Topical questions in the experimental neutrino physics

Agnieszka Zalewska

Ustroń 2003

From the romantic era of great discoveries (1998-2002)

SuperKamiokande, K2K, SNO, KamLAND

to the realistic era of precise measurements (from 2003 onwards)

tens of experiments in the near or further future to study neutrino oscillations and properties

in order to answer a few fundamental questions and to help theorists to select good models (out of hundreds)

Neutrino physics - outlook

1998 - 2002 - romantic era of great discoveries

1998 SuperKamiokande - atmosferic neutrinos 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 $\nu_e \to \nu_{\mu,\tau}$ oscillations
Dec 2002 KamLAND shows that reactor anti-ν_e's oscillate like solar ν_e's

from 2003 onwards - realistic era of precise measurements

- better determination of the oscillation parameters and neutrino mixing matrix elements
- determination of absolute mass scale
- neutrinoless double beta decay ($\beta\beta0\nu$) down to 0.01 eV

LBL accelerator (on-, off-axis) and reactor expts, superbeams, niu-factories, underground cryogenic detectors, beta spectrometers, CMB surveys, ...

and still a bit of romanticism...

- searches for very high energy astrophysical neutrinos

A.Zalewska, Ustron, 20.09.2003

A few important questions

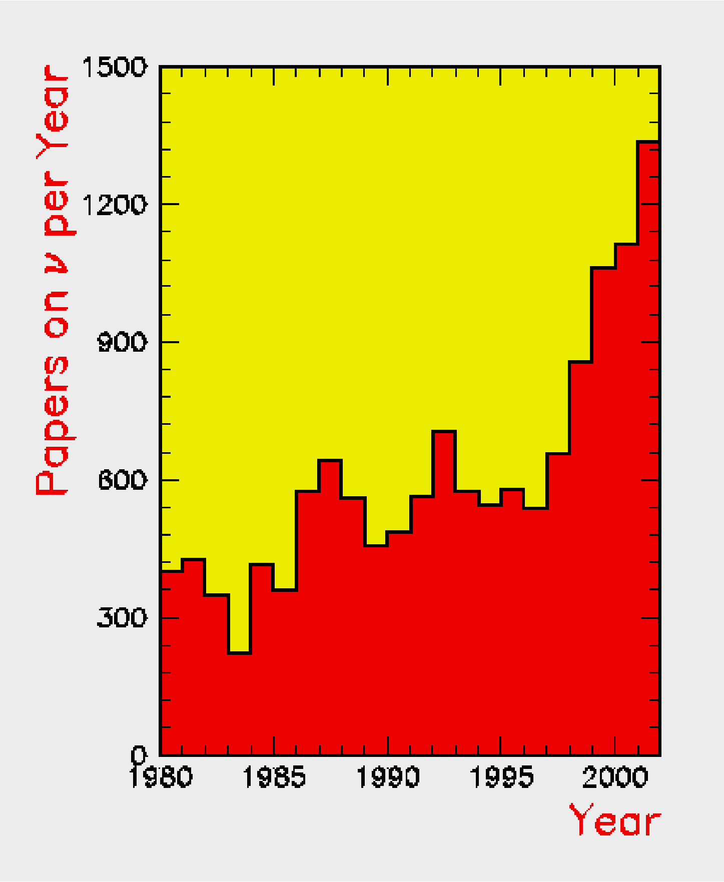
Seven questions of Murayama at EPS2003:

Dirac or Majorana?
Absolute mass scale?
How small is θ_{13}?
CP Violation?
Mass hierarchy?
Verify Oscillation?
LSND? Sterile neutrino(s)? CPT violation?

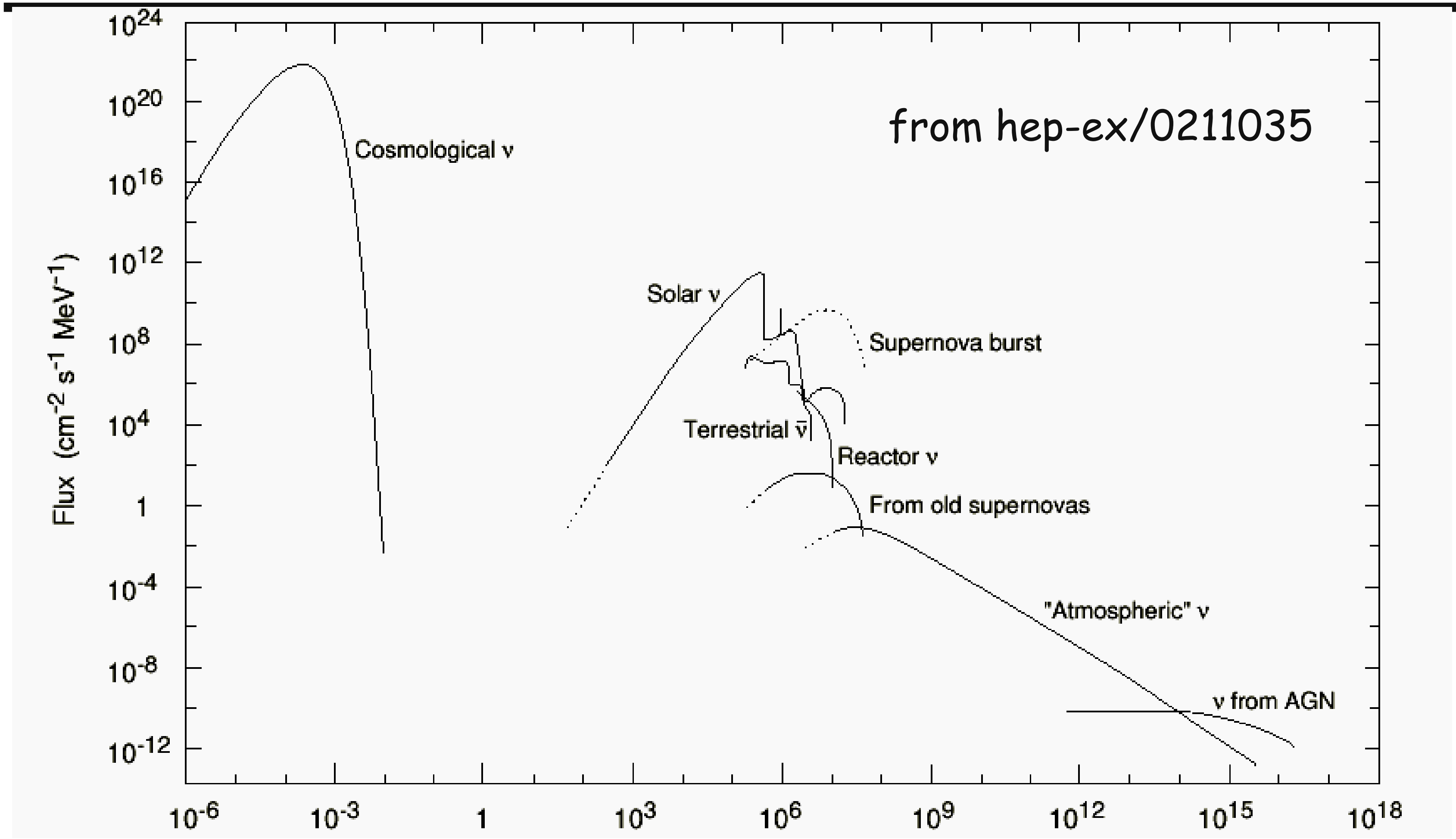
Why?

To understand the mechanism given rise to neutrino masses and oscillations, the possible relation between CP-violation in the lepton sector at low energies and the generation of the baryon asymmetry of the Universe, new symmetries,...

... and do not forget hundreds of theoretical models to be checked ...



Neutrino sources



Three light active neutrinos: ν_e, ν_μ, ν_τ - result from LEP, others must be sterile

Neutrino oscillations primer

In the two-neutrino oscillation scheme the probability that :

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

Appearance experiment:

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

Disappearance experiment:

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

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

A.Zalewska, Ustron, 20.09.2003

Neutrino oscillations after SNO

Two oscillation regions with a very solid experimental evidence:

atmospheric region

solar region

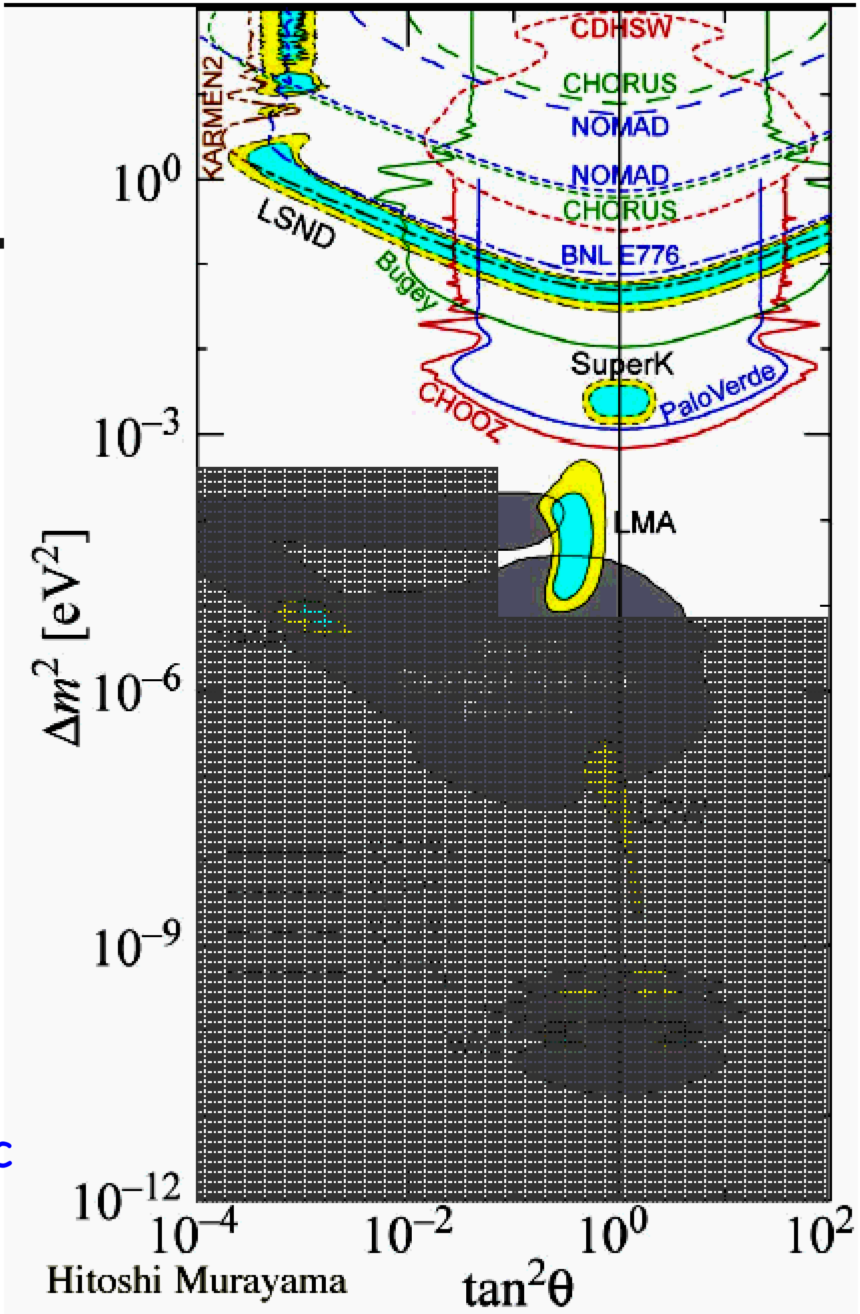
Third region:

LSND

being checked by the dedicated MiniBOONE experiment

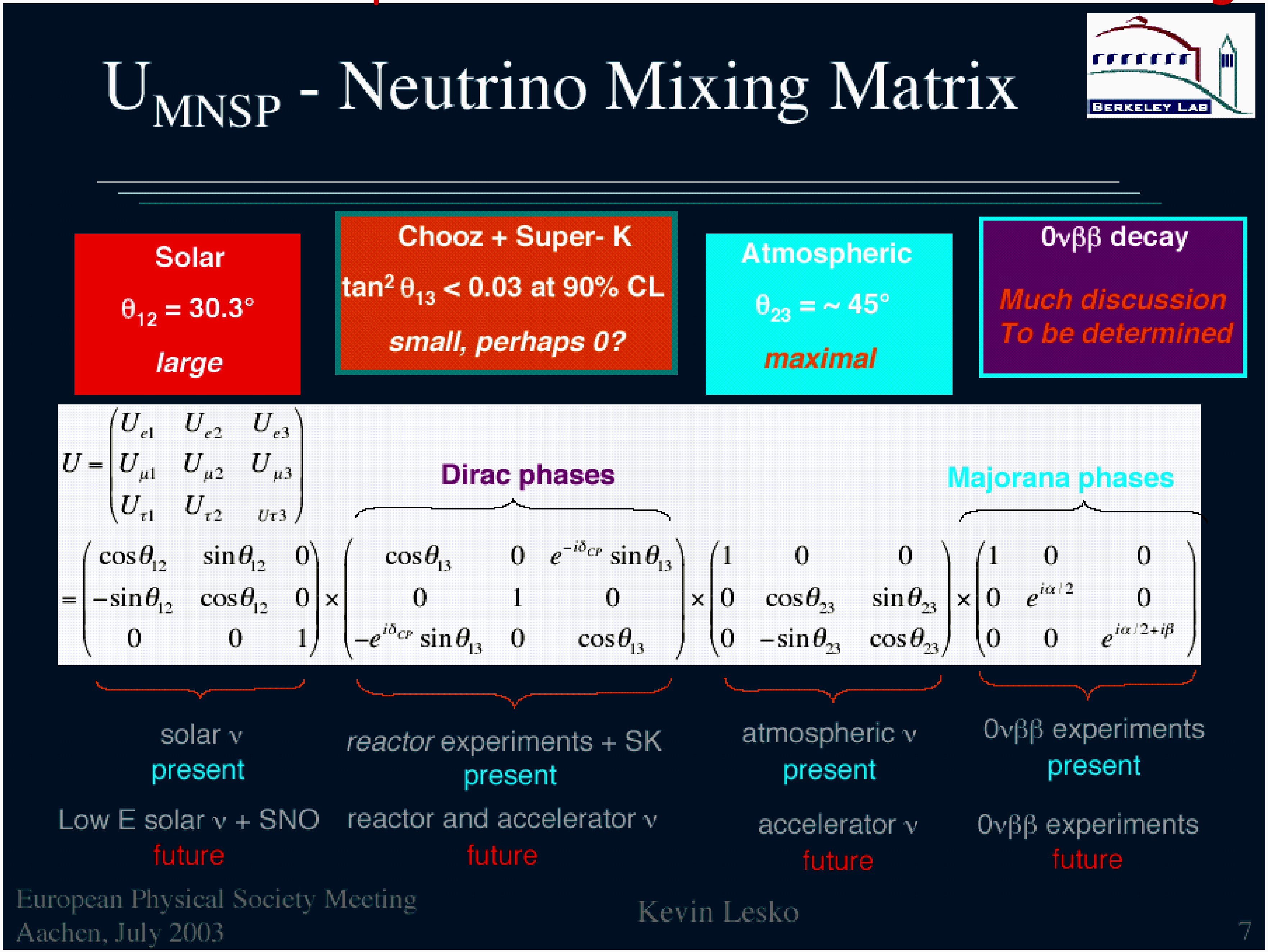
Note: SNO reduced the allowed oscillation space for solar neutrinos by 7 orders of magnitude

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



Hitoshi Murayama

let us be more professional-three neutrino mixing



U_{MNSP} - Neutrino Mixing Matrix

Solar
$\theta_{12} = 30.3°$
large

Chooz + Super- K
$\tan^2\theta_{13} < 0.03$ at 90% CL
small, perhaps 0?

Atmospheric
$\theta_{23} = \sim 45°$
maximal

0νββ decay
Much discussion
To be determined

$$U=\begin{pmatrix}U_{e1}&U_{e2}&U_{e3}\\U_{\mu1}&U_{\mu2}&U_{\mu3}\\U_{\tau1}&U_{\tau2}&U_{\tau3}\end{pmatrix}$$

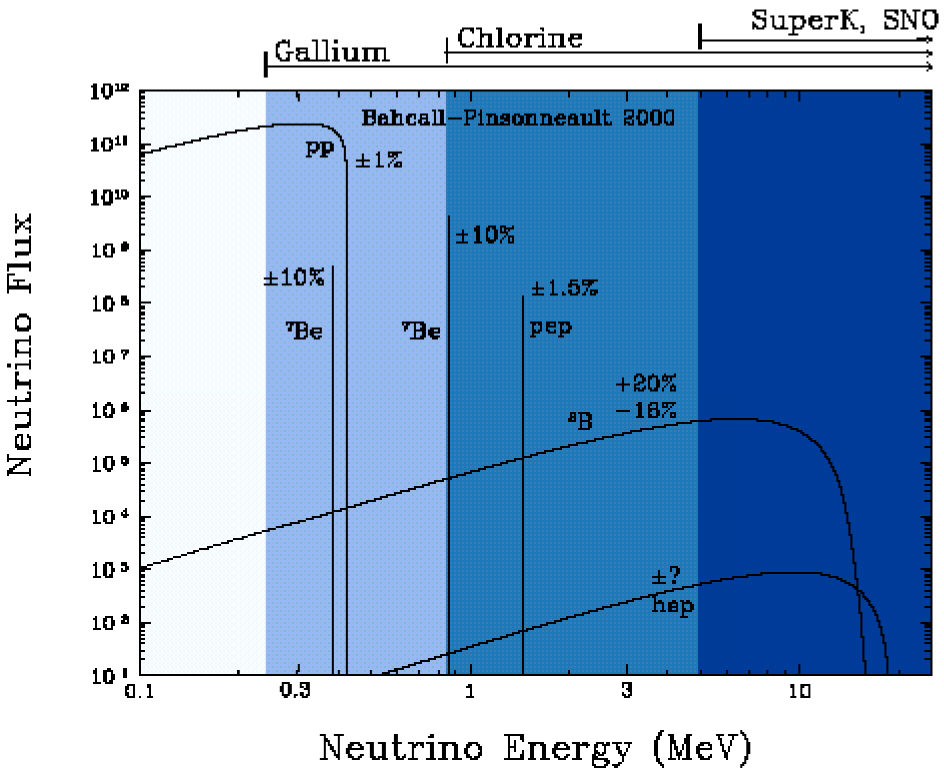
$$=\underbrace{\begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix}}_{}\times\overbrace{\underbrace{\begin{pmatrix}\cos\theta_{13}&0&e^{-i\delta_{CP}}\sin\theta_{13}\\0&1&0\\-e^{i\delta_{CP}}\sin\theta_{13}&0&\cos\theta_{13}\end{pmatrix}}_{}}^{\text{Dirac phases}}\times\underbrace{\begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix}}_{}\times\overbrace{\underbrace{\begin{pmatrix}1&0&0\\0&e^{i\alpha/2}&0\\0&0&e^{i\alpha/2+i\beta}\end{pmatrix}}_{}}^{\text{Majorana phases}}$$

solar ν	*reactor* experiments + SK	atmospheric ν	0νββ experiments
present	present	present	present
Low E solar ν + SNO	reactor and accelerator ν	accelerator ν	0νββ experiments
future	future	future	future

European Physical Society Meeting
Aachen, July 2003

Kevin Lesko

Solar neutrinos primer



Most of the solar neutrinos in pp cycle

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

Experiments measure the reactions:

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

In particular:

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

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

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

$\nu_\ell + n \longrightarrow \nu_\ell + n$ 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 t
the detector
total neutrino flux in agreement with th
Standard Solar Model

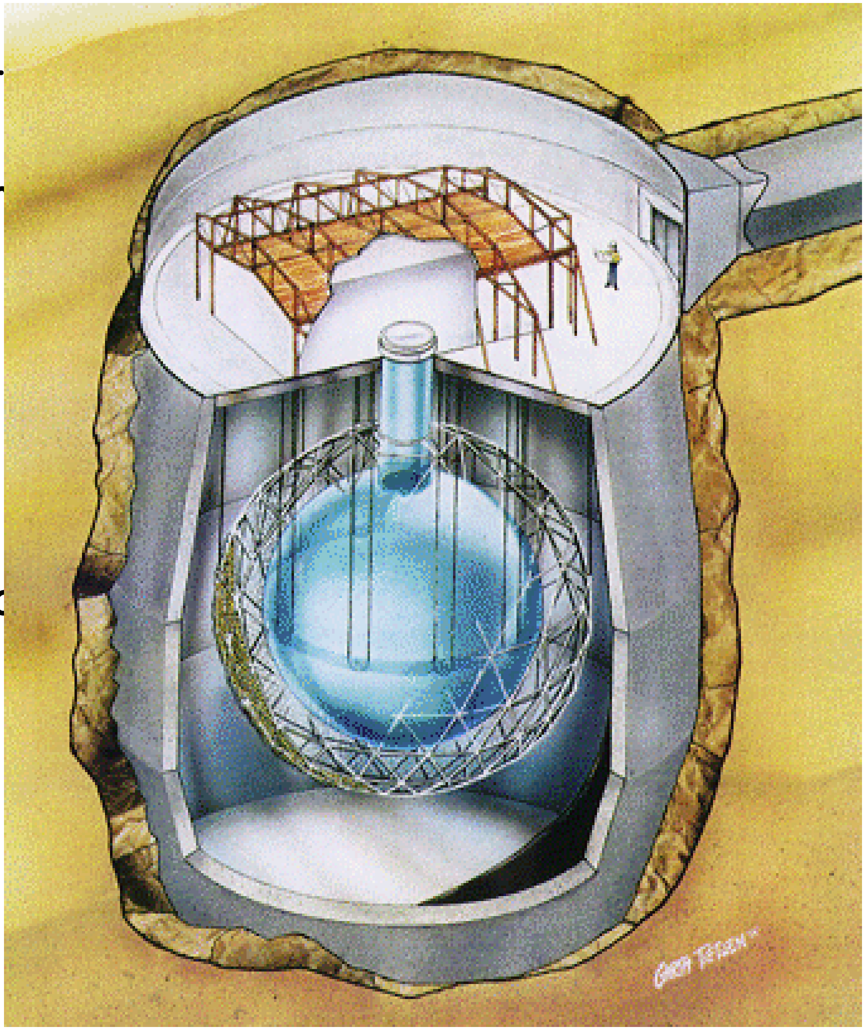
Phase 1: 1000 tons of D_2O, 9456 photomultipliers, 7 kton H_2O, 2000 m. under surface, detection of the Cherenkov radiation

Phase 2: addition of two tons of salt t
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's, good energy measurement weak dependence on the neutrino direction 1-1/3cosθ

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

all three types of neutrinos with the same cross section, measurement of the total neutrino flux

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

relatively small cross section, sensitive mostly to ν_e's, sensitive to the neutrino direction, reaction measured also by SuperK

SNO Phase II - Salt

D_2O

NC Sensitivity

$\varepsilon_n \sim 24\%$

$n + {}^{2}H \rightarrow {}^{3}H + \gamma$

$E_\gamma = 6.25$ MeV

NC and CC separation by energy, radial, and directional distributions

Salt

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

The Neutral Current Detectors

Array of ^{3}He counters

96 Strings on 1-m grid

775 m total active length

Detection Principle

$^2H + \nu_x \rightarrow p + n + \nu_x$ -2.22 MeV (NC)

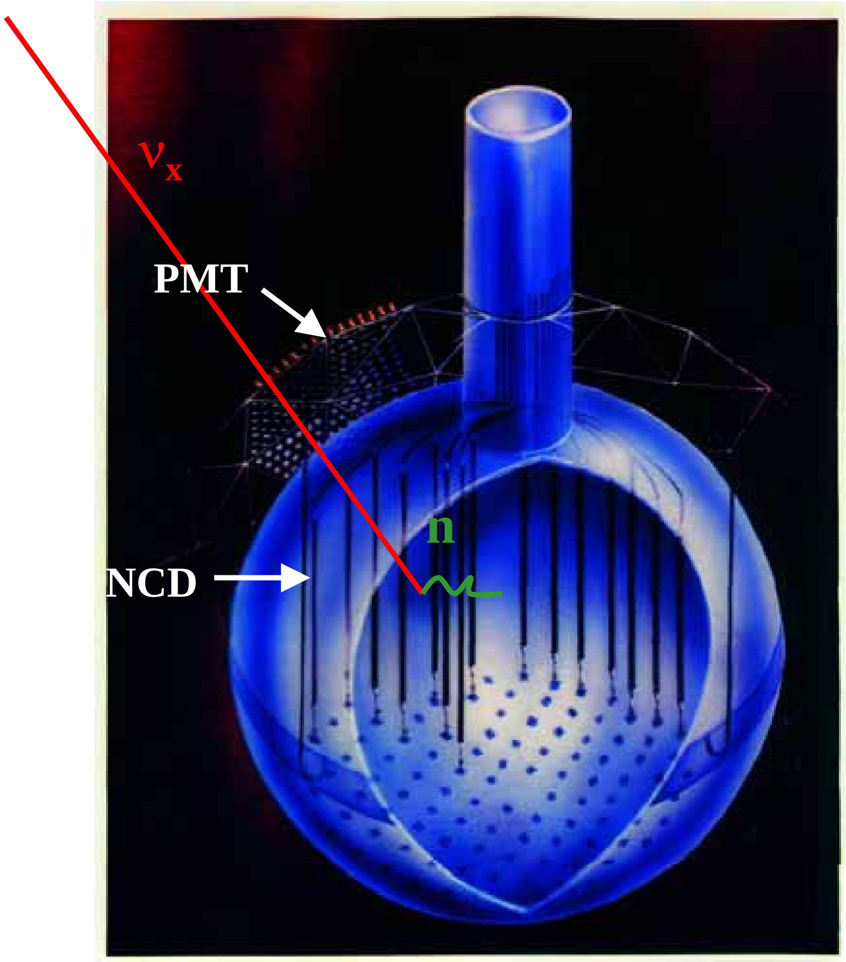
↘ $^3He + n \rightarrow p + {}^3H$

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

NCD array as a neutron absorber.



