Neutrino oscillations today and tomorrow

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Masurian Lakes School, 5.09.2005

Present status of measurements:

SuperKamiokande, K2K, SNO, KamLAND, LNSD, MiniBooNE

Future projects:

MINOS, OPERA, ICARUS, T2K, NOνA, reactor experiments, new sources of neutrinos

With neutrinos physics is unified

Neutrino oscillations – one page summary

1998 - 2002 - romantic era of great discoveries

1998 SuperKamiokande - atmospheric anomaly explained by the $\nu_\mu \to \nu_\tau$ oscillations

2002 confirmed by the long base accelerator experiment K2K

2001-2002 SNO solves the 35 years old solar neutrino puzzle by the $\nu_e \to \nu_{\mu,\tau}$ transmissions

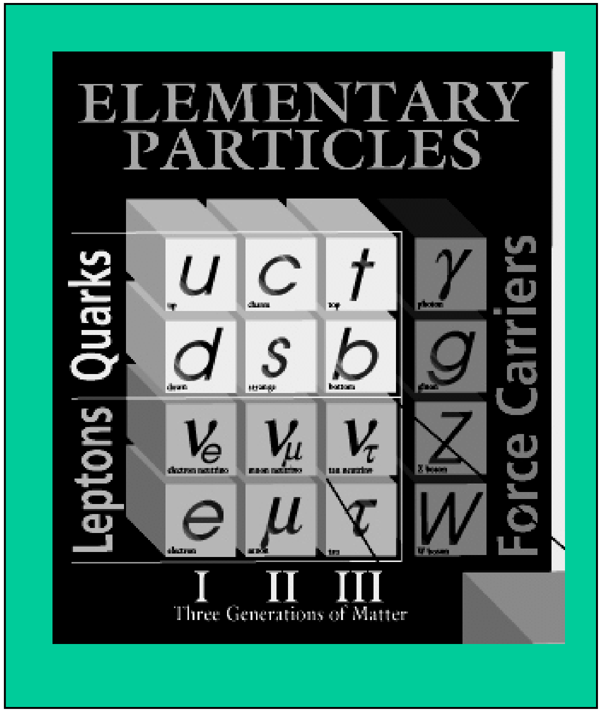
Dec 2002 KamLAND shows that reactor anti-ν_e's oscillate like solar ν_e's

from 2003 onwards - realistic era of precise measurements

- precise determination of the oscillation parameters and neutrino mixing matrix elements
- determination of the neutrino absolute masses
- character of neutrinos - neutrinoless double beta decay ($\beta\beta0\nu$) down to 0.01 eV

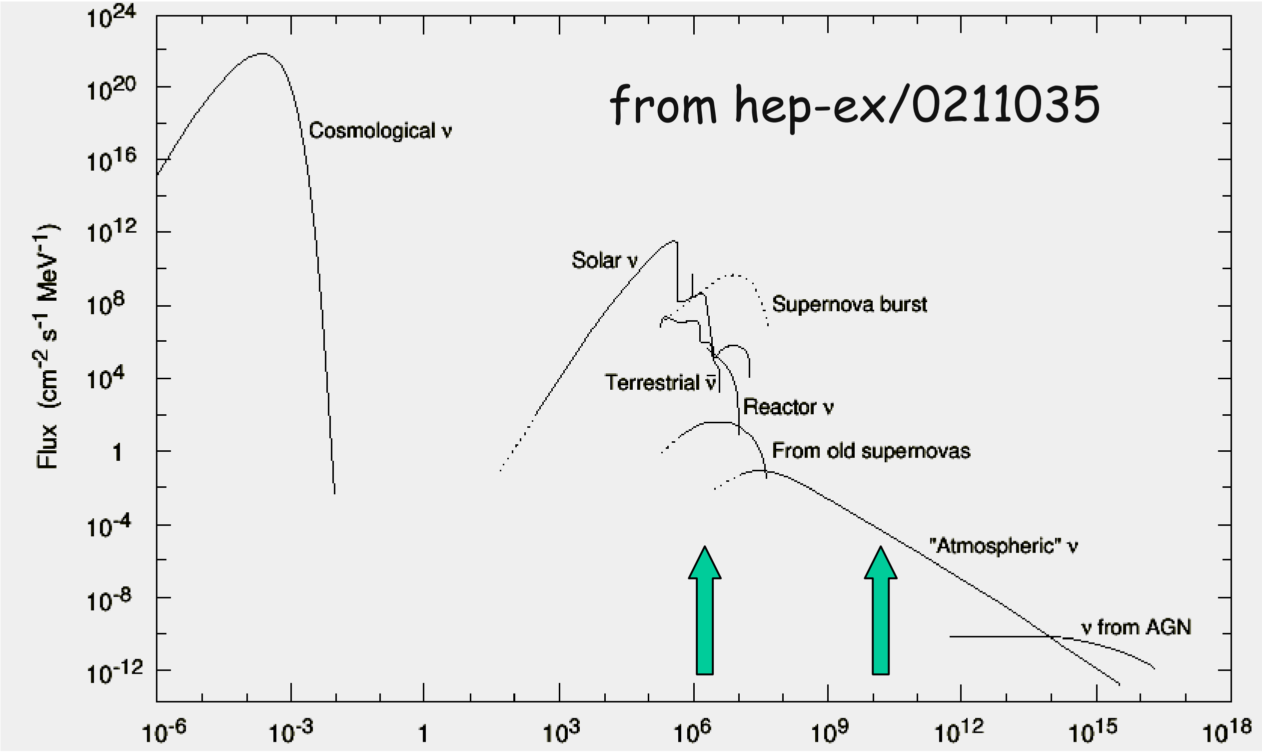
LBL accelerator (on-, off-axis) and reactor expts, superbeams, niu-factories, β-beams, bigger and improved detectors for all kinds of neutrino experiments, sky surveys, ...

Neutrino basics



Three light active neutrinos: ν_e, ν_μ, ν_τ
- result from LEP,
if others then sterile

Oscillations: studied with solar, reactor, atmospheric and accelerator neutrinos



Present status of neutrino oscillations

Neutrino oscillations primer

In the two-neutrino oscillation scheme with two flavour eigenstates α and β and two mass eigenstates 1 and 2, the probability that neutrino of flavour α transforms into neutrino of flavour β:

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

Appearance experiment:

$$P\left(\nu_\alpha \to \nu_\beta\right) \geq 0$$

Disappearance experiment:

$$P\left(\nu_\alpha \to \nu_\alpha\right) \leq 1$$

Matter effects: the same formulae for probabilities like for vacuum oscillations but effective masses and effective mixing angles

Neutrinos are born in weak interactions as flavour eigenstates but propagate in vacuum or matter as mass eigenstates

Three neutrino mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillation parameters: 3 mixing angles, 2 differences of mass squares, 1 phase
If neutrino is the Majorana particle, 2 additional phases

Atmospheric neutrinos

CP phase

solar neutrinos

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

connects solar and atmospheric regions

If $\delta \neq 0, \pi, 2\pi \ldots$ then CP is violated for leptons (like for quarks), θ_{13} is a gateway to a measurent of δ

Three neutrino mixing

Present values of the oscillation parameters:

$\theta_{23} = 45^0$ (maximal mixing), $\theta_{12} = 33^0$ (large), $\theta_{13} < 10^0$ (small),

$\Delta m^2_{23} = 2.5 \times 10^{-3}\ eV^2$, $\Delta m^2_{12} = 8 \times 10^{-5}\ eV^2$,

$| \Delta m^2_{13} | = | \Delta m^2_{23} - \Delta m^2_{12} |$

Neutrino oscillations

Two oscillation regions with a very solid experimental evidence:

atmospheric region

solar region

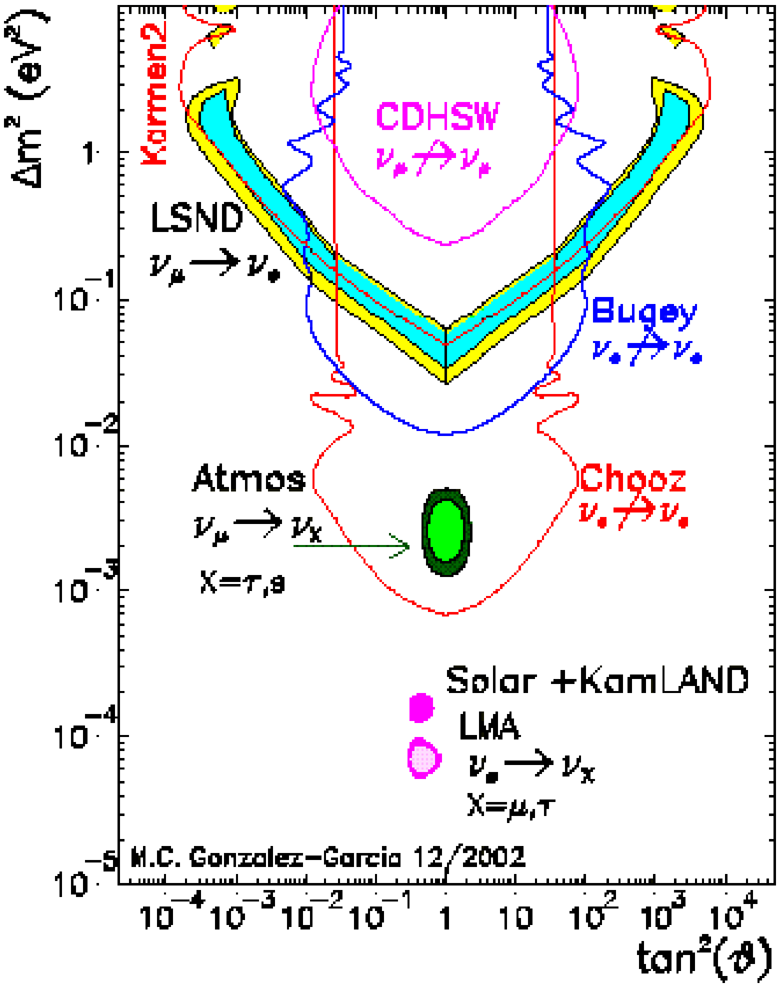
Third region:

LSND

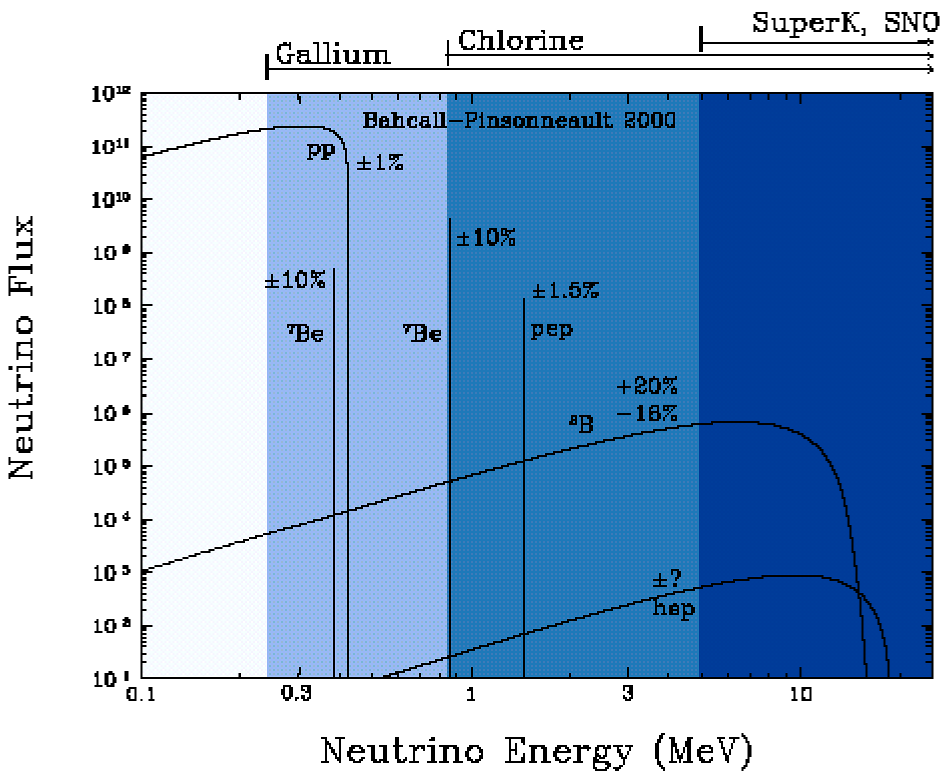
being checked by the dedicated MiniBooNE experiment

Note: SNO reduced the allowed oscillation space for solar neutrinos by 7 orders of magnitude

CHOOZ excludes $\nu_\mu - \nu_e$ oscillations in the atmospheric region



Solar neutrinos primer



Most of the solar neutrinos in pp cycle

$$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 2\gamma$$

Experiments measure the reactions:

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

In particular:

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

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

$\nu_\ell + e^- \rightarrow \nu_\ell + e^-$ SuperK, SNO

$\nu_\ell + n \rightarrow \nu_\ell + n$ SNO

--Matter effects in the Sun are important for flavor conversion

--We have to count on solar models to provide the needed input $R = N_{obs}/N_{MC}$

--The distance to the Sun varies by about 7% during the year

--During the night neutrinos pass through the Earth on their way to the detector, while during the day they do not -> the Earth matter effect provides further sensitivity to the neutrino parameters.

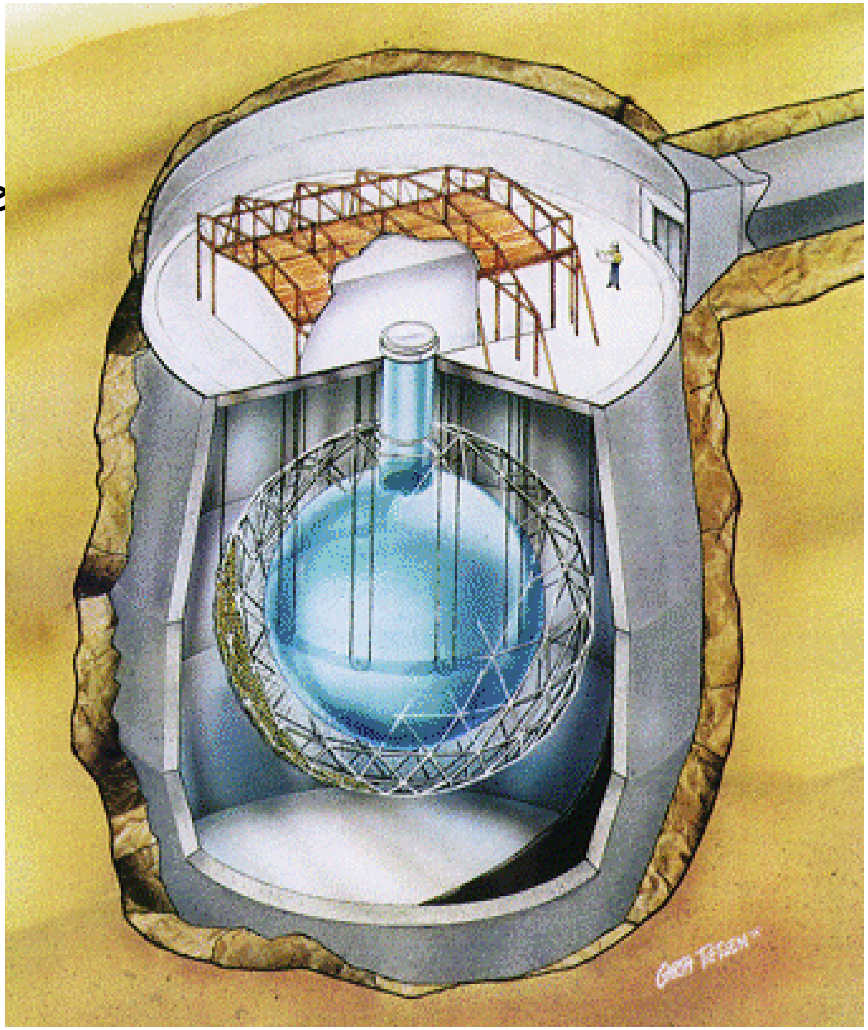
SNO - oscillations of solar neutrinos

ν_e neutrinos produced in Sun
$\nu_e \rightarrow \nu_{\mu,\tau}$ on the way from the Sun core to the Sun surface
total neutrino flux in agreement with the Standard Solar Model

Phase 1: 1000 tons of D_2O, 9456 photomultipliers, 7 kton H_2O, 2000 m. under surface, detection of the Cherenkov radiation

Phase 2: addition of two tons of salt to improve the neutron capture efficiency

Phase 3: addition of He detectors

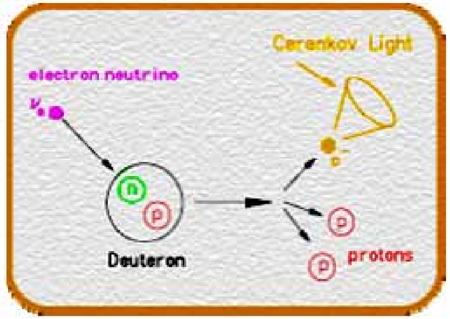


Phase 1 publications
PRL 87, 071301 (2001) (SNO + SK)

PRL 89, 011301 (2002) (SNO only)

Processes measured in the SNO experiment

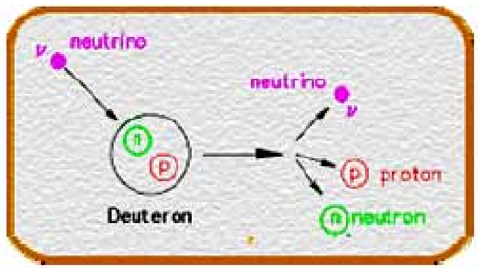
CC $\nu_e + d \Rightarrow p + p + e^-$



Only ν_e, good measurement of ν_e energy, weak dependence on the neutrino direction 1-1/3cosθ

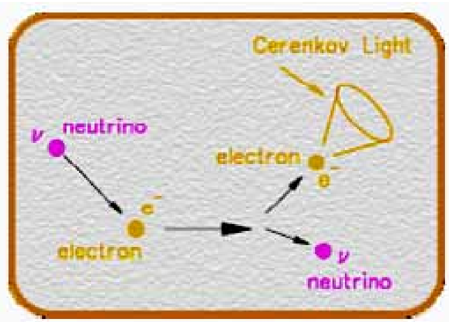
E_{th}=1.4MeV

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



All three flavours with the same cross section, measurement of the total neutrino flux E_{th}=2.2MeV

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



Mostly sensitive to ν_e, very sensitive to the neutrino direction, relatively small cross section

Reaction measured in SuperK

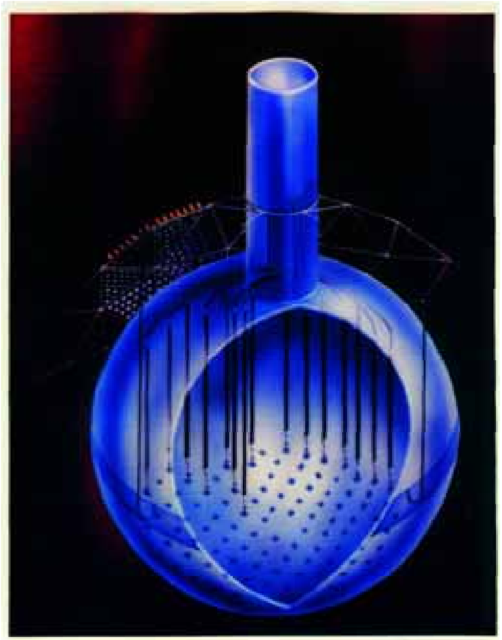
SNO - comparison of phase I and II

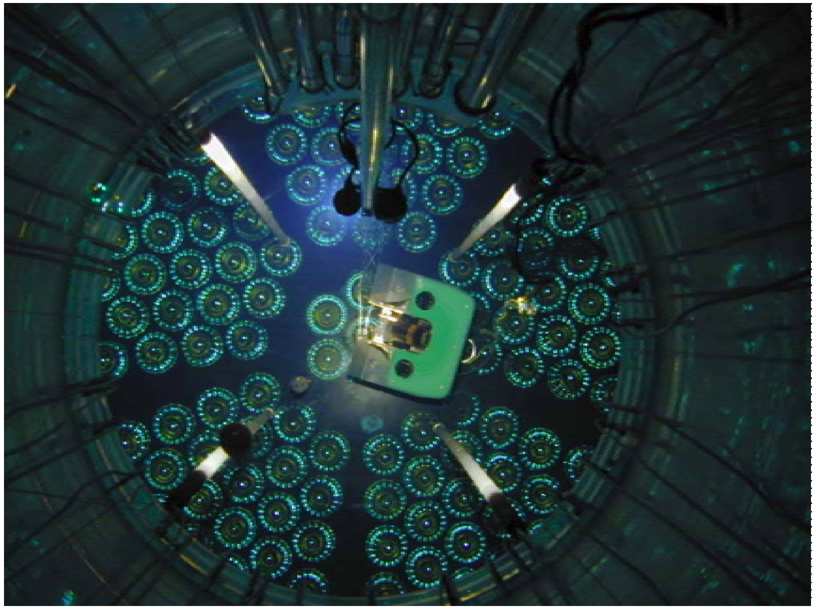
D_2O	Salt
NC Sensitivity $\varepsilon_n \sim 24\%$ $n + {}^2H \rightarrow {}^3H + \gamma$ $E_\gamma = 6.25$ MeV NC and CC separation by energy, radial, and directional distributions	**Enhanced NC Sensitivity** $\varepsilon_n \sim 83\%$ $n + {}^{35}Cl \rightarrow {}^{36}Cl + \sum\gamma$ $E_{\Sigma\gamma} = 8.58$ MeV NC and CC separation by event isotropy

SNO - phase III

D_2O + ^3He Proportional Counters

- Good neutron sensitivity
- Great neutron/electron separation





775 m total active length of He counters

SNO - answers to the questions:

$$\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)} = 1\ ?$$

$$\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 1\ ?$$

$$\Phi_{day} = \Phi_{night}\ ?$$

$A = 0.037 \pm 0.040$

Day/night ϕ_{ν_e} assymetry

SNO phase I+II results on solar fluxes

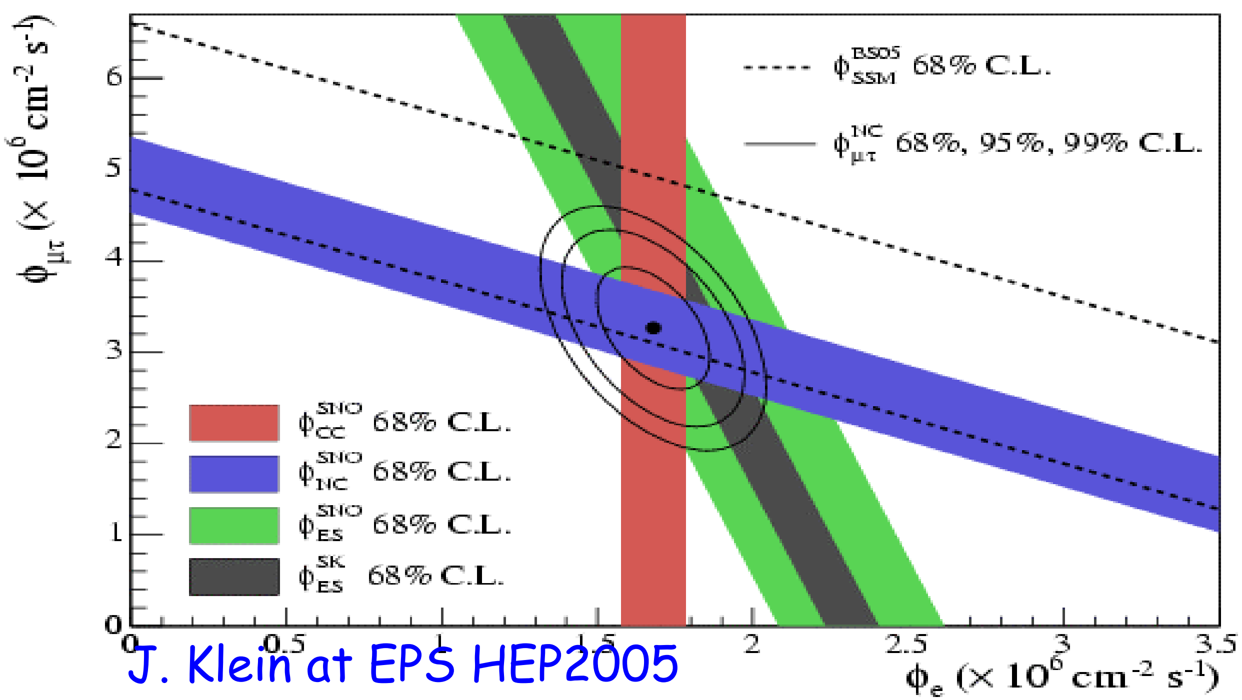
$$\Phi_{CC} = 1.68^{+0.06}_{-0.06}(stat.)^{+0.08}_{-0.09}(sys.) \times 10^{6}\, cm^{-2} s^{-1}$$

$$\Phi_{ES} = 2.35^{+0.22}_{-0.22}(stat.)^{+0.15}_{-0.15}(sys.) \times 10^{6}\, cm^{-2} s^{-1}$$

$$\Phi_{NC} = 4.94^{+0.21}_{-0.21}(stat.)^{+0.38}_{-0.34}(sys.) \times 10^{6}\, cm^{-2} s^{-1}$$

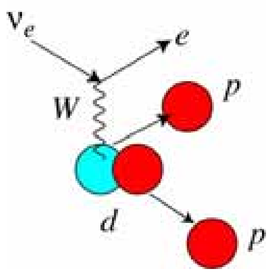
$$\Phi_{BP\,04} = 5.82 \pm 1.34 \times 10^{6}\, cm^{-2} s^{-1}$$

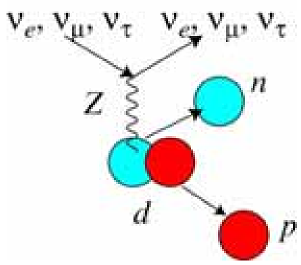
Flavor content of solar flux.



