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The liquid Argon Time Projection chamber: mid & long term strategy and on-going R&D

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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 an 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.

- In this talk, I will discuss possible future and independent applications of the technique. More details can be found in the following references:

- 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
- Ideas for future liquid Argon detectors, A. Ereditato and A.Rubbia, Proc. Third International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region, NUINT04, March 2004, Gran Sasso, Italy,
- Ideas for a next generation liquid Argon TPC detector for neutrino physics and nucleon decay searches, A. Ereditato and A.Rubbia, Proc. Workshop on Physics with a Multi-MW proton source, May 2004, CERN, Switzerland
- Very massive underground detectors for proton decay searches, A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, March 2004, hep-ph/0407297

Liquid Argon medium properties

• A Historical View On the R&D for liquid Rare Gas detectors, T. Doke, NIM A 327 (1993) 113 and references therein.

	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

$W_e = 23.6 \pm 0.3$ eV

2) Scintillation (luminescence)

$W_\gamma = 19.5$ 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)**

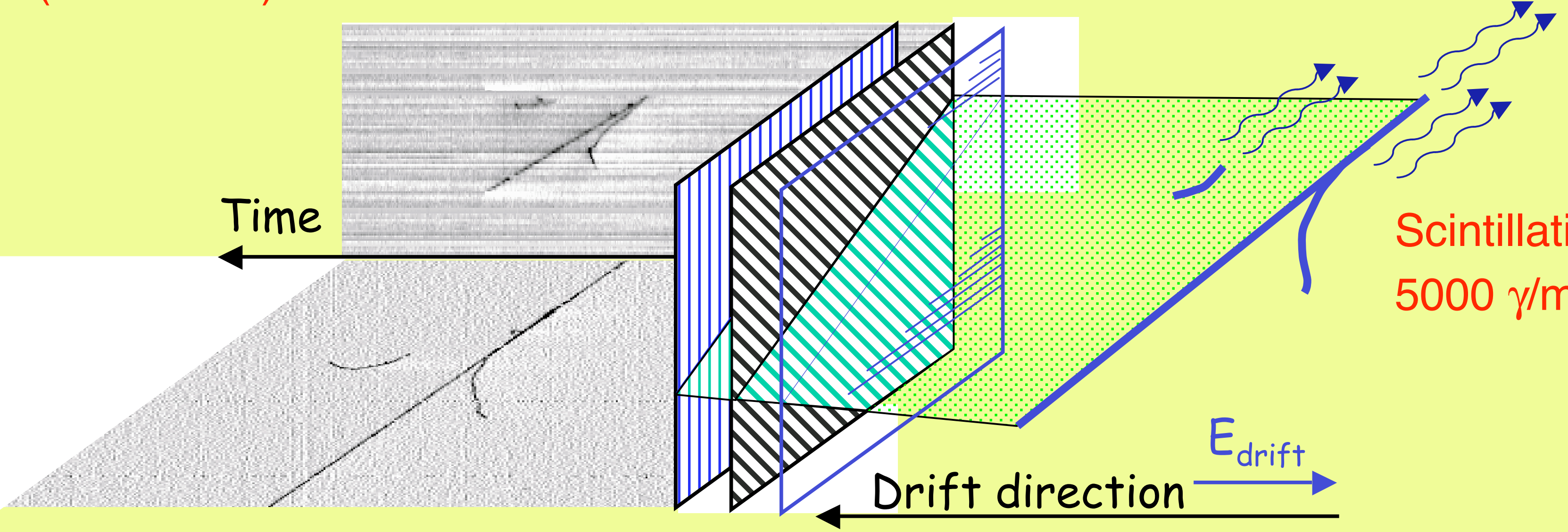
Scintillation & Cerenkov light can be detected independently !

The Liquid Argon TPC principle

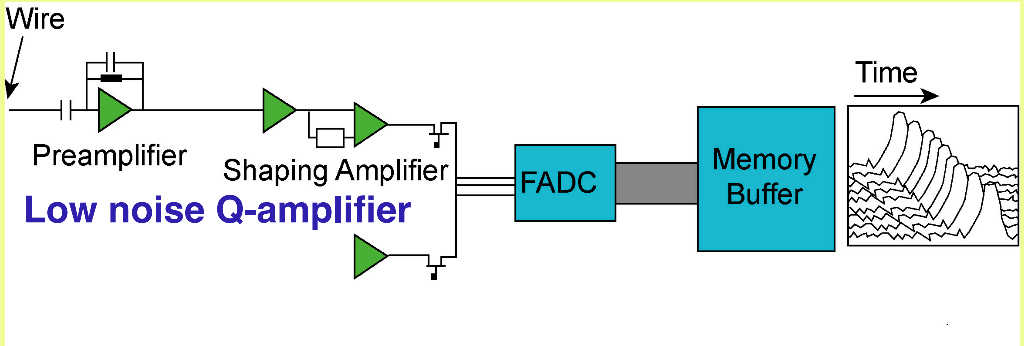
Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

Charge readout planes: Q

UV Scintillation Light: L



Scintillation light yield ~
5000 γ/mm @ 128 nm



Continuous waveform recording → image

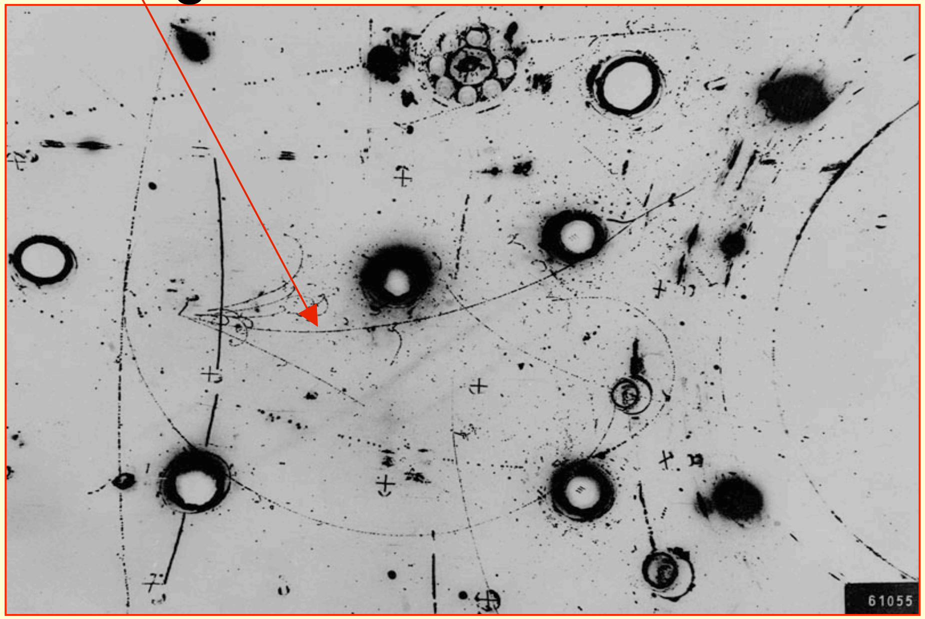
- The Liquid Argon Time Projection Chamber: a new concept for Neutrino Detector, C. Rubbia, CERN-EP/77-08 (1977).
- A study of ionization electrons drifting large distances in liquid and solid Argon, E. Aprile, K.L. Giboni and C. Rubbia, NIM A251 (1985) 62.
- A 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A332 (1993) 395.
- Performance of a 3 ton liquid Argon Time Projection Chamber, ICARUS Collab., NIM A345 (1994) 230.
- The ICARUS 50 l LAr TPC in the CERN neutrino beam, ICARUS Collab, hep-ex/9812006 (1998).

Liquid Argon TPC: an electronic bubble chamber

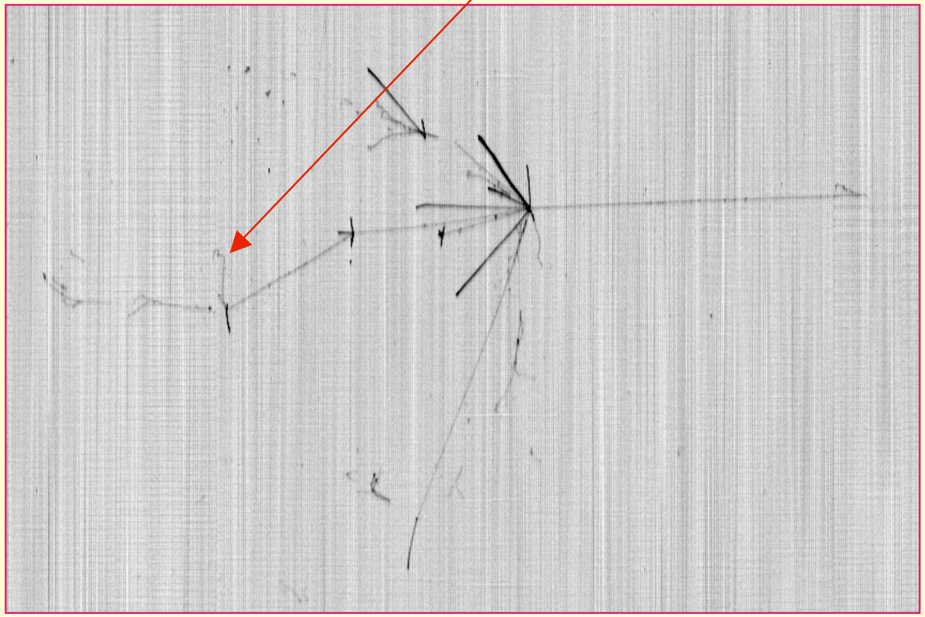
Bubble diameter ≈ 3 mm (diffraction limited)

