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NUFACT04

Neutrino detectors

for Super-Beams, β-Beams and ν Factories

Low-Z Tracking Calorimeter
Water Čerenkov
Liquid Argon TPC
Magnetised Iron Calorimeter
Emulsion Cloud Chamber

For each technique:

main issues on
R&D
and detector design

Physics potential:

see specific talks
(also depends on beam)

Main detector tasks

- **Lepton identification → identify ν flavour**

- **Measure ν energy**
  - For Quasi-Elastics ($\nu_l N \rightarrow l\ N'$)
    Lepton energy → ν energy
    with corrections due to Fermi motion in nucleus and to quark binding in nucleon
  - For DIS ($\nu_l N \rightarrow l\ X$):
    measure energy of lepton <u>and</u> of X

- **Measure muon charge (by magnetic field)**

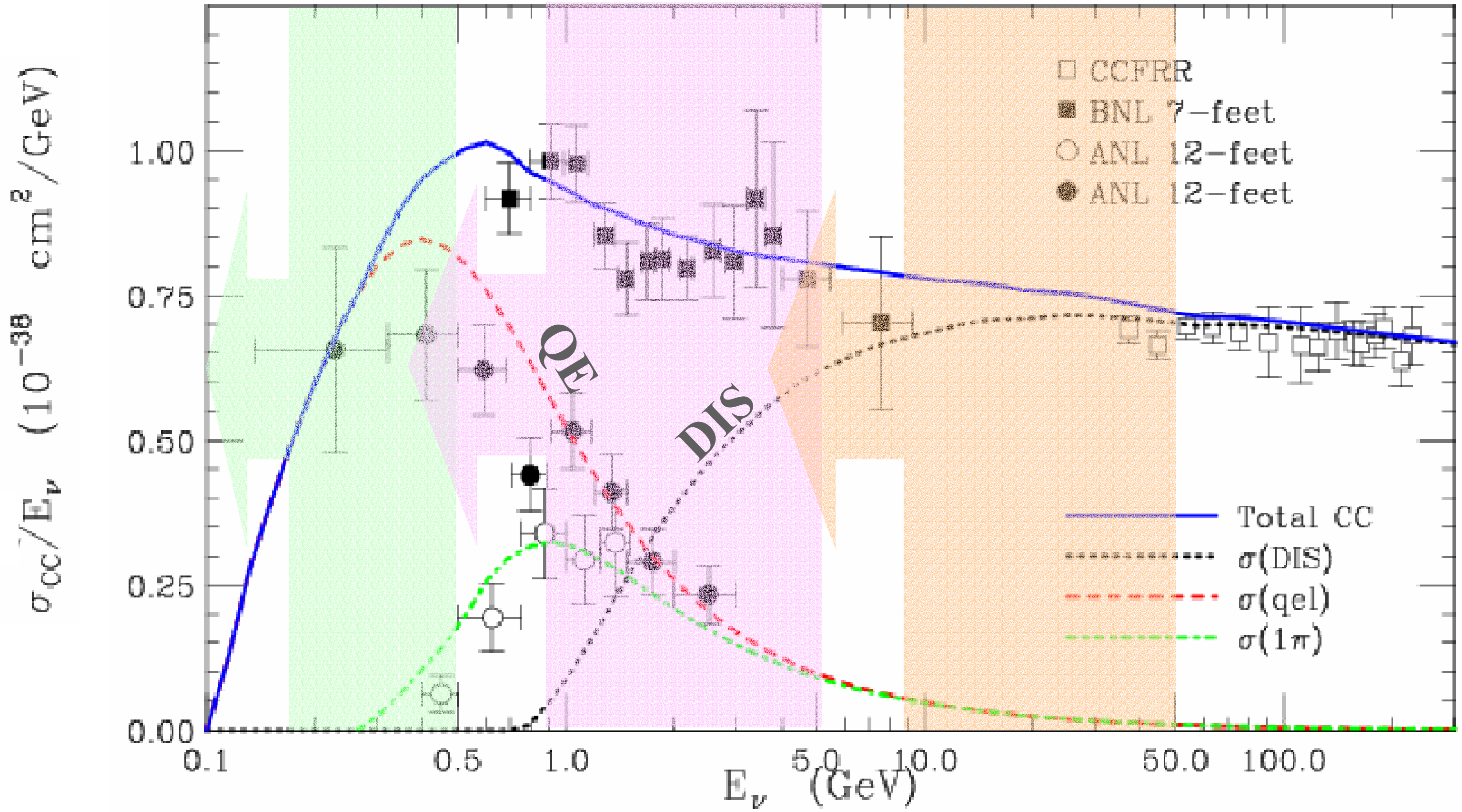
  required at ν-Factories → flavour of initial lepton (ν_e-ν_μ oscillation or $\bar{\nu}_\mu$?)

- **Provide adequate target mass**

  50 kton – 1 Mton
  depending on physics aims (θ_{13} , mass hierarchy, δ), exp. technique and beam

ν energy ranges
and related dominant reactions (event topologies)

P. Lipari, Nucl. Phys. Proc. Suppl. 112, 274 (2002) (NuInt01)



β-beam* **Super-beams** **ν–Factory**

*) $E_\nu <\sim 10$ GeV if the radioactive ions are stored at LHC energy ($\gamma \sim 1000$)

Envisaged baselines: *130 - 3000 km*

(not discussed in this talk on detectors)

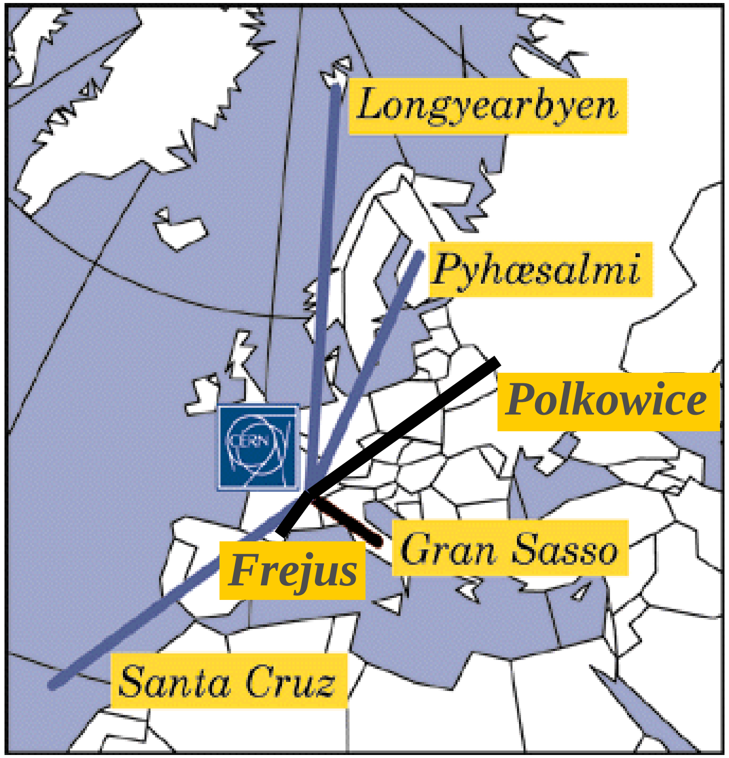
Complexity of choice

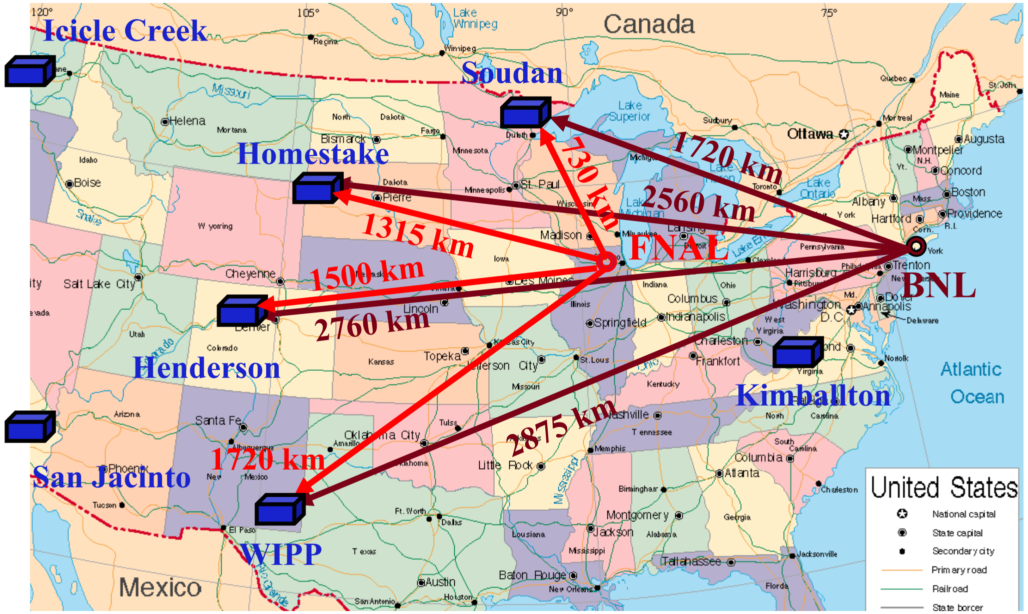
L/E , matter effects, E

↕

Detector design

Sensitivity to θ_{13} , mass hierarchy, δ





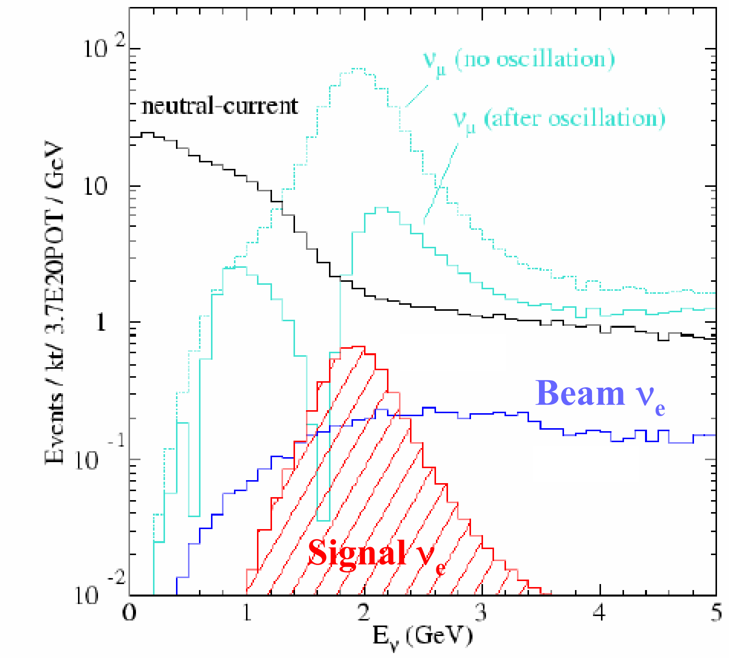
Low-Z Tracking Calorimeter

A detector specialised for ν_μ-ν_e oscillations

Main backgrounds and tools for their reduction

- **Beam ν_e**
  → $\Delta E/E$ combined with off-axis NBB

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



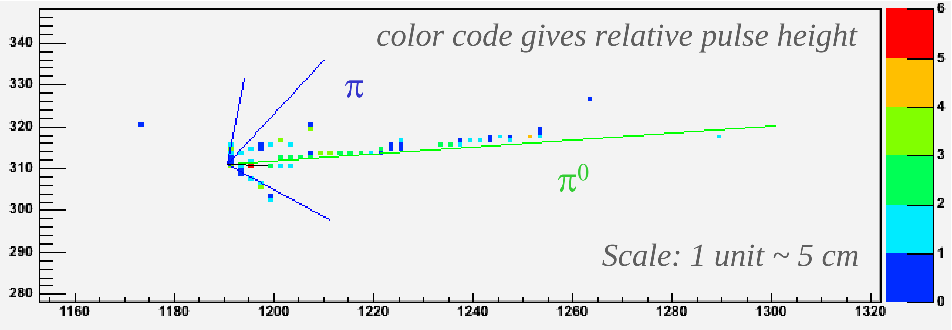
Neutrino spectra at NuMI off-axis

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 π
(one projection)

