Neutrinos: summary of new results

" The year 2002 is likely to be remembered as the annus mirabilis of solar neutrino physics"

G. Fogli, et al., Phys. Rev. D **67**, 073002 (2003)

- SNO
- Nobel Prize Davis, Koshiba
- KamLAND

ν_e ν_μ ν_τ

Summary of new neutrino results

1. Neutrino Physics parameters

2. The pre-(SNO-KamLAND) experimental situation

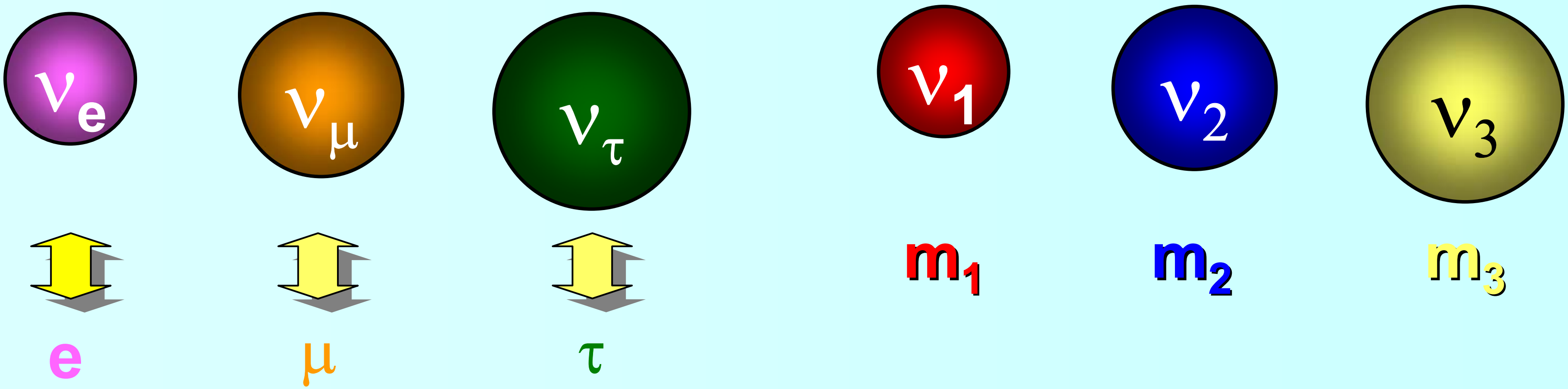
3. The new results : SNO, KamLAND, K2K, WMAP

4. A quick look to the next experimental steps

Physics introduction

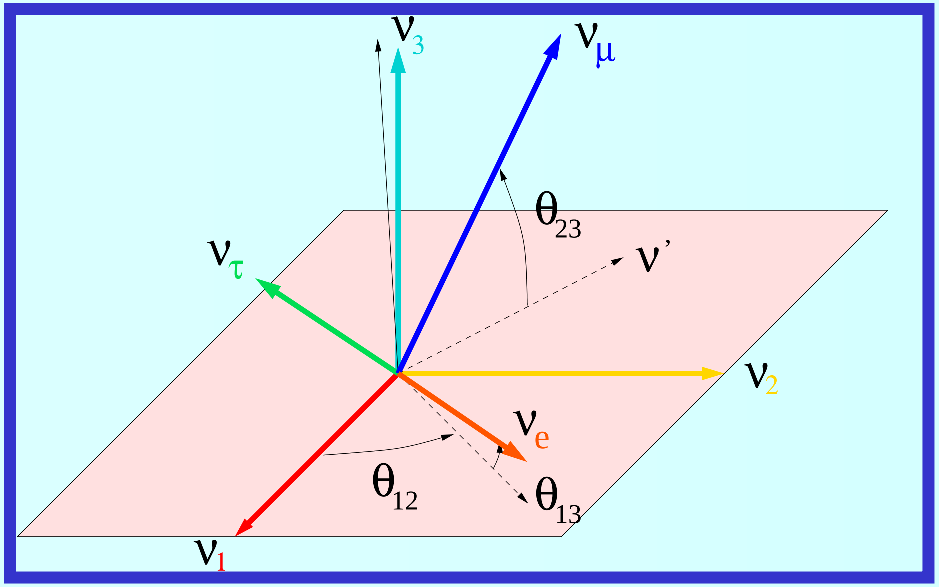
Neutrino Physics Parameters

Flavor neutrino states **Mass eigenstates**



- 3 masses : m_1, m_2, m_3
- 3 mixing angles : Θ_{12}, Θ_{23}, Θ_{13},
- 1 Dirac CP Phase : δ
- Dirac or Majorana ?
  - 2 Majorana CP Phases : α_1,α_2

Pontecorvo-Maki-Nakagawa-Sakata



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} V_M^{CP} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$V_M^{CP} = \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$U_{PMNS} = R_1(\theta_{23}) R_2(\theta_{13}) R_3(\theta_{12})$$

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

$e^{i\delta}$ Dirac CP Phase

2 Neutrino Oscillation

Disappearance

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \sin^2 \Phi$$

Appearance

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \Phi$$

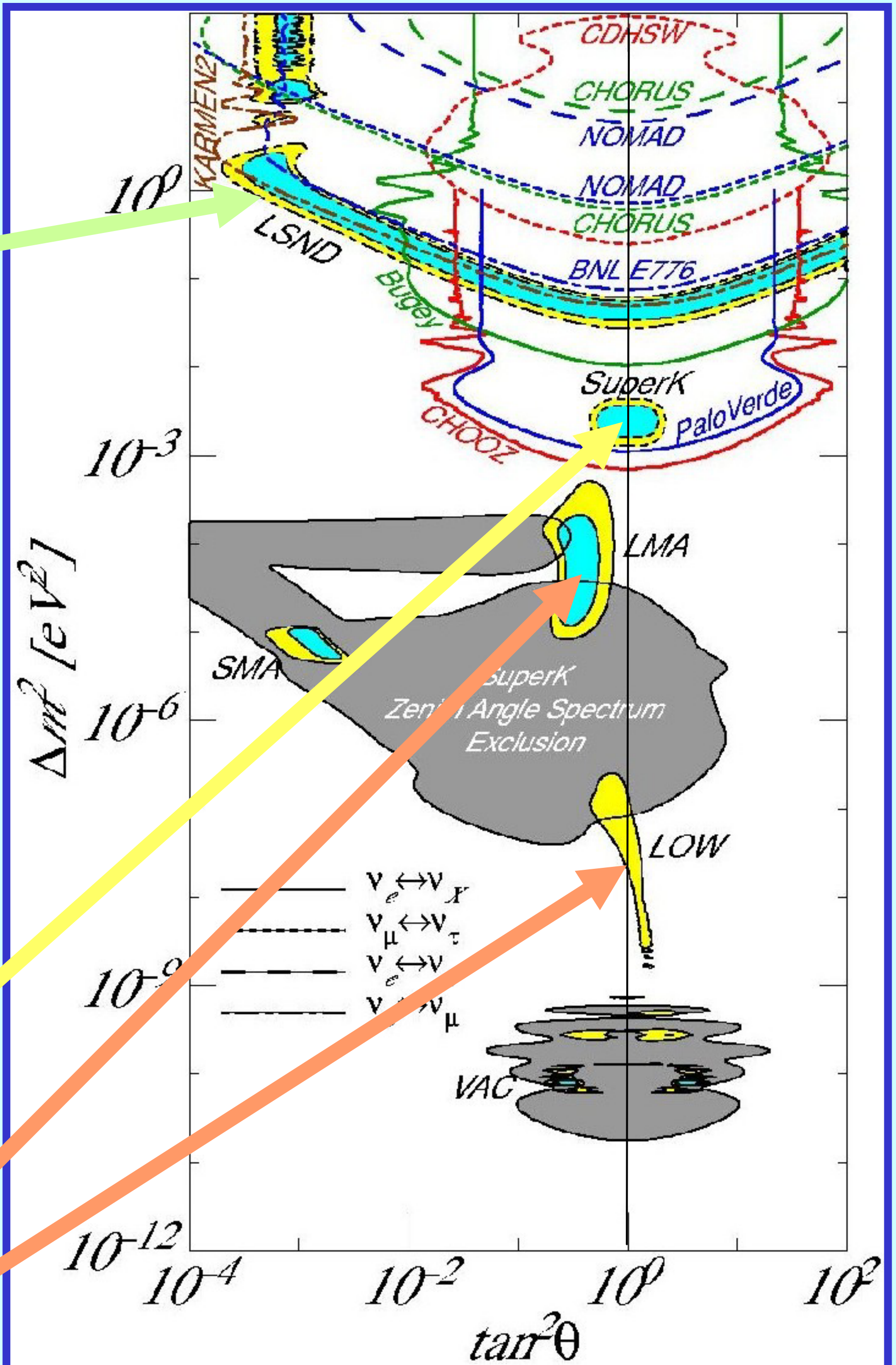
$$\Phi = 1.27 \Delta m^2 (eV^2) \frac{L(km)}{E(GeV)}$$

Situation before SNO & KamLAND

LSND

Atmospheric

Solar



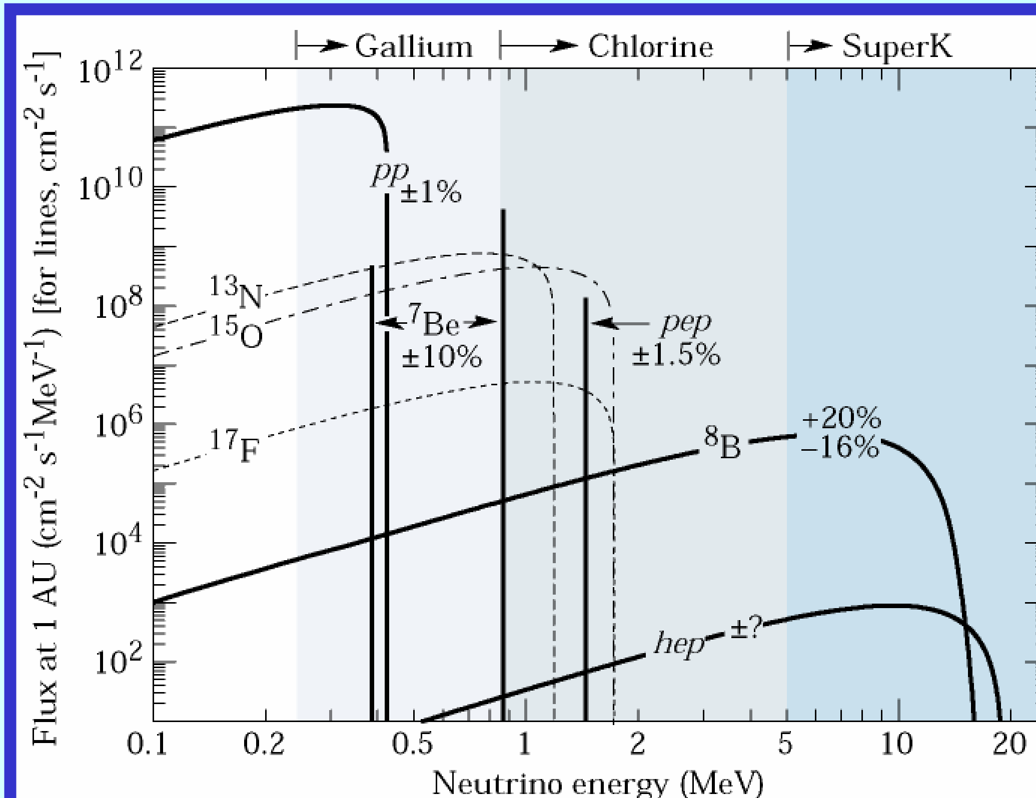
Solar Neutrinos

Solar ν_e : the SSM (J. Bahcall)

$4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e + 27MeV$

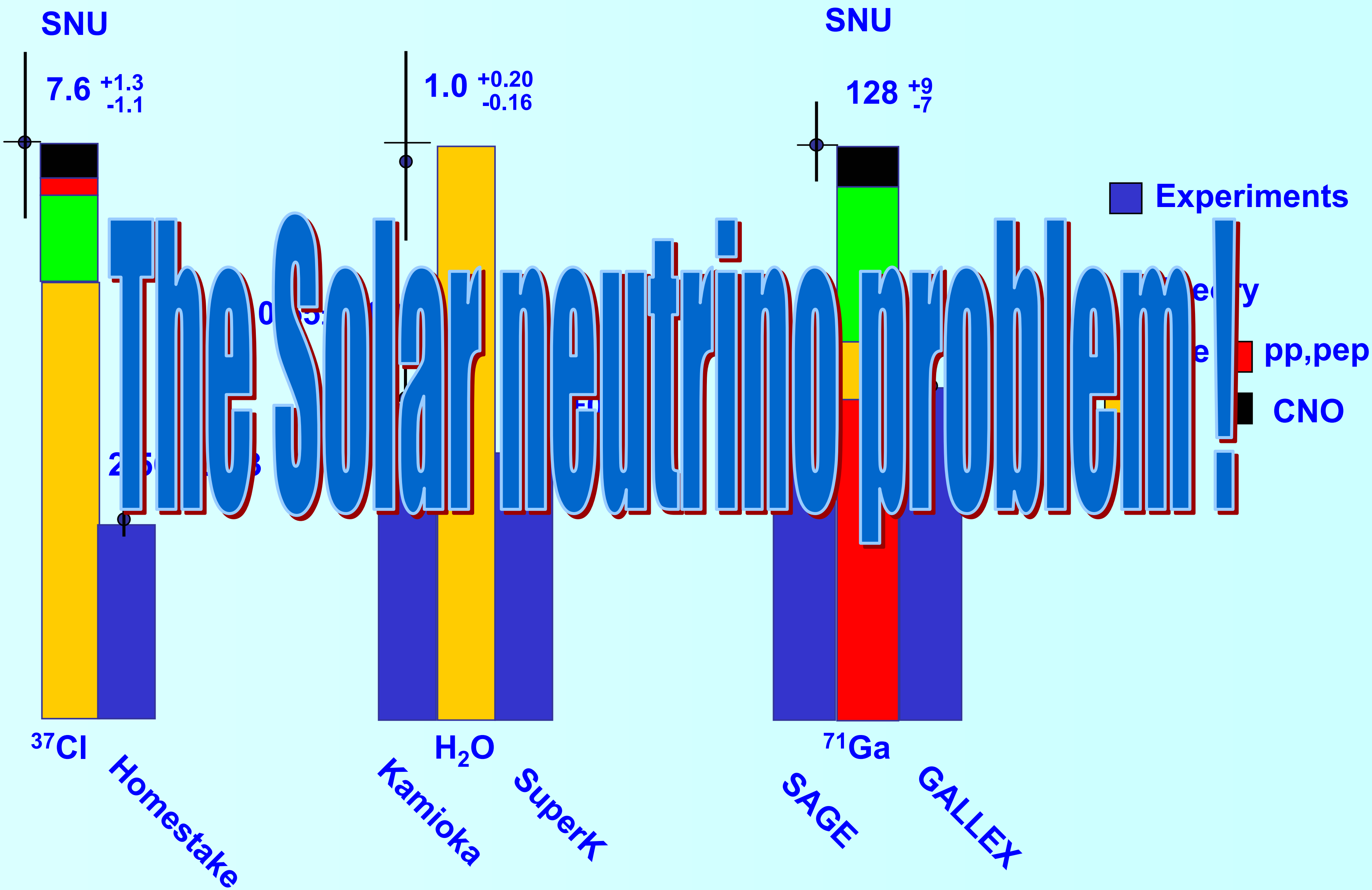
Flux (10^{10} $cm^{-2}\,s^{-1}$)

pp	5.96	±1%
pep	1.40×10^{-2}	±1.5%
hep	9.3×10^{-7}	?
^{7}Be	4.82×10^{-1}	±10%
^{8}B	5.05×10^{-4}	+20% -16%



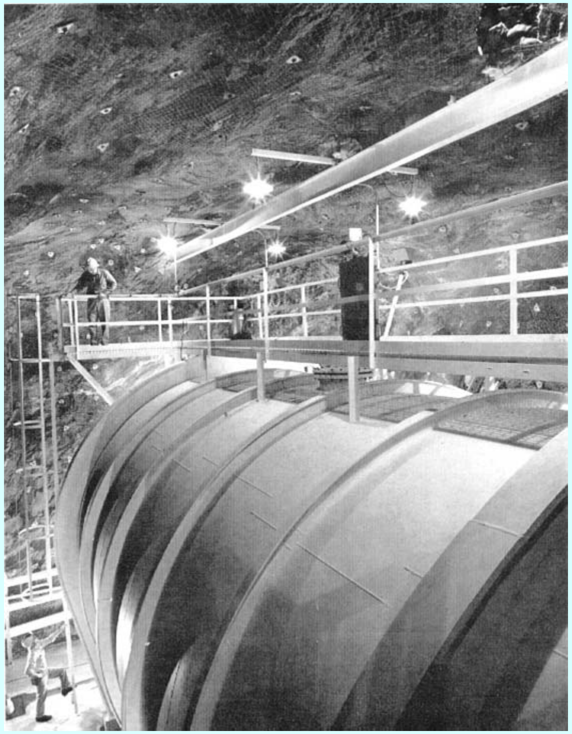
$\Phi(^8B) \sim 5\ 10^6\ cm^{-2}s^{-1}$ **expected** ν

Solar ν : before SNO & KamLAND



The Solar neutrino problem !

Solar ν : Pre-SNO Experiments

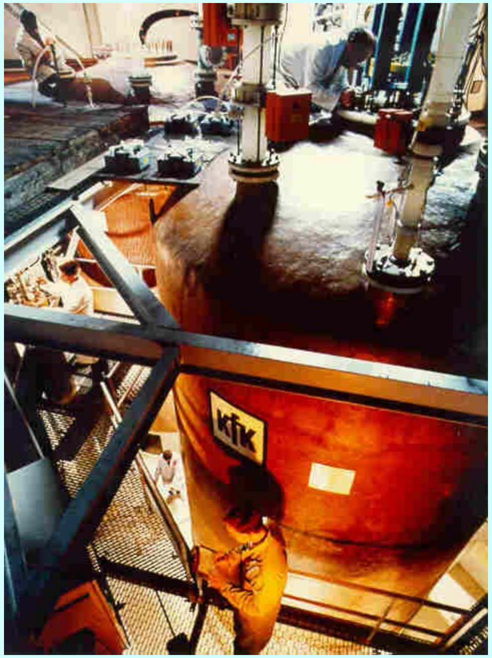


Homestake

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

$E_\nu > 0.814 MeV$

ν_e

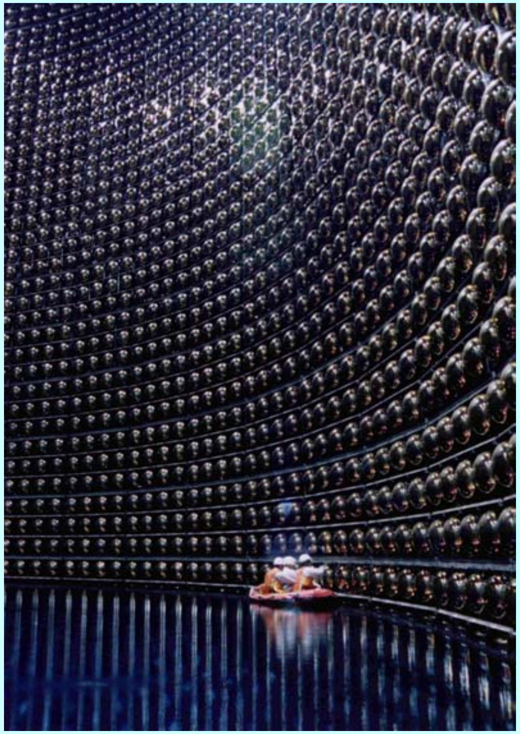


Gallex+Sage

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

$E_\nu > 0.233 MeV$

ν_e



(S)-Kamiokande

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

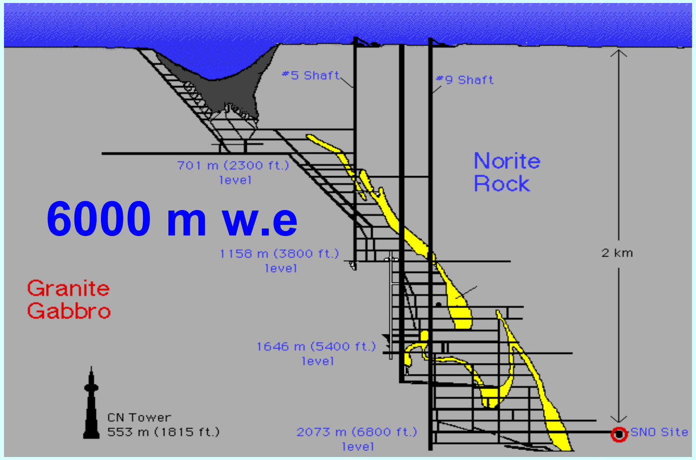
$E_\nu > 5 MeV$

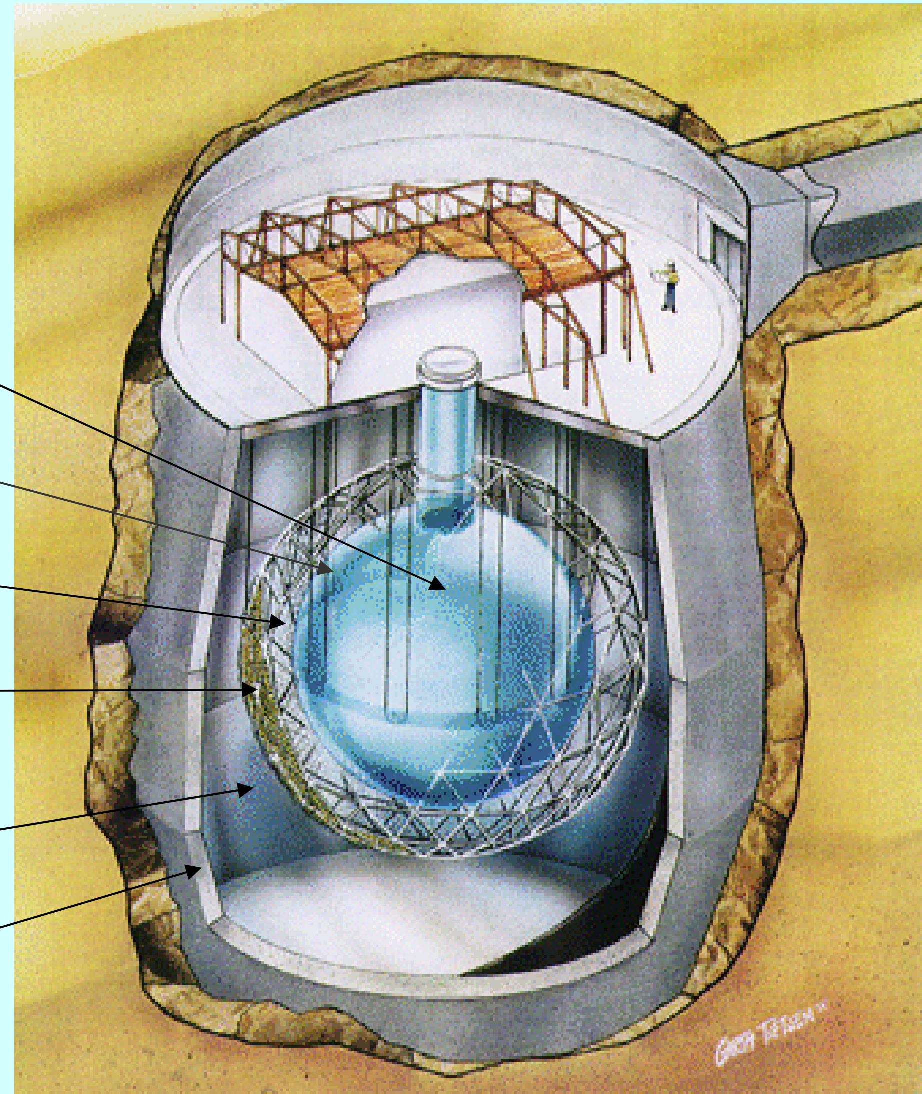
$\nu_e + 0.15(\nu_\mu + \nu_\tau)$

SNO or...

CES HOMMES ONT PEUT-ETRE CHANGE
LE DESTIN DU MONDE...
GRACE A EUX, HITLER N'A JAMAIS EU
SA BOMBE ATOMIQUE
LA BATAILLE DE L'EAU LOURDE
AFPH

Sudbury Neutrino Observatory





Cerenkov detector
1000 tonnes D_2O

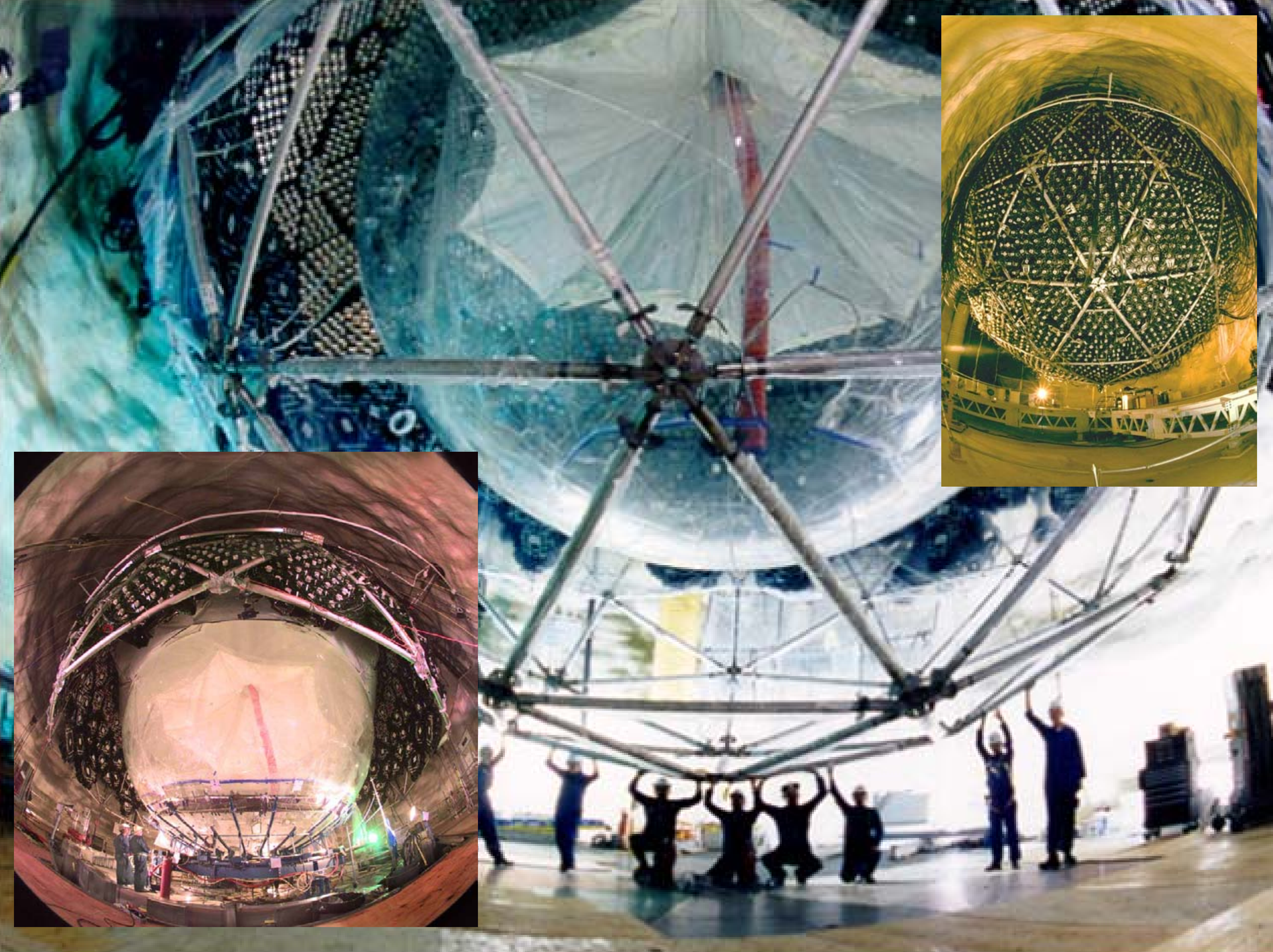
12 m Diameter
Acrylic Vessel

Inner Shielding
1700 tonnes H_2O

Support Structure
9500 20cm-PMTs
60% coverage

Outer Shield
5300 tonnes H_2O

Urylon Liner &
Radon Seal



ν Reactions in SNO

ES

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

- Both SK, SNO
- $\nu_e + 0.15\,(\nu_\mu + \nu_\tau)$
- Strong directional sensitivity

CC

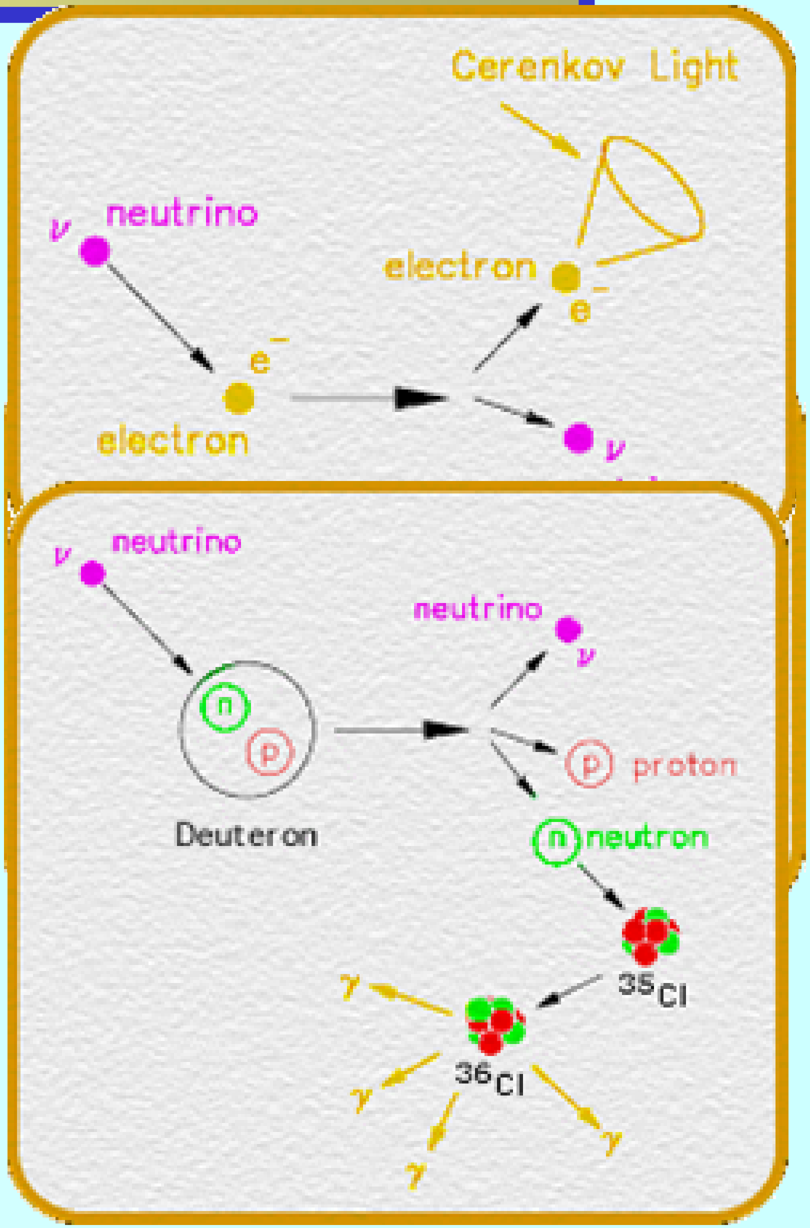
$\nu_e + d \Rightarrow p + p + e^-$

- Good measurement of $E(\nu_e)$
- ν_e only
- Weak directional sensitivity

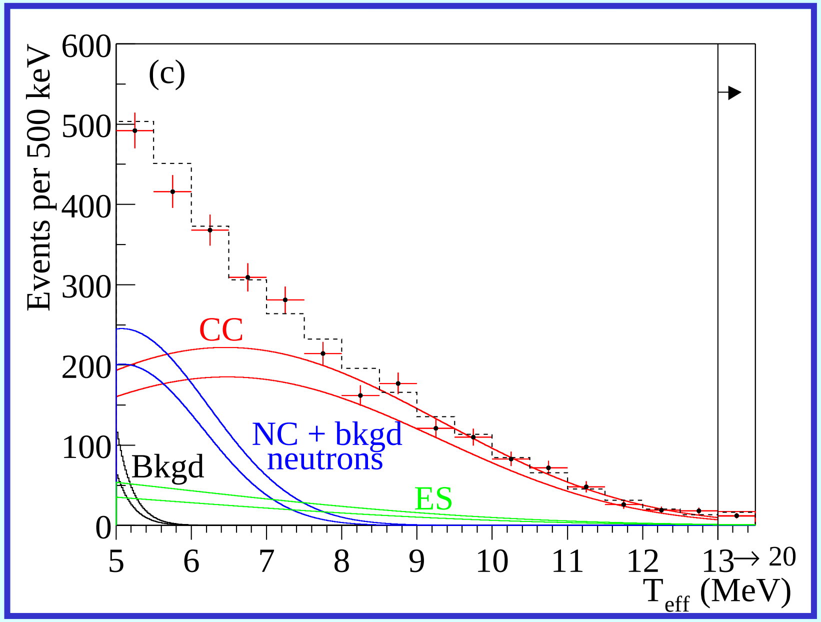
NC

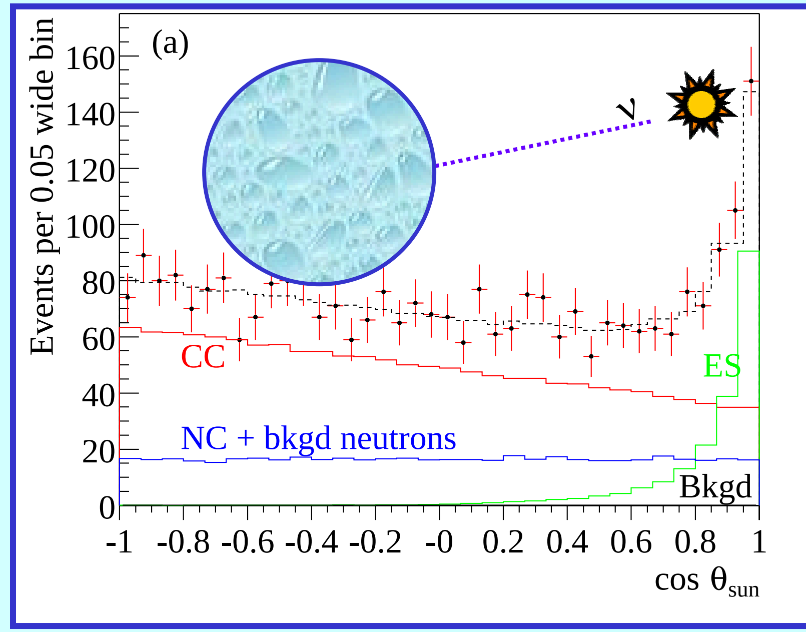
$\nu_x + d \Rightarrow p + n + \nu_x$

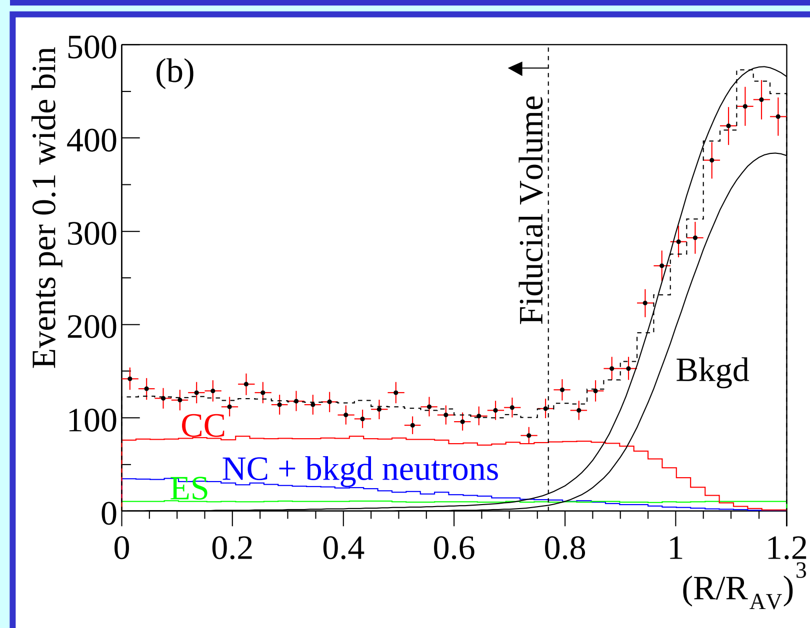
- $\nu_e + \nu_\mu + \nu_\tau$
- $n + d \rightarrow t + \gamma$ (6.3 MeV)… $\rightarrow e^-$