Bubble size ≈ 3x3x0.4 mm^3

Gargamelle bubble chamber



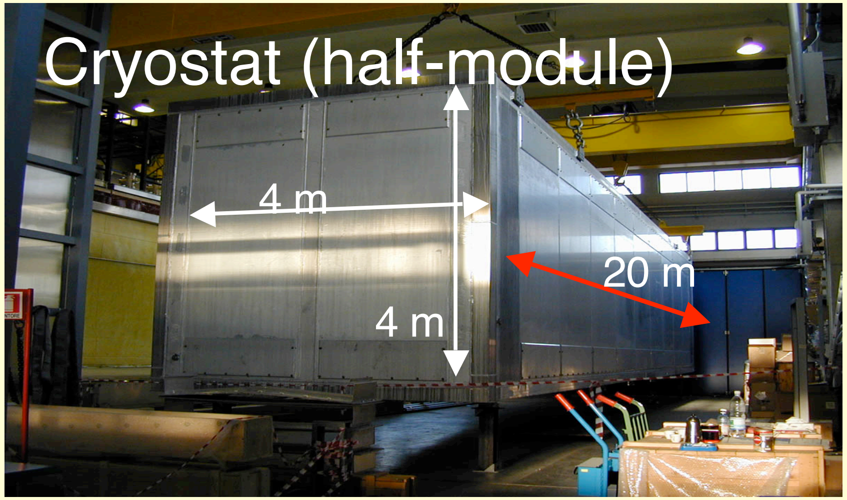
ICARUS electronic chamber

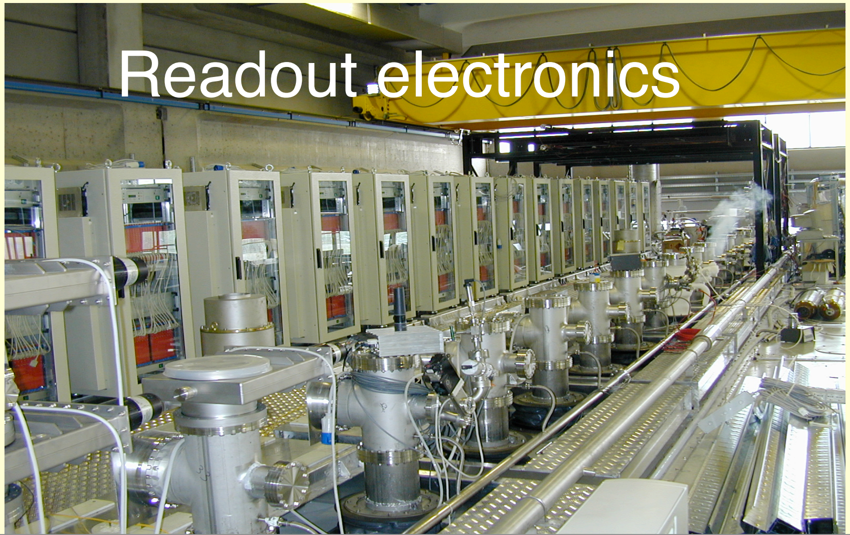


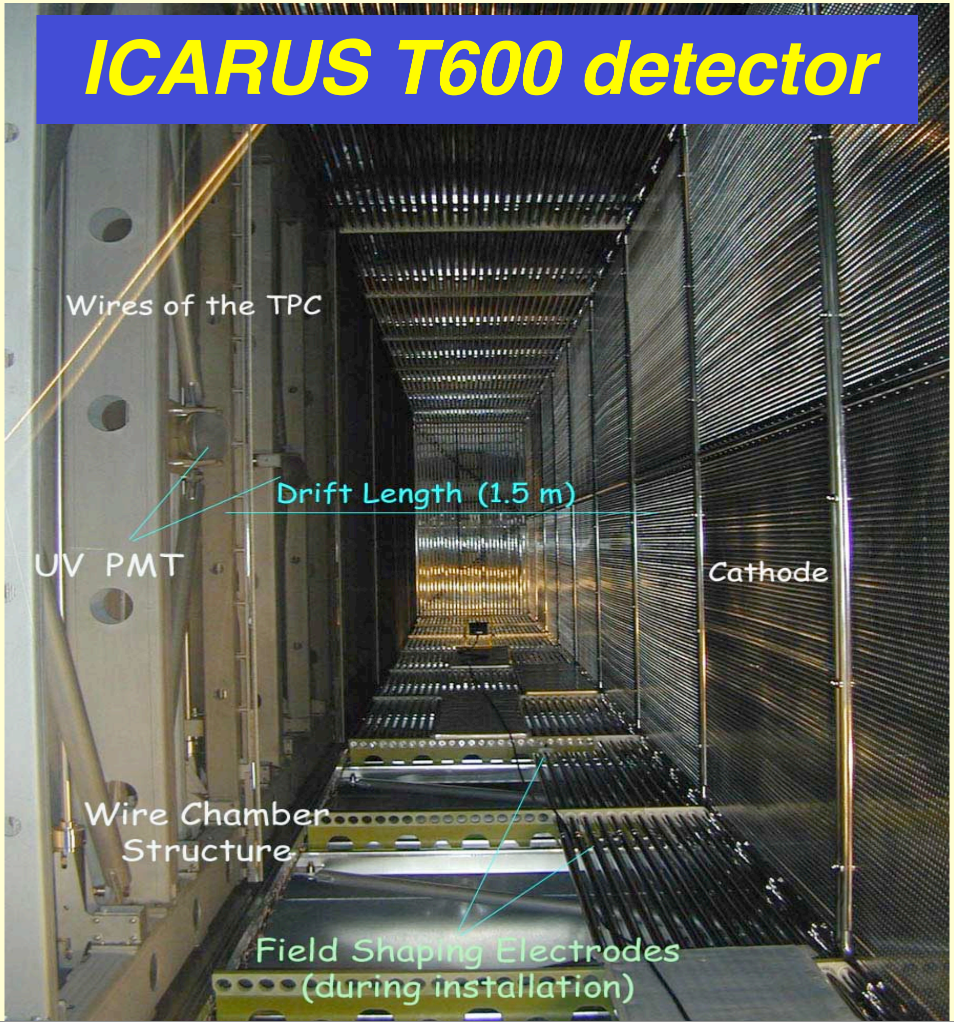
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

↔

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







- Design, construction and tests of the ICARUS T600 detector, ICARUS Collab, NIM A527 329 (2004).
- Study of electron recombination in liquid Argon with the ICARUS TPC, ICARUS Collab, NIMA523 275-286 (2004).
- Detection of Cerenkov light emission in liquid Argon, ICARUS Collab, NIM A516 348-363 (2004).
- Analysis of the liquid Argon purity in the ICARUS T600 TPC, ICARUS Collab, NIM A516 68-79 (2004).
- Observation of long ionizing tracks with the ICARUS T600 first half module, ICARUS Collab, NIM A508 287 (2003).
- Measurement of the muon decay spectrum with the ICARUS liquid Argon TPC, ICARUS Collab, EPJ C33 233-241 (2004).

What the Liquid Argon TPC provides

- **Bubble-chamber-like event reconstruction capability**
  - Tracking, full-sampling calorimetry, unbiased imaging
  - Very good resolution (energy, angular)
  - Broad energy range (from MeV, multi-GeV, tens of GeV)
  - kaon, proton particle ID
  - e/π^0 separation
  - $\mu/\pi^{\pm}$ separation
  - Shallow depth conceivable
  - Possible to embed in magnetic field for charge discrimination (muons and electrons)

- **Broad physics programme**
  - Nucleon decay, neutrino astrophysics (supernovae, …) and accelerator (neutrino oscillations, θ_{13}, CP violation)

- **Very good scaling properties**
  - ICARUS T600 retained exactly the performance of the 3 ton prototype (x200 in mass in ≈10 years!)
  - 100 kton mass technically conceivable (x200 compared to ICARUS T600)
  - Many possible applications: From 100 ton to 100 kton… 10 kton (10%) prototype ?

