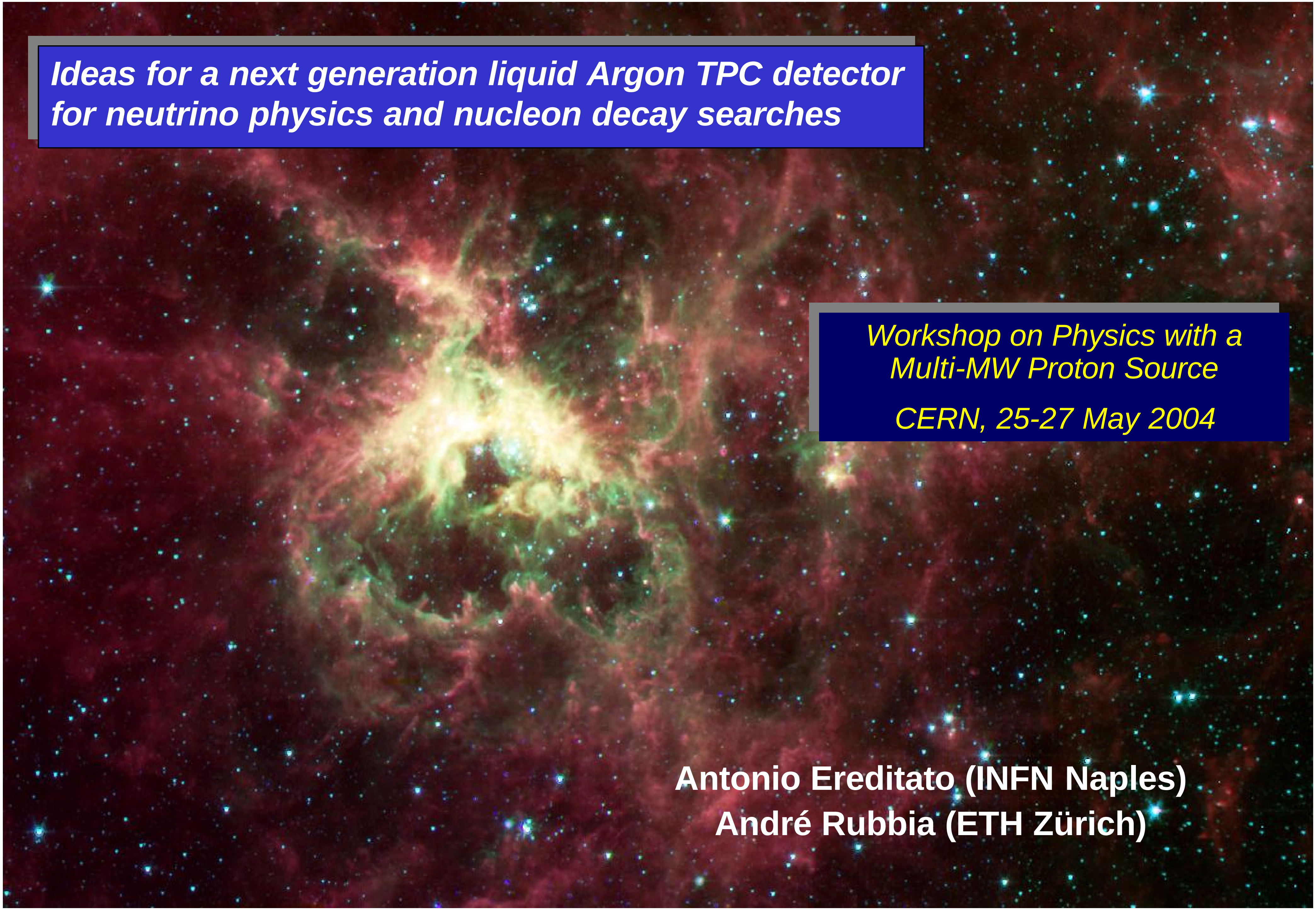


Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches

Workshop on Physics with a Multi-MW Proton Source

CERN, 25-27 May 2004

Antonio Ereditato (INFN Naples)
André Rubbia (ETH Zürich)

Introduction

This presentation is based on the note submitted to the SPSC in view of the Villars meeting of September 2004:

A.Ereditato and A.Rubbia, Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches, April 27, 2004.

- **Liquid Argon TPC technique: high level of maturity reached thanks to many years of R&D effort conducted by the ICARUS collaboration**

  successful operation of a **300 ton** module at surface:
  1) long electron drift with high LAr purity 2) scalability to large detector mass (kton)

- **ICARUS CNGS2 @ LNGS: ultimate proof of detector imaging performance with astroparticle & neutrino beam events**

- **As of today, physics is calling for at least two applications of the LAr TPC technique with a monolithic design at two different mass scales:**

  ˜ **100 kton**: proton decay, high statistics astrophysical & accelerator neutrinos, …
  ˜ **100 ton**: systematic study of neutrino interactions, near detectors in LBL beams,…

- **Synergy between small & large scales with high degree of interplay**

- **Work is in progress along these lines of thoughts**

  We present here a brief overview of our current ideas & activities

- **A 100 kton LAr TPC: a detector for the next generation CERN neutrino facility?**

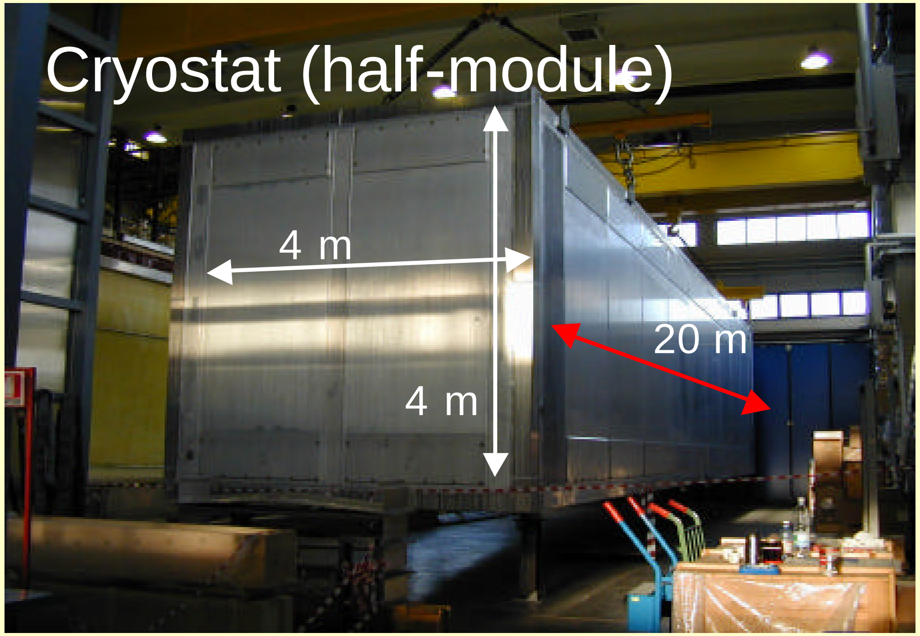
  A conceptual design is given and the main features are outlined

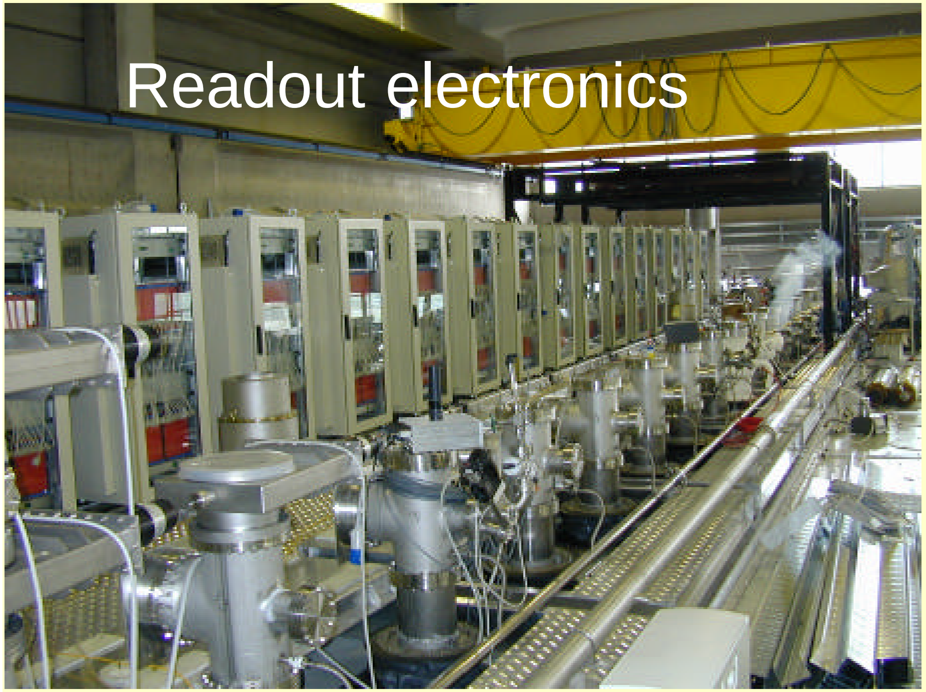
Liquid Argon TPC Overview

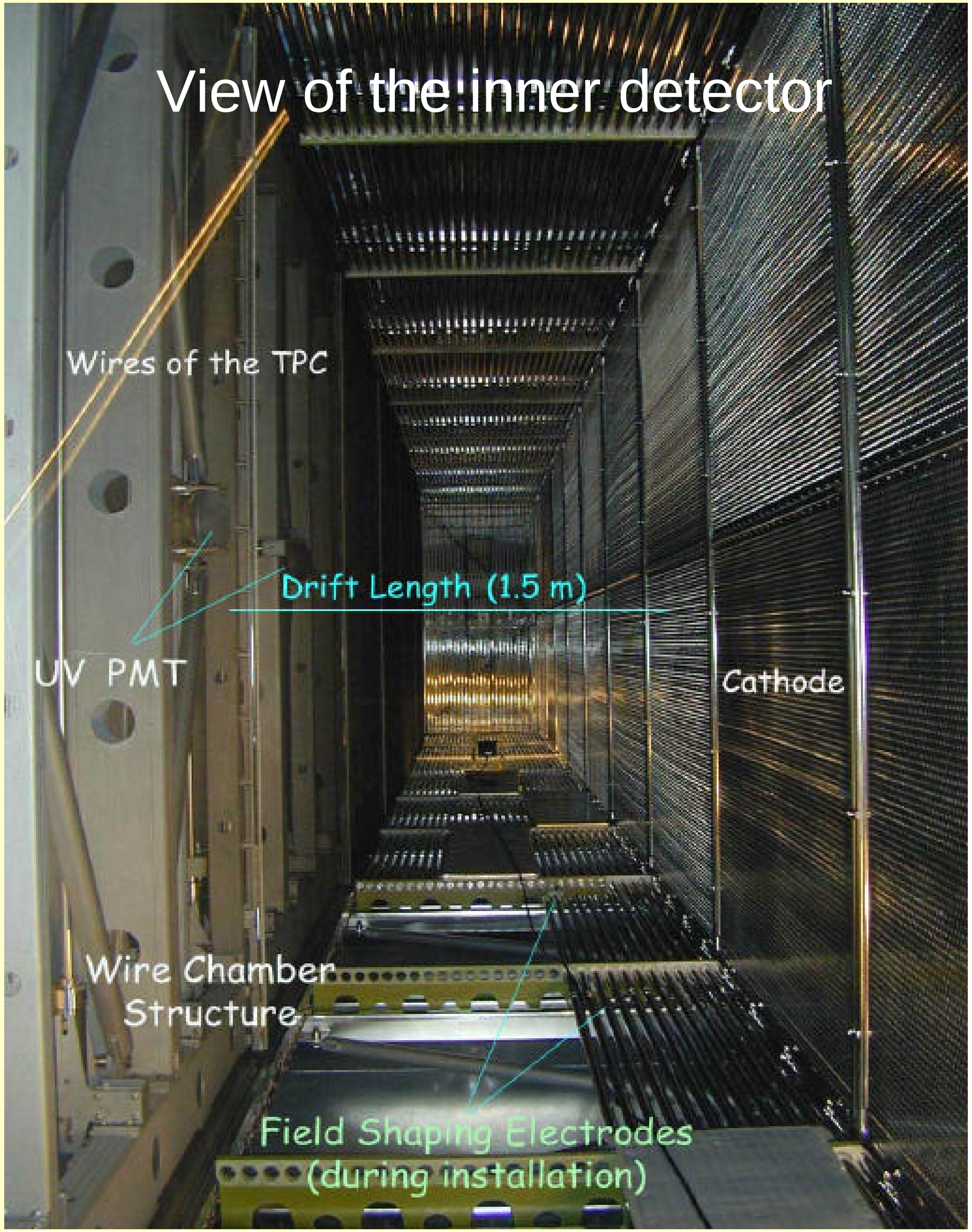
LAr TPC story…

• L.W.Alvarez (late 60'):	noble liquids for position sensitive detectors
• T.Doke (late 60'):	systematic studies of noble liquids properties
• W.J.Willis & V.Radeka (70'):	large calorimeters for HEP experiments
• C.Rubbia (1977):	<u>LAr TPC conceived and proposed</u>
• E.Aprile, C.Giboni, C.Rubbia (1985):	high purity → long drift distances
• ICARUS Coll. (1993-1994):	3 ton LAr TPC prototype
• ICARUS Coll. (1998):	Neutrino detection at CERN with a 50 l LAr TPC
• ICARUS Coll. (2001):	cosmic-ray test of the 300 ton industrial module
• ICARUS Coll. (2003-2004):	detector/physics papers from the T300 test
• ICARUS Coll. (2004-2005):	<u>T600 installation and commissioning at LNGS</u>
• …	

ICARUS T300 detector







Liquid Argon medium properties

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov $d^2N/dEdx$ (b=1)	~ 160 eV^{-1} cm^{-1}	~ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation (E=0 V/cm)	No	Yes (~ 50000 g/MeV @ l=128nm)
Long electron drift	Not possible	Possible (μ = 500 cm^2/Vs)
Boiling point @ 1 bar	373 K	87 K

When a charged particle traverses LAr:

1) Ionization process

W_e = 23.6 ± 0.3 eV

2) Scintillation (luminescence)

W_γ = 19.5 eV

UV "line" (λ=128 nm ⇔ 9.7 eV)

No more ionization: Argon is transparent

Only Rayleigh-scattering

3) Cerenkov light (if relativistic particle)

☞ **Charge**

☞ **Scintillation light (VUV)**

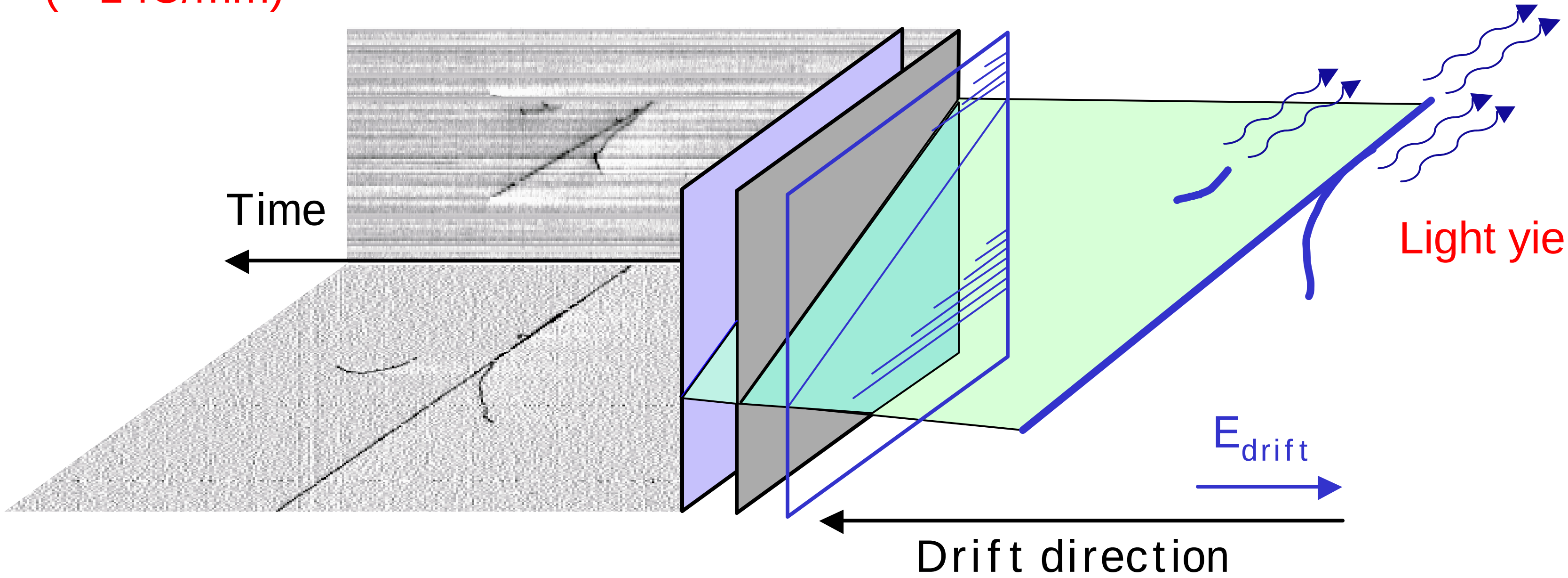
☞ **Cerenkov light (if b>1/n)**

The Liquid Argon TPC principle

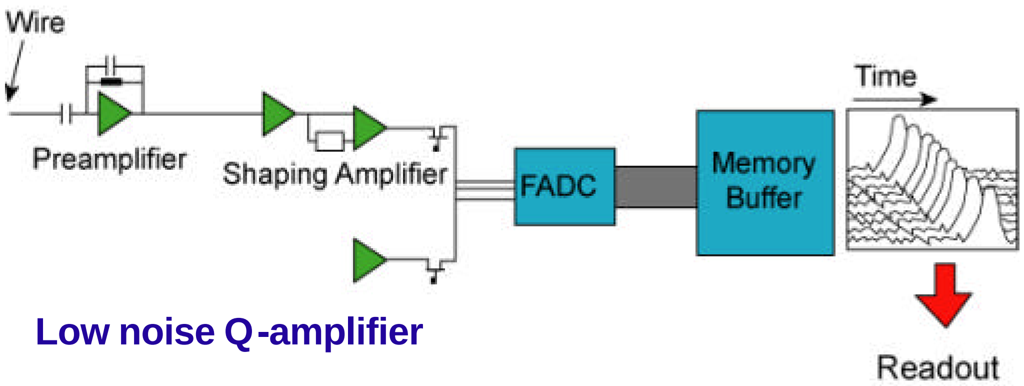
Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L