Signal Extraction







^{8}B shape from SSM

#EVENTS

CC	1967.7 $^{+61.9}_{-60.9}$
ES	263.6 $^{+26.4}_{-25.6}$
NC	576.5 $^{+49.5}_{-48.9}$

SNO an appearance experiment

Flux (10^6 cm^{-2} s^{-1})

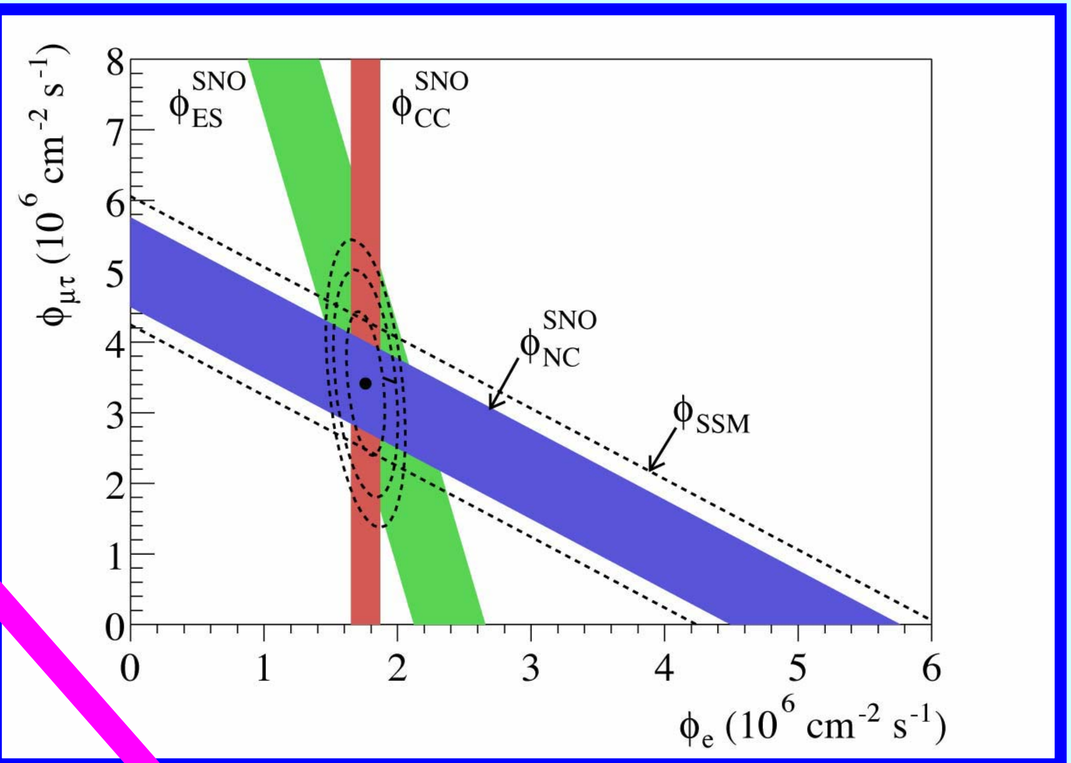
$$\Phi_{CC} = 1.76 \pm 0.05 \pm 0.09$$

$$\Phi_{ES} = 2.39 \,^{+0.24}_{-0.23} \,^{+0.12}_{-0.12}$$

$$\Phi_{NC} = 5.09 \,^{+0.44}_{-0.43} \,^{+0.46}_{-0.43}$$

$$\Phi_{e} = 1.76 \pm 0.05 \pm 0.09$$

$$\Phi_{\mu\tau} = 3.41 \pm 0.45 \,^{+0.48}_{-0.45}$$



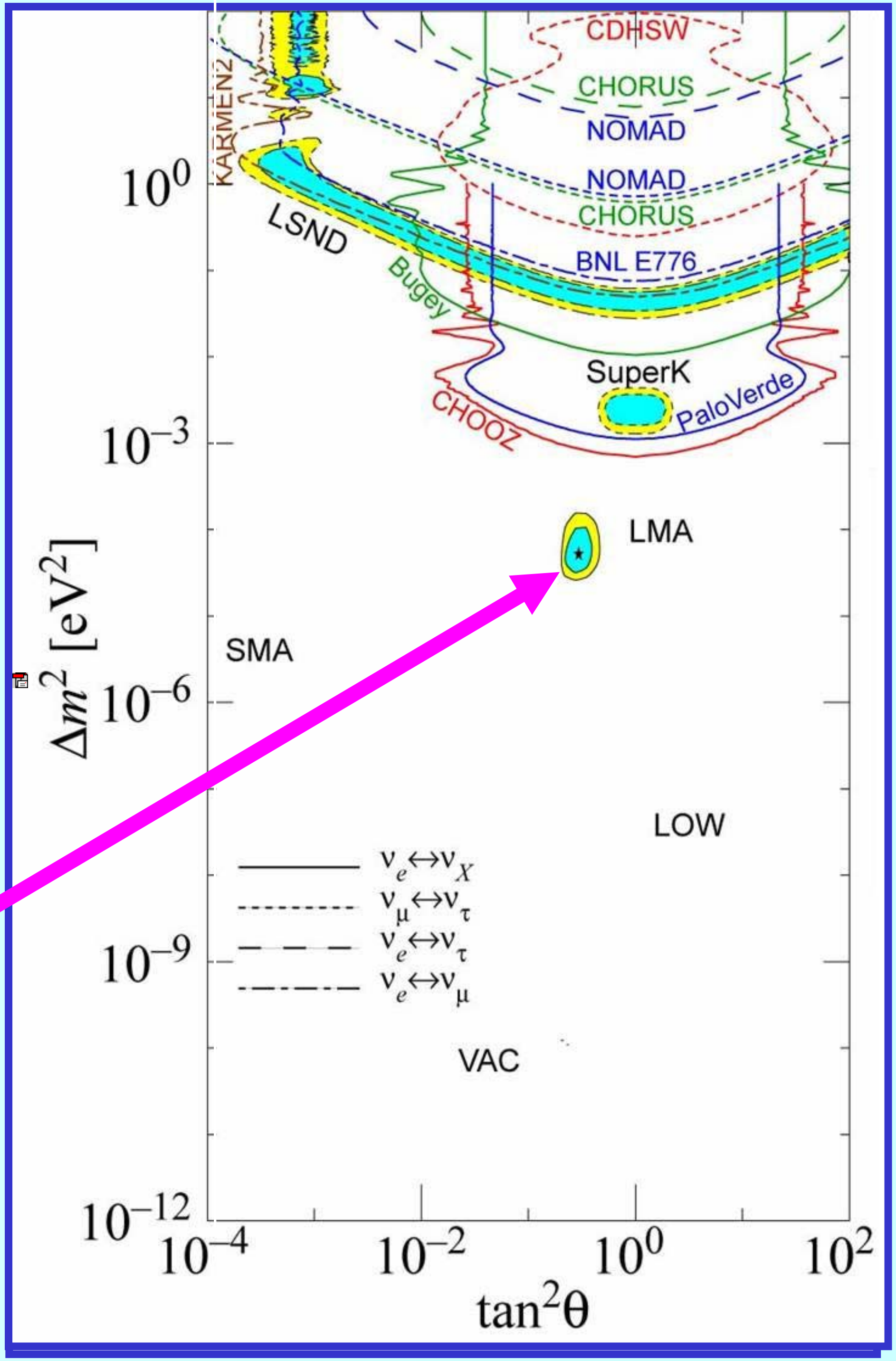
5.3σ above zero flavor transformation $\nu_{\mu,\tau}$ from the Sun!

SNO ^{8}B flux agrees with SSM!

$$\Phi_{SSM}^{^8B} = 5.05 \,^{+1.01}_{-0.81}$$

SNO Impact on Δm^2-$\sin^2 2\theta$

Large Mixing Angle
$2.10^{-5}<\Delta m^2(eV^2)<2.10^{-4}$
$0.2<\tan^2\theta<0.7$
(95%CL)

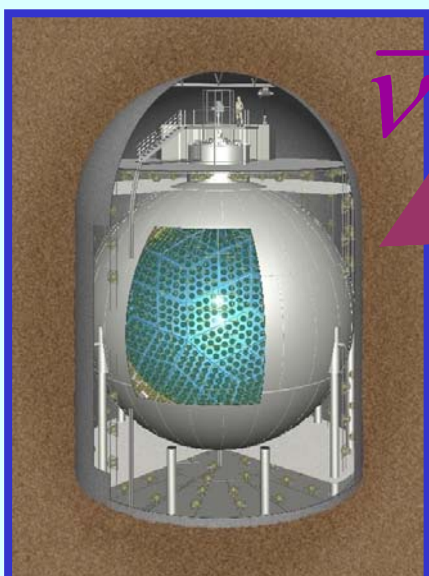


KamLAND Experiment

Nuclear reactor

Testing LMA with
man made (anti-)neutrinos

$\bar{\nu}$ **detector**



Maximum Oscillation

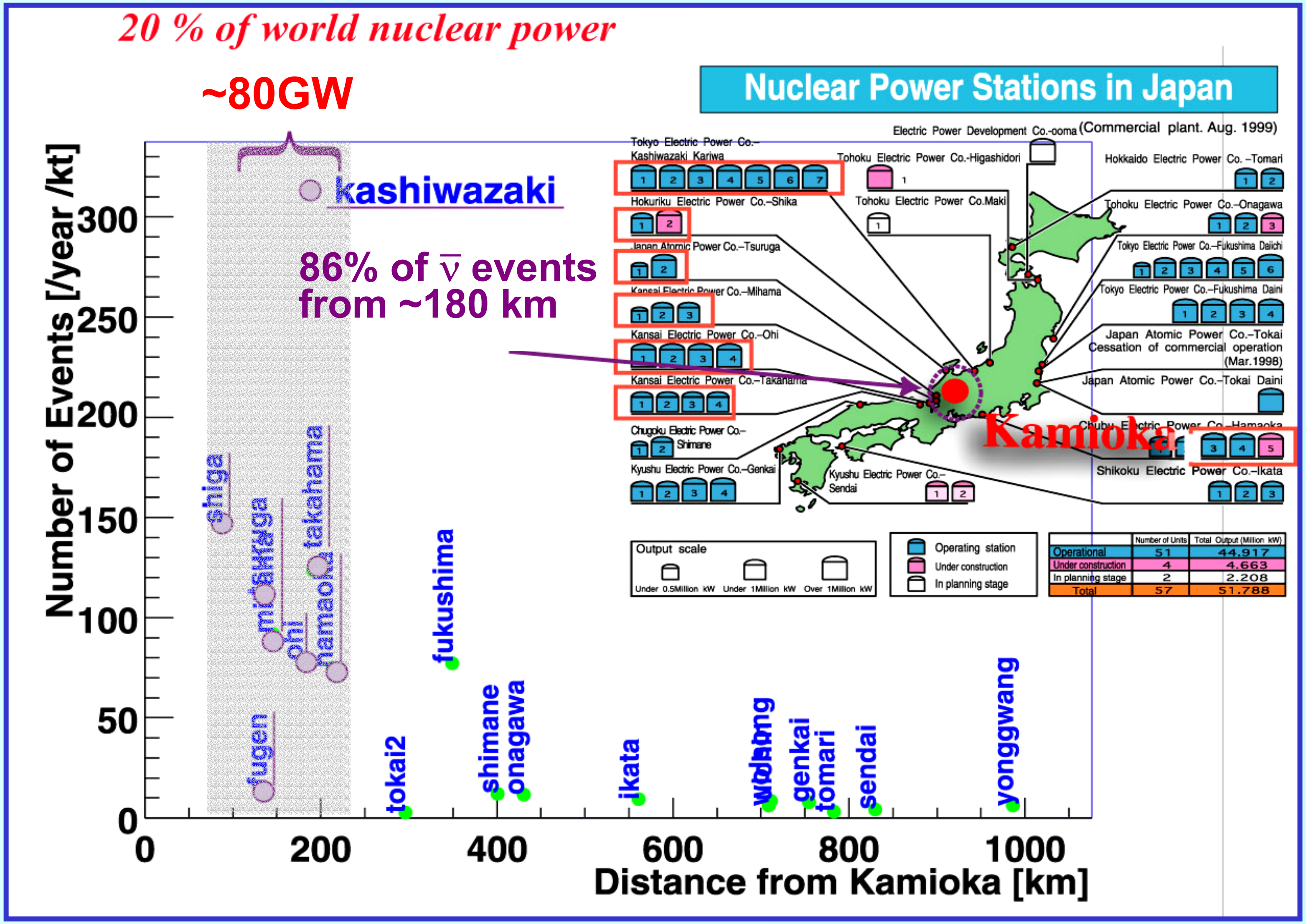
$$1.27\Delta m^2(eV^2)\frac{L(m)}{E(MeV)} = \frac{\pi}{2}$$

$$E_{\bar{\nu}} \approx 3\ \mathrm{MeV}$$

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

$$L \approx 74\ \mathrm{km}$$

Nuclear Reactors in Japan



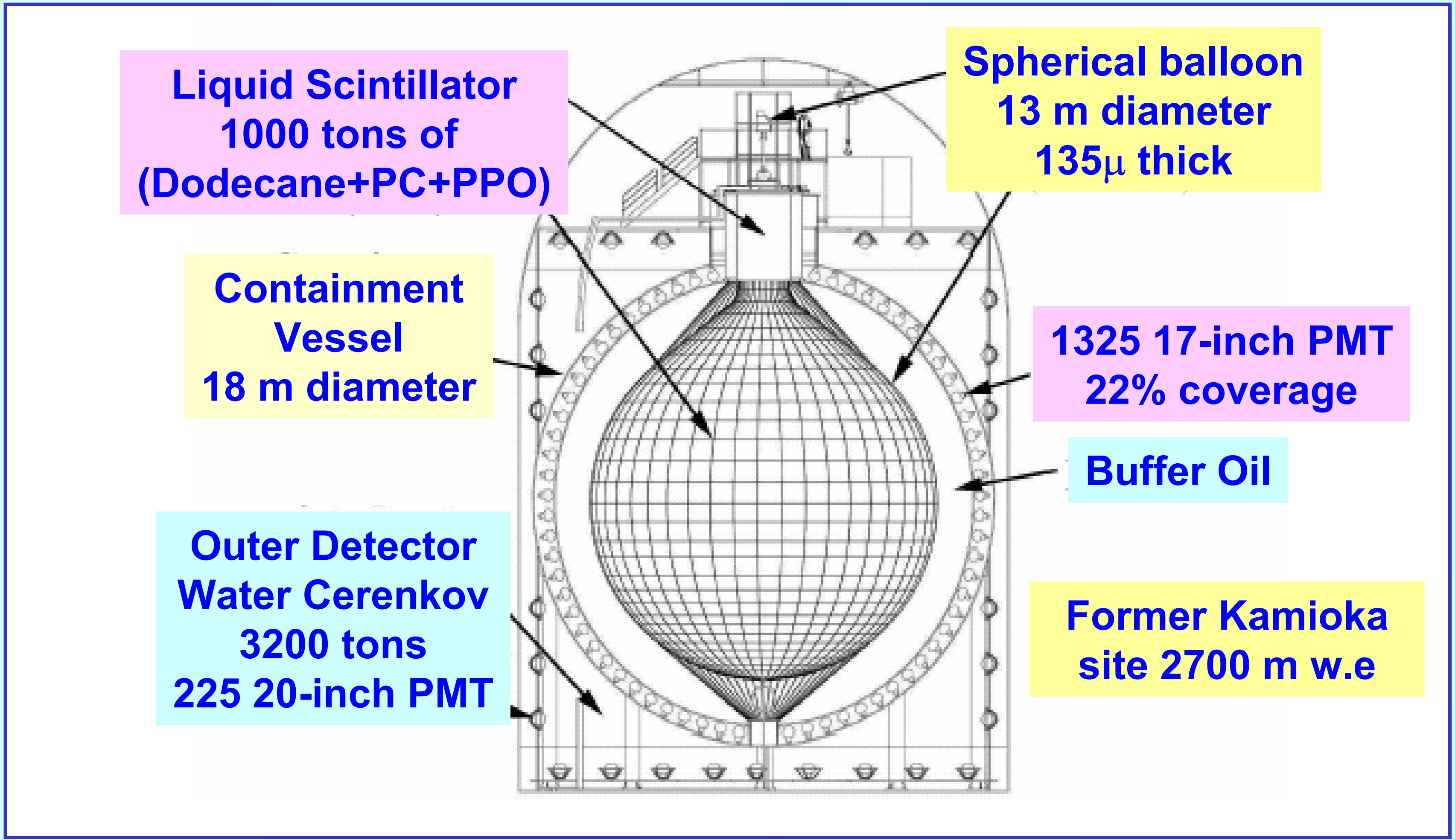
	Number of Units	Total Output (Million kW)
Operational	51	44.917
Under construction	4	4.663
In planning stage	2	2.208
Total	57	51.788

KamLAND Detector

$\overline{\nu}$ + p → e^+ + n, e^+ + e^- → 2γ (prompt)

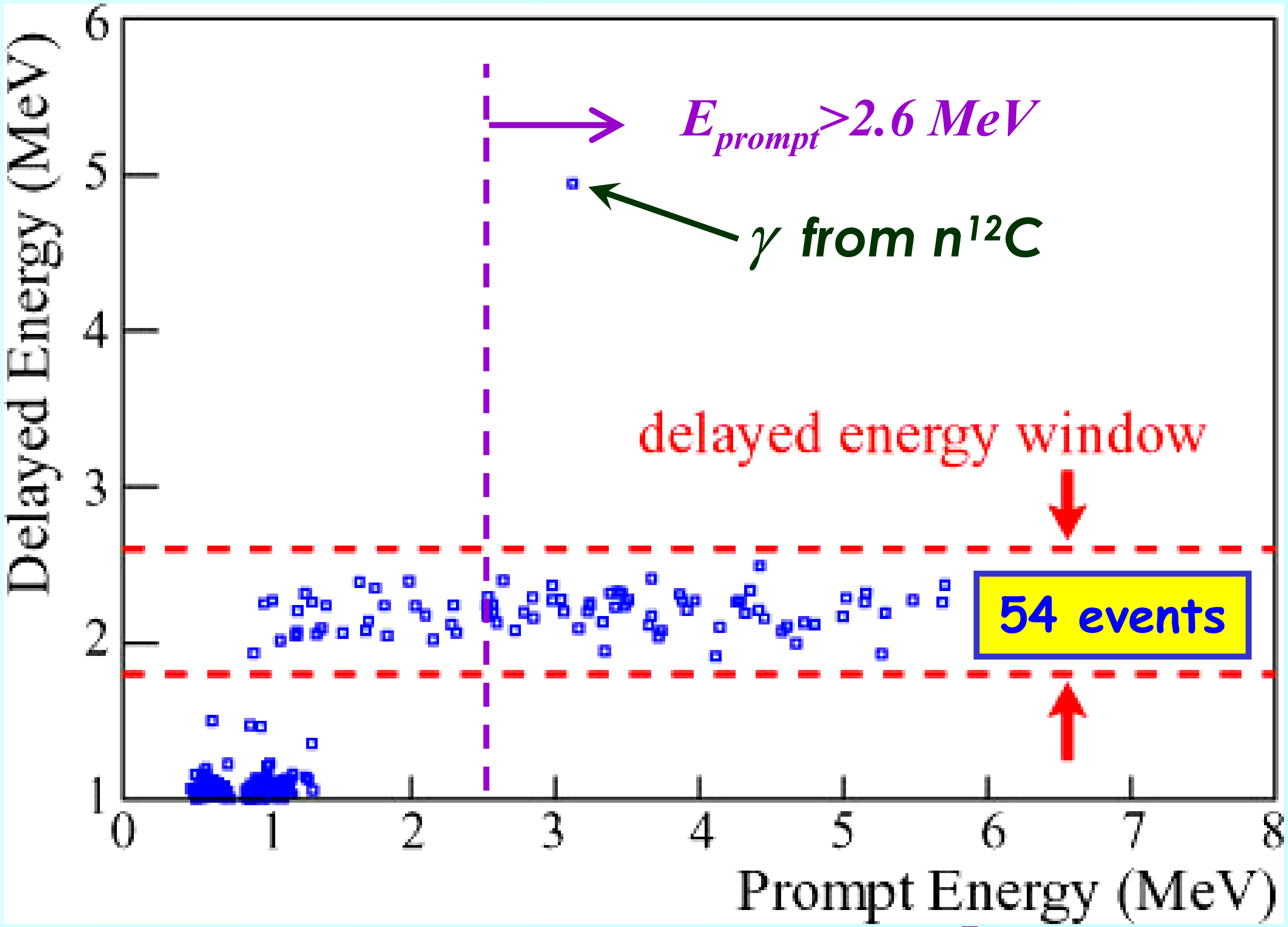
n + p → d + γ (2.2 MeV) (delayed)

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




13 m diameter balloon

Prompt and Delayed Energies



$$E_\nu = (E_e + \Delta)\left(1 + \frac{E_e}{M_p}\right) + \frac{\Delta^2 - m_e^2}{2M_p}$$

$$E_e = E_{prompt} - m_e$$

Observed Event Rates

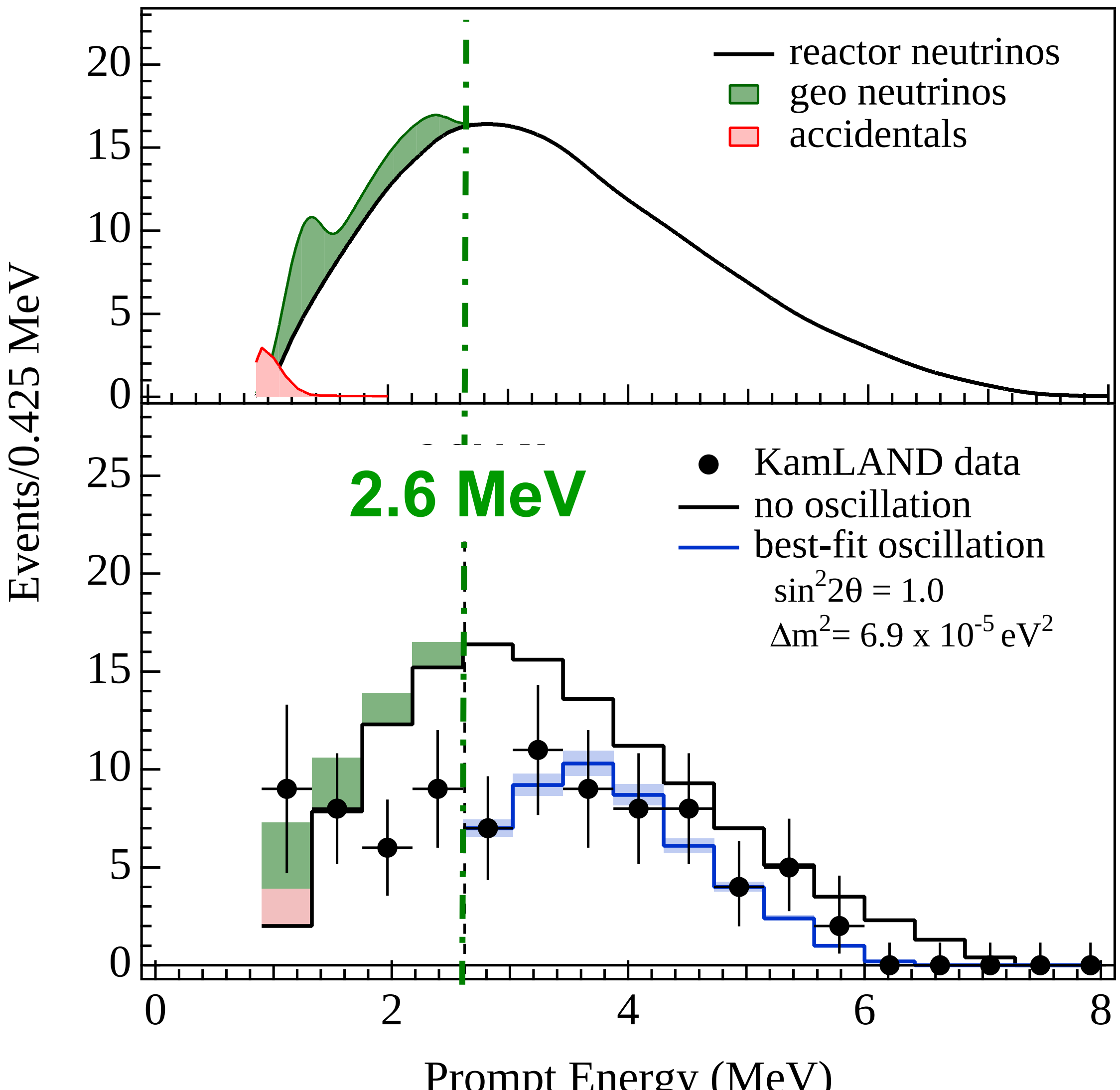
Mar. 4 – Oct. 6, 2002
162 ton•yr (145.1 days)

Final sample	**54**
Background	**0.95 ± 0.99**
accidental	0.0086 ± 0.0005
$^{9}Li/^{8}He$ (β, n)	0.94 ± 0.85
fast neutron	0 ± 0.5
Expected	**86.8 ± 5.6**

$$\frac{N_{obs}-N_{BG}}{N_{exp}}=0.611\pm0.085\pm0.041$$

P(no disappearance)<0.05% (4.1σ)

Energy Spectrum



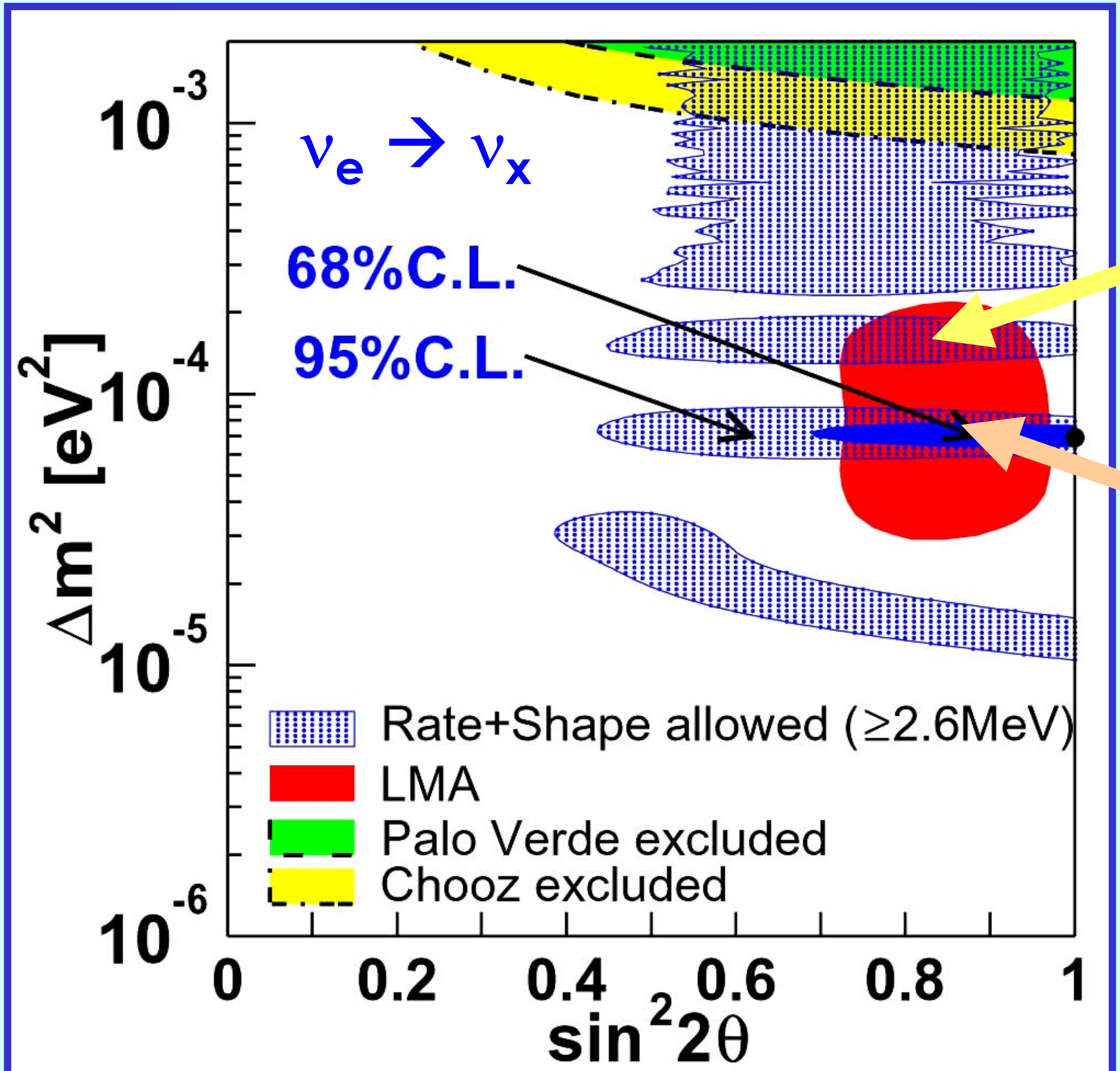
Consistent with :

- **distorted shape @ 93 % C.L.**

&

- **no oscillation shape @ 53% C.L.**

KamLand Impact on Δm^2-$\sin^2 2\theta$



LMA-II
$1.3\ 10^{-4} < \Delta m^2$ (eV^2)$< 2\ 10^{-4}$
@95%CL

LMA-I
$5.8\ 10^{-5} < \Delta m^2$ (eV^2)$< 9.1\ 10^{-5}$
@95%CL

Best fit
$\Delta m^2 = 6.9\ \ 10^{-5}$ eV^2
$\sin^2 2\theta = 1.01$

Solar Conclusions

SNO & Kamland have demonstrated that neutrino oscillation with LMA is likely to be the solution to the solar neutrino problem.

We are entering the precision era in the determination of the parameters governing the neutrino flavor evolution, more data to come from SNO, KamLAND and SK-II.