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* 2.4 kton transition radiation detector proposed for CNGS

Main lines of NOνA design

(Proposal P929 submitted on March 2004)

Evolution of proven experimental techniques

Low Z, short 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 wrt MINOS

- Two detector options
  - Baseline design: 0.3 X_0 sampling
  - Totally Active liquid scintillator Detector (TASD)

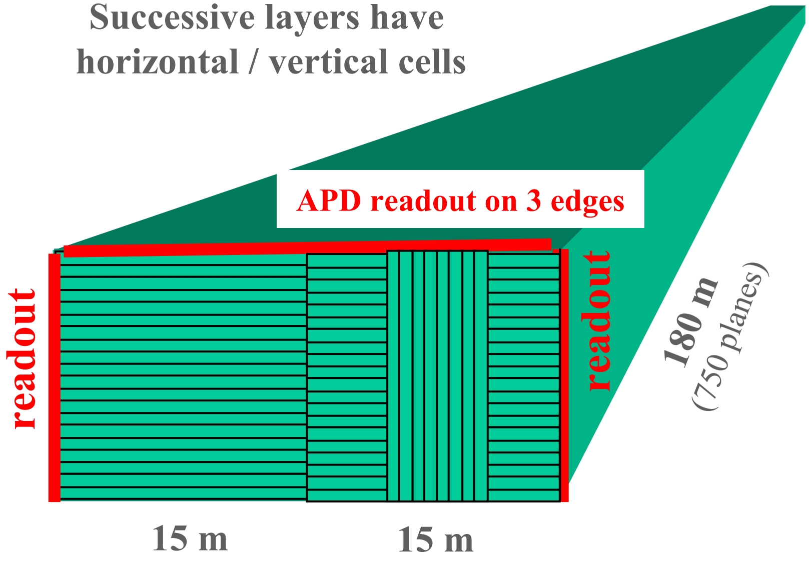
  (RPC as active detector option has been studied: two-dim. readout but no dE/dx)
- No need of underground location (live-time ~100 s/year)
  Active shielding from cosmic rays foreseen (cheaper than passive overburden)

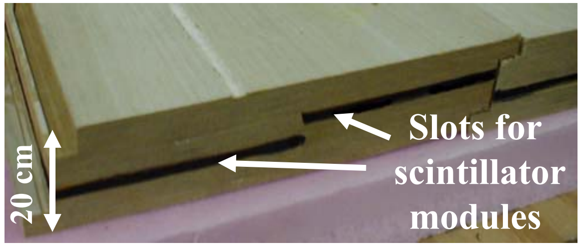
Baseline Design

50 kton (7 kton scintillator, 0.3 X_0 sampling)

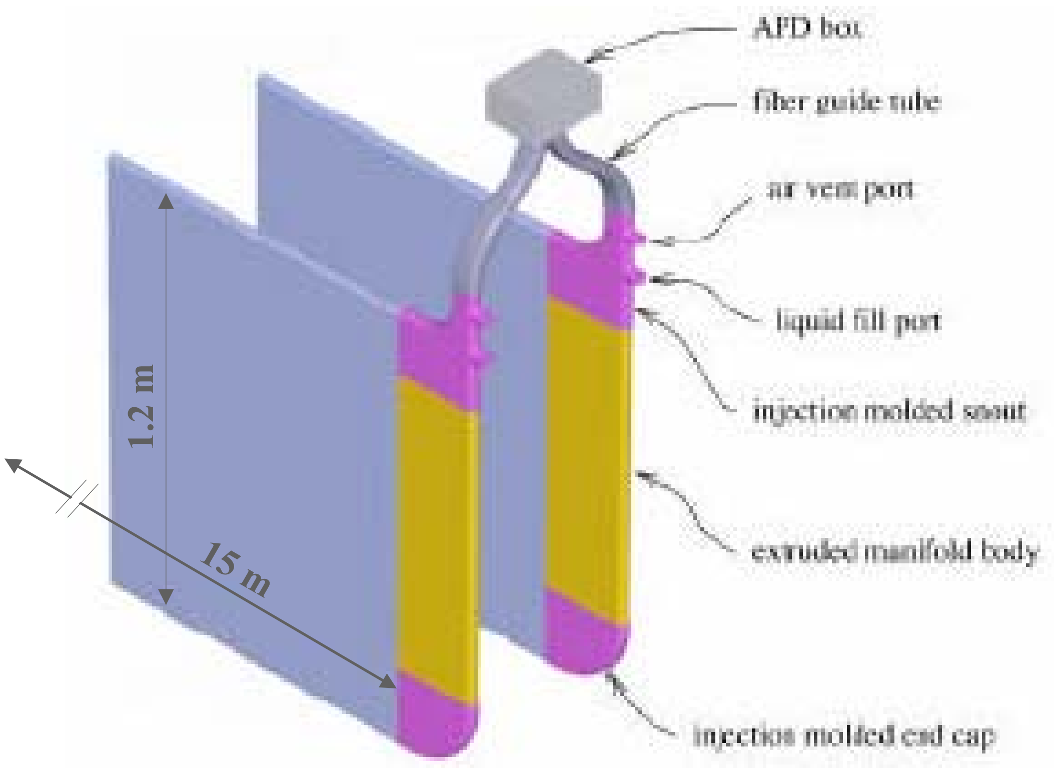
View of the detector

Successive layers have
horizontal / vertical cells



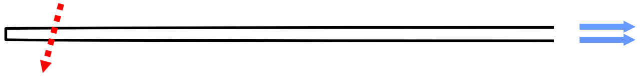


Particle-board as passive material
(provides also the support structure)



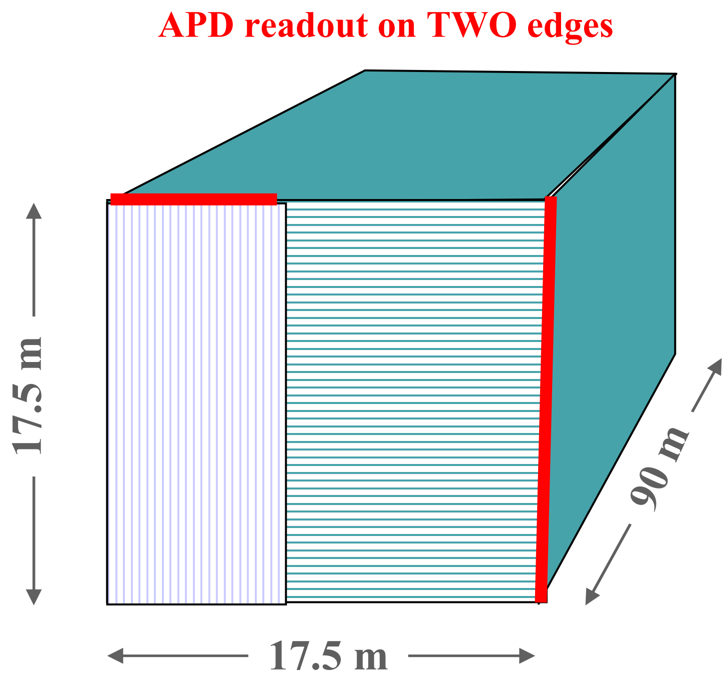
Liquid scintillator modules

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



Totally Active liquid Scintillator Detector (TASD)

25 kton (21 kton scintillator)



The detector is wider and taller than the baseline detector but 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

↓

see next slide

Baseline design (0.3 X_0 sampling) → TASD

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

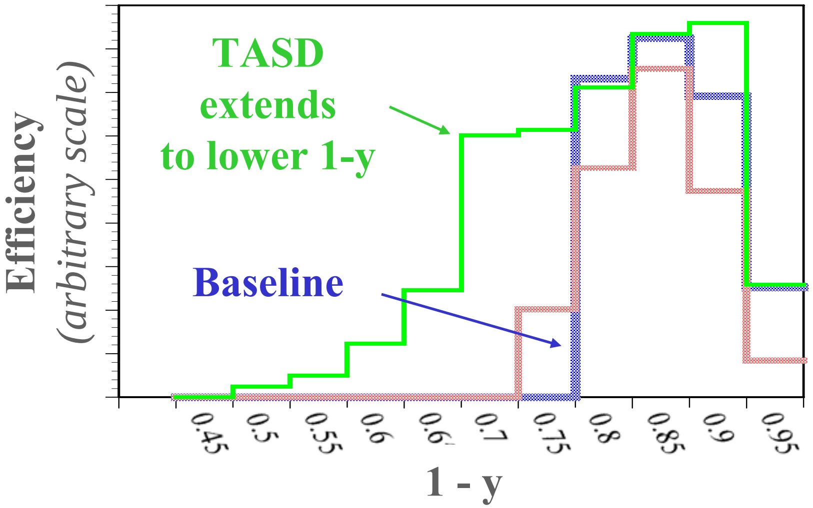
- TASD has
  ~ 4 times as many hits / unit track length
  - 2.5cm liquid + 17.8 cm particle-board
    → 4.5cm liquid + 0.4cm PVC
  - pulse height information in every sample
    (favours e/π^0)

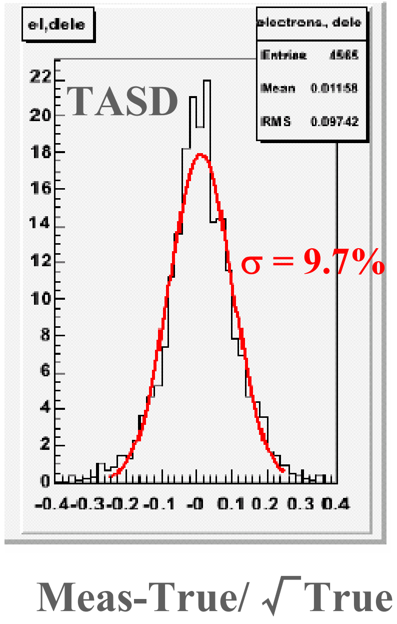
- TASD has better energy resolution

  For e^- $\Delta E/E = 15\,\%/\sqrt{E}$ → $10\,\%/\sqrt{E}$

  (23% /√E with RPCs)

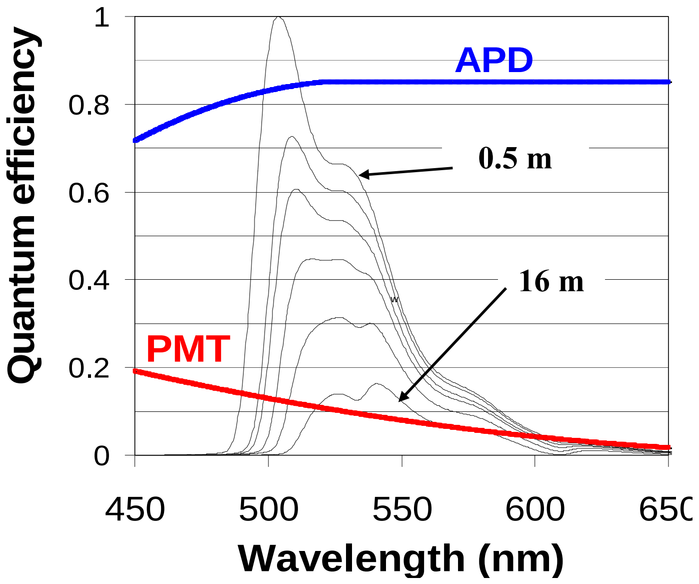
- About the same cost and time scale
  (detector completed in late 2011 if funding begins in late > 2006)



