“Neutrino Physics” Experimental

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ETH Zürich

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On Fundamental Physics

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Focus of this talk

- **In this talk, I will focus on (some) experimental techniques of (some) neutrino experiments and not discuss experimental results**
  - ➥Theory&discussion of results: Gonzalez-Garcia
- **Also**
  - ➥Neutrino telescopes: Montaruli
  - ➥UHE neutrinos: Zas

Mysterious neutrinos

- Neutrinos come in (almost) three flavors (LEP: N_ν=2.984±0.008)
- They are much lighter than their charged lepton partner (⇒ why?)

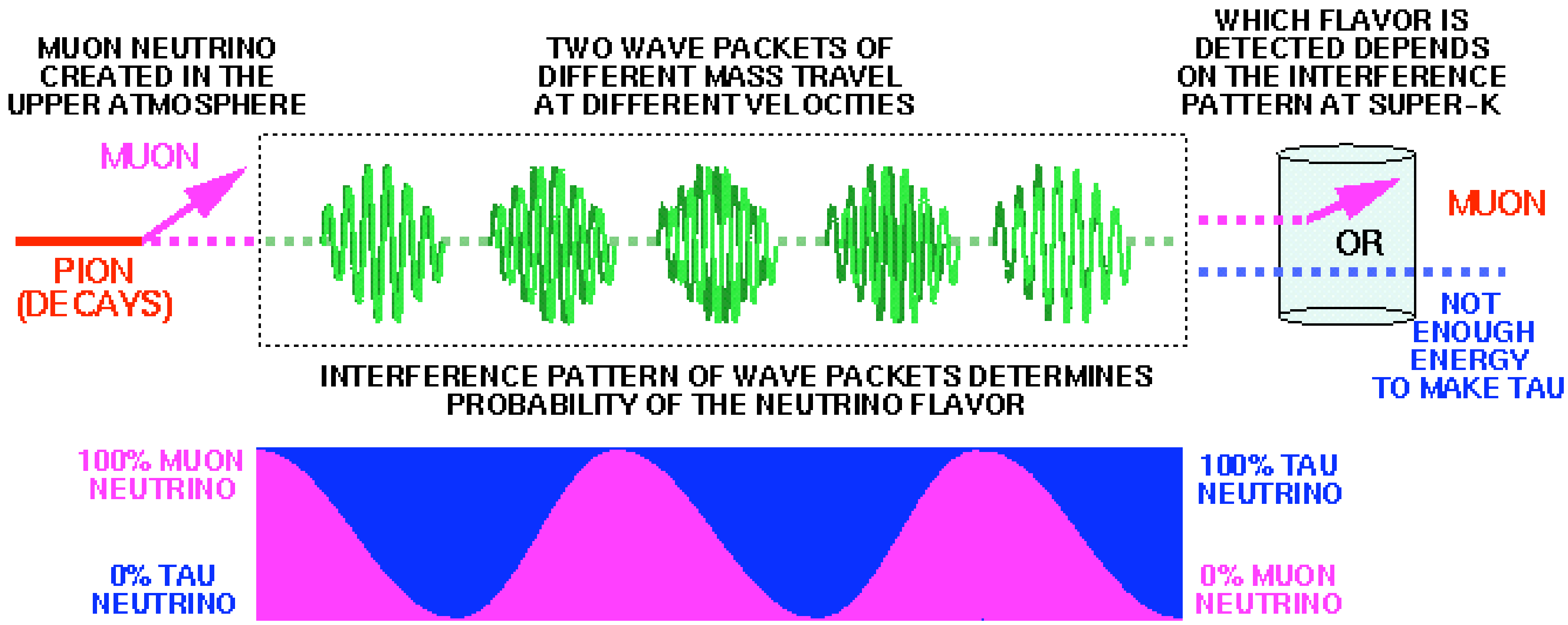
e	511 keV	ν_e	< 3 eV
μ	106 MeV	ν_μ	<0.19 MeV
τ	1.78 GeV	ν_τ	<18.2 MeV

- Mass and weak eigenstates differ (⇒mixing)
- 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)

Neutrino flavor oscillations

Example: disappearance of atmospheric due to neutrino flavor oscillation

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)}\right)$$

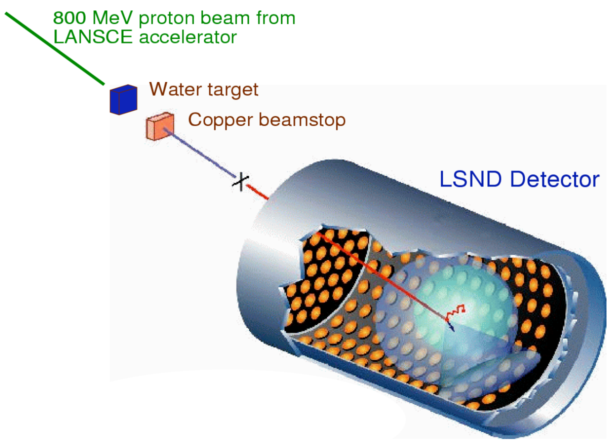


Three Experimental Indications for Neutrino Oscillations

LSND Experiment

L = 30m
E = ~40 MeV

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

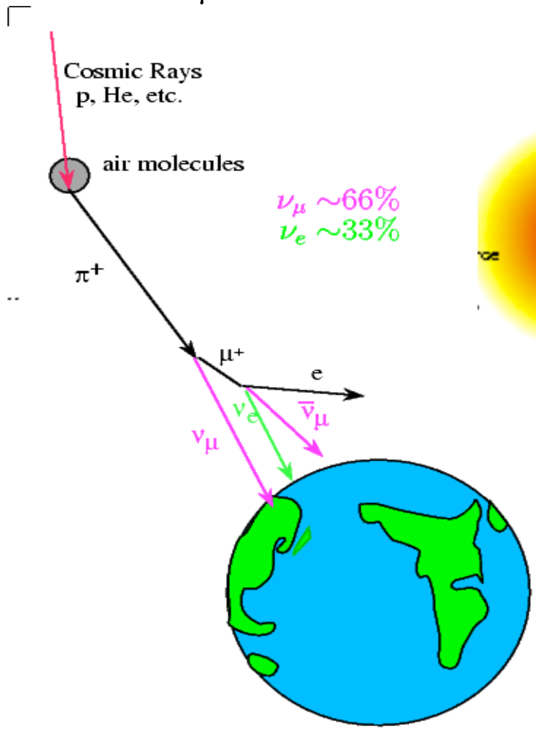


Δm^2 = .3 to 3 eV^2
Prob$_{OSC}$ = 0.3 %

Atmospheric Neutrinos

L = 15 to 12,000 km
E =300 to 2000 MeV

$$\nu_\mu \rightarrow \nu_x$$

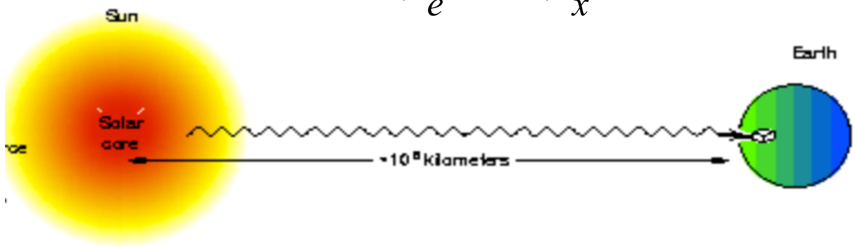


Δm^2 = ~ 1 to 7 × 10^{-3} eV^2
Prob$_{OSC}$ = ~100%

Solar Neutrinos

L = 10^8 km
E =0.3 to 15 MeV

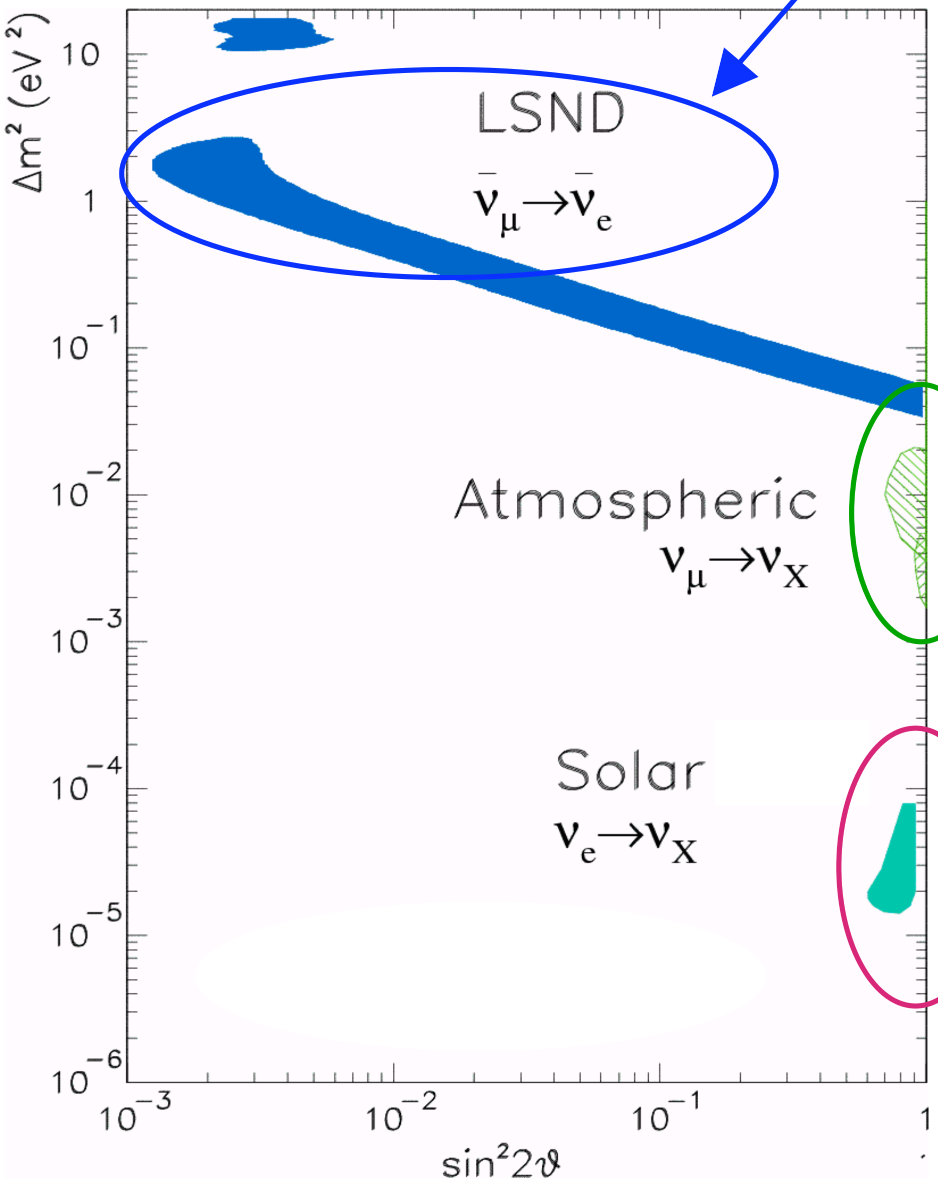
$$\nu_e \rightarrow \nu_x$$



Δm^2 = ~ 2 to 8 × 10^{-5} eV^2
Prob$_{OSC}$ = ~100%

Questions addressed by current experiments

- **LSND Δm^2**
  - Determination if osc.
  - Measure Δm^2&$\sin^2 2\theta$
- **Atmospheric Δm^2**
  - Know if $\nu_\mu \rightarrow \nu_\tau$ or ν_s
  - Measure Δm^2&$\sin^2 2\theta$
  - Maybe see $\nu_\mu \rightarrow \nu_e$
  - CERN observe ν_τ
- **Solar Δm^2**
  - Restrictions to one solar solution
  - Know if $\nu_e \rightarrow \nu_{\mu,\tau}$ or ν_s
  - Measure Δm^2



Three neutrino formalism

Standard parameterization: 3 angles + 3 complex phases

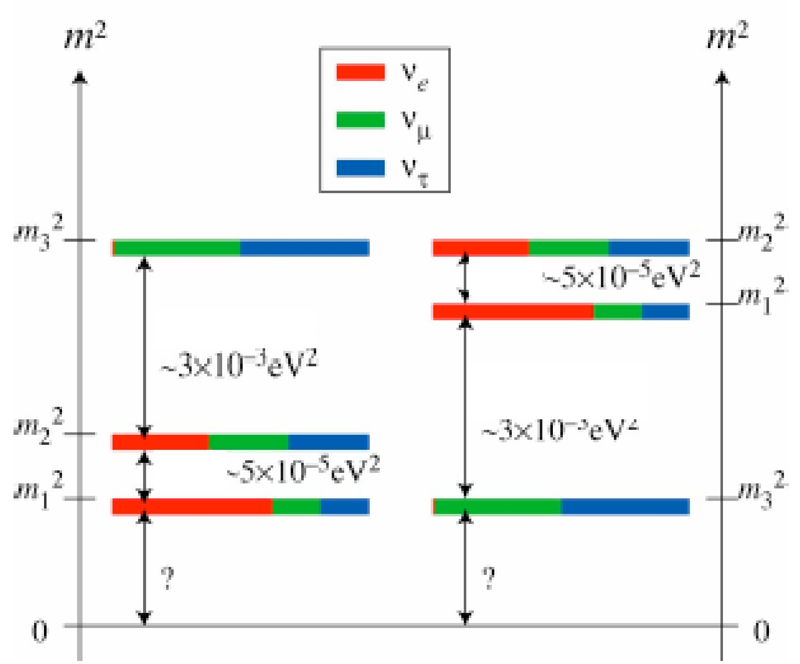
$$U_{MNSP} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot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

$\theta_{23} \sim 45°$ $\tan^2\theta_{13} < 0.03$ at 90% CL $\theta_{12} \sim 32°$

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

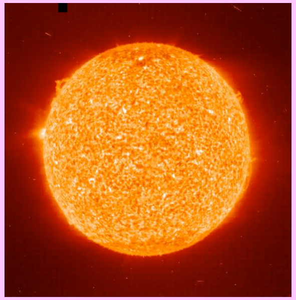
(Disregarding LSND result)

Mass Hierarchy



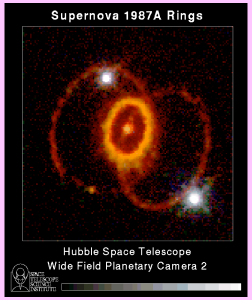
Which sources of neutrinos can be used?

Astrophysical sources



Solar

Atmospheric

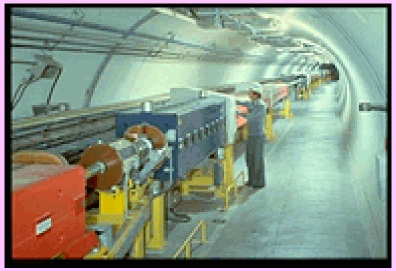


Supernovae

BigBang

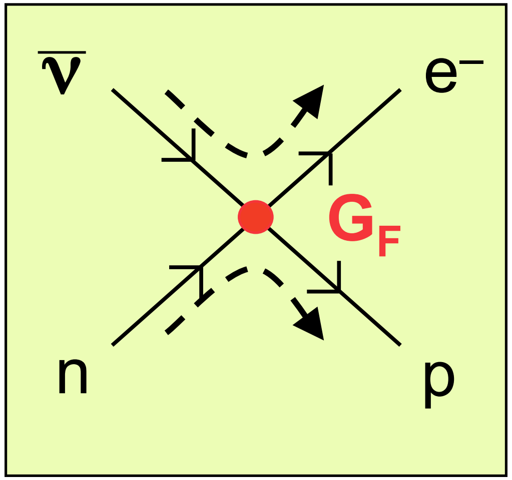
Man-made sources

Accelerators



Reactors

Fermi theory including neutrino hypothesis



Neutrino hypothesis — Pauli, 1930

Weak interaction

$$n \to p + e^- + \nu$$

$$G_F\left(\overline{\psi}_p \gamma^\mu \psi_n\right)\left(\overline{\psi}_e \gamma_\mu \psi_\nu\right)$$ Fermi, 1932

Implies the existence of the related process (inverse):

Inverse β decay ⇒

$$\overline{\nu}_e + p \to e^+ + n$$

$E_\nu > (m_n - m_p) + m_e \approx 1.8$ MeV

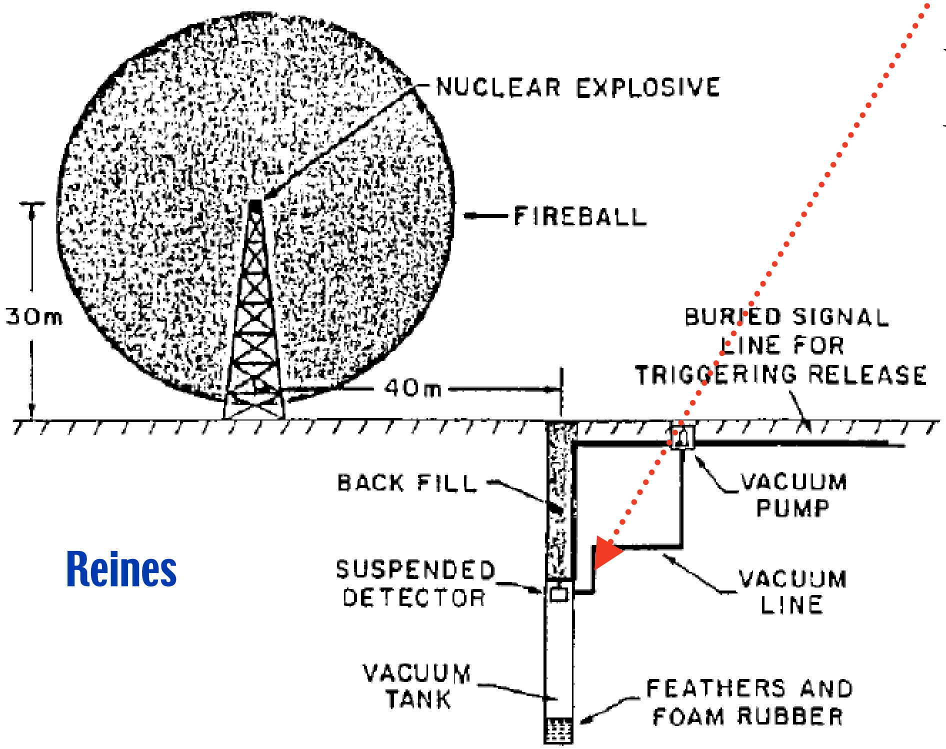
Incoming neutrino ($\overline{\nu}_e$), Free proton (p), Positron emission (e^+), Neutron emission (n)

$$\sigma(\overline{\nu}_e + p \to e^+ + n) = 10^{-43}\left(\frac{E}{MeV}\right)^2 cm^2$$ Bethe, Peierls

⇒ *Mean free path in water:*
$\lambda \approx 30$ light-years at E=1 MeV

Attempts to detect free neutrinos

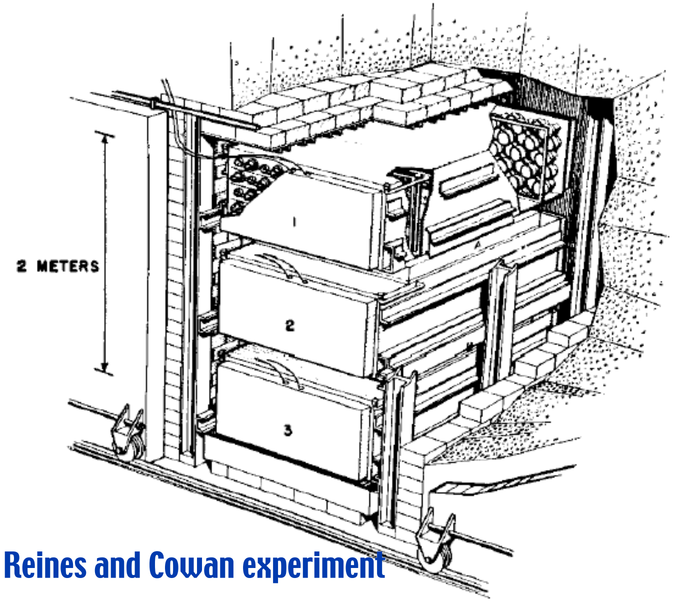
"I have done a terrible thing. I have postulated a particle that cannot be detected." (Pauli)



Reines

The experiment was approved but was superseded by the approach that used a fission reactor.

$$\text{Flux} \approx 2\times 10^{20} \times \frac{Power}{GW} \quad \bar{\nu}_e / s \qquad E \approx \text{MeV}$$



Reines and Cowan experiment

Savannah River Power Plant (South Carolina, USA)

The nuclear bombs used in World War II were equivalent to about 15kton of TNT or about 60 TJ of energy. Modern nuclear weapons can carry up to 84000 TJ.

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,

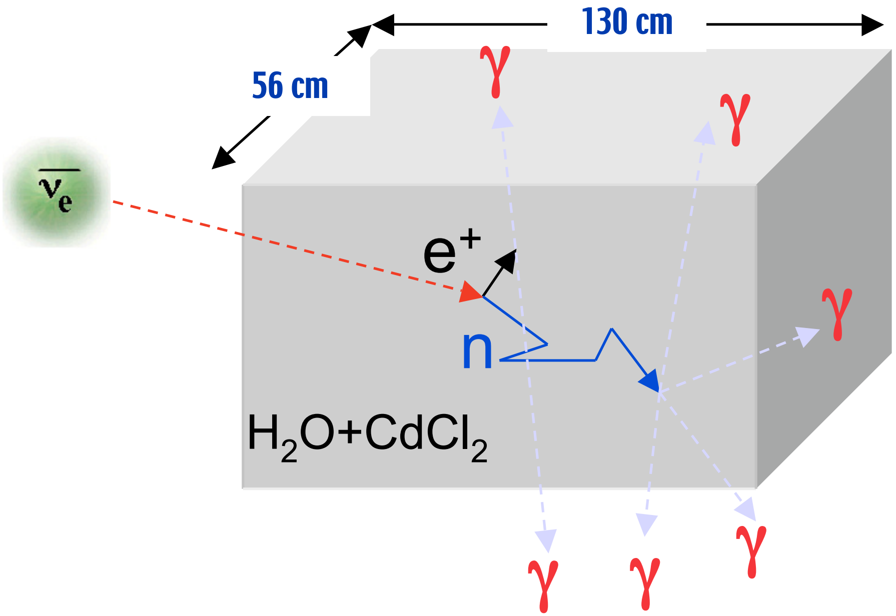
Enrico

Enrico Fermi

ETH Institute for Particle Physics

Reines & Cowan detection technique

Prompt-positron-delayed-neutron correlation technique invented: background reduction!



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$e^+ + e^- \rightarrow \gamma + \gamma$$

Prompt signal:
2x0.51 MeV

$$n + Cd \rightarrow Cd^* \rightarrow Cd + \gamma's$$

Delayed signal: ≈9 MeV

Measured rate:
2.88±0.22 counts per hour !
With signal/background ≈ 3/1

$$\sigma = (1.1 \pm 0.3) \times 10^{-43} cm^2$$

Reines and Cowan, Science 124 (1956) 103; Phys. Rev. 113 (1959) 273

Study of weak interactions (≈1960)

The Fermi theory which was known to work well at low energies implied that the cross-section increases as phase space

$$\sigma \propto G_F^2 s = G_F^2 M_N E_\nu^{lab}$$

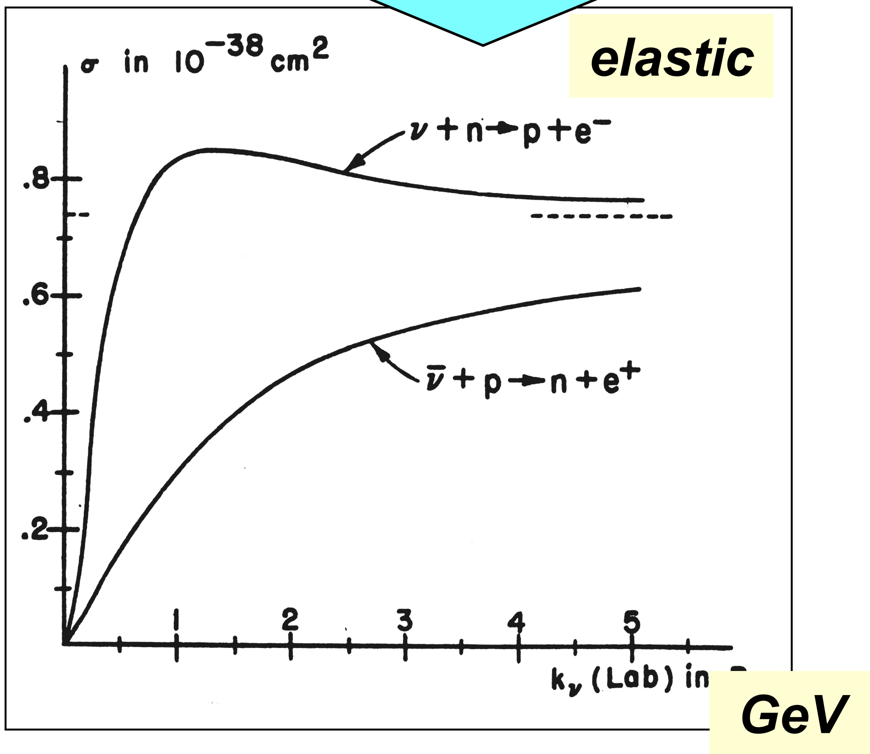
$\sigma \approx 10^{-38}\ \text{cm}^2$

In a fixed target experiment (e.g. neutrino beam with nucleon target), the cross-section increases linearly with the laboratory neutrino energy

Lee & Yang computed the quasi-elastic processes:

$$\nu_e + n \rightarrow e^+ + p$$

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



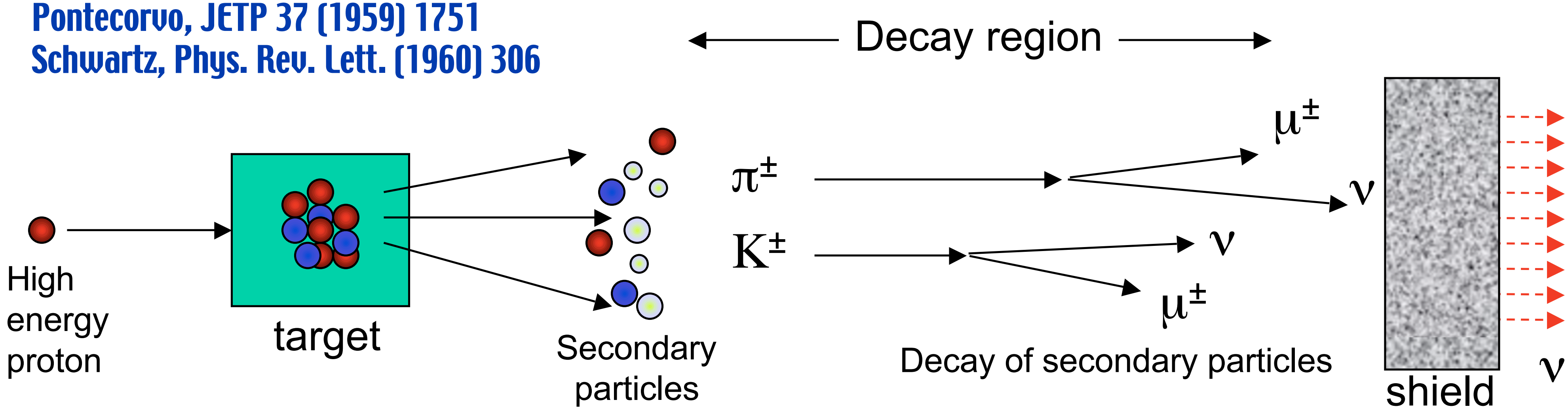
T.D. Lee, C.N. Yang, Phys. Rev. Lett. 4 (1960) 307

Sources of high energy neutrino (≈1960)

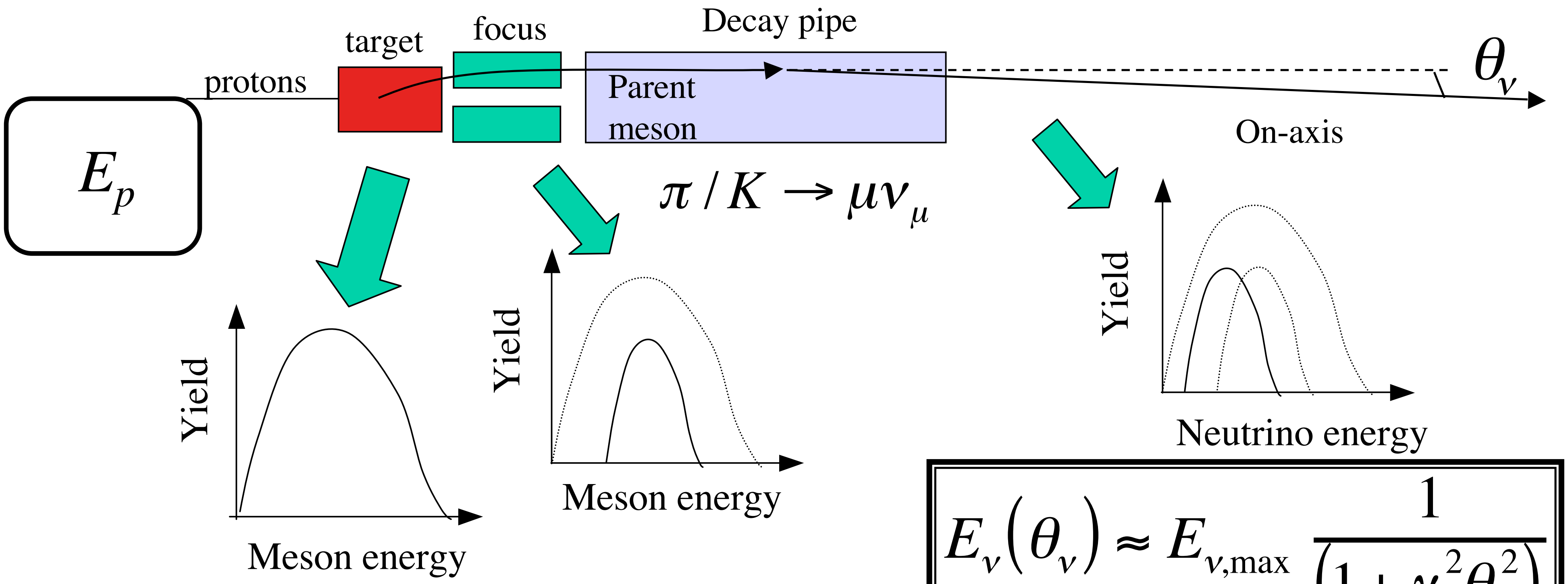
B. Pontecorvo and M. Schwartz independently proposed to study these reactions with an artificial beam of energetic muon-neutrinos produced at a proton accelerator. The basic scheme for the production of energetic muon neutrinos is based on the following facts:

1. During the collision of high energy protons on a fixed target, **a large number of secondary hadrons** (in particular pion and kaons if the proton energy is sufficiently high) **are produced** in the forward direction.
2. In order to let the secondary hadrons decay, **the target region is followed by a decay region**.
3. **The *V–A* theory predicts that most decays will produce muon neutrinos**, since the electronic decay is highly suppressed by the "wrong helicity" of the charged lepton in the decay
4. **The decay tunnel is followed by a thick shielding** that stops all particles except neutrinos (and the some penetrating muons). Behind the shielding, a beam of neutrinos is present.

Pontecorvo, JETP 37 (1959) 1751
Schwartz, Phys. Rev. Lett. (1960) 306



Modern neutrino beam



$$E_\nu(\theta_\nu) \approx E_{\nu,\max} \frac{1}{(1+\gamma^2\theta_\nu^2)}$$

$$E_{\nu,\max} \approx \left(1 - \frac{m_\mu^2}{m_M^2}\right) E_M = \begin{cases} 0.427\, E_\pi \\ 0.954\, E_K \end{cases}$$

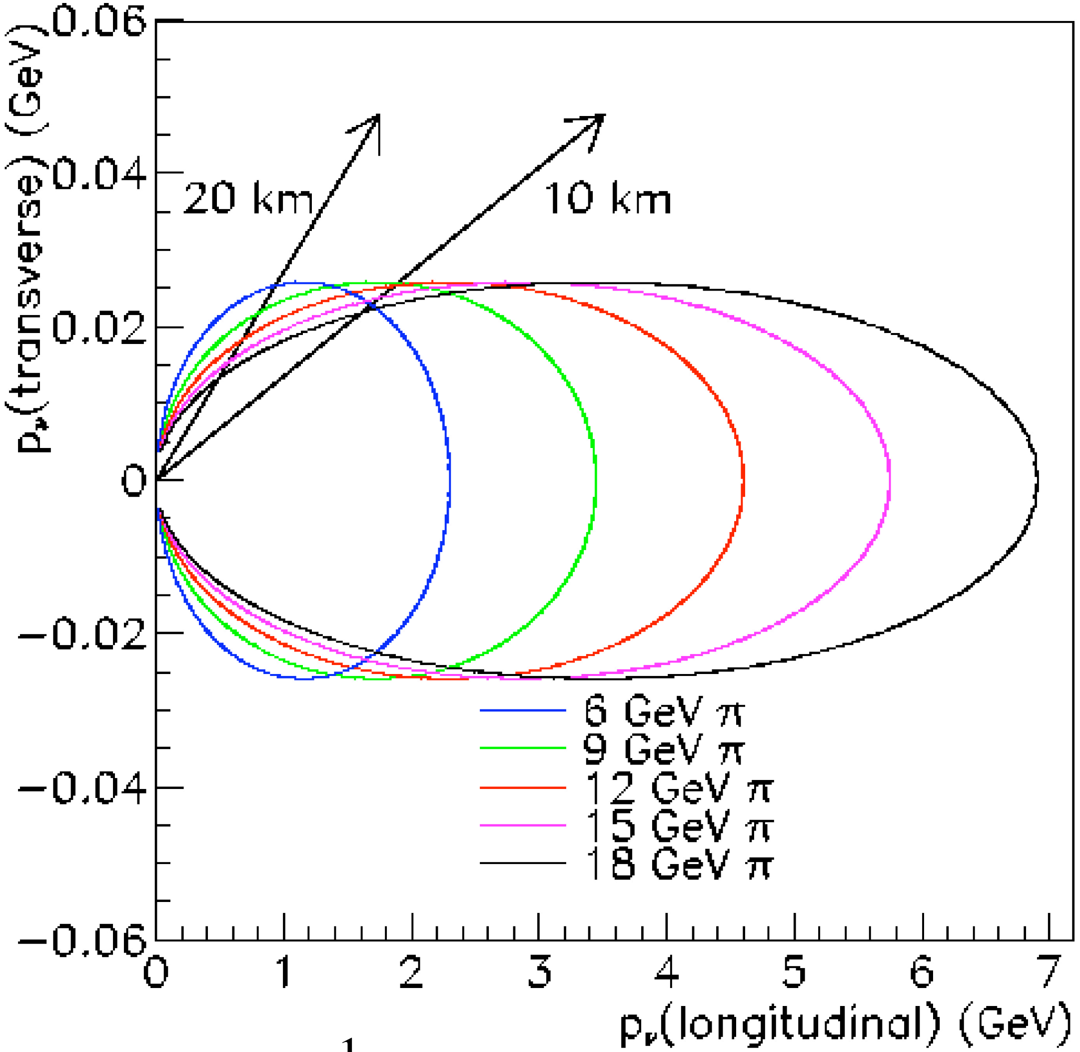
For long baseline (i.e. in the forward direction):

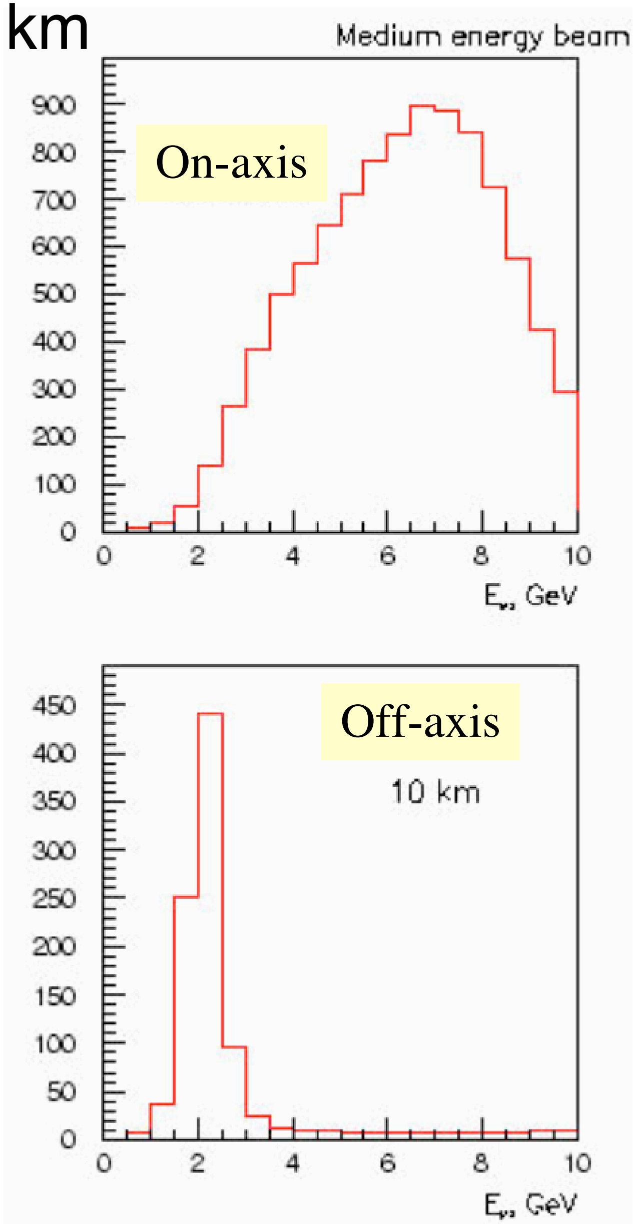
- Neutrino energy ≈ 0.43 × pion energy
- Lorentz-boost gives a factor E_ν^2 on solid angle
- Cross-section increases linearly with E_ν

Event rate $\propto E_\nu^3$
But oscillation probability $\propto E_\nu^{-2}$
Hence oscillated event rate $\propto E_\nu$

Off-axis long baseline

Example: Fermilab NUMI beam, ME, L=730 km





$$E_\nu(\theta_\nu) \approx E_{\nu,\max} \frac{1}{(1+\gamma^2\theta_\nu^2)}$$

The first accelerator neutrino beam (1962)

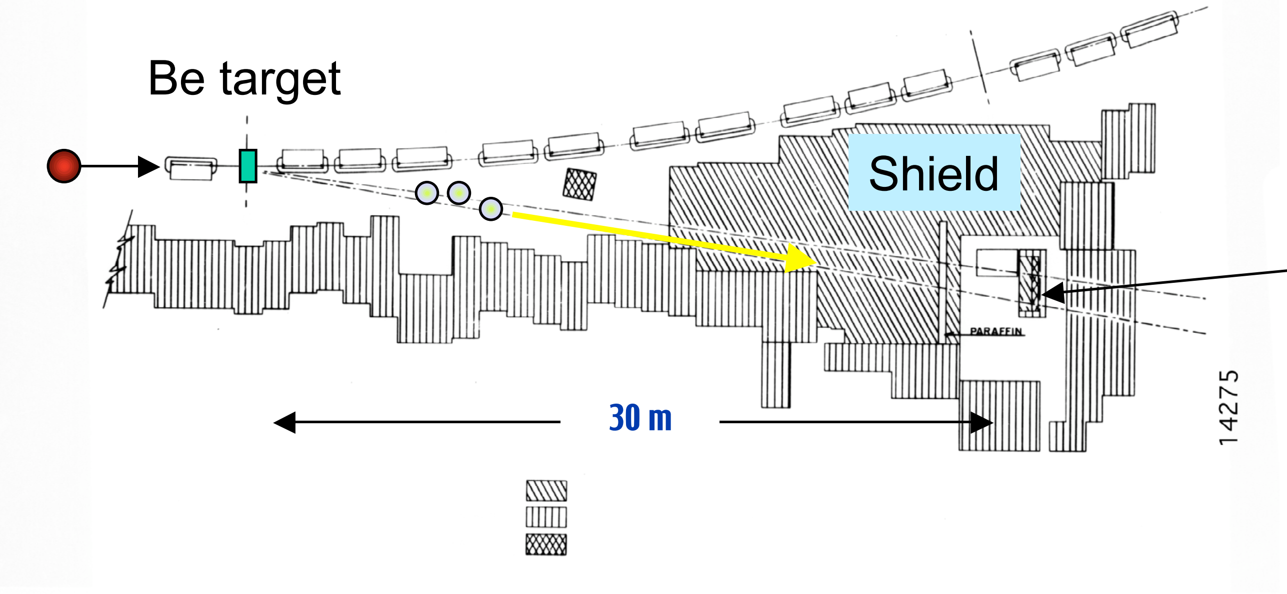
In 1962 at the Brookhaven AGS accelerator

proton energy : 15 GeV

proton intensity: $4x10^{11}$ protons/pulse

3000 pulses/hour

neutrinos: energy≈1 GeV, to test if mostly ν_μ



1 neutrino interaction per 1000 kg per day!

Basic design of neutrino detector

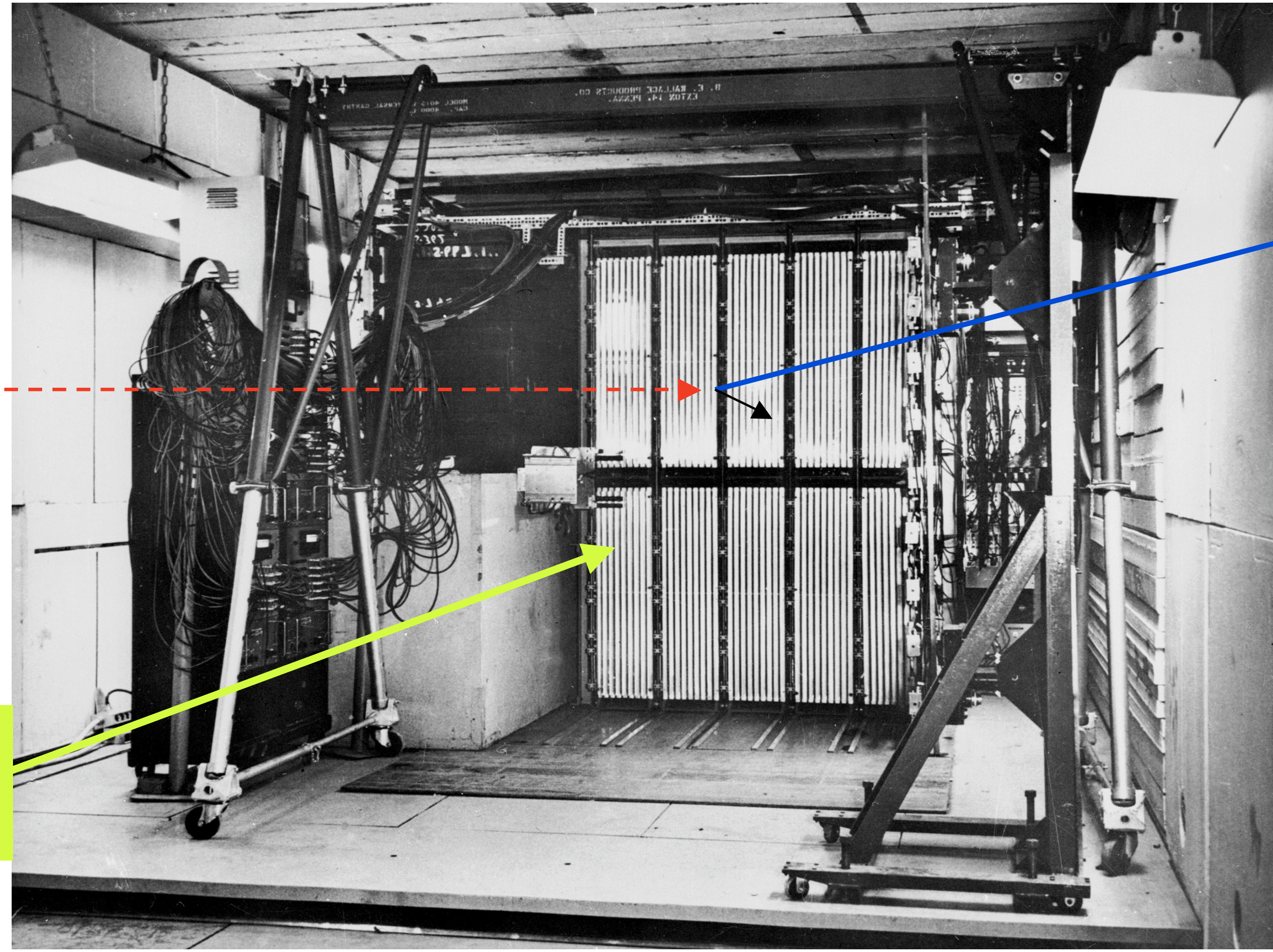
- **Neutrino flavor detection**
  - ➥The type of neutrino (the neutrino flavor) will be tagged via a charged current interaction, which produces a charged lepton of the corresponding flavor: electron-neutrinos produce leading electrons and muon-neutrinos produce muon neutrinos.
- **A neutrino detector must be a massive device in order to collect a sufficiently large number of events but at the same time provide enough granularity to distinguish final state particles.**
- **It must provide "background reduction" (neutrino interact very rarely with respect to other particles that might penetrate the detector)**
  - ➥Very high intensity neutrino source
  - ➥And/or Underground location (shield)
- **The neutrino detector plays two roles:**
  - ➥(1) the neutrino target
  - ➥(2) the detection device.

BNL-Columbia experiment (1962)

10 ton “spark chamber” detector

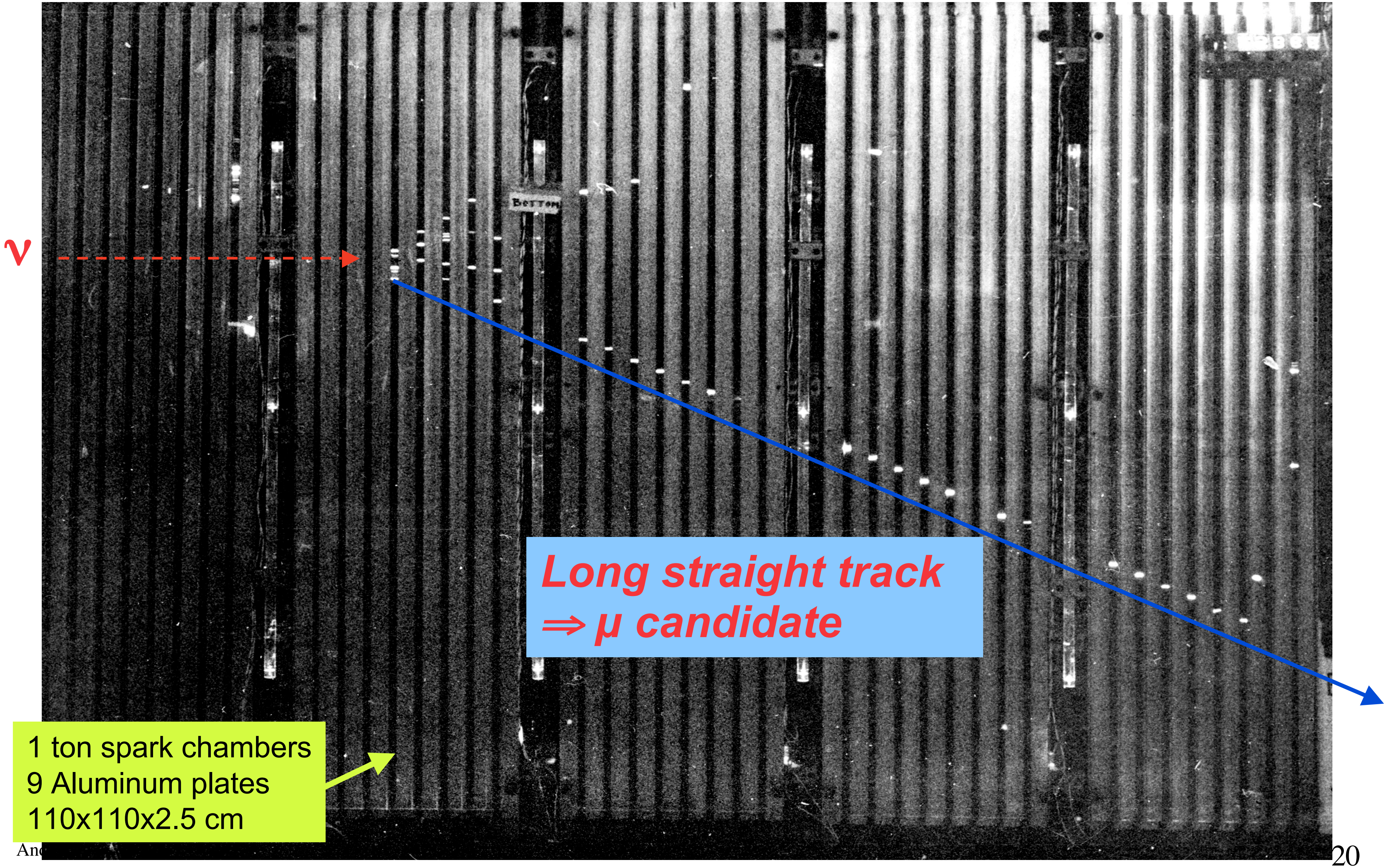
Danby, Gaillard, Goulianos, Lederman, Mistry, Steinberger, Schwartz, Phys. Rev. Lett. 9 (1962) 36

ν



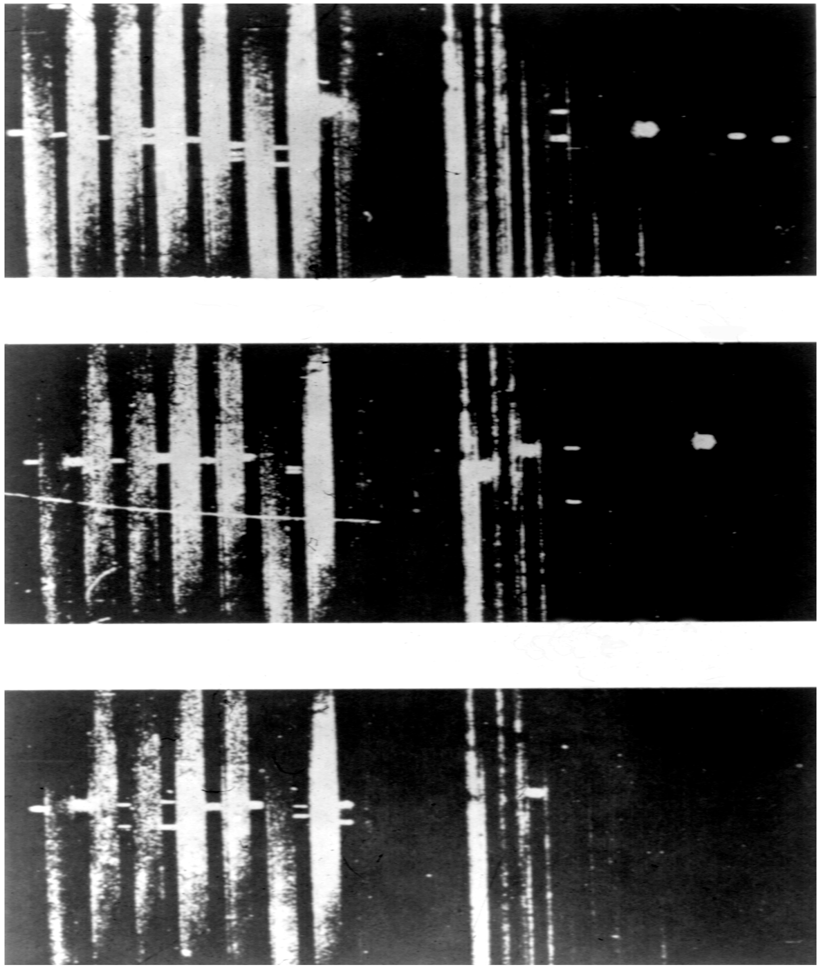
1 ton spark chambers
9 Aluminum plates
110x110x2.5 cm

One "muon-like" event in spark chamber



Results from BNL-Columbia experiment

400 MeV electron test beam



	Number of events
Single tracks	34
Multi tracks	22
"Showers"	**8**

Only 2 are compatible with electrons

$$\nu_e \neq \nu_\mu$$

Absolute mass measurement

‚indirect' approaches

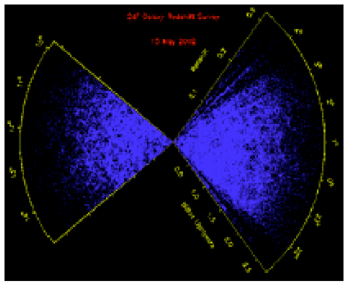
- Cosmology: LSS & CMBR
  depends on priors

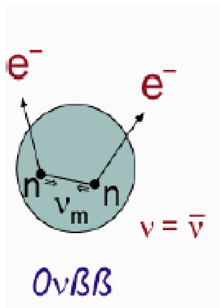
- $0\nu\beta\beta$
  Majorana: $m_{ee}(\nu)$, CP-phases

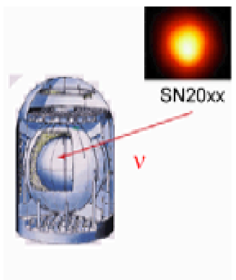
Direct measurements

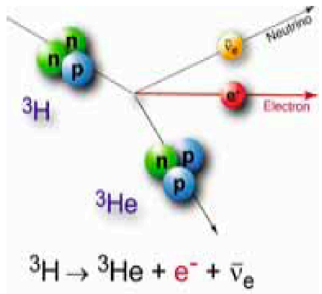
- Supernova ToF
  waiting for SN20xx
- Kinematics of particle decays

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









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}

http://lambda.gsfc.nasa.gov/

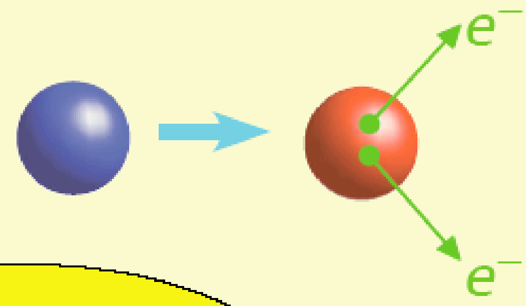
$$\Omega_\nu h^2 \approx 0.01 \frac{m_\nu}{eV} \Rightarrow m_\nu < 1\ eV$$

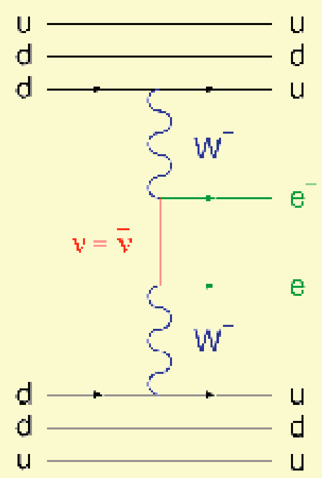
ETH Institute for Particle Physics

Neutrinoless double-beta decays

$\beta\beta$-0ν: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

- **not allowed in Standard Model:**
  - *lepton number violation ($\Delta L=2$)*
  - *Majorana nature of neutrino*
  - *massive neutrino*





$$\beta\beta\text{-}0\nu \Leftrightarrow \begin{array}{c} m_\nu \neq 0 \\ \nu \equiv \bar{\nu} \end{array}$$

- **expected lifetime:**

Phase space factor

nuclear matrix element

uncertainties

$$\tau^{-1} = G_{0\nu} |M^{0\nu}|^2 |\langle m_\nu \rangle|^2$$

Effective neutrino mass

$$\langle m_\nu \rangle = \sum_k m_{\nu_k} \eta_k |U_{ek}|^2$$

neutrino mixing matrix

⇨ **constraints on $\langle m_\nu \rangle$ can translate in constraints on m_{min}**

Cremonesi, NOON04

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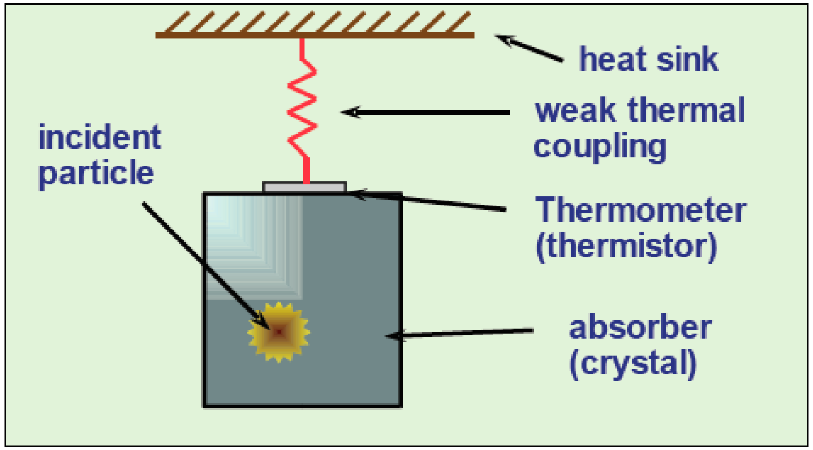
Cryogenic detectors

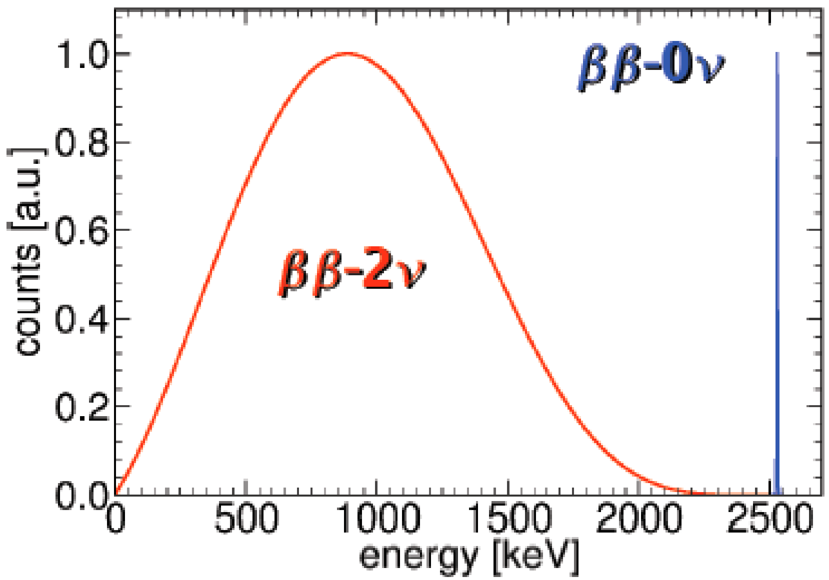


Detection Principle

- $\Delta T = E/C$
  C thermal capacity
  - low C
    - low T (i.e. $T \ll 1$K)
    - dielectrics, superconductors

Calorimeters

- source ⊆ detector
  - large N_{nuclei}
  - high energy resolution ΔE
  - high efficiency
- measure $E = E_{\beta_1} + E_{\beta_2}$
- signature: a peak at $Q_{\beta\beta}$



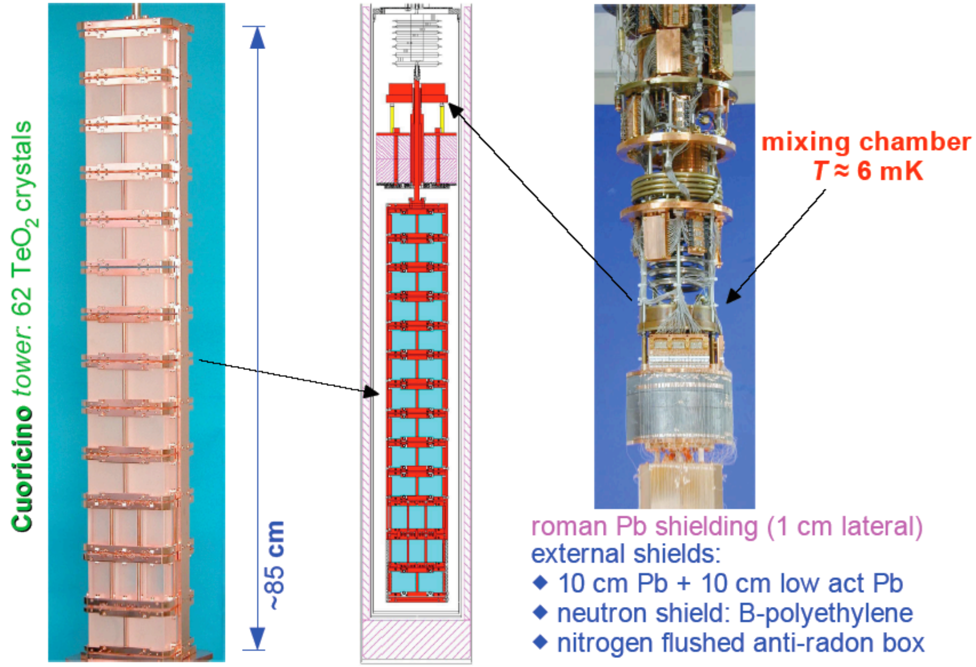
Cremonesi, NOON04

CUORE / CUORICINO

- **Cryogenic Underground Observatory for Rare Events**
  - ➥ Array of 1000 TeO2 crystals (5x5x5 cm^3, 750 g)
  - ➥ 750 kg TeO2 granular calorimeter
  - ➥ 600 kg Te = 203 kg ^{130}Te active isotope

TeO_2 thermal calorimeters

- Active isotope ^{130}Te
  - natural abundance: a.i. = 33.9%
  - transition energy: $Q_{\beta\beta}$ = 2529 keV



CUORICINO: 19st April 2003 →

- successfully operating independent experiment on $^{130}Te\ \beta\beta(0\nu)$
  - ▶ 40.7 kg of TeO_2, $B_{\beta\beta(0\nu)}$ = 0.19 ± 0.04 c/keV/kg/y, ΔE = 8keV
  - ▶ $\tau_{1/2} \geqslant 7.5 \times 10^{23}$ years at 90% C.L. ($\langle m_\nu \rangle \leqslant 0.32 \div 1.68$ eV)
  - ▶ $S^{1\sigma}_{3\ years} \geqslant 6 \times 10^{24}$ years - $\langle m_\nu \rangle \leqslant 0.11 \div 0.60$ eV

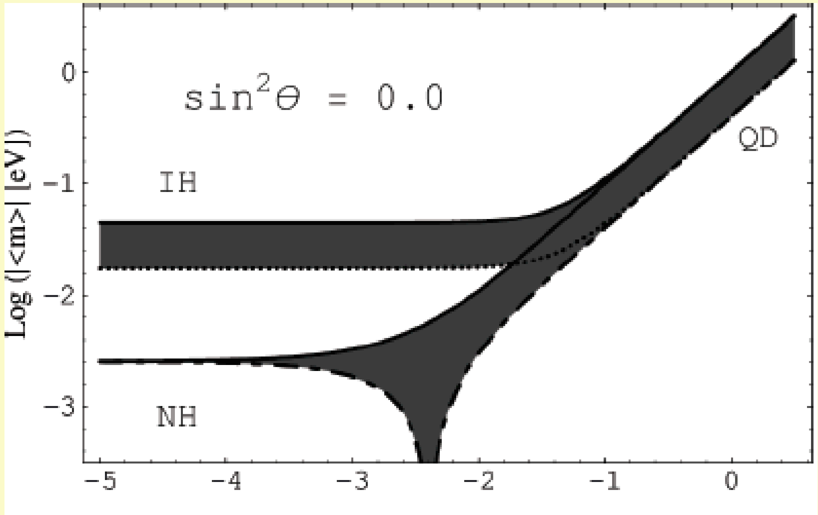
Cremonesi, NOON04

CUORE proposal

CUORE $\beta\beta(0\nu)$ sensitivity will depend strongly on the background level and detector performance. In five years:

B(counts/keV/kg/y)	Δ(keV)	$T_{1/2}$(y)	$\lvert\langle m_\nu\rangle\rvert$ (meV)
0.01	10	1.5×10^{26}	23–118
0.01	5	2.1×10^{26}	19–100
0.001	10	4.6×10^{26}	13–67
0.001	5	6.5×10^{26}	11-57

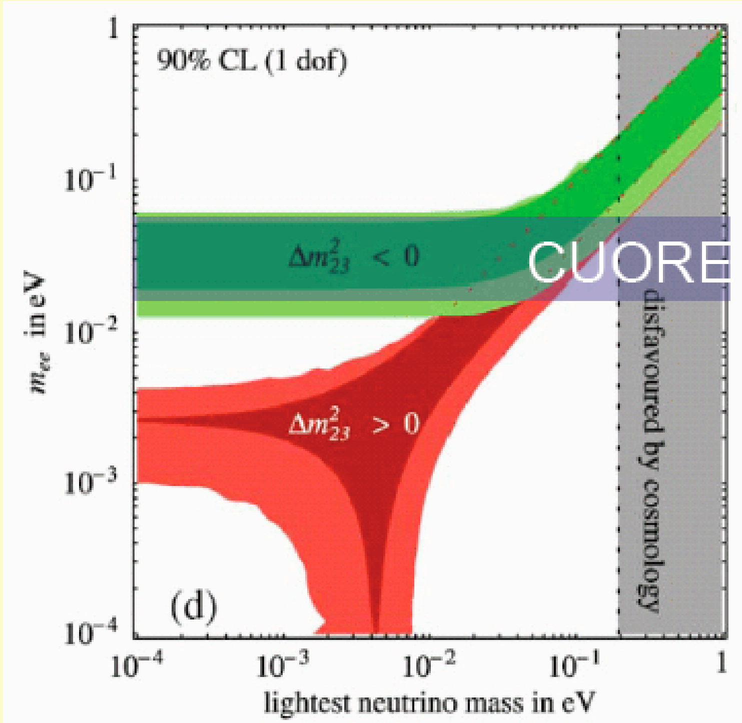
Pascoli and Petcov.: hep-ph/0310003



2003 LMA update

(SNO+salt, atmospheric,CHOOZ, KamLAND

Feruglio et al.: Nucl. Phys. B659 (2003) 359

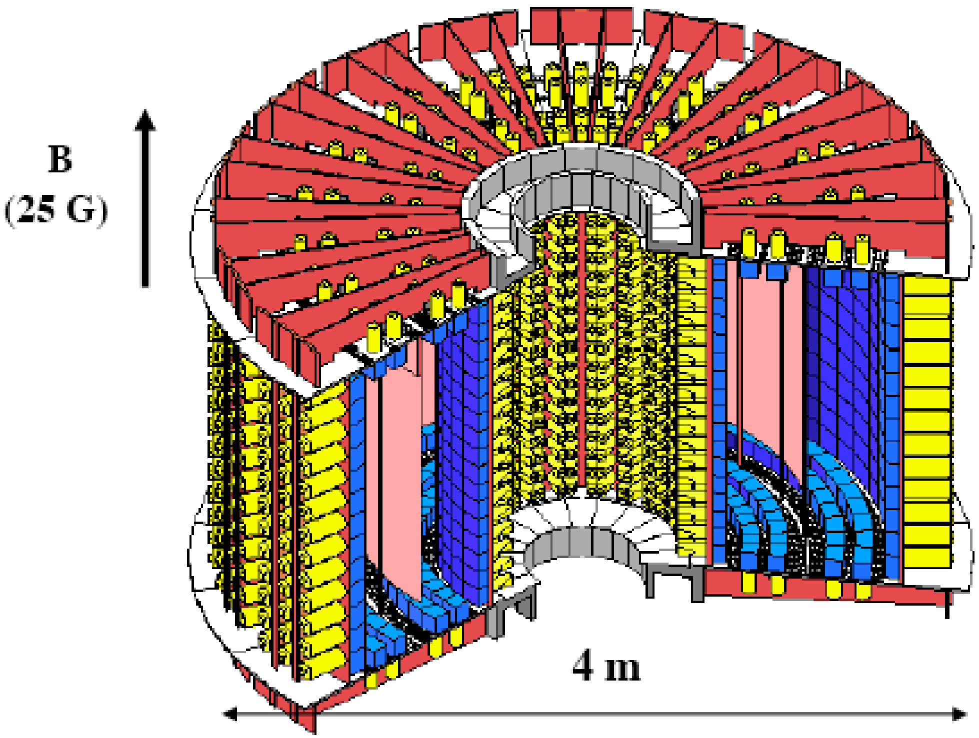


Spread in $\langle m_\nu\rangle$ from nuclear matrix element uncertainty

Cremonesi, NOON04

CUORE: Data taking T0 + 5 years

NEMO-3



Source:
10 kg of ββ isotopes (20 m^2, 50 μm)

Tracking detector:
Gas mixture of Helium
+ ethyl alcohol(4%) + Ar(1%)
Drift wire chamber operating
in Geiger mode (6180 cells)
$\sigma_l = 0.8$ cm $\sigma_t = 0.5$ mm

Calorimeter:
1940 plastic scintillators coupled
to low radioactivity PMs
FWHM ~8 % at 3 MeV
σ(t)= 250 ps at 1 MeV

Selection of materials by γ spectroscopy
+ Magnetic field
+ Iron shielding + Neutrons shielding
+ Fréjus Laboratory (4800 m.w.e.)

Identification: e^-,e^+,γ and delayed-α
and ToF
Measurement of source radiopurity
Background rejection

Simultaneous study of many elements

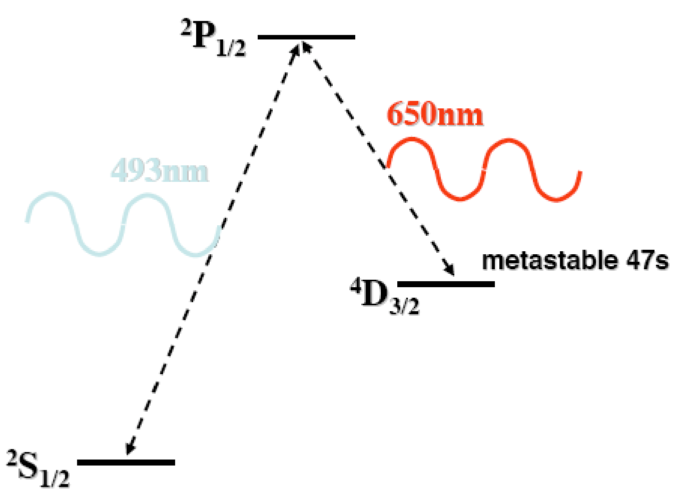
EXO

$^{136}Xe \rightarrow ^{136}Ba^{++} + e^- + e^-$

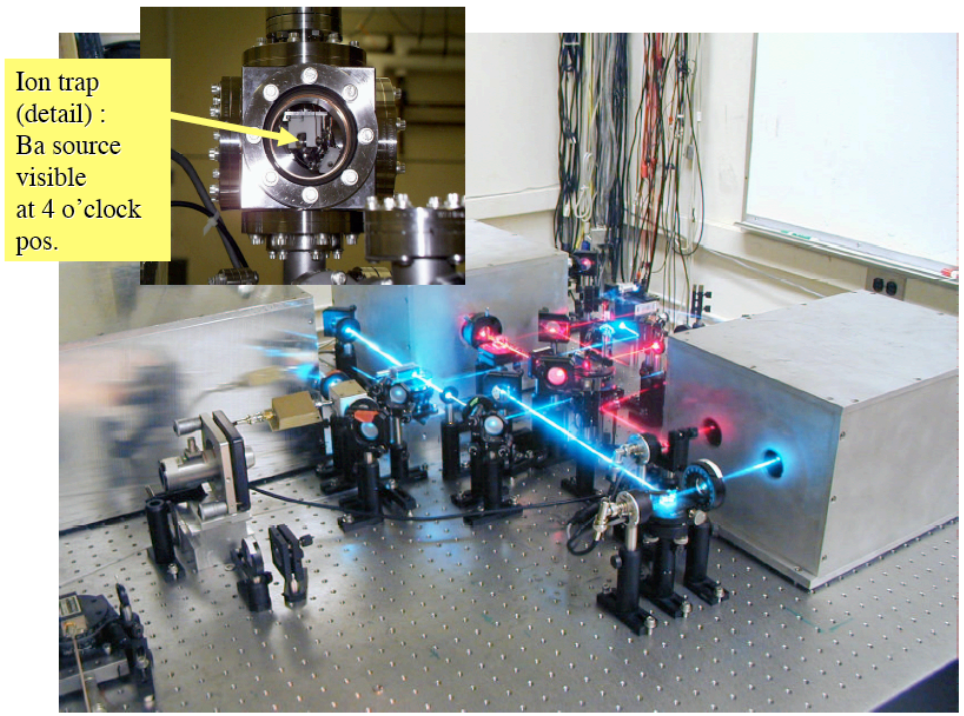
100 ton (2008?)