Liquid Argon TPC: two mass scales

physics calls for two different applications

100 ton

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

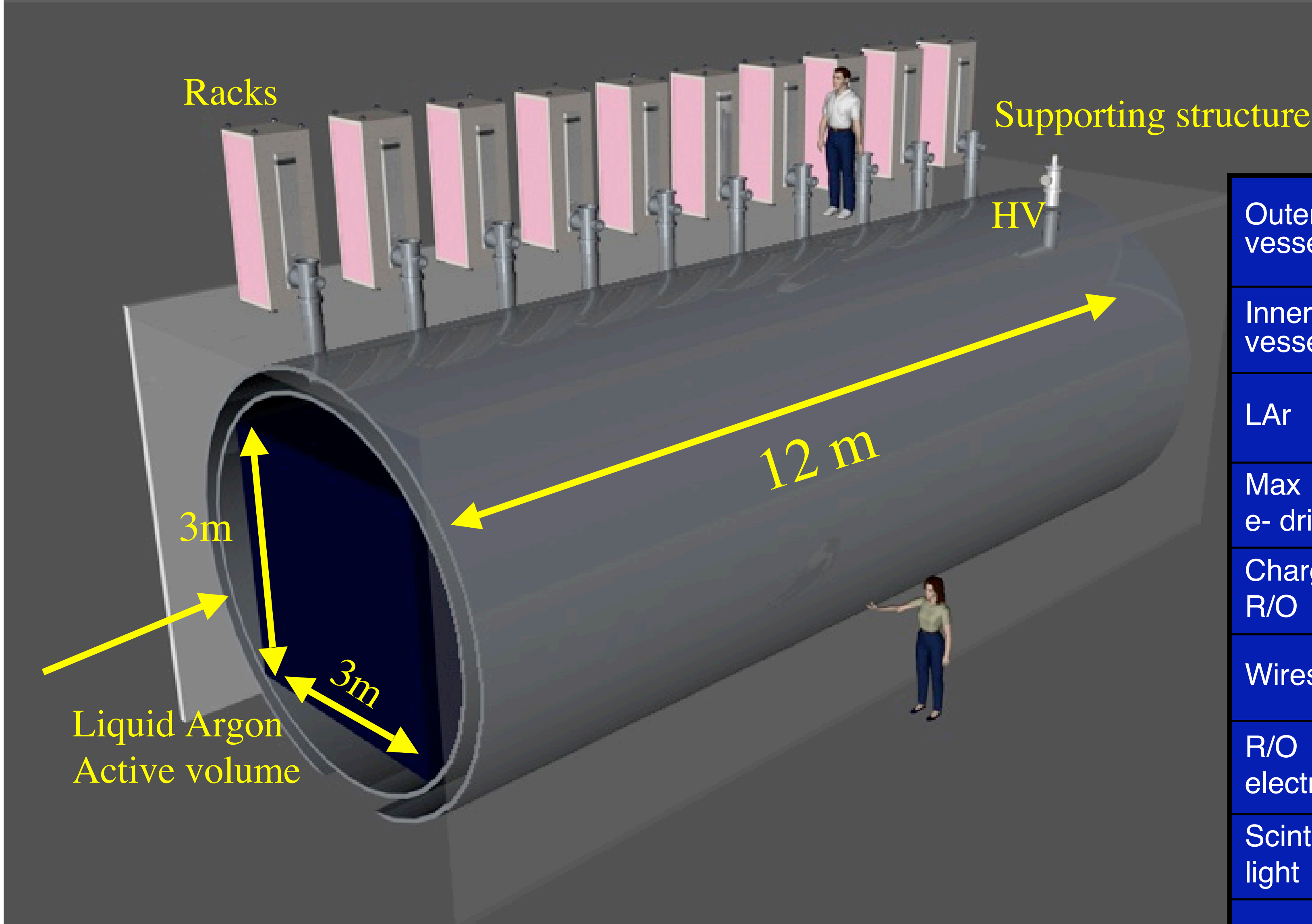
100 <u>k</u>ton

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

Strong synergy and high degree of interplay

100 ton

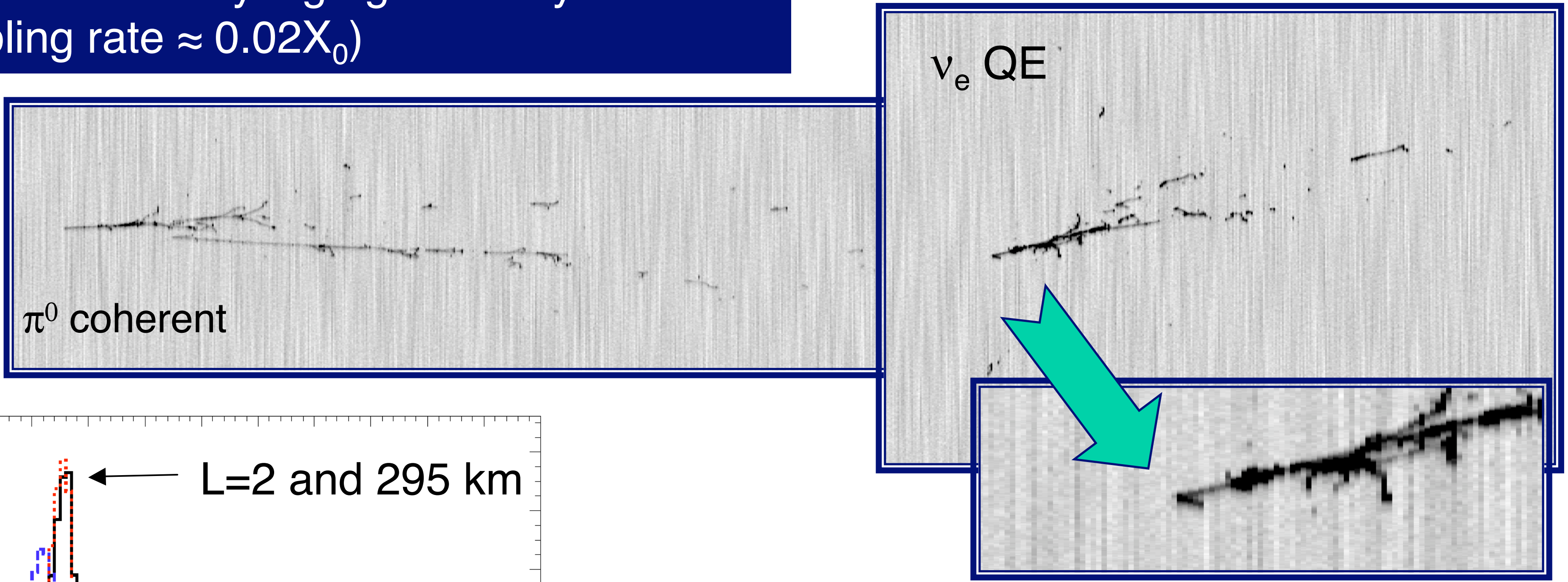
Conceptual design of a ~100 ton LAr TPC for a near station in a LBL facility:

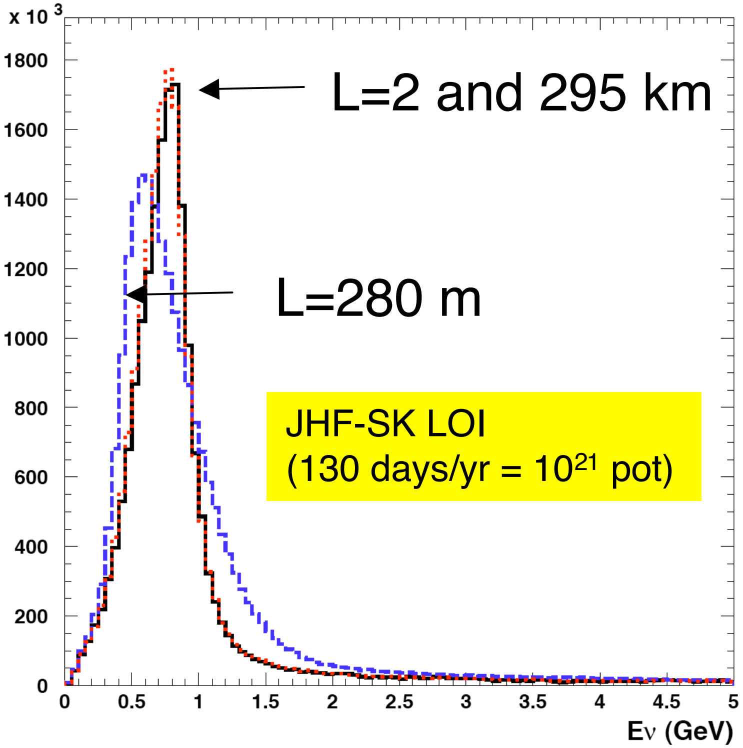


Outer vessel	ϕ ≈ 5m, L≈13m, 15mm thick, weight ≈ 22 t
Inner vessel	ϕ ≈ 4,2 m, L ≈ 12 m, 8 mm thick, ≈ 10 t
LAr	Total ≈ 240 t Fiducial ≈ 100 t
Max e- drift	3 m @ HV=150 kV E = 500 V/cm
Charge R/O	2 views, ± 45° 2 (3) mm pitch
Wires	≈10000 (7000) $\phi = 150\ \mu m$
R/O electr.	on top of the dewar
Scintill.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

The liquid Argon TPC allows for large detectors with very high granularity (sampling rate ≈ $0.02X_0$)

full simulation, digitization, and noise inclusion





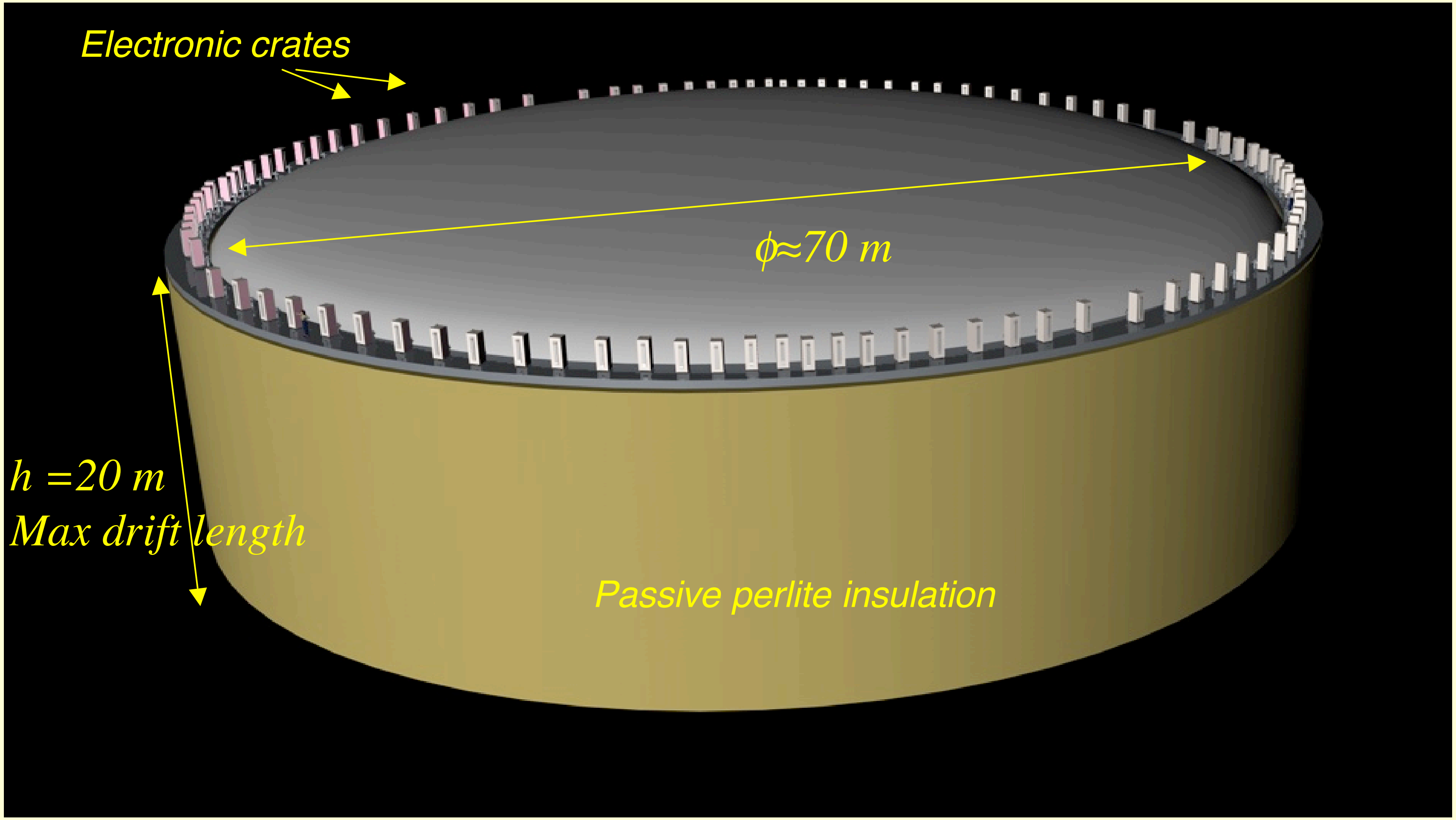
JHF-SK LOI
(130 days/yr = 10^{21} pot)

For example: 100 ton @ L=2000 m

Beam	E_{peak}(GeV)	ν_μ	ν_e
OA2	0.7	300000/yr 0.1/spill	5800/yr 45/day

100 kton

A 100 kton liquid Argon TPC detector



A detector for ν astrophysics, ν beams, and nucleon decay

Single module cryo-tanker based on industrial LNG technology

100 kton LAr delivers "megaton-physics"

	Liquid Argon TPC
Total mass	100 kton
$p \to e\,\pi^0$ in 10 years	0.5×10^{35} years, ε= 45%, <1 BG event
$p \to \nu K$ in 10 years	1.1×10^{35} years, ε= 97%, <1 BG event
$p \to \mu\pi K$ in 10 years	1.1×10^{35} years, ε= 98%, <1 BG event
SN cool off @ 10 kpc	38500 (all flavors) (64000 if NH-L mixing)
SN in Andromeda	7 (12 if NH-L mixing)
SN burst @ 10 kpc	380 ν_e CC (flavor sensitive)
SN relic	Yes
Atmospheric neutrinos	10000 events/year
Solar neutrinos	324000 events/year $E_e > 5$ MeV