J. Klein at EPS HEP2005

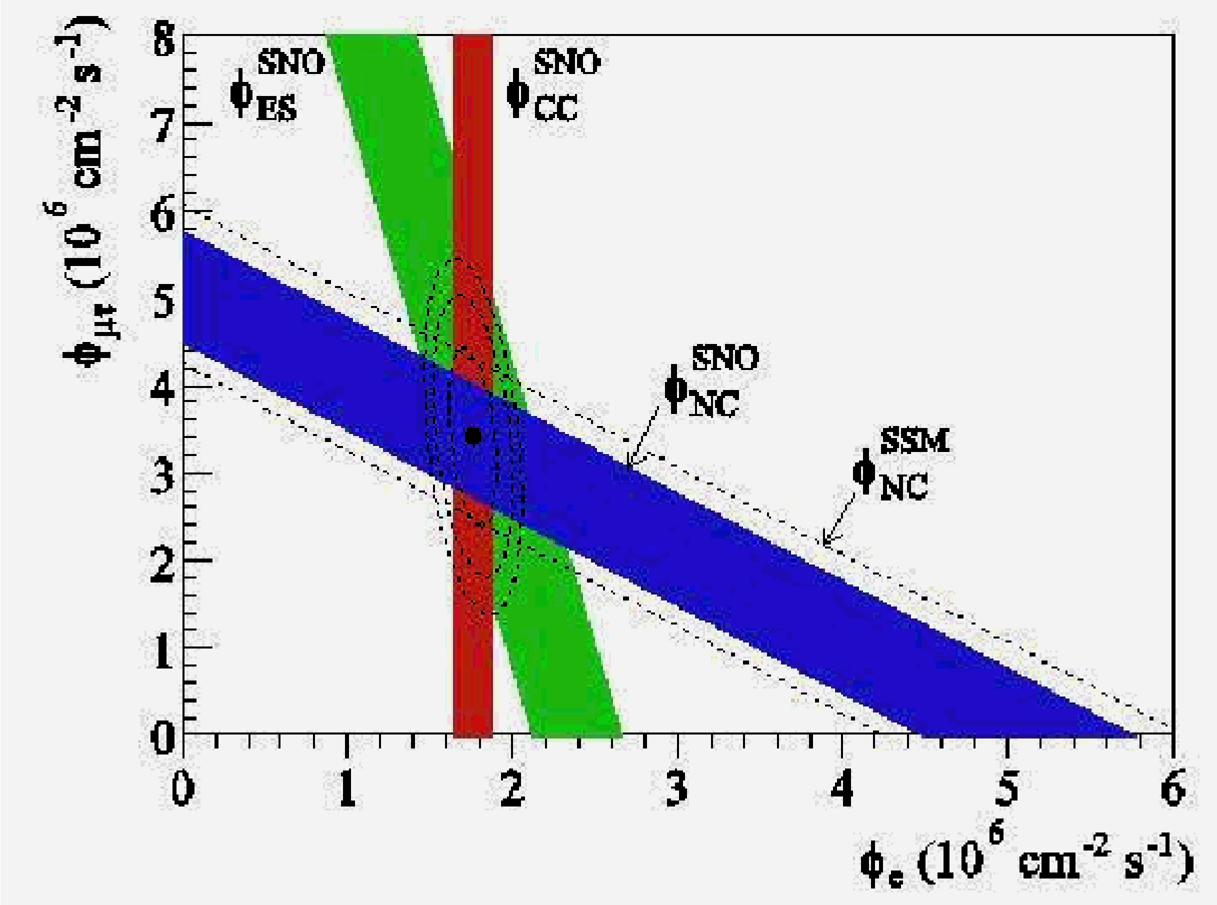
2002 SNO results on solar fluxes





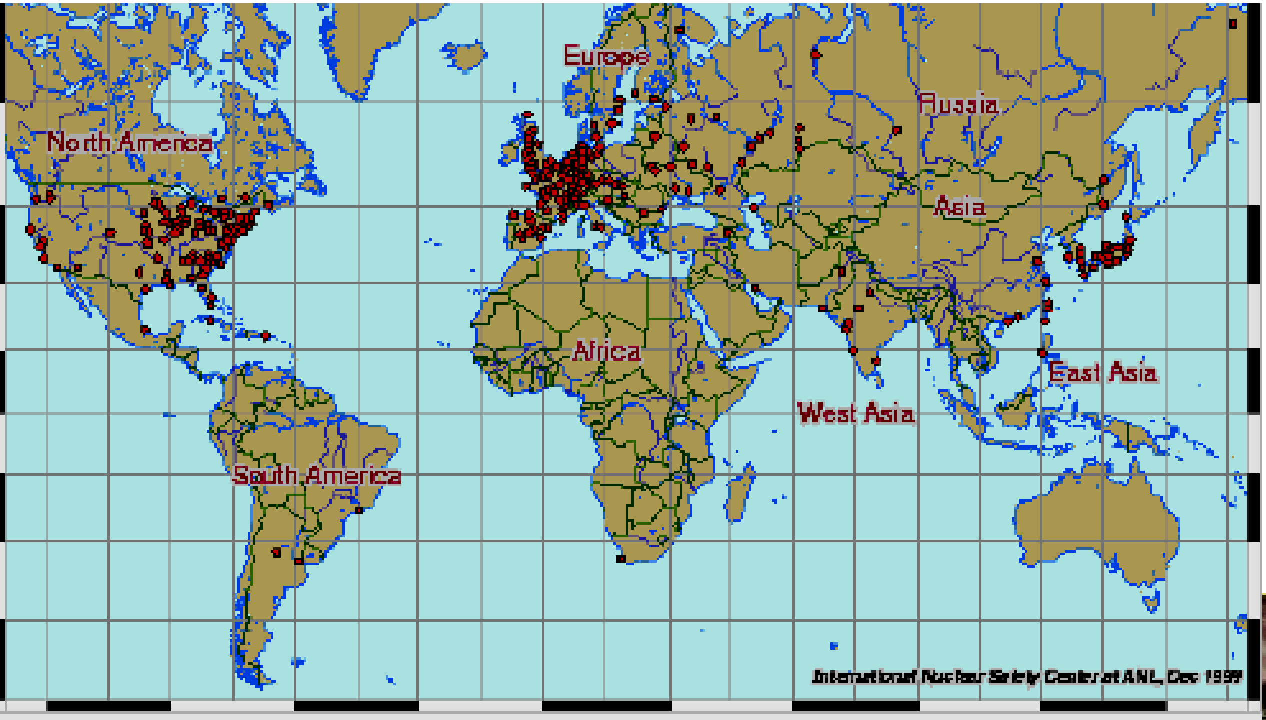
$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6 \,\text{cm}^{-2}\,\text{sec}^{-1}$$

$$\Phi_{NC} = 5.09 \,{}^{+0.44}_{-0.43}\,{}^{+0.46}_{-0.43} \cdot 10^6 \,\text{cm}^{-2}\,\text{sec}^{-1}$$



$$\Phi_{ssm} = 5.05^{+1.01}_{-0.81}$$

Reactor antineutrinos



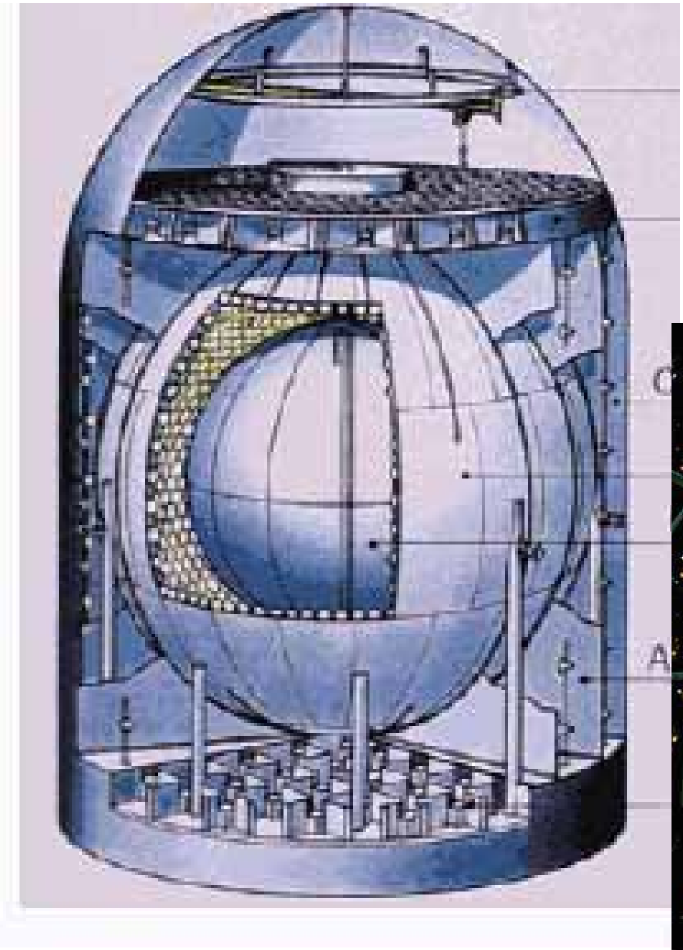
Long tradition, started by the first observation of neutrino interactions by Reines and Cowan

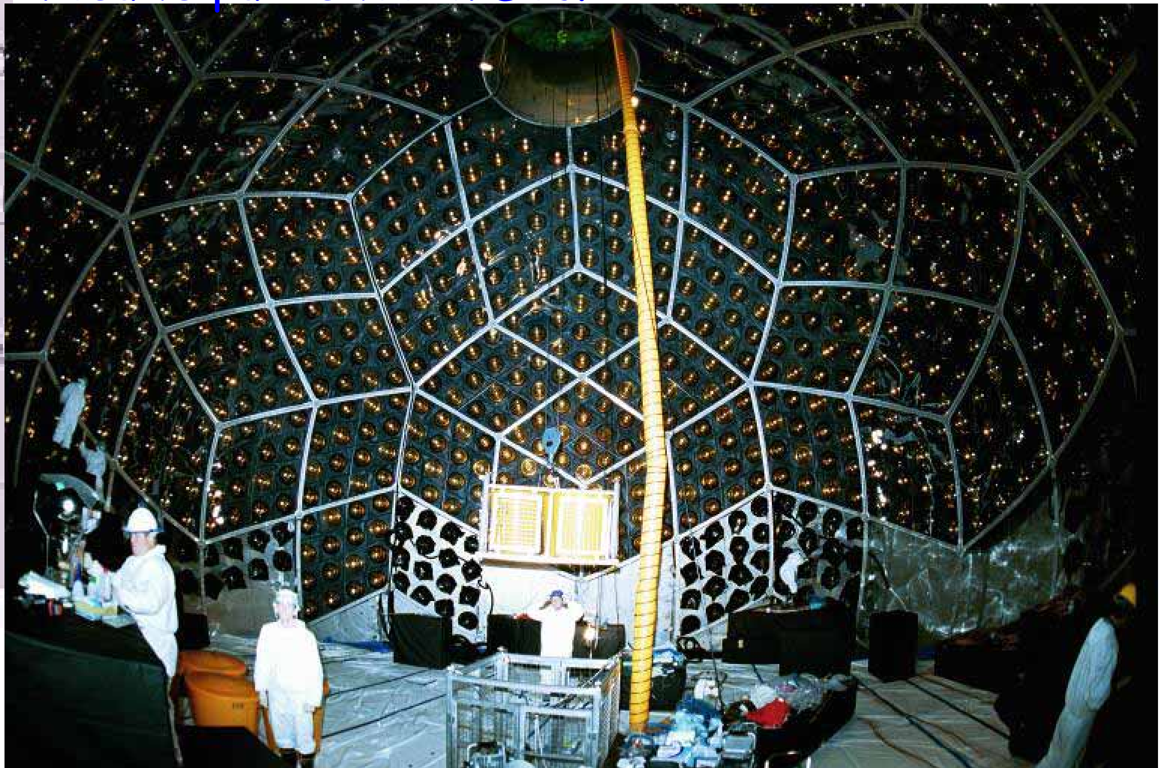
Typical power station gives $6x10^{20}$ anty-ν/s and 3GW of power

The Palo Verde reactor experiment

KamLAND - very long baseline reactor experiment

Detector: inner detector - 1 kton of liquid scintillator, light registered by about 2000 photomultipliers, outer detector filled with oil, veto part filled with water,
Detector "looks" at more than 30 reactors in Japan and Korea at average distance of 180 km
Experiment started in January 2002, first results published in Dec. 2002





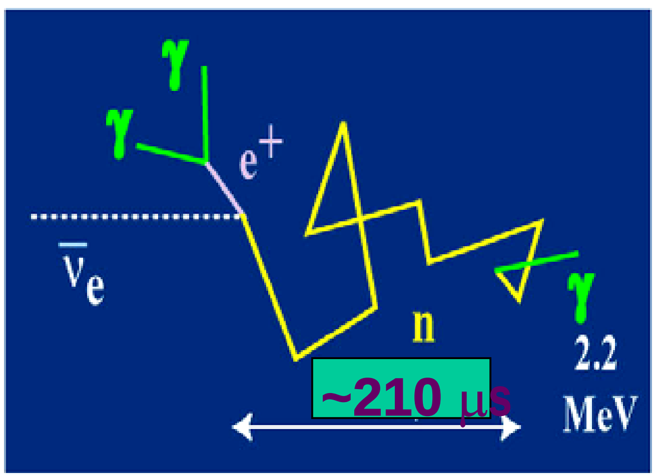
Reactor $\bar{\nu}_e$ Detection in Liquid Scintillator

A.Suzuki at
Neutrino telescopes 2003

reaction process : inverse- β decay ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$+ p \longrightarrow d + \gamma$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- **prompt part : e^+**

  $\bar{\nu}_e$ energy measurement

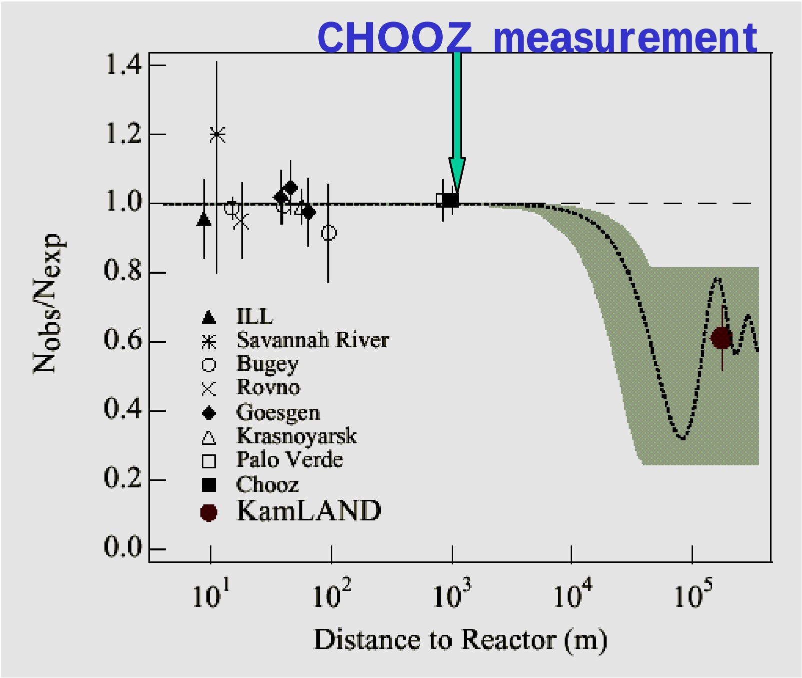
  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

- **delayed part : γ (2.2 MeV)**

- **tagging : correlation of time, position and energy between prompt and delayed signal**

KamLand results



KamLAND, PRL 90, 2003

Interesting: distance between the detector and the most powerfull reactors is too long

L=70 km corresponds to the first oscillation minimum

Event numbers for 766 ton-years of data:

Expected (no oscillation)=365.2 ± 23.7

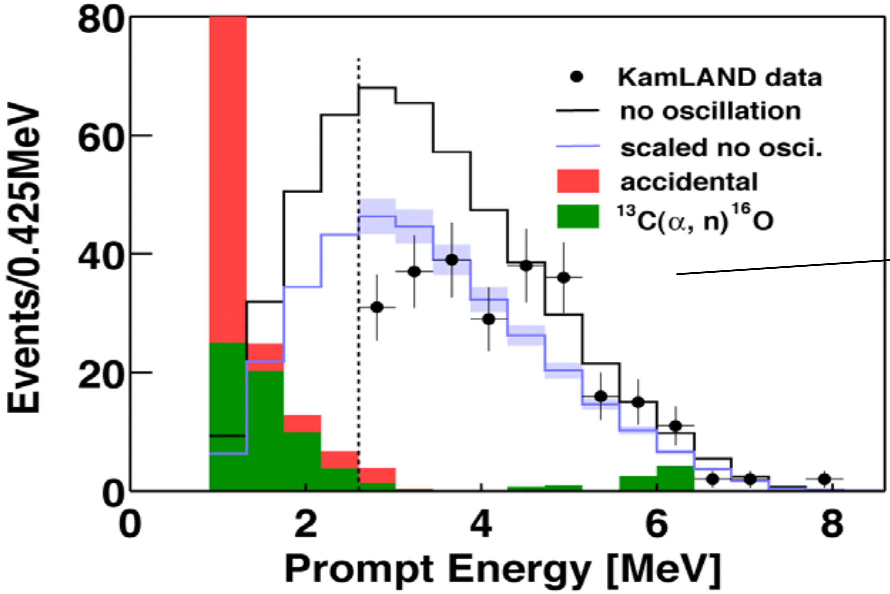
Expected background =17.8 ± 7.3

Observed =258

KamLAND, EPS HEP2005

Disappearance with significance of 99.998%

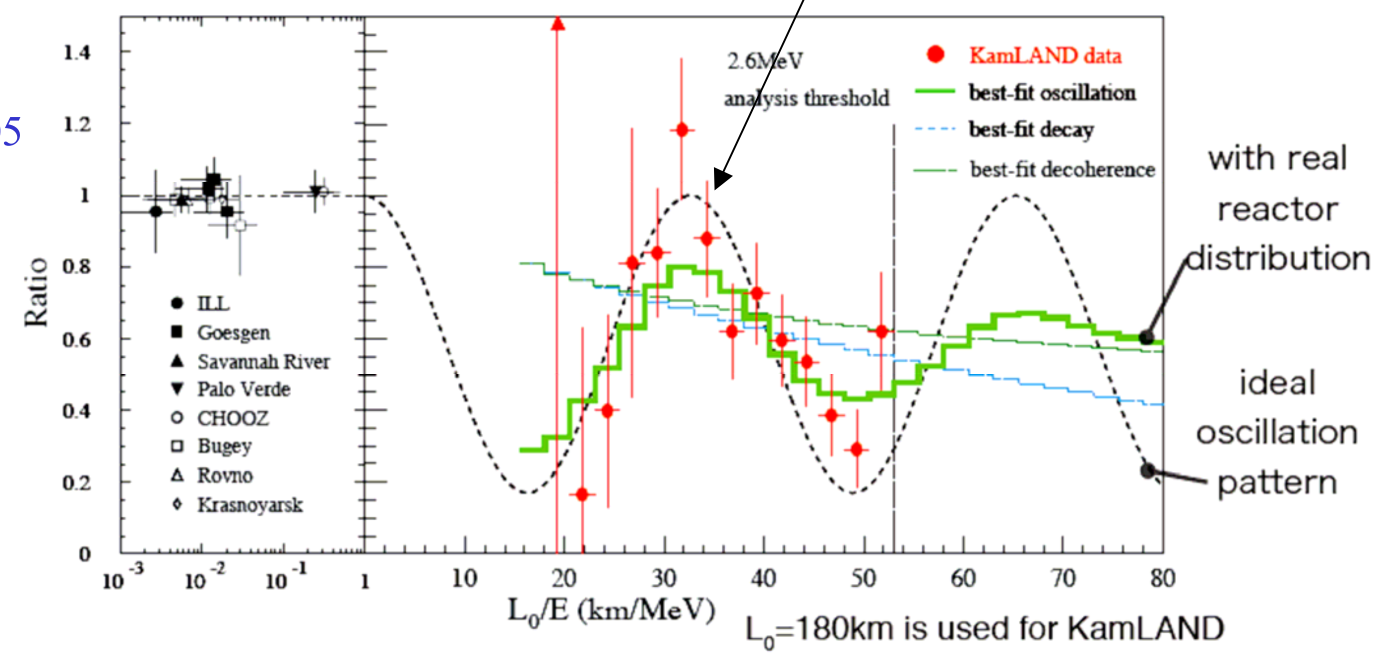
KamLAND: Testing the Model with L/E Behavior



- Rate + Shape: Oscillations at 99.999995% C.L.

