The liquid Argon Time Projection Chamber : a new, mature technology for the detection and imaging of rare events

Particle Physics Seminar
Université de Genève

June 2, 2004

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Abstract

- After several years of R&D, the liquid Argon TPC technique has reached maturity.

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

- In this seminar, I will attempt to describe this new technology, and discuss possible future mid and long term applications in new-generation experiments for matter instability searches, CP-violation in neutrino physics and dark matter searches.

Physics programme

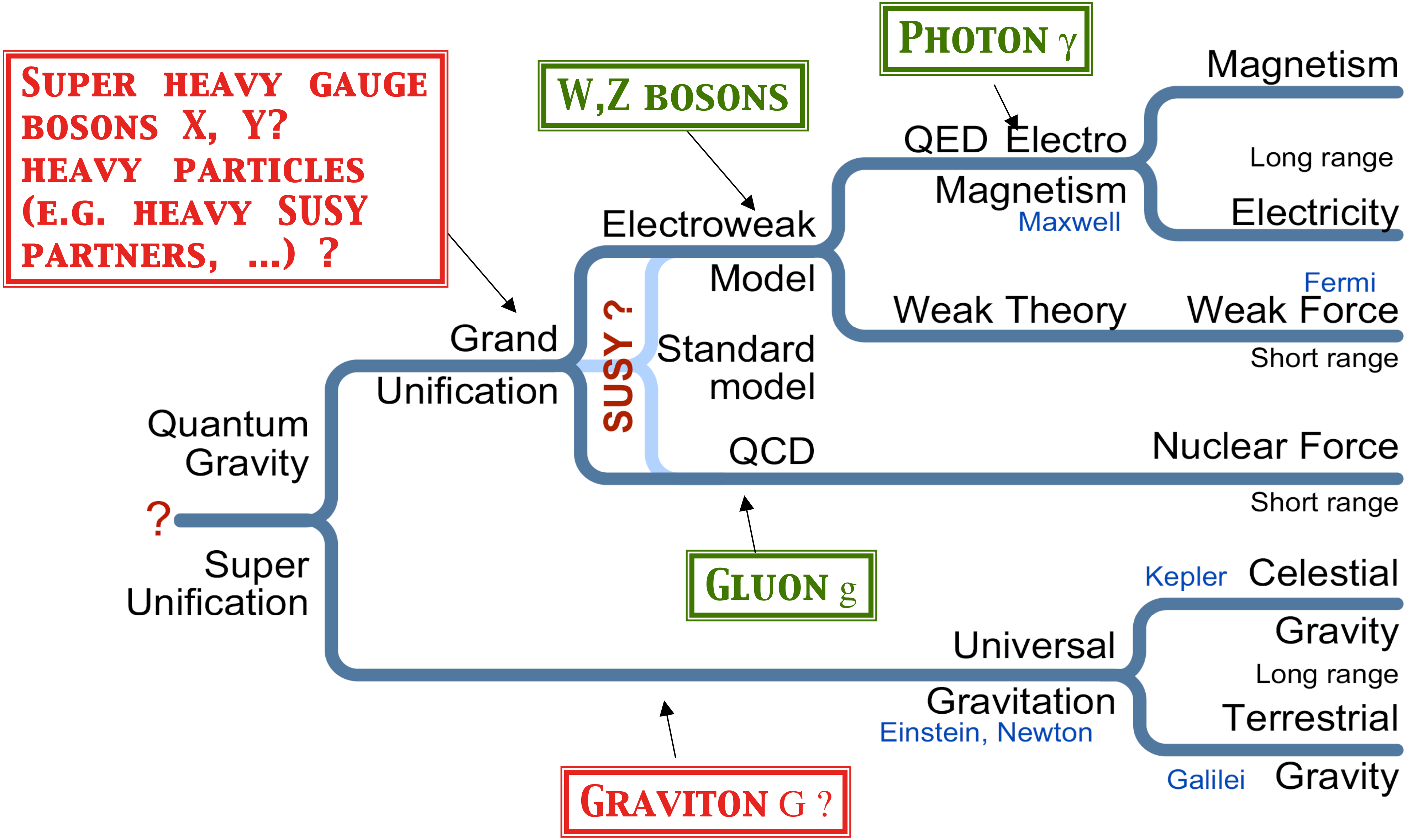
Overview

- (A) Matter instability (nucleon decay)
- (B) Neutrino properties
- (C) Direct dark matter search
- (D) Atmospheric neutrinos
- (E) Solar neutrinos
- (F) Supernova neutrinos
- (G)…

Usually classified as accelerator & non-accelerator physics

Complementary to electroweak physics at colliders

(A) Matter instability (nucleon decay)



SUPER HEAVY GAUGE BOSONS X, Y? HEAVY PARTICLES (E.G. HEAVY SUSY PARTNERS, ...) ?

W,Z BOSONS

PHOTON γ

GLUON g

GRAVITON G ?

?

Quantum Gravity

Super Unification

Grand Unification

SUSY ?

Electroweak Model

Standard model

QCD

QED Electro Magnetism

Maxwell

Weak Theory

Universal Gravitation

Einstein, Newton

Magnetism

Long range

Electricity

Fermi

Weak Force

Short range

Nuclear Force

Short range

Kepler Celestial

Gravity

Long range

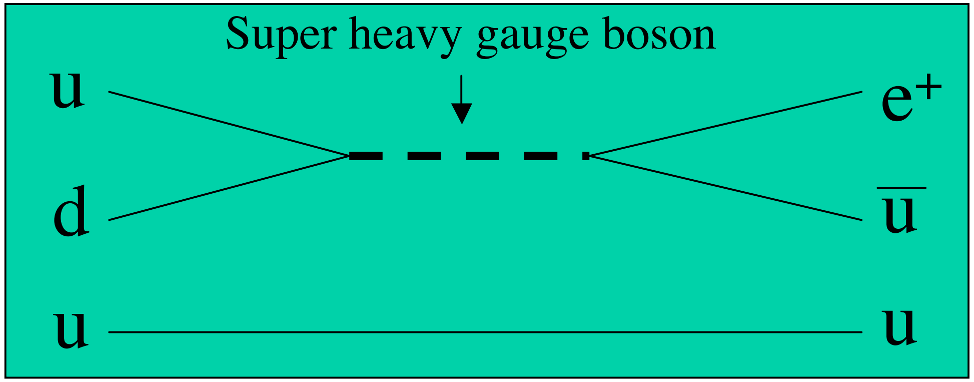
Terrestrial

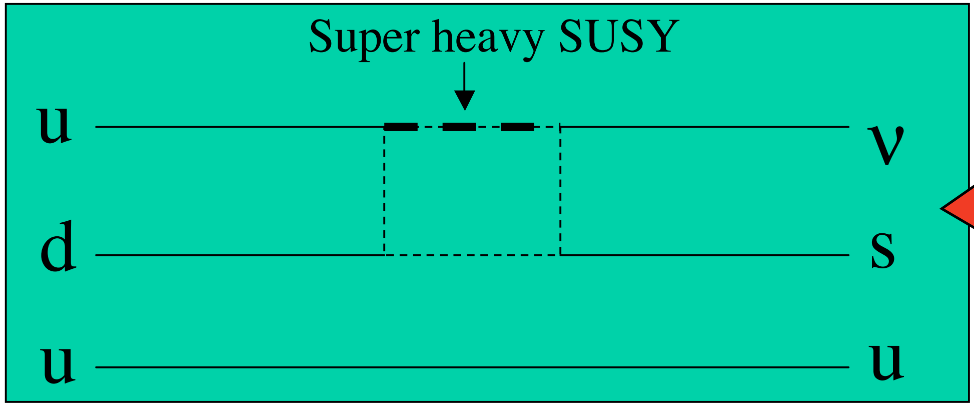
Galilei Gravity

B violation is a sign of **physics beyond the SM** (⇒ new forces)

Proton decay processes

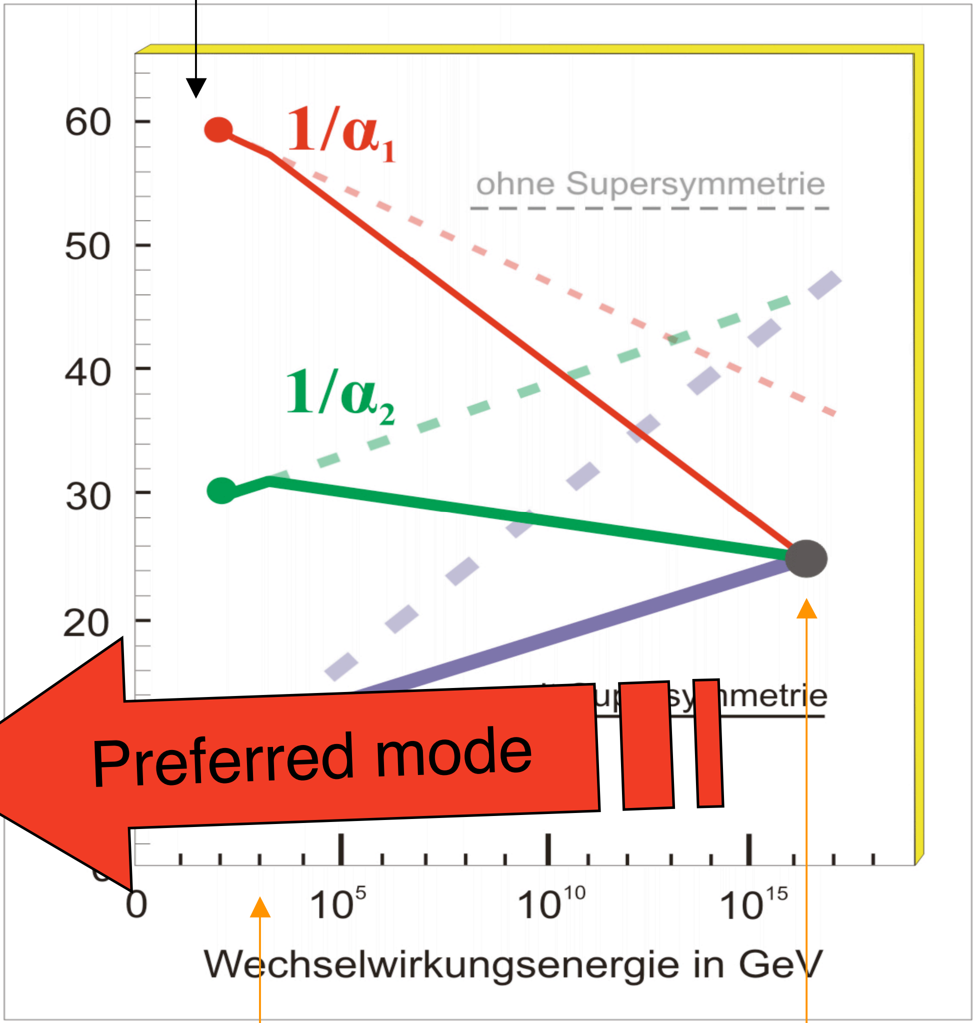
$$p \to e^+ \pi^0$$





$$p \to \bar{\nu} K^+$$

LEP precision measurements



Preferred mode

LHC domain
$\approx 10^3$ GeV

Unification ?
$\approx 10^{17\pm1}$ GeV

(B) Neutrino properties

- **Neutrinos come in (almost) three flavors** (LEP: $N_\nu=2.984\pm0.008$)
- They are **much lighter** than their charged lepton partner (⇒ why?)

e	511 keV	ν_e	< 3 eV
μ	106 MeV	ν_μ	<0.19 MeV
τ	1.78 GeV	ν_τ	<18.2 MeV

$<m_{\nu e}>$

- **Mass and weak eigenstates differ** (⇒ mixing ⇒ neutrino flavor oscillation)
- They are **not all massless** (⇒ neutrino flavor oscillation)
- Neutrinos could be **Dirac** ($\nu\neq\bar{\nu}$) or **Majorana** ($\nu=\bar{\nu}$) particles (⇒ mass generation mechanism)
- Neutrino mass is a sign of **physics beyond the SM** (⇒ RHν, LNV)

Three Experimental Indications for Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right) \qquad \alpha \neq \beta$$

LSND Experiment

L = 30m

E = ~40 MeV

Atmospheric Neutrinos

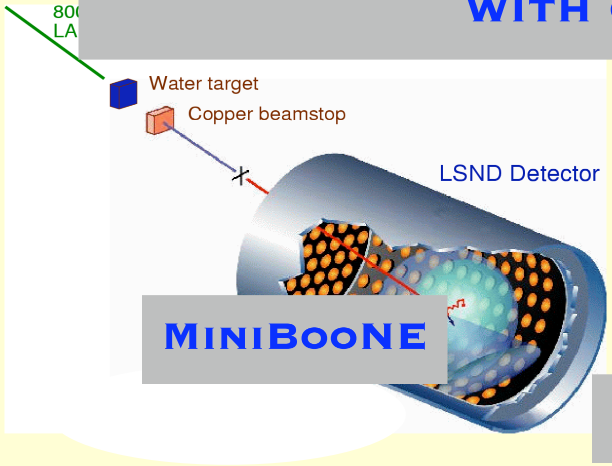
L = 15 to 12,000 km

E =300 to 2000 MeV

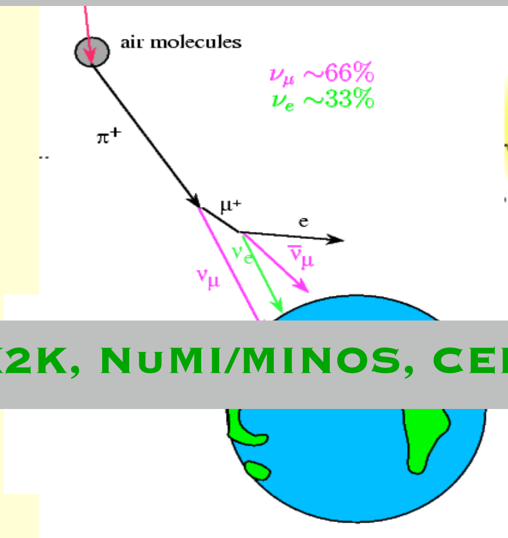
Solar Neutrinos

Seek confirmation of effects & oscillatory (L/E) dependence

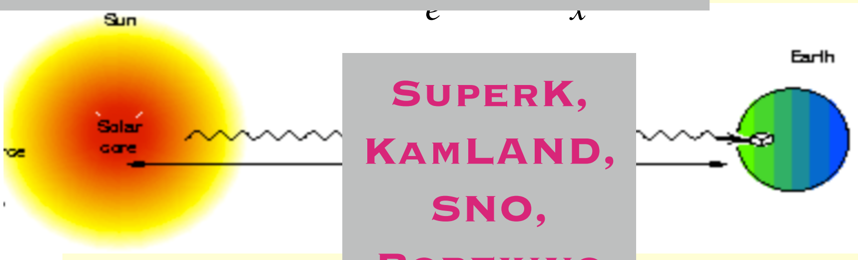
with current round of experiments



MiniBooNE



K2K, NuMI/MINOS, CERN-GS



SuperK, KamLAND, SNO, Borexino

$\Delta m^2 = \sim 6$ ... ^{2}

rob$_{OSC}$ ~ large

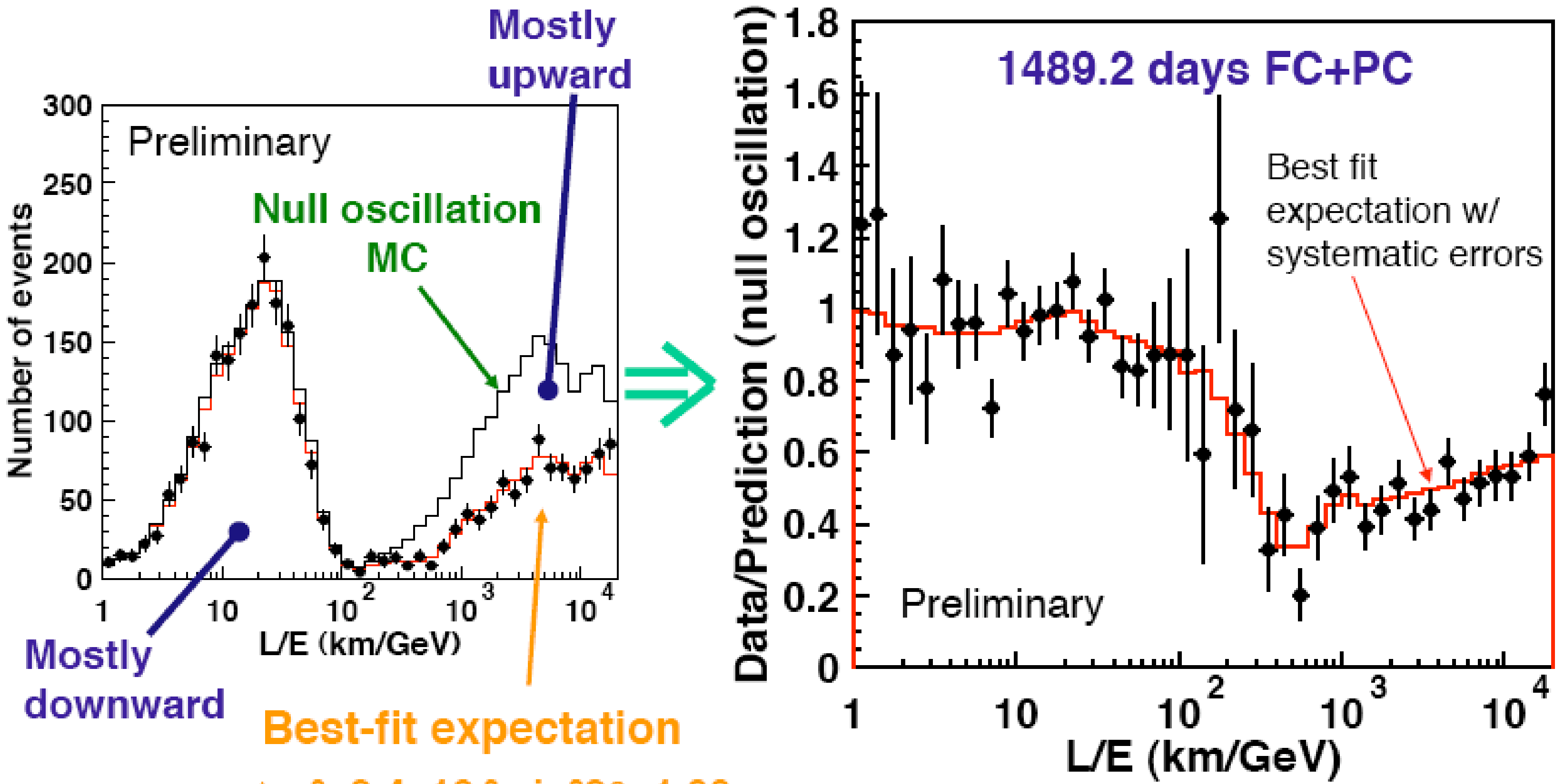
Δm^2 = .3 to 3 eV^2

Prob$_{OSC}$ = 0.3 %

$\Delta m^2 = \sim 1.4$ to 3×10^{-3} eV^2

Prob$_{OSC}$ ~ maximal

L/E in atmospheric neutrino data



Mostly upward

Null oscillation MC

Mostly downward

Best-fit expectation

Best fit expectation w/ systematic errors

$\Delta m^2=2.4\times10^{-3}, \sin^2 2\theta=1.00$

$\chi^2_{\min}=37.8/40$ d.o.f

First dip is observed as expected from neutrino oscillation

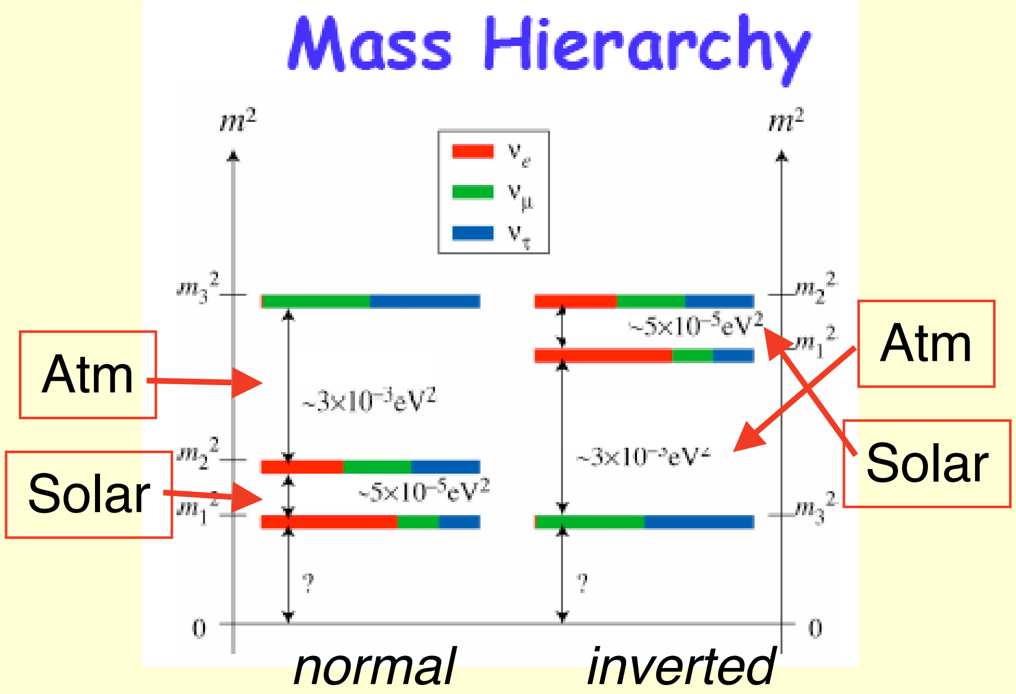
SUPERKAMIOKANDE, hep-ex/0404034 , Submitted to Phys.Rev.Lett.

Three neutrino formalism: accommodating (almost) all evidences

(Disregarding LSND result)

$$\Delta m^2_{atm} \qquad \Delta m^2_{solar}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \equiv U_{MNSP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Standard parameterization: 3 angles + 3 complex phases

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \cancel{\mathrm{diag}(1, e^{i\alpha}, e^{i\beta})}$$

Atmospheric

$\theta_{13} \neq 0$?

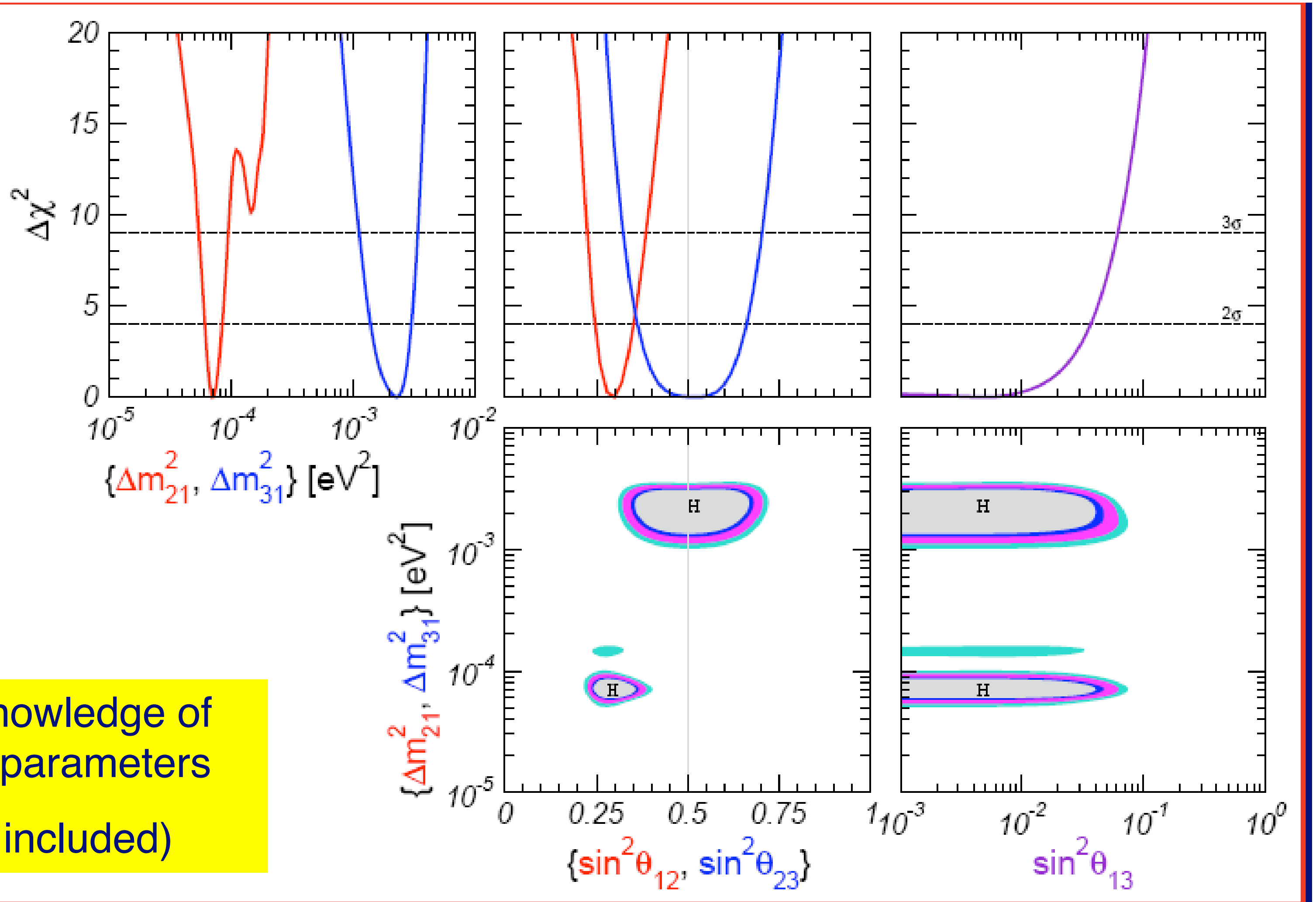
$\delta \neq 0$?

Solar

Majorana phases

Global fit

See e.g.
Maltoni et al.,
hep-ph/0405172



our best knowledge of
oscillation parameters

(all data included)

parameter	best fit	2σ	3σ	5σ
Δm^2_{21} [10^{-5}eV^2]	6.9	6.1–8.4	5.4–9.4	2.1–29
Δm^2_{31} [10^{-3}eV^2]	2.3	1.4–3.0	1.1–3.4	0.68–4.4
$\sin^2\theta_{12}$	0.30	0.25–0.35	0.23–0.39	0.16–0.47
$\sin^2\theta_{23}$	0.52	0.36–0.66	0.32–0.70	0.26–0.78
$\sin^2\theta_{13}$	0.005	≤ 0.037	≤ 0.061	≤ 0.13

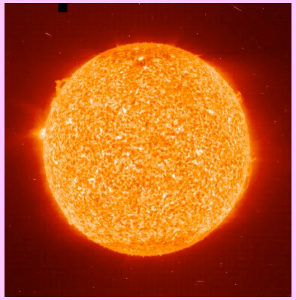
$$\theta_{13} \neq 0 \ ?$$

$$\delta \neq 0 \ ?$$

$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

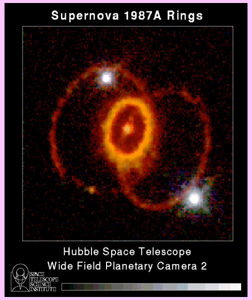
Sources of neutrinos

Astrophysical sources



SOLAR

ATMOSPHERIC

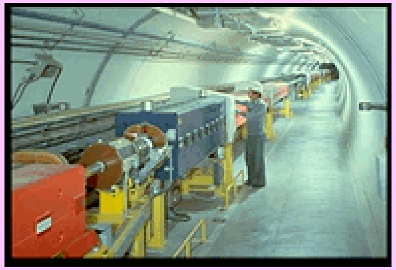


SUPERNOVAE

BIGBANG

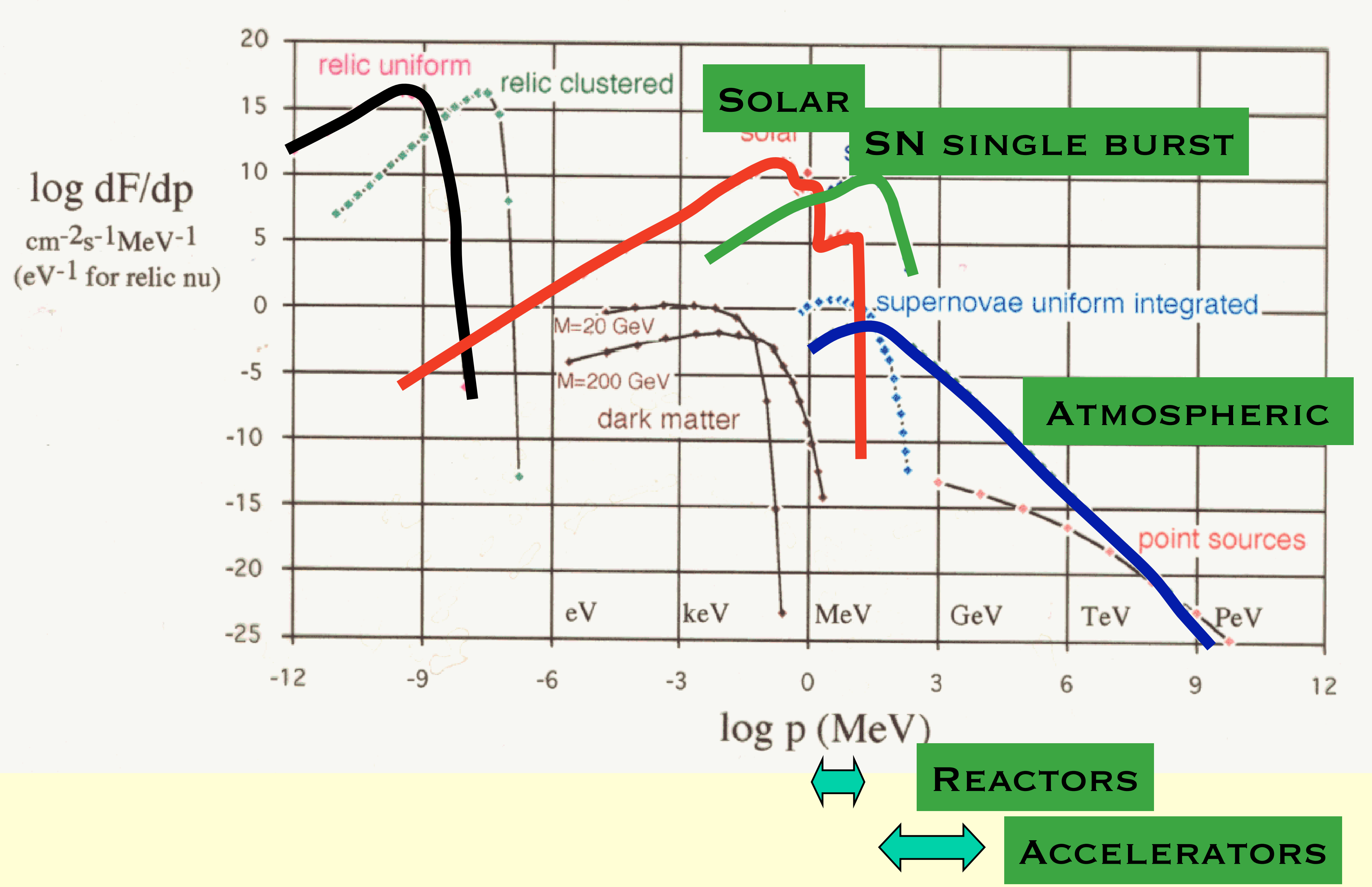
Man-made sources

ACCELERATORS



REACTORS

Energy spectrum of neutrinos



Absolute mass measurement

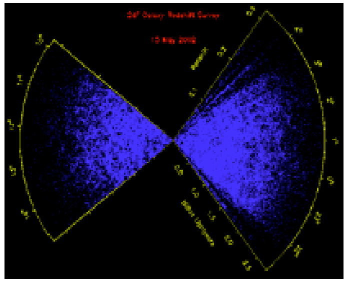
‚indirect‘ approaches

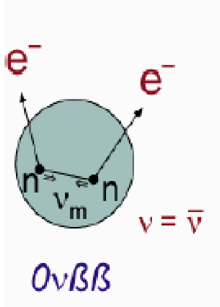
- **Cosmology: LSS & CMBR**
  depends on priors
- **0νββ**
  Majorana: $m_{ee}(\nu)$, CP-phases

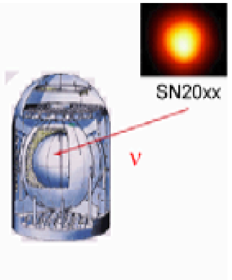
Direct measurements

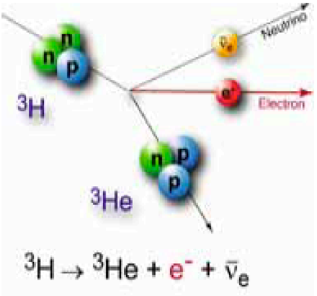
- **Supernova ToF**
  waiting for SN20xx
- **Kinematics of particle decays**

$$E^2 = p^2c^2 + m^2c^4$$

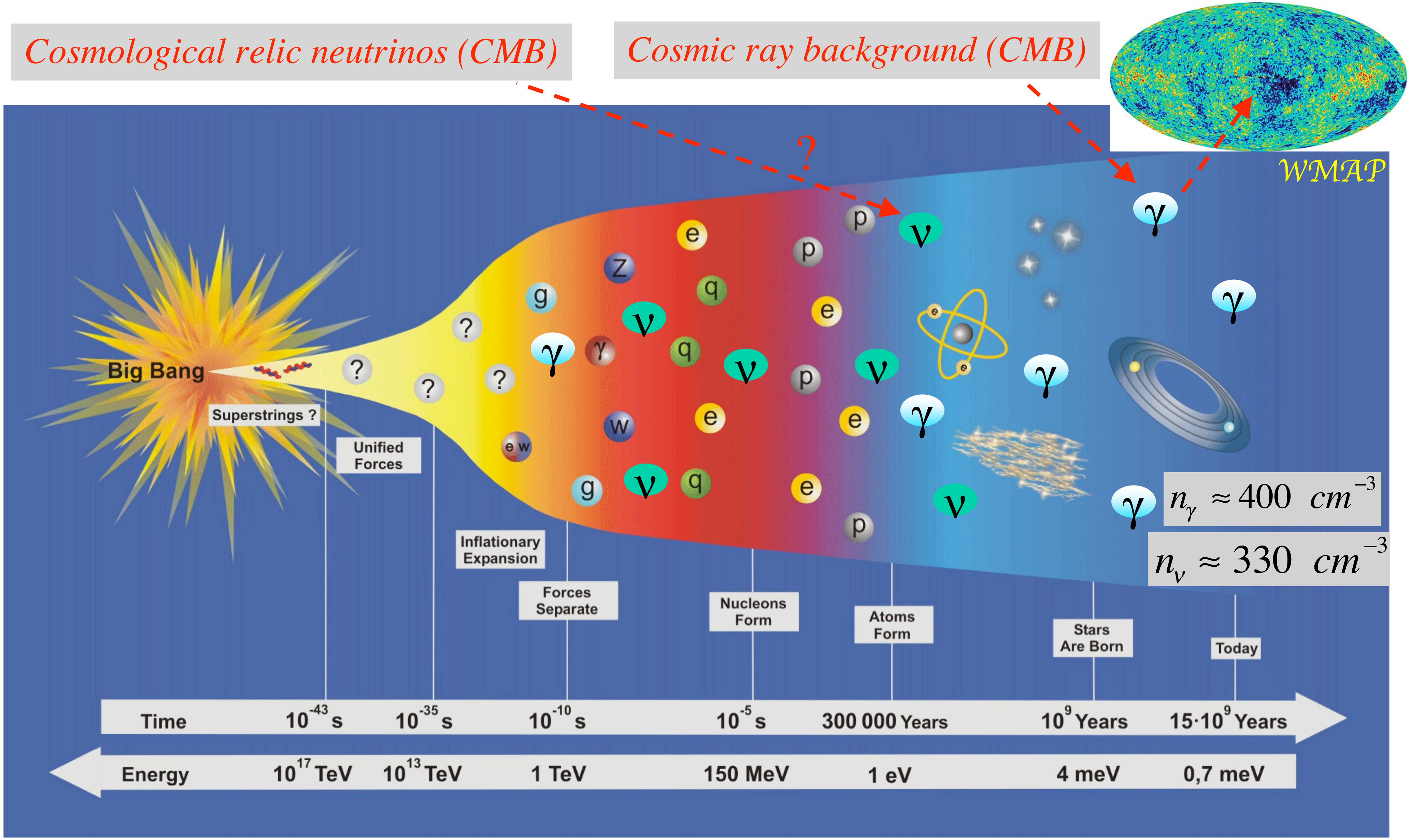








Cosmological relic neutrinos



Cosmological relic neutrinos (CMB)

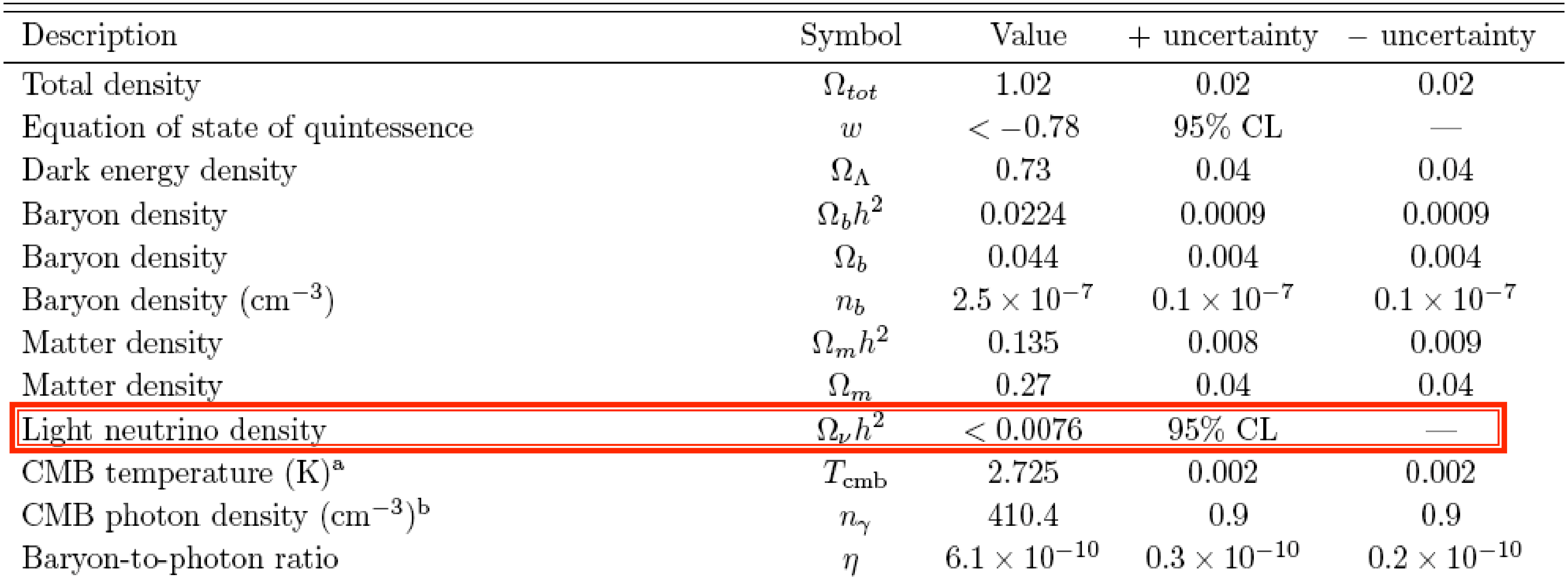
Cosmic ray background (CMB)

$n_\gamma \approx 400 \;\; cm^{-3}$

$n_\nu \approx 330 \;\; cm^{-3}$

Best-Fit Cosmological Parameters

Indirect evidence that neutrinos are light particles



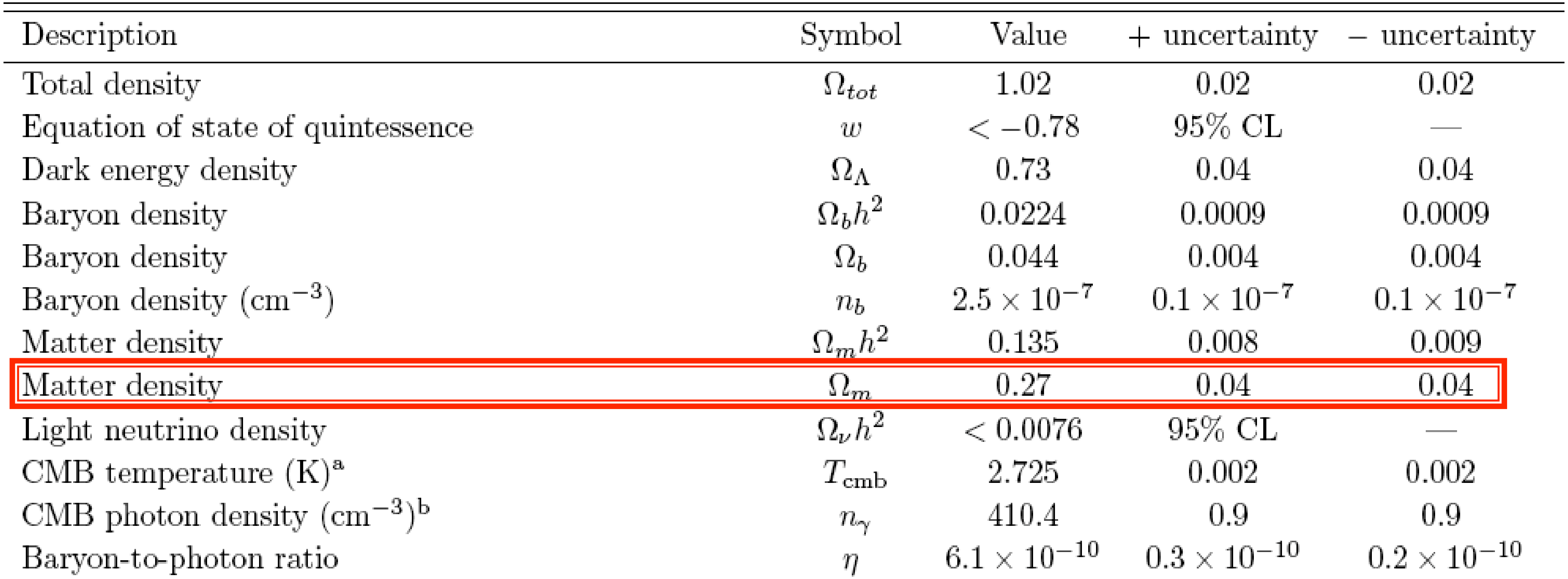
Description	Symbol	Value	+ uncertainty	– uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	T_{cmb}	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}

WMAP best fit from Legacy Archive Microwave Background Data Analysis (LAMBDA) http://lambda.gsfc.nasa.gov/

$$\Omega_\nu h^2 \approx 0.01 \frac{m_\nu}{eV} \Rightarrow m_\nu < 1\ eV$$

(C) Dark Matter in the Universe

Evidence for existence of dark matter



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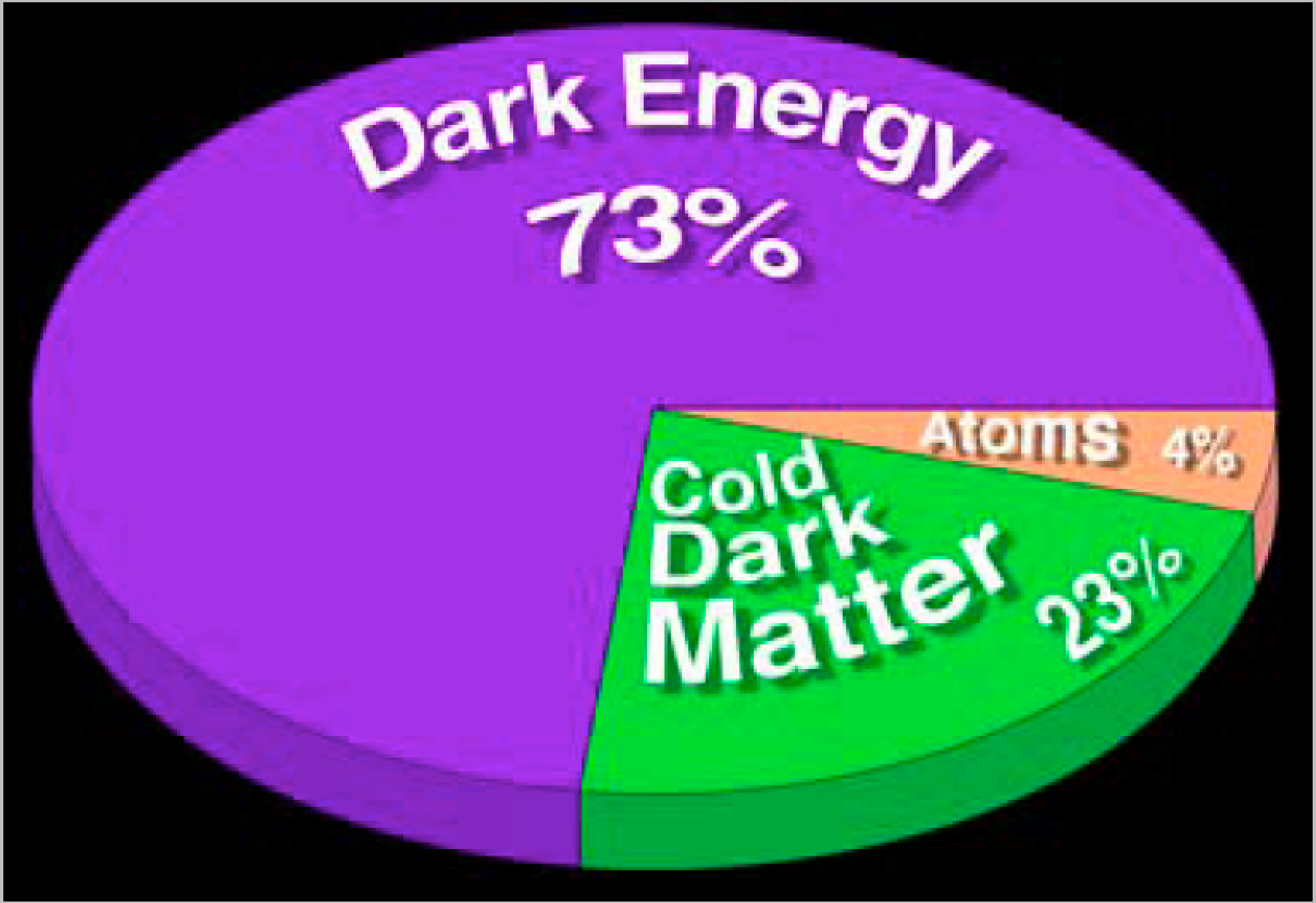
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}

The matter density indicates a much greater value than the one anticipated from luminous matter ⇒ existence of dark matter

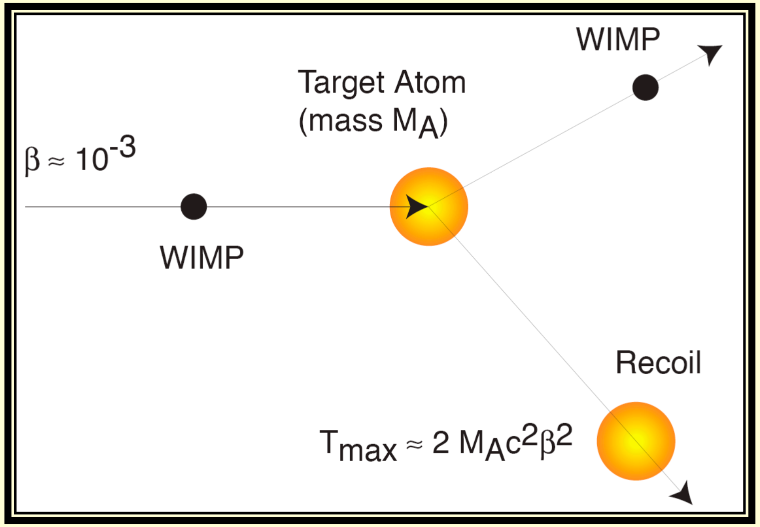
Dark matter is a strong hint for **physics beyond the SM** (⇒ existence of new kinds of particles (LSP?))

