A long term strategy for the liquid argon TPC technique

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Abstract

- 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 ICARUS experiment, which acts as a sort of observatory for the study of neutrinos and the instability of matter, is starting to come together. In the summer of 2001, the first module of the ICARUS T600 detector passed brilliantly a series of tests. The year 2004 should see the detector's installation at the Underground Gran Sasso Laboratory and first data-taking should follow afterwards.

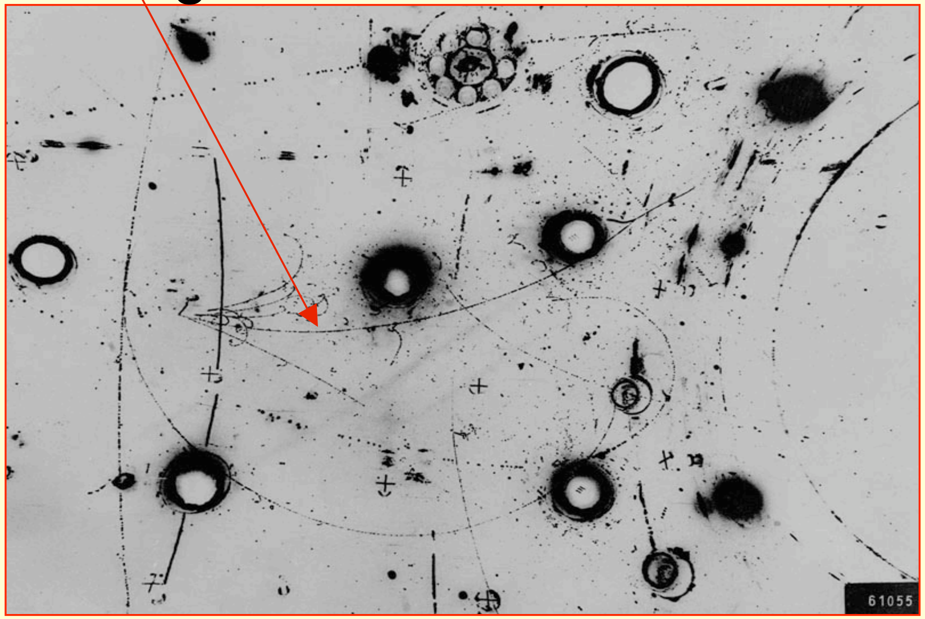
- In this talk, I will give a status report on independent ideas and on-going R&D for a 100 kton “single module” liquid Argon TPC . The scale of this module is set by the maximum size realistically achievable of the underground cavern. Larger masses can be achieved with multiple “modules”. On surface, it is possible to conceive >300 kton modules. However, we think that physics calls for underground operation.

Liquid Argon TPC: an electronic bubble chamber

Bubble diameter ≈ 3 mm (diffraction limited)

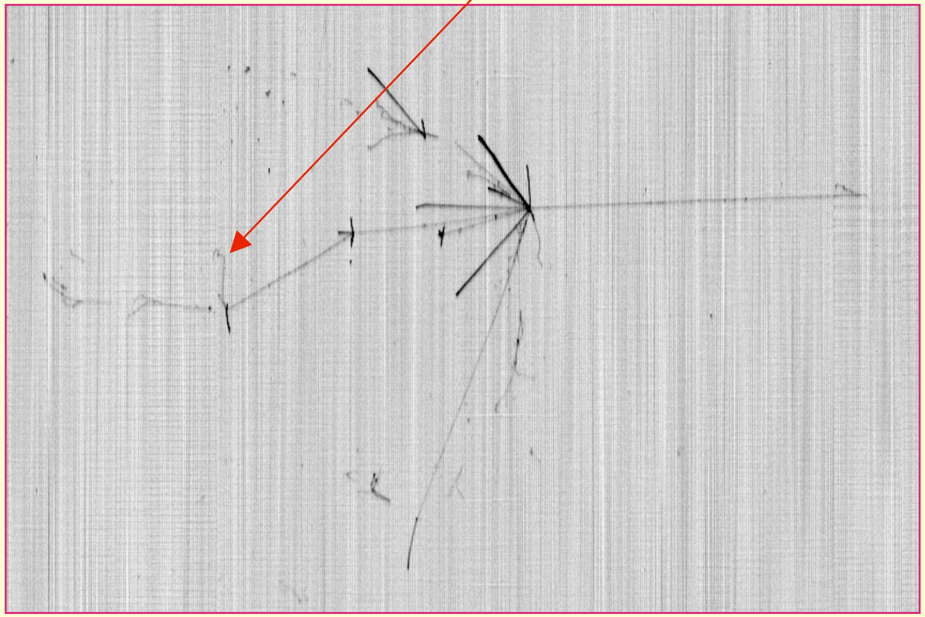
Bubble size ≈ 3x3x0.4 mm^3

Gargamelle bubble chamber



Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

ICARUS electronic chamber



Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

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 $d^2N/dEdx$ (β=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 γ/MeV @ λ=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 β>1/n)**

Scintillation & Cerenkov light can be detected independently !

Liquid Argon TPC: the big picture

physics calls for applications at two different mass scales

100 ton

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

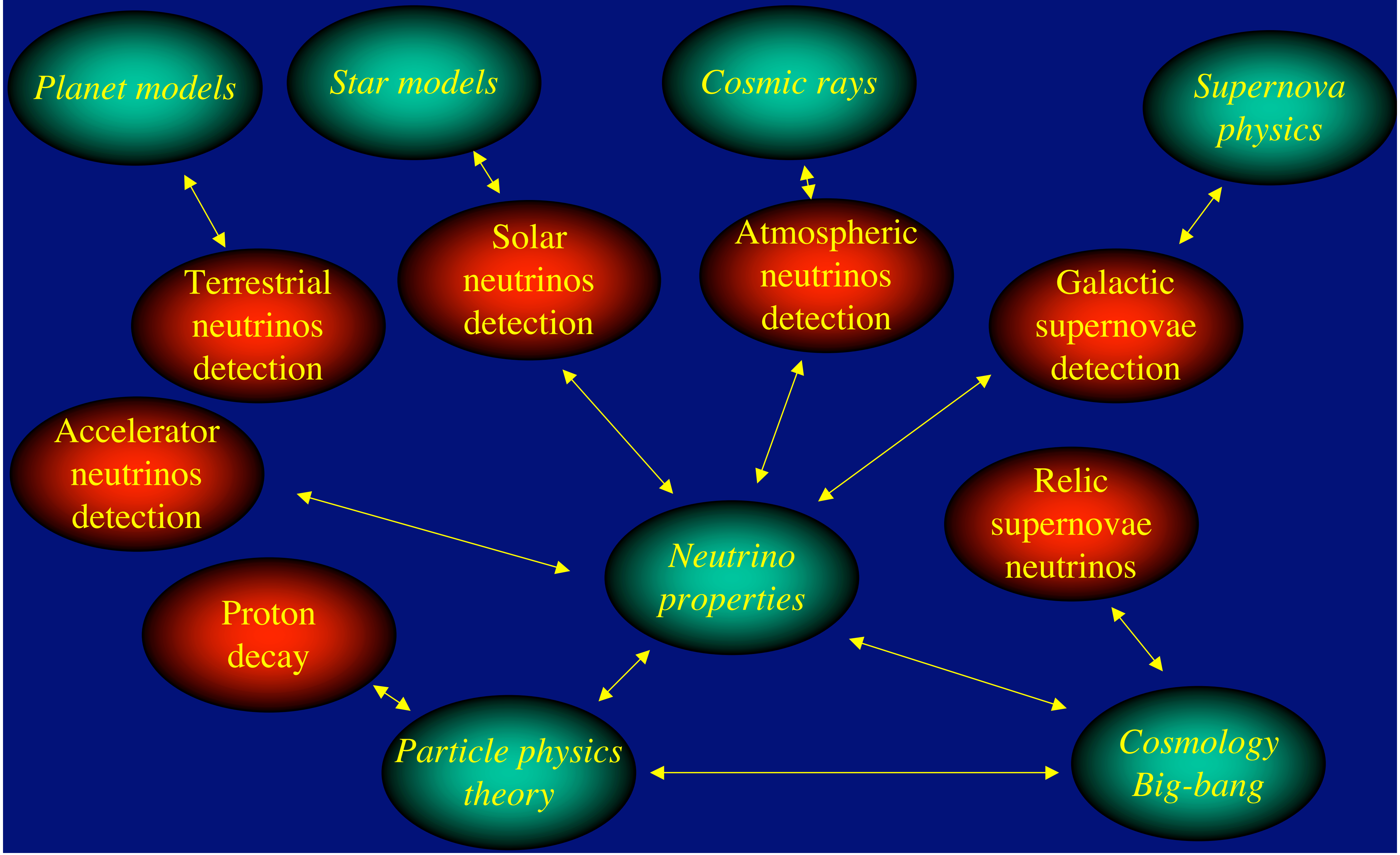
100 kton

- 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

Vast "megaton" physics program

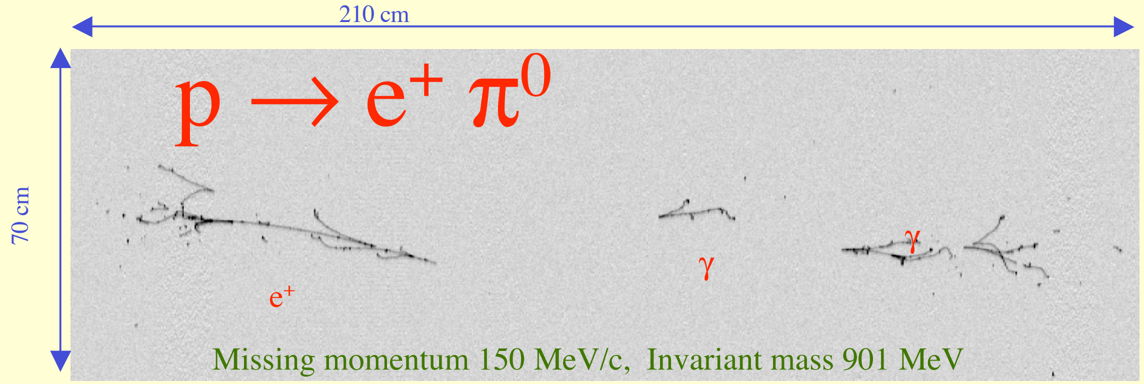


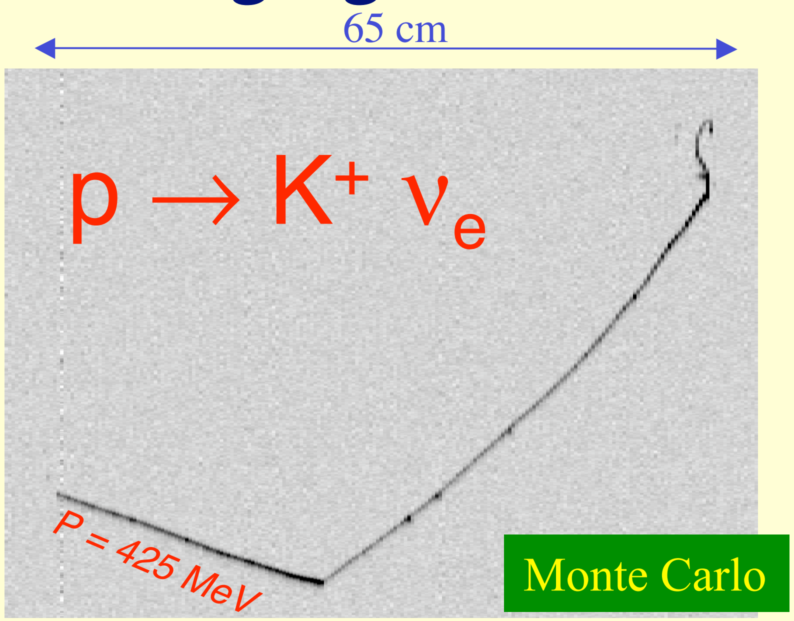
	Water Cerenkov (UNO)	Liquid Argon TPC
Total mass	650 kton	100 kton
Cost	≈ 500 M$	Under evaluation
$p \to e\,\pi^0$ in 10 years	$1.6\text{x}10^{35}$ years ε= 17%, ≈ 1 BG event	$0.5\text{x}10^{35}$ years ε= 45%, <1 BG event
$p \to \nu K$ in 10 years	$0.2\text{x}10^{35}$ years ε= 8.6%, ≈ 37 BG events	$1.1\text{x}10^{35}$ years ε= 97%, <1 BG event
$p \to \mu\pi K$ in 10 years	No	$1.1\text{x}10^{35}$ years ε= 98%, <1 BG event
SN cool off @ 10 kpc	194000 (mostly $\bar{\nu}_e p \to e^+ n$)	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	40 events	7 (12 if NH-L mixing)
SN burst @ 10 kpc	≈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