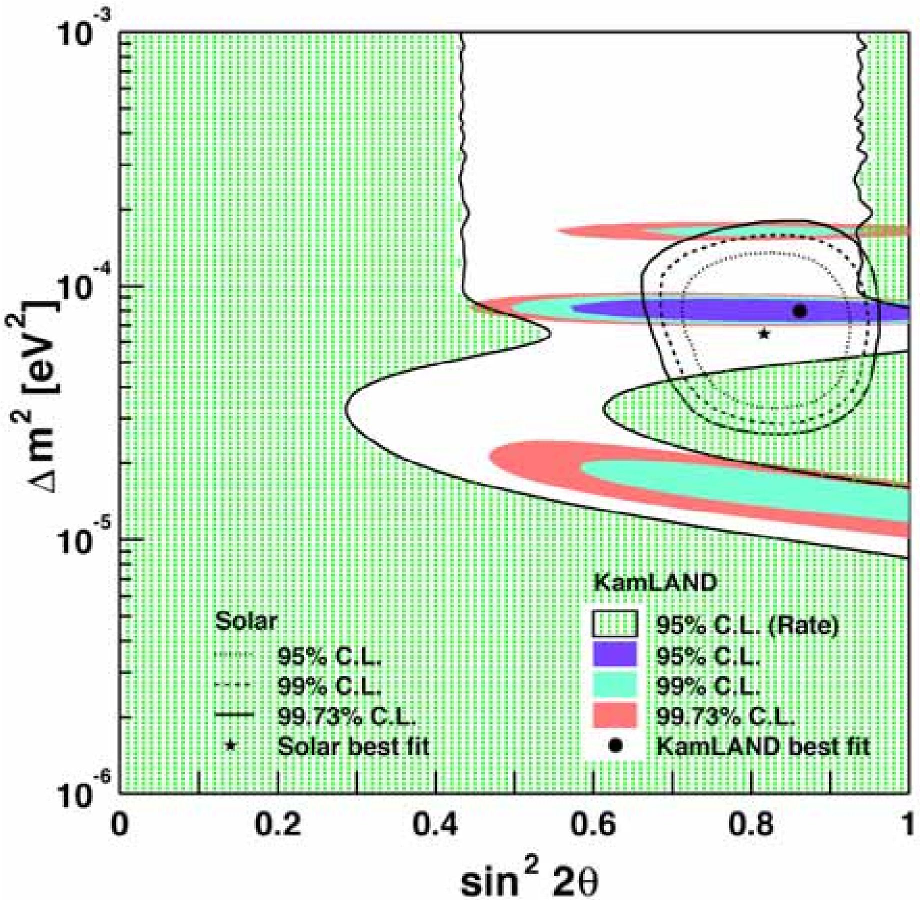
$$P_{\nu_e \to \nu_e} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\Delta m_{12}{}^2 L}{E}\right)$$

KamLAND, PRL 94, 2005
J.Klein, EPS HEP2005



A.Zalewska, Mazı

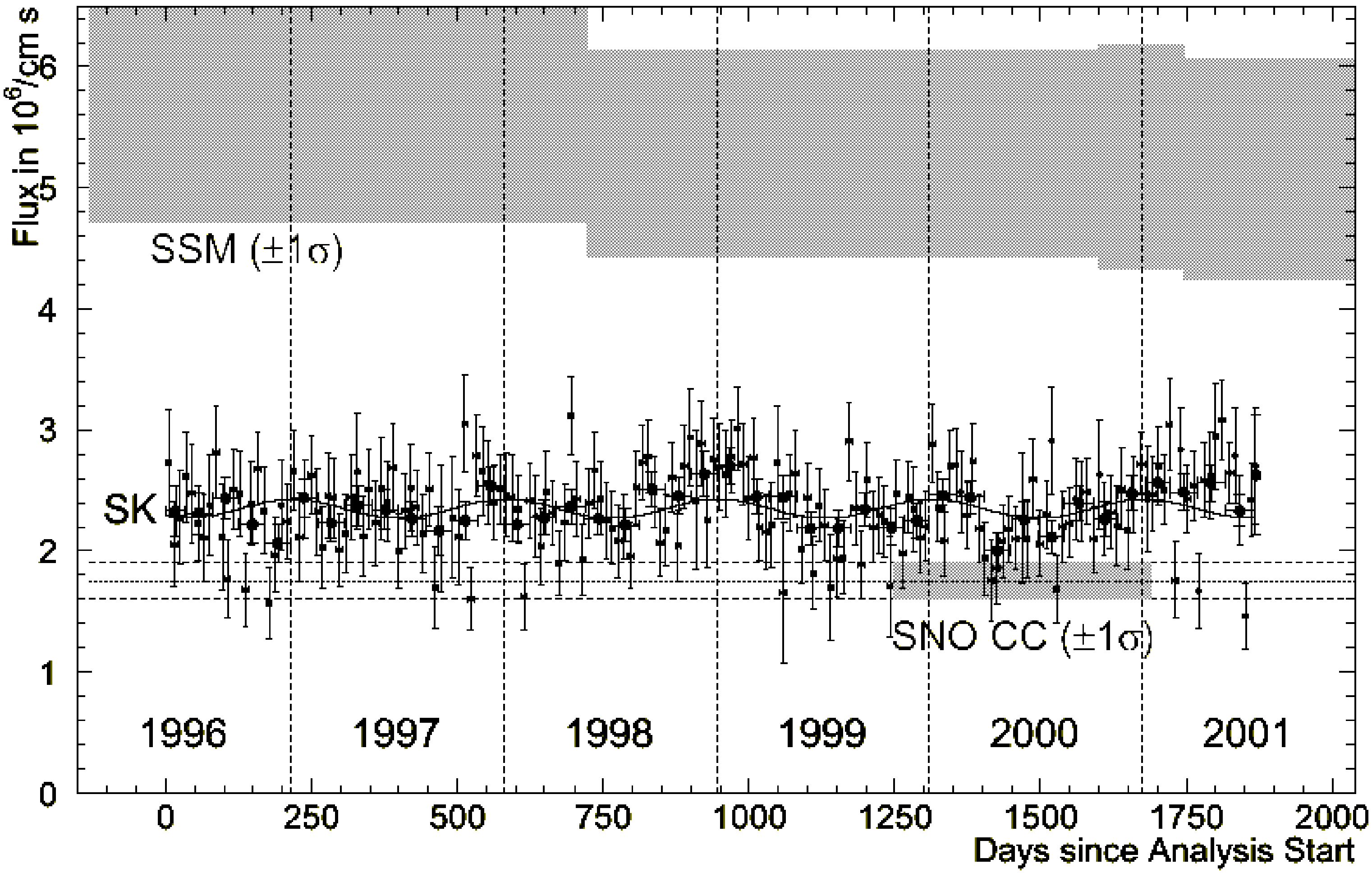
➢ KamLAND+SNO: Testing the Model



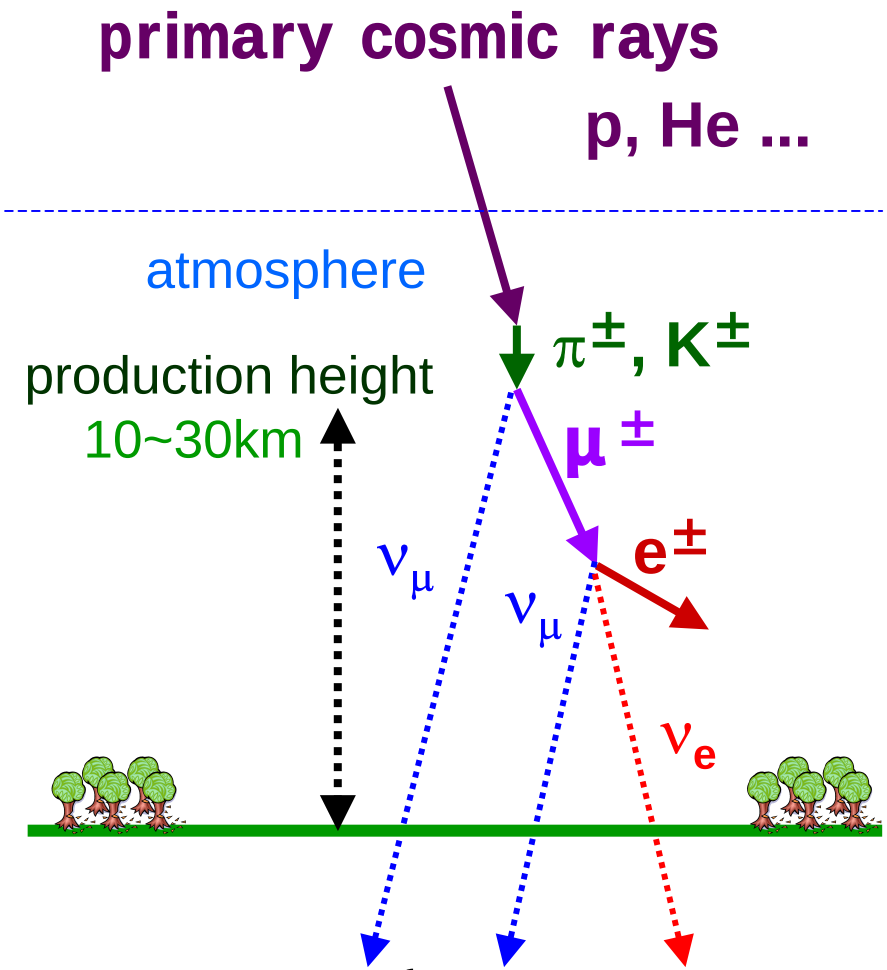
	Reactor	Solar
E	2-10 MeV	0.1-15 MeV
L	150 km	1.5 x 10^8 km
MSW	No	Yes
ν	Anti-ν_e	ν_e

KamLAND, PRL 94, 2005
J.Klein, EPS HEP2005

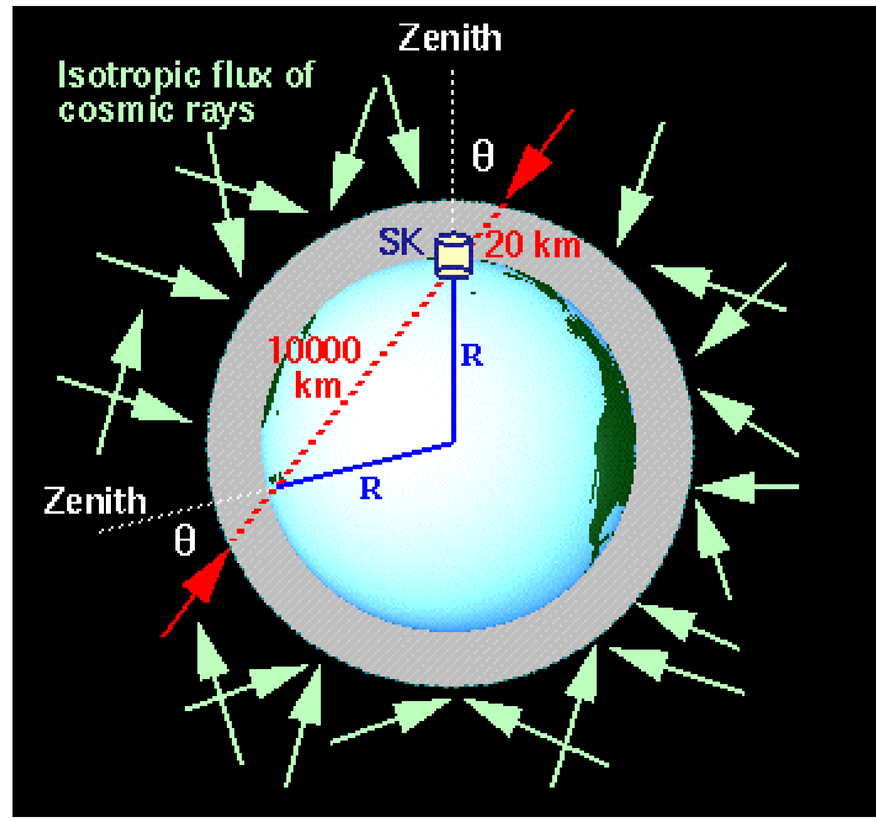
SuperKamiokande - solar neutrinos flux modulation in time



Atmospheric neutrinos primer



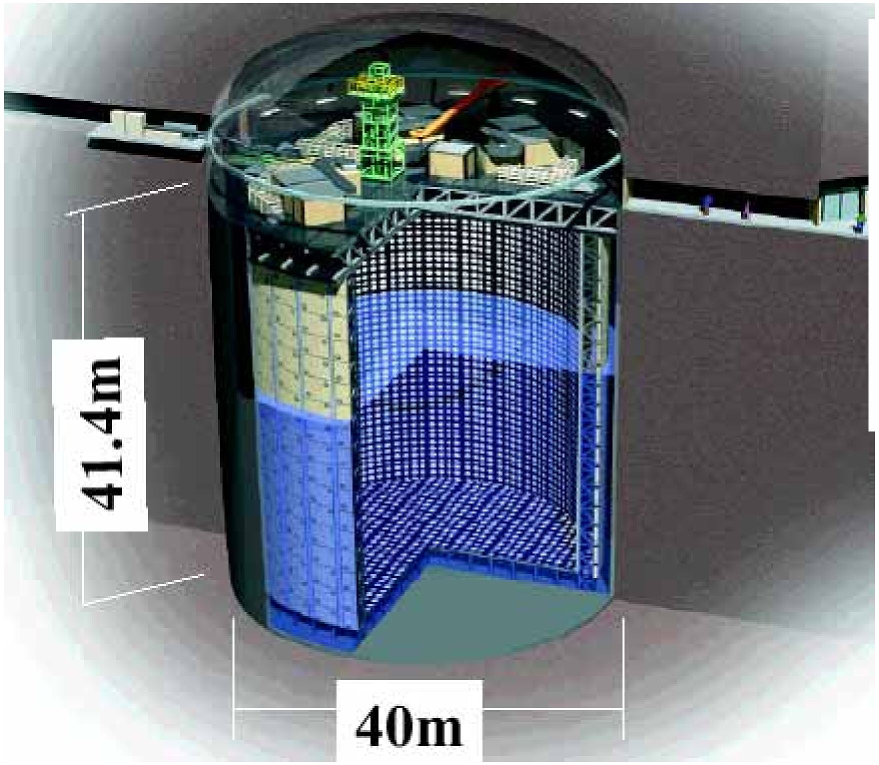
For E_ν > a few GeV,
(Up-going / down-going) $\mu \sim 1$

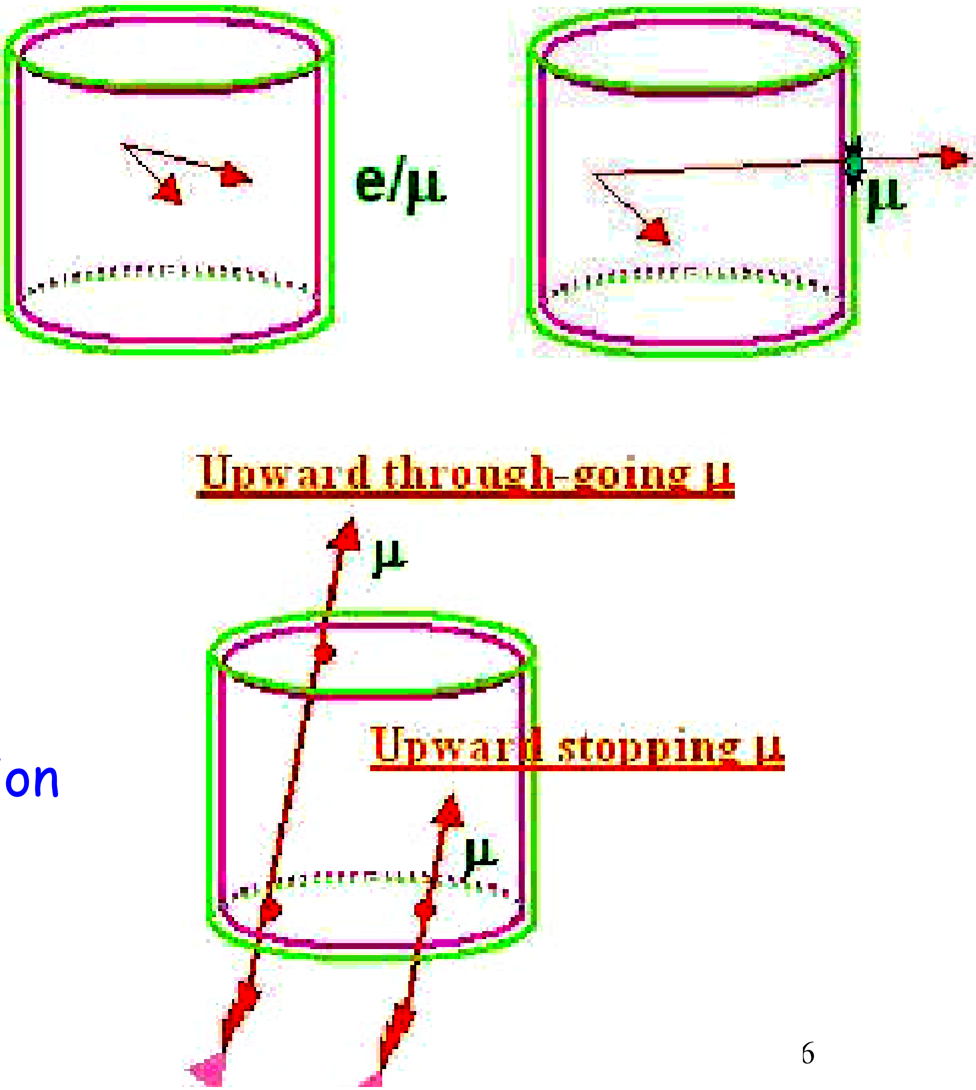


$$\frac{\phi(\nu_\mu+\bar{\nu}_\mu)}{\phi(\nu_e+\bar{\nu}_e)} \begin{cases} \sim 2 \text{ (for } E_\nu < 1\text{GeV)} \\ > 2 \text{ (for } E_\nu > 1\text{GeV)} \end{cases}$$

Can't measure E_ν or L_ν, but can look at $\cos\theta_{zenith}$ in bins of E_{lepton}

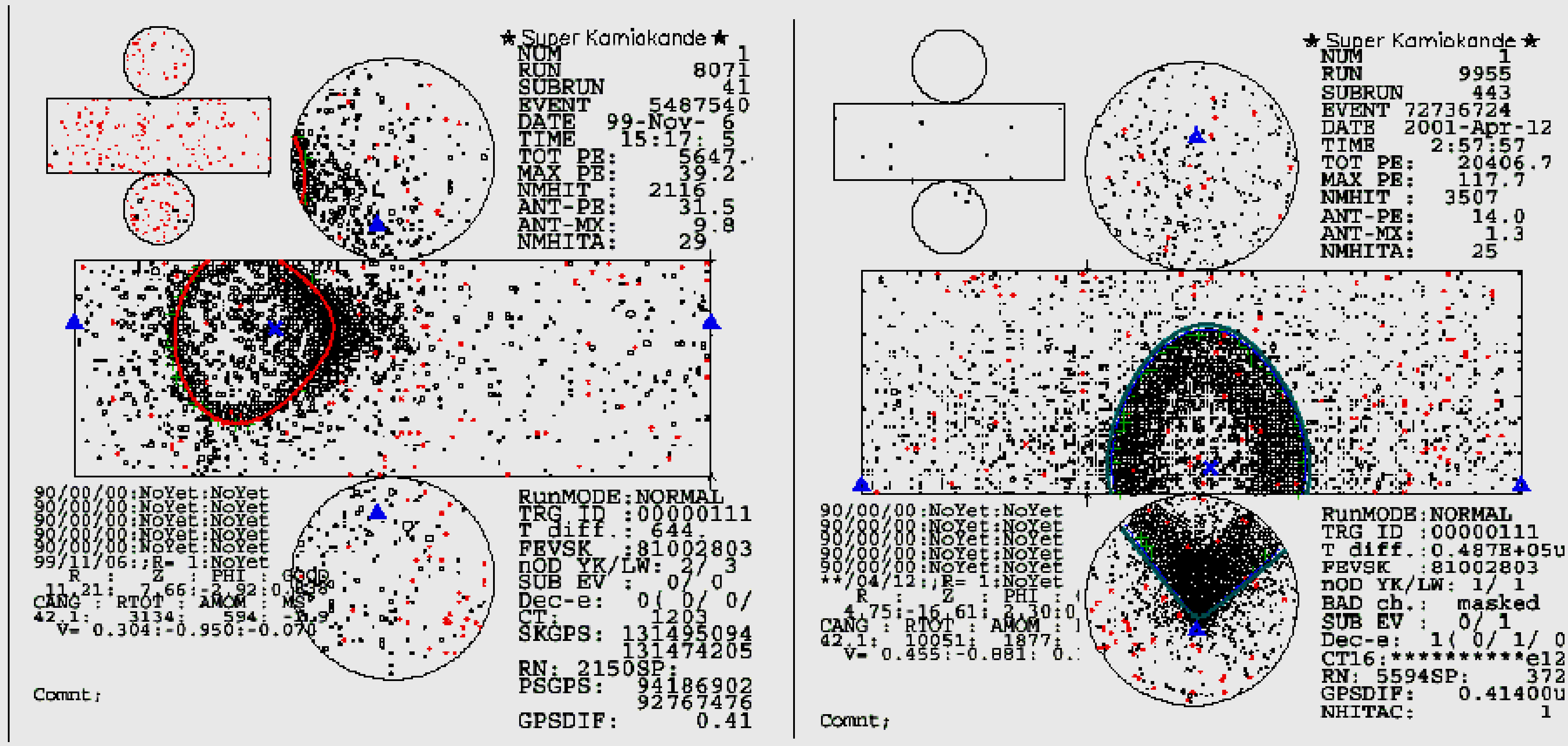
SuperKamiokande - oscillations $\nu_\mu \leftrightarrow \nu_\tau$



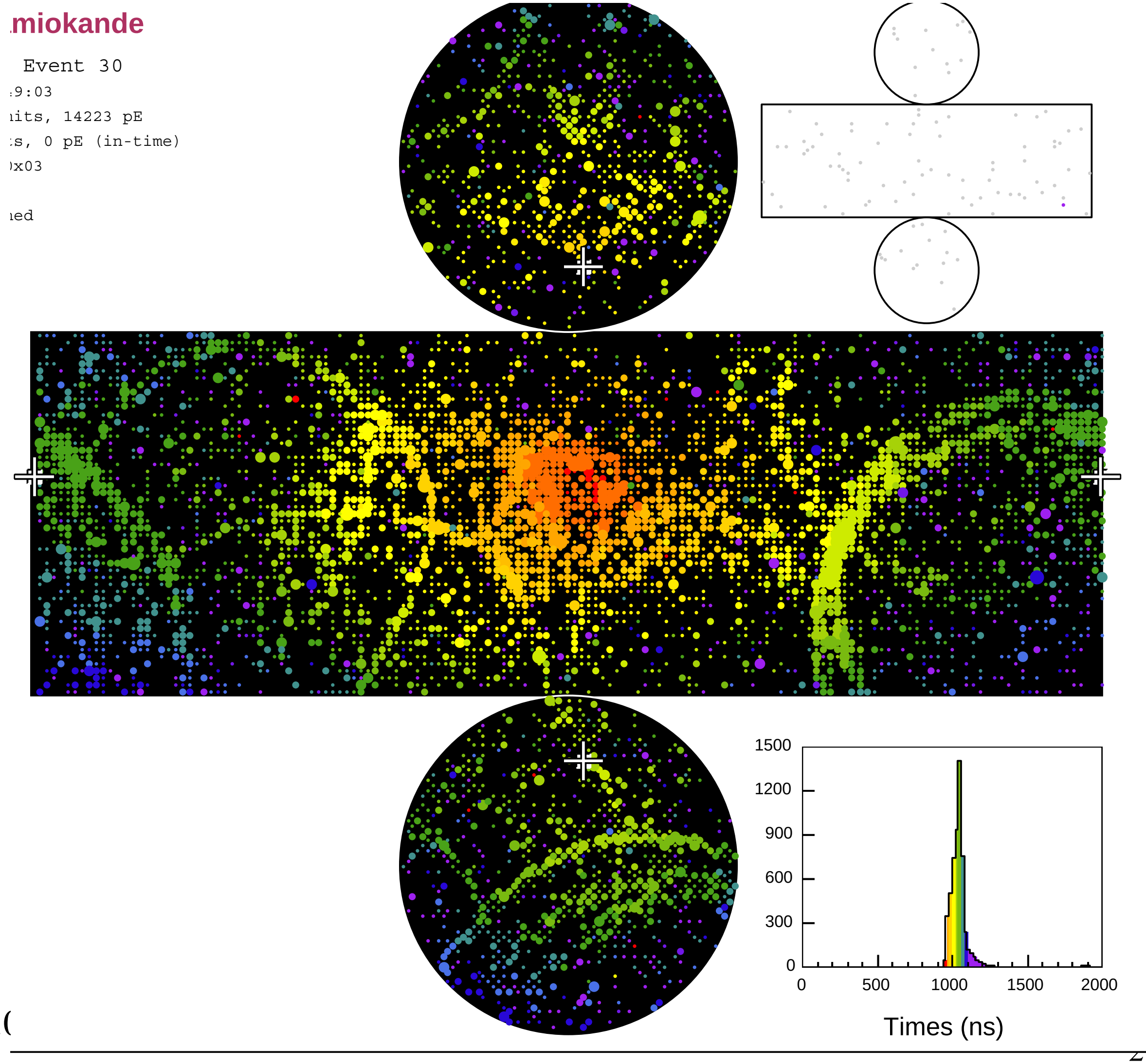


Measurement of energy and direction of muons and electrons from CC neutrino interactions, about 15000 events from SuperK I

SuperK - e and μ.