The cosmological "raclette"

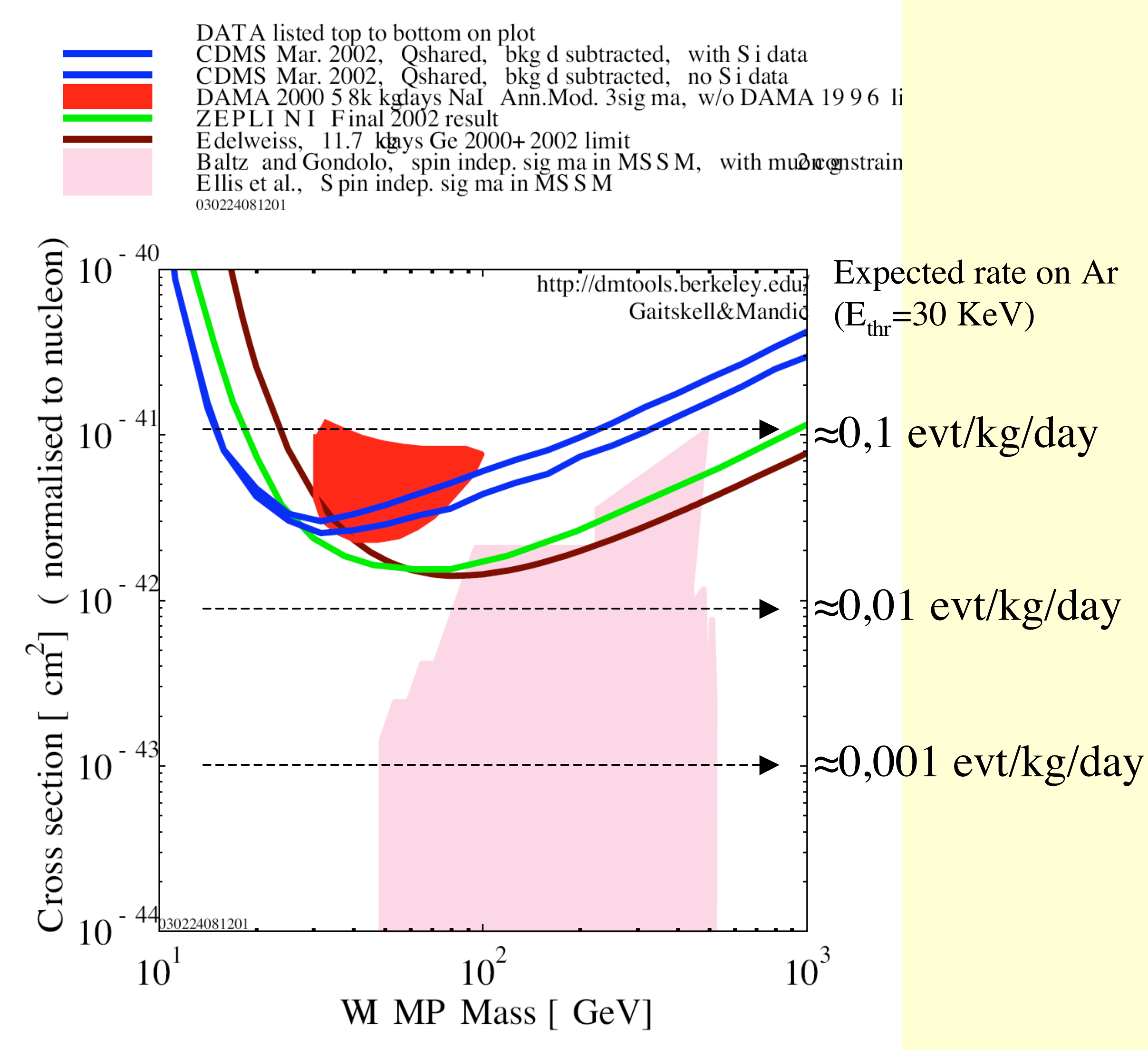


Direct dark matter searches

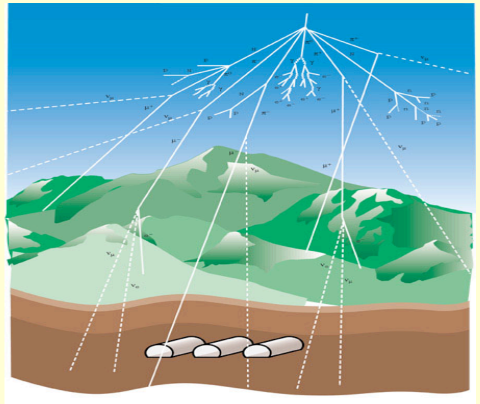
- Finding direct evidence for the existence of dark matter through the detection of nuclear recoils



Recoil region
of interest ≈
1-30 KeV

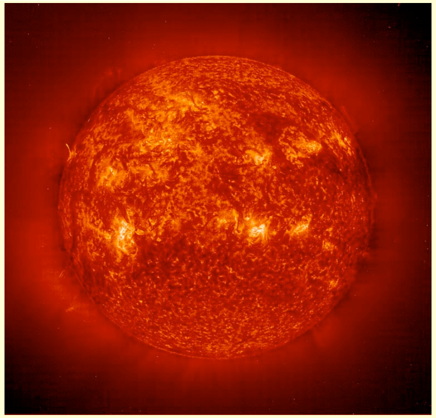


(E), (F), (G), …



Atmospheric neutrinos:

- High statistics, precision measurements
- L/E dependence
- Tau appearance, electron appearance
- Earth matter effects
- …



Solar neutrinos:

- High statistics, precision measurement of flux
- Time variation of flux
- Solar flares
- …

JCAP 0310:009,2003
& hep-ph/0404151

Supernova type-II neutrinos:

- Access supernova and neutrino physics simultaneously
- Decouple supernova & neutrino properties via different detection channels
- Relic supernova
- Supernova in our galaxy or in Andromeda (1/15 years)
- Initial burst
- …

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

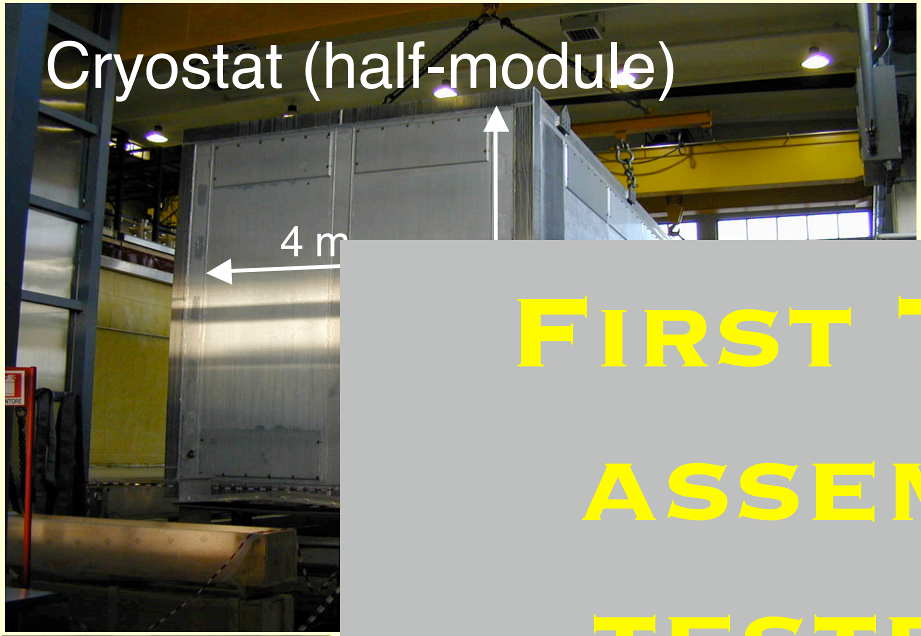
ESO PR Photo 40f/99 (17 November 1999)

Liquid Argon TPC
Overview

LAr TPC story…

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

ICARUS T300 detector



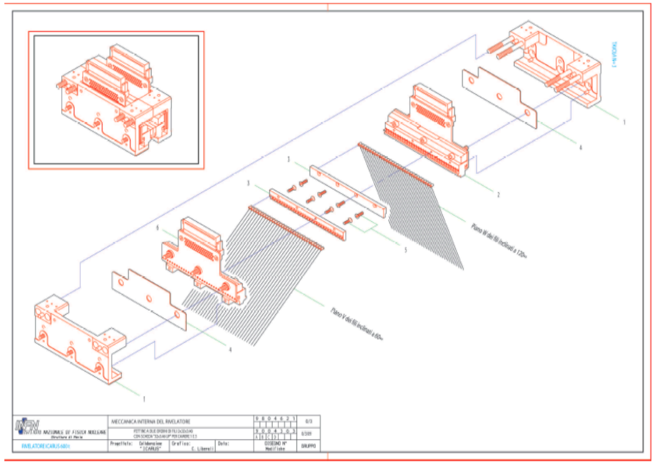
First T300 Fully assembled and tested in 2001

Second T300 in 2002

ICARUS wiring

Twisting mandrel

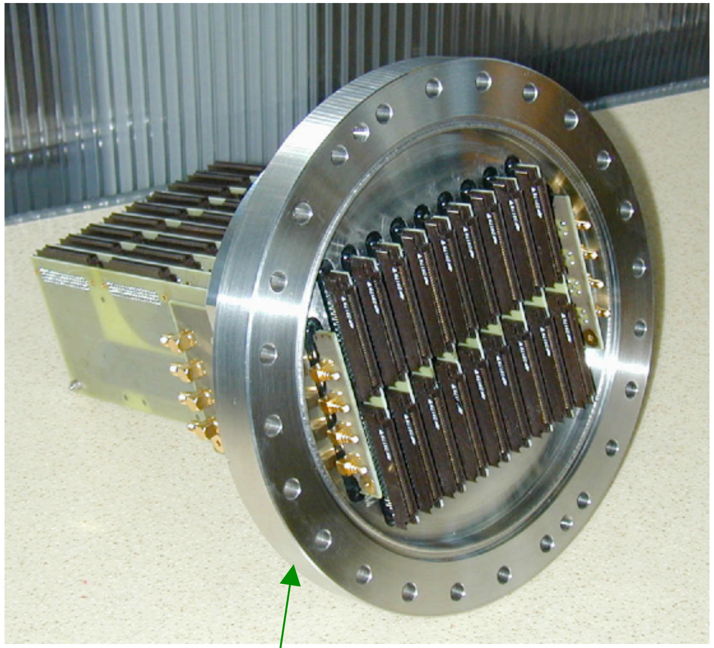
Wires on a comb



Stocking coil

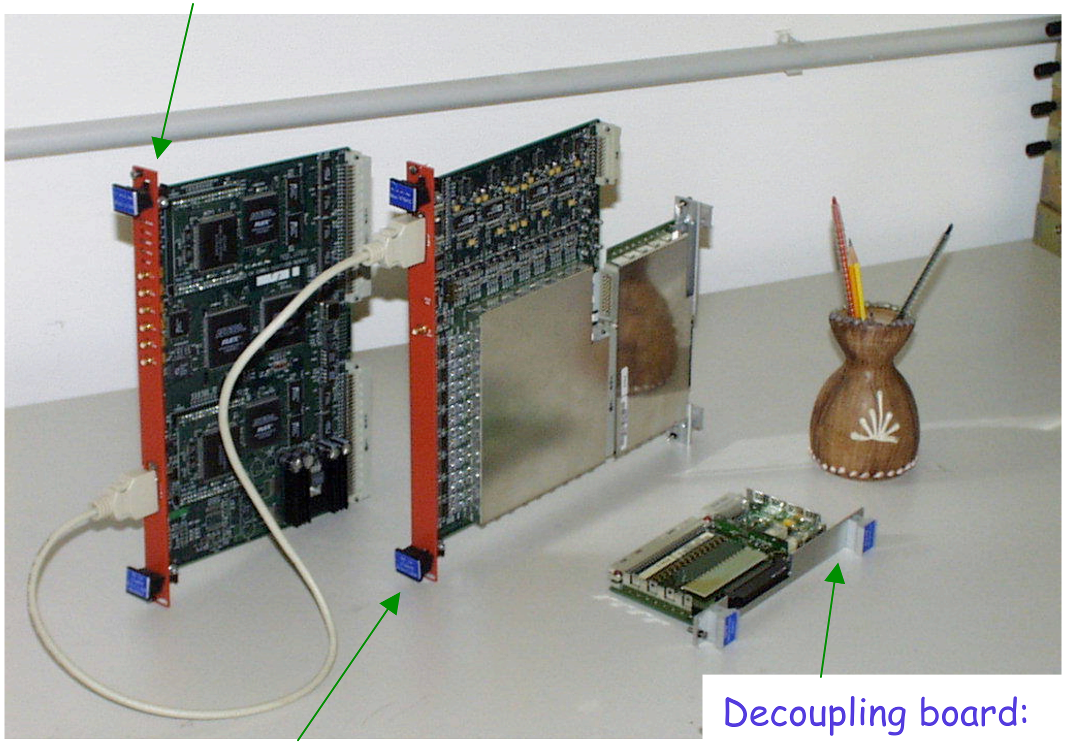
The washing machine.

Read-out chain



Signal UHV feed-through:
576 channels (18 connectors x 32)
+ HV wire biasing

CAEN-V789 board: 2 Daedalus VLSI * 16 input channels
(local self-trigger & zero suppression) + memory buffers +
data out on VME bus

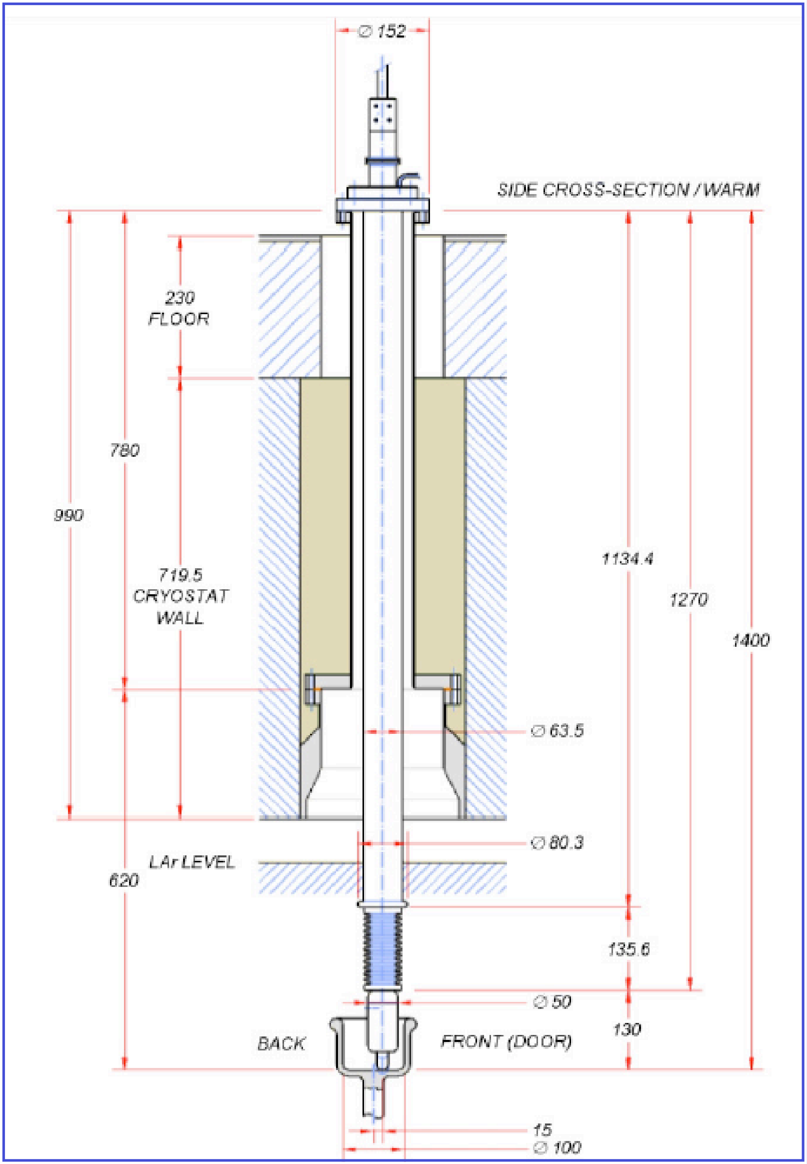


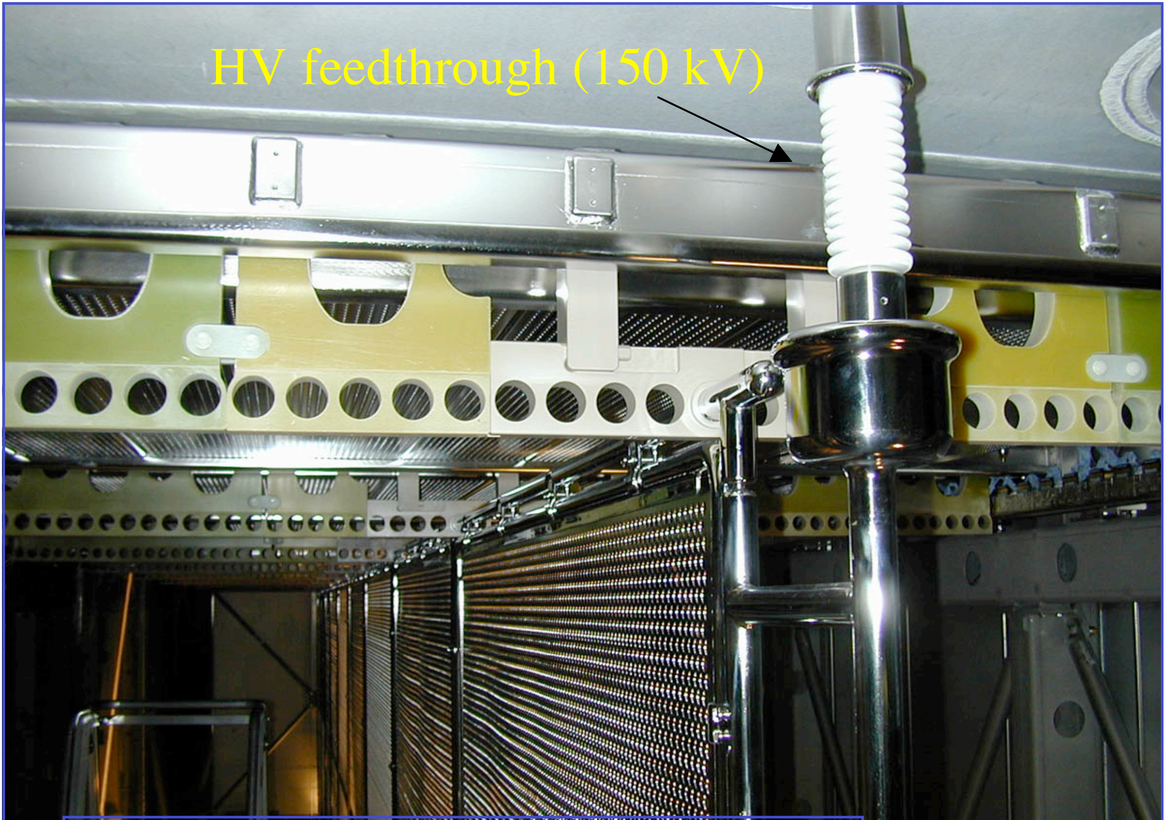
CAEN-V791 board: 32 pre-amplifiers +
4 multiplexers (8:1) + 4 FADC's (10 bits - 20 MHz)

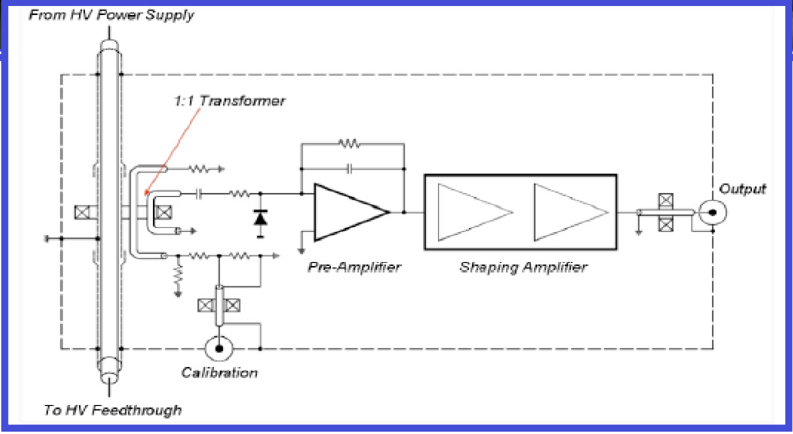
Decoupling board:
HV distribution
and signal input

commercially available

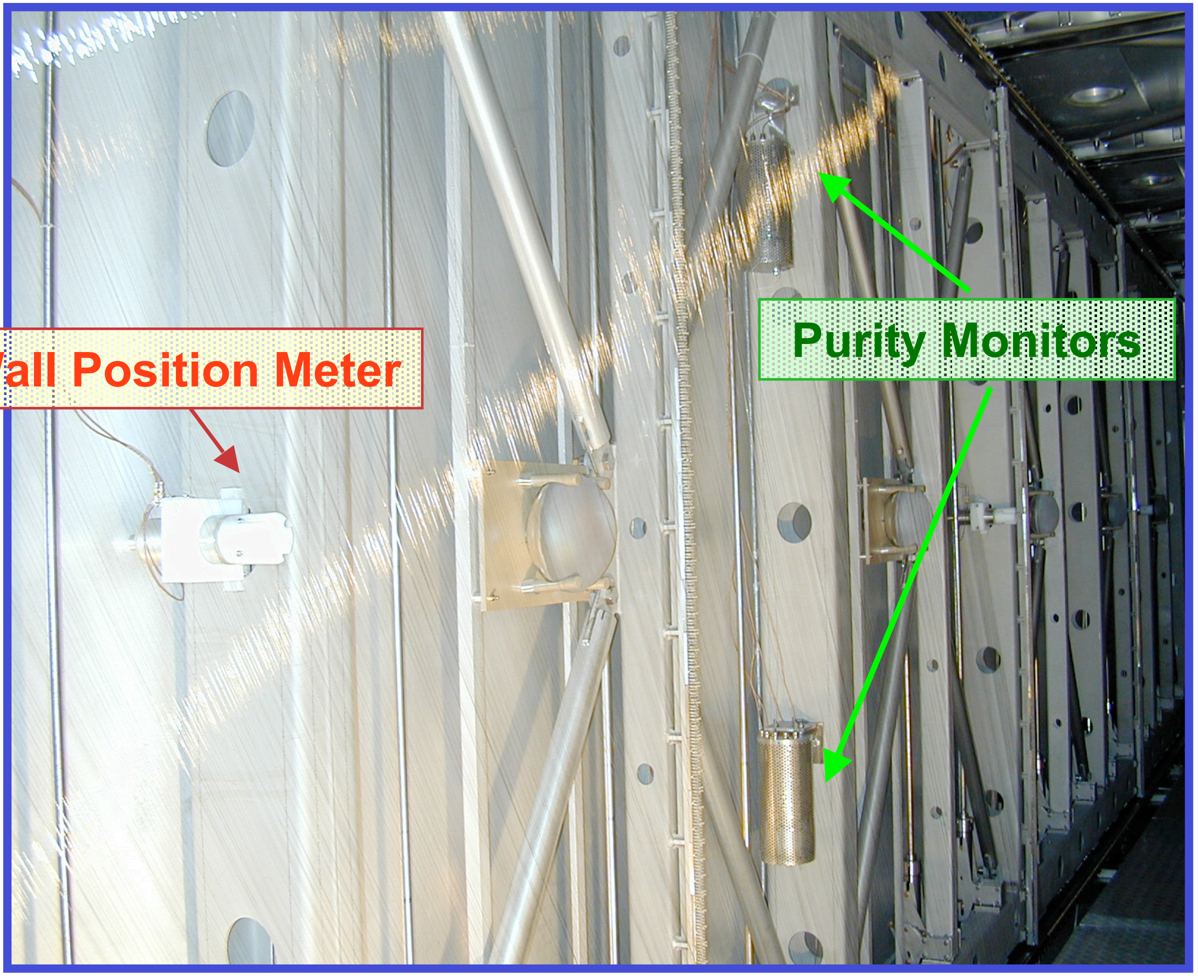
ICARUS H.V.

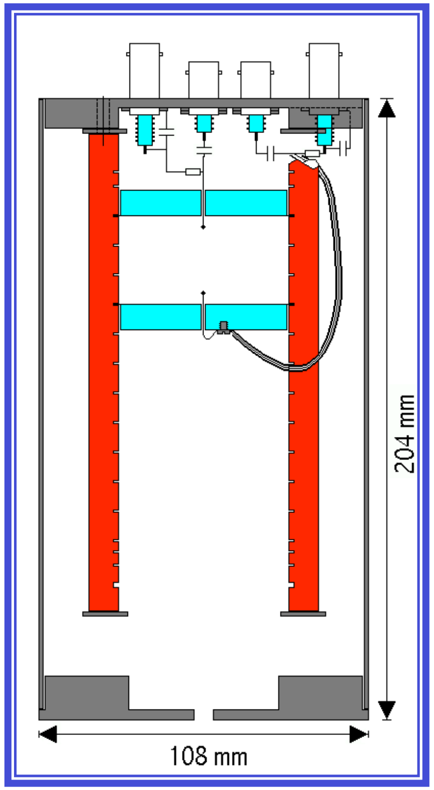

∅ 152
SIDE CROSS-SECTION / WARM
230
FLOOR
780
990
719.5
CRYOSTAT
WALL
1134.4
1270
1400
∅ 63.5
∅ 80.3
LAr LEVEL
620
135.6
∅ 50
130
BACK
FRONT (DOOR)
15
∅ 100

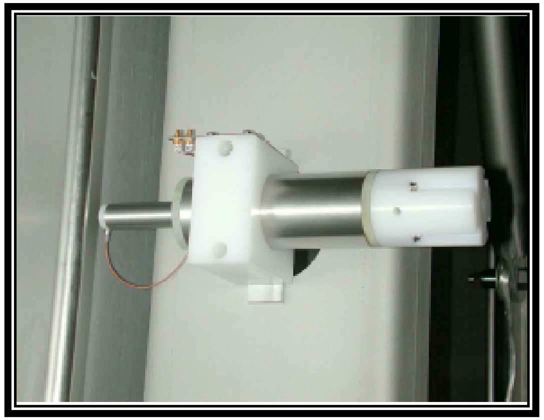

HV feedthrough (150 kV)


From HV Power Supply
1:1 Transformer
Pre-Amplifier
Shaping Amplifier
Output
Calibration
To HV Feedthrough

ICARUS slow control







purity monitors, level meters, wire position meters, wall position meters, temperature probes

Liquid Argon medium properties

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov d^{2}N/dEdx (β=1)	$\approx$ 160 eV^{-1} cm^{-1}	$\approx$ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation (E=0 V/cm)	No	Yes ($\approx$ 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)

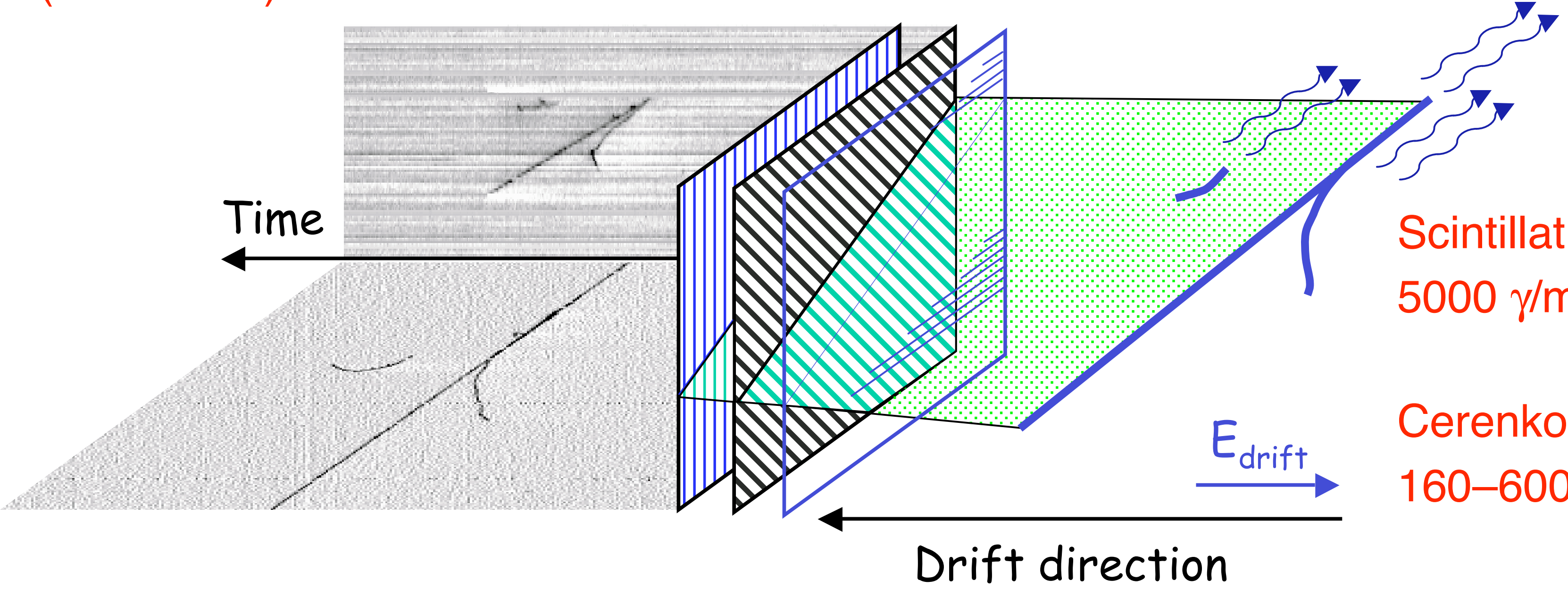
- ☞ **Charge**
- ☞ **Scintillation light (VUV)**
- ☞ **Cerenkov light (if β>1/n)**

The Liquid Argon TPC principle

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

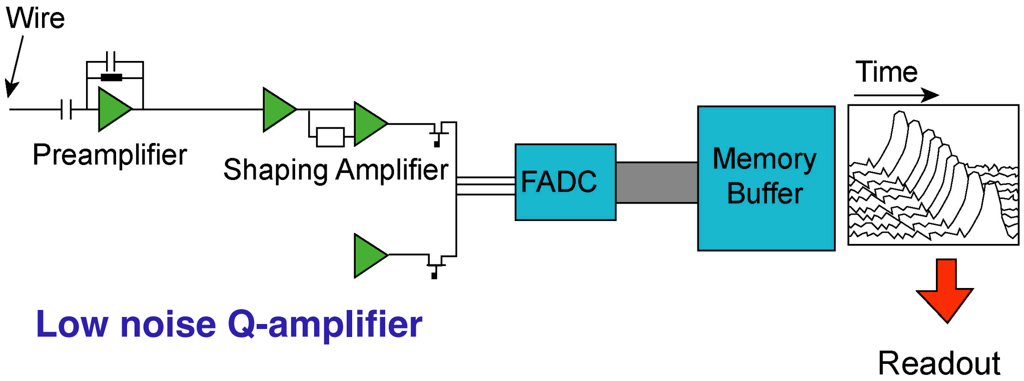
Charge readout planes: Q

UV Scintillation Light: L



Scintillation light yield ~
5000 γ/mm @ 128 nm

Cerenkov ~ 70 γ/mm in
160–600 nm (β≈1)



Low noise Q-amplifier

**Continuous
waveform recording**

HIGH DENSITY

NON-DESTRUCTIVE READOUT

CONTINUOUSLY SENSITIVE

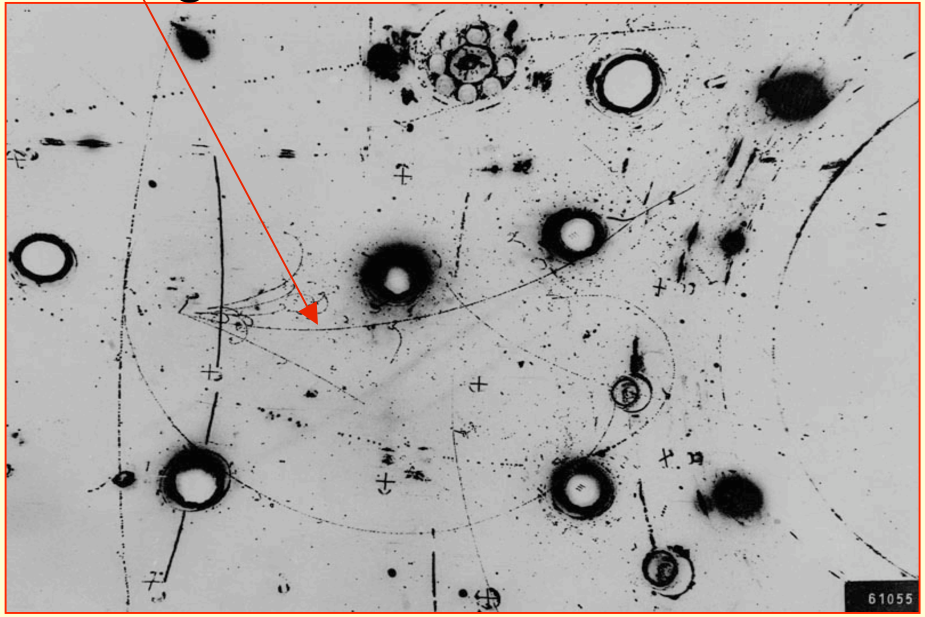
SELF-TRIGGERING

T_0 AVAILABLE (SCINTILLATION)

…an electronic bubble chamber

Bubble diameter ≈ 3 mm
(diffraction limited)