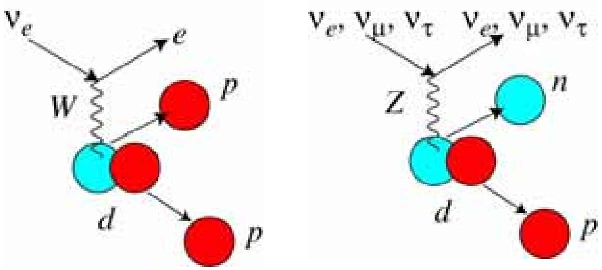
SNO - answers to the questions:

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

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

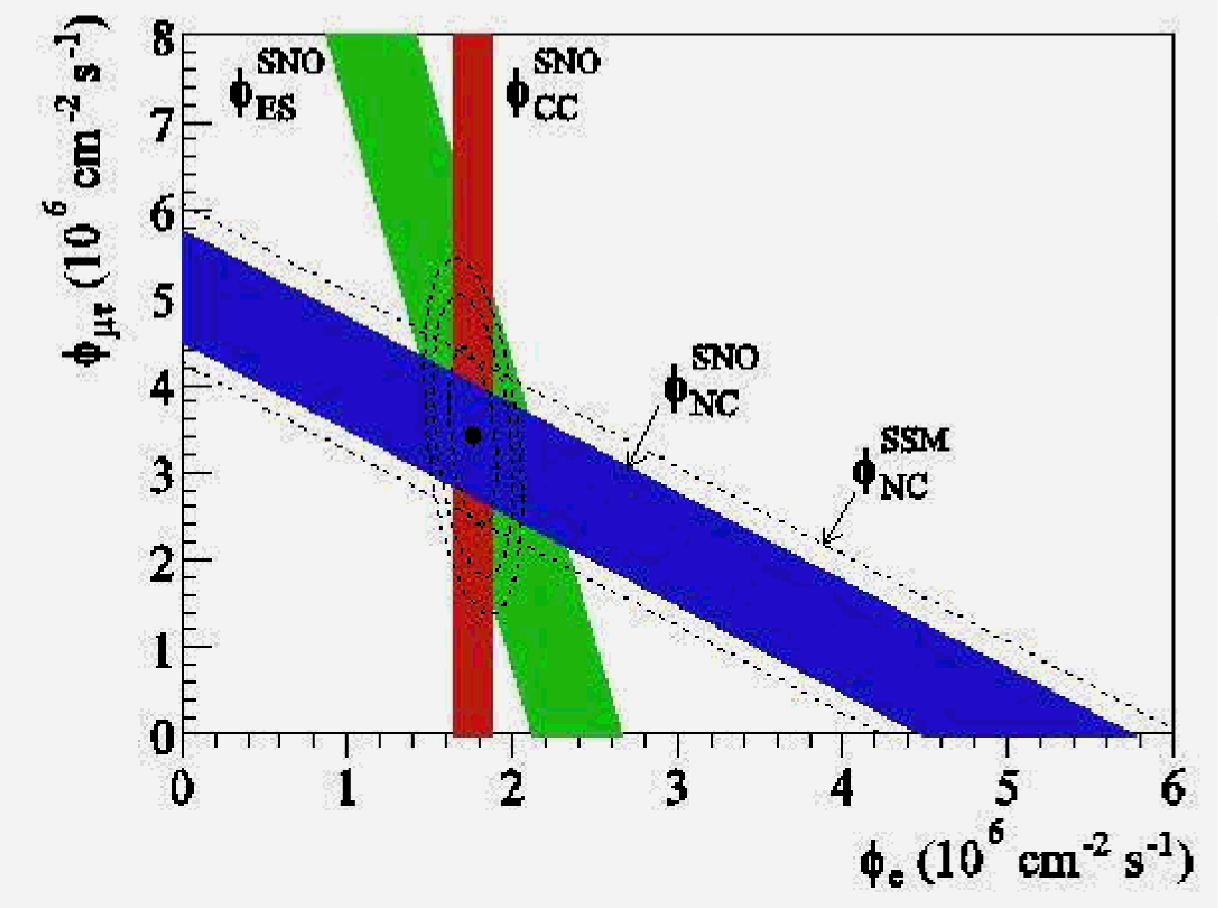
$$\Phi_{day} = \Phi_{night}\ ?$$

2002 SNO results - solar flux analysis



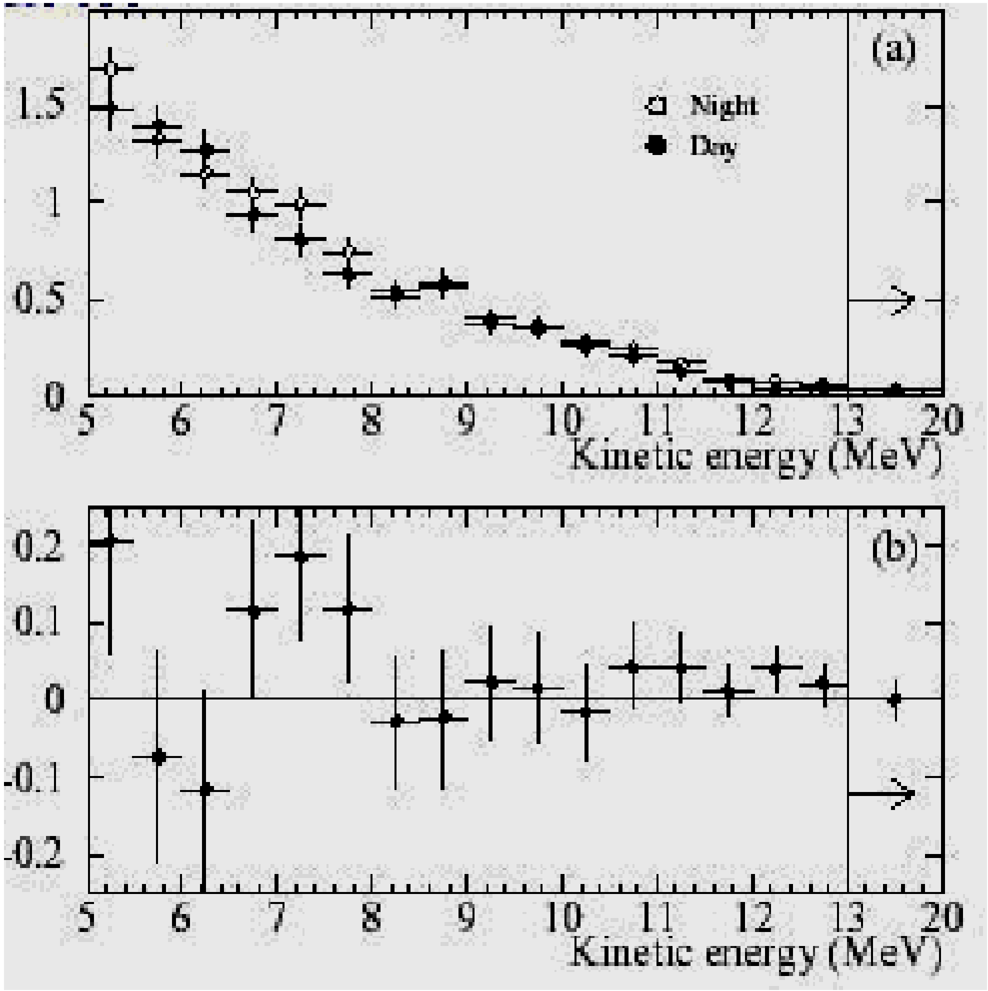
$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$

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



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

2002 SNO results - day/night asymmetry



$$A_X = 2*\frac{(\Phi_{N,X} - \Phi_{D,X})}{(\Phi_{N,X} + \Phi_{D,X})}$$

$$A_e = 12.8 \pm 6.2^{+1.5}_{-1.4}$$

$$A_{tot} = -24.2 \pm 16.1^{+2.4}_{-2.5}$$

It will be a very important measurement for Borexino and/or upgraded KamLAND!

2003 SNO results from phase 2

nucl-ex/0309004

Phase 2

n capture efficiency almost doubled

$$\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07}(\text{stat})^{+0.06}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26}(\text{stat}) \pm 0.10\ (\text{syst})$$

$$\phi_{NC}^{SNO} = 5.21 \pm 0.27\ (\text{stat}) \pm 0.38\ (\text{sy}$$

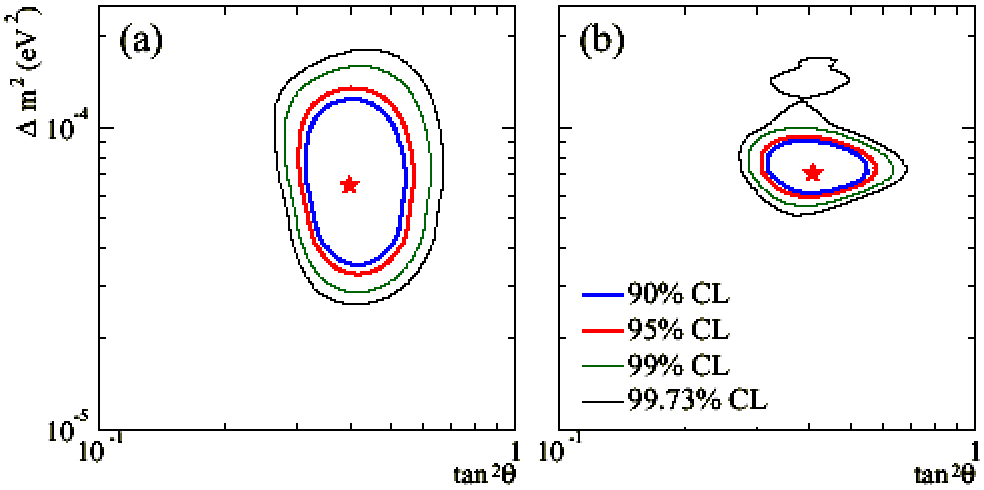


FIG. 5: Global neutrino oscillation contours. (a) Solar global: D_2O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is $\Delta m^2 = 6.5 \times 10^{-5}$, $\tan^2\theta = 0.40$, $f_B = 1.04$, with χ^2/d.o.f.=70.2/81. (b) Solar global + KamLAND. The best-fit point is $\Delta m^2 = 7.1 \times 10^{-5}$, $\tan^2\theta = 0.41$, $f_B = 1.02$. In both (a) and (b) the ^{8}B flux is free and the *hep* flux is fixed.

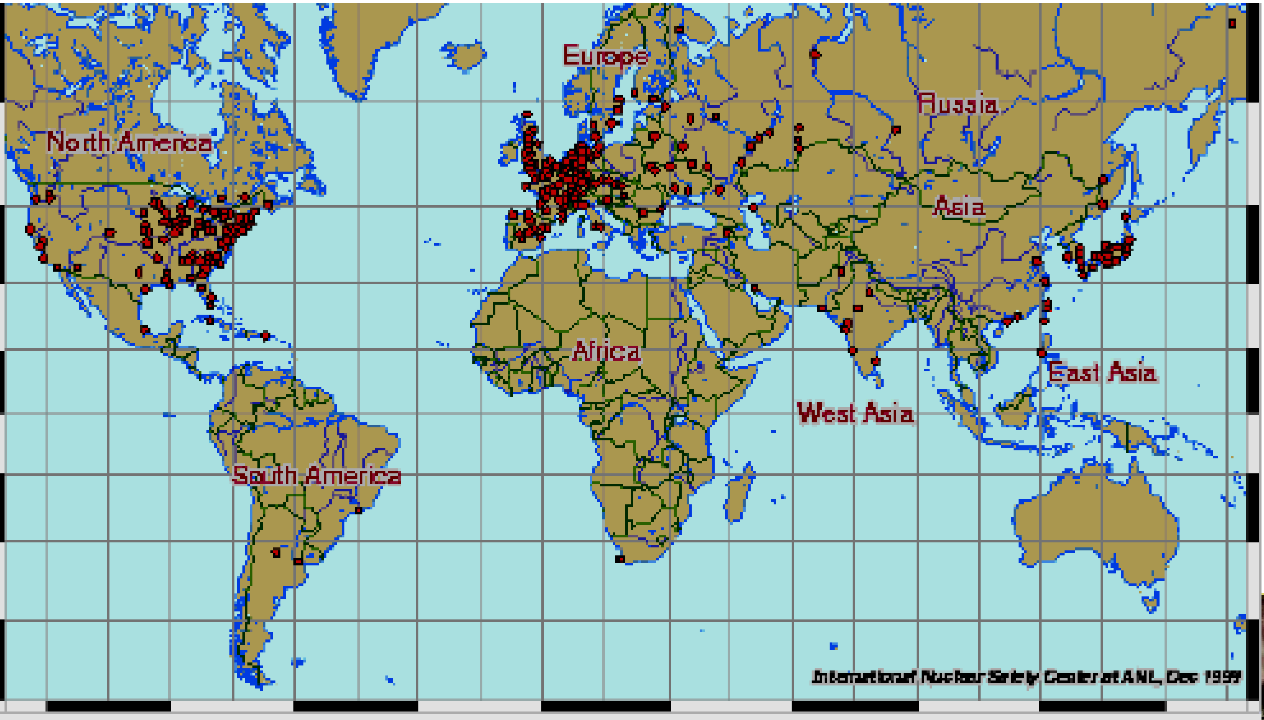
Phase 1

$$\Phi_{cc}(\nu_e) = 1.76^{+0.06}_{-0.05}\ (\text{stat.})\ ^{+0.09}_{-0.09}\ (\text{syst.})\ \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{es}(\nu_x) = 2.39^{+0.24}_{-0.23}\ (\text{stat.})\ ^{+0.12}_{-0.12}\ (\text{syst.})\ \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{nc}(\nu_x) = 5.09^{+0.44}_{-0.43}\ (\text{stat.})\ ^{+0.46}_{-0.43}\ (\text{syst.})\ \times 10^6\ \text{cm}^{-2}\text{s}^{-1}$$

Reactor antineutrinos



International Nuclear Safety Center at ANL, Dec 1999

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

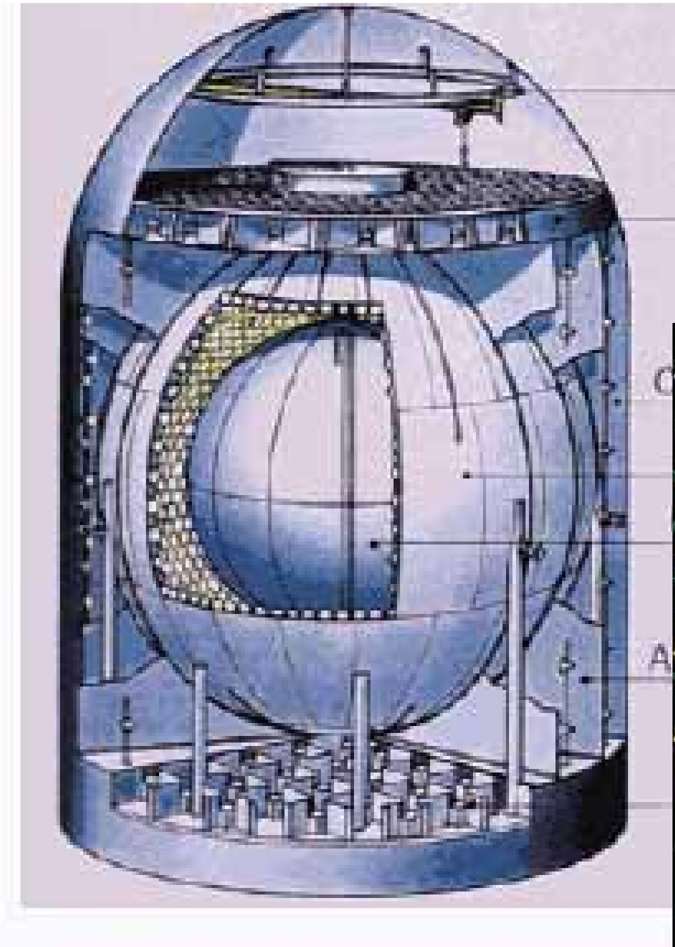
Typical power station gives $6x10^{20}$ anty-ν/s and 3GW of power

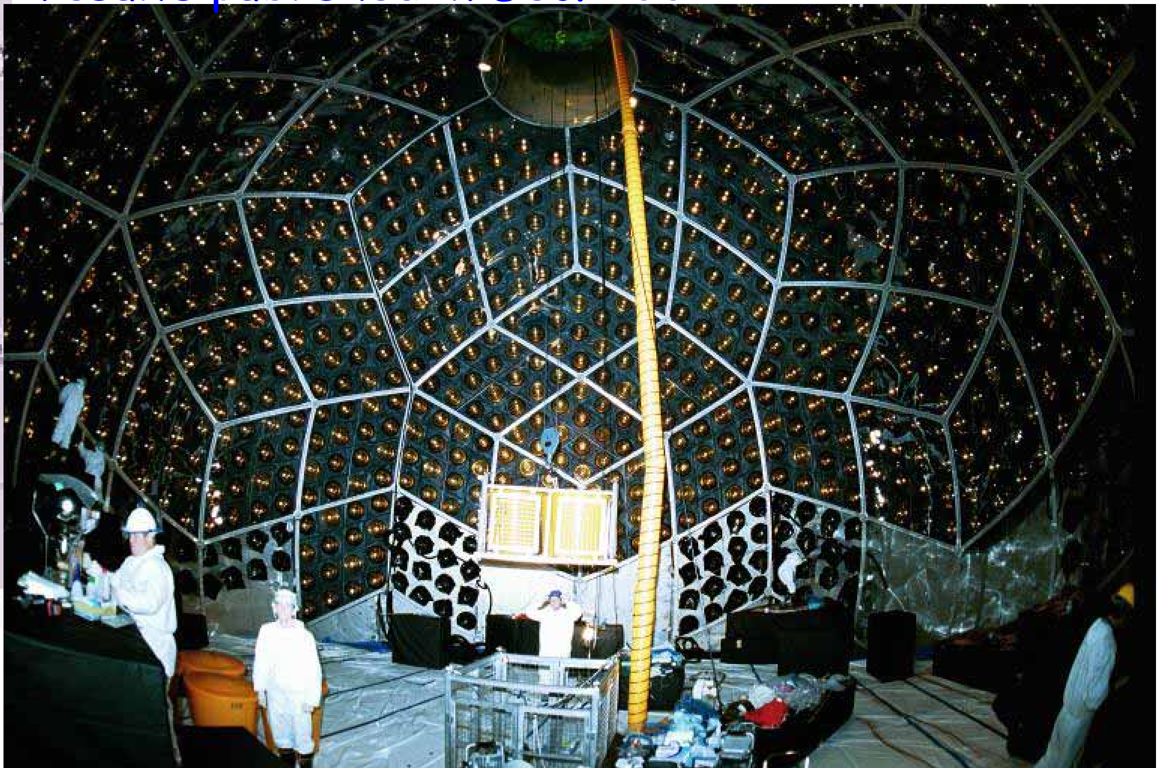
The Palo Verde reactor experiment

A.Zalewska, Ustron, 20.09.2003

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





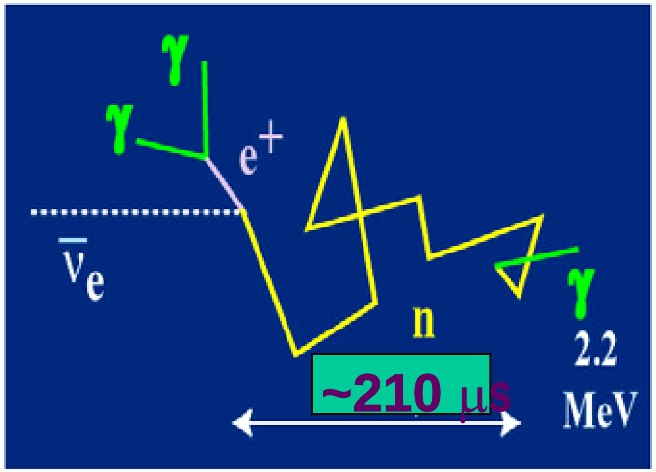
Reactor $\bar{\nu}_e$ Detection in Liquid Scintillator

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



- **prompt part :** e^+

$\bar{\nu}_e$ **energy measurement**

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

$$\Delta = M_n - M_p$$

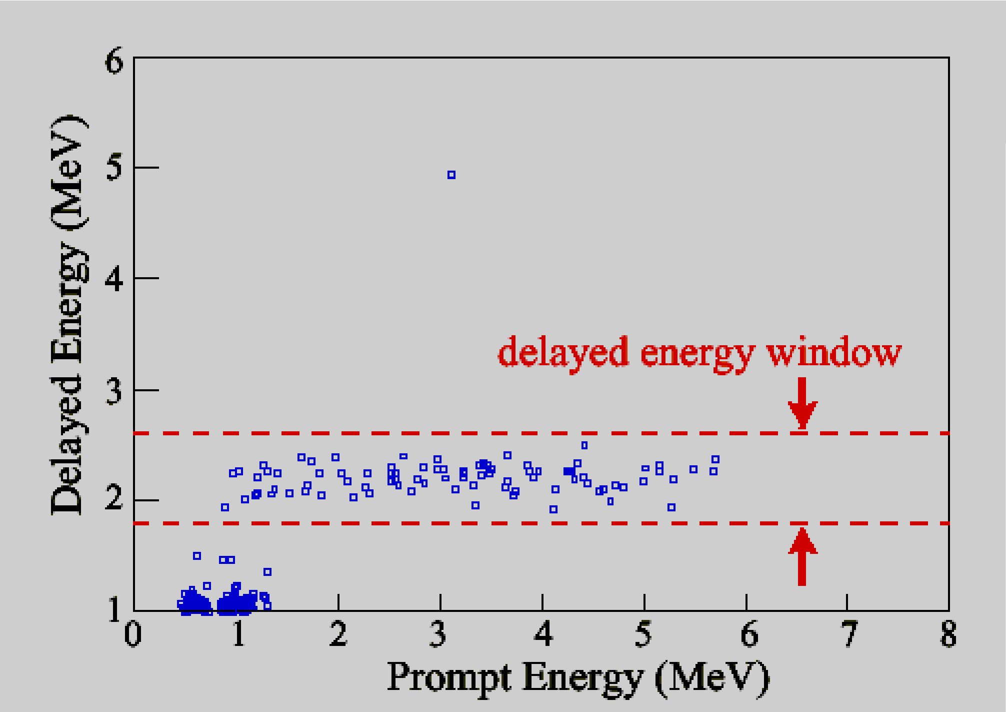
- **delayed part :** γ (2.2 MeV)

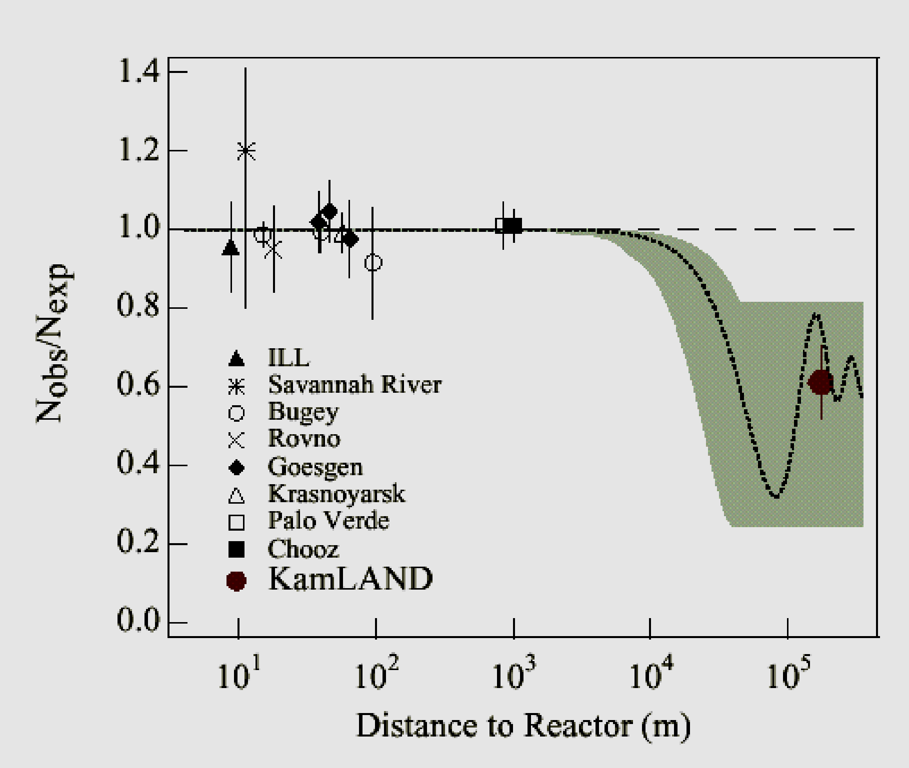
- **tagging : correlation of time, position and energy between prompt and delayed signal**

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

KamLand results - from Dec.2002

54 obsevred events,
86.8+-5.6 expected events if no oscillations

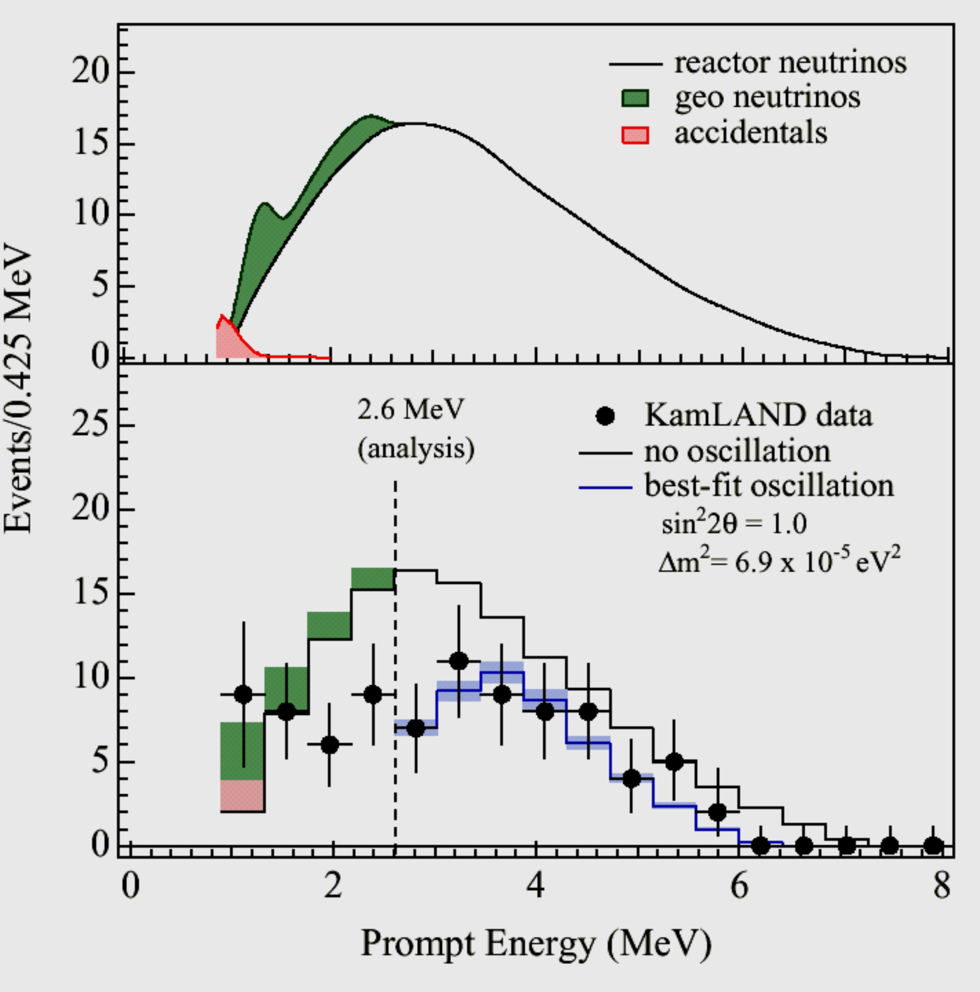


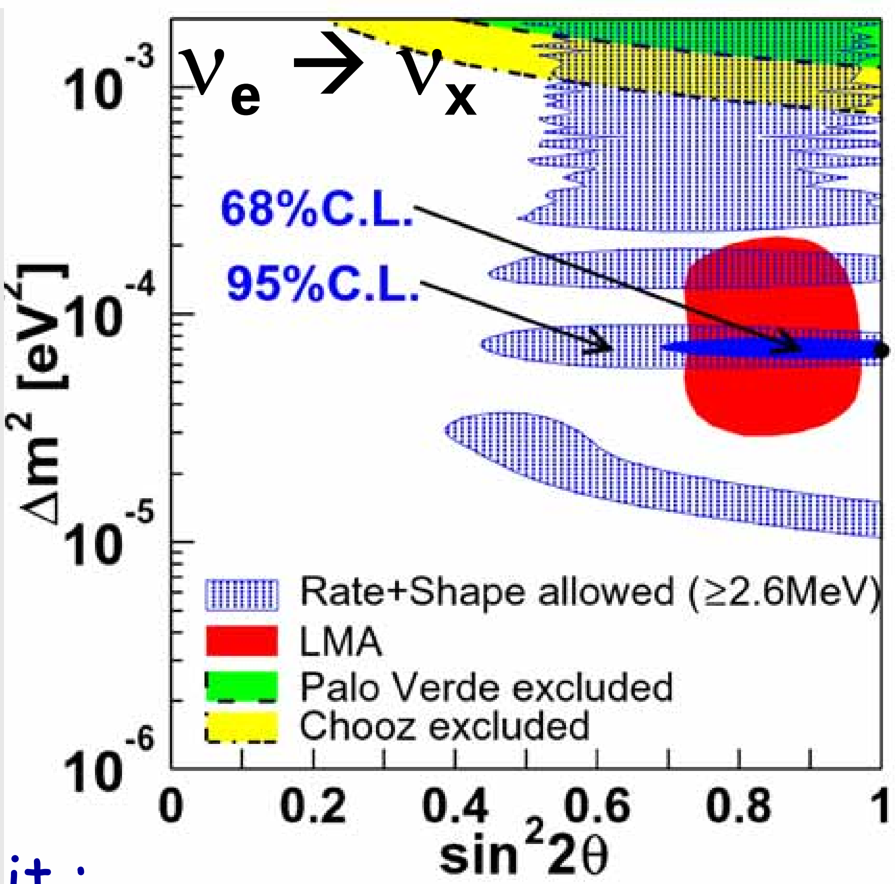


Fast signal of positron annihilation in coincidence with slower signal of neutron capture

