

Neutrino detectors

for Super-Beams, b-Beams and n Factories

Main issues in:

R&D

Detector design and realisation

for

Low-Z Tracking Calorimetry

Water Cerenkov

Liquid Argon TPC

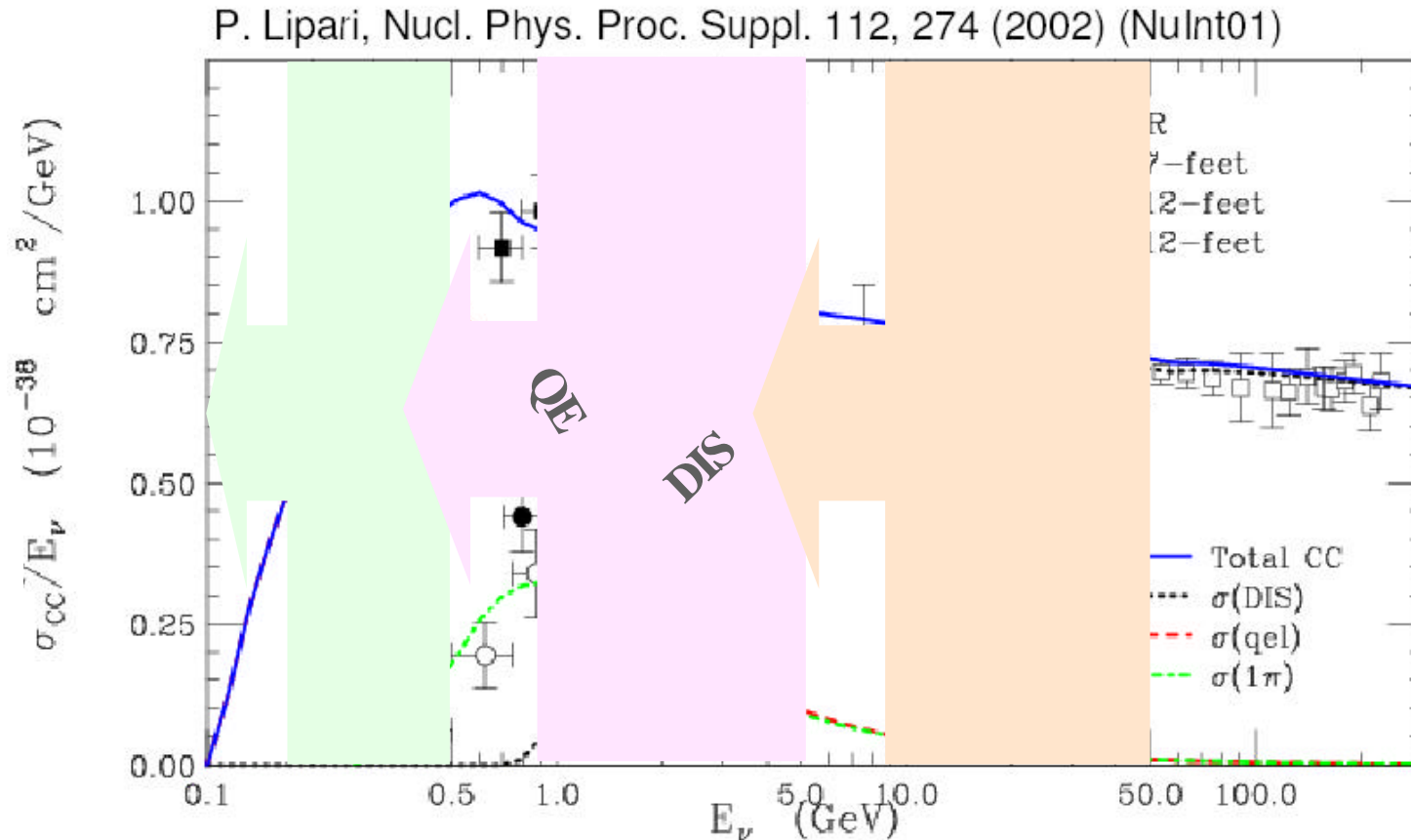
Magnetised Iron Calorimetry

Emulsion Cloud Chamber

Main detector tasks

- **Lepton identification ? identify n flavour ? signal**
- **Background rejection:** π^0 in ν_μ NC ? e^- in ν_e CC ,
- **Measure n energy**
 - For Quasi-Elastics ($\nu_l N \rightarrow l N'$)
Lepton energy ? ν energy
with corrections due to Fermi motion in nucleus and to nucleon recoil
 - For DIS ($\nu_l N \rightarrow l X$):
measure energy of lepton and of X
- **Measure muon charge** (by magnetic field)
required at ν -Factories (where $\mu \rightarrow e \bar{\nu}_e \nu_\mu$) to distinguish ν_μ CC
from the searched events, with “wrong sign” muons from $\bar{\nu}_e$ - $\bar{\nu}_\mu$ oscillation
- **Provide adequate target mass**
50 kton – 1 Mton
depending on physics aims (θ_{13} , mass hierarchy, δ), experimental technique and beam

n energy ranges and related dominant reactions (event topologies)



b-beam* **Super-beams** **n-Factory**

*) higher energies if the radioactive ions are stored at higher γ than in the original proposal

Envisaged baselines: 130 - 3000 km

(not discussed in this talk on detectors, see talk by Andrea Donini)

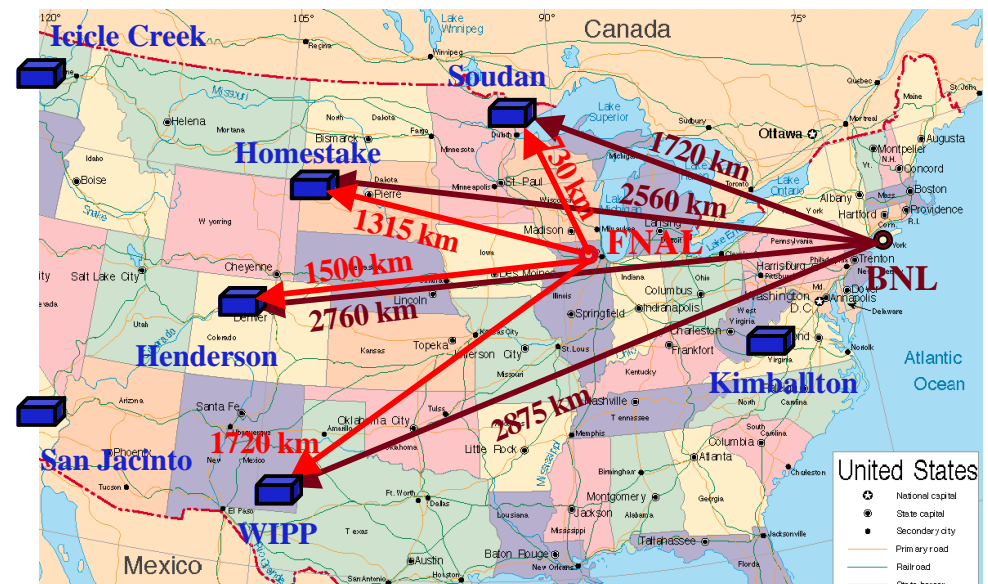
Complexity of choice

L/E, E, matter effects

?

Detector design, S/B

Sensitivity to θ_{13} , mass hierarchy, δ



Low-Z Tracking Calorimetry

Designing a detector specialised for n_m - n_e oscillations

Main backgrounds and tools for their reduction

- Beam n_e contamination

- ? $\Delta E/E$ combined with off-axis beam
- ? ν_e from K-decays suppressed in off-axis beam

- p^0 in n_m NC interactions

- ? e/π^0 separation by:
 - Tracking (e vs $\gamma\gamma$)
 - dE/dx at beginning of the shower (e vs e^+e^-)



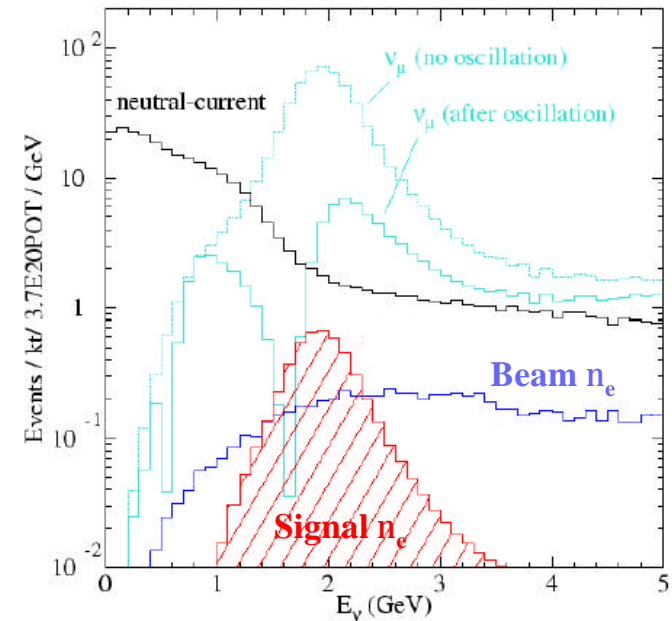
Low Z (small ΔX^0 sampling)

tracking calorimeter

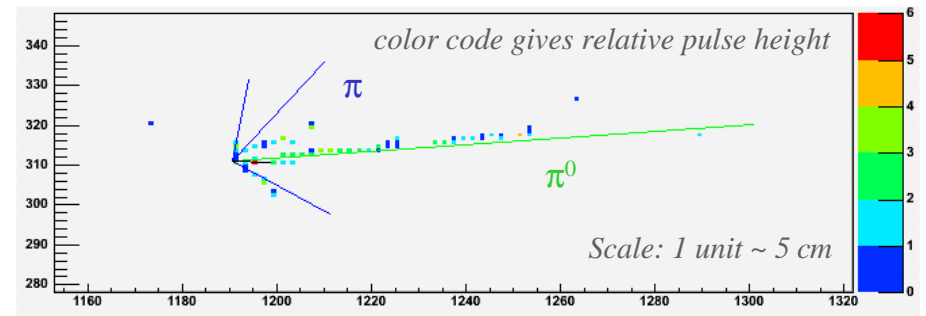
(CHARM II, ...NOE*, NO_nA at NuMI)

e/h , e/m separation: turns out to be adequate

* 2.4 kton transition radiation detector proposed for CNGS



Neutrino spectra at NuMI off-axis



n_m NC event in NO_nA TAsD, with leading p^0 and charged p
(one projection)

