Solar Neutrino Experiments – Results and Prospects

IoP ½ Day
RAL
June 28, 2005

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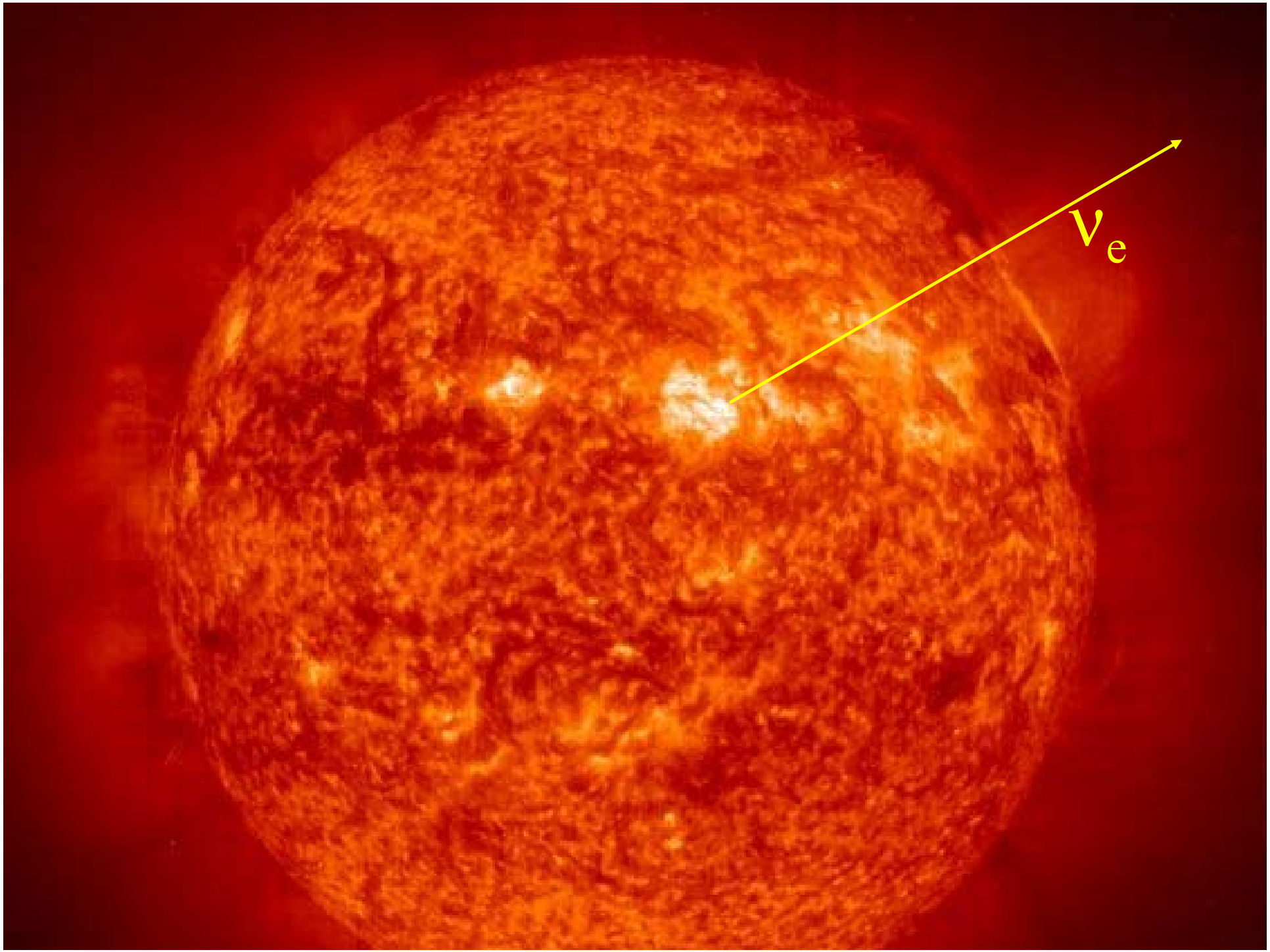
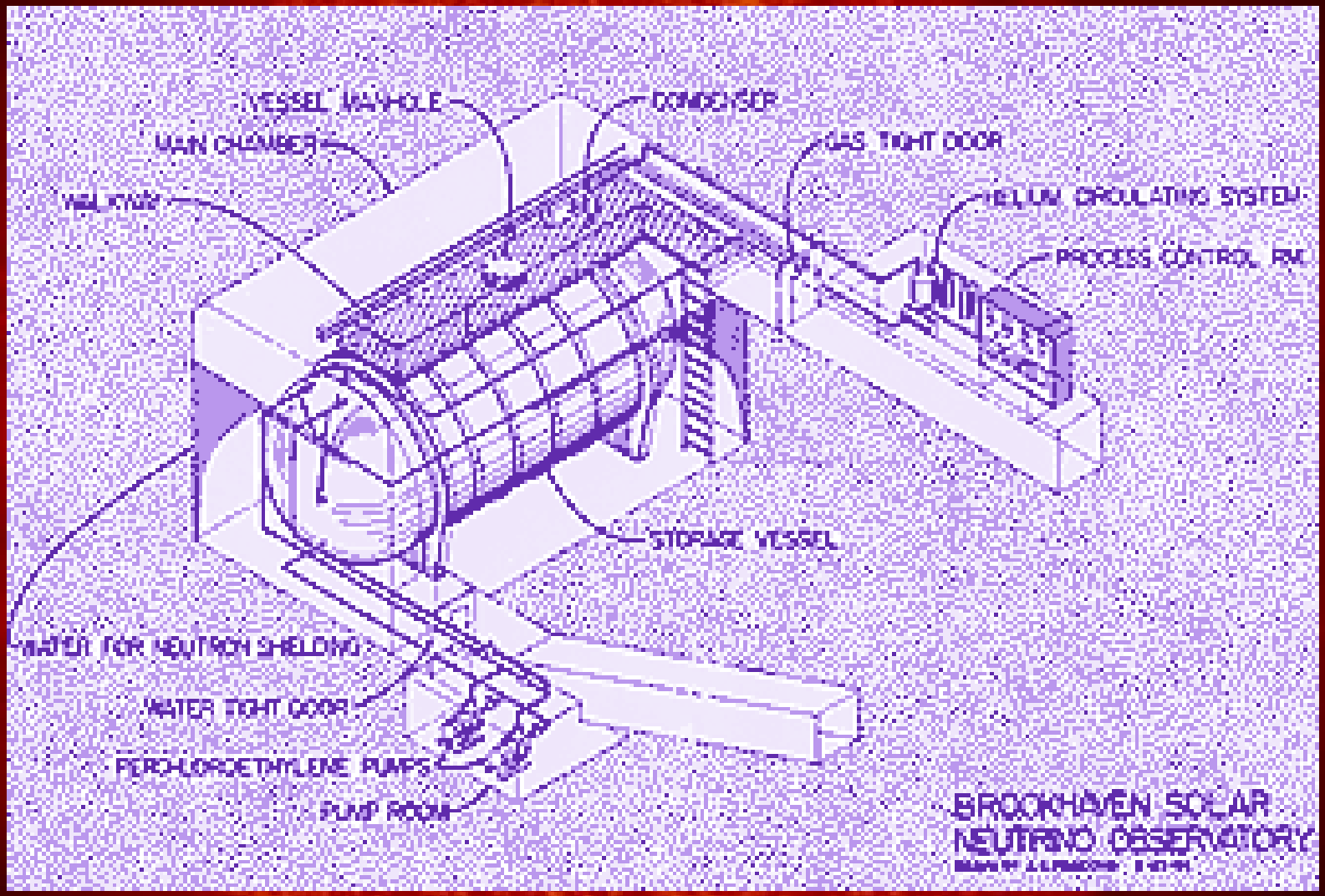
Imperial/RAL