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085(\mathrm{stat}) \pm 0.041(\mathrm{syst})$$

KamLand - oscillation study
combining rate and energy spectrum





it :

6.9×10^{-5} eV^2

$\sin^2 2\theta = 1.01$

A.Zalewska, Ustron, 20.09.2003

Neutrino Oscillation Study, Using Rate & Energy Spectrum

A.Suzuki at
Neutrino telescopes 2003

$E_{prompt} > 0.9$ MeV

Best fit :

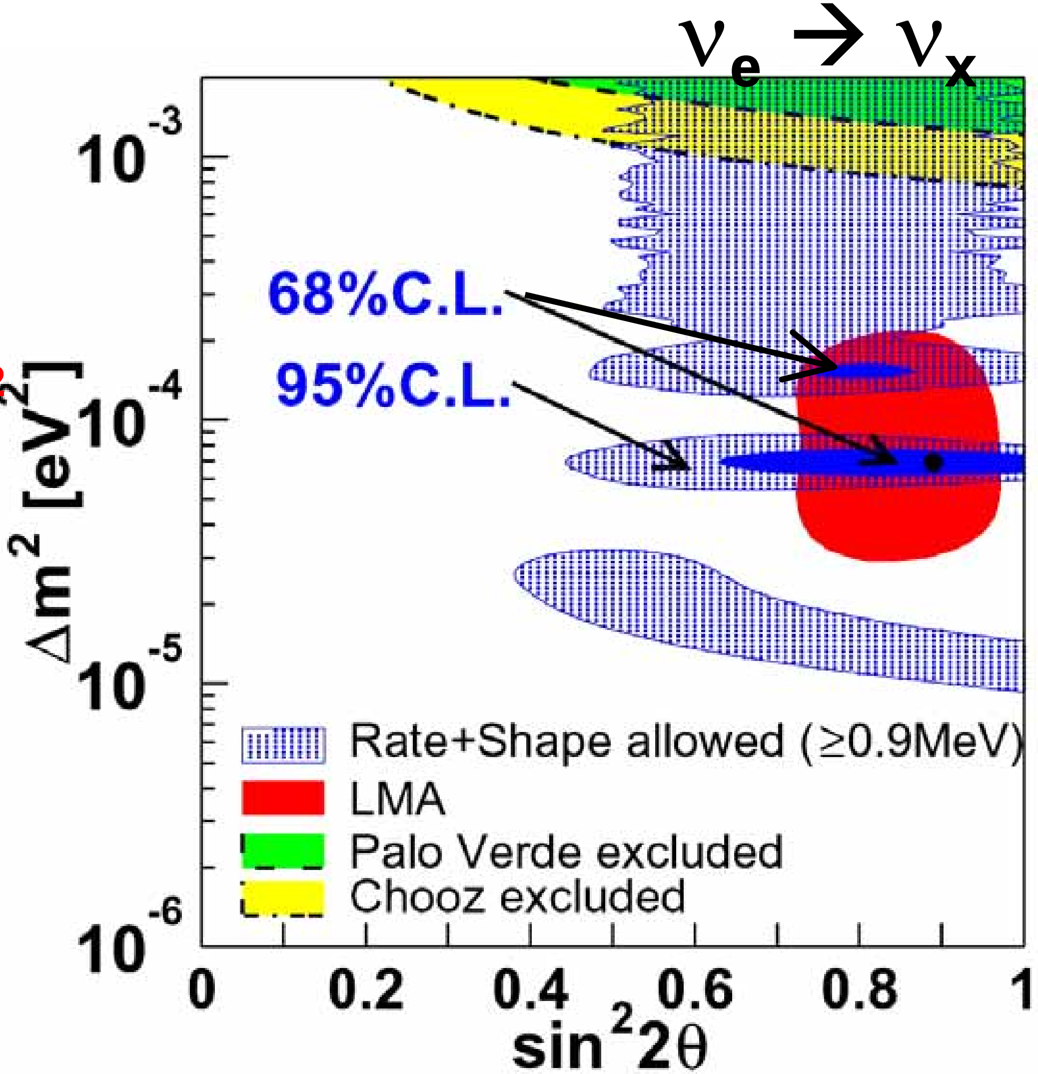
$\Delta m^2 = 6.9 \times 10^{-5} eV^2$

$\sin^2 2\theta = 0.91$

Note: Best fit (with SNO-phase 2:

$\Delta m^2 = 7.1 \times 10^{-5} eV^2$

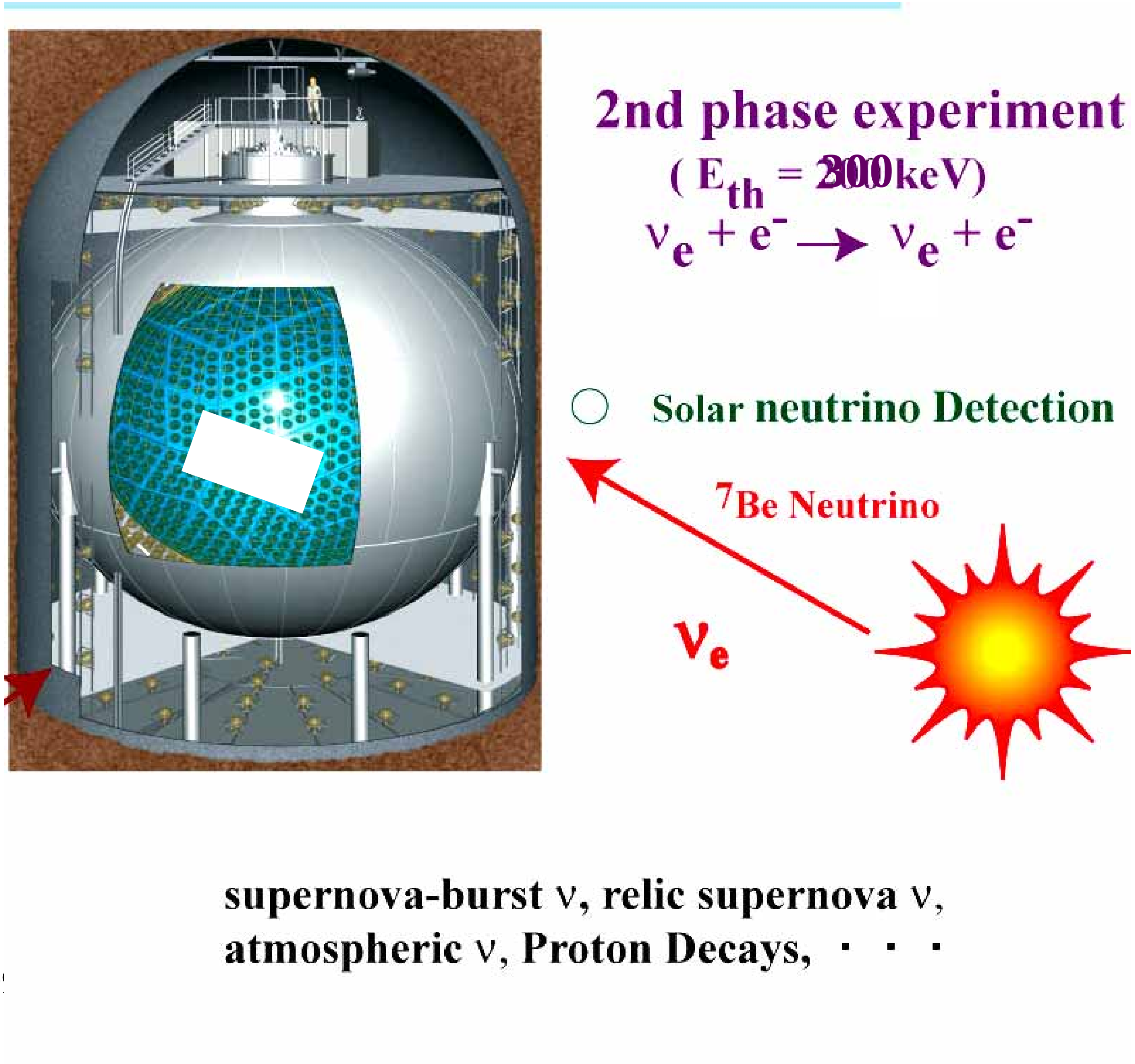
$\tan^2 \theta = 0.41$



KamLAND - future

phase 1
after three years
of data taking
much better Δm^2_{12}
small improvement on θ_{12}

phase 2
studies of Be and pp
neutrinos

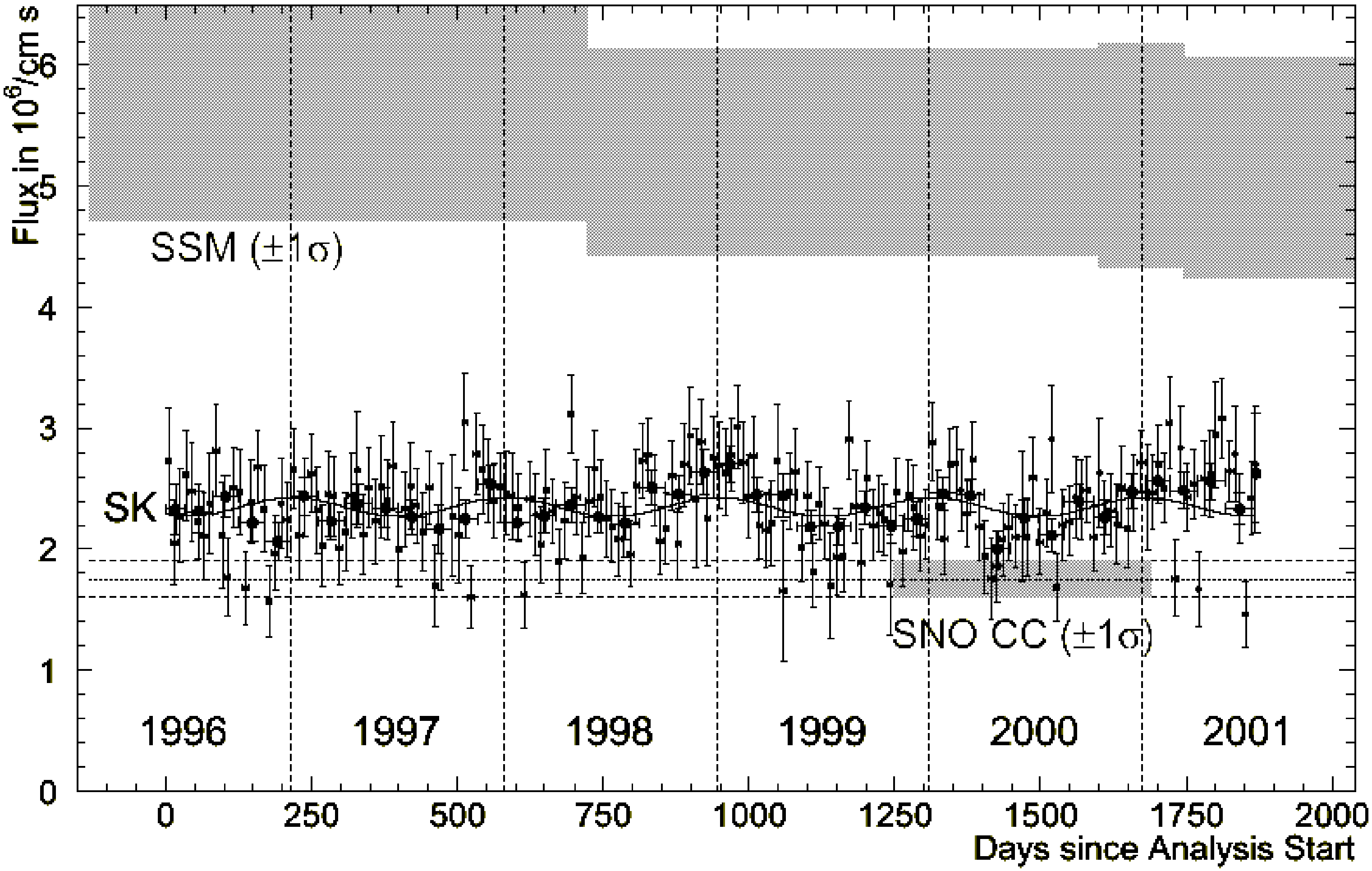


2nd phase experiment
$(E_{th} = 300\,\mathrm{keV})$
$\nu_e + e^- \longrightarrow \nu_e + e^-$

○ **Solar neutrino Detection**

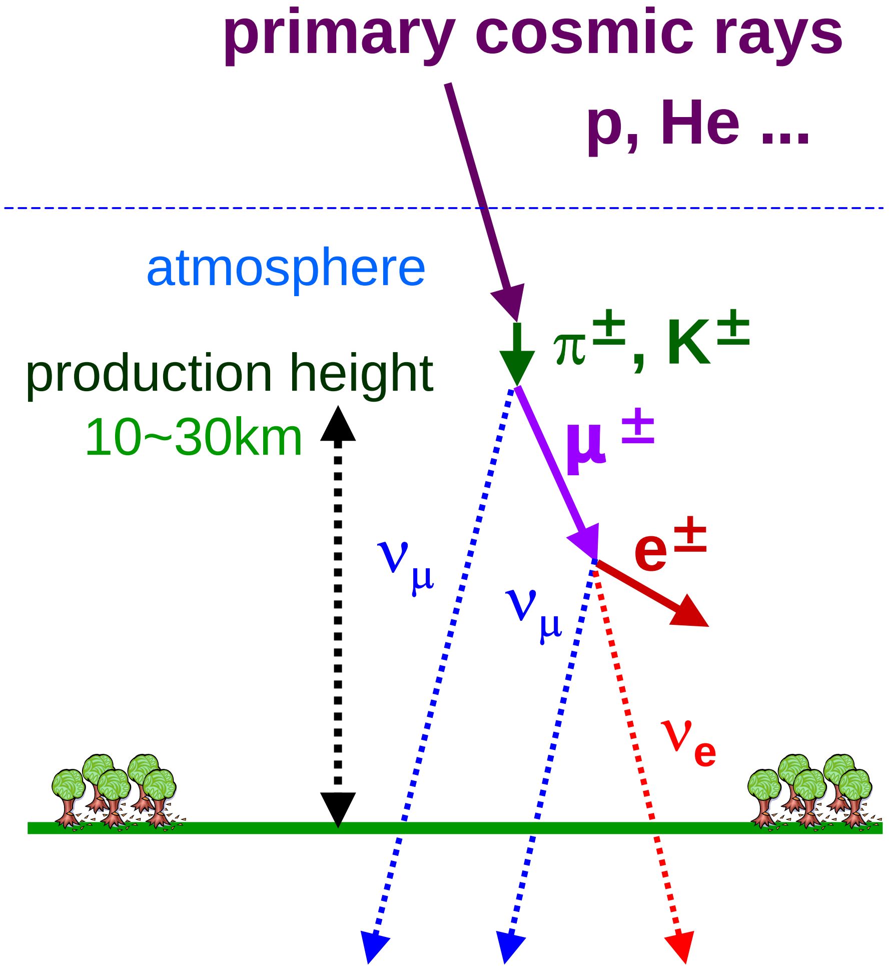
supernova-burst ν, relic supernova ν,
atmospheric ν, Proton Decays, · · ·

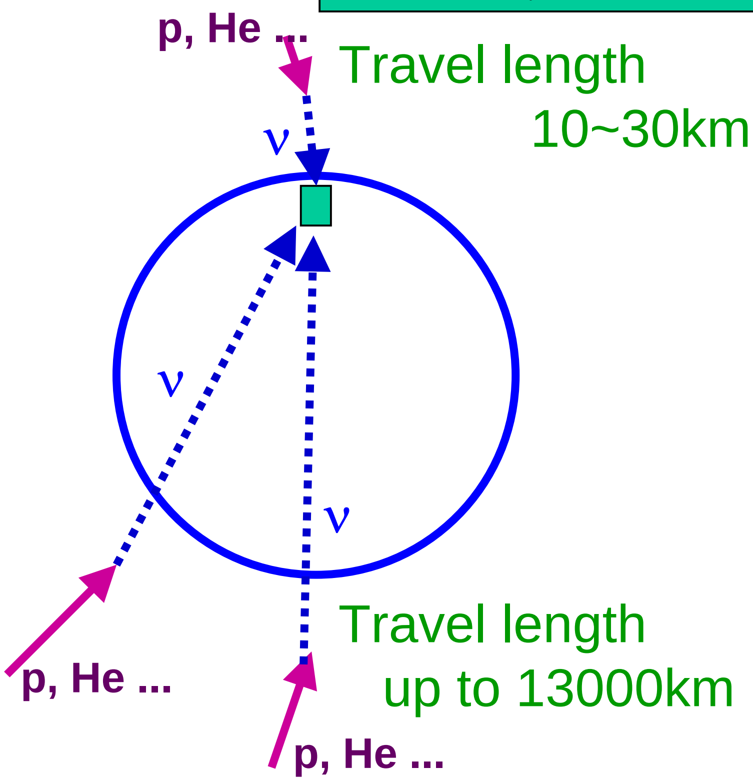
SuperKamiokande - solar neutrinos flux modulation in time



Atmospheric neutrinos primer

from Hayato at EPS2003





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

For E_ν > a few GeV,

(Up-going / down-going) ~ 1

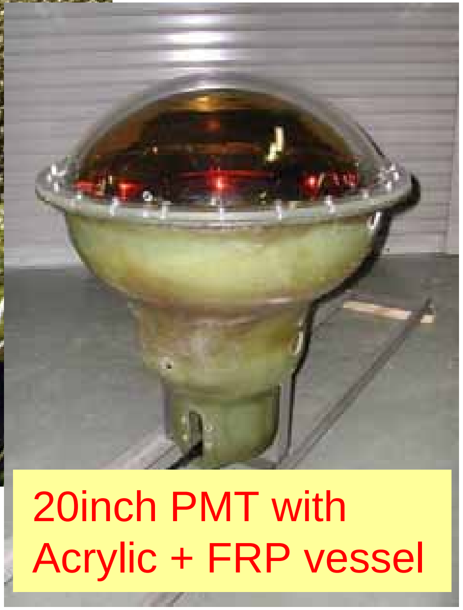
Uncertainty of up/down ratio

< a few %

Super Kamiokande-II

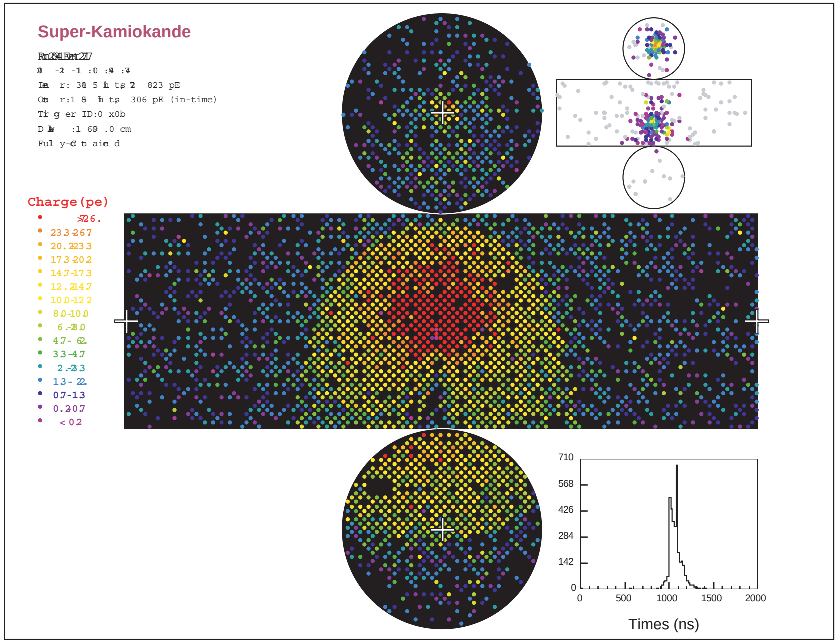
from Hayato at EPS2003

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



20inch PMT with
Acrylic + FRP vessel

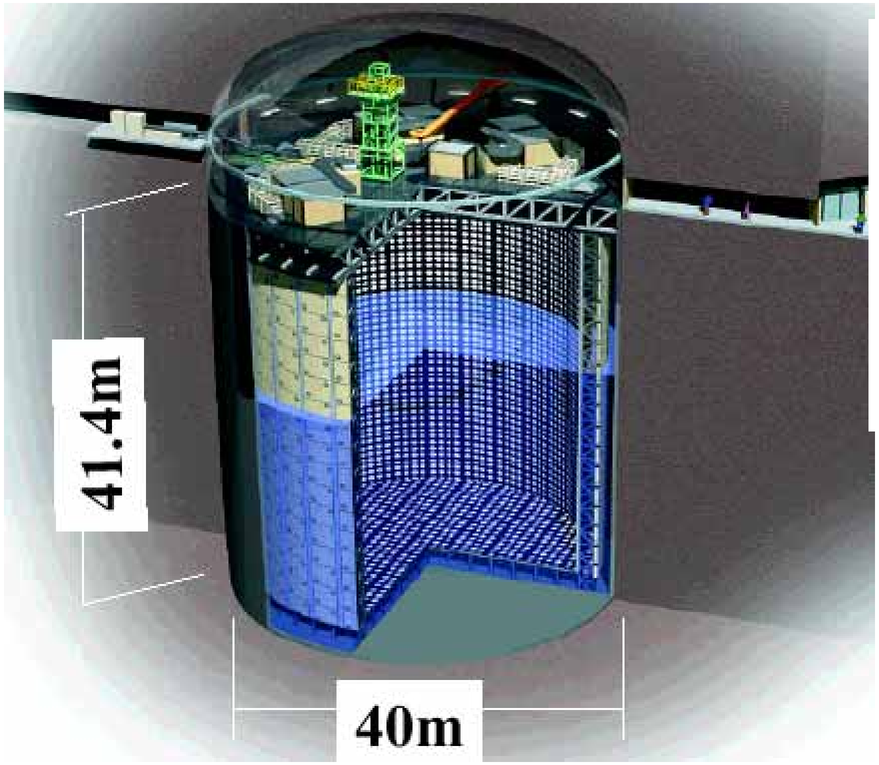
SK-II Cosmic ray muon sample

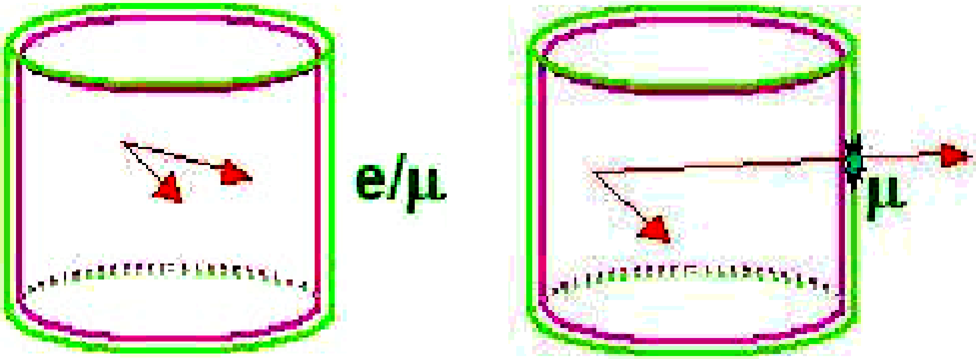


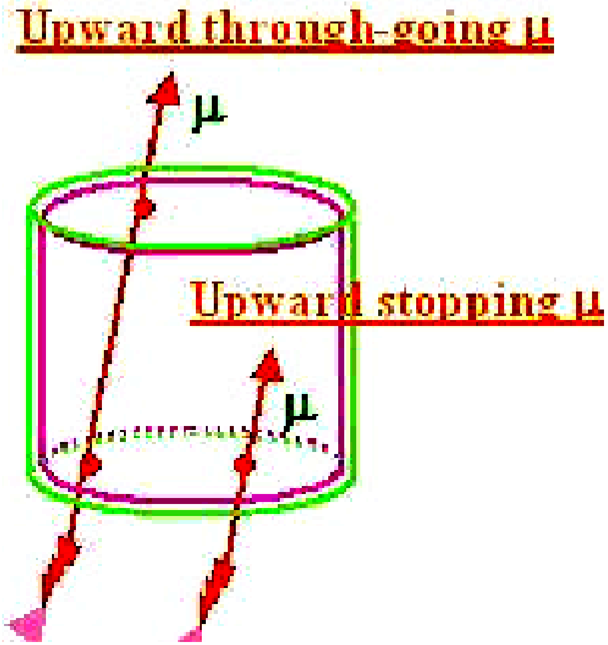
Inner detector
- ~5200 20inch PMTs with covers

Outer detector :1885 8inch PMTs

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

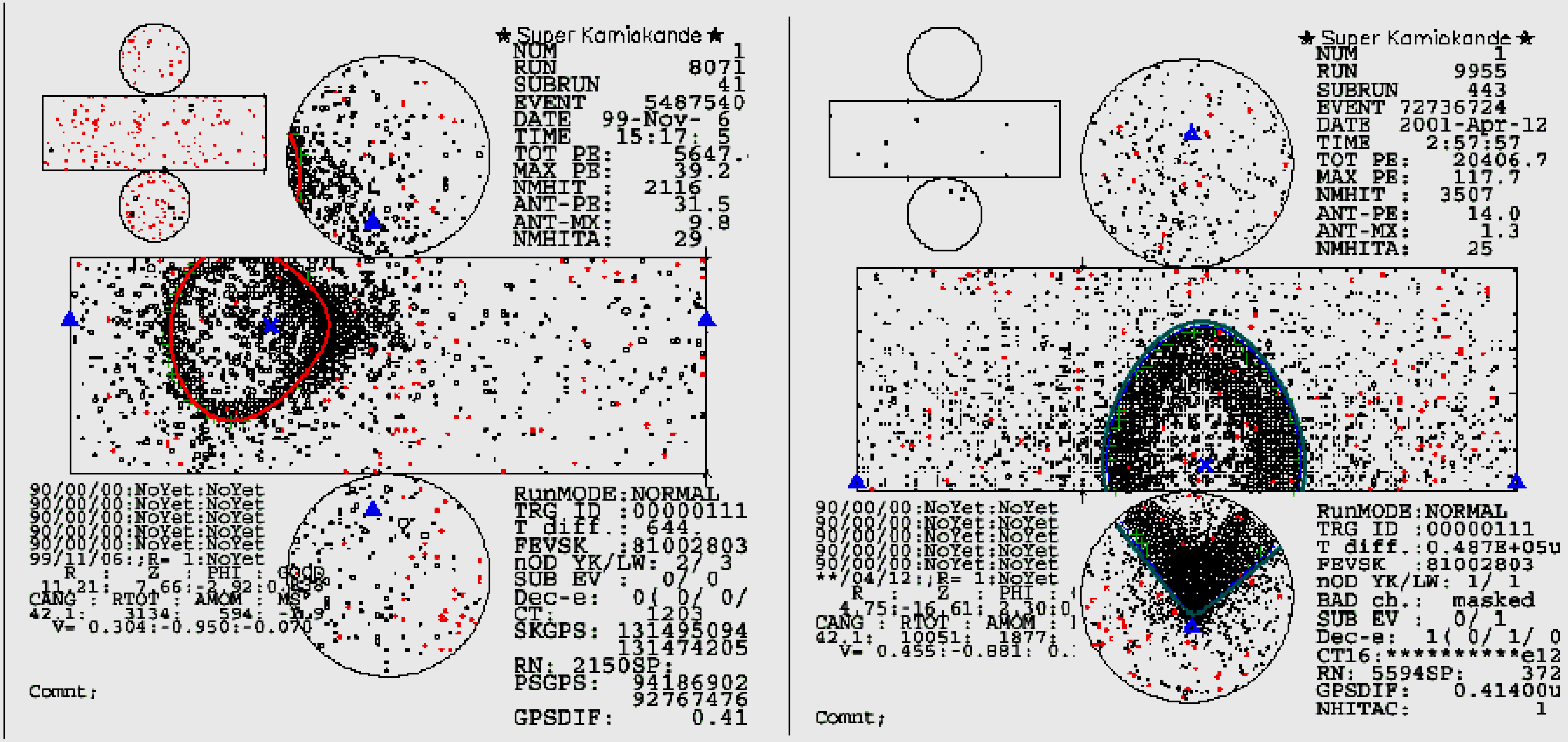






Measurement of energy and direction of muons and electrons from CC neutrino interactions

