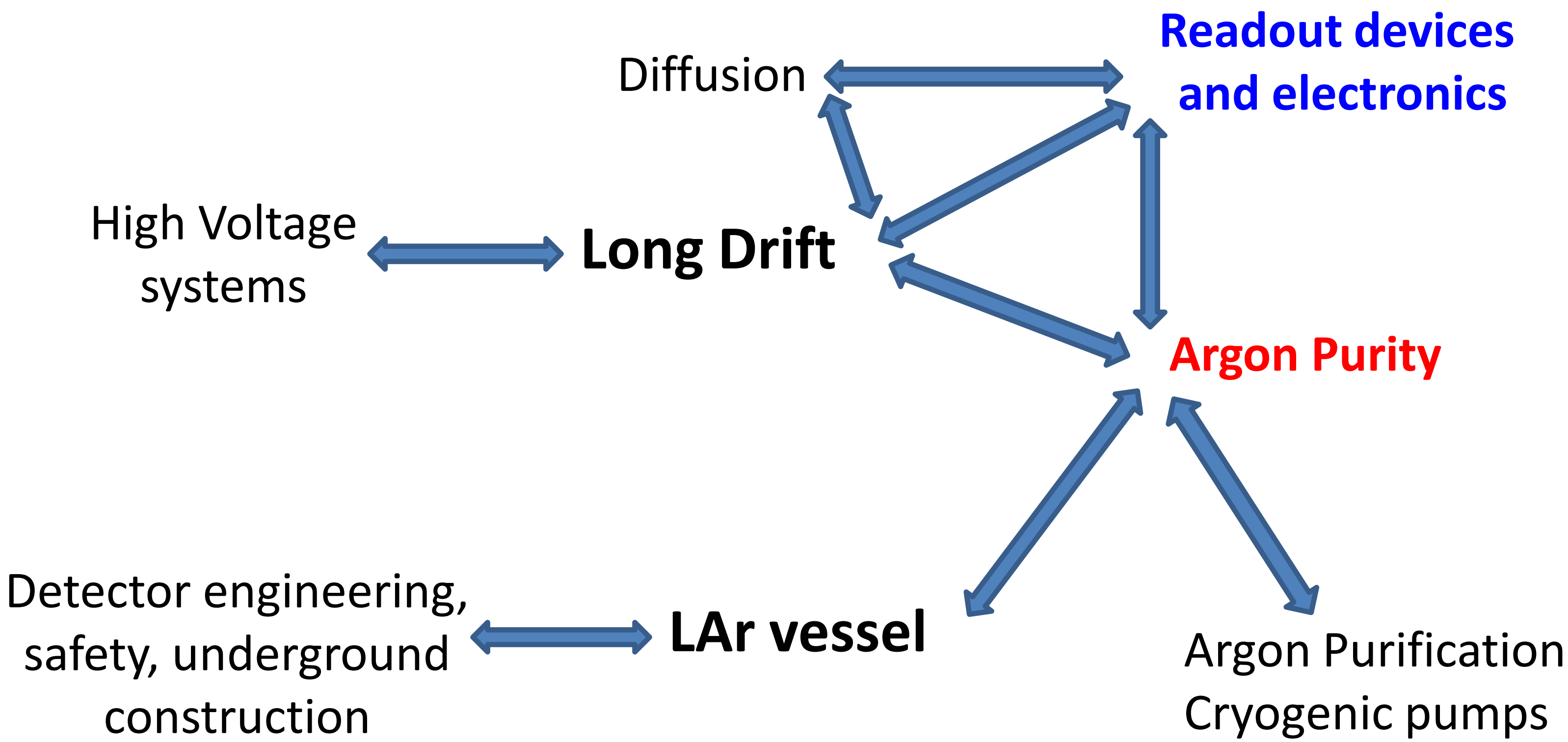


Towards large flat-panel photosensors?

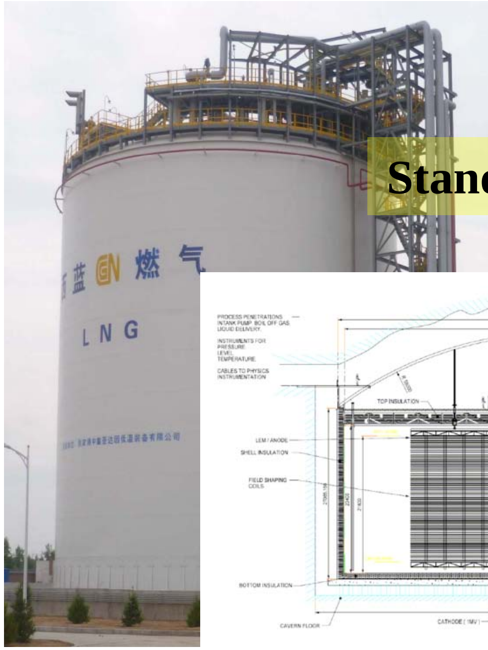
Gas photo-multiplier (GPM)

- Electron multiplication by gaseous avalanche
- single photoelectron sesitivity
- position resolution
- possibly large area