- Next-generation search for ββ decay in ^{136}Xe
- Ultimate goal is 100 ton-year experiment with "laser tagging"
- currently in R&D phase, with development of a 200kg prototype, for operation at WIPP, now underway

$^{136}Xe \rightarrow ^{136}Ba^{++} + e^- + e^-$



Ba^+



Direct kinematical search: Tritium beta decays

ETH Institute for Particle Physics

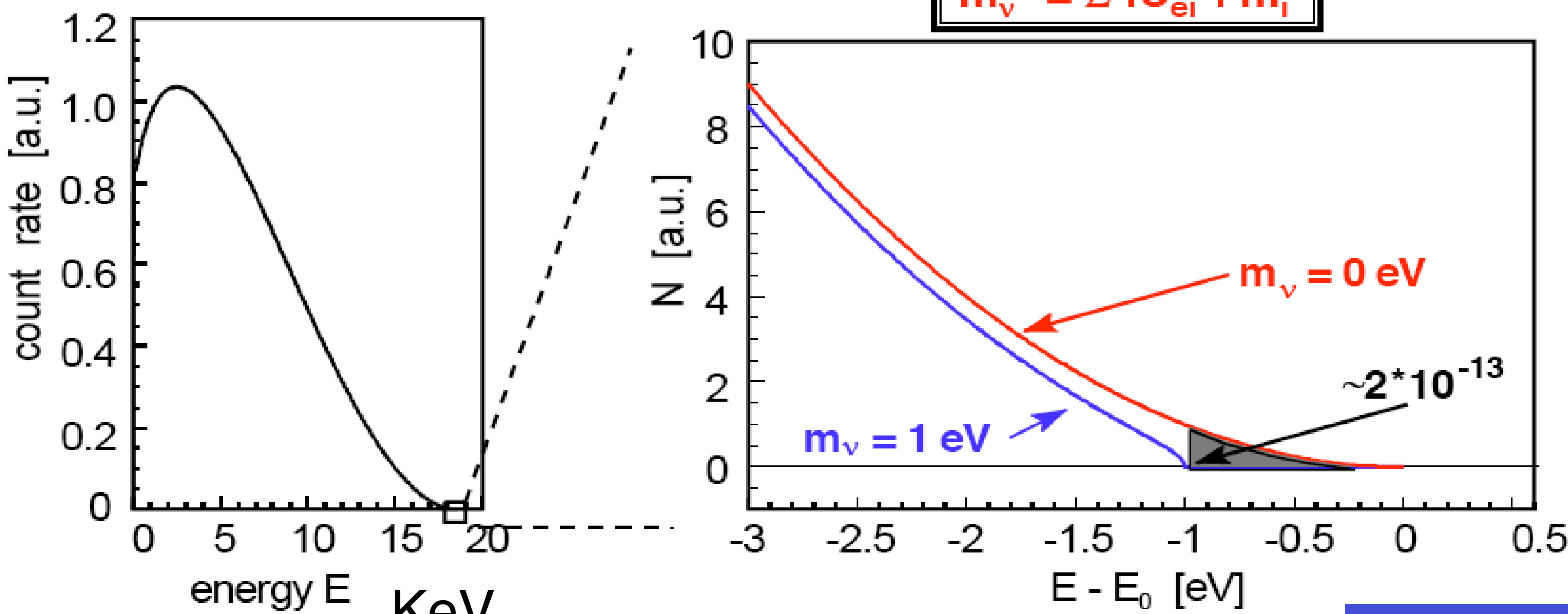
$$N(E) = \text{const} * |M|^2 F(Z,E)\, p(E + m_e c^2)(E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2 c^4}$$

tritium β-spectrum

$$E_0 = 18.6 \ keV$$

experimental observable

$m_\nu^2 = \Sigma\, |U_{ei}^2|\, m_i^2$



KeV

Kraus, NOON04

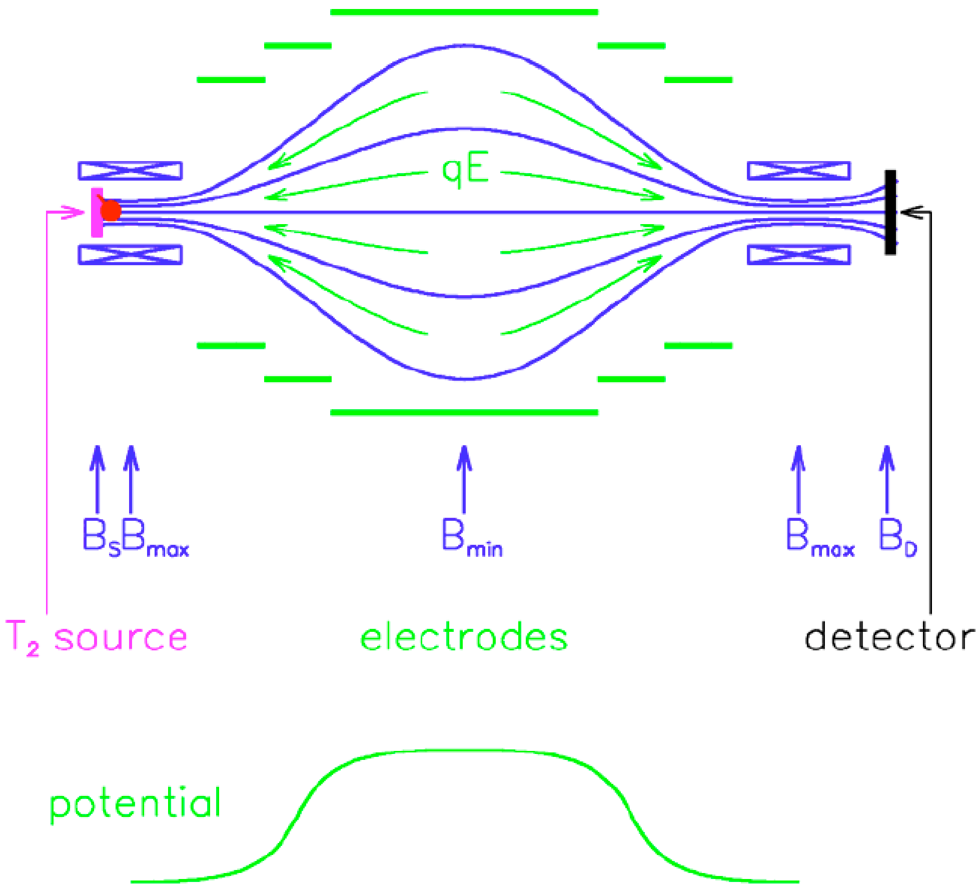
Need: high luminosity, high energy resolution and low background

Principle of measurement

- **Magnetic Adiabatic Collimation and Electrostatic filter**
- **We assume for simplicity that the field is exactly axially symmetric. The change of longitudinal component of the magnetic field must according to Maxwell divergence equation of the B-field imply a non-vanishing radial component of the field.**
- **A particle of charge e and total energy E moving in a static, non-uniform axially symmetric field, at a distance r from the field axis has a constant of motion defined by**

$$\gamma m r \frac{d\phi}{dt} + \frac{q}{2\pi}\left(\pi r^2 B_z\right) = constant$$

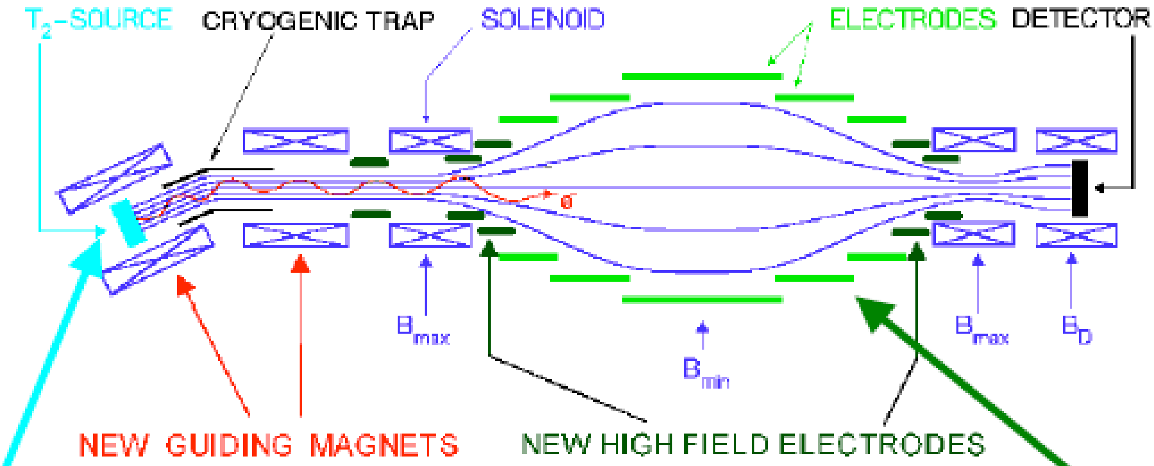
- **Since the magnetic field cannot change the energy of the particle, the field gradient actually transforms the azimuthal motion into longitudinal one. When this is achieved, the application of the electrostatic barrier to the electrons which are mostly longitudinal results in a very clean transmission function.**



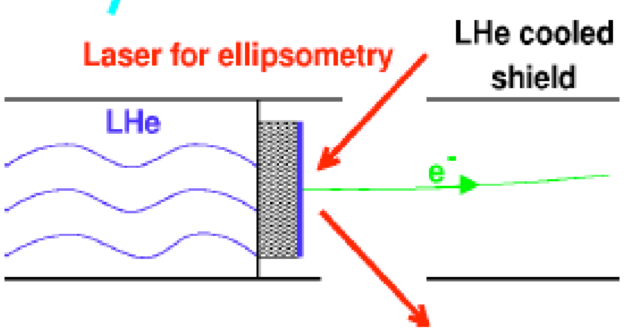
Energy resolution: $\Delta E = E\,\frac{B_{min}}{B_{max}}$

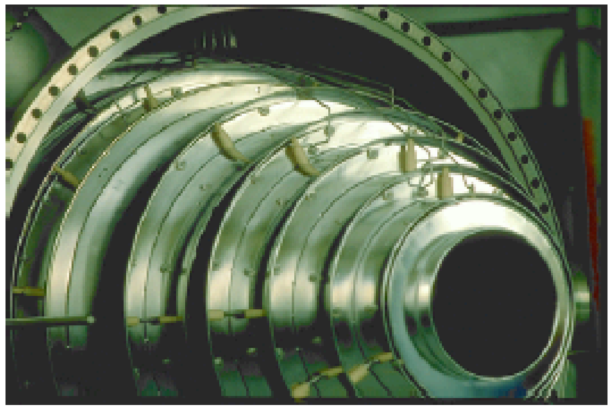
Kraus, NOON04

Mainz Neutrino Mass Experiment (1997-2001)



$$\frac{B_{\min}}{B_{\max}} \approx \frac{1}{3000} \approx \frac{8 Gauss}{2.4 T}$$





- T_2 Film at 1.86 K
- quench-condensed on graphite (HOPG)
- 45 nm thick (≈130ML), area 2cm^2
- Thickness determination by ellipsometry

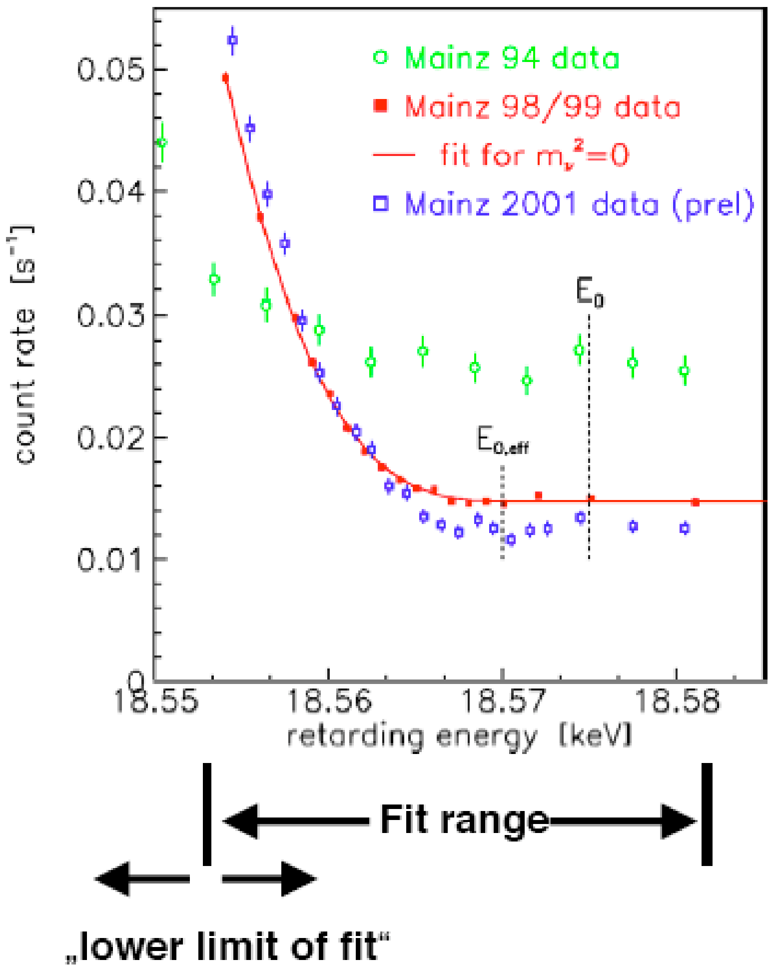
$$\Delta E = E \frac{B_{\min}}{B_{\max}} \approx \frac{1}{3000} T \approx 6 \ \ eV$$

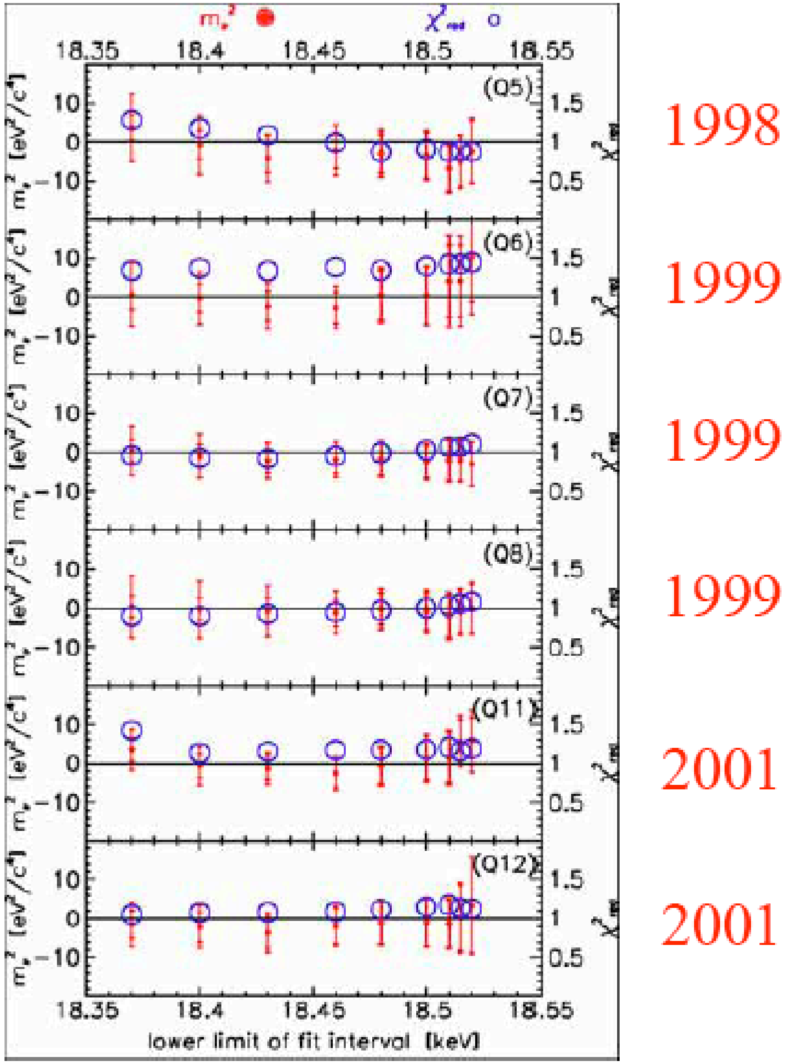
Kraus, NOON04

Mainz data of 1998 - 2001

9 month measurement time (only possible with remote experiment control)

119 days analysed data





Kraus, NOON04

The Karlsruhe Tritium Neutrino experiment KATRIN

Data taking 2008

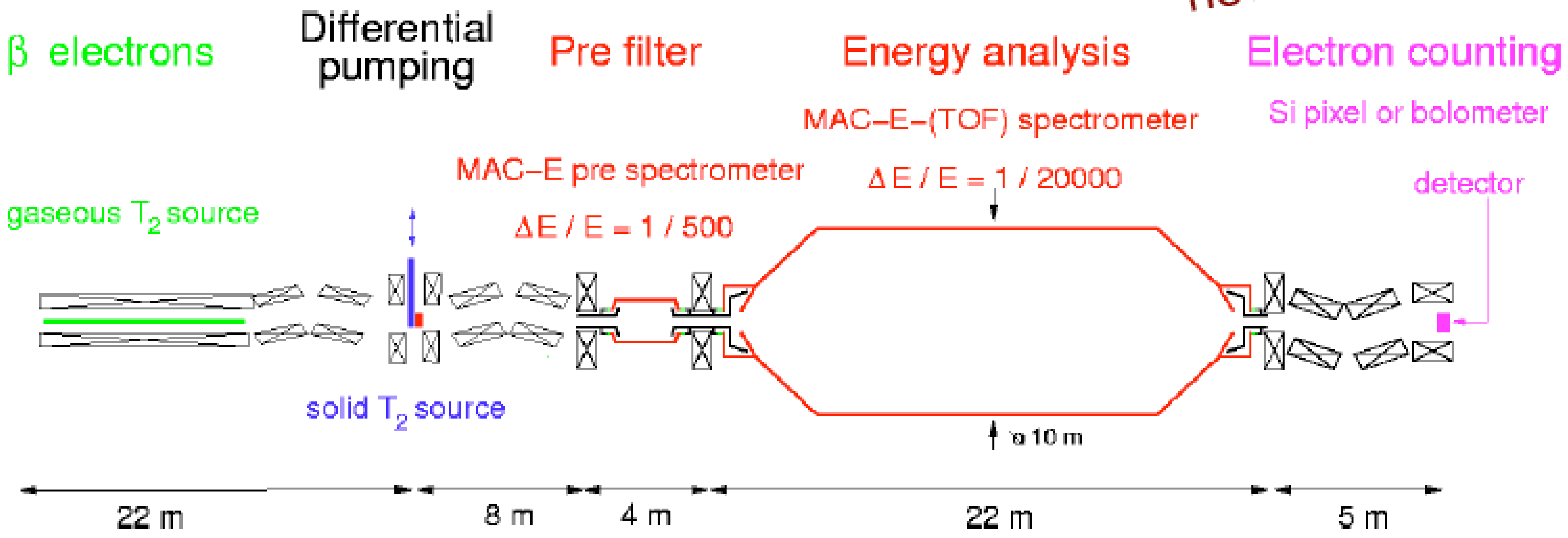
Physics aim:

Sensitivity on neutrino mass scale: $m(\nu) << 1eV$

- Higher energy resolution: $\Delta E \approx 1eV$
  since $E/\Delta E \sim A_{spectrometer}$ ⇒ larger spectrometer
- Relevant region below endpoint is smaller
  even less count rate $dN/dt \sim A_{spectrometer}$ ⇒ larger spectrometer

} ∅10m

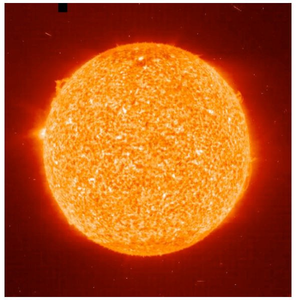
new, since 12/2002



Kraus, NOON04

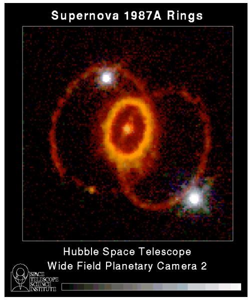
(hep-ex/0109033)

Underground experiments: Astrophysical neutrinos

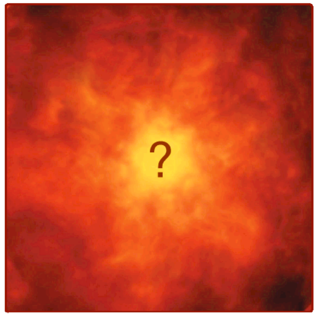


Stellar (solar)

Atmospheric



Supernovae



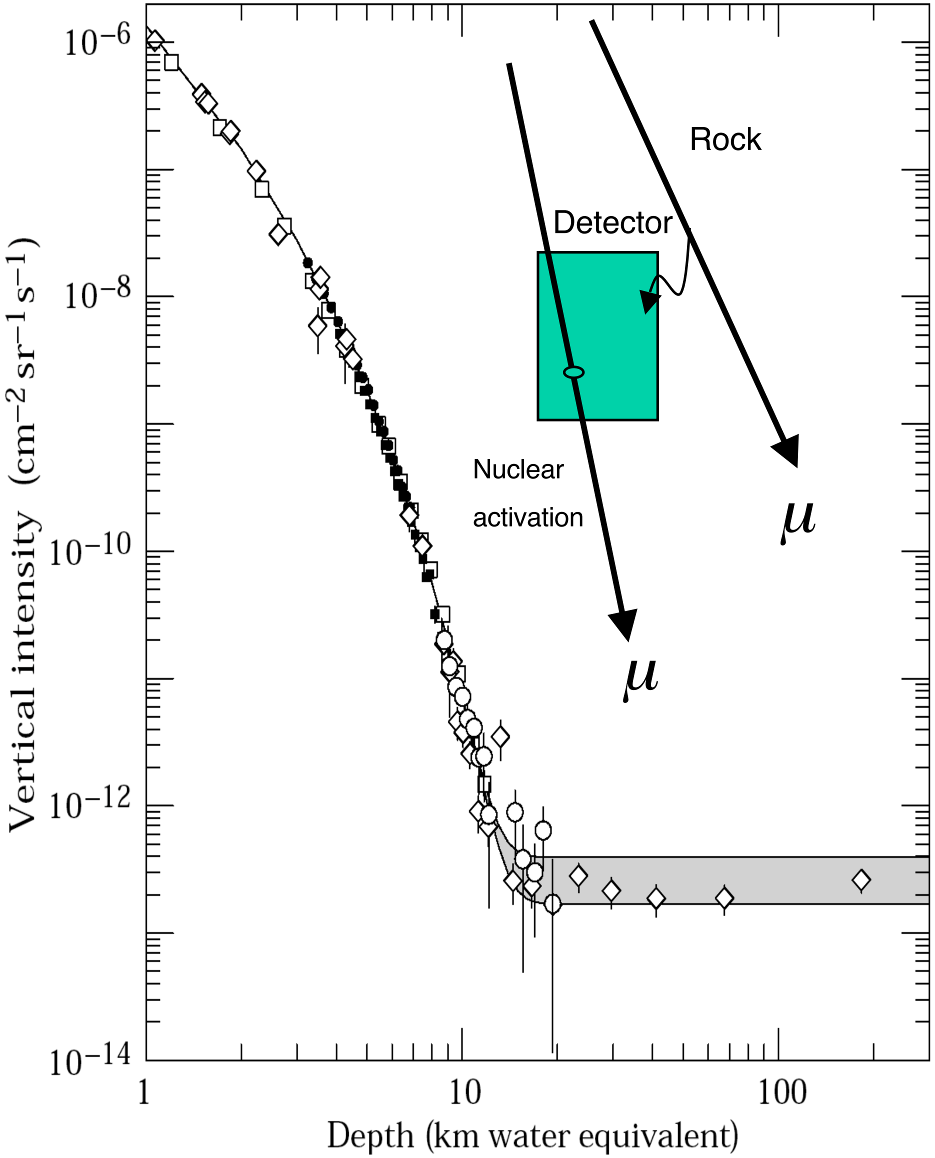
BigBang

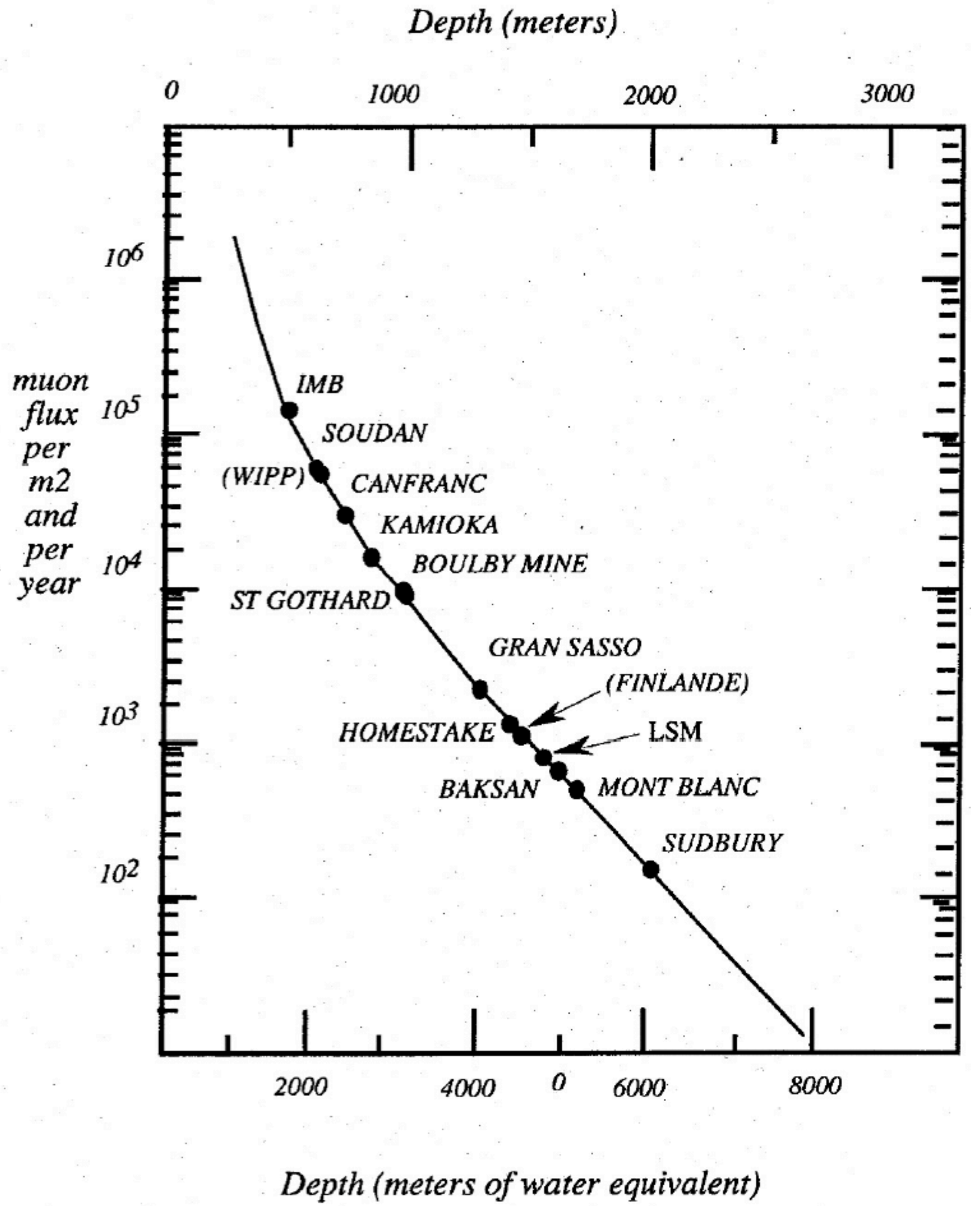
Other stars only visible at night ! But solar neutrinos can never be „switched" off!

And proton decay!

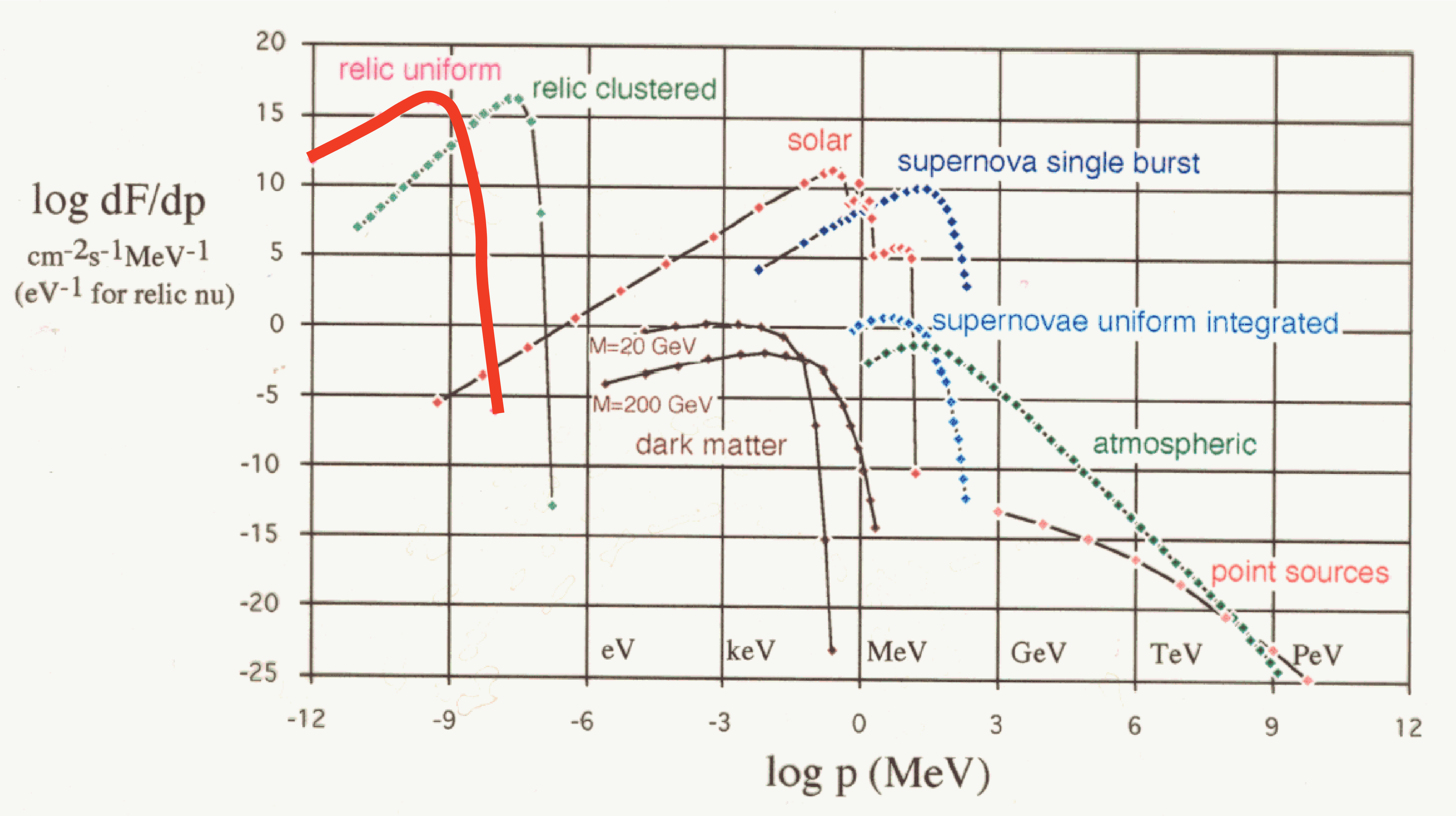
Cosmogenic background suppression

Flux of vertical muons





Spectrum of astrophysical neutrinos



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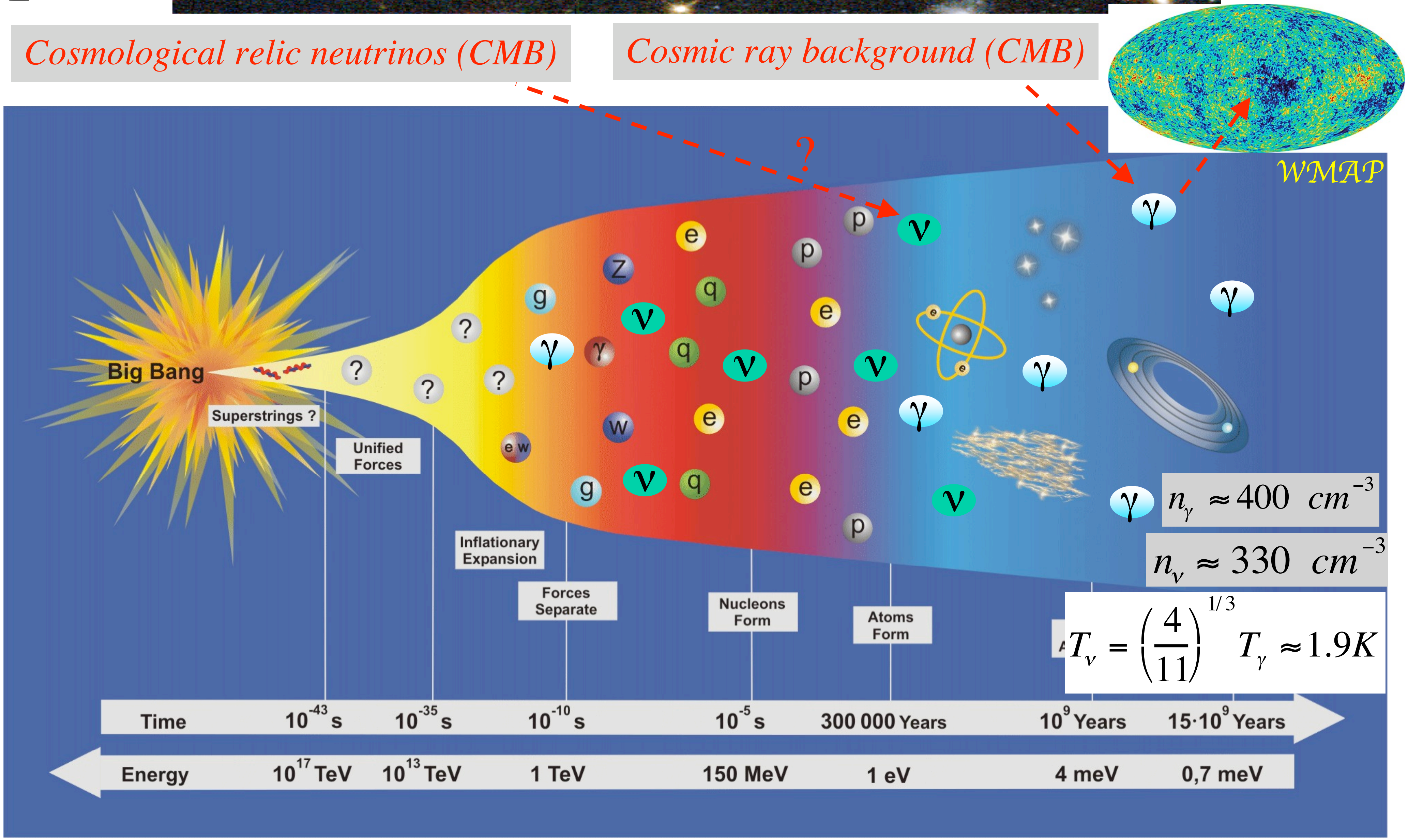
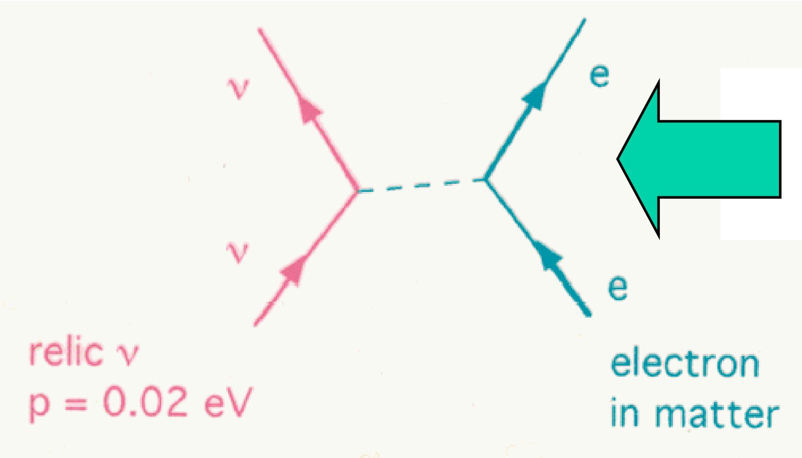
Cosmological relic neutrinos

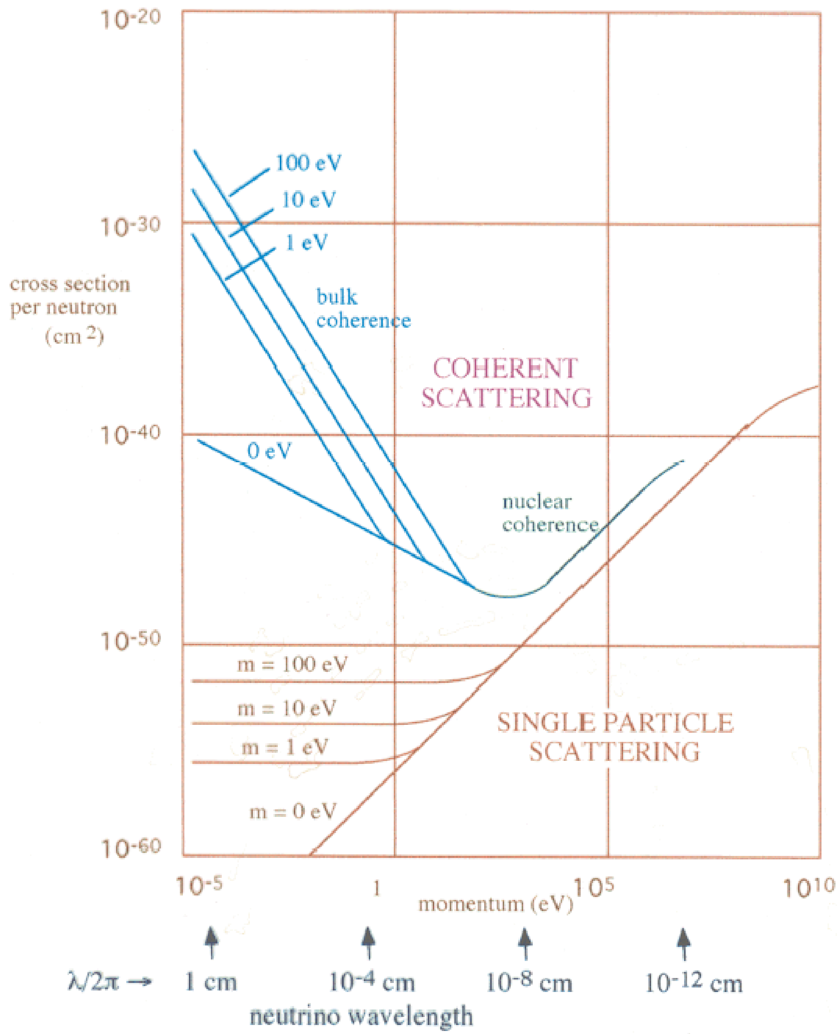


Relic neutrino scattering processes



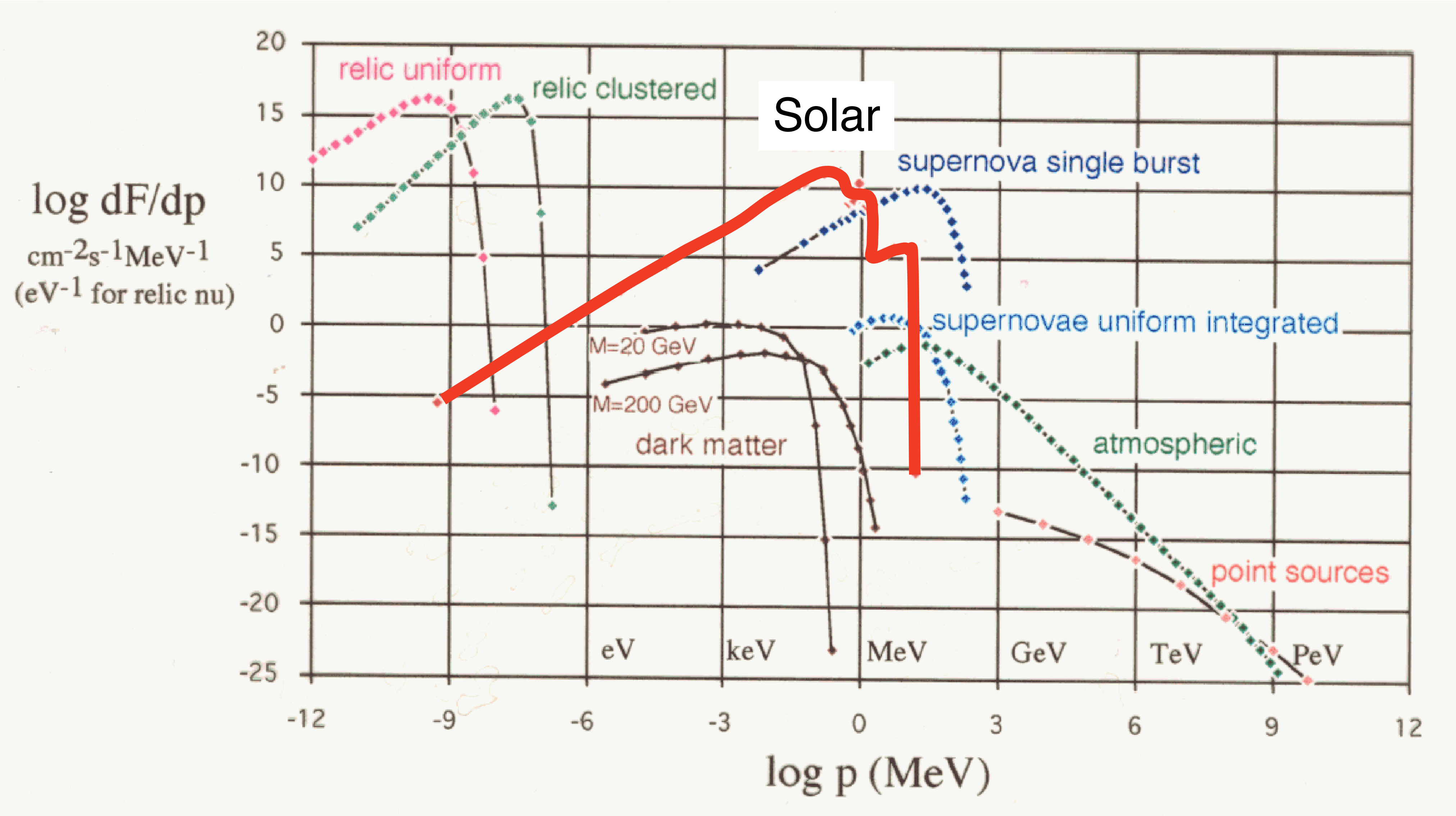
Typical recoil energy: ≈10^{-9} eV !!
$\sigma < 10^{-50}$ cm^2 (<1 day/kton)

Nuclear processes:
Coherence
(even bulk coherence)
But cancellation between
neutrinos and antineutrinos
(unless large asymmetry)

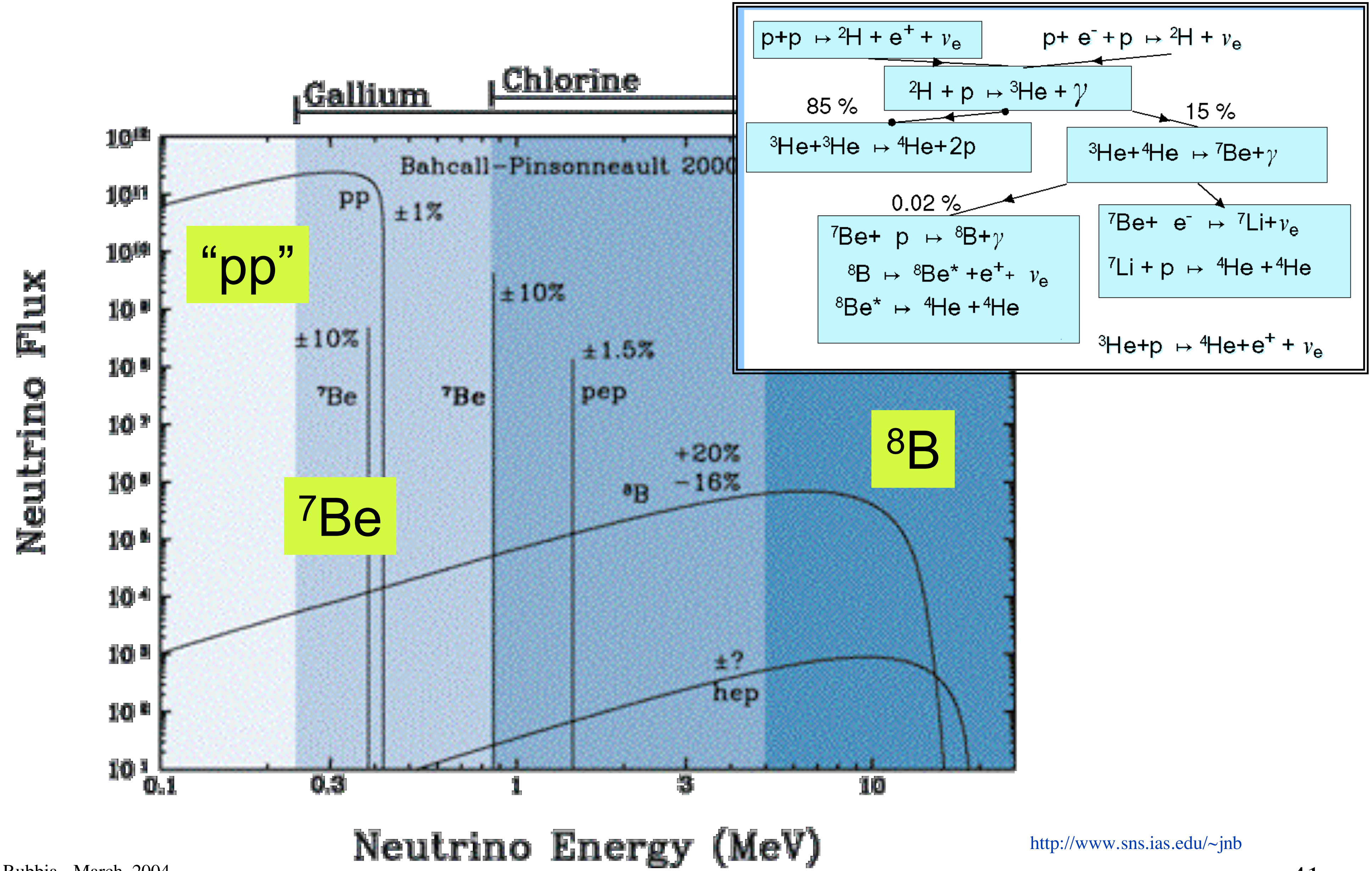


- **With current known technologies observation of relic neutrinos seems impossible**
  - ➥Z-Bursts ?

Spectrum of astrophysical neutrinos



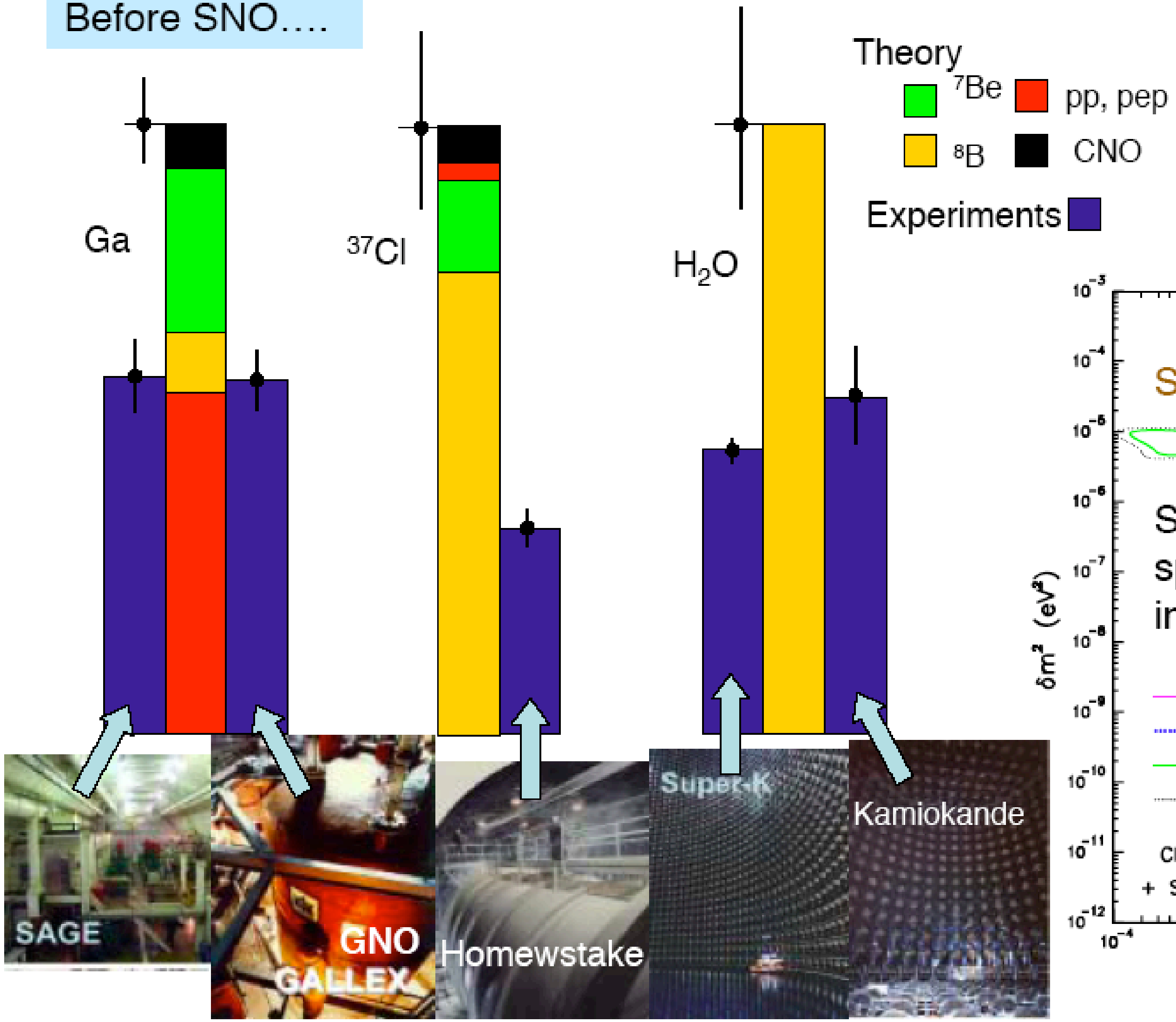
Predicted solar neutrino spectrum

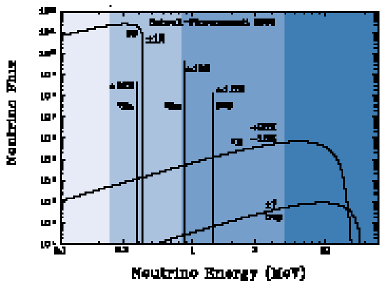


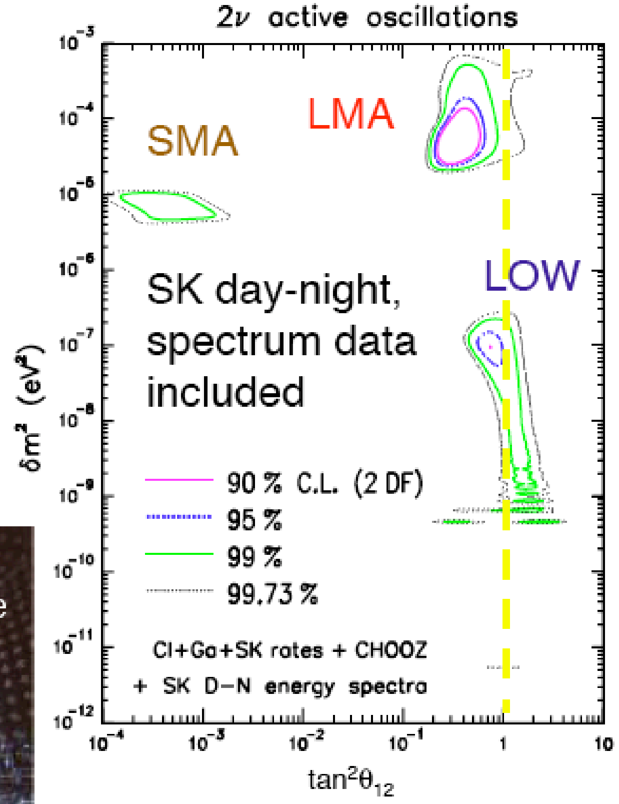
http://www.sns.ias.edu/~jnb

Solar neutrino experiments

Before SNO….







Solar neutrino measurements

- ✓ **1968 Homestake**
  600 tons C_2Cl_4
  $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
  $E_\nu > 814$ KeV
  Radiochemical
- ✓ **1989 Kamiokande**
  1000 tons H_2O
  $\nu_x + e^- \rightarrow \nu_x + e^-$
  $E_e > 5$ MeV
  Real-time
- ✓ **1990 SAGE 1992 Gallex**
  90 tons Ge
  $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
  $E_\nu > 236$ KeV
  Radiochemical
- ✓ **1998 SuperKamiokande**
  22500 tons H_2O
  $\nu_x + e^- \rightarrow \nu_x + e^-$
  $E_e > 5$ MeV
  Real-time
- ✓ **1999 SNO**
  1000 tons D_2O
  $\nu_e + d \rightarrow p + p + e^-$
  $\nu_x + d \rightarrow p + n + \nu_x$ in 2002
  $E_e > 5$ MeV
  Real-time

$$\Phi = 6.6 \times 10^{10}\ cm^{-2}\ sec^{-1}$$

Experimental Results

SAGE+GALLEX/GNO

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

Flux = 0.58 SSM

Homestake

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

Flux = 0.33 SSM

Kamiokande+Superkamiokande

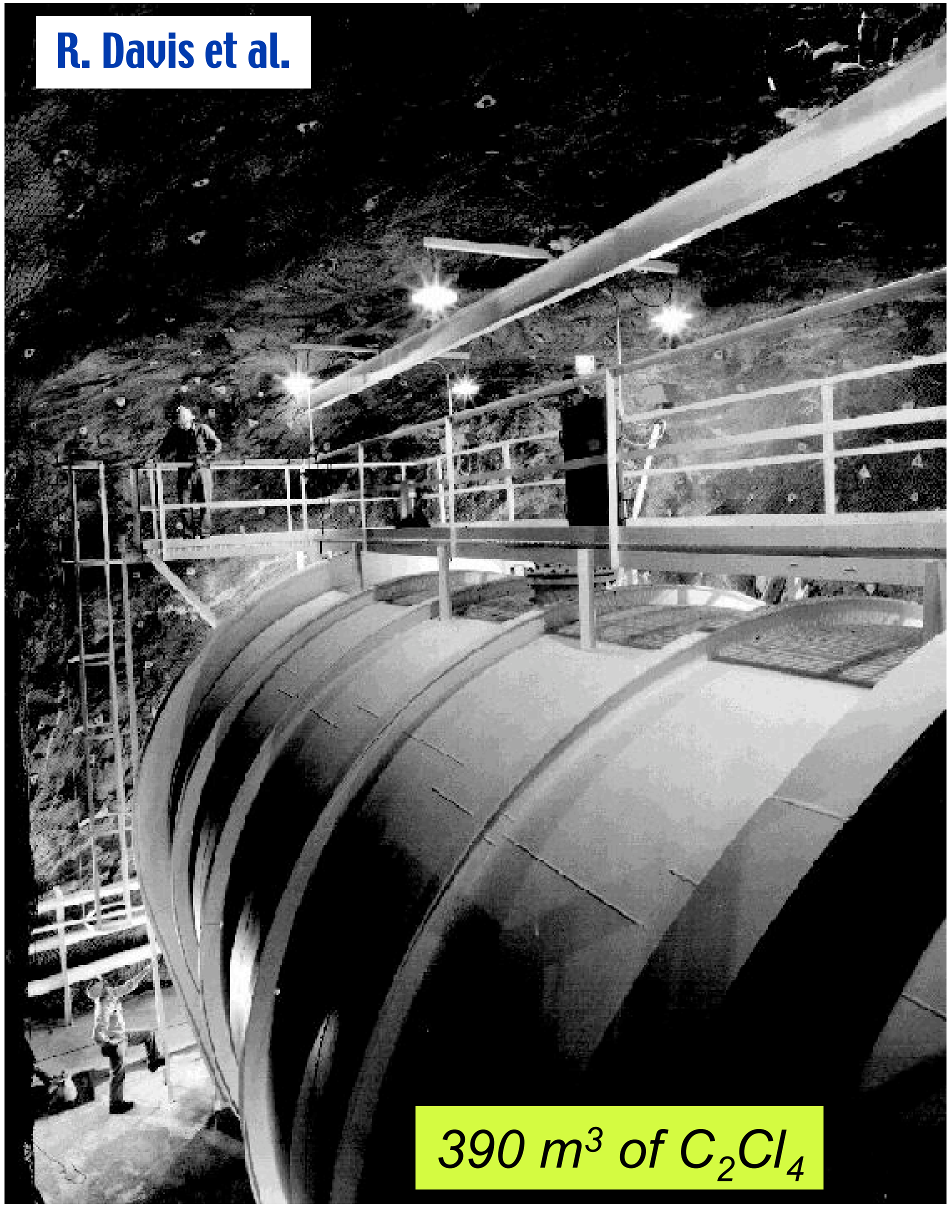
$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \sigma_{\mu\tau} = \frac{1}{6} \times \sigma_e$$

Flux = 0.46 SSM

SNO (CC 0.35)

Flux = 1 SSM

Chlorine experiment– Homestake Mine



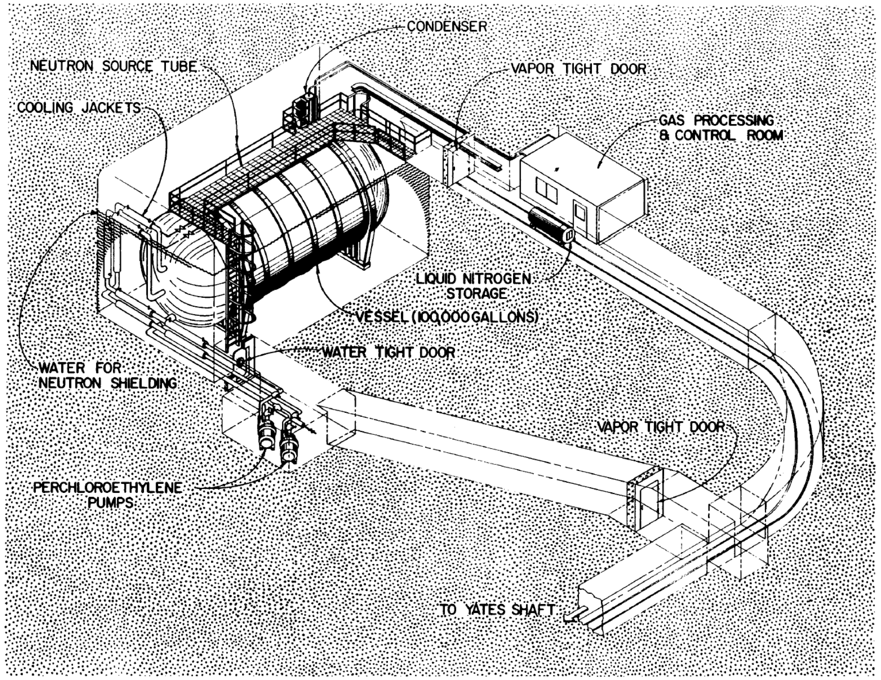
$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

$E_\nu > 814$ KeV

Expected rate: ***9.5±1.4 SNU***

1 SNU≡1 evt/s per 10^{36} target atoms

Expected production: 1.5 Ar nuclei/day



Homestake results (1970-1995)

B.T. Cleveland et al., Astroph. J. ***496*** *(1998) 505*

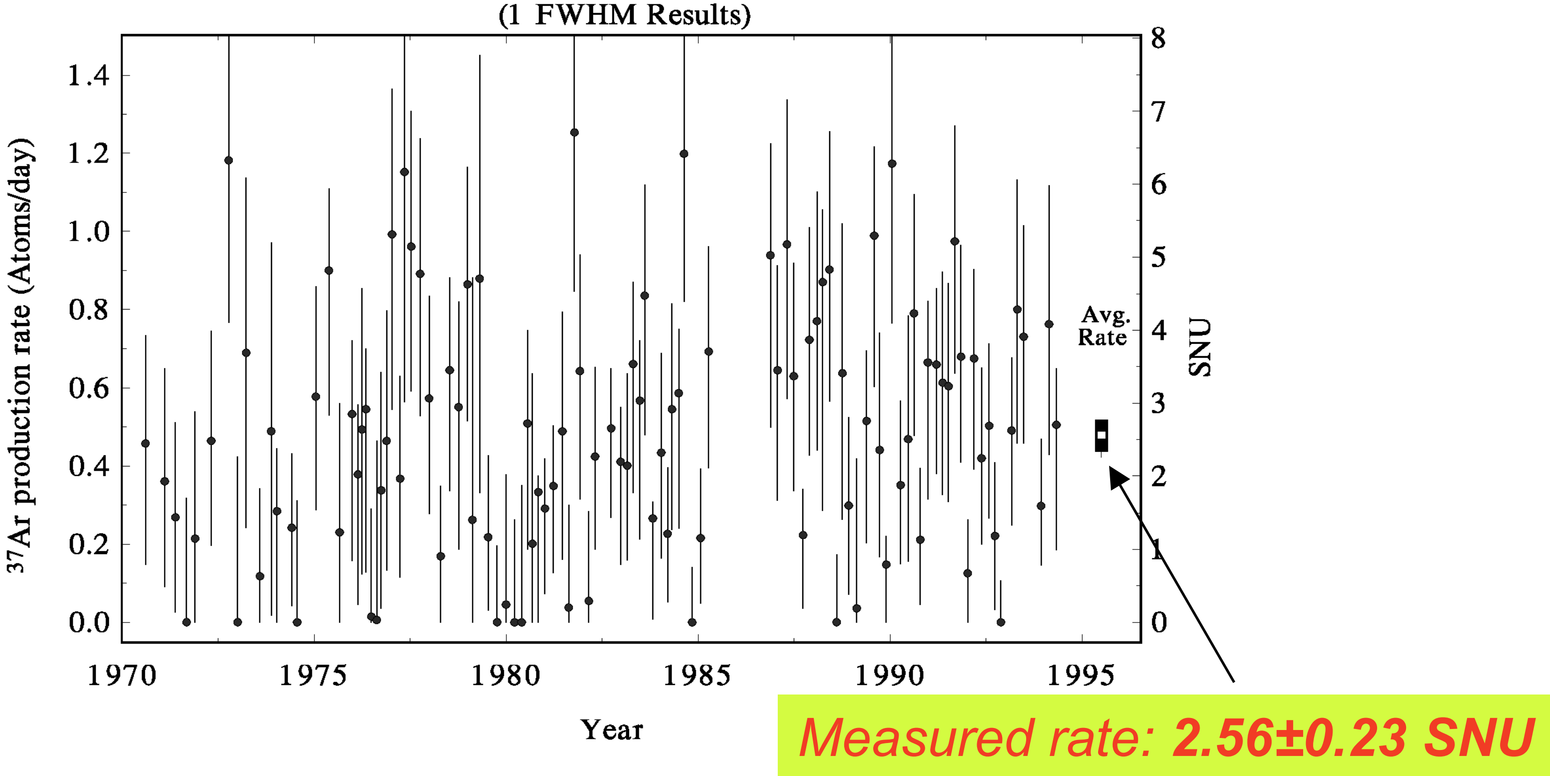


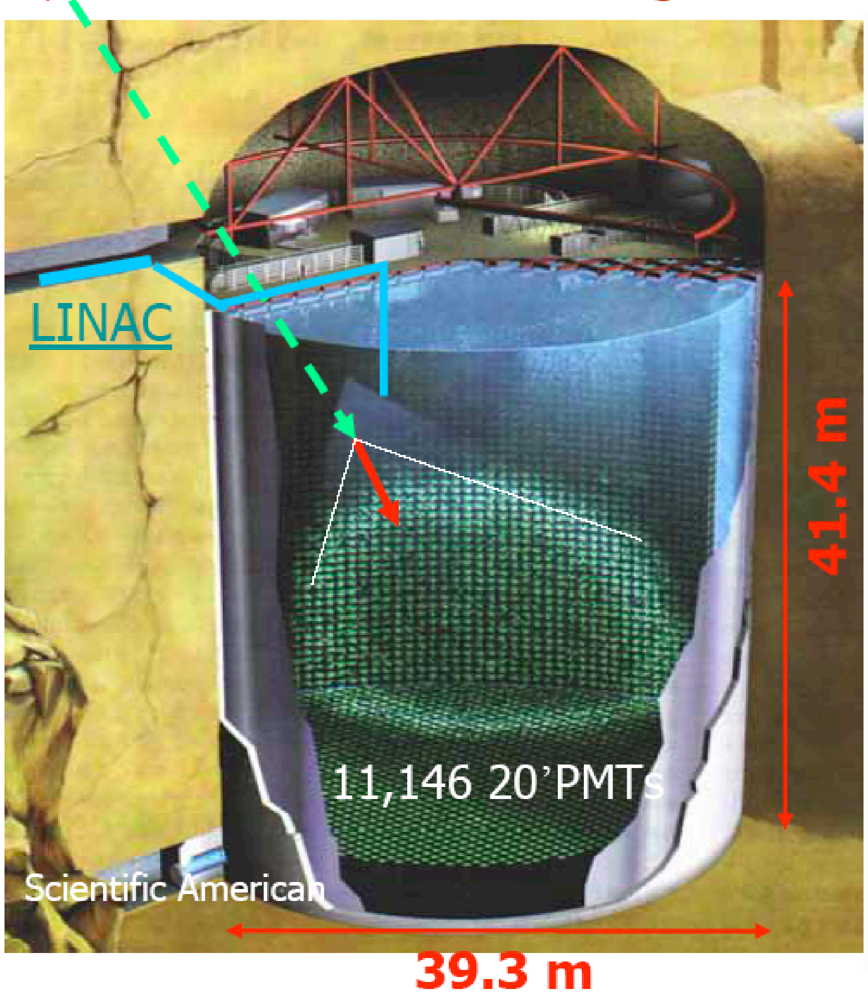
FIG. 13.—Homestake Experiment—one FWHM results. Results for 108 individual solar neutrino observations made with the Homestake chlorine detector. The production rate of ^{37}Ar shown has already had all known sources of nonsolar ^{37}Ar production subtracted from it. The errors shown for individual measurements are statistical errors only and are significantly non-Gaussian for results near zero. The error shown for the cumulative result is the combination of the statistical and systematic errors in quadrature.

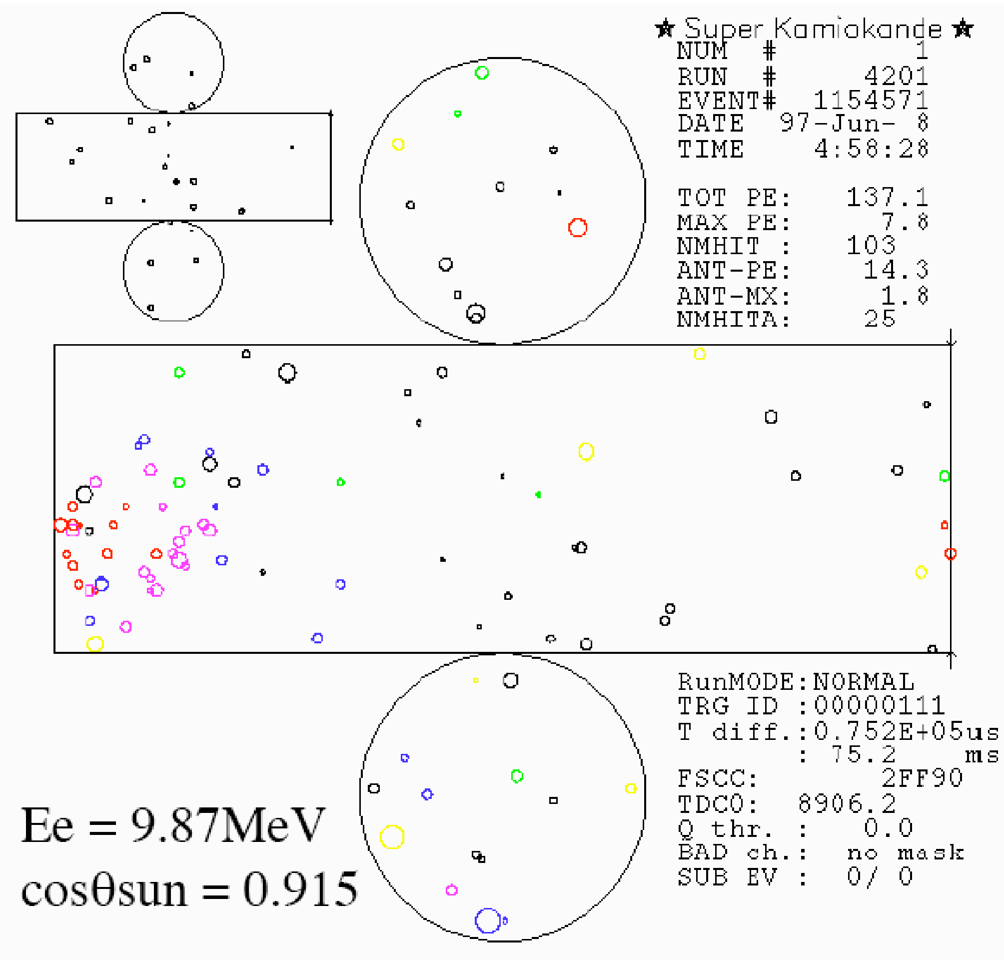
Superkamiokande

50kton Water Cherenkov detector located at 1000m underground

$\nu_{solar} + e \rightarrow \nu + e$ (elastic scattering)

Strong directionality



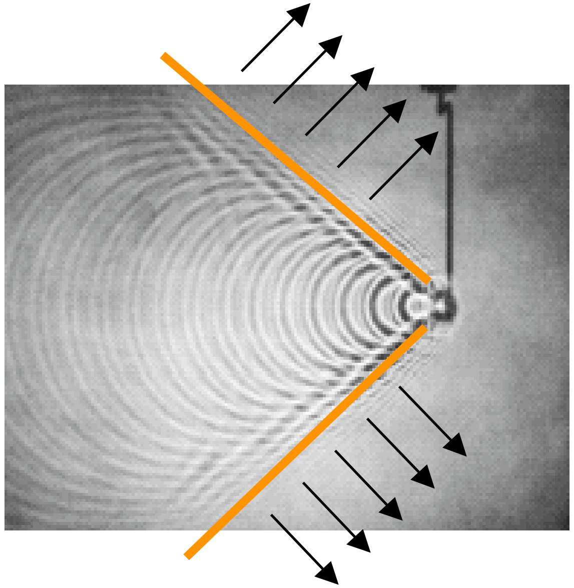


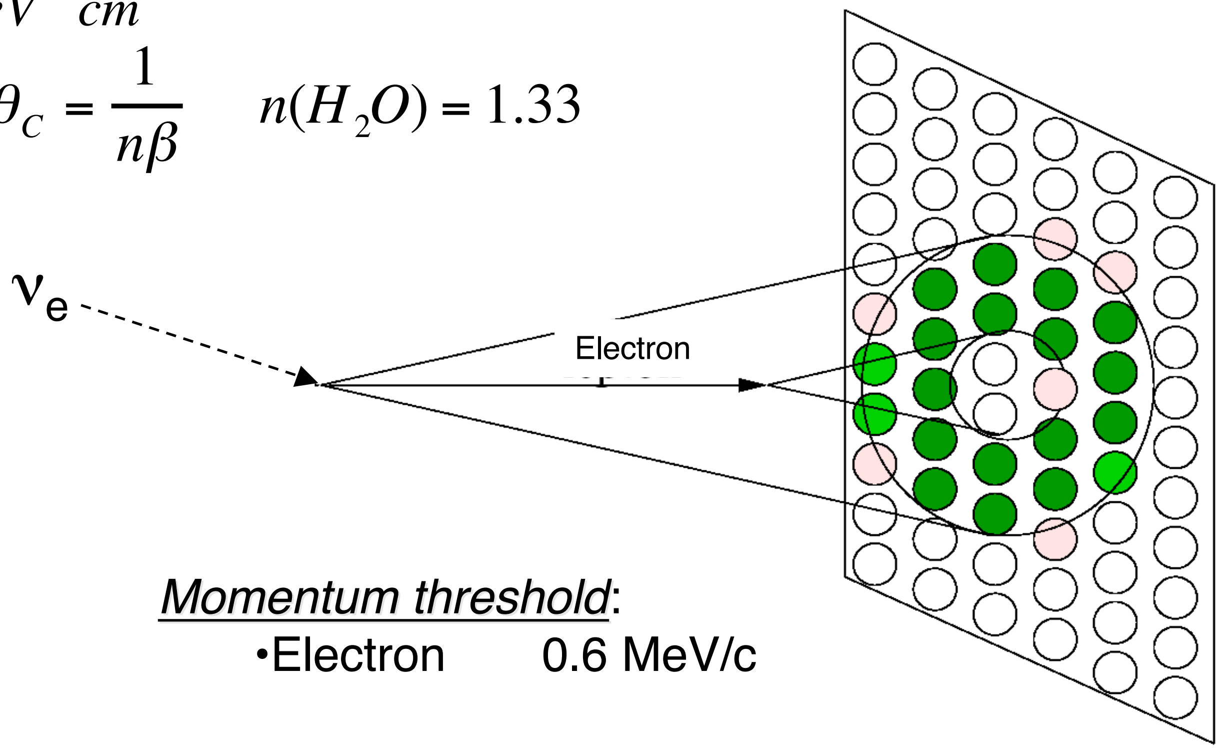
≈7 p.e. per MeV

Electron Cerenkov rings in water

$$\frac{d^2N}{dEdx} = \frac{\alpha}{\hbar c}\sin^2\theta_C \approx 370\sin^2\theta_C \quad eV^{-1}cm^{-1}$$

$$\cos\theta_C = \frac{1}{n\beta} \qquad n(H_2O) = 1.33$$





Momentum threshold:

•Electron 0.6 MeV/c

About 170 γ/cm in $350 < \lambda < 500$ nm
With 40% PMT coverage, Q.E.≈20%
Relativistic particle produces
⇒≈14 photoelectrons / cm
⇒≈7 p.e. per MeV

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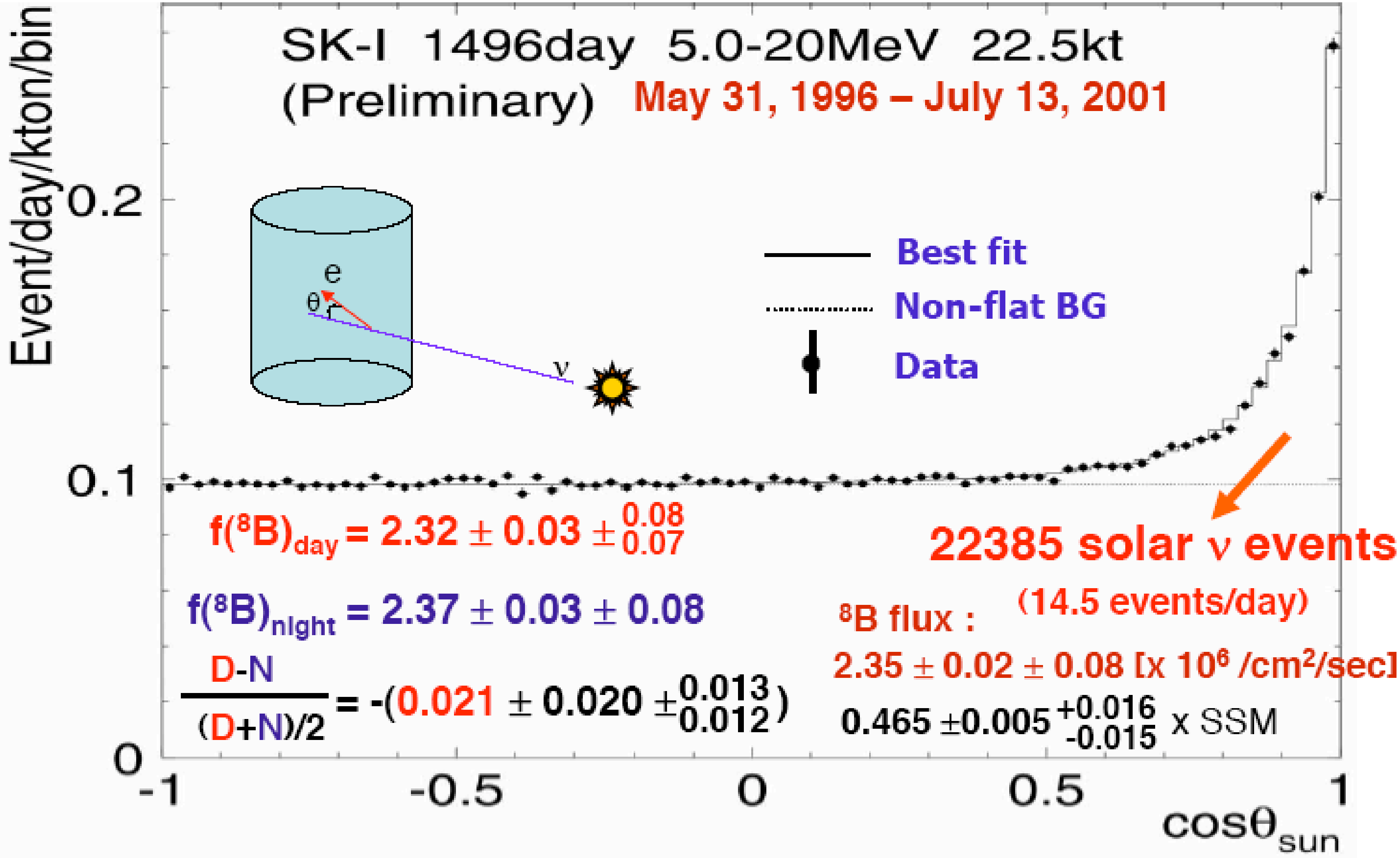
Signal and background



Koshio, NOON04

Accident on Nov. 12

Broken PMTs

Inner : ～60%

Outer: ～50%

Most possible cause

One PMT broken

and chain reaction occurred

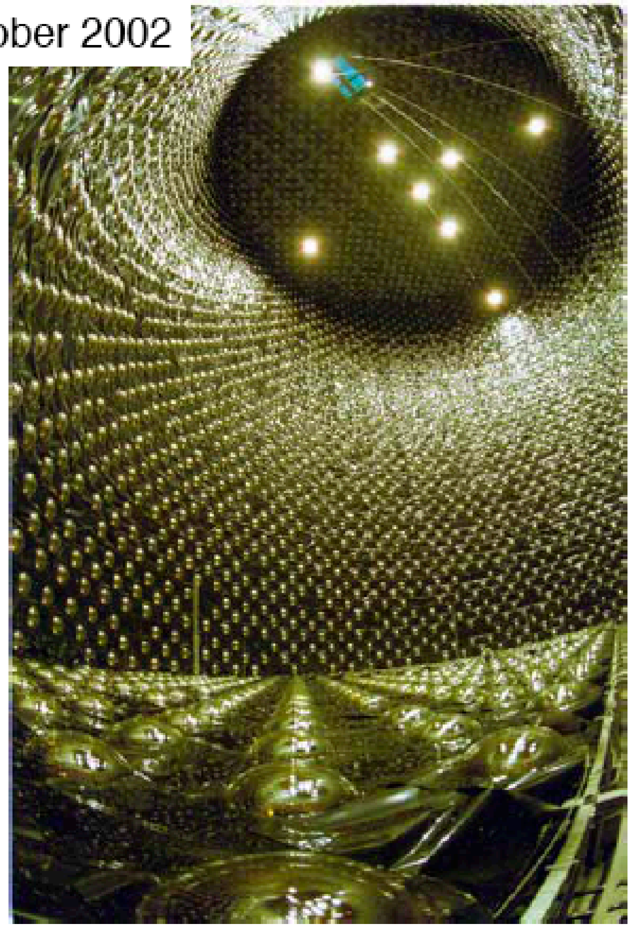
by shock waves.

http://www-sk.icrr.u-tokyo.ac.jp/doc/news/appeal.html

Super-K reconstruction

15

October 2002



Acrylic (13 mm; front) and Fiberglass (~5mm; back)

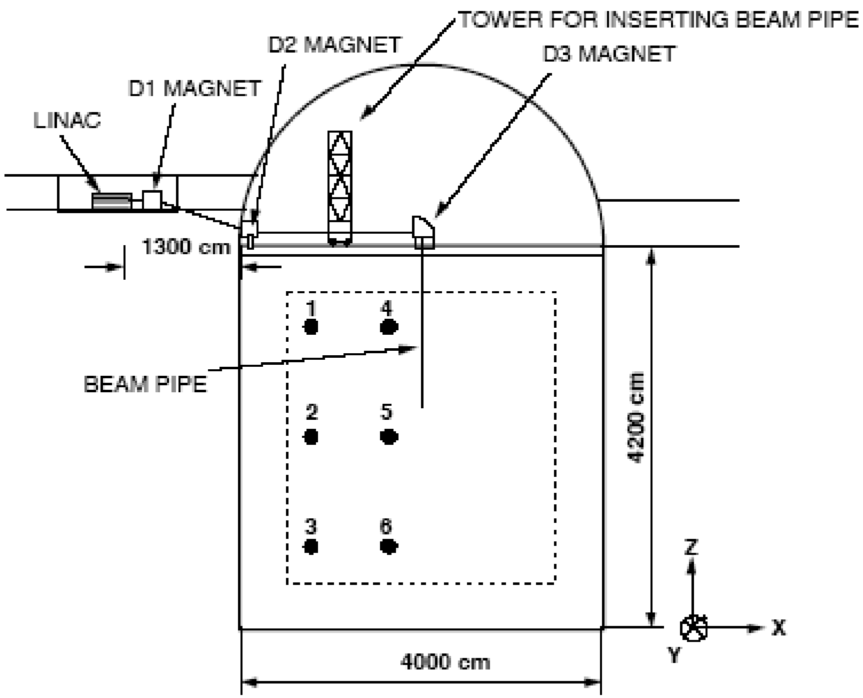
↓ Fill water

Start data taking from 10th of December,2002

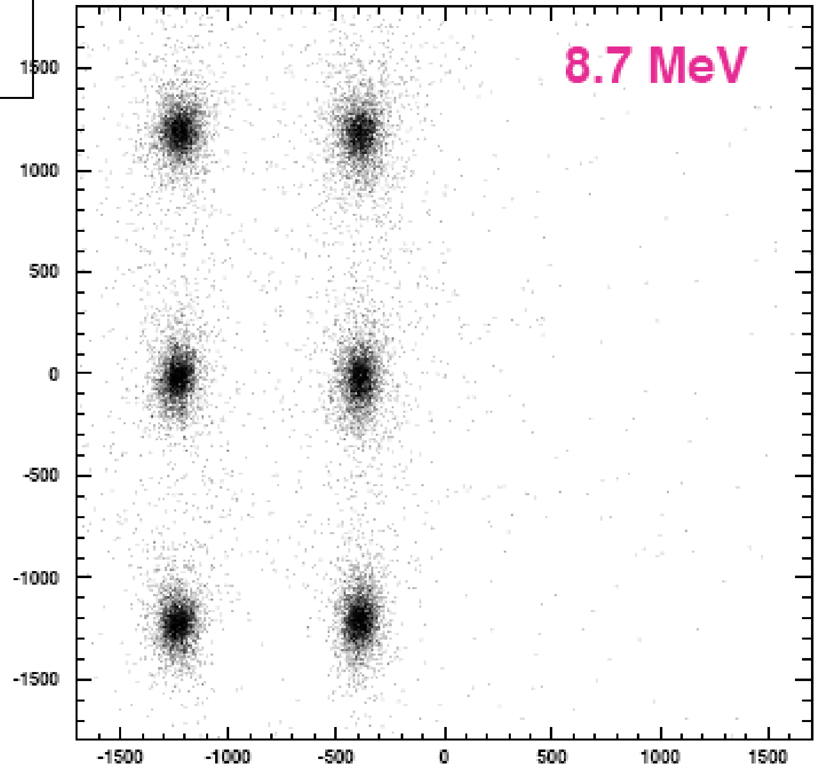
SK-II calibration

- PMT relative gain calibration by using Ni(n,γ)Ni source and an uniform light source (Xe-scintillation ball).
- Timing calibration by N_2-DYE laser ball.

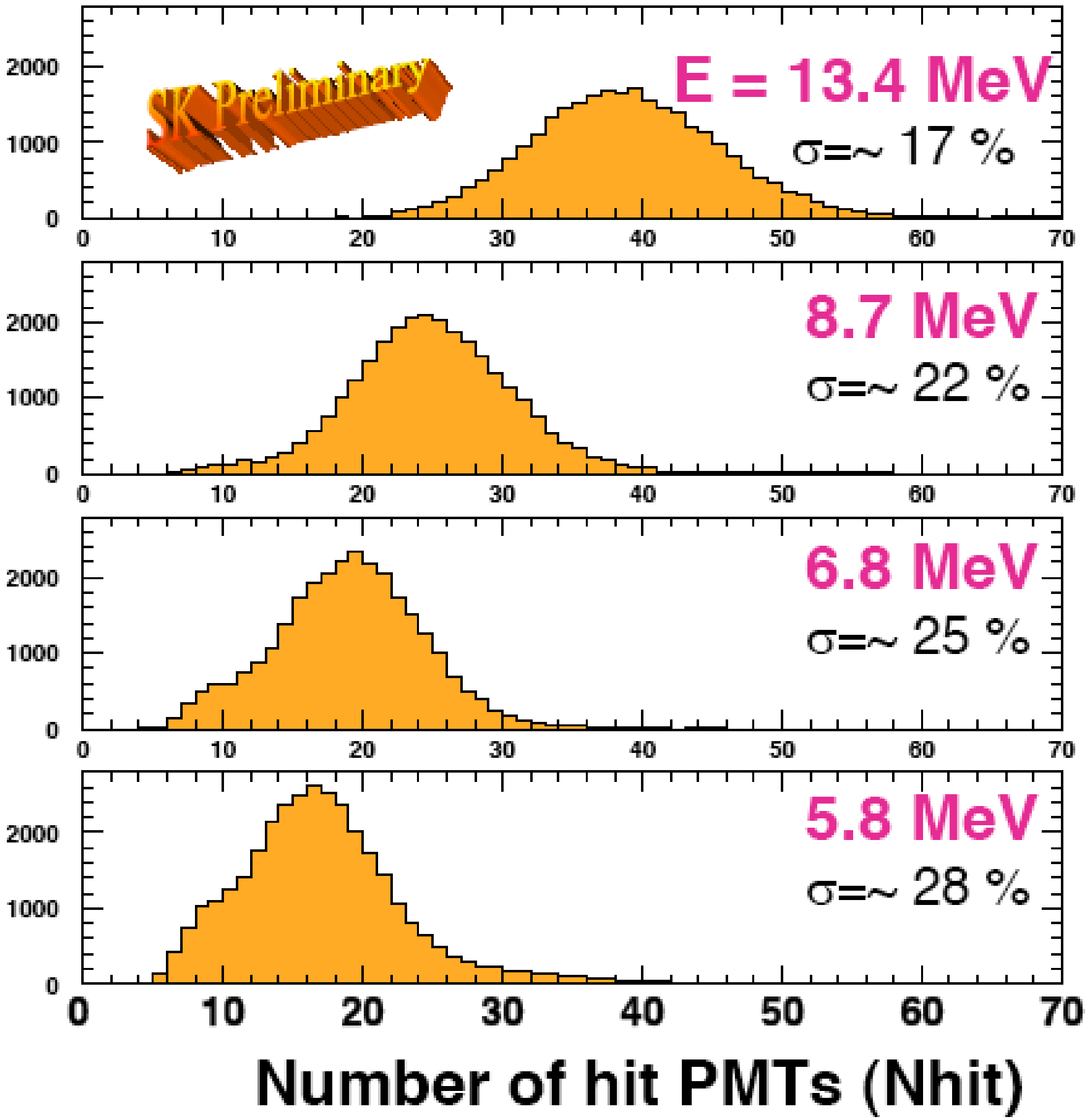
LINAC calibration data were taken at 6 positions, its energy is 13.4, 8.7,6.8, and 5.8MeV.



Reconstructed vertex position



SK-II resolution



20% coverage

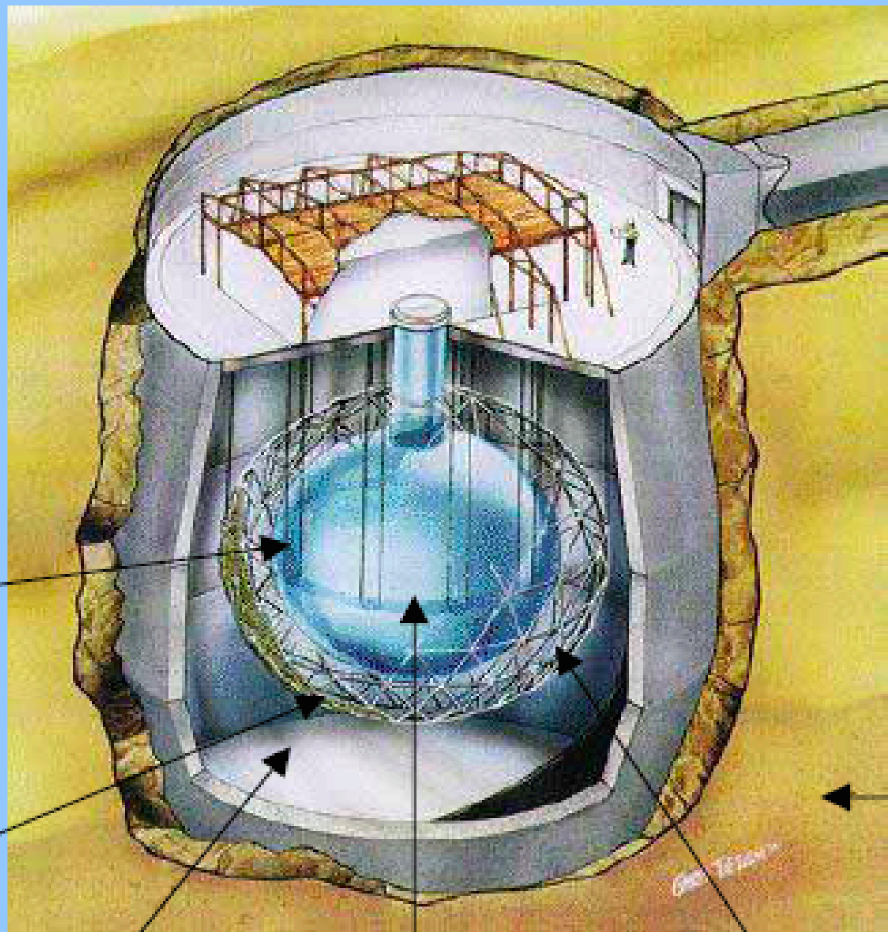
Energy resolution is about 30-40% worse than SK-I as expected from the total number of PMTs.