Main lines of NOnA design

Proposal P929 submitted in 2004 , for q_{13} in off-axis NuMI beam

Low Z, good sampling and mass 10 x MINOS ? new technologies to reduce cost

Design features

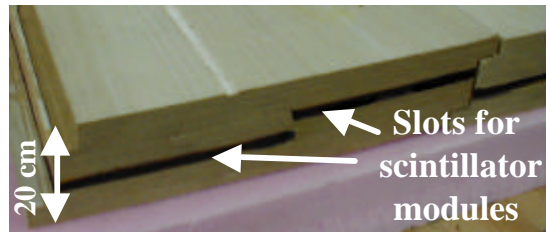
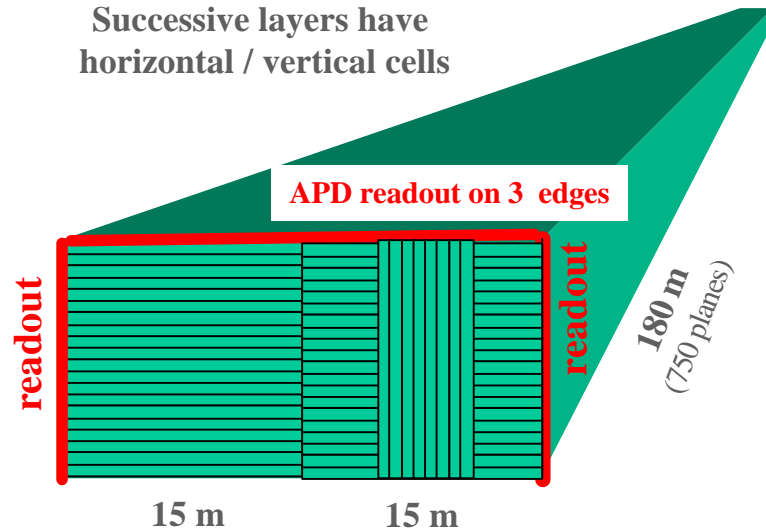
- Low Z and $< 0.3 X_0$ sampling (Fe and $1.5 X_0$ in MINOS)
 - Liquid (plastic in MINOS) scintillator
 - Avalanche Photo Diode (APD) readout (PMTs in MINOS)
- } Main new technologies with respect to MINOS
- Two detector options
 - Baseline design: $0.3 X_0$ sampling
 - Totally Active liquid scintillator Detector (TASD)
(RPC as active detector option has been studied: two-dim. readout but no dE/dx)
 - No need of underground location (live-time ~ 100 s/year)
Active shielding from cosmic rays foreseen (cheaper than passive overburden)

Baseline Design

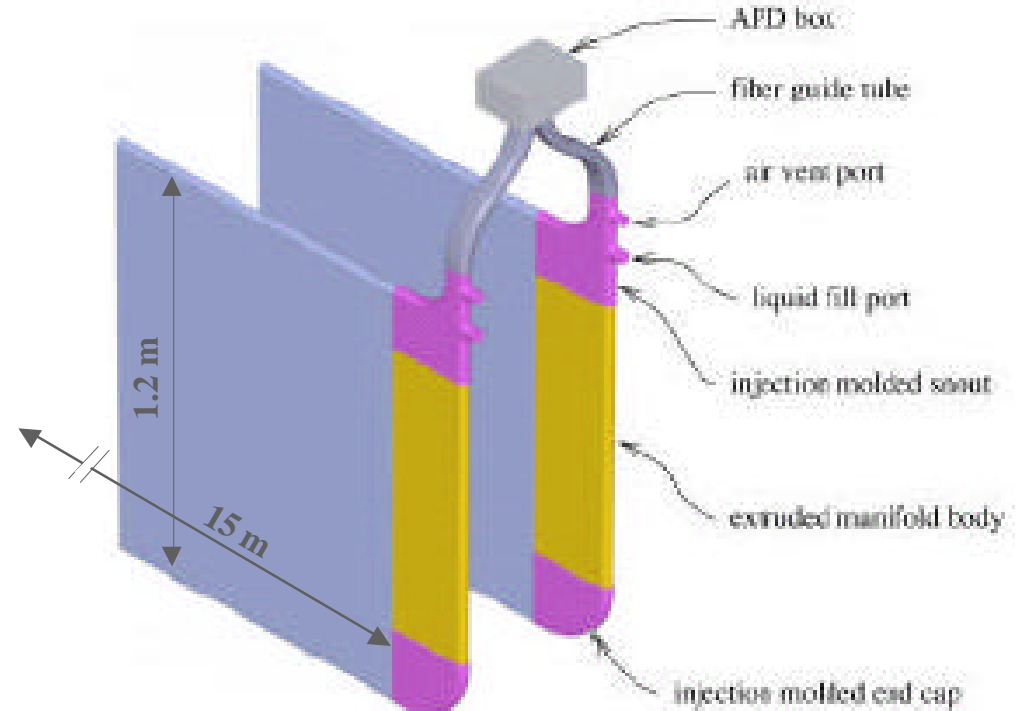
50 kton (7 kton scintillator, 0.3 X_0 sampling)

View of the detector

Successive layers have horizontal / vertical cells

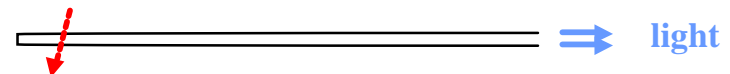


Particle-board as passive material (provides also the support structure)



Liquid scintillator modules

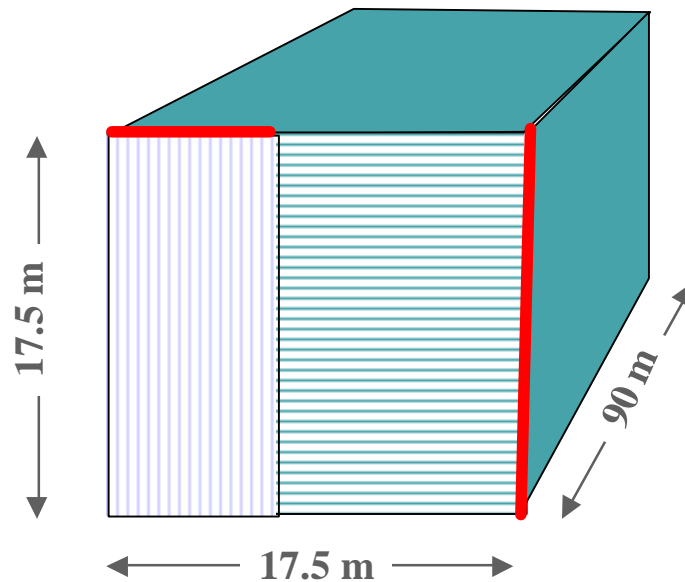
- 1.2 m wide, 15 m long PVC extrusions with 30 cells (3 cm wide)
- U-loop Wavelength Shifting Fibre ($f = 0.8$ mm) in each cell: ~ doubled light collection



Totally Active liquid Scintillator Detector (TASD)

25 kton (21 kton scintillator)

APD readout on TWO edges



The detector is wider and taller than the baseline detector, Hence shorter along the beam

No crack down the center

With respect to the baseline design:

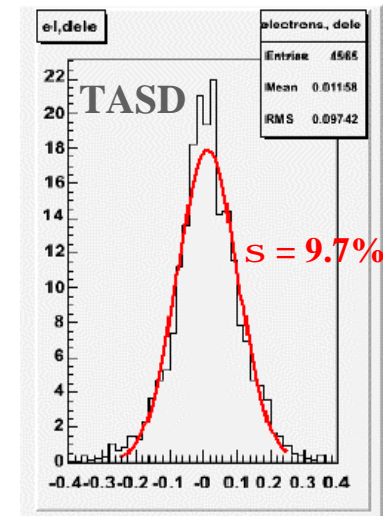
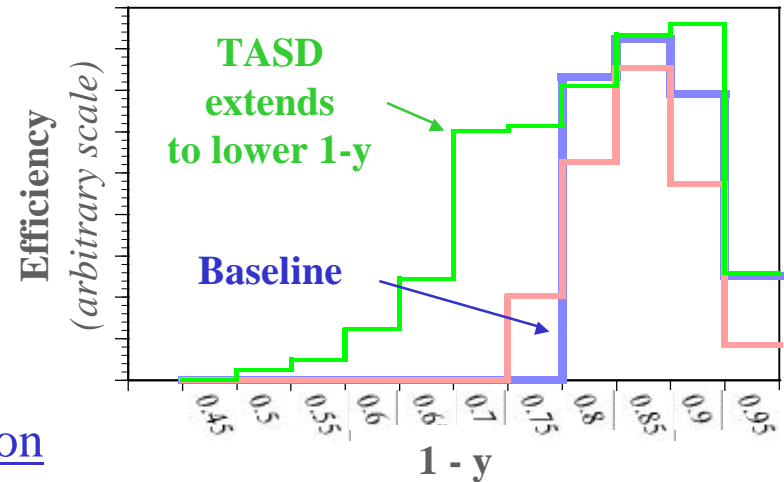
- **Similar scintillator modules**
 - thicker cells along the beam
4.5 cm vs. 2.56 cm (more light)
 - Longer extrusions
17.5 m long vs. 15 m (less light)
 - 32 cells wide vs. 30 cells: matches 16 ch. APD
- **Same U-Loop WLS fibres**
- **Same APD readout**
but only on two detector edges
- **PVC must provide a self-supporting structure:** mechanics to be carefully studied (a PVC 5-story building)
- **85% scintillator, 15% PVC**
~ same cost as with baseline design
implies $\frac{1}{2}$ detector mass, but



see next slide

Baseline design (0.3 X₀ sampling) ? T ASD

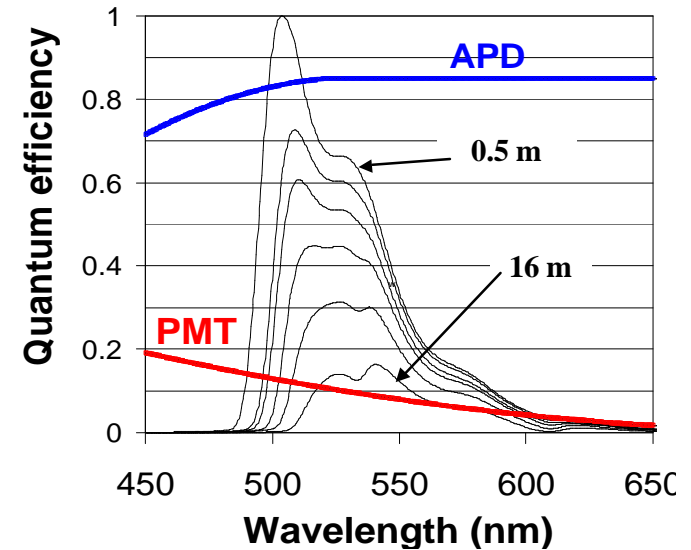
- 50 kton ? 25 kton but higher oscillated ν_e efficiency 18% ? 32%
- 2.5cm liquid + 17.8 cm particle-board
? 4.5cm liquid + 0.4cm PVC
 - ~ 4 times as many hits / unit track length
 - Almost continuous pulse height information (favours e/π^0)
- T ASD has better energy resolution
For e^- $\Delta E/E = 15\% / \sqrt{E}$? $10\% / \sqrt{E}$
(with RPCs $23\% / \sqrt{E}$)
- About the same cost and time scale
(detector completed in late 2011 if funding begins in late 2006)