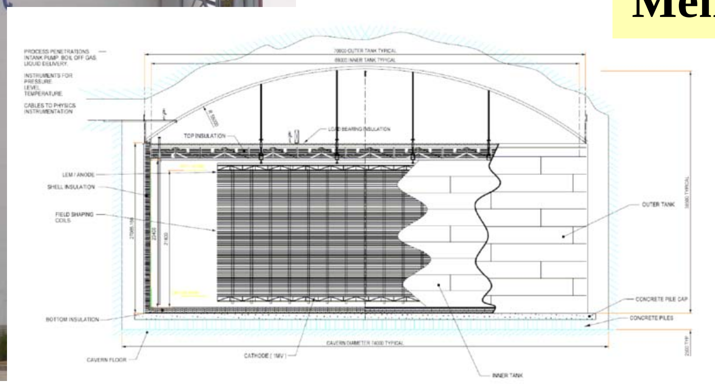
Technical issues for large LAr TPCs



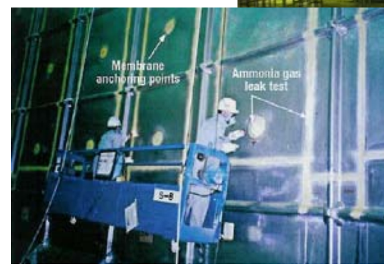
LAr R&D

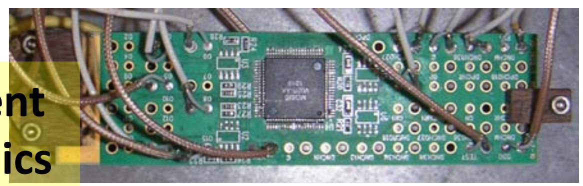


Standard LNG tank

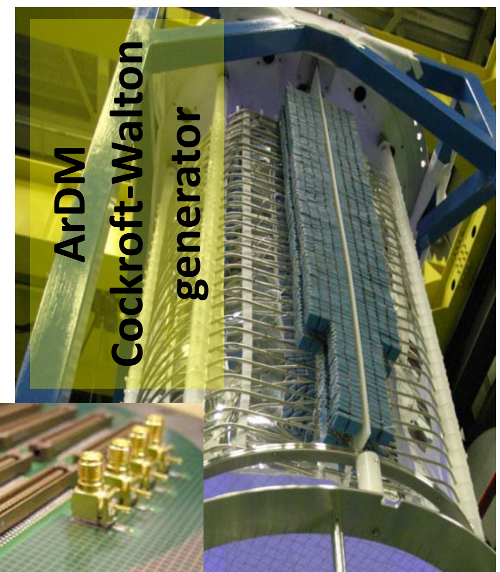


Membrane LNG tank





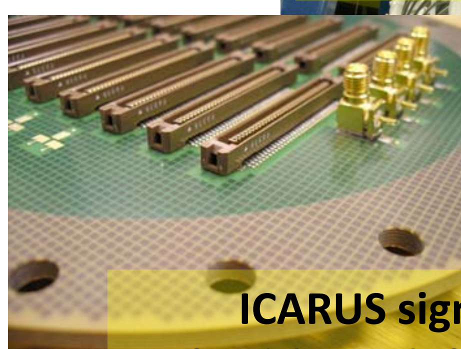
BNL development of cold electronics



ArDM Cockroft-Walton generator

ArgonTube, 5 m drift

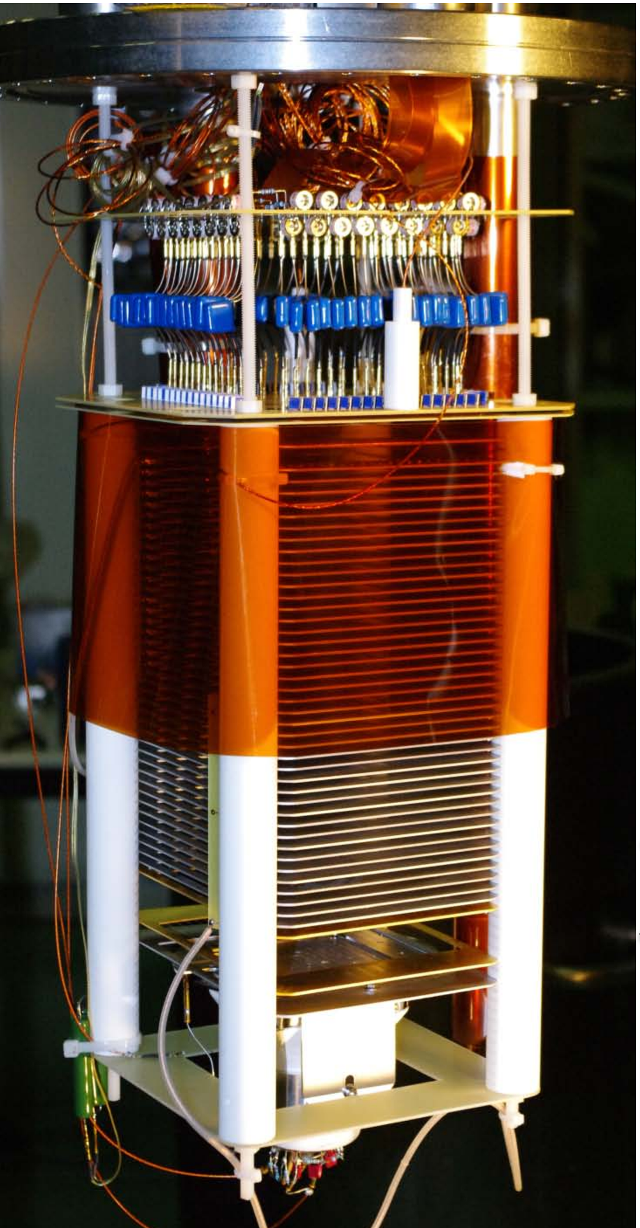
FNAL LAr Purity Demonstrator

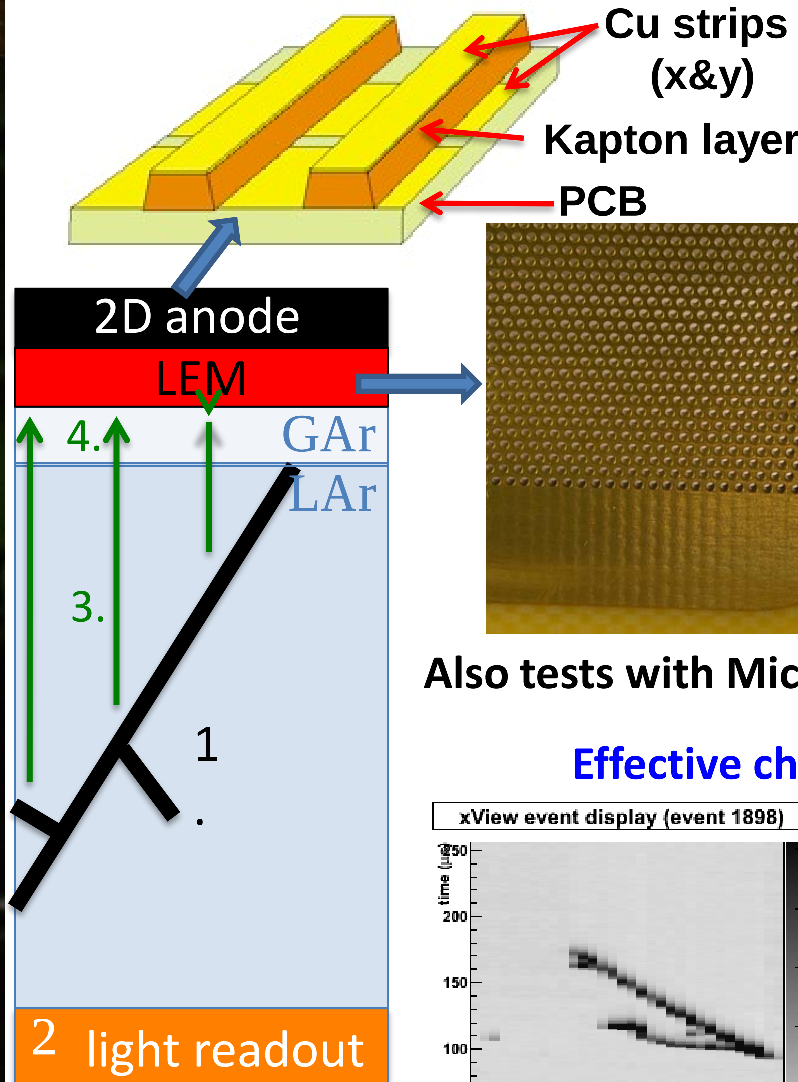


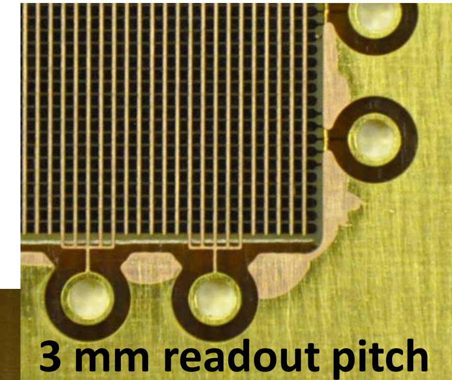
ICARUS signal feedthrough flange

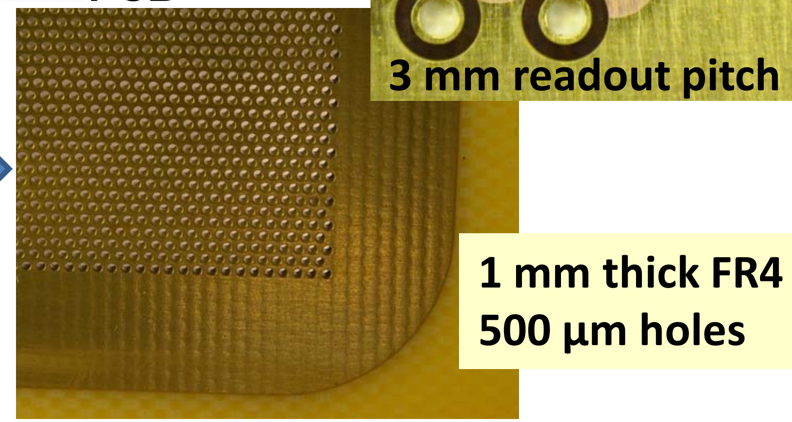
Charge readout in double phase LAr

A. Badertscher et al., NIM A641 (2011) 48



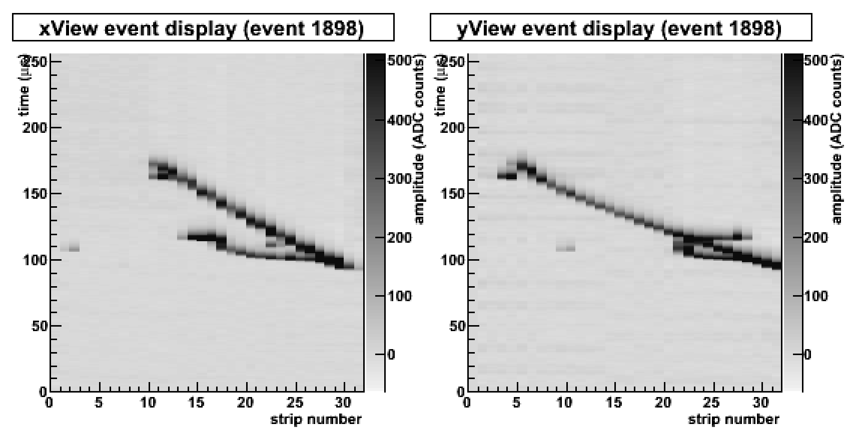






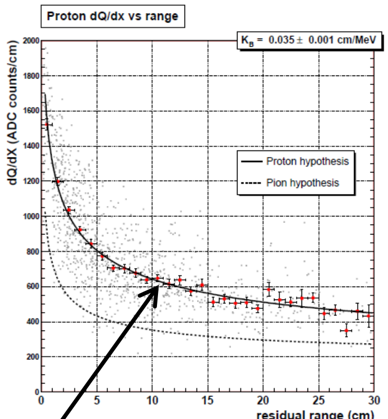
Also tests with Micromegas (Saclay group)

Effective charge gain of ≈27

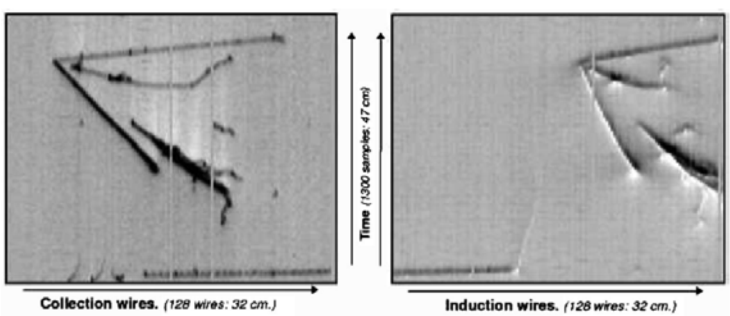


World-wide effort on event reconstruction in LAr I

ICARUS 50 L @ CERN



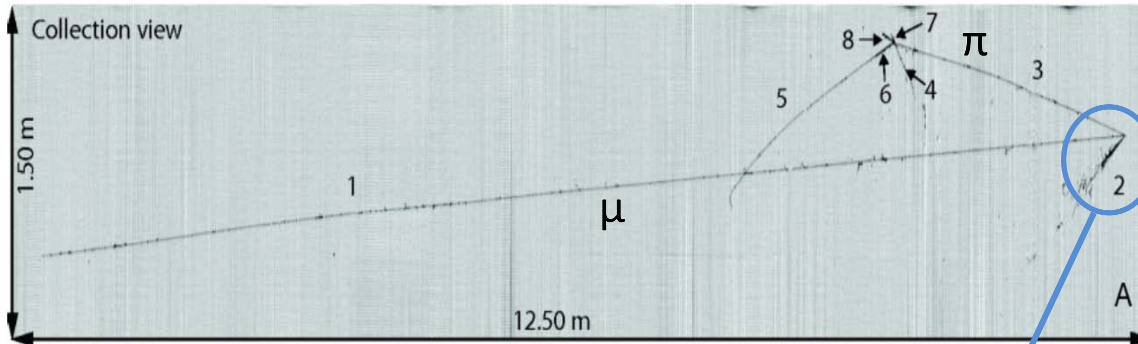
proton identification in ν interactions

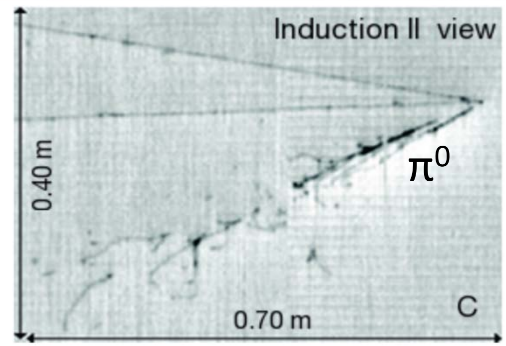


$$\nu_\mu n \to \mu^- \Delta^+ \to \mu^- p \pi^0$$

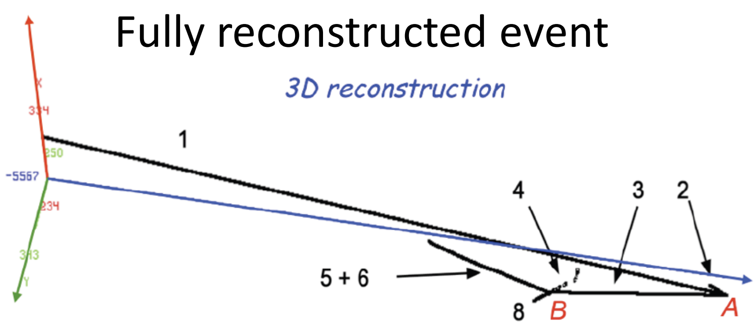
ICARUS-Milano, Phys.Rev. D74 (2006) 112001