40% coverage in 2006

Koshio, NOON04

The SNO Detector

2039 m to surface



9438 Inward-Looking PMTs

91 Outward Looking PMTs (Veto)

12 m diameter Acrylic vessel

Norite Rock

PMT Support Structure (PSUP)

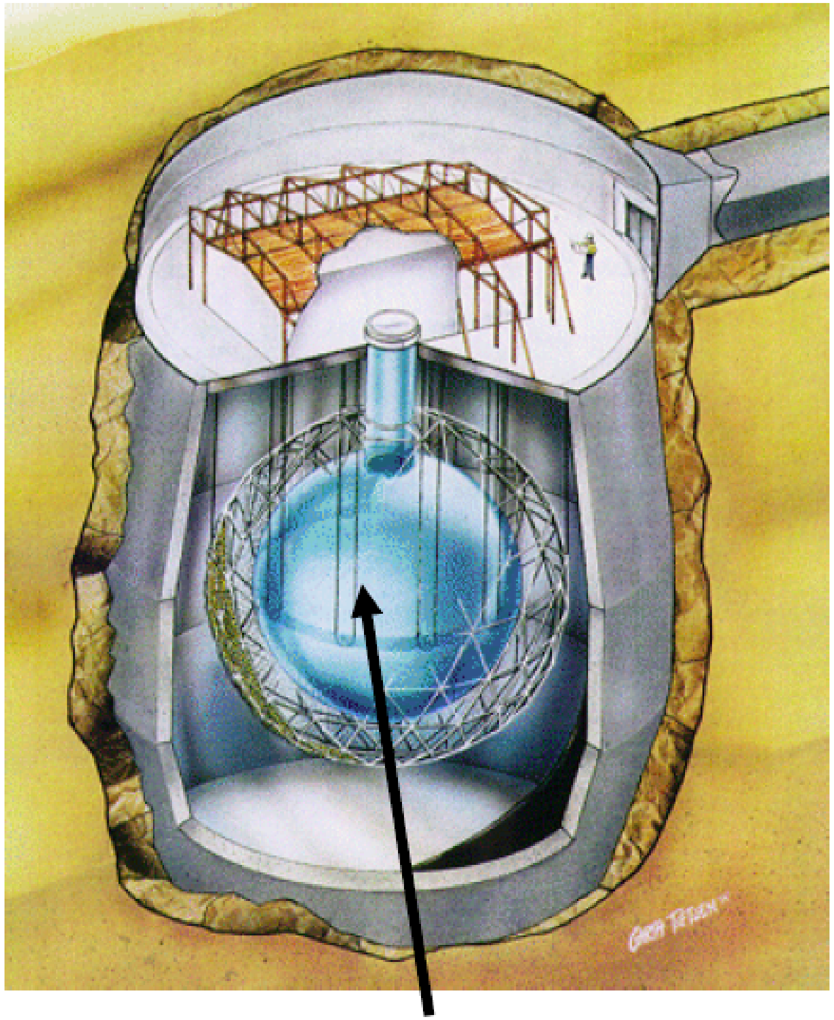
5300 tonnes light water

1000 tonnes heavy water

1700 tonnes light water

60% coverage

SNO



^{8}B ν Reactions in SNO

CC $\nu_e + d \rightarrow p + p + e^-$

- ν_e ONLY

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

Mainly sensitive to ν_e, less to ν_μ and ν_τ

NC $\nu_x + d \rightarrow p + n + \nu_x$

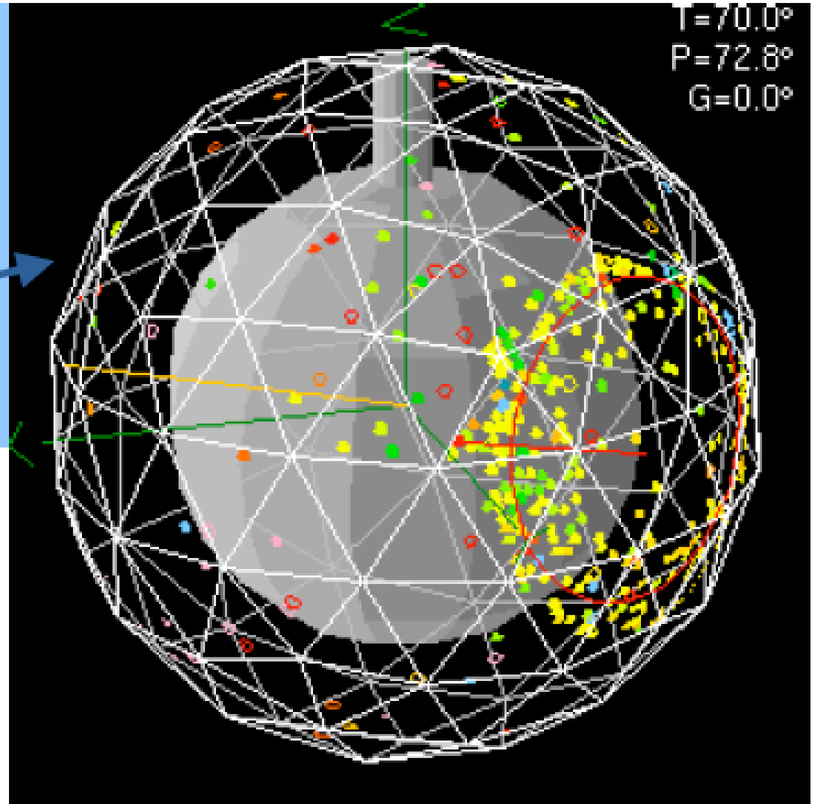
$n + d \rightarrow t + \gamma$ (E_γ = 6.25 MeV) (pure D_2O phase)

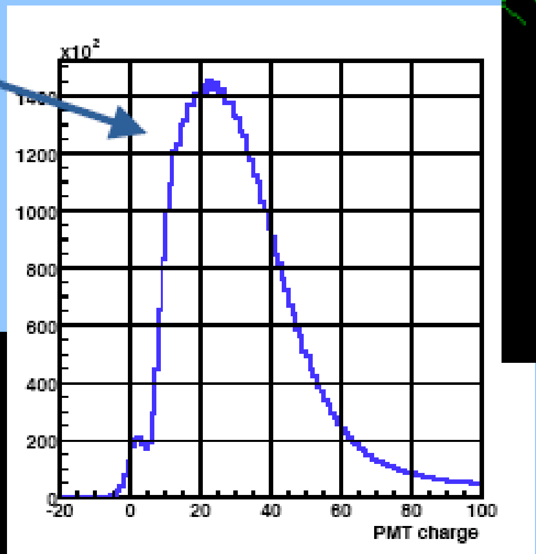
- Equal cross section for all ν types

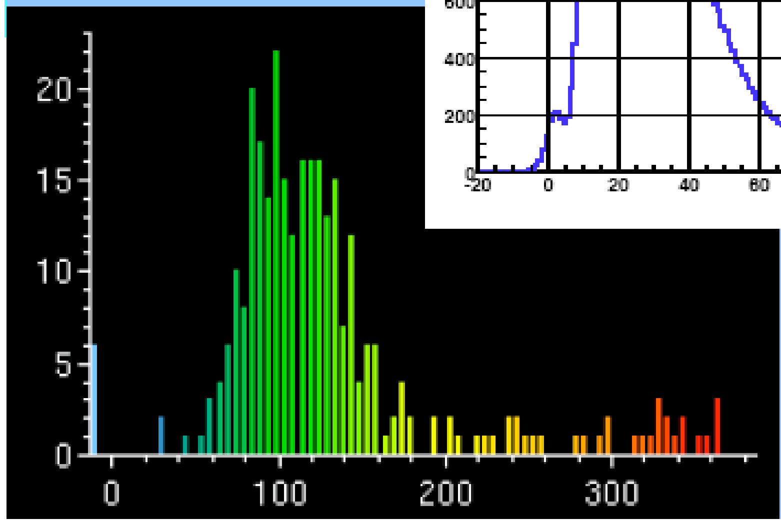
WHAT SNO MEASURES

PMT Measurements

- -position
- -charge
- -time







Reconstructed Event

- -event vertex
- -event direction
- -energy
- -isotropy

SNO data taking periods

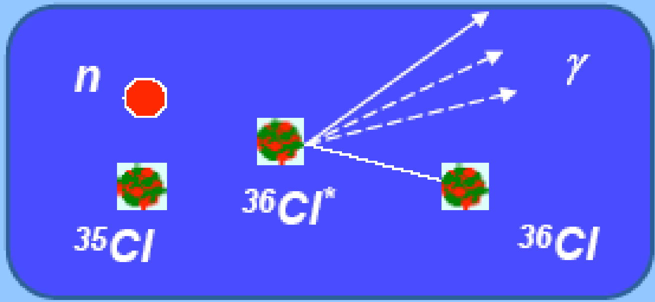
ETH Institute for Particle Physics

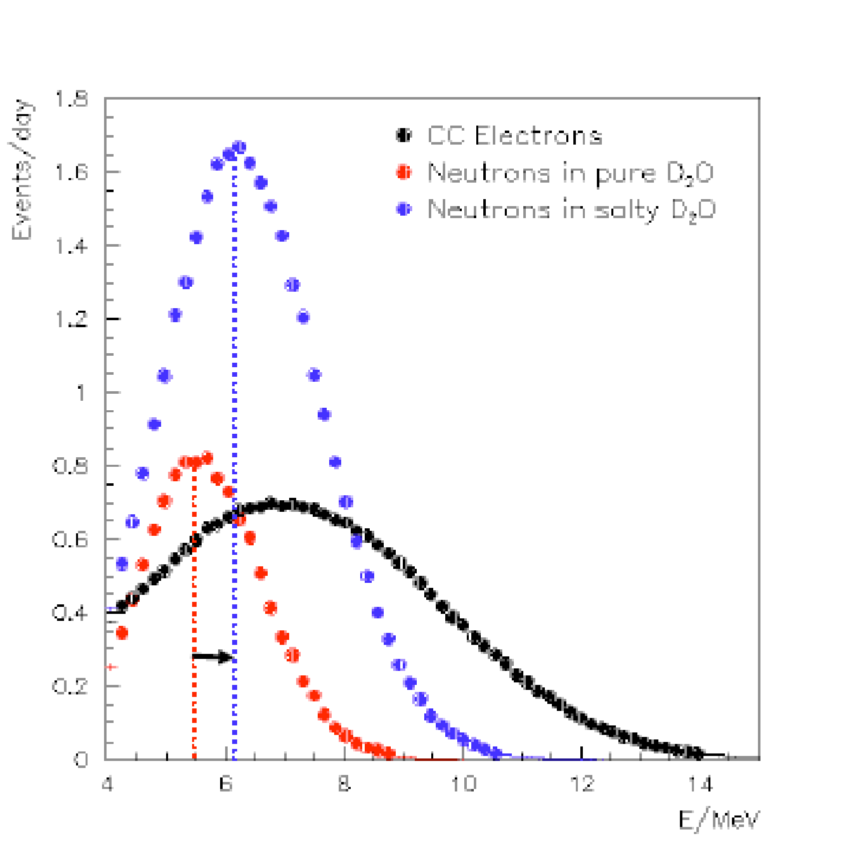
Past	Present	Future
Phase I (pure D2O):	Phase II (salty D_2O):	Phase III (^{3}He n counters):
306.4 live days	254.2 (~400) days	Counters in!
$T_e > 5$ MeV $R < 550$ cm 2928 events	$T_e > 5.5$ MeV $R < 550$ cm 3055 events	n capture on ^{3}He $n + {}^3He \rightarrow p + t$
n capture on D Single 6.25 MeV γ	n capture on Cl Multiple γ's 8.6 MeV	Channels indep. →no correlation
High CC-NC corr. T_e constrained	High CC-NC corr. T_e unconstrained	Reduced NC systematics

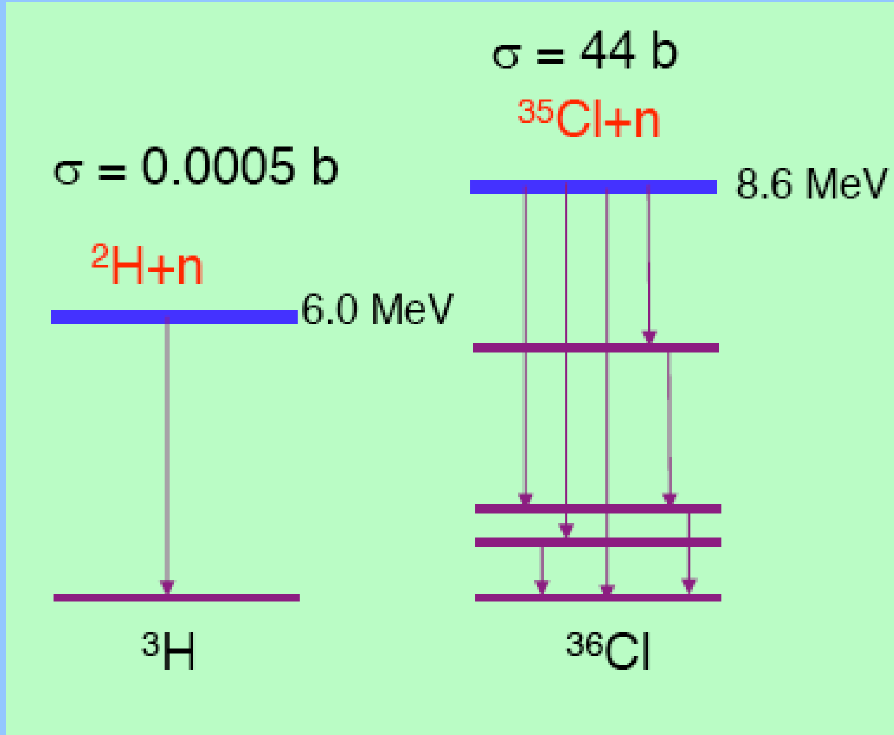
Graham, NOON04

Neutrons in Salt → NaCl Capture

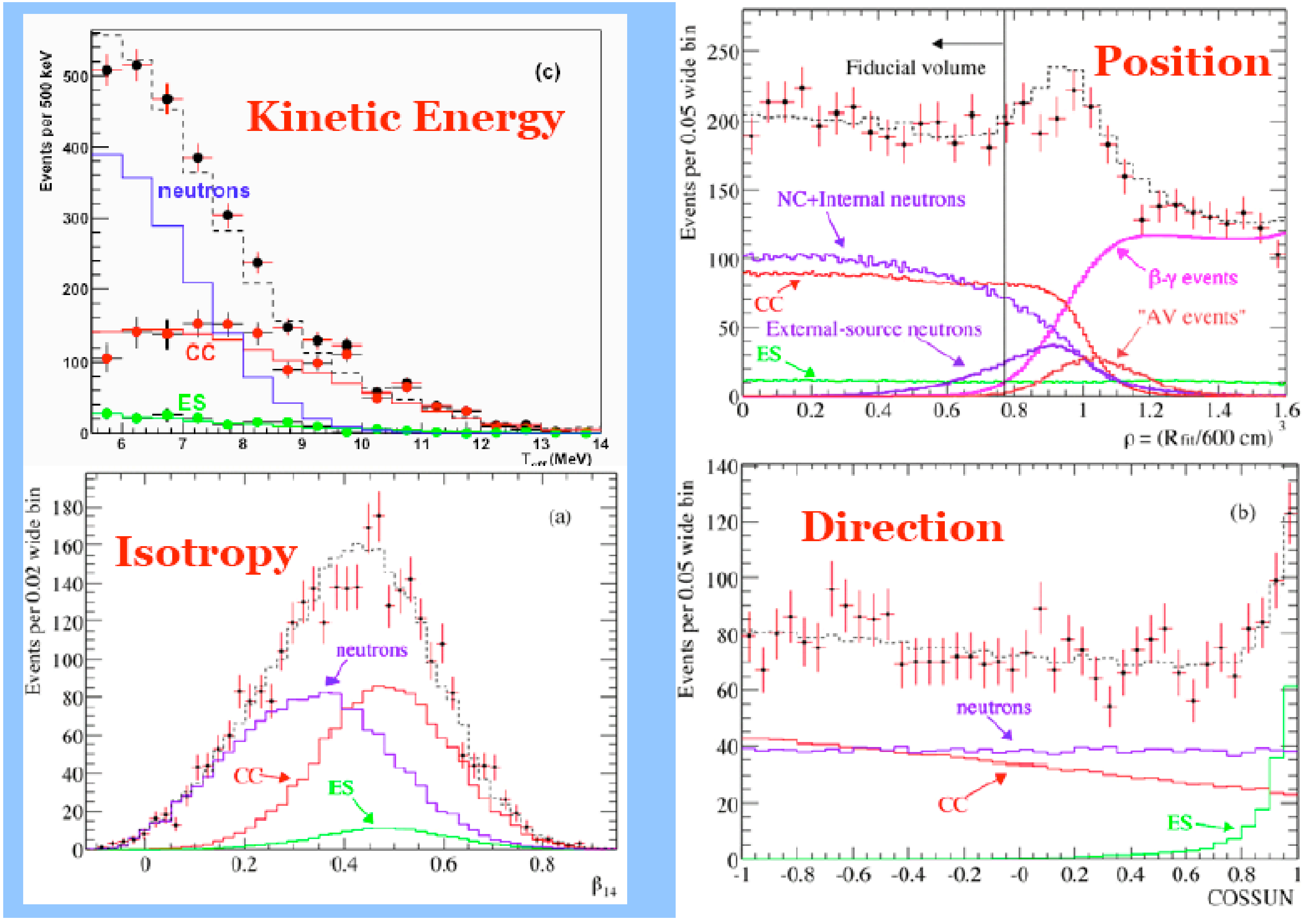
- Higher capture cross section
- Higher energy release
- Many gammas



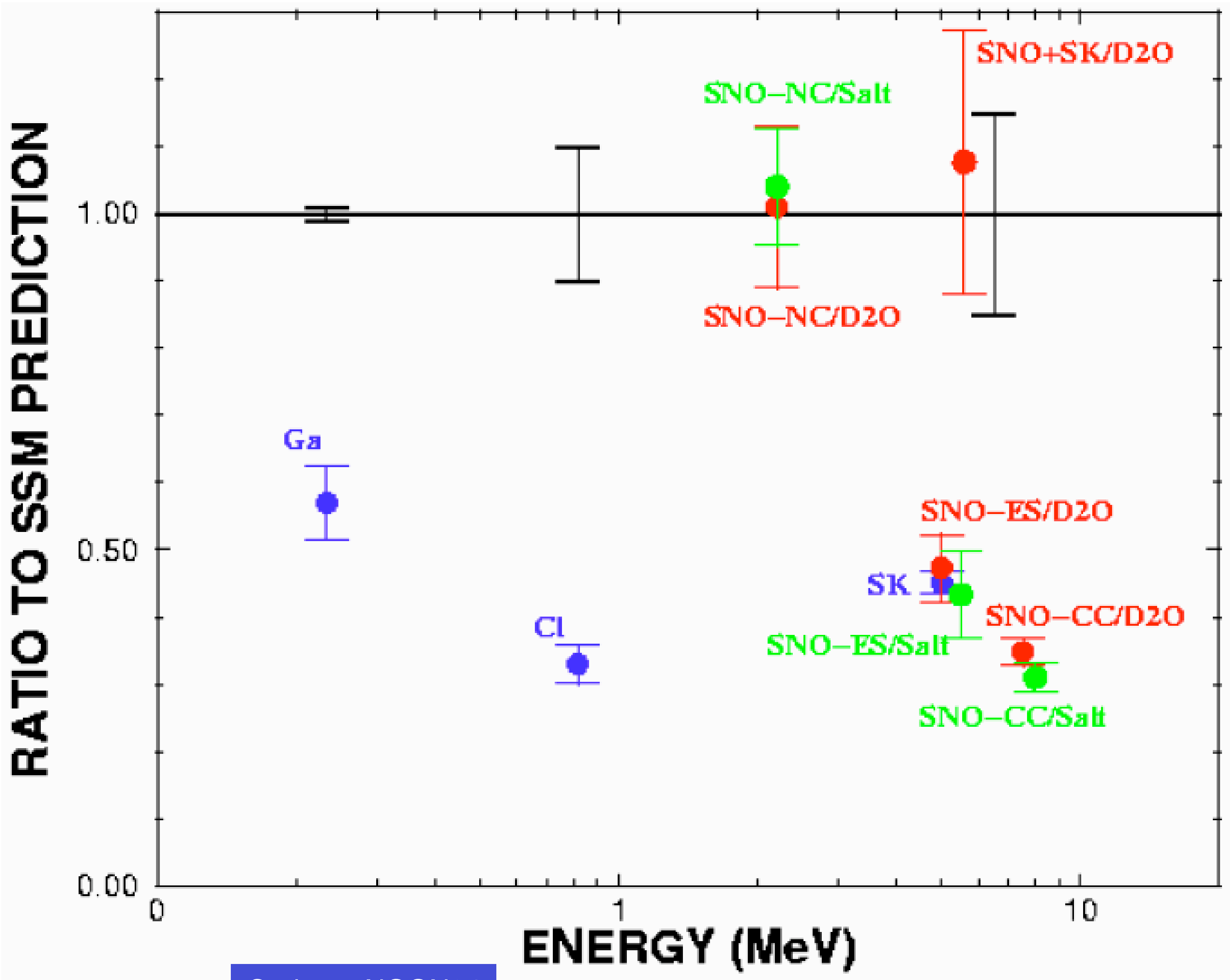




Graham, NOON04

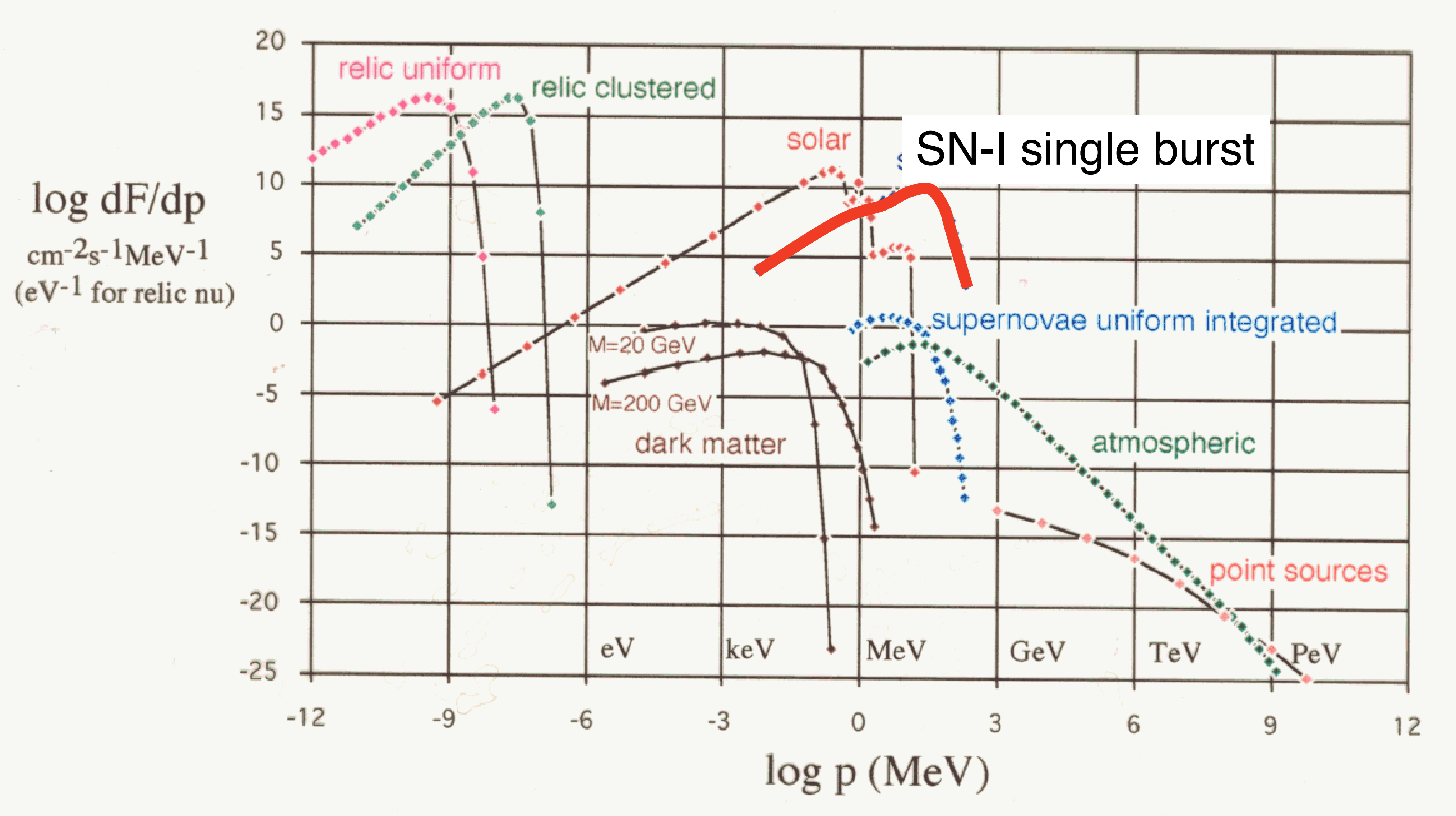


Graham, NOON04



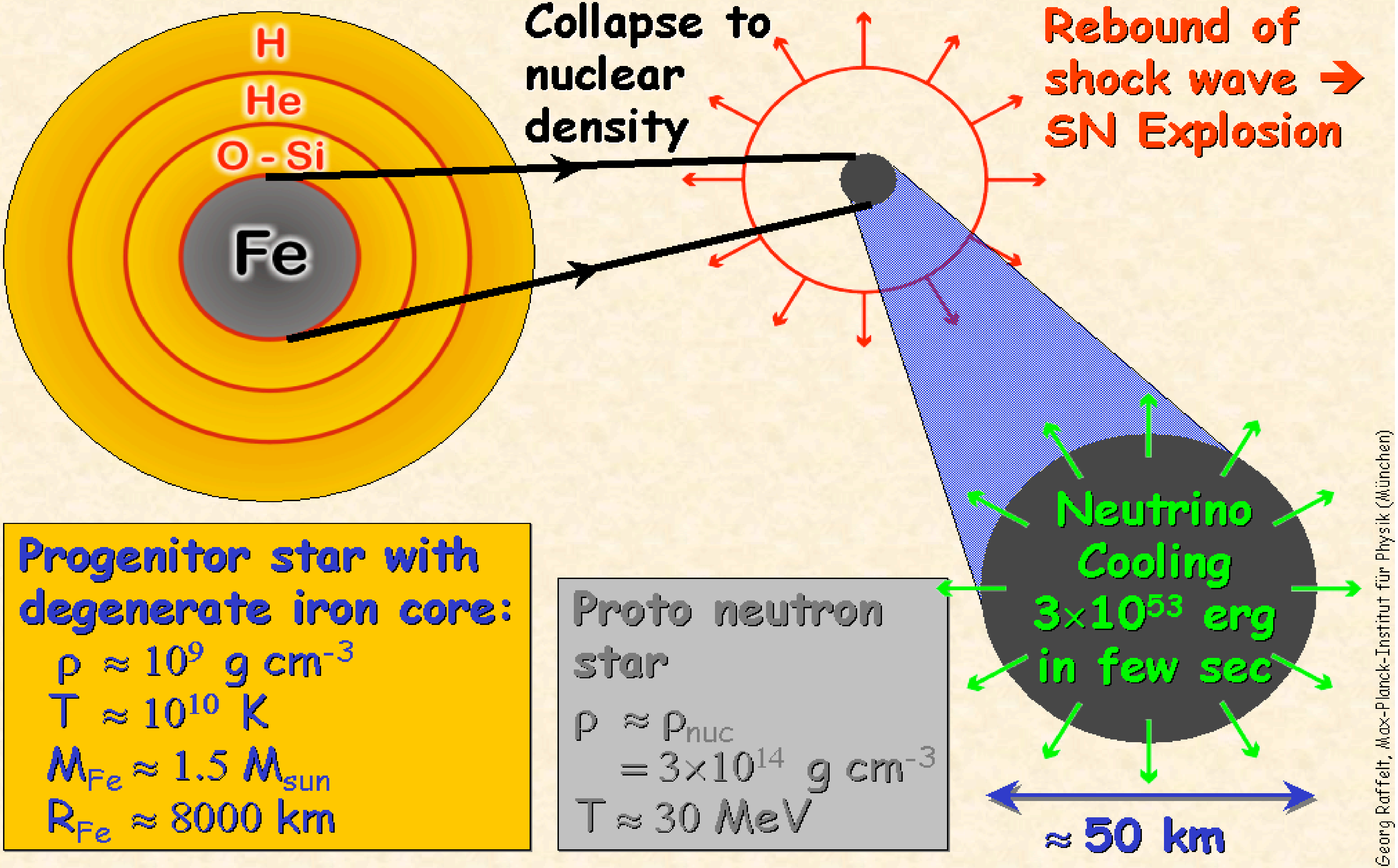
Graham, NOON04

Spectrum of astrophysical neutrinos




Supernova 1987 A

Stellar Collapse and Supernova Explosion



Progenitor star with degenerate iron core:

$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 8000$ km

Proto neutron star

$\rho \approx \rho_{nuc} = 3\times10^{14}$ g cm^{-3}

$T \approx 30$ MeV

Core Collapse Supernova Energetics

Liberated gravitational binding energy of neutron star:

$$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% \, M_{SUN} c^2$$

This shows up as

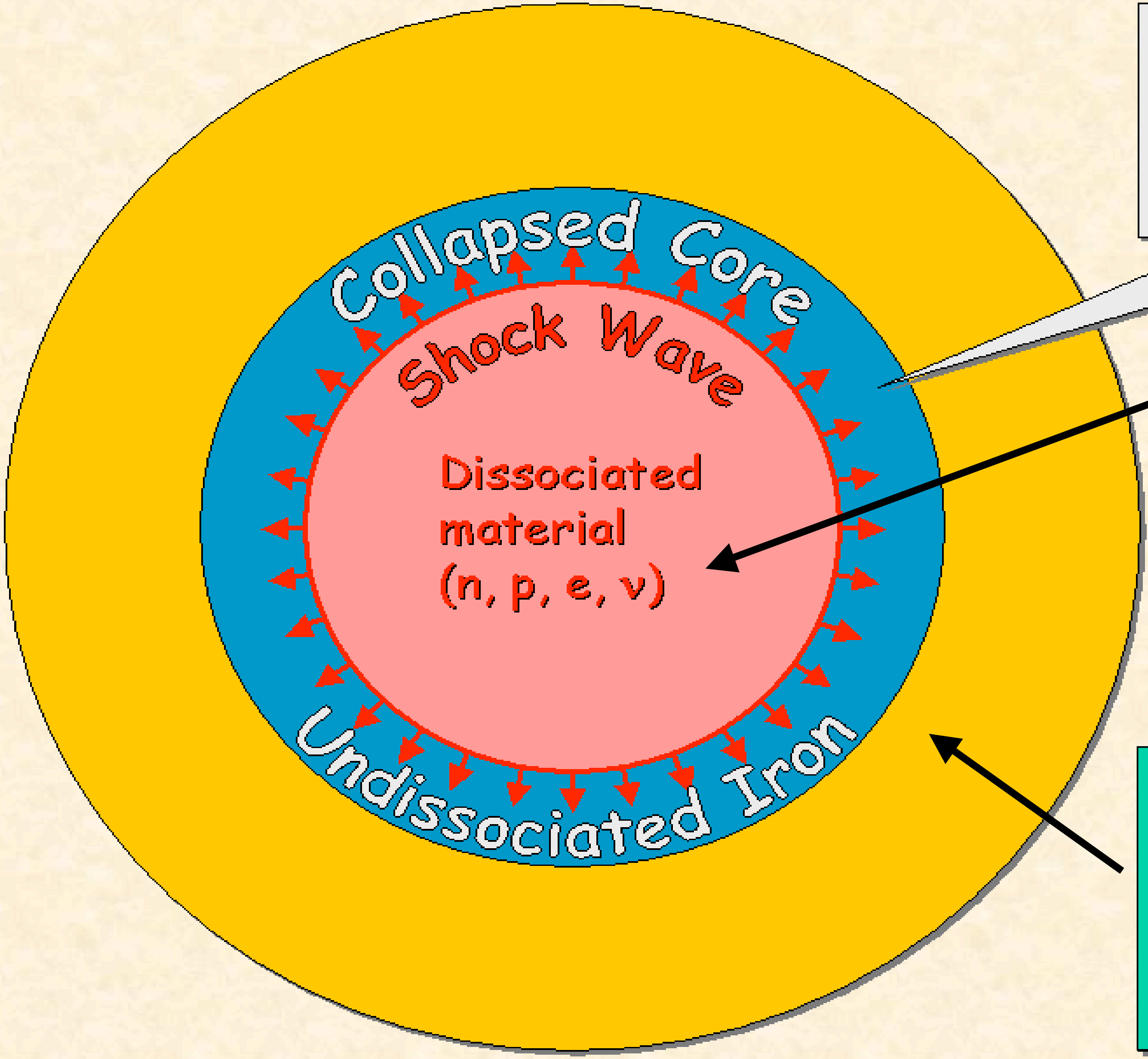
99%	Neutrinos
1%	Kinetic energy of explosion (1% of this into cosmic rays)
0.01%	Photons (outshine host galaxy)

Neutrino luminosity

$$L_\nu \approx 3\times10^{53} \text{ erg} / 3 \text{ sec} \approx 3\times10^{19} \, L_{SUN}$$

While it lasts, outshines the photon luminosity of the entire visible universe!

Why No Prompt Explosion?



Nuclear binding energy of 0.1 M_{sun} of iron $\approx 1.7 \times 10^{51}$ erg

$$e^- + p \rightarrow n + \nu_e$$

$$\nu_e n \leftrightarrow p e^-; \quad \bar{\nu}_e p \leftrightarrow n e^+$$

$$e^+ e^- \leftrightarrow \nu\bar{\nu}; \quad \nu e \leftrightarrow \nu e$$

Thermal equilibrium

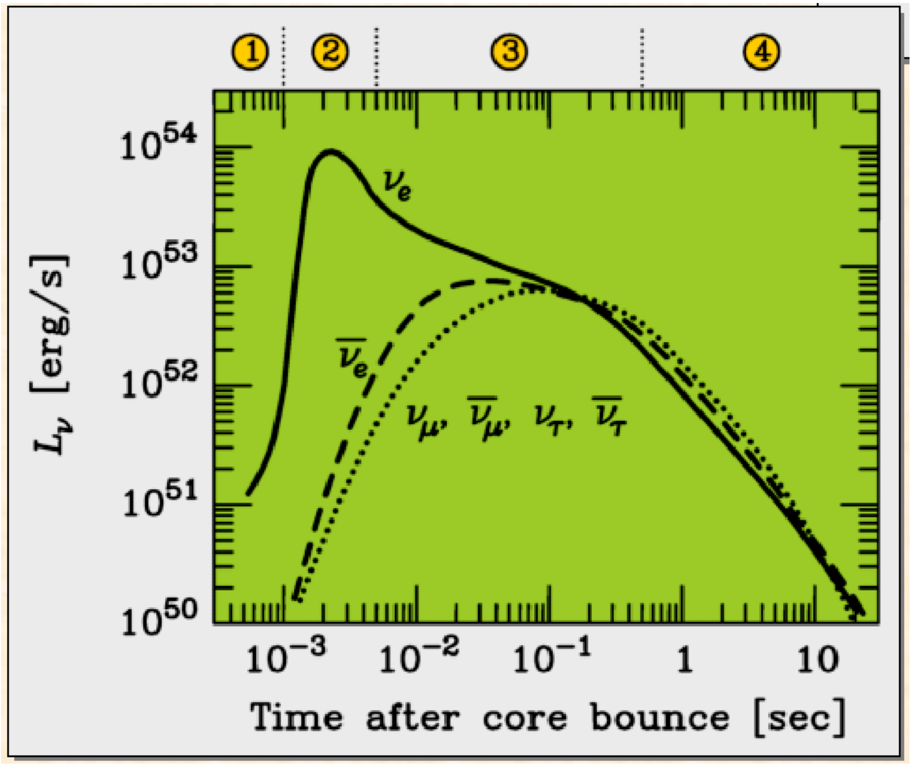
Energies: $\langle E\nu_e \rangle \sim$ 12 MeV

$\langle E\bar{\nu}_e \rangle \sim$ 15 MeV

$\langle E\overset{(-)}{\nu}_{\mu,\tau} \rangle \sim$ 18 MeV

Deeper
ν-sphere
=> hotter ν's

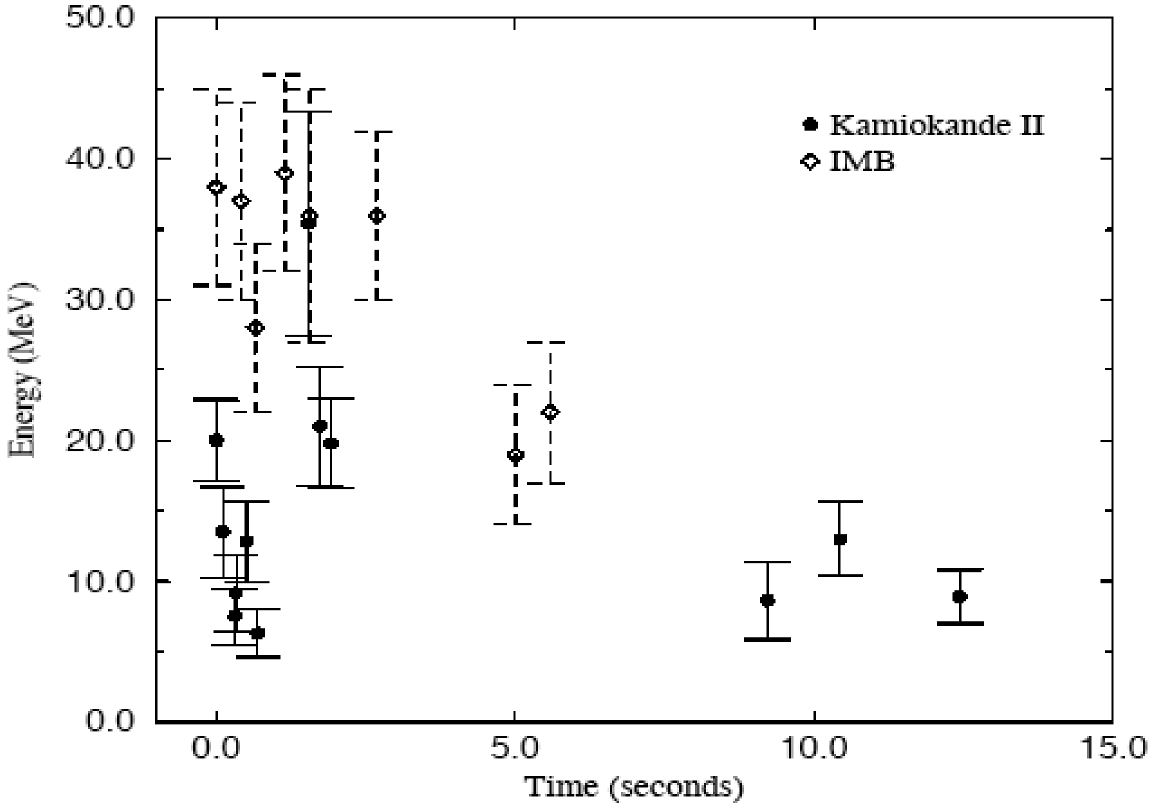
Timescale: prompt after core collapse
Δt~10's of seconds (possible sharp cutoff if BH forms)



SN1987A

Type II in LMC (~55 kpc)

Water Cherenkov:	IMB	E_{th} ~ 29 MeV, 6 kton	8 events
	Kam II	E_{th} ~ 8.5 MeV, 2.4 kton	11 events
Liquid Scintillator:	Baksan	E_{th} ~ 10 MeV, 130 ton	3-5 events
	Mont Blanc	E_{th} ~ 7 MeV, 90 ton	5 events??



Confirmed baseline model... but still many questions

Scholberg, NESS02

Detecting SN neutrinos – why?

1. Supernova physics:

- Core collapse mechanism
- Supernova evolution in time
- Cooling of the proto-neutron star
- Nucleosynthesis of heavy elements
- Black hole formation
- Exotic effects

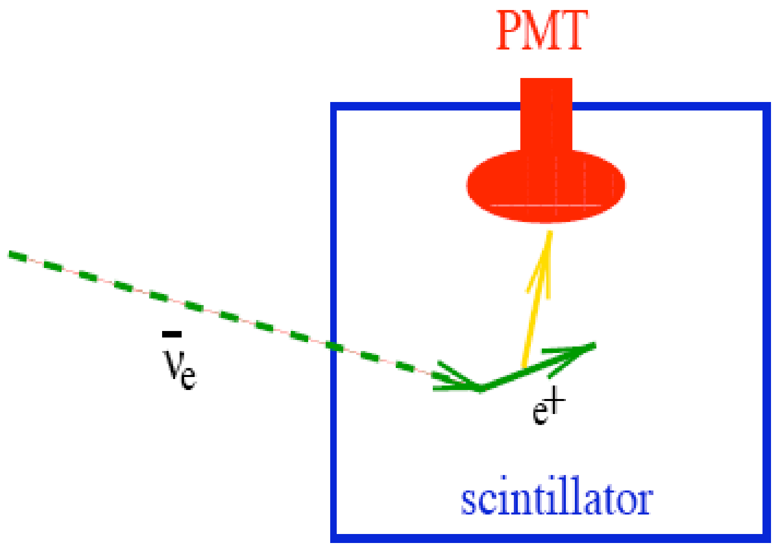
2. Neutrino physics

- Neutrino mass (time of flight delay)
- Oscillation parameters (flavor transformation in SN core and/or in Earth)
  - Type of mass hierarchy and θ_{13} mixing angle

3. Early alert for astronomers

- Pointing to the supernova

SCINTILLATION DETECTORS



Liquid scintillator
C_nH_{2n} volume
surrounded by
photomultipliers

Mont Blanc, Palo Verde,
Chooz, MACRO, Baksan, LVD
Borexino, KamLAND, BooNE

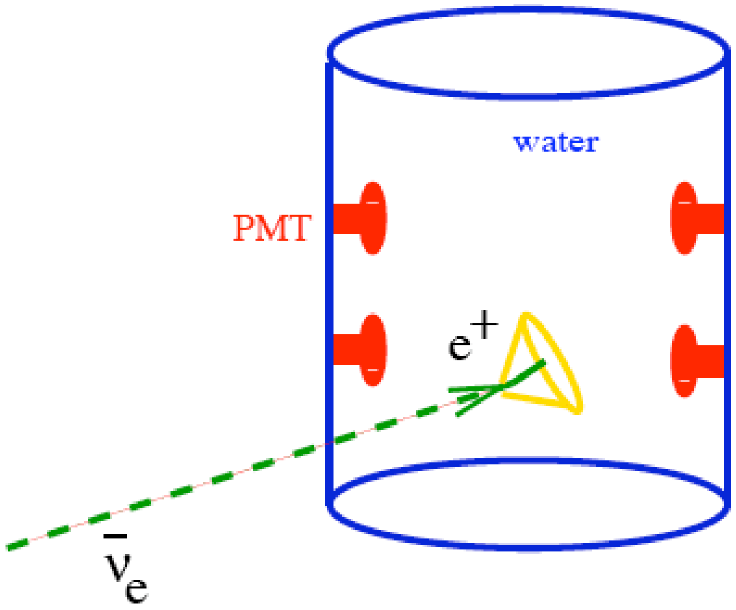
Inverse Beta Decay (CC)	$\bar{\nu}_e + p \rightarrow e^+ + n$	
NC Excitation of ^{12}C (NC)	$\nu_x + {}^{12}C \rightarrow \nu_x + {}^{12}C^*$	~5%
Elastic Scattering (CC,NC)	$\nu_x + e^- \rightarrow \nu_x + e^-$	~few %
Proton Scattering (NC)	$\nu_x + p \rightarrow \nu_x + p$	low energy

NEW J. Beacom et al., hep-ph/0205220

Very little pointing capability

Scholberg, NESS02

WATER CHERENKOV DETECTORS



Volume of clear water viewed by PMTs

IMB, Kam II, Super-K, part of SNO

Inverse Beta Decay (CC)

$\bar{\nu}_e + p \rightarrow e^+ + n$ Still dominates

Also: CC on oxygen

$\nu_e + {}^{16,18}O \rightarrow {}^{16,18}F + e^-$

$\bar{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+$

NC on oxygen

$\nu_x + {}^{16}O \rightarrow \nu_x + {}^{16}O^*$

Elastic Scattering (CC,NC) $\nu_x + e^- \rightarrow \nu_x + e^-$ ~few %

POINTING from Ch cone $\delta\theta \sim 25^\circ/n^{1/2}$

Scholberg, NESS02

SN neutrino detection channels in Argon

- **Elastic scattering on electrons (ES)**

$$\overset{(-)}{\nu} + e^- \rightarrow \overset{(-)}{\nu} + e^-$$

- **Charged-current (CC) interactions on Argon**

$Q\nu_e CC = 1.5$ MeV

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

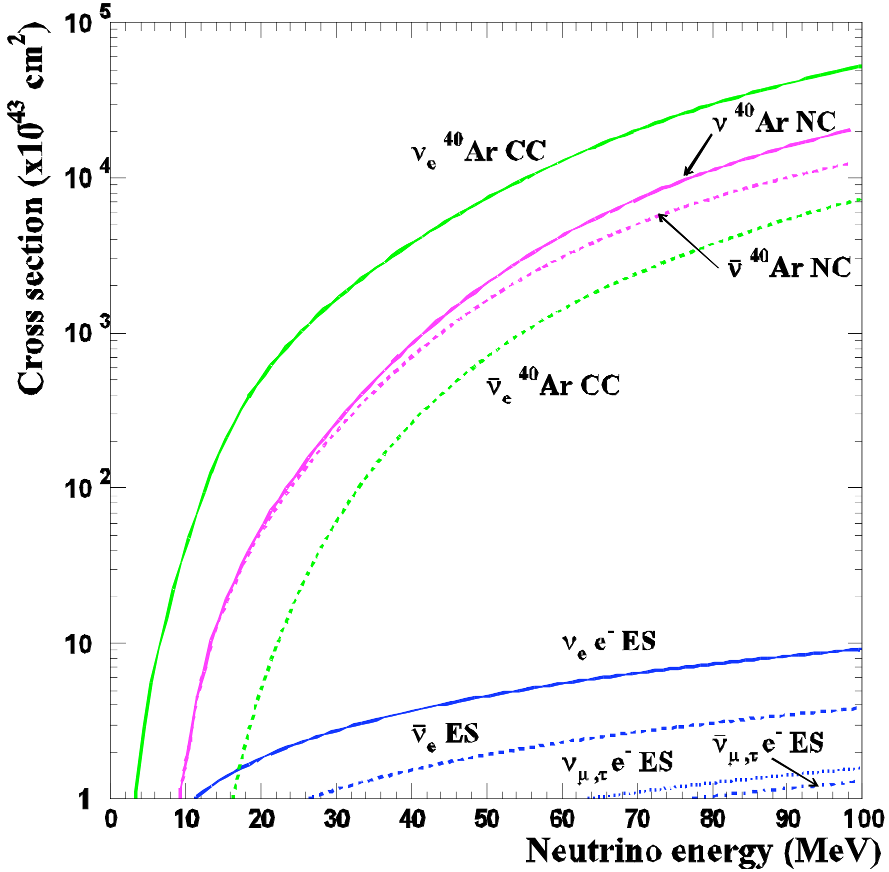
$Q\bar{\nu}_e CC = 7.48$ MeV

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

- **Neutral current (NC) interactions on Argon**

$Q_{NC} = 1.46$ MeV

$$\overset{(-)}{\nu} + {}^{40}Ar \rightarrow \overset{(-)}{\nu} + {}^{40}Ar^*$$



Possibility to separate the various channels by a classification of the associated **photons from the K, Cl or Ar deexcitation** (specific spectral lines for CC and NC) or by the **absence of photons** (ES)

Detector	Type	Mass (kton)	Location	No. of events at 8.5 kpc	Status
Super-K	Water Cherenkov	32	Japan	7000	Running again for SN by Nov 2002
SNO	Heavy water	1.4 (D_2O), 1 (H_2O)	Canada	300 450	running
LVD	Scintillator	1	Italy	200	running
KamLAND	Scintillator	1	Japan	300	running
Borexino	Scintillator	0.3	Italy	100	2003
Baksan	Scintillator	0.33	Russia	50	running
Mini-BooNE	Scintillator	0.7	USA	200	running
AMANDA	Long string	M_{eff}~0.4/PMT	South Pole	N/A	running
Icarus	Liquid argon	2.4	Italy	200	2002
OMNIS	Pb	2-3	USA?	>1000	proposed
LANNDD	Liquid argon	70	USA?	6000	proposed
UNO	Water Cherenkov	600	USA?	>100,000	proposed
Hyper-K	Water Cherenkov	1000	Japan	>100,000	proposed 2009

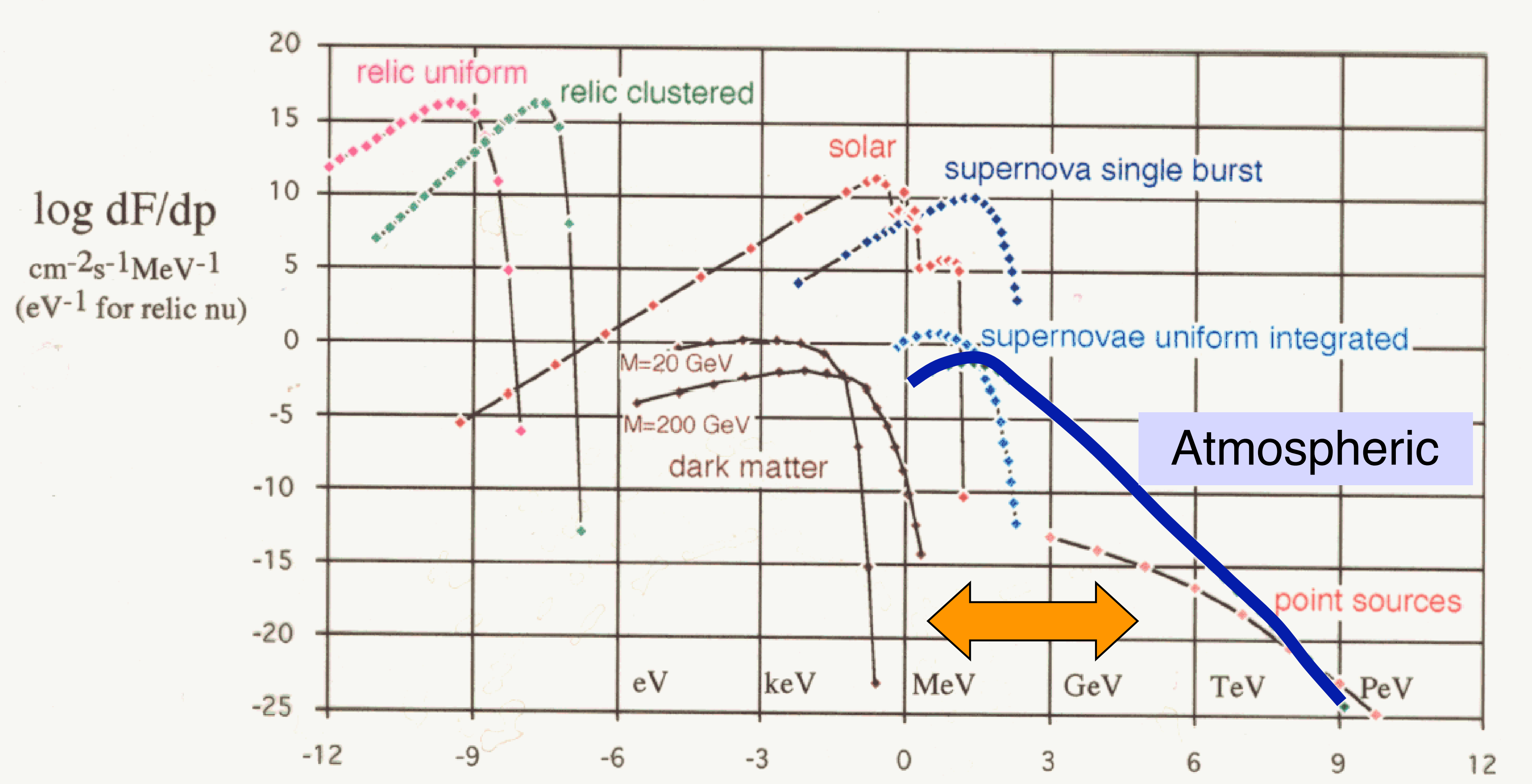
Galactic sens-itivity

≈1 every 30 years!

Extra Galactic

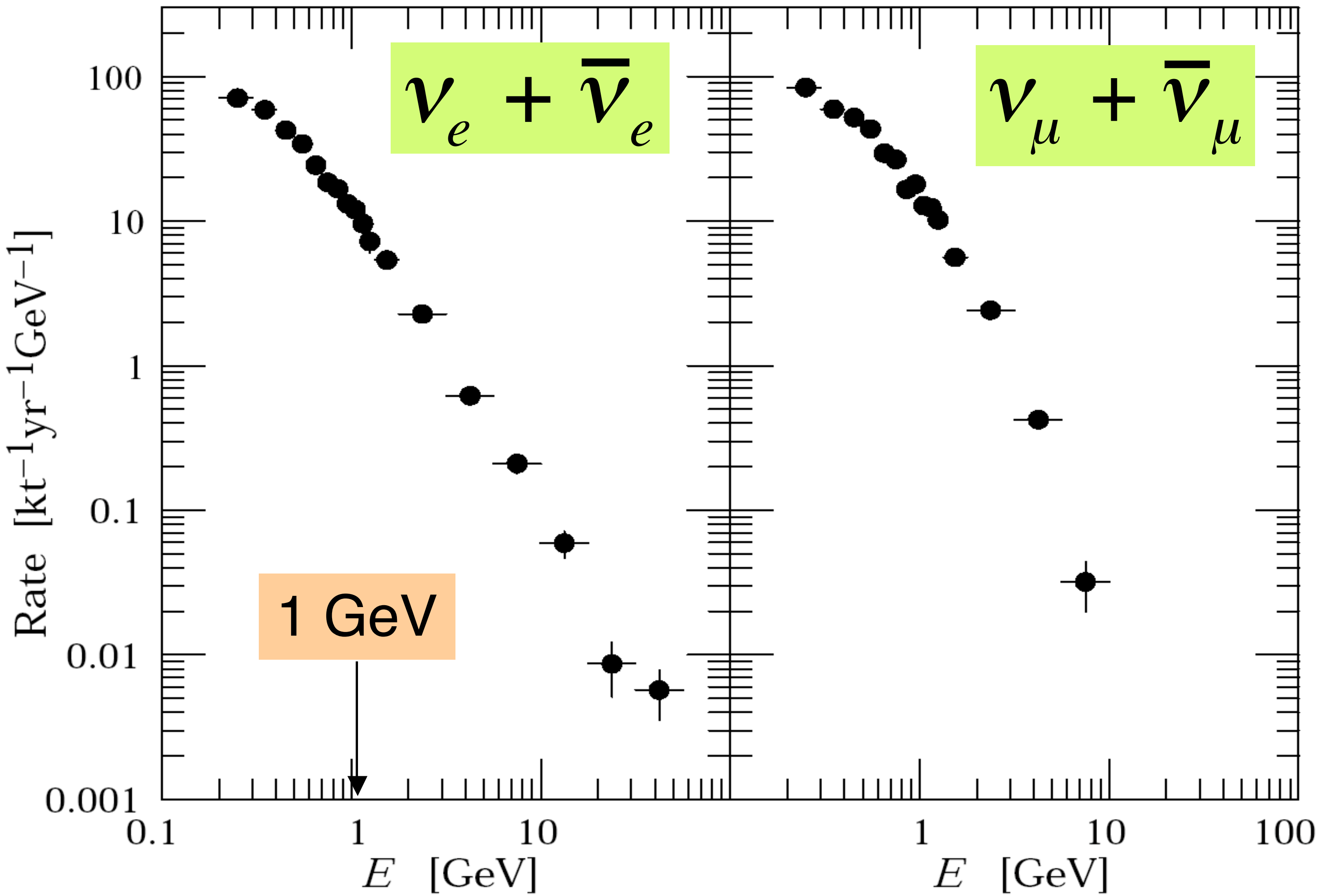
Scholberg, NESS02

Atmospheric neutrinos



From 100 MeV up to ≈100 GeV

Absolute charged current event rates



Neutrino interaction rate is small: ≈150 CC events/kton/year
Average energy: ≈400 MeV
Spectrum ≈ $E^{-1.7}$ above 1 GeV

KGF– The 1st reported Atmospheric ν

Several detectors in KGF mine at various depths.

3 ν published 15 Aug 65

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

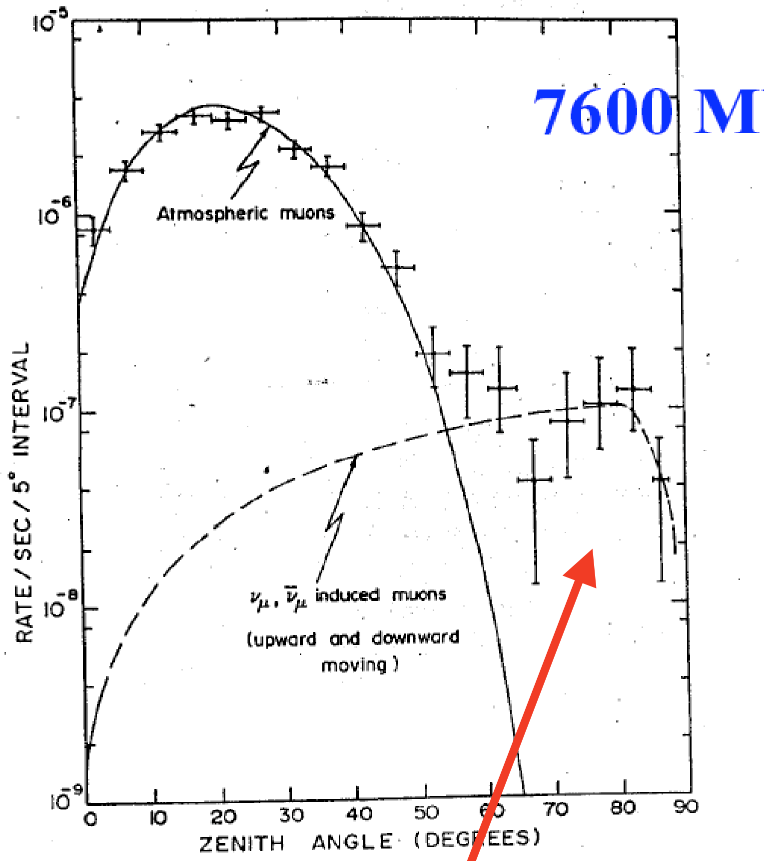
C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

K. HINOTANI and S. MIYAKE,
Osaka City University, Osaka, Japan

D. R. CREED, J. L. OSBORNE, J. B. M. PATTISON and A. W. WOLFENDALE
University of Durham, Durham, U.K.

Received 12 July 1965

Event number	Type of coincidence	Projected zenith angle	Date	Time
1	TEL. 2 $N_4 + S_4$	37°	30.3	20.04
2	TEL. 1 $N_1 + S_1$	48 ± 1°	27.4	18.26
3	TEL. 2 $N_6 + S_6$	75 ± 10°	25.5	20.03



Most neutrinos cross the Earth! Look for upward muons!

Past and present atmospheric ν experiments

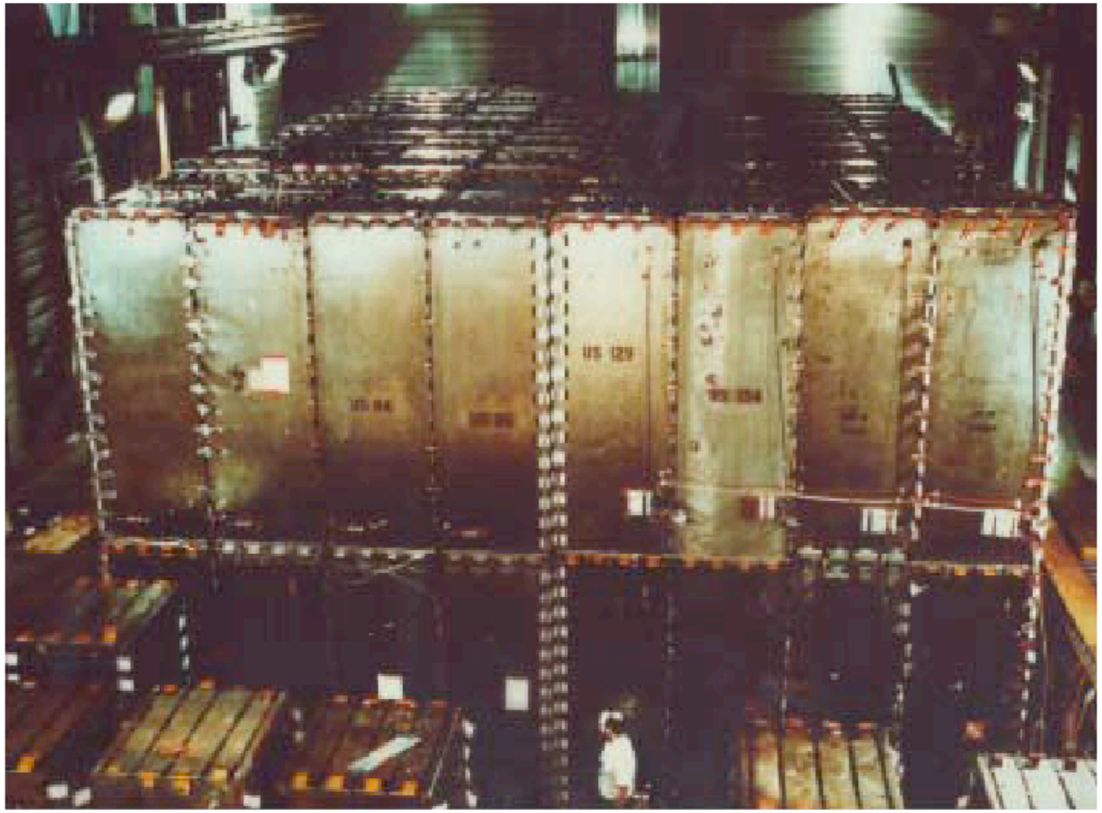
Table 1.1: Summary of atmospheric neutrino experiments.

Experiment	Detector	Location	Mass
IMB	Water Cherenkov	Cleveland, Ohio, USA	3.3 kton
Kamiokande	Water Cherenkov	Kamioka, Gifu, Japan	0.88 kton
Super-Kamiokande	Water Cherenkov	Kamioka, Gifu, Japan	22.5 kton
Nusex	Iron Calorimeter	Mont B lanc, France	0.15 kton
Fréjus	Iron Calorimeter	Fréjus, Alps, France	1.56 kton
Soudan 2	Calorimeter	Soudan, Minnesota, USA	3.9 kton
MACRO	streamer tubes	Gran Sasso, Italy	

1. *They all stopped data taking except SuperK*
2. *SuperK is the only experiment that will continue data taking in the future.*
3. *In addition, only one new experiment ICARUS is under construction. It is the only approved new experiment.*
4. *Other bigger experiments are being discussed (>2010)*

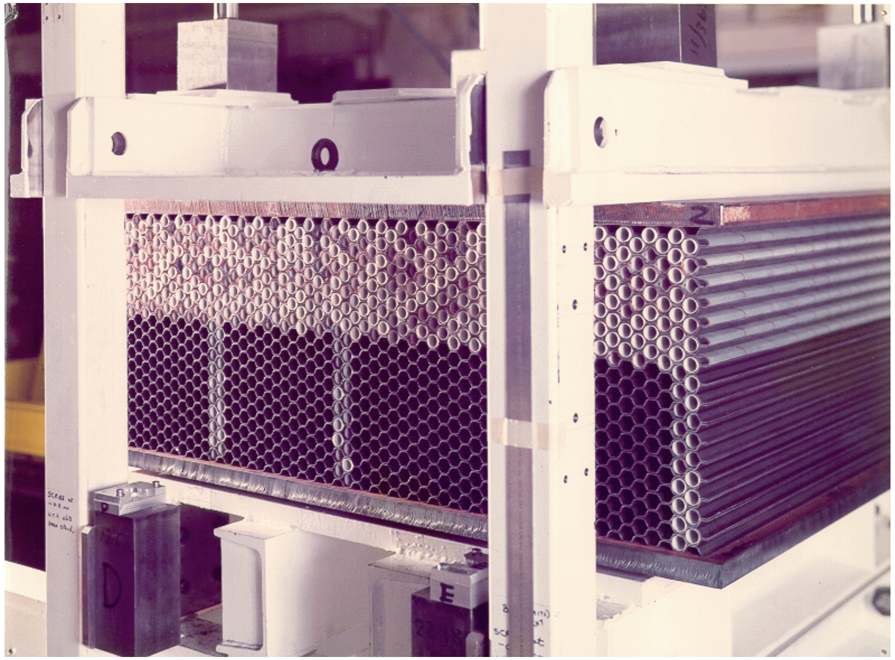
SOUDAN-2 detector (1989-2000)

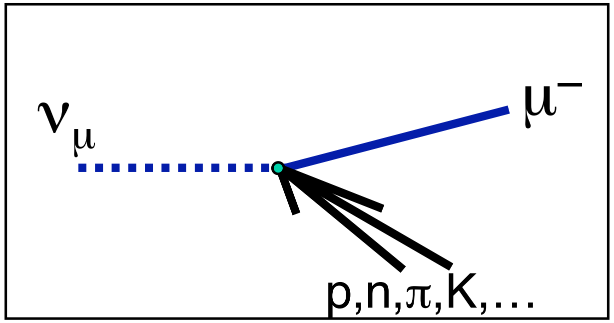
Soudan II detector is located in an underground laboratory in the Tower-Soudan Iron Mine 1/2 mile (2,090 metres of water equivalent) beneath Soudan, Minnesota, USA

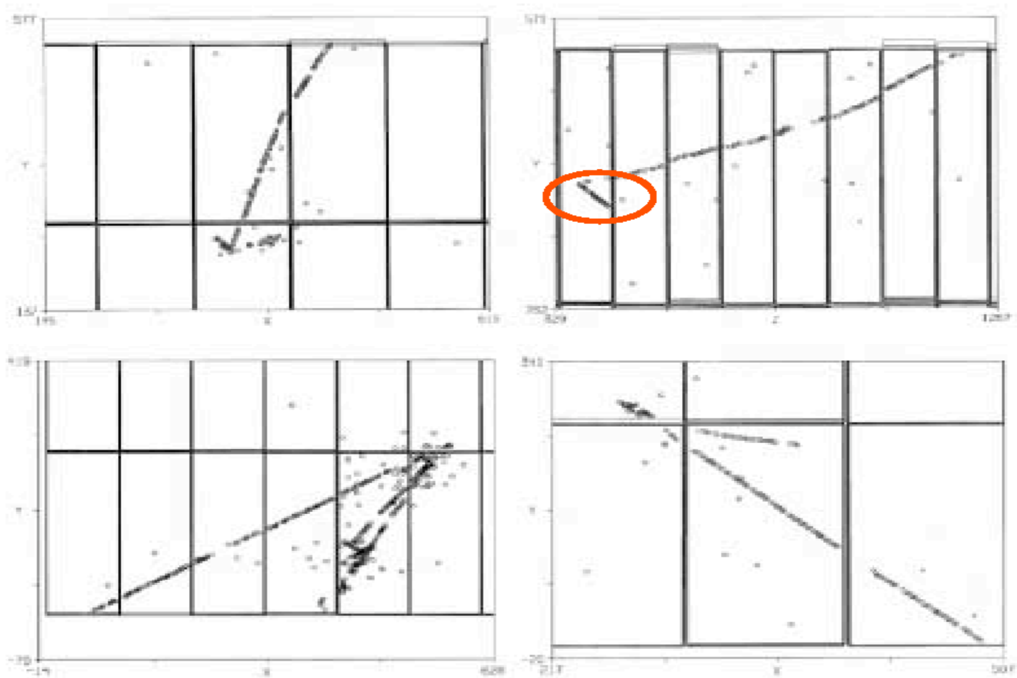


Soudan II detector was **960 ton tracking calorimeter** composed 224 modules of steel sheets shaped as honeycombs to host drift tubes.

Atmospheric neutrino events in SOUDAN

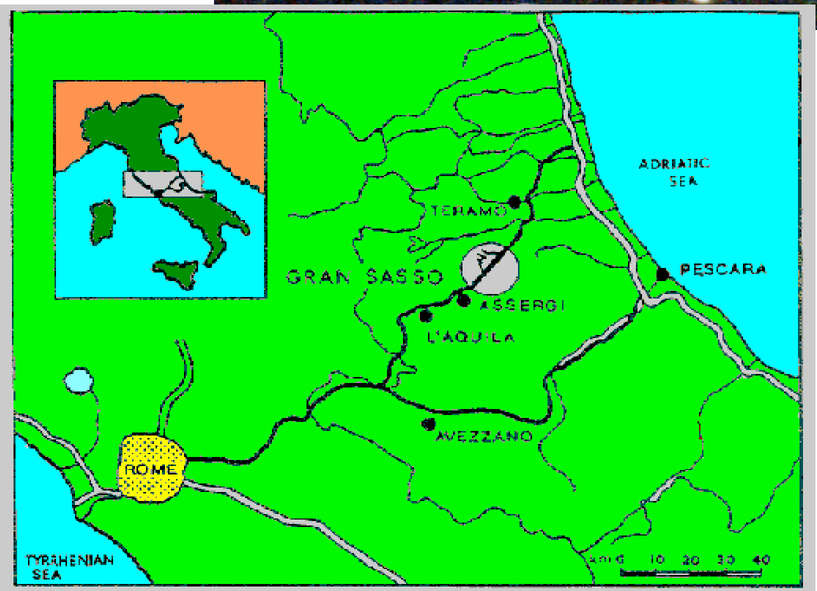




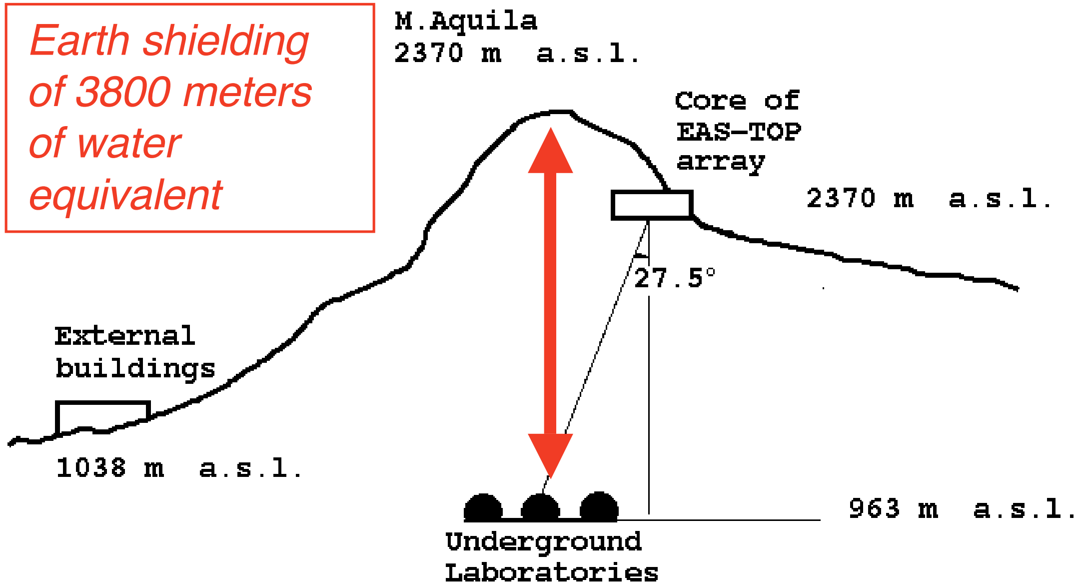


The entire calorimeter is comprised of 224 modules
Each module contained a tightly packed honeycomb array of 15,120 drift tubes
The drift tube array provides 3-dimensional hit reconstruction, with an r.m.s. accuracy of 1.12cm in the drift direction and 3.5mm in the orthogonal plane, together with dE/dX sampling.

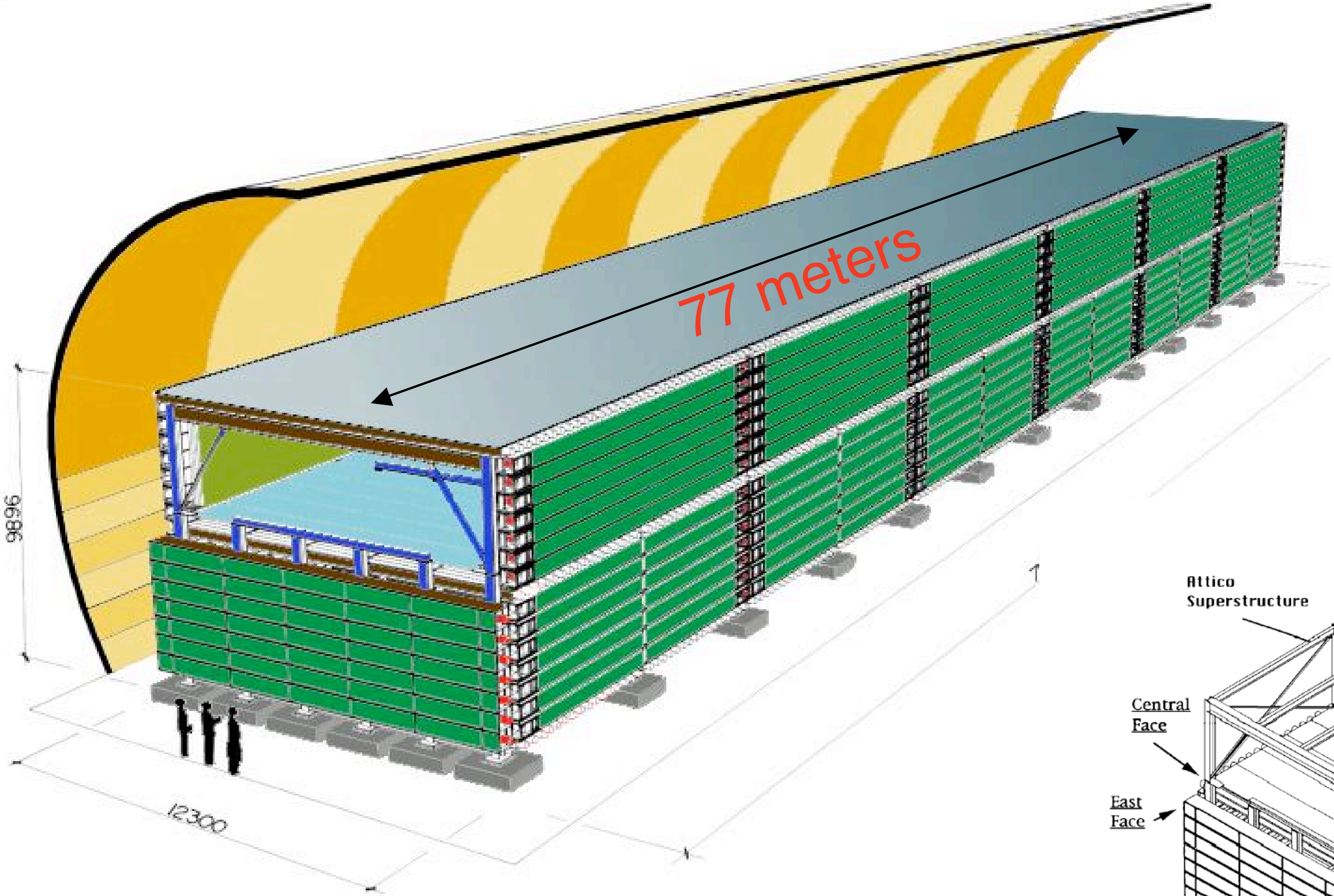
Gran Sasso Underground Laboratory



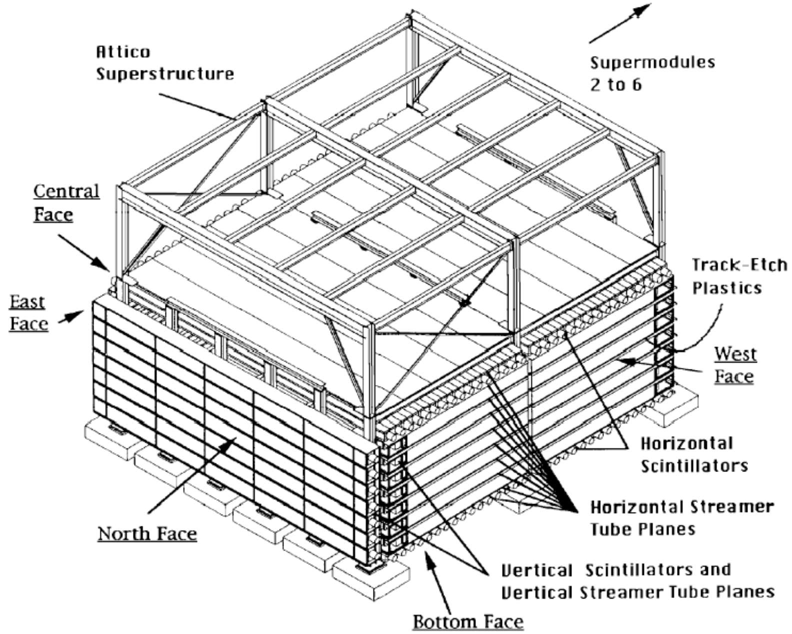
Earth shielding of 3800 meters of water equivalent



MACRO experiment (until 2001)



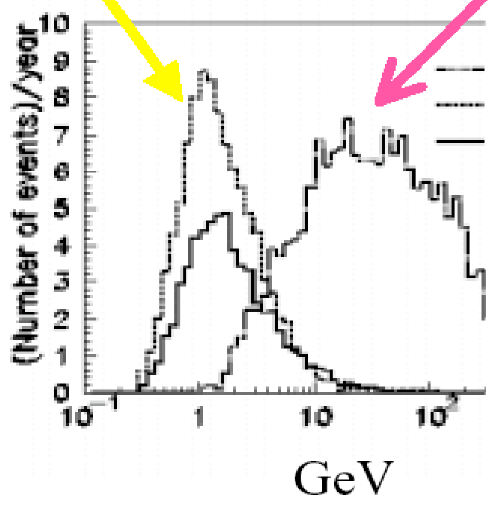
MACRO was built to search for monopoles, but is also sensitive to C.R. muons and atmospheric neutrinos

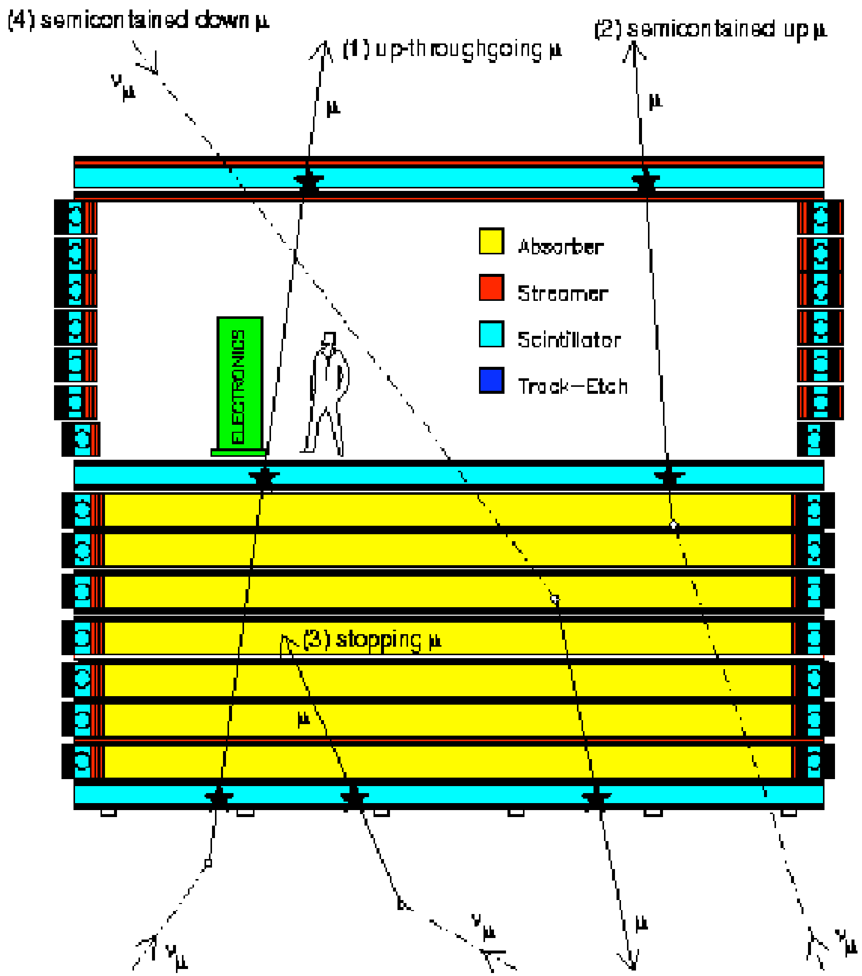


MACRO was composed of 6 supermodules, each consisting of **streamer tubes planes and scintillators** for precise timing

Detection of Atmospheric ν's **MACRO**

- Interaction in Detector
  - Fully Contained Events
  - Partially Contained Events
- Interaction Outside Detector
  - Throughgoing μ's
  - Up-stopping μ's



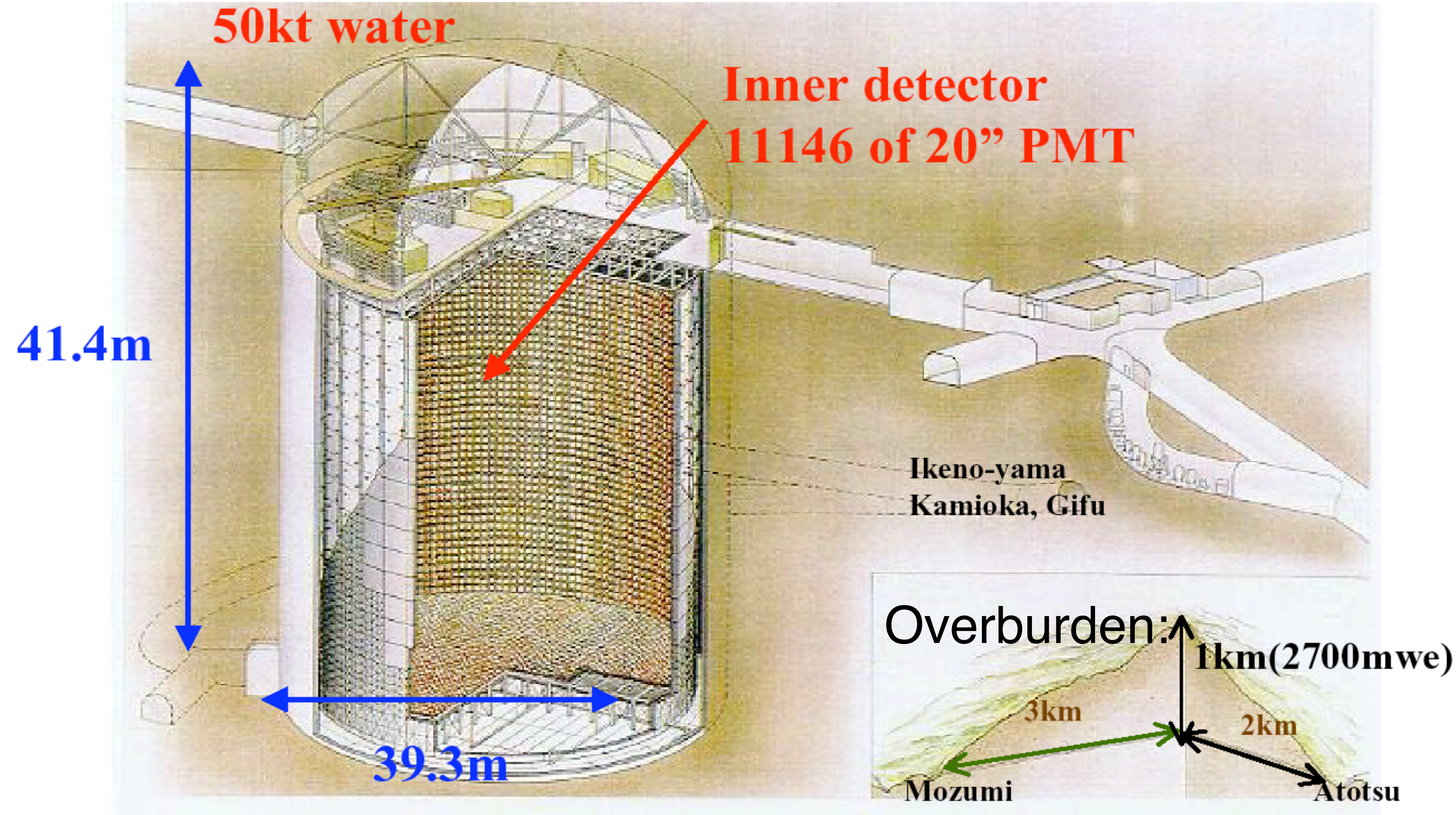


May 26, 2002

Maury Goodman, Neutrino 2002
"Other Atmospheric ν Experiments"

SuperKamiokande Detector

Very large Water Cerenkov detector: Fiducial mass 22.5 kton

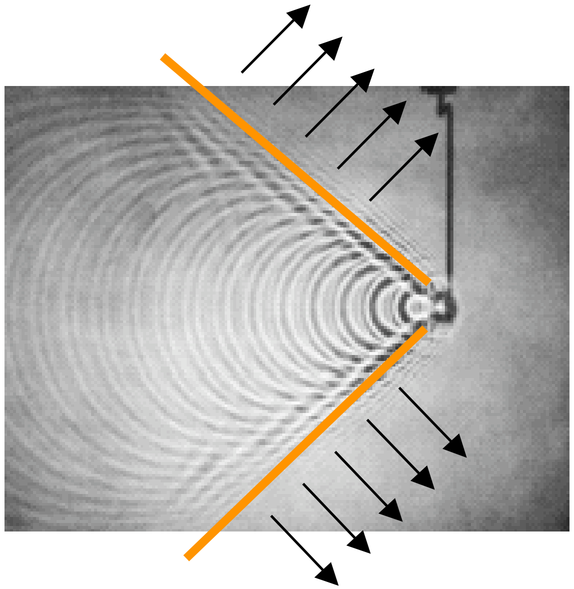


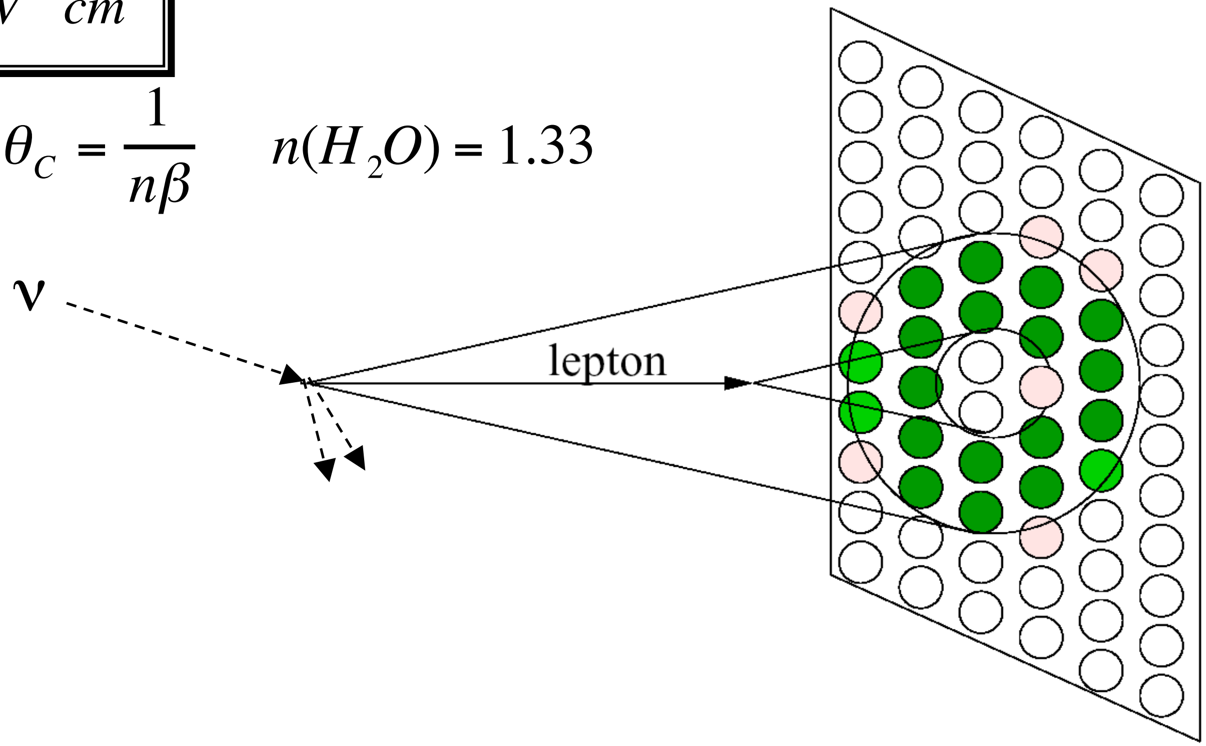
Operation from April 1996

Cerenkov rings in water

$$\frac{d^2N}{dEdx} = \frac{\alpha}{\hbar c}\sin^2\theta_C \approx 370\sin^2\theta_C \quad eV^{-1}cm^{-1}$$

$$\cos\theta_C = \frac{1}{n\beta} \qquad n(H_2O) = 1.33$$





About 170 γ/cm in 350 < λ < 500 nm
With 40% PMT coverage, Q.E.≈20%
Relativistic particle produces
⇒≈14 photoelectrons / cm
⇒≈7 p.e. per MeV