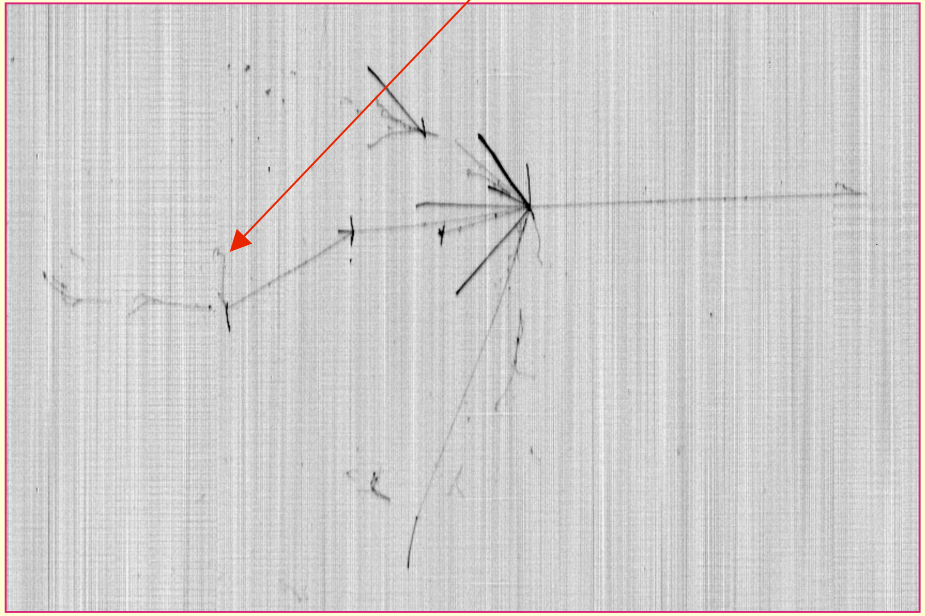
Gargamelle bubble chamber



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

Bubble size ≈ $3x3x0.4 \, mm^3$

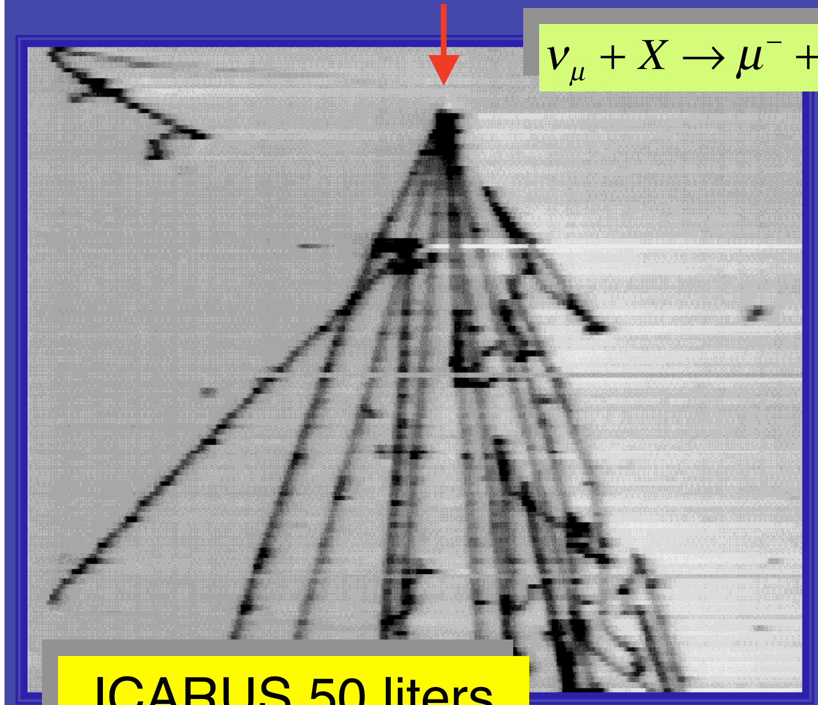
ICARUS electronic chamber



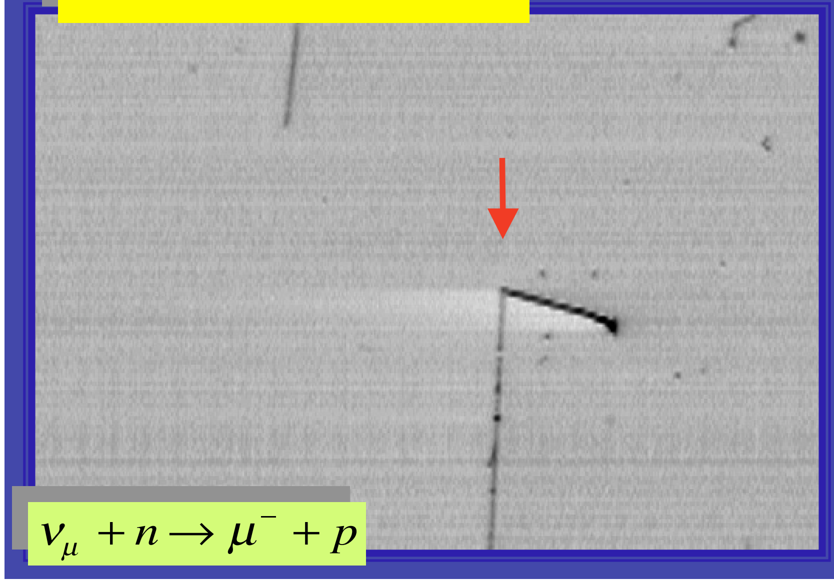
Medium	Liquid Argon	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

Real neutrino events observed by LAr TPC and water Cerenkov

$\nu_\mu + X \rightarrow \mu^- + many\ \ prongs$

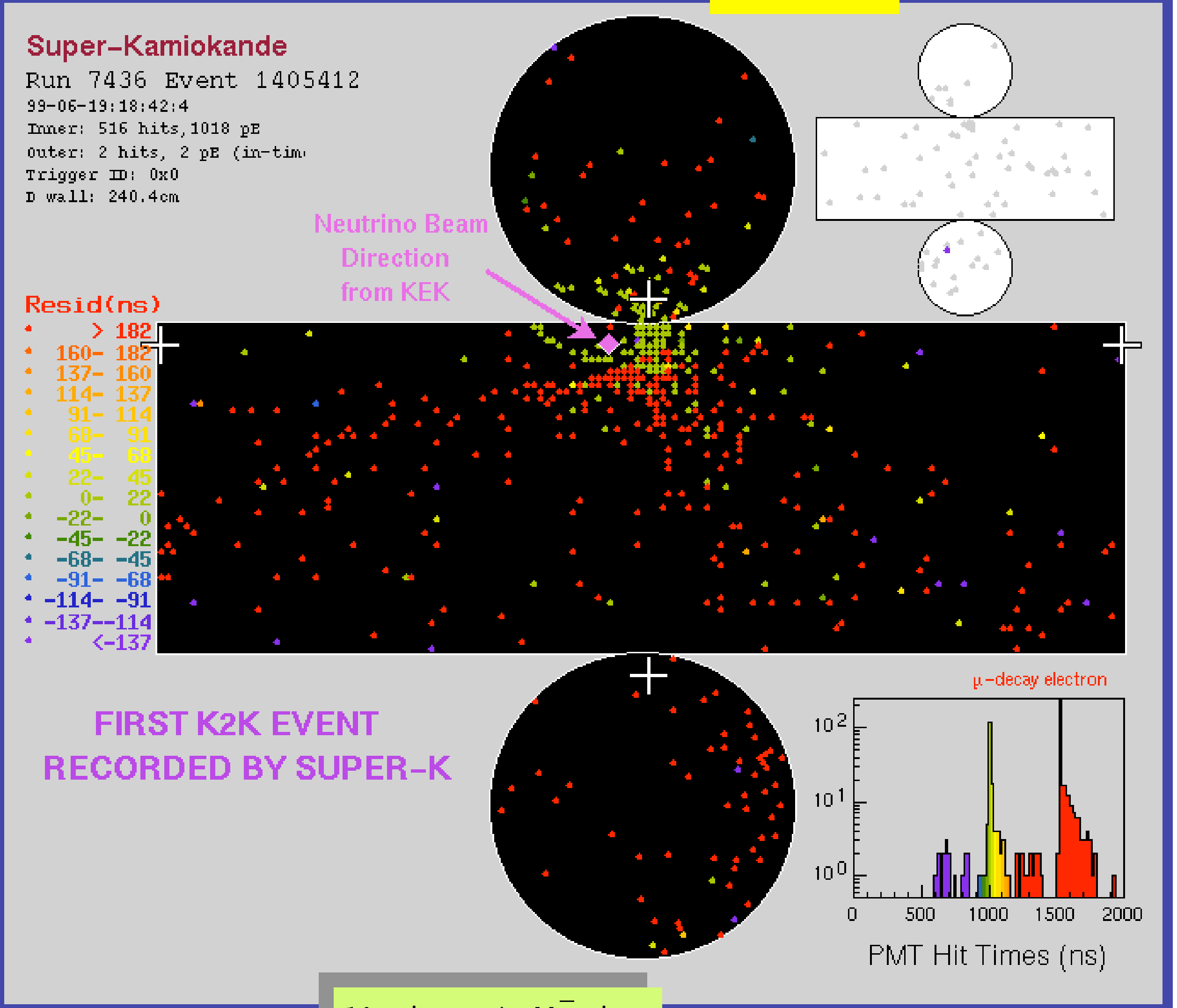


ICARUS 50 liters



$\nu_\mu + n \rightarrow \mu^- + p$

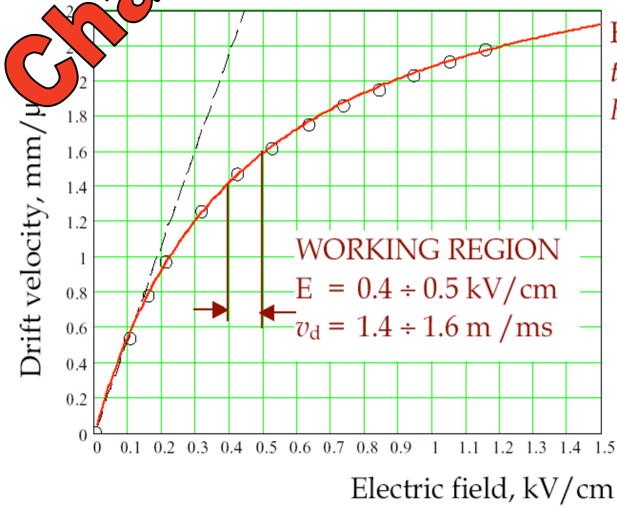
K2K



$\nu_\mu + n \rightarrow \mu^- + p$

Charge

Electron drift properties in liquid Argon

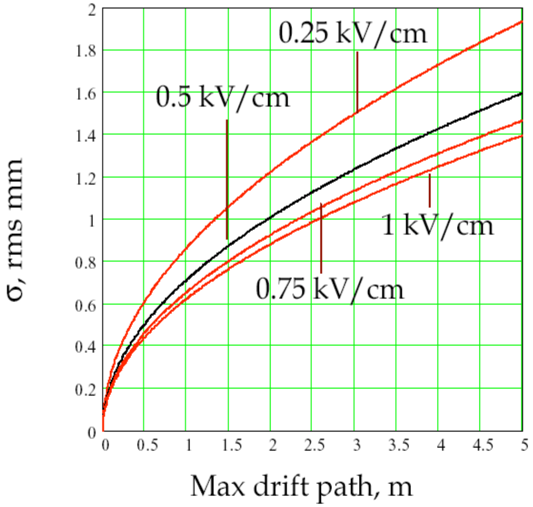


Drift velocity versus electric field in liquid argon

FOR 5 m MAX. DRIFT:

t_{max} = 3.6 ÷ 3.1 ms

HV_{max} = 200 ÷ 250 kV



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

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

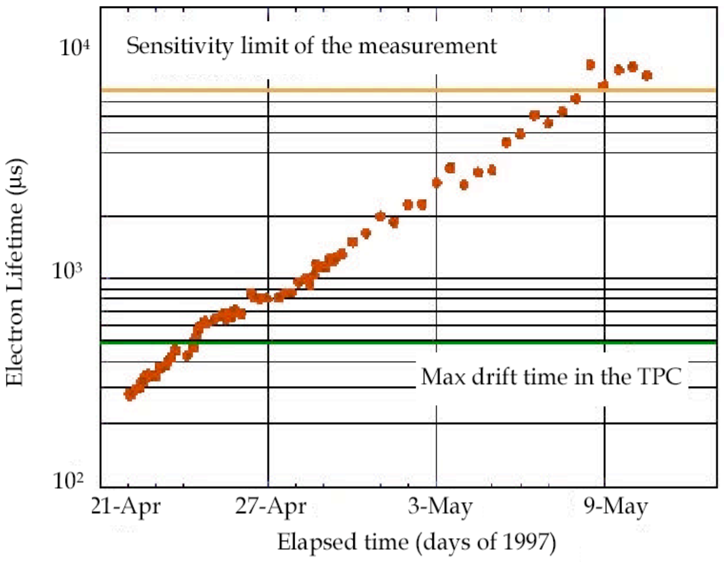
D = 4.06 cm²/s

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

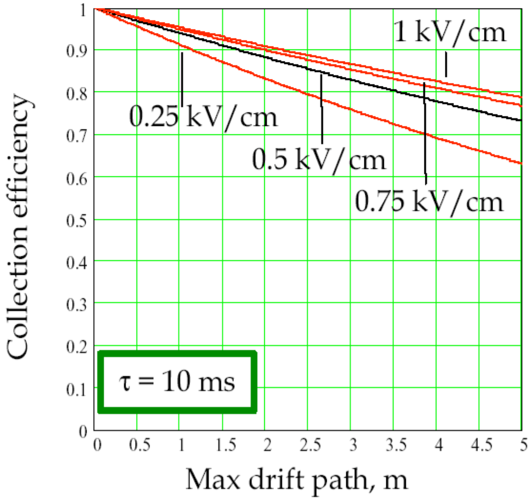
Longitudinal rms diffusion spread at 0.5 kV/cm

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

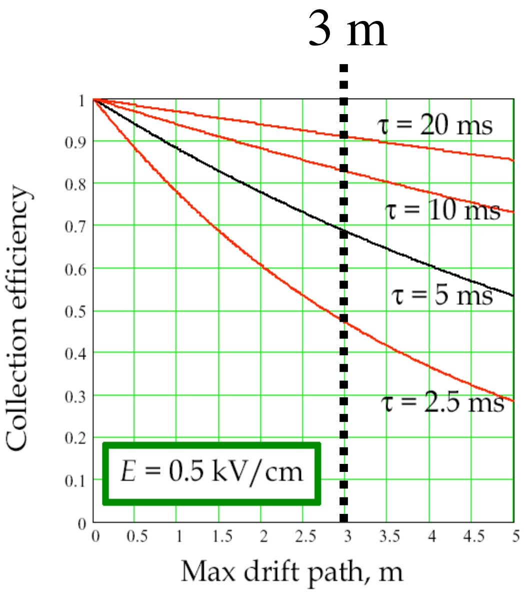
Maximum $\sigma_{D\max}$ = 1.6 mm



Purification rate for the 50L TPC



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



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

Dependence of the electron lifetime to the drift field

- By direct injection of given amounts of impurities:

$$\boxed{\tau \approx 300\mu s \times \frac{1\,ppb}{N(O_2)}}$$

- Essentially independent of the electric field for O_2

Purity goal (achieved):

< 0.1 ppb O_2-equivalent

A. Bettini et al., NIM A305 (1991) 177

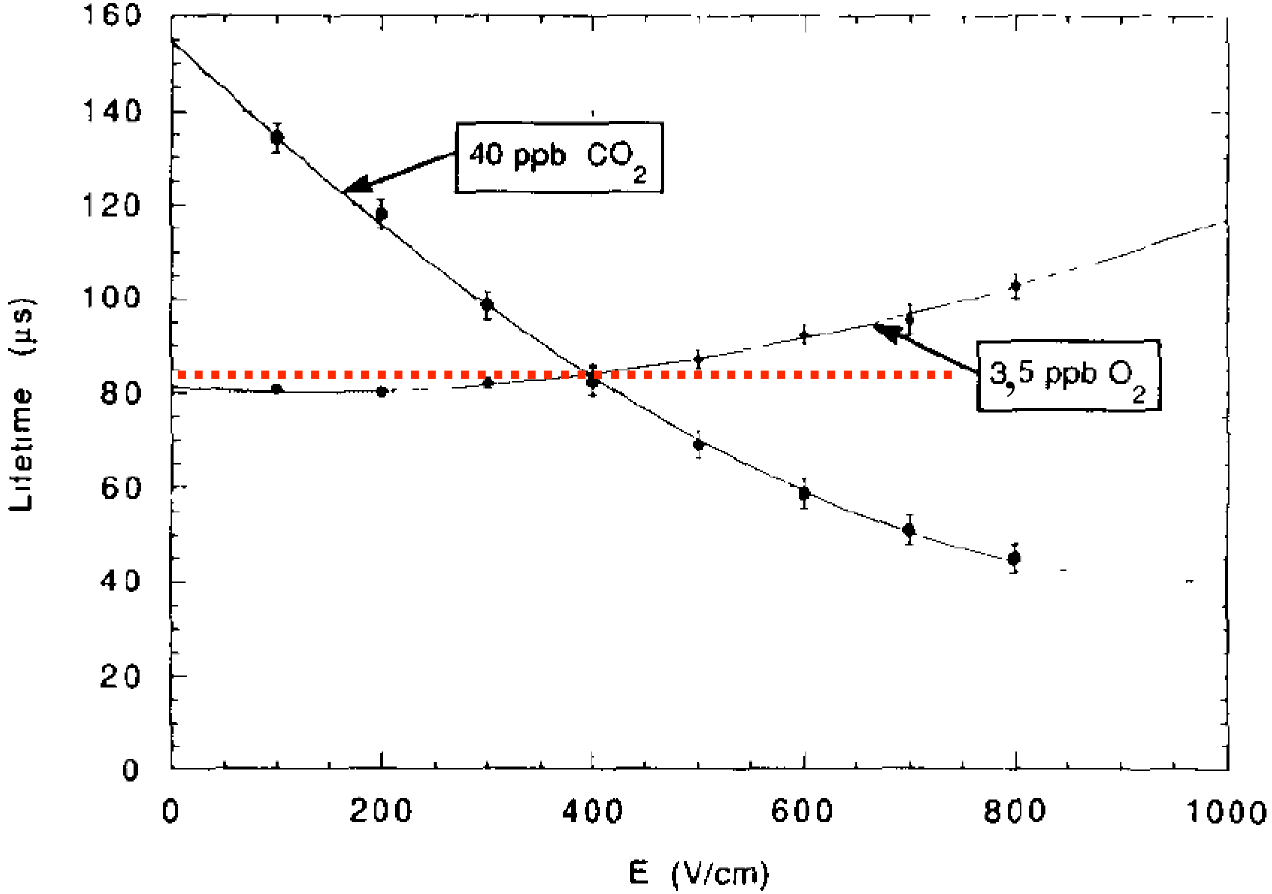
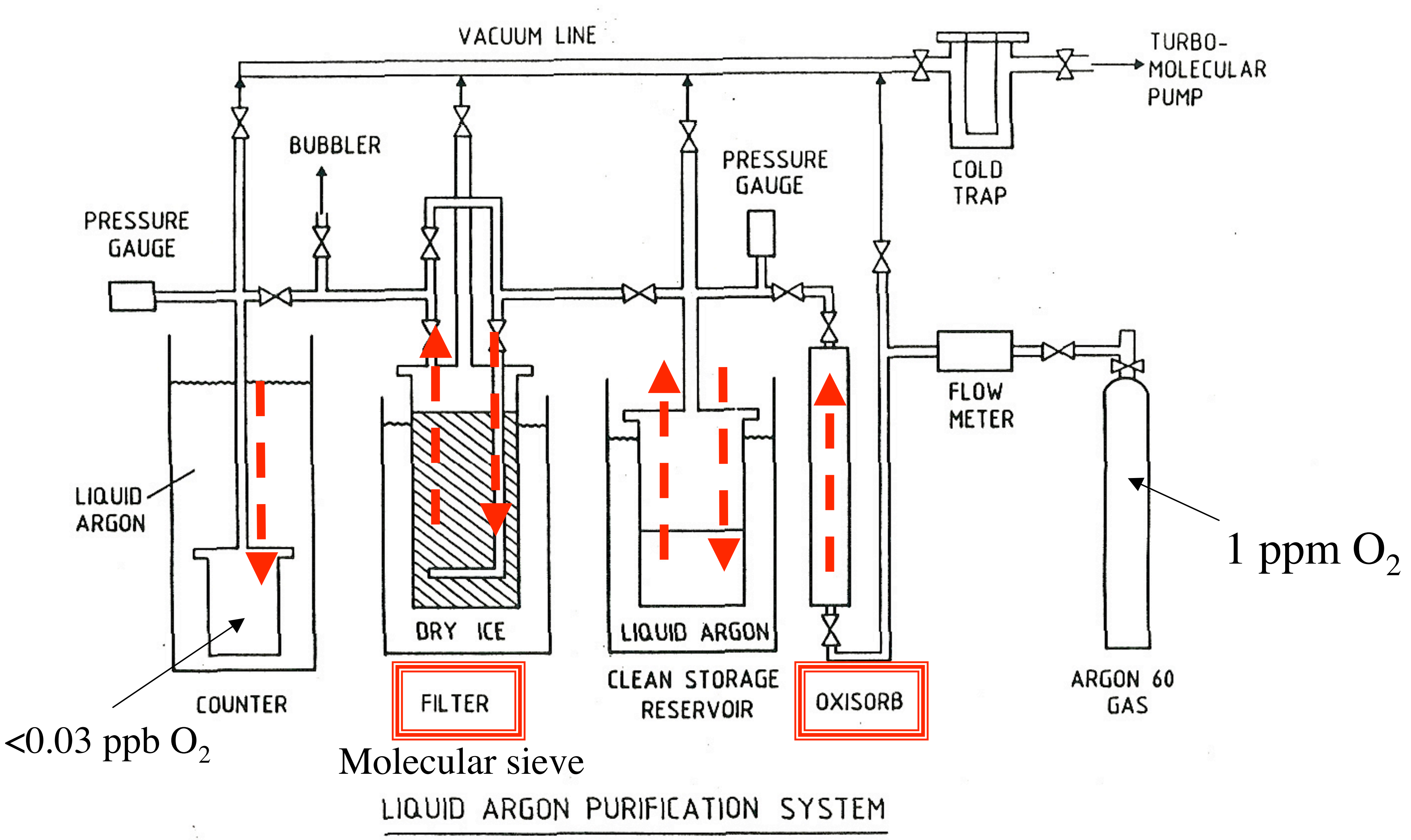


Fig. 12. Electric field dependence of the electron lifetime τ in purified LAr doped with 40 ppb CO_2 and 3.5 ppb O_2. Lines are drawn to guide the eye.

Argon purification system

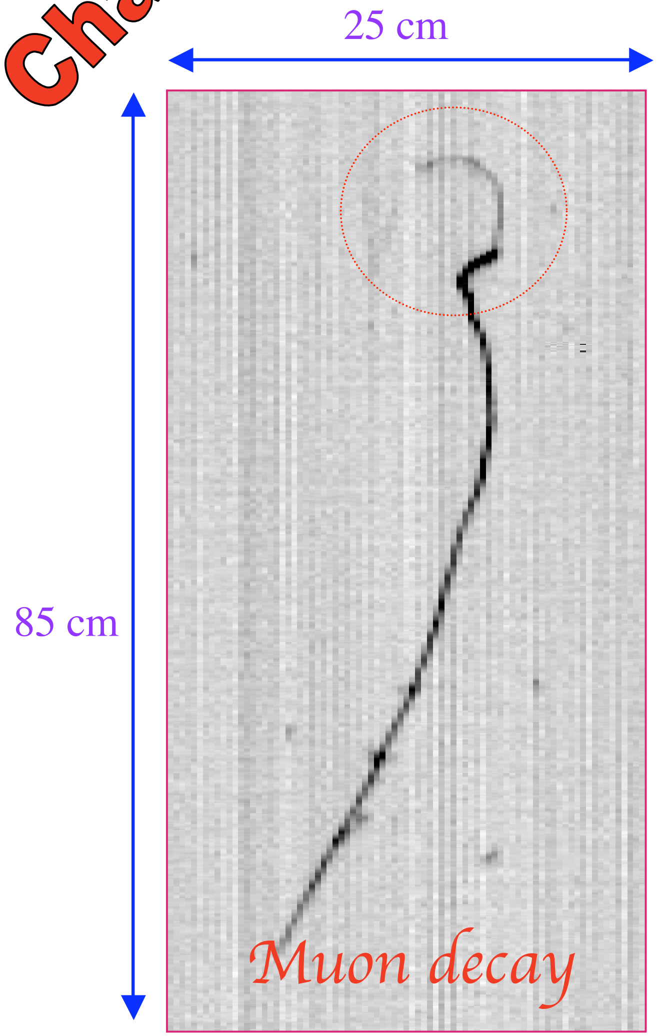


LIQUID ARGON PURIFICATION SYSTEM

All parts in stainless steel and baked under UH vacuum. Surfaces treated (electro-polishing)

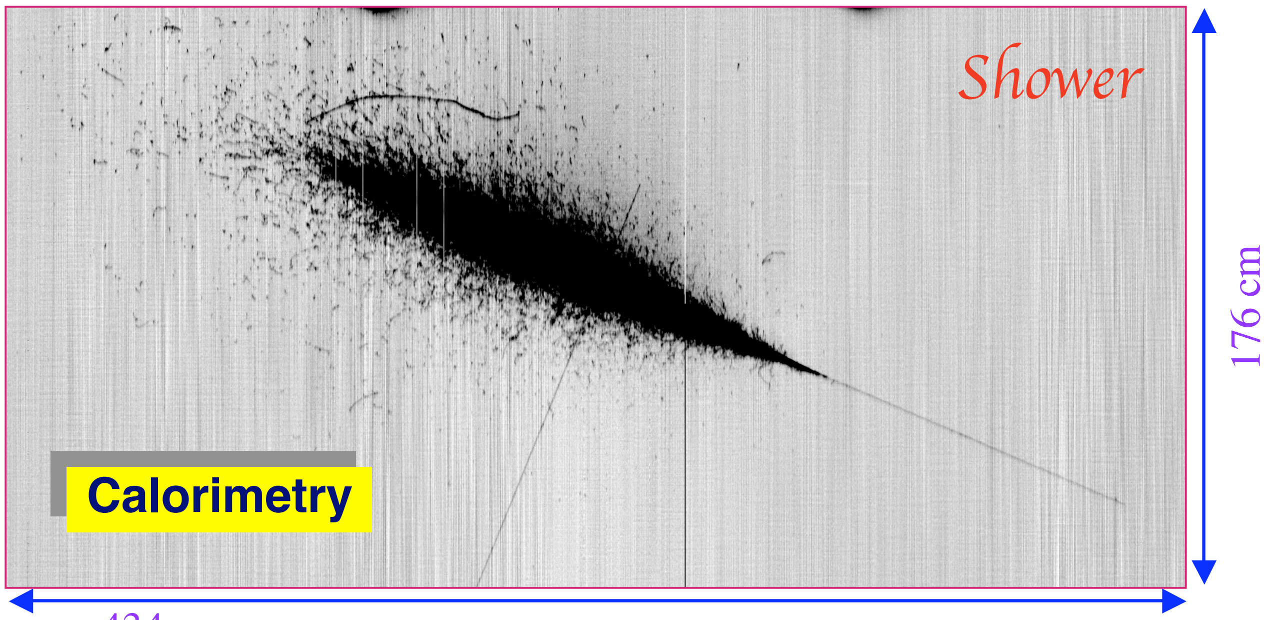
Cosmic rays events in the ICARUS T300

Charge

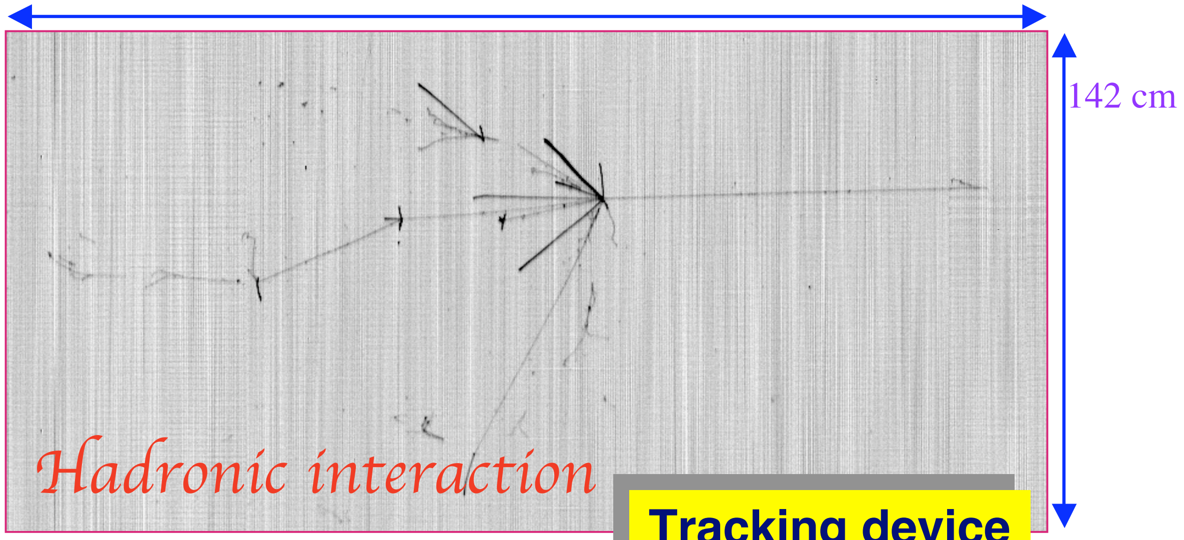


Run 960, Event 4 Collection Left

Measurement of local energy deposition dE/dx



Calorimetry



Run 308, Event 160 Collection Left

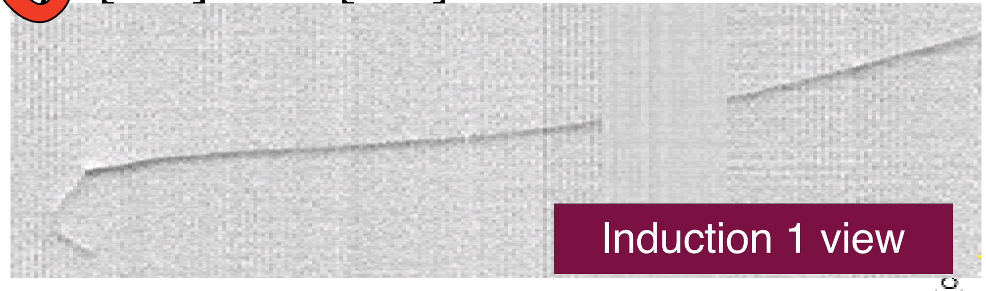
Tracking device

3D reconstruction of a stopping muon

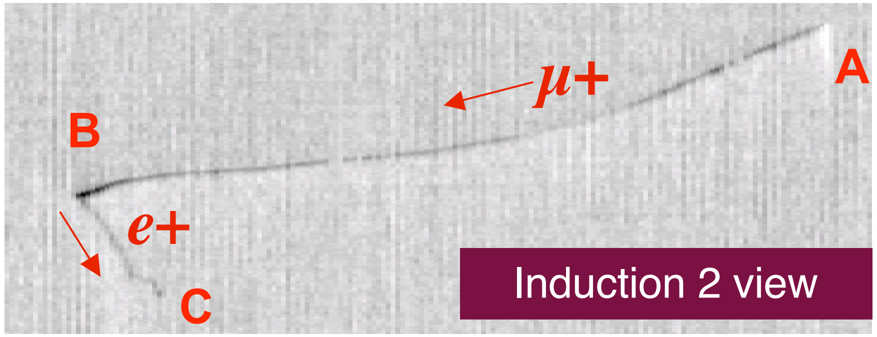
Charge

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

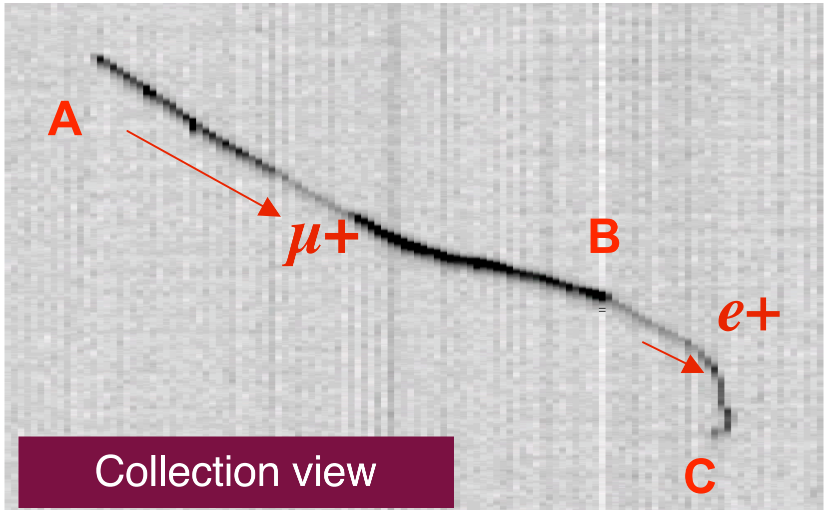
(Reconstruction is automatic)



Induction 1 view

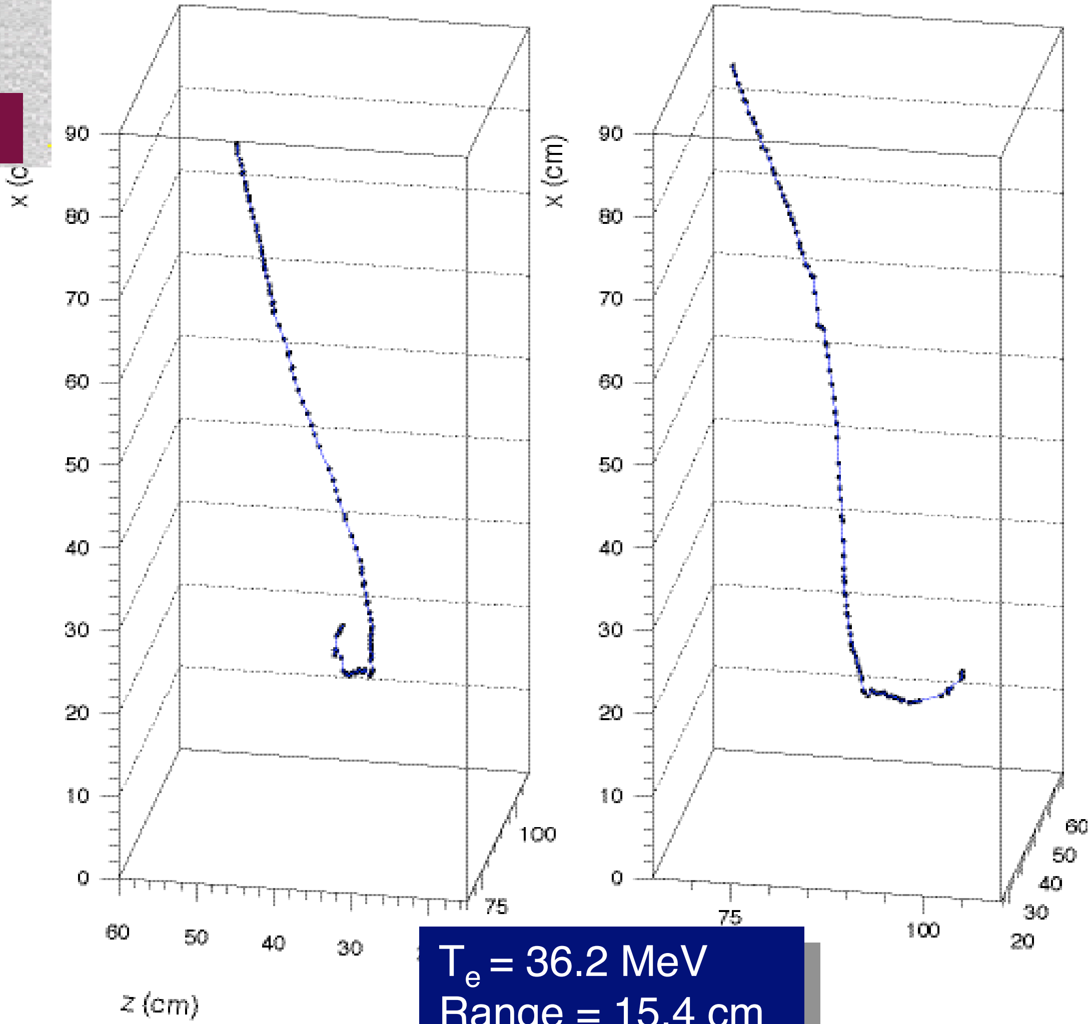


Induction 2 view



Collection view

Run 939 Event 95 Right chamber

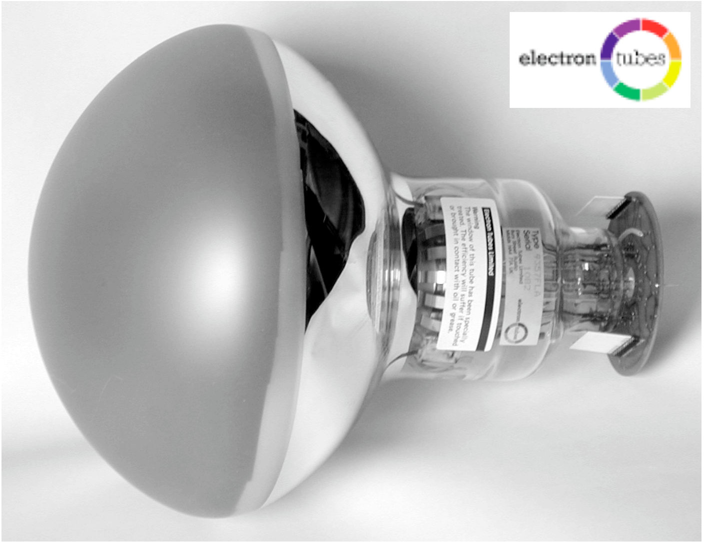


T_e = 36.2 MeV
Range = 15.4 cm

Scintillation

UV light readout

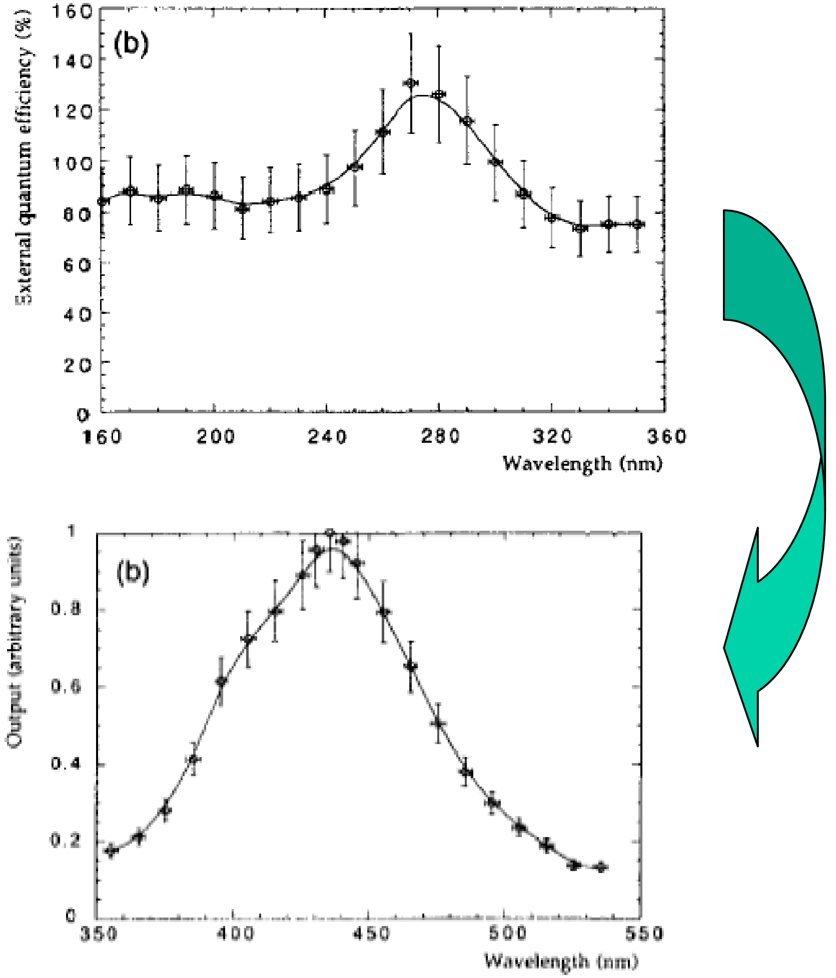
- Commercial PMT with large area
  - ➥Glass-window
- For scintillation VUV λ= 128 nm
  - ➥Wavelength-shifter
- Immersed T(LAr) = 87 K



Electron Tubes 9357FLA

8” PMT (bialkali with Pt deposit)
G = 1 x 10^7 @ ~1400 V
peak Q.E. (400-420 nm) ~ 18 % (≈10% cold)
T_{rise} ~ 5 ns, FWHM ~ 8 ns