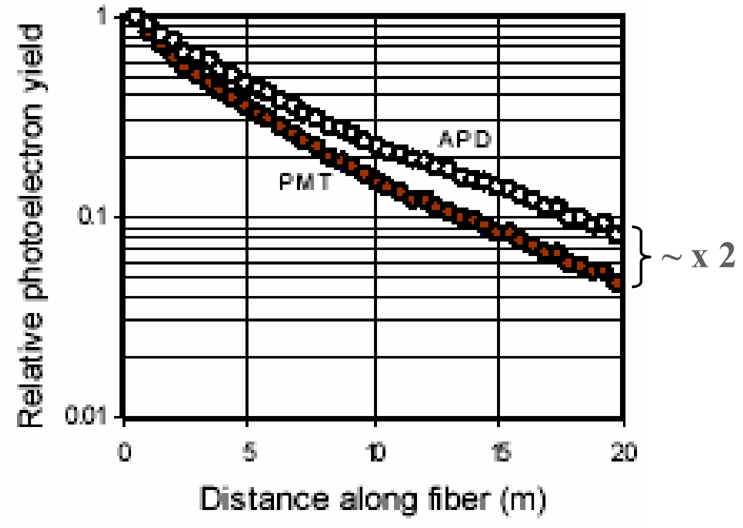


Avalanche Photo Diodes (APD)

- 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)
- Spectral shift at far-end improves the relative yield
- 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

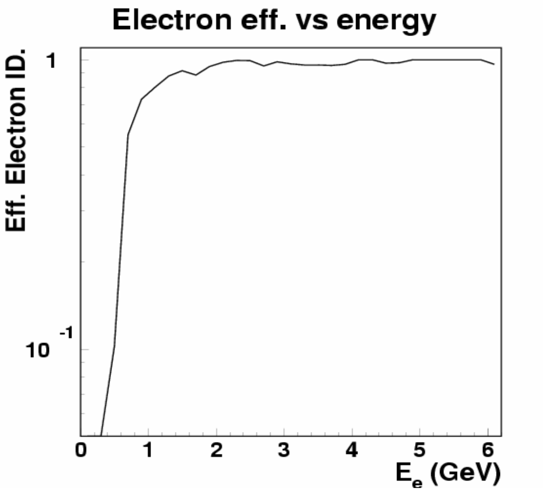
- **Sensitivity to low energy** (if PM density is adequate)
  → ν oscillation, ν astrophysics, proton decay

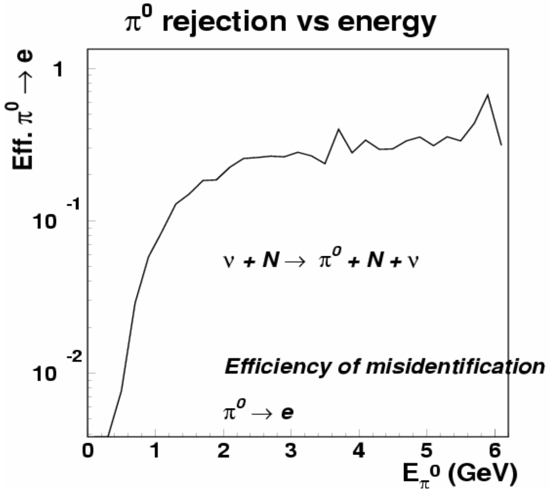
- **Difficulties at high energy**
  - Frequent multi-ring events, DIS dominates
  - e/π^0 separation: ~ 30 % π^0 mis-identification above a few GeV (because of $\gamma\gamma$ collimation)
  - Hence not suitable at ν-Factory (where, moreover, the muon charge measurement would be needed)

- **Proven technique**
  - A third generation of successful underground detectors:

    IMB / Kam → Super-Kam → Hyper-Kam / UNO

    In each generation **one** order of magnitude increase in mass
  - Performance as well as limitations known from SK and K2K, extrapolated by MC

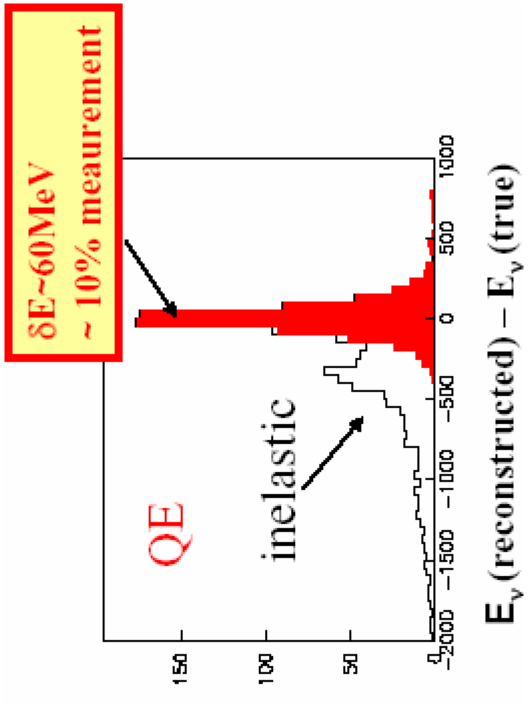




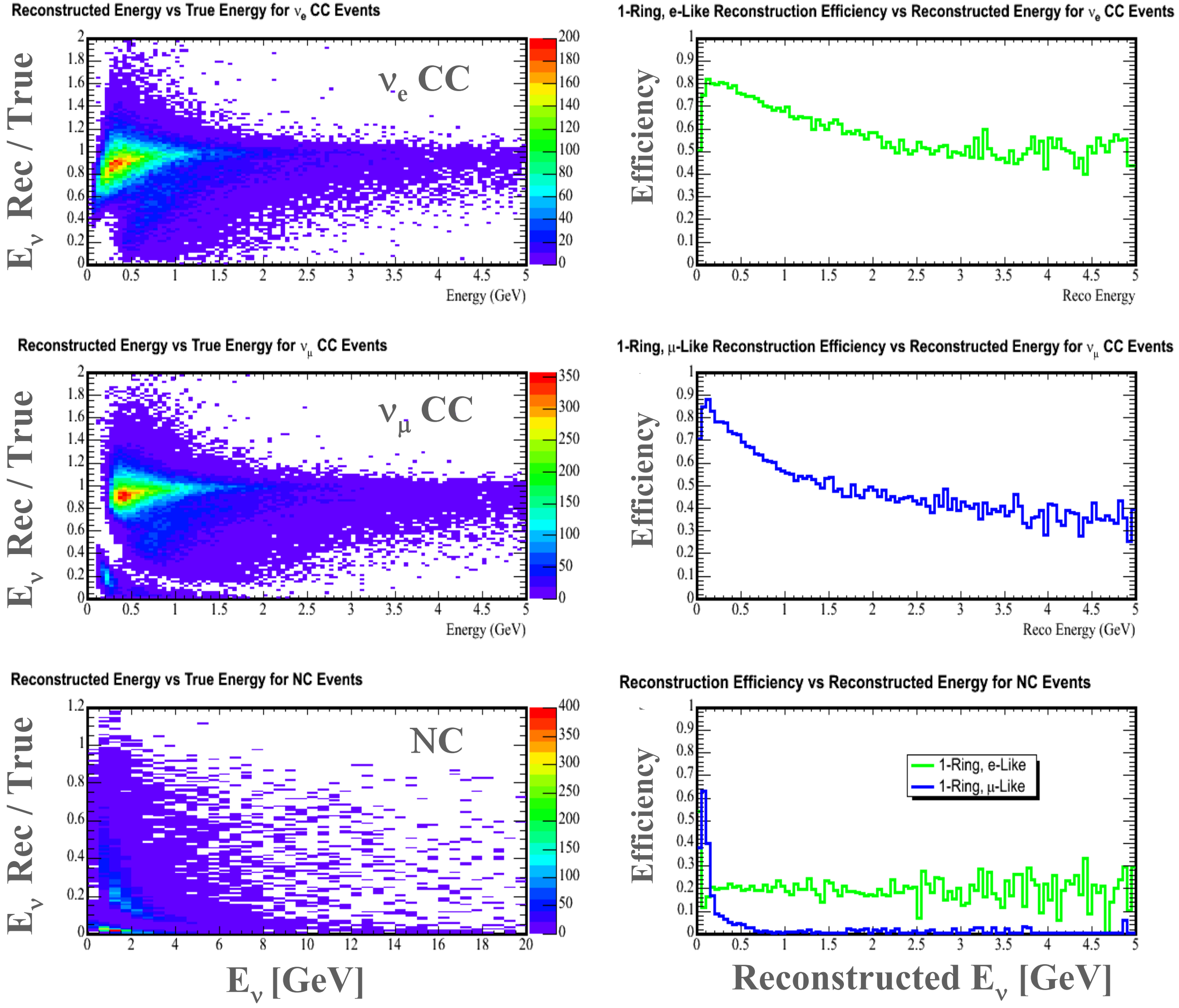
From Report BNL-69395

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

Energy resolution in Super-Kamiokande



M. Messier



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
- Cavern should have rounded edges, to reduce rock stresses

⬇

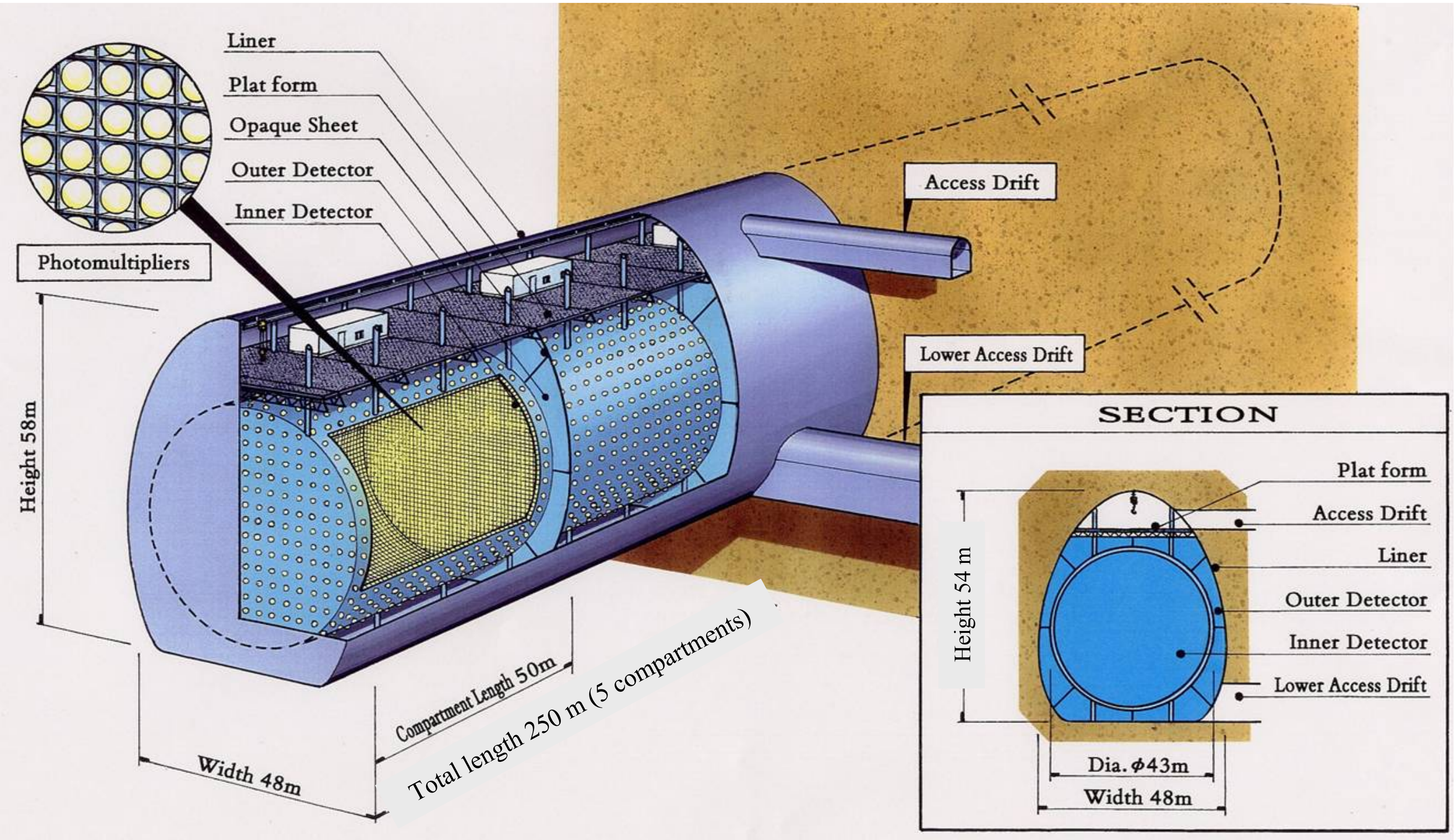
Elongated shape

(transverse dimensions ~ 60 m)