Atmospheric Neutrinos

K2K Experiment

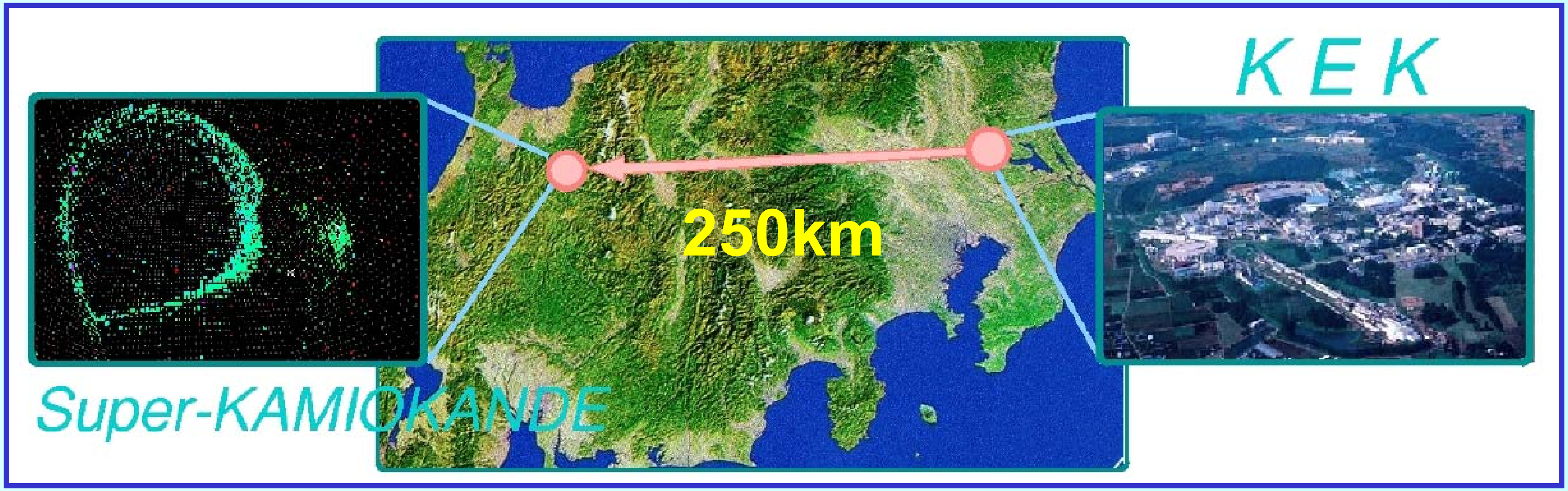
Testing SK atmospheric results with … man made neutrinos

Maximum Oscillation

$$1.27\Delta m^2(eV^2)\frac{L(km)}{E(GeV)} = \frac{\pi}{2}$$

$E_\nu \approx 1.3$ GeV, $\Delta m^2 = 3\ 10^{-3} eV^2$

→ $L = 535km$



Near neutrino detectors

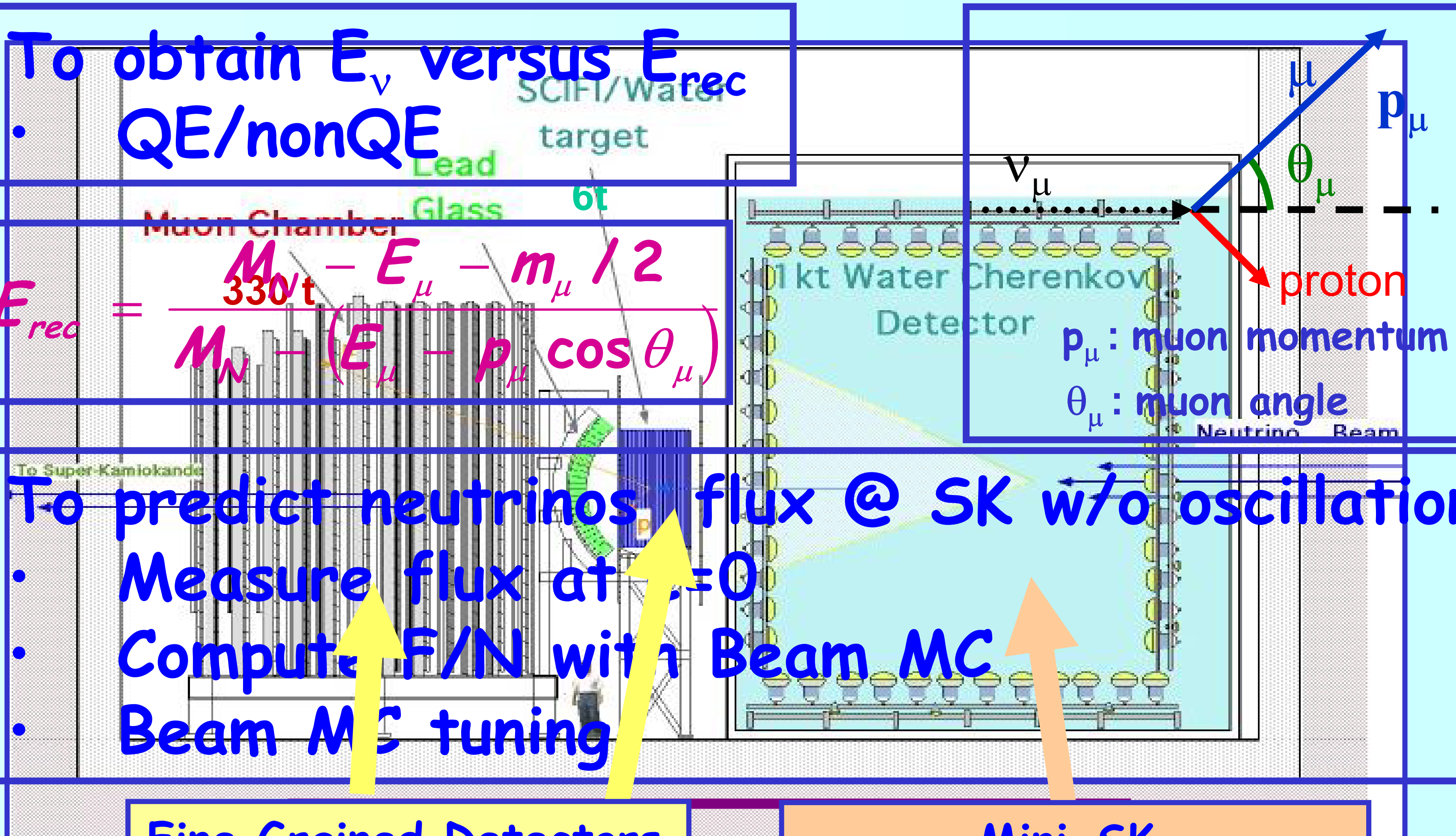
1. To obtain E_ν versus E_{rec}
   - QE/nonQE

$$E_{rec} = \frac{M_N - E_\mu - m_\mu / 2}{M_N - (E_\mu - p_\mu \cos\theta_\mu)}$$

p_μ : muon momentum

θ_μ : muon angle

2. To predict neutrinos' flux @ SK w/o oscillation
   - Measure flux at [illegible]=0
   - Compute F/N with Beam MC
   - Beam MC tuning



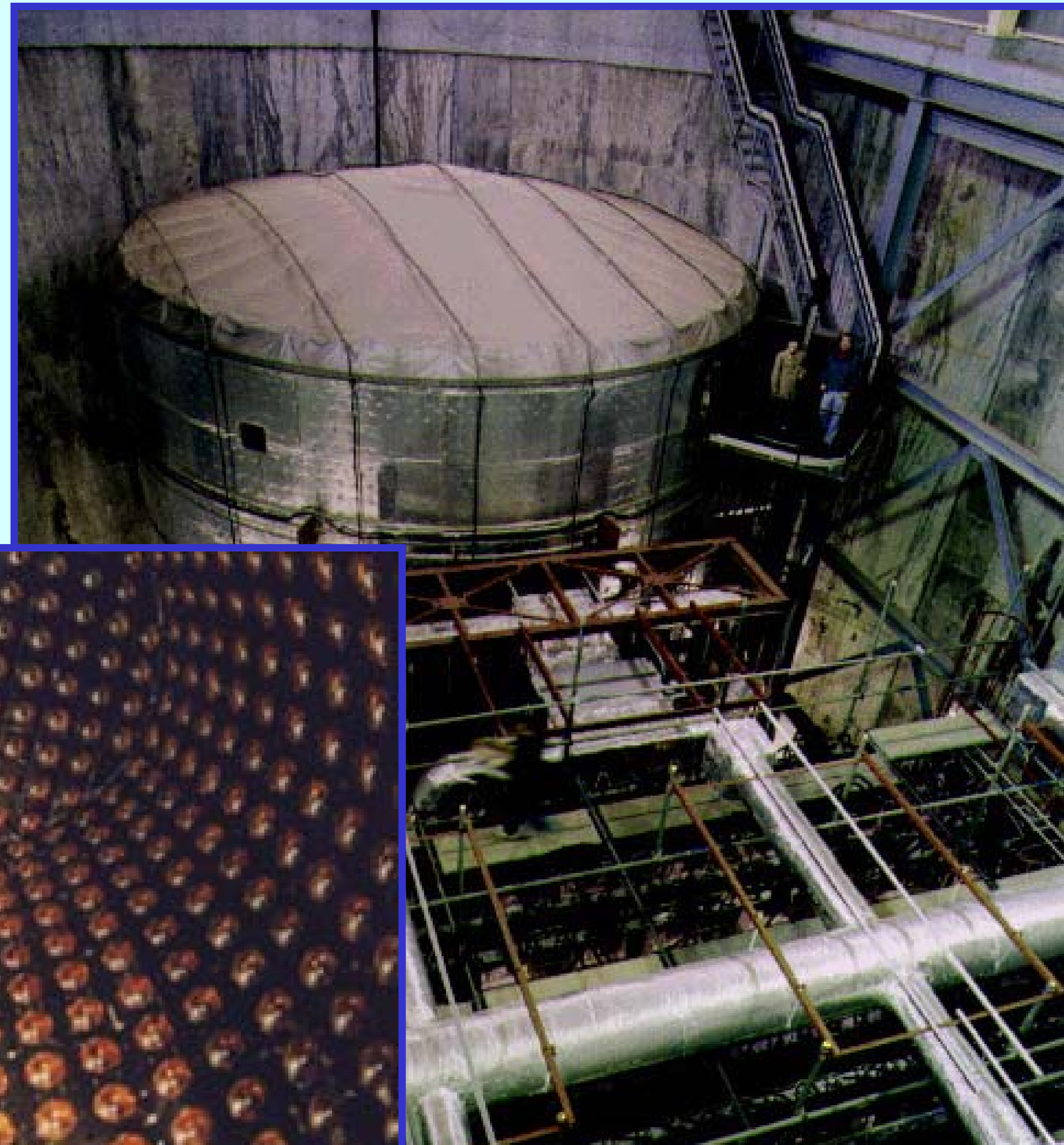
Fine Grained Detectors
- QE/nonQE
- dN/dE for p_μ>1GeV
- ν monitor (direction)

dN/dE

Mini-SK

1 kt (25t) H_2O Cerenkov
- N_ν
- dN/dE for p_μ<1GeV

K2K 1KT



Observed Event Rates

June '99 to July '01

4.8×10^{19} POT

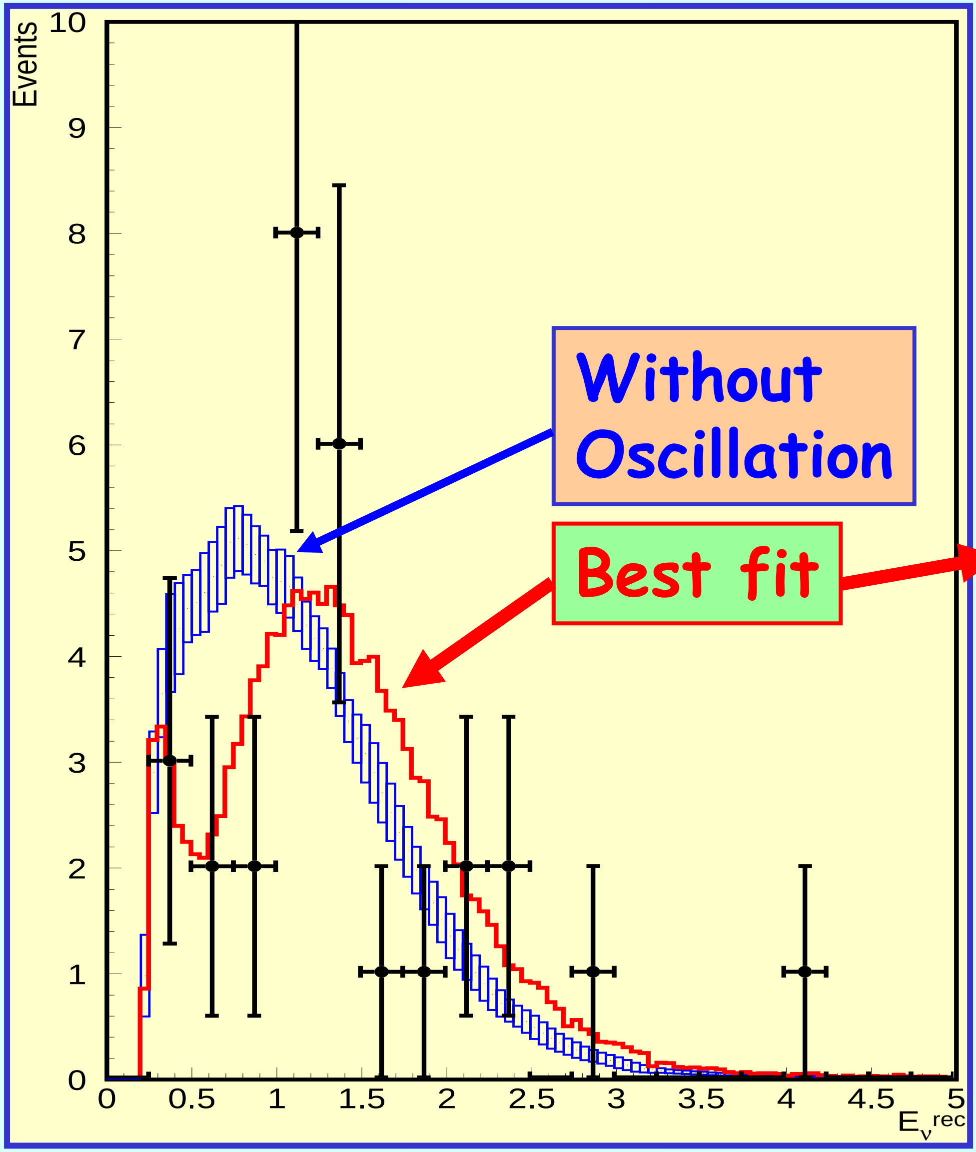
Final sample	56
accidental	$<10^{-3}$
Expected	$80.1^{+6.2}_{-5.4}$

Deficit

$$\frac{N_{obs}-N_{BG}}{N_{exp}} = 0.70 \pm 0.09 \,^{+0.054}_{-0.047}$$

P(no disappearance)=1% (2.8σ)

Energy Spectrum



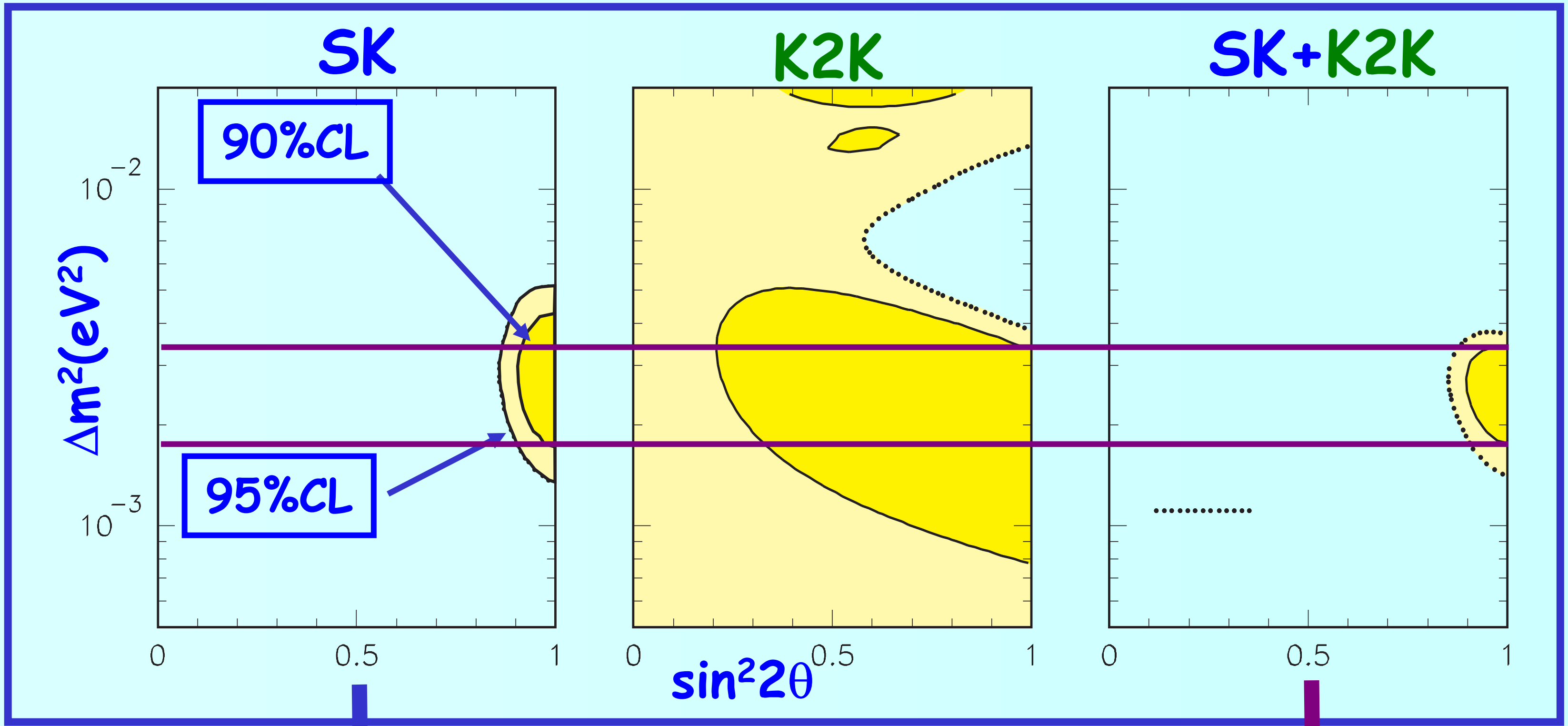
E_{rec} of the 29(/56)
ν 1Ring μ-like

($\sin^2 2\theta, \Delta m^2$)
(1.0 , 2.8x10^{-3} eV^2)

- N_{SK}
  Expected (W/osc.)= 54
  Observed = 56
- Shape
  KS test 79%

K2K Impact on Δm^2-$\sin^2 2\theta$

G. Fogli, et al., hep-ph/0303064



90%CL

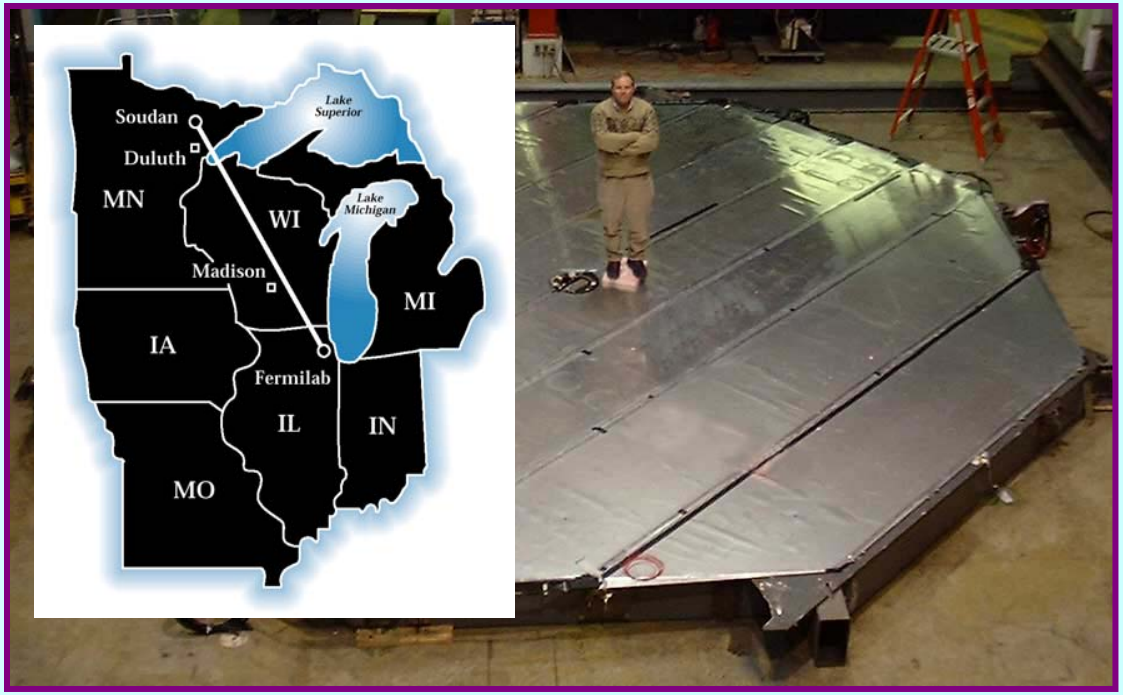
$$\Delta m^2 = 2.6\,^{+1.2}_{-0.7}\ 10^{-3}\,eV^2$$

$$\Delta m^2 = 2.6\,^{+0.7}_{-0.7}\ 10^{-3}\,eV^2$$

Atmospheric Conclusions

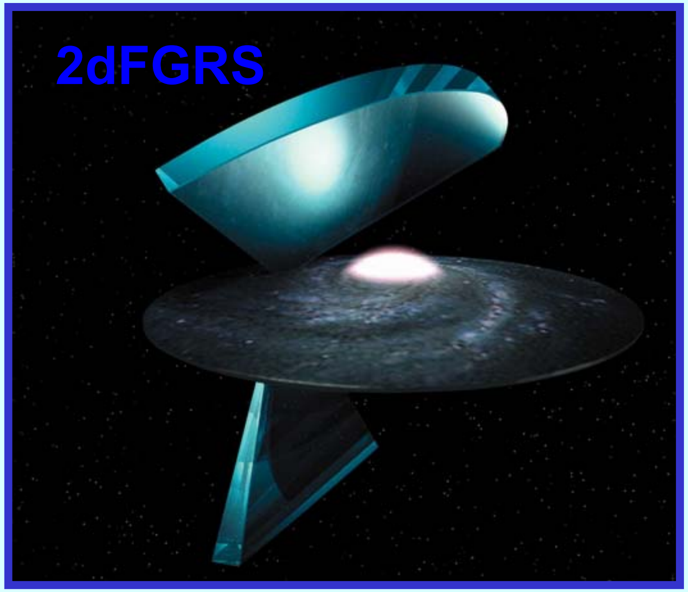
K2K is confirming the atmospheric neutrinos oscillation with man made neutrinos. They should reach the 3.5σ level in 2005 ($10\ 10^{19}$ POT).

The atmospheric precision era will start with the launching of MINOS (2005).



Cosmology

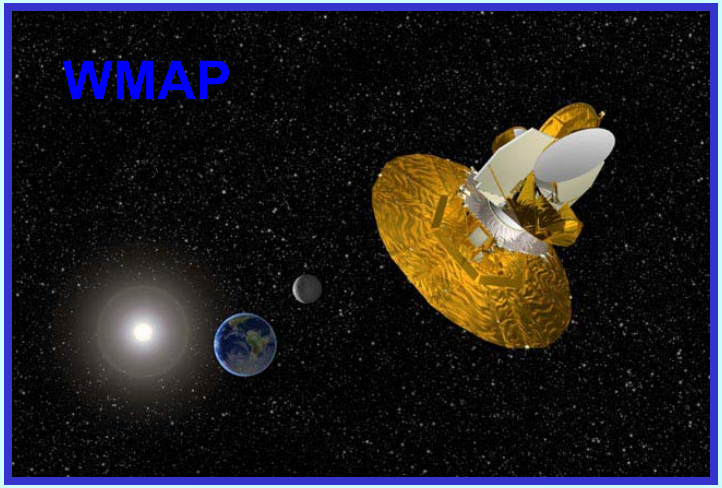
Cosmology and ν masses



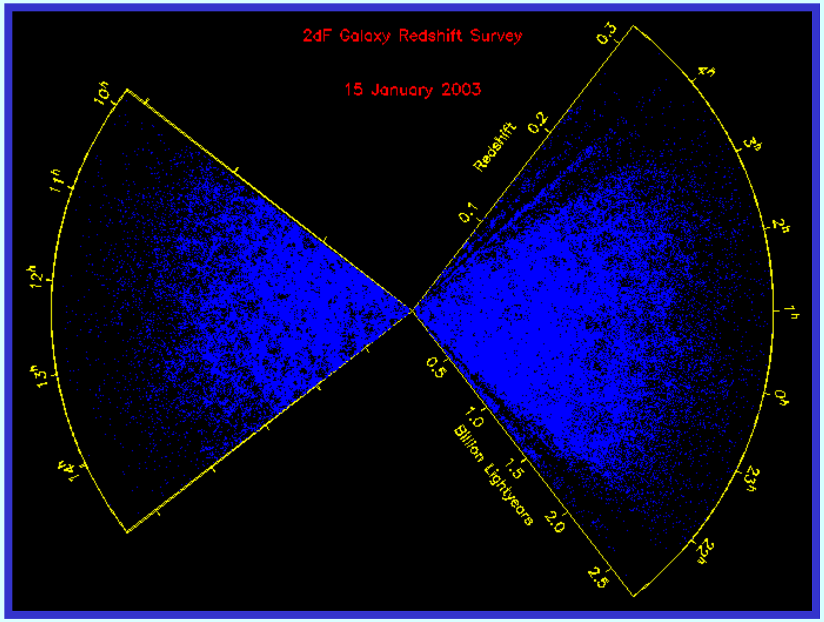
$$\sum_i m_i \leq 0.71\,\text{eV}$$

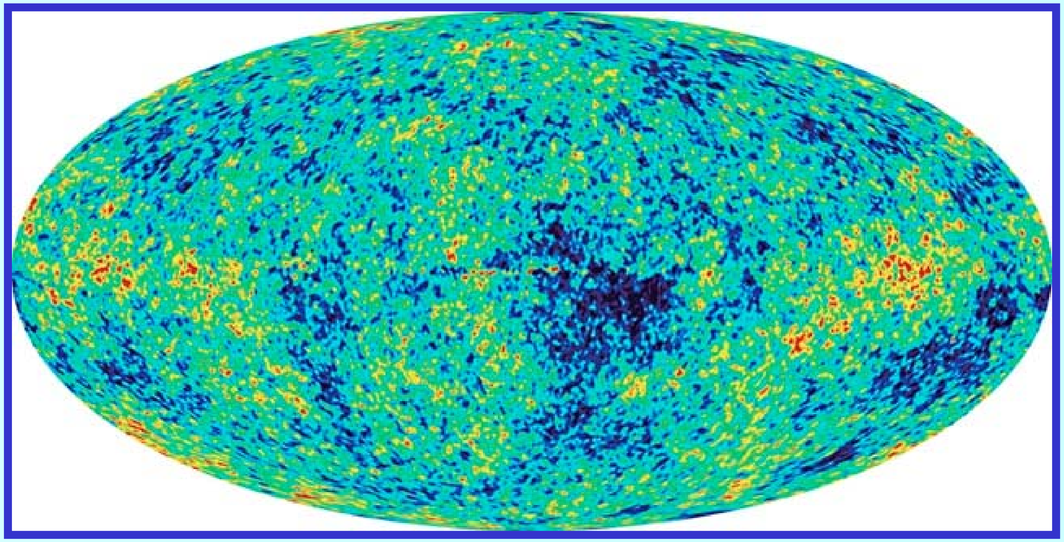
$$\boxed{\sum_i m_i \leq 1.01\,\text{eV}^{*}}$$

(95 % CL)



*S. Hannestad, JCAP 05(2003)004





The next steps

Neutrino Parameters to be measured

Δm^2_{12} ● ☜ Solar+KamLAND
$6.10^{-5} < \Delta m^2_{12}(eV^2) < 2.10^{-4}$

θ_{12} ● ☜ Solar+KamLAND
$0.2 < \sin^2\theta_{12} < 0.5$

Δm^2_{23} ● ☜ SK+K2K
$\Delta m^2_{23} = (2.6 \pm 0.7) 10^{-3} eV^2$

θ_{23} ● ☜ SK
$0.9 < \sin^2 2\theta_{23} < 1$

δ_{CP} ❍ ⌛

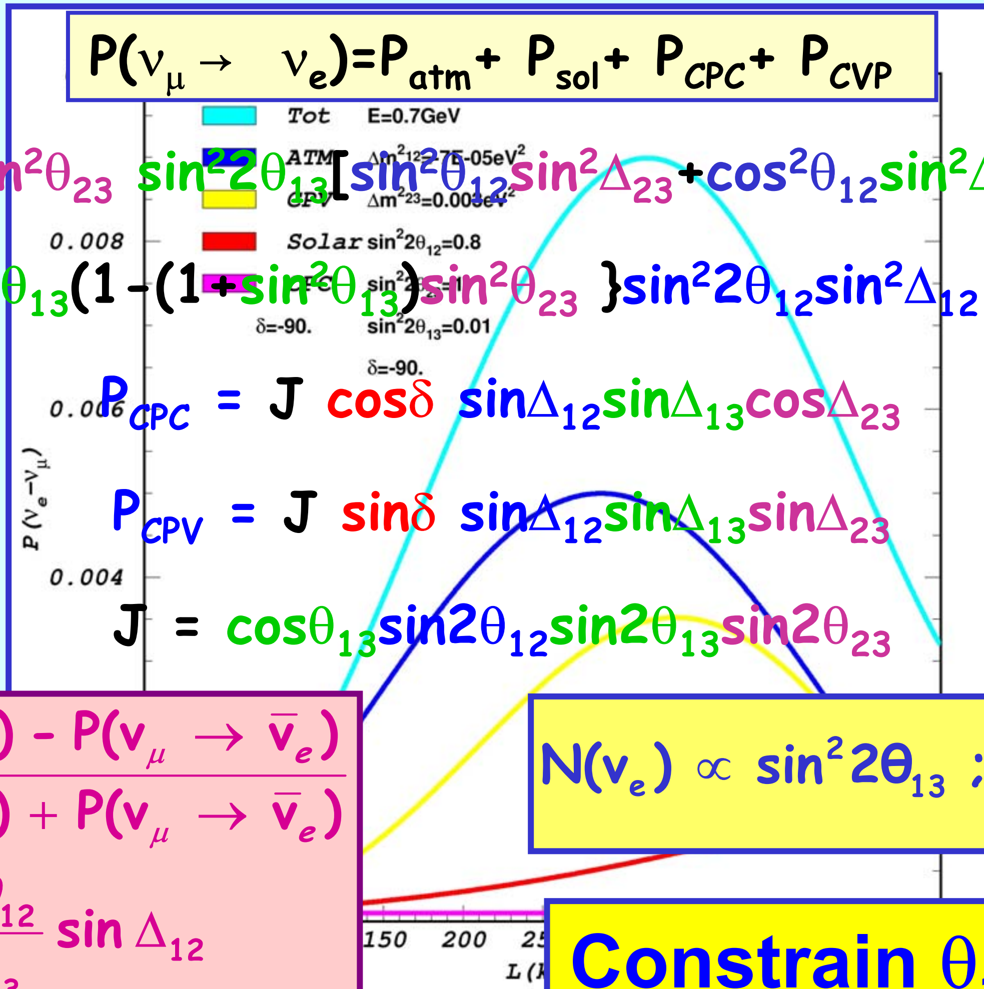
θ_{13} ❍ ⌛
$\sin^2 2\theta_{13} < 0.1$ (CHOOZ)

Mass Hierarchy ❍ ⌛

Majorana/Dirac ❍ ⌛

Σm_ν ❍ ⌛
$\Sigma m_\nu < 6.6$ eV (Mainz)

Opening the road to CP violation
Sub-leading appearance $\nu_\mu \rightarrow \nu_e$



$$P(\nu_\mu \rightarrow \nu_e) = P_{atm} + P_{sol} + P_{CPC} + P_{CVP}$$

$$P_{atm} = \sin^2\theta_{23}\ \sin^2 2\theta_{13} [\sin^2\theta_{12} \sin^2\Delta_{23} + \cos^2\theta_{12} \sin^2\Delta_{13}]$$

$$P_{sol} = \{\cos^2\theta_{13}(1-(1+\sin^2\theta_{13})\sin^2\theta_{23}\ \} \sin^2 2\theta_{12} \sin^2\Delta_{12}$$

$$P_{CPC} = J\ \cos\delta\ \sin\Delta_{12} \sin\Delta_{13} \cos\Delta_{23}$$

$$P_{CPV} = J\ \sin\delta\ \sin\Delta_{12} \sin\Delta_{13} \sin\Delta_{23}$$

$$J = \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23}$$

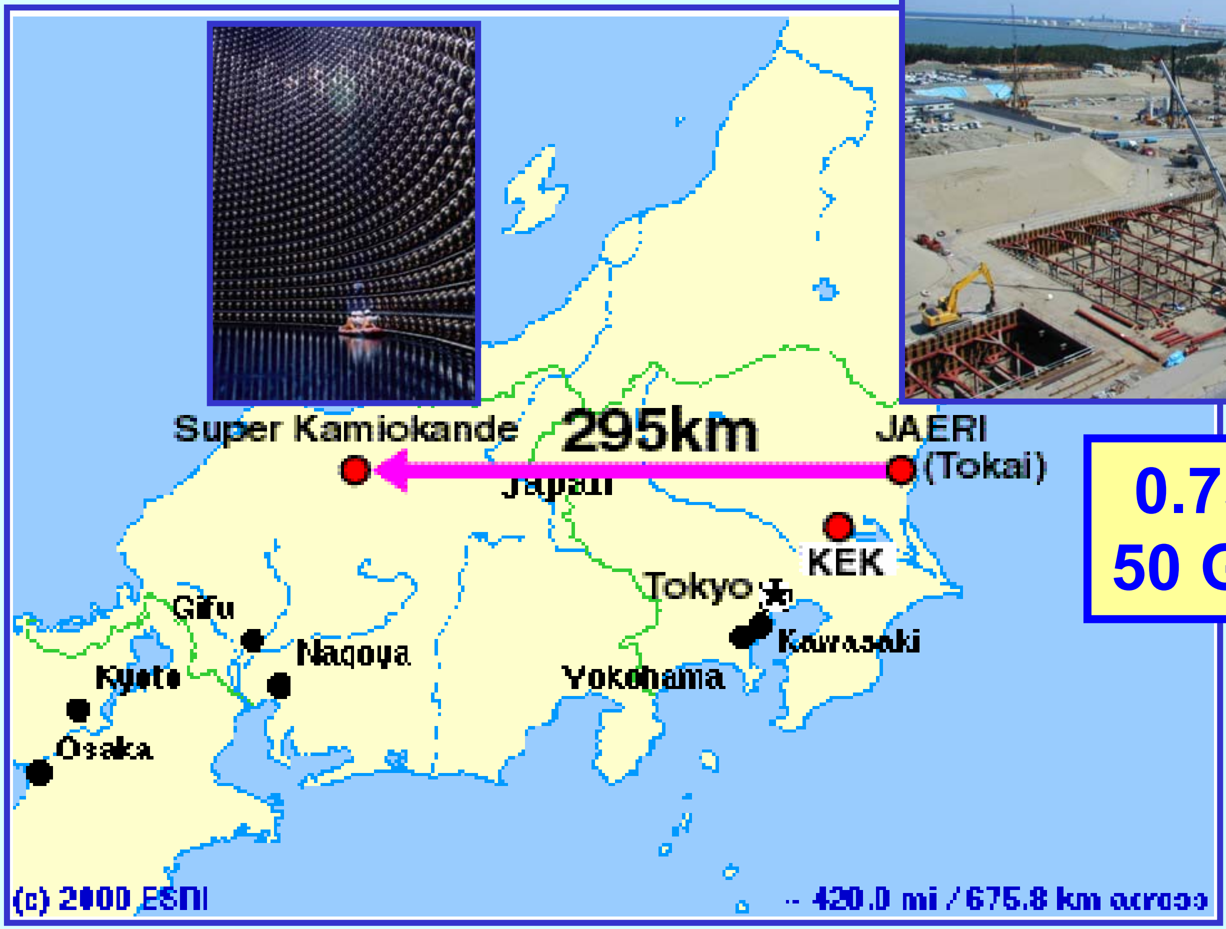
$$A_{CP} = \frac{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) - P(\nu_\mu \rightarrow \bar{\nu}_e)}{P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) + P(\nu_\mu \rightarrow \bar{\nu}_e)}$$

$$A_{CP} = \sin\delta \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \sin\Delta_{12}$$

$$N(\nu_e) \propto \sin^2 2\theta_{13}\ ;\ A_{CP} \propto \frac{1}{\sin\theta_{13}}$$

Constrain θ_{13} first !

