Liquid Argon Imaging Detectors

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Outline

- The ICARUS Liquid Argon TPC:
  - General principles
  - Technological challenges
  - Detector performance
- The WArP double-phase Ar-TPC
  - Physics motivation
  - Detector technology and performance
- Further developments

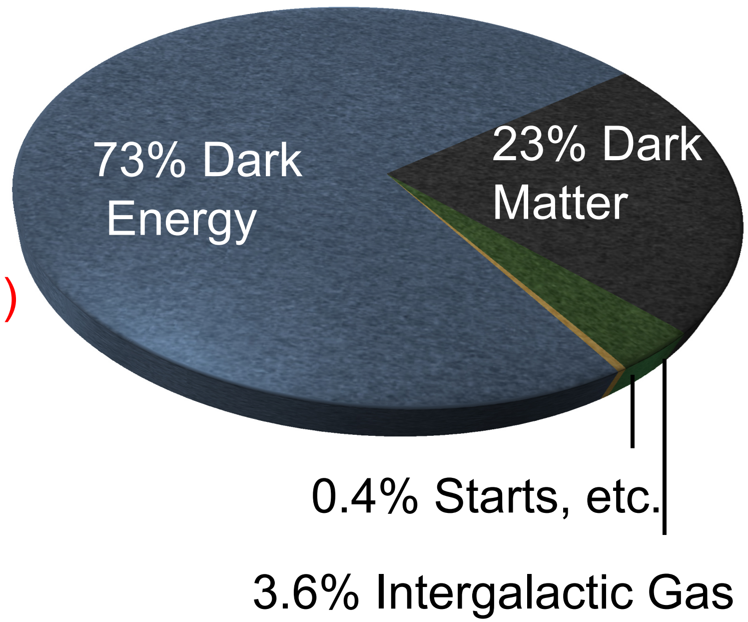
Evidences of Dark Matter

$\Omega_{tot} = 1$

- All present observations
  - Galaxies rotational curves
  - Gravitational lensing
  - Dynamics of merging galaxies
  - Observation of CMB anisotropies (WMAP)
  - Regression velocity of Type 1A SN
  - Structures Formation

fit into a single unitary picture:
the so called

CONCORDANCE MODEL



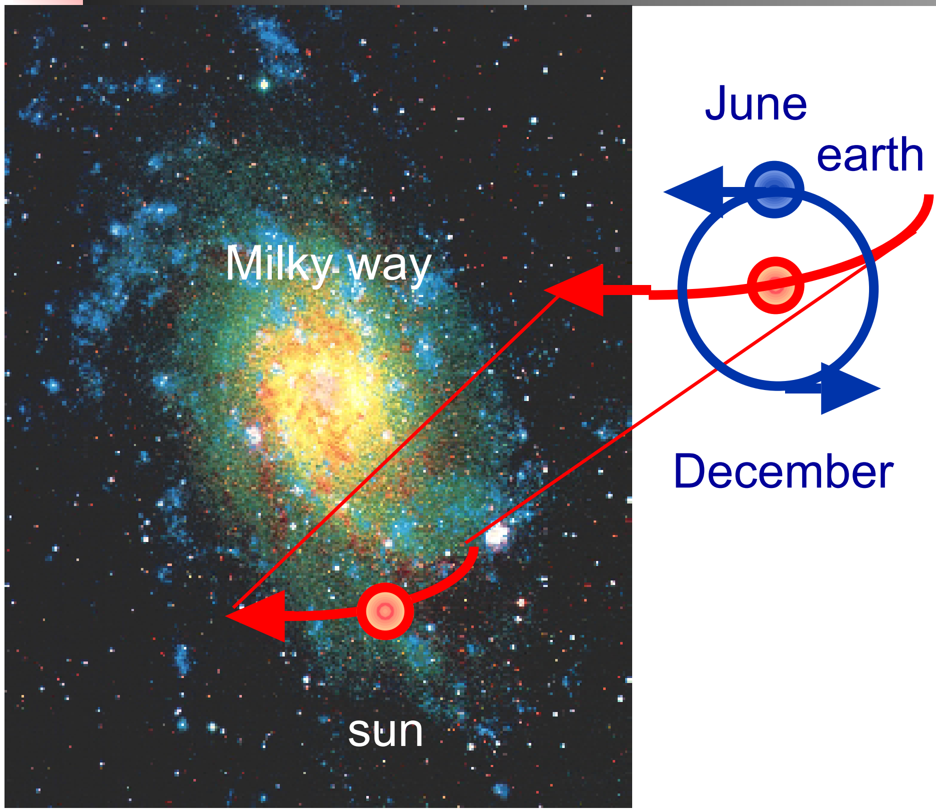
The matter content of the Universe being largely dominated by some form of cold, non-baryonic Dark Matter is presently considered as a *well established fact*.

Dark Matter Candidates

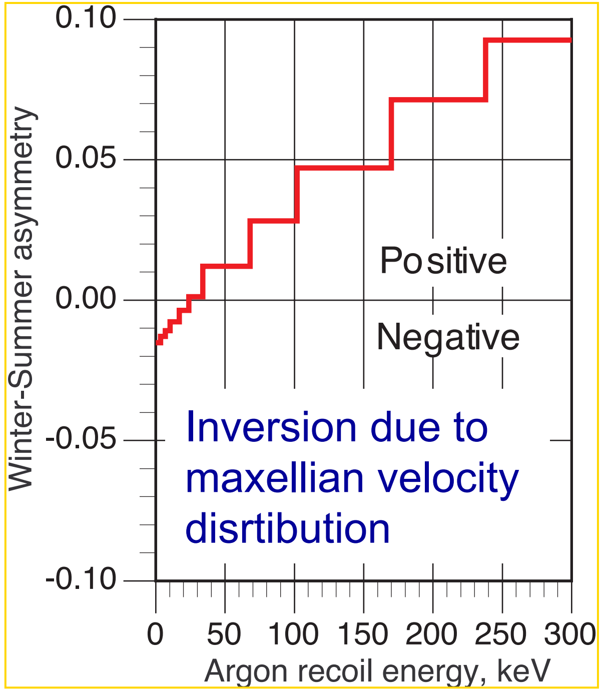
- Despite the impressive amount of astrophysical and astronomical positive observations, the exact nature of Dark Matter is still unknown.
- Elementary particle physics provides a number of possible candidates in the form of long lived, Weakly Interacting Massive Particles (WIMPs).
- Favorite candidates are, at the moment, the lightest SUSY particle (the Neutralino) and the Axion.
- However, other possibilities exist...
- Clearly, we need non-gravitational evidences...

- Kaluza-Klein DM inUED
- Kaluza-Klein DM in RS
- **Axion**
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworls DM
- Heavy neutrino
- **NEUTRALINO**
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

Flux and annual modulation



- Annual Modulation is considered one of the Smoking Guns of Dark Matter Detection. A signal has been observed by the DAMA collaboration, but it has not yet been confirmed by any other experiment.



Sun moves in the Galaxy @ 230 km/s
Earth moves around the Sun @ 30 km/s
Incoming WIMP mean velocity, β ~ 10^{-3}
Local DM density ~0.3 GeV c^{-2} cm^{-3}
Incoming flux ~10^3 cm^{-2} s^{-1} (mass ~100 GeV c^{-2})

Direct Dark Matter search

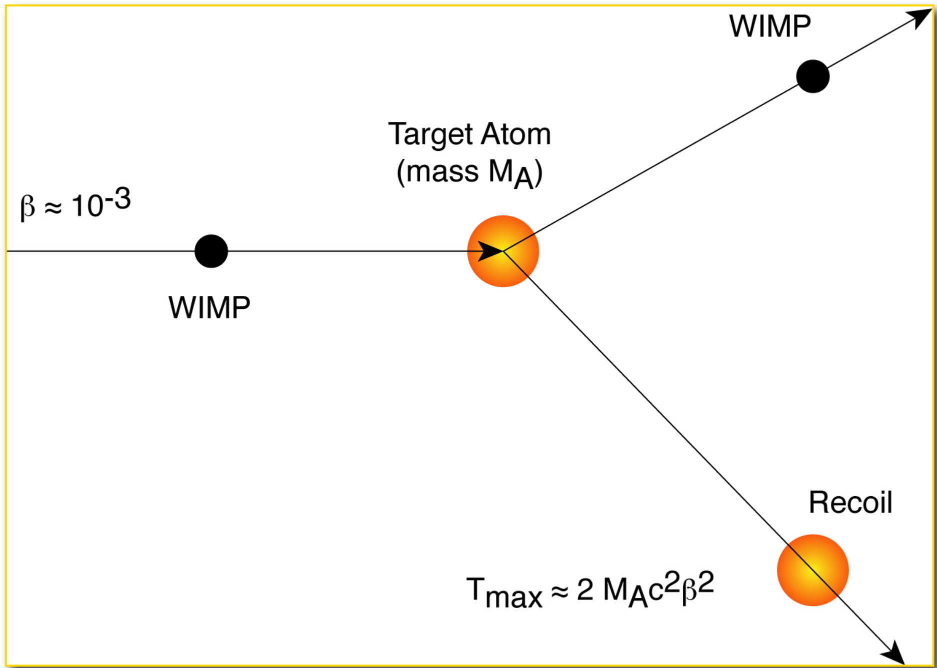
- Direct WIMP detection is based on the identification of nuclear recoils from elastic WIMP-nucleus interactions.

$$\frac{dR}{dE} = R_0 \cdot S(E) \cdot F^2(E) \cdot I$$

Spectral Function

Nuclear Form Factor

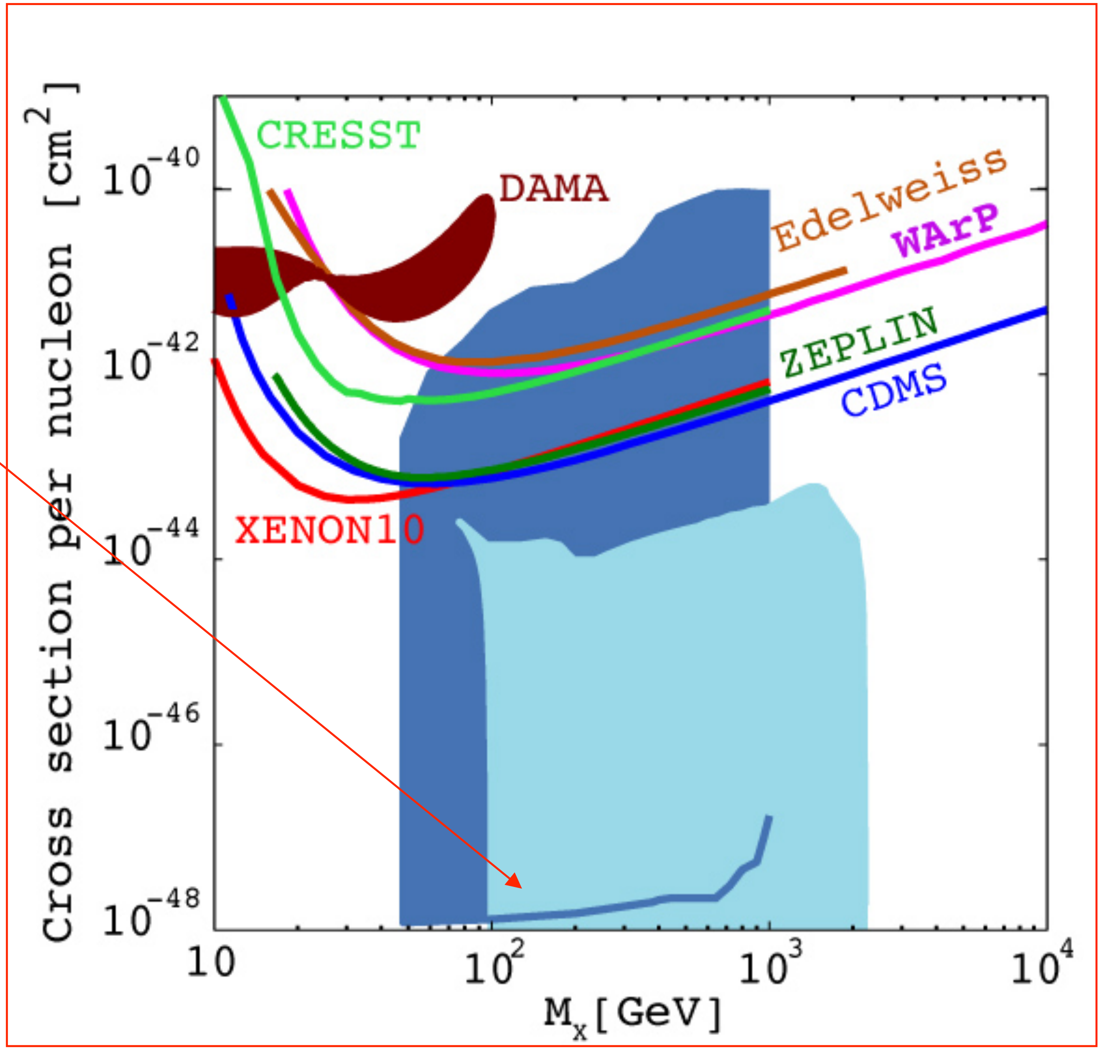
Spin-dependent Term



Typical recoil energies: 0 ÷ 100 keV

Expected rates

- According to the simplest scenario (Minimal SUSY), and the present best limits, the allowed parameter space for WIMP-nucleon interaction leads to **rates in the range from 10^{-1} to 10^{-6} events / (kg • day)**
- The recoil event rate is seasonally dependent on the relative motion of the earth's and galactic frames.
  - about 4% at 100 keV recoils
  - Inversion below 33 keV
- **Next generation experiments should eventually reach exposures in the range of kton • day!**



The WArP experiment

The WArP programme for direct Dark Matter searches with a novel, argon based, detector

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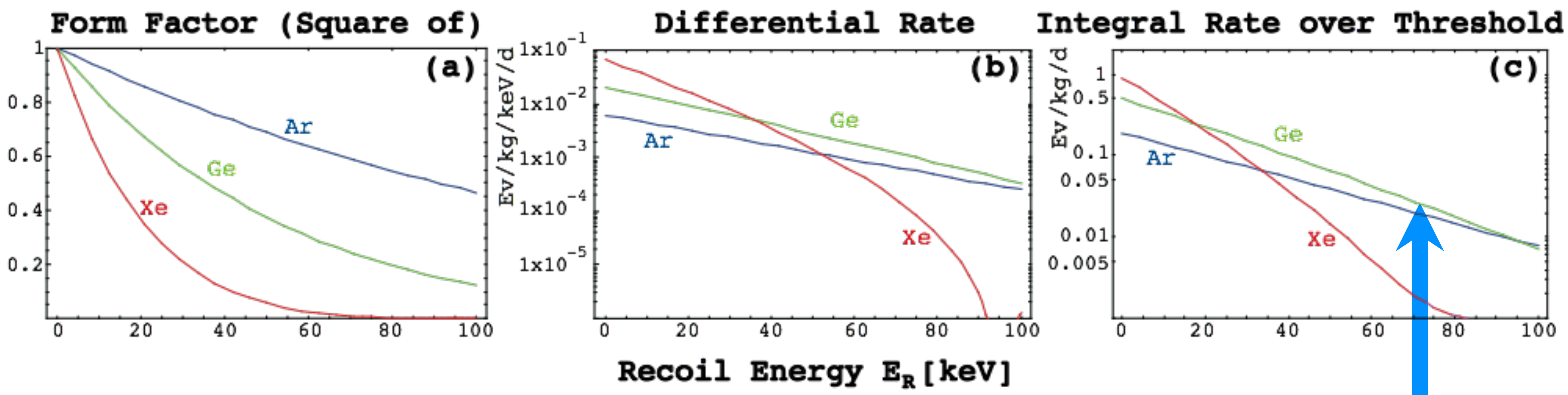
Choice of the target



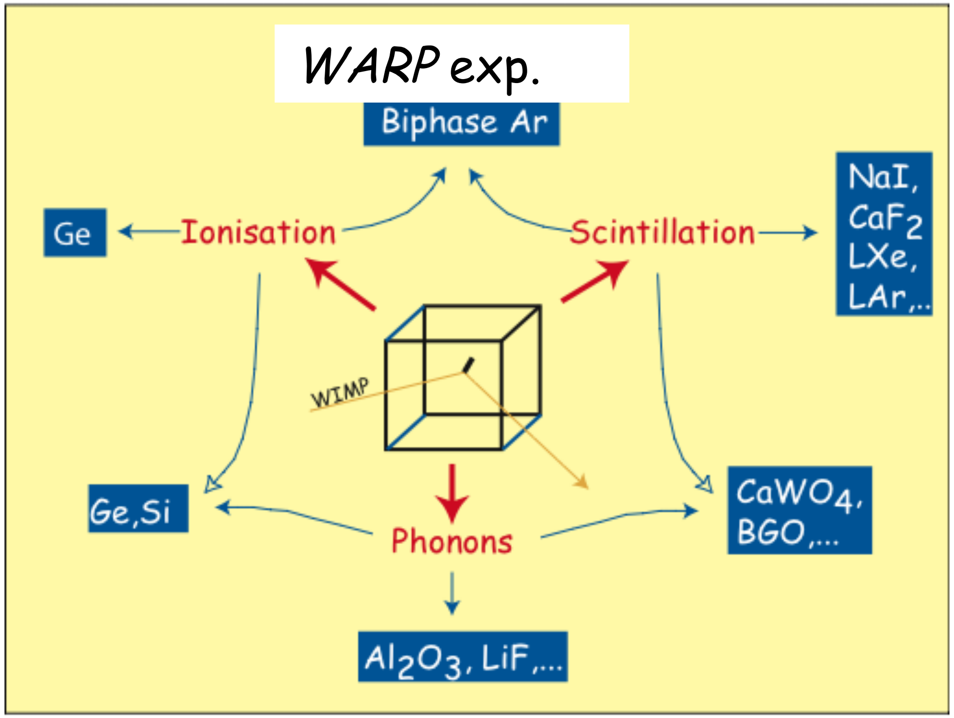
- Increase of interaction rate due to coherence ($\propto A^2$) is typically compensated, at increasing recoil energies, by the form factor.
- For energy thresholds in the range 20 ÷ 30 keV the integral rate for most commonly used targets is very similar.
- For WIMP masses > 100 GeV low A targets retain a significant rate of “gold plated” events with recoil energy > 60 keV.

Background discrimination methods

Use of detectors with very response to incoming radations:

Nuclear Recoils (Neutrons, WIMPs)

Electron Recoils (gammas, betas)



EDELWEISS
CDMS

DAMA

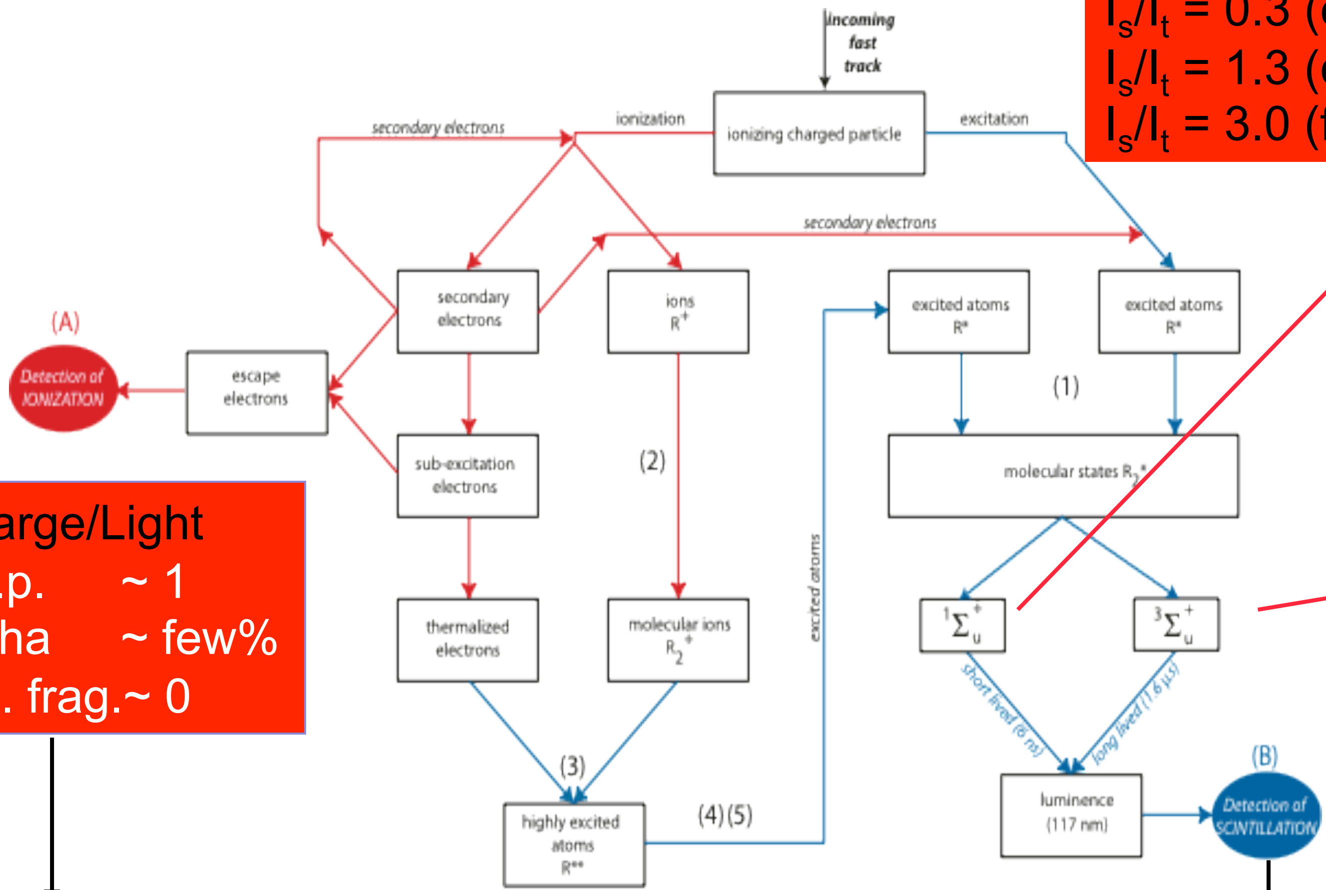
ZEPLIN
XENON

CRESST

Simultaneous use of several detection mechanism allow better background rejection and better control of systematics

Recall: Scintillation and ionisation from LAr

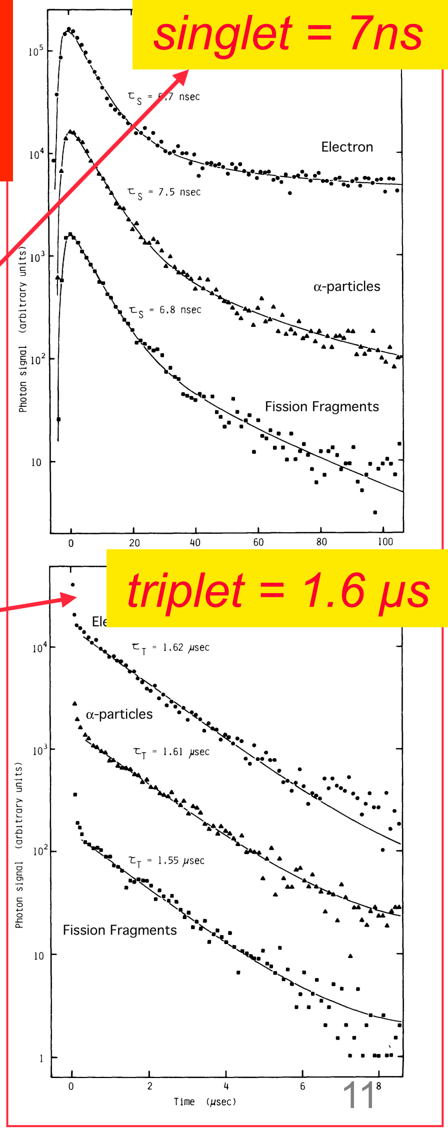
I_s/I_t = 0.3 (e)
I_s/I_t = 1.3 (α)
I_s/I_t = 3.0 (ff)



Charge/Light
m.i.p. ~ 1
Alpha ~ few%
fiss. frag.~ 0

singlet = 7ns

triplet = 1.6 μs



Ionization/scintillation discrimination

Statistically independent

Scint. pulse shape discrimination

Ionization/scintillation vs E-field

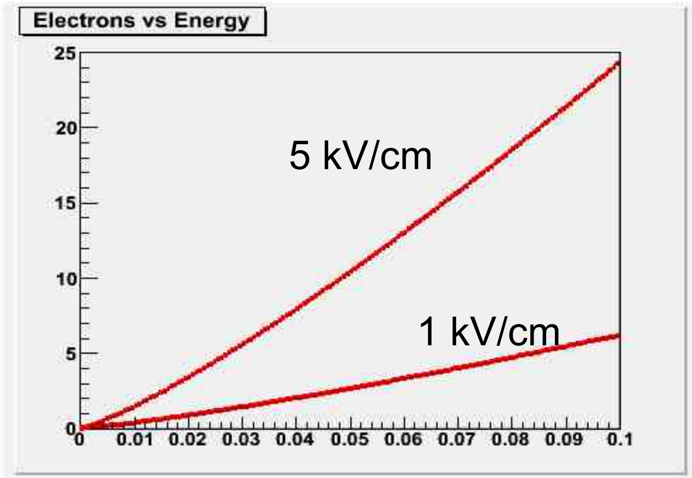
Nuclear recoils

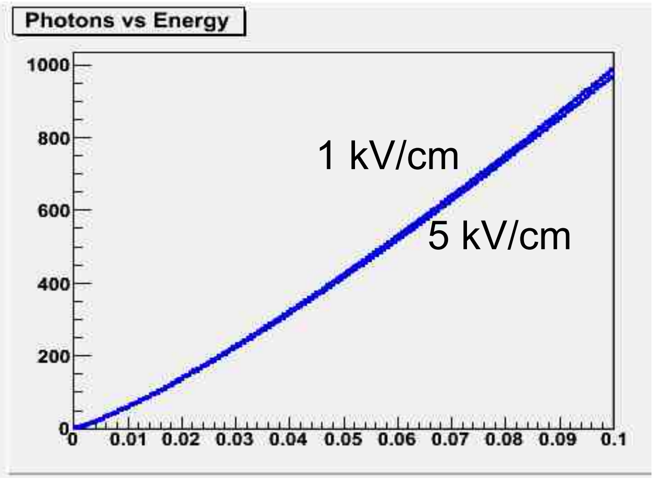
Effect of reconbination

$$L(\varepsilon) = \frac{E}{W_\gamma} A_L \left(\frac{E}{1keV}\right)^{\alpha_L} - Q(\varepsilon)(1-\chi)$$

$$Q(\varepsilon) = \frac{E}{W_{ion}} A_C \left(\frac{E}{1keV}\right)^{\alpha_C} \frac{1}{\xi}\ln(1+\xi)$$