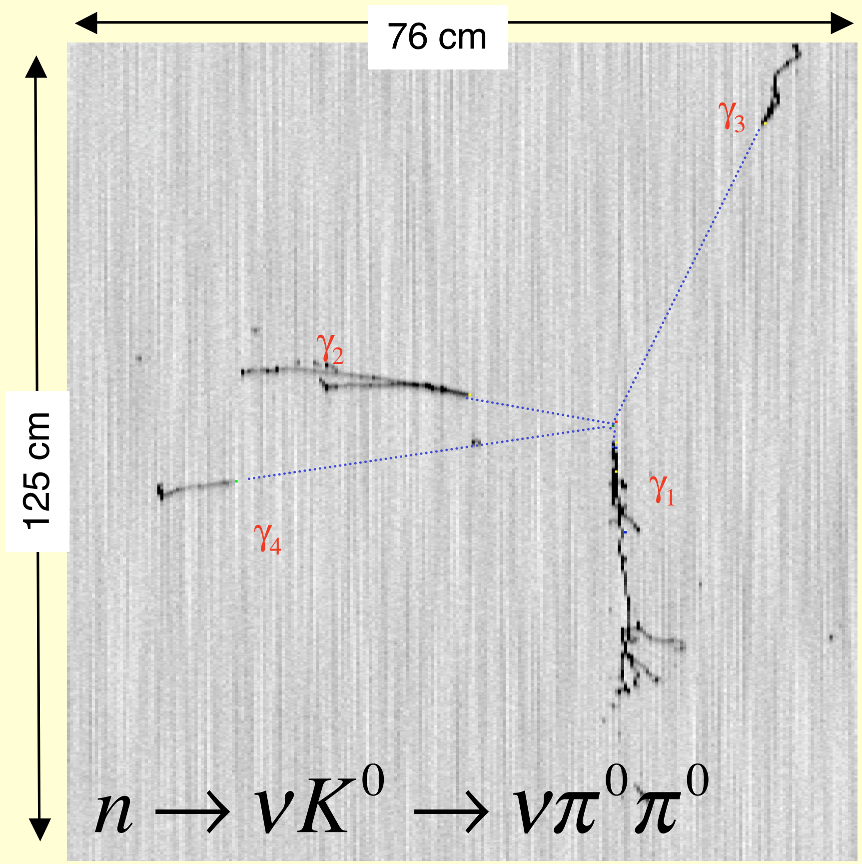
Review of massive underground detectors

A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, March 2004

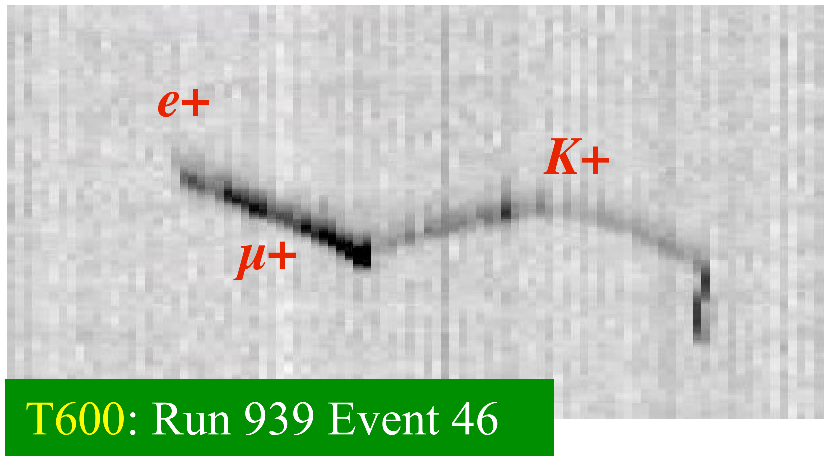
Proton decay: power of imaging



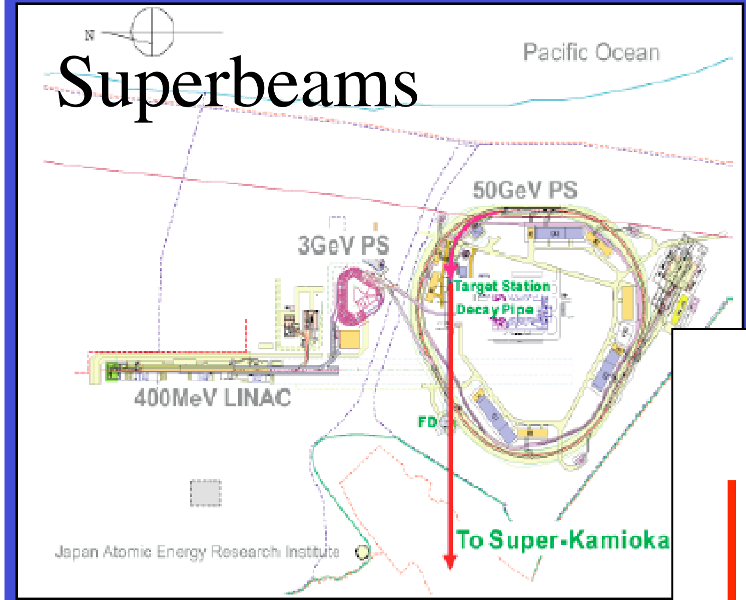




"Single" event detection capability

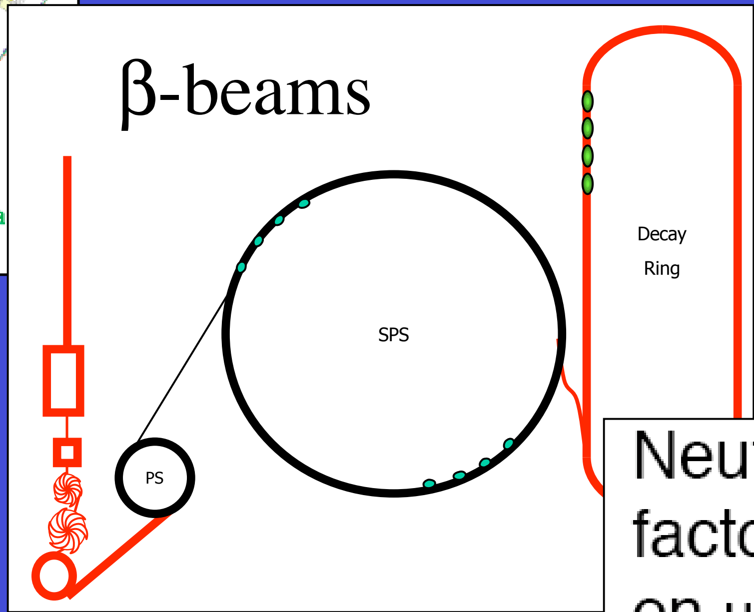


Accelerator neutrinos (I)



$$\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu}$$

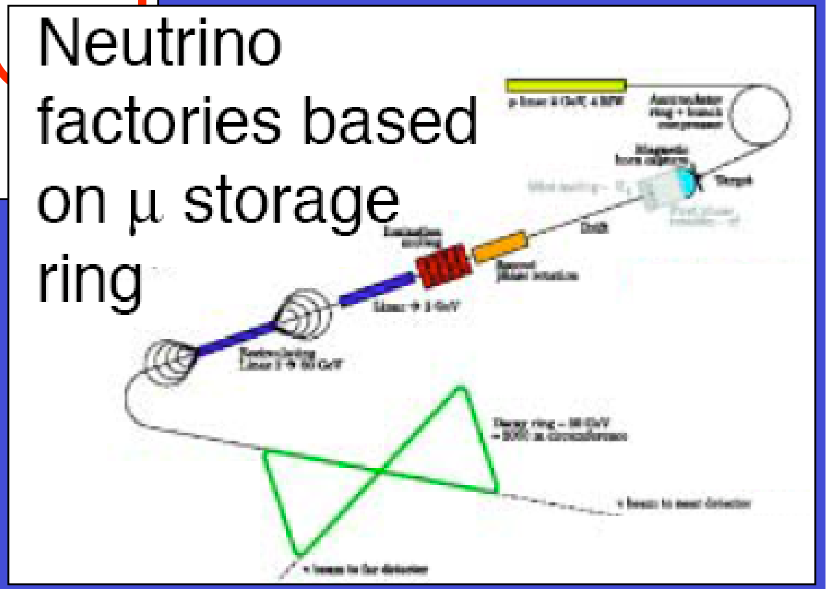
Select focusing sign



$${}^{Z}A \rightarrow {}^{Z\mp1}A \;\; \beta^{\pm} \;\; \overset{(-)}{\nu}_{e}$$

Select ion

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.



Select ring sign

$$\left.\begin{array}{l} \mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu} \\ \mu^{+} \rightarrow e^{+}\nu_{e}\bar{\nu}_{\mu} \end{array}\right\}$$

Accelerator neutrinos (II)

- **To my mind, the Phase-II program should be designed to address as many issues as possible…**
  - See the L/E dependence (at fixed L this means a WBB)
  - Measure $\delta(\Delta m^2_{23}) \approx 1\%$
  - Measure $\delta(\sin^2\theta_{23}) < 1\%$
  - Should improve sensitivity to $\sin^2 2\theta_{13}$ by a factor x5 or x10 w.r.t. to T2K phase I or precisely measure it ($\delta(\sin^2 2\theta_{13})$ to be defined) if a signal was found at T2K
  - Find evidence for CPV ($\delta \neq 0$)
  - Fix the sign of Δm^2_{23}(in fact, study matter effect via resonance, …)
  - Observe (Δm^2_{21}, $\sin^2\theta_{12}$) oscillations in terrestrial experiments
  - Over-constrain the U_{PMNS} matrix (unitarity tests)
  - Search for non-standard interactions (LFV other than through oscillations in space)
  - … (any other good idea) …

Operation of a 100 kton LAr TPC in a future neutrino facility:

Super-Beam: 460 ν_μ CC per 10^{21} 2.2 GeV protons @ L = 130 km

Beta-beam: 15000 ν_e CC per 10^{19} ^{18}Ne decays with γ=75

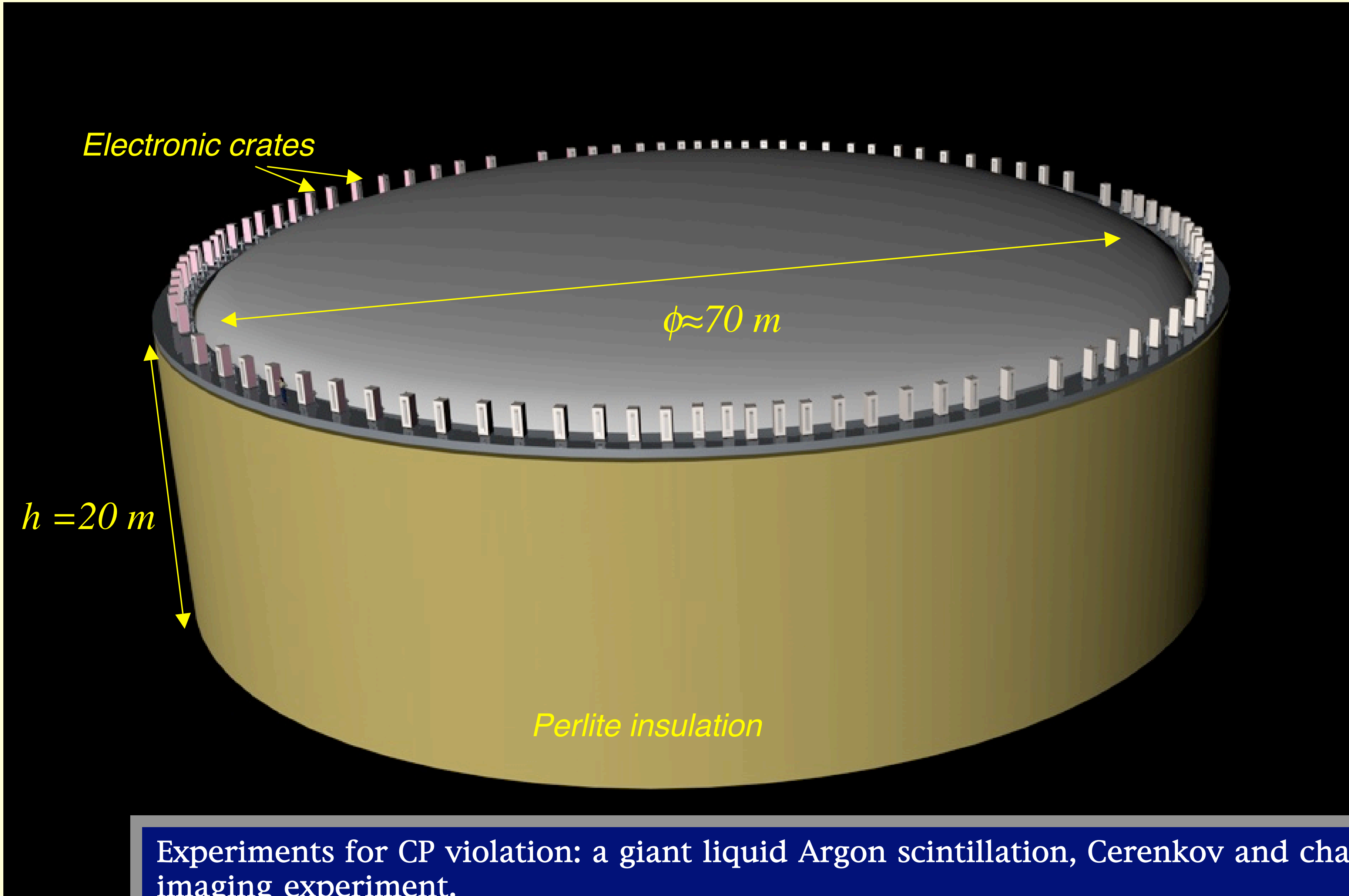
A general purpose facility

- **We are considering which detector will give us the largest chance to perform interesting and new physics in the years 2015-2025.**

- **It appears that the ideal detector**
  - ➥ Should be **very massive** & **general purpose**, and not solely “tuned” to a given physics topic which might be relevant today, but not necessarily tomorrow…
  - ➥ Should have the proper **energy resolution** to “see the oscillations”, measure the oscillations parameters precisely and disentangle possible degeneracy
  - ➥ Should have the **granularity** to potentially address all the existing $e/\mu/\tau$ flavors in the final states
  - ➥ Should have a **clean NC, CC separation** and good **background suppression**
  - ➥ Should address **both accelerator & non-accelerator physics**, hence be located underground (depth to be optimized)
  - ➥ Should be ready to find the **unexpected** (many years will pass from design to data taking…)
  - ➥ Should be **cost effective** (“physics-return”-wise)

- **It is also clear that one needs to consider the complete system detector + accelerator + beams simultaneously**
  - ➥ Need to systematically consider the physics of all possible beams, energies, baselines, intensities, …
  - ➥ This is a challenging task that is somehow in progress, but has obviously not been fully completed.