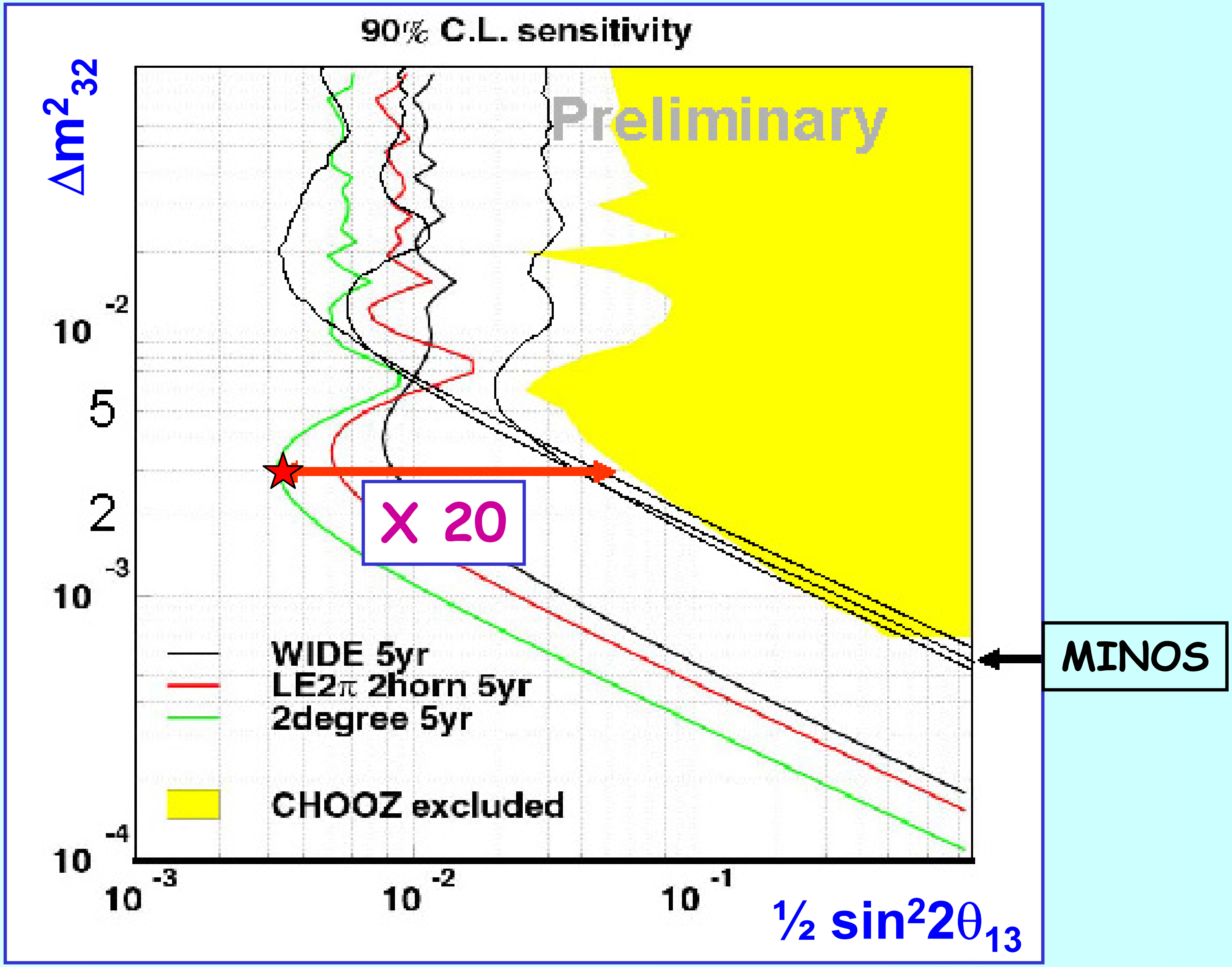
JHF-Kamioka Neutrino Experiment



0.75MW
50 GeV PS

2008 ~ K2K × 140
Super-K2K

ν_e Apparearance @ JHF



More ?

Solar

SNO Run Sequence

The Three Phases	Neutron Detection Method
Pure D_2O — Nov. 1999- May 2001 – Good CC sensitivity	Capture on D $n + d \rightarrow t + \gamma \ldots \rightarrow e^-$ (E_γ = 6.3 MeV)
Added Salt in D_2O – Enhanced NC sensitivity Counting Since June 2001	Capture on Cl $n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma \ldots \rightarrow e^-$ ($E_{\Sigma\gamma}$ = 8.6 MeV)
Neutral Current Detectors – ^{3}He proportional counters in the D_2O	Capture on ^{3}He $n + {}^3He \rightarrow p + t$ Event by event separation of CC and NC events

$\bar{\nu}_e$ Event Selection in KamLAND

Inverse β - decay selection

E_{prompt} > 2.6 MeV

no OD signals

0.5 <ΔT<660 μ sec

ΔR<1.6m

1.8<E_{delay}<2.6 MeV

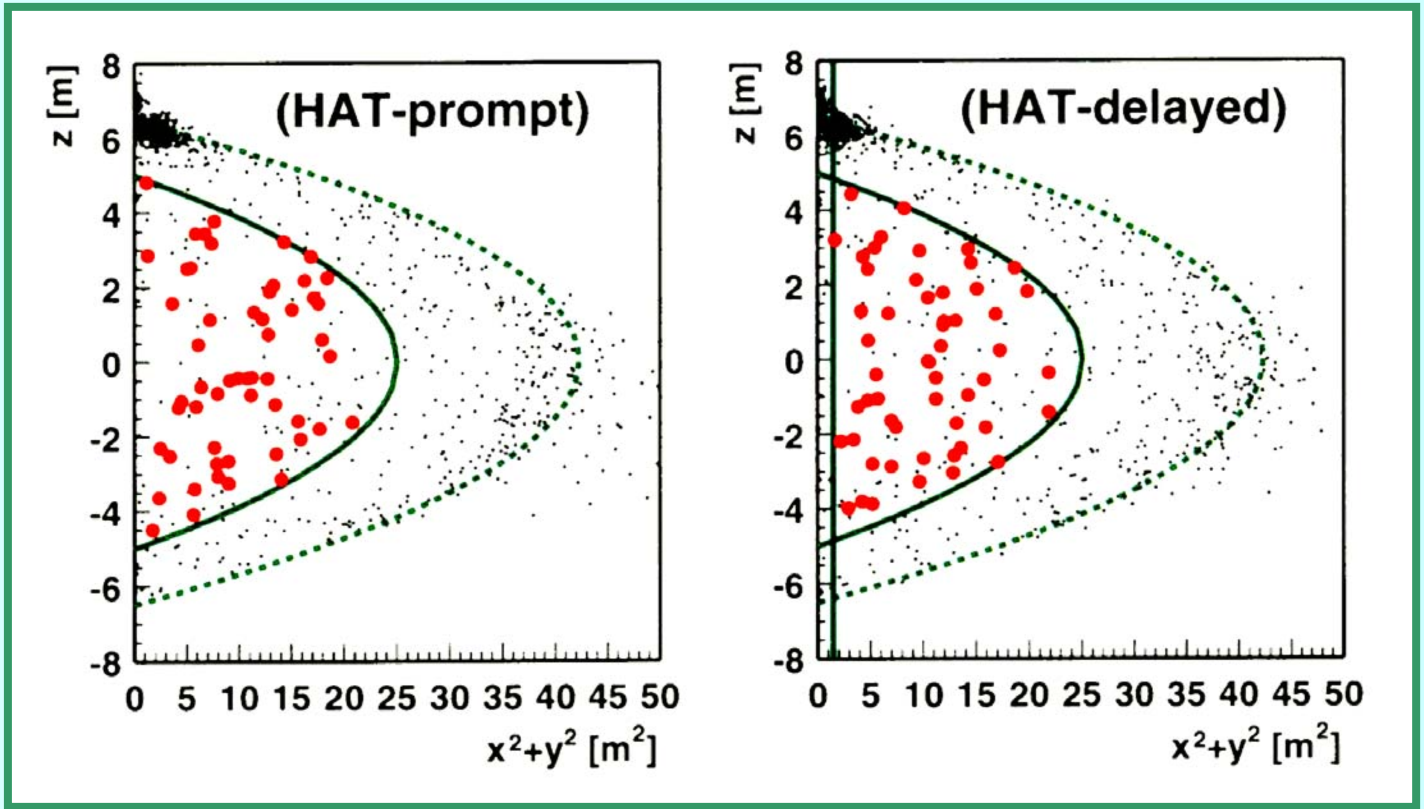
Fiducial Cut

R<5m: 408 tons

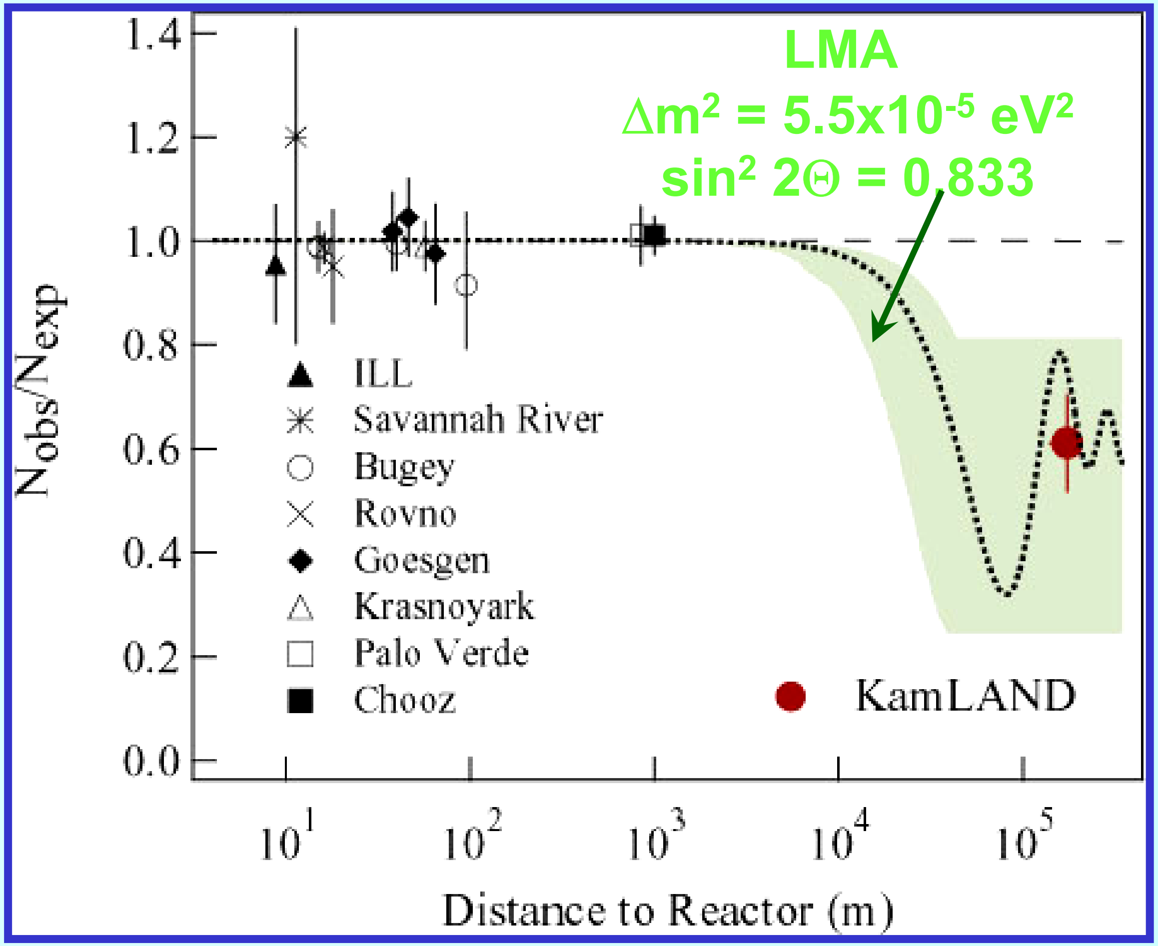
Rejection of μ-induced spallation β,n emmitter

ΔT_{μ} < 2sec , ΔE_{μ} >3 GeV

or ΔR_{μ}<3m



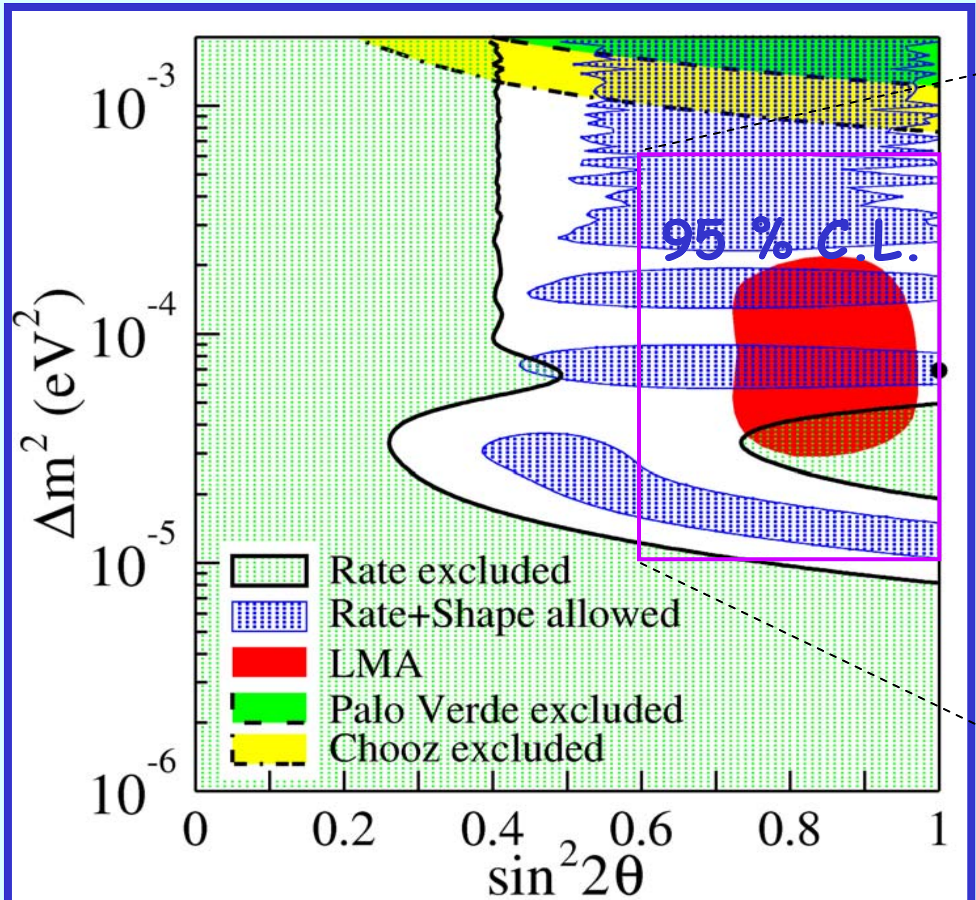
Measured/Expected Flux from Reactor Neutrino Experiments