Quenching included

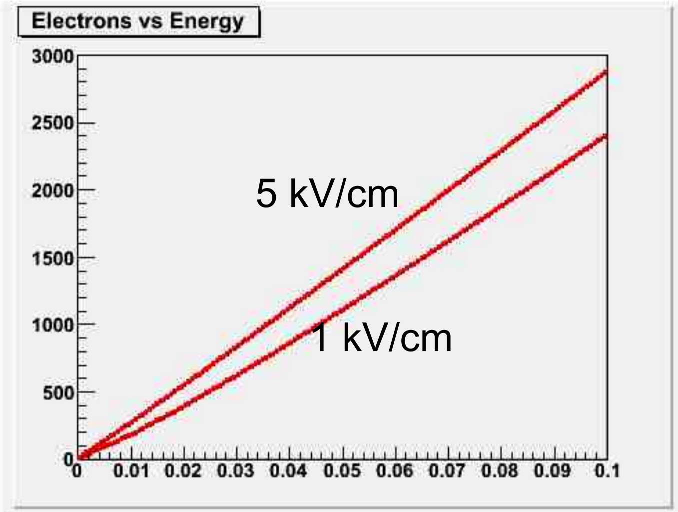


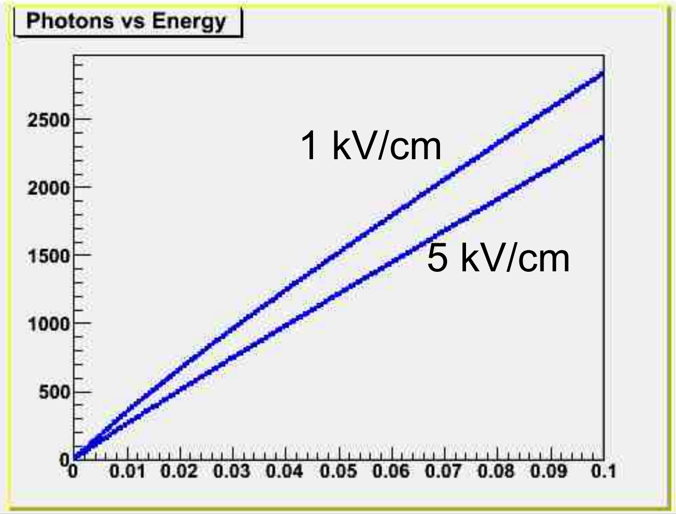


True recoil Energy (MeV)

True recoil Energy (MeV)

Electrons (gammas)





True energy (MeV)

True energy (MeV)

Nuclear recoil quenching factor

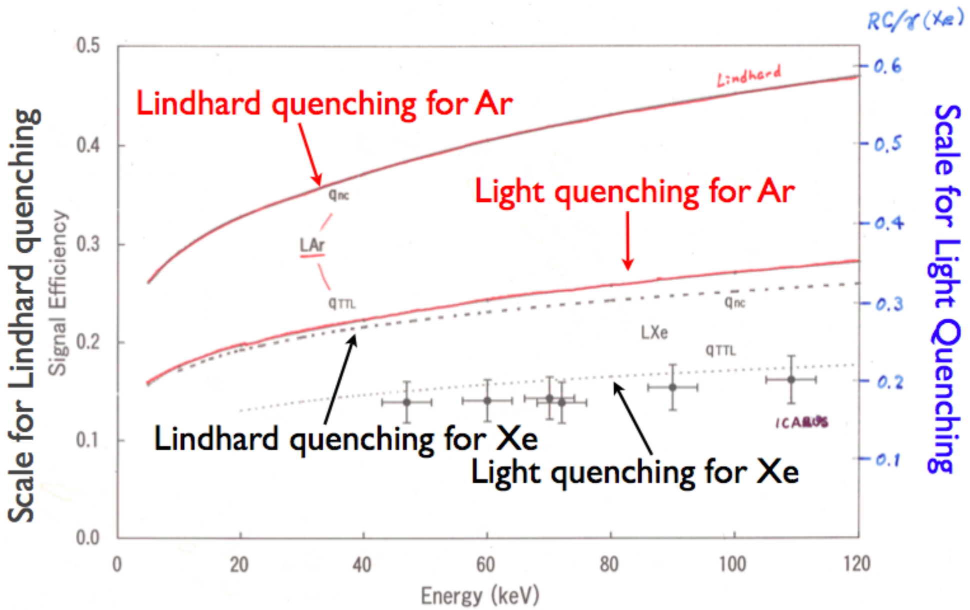
A. Hitachi @ IDM 2004:

- Beside ionization and scintillation, energy of incident particle in Liquid noble gasses can be dissipated through other mechanisms (e.g. atom-atom interactions,…), leading to charge and light effective "quenching".
- High dE/dx increases both recombination and atomic motions.
- The nuclear recoils suffer practically full recombination (few residual free electrons and considerable "nuclear quenching q_{nc}".

Theoretical "quenching" models predict 0.3 - 0.4 for LAr

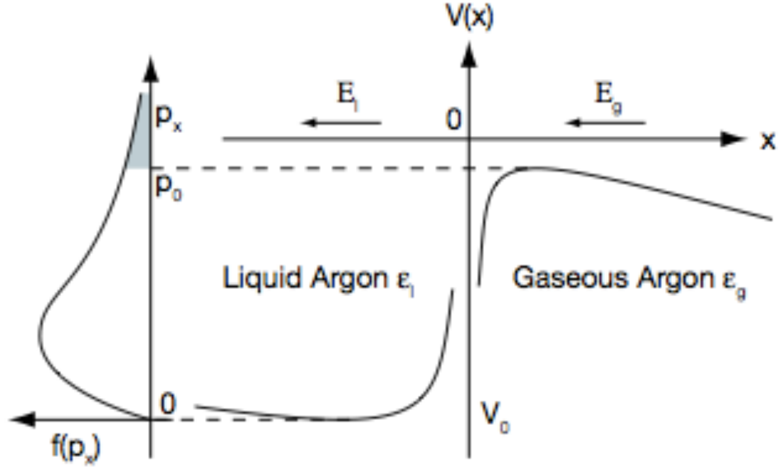
Preliminary measurements in progress confirm value range

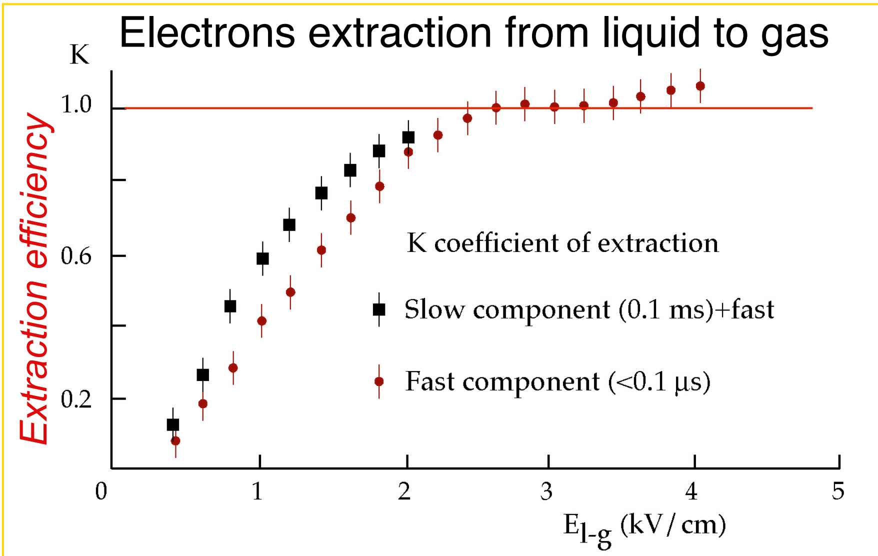
LAr more favourablethan in LXe (heavier atom)



Extraction of electrons from liquid to gas

- Electron extraction process strongly depends on the value of the minimum energy of the conduction band in liquid
  - $V_0 \sim 0.2$ eV in LAr.
- Need to overcome the potential barrier binding electrons to the liquid, introducing a local accelerating electric field at the interface.
  - ⇨ At low fields, electrons require a long time to be freed (slow component, typically a fraction of ms)
  - ⇨ above a given threshold, the extraction is prompt





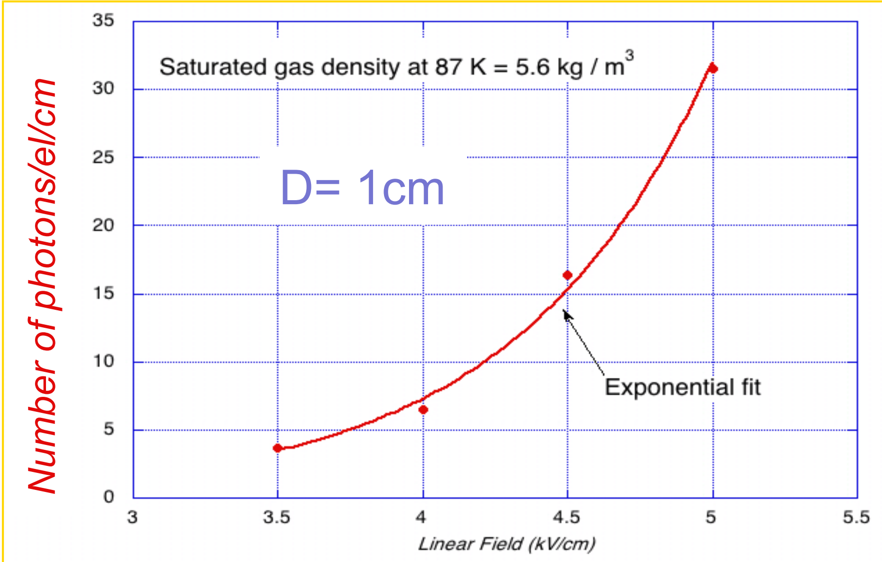
Electro-Luminescence in Gas phase

- Under strong drift field, free electrons acquire enough energy to excite the gaseous medium, leading to formation of Ar excitons followed by the emission of 128 nm γ (electroluminescence).
- The process depends only on the value of the reduced field E/ρ (ρ is the GAr density)
- The density of the GAr vapor at 87 K is 2.8x that at room T
- A threshold at 1.7 Kv/cm correspond to the minimum energy required to excite Ar*

- Tens of photons per electron are easily produce in ~cm gap at few kV/cm

- A much stronger field is needed to ionize (charge multiplication)
- Threshold at 9-10 kV

Proportional Light Production in LAr



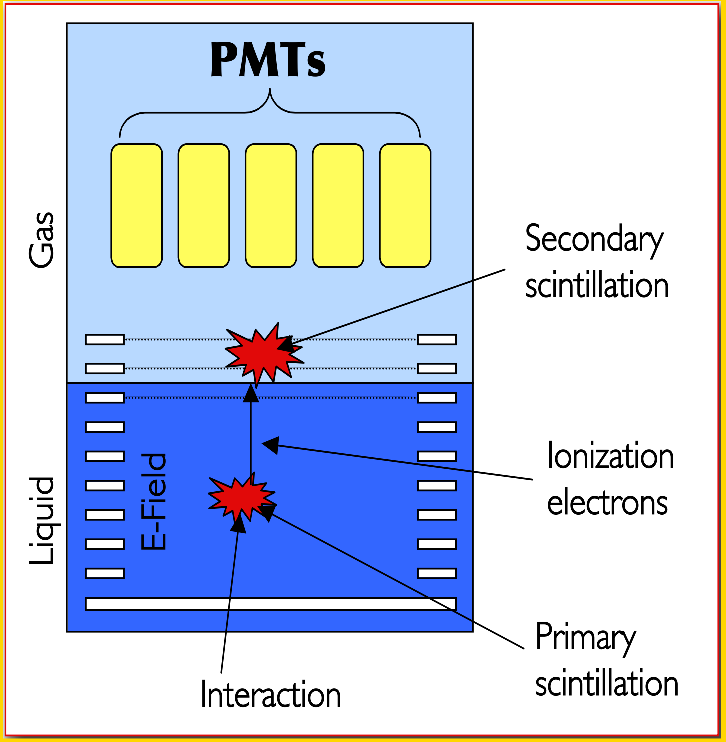
$$Gain = \exp(\alpha d)$$

d = detector thickness
α= Townsend coefficient
depends on E-field, pressure, and thickness)

WIMP Detection in WArP

- Two simultaneous criteria to discriminate potential WIMP recoils from backgrounds:
  1. Simultaneous detection of prompt scintillation and drift time-delayed ionisation in Liquid Argon:
     - ➥ pulse height ratio strongly dependent from columnar recombination of ionizing tracks.
     - ➥ 3D reconstruction of event position.
  2. Pulse shape discrimination of primary scintillation:
     - ➥ wide separation in rise times between fast (≈ 7 ns) and slow (≈ 1.6 μs) components of the emitted UV light.

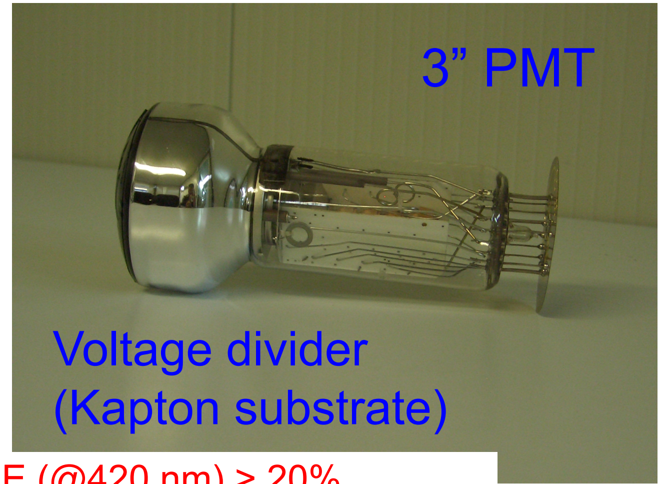
Double Phase Argon Chamber



Only detector with double discrimination technology.
Largest discrimination of γ-induced backgrounds.

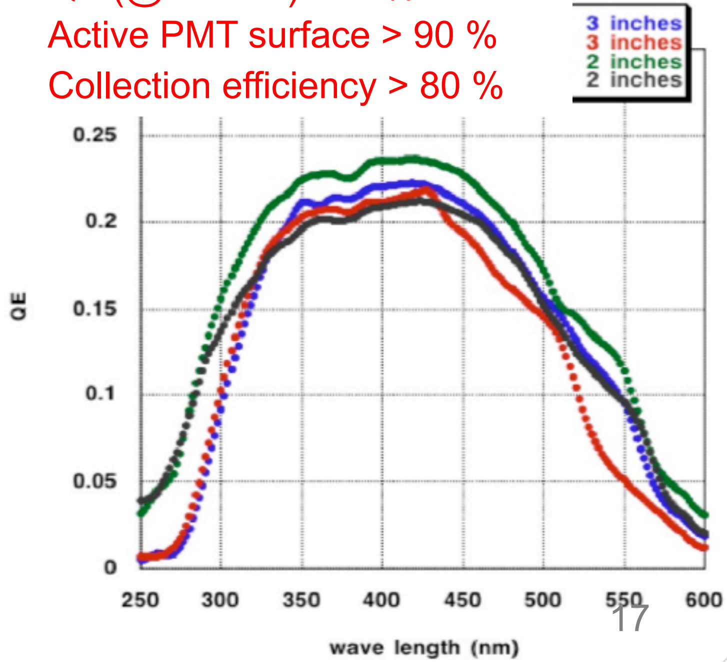
Light collection: photomultiplier

- Use photomultipliers developed in co-operation with Electron Tubes EMI to work at LAr temperature with high photocathode efficiency.
- Low activity glass window.
- High level of quality testing implemented both from manufacturer and on WArP Collaboration side.



Photocathode	Bialkali with Pt and MnO underlayers
Typical quantum efficiency at 400 nm	19% (min 16%)
Diameter	2” and 3”
Active diameter	46 mm (2” PMTs) ; 68 mm (3” PMTs)
Number of dynodes	12 LF Cs Sb
Nominal gain (*)	5 x 10^6
First dynode gain	≈ 10
Single Electron Peak width (FWHM)	≈ 25%
Typical operating voltage	±1100 ÷ ±1600 V
Dark counts (at room temperature)	≈ 1000 cps
Max cathode current (at room temperature)	500 nA
Max anode current (at room temperature)	100 μA
Single electron rise time	2.5 ns

QE (@420 nm) > 20%
Active PMT surface > 90 %
Collection efficiency > 80 %

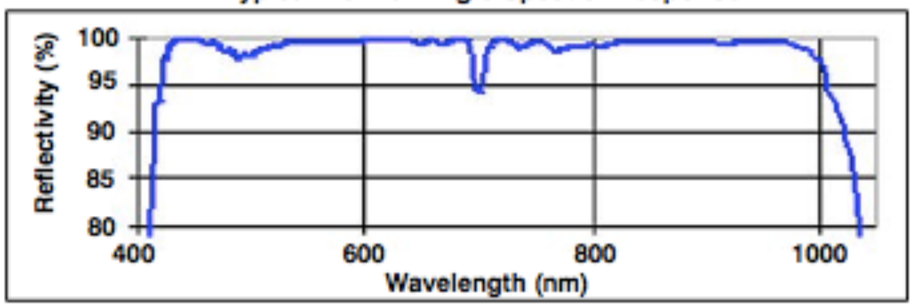


Light collection efficiency: reflector

- Both primary and secondary light are emitted isotropically at 128 nm.
- Collection efficiency:
  - Large coverage with high Q.E. PMT's coated with wavelength shifter
  - Detector inner walls covered with reflector material () coated with TPB:

    3M VM2000: thin polymeric film with mirror reflectivity > 99%: stand LAr temperature

Typical Normal Angle Spectral Response



Optical Characteristics (continued)

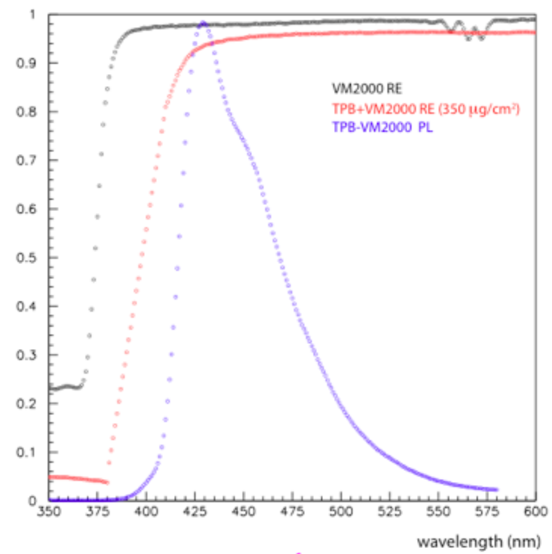
Characteristic	Value	Test
Wavelengths Absorbed	< 400 nm	3M
Usage Angle	0 to 90 degrees	3M

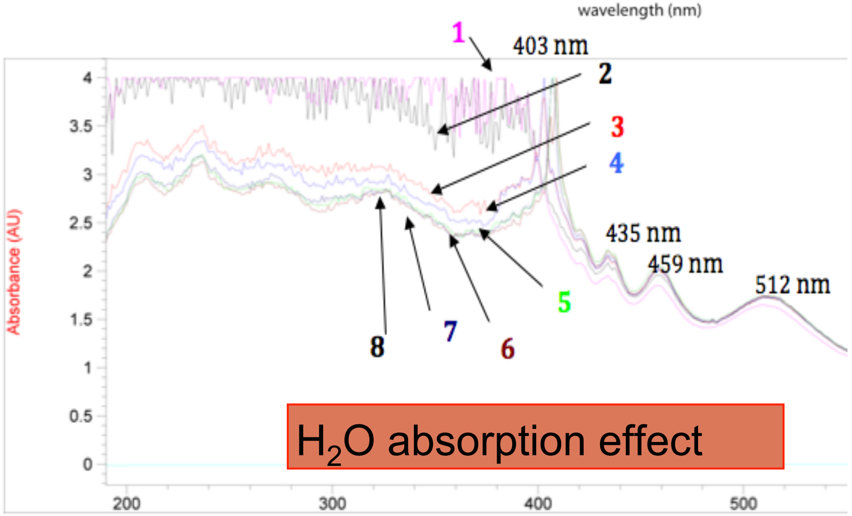
Physical Characteristics

Characteristic	Value	Test
Film	Polymeric film	-
Liner, Adhesive	Paper	-
Liner, Protective	Polyethylene	-
Adhesive	Pressure-sensitive	-
Width Film and Liners Adhesive	 51 inches (130 cm) > 49 inches (125 cm)	-
Total Thickness (nominal) Film Adhesive Liner, Adhesive Liner, Protective	8.1 mils (206 μm) 2.6 mils (66 μm) 1.5 mils (38 μm) 2.9 mils (74 μm) 1.1 mils (28 μm)	3M
Total Density (film, adhesive and liners)	20 ft^2/lb (4 m^2/kg)	3M
Tensile Strength (film)	> 35 lb/in (6.2 kg/cm)	ASTM D-882
Elongation at Break (film)	> 60%	ASTM D-882
Modulus (film)	> 550 lb/in^2 (39 kg/cm^2)	ASTM D-882
Heat Shrinkage (film)	< 1% at 302°F (150°C), 15 minutes	ASTM D-1204-02

TPM + reflector optical properties

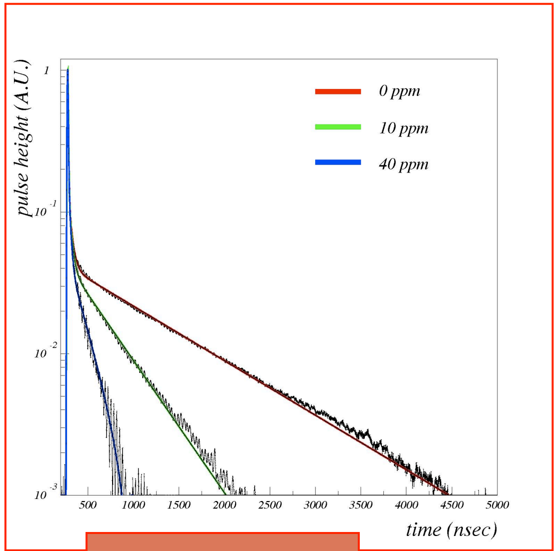
- Coating method: evaporation (200°C)
  - Best uniformity
  - Controlled thickness
  - Resists immersion in LAr
  - no contact with humidity (Both VM2000 and TPB are hygroscopic, TPB coating degrades like CsI)
- TPB thickness:
  - on PMT: 50-100 µg/cm^2 optimized for transmission
  - on VM2000: 300-600 µg/cm^2 optimized for reflection
- Storage and mounting:
  - Dry atmosphere (N2)
  - Protection from sun-light (UV light possibly breaks the TPB molecule)





Light collection efficiency: Argon purity

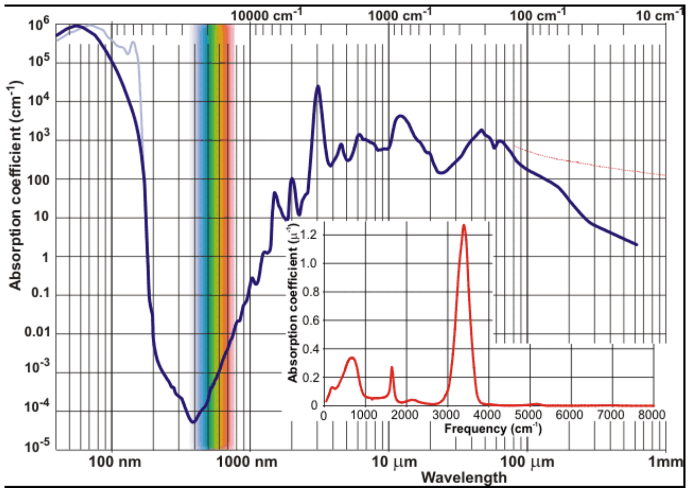
- Dangerous impurities:
- O_2, CO_2 removed like in ICARUS
  - Low activity filtering materials (Rn, Th)
- N_2: affect slow component intensity and lifetime (breaking the Ar_2^* dimer before it decays)
  - Low N2 conceration LAr from provider

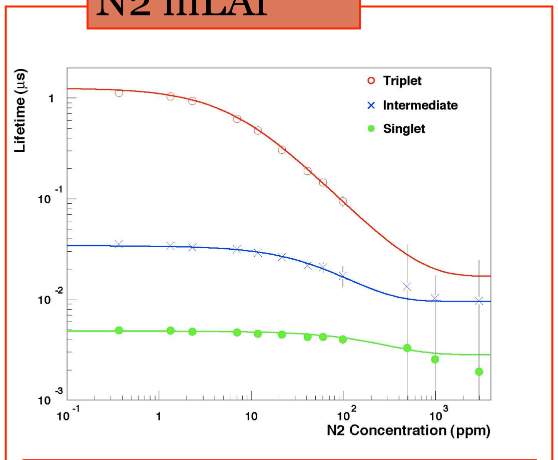


N2 inLAr

- Residual H_2O sticking on TPB surface absorbs 128 nm photons before wave-shifting (few atomic layers produce detectable effect):
  - Excellent UHV pre-evacuation of detector volume before filling (monitored with mass spectrometer)

H_2O absorption

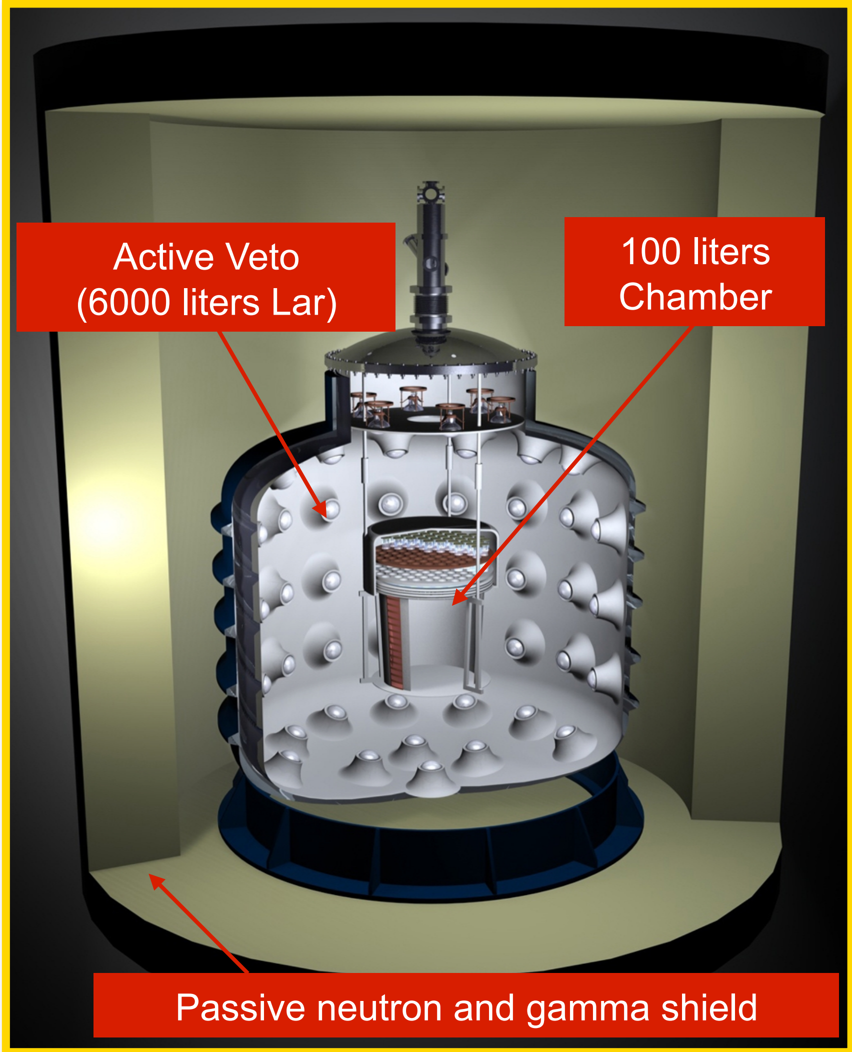




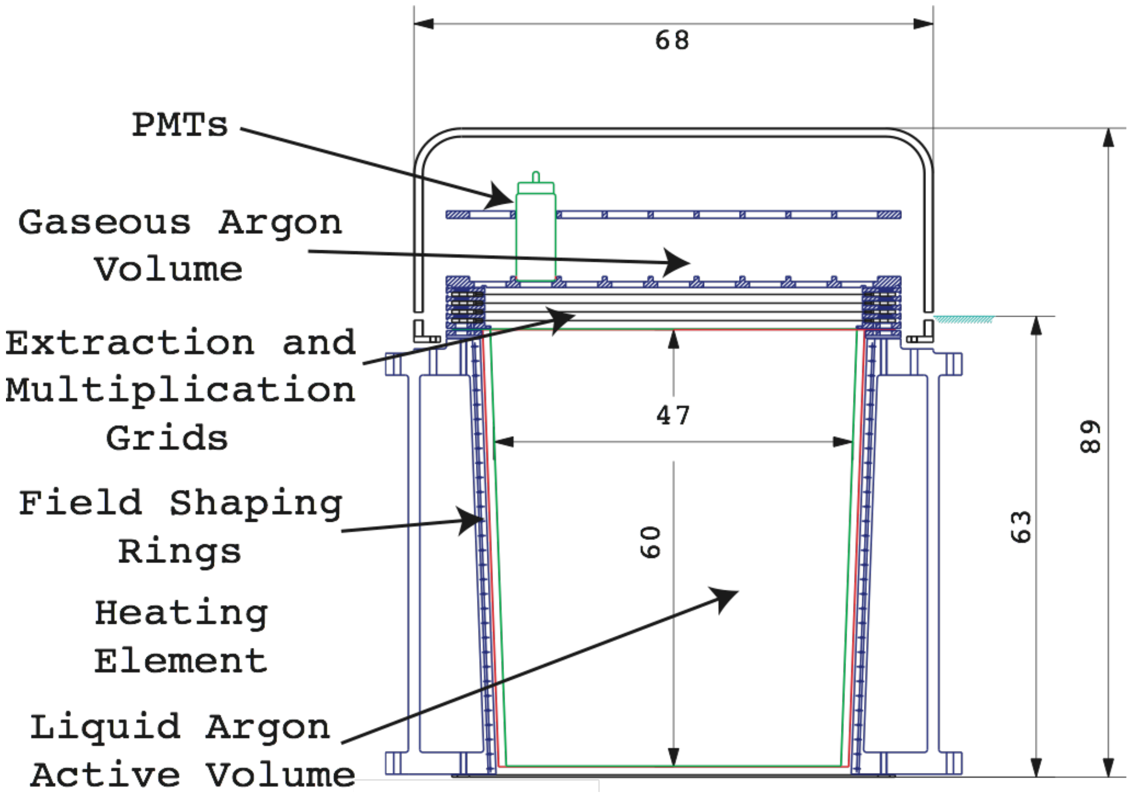
Rate Constant:
$k_{N_2} = 0.11 \pm 0.01\ ppm^{-1} \mu s^{-1}$

WArP 140 kg detector

- Sensitive volume = 100 liters (140 kg).
  - 40 PMT's on gas phase looking into the detector (10% active coverage)
  - ➥ 3-D event localization by means of:
  - Drift time recording (vertical axis);
  - Centroid of PM's secondary signal amplitudes (horizontal plane).
- 4π active 8 ton active VETO system:
  - 400 PMT's (7% coverage)
  - ➥ tags and measures the neutron-induced background with an ID-factor ≈ 99.99 %;
- Construction completed in LNGS hall B
  - First technical run in 2009. Now under refurbishing (HV, TPB coating).
  - Fully operational during first half of 2010.
- Designed also to host a 1 ton detector.