SuperK - e and μ.



```
NUM                1
RUN             8071
SUBRUN            41
EVENT        5487540
DATE    99-Nov- 6
TIME     15:17: 5
TOT PE:      5647.
MAX PE:      39.2
NMHIT :    2116
ANT-PE:      31.5
ANT-MX:       9.8
NMHITA:      29
```

```
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
99/11/06:;R= 1:NoYet
   R   :    Z   : PHI  : GOOD
 11.21:   7.66:-2.92:0.838
CANG  : RTOT  : AMOM  : MS
42.1:    3134:    594: -1.9
  V= 0.304:-0.950:-0.070

Comnt;
```

```
RunMODE:NORMAL
TRG ID :00000111
T diff.:  644.
FEVSK  :81002803
nOD YK/LW: 2/ 3
SUB EV  :  0/ 0
Dec-e:  0( 0/ 0/
CT:      1203
SKGPS: 131495094
       131474205
RN: 2150SP:
PSGPS:  94186902
        92767476
GPSDIF:      0.41
```

```
NUM              1
RUN           9955
SUBRUN         443
EVENT  72736724
DATE   2001-Apr-12
TIME     2:57:57
TOT PE:   20406.7
MAX PE:    117.7
NMHIT :  3507
ANT-PE:     14.0
ANT-MX:      1.3
NMHITA:    25
```

```
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
90/00/00:NoYet:NoYet
**/04/12:;R= 1:NoYet
   R   :    Z   : PHI  :
  4.75:-16.61: 2.30:0
CANG  : RTOT  : AMOM  :
42.1:   10051:   1877:
  V= 0.455:-0.881: 0.

Comnt;
```

```
RunMODE:NORMAL
TRG ID :00000111
T diff.:0.487E+05u
FEVSK  :81002803
nOD YK/LW: 1/ 1
BAD ch.:  masked
SUB EV :  0/ 1
Dec-e:  1( 0/ 1/ 0
CT16:**********e12
RN: 5594SP:     372
GPSDIF:   0.41400u
NHITAC:          1
```

A.Zalewska, Ustron, 20.09.2003

SuperK I - new analysis of the whole data

Up/Down double ratio $R=(Nobs_{\mu}/Nobs_{e})/(Nexp_{\mu}/Nexp)_{e}$ and zenith angle distributions

for different event categories and energy subsamples

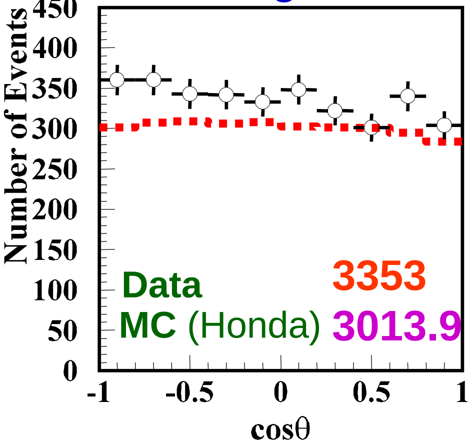
preliminary results presented at EPS03 in Aachen

Summary of the atmospheric ν events

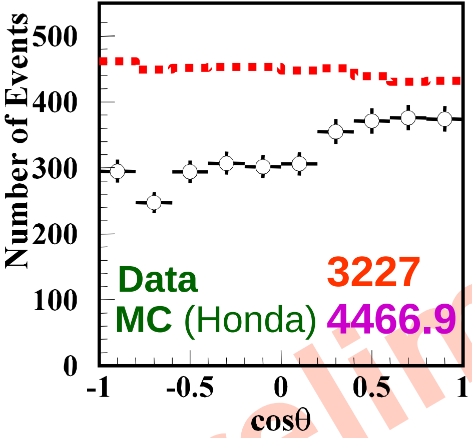
1.contained events

(complete SK-I dataset)

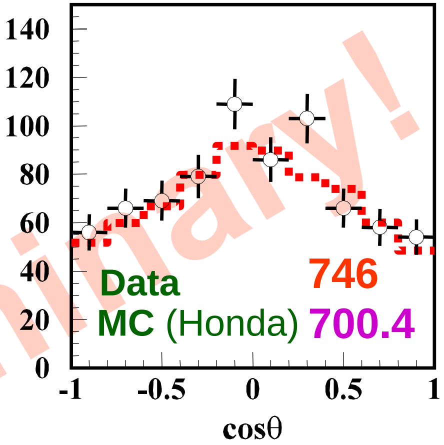
Sub GeV 1ring e-like



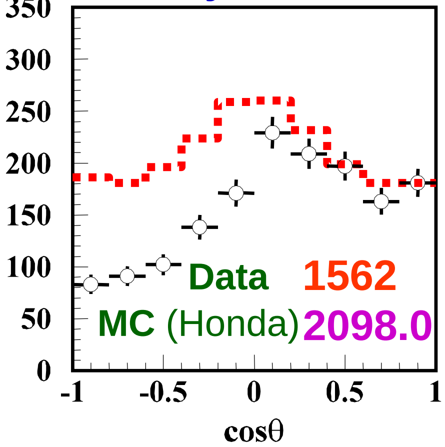
Sub GeV 1ring μ-like



Multi GeV 1ring e-like



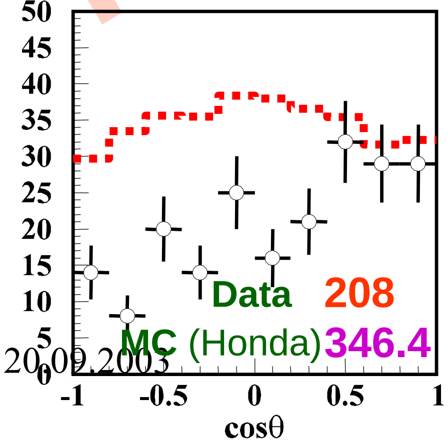
Multi-GeV 1ring μ-like + Partially Contained



Sub GeV

$$\frac{(\mu / e)_{data}}{(\mu / e)_{MC}} = 0.649 \pm 0.016 \text{ (stat.)} \pm 0.051 \text{ (syst.)}$$

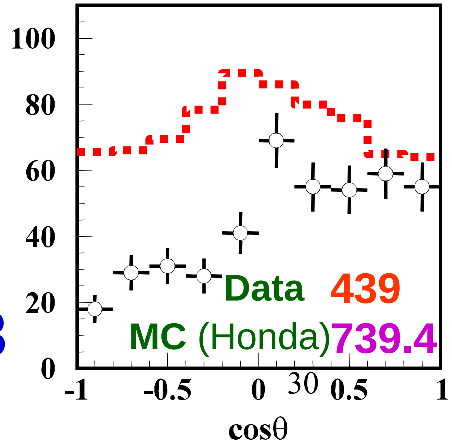
Sub GeV Multi ring (μ)



Multi GeV+PC

$$\frac{(\mu / e)_{data}}{(\mu / e)_{MC}} = 0.699 {}^{+0.032}_{-0.030} \text{ (stat.)} \pm 0.083 \text{ (syst.)}$$

Multi GeV Multi ring (μ)



Summary of the atmospheric ν events
2.up-going μ events

(complete SK-I dataset)

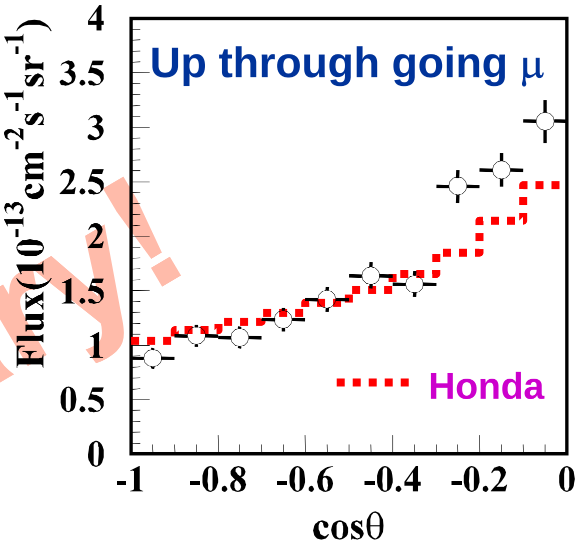
Up through going μ

Measured flux

$$1.70 \pm \underset{\text{(stat.)}}{0.02} \pm \underset{\text{(syst.)}}{0.04} \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

Theoretical calc. (Honda)

$$1.57 \pm \underset{\text{(theo.)}}{0.35} \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



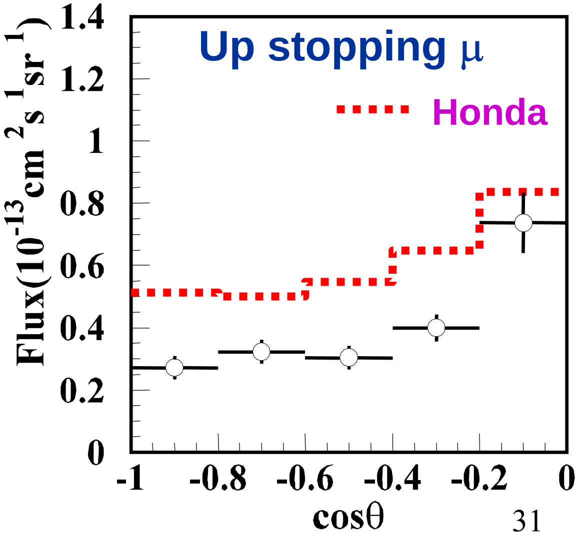
Up stopping μ

Measured flux

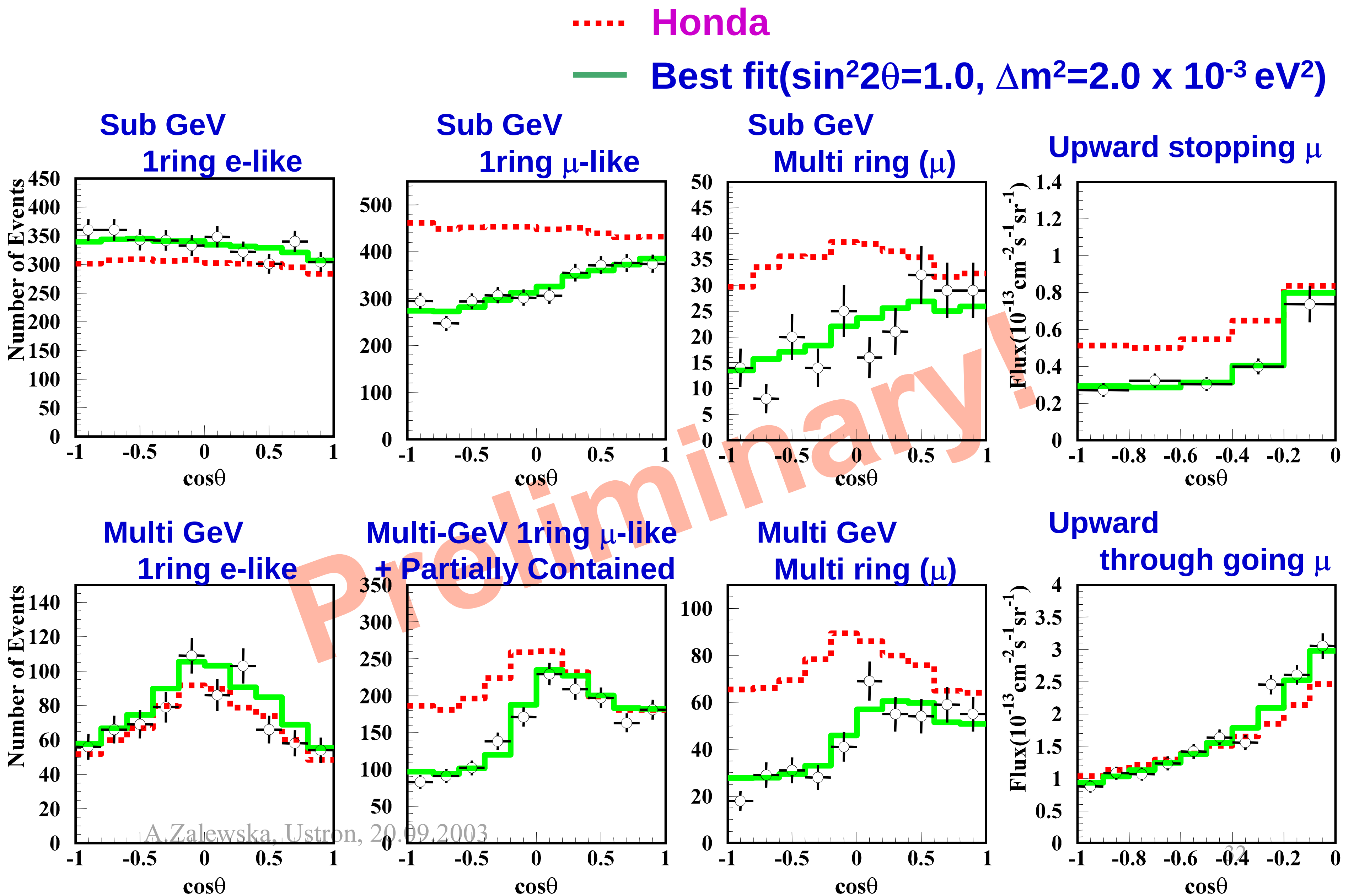
$$0.41 \pm \underset{\text{(stat.)}}{0.02} \pm \underset{\text{(syst.)}}{0.02} \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

Theoretical calc. (Honda)

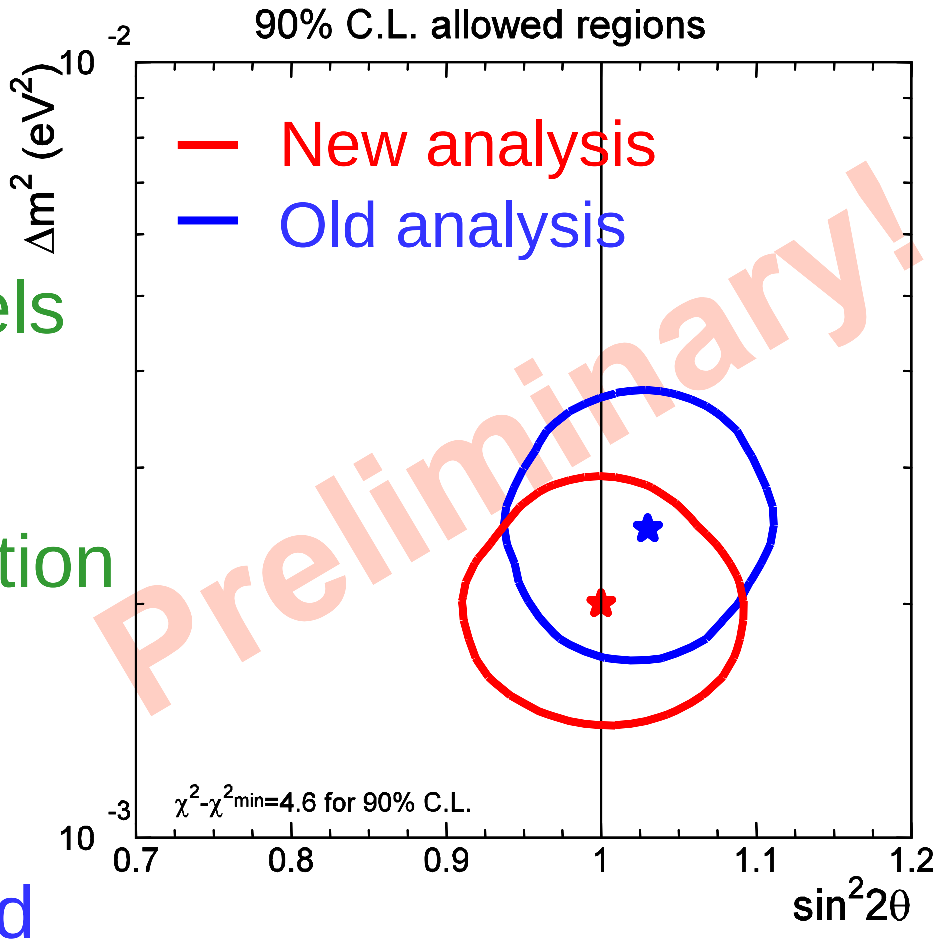
$$0.61 \pm \underset{\text{(theo.)}}{0.14} \times 10^{-13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



Atmospheric ν zenith angle distribution



Comparison between old and new results **from atmospheric ν data**



- Neutrino flux

  (Honda 1995 → Honda 2001)

- Neutrino interaction models

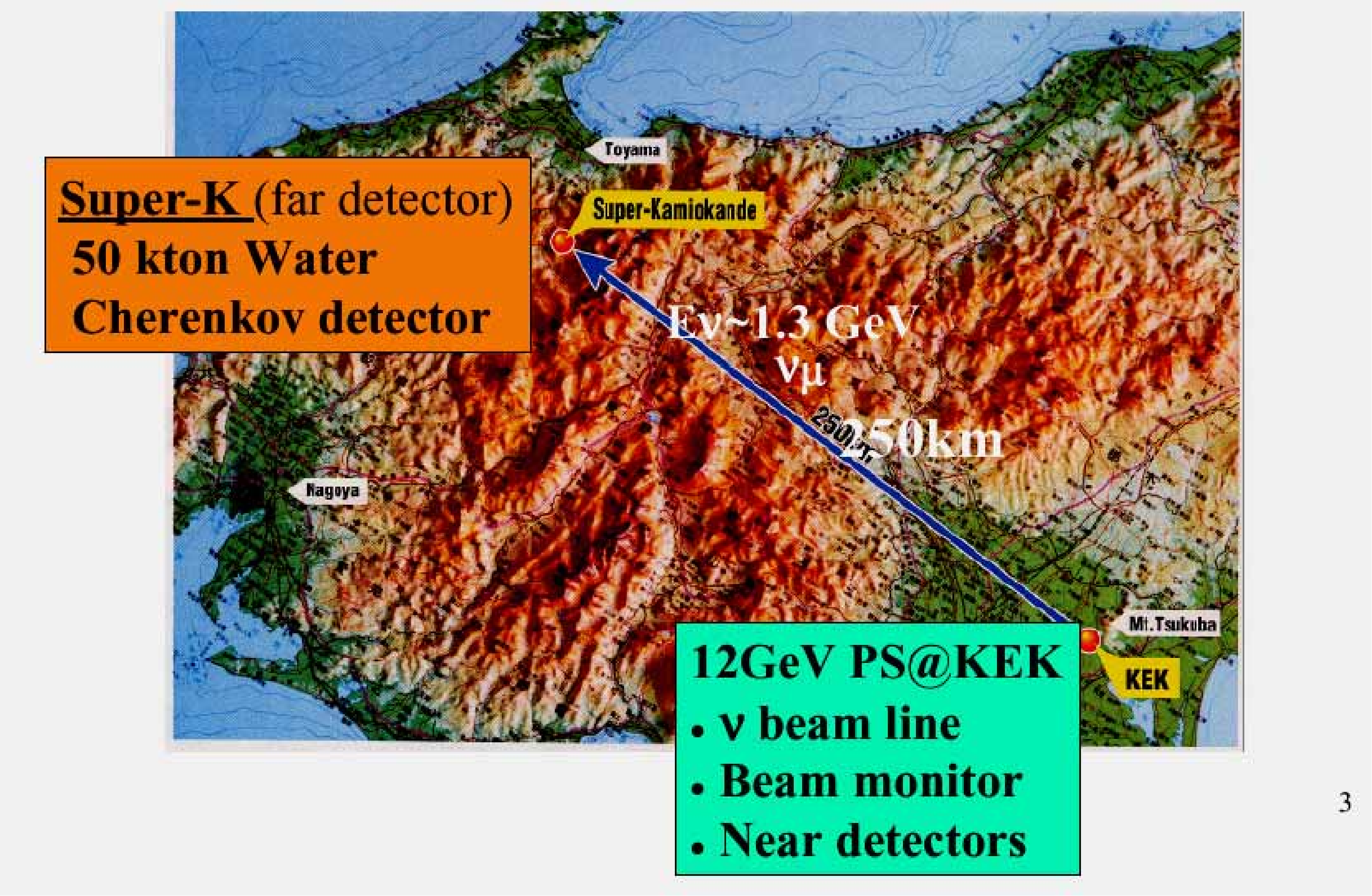
  (several improvements,
  agree with K2K near data)

- Improved detector simulation

- Improved event reconstruction tools

Each change slightly shifted the allowed region to lower Δm^2

K2K - first LongBaseLine accelerator experiment



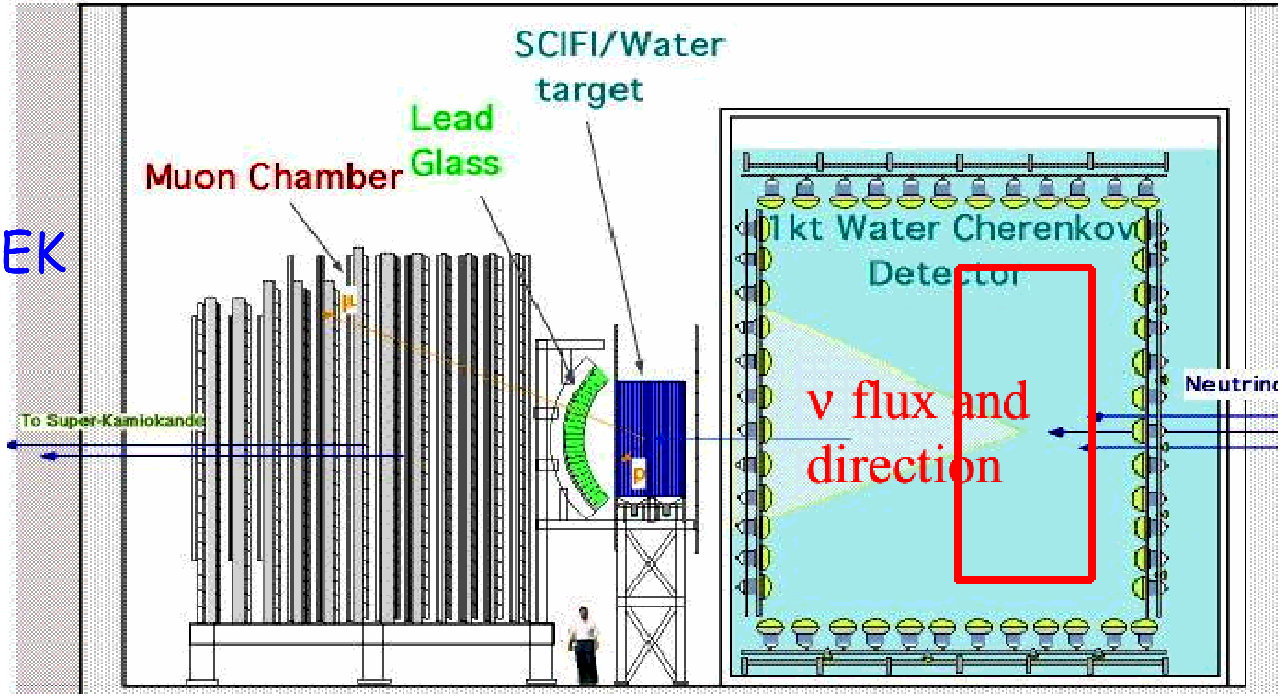
Super-K (far detector)
50 kton Water
Cherenkov detector

12GeV PS@KEK
- **ν beam line**
- **Beam monitor**
- **Near detectors**

$< E_{\nu} > \sim 1.3\text{GeV}$
almost pure $\nu_{\mu} (\sim 98\%)$

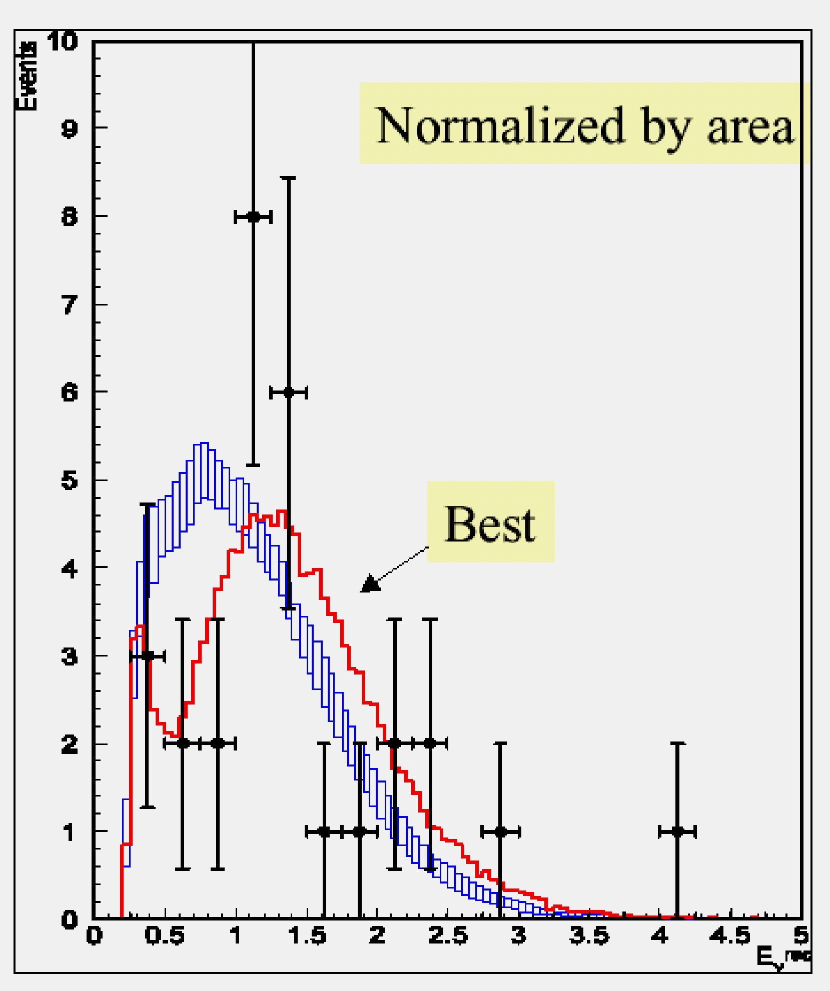
K2K - measurement principle

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 I - measurement results



- **Flux desappearance:**
56 events observed
80.1+6.2-5.4 expected
- **Modification of the energy spectrum**
- **Oscillation parameters compatible with the SuperK results for atmospheric oscillations**