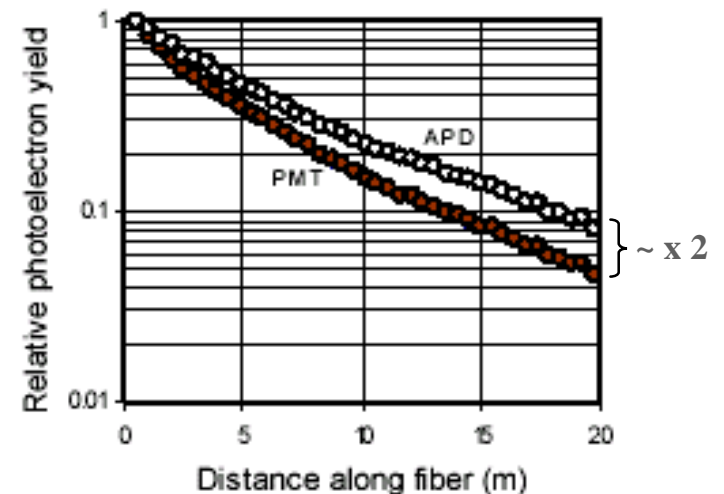
Meas-True/ ν True

Avalanche Photo Diodes (APD)

- Cheaper than PMTs
- 2x16 pixel APDs commercially produced at large scale:
CMS/LHC n^0 pixels $\sim 8 \times$ NOvA
- High QE ($\sim 85\%$)
? longer scintillator cells
(~ 40 photons/mip from far-end)
- Spectrum at far-end shifted towards higher Q.E. ? improved yield uniformity
- Dark noise from thermally generated electron-hole pairs: reduced to ~ 10 $e^-/\mu s$ by cooling (Peltier effect) at -15 $^{\circ}C$
- Low gain (operated at $\sim x 100$)
? need of stable and reliable amplifiers



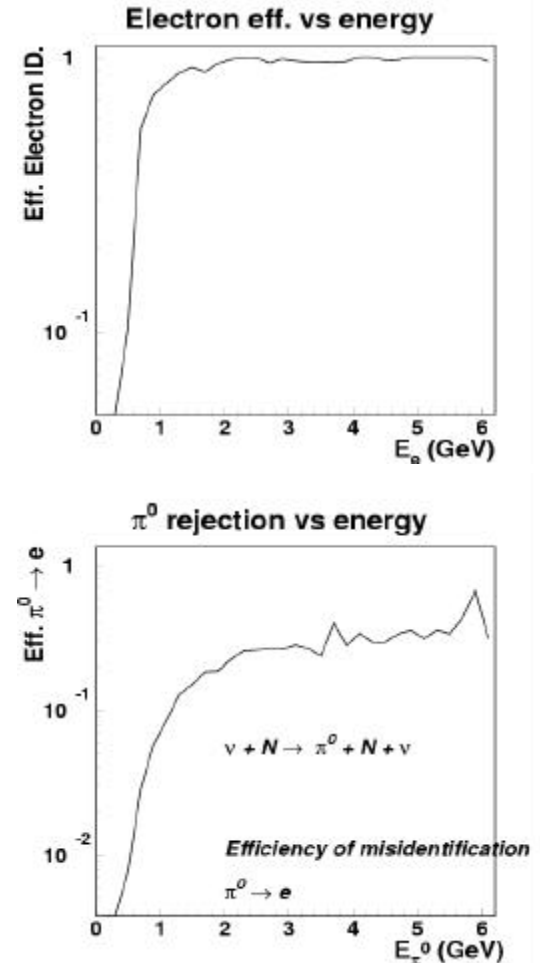
(spectra at various distances from photo-detector)



Water Cerenkov

Water Cerenkov

- **Sensitivity to low energy** (if photo-sensor density is adequate)
Large target mass at cheap cost
? ν oscillation, ν astrophysics, proton decay
- **Difficulties at high energy**
 - Frequent multi-ring events, DIS dominates
 - e/π^0 separation: $\sim 30\%$ π^0 mis-identification above a few GeV (because of $\gamma\gamma$ collimation)
 - Hence not suitable at ν -Factory (where, moreover, the muon charge must be measured)
- **Proven technique**
 - A third generation of successful underground detectors:
IMB/KamiokaNDE ? Super-K ? Hyper-K/UNO/Frejus
In each generation one order of magnitude increase in mass
 - Performance as well as limitations
known from SK and K2K, extrapolated by MC

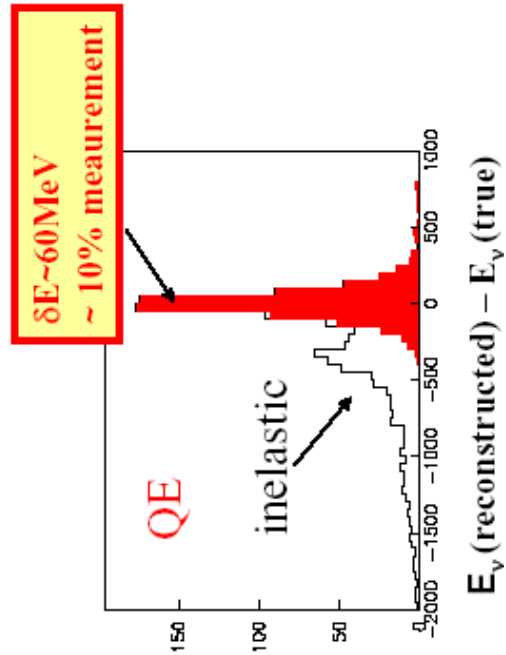


From Report BNL-69395

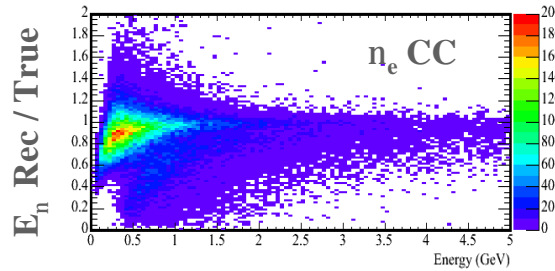
Super-K: a large Water Cerenkov detector of which the performance has been simulated and observed

Energy resolution in Super-KamiokaNDE

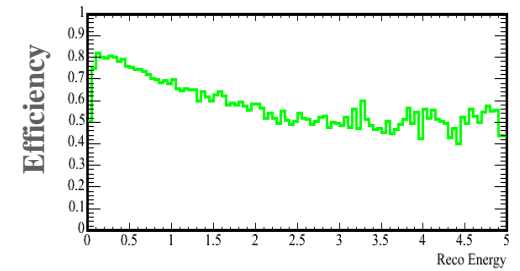
M. Messier



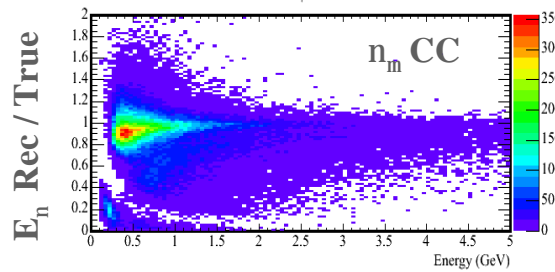
Reconstructed Energy vs True Energy for ν_e CC Events



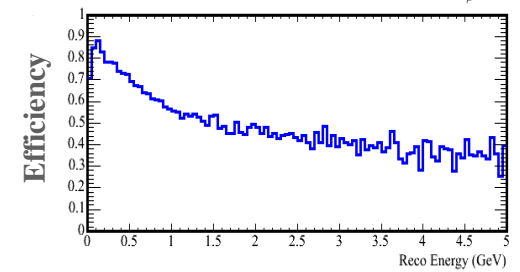
1-Ring, e-Like Reconstruction Efficiency vs Reconstructed Energy for ν_e CC Events



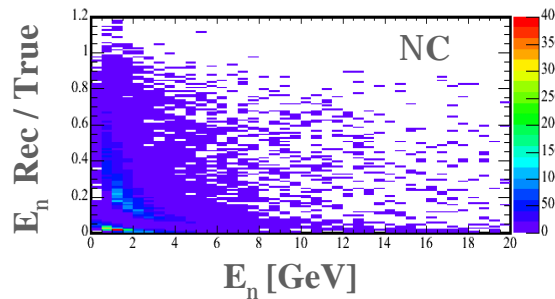
Reconstructed Energy vs True Energy for ν_μ CC Events



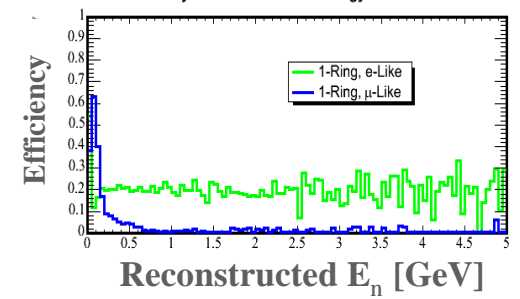
1-Ring, μ -Like Reconstruction Efficiency vs Reconstructed Energy for ν_μ CC Events



Reconstructed Energy vs True Energy for NC Events



Reconstruction Efficiency vs Reconstructed Energy for NC Events



E_n reconstructed accounts for p_m , q_m and, in case of DIS, for E_{had}

Geometry of next Water Cerenkov generation

- Max 50 m water depth pressure, with current 20" Hamamatsu PMTs
- ~ 80 m light attenuation length in pure water
- Mining cost \propto total detector volume
- Instrumentation cost \propto detector surface area
- A careful study of rock stresses is required, accounting for specific local features; to reduce rock stresses; the cavern should anyhow have rounded edges