Segmentation

- ➢ reduction of backgrounds from PMT discharges
- ➢ increased operational live-time due to independent module calibration (and maintenance, in case of complete separation)

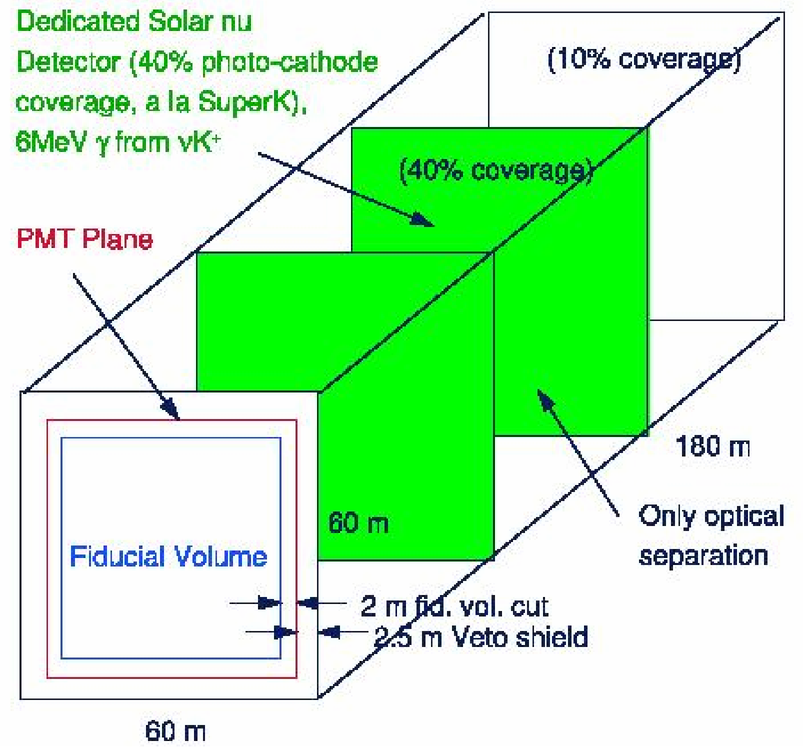
Hyper-Kamiokande

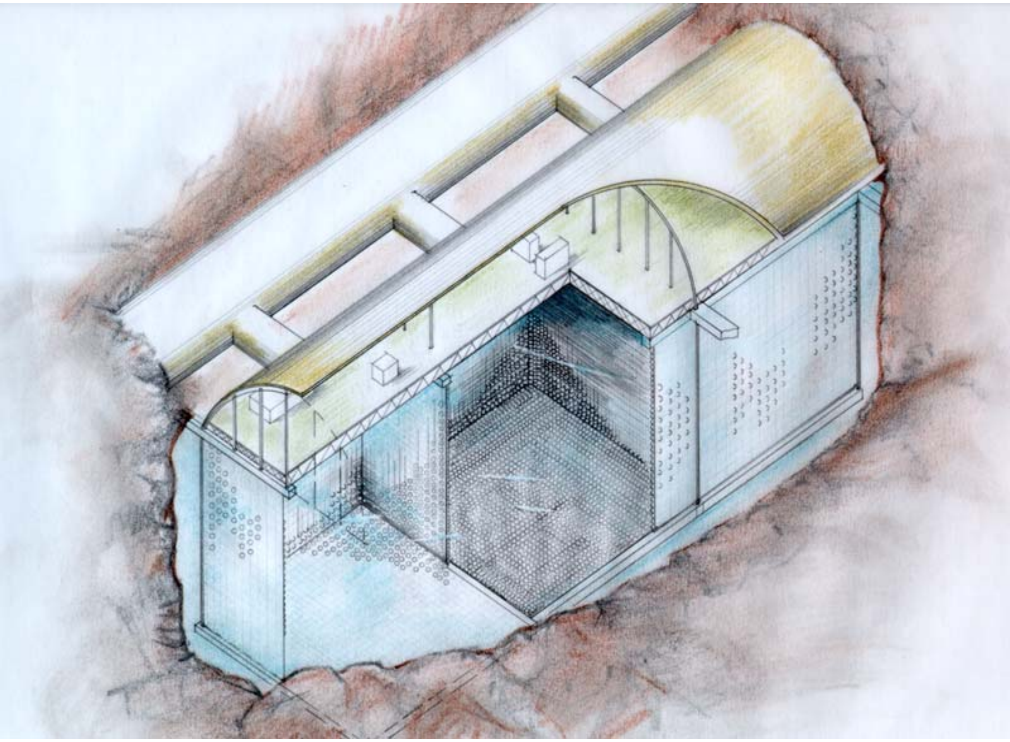


One of the two 500 kton modules

- 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, t_0 wished after a fee years of operation of T2K

UNO





- **Total (fiducial) mass 650 (445) kton**
- **Three zones with different photo-sensor density, to <u>reduce cost</u>**
  - middle zone high density (40% PMT coverage like Super-K) for N decay and solar ν
  - edge zones with 10% PMT coverage: suitable for atmospheric and beam ν
- **56,650 20” PMTs** (~ ½ wrt to full 40% coverage); **15,000 8” PMTs**

Comparison to Super-Kamiokande

	S-K	**Hyper-K**	**UNO**
Total mass [kt]	50	2 x 500	650
Fiducial mass [kt]	22.5	2 x 270	440
Fiducial mass (solar ν) [kt]	22.5	2 x 270	145
Size [m^3]	Φ 41 m x 39 m	2 x Φ 43 m x 250 m	60 m x 60 m x 180 m
photocathode 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

Increasing the mass …

- **Champagne**:
  taste improves from Standard to "Magnum" to "Jeroboam" bottles
  (lower surface/volume)

- **Water Čerenkov:**
  - better energy containment
  - larger "effective" granularity of photo-sensors
    (due to larger average distance from event vertex)

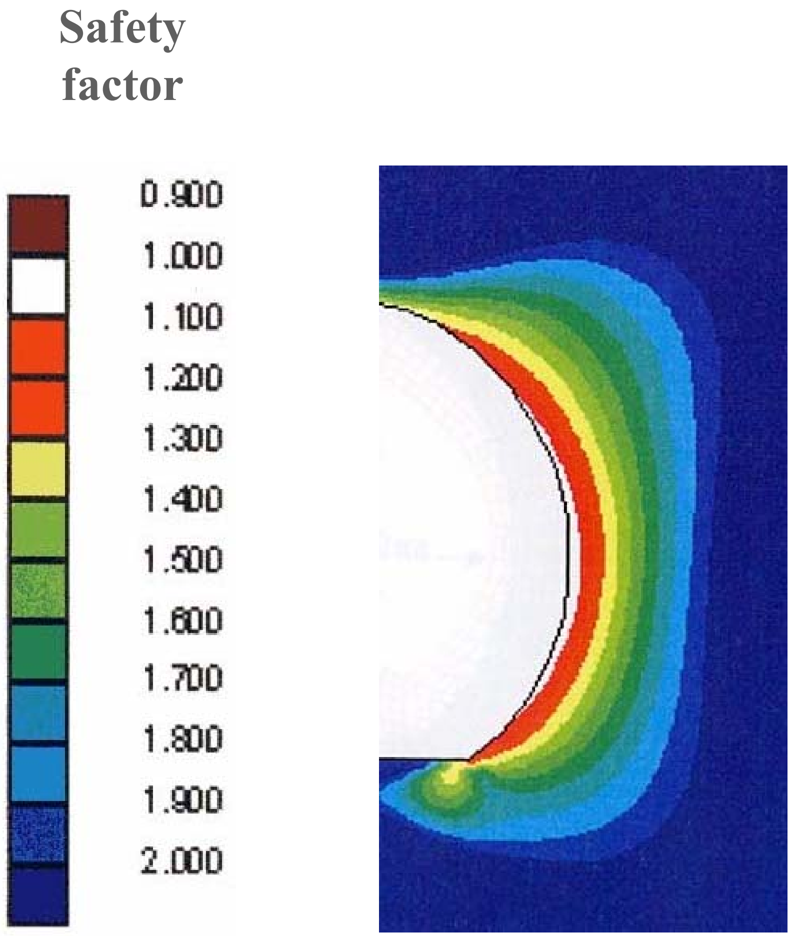
Main issues

- ➢ Design of a large cavern
- ➢ R&D on photo-sensors, in strong collaboration with industry*, to improve:
  - cost
  - production rate: ~ 8 years for 100,000-200,000 PMTs (with related storage problems)

* the development of 20" PMTs is at the basis of the success of Kamiokande and Super-Kamiokande

Finite element analysis of Hyper-K cavern

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

R&D on photo-sensors for Water Čerenkov

- **PMTs**

  R&D with industry to reduce cost, speed-up production rate, improve performance

- **New photo-sensors**
  - **Spherical hybrid photo-sensor (HPD)**

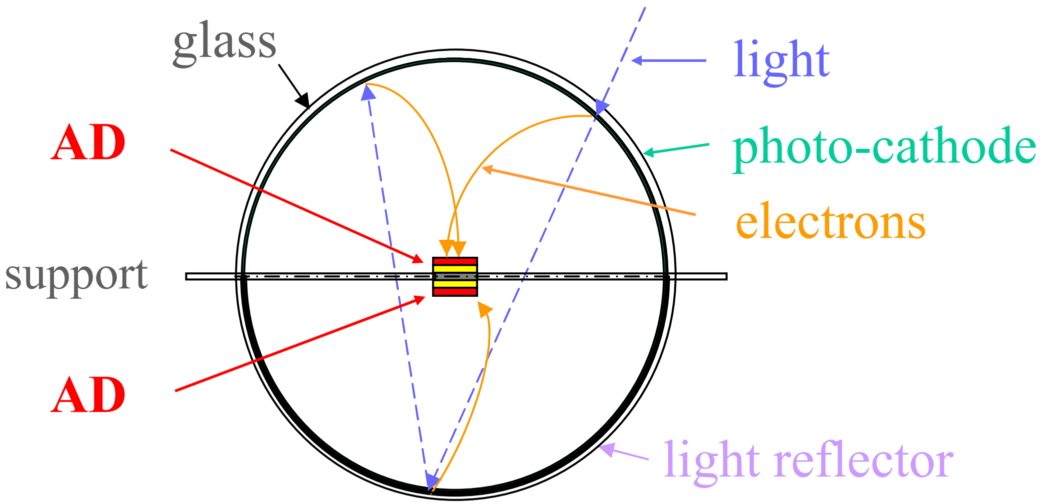
    ICRR Tokyo - Hamamatsu
  - ***"ReFerence"*** **tube**: photo-cathodes operating in reflection mode