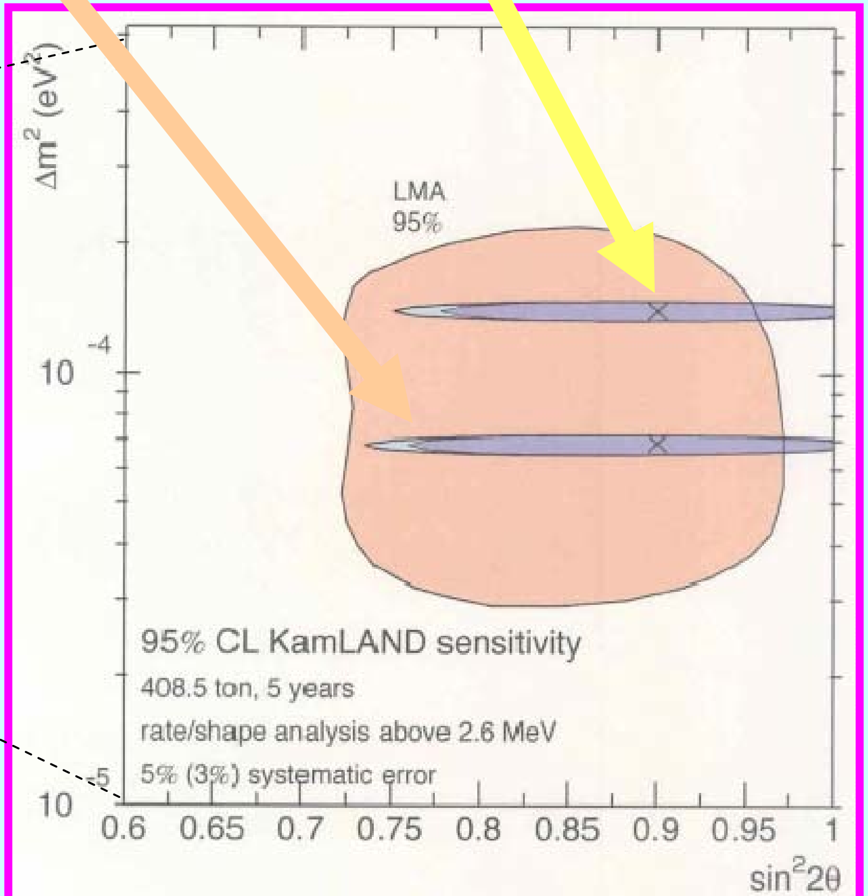


KamLAND after 5 years

LMA-I
6.4 10^{-5} <Δm^2 (eV^2)<7.2 10^{-5}
@95%CL

LMA-II
1.3 10^{-4} <Δm^2 (eV^2)<1.5 10^{-4}
@95%CL

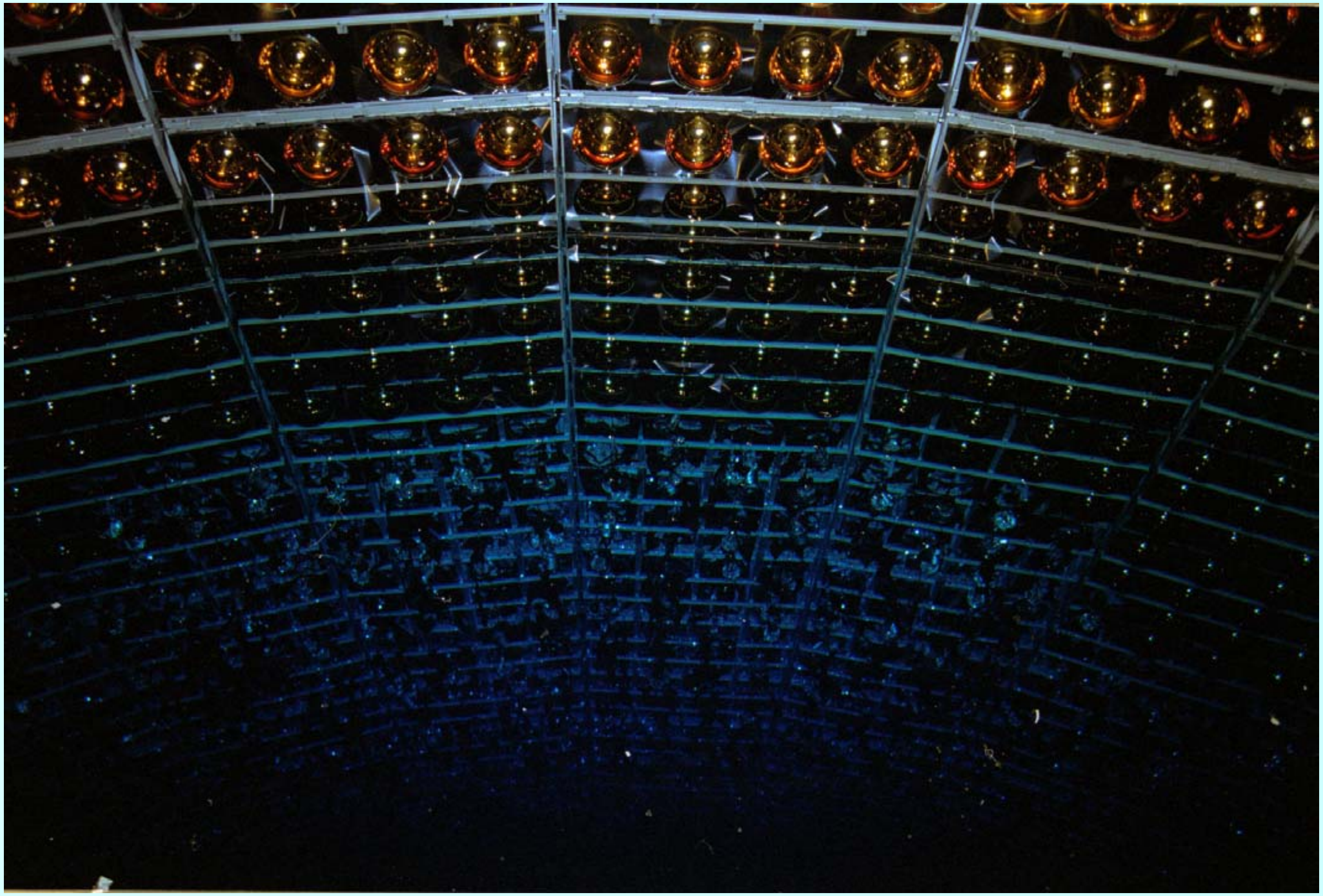




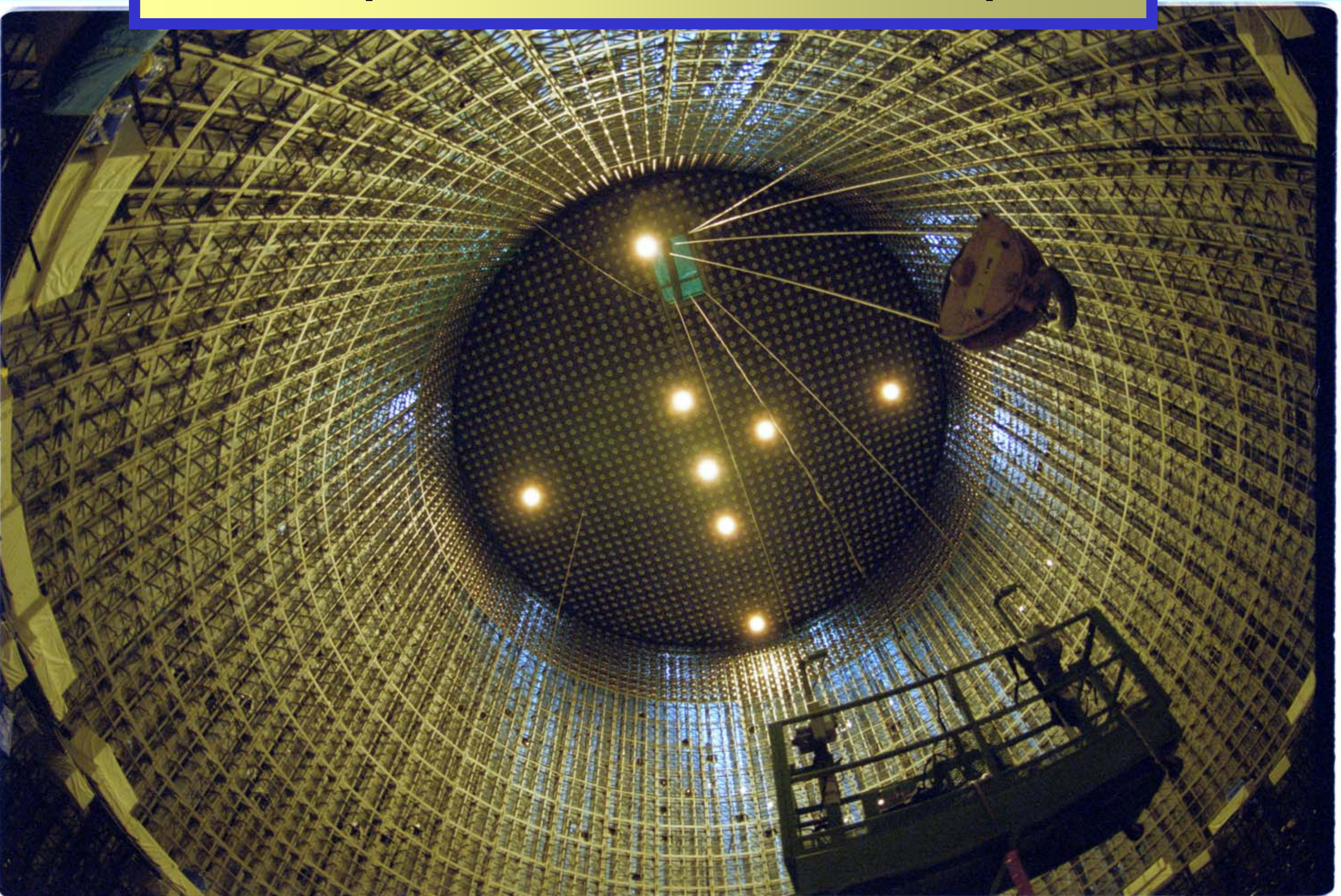
Atmospherics

Super-K accident and rebuild

12th of November, 2001

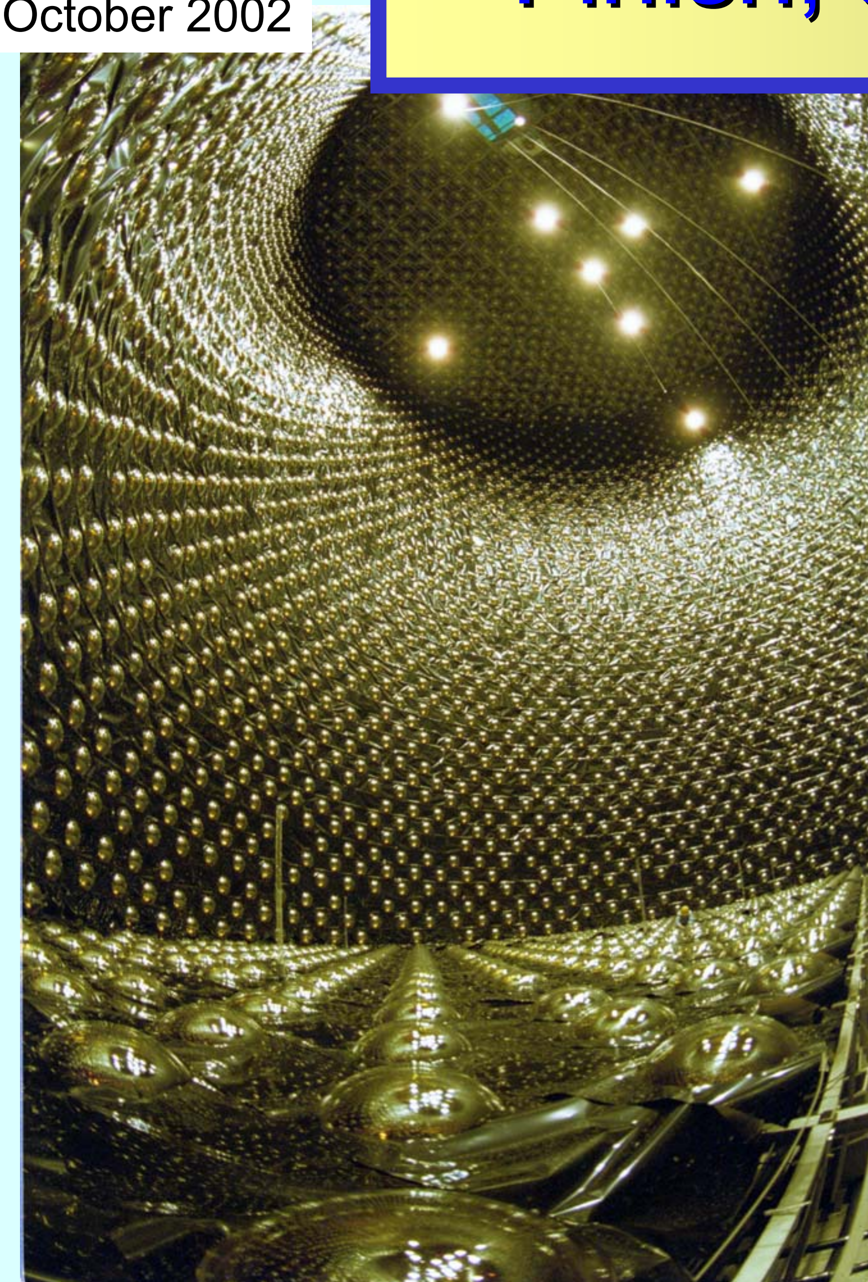


Super-K after clean-up



Finish, and work again

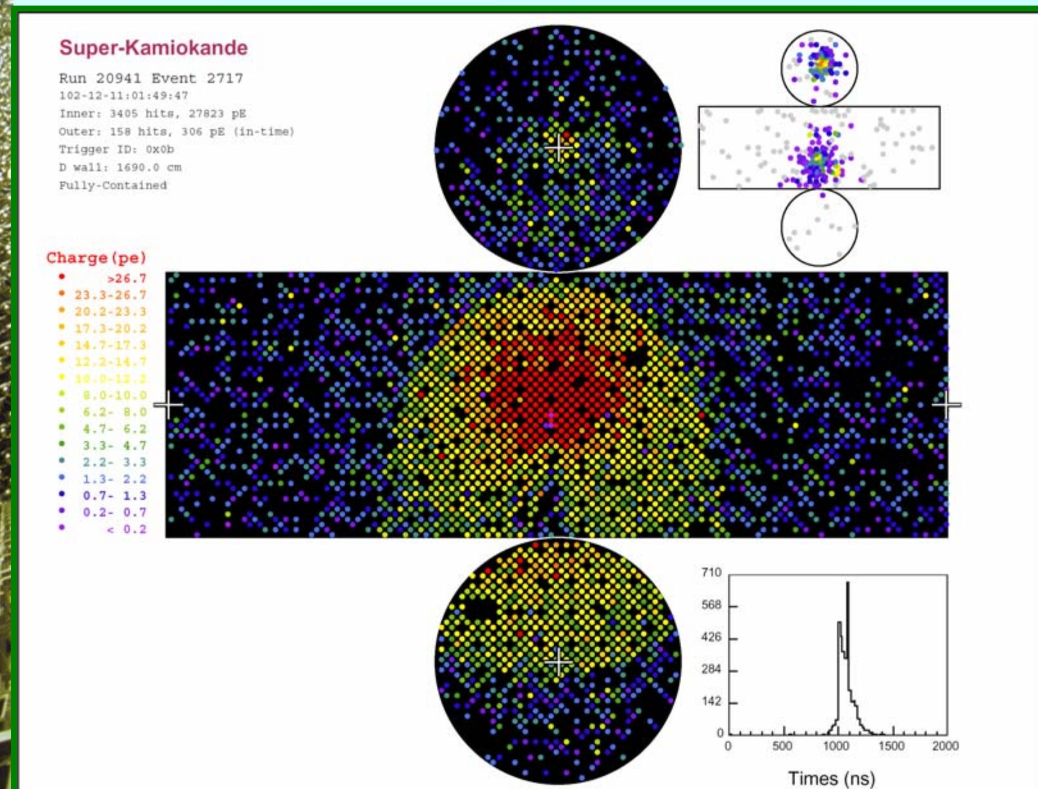
October 2002



Fill water from Oct. to Dec, 2002

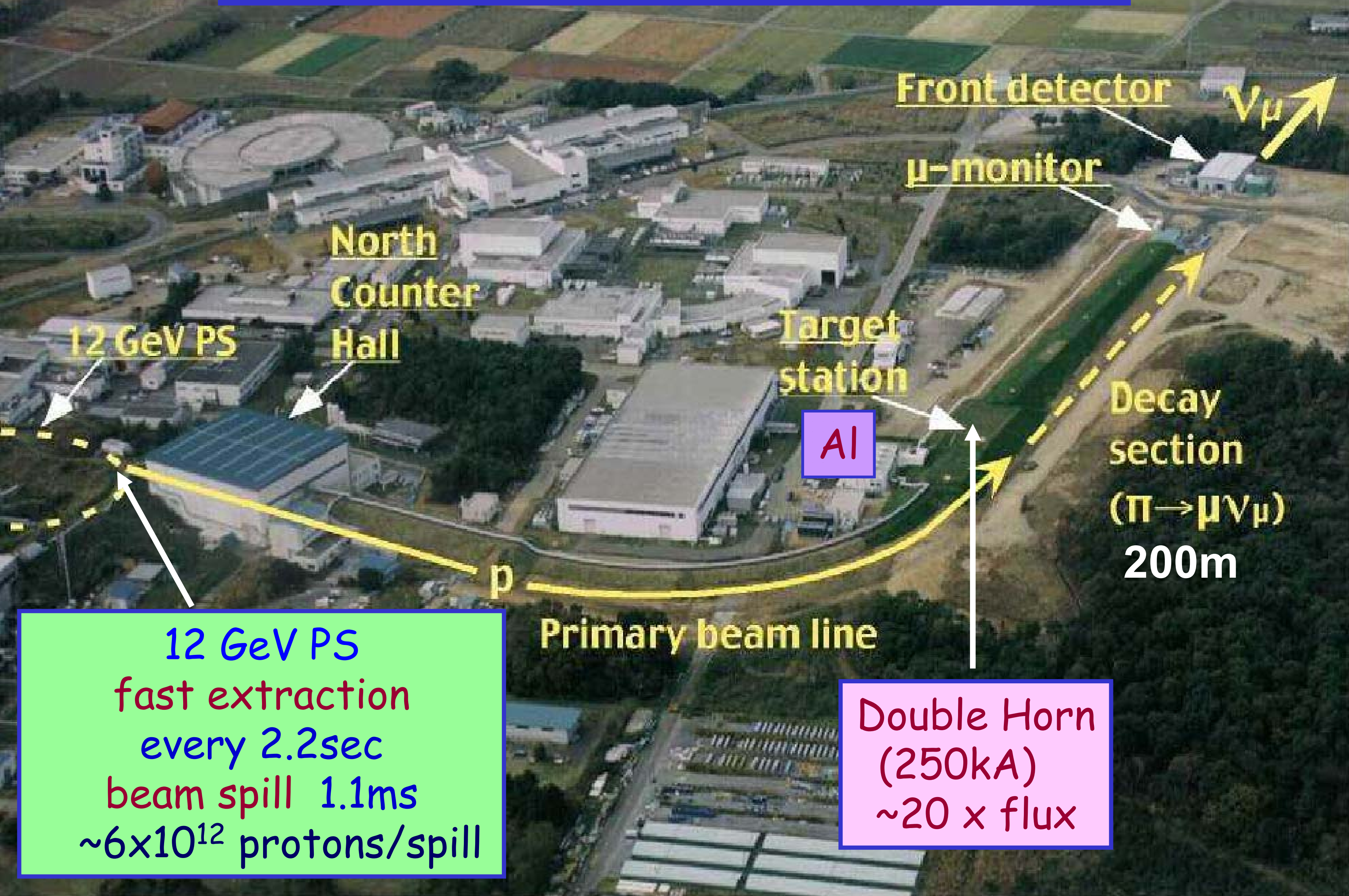
↓

Start data taking from 10th of December,2002

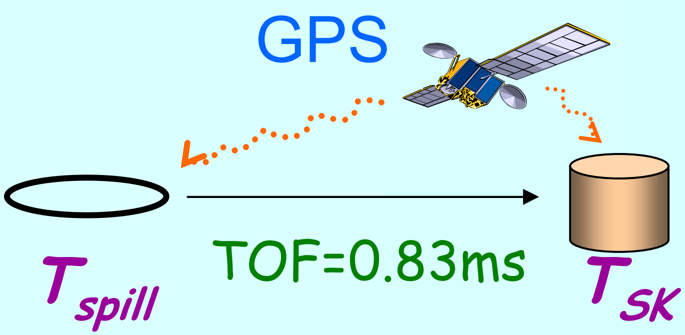


Cosmic ray muon sample

KeK Neutrino beamline



Event selection @ SK

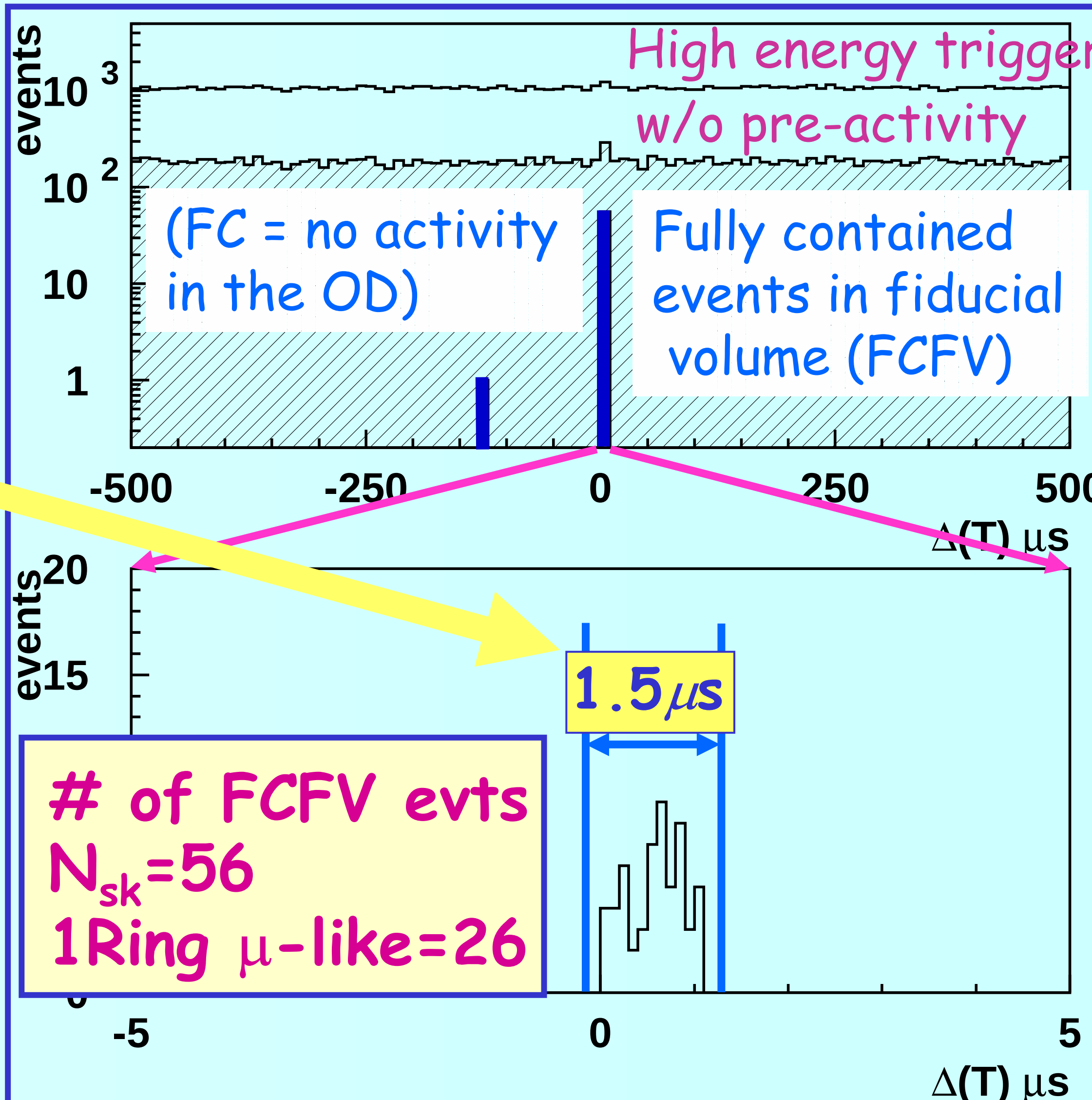


$\Delta T = T_{SK} - T_{spill} - TOF$

$-0.2\mu s < \Delta T < 1.3\mu s$

Expected # of atmospheric ν BG <10^{-3} events

June '99 to July '01 (4.8×10^{19} POT)



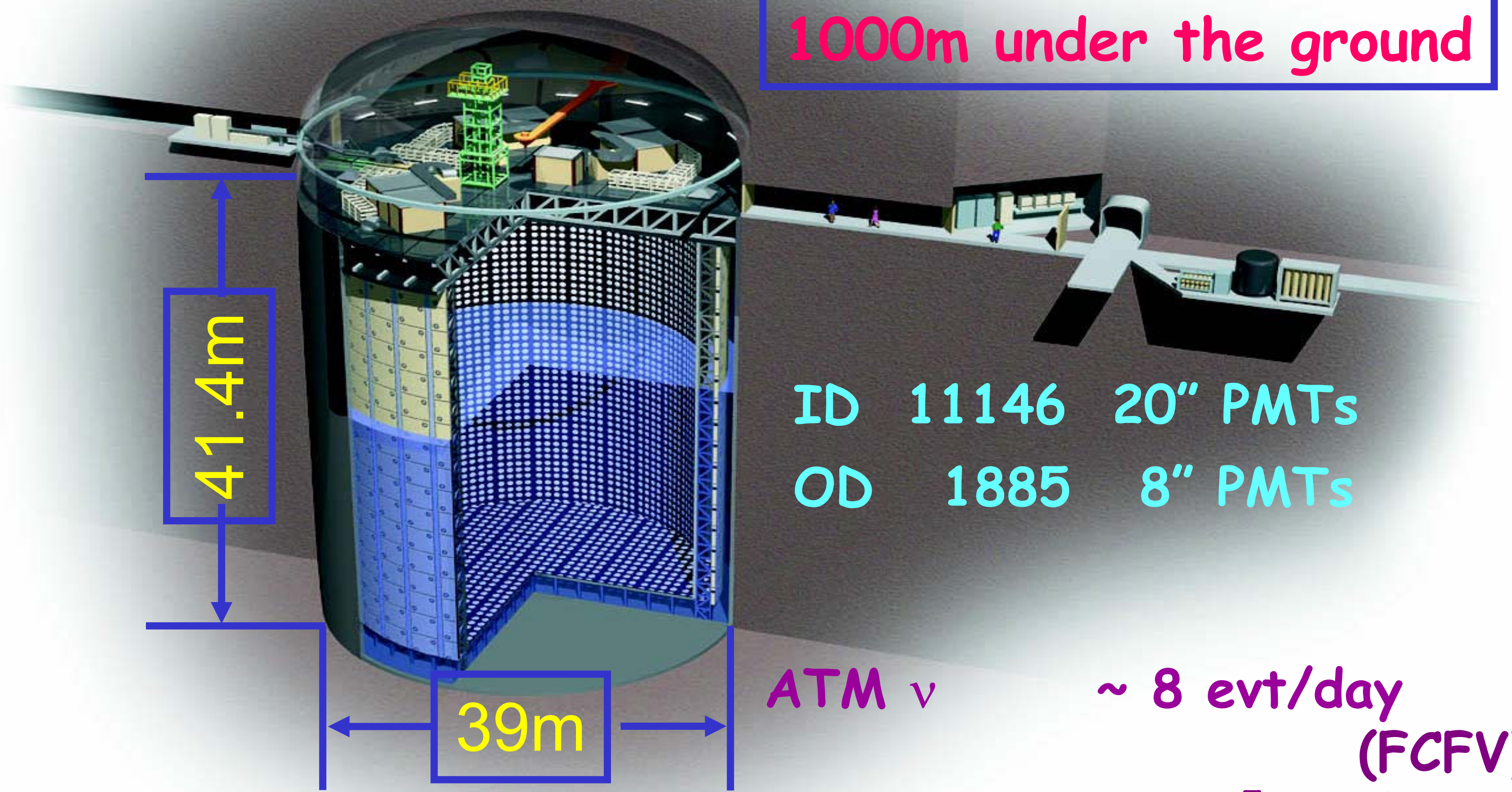
# of FCFV evts

N_{sk}=56

1Ring μ-like=26

Super-Kamiokande (Far detector)

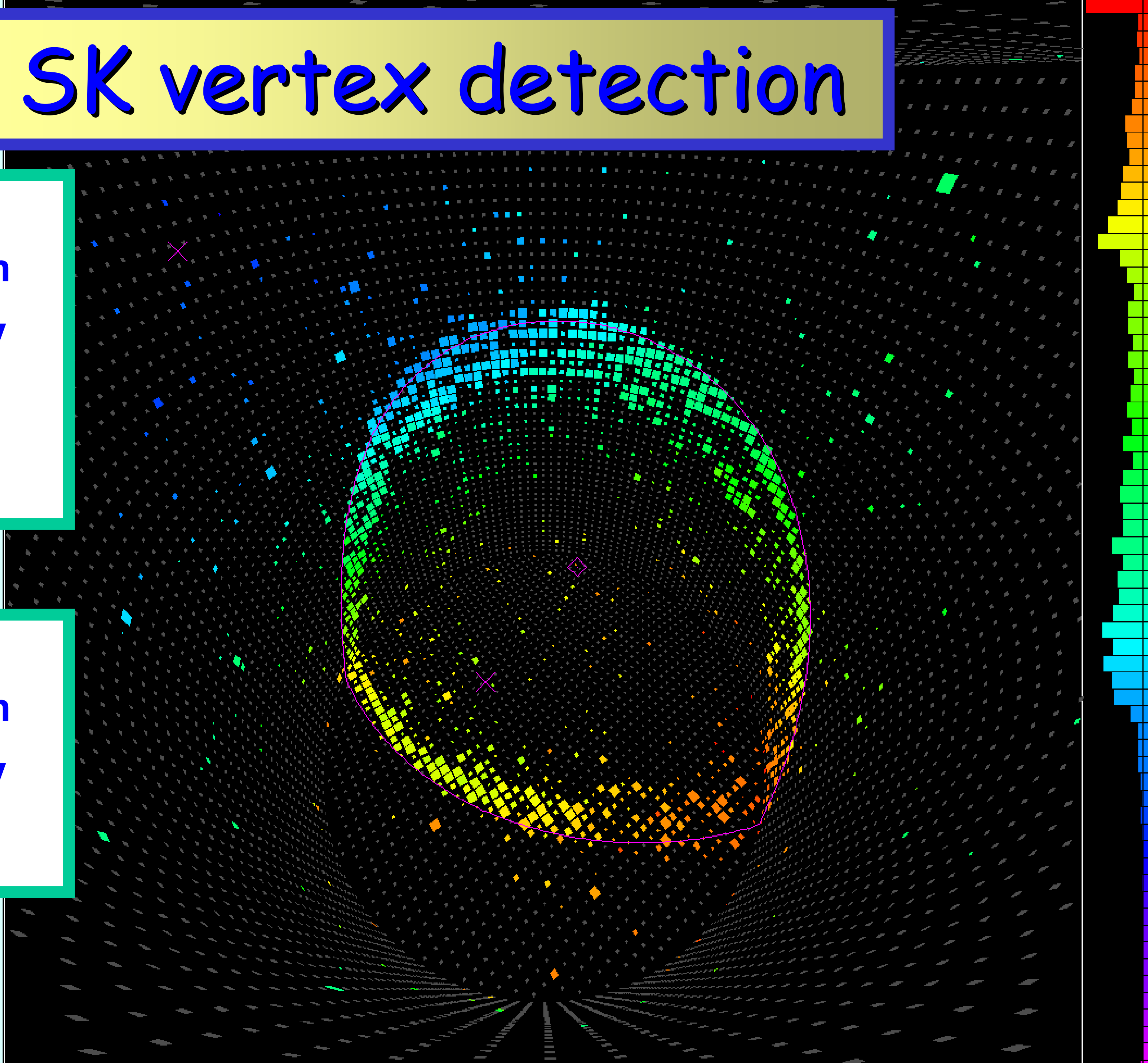
50kt H_2O Cerenkov
Fiducial volume 22.5kt
1000m under the ground



ID 11146 20" PMTs
OD 1885 8" PMTs

ATM ν ~ 8 evt/day (FCFV)
Accidentals ~ 10^{-5} evt/day

SK vertex detection



Spatial Resolution

μ @ 1 GeV

30 cm

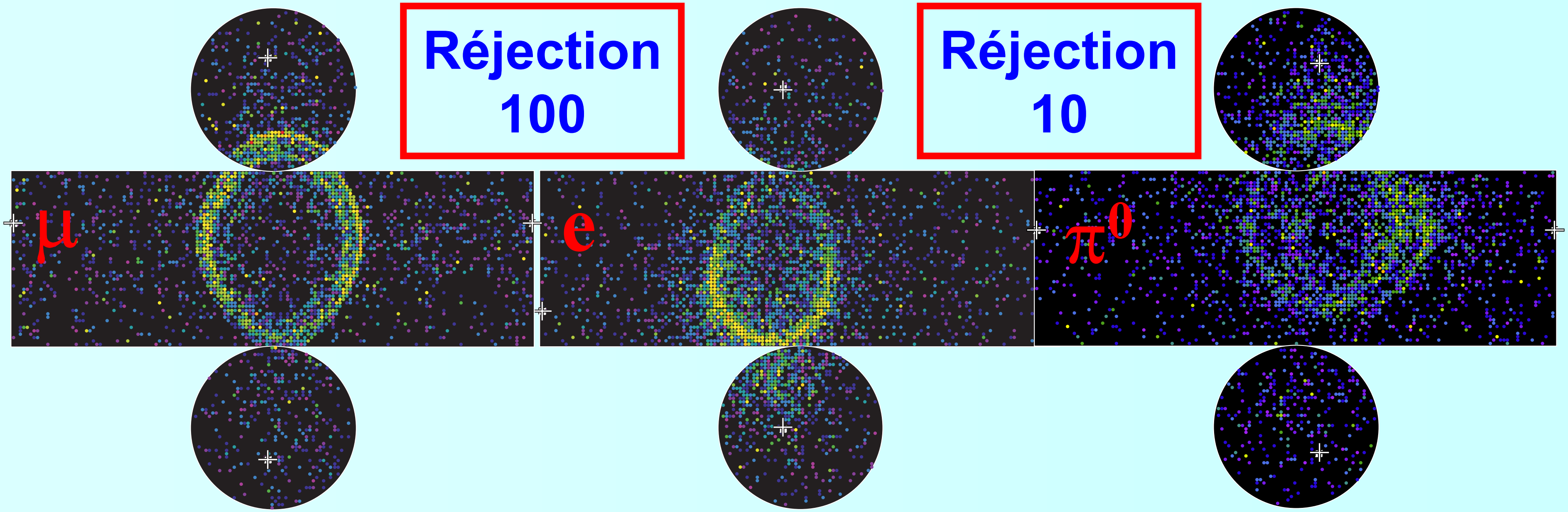
3° (Θ_μ)

Energy Resolution

μ @ 1 GeV

3% (E_μ)

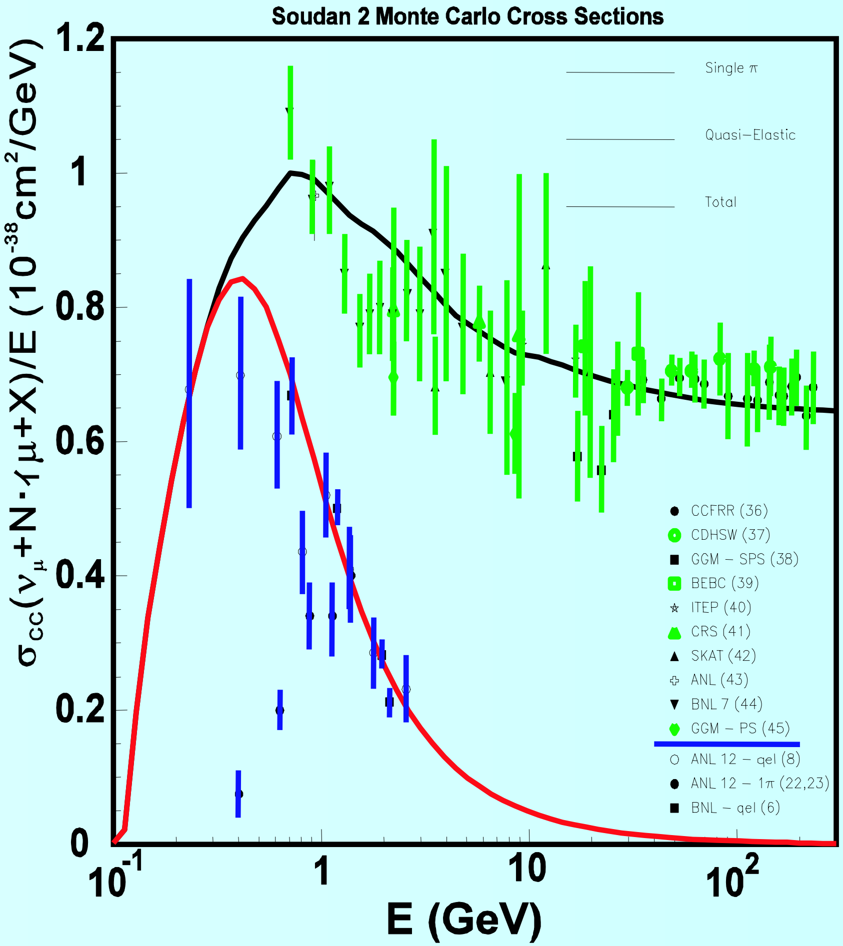
SK : Discrimination μ, e, π^0



Background for ν_e appearance :

- **Intrinsic beam ν_e du faisceau**
- **ν_μ CN inélastiques : 2 anneaux π^0 confondus**

SK : Eν ≤ 1GeV region

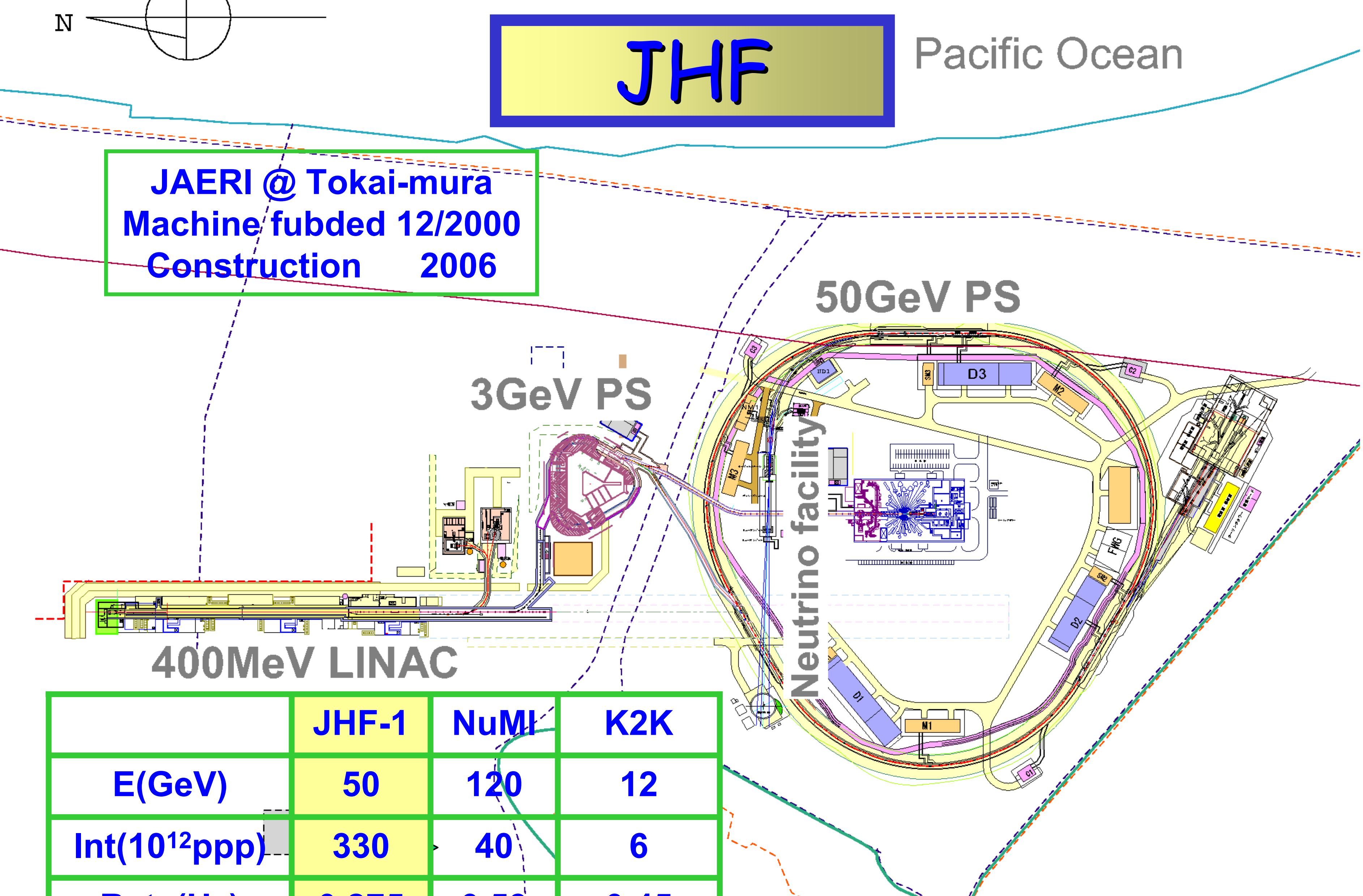


CC Interaction QE dominated below 1 GeV

JHF

JHF

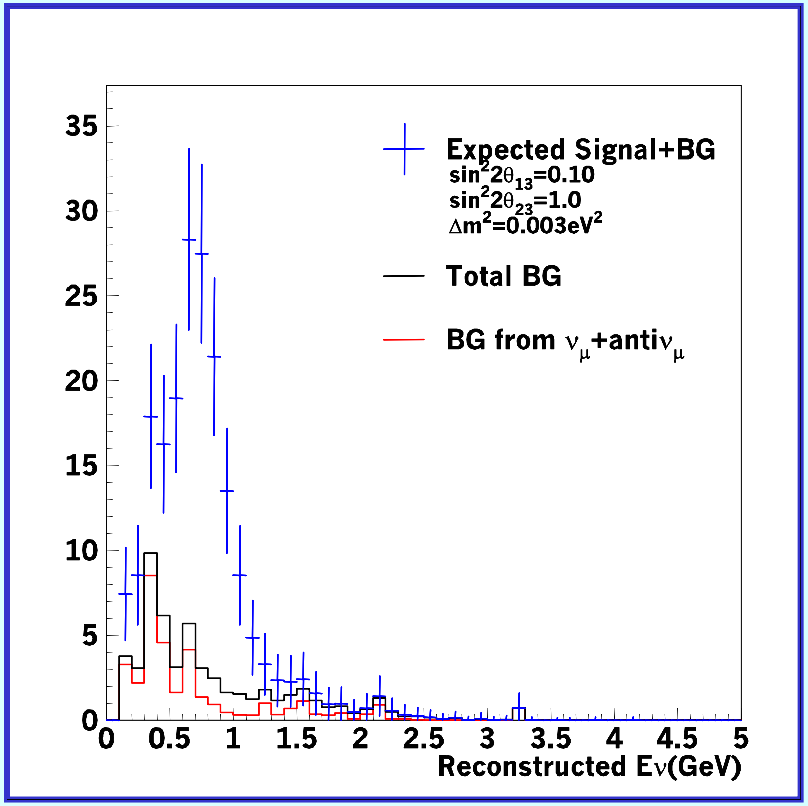
JAERI @ Tokai-mura
Machine fubded 12/2000
Construction 2006



	JHF-1	NuMI	K2K
E(GeV)	50	120	12
Int(10^{12}ppp)	330	40	6
Rate(Hz)	0.275	0.53	0.45
P(MW)	0.75	0.41	0.0052

ν_e Appearance : $\sin^2 2\theta_{13}$ measurement

OAB2° 5 ans 22.5kT	ν_μ (CC)	ν_μ (NC)	ν_e (Beam)	ν_e (Osc.)
Générés	10713	4080	292	301
0.4<E<1.2	1.8	9.3	11.1	123



$$\rho = \left[\frac{N^{Obs}_{\nu_e} - N^{fond}_{\nu_e}}{\varepsilon_{signal}}\right]\frac{1}{N^{CC}_{\nu_\mu}} = \frac{1}{2}\sin^2 2\theta_{13}\left\langle \sin^2\Phi_{23}\right\rangle$$

ε_{signal}=123/301=41% ; < $\sin^2\Phi_{23}$>=0.56

$$\frac{\sigma(\rho)^{stat}}{\rho} = \frac{\sqrt{145}}{123} = \frac{\delta\left(\sin^2 2\theta_{13}\right)}{\sin^2 2\theta_{13}} = 10\%$$

$$\frac{\sigma(\rho)^{syst}}{\rho} = \frac{\sigma(BG)}{BG}\cdot\frac{22}{123} = 1.8\% \ @ \ \frac{\sigma(BG)}{BG} = 10\%$$

$\sin^2 2\theta_{13}$ =0.1

$\delta\sin^2 2\theta_{13}$ =0.01

ν_e appearance : limit on $\sin^2 2\theta_{13}$

OAB2° 5 ans 22.5kT	ν_μ (CC)	ν_μ (NC)	ν_e (Beam)	ν_e (Osc.)
Générés	10713	4080	292	0
0.4<E<1.2	1.8	9.3	11.1	0

$$N_{\nu_e}^{Obs} = N_{\nu_e}^{fond} = 22$$

$$\sin^2 2\theta_{13} \le \frac{2}{\langle \sin^2 \Phi_{23} \rangle} 1.64 \left[\frac{\sqrt{N_{\nu_e}^{fond}}}{N_{\nu_\mu}^{CC}} \right] \frac{1}{\varepsilon_{signal}} = 0.006 \text{ @ } 90\%\text{CL}$$

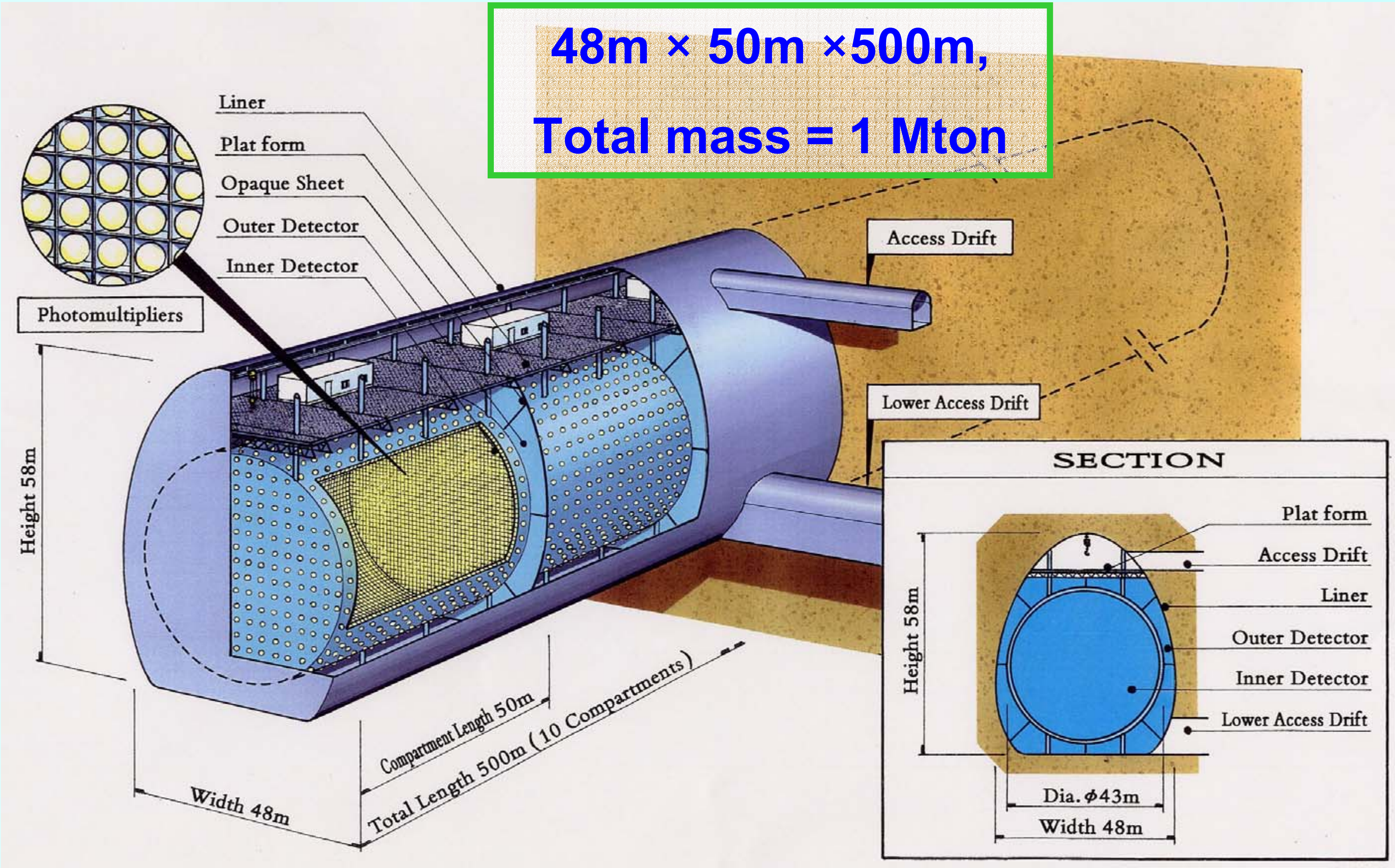
θ_{13} <2.2° @ 90% CL (stat.)