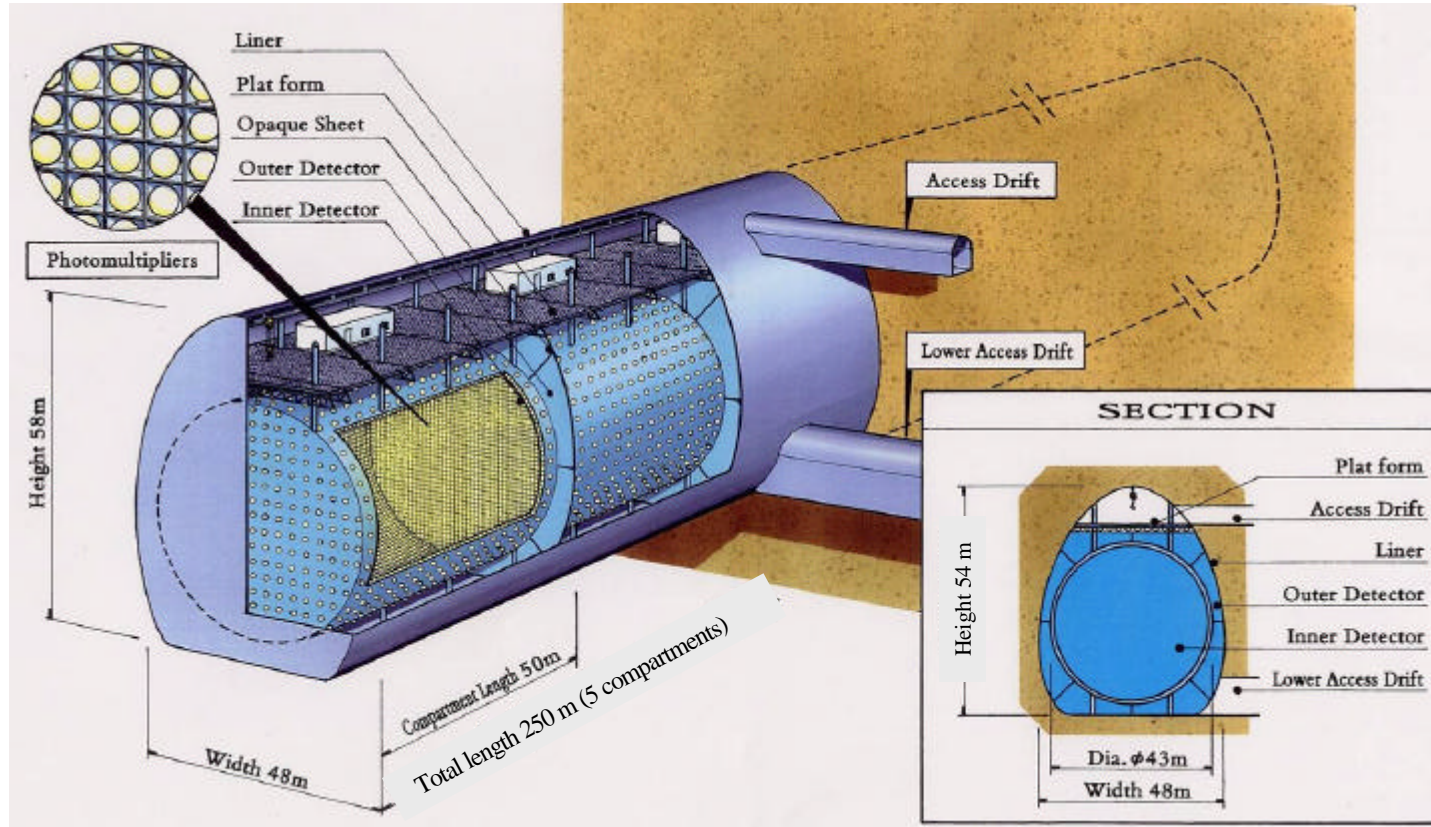
Elongated shape

(transverse dimensions \sim 50 m)

Segmentation

- Optical
 - ? reduction of backgrounds from PMT discharges
 - ? increased operational live-time due to independent module calibration
- If also mechanical
 - ? higher cost, but independent module maintenance and possibility of staging

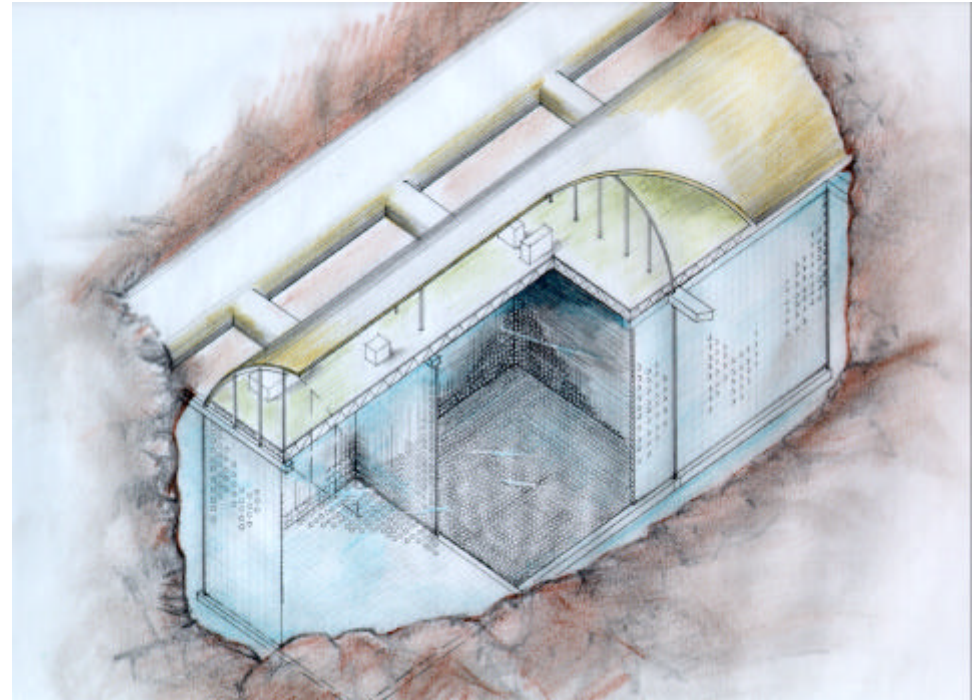
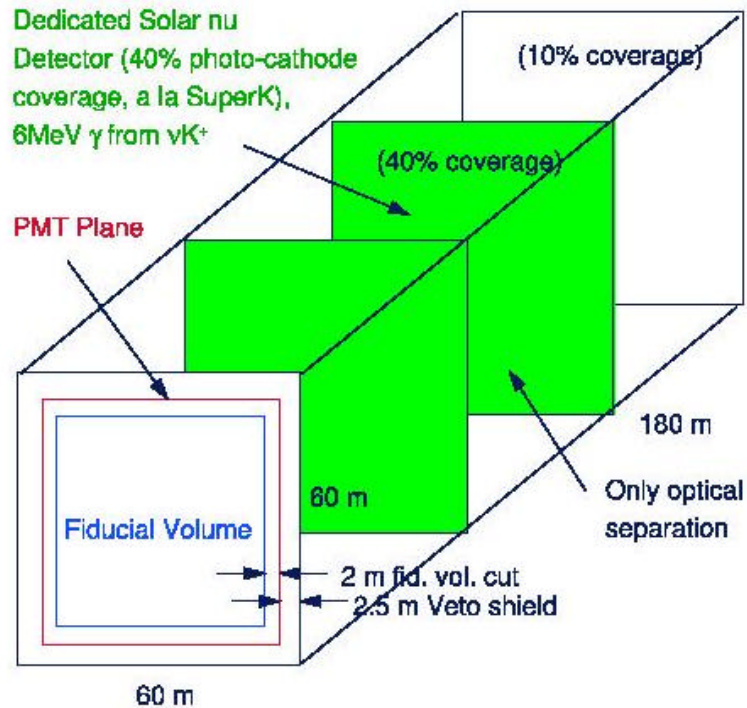
Hyper-KamiokaNDE



One of the two 500 kton modules

- Two modules placed sideways, each with 5 compartments (50 m long)
- Higher cost than for a single module, but maintenance possible with one module always alive
- Both cavities should be excavated at the same time. But a staging scenario is possible.
- ~ 10 years construction time, with t_0 after a few years of operation of T2K

UNO



- **Total (fiducial) mass 650 (445) kton**
- **Three optical zones with different photo-sensor density, to reduce cost**
 - middle zone with high density (40% PMT coverage like Super-K) for solar ?
 - edge zones with 10% PMT coverage
 - ? 10% adequate? Are different densities the optimal solution to the financial problem?
- **56,650 20'' PMTs (~ 1/2 compared to full 40% coverage); 15,000 8'' PMTs**

Comparison of Hyper-K and UNO designs to Super-K

	Super-K	Hyper-K	UNO
Total mass [kton]	50	2 x 500	650
Fiducial mass [kton]	22.5	2 x 270	440
Size	Φ 41 m x 39 m	2 x Φ 43 m x 250 m	60 m x 60 m x 180 m
Photo-sensor coverage [%]	40	40	? 40 (5 MeV threshold) ? 10 (10 MeV threshold)
PMTs	11,146 (20")	200,000 (20")	56,650 (20") 15,000 (8")

**A large fraction ($\sim 1/2$ or more, in case of PMTs)
of the total detector cost comes from the photo-sensors**

General considerations similar for a Frejus detector

Increasing the mass ...