Light yield ~ 5000 γ/mm



Continuous waveform recording

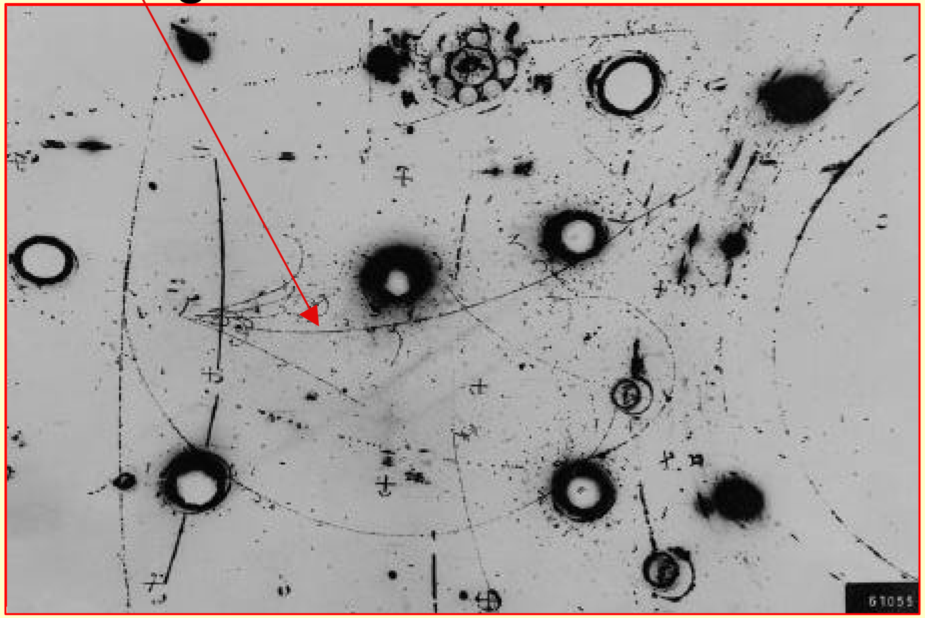
- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- t_0 available (scintillation)

…an electronic bubble chamber

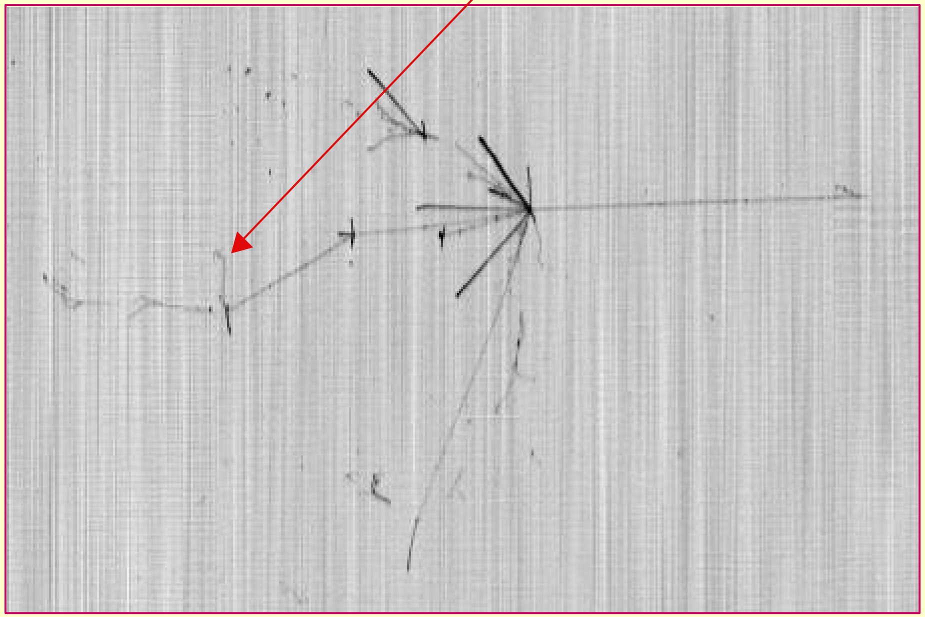
Bubble diameter ~ 3 mm (diffraction limited)

Bubble size ~ 3x3x0.4 mm^3

Gargamelle bubble chamber



ICARUS electronic chamber

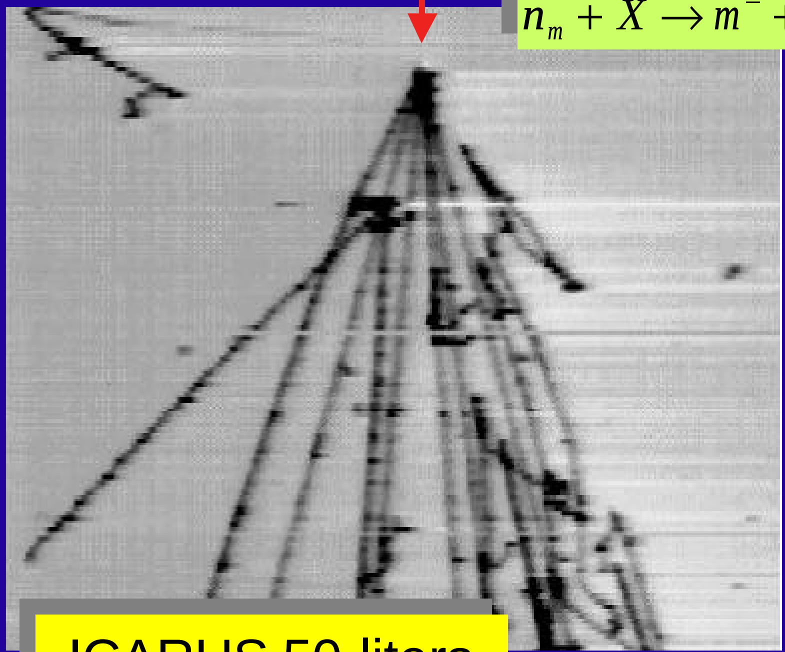


Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

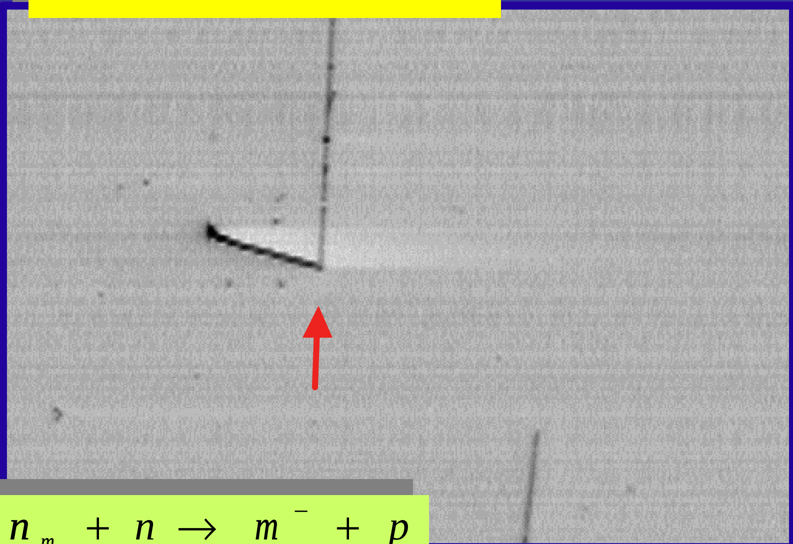
Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Real neutrino events observed by LAr TPC and water Cerenkov

$n_m + X \rightarrow m^- + many\ prongs$

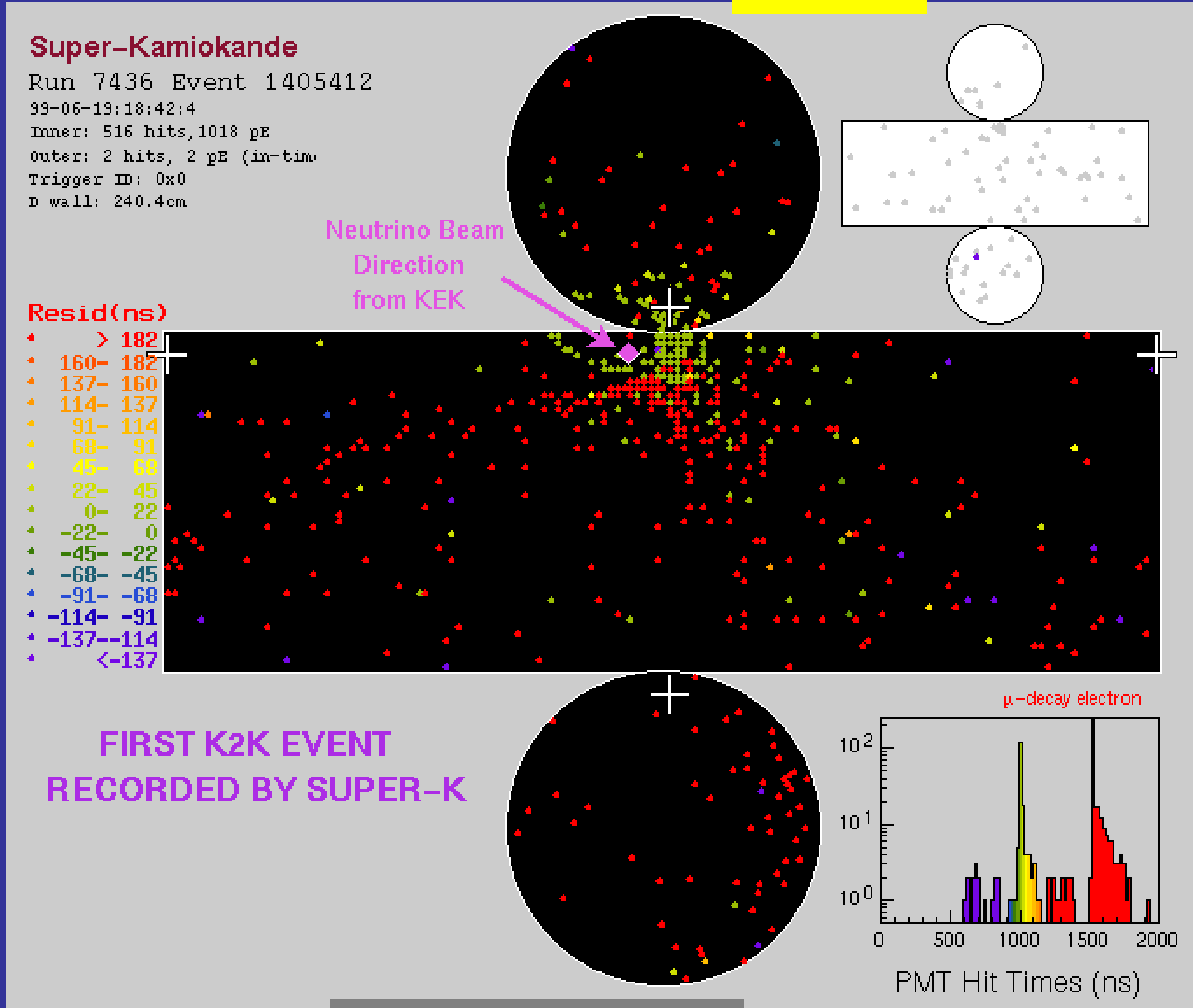


ICARUS 50 liters



$n_m + n \rightarrow m^- + p$

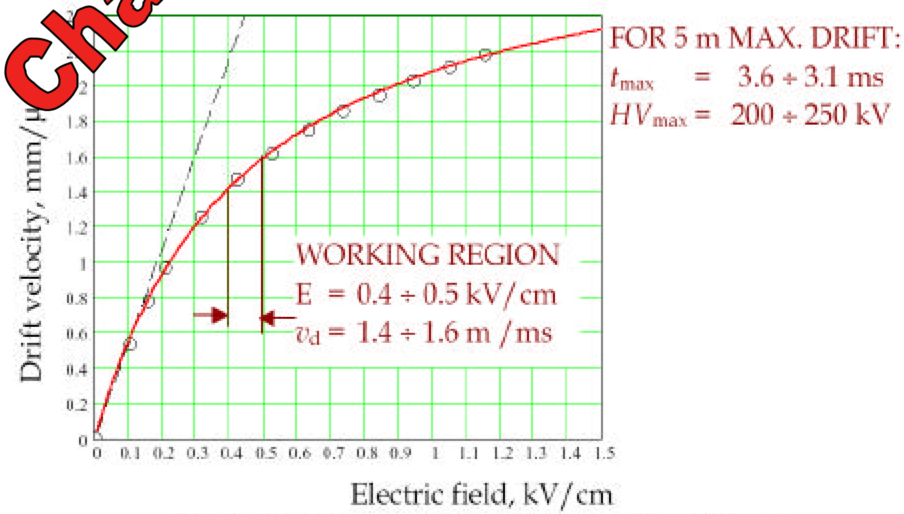
K2K



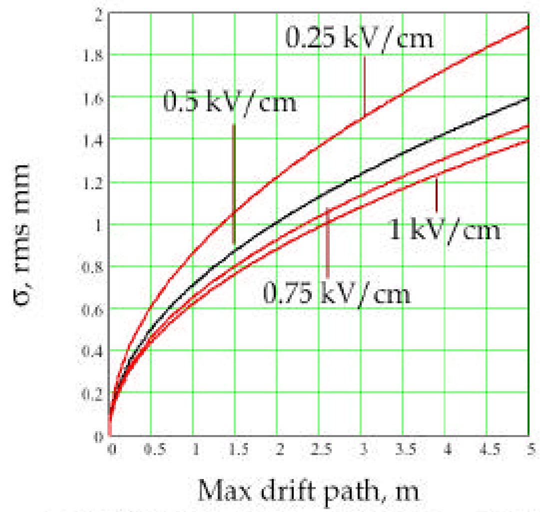
$n_m + n \rightarrow m^- + p$

Charge

Electron drift properties in liquid Argon



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

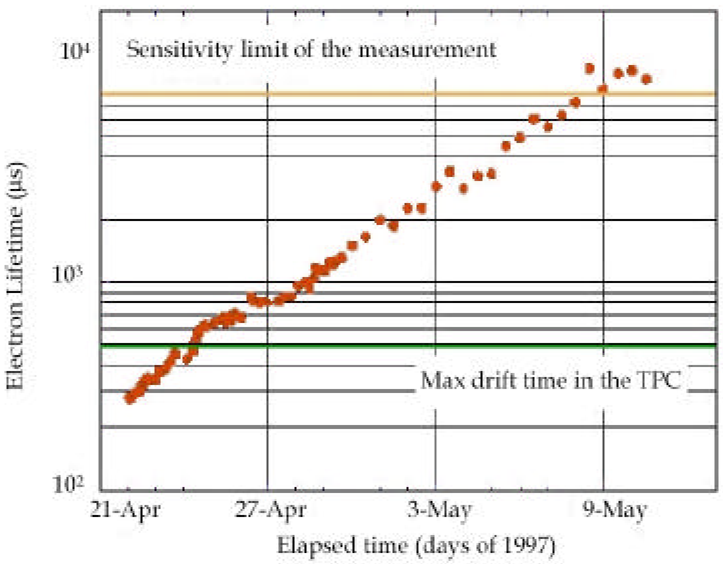
$$D = 4.06\ \mathrm{cm^2/s}$$

$\sigma_D = 0.9\ \mathrm{mm} \cdot \sqrt{T_D[\mathrm{ms}]}$

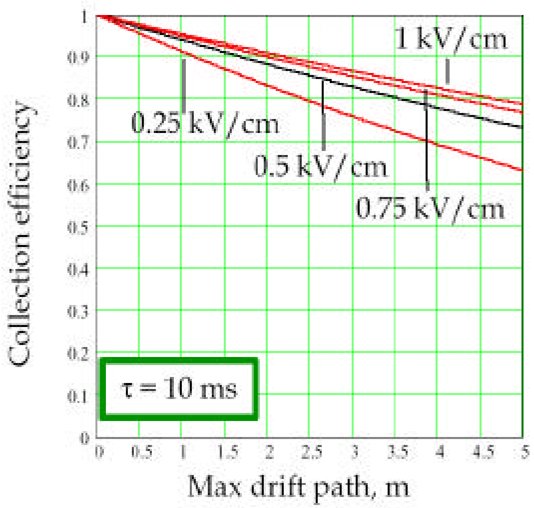
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

