Neutrino detectors

for Super-Beams, β-Beams and ν Factories

Main issues in:

R&D

Detector design and realisation

for

Low-Z Tracking Calorimetry

Water Čerenkov

Liquid Argon TPC

Magnetised Iron Calorimetry

Emulsion Cloud Chamber

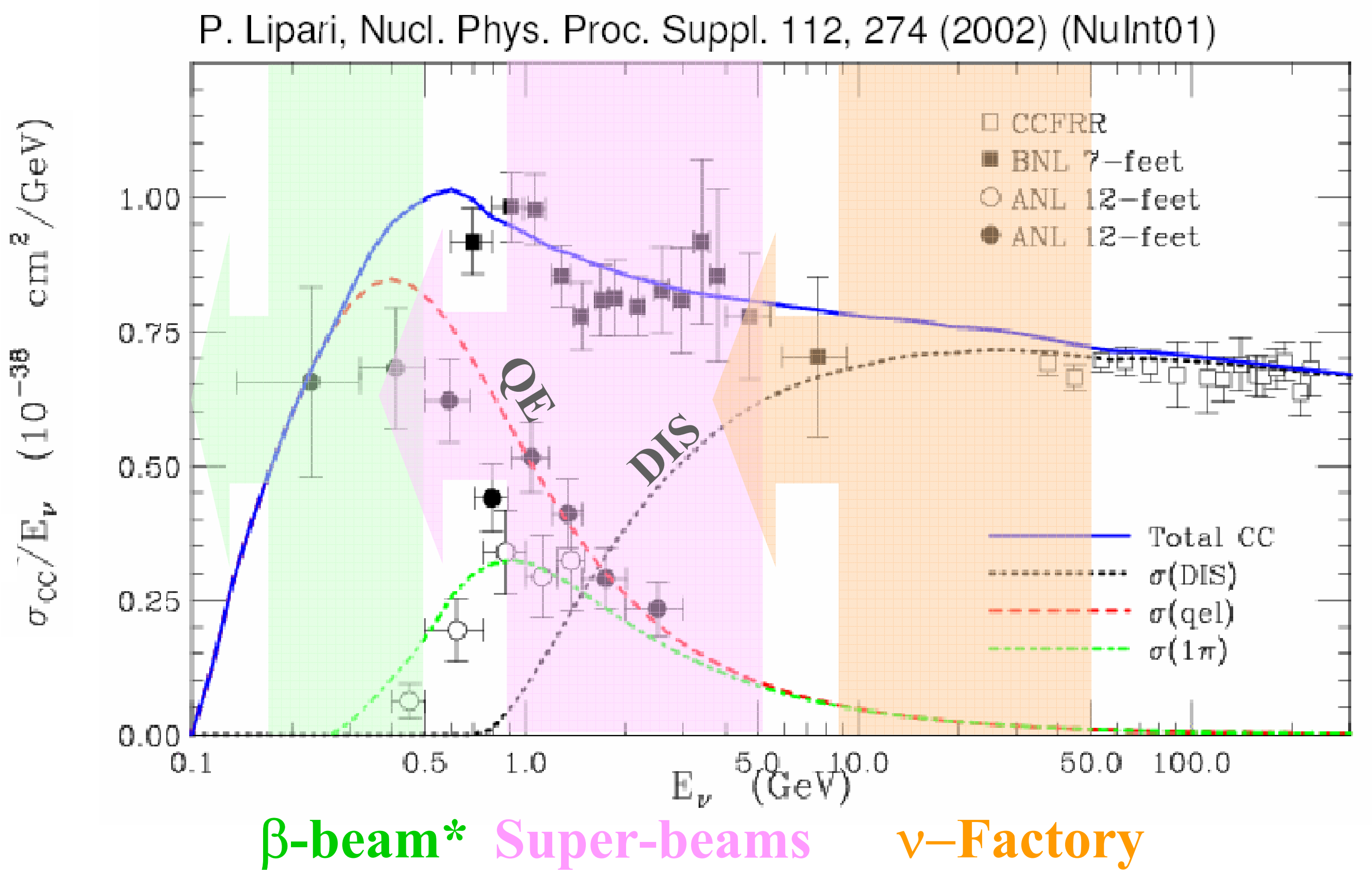
Main detector tasks

- **Lepton identification $\rightarrow$ identify ν flavour $\rightarrow$ signal**
- **Background rejection:** π^0 in ν_μNC $\leftrightarrow$ e^- in ν_eCC , ….
- **Measure ν energy**
  - For Quasi-Elastics (ν_l N $\rightarrow$ l N')
    Lepton energy $\rightarrow$ ν energy
    with corrections due to Fermi motion in nucleus and to nucleon recoil
  - For DIS (ν_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

ν energy ranges
and related dominant reactions (event topologies)



*) 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)

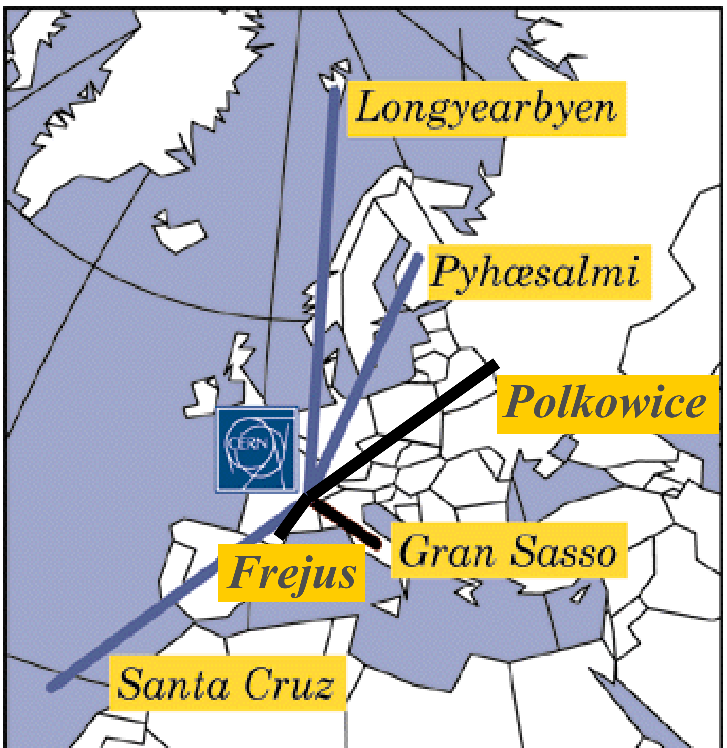
Complexity of choice

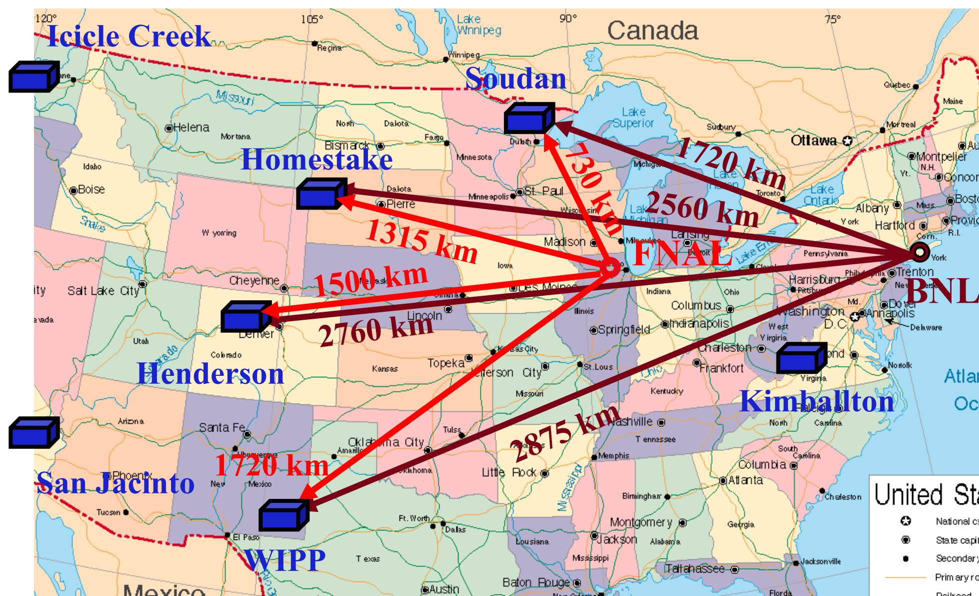
L/E, E , matter effects

↕

Detector design, S/B

Sensitivity to θ_{13} , mass hierarchy, δ





Low-Z Tracking Calorimetry

Designing a detector specialised for ν_μ-ν_e oscillations

Main backgrounds and tools for their reduction

Beam ν_e contamination

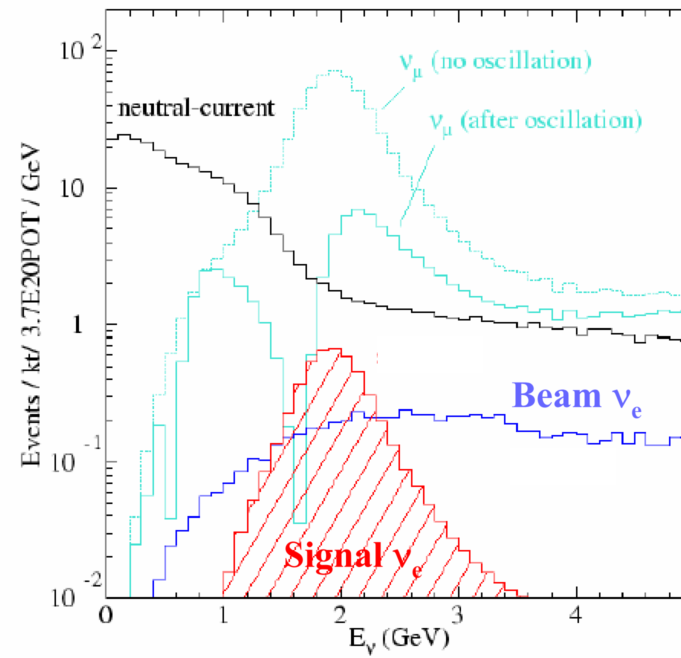
→ ΔE/E combined with off-axis beam

→ ν_e from K-decays suppressed in off-axis beam

π^0 in ν_μ interactions

→ e/ π^0 separation by:

- Tracking (e vs γγ)
- dE/dx at beginning of the shower (e vs e^+e^-)



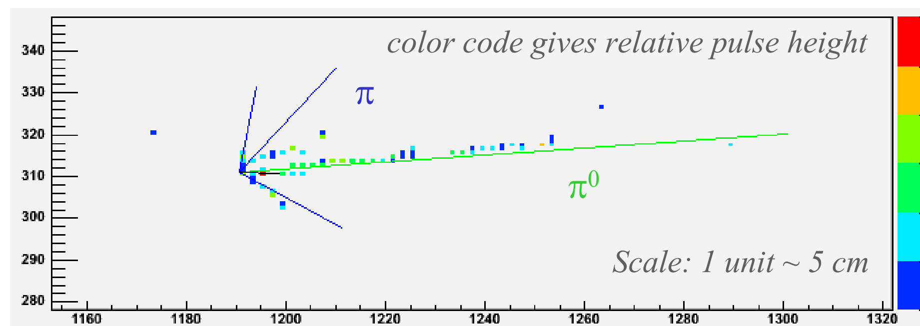
Neutrino spectra at NuMI off-axis

Low Z (small ΔX^0 sampling)

tracking calorimeter

(CHARM II, …NOE* , **NOνA at NuMI**)

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



ν_μ NC event in NOνA TASD, with leading π^0 and charged

(one projection)

* 2.4 kton transition radiation detector proposed for CNGS

Main lines of NOνA design

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

Low Z, good sampling and mass 10 x MINOS → new technologies to reduce cos

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)

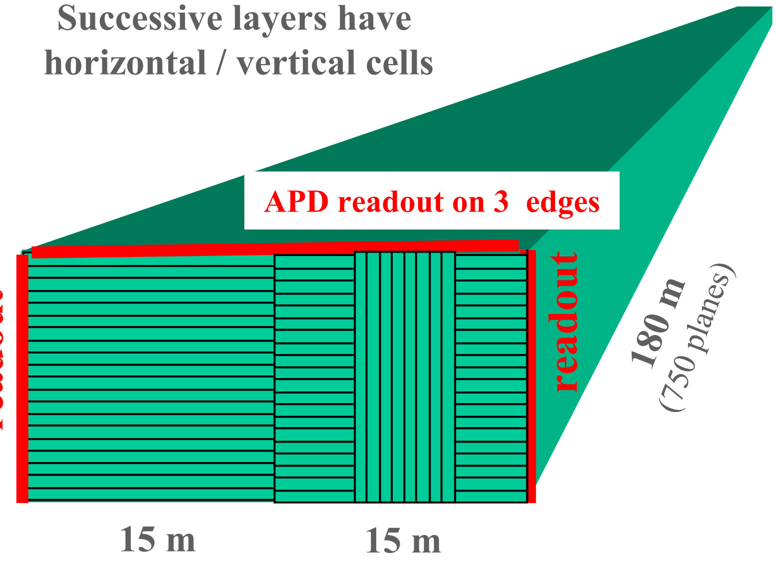
    (RPC as active detector option has been studied: two-dim. readout but no dE/dx)
- No need of underground location (live-time ~100 s/year)
  Active shielding from cosmic rays foreseen (cheaper than passive overburden)

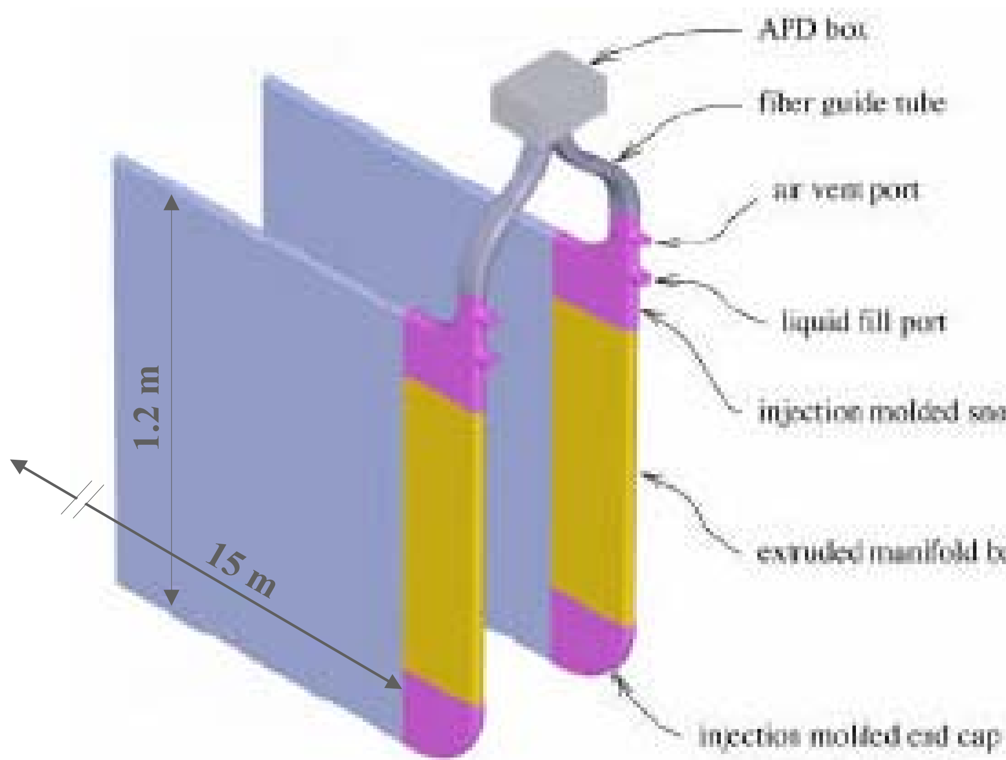
Baseline Design

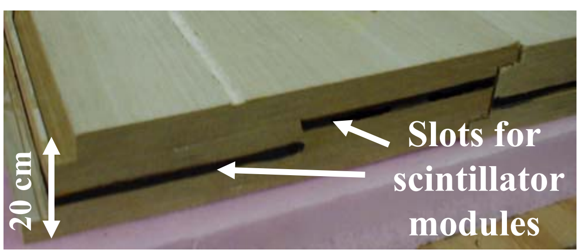
50 kton (7 kton scintillator, 0.3 X_0 sampling)

View of the detector

Successive layers have
horizontal / vertical cells







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

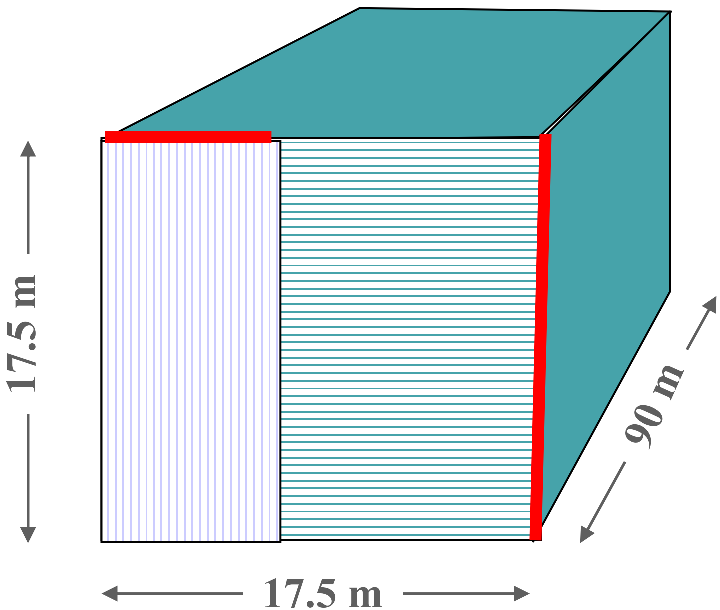
Liquid scintillator modules

- 1.2 m wide, 15 m long PVC extrusions with 30 cells (3 cm wide)
- U-loop Wavelength Shifting Fibre (ϕ = 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 ½ detector mass, but ….