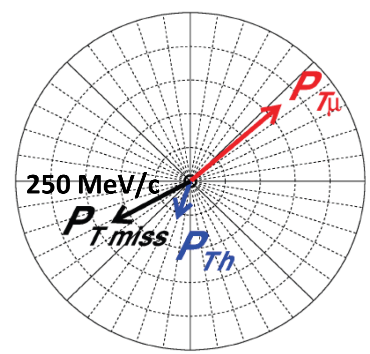
ICARUS 600 ton @ LNGS





Fully reconstructed event

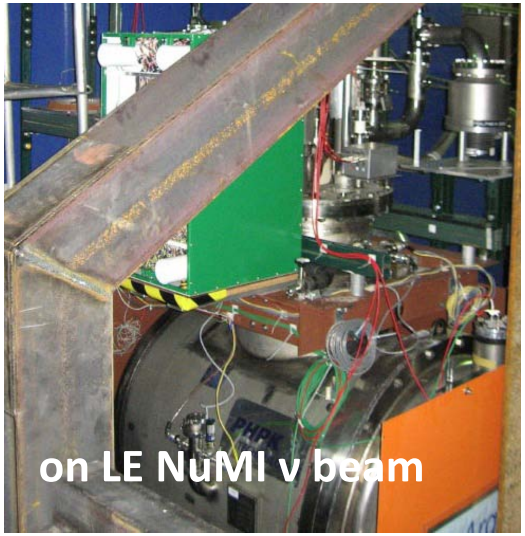




C. Rubbia et al., arXiv:1106.0975 [hep-ex]

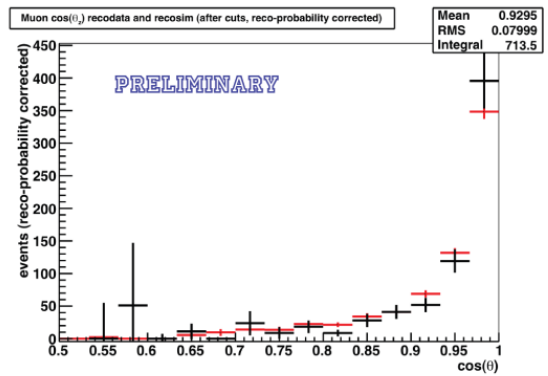
World-wide effort on event reconstruction in LAr II

ArgoNeut 175 L @ FNAL

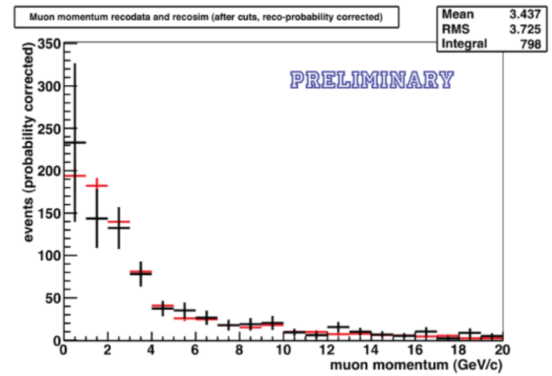


Data in black, MC in red

$\cos(\theta_\mu)$

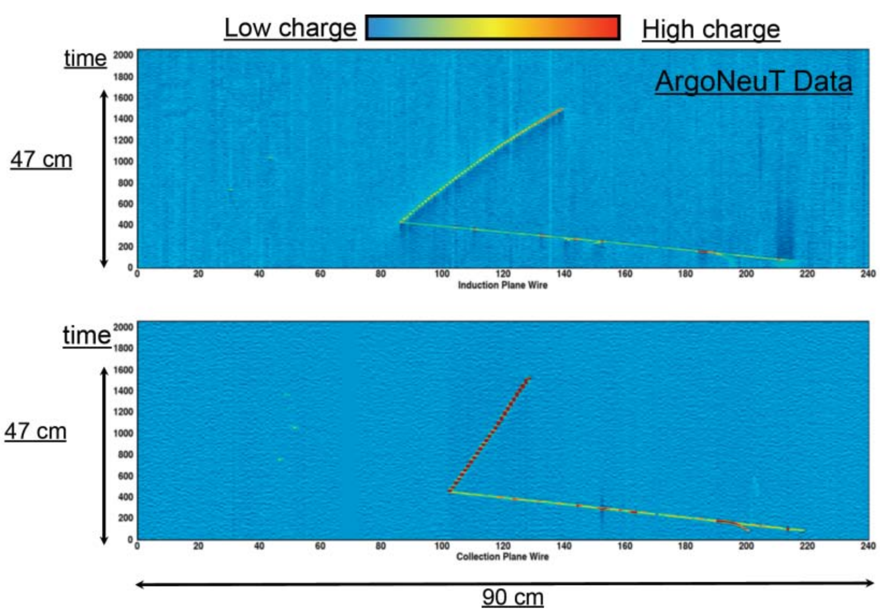


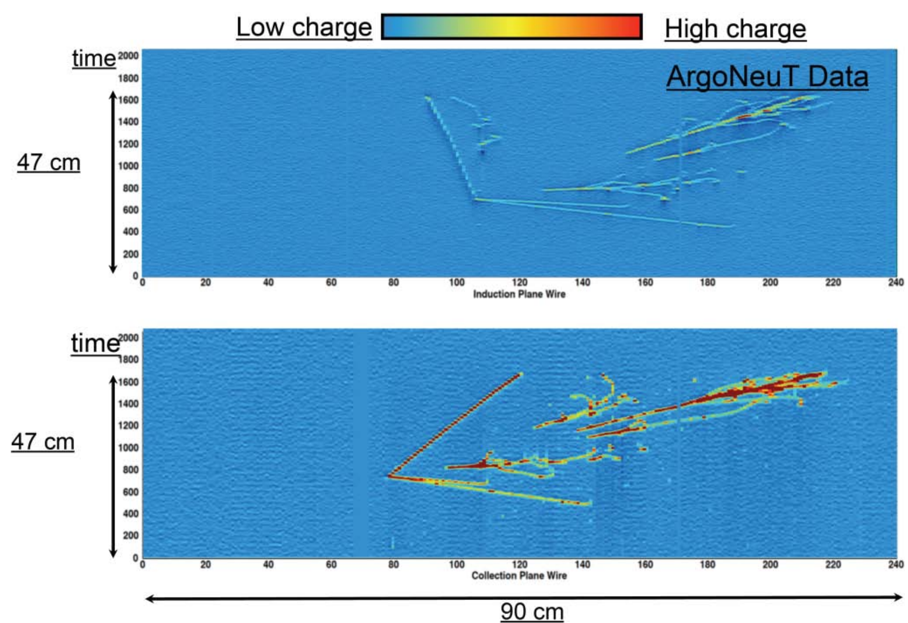
p_μ (GeV/c)



ν_μ CC events

C. Bromberg, GLA2011





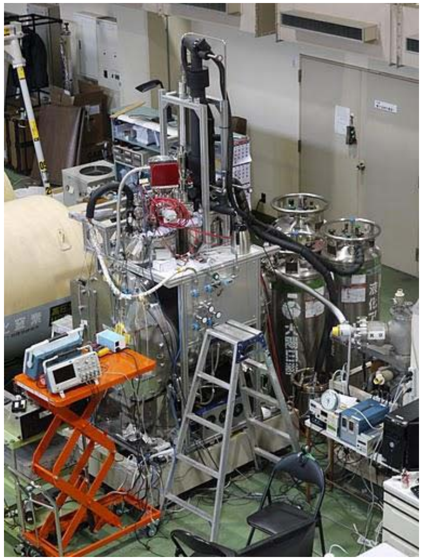
World-wide effort on event reconstruction in LAr III