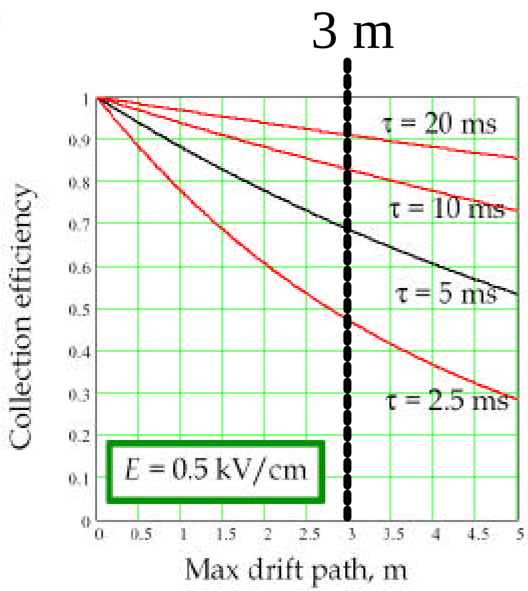
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC



Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



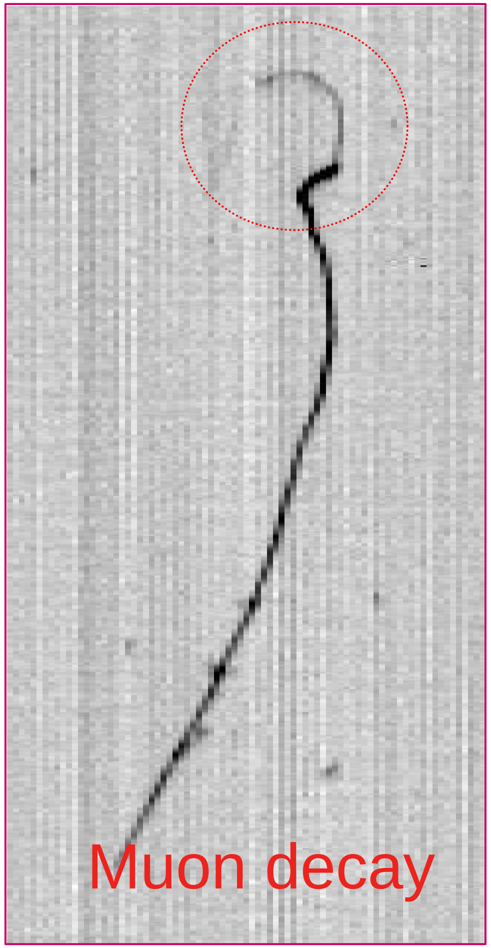
Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

Charge

Cosmic rays events in the ICARUS T300

25 cm

85 cm



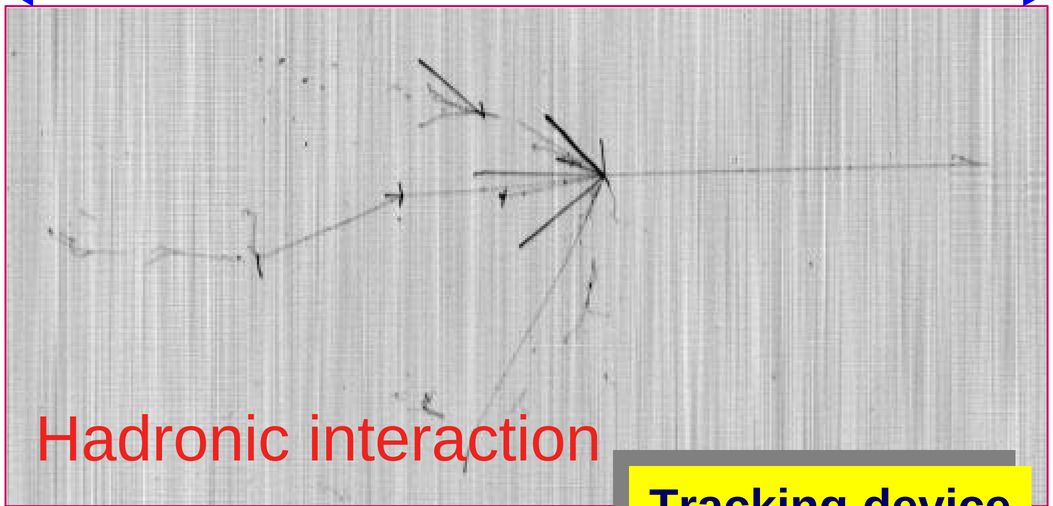
Run 960, Event 4 Collection Left

Measurement of local energy deposition dE/dx

176 cm

434 cm

265 cm



142 cm

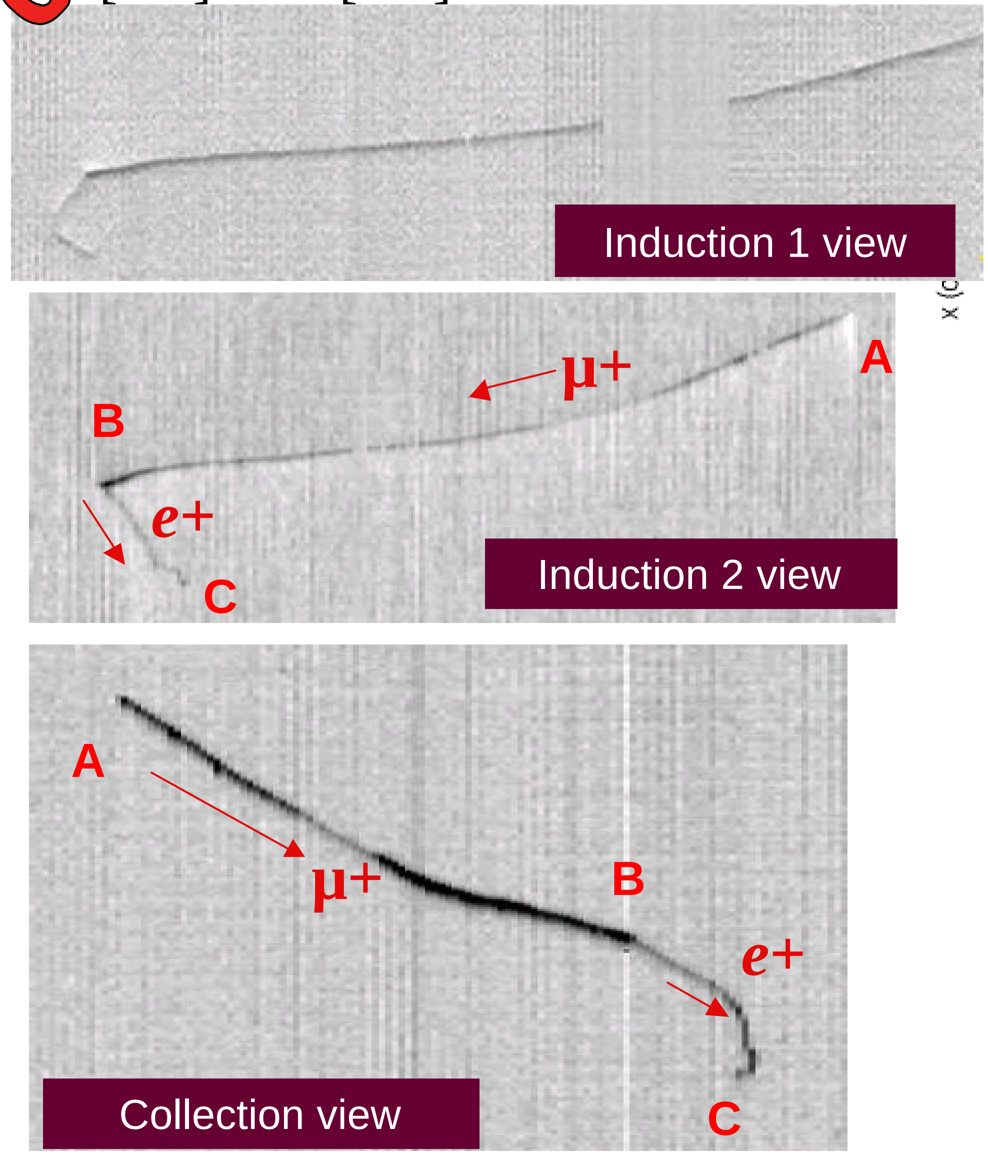
Run 308, Event 160 Collection Left

Tracking device

Charge

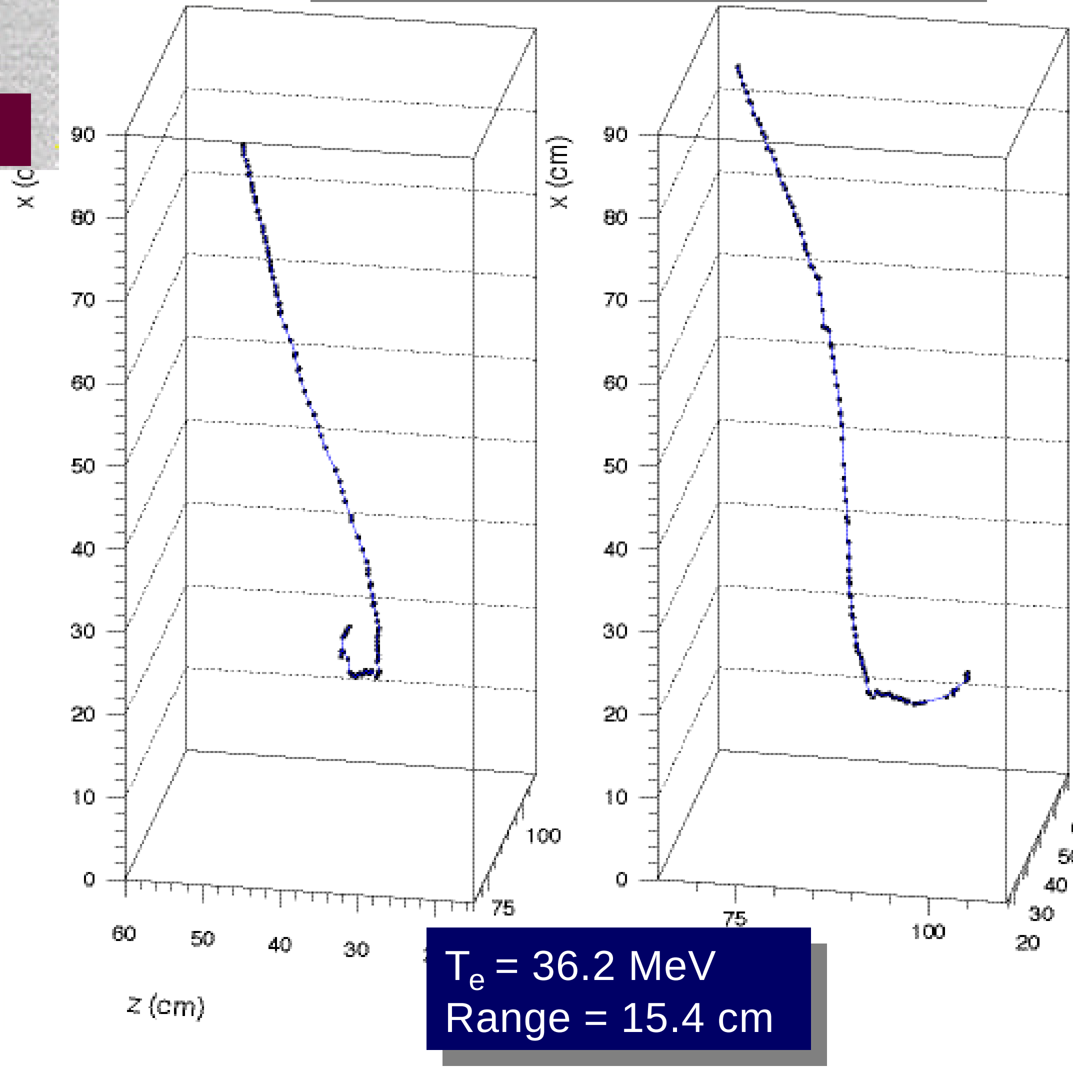
3D reconstruction of a stopping muon

$\mu^+[AB] \to e^+[BC]$

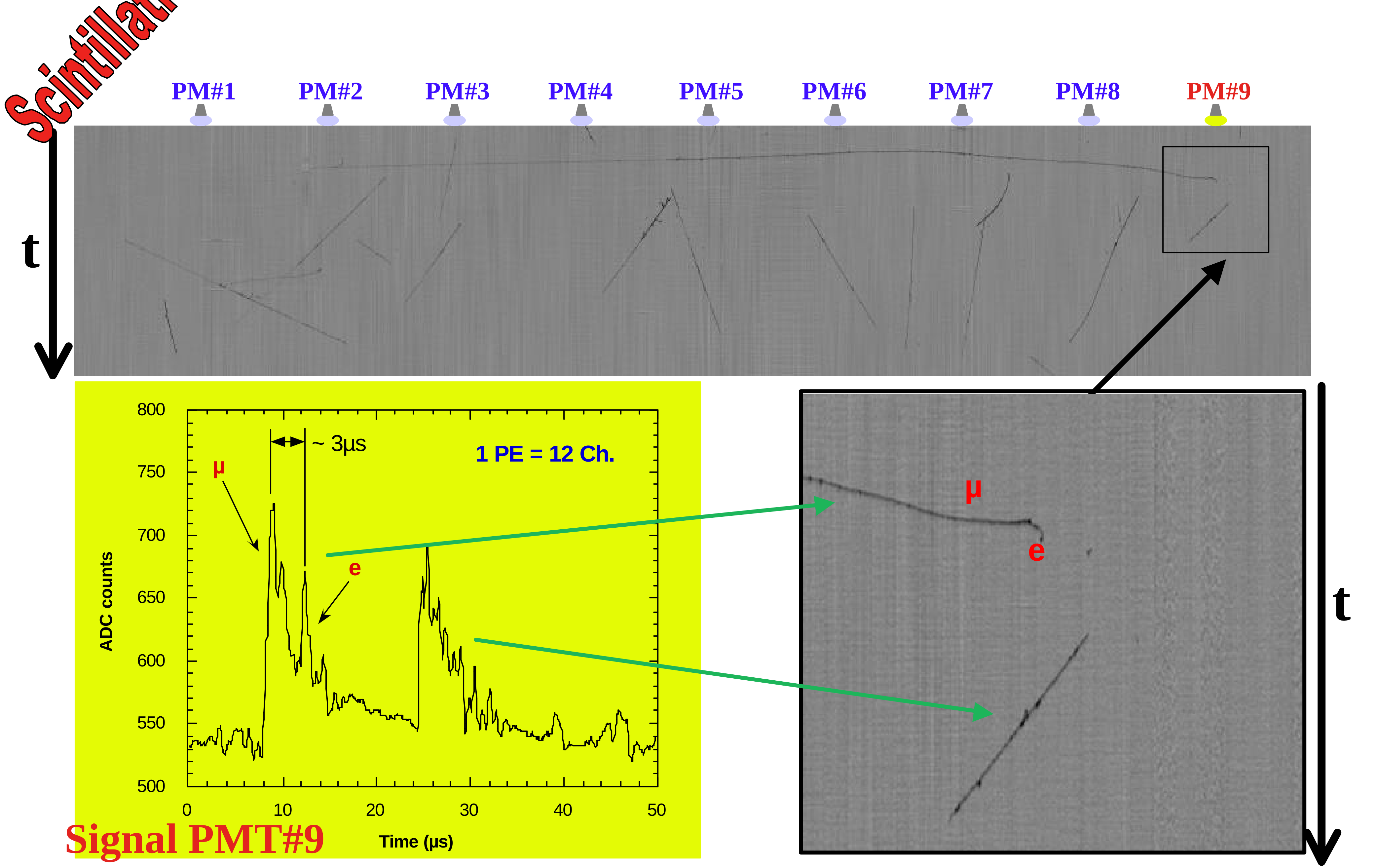


(Reconstruction is automatic)