θ_{13} <2.3° @ 90% CL (stat.+syst 10%BG)

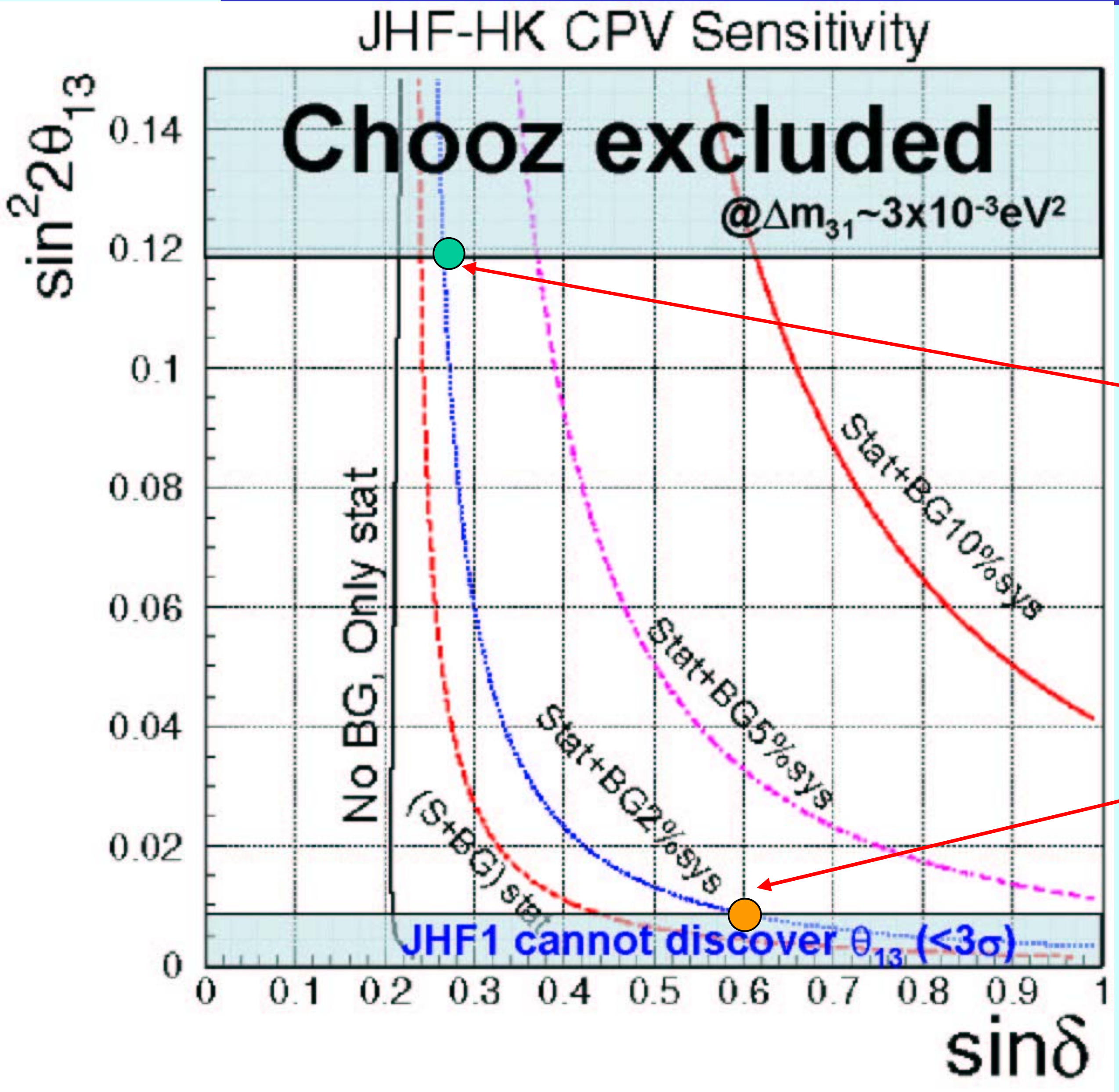
JHF-II : 4MW + HK

48m × 50m ×500m,

Total mass = 1 Mton



Sensitivity(3σ) to CPV



4MW,1Mt
2yr for ν_μ
6.8yr for $\bar{\nu}_\mu$

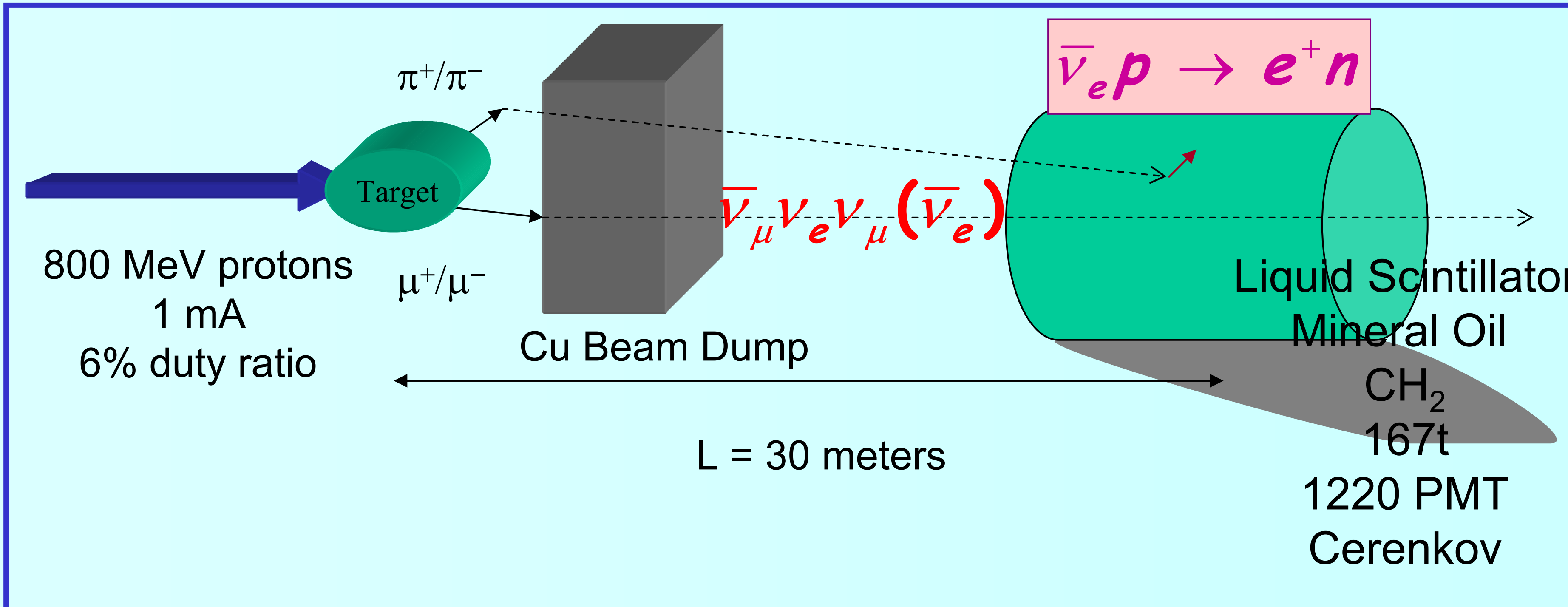
δ>~14°

δ>~27°

BG estimation

LSND & MiniBooNE

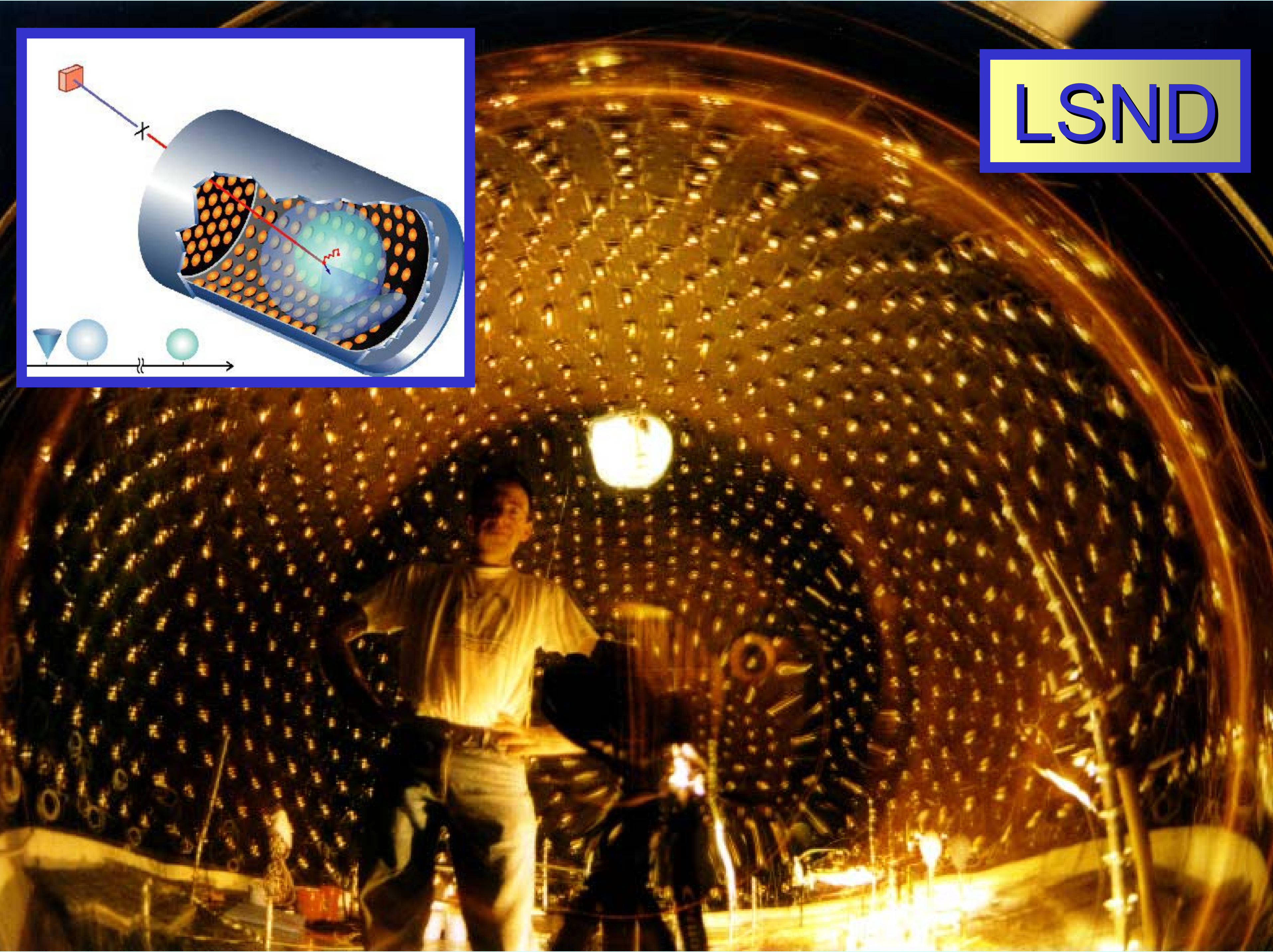
LSND



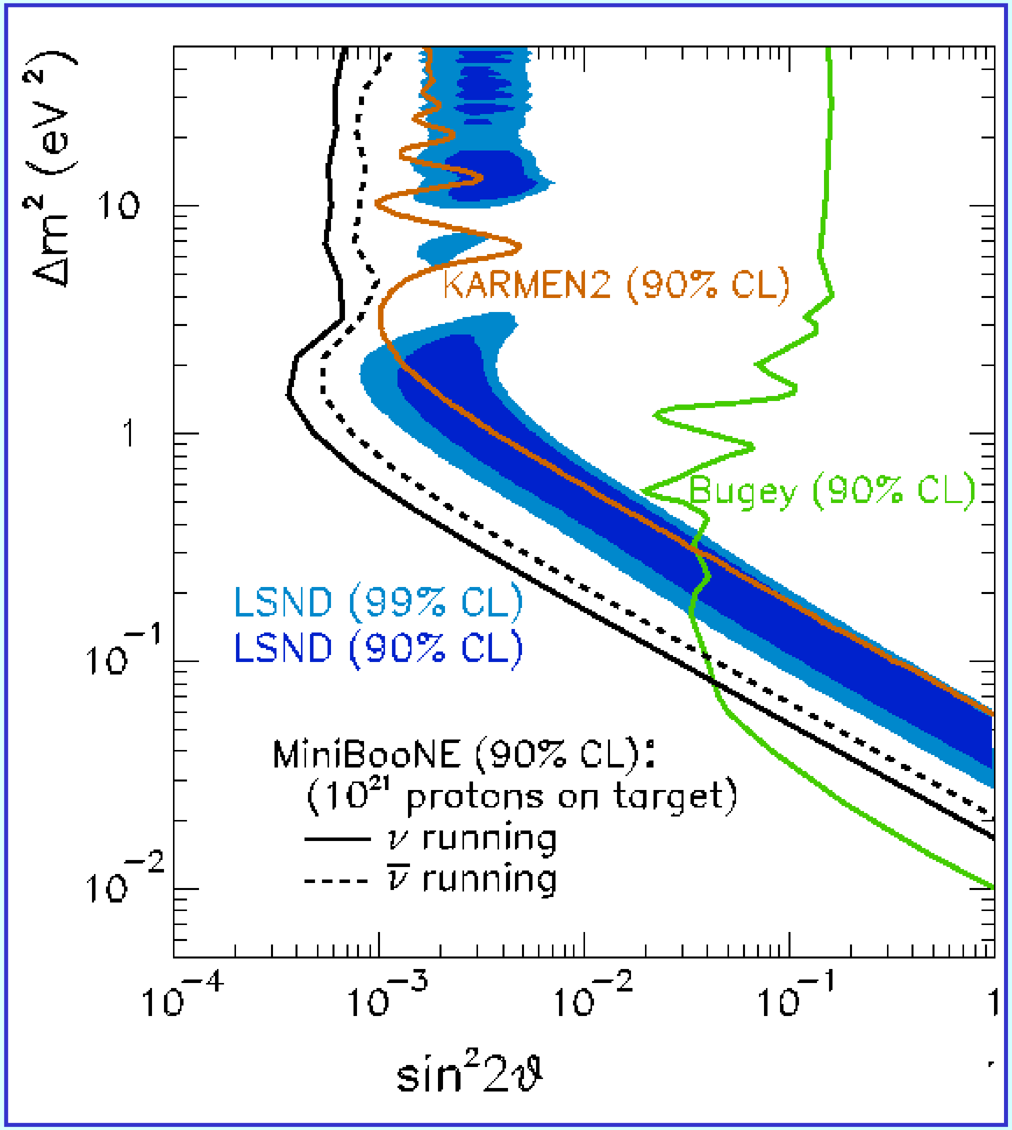
$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

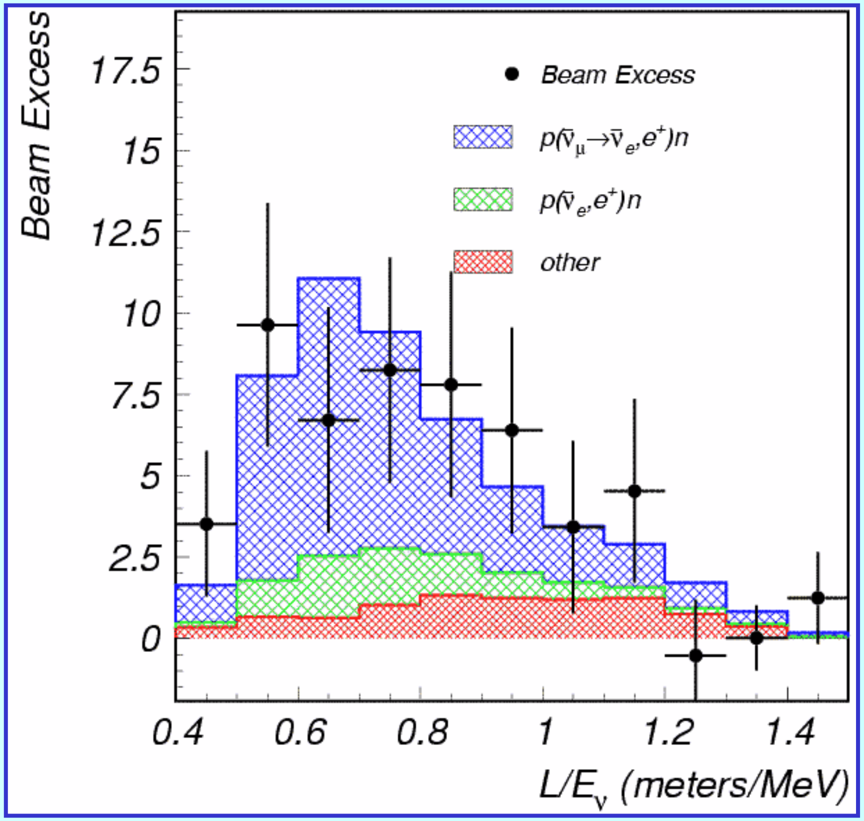
μ^+ decay at rest
prompt e^+ track, $20 < E_e < 60$ MeV
n capture: $np \rightarrow d\gamma$ (2.2MeV)

γ correlated in position and in time with e^+

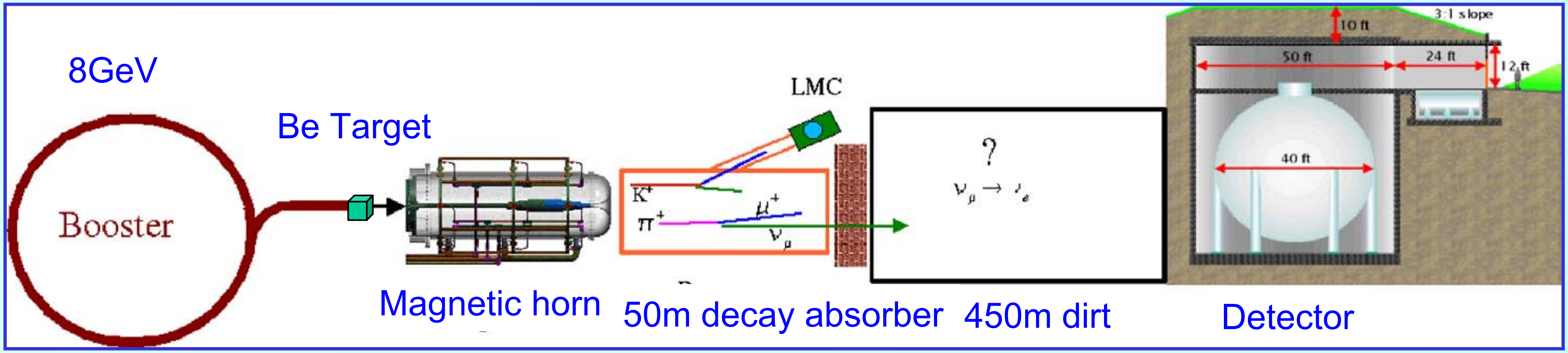

LSND

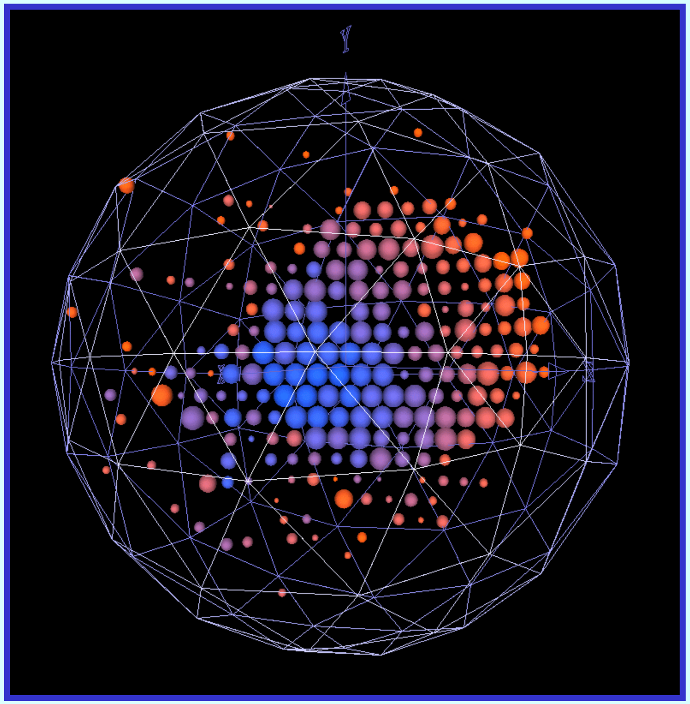
LSND & KARMEN Results





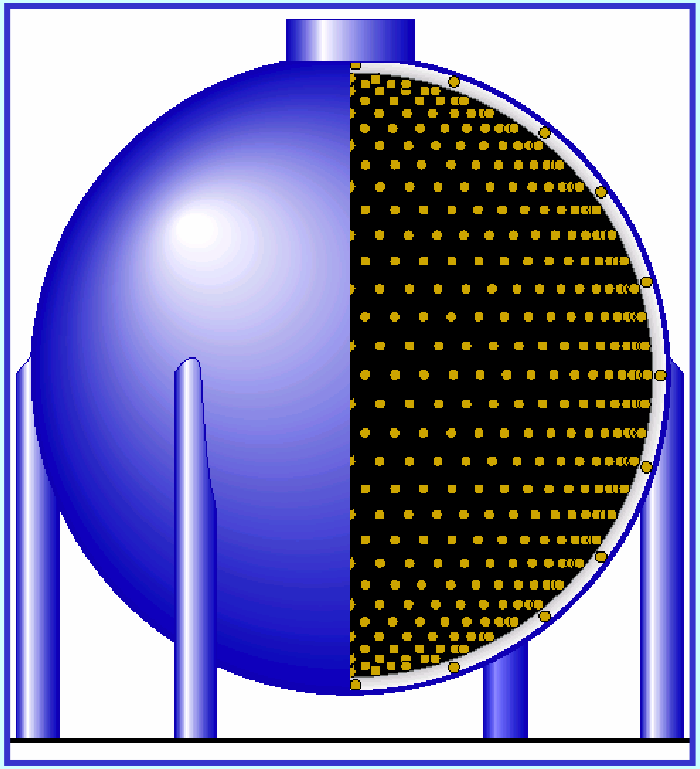
MiniBooNE





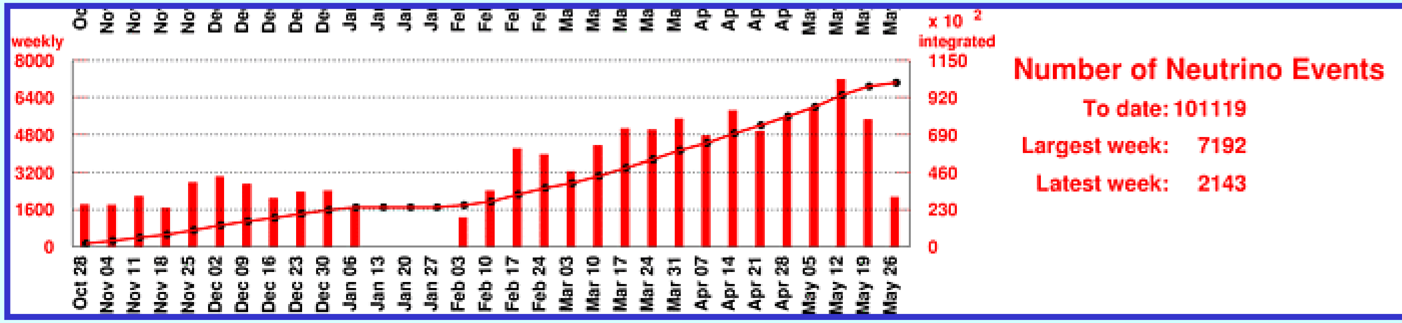
Cerenkov
800 tons
mineral oil
(6 m radius)
445 tons (fid.)
(5m radius)

1280 PMTs
10% coverage

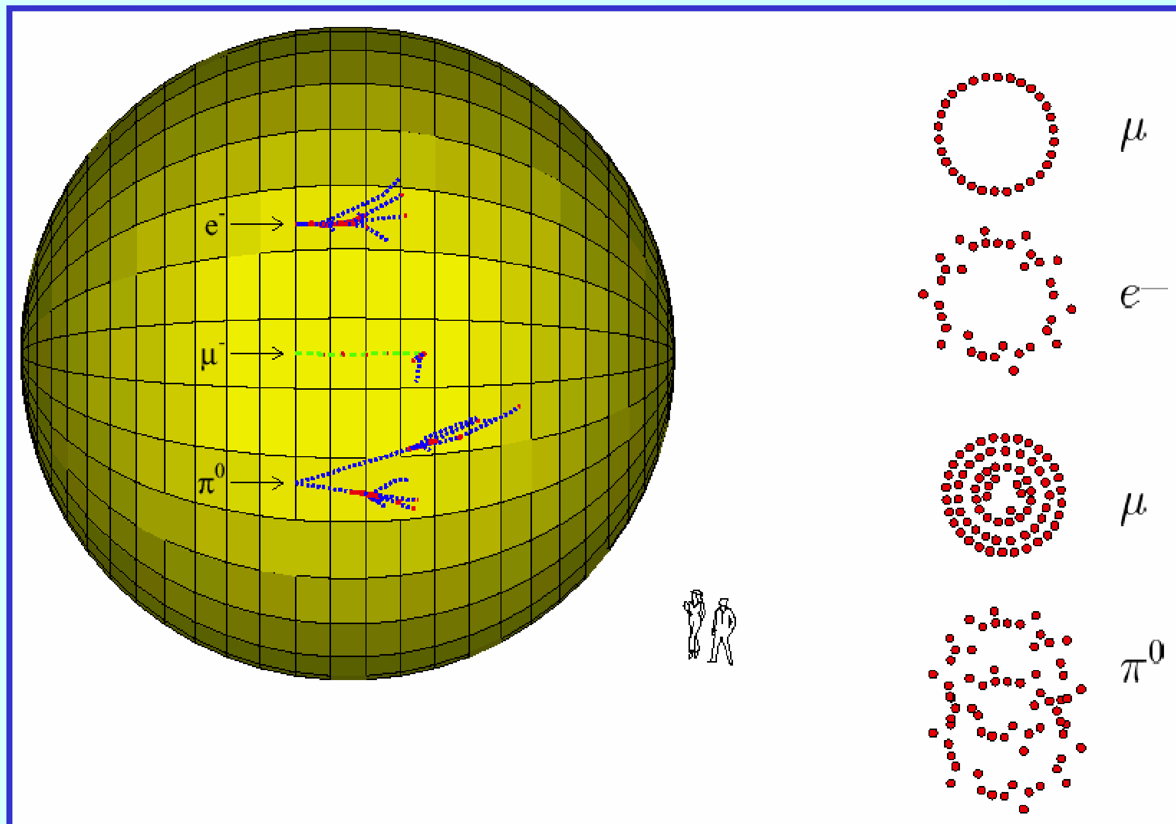


First neutrino events
September, 2002.

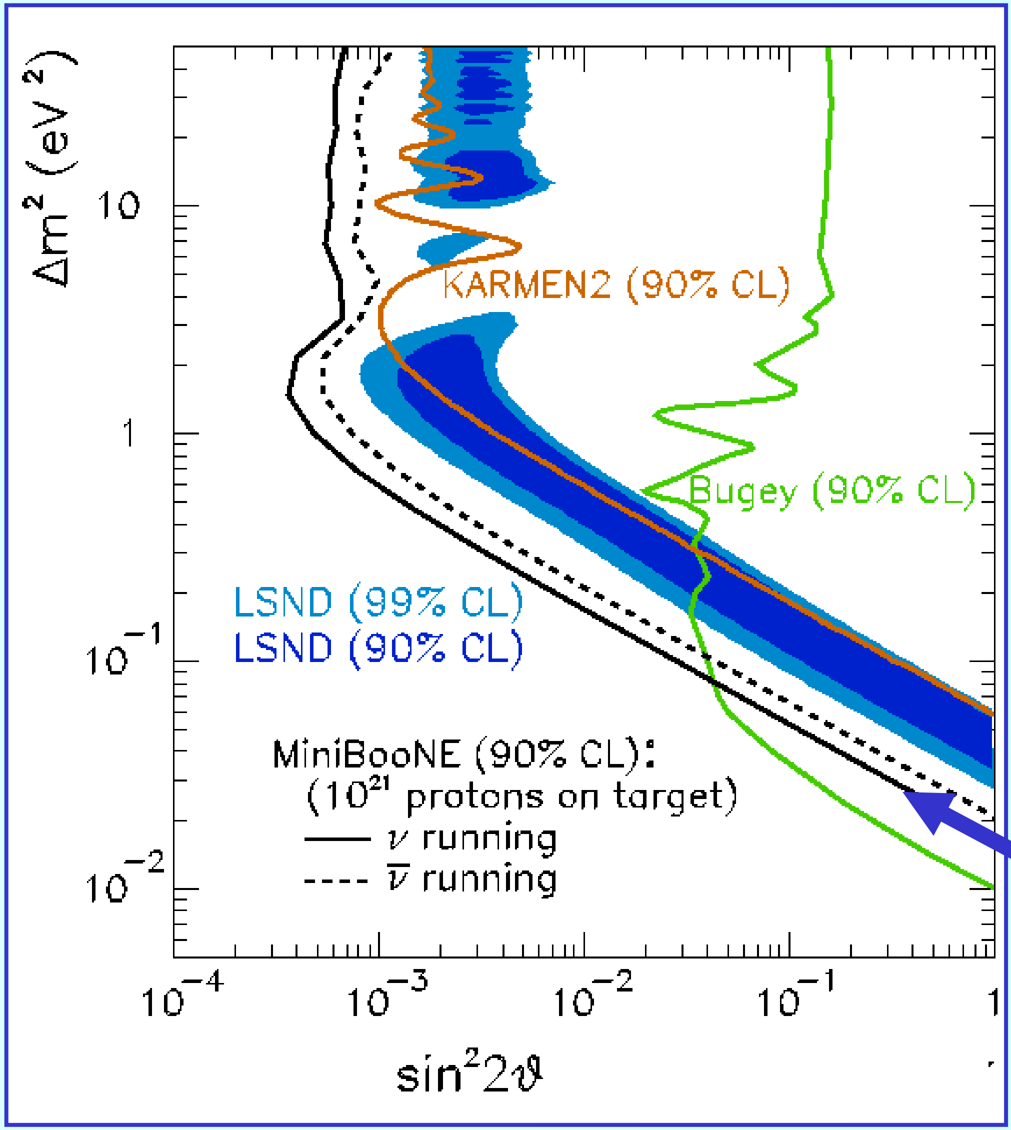
MiniBooNE

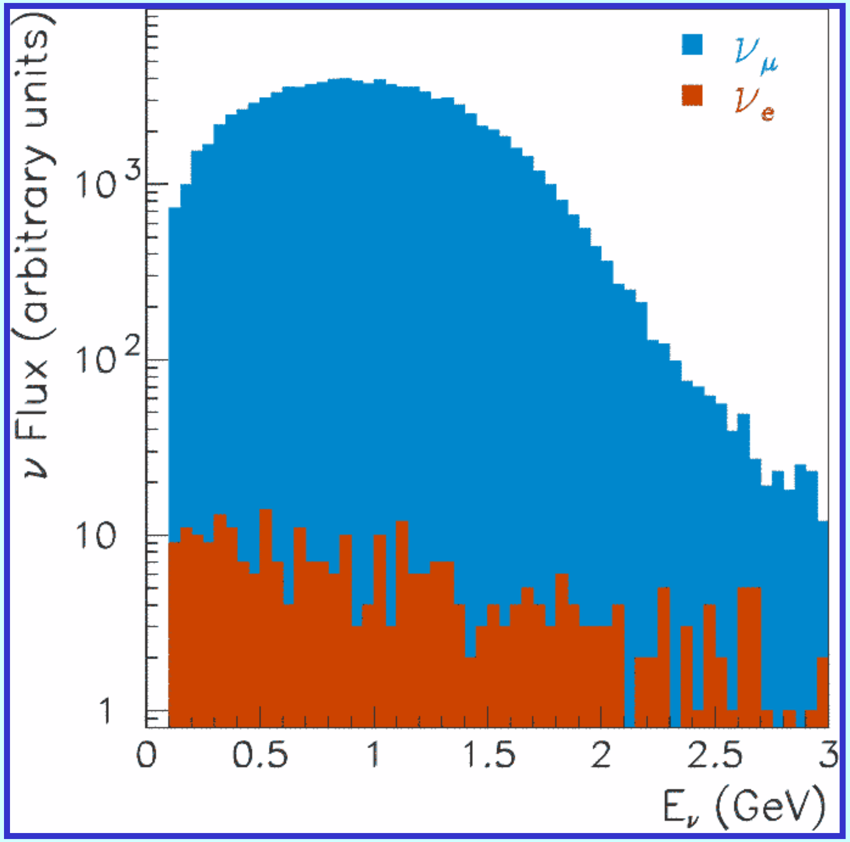


$\nu_\mu C \to \mu^- N^*$	500 000
$\nu_\mu C \to \nu_\mu \pi^0 N^*$	50 000
$\nu_\mu e \to \nu_\mu e$	100
$\nu_e C \to e^- N^*$	1-2 years
LSND Oscillated	1000
Intrinsic	1500
π^0 mis-Id	500
μ^- mis-Id	500



MiniBooNE

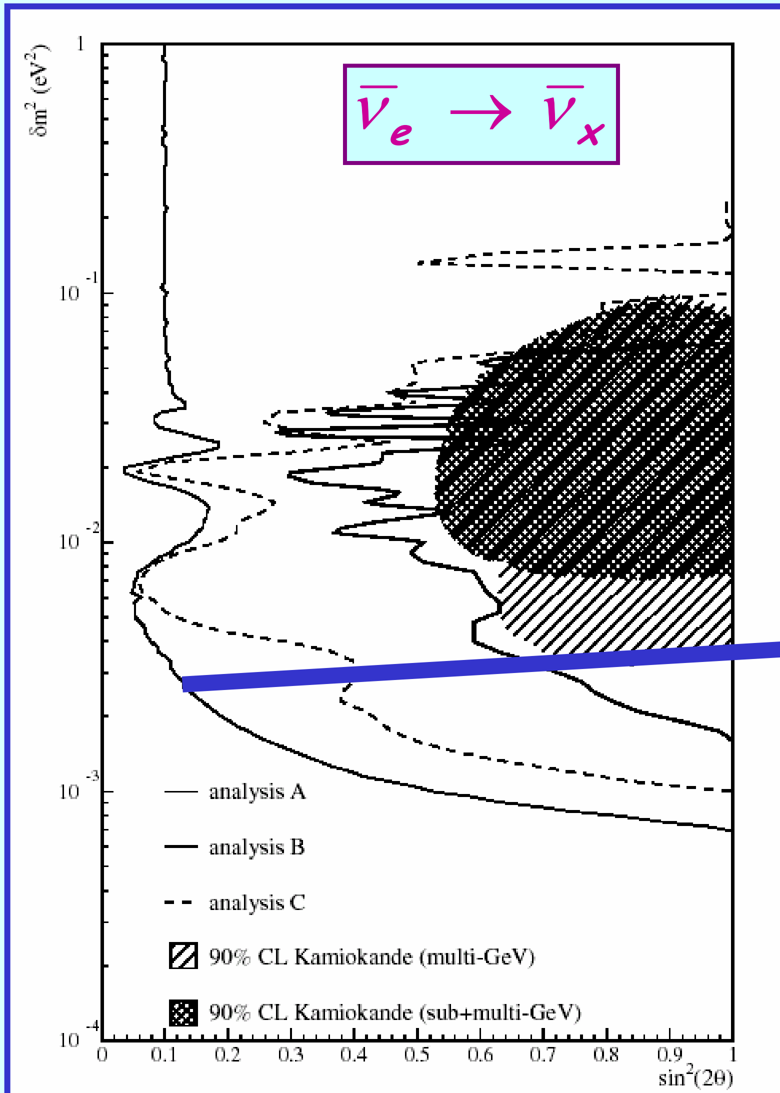


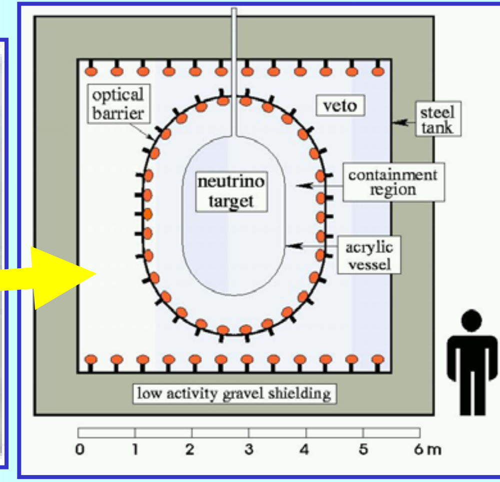


1-2 years

CHOOZ

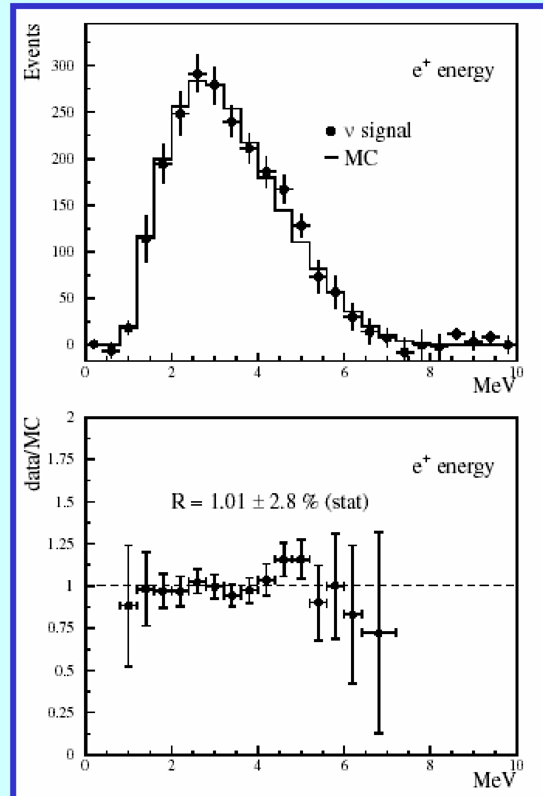
CHOOZ





5t Liquid Scintillator
H richparaffin
Gd loaded (γ 8MeV)

