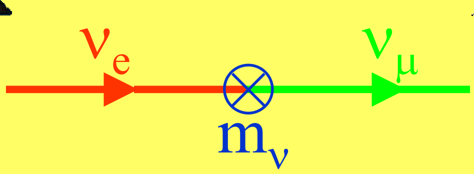
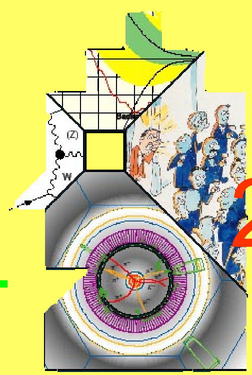
Neutrino Masses and Mixings – Experiments Past, Present, and Future

Dave Wark
University of Sussex/RAL

ICHEP  

 2002

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For three neutrinos:

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$$\textit{where } c_{ij} = \cos\theta_{ij}, \textit{ and } s_{ij} = \sin\theta_{ij}$$

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

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Three Angles

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

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Two mass differences - each has a sign

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

Matter Effects – the MSW effect

$$i\frac{d}{dt}\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix} = H\begin{bmatrix}\nu_e\\ \nu_x\end{bmatrix}$$

In vacuum:

$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$

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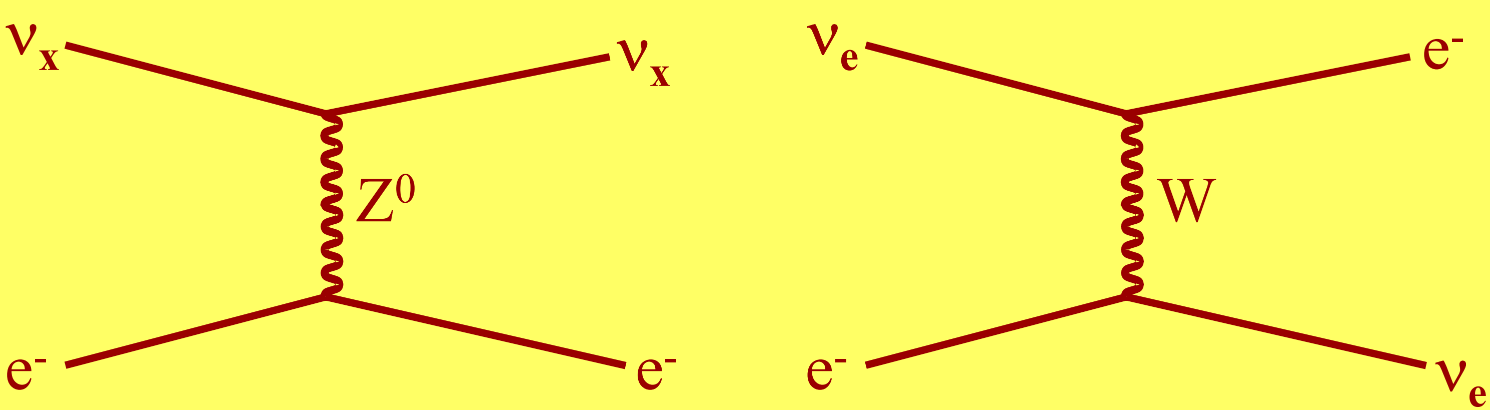

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ν masses…

Matter Effects – the MSW effect

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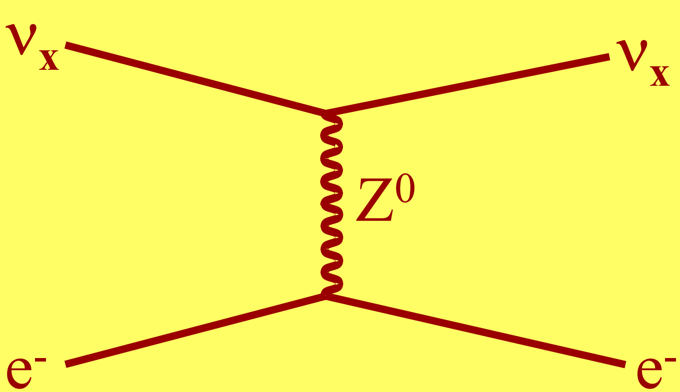
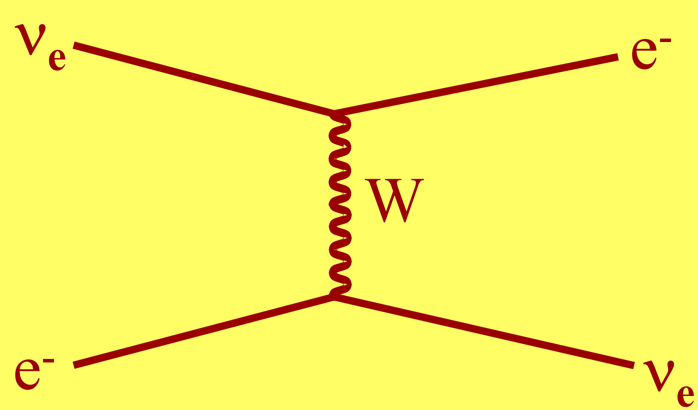
$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & -\frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$





…and mixings

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$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{(\omega - \cos 2\theta)^2 + \sin^2 2\theta}$$

$$\omega = -\sqrt{2}G_F N_e E / \Delta m^2$$

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CP violating phase!

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

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So what do we have to measure?

- Three Angles
- Two mass differences
- Two signs of the mass differences
- One CP phase

But Also:

- The absolute mass scale
- Are neutrinos Dirac or Majorana (or both)?
- Are there more - sterile - neutrinos (neuterinos)?

So what do we have to measure?

Most Importantly:

- **Is this the right model ?!?**
- **Many others have been proposed:**

FCNC, extra dimensions, violations of the EP, neutrino decay, neutrino magnetic moments, etc….

- **Must find signatures of oscillations:**

✓Appearance of the wrong-flavour neutrinos

✓Oscillation pattern

✓Day/night or other matter effects

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Solar Neutrinos

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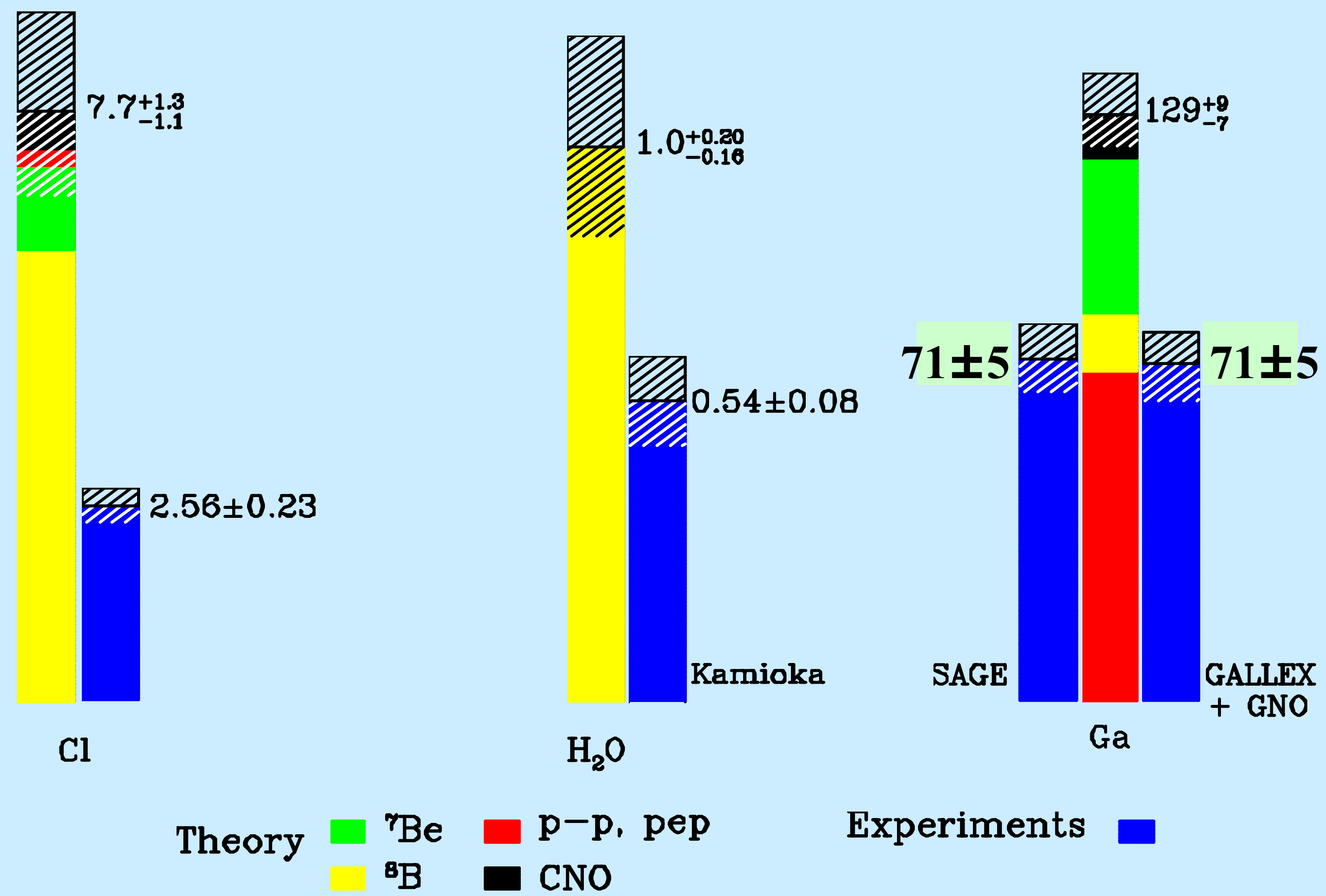
Total Rates: Standard Model vs. Experiment

Bahcall–Pinsonneault 2000



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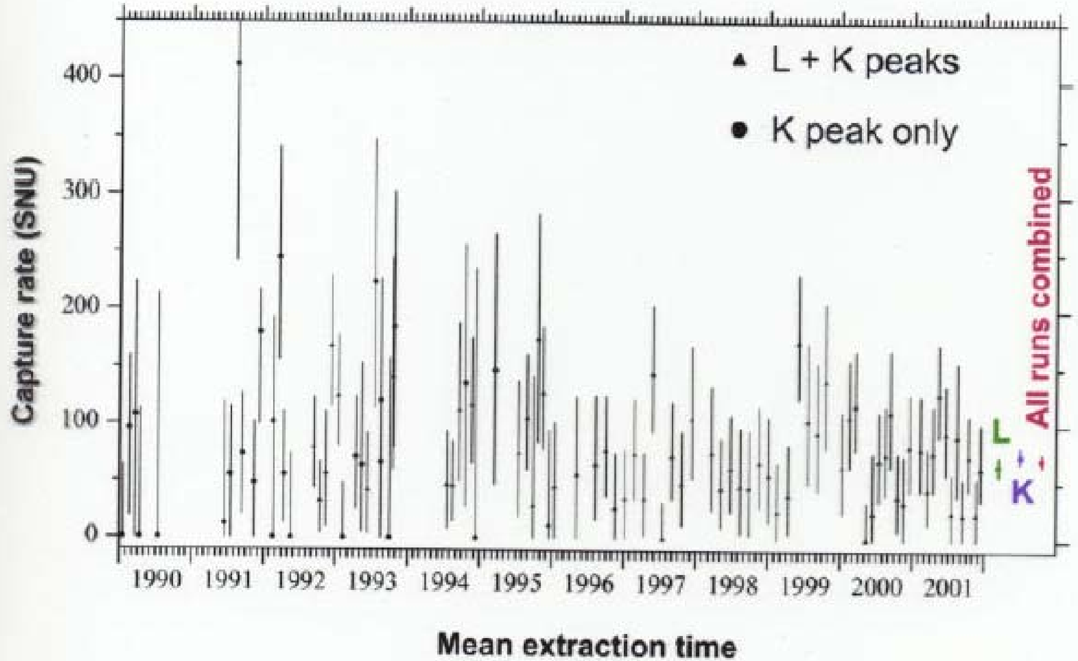
SAGE

January 1990 - December 2001

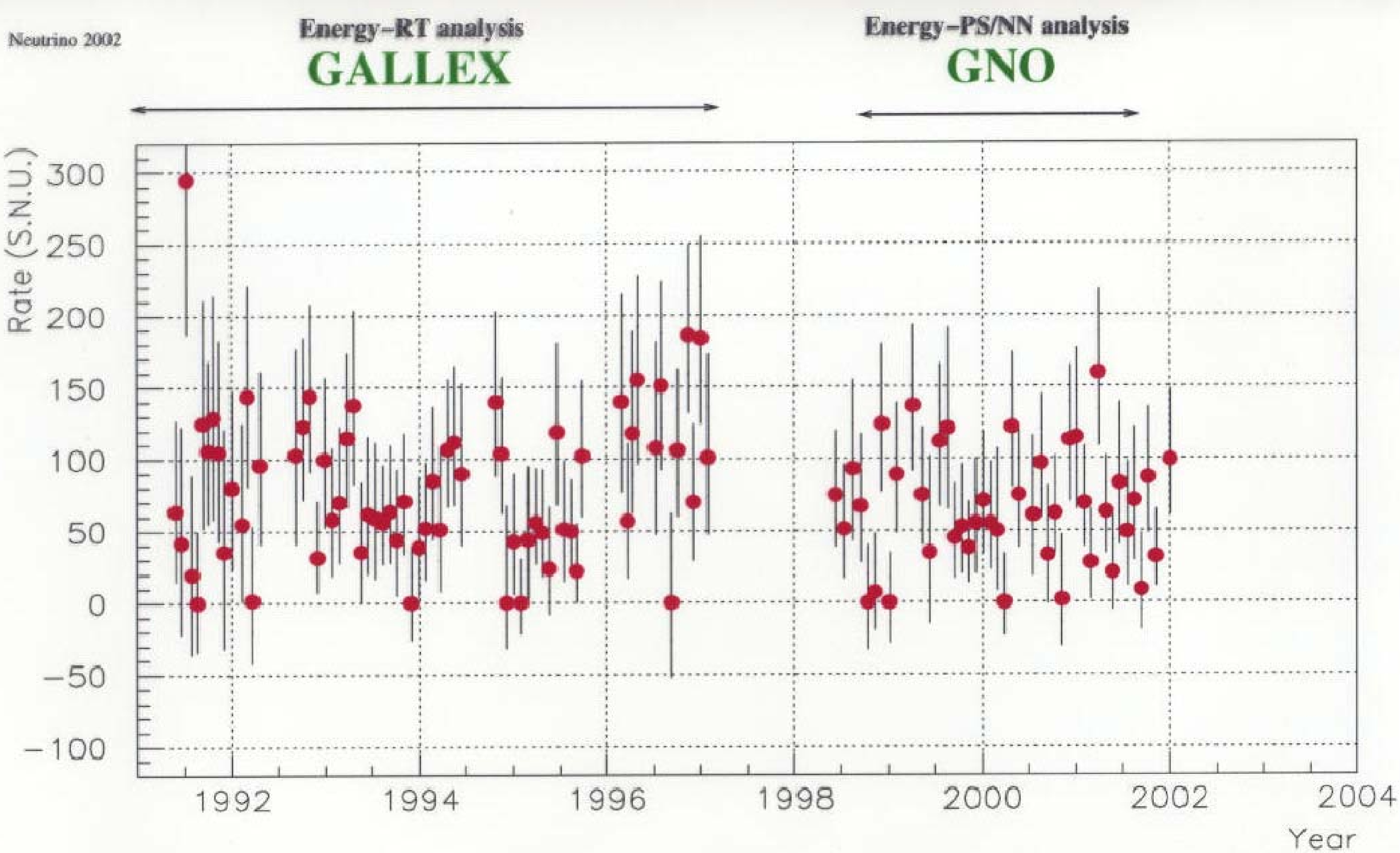


Combined result:

L-peak - 64.8 +8.5/-8.2 SNU
K-peak - 74.4 +6.8/-6.6 SNU

Overall - 70.8 +5.3/-5.2 SNU

1 SNU = 1 interaction of ν_e /sec in 10^{36} atoms/day



GALLEX	65 SR	77.5 +– 6.2 (stat) +– 4.5 (sys) SNU
GNO	43 SR	65.2 +– 6.4 (stat) +– 3.0 (sys) SNU
GNO+GALLEX	108 SR	70.8 +– 4.5 (stat) +– 3.8 (sys) SNU

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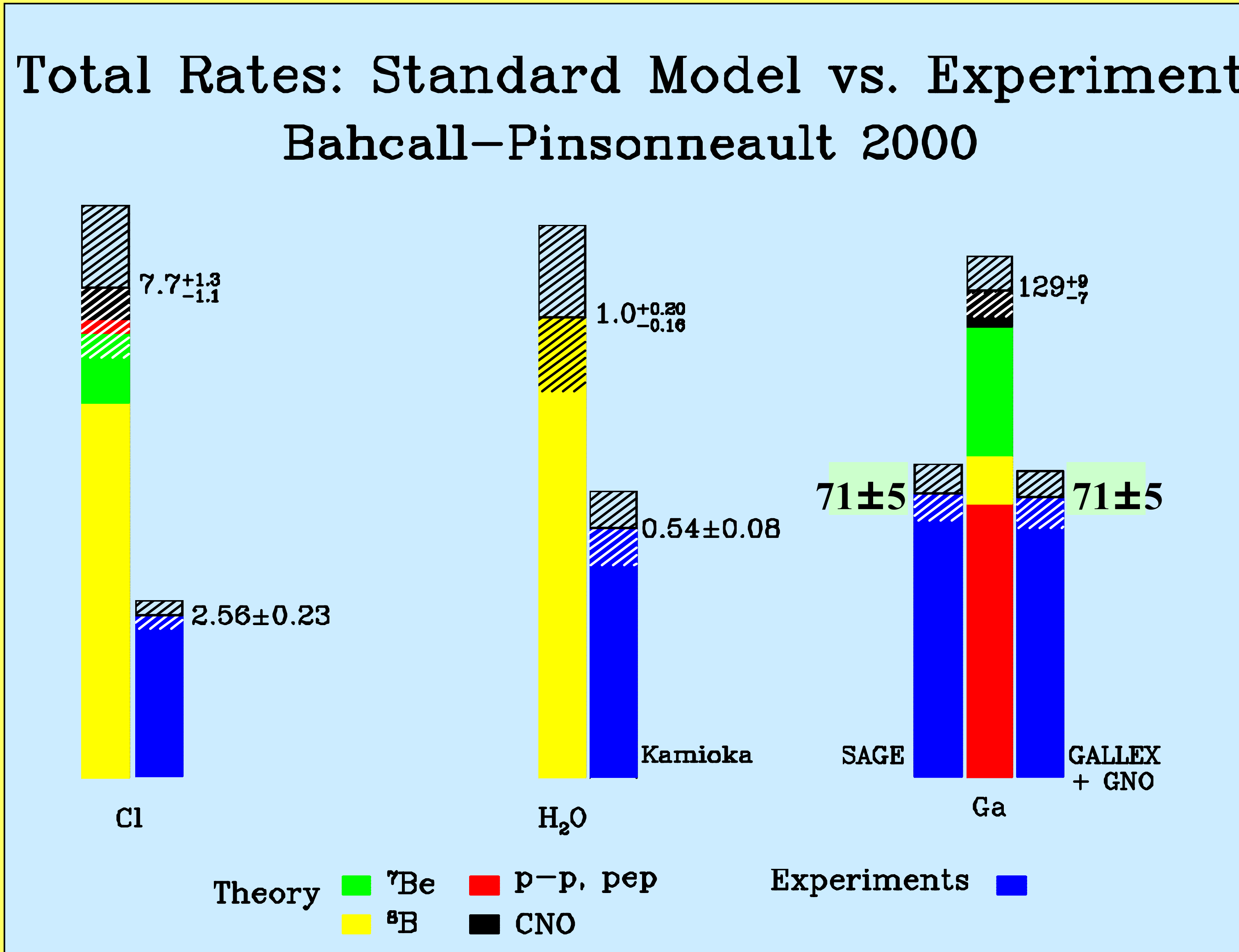

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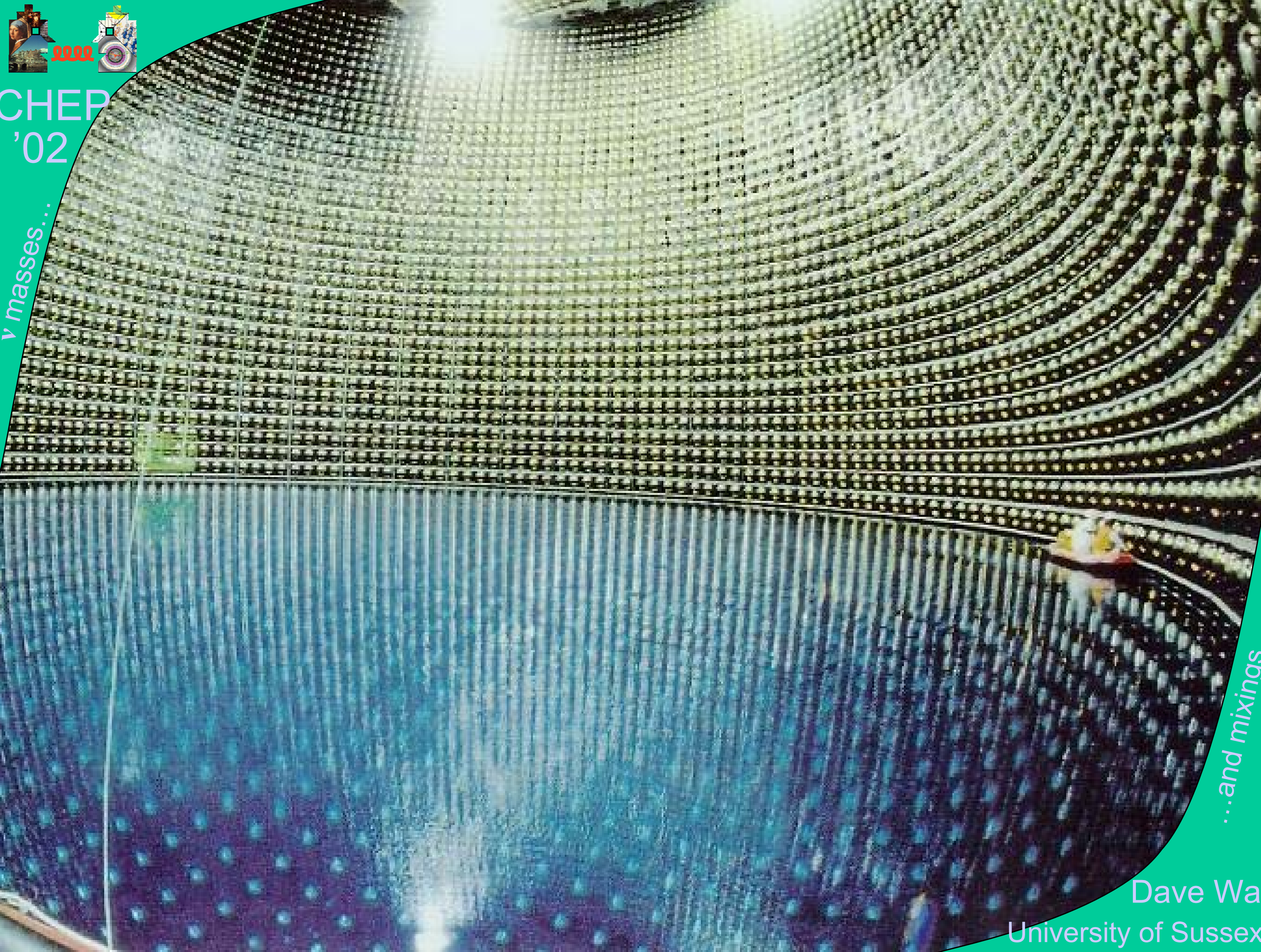

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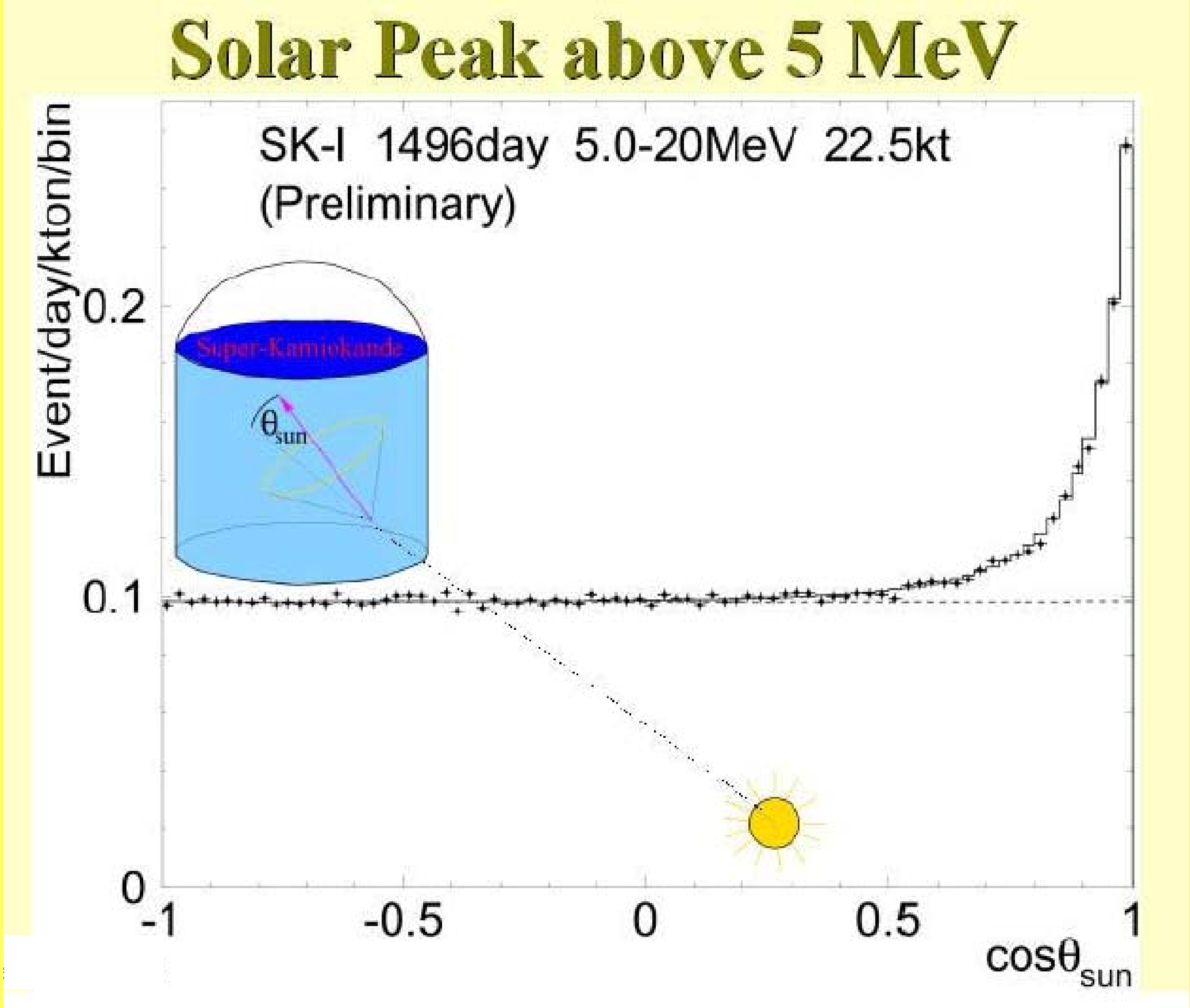
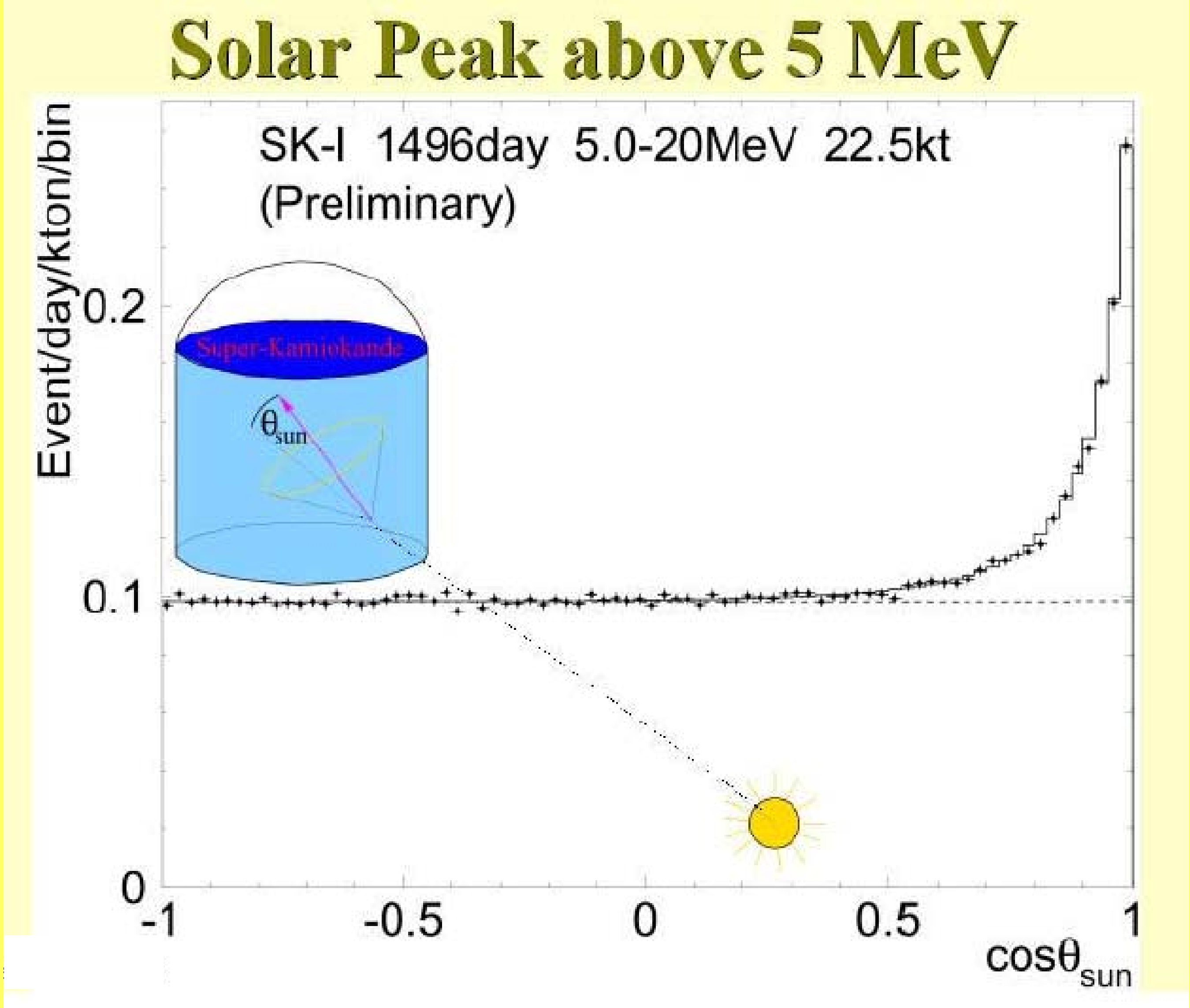
22,400 solar neutrino events!