Δm^2=**1.5~3.9 x 10^{-3}** eV^2 @$\sin^2 2\theta=1$(90%CL)

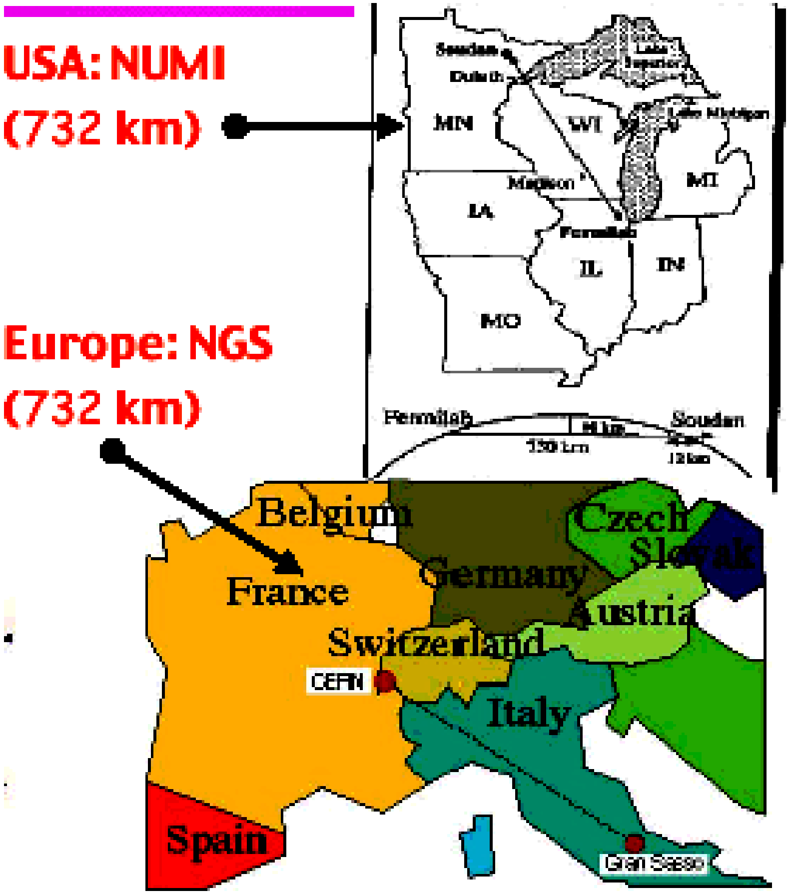
A.Zalewska, Ustron, 20.09.2003

Long BaseLine accelerator projects

In realisation:

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

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



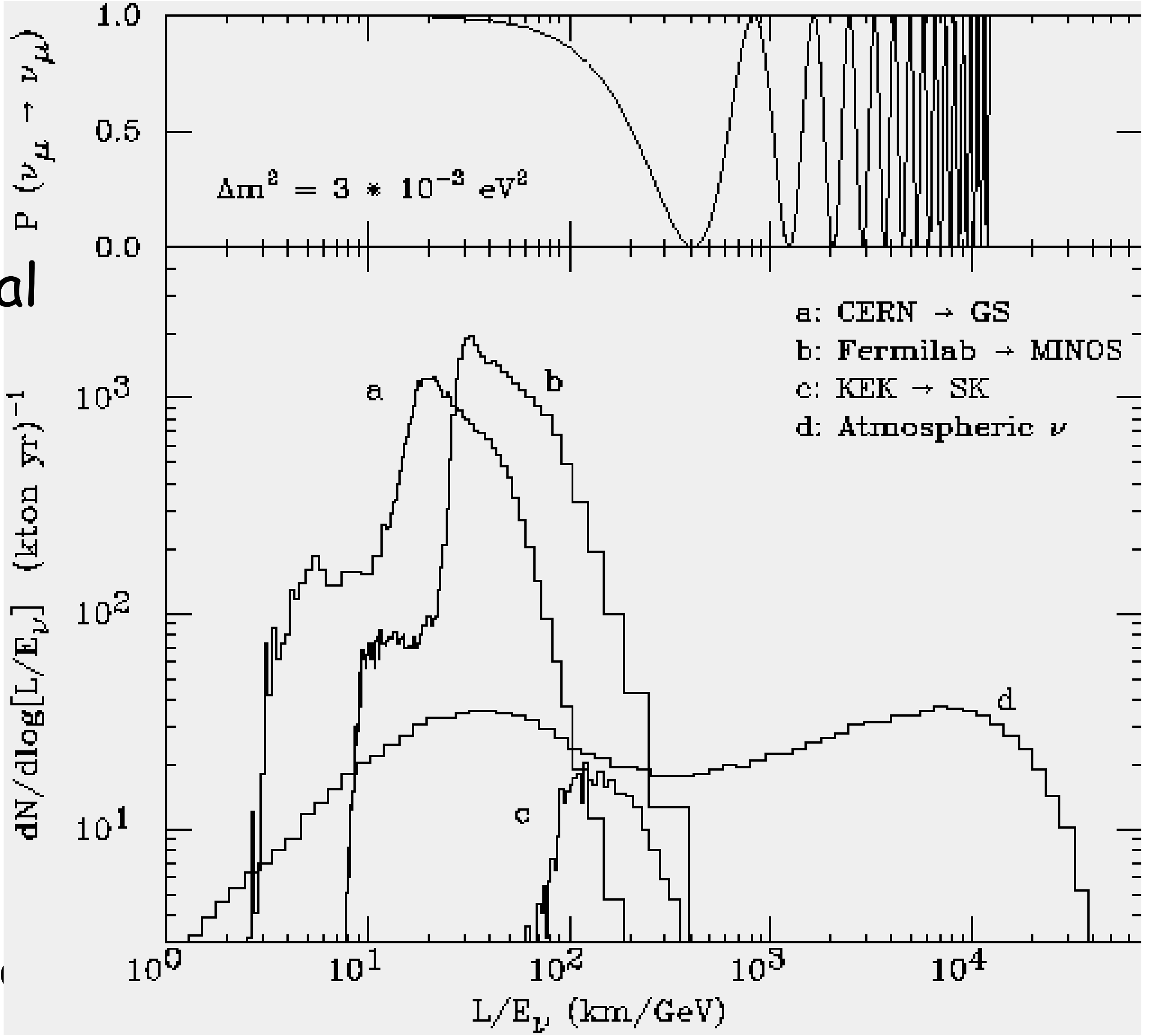
USA: NUMI (732 km)

Europe: NGS (732 km)

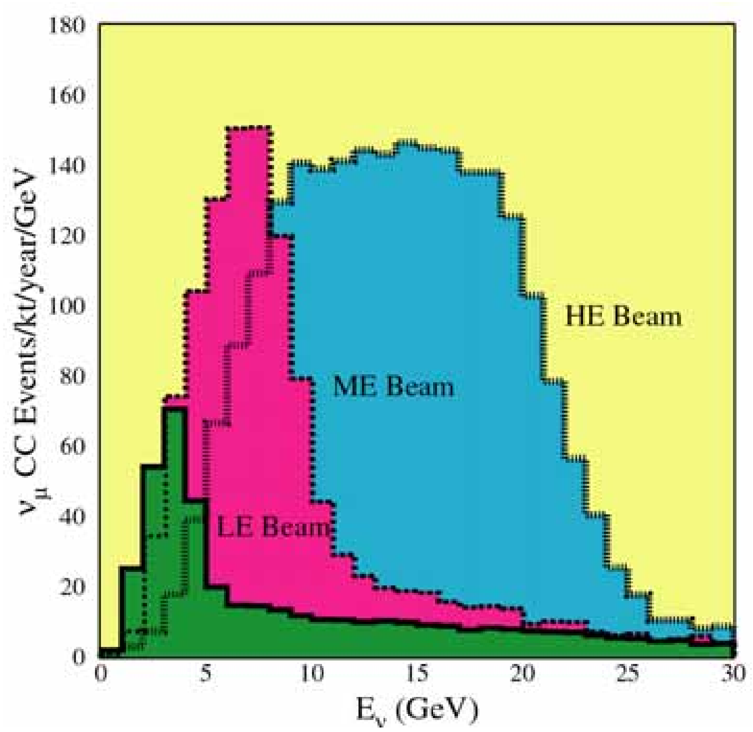
A.Zalewska, Ustron, 20.09.2003

Long BaseLine accelerator projects

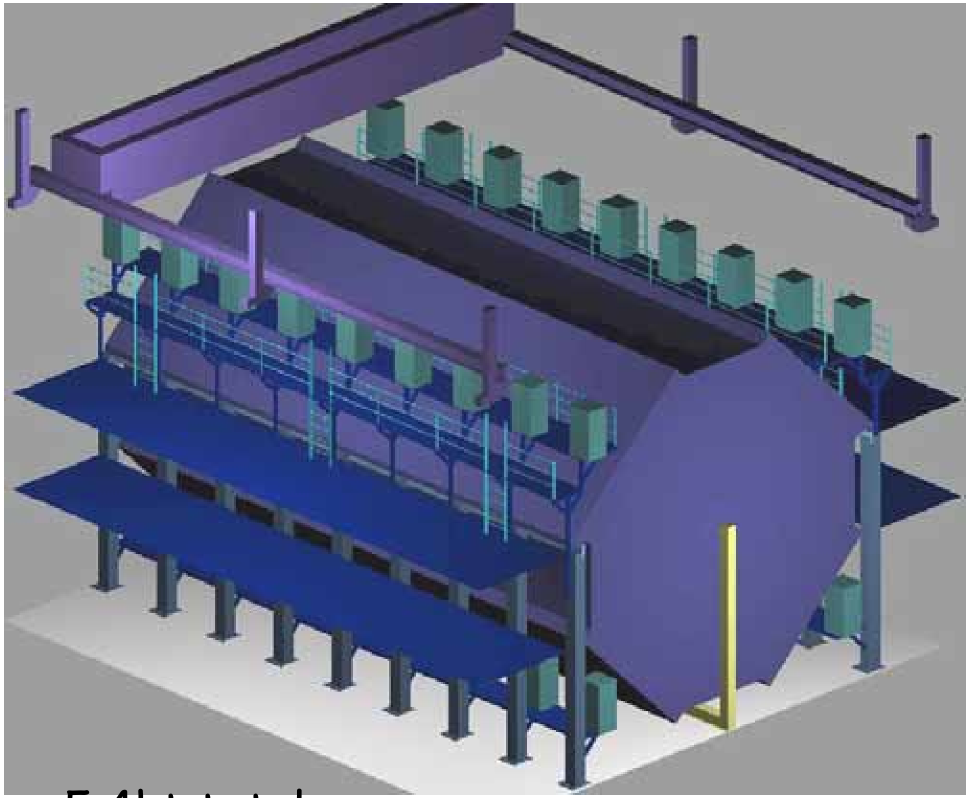
Optimisation
of the experimental
setup:



MINOS experiment



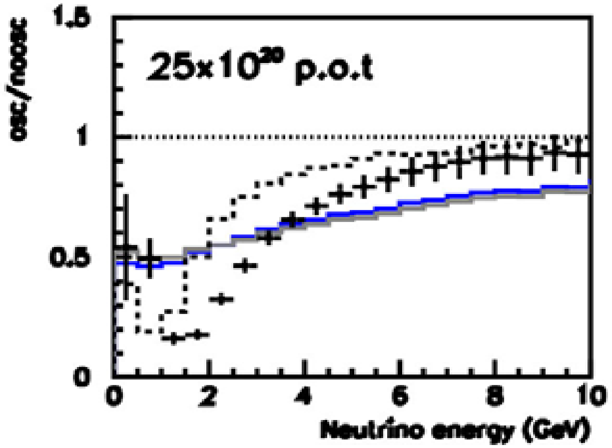
NuMi beams

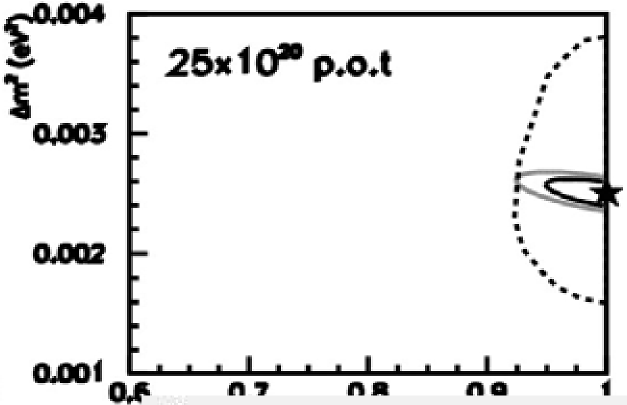


- 5.4kt total
  - 484 planes in two ~14.5m long "super modules", each plane 8m octagon
  - 2.54cm Fe, 1cm Scintillator
  - ~1.5T Magnetic field

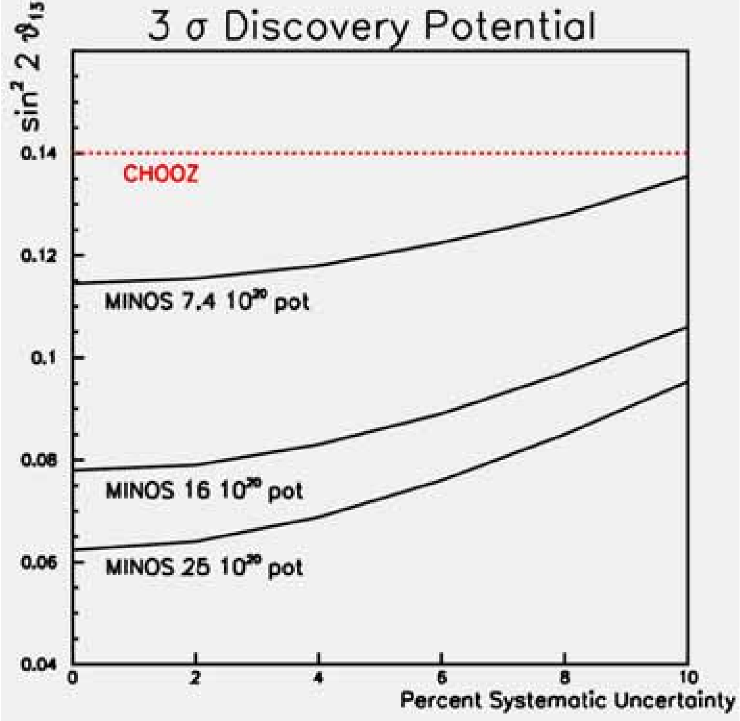
MINOS experiment

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





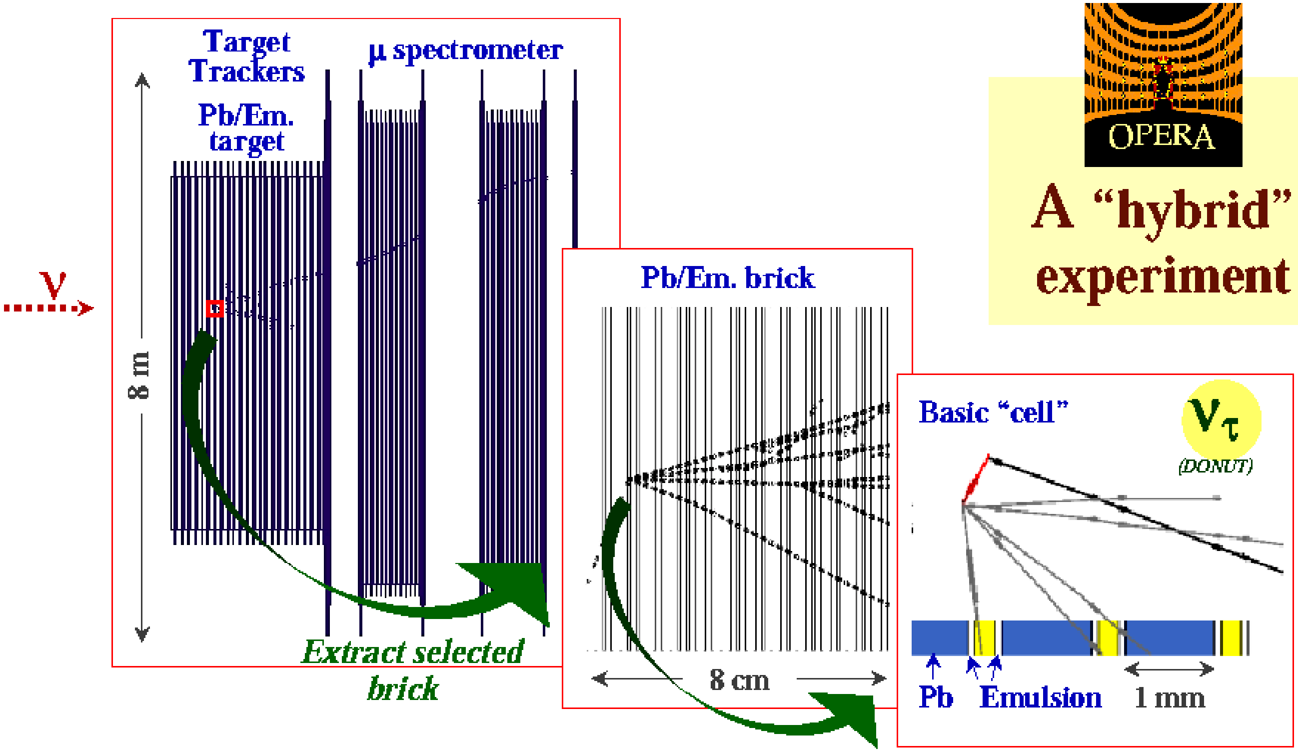
improved Δm^2_{23}



improved θ_{13}

CNGS programme

High energy neutrino beam, optimized for ν_τ appearance
Two experiments: OPERA and ICARUS - small signal with no background



OPERA

A "hybrid" experiment

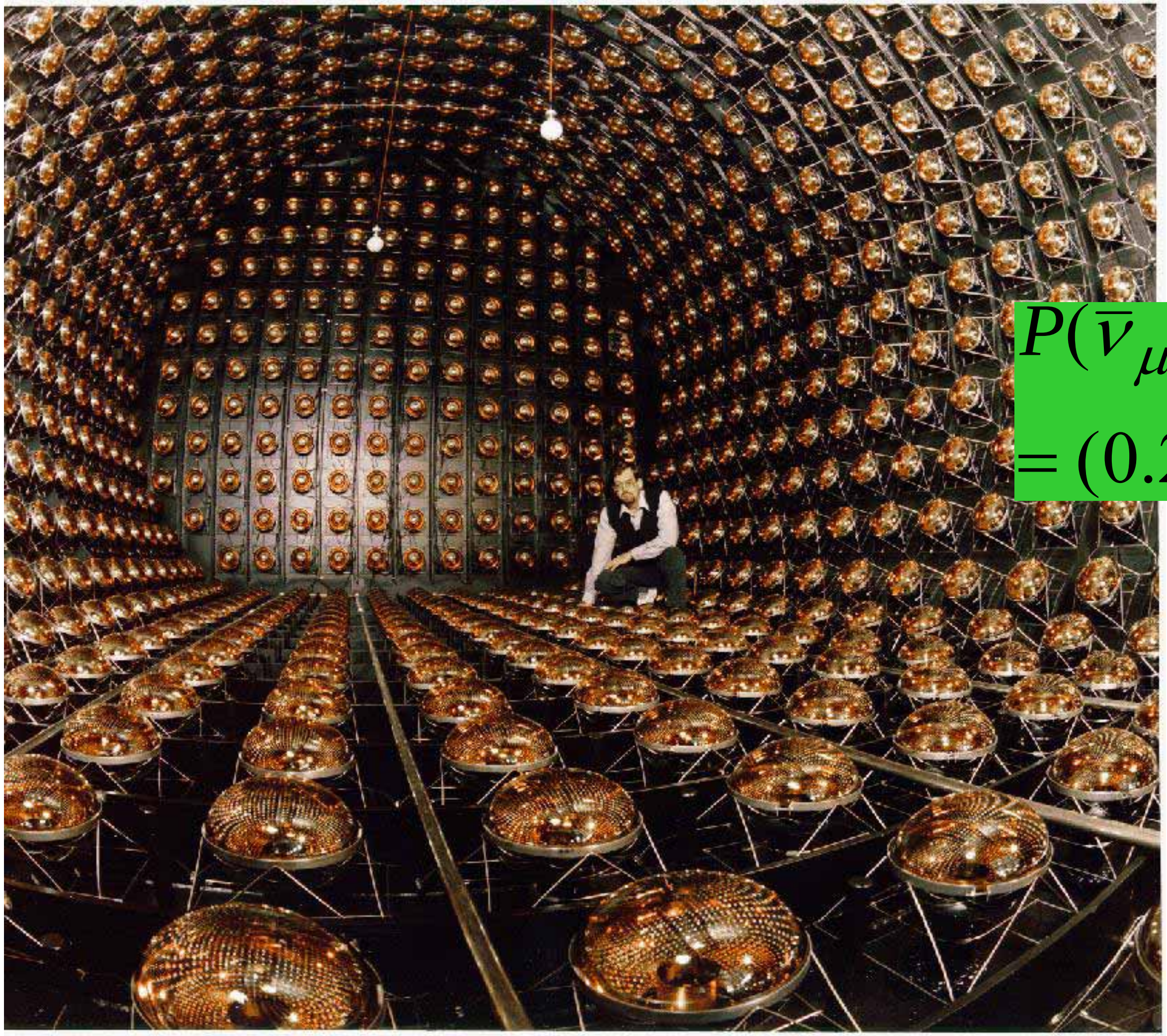
Electronic detectors

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

Emulsion scanning

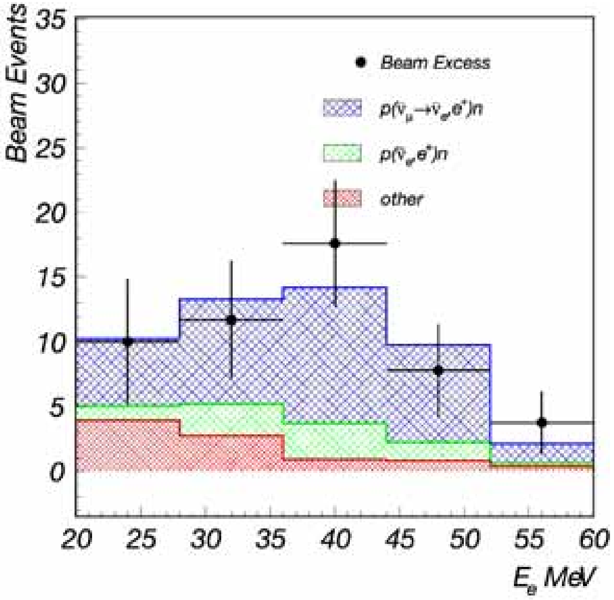
→ vertex search
→ decay search
→ e/γ ID, kinematics

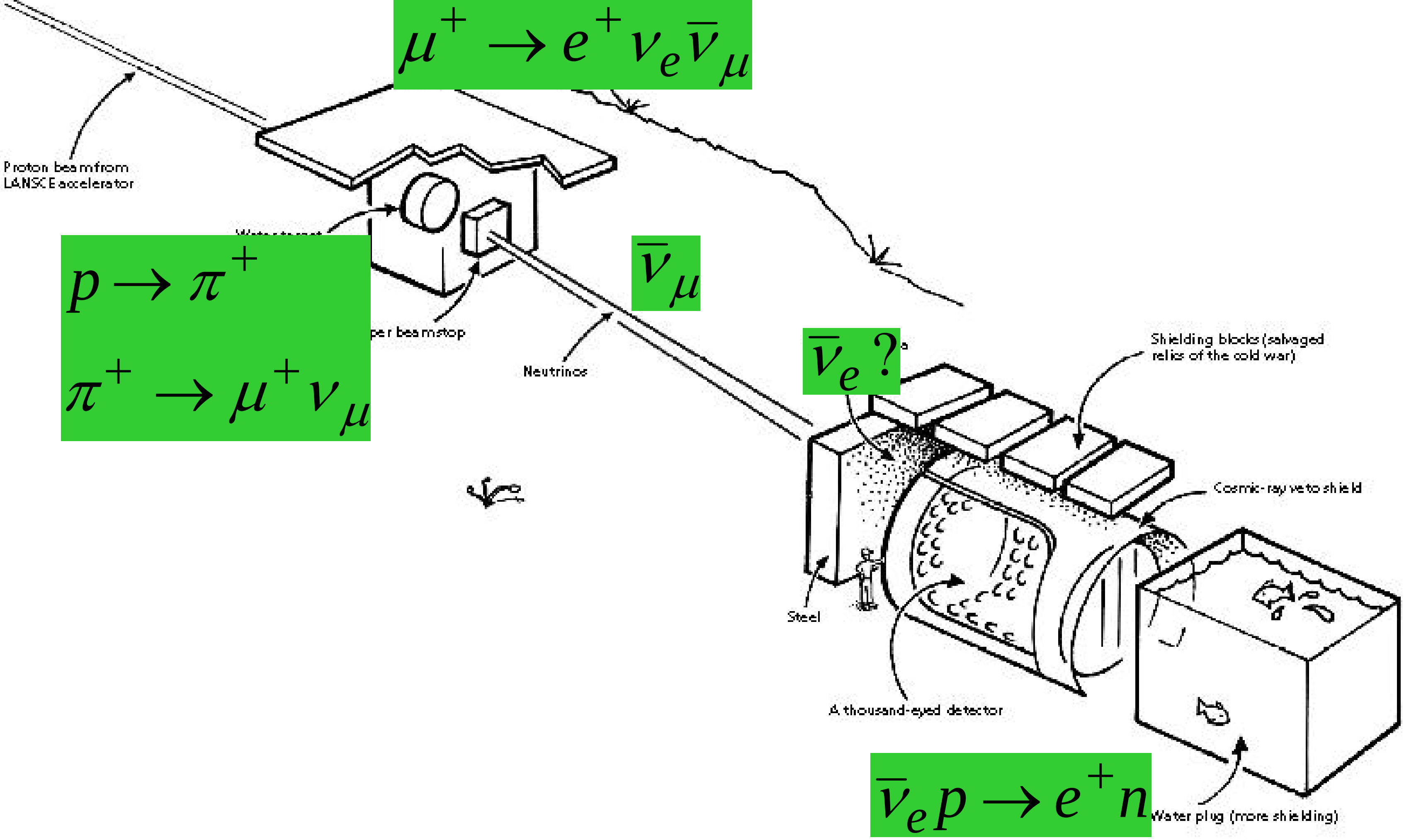
LNSD effect



Excess of positrons above background interpreted as anty-ν$_e$ appearance due to oscillations