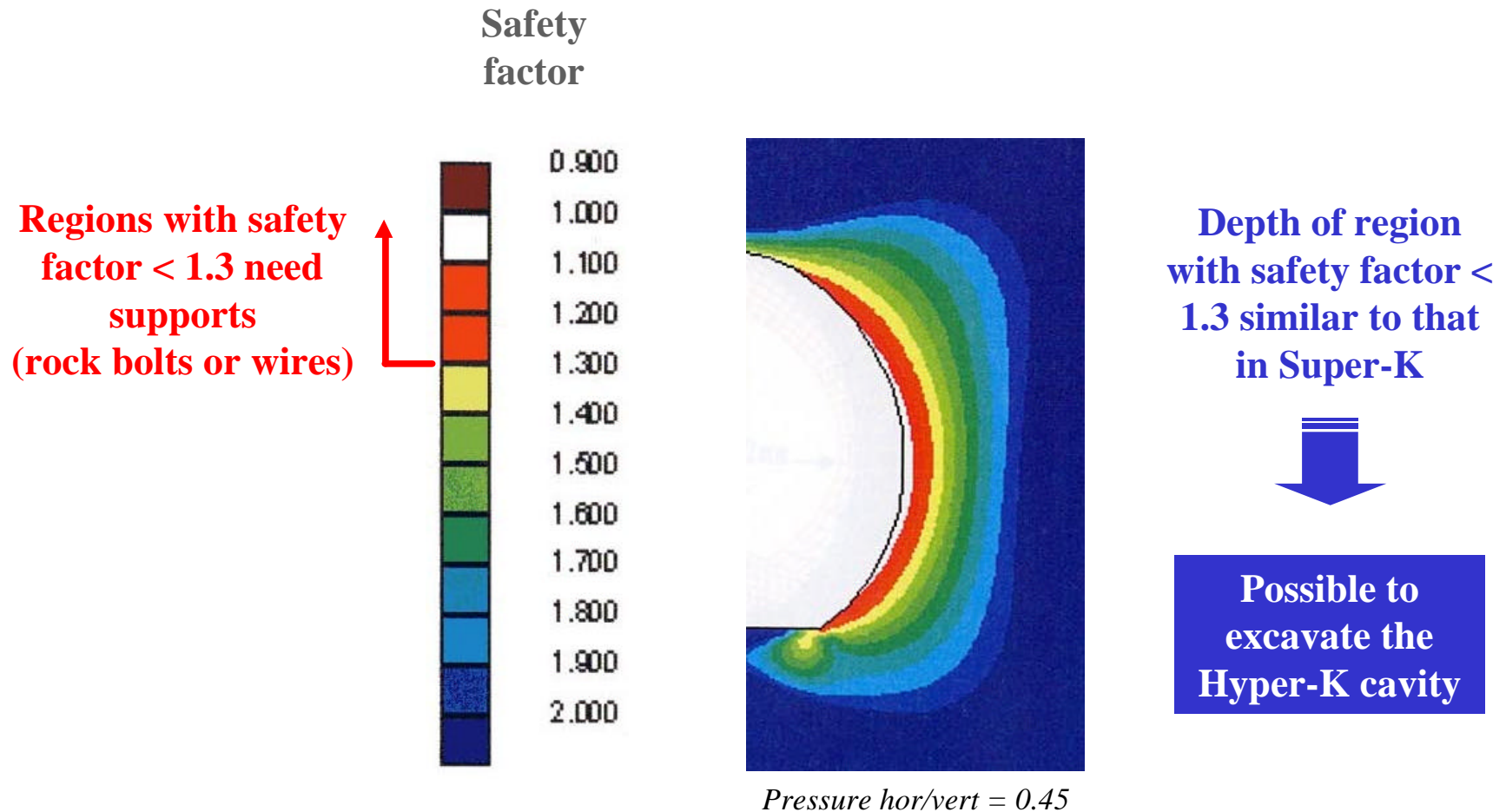
- **Wine:** taste improves from Standard to “Magnum” to “Jeroboam” bottles (decreasing surface/volume ratio and surface effects not good for quality)
- **Water Cerenkov:**
 - better energy containment
 - larger “effective” granularity of photo-sensors (due to larger average distance from event vertex)

Main issues

- Design of a large cavern
- R&D on photo-sensors, in strong collaboration with industry*, to improve:
 - cost
 - production rate: affects construction time, storage problems have to be faced
 - performance

* Development of 20” PMTs is at the basis of the success of KamiokaNDE and Super-KamiokaNDE

Finite element analysis of Hyper-K cavern at the Tochibora mine* at Kamioka



* Insufficient depth to pursue the studies on solar neutrinos

R&D on photo-sensors for Water Cerenkov

- PMTs

Automatic glass manufacturing does not seem (Hamamatsu) a practical way to reduce the cost and speed-up the production rate:
the required quantity is still small compared to standard commercial PMTs

- New photo-sensors

- Spherical Hybrid Photo-Detector (HPD)

ICRR Tokyo - Hamamatsu

- “ReFERENCE” tube: photo-cathodes operating in reflection mode

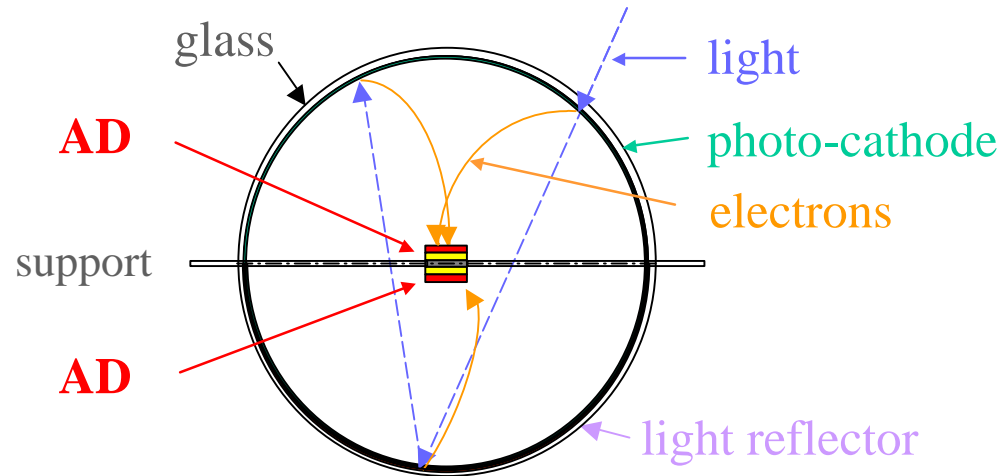
U.C. Davis - ITT Night Vision, at an early stage of development

General comment:

Long term stability and reliability are a must

Proven for PMTs

Spherical HPD

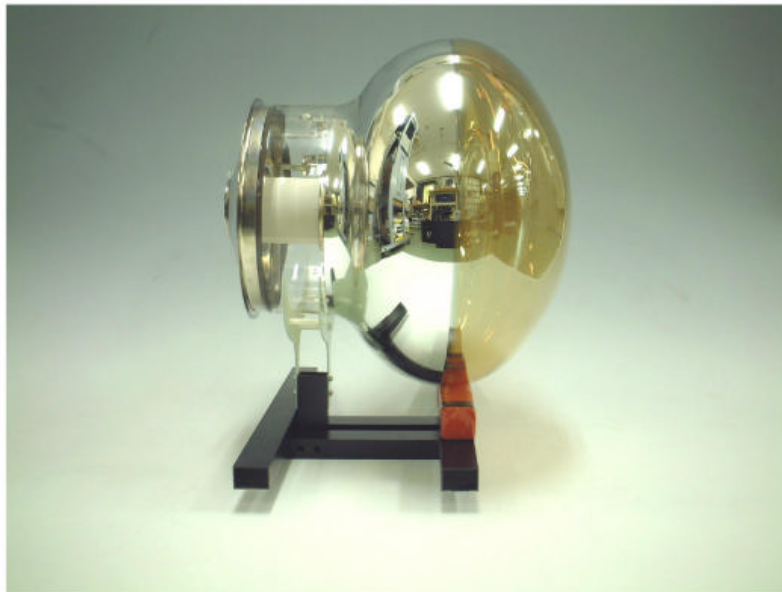


- Spherical glass envelope, coated with photo-cathode and light reflector
- Avalanche Diodes (AD) at the centre of the sphere
- Electrons accelerated by 20 KV between photo-cathode and AD:
 - high gain (~ 4000) in the 1st amplification stage, by the strong electron bombardment
 - ? single photon sensitivity
 - ? noise thermally generated in the AD becomes ineffective
 - gain still lower than with PMTs: need of stable and highly reliable amplifiers
 - resolve 2-3 events per 50 ns

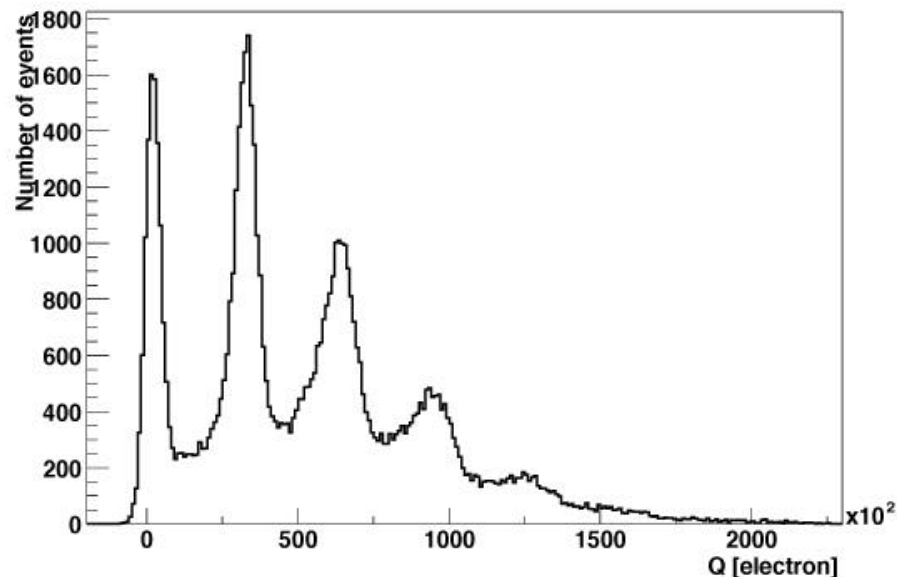
**Cost reduction from use of solid state devices (AD)
avoiding the complicated PMT dynode structure**