Inner detector

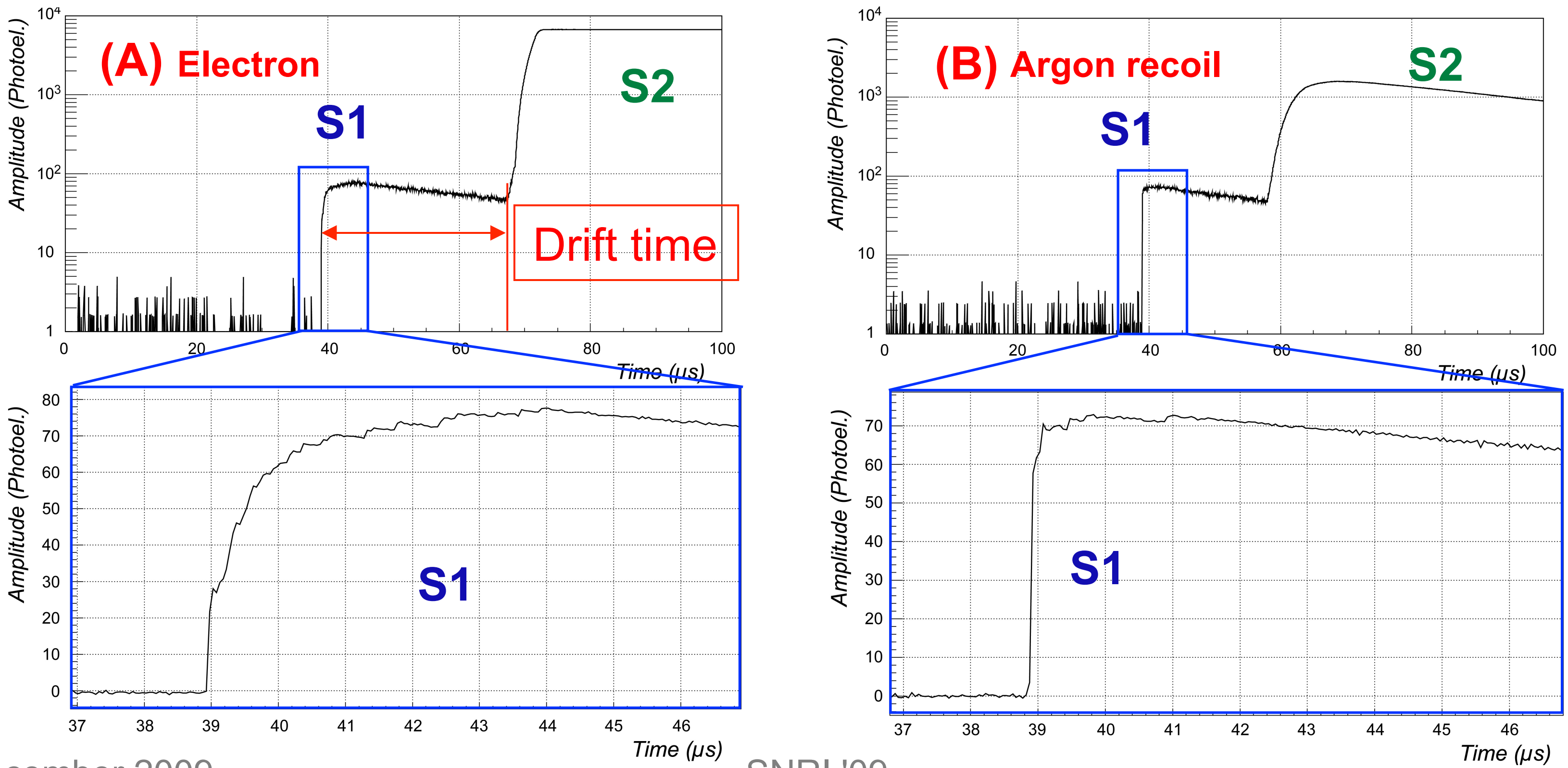


External Heigth	89 cm
External Diameter	68 cm
Internal Heigth	60 cm
Max Int. Diam.	50 cm
Min. Int. Diam.	46 cm
LAr Volume	100 liters
LAr Mass	140 kg
PMTs	41 x 3" ∅
Coverage	7%
Walls Reflectivity	94%
Light Yield	2.8 phel/keV
Trigger Threshold	$\lesssim$ 5 keV
Drift Field	1 kV/cm
Max Drift Field	1.5 kV/cm

Discrimination technique

- ➔ **S1** = primary (prompt) scintillation signal
- ➔ **S2** = secondary (delayed) scintillation signal (proportional to ionization)

- **Minimum ionizing particles**: high S2/S1 ratio (~100) + slow S1 signal.
- **α particles and nuclear recoils (R-like events)**: low (<30) S2/S1 + fast S1.



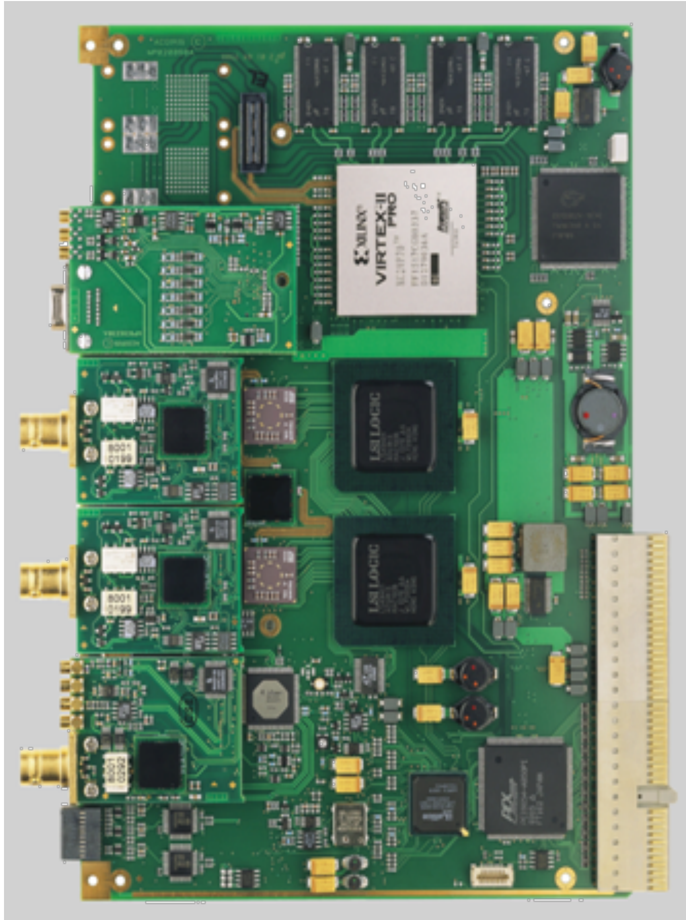
Data rate and trigger

- For 140 kg :
  - ~300 Hz (Ar39 + natural radioactivity)
- Event size:
  - 40 PMT's x 300kB (Full drift 300 μs @ 1 GHz sampling) = 12 MB
- Raw data rate 3.6 GB/s !
- Trigger:
  - single photoelectron multiplicity on fast scintillation components (within few ns time window)
- Event decimation; on line recognition of events with large slow-lifetime scintillation component:
  - Single photoelectron counting on line on dedicated on on-board FPGA
  - Retain full recoil-like events sample
  - Retain fraction of e-like sample for efficiency determination and calibration

WArP front-end

PMT's directly read by Acqiris AC240 8-bit, 2 GS/s digitizer with on-board FPGA

- 1 GS/s 8-bit synchronous dual-channel data acquisition with independent gain and offset on each channel
- Min sensitivity = 0.2 mV, Max full scale = 1. V
- 1 GHz bandwidth
- Fully-featured 50 Ω mezzanine front-end design with internal calibration and input protection
- Memory depth >> 2 * 500 μs (2 drift times): multi-buffering
- On-board reconfigurable data processing unit (DPU FPGA) for real-time operations
- External processing memory providing 512 MB of SDRAM and 2 MB dual-port SRAM
- Front-panel digital I/O connectors for real-time data processing control (DPU Ctrl2)
- Dedicated I/O for trigger distribution and synchronization
- Multipurpose I/O connectors for trigger, clock, reference and status control signals (Ctrl I/O)
- Modular, 6U Compact-PCI standard (PXI compliant)
- High-speed PCI bus for data transfer to host PC at sustained rates up to 100 MB/s

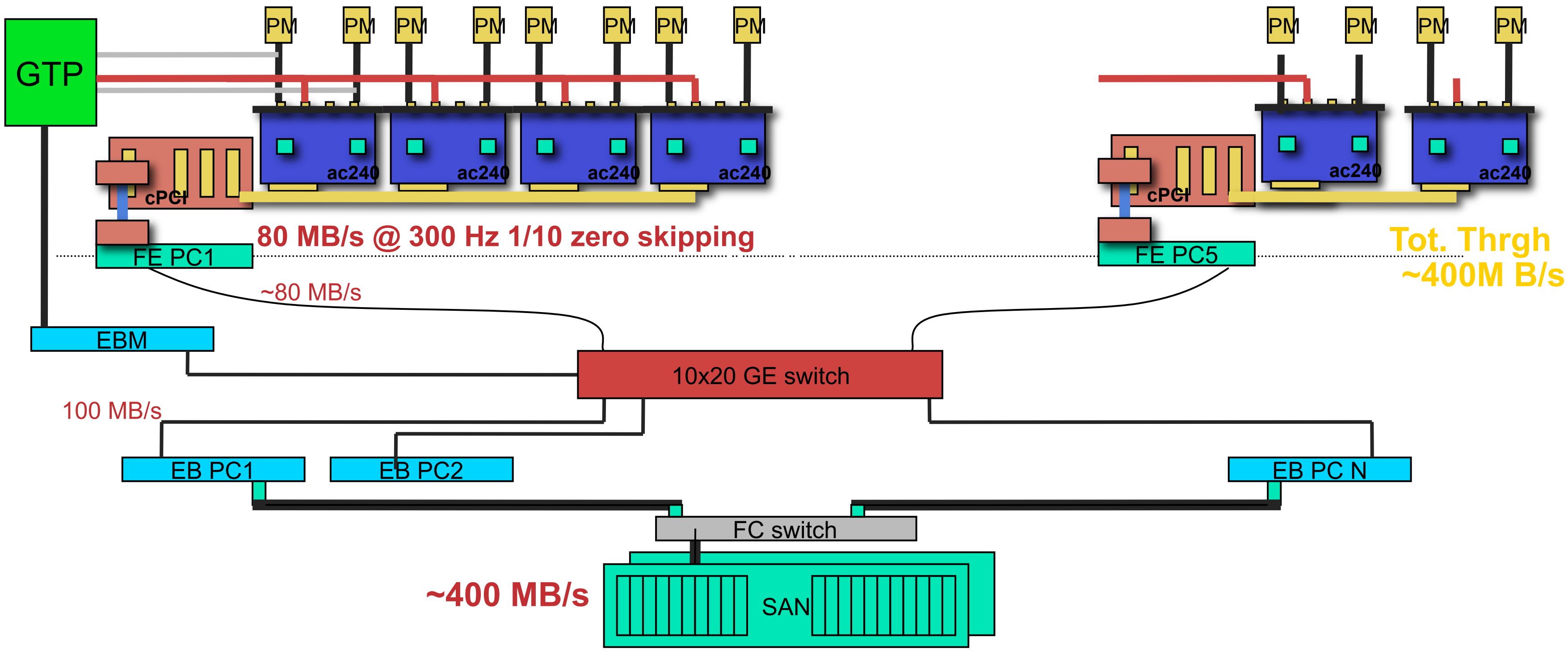


DAQ Architecture

On board signal processing with ACQIRIS AC240

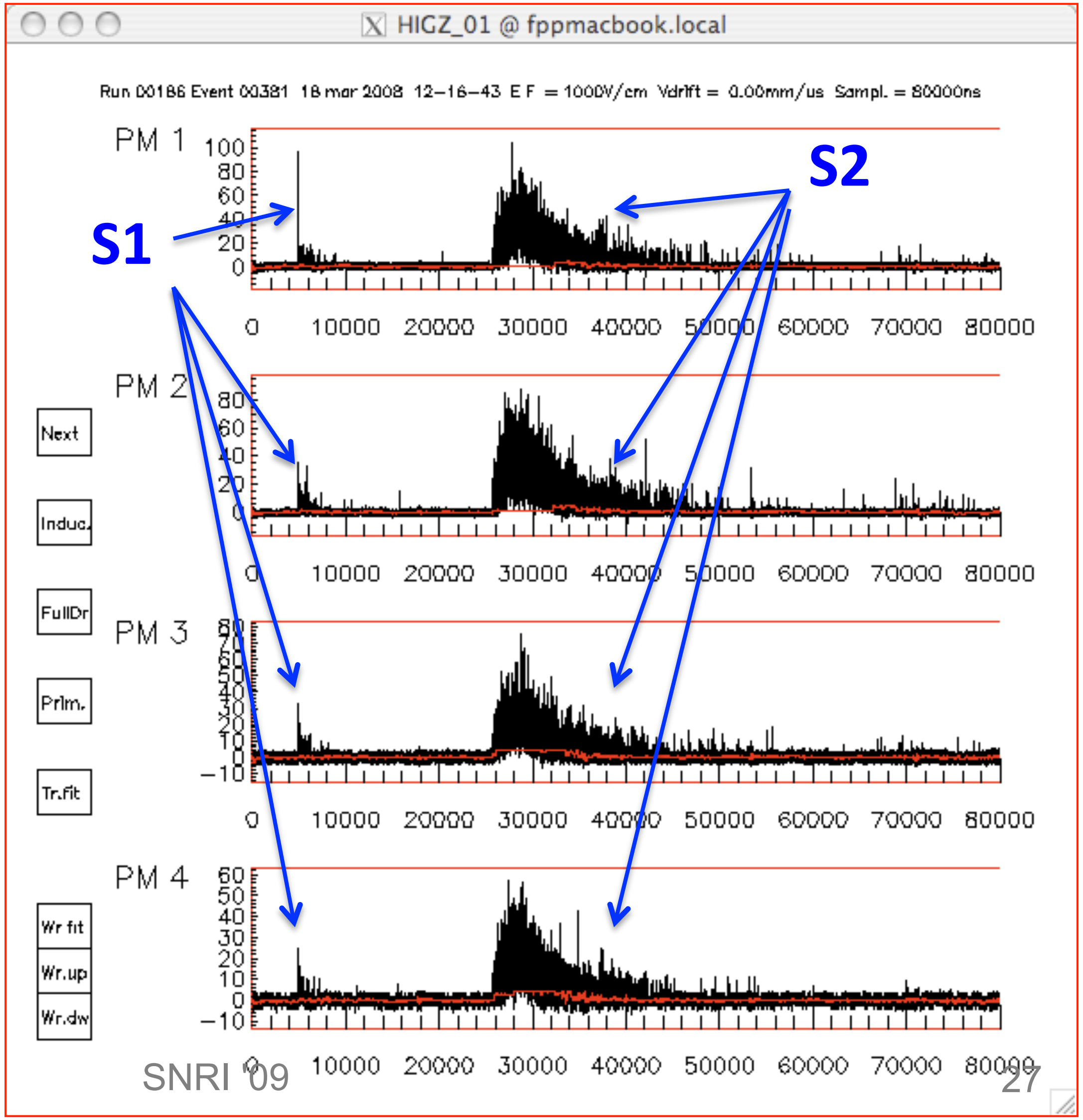
Pros: Pipelined hw data reduction
Local sig info available to GTP
and/or event filtering
Scalability

Cons: **FPGA customization required**
(basic functionalities available though)
Cost x channel



Warp display: e-like events

- Chamber equipped with 4 x 3" PMTs
- Photoelectrons can be identified and measured individually
- Shape and amplitude of both S1 and S2 perfectly reconstructed
- All events (more than 3 millions recorded) completely understood in terms of their physical properties (nature, energy, number of interactions)

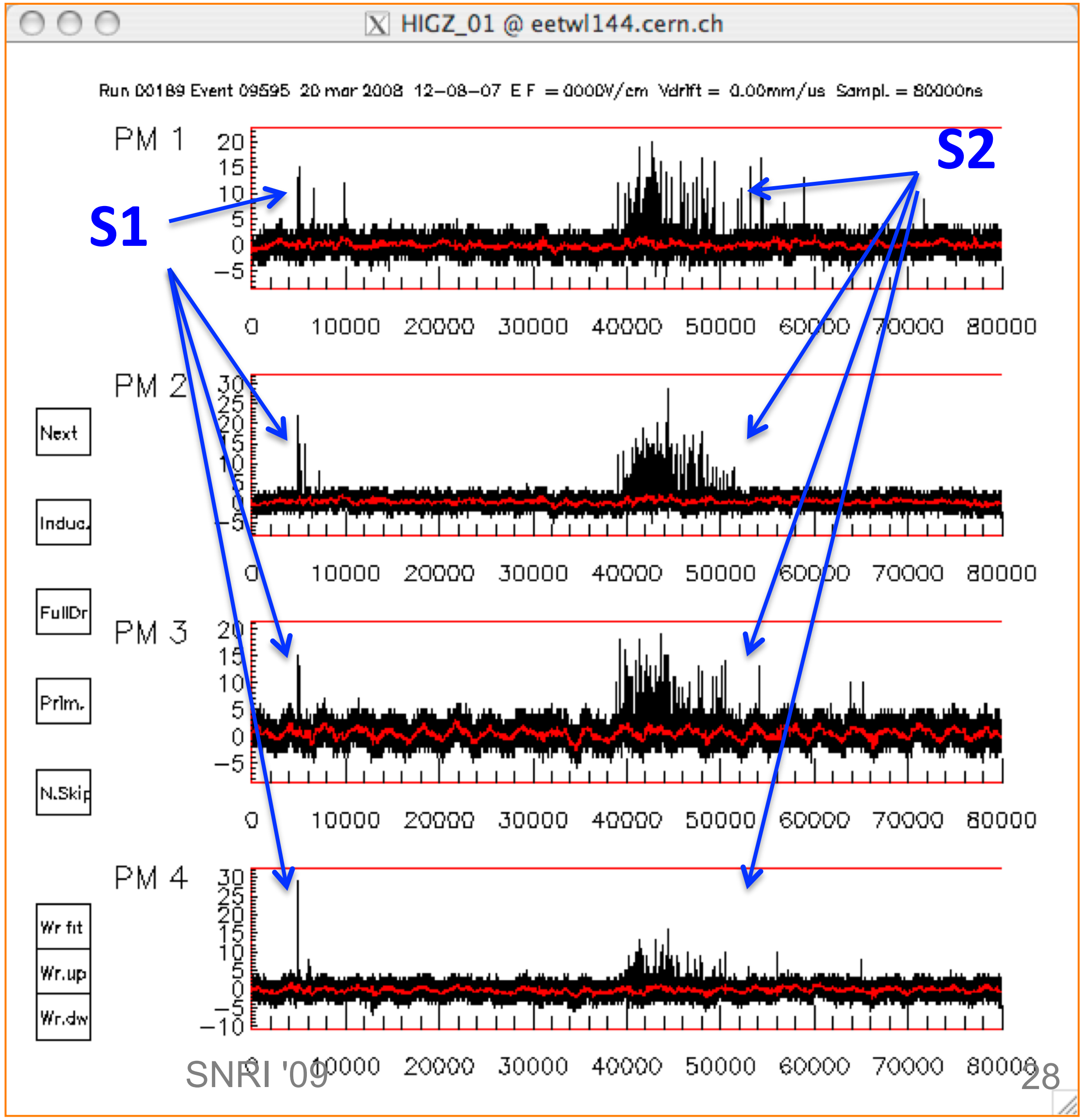


Warp display: recoil-like events

Average S2/S1 for e-like events = 60

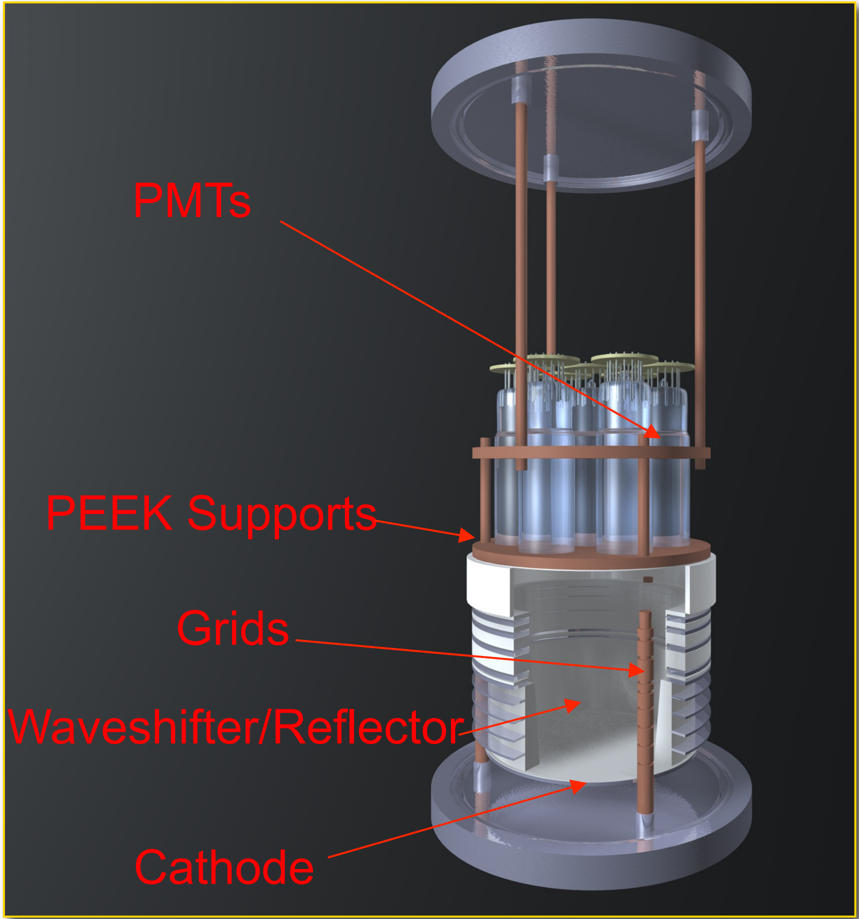
Cuts (recoil-like):
0.7<F_prompt <1.0
0.1< S2/S1<15

Run: 189
Event: 9595
PhE-Fast: 21.1
(*Ion Kin En. ~ 66 keV*)
PhE-Slow:2.3
Fprompt:0.90
S2/S1:11.0
Tdrift (us):35.6



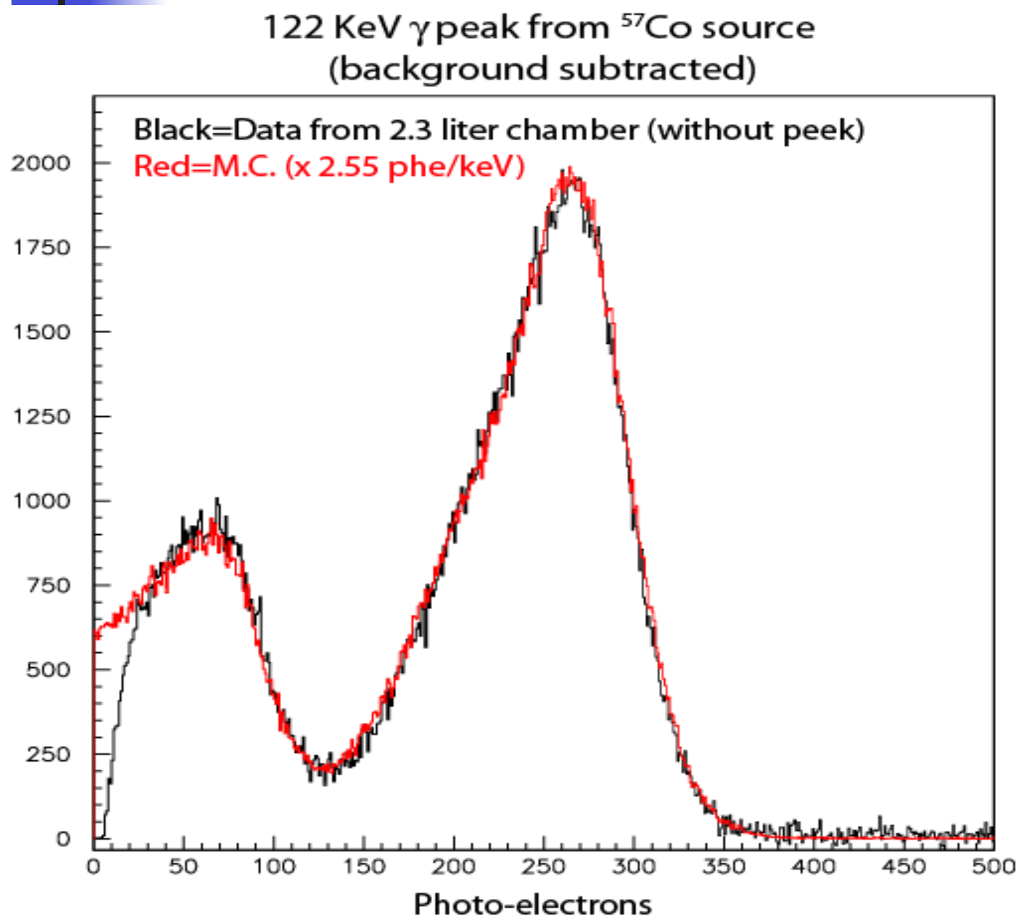
The 2.3 liters test chamber

- The 2.3 liters prototype is equipped with seven 2" PMs made of low background materials and designed to work at LAr temperature, 10 % coverage.
- Scaled version of the final detector, with field-shaping electrodes and gas to liquid extraction and acceleration grids.
- Equipment contained in a high-vacuum tight container immersed into an external, refrigerating, liquid argon bath.
- LAr Purity kept stable by means of argon recirculation:
  - ➥ continuous and stable operation during several months.