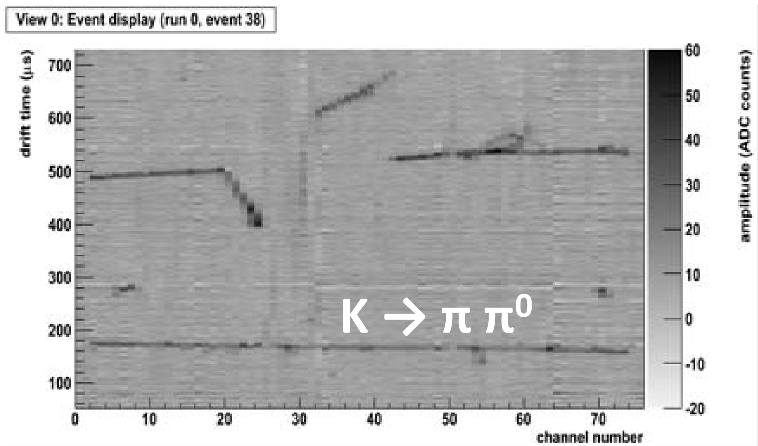
250 L @ J-PARC

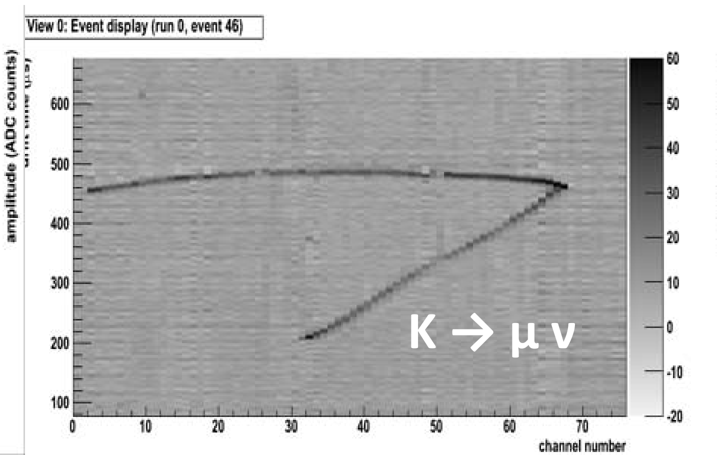
J.Phys.Conf.Ser. 308 (2011) 012008

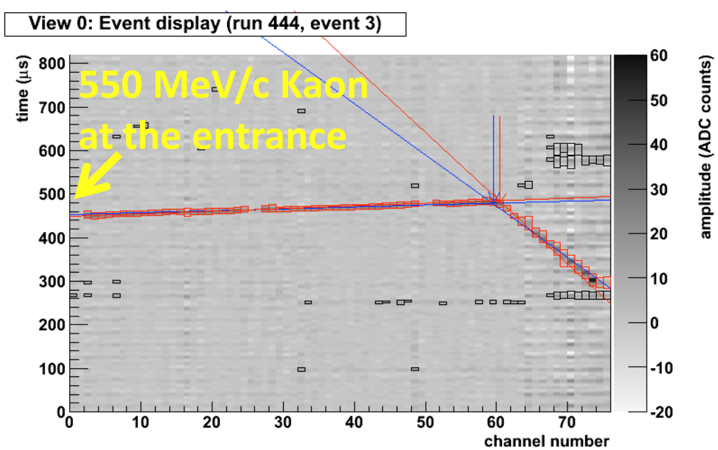
Tagged low-momentum Kaon test beam

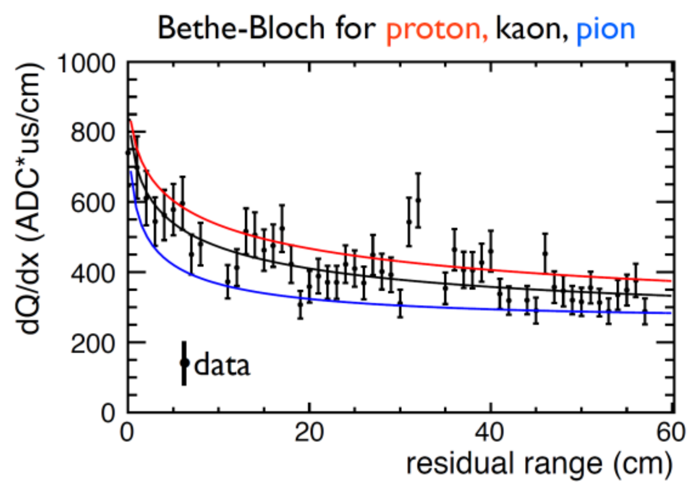
Prototype setup with 1 cm readout pitch operated in single-phase LAr



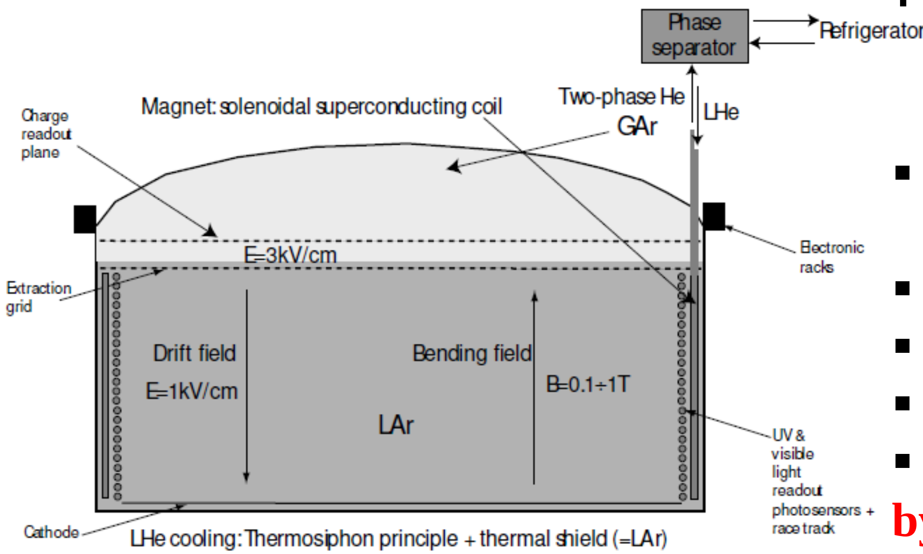








R&D on a magnetized LAr



A. Ereditato, and A. Rubbia, Nucl Phys B (Proc Suppl) 155 (2006) 233

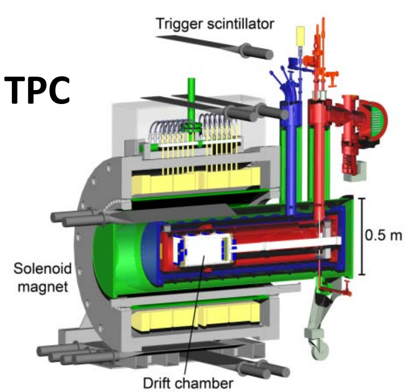
- **superconducting solenoid immersed in LAr**
  - **LHe or HTS superconductor?**
- **B** parallel to **E**
- low field (B=0.1 T) to measure μ charge
- strong field (B=1 T) to to measure ‘e’ charge
- **now part of WP4 Laguna-LBNO managed by CERN**

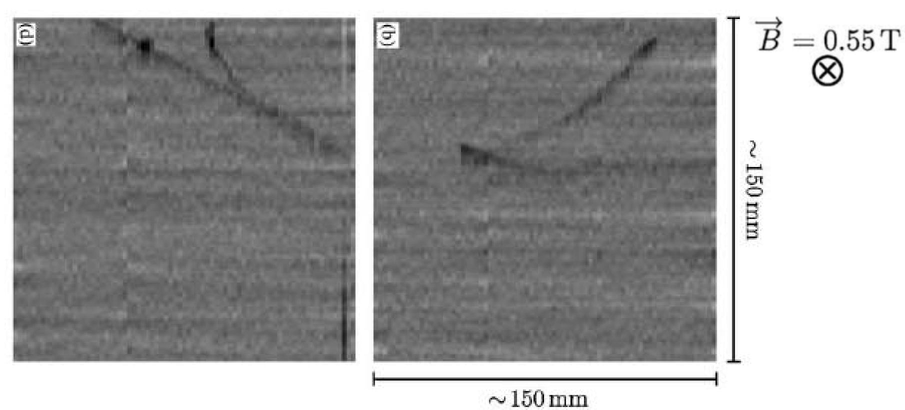
Comparison of superconducting solenoidal magnets. ATLAS column corresponds to the solenoid.

	10 kton LAr	100 kton LAr	ATLAS	CMS
Magnetic induction (T)	0.1/0.4/1.0	0.1/0.4/1.0	2.0	4.0
Solenoid diameter (m)	30	70	2.4	6
Solenoid length (m)	10	20	5.3	12.5
Magnetic volume (m^3)	7700	77000	21	400
Stored magnetic energy (GJ)	0.03/0.5/3	0.3/5/30	0.04	2.7

First operation of a LAr TPC in a magnetic field @ ETHZ

NIM A 555 (2005) 294





Some concluding thoughts

- **Maximize physics output of next generation large neutrino detectors**
  - sensitivity to different channels and extended energy range, possibly down to ~10 MeV
  - magnetization is an essential requirement if on a neutrino factory beam
- **Synergy between precise detectors for long baseline neutrino experiments, proton decay and astrophysical neutrinos**
  - Water Cherenkov and LAr TPCs detectors are appealing options for superbeam (and β beam) ν sources, with excellent sensitivity to proton decay and astrophysical ν sources
  - underground location (> 500 m.w.e.) is a must
- **Reduced systematics of a ν factory beam** offers unique sensitivity for short baseline physics (cross sections, high Δm^2 oscillations)
  - mini-NuFactory with lower energy and intensity?
- **R&D on photodetectors** is important for all considered technologies
  - also for LAr TPCs, since LAr is a very good scintillator

…detector specific

- **TASD segmented detectors** are interesting options as near detectors
  - can they identify τ's?
  - if considered for large far detectors, sensitivity to astrophysical sources, proton decay (?) must be studied and an underground siting must be considered
- **Proposals for up to 1 Mton Water Cherenkov detectors**
- **World-wide effort on LAr technology**
  - **600 ton ICARUS detector operating at LNGS**
  - R&D on double-phase LAr-TPC, cold electronics, long drifts, purification, HV systems
  - ongoing studies for LAr vessels in underground conditions
  - R&D on LAr detector magnetization
  - exposure of small LAr setups (0.2 – 10 ton) on intense ν beams or low energy particle test beams already accomplished, ongoing or planned
  - extensive efforts on automated event reconstruction in LAr
  - 170 ton MicroBoone detector approved at FNAL to run on the Booster ν beam
  - kton-scale LAr prototype seen as necessary step towards 50-100 kton detectors
- **… towards realistic proposals for large LAr TPC**

