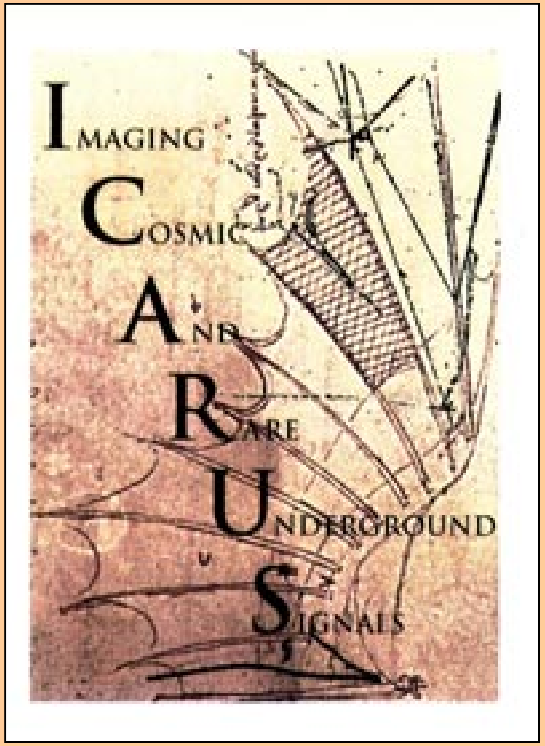
Results from the Technical Run with the First ICARUS T600 Half-Module



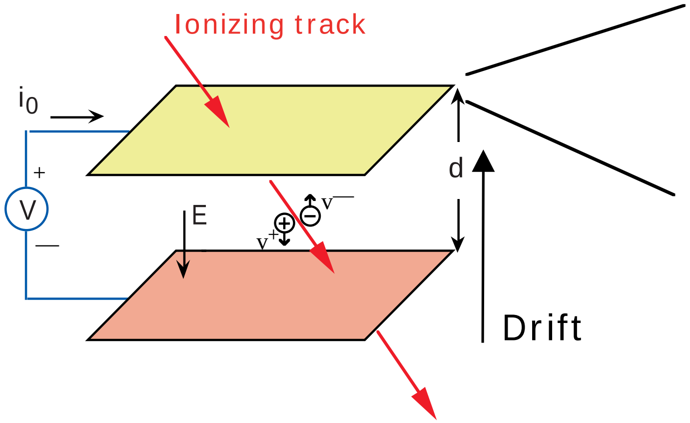
Javier Rico

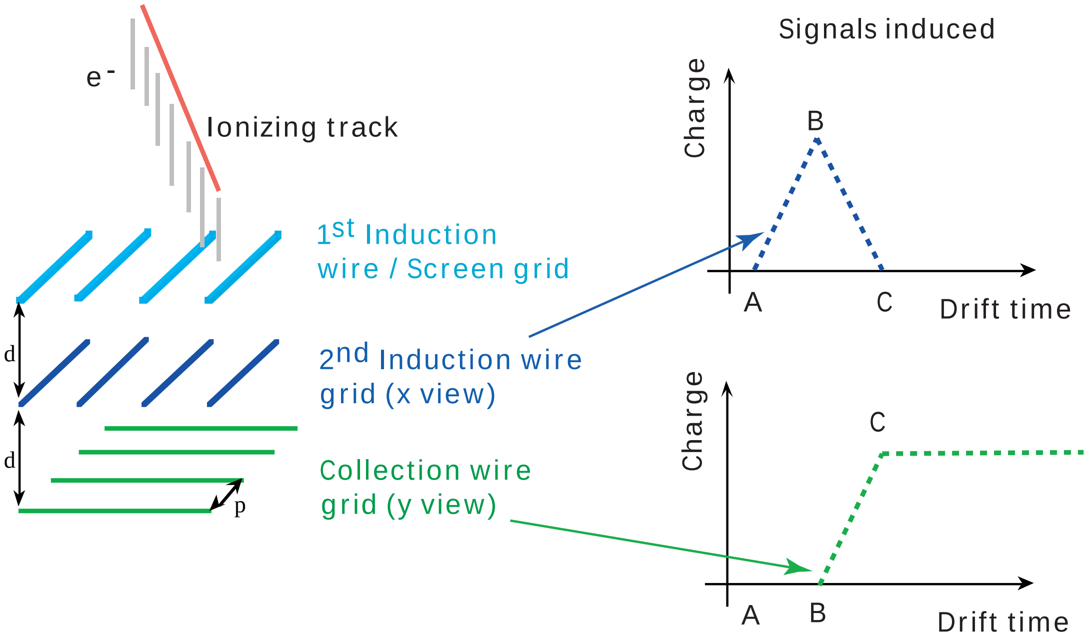
- Detection Technique
- Physics potential
- T600 technical run in Pavia

ETH/UNI Zurich Doktorandenseminar, 10-11 October 2001

Liquid Argon TPC detection principle

★ Ionization electrons can drift over large distances (meters) in a volume of purified liquid Argon under a strong electric field. If a proper readout system is realized it is possible to realize a massive "electronic bubble chamber".





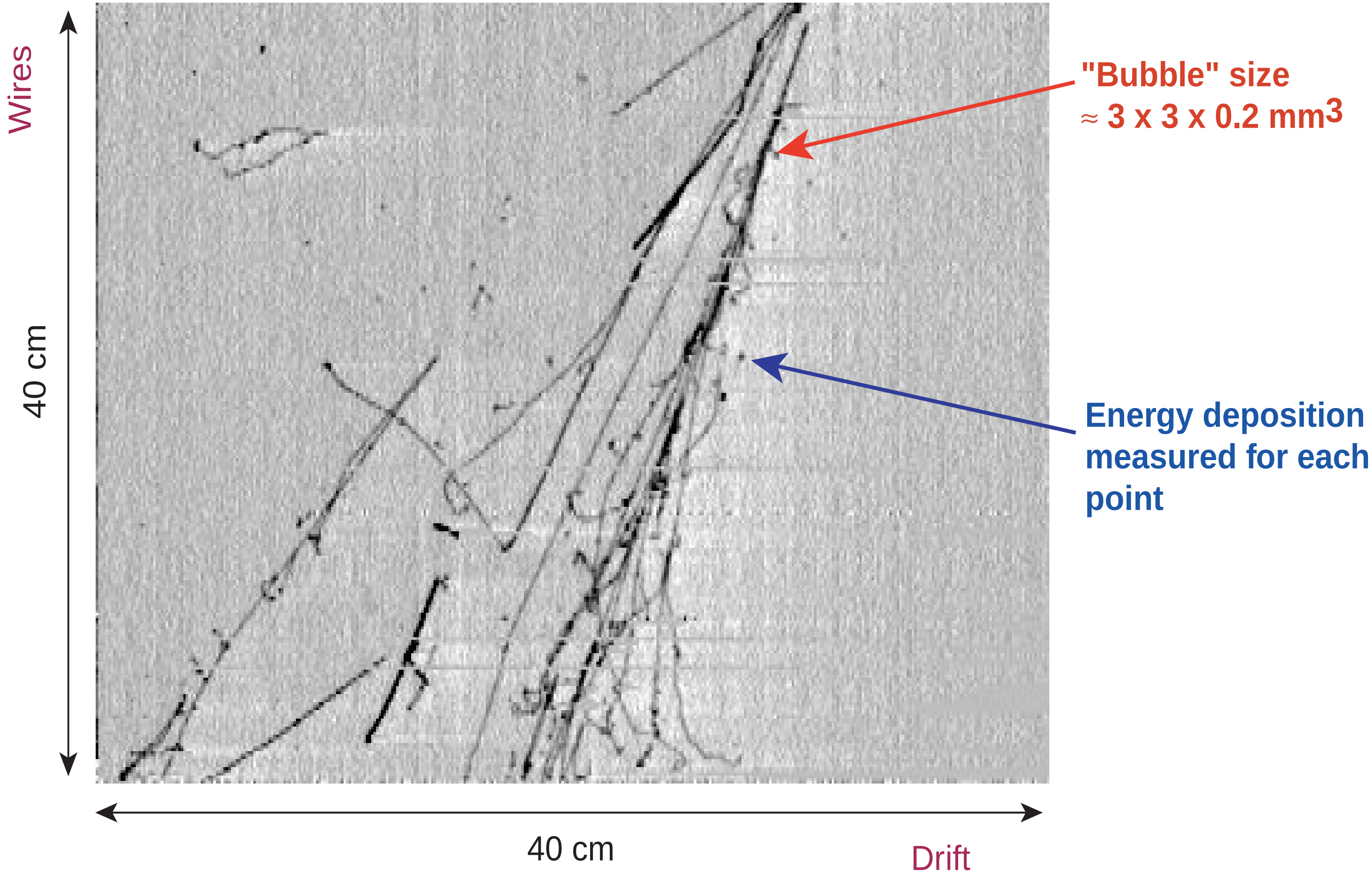
E = 500 V/cm

$I_0 = e(v^+ + v^-)/d$

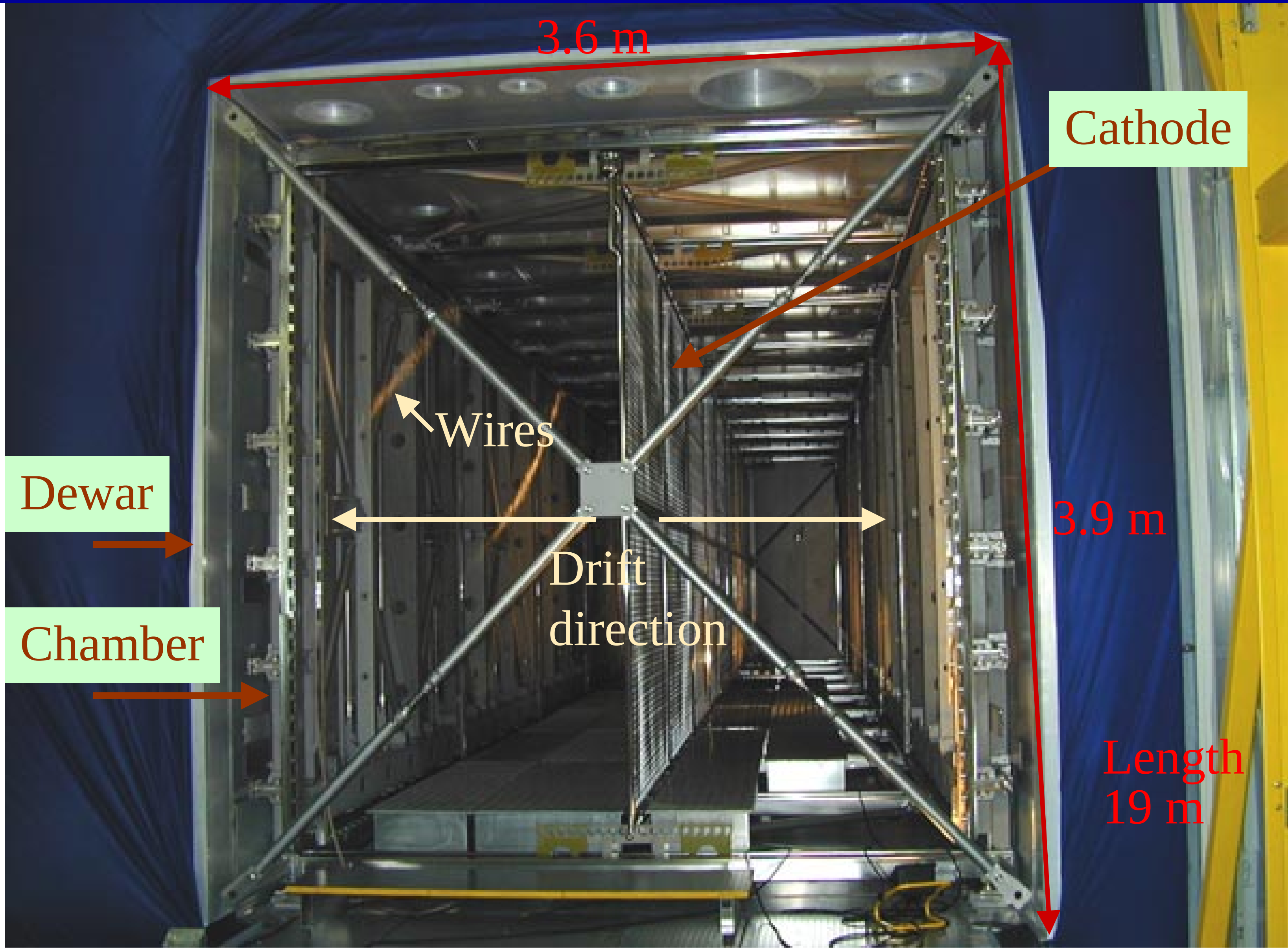
Electron-ion pairs are produced
Electrons give the main contribution to the induced current due to the much larger mobility