"Complementary to Megaton Water Cerenkov detector"

Very massive underground detectors for proton decay searches, A.Rubbia, Proc. XI Int. Conf. on Calorimetry in H.E.P., CALOR04, Perugia, March 2004, hep-ph/0407297

Some recent physics references for liquid Argon TPCs

Proton driver optimization for new generation neutrino superbeams to search for subleading oscillations, A.Ferrari et al., New J. Phys 4 (2002) 88, hep-ph/0208047

On the energy and baseline optimization to study effects related to the delta phase (CP/T-violation) in neutrino oscillations at a neutrino factory, A. Bueno et al., Nucl. Phys. B631 (2002) 239, hep-ph/0112297 and references therein

Decoupling supernova and neutrino oscillations physics with LAr TPC detectors, I. Gil-Botella and A.Rubbia, accepted for publications in JCAP, hep-ph/0404151

Oscillation effects on supernova neutrino rates and spectra and detection of the shock breakout in a liquid Argon TPC, I. Gil-Botella and A.Rubbia, JCAP 10 (2003) 009, hep-ph/0307244

Supernova neutrino detection in a liquid Argon TPC, A. Bueno, I. Gil-Botella and A.Rubbia, hep-ph/0307222

Relic supernova neutrino detection with liquid Argon TPC detectors, A. Cocco et al., in preparation

Nucleon decay studies in a large liquid Argon detector, A.Bueno, M. Campanelli, A. Ferrari and A.Rubbia, Proceedings International Workshop on next generation nucleon decay and neutrino detector (NNN99), Stony Brook, NY, USA (1999)

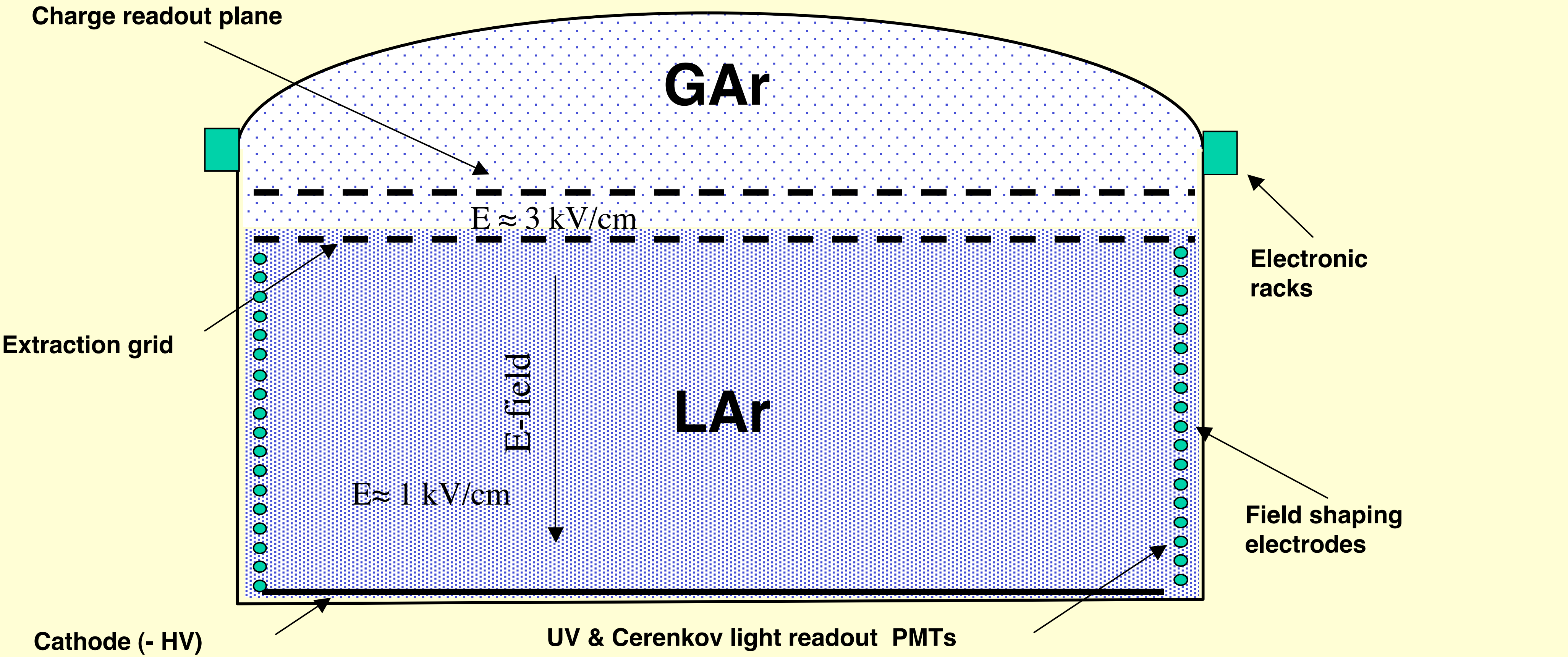
Nucleon decay searches: study of nuclear effects and background, A. Ferrari, S. Navas, A.Rubbia and P. Sala, ICARUS technical memo TM/01-04 (2001)

Simulation of Cosmic Muon Induced Background to Nucleon Decay Searches in a Giant 100 kton LAr TPC, Z. Dai, A.Rubbia and P. Sala, in preparation

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light

Dewar	$\phi \approx$ 70 m, height $\approx$ 20 m, perlite insulated, heat input $\approx$ 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



Design considerations

•**Single "boiling" cryogenic tanker at atmospheric pressure for a stable and safe equilibrium condition** (temperature is constant while Argon is boiling). The evaporation rate is small (less than 10^{-3} of the total volume per day given by the very favorable area to volume ratio) and is compensated by corresponding refilling of the evaporated Argon volume.

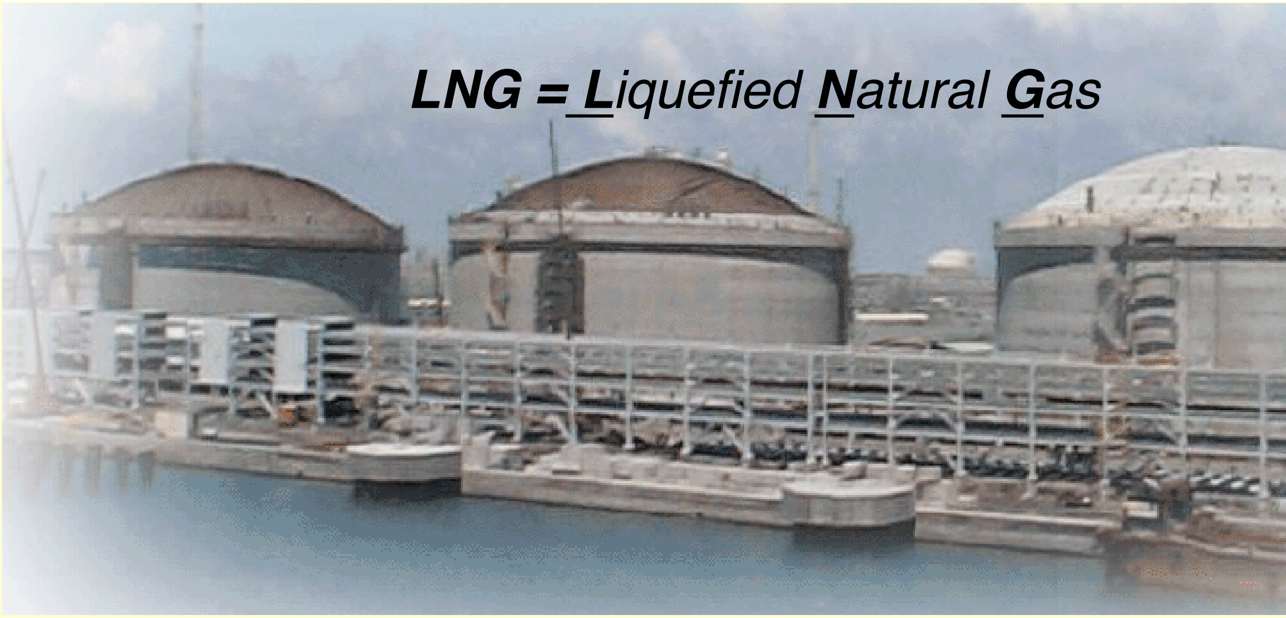
•**Charge imaging, scintillation and Cerenkov light readout for a complete (redundant) event reconstruction**. This represents a clear advantage over large mass, alternative detectors operating with only one of these readout modes. The physics benefit of the complementary charge, scintillation and Cerenkov readout are being assessed.

•**Charge amplification to allow for very long drift paths**. The detector is running in bi-phase mode. In order to allow for drift lengths as long as ≈20 m, which provides an economical way to increase the volume of the detector with a constant number of channels, charge attenuation will occur along the drift due to attachment to the remnant impurities present in the LAr. We intend to compensate this effect with charge amplification near the anodes located in the gas phase.

•**Absence of magnetic field, although this possibility might be considered at a later stage**. R&D studies for charge imaging in a magnetic field are on-going and results are expected soon. Physics studies indicate that a magnetic field is really only necessary when the detector is coupled to a Neutrino Factory and can be avoided in the context of Superbeams and Betabeams.