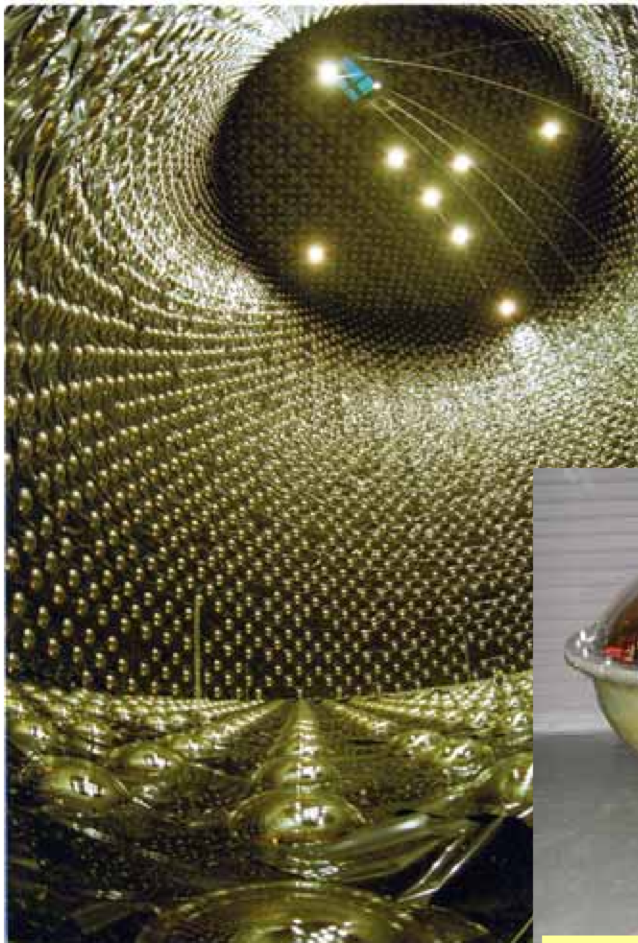


SuperK – multi-ring event



Super Kamiokande-II

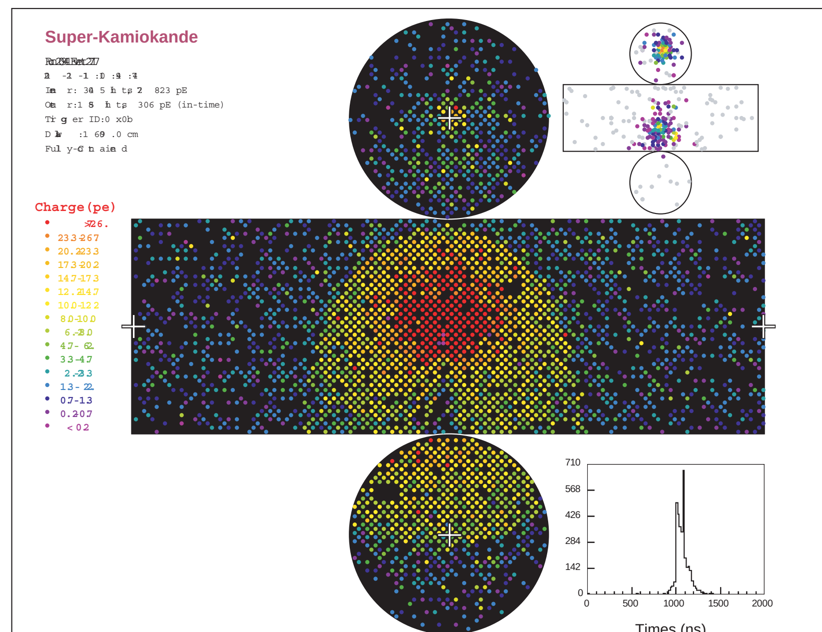
from Hayato at EPS2003



the detector rebuilt successfully
and
resumed data taking in Dec. 2002.

20inch PMT with Acrylic + FRP vessel

SK-II Cosmic ray muon sample

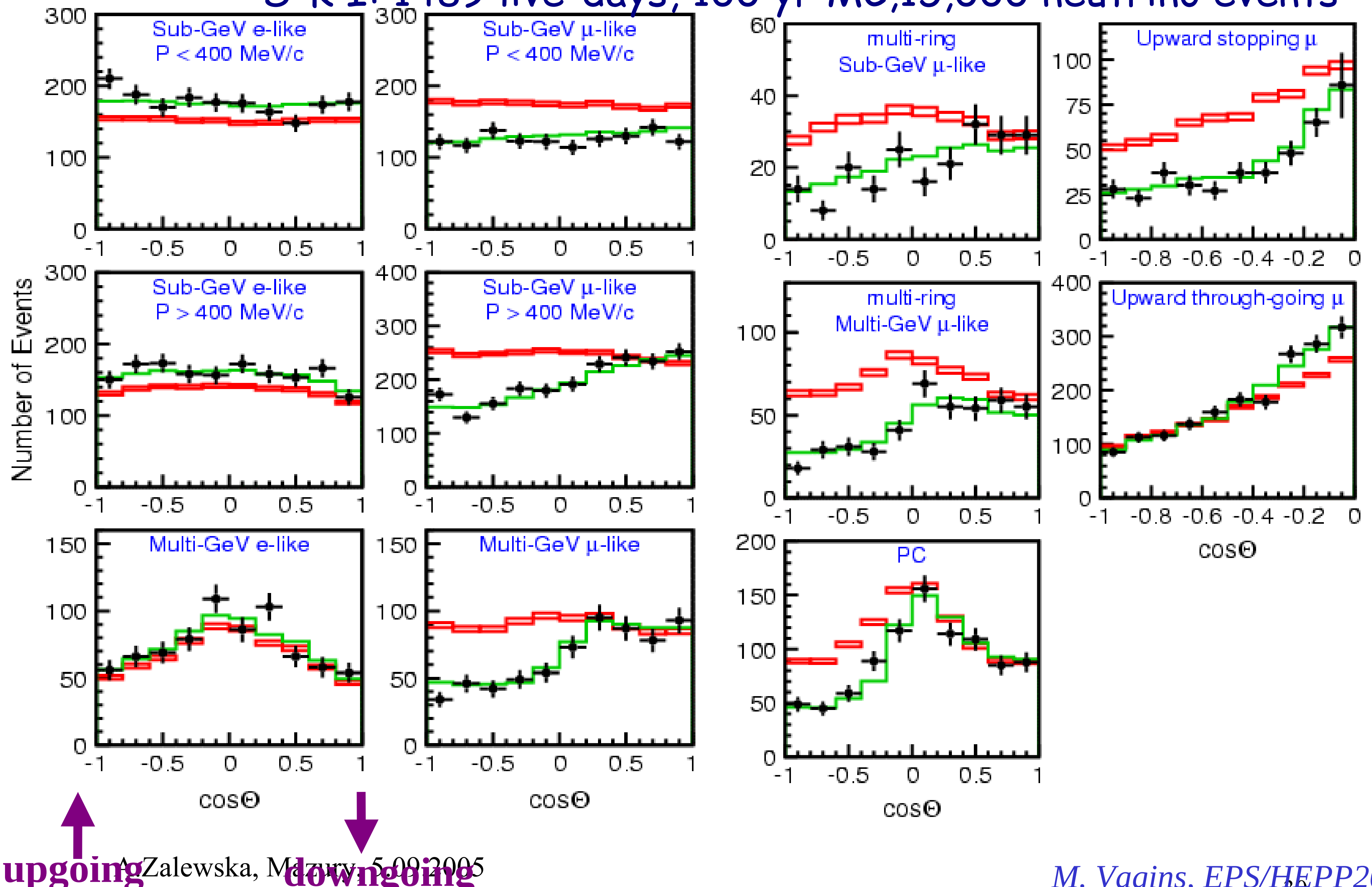


Inner detector
- ➔ ~5200 20inch PMTs with covers

Outer detector :1885 8inch PMTs

➢Zenith angle distributions showing ν_μ disappearance

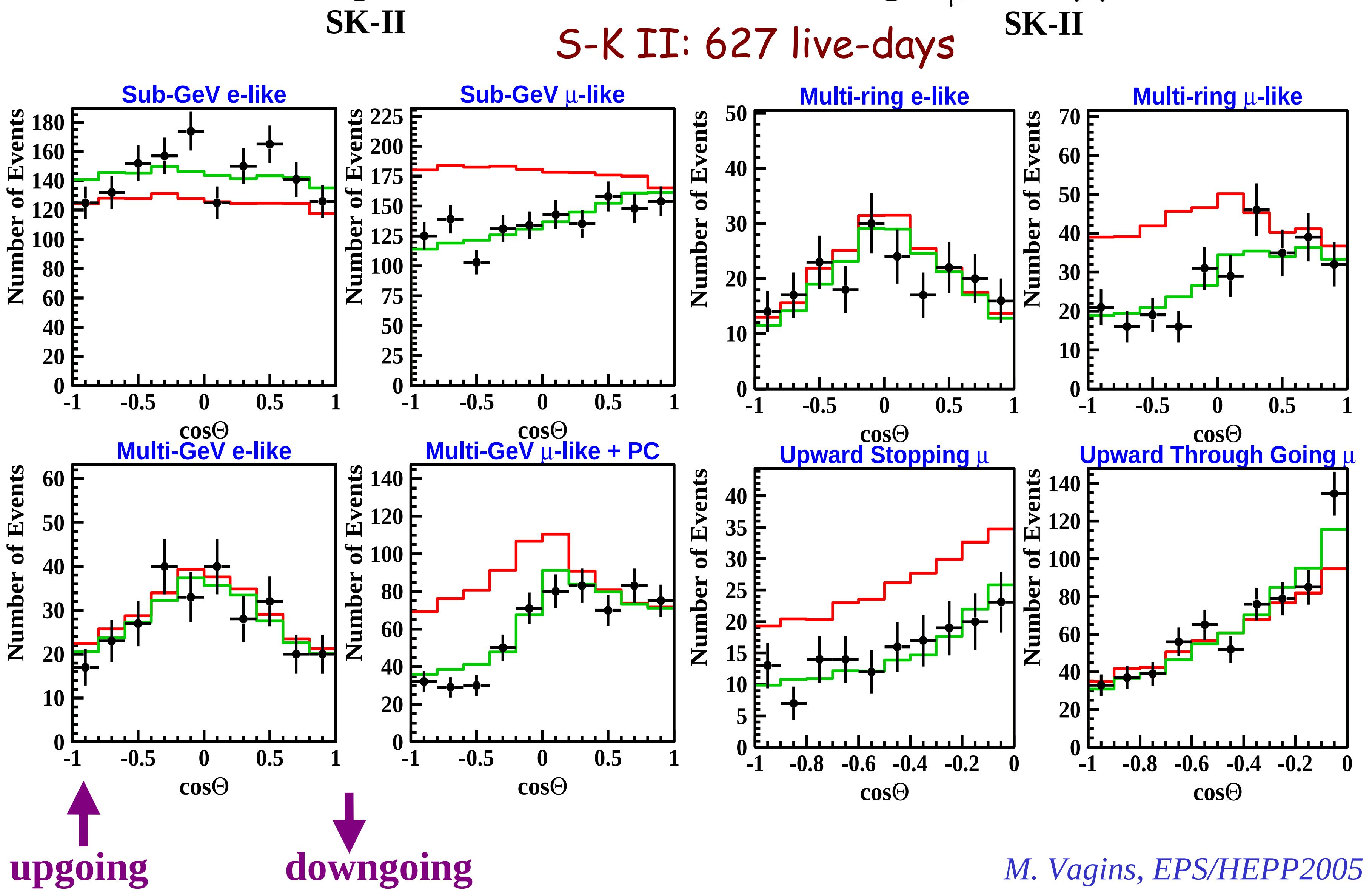
S-K I: 1489 live-days, 100 yr MC,15,000 neutrino events



M. Vagins, EPS/HEPP2005

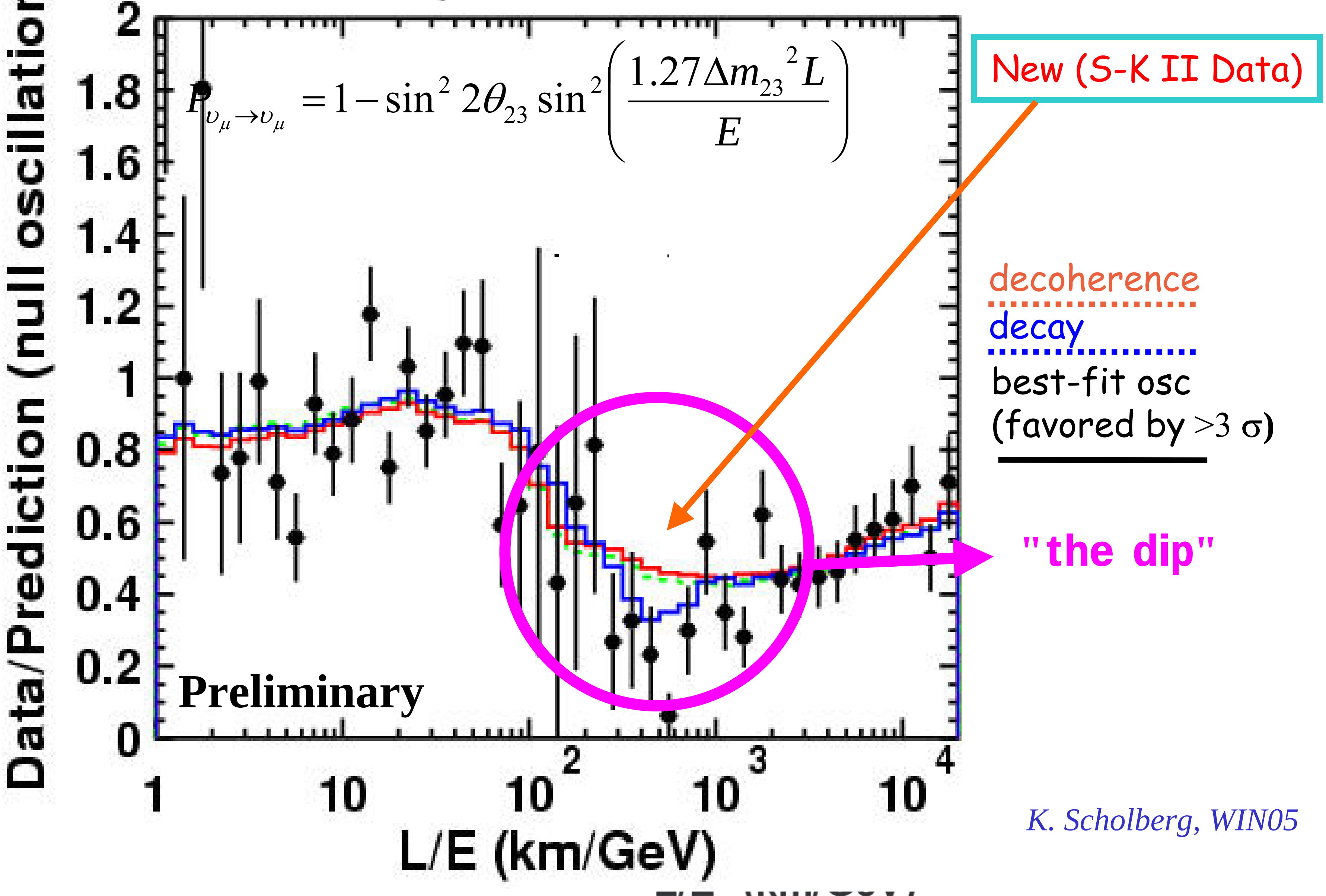
➢Zenith angle distributions showing ν_μ disappearance

S-K II: 627 live-days



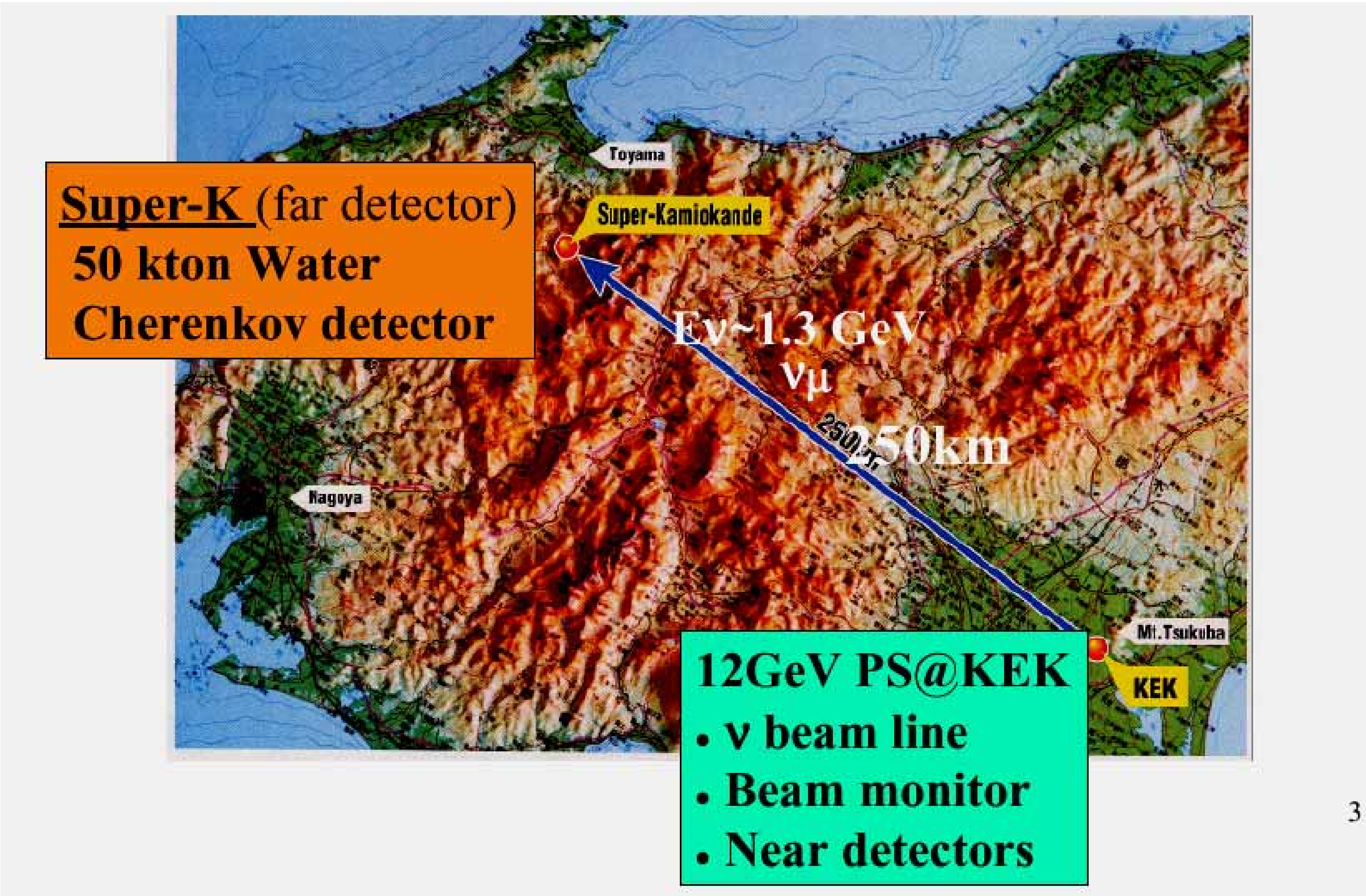
M. Vagins, EPS/HEPP2005

➢ Testing the Model: L/E Behavior



K. Scholberg, WIN05

K2K - first LongBaseLine accelerator experiment

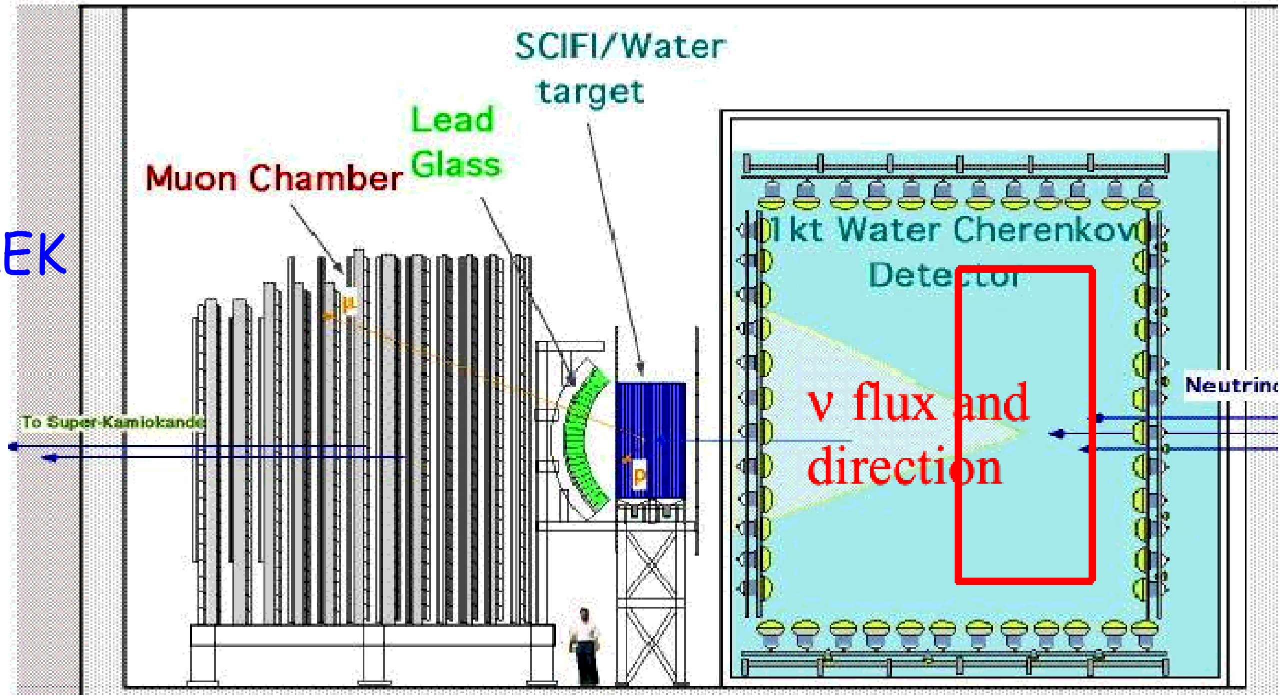


$< E_\nu > \sim 1.3$GeV

almost pure $\nu_\mu (\sim 98\%)$

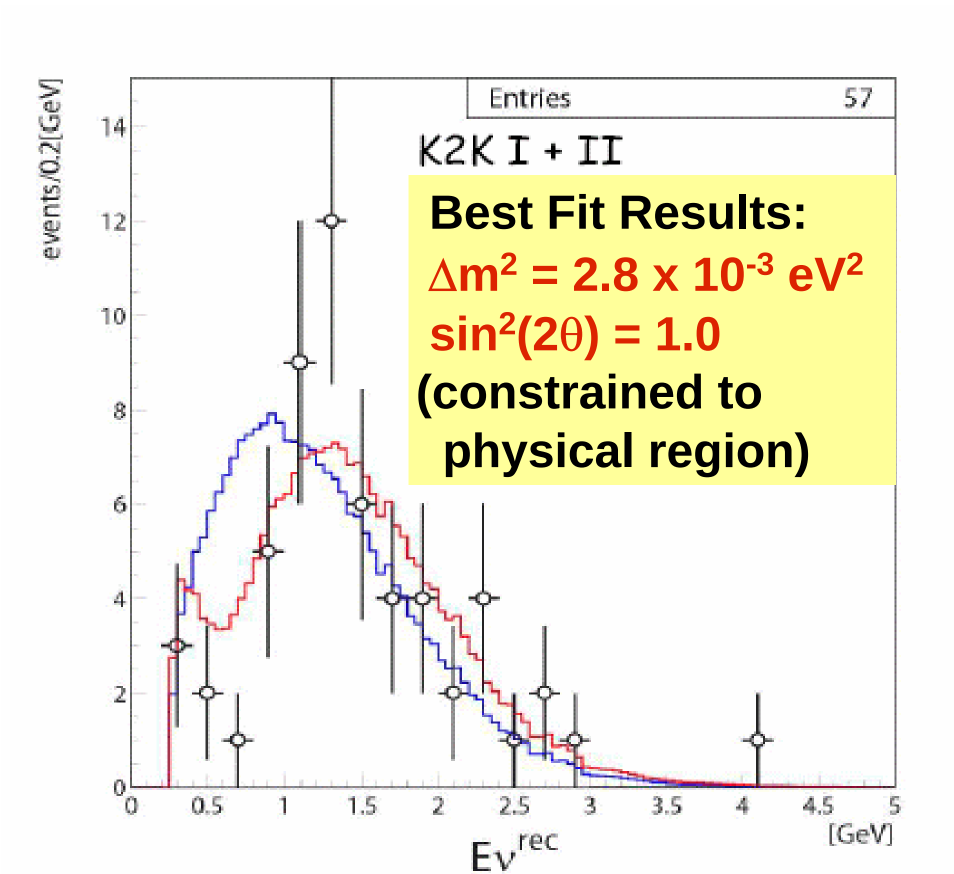
K2K - measurement principle

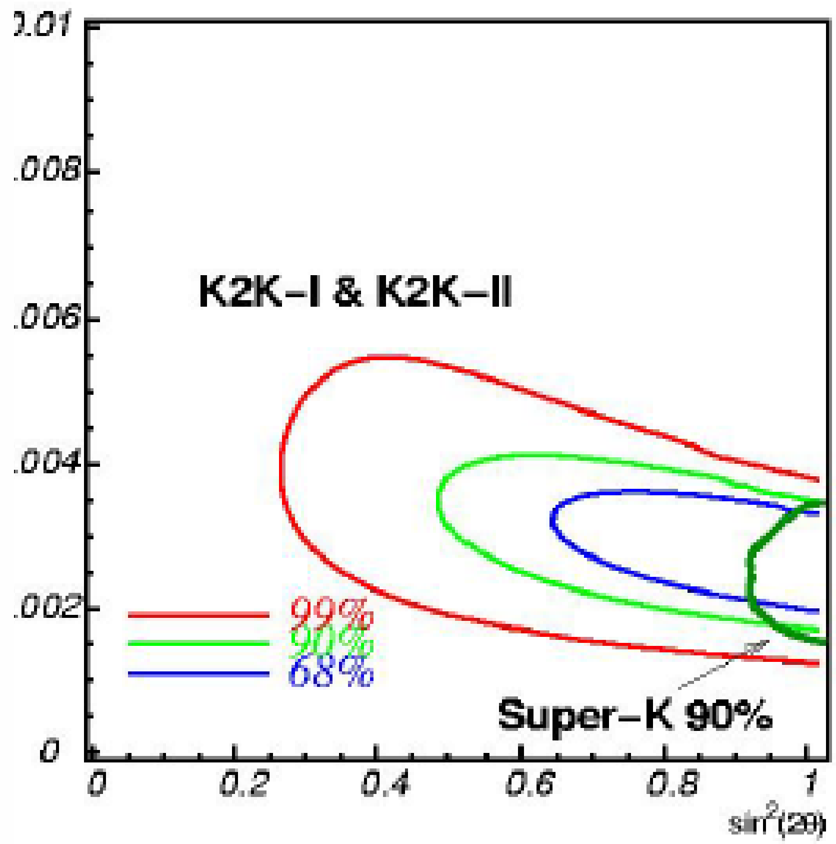
Near detector at KEK
- K2K I
upgrade in 2003
for K2K II