Building block: 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

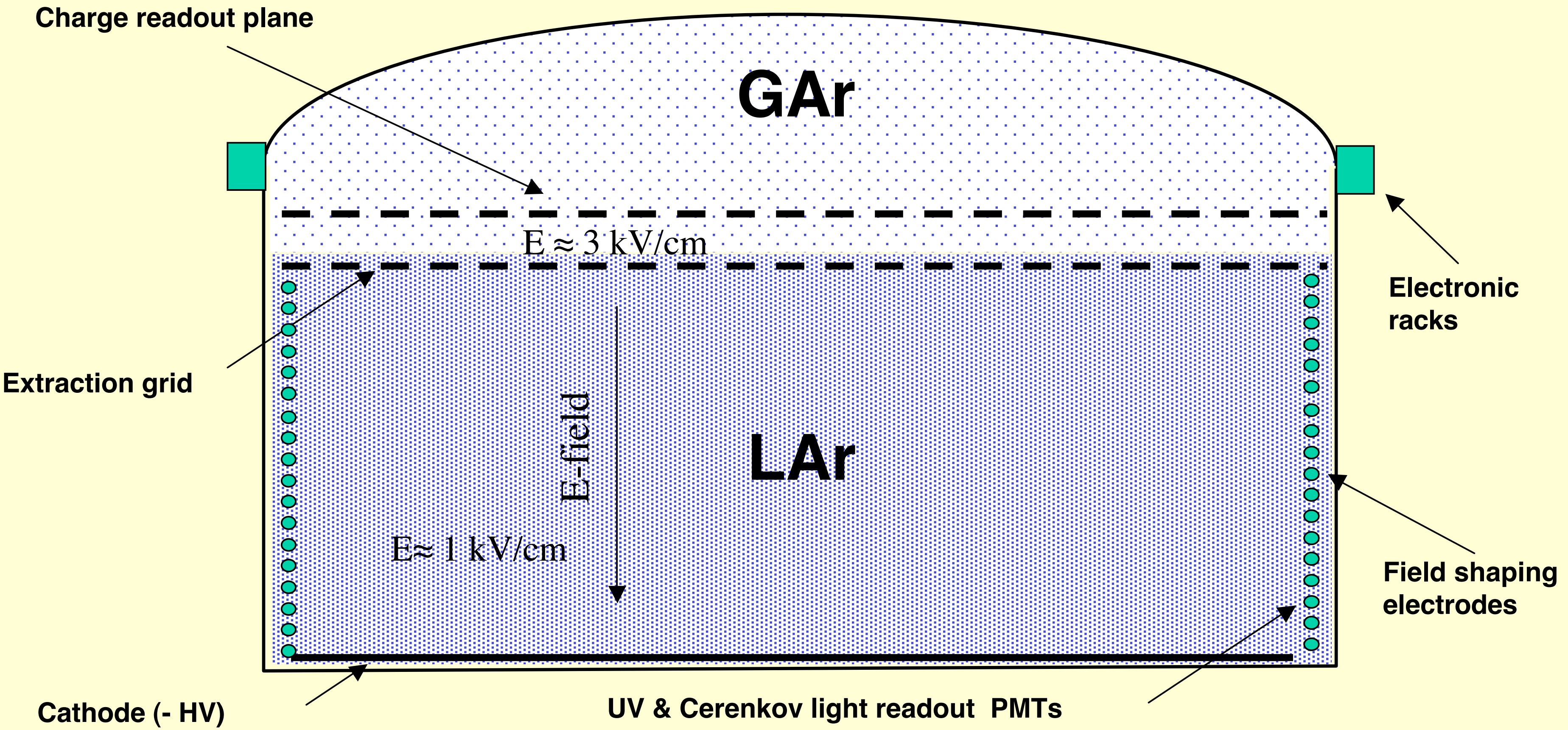
100 kton detector: milestones

- **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)**
- **May 2004 : CERN Workshop on a future Multi MW proton source**
  - Envision a possible 10 kton full scale prototype (10% of the full detector)
  - Site/physics optimization deep underground ($\rightarrow$ proton decay) or shallow ($\rightarrow$ neutrino beam)

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light

Dewar	$\phi \approx 70$ 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 $\approx$ 15%
Argon total mass	102000 tons
Hydrostatic pressure at bottom	3 atmospheres
Inner detector dimensions	Disc $\phi \approx 70$ 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 γ 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, $v_d \approx$ 2 mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch, 100000 readout channels**
Maximum charge diffusion	**$\sigma \approx$ 2.8 mm ($\sqrt{2Dt_{max}}$ for D = 4 cm^2/s)**
Maximum charge attenuation	**$e^{-(t_{max}/\tau)} \approx$ 1/150 for τ = 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 ($\phi \approx$ 30 μm) + pad readout, GEM, LEM, …**

Cryogenic storage tankers for LNG

LNG = Liquefied Natural Gas

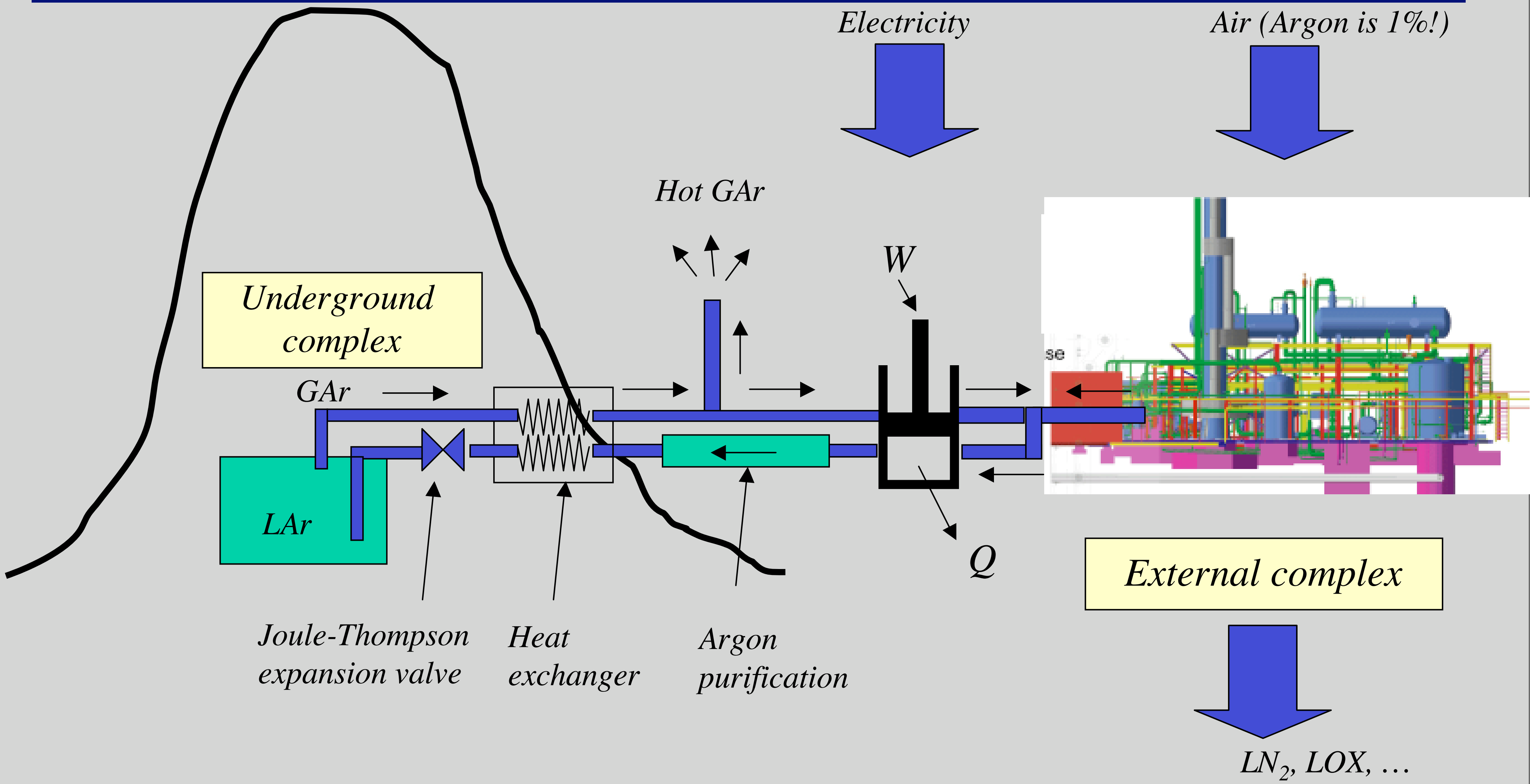
About 2000 cryogenic tankers exist in the world, with volume up to ≈ 200000 m^3

Process, design and safety issues already solved by petrochemical industry

Cooling by "auto-refrigeration"

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 and/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



Ongoing studies and initial R&D strategy

Engineering studies, dedicated test measurements, detector prototyping, simulations, physics performance studies in progress:

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 large liquid underground storage tank, costing**

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

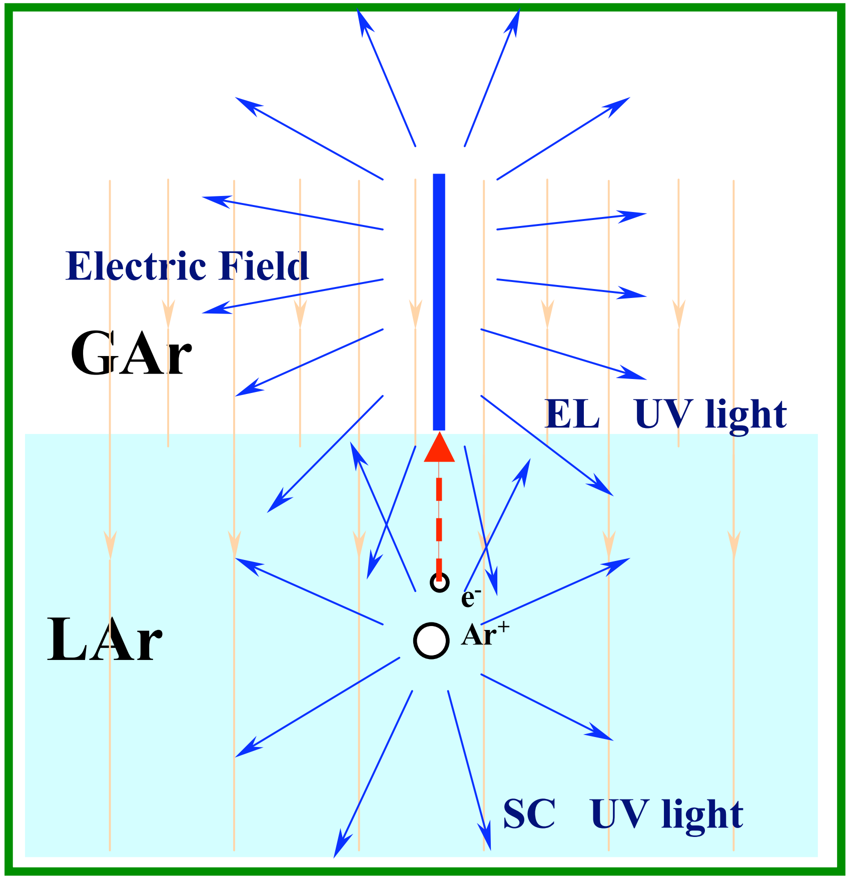
7) **Physics studies and phenomenology**

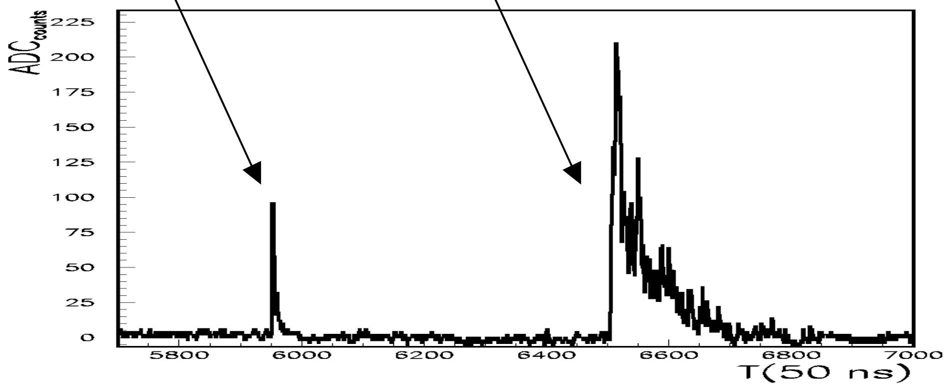
1) Electron extraction in LAr bi-phase

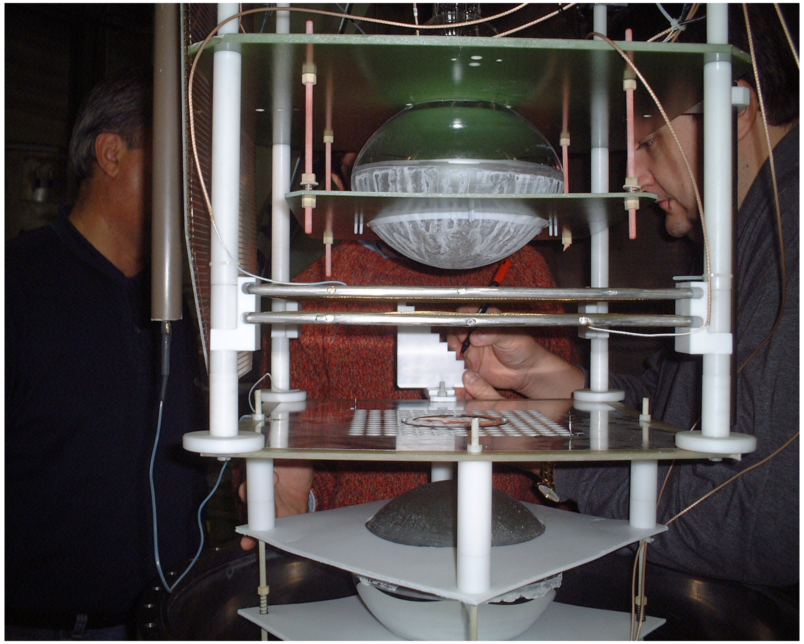
Particle produces excitation (Ar*) and ionization (Ar^+, e)