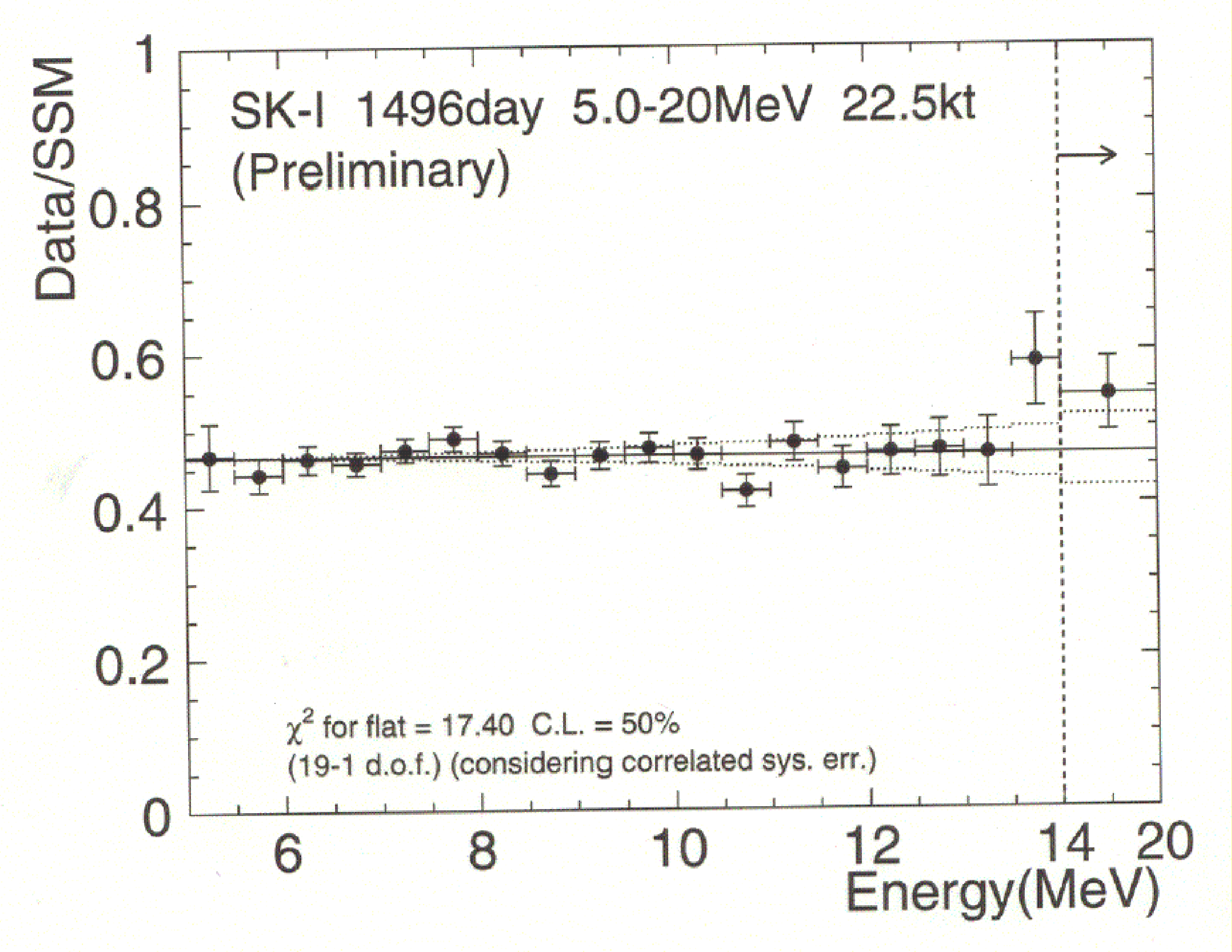
"Flux" is $2.35 \pm 0.02(\text{stat.}) \pm 0.08(\text{sys.}) \times 10^6/\text{cm}^2 \cdot \text{s}$

22,400 solar neutrino events!



$$0.465 \pm 0.005(\mathrm{stat.})^{+0.016}_{-0.015}(\mathrm{sys.}) \times \mathrm{SSM}$$

Super-Kamiokande Energy Spectrum



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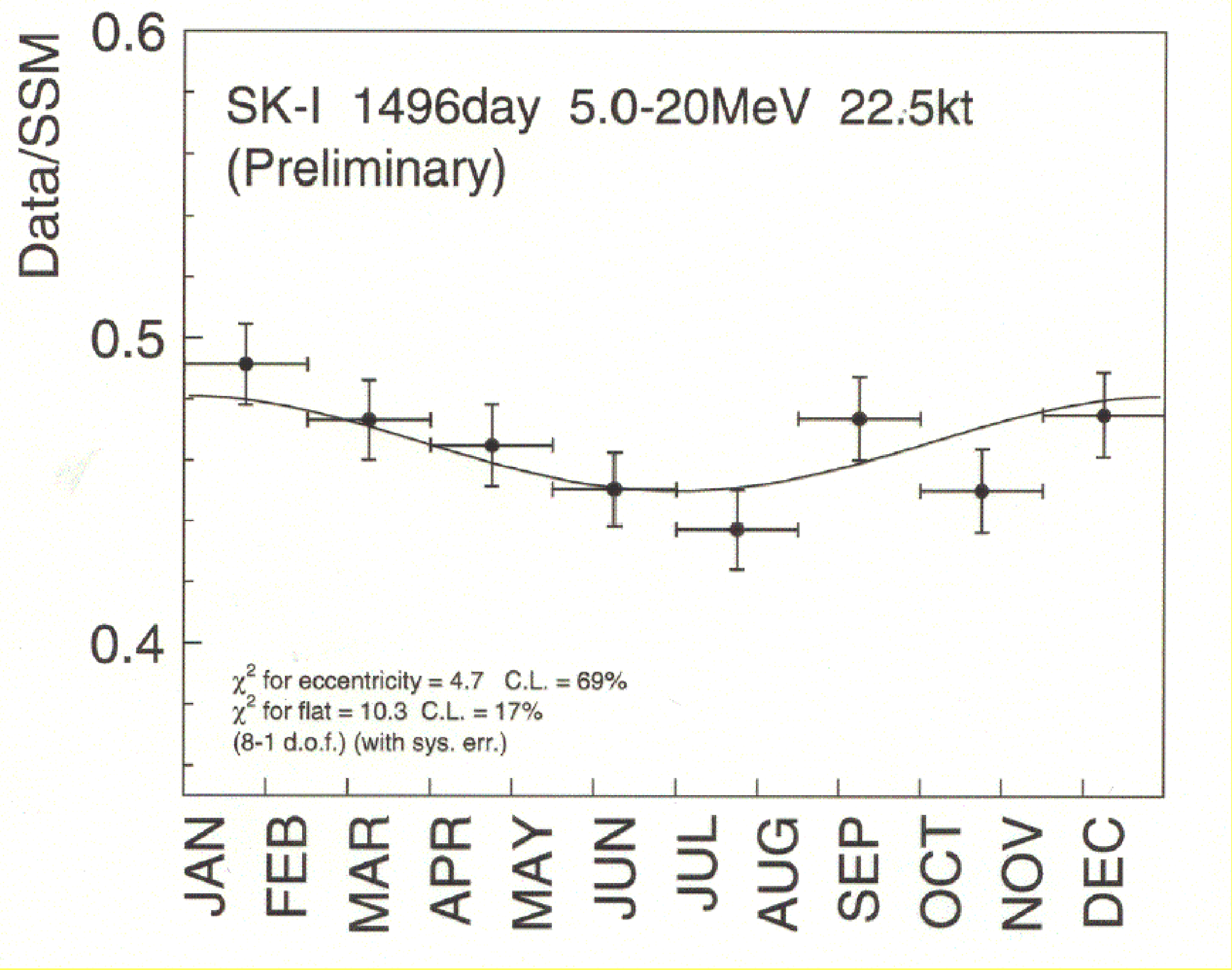
Super-Kamiokande seasonal variation



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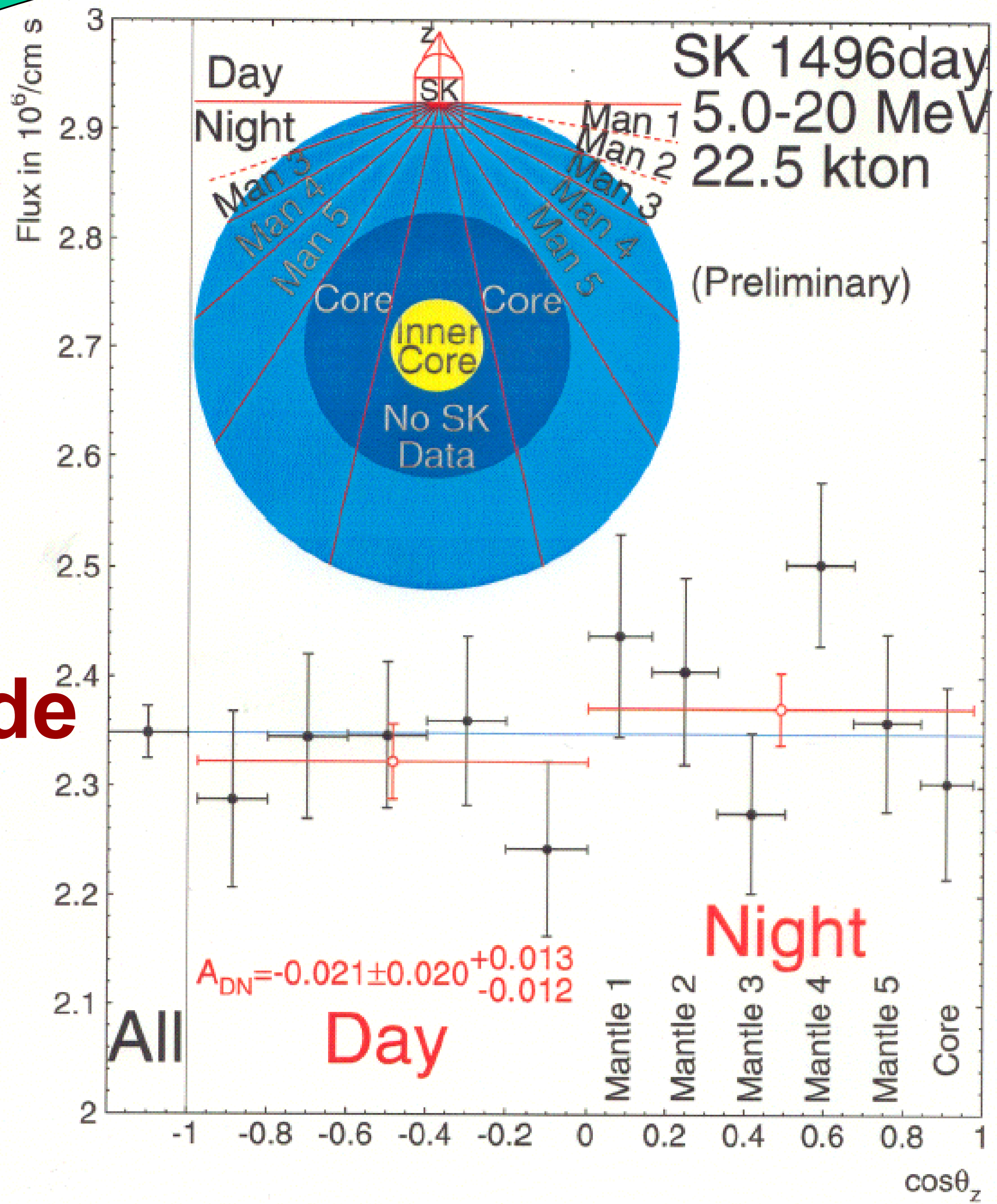
Super
amiokande



Day-nigh
variation

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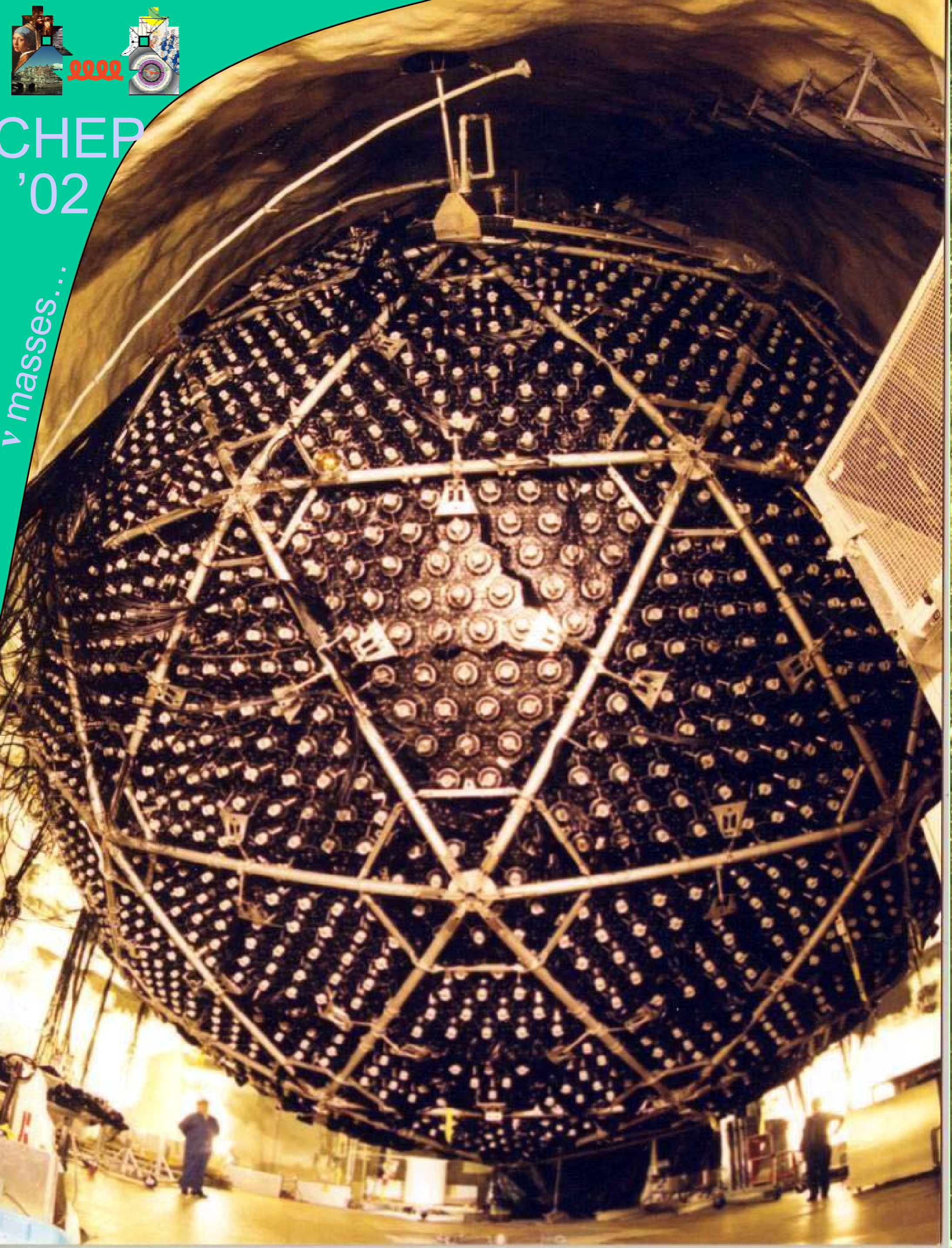

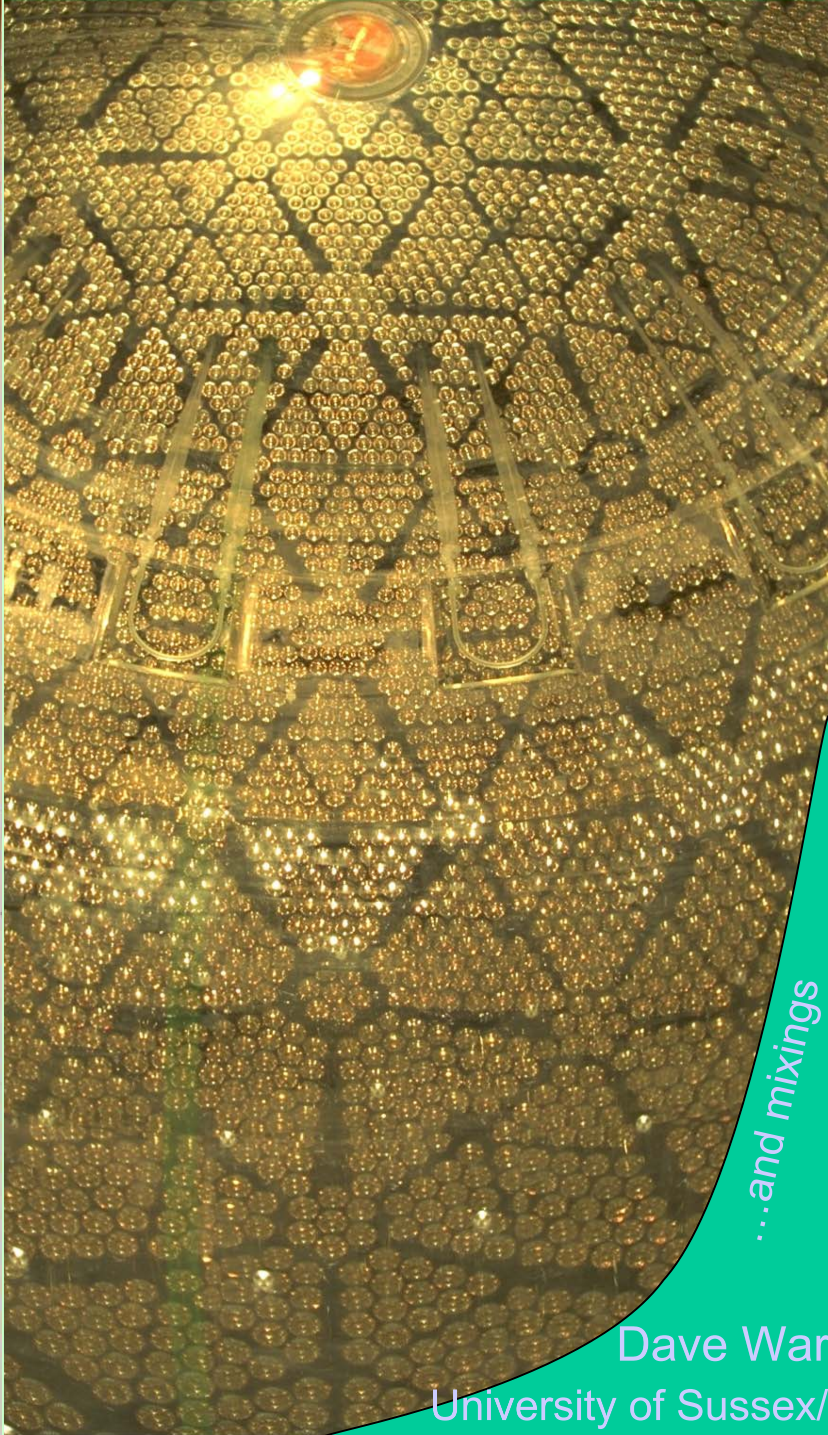

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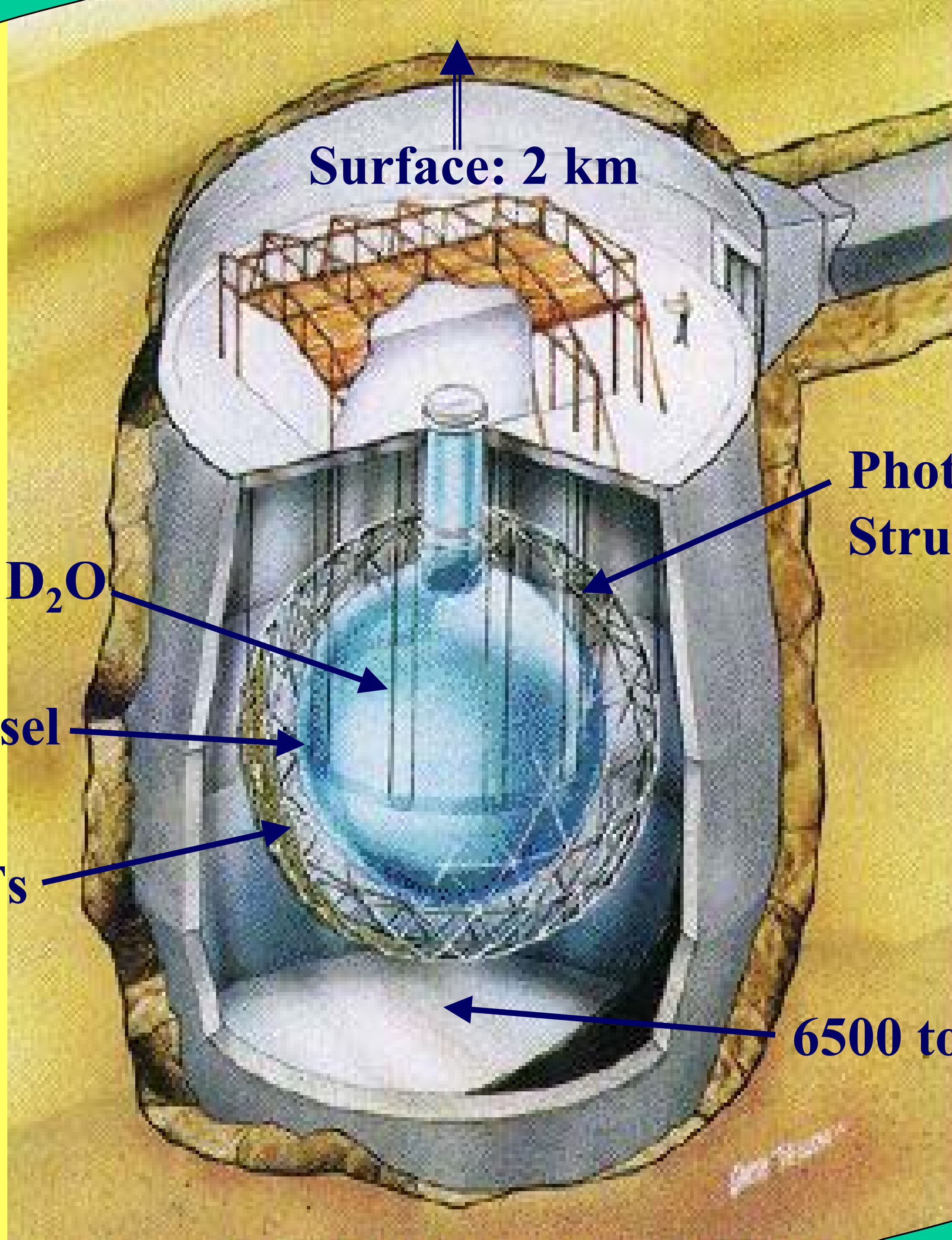
Surface: 2 km
Phototube Support Structure (PSUP)
1000 tonnes D_2O
Acrylic Vessel
10^4 8" PMTs
6500 tonnes H_2O

Solar ν Interactions in SNO

Elastic Scattering (ES) $\quad \boldsymbol{\nu_x + e^- \rightarrow \nu_x + e^-}$

- Directional sensitivity (e^- forward peaked)
- Cross-section for ν_e is $6.5\times$ larger than for $\nu_{\mu\tau}$

Charged Current (CC) $\quad \boldsymbol{\nu_e + d \rightarrow p + p + e^-}$

- Some directional information $(1 - \frac{1}{3}\cos\theta_{e\nu})$
- good E_ν sensitivity (ν_e spectrum)

Neutral Current (NC) $\quad \boldsymbol{\nu_x + d \rightarrow n + p + \nu_x}$

- Total flux of active neutrinos above 2.2 MeV
- Detect neutrons by $n + d \rightarrow t + 6.25$ MeV γ

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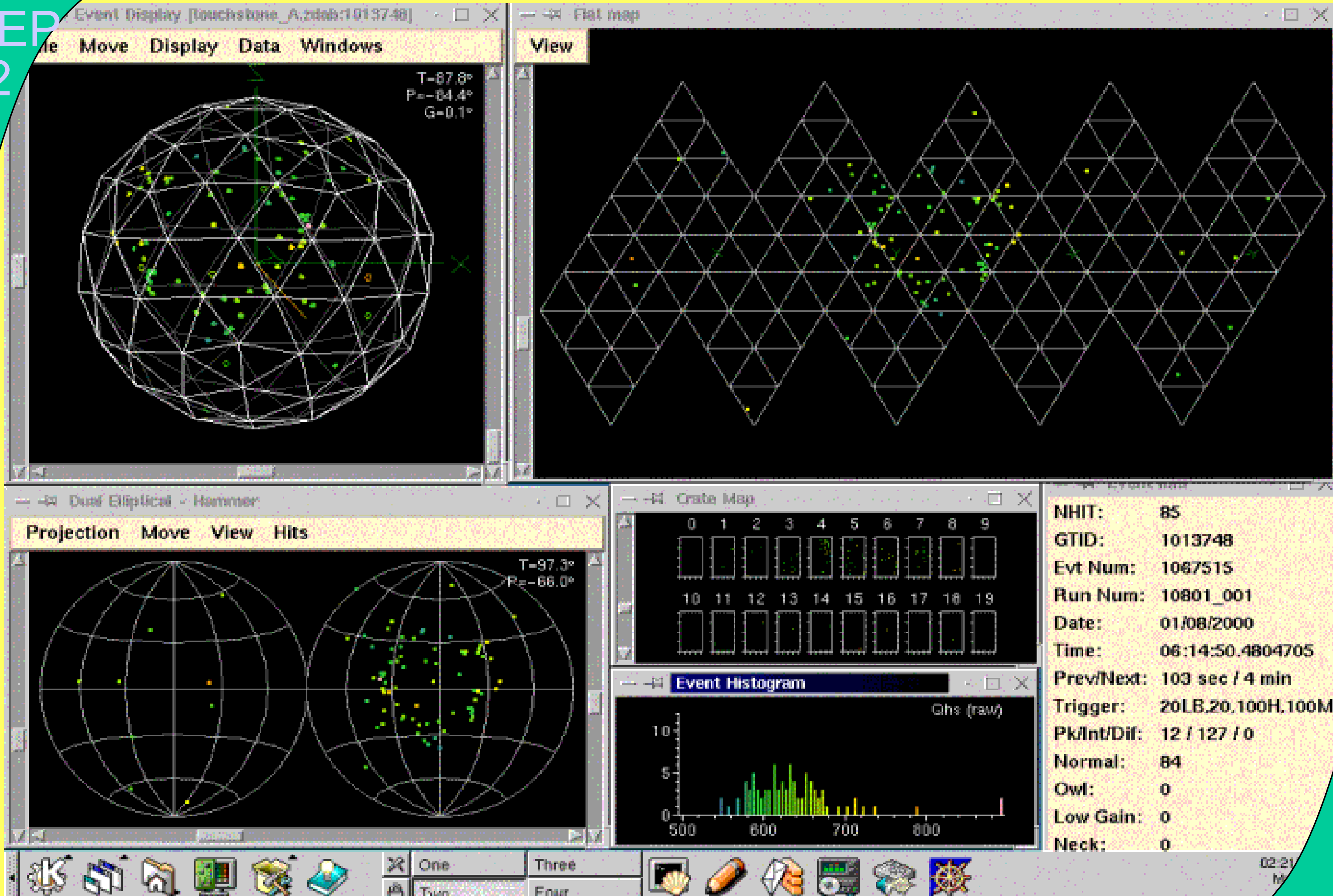

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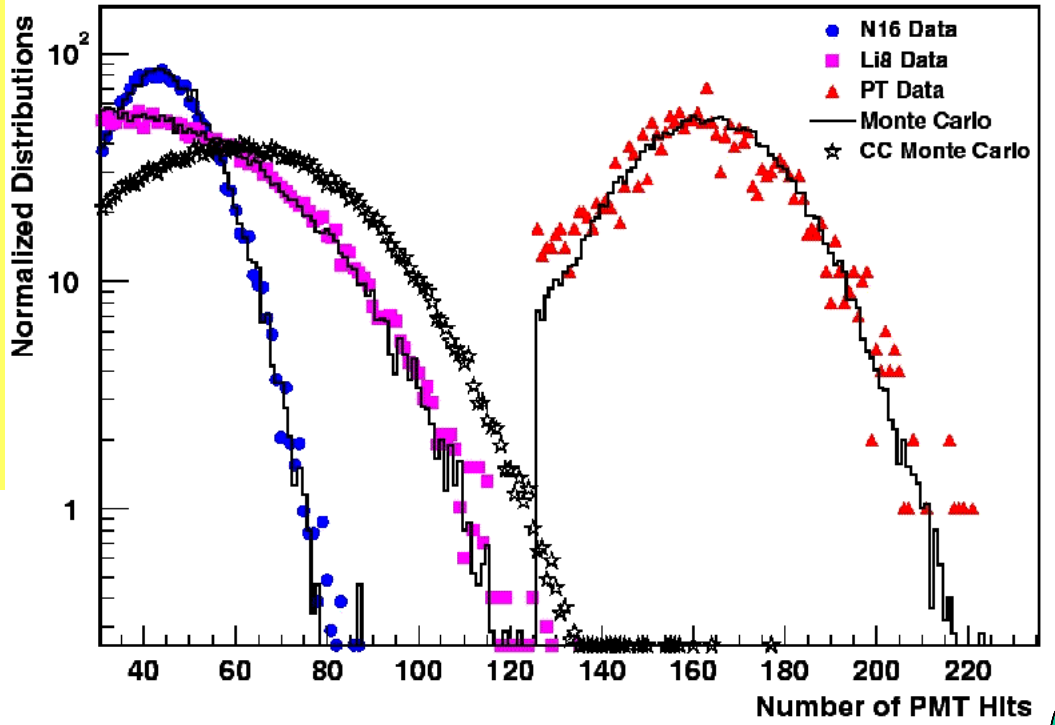
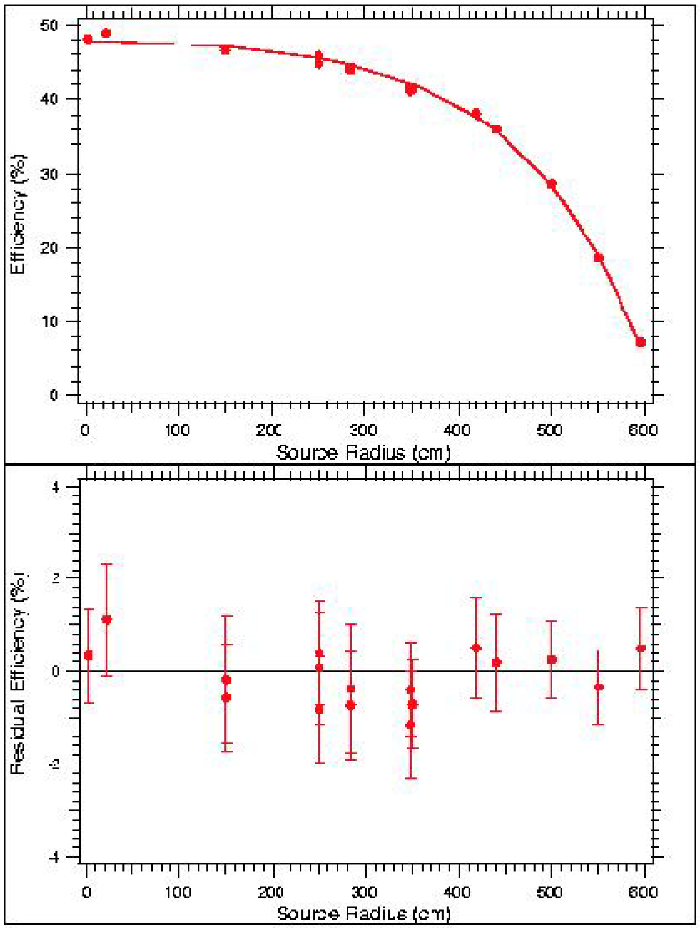
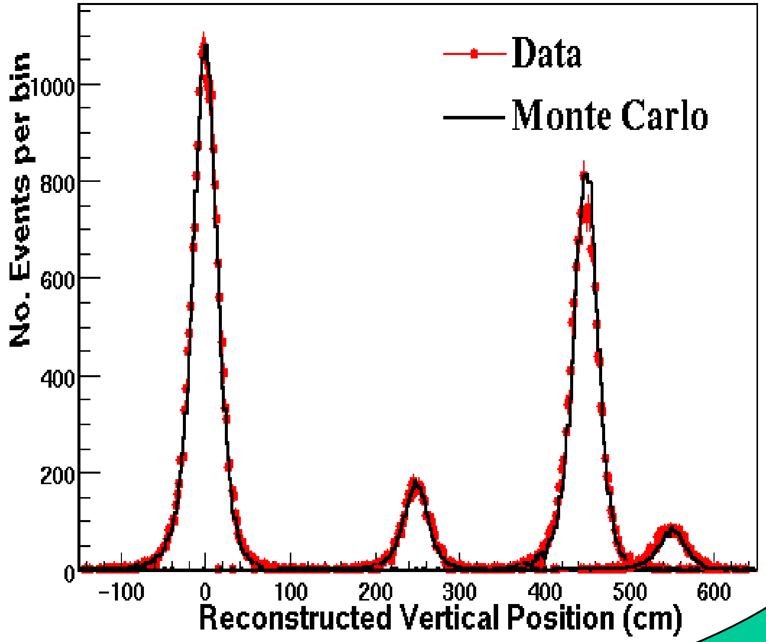
Calibrations:







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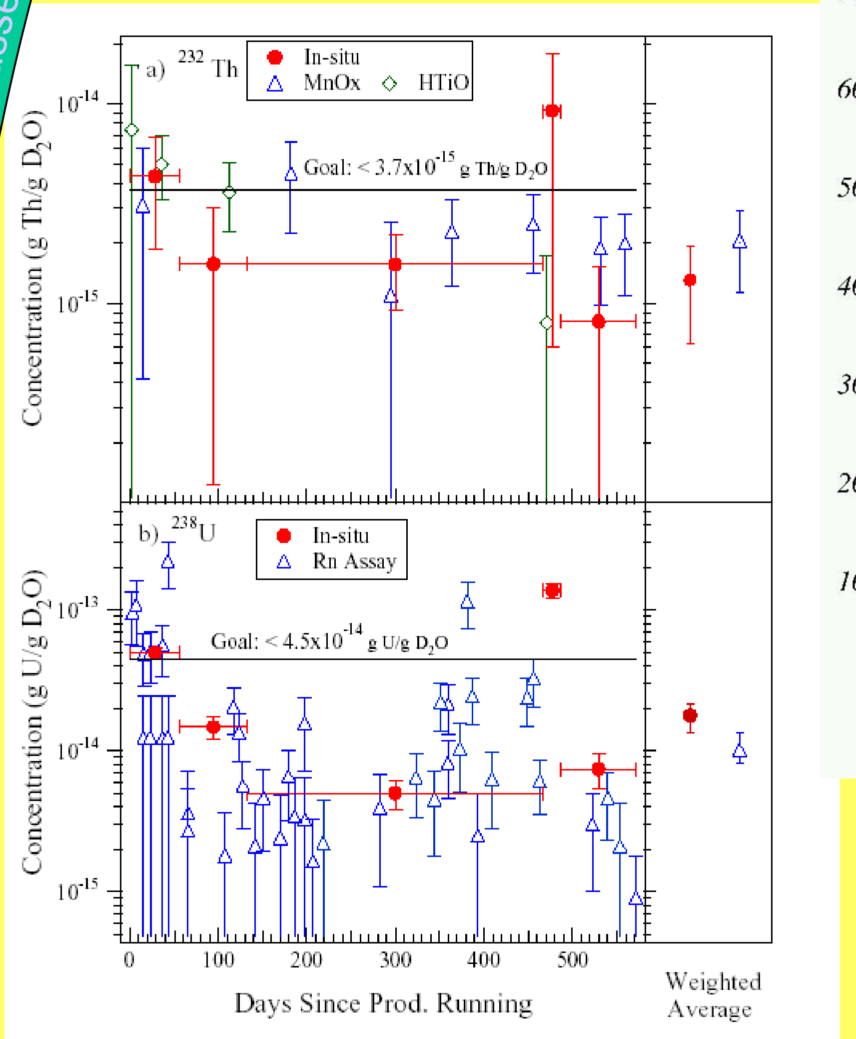
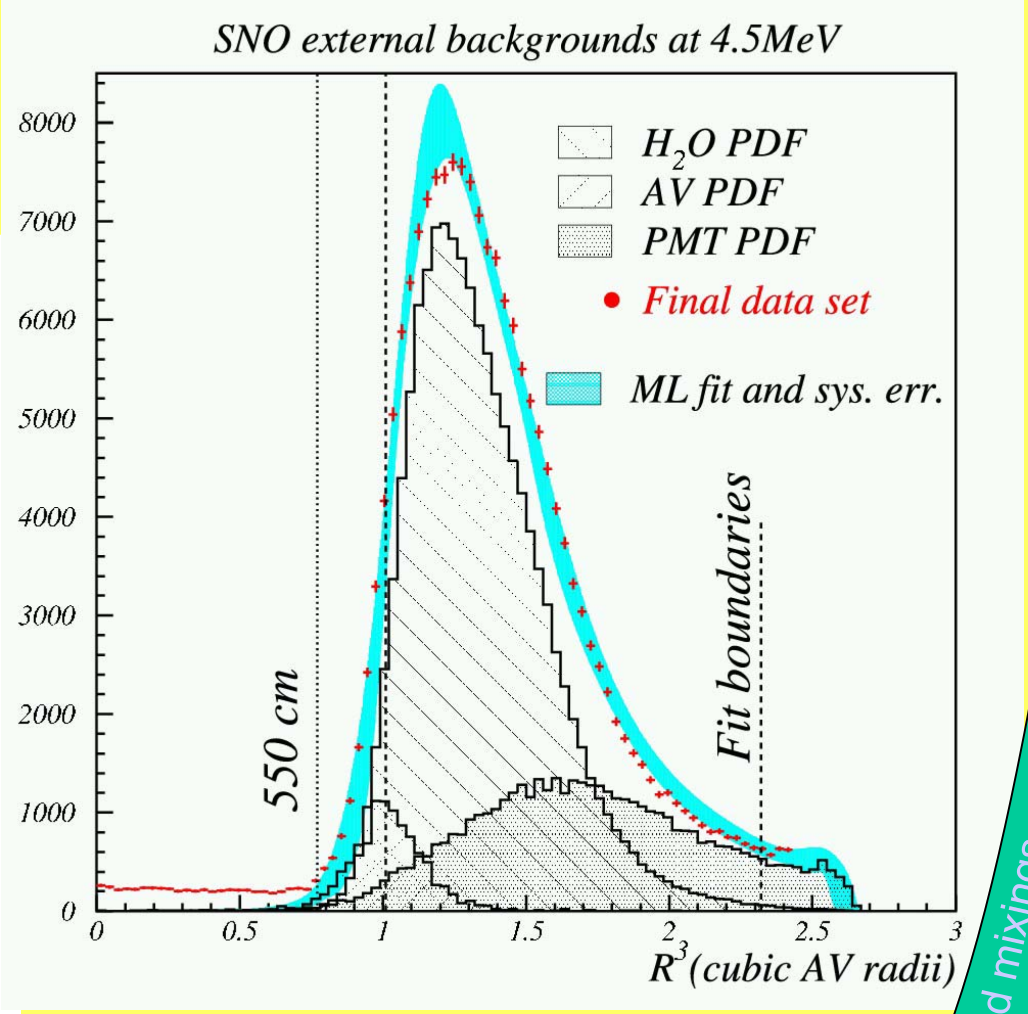
SNO Backgrounds

Internal





External

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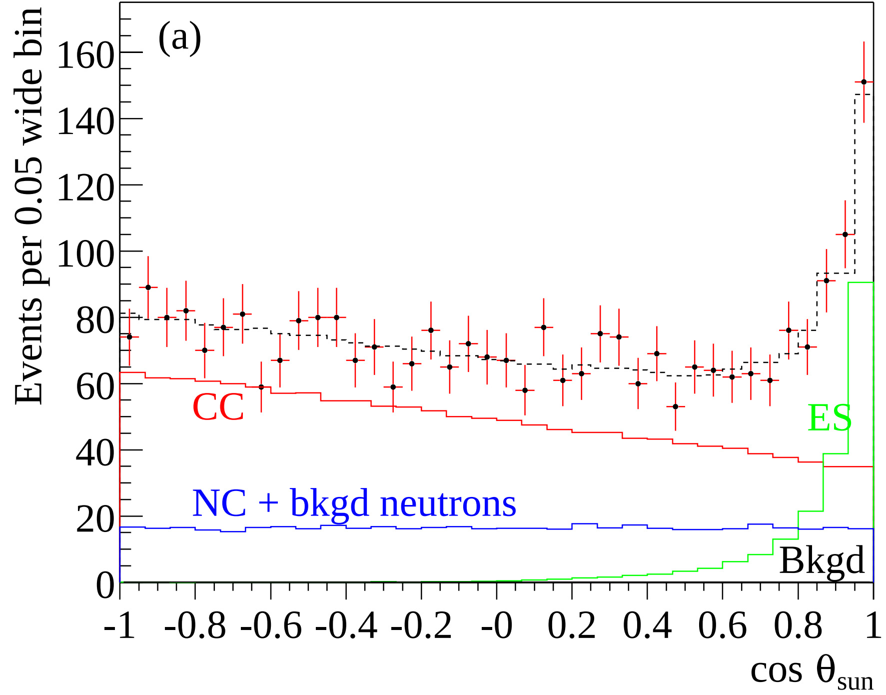
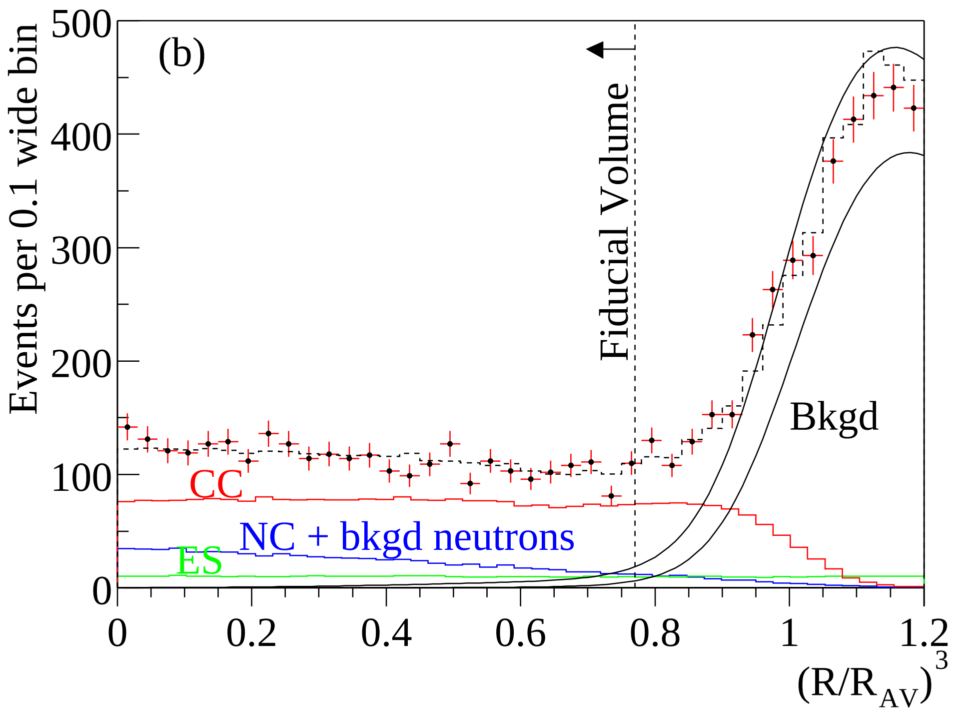
#EVENTS

CC	1967.7	+61.9 +60.9
ES	263.6	+26.4 +25.6
NC	576.5	+49.5 +48.9





The energy spectrum→

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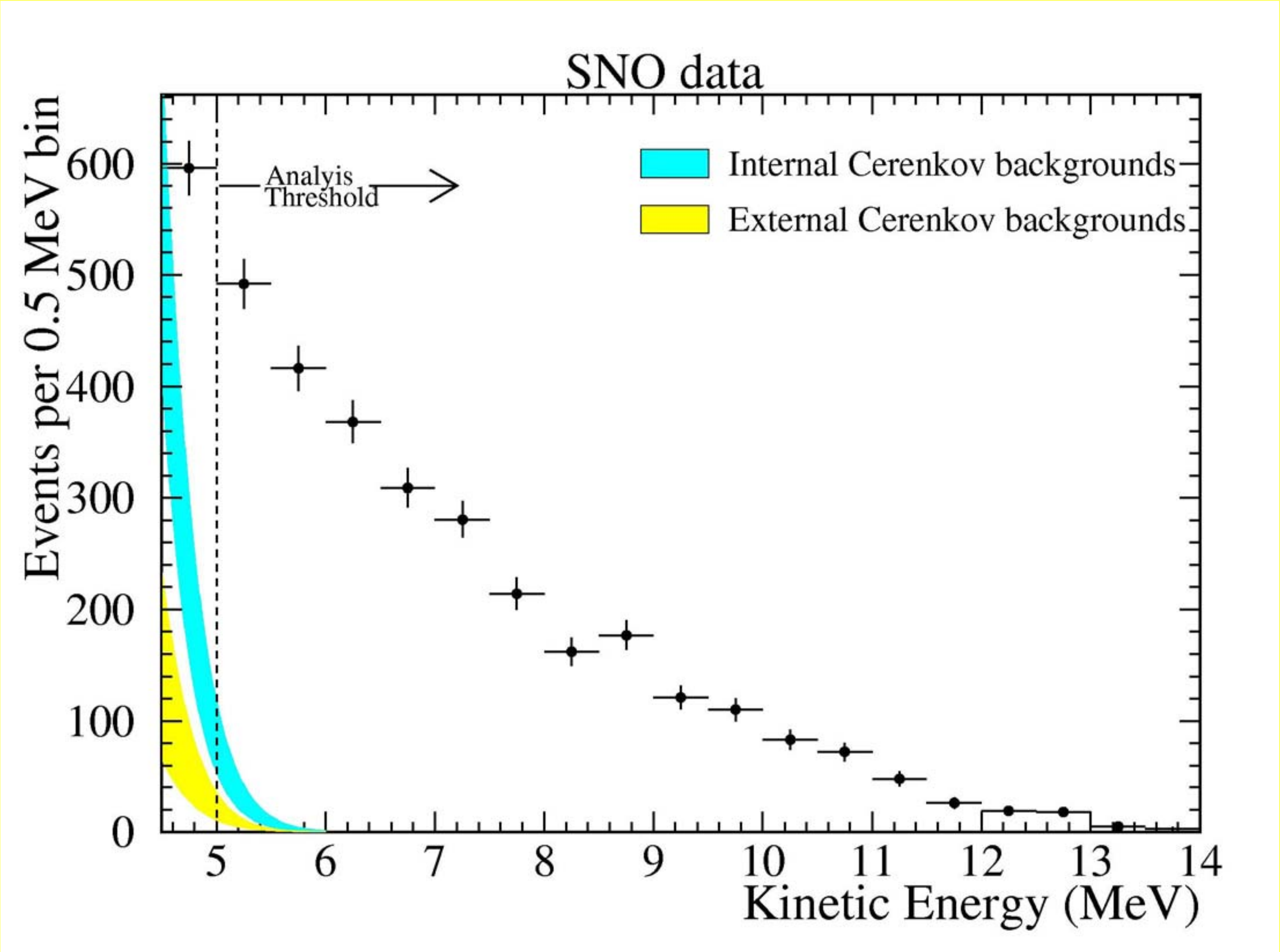

So subtract these backgrounds ☑

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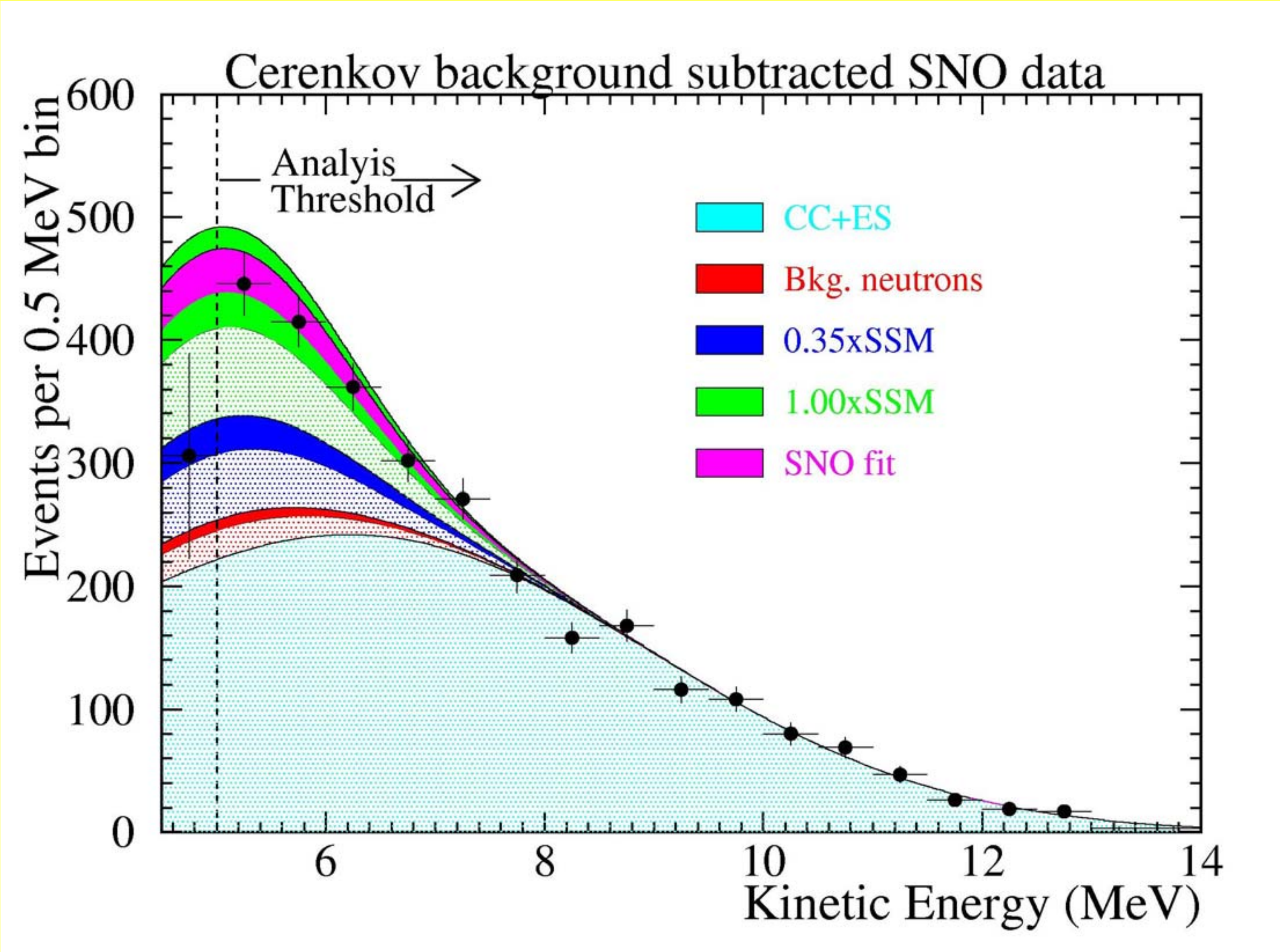
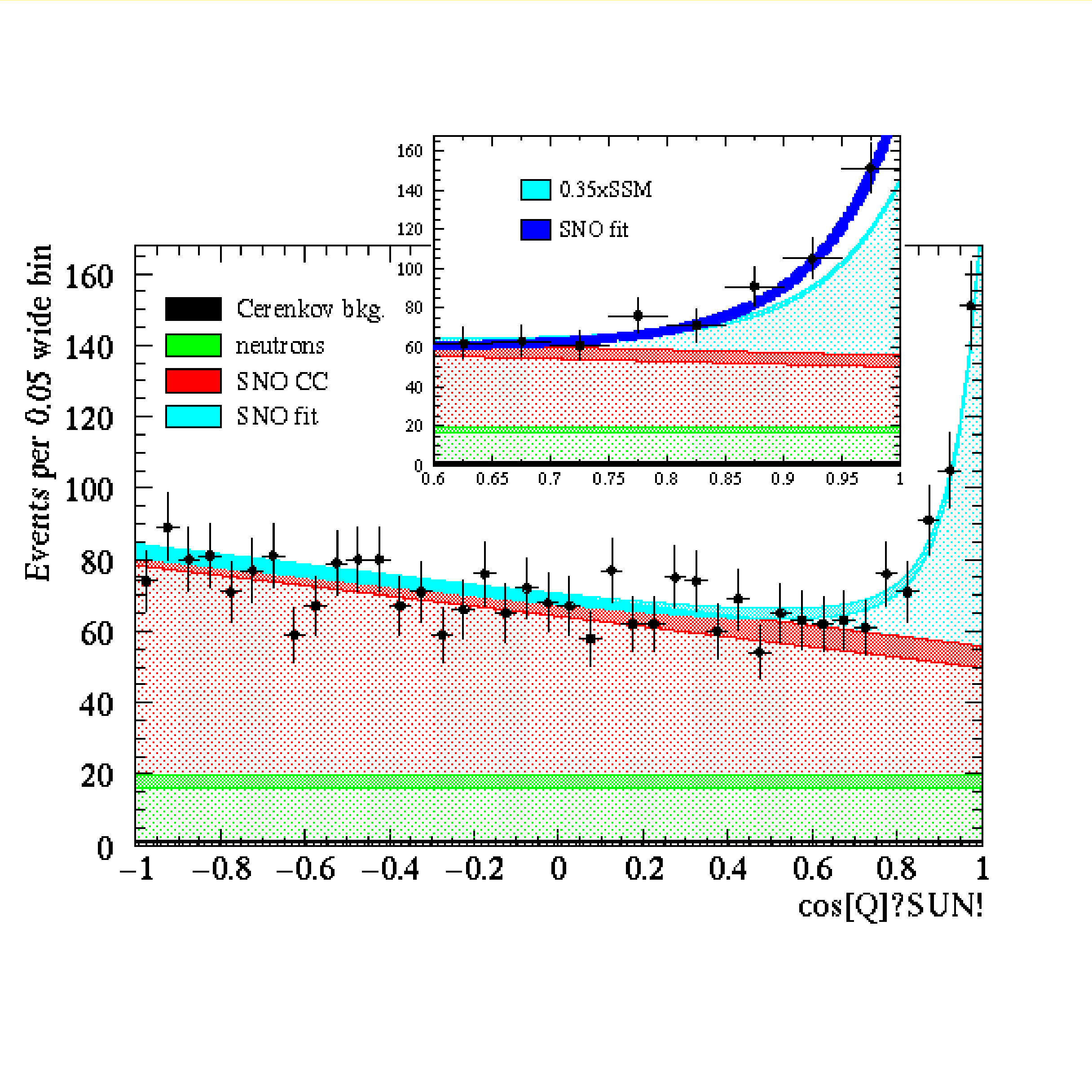
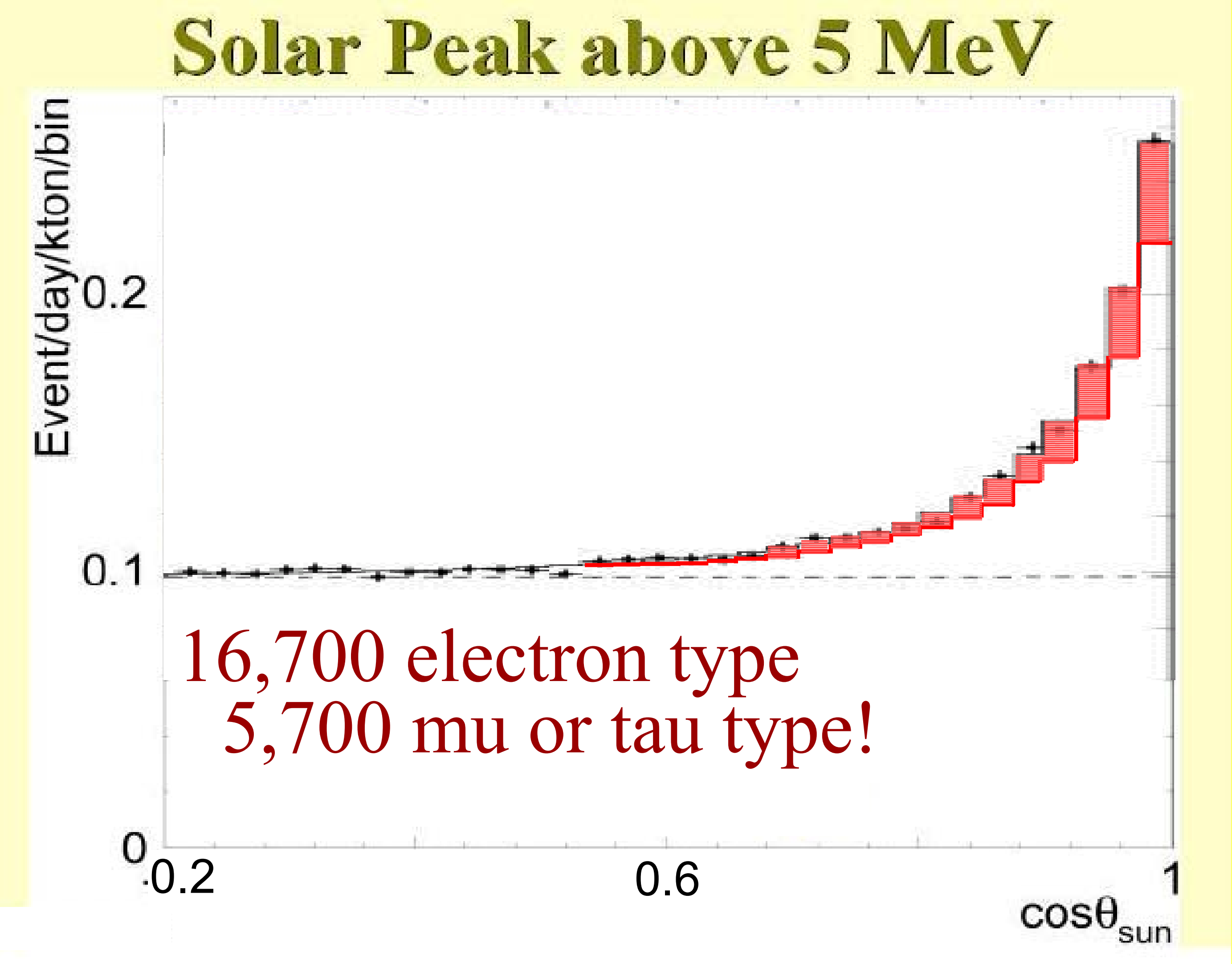

Cerenkov background subtracted SNO data
Events per 0.5 MeV bin
Kinetic Energy (MeV)
Analyis Threshold
CC+ES
Bkg. neutrons
0.35xSSM
1.00xSSM
SNO fit
0
100
200
300
400
500
600
6
8
10
12
14

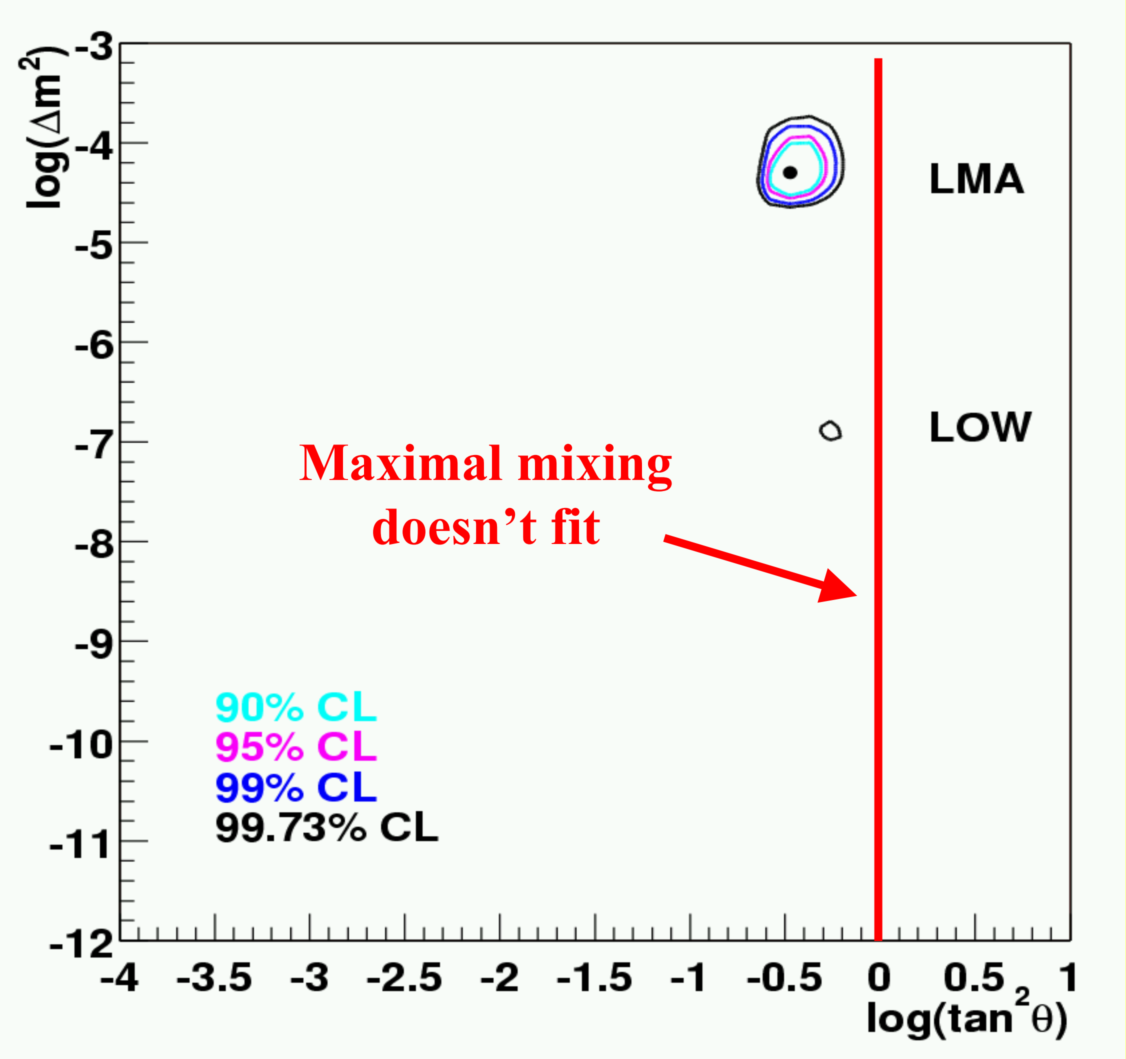
Do they come from the sun?



What does SuperK see?



16,700 electron type
5,700 mu or tau type!



All SNO, SK D/N spectra;
Ga, Cl, SSM but ^{8}B free.

How will we learn more?

- From SNO:
  - Currently running with NaCl in the D_2O
  - Shortly to install discrete neutron counters
  - Stringent test of NC systematics
- From others:
  - Long term – too many to discuss here
  - Short term:
    - KamLAND
    - BOREXINO

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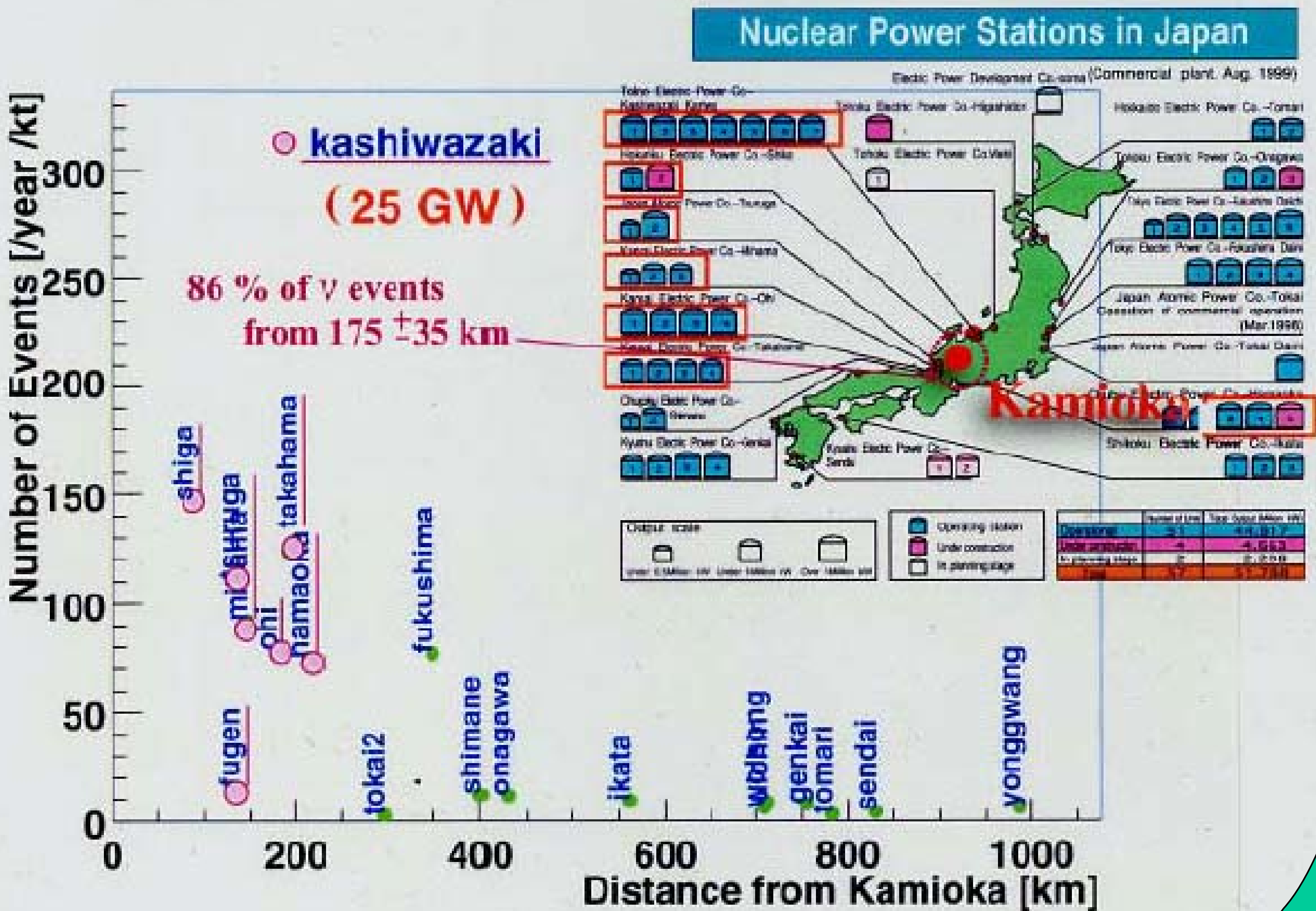
Power Plant Reactors and Event Rate



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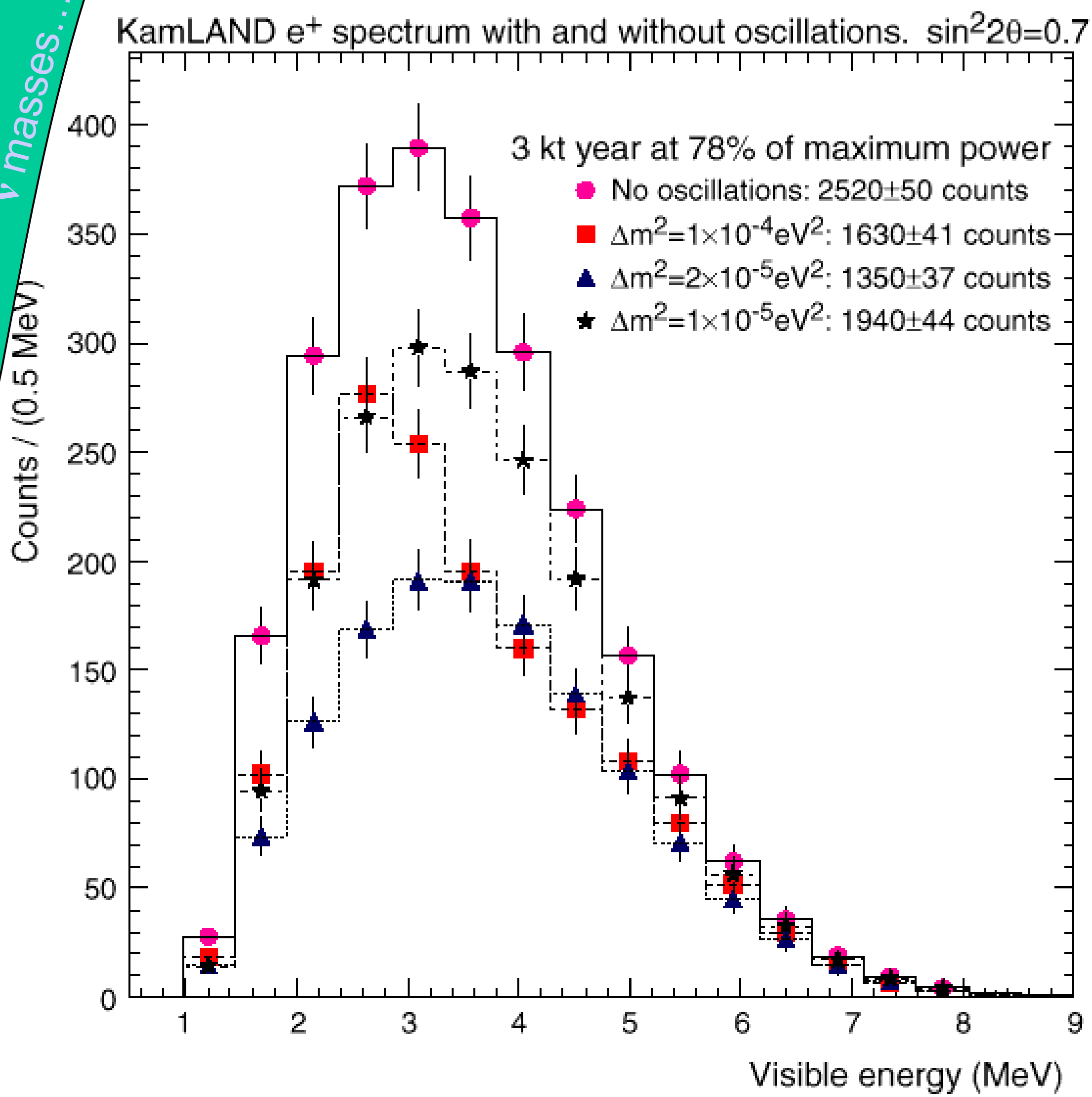