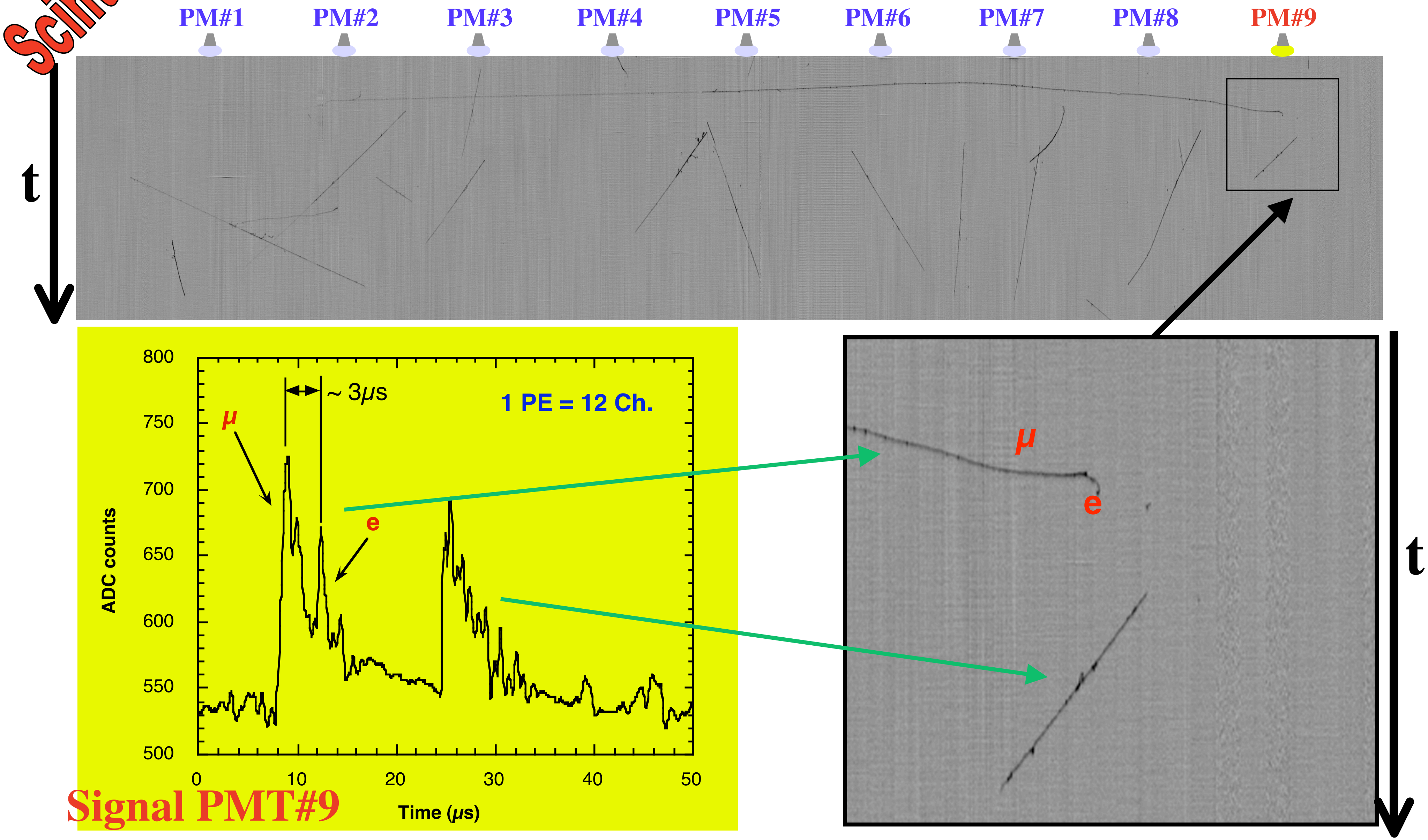
With TPB as WLS



Lally et al., NIMB 117 (1996) 421

Scintillation

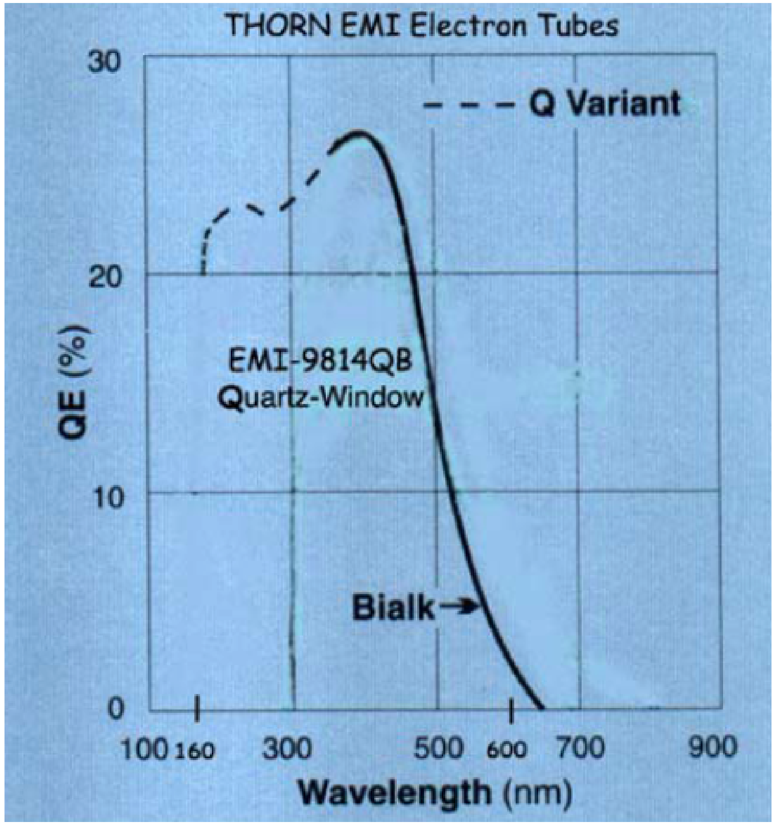
VUV scintillation light readout

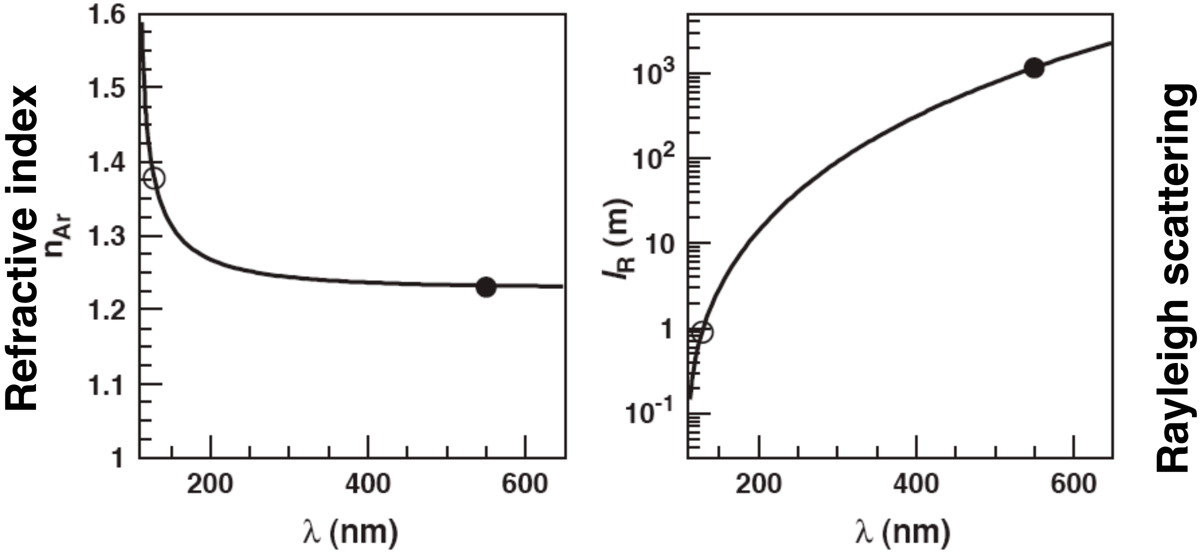


Cerenkov

Cerenkov light readout

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



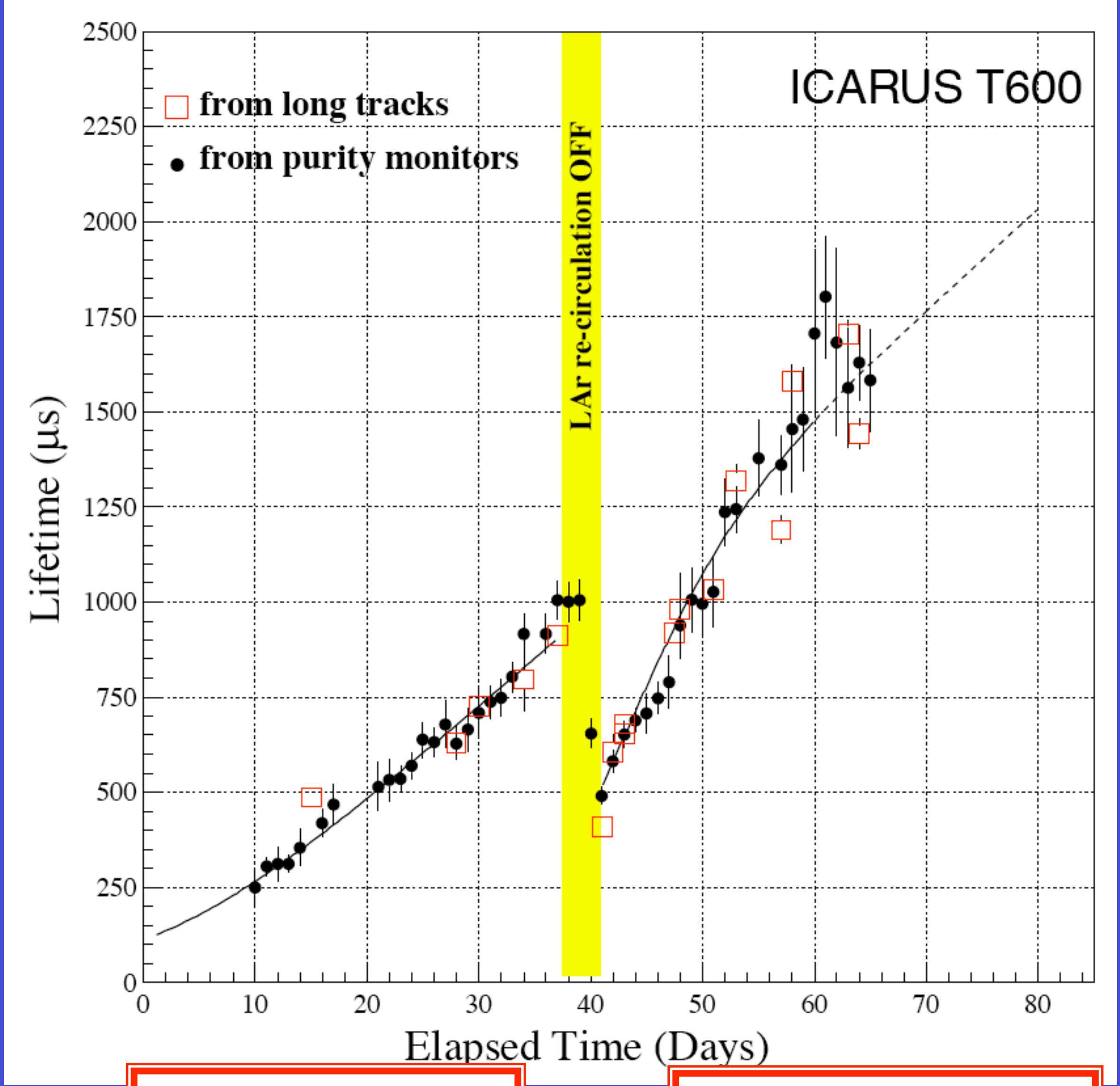


Data consistent with Cerenkov emission:

dN/dx (160-600 nm) ≈ 700 γ/cm (β≈1)

Liquid Argon purity in large volumes

ICARUS Collab., *Analysis of the liquid Argon purity in the ICARUS T600 TPC,* NIM A 516 (2004) 68



$\tau_{max} \approx 1.8$ ms

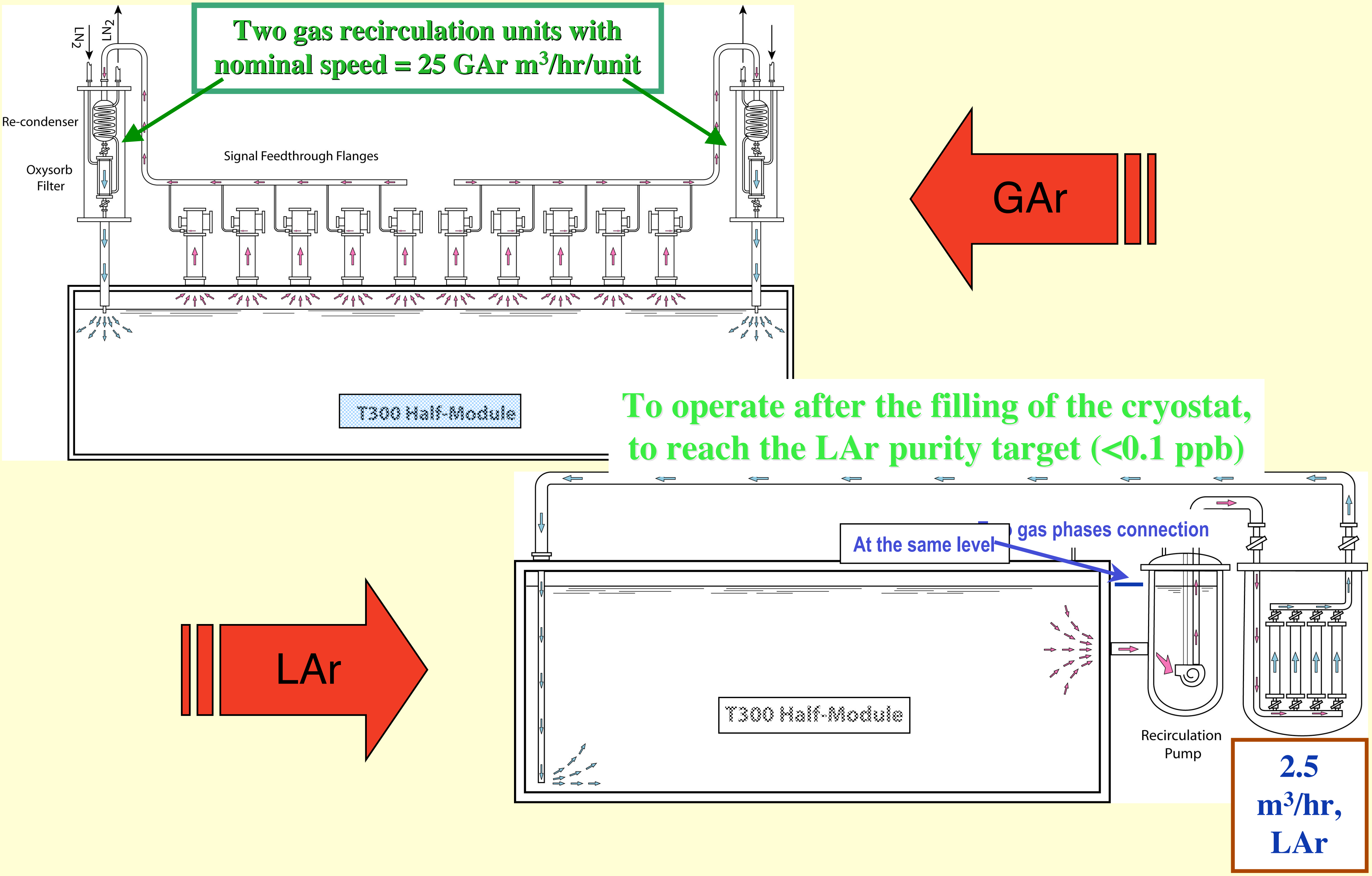
$N_{min} \approx 0.2$ ppb

Interpretation of purity curve as a function of time

- Results consistent with the assumption that a dominant source of outgassing is located in the "hot" parts of the detector (e.g. readout cables outside the liquid, etc.) and no significant time-independent contribution (leak, etc.).

Under these assumptions, one can extrapolate to infinite time to find an asymptotic drift electron lifetime >13 ms. This result makes us confident about the understanding and the control of the liquid argon purity.

ICARUS T600 purification system (recirculation scheme)

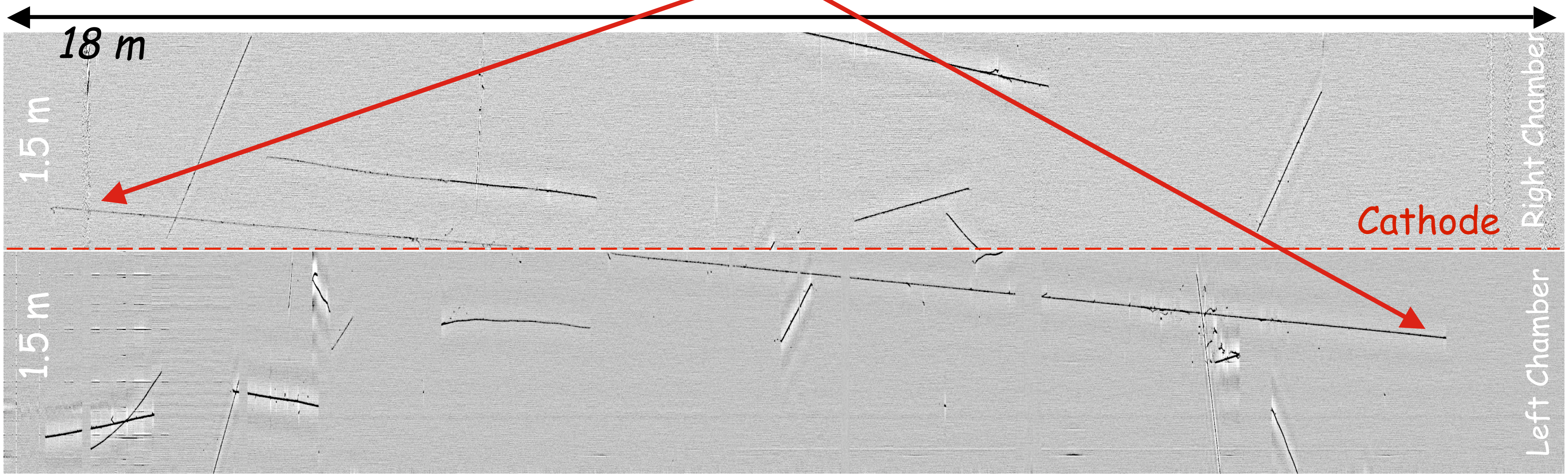


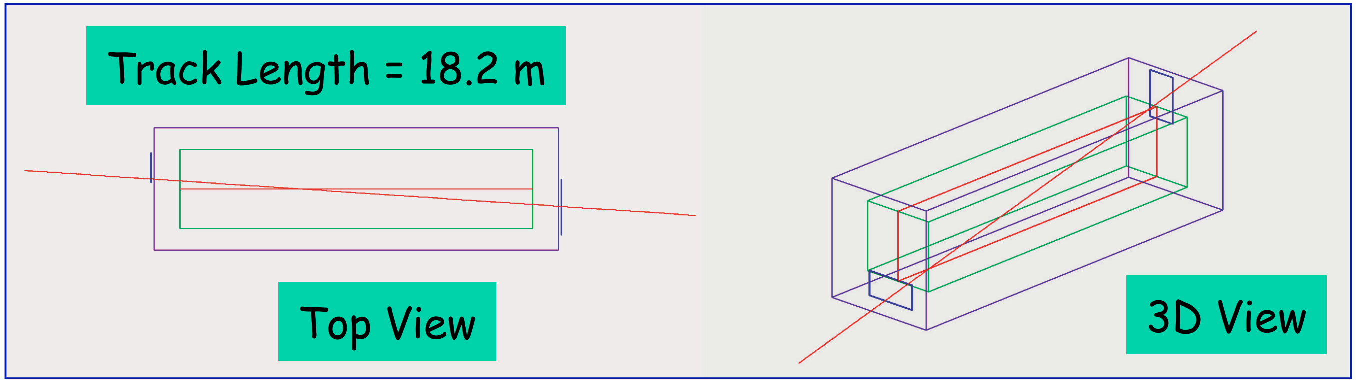
Two gas recirculation units with nominal speed = 25 GAr m^3/hr/unit

To operate after the filling of the cryostat, to reach the LAr purity target (<0.1 ppb)

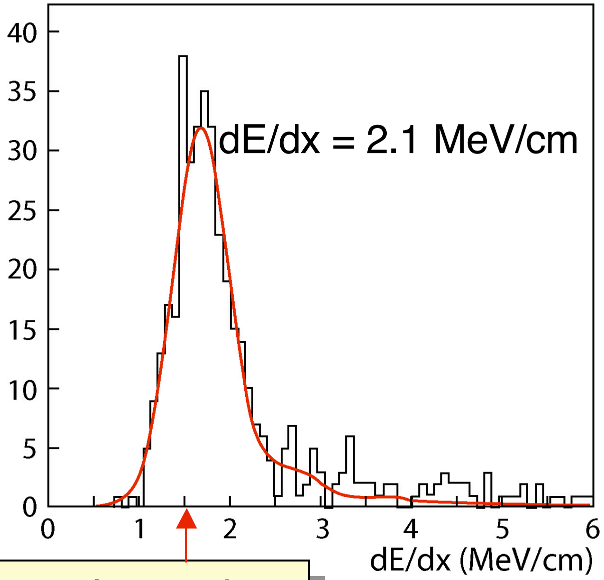
2.5 m^3/hr, LAr

Long longitudinal muon track crossing the cathode plane



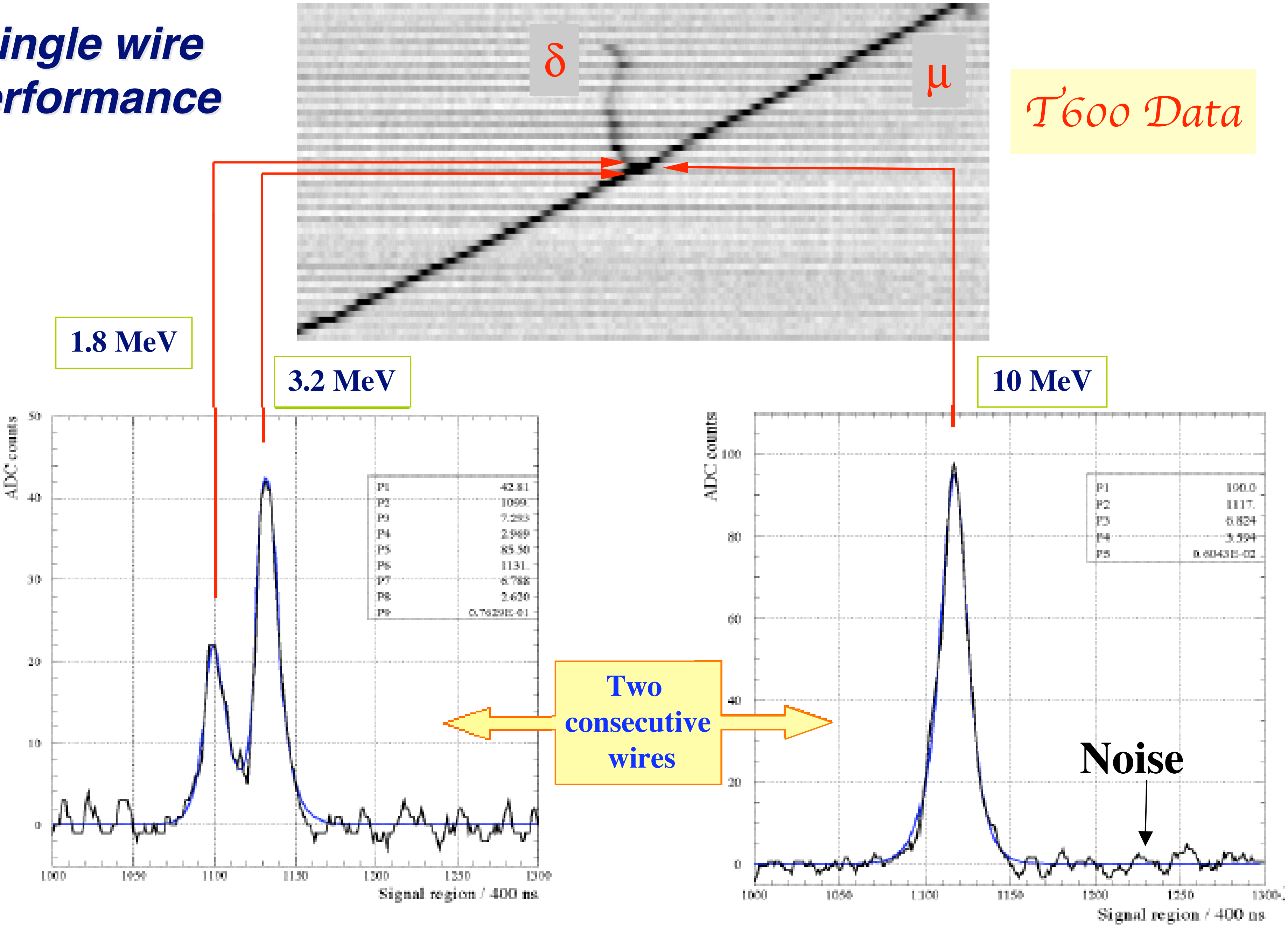


3-D reconstruction of the long track



dE/dx distribution along the track

Single wire performance



T600 Data

1.8 MeV

3.2 MeV

10 MeV

Two consecutive wires

Noise

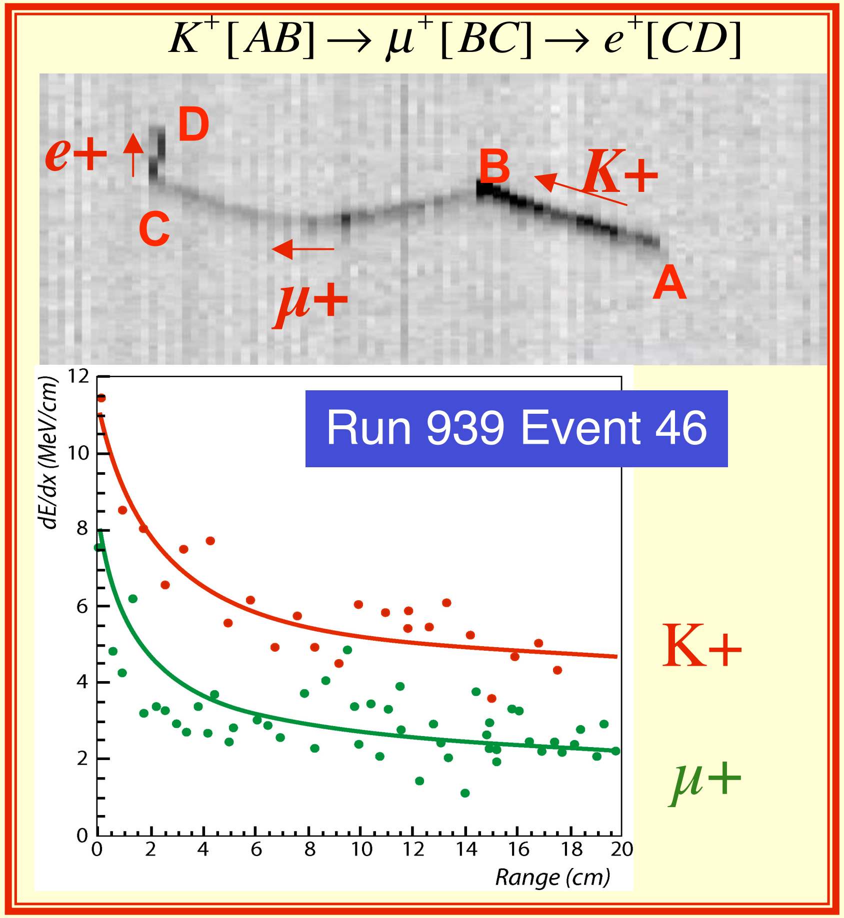
Threshold above noise ≈ 200 KeV

Detector performance

- **Tracking device**
  - ➥ Precise event topology
  - ➥ Momentum via multiple scattering
- **Measurement of local energy deposition dE/dx**
  - ➥ e / γ separation (2%X_0 sampling)
  - ➥ Particle ID by means of dE/dx vs range measurement
- **Total energy reconstruction of the events from charge integration**
  - ➥ Full sampling, homogeneous calorimeter with excellent accuracy for contained events

ENERGY RESOLUTION

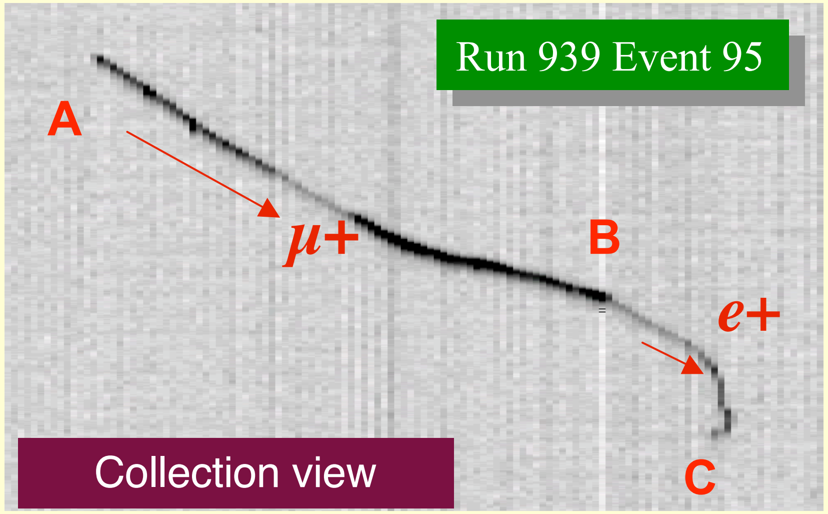
Low energy electrons:	σ(E)/E = 11% / √E(MeV)+2%
Electromagn. showers:	σ(E)/E = 3% / √E(GeV)
Hadron shower (pure LAr):	σ(E)/E ≈ 30% / √E(GeV)
Hadron shower (+TMG):	σ(E)/E ≈ 17% / √E(GeV)



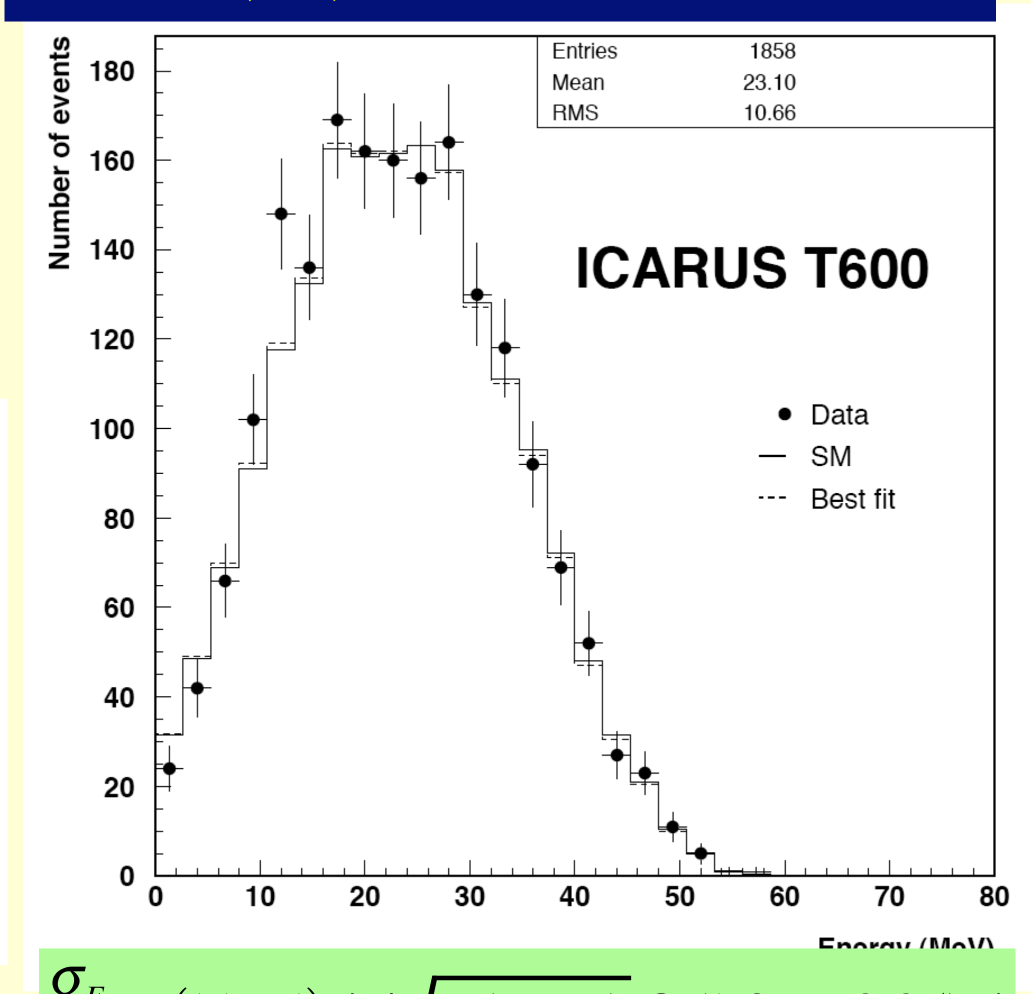
$$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$$

Measurement of the muon decay spectrum and ρ parameter

ICARUS Collab., "Measurement of the muon decay spectrum with the ICARUS T600 liquid Argon TPC", Eur. Phys. J. C33, 233-241 (2004)



Author	Value	Assumption
Peoples	0.750 ± 0.003	$\eta \equiv 0$
Sherwood	0.760 ± 0.009	$\eta \equiv 0$
Fryberger	0.762 ± 0.008	$\eta \equiv 0$
Derenzo	0.752 ± 0.003	$-0.13 < \eta < 0.07$
SLD	$0.72 \pm 0.09 \pm 0.03$	lepton univers.
CLEO	$0.747 \pm 0.010 \pm 0.006$	lepton univers.
ARGUS	0.731 ± 0.031	lepton univers.
L3	$0.72 \pm 0.04 \pm 0.02$	lepton univers.
OPAL	$0.78 \pm 0.03 \pm 0.02$	lepton univers.
DELPHI	$0.78 \pm 0.02 \pm 0.02$	lepton univers.
ALEPH	0.742 ± 0.016	lepton univers.
This analysis	$0.72 \pm 0.06 \pm 0.08$	$-0.020 < \eta < 0.006$



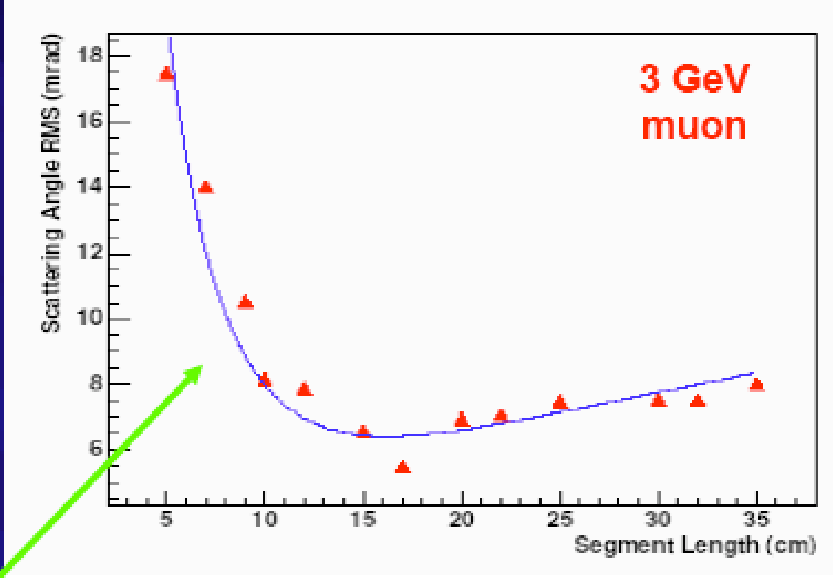
$$\frac{\sigma_E}{E} = (11 \pm 1)\% / \sqrt{E(MeV)} \oplus (1.97 \pm 0.05)\%$$

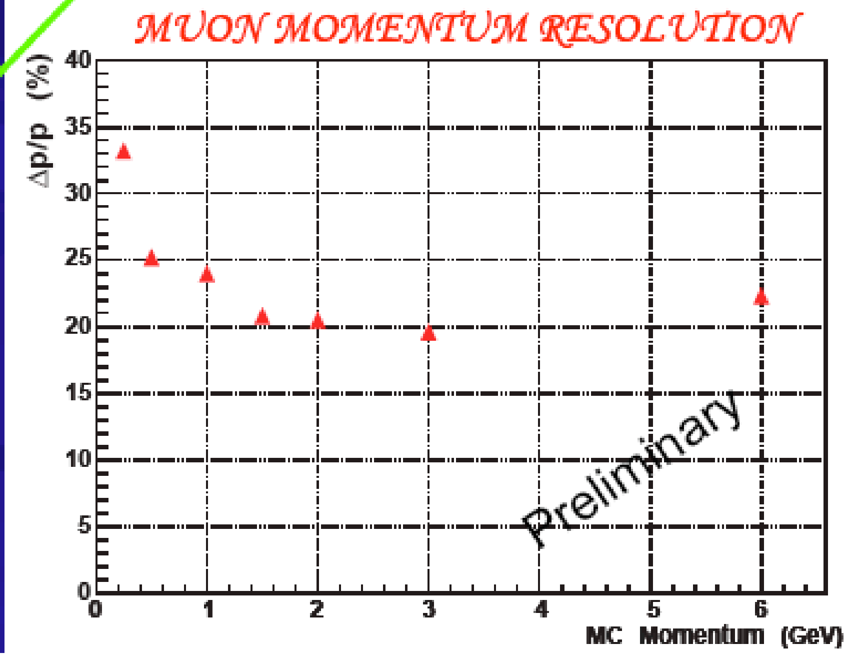
Momentum measurement via multiple scattering

- Essential to measure kinematics properties of non-contained events
  - Interest focused on atmospheric events
- Full simulation of muon events for a broad momentum range
  - Include all detector effects
- Split track into segments. Measured angles have two contributions:

$$\left(\vartheta^{RMS}_{meas}\right)^2 = \left(\vartheta^{RMS}_{0}\right)^2 + \left(\vartheta^{RMS}_{noise}\right)^2; \quad \vartheta^{RMS}_{0} \propto \sqrt{L_{seg}}\,/\,p; \quad \vartheta^{RMS}_{noise} \propto L_{seg}^{-3/2}$$

- Momentum extracted from fit over a sample of different segment lengths
- Resolutions ≈20-25%
- Future analysis…
  - Resolution improvement with alternative methods (e.g. Kalman Filter)?
  - Validate conclusions with real data: large sample of stopping muons

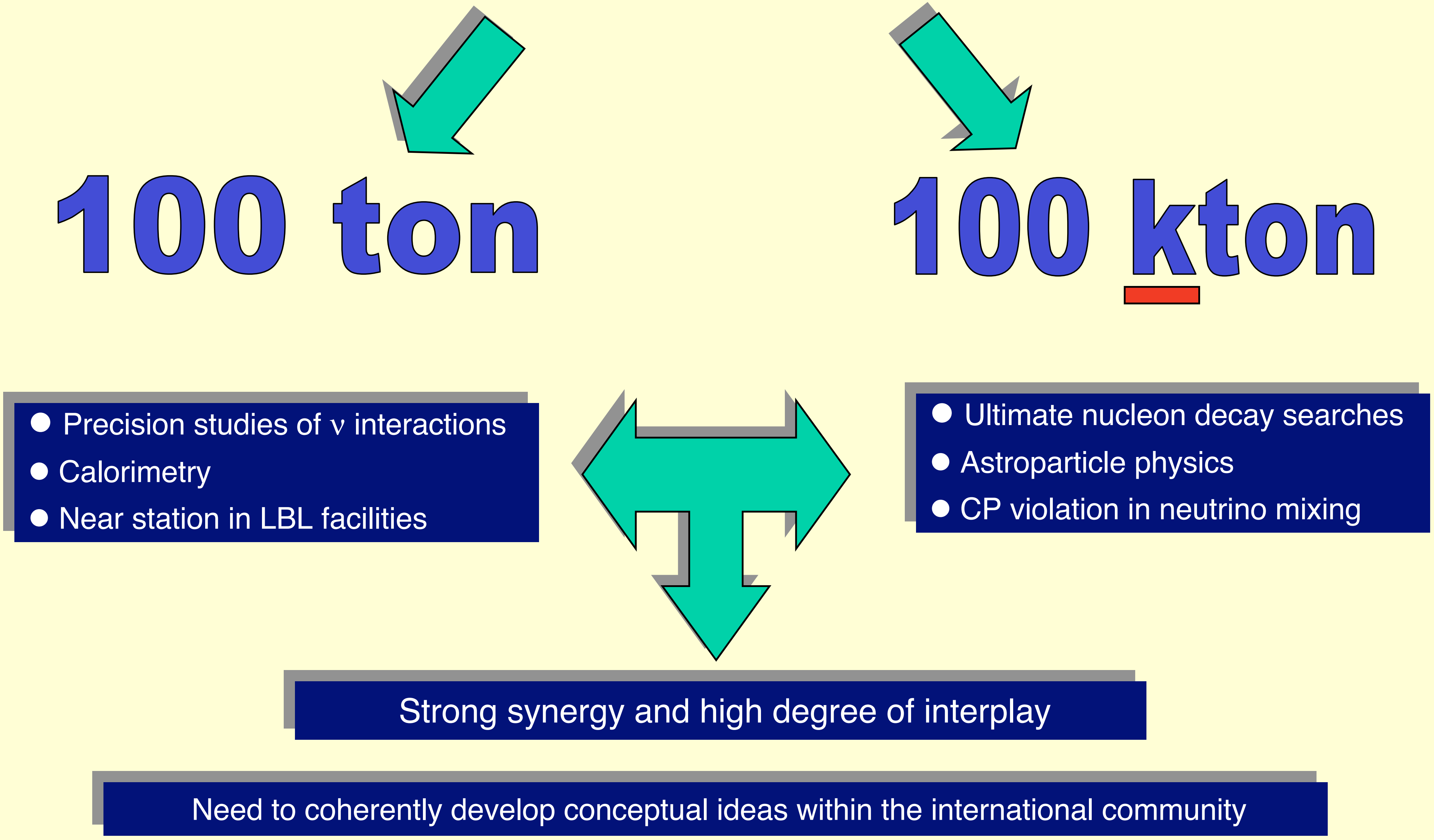




Future applications

Liquid Argon TPC:

physics calls for applications at two different mass scales



100 ton

100 kton

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

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

Strong synergy and high degree of interplay

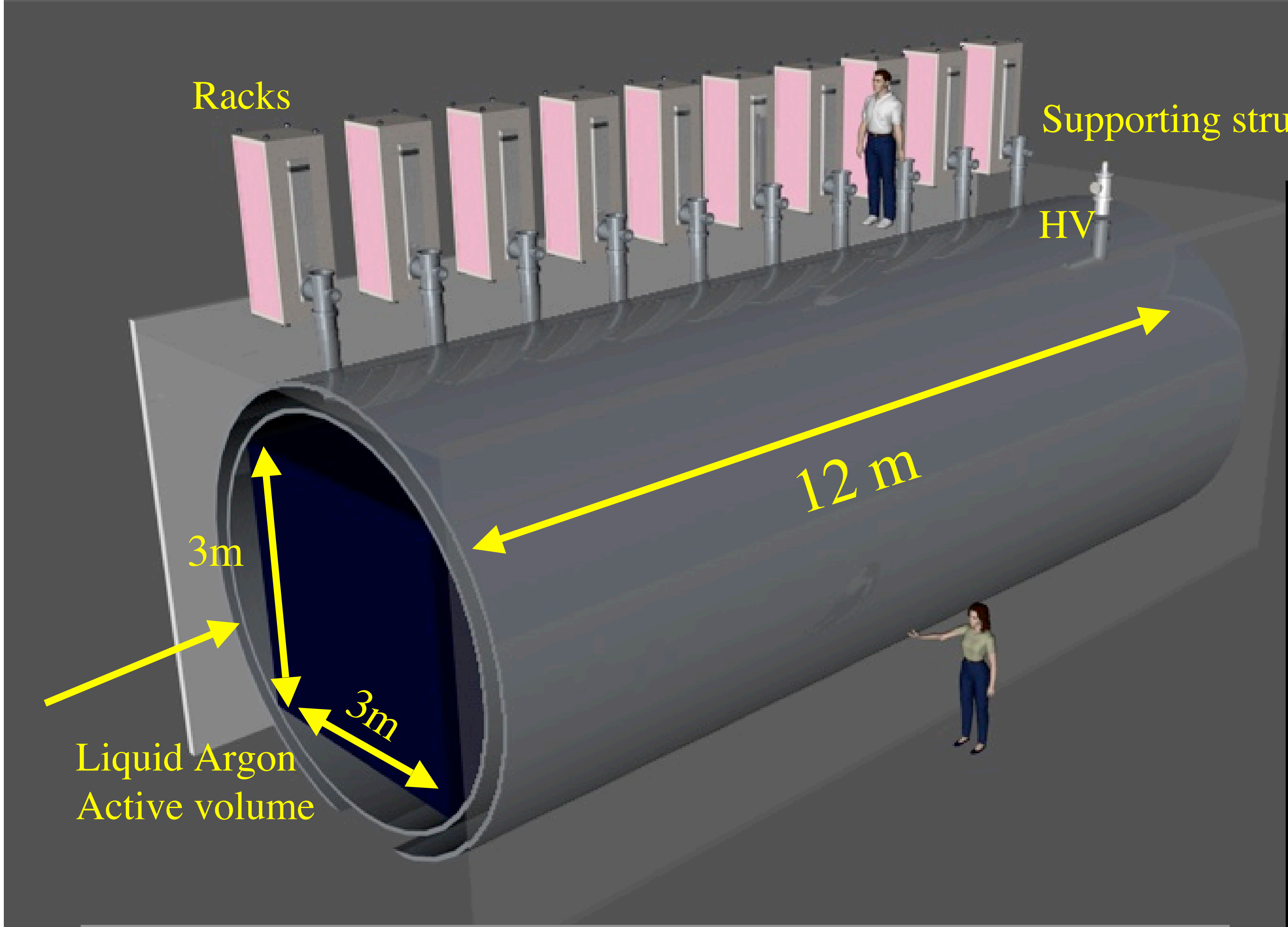
Need to coherently develop conceptual ideas within the international community