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

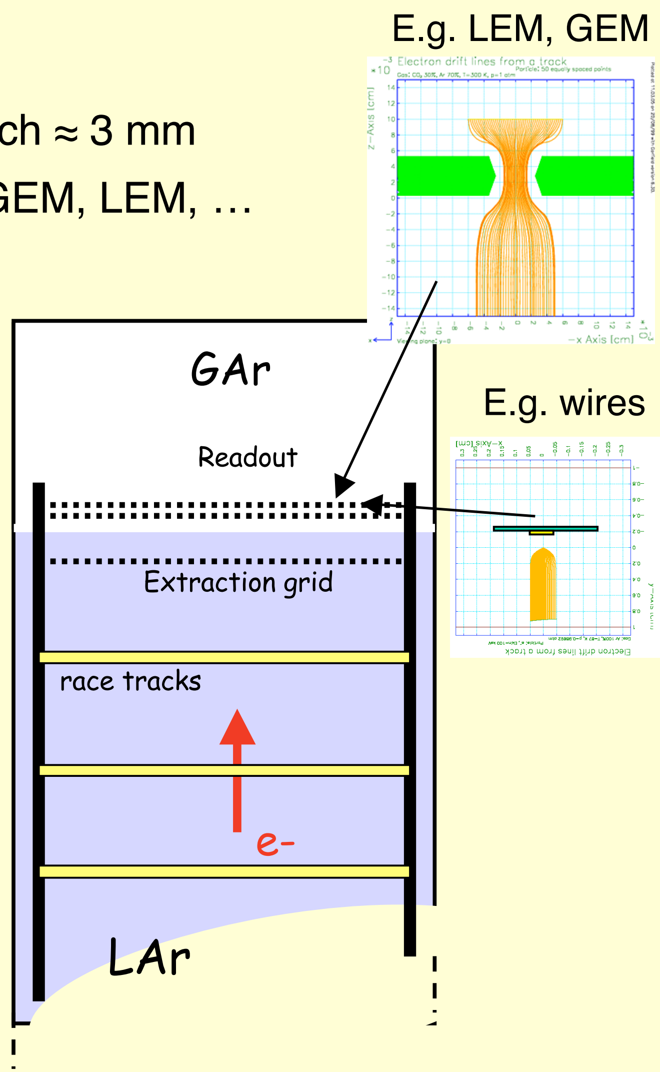
Cooling by "auto-refrigeration"

Charge extraction, amplification, readout

Detector is running in **BI-PHASE MODE** to allow for a very long drift path

- 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
- Amplification can be implemented in different ways: wires+pad, GEM, LEM, …

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, …**



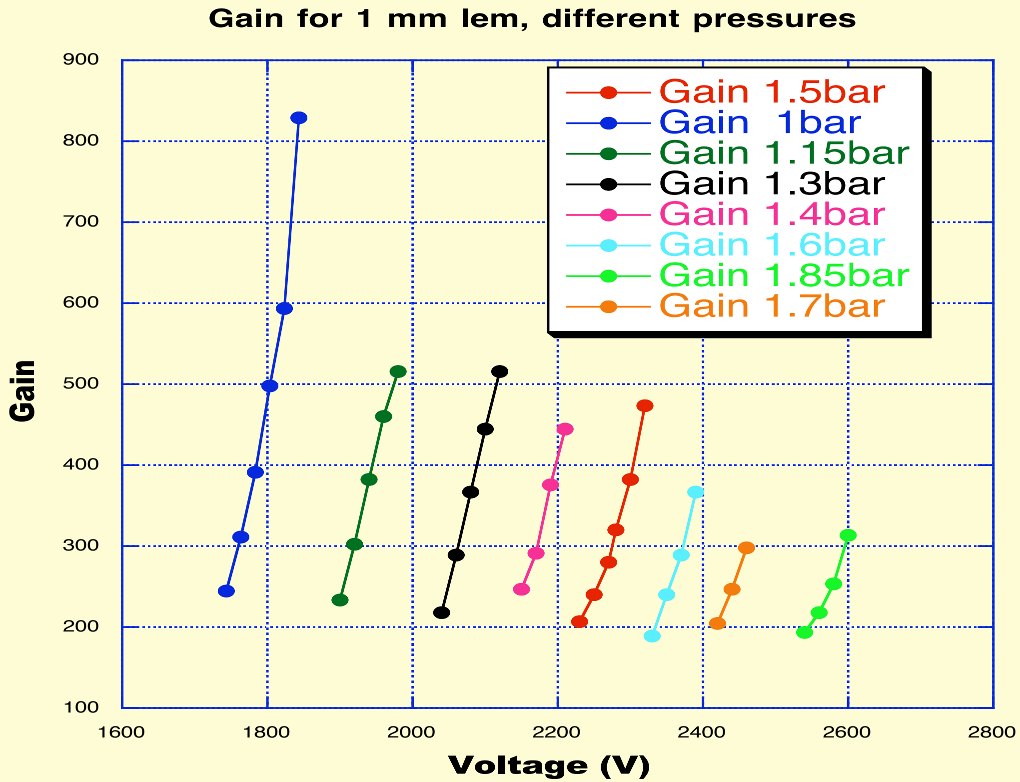
Ongoing studies and R&D strategy

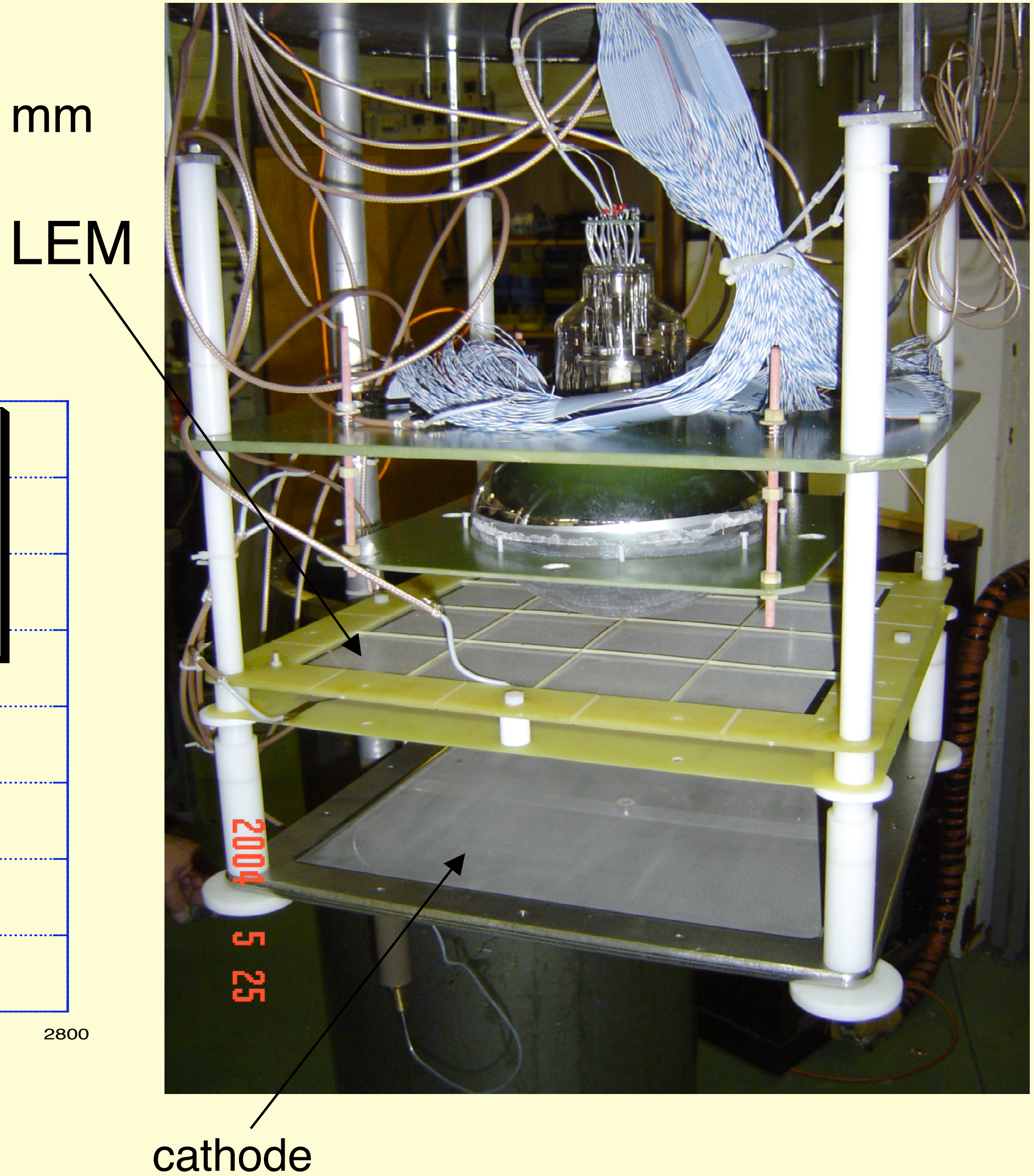
Engineering studies, dedicated test measurements, detector prototyping, simulations, physics performance studies in progress:

- Study of suitable charge extraction, amplification and imaging devices
- Understanding of charge collection under high pressure
- Realization and test of a 5 m long detector column-like prototype
- Study of LAr TPC prototypes immersed in a magnetic field
- Study of large liquid underground storage tank, costing
- Study of logistics, infrastructure and safety issues for underground sites
- Physics studies and phenomenology

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





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)

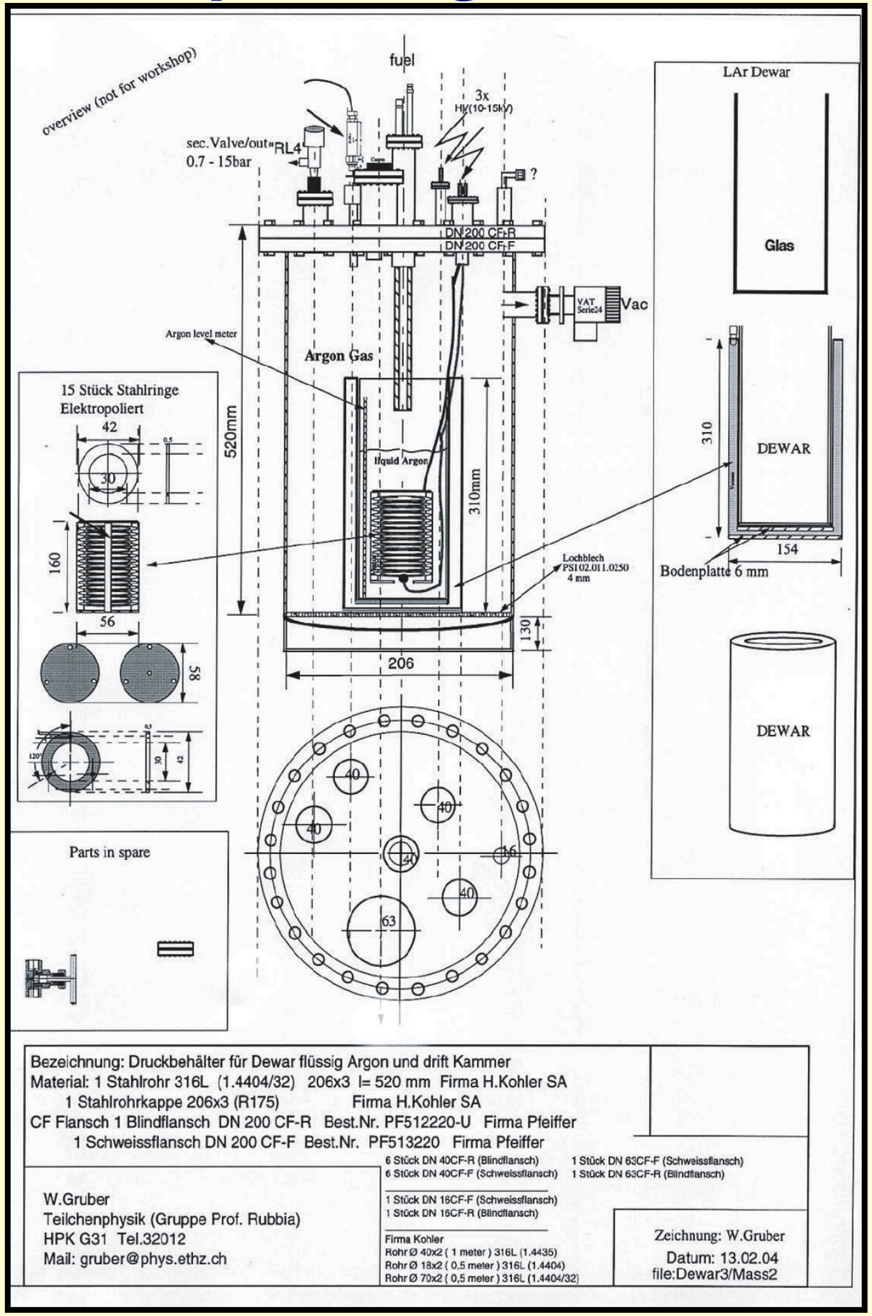
- **Test of electron drift properties in high pressure liquid Argon**