Scintillation SC is a result of direct excitation and recombination

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



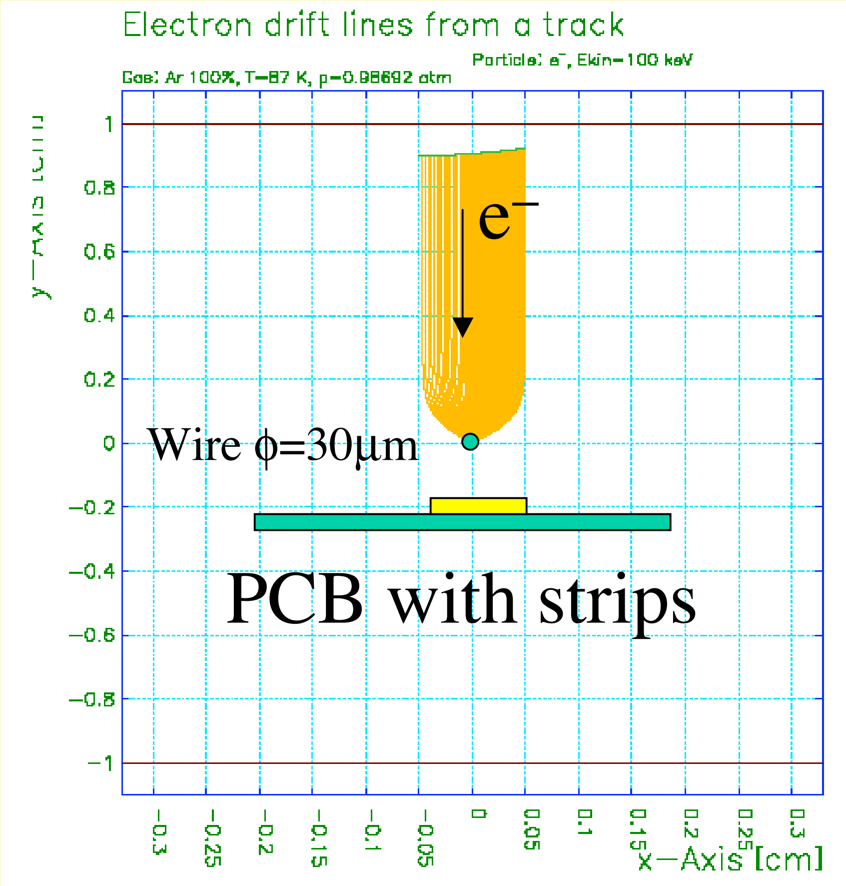


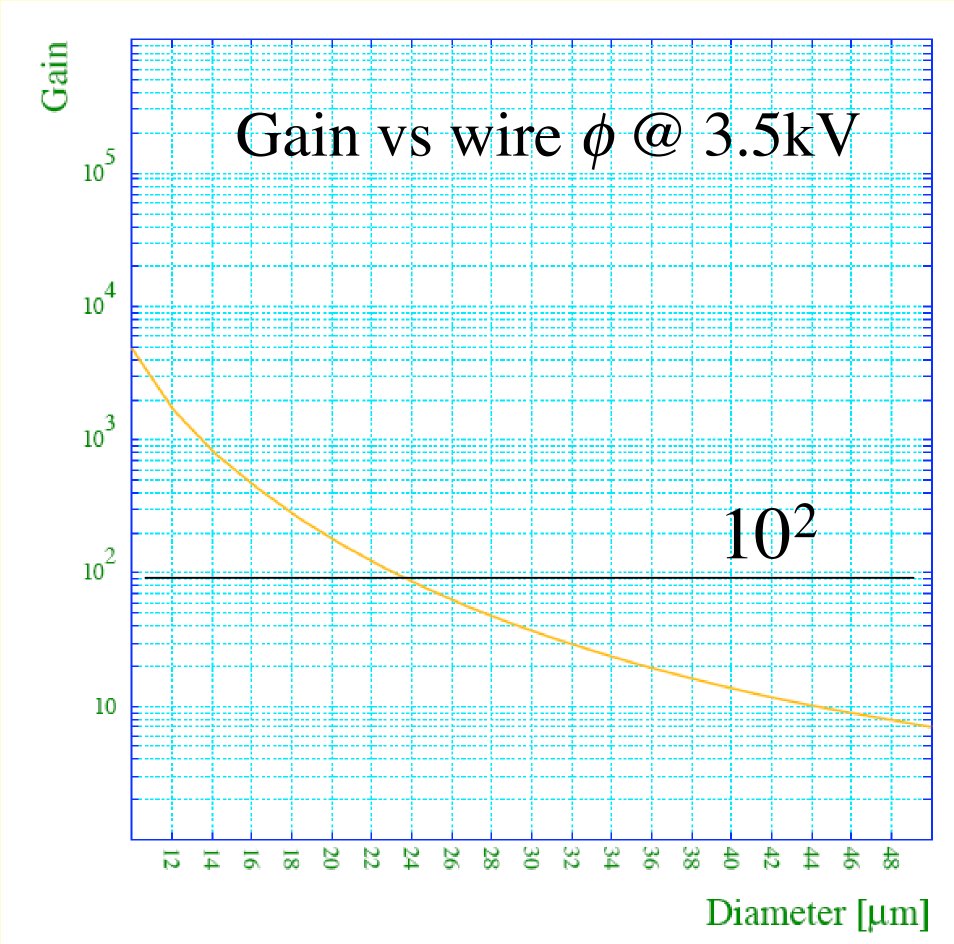


Both SC and EL can be detected by the same photo-detector

1) Amplification near wires à la MWPC

- **Amplification in Ar 100% gas up to factor G≈100 is possible**
- **GARFIELD calculations in pure Ar 100%, T=87 K, p=1 atm**
- **Amplification near wires, signal dominated by ions**
- **Readout views: induced signal on (1) wires and (2) strips provide two perpendicular views**



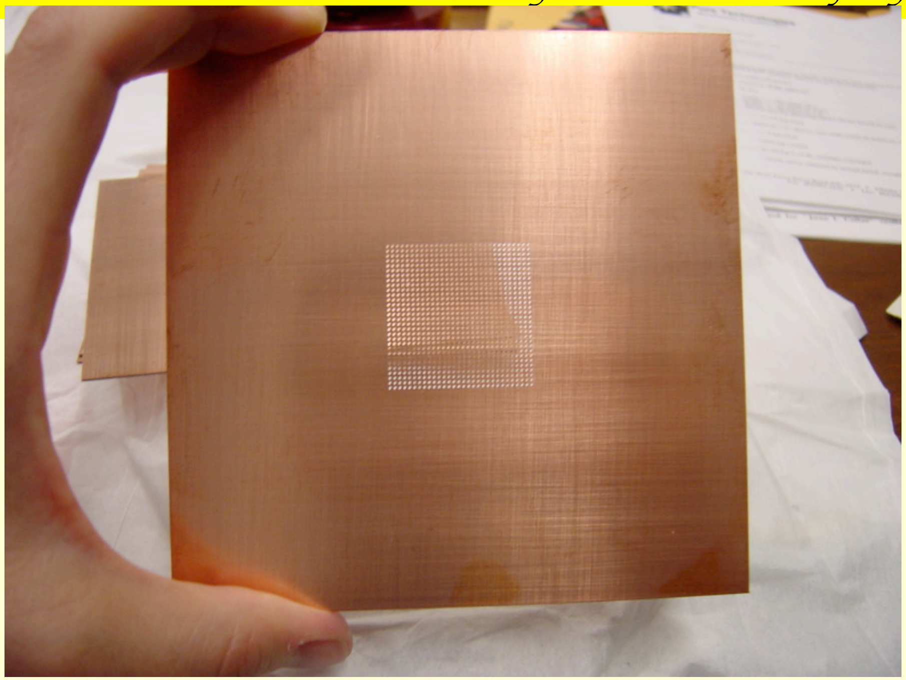


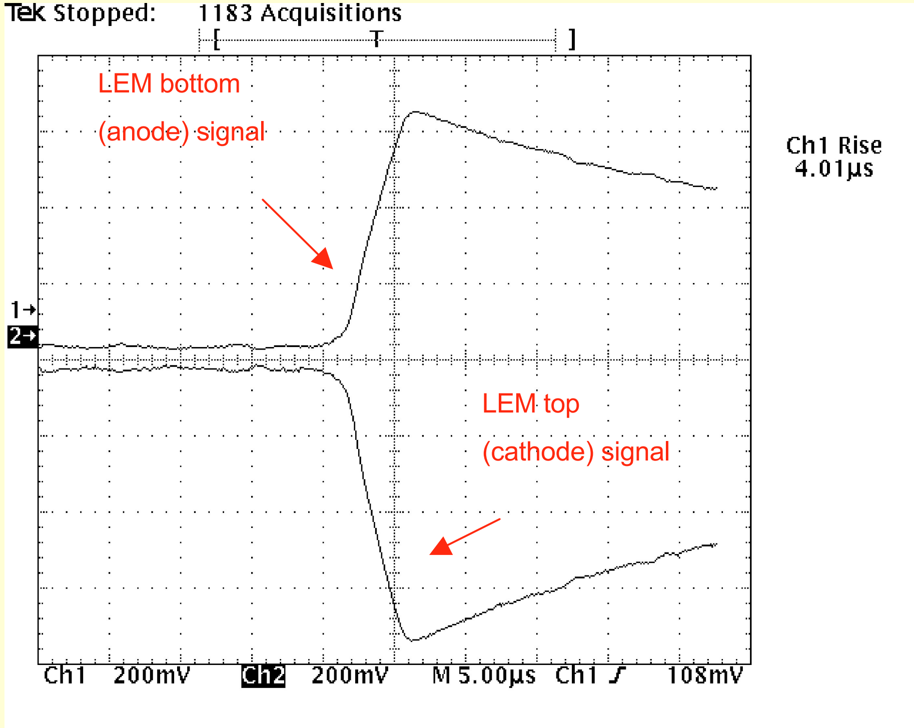
1) Amplification with Large Electron Multiplier (LEM)

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

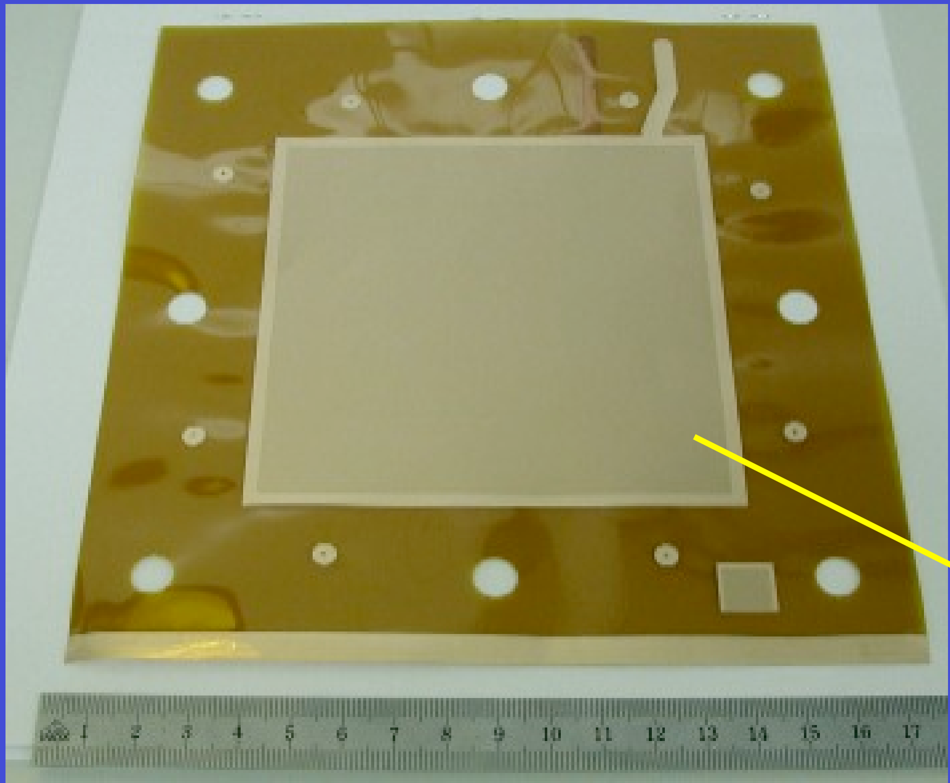
- **A large scale GEM (x10) made with ultra-low radioactivity materials (copper plated on virgin Teflon)**
  - In-house fabrication using automatic micro-machining
  - Modest increase in V yields gain similar to GEM
  - Self-supporting, easy to mount in multi-layers
- **Resistant to discharges (lower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