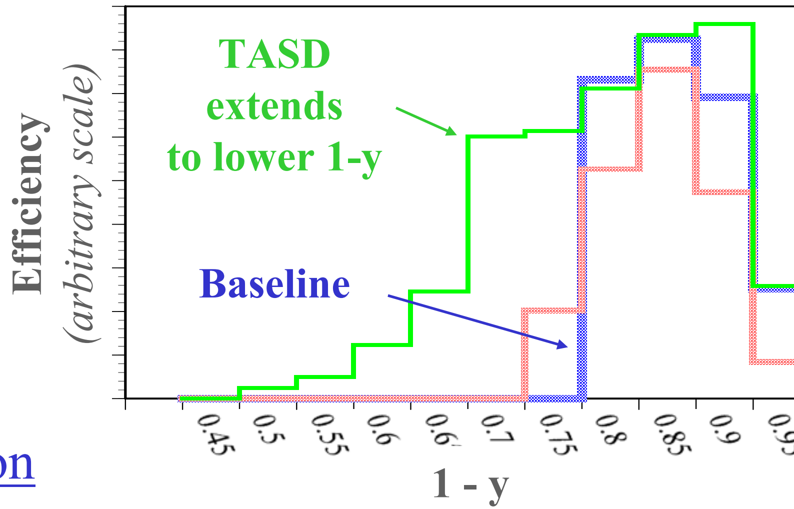
↓

see next slide

Baseline design (0.3 X_0 sampling) → TASD

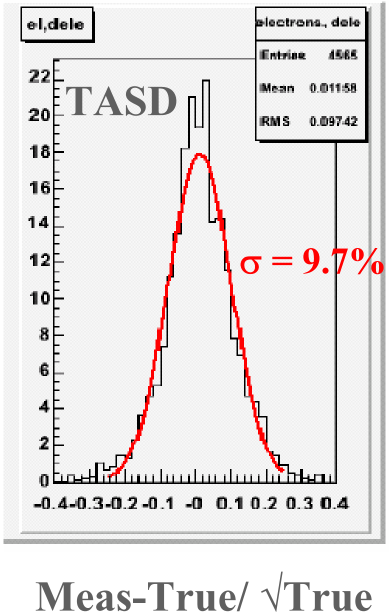
- 50 kton → 25 kton but
  higher oscillated ν_e efficiency 18% → 32%

- 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)



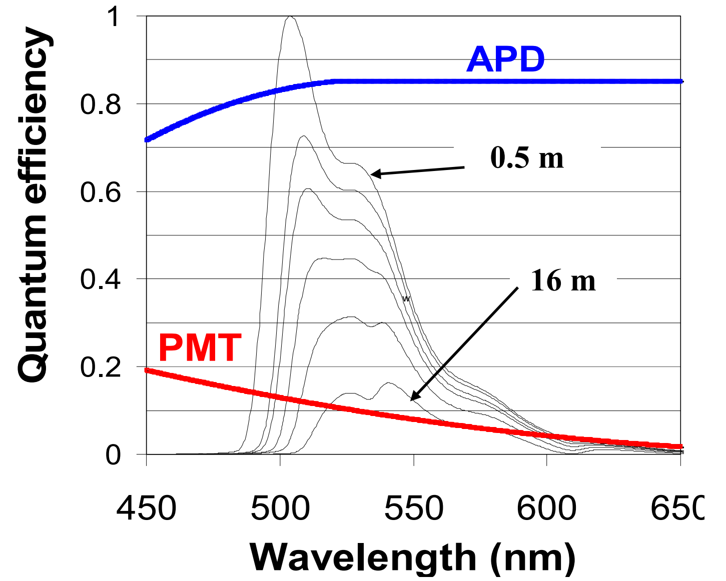
- TASD has better energy resolution
  For e^- $\Delta E/E = 15\,\%/\sqrt{E}$ → $10\,\%/\sqrt{E}$
  (with RPCs $23\%/\sqrt{E}$)

- About the same cost and time scale
  (detector completed in late 2011 if funding begins in late 2006)

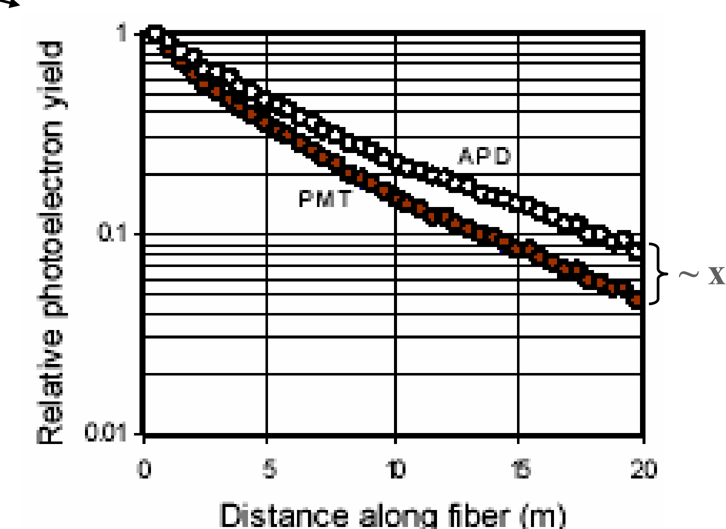


Avalanche Photo Diodes (APD)

- Cheaper than PMTs
- 2x16 pixel APDs commercially produced at large scale:
  CMS/LHC n^0 pixels ~ 8 x NOνA
- High QE (~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$^-$/μs by cooling (Peltier effect) at -15 ^{0}C
- Low gain (operated at ~ x 100)
  → need of stable and reliable amplifiers



(spectra at various distances from photo-detector



Water Čerenkov

Water Čerenkov

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: ~ 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)

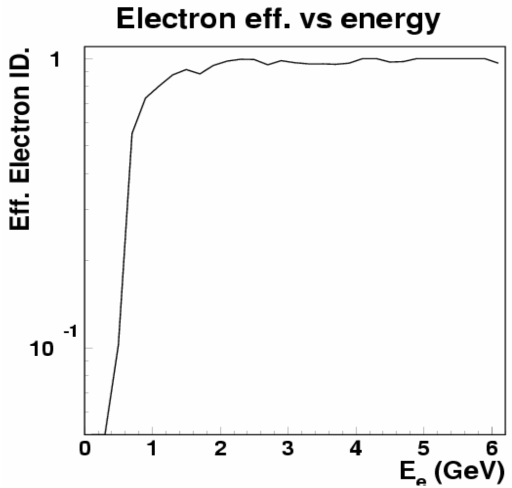
Proven technique

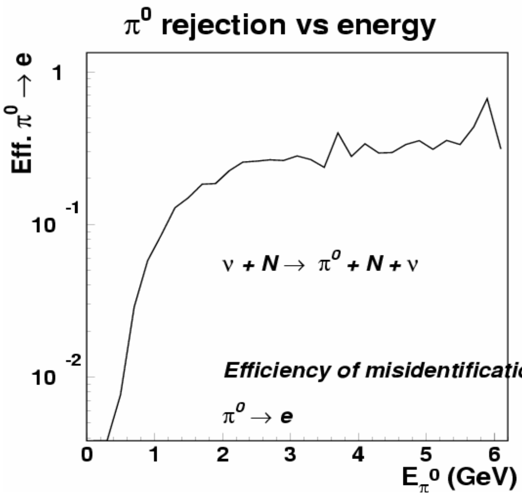
- A third generation of successful underground detectors:

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

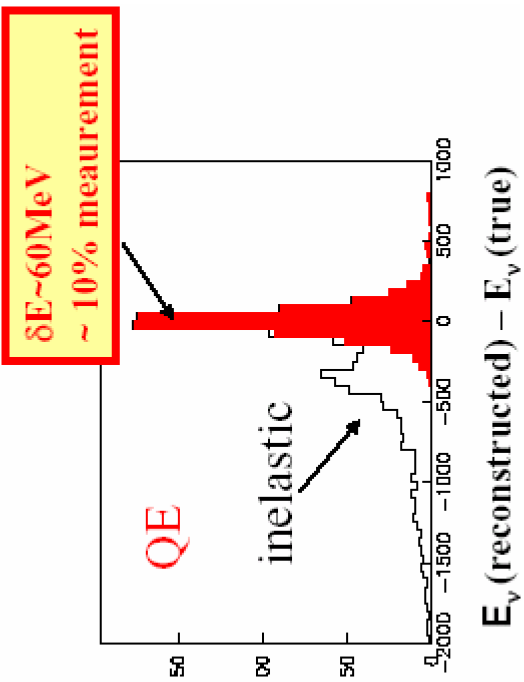


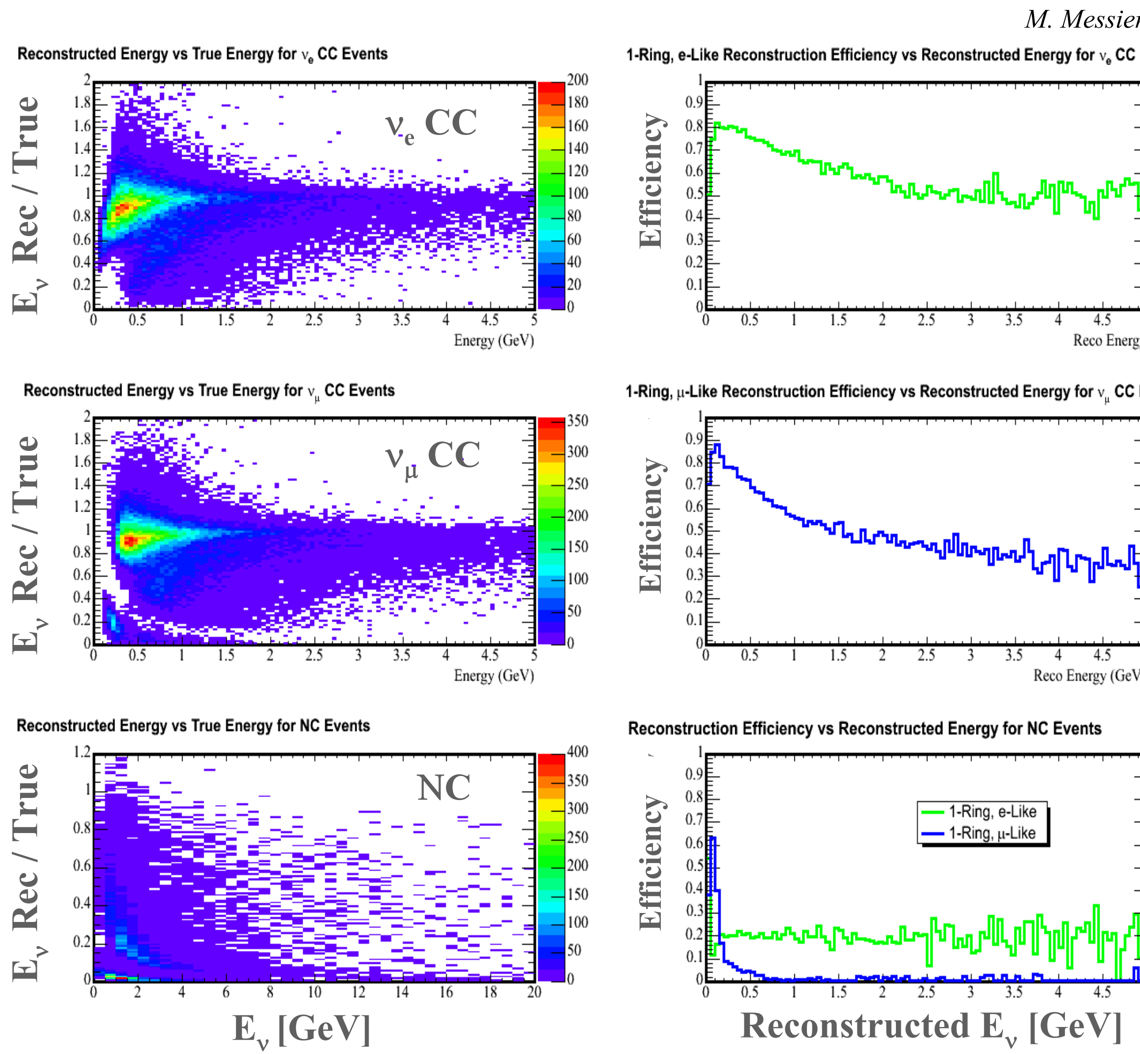


From Report BNL-69395

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

Energy resolution in Super-KamiokaNDE





E_ν reconstructed accounts for p_μ , θ_μ and, in case of DIS, for E_{had}

Geometry of next Water Čerenkov 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

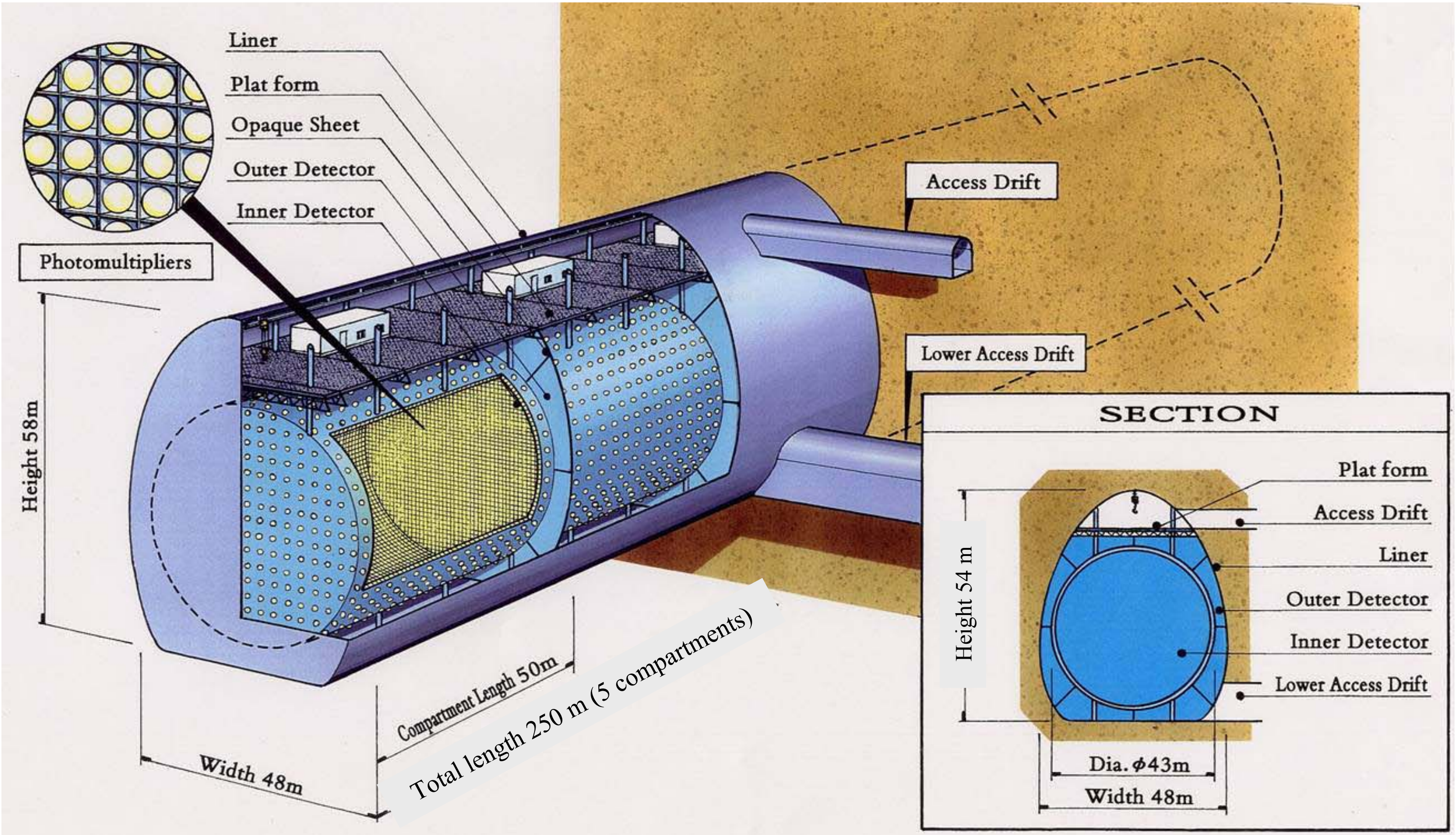
(transverse dimensions ~ 50 m)

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

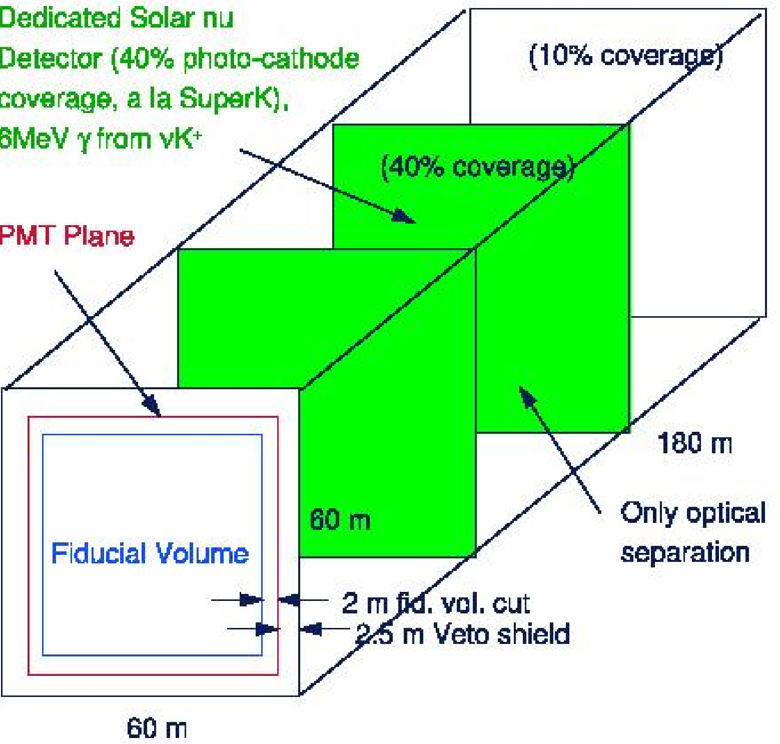
Two modules placed sideways, each with 5 compartments (50 m long)

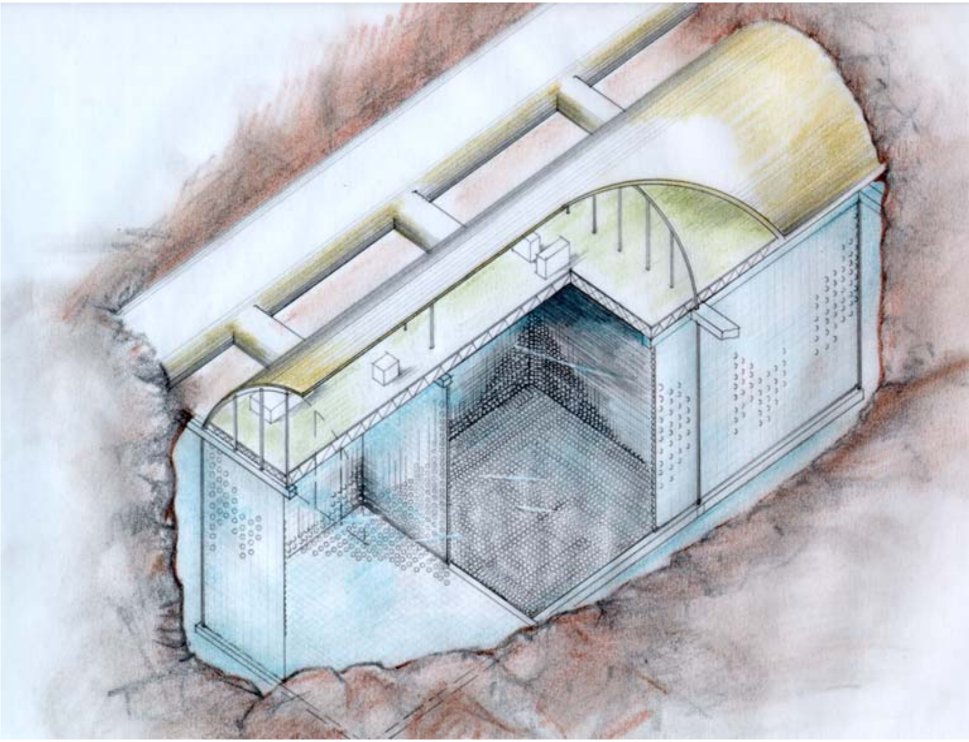
Higher cost than for a single module, but maintenance possible with one module always alive

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 <u>reduce cost</u>**
  - middle zone with high density (40% PMT coverage like Super-K) for solar ν
  - edge zones with 10% PMT coverage
  - → 10% adequate? Are different densities the optimal solution to the financial problem?
- **56,650 20" PMTs** (~ ½ 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	⅓ 40 (5 MeV threshold) ⅔ 10 (10 MeV threshold)
PMTs	**11,146** (20")	**200,000** (20")	**56,650** (20") 15,000 (8")

A large fraction (~ ½ 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 Čerenkov:**
  - better energy containment
  - larger "effective" granularity of photo-sensors (due to larger average distance from event vertex)

Main issues

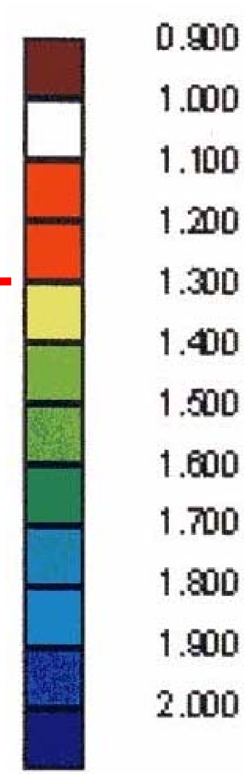
- Design of a large cavern
- R&D on photo-sensors, in strong collaboration with industry*, to improve:
  - cost
  - production rate: affects construction time, storage problems have to be faced
  - performance

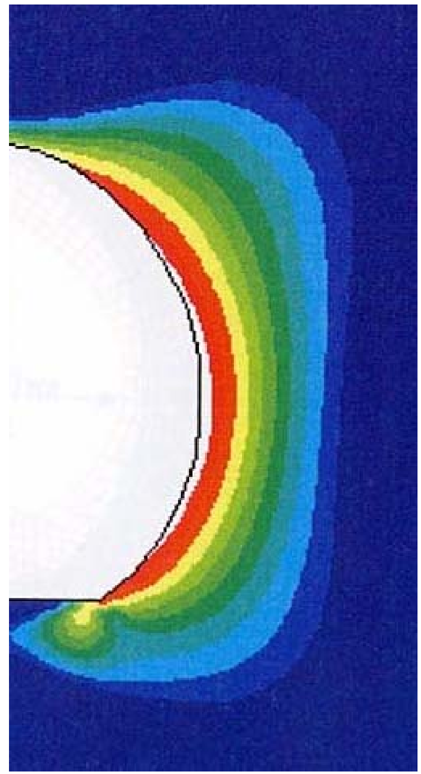
Development of 20" PMTs is at the basis of the success of KamiokaNDE and Super-KamiokaNDE

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

Safety factor

Regions with safety factor < 1.3 need supports (rock bolts or wires)





Pressure hor/vert = 0.45

Depth of region with safety factor < 1.3 similar to that in Super-K

Possible to excavate the Hyper-K cavity

* Insufficient depth to pursue the studies on solar neutrinos

R&D on photo-sensors for Water Čerenkov

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

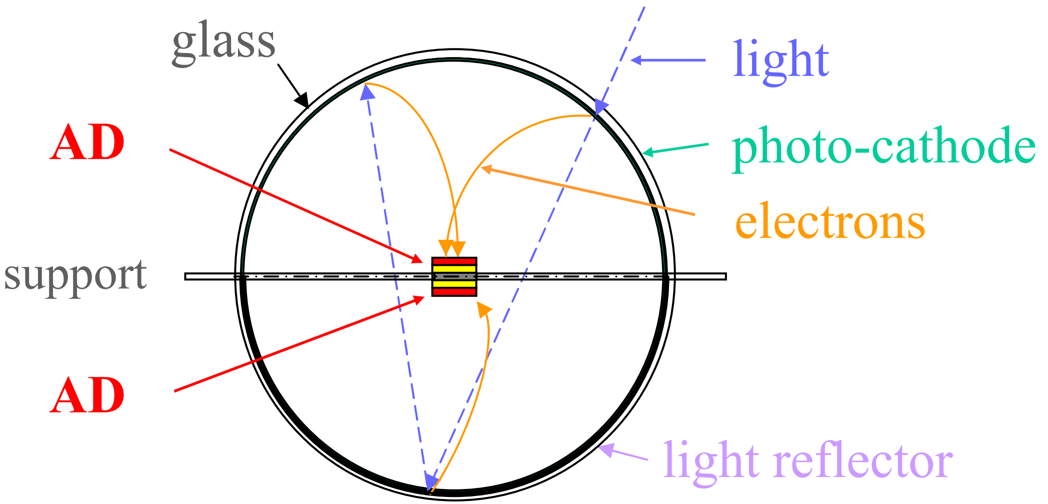
New photo-sensors

- **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

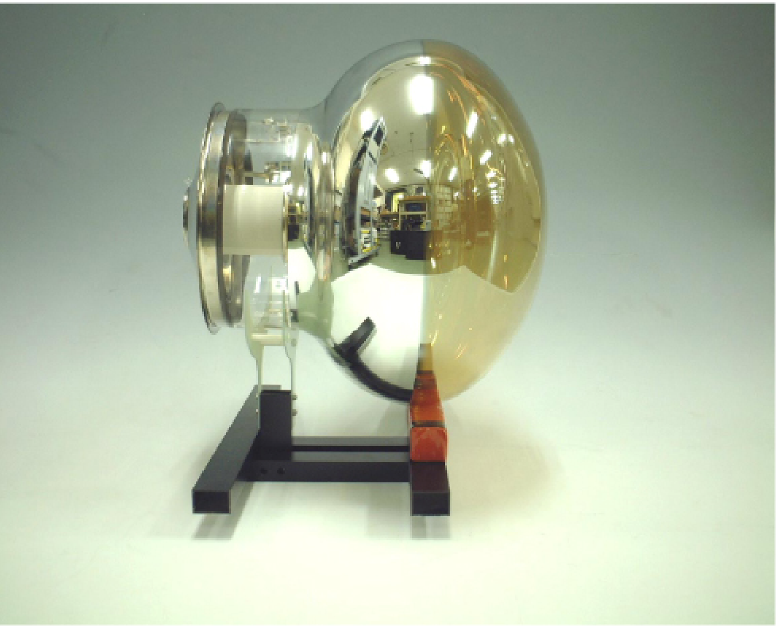
Electrons accelerated by 20 KV between photo-cathode and AD:

- 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

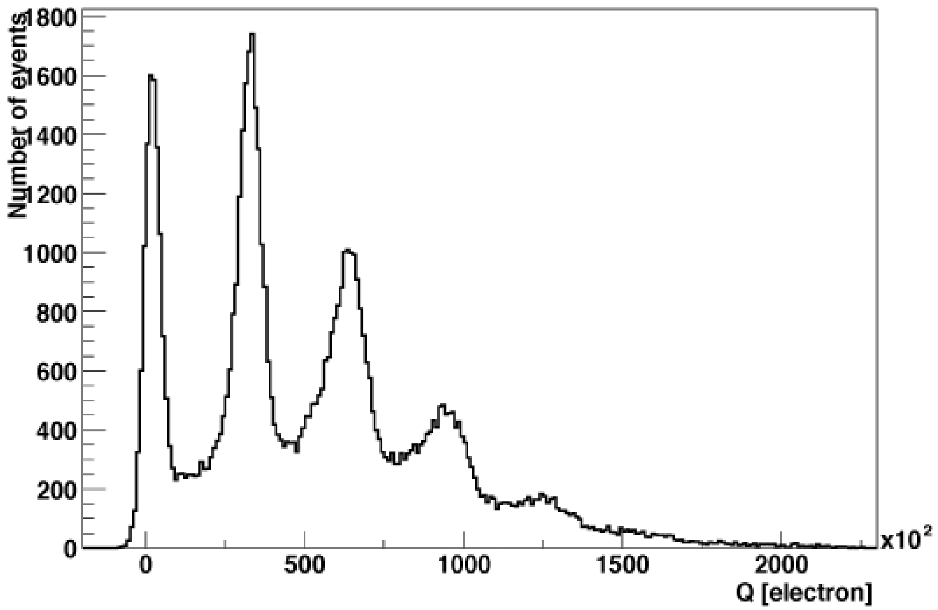
Cost reduction from use of solid state devices (AD) avoiding the complicated PMT dynode structure

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

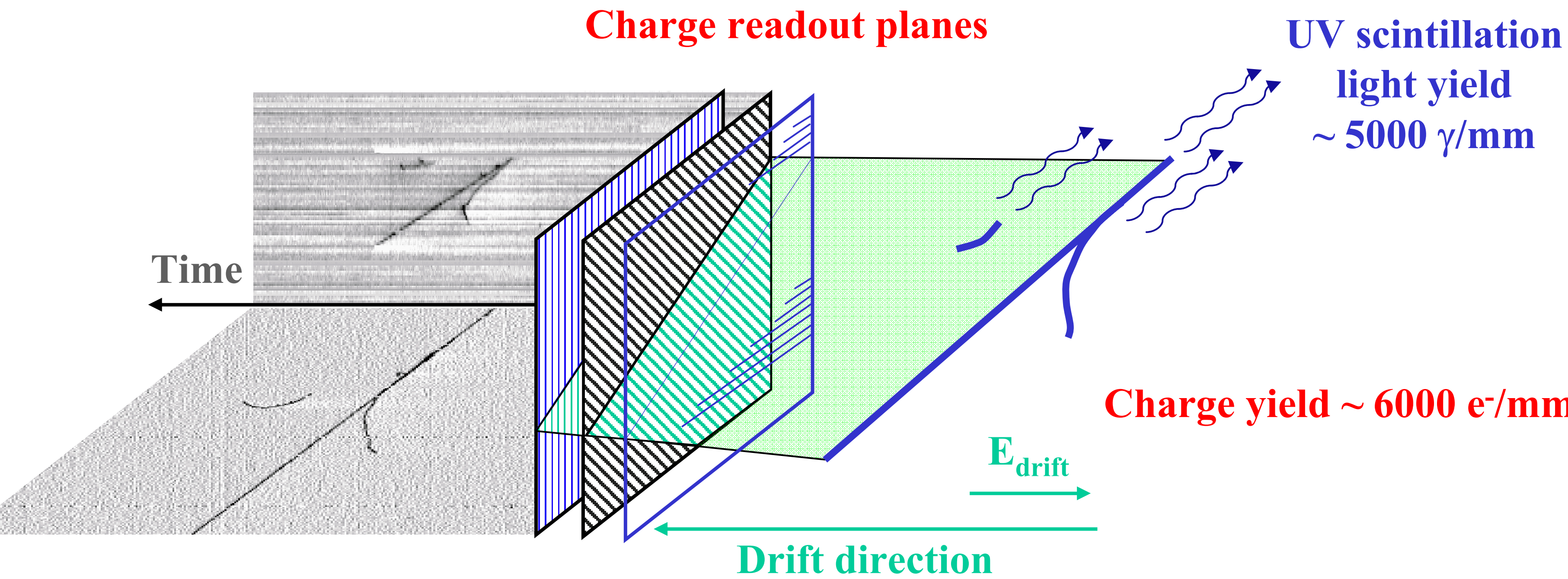
Next: design of Spherical 20" HPDs (requires higher field or development of larger AD

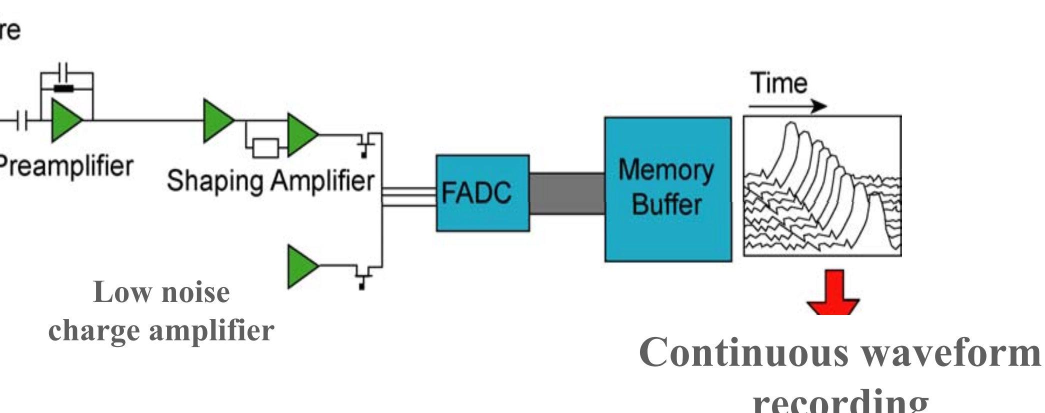
Liquid Argon Time Projection Chamber

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

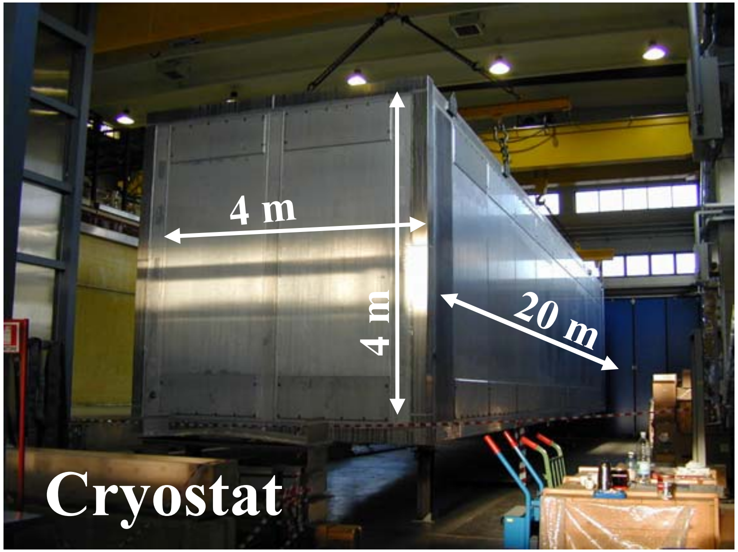
Induction and charge collection readout

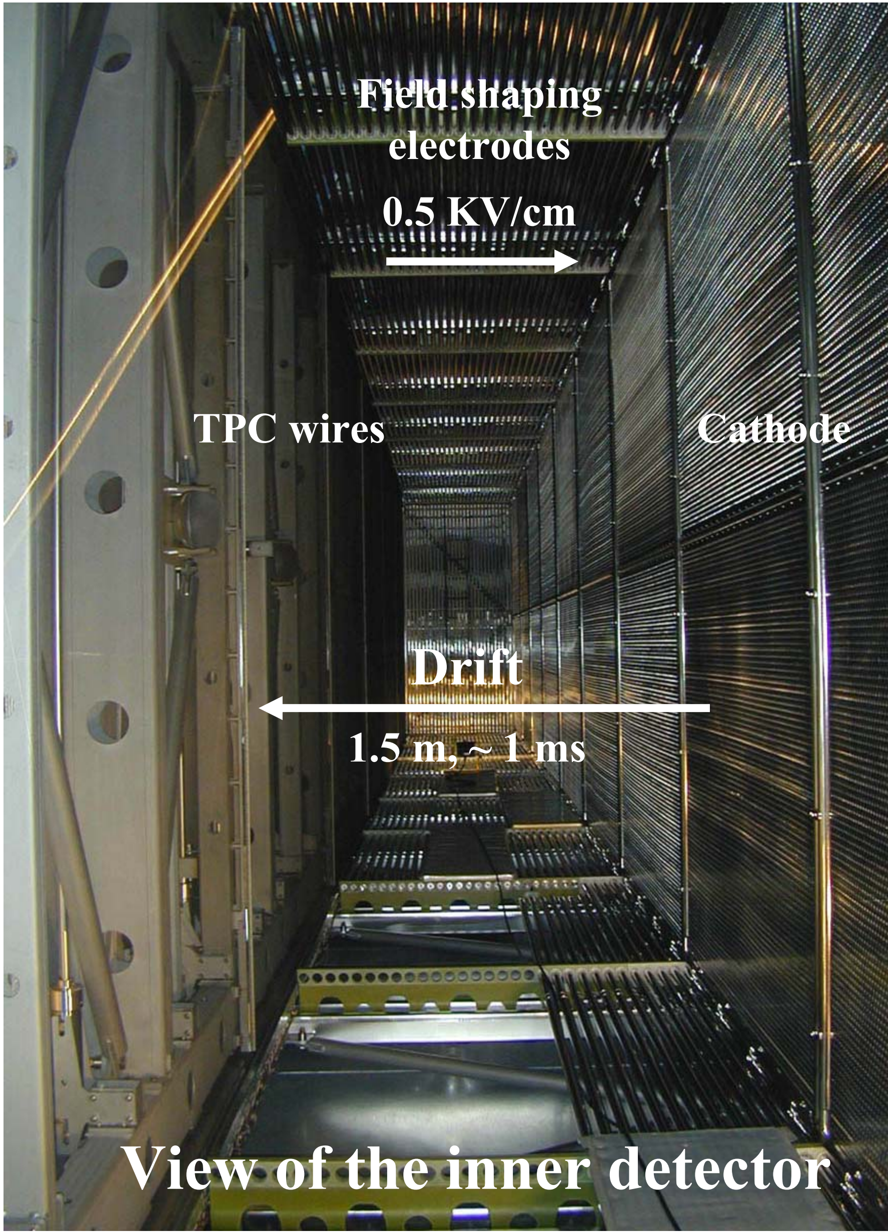
Continuously sensitive

Self-triggering

t_0 from scintillation

ICARUS T300 module (0.3 kton)





Tested in a ground level laboratory (Pavia)

This is the present "<u>status of the art</u>"

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

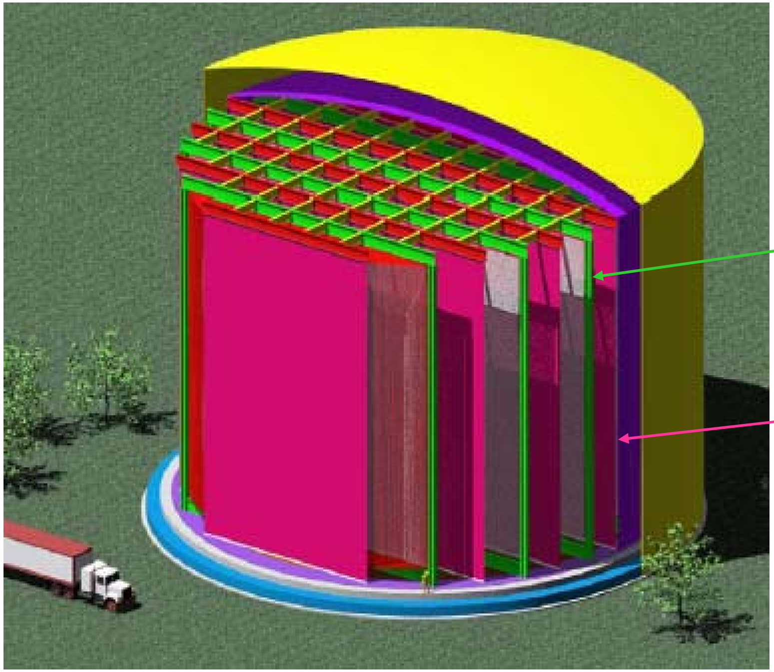
Two approaches:

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

In both cases, the signal attenuation imposes a high LAr purity (~ 0.1 ppb O_2 equiv.)

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

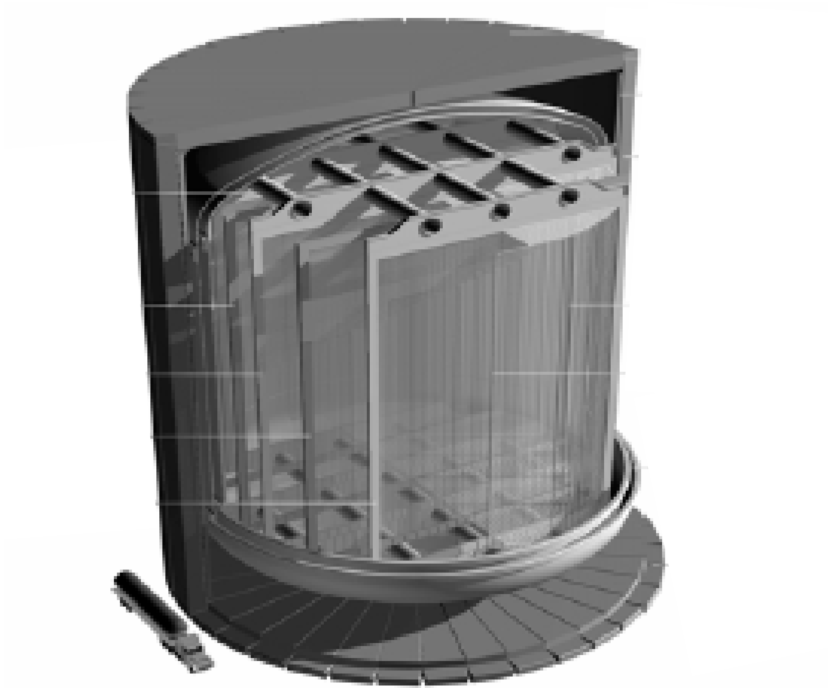
Letter of Intent, hep-ex/0408121 (2004)



- **A detector for ν oscillation**
- **Readout** as in ICARUS, with detector subdivided in readout sections
- **50 kton** : ~ $1.5x10^2$ extrapolation in mass from ICARUS T300
- **3 m max drift length** (1.5 m in ICARUS T300**)** with E = 0.5 KV/cm
- **Surface location** (operated only with ν beam)

LANNDD

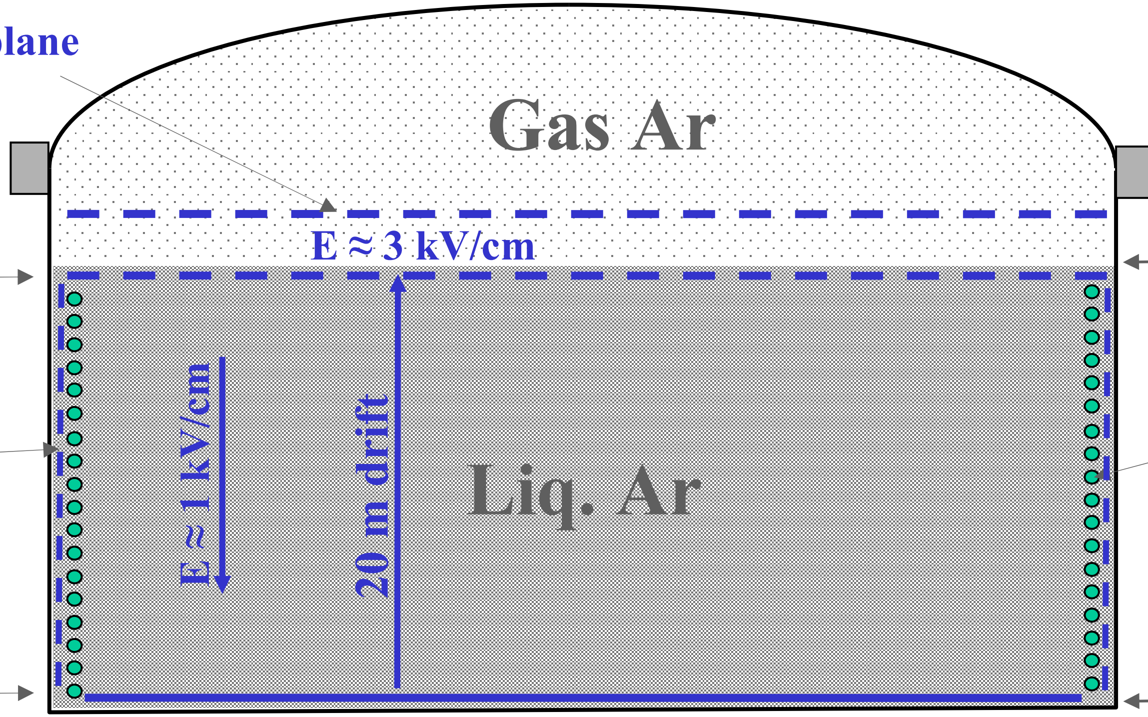
D. Cline et al., Nucl. Instr. and Meth. A503 (2003) 136



- **A detector for ν oscillation,**
  as well as for ν astrophysics and proton decay (if located underground)
- **Readout** as in ICARUS, with detector subdivided in readout sections
- **50-100 kton** : 1.5- 3 x 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 ν oscillation, ν astrophysics, proton decay

A single cryogenic <u>and</u> readout module

<u>20 m</u> max drift length, <u>10 ms</u> drift time with as much as **<u>1 KV/cm</u>** (0.5 in ICARUS T300

Liquid Ar at boiling temperature, as for transportation and storage of Liquefied Natural Ga

(gas exhaust to be provided; feature not foreseen for ICARUS)

3×10^2 extrapolation in mass from ICARUS T300

Double-Phase (Liquid – Gas) readout

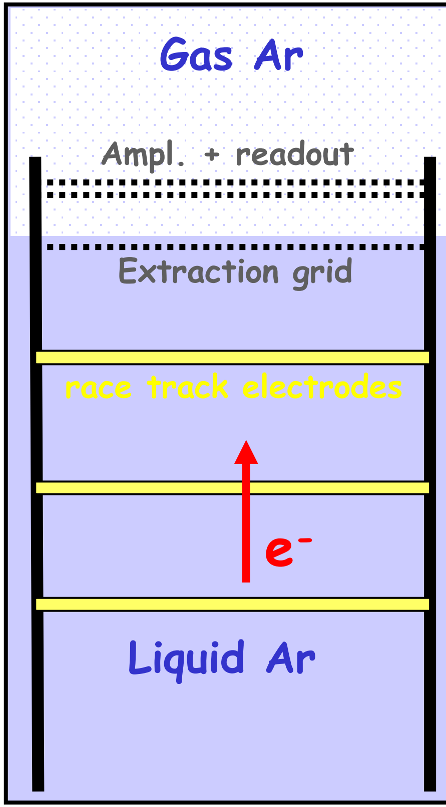
Basic references: Dolgoshein et al. (1973); Cline, ... Picchi ... et al. (2000)
Tested on the ICARUS 50 l chamber

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

With 2 ms e-lifetime, the charge attenuation in 10 ms is $e^{-t/\tau} \approx 1/150$
(original signal 6000 e^- /mm for a MIP in LAr)

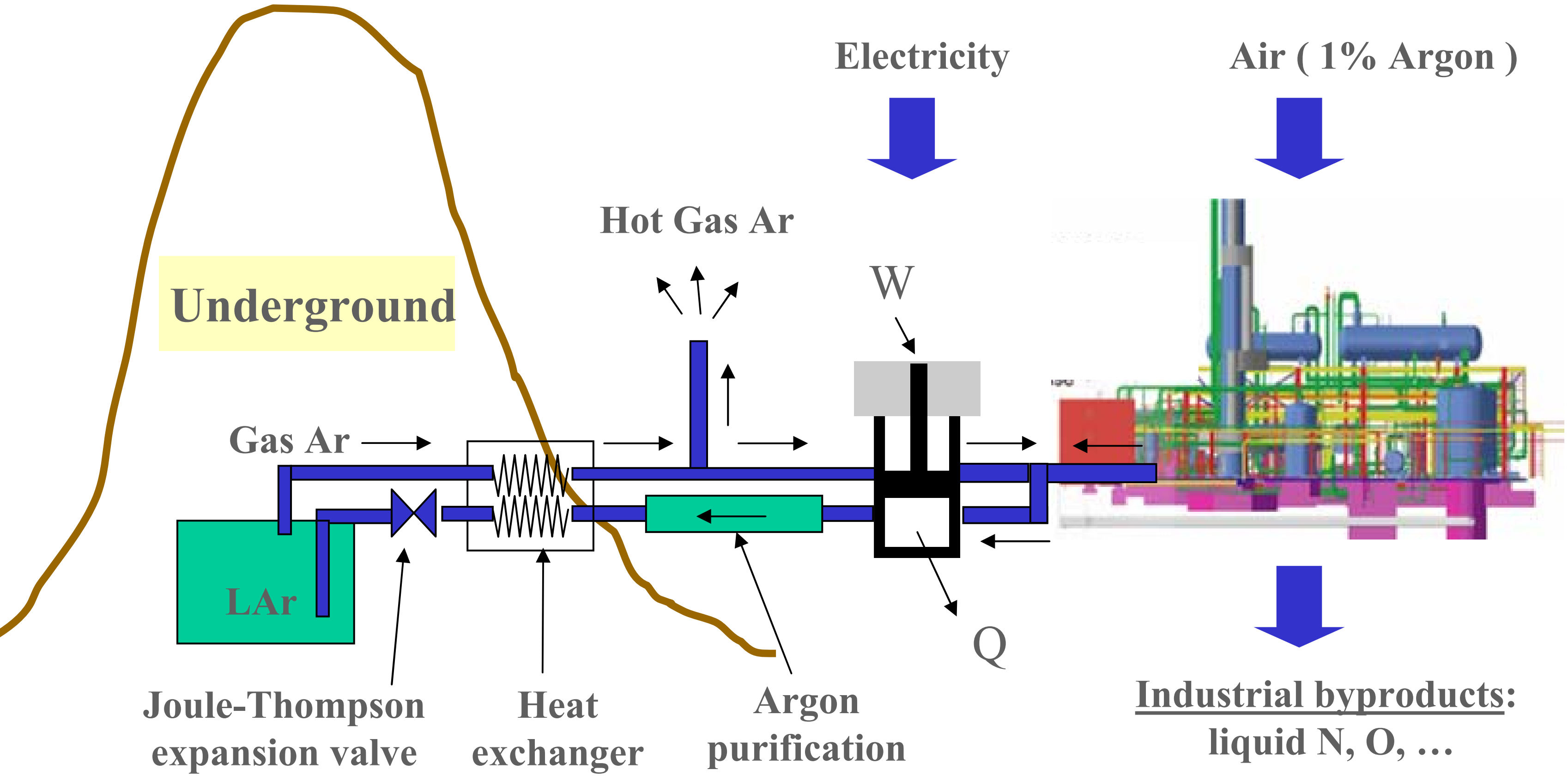
Amplification in proportional mode (x 100-1000)
on thin wires ($\phi \approx 30\ \mu m$) with pad readout or .....

Diffusion after 20 m drift → $\sigma \approx$ <u>3 mm</u> :
gives a limit to the practical readout granularity



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/m² heat input → 30 ton/day needed
- Continuous re-circulation (purity)

Ongoing studies and initial R&D strategy

(A. Rubbia)

- **Electron drift under high pressure** (p ~ 3 atm at the bottom of the tank)
- **Charge extraction, amplification and imaging devices**
- **Cryostat design, in collaboration with industry**
- **Logistics, infrastructure and safety issues**
  (in part. 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

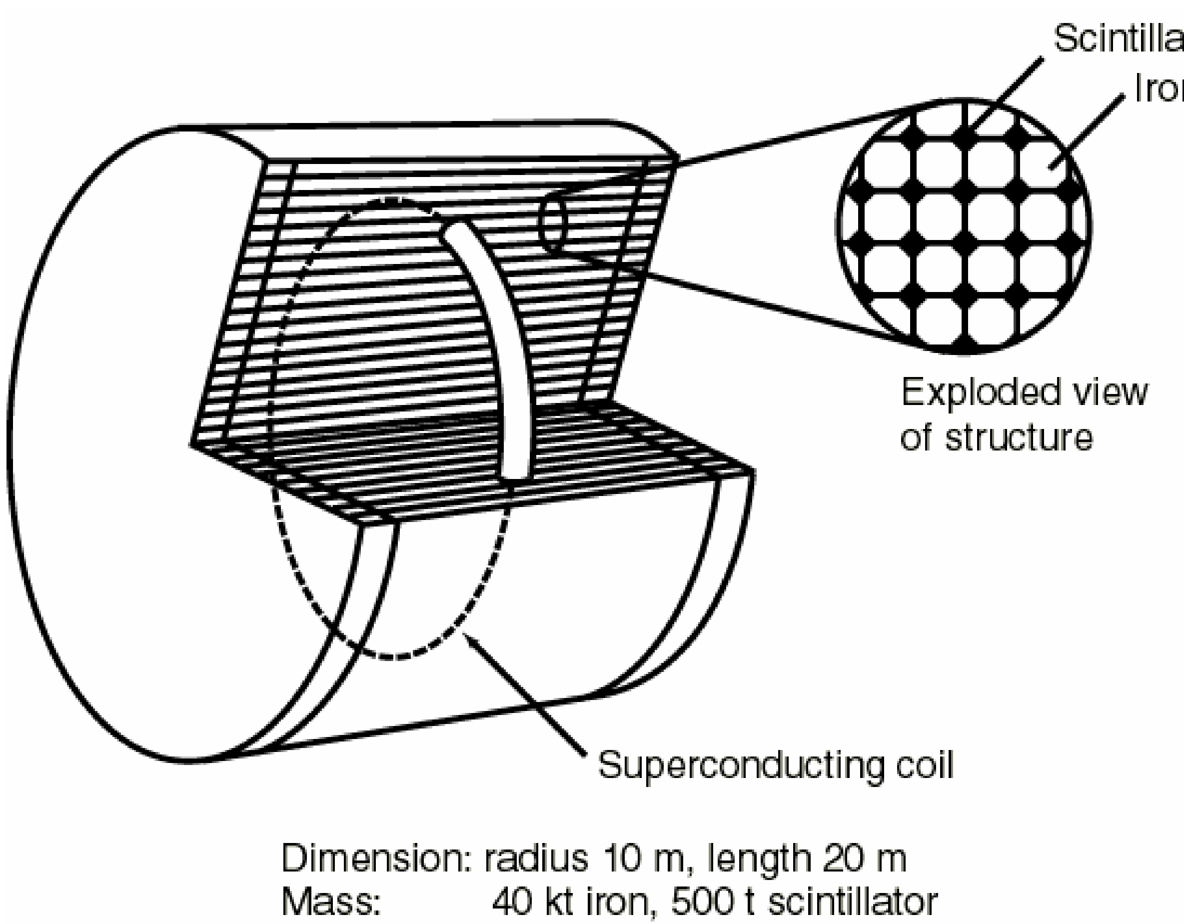
A Magnetised Iron Detector for a ν Factory

Iron calorimeter,
plastic scintillator rods as active detector

Magnetised at B = 1 T
→ see "wrong sign" muons from ν_e-ν_μ

Conventional technique, but <u>40 kton mass one order of magnitude > MINOS</u>

<u>Only concept presented</u>: practical problems (mechanics, magnet design, ….) must be addressed to assess the feasibility



Another possible design:
a dipole magnet equipped with RPCs, à la MONOLITH

The Emulsion Cloud Chamber (ECC)
for $\nu_e \to \nu_\tau$ appearance at ν Factories

$\nu_e \to \nu_\mu$ (golden events) and $\nu_e \to \nu_\tau$ (silver events) to resolve θ_{13} - δ ambiguities

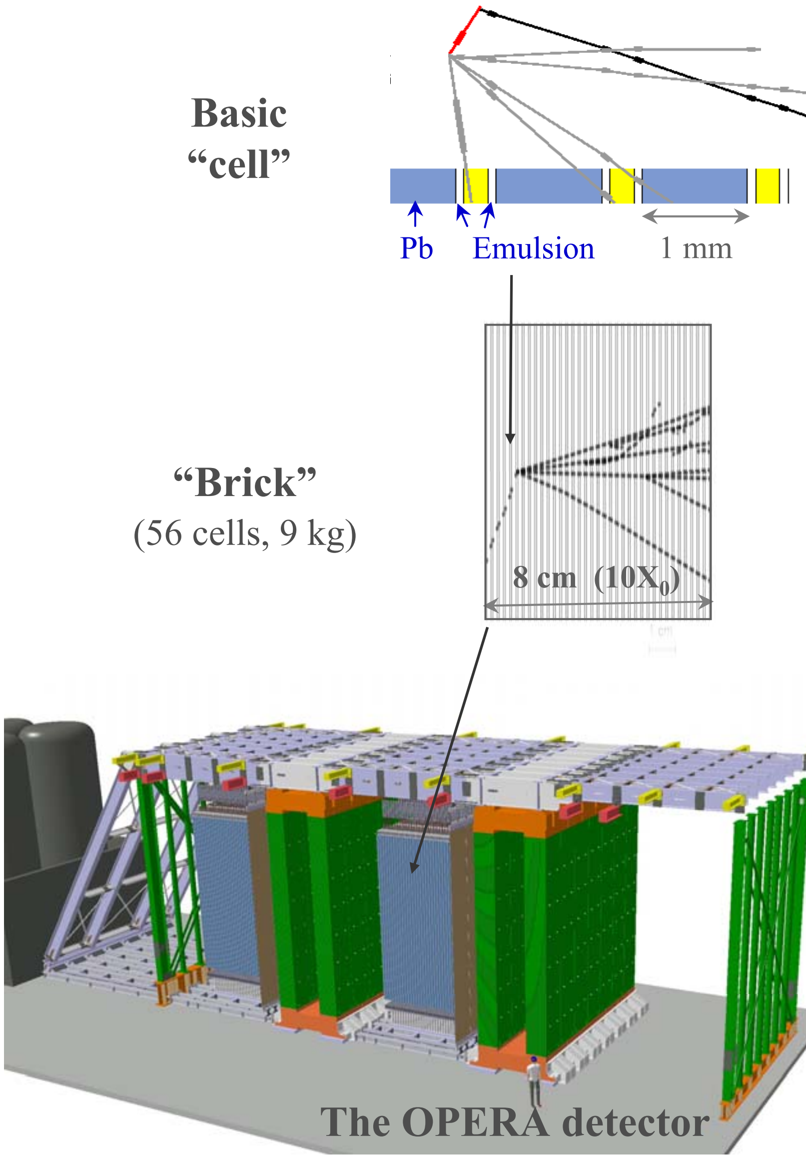
Pb as passive material,
emulsion as sub-μm precision tracker:
unique to observe τ production and decay

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 is a "milestone" for the technique



Summary (1)

Low-Z Calorimetry

- ν_μ- ν_e oscillations $\rightarrow$ θ_{13} in off-axis NuMI beam: **NOνA**
- Evolution of a proven technique
- NOνA mass ~ 10 x MINOS
- New technologies with respect to MINOS

  plastic $\rightarrow$ liquid scintillator (sampling or totally active detector)

  PMTs $\rightarrow$ Avalanche Photo Diodes (APD)
- Main issue: improve performance and reduce cost of trackers

Summary (2)

Water Čerenkov

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 ~ x10

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 $\nu_e \rightarrow \nu_\mu$ oscillations at ν-Factories
- Technique proven at smaller scale
- Target mass ~ 10 x MINOS
- Proceed from concept to conceptual design

Emulsion Cloud Chamber (ECC)

- $\nu_e \rightarrow \nu_\tau$ at ν-Factories, to complement $\nu_e \rightarrow \nu_\mu$ 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 ν masses & mixing, ν 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 <u>and</u> far ahead
  - Stimulate new ideas