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

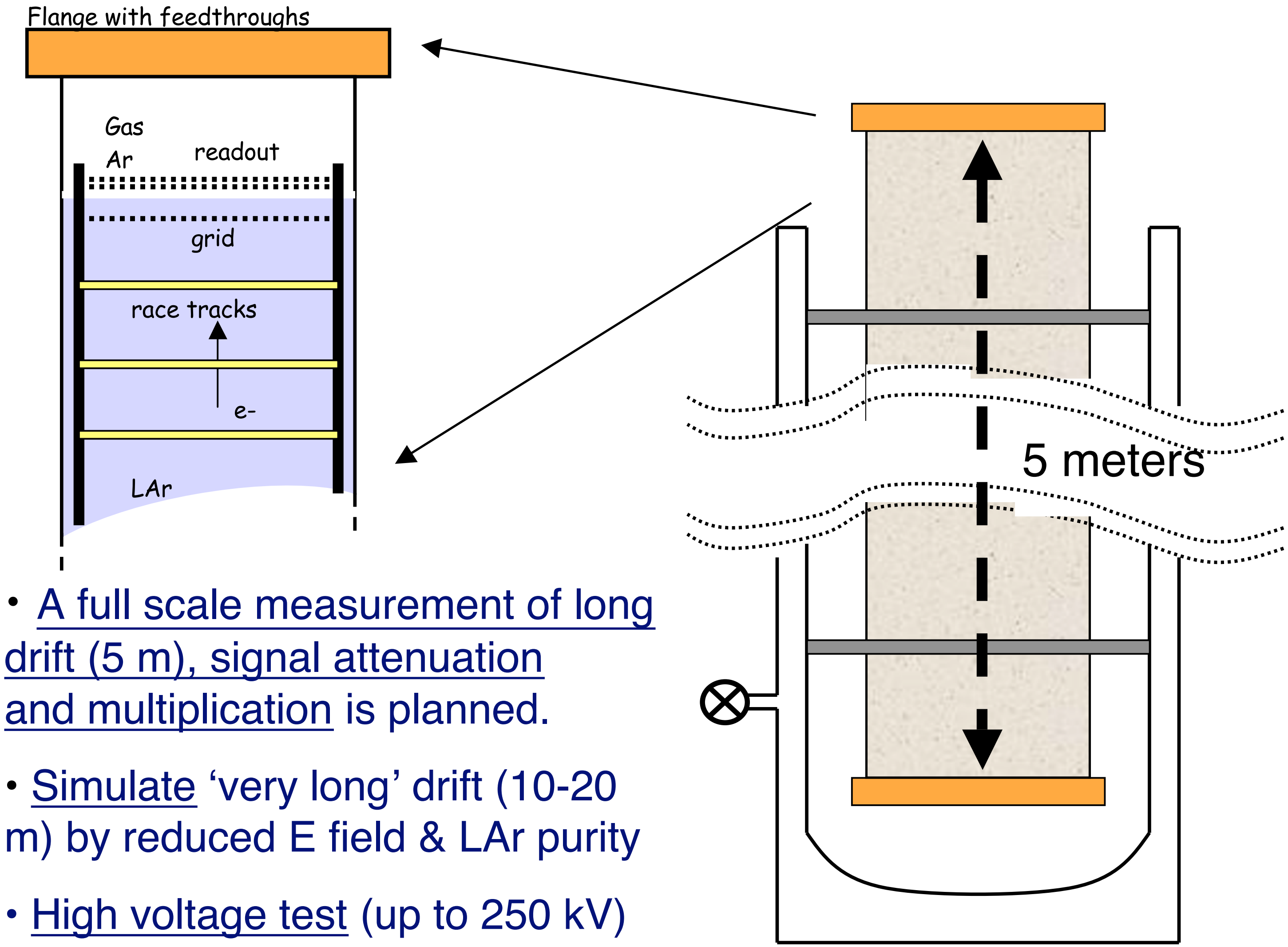
- **Study in progress**

  ✓ Prototype designed

  ✓ Parts being assembled at PSI



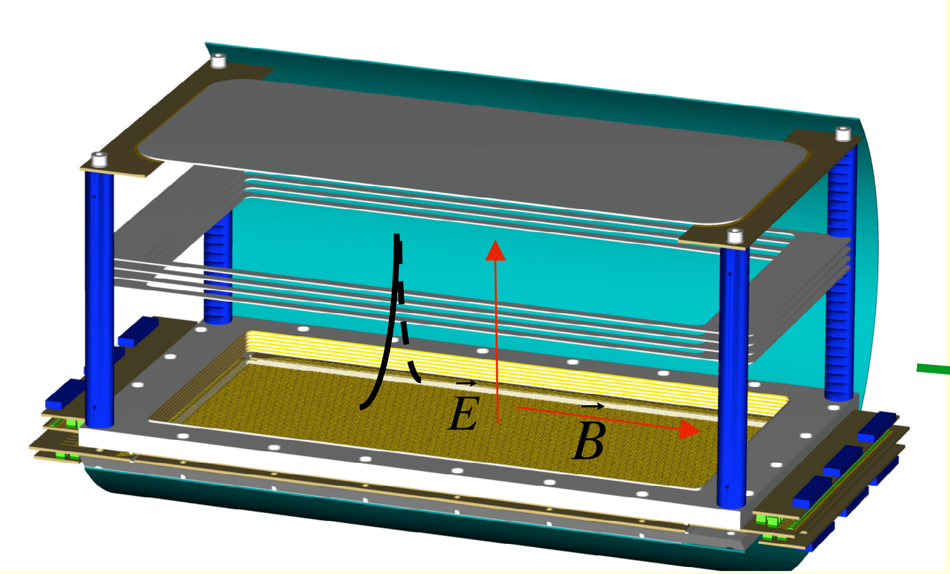
Long drift, extraction, amplification: test module

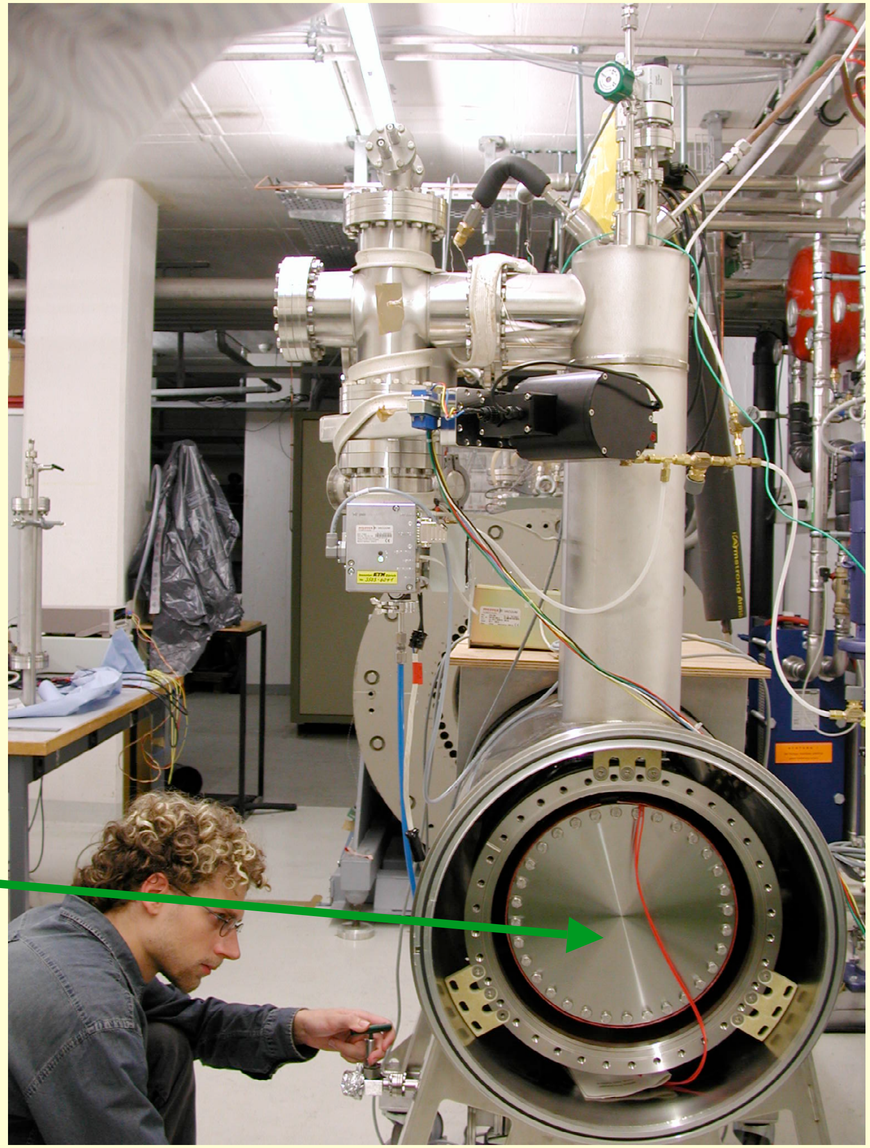


- A full scale measurement of long drift (5 m), signal attenuation and multiplication is planned.
- Simulate 'very long' drift (10-20 m) by reduced E field & LAr purity
- High voltage test (up to 250 kV)
- Design in progress: external dewar, detector container, inner detector, readout system, …