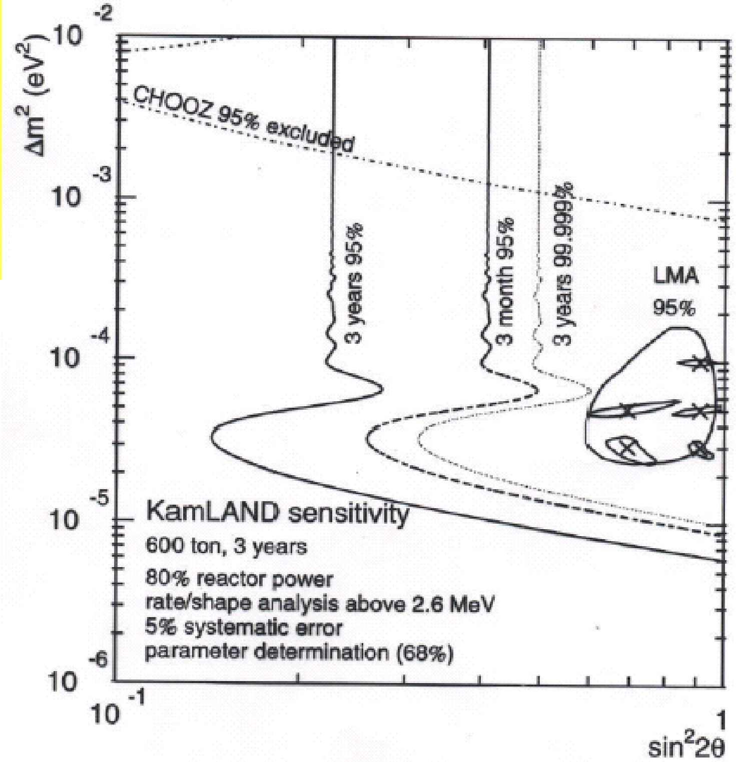

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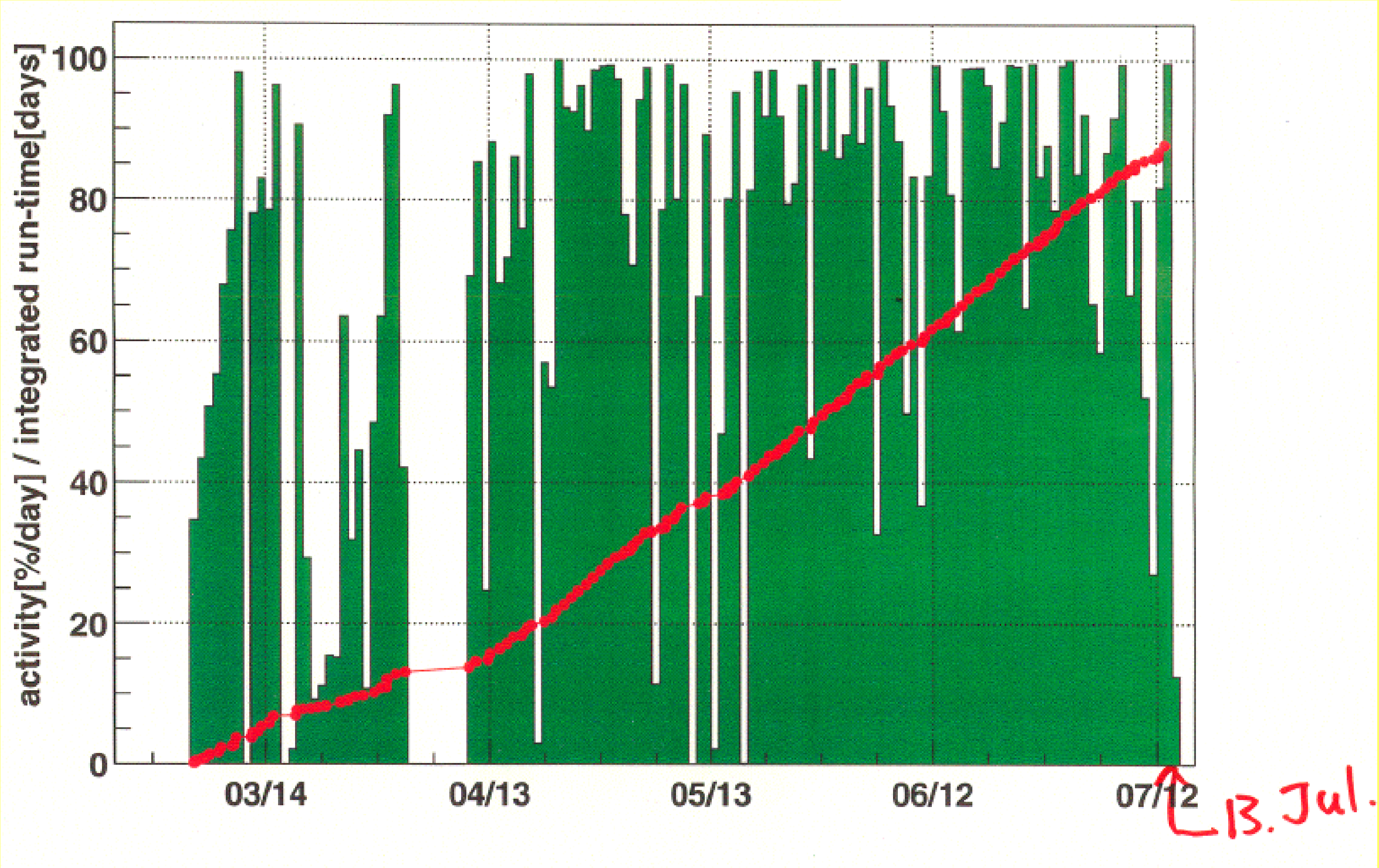
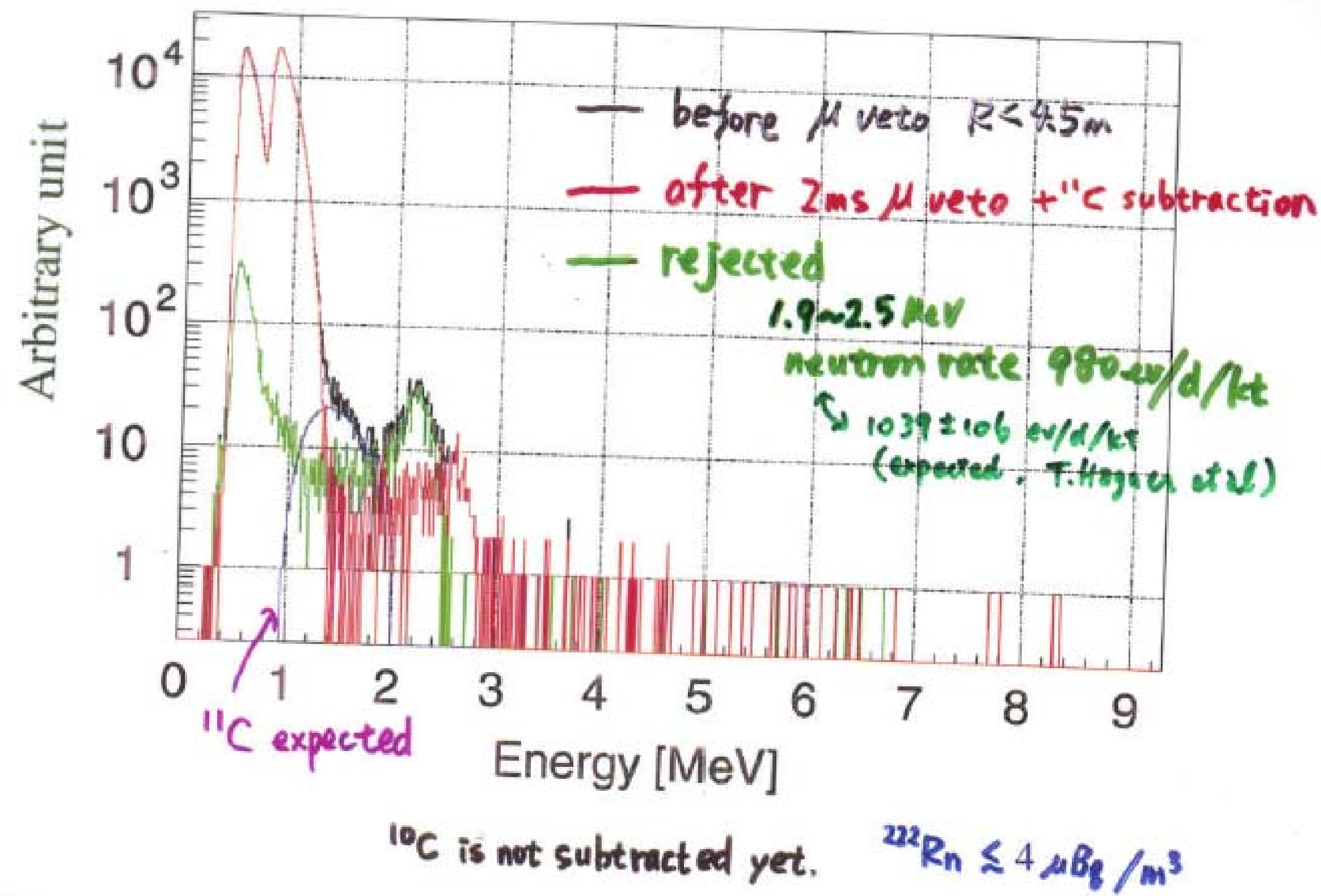
KamLAND is taking data!



Backgrounds are low!



First Results at PANIC?!?

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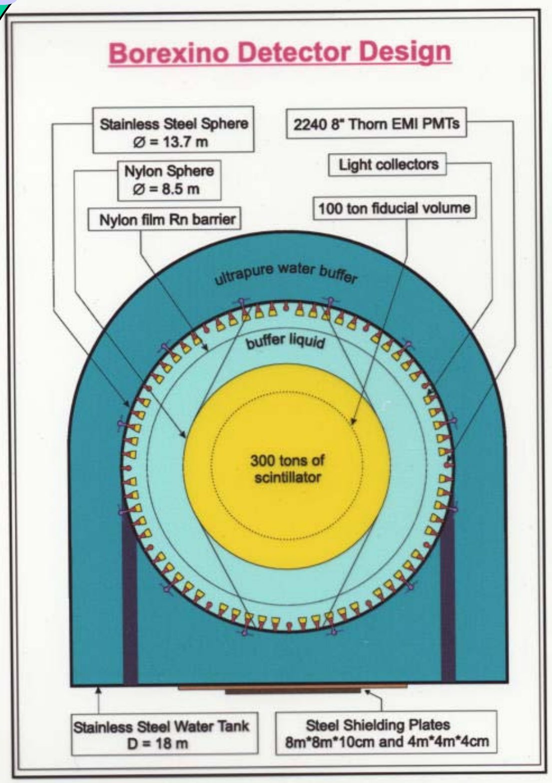

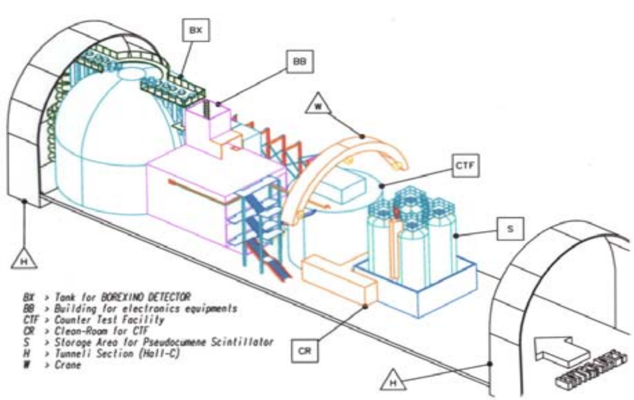

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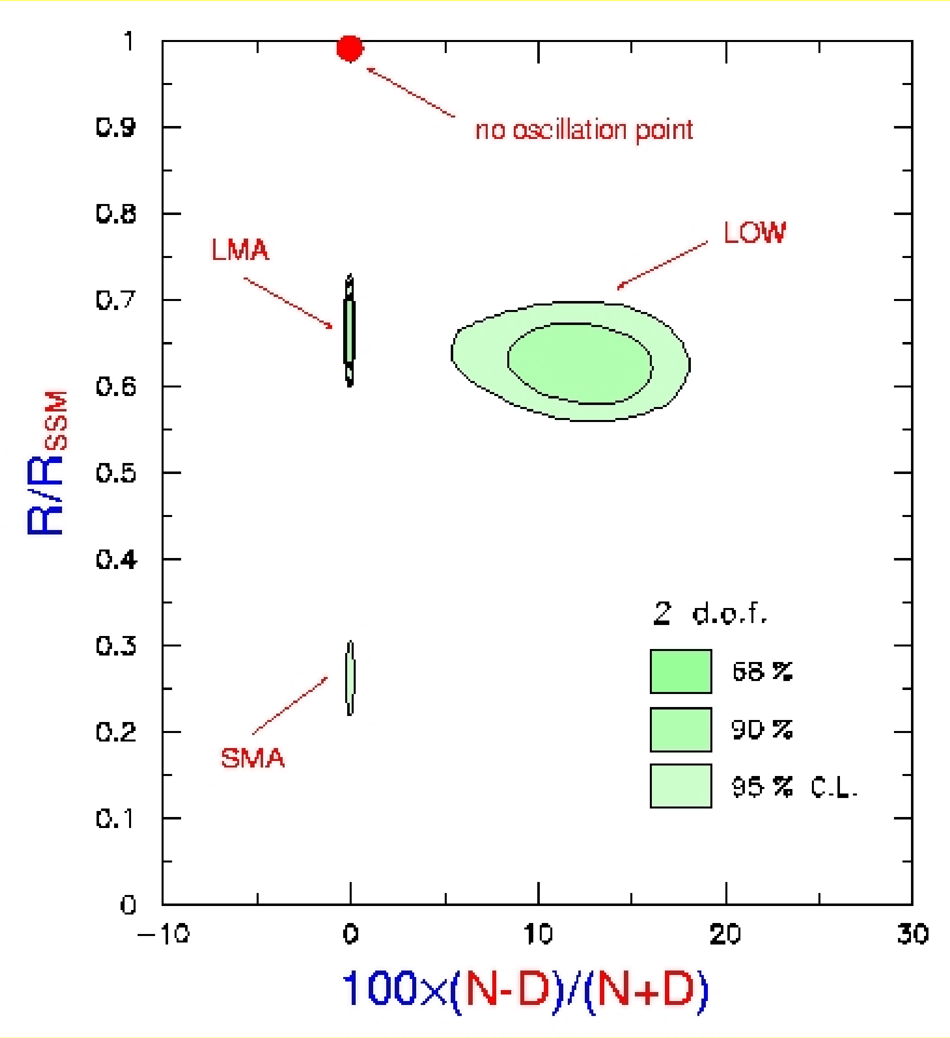
Borexino Physics Target – ^{7}Be neutrinos



Fill to start November 2002,
data spring 2003

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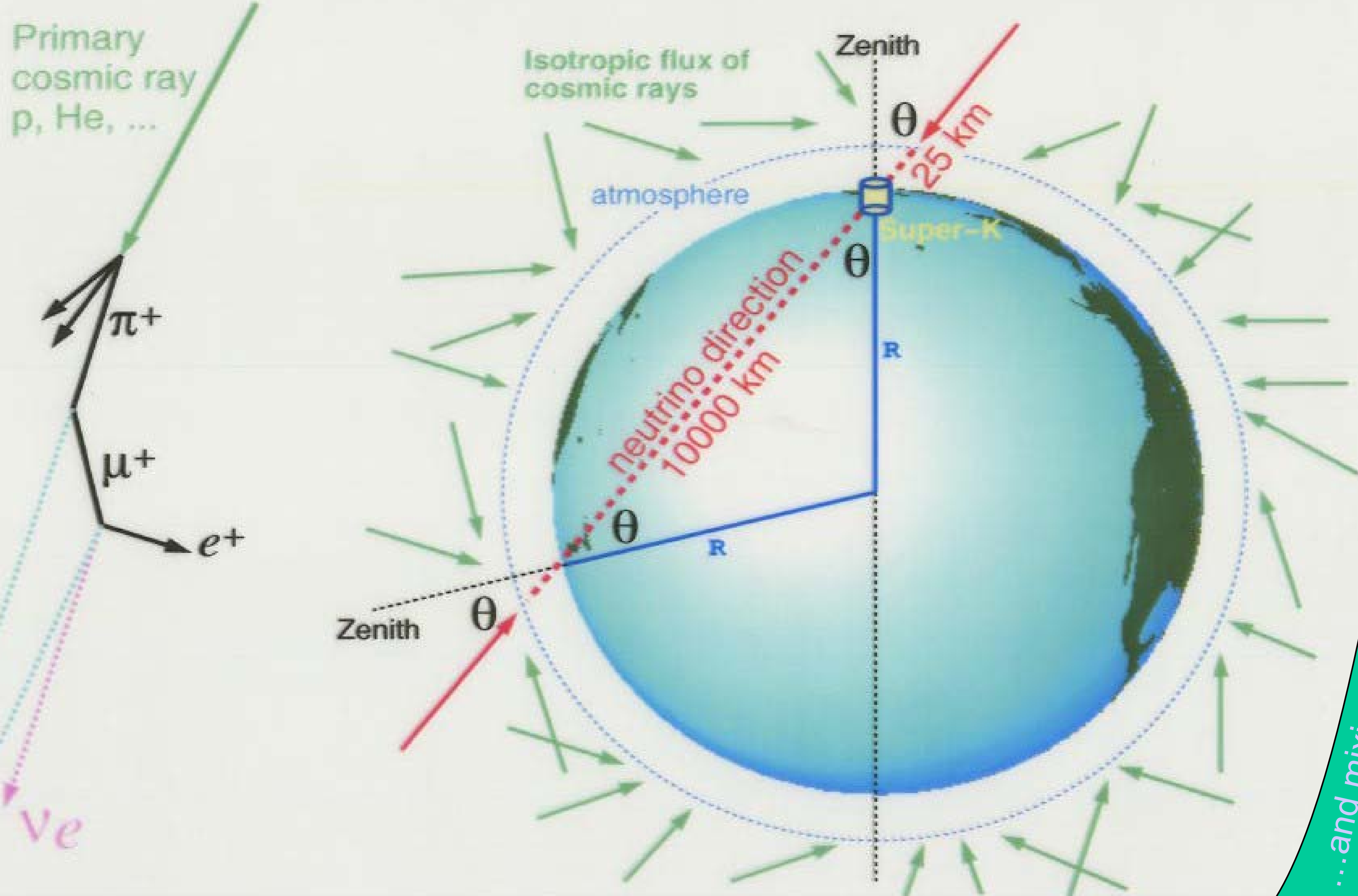
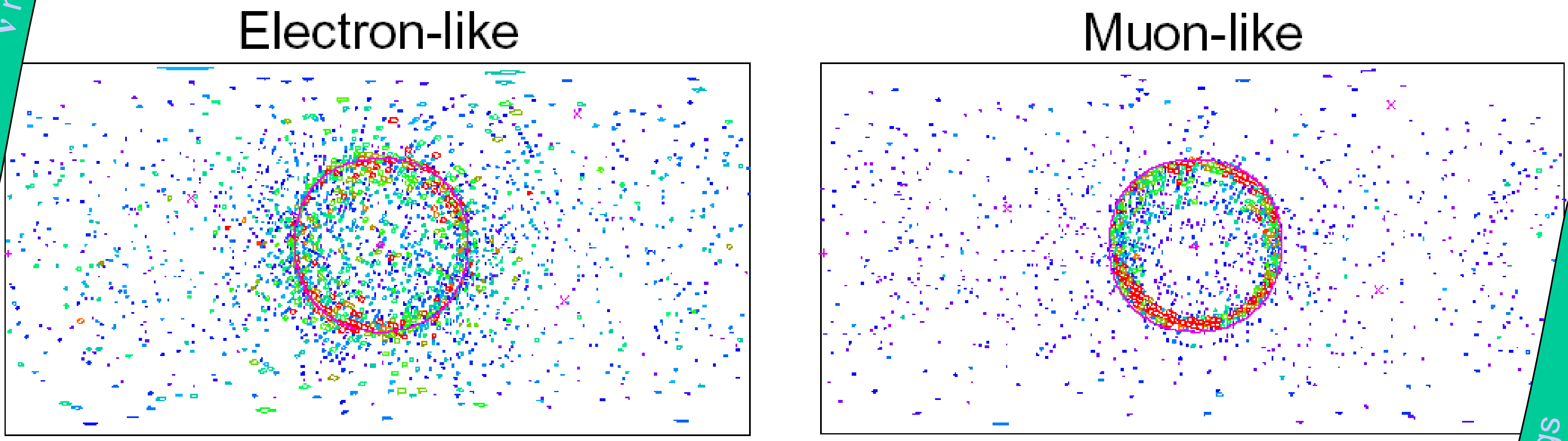
ATMOSPHERIC NEUTRINOS



Ratio of $\nu_\mu/\nu_e \sim 2$
(for E_ν < few GeV)

Up–Down Symmetric Flux
(for E_ν > few GeV)

SK can distinguish muons from electrons with impressive precision



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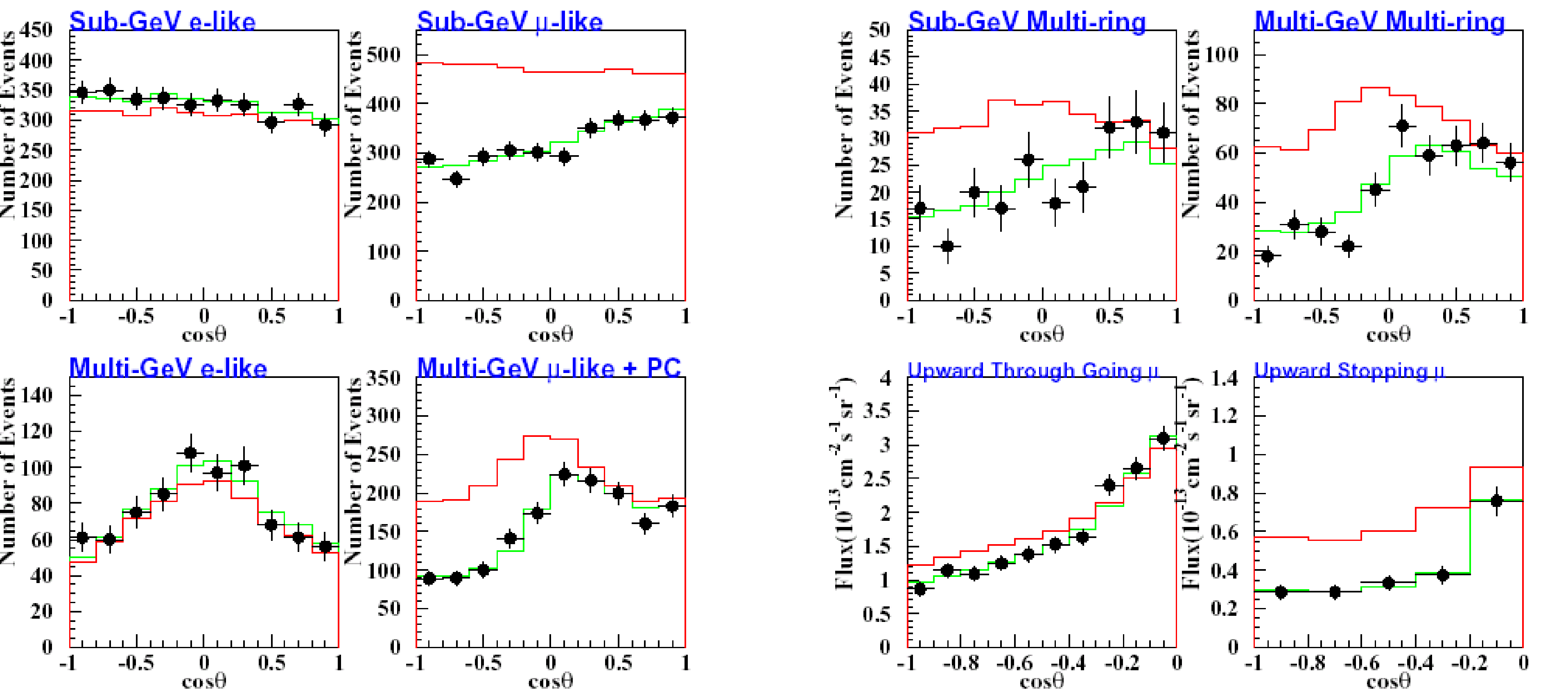
SK data as a function of zenith angle



…and

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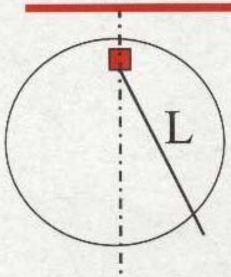
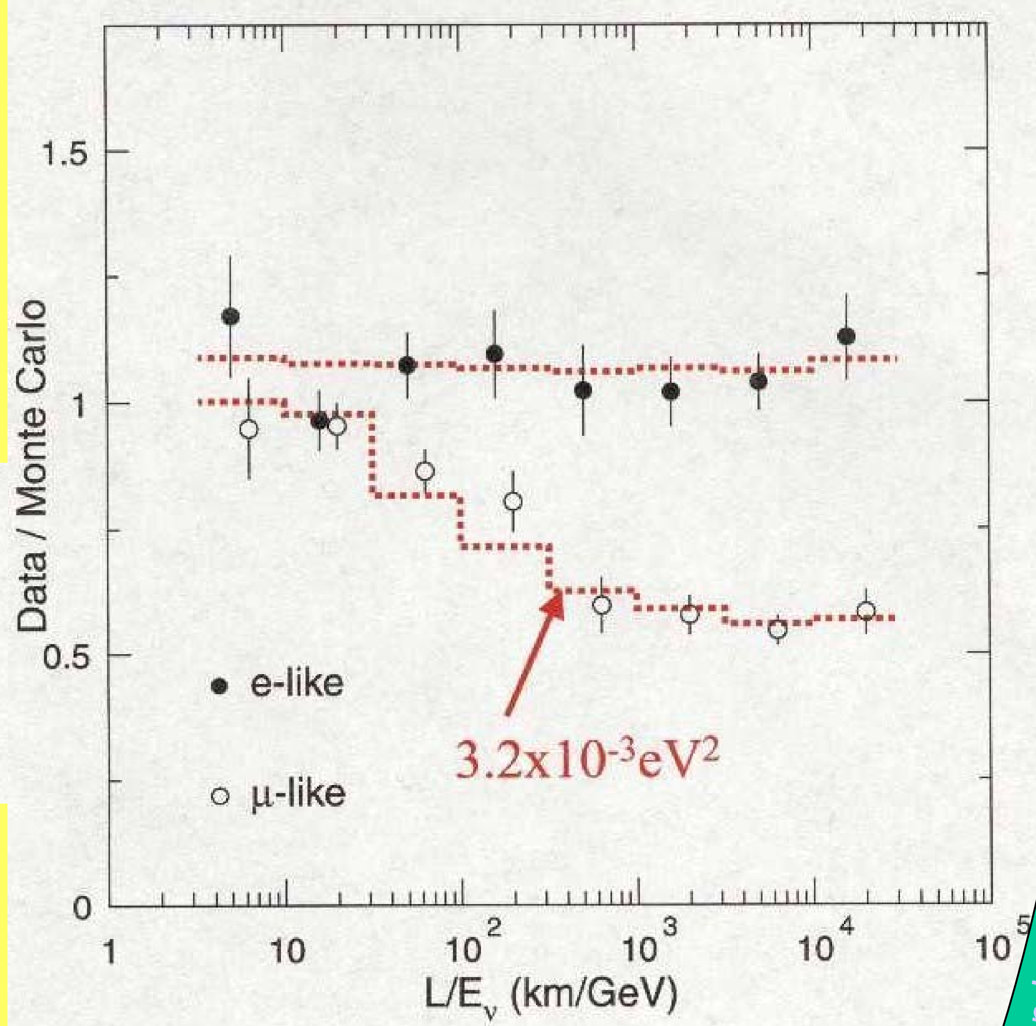
Bin data as a function of L/E_ν



$$P_{\nu\nu'} = \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E_\nu)$$



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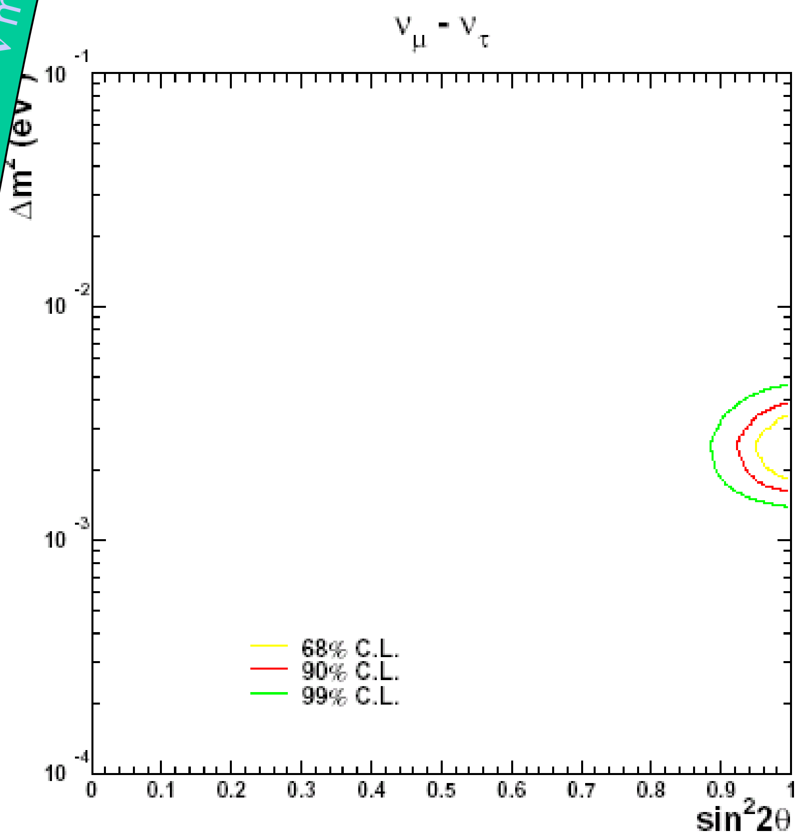
Excellent fit to ν_μ ⌧ ν_τ

Very poor fit to ν_μ ⌧ ν_e



No oscillation

$\chi^2_{min} = 456.5/170$ d.o.f.)

$\nu_\mu \leftrightarrow \nu_\tau$

Best fit:

$\Delta m^2 = 2.5 \times 10^{-3} eV^2$, $\sin^2 2\theta = 1.0$

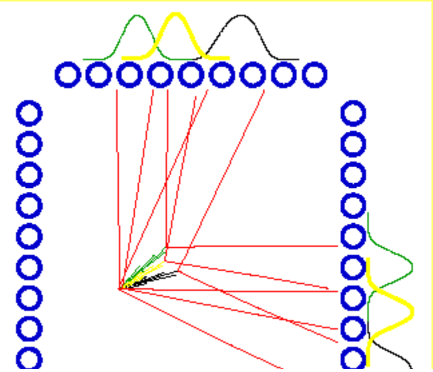
$\chi^2_{min} = 163.2/170$ d.o.f.)