CCLRC
Rutherford Appleton Laboratory

Imperial College
London


ν_e

Where it all began – the Davis Experiment



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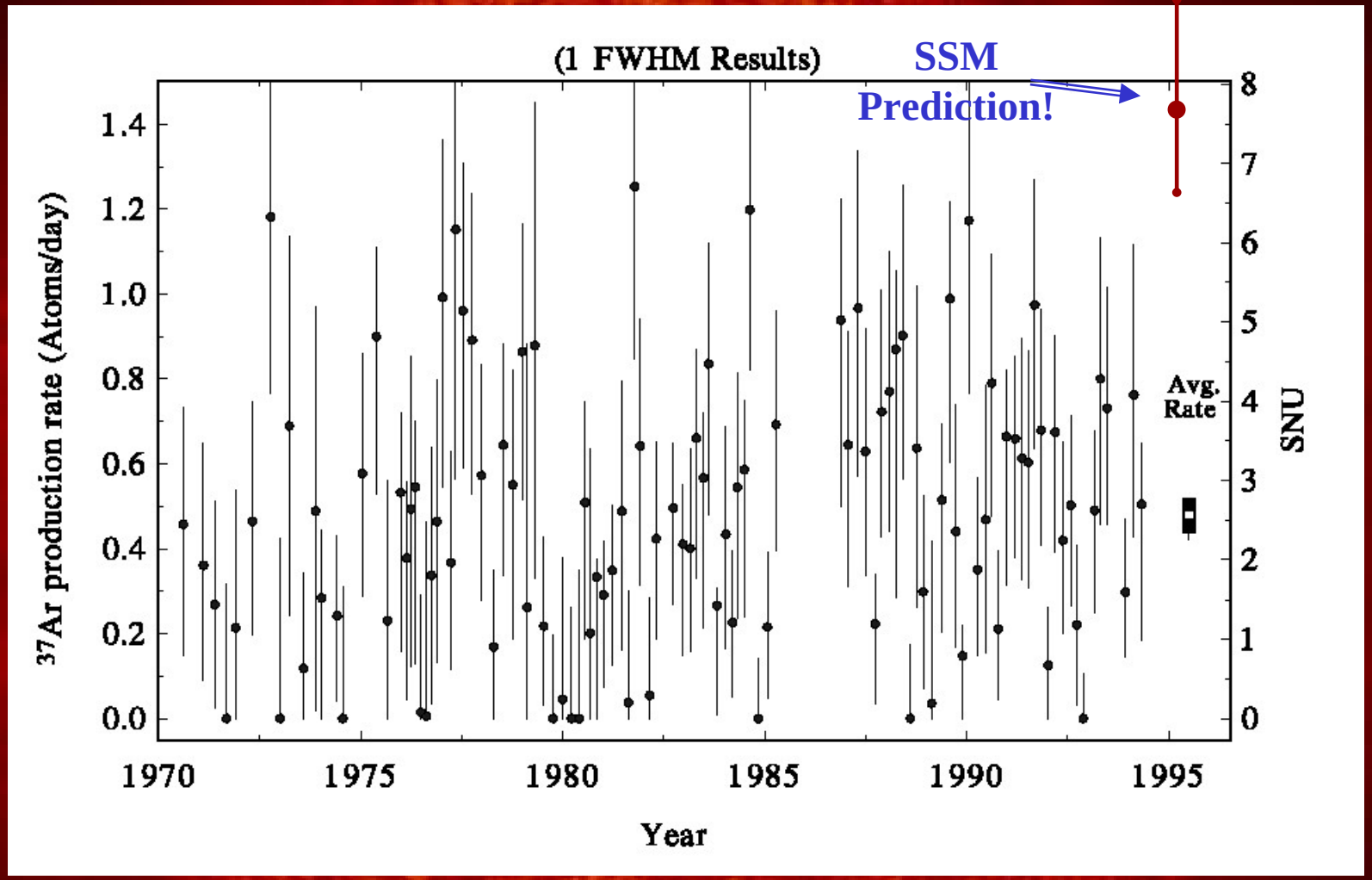
Where it all began – the Davis Experiment