Measurement of the muon momenta and directions in the near detector at KEK
-> neutrino flux and energy spectrum in the near detector
-> extrapolation of the flux and energy spectrum to the far detector, assuming no oscillations
Measurement of the neutrino flux and energy spectrum in the far detector
-> conclusions concerning the oscillations based on the flux reduction and modification of the energy spectrum

➢ K2K Long Baseline Accelerator (KEK to Kamioka)





Single-ring μ-like events

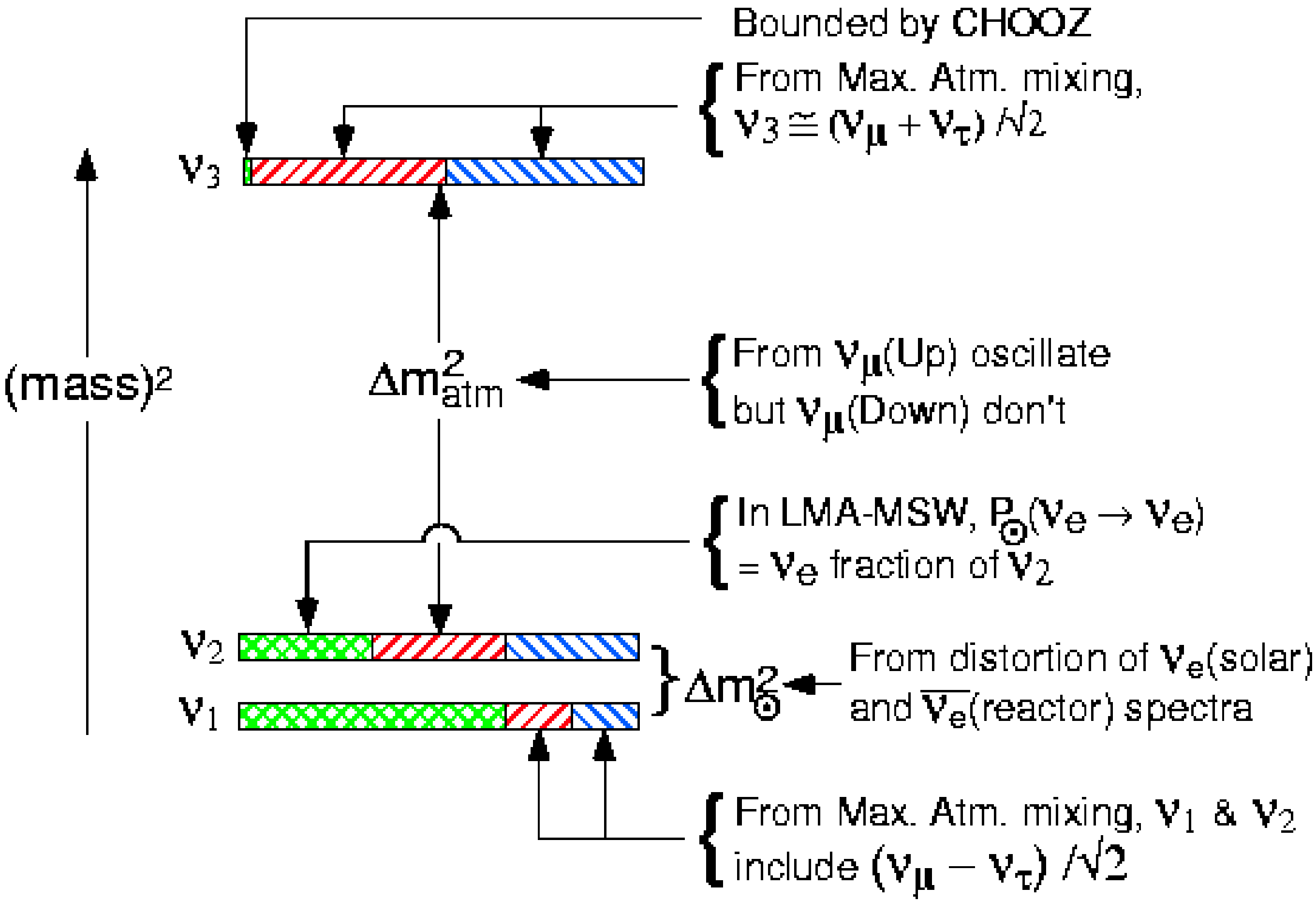
Total 107 beam events observed; expect 149.7

K. Scholberg, WIN05

No-oscillation excluded at >4σ

Consistent with SK atmospheric ν's

Neutrino mass hierarchies

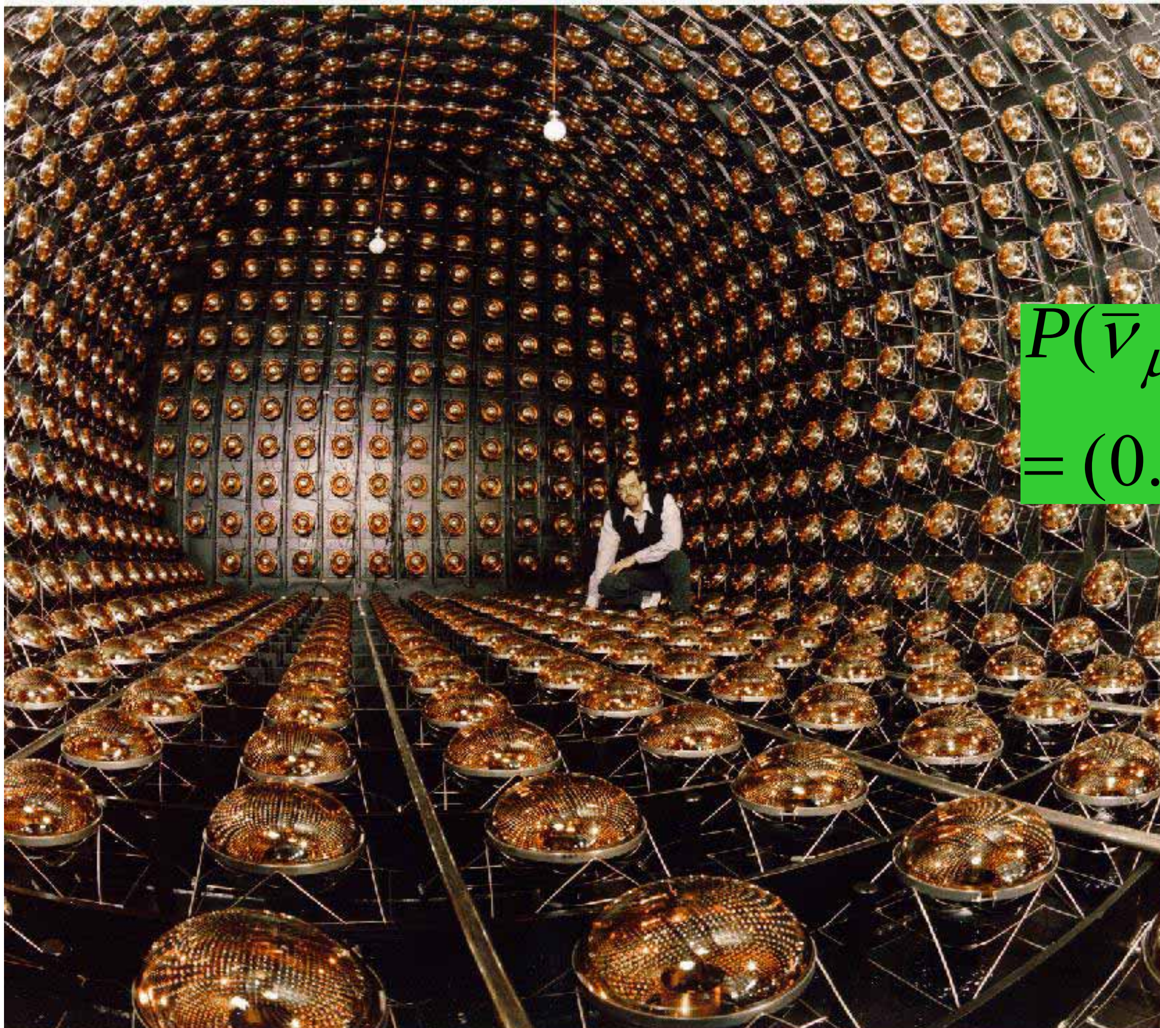


Two important questions:

How far from zero the whole picture is?

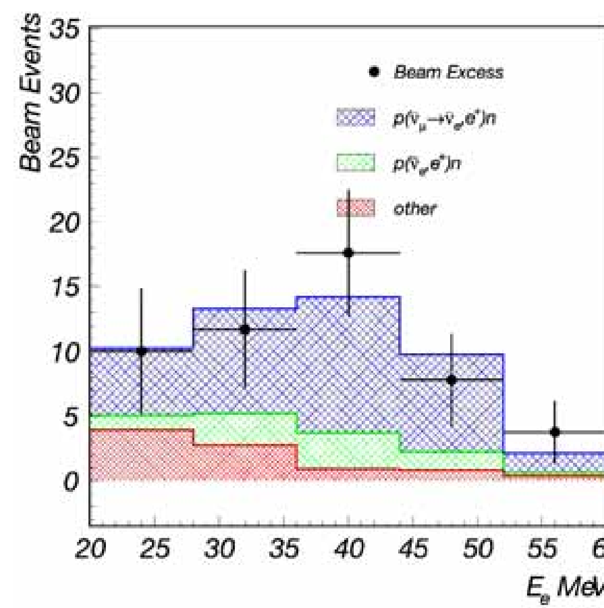
Normal hierarchy (above) or inverted hierarchy (w.r.t. Δm^2_{atm})

LNSD effect

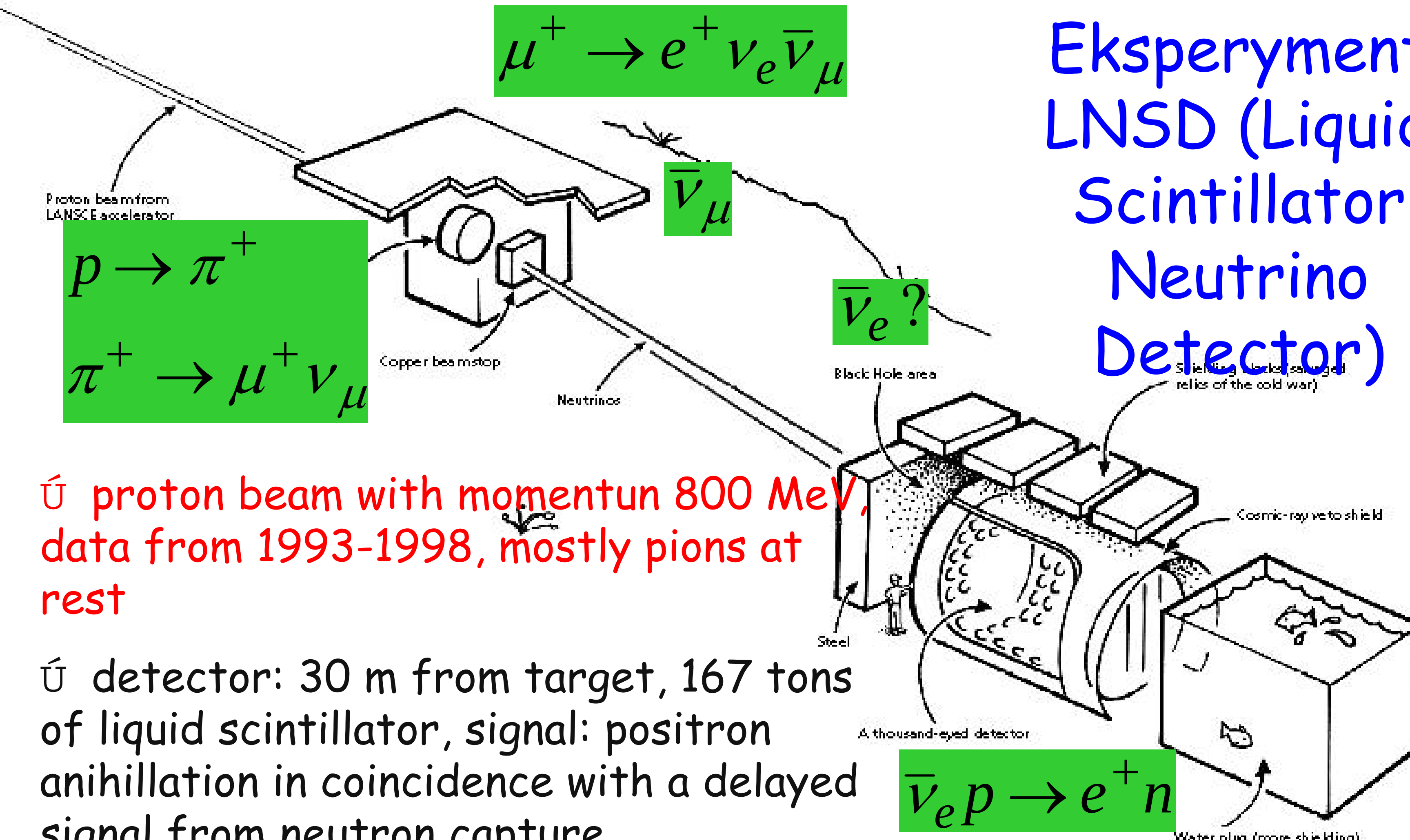


Excess of positrons above background interpreted as anty-ν_e appearance due to oscillations

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$
$$= (0.264 \pm 0.067 \pm 0.045)\%$$



Eksperyment LNSD (Liquid Scintillator Neutrino Detector)



$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

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

$$\bar{\nu}_e\,?$$

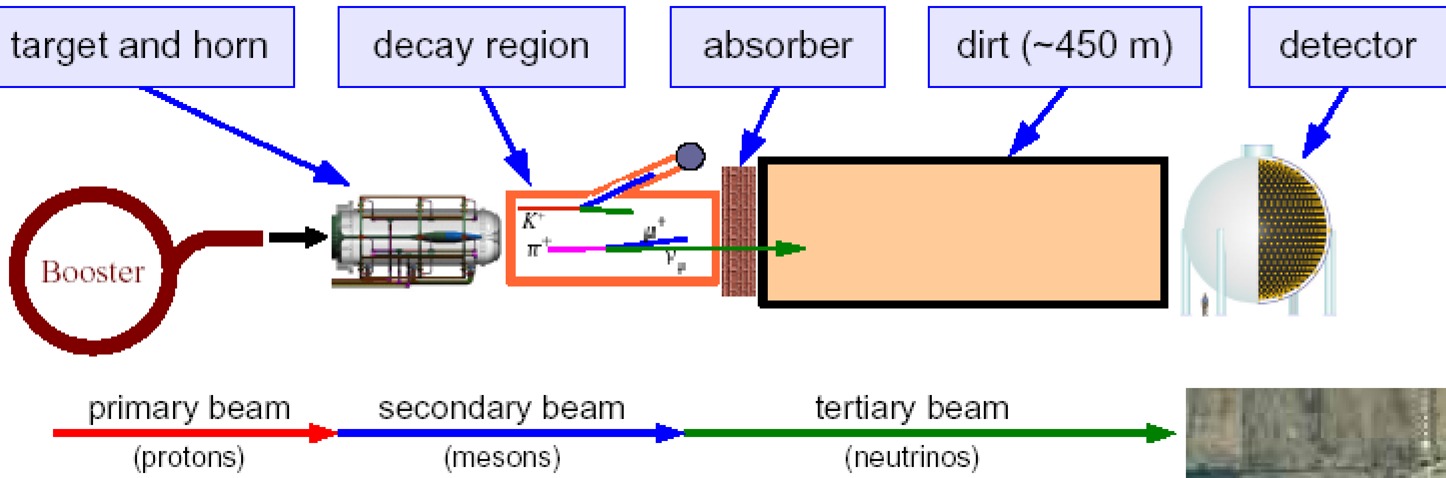
$$p \to \pi^+$$

$$\pi^+ \to \mu^+ \nu_\mu$$

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

- proton beam with momentun 800 MeV, data from 1993-1998, mostly pions at rest
- detector: 30 m from target, 167 tons of liquid scintillator, signal: positron anihillation in coincidence with a delayed signal from neutron capture
- Effect not confirmed by the KARMEN experiment but allowed region not fully covered

➢ MiniBooNE - checking the LNSD effect

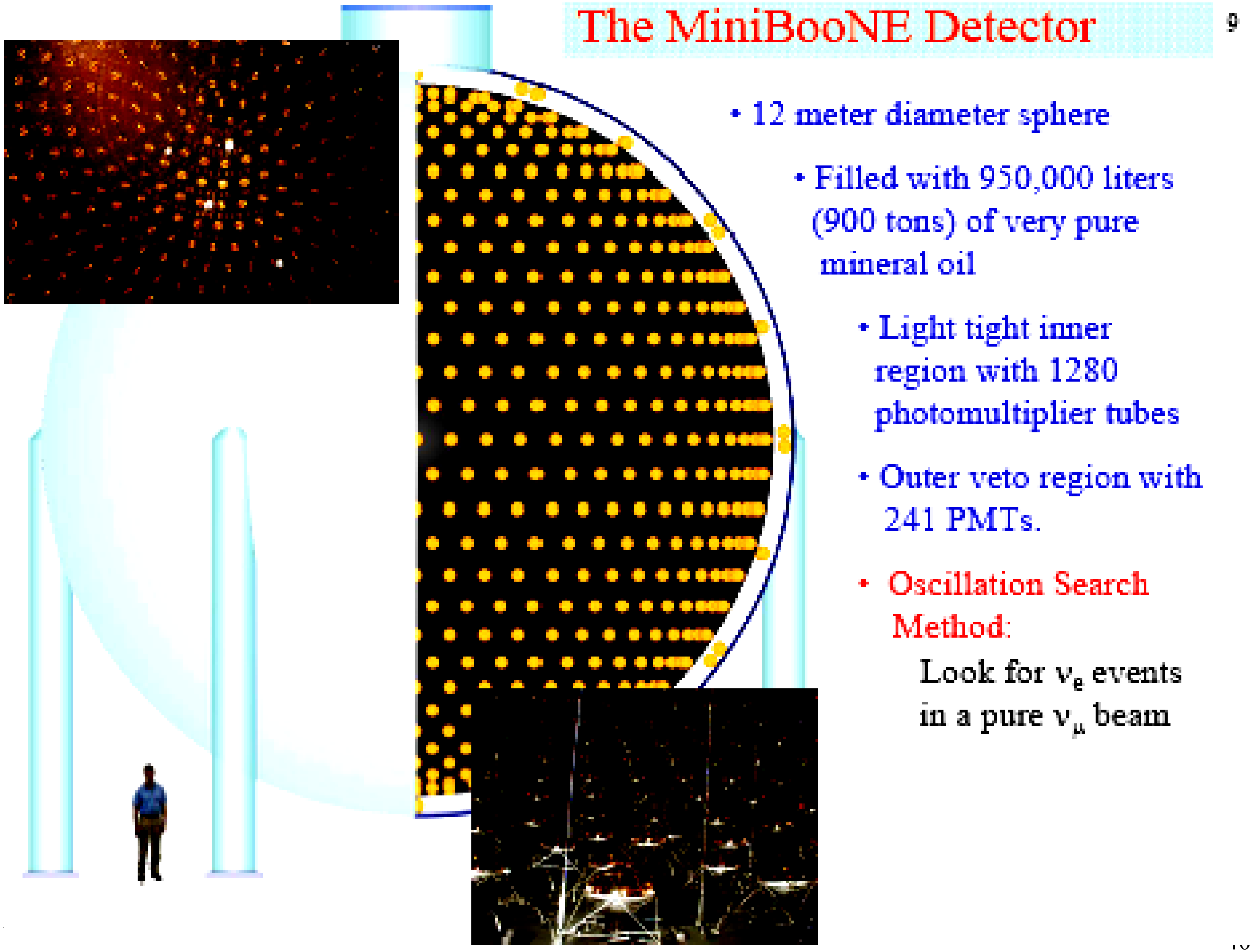


- 8 GeV protons from the Fermilab booster neutrino beam of energy about 1 GeV
- detektor at a distance of 500 m from the target
- 10^{21} p.o.t. to confirm/exclude the LNSD effect

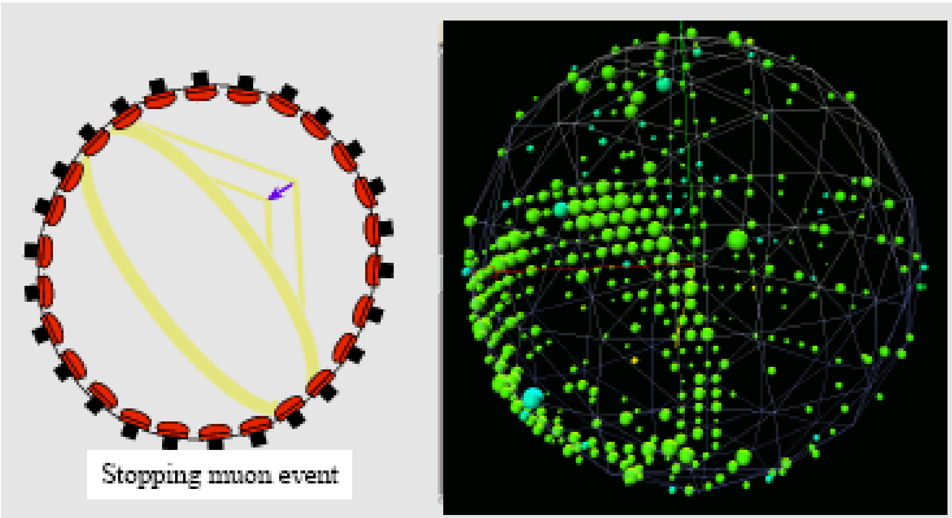
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin(\frac{1.27\Delta m^2 L}{E})$$

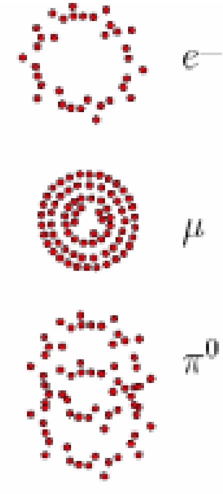
Results expected ~end of 2005

The MiniBooNE detector

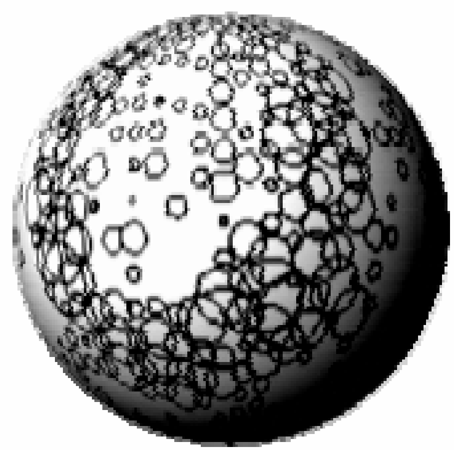


MiniBooNE – event examples

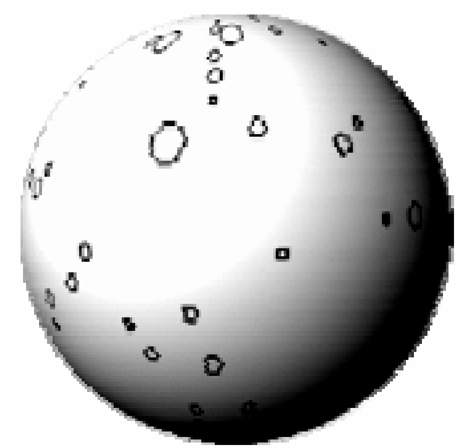




Stopping muon



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

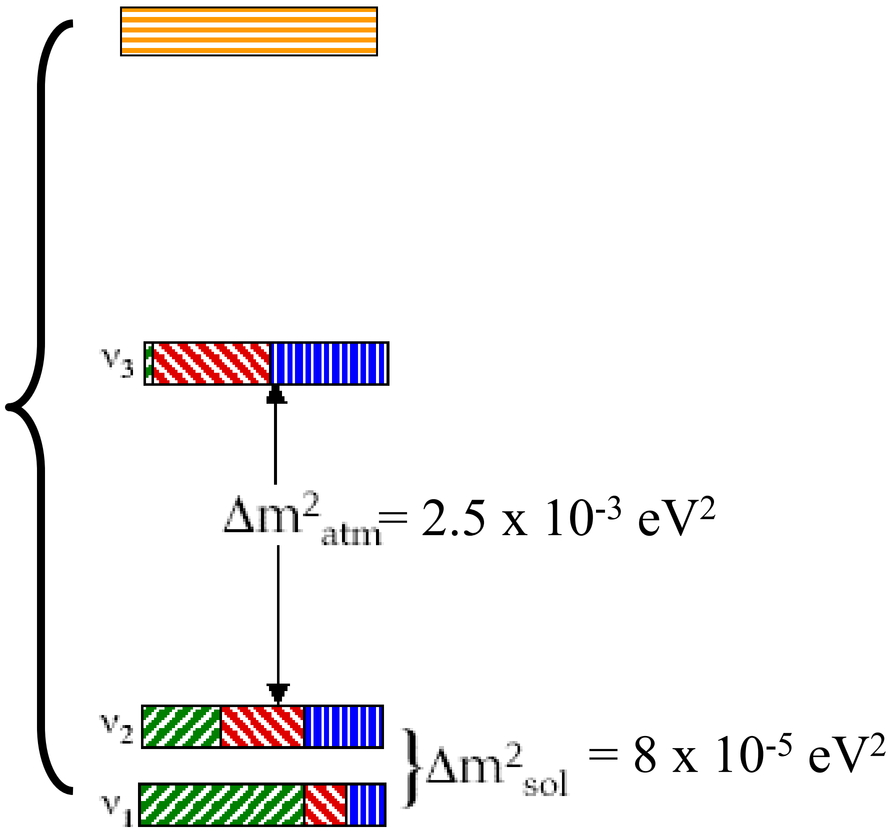


$$\nu_\mu + n \rightarrow \nu_\mu + p + \pi^0$$

$$\pi^0 \rightarrow \gamma + \gamma$$

If LSND confirmed ... revolution !

$$\Delta m^2_{\rm LSND} = 0.24\ {\rm eV}^2$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & U_{\mu 5} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & U_{\tau 5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ & & \cdots & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

Future of neutrino oscillations

A few important questions

Future oscillation experiments should/could answer:

Is θ_{23} really maximal?