Run 939 Event 95 Right chamber



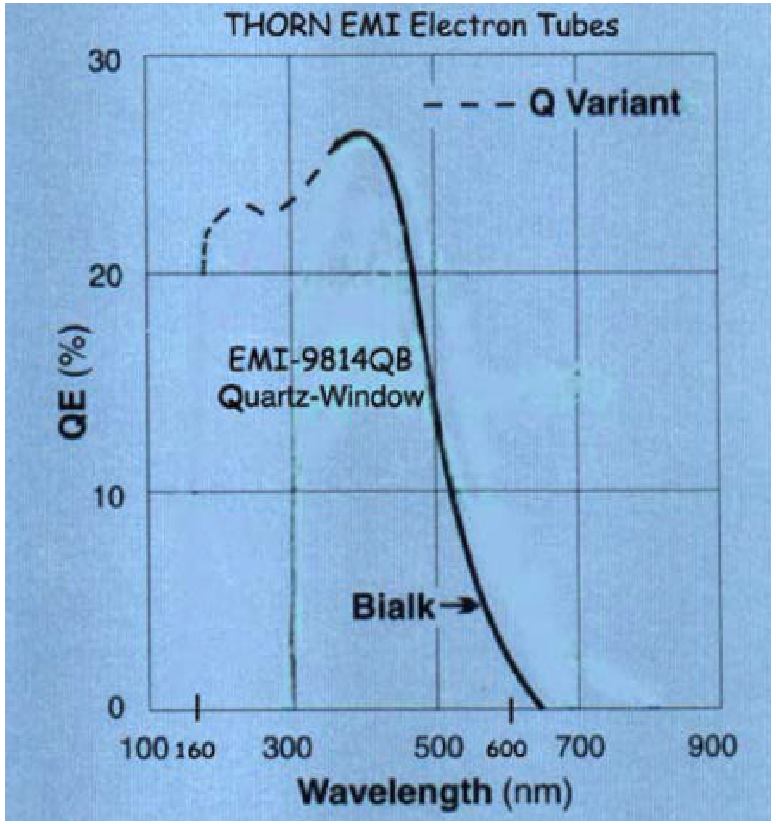
VUV scintillation light readout

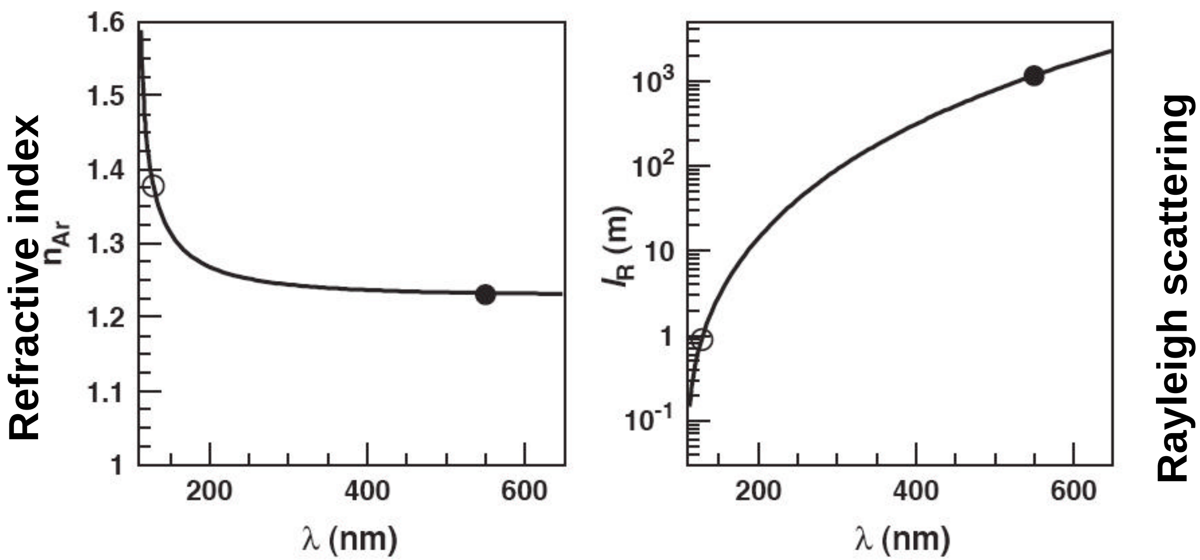


Cerenkov

Cerenkov light readout

ICARUS Collab., *Detection of Cerenkov light emission in liquid Argon,* NIM A 516 (2004) 348
(Immersed PMT 2" EMI-9814 BQ with sensitivity up to 160 nm)





Data consistent with Cerenkov emission:

dN/dx (160-600 nm) ˜ 700 γ/cm (β˜ 1)

Future applications

Liquid Argon TPC:

physics calls for applications at two different mass scales

100 ton

- Precision studies of ν interactions
- Calorimetry
- Near station in LBL facilities

100 kton

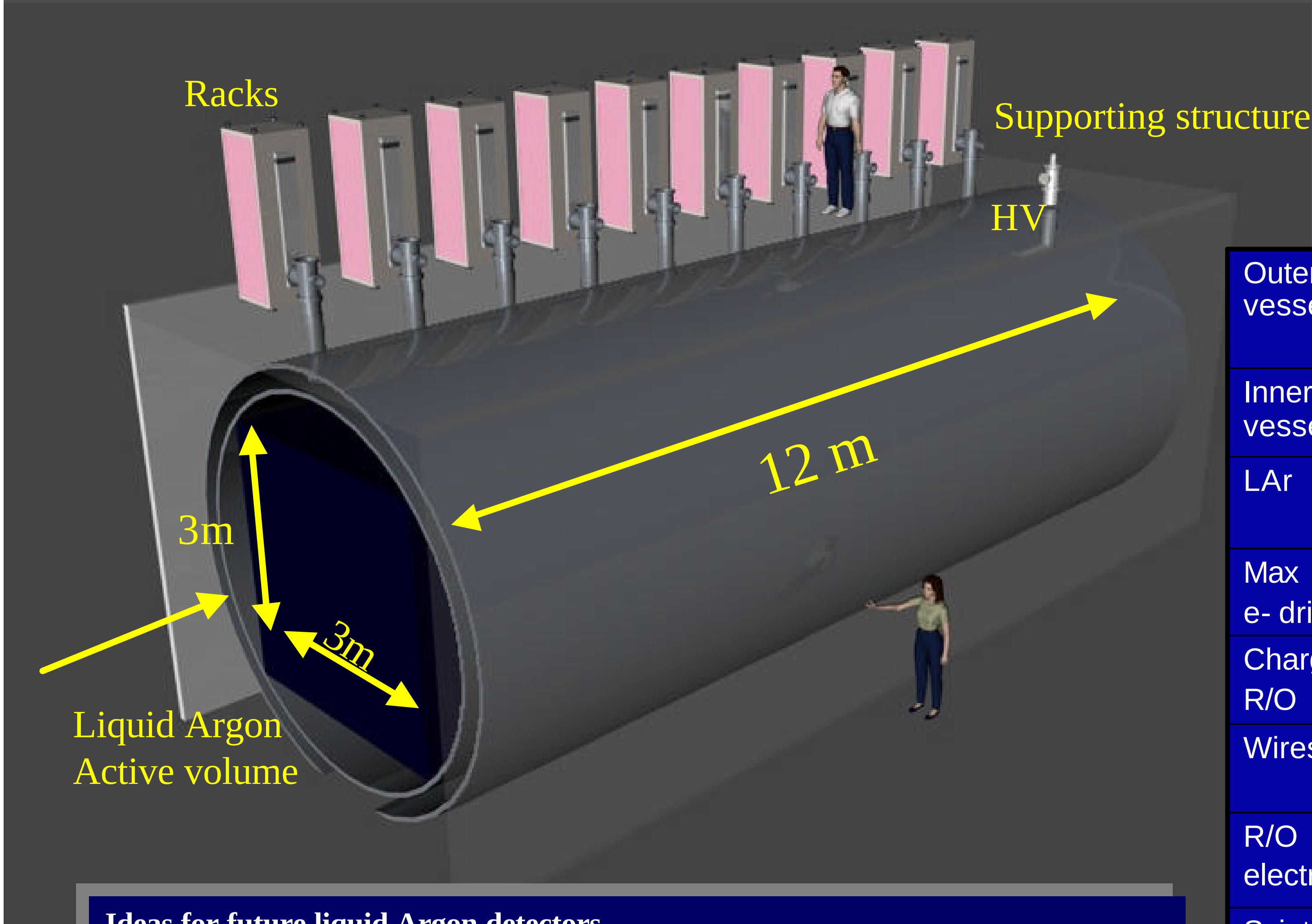
- Ultimate nucleon decay searches
- Astroparticle physics
- CP violation in neutrino mixing

Strong synergy and high degree of interplay

Need to coherently develop conceptual ideas within the international community

Conceptual design of a ~100 ton LAr TPC for a near station in a LBL facility:

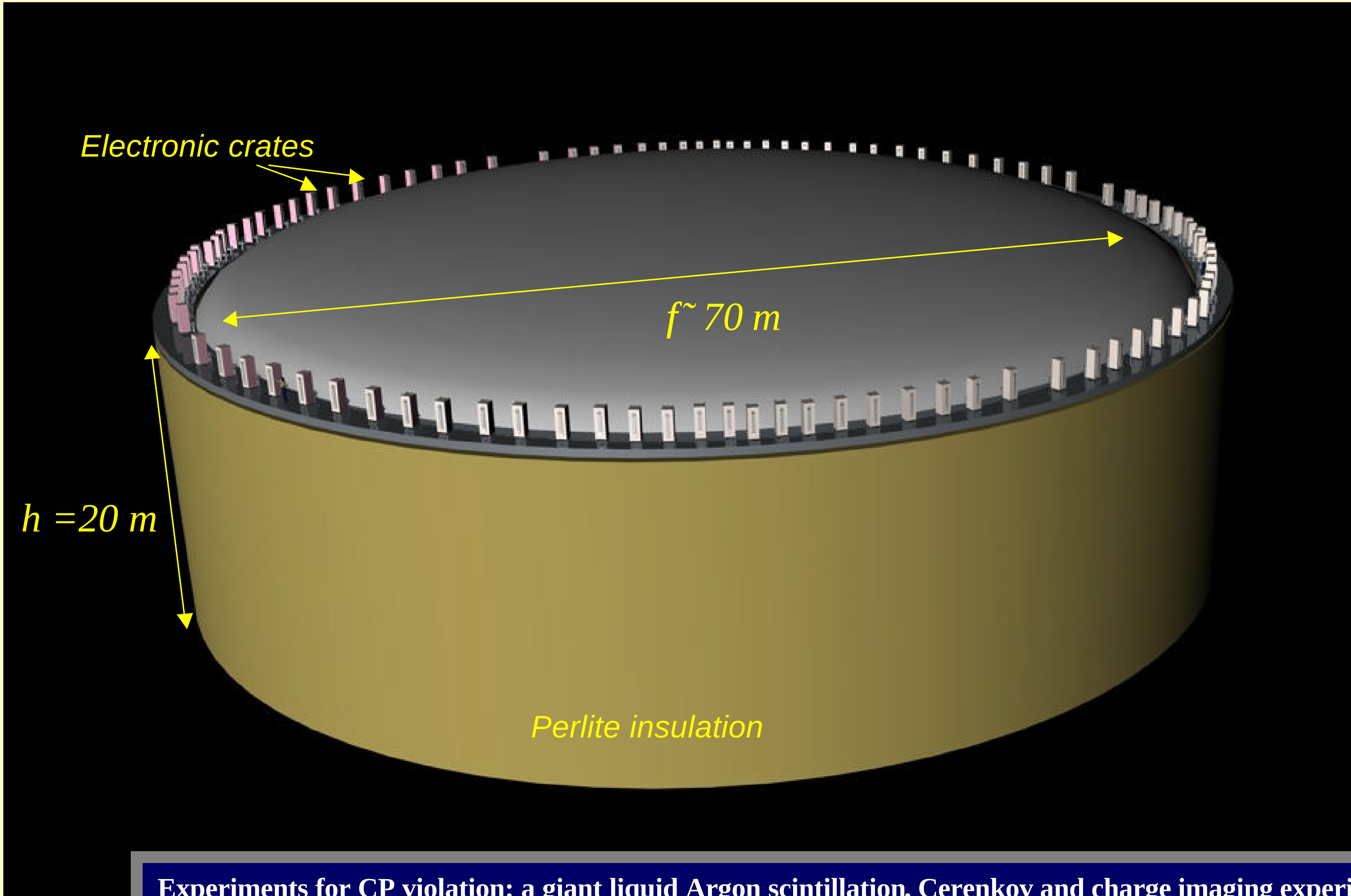
a possibility to be further explored



Outer vessel	ϕ ˜ 5m, L˜13m, 15mm thick, weight ˜ 22 t
Inner vessel	ϕ ˜ 4,2 m, L ˜ 12 m, 8 mm thick, ˜ 10 t
LAr	Total ˜ 240 t Fiducial ˜ 100 t
Max e- drift	3 m @ HV=150 kV E = 500 V/cm
Charge R/O	2 views, ± 45° 2 (3) mm pitch
Wires	˜10000 (7000) f = 150 μm
R/O electr.	on top of the dewar
Scintill. light	Also for triggering

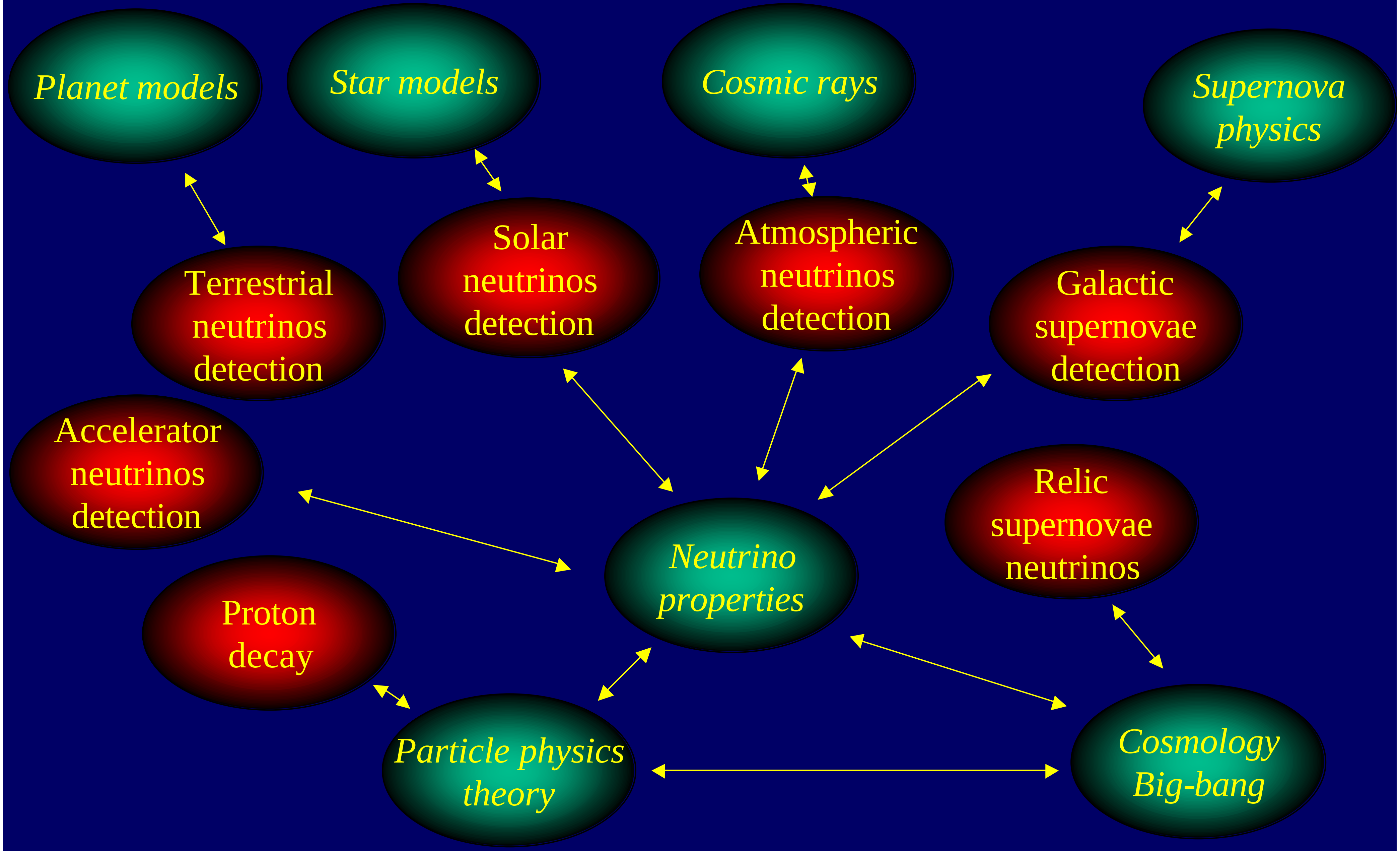
Ideas for future liquid Argon detectors
A.Ereditato, A.Rubbia, to appear in Proc. of NUINT04, LNGS, March 2004

100 kton liquid Argon TPC detector



Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment.
A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, hep-ph/0402110