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

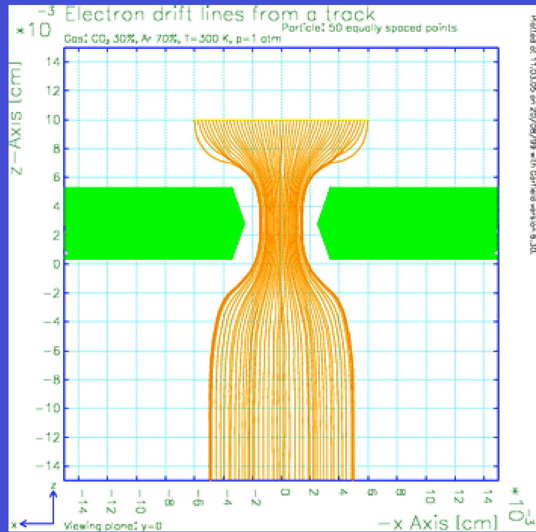


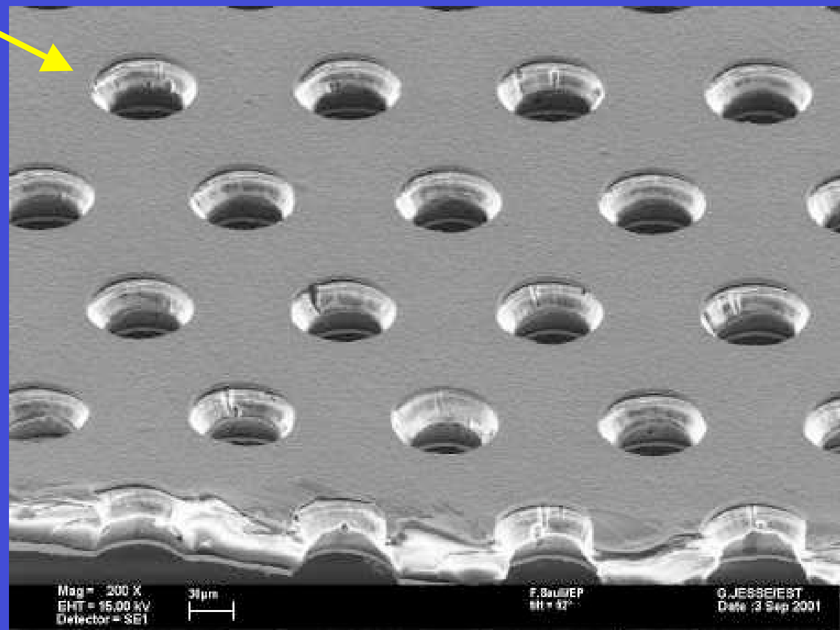


Gas Electron Multiplier GEM (F. Sauli et al., CERN)



100x100 mm^2





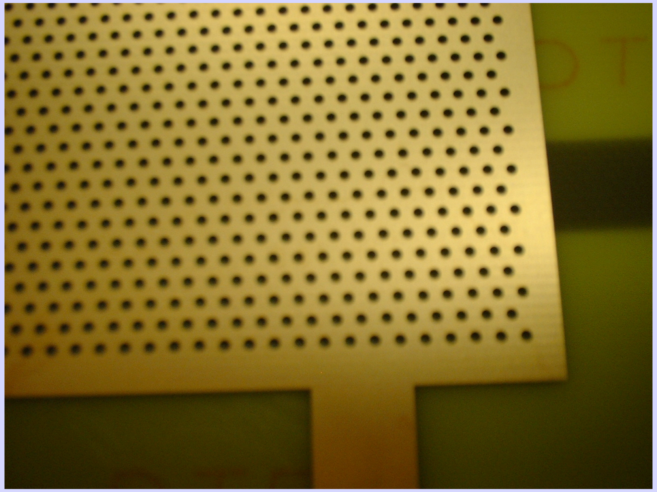
A gas electron multiplier (GEM) consists of a thin, metal-clad polymer foil, chemically pierced by a high density of holes. On application of a difference of potential between the two electrodes, electrons released by radiation in the gas on one side of the structure drift into the holes, multiply and transfer to a collection region.

LEM with pure Argon-100%

R&D in progress

Detection of charge signal and scintillation light produced during amplification

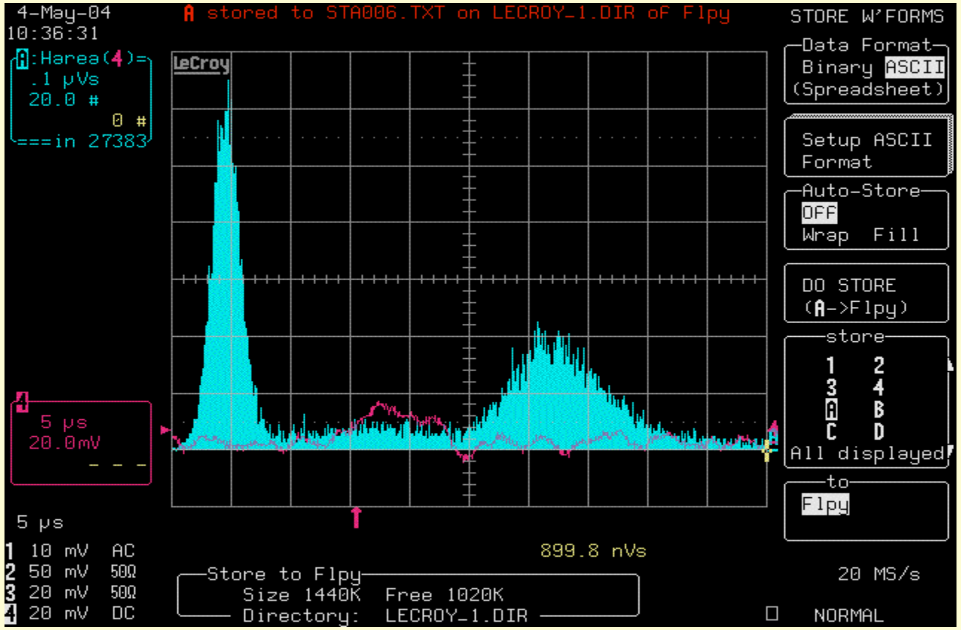
400 x 400 mm^2



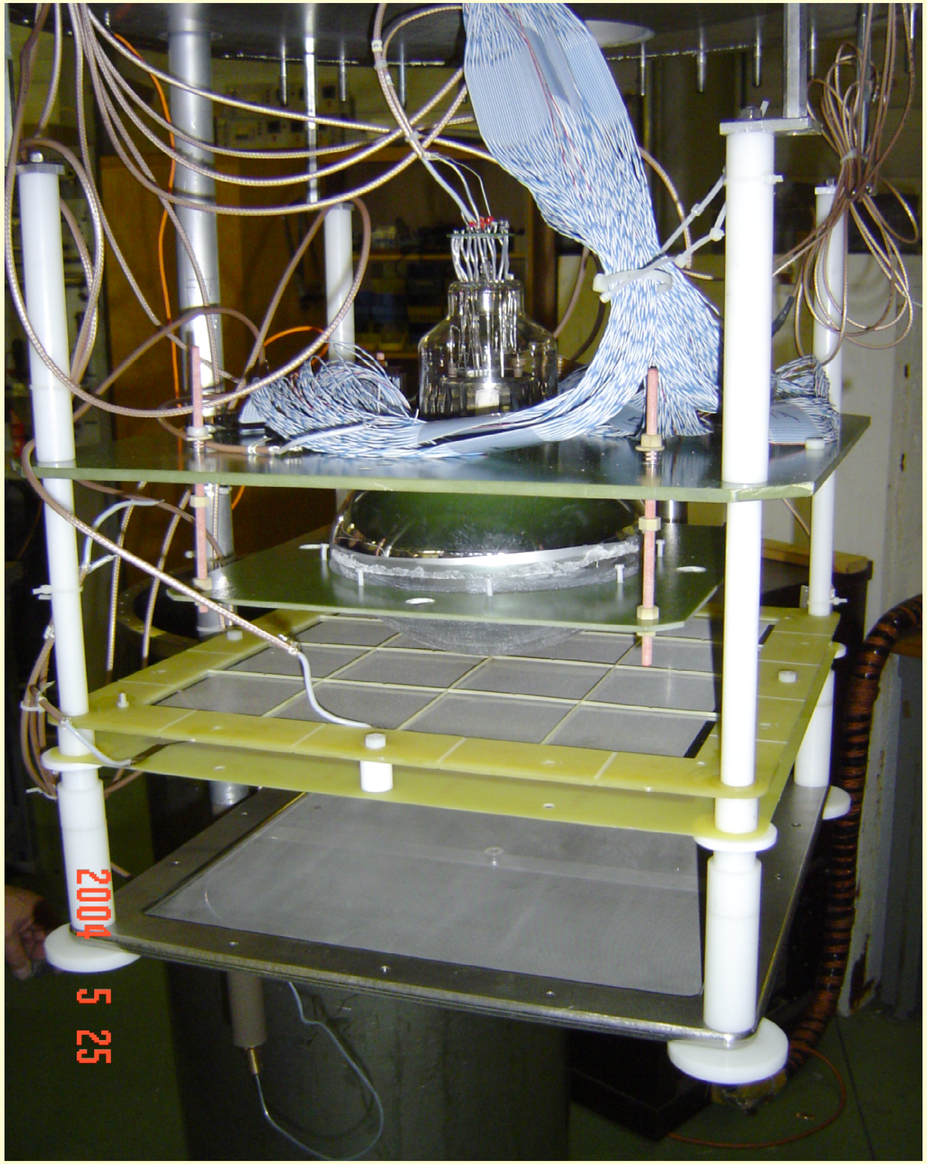
Holes ϕ = 1 mm

Amplification with self-made LEMs

- Fe source (5.9 keV γ), Argon 100%
- Three LEM thicknesses: 1, 1.6 and 2.4 mm
- Varying pressures
- Room temperature

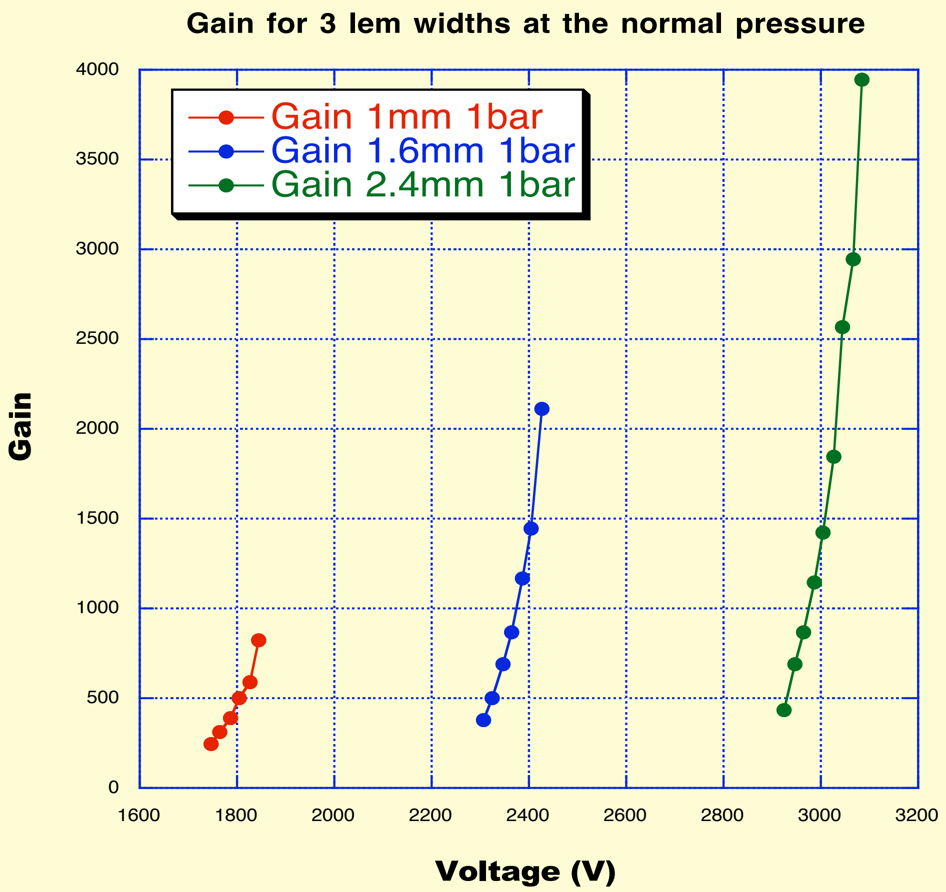


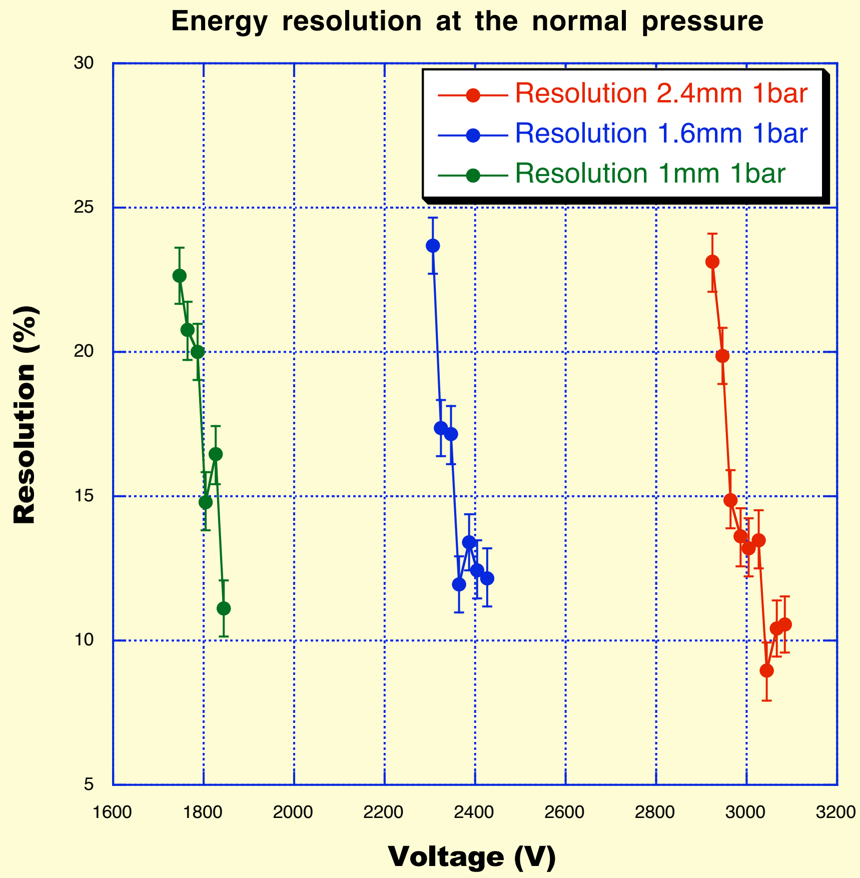
Raw charge spectrum



Gain and resolution: effect of LEM geometry

- Fe source (5.9 keV γ), Argon 100%
- Three LEM thicknesses: 1, 1.6 and 2.4 mm
- Normal pressure and room temperature