100 ton

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

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

a possibility being further explored

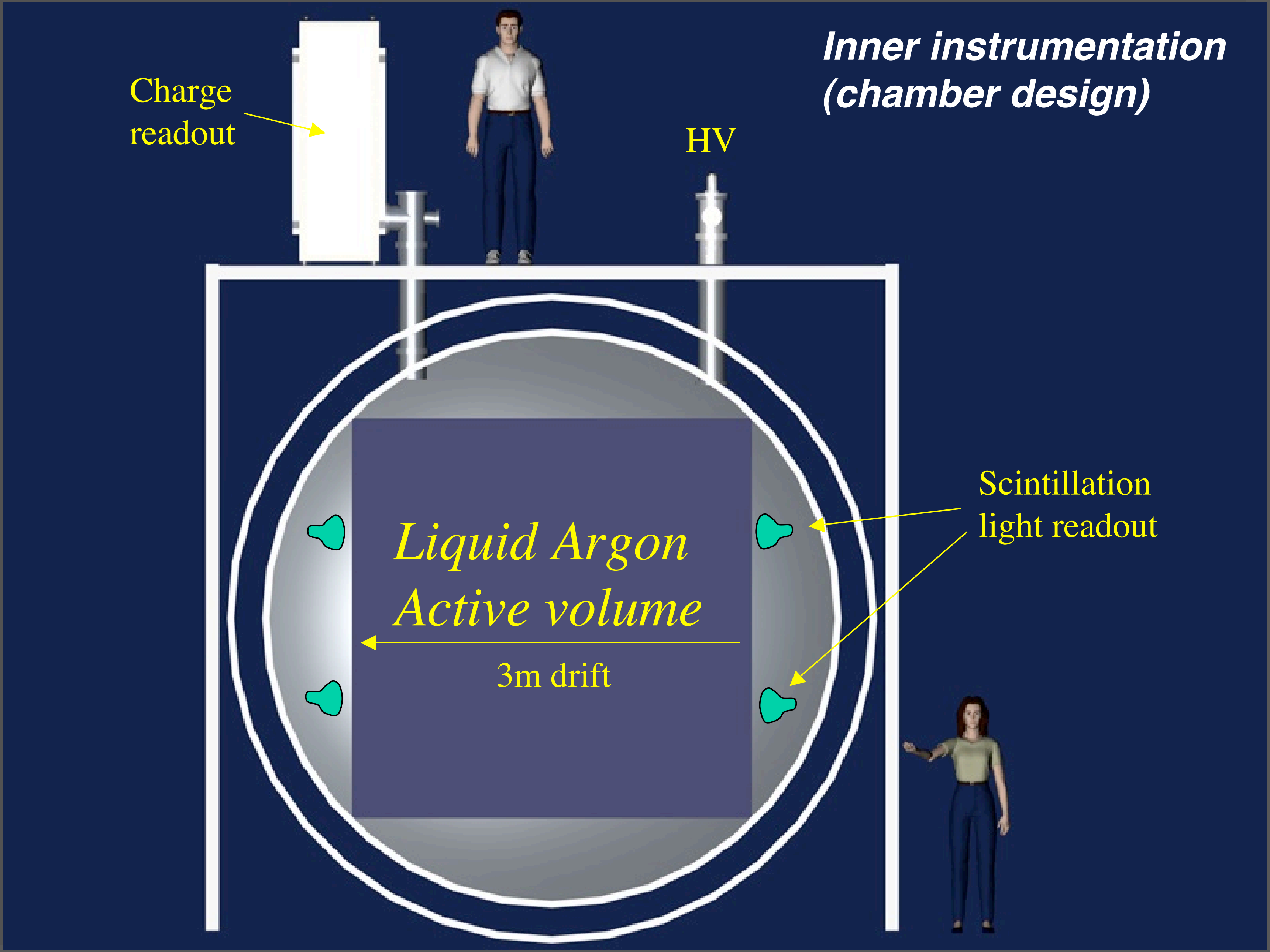


Outer vessel	$\phi \approx$ 5m, L≈13m, 15mm thick, weight ≈ 22 t
Inner vessel	$\phi \approx$ 4,2 m, L ≈ 12 m, 8 mm thick, ≈ 10 t
LAr	Total ≈ 240 t Fiducial ≈ 100 t
Max e- drift	3 m @ HV=150 kV E = 500 V/cm
Charge R/O	2 views, ± 45° 2 (3) mm pitch
Wires	≈10000 (7000) $\phi = 150\ \mu m$
R/O electr.	on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

Ideas for future liquid Argon detectors

A.Ereditato, A.Rubbia, to appear in Proc. of NUINT04, LNGS, March 2004

Inner instrumentation (chamber design)



Design process on-going

Location of current/planned neutrino beams

FNAL

120 GeV Main Injector **NUMI (0.4MW)**

8 GeV booster **BOONE**

JAERI

50 GeV PS

J-PARC (0.75MW)

(under construction, ν-beam>2009)

BNL

24 GeV AGS

CERN

400 GeV SPS

CNGS (0.3MW)

KEK

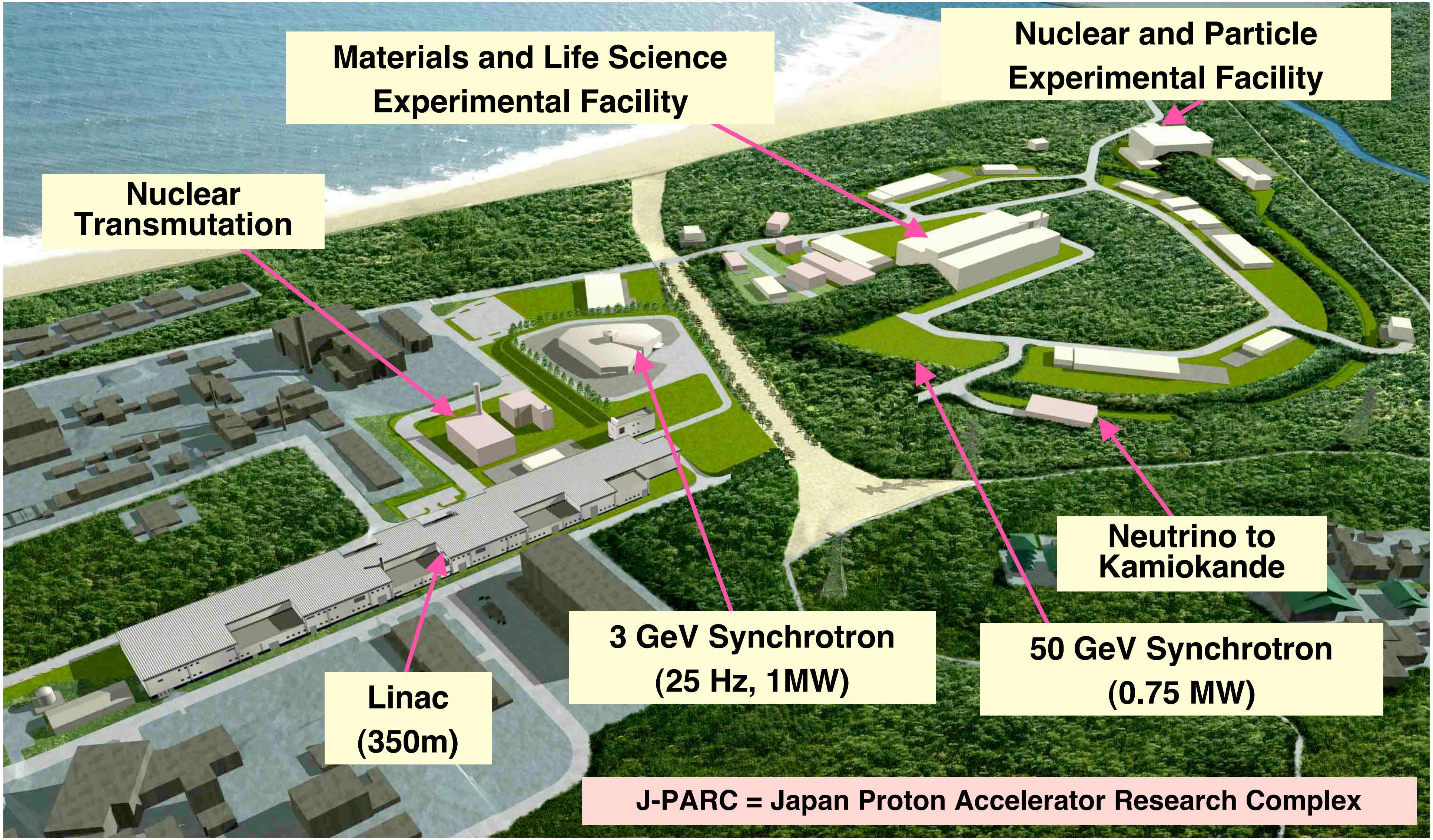
12 GeV PS

K2K

0.005 MW

The reality: the approved J-PARC Facility

0.75 MW at start, plans for upgrades



Materials and Life Science Experimental Facility

Nuclear and Particle Experimental Facility

Nuclear Transmutation

Neutrino to Kamiokande

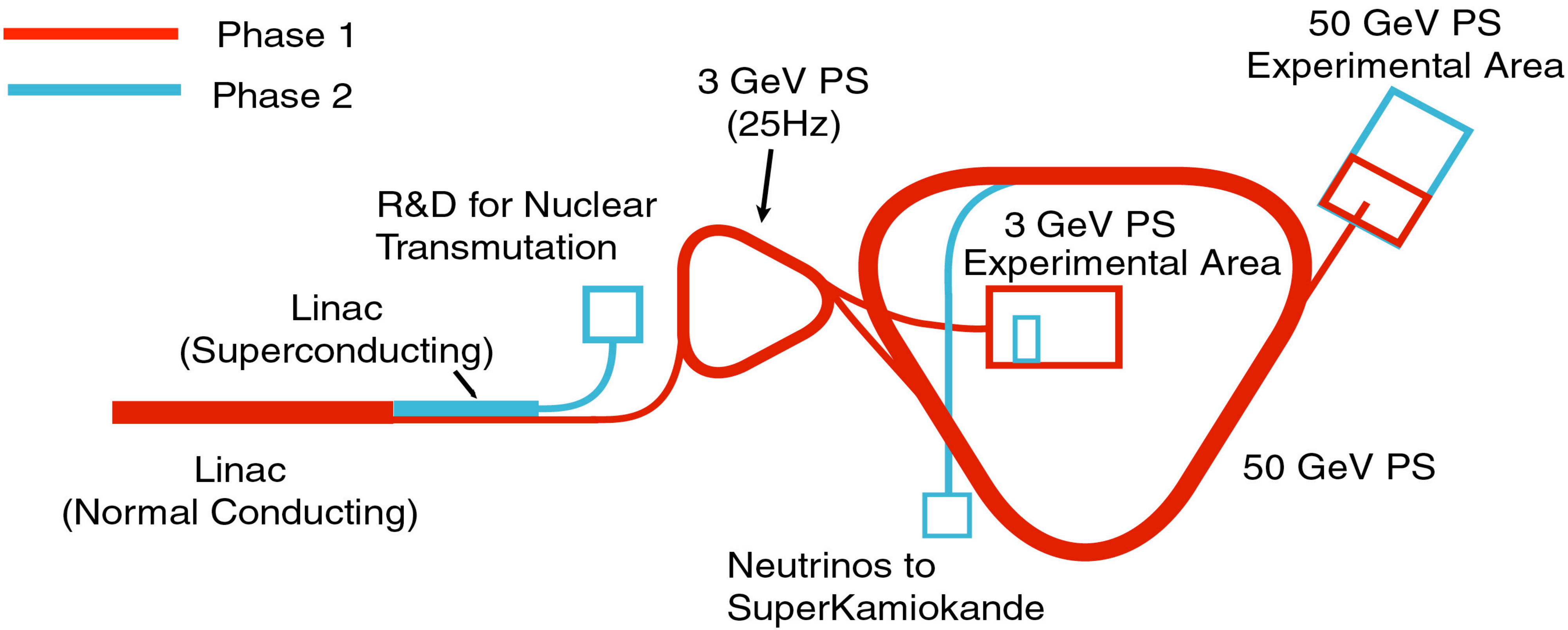
3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

Linac (350m)

J-PARC = Japan Proton Accelerator Research Complex

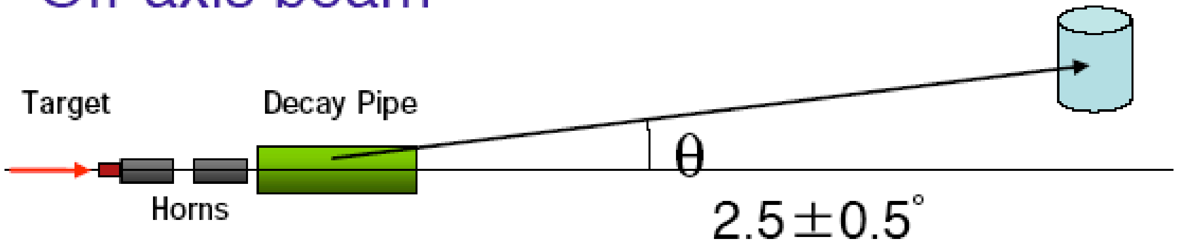
Phase 1 and Phase 2 (as of 2001)

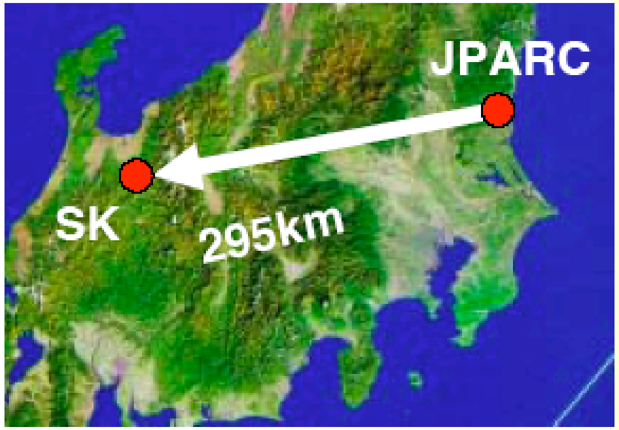


- Phase 1 + Phase 2 = 189 billion Yen (= $1.89 billion if $1 = 100 Yen).
- Phase 1 = 133.5 billion Yen for 6 years (= 2/3 of 189 billion Yen).
- Construction budget does not include salaries.

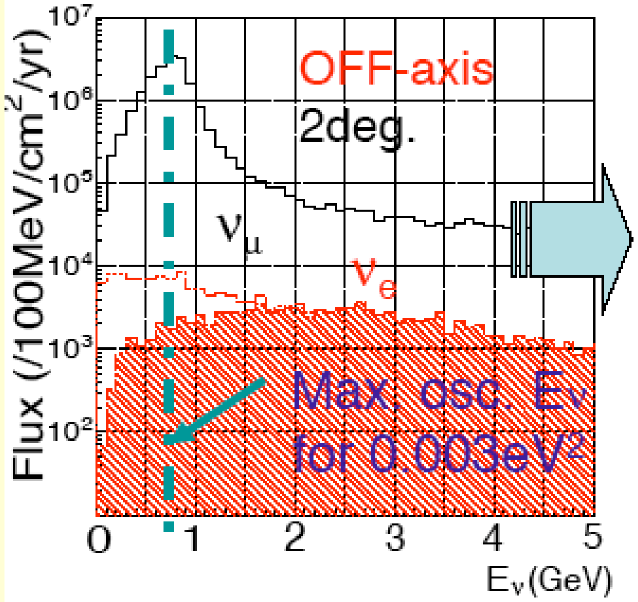
JPARC neutrino project = T2K

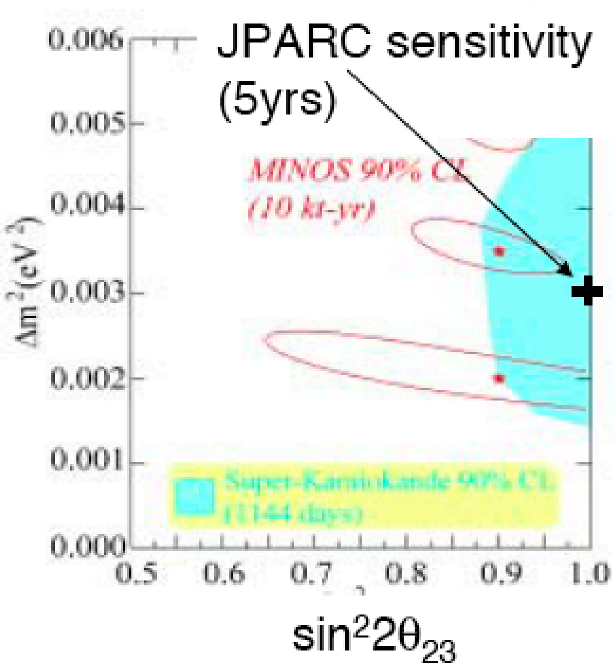
Off-axis beam

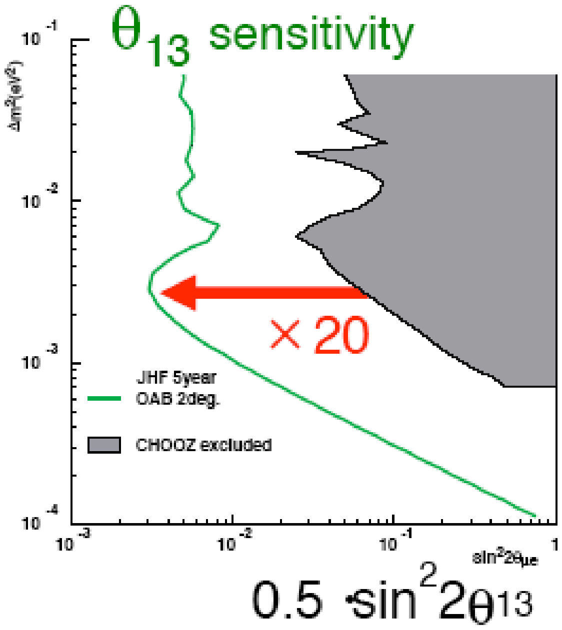


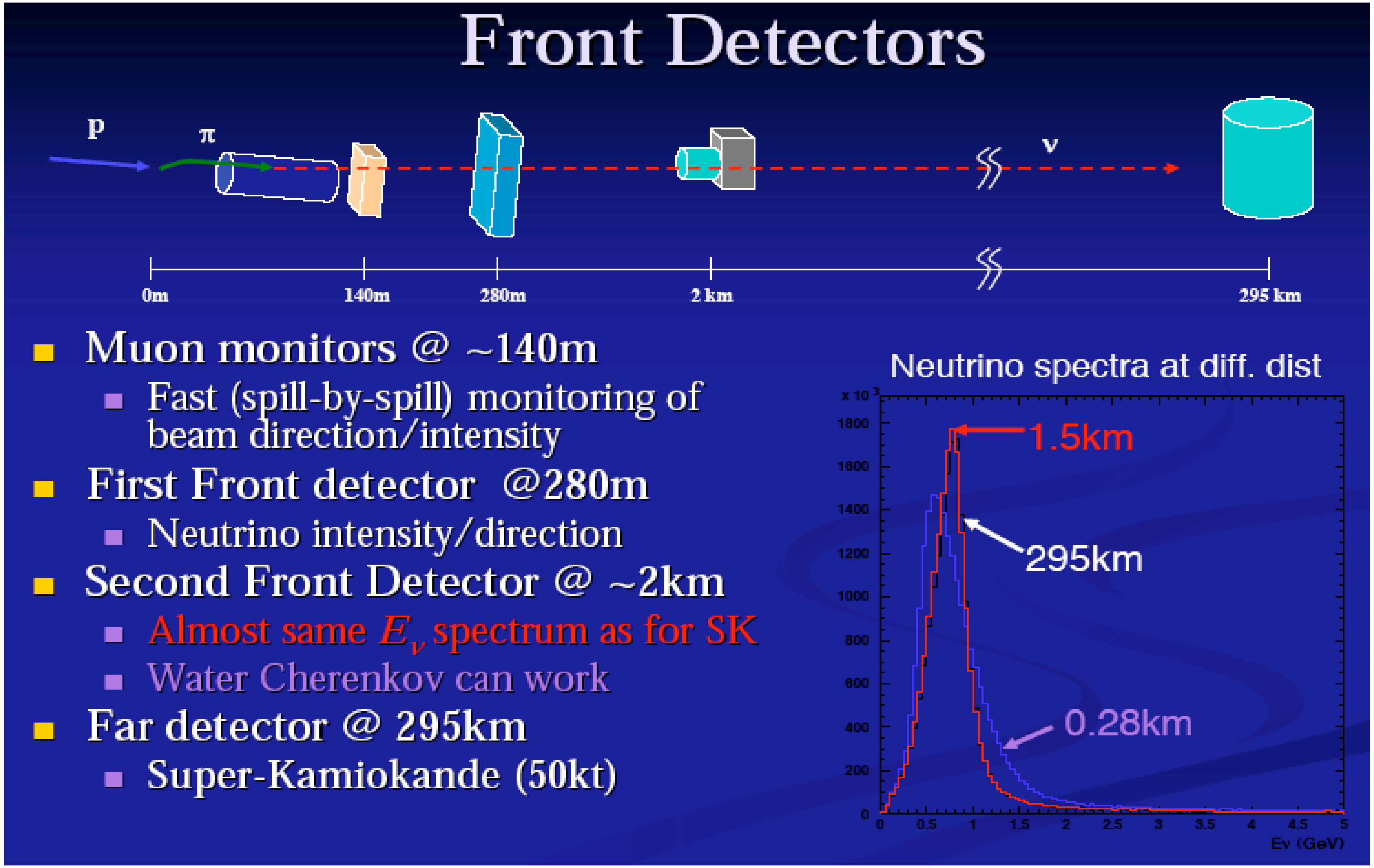


×100 more intensity than K2K, Eν < 1GeV









Front Detectors

- Muon monitors @ ~140m
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- First Front detector @280m
  - Neutrino intensity/direction
- Second Front Detector @ ~2km
  - Almost same E_ν spectrum as for SK
  - Water Cherenkov can work
- Far detector @ 295km
  - Super-Kamiokande (50kt)

Neutrino spectra at diff. dist

The 2 km location would be ideally complemented by a ≈100 ton liquid Argon detector

100 ton @ L=2000 m:

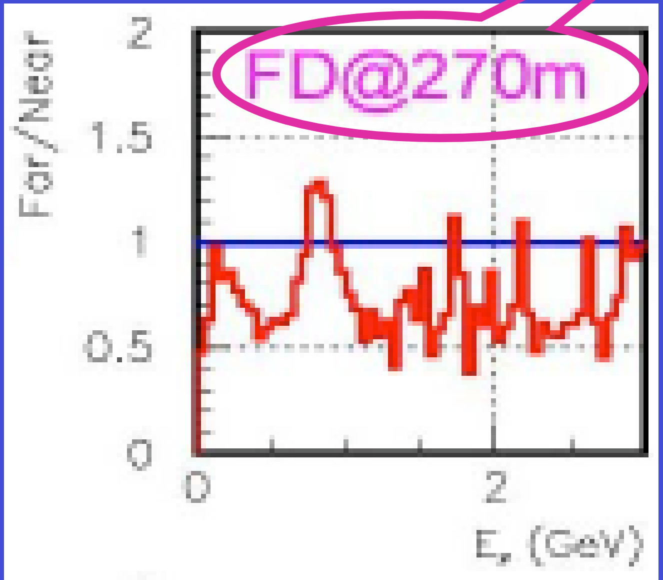
Beam	E_{peak}(GeV)	ν_μ	ν_e
OA2	0.7	300000/yr 0.1/spill	5800/yr 45/day

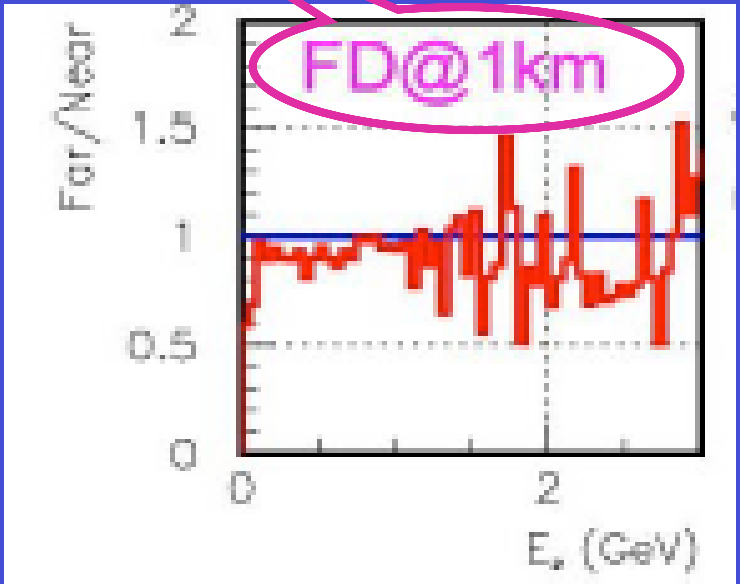
…why? At least for this reason…

Let's consider the Far/Near ratio @T2K Vs ν energy

Baseline of the Near Detector

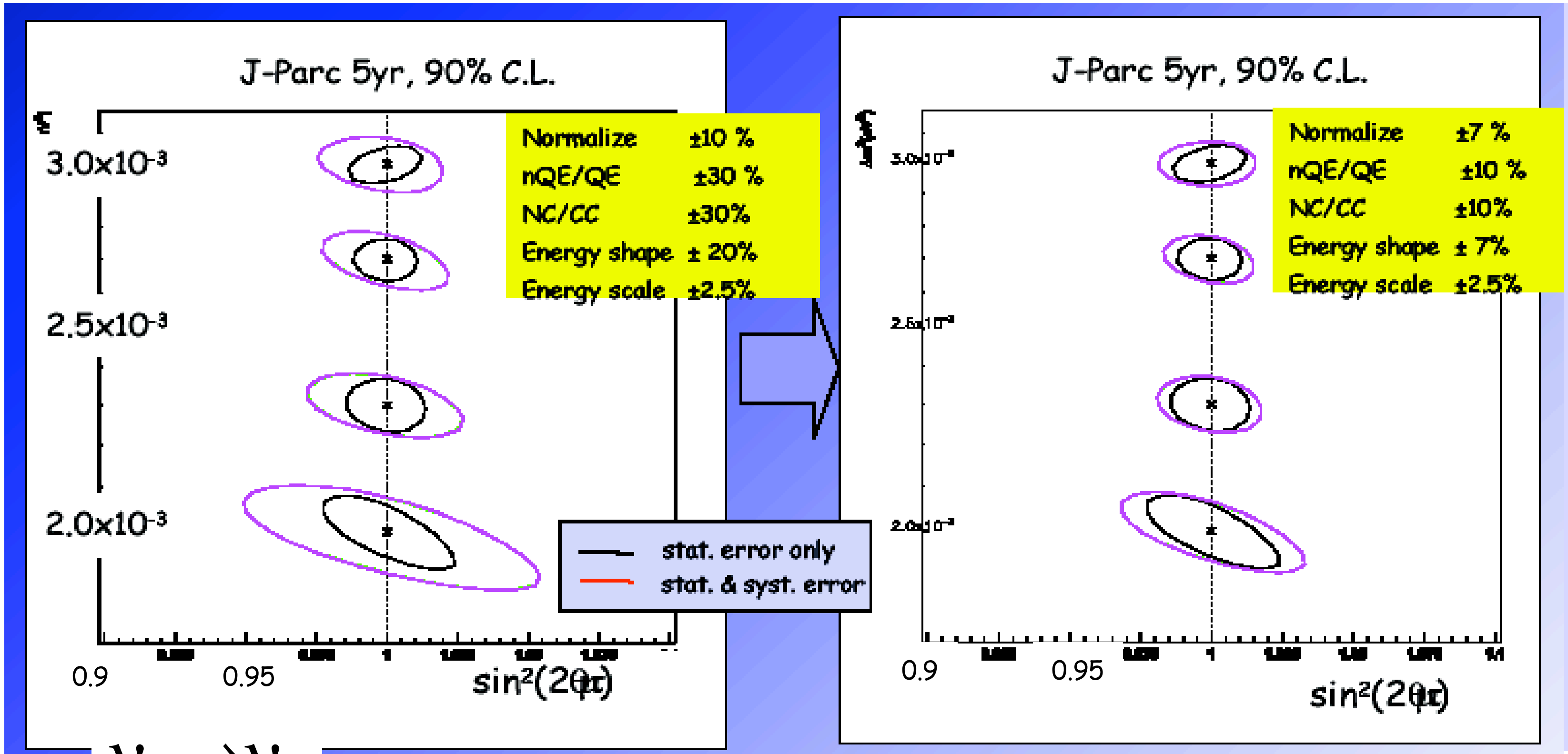
Similar to K2K



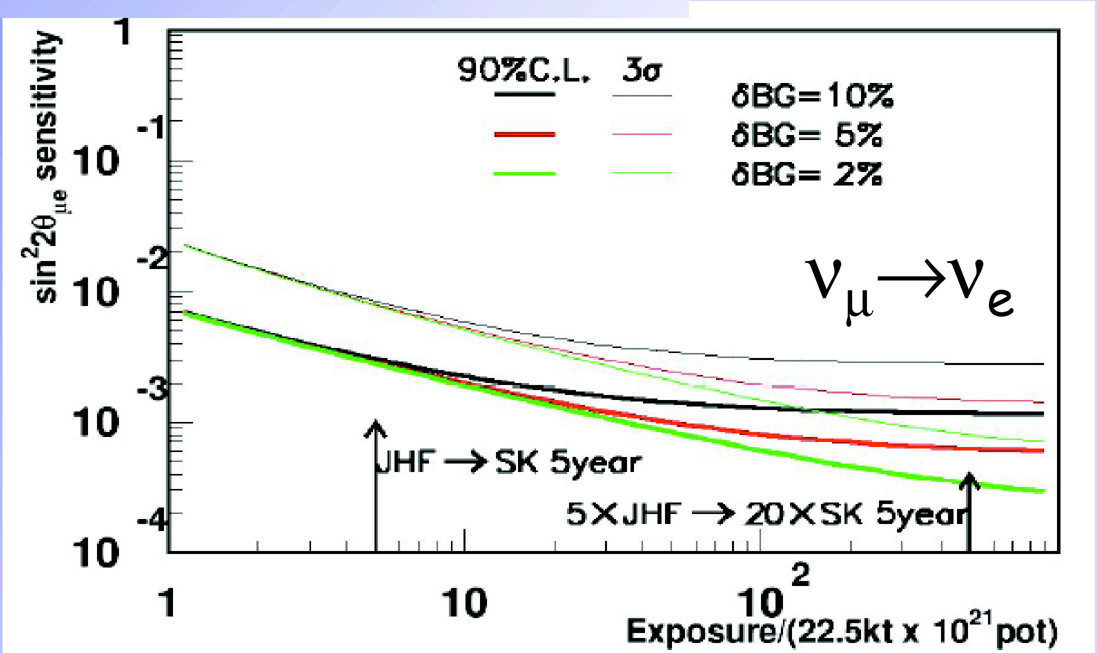


The Far/Near ratio has a strong energy dependence that depends on the Near Baseline

From Migliozzi, Physics Multi-MW proton source, CERN May 2004



$\nu_\mu \rightarrow \nu_\tau$

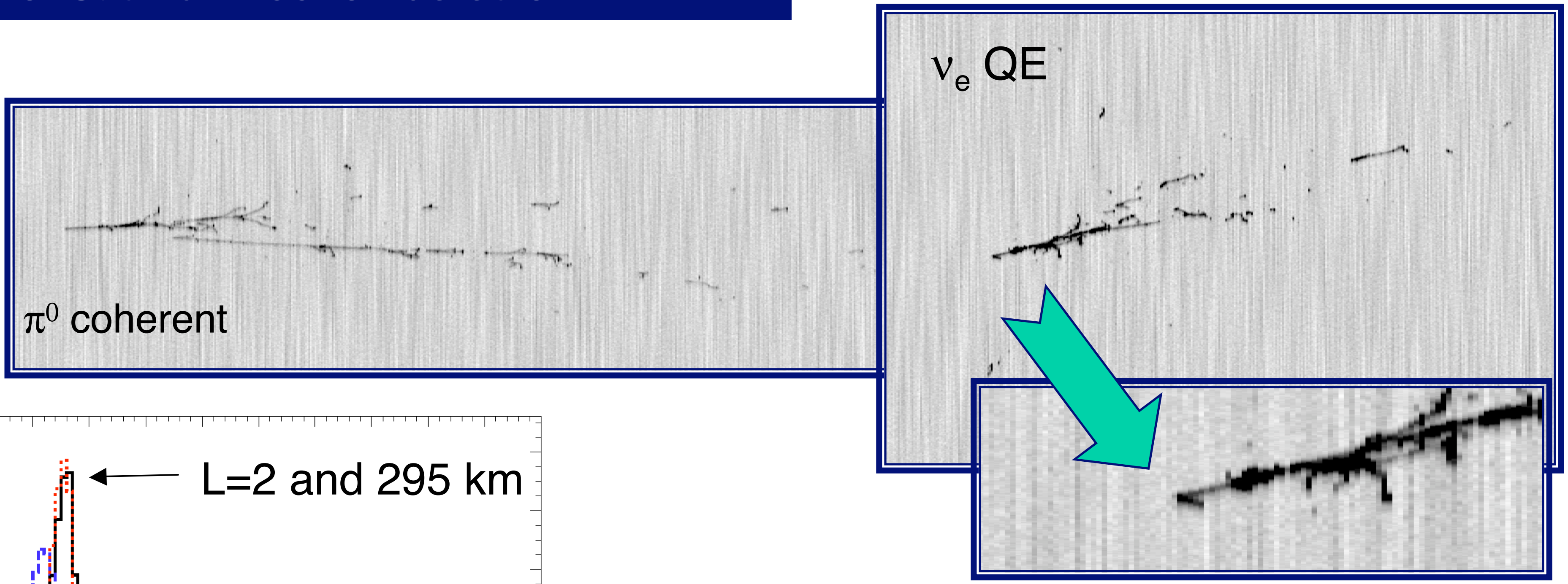


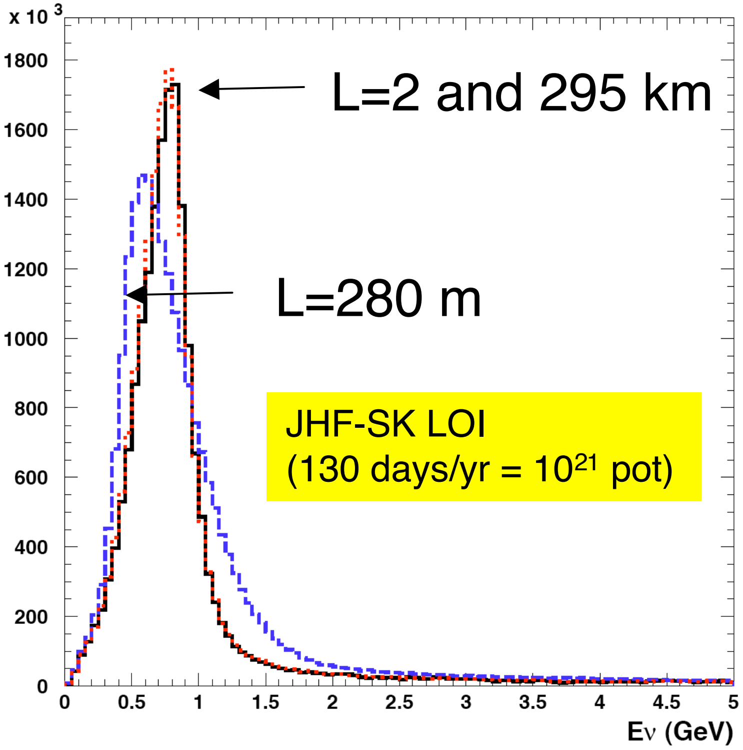
Impact of systematic errors on the T2K sensitivity

From Migliozzi, Physics Multi-MW proton source, CERN May 2004

T2K would provide an ideal & high intensity beam for such a ≈100 ton detector

full simulation, digitization, and noise inclusion



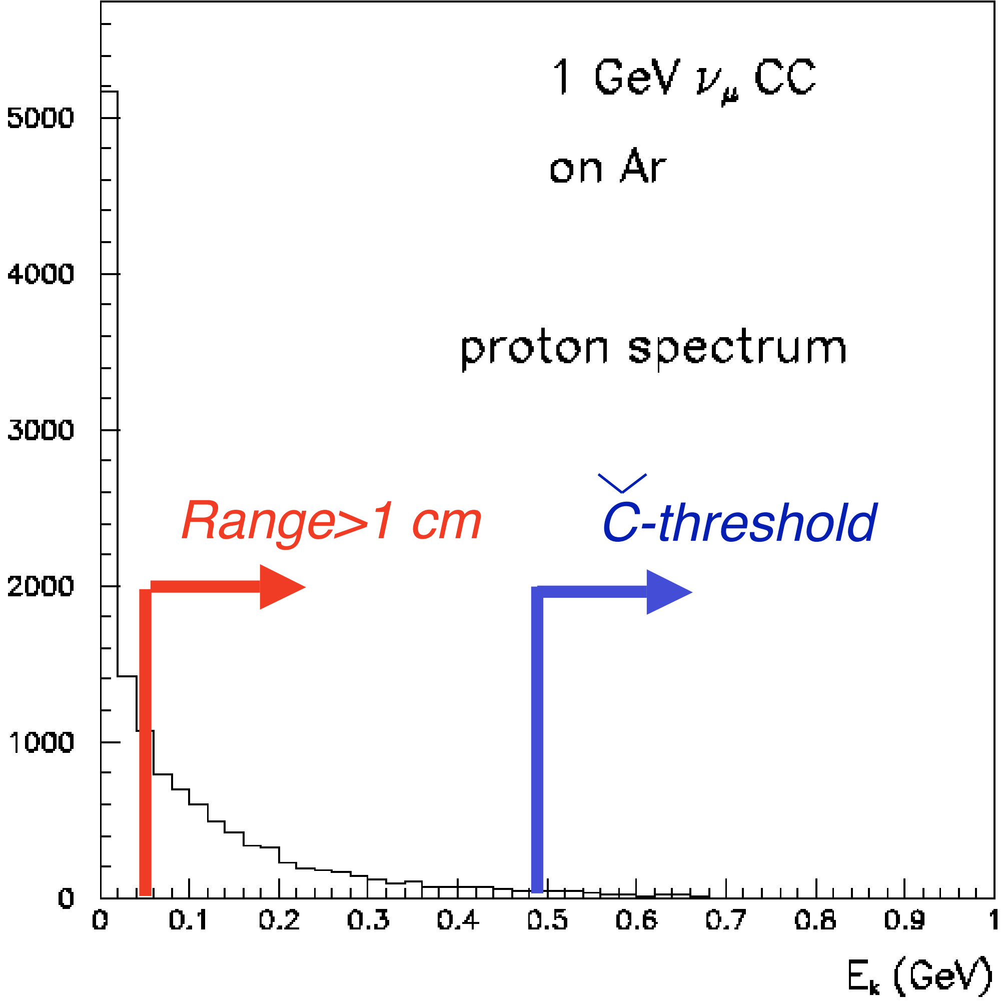


For example: 100 ton @ L=2000 m

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

Particle detection thresholds

E_ν = 1 GeV (NUX-FLUKA)



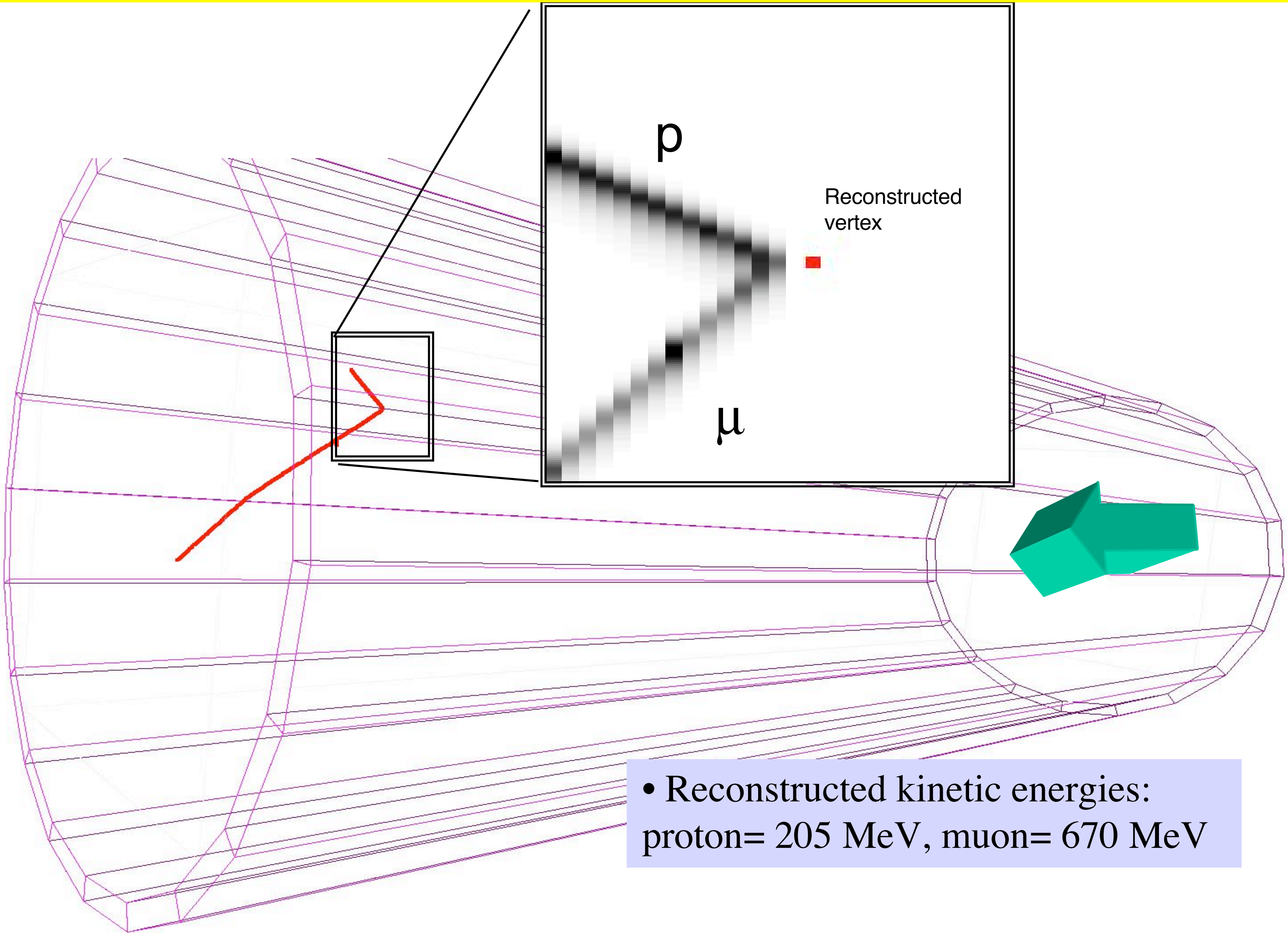
Protons

Kinetic energy T (MeV)	Momentum p (MeV/c)	Range in LAr (cm)
10	43	0.14
40	280	0.93
70	370	4.19
100	446	7.87
300	813	51.9
500	1094	116