A set of wires at the end of the drift give a sampling of the track. No charge multiplication occurs near the wires ➨ electrons can be used to induce signals on subsequent wires planes with different orientations ⇒ 3D imaging

ICARUS liquid argon imaging TPC

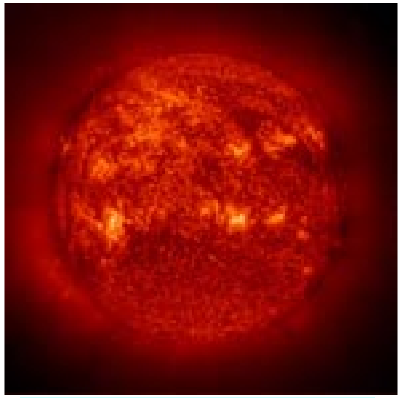


T600 half module internal view

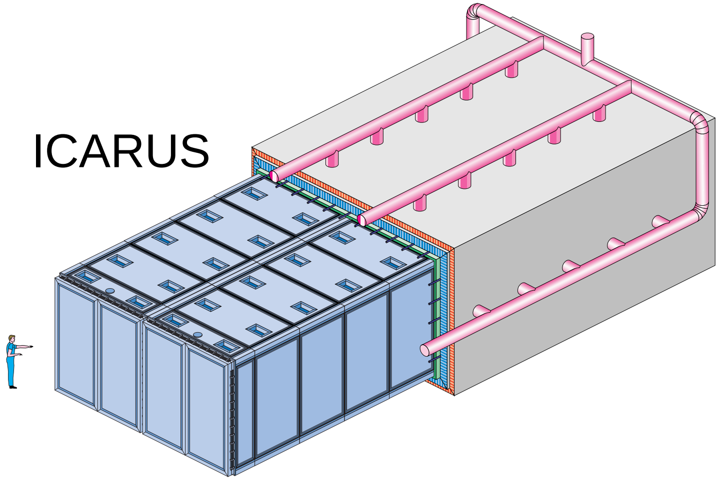


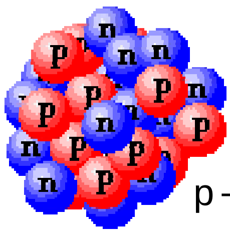
ICARUS Physics program

Supernova neutrinos



Solar neutrinos

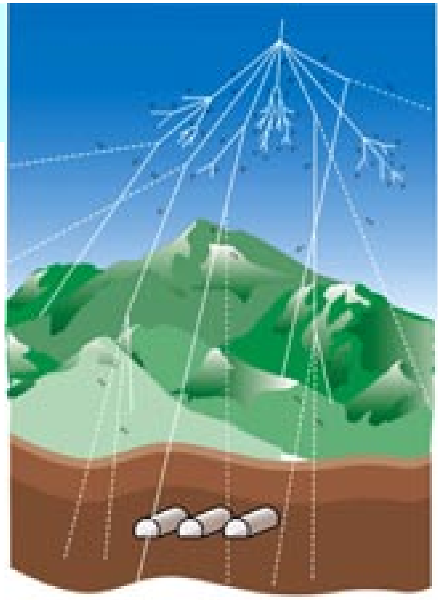




$p \longrightarrow e^{+}+\pi^{0}$

Nucleon stability

Atmospheric neutrinos



Long Baseline neutrinos

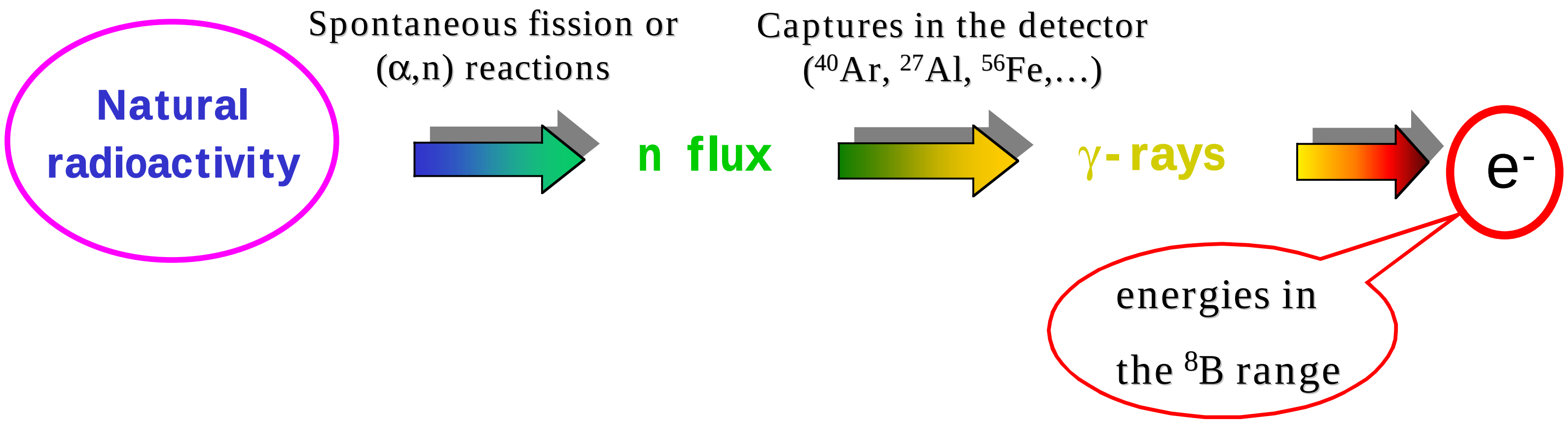
Solar neutrino detection

- Real-time detection of neutrinos through two independent reactions

Elastic scattering on atomic electron	$\nu_x + e^- \rightarrow \nu_x + e^-$
ν absorption on Argon nuclei	$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

Signature: **primary electron**

- Detection threshold: E_{thres} = 5 MeV (^{8}B and *hep* components of the solar spectrum)
- Elastic/absorption events separation (by event multiplicity) ⇒ sensitivity to the oscillations
- Background source:



Solar neutrino rates

Before cuts:

Expected events (no oscillation)		
Process	1 kton x year	5 kton x year
Elastic scattering	792	3960
Absorption events		
Fermi	730	3650
GT	1454	7270
TOTAL	2976	14880
Background	306	1530

Off-line event selection done in terms of **energy of the primary electron** plus:

a) **Elastic:** Angle between electron and solar direction < 25^o (ε=57%)

b) **F+GT:** correlation between multiplicity and energy of the associated Compton electrons (ε_F=70%, ε_{GT}=82%)

All cuts imposed

$E_e > 5$ MeV

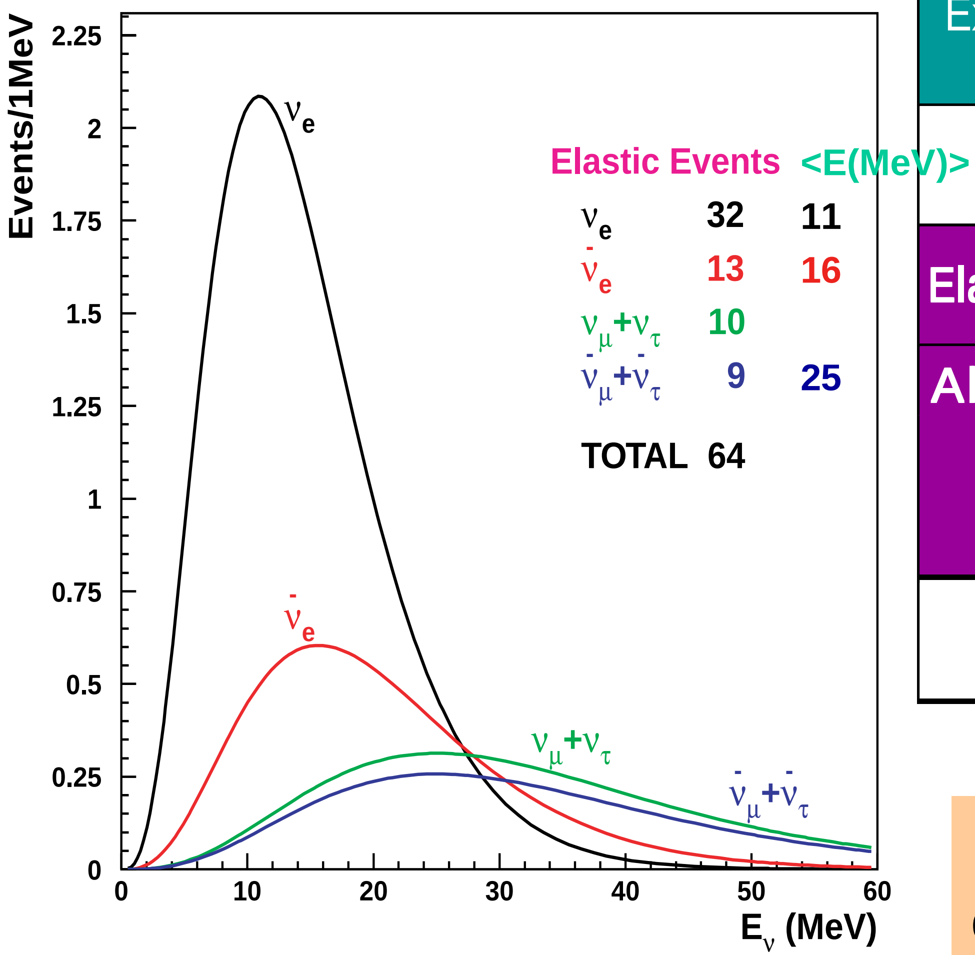
Expected events/year (for a 600 ton detector in case of no oscillations)	
Elastic channel	212
Background	6
Absorption channels	759
Background	26

Nucl Instr. And Methods **A455** (2000) 376

Supernova neutrinos expected rates

- ICARUS can detect neutrinos coming from stellar collapses in our Galaxy via the absorption and elastic events

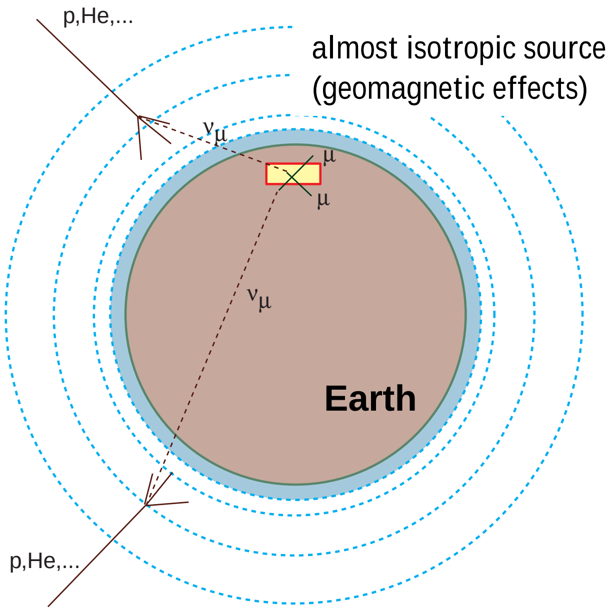
Supernova neutrino rates in 5 KTON ICARUS



Expected events from a stellar collapse ocurred at 10 kpc		
Process	600 ton	5 kton
Elastic scattering	7	64
Absorption events		
Fermi	14	120
GT	28	240
TOTAL	**49**	**424**

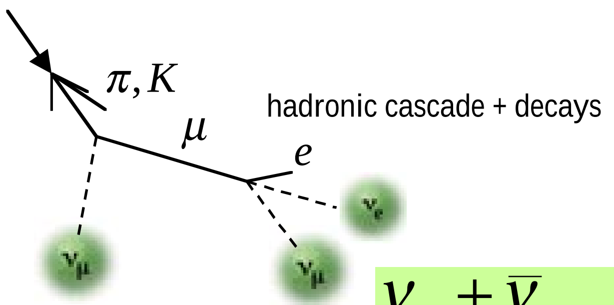
Supernova direction determined within 9º (5 kton)