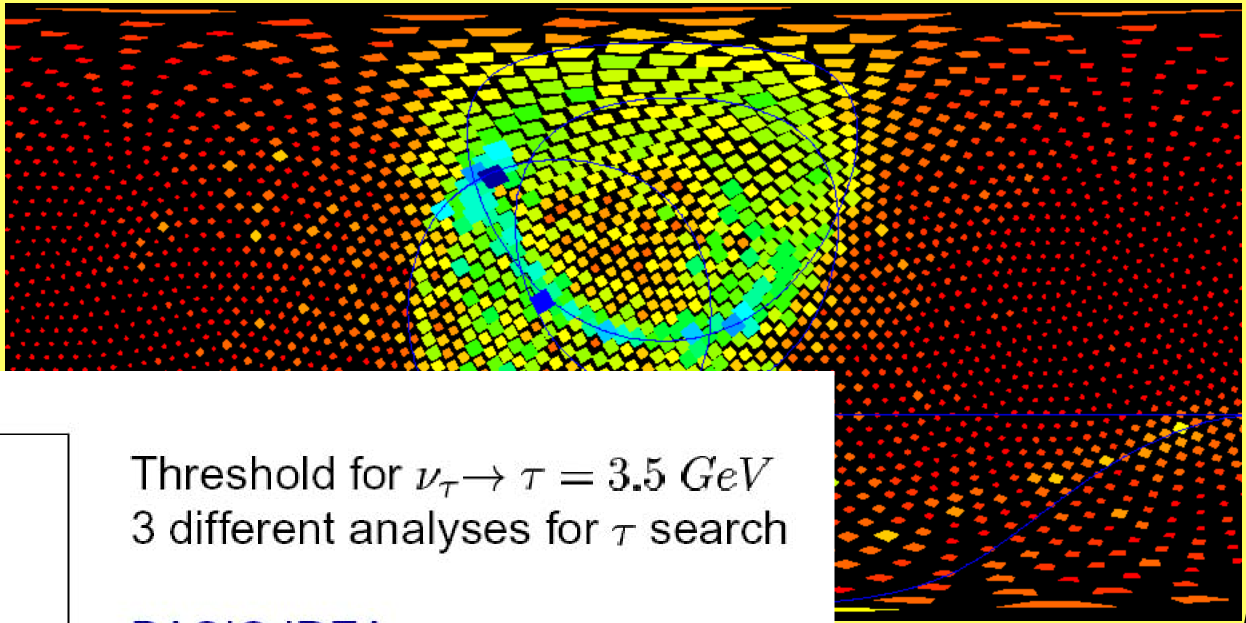
$\Delta m^2 \in 1.6 \sim 3.9 \times 10^{-3} eV^2$

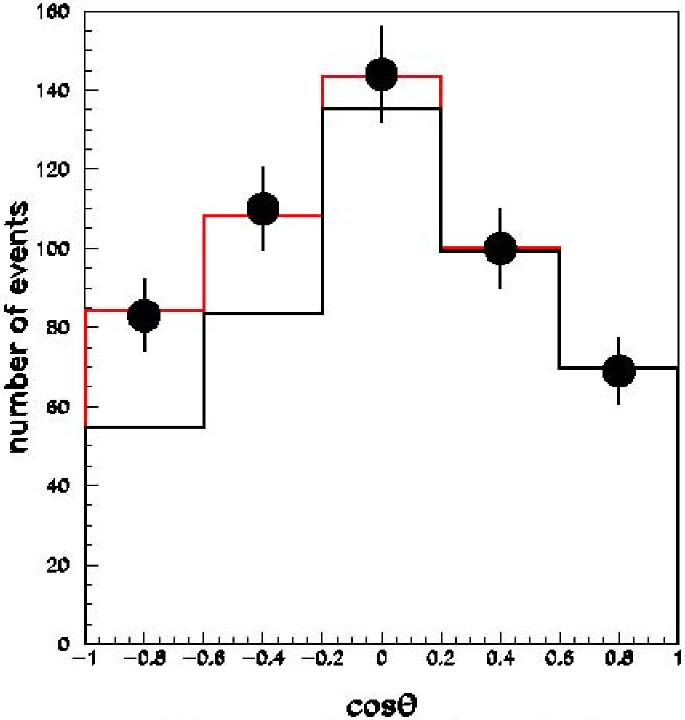
$\sin^2 2\theta > 0.92$ 90% C.L.

Also results from Soudan II, MACRO

τ-appearance in Super-K







Threshold for $\nu_\tau \rightarrow \tau = 3.5\ GeV$

3 different analyses for τ search

BASIC IDEA

- hadronic decays
- τ heavy - fat events

RESULTS

$145 \pm 44(stat.) + 11/-16(sys.)$

$99 \pm 39(stat.) + 13/-21(sys.)$

Super–Kamiokande is consistent with τ appearance.

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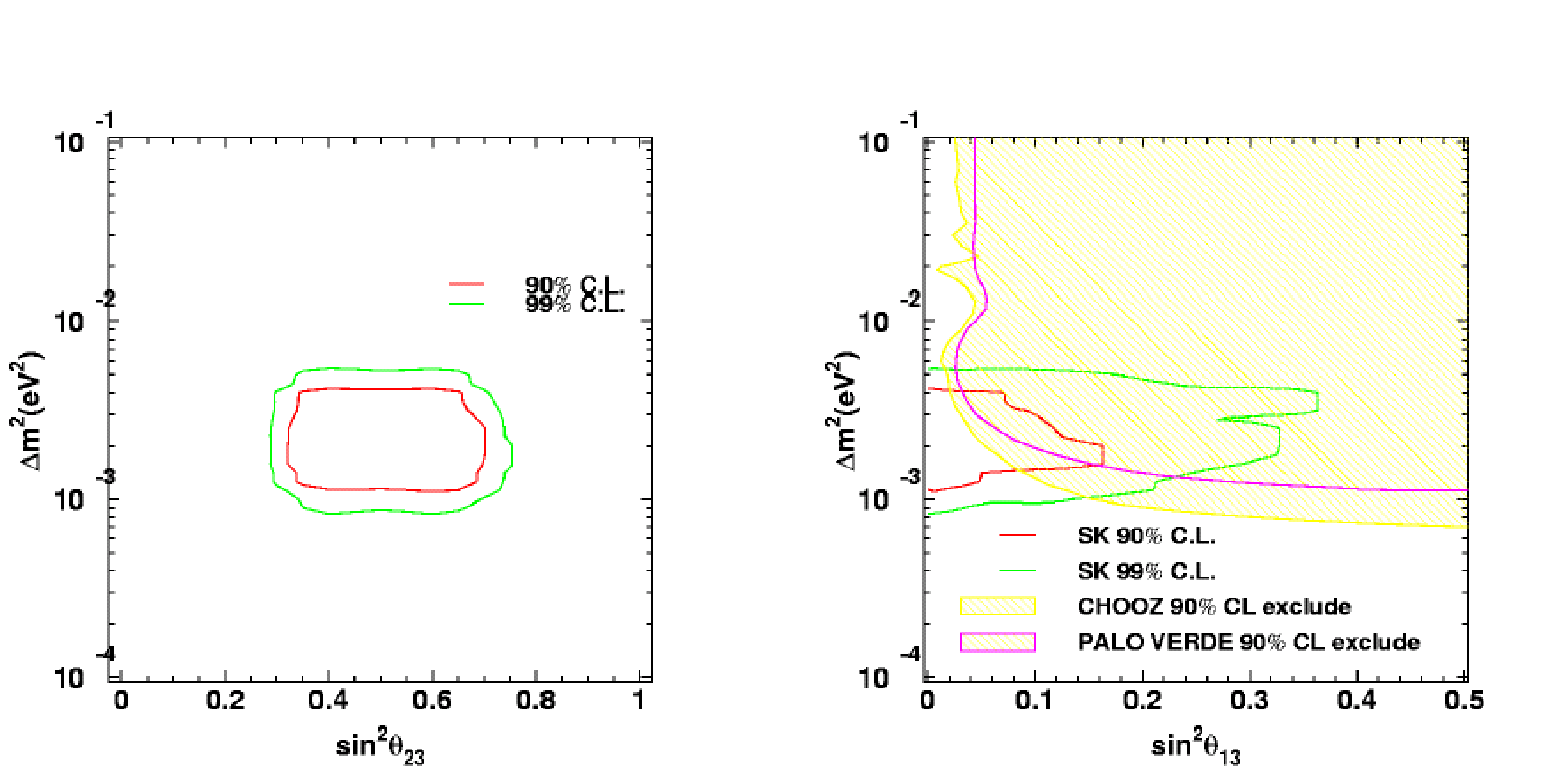
Consequences for Θ_{13}



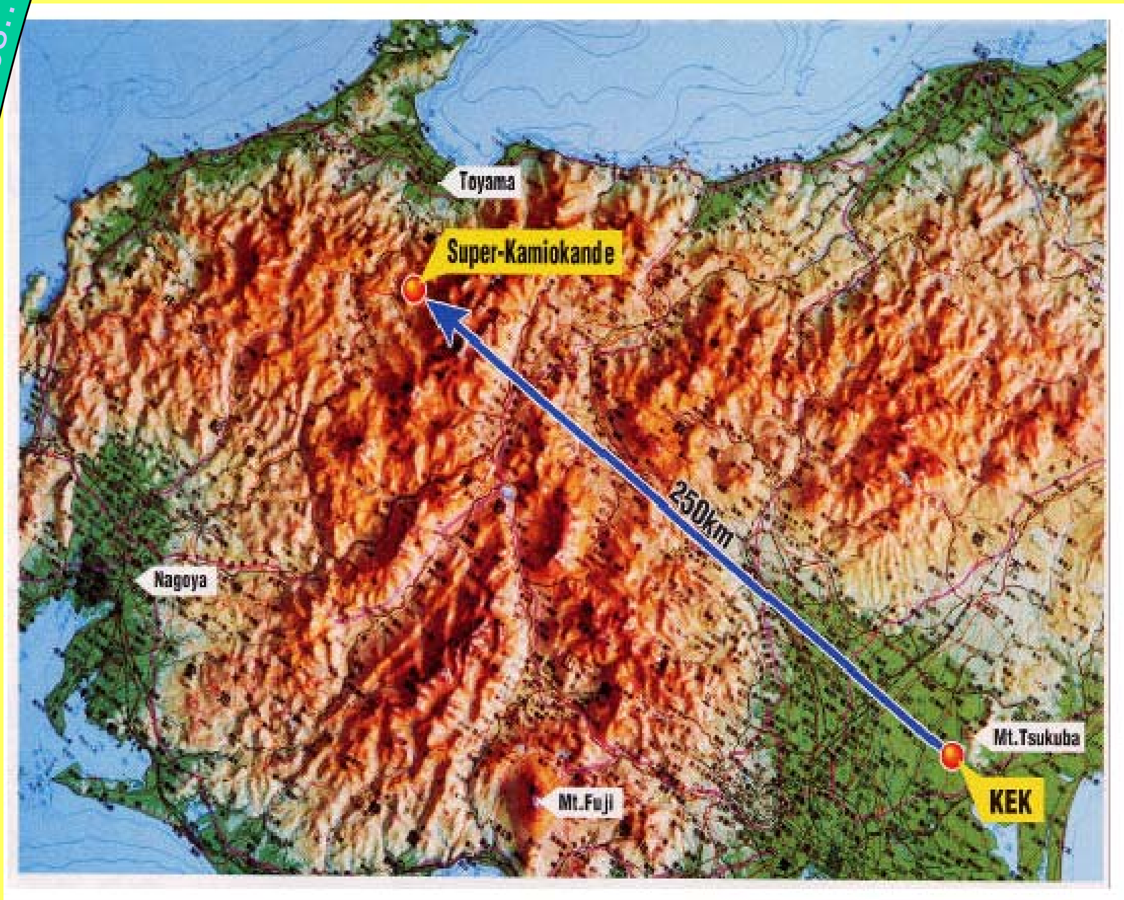
(Super) Neutrino Beams

	$\langle E_\nu \rangle$ (GeV)	L (km)	#CC ν/kt/yr	$L/L_{osci.}$*	$f(\nu_e)$ @peak
K2K	1.3	250	2	0.47	~1%
NuMi (High E)	15	730	3100	0.12	0.6%
NuMi (Low E)	3.5	730	469	0.51	1.2%
CNGS	17.7	732	2448	0.10	0.8%
JHF-I	0.7	295	133	1.02	0.2%
Numi off-axis	2.0	730	~80	0.89	0.5%
Super AGS	1.5	2540	11	4.1	0.5%
JHF-II	0.7	295	691	1.02	0.2%
SPL	0.26	130	16.3	1.21	0.4%
β beam**	0.58	130	84	0.54	-------

(*) $L_{osci.} = \frac{\pi}{2} \bullet \frac{\langle E_\nu \rangle}{1.27 \Delta m_{23}^2}$ w/ $\Delta m_{23}^2 = 3 \times 10^{-3} eV^2$ (**) $\gamma=150$, ^6He ($\bar{\nu}_e$)

From Nakaya's talk at ν02

The first LBL Experiment – K2K



- ν_μ (99%) beam
- $<E_\nu>$ ~1.3GeV
- **Near detector**

  @300m
- **Far detector**:

  Super Kamiokande(SK)

  @**250km**
- Sensitive for

  $\Delta m^2 > 2x10^{-3}$ eV^2

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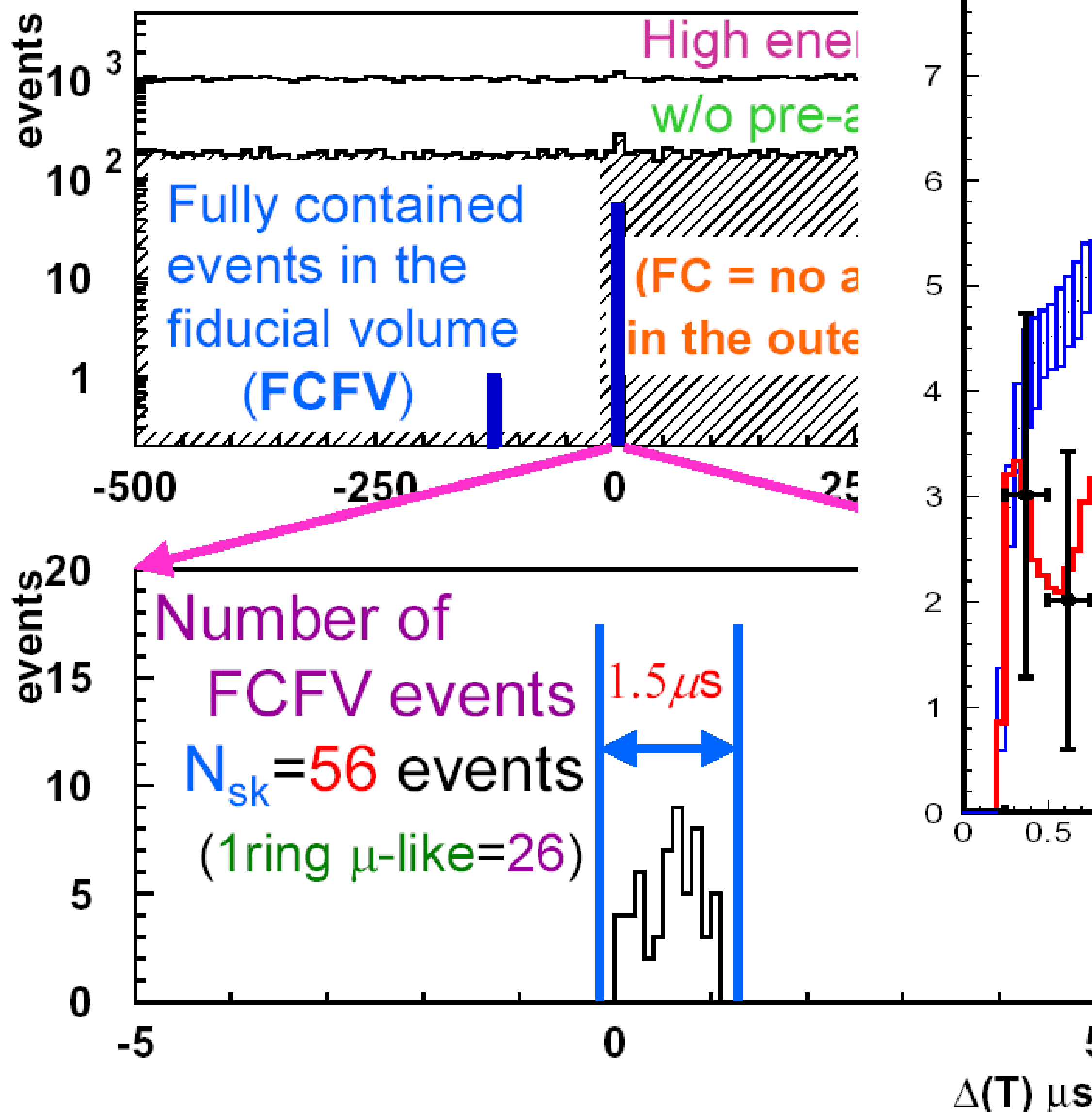
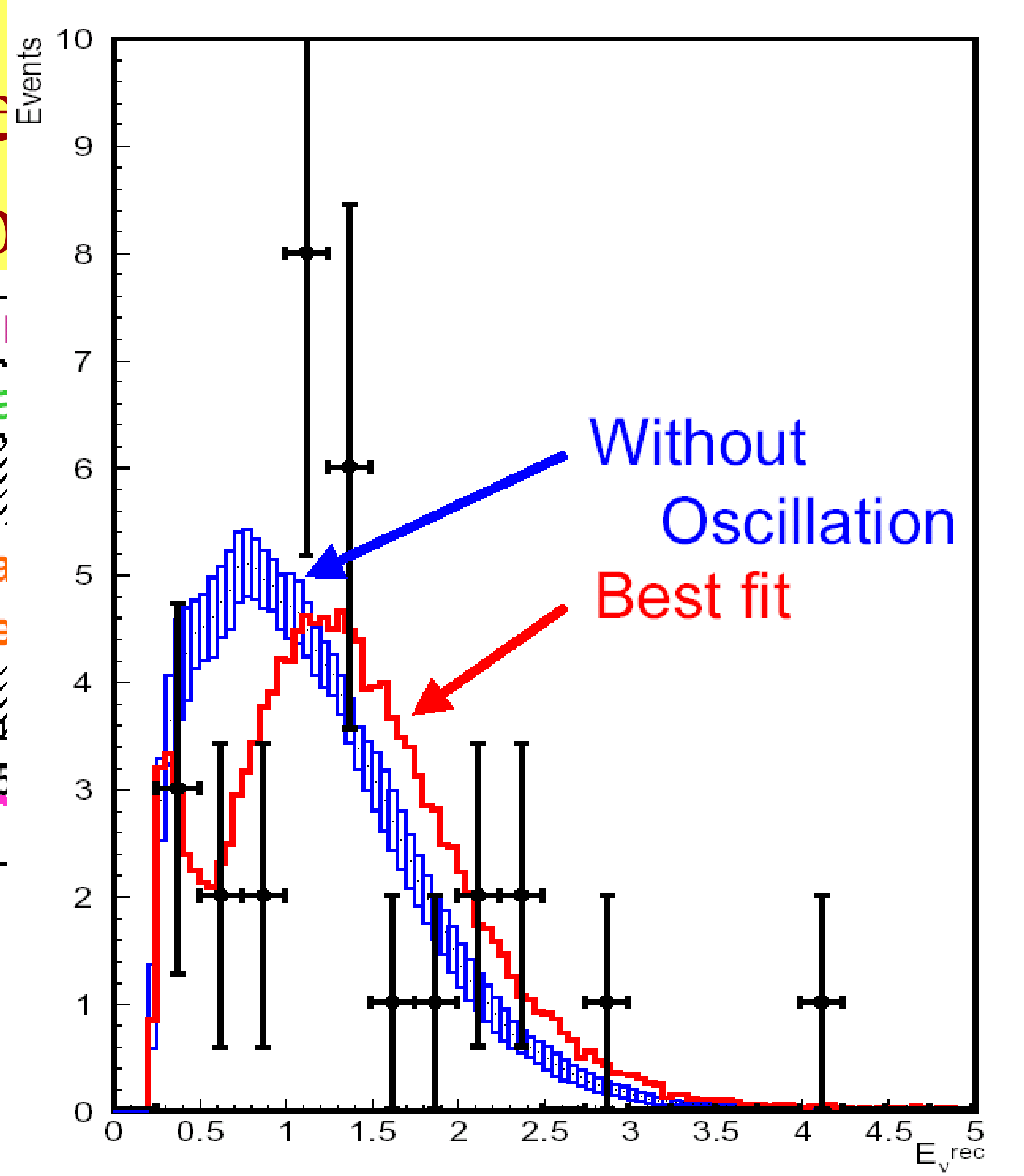
This conference presentation o





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K2K's statement of the significance:

Null oscillation probability

Use Δlog(likelihood) from best fit point in the physical region

	method-1	method-2
N_{SK} only	1.3%	0.7%
Shape only	15.7%	14.3%
N_{SK} + Shape	**0.7%**	**0.4%**

⇩

Probability of null oscillation is **less than 1%.**

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ν masses....

The MINOS Experiment

...and mixings

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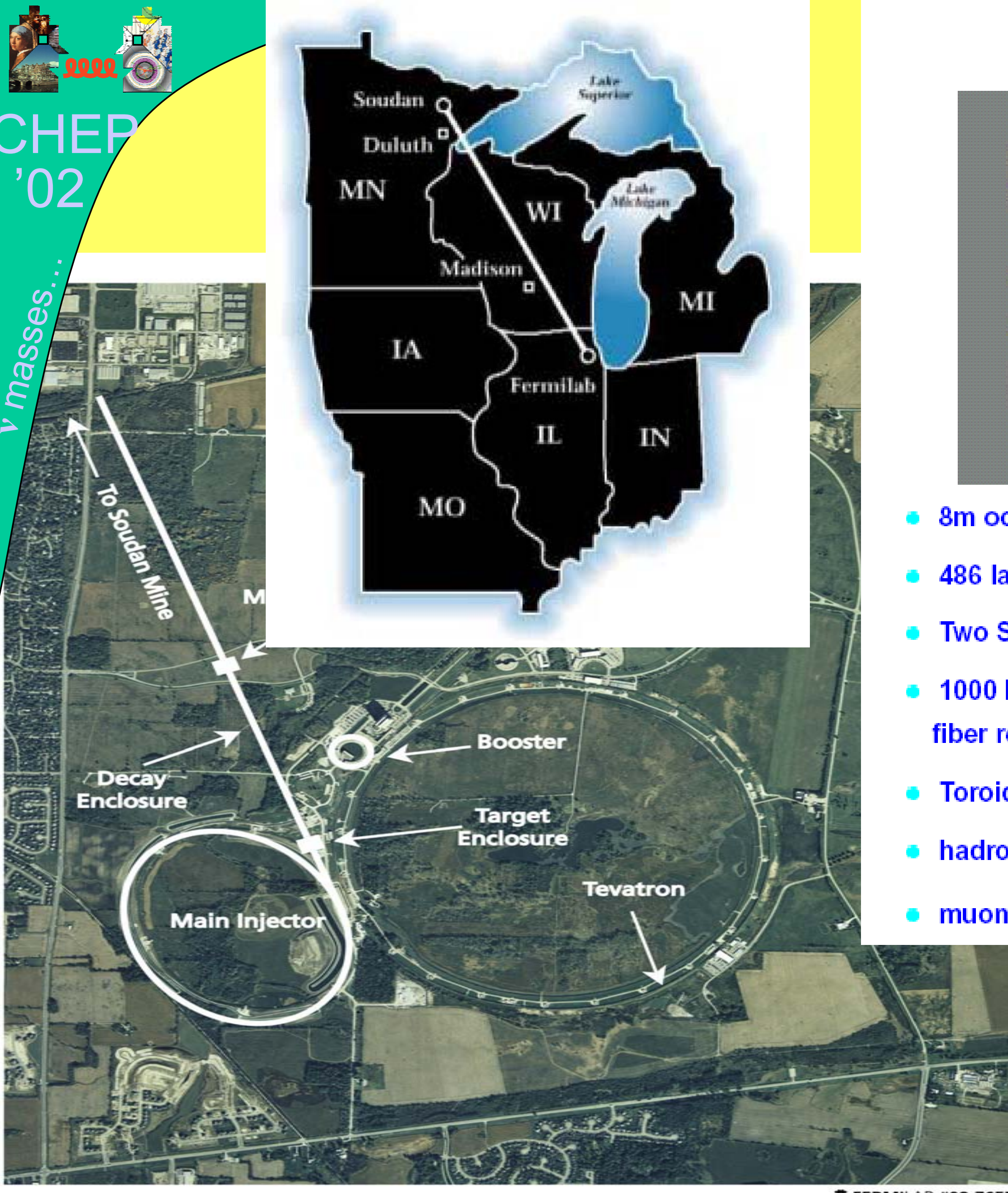
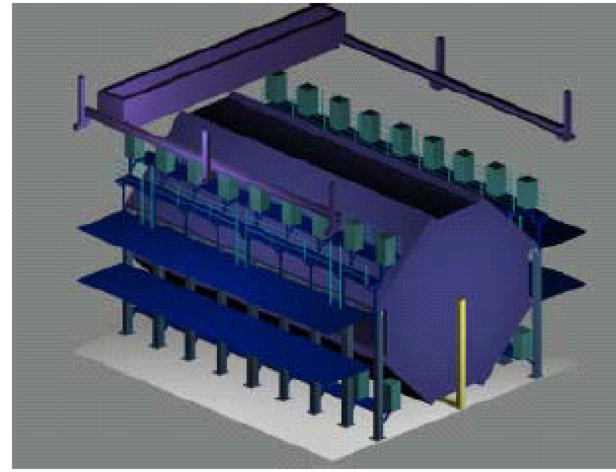


MINOS Far Detector



- 8m octagonal tracking calorimeter
- 486 layers of 2.54 cm Fe
- Two Supermodules (15m each)
- 1000 km of scintillator, 2000 km of WLS and clear fiber readout (25,800 m^2 of active detector planes)
- Toroidal $\langle B \rangle \approx$ 1.3T. Total mass 5.4 kT
- hadron energy : $\frac{\Delta E}{E} \approx \frac{55\%}{\sqrt{E}}$
- muon momentum : $\frac{\Delta p}{p} \approx$ 12% (by curvature)

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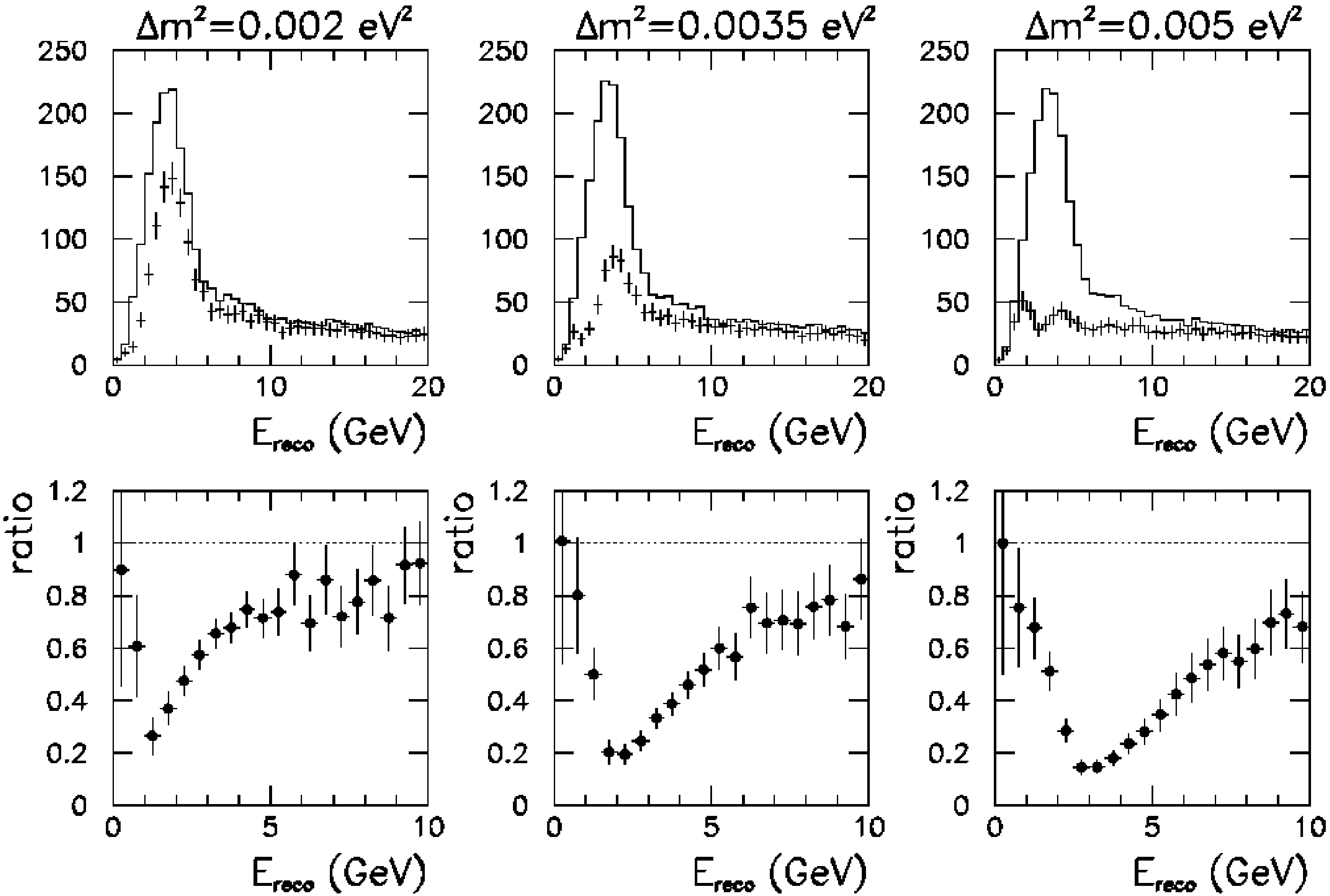
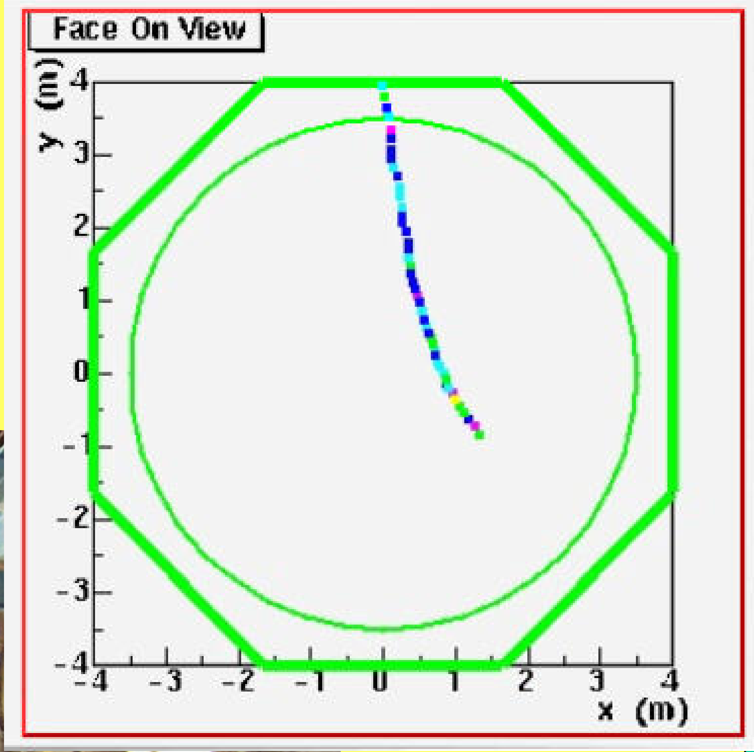
CC energy distributions – Ph2le, 10 kt.yr., $\sin^2(2\vartheta)=0.9$



1st Supermodule (1/2 detector) done, other well begun

Meanwhile first magnetized data on atmospheric ν



Core Energized !!!