Particle	Cerenkov thr. in H_2O MeV/c	range in LAr cm
e	0.6	0.07
μ	120	12
π	159	16
K	568	59
p	1070	110

Automatic reconstruction in liquid Argon TPC

The excellent imaging capabilities allow for fully automatic event reconstruction
⇒ ***high statistics experiment !***

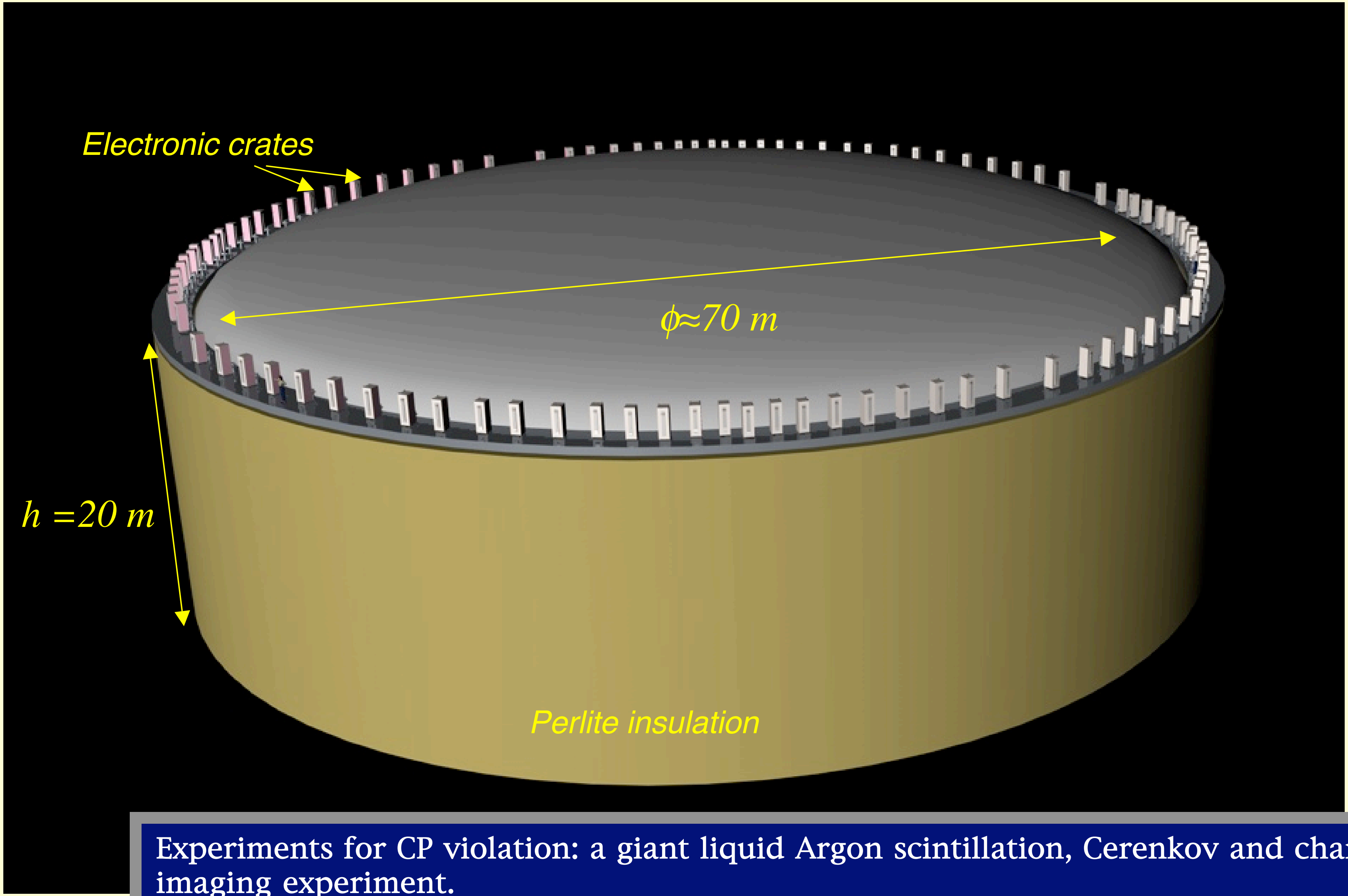


- Reconstructed kinetic energies:
proton= 205 MeV, muon= 670 MeV

100 kton

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

100 kton liquid Argon TPC detector

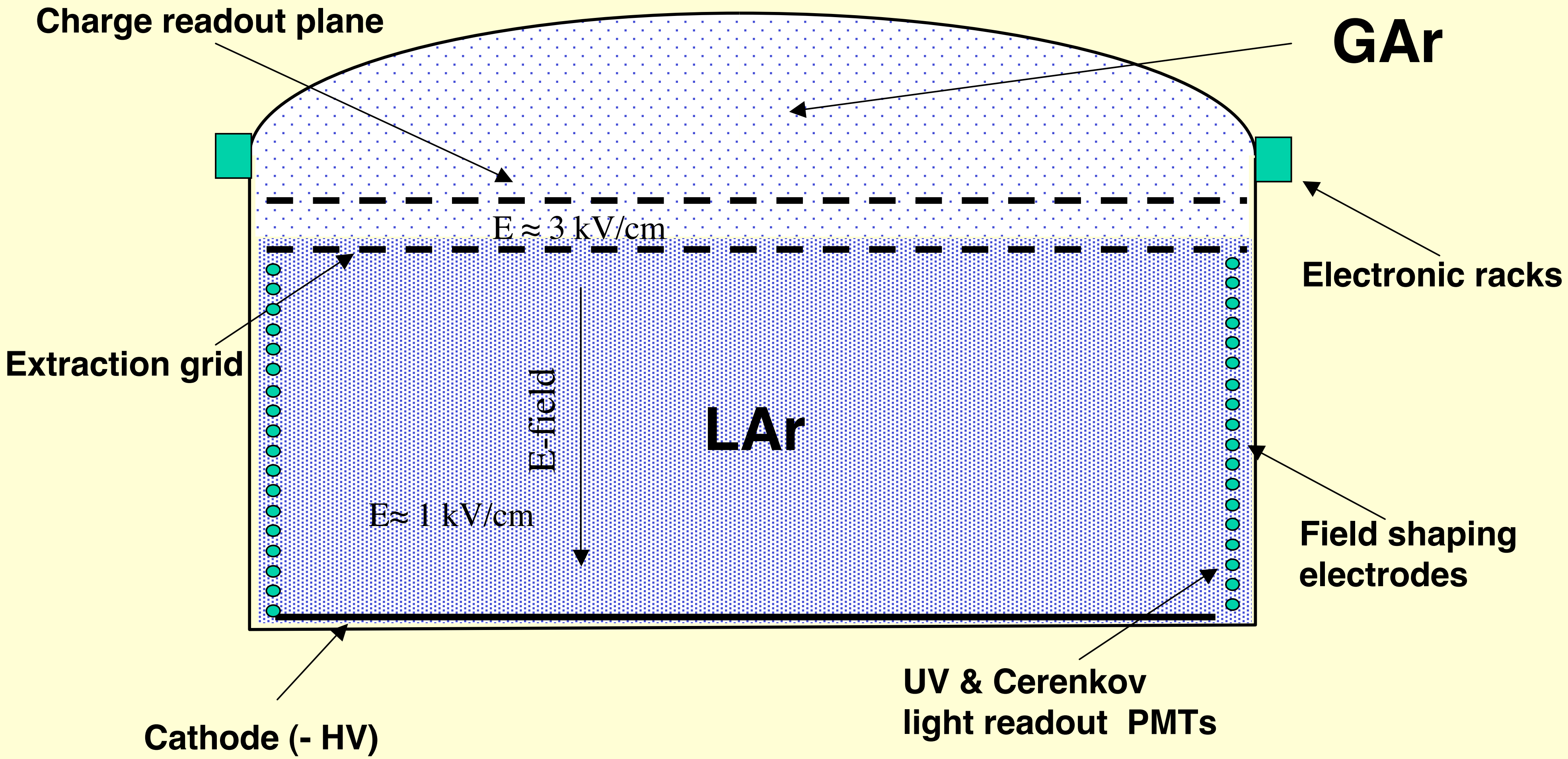


Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment.

A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, hep-ph/0402110

A tentative detector layout

Single detector: charge imaging, scintillation, Cerenkov light



Tentative parameter list

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

Charge extraction, amplification, readout

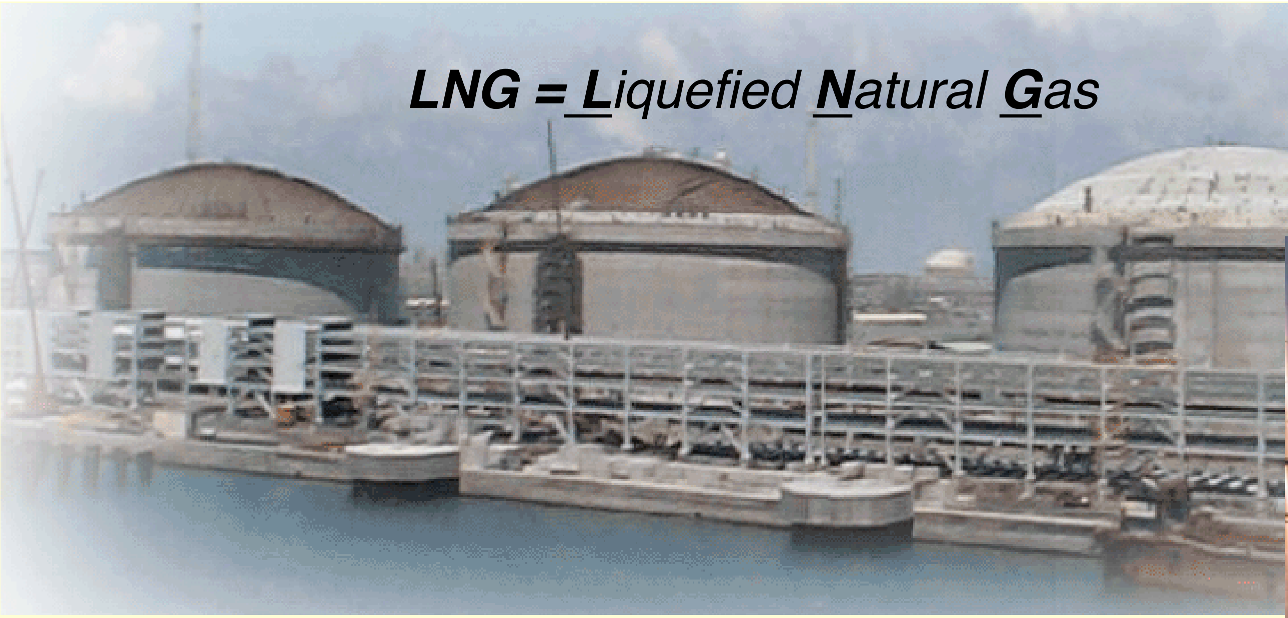
Detector is running in BI-PHASE MODE

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

Electron drift in liquid	**20 m maximum drift, HV = 2 MV for E = 1 kV/cm,** **$v_d \approx 2$ mm/μs, max drift time ≈ 10 ms**
Charge readout view	**2 perpendicular views, 3 mm pitch,** **100000 readout channels**
Maximum charge diffusion	**$\sigma \approx 2.8$ mm ($\sqrt{2Dt_{max}}$ for $D = 4$ cm²/s)**
Maximum charge attenuation	**$e^{-(t_{max}/\tau)} \approx 1/150$ for $\tau = 2$ ms electron lifetime**
Needed charge amplification	**From 100 to 1000**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires ($\phi \approx 30$ μm) + pad readout, GEM, LEM, …**

Cryogenic storage tankers for LNG

LNG = *Liquefied Natural Gas*



"I learned a lot from the Shell training course. It was detailed, relevant to our business and moved at the right pace"

An employee, Nigeria LNG

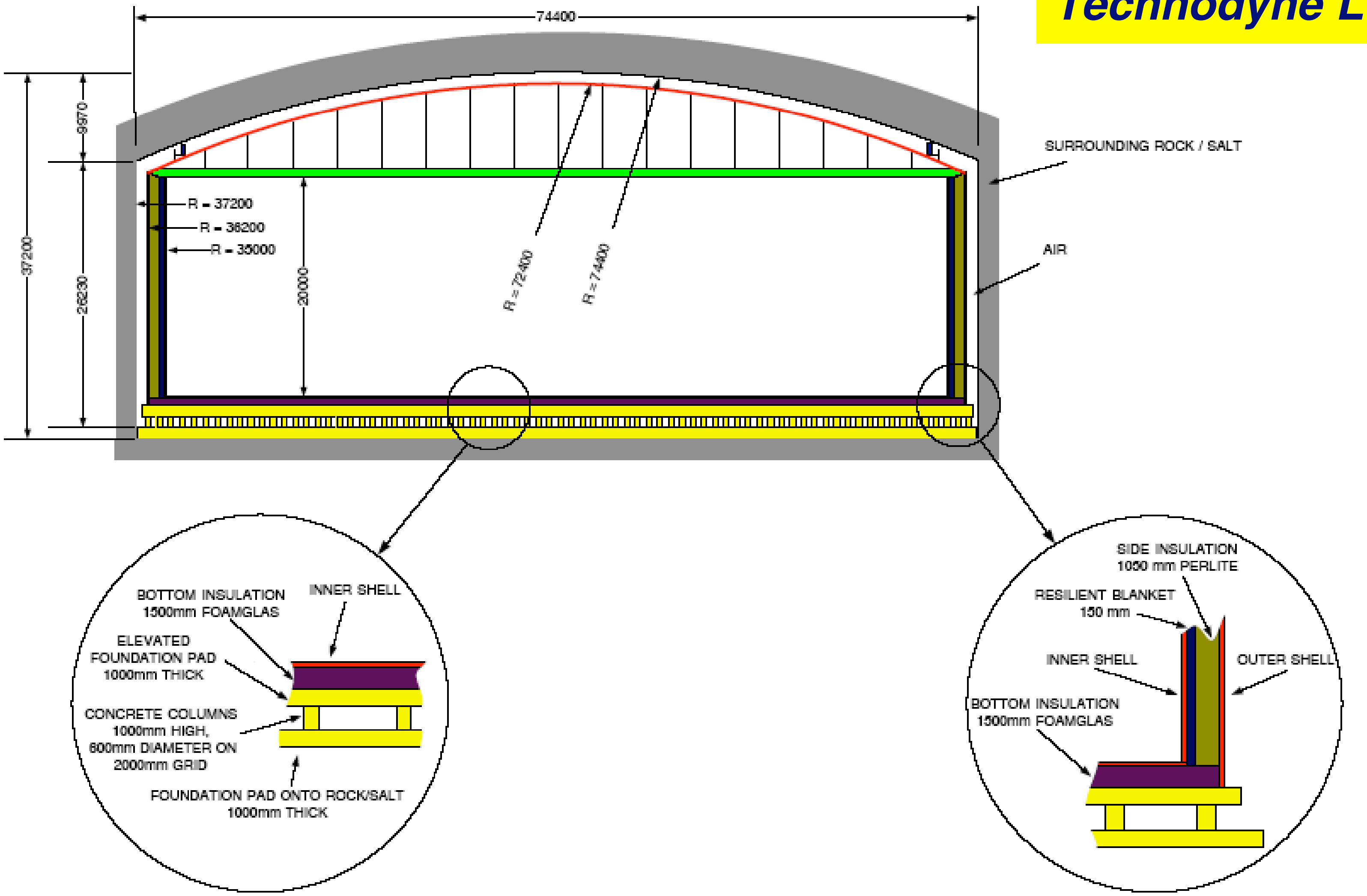
About 2000 cryogenic tankers exist in the world, with volume up to ≈ 200000 m^3

Process, design and safety issues already solved by petrochemical industry

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

TECHNODYNE INTERNATIONAL LIMITED

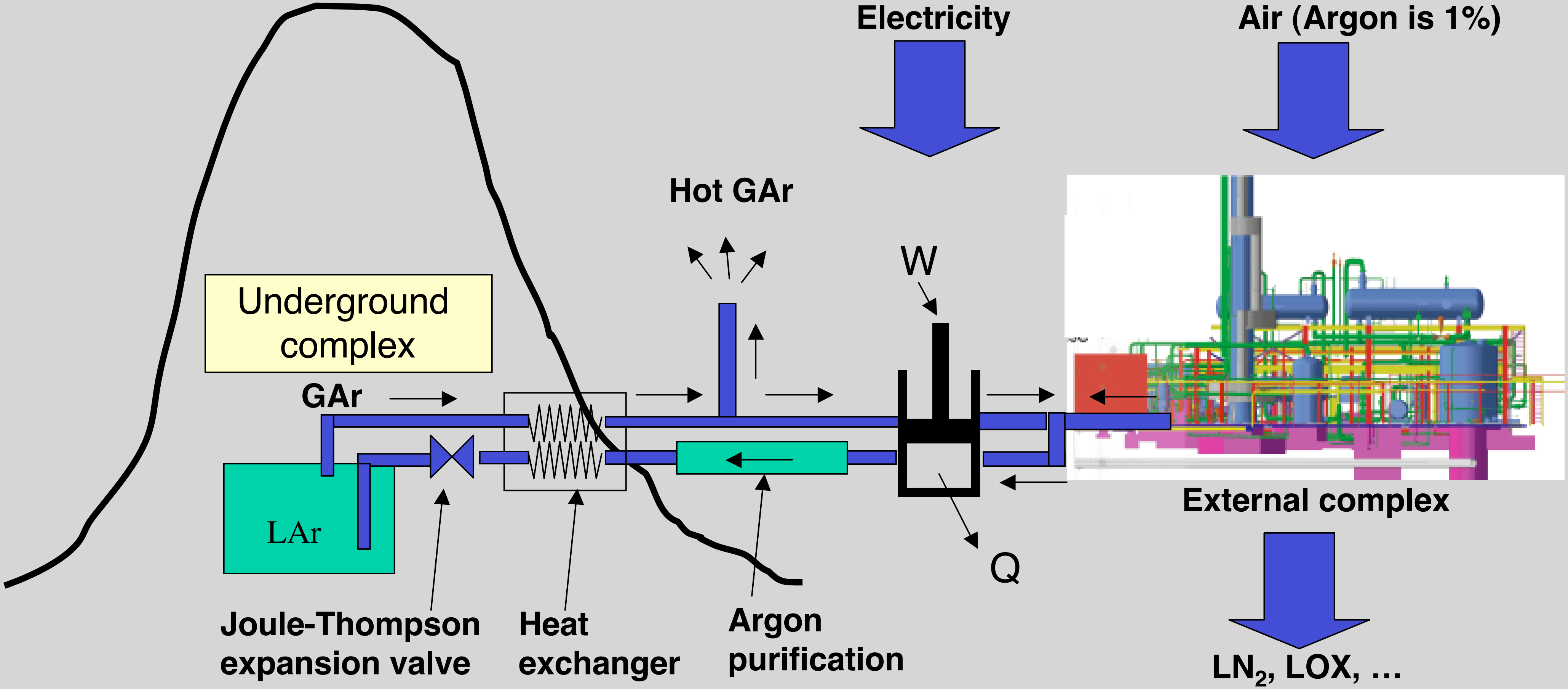
LARGE UNDERGROUND LIQUID ARGON STORAGE TANK



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

Process system & equipment

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



Electricity

Air (Argon is 1%)

Hot GAr

W

Underground complex

GAr

LAr

Q

External complex

Joule-Thompson expansion valve

Heat exchanger

Argon purification

LN_2, LOX, …

Cryogenic storage tankers for LNG

WHAT ARE THEY ?

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

HOW ARE LNG STORED ?

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

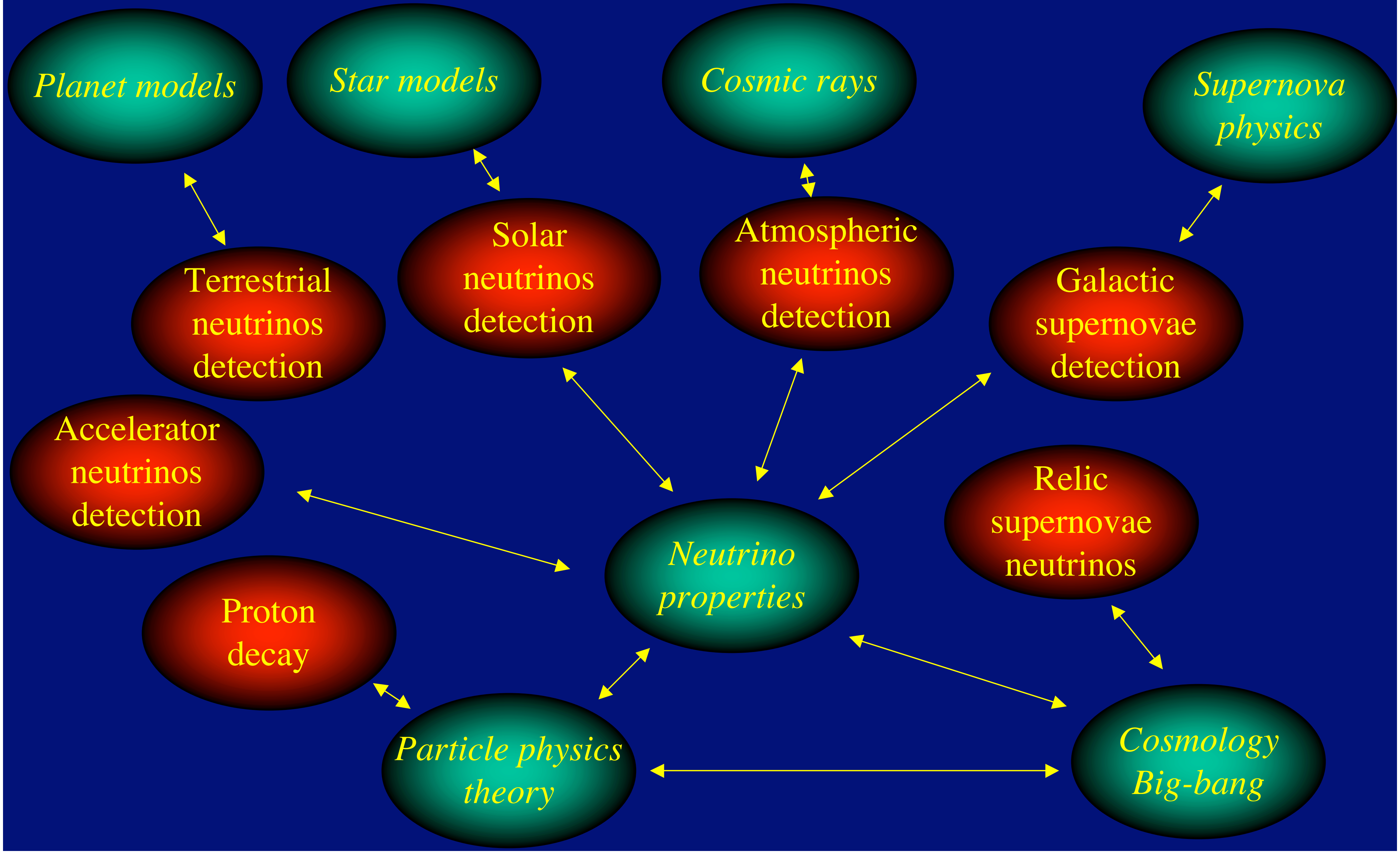
HOW ARE LNG KEPT COLD ?

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

HAVE THERE BEEN SERIOUS LNG ACCIDENTS ?

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

Vast physics program



Planet models

Star models

Cosmic rays

Supernova physics

Terrestrial neutrinos detection

Solar neutrinos detection

Atmospheric neutrinos detection

Galactic supernovae detection

Accelerator neutrinos detection

Neutrino properties

Relic supernovae neutrinos

Proton decay

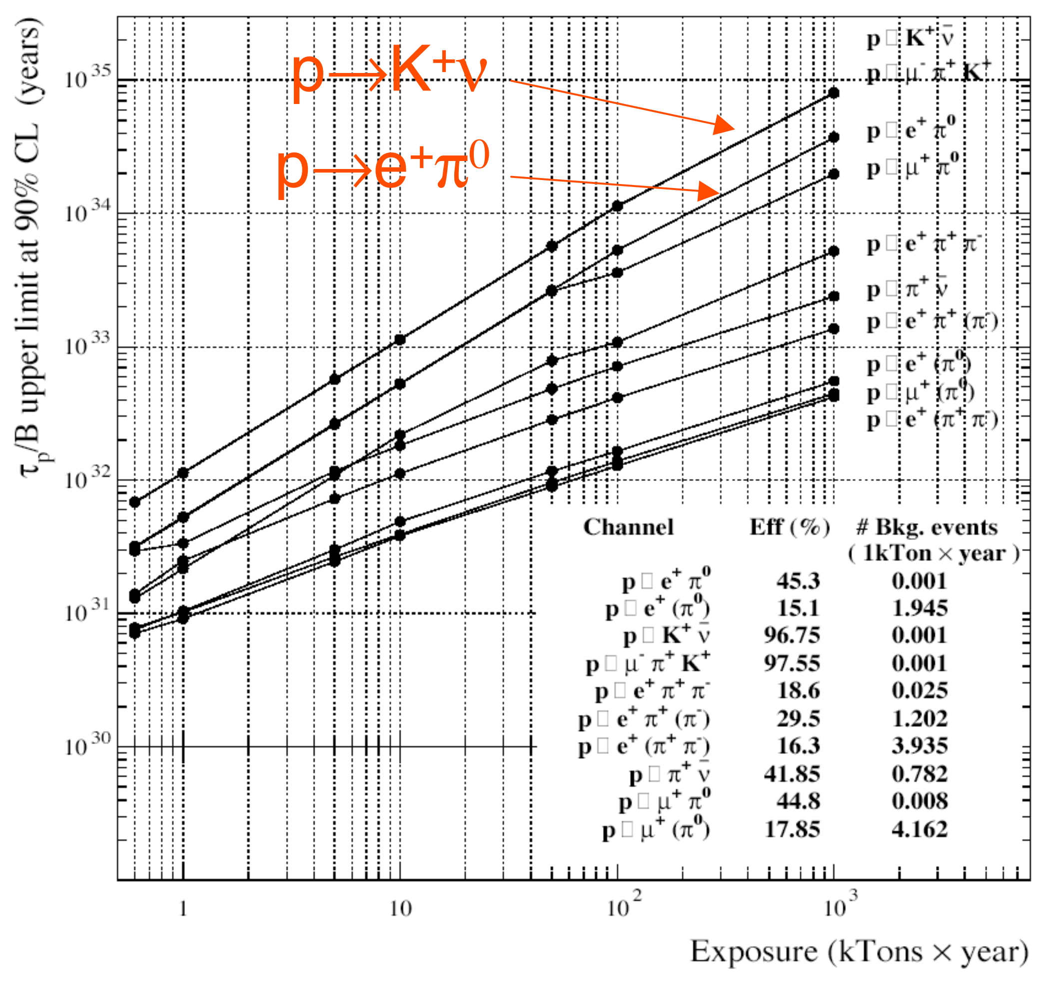
Particle physics theory

Cosmology Big-bang

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

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

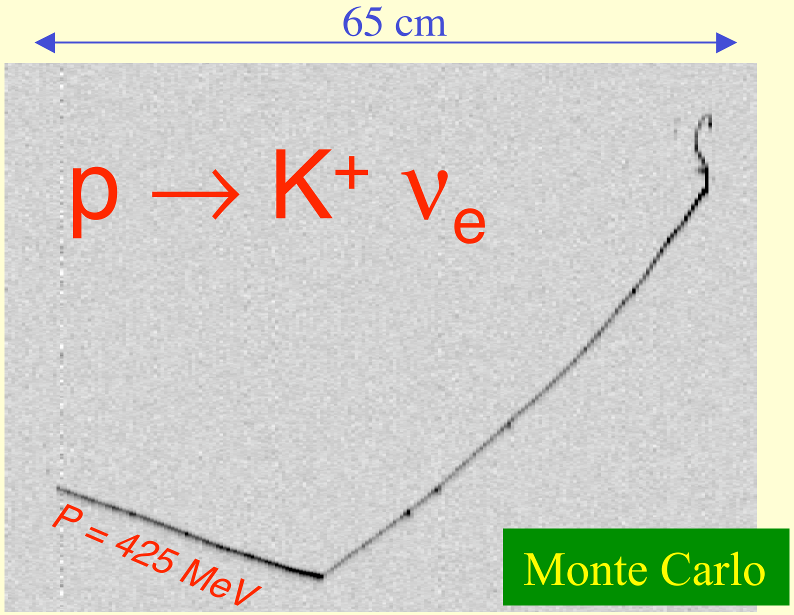
Proton decay: sensitivity vs exposure



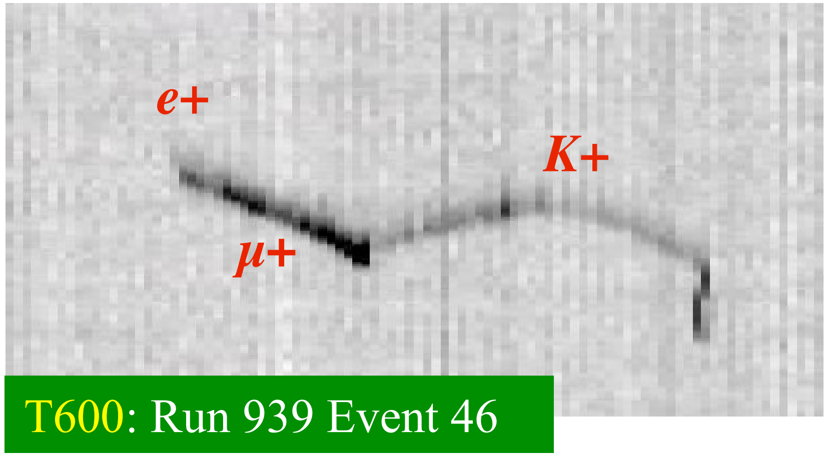
Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \square e^+ \pi^0$	45.3	0.001
$p \square e^+ (\pi^0)$	15.1	1.945
$p \square K^+ \bar{\nu}$	96.75	0.001
$p \square \mu^- \pi^+ K^+$	97.55	0.001
$p \square e^+ \pi^+ \pi^-$	18.6	0.025
$p \square e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \square e^+ (\pi^+ \pi^-)$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

6×10^{34} nucleons ⇒

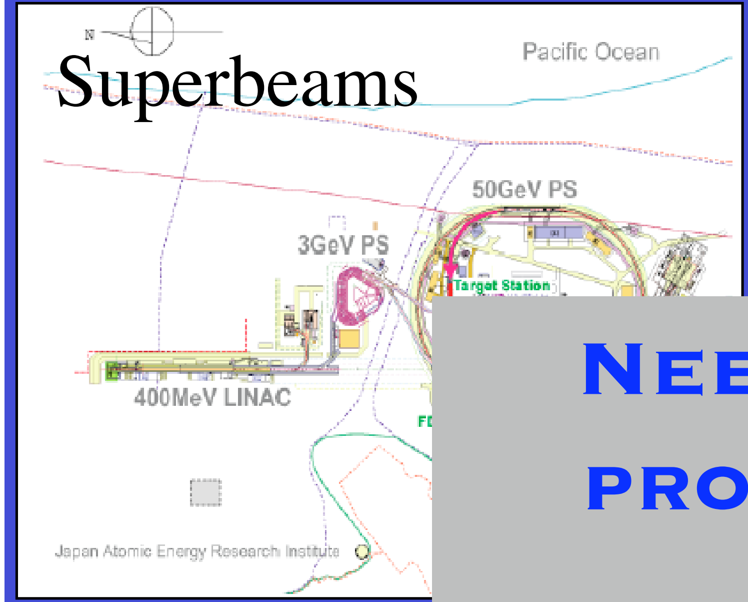
$\tau_p / Br > \approx 10^{34}$ years $\times$ T(yr) $\times \varepsilon$ @ 90 CL



"Single" event detection capability



Accelerator neutrinos


Superbeams

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

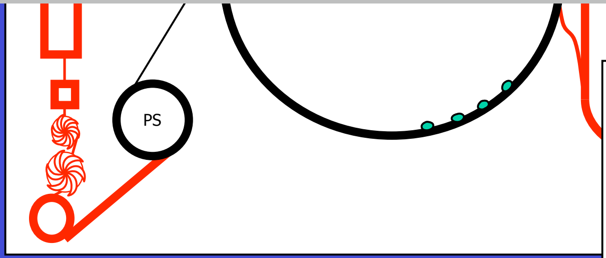
Select focusing sign

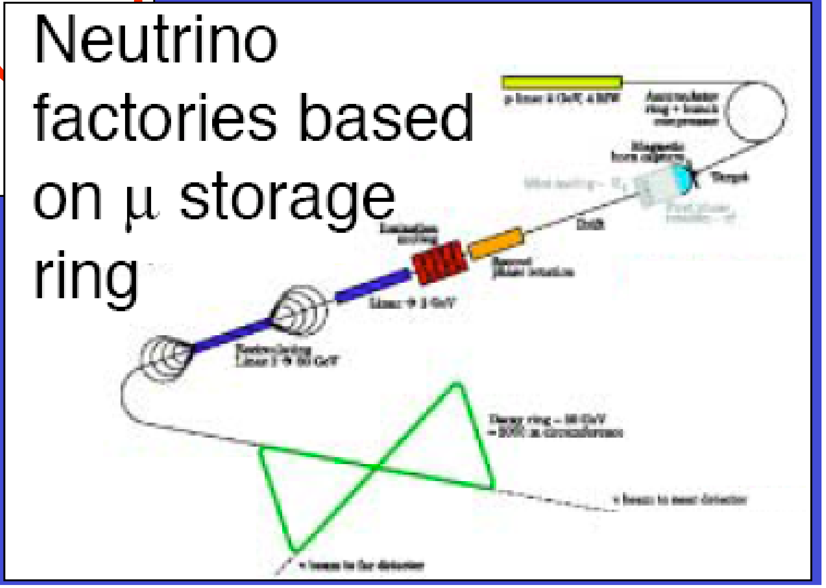
Need a high intensity proton source at the Mwatt level !

$$A\ \beta^{\pm}\ \overset{(-)}{\nu}_{e}$$

on

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




Neutrino factories based on μ storage ring

Select ring sign

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

CERN SPL : 2.2 GeV SC linac (>2014)

EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

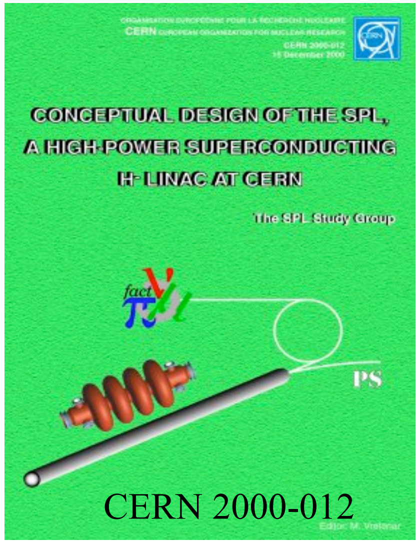
→

10^{23} protons/year

Study group since 1999

design of a Superconducting Proton Linac (H-, 2.2 GeV).