Schematic view of the 2.3 liters chamber

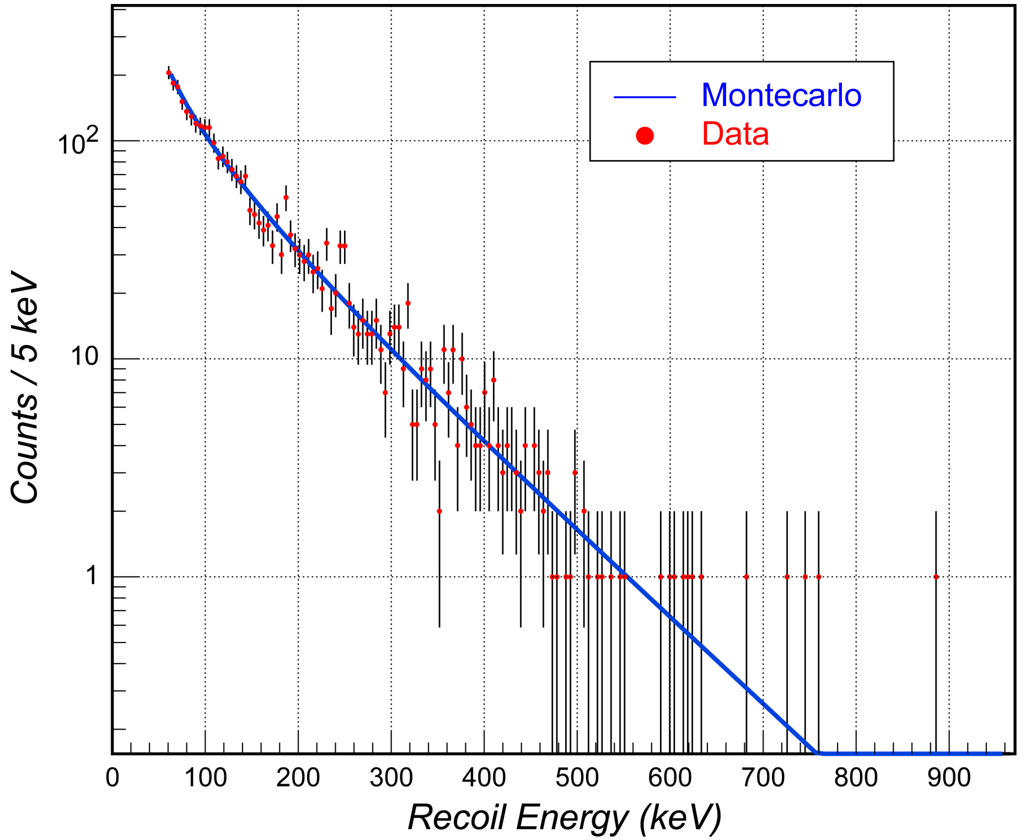
Measured photon yield in LAr



- The ^{57}Co source 122 KeV gamma peak and compton edge (40 KeV).
- Measurement of Ar39 beta spectrum (end point = 565 KeV) gives comparable results
- Slight N2 contamination
  T_{slow} = 1.2μs
  instead of 1.5 μs
- Real yield ~20% higher

$Y_{e/\gamma}$=2.55±0.15 phe/keV @ E-field =0.

Nuclear recoil photoelectron yield



- The Am-Be neutron-induced recoil spectrum is compared with MC predictions.

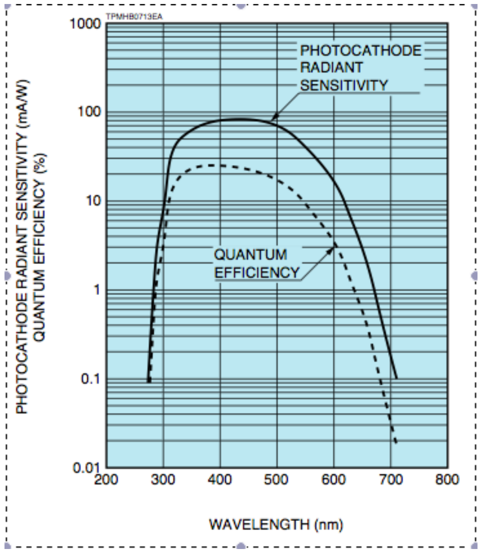
- Additional dedicated measurements with mono-energetic neutron beams is being setup in order to precisely determine the quenching factor.

Y_{Ar}=(1.1±0.15) phe/keV ➔ nucl. rec. quenching factor ~ 0.4

High yield detectors

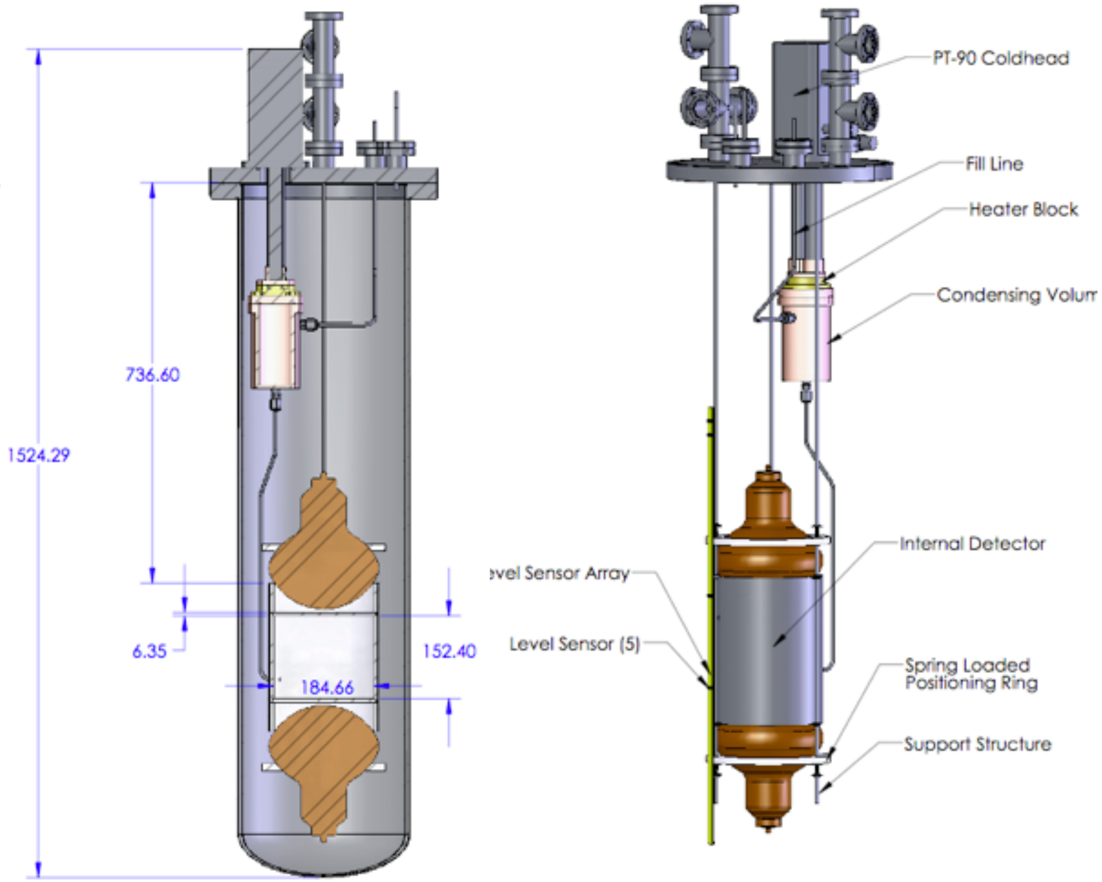
Light Yield: 4.8 pe/keV

- 65 kg LAr
- 5.7 kg active mass
- 30% PMT's coverage
- 2 PMTs: Hamamatsu R5912-MOD
  - 14 dynodes
  - Gain 10^7 @ 1.1kV;10^9 @ 1.7kV

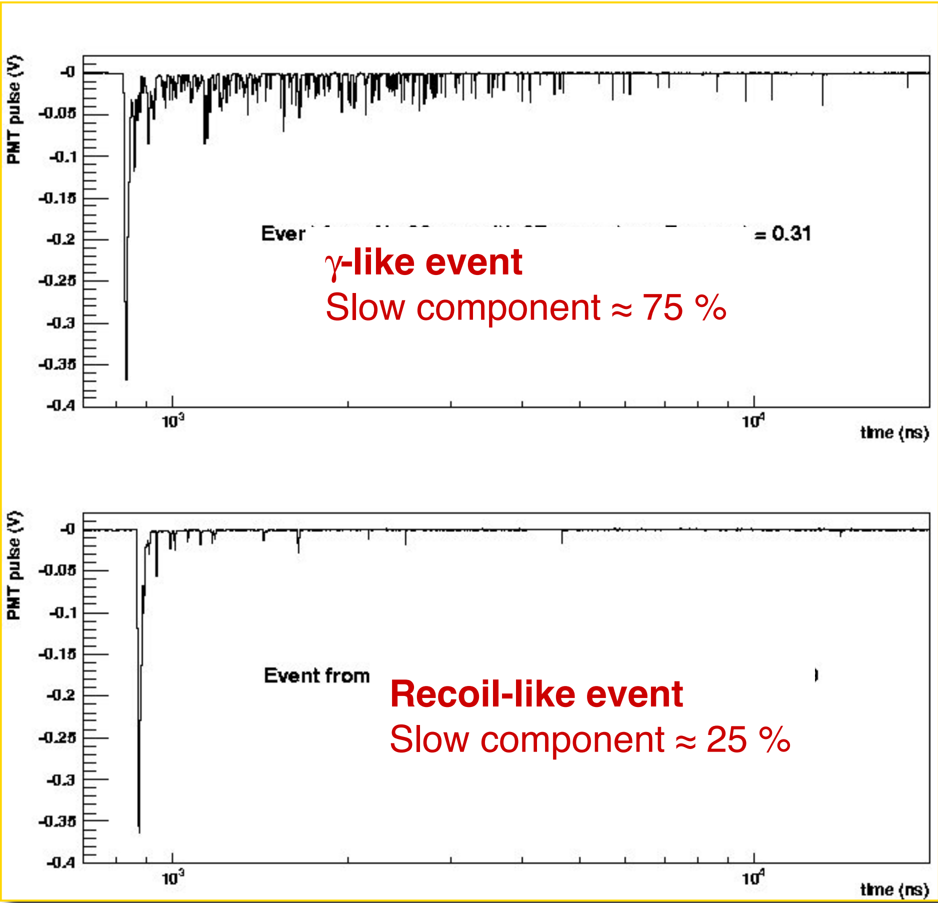


Peak sensitivity
~ 420 nm

QE ~ 20 %



Pulse shape discrimination



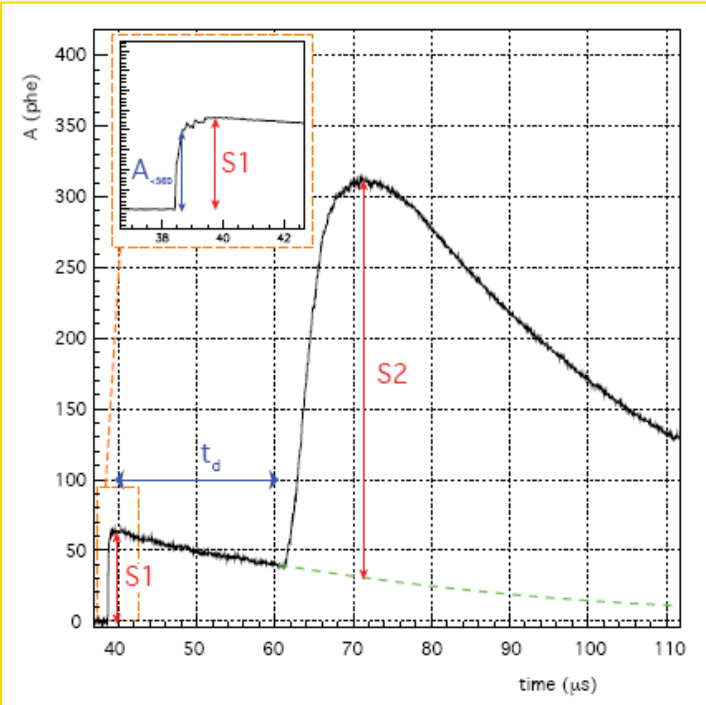
- Pulse shape discrimination of primary scintillation (S1) based on the very large difference in decay times between fast (≈ 7 ns) and slow (1.6 μs) components of the emitted UV light
  - M.i.p.: slow/fast ~ 3/1
  - Nuclear recoils: slow/fast ~ 1/3

  Hitachi *et al.*, Phys. Rev. B **27**, 5279 (1983)
- Theoretical Identification Power exceeds 10^6 for > 60 photoelectrons
- S1/S2: Event localization + Rejection ~ 10^3

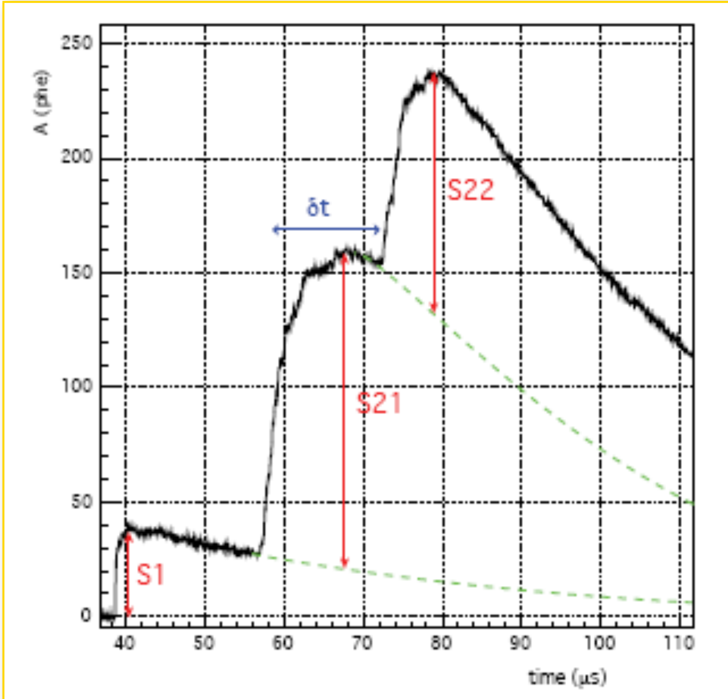
P. Benetti *et al.*, NIM A **332**, 395 (1993)

Neutron identification

Single Hit



Double Hit



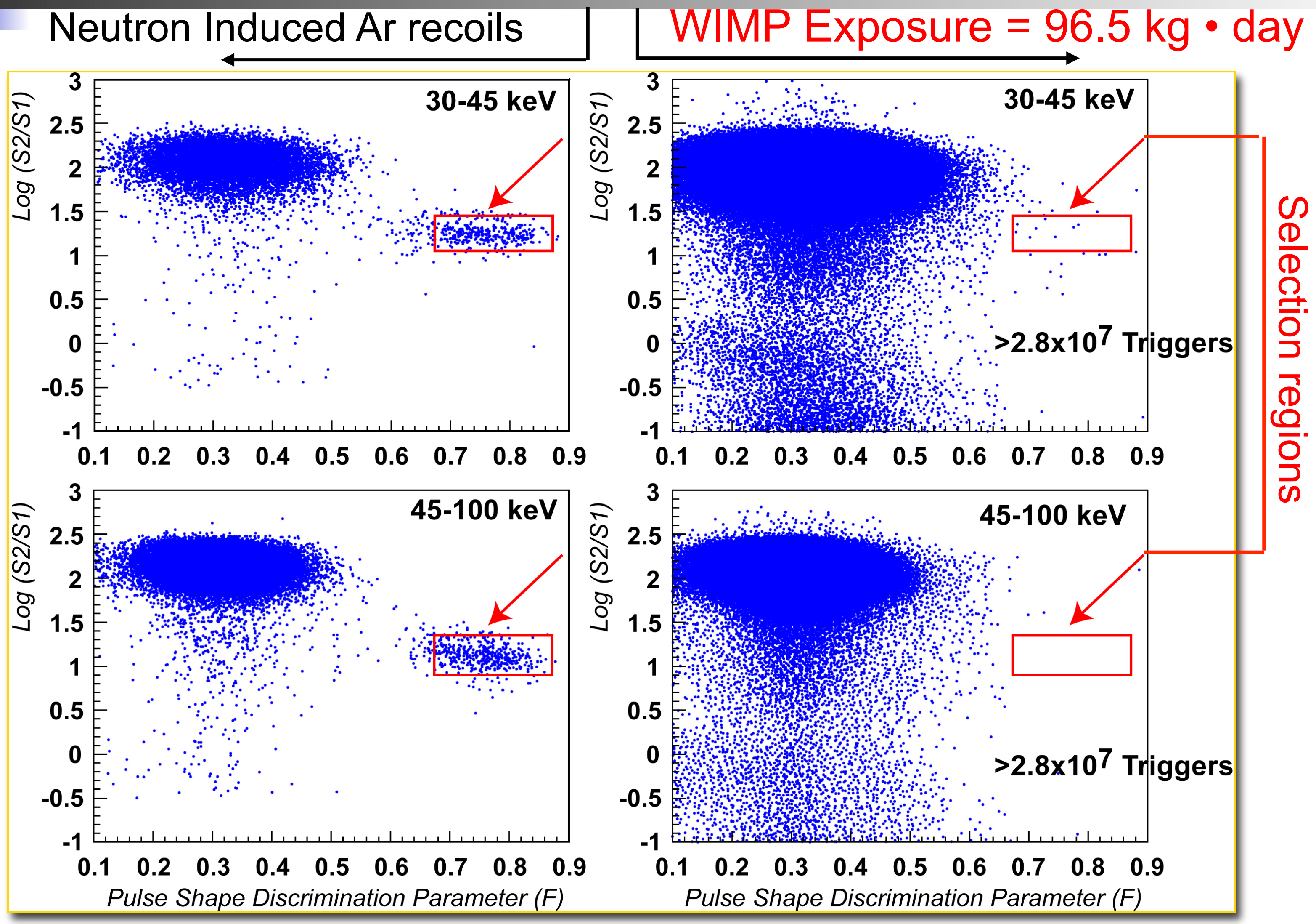
- Typical scattering length for fast neutron in LAr ~ 40 cm
- Mean recoil energy 1/40 T_n
- Multiple recoils can be identified and measured, if separated along the drift coordinate at least a few mm (few μs drift)

Active veto efficiency (MC): Residual Neutron Background

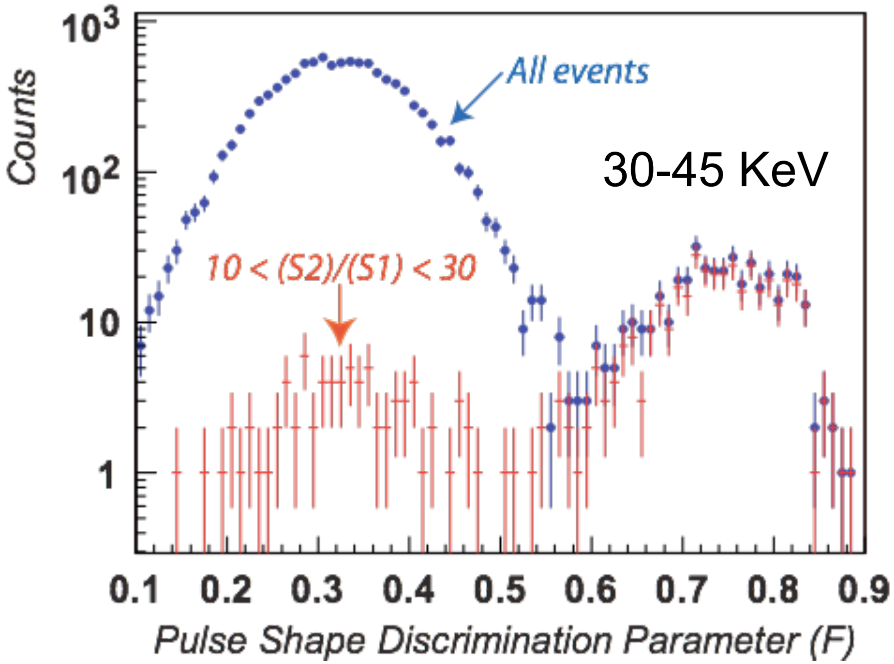
Source	Residual, non-Vetoed Recoil Events in Inner Detector (20-100 keV) [events/year]
Dewar (12 tons)	0.22
Veto PMTs (300 units)	0.70
Internal PMTs (40 units)	1.03
Steel in chamber (20 kg)	0.05
Steel in shielding (8 tons)	< 0.15
External neutrons	0.02
Cosmic rays	~ 1
Total	3.3
After cuts [multiplicity of hits in Internal Detector, coincidence with gammas]	<1

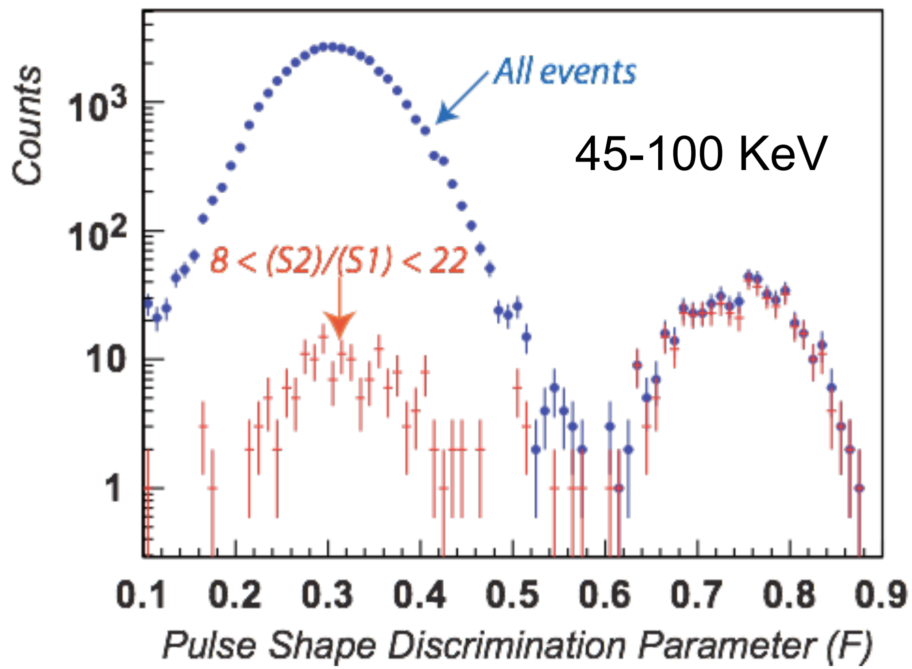
Spectrum from all sources dominated by nuclear form factor
Neutron background becomes negligible above 50 keV
4-5 yrs of neutron-free data taking above 50 keV

Identifying WIMP Candidates



Argon recoils selection





F = Fast component / total scintillation

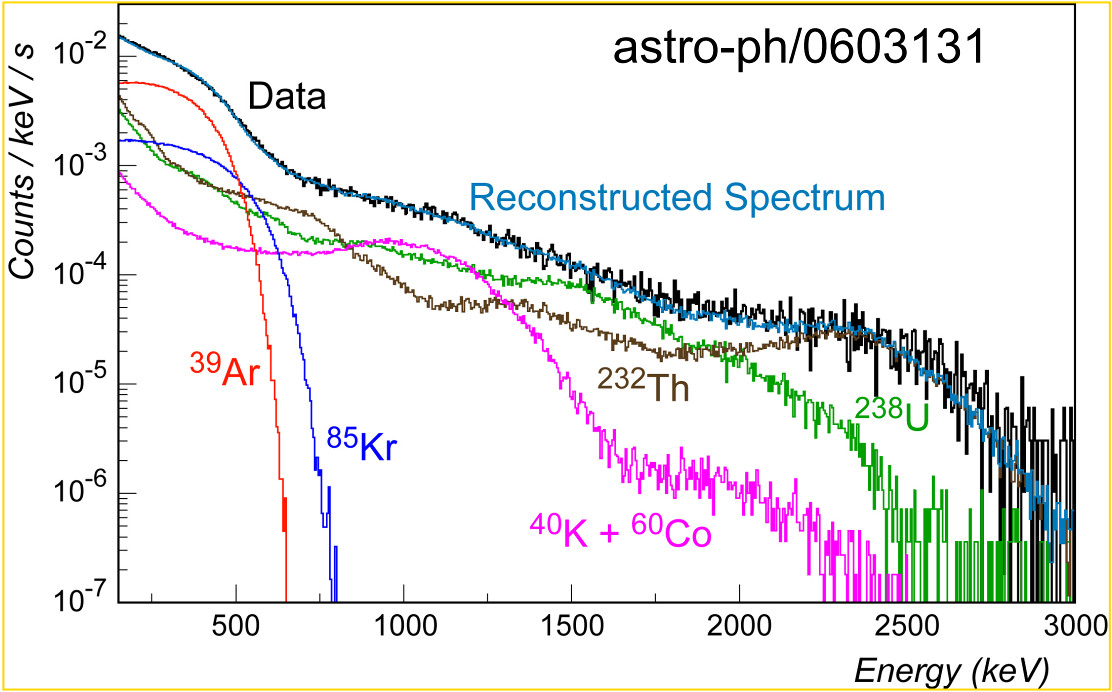
The effect of the S2/S1 ratio cuts (energy dependent) is shown for neutron-calibration data.