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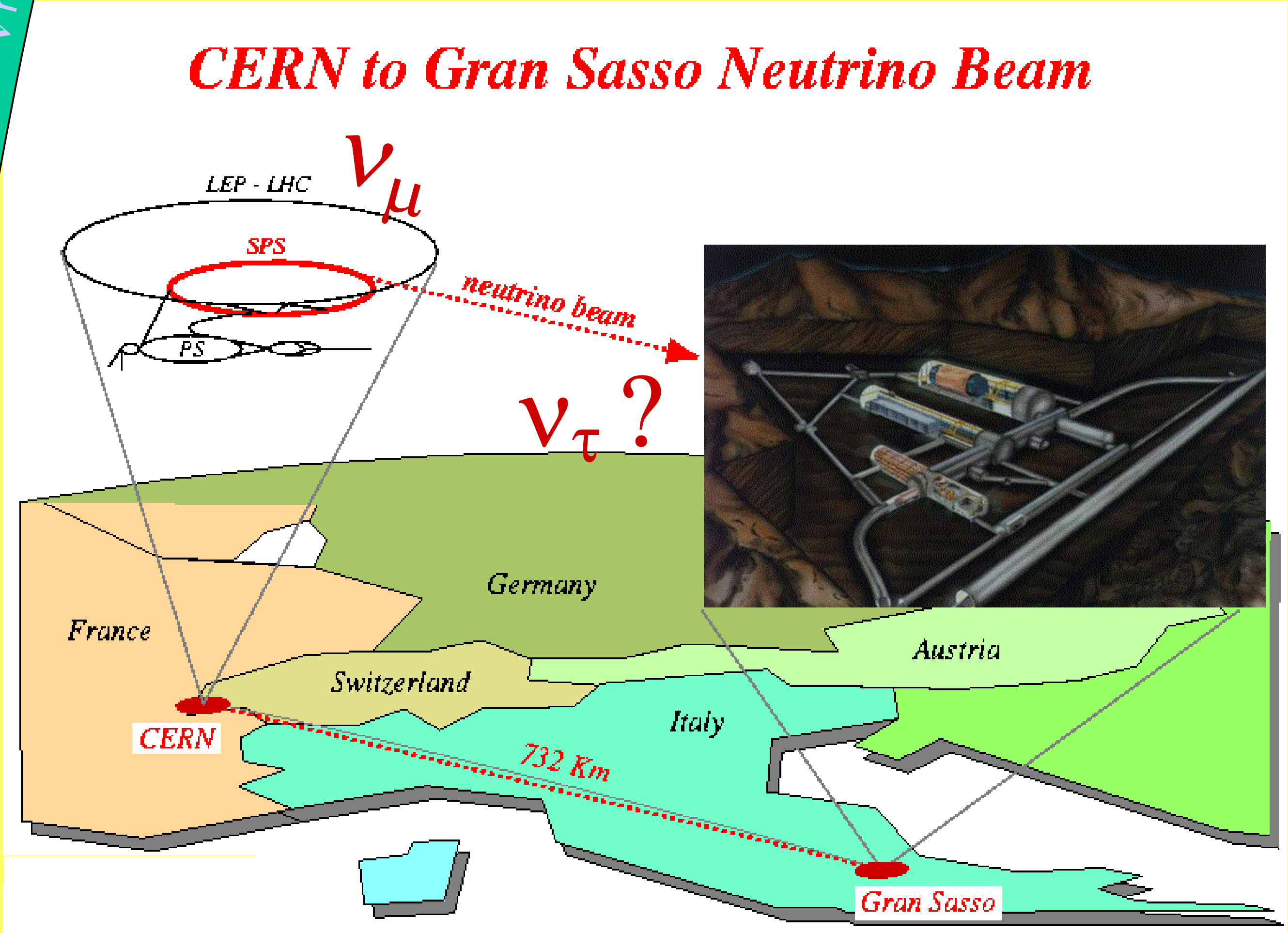
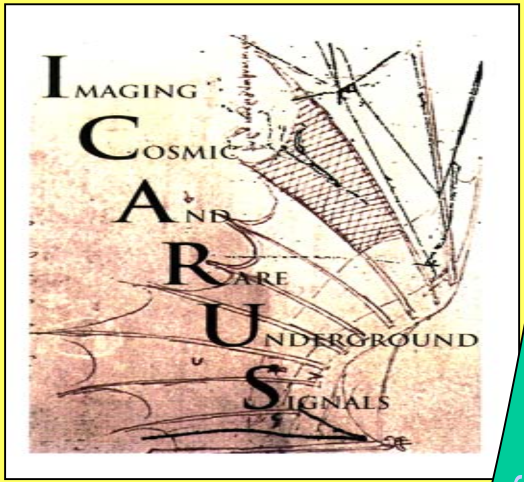
Beam construction is well advanced, first beams in 2006





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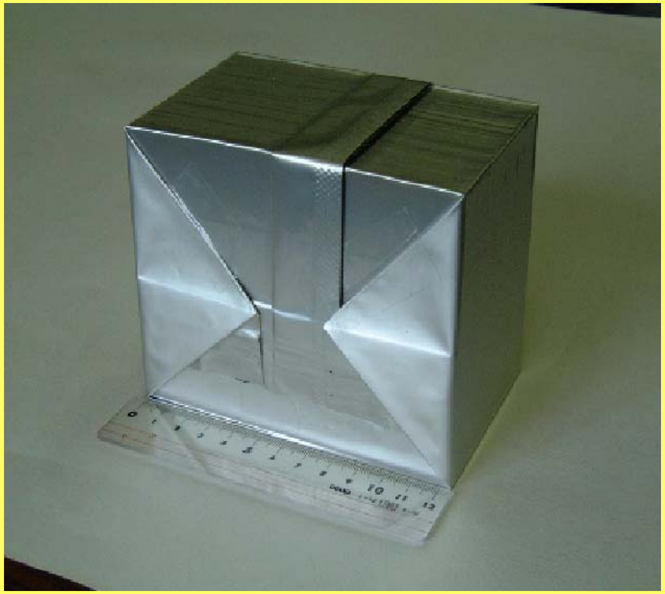
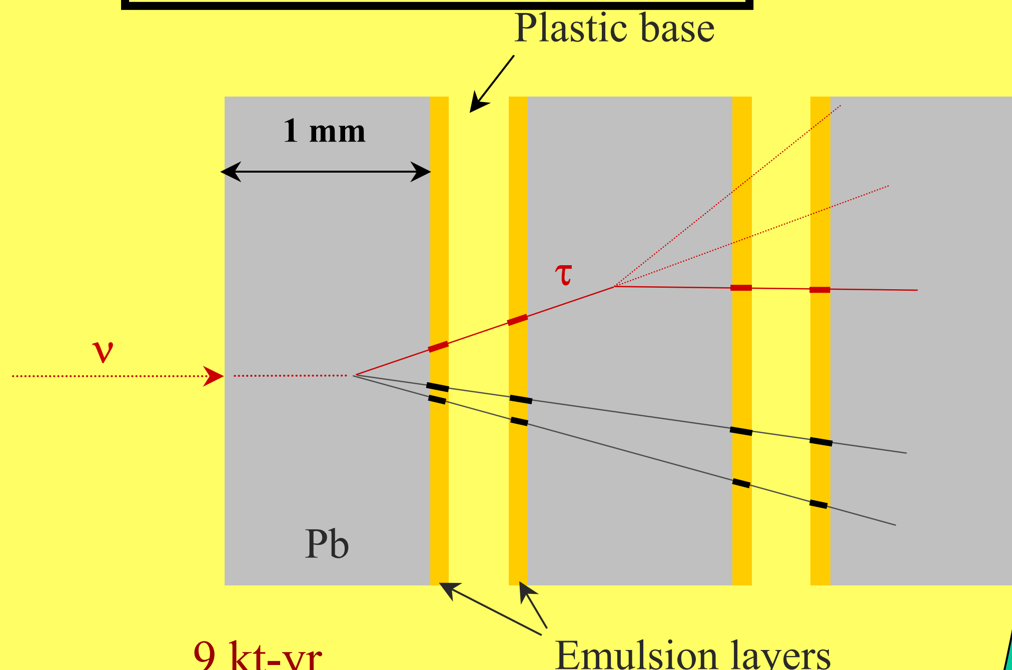
OPERA Detector: Emulsion

~2 kTon (Pb)
0.04 kTon emulsion



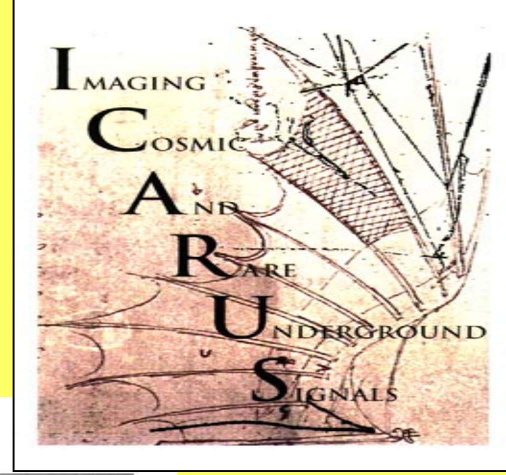
56 emulsion films / brick

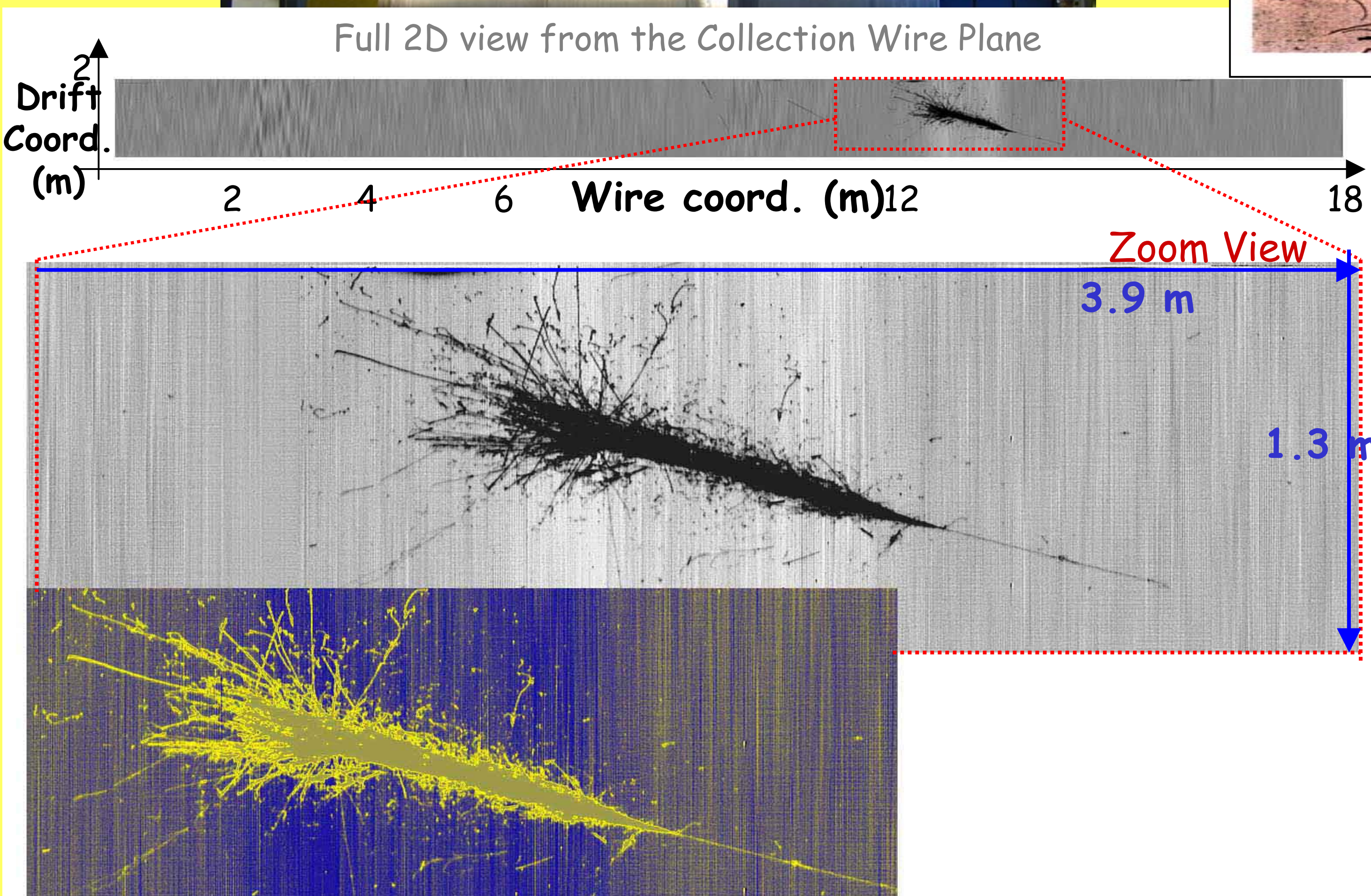


9 kt-yr

- $\Delta m^2 = 1.2 \times 10^{-3}\ eV^2$: **2.7 events**
- $\Delta m^2 = 2.4 \times 10^{-3}\ eV^2$: **11 events**
- $\Delta m^2 = 5.4 \times 10^{-3}\ eV^2$: **54 events**

- To the full detector:
  - 2 supermodules
  - 31 walls / supermodule
  - 52 x 64 bricks /wall
  - 200 000 bricks

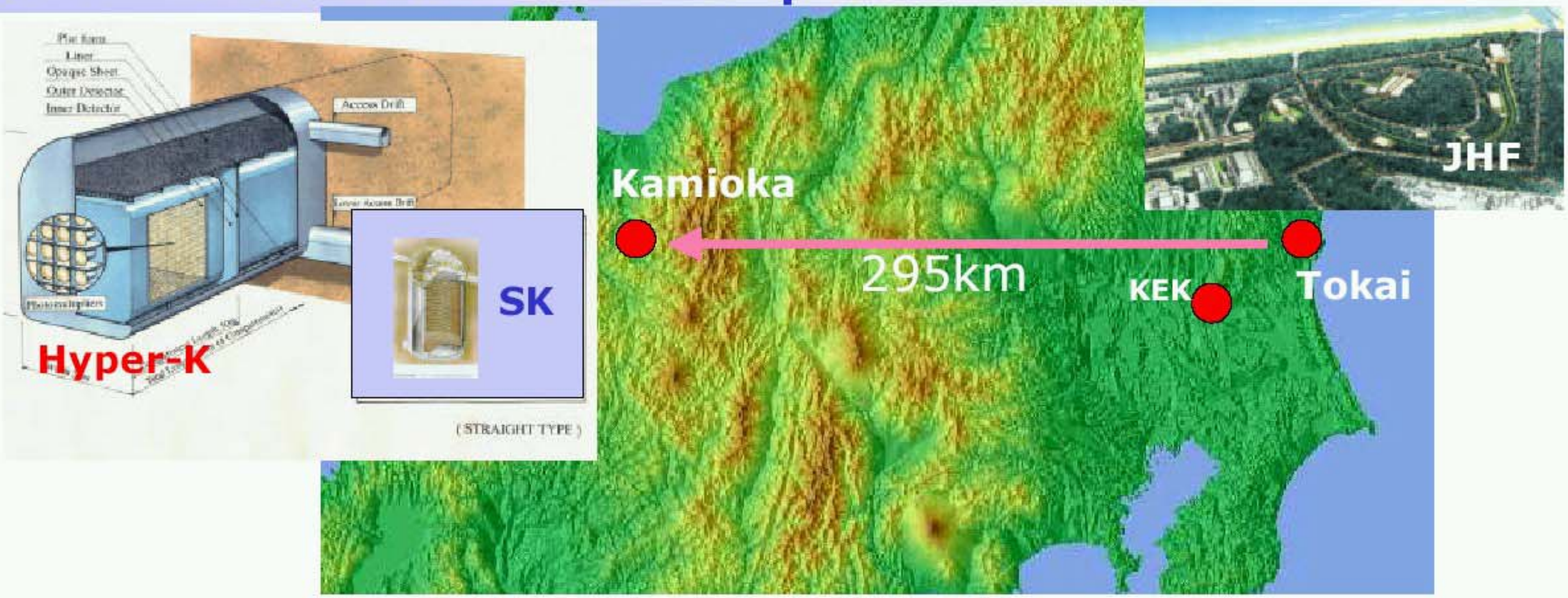




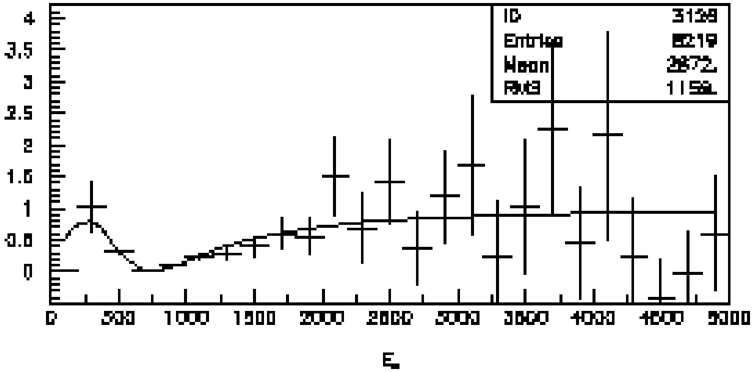
~3 kt to be in LNGS by 2005

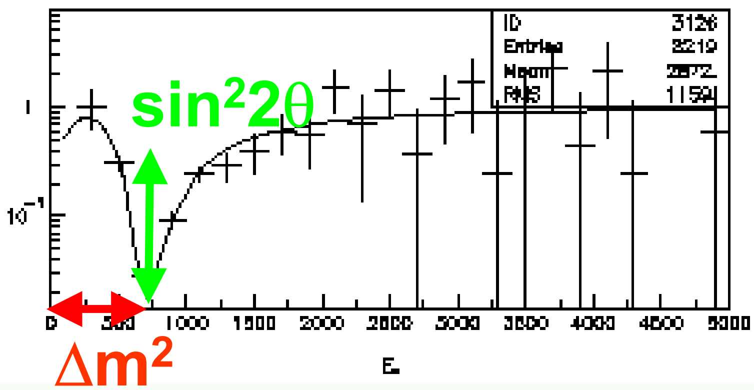
T600 test @ Pv: Run 308 - Evt 7

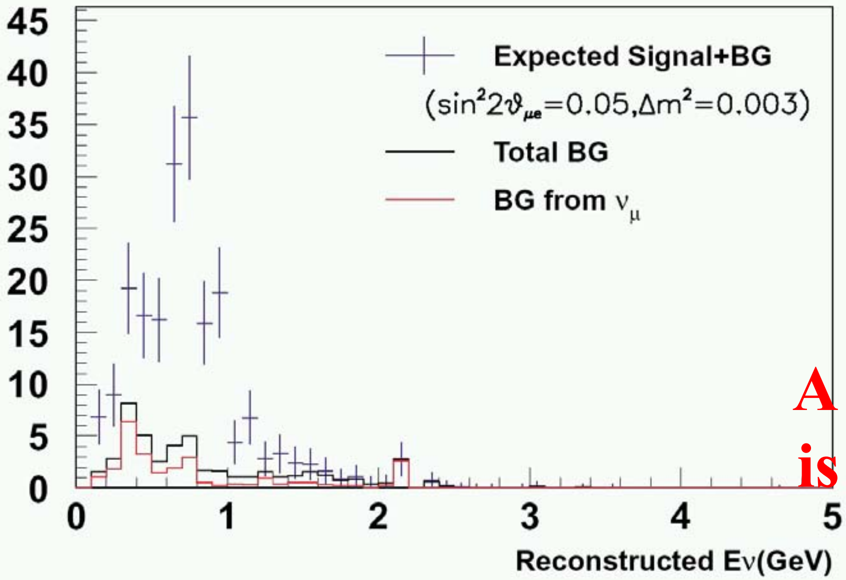
JHF-Kamioka ν Experiments

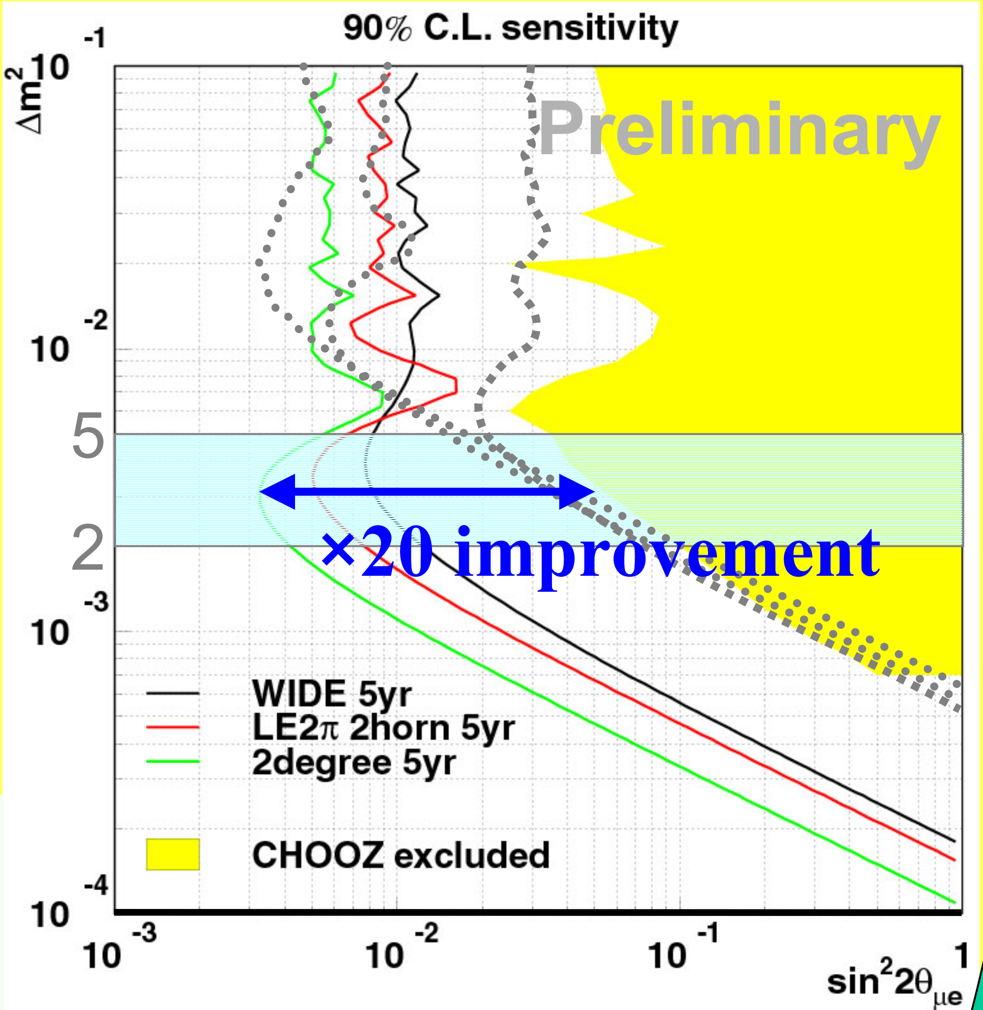


- Phase I: 2007(?)~201x
  - ~1MW 50GeV PS → 22.5kt detector (Super-Kamiokande)
    - $\nu_\mu \rightarrow \nu_x$ disapp., $\nu_\mu \rightarrow \nu_e$ app., NC measurement
- Phase II: 201x(?)~202y(??)
  - ~4MW 50GeV PS → ~1Mt detector (Hyper-Kamiokande)
    - CPV search, Proton Decay, . . .









Dashed lines: MINOS Ph2le, Ph2me, Ph2he from right (A.Para, hep-ph/0005012)

A European proto-collaboration is organizing, interested parties should contact me

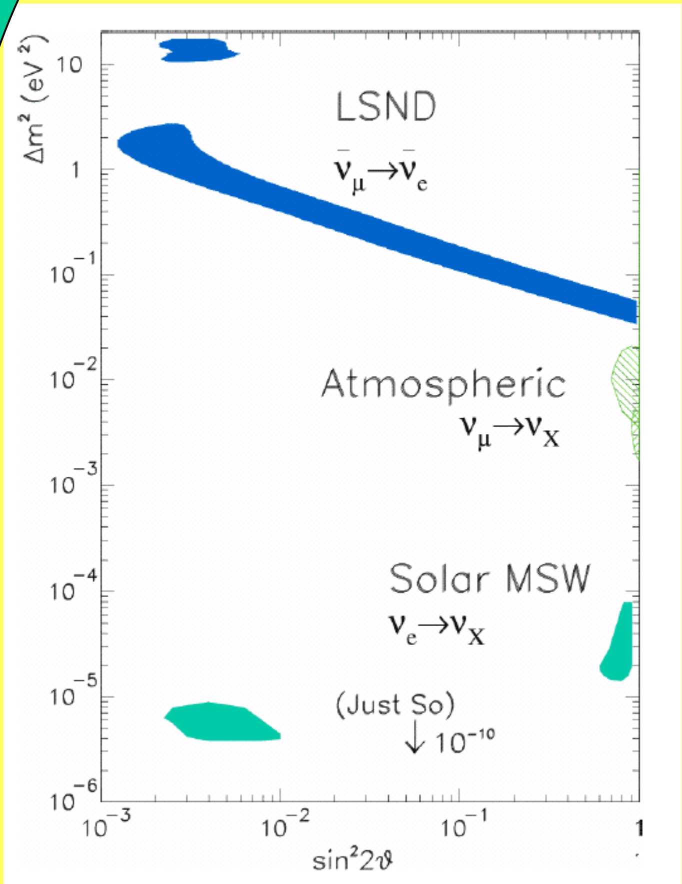
…and mixings

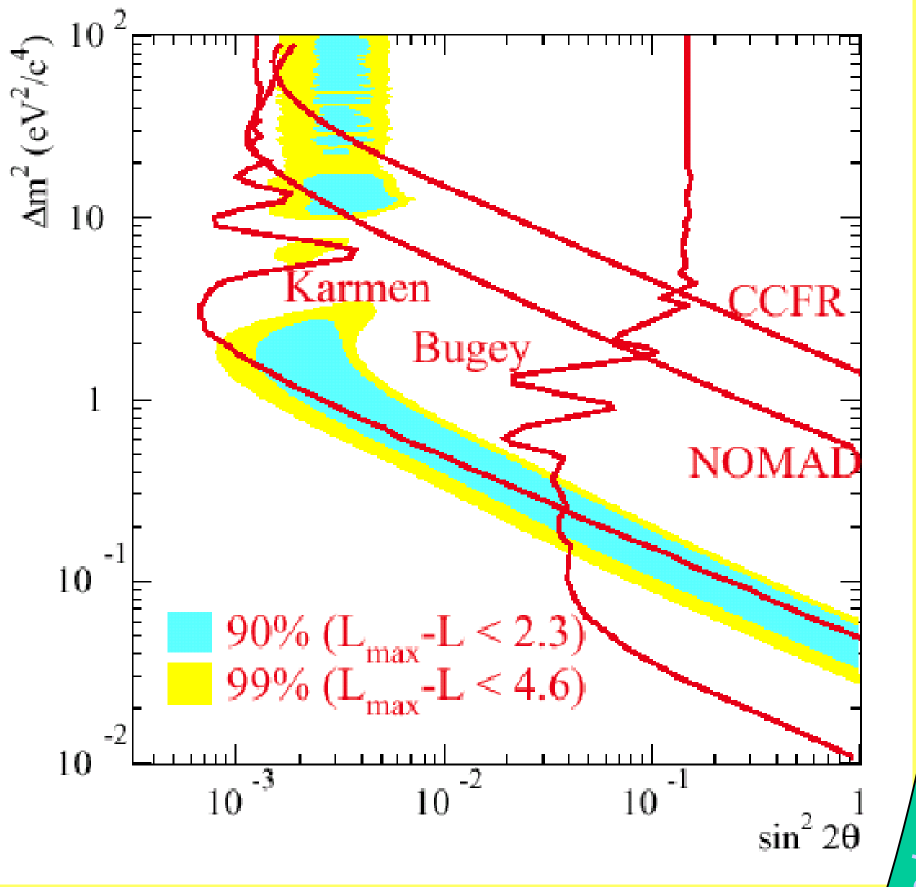
– **Off-Axis (0.5-1^0) NuMI beam to surface detector**

- **sites in Minnesota (~700+ km) & Canada (~900 km) possible**
- **20 kTon detector, possibly H_20, possibly RPC, possibly scint.**
- **Sensitivity to θ_{13} at 1.5 x 10^{-3} level**
- **LOI (Fermilab P929):**

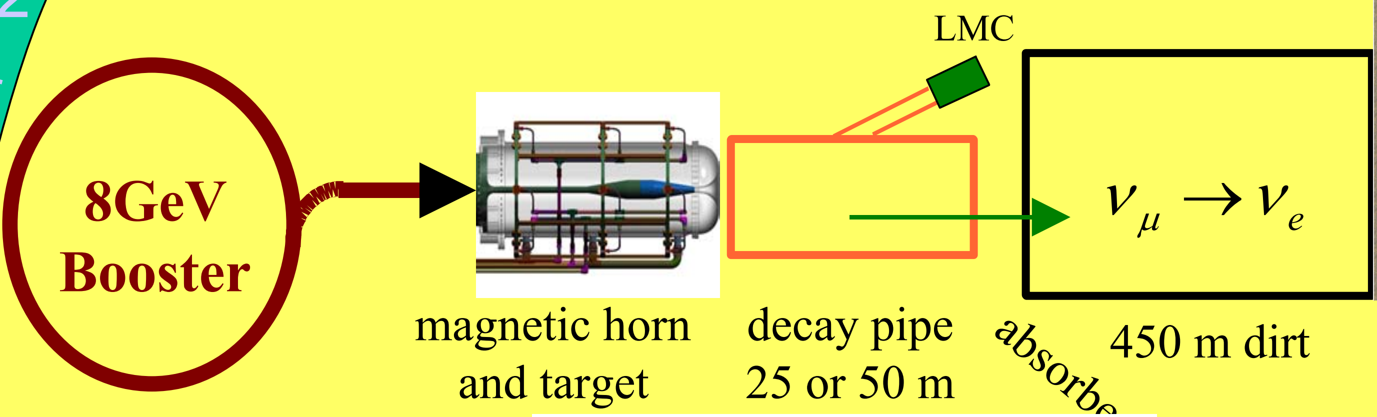
  http://www-numi.fnal.gov/fnal_minos/new_initiatives/
- **Note: 1-Day meeting at UC London, Monday September 16**

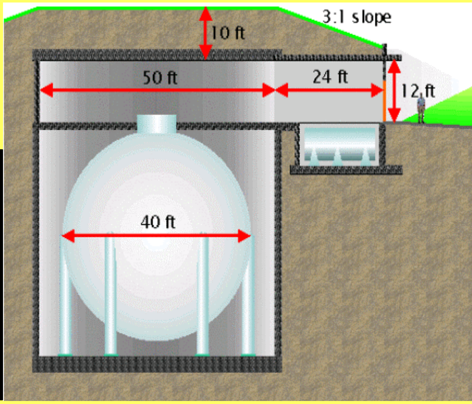
And beyond these lies the Neutrino Factory….