Atmospheric neutrinos



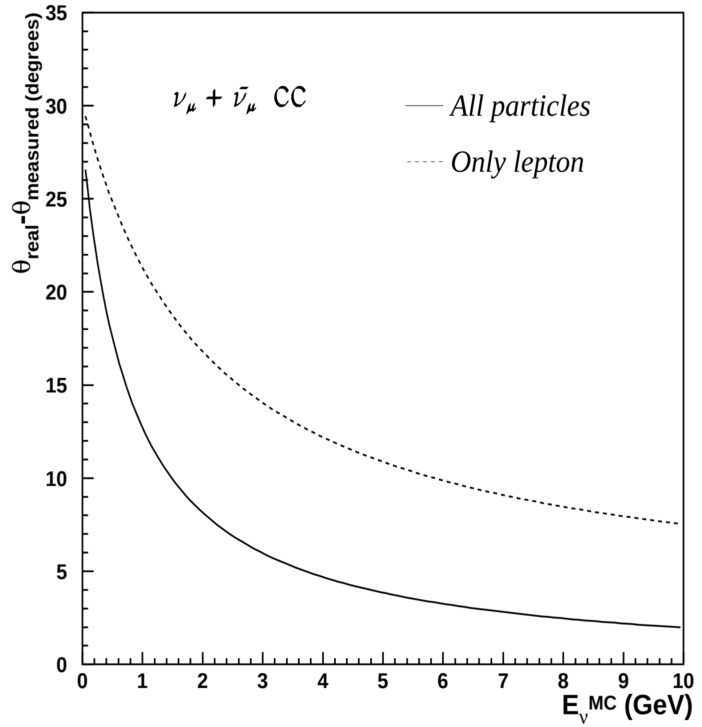
E_ν : 0.1 to 100 GeV

~200 event/kton/year



$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \approx 2$$

✻Complicated final events with multi-pion products will be completely analyzed and reconstructed ⇒ **Zenith angle reconstruction significantly improved!**



✻Events can be fully reconstructed up to kinematics production threshold (50% of the total predicted rate has P_{lepton} < 400 MeV) ⇒ **Fundamental contribution to the understanding of the low energy part of the atmospheric neutrino spectrum**

Rates for upward/downward events

For a 2 kton x year exposure, we expect to measure a
significant deficit of upward-going muon-like events

	2 kton×year				
		Δm^2_{23} (eV^2)			
	No osci	5×10^{-4}	1×10^{-3}	3.5×10^{-3}	5×10^{-3}
Muon-like	270 ± 16	206 ± 14	198 ± 14	188 ± 14	182 ± 13
Downward	102 ± 10	102 ± 10	102 ± 10	98 ± 10	95 ± 10
Upward	94 ± 10	46 ± 7	46 ± 7	47 ± 7	49 ± 7
Electron-like	152 ± 12	152 ± 12	152 ± 12	152 ± 12	152 ± 12
Downward	56 ± 7	56 ± 7	56 ± 7	56 ± 7	56 ± 7
Upward	48 ± 7	48 ± 7	48 ± 7	48 ± 7	48 ± 7

Confirmation of ν_μ disappearance

Tau appearance experiment

- Analysis of the electron sample
  - Exploit the small intrinsic ν_e contamination of the beam (0.8% of ν_μ CC)
  - Exploit the unique e/π^0 separation

$\nu_\mu \to \nu_\tau$

$$\nu_\tau + \mathbf{N} \to \tau + \mathbf{jet};\ \tau \to e\nu\nu$$

Charged current (CC) Br ≈ 18%

Before cuts (5 years 5 T600):

$262\ \nu_e\ CC$

$49\ \nu_\tau\ CC, \tau \to e$

$\Delta m^2 = 3\times 10^{-3} eV^2$

Background:

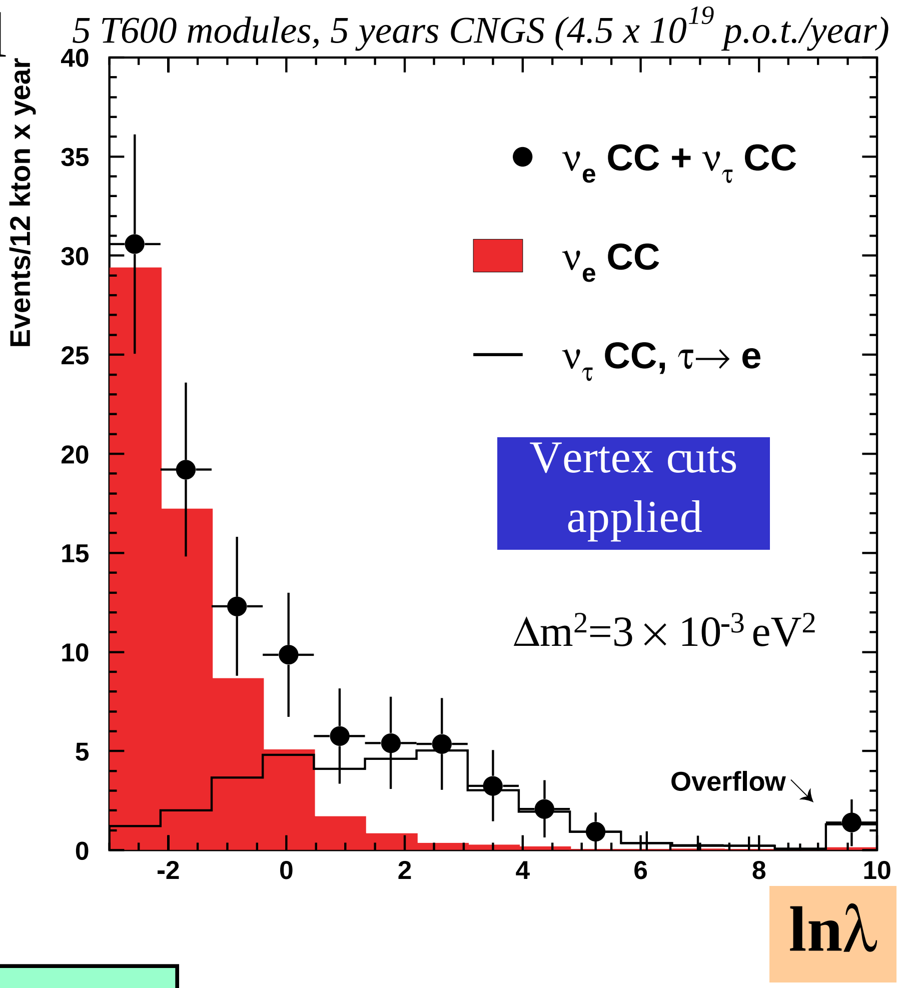
$$\nu_e + \mathbf{N} \to \mathbf{e} + \mathbf{jet}$$

Charged current (CC)

Statistical excess visible before cuts ⇒ this is the main reason for performing this experiment at long baseline !

$\tau \rightarrow e$ search: 3D likelihood

- Analysis based on 3 dimensional likelihood
  - $E_{visible}$, P_T^{miss}, $\rho_l \equiv P_T^{lep}/(P_T^{lep+} P_T^{had} + P_T^{miss})$
  - **Exploit correlation between variables**
  - Two functions built:
    - L_S ([Evisible, P_T^{miss}, ρ_l]) (signal)
    - L_B ([Evisible, P_T^{miss}, ρ_l]) (ν_e CC background)
  - Discrimination given by



$$\ln\lambda \equiv L([\text{Evisible}, P_T^{miss}, \rho_l]) = L_S / L_B$$

$\nu_\mu \rightarrow \nu_\tau$ appearance search summary

5 T600 modules

(2.35 kton active LAr)

5 year CNGS running

(2.25 x 10^{20} p.o.t.)

τ decay mode	Signal $\Delta m^2 = 1.6 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 2.5 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 3.0 \times 10^{-3}$ eV^2	Signal $\Delta m^2 = 4.0 \times 10^{-3}$ eV^2	BG
$\tau \rightarrow e$	3.7	9	13	23	0.7
$\tau \rightarrow \rho$ DIS	0.6	1.5	2.2	3.9	< 0.1
$\tau \rightarrow \rho$ QE	0.6	1.4	2.0	3.6	< 0.1
Total	**4.9**	**11.9**	**17.2**	**30.5**	**0.7**

Super-Kamiokande: $1.6 < \Delta m^2 < 4.0$ at 90% C.L.

Nucleon decay search

Thanks to excellent tracking and particle *id* capabilities

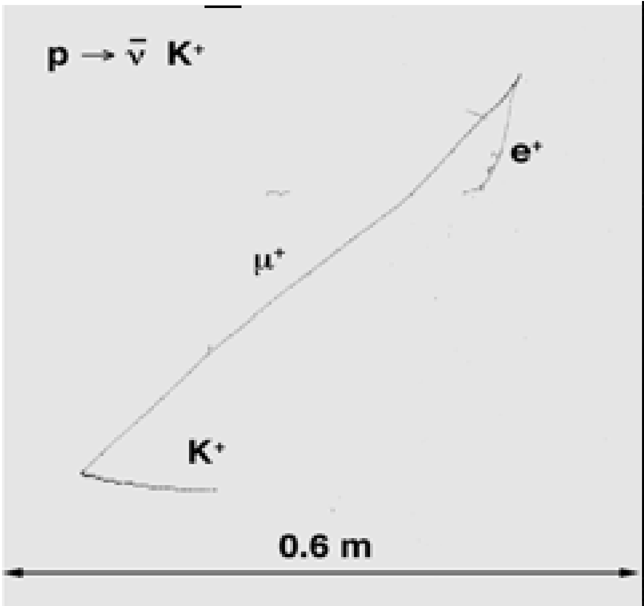
LAr unique tool

Extremely efficient background rejection

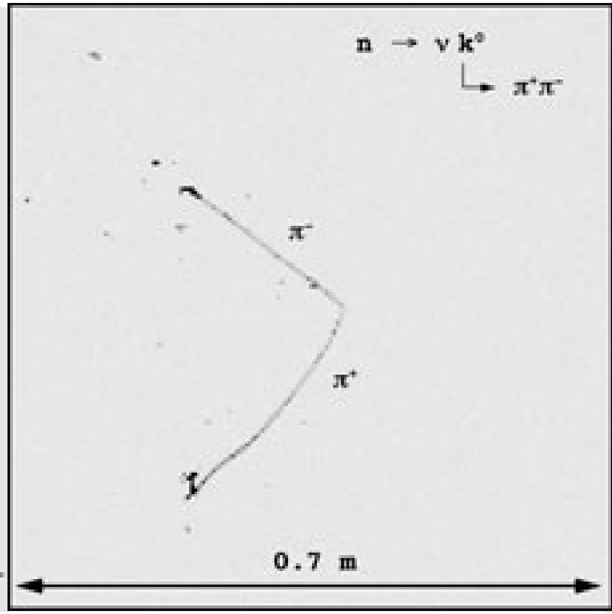
High detection efficiency

Bias-free, fully exclusive channel searches!

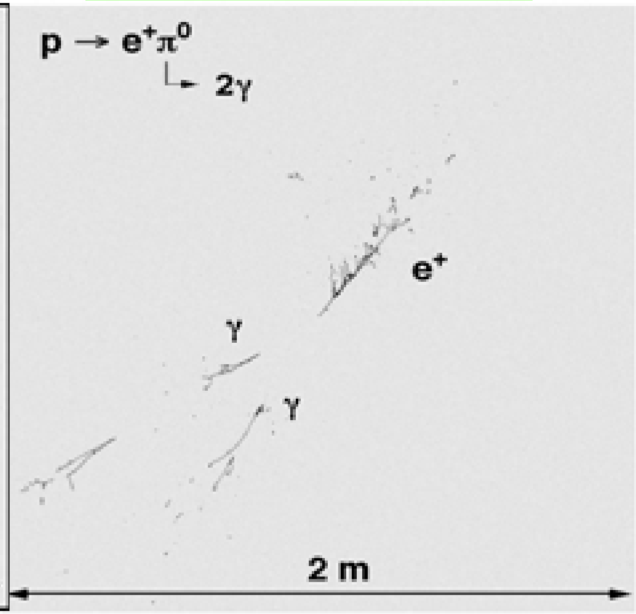
$p \rightarrow \nu K^+$ decay



$n \rightarrow \nu K^0$ decay



$p \rightarrow e^+ \pi^0$ decay



5 kTons detector ⇨ 3×10^{33} nucleons $\Rightarrow$ τ_p (10^{32} years) > $6 \times T(yr) \times \varepsilon$ @ 90 C.L.