$\sin^2 2\theta_{13} < 0.10$
9°
90%CL



$\sin^2 2\theta_{13} < 0.17$
12°

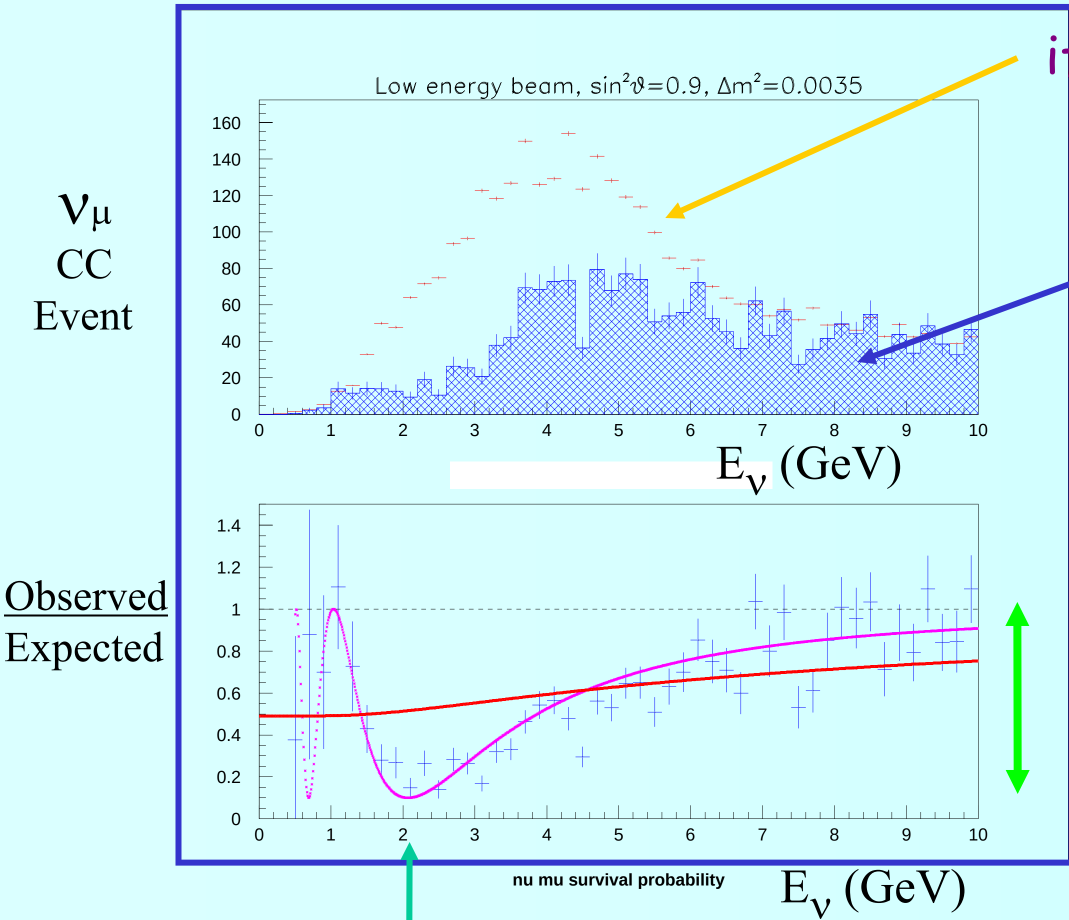
MINOS

Possible MINOS result in 2006

Expected event spectrum

if no oscillations

Possible observed event spectrum

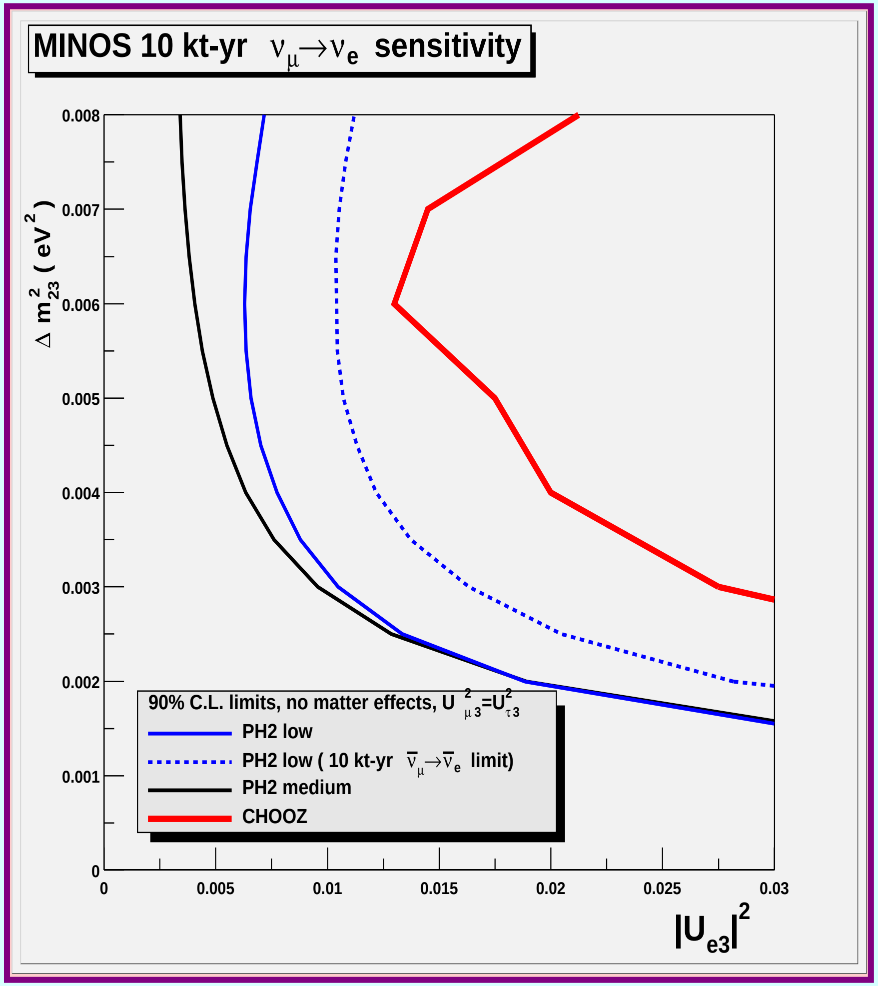


Gives Mixing angle

Gives Δm^2

<u>If</u> oscillations => precise (~10%) measurement of the parameters

MINOS Limits on νμ to ν_e



10 kton-yr exposure,

$\Delta m^2 = 0.003\ eV^2$, $|U_{e3}|^2 = 0.01$:

Signal (ε = 25%) - 8.5 ev

ν_e background - 5.6 ev

Other (NC,CC,ν_τ) - 34.1 ev

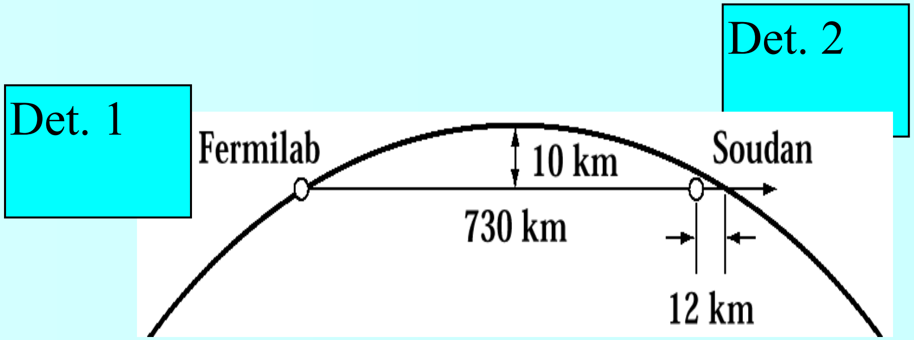
M. Diwan, M. Mesier, B. Viren, L. Wai, NuMI-L-714

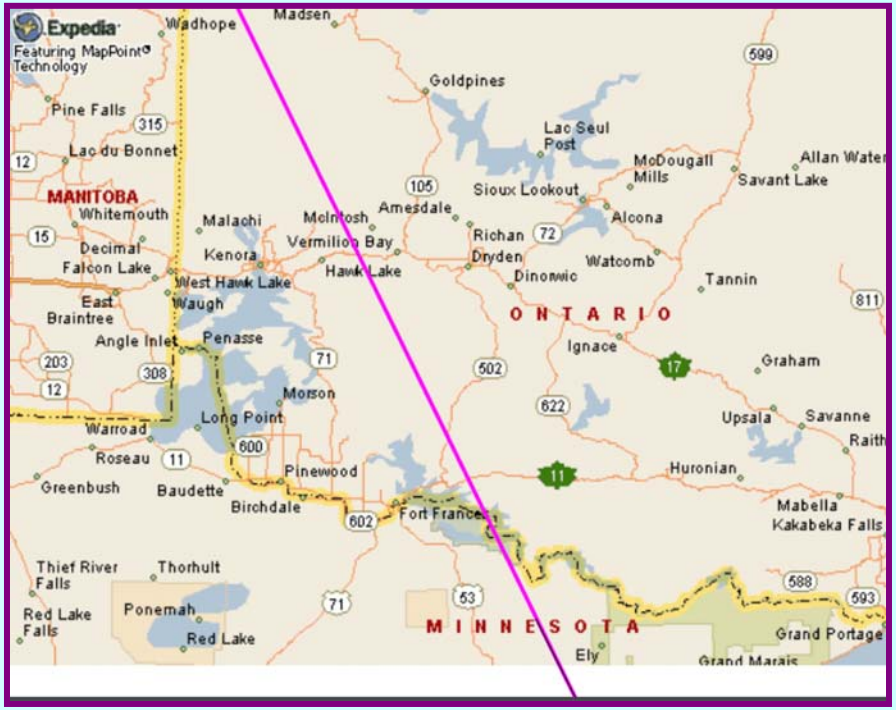
90% CL: $|U_{e3}|^2 < 0.01$

$\sin^2 2\theta_{13} < 0.04 (6°)$

Off-axis NUMI

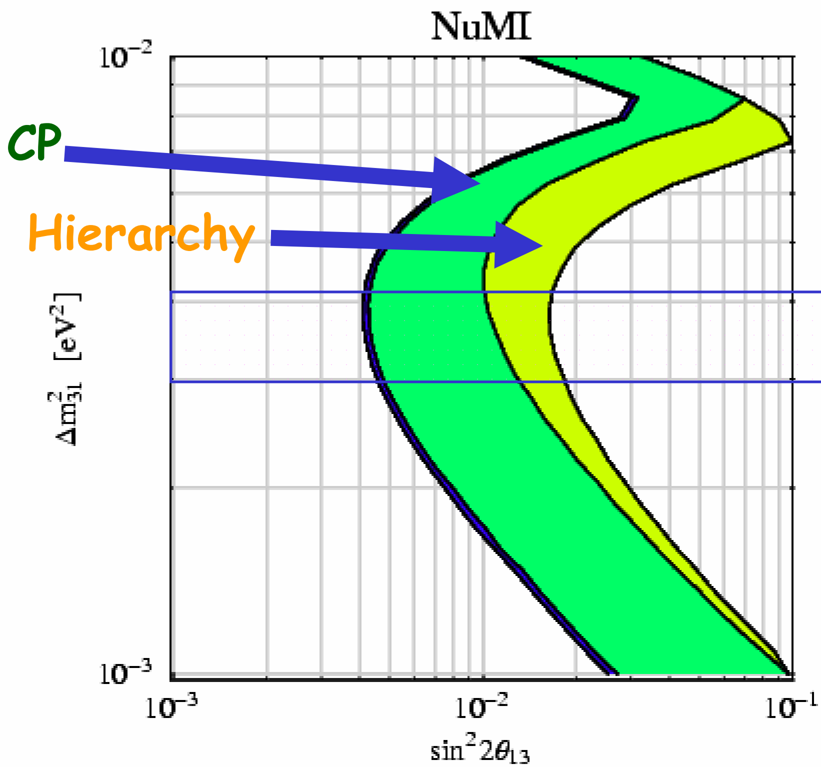
NuMI Beam: on and off-axis



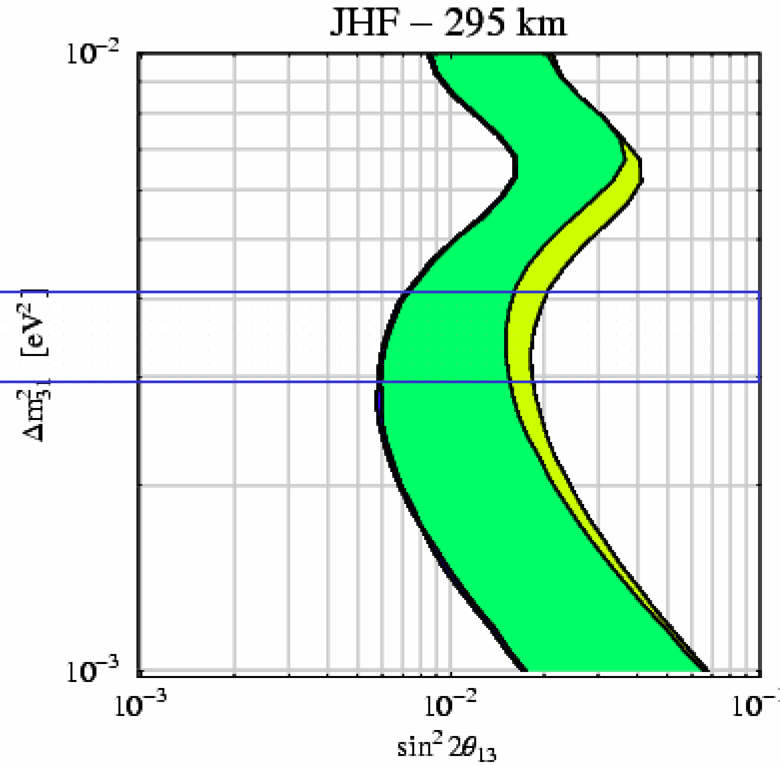


Off-Axis NuMI and JHF

5yrs @ 4x10^{20} p/yr
20 kton detector



5yrs @ 4x10^{20} p/yr
SuperK detector

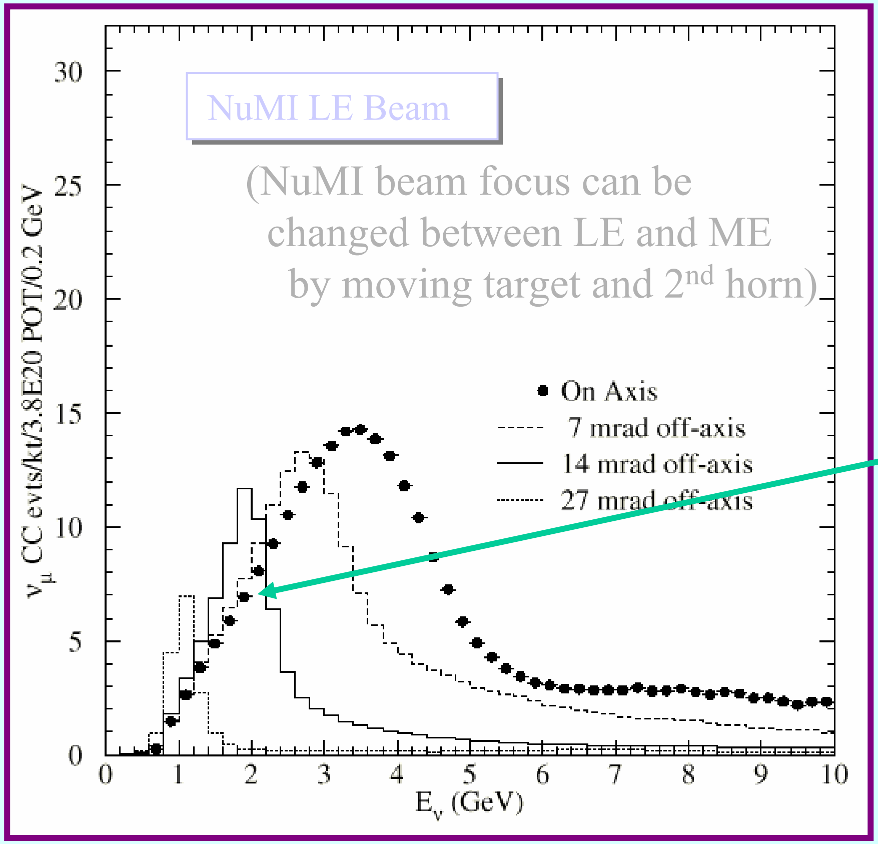


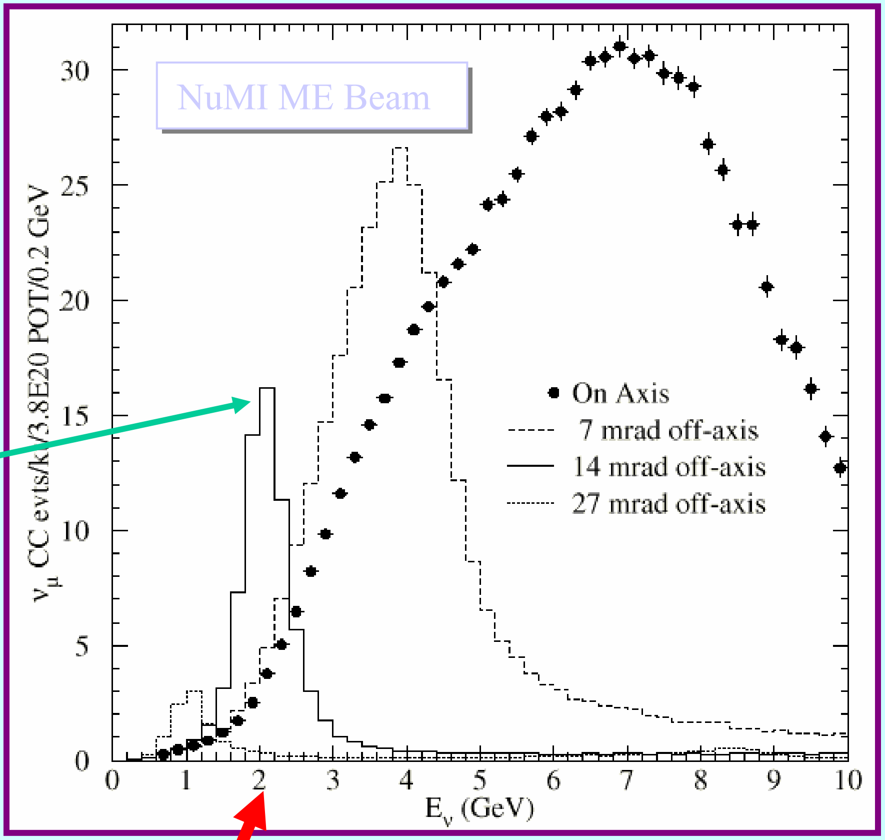
	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	12104	5696	295.4	293
after cuts		10.2	10.2	85.5

	ν_μ CC	NC	Beam ν_e	Signal ν_e
all	10714	4080	292	302
after cuts	1.8	9.3	11	123

Above event samples assume $\sin^2 2\theta_{13}$=0.1 and Δm^2 = 3x10^{-3}eV^2

Moving off-axis in NuMI beam





SuperK results indicate want ~ 2 GeV ν at NuMI baseline of 735 km

- Off-axis doubles 2 GeV ν rate compared to on-axis
- Gets rid of higher energy ν which produce NC, ν_τ backgrounds

Possible off-axis detector sites

Canadian Compressor Station

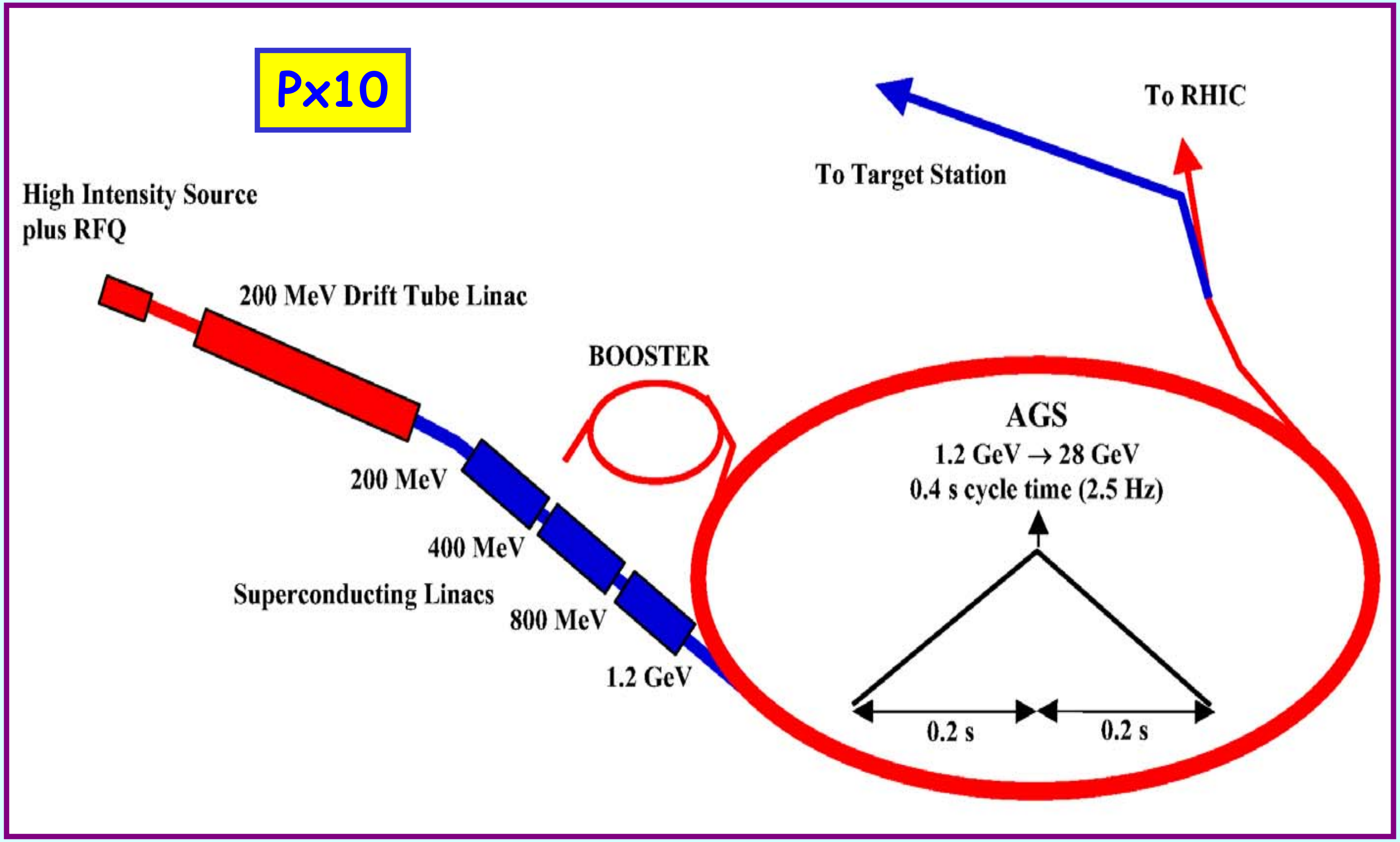
U.S. Abandoned Mine

BNL nu

BNL → Homestake Super ν Beam

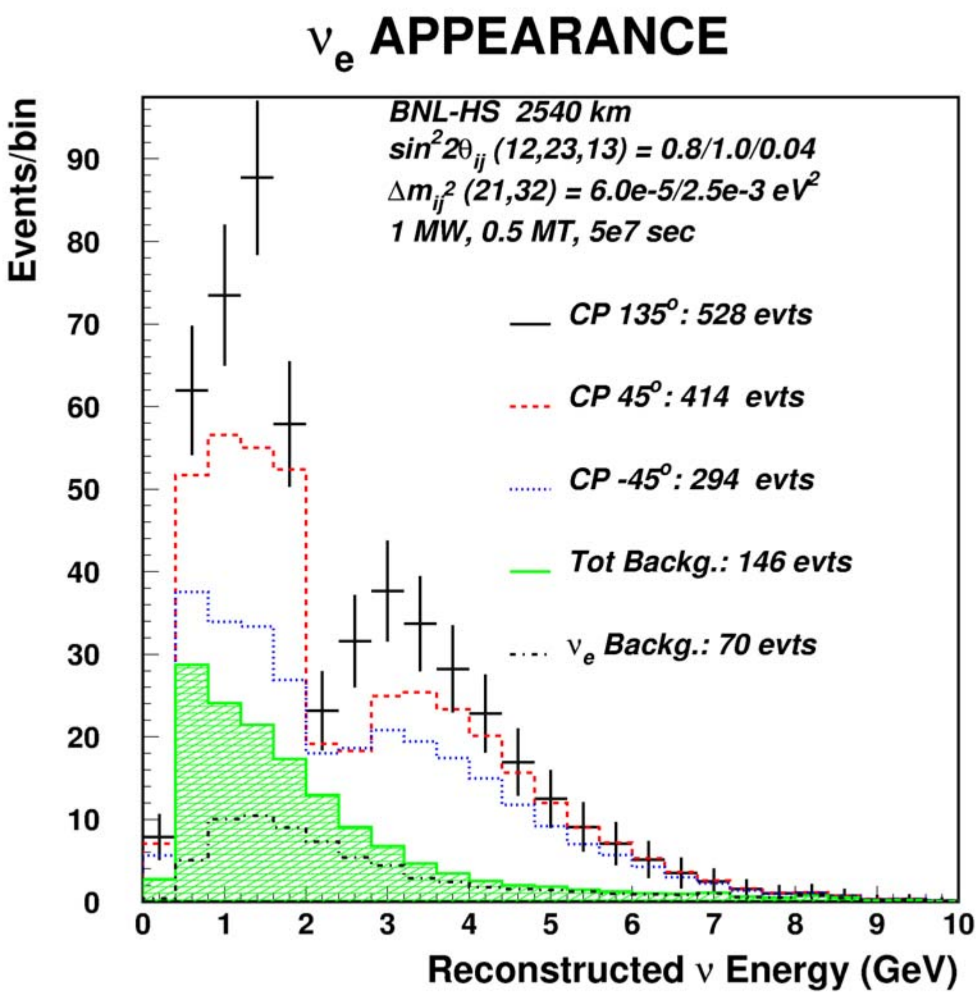
Very Long Baseline !

AGS Power Upgrade to 1 MW



- the *AGS Upgrade* to provide a source for the 1.0 MW Super Neutrino Beam will cost $265M FY03 (TEC) dollars

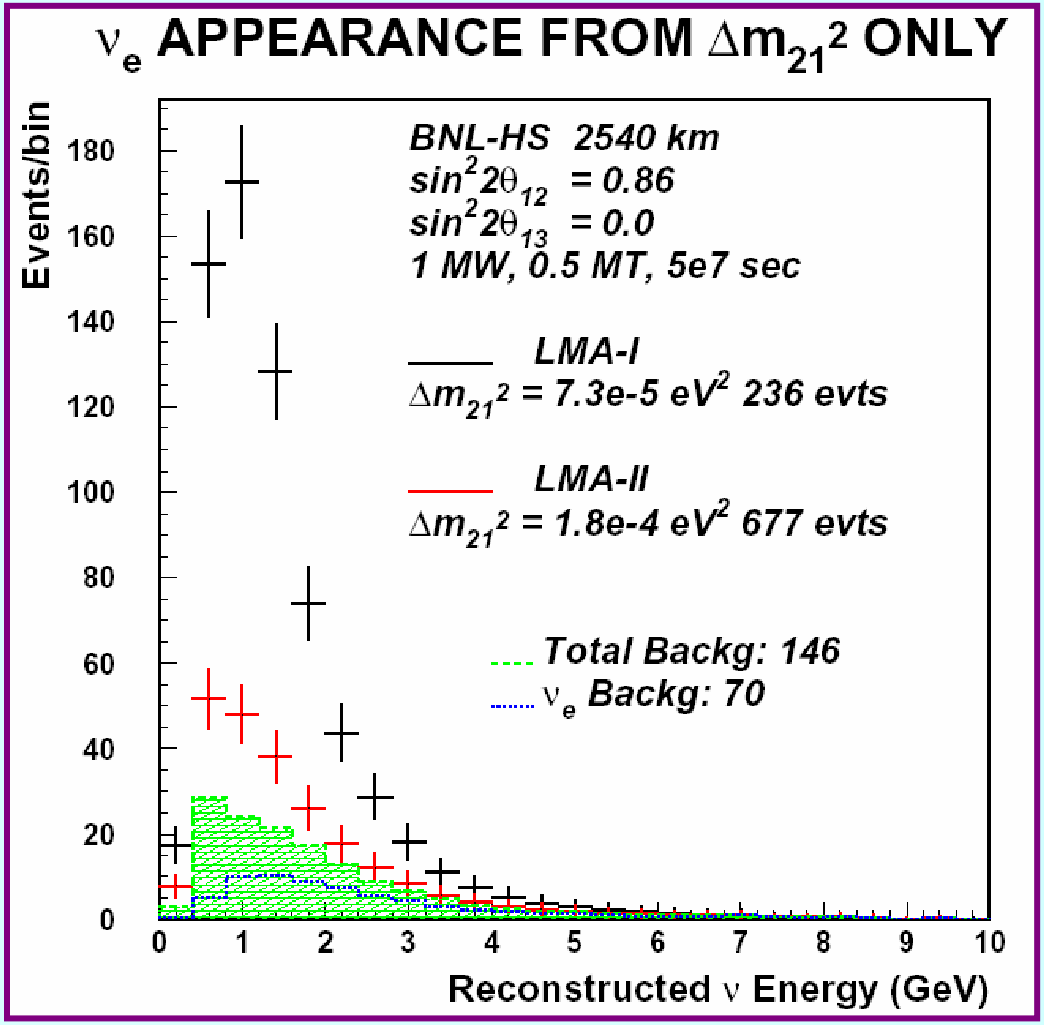
ν_e Appearance Measurements



$\sin^2 2\theta_{13} < 0.01$ (2.9°)

"for most of the possible range of $\sin^2 2\theta_{13}$, a good measurement of θ_{13} and the CP-violation parameter δ_{CP} can be made by the VLB experimental method"