LSND
$\bar{\nu}_\mu \to \bar{\nu}_e$
Atmospheric
$\nu_\mu \to \nu_X$
Solar MSW
$\nu_e \to \nu_X$
(Just So)
↓ 10^{-10}
Δm^2 (eV^2)
$\sin^2 2\vartheta$


Karmen
Bugey
CCFR
NOMAD
90% (L_{max}-L < 2.3)
99% (L_{max}-L < 4.6)
Δm^2 (eV^2/c^4)
$\sin^2 2\theta$

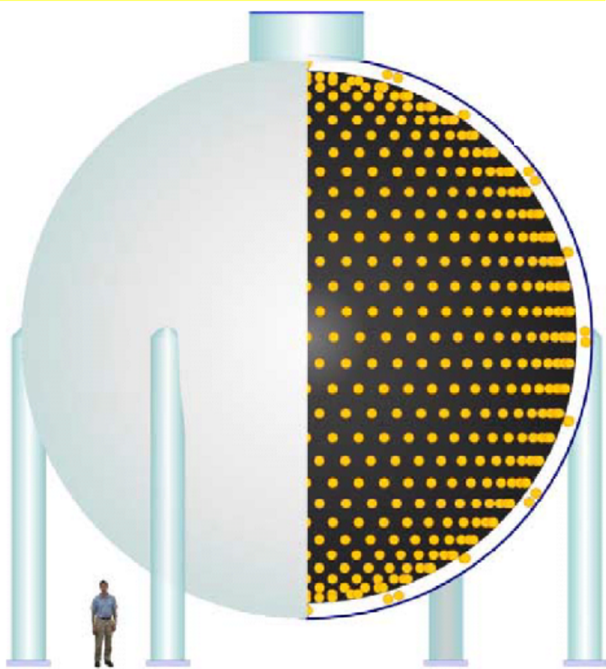
MiniBooNE

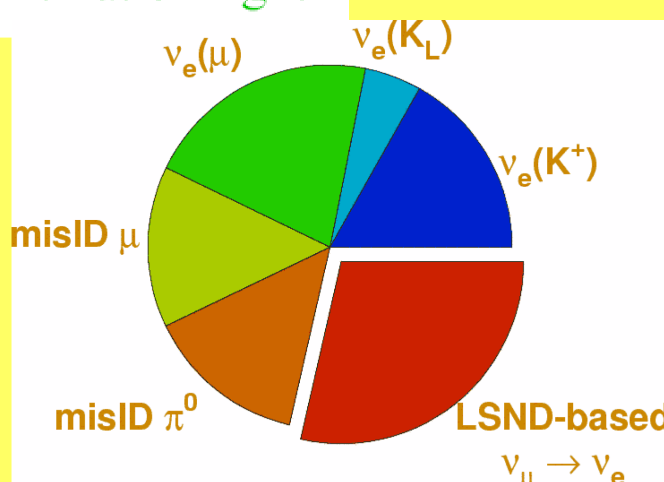




Neutrino interactions in oil produce:

- Prompt Čerenkov light
- Delayed scintillation light





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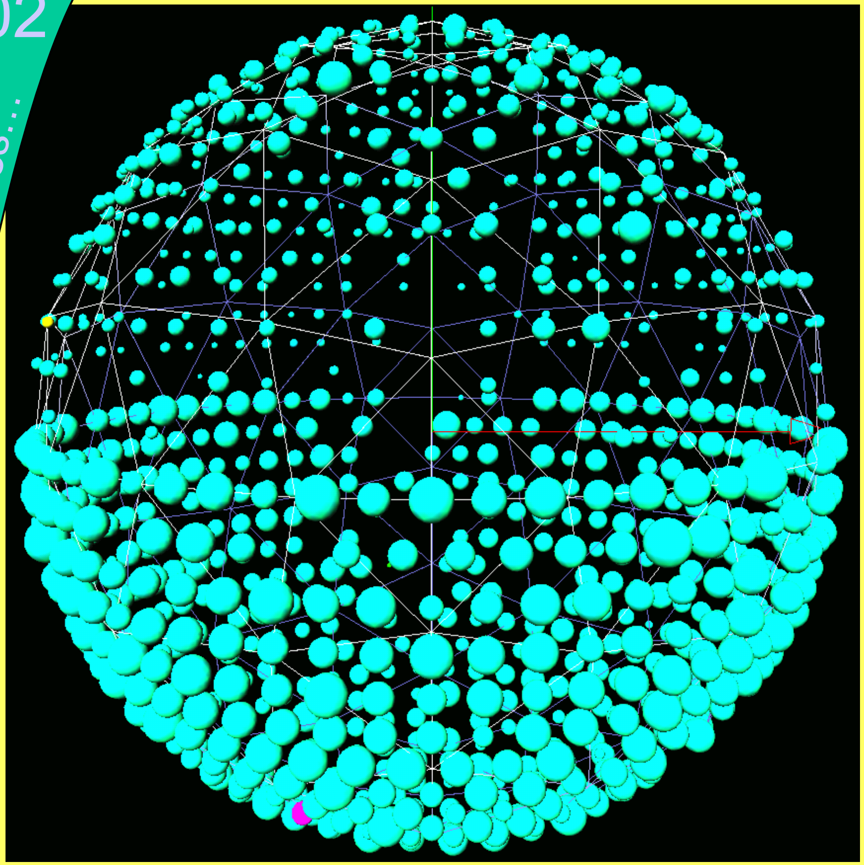
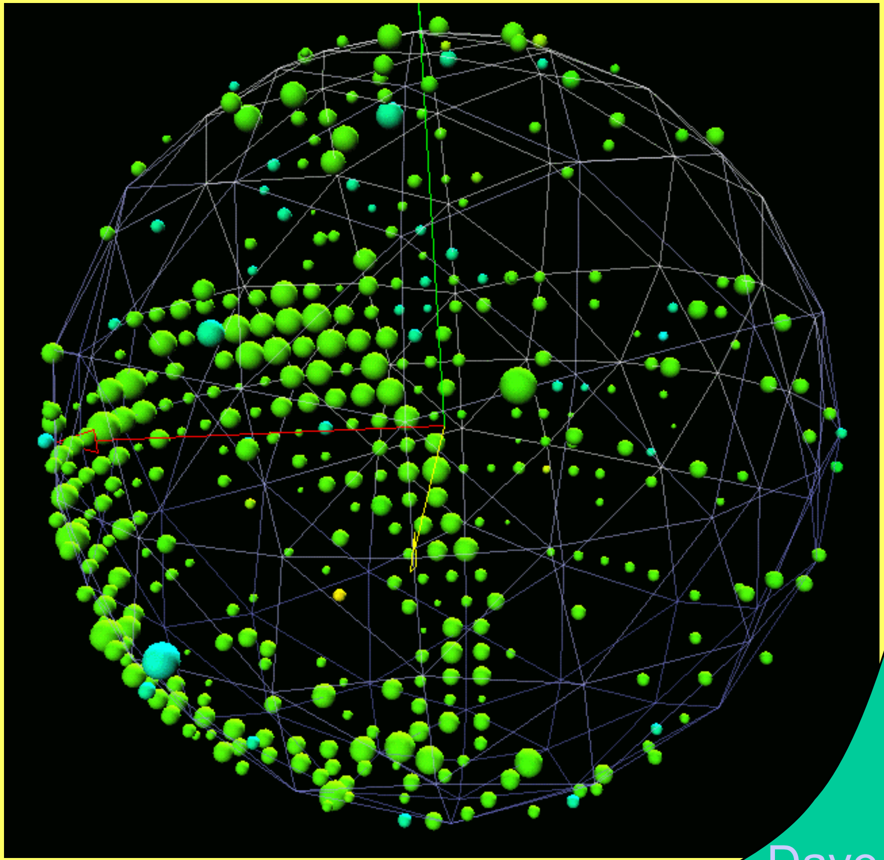
Calibration events are being collected

(size of each hit is proportional to charge)



laser event, tank ~1/2 full of oil

cosmic muon



ν masses… …and mixings

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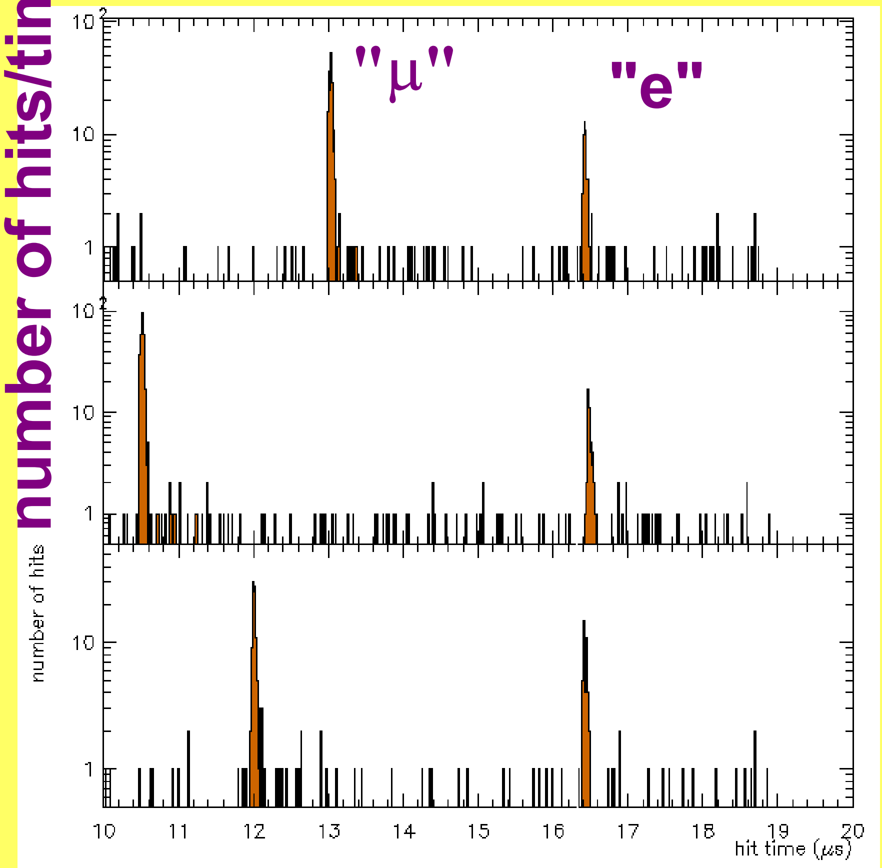
hit times for 3 "Michel" events

number of hits/time



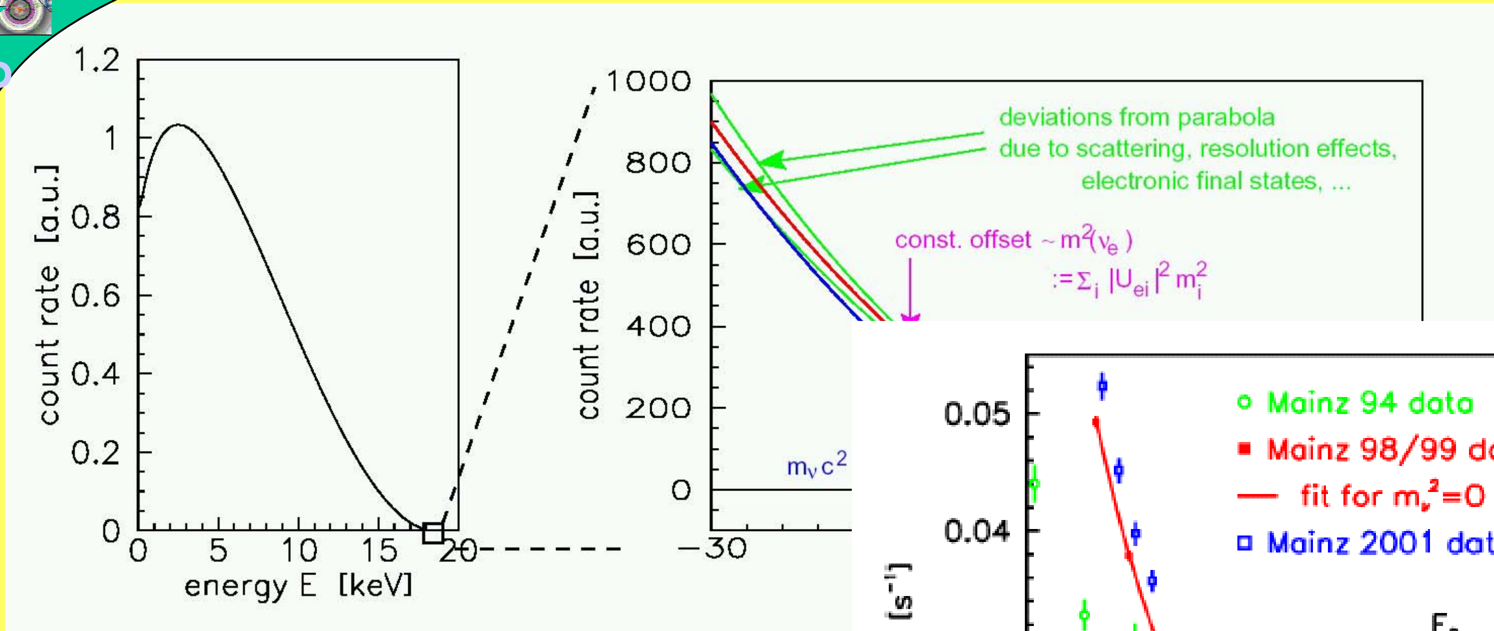
PMT hit time (μs)

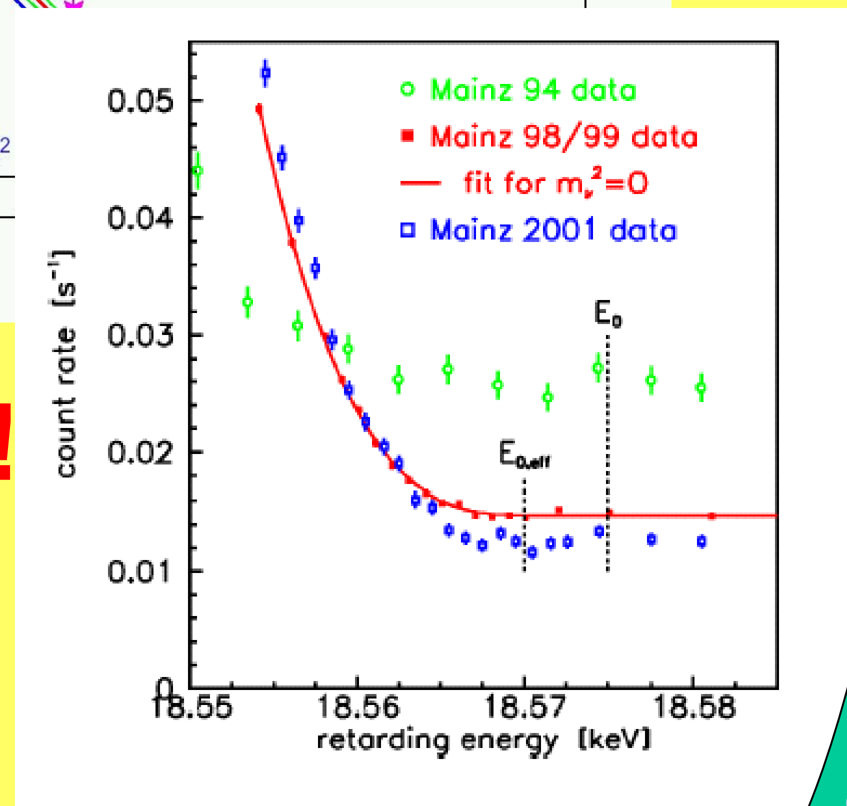
First beam in August '02

First results?

Determining the absolute mass scale

- Kinematic limits: If you believe the oscillation results, all $\Delta m^2 \ll 1$ eV, therefore only ν_e measurements have useful sensitivity -> current best is Tritium Beta Decay
- If neutrinos have Marjorana masses, then zero-neutrino double-beta decay is allowed -> observation of 0vBB decay would be direct evidence for neutrino mass
- Neutrinos are the second most numerous particle in the Universe -> even a tiny neutrino mass could have





Model Independent!

State-of-the-art experiments in Mainz and INR (Troitsk)

Current limit: m_{ν_e} < 2.2 eV (95% c.l.)

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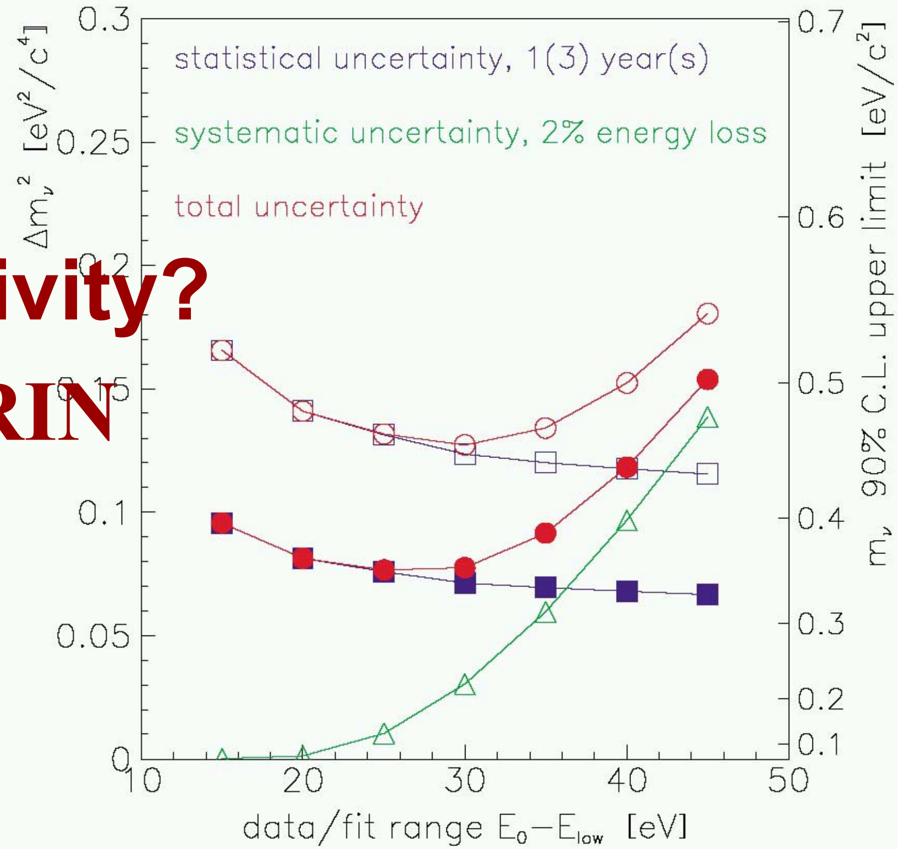
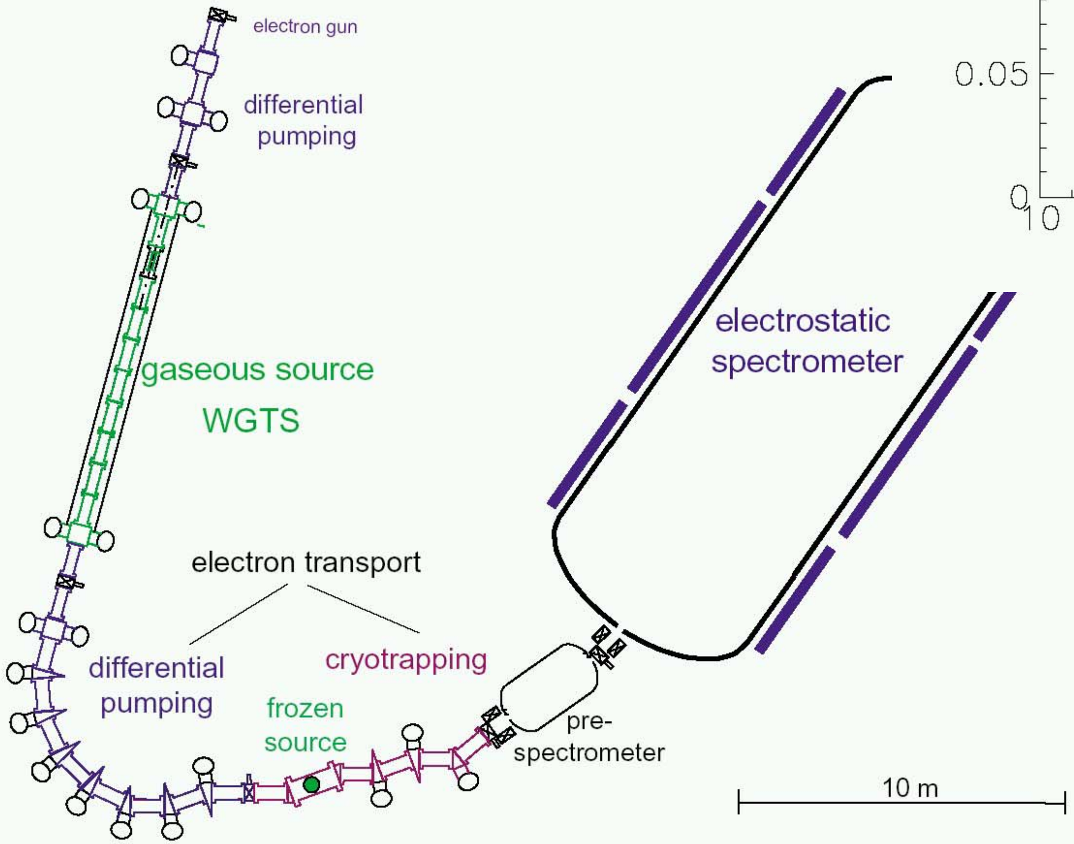
v masses...

w to reach sub-eV sensitivity?

lake 'em bigger! -> KATRIN





Troitsk Anomaly?

...and mixings

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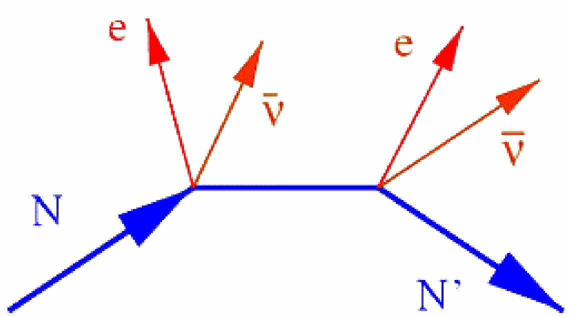
Most sensitive neutrino mass measurements can be obtained from double-beta decay

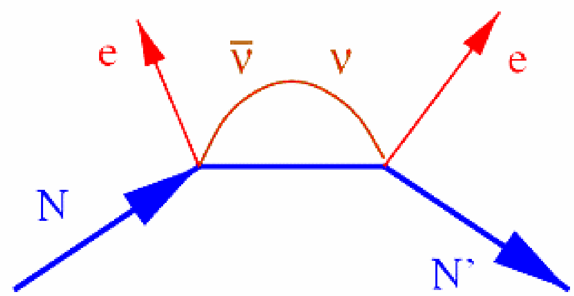
$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



$0\nu\ \beta\beta$ decay: a hypothetical process

→ $m_\nu \neq 0$ since helicity has to "flip"

→ $\bar{\nu} = \nu$



$$\langle m_\nu \rangle = m_{ee} = \left| \sum_k U_{ek}^2 m_k \right| = \left| \sum_k |U_{ek}|^2 e^{i\alpha_{ek}} m_k \right|$$

Each is ±1 if CP conserved, but there can still be cancellations

Neutrinoless BB-decay limits

Isotope	$T^{0\nu}_{1/2}$ (y)	$\langle m_\nu \rangle$ (eV)
^{48}Ca	$> 9.5 \times 10^{21} (76\%)$	< 8.3
^{76}Ge	$> 1.9 \times 10^{25}$	< 0.35
	$> 1.6 \times 10^{25}$	$< 0.33 - 1.35$
^{82}Se	$> 2.7 \times 10^{22} (68\%)$	< 5
^{100}Mo	$> 5.5 \times 10^{22}$	< 2.1
^{116}Cd	$> 7 \times 10^{22}$	< 2.6
$^{128,130}Te$	$\frac{T_{1/2}(130)}{T_{1/2}(128)} = (3.52 \pm 0.11) \times 10^{-4}$ (geochemical)	$< 1.1 - 1.5$
^{128}Te	$> 7.7 \times 10^{24}$	$< 1.1 - 1.5$
^{130}Te	$> 1.4 \times 10^{23}$	$< 1.1 - 2.6$
^{136}Xe	$> 4.4 \times 10^{23}$	$< 1.8 - 5.2$
^{150}Nd	$> 1.2 \times 10^{21}$	< 3

From Elliot and Vogel, hep-ph/0202264

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University of Sussex/

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'02

ν masses…

EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

H.V. KLAPDOR-KLEINGROTHAUS[1,3],
A. DIETZ[1], H.L. HARNEY[1], I.V. KRIVOSHEINA[1,2]

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[3] *Spokesman of the GENIUS and HEIDELBERG-MOSCOW Collaborations,*
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home page: http://www.mpi-hd.mpg.de/non_acc/

hep-ph/0201231

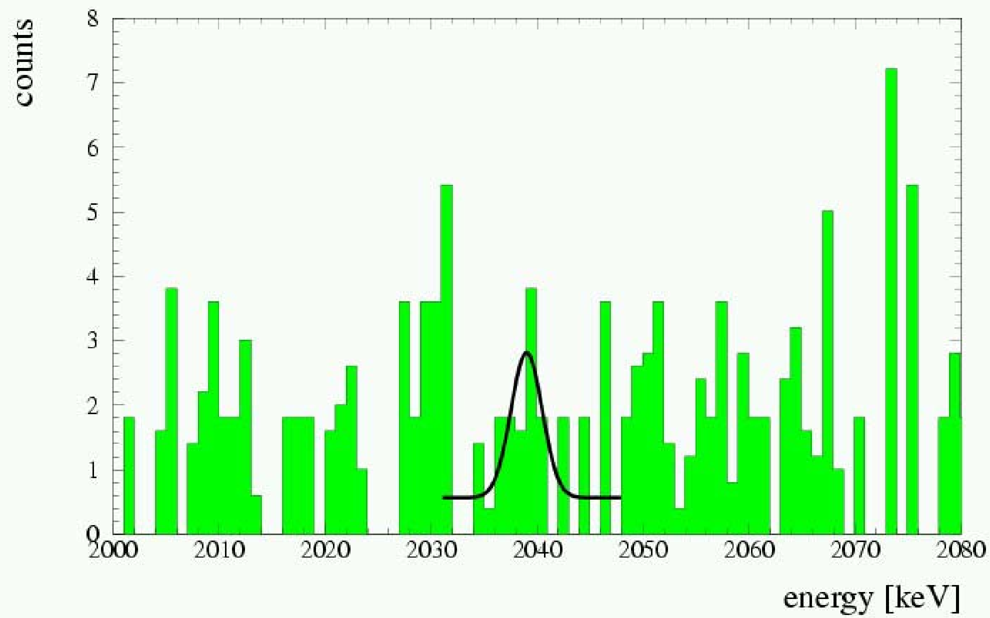

Figure 3. Sum spectrum, measured with the detectors Nr. 2,3,5 operated with pulse shape analysis in the period November 1995 to May 2000 (28.053 kg y), in the region of interest for the $0\nu\beta\beta$ - decay. Only events identified as single site events (SSE) by all three pulse shape analysis methods [18,19] have been accepted. The spectrum has been corrected for the efficiency of SSE identification (see text). The curve results from Bayesian inference in the way explained in the text. The signal corresponds to a half-life $T^{0\nu}_{1/2}=(0.88-22.38)\times10^{25}$ y (90% c.l.).

…and mixings

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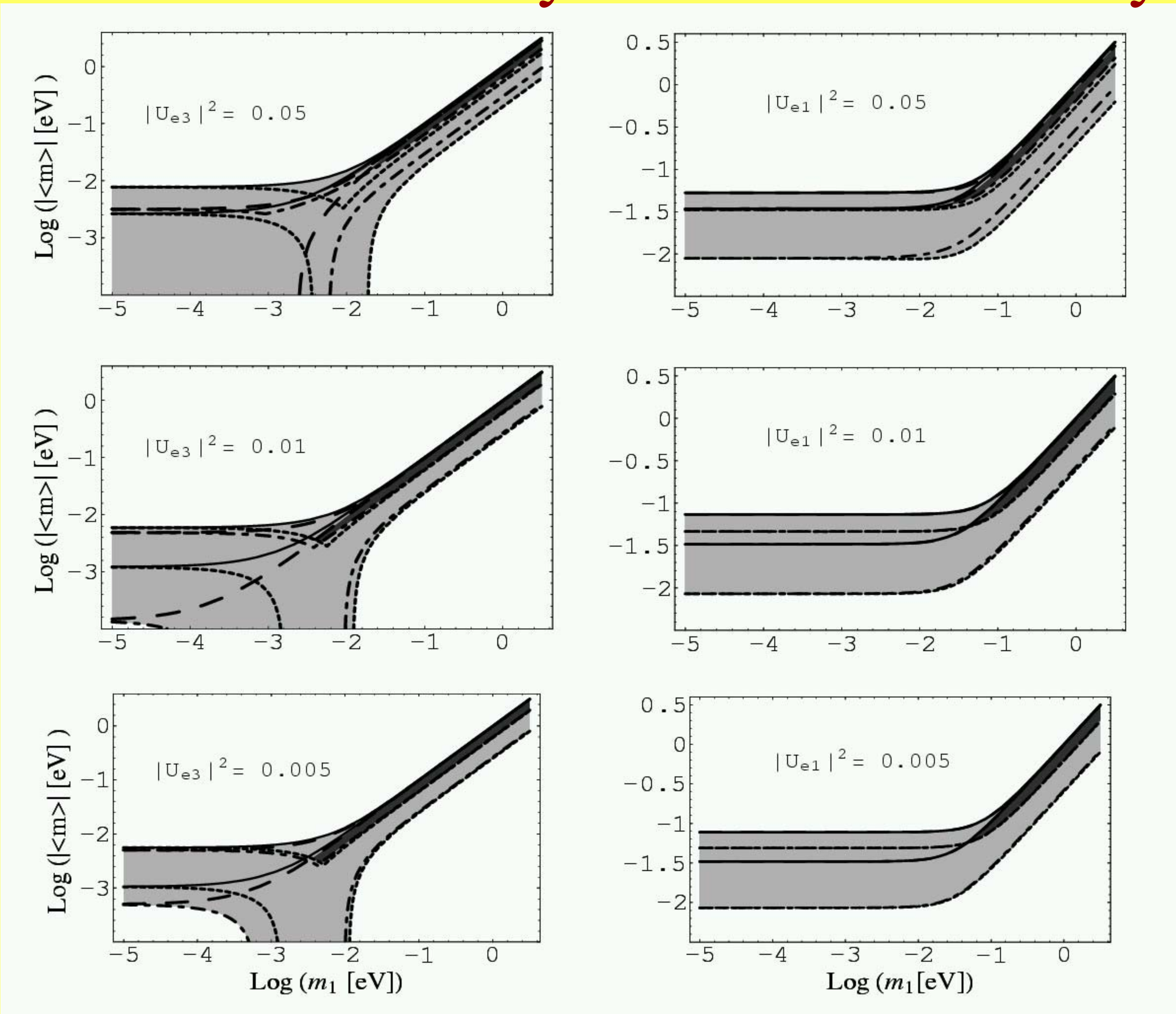
Normal hierarchy   Inverted hierarchy



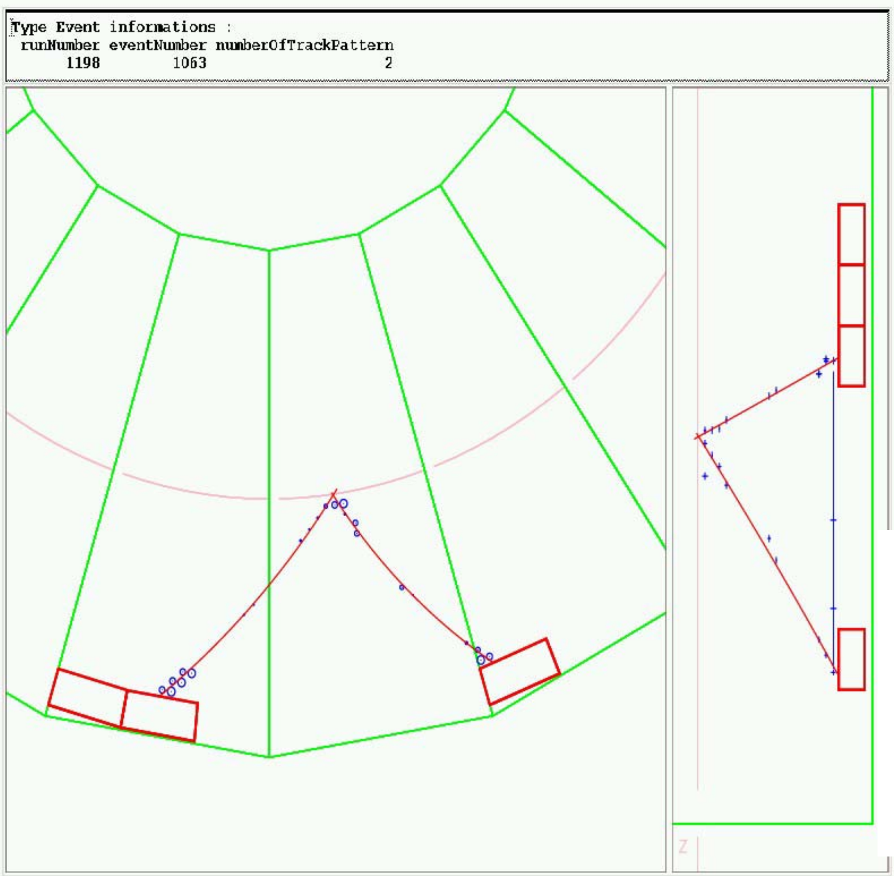
From Pascoli and Petcov, hep-ph/0205022

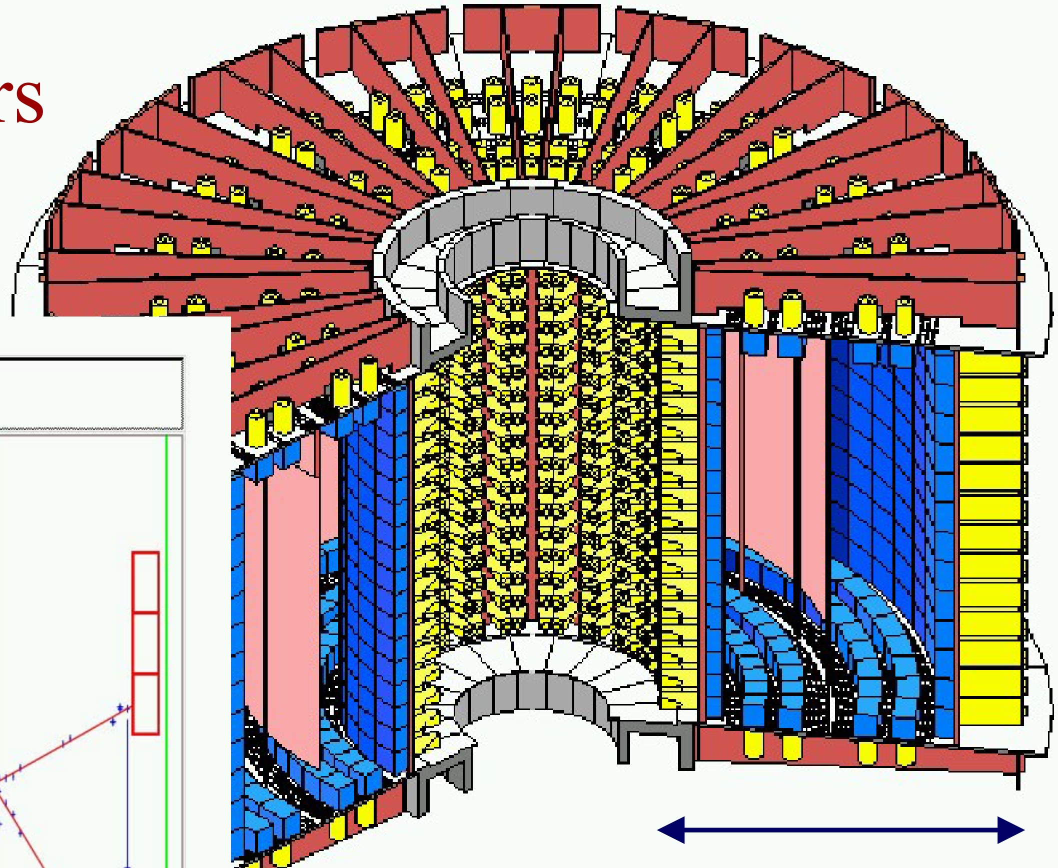
Need new experiments on much larger scale

NEMO-3

CHEP '02

^{100}Mo at 10^{25} years





Many many more, see Elliott and Vogel hep-ph/0202264

Cosmological studies of neutrino mass

- There are many cosmological consequences of neutrino mass – too many to discuss here
- Specifically, however, neutrino mass will tend to wash out intermediate scale structure during galaxy formation
- This has recently been studied by the 2dF Galaxy Redshift Survey team (see astro-ph/0204152)