Particle momentum thresholds in water:

•Electron	0.6 MeV/c
•Muon	120 MeV/c
•Pion	159 MeV/c
•Kaon	568 MeV/c
•Proton	1070 MeV/c

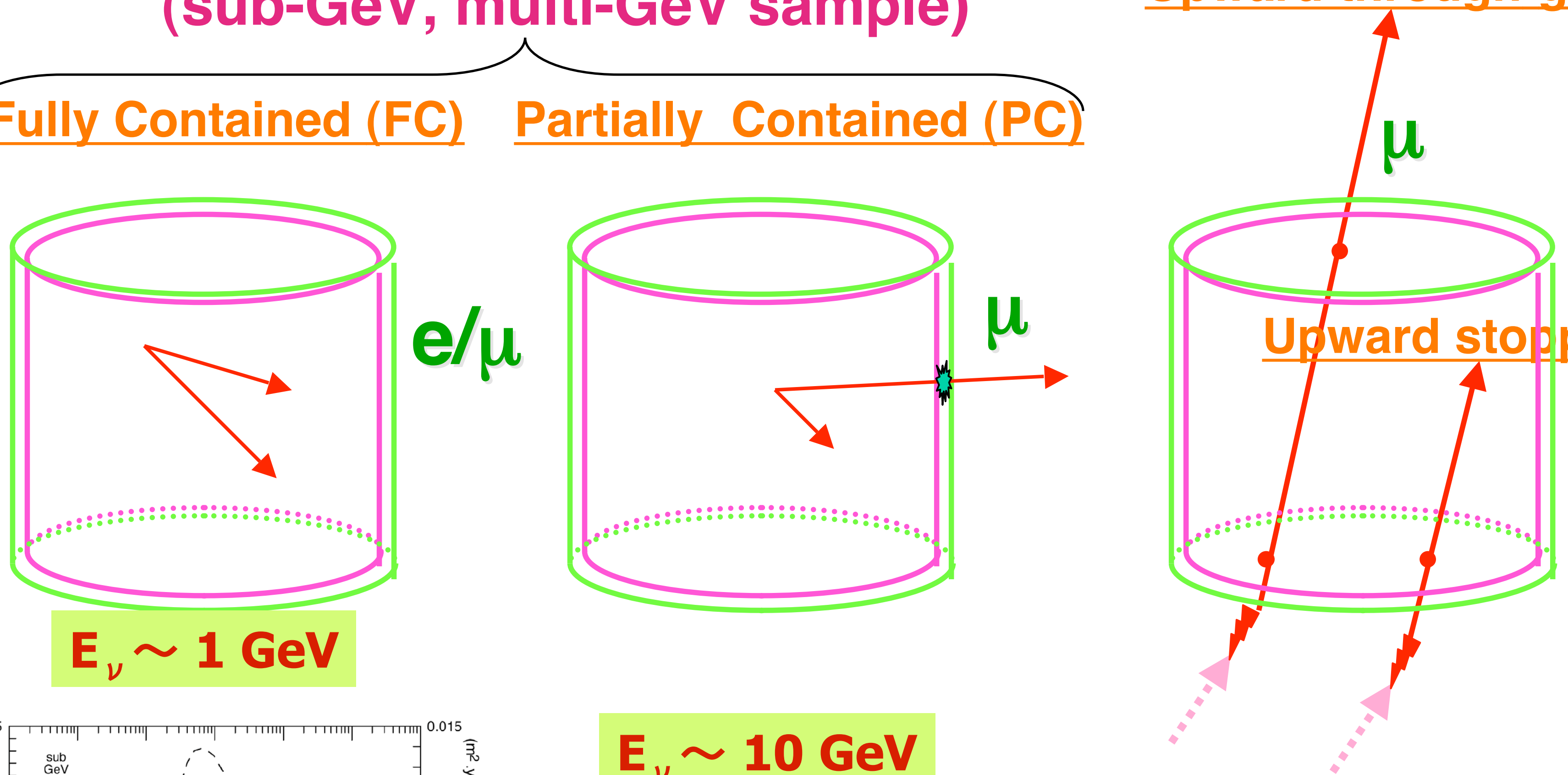
Event classification of atmospheric ν

ETH Institute for Particle Physics

Contained event
(sub-GeV, multi-GeV sample)

Fully Contained (FC) **Partially Contained (PC)**

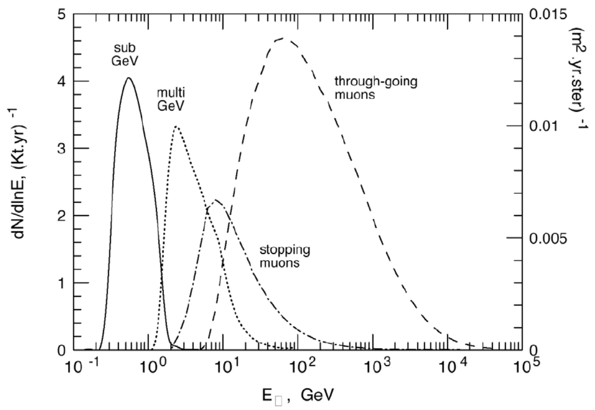
Upward through-going μ



$E_\nu \sim 1$ GeV

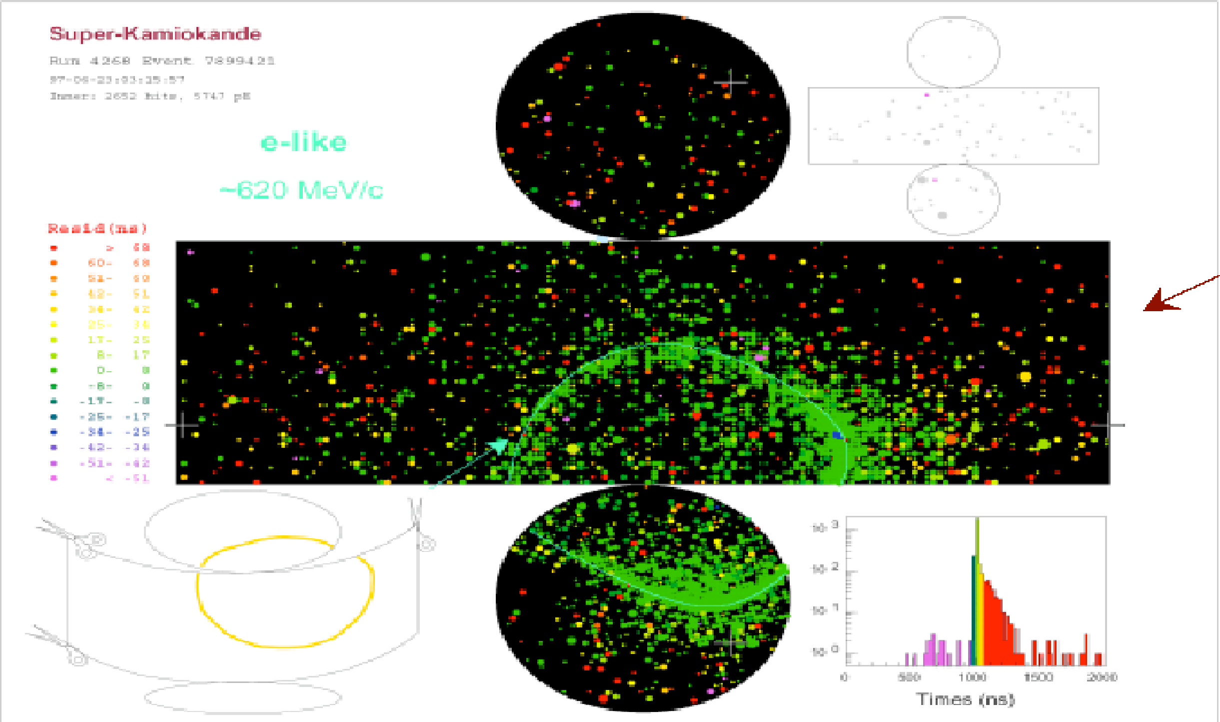
$E_\nu \sim 10$ GeV

$E_\nu \sim 10$ GeV (stop μ)
100 GeV (through μ)

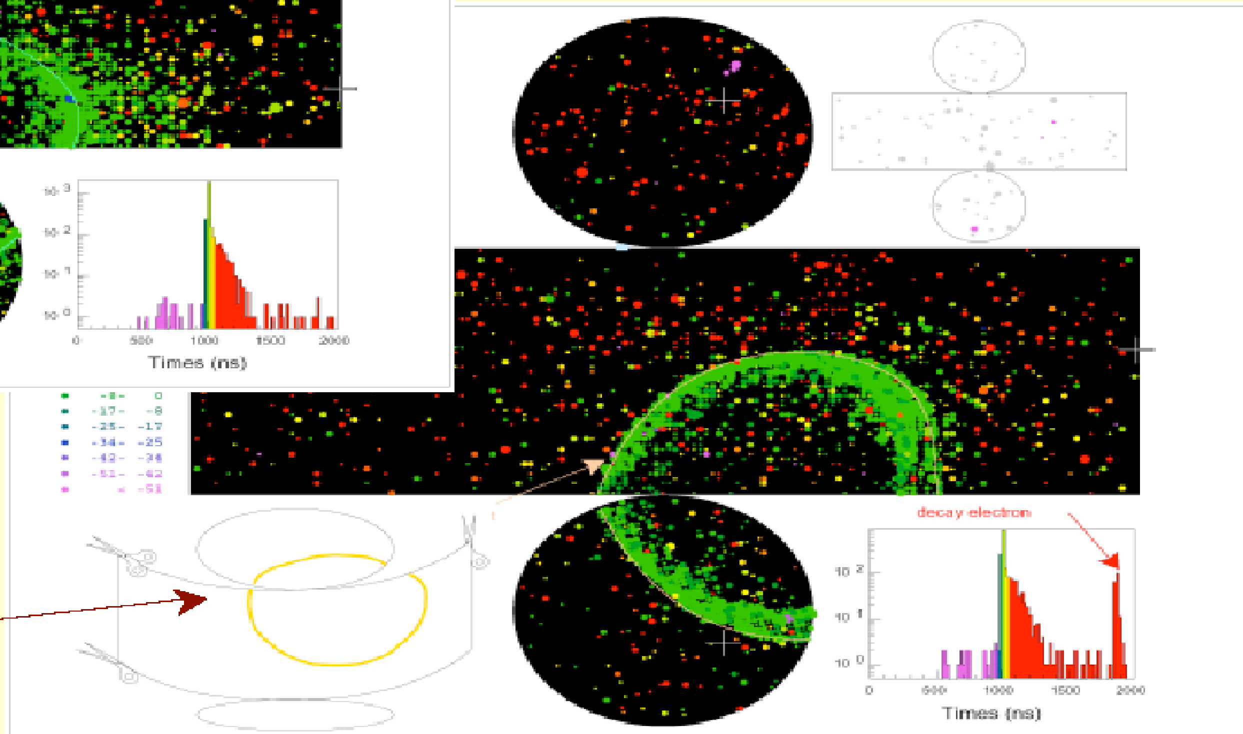


Electron and muon events in SuperK

Particle Identification



- Showering ring (e-like)
- Electron or photon (e.g. from π^0)



- Non-Showering ring (μ-like)
- Sometimes decay electron

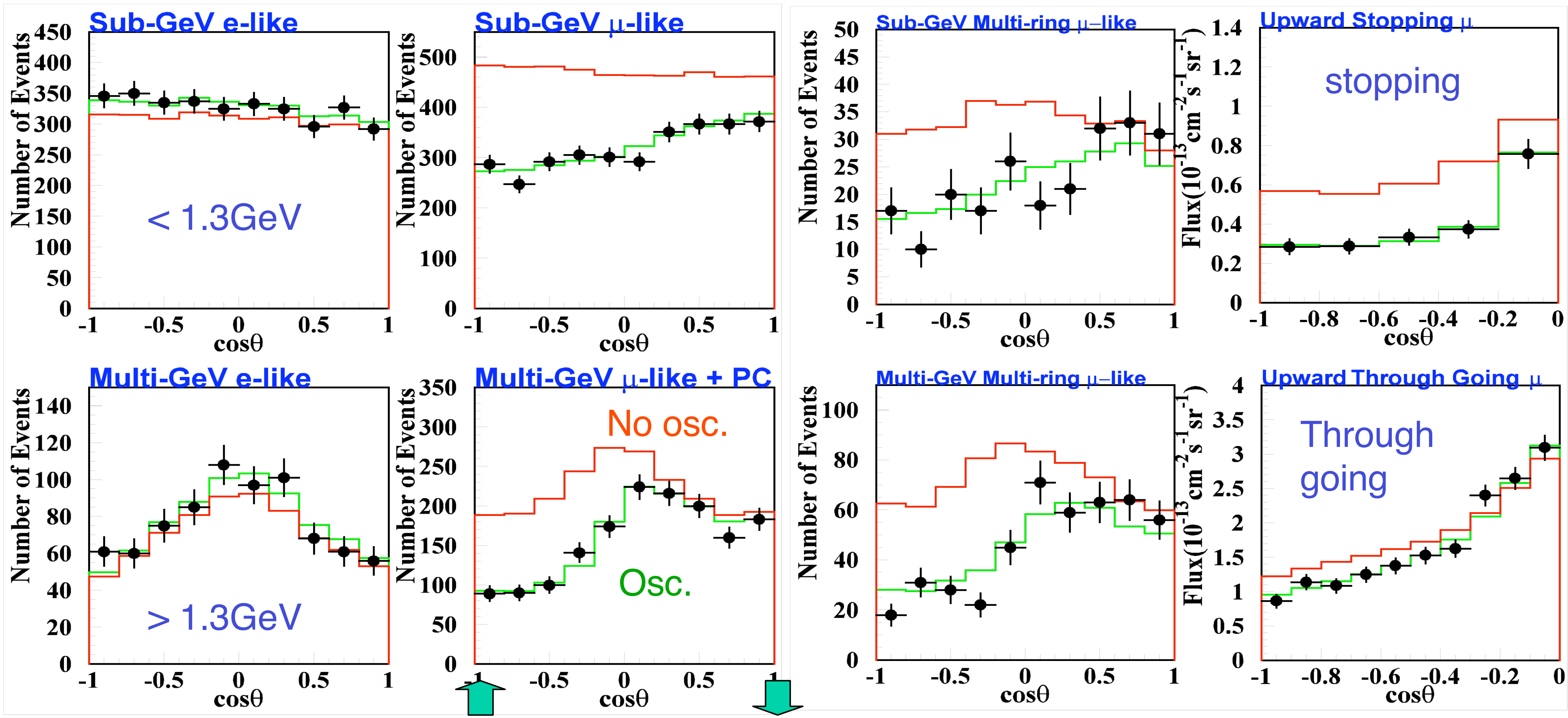
Michael Smy, UC Irvine

Super-Kamiokande data

- **Whole SK-1 data have been analyzed.**

1489day FC+PC data + 1678day upward going muon data

1-ring e-like | 1-ring μ-like | multi-ring μ-like | up-going μ



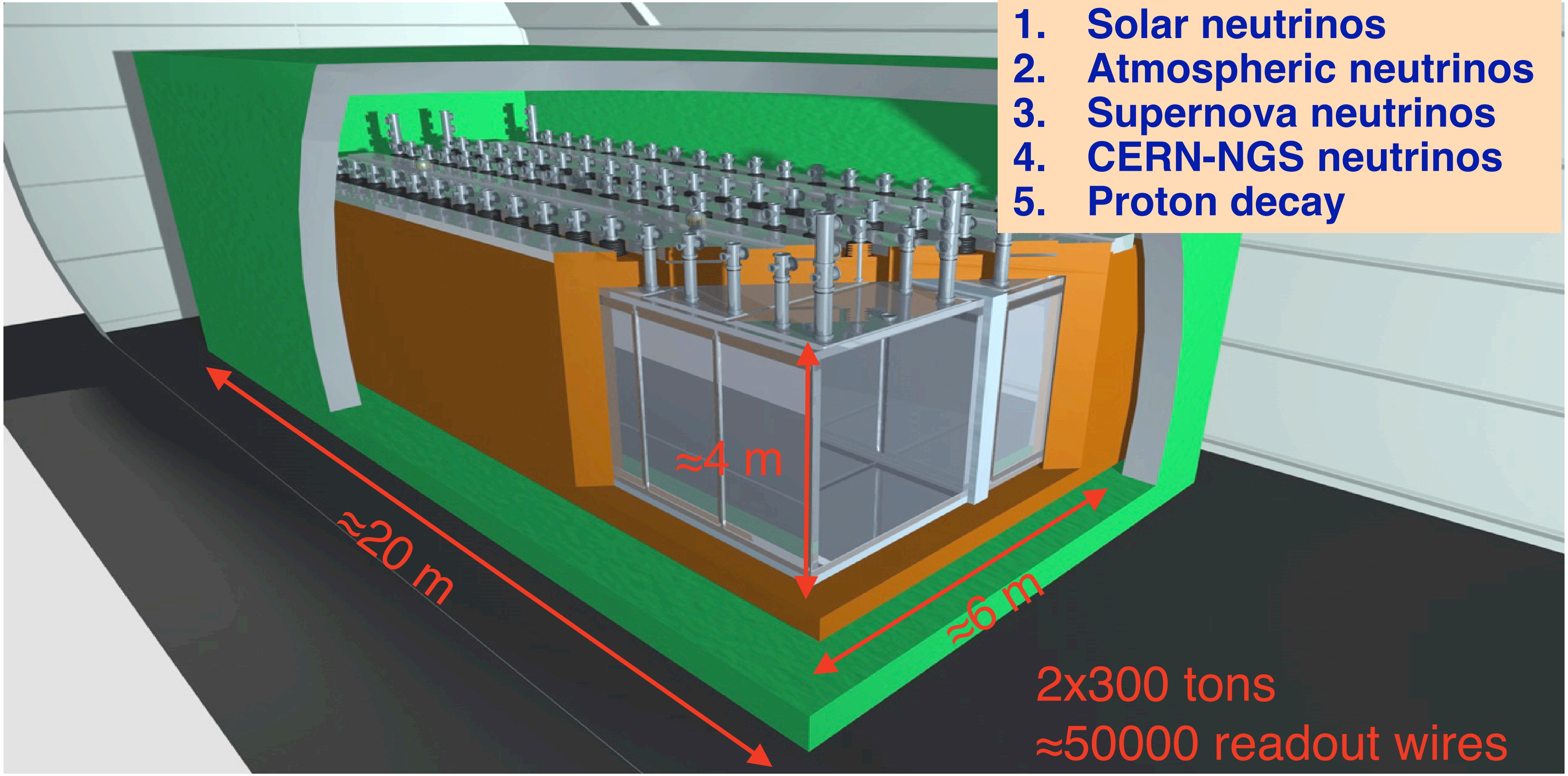
Up-going Down-going

ETH Institute for Particle Physics

ICARUS detector @ Gran Sasso

<u>Novel</u> liquid Argon imaging TPC technique: Initial mass 0.6 kton

1. **Solar neutrinos**
2. **Atmospheric neutrinos**
3. **Supernova neutrinos**
4. **CERN-NGS neutrinos**
5. **Proton decay**



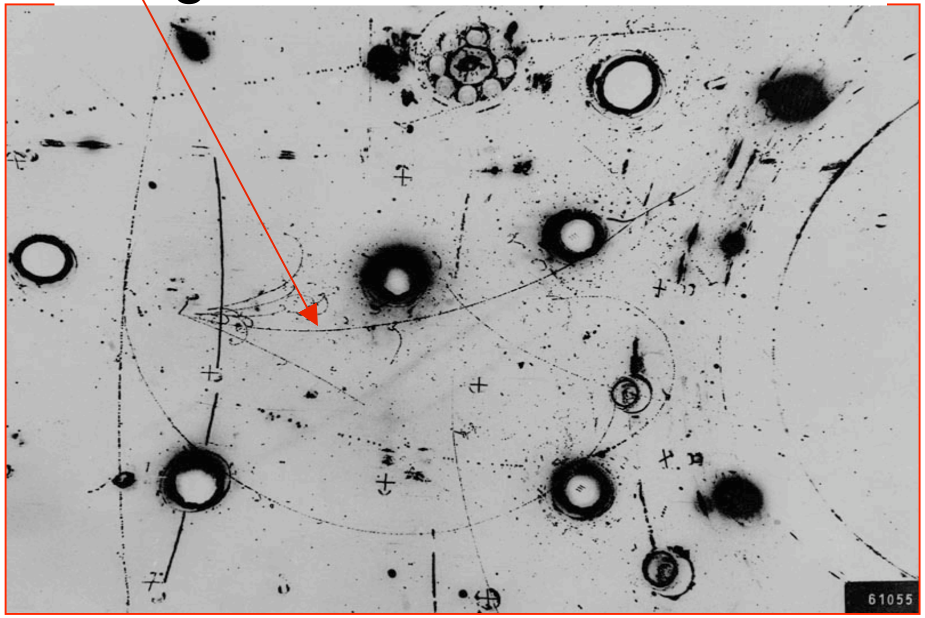
Planned start data taking in middle 2005

Electronic bubble chamber

Bubble diameter ≈ 3 mm (diffraction limited)

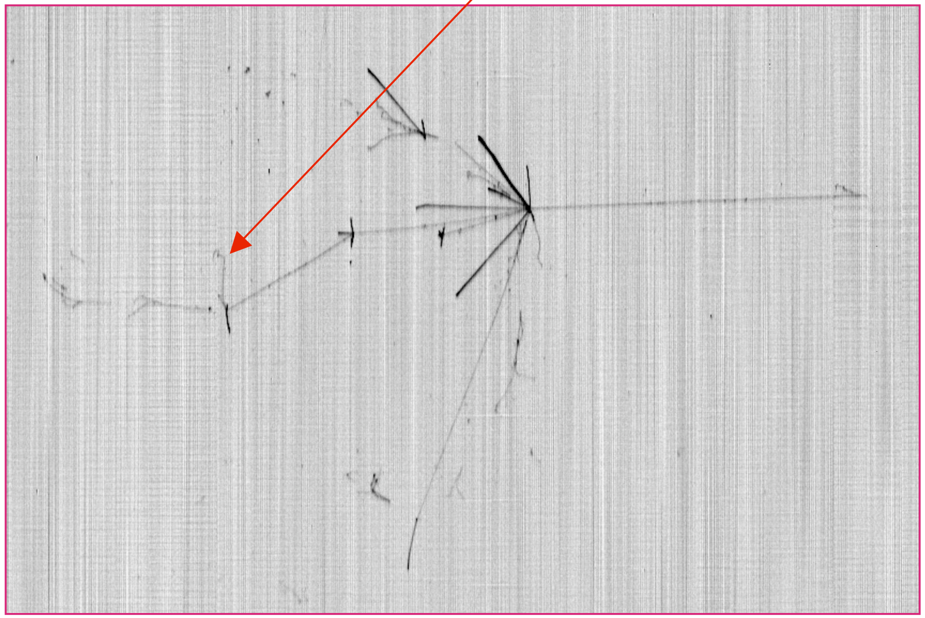
Bubble size ≈ 3x3x0.2 mm^3

Gargamelle bubble chamber



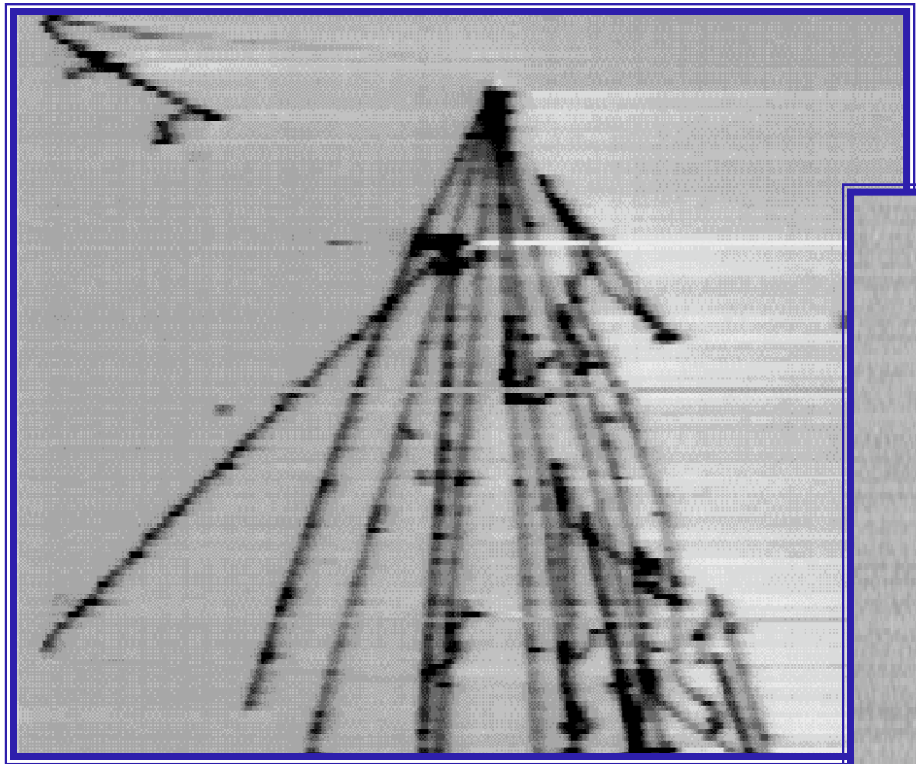
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

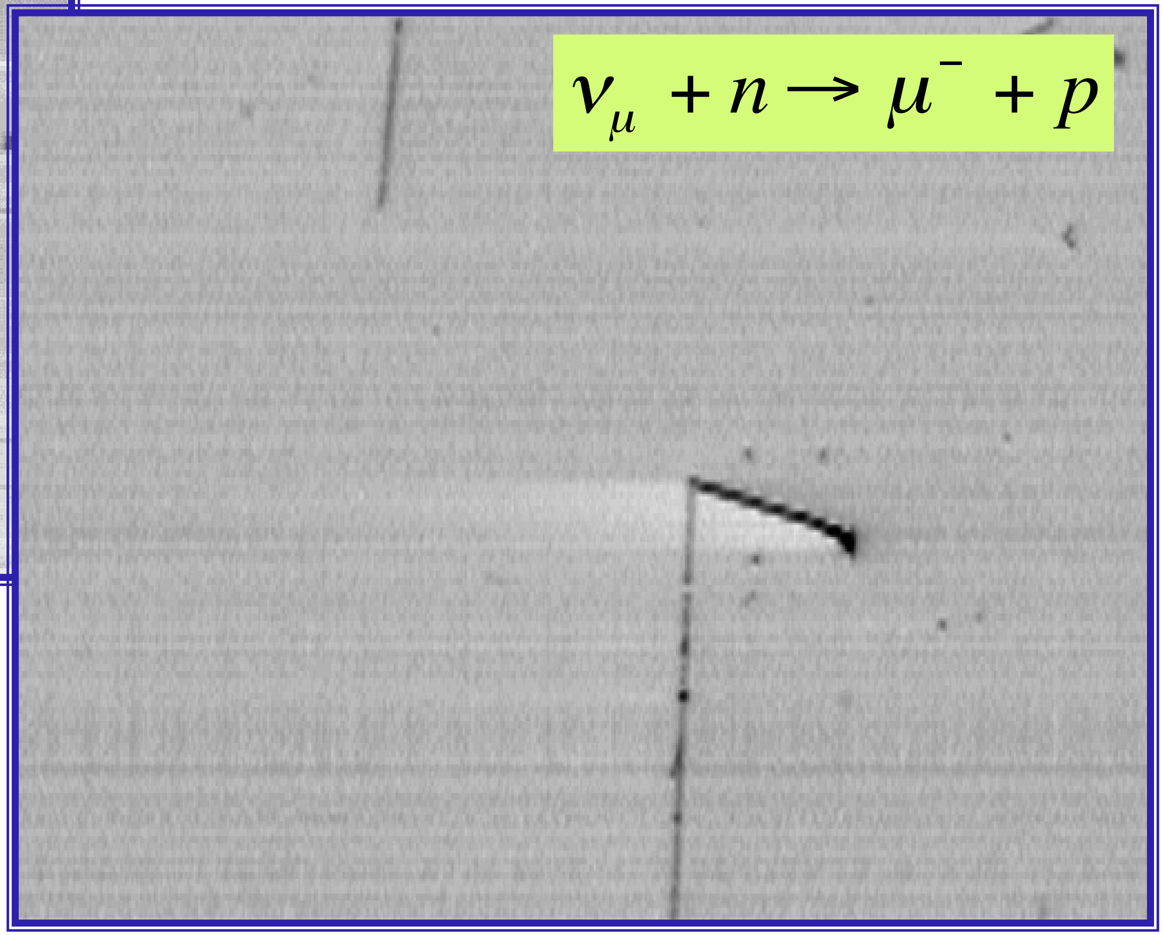
ICARUS electronic chamber



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

Prototype in CERN WA neutrino beam



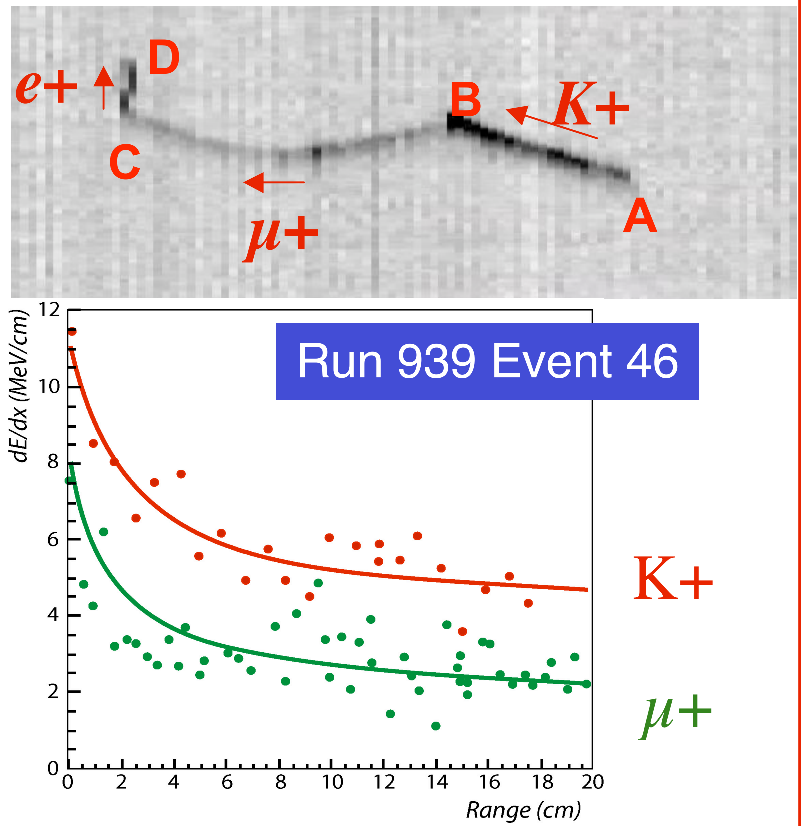


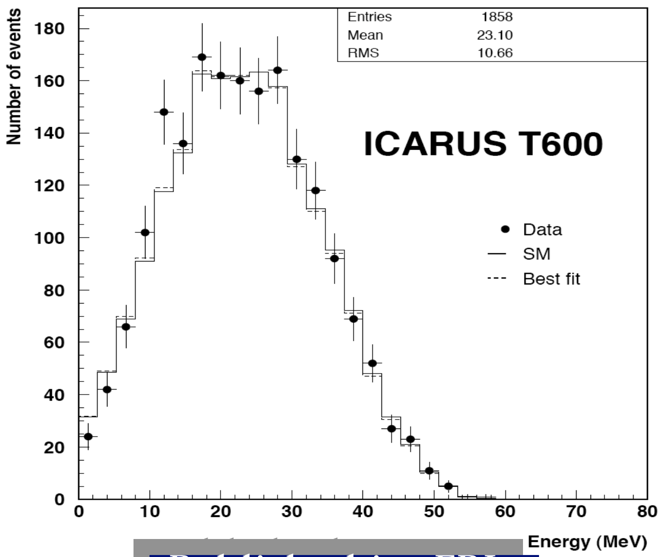
Excellent tracking
also near vertex

Liquid Argon TPC 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

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



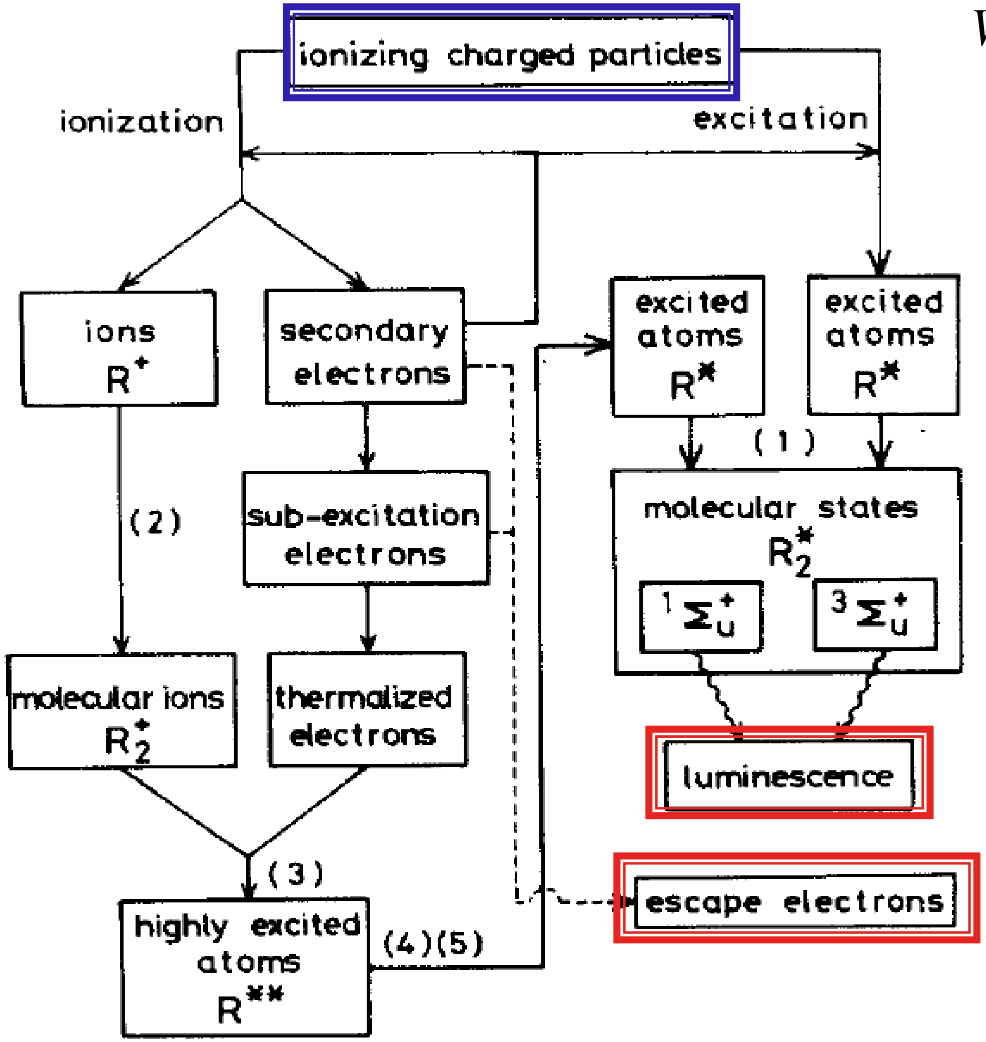


Published in EPJ

RESOLUTIONS

Low energy electrons:	$\sigma(E)/E = 11\% / \sqrt{E(MeV)} + 2\%$
Electromagn. showers:	$\sigma(E)/E = 3\% / \sqrt{E(GeV)}$
Hadron shower (pure LAr):	$\sigma(E)/E \approx 30\% / \sqrt{E(GeV)}$
Hadron shower (+TMG):	$\sigma(E)/E \approx 17\% / \sqrt{E(GeV)}$

Processes induced by charged particles



M. Suzuki et al., NIM 192 (1982) 565

When a charged particle traverses medium:

- **Ionization process**
- **Scintillation (luminescence)**
  - ➥ UV spectrum (λ=128 mn)
  - ➥ Not energetic enough to further ionize, hence, argon is transparent
  - ➥ Rayleigh-scattering
- **Cerenkov light (if fast particle)**

→ *UV light*

→ *Charge*

→ *Cerenkov light (if β>1/n)*

ETH Institute for Particle Physics

Comparison rare gases

		LAr	LKr	LXe
Density	*g/cm³*	1.39	2.45	3.06
dE/dx	*MeV/cm*	2.11	3.45	3.89
I	*eV*	15.76	14.00	12.13
$W_{e\text{-}ion}$	*eV*	23.6±0.3	20.5±1.5	15.6±0.3
W_{γ}	*eV*	19.5	20 (15 for α)	14.7
Scintillation photons/MeV	*photons*	≈50000	≈50000	≈70000
Decay const	*ns*	6(23%), 1600(77%)	2(1%),85(99%)	2(77%),30(33%)
Scintillation peak	*nm*	128	147	174
Rayleigh scattering length for scintillation	*cm*	≈90	≈60	≈30

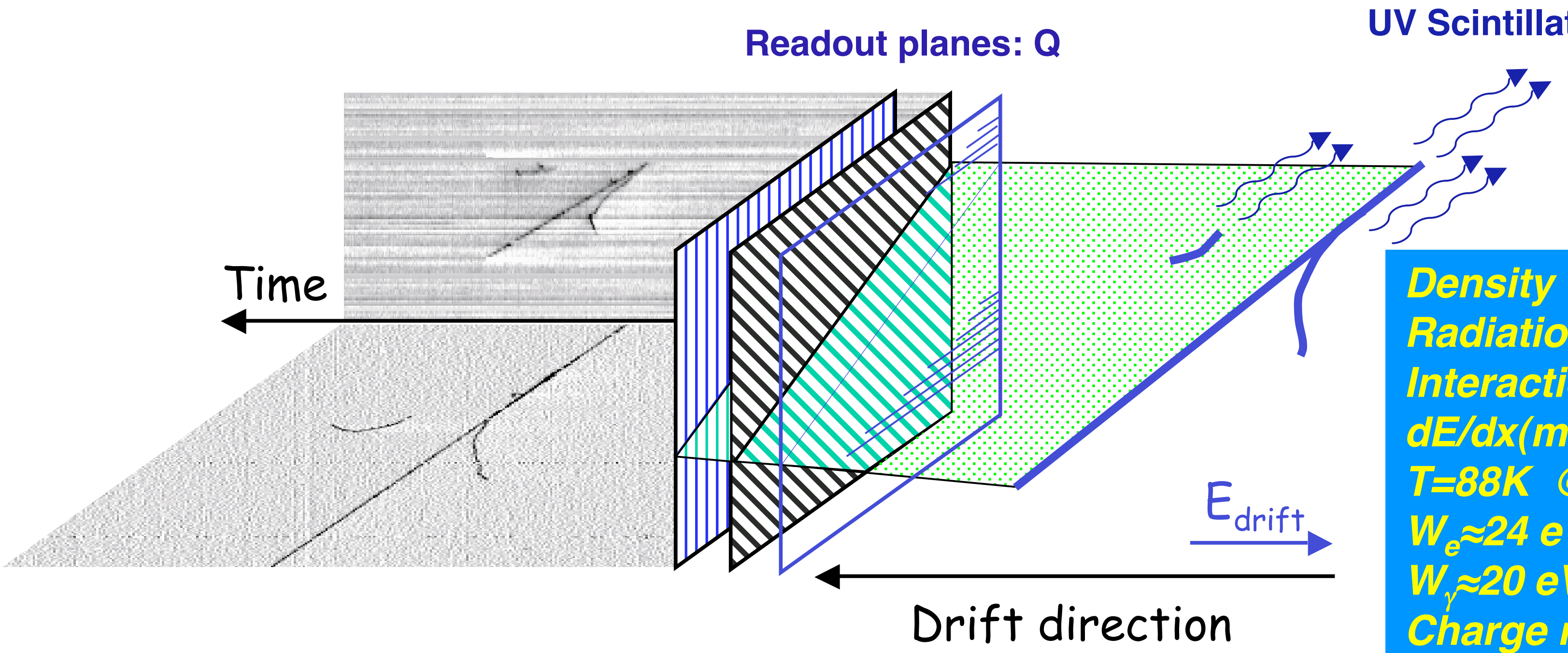
Liquefied rare gases TPC: basic ideas

- **Ideal materials for detection of ionizing tracks:**
  - ➥ Dense (≈g/cm^3 ≈ 10^3 x ρ_{gas}), homogeneous, target and detector
  - ➥ Do not attach electrons (⇒ long drift paths possible in liquid phase)
  - ➥ High electron mobility (≈quasi-free drift electrons, not neon)
  - ➥ Commercially easy to obtain (in particular, liquid Argon)
  - ➥ Can be made very pure and many impurities freeze out at low temperature
  - ➥ Inert, not flammable

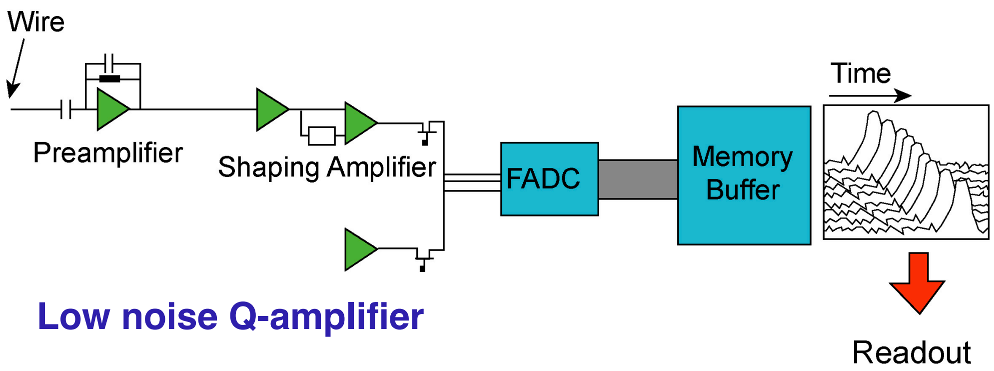
Type	Density (ρ/cm^3)	Energy loss dE/dx (MeV/cm)	Radiation length X_0 (cm)	Collision length λ (cm)	Boiling point @ 1 bar (K)	Electron mobility (cm^2/Vs)	
Neon	1.2	1.4	24	80	27.1	high&low	
Argon	1.4	2.1	14	80	87.3	500	€
Krypton	2.4	3.0	4.9	29	120	1200	€€
Xenon	3.0	3.8	2.8	34	165	2200	€€€

ETH Institute for Particle Physics

The Liquid Argon TPC



Density 1.4 g/cm³
Radiation length 14 cm
Interaction length 80 cm
dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar
W_e≈24 eV
W_γ≈20 eV
Charge recombination (mip) @ E = 500 V/cm ≈ 40%

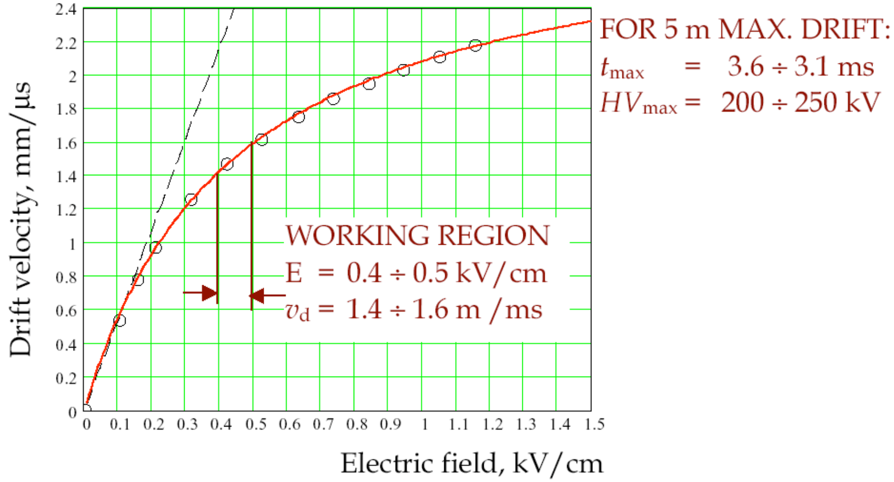


Low noise Q-amplifier

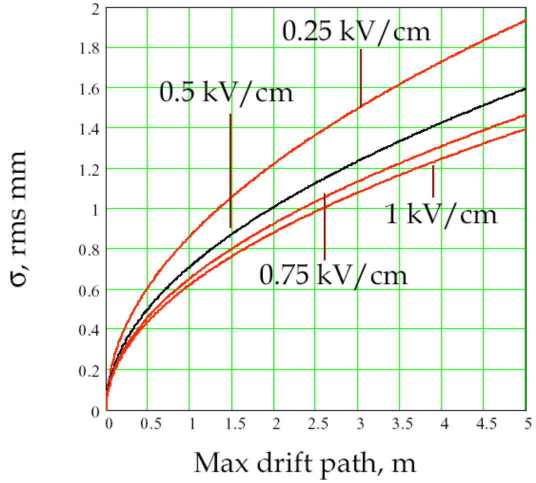
Continuous waveform recording

- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T_0

Electron drift properties in liquid Argon



Drift velocity versus electric field in liquid argon



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

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

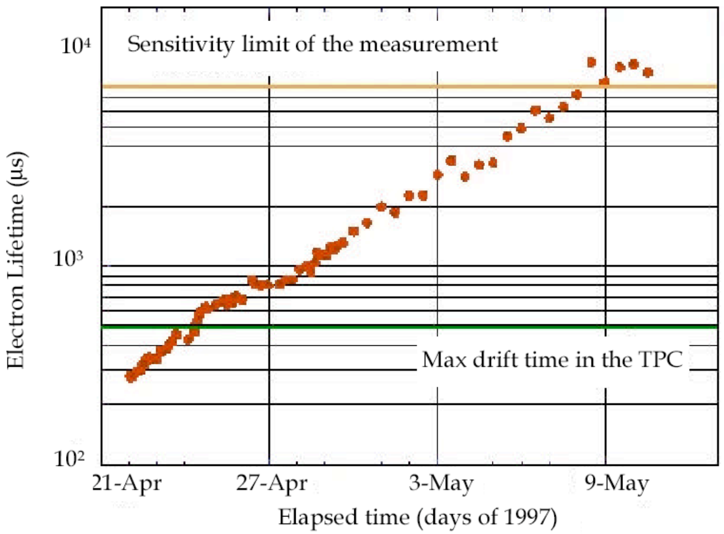
$D = 4.06\ cm^2/s$

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

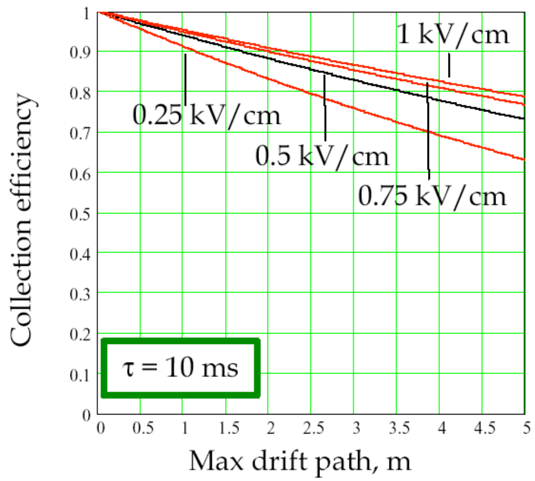
Longitudinal rms diffusion spread at 0.5 kV/cm

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

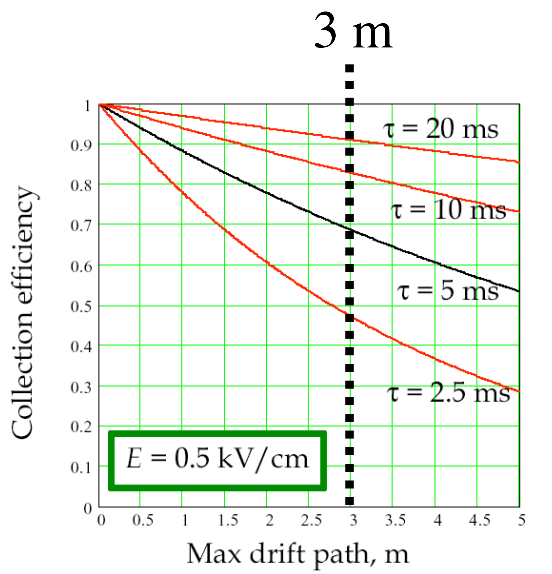
Maximum σ_{Dmax} = 1.6 mm



Purification rate for the 50L TPC

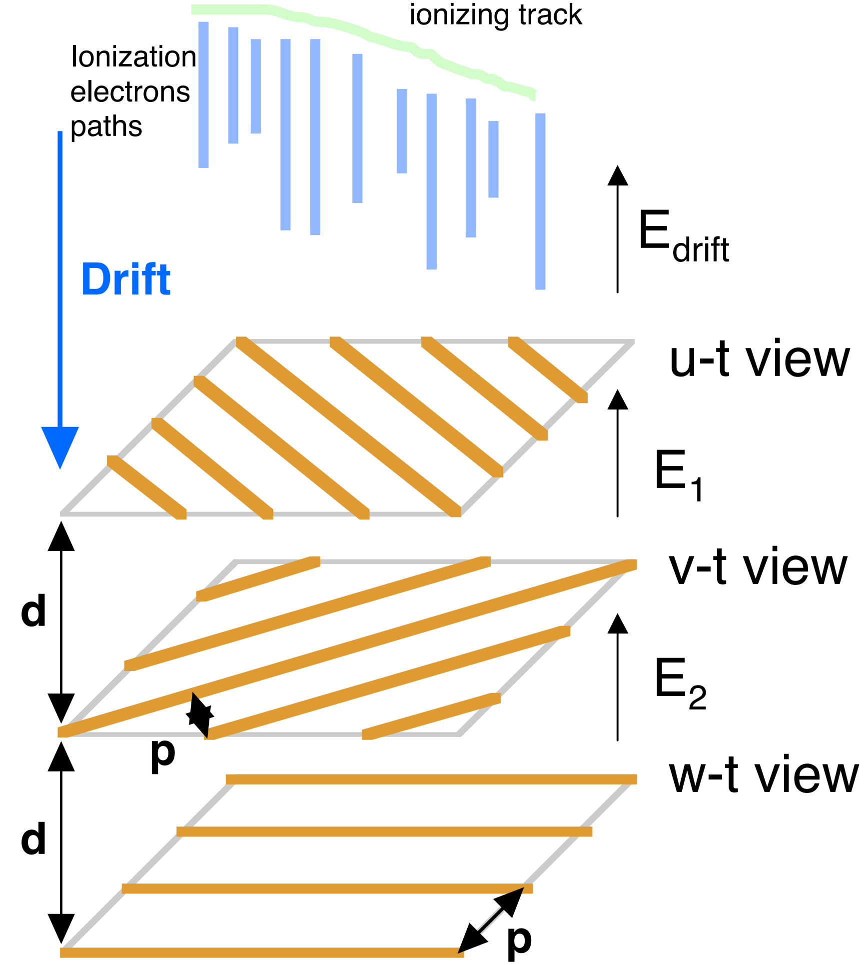


Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



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

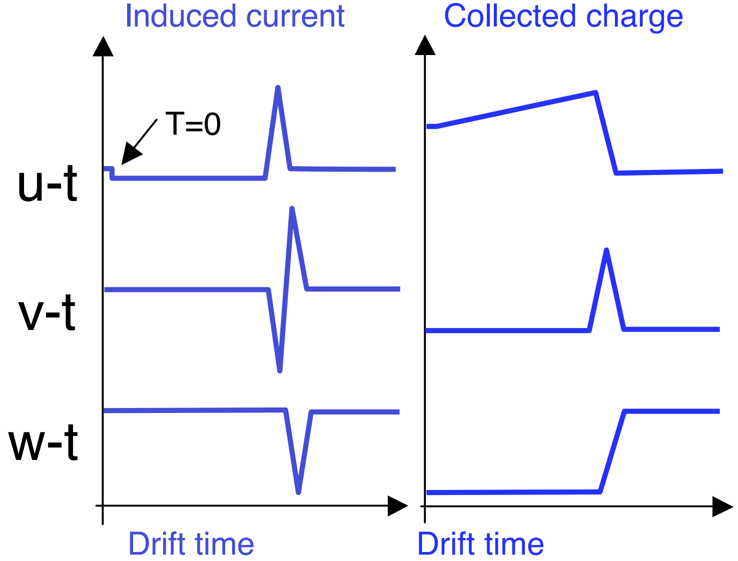
Non destructive charge readout



Yield ~ 6000 electrons/mm
≈1 fC/mm

In the ICARUS T600

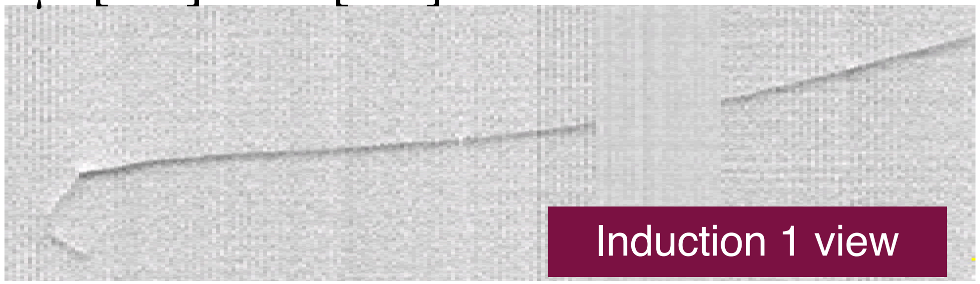
E_{drift} = 500 V/cm
p = 3 mm
d = 3 mm
r = 0.1mm

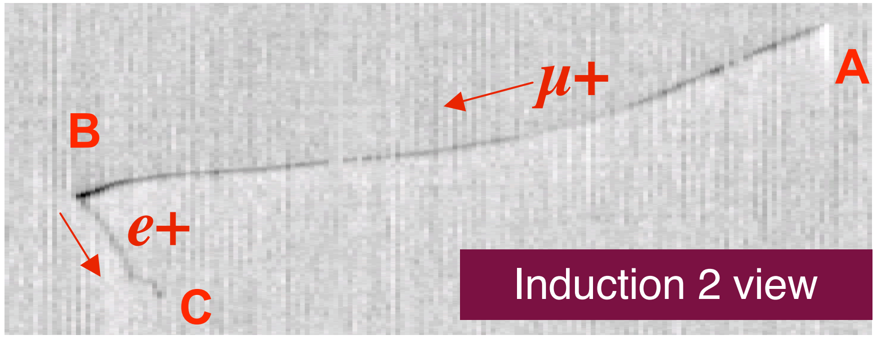


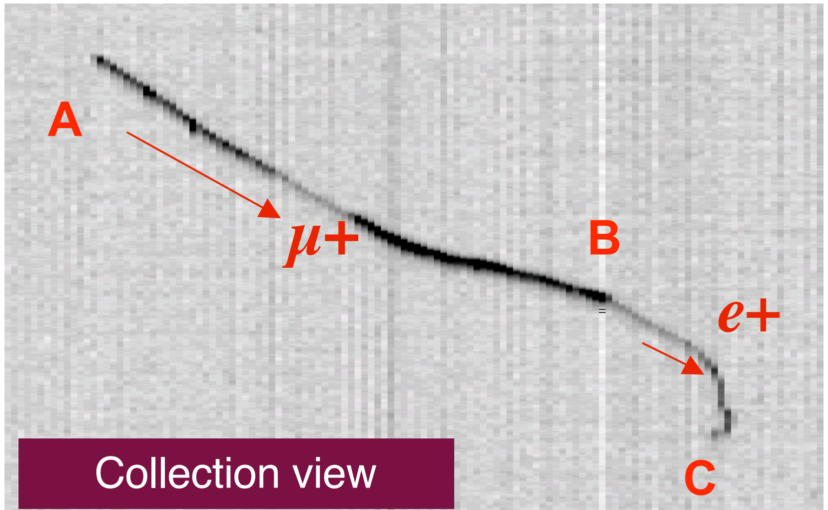
Planes can be combined offline to reconstruct 3D view of event

3D reconstruction stopping muon

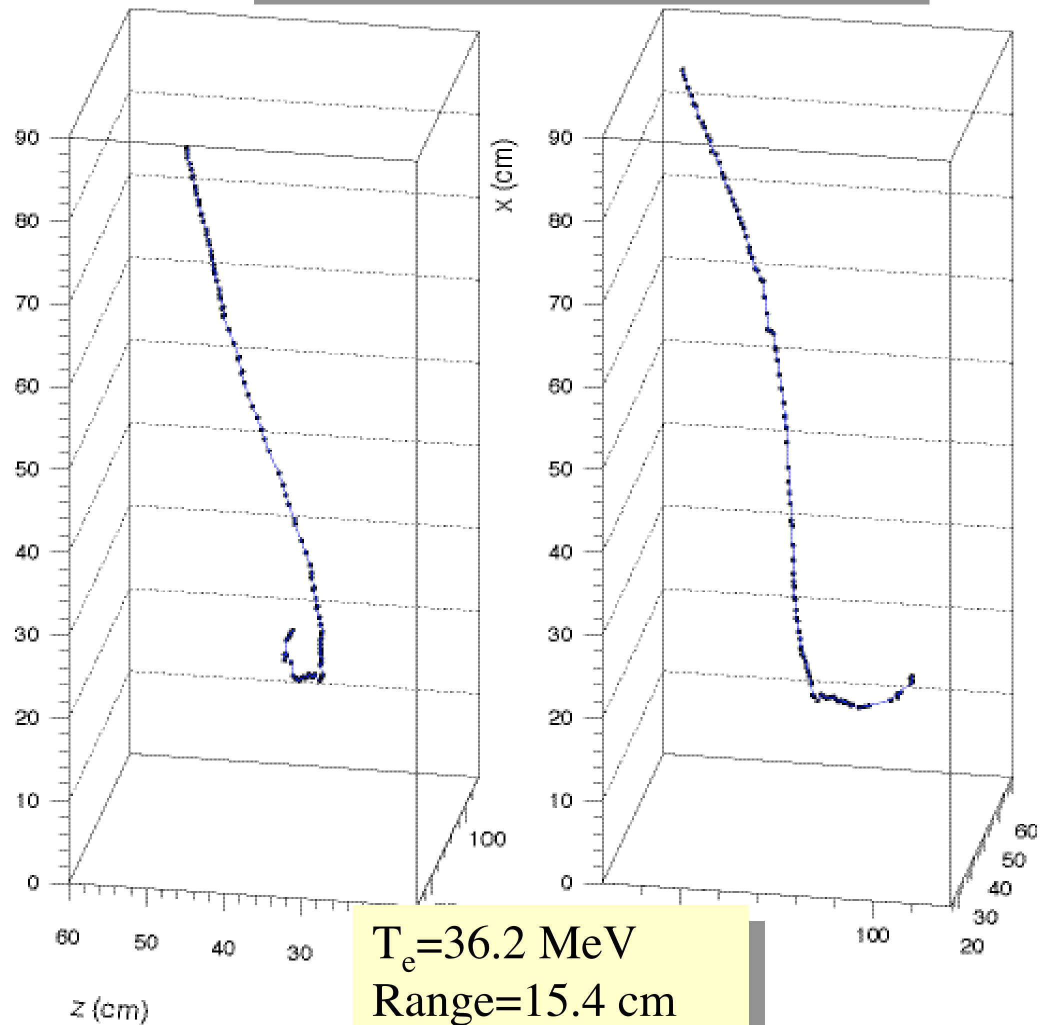
$\mu^+[AB] \rightarrow e^+[BC]$





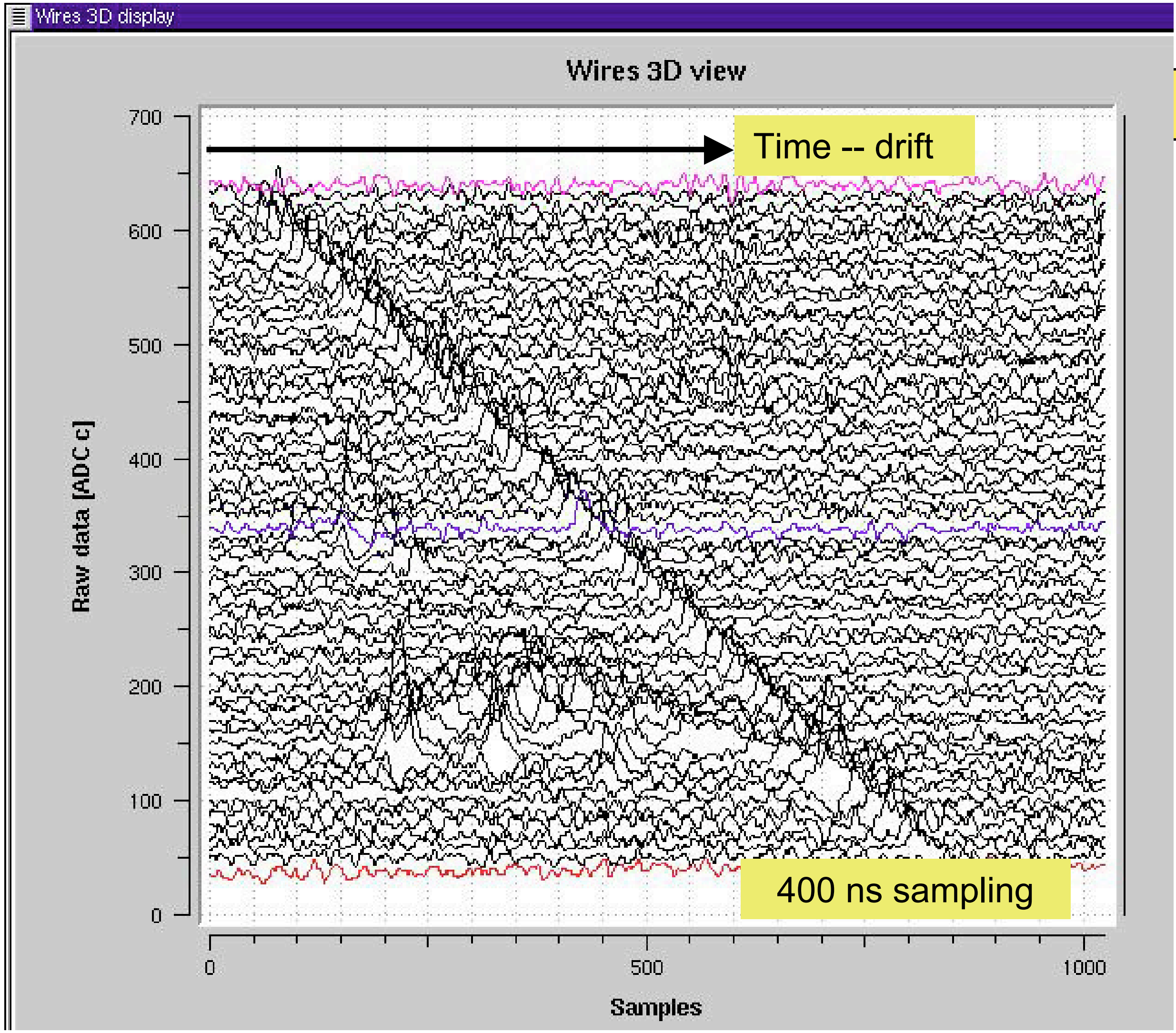


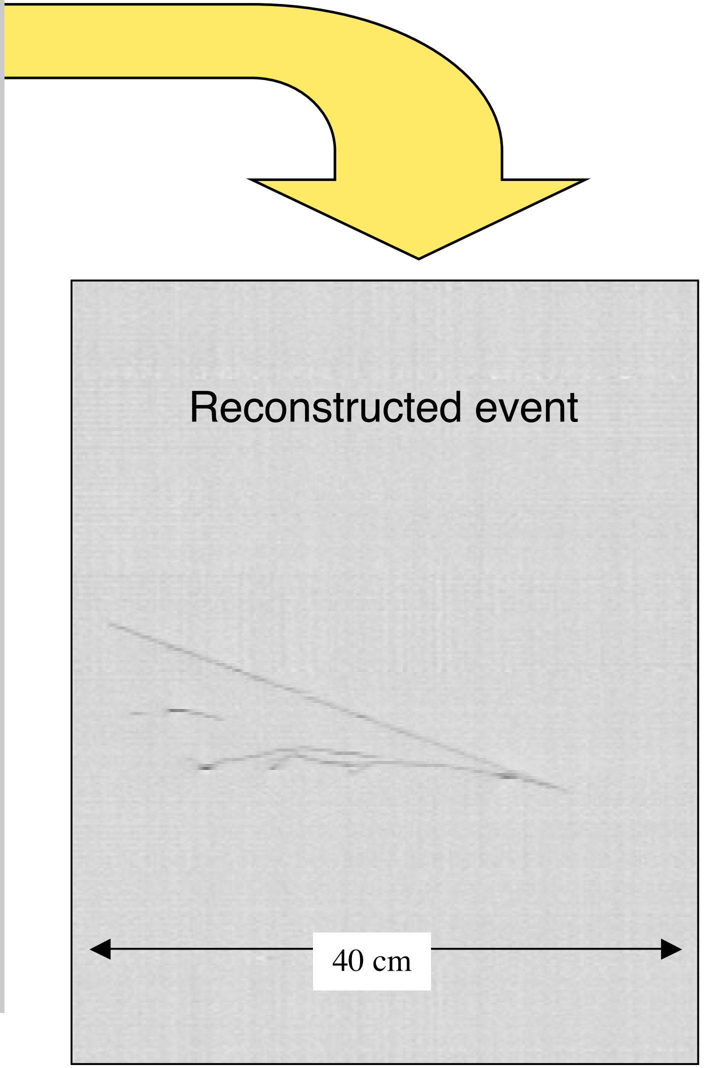
Run 939 Event 95 Right chamber



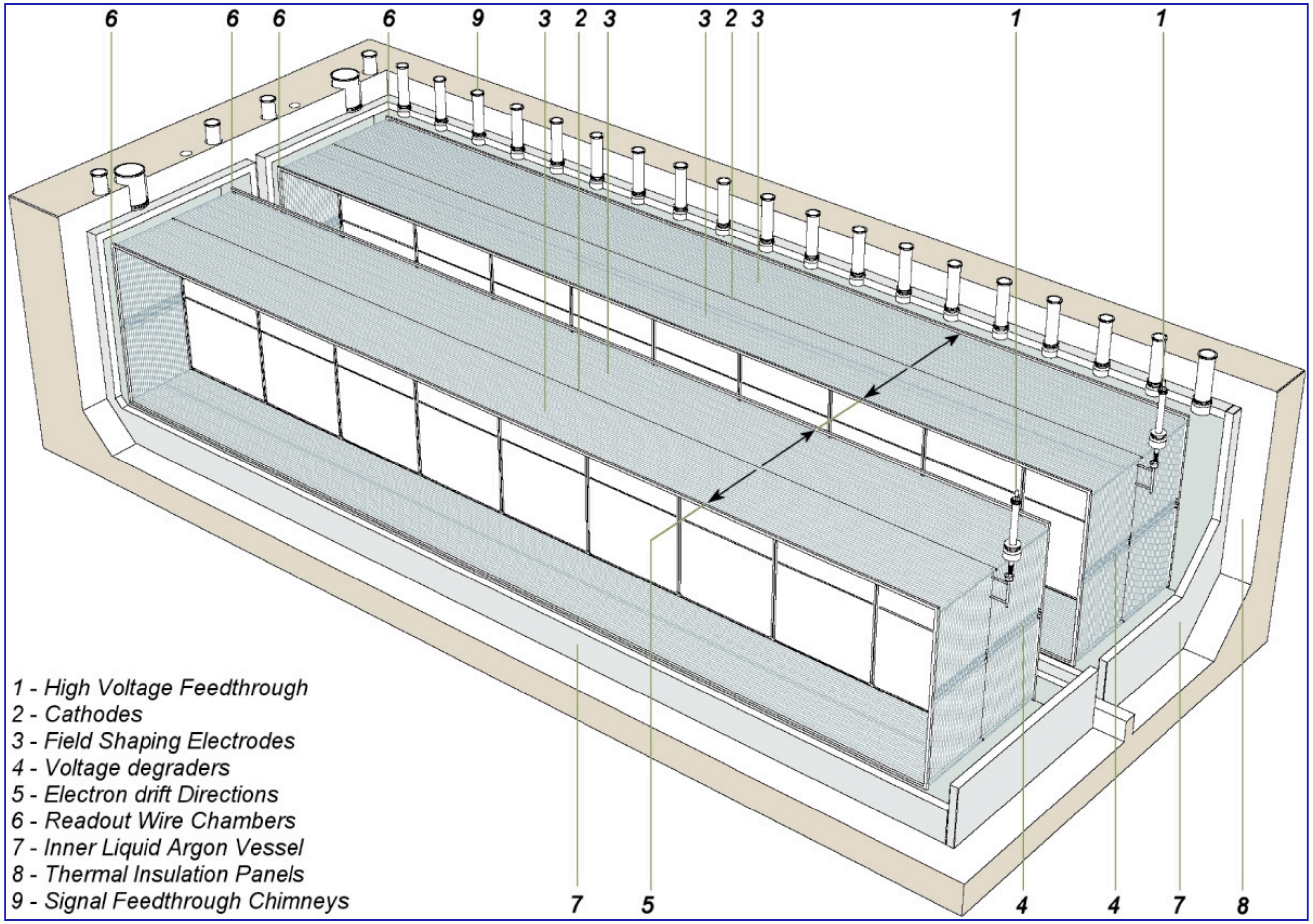
T_e=36.2 MeV
Range=15.4 cm

Principle of signal recording





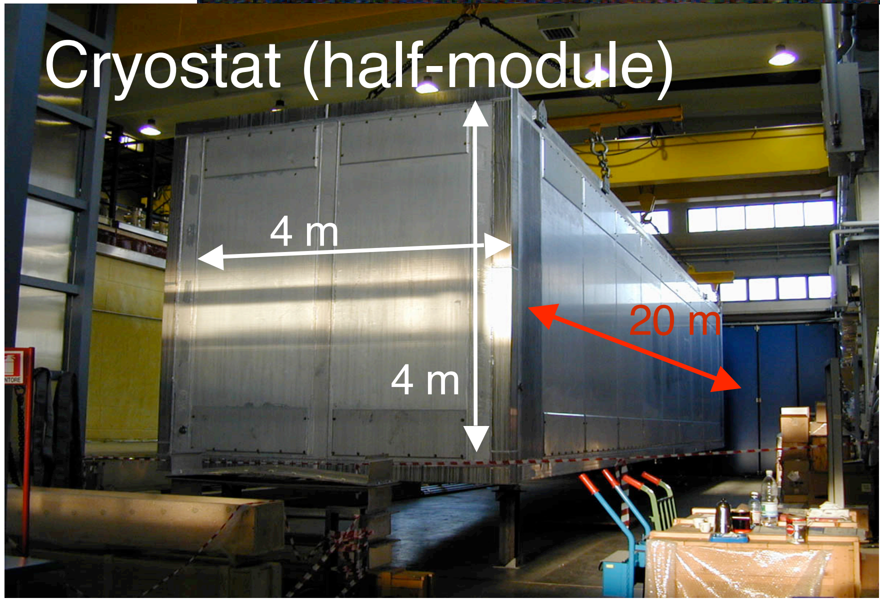
The "first unit": T600 = 2 x T300

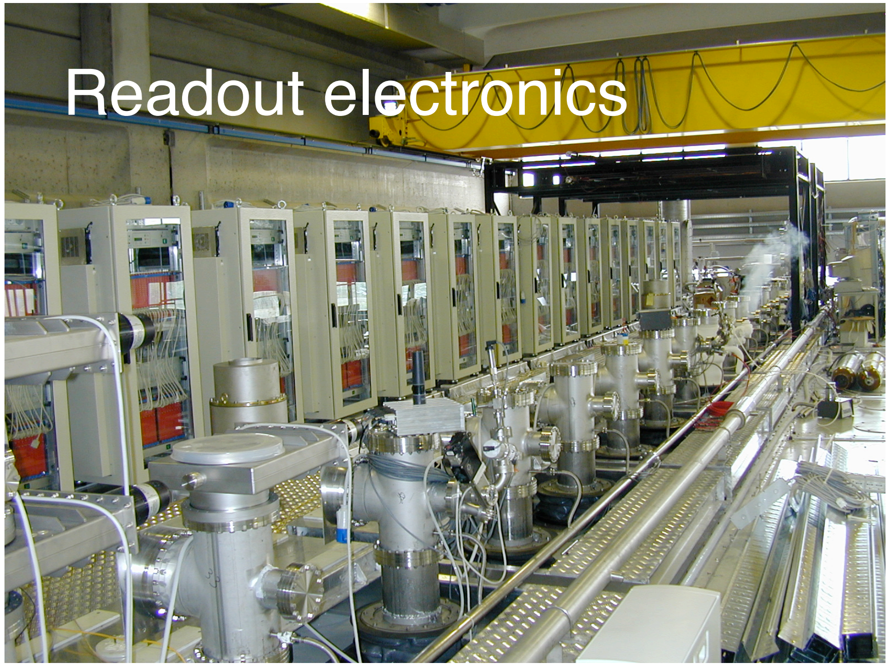


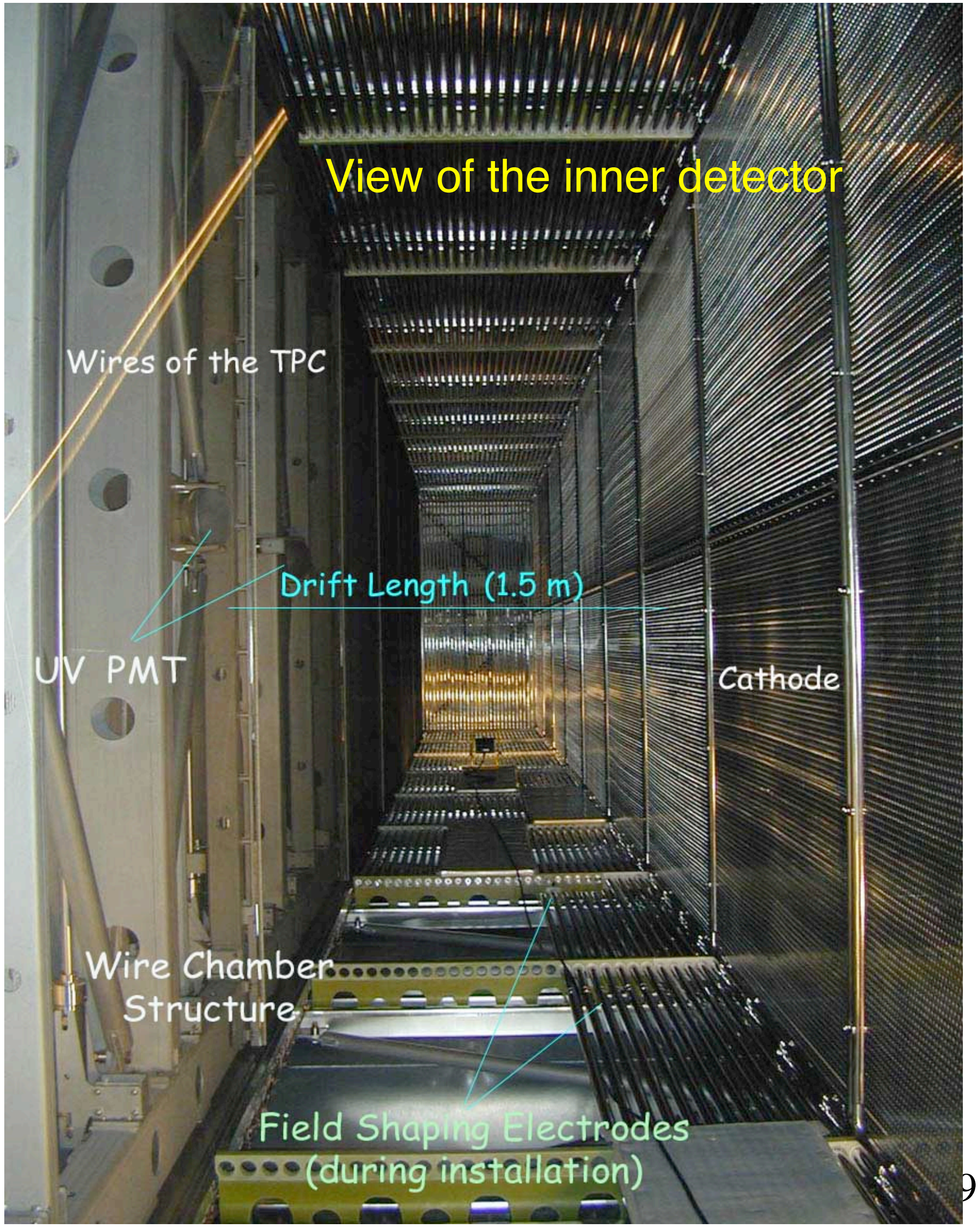
- **Two separate containers**
  - ➥inner volume/cont. = **3.6 x 3.9 x 19.6 m^3**
- **SENSITIVE MASS = 476 TON**
- **4 wire chambers with 3 readout planes at 0°, ±60° (two chambers / container)**
  - ➥≈ **54000 WIRES** (None broke during test)
- **Maximum drift = 1.5 m**
  - ➥HV = -75 kV @ 0.5 kV/cm
- **SCINTILLATION LIGHT READOUT with 8" VUV sensitive PMTs**

Design, construction and tests of the ICARUS T600 detector.
To appear on N.I.M.