R&D on HPDs

13 Inch-Dia. HPD



HAMAMATSU
HAMAMATSU PHOTONICS K.K., Electron Tube Center



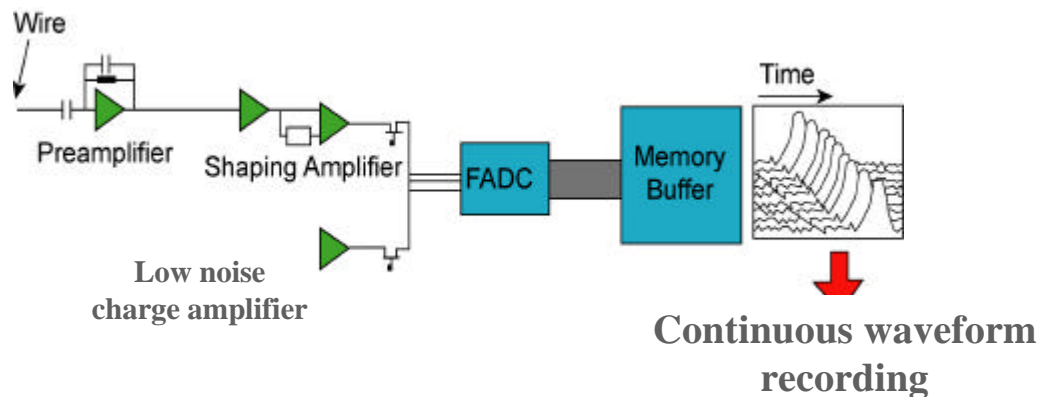
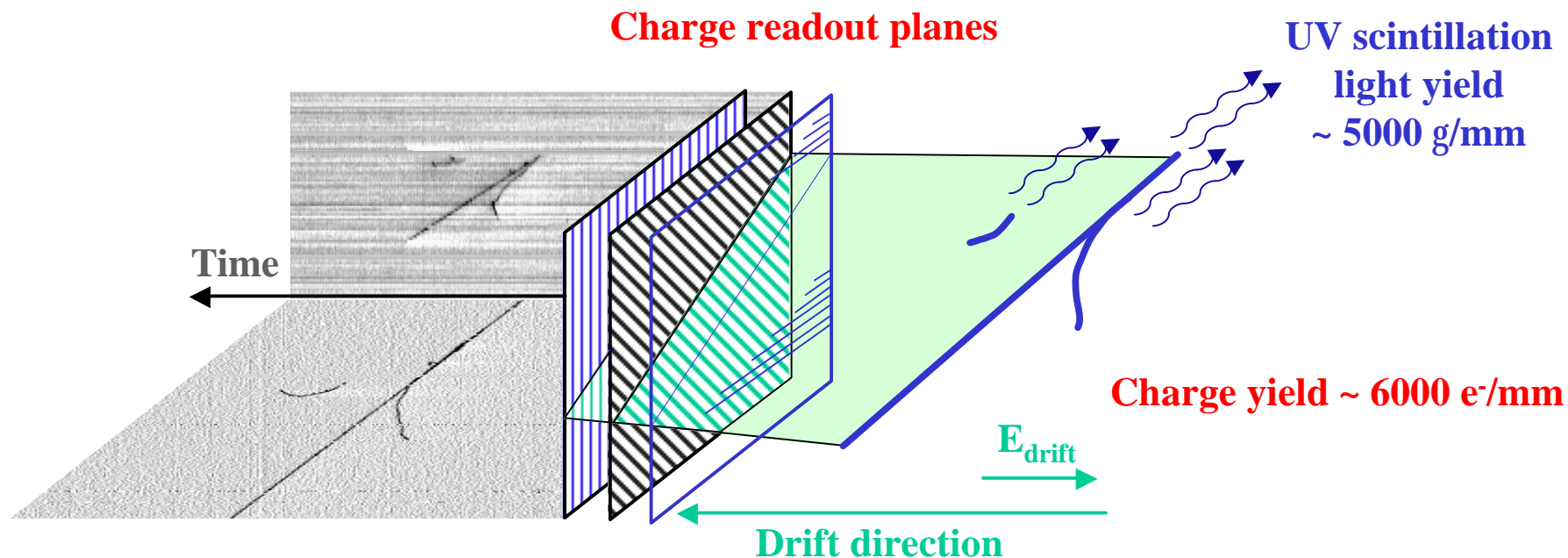
- 5" prototype tested
- Tests of 13" prototype in progress:
gain $\sim 10^5$, transit time spread ~ 1 ns, single photon sensitivity
- 13" production model by spring 2005
- Amplifier, Digital Filter, Analog Memory Cell: design in progress
- Next: design of Spherical 20" HPDs (requires higher field or development of larger AD)

Liquid Argon Track Projection Chamber

Two target mass scales for future projects:

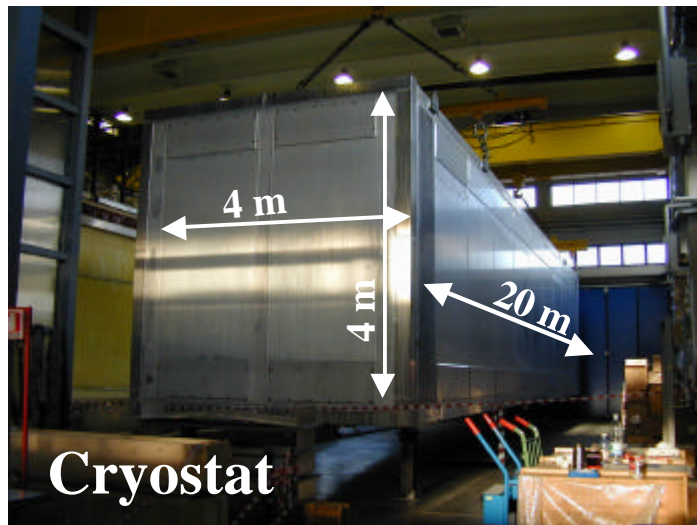
- **100 ton** as near detector in Super-Beams (not discussed here)
- **50-100 kton** for ν oscillation, ν astrophysics, proton decay

The Liquid Argon TPC principle

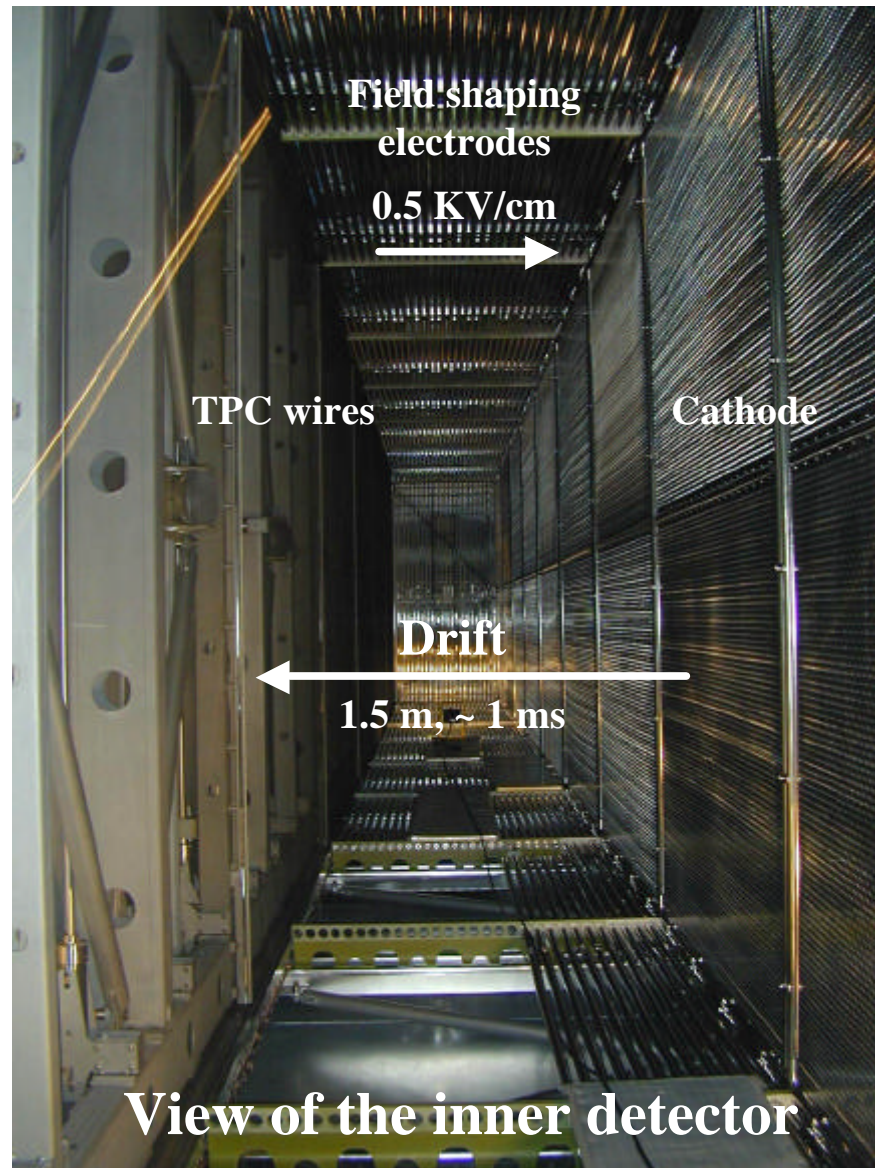


High target density
Induction and charge collection readout
Continuously sensitive
Self-triggering
 t_0 from scintillation

ICARUS T300 module (0.3 kton)



- Tested in a ground level laboratory (Pavia)
- This is the present “status of the art”



T300 module: 0.3 kton, 1.5 m drift length, ~1 ms drift time

ICARUS: a 3 kton modular detector

to be operated underground at Gran Sasso ? important safety issues

To reach 50-100 kton mass

- Cryogenic insulation requires minimal surface/volume
? A **single very large cryogenic module** with aspect ratio ~ 1:1
Do not pursue the ICARUS multi-module approach

- **Longer drift length**, to limit the number of readout channels

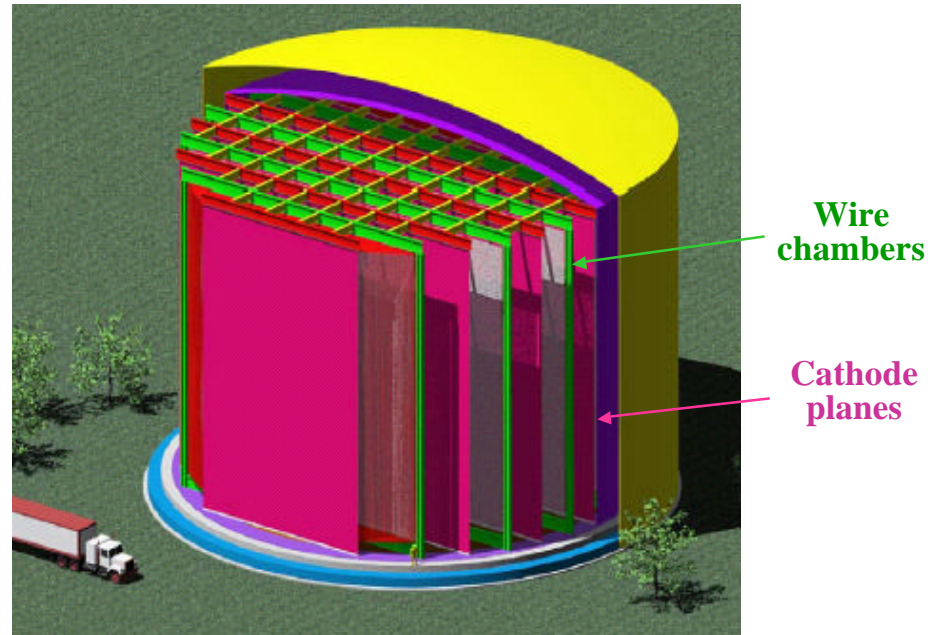
Two approaches:

1. **3- 8 m** drift length, with readout as in ICARUS
2. Very long drift length (~ **20 m**) and “**Double Phase**” readout
(amplification and readout in Gas Argon to cope with signal attenuation)

In both cases, the signal attenuation imposes a high LAr purity (~ 0.1 ppb O₂ equiv.)