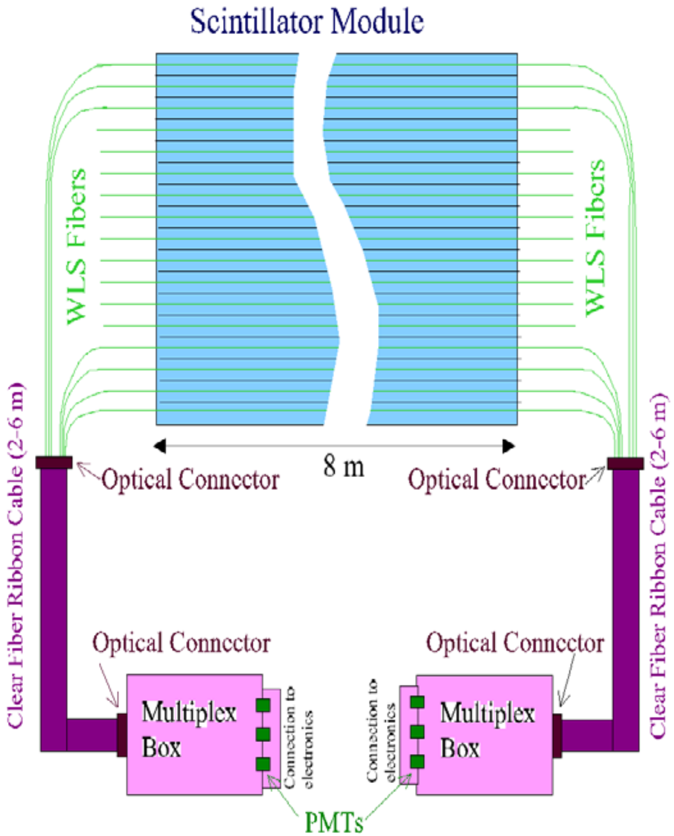
Backup

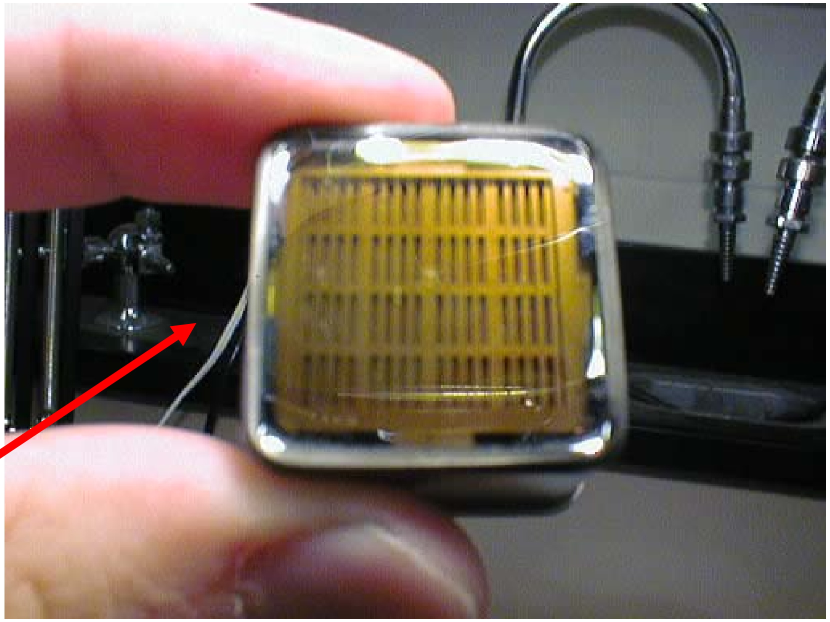
MINOS Detector Planes

Detector module with 20 scintillator strips

Assembled plane ready to be lifted

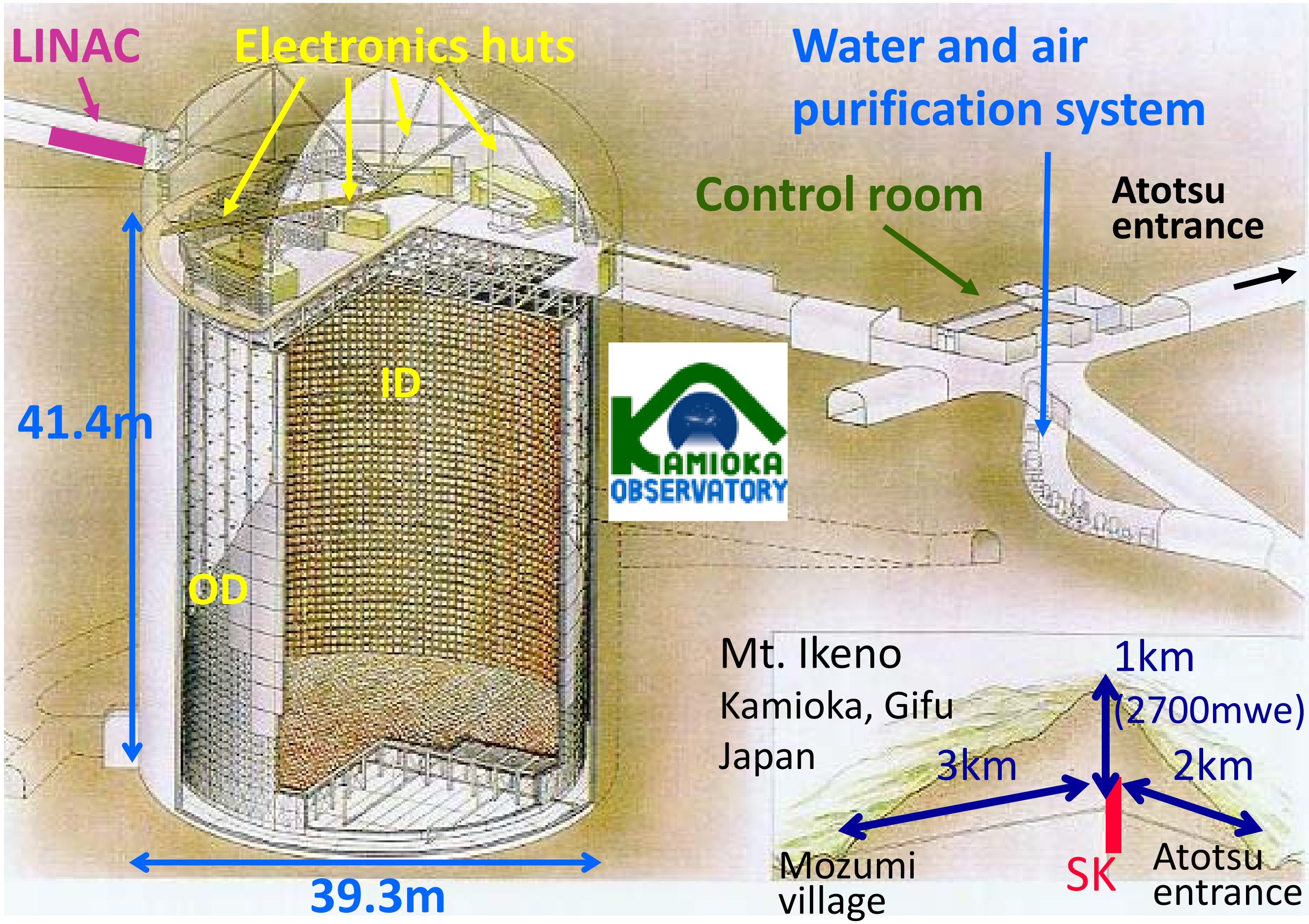
MINOS Detector Readout





MUX boxes route 8 (1 in Near Detector) fibers to one MAPMT pixel

Super-Kamiokande detector



50 kton water Cherenkov

22.5 kton fiducial volume

(~ 2m away from wall)

2700 m.w.e overburden

cosmic ray BG ~3 Hz

~10 Solar ν /day

~10 Atmospheric ν / day

Inner detector (ID):

~11,100 50 cm PMTs

~ 2ns timing resolution

~ 4.5MeV threshold

Outer detector (OD):

water layer ~ 2m thick,

1,885 20 cm PMTs

Multi-purpose observatory:

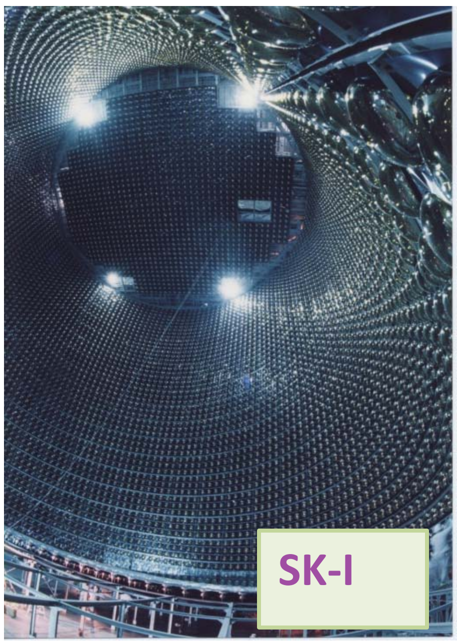
Neutrinos from Sun, atmosphere, supernova, relic SN's, astrophysical point sources, and beams from K2K and T2K

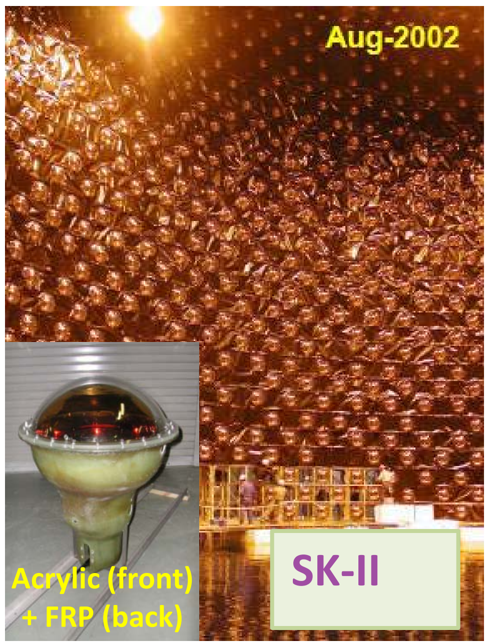
Also: search for nucleon decay, WIMPS, other exotic particles