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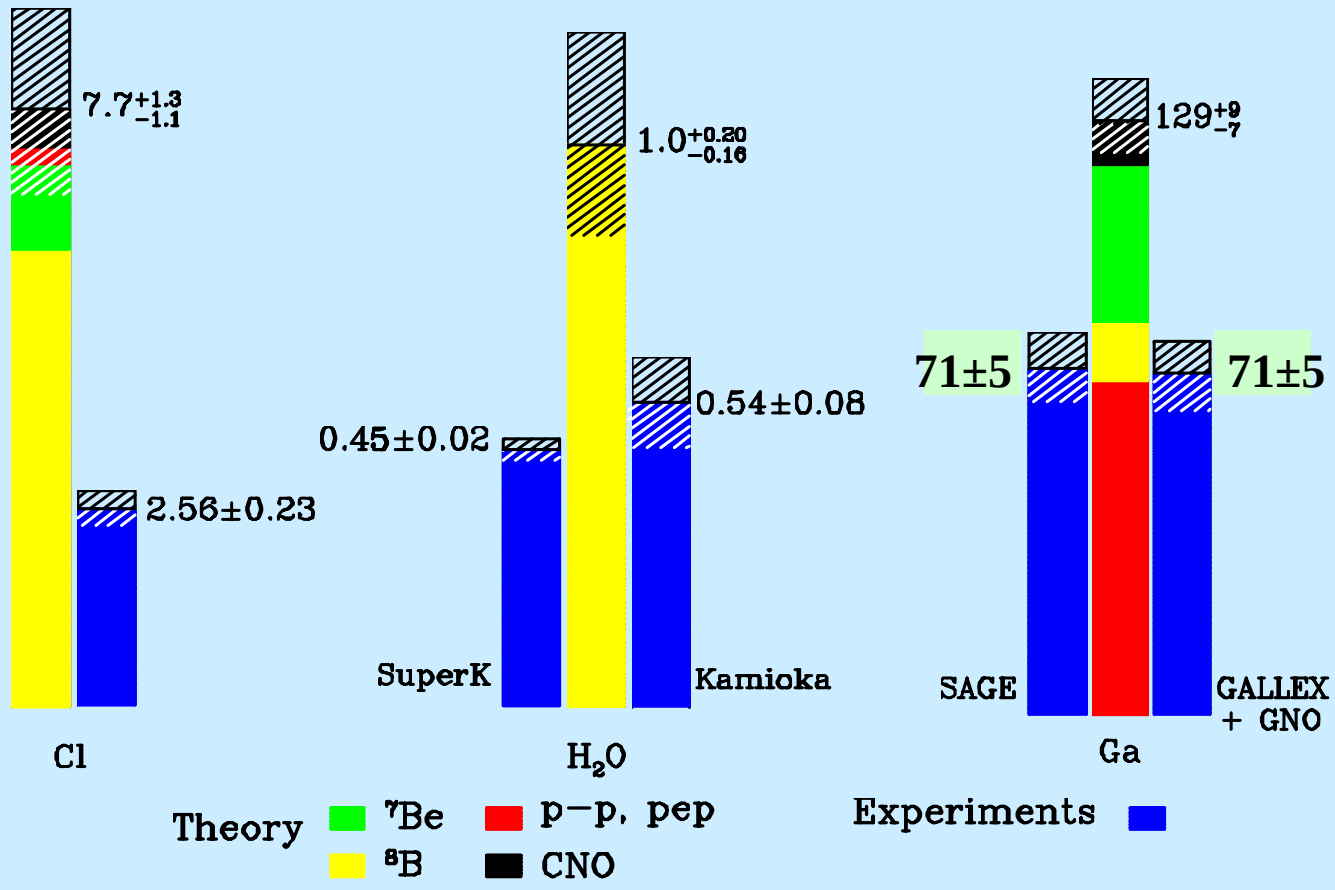
Total Rates: Standard Model vs. Experiment
Bahcall–Pinsonneault 2000