FLARE - an off-axis Liquid Ar TPC for the NuMI beam

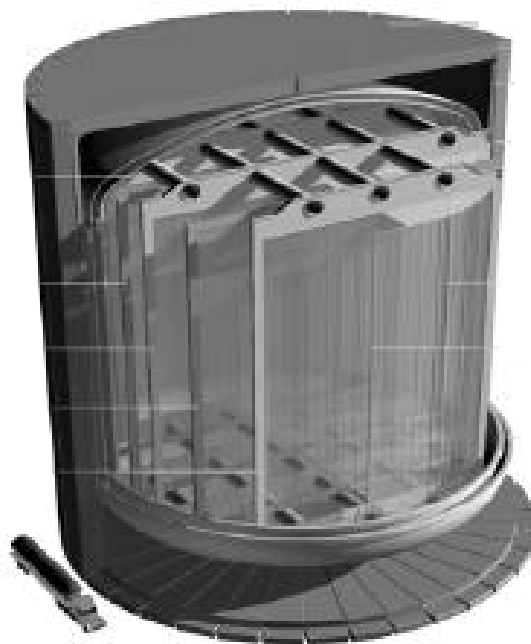
Letter of Intent, hep-ex/0408121 (2004)



- **A detector for n oscillation**
- **Readout** as in ICARUS, with detector subdivided in readout sections
- **50 kton** : $\sim 1.5 \times 10^2$ extrapolation in mass from ICARUS T300
- **3 m max drift length** (1.5 m in ICARUS T300) with $E = 0.5 \text{ KV/cm}$
- **Surface location** (operated only with ν beam)

LANNDD

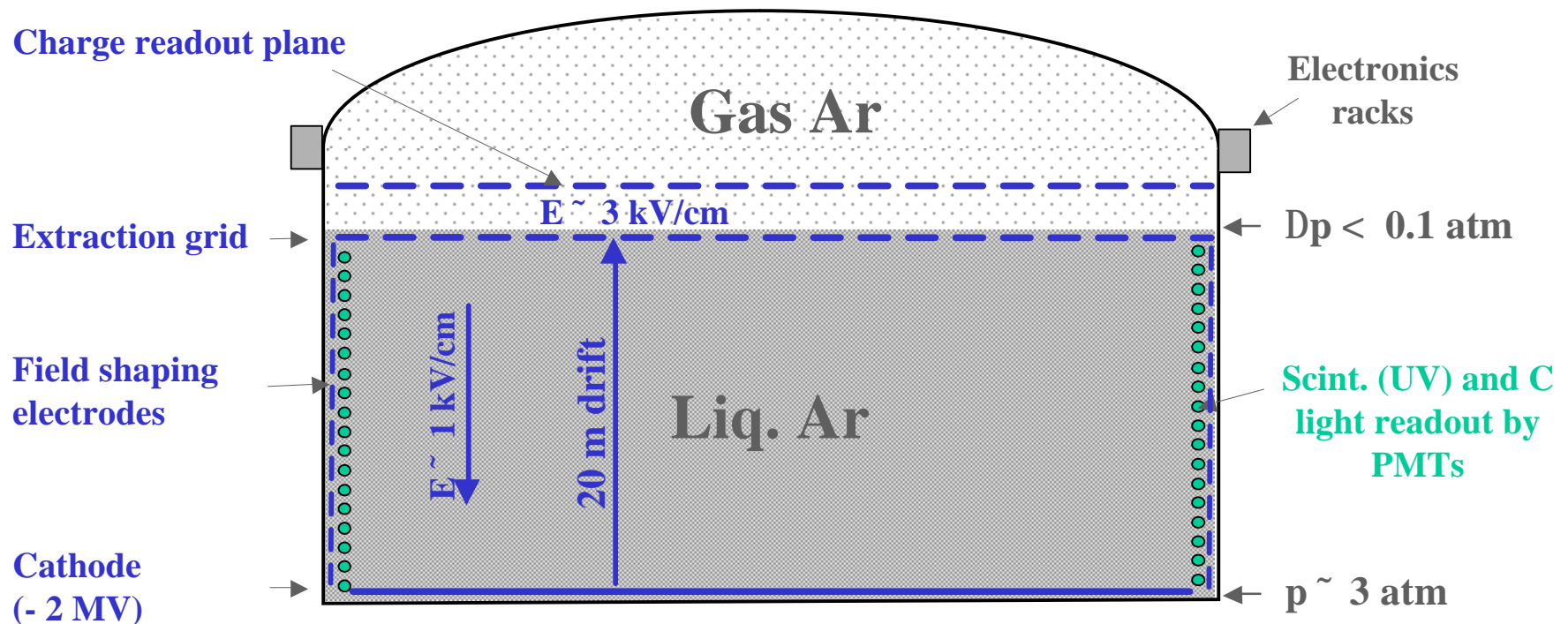
D. Cline et al., Nucl. Instr. and Meth. A503 (2003) 136



- **A detector for n oscillation, as well as for n astrophysics and proton decay (if located underground)**
- **Readout** as in ICARUS, with detector subdivided in readout sections
- **50-100 kton** : $1.5 - 3 \times 10^2$ extrapolation in mass from ICARUS T300
- **4-8 m max drift length** (1.5 m in ICARUS T300)
(~ 3 ms drift time for $E = 0.5$ KV/cm and 5 m drift)
- **Tests foreseen with 5 m drift length**

A 100 kton Liquid Argon TPC with “Double-Phase” readout

A. Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003



- A detector for n oscillation, n astrophysics, proton decay
- A single cryogenic and readout module
- 20 m max drift length, 10 ms drift time with as much as 1 KV/cm (0.5 in ICARUS T300):
- **Liquid Ar at boiling temperature**, as for transportation and storage of Liquefied Natural Gas (gas exhaust to be provided; feature not foreseen for ICARUS)
- $\sim 3 \times 10^2$ extrapolation in mass from ICARUS T300

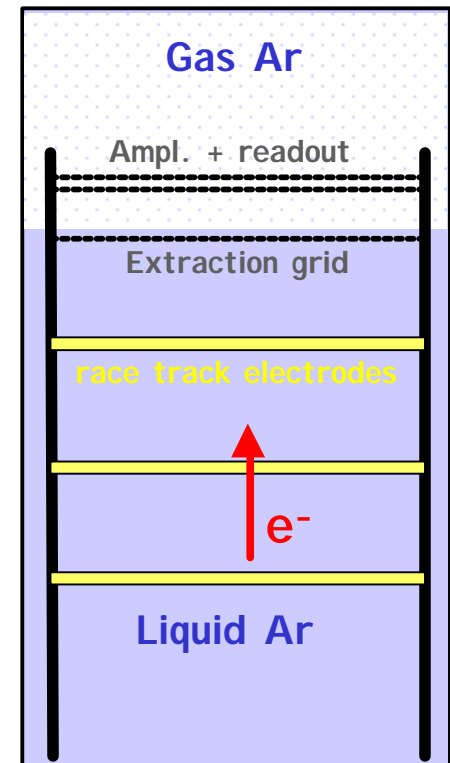
Double-phase (Liquid – Gas) readout

Basic references: Dolgoshein et al. (1973); Cline, ... Picchi ... et al. (2000)

Tested on the ICARUS 50 l chamber

Charge attenuation after very long drift in liquid compensated by charge amplification near anodes in gas phase

- With 2 ms e-lifetime, the charge attenuation in 10 ms is $e^{-t/\tau} \sim 1/150$
(original signal 6000 e^- /mm for a MIP in LAr)
- Amplification in proportional mode (x 100-1000) and readout by thin wires ($\phi \sim 30 \mu\text{m}$) with pad readout,
- Diffusion after 20 cm drift ? $\sigma \sim 3 \text{ mm}$:
gives a limit to the practical readout granularity



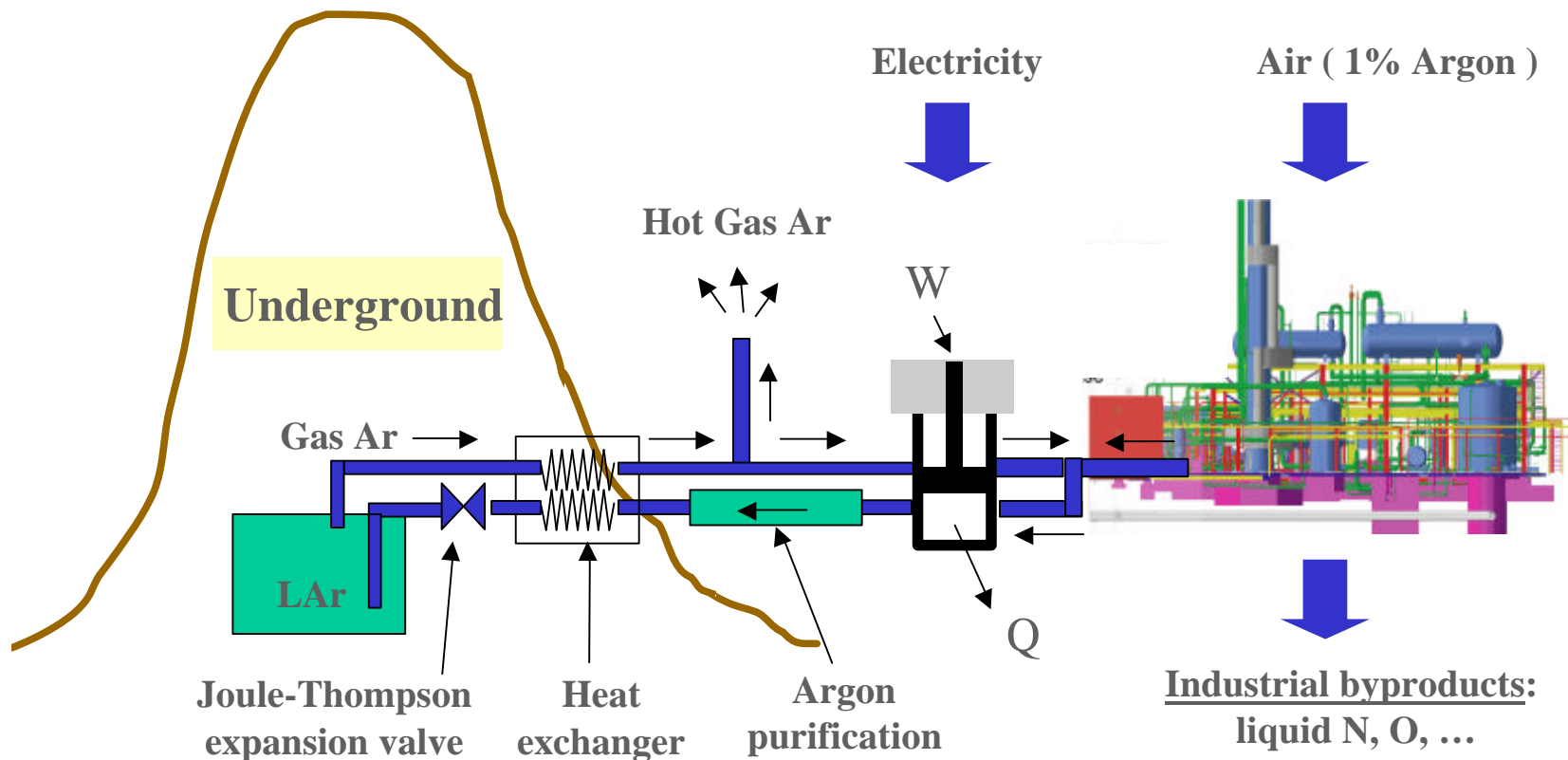
Ongoing studies and initial R&D strategy