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 ($\alpha \approx 30$mrad @ E=500 V/cm, B=0.5T)
- **Results expected in 2004**





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

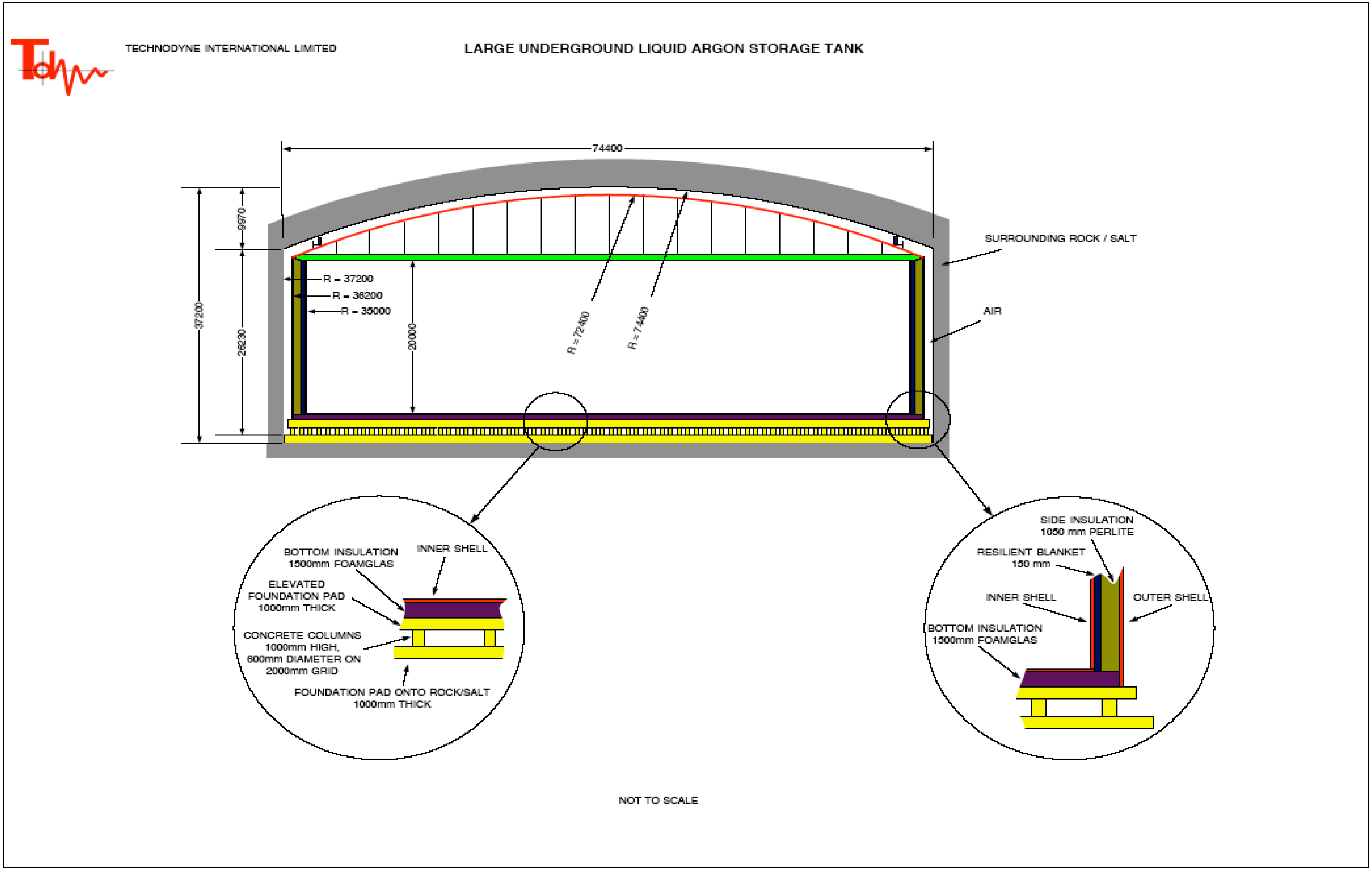
Study of large underground storage tank

	Project: Large Underground Argon Storage Tank
Issued By: JMH	Document Title
Date:	

A feasibility study mandated to Technodyne LtD (UK)

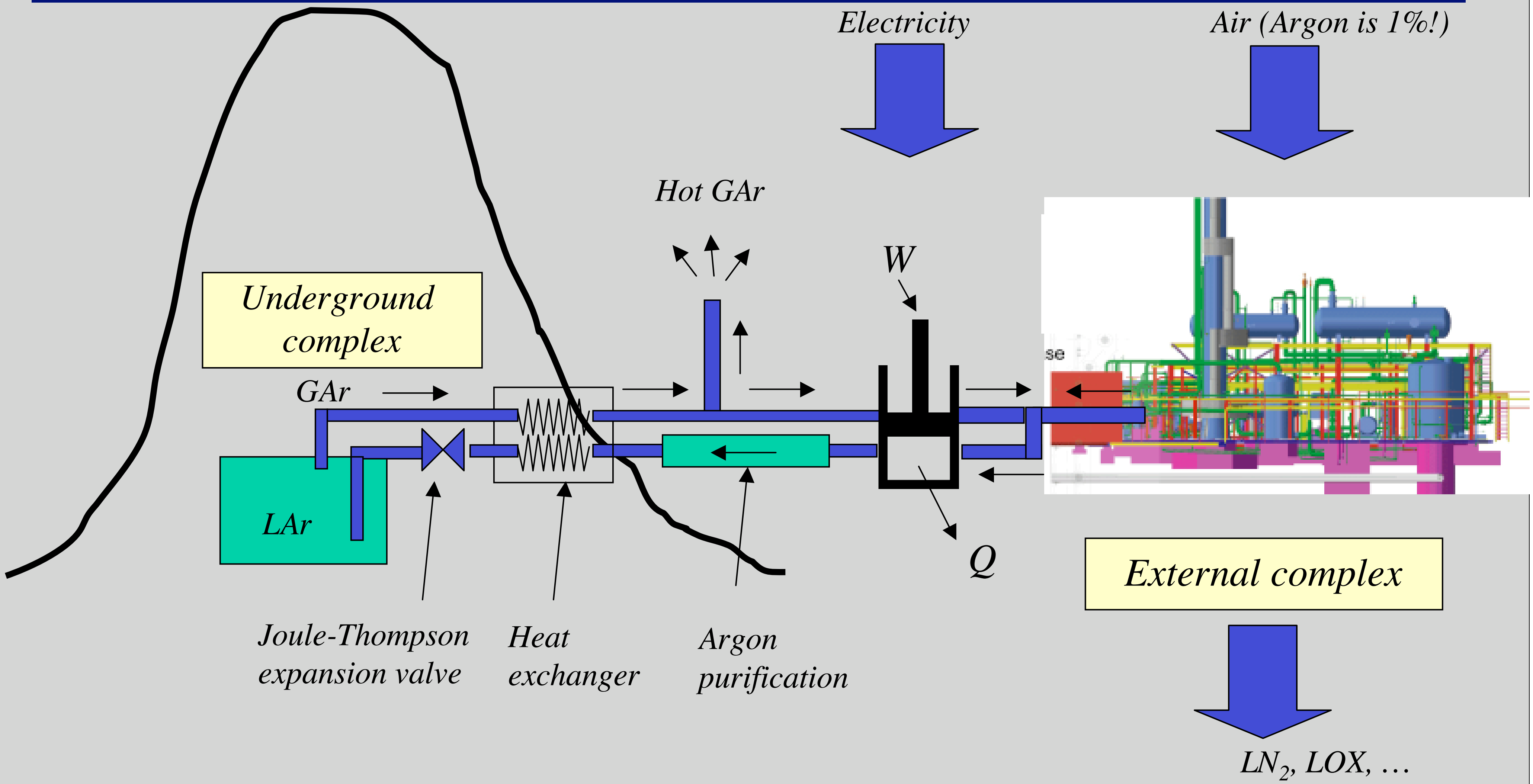
Work in progress: Underground storage, engineering issues, process system & equipment, civil engineering consulting, safety, cost & time