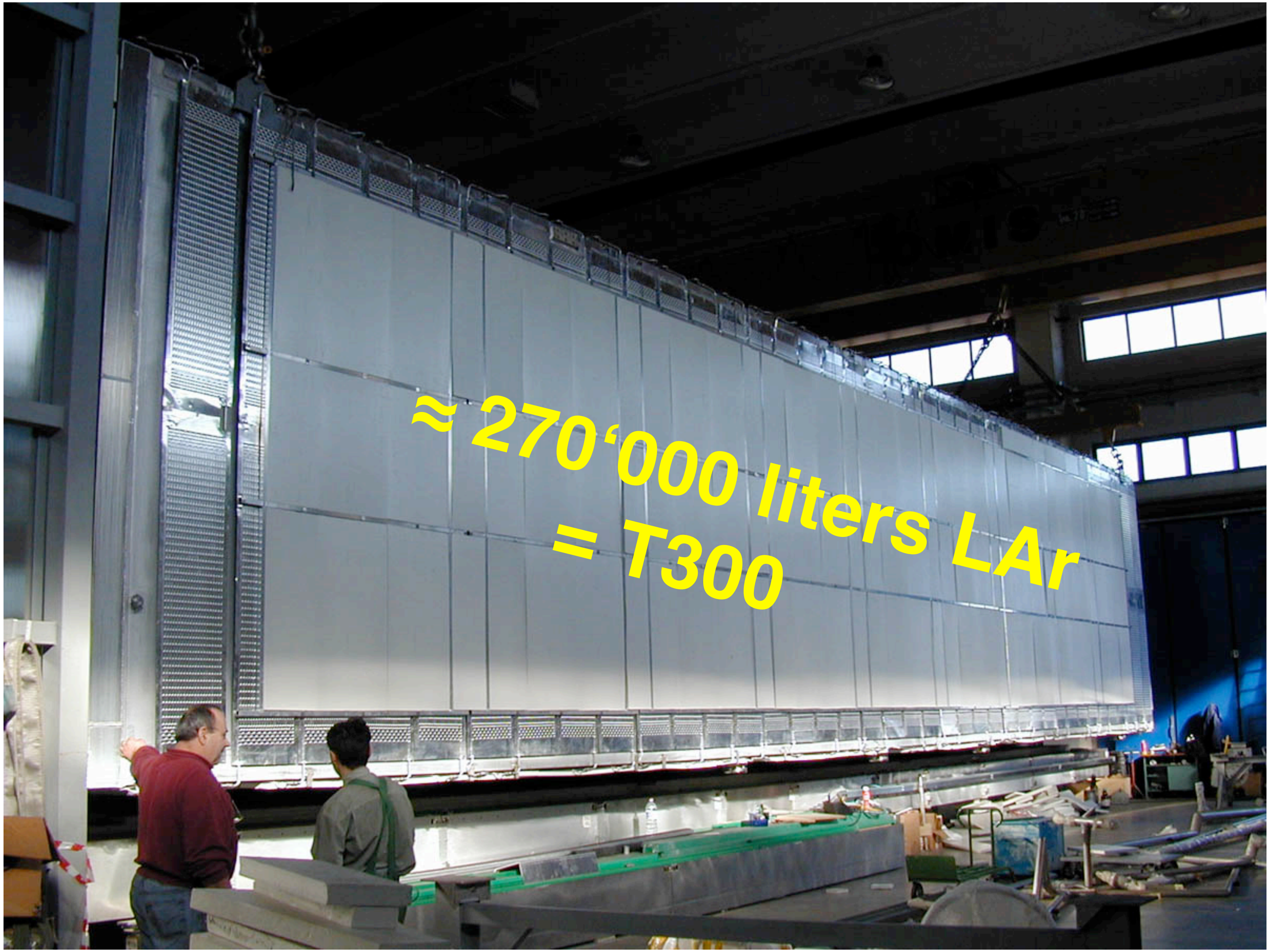
ICARUS T300 prototype







First T300 cryostat during construction (2001)

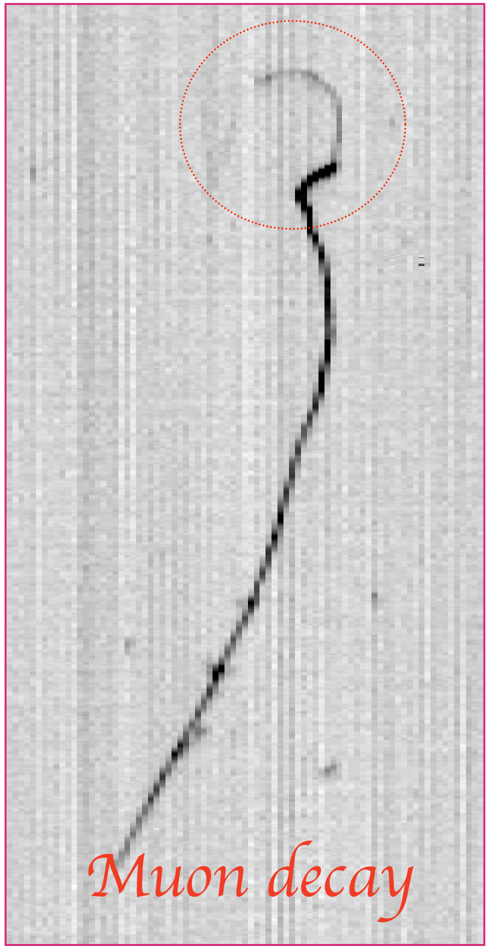


Cosmic rays events

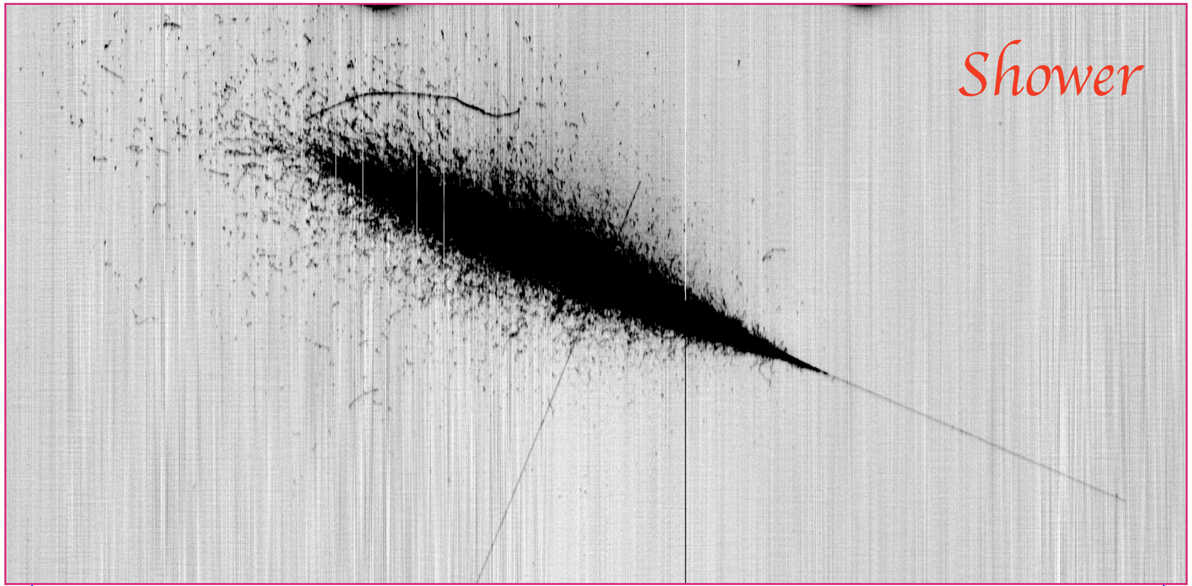
ETH Institute for Particle Physics

25 cm

85 cm



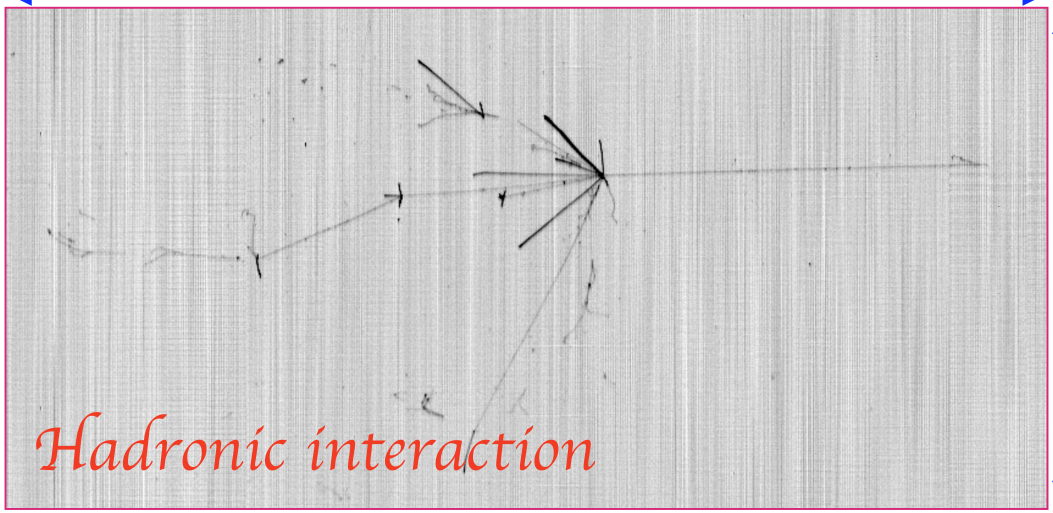
Run 960, Event 4 Collection Left



176 cm

434 cm

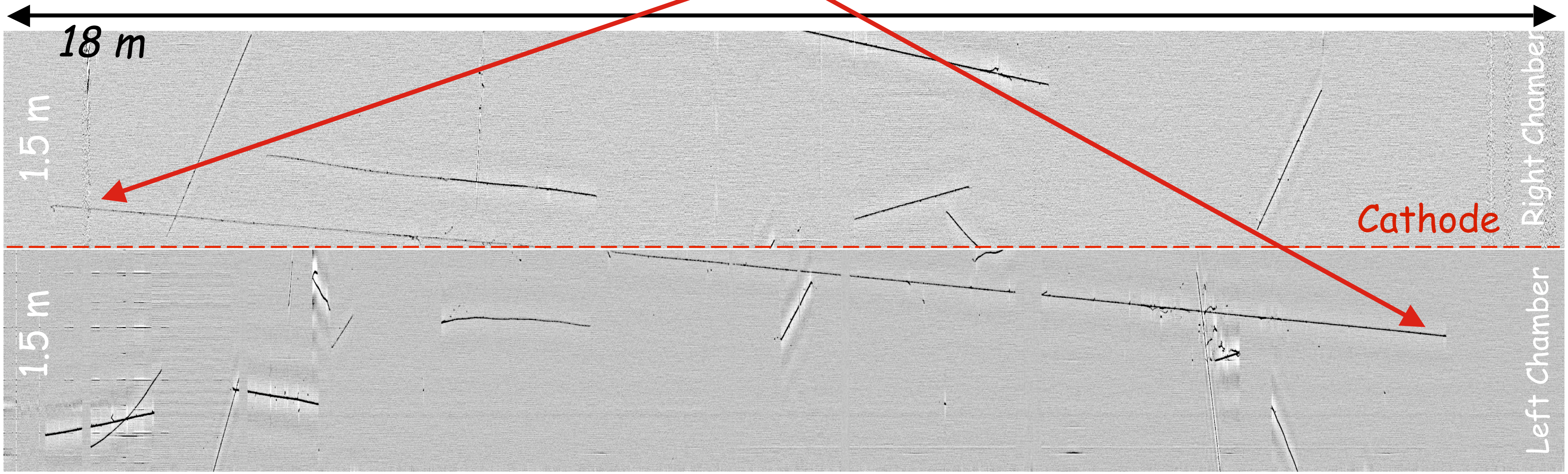
265 cm

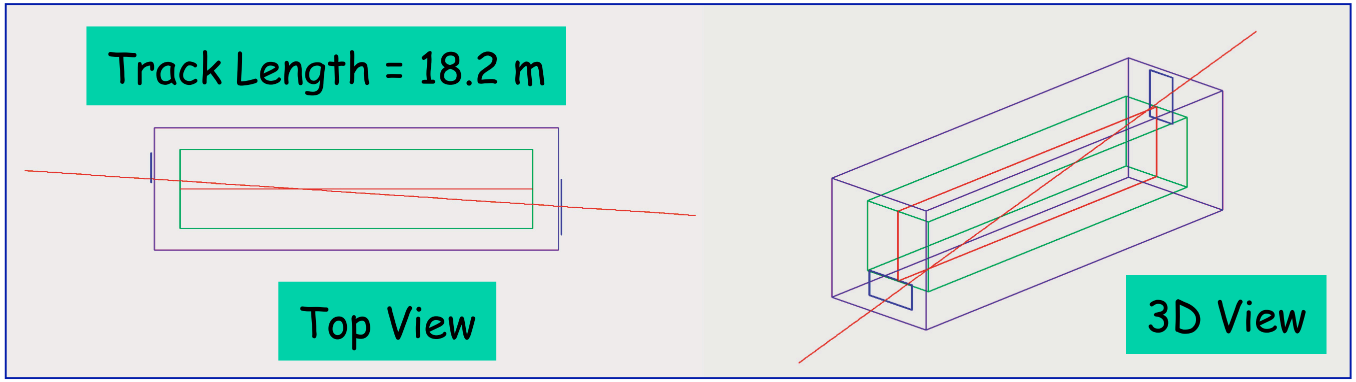


142 cm

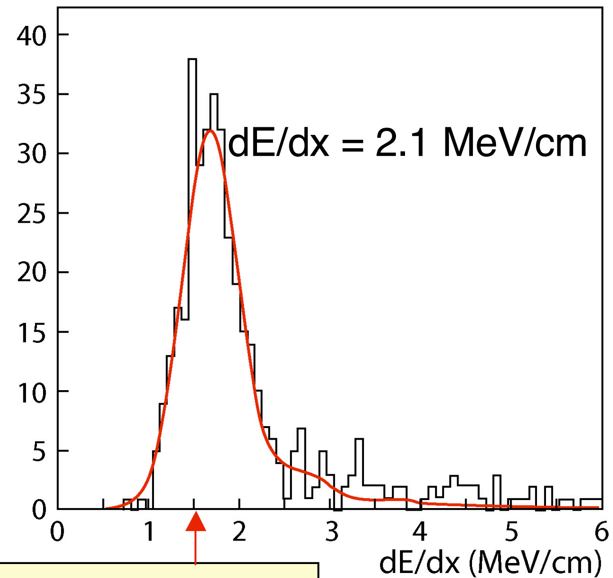
Run 308, Event 160 Collection Left

Long longitudinal muon track crossing the cathode plane



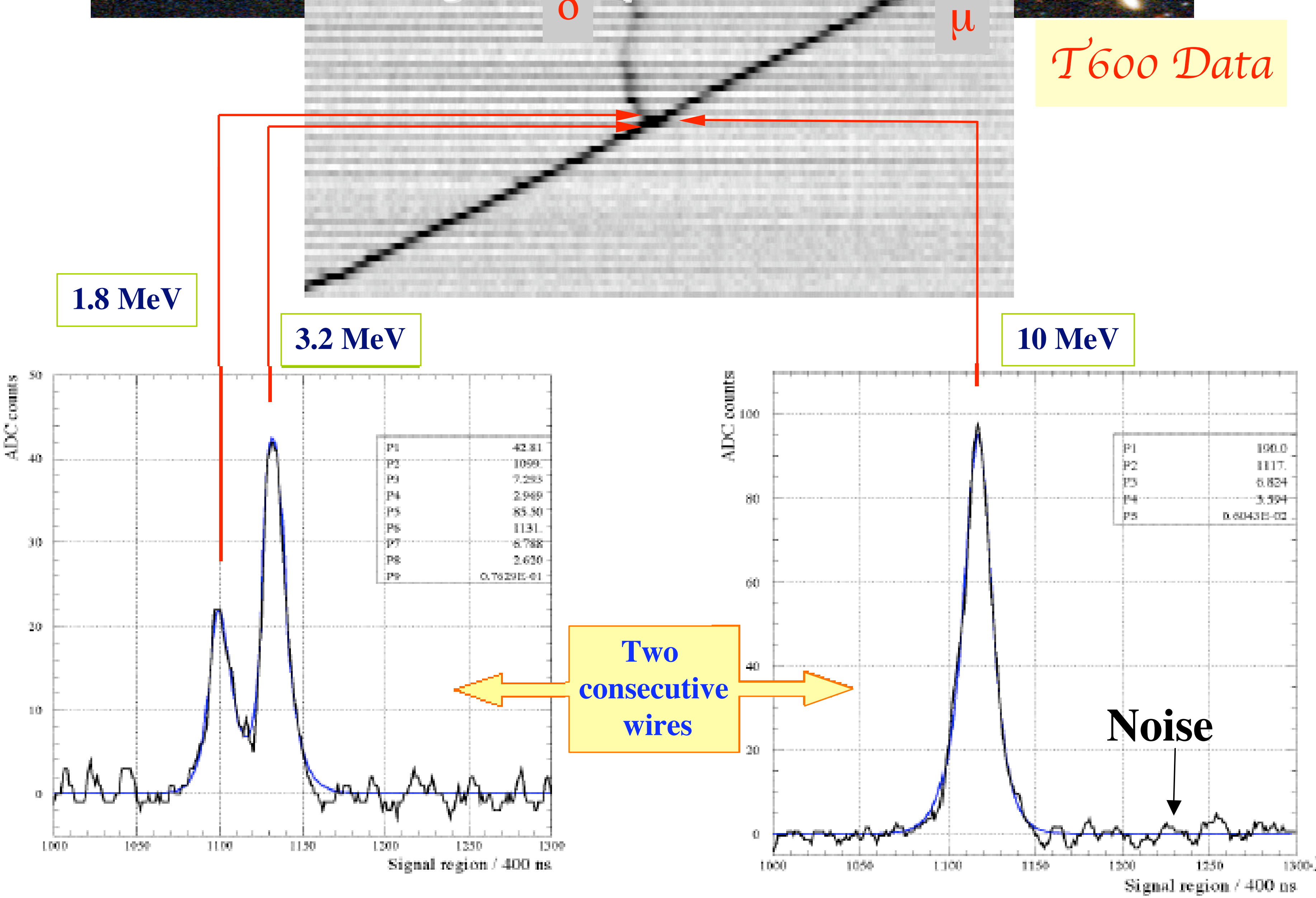


3-D reconstruction of the long track



dE/dx distribution along the track

Single wire performance



Threshold above noise ≈ 200 KeV

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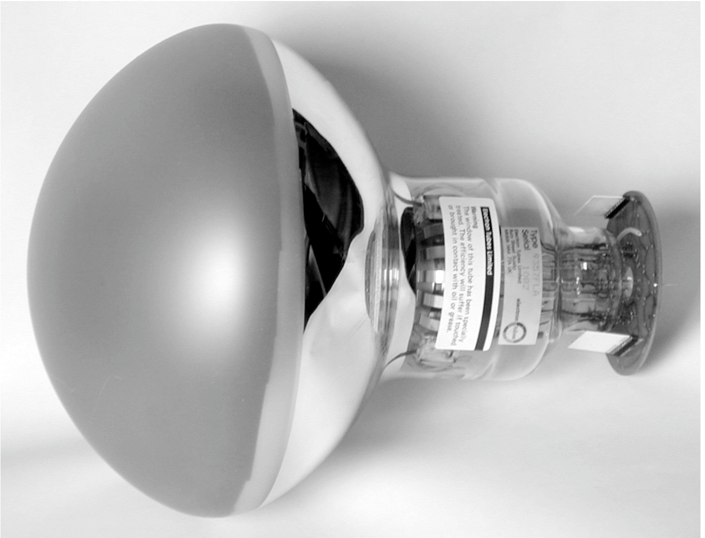
Scintillation light readout

- Commercial PMT with large area
  - ➥Glass-window
- Scintillation VUV $\lambda = 128$ nm
  - ➥Wavelength-shifter
- Immersed T(LAr) = 87 K



Electron Tubes 9357FLA

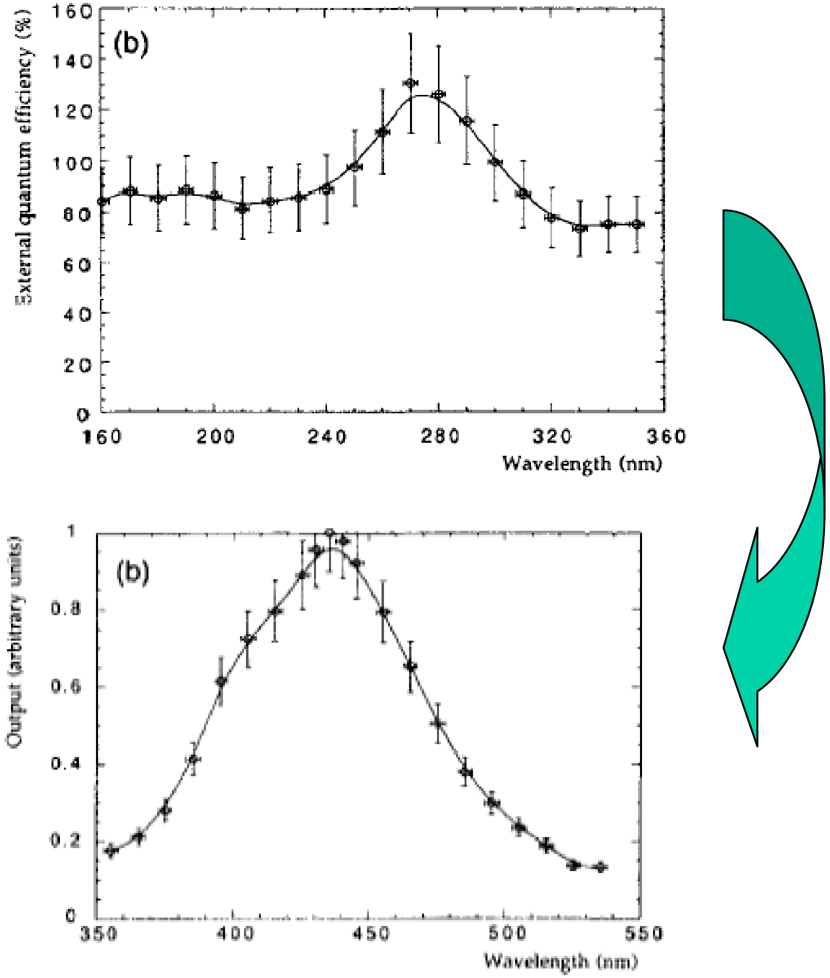
8” PMT (bialkali with Pt deposit)

G = 1 x 10^7 @ ~1400 V

peak Q.E. (400-420 nm) ~ 18 % (≈10% cold)

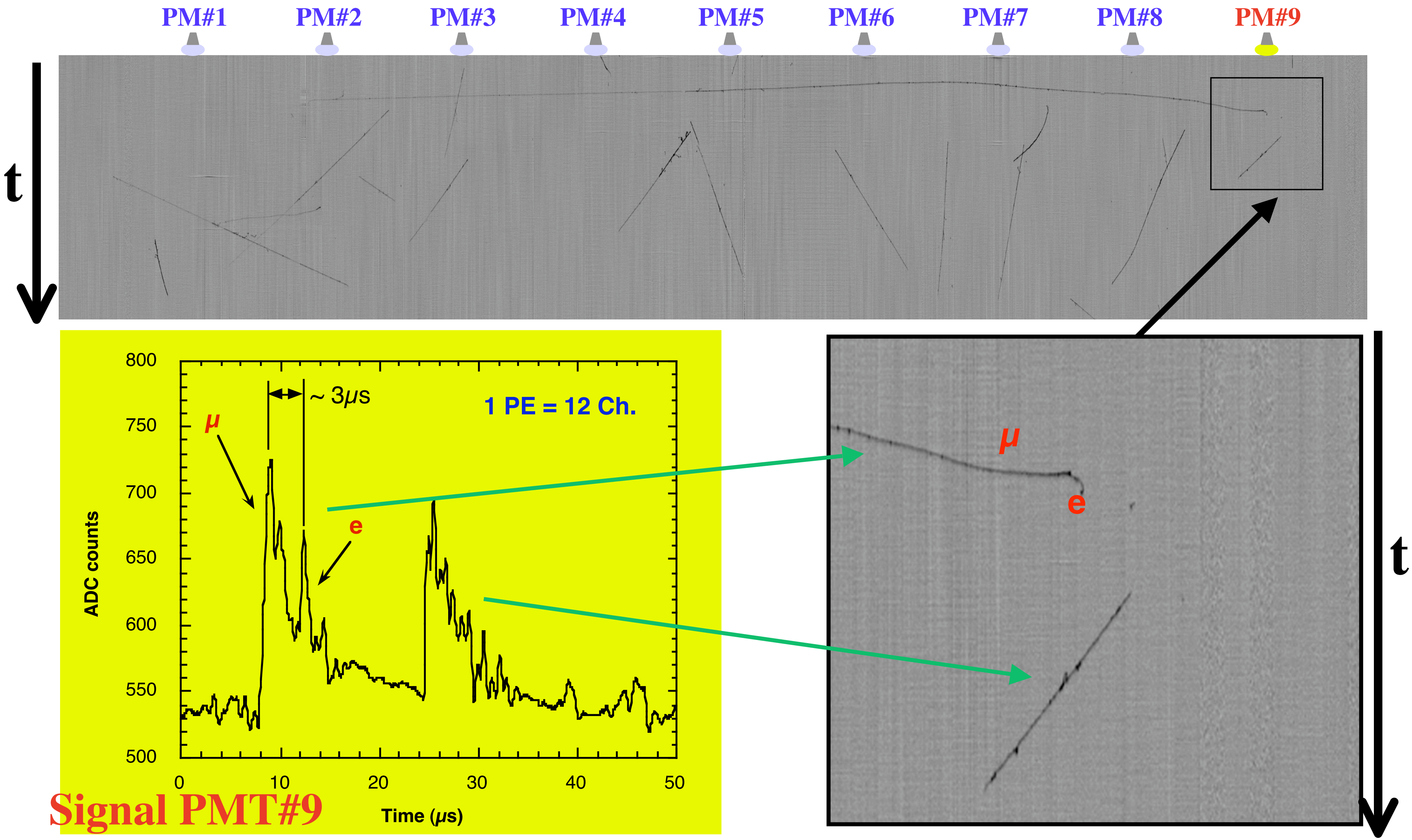
T_{rise} ~ 5 ns, FWHM ~ 8 ns

TPB as WLS

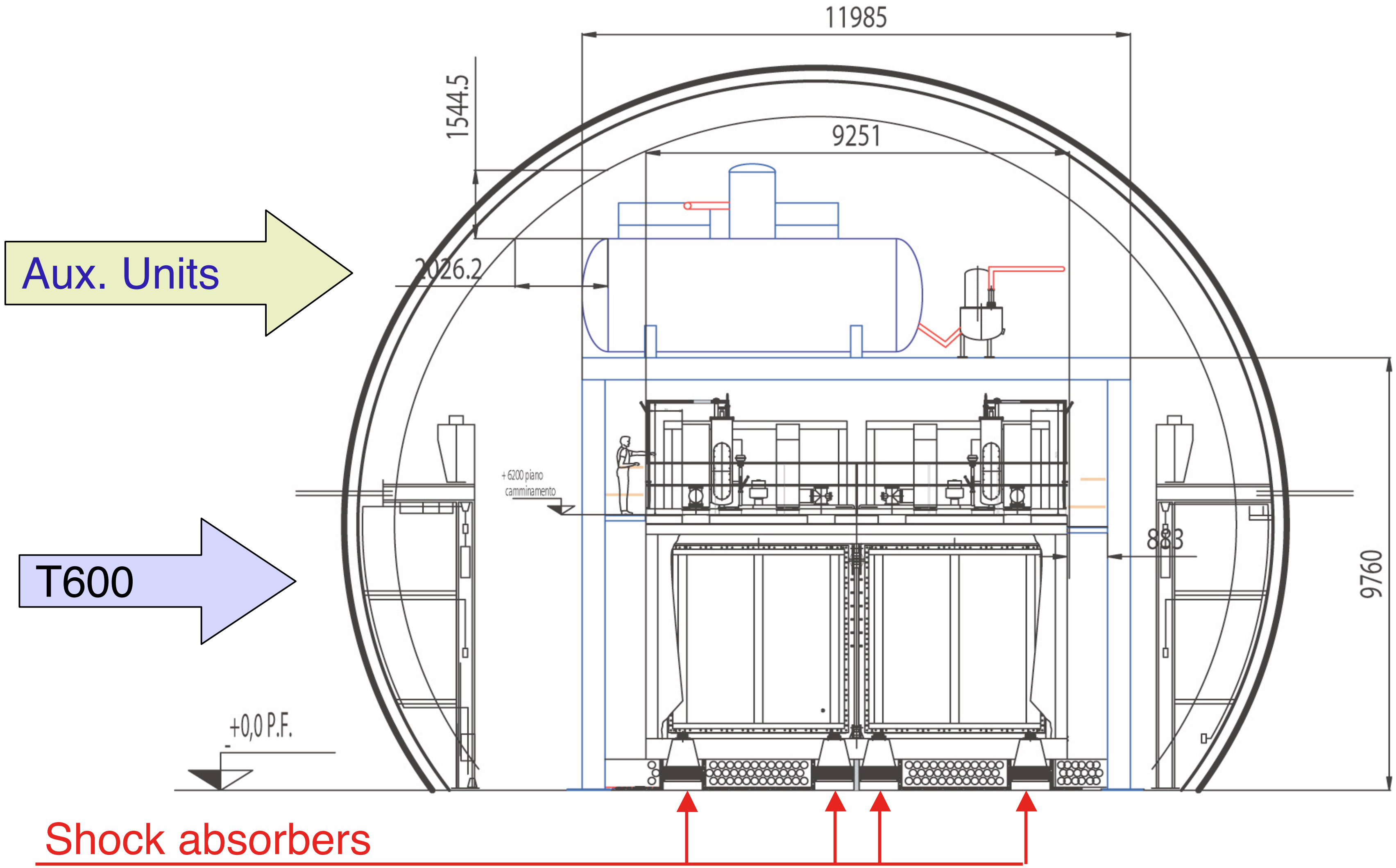


Lally et al., NIMB 117 (1996) 421

Scintillation light readout



T600 installation at LNGS



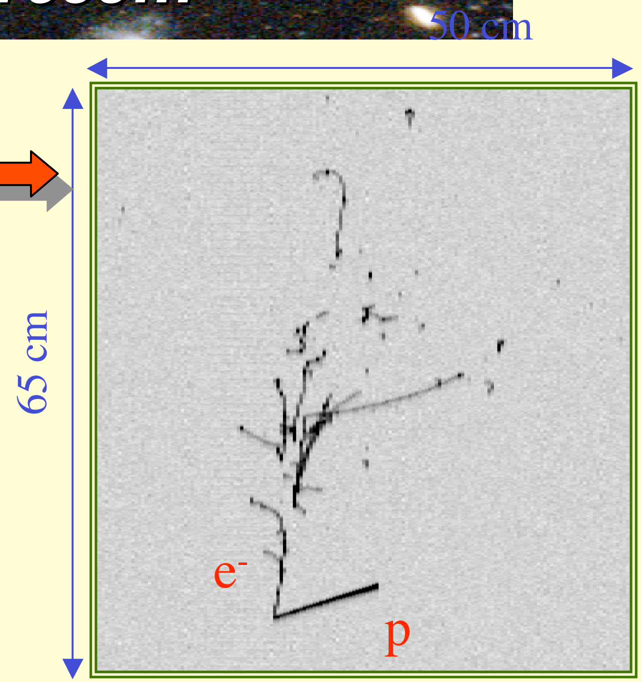
Installation procedure

The T600 installation procedure of the T600 in Hall B has started:

- contract for transportation (Pavia→ LNGS) signed
- interventions on the floor (Government Commissionersafety requirements) being defined
- goal: T600 in Hall B by mid 2004 (parking lot position); infrastructure & support structure completed by end 2004; data taking with cosmic events by mid 2005

Soon, physics with the T600…

In 1 year of T600 running ICARUS will collect about 100 events of this quality (in presence of oscillations)



BG free detection of solar neutrino events (E>8MeV)

Solar ν events per year in T600

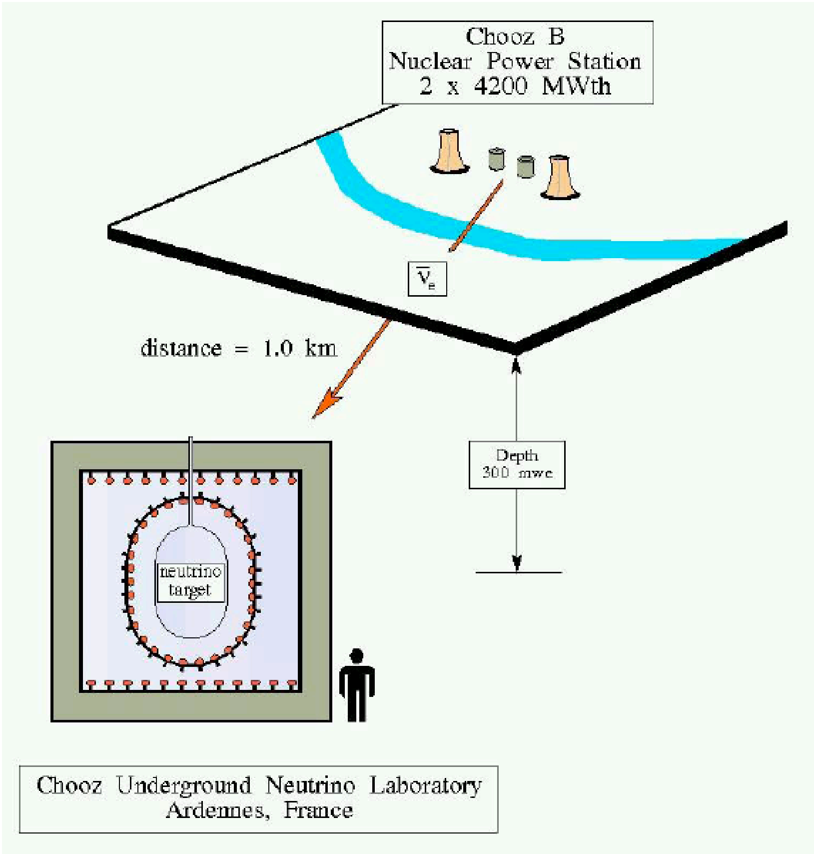
Elastic	Fermi	Gamow-Teller
38	165	295

Search for proton decay event topologies

Supernova observatory

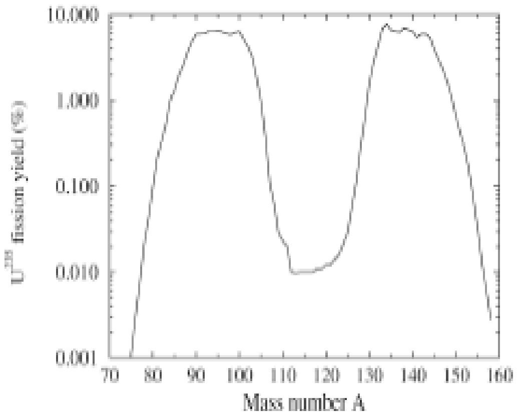
..and more: learn about a new technology for astroparticle physics

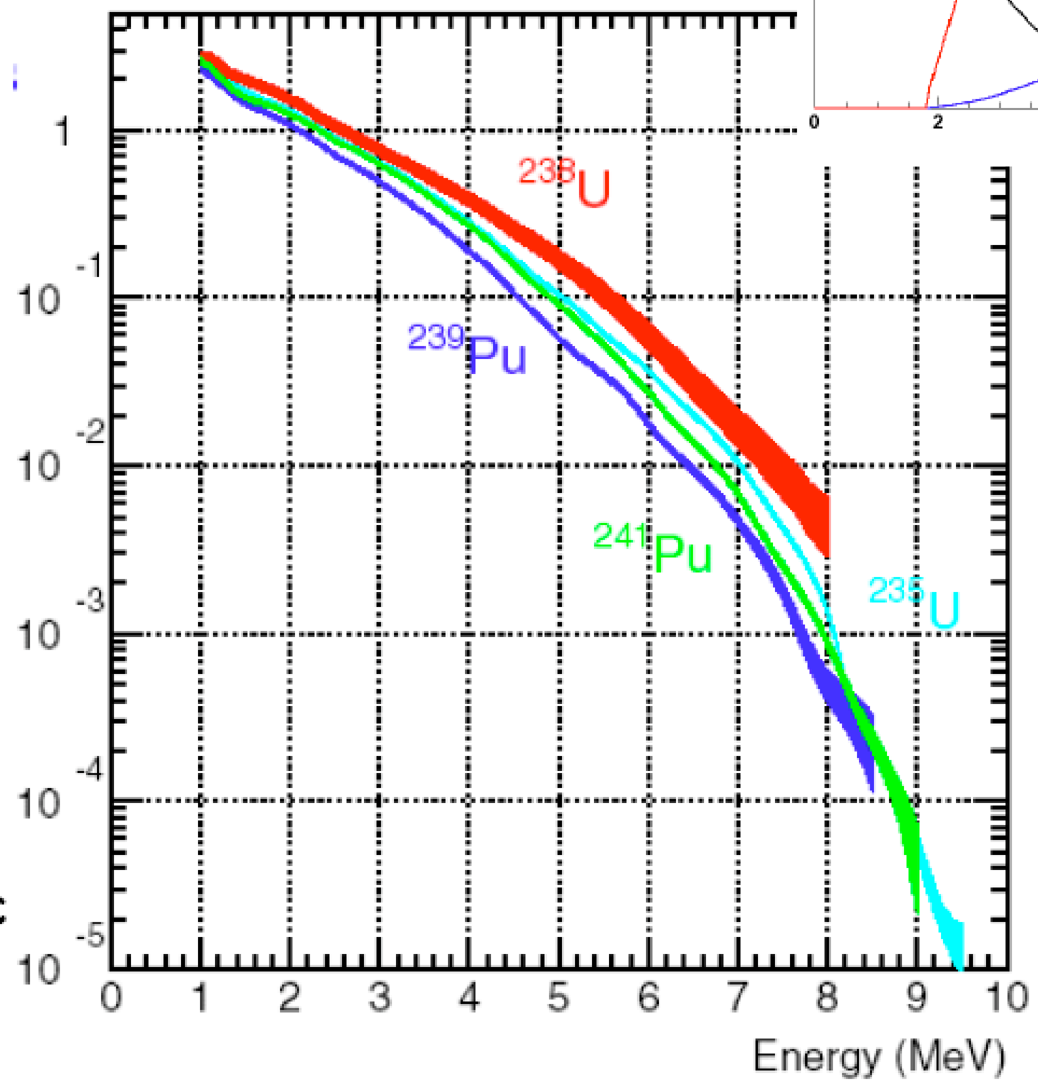
Experiments at reactors

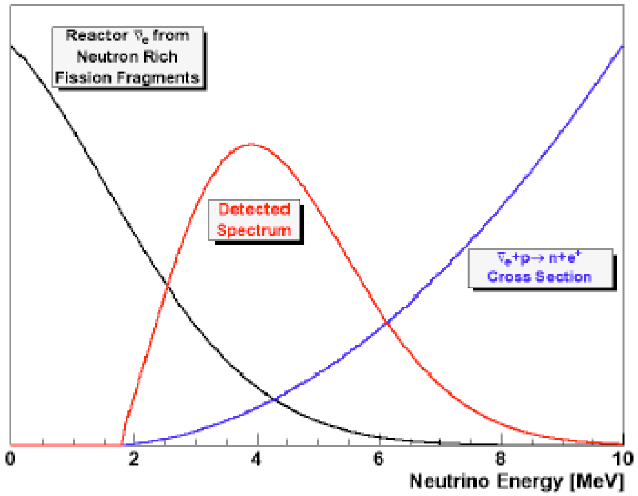


Neutrinos from reactors:

^{235}U fission



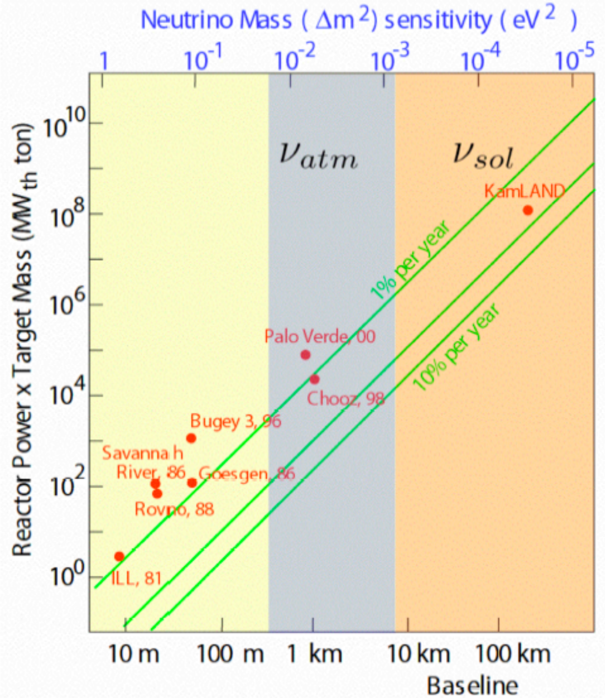


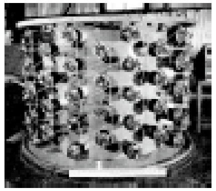


~200 MeV per fission

~6 $\bar{\nu}_e$ per fission

~2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec



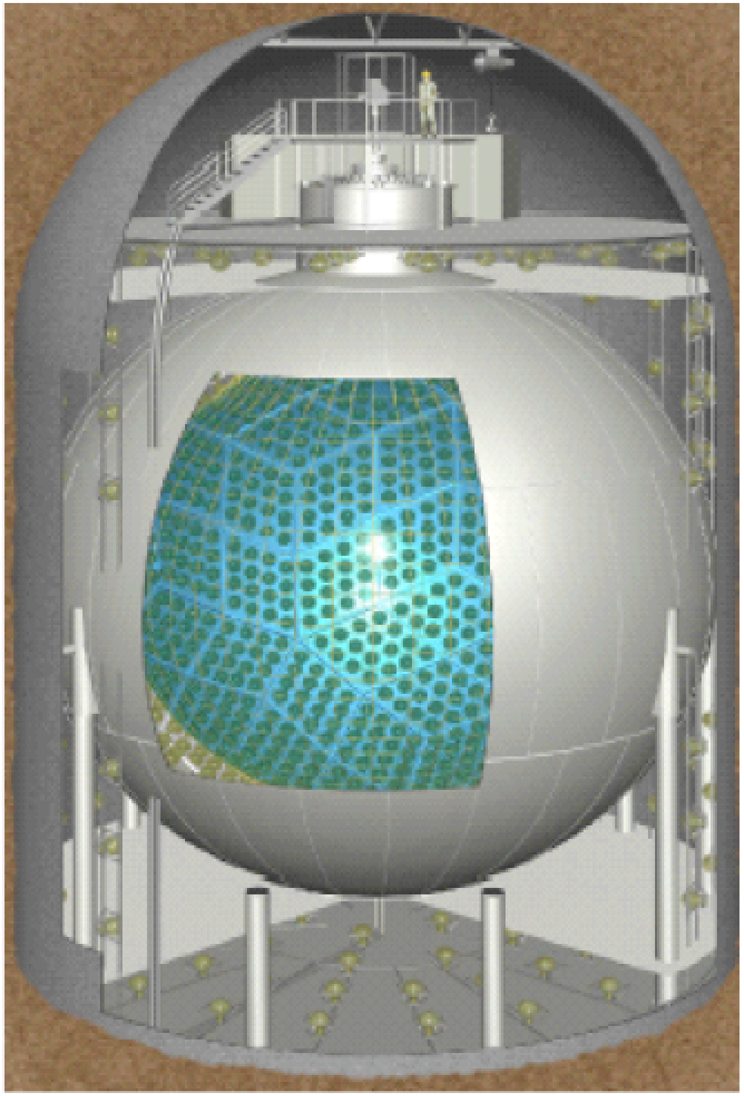


← 1m →

Poltergeist

← 4 m →

CHOOZ

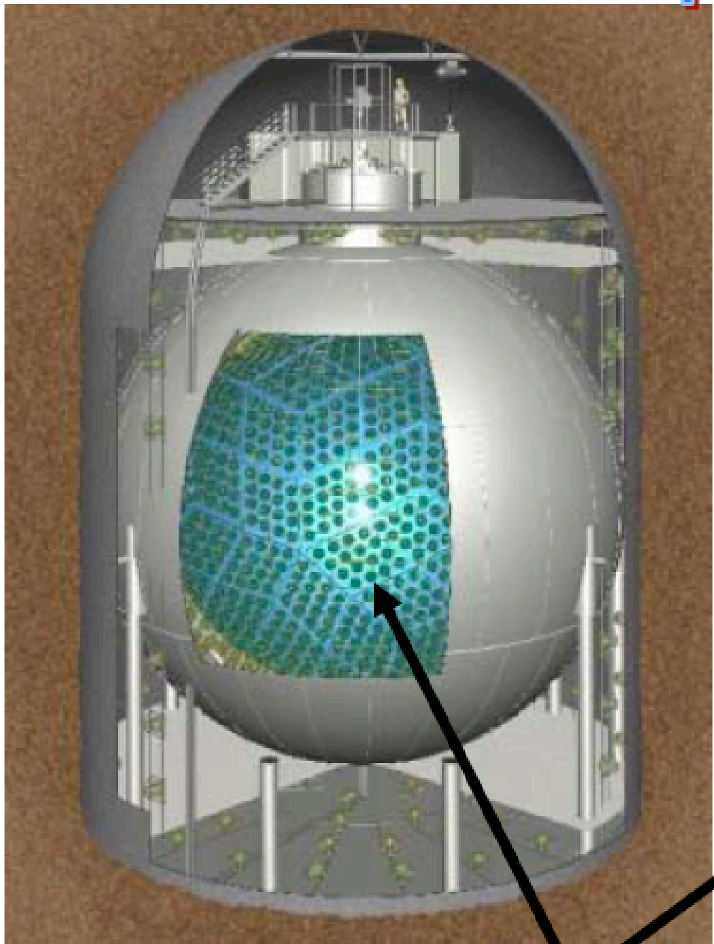


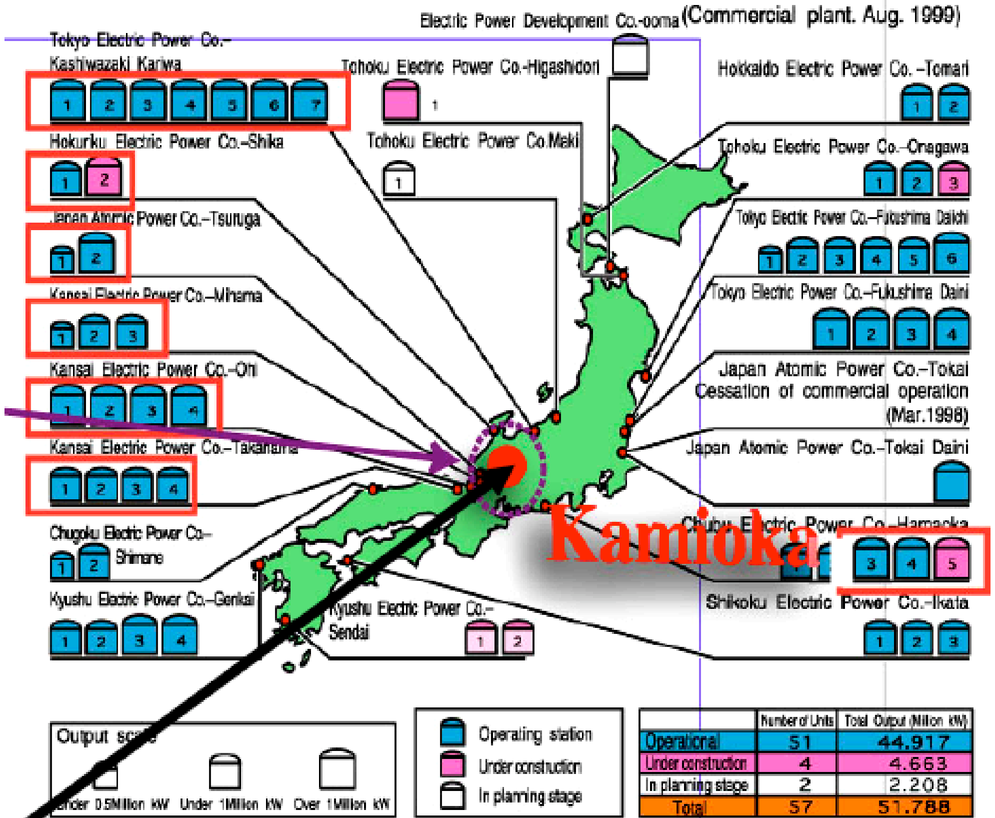
← 20 m →

KamLAND

From Reines to Kamland…

KamLAND





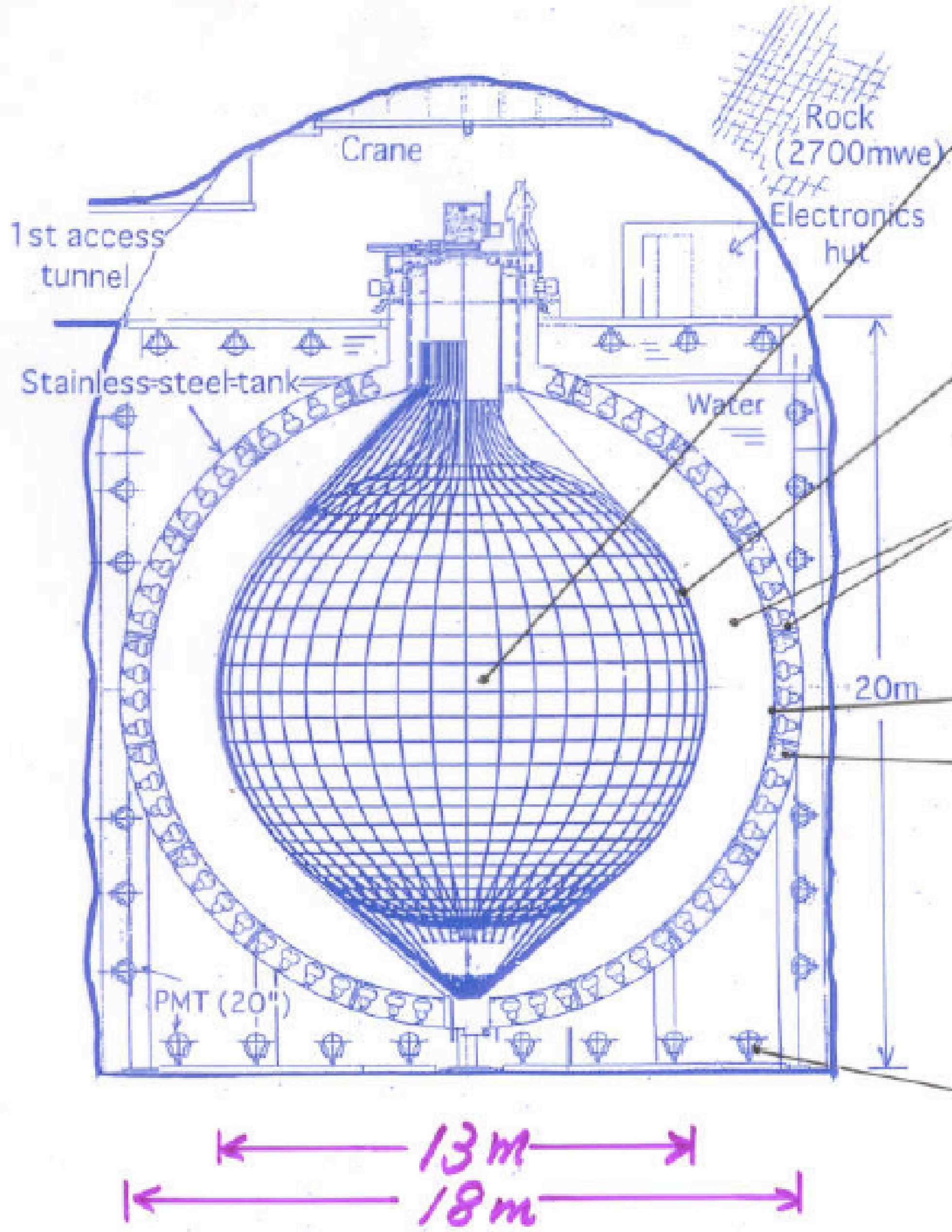
1,000ton liquid scintillator detector

Thermal power ~ 80GW

<E> ~ 3 MeV

<base line> ~ 180 km

KamLAND Detector



Liquid scintillator (1000ton)

Dodecane(80%)
+Pseudocumene(20%)+PPO(1.5g/l)

Balloon+Kevlar ropes

13mϕ, EVOH/3Ny/EVOH, 135μm

Buffer Oil (inner+outer)

Dodecane(50%)+Isoparaffin (50%

$\rho_{LS}/\rho_{BO}=1.003$

Acrylic plate (3mmt)

PMT 17"(σ~1ns)×1325+ 20"(σ~5ns)×554

Ω=35%of 4π

440pe/MeV, σ/E=5%/√E,

σ_{vtx}~10cm (@1MeV)

Outer Detector Water Č

PMT 20"×225 in purified water

$\bar{\nu}_e$ Detection

$$\bar{\nu}_e\, p \rightarrow e^+ n \quad (E_\nu > 1.8\,\text{MeV})$$

- $e^+ e^- \rightarrow 2\gamma$ (0.51MeV) — "Prompt" ($= E_\nu - 0.77\,\text{MeV}$)
- 180μs: $np \rightarrow d\gamma$ (2.2MeV) — "Delayed"

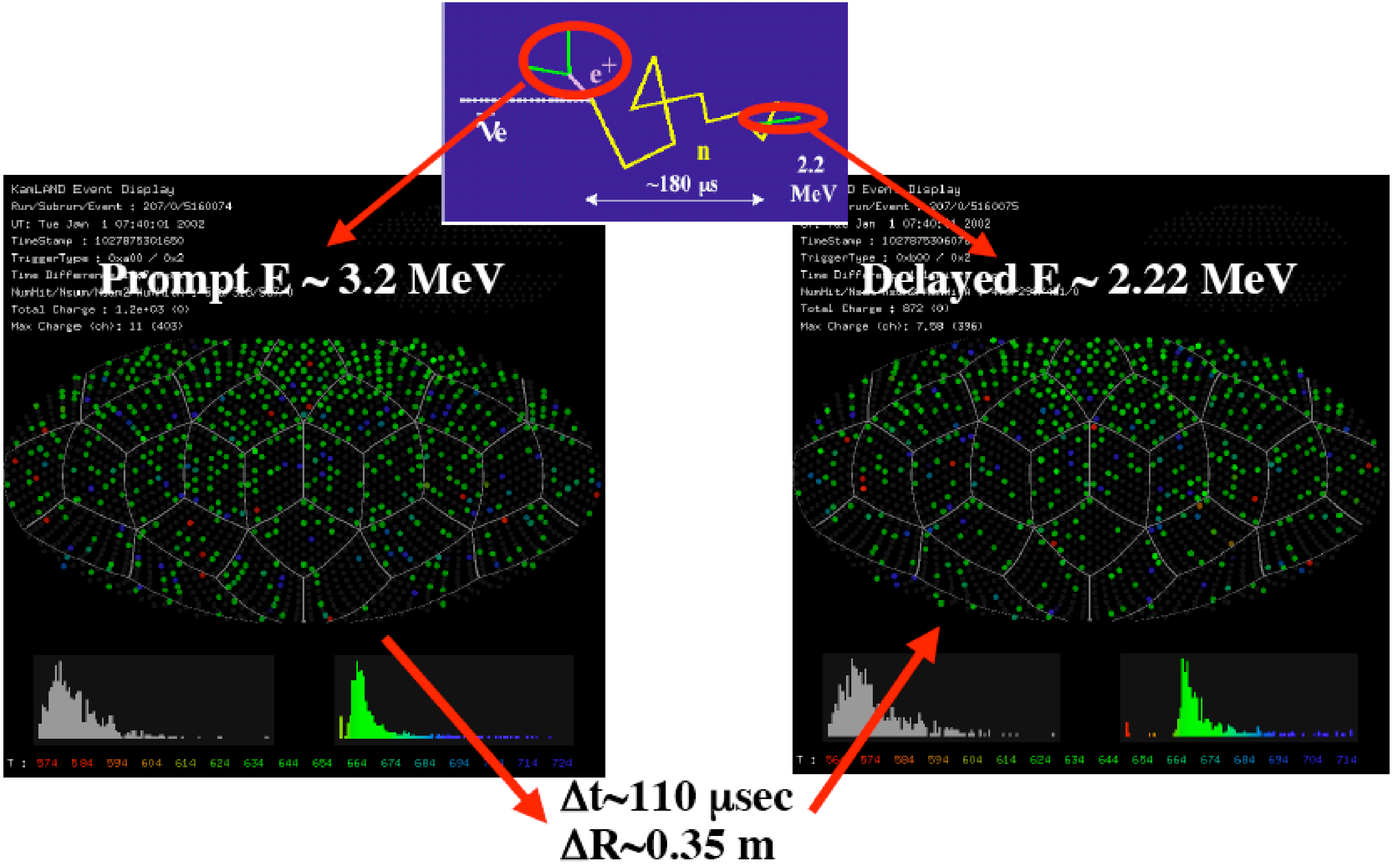
- $\bar{\nu}_e$ only (CC)
- Reject BG (delayed signal ← timing, distance, energy)
- σ is large ($\sim 100\,\sigma(\nu e \rightarrow \nu e)$) and well known.
- E_ν is measured by prompt energy.

- KamLAND Liquid Scintillator

  Large light yield, High purity, Pulse shape discrimination (n/γ, α/γ)

  Fast response, cheap, safe

  ≈300 p.e./MeV



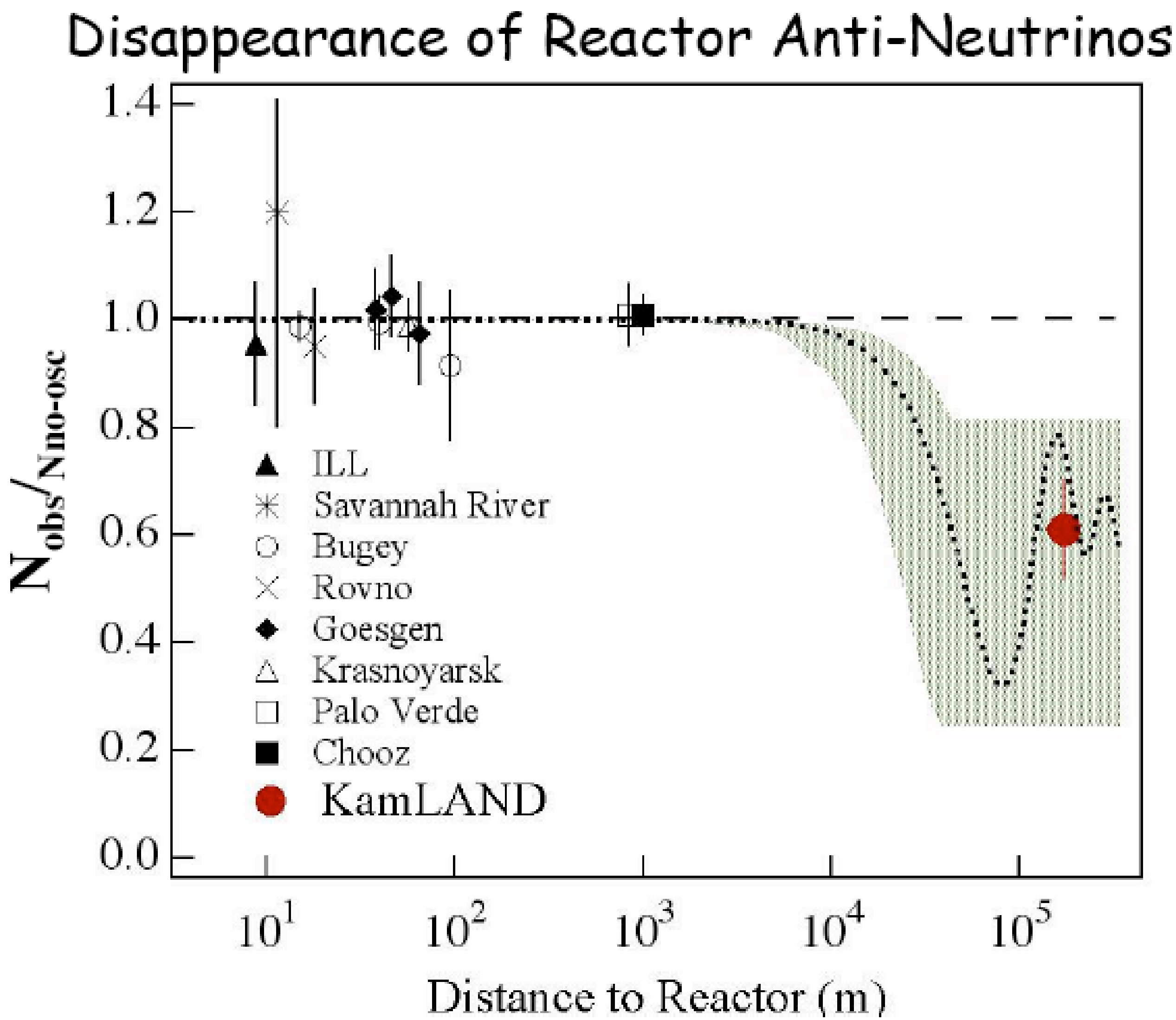
Candidate Neutrino Event

145 days

Expected
86.8 + 5.6

Background
1 + 1

Observed
54



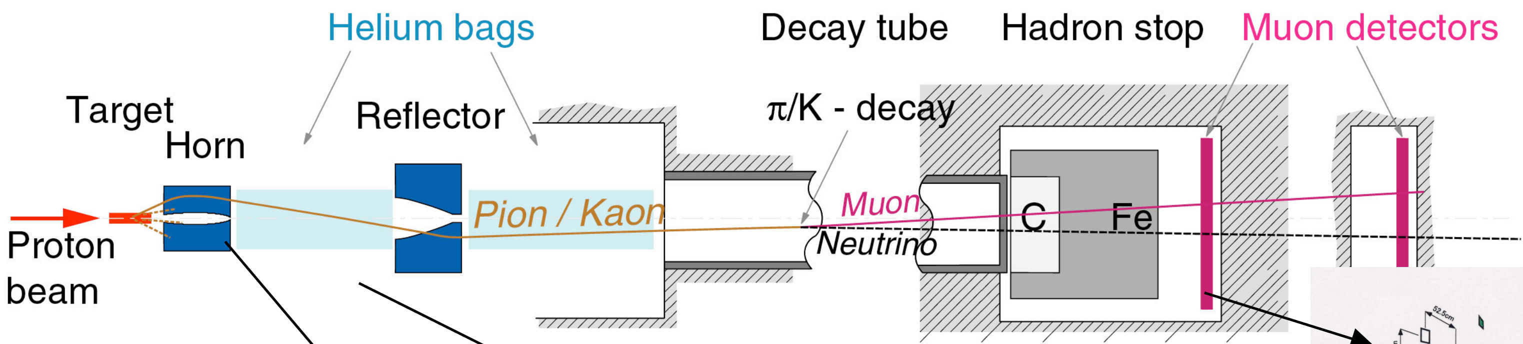
N_{obs}/N_{no-osc} = 0.611 ± 0.085 (stat) ± 0.041 (syst)

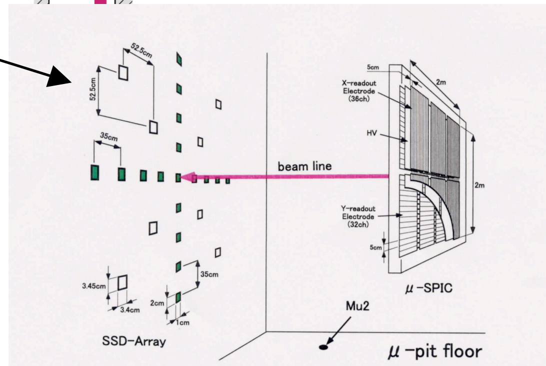
Total systematic flux uncertainty ≈ 6%

Experiments at accelerators

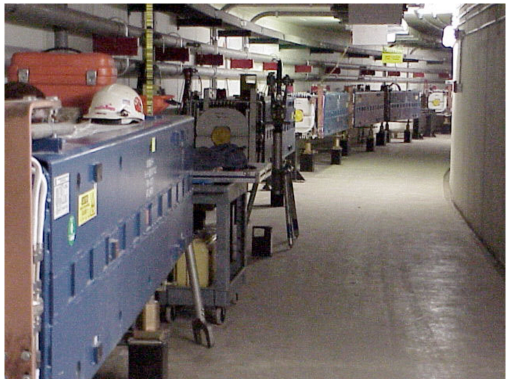
$p + C \rightarrow$ (interactions) $\rightarrow \pi^+, K^+, (\mu^+) \rightarrow$ (decay in flight) $\rightarrow \mu^+ + \nu_\mu$

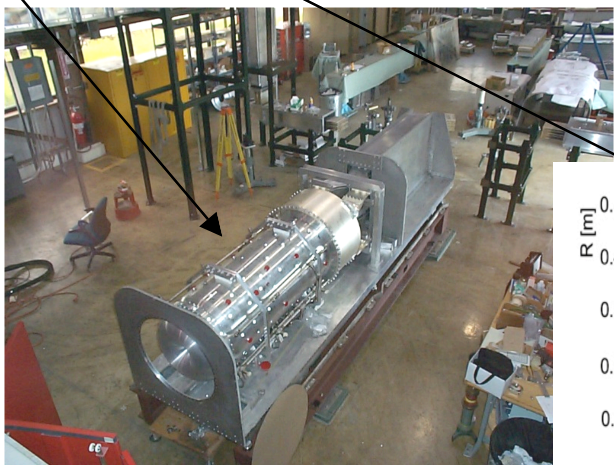
+ few % of (ν_μ , ν_e)



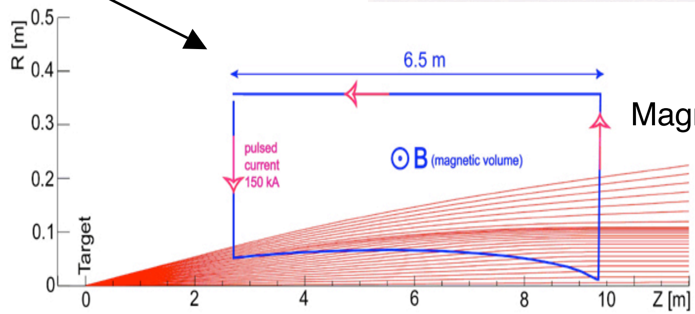


Proton accelerator





Boone Horn



Magnetic focusing

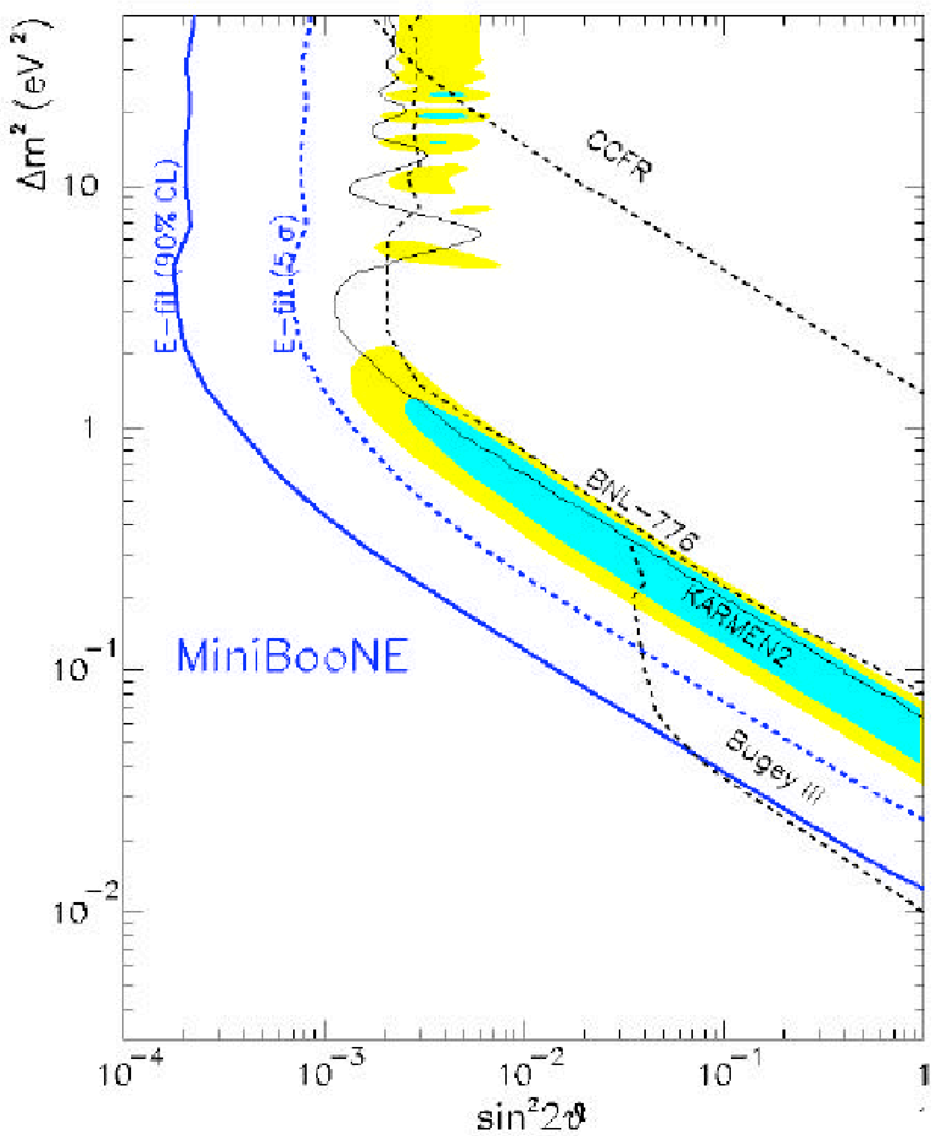
MiniBoone at FNAL

ETH Institute for Particle Physics

- **Within two years of running, should**
  - ➥ **confirm or refute whether LSND excess is due to <u>neutrino flavor oscillations</u>** (if it refutes LSND, it will still not explain the LSND excess !)
- **A fundamental result for the overall understanding of the neutrino data in terms of neutrino oscillations !!!**
- **In case of positive result from MiniBOONE the roadmap for the future neutrino physics would have to be re-thought !**

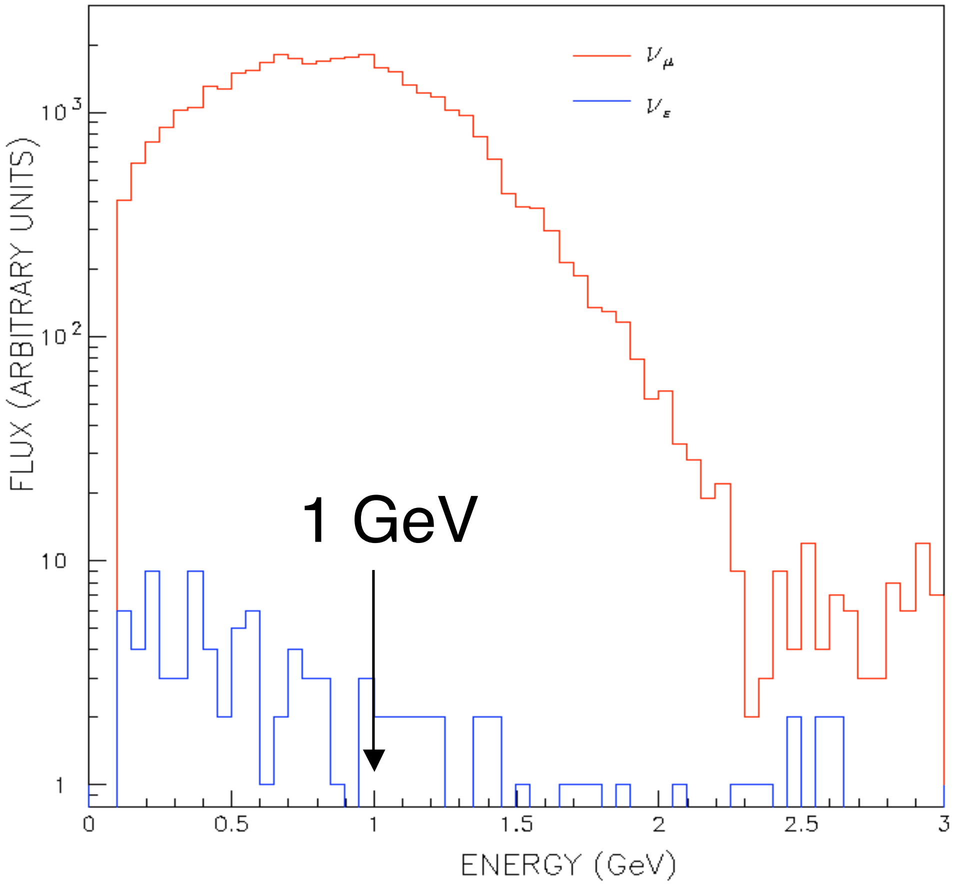
MiniBooNE has been collecting data for > 1 year
  1.8×10^{20} protons on target
  204K contained neutrino candidates

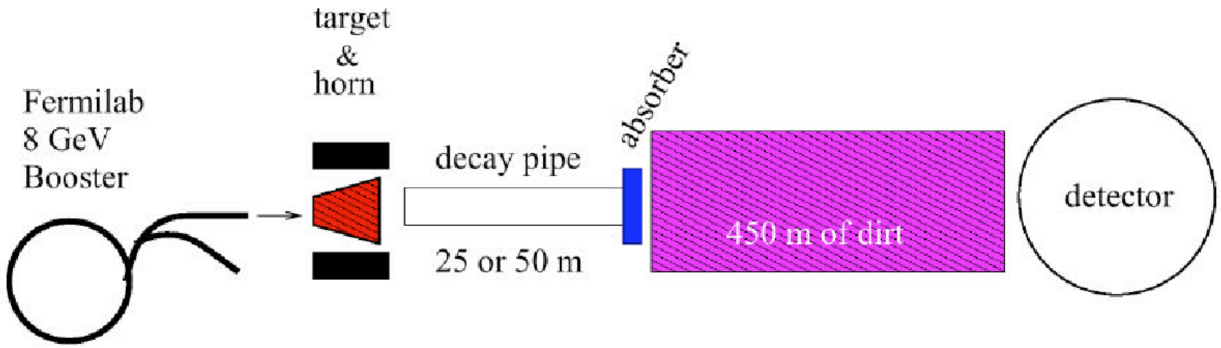
Detector working as expected



The MiniBoone Neutrino Beam

- 8 GeV proton from FNAL Booster
- **Repetition rate: 5 Hz**
- **Average neutrino energy 1 GeV**
  - ➥ $L/E_{boone} \approx L/E_{LSND} \approx 1$ km/GeV
- **Intrinsic ν_e contamination can be ..**
  - ➥ Inferred from ν_μ events
  - ➥ Simulated using hadroproduction measurements
  - ➥ Measured using muon counters in and around the decay pipe
  - ➥ Checked by comparing 50m and 25m absorber results





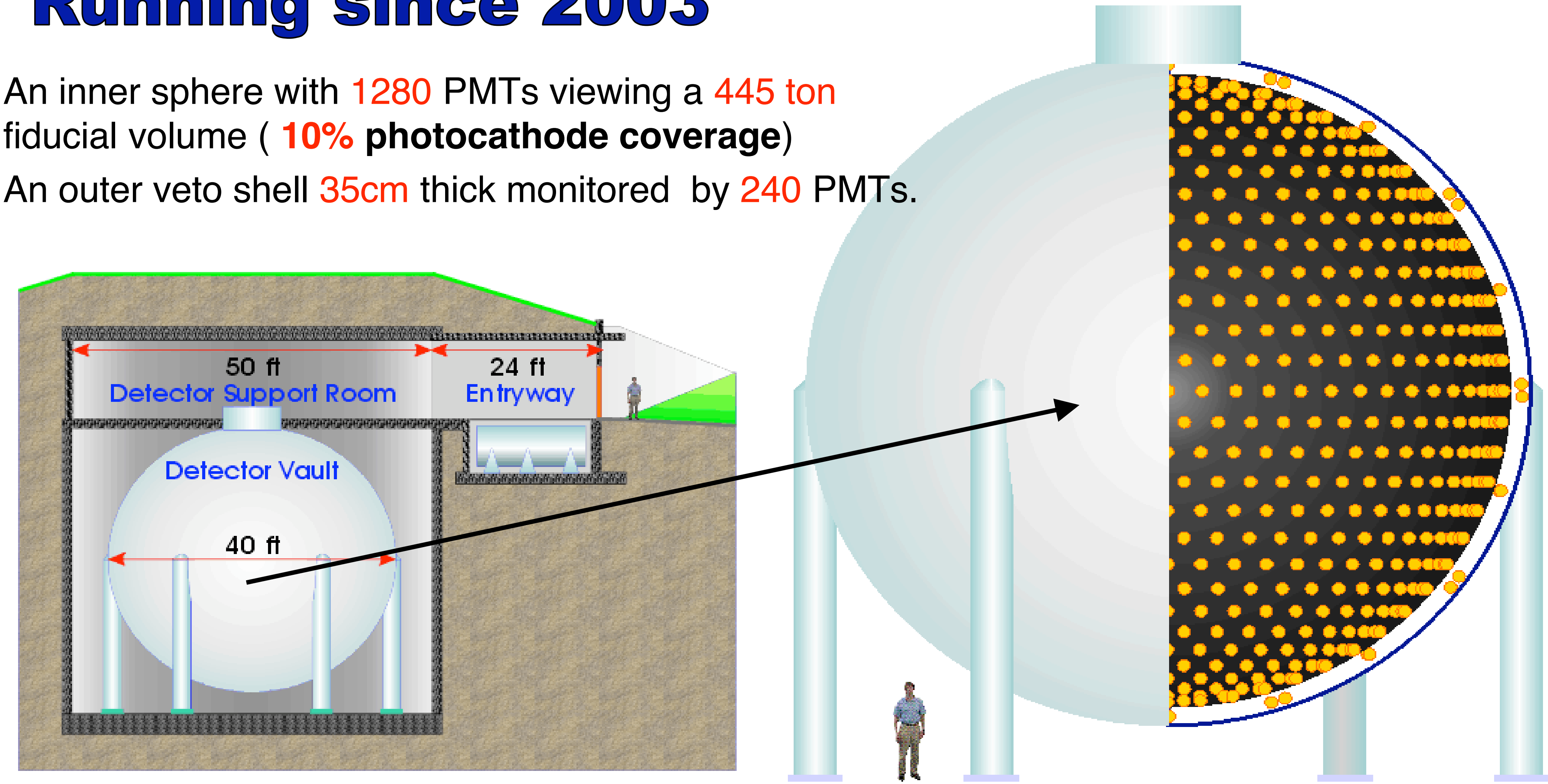
The MiniBoone Detector

- **The detector is a 40ft (12.2m) diameter sphere filled with 800 tons of pure mineral oil and instrumented with ~1500 8” PMTs.**

Running since 2003

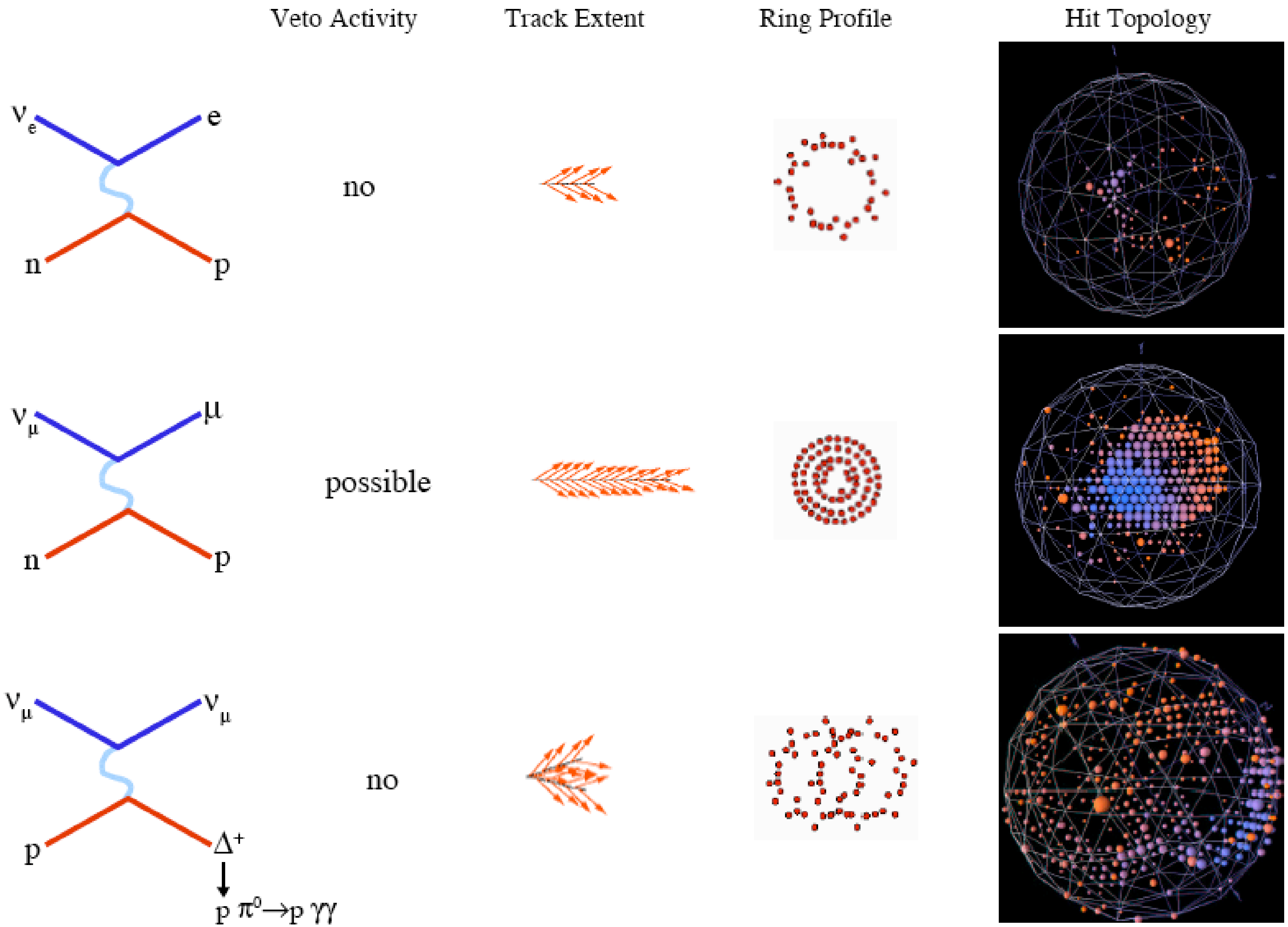
An inner sphere with 1280 PMTs viewing a 445 ton fiducial volume (**10% photocathode coverage**)

An outer veto shell 35cm thick monitored by 240 PMTs.



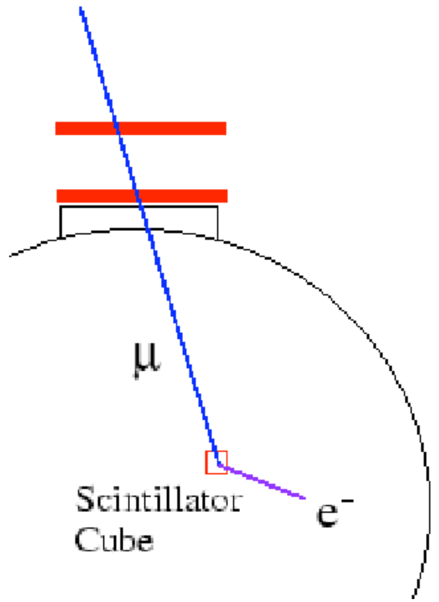
Event Reconstruction

- MiniBooNE will reconstruct quasi-elastic ν_e interactions by identifying the characteristic Cerenkov rings produced by the electrons ... (Detect also scintillation light)

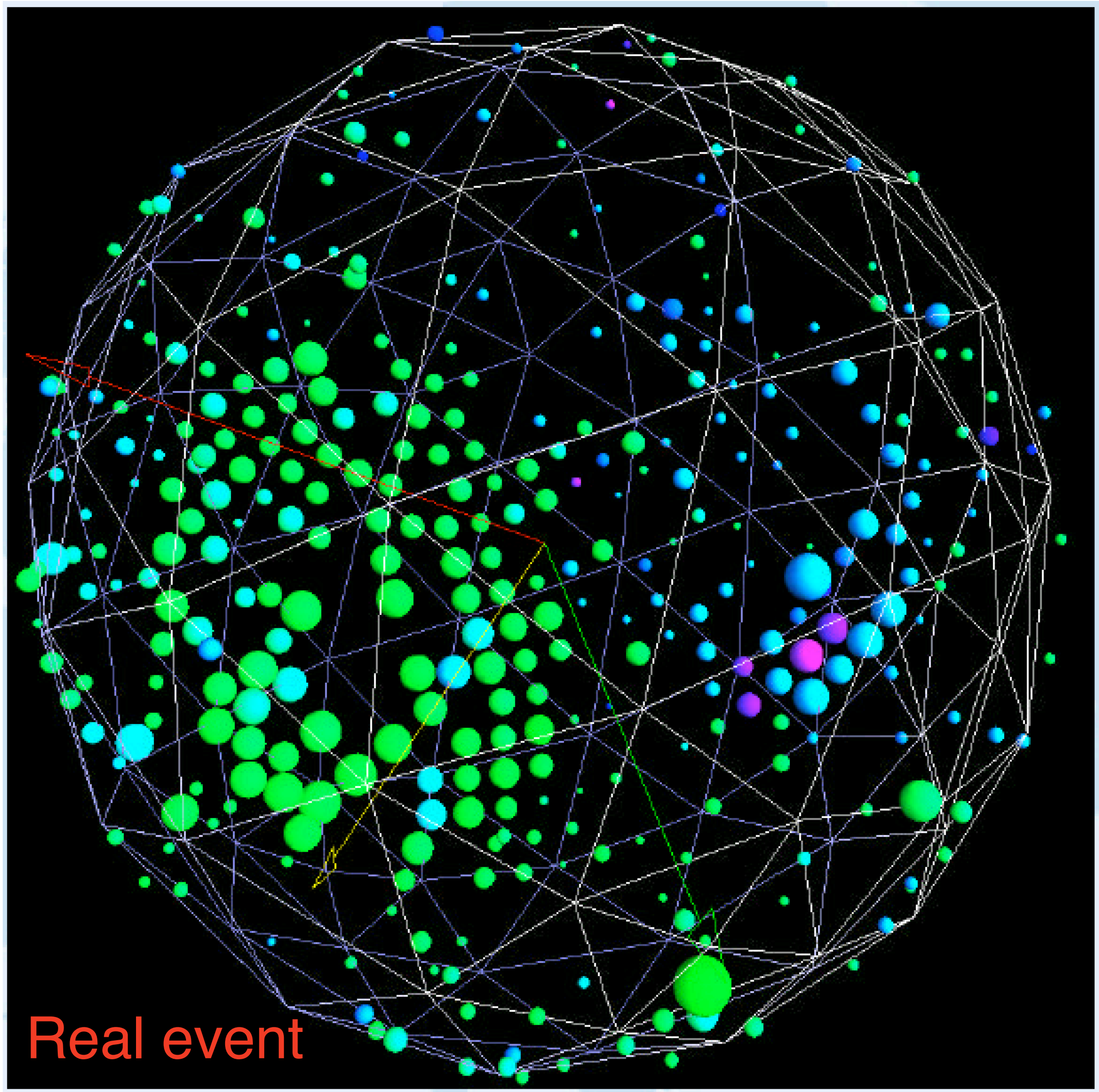


MiniBoone "calibration μ tracker"

Scintillator strips to tag cosmic muons

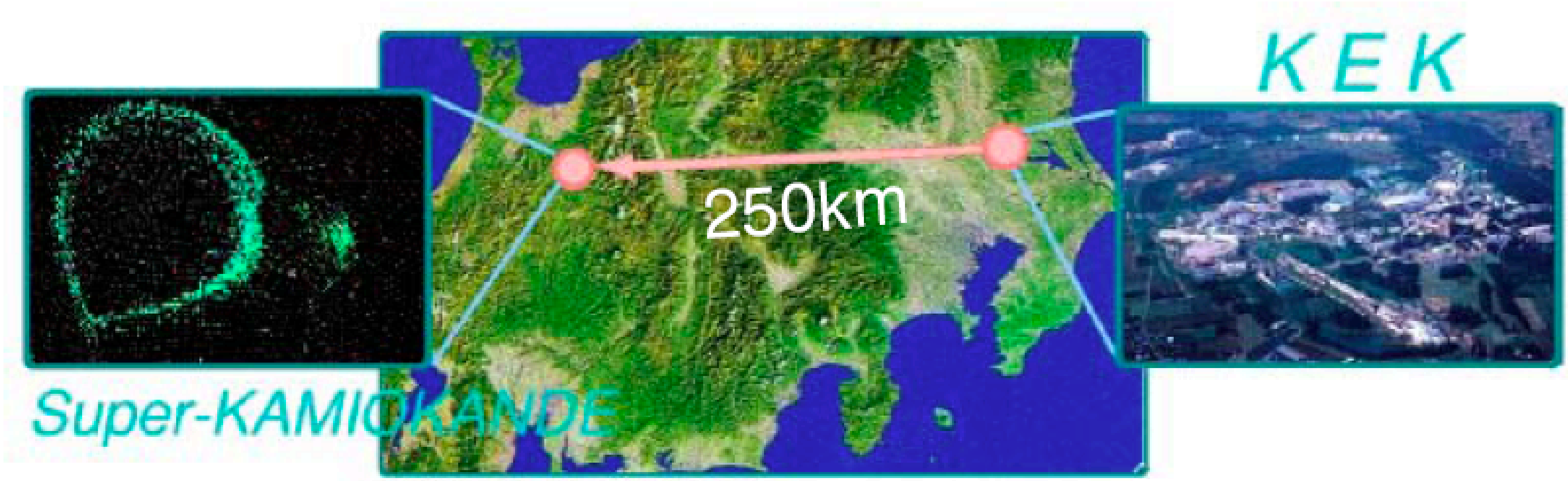


Study stopping muons and Michel electrons

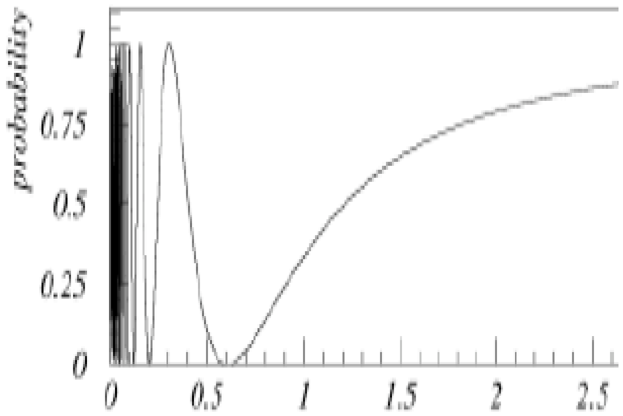


K2K

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



Neutrino oscillation probability for $\Delta m^2 = 0.003 eV^2$ and at 250km.