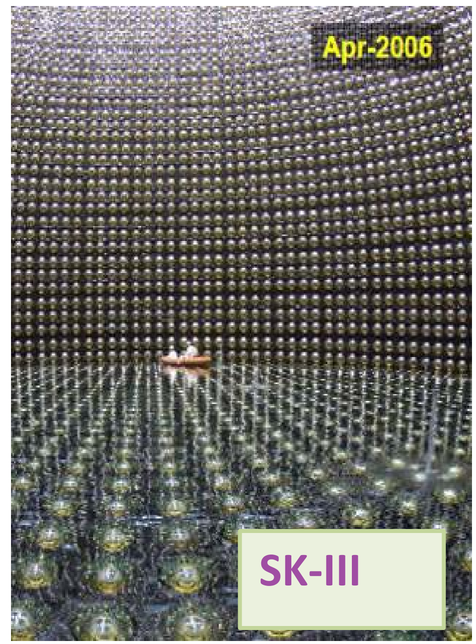
History of Super-Kamiokande

1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010

SK-I (Rebuild) SK-II (Rebuild) SK-III SK-IV



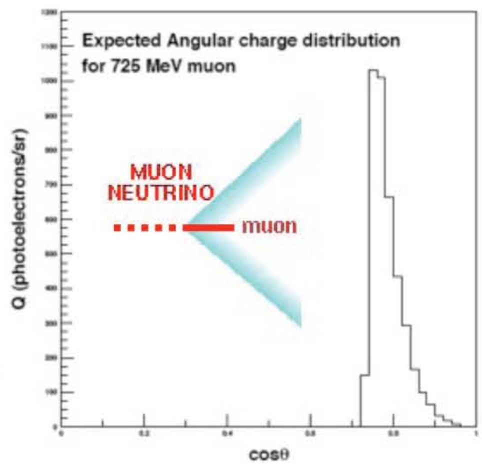




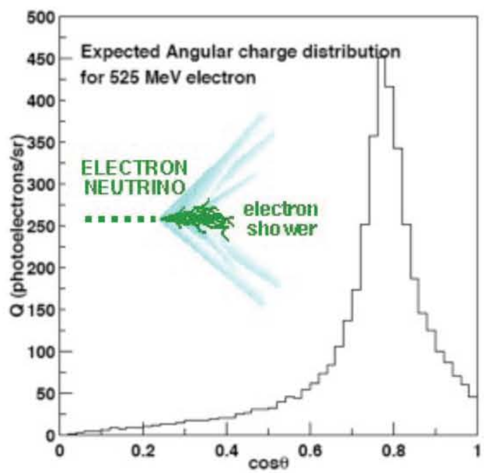
	SK-I	SK-II	SK-III	SK-IV	
	11146 ID PMTs (40% coverage)	**5182 ID PMTs (19% coverage)**	**11129 ID PMTs (40% coverage)**	**Electronics Upgrade**	
Threshold: (Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	~4.5 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	~4.0 MeV	<~3.5 MeV
				Now	Goal

Water Cherenkov: e/μ identification

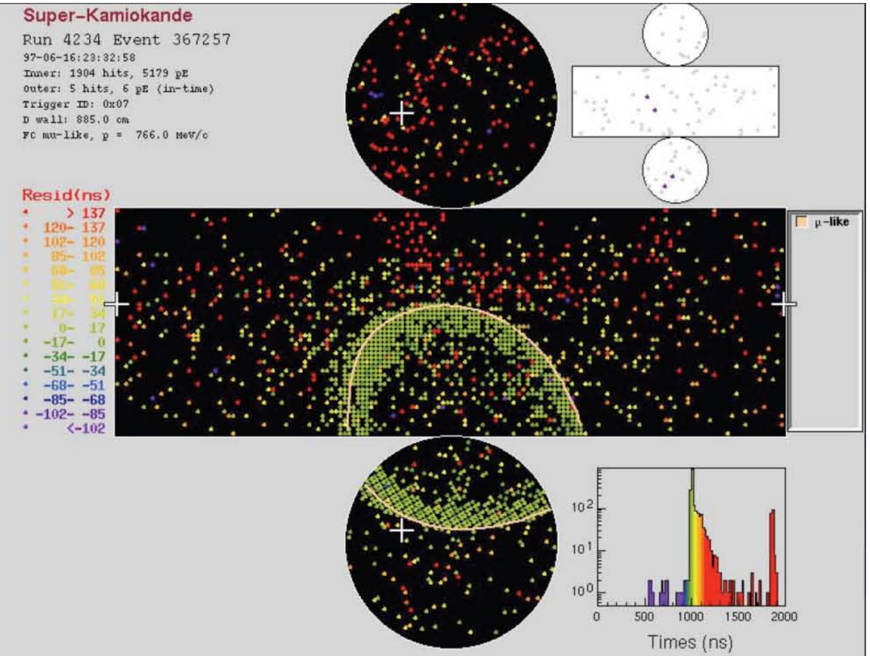
- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are ~always at 42°.

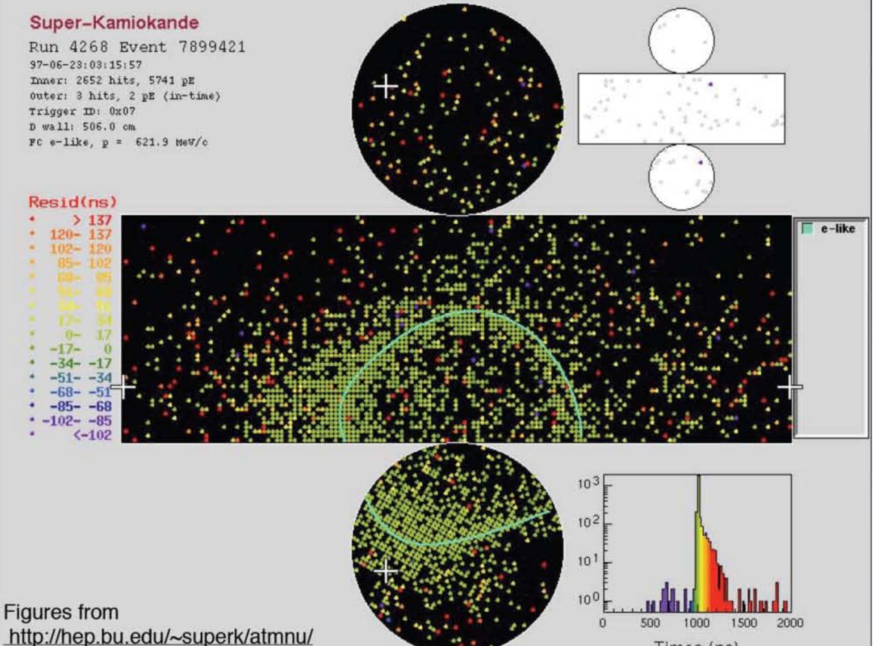


- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.



Figures from M. Earl's PhD Thesis

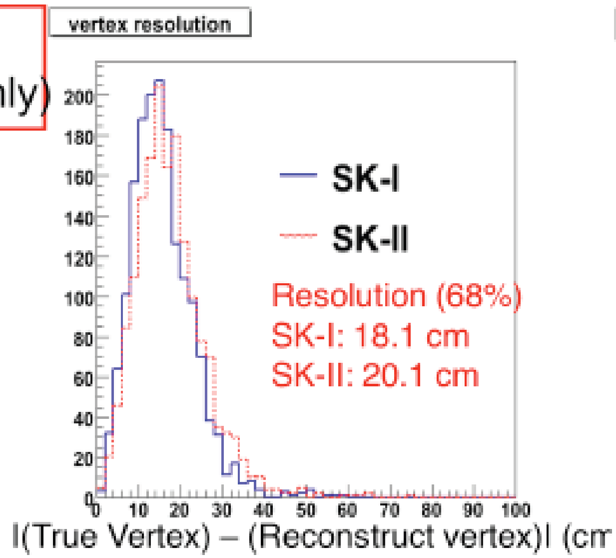


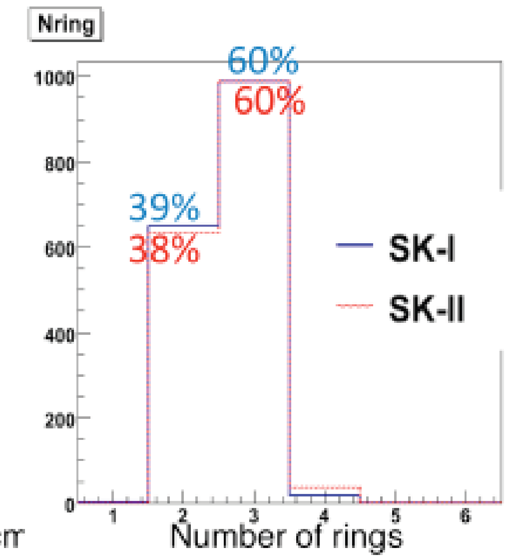


Figures from
http://hep.bu.edu/~superk/atmnu/

Reconstruction performance

$p \rightarrow e^{+}+\pi^{0}$ MC
(free proton only)





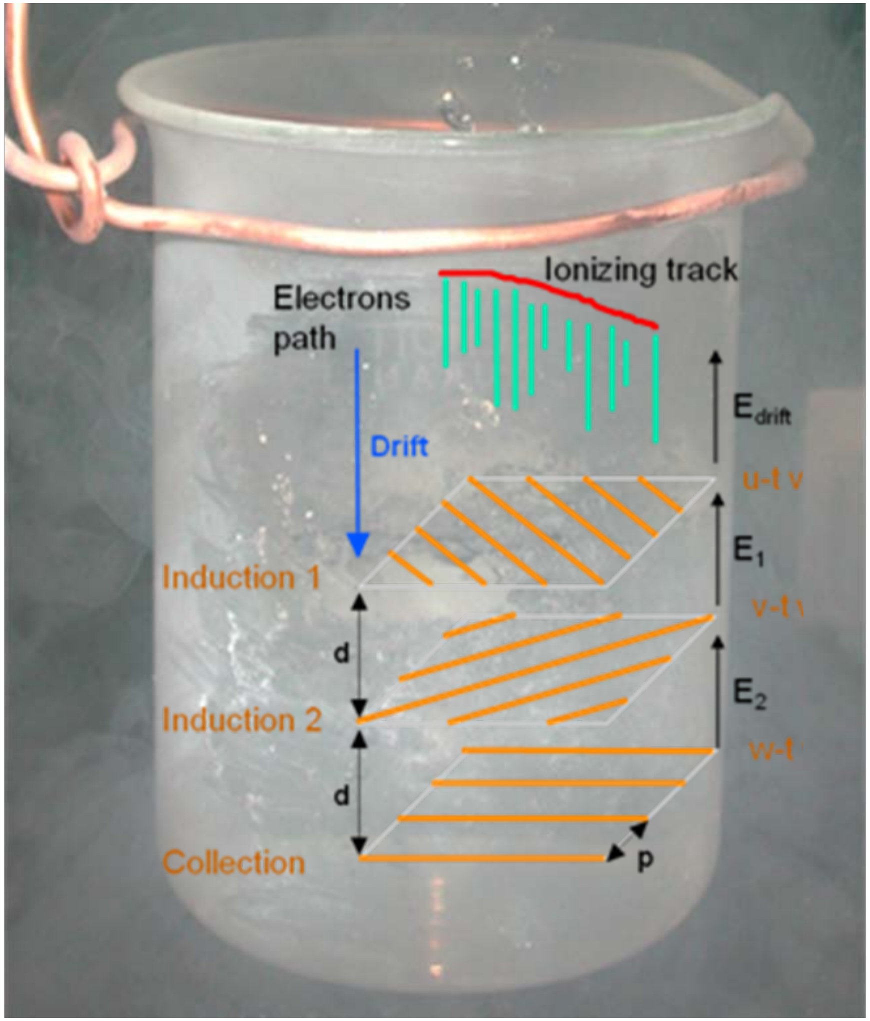
mode	Period (coverage)	Detection efficiency
$p \rightarrow e^{+}+\pi^{0}$	SK-I (40%)	44.6%
	SK-II (19%)	43.5%
$p \rightarrow \mu^{+}+\pi^{0}$	SK-I (40%)	35.5%
	SK-II (19%)	34.7%