- It strongly depletes the β/γ-like population (F<0.6)
- It leaves the Ar-recoil population unaffected (F>0.6)

Gamma background

	Rate (Hz)
^{232}Th chain	0.74
^{238}U chain	0.64
^{40}K + ^{60}Co	0.26
^{85}Kr	**0.56**
^{39}Ar	**1.50**
Total reconstr.	3.70
Total measured	3.71

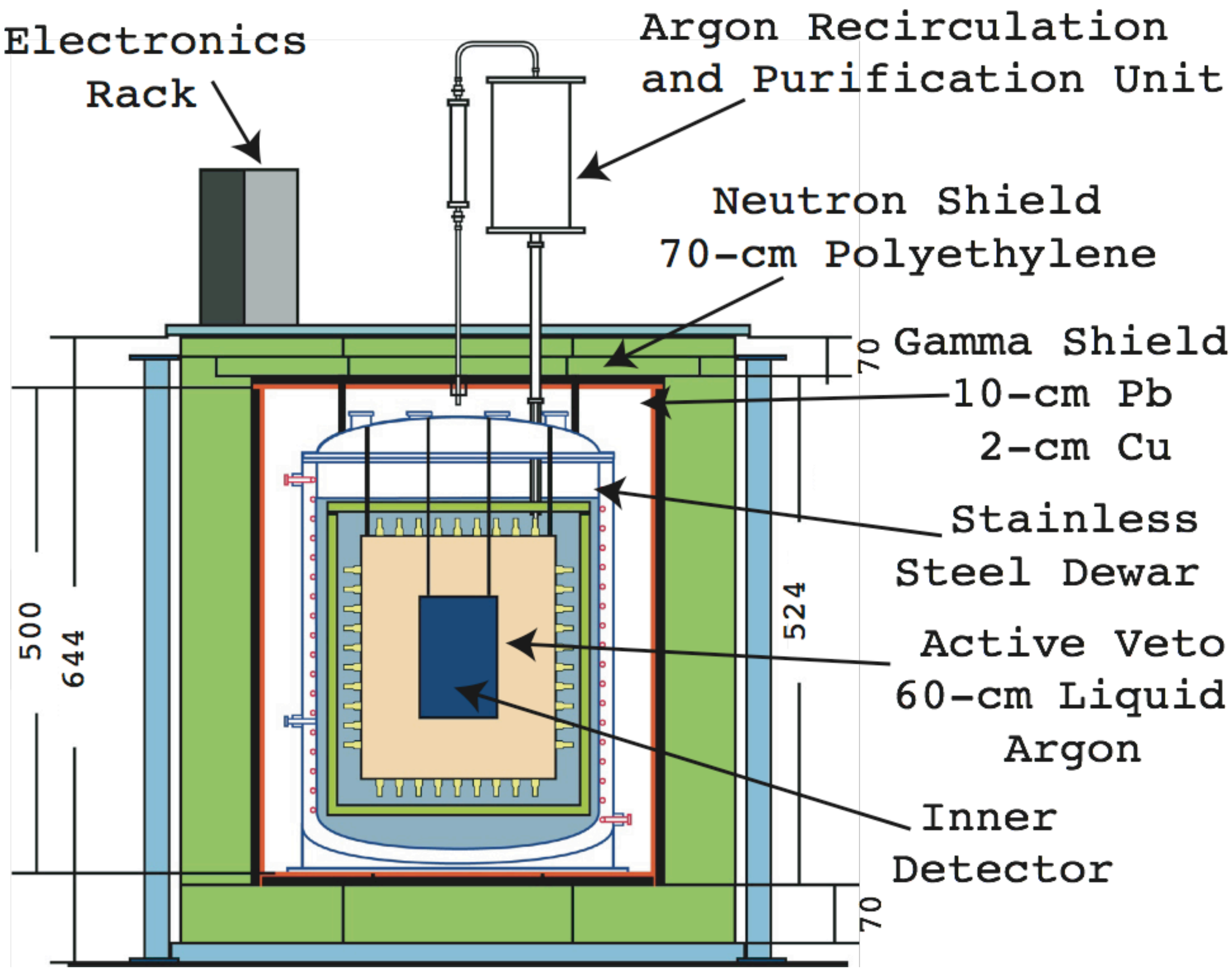
Spectrum observed in the 2.3 liters chamber with 10 cm lead shield @ LNGS



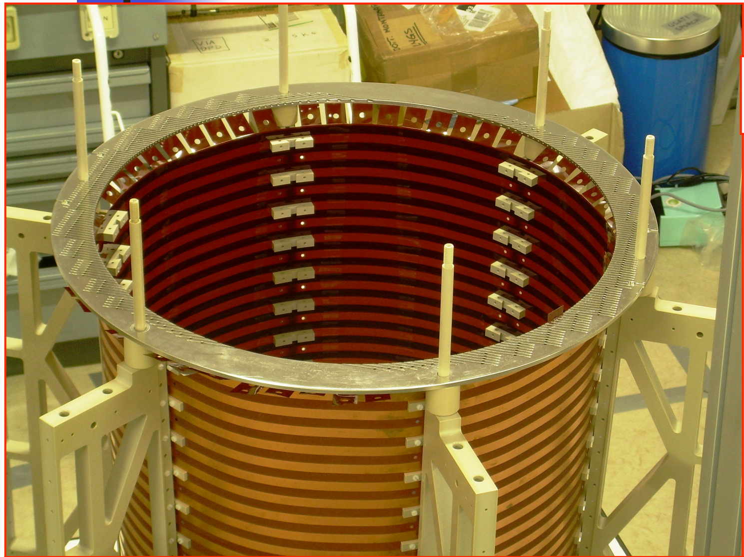
Re-determination of the ^{39}Ar specific activity: 0.87 ± 0.02 ± 0.08 Bq/kg

Could be **substantially reduced** with selection of radio-pure materials and, possibly, with argon depleted in ^{39}Ar (by isotopic separation or using Argon from geological sources)

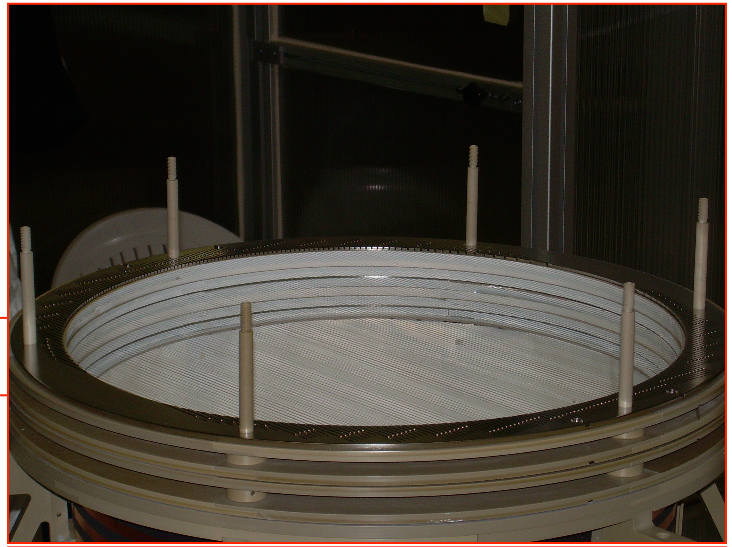
Installation Layout



Inner Detector Assembly

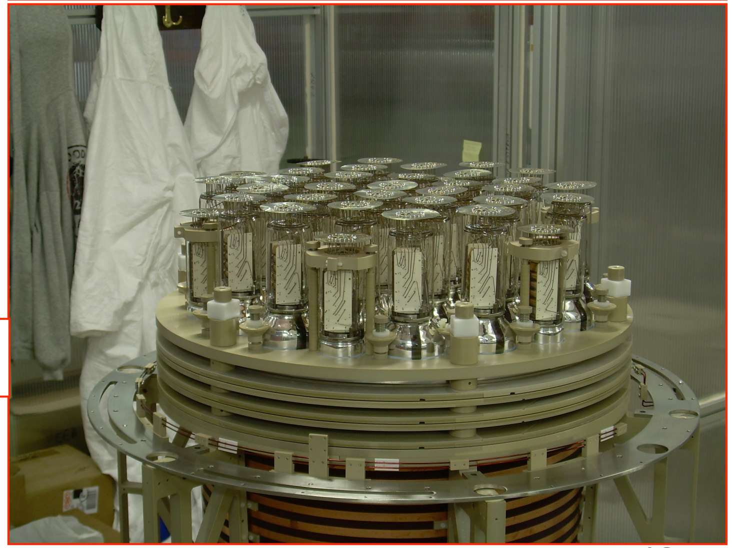


Race Tracks



Grids

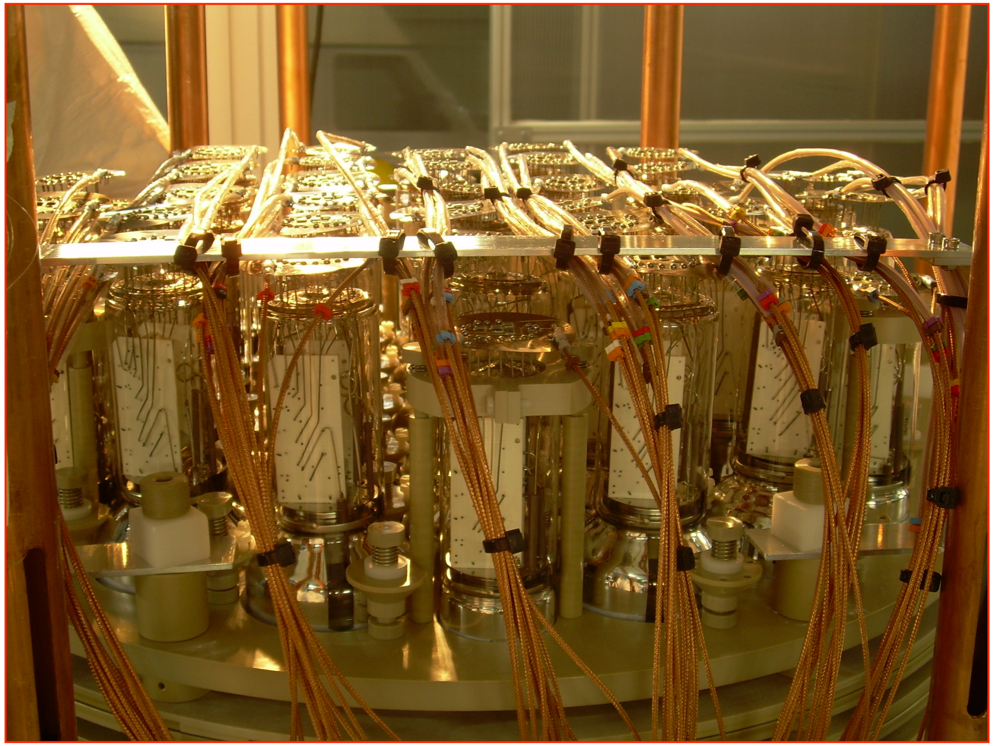
Reflector



Phototubes

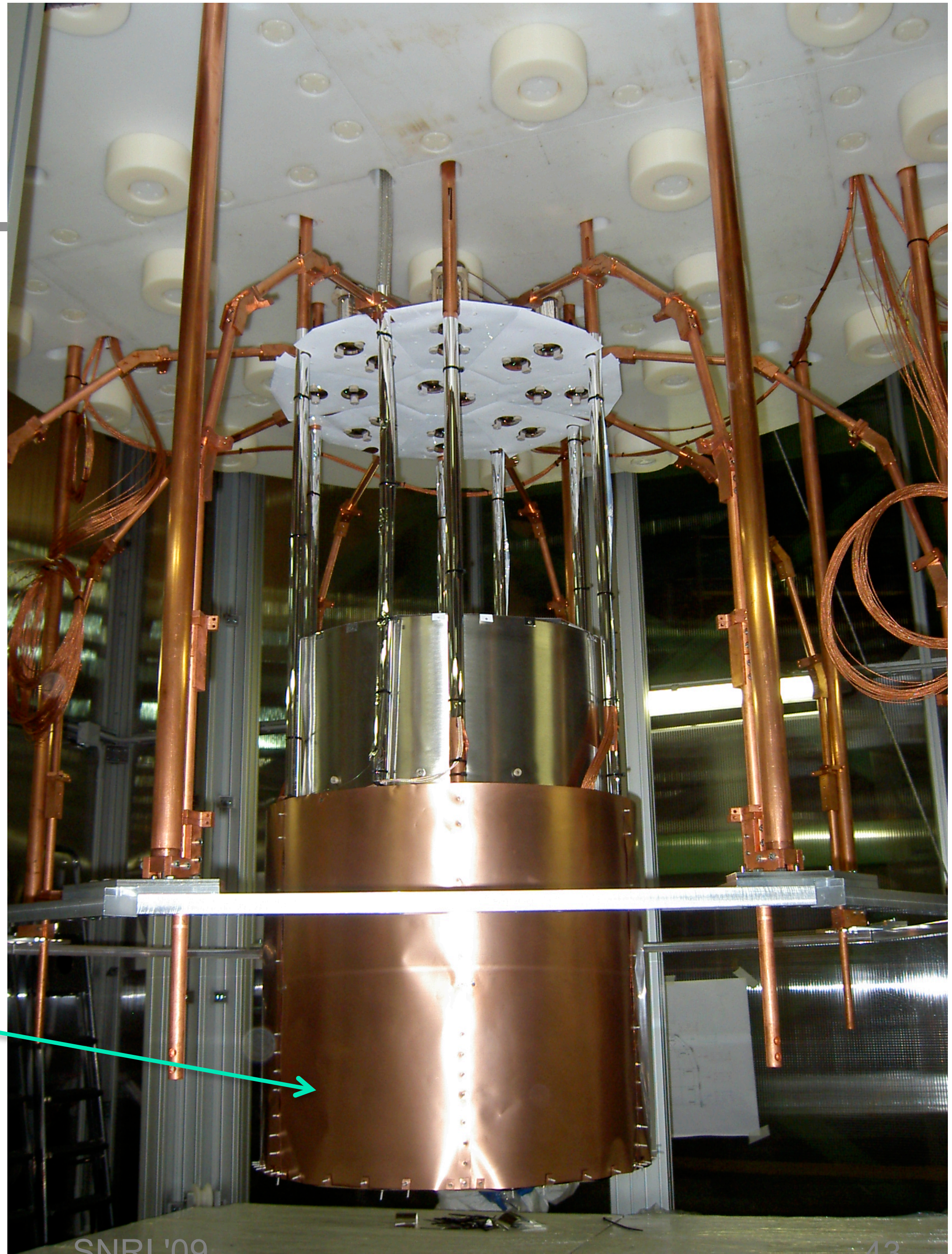
Inner Detector Assembly

Cabling



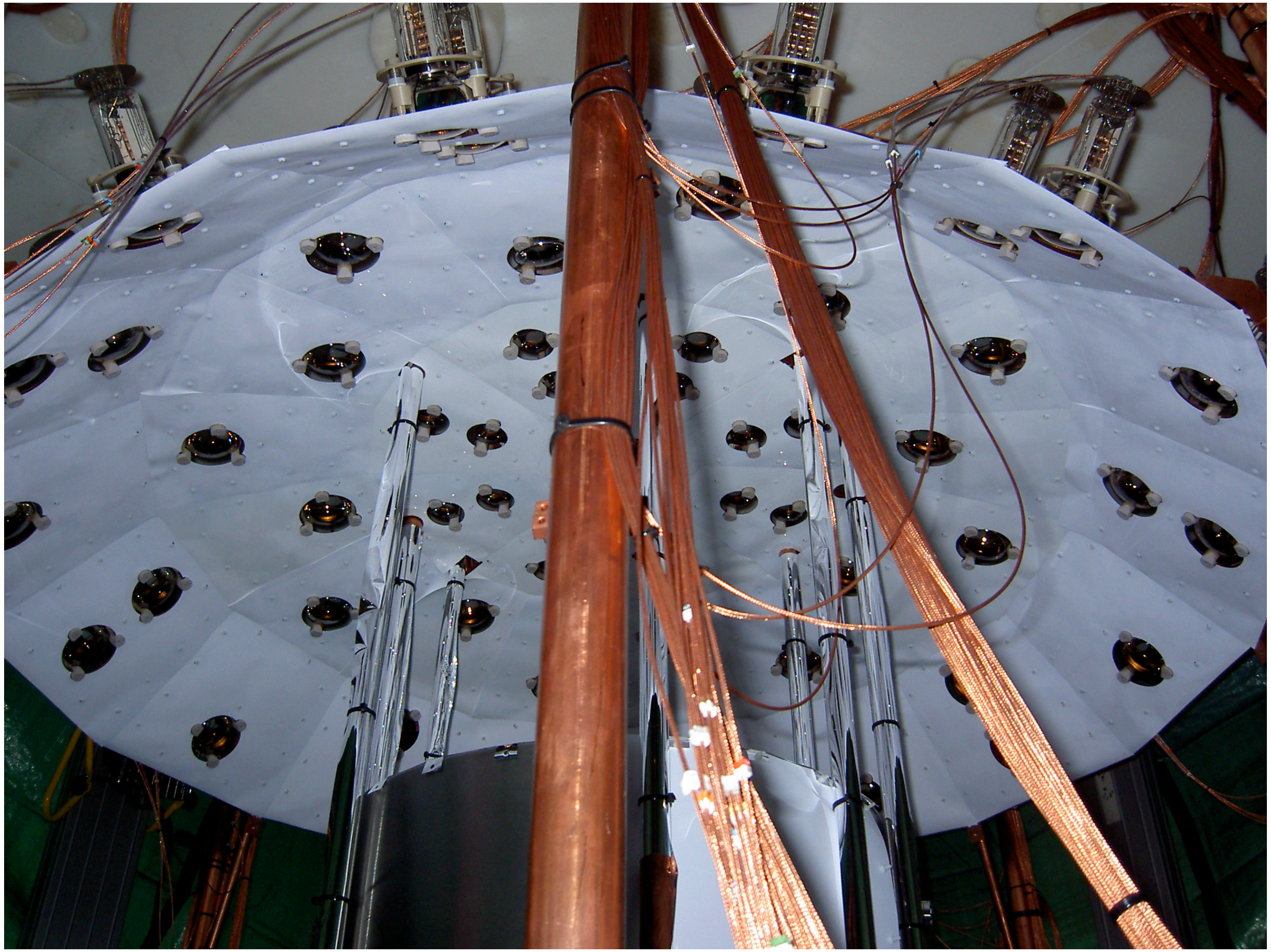
Inner Detector Assembly

Active Shield Assembly

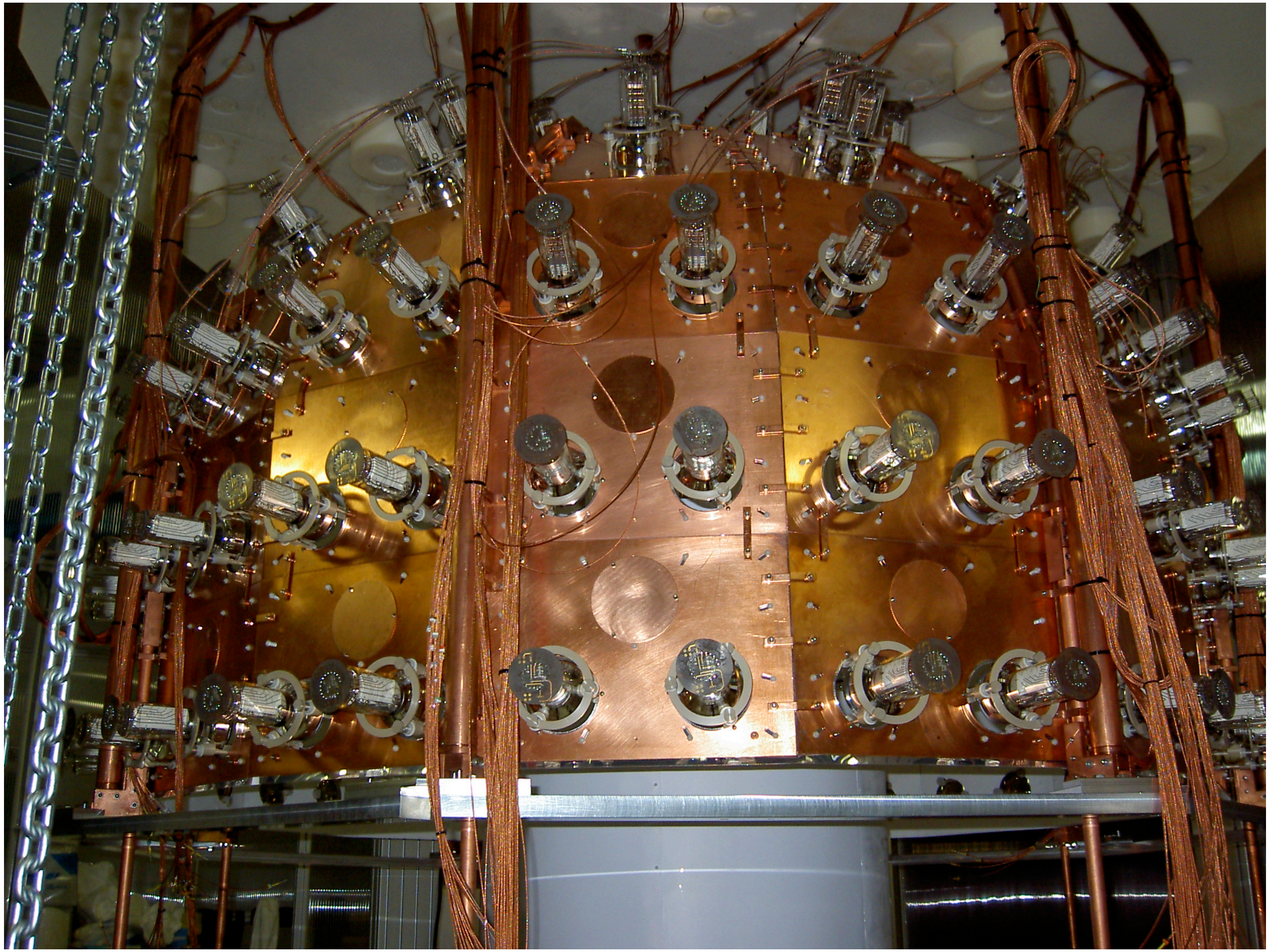


Electrostatic Shield

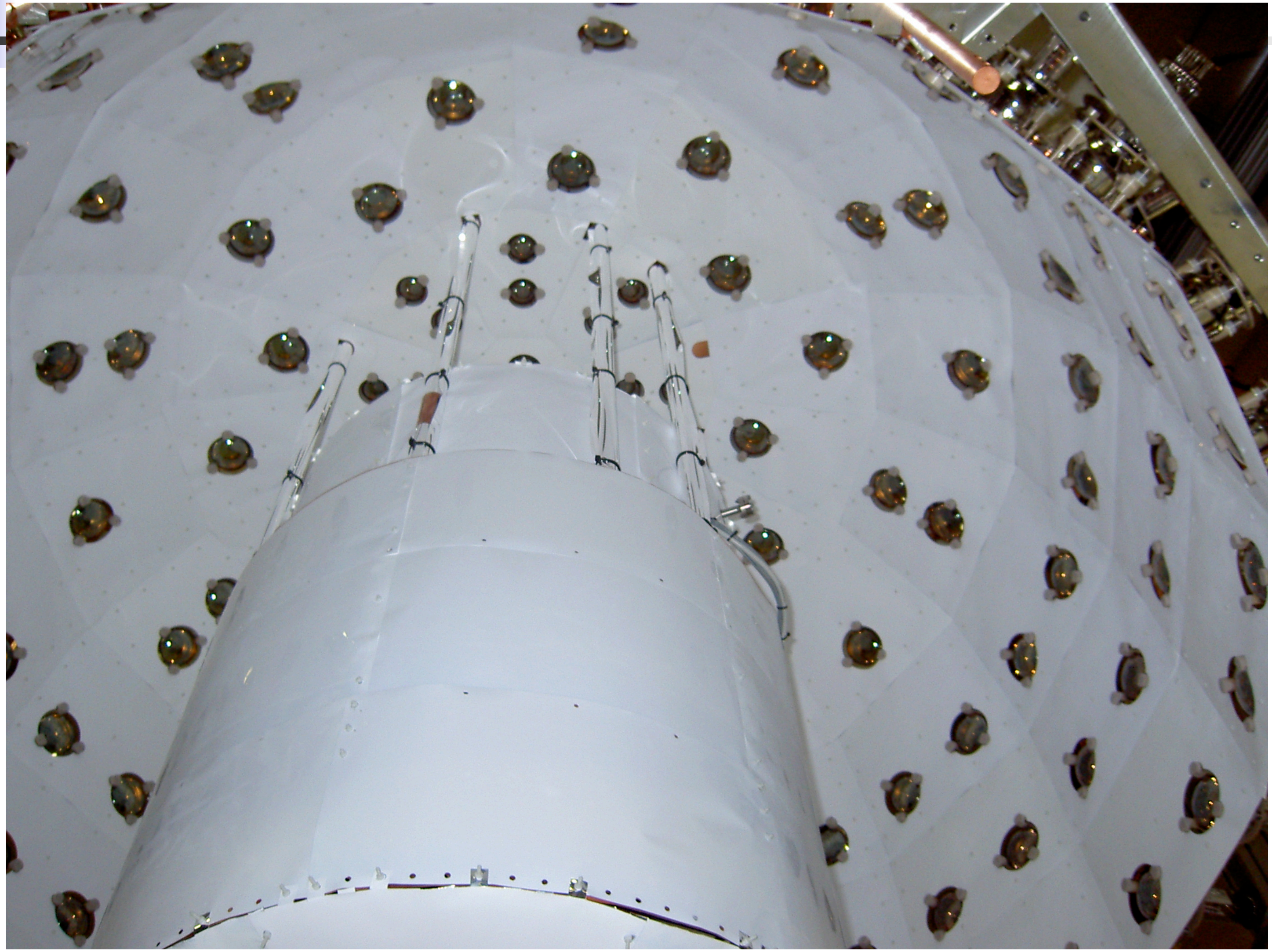
Active Shield Assembly



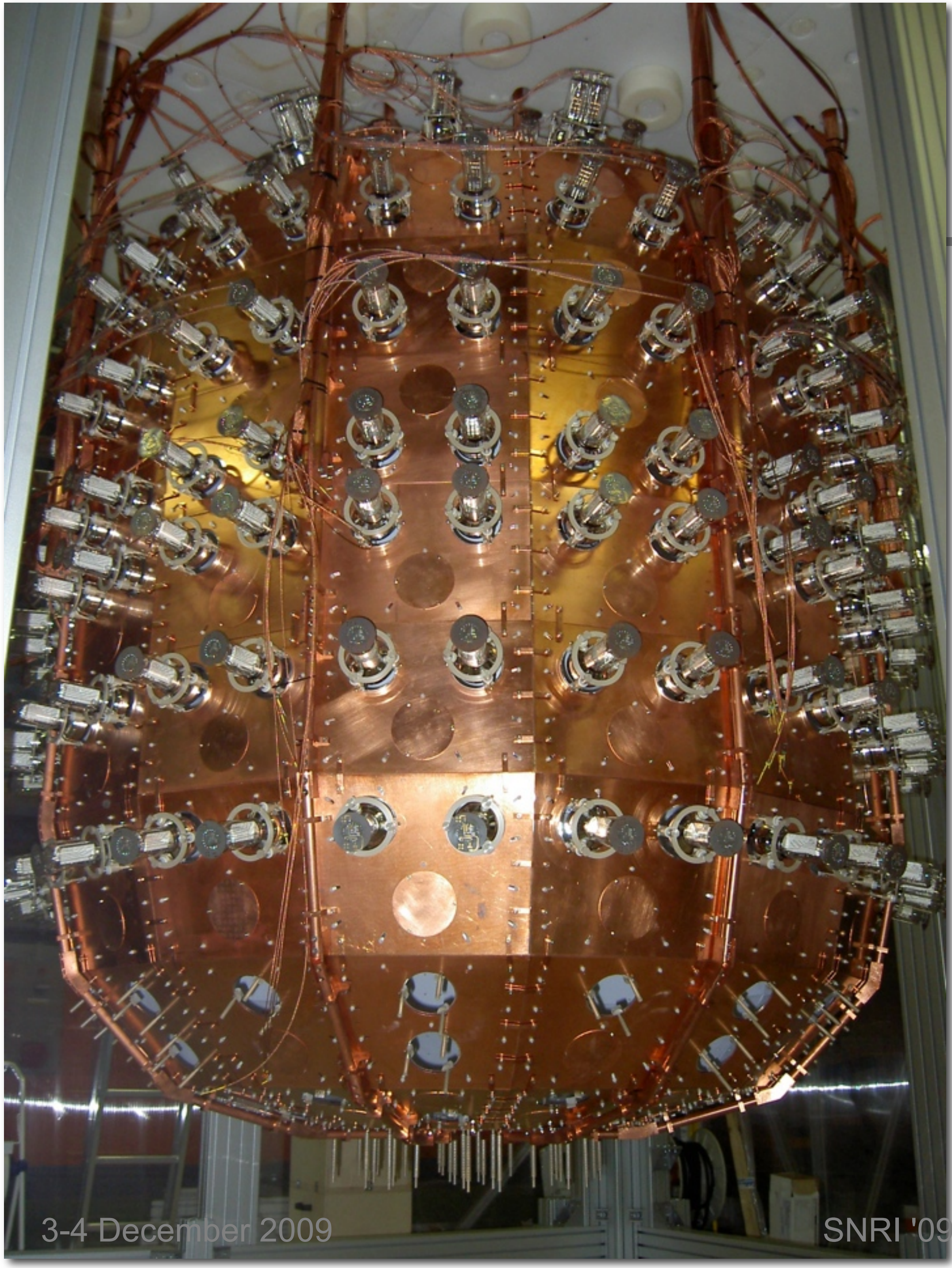
Active Shield Assembly (Oct, 2009)