How small is θ_{13}?

Is CP violated for neutrinos?

Mass hierarchy – normal or inverted?

Is LSND effect true? Sterile neutrino(s) are needed?

θ_{13} Oscillation Experiments

Measurement	Method	Comment
Δm_{23}	ν_μ disap.	LBL
θ_{23}	ν_μ disap.	Maximal? LBL
θ_{13}	$\nu_\mu \to \nu_e$	LBL
	ν_e disap.	Reactor
CPV	$\nu_e \to \nu_\mu$ vs $\bar{\nu}_e \to \bar{\nu}_\mu$	LBL + charge
matter effects	$\nu_e \to \nu_\mu$ vs $\bar{\nu}_e \to \bar{\nu}_\mu$	VLBL
Hierarchy	$\nu_e \to \nu_\mu$ vs $\bar{\nu}_e \to \bar{\nu}_\mu$	VLBL

θ_{13} Oscillation Experiments

$\nu_\mu \to \nu_e$

$$P_{e\mu} \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$$\pm\alpha \sin 2\theta_{13} \xi \sin\delta_{CP} \sin\Delta \frac{\sin(\hat{A}\Delta)\sin[(1-\hat{A})\Delta]}{\hat{A}(1-\hat{A})}$$

$$+\alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos\Delta \frac{\sin(\hat{A}\Delta)\sin[(1-\hat{A})\Delta]}{\hat{A}(1-\hat{A})}$$

$$+\alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \Delta = \frac{\Delta m^2_{31} L}{4E}, \xi = \sin 2\theta_{12} \sin 2\theta_{23}, \hat{A} = \frac{\pm 2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$$

Sensitivity to:

- θ_{13}
- δ_{CP}
- matter effects
- hierarchy

Large correlations & degeneracies.

$\nu_e \to \nu_e$

$$1 - P_{ee} \approx \sin^2 2\theta_{13} \sin^2\Delta + \alpha^2 \cos^4\theta_{13} \sin^2 2\theta_{12}$$

Sensitivity to:

- θ_{13}

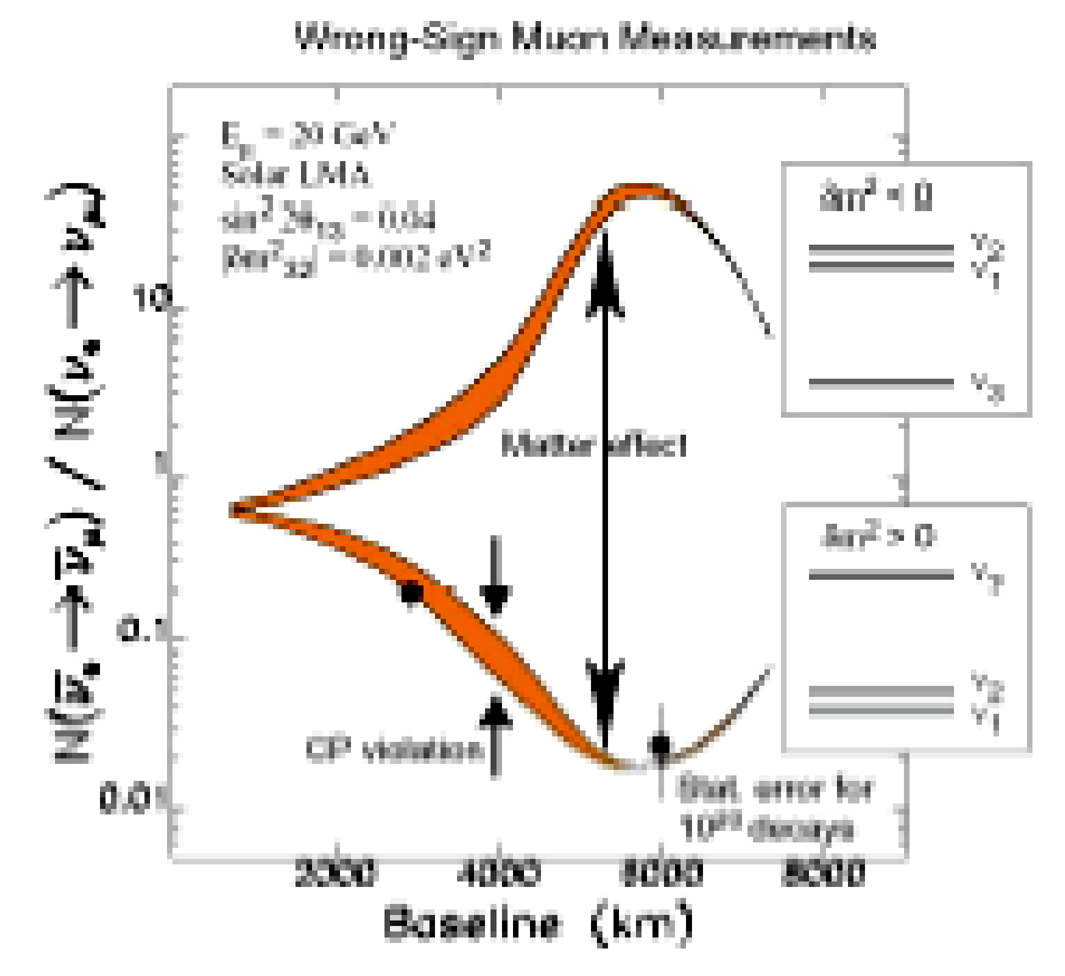
θ_{13} Oscillation Experiments

Degeneracies

- The sign of Δm_{23}, octanct of θ_{23} and the coupling between θ_{23} and δ_{cp} reduce the sensitivity to θ_{13}.
- To resolve this problem several experiments has to be combined:
  - ν_e dissapearance and $\nu_\mu \to \nu_e$ transition.
  - different matter effects in $\nu_\mu \to \nu_e$ transition.
  - several transitions measured in a single experiment.
  - measure different oscillation maxima.

Oscillation Experiments: mass hierarchy

- Asymmetry similar to CPV.
- Maximal at ~7000km for atmospheric oscillation.
- Also correlation to θ_{13} and δ_{CP}



Three phases of experiments

Phase I (years 2005-2010):

- MINOS experiment on the NuMi beam
- OPERA and ICARUS nexperiments on the CNGS beam
- Double-CHOOZ reactor experiment

Phase II (approved experiments – years 2010-2015):

- T2K off-axis experiment (Tokai to Kamioka) on the Japonese superbeam
- NOνA off-axis experiment on the superbeam NuMi
- More sophisticated reactor experiments?

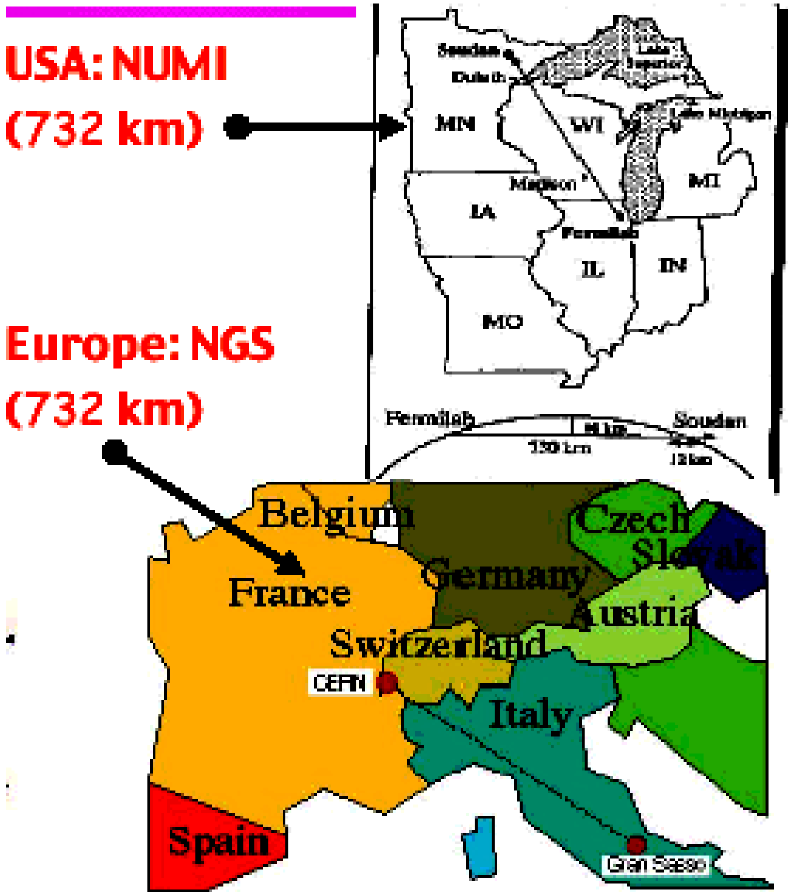
Phase III (now only R&D programs) ~ 2020 ?

- New neutrino sources: neutrino factories, β beams, ???
- Huge detectors: 1 Mton water Cherenkov, 100 ktons Liquid Argon, ???

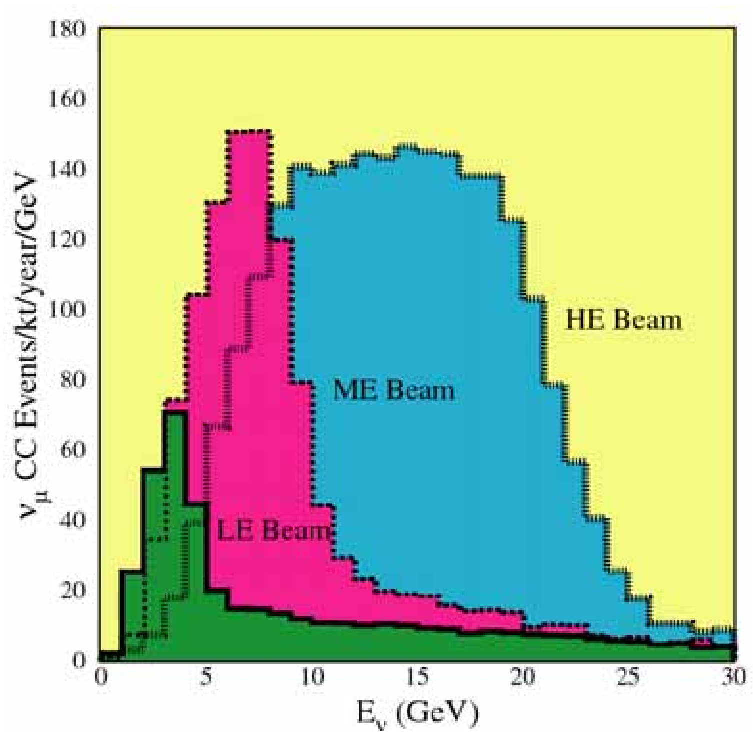
PhaseI - Long BaseLine accelerator projects

♦ NuMi - neutrino beam from FNAL to the MINOS detector in the Soudan mine, started in January 2005, near and far detector, ν_μ disappearance

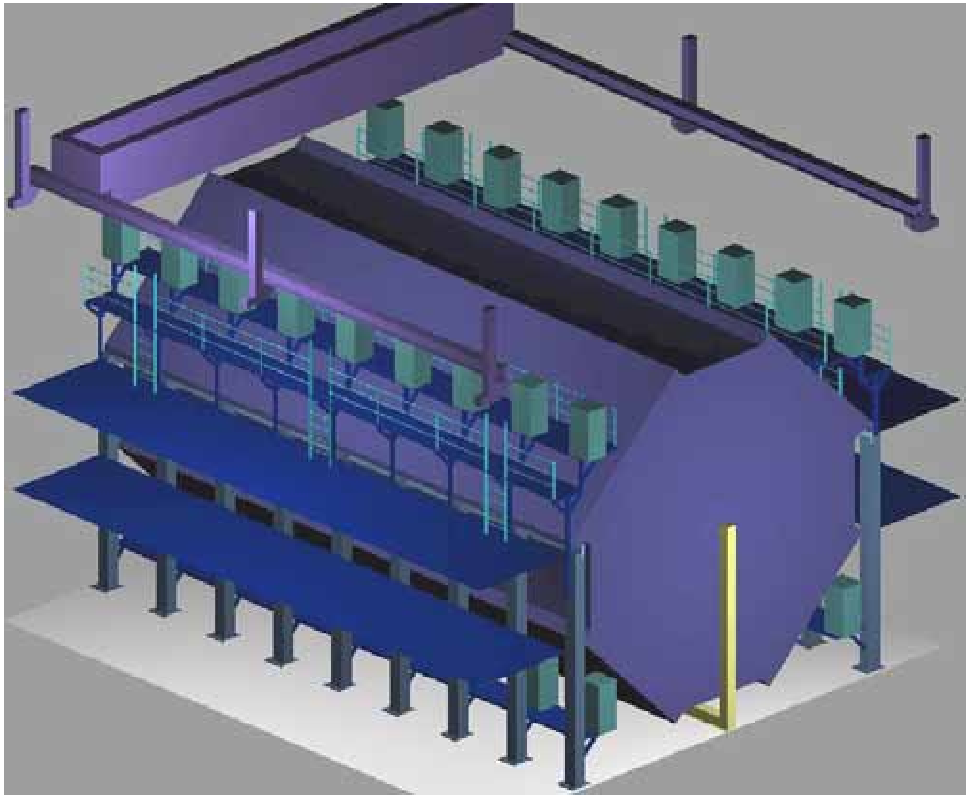
♦ CNGS - neutrino beam from CERN to Gran Sasso, far detectors OPERA and ICARUS, start in 2006, ν_τ appearance



MINOS experiment



NuMi beams

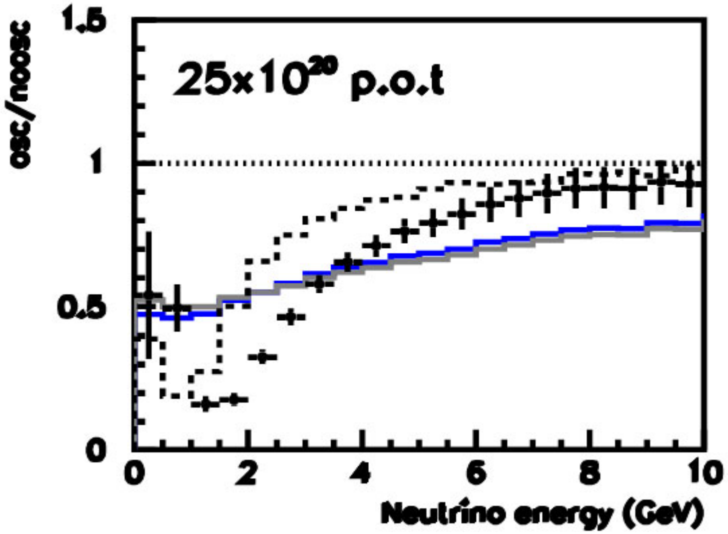


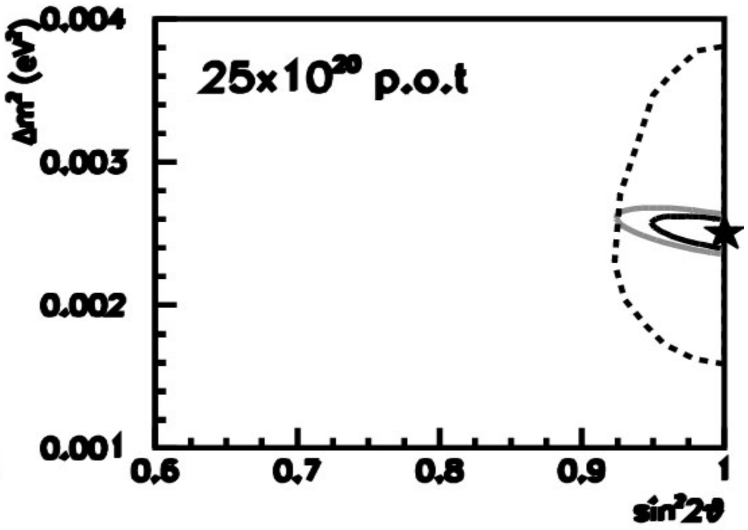
- 5.4kt in total, calorimetric detector
  - 484 planes in two ~14.5m long "super modules", each plane 8m octagon
  - 2.54cm Fe, 1cm Scintillator
  - ~1.5T Magnetic field

MINOS experiment

5 years of data taking - 25 x 10^{20} p.o.t

oscillation pattern | improved Δm^2_{23}

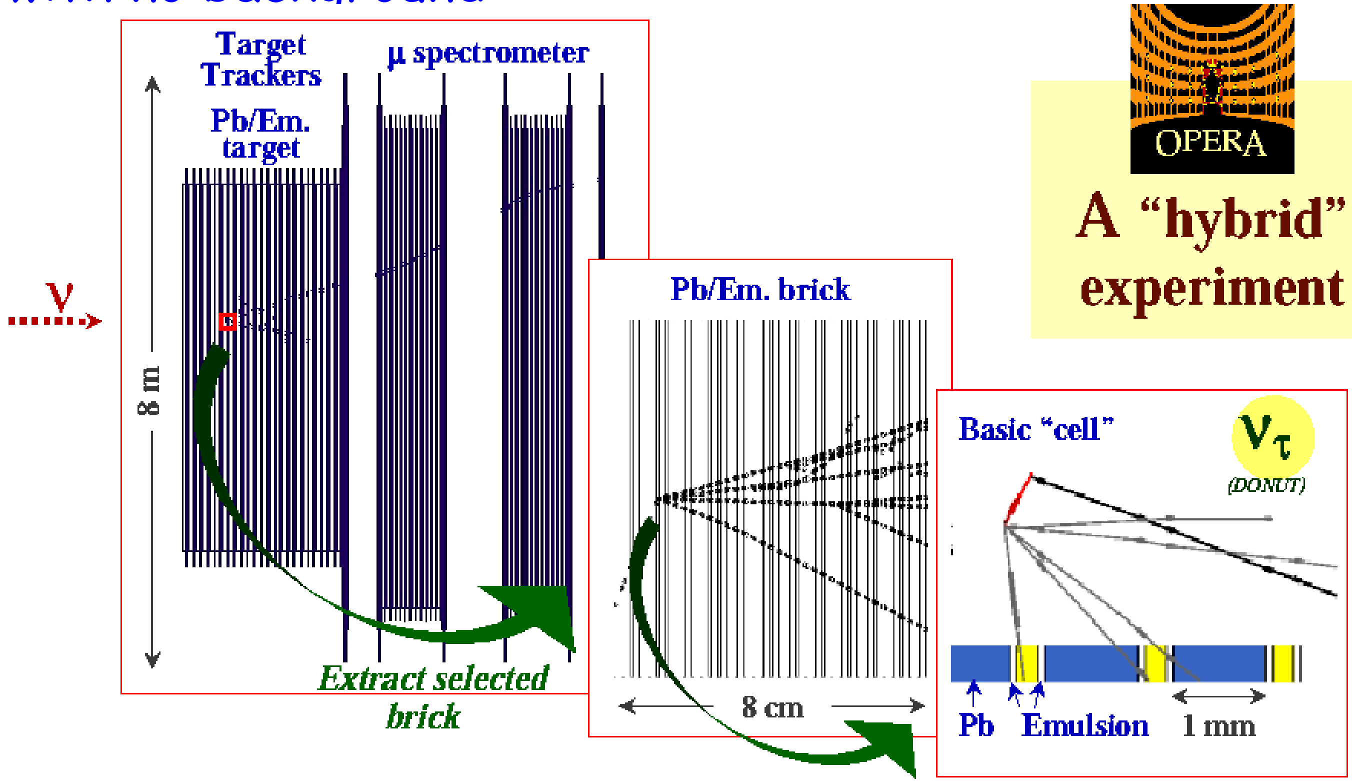




Will improve the CHOOZ limit on θ_{13} by a factor 2

CNGS – the OPERA experiment

High energy neutrino beam, optimized for ν_τ appearance
The OPERA experiment: emulsions + magnetic spectrometer, small signal with no background



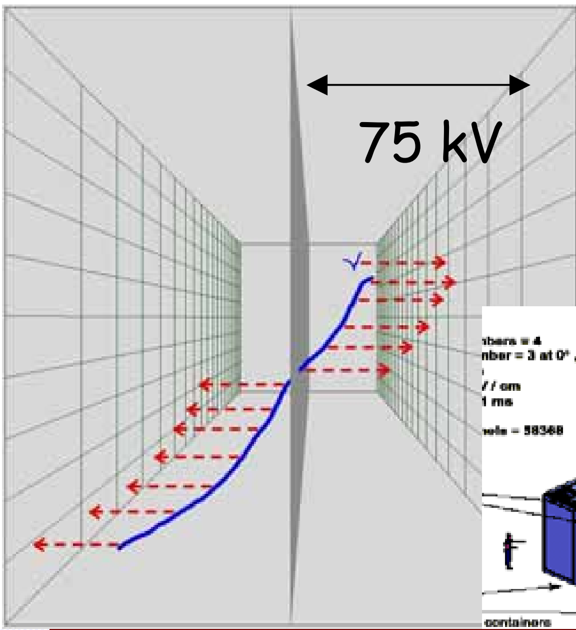
A "hybrid" experiment

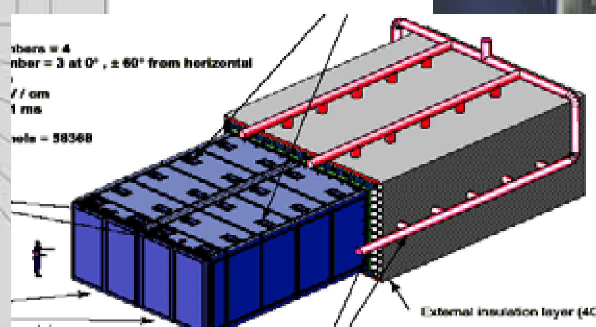
Electronic detectors
→ select ν interaction brick
→ μ ID, charge and p

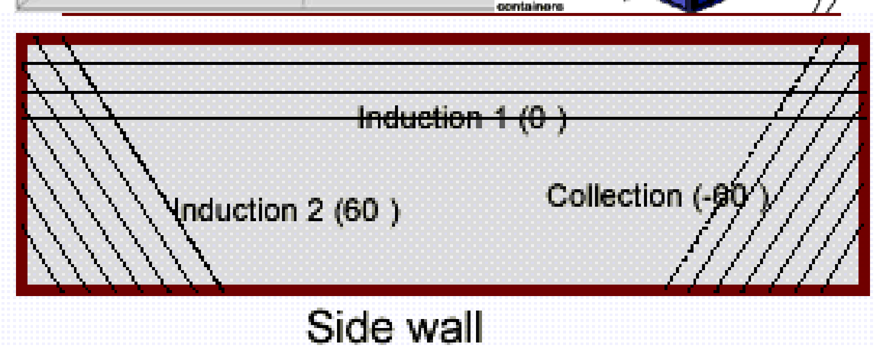
Emulsion scanning
→ vertex search
→ decay search
→ e/γ ID, kinematics

LAr TPC - principle of operation

Ionization electrons drift (msec) over large distances (meters) in a volume of highly purified liquid Argon (0.1 ppb of O_2) under the action of an E field. With a set of wire grids (traversed by the electrons in ~ 2-3 μs) one can realize a massive, continuously sensitive electronic "bubble chamber".