$p \to e^+ \pi^0$ and $p \to K^+ \nu$ decay kinematics

Exposure: 1000 kton x year

Nuclear effects: pion absorption and rescattering included (FLUKA)

Exclusive Channel Cuts	$p \to e^+ \pi^0$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One π^0	54.00%	6610	2137	15264	5808	8089	3100
One electron	54.00%	6577	2127	20	0	0	0
No $\pi^\pm$, No protons	51.50%	1234	668	2	0	0	0
Total Momentum < 0.4 GeV	46.85%	461	128	0	0	0	0
0.93 GeV < Total E < 0.97 GeV	45.65%	0	0	0	0	0	0

≈ 45% π^0 absorbed in Ar nucleus

Cuts	$p \to K^+ \bar{\nu}$	ν_e CC	$\bar{\nu}_e$ CC	ν_μ CC	$\bar{\nu}_\mu$ CC	ν NC	$\bar{\nu}$ NC
One Kaon	97.30%	310	59	921	214	370	104
No π^0	97.15%	161	30	462	107	197	51
No electrons	97.15%	0	0	455	107	197	51
No muons	97.15%	0	0	0	0	197	51
No charged pions	97.15%	0	0	0	0	109	22
Total Energy < 0.8 GeV	97.15%	0	0	0	0	0	0

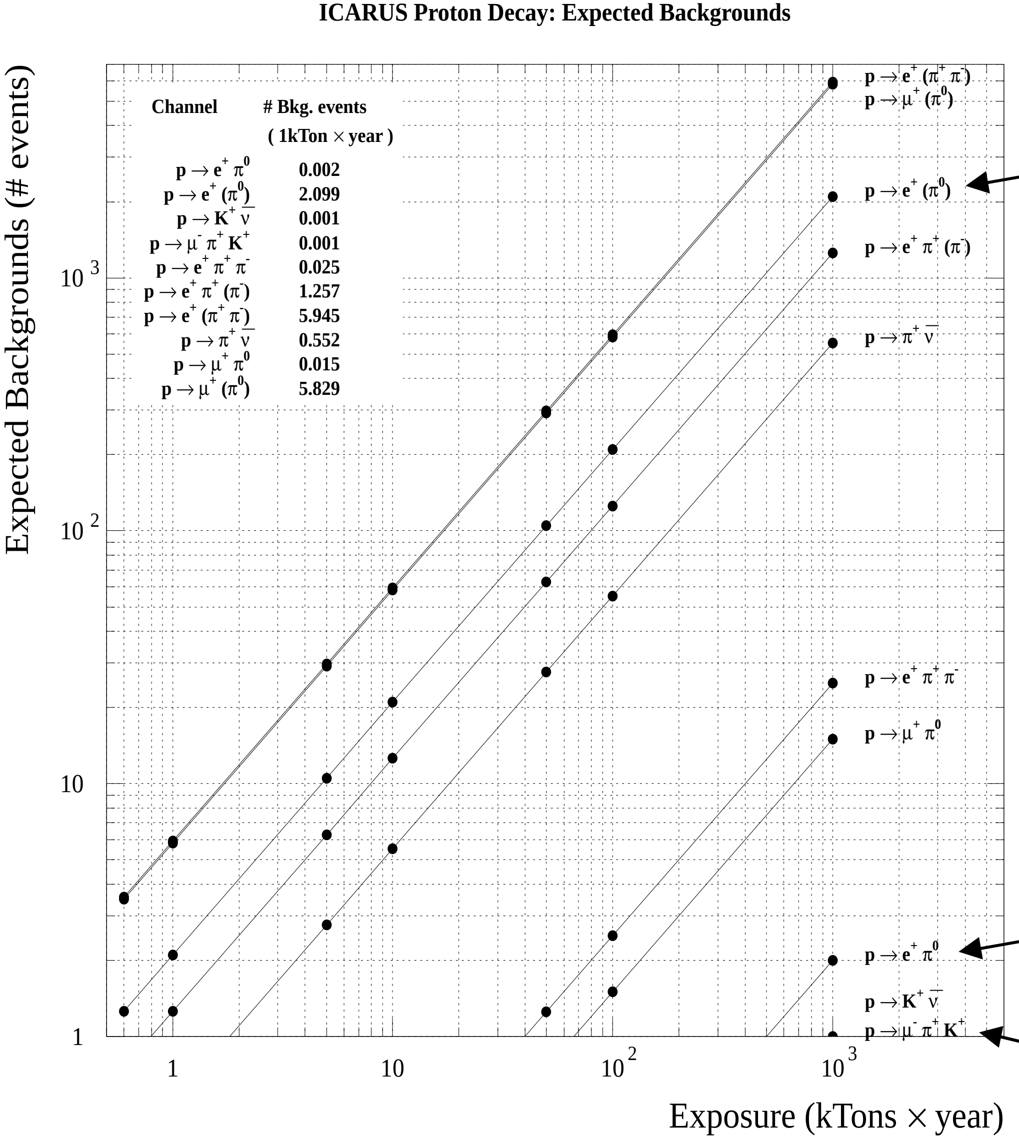
We see the kaon!

5 kTon x year

$$\tau_p (p \to e^+ \pi^0) > 2.5 \times 10^{32} \text{ yrs}$$
$$\tau_p (p \to K^+ \bar{\nu}) > 5 \times 10^{32} \text{ yrs}$$

Background free !!

Proton decay: expected backgrounds vs channel



$p \rightarrow e^+X$

$p \rightarrow e^+\pi^0$

$p \rightarrow K^+\nu$

Extremely good exclusive signal signatures

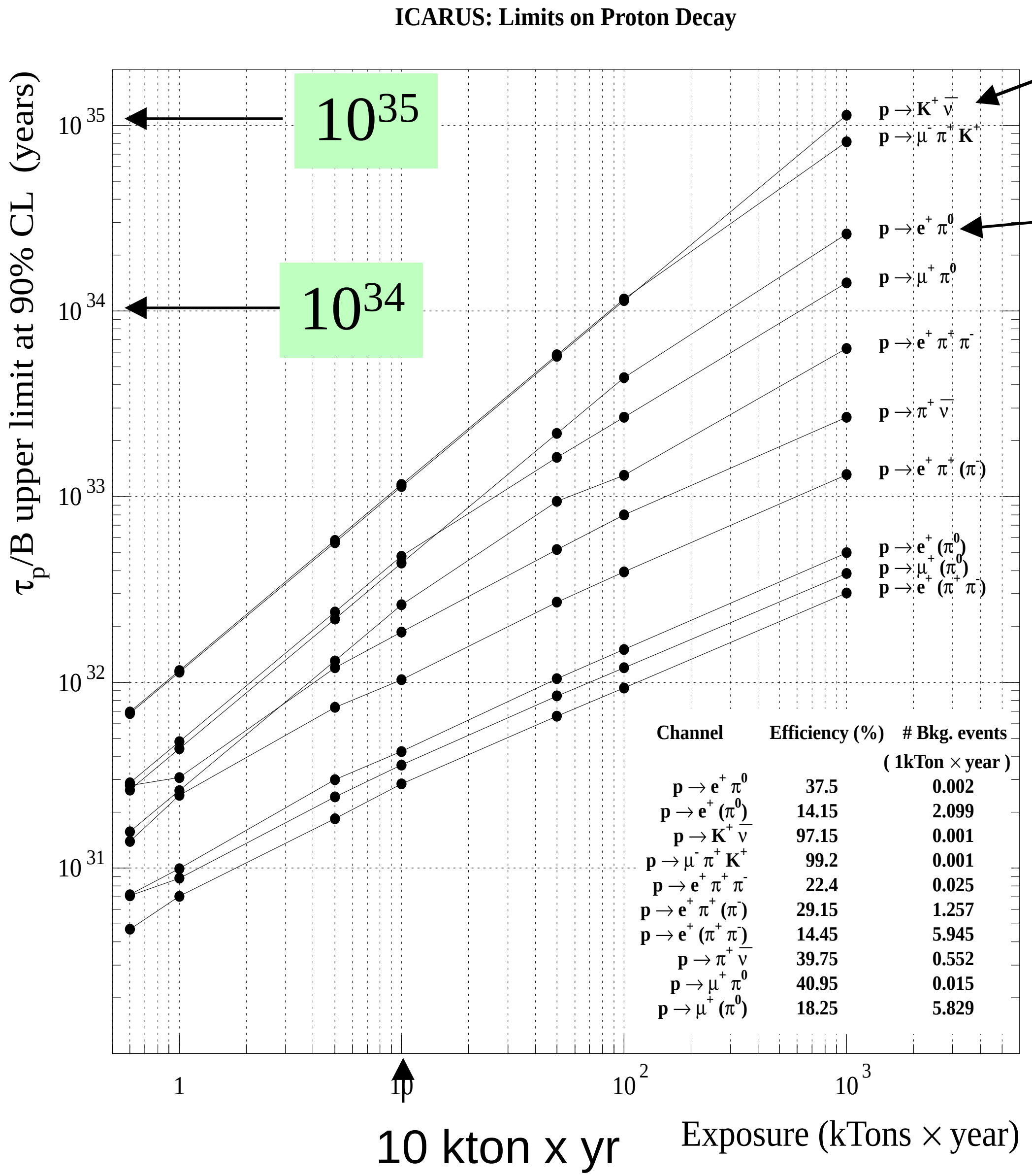
$\Rightarrow$ Excellent background rejection

Discovery with a single event!

↑1 Mton x yr

Nuclear effects in backgrounds: fully embedded in FLUKA nuclear model

Sensitivity vs exposure



Channel	Efficiency (%)	# Bkg. events (1kTon × year)
$p \to e^+ \pi^0$	37.5	0.002
$p \to e^+ (\pi^0)$	14.15	2.099
$p \to K^+ \bar{\nu}$	97.15	0.001
$p \to \mu^- \pi^+ K^+$	99.2	0.001
$p \to e^+ \pi^+ \pi^-$	22.4	0.025
$p \to e^+ \pi^+ (\pi^-)$	29.15	1.257
$p \to e^+ (\pi^+ \pi^-)$	14.45	5.945
$p \to \pi^+ \bar{\nu}$	39.75	0.552
$p \to \mu^+ \pi^0$	40.95	0.015
$p \to \mu^+ (\pi^0)$	18.25	5.829

$p \to K^+ \nu$

$p \to e^+ \pi^0$

Extremely good exclusive signal signatures

$\Rightarrow$ Excellent background rejection

Discovery with a single event!

Nuclear effects in signal: fully embedded in FLUKA nuclear model

ICARUS: a graded strategy

After several years of R&D and prototyping, the ICARUS collaboration has built and **FULLY OPERATED** the first **600 ton module** (T600), which will be installed in the Gran Sasso in the year 2002.

Lab activities:

Small-scale prototypes (3 tons, 50 l) → **15 ton** → **T600** (2x300 ton) ⇢ **?**

We are here!