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ν masses…

…and mixings

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University of Sussex/

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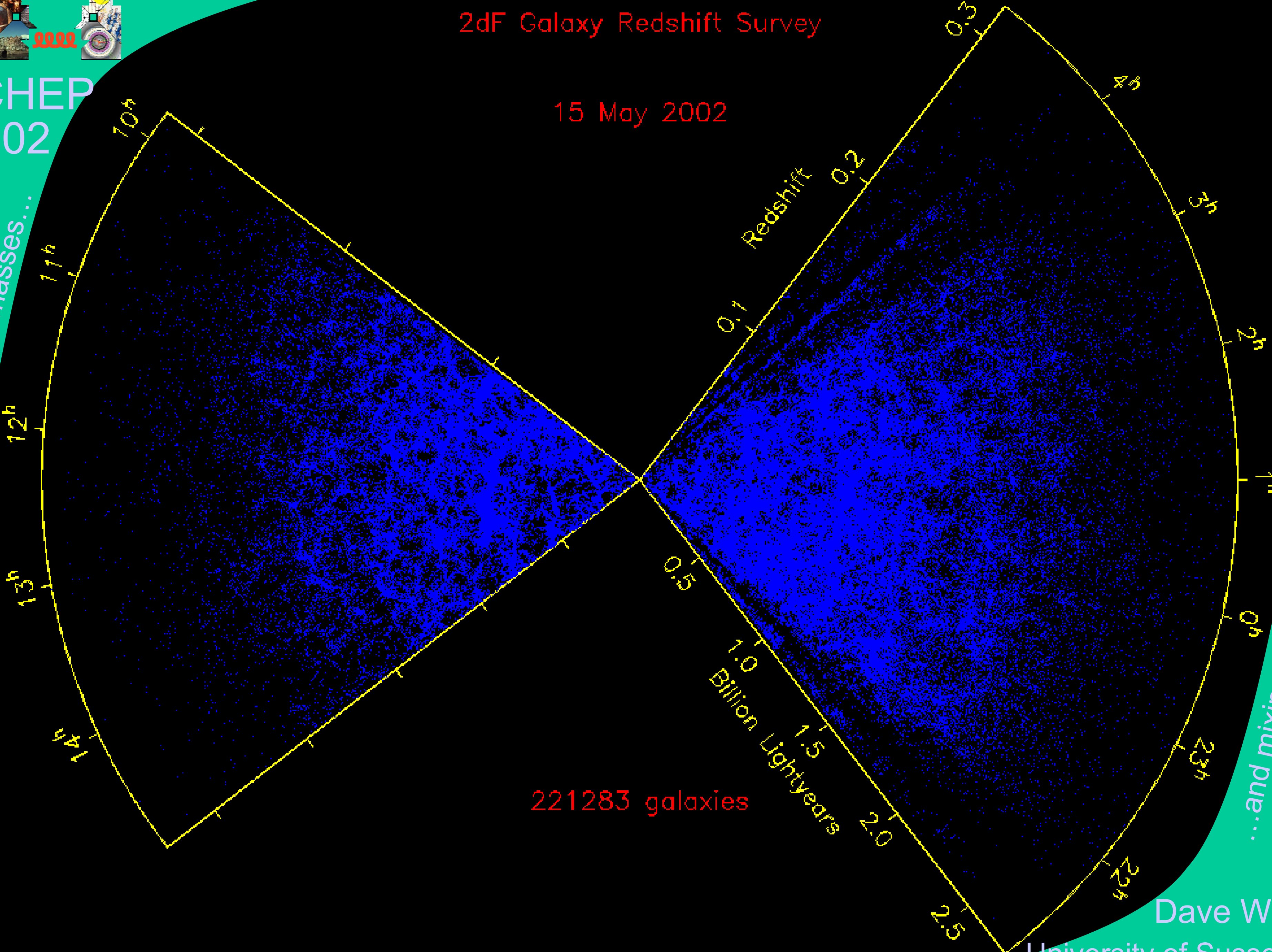
ν masses…



…and mixings

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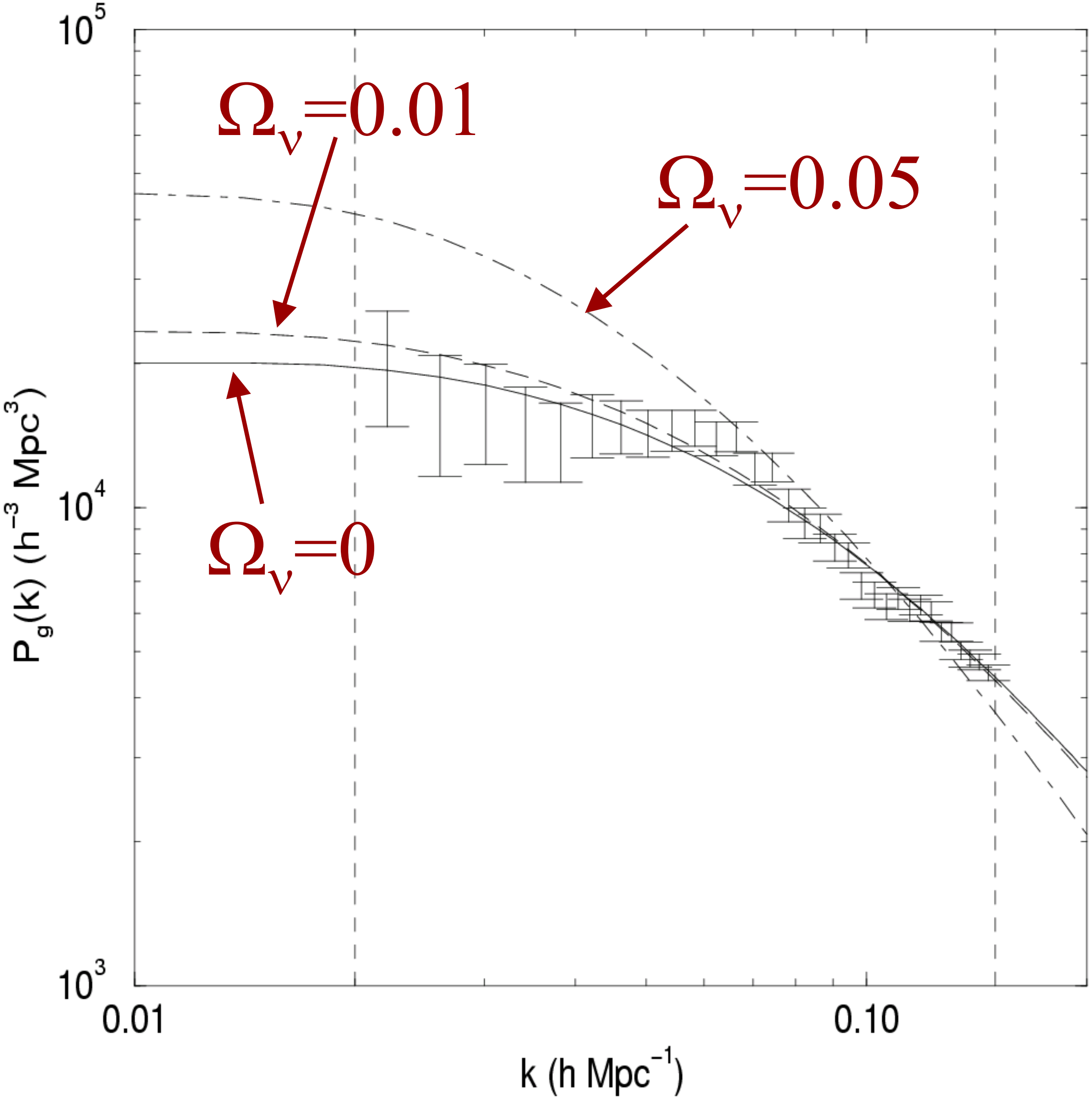
ν masses…



They derive $m_{\nu,tot} < 2.2$ eV

…and mixings

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There is no time (and I haven't really got the expertise) to discuss this in detail here.

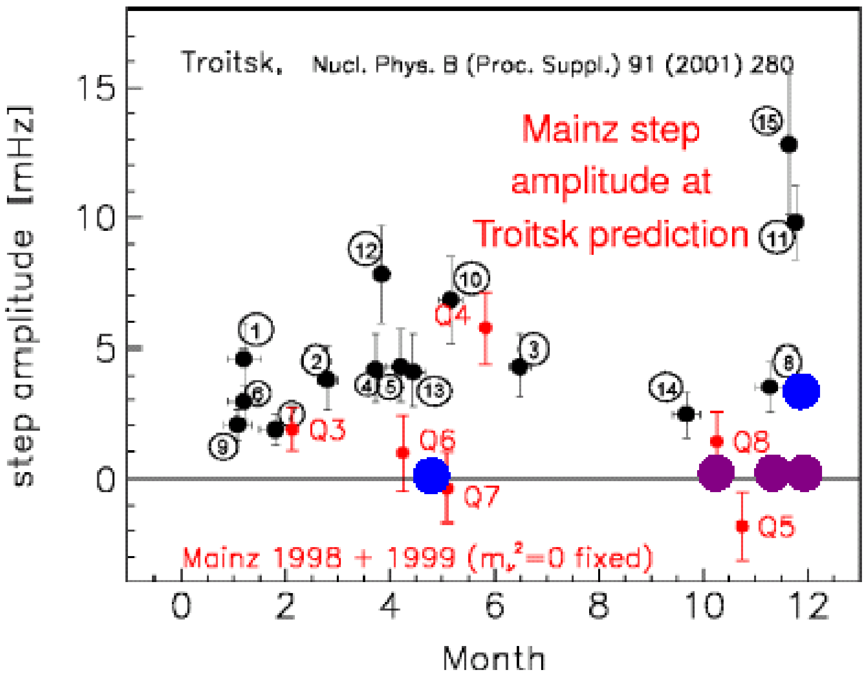
- I think it is tremendously exciting that cosmology and laboratory measurements are on the same scale, and therefore the information flows both ways.
- The cosmological measurements will push to greater sensitivity, down towards 0.1 eV.
- In my opinion such measurements are no substitute for good laboratory measurements, because they are inherently dependent on cosmological models we should be trying to test.
- For instance, there is the "bias" b, and if this is higher on small scales the 2dF analysis would derive a non-zero mass
- Laboratory limits therefore are potentially measures of b, which is very hard to measure otherwise!

Conclusions!

- Neutrino mixing has moved from a speculation to an observed property of nature.
- For the simplest model we have measured 2 of the 3 angles, 3 of the 2 mass differences, and the sign of one mass difference.
- Results over the next few years will be of great interest, with SNO, KamLAND, MiniBooNE, K2K, BOREXINO, MINOS, CNGS, and others all contributing new data
- The farther future leads from Superbeams through the Neutrino Factory, and we can look forward to new discoveries at each step
- Direct mass measurements, including double-beta decay, must be a priority
- There is much work to be done – JOIN US!
- Thanks to everybody who I stole transparencies from!

Status of Troitsk anomaly

Amplitude of anomaly: Troitsk, Mainz



Troitsk 2001:

- **No anomaly in May 2001**
- **Only small anomaly in Dec. 2001**

Mainz:

- **Clear contradiction to 0.5 y period**
- Similiar effect observed only once (Q4 1998)
- **Does not show up in in newest Mainz data:** of 2000 (Q9,Q10, partially in parallel with Troitsk) and of 2001 (Q11,Q12)

⇒ Troitsk anomaly is very likely experimental artefact, which can be avoided (Mainz)

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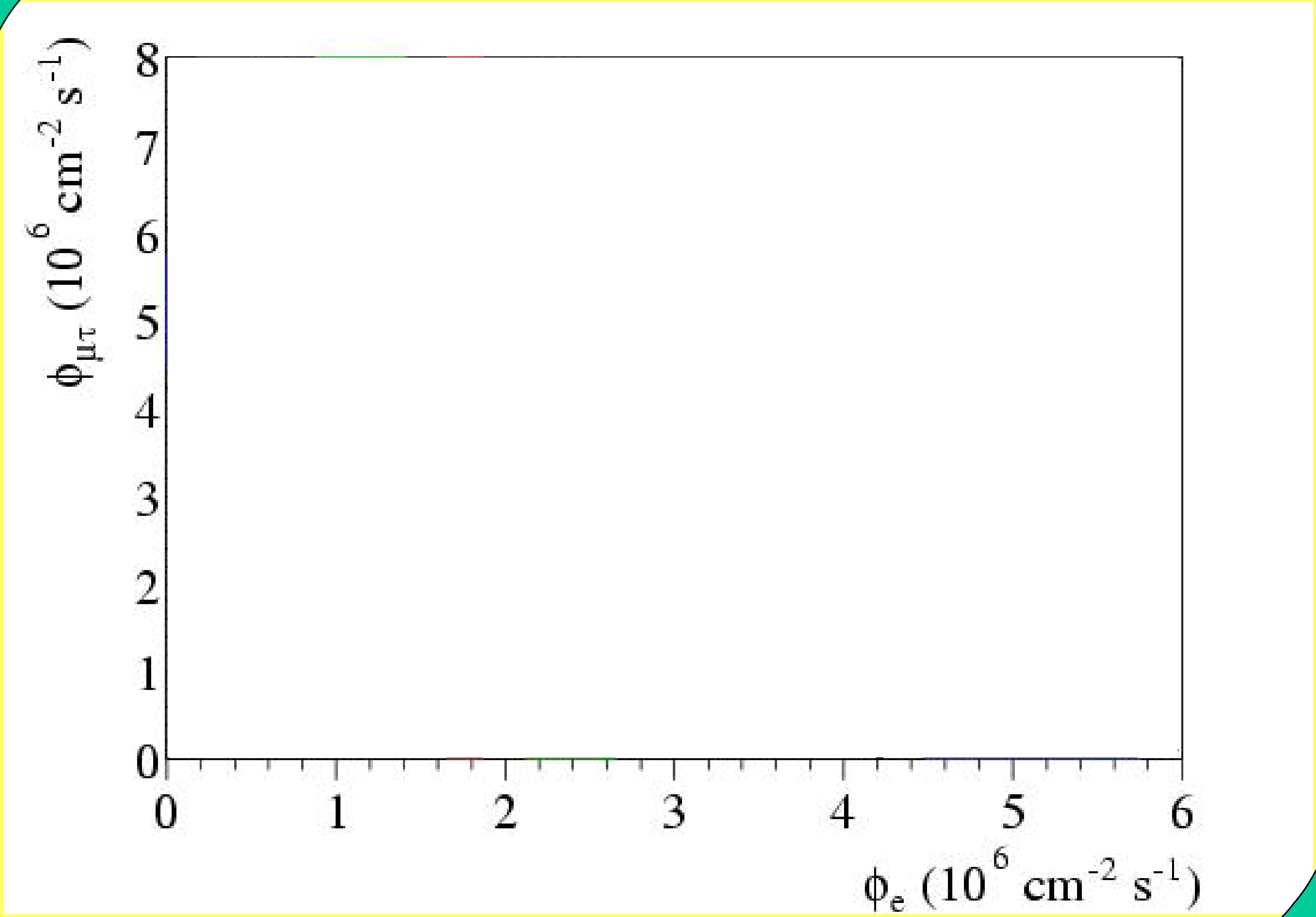

…and mixings

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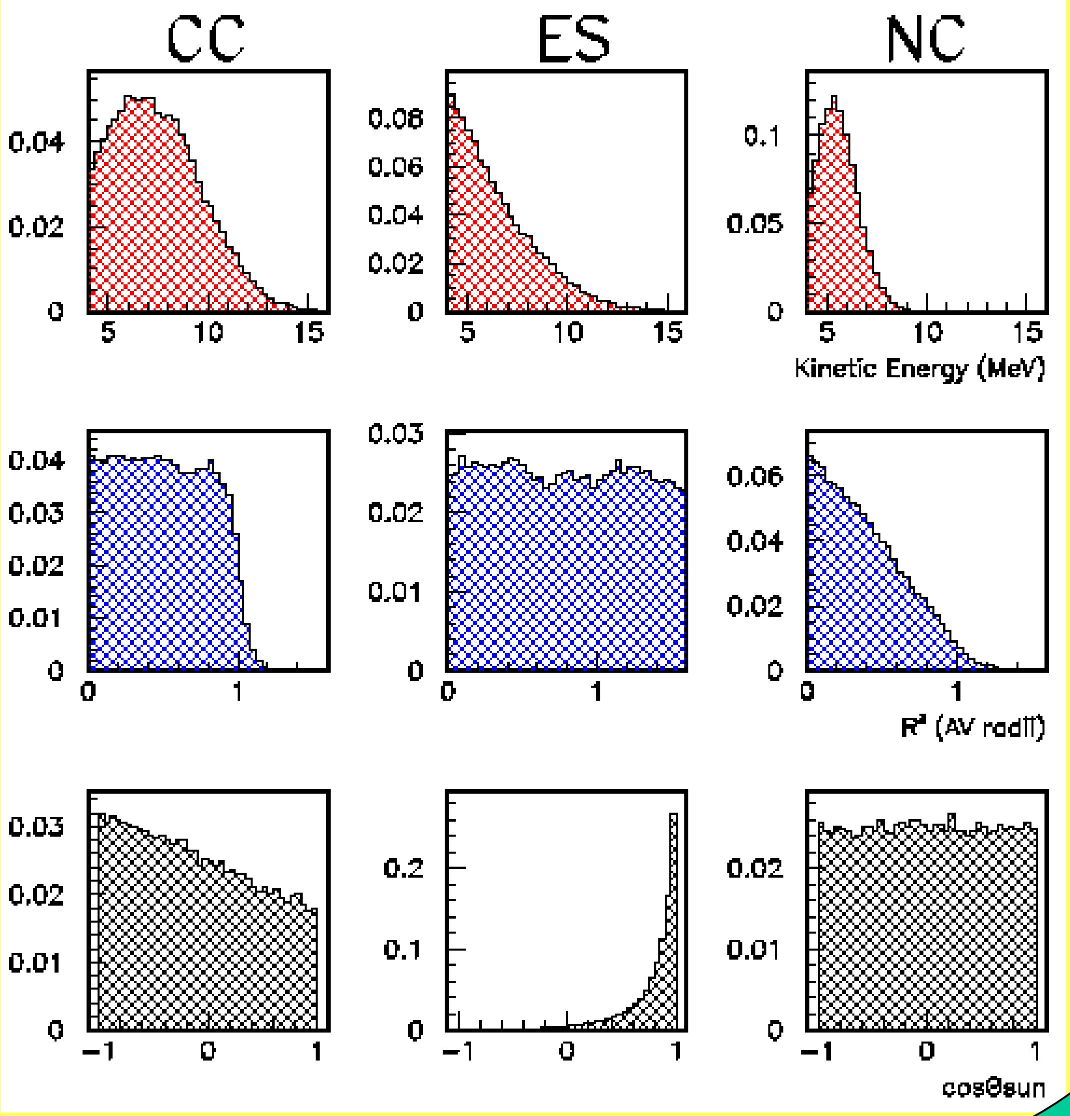
Signal PDF's for pure D_2O

T_{eff} →

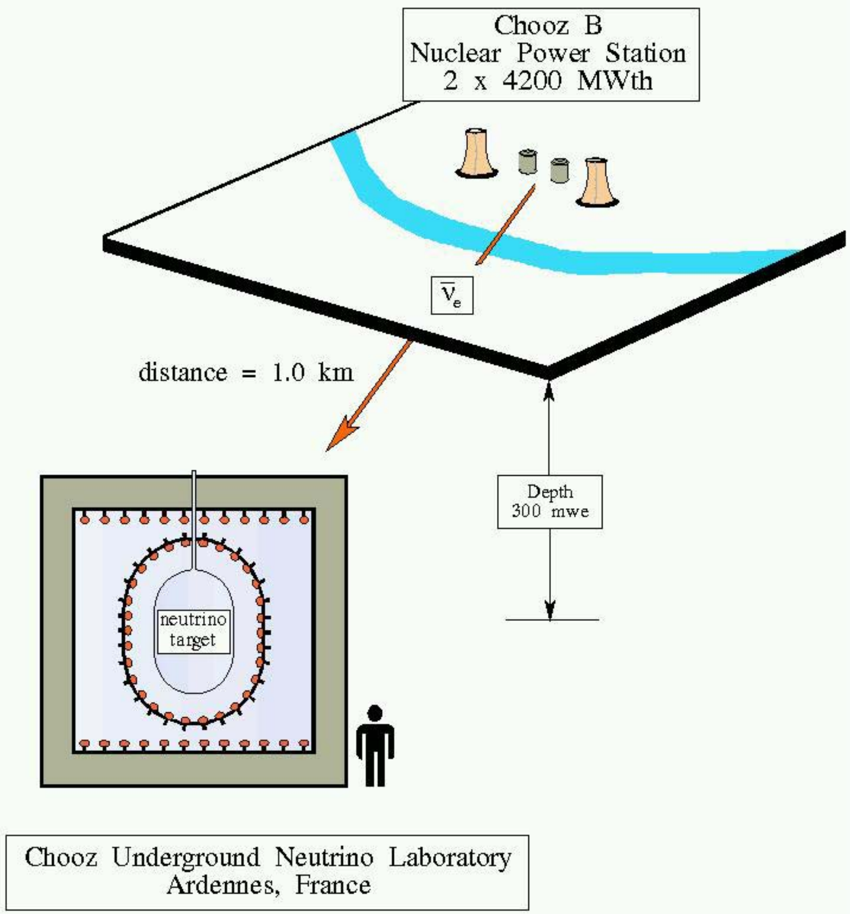
$(R/R_{AV})^3$ →

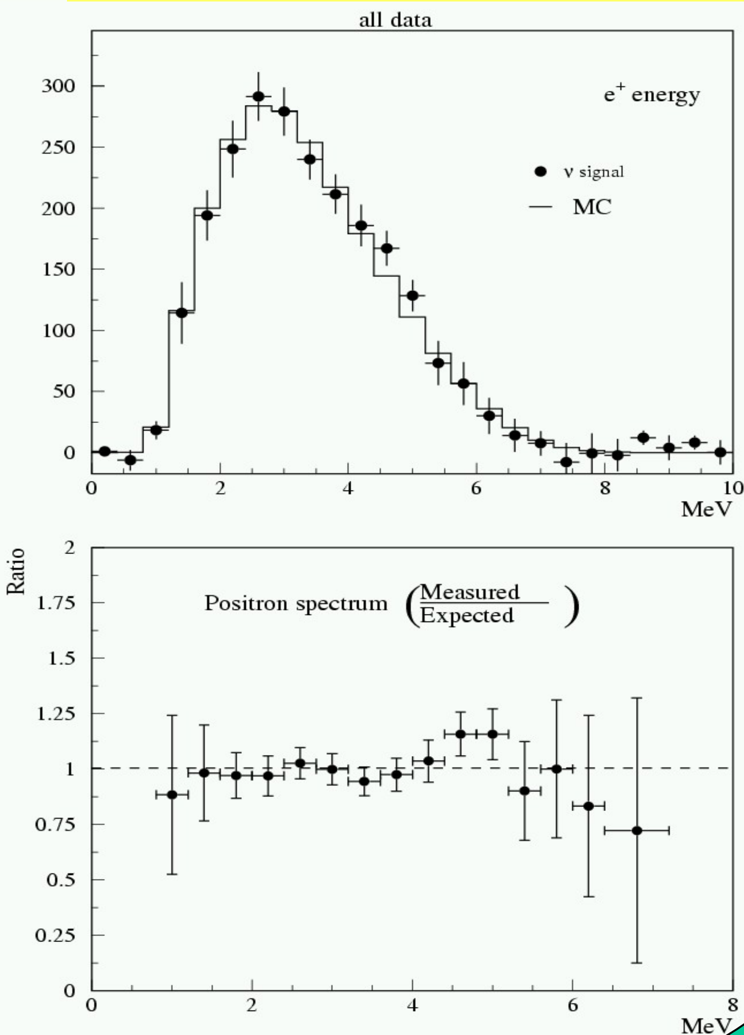
$\cos\theta_\odot$ →



CHOOZ / Palo Verde

Search for disappearance of reactor ν_e





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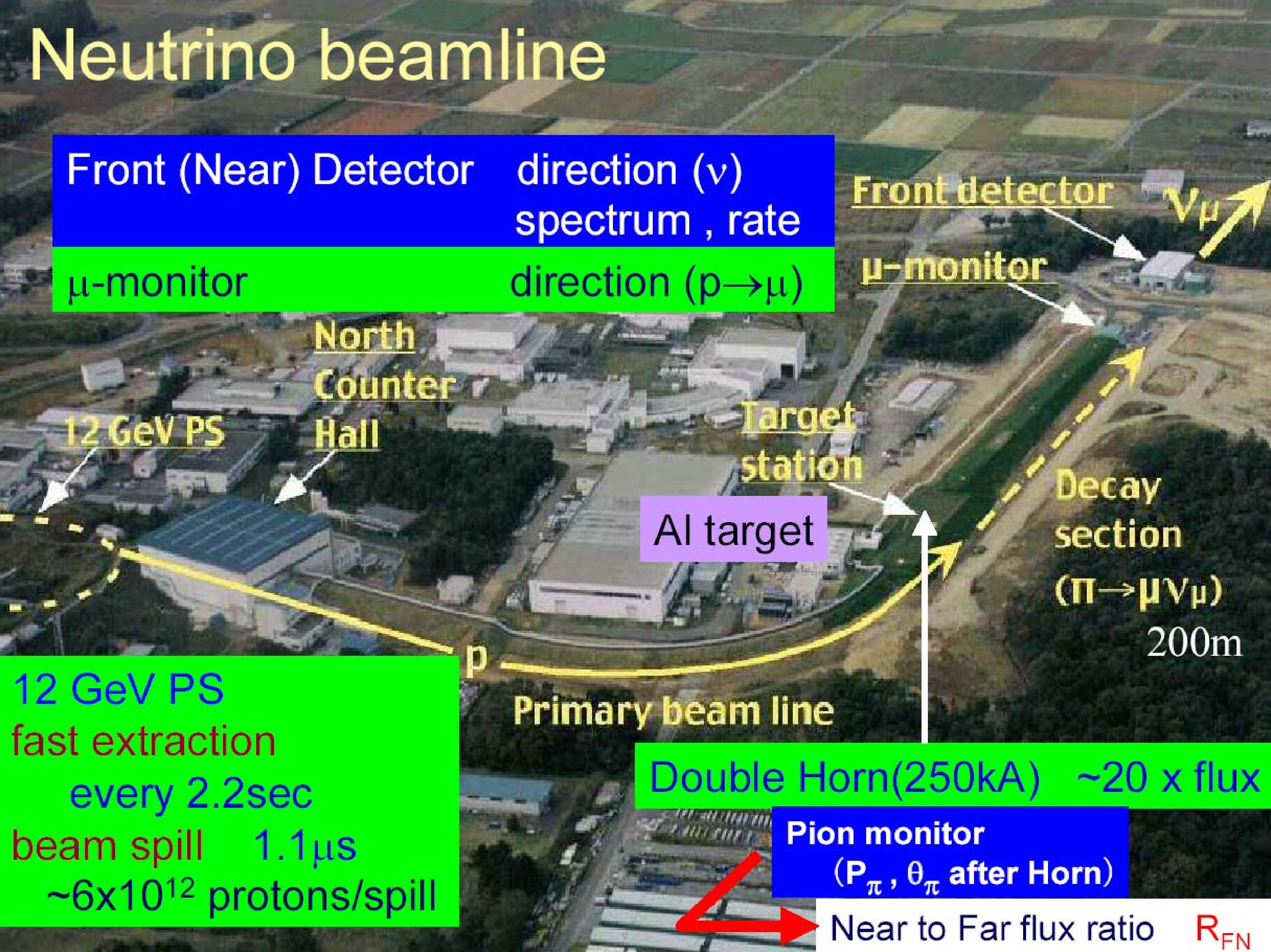
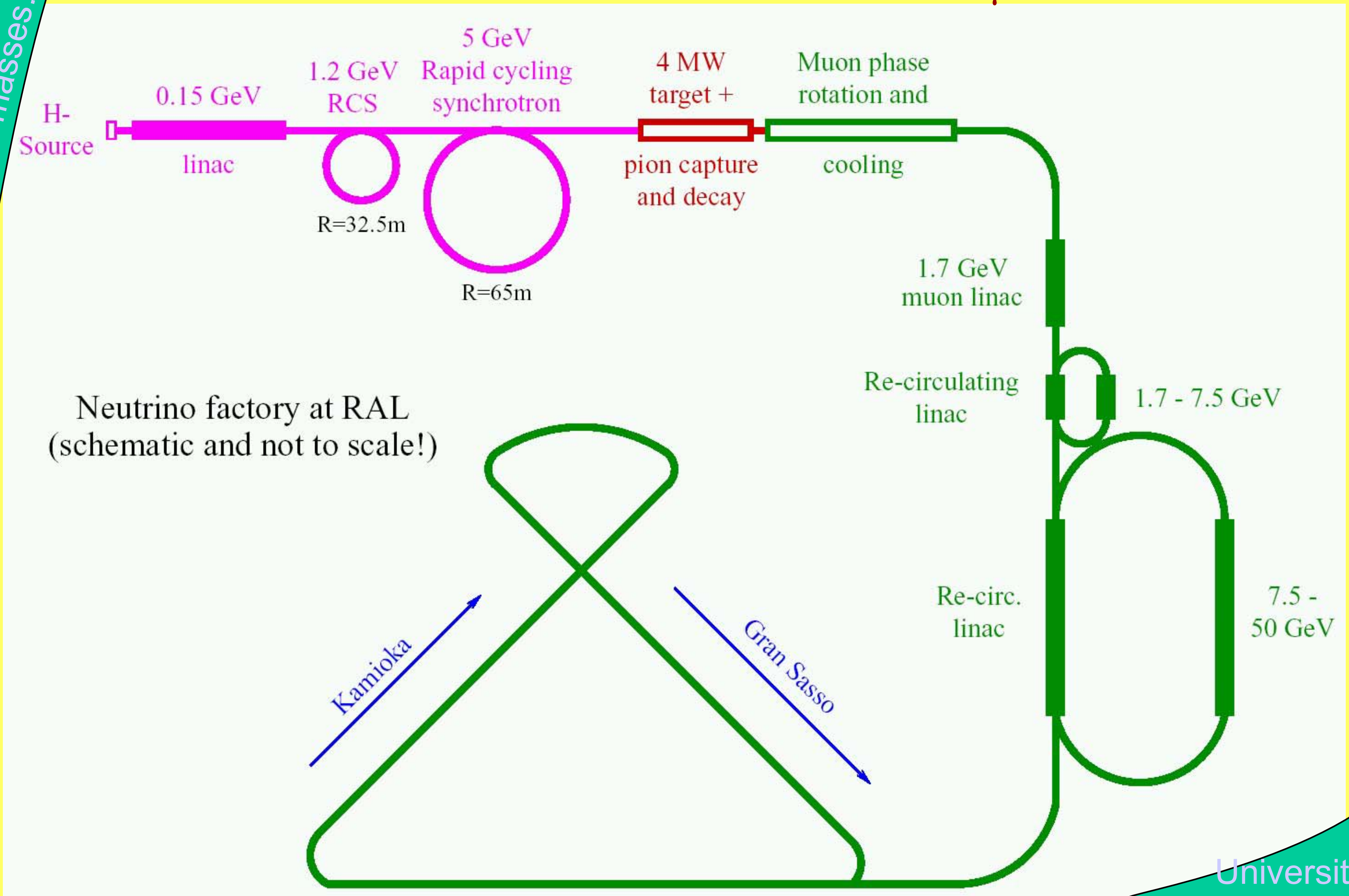
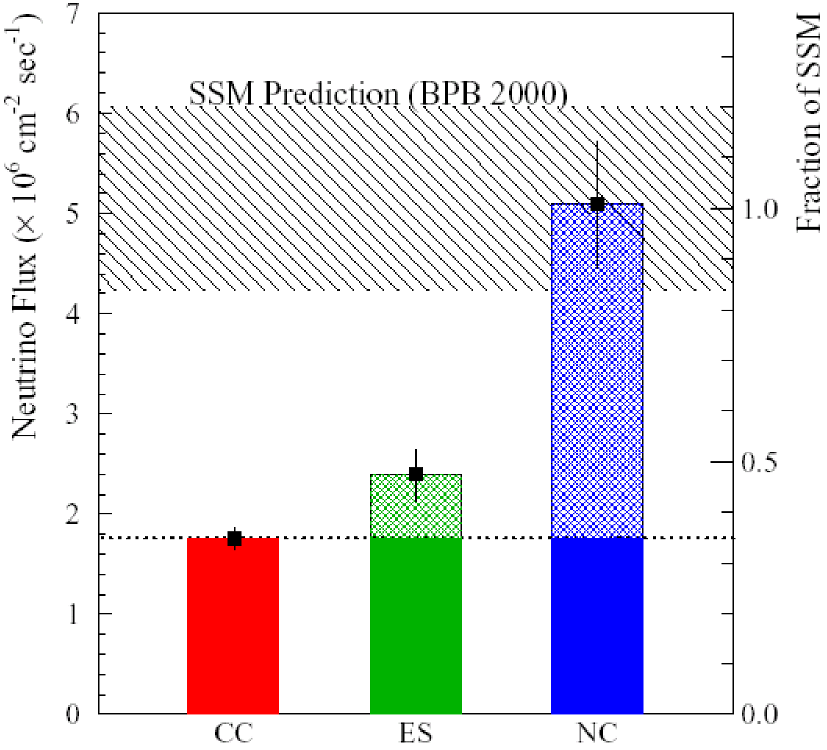

Neutrino beamline
Front (Near) Detector direction (ν) spectrum , rate
μ-monitor direction (p→μ)
Front detector
ν_μ
μ-monitor
North Counter Hall
12 GeV PS
Target station
Al target
Decay section
(π→μν_μ)
200m
p
Primary beam line
12 GeV PS
fast extraction
every 2.2sec
beam spill 1.1μs
~6x10^{12} protons/spill
Double Horn(250kA) ~20 x flux
Pion monitor
(P_π , θ_π after Horn)
Near to Far flux ratio R_{FN}

Make intense, energetic, clean, sign-selected neutrino beams from

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



Measured SNO Fluxes



Assuming ^{8}B energy spectrum ...

Fluxes ($\times 10^6$ cm^{-2} sec^{-1})

$$\phi_{CC} = 1.76^{+0.06}_{-0.05}\,(\text{stat.}) \pm 0.09\,(\text{sys.})$$

$$\phi_{ES} = 2.39^{+0.24}_{-0.23}\,(\text{stat.}) \pm 0.12\,(\text{sys.})$$

$$\phi_{NC} = 5.09^{+0.44}_{-0.43}\,(\text{stat.})^{+0.46}_{-0.43}\,(\text{sys.})$$

$$\phi_{CC} < \phi_{ES} < \phi_{NC}$$

NC flux in agreement with SSM prediction!