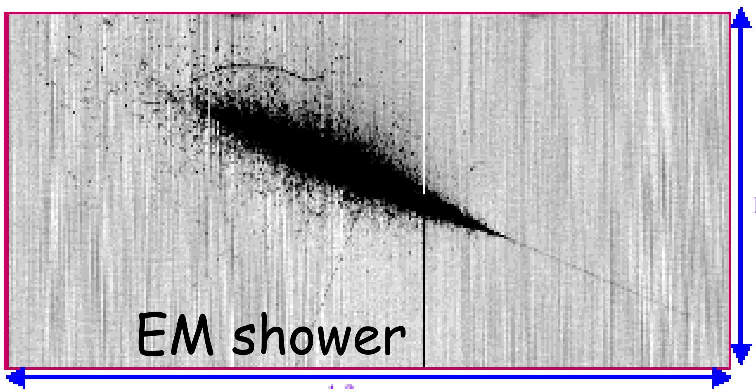


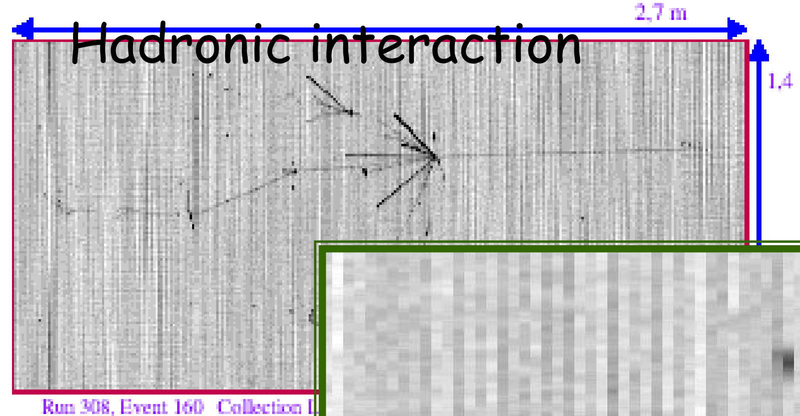


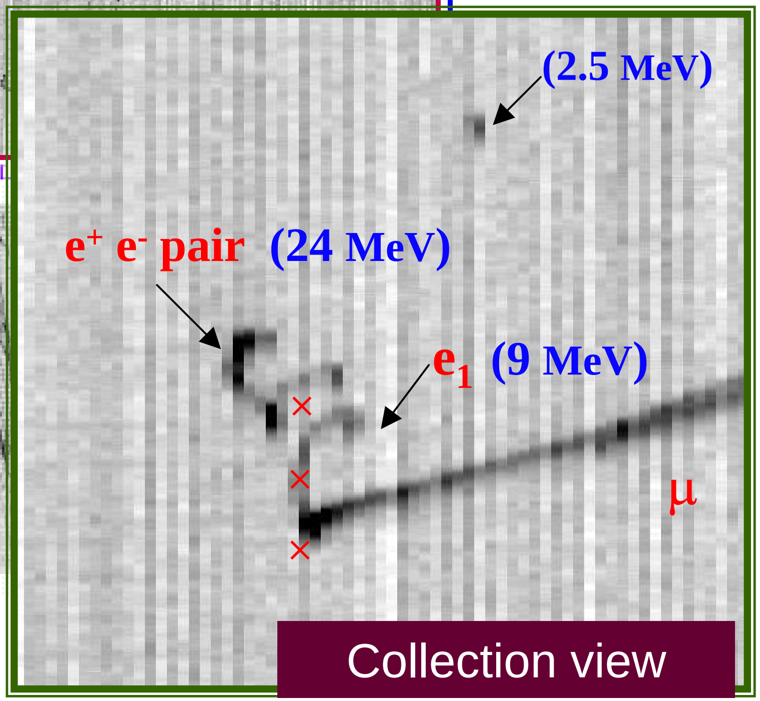


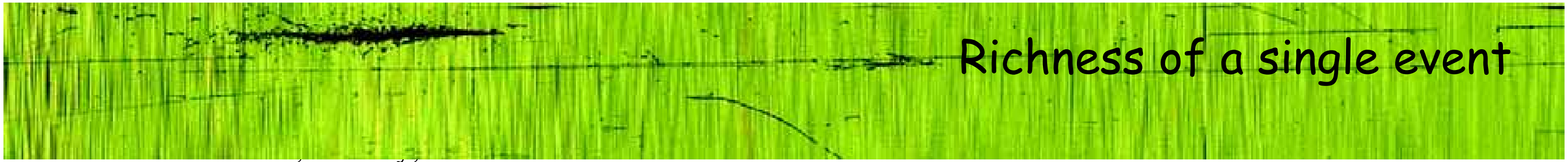
Single "bubble" 3x3x0.6 mm^3
no signal multiplication, about
8000 e^--ion pairs per mm

T600 - data quality



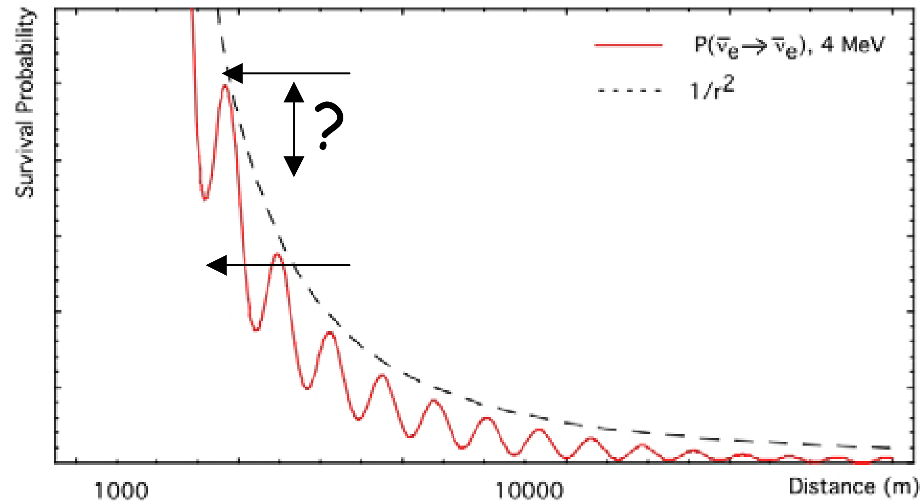






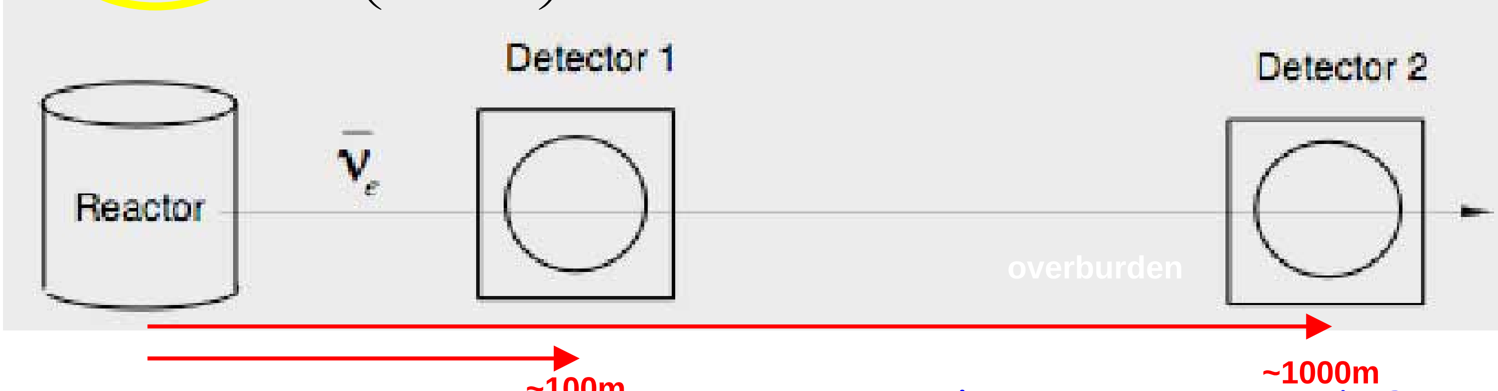
Complementary experiment: Reactors

- Long Baseline (~1 km from source)
- Disappearance $\bar{\nu}_e \to \bar{\nu}_e$
- Use near detector to measure reactor flux, spectrum and detector efficiency to cancel "all systematics"
- Look for small deviation from $1/r^2$ with plenty of reactor signal



$$1-P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\alpha^2)$$

- Very clean θ_{13} measurement (no ambiguities, no matter effects)



- Several sites proposed: Brasil, China, France, Japan, Russia, Taiwan, USA

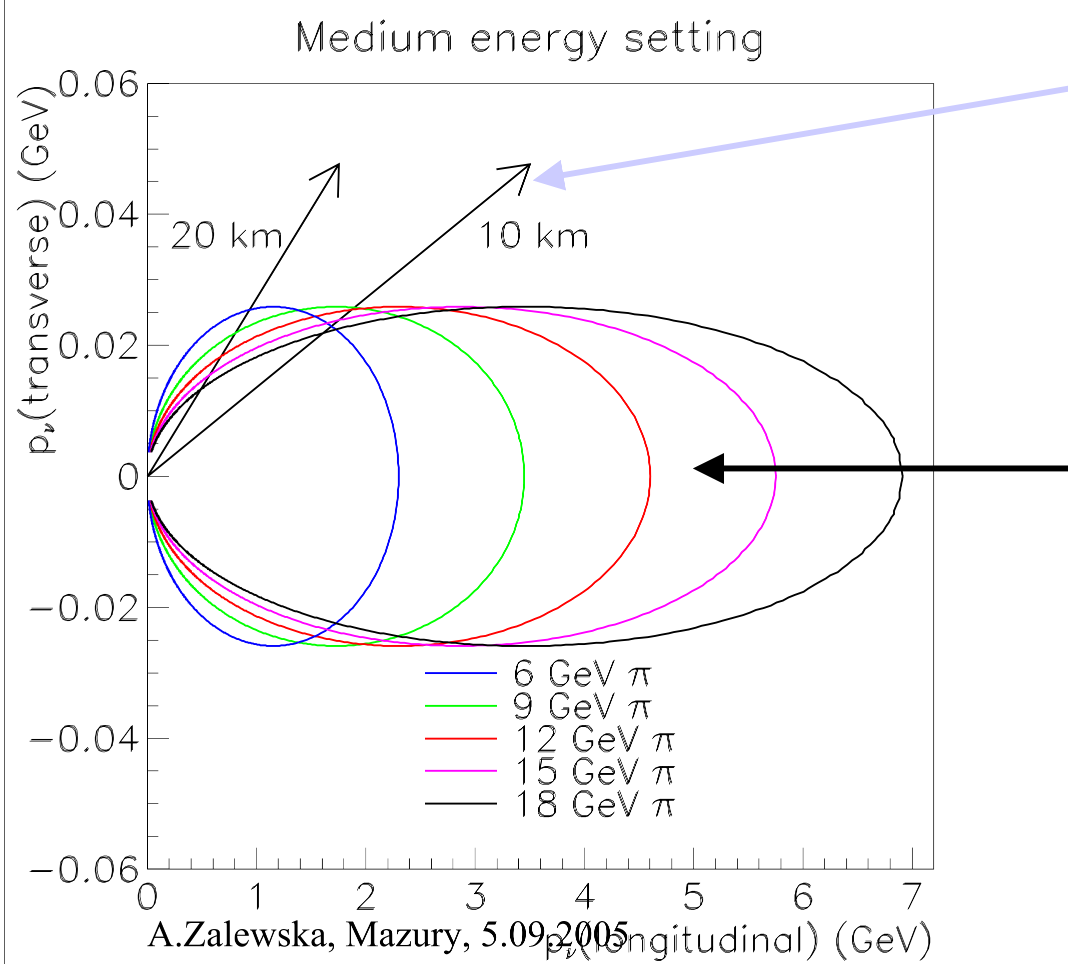
Osc. Experiments: double CHOOZ

- Existing facilities can be reused,...
- ...but, not optimal length (1.1km instead of 1.5km). Near site at 100/200 m.
- 56 ev/day at the far detector (from 12 to 200 GW/ton/year)
- Starts in 2007 with far detector.

Improved detector design: double the fiducial volume, better stability, reduced background (veto and buffer detectors),...

Phase II - off-Axis principle

Two body decay kinematics



At an angle of 15 mrad, the energy of produced neutrinos is 1.5-2 GeV for all pion energies ➔ very intense, narrow band beam

'On axis': $E_\nu = 0.43 E_\pi$

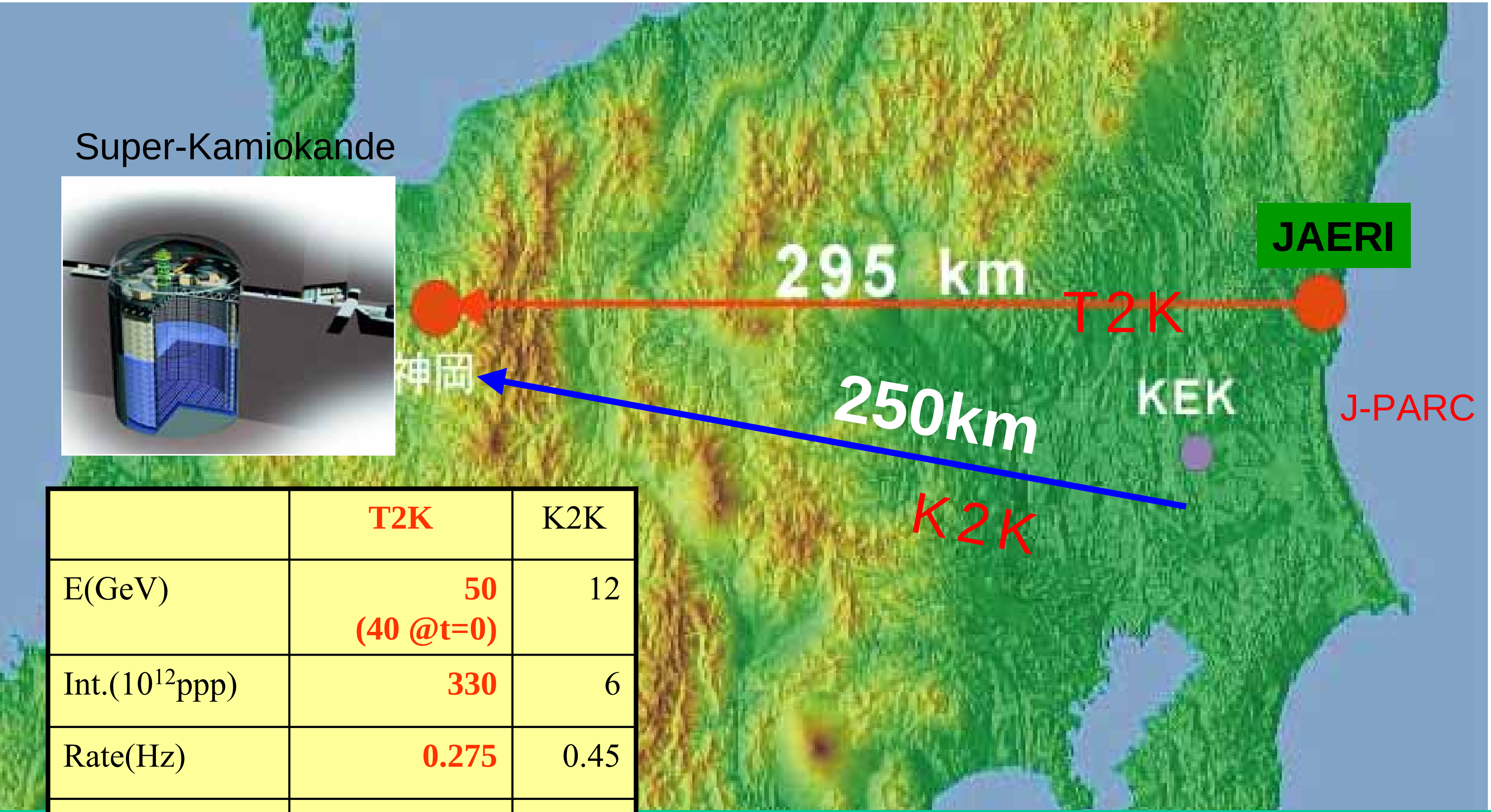
$$p_L = \gamma(p^* \cos\theta^* + \beta E^*)$$
$$p_T = p^* \sin\theta^*$$

A.Zalewska, Mazury, 5.09.2005

T2K (Tokai to Kamioka) experiment

From Kajita-son presentation

Super-Kamiokande



	T2K	K2K
E(GeV)	50 (40 @t=0)	12
Int.(10^{12}ppp)	330	6
Rate(Hz)	0.275	0.45
Power(MW)	0.75	0.0052

China, France, Italy, Japan, Korea, Poland, Russia,
Spain, Switzerland, UK, USA

Next generation LBL experiments in Japan

"J-PARC - Kamioka neutrino project"

First superbeam

Baseline ~295km

Conventional ν_μ beam

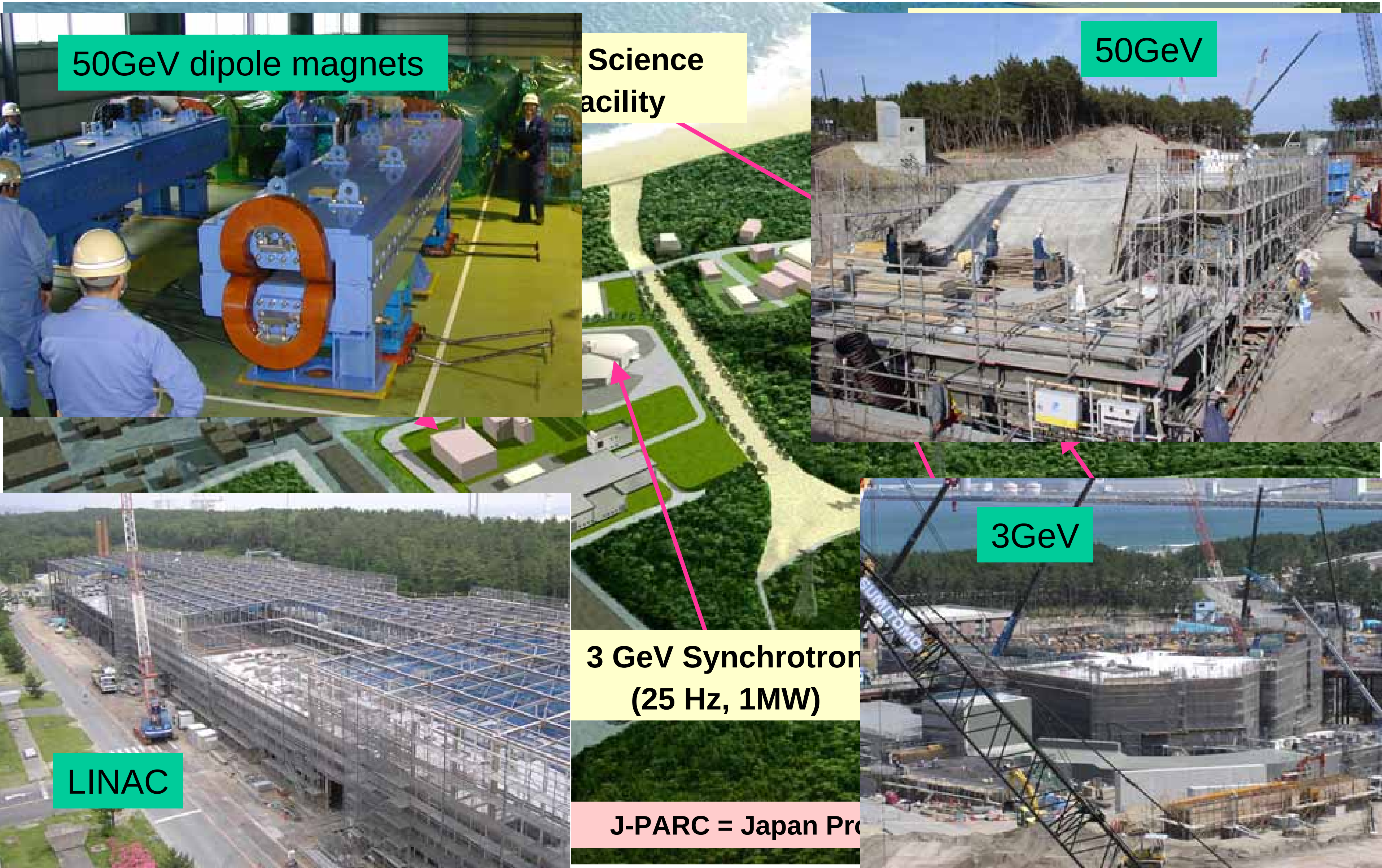
Beam Energy ~1GeV

→ Will be adjusted to the oscillation maximum

	Beam power	Far detector	Physics
1st phase	0.75MW	Super Kamiokande(50kt)	disappearance $\nu_\mu \to \nu_X$ appearance $\nu_\mu \to \nu_e$ NC measurements
2nd phase	~4MW	Hyper Kamiokande(1Mt)	CP violation Proton decay