Cooperation with specialized industries:

Air Liquide: Cryostat and Argon purification
BREME Tecnica: internal detector mechanics
CAEN for readout electronics

Mounted at Pavia from March 2000 to March 2001

Full test run from April to August 2001

T600: internal frame assembly

T600: slow control sensor installation

T600: wires installation

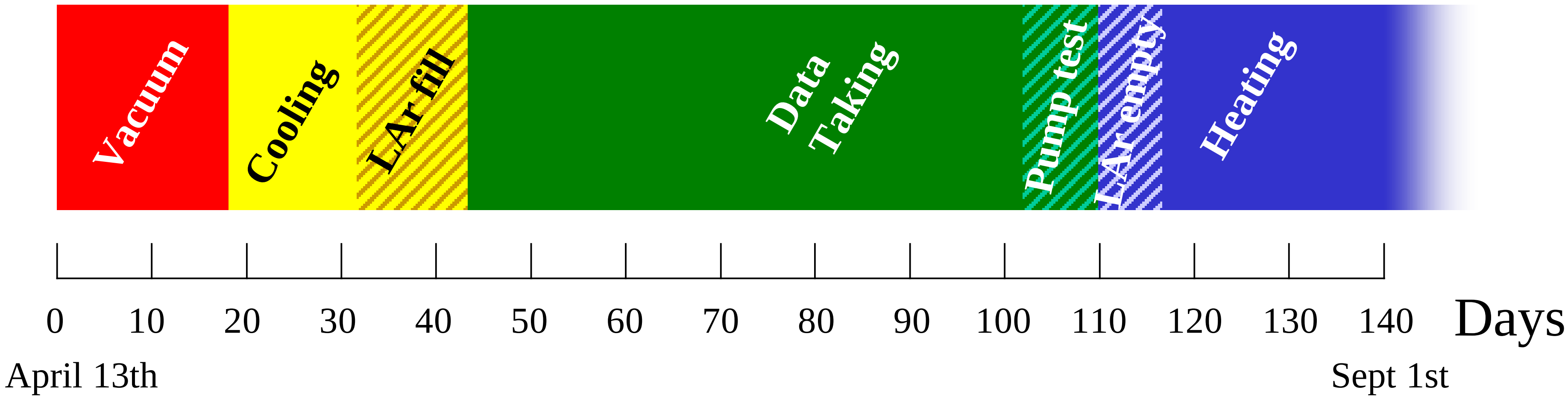
T600 test run program (I)

- Vacuum : Leak rates and final vacuum level
- Cryogenics
  - Cool down speed
  - LN_2 consumption rates
  - Temperature uniformity
  - Cryostat walls deformation (under vacuum and after filling)
  - Pressure control
  - System stability (possible failures and relative consequences)
- Purification
  - Purity during and after filling
  - Filling speed
  - Gas and liquid recirculation rates
  - Final purity measurement and stability check (with purity monitors and C.R. tracks)
- Mechanics
  - Tensioning system movements during the cool down
  - Wires alignment (using C.R. tracks)

T600 test run program (II)

- HV system
  - Max drift field
  - Check field uniformity (using C.R. tracks)
- LV system
  - Check signals behavior (shapes).
  - System stability
- A.L. control system
  - Remote, Alarms handling
- Slow Control system (including HV control)
  - Remote, alarms handling
  - Performance measurements (efficiency, volume coverage, rates)
  - Flexibility
- Software
  - Data handling & reconstruction
  - Event Display
  - Analysis tools test

T600 test run main phases



Vacuum:	**18 days**
Cooling:	**24 days**
Filling:	**10 days**
Data taking:	**68 days**
Emptying:	**7 days**
Heating:	**~ 30 days**

Event size:
≈ 100 Mbytes/chamber
Recorded data:
27700 events
≈ 5 Tbytes

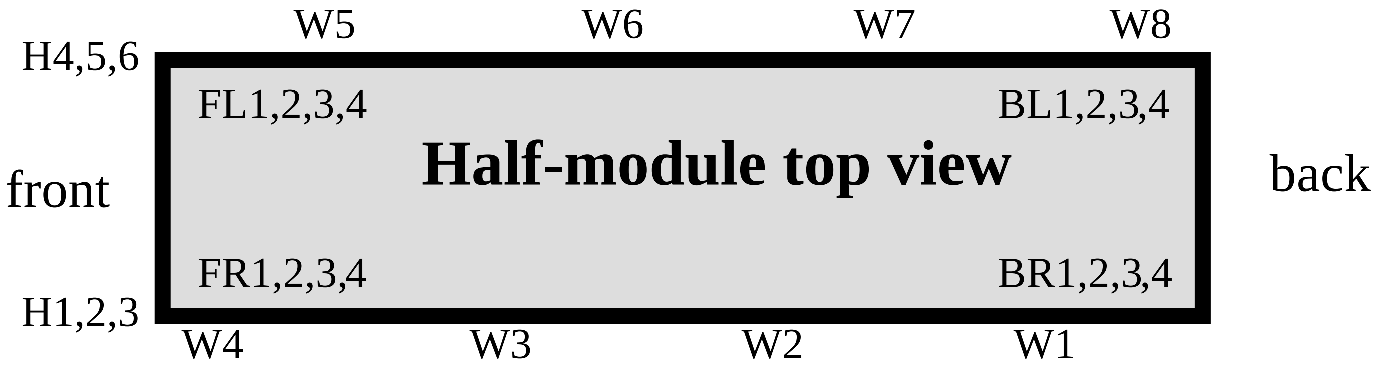
Slow Control: summary of sensors

• 16 LAr **level meters** to monitor the LAr filling of the cryostat (FLn, FRn, BLn, BRn, with n=1,…, 4).

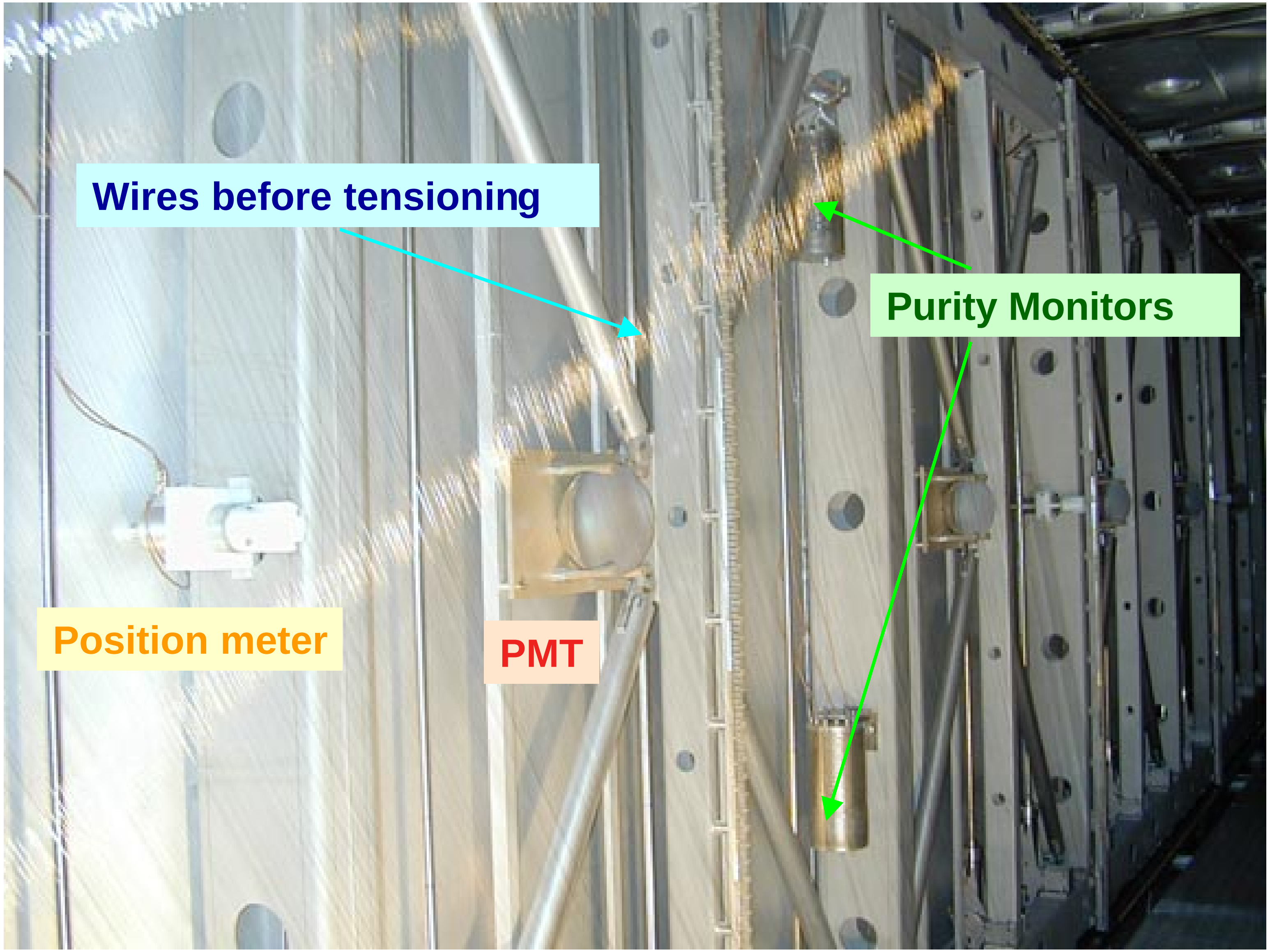
• 8 **position meters** to measure the inward an outward movement of the cryostat **walls** during the pumping, leak test and filling with LAr (Wn, with n=1,…,8)

• 7 **position meters** to measure the movement of the springs attached to the **wires** (Hn with n=1,…,6 for the horizontal springs, and V1 for the vertical spring)

• 30 internal + 13 external platinum resistors (**Pt1000**) for the temperature measurement.



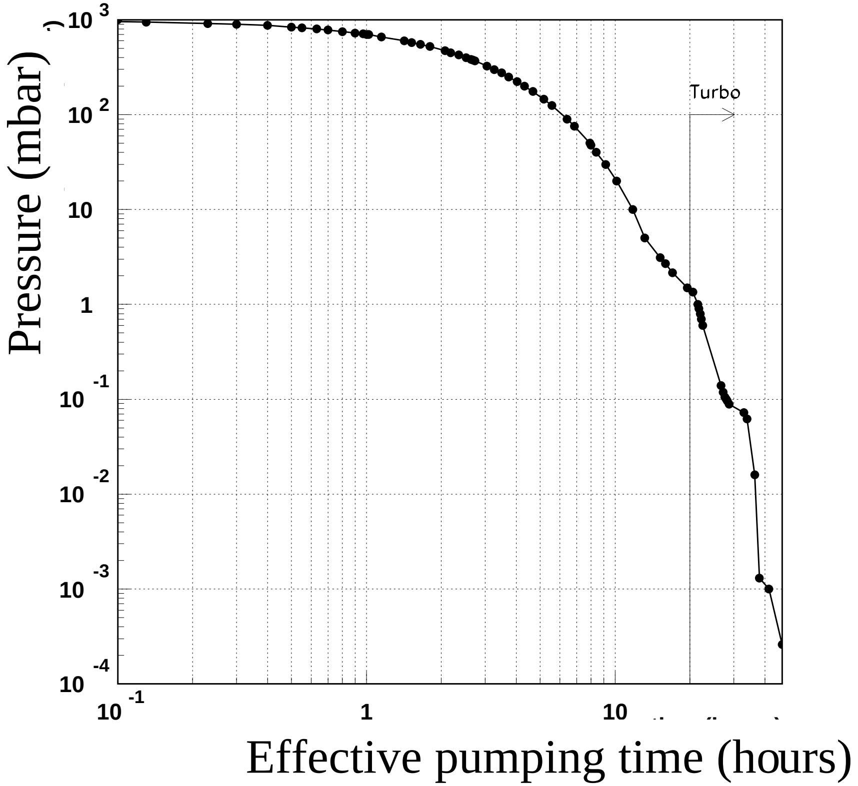
T600: some instrumentation

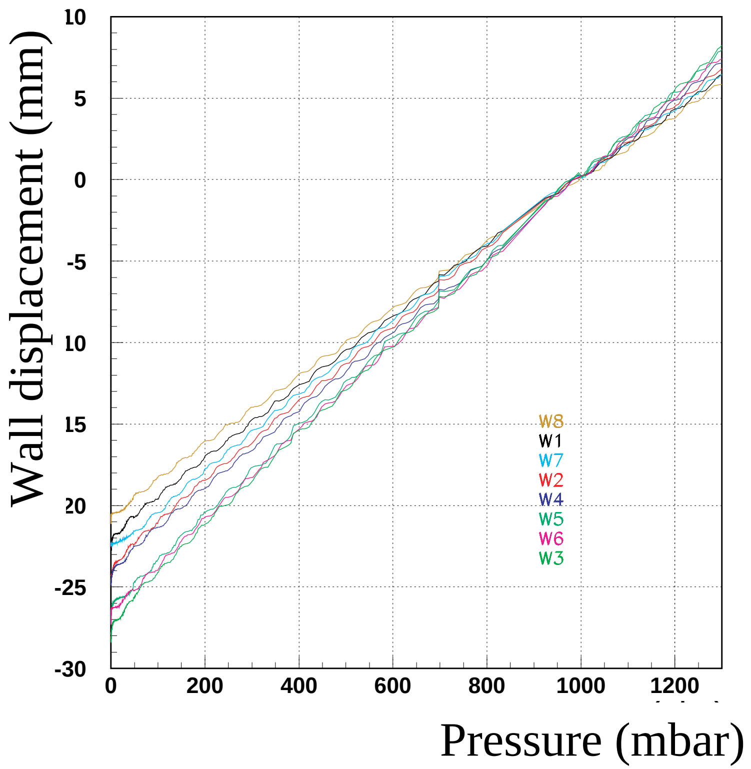


LAr level meters

Vacuum phase

The cryostat is **pumped to vacuum** (~10^{-4} mbar) in order to **clean** it of any impurity **before filling** it with LAr.