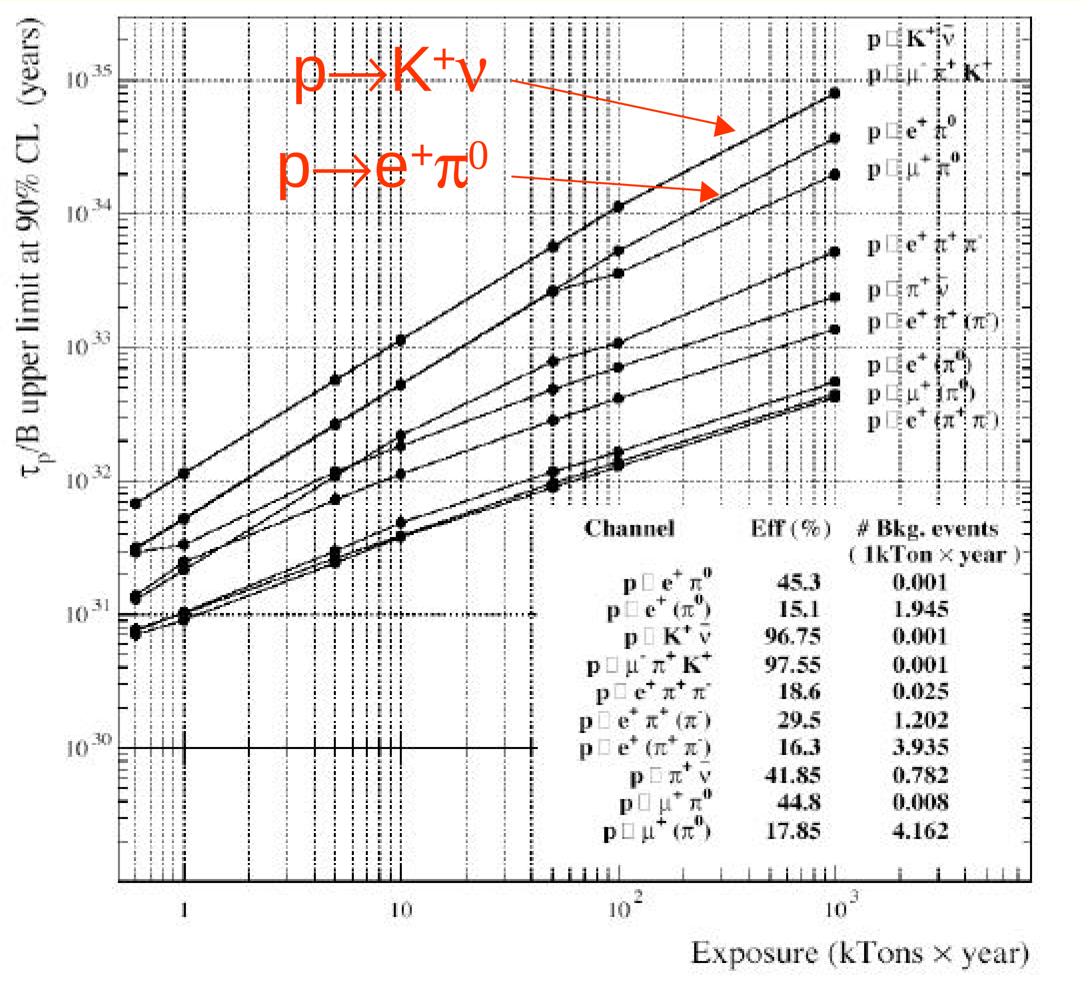
Vast physics program



	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
Cost	$\approx$ 500 M$	Under evaluation
$p \rightarrow e\,\pi^0$ in 10 years	10^{35} years ε = 43%, $\approx$ 30 BG events	3×10^{34} years ε = 45%, 1 BG event
$p \rightarrow \nu K$ in 10 years	2×10^{34} years ε = 8.6%, $\approx$ 57 BG events	8×10^{34} years ε = 97%, 1 BG event
$p \rightarrow \mu\,\pi\,K$ in 10 years	No	8×10^{34} years ε = 98%, 1 BG event
SN cool off @ 10 kpc	194000 (mostly $\bar{\nu}_e p \rightarrow e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	$\approx$330 ν-e elastic scattering	380 ν_e CC (flavor sensitive)
SN relic	Yes	Yes
Atmospheric neutrinos	60000 events/year	10000 events/year
Solar neutrinos	E_e > 7 MeV (central module)	324000 events/year E_e > 5 MeV

Review of massive underground detectors
A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, March 2004

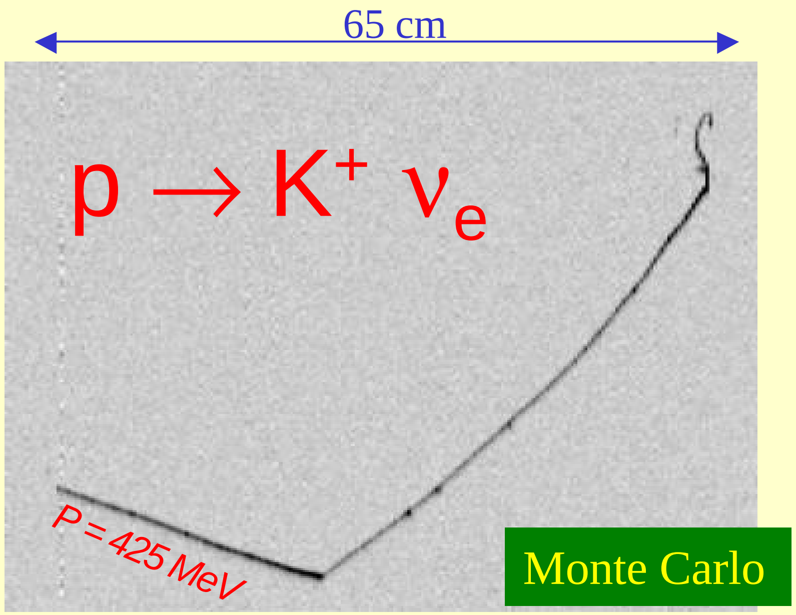
Proton decay: sensitivity vs exposure



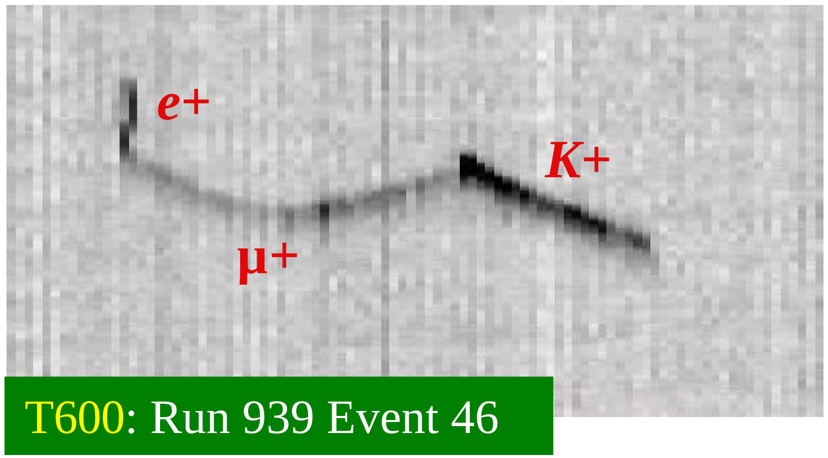
Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	45.3	0.001
$p \to e^+ (\pi^0)$	15.1	1.945
$p \to K^+ \bar{\nu}$	96.75	0.001
$p \to \mu^- \pi^+ K^+$	97.55	0.001
$p \to e^+ \pi^+ \pi^-$	18.6	0.025
$p \to e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \to e^+ (\pi^+ \pi^-)$	16.3	3.935
$p \to \pi^+ \bar{\nu}$	41.85	0.782
$p \to \mu^+ \pi^0$	44.8	0.008
$p \to \mu^+ (\pi^0)$	17.85	4.162

6×10^{34} nucleons $\Rightarrow$

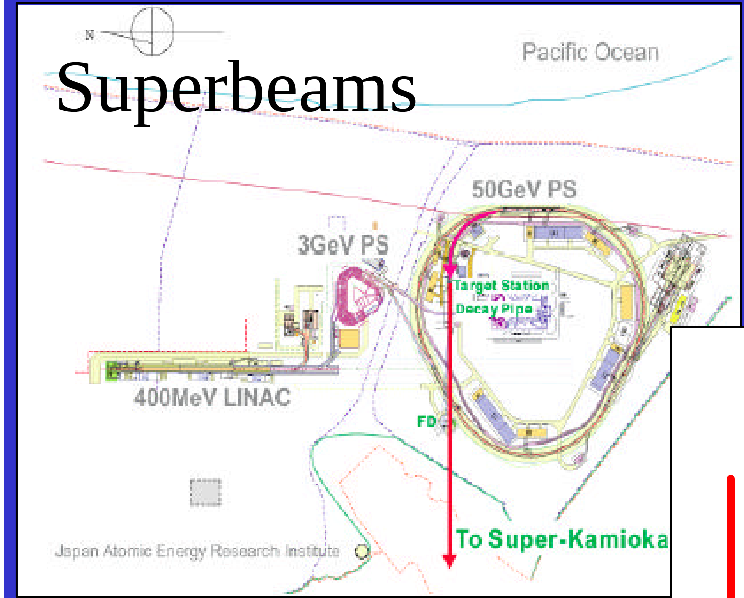
$\tau_p/Br > \sim 10^{34}$ years $\times$ T(yr) $\times\ \varepsilon$ @ 90 CL



"Single" event detection capability

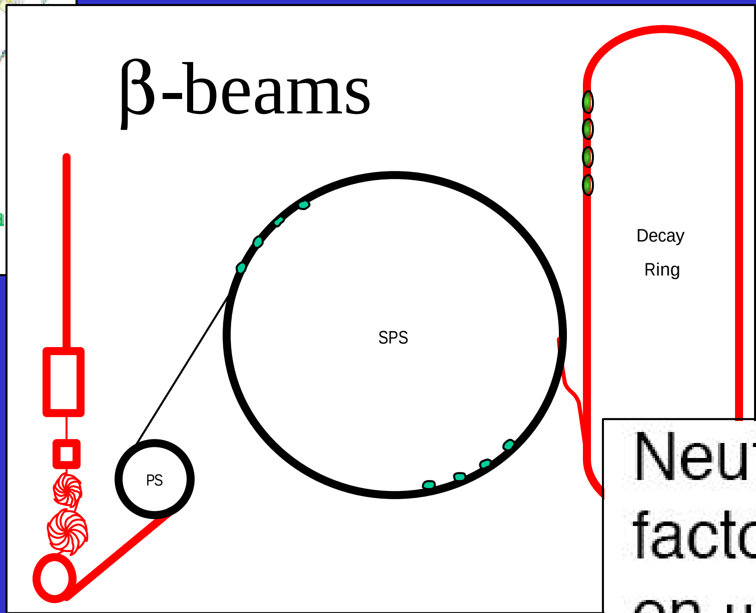


Accelerator neutrinos



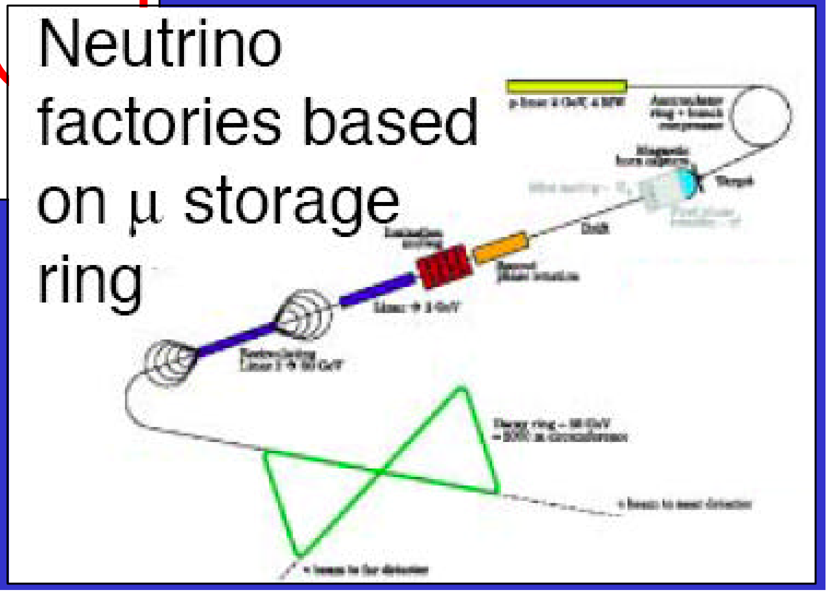
$$p^{\pm} \rightarrow m^{\pm} \overset{(-)}{n}_m$$

Select focusing sign



$$^{Z}A \rightarrow {}^{Z\mp1}A\ b^{\pm}\ \overset{(-)}{n}_e$$

Select ion



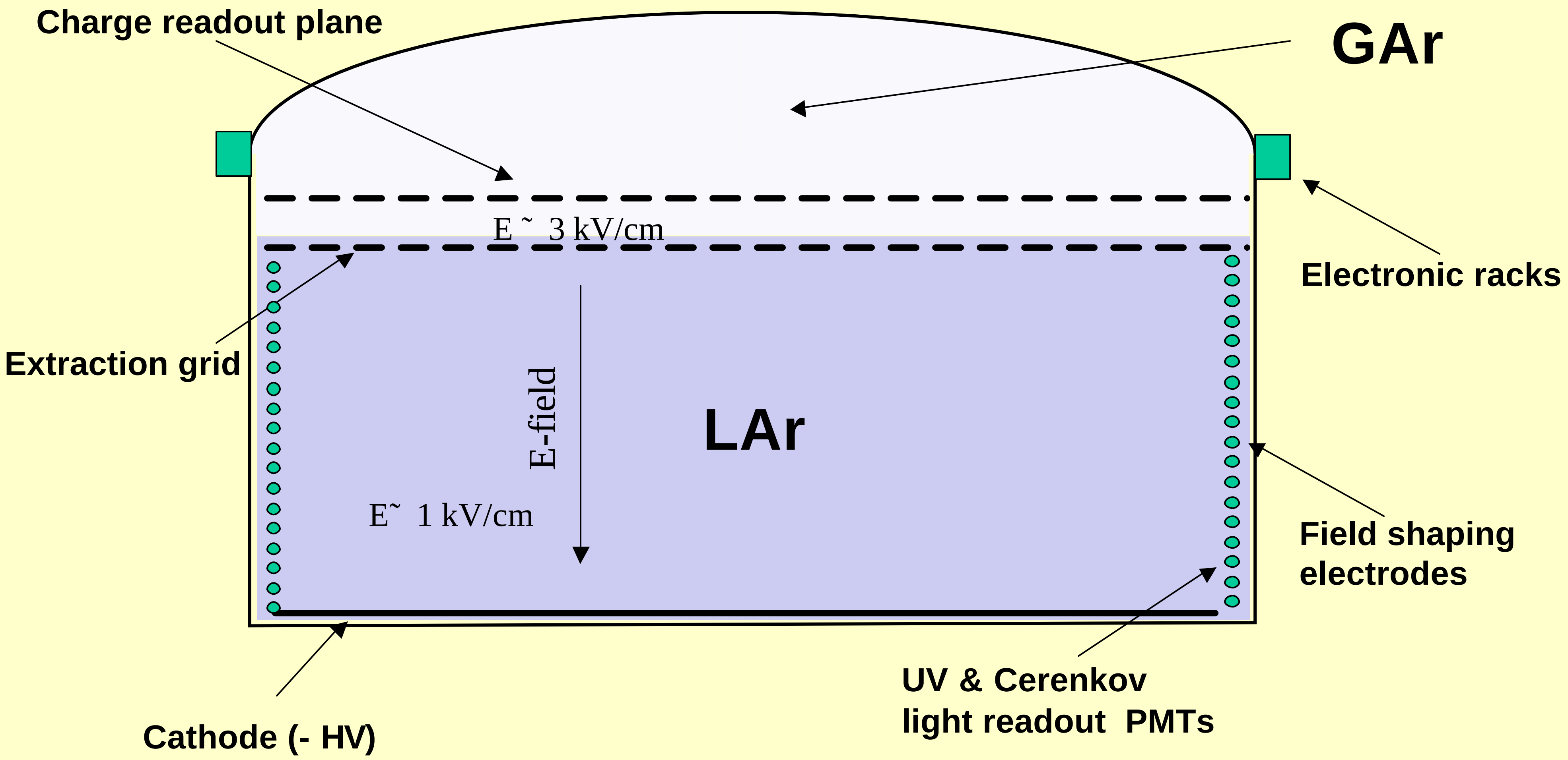
$$\left.\begin{aligned} m^- &\rightarrow e^- \bar{n}_e n_m \\ m^+ &\rightarrow e^+ n_e \bar{n}_m \end{aligned}\right\}$$

Select ring sign

Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches, A.Ereditato, A.Rubbia, Memo to the SPSC, April 2004.