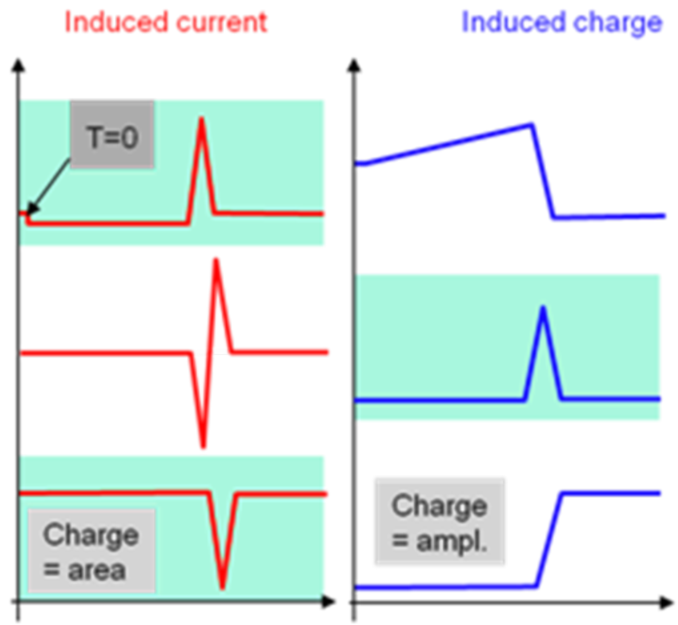
Reconstruction performance is not degraded much for $p \rightarrow e^{+}(\mu^{+})+\pi^{0}$ modes.

Excellent efficiency even with half PMT density

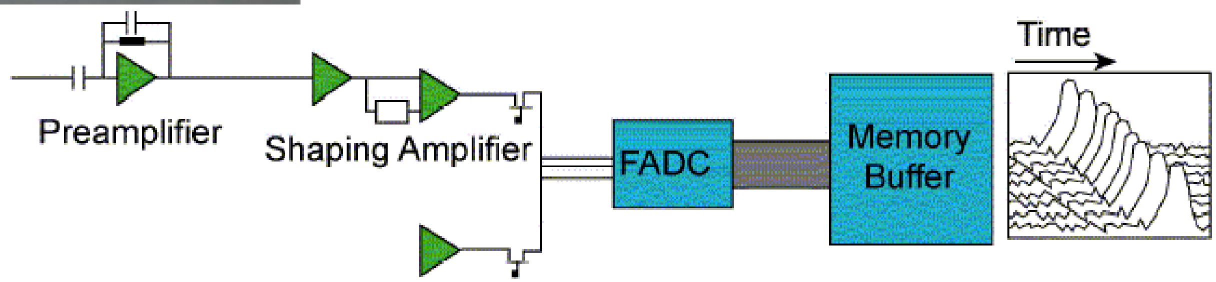
H. Aihara, Workshop for European Strategy for Neutrino Physics, 2009 CERN

Liquid Argon Time Projection Chamber

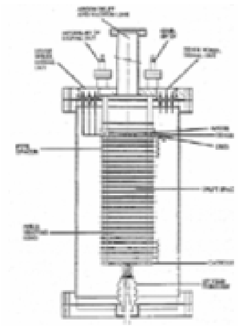




C. Rubbia,
CERN Report 77-8
May 1977



The ICARUS steps

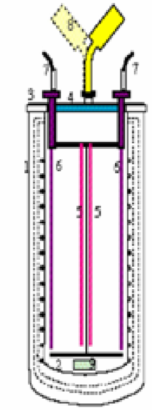


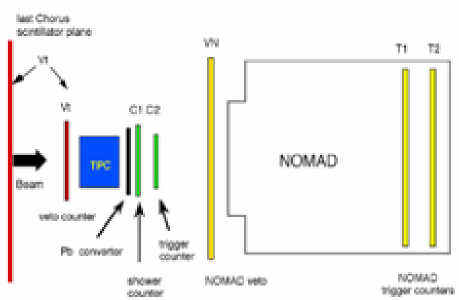
24 cm drift wires chamber

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 m3 industrial prototype

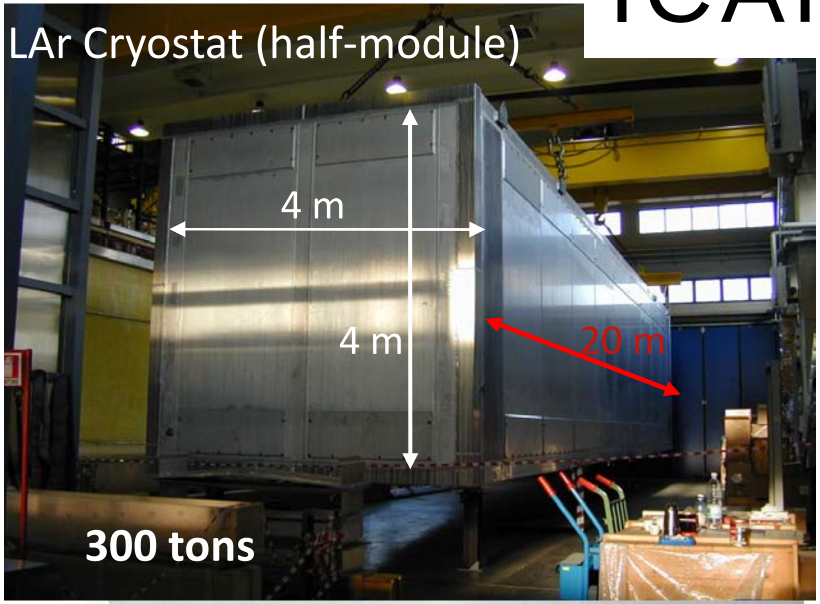
1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

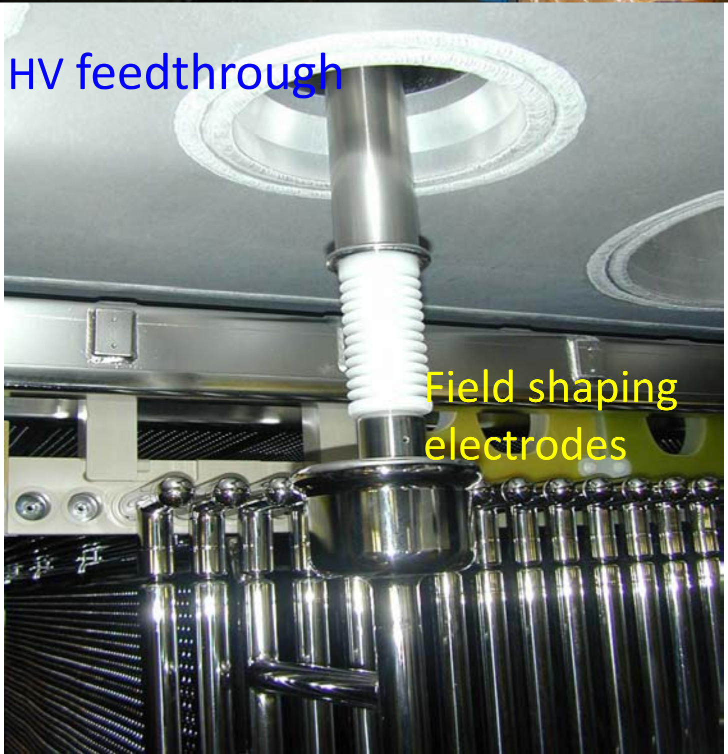
600 ton detector

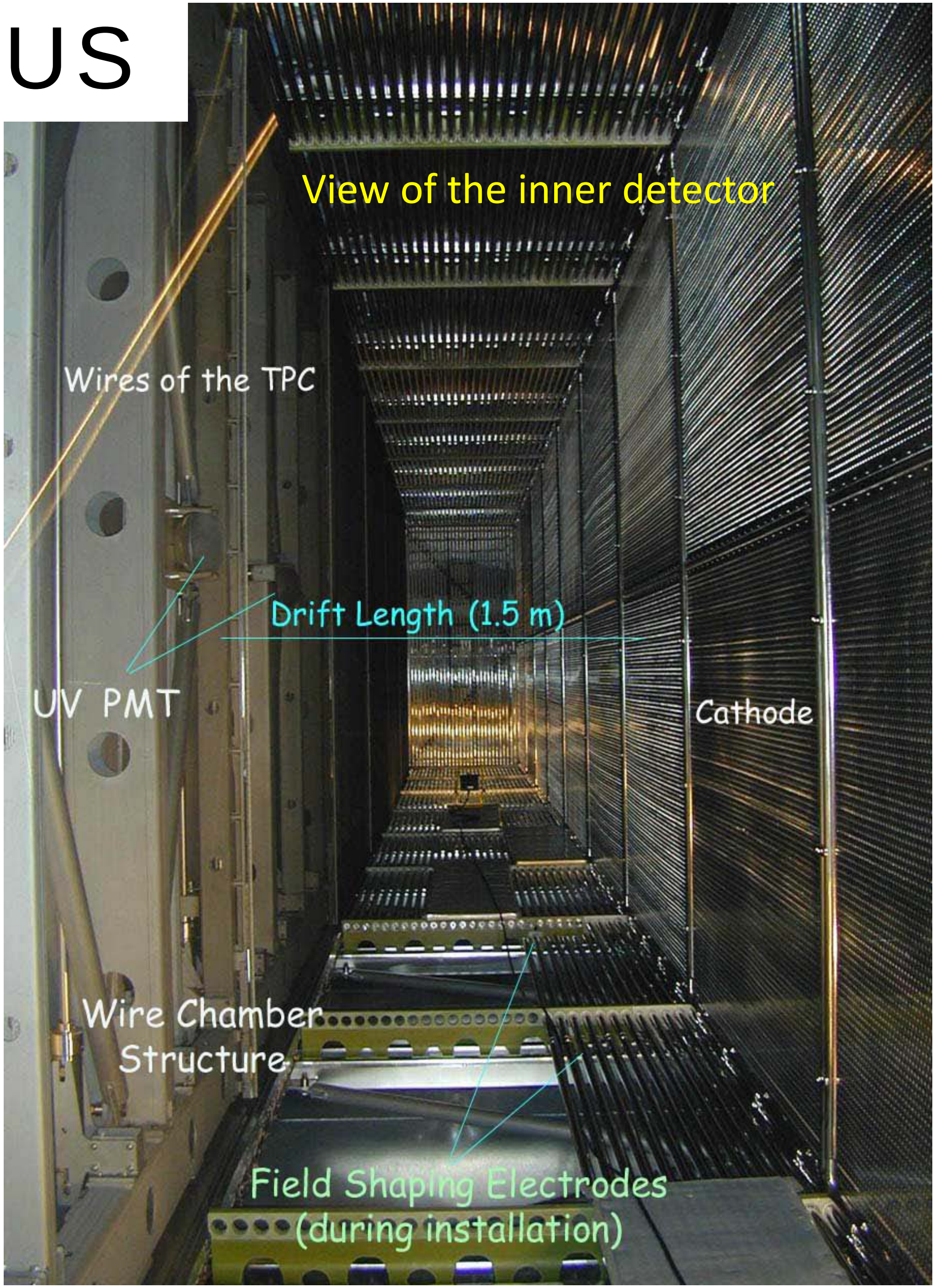
2001: 300 ton detector tested on surface in Pavia. 600 ton
2010: 600 ton detector operational at LNGS.