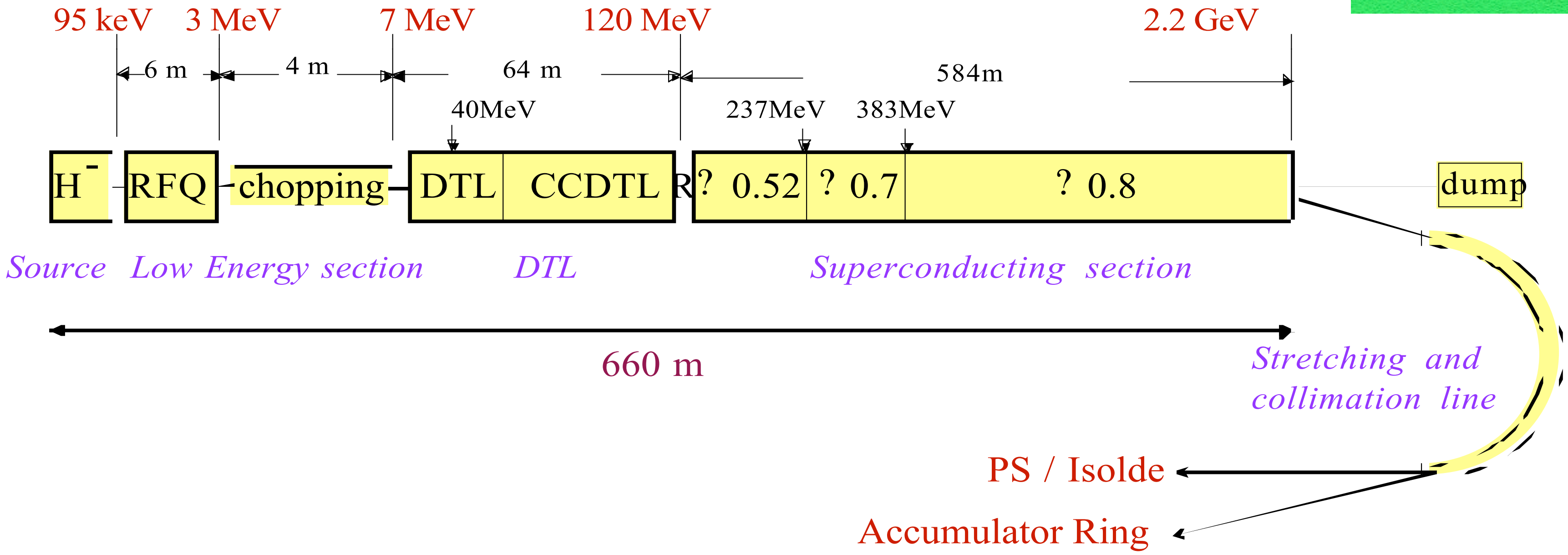
- ✓ higher brightness beams into the PS for LHC
- ✓ intense beams (4 MW) for neutrino and radioactive ion physics



CONCEPTUAL DESIGN OF THE SPL,
A HIGH-POWER SUPERCONDUCTING
H⁻ LINAC AT CERN

The SPL Study Group

CERN 2000-012



95 keV 3 MeV 7 MeV 120 MeV 2.2 GeV

6 m 4 m 64 m 584m

40MeV 237MeV 383MeV

H⁻ RFQ chopping DTL CCDTL R? 0.52 ? 0.7 ? 0.8 dump

Source *Low Energy section* *DTL* *Superconducting section*

660 m

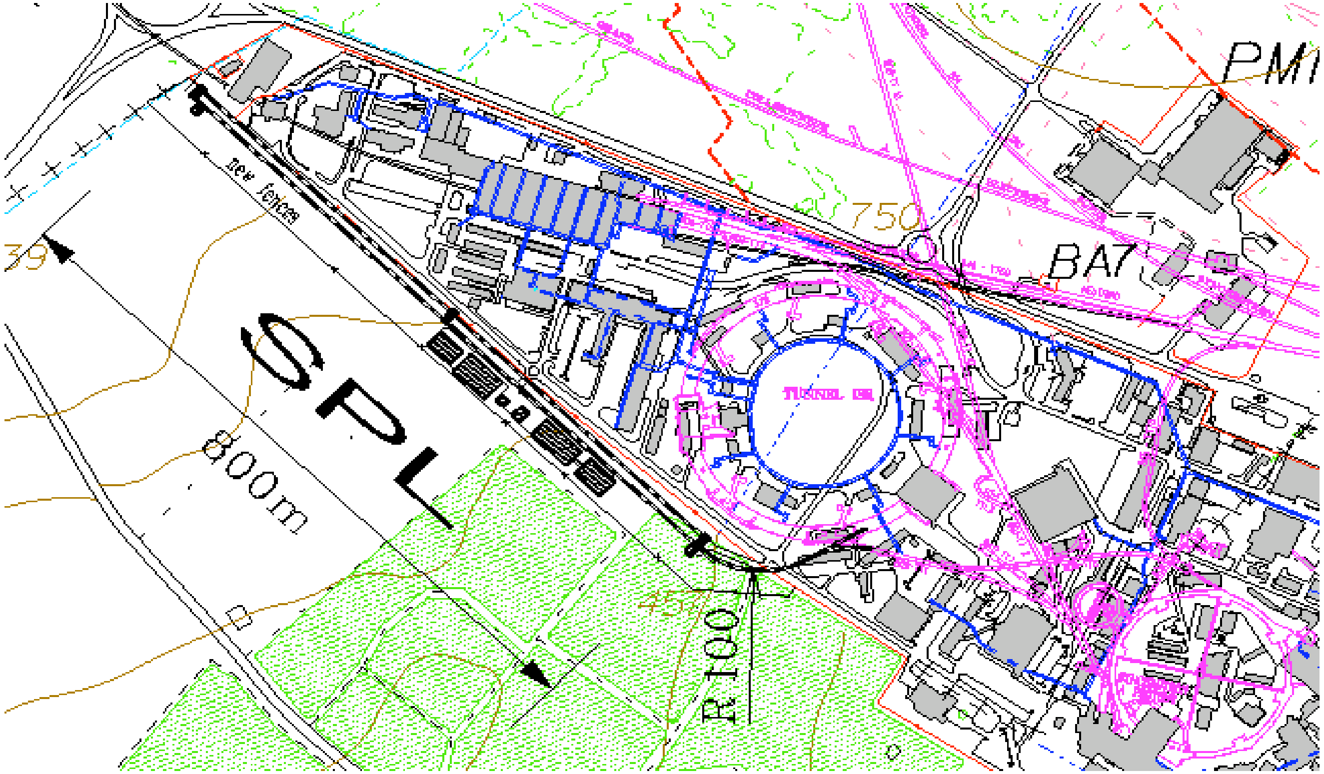
Stretching and collimation line

PS / Isolde

Accumulator Ring

CERN Layout (CDR 1)

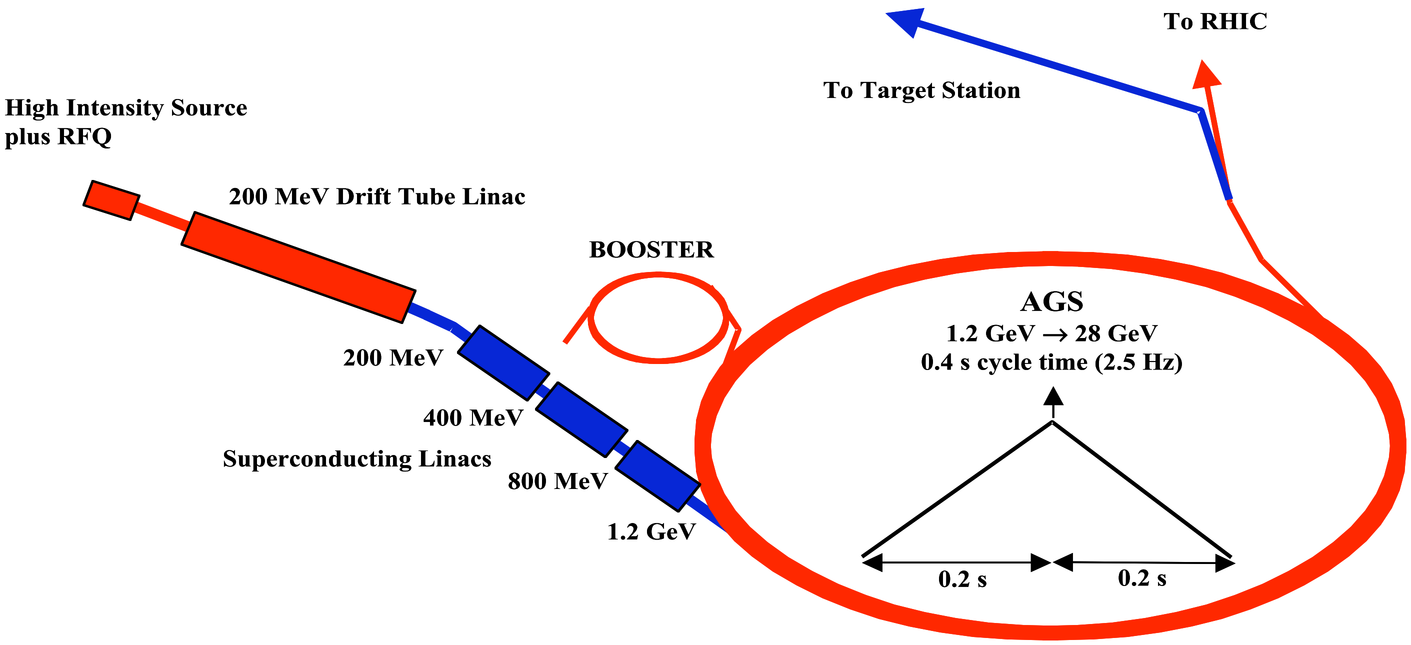
CERN SPL will be integrated in the existing accelerator complex



Benefits:

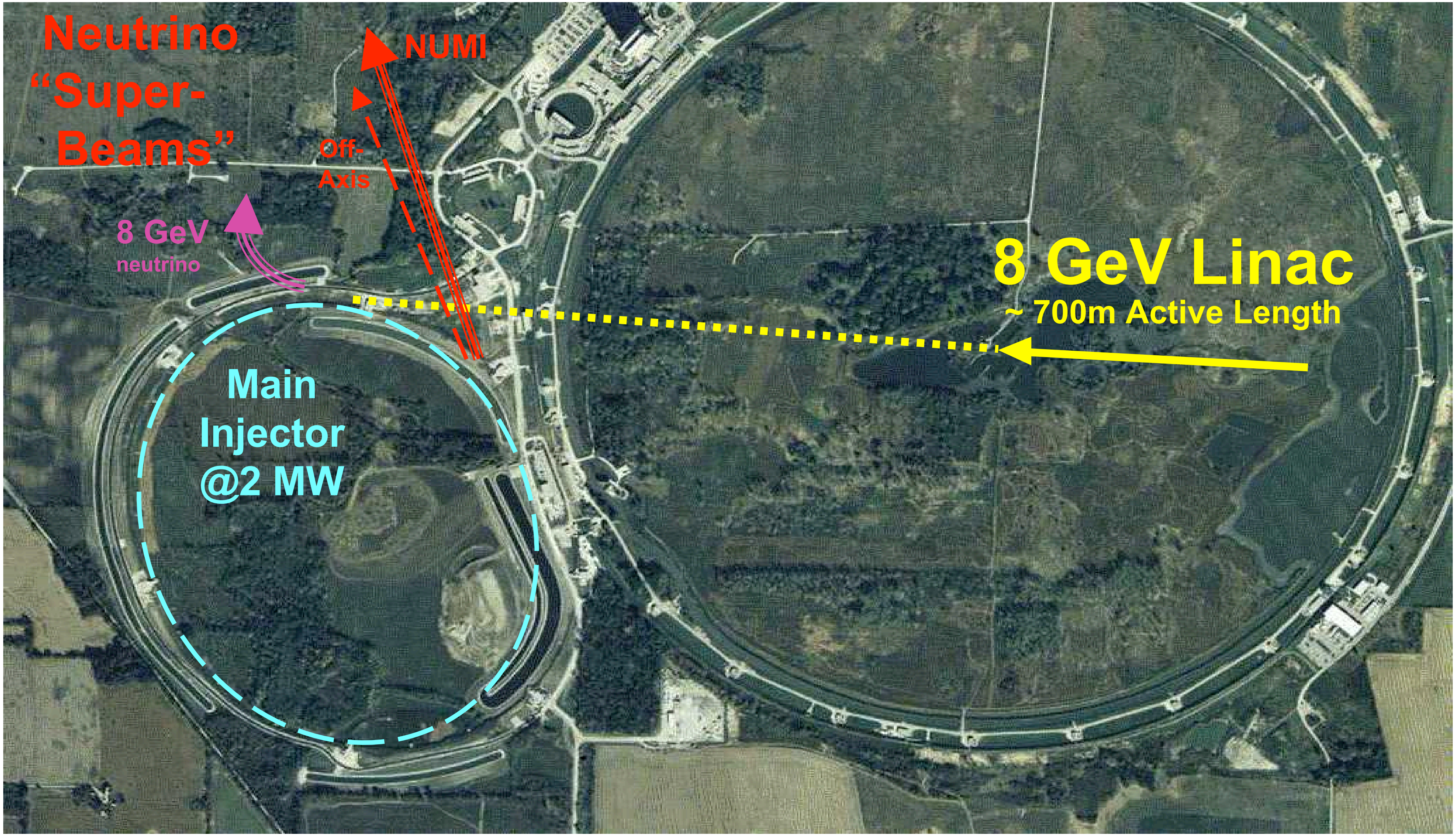
- Reduce the LHC filling time,
- Improve the reliability in the generation of the ultimate beam actually foreseen for LHC,
- Increase the proton flux onto the CNGS target,
- Increase the proton flux to ISOLDE,
- Prepare for further upgrades of the LHC performance beyond the present ultimate.

Brookhaven AGS Upgrade (>20xx ?)



- **Direct injection of ~ 1×10^{14} protons via a 1.2 GeV sc linac extension**
  - ➥ low beam loss at injection; high repetition rate possible
  - ➥ further upgrade to 1.5 GeV and 2×10^{14} protons per pulse possible (x 2)
- **2.5 Hz AGS repetition rate**
  - ➥ triple existing main magnet power supply and magnet current feeds
  - ➥ double rf power and accelerating gradient
  - ➥ further upgrade to 5 Hz possible (x 2)
- **Goal: 1 MW power**

Fermilab Proton Driver (>20xx ?)
New 8 GeV SC linac



Neutrino fluxes: comparison between future beams

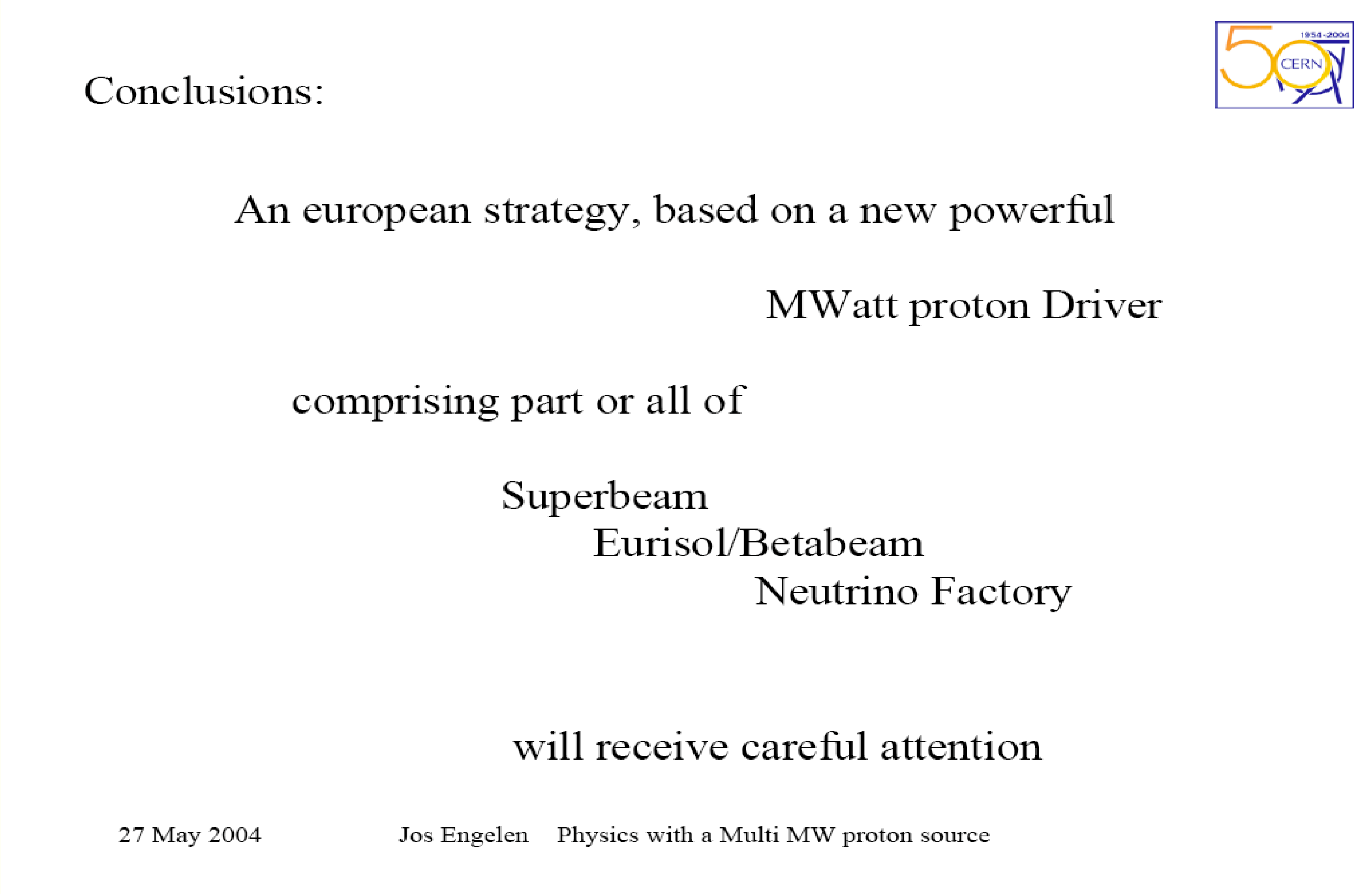
A wide variety of possible optimizations...

Requires International Collaboration & coordination to define future global physics programme

Future experiments with superbeams, β-beams and neutrino factories, D. Harris, LP2003.

Physics with a Multi-MW proton source Workshop held @ CERN 25-27 May 2004

Concluding remarks from J. Engelen, CERN director of research



Conclusions:

An european strategy, based on a new powerful MWatt proton Driver

comprising part or all of

Superbeam
Eurisol/Betabeam
Neutrino Factory

will receive careful attention

27 May 2004 Jos Engelen Physics with a Multi MW proton source

100 kton detector: milestones

- **Nov 2003: Venice Workshop**
  - Basic concepts: LNG tanker, signal amplification, single detector for charge imaging, scintillation and Cerenkov light readout
  - Design given for proton decay, astrophysics ν's, Super-Beams, Beta-Beams
  - Stressed the need for detailed comparison: 1 Mton water versus 100 kton LAr detector
- **Feb 2004: Feasibility study launched for underground liquid Argon storage**
  - Industry: Technodyne (UK) mandated for the study (expert in LNG design)
  - Design provided as input to the Fréjus underground lab study
  - Salt mine in Poland being investigated as well as other possible sites
- **March 2004: NUINT04 Workshop**
  - Identification of a global strategy: synergy between 'small' and 'large' mass LAr TPC
  - Intent to define a coherent International Network to further develop the conceptual ideas
- **April 2004 : Memo to the SPSC in view of the Villars special session (Sept. 2004)**
- **May 2004 : CERN Workshop on a future Multi MW proton source**
  - Envision a possible 10 kton full scale prototype (10% of the full detector)
  - Site/physics optimization deep underground (→ proton decay) or shallow (→ neutrino beam)

Ongoing studies and initial R&D strategy

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

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

2) **Understanding of charge collection under high pressure**

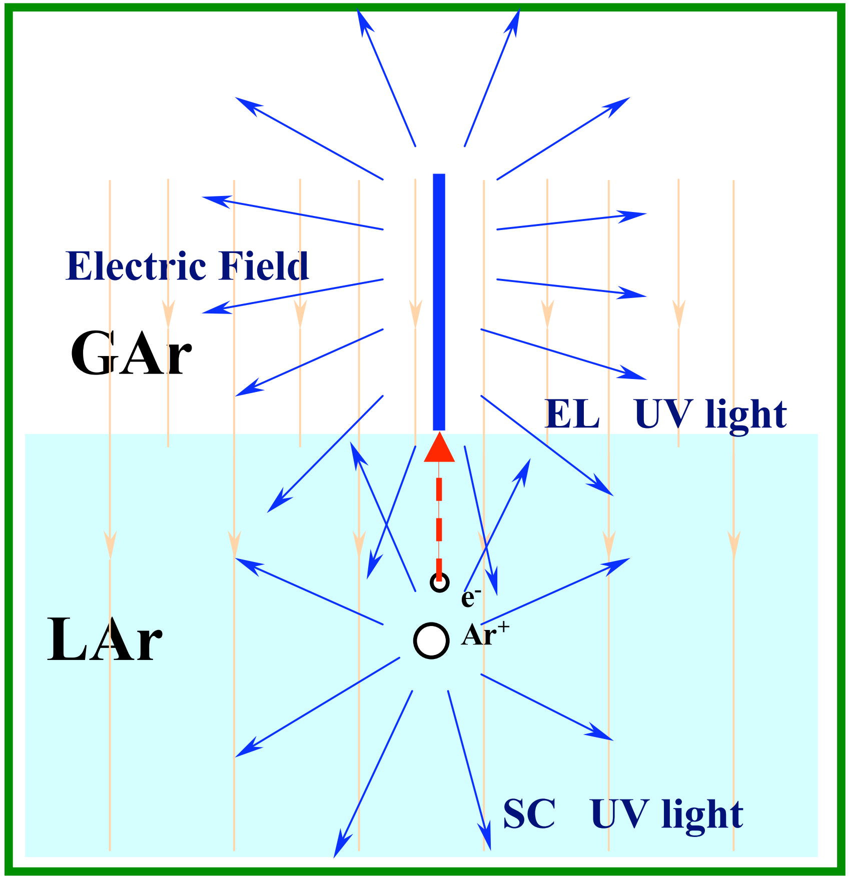
3) **Realization and test of a 5 m long detector column-like prototype**

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

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

1) Electron extraction in LAr bi-phase

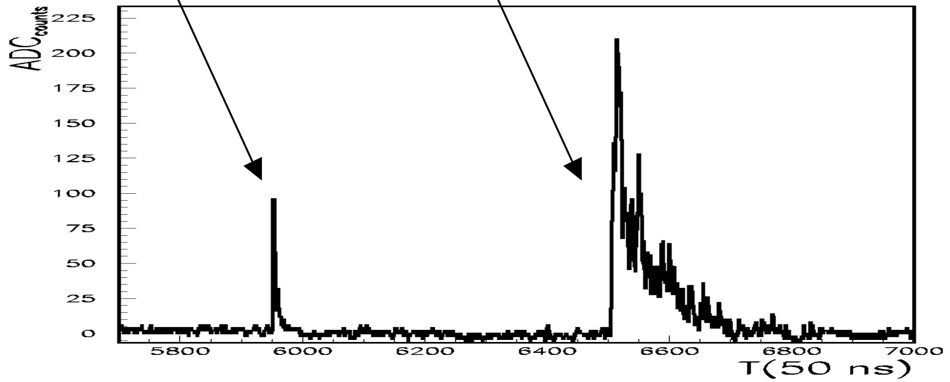
Particle produces excitation (Ar*) and ionization (Ar$^+$, e)

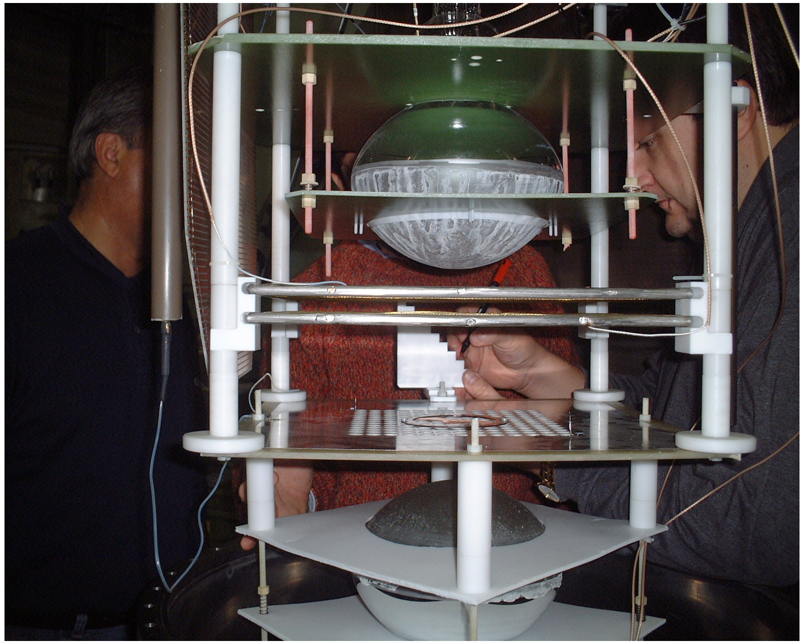


Both SC and EL can be detected by the same photo-detector

Scintillation SC is a result of direct excitation and recombination

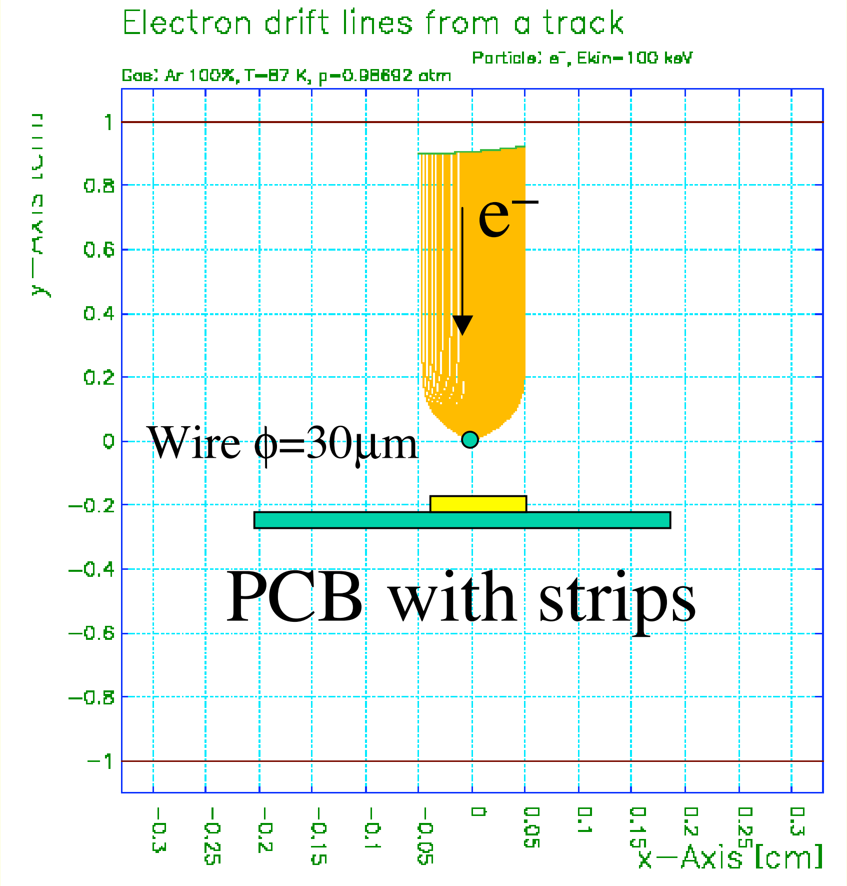
Electro-luminescence EL (proportional scintillation) is a result of electron acceleration in the gas

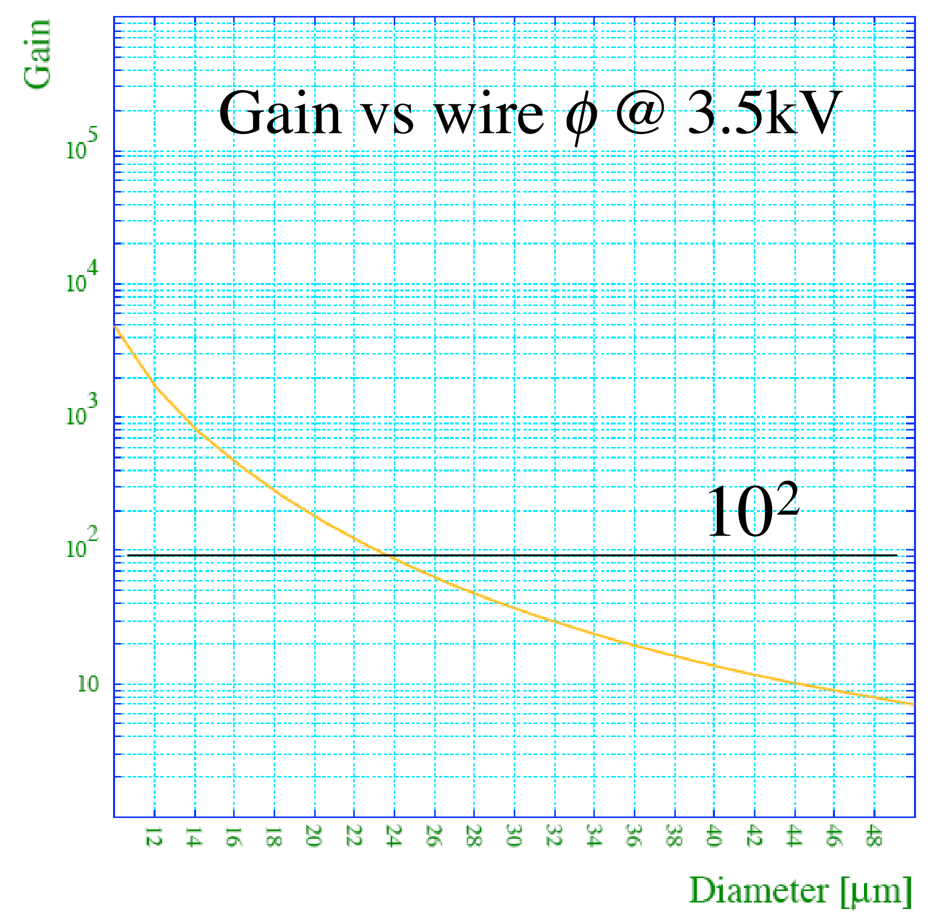




1) Amplification near wires à la MWPC

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



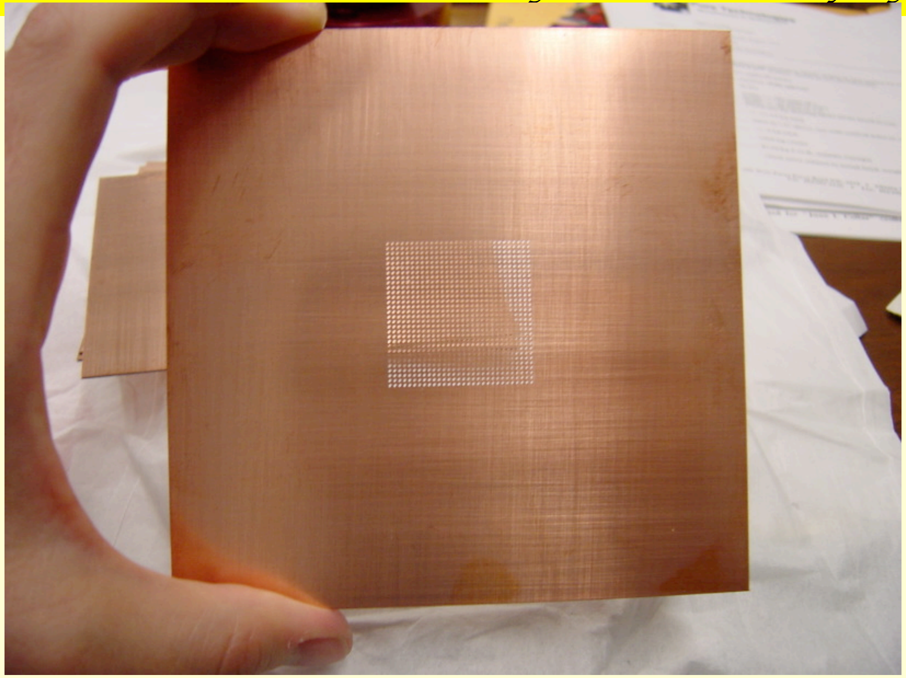


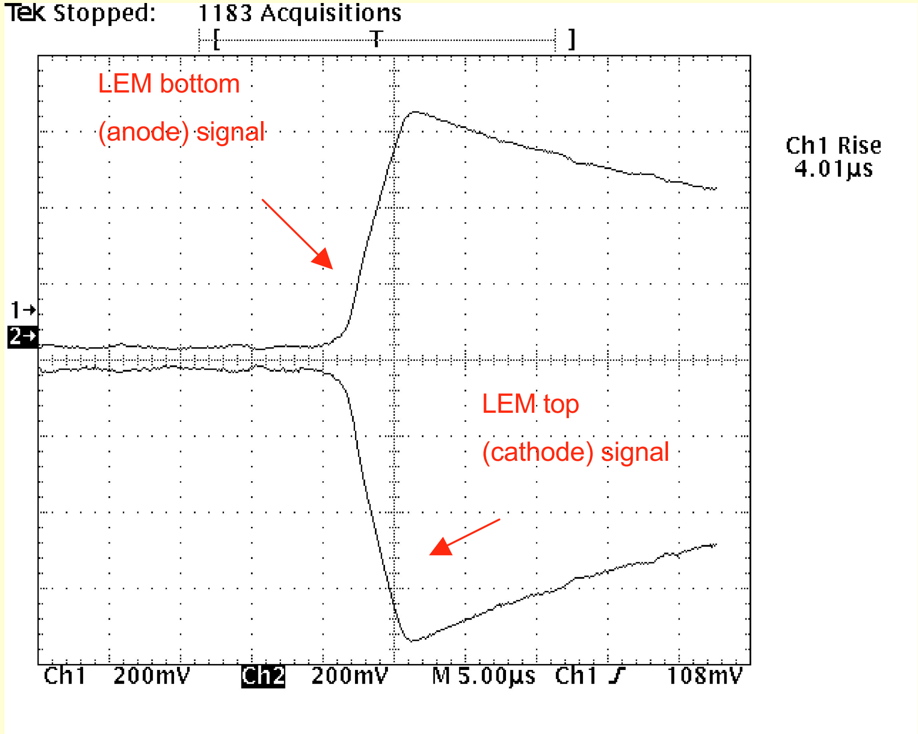
1) Amplification with Large Electron Multiplier (LEM)

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

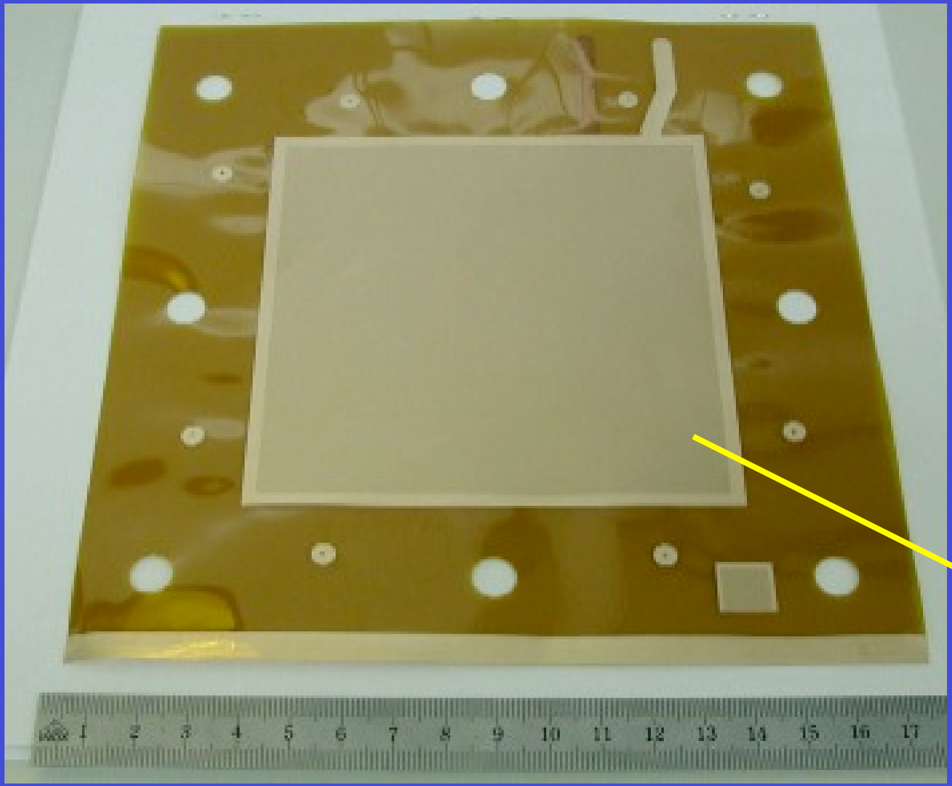
- **A large scale GEM (x10) made with ultra-low radioactivity materials (copper plated on virgin Teflon)**
  - In-house fabrication using automatic micro-machining
  - Modest increase in V yields gain similar to GEM
  - Self-supporting, easy to mount in multi-layers
- **Resistant to discharges (lower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

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



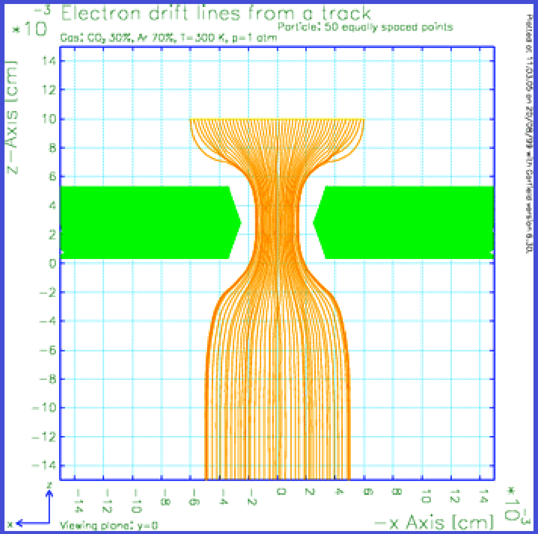


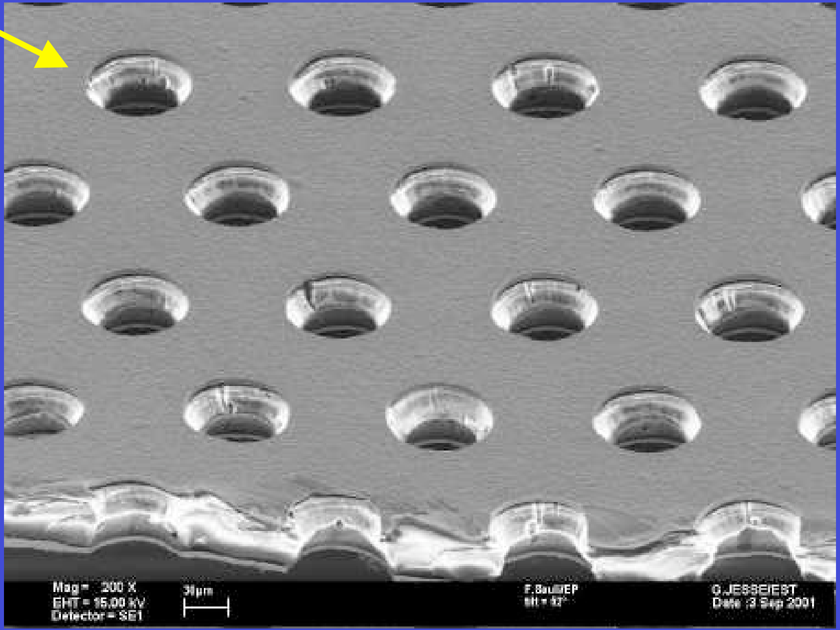
Gas Electron Multiplier GEM (F. Sauli et al., CERN)