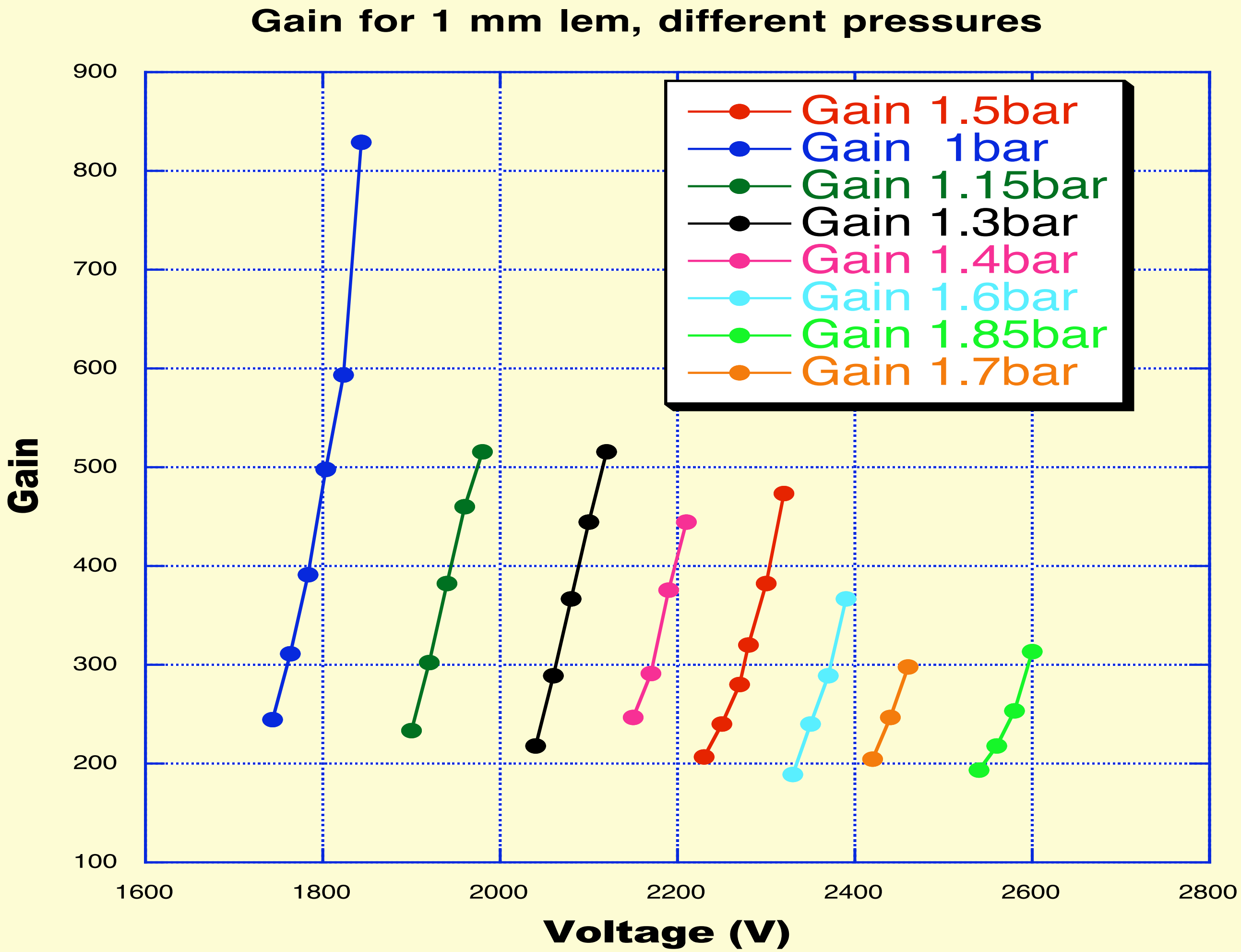




Stable operation possible in pure argon

Gain for different gas pressures

- Fe source (5.9 keV γ), argon 100%
- Room temperature



Stable operation possible in pure argon

2) High-pressure drift properties in liquid Argon

- **Future large tankers:**

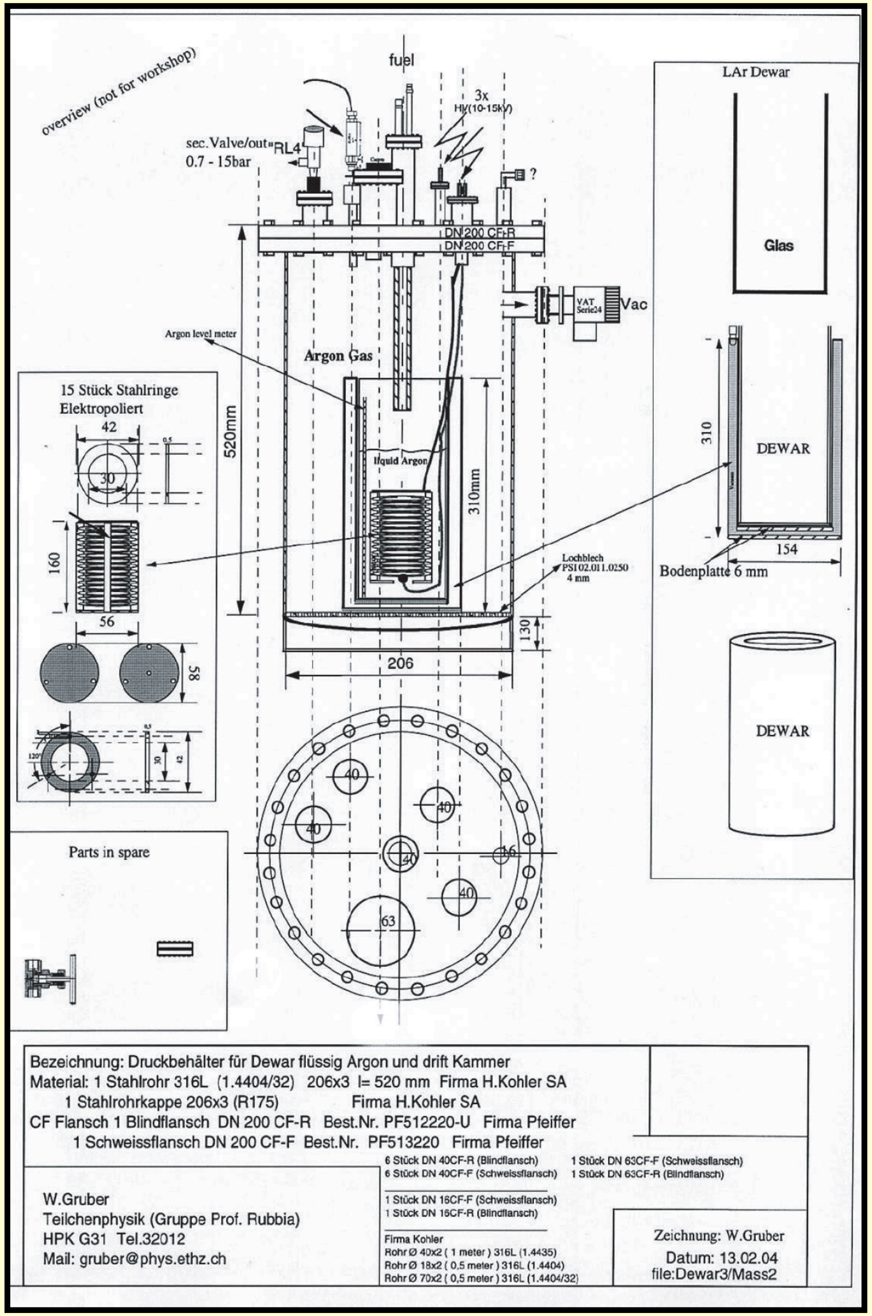
  Hydrostatic pressure could be quite significant (3-4 atmosphere at the bottom of the tanker)

- **Test of electron drift properties in high pressure liquid Argon**

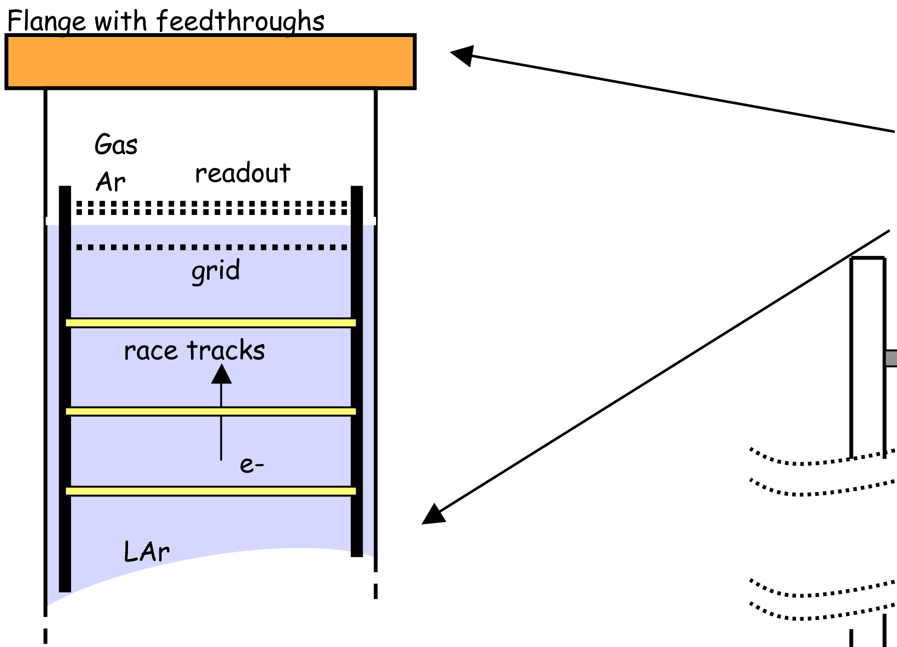
  Important to understand the electron drift properties and imaging under high pressure

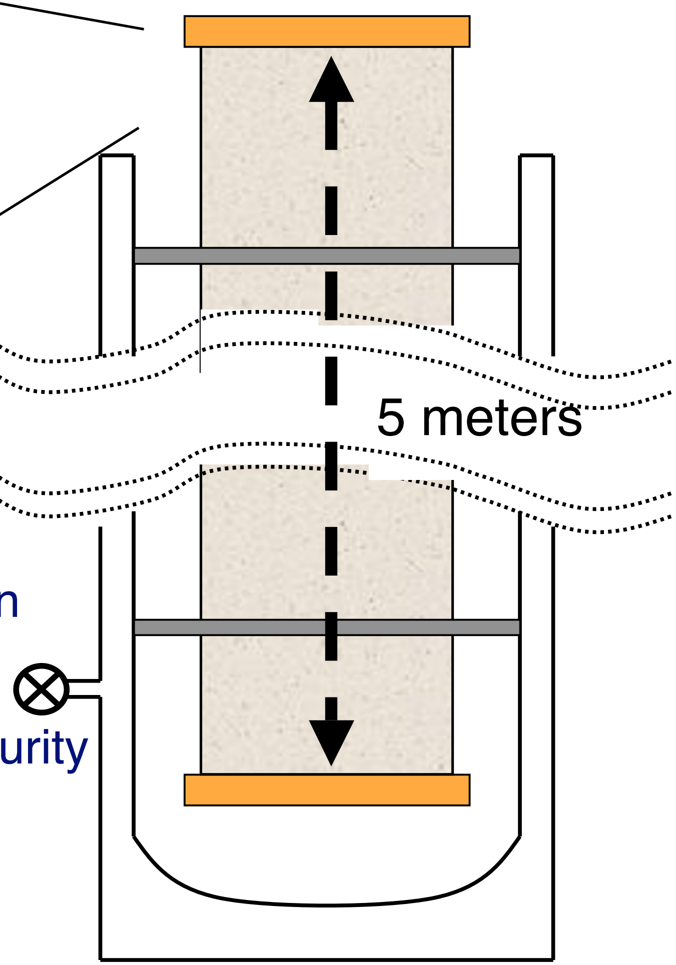
- **Study in progress**
  - ✓ Prototype designed
  - ✓ Parts being assembled at PSI