    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

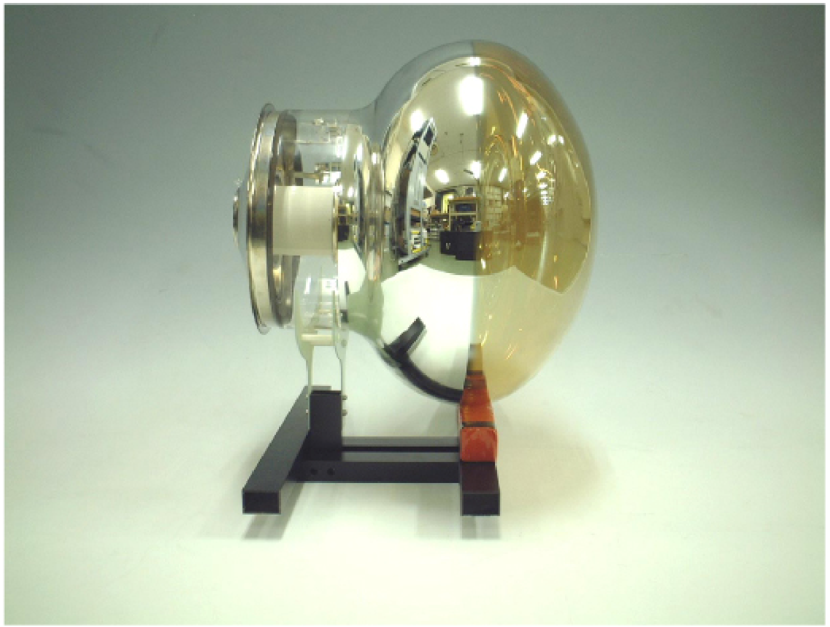


- **Spherical glass envelope, coated with <u>photo-cathode</u> and <u>light reflector</u>**
- **Electrons accelerated by <u>20 KV</u> between photocathode and AD**
- **<u>Avalanche Diodes</u> (AD)**
  - strong amplification in the electron bombardment of AD
    → single photon sensitivity from the high gain (~ 4000) in this 1st amplification stage
    → the noise thermally generated in the AD itself becomes ineffective
  - resolve 2-3 events per 50 ns
  - overall gain (~ 10^5) lower than with PMTs: need of stable and highly reliable amplifiers

➡ **Cost reduction from AD instead of PMT dynode structure**

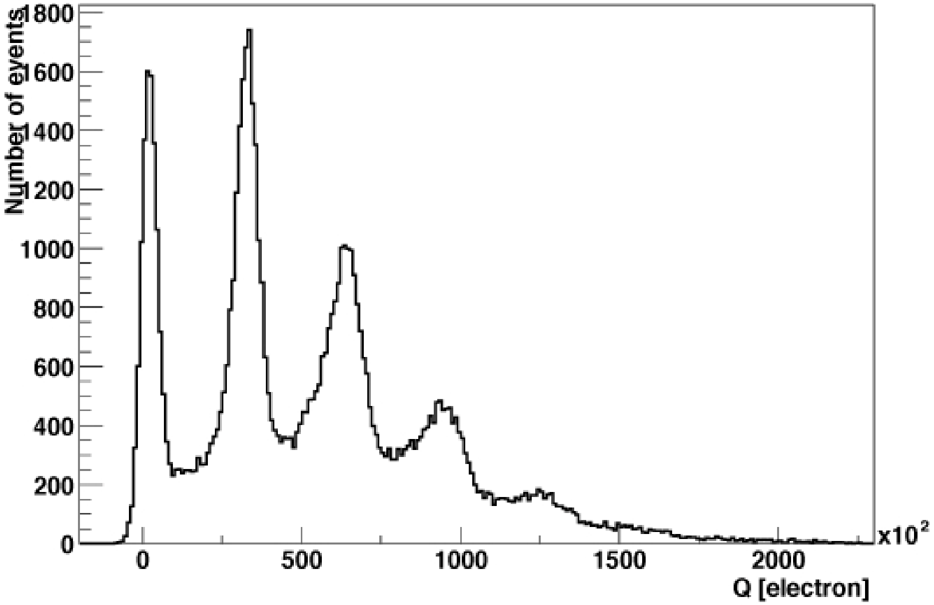
R&D on HPDs

13 Inch-Dia. HPD



HAMAMATSU

HAMAMATSU PHOTONICS K.K., Electron Tube Center

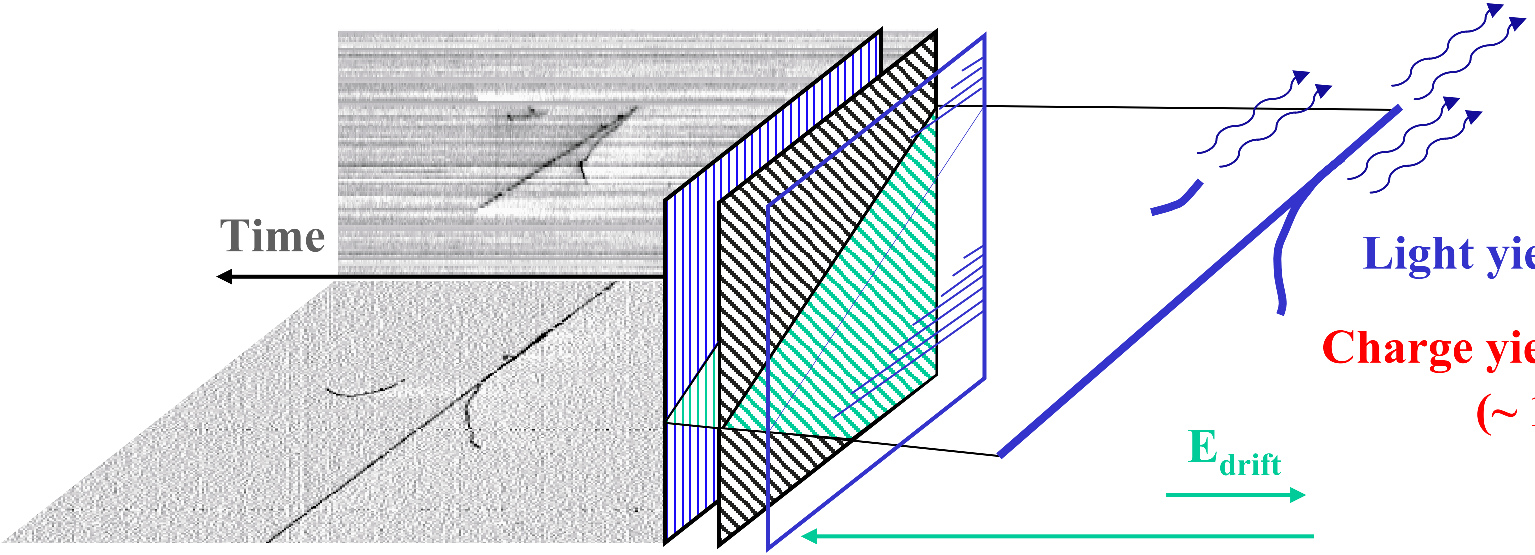


- 5” prototype tested
- Tests of 13” prototype in progress:

  gain >10^5, Transit Time Spread ~1 ns, single photon sensitivity
- Amplifier, Digital Filter, Analog Memory Cell: in progress
- 13” production model by spring 2005
- Next: design of Spherical 20” HPDs (requires higher field or development of larger AD)

Liquid Argon
Track Projection Chamber

The Liquid Argon TPC principle



Charge readout planes

UV Scintillation Light

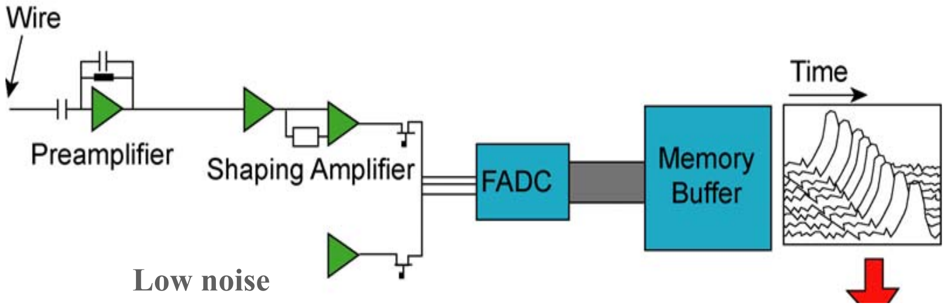
Time

Light yield ~ 5000 γ/mm

Charge yield ~ 6000 e^-/mm
(~ 1 fC/mm)

E_{drift}

Drift direction



Low noise
charge amplifier

Continuous waveform
recording

High density

Non-destructive readout

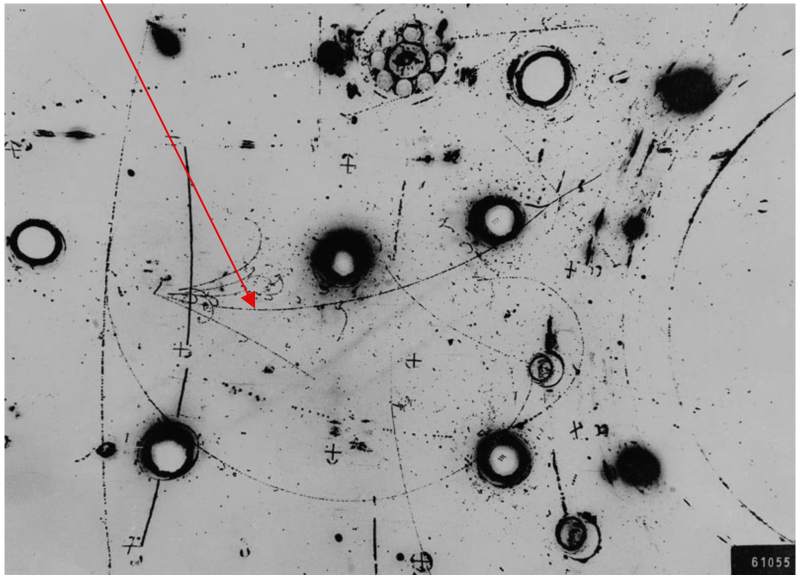
Continuously sensitive

Self-triggering

t_0 from scintillation

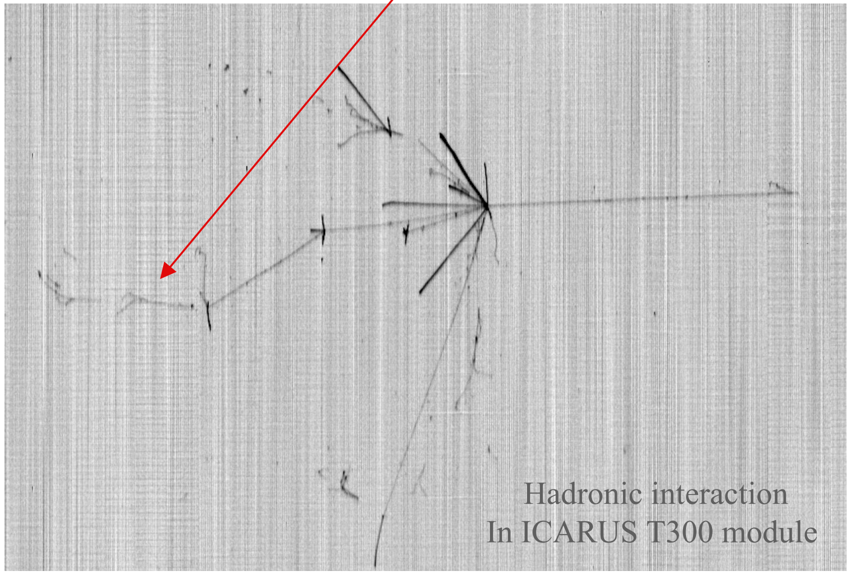
…an “electronic bubble chamber”
with broad physics potential and energy range

Bubble diameter ≈ 3 mm (diffraction limited)