100x100 mm^2

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

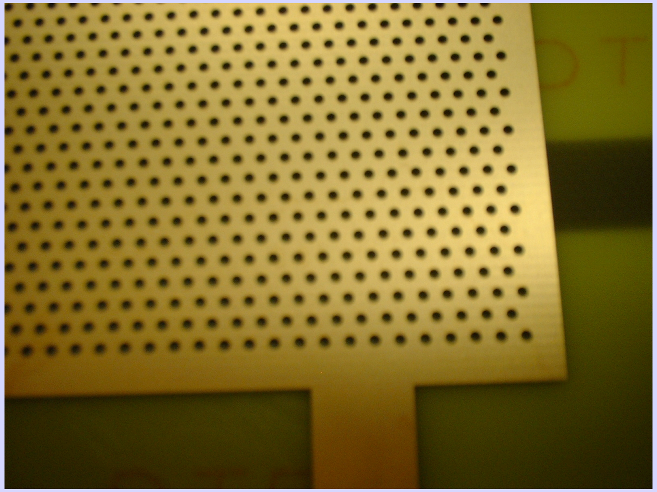




LEM with pure Argon-100%

Detection of charge signal and scintillation light produced during amplification

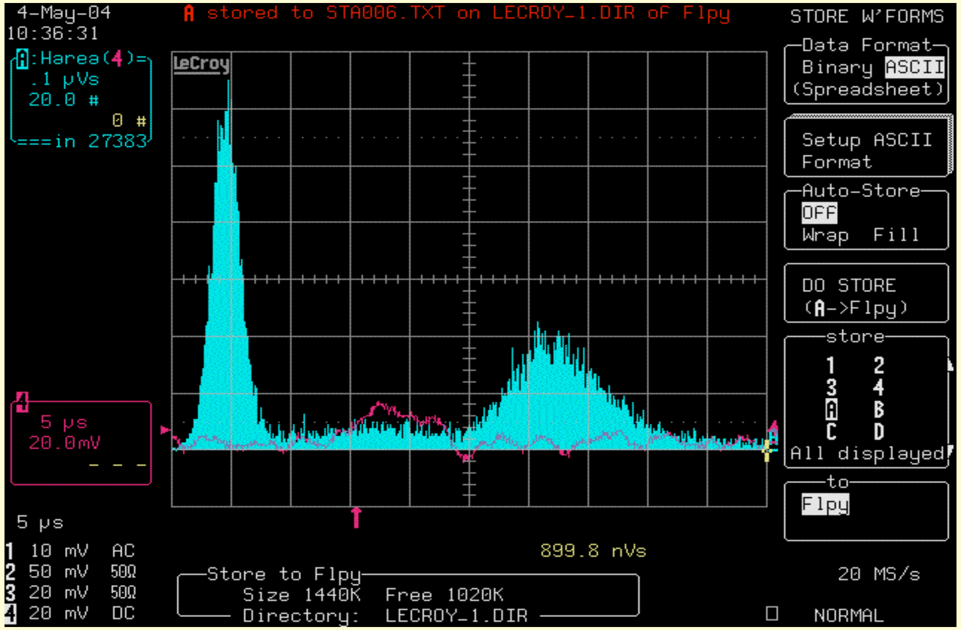
400 x 400 mm^2



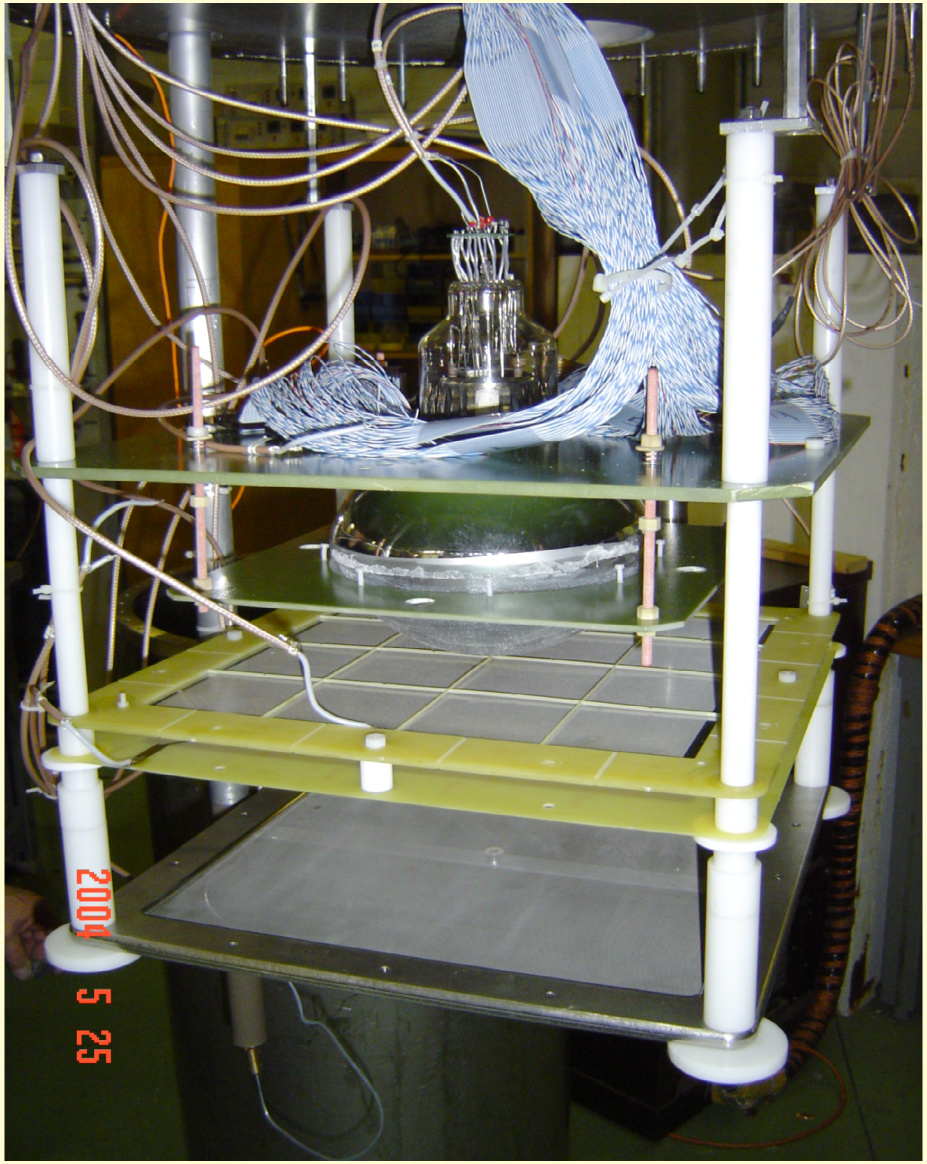
Holes ϕ = 1 mm

Amplification with self-made LEMs

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

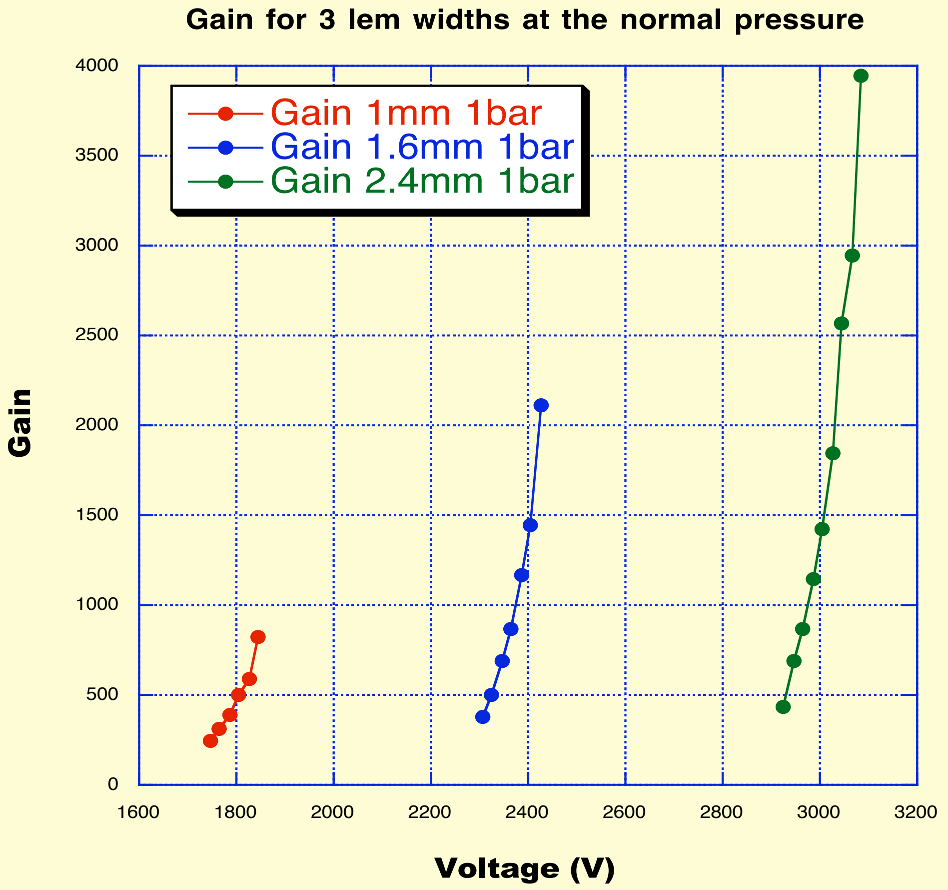


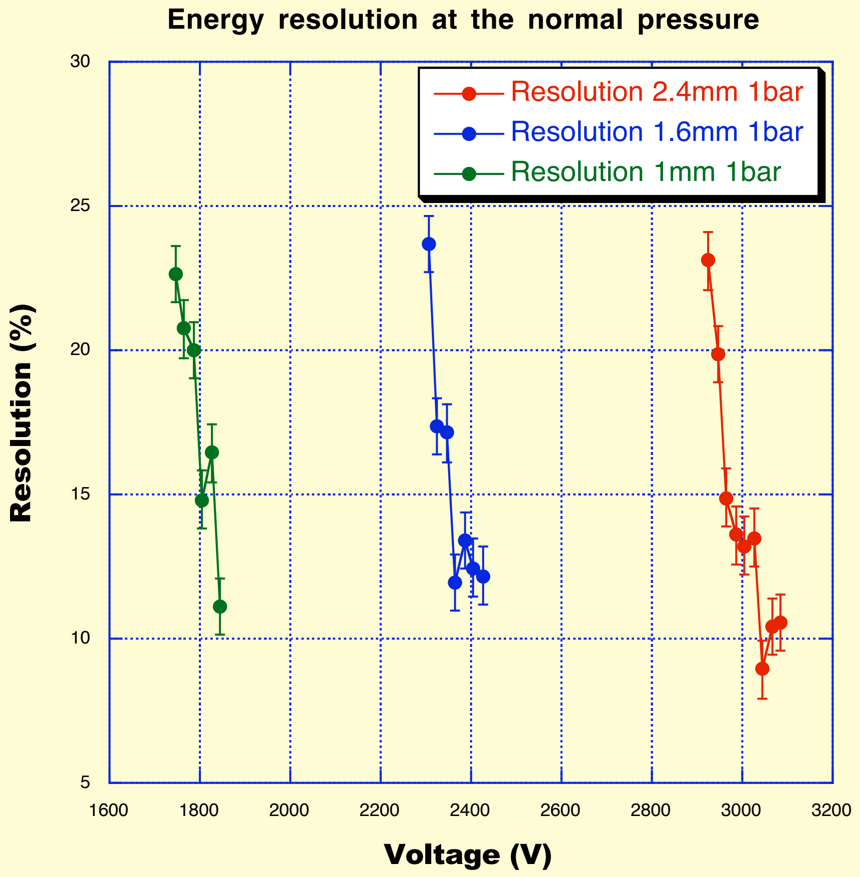
Raw charge spectrum



Gain and resolution: effect of LEM geometry

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

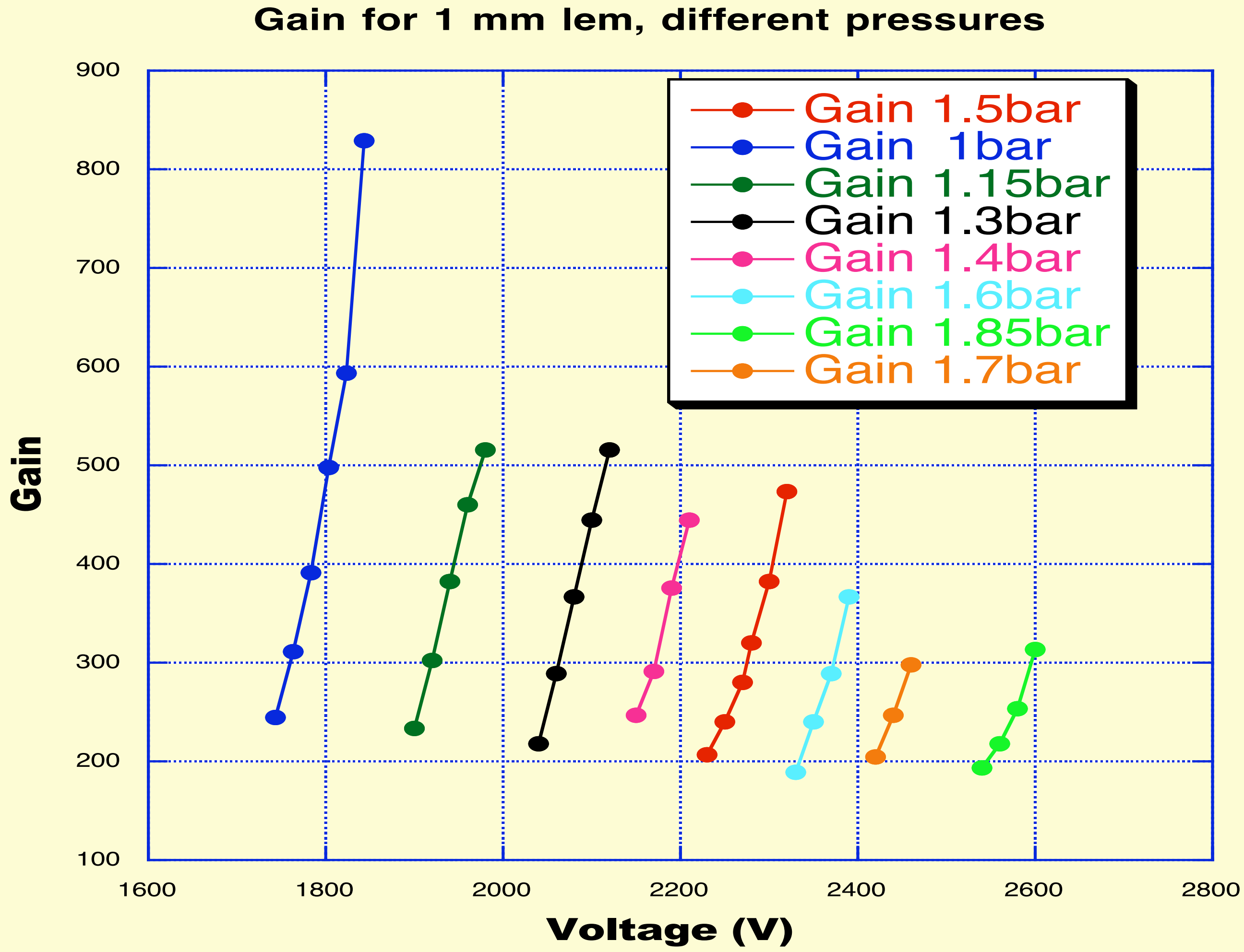

Gain for 3 lem widths at the normal pressure


Energy resolution at the normal pressure

Stable operation possible in pure argon

Gain for different gas pressures

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



Stable operation possible in pure argon

2) High-pressure drift properties in liquid Argon

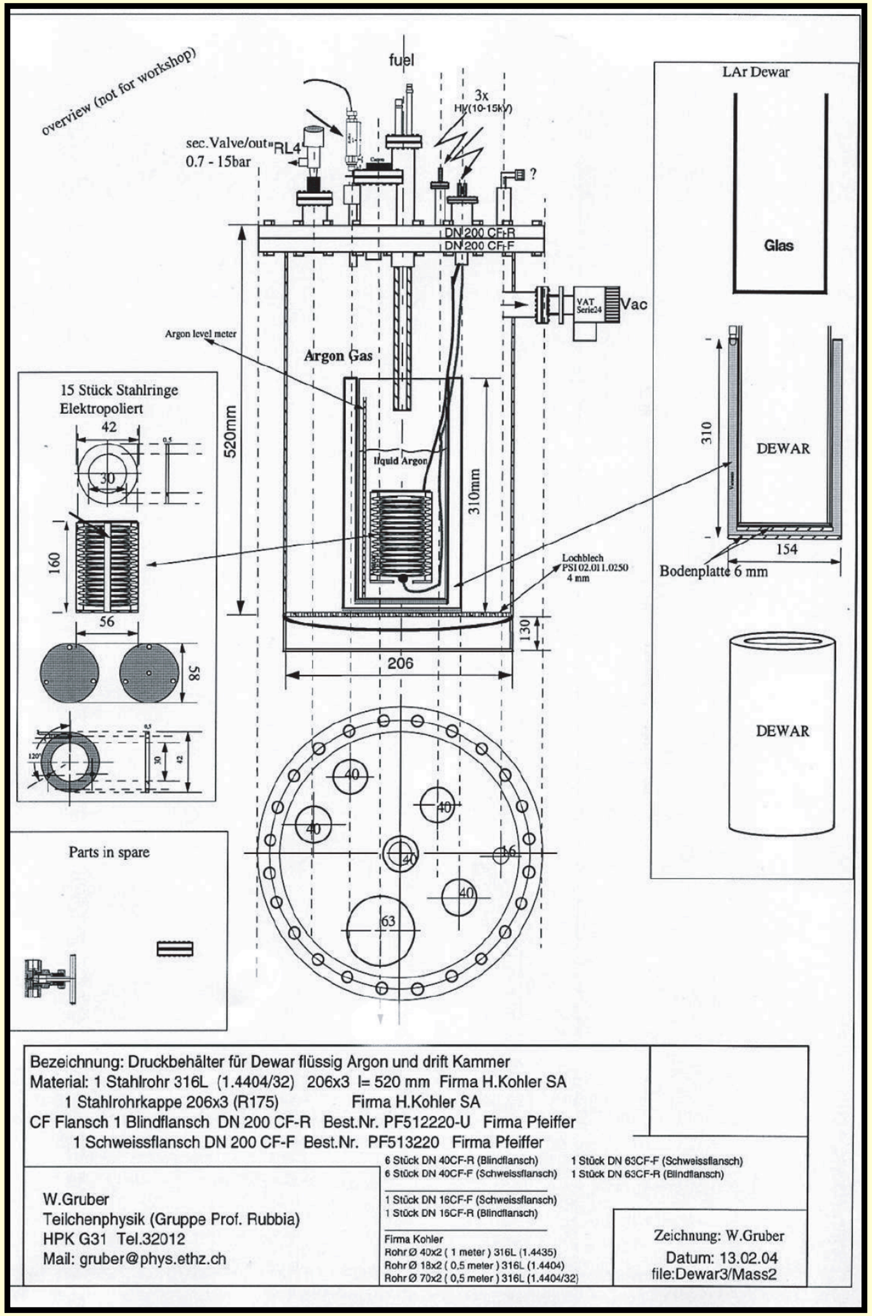
- **Future large tankers:**

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

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

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

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



Bezeichnung: Druckbehälter für Dewar flüssig Argon und drift Kammer
Material: 1 Stahlrohr 316L (1.4404/32) 206x3 l= 520 mm Firma H.Kohler SA
1 Stahlrohrkappe 206x3 (R175) Firma H.Kohler SA
CF Flansch 1 Blindflansch DN 200 CF-R Best.Nr. PF512220-U Firma Pfeiffer
1 Schweissflansch DN 200 CF-F Best.Nr. PF513220 Firma Pfeiffer

6 Stück DN 40CF-R (Blindflansch)
6 Stück DN 40CF-F (Schweissflansch)
1 Stück DN 63CF-F (Schweissflansch)
1 Stück DN 63CF-R (Blindflansch)

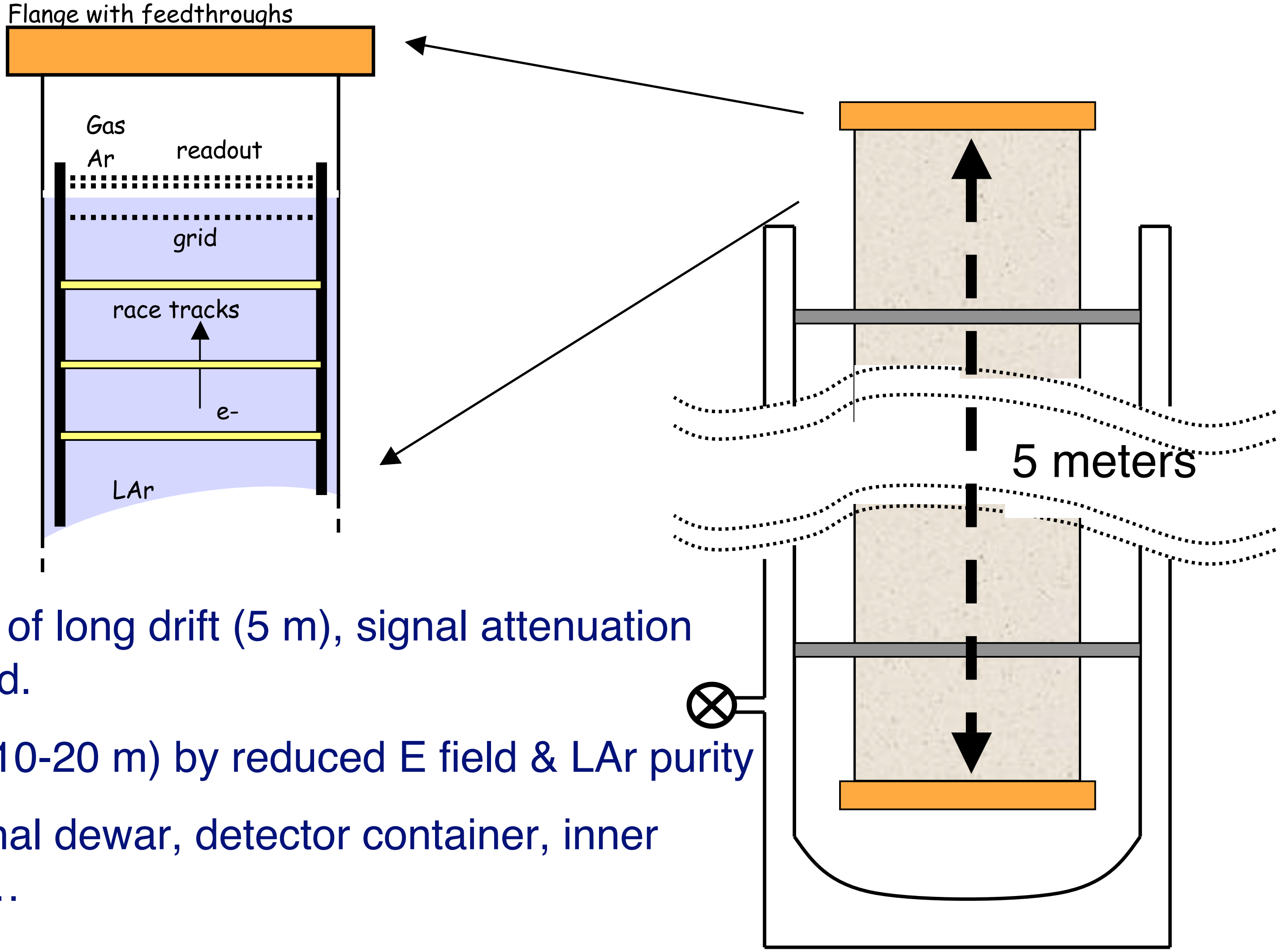
1 Stück DN 16CF-F (Schweissflansch)
1 Stück DN 16CF-R (Blindflansch)

Firma Kohler
Rohr Ø 40x2 (1 meter) 316L (1.4435)
Rohr Ø 18x2 (0,5 meter) 316L (1.4404)
Rohr Ø 70x2 (0,5 meter) 316L (1.4404/32)

W.Gruber
Teilchenphysik (Gruppe Prof. Rubbia)
HPK G31 Tel.32012
Mail: gruber@phys.ethz.ch

Zeichnung: W.Gruber
Datum: 13.02.04
file:Dewar3/Mass2

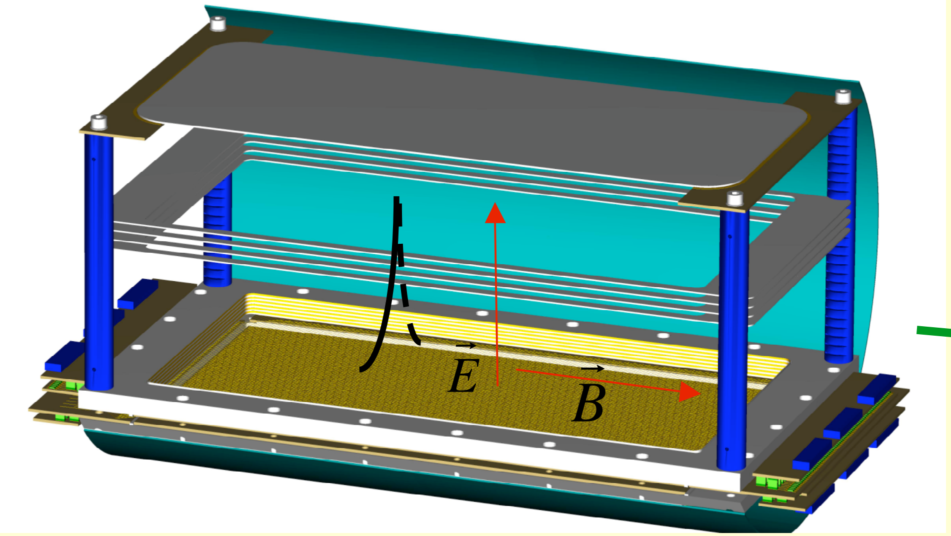
3) Long drift, extraction, amplification: test module



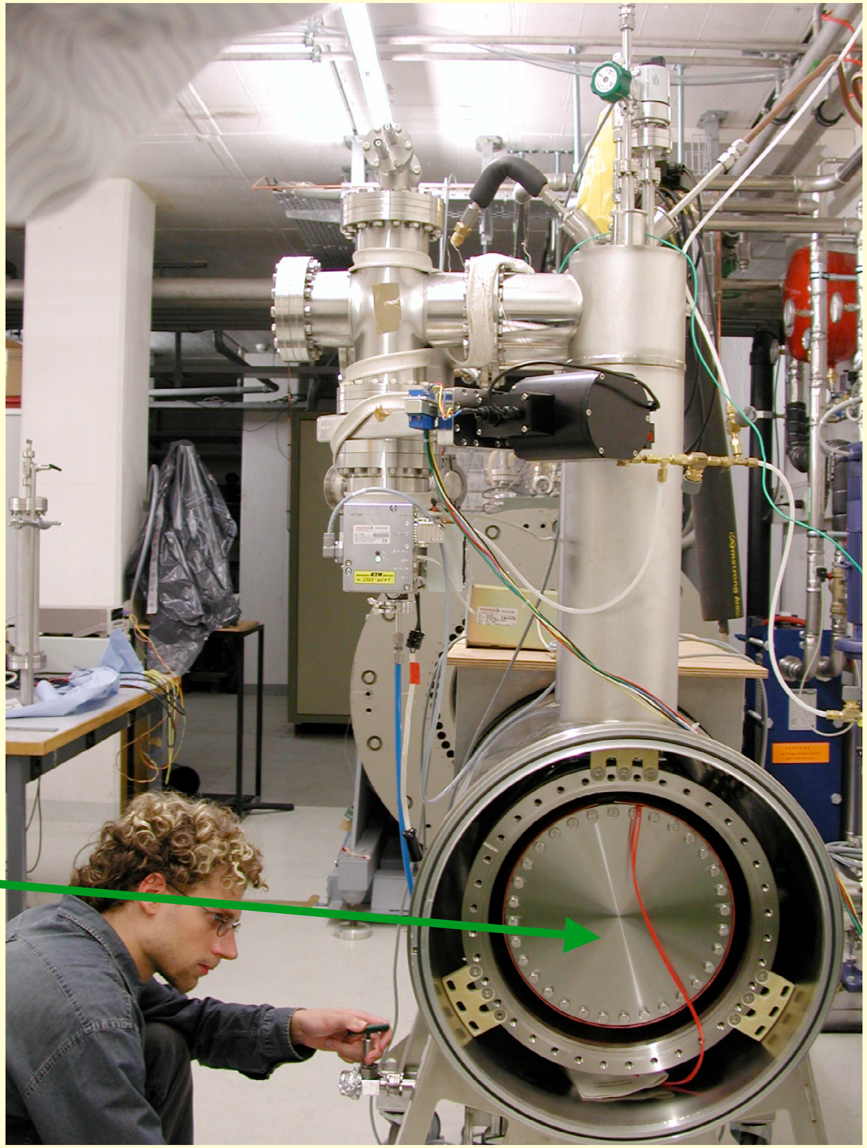
- A full scale measurement of long drift (5 m), signal attenuation and multiplication is planned.
- Simulate ‘very long’ drift (10-20 m) by reduced E field & LAr purity
- Design in progress: external dewar, detector container, inner detector, readout system, …

4) Test of liquid Argon imaging in B-field

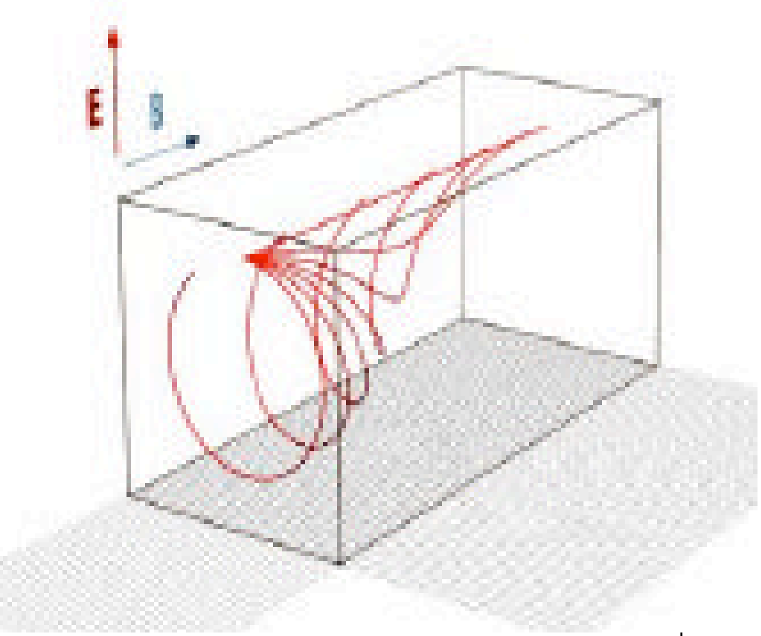
- **Small chamber in SINDRUM-I recycled magnet up to B=0.5T (230KW) given by PSI, Villigen**
- **Test program:**
  - ➥ Check basic imaging in B-field
  - ➥ Measure traversing and stopping muons bending
  - ➥ Charge discrimination
  - ➥ Check Lorentz angle (α≈30mrad @ E=500 V/cm, B=0.5T)
- **Results expected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



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



R&D for liquid argon in magnetic field



- **Opens new possibility**
  - ➥ Charge discrimination
  - ➥ Momentum measurement of particles escaping detector (e.g. muons)
  - ➥ MS dominated (Δp/p≈4% at L=12m, B=1T)
- **Orientation of the field**
  - ➥ Bending in the direction of the drift where resolution is the best
    - ☛ Achieved point resolution in T600 : 400 μm
  - ➥ B-field perpendicular to E-field
  - ➥ Lorentz angle small in liquids α≈30mrad @ E=500 V/cm, B=0.5 T
- **Required magnetic field strength for charge discrimination (*x=path in LAr*)**

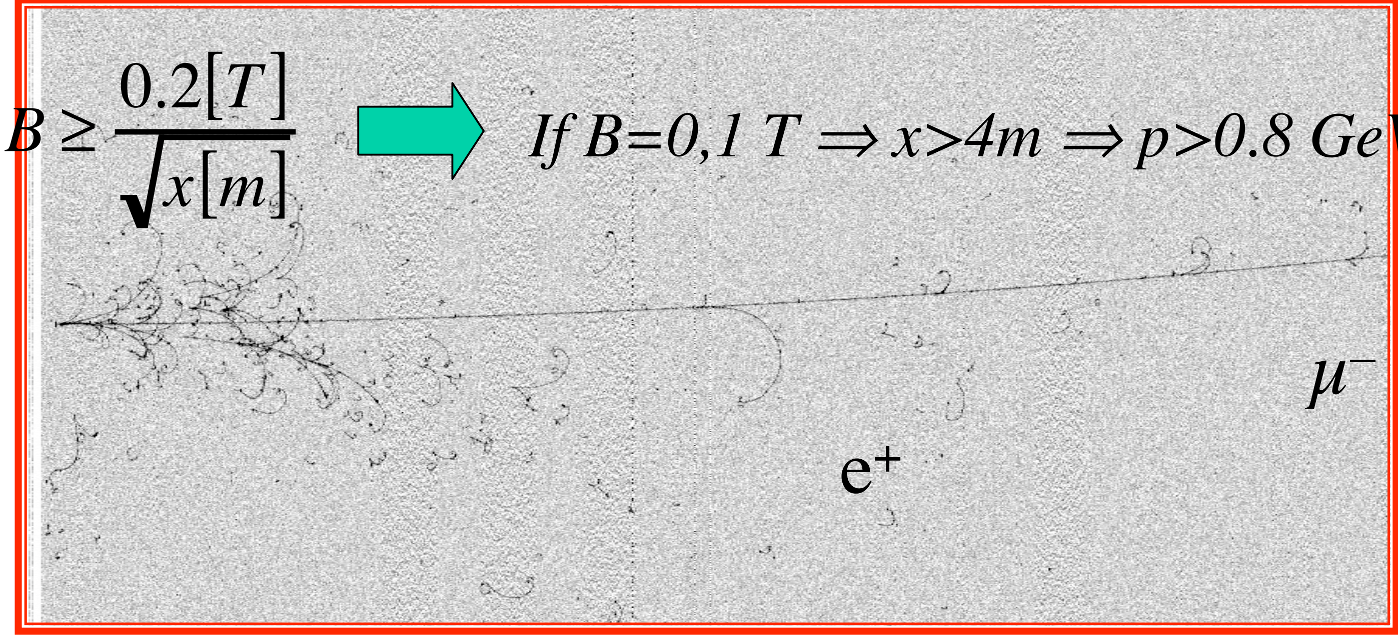
$$b \approx \frac{l^2}{2R} = \frac{0.3B[T]\left(x[m]\right)^2}{2p[GeV]}$$

$$MS \approx \frac{0.02\left(x[m]\right)^{3/2}}{p[GeV]}$$

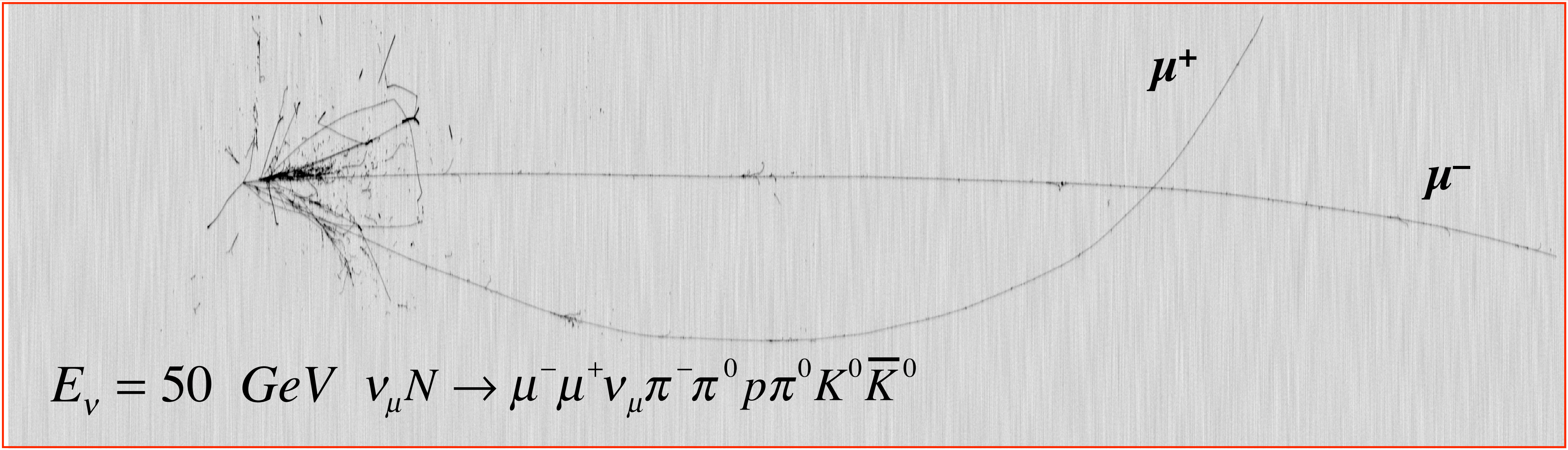
3 sigmas discrimination:

$$b^+ - b^- = 2b > 3MS \quad \Rightarrow \quad B \geq \frac{0.2[T]}{\sqrt{x[m]}}$$

Simulated ν_μ CC events in B=0.2 T

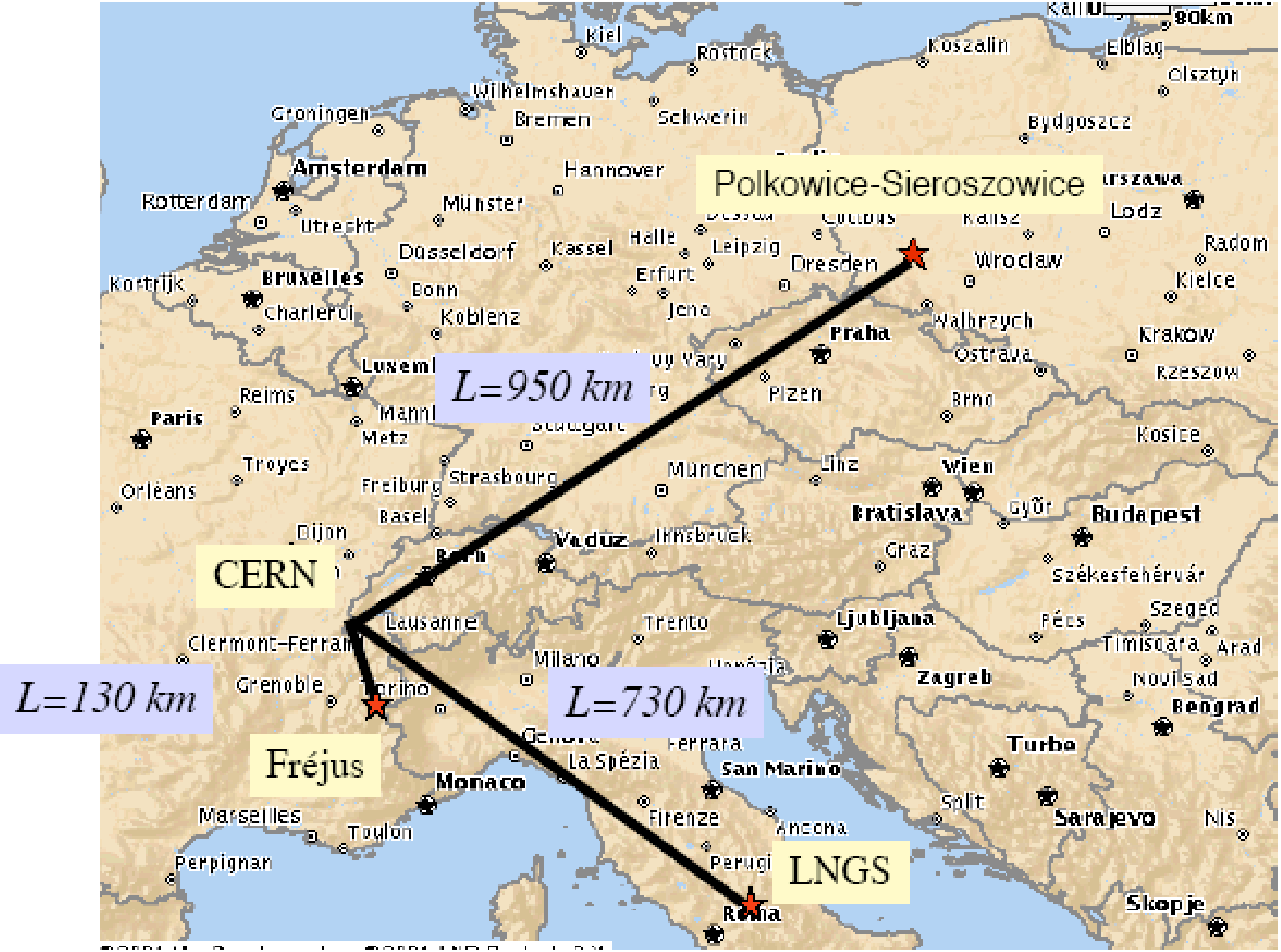


$$B \geq \frac{0.2[T]}{\sqrt{x[m]}}$$ ⇒ *If* $B=0{,}1\ T \Rightarrow x>4m \Rightarrow p>0.8\ GeV/c$



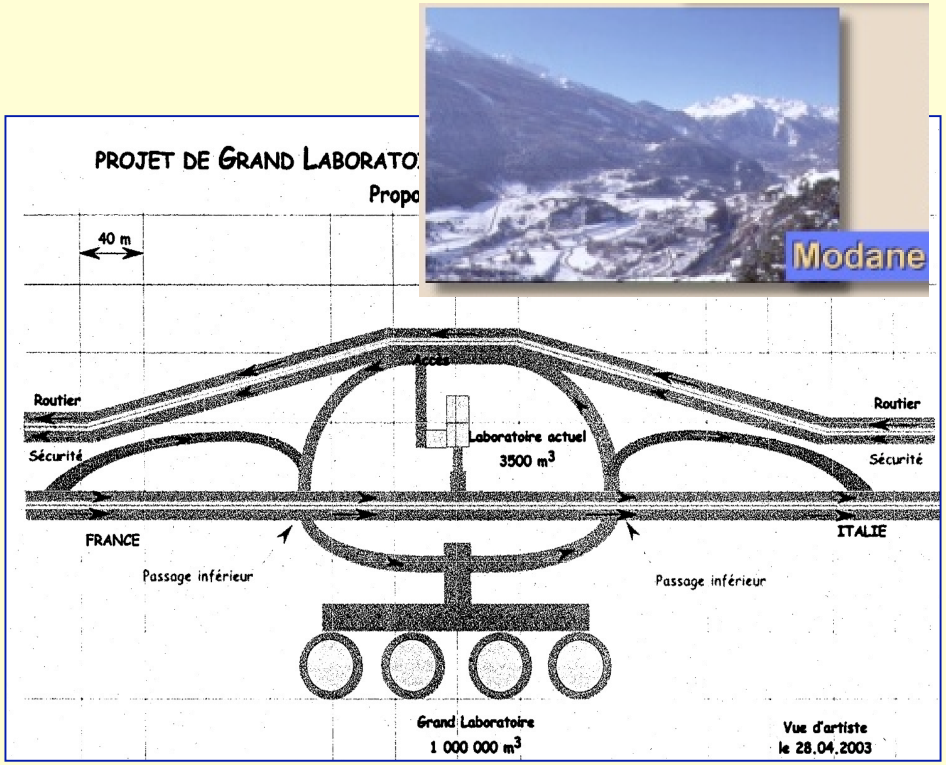
$E_\nu = 50\ \ GeV\ \ \nu_\mu N \rightarrow \mu^- \mu^+ \nu_\mu \pi^- \pi^0 p \pi^0 K^0 \overline{K}^0$

5) Location study: underground sites in Europe



Two different topologies envisioned for the site:

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



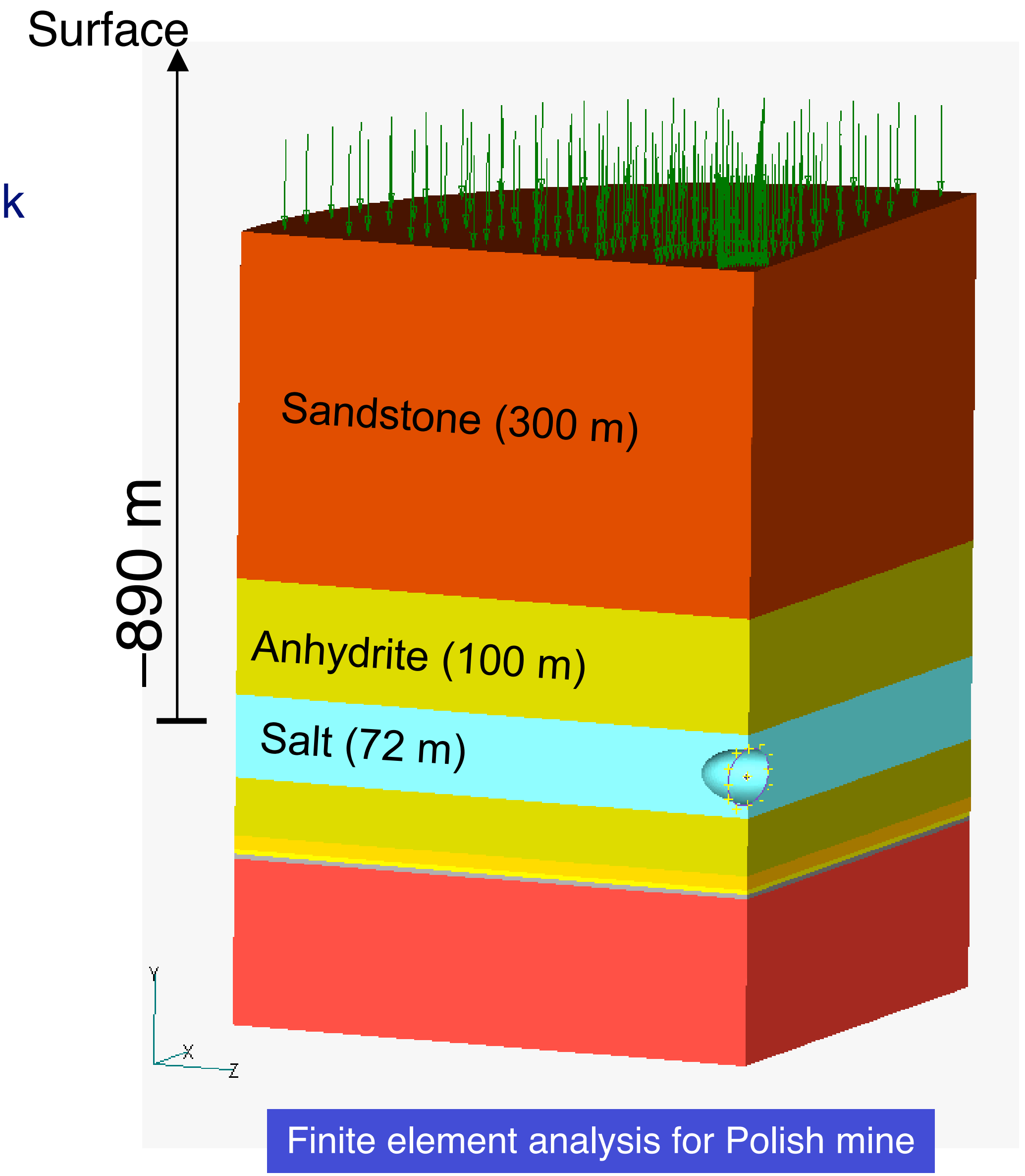
- cooperation agreement: IN2P3/CNRS/DSM/CEA & INFN
- international laboratory for underground physics
- easy access
- safety issues (highway tunnel)
- caverns have to be excavated

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

Feasibility of a large underground cavern

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

cavern ≈ 100000 m^3
or
tunnel-like geometry



Finite element analysis for Polish mine

Creation of an international "Argon-Net"

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

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

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

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

Outlook

- The liquid Argon TPC imaging has reached a high level of maturity thanks to many years of R&D effort conducted by the ICARUS collaboration. The plan is to operate a kton mass scale detector at LNGS with the ICARUS project: ultimate proof of detector imaging performance with astroparticle & neutrino beam events.
- Today, physics is calling for applications at two different mass scales:
  - ≈ 100 kton: proton decay, high statistics astrophysical & accelerator neutrinos
  - ≈ 100 ton: systematic study of neutrino interactions, near detectors at LBL facilities
- A large mass (100 kton), monolithic LAr TPC based on the industrial technology of LNG tankers and on the bi-phase operation is conceivable (cost compatible with Mton physics program). A tentative design was given. R&D studies are in progress and a global strategy is being defined.
- The 100 kton detector can well match future high-intensity neutrino facilities. Choice on site and beam parameters will be physics-driven. Rich non-accelerator physics program (ultimate nucleon decay searches and astroparticle physics).
- A 10 kton full-scale prototype is conceivable today (cost compatible with a CNGS experiment).
- A 100 ton detector in a near-site of an artificial neutrino beam is needed to provide a detailed study of neutrino interactions. Could provide the “near” measurement in a LBL facility (cost compatible with CHIPP…!).
- Even though I did not elaborate on it, we are pursuing R&D for dark matter detection.
- We presented here an overview of our current thinking & activities. Work will be further pursued along these lines of thoughts. Hope to stimulate feed-back from the community through the creation of a dedicated world-wide Network.