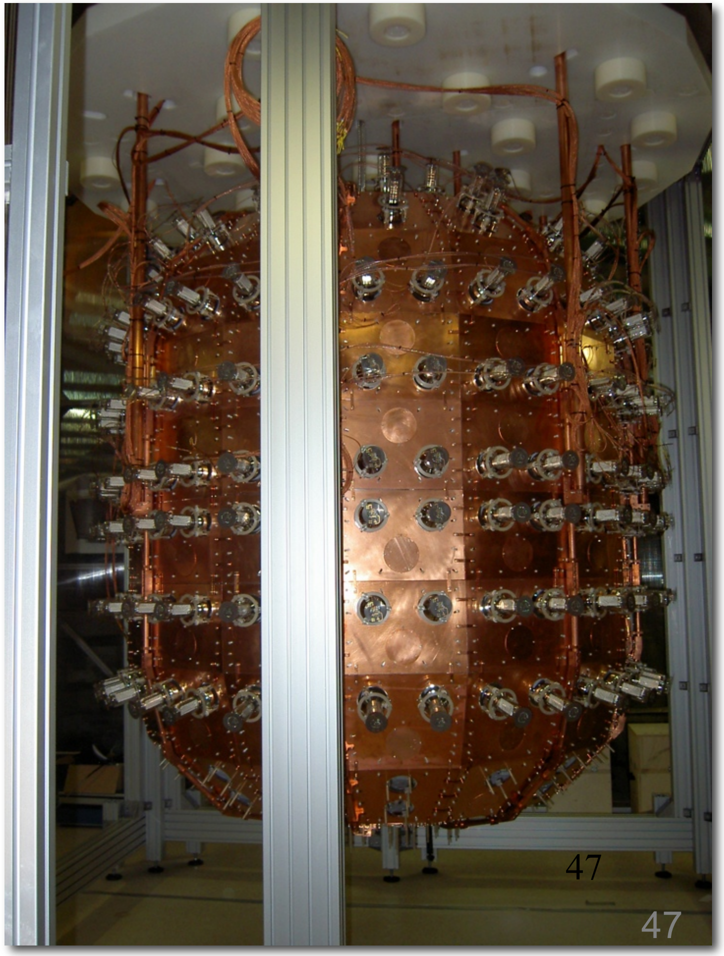


Active Shield Assembly (Oct, 2009)

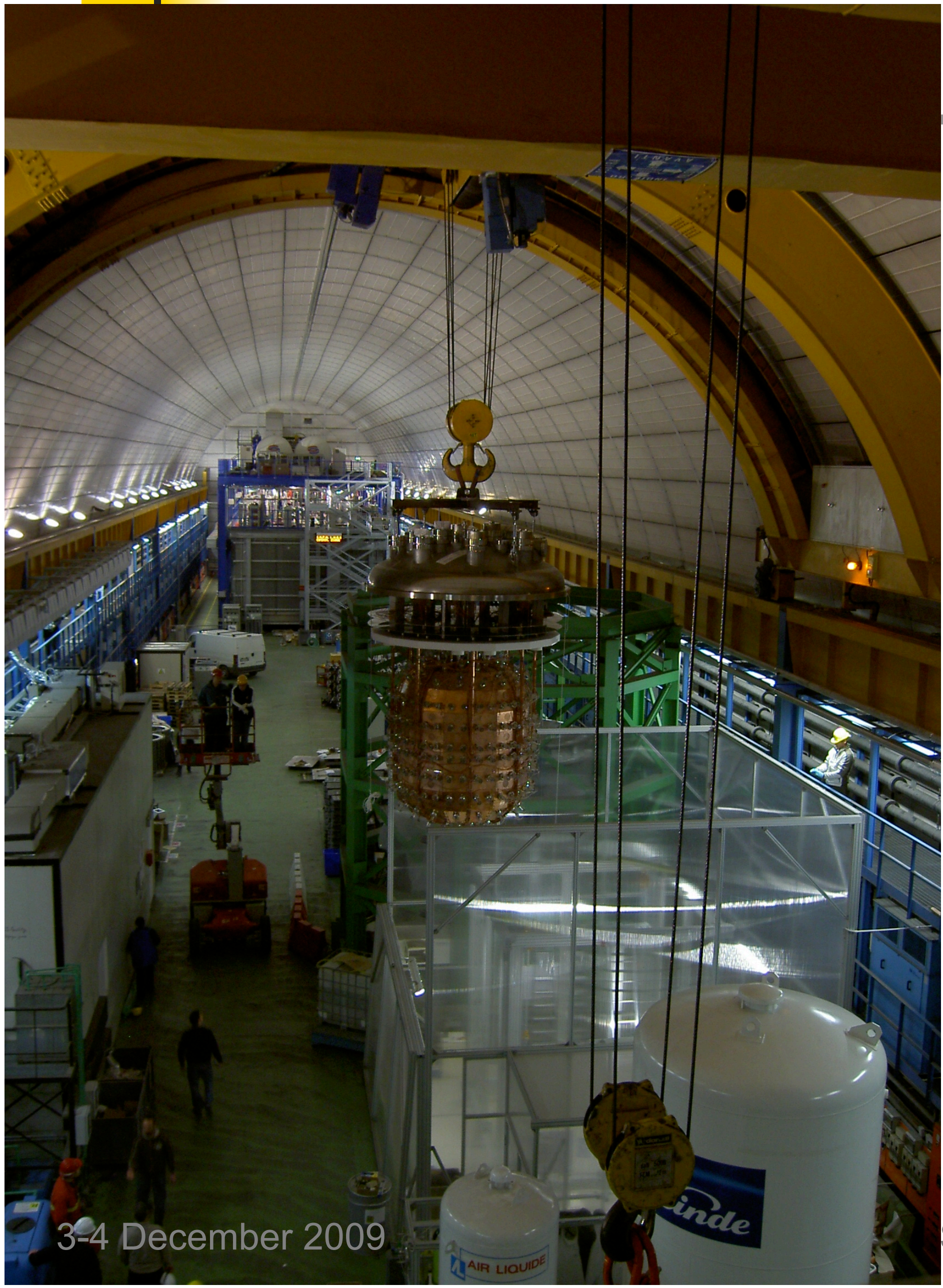


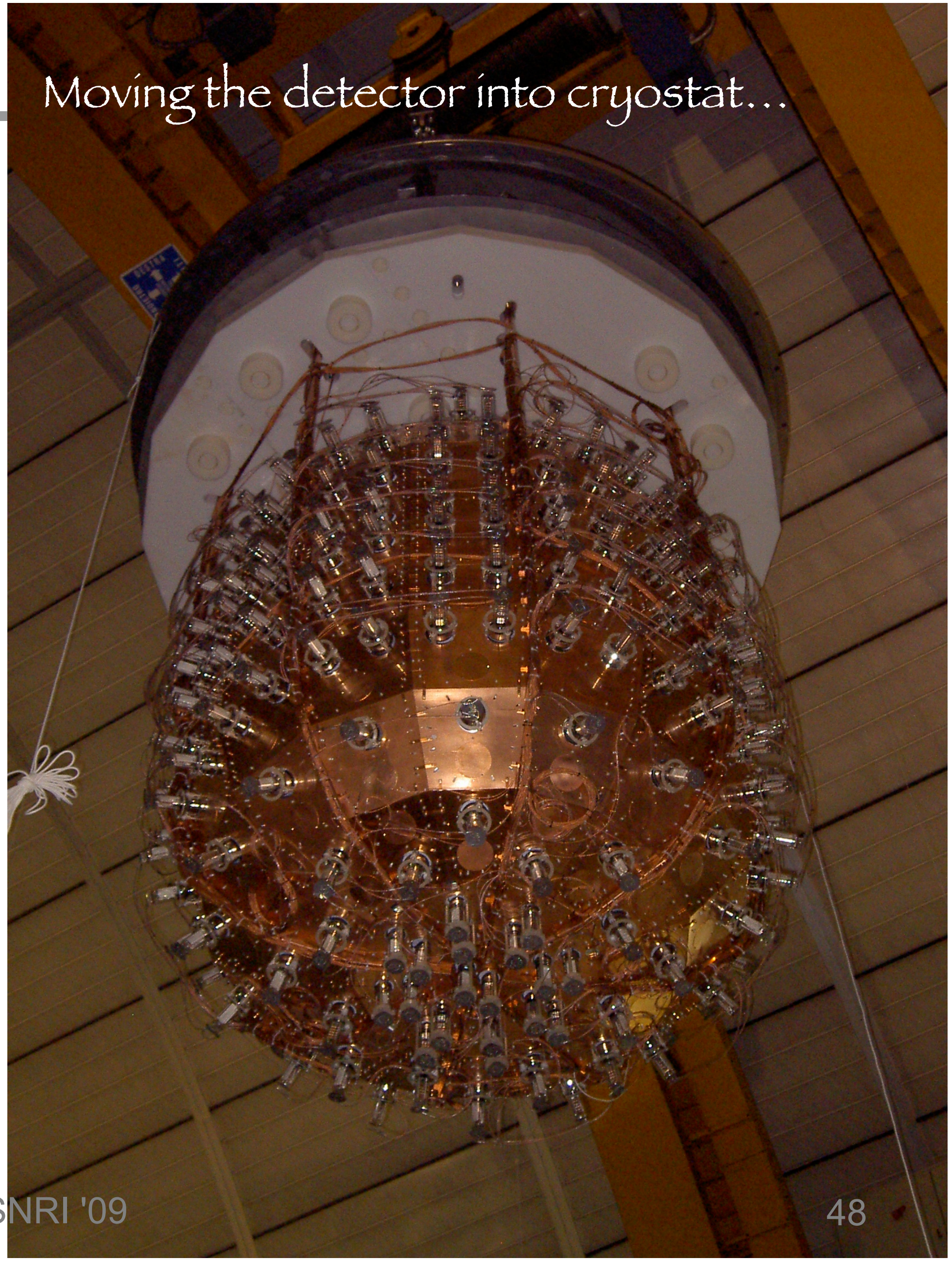
Active Shield Assembly





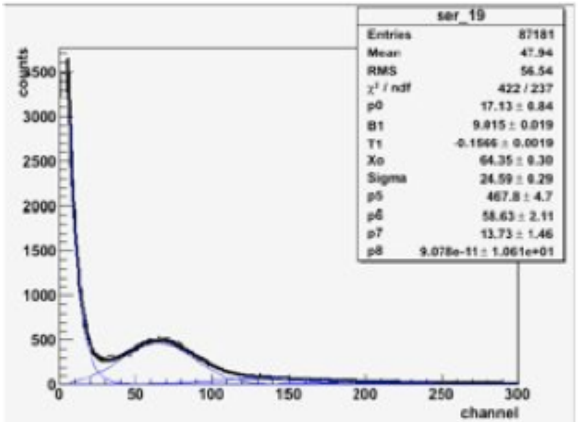
Installation in the main cryostat



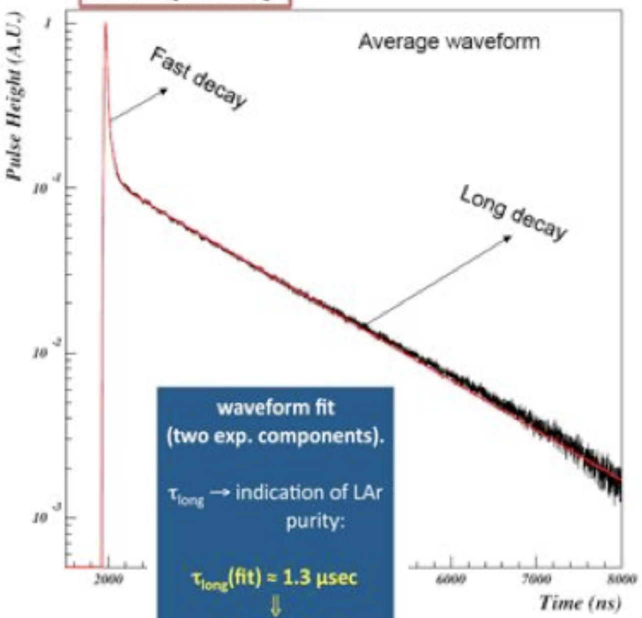


Technical run (summer 2009)

- Electronics test, noise reduction + Validation of DAQ and OffLine Reconstruction
- Time Constants measurement from fit of the Light Signal
- Single Electron Response (for all 37 PMT of the Inner Detector)
- Light Yield Measurement from ^{39}Ar β-spectrum



LAr purity



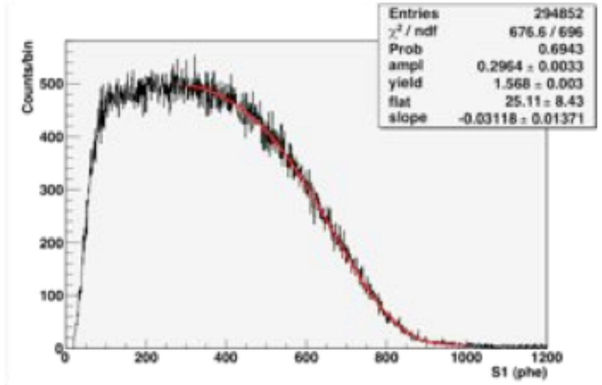
waveform fit (two exp. components).

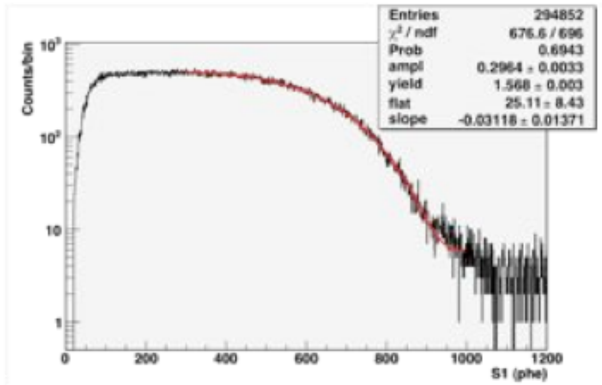
τ_{long} → indication of LAr purity:

τ_{long}(fit) ≈ 1.3 μsec

⇓

good LAr purity (after three months of recirculation)





LY values from different algorithms and data samples have been used for internal cross check. Results are stable.

- **from 36/37 PMTs:**

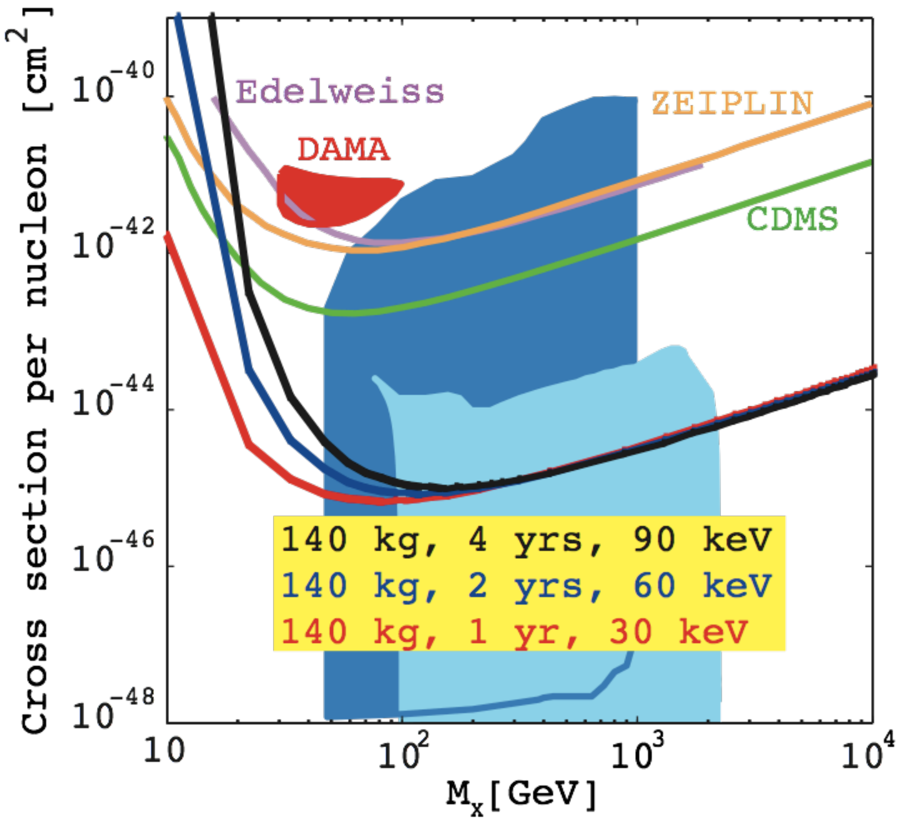
LY = 1. 630 ± 0.002$_{stat}$ phel/keV

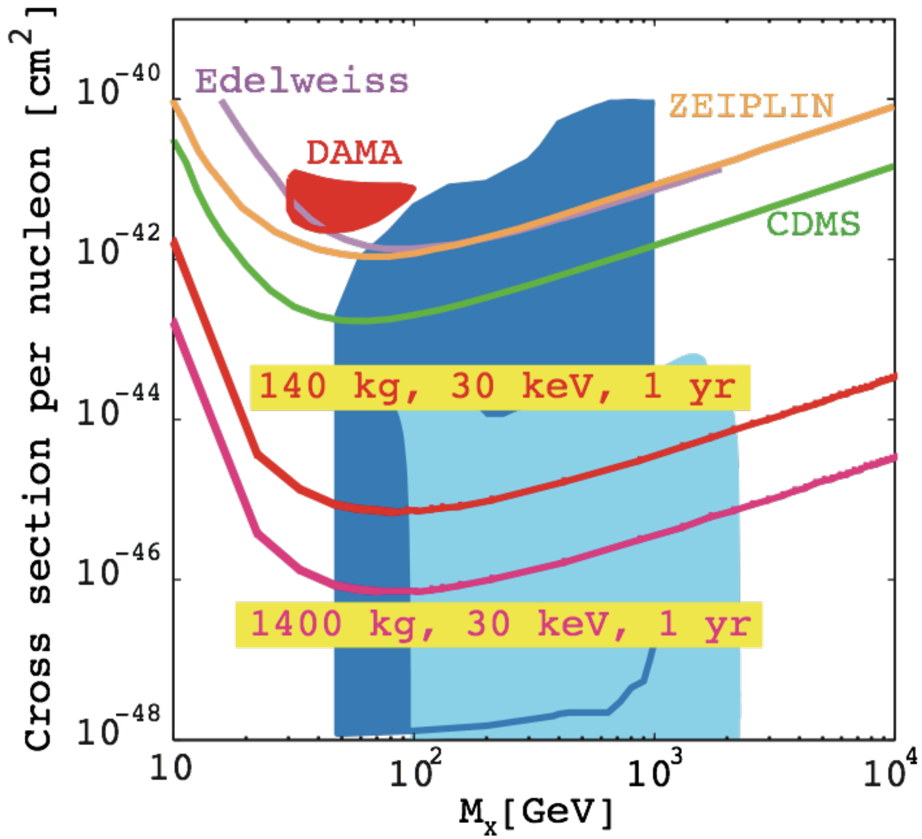
Next steps

- In 2009 technical run, no secondary signal analysis due to HV mis-functioning.
- New long term physics run foreseen early in 2010 after repair and improvement of TPB coating (to reach 3 phe/keV).
- R&D started for possible upgrade to1400 kg double phase detector and/or single phase 8 t detector depending on physics results on WArP 140 kg
- Use of depleted argon (isotopic separation or from underground sources) also foreseen if further background reduction is needed

Achievable limits

Null measurement results for WArP 140 kg and a possible upgrade to 1400 kg in the active veto detector.





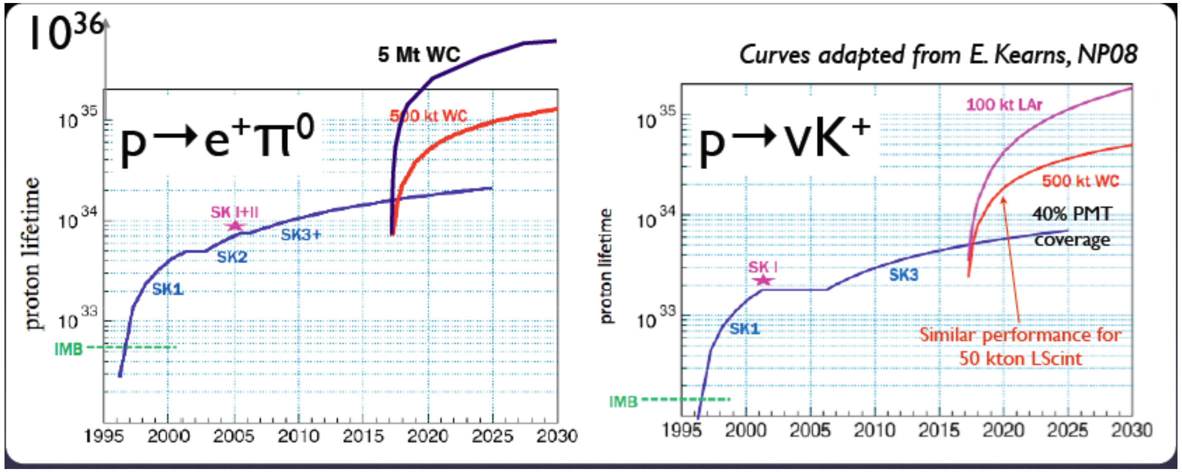
Further developments towards a multi-kton LAr-TPC

- Physics reasons for a large LAr TPC detector
- Review of the existing main design concept
- R&D items towards large LAr TPC
  - Readout devices and electronics
  - Cryostats
  - Argon purity
  - High voltage systems

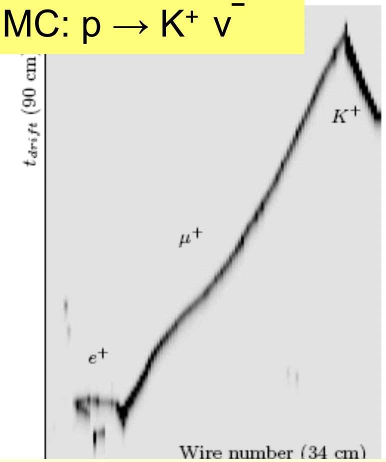
Multi-kton LAr detectors?