R&D in progress



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, …

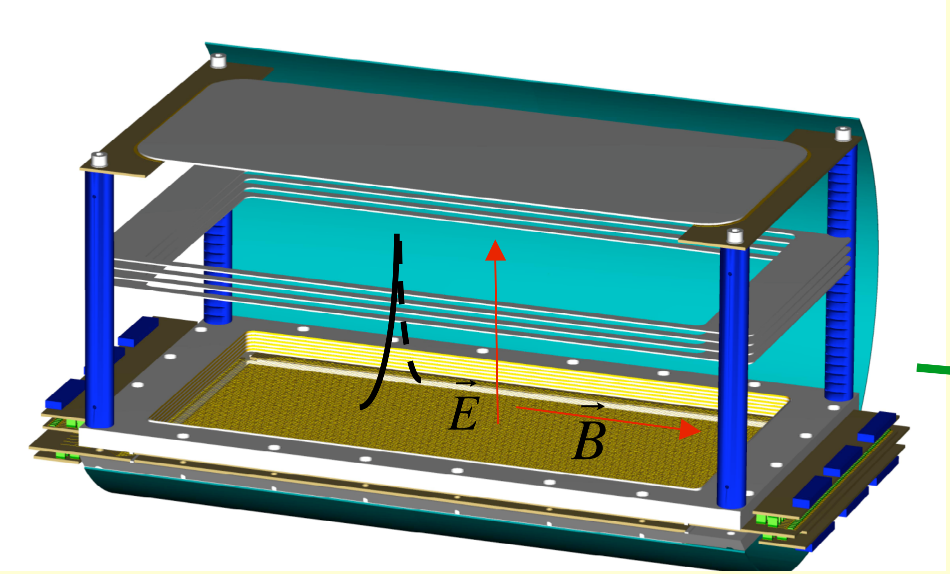
R&D in progress

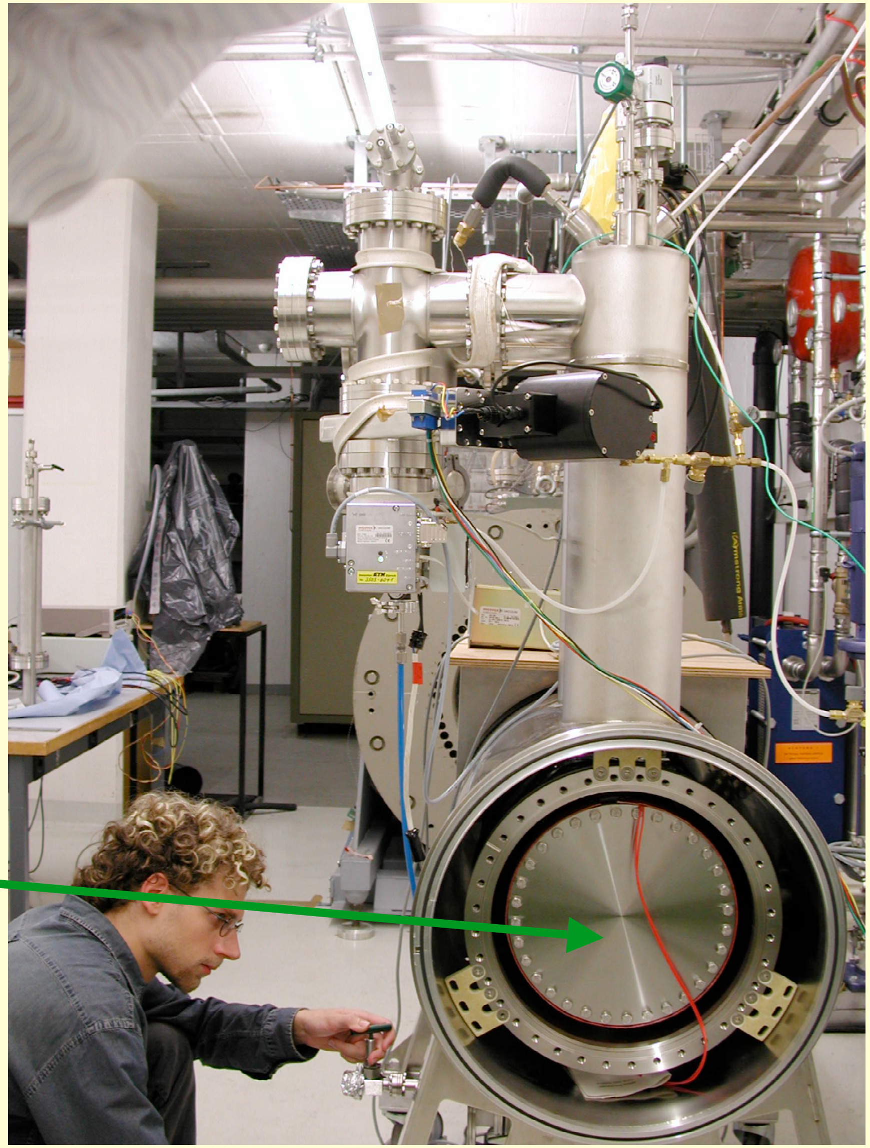
Long drift, extraction, amplification: delivery tubes

6th June 2004

4) Test of liquid Argon imaging in B-field

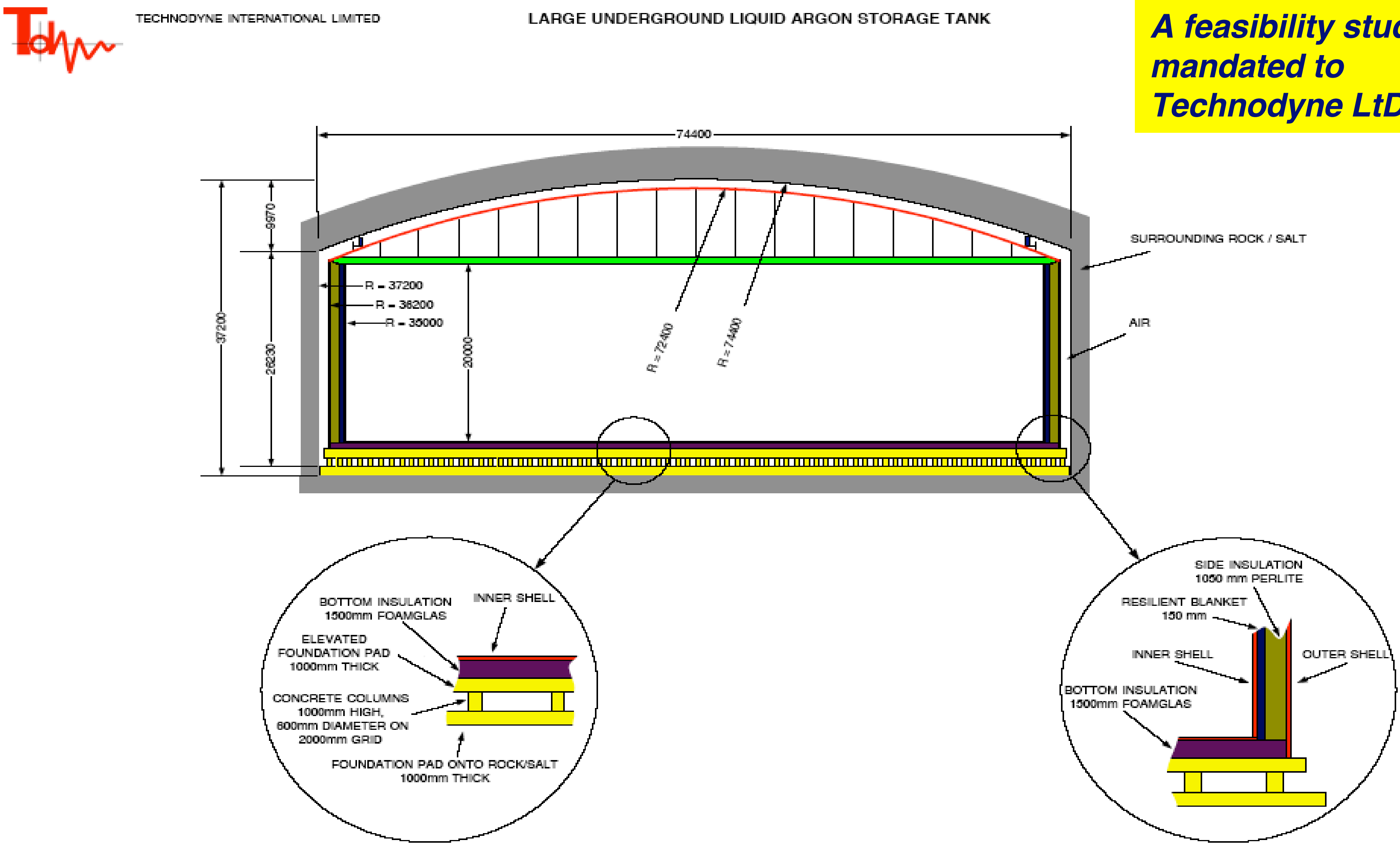
- **Small chamber in SINDRUM-I recycled magnet up to B=0.5T (230KW) given by PSI, Villigen**
- **Test program:**
  - ➥ Check basic imaging in B-field
  - ➥ Measure traversing and stopping muons bending
  - ➥ Charge discrimination
  - ➥ Check Lorentz angle (α≈30mrad @ E=500 V/cm, B=0.5T)
- **Results expected in 2004**





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

5) Study of large underground storage tank



A feasibility study mandated to Technodyne LtD (UK)

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

Cryogenics for liquid Argon TPCs

3 ton @CERN

Standard cryostat

Modular, light, transportable cryostat (INFN R&D with Airliquide)

Separate nitrogen cooling circuit

ICARUS T600

≈20 ton prototype

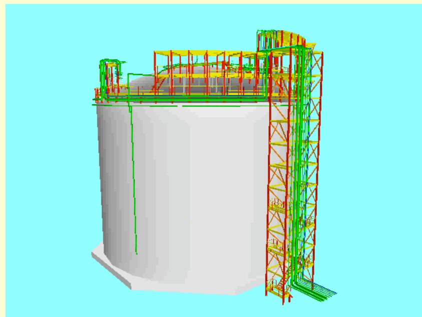
Standard cylindrical cryostat
Slow-rate purification
Closed argon cooling circuit

100 ton

Low-consumption cylindrical cryostat for underground, near site LBL

Closed argon cooling circuit

10 kton prototype

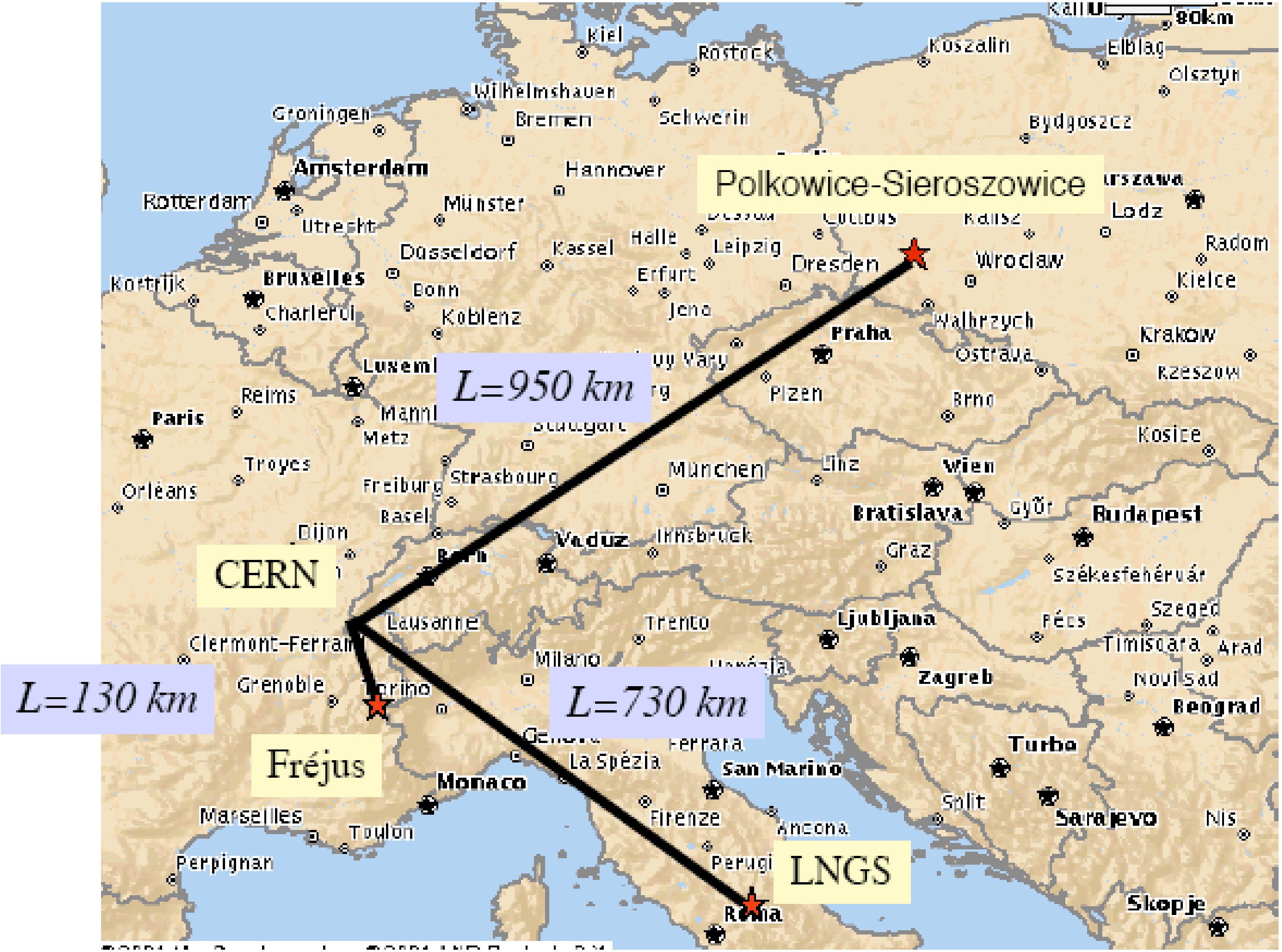


Efficient A/V ratio
LNG technology
Underground
Temperature constant by boil-off with slow argon refilling