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





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

$$p \to \pi^+$$

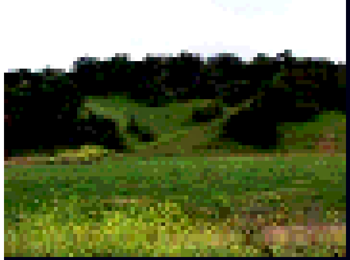
$$\pi^+ \to \mu^+ \nu_\mu$$

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

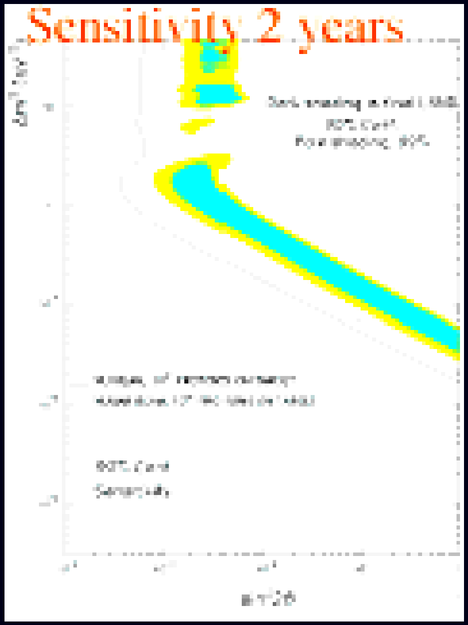
$$\bar{\nu}_e\ ?$$

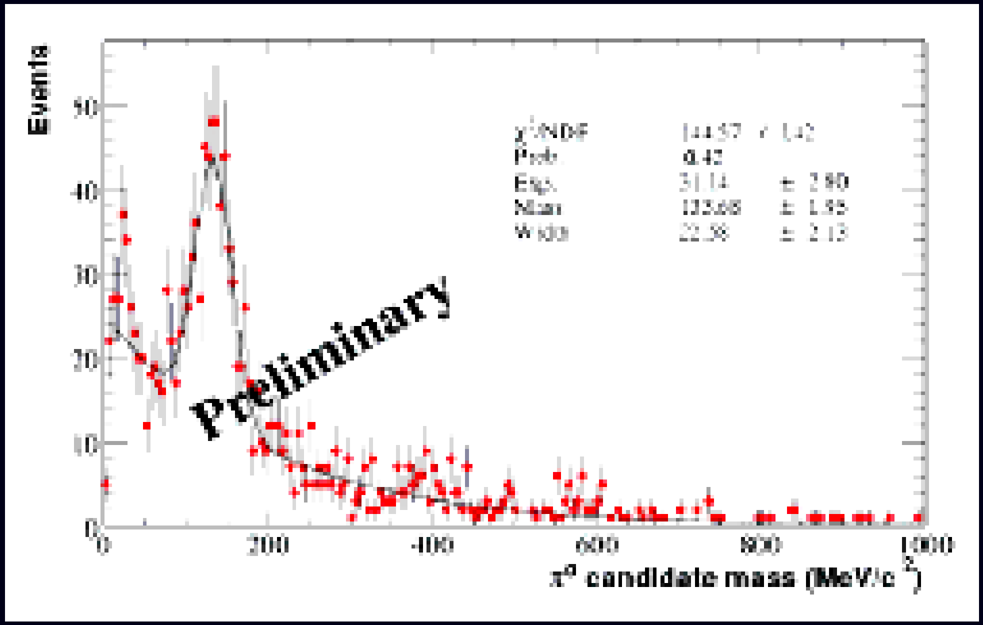
$$\bar{\nu}_e p \to e^+ n$$

- proton beam with momentun 800 MeV, data from 1993-1998, mostly pions at rest
- Efect not confirmed by the KARMEN experiment

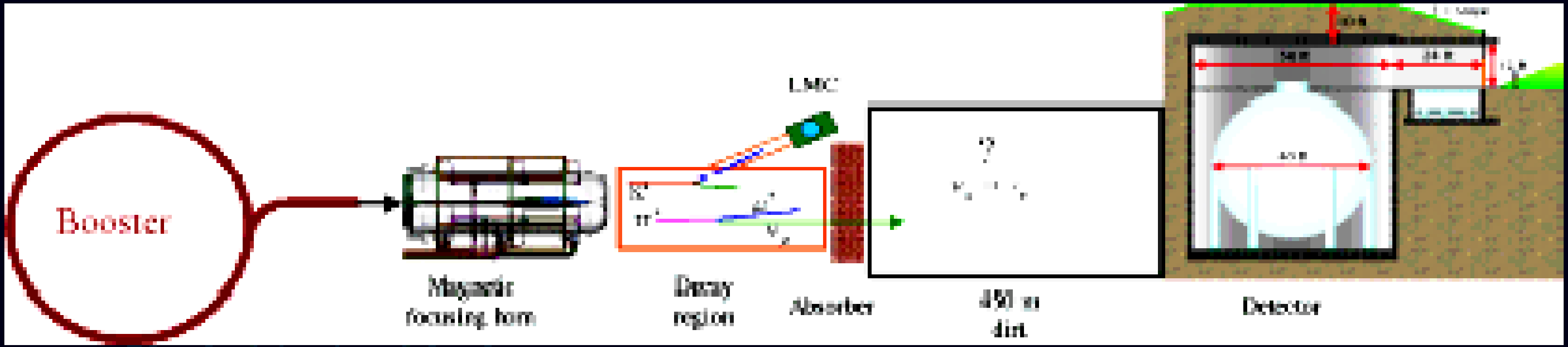


miniBOONE

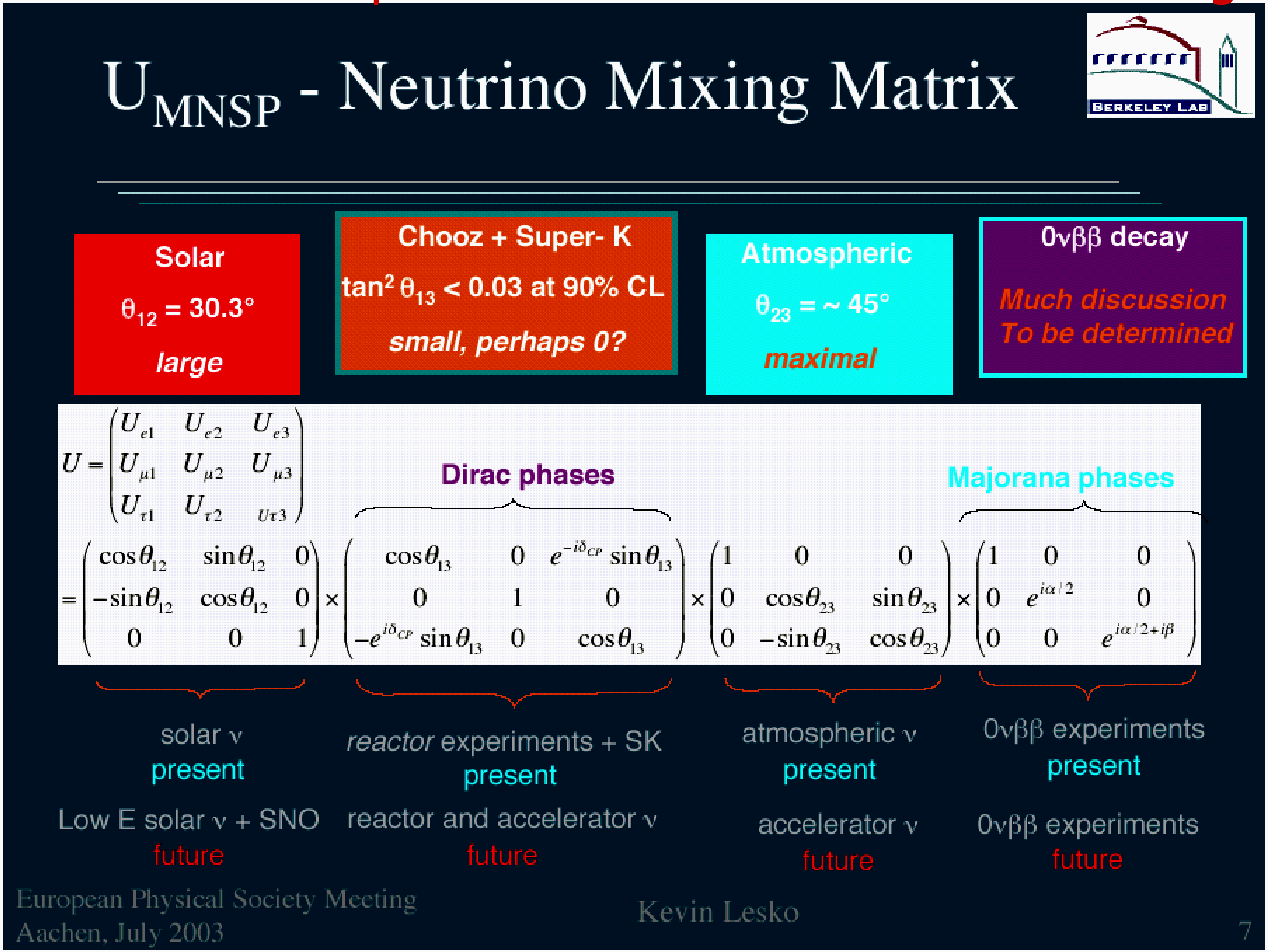




Results:
~ 2005



let us be more professional-three neutrino mixing



U_{MNSP} - Neutrino Mixing Matrix

Solar
$\theta_{12} = 30.3°$
large

Chooz + Super- K
$\tan^2\theta_{13} < 0.03$ at 90% CL
small, perhaps 0?

Atmospheric
$\theta_{23} = \sim 45°$
maximal

0νββ decay
Much discussion
To be determined

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U\tau 3 \end{pmatrix}$$

$$= \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \overbrace{\underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}}^{\text{Dirac phases}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \overbrace{\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}}^{\text{Majorana phases}}$$

solar ν present	*reactor* experiments + SK present	atmospheric ν present	0νββ experiments present
Low E solar ν + SNO future	reactor and accelerator ν future	accelerator ν future	0νββ experiments future

Subdominant oscillation $\nu_\mu - \nu_e$, measurement of θ_{13}

The most important measurement at present:

e.g. CP violation measurement possible, if θ_{13} not too small

Present limit for θ_{13} comes from CHOOZ $\sin_2 2\theta<0.12$

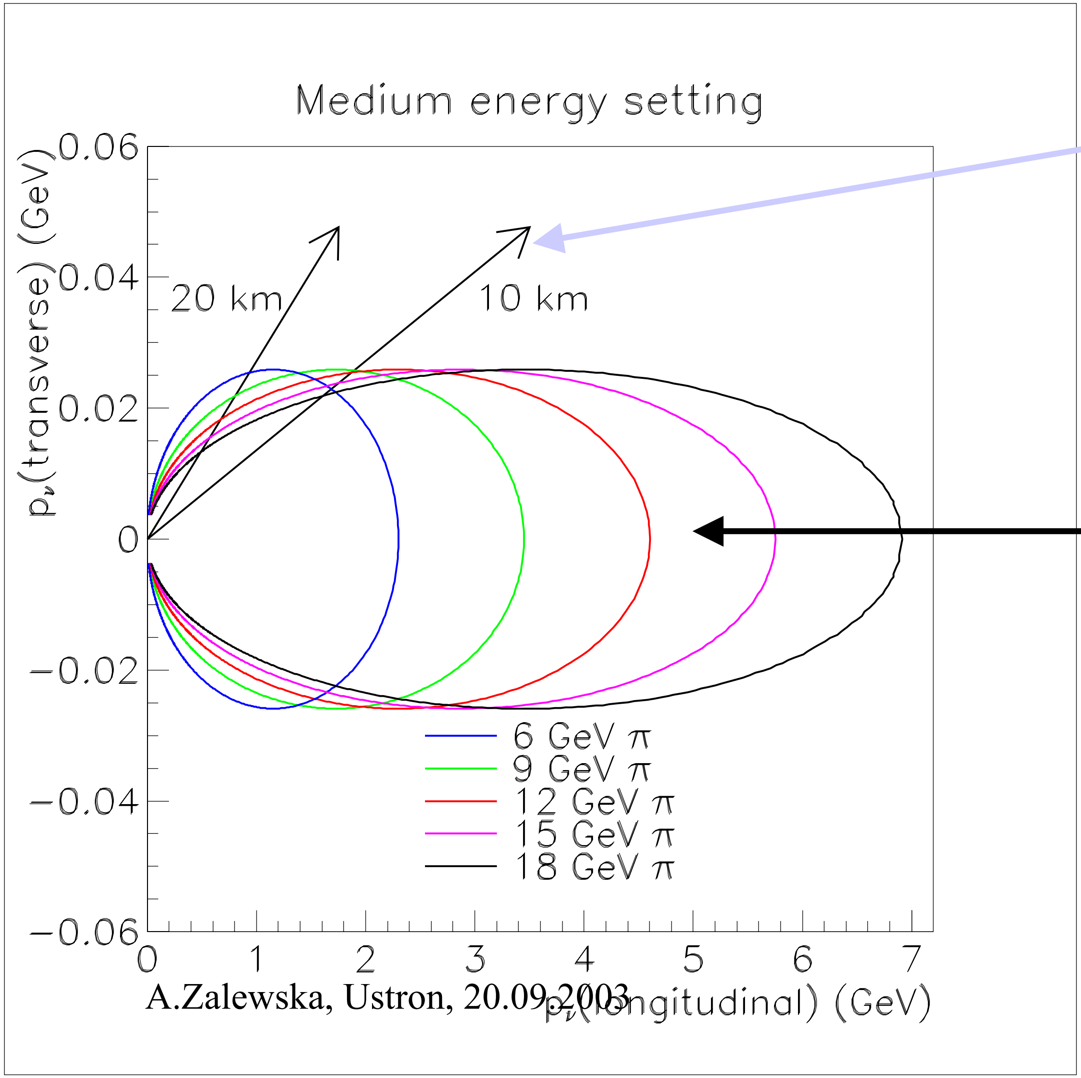
Improved measurements require very massive detectors, intensive neutrino source and reduced background:

NuMi off-axis experiment
JHF (now J-PARC) superbeam - SuperKamiokande
dedicated LBL reactor experiment with two detectors and optimised baseline
eventually LBL experiment at the neutrino factory

Very difficult measurement because depends on other oscillation parameters (->correlations) - dependence is quadratic for some parameters and trigonometric for others (->degeneracies) --> both neutrino and antineutrino beams are needed

NuMi Off-Axis principle

Two body decay kinematics



A.Zalewska, Ustron, 20.09.2003

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

'On axis': $E_n=0.43E_p$

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

Two phase program

Phase I (running 2007 – 2014)

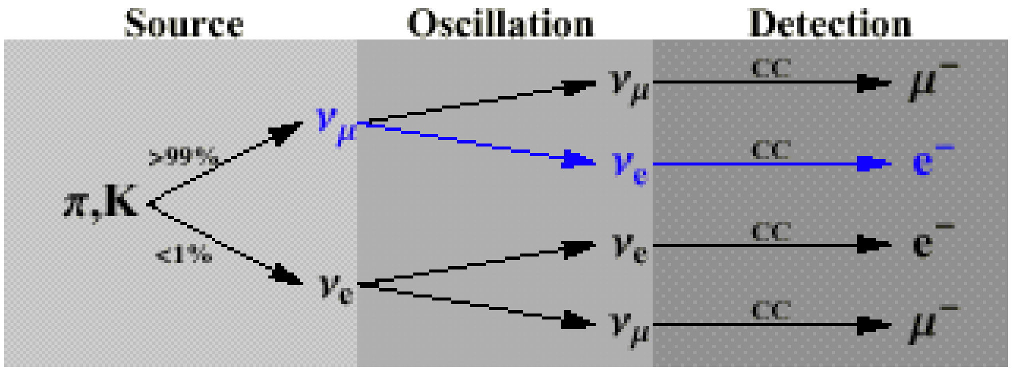
- 50 kton (fiducial) detector with e~40%
- 4x10^{20} protons per year
- 1.5 years neutrino (6000 n_m CC, 70-80% ‘oscillated’)
- 5 years antineutrino (7000 n_m CC, 70-80% ‘oscillated’)

Phase II (running 2014-2020)

- 200 kton (fiducial) detector with e~40% or 100 kton Liquid Argon
- 20x10^{20} protons per year
- 1.5 years neutrino (120000 n_m CC, 70-80% ‘oscillated’)
- 5 years antineutrino (130000 n_m CC, 70-80% ‘oscillated’)

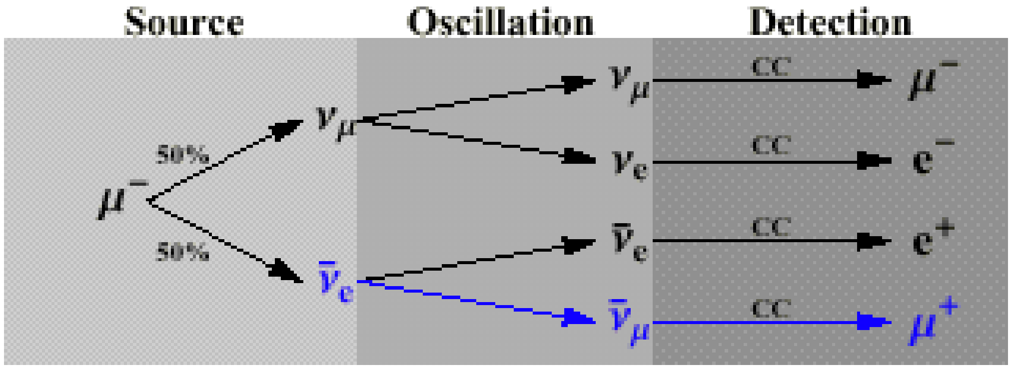
LBL accelerator projects - further future

Superbeams



High intensity
conventional beams

Neutrino Factories



New type
of accelerator

Next generation LBL experiments in Japan
"J-PARC - Kamioka neutrino project"

First superbeam

Baseline ~295km

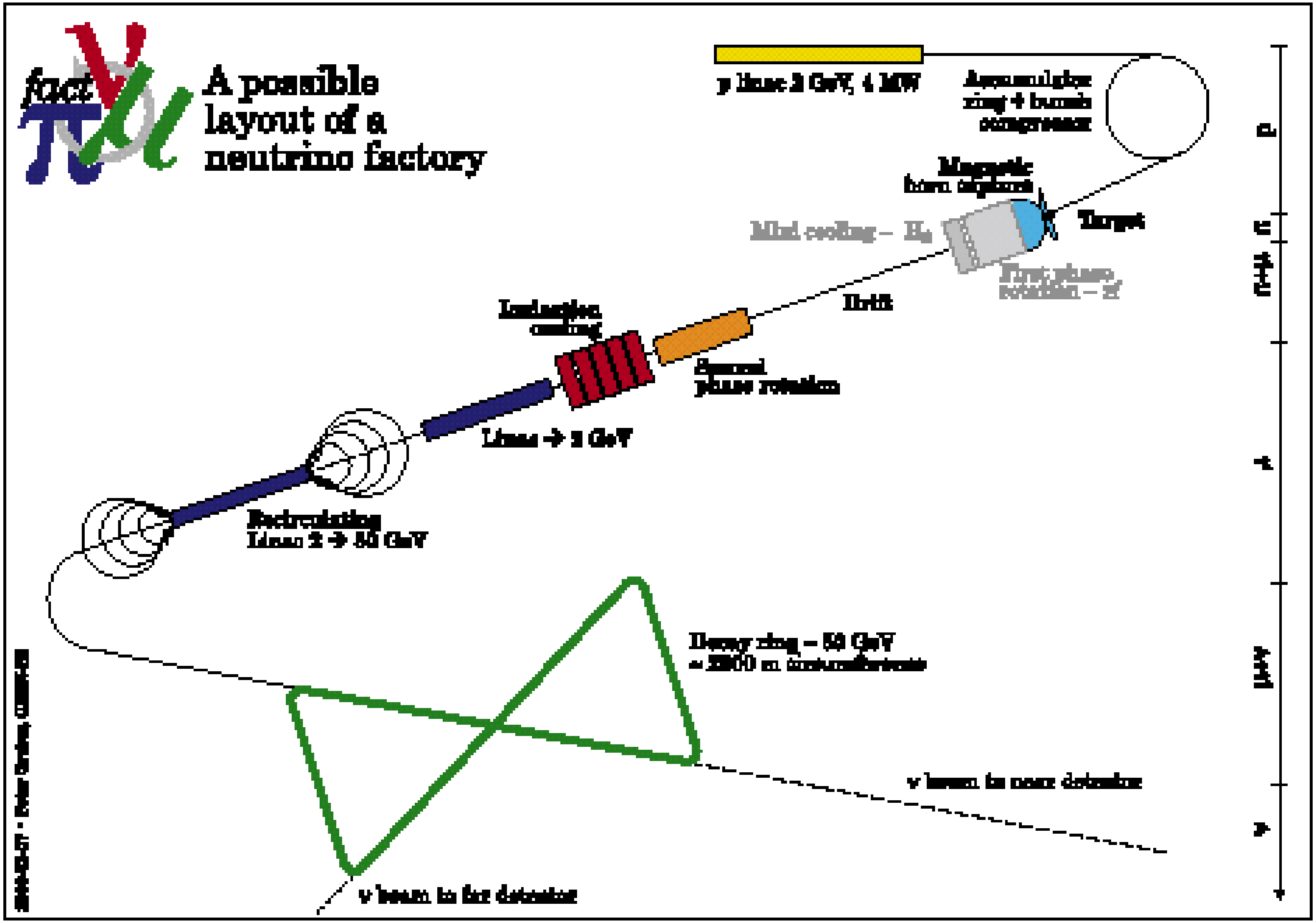
Conventional ν_μ beam

Beam Energy ~1GeV

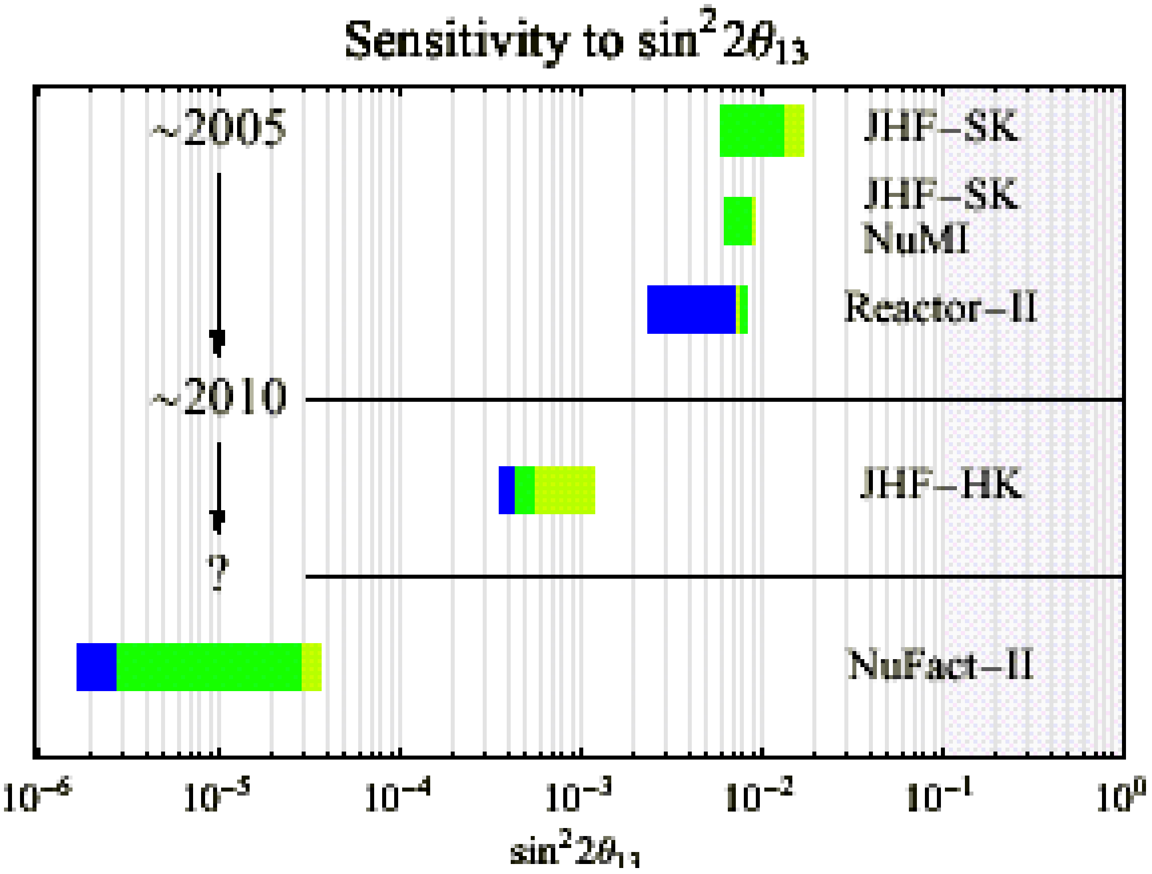
→ Will be adjusted to the oscillation maximum

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

CERN concept of the neutrino factory



Sensitivity on the θ_{13} measurement

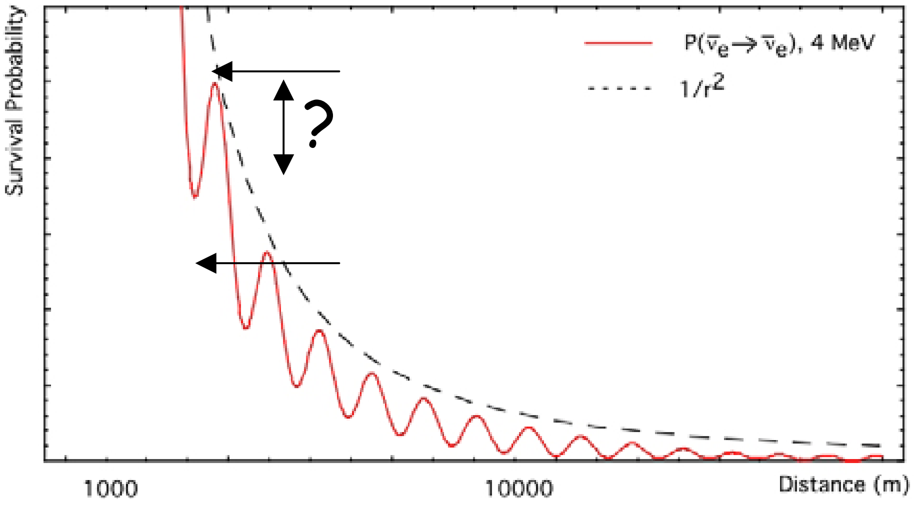


- NuMI and JHF-SK have a similar performance
- JHF-SK and NuMI statistics limited
- JHF-HK systematics limited
- NuFact far away from systematic limit
- correlations and degeneracies require a clever setup