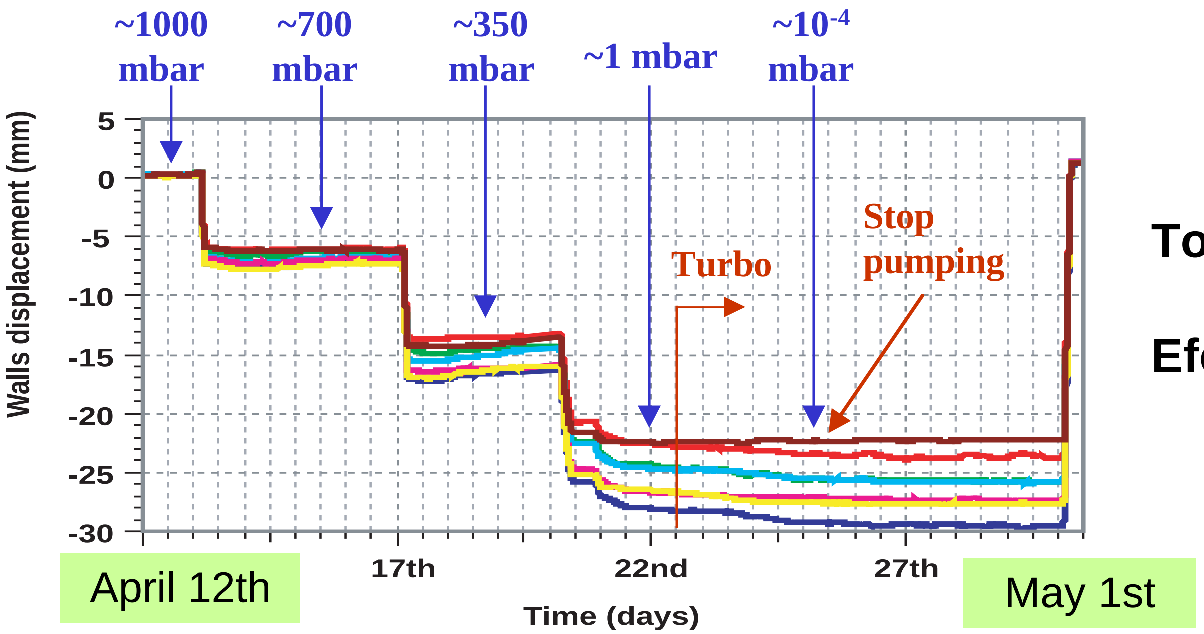




Pressure decreases linearly with time in the absence of leaks

Walls move linearly with pressure
Slope: 21 to 28 μm/mbar

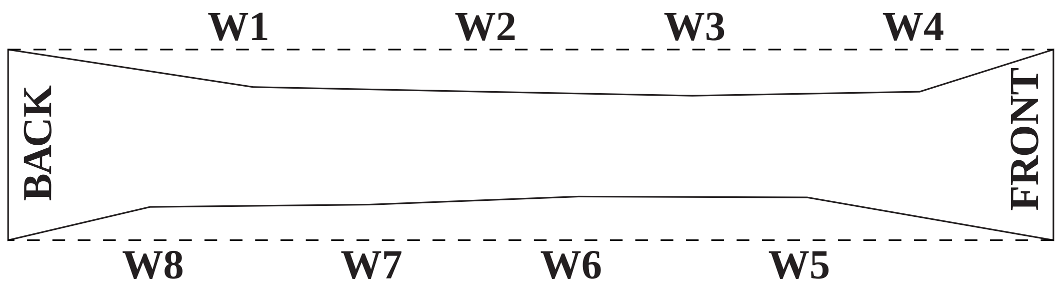
Walls movement during vacuum



Total pumping time: 12 days.

Efective pumping time: 47 hours.

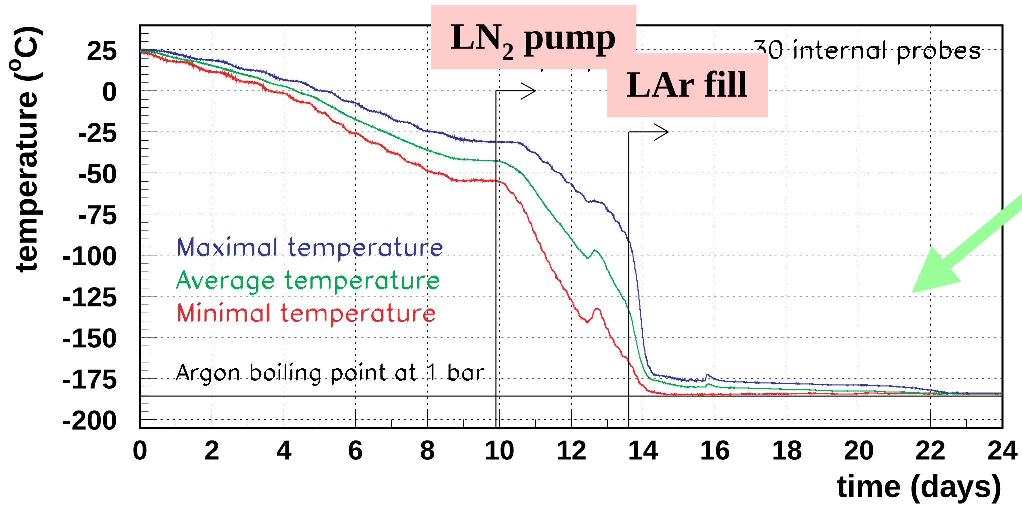
Maximal deformation:



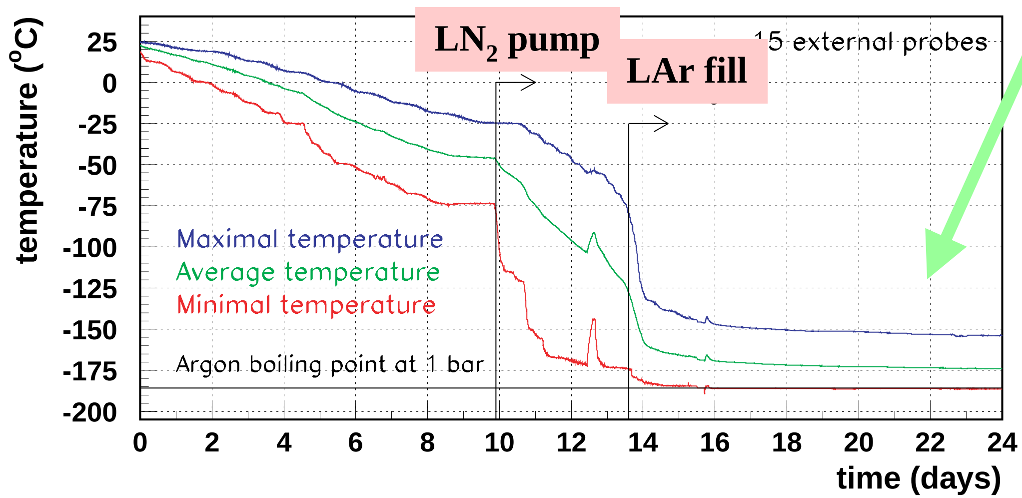
W1…8: measuring points

Deformation magnified

Cooling down of the cryostat



Internal temperature

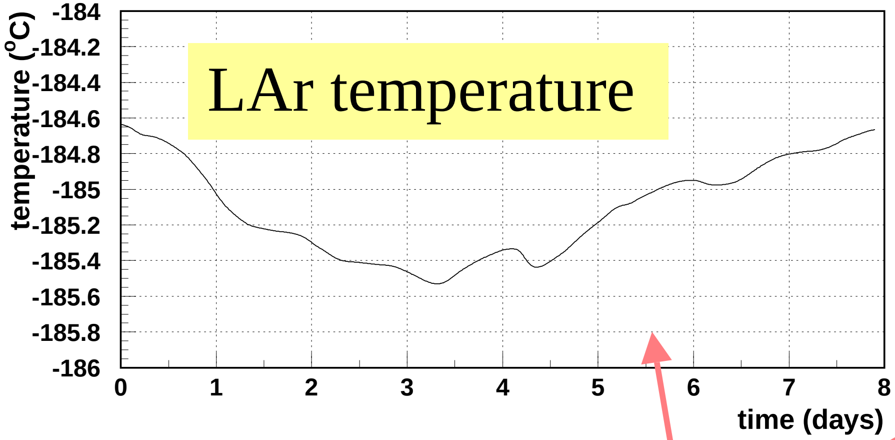


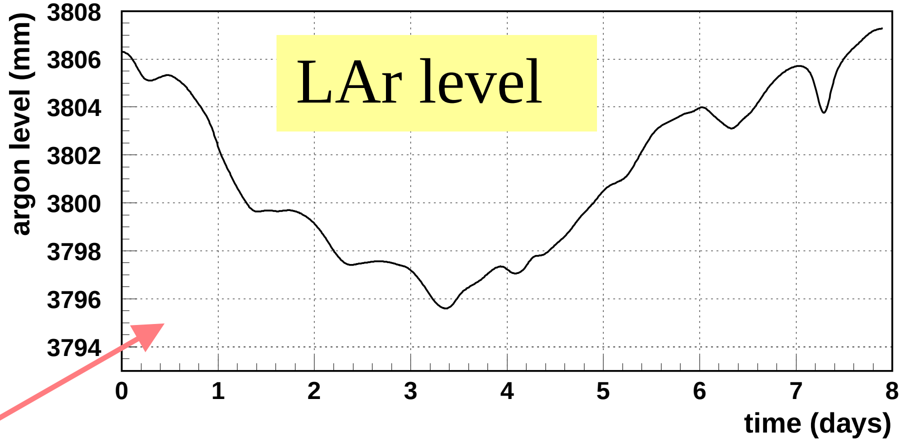
External temperature

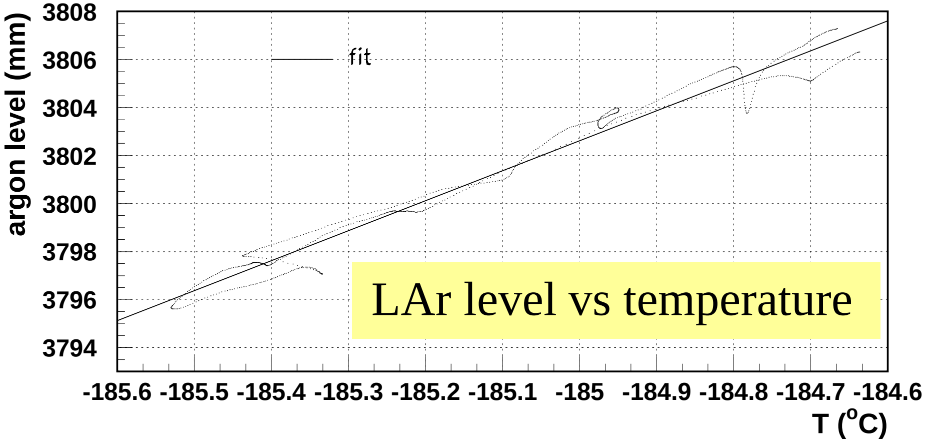
Cooling steps:

- Precooling: Gas and liquid N_2 mixture
- Cooling: LN_2
- LAr injection

LAr thermal compression



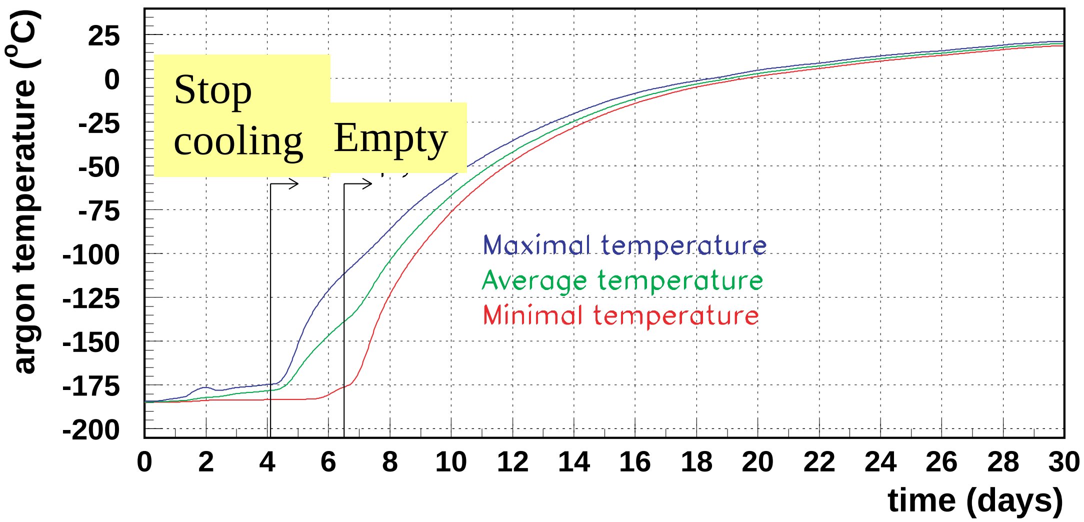


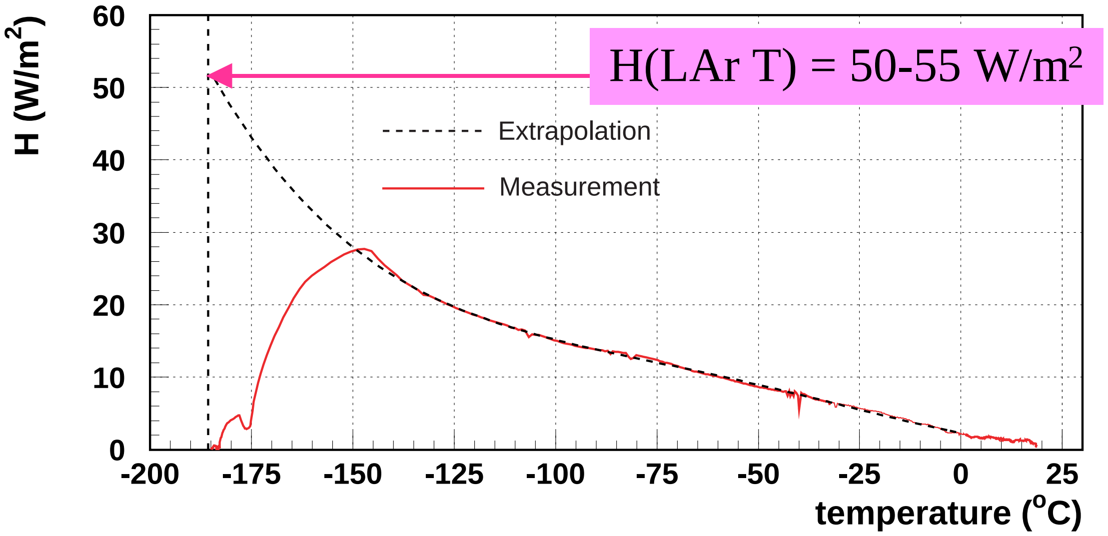


During the 2nd half-module cooling system test, the LAr on the 1st half-module is **cooled down** and **compressed**:

LAr thermal compression factor: $$\frac{1}{V}\frac{dV}{dT}(T \approx 88K) = (3.3 \pm 0.1)\cdot 10^{-3} K^{-1}$$

Heat transfer





When the cooling system is stopped and the cryostat emptied, the temperature grows following:

$$dT = \frac{1}{NC} dQ$$

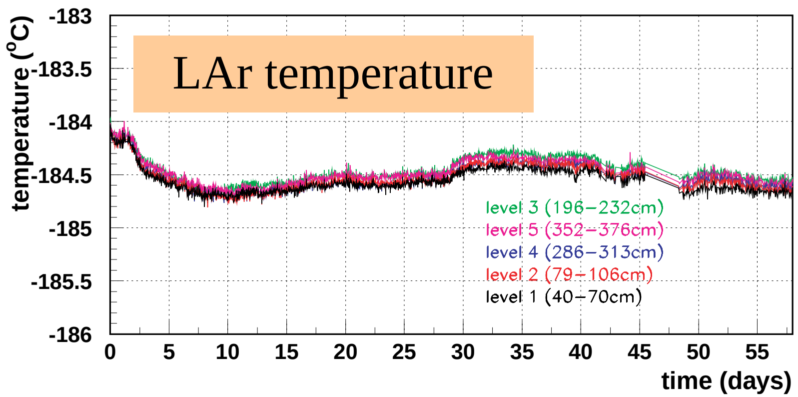
N = mass (frame and cryostat)
C = heat capacity
Q = transferred heat

Power transferred through the insulation walls:

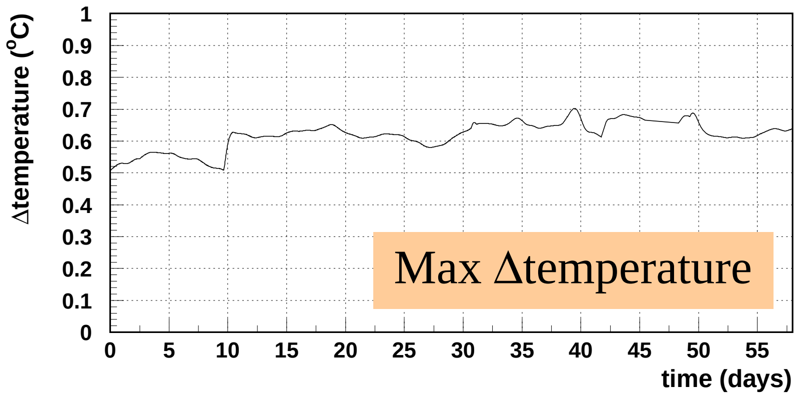
$$H \equiv \frac{1}{A}\frac{dQ}{dt} = \frac{NC}{A}\frac{dT}{dt}$$

A = walls total area

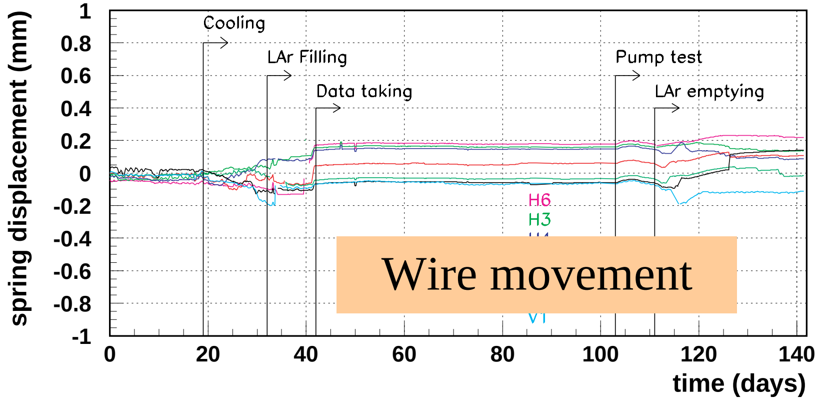
Other slow control results



No vertical temperature **gradient** observed

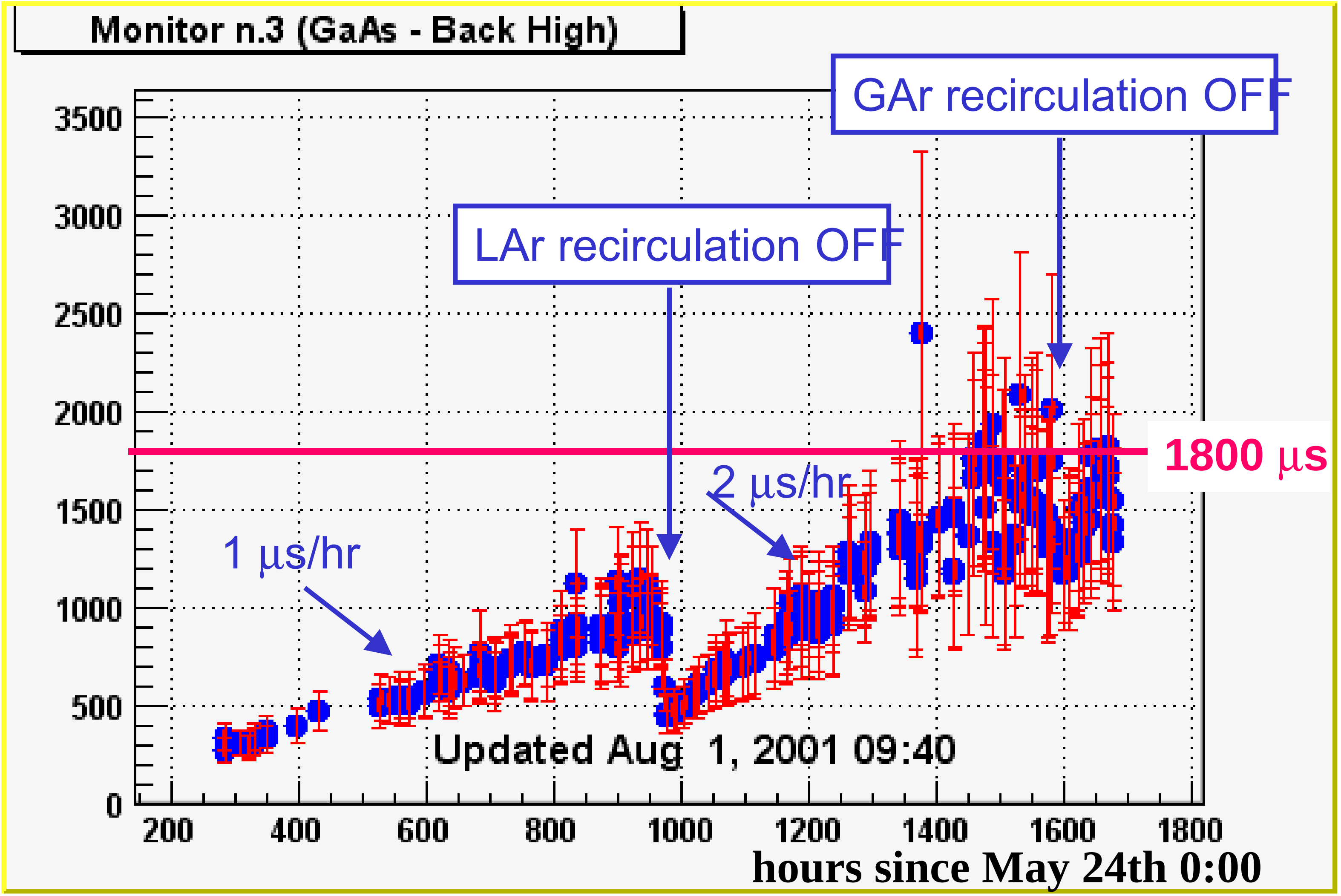


Maximum LAr **temperature gradient** kept below the required **1°**



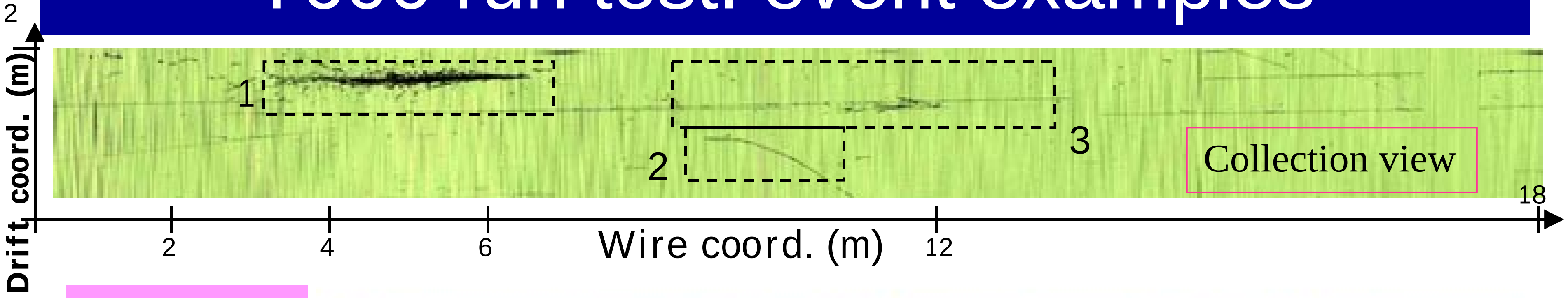
The **elongation of the springs** attached to the wires is less than **300 µm**