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light



Tentative parameter list

Dewar	**ϕ ~ 70 m, height ~ 20 m, perlite insulated, heat input ~ 5 W/m^2**
Argon storage	**Boiling Argon, low pressure (<100 mbar overpressure)**
Argon total volume	**73000 m^3, ratio area/volume ~ 15%**
Argon total mass	**102000 tons**
Hydrostatic pressure at bottom	**3 atmospheres**
Inner detector dimensions	**Disc f ~70 m located in gas phase above liquid phase**
Charge readout electronics	**100000 channels, 100 racks on top of the dewar**
Scintillation light readout	**Yes (also for triggering), 1000 immersed 8“ PMTs with WLS**
Visible light readout	**Yes (Cerenkov light), 27000 immersed 8“ PMTs of 20% coverage, single g counting capability**

Charge extraction, amplification, readout

Detector is running in bi-phase mode

- Long drift (˜ 20 m) ⇒ charge attenuation to be compensated by charge amplification near anodes located in gas phase (18000 e^- / 3 mm for a MIP in LAr)
- Amplification operates in proportional mode
- After maximum drift of 20 m @ 1 kV/cm ⇒ diffusion ˜ readout pitch ˜ 3 mm

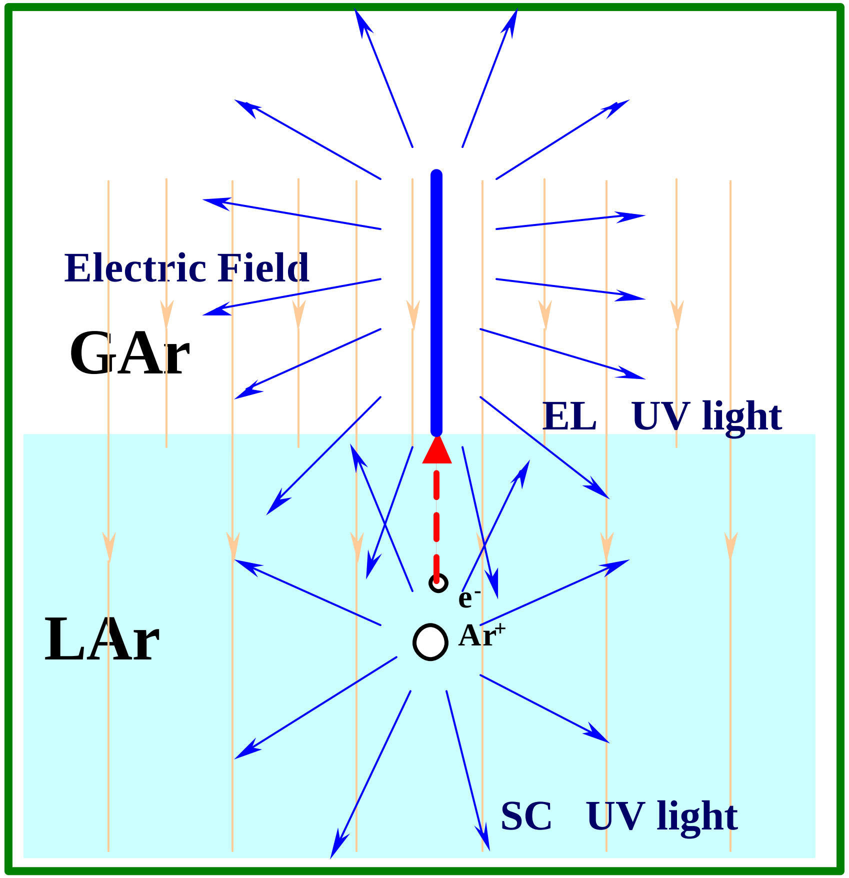
Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm, v_d ˜ 2 mm/µs, max drift time ˜ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**s ˜ 2.8 mm (v2Dt$_{max}$ for D = 4 cm^2/s)**
Maximum charge attenuation	**$e^{-(tmax/t)}$ ˜ 1/150 for t = 2 ms electron lifetime**
Needed charge amplification	**From 100 to 1000**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires (f ˜ 30 mm) + pad readout, GEM, LEM, …**

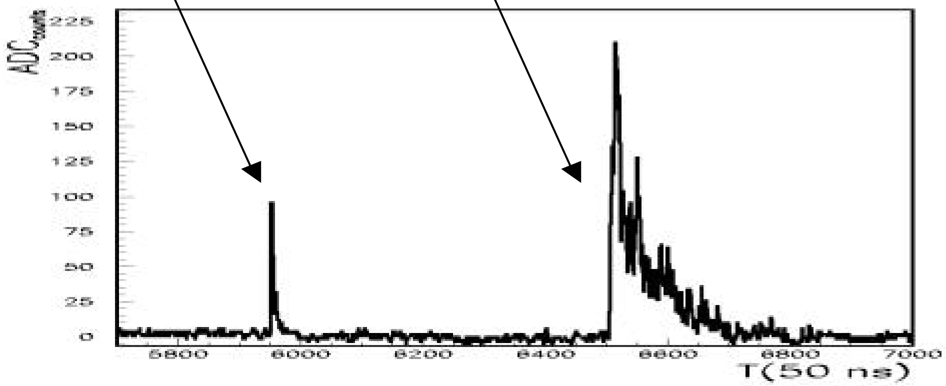
Electron extraction in LAr bi-phase

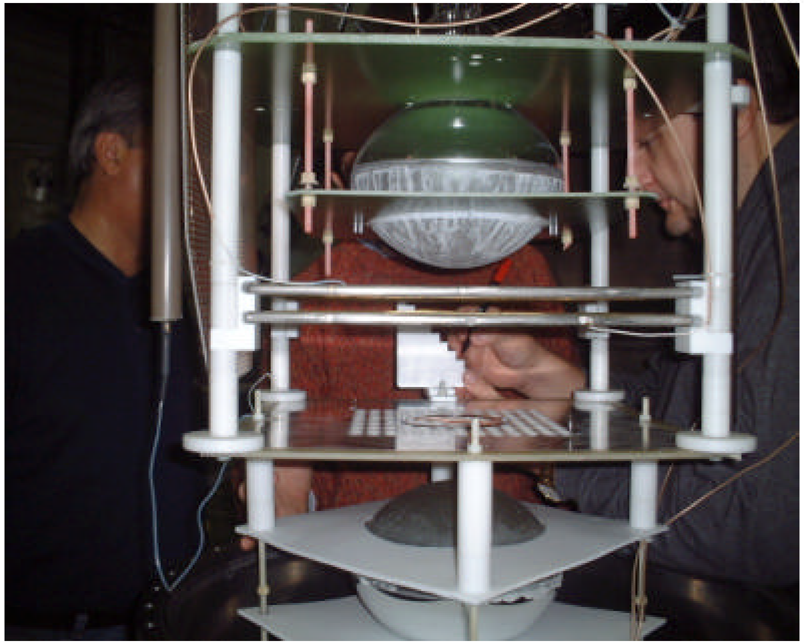
Particle produces excitation (Ar*) and ionization (Ar^+, e)

Scintillation **SC** is a result of direct excitation and recombination

Electro-luminescence **EL** (proportional scintillation) is a result of electron acceleration in the gas







Both SC and EL can be detected by the same photo-detector

Cryogenic storage tankers for LNG

LNG* = <u>*L*</u>*iquefied* <u>*N*</u>*atural* <u>*G*</u>*as

About 2000 cryogenic tankers exist in the world, with volume up to ~ 200000 m^3

Process, design and safety issues already solved by petrochemical industry

Cryogenic storage tankers for LNG

WHAT ARE THEY ?

- A natural gas cooled to about -160°C at atmospheric pressure condenses to a liquefied natural gas (LNG).
- If vaporized it burns in concentrations of 5% to 15% mixed with air.
- Natural gas mostly contains methane (> 90%) together with ethane, propane and heavier hydrocarbons.

HOW ARE LNG STORED ?

- LNG tankers are of double-wall construction with very efficient insulation between the walls.
- Large tankers have low aspect ratio (height to width), cylindrical in design with a domed roof.
- Storage pressures are very low.

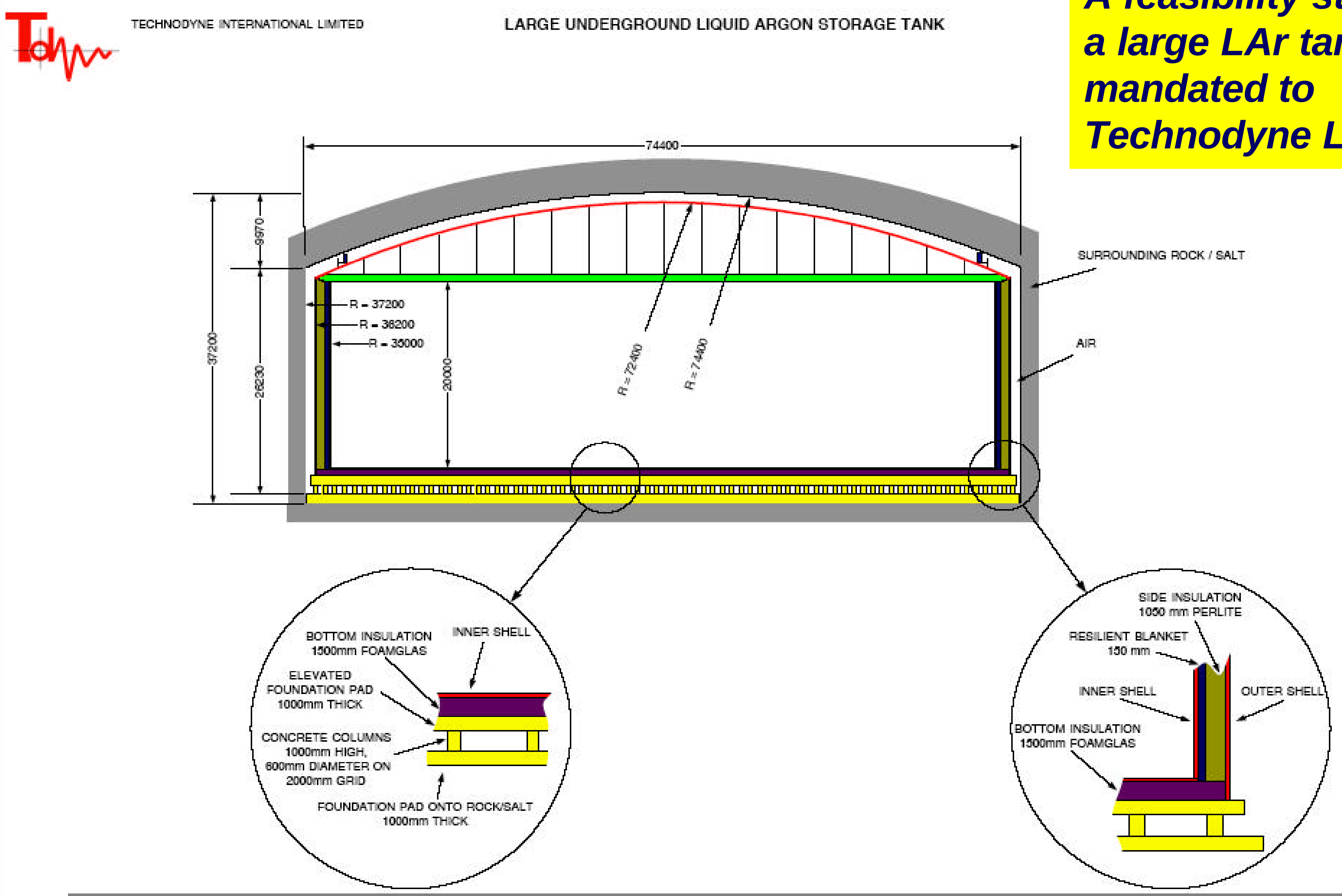
HOW ARE LNG KEPT COLD ?

- The insulation (although efficient) cannot keep LNG cold by itself.
- LNG is stored as a boiling cryogen: a cold liquid at its boiling point for the pressure it is being stored.
- LNG stays at constant T if kept at constant P (auto-refrigeration),
- If the steam of LNG vapor boil-off can leave the tanker, the temperature will remain constant.

HAVE THERE BEEN SERIOUS LNG ACCIDENTS ?

- In the last 60 years: only 2 spontaneous ruptures of large refrigerated tankers.
- The first one in Cleveland in 1944 with a resulting explosion: caused by a brittle fracture of the steel (3.5% Ni).
- Since then: grade of steel increased to a minimum of 9% Ni.
- The second incident was in Qatar in 1977: caused by the failure of a weld repaired following a leak found in 1976.
- The worldwide refrigerated tank population is estimated to about 2000, mostly built in the last 40 years: this gives a catastrophic rupture frequency of 2.5×10^{-5} per tanker year.
- There has been no failure for LNG tankers built to recent codes, materials and quality standards.
- **Catastrophic failure is definitely discounted as a mode of failure.**

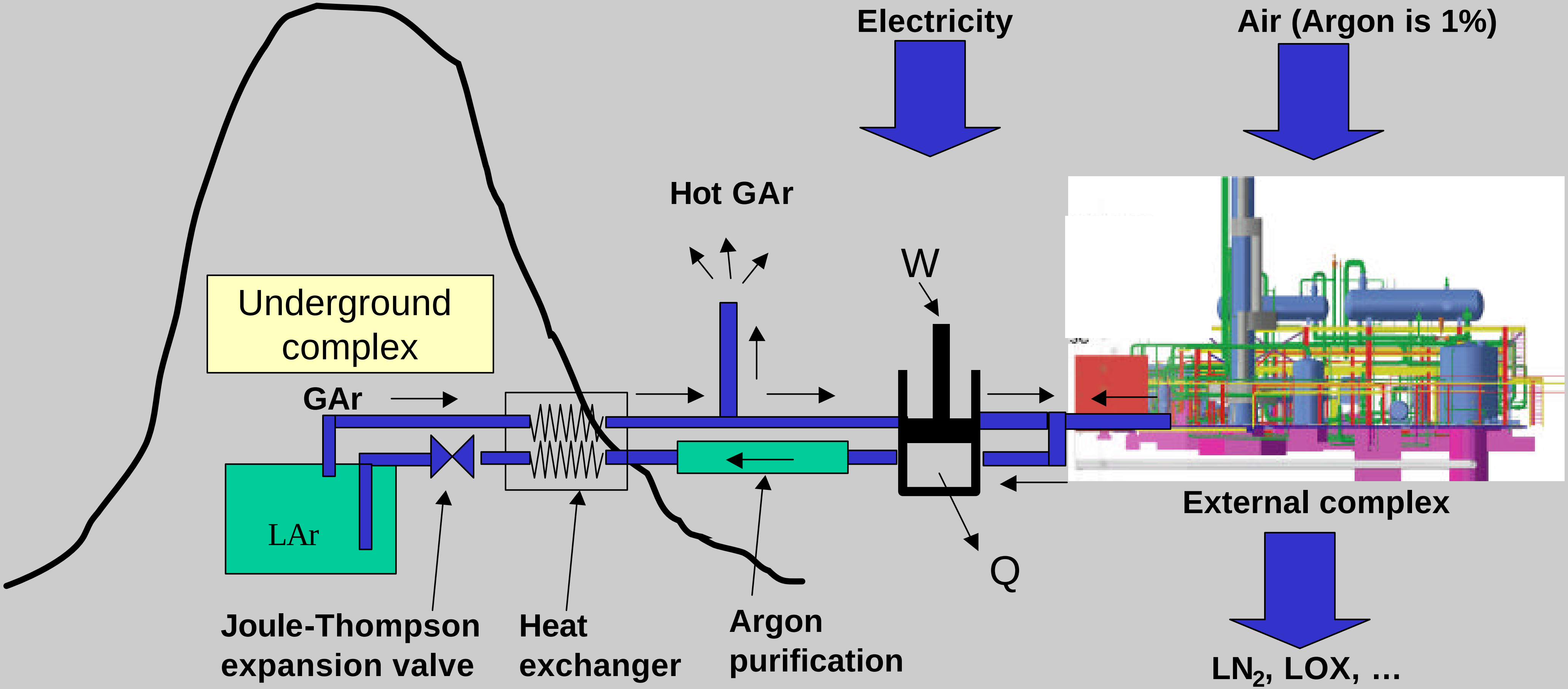
A feasibility study for a large LAr tanker mandated to Technodyne LtD (UK)



Work in progress: Underground storage, engineering issues, process system & equipment, civil engineering consulting, safety, cost & time

Process system & equipment

- Filling speed (100 kton): 150 ton/day → 2 years to fill, 10 years to evaporate !!
- Initial LAr filling: decide most convenient approach: transport LAr or in situ cryogenic plant
- Tanker 5 W/m^2 heat input, continuous re-circulation (purity)
- Boiling-off volume at regime: 30 ton/day: refilling



100 kton detector: milestones

- **Nov 2003: Venice Workshop**
  - Basic concepts: LNG tanker, signal amplification, single detector for charge imaging, scintillation and Cerenkov light readout
  - Design given for proton decay, astrophysics ν's, Super-Beams, Beta-Beams
  - Stressed the need for detailed comparison: 1 Mton water versus 100 kton LAr detector
- **Feb 2004: Feasibility study launched for underground liquid Argon storage**
  - Industry: Technodyne (UK) mandated for the study (expert in LNG design)
  - Design provided as input to the Fréjus underground lab study
  - Salt mine in Poland being investigated as well as other possible sites
- **March 2004: NUINT04 Workshop**
  - Identification of a global strategy: synergy between 'small' and 'large' mass LAr TPC
  - Intent to define a coherent International Network to further develop the conceptual ideas
- **April 2004 : Memo to the SPSC in view of the Villars special session (Sept. 2004)**
- **Engineering studies, dedicated test measurements, detector prototyping, simulations, physics performance studies in progress** →
- **200x : 10 kton full-scale prototype ? 201x: 100 kton detector…**