Gargamelle

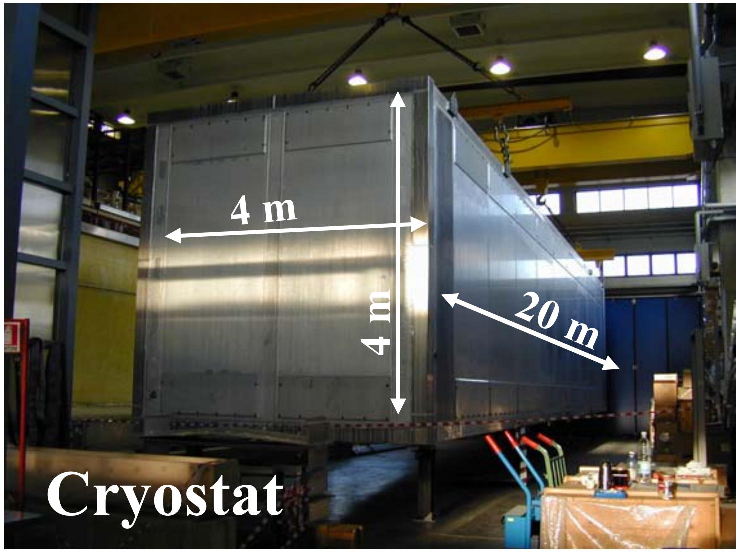
Bubble size ≈ 3 x 3 x 0.4 mm^3

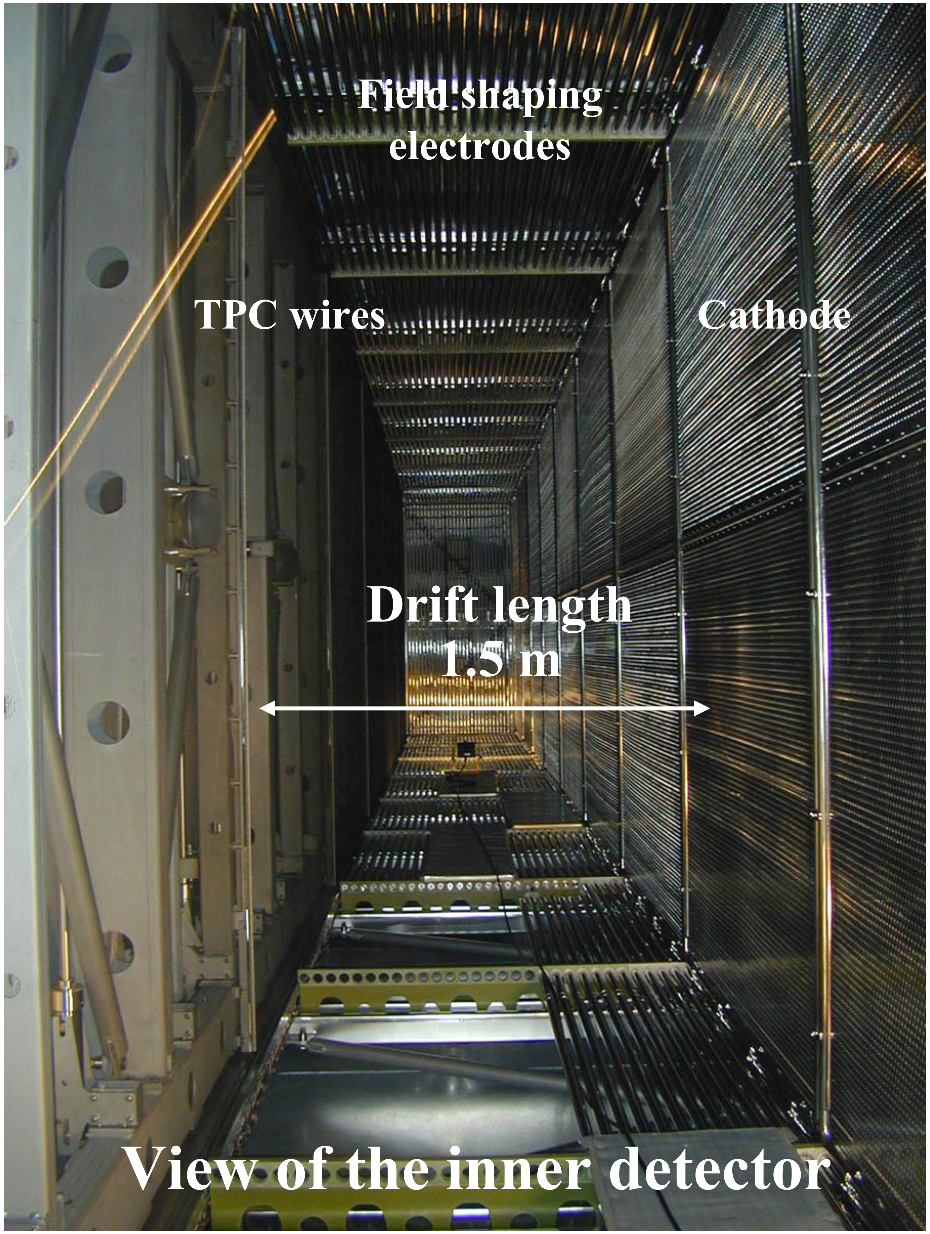

Hadronic interaction
In ICARUS T300 module

Liquid Ar TPC

Medium	Heavy Freon	Liquid Argon
Sensitive mass	**3 ton**	**300 ton - …. kton**
Density (g/cm^3)	1.5	1.4
Radiation length (cm)	11.0	14.0
Collision length (cm)	49.5	54.8
dE/dx (MeV/cm)	2.3	2.1
		continuously sensitive

ICARUS T300 module (0.3 kton)





- Operated in a ground level laboratory (Pavia)
- "The present status of the art"

T300: 300 ton, with 1.5 m drift length

ICARUS design: a ~ 2.5 kton modular detector

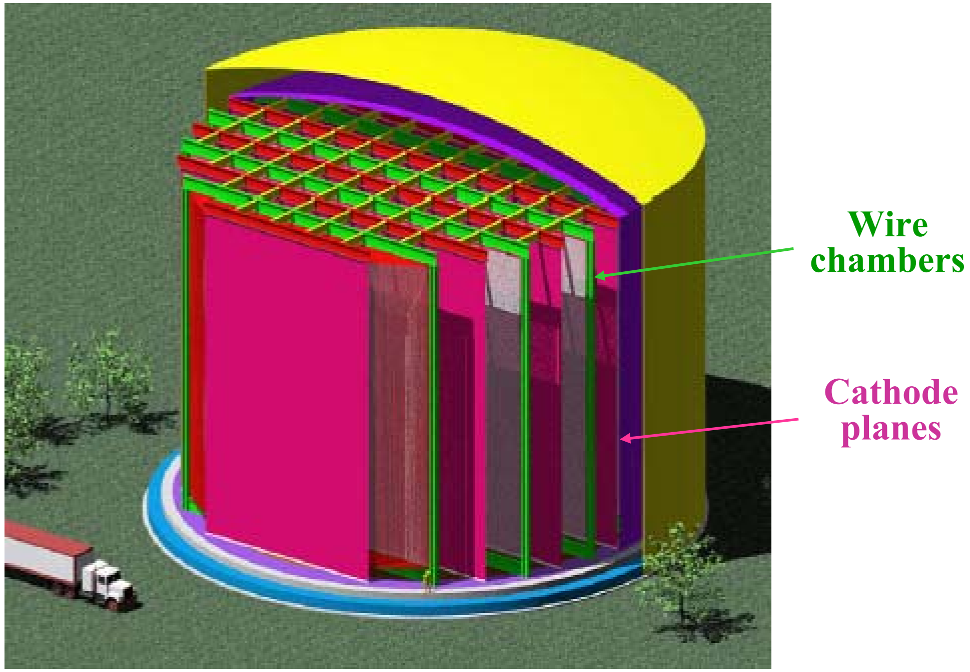
To reach a 50-100 kton mass:

- **Module size and geometry**
  - Cryogenic insulation imposes constraints
  - Do not pursue the ICARUS multi-module approach, design a single large module
  - Aspect ratio ~ 1:1 for larger volume/surface ratio

- **Drift length: larger to limit the number of readout channels**
  - Drift lengths ~ 5 m and readout in Liquid Argon as in ICARUS (FLARE and LANNDD)
  - Very long drift lengths (~ 20 m) in Liquid Argon, with amplification and ("Double Phase") readout in Gas Argon
  - Purity and signal attenuation to be kept under control

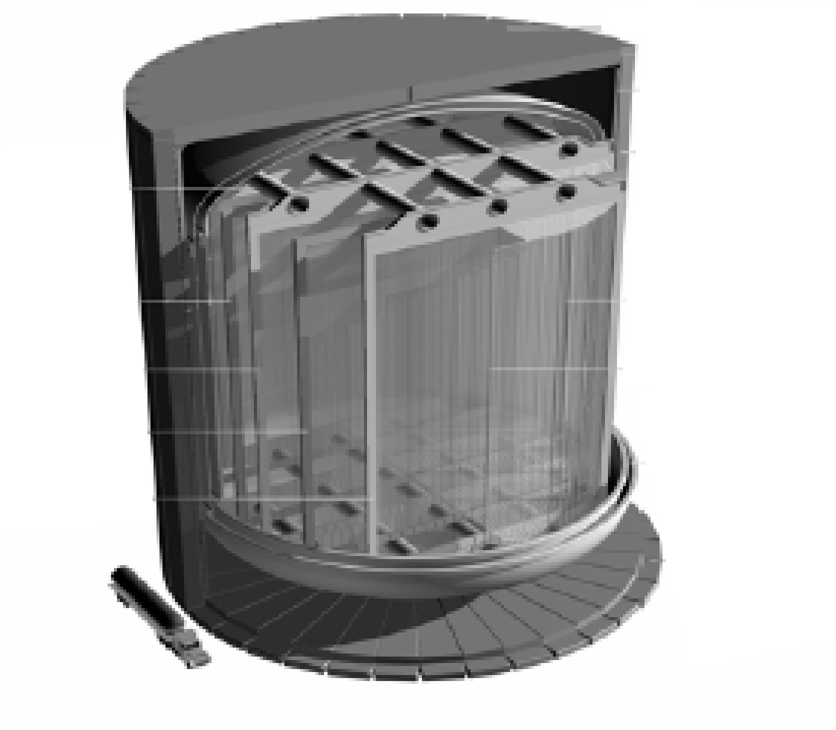
An off-axis Liquid Ar TPC for the NuMI beam

(FLARE, LoI in preparation)



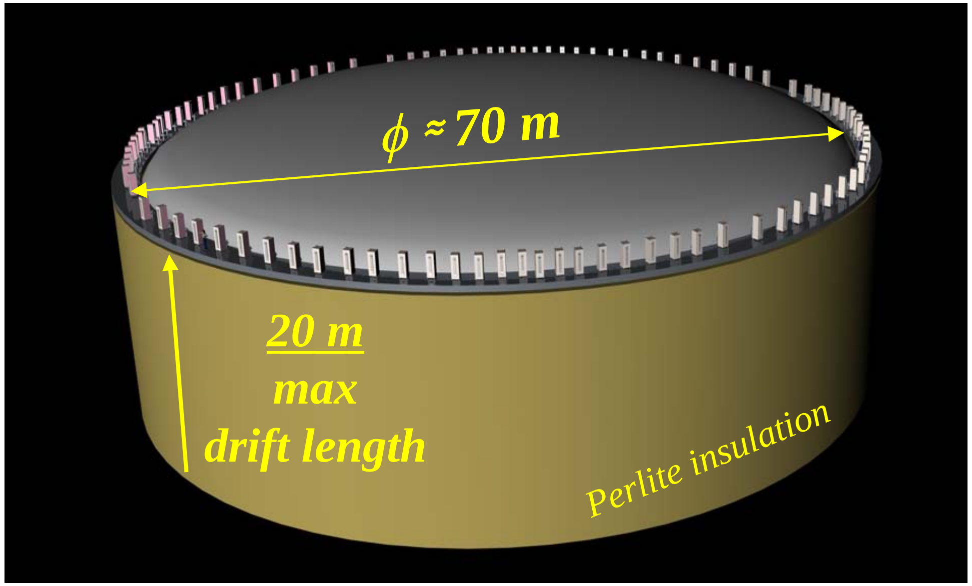
- **Readout in liquid phase**, as in ICARUS
- **50 kton** : ~ 1.5x10^2 extrapolation in mass wrt ICARUS T300
- **3 m max drift length** (1.5 m in ICARUS T300)
- **Surface location** (operated only with beam, for ν oscillation studies)

LANNDD



- **A detector for ν oscillation, as well as (if located underground) for ν astrophysics and proton decay**
- **Readout in liquid phase**, as in ICARUS
- **50-100 kton** : 1.5- 3 x 10^2 extrapolation in mass wrt ICARUS T300
- **4-8 m max drift length** (1.5 m in ICARUS T300)
- **Tests foreseen at 5 m drift length**