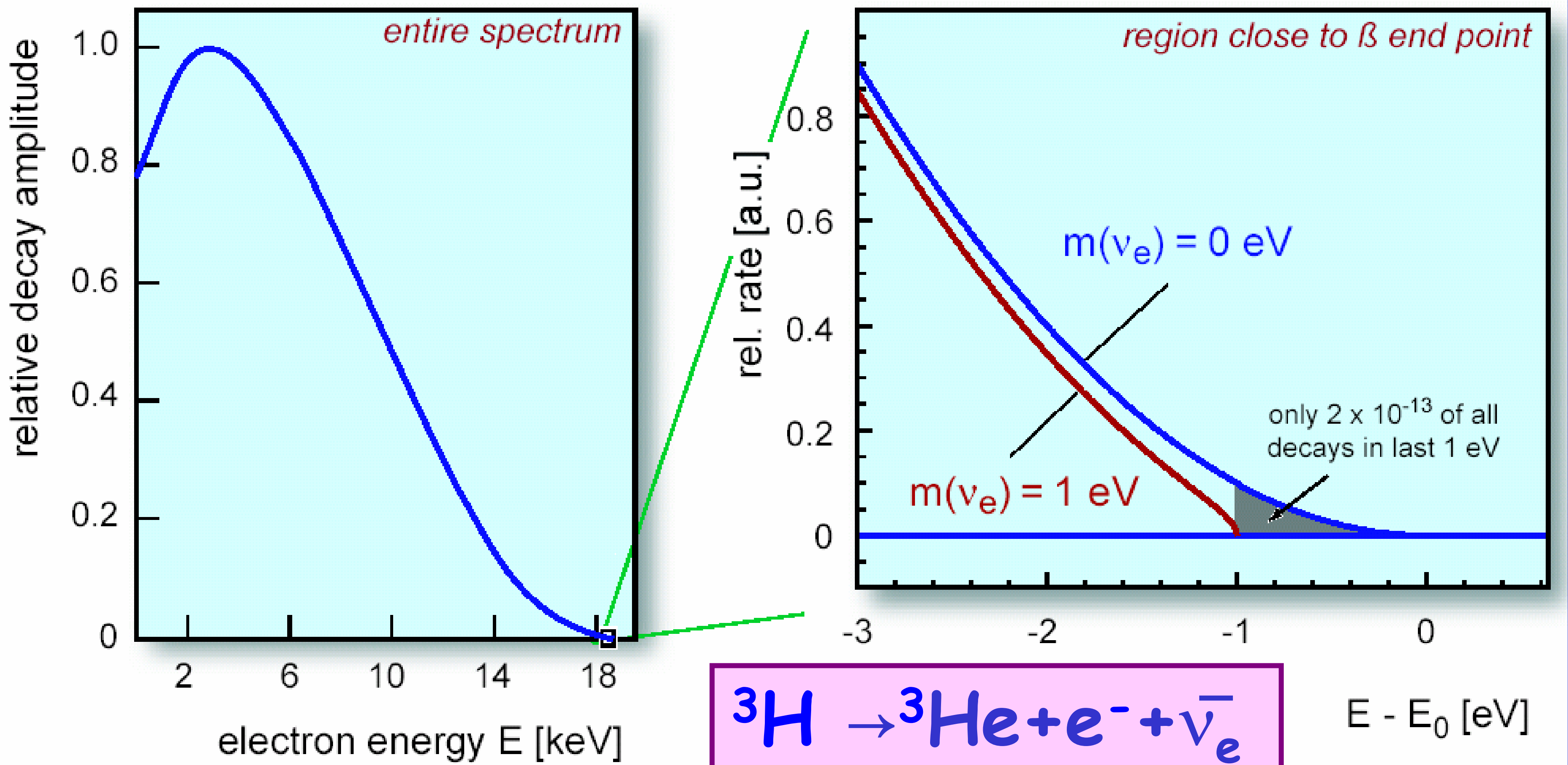
ν_e Appearance Measurements



- even if $\sin^2 2\theta_{13} = 0$, the current best-fit value of $\Delta m_{21}^2 = 7.3\times10^{-5}$ induces a ν_e appearance signal

Tritium

^3H β decay : Troisk & Mainz

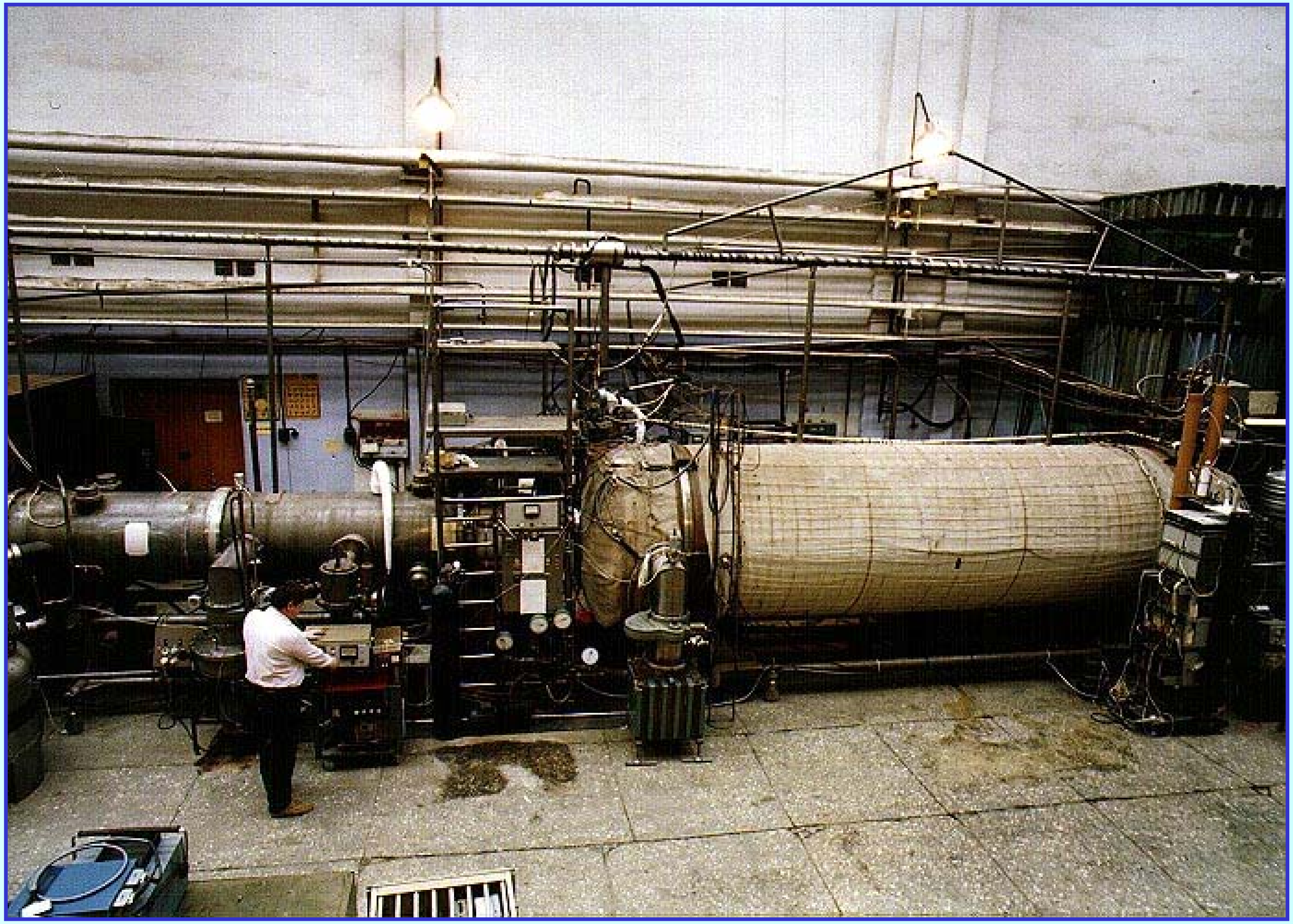


$$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$$

$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2$$

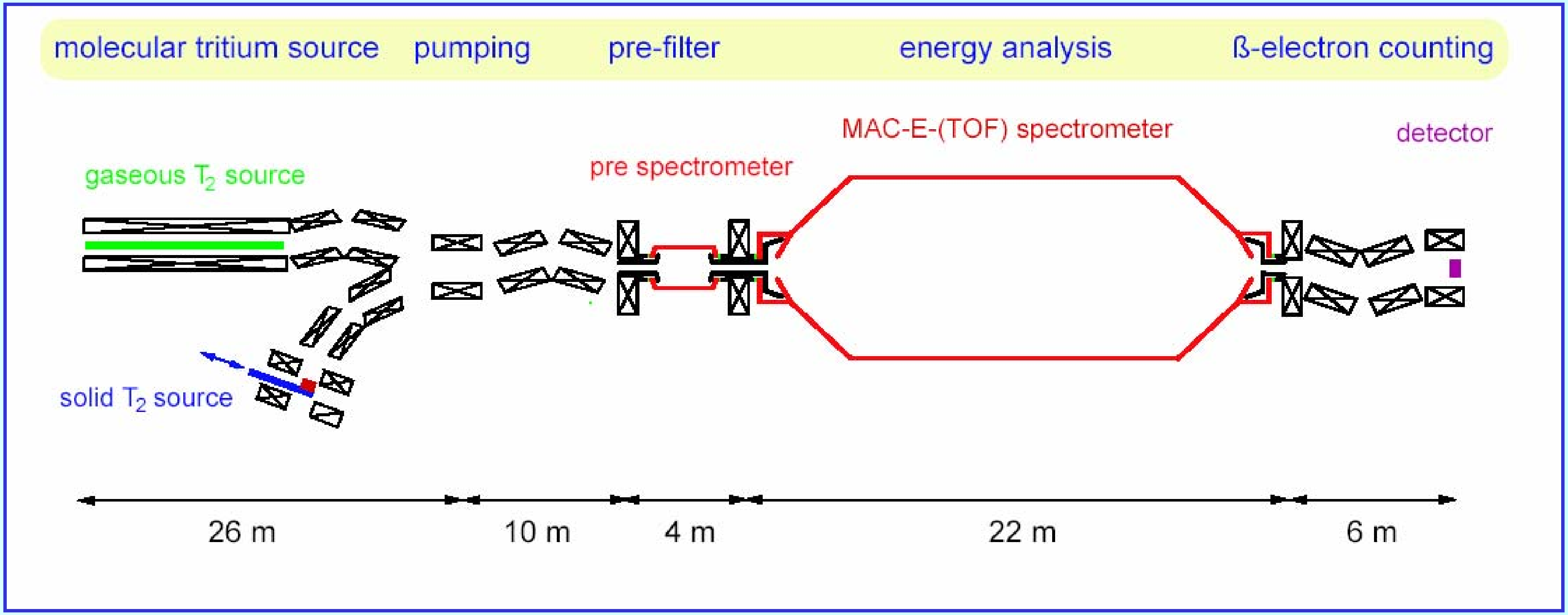
m_β < 2.2 eV (95%CL)

^{3}H β decay Troisk



^3H β decay Katrin

Improve m_β by one order of magnitude: 3eV to .3 eV
Improve m_β^2 by two order of magnitude: $9eV^2$ to $.09eV^2$



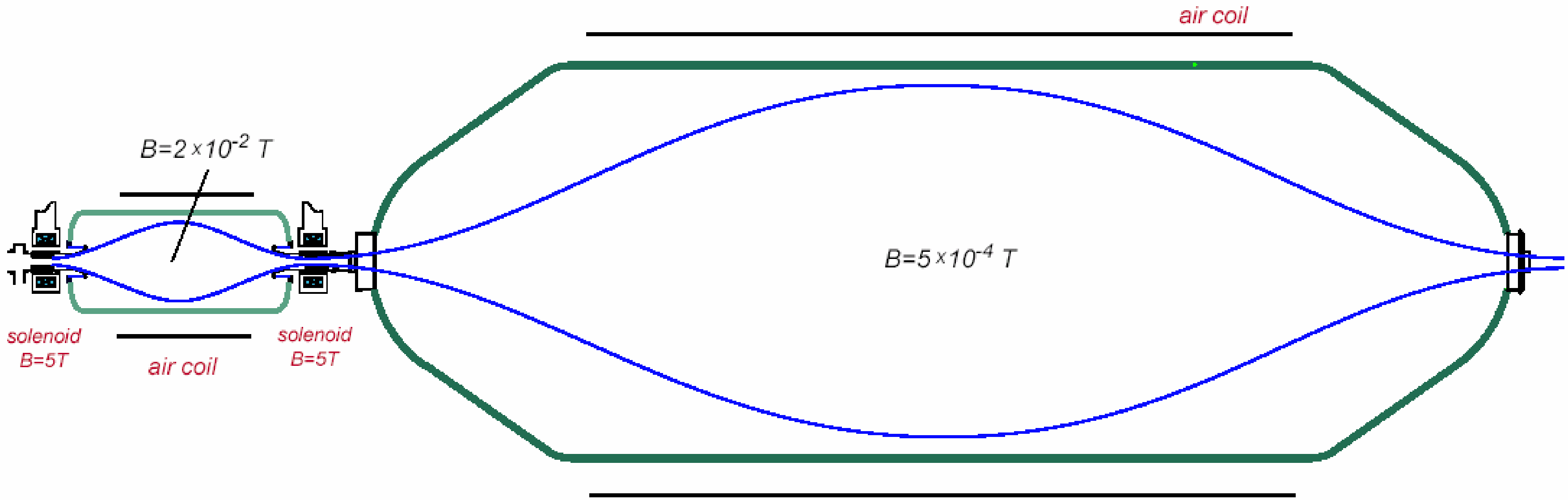
x40

from 100 to 1000 days

DE=1eV (/4)

^3H β decay Katrin

Improve m_β by one order of magnitude: 3eV to .3 eV
Improve m_β^2 by two order of magnitude: $9eV^2$ to $.09eV^2$



pre-spectrometer

fixed retarding potential 18.4 kV

Ø = 1.7 m / L = 4.0 m
ΔE = 80 eV

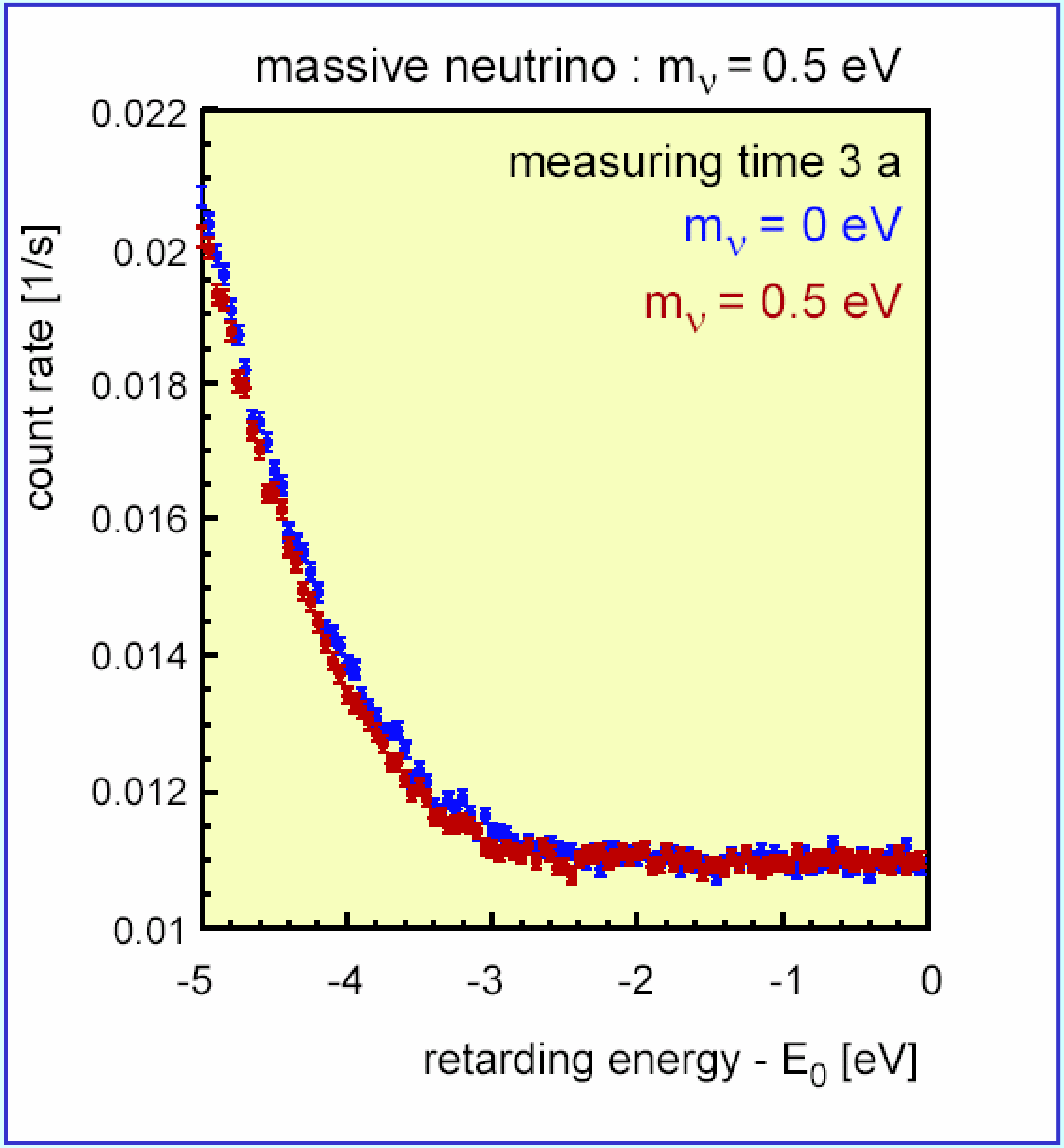
main spectrometer

variable retarding potential 18.5-18.6 kV

Ø = 7 m / L = 20 m

ΔE = 1 eV

^3H β decay Katrin

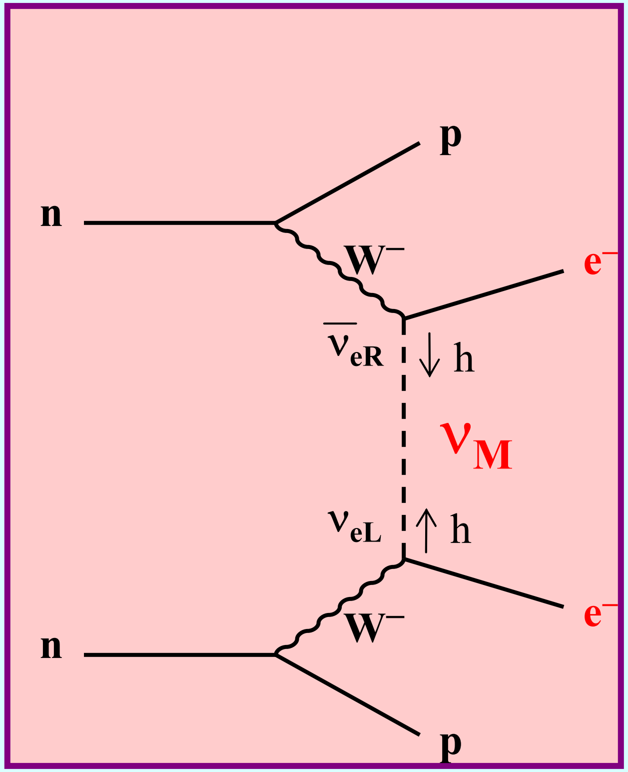


m_β < 0.35 eV
(90%CL)
3 years

β β

$\beta\beta(0\nu)$ decay

$\beta\beta(0\nu)$: $2n \rightarrow 2p + 2e^-$

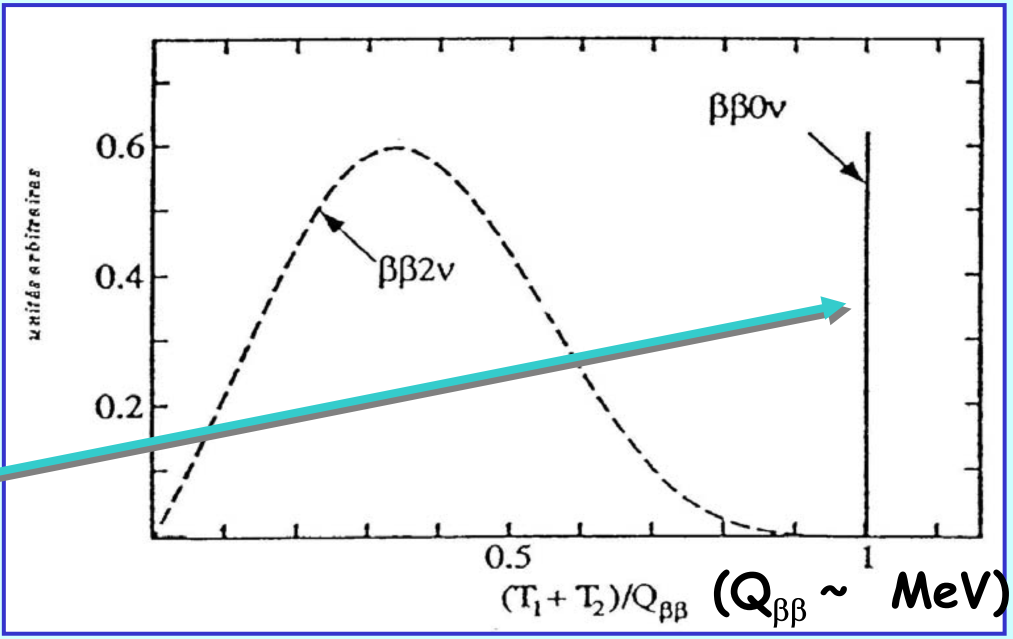


ΔL=2 Process

$$m_{ee}^2 = \left| \sum_{i=1}^{3} U_{ei} m_i \right|^2$$

CP Phases sensitive !

$$T_{\frac{1}{2}}^{0\nu} \propto \frac{1}{m_{ee}^2}$$



$(Q_{\beta\beta} \sim$ MeV$)$

Heidelberg-Moscow & IGEX

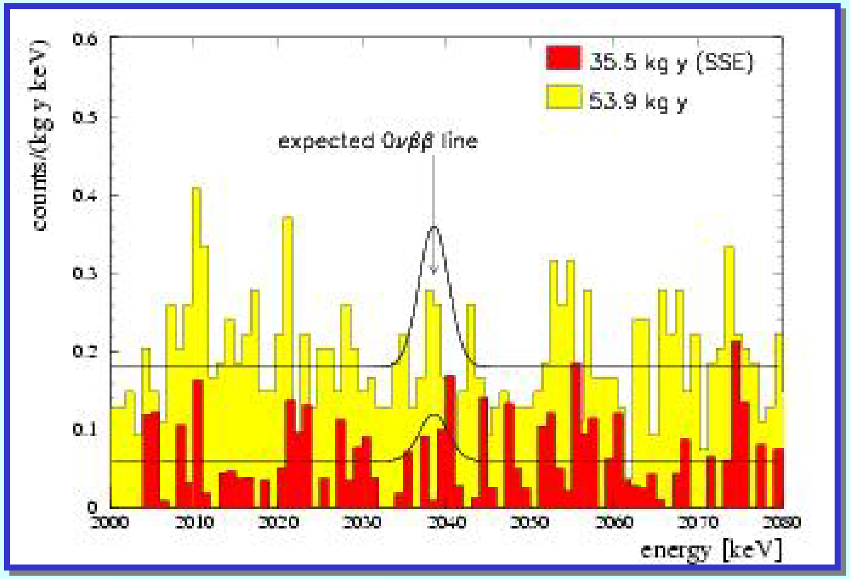
(86% ^{76}Ge, $Q_{\beta\beta}$=2038,5 keV)

Heidelberg-Moscow

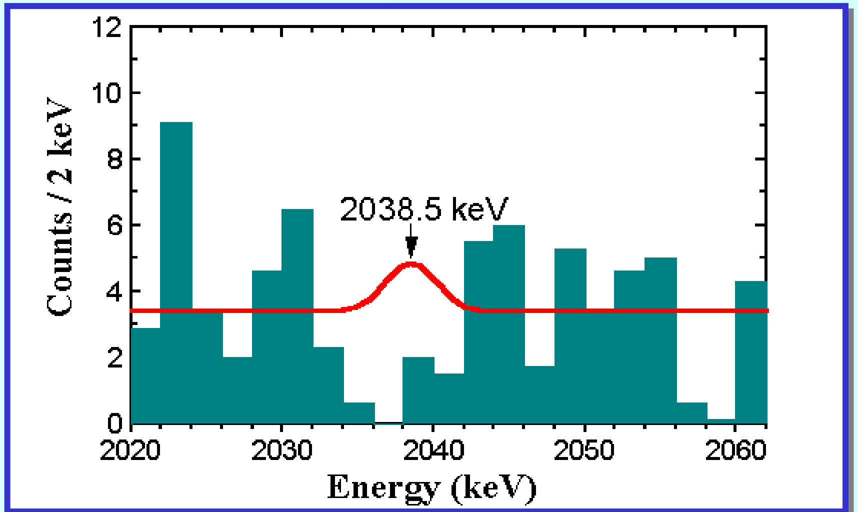
1990-2000 Gran Sasso Underground Lab.

5 detectors Ge (total mass = 10,9 kg)
FWHM = 3,85 keV
N_{Bkg} = 0,06 counts y^{-1} kg^{-1} keV^{-1} (SSE)

$T^{0\nu}_{\frac{1}{2}} > 1.9\ 10^{25}$ y (90% C.L.)
$\langle m_{ee} \rangle < 0.3 - 1.0$ eV



IGEX (International Ge EXperiment)



1994-2000 Baksan – Canfranc Underground Lab.

3 detectors Ge (total mass = 6 kg)
FWHM = 4 keV
N_{Bkg} = 0,07 counts y^{-1} kg^{-1} keV^{-1} (SSE)

$T^{0\nu}_{\frac{1}{2}} >$ 1,57 1025 y (90% C.L.)
$\langle m_{ee} \rangle <$ 0,36 – 1.07 eV

Past, Present and Future…

Calorimeters: | PRESENT | FUTURE

Mibeta - - - → CUORICINO
M=13 kg ^{130}Te (40 kg)
> 3–7 10^{24} y
< 0.1 – 0.3 eV
- - - → CUORE
M= 760 kg TeO_2
> 2.10^{26} y
< 0.03 – 0.1

^{76}Ge
M=6-11 kg ^{76}Ge
> 1.9 10^{25} y
< 0.3 – 1 eV

External Bkg → GENIUS

Cosmogenic Bkg → MAJORANA
M=500 kg enr. Ge
> 4.10^{27} y
< 0.02 – 0.07 eV

Tracking:

NEMO-1-2 - - - → NEMO-3
M=7 kg ^{100}Mo (10 kg)
> 8 10^{24} y
< 0.1 – 0.3 eV
- - - → "à la NEMO"
M=100 kg ^{100}Mo
> 10^{26} y
< 0.03 – 0.07 eV

Neuchatel
TPC Moe
- - - → EXO
M=1 (10) tons ^{136}Xe
> 8.10^{26} y (1.3 10^{28})
< 0.05 – 0.14 (0.013-0.037) eV

ELEGANT-I-V - - - → MOON

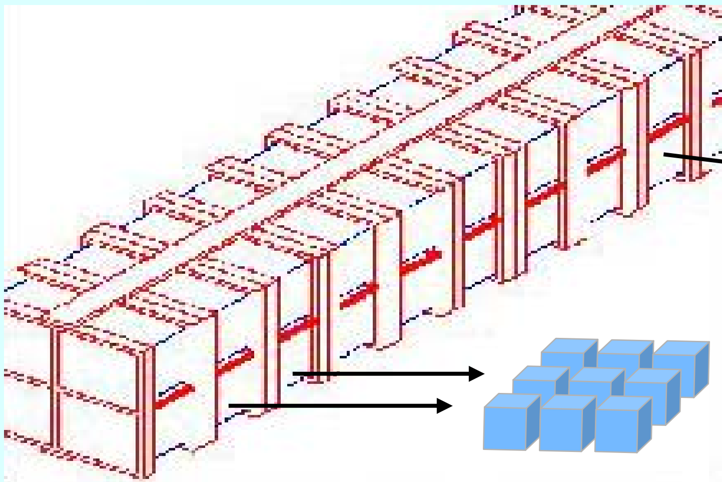
CUORICINO : “little” Cryogenic Underground Observatory for Rare Events

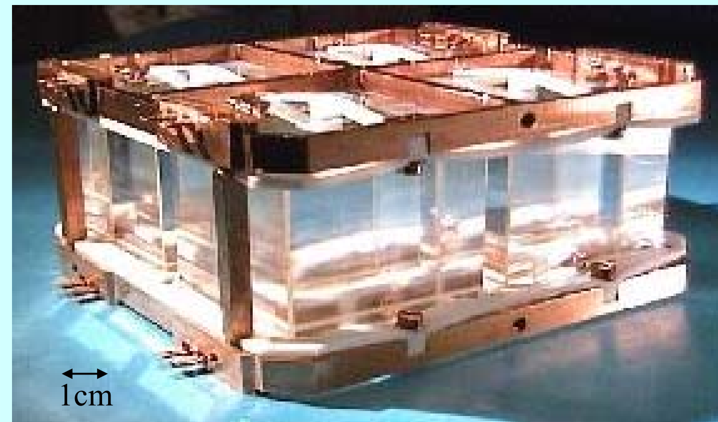
Italy, Spain, United-States, Nederland
Gran Sasso Underground Laboratory

Begin operation : 2003

Bolometers : 1 tower with - 11 modules of 4 crystals $^{nat}TeO_2$ de 750 g
- 2 modules of 9 crystals $^{nat}TeO_2$ de 340 g
T ~ 10 mK => C ~ 2 nJ/K => 1 MeV/0,1 mK

⇒13 kg ^{130}Te (40 kg TeO_2)
$Q_{\beta\beta}$=2528 keV





Un module de 4 cristaux TeO_2 de 760 g

1st hypothesis :

With performances of the 20 crystals (MI-BETA):
FWHM = 8 keV
N_{BDF} : 0,5 event year^{-1} keV^{-1} kg^{-1}

$T^{0\nu}_{1/2}$ **> 3,3 10^{24} years (90% C.L.)**
< m_ν> < 0,2 – 0,3 eV (in 1 year)

2nd hypothesis :

FWHM = 4 keV Best value with 750 g crystal
N_{BDF} : 0,1 event year^{-1} keV^{-1} kg^{-1}
if bkg dominated by a surface pollution

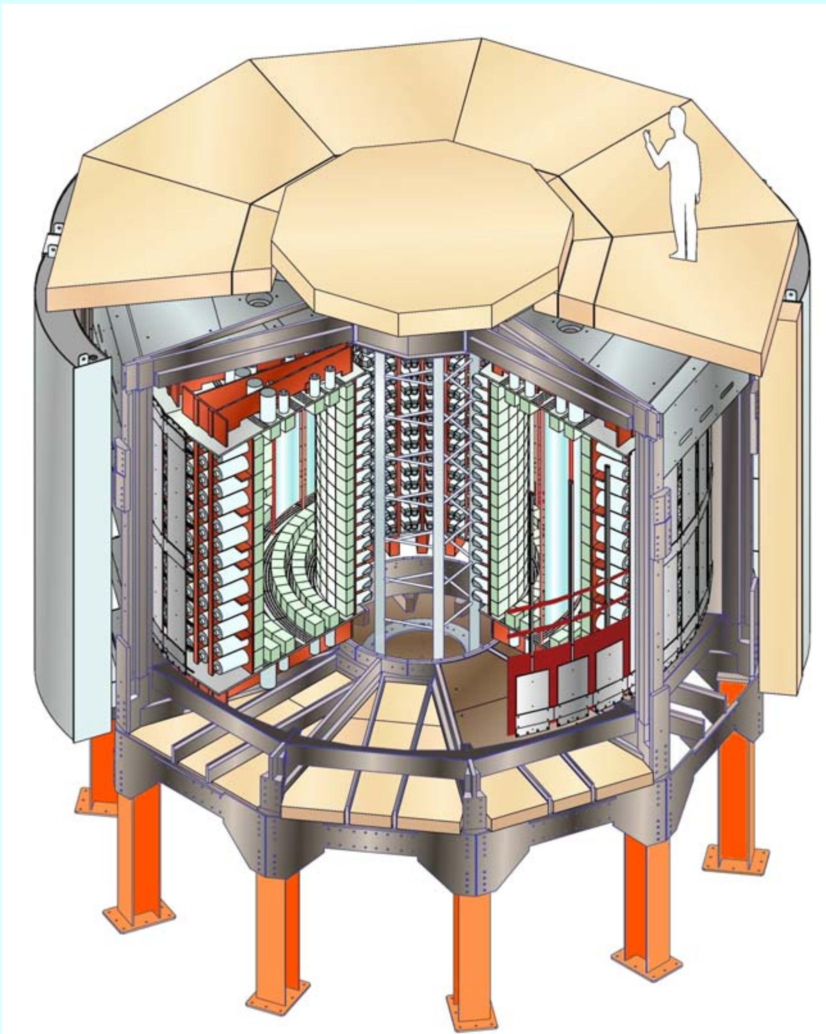
$T^{0\nu}_{1/2}$ **> 7,2 10^{24} ans (90% C.L.)**
< m_ν> < 0,1 – 0,2 eV (in 1 year)

NEMO3 : Neutrino Ettore Majorana Observatory

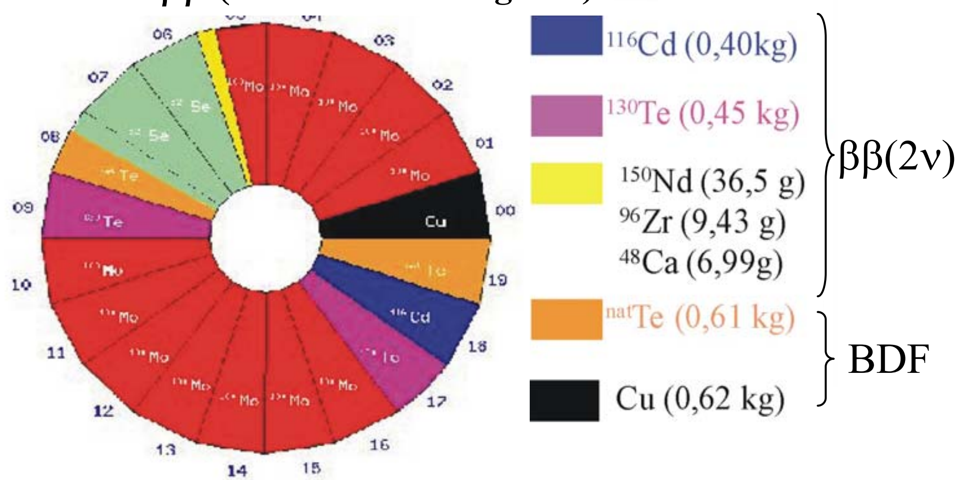
France, United-States, England, Japan, Tcheck Rep., Ru
Laboratoire Souterrain de Modane (4800 m.w.e)

Begin operation : 2003

Tracking detector (6180 Geiger cells in He+alcohol): Vertex $\sigma_t = 5$ mm, $\sigma_z = 1$ cm
Calorimeter (1940 plastic scintillators – PMTs low radioactivity) FWHM=14% (1 MeV)
Bkg: gamma + neutrons shield, magnetic field, materials low radioactivity



Sources ββ (thickness ~ 60 mg/cm²)



^{100}Mo (6,9 kg)
$Q_{\beta\beta}$ = 3034 keV

^{82}Se (0,93 kg)
$Q_{\beta\beta}$ = 2995 keV

^{100}Mo	^{82}Se
N_{Bkg}=0,2 evts y^{-1} kg^{-1}	**N_{Bkg}=0,02 evts y^{-1} kg^{-1}**
$T^{0\nu}_{1/2} > 8.\ 10^{24}$ y	**$T^{0\nu}_{1/2} > 1{,}5\ 10^{24}$ y**
$<m_\nu> < 0{,}1 – 0{,}3$ eV (90% C.L.)	**$<m_\nu> < 0{,}45 – 1{,}2$ eV** (90% C.L.)