K2K-I

$80.1^{+6.2}_{-5.4}$ expected

56 observed

obs/exp=**0.70±0.09**(stat)

K2K-II (until April 2003)

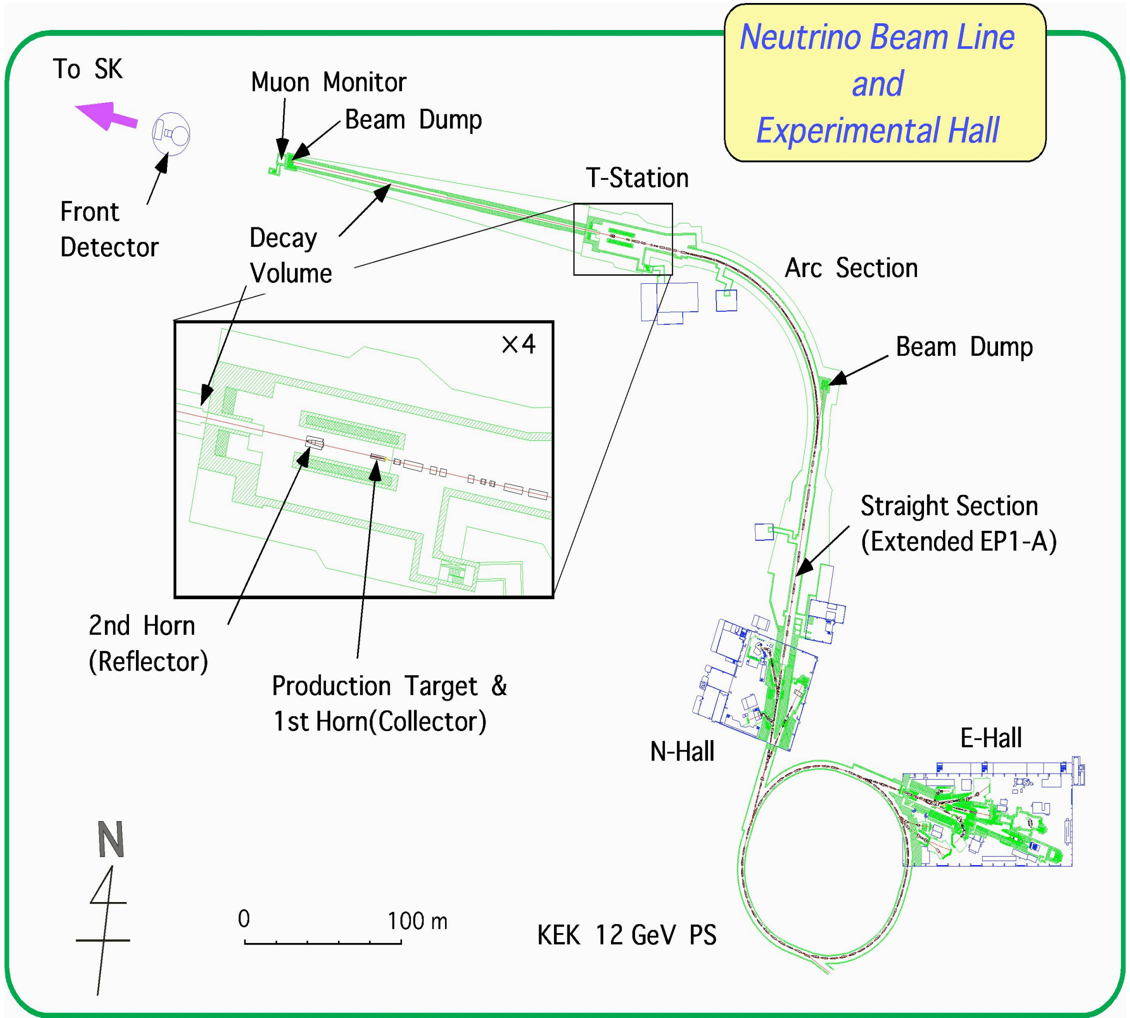
$26.4^{+2.3}_{-2.1}$ expected

16 observed

obs/exp=**0.61±0.15**(stat)

Since 1999

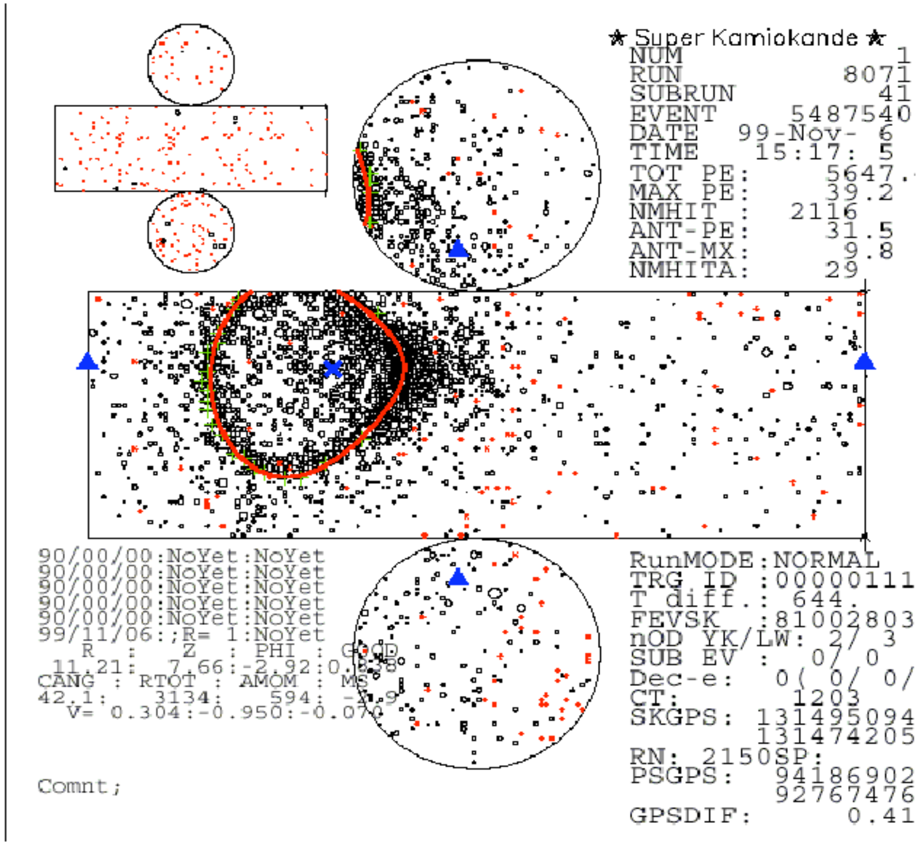
K2K (KEK-to-Kamioka)

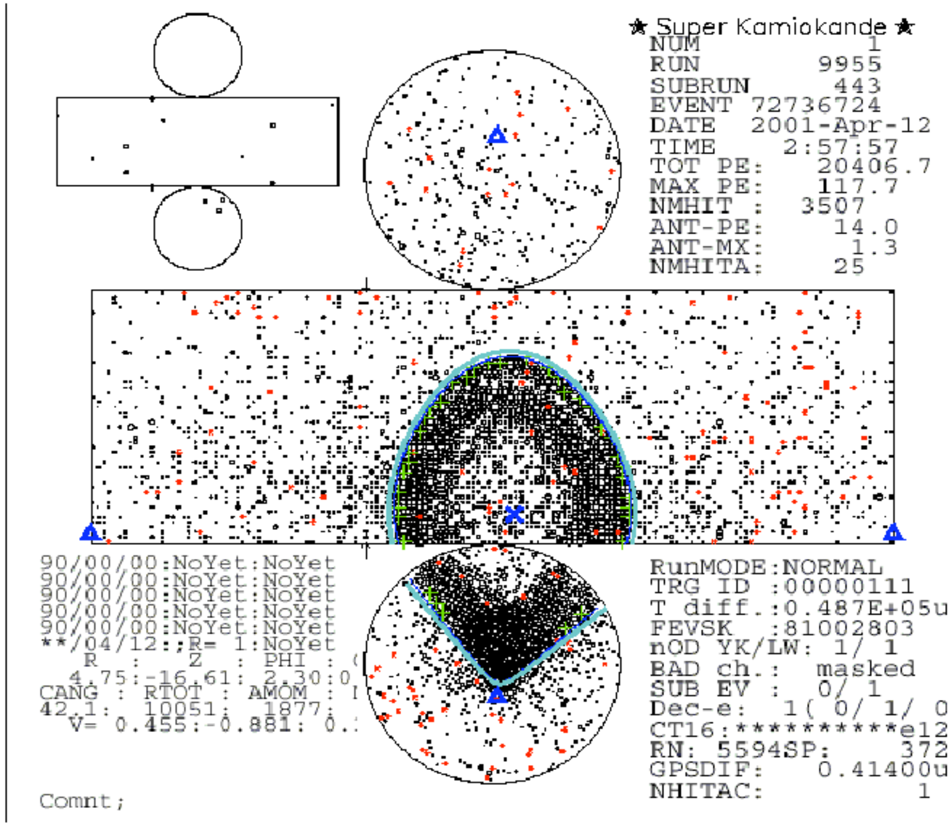


- **Accelerator: 12 GeV proton synchrotron**
  - Intensity 6x10^{12} protons/pulse
  - Repetition rate: 1 pulse/ 2.2 sec
  - Pulse width: 1.1 μs
- **Horn-focused wide-band beam**
  - **Average neutrino energy: 1.4 GeV ⇒ below τ-threshold**
- **Near detector: 300 m from target**
- **Far detector: SuperK@ 250km from the target**
  - **L/E ≈ 180 km/GeV**
- **Goal: 10^{20} protons on target**

$$\nu_\mu \rightarrow \nu_\mu \qquad \nu_\mu \rightarrow \nu_e$$

e-like and μ-like events in Super-Kamiokande





Total rate with low threshold (>30MeV) ~100% efficient for CC
Identification of μ (1Rμ) , e (1Re)

K. Nishikawa, Neutrino 2002

Flow of Neutrino Oscillation Analysis

Observed (p_μ,θ_μ) distributions at Near Detectors

↓ ν *Int. Model*

Neutrino Spectrum at Near detector $\phi_{near}(E\nu)$,

↓

Far/Near Extrapolation vs Eν $R_{FN}(E\nu)$

Neutrino Spectrum w/o oscillation at SK $\phi_{SK}(E\nu)$

$\phi_{SK}(E\nu)$ ⊗ Oscillation $(\sin^2 2\theta, \Delta m^2)$ ⊗ *Int. Model*

Prediction

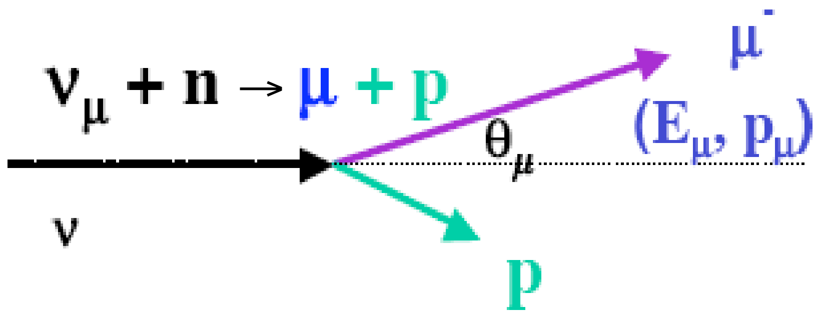
- N_{SK}(exp't) : Expected no. of SK events
- $S_{SK}(E_\nu^{rec})$:1Rμ E_{rec}distribution(shape)

SK observation

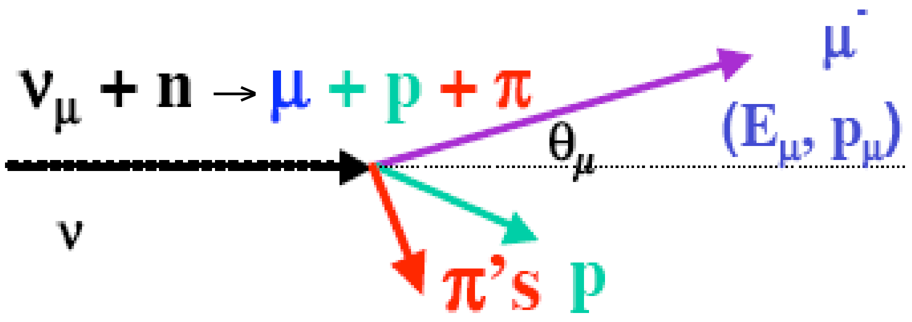
- N_{SK}(obs)
- 1Rμ E_{rec} distribution

Maximum Likelihood Fit in $(\sin^2 2\theta, \Delta m^2)$

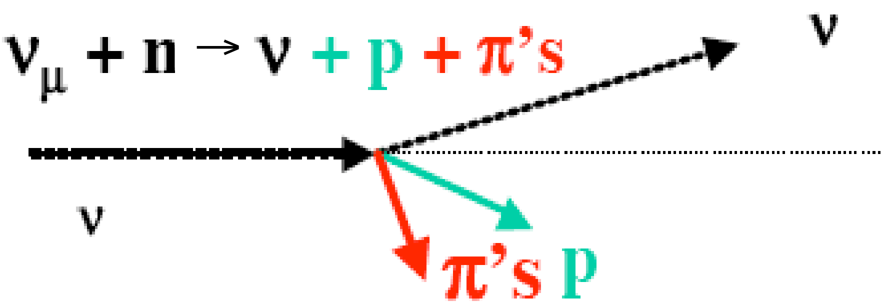
Water Cerenkov see only relativistic particles!



- ✧ CC QE
  - ✧~100% efficiency for N_{SK}
  - ✧can reconstruct Eν ←(θ_μ, p_μ)



- ✧ CC nQE
  - ✧~100% efficiency for N_{SK}
  - ✧Bkg. for E_ν measurement

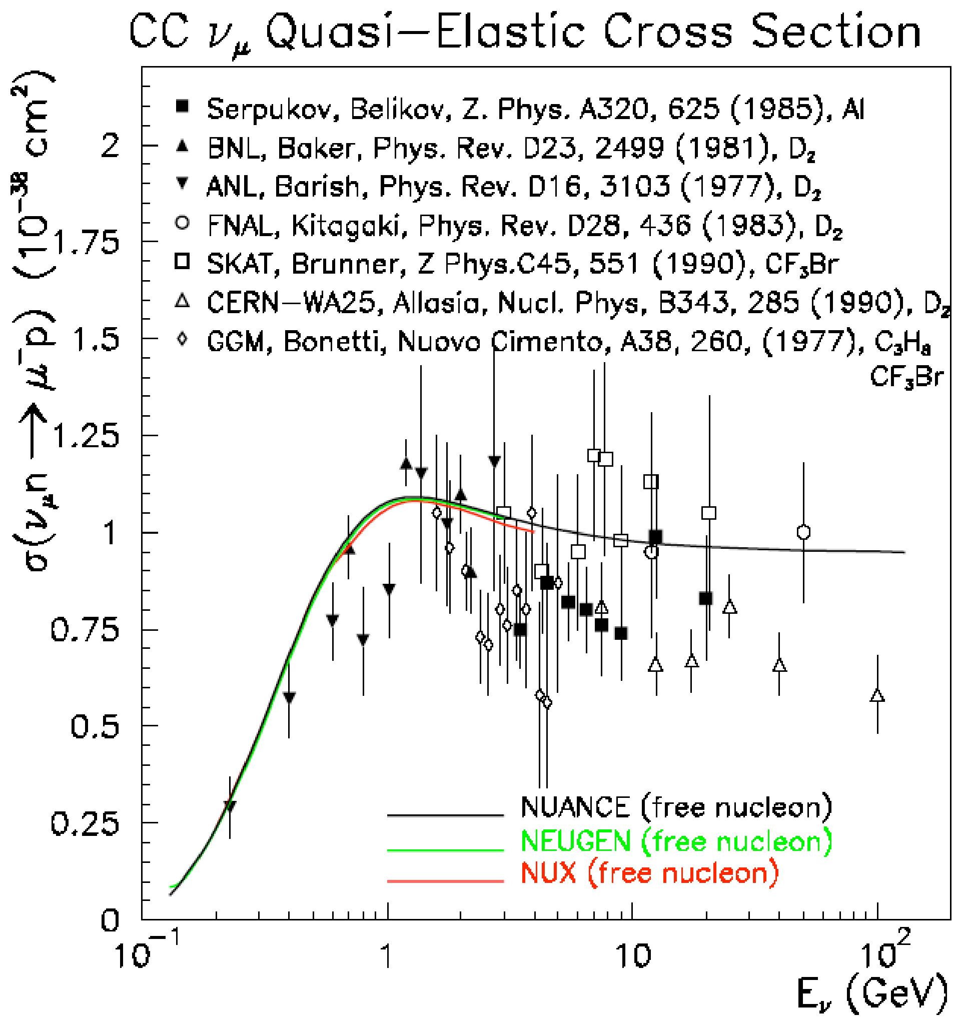


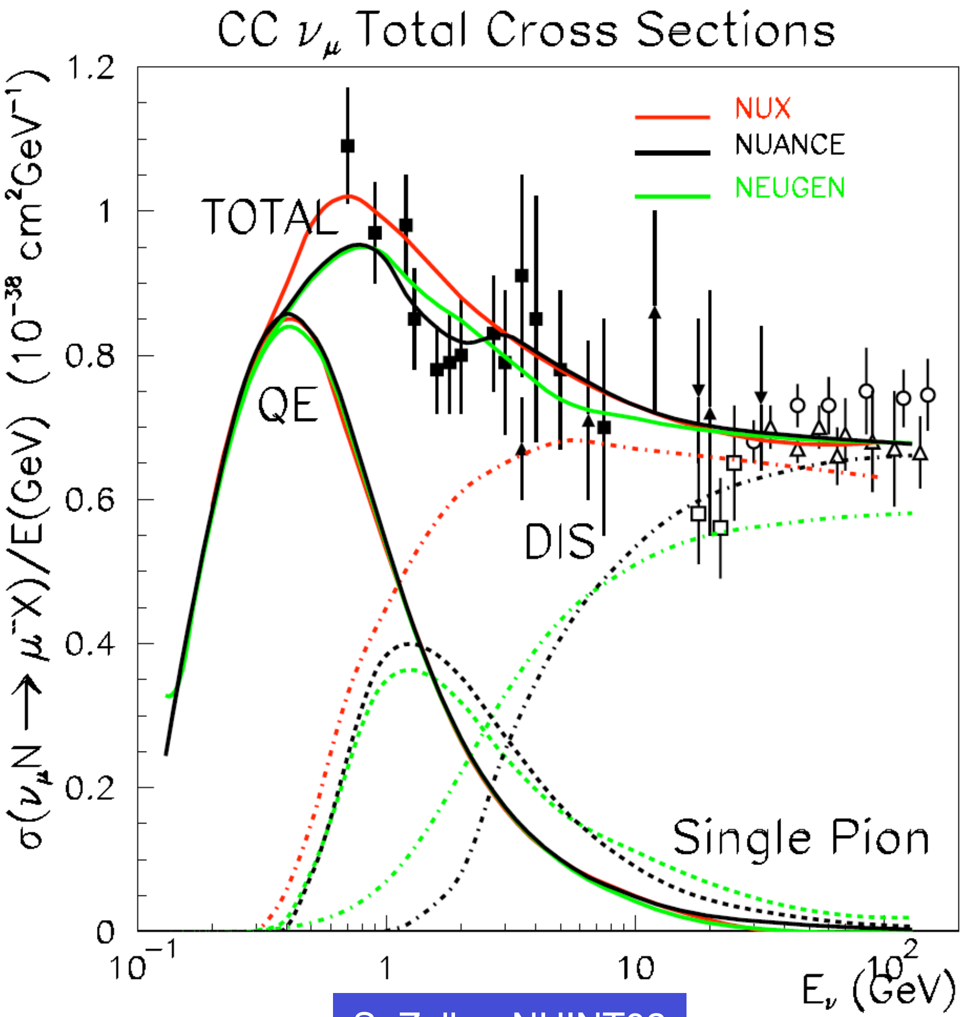
- ✧ NC
  - ✧~40% efficiency for N_{SK}

14

Neutrino cross-sections

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



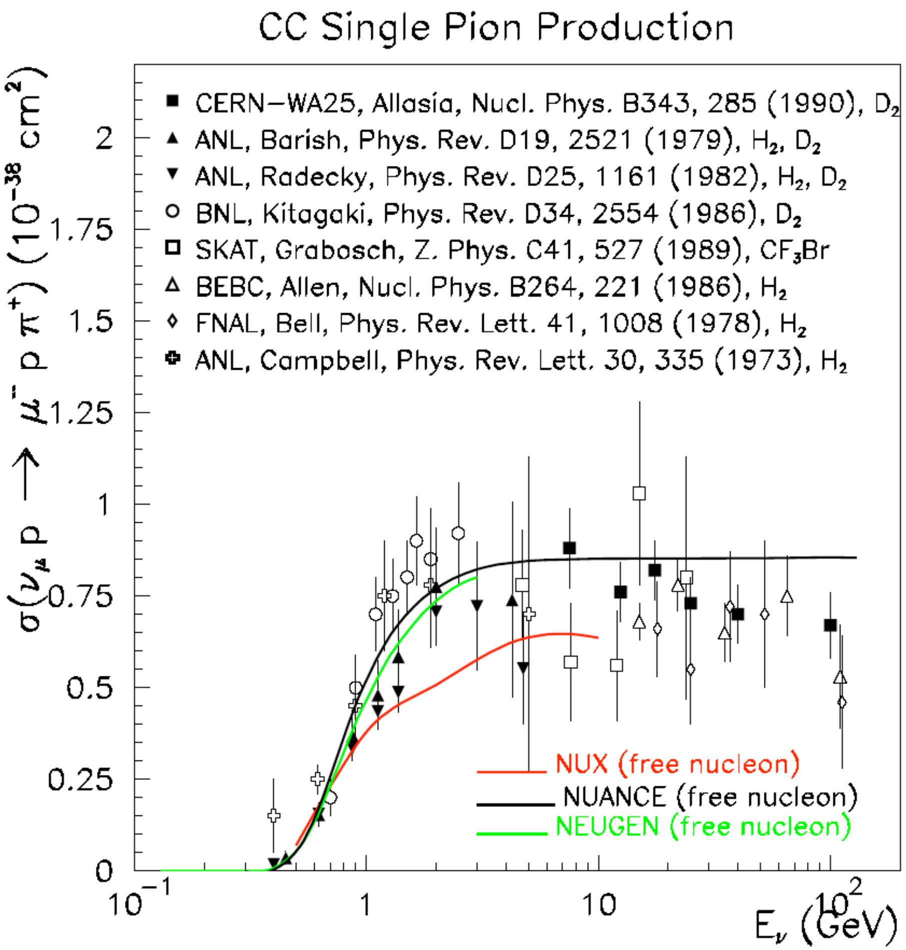


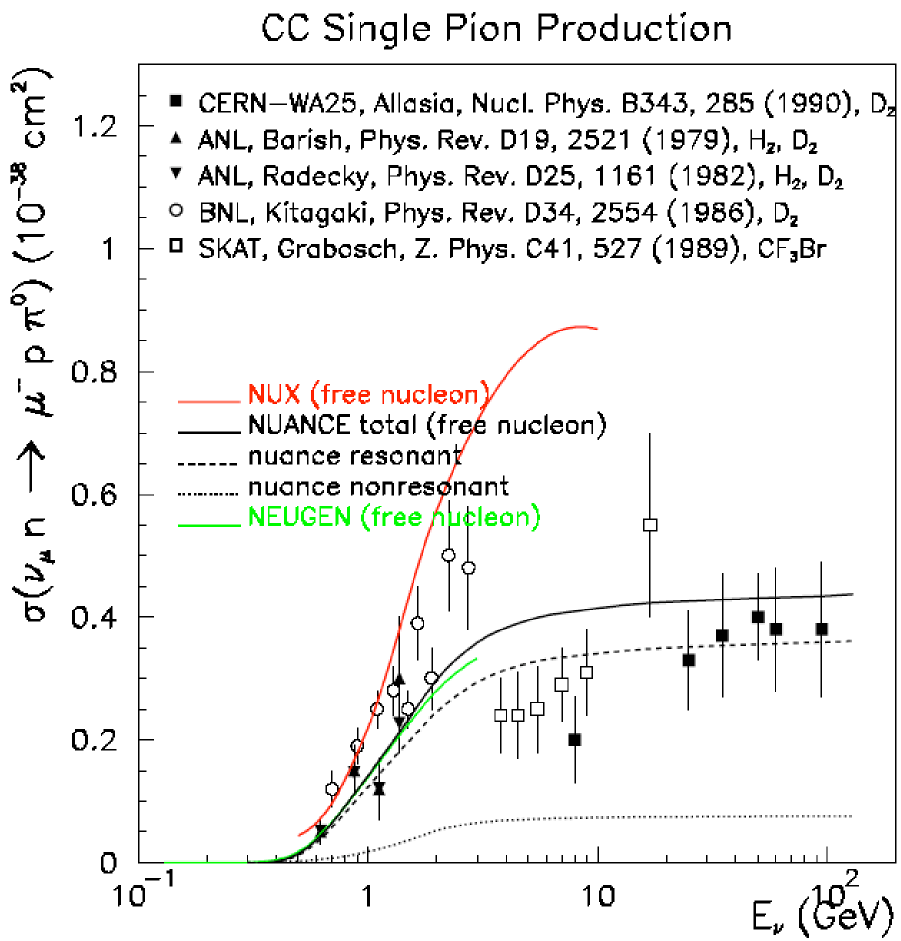
S. Zeller, NUINT02

Example for single pion production

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

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

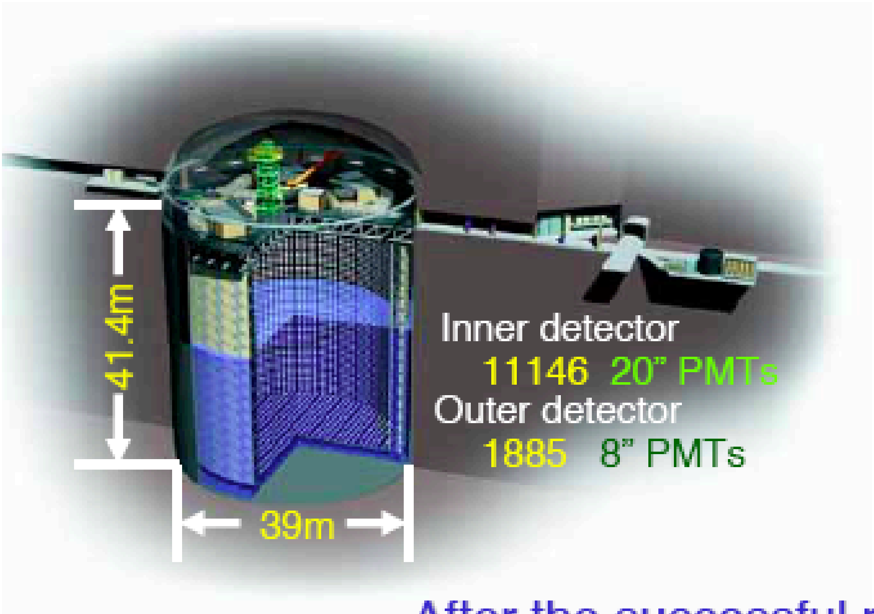




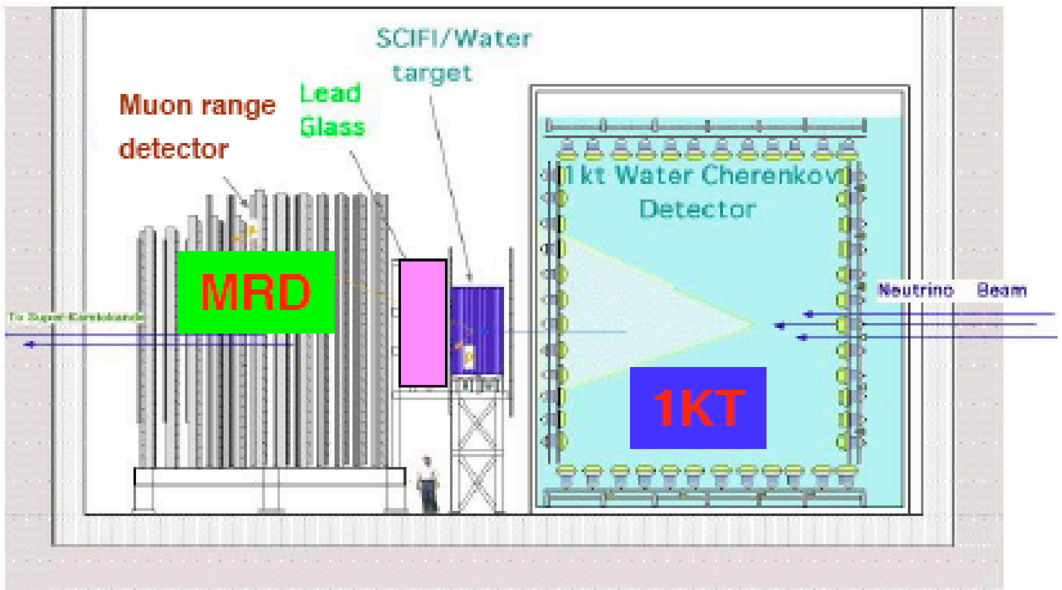
S. Zeller, NUINT02

K2K-I From Mar.1999 ~ Jul.2001

Super-Kamiokande I



Near neutrino detectors



After the successful resume of the experiment

K2K-IIa Dec.21,2002~

Super-Kamiokande II

- Inner detector

~5200 PMTs with FRP+Acrylic cover

Near neutrino detectors

- Remove Lead Glass detector to explore lower energy region

K2K-IIb Oct.3,2003~

Upgraded near neutrino detectors

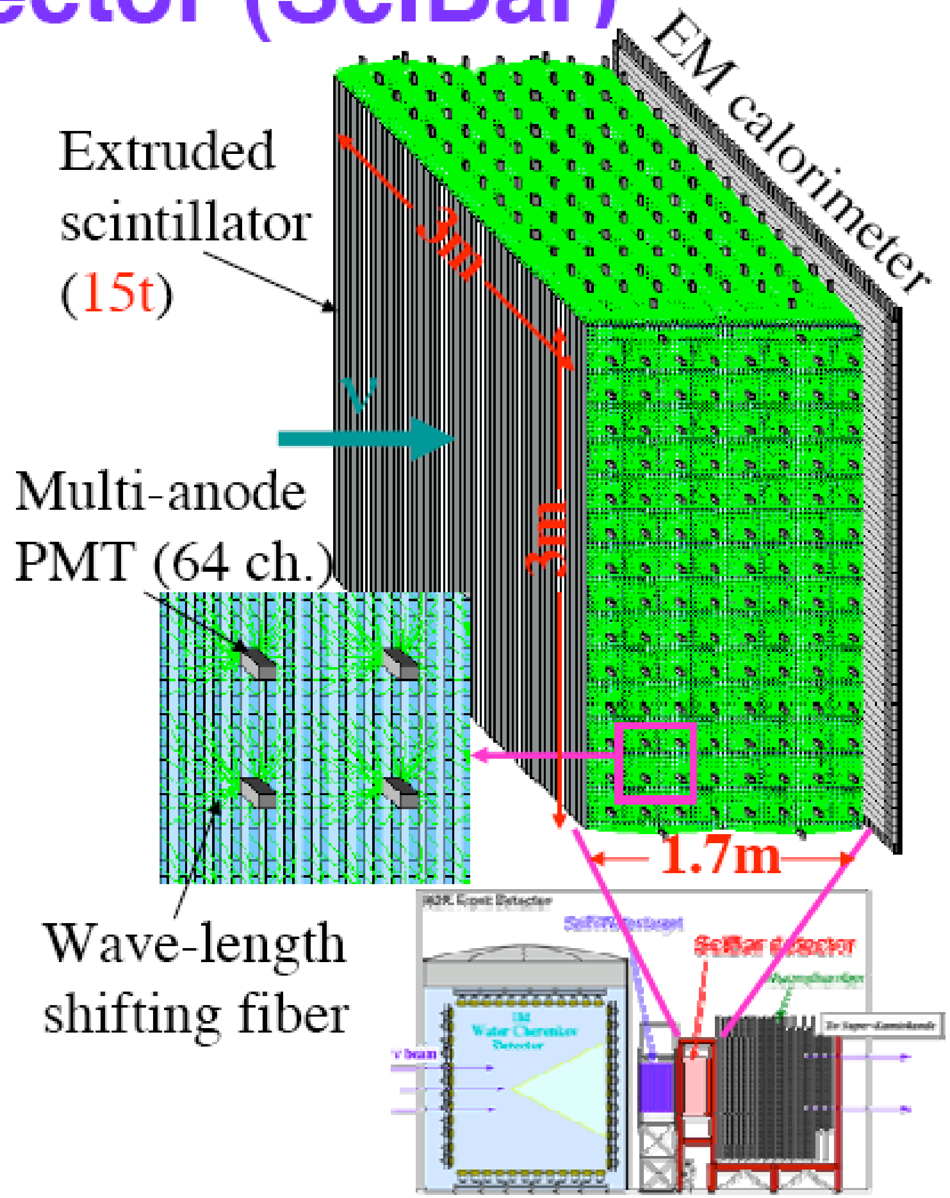
- **SciBar** detector

6. New Near Detector (SciBar)

- Extruded scintillator with WLS fiber readout
- Neutrino target is scintillator itself
- 2.5 x 1.3 x 300 cm^3 cell
- ~15000 channels
- Light yield
  7~20p.e./MIP/cm (2 MeV)
- Detect 10 cm track
- Distinguish proton from pion by using dE/dx

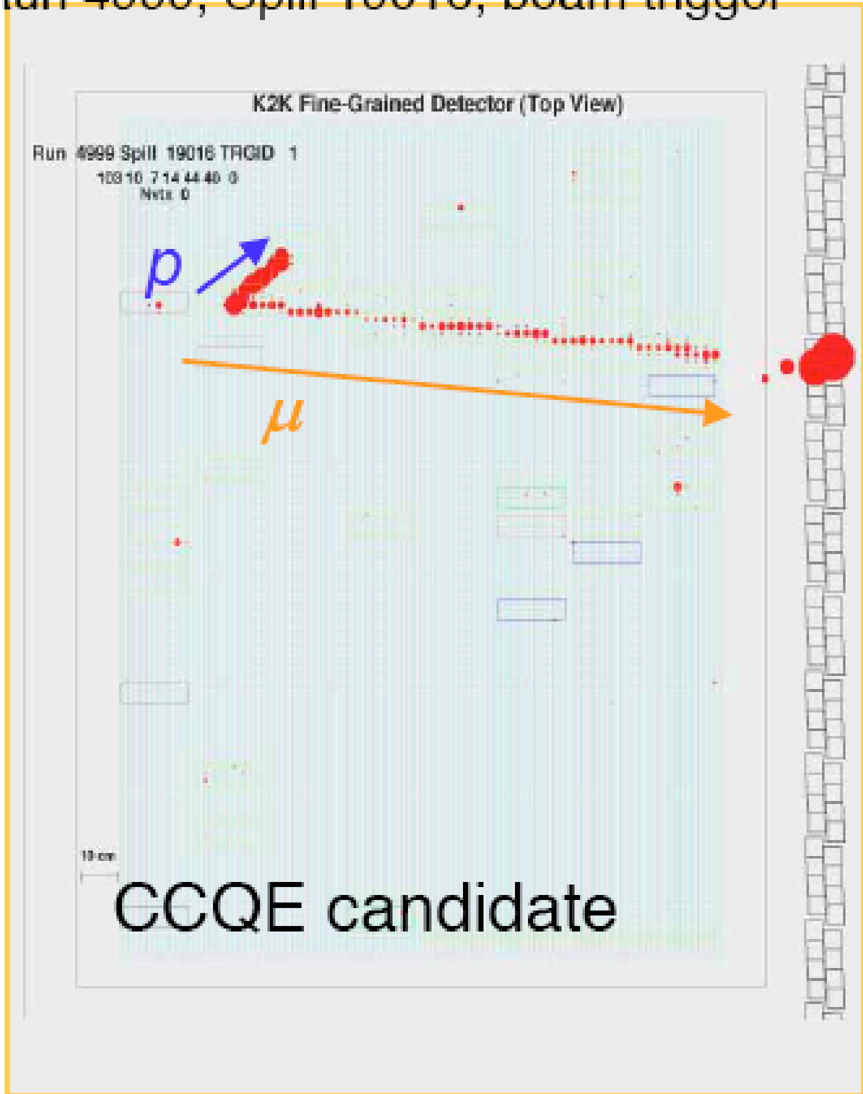
➔High 2-track CC-QE efficiency

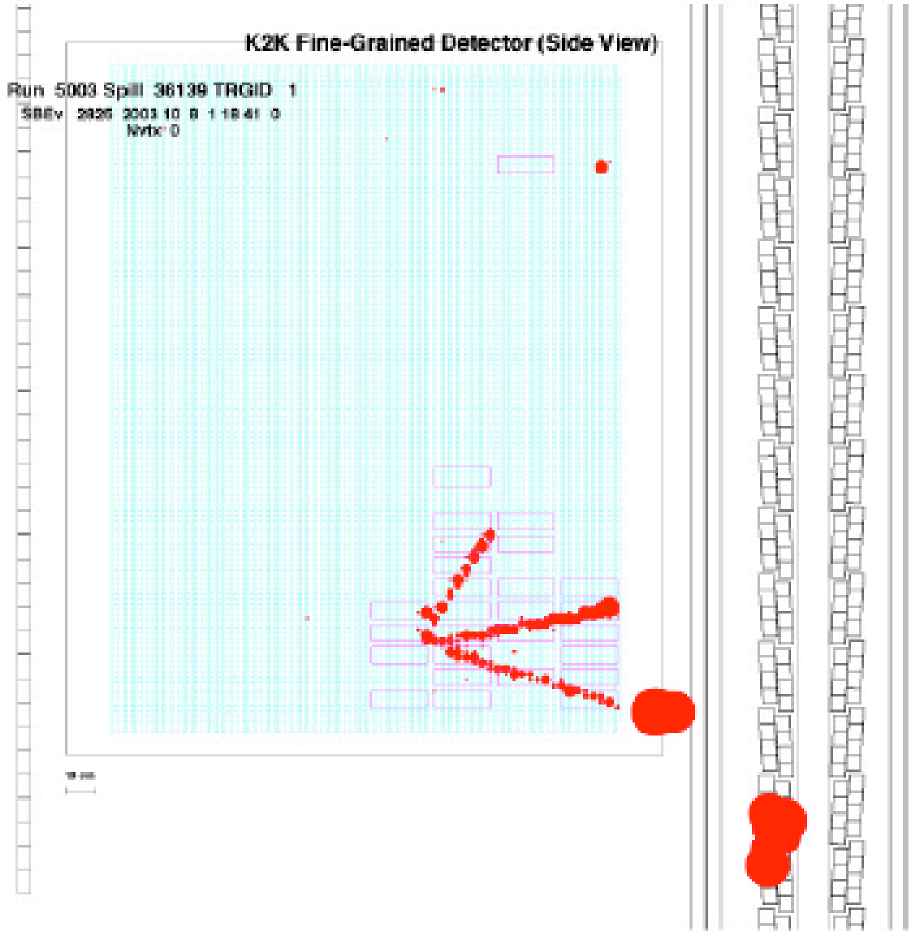
➔Low non-QE backgrounds



SCIBAR is working well since October 2003

Run 4999, Spill 19016, beam trigger





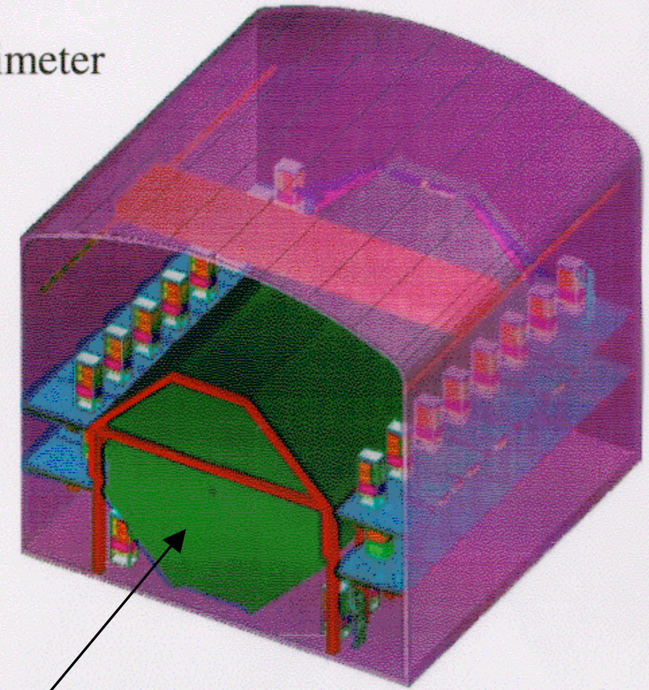
3track event

→ Fine grain detector !

NUMI-MINOS program

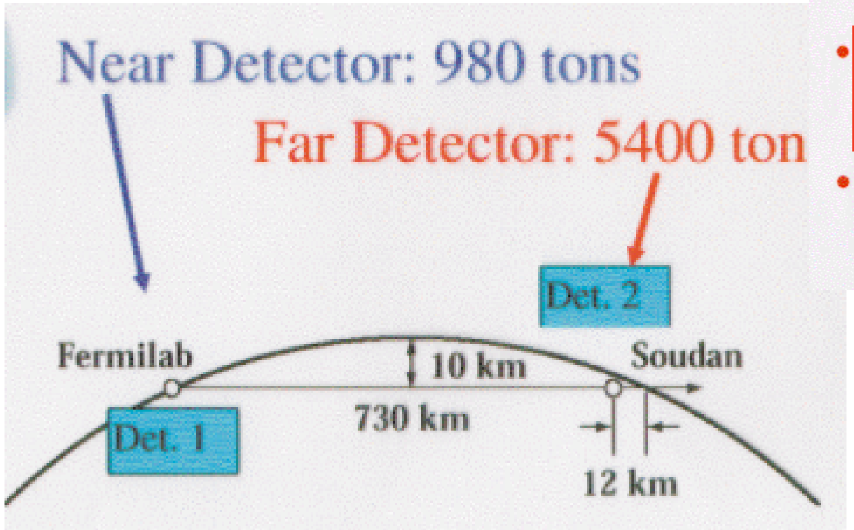
Two detector Neutrino Oscillation Experiment (Start 2004)

- 8m Octagonal Tracking Calorimeter
- 486 layers of 2.54cm Fe
- 2 sections, each 15m long
- 4.1cm wide solid scintillator strips with WLS fiber readout
- 25,800 m² active detector planes
- Magnet coil provides <B> ≈ 1.3T
- 5.4kt total mass



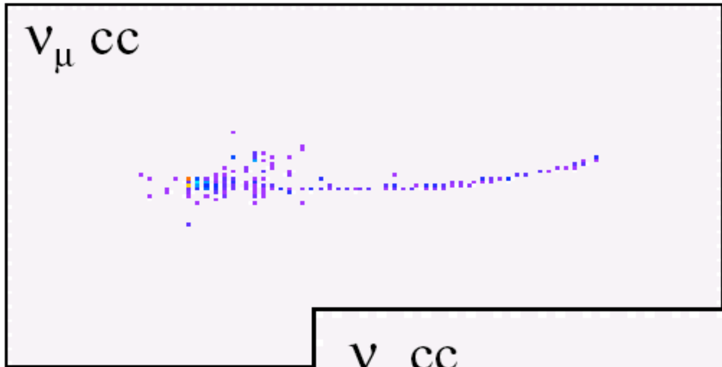
Half of the MINOS Far Detector

beam

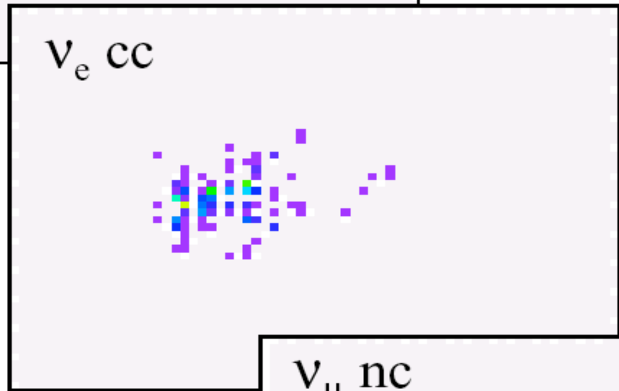


Topology of Neutrino Events

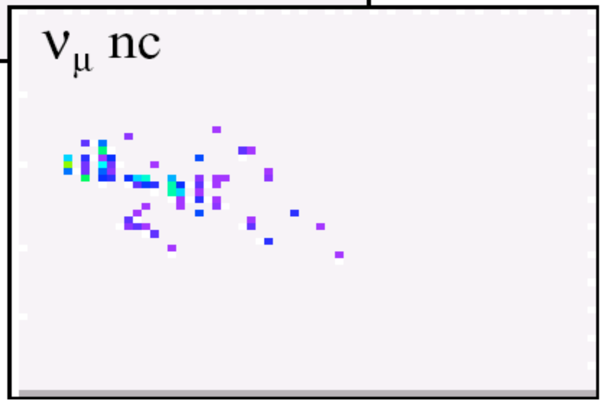
Identified by a relatively long track in an event. At very low energies, there can be some BG from NC π^-.



Identified by lack of a long track and a relatively concentrated EM shower in the core. Main BG comes from NC π^0 events From higher energy ν's.



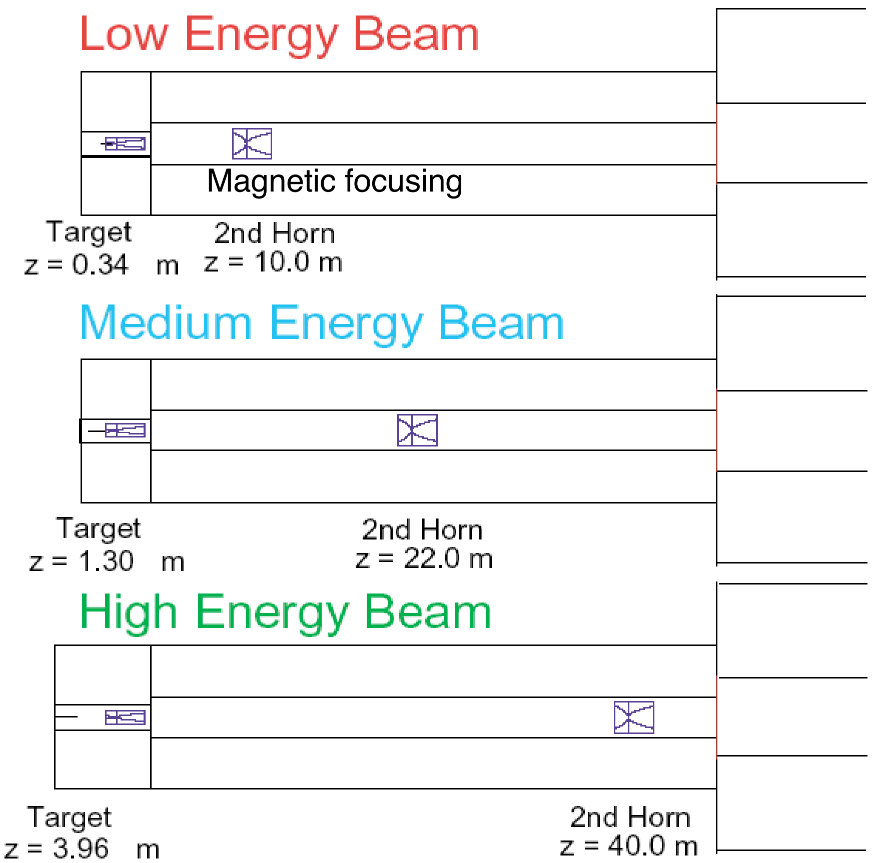
Identified by lack of a long track and lack of strong EM core. Some high y CC events are BG.

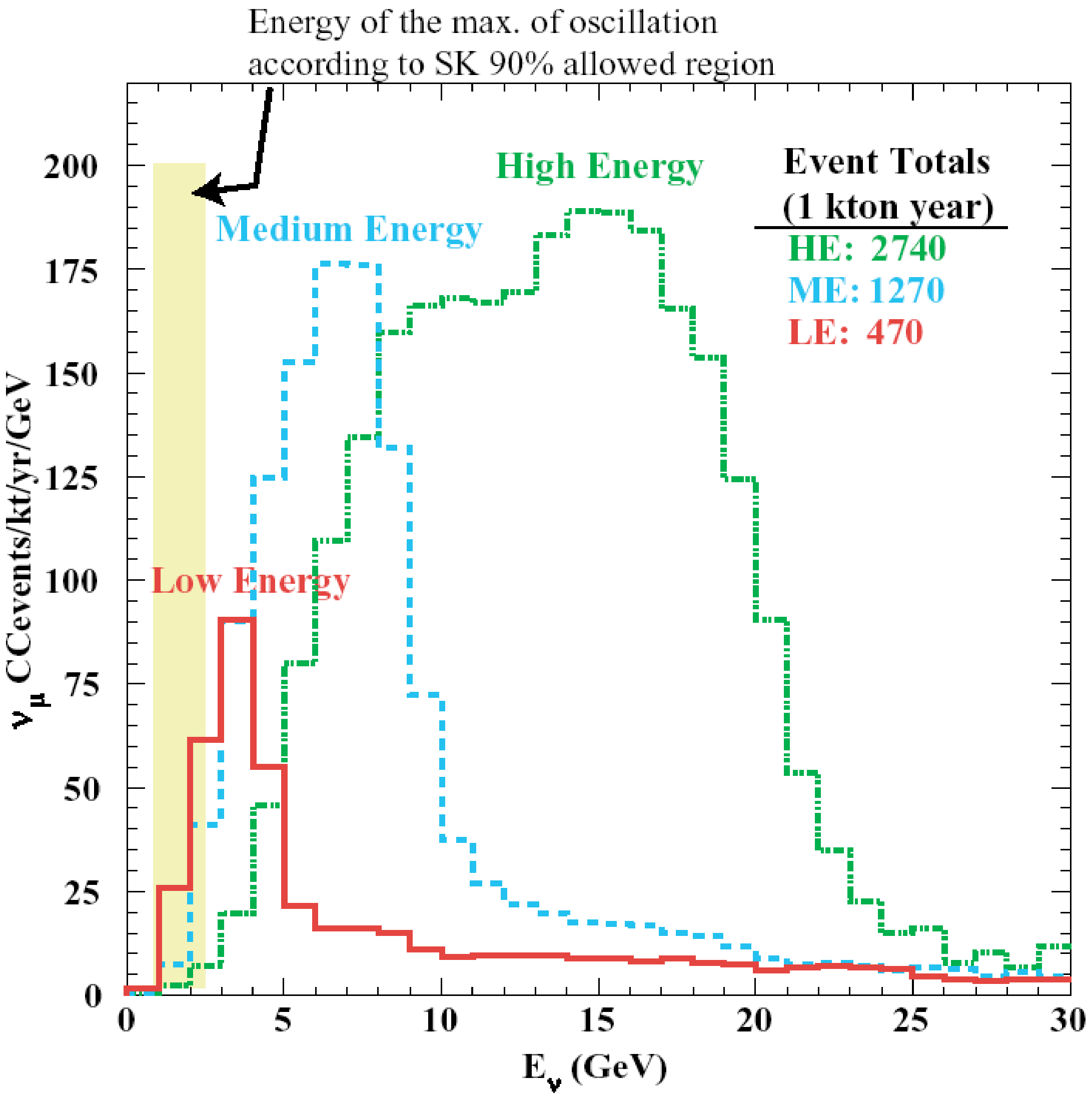


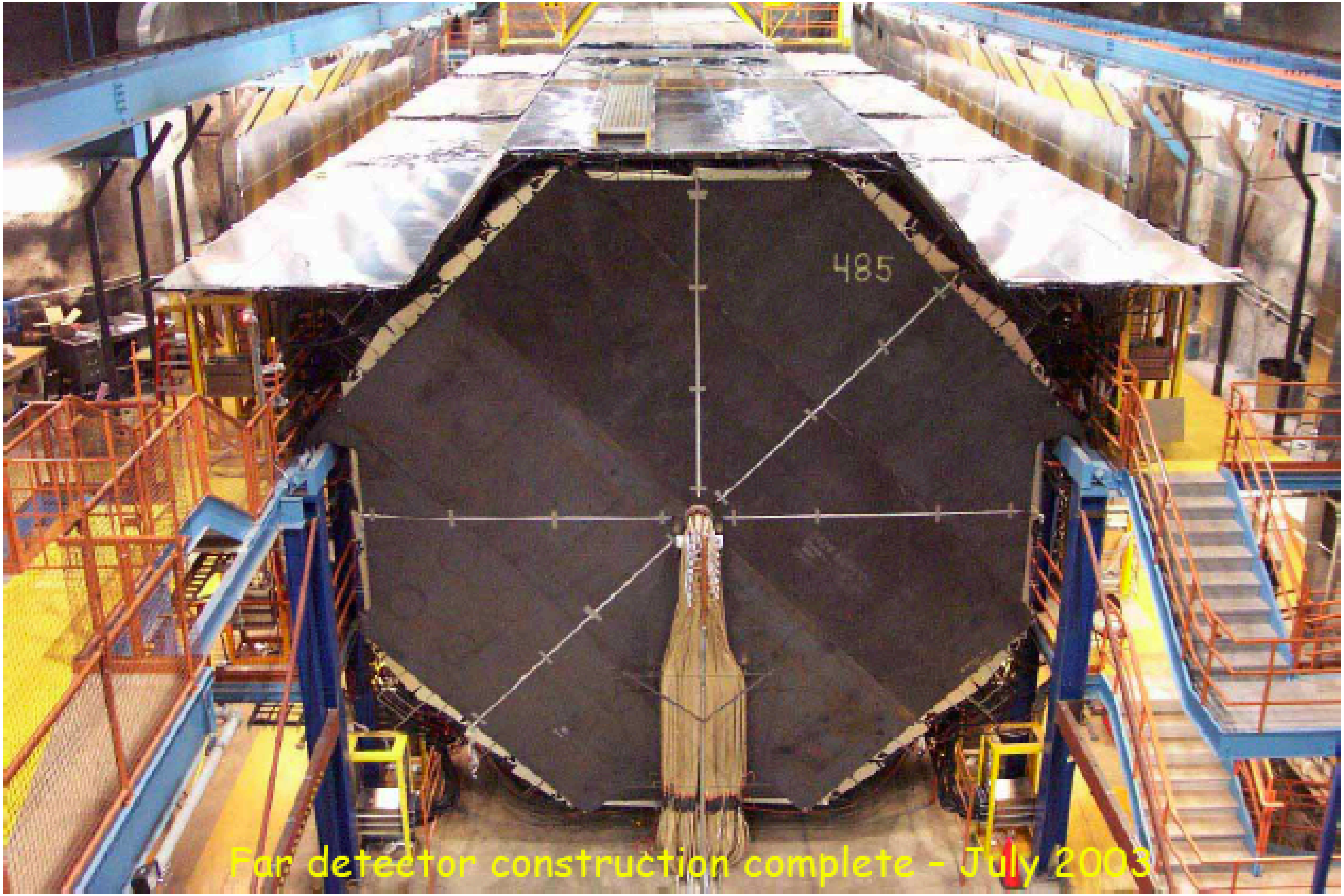
D. Michael, Neutrino 2002

NUMI neutrino beam

“Sacrifice neutrino flux to fit the expected energy of oscillated events”



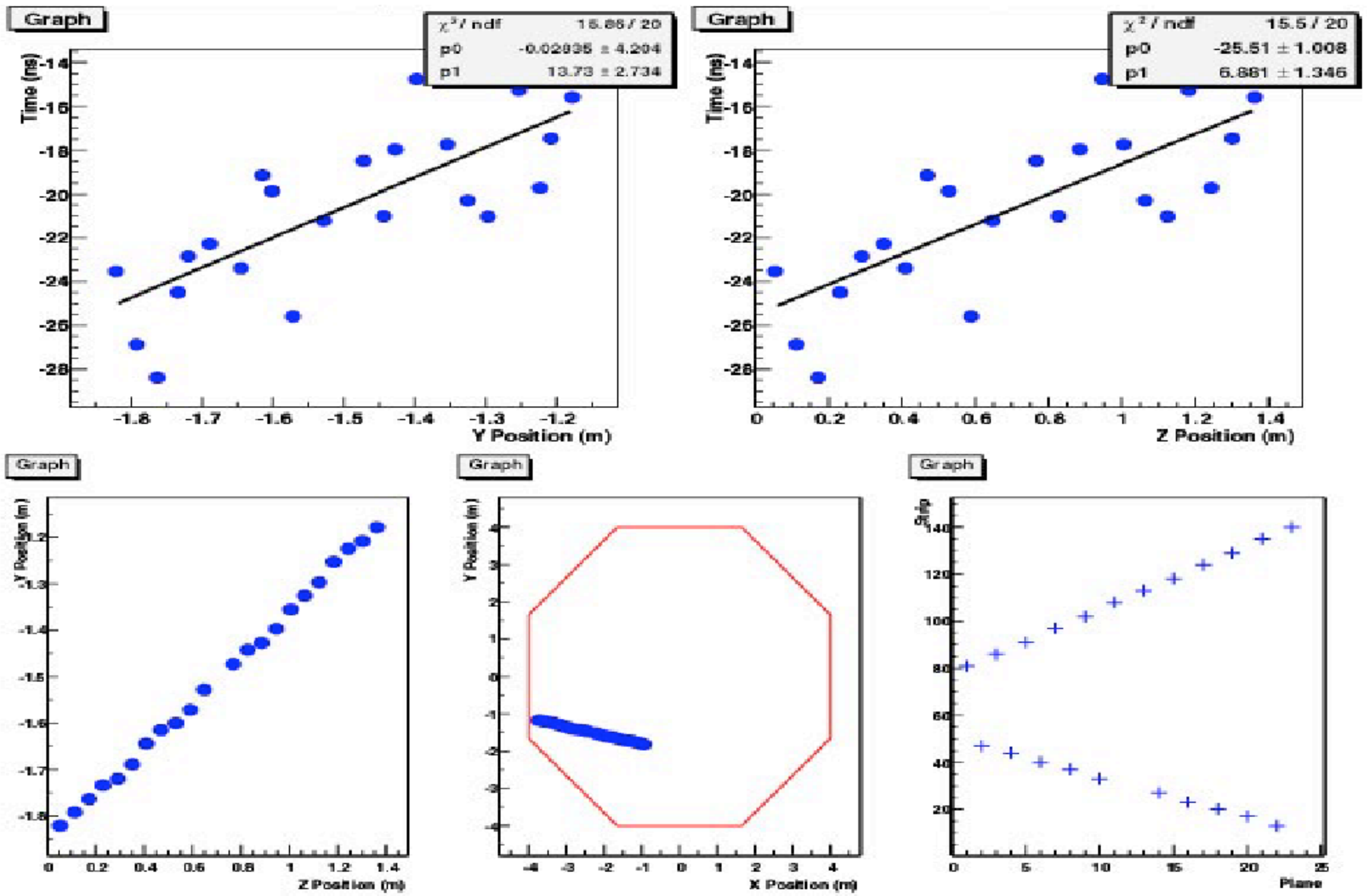




First data taking with FNAL beam: April 2005

The First MINOS Neutrino Event!

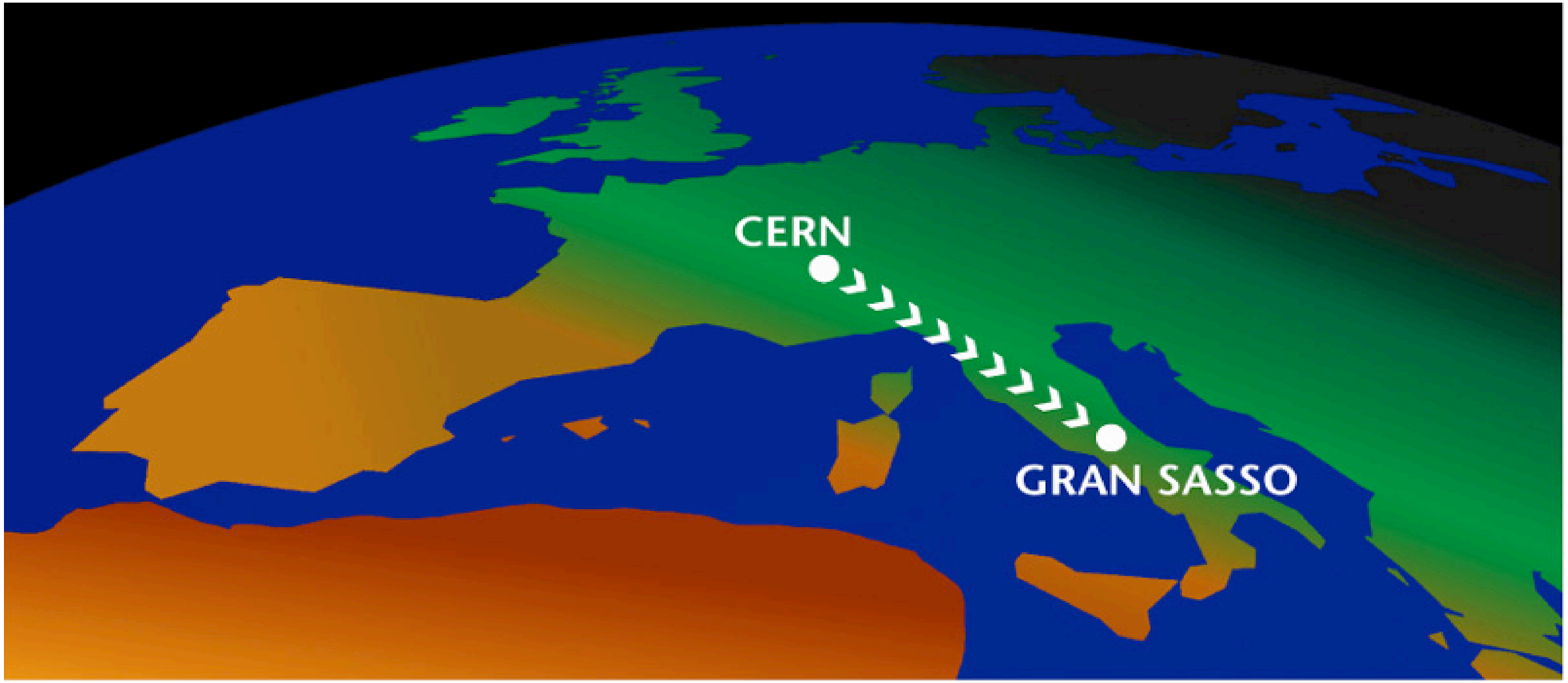
- The first neutrino-induced event has recently been observed!
- Upgoing muon passing through about 3.5 m of the detector. ($p_{\mu} > 1.9$ GeV/c)
- Magnetic field not on yet so no measurement of the momentum.



D. Michael, Neutrino 2002

ETH Institute for Particle Physics

Goal of the CNGS project

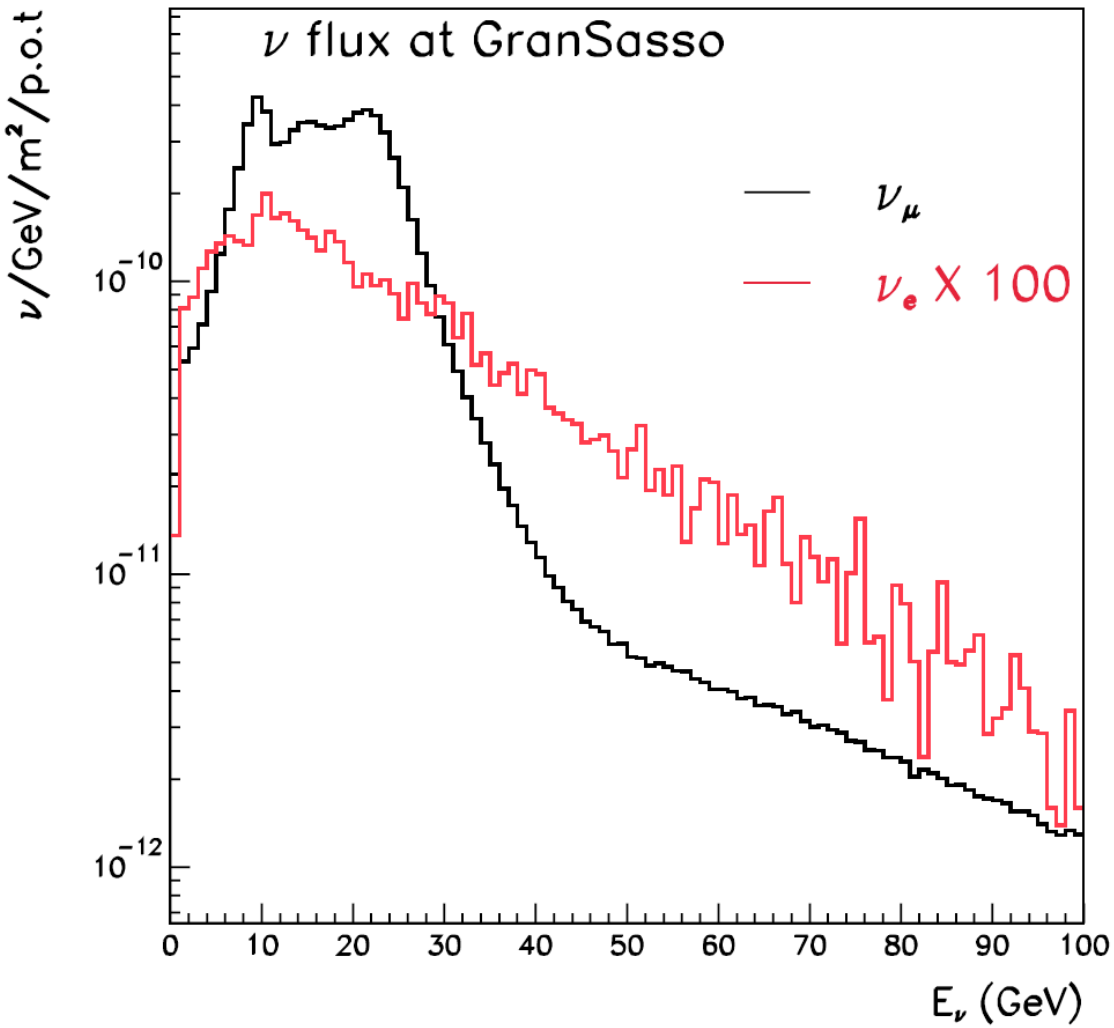


"Long Base-Line" $\nu_\mu \rightarrow \nu_\tau$ oscillation experiments

- build an intense high energy ν_μ beam at CERN-SPS
- optimized for ν_τ appearance search at Gran Sasso laboratory (730 km from CERN)

First physics: 2007

CNGS neutrino fluxes and rates



CERN SL-note 2000-063 EA

Energy region E_{ν_μ} [GeV]	1 - 30	1 - 100
ν_μ [m^{-2}/pot] ν_μ CC events/pot/kt	7.36×10^{-9} 5.05×10^{-17}	7.78×10^{-9} 5.85×10^{-17}
$\langle E \rangle_{\nu_\mu\, fluence}$ [GeV]		17.7
fraction of other neutrino events: ν_e/ν_μ $\overline{\nu}_\mu/\nu_\mu$ $\overline{\nu}_e/\nu_\mu$	 0.8 % 2.1 % 0.07 %	

- **Small ν_e contamination**

$$\nu_e / \nu_\mu = 0.8\%$$

- **Error on knowledge relative to ν_μ**

$$\Delta\nu_e / \nu_\mu \approx \left(\pm 5\% \nu_e\right) / \nu_\mu$$

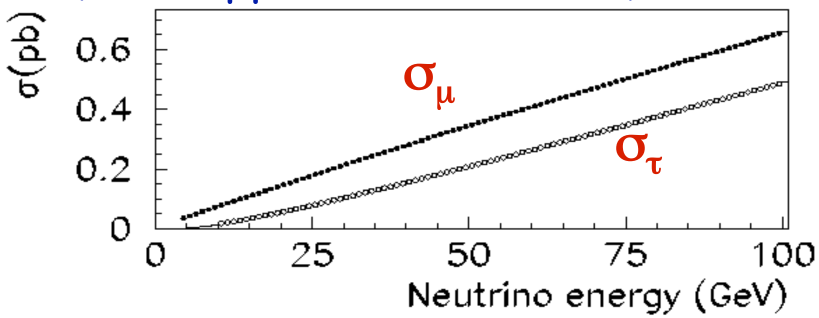
$$\approx \pm 4 \times 10^{-4}$$

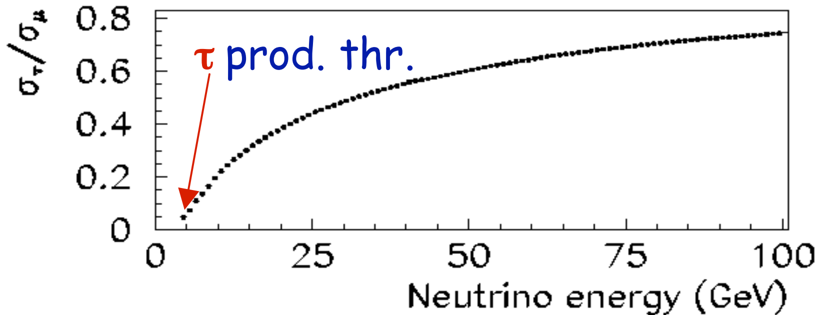
CNGS Optimization for ν_τ Appearance

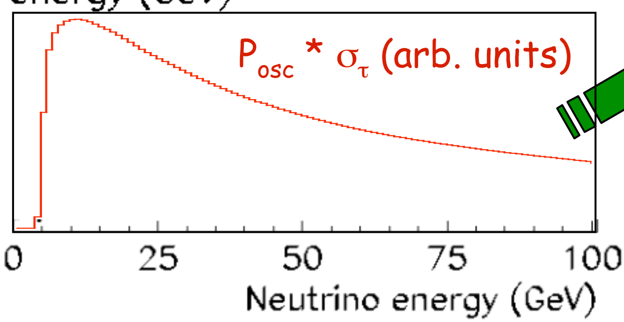
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2\left(1.27\,\Delta m^2 \frac{L}{E}\right)$$

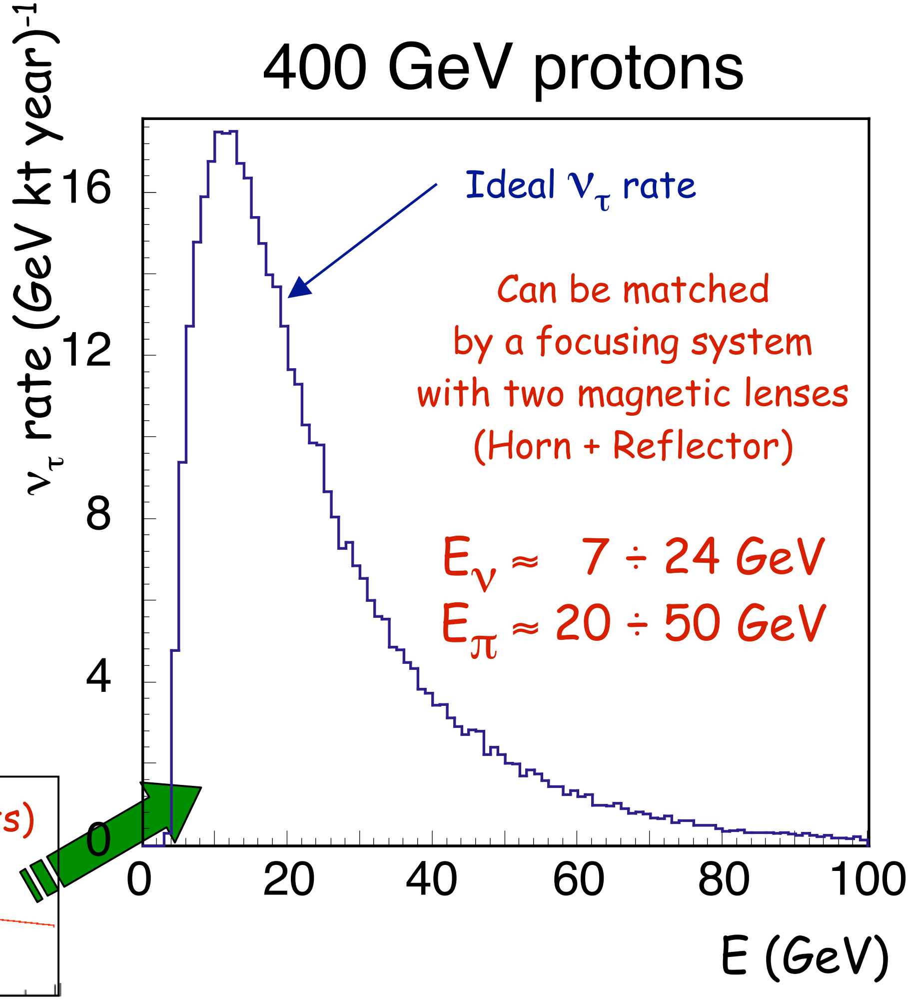
P_{osc} ↓ E_ν ↑

σ_τ/σ_μ CC increases with energy
(kin. suppr. due to τ mass)

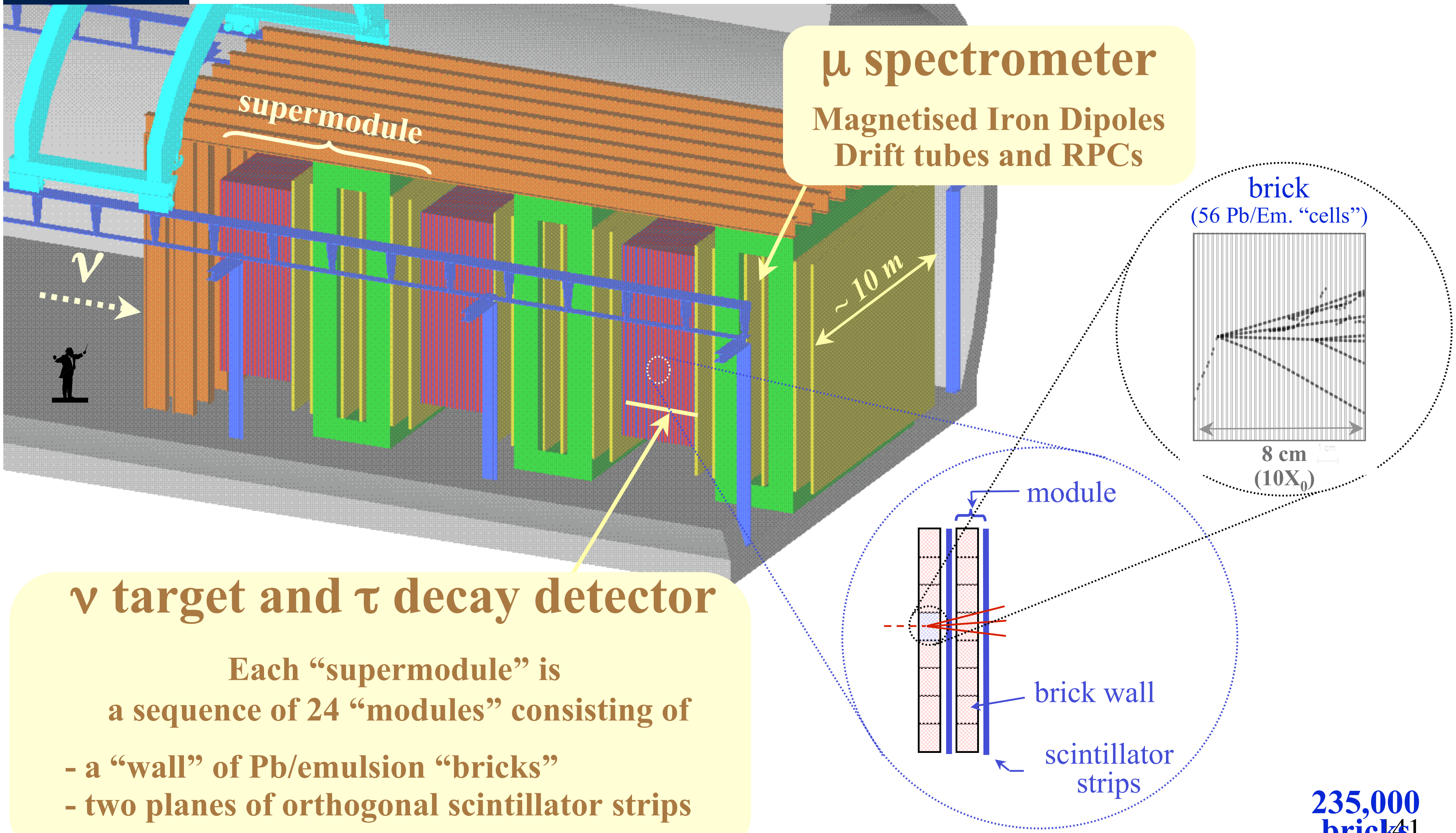








The OPERA (CNGS-1) detector structure



μ spectrometer

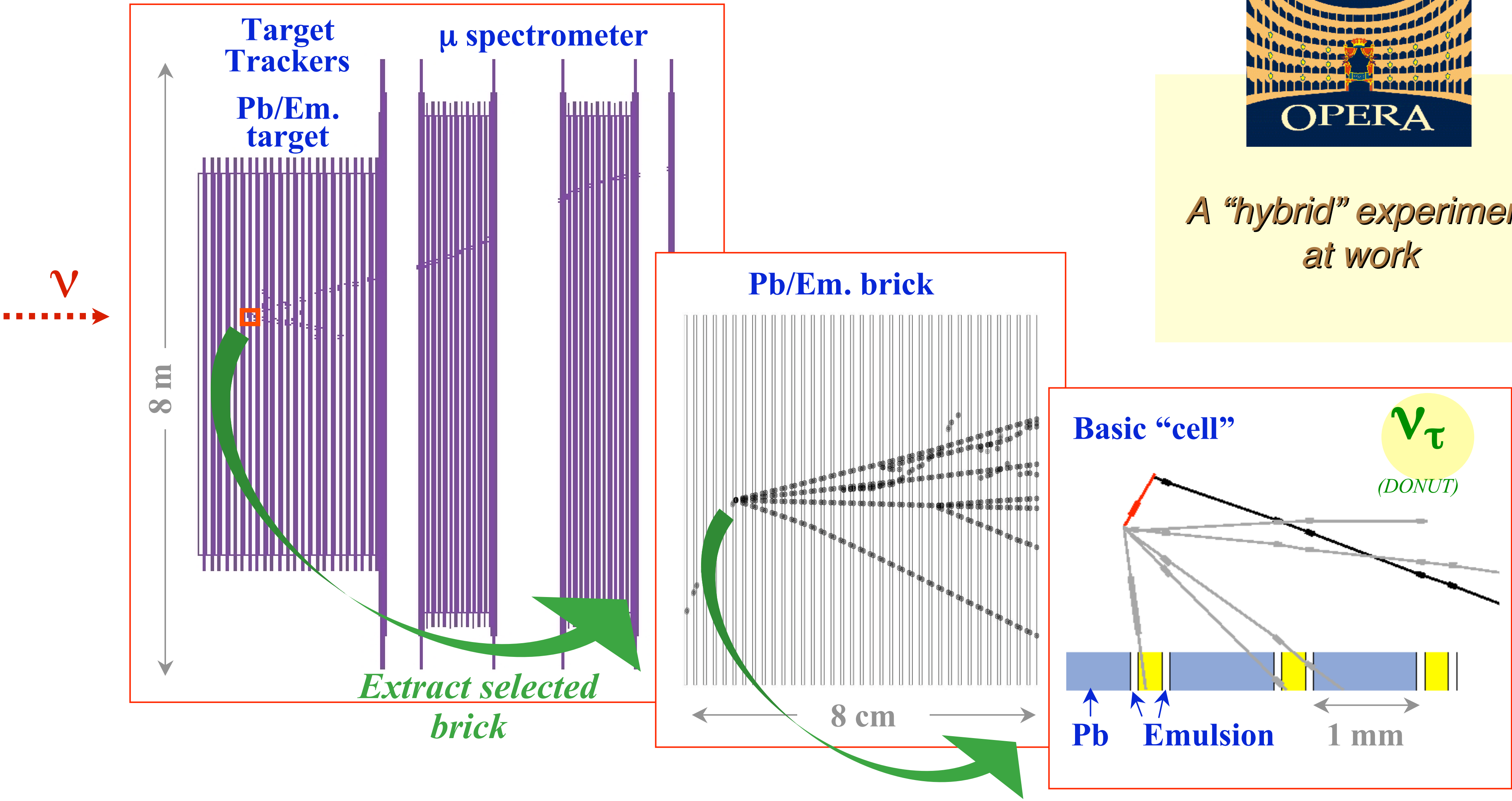
Magnetised Iron Dipoles
Drift tubes and RPCs

ν target and τ decay detector

Each "supermodule" is
a sequence of 24 "modules" consisting of

- a "wall" of Pb/emulsion "bricks"
- two planes of orthogonal scintillator strips

A “hybrid” experiment at work



Electronic detectors

→ select ν interaction brick

→ μ ID, charge and p

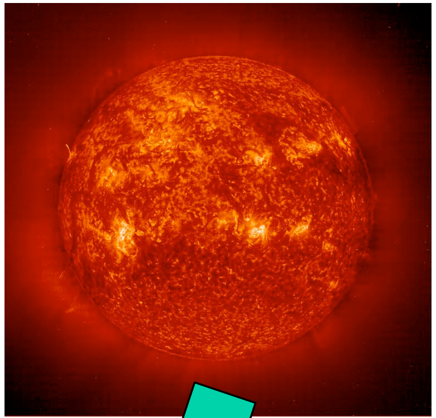
Emulsion analysis

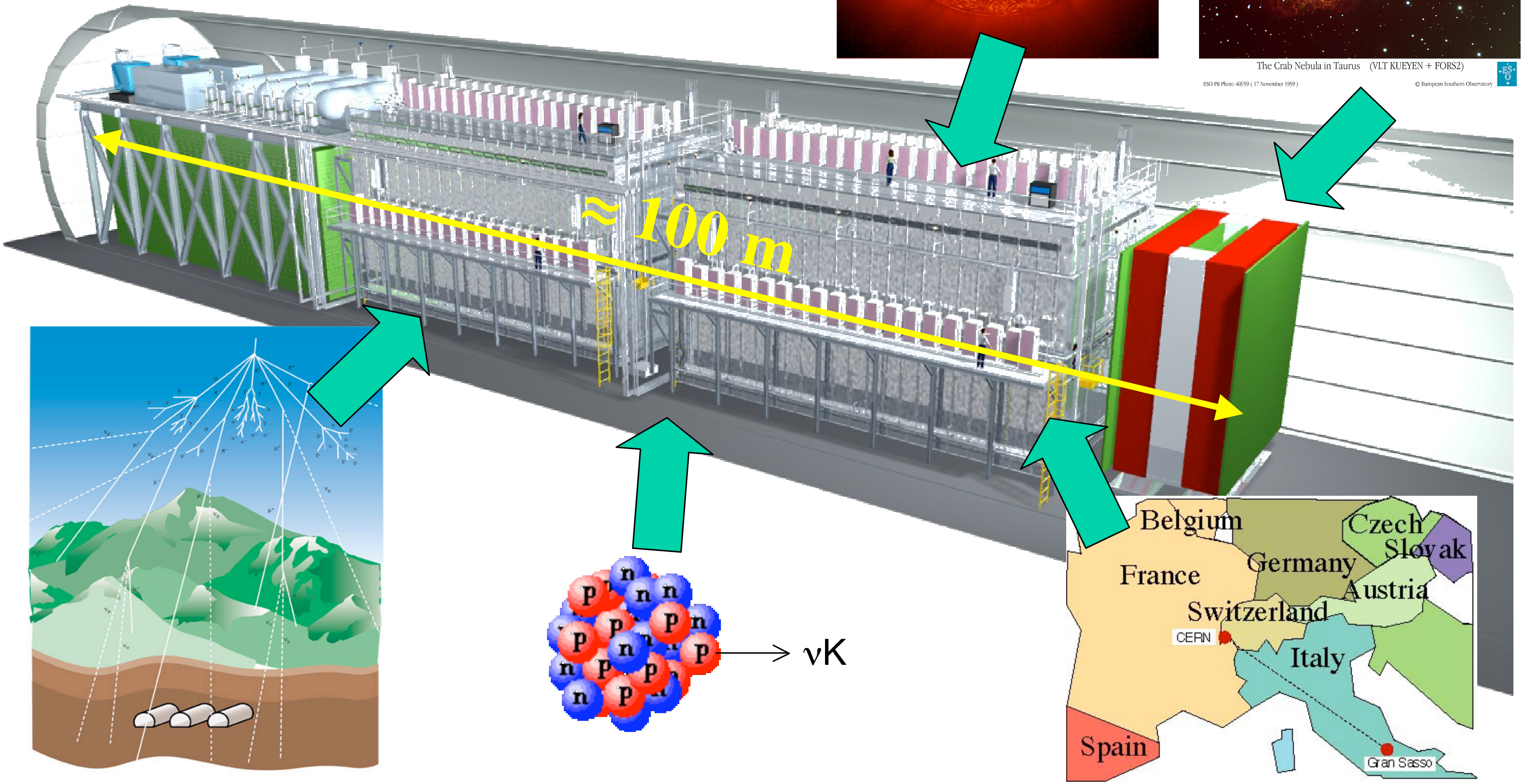
→ vertex search

→ decay search

→ e/γ ID, kinematics

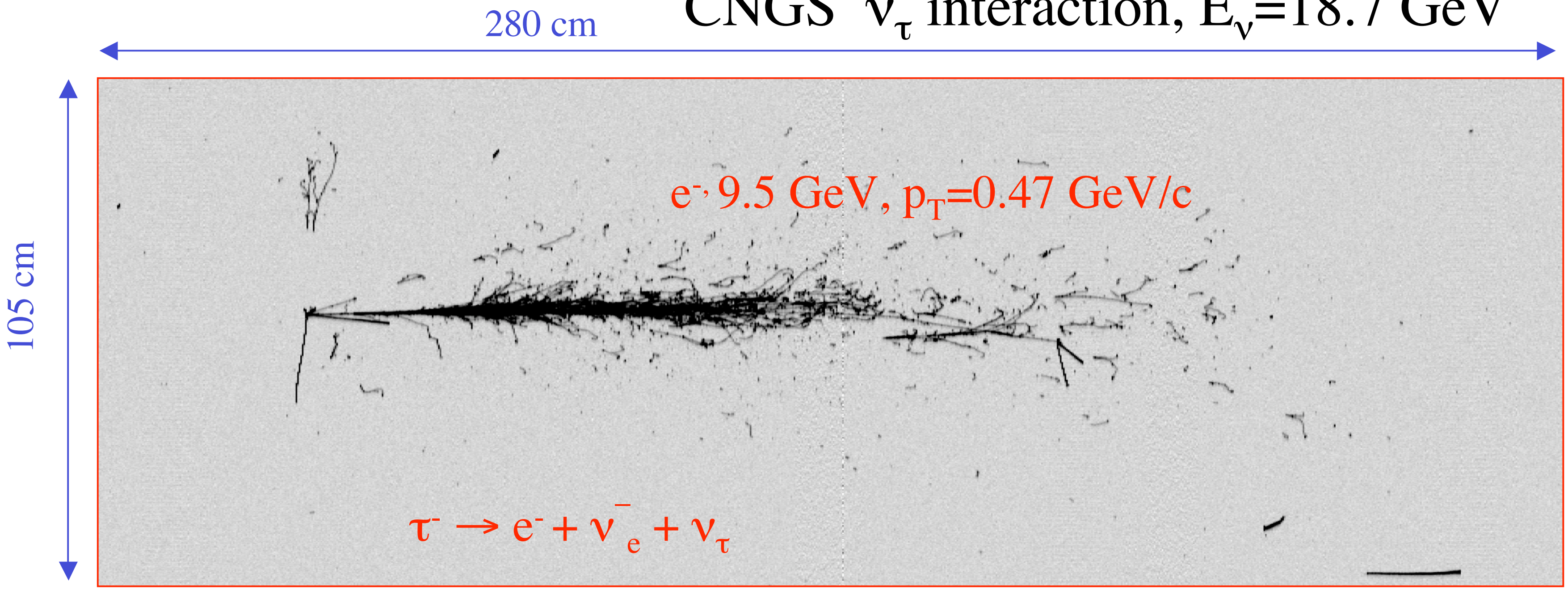
ICARUS T3000 (CNGS-2): "A Second-Generation Proton Decay Experiment and Neutrino Observatory at the Gran Sasso Laboratory"