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



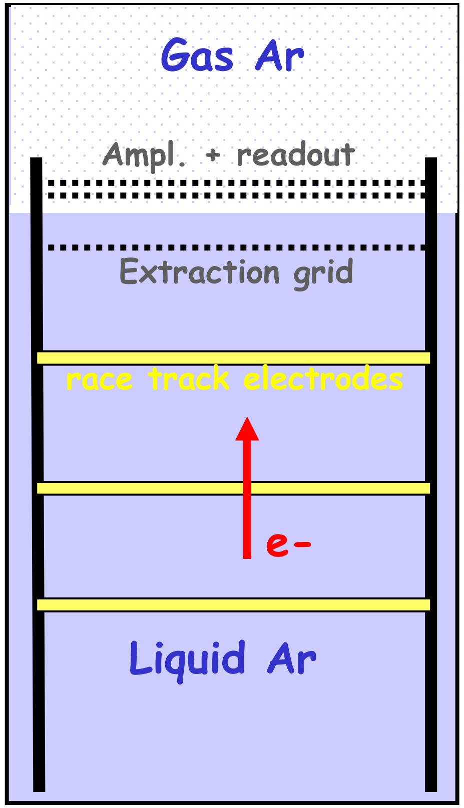
A giant Liquid Argon scintillation, Čerenkov and charge imaging experiment
A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003

- **A detector for ν oscillation, ν astrophysics, proton decay**
- **20 m max drift length**
- **Use of Liquid Natural Gas storage techniques**
  (technical study with industry)
- **~ $3\text{x}10^2$ extrapolation in mass wrt ICARUS T300**

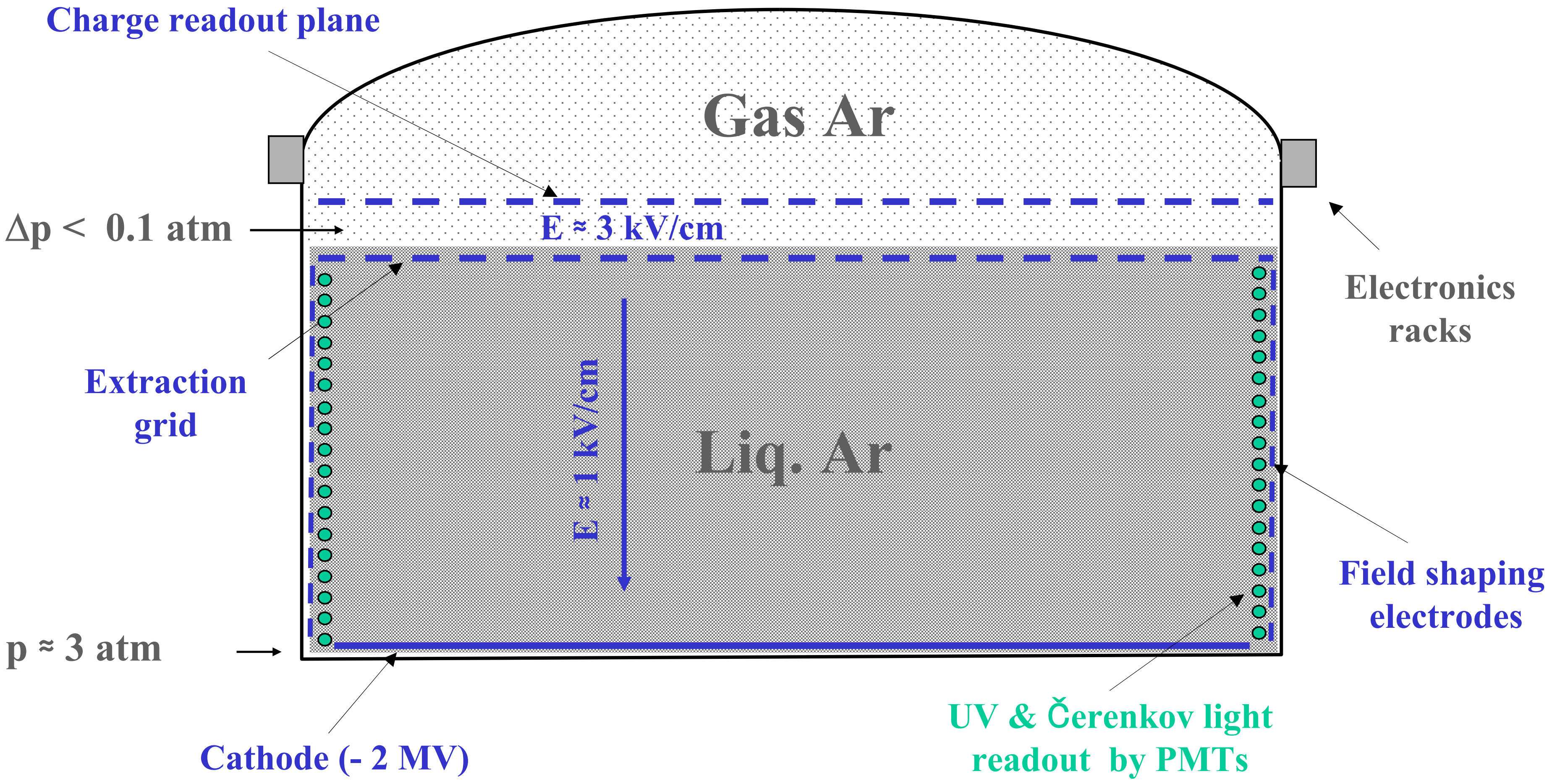
Double-phase (Liquid – Gas) readout

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

- Basic references: Dolgoshein et al. (1973); Cline, … Picchi ... et al. (2000)
- Tested on the ICARUS 50 litres chamber
- $v_d \approx 2$ mm/μs at 1 kV/cm: drift time ≈ 10 ms over 20 m max drift length, high purity required
- With 2 ms e-lifetime, max charge attenuation is $e^{-t/\tau} \approx 1/150$ (allowed because 6000 e- / mm for a MIP in LAr)
- Electron extraction to gas phase
- Amplification in proportional mode (x 100-1000) and readout: thin wires ($\phi \approx 30$ mm) with pad readout, .….
- Diffusion after 20 m drift: $\sigma \approx$ 3 mm gives a limit to the practical readout granularity



A tentative detector layout

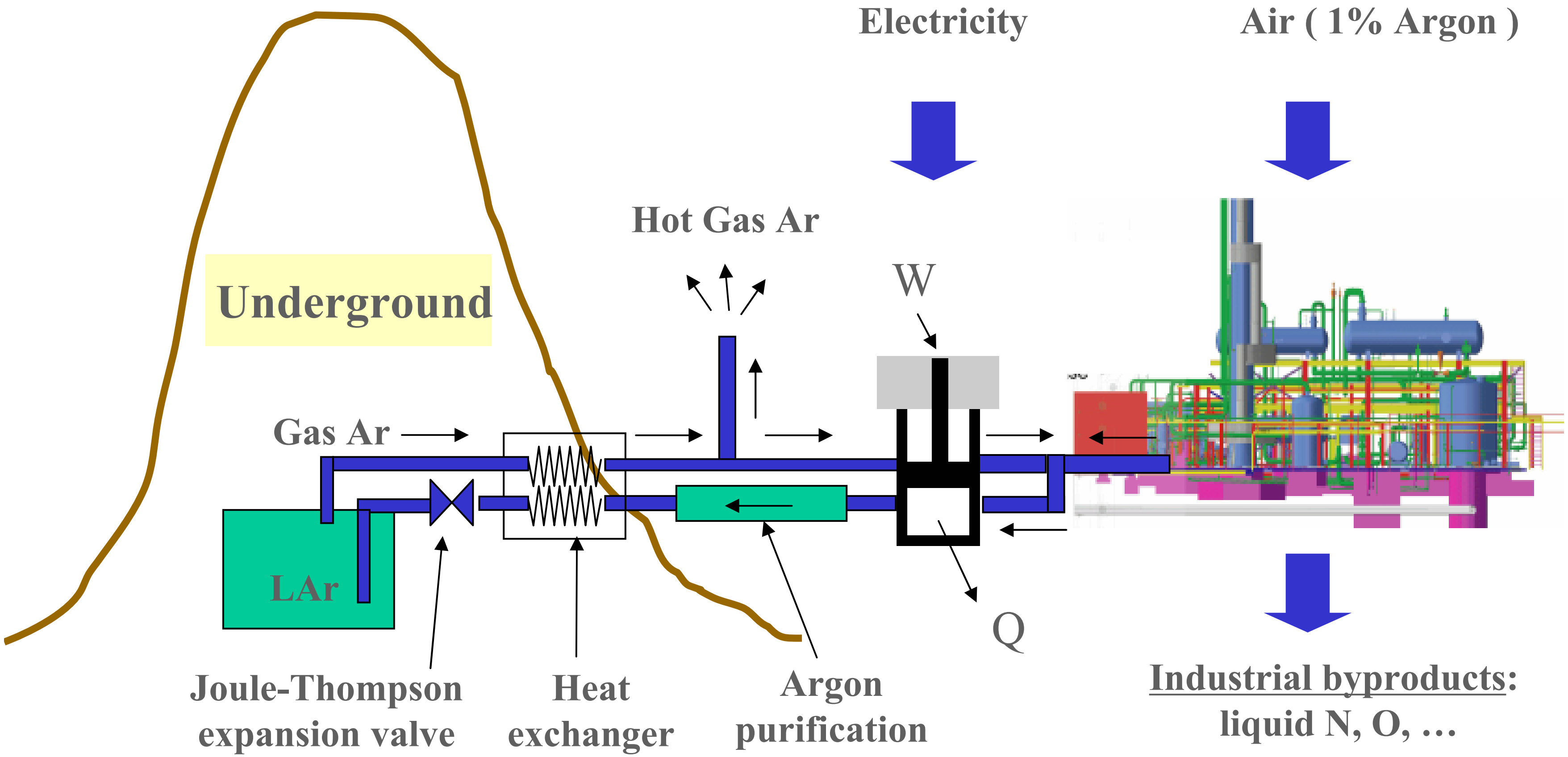


Liquid Ar at boiling temperature

If a gas exhaust is provided (feature not foreseen for ICARUS) the temperature remains constant

Same technique is used for transportation and storage of Liquefied Natural Gas

A large cryogenic plant is needed



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

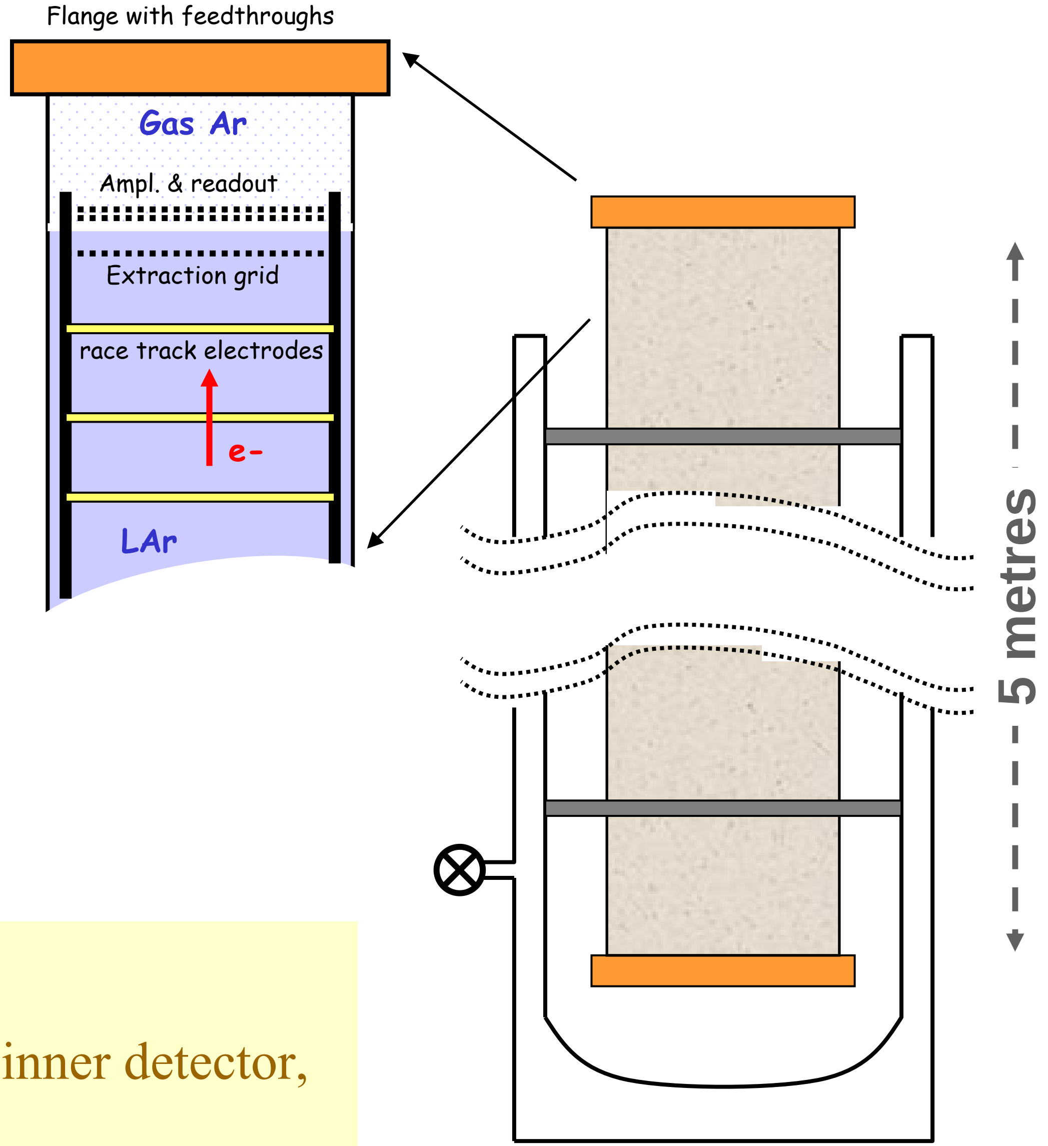
Ongoing studies and initial R&D strategy