NIM A 527 (2004) 329

ICARUS

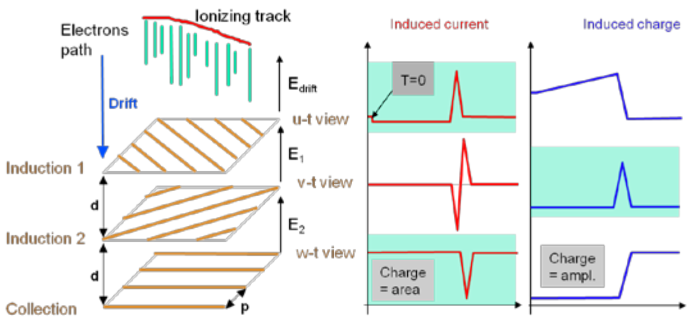

LAr Cryostat (half-module)
4 m
4 m
20 m
300 tons


HV feedthrough
Field shaping
electrodes


View of the inner detector
Wires of the TPC
Drift Length (1.5 m)
UV PMT
Cathode
Wire Chamber
Structure
Field Shaping Electrodes
(during installation)

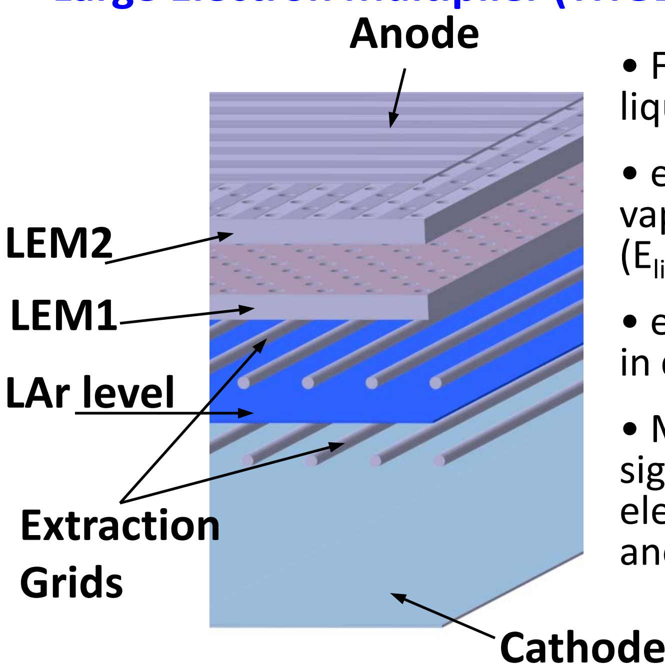
Ionization charge readout techniques in LAr

single LAr phase, wire planes



C. Rubbia, CERN Report 77-8, May 1977

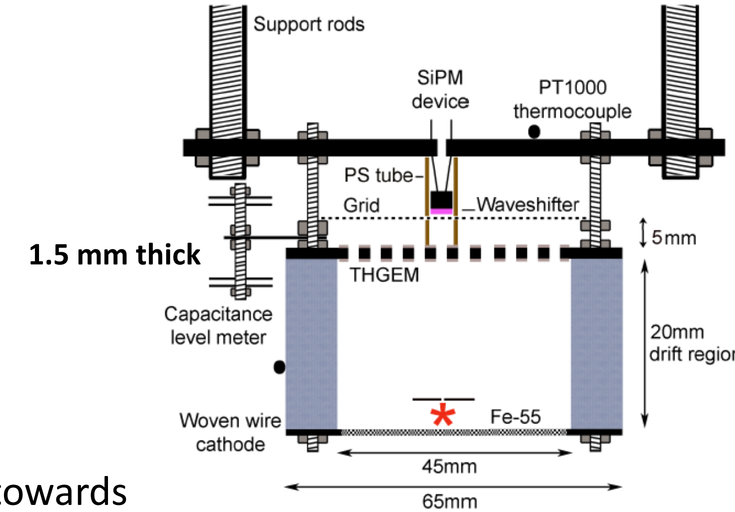
double phase Ar
Large Electron Multiplier (THGEM)

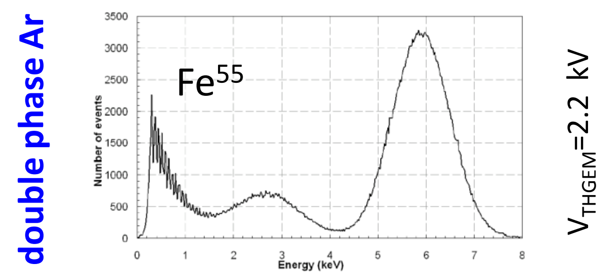


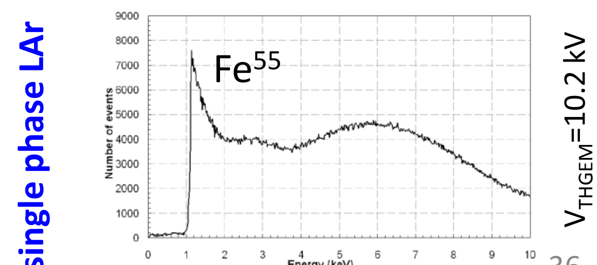
- Free e^- drift in LAr towards liquid-vapour interface.
- e^- are extracted to the vapour via extraction grids ($E_{liq} > 2.5$ kV/cm).
- e^- undergo multiplication in double stage LEM.
- Multiplied charge induces signals on the segmented electrodes of top LEM and anode.

A. Badertscher et al., arXiv:0811.3384

secondary scintillation from THGEM





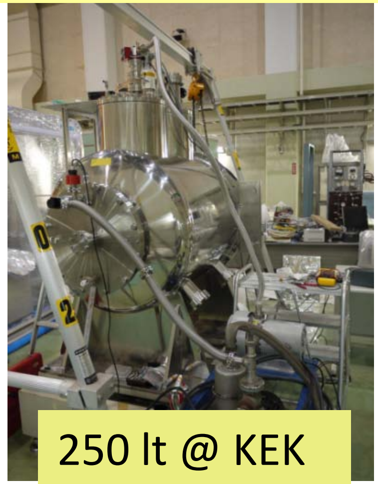


P.K. Lightfoot et al., JINST 4 (2009) P04002

GLACIER Roadmap

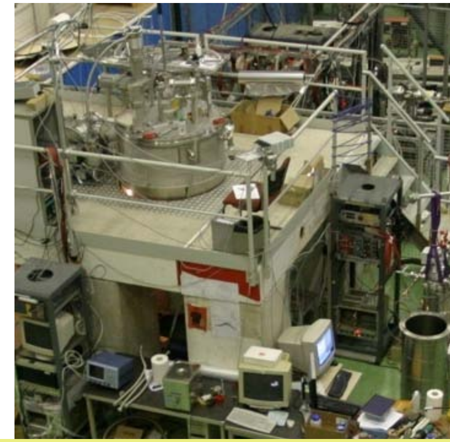
@ CERN

small test setups for readout devices, electronics



250 lt @ KEK

low energy K test beam @ J-PARC

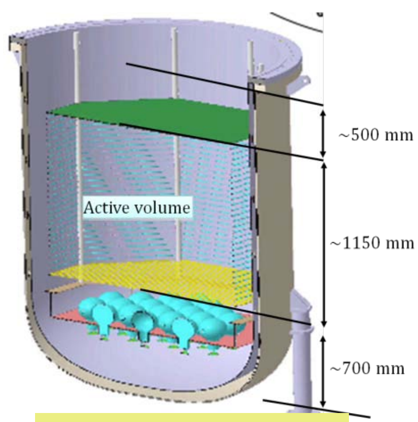


ArDM (RE18), presently @ CERN

1 ton LAr, Cockroft-Walton, LAr recirculation and purification, industrial electronics, safety, optimized for dark matter searches, in operation

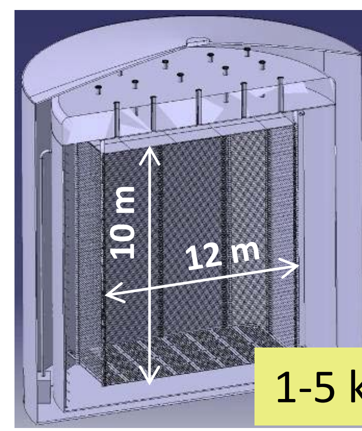
ArgonTube@ Bern

5 m drift, 0.4 ton under assembly



6 m^3 @ CERN

to be proposed for test beams in NA @ CERN



1-5 kton

full engineering demonstrator for larger detectors + physics