A.Zalewska, Ustron, 20.09.2003

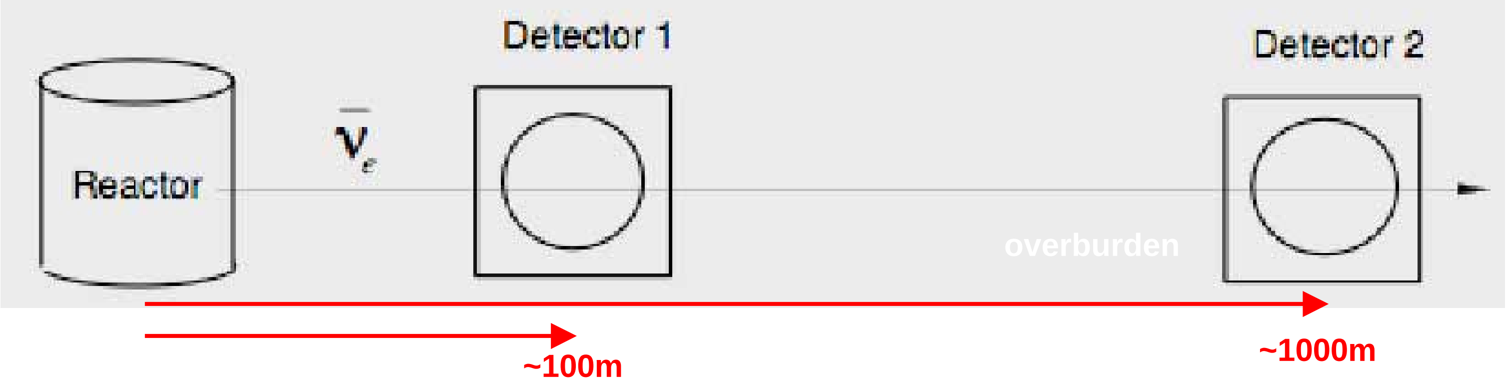
Complementary experiment: Reactors

- 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

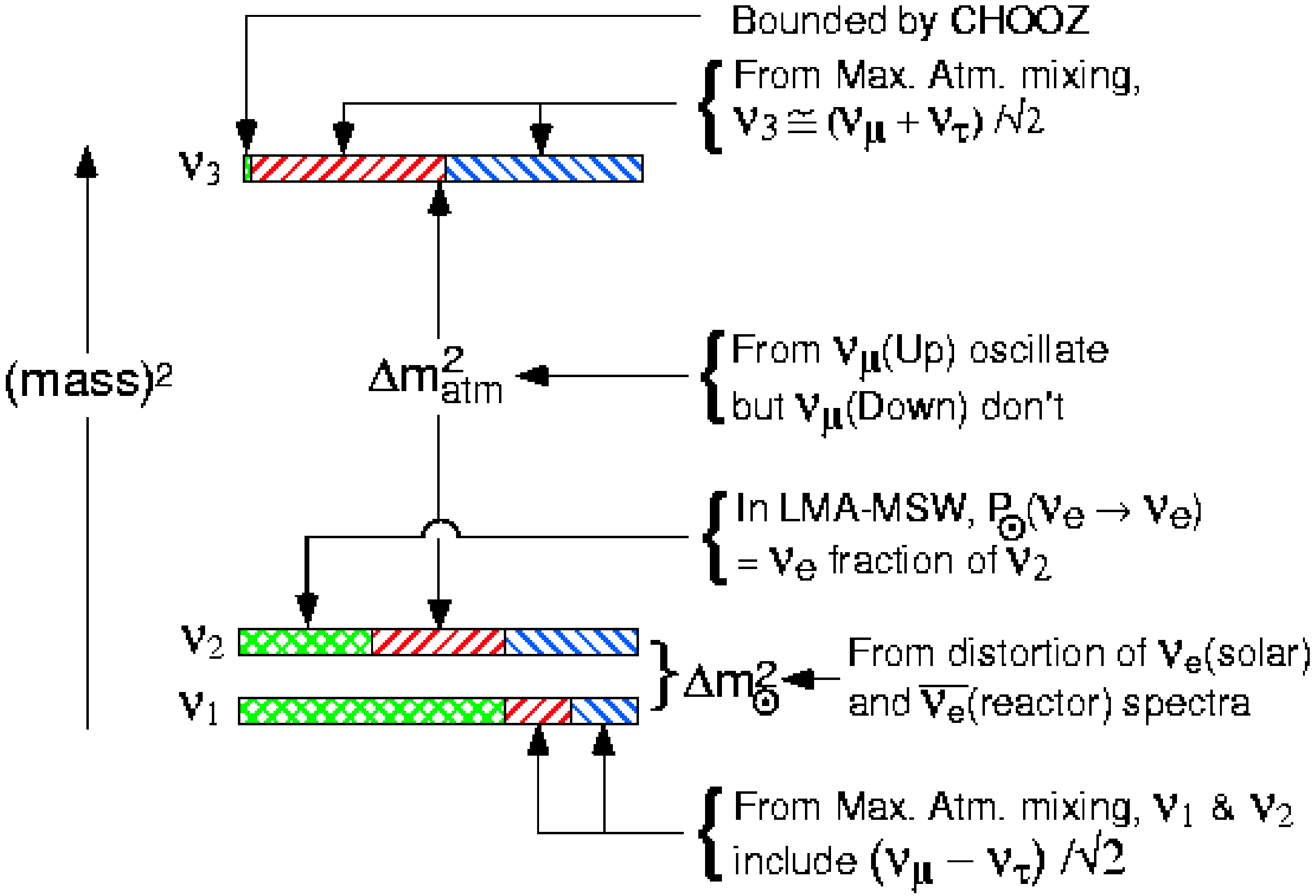


$$1 - P_{\bar{e}\bar{e}} \cong \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(\alpha^2)$$

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



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})

Mass determination

Direct measurements based on end-point in the beta decays

the best measured $m_{\nu e}$ <2.2 eV - from the end-point of the tritium beta decay by the Mainz and Tritsk experiments
future: KATRIN experiment with a sensitivity of 0.2 eV

Cosmological limits

resent cosmic microwave background measurements by the Wilkinson Microwave Anisotropy Probe (WMAP) together with earlier infrared servey experiment (2dF) give an upper limit of 0.71 eV for a sum of neutrino masses, hence 0.23 eV for a single neutrino.

Based on the lifetime measurements for the neutrinoless double beta decays

several experiments running or being prepared with an ultimate goal of achieving an accuracy of 0.01 eV

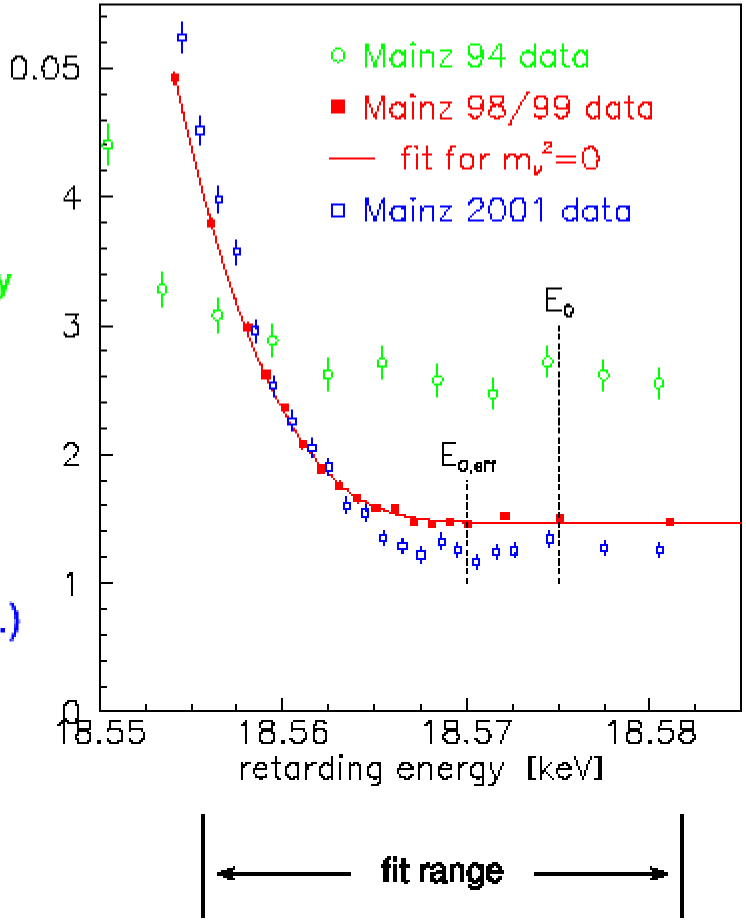
Mass determination from the ^{3}T endpoint

Ch.Kraus@EPS2003

- final analysis 6 data sets (119 days of data taking)
- no indication for disturbancies, especially no Troitsk anomaly
- 2001 low and stable background due to carful preparation
- standard analysis of data 98/99/01:

$$m_\nu^2 c^4 = -1.2 \pm 2.2_{stat} \pm 2.1_{sys}\ \mathrm{eV}^2$$

$$\Rightarrow m_\nu c^2 \leq 2.2\ \mathrm{eV} \qquad \text{(95\% C.L., unif. appr.)}$$



(15 weeks

(5.5 weeks

A.Zalewska, Ustron, 20.09.2003

KATRIN -next generation experiment

start of data taking in 2007, big collaboration including Mainz and Troitsk

experimental observable in ß-decay is m_ν^2

aim : improve m_ν by one order of magnitude (2 eV → 0.2 eV)

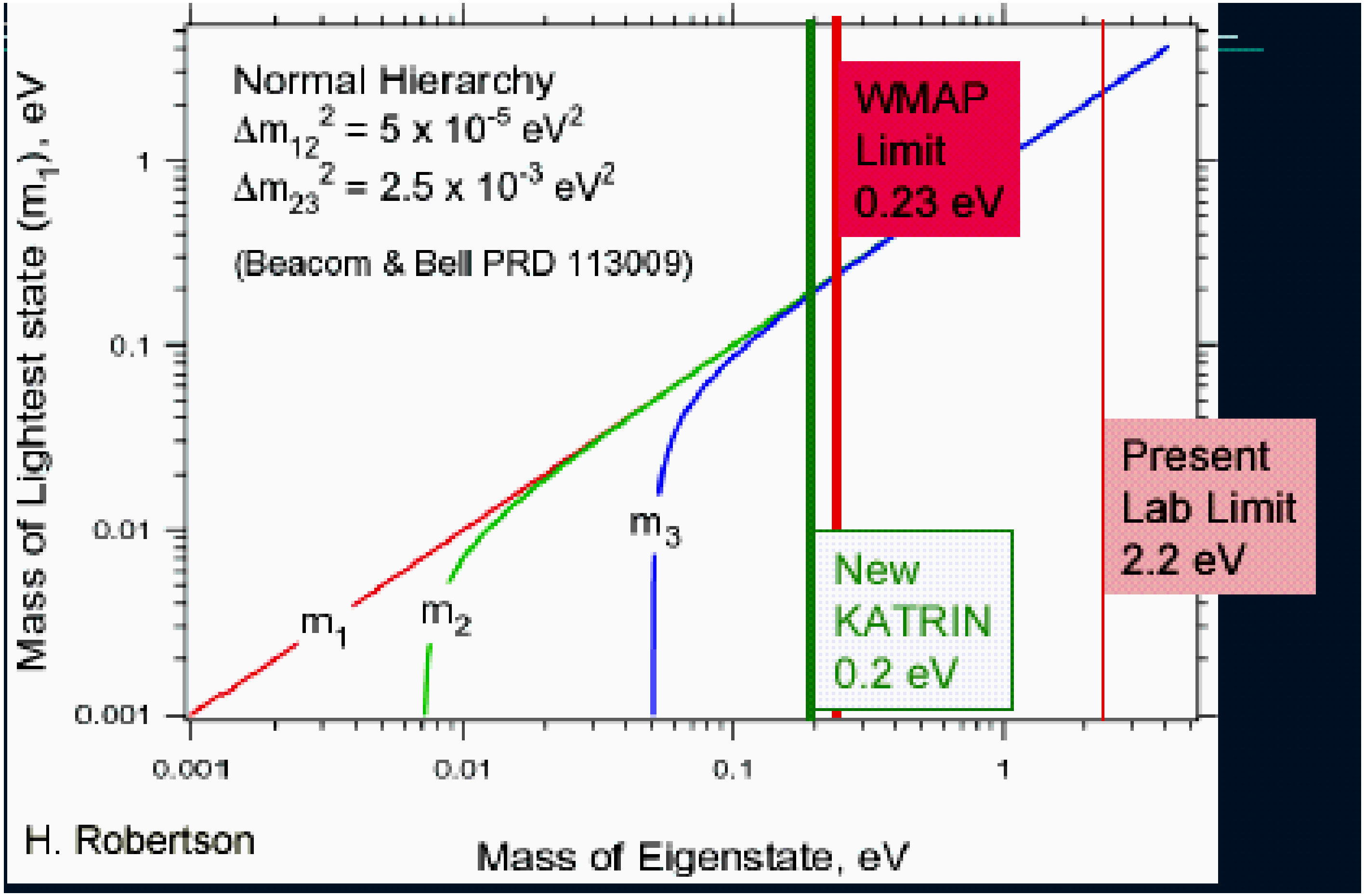
requires : improve m_ν^2 by two orders of magnitude (4 eV^2 → 0.04 eV^2)

problem : count rate close to ß-end point drops very fast ($\sim\delta E^3$)

last 10 eV : 2 x 10^{-10} / last 1 eV : 2 x 10^{-13} of total ß-activity

- **improve statistics :**
- stronger tritium source (factor 80) (& larger analysing plane, Ø=10m)
- longer measuring period (~100 days → ~1000 days)
- **improve energy resolution :**
- large electrostatic spectrometer with ΔE=1 eV (factor 4 improvement)
- **reduce systematic errors :**
- better control of systematics, energy losses (reduce to less than 1/10)

Neutrino mass hierarchies



Effective neutrino mass in tritium beta decay as a function of the lightest neutrino mass

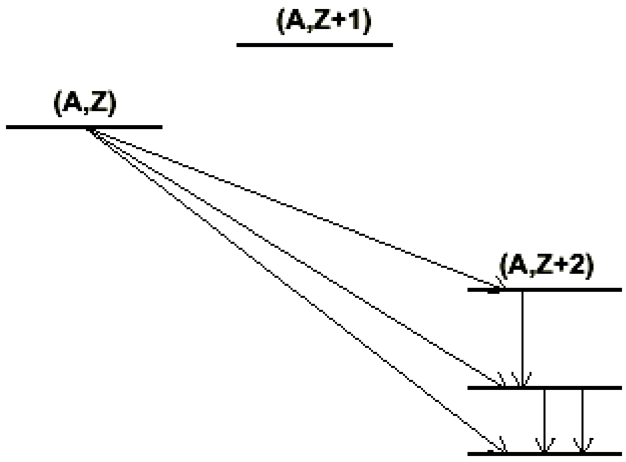
Double beta decay primer

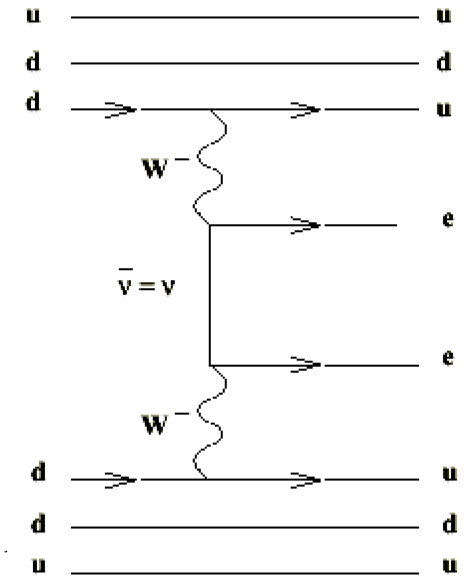
For some even-even nuclei the decay chain

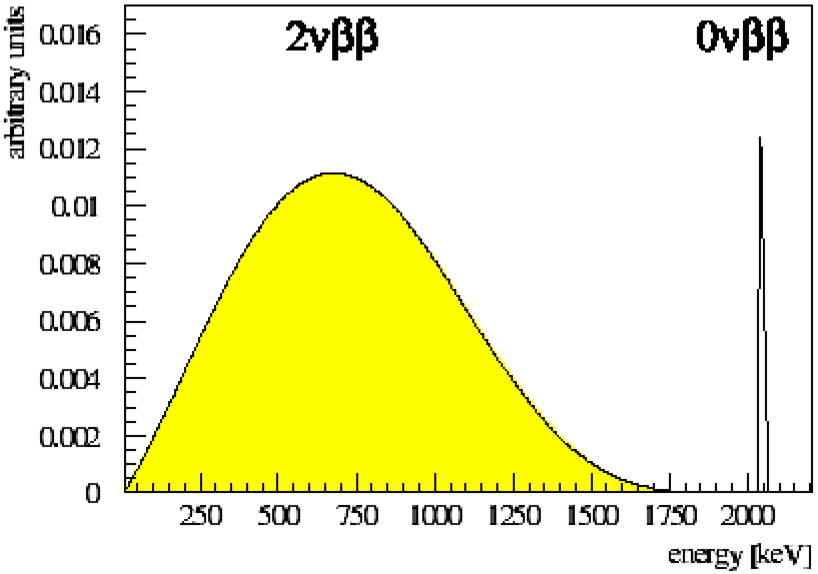
$$(A,Z) \to (A,Z+1) + e^- + \overline{\nu}_e$$
$$\hookrightarrow (A,Z+2) + e^- + \overline{\nu}_e$$

is forbidden by energy conservation and one could have

$$(A,Z) \to (A,Z+2) + 2e^- + 2\overline{\nu}_e$$
$$(A,Z) \to (A,Z+2) + 2e^-$$







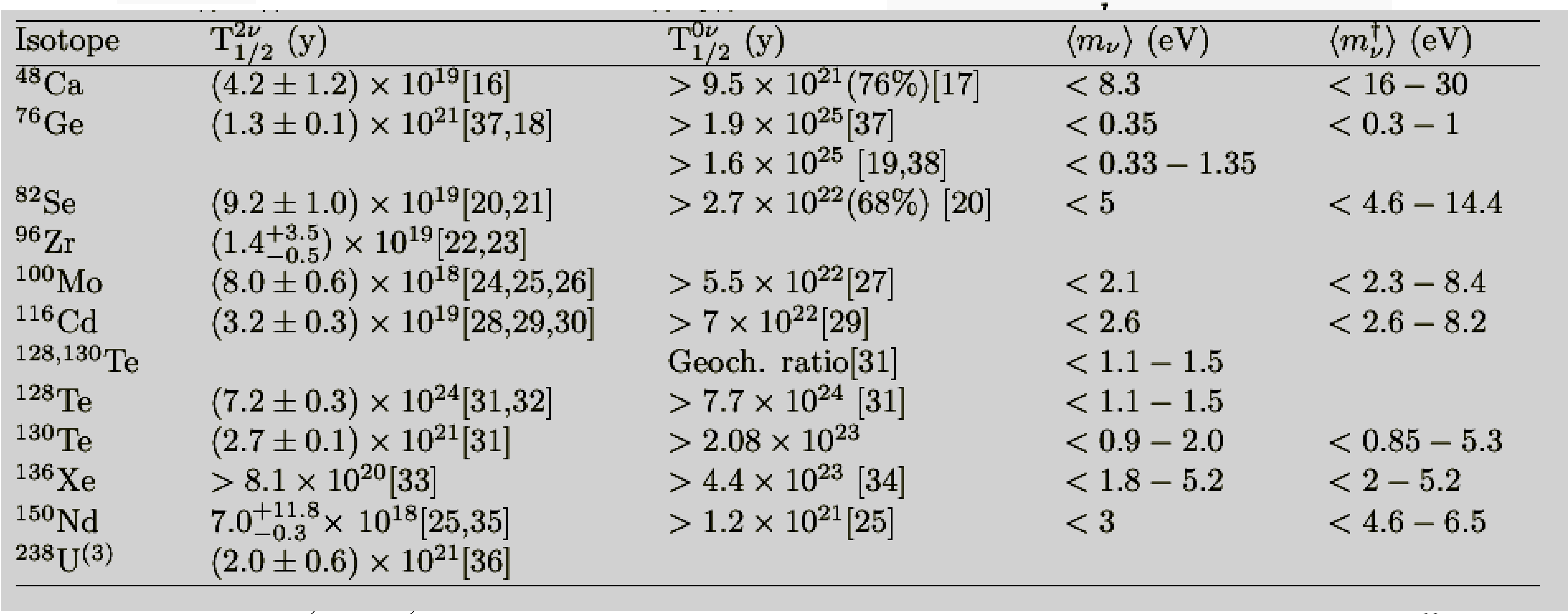
Double beta decay

hep-ex/0210007

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

$|M^{0\nu}|^2$ The nuclear matrix element

$\langle m_\nu\rangle^2$ effective neutrino mass $\langle m_\nu\rangle = \sum \phi_k m_k U^2_{e,k}$

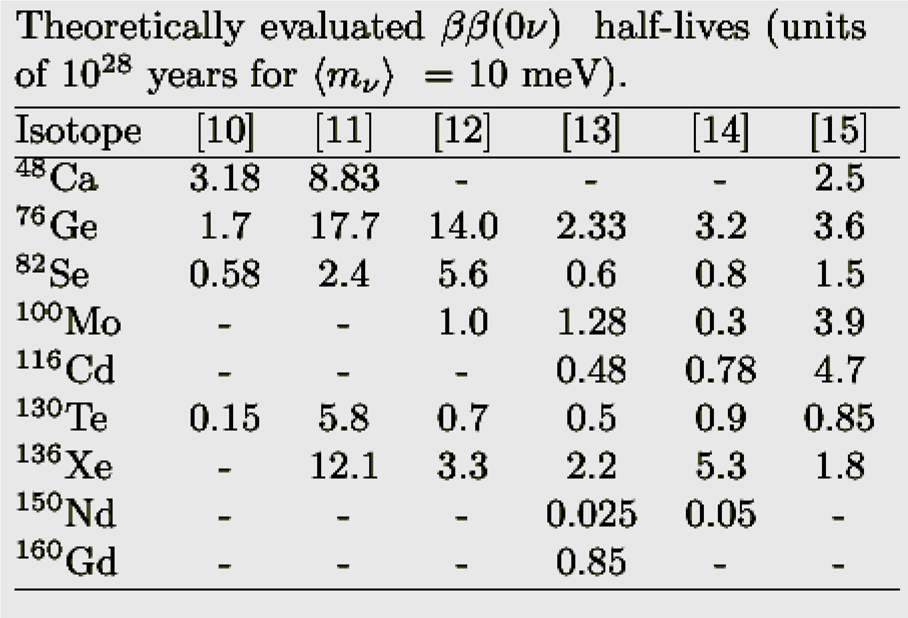


Isotope	$T^{2\nu}_{1/2}$ (y)	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu\rangle$ (eV)	$\langle m^\dagger_\nu\rangle$ (eV)
^{48}Ca	$(4.2 \pm 1.2) \times 10^{19}$[16]	$> 9.5 \times 10^{21}$(76%)[17]	< 8.3	$< 16 - 30$
^{76}Ge	$(1.3 \pm 0.1) \times 10^{21}$[37,18]	$> 1.9 \times 10^{25}$[37]	< 0.35	$< 0.3 - 1$
		$> 1.6 \times 10^{25}$ [19,38]	$< 0.33 - 1.35$	
^{82}Se	$(9.2 \pm 1.0) \times 10^{19}$[20,21]	$> 2.7 \times 10^{22}$(68%) [20]	< 5	$< 4.6 - 14.4$
^{96}Zr	$(1.4^{+3.5}_{-0.5}) \times 10^{19}$[22,23]			
^{100}Mo	$(8.0 \pm 0.6) \times 10^{18}$[24,25,26]	$> 5.5 \times 10^{22}$[27]	< 2.1	$< 2.3 - 8.4$
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$[28,29,30]	$> 7 \times 10^{22}$[29]	< 2.6	$< 2.6 - 8.2$
^{128,130}Te		Geoch. ratio[31]	$< 1.1 - 1.5$	
^{128}Te	$(7.2 \pm 0.3) \times 10^{24}$[31,32]	$> 7.7 \times 10^{24}$ [31]	$< 1.1 - 1.5$	
^{130}Te	$(2.7 \pm 0.1) \times 10^{21}$[31]	$> 2.08 \times 10^{23}$	$< 0.9 - 2.0$	$< 0.85 - 5.3$
^{136}Xe	$> 8.1 \times 10^{20}$[33]	$> 4.4 \times 10^{23}$ [34]	$< 1.8 - 5.2$	$< 2 - 5.2$
^{150}Nd	$7.0^{+11.8}_{-0.3} \times 10^{18}$[25,35]	$> 1.2 \times 10^{21}$[25]	< 3	$< 4.6 - 6.5$
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$[36]			

Double beta decay

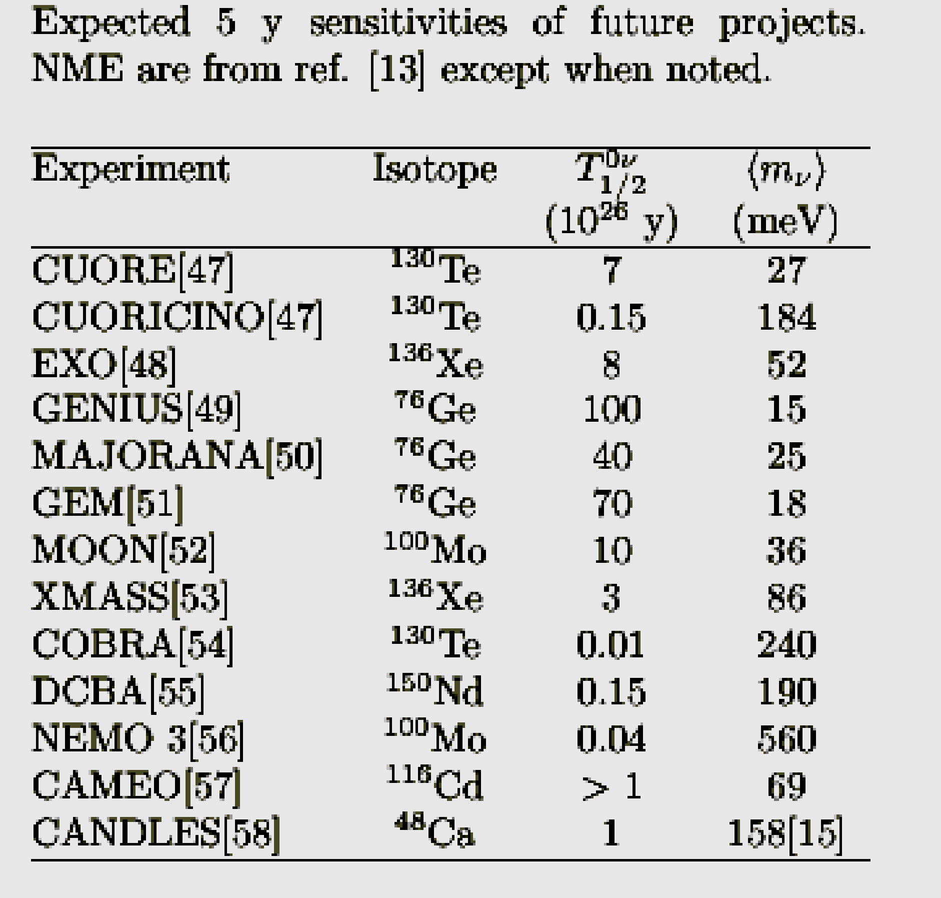
hep-ex/0210007

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$



Theoretically evaluated $\beta\beta(0\nu)$ half-lives (units of 10^{28} years for $\langle m_\nu\rangle = 10$ meV).

Isotope	[10]	[11]	[12]	[13]	[14]	[15]
^{48}Ca	3.18	8.83	-	-	-	2.5
^{76}Ge	1.7	17.7	14.0	2.33	3.2	3.6
^{82}Se	0.58	2.4	5.6	0.6	0.8	1.5
^{100}Mo	-	-	1.0	1.28	0.3	3.9
^{116}Cd	-	-	-	0.48	0.78	4.7
^{130}Te	0.15	5.8	0.7	0.5	0.9	0.85
^{136}Xe	-	12.1	3.3	2.2	5.3	1.8
^{150}Nd	-	-	-	0.025	0.05	-
^{160}Gd	-	-	-	0.85	-	-

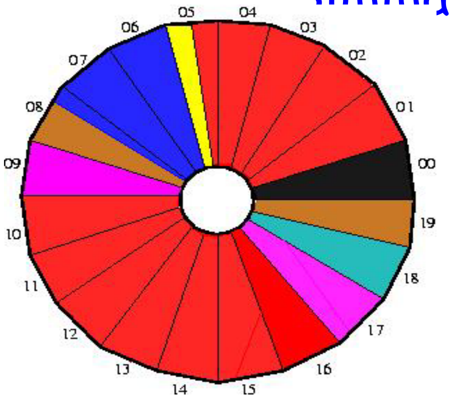


Expected 5 y sensitivities of future projects. NME are from ref. [13] except when noted.