J-PARK construction

spring 2005



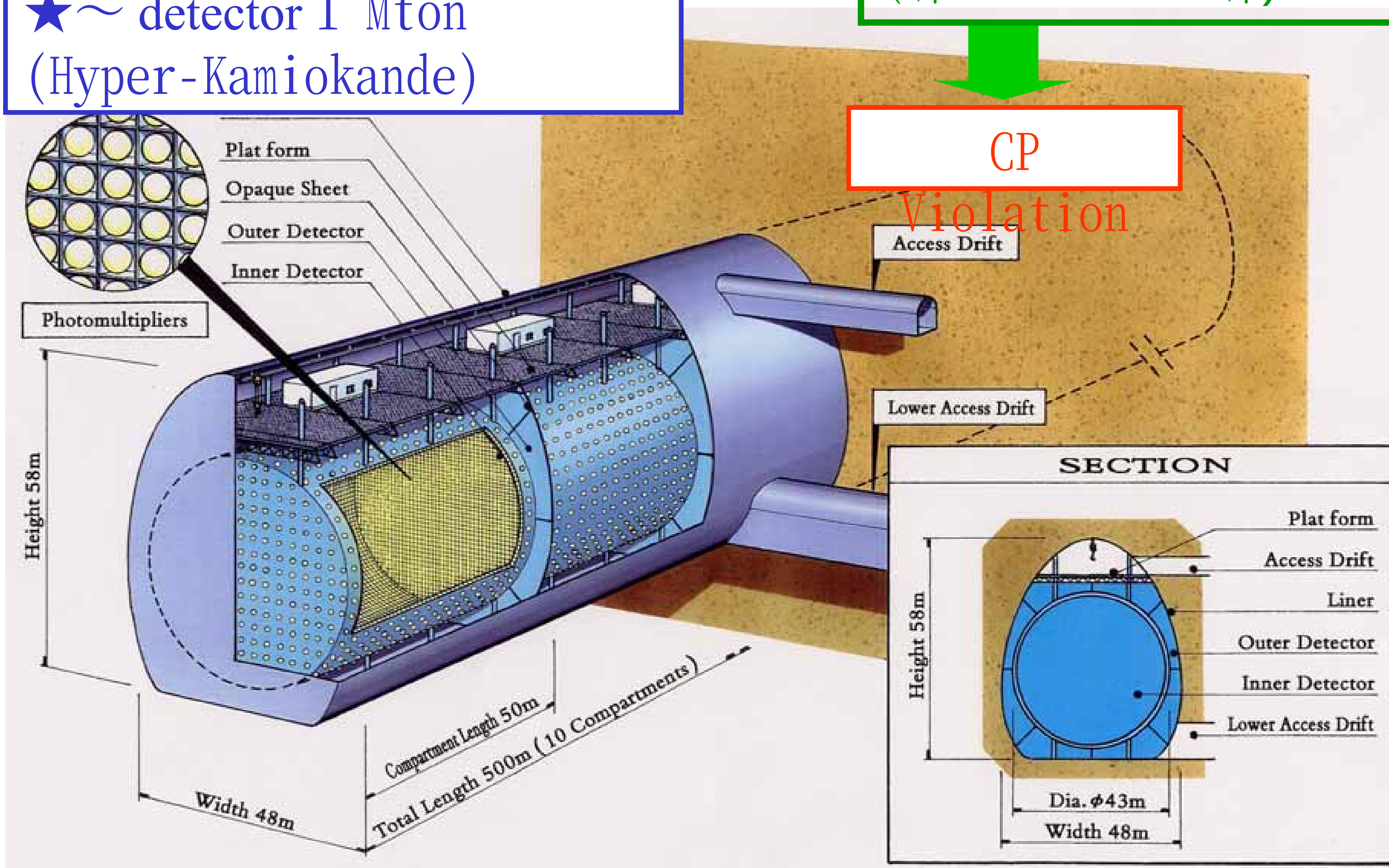
T2K – further future

★0.77 → 4 MW

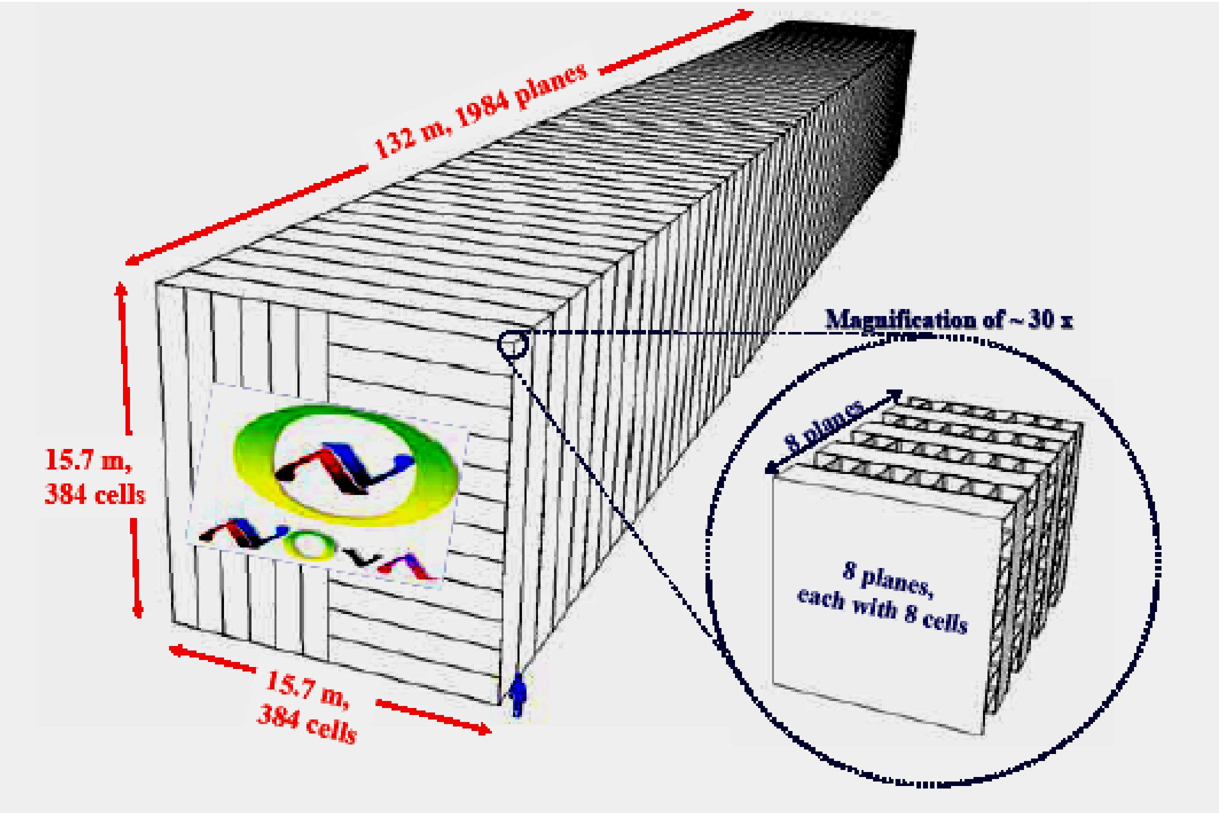
★∼ detector 1 Mton (Hyper-Kamiokande)

10^6 przypadków (ν_μ and anti-ν_μ)

CP Violation



NOνA experiment



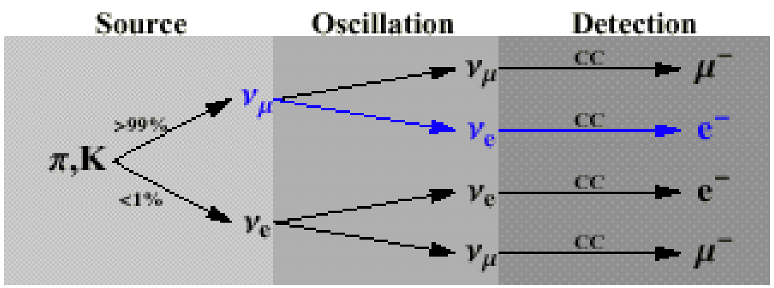
• 30 ktons in total, 80% of mass in a form of liquid scintillator i.e. active medium (5% for MINOS), individual cells are 3.9 cm wide, 6 cm deep and 15.7 m long

• Design optimized for the identification of ν_e-type events, longitudinal sampling of 0.15% (1.5% for MINOS)

• Detector will work on a surface at Ash River (810 km from the NuMi target, 12 km off-axis

Phase III – new sources of neutrinos

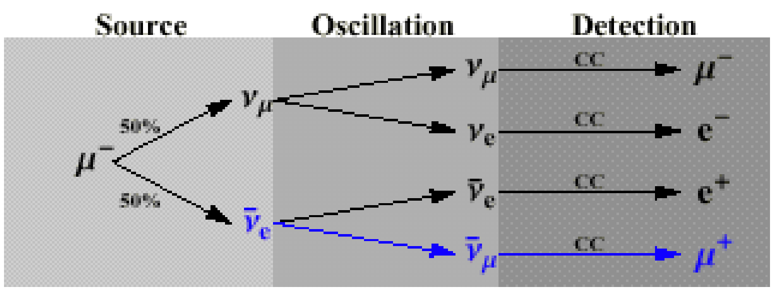
Superbeams



Conventional beams
of ν_e high intensity

Świeży pomysł (2002 rok) -przyspieszać ^{6}He (źródło antyneutrin) i ^{18}Ne (źródło neutrin)

Neutrino Factories

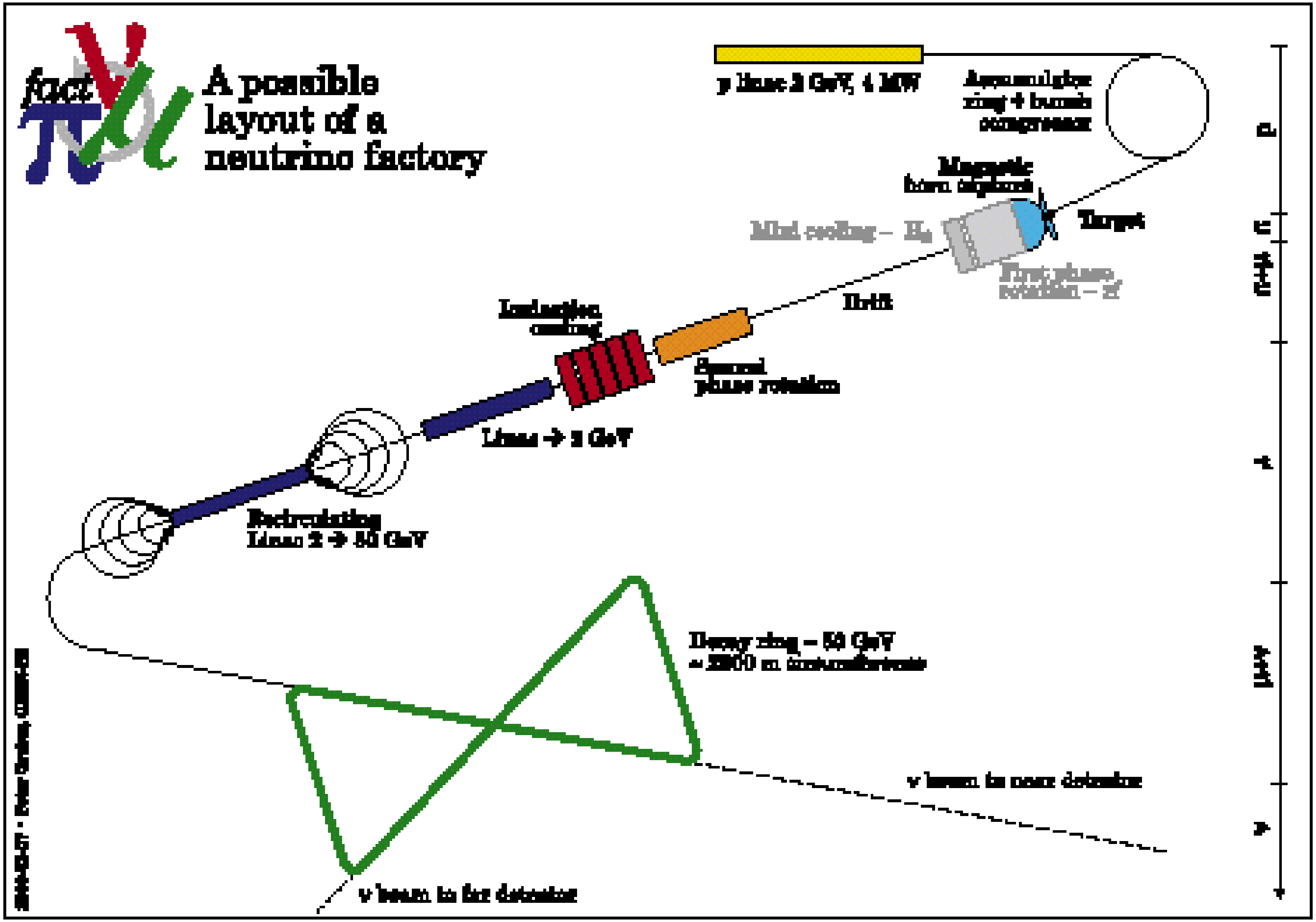


New type of accelerator:
neutrinos from decays of accelerated muons

β beams
very fresh idea

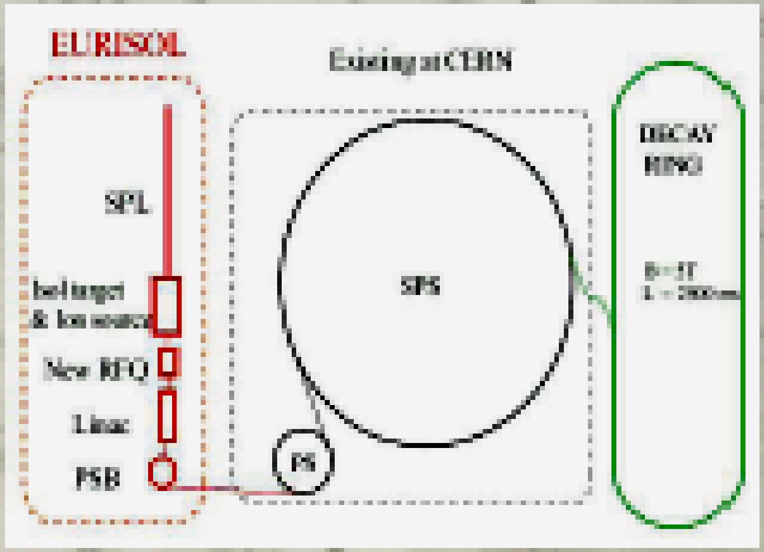
New type of accelerator:
neutrinos (antineutrinos) from accelerated ^{18}Ne (^{6}He)

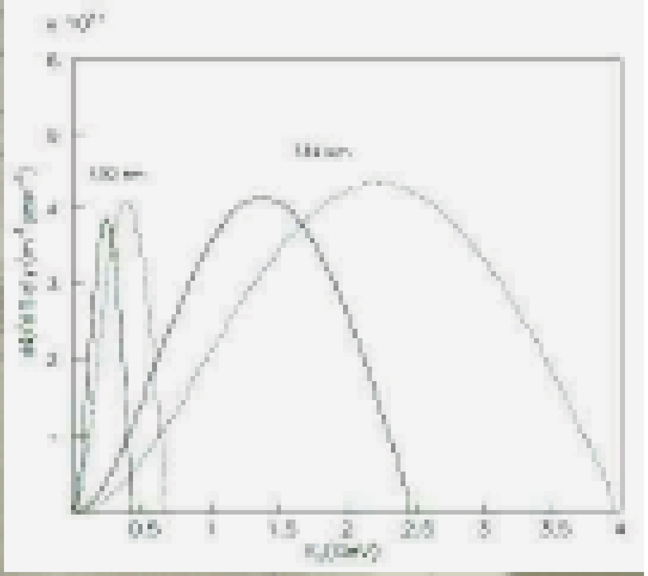
CERN concept of the neutrino factory



β beam concept

- β beams have been introduced in 2001 by P.Zuchelli.
- the idea is to generate a pure ν_e ($\bar{\nu}_e$), precisely known E spectrum, with accelerated radioactive ions (^{18}Ne, ^{6}He).
- Studies with several γ factors and baselines.
- Design study in relation to the EURISOL facility at CERN.

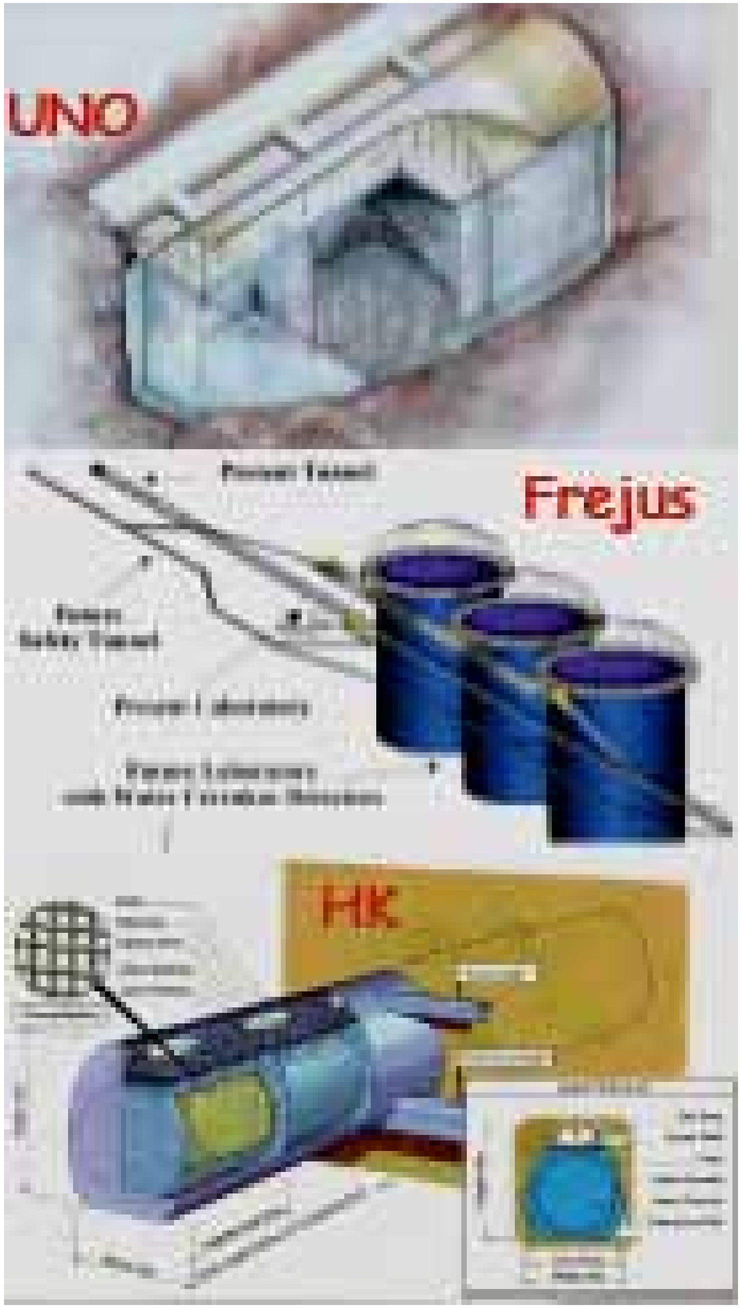




P.Sánchez (UAM/IFAE), EPS Conference, Lisbon July 2005.

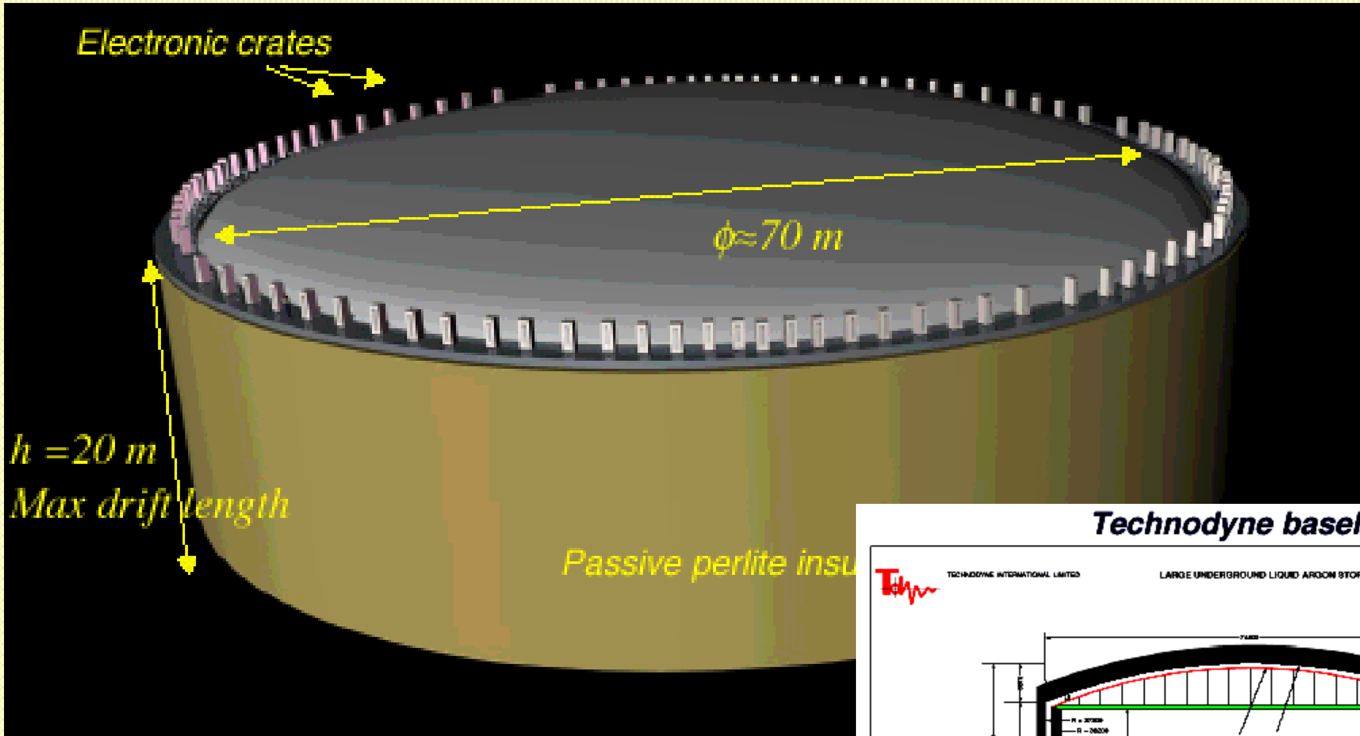
Future detectors ?

What about 1 Mton of water?

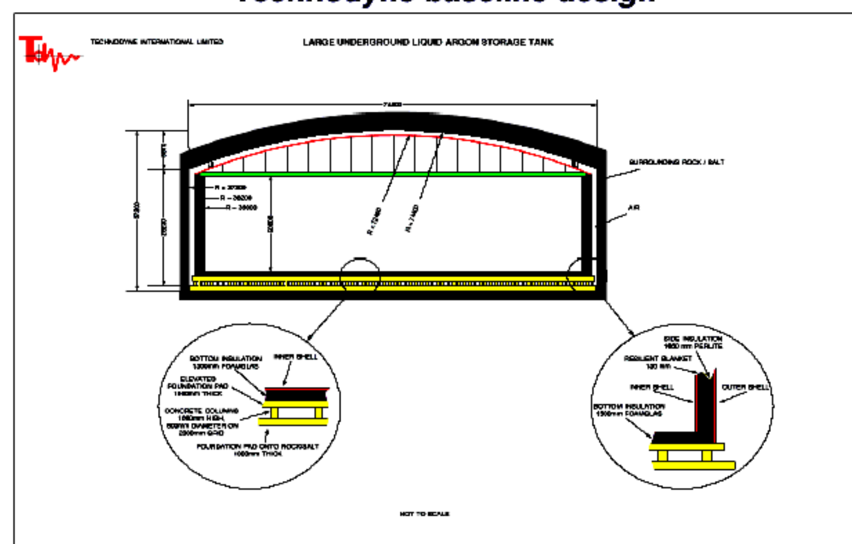


And why not

A 100 kton liquid Argon TPC detector



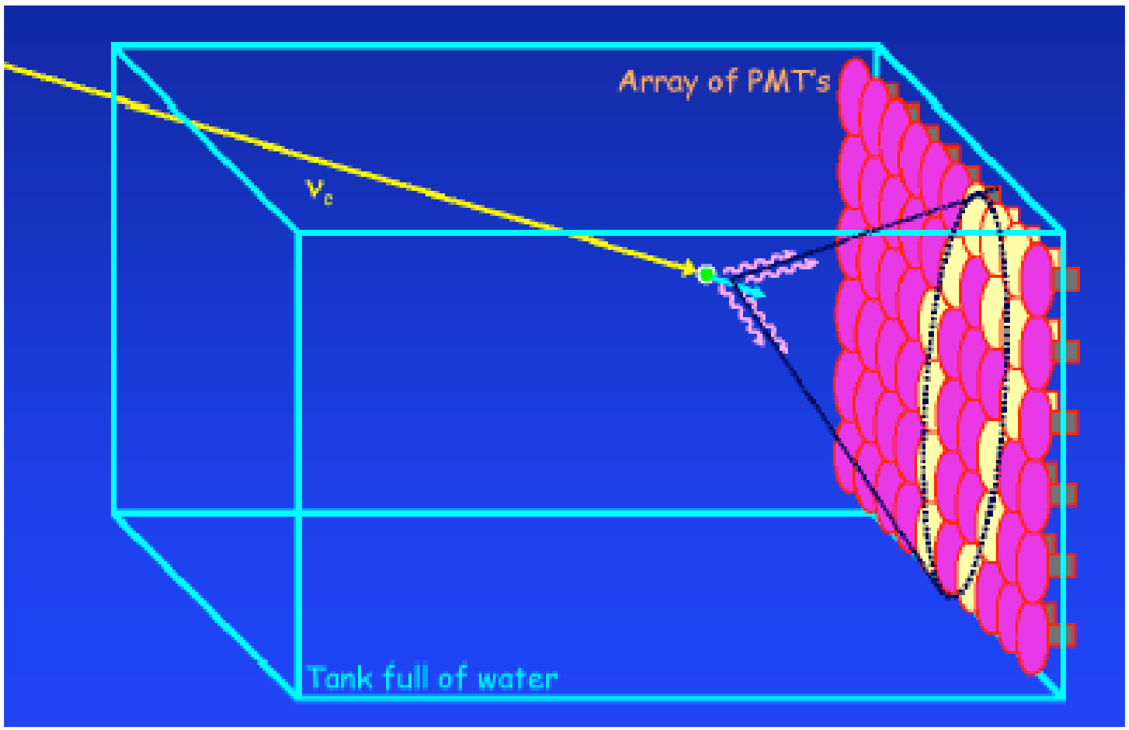
Technodyne baseline design



From A.Rubbia presentation at the TPC conf., Paris 2004

Cherenkov detector – principles of work

Cherenkov radiation is emitted along the particle path if particle moves faster than light in the detector medium (bluish light in water).



Cherenkov light emitted into a cone is detected by photomultipliers

- signal distribution and its timing serves the reconstruction of charged particle direction → neutrino direction ,

- signal amplitude measures particle energy

- shape of the ring („fuzzy" or sharp) → particle ID