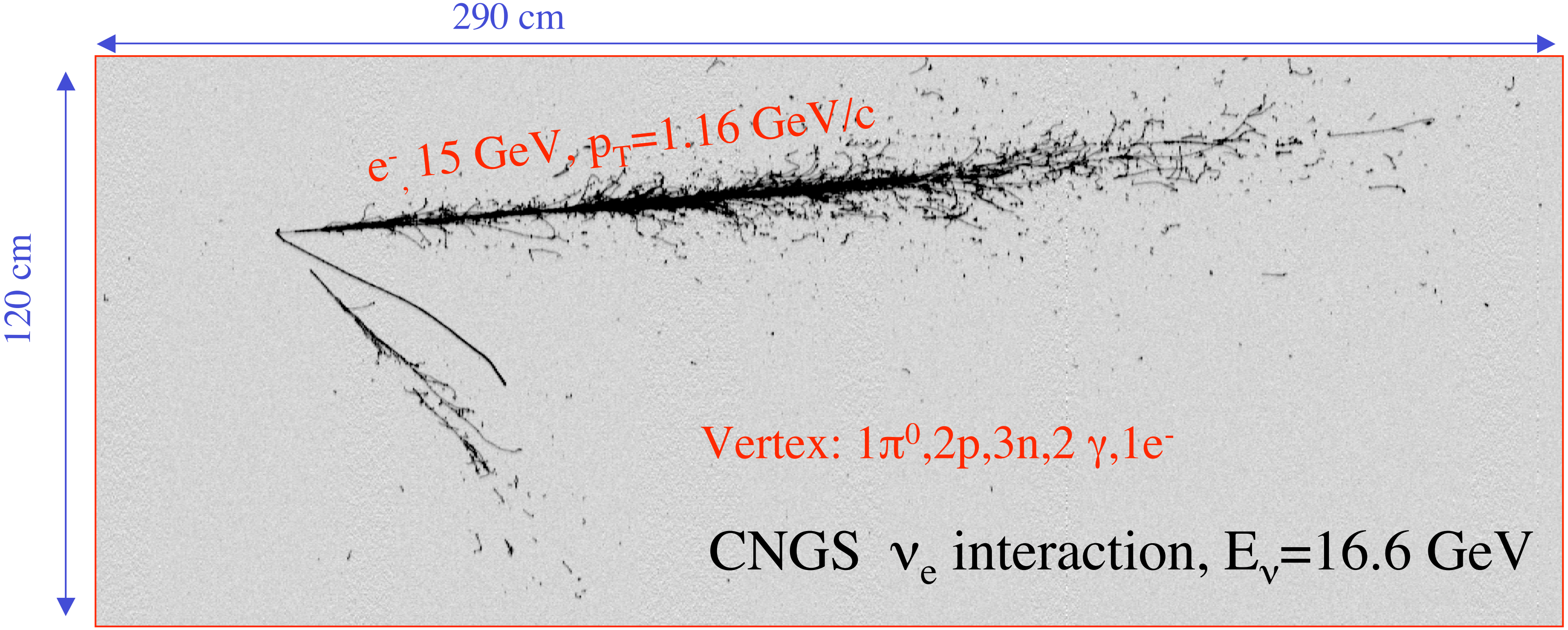




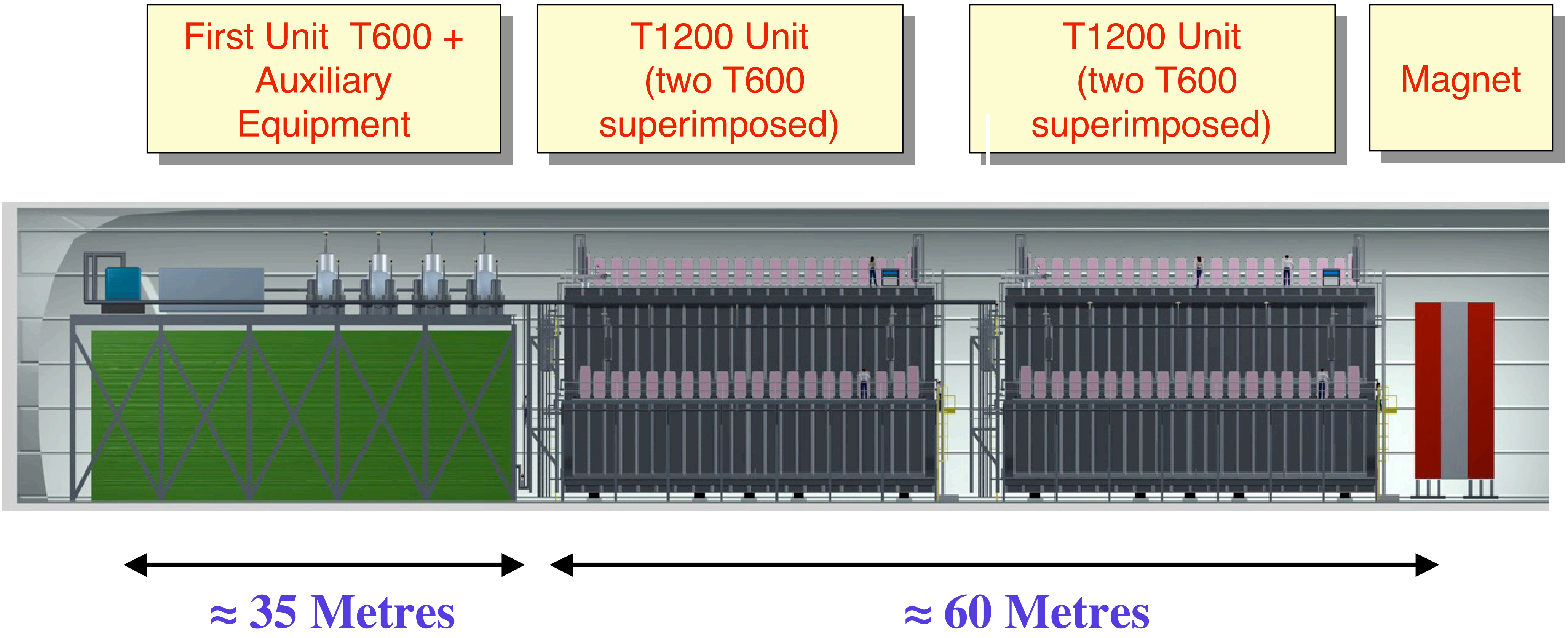
Kinematical separation

CNGS ν_τ interaction, E_ν=18.7 GeV

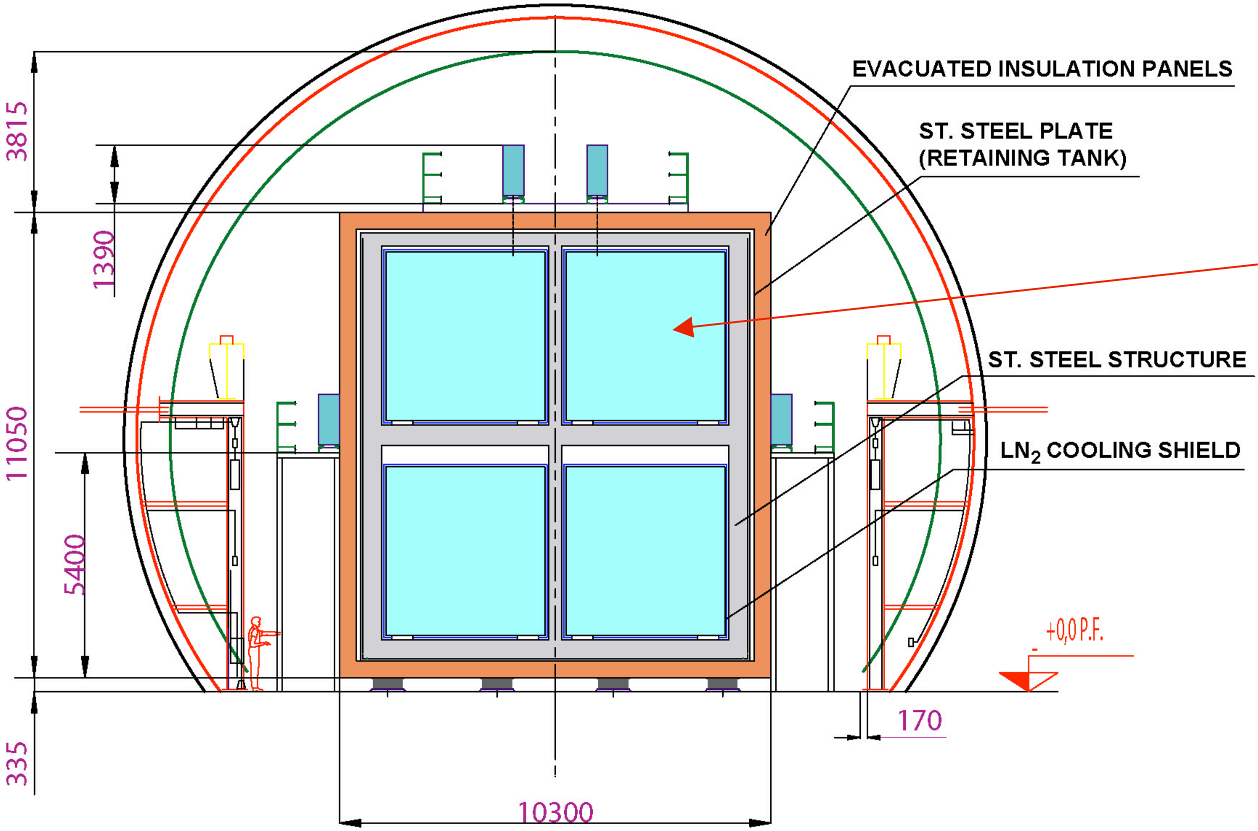




ICARUS detector configuration in LNGS Hall B (T3000)



The T1200 "Unit"

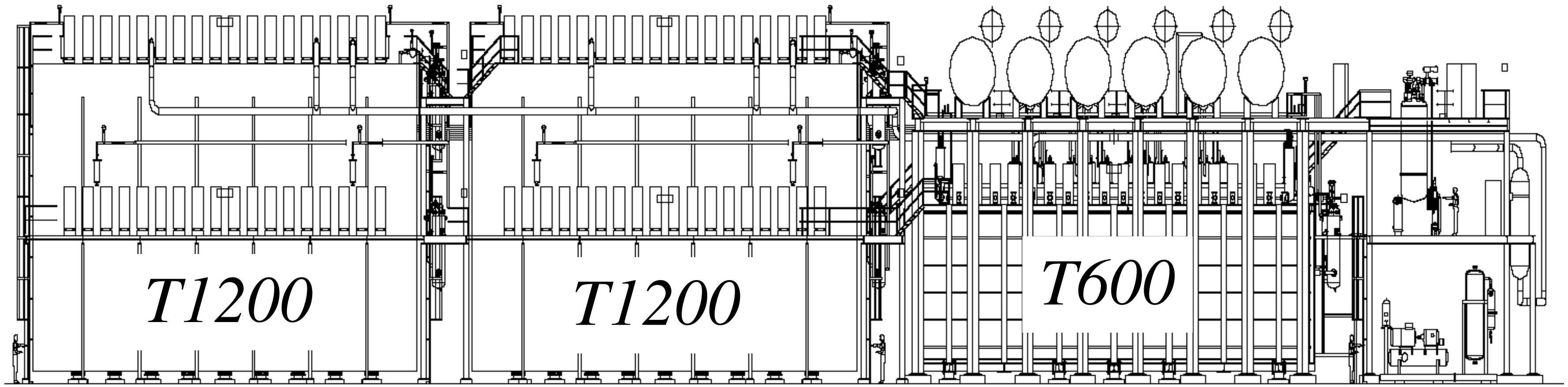


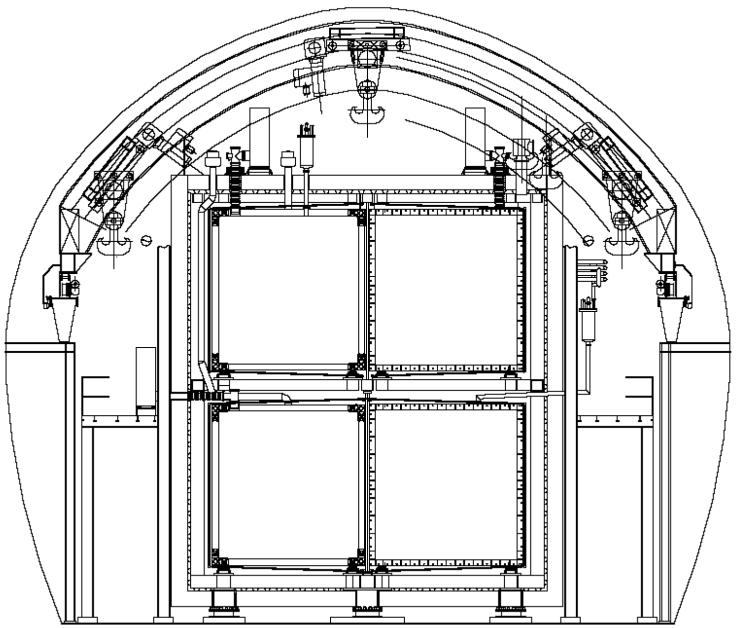
- Based on cloning the present T600 containers
  - ➥ A cost-effective solution given tunnel access conditions
- Preassembled modules outside tunnel are arranged in supermodules of about 1200 ton each (4 containers)
  - ➥ Time effective solution (parallelizable)
- Drift doubled 1.5 m ➔ 3 m
  - ➥ Sensible solution given past experience
- Built with large industrial support (AirLiquide, Breme-Tecnica, Galli-Morelli, CAEN, …)
  - ➥ "Order as many as you need" solution

Detailed engineering project was produced by Air Liquide (June 2003)

T1200 CRYOSTAT READY FOR TENDERING

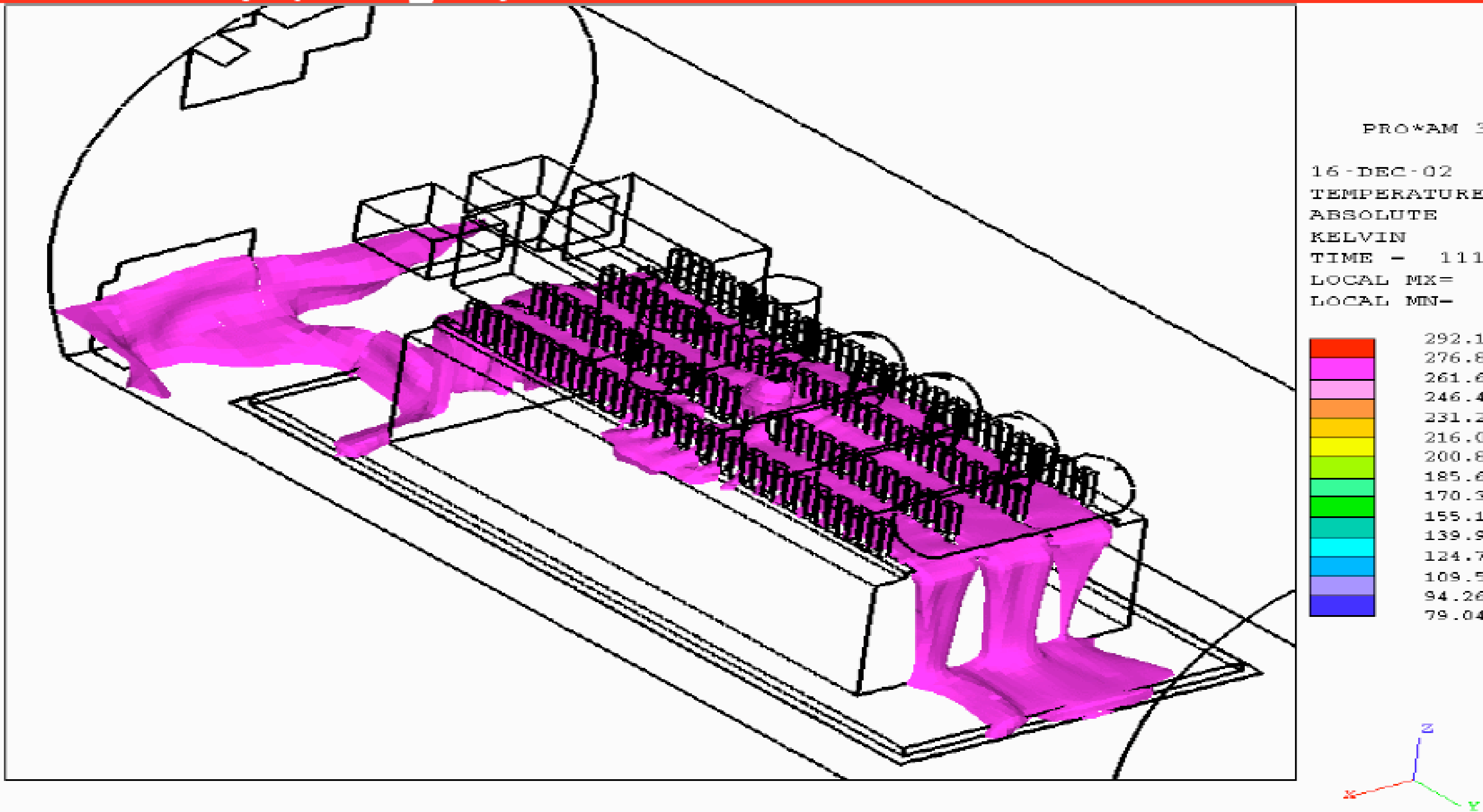
T3000 "definitive" project at LNGS Hall B



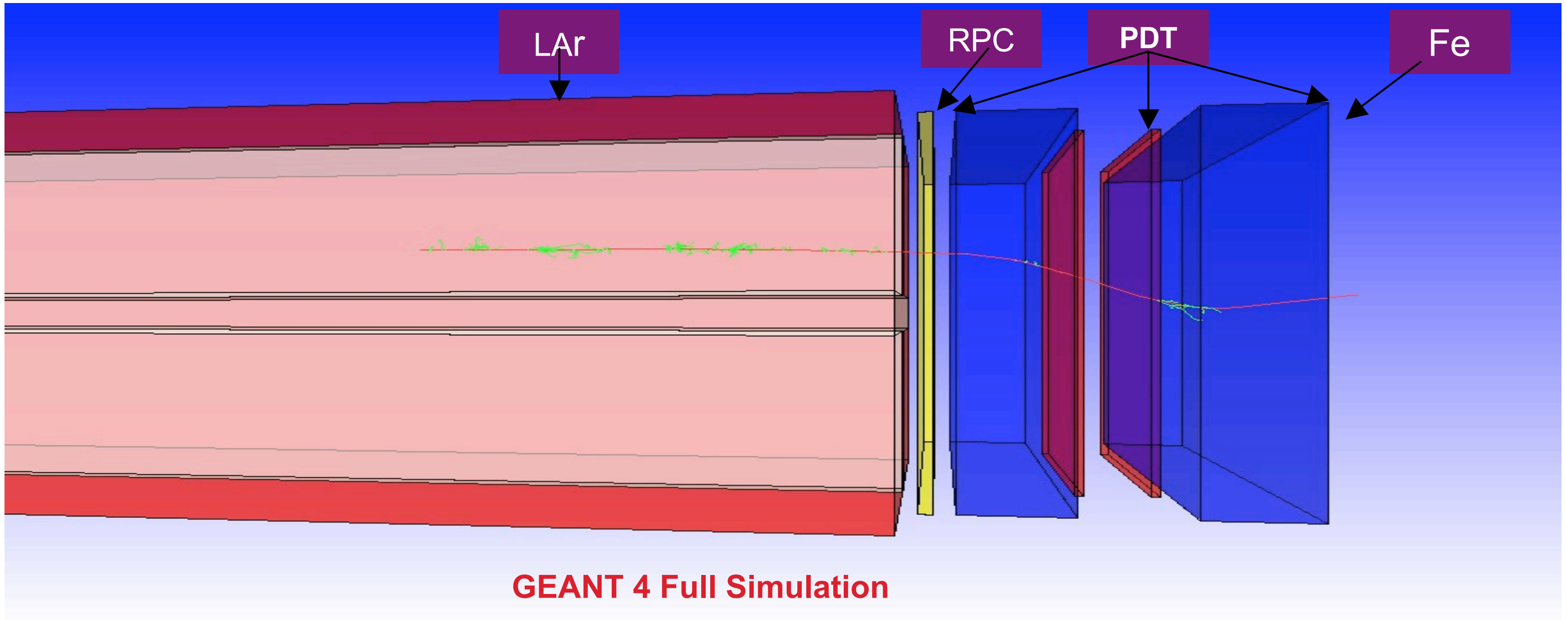


Complete engineering

LN2 release from broken connections of storage tank (Q=2Kg/s) – Isotherm 0°C after 2 min



Muon spectrometer



- **Simultaneous optimization of Physics performance and cost**
- **Simplest solution (known technology, no R&D needed)**
  - ➥ Passive material: Magnetized non-instrumented iron
    - ☛ B=1.8 T
    - ☛ Cross Section: 8.5 x 8.5 m^2, two bending sections 1.5 m long each
  - ➥ Sensitive part: Planes of proportional drift tubes
  - ➥ External device to provide trigger: RPC (precise t0 measurement)

Next major issue

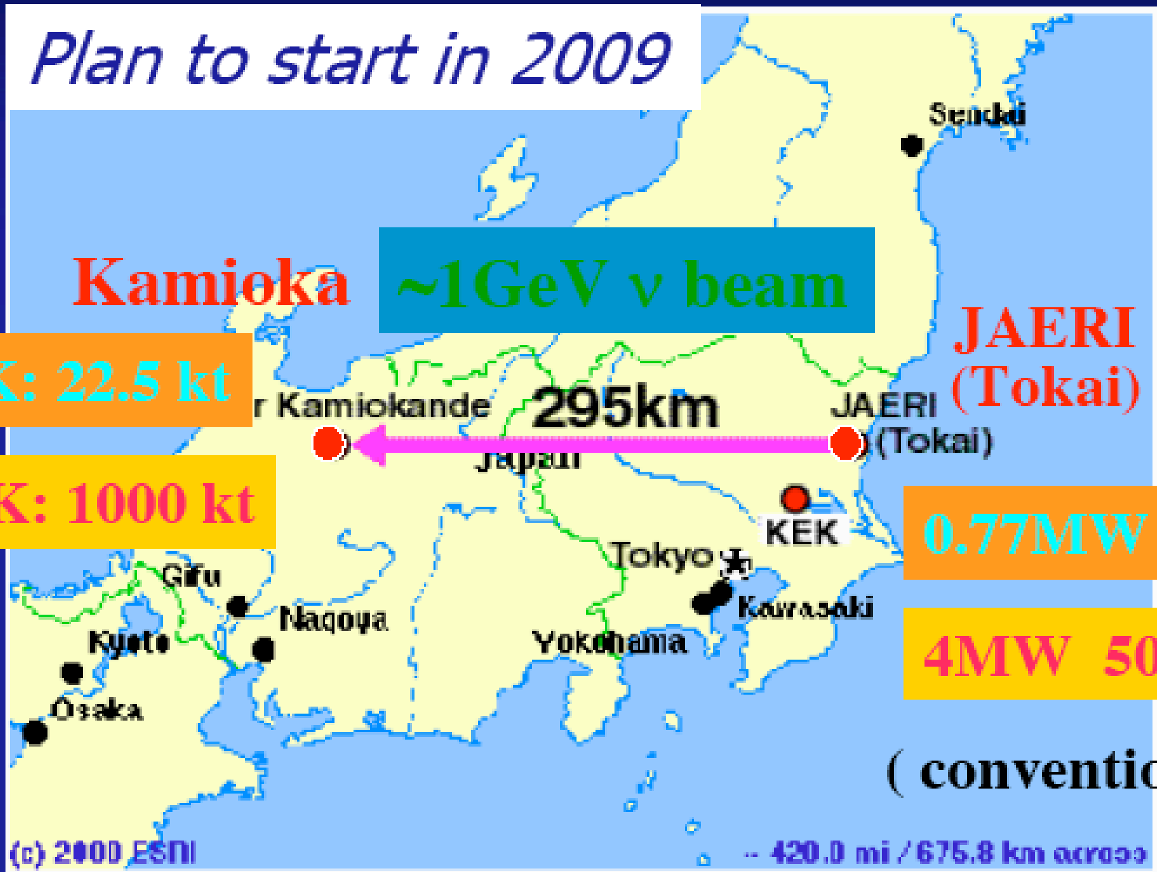
Determine the magnitude of θ_{13}

Towards the measurement of CP-phase

JHF-Kamioka Neutrino Experiment

(hep-ex/0106019)

Plan to start in 2009



Kamioka

~1GeV ν beam

Super-K: 22.5 kt

Hyper-K: 1000 kt

JAERI (Tokai)

0.77MW 50 GeV PS

4MW 50 GeV PS

(conventional ν beam)

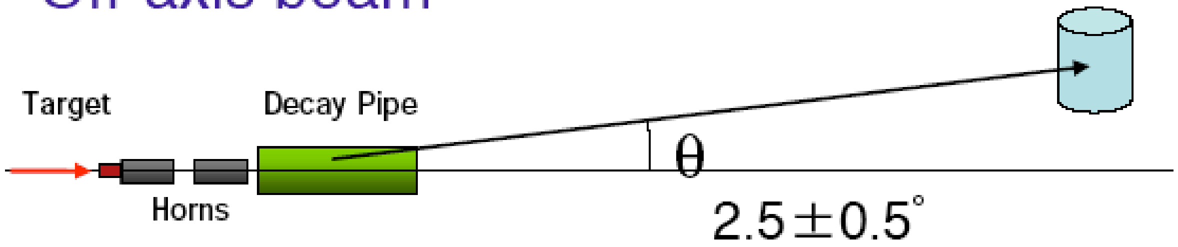
Phase-I (0.75MW + Super-Kamiokande)

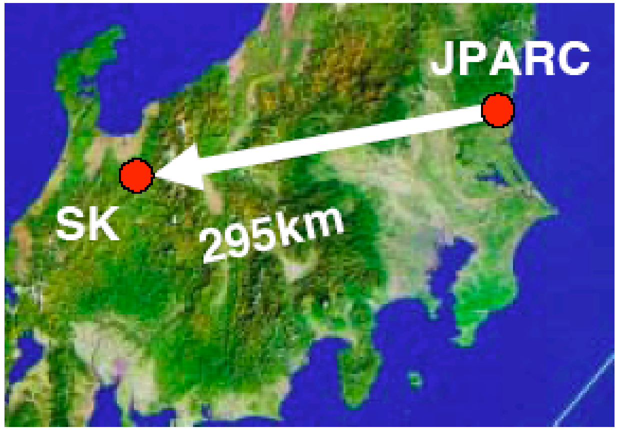
Phase-II (4MW+Hyper-K) ~ Phase-I × 200

Itow, NOON04

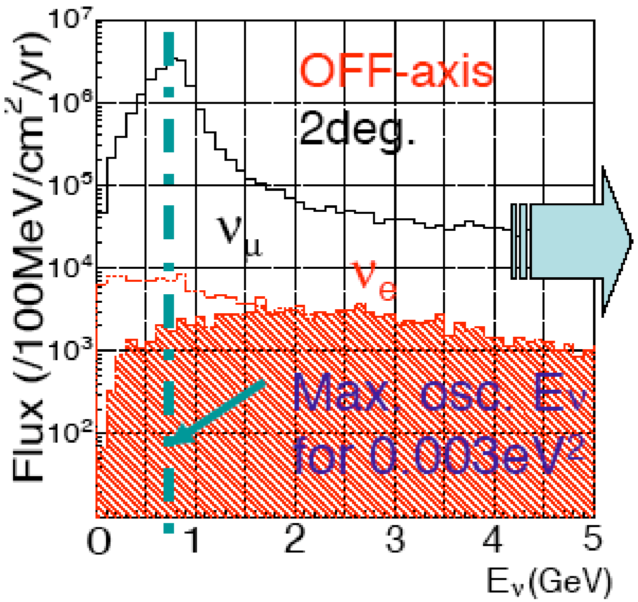
JPARC neutrino project

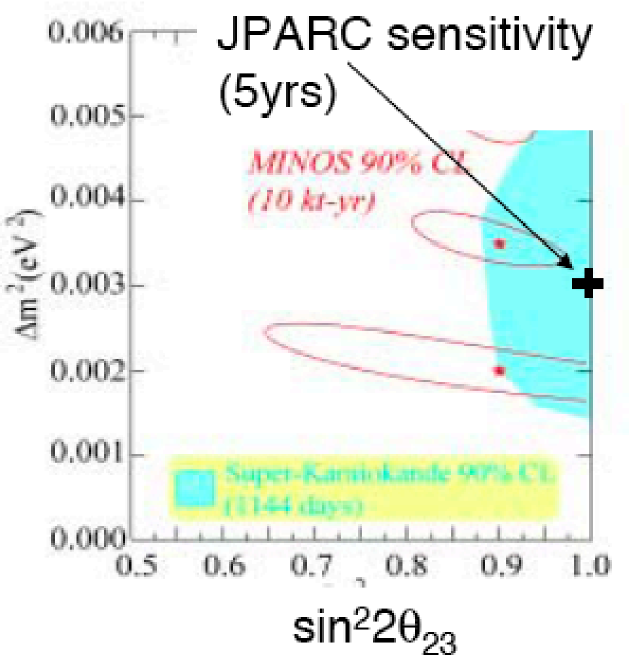
Off-axis beam

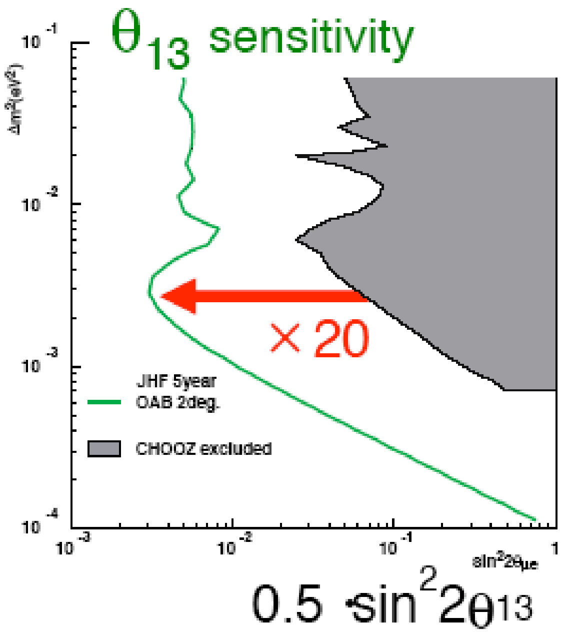




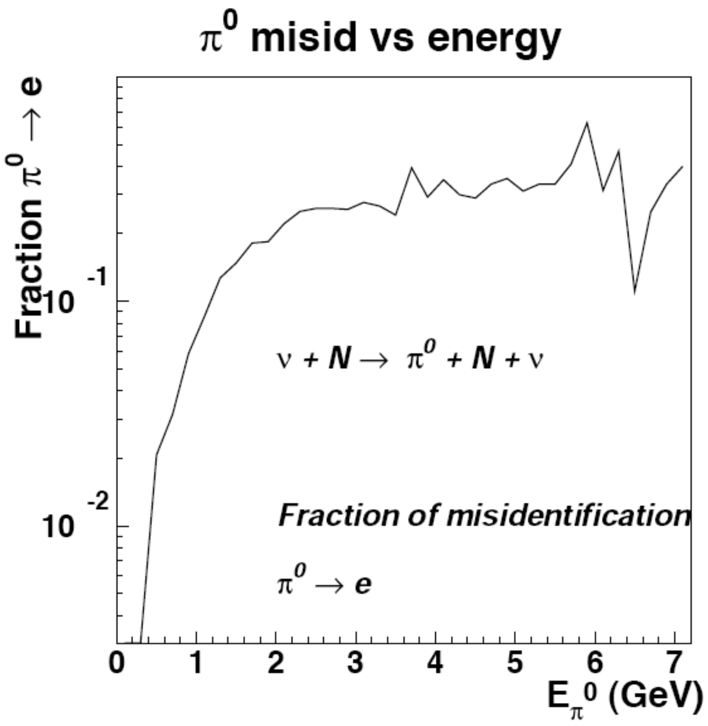
×100 more intensity than K2K, Eν < 1GeV

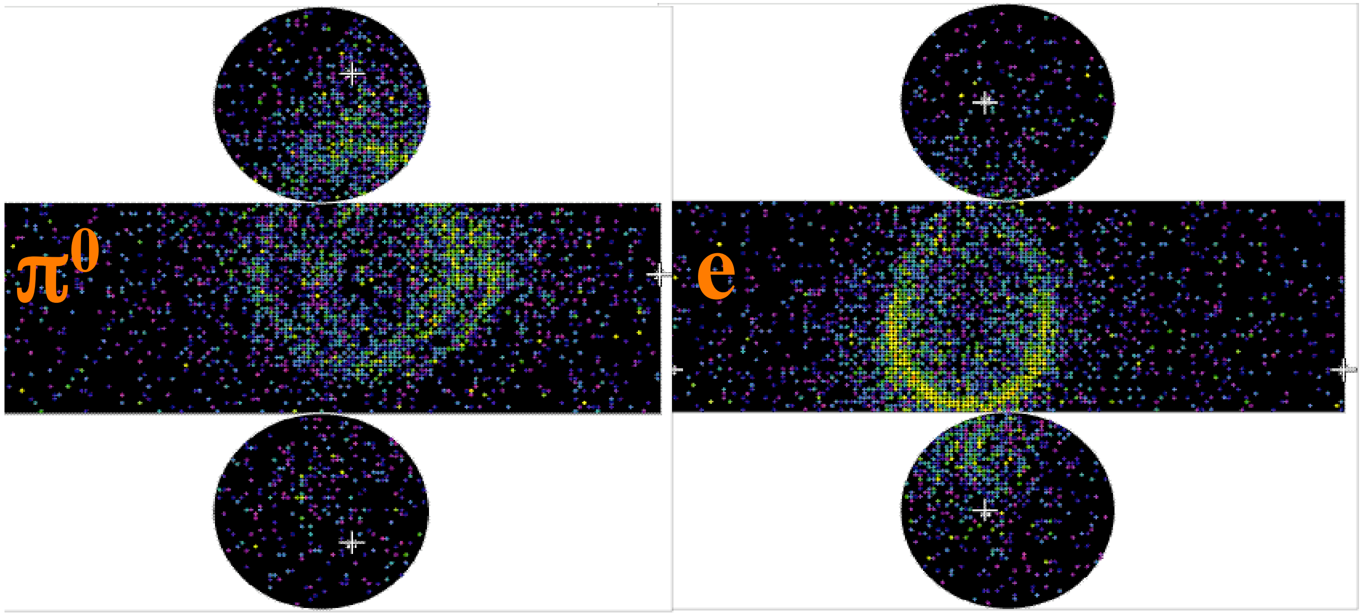






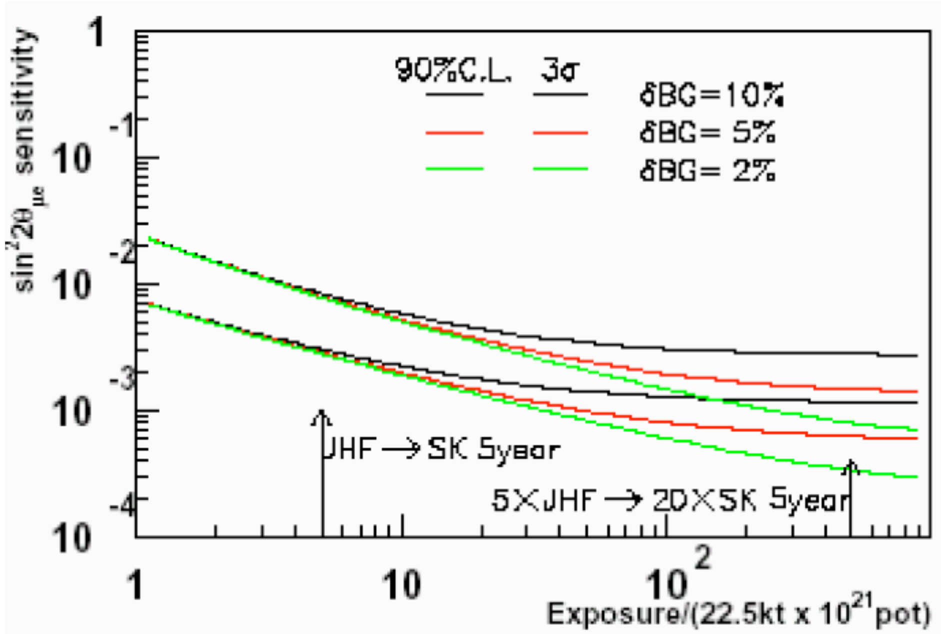
ν_e appearance in Water-Cerenkov





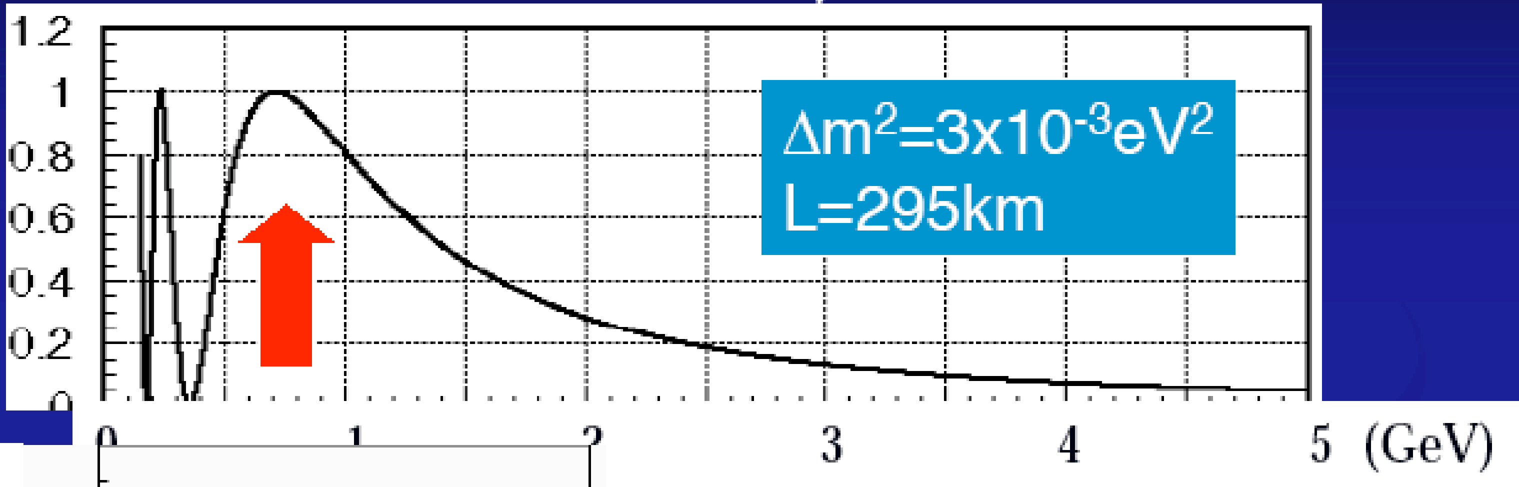
Assumed 80% efficiency for electrons

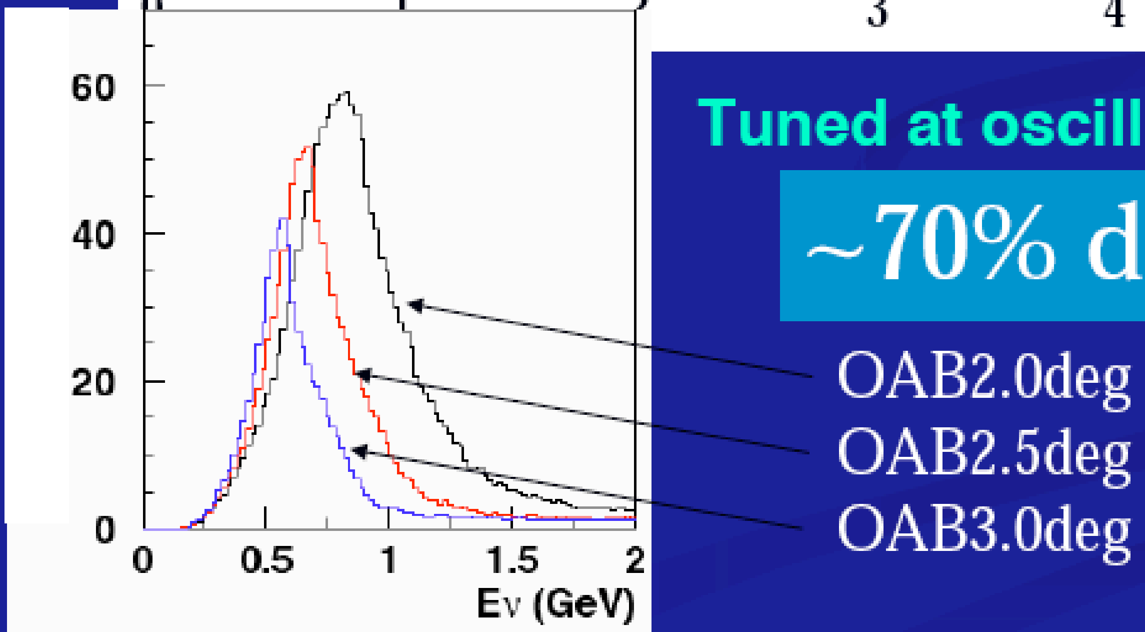
$$\nu_\mu \rightarrow \nu_e$$



Eν~0.7GeV oscillation maximum

Osc. Prob.=$\sin^2(1.27\Delta m^2 L/E_\nu)$

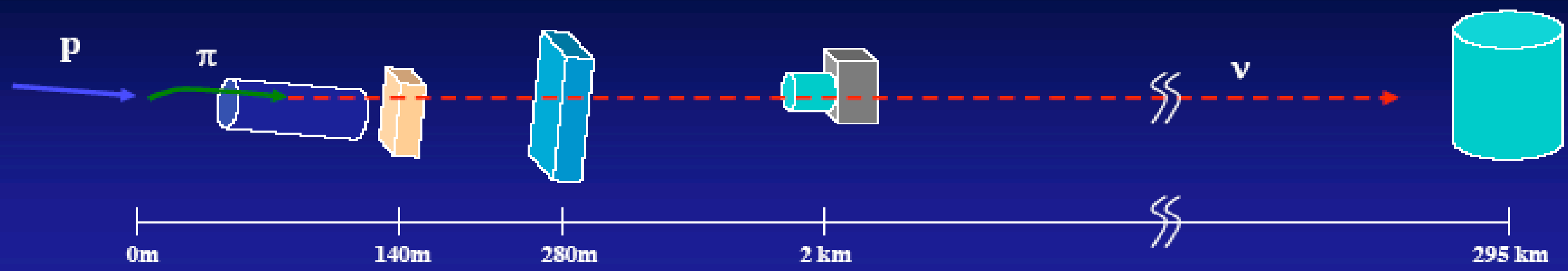




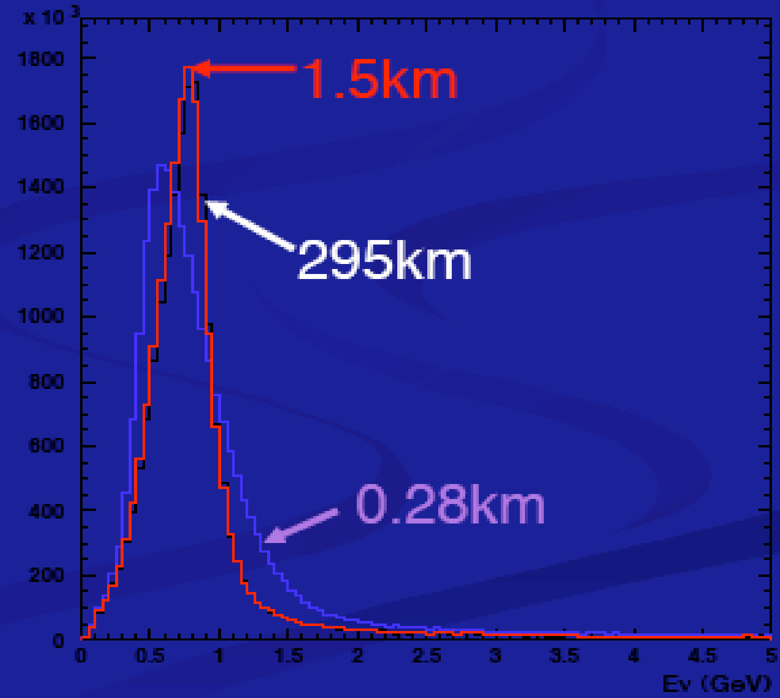
Tuned at oscillation maximum

~70% deficit !

Front Detectors

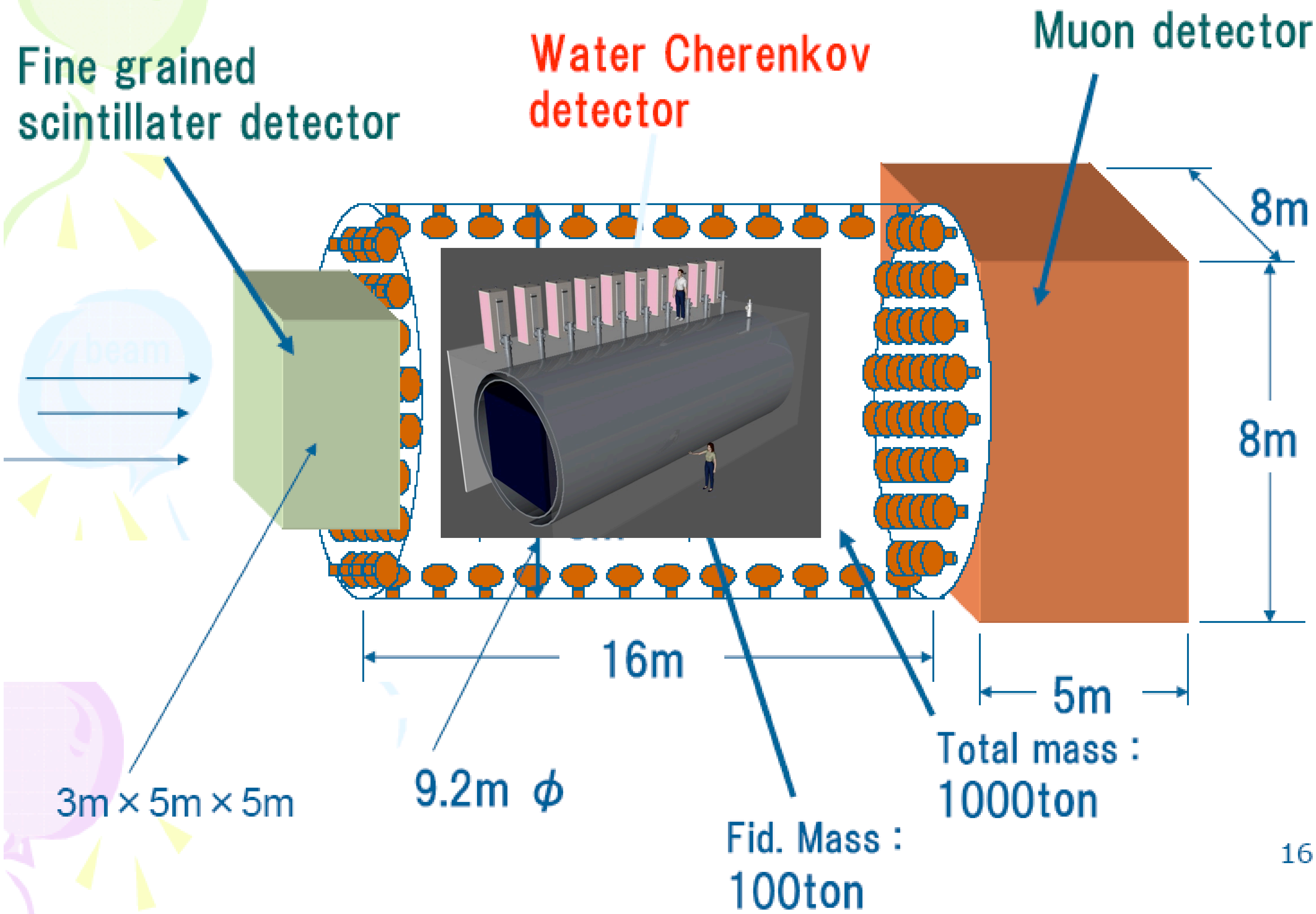


- Muon monitors @ ~140m
  - Fast (spill-by-spill) monitoring of beam direction/intensity
- First Front detector @280m
  - Neutrino intensity/direction
- Second Front Detector @ ~2km
  - Almost same E_ν spectrum as for SK
  - Water Cherenkov can work
- Far detector @ 295km
  - Super-Kamiokande (50kt)



FDs being currently defined (K2K model)

A 2km Detector



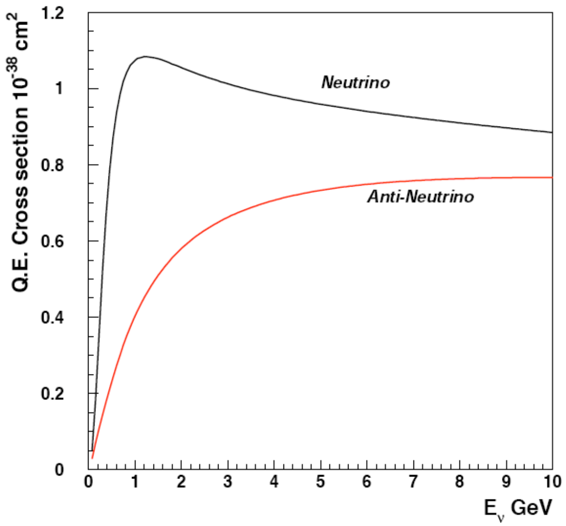
Many initiatives have been discussed…

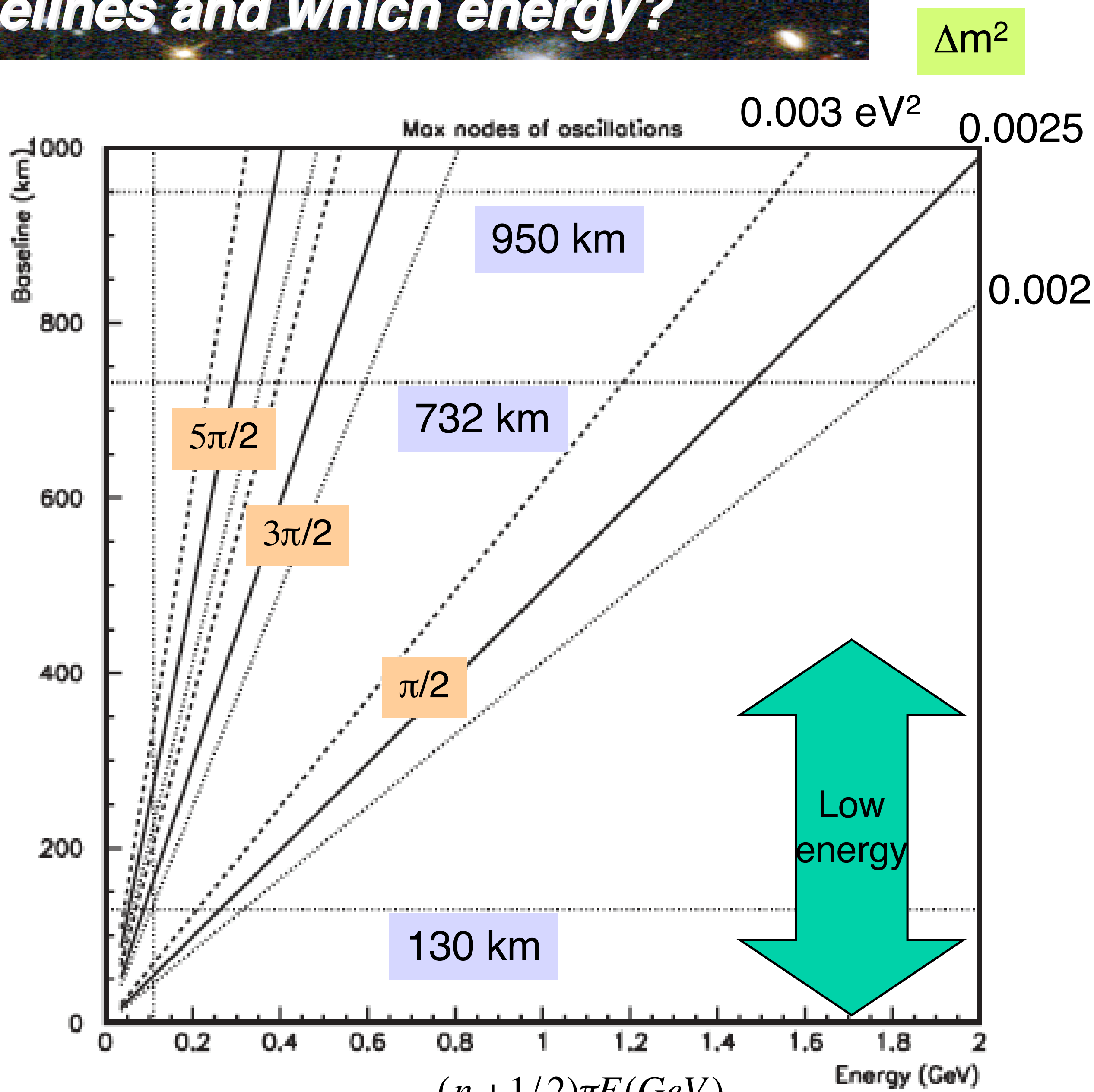
	E_p (GeV)	Power (MW)	Beam	$<E_\nu>$ (GeV)	L (km)	M_{det} (kt)	ν_μCC (/yr)	ν_e @peak
K2K	12	0.005	WB	1.3	250	22.5	~50	~1%
MINOS(LE)	120	0.41	WB	3.5	730	5.4	~2,500	1.2%
CNGS	400	0.3	WB	18	732	~2	~5,000	0.8%
JHF-SK	50	0.75	OA	0.7	295	22.5	~3,000	0.2%
JHF-HK	50	4	OA	0.7	295	1,000	~600,000	0.2%
OA-NuMI	120	0.3	OA	~2	730?	20kt?	~1,000?	0.5%
OA-NuMI2	120	1.2	OA	~2	730?	20kt?	~4,000?	0.5%
AGS→??	28	1.3	WB/OA	~1	2,500?	1,000?	~1,000?	
SPL-Frejus	2.2	4	WB	0.26	130	40(400)	650(0)	0.4%
OA-CNGS	400	0.3	OA	0.8	~1200	1,000?	~400	0.2%

ETH Institute for Particle Physics

Which baselines and which energy?

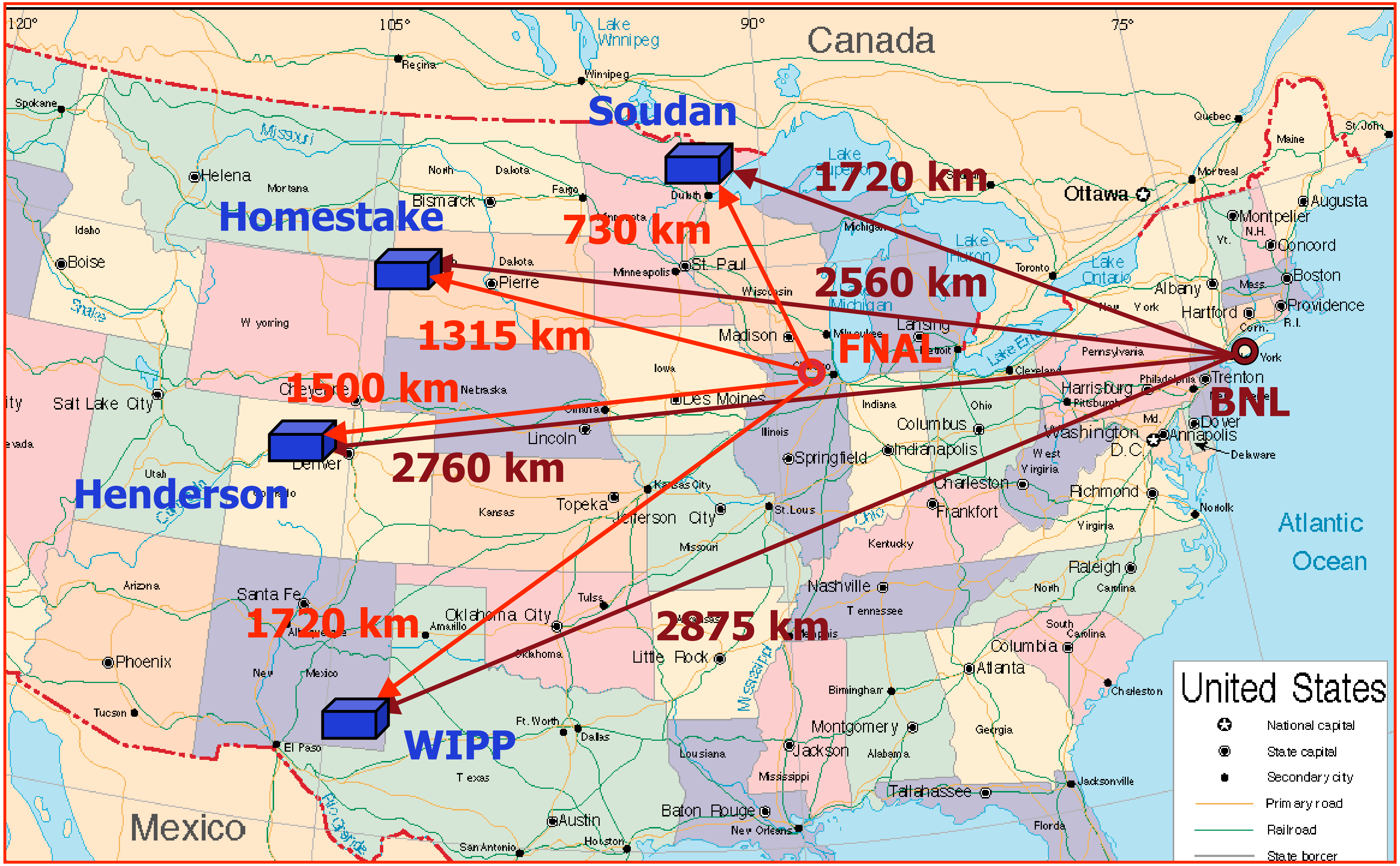
- New generation experiments want to optimize the energy and baseline to observe the maximums of the oscillation
- In the low energy region (<500 MeV), measurements suffer from
  - ➥ Low cross-section (especially for antineutrinos!)
  - ➥ Worsening of resolution due to Fermi motion
  - ➥ Atmospheric neutrino background





$$L(km) = \frac{(n+1/2)\pi E(GeV)}{1.27\,\Delta m^2(eV^2)}$$

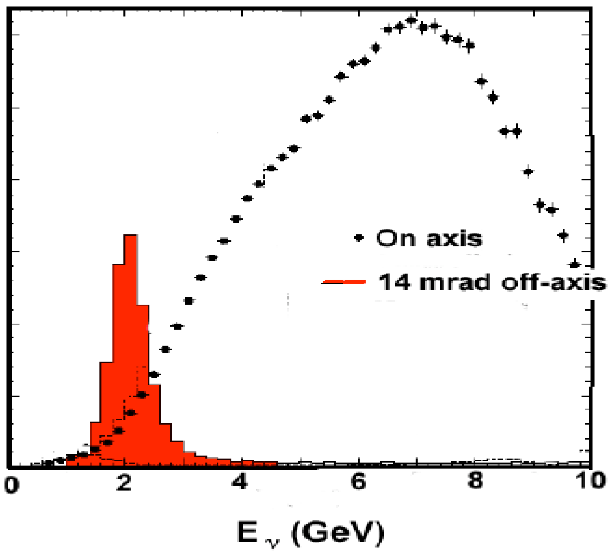
Long baselines in the USA

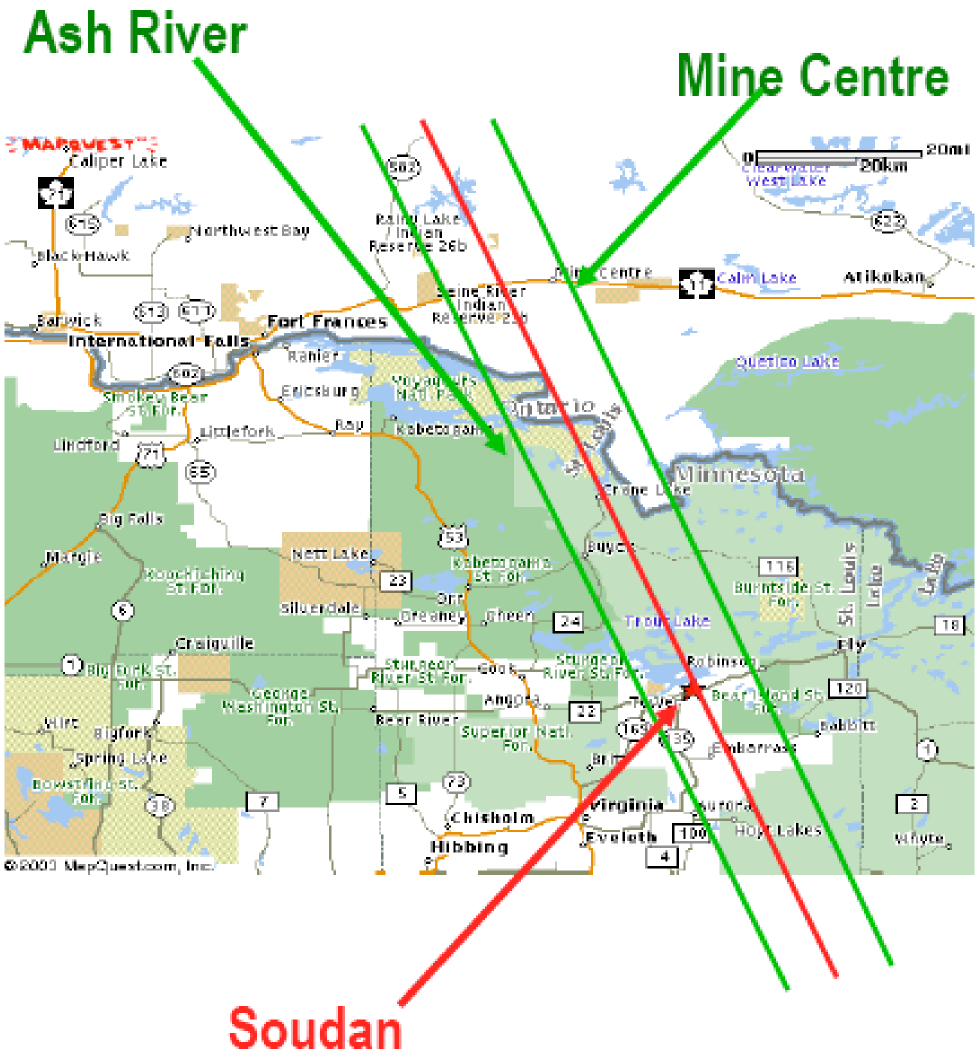


J. Wilkes

NUMI off-axis experiment

- Detector will be on surface
- Baseline L = 820 km
- Sampling calorimeter made of Wood
- Large mass: 50 kton
- Not magnetized
- Good sampling for clean low-energy electron identification
- Two options:
  - ➥ Scintillator
  - ➥ RPC

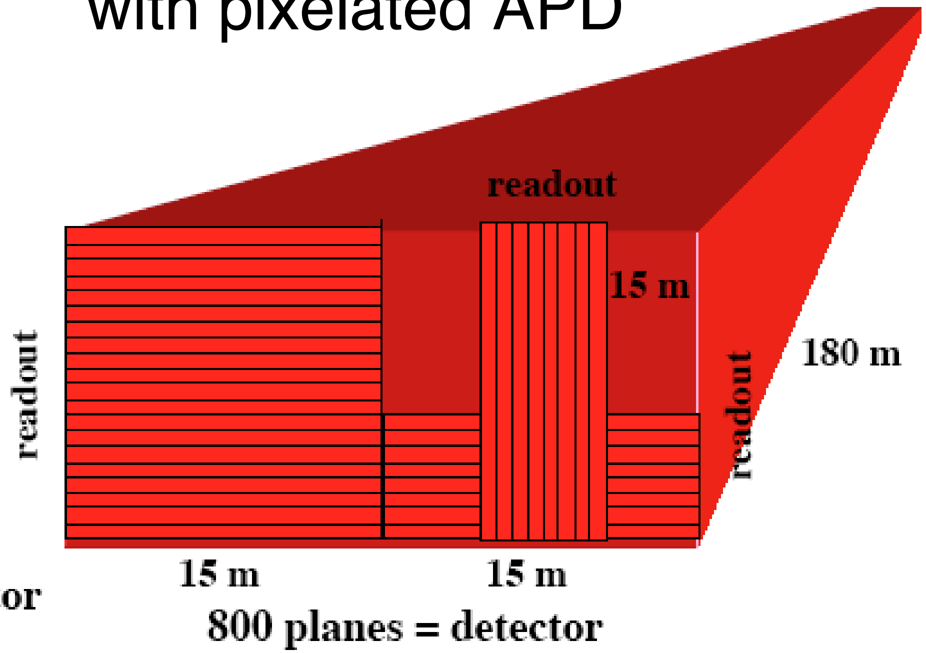


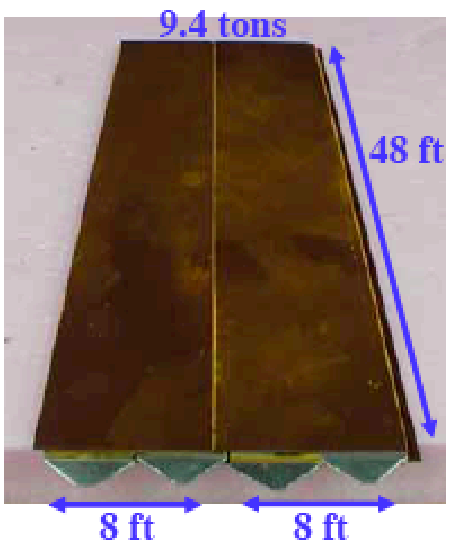


The Scintillator Detector.

- *Height 15 m*
- *Width 30 m*
- *Scintillator Active Detector*
- *Particle Board Passive Material (density .6 - .7)*
- *Alternating horizontal and vertical detector planes*
- *1/3 radiation length between detector planes*

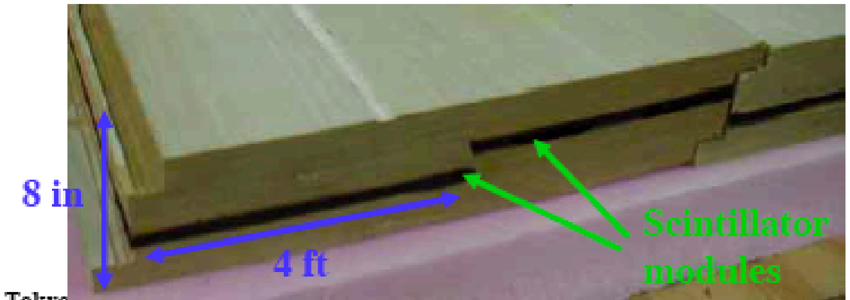
Scintillator read without WLS fiber with pixelated APD



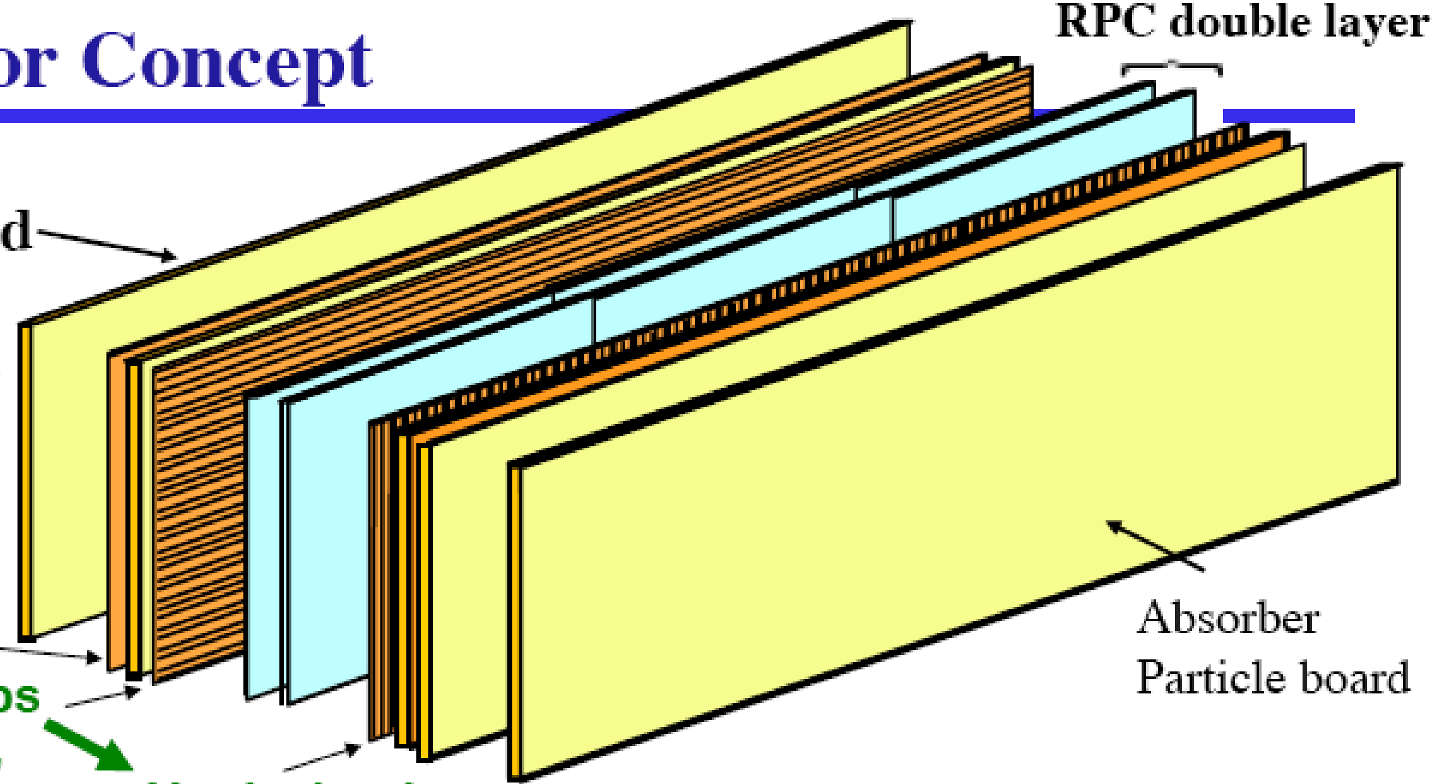


6 = 1 plane

5300 = detector



Detector Concept



596,000 m^2 RPC.
3.7 million channels.

- *RPC’s arranged in two layers to get full efficiency - 4 layers of glass,*
- *2 layers of strips on Particle Board, ground plane on opposite side.*

Detector performance:

ν_μ suppressed at 10^{-5}.
Neutral currents at 10^{-3}.
Beam ν_e at $2\ 10^{-3}$.
Detection of ν_e from oscillations 18%.

Event length

Rejects ν_μ CC events

Total pulse height

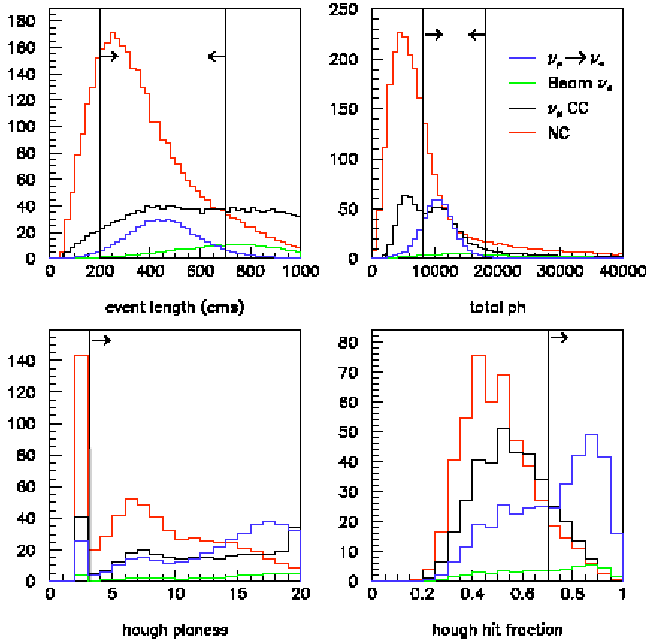
Rejects high energy ν_e CC events and low visible energy events

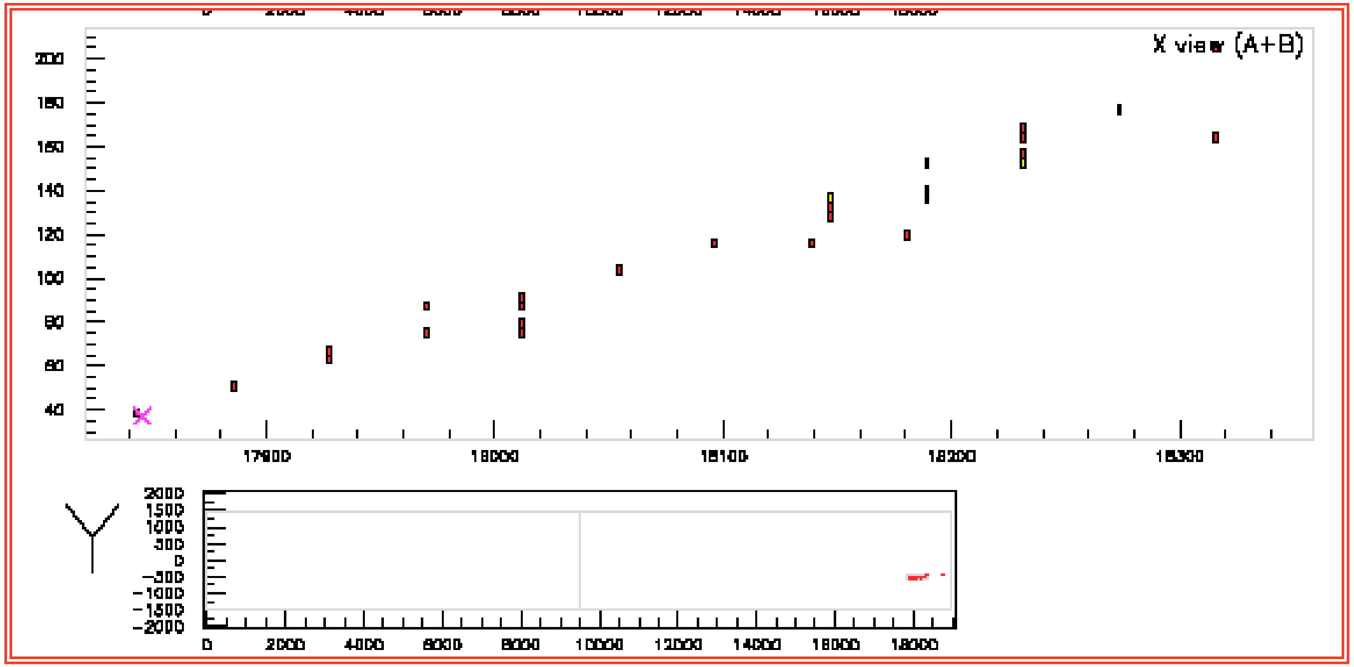
Number of planes in the Hough track.

Requires a good track

Fraction of hits in the Hough track

Selects low-y or quasi-elastic events

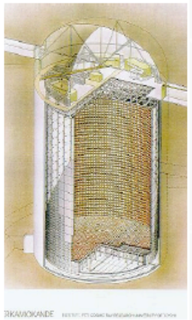




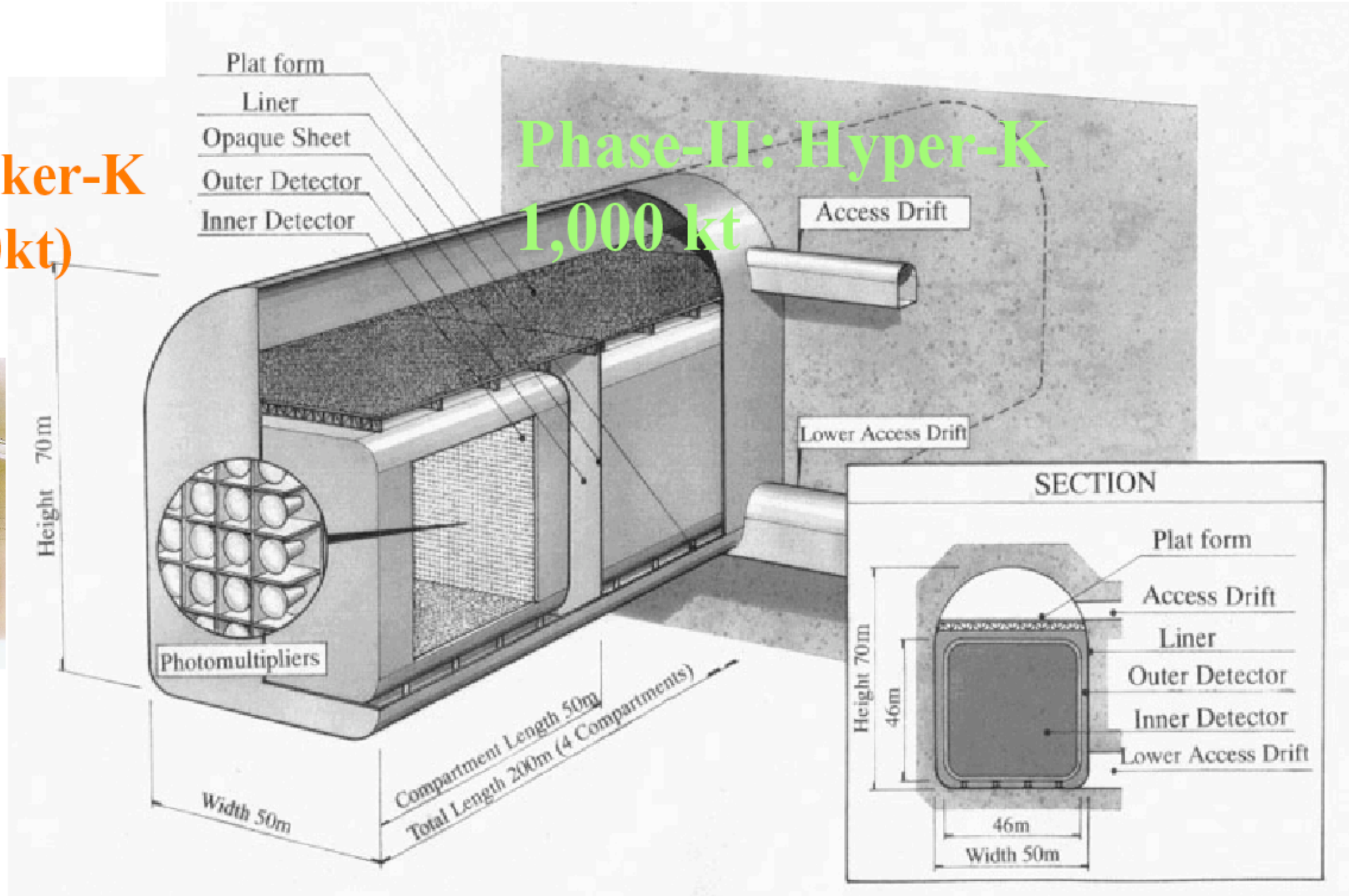
Giant water Cerenkov (up to 1Mton)

- Perceived widely as a "straightforward" extension of SK (?)
- Many "proposals", e.g., Hyper-K, UNO, 3M, …
- Many sites, e.g., Frejus, Kamioka, Homestake, etc.
- Physics case is "broad": proton decay, neutrino properties, galactic supernovae, …

Phase-I: Suker-K
22.5kt (50kt)



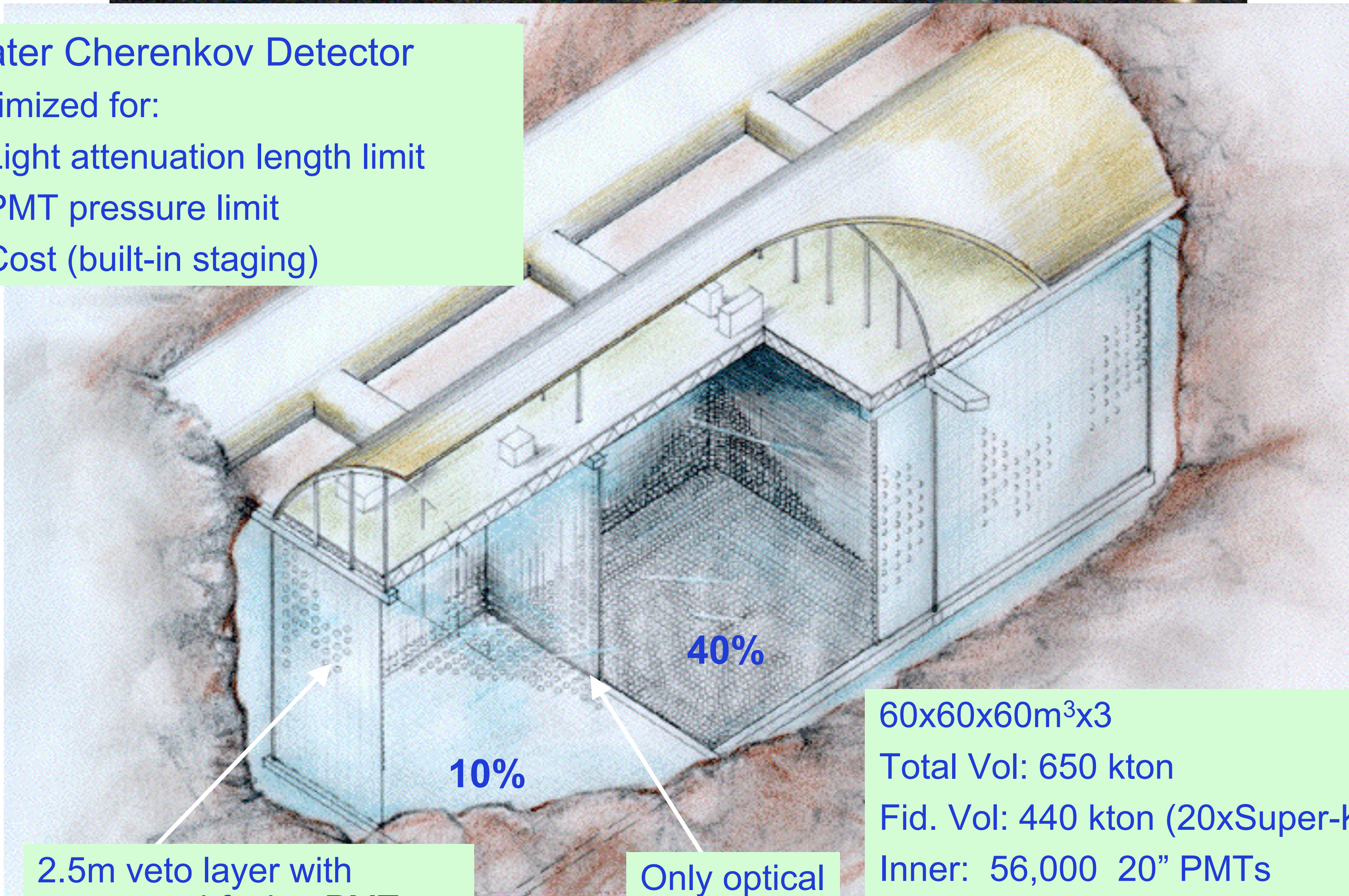
Phase-II: Hyper-K
1,000 kt



UNO Detector Concept

Water Cherenkov Detector
optimized for:

- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)



$60x60x60m^3x3$
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuper-K)
Inner: 56,000 20” PMTs
Outer: 14,900 8” PMTs

Comparison of Water Cerenkov detectors

Executive Summary table: Comparison of water Cherenkov detector parameters.