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Neutrino Oscillations

- If neutrinos have mass, then there are two distinct types of neutrino state we must consider – the eigenstates of the weak Hamiltonian $\nu_l = \nu_e, \nu_\mu, \nu_\tau$; and the eigenstates of the free particle Hamiltonian $\nu_i = \nu_1, \nu_2, \nu_3$.
- There is absolutely no reason to believe that these are the same thing.
- In general:

$$|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$$

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2ν Vacuum Oscillations

- For two neutrino flavours this leads to the appearance of a new neutrino flavour

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

$$\Delta m^2 = m_2^{\,2} - m_1^{\,2} \text{ in } eV^2,\ L \text{ in meters},\ E \text{ in MeV}$$

- With the corresponding disappearance of the original neutrino flavour
- These oscillations can be significantly modified by the MSW effect when the neutrinos pass through matter…

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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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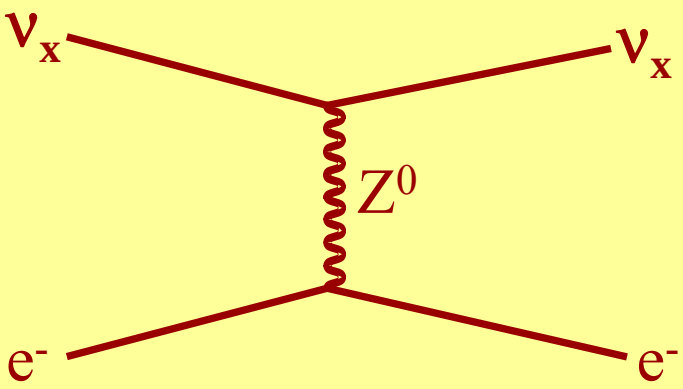

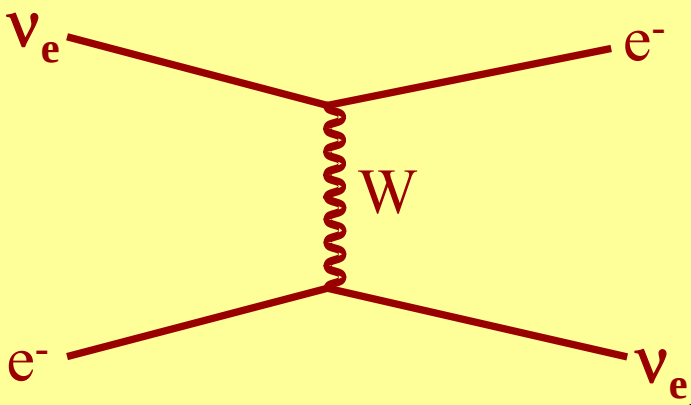

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Matter Effects – the MSW effect