100 kton

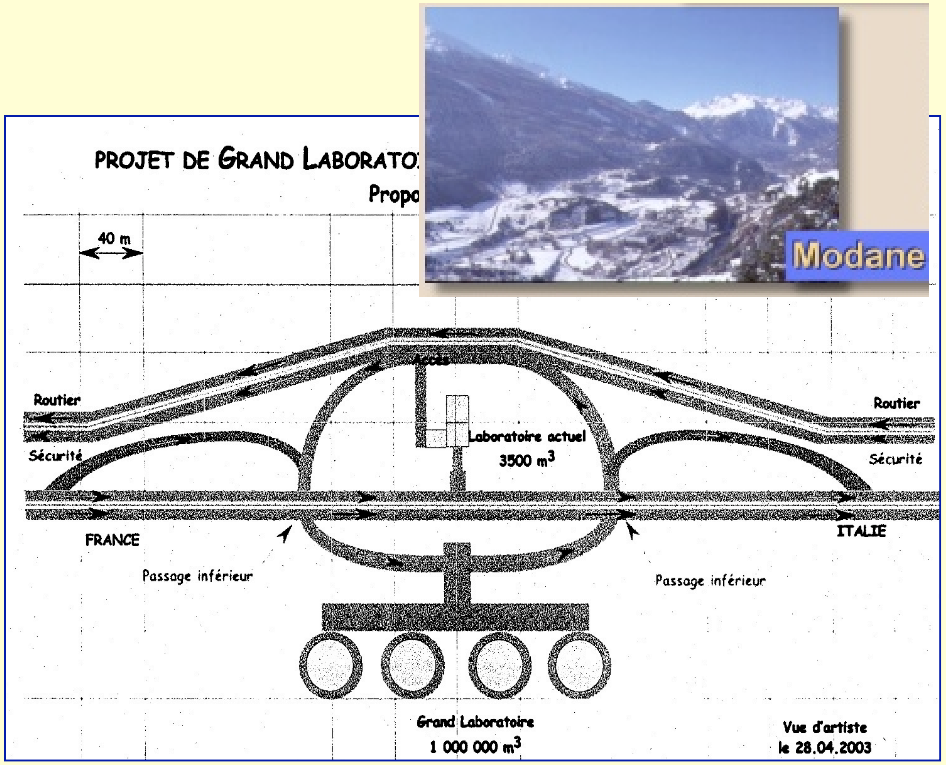
Extrapolation

6) Location study: 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)**



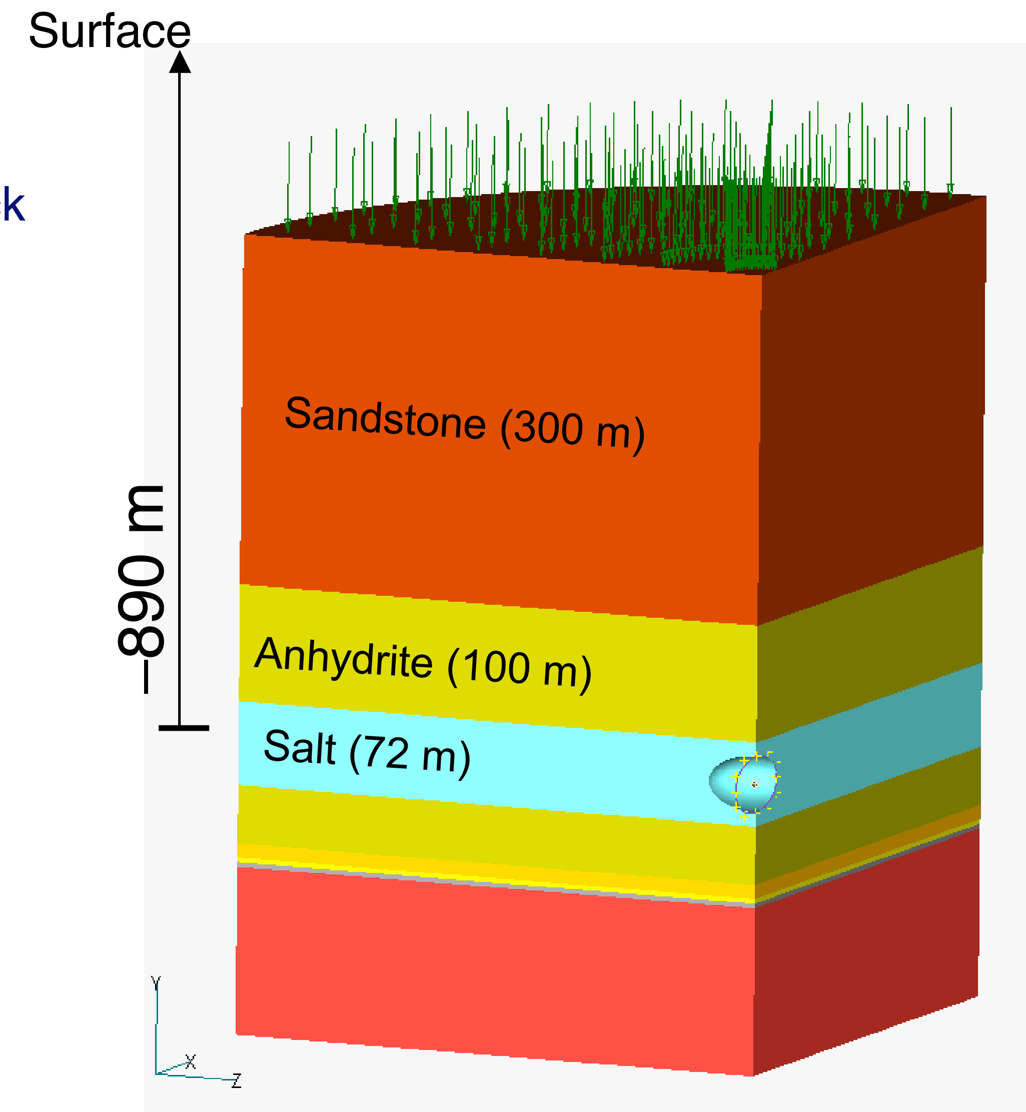
- cooperation agreement: IN2P3/CNRS/DSM/CEA & INFN
- international laboratory for underground physics
- easy access
- safety issues (highway tunnel)
- caverns have to be excavated

- 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 m^3 (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)

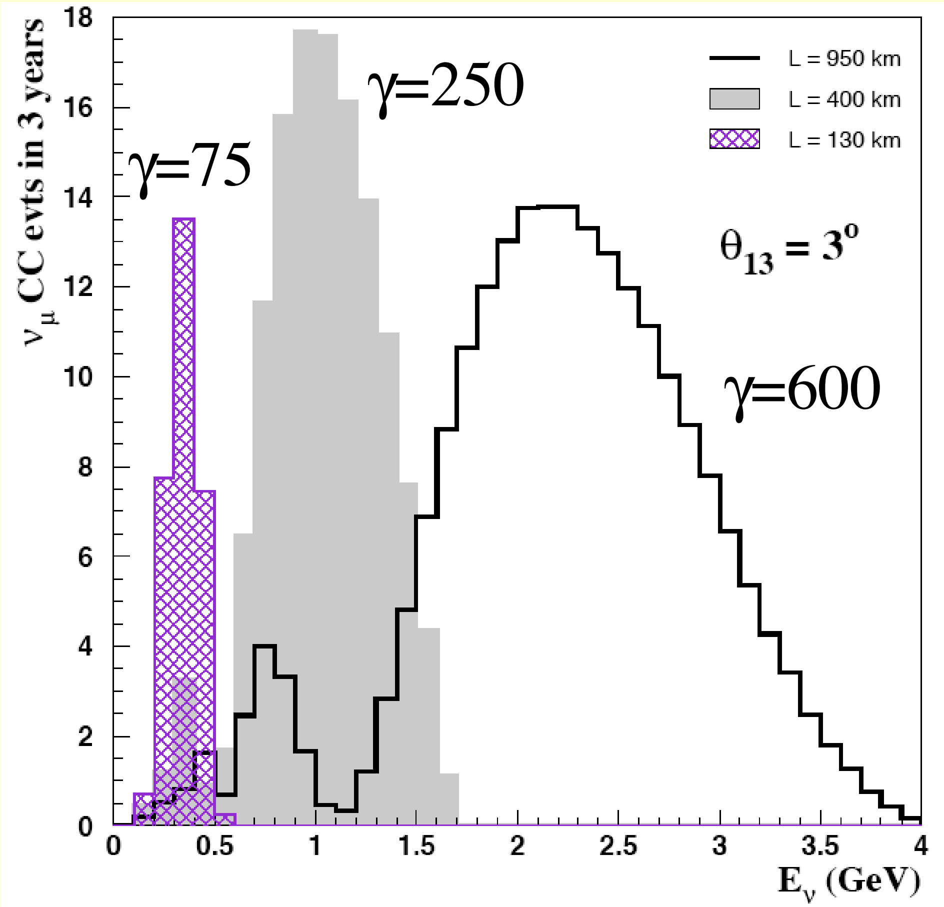
cavern ≈ 100000 m^3
or
tunnel-like geometry



Finite element analysis for Polish mine

7) Physics simulation and phenomenology

- **Explore both accelerator & non-accelerator physics**
- **Optimize physics in conjunction with different beams, energies and baseline options, …**
  - ➥e.g. Trying to see oscillations with beta-beams



$\nu_e \rightarrow \nu_\mu$

1.1×10^{18} ^{18}Ne

Baselines L=130, 400, 950 km

γ=75, 250, 600

$E_p \approx 1$ TeV
with Super-SPS
(see W. Scandale)

Work in progress

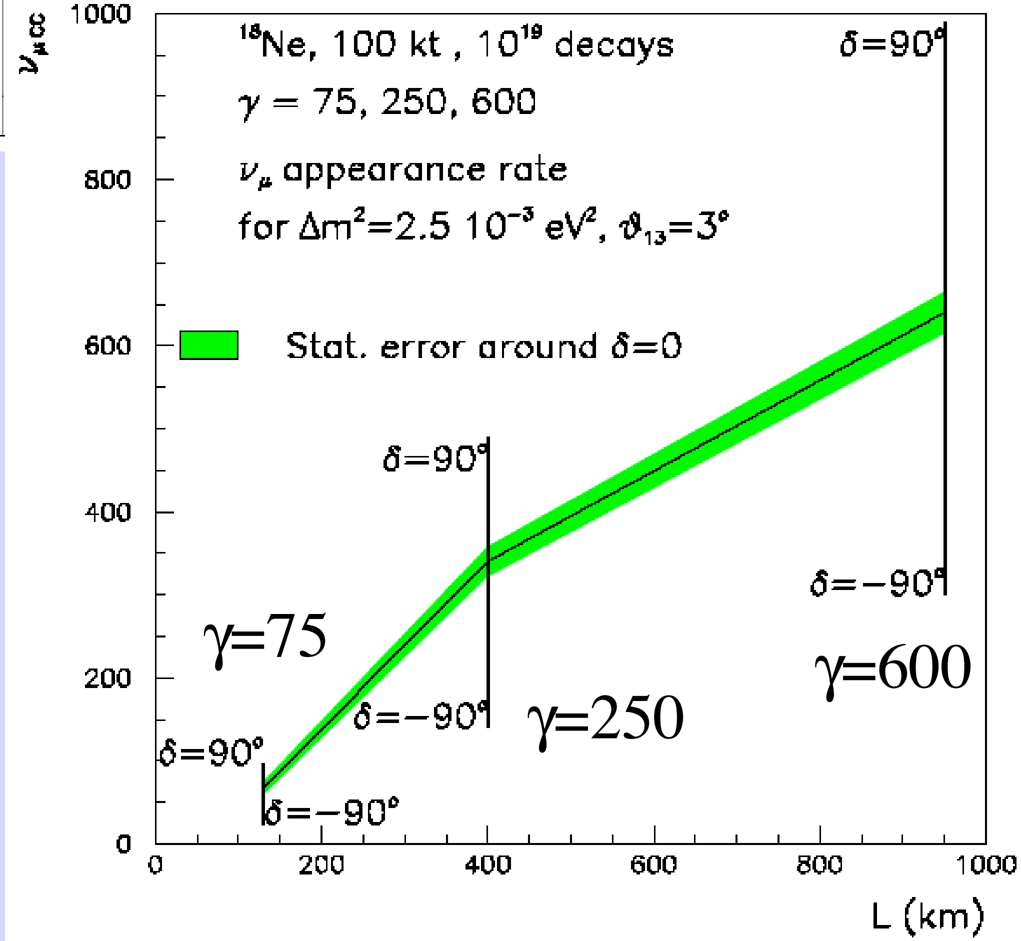
$\theta_{13} = 3°$		^{18}Ne ν_eCC	ν_μCC δ=0	ν_μCC $\pi/2$	ν_μCC $-\pi/2$	ν_μCC π	^{6}He $\overline{\nu}_e$CC	$\overline{\nu}_\mu$CC δ=0	$\overline{\nu}_\mu$CC $\pi/2$	$\overline{\nu}_\mu$CC $-\pi/2$	$\overline{\nu}_\mu$CC π
L = 950 km γ=600(360) 3 years	No osc.	33538	–	–	–	–	10169	–	–	–	–
	Vacuum	33177	183	287	74	178	9890	46	20	92	65
	Matter (n.h.)	33084	220	348	105	233	9918	39	14	70	45
	Matter (i.h.)	33260	149	226	52	129	9856	56	30	115	90
L = 400 km γ=250(150) 3 years	No osc.	22201	–	–	–	–	3426	–	–	–	–
	Vacuum	21974	120	178	49	107	3278	16	6	31	21
	Matter (n.h.)	21951	131	194	57	120	3282	14	5	27	18
	Matter (i.h.)	21997	110	162	42	94	3273	17	8	34	24
L = 130 km γ=75 3 years	No osc.	5214	–	–	–	–					
	Vacuum	5160	29	42	12	24					
	Matter (n.h.)	5158	30	43	12	25					
	Matter (i.h.)	5162	28	40	11	23					

$\nu_e \rightarrow \nu_\mu$

1.1 x 10^{18} ^{18}Ne and
2.9 x 10^{18} ^{6}He
Baselines L=130, 400, 950 km
γ=75, 250(150), 600(360)

$E_p \approx 1$ TeV
with Super-SPS
(see W. Scandale)

Work in progress



Creation of an international "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 22 institutions have already expressed their Interest in joining Argon-Net, to act as 'nodes' of the network

Outlook

- **Very large liquid Argon TPC will provide a rich physics programme, including both accelerator & non-accelerator aspects, as important as electroweak physics at colliders**

- **The liquid Argon TPC is a new and challenging technology.**
  - ➥ It is the fruit of many years of R&D effort conducted by the ICARUS collaboration.
  - ➥ It was demonstrated to the 0.6 kton scale on the surface test in summer 2001
  - ➥ Extrapolation from 0.6 to 100 kton is a big step
  - ➥ It might require a 10% prototype (10 kton) — cost comparable to a CNGS experiment
  - ➥ R&D is on-going
  - ➥ It would provide a qualitative & quantitative improvement in physics
  - ➥ High statistics, precision physics will require a ≈100 ton detector in a neutrino beam (near site)

- **Given the challenging aspect of the ideas reviewed in this talk:**
  - ➥ Creation of international Argon-Net **"for the further development of the Liquid Argon TPC and for its application to future experiments". Work in progress…**