Parameters	Kamiokande Japan II	IMB-3 USA	Super Kamiokande Japan	SNO Canada	UNO (proposed)	3M (proposed) ten unit array
Total mass	4.5 kT	8 kT	50 kT	8 kT	650 kT	1,000 kT
Fiducial mass						
proton decay	1.0 kT	3.3 kT	22 kT	2 kT	440 kT	800 kT
solar	0.7 kT	-	22 kT	1 kT	440 kT	800kT
supernova	2.1 kT	6.8 kT	32 kT	3 kT	580 kT	800 kT
Effective Photocathode coverage	20%	4%	40%	60%	1/3 10% 2/3 40%	14%
Total size	$16m\times$ $19m\phi$	$22\times17\times$ $18m^3$	$41m\times$ $39m\phi$	$30\times$ $22m\phi$	60×60 $180m^3$	1 unit $50\times50m\phi$ 10 units See Fig. 1

Comparison of Possible Next-Generation Detectors

	UNO	*Liquid Ar*	*SciPIO*
Total Mass	650 kton	70 kton	50 kton
Cost	~$500M	N/A*	N/A
$p \rightarrow e^{+} \pi^{0}$ in 5 years	5×10^{34} year	1.3×10^{34} years	none
$p \rightarrow \nu K^{+}$ in 5 years	1×10^{34} year	3×10^{34} years	1×10^{34} year
SN at Gal. Center	194,000 events	3000 events	N/A
SN in Andromeda	40 events	No	N/A
SN msec structure	yes	No	N/A
SN relic neutrino	yes	yes	N/A
Atm. Neutrino	60,000 event/year	15,000 event/year	N/A
Solar Neutrino	$E_e > 7$MeV (central Module) ν_e scattering	$E_e > 10$ MeV inverse beta-decay	N/A
Astrophysical Neutrino	$E_\nu > 10$ GeV	No	No

* assumes ~$200M for 70 kton of liquid argon.

Source for LANDD: astro-ph/0104552 and astro-ph/0208381

Source for SciPIO: R. Svobada's presentation at the Neutrino Facilities Assessment Committee, NAS in 2002.

J. Wilkes, UCLA 2003

US HEPAP Subpanel (2001) on Long Range Planning

Remarks on Proton Decay and UNO

A.4.1 Proton Decay

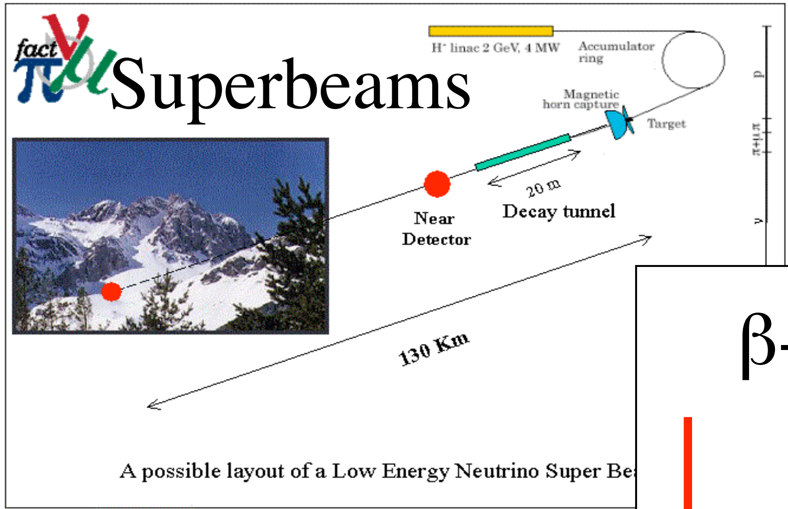
If protons decay, their lifetimes are long, so proton decay experiments require massive detectors. A worldwide collaboration has begun to develop the design for a next-generation proton decay experiment. Such a detector should be at least an order of magnitude larger than Super Kamiokande. A next-generation experiment would extend the search for proton decay into the regime favored by unified theories.

Current thinking favors the use of a large water Cherenkov detector, as in the UNO approach. The detector would be situated underground to reduce cosmic-ray backgrounds. A large water Cherenkov detector could simultaneously serve as the long-baseline target for an accelerator neutrino beam. It would also expand our ability to observe neutrinos from supernovae.

Present estimates suggest a price of about $650M for such a detector. Given its strong science program, and assuming that an affordable design can be reached, we believe it likely that a large proton decay detector will be proposed somewhere in the world, and that U.S. physicists will participate in its construction and utilization. The R&D effort should be completed over the next several years. A decision might be made near the middle of the decade, perhaps in conjunction with a decision on a neutrino superbeam facility.

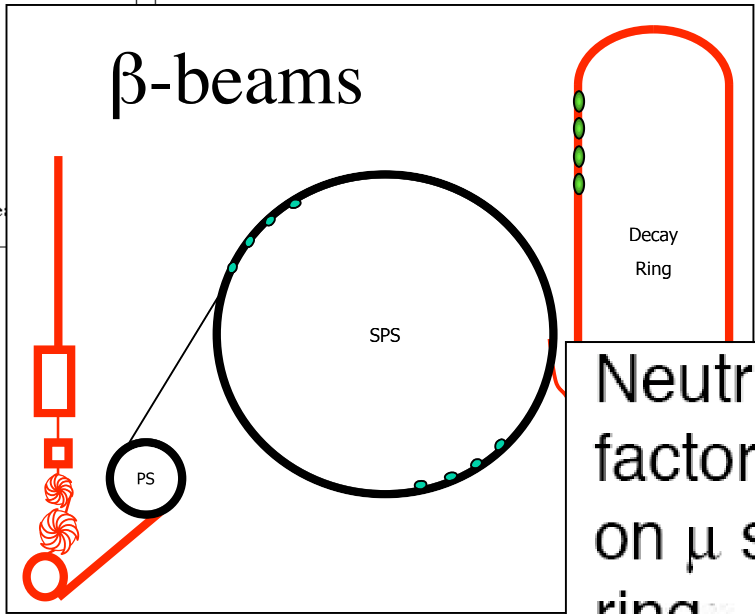
CERN: three types of beams

- CERN still considers three types of neutrino beams:



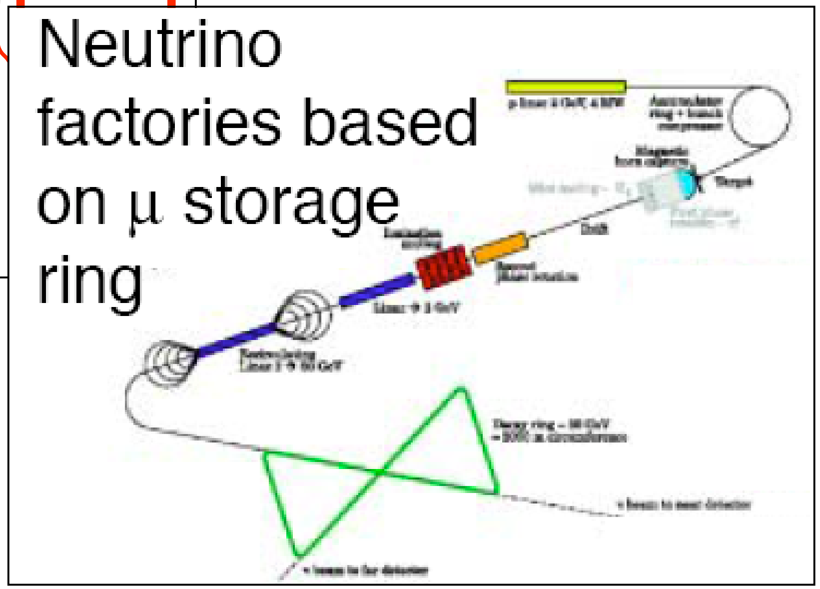
$$\pi^{\pm} \rightarrow \mu^{\pm} \overset{(-)}{\nu}_{\mu}$$

Select focusing sign



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

Select ion



Select ring sign

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

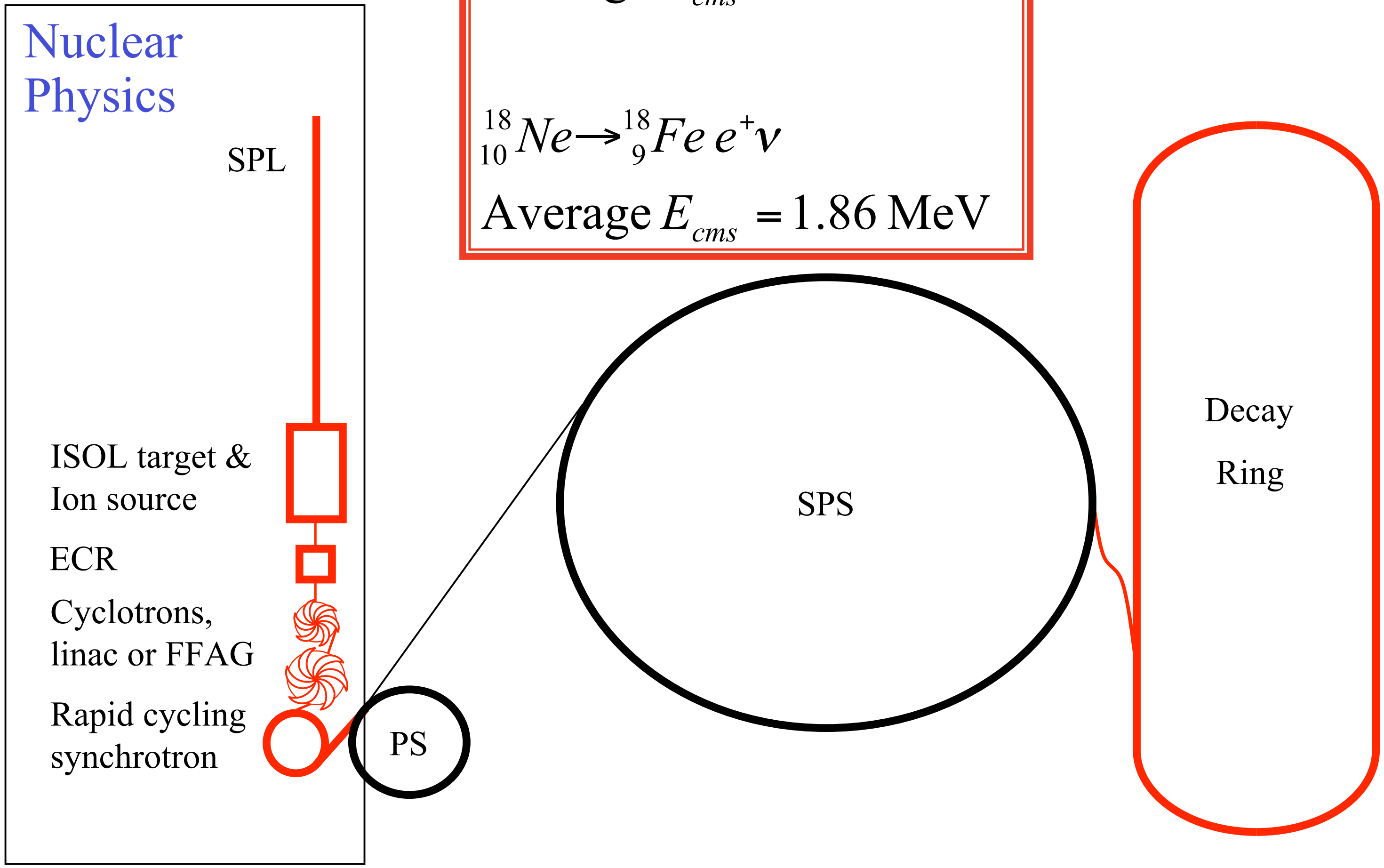
CERN: β-beam baseline scenario

$${}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-} \bar{\nu}$$

$$\text{Average } E_{cms} = 1.937 \text{ MeV}$$

$${}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\, e^{+} \nu$$

$$\text{Average } E_{cms} = 1.86 \text{ MeV}$$



Decay ring

Brho = 1500 Tm

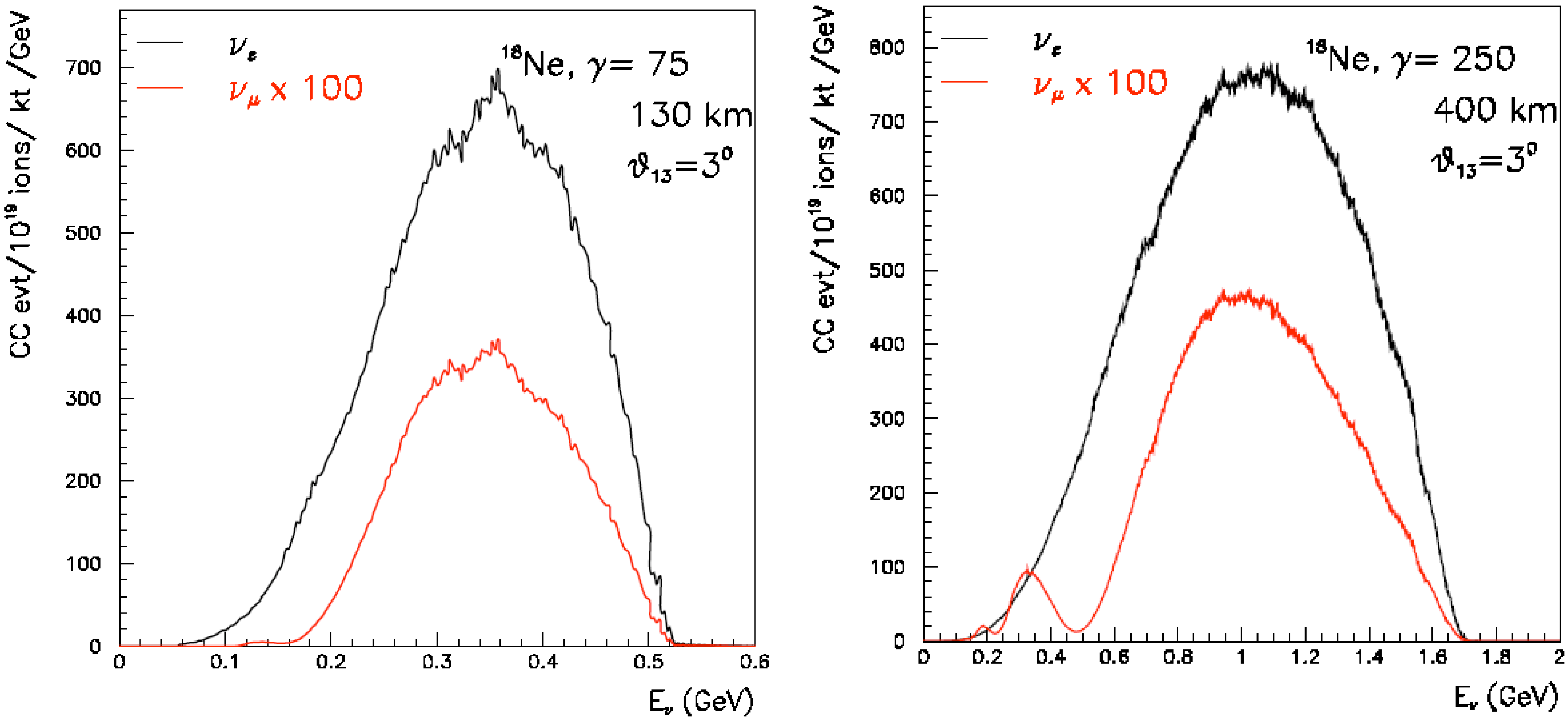
B = 5 T

L_{ss} = 2500 m

- 1 ISOL target to produce He^{6}, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.

Beta-beam spectra

$\theta_{13} = 3^\circ$



^{18}Ne γ=75
L=130 km

^{18}Ne γ=250
L=400 km

The starting point: the CERN SPL !

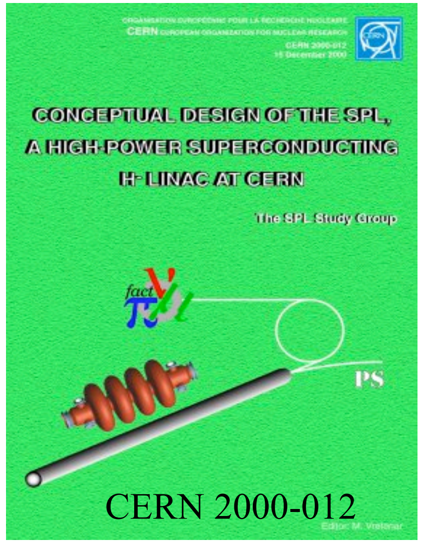
EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

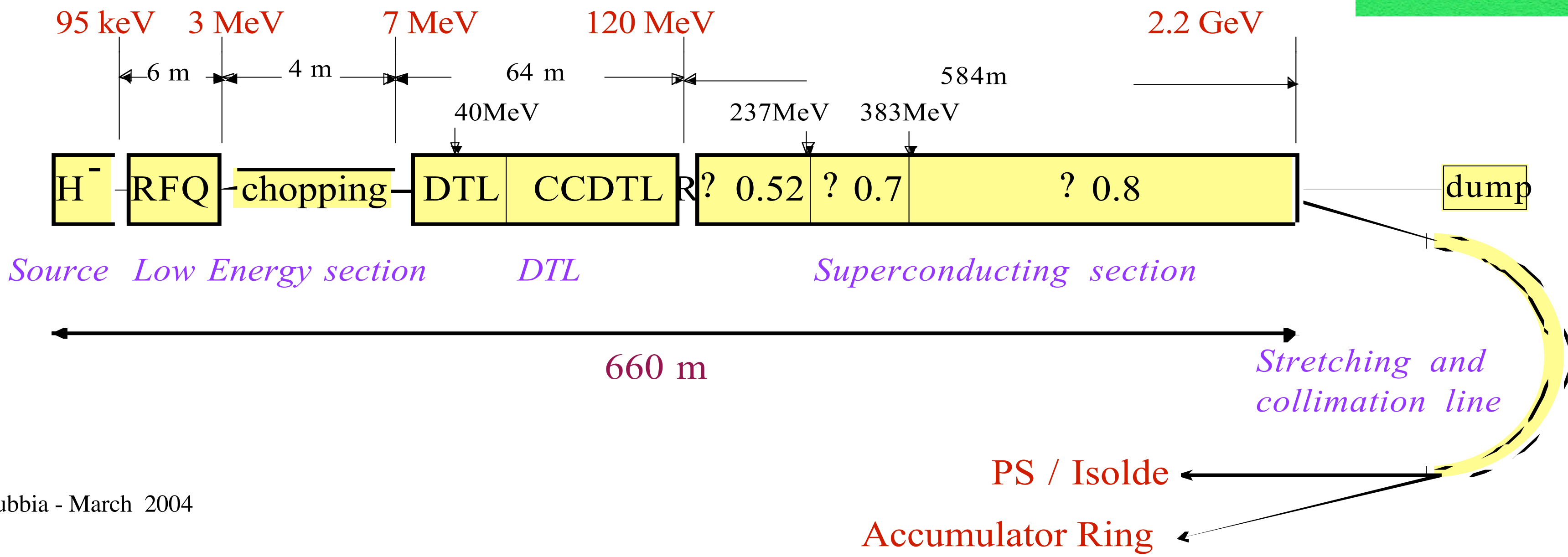
→ 10^{23} protons/year

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





Benefit to approved physics programme

- **Need for higher beam performance (brightness*, intensity) to:**

  - ➥ Reduce the LHC filling time,
  - ➥ Improve the reliability in the generation of the ultimate beam actually foreseen for LHC,

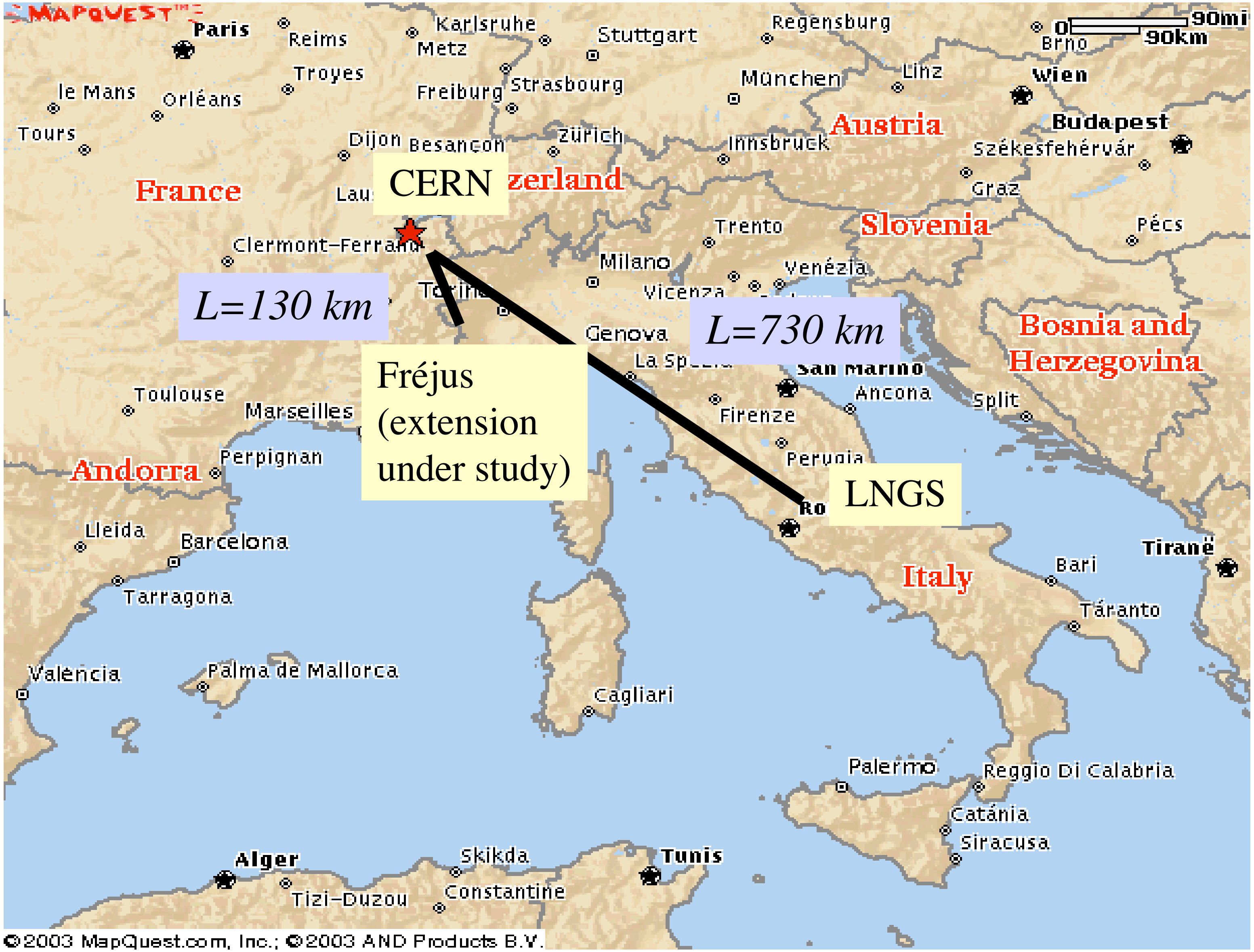
  ⇒ **Higher integrated luminosity**

  - ➥ Increase the proton flux onto the CNGS target, ⇒ **More events**
  - ➥ Increase the proton flux to ISOLDE, ⇒ **Upgrade**
  - ➥ Prepare for further upgrades of the LHC performance beyond the present ultimate. ⇒ **Upgrades beyond ultimate**

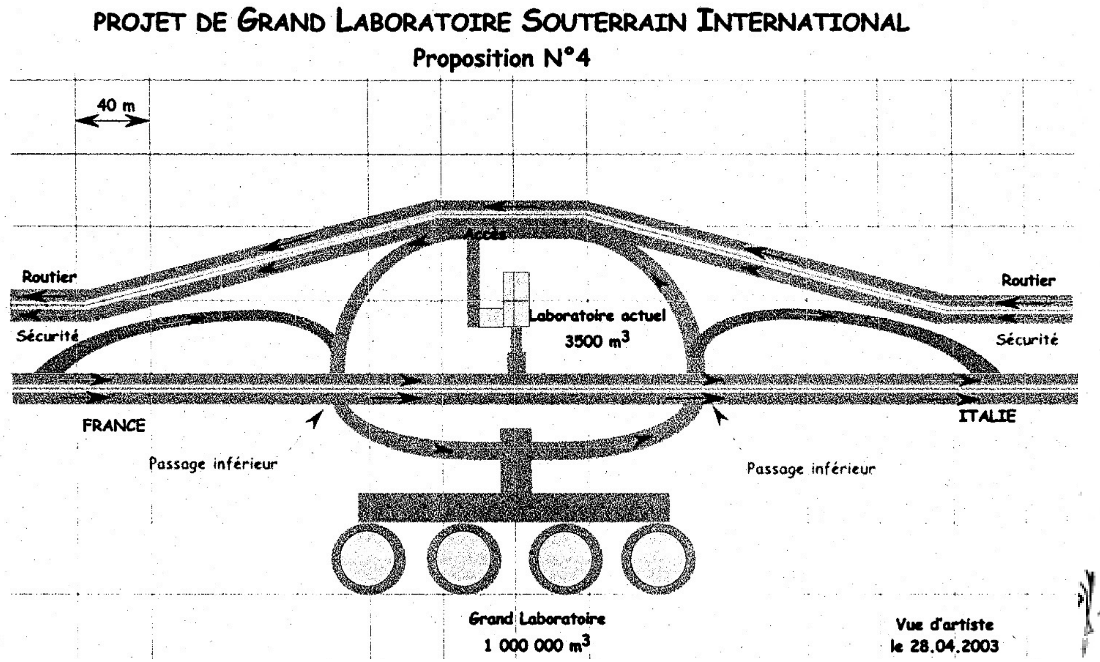
*** For protons, brightness can only degrade along a cascade of accelerators**
⇒ Any improvement has to begin at the low energy (linac) end

courtesy of R. Garoby

Long baselines in Europe



Fréjus laboratory



"Cooperation agreement"
between
French (IN2P3/CNRS, DSM/CEA)
and Italian (INFN) Institutions

……………………

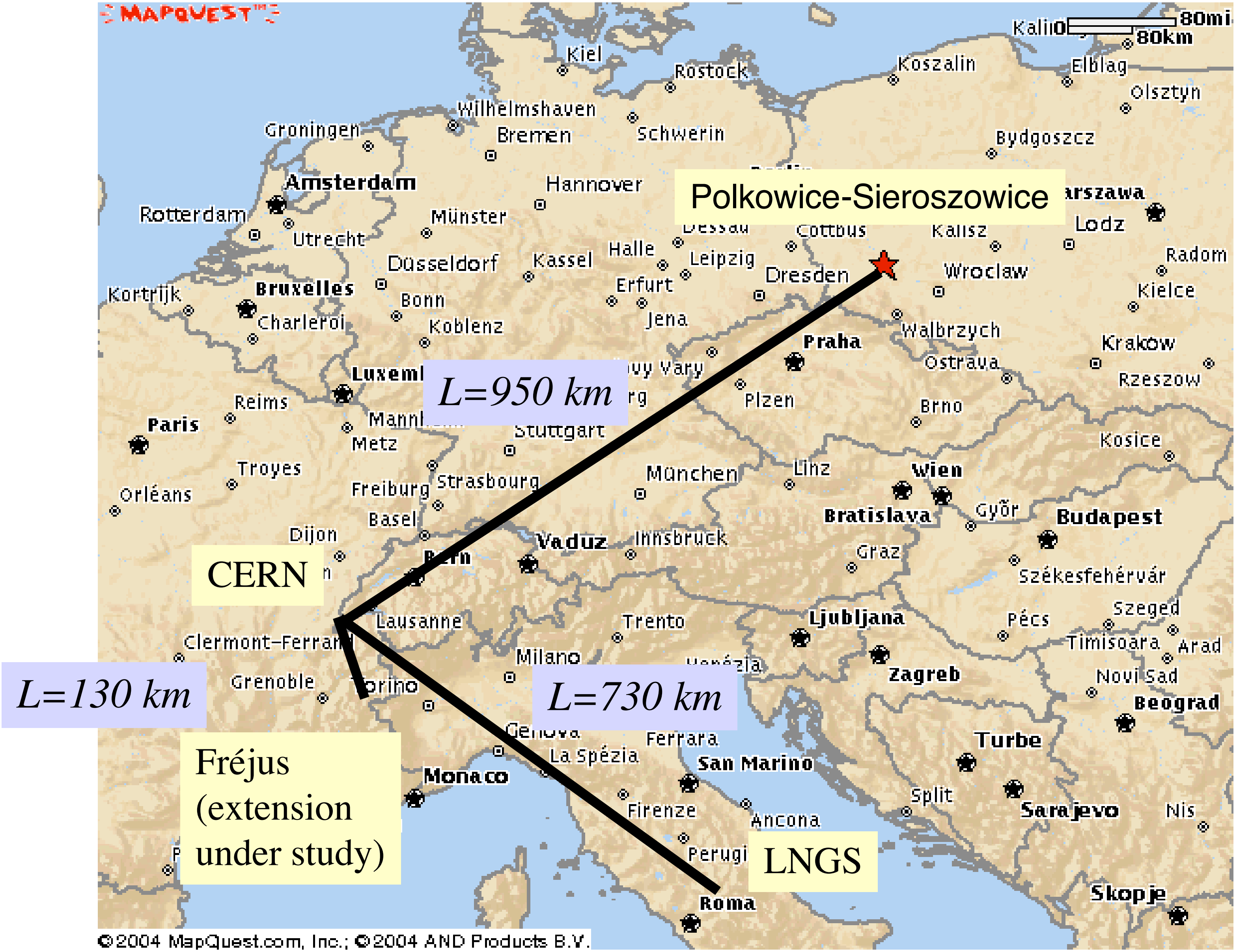
« The DSM, IN2P3 and the INFN agree to prepare the design of a very Large Underground Laboratory in the new Fréjus tunnel, with complementary features with respect to the Gran Sasso laboratory, to be submitted as a joint proposal to the French and Italian governements.

The institutions aim at associating the Fréjus and Gran Sasso laboratories in a single entity, a European Joint Laboratory, open to the world scientific community to carry out advanced experiments in particle, astroparticle and nuclear physics in the coming decades, on topics such as matter stability, neutrino mixing and mass, stellar collapses and nuclear astrophysics »

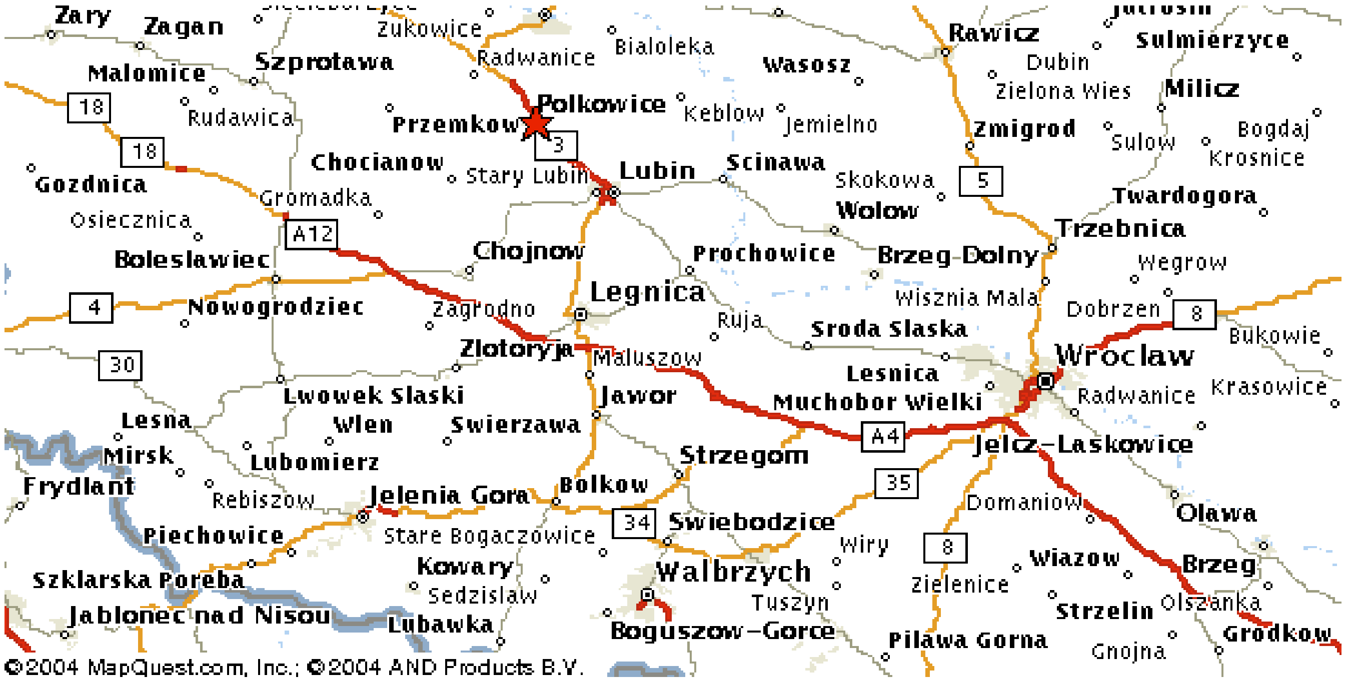
March 2004: Start study for major caverns totalling 1'000'000 m^3

If approved, excavation start in 2008
Physics >2015

Long baselines in the new Europe...



CUPRUM mines Polkowice-Sieroszowice



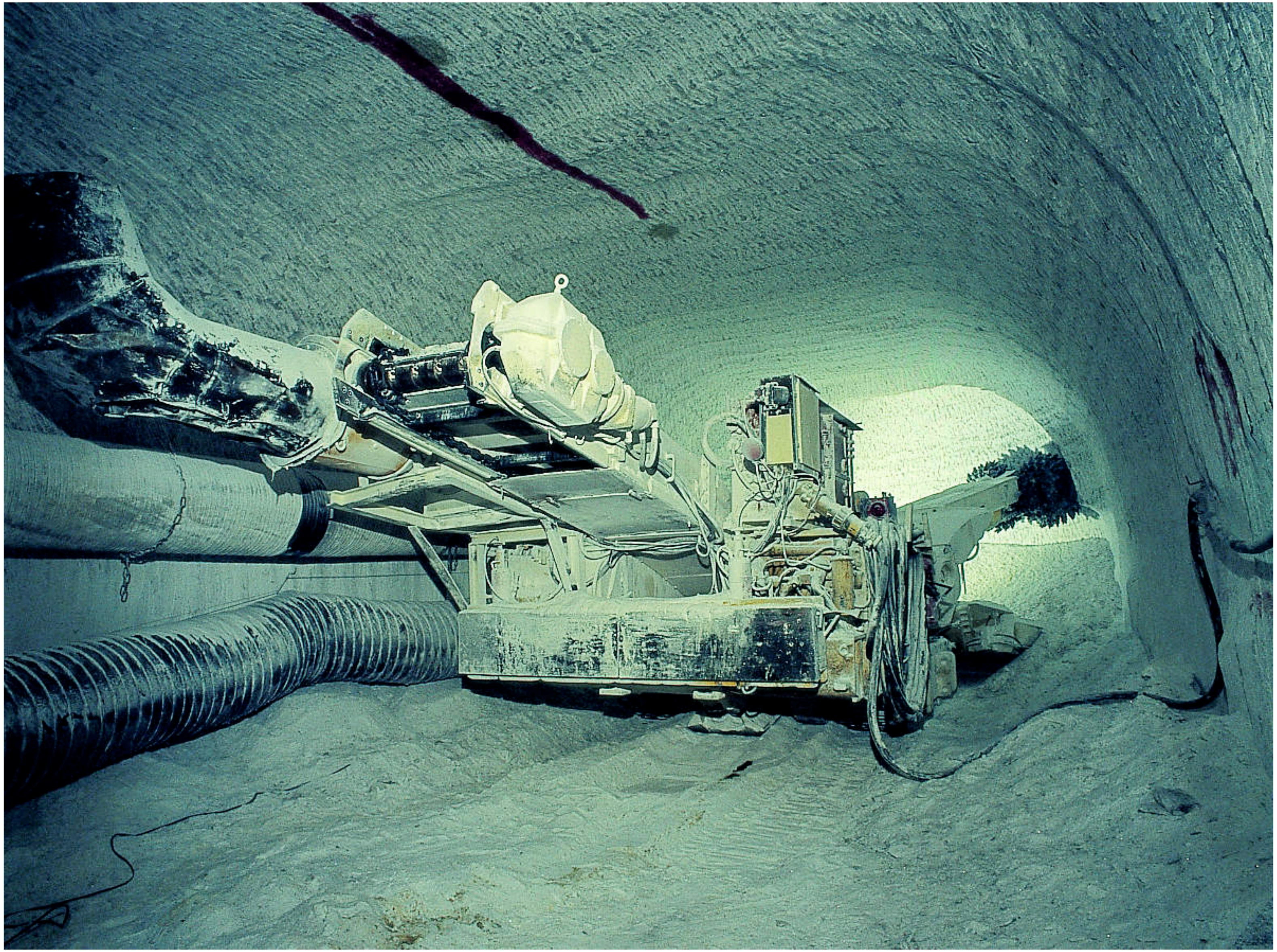
Copper mines (owned by KGHM, one of the largest producers of copper and silver in the world)

Salt layer at 1000 underground (dry)

Very large caverns already exist (from mine exploitation)

Possibility to host ≈80’000 m^3 detector in salt cavern under study

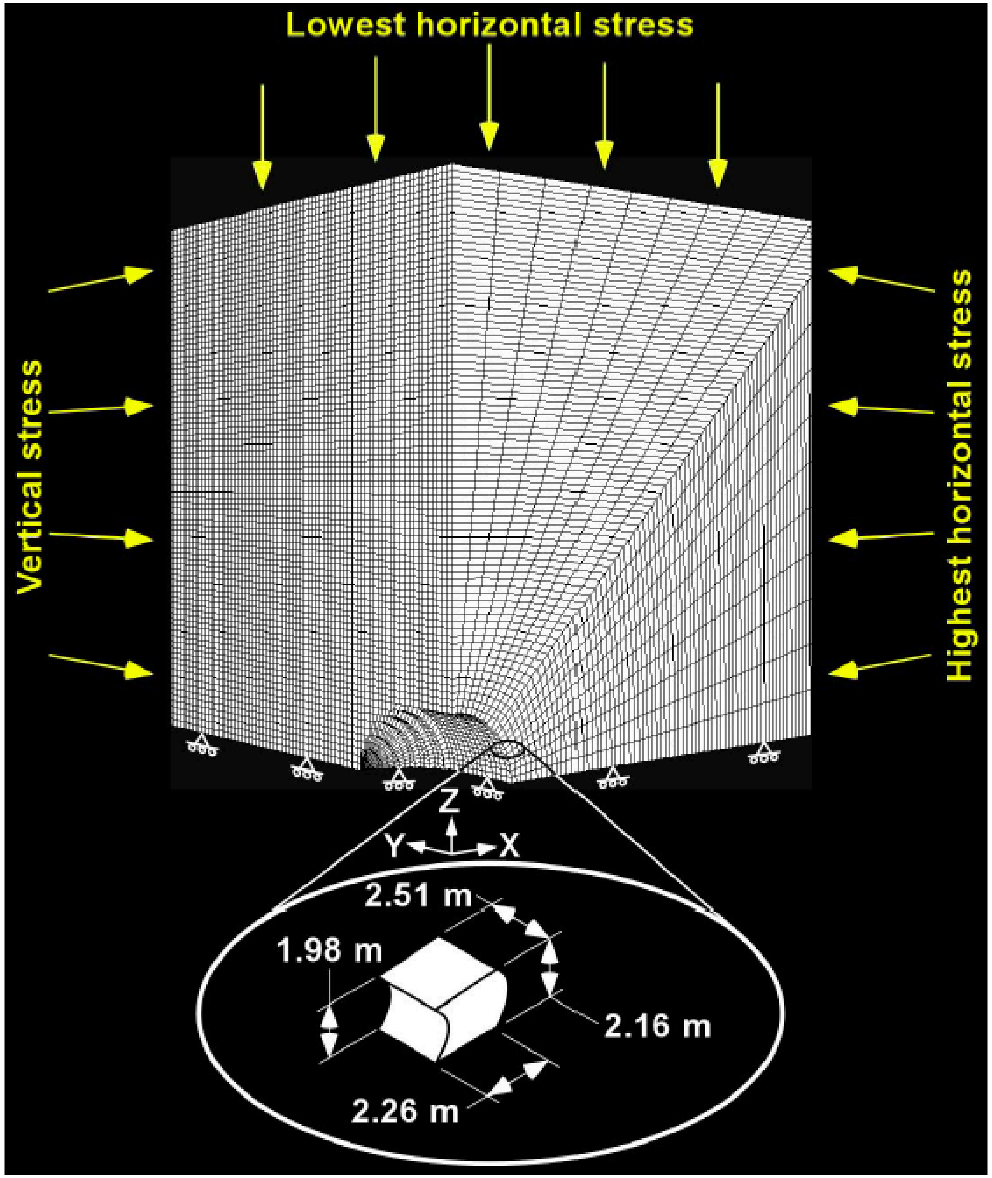
Salt mine (depth ≈1000 m)



Feasibility of large underground cavern

- Geophysical instabilities limit the size of the underground cavern
- In practice, the "tunnel" approach is stable (I.e. small span, span/height ≈ 1, length unlimited)
- For large underground detector, we require large span, large height, length is small (compared to tunnel)
- Actual size limit depends on details of rock and depth and on the wished cavern geometry
- Homestake study: span ≈ 50-60 m, height 50 m is maximum feasible

Modularity ≈ 100'000 m^3
or
Tunnel-like geometry



Finite element analysis for Homestake mine

Comparison Water - liquid Argon

	Water	Liquid Argon
Density (g/cm^3)	1	1.4
Radiation length (cm)	36.1	14.0
Interaction length (cm)	83.6	83.6
dE/dx (MeV/cm)	1.9	2.1
Refractive index (visible)	1.33	1.24
Cerenkov angle	42°	36°
Cerenkov $d^2N/dEdx$ (β=1)	$\approx$160 eV^{-1} cm^{-1}	$\approx$130 eV^{-1} cm^{-1}
Muon Cerenkov threshold (p in MeV/c)	120	140
Scintillation	No	Yes ($\approx$50000 γ/MeV @ λ=128nm)
Cost	1 CHF/liter (Evian)	$\approx$1 CHF/liter

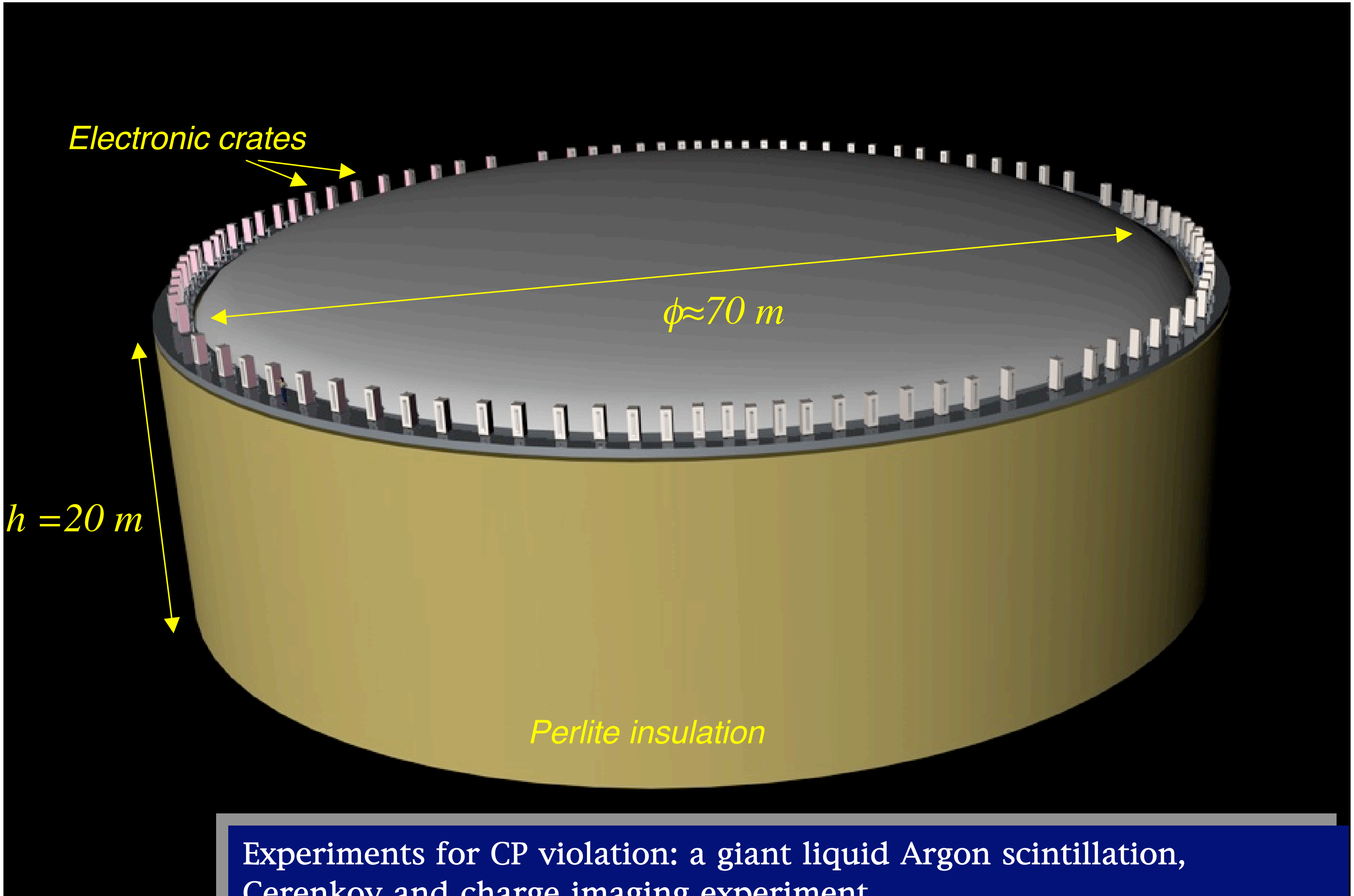
Comparison Water - liquid Argon

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	80

→ *A "new way" to look at rare events…*

A 90 kton liquid argon TPC ?

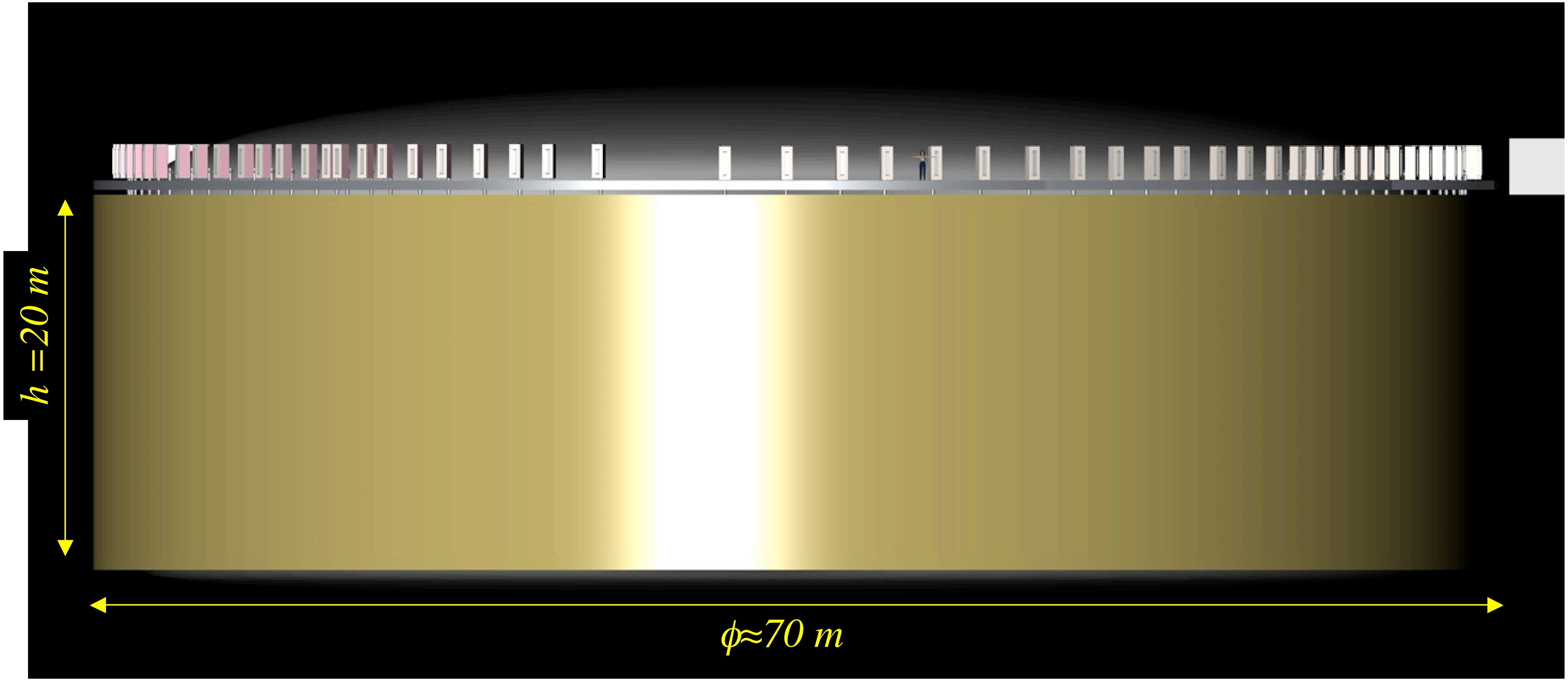
100 kton liquid Argon detector



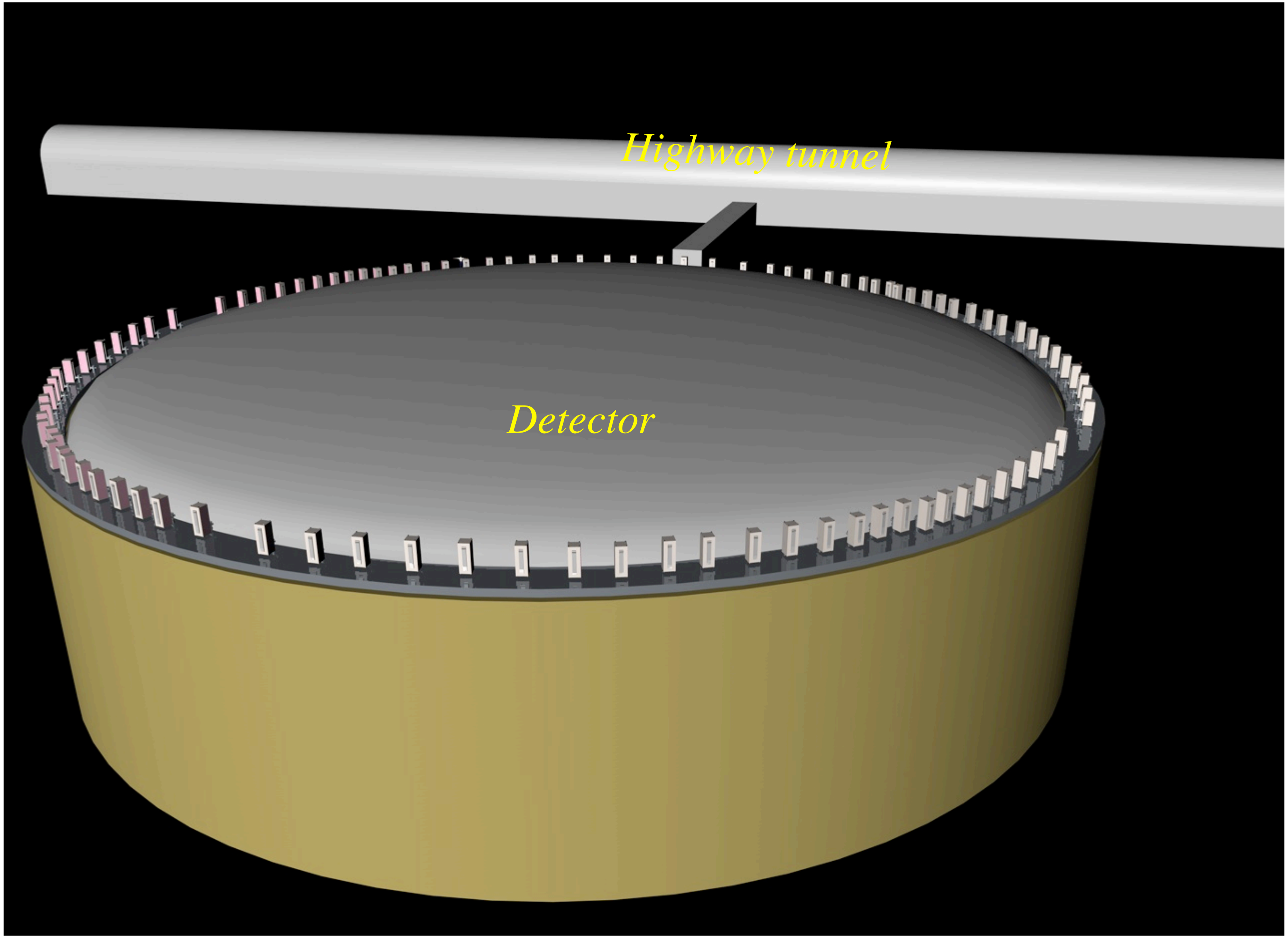
Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment.

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

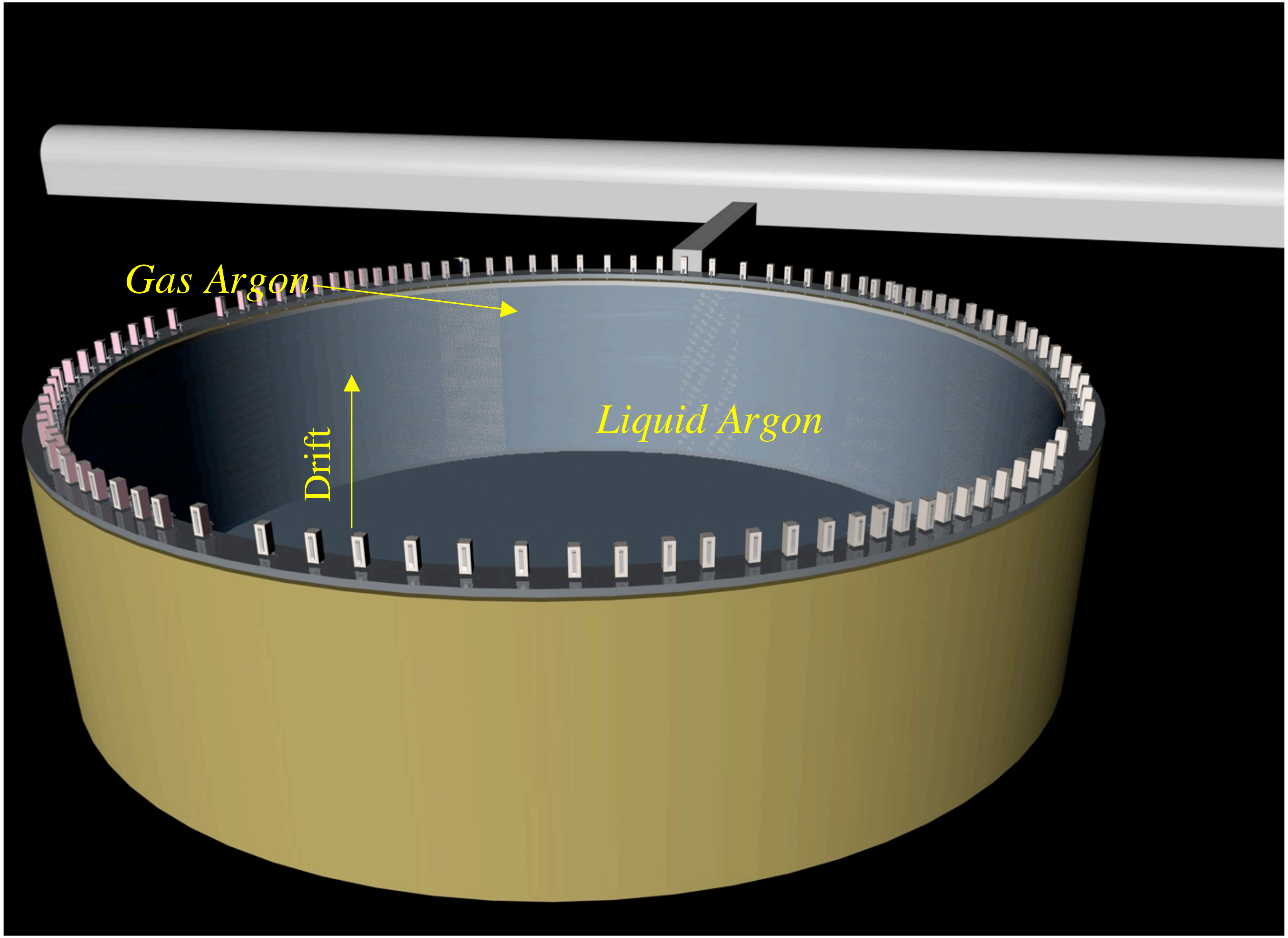
Front view



Detector and highway tunnel



Open detector

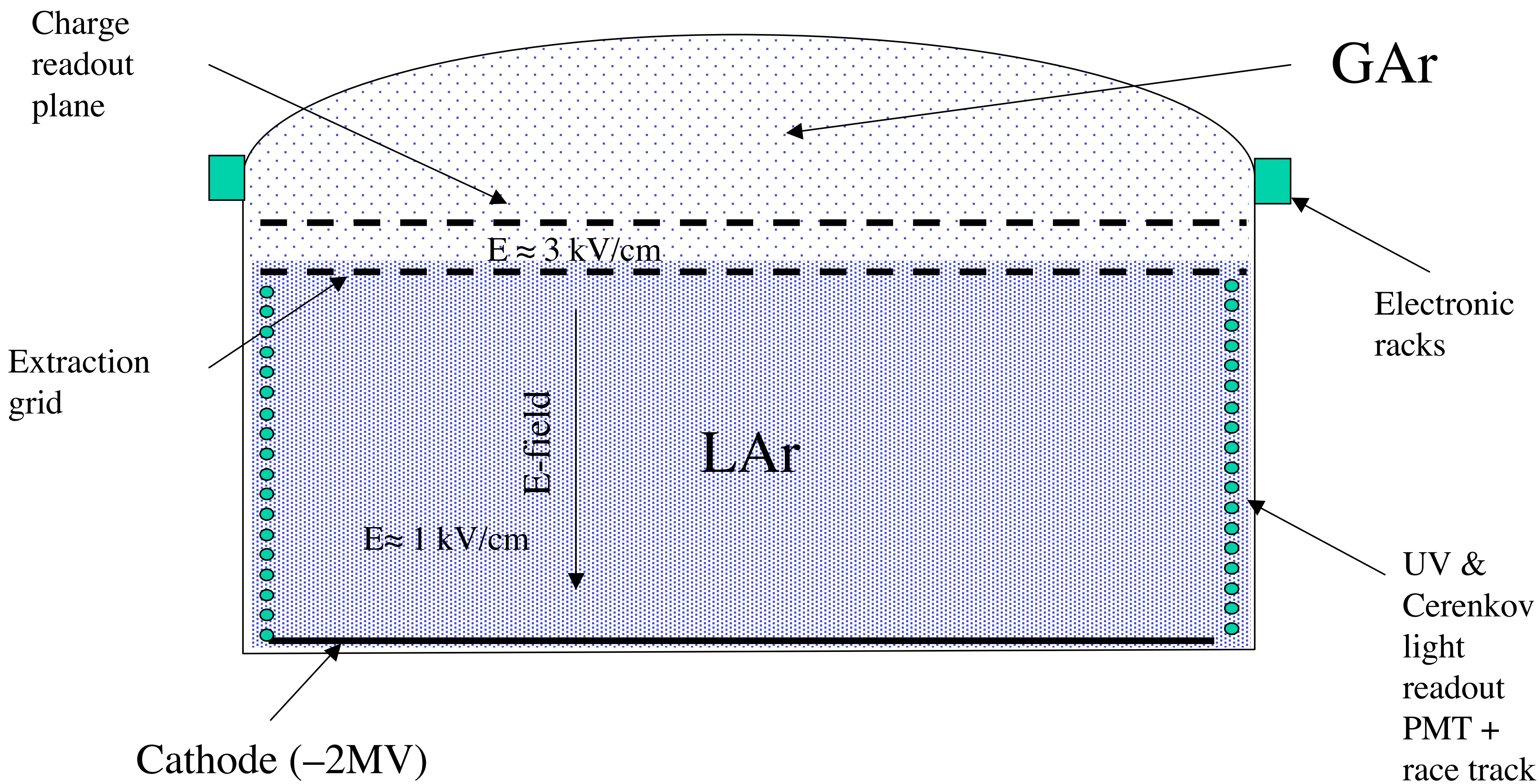


Summary parameters

Dewar	ϕ≈70 m, height ≈ 20 m, passive perlite insulated, heat input ≈5W/m^2
Argon storage	Boiling argon, low pressure (<100 mbar overpressure)
Argon total volume	73118 m^3 (height = 19 m), ratio area/volume≈15%
Argon total mass	102365 TONS
Hydrostatic pressure at bottom	≈3 atm
Inner detector dimensions	Disc ϕ ≈70 m located in gas phase above liquid phase
Electron drift in liquid	20 m maximum drift, HV=2 MV for *E*=1KV/cm, v_d≈2 mm/μs, max drift time ≈10 ms
Charge readout view	2 independent perpendicular views, 3mm pitch, in gas phase (electron extraction) with charge amplification (typ. x100)
Charge readout channels	≈100000
Readout electronics	100 "ICARUS-like" racks on top of dewar (1000 channels per crate)
Scintillation light readout	Yes (also for triggering), 1000 immersed 8" PMT with WLS (TPB)
Visible light readout	Yes (Cerenkov light), 27000 immersed 8" PMTs or 20% coverage, single photon counting capability

A possible detector layout

Single detector: charge imaging, scintillation, Cerenkov light



Charge readout

- **Detector is running in BI-PHASE MODE**
  - ➥ In order to allow for long drift (≈20 m), we consider charge attenuation along drift and compensate this effect with charge amplification near anodes located in gas phase
  - ➥ Amplification operates in proportional mode
  - ➥ After max 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*=1KV/cm, *v_d≈2 mm/μs, max drift time ≈10 ms***
Charge readout view	**2 independent perpendicular views, 3mm pitch**
Maximum charge diffusion	**σ≈2.8 mm ($\sqrt{2Dt_{max}}$ for D=4 cm^2/s)**
Maximum charge attenuation	***$e^{-(\tau/t_{max})}$≈ 1/150* for τ=2 ms electron lifetime**
Needed charge amplification	**10^2 to 10^3**
Methods for amplification	**Extraction to and amplification in gas phase**
Possible solutions	**Thin wires (ϕ≈30μm)+pad readout, GEM, LEM, …**

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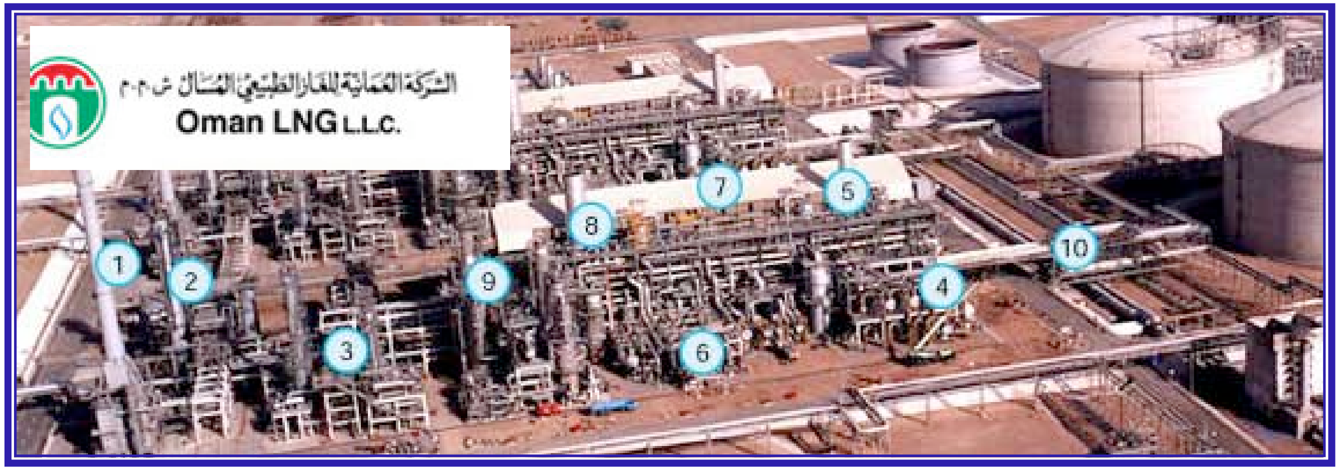
Cryogenic storage tanks for LNG

About 200 cryo-tanker exist in the world… up to ≈200'000 m^3

Process, design and safety issues already solved by petrochemical industry !

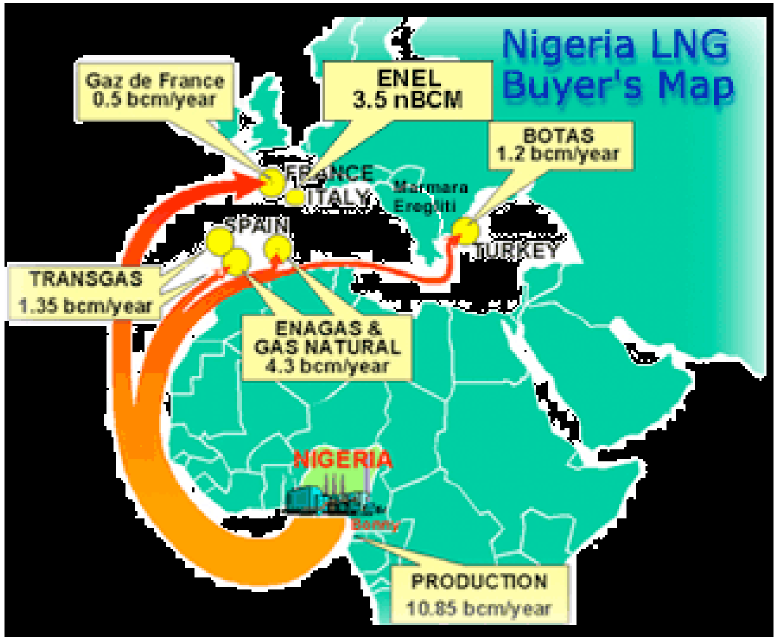
Liquefaction of LNG and transport via ships



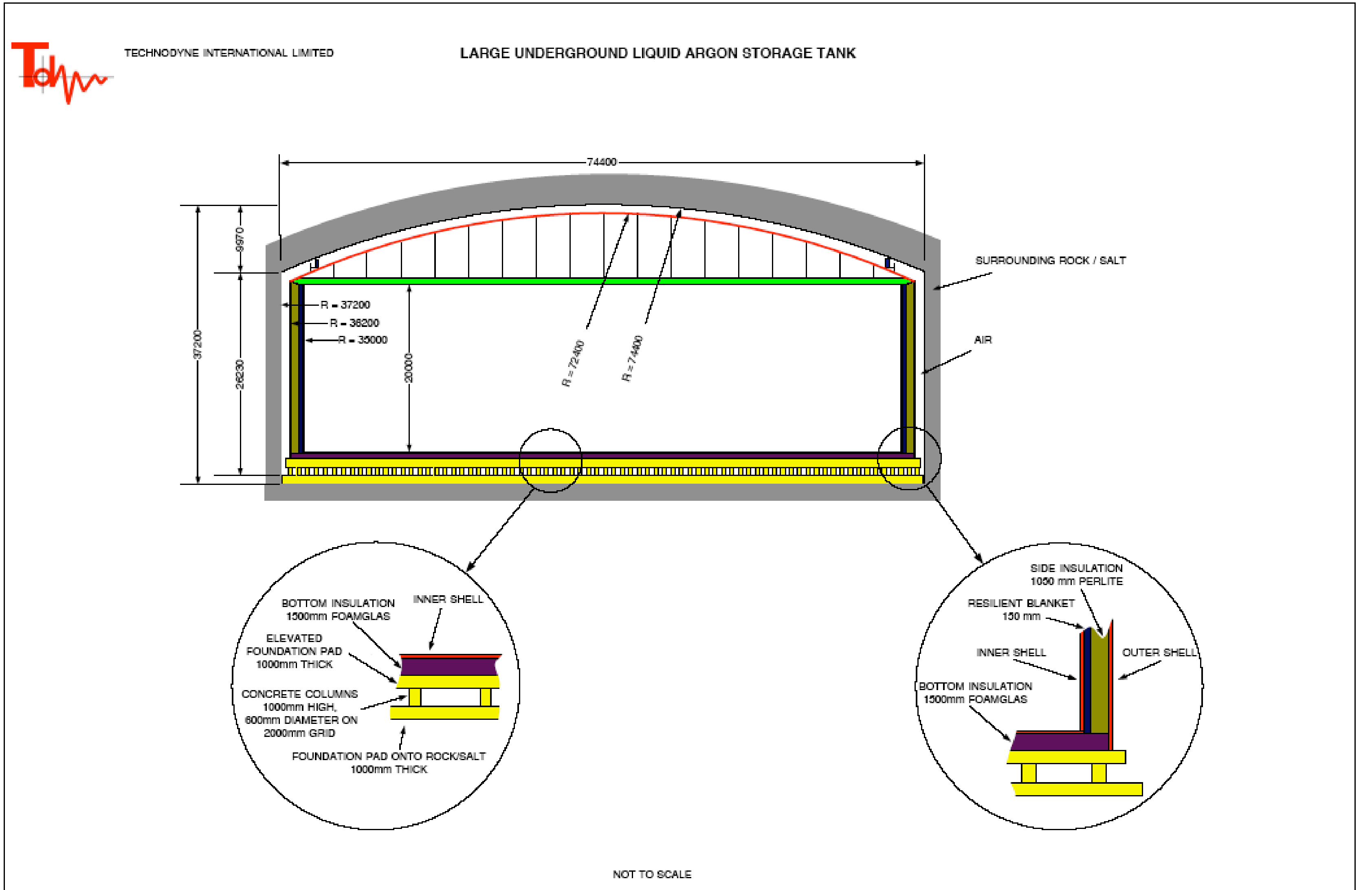
Liquefaction plant in Oman

e.g. Nigeria LNG (≈10^{10} m^3/year)

Up to 145,000m^3



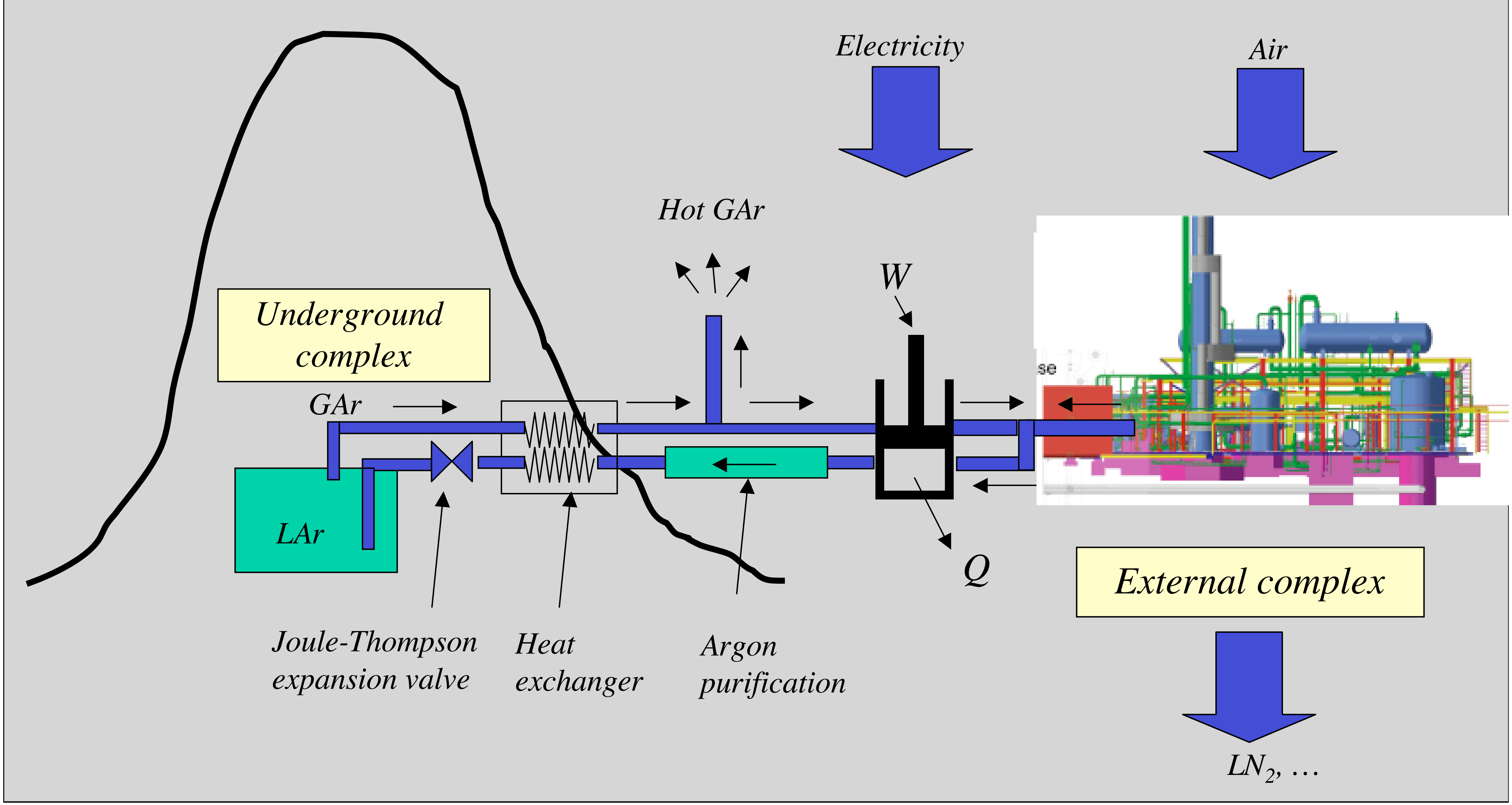
Large underground liquid Argon tanker



Preliminary baseline design for the Fréjus study

The "dedicated" cryogenic complex

- In situ cryogenic plant: tanker 5 W/m^2 heat input, continuous re-circulation (purity)
- Filling speed (100 kton): 150 ton/day → 2 years to fill



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Events for 100 kton detector mass

Number of targets for nucleon stability:

6×10^{34} nucleons $\Rightarrow$ τ_p/Br > 10^{34} years × T(yr) × ε @ 90 CL

Low energy Super-Beams or beta-beams:

460 ν_μ CC per 10^{21} 2.2 GeV protons (real focus) @ L = 130 km

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

Atmospheric:

10000 atmospheric events/year

100 ν_τ CC /year from oscillations

Solar:

324000 solar neutrinos/year @ E_e > 5 MeV

Supernova type-II:

≈20000 events @ D=10 kpc

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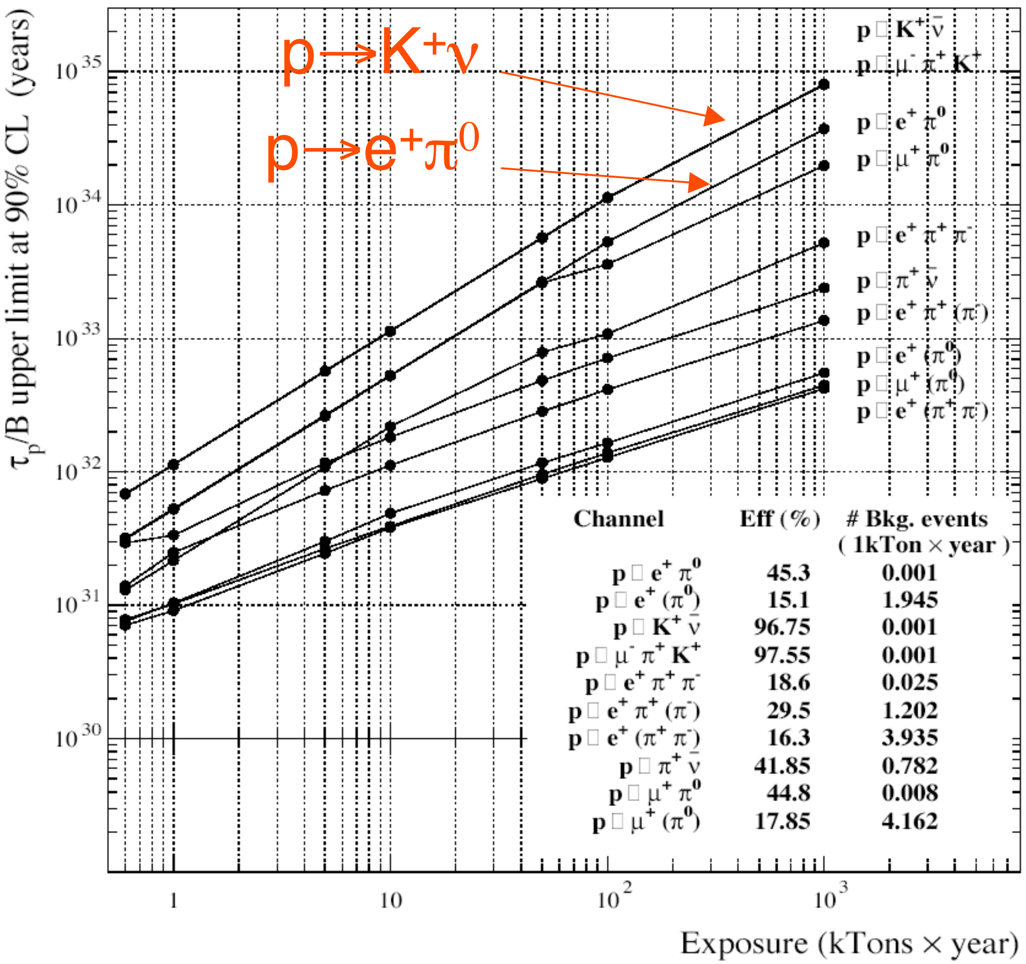
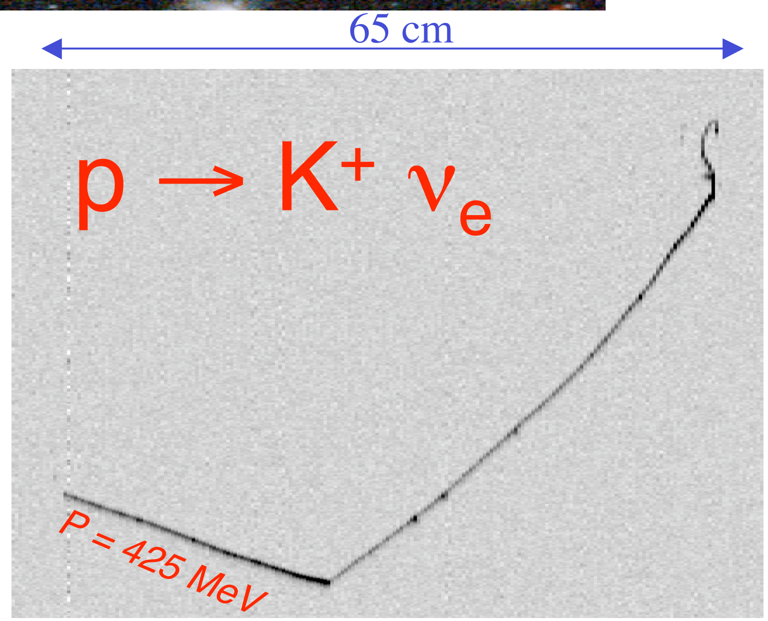
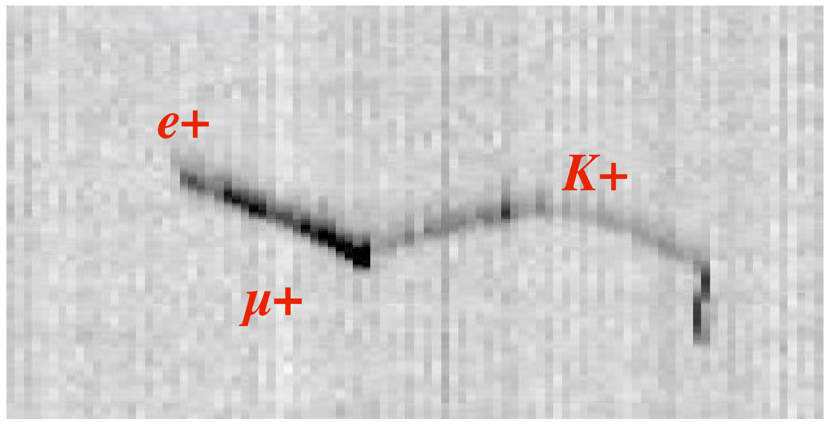
Proton decay: sensitivity vs exposure



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



"Single" event detection capability



T600: Run 939 Event 46

6×10^{34} nucleons ⇒

τ_p/Br > 1 10^{34} years × T(yr) × ε @ 90 CL

Conclusion

- **Neutrino physics experiments are exciting !**
- **Since Pauli's neutrino postulate in 1930, the field has been characterized by**
  - ➥A huge number of experiments
  - ➥In very different energy ranges…
  - ➥From very different sources (astrophysical, man-made)
  - ➥In very different environments (near accelerators, deep underground, …)
  - ➥With very different techniques (…)
- **The results of these experiments have dramatically improved our understanding of the neutrino particle**
- **However, still many unanswered questions remain**
  - ➥Solving these questions will continue to require new, inventive experiments to pursue progress in the field