Electron lifetime



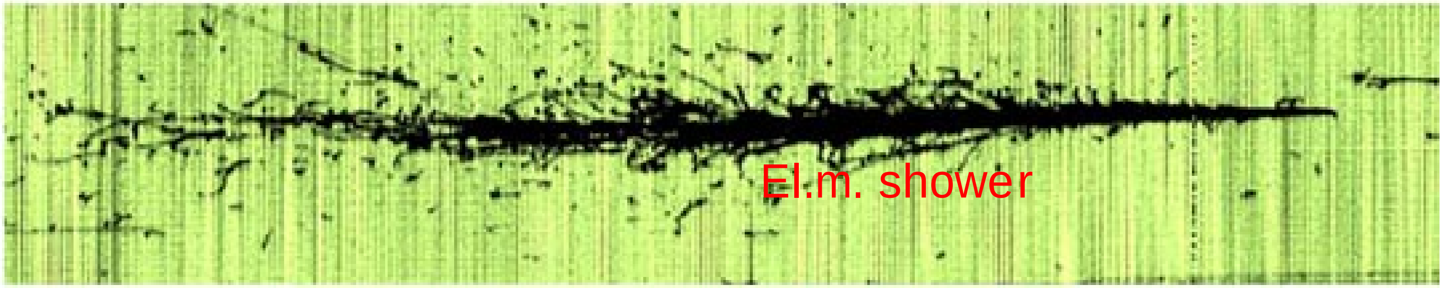
Maximum electron lifetime: 1800 μs

T600 run test: event examples

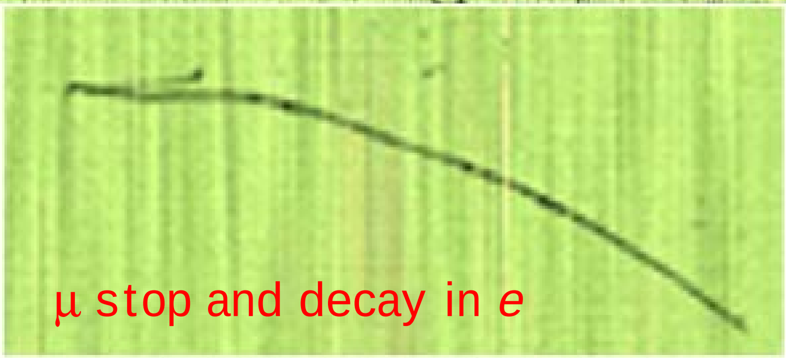


Zoom views

1

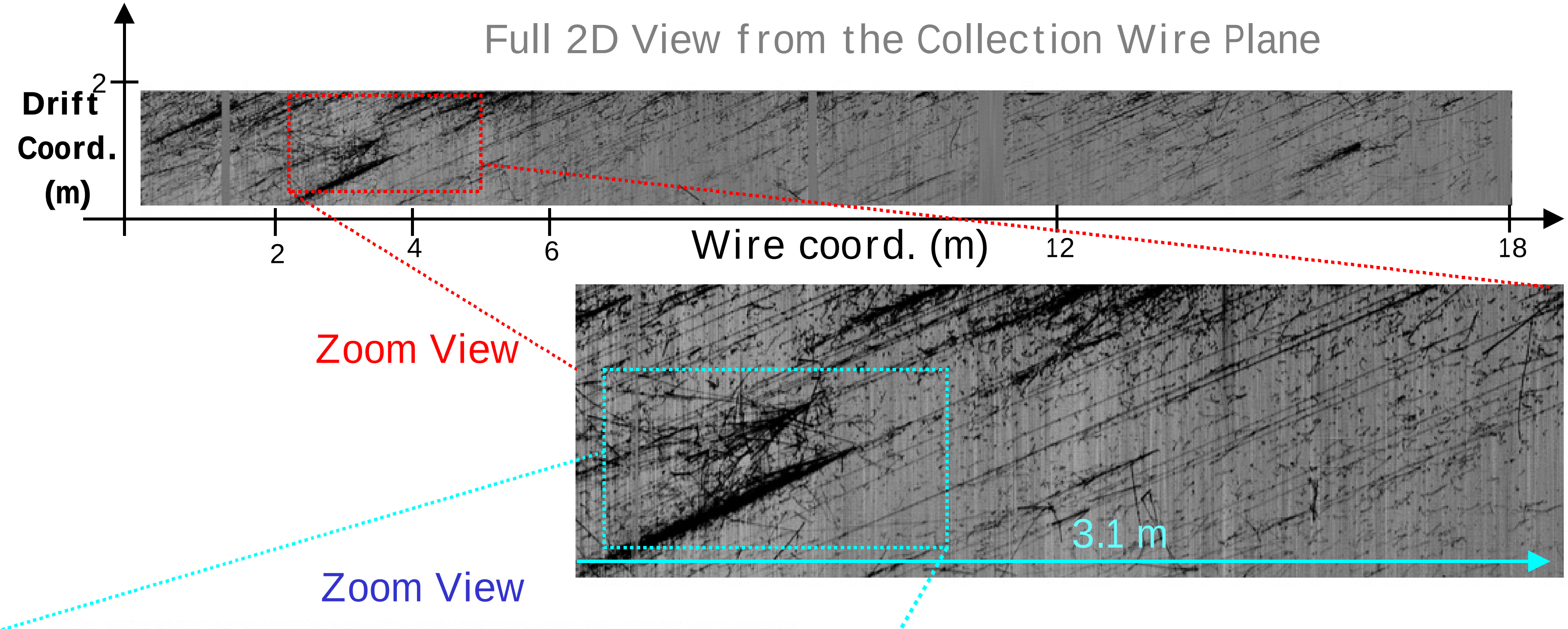


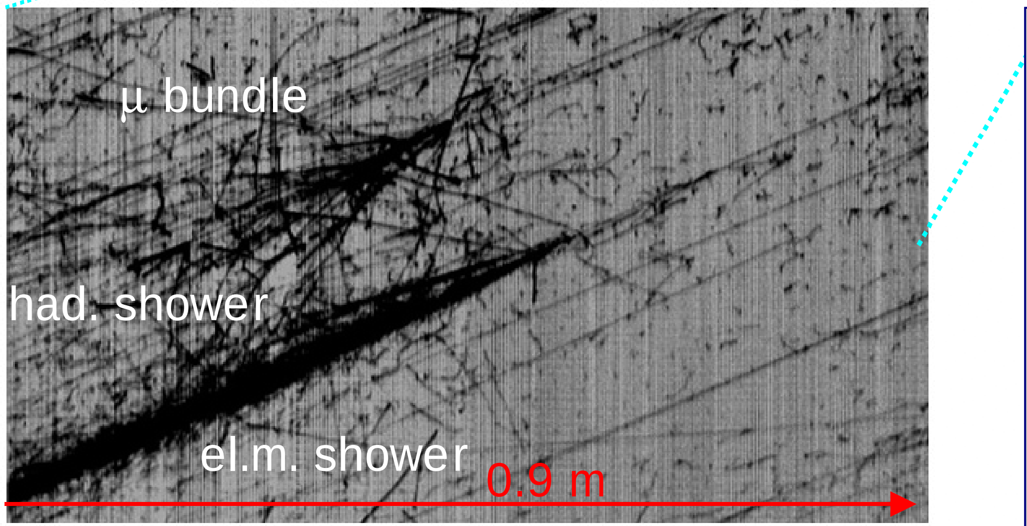
2



3

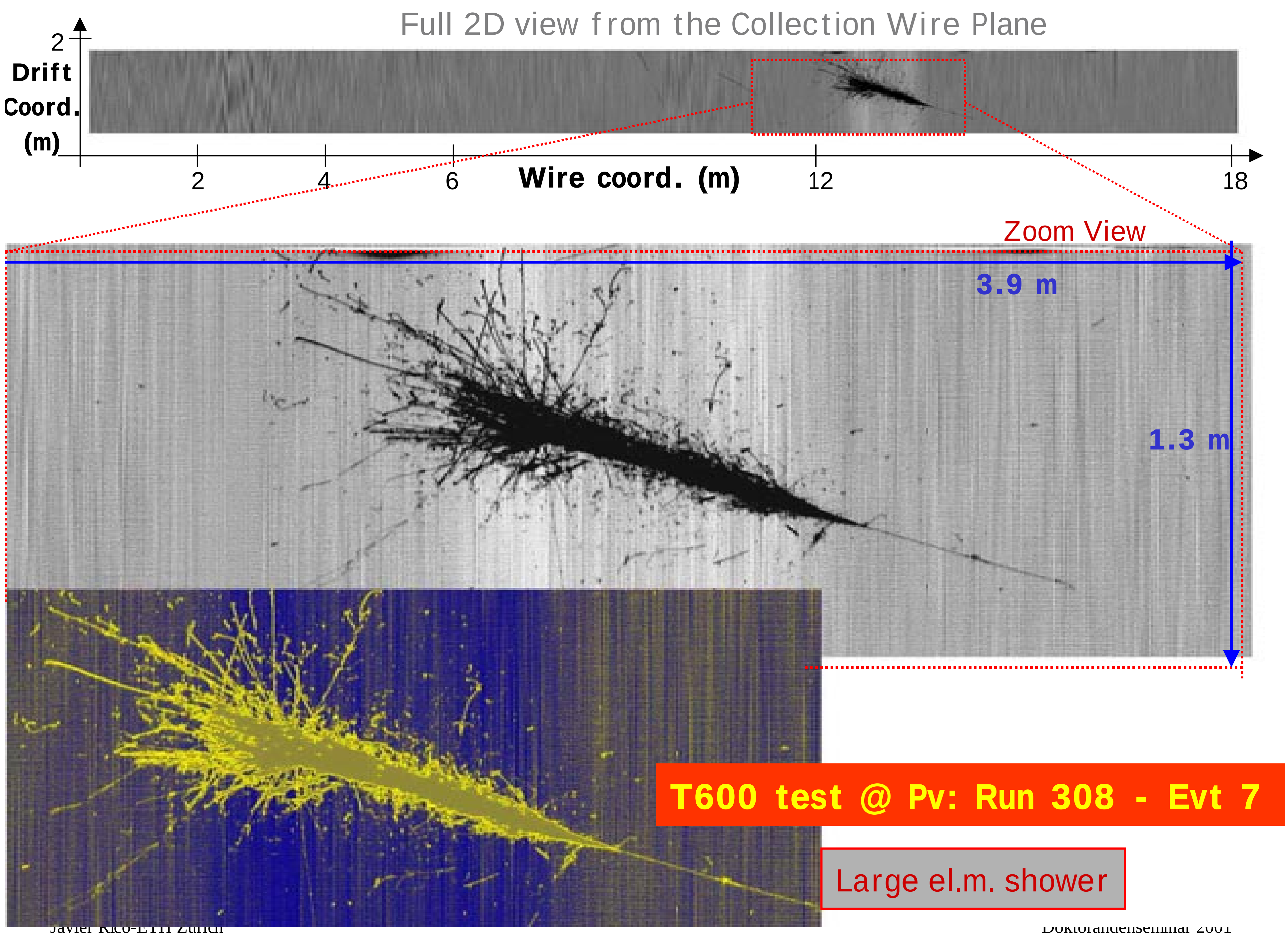
T600 test @ Pv: Run 201 - Evt 12





A spectacular event showing a dense Air Shower formed by hundreds of parallel tracks (muons and pions) and low energy γ's converting into electrons. Also visible in the zoom views a hadr. shower, an el.m. shower and a muon bundle.

T600 test @ Pv: Run 308 - Evt 4 (July 2nd, 2001)


Full 2D view from the Collection Wire Plane
2
Drift
Coord.
(m)
2
4
6
Wire coord. (m)
12
18
Zoom View
3.9 m
1.3 m
T600 test @ Pv: Run 308 - Evt 7
Large el.m. shower

Conclusions

• The first ICARUS 600 tons half-module has been **constructed** and **fully tested** in Pavia (Italy) from April to August 2001

• A better understanding of the **detector behaviour** during the different run phases has been achieved thanks to the **Slow Control** data

• The ICARUS technology will provide a **powerful tool** in order to explore

- ✓ **neutrino oscillations** from both, accelerator and non-accelerator beams
- ✓ **Solar** and **Supernova neutrinos**
- ✓ and **nucleon decay** searches.