Ongoing studies and initial R&D strategy

1) Study of suitable charge extraction, amplification and imaging devices

2) Understanding of charge collection under high pressure

3) Realization and test of a 5 m long detector column-like prototype

4) Study of LAr TPC prototypes immersed in a magnetic field

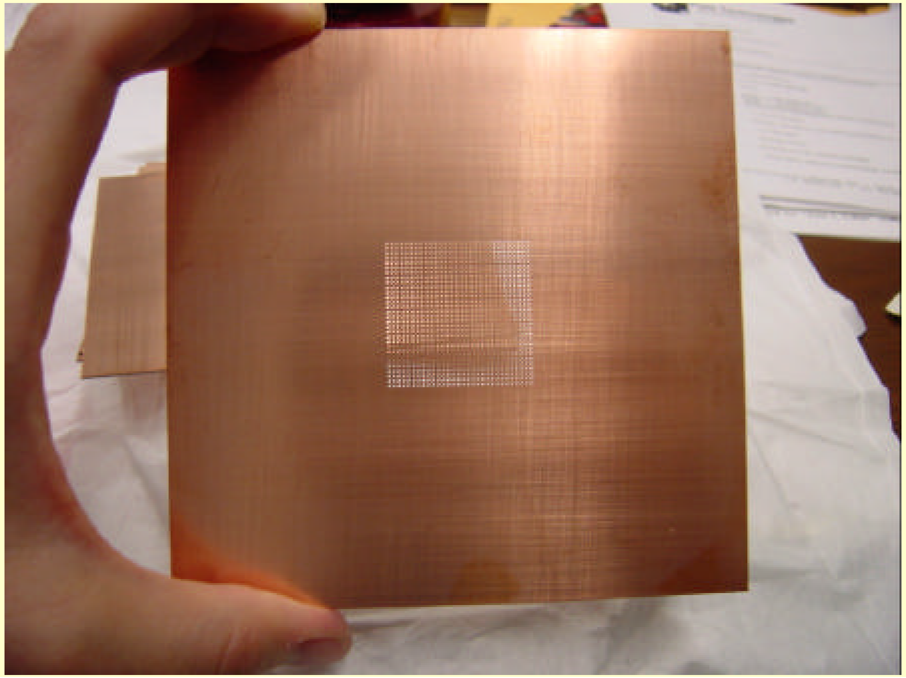
5) Study of logistics, infrastructure and safety issues for underground sites

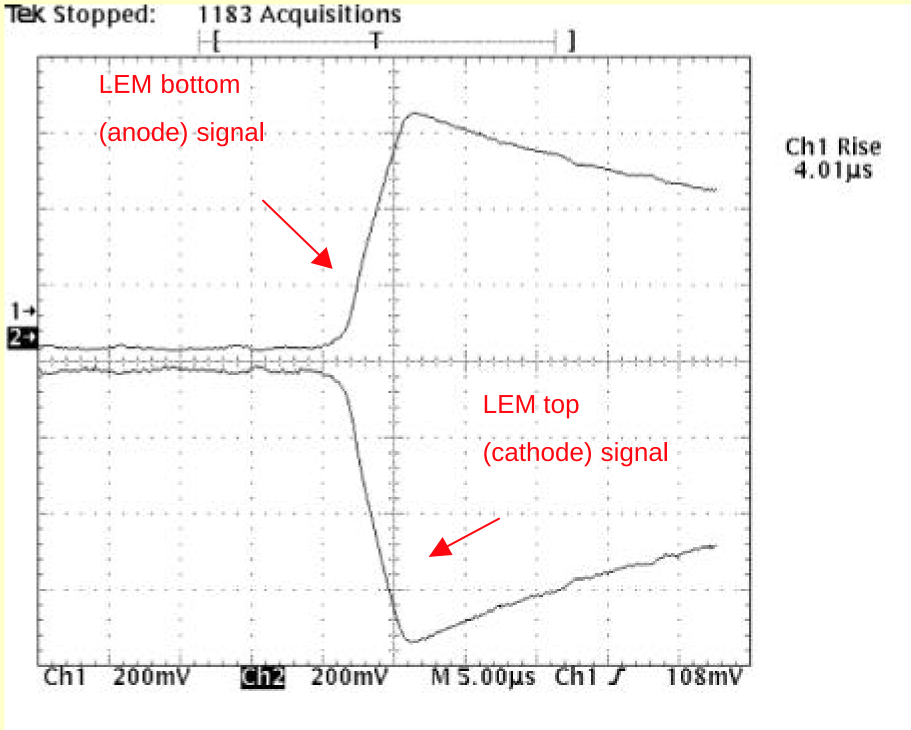
1) Amplification with Large Electron Multiplier (LEM)

P. Jeanneret et al.,
NIM A 500 (2003) 133-143

- **A large scale GEM (x10) made with ultra-low radioactivity materials (copper plated on virgin Teflon)**
  - In-house fabrication using automatic micro-machining
  - Modest increase in V yields gain similar to GEM
  - Self-supporting, easy to mount in multi-layers
- **Resistant to discharges (lower capacitance by segmentation)**
  - Cu on PEEK under construction (zero out-gassing)

P.S. Barbeau J.I. Collar J. Miyamoto I.P.J. Shipsey

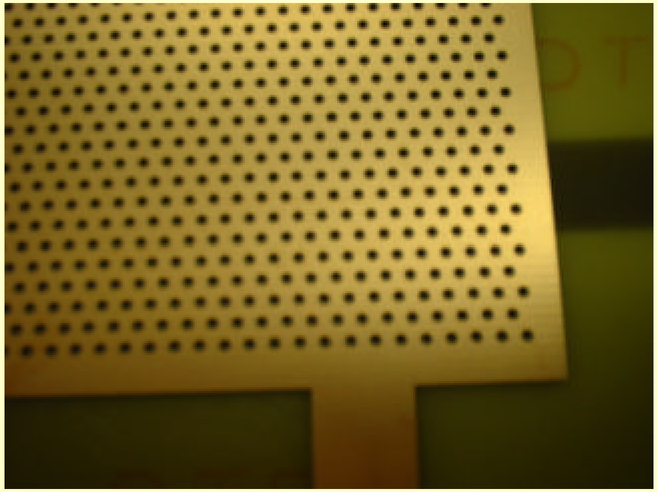




LEM with Argon

Detection of charge signal and scintillation light produced during amplification

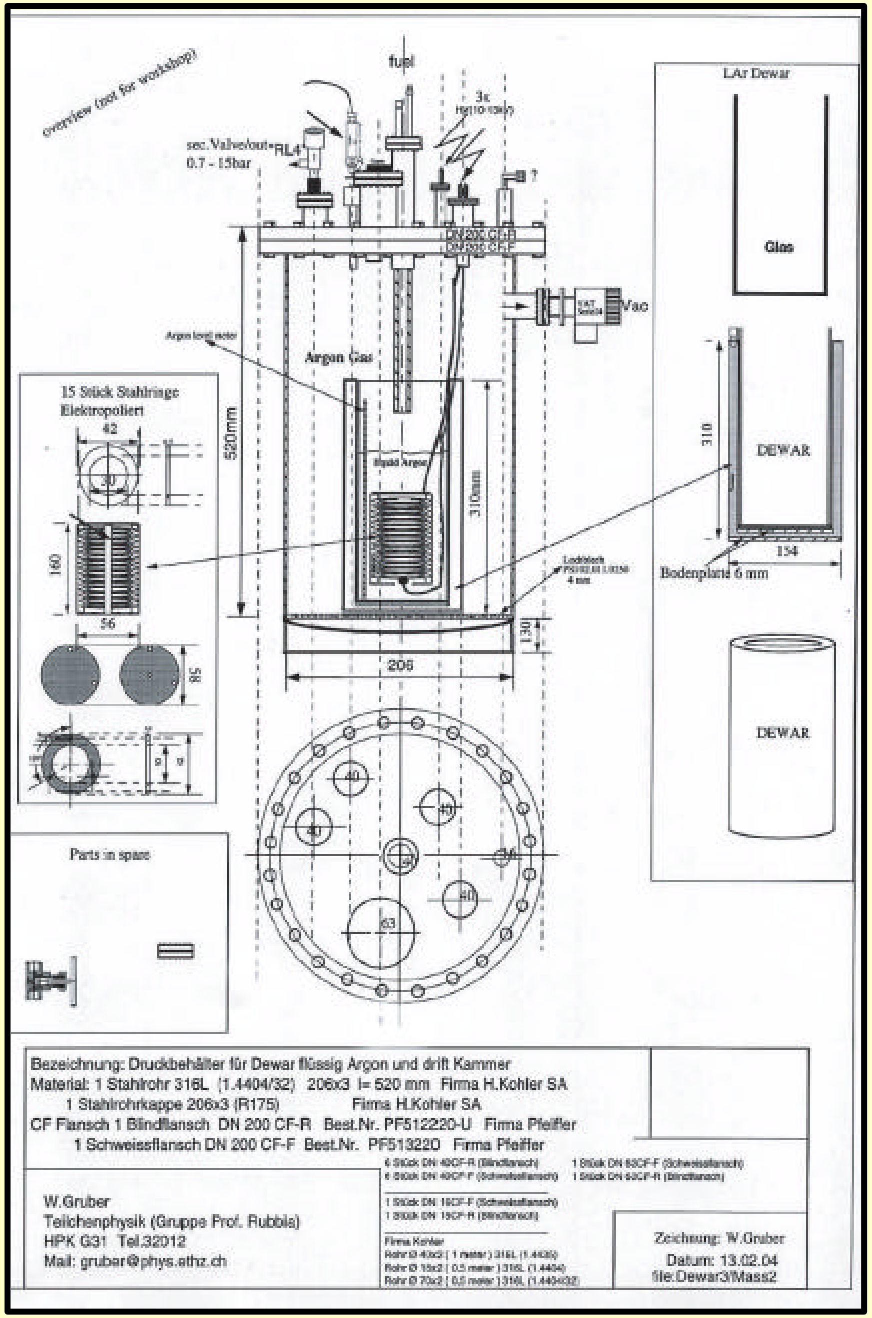
400 x 400 mm^2



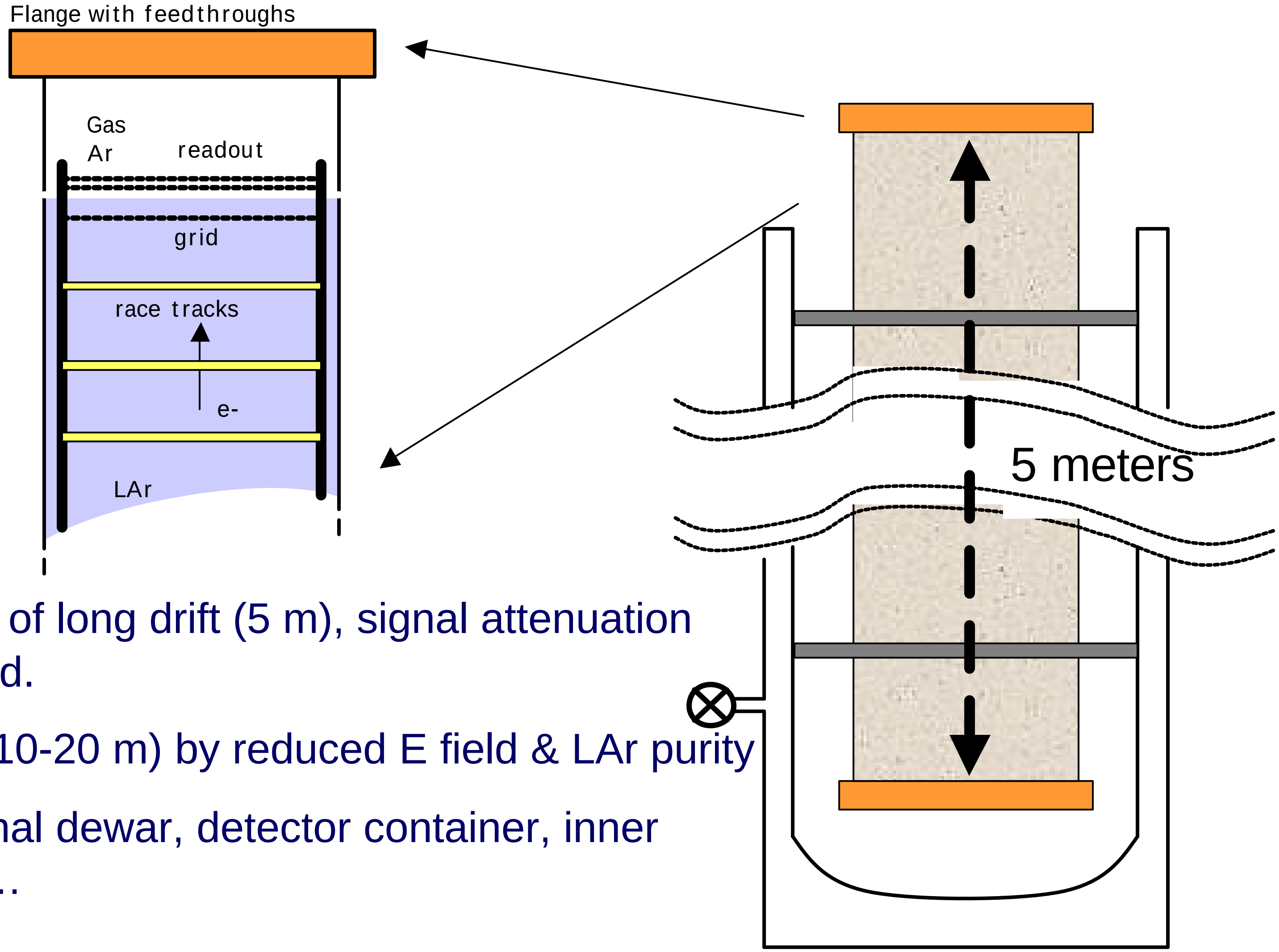
Holes ϕ = 1 mm

2) High-pressure drift properties

- **Future large tankers:**
  Hydrostatic pressure could be quite significant (3-4 atmosphere at the bottom of the tanker)
- **Test of electron drift properties in high pressure liquid Argon**
  Important to understand the electron drift properties and imaging under high pressure
- **Study in progress**
  Prototype designed



3) Long drift, extraction, amplification: test module



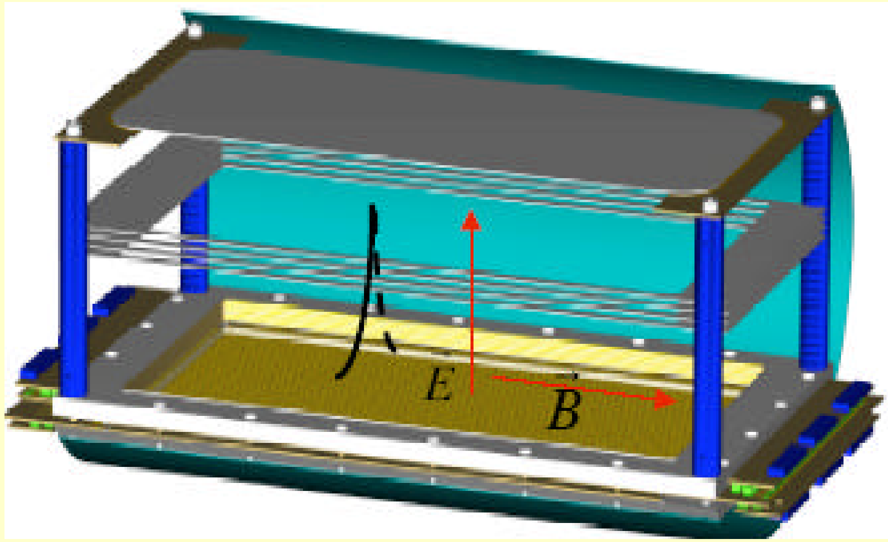
• A full scale measurement of long drift (5 m), signal attenuation and multiplication is planned.

• Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity

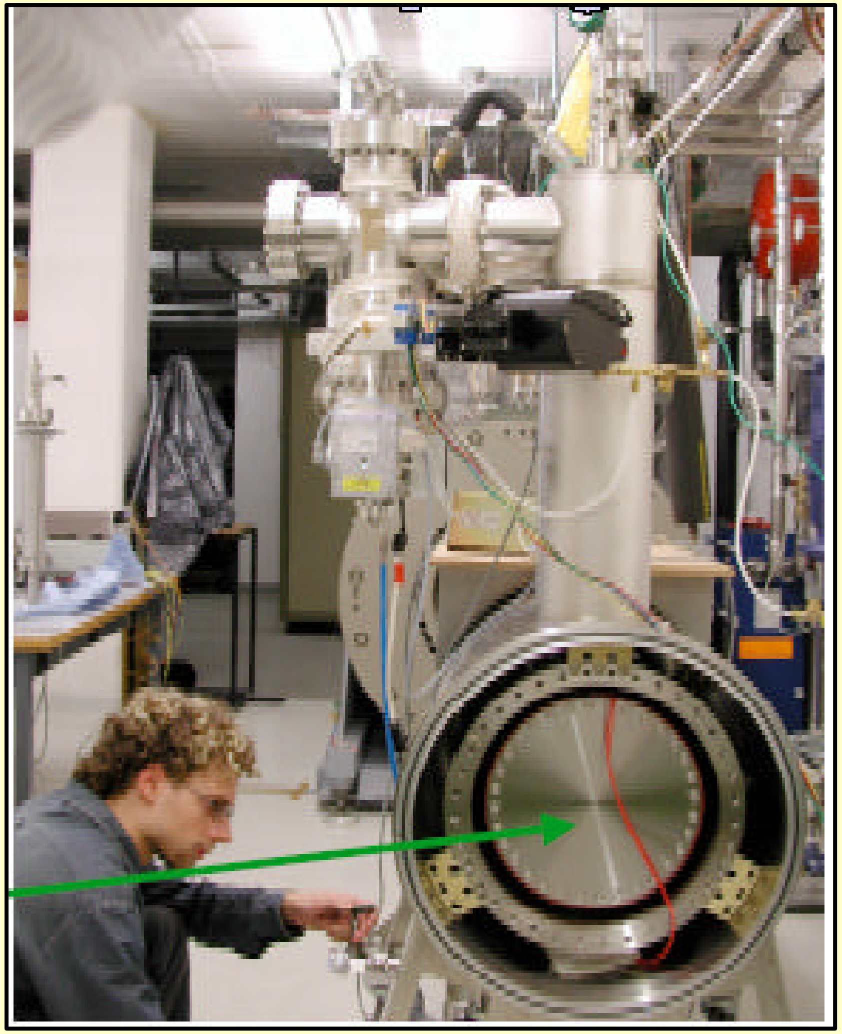
• Design in progress: external dewar, detector container, inner detector, readout system, …

4) Test of liquid Argon imaging in B-field

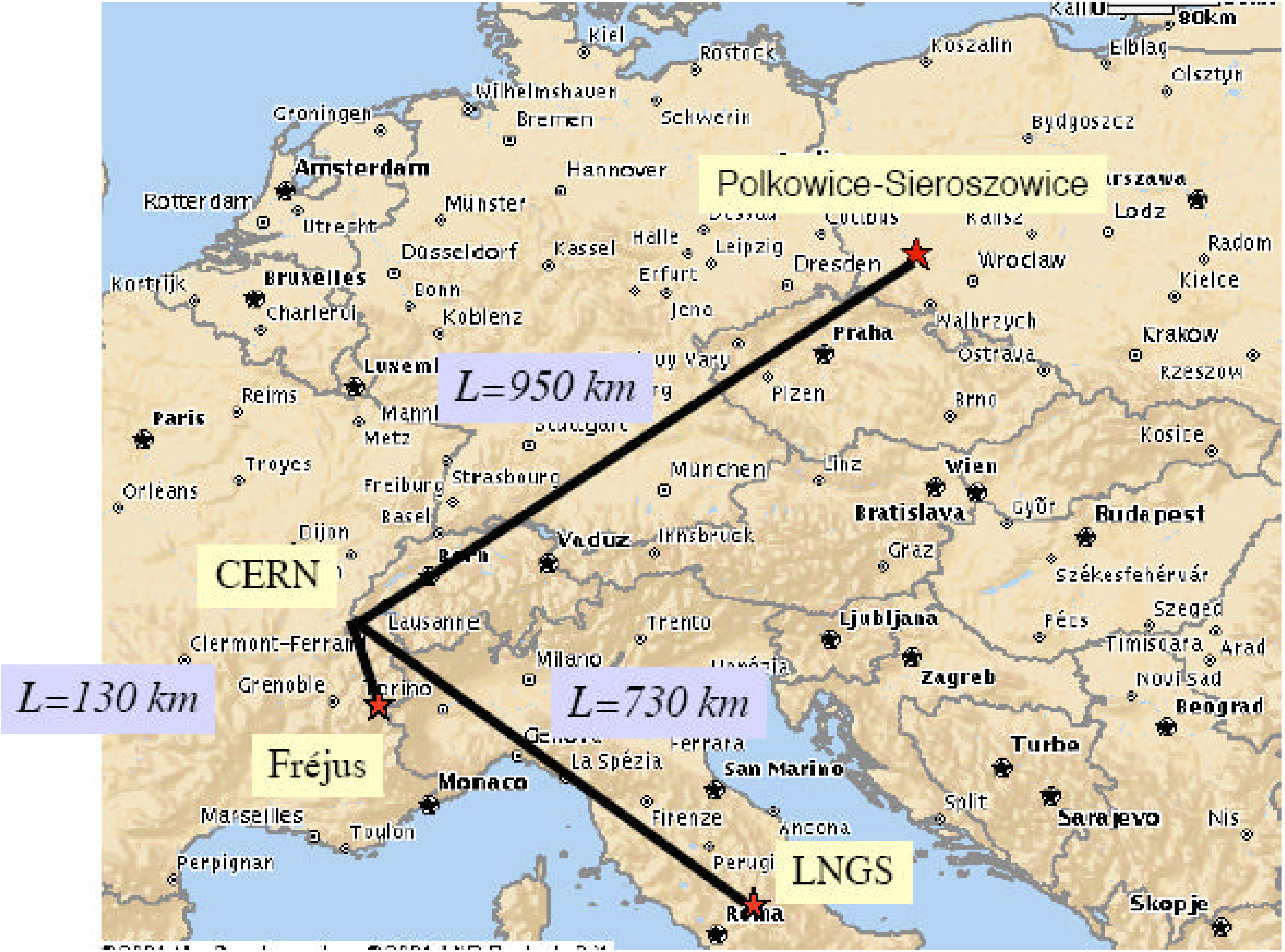
- **Small chamber with recycled magnet up to B = 0.5 T (230 kW) given by PSI**
- **Test program:**
  - Check basic imaging in B-field
  - Measure traversing and stopping μ bending
  - Charge discrimination
  - Lorentz angle α ˜ 30mrad @ E= 500 V/cm, B= 0.5 T



Width 300 mm, height 150 mm, drift length 150 mm

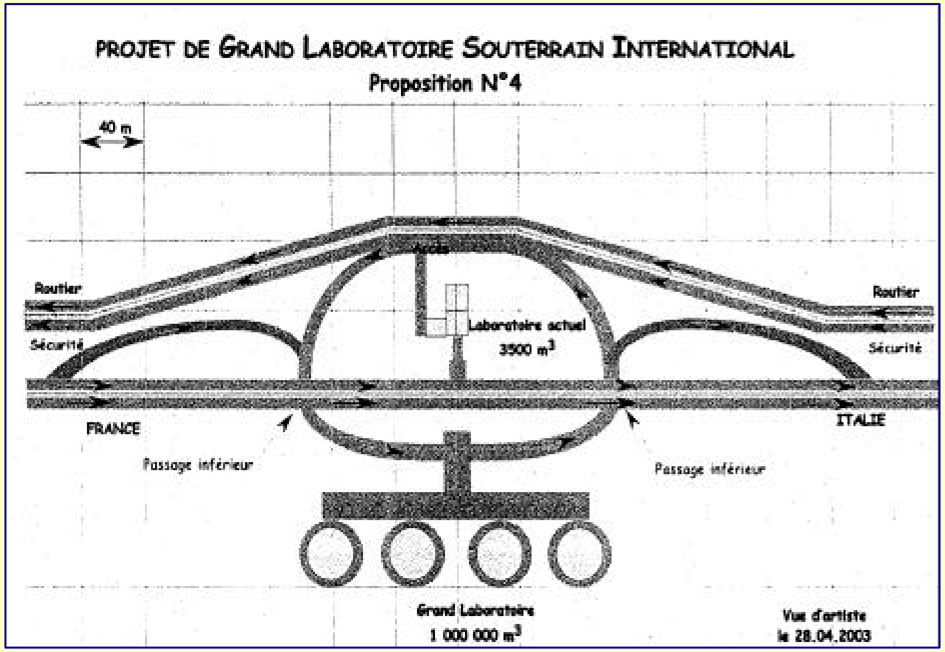


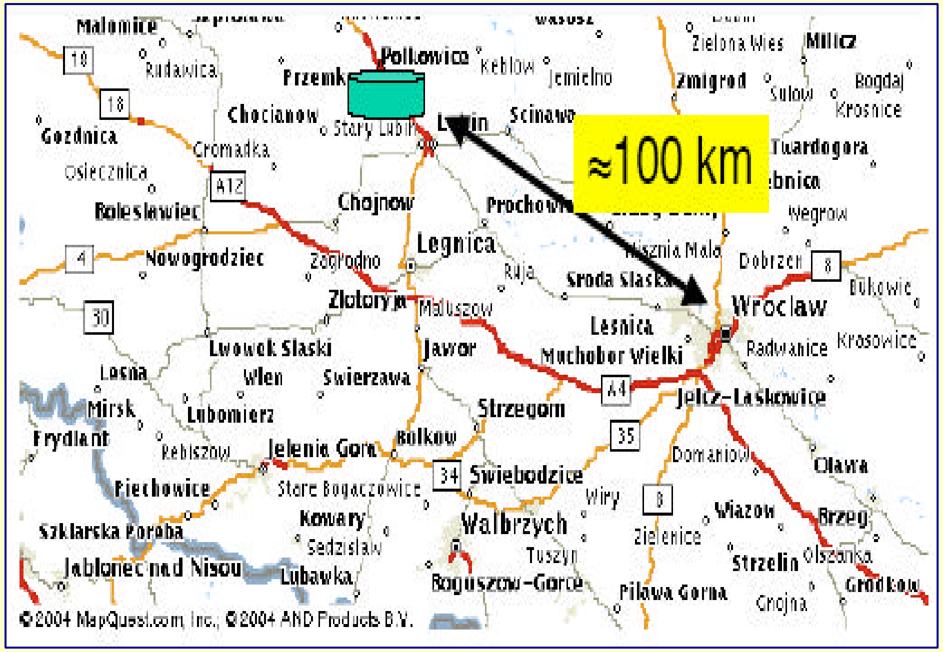
5) Example: underground sites in Europe



Two different topologies envisioned for the site:

1. **Hall access via highway tunnel tunnel (Fréjus laboratory project)**
2. **Deep mine-cavern with vertical access (CUPRUM mines, Polkowice-Sieroszowice)**



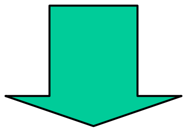


- cooperation agreement: IN2P3/CNRS/DSM/CEA & INFN
- international laboratory for underground physics
- easy access
- safety issues (highway tunnel)
- caverns have to be excavated

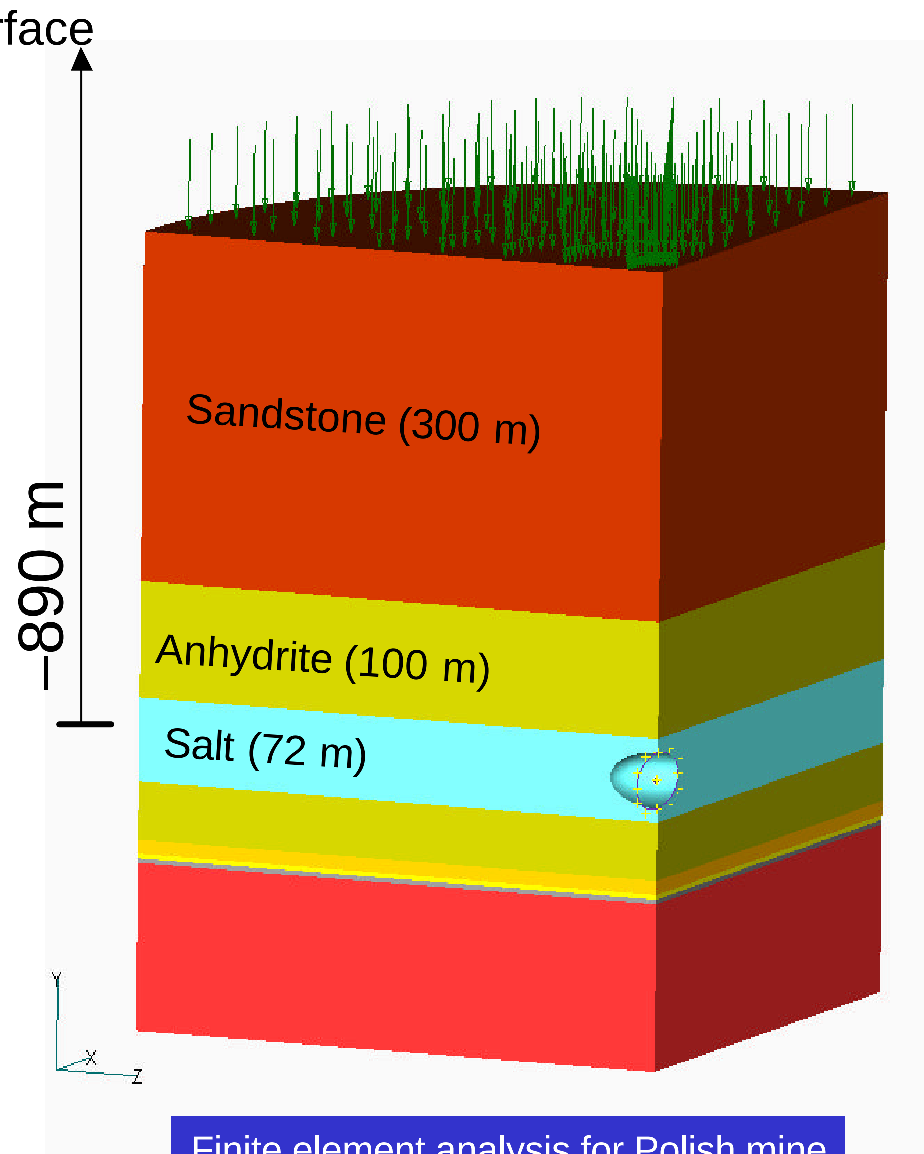
- mines by one of the largest world producers of Cu and Ag
- salt layer at ˜1000 m underground (dry)
- large caverns exist for a ˜ 80000 m³ (100 kton LAr) detector
- geophysics under study
- access through vertical shaft

Feasibility of a large underground cavern

- Geophysical instabilities limit the size of the underground cavern
- Actual size limits depend on details of rock and depth and on the wished cavern geometry
- Contact with Mining and Metallurgy department (Krakow University) and with mining companies (A. Zalewska)
- Finite element analysis calculation for Polish mine (courtesy of Witold Pytel, CBPM "Cuprum" OBR, Wroclaw)



cavern ˜ 100000 m^3
or
tunnel-like geometry



Finite element analysis for Polish mine

Argon-Net

● The further developments of the LAr TPC technique, eventually finalized to the proposal and to the realization of actual experiments, could only be accomplished by an international community of colleagues able to identify and conduct the required local R&D work and to effectively contribute, with their own experience and ideas, to the achievement of ambitious global physics goals. In particular, this is true for a large 100 kton LAr TPC detector that would exploit next generation neutrino facilities and perform ultimate non-accelerator neutrino experiments.

● We are convinced that, given the technical and financial challenges of the envisioned projects, the creation of a Network of people and institutions willing to share the responsibility of the future R&D initiatives, of the experiment's design and to propose solutions to the still open questions is mandatory.

● The actions within the Network might include the organization of meetings and workshops where the different ideas could be confronted, the R&D work could be organized and the physics issues as well as possible experiments could be discussed. One can think of coherent actions towards laboratories, institutions and funding agencies to favor the mobility of researchers, to support R&D studies, and to promote the visibility of the activities and the dissemination of the results.

So far colleagues from 21 institutions have already expressed their Interest in joining Argon-Net, to act as 'nodes' of the network

Outlook

- **The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration. The plan is to operate a kton mass scale detector at LNGS with the ICARUS project.**

- **Today, physics is calling for applications at two different mass scales:**
  - **100 kton: proton decay, high statistics astrophysical & accelerator neutrinos**
  - **100 ton: systematic study of neutrino interactions, near detectors at LBL facilities**

- **A large mass (100 kton), monolithic LAr TPC based on the industrial technology of LNG tankers and on the bi-phase operation is conceivable (cost compatible with Mton physics program). A tentative design was given. R&D studies are in progress and a global strategy is being defined.**

- **The 100 kton detector can well match future (CERN, …) high-intensity neutrino facilities. Choice on site and beam parameters will be physics-driven. Rich non-accelerator physics program (ultimate nucleon decay searches and astroparticle physics). A 10 kton full-scale prototype is conceivable today.**

- **We presented here an overview of our current thinking & activities. Work has to further pursued along these lines of thoughts. Hope to stimulate feed-back from the community. Look forward to the creation of a dedicated world-wide Network.**