- Proton decay searches

Rubbia Neutrino 08



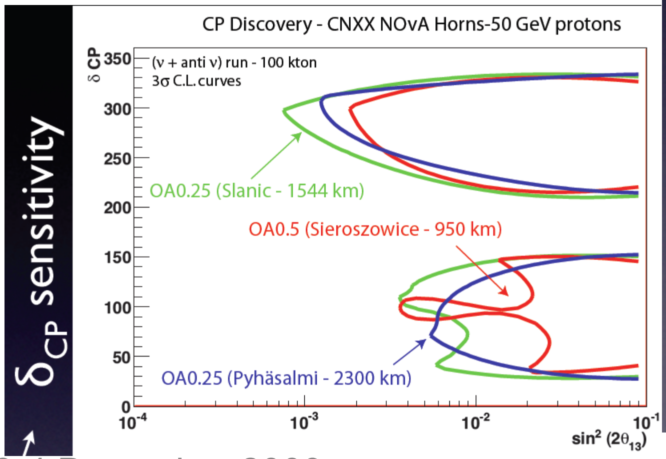
LAr MC: $p \to K^+ \bar{\nu}$

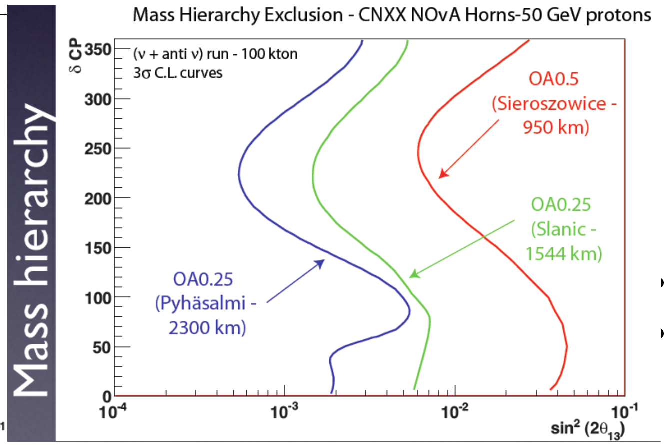


10x efficiency than WC
only way to reach 10^{35} years

- Long baseline neutrino oscillation

Rubbia WIN09





δ_{CP} and mass hierarchy sensitivities for different baselines in Europe

- 1.6 MW WBB from CERN
- 100 kton LAr detector

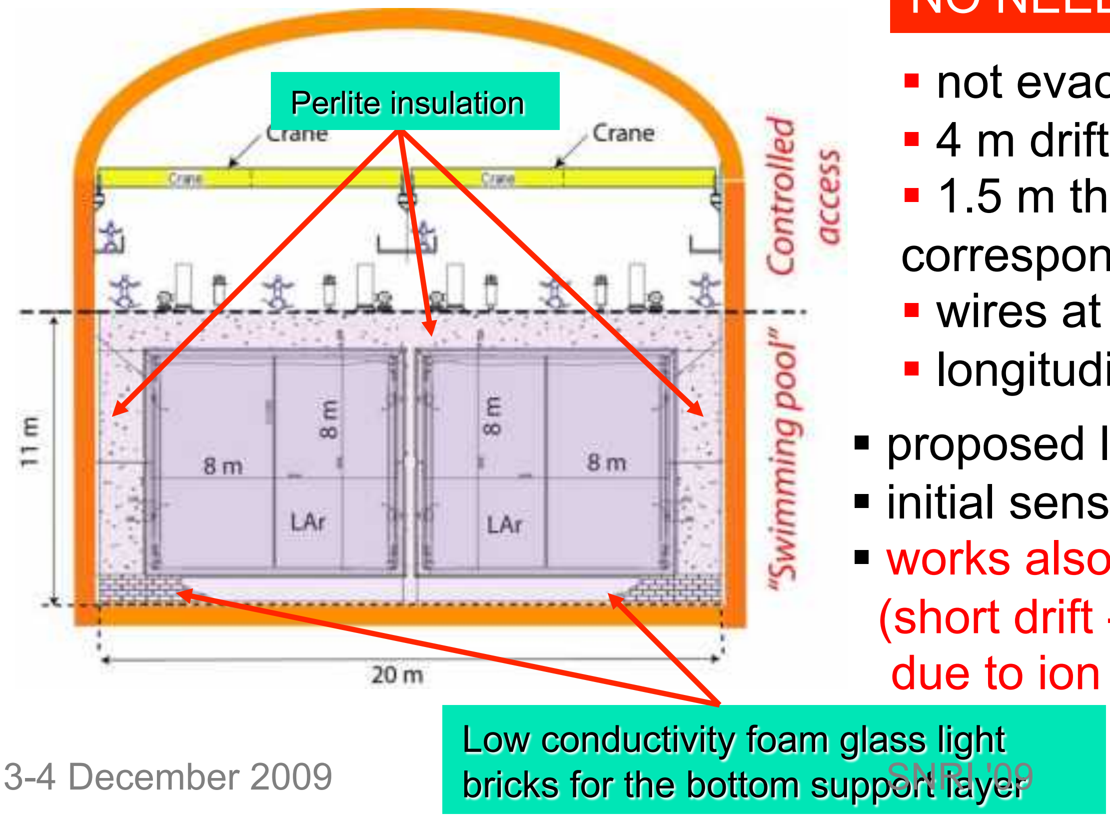
Design concepts for large LAr-TPC's, I

MODULAr

B. Baibussinov et al., Astr. Phys. 29 (2008) 174
D. Angeli et al., JINST 4 (2009) P02003

Geometry of an ICARUS-T600 half-module (T300) "cloned" into a larger detector scaled by a factor **8/3 = 2.66**: the cross sectional area of the planes is **8 x 8 m^2** rather than 3 x 3 m^2. The length of such a detector is **~60 meters.**

2x10 kton



NO NEED FOR Major R&D efforts

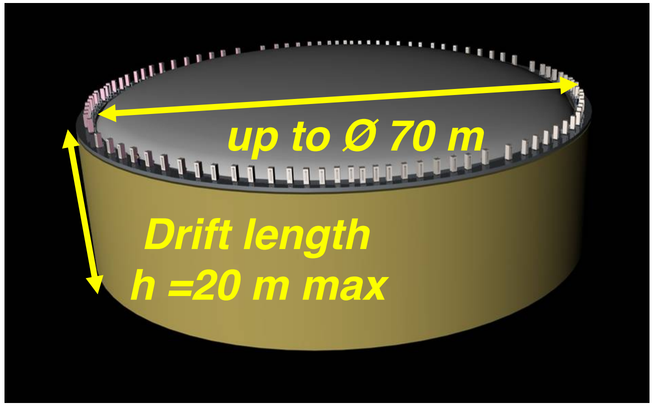
- not evacuable (R&D in progress)
- 4 m drift length
- 1.5 m thickness of perlite, corresponding to ~ 4 W/m^2 thermal loss
- wires at 0°, ±60°, with ~6 mm pitch
- longitudinal wires ~30 m long

- proposed location: 10 km off-axis from LNGS
- initial sensitive volume of at least 20 kton
- works also at shallow depth (short drift -> negligible E-field distortions due to ion space charge)

Design concepts for large LAr-TPC's, II

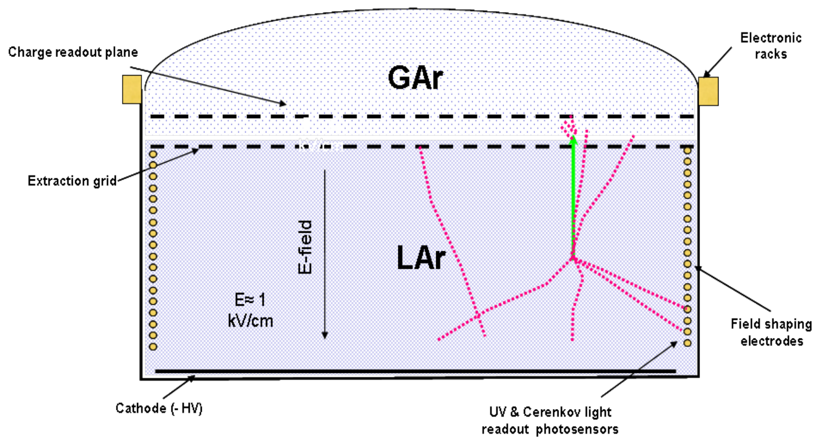
A. Rubbia hep-ph/0402110

Giant Liquid Argon Charge Imaging ExpeRiment up to 100 kton

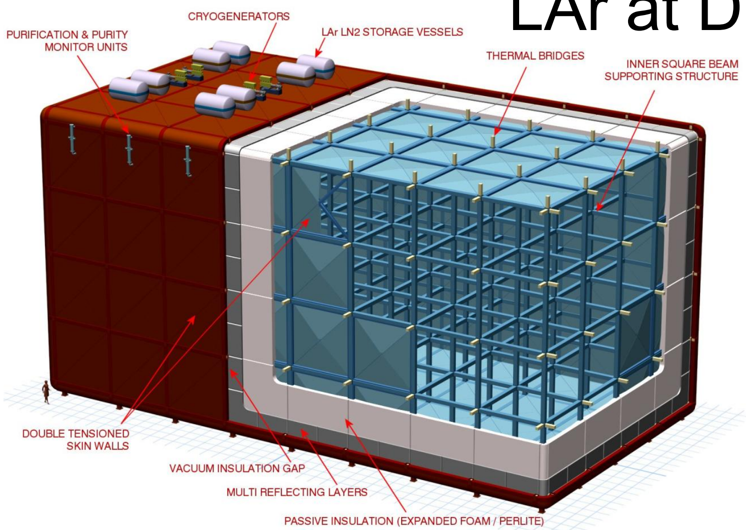


- Single module cryo-tank based on industrial LNG technology
- Scalable with aspect ratio close to standard LNG tanks
- Cylindrical shape with excellent surface / volume ratio
- Simple, scalable detector design, possibly up to 100 kton
- Single very long vertical drift with full active mass
- A very large area LAr LEM-TPC for long drift paths
- Possibly immersed light readout for Cerenkov imaging
- Possibly immersed (high Tc) superconducting solenoid to obtain magnetized detector
- Reasonable excavation requirements (<250000 m^3)

- Passive insulation heat loss ≈ 80kW@LAr
- LEM+anode readout with 3mm readout pitch, modular readout, strip length modulable, $2.5x10^6$ channels
- Purity < 0.1 ppb (O2 equiv.) in nonevacuable vessel
- Immersed HV Cockcroft-Walton for drift field (1 kV/cm)
- Readout electronics (digital F/E with CAEN; cold preamp R&D ongoing; network data flow & time stamp distrib.)
- WLS-coated 1000x 8" PMT and reflectors for DUV light detection



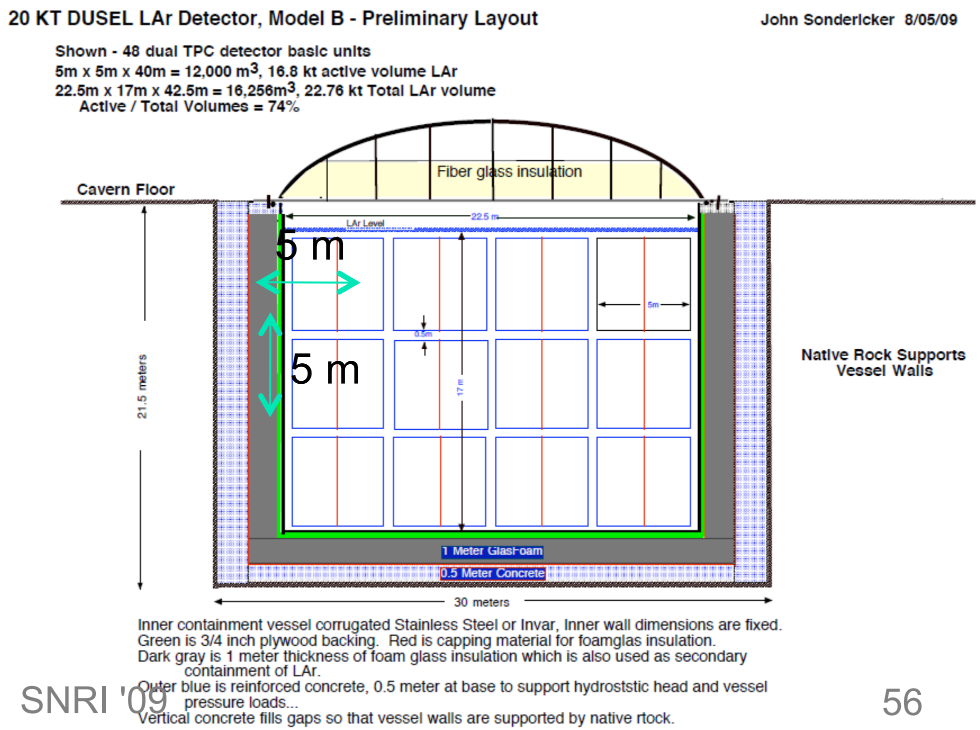
Design concepts for large LAr-TPC's, III



LAr at DUSEL

D.B. Cline, F. Raffaelli, F. Sergiampietri
JINST 1 T09001 2006

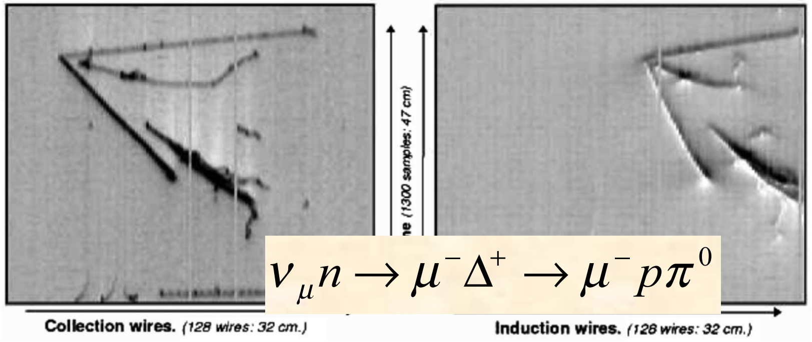
- LANDD Concept
- Double wall cryostat, vacuum insulated, internally supported
- Evacuation possible



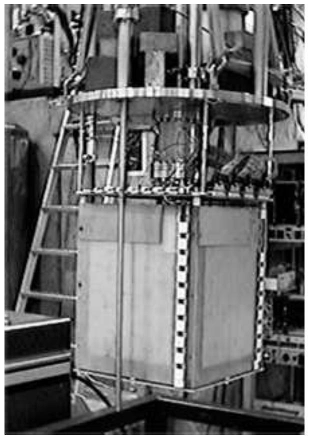
- Inner containment vessel: corrugated stainless steel or Invar
- Externally supported by cavern walls
- Not evacuable
- ~20 kton LAr module
- Max drift length 2.5 m
- Readout with wire planes

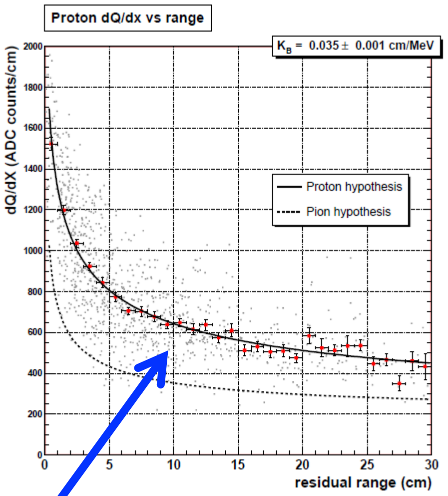
Neutrino interaction in LAr-TPC

ICARUS 50 lt @ CERN



$$\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- p \pi^0$$

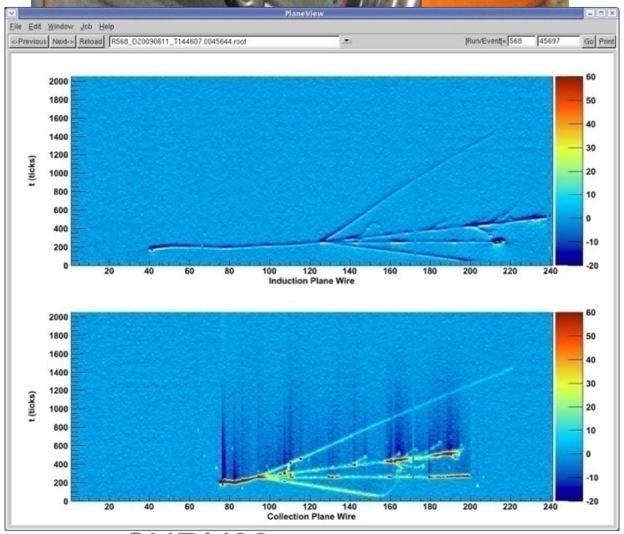




proton identification in ν interactions

ArgoNeut@ FNAL

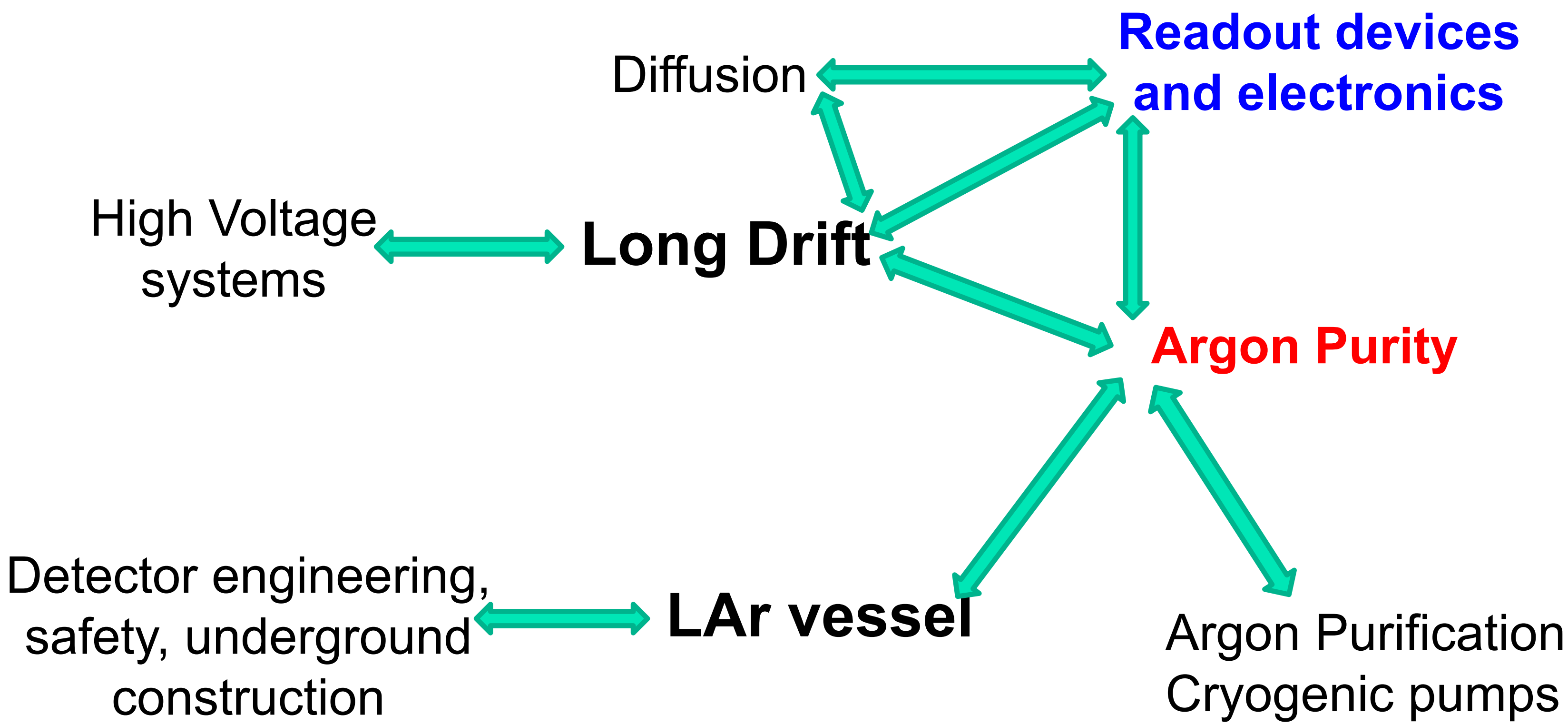
~175 lt on NuMI ν beam



250 lt @ KEK

cosmic rays in 2010
ν beam @ J-PARC

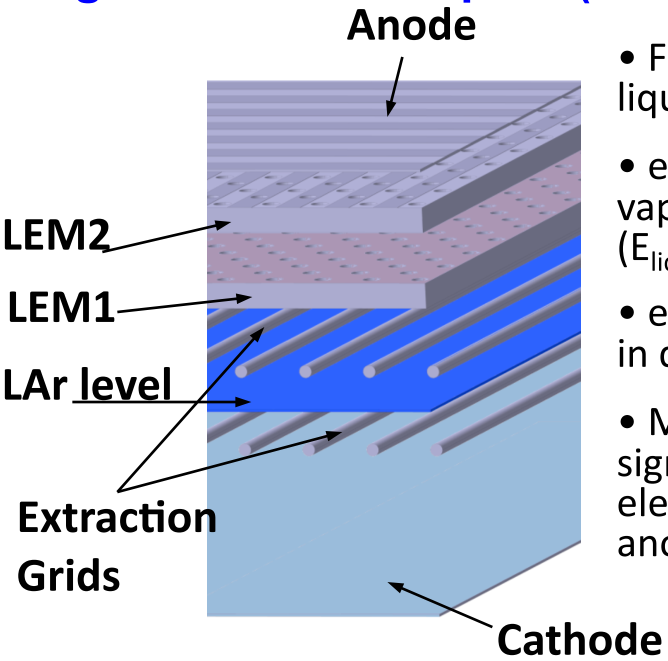
Technical issues for LAr-TPC



Ionization charge readout techniques in LAr

secondary scintillation from THGEM

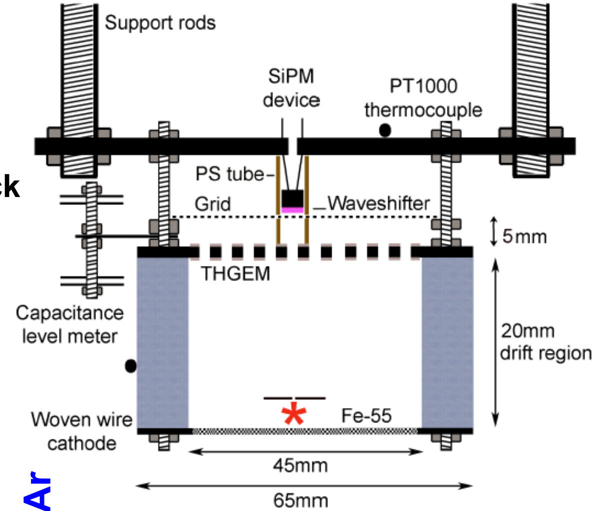
double phase Ar
Large Electron Multiplier (THGEM)



- Free e⁻ drift in LAr towards liquid-vapour interface.
- e⁻ are extracted to the vapour via extraction grids (E_{liq} > 2.5 kV/cm).
- e⁻ undergo multiplication in double stage LEM.
- Multiplied charge induces signals on the segmented electrodes of top LEM and anode.

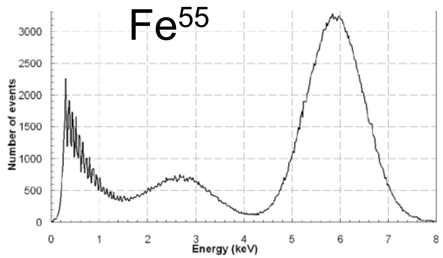
A. Badertscher et al., arXiv:0811.3384

1.5 mm thick



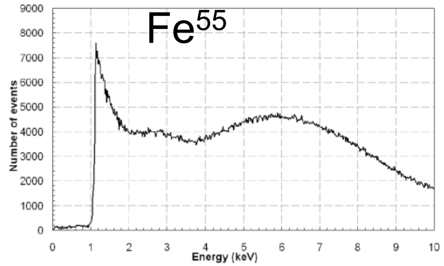
P.K. Lightfoot et al., JINST 4 (2009) P04002

double phase Ar



V_{THGEM}=2.2 kV

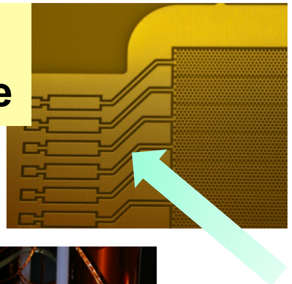
single phase LAr



V_{THGEM}=10.2 kV

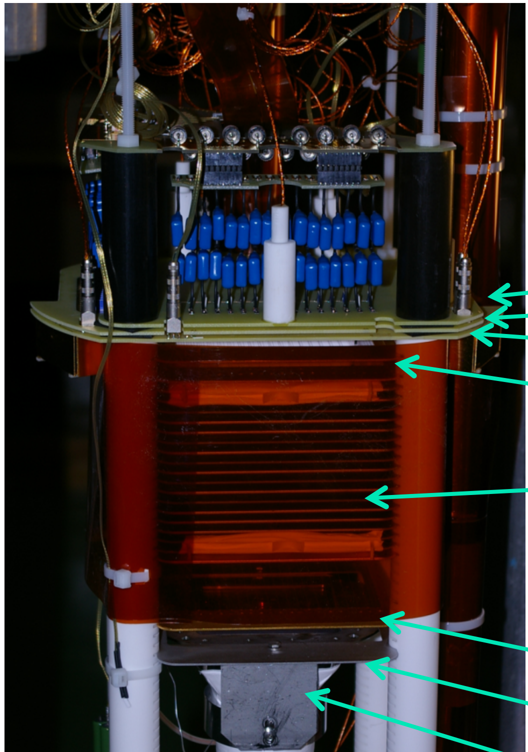
TH-GEM readout

LEM 10 x 10 cm^2
16 strips 6 mm wide

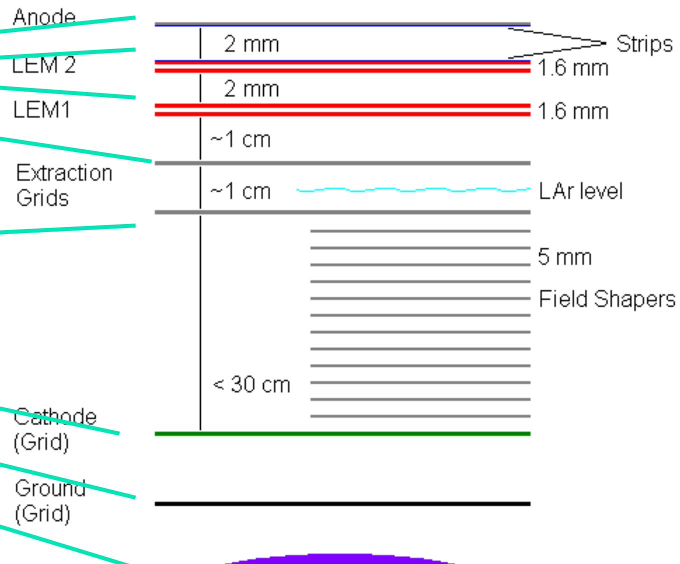


A novel kind of LAr TPC based on
- **operation in double phase Argon**
- **amplification in pure GAr by 1 or more stages of Large Electron Multipliers (LEM)**
- **extrapolated from GEM technology**

- **Produced by standard Printed Circuit Board methods**
- **Double-sided copper-clad (18 µm layer) FR4 plates**
- **Precision holes (500µm) by drilling**



Test setup @ CERN



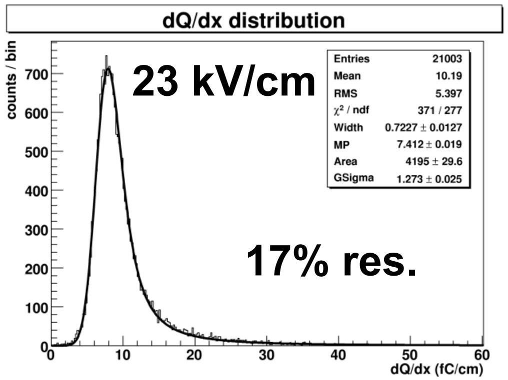
A. Badertscher et al., arXiv:0907.2944

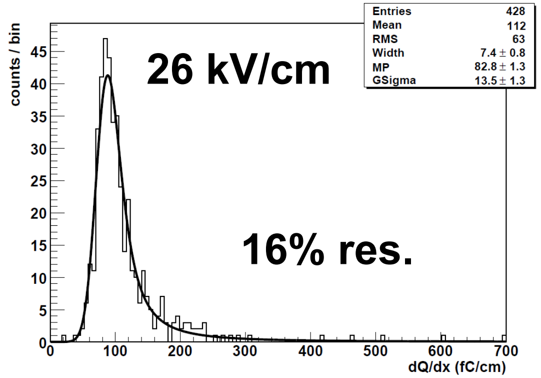
Maximum sensitive volume
10 x 10 x 30 cm^3