Technodyne baseline design

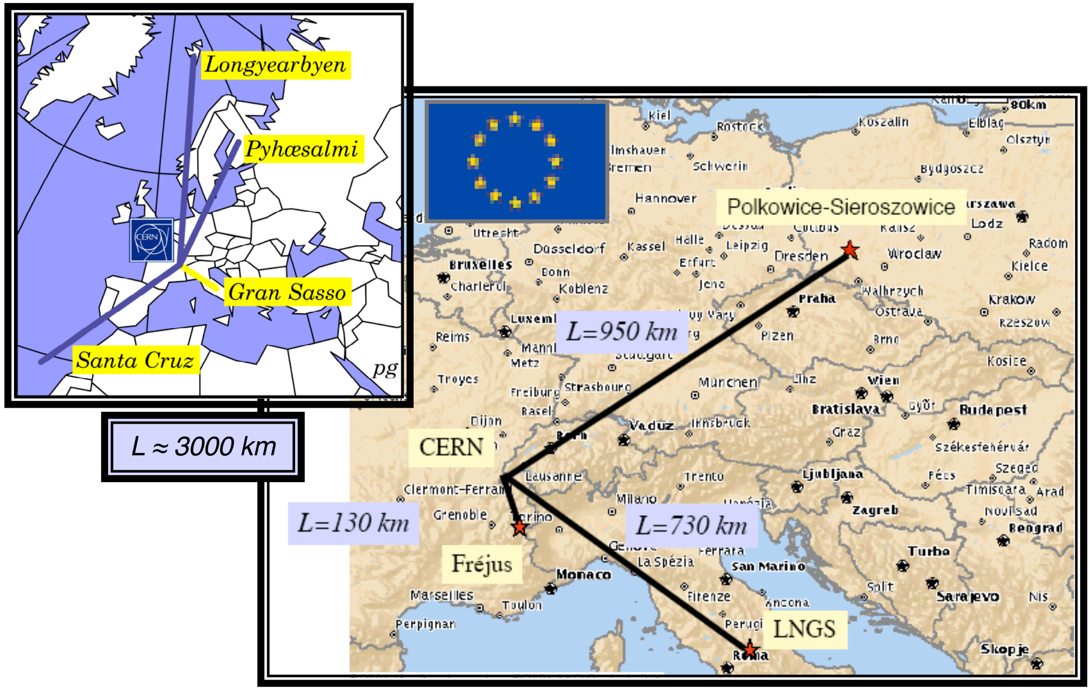


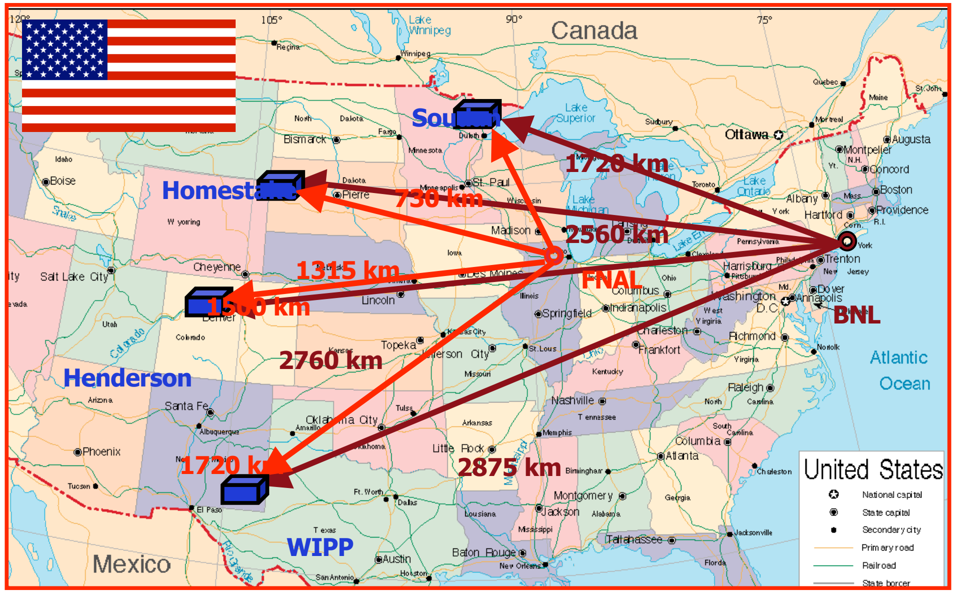
Process system & equipment

- 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/m² heat input, continuous re-circulation (purity)
- Boiling-off volume at regime: 30 ton/day: refilling



Underground site location: multiple parameter optimization

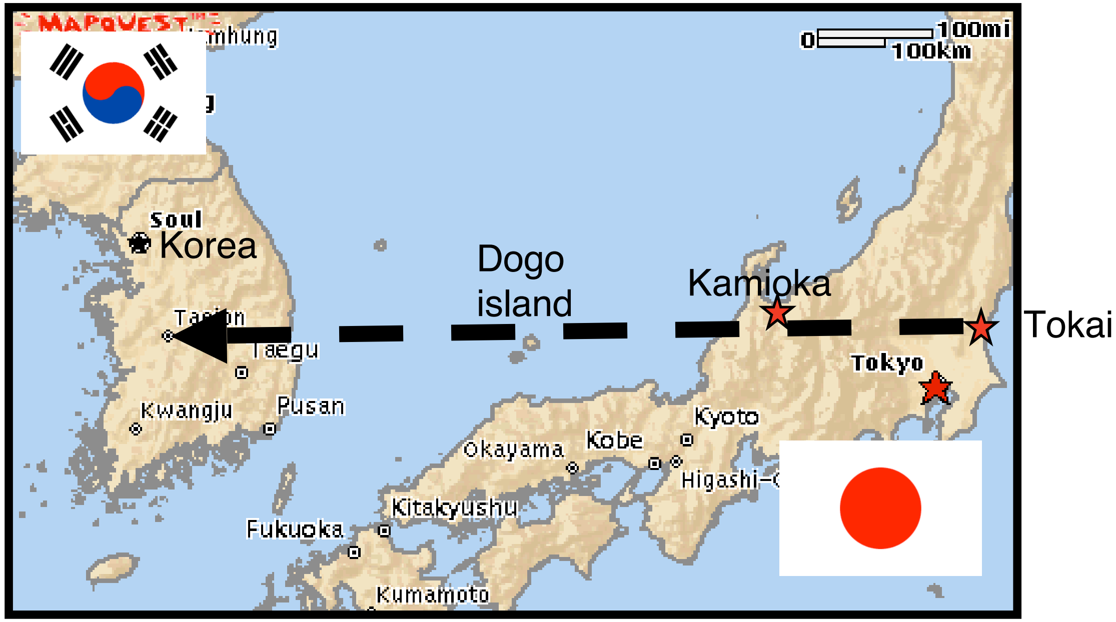




Infrastructure, depth, location, baseline, cavern size…

New:

Simulation of Cosmic Muon Induced Background to Nucleon Decay Searches in a Giant 100 kton LAr TPC, Z. Dai, A.Rubbia and P. Sala, in submission phase (2004)

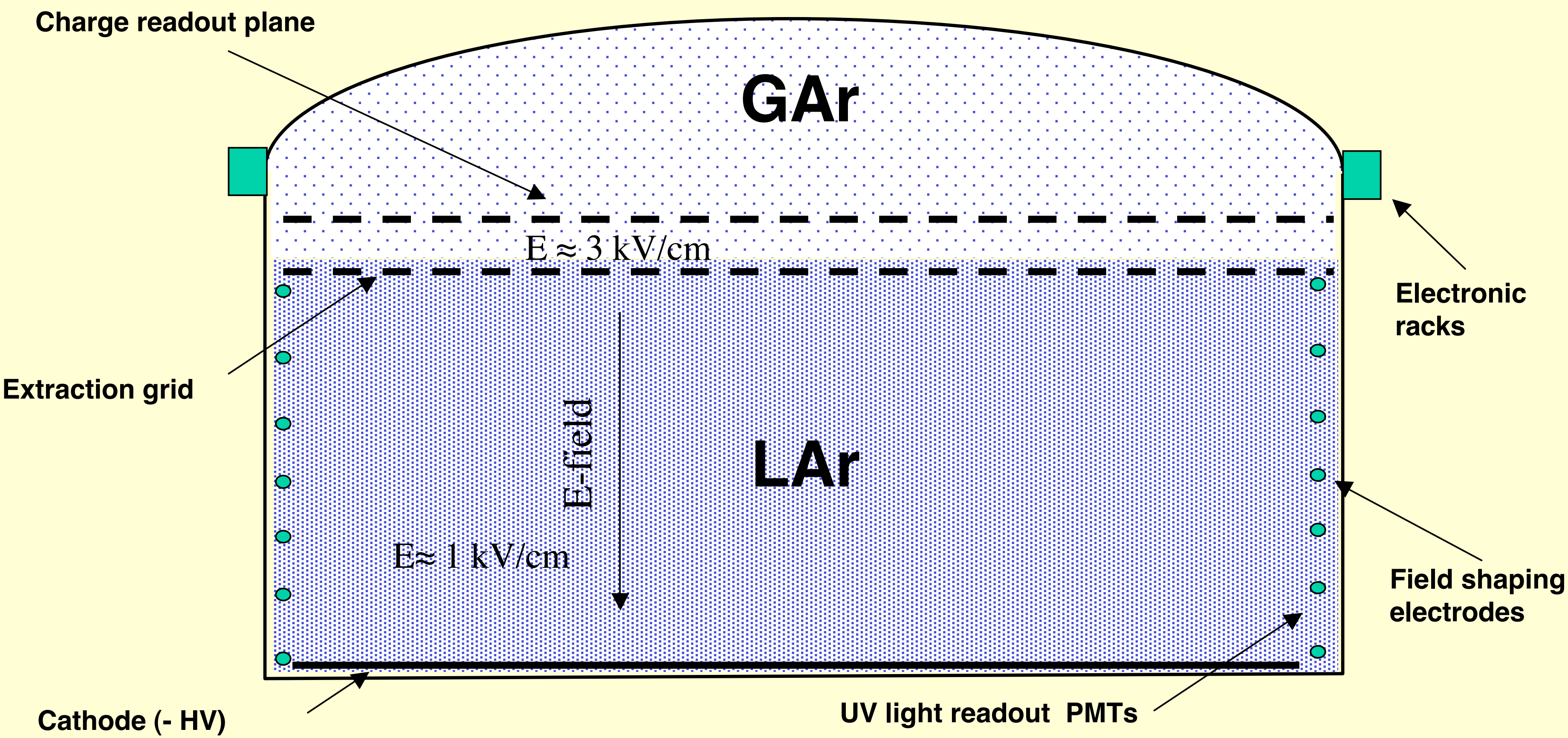


10 kton detector

- 10% full-scale prototype
- Shallow depth acceptable
- Physics program on its own

(e.g. sensitivity for $p \rightarrow \nu K$: $\tau > 10^{34}$ yrs for 10 years running)

Dewar	$\phi \approx 30$ m, height ≈ 10 m, perlite insulated, heat input ≈ 5 W/m^2
Argon storage	Boiling Argon, low pressure (<100 mbar overpressure)
Argon total volume	7000 m^3, ratio area/volume $\approx$ 33%
Argon total mass	9900 tons
Hydrostatic pressure at bottom	1.5 atmospheres
Inner detector dimensions	Disc $\phi \approx 30$ m located in gas phase above liquid phase
Charge readout electronics	30000 channels, 30 racks on top of the dewar
Scintillation light readout	Yes (also for triggering), 300 immersed 8" PMTs with WLS



Rough Cost Estimate in MEuro : 100 & 10 kton

Item	100 kton	10 kton
LNG tanker (see notes 1-2)	50÷100	20 ÷ 30
Merchant cost of LAr (see note 3)	100	10
Refilling plant	25	10
Purification system	10	2
Civil engineering + excavation	30	5
Forced air ventilation	10	5
Safety system	10	5
Inner detector mechanics	10	3
Charge readout detectors	15	5
Light readout	60 (with Č)	2 (w/o Č)
Readout electronics	10	5
Miscellanea	10	5
Total	**340 ÷ 390**	**≈ 80 ÷ 90**

Notes:

(1) Range in cost of tanker comes from site-dependence and current uncertainty in underground construction

(2) Cost of tanker already includes necessary features for LAr TPC (surface electropolishing, hard roof for instrumentation, feed-throughs,…)

(3) LAr Merchant cost ≠ production cost. Fraction will be furnished from external companies and other fraction will be produced locally (by the refilling plant)

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.

- 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 tentative layout for a 100 kton underground liquid argon detector has been presented based on LNG cryogenic self-refrigerated (boiling) tanker, bi-phase operation for very long drifts with charge imaging, scintillation and Cerenkov light readout. R&D is on-going to ascertain the technical feasibility and performance of this design.

- A 10% full-scale, cost-effective prototype could be envisaged as an engineering design test with a physics program on its own.

- A 100 ton detector in a near-site of an LBL facility is a straight forward and very desirable application of the technique.