Experiment	Isotope	$T^{0\nu}_{1/2}$ (10^{26} y)	$\langle m_\nu\rangle$ (meV)
CUORE[47]	^{130}Te	7	27
CUORICINO[47]	^{130}Te	0.15	184
EXO[48]	^{136}Xe	8	52
GENIUS[49]	^{76}Ge	100	15
MAJORANA[50]	^{76}Ge	40	25
GEM[51]	^{76}Ge	70	18
MOON[52]	^{100}Mo	10	36
XMASS[53]	^{136}Xe	3	86
COBRA[54]	^{130}Te	0.01	240
DCBA[55]	^{150}Nd	0.15	190
NEMO 3[56]	^{100}Mo	0.04	560
CAMEO[57]	^{116}Cd	> 1	69
CANDLES[58]	^{48}Ca	1	158[15]

NEMO3 experiment as an example

Simmard@EPS2003



7.2 kg ^{100}Mo
1 kg ^{82}Se
0.4 kg ^{116}Cd
0.6 kg ^{130}Te

ββ0ν
,
ββ2ν

1 kg ^{nat}Te
0.6 kg Cu

backgrou
d

48 g ^{150}Nd
20 g ^{96}Zr
7 g ^{48}Ca

ββ2ν
(ββ0ν)

Extremely High Energy neutrinos

Do they exists?

Where do they come from?

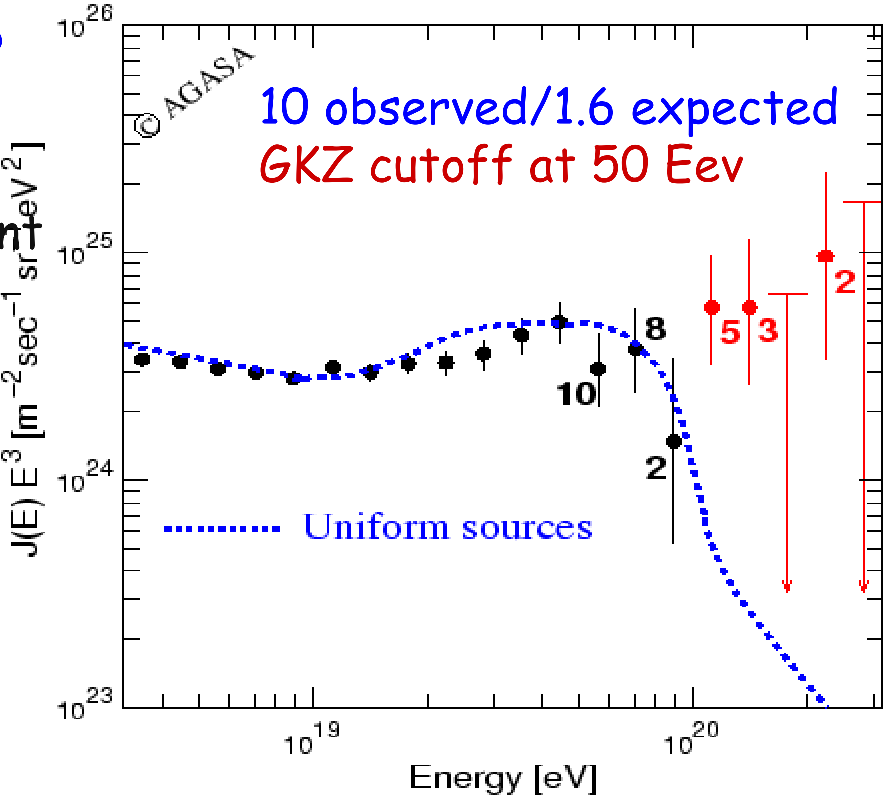
Boosted by the observation of EHE cosmic rays in the AGASA experiment

It is a part of the experimental program realized with big volume detectors (up to 1 km^3) based on a detection of Cherenkov radiation in ice

Amanda, Icecube

or deeply in a sea or lake water

Antares, Nestor, (pioneered by Baikal)



10 observed/1.6 expected

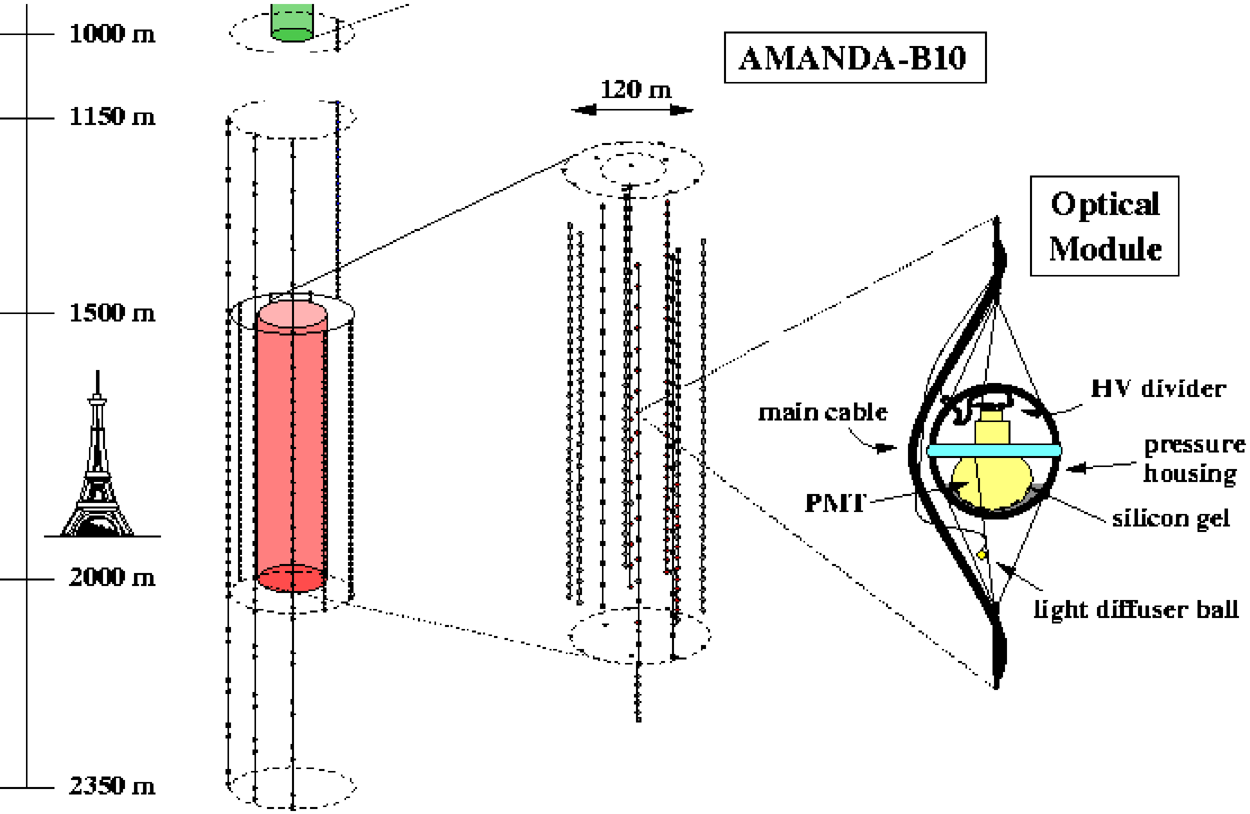
GKZ cutoff at 50 Eev

AMANDA/ICECUBE - Antarctic experiments

- 80 Strings
- 4800 PMTs
- 1 km^3
- 2004 - 2010

IceCube
Planned Location 1 km east

Neutrino Telescope in the Ice



AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

zoomed in on one
optical module (OM)

1997:

AMANDA-B10

302 OMs on 10 Strings

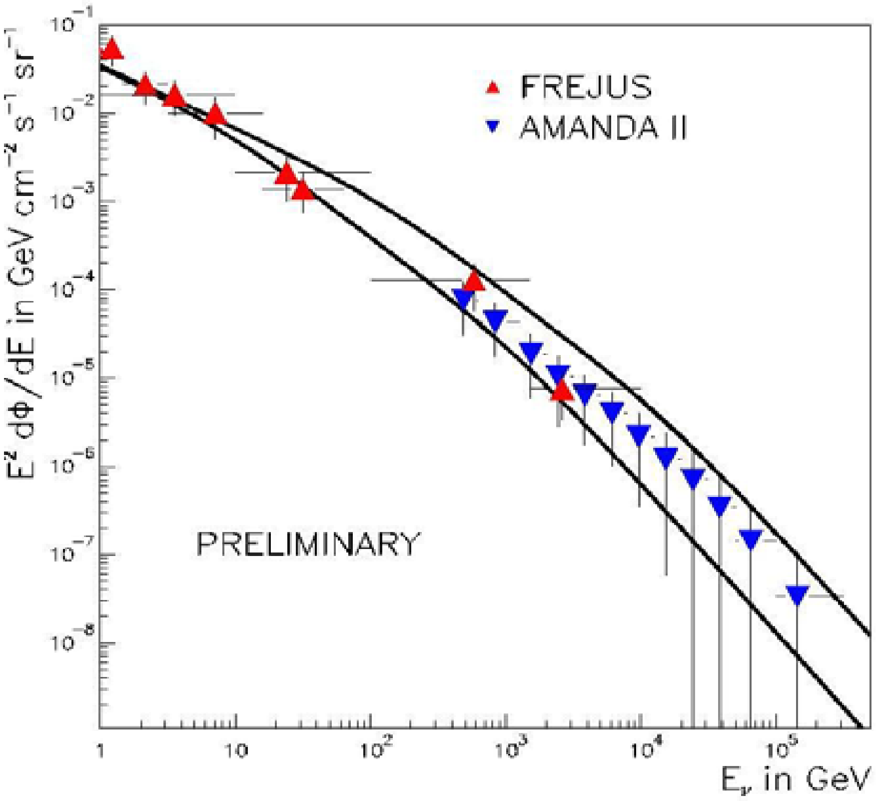
2000:

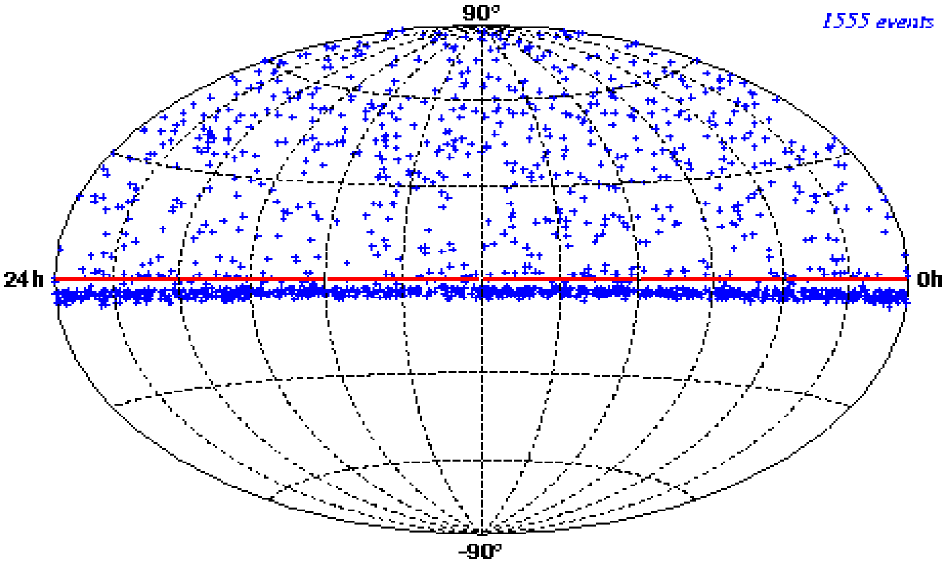
AMANDA-II

677 OMs on 19 Strings

First results from AMANDA

Atmospheric neutrino spectrum





Search for extraterestial point sources

ICRC 2003: Geenen for AMANDA

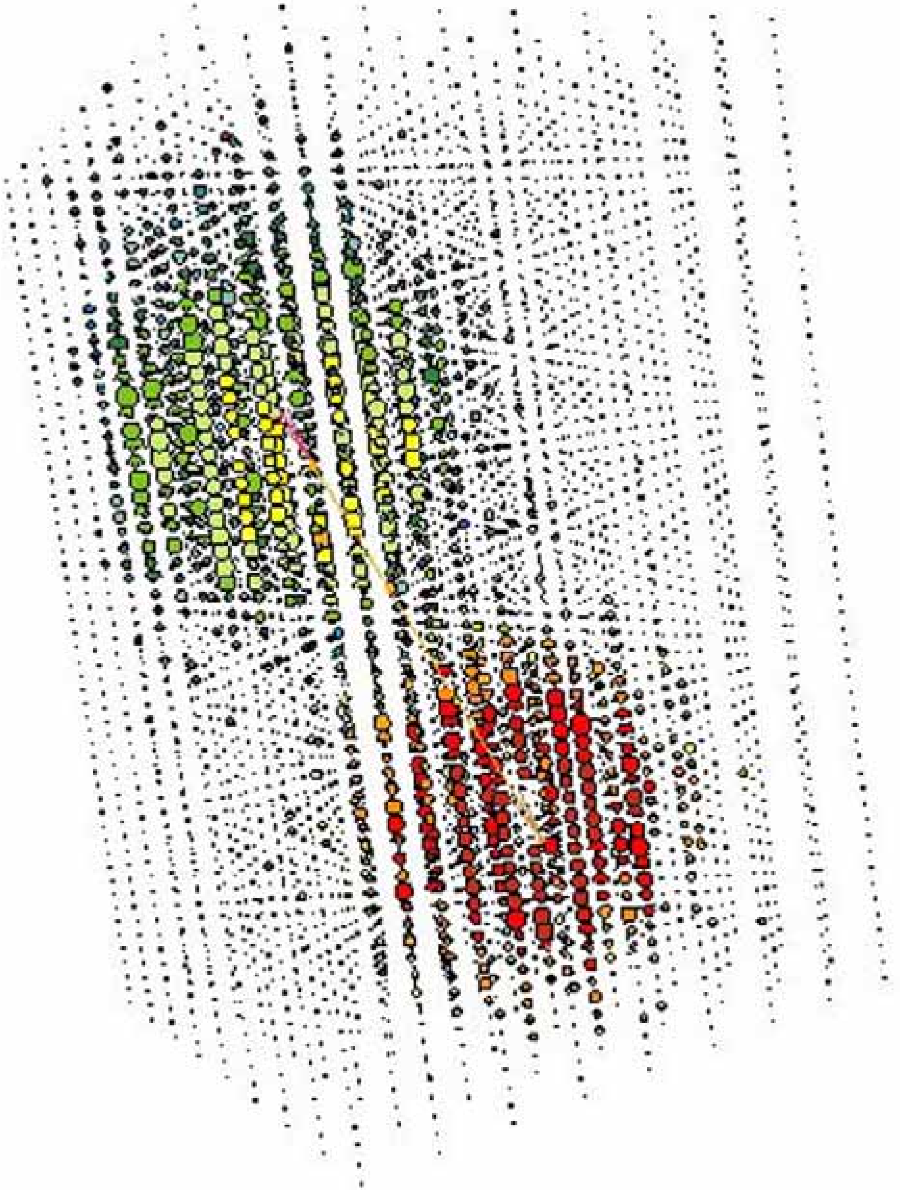
Special role of tau neutrinos

Simulation of the PeV ν_τ interaction in the ICECUBE detector

Shower due to ν_τ interaction and shower due to τ decay separated by 500 meters!

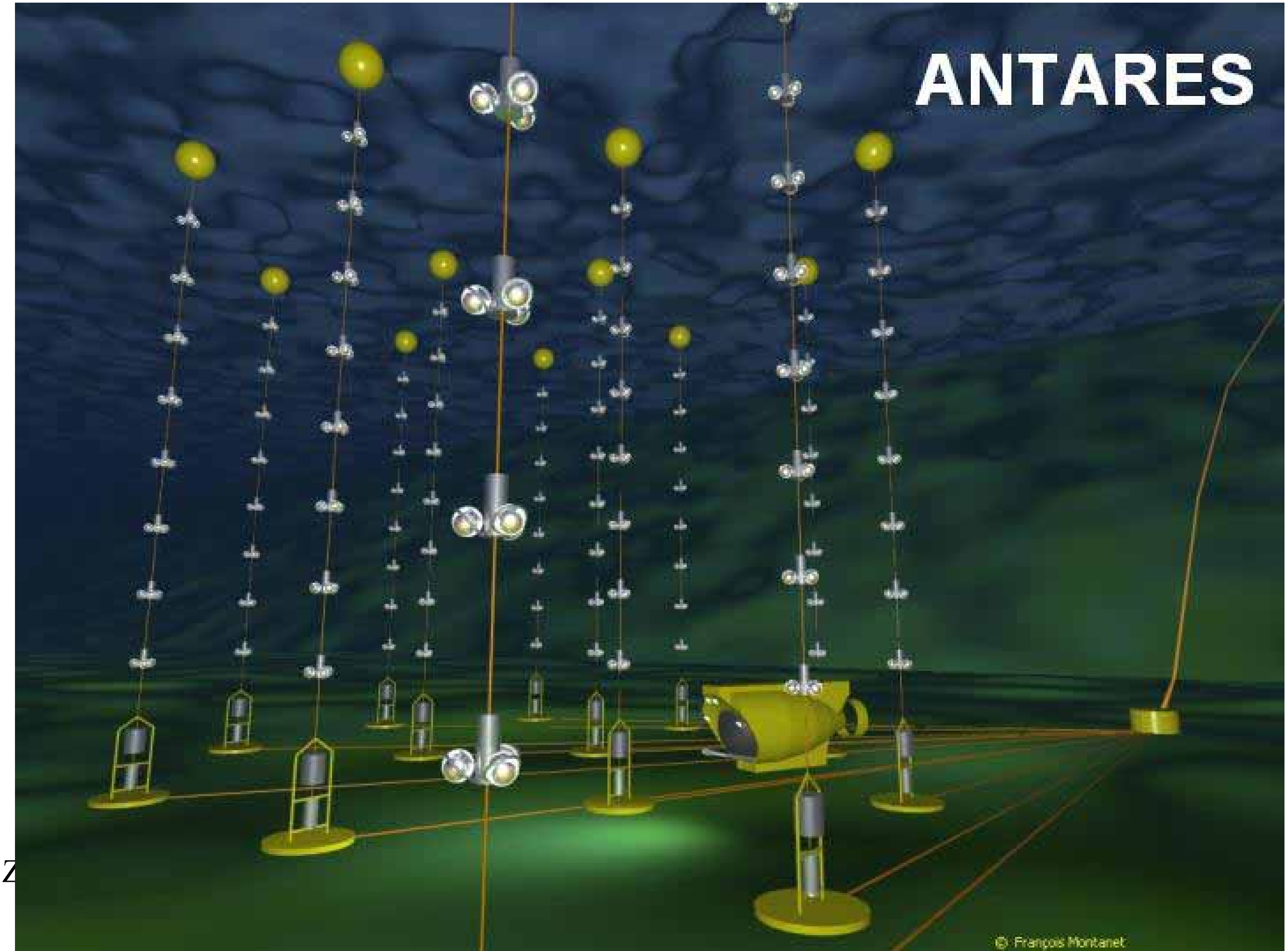
1/3 of UHE neutrinos are ν_τ neutrino
(because of oscillations)
not absorbed in the Earth
(regeneration)

Also note: ICECUBE (and other exps
will be v. good laboratories for
studies of h.e. atmospheric neutrinos



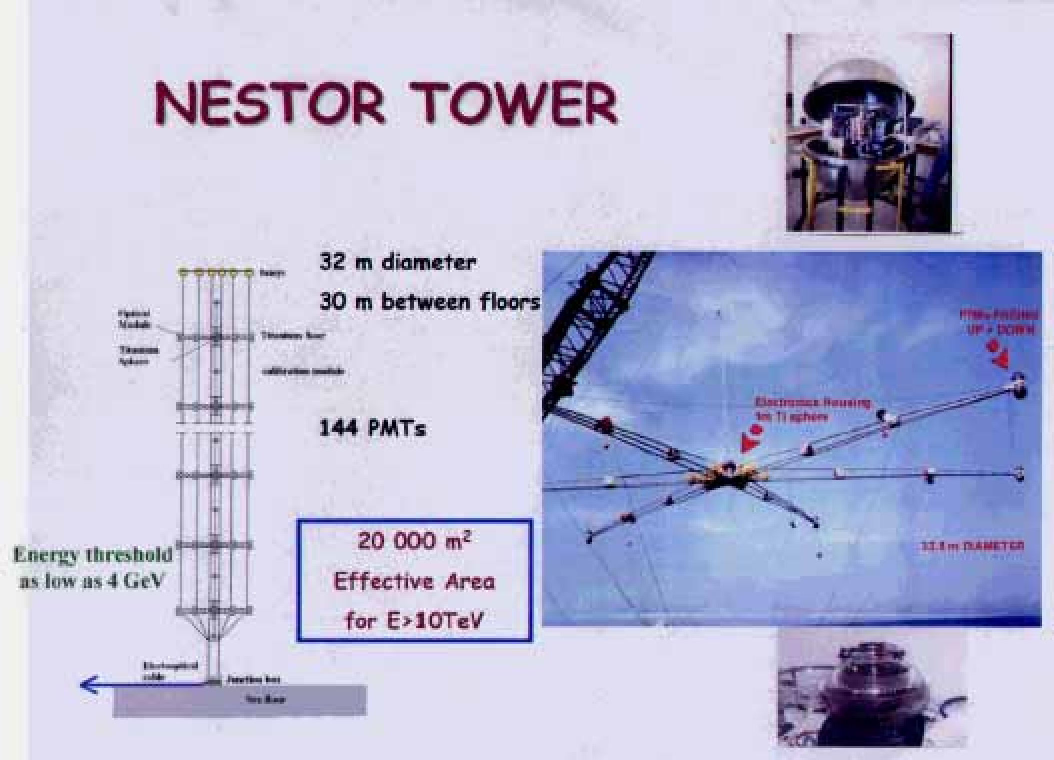
Deep water neutrino telescopes

Close to Toulon, at a death of 2400 m., successful first tests, problems with bioluminescence



Deep water neutrino telescopes

At a death of 4000 m.!


NESTOR TOWER

32 m diameter

30 m between floors

144 PMTs

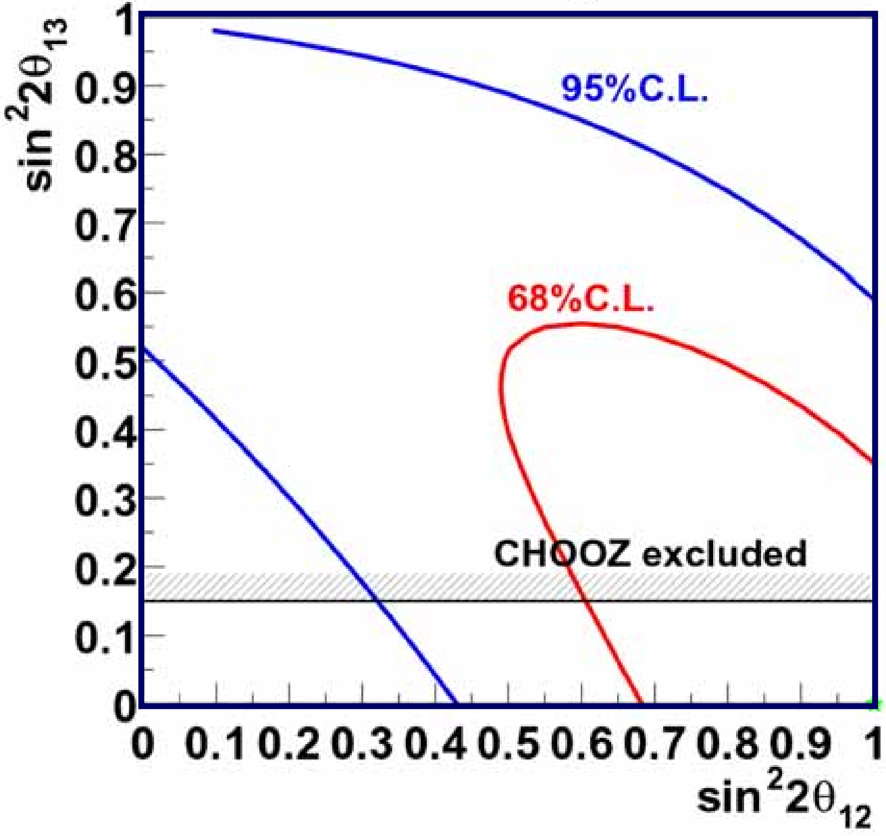
20 000 m^2
Effective Area
for E>10TeV

Energy threshold
as low as 4 GeV

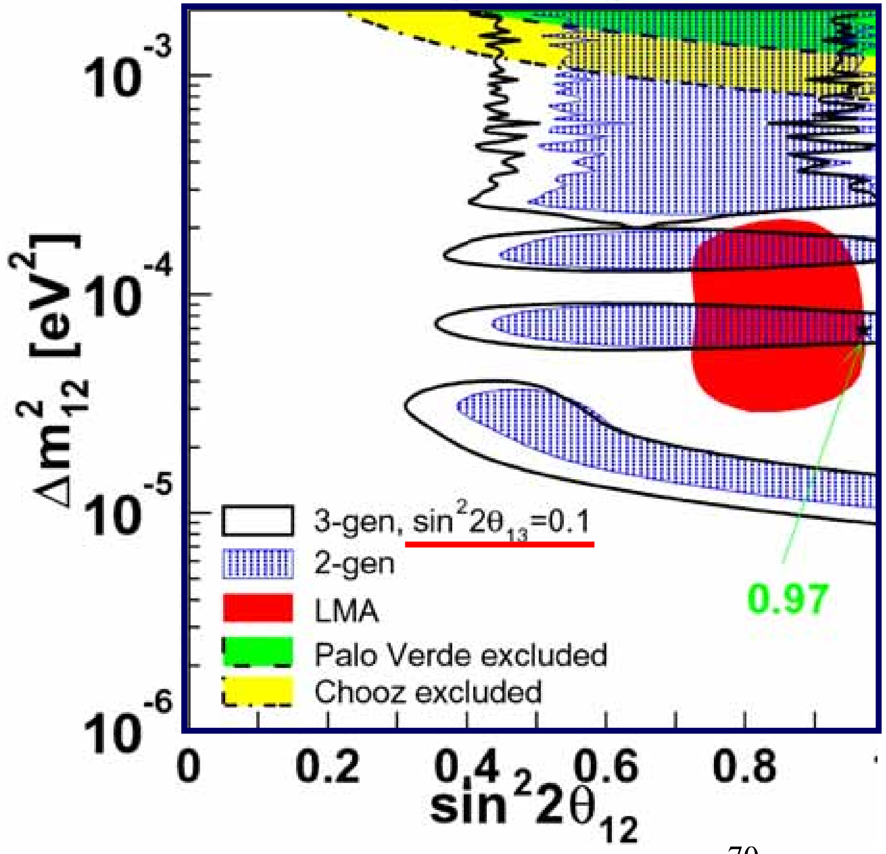
Rate + Shape Analysis in 3 Generation Case

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \cong \sin^4\theta_{13} + \cos^4\theta_{13}\left[1 - \sin^2 2\theta_{12}\sin^2\left(\frac{1.27\,\Delta m^2_{12}\,[\mathrm{eV}^2]\,L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)\right]$$

Sensitivity for θ_{13} $\Delta m^2_{12} = 6.9 \times 10^{-5}$ eV^2



Sensitivity for 3−generation



2003 SNO results from phase 2

-- higher efficiency for the neutron capture on Cl
-- greater isotropy of the Cherenkov light for NC events as compared to CC and ES samples -> better separation of event types
-- NC flux determined with almost twice smaller errors, CC and ES fluxes with errors comparable to phase 1 errors