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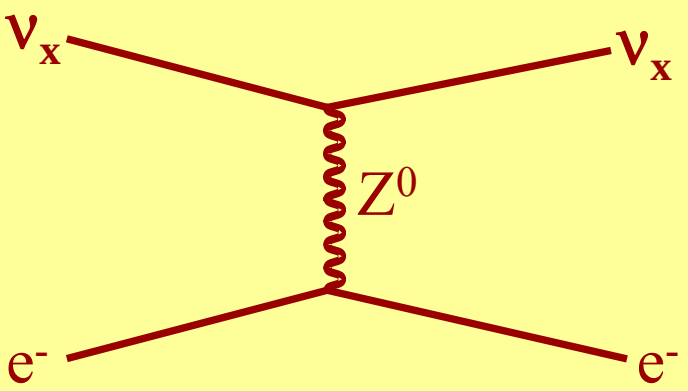
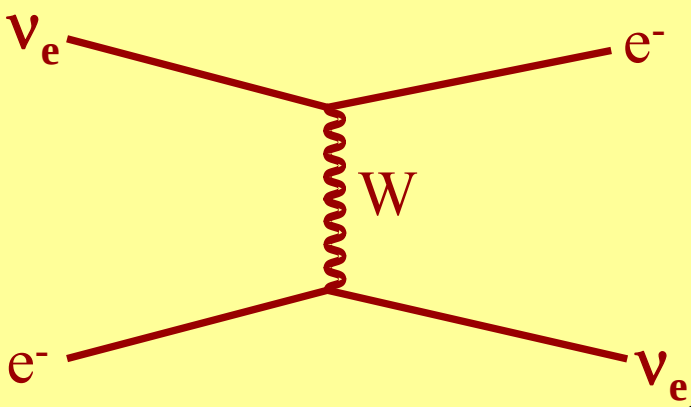
$$H = \begin{bmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{bmatrix}$$





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Matter Effects – the MSW effect

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

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

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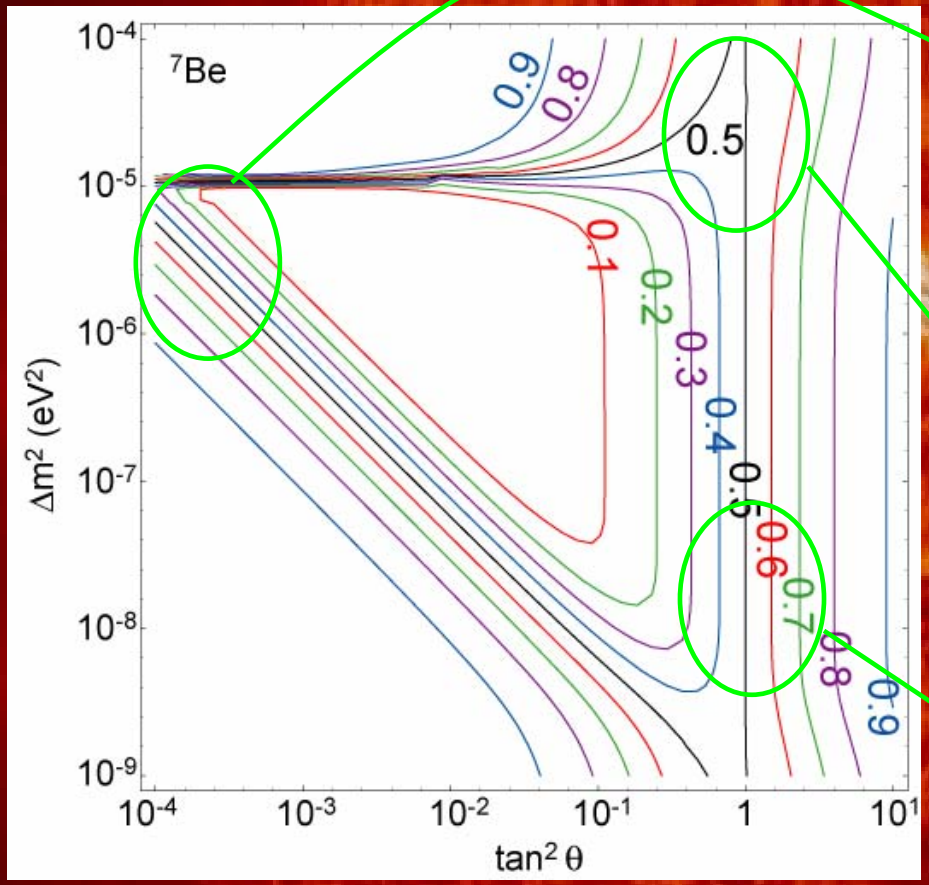