(A. Rubbia)

- **Electron drift under high pressure** ($p \sim 3$ atm at tank bottom)
- **Charge extraction, amplification and imaging devices**
- **Cryostat design, in collaboration with industry**
- **Logistics, infrastructure and safety issues for underground sites**
- **Study of LAr TPC prototypes in a magnetic field** (for ν Factory)
- **Realization and test of a column-like detector prototype:**
 - ? 5 m long drift and double-phase readout
 - ? Simulate 20 m drift by reduced E field and LAr purity

A large cryogenic plant is needed

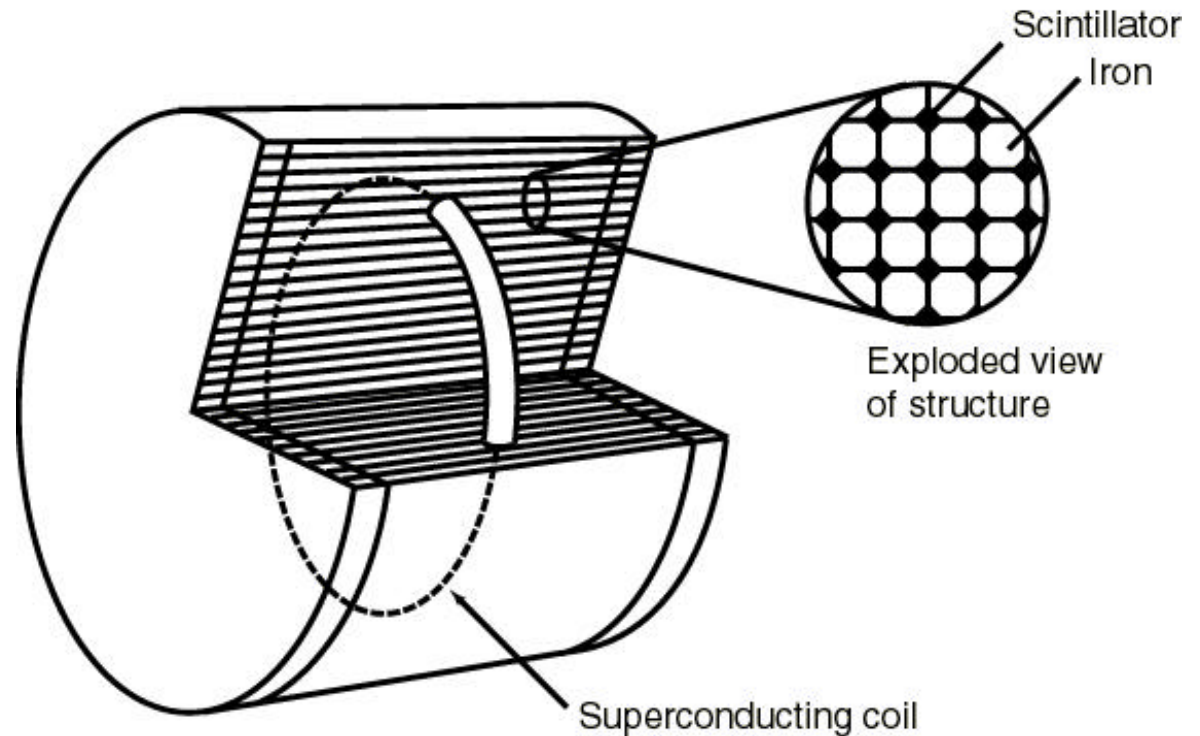
(A. Rubbia)



- Initial filling: transport LAr or in situ cryogenic plant
Filling speed 150 ton/day ? 2 years to fill
- Refilling to compensate evaporation: 5 W/m^2 heat input ? 30 ton/day needed
- Continuous re-circulation (purity)

A Magnetised Iron Detector for a n Factory

- Iron calorimeter, plastic scintillator rods as active detector
- Magnetised at $B = 1 \text{ T}$
? see “wrong sign” muons from $\nu_e - \nu_\mu$
- Conventional technique, but 40 kton mass one order of magnitude > MINOS and magnetic field
- Only concept presented: practical problems (mechanics, magnet design....) must be addressed to assess the feasibility



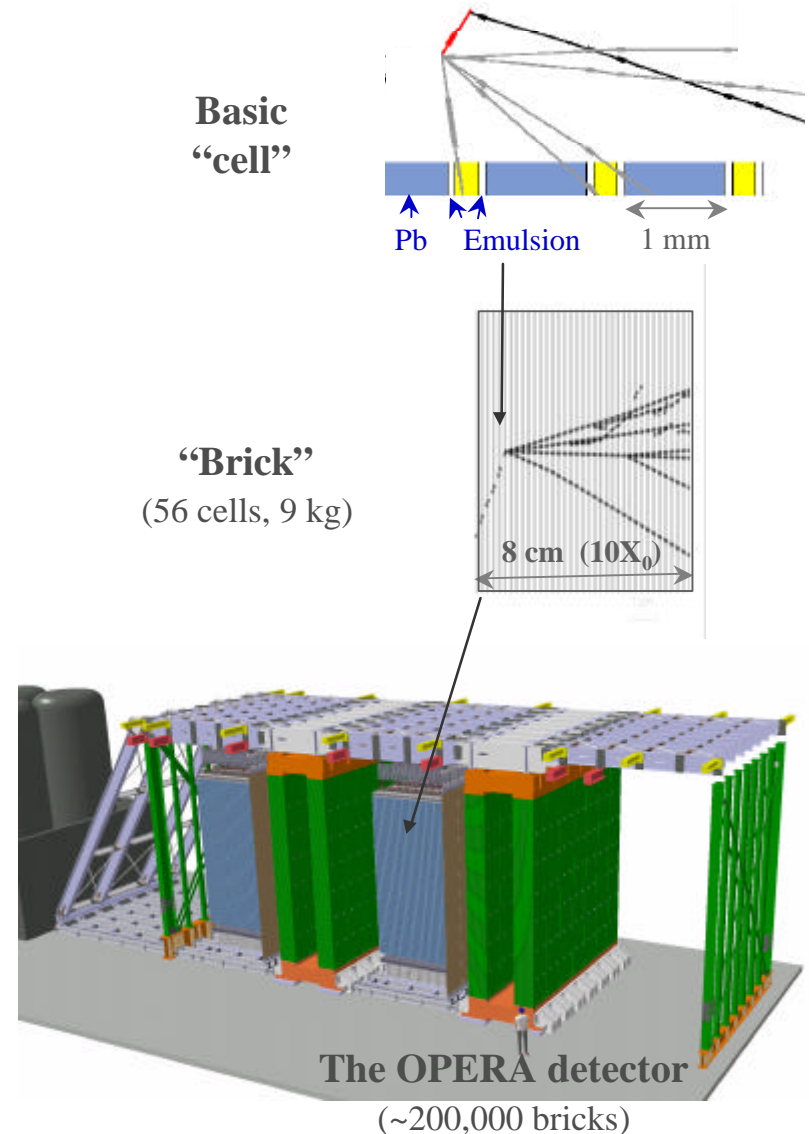
Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

Another possible design:

a dipole magnet equipped with RPCs, à la MONOLITH

The Emulsion Cloud Chamber (ECC) for ν_e ? ν_t appearance at ν Factories

- ν_e ? ν_μ (golden events) and ν_e ? ν_τ (silver events) to reduce θ_{13} - δ ambiguities
- Pb as passive material, emulsion as sub- μm precision tracker: unique to observe τ production and decay
- Hybrid experiment: emulsion + electronic detectors
- 1.8 kton OPERA target mass
? ~ 4 kton at ν Factory
- Scan events with a “wrong sign” muon:
x 2 increase of scanning power required
- OPERA as a “milestone” for the technique



Summary (1)

Low-Z Calorimetry

- ν_{μ} - ν_e oscillations ? θ_{13} in off-axis NuMI beam: **NOvA**
- Evolution of a proven technique
- NOvA mass ~ 10 x MINOS
- New technologies with respect to MINOS
 - plastic ? liquid scintillator (sampling or totally active detector)
 - PMTs ? Avalanche Photo Diodes (APD)
- Main issue: improve performance and reduce cost of trackers

Summary (2)

Water Cerenkov

- ν oscillation , ν astrophysics, proton decay
- Proven and very successful technique, well known also in its limitations
- K ? Super-K ? Hyper-K/UNO/Frejus: in each step mass $\sim \times 10$
- Main issues:
 - cost and production of PMTs
 - ? strong collaboration with industry needed
 - ? can one develop other photo-detectors with adequate long-term reliability?
 - design of a large cavern

Summary (3)

Liquid Argon TPC

- A beautiful detector for ν oscillation , ν astrophysics, proton decay
- Broad energy range
- Tested at the scale of the 0.3 kton ICARUS T300 module: extrapolation in mass by $>$ two orders of magnitudes
- New features envisaged to reach 50-100 kton: longer or much longer drifts, double-phase amplification and readout
- Substantial R&D required on various aspects, partly depending on the design parameters and on the (underground) location: signal propagation and readout; electric field shaping; cryogenics, civil engineering, safety and logistics issues;

Summary (4)

Magnetised Fe Sampling Calorimetry

- “wrong sign” μ from ν_e ? ν_μ oscillations at ν -Factories
- Technique proven at smaller scale
- Target mass ~ 10 x MINOS
- Proceed from concept to conceptual design

Emulsion Cloud Chamber (ECC)

- ν_e ? ν_τ at ν -Factories, to complement ν_e ? ν_μ oscillation in resolving θ_{13} - δ ambiguities
- Technique used in DONUT and being implemented in OPERA
- Mass ~ 2 x OPERA
- OPERA as “milestone” for the technique

General conclusions

A physics program to be planned over decades,
aiming at discoveries and precision measurements
on n masses & mixing, n astrophysics, nucleon decay, unexpected physics



Large and reliable detectors
with appropriate performance and acceptable cost



- **Detectors now in preparation: a source of important experience**
- **Lay down the bases for the future:**
 - R&D must look to near future and far ahead
 - Stimulate new ideas