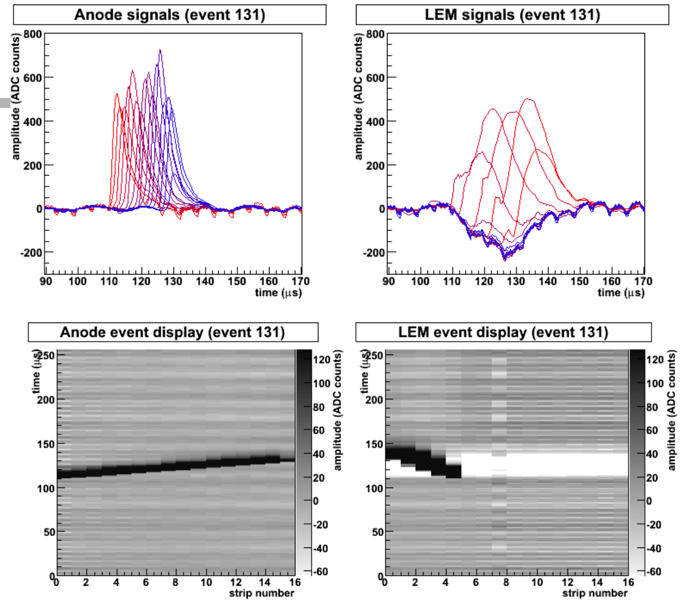
Synergy with RD51 @ CERN

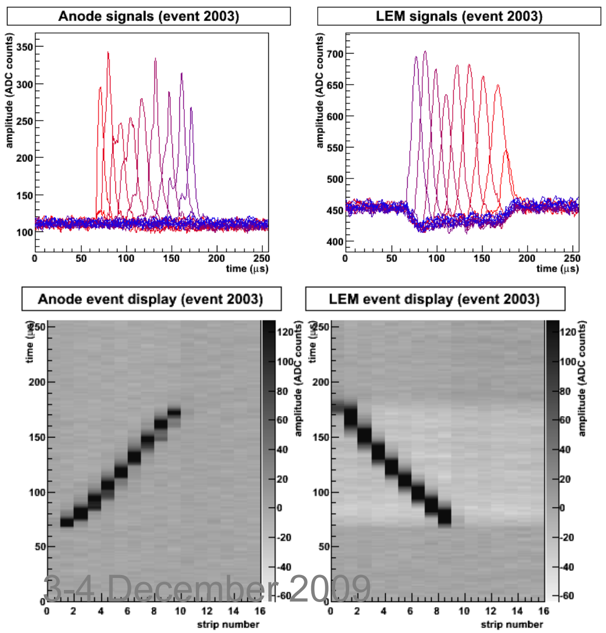
Performance of double phase LEM LAr-TPC

Double stage 1.6 mm LEM

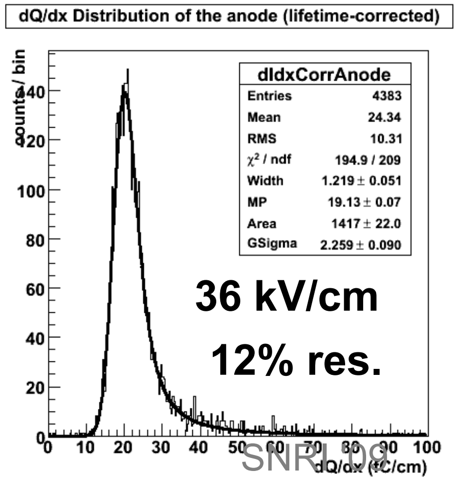


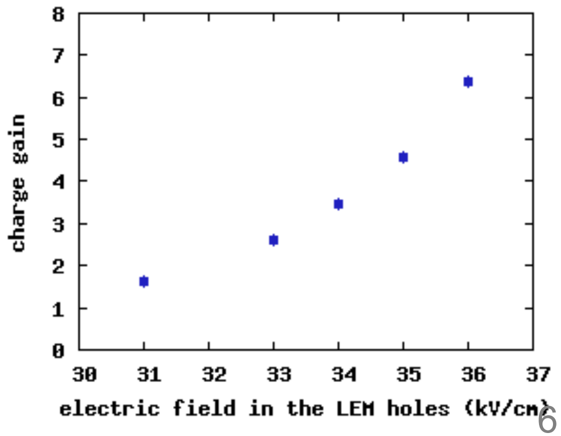






Single stage 1.0 mm LEM

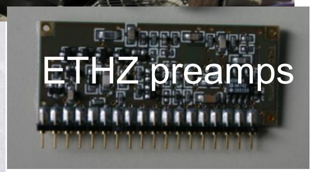




R&D on read-out electronics

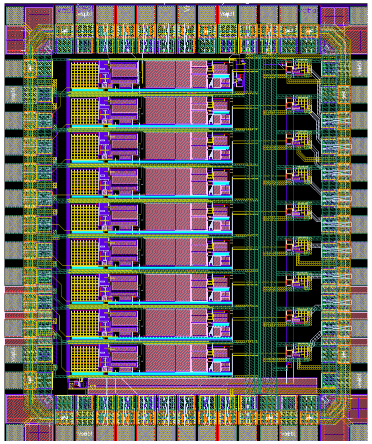
❑ Development of LAr TPC electronics for small scale devices

- CAEN, in collaboration with ETHZ, developed A/D and DAQ system
- 12 bit 2.5 MS/s flash ADCs + FPGA



~11 mV/fC
S/N =10
@ 1 fC, C_i=200 pF
MIP ~10 fC/cm

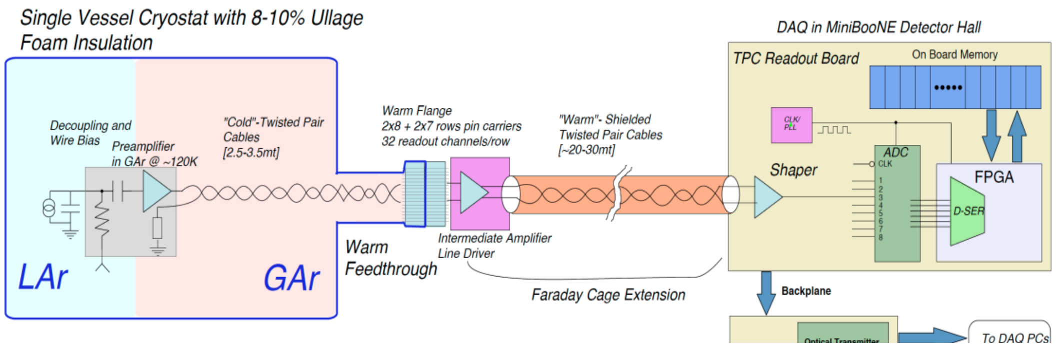
❑ R&D on electronics integrated on the detector



C. Girerd et al.

- IPNL Lyon - 0.35µm CMOS charge amplifier working at cryogenic temperature
- 1^{st} version bench-tested in 2008
- new version with shaper optimization under development
- to be tested on a LEM TPC setup

MicroBoone electronics



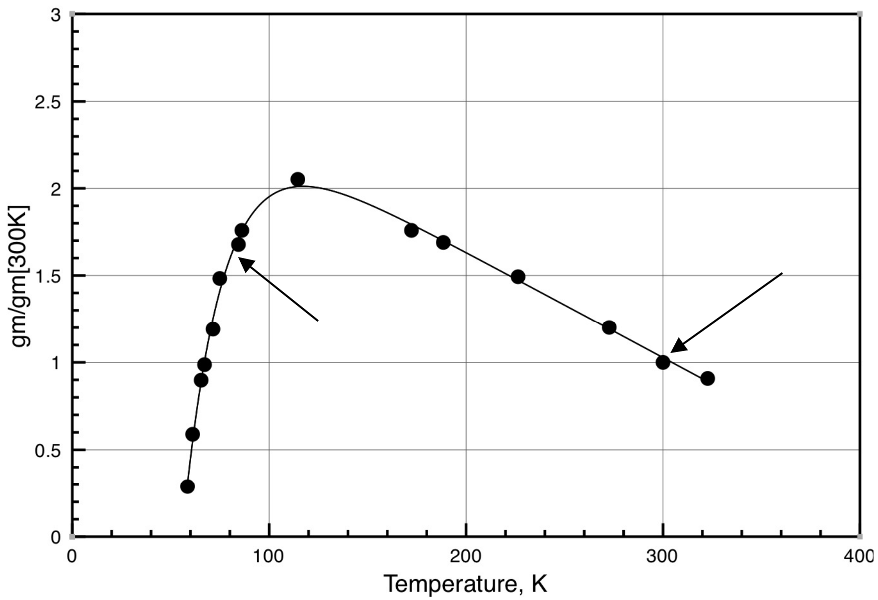
- 10^4 electronic channels : JFET in cold Gar
- Radeka group @ BNL working on 87K CMOS ASIC

Electronics in LAr ?

Deeply investigated within ICARUS collaboration (since 1988)

- Limited choice of active devices working at LAr temperature
  - GAs-jFET (High Electron Mobility Transistor technology)
  - Silicon jFET (High Resistive Substrate technology)
  - CMOS very low temp. **now** available but…
  - **Issues:**
    - Better S/N due to improved g_m at cryogenic temperature
    - Reliability at LAr temperature
    - Availability on the market

U310 jFET



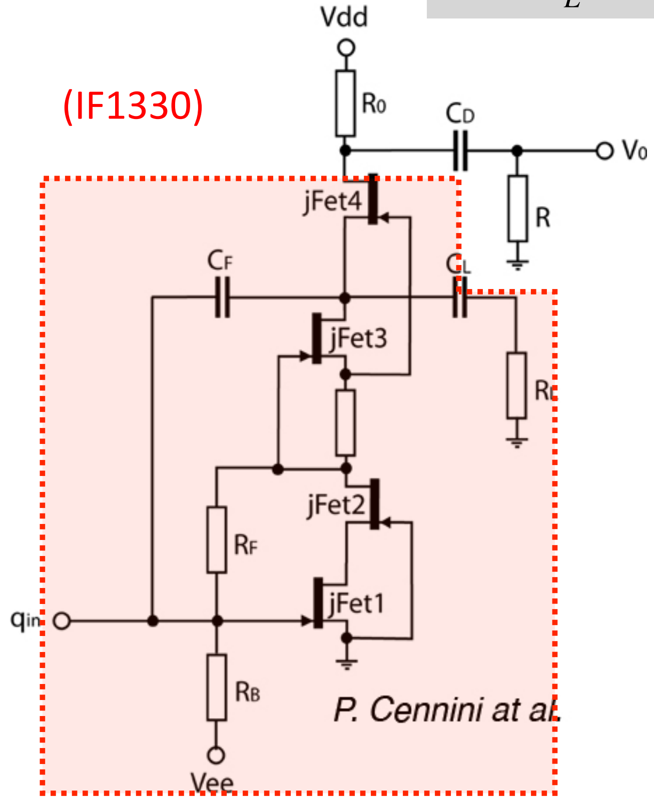
The TOTEM architecture

- Charge Integrator made on Thick Film Hybrid technology with discrete j-FET only
  - Minimum active and passive components
  - Ability to drive long transmission line
  - Reduced power consumption
  - Minimum cable connections
    - Current signal from Positive Power Supply
    - Common Negative polarization
- Characteristics
  - Optimized for low detector capacitance

Sensitivity ≈ 0.45 mV/fC (0.9 µA/fC)
Dynamic range ±1.5 pC
Linearity < 0.5% @ full scale
Input impedance ≈ 420 Ω
Input capacitance ≈ 20 pF
E.N.C. ≈ (390 + 7 x C_D) el
Power consumption ≈ 11 mW

$$V_0 = \frac{R_0}{R_L} * \frac{q_{in}}{C_F}$$

(IF1330)



Electronics in LAr (Pro & Contra)

- Advantages
  - Reduction of input capacitance due to cable absence
  - Reduction of micro-phonic noise (detector = Faraday cage)
  - Improvement of S/N [~ **2.4**] due the **combined effect** of lower [~1.9] Johnson noise and higher [~1.26] g_m @ 87ºK
- Disadvantages
  - Inaccessibility during detector operation
  - Need of careful selection of components, extensive burn-in and temperature cycles before installation to minimize components failure
  - Design architecture and technology restricted by limited choice of active components
  - Limit on power dissipation (< 100 mW/mm^2 to avoid LAr boil-off)

NOT the ICARUS choice (under investigations by other groups)

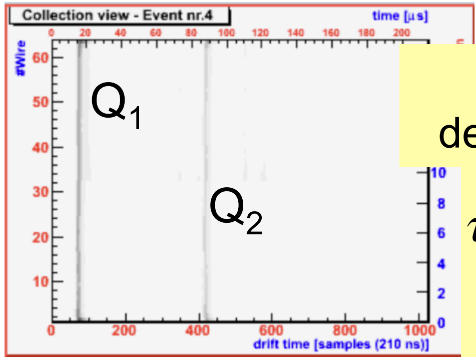
R&D on long drifts

- Full scale measurement of long drift, signal attenuation, effect of diffusion
- High voltage test

ArgonTube @ Bern University

- 5 m drift
- Infrastructure ready
- External dewar delivered
- Detector vessel, inner detector in procurement phase

UV laser ionization in LAr

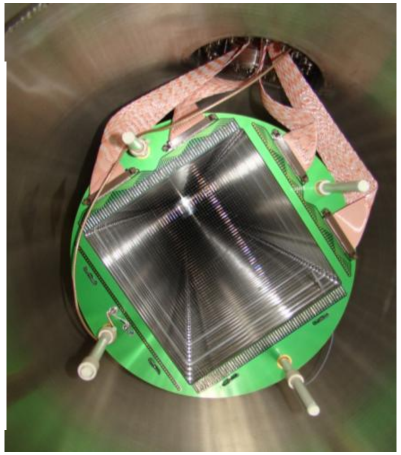


Lifetime determination

$$\tau = \frac{\Delta t}{\ln \frac{Q_1}{Q_2}}$$

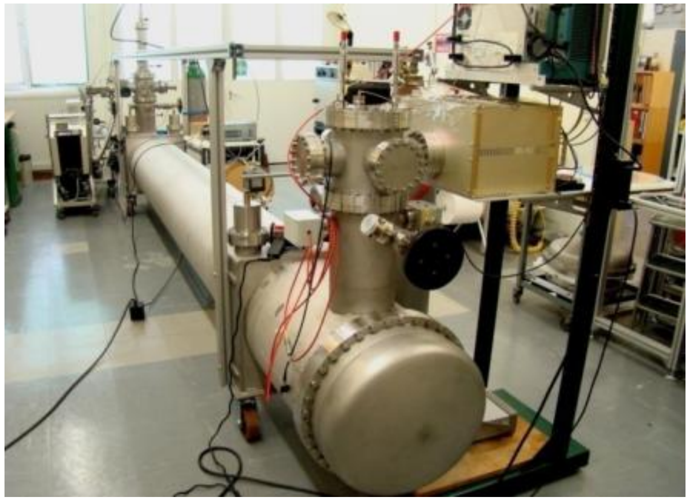
JINST 4 (2009) P07011

LANDD – 5 m drift test @ CERN



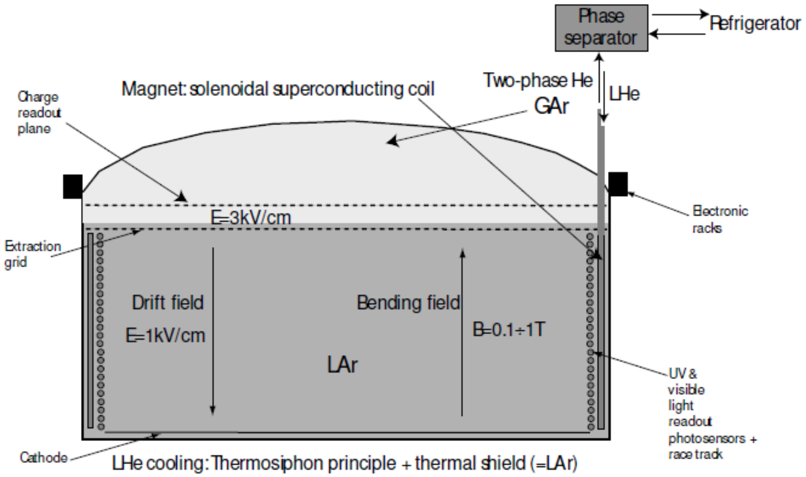
F. Sergiampietri, D.B. Cline

- detector fully assembled
- vacuum debugging
- readout electronics in preparation



R&D on magnetized LAr

A. Ereditato, and A. Rubbia, Nucl Phys B (Proc Suppl) 155 (2006) 233



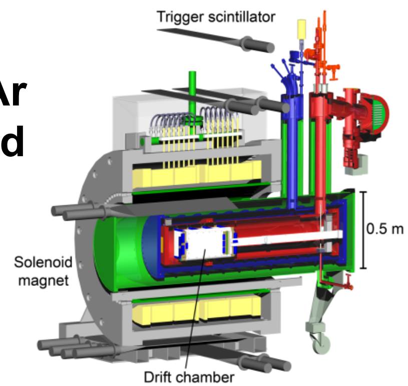
- superconducting solenoid immersed in LAr
  - LHe or HTS superconductor?
- B parallel to E
- low field (B=0.1 T) to measure μ charge
- strong field (B=1 T) to to measure 'e' charge
- need to monitor market of HTS cables

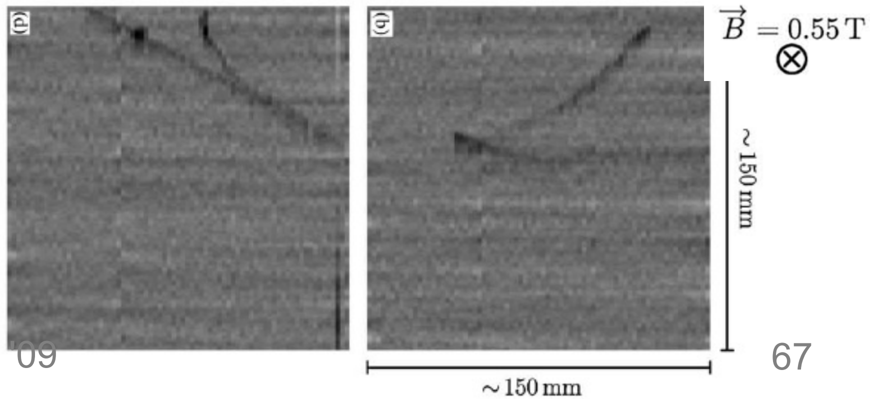
Comparison of superconducting solenoidal magnets. ATLAS column corresponds to the solenoid.

	10 kton LAr	100 kton LAr	ATLAS	CMS
Magnetic induction (T)	0.1/0.4/1.0	0.1/0.4/1.0	2.0	4.0
Solenoid diameter (m)	30	70	2.4	6
Solenoid length (m)	10	20	5.3	12.5
Magnetic volume (m^3)	7700	77000	21	400
Stored magnetic energy (GJ)	0.03/0.5/3	0.3/5/30	0.04	2.7
[illegible]	[illegible]			

First operation of a LAr TPC in a magnetic field @ ETHZ

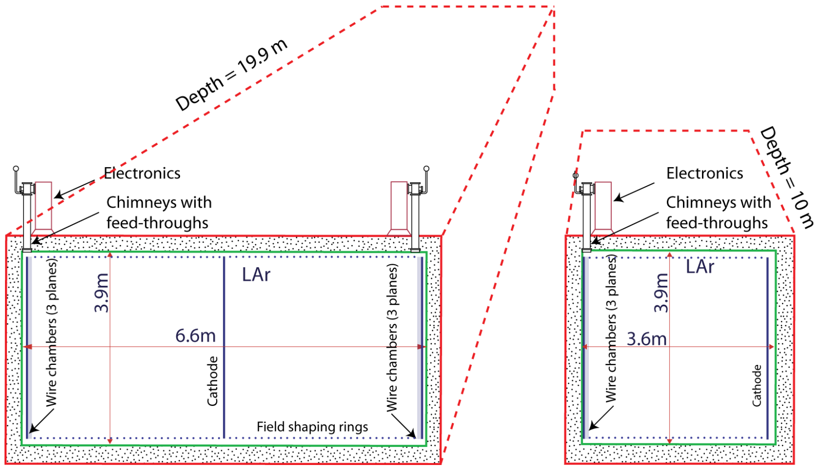
NIM A 555 (2005) 294

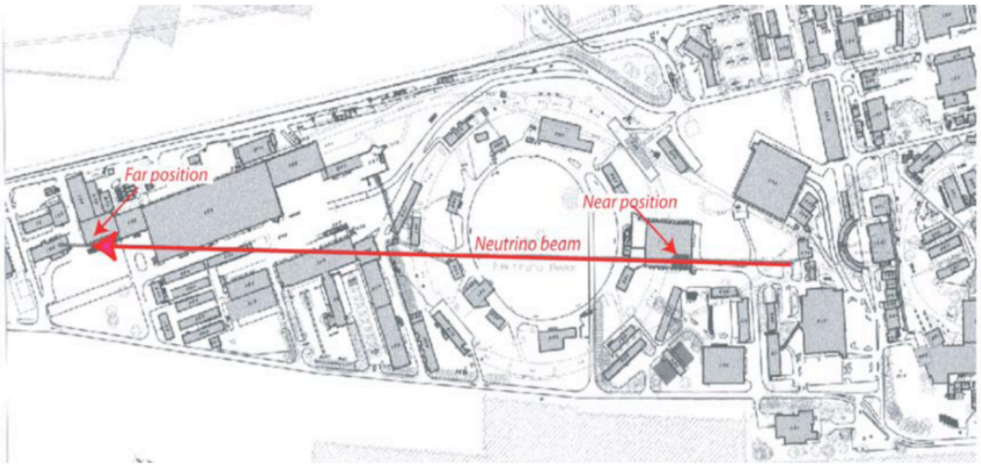




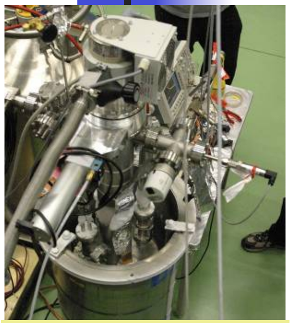
MODULAr Intermediate steps

- ICARUS-like LAr-TPC @ a refurbished CERN-PS neutrino beam (E ~ 1 GeV)
  - High statistics test of LSND/MiniBoone neutrino anomaly:
    - neutrino oscillation? Sterile neutrinos? Neutrino/antineutrino CP violation?
    - Two identical detectors at near (120m - 100 t) and far (870m - 500 t) locations to cancel systematic errors.
  - High precision measurements of neutrino cross-sectiosn in the GeV range
  - Detector performance optimization
  - Test of new construction techniques towards large scale detectors.
- Proposal in preparation, few years construction (beam/detectors > 2013)



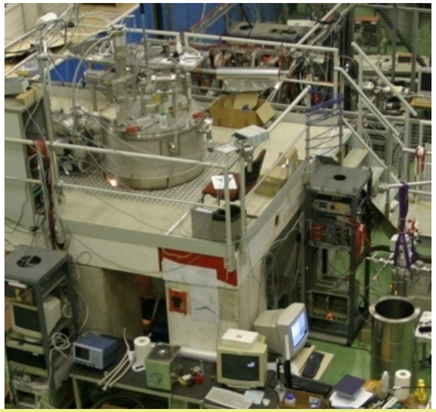


GLACIER roadmap



3 lt @ CERN, 10 lt @ KEK

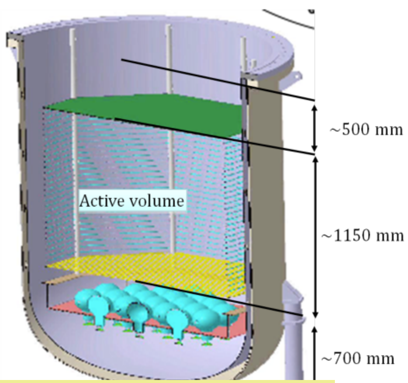
250 lt @ KEK



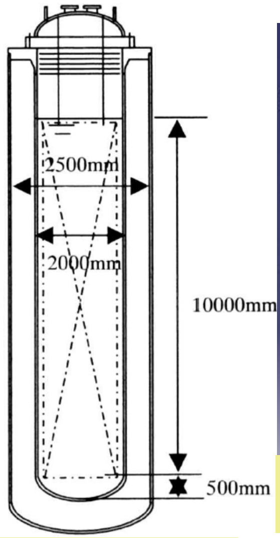
ArDM (RE18) @ CERN

5 m drift under procurement

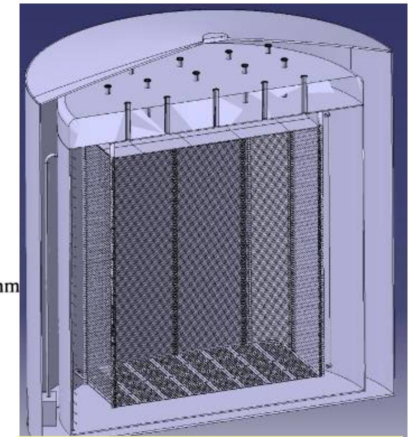
ArgonTube@ Bern



6 m^3 @ CERN (?)



30 m^3 @ KEK

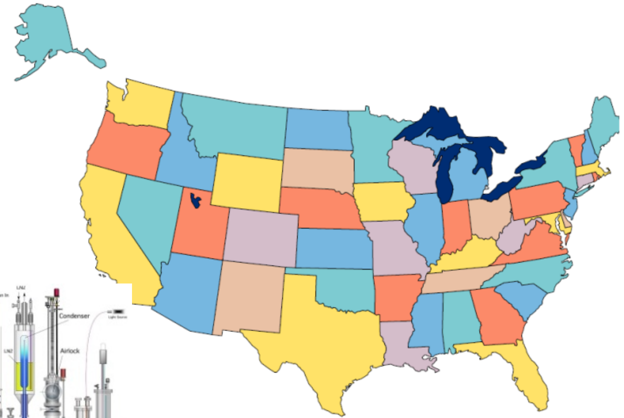


1 kton @ CERN

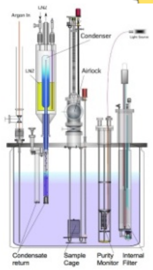
- Electron, neutral pion, charged pion, muon reconstruction
- Electron/π^0 separation
- Calorimetry
- Hadronic secondary interactions
- [+ purity tests in non-evacuated vessel, cold readout electronics, DAQ development, ...]

to be proposed in 2010

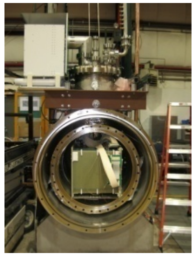
US LAr roadmap



Materials Test Stand, Cosmic Ray Test Stand



R&D	Purity, electronics development



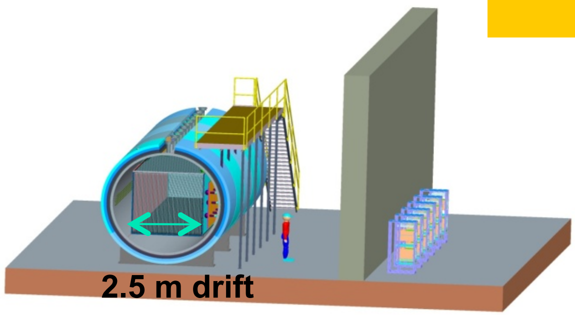
ArgoNeut (0.2t)

R&D	Physics	Underground safety, TPC operation, reconstruction

Liquid Argon Purity Demonstration

R&D	Large tank purity, insulation

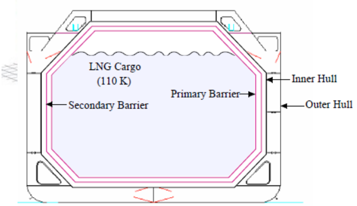
20 ton LAr
no TPC



MicroBooNE (70t fiducial)

R&D	Physics	120°K electronics, large tank purity, insulation

Ship carries up to 200,000 m³ of LNG



LAr at DUSEL (16.7kt + 2 x 16.7kt fiducial)

Physics

Conclusions

- Cryogenic noble liquids and Argon “in primis” have recently regained a strong interest in the scientific community
  - the successful assembly and imminent operation of the T600 LAr detector by the ICARUS Collaboration demonstrate that the technology is mature
- Thepotentiality offered by high granularity imaging and extremely high resolution will significantly contibute to progress in
  - Underground physics (proton decay, solar, supernova, …)
  - Long-baseline, high precision neutrino physics
  - Unambiguous detection of a WIMP galactic recoil signal.
- Currently, we can state safely that :
  - The ICARUS experiment at the Gran Sasso Laboratory is so far the most important milestone for this technology and acts as a full-scale test-bed located in a difficult underground environment.
  - The possible extrapolation to a giant LAr detector, of mass comparable to water Cerenkov counters but with much better resolution, is under active consideration both in Gran Sasso and elsewhere (underground or on surface?)
  - The realization of a large (ultimately tens of of tons) WIMP detector for Dark matter detection is on its way with Argon, Xenon and recently Neon.