- **Study of electron drift under high pressure** (p ~ 3 atm at tank bottom)
- **Charge extraction, amplification and imaging devices**
- **Cavern design: large volume with aspect ratio ~1 : 1**
- **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)
- **<u>Realization and test of a column-like detector prototype:</u>**
  5 m long drift and double-phase readout

Test module for long drift, extraction, amplification

- Measurement of 5 m long drift, signal attenuation and multiplication

- Simulate 'very long' drift (20 m) by reduced E field and LAr purity

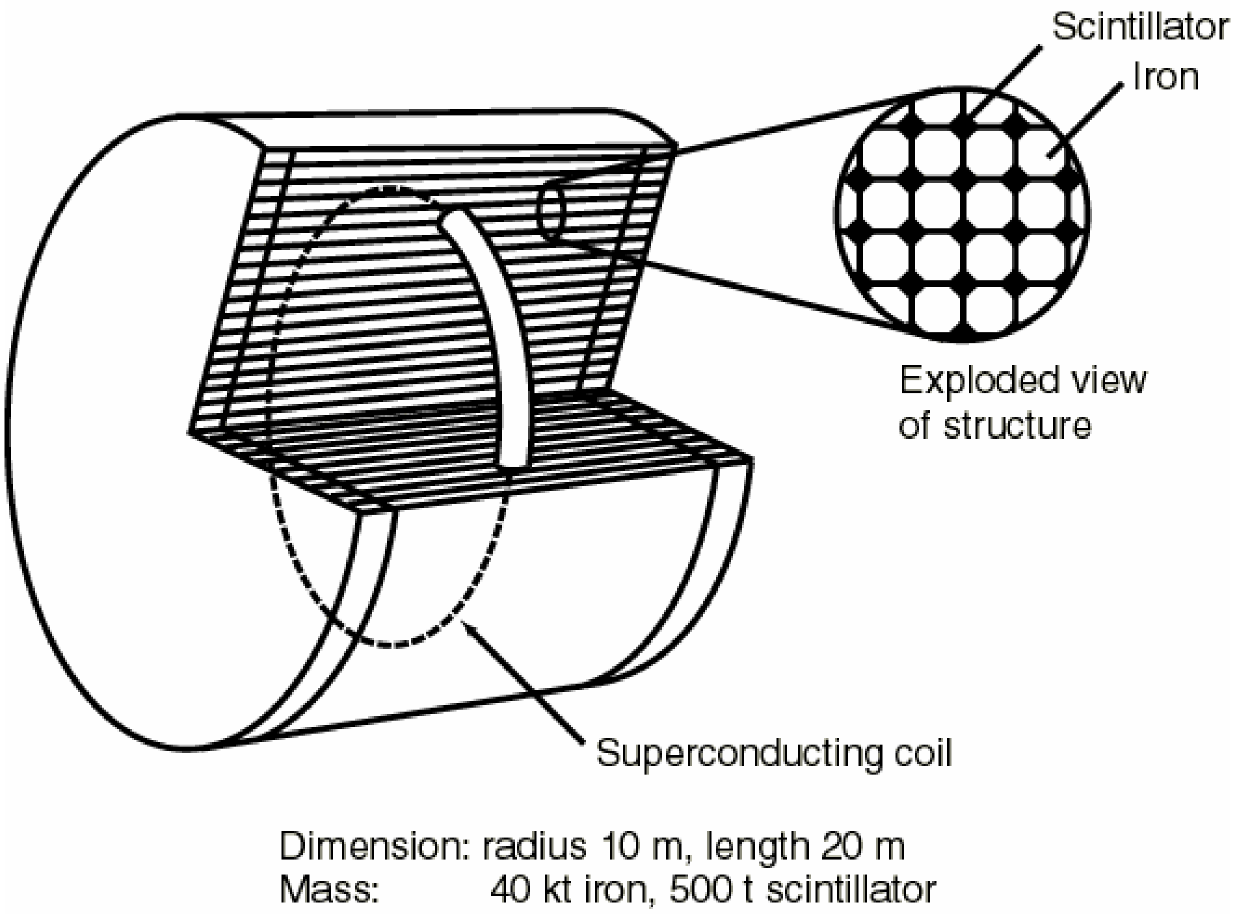


Design in progress:

external dewar, detector container, inner detector, readout system, …

A Magnetised Iron Detector for a ν Factory

- Iron calorimeter, with scintillator rods as active detector
- Magnetised at B = 1 T → "wrong sign" muons from ν_e-ν_μ oscillations or $\bar{\nu}_\mu$ CC?
- Conventional technique, but mass one order of magnitude > MINOS
- Only conceptual drawing available: practical problems (mechanics, magnet design….) must be addressed to assess the feasibility

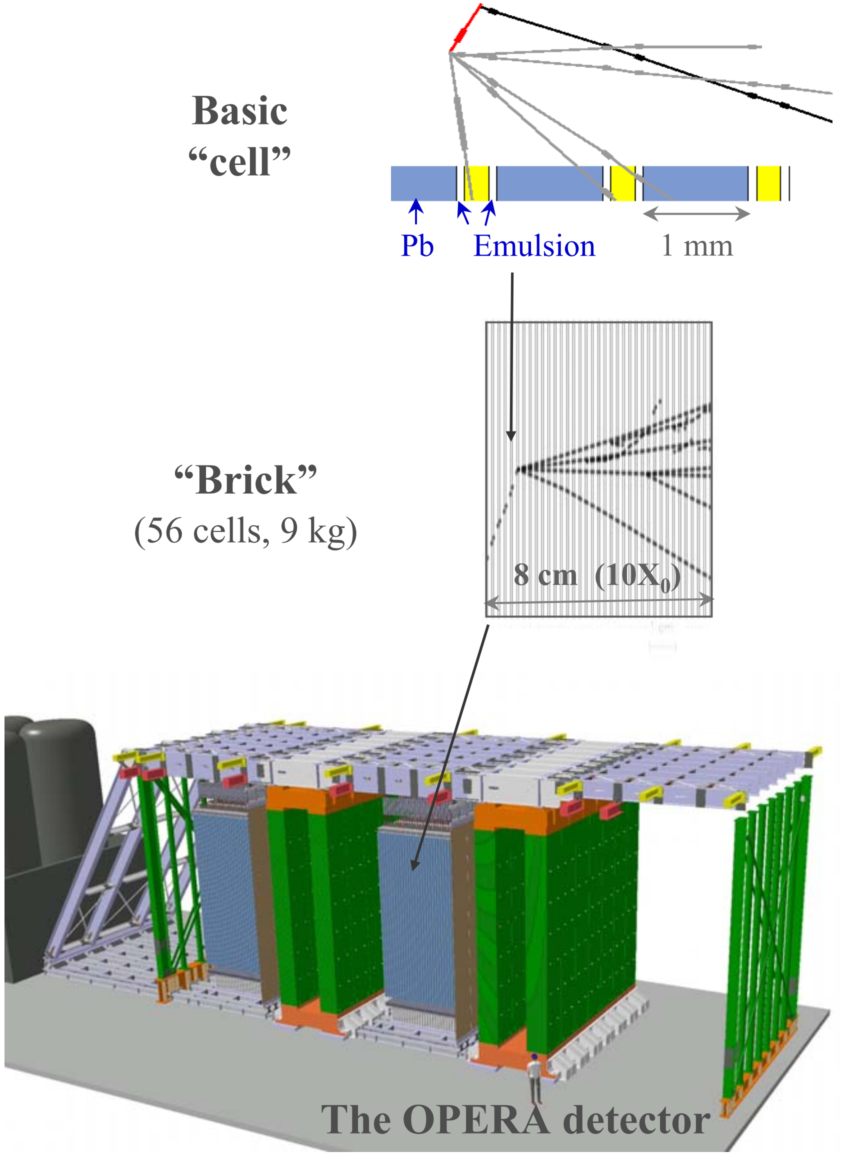


Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

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

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

- $\nu_e \rightarrow \nu_\mu$ (golden events) and $\nu_e \rightarrow \nu_\tau$ (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
- 1.8 kton OPERA target mass → ~ 4 kton at ν Factory
- Search for τ-decay only in events with a "wrong sign" muon: x 2 increase of scanning power required
- Hybrid experiment: emulsion + electronic detectors
- OPERA as a "milestone" for the technique



The OPERA detector
(~200,000 bricks)

Summary (1)

Low-Z Calorimeter

- ν_μ- ν_e oscillations → θ_{13} in off-axis NuMI beam: NOνA
- Follow-up of a proven technique
- NOνA mass ~ 10 x MINOS
- Main issue: improve performance and reduce cost of trackers
- Main new technologies with respect to MINOS
  plastic → liquid scintillator (sampling or totally active detector)
  PMTs → APDs

Summary (2)

Water Čerenkov

- ν oscillation , ν astrophysics, proton decay
- Proven and very successful technique, well known also in its limitations
- Hyper-K, UNO and Frejus detector: mass ~ 10 x Super-K
- Main issues:

  - cost and production of PMTs
    - → strong collaboration with industry
    - → 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 300 ton ICARUS module:
  to be extrapolated in mass by > two orders of magnitudes
- New features envisaged to reach 100 kton: longer or much longer drifts, double-phase amplification and readout
- Very substantial R&D required on various aspects, depending on the design features and on the (underground) location: signal propagation and readout; electric field shaping; cryogenics, civil engineering, safety and logistics issues; …..

Summary (4)

Magnetised Fe Sampling Calorimeter

- “wrong sign” μ from $\nu_e \rightarrow \nu_\mu$ oscillations at ν-Factories
- Proven technique, at smaller scale
- Mass ~ 10 x MINOS
- Only conceptual drawing available

Emulsion Cloud Chamber

- $\nu_e \rightarrow \nu_\tau$ at ν-Factories, to complement $\nu_e \rightarrow \nu_\mu$ oscillation in order to resolve 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 neutrino masses and mixing matrix
as well as on neutrino astrophysics, nucleon decay,
unexpected physics ….**

**Requires large and reliable detectors
with appropriate performance and acceptable cost**

Depending on physics, detector developments and funding:

- **Initiate what is now possible and advisable, carry out the related R&D**
- **Lay down the bases of further future:**
  - **R&D must look far ahead**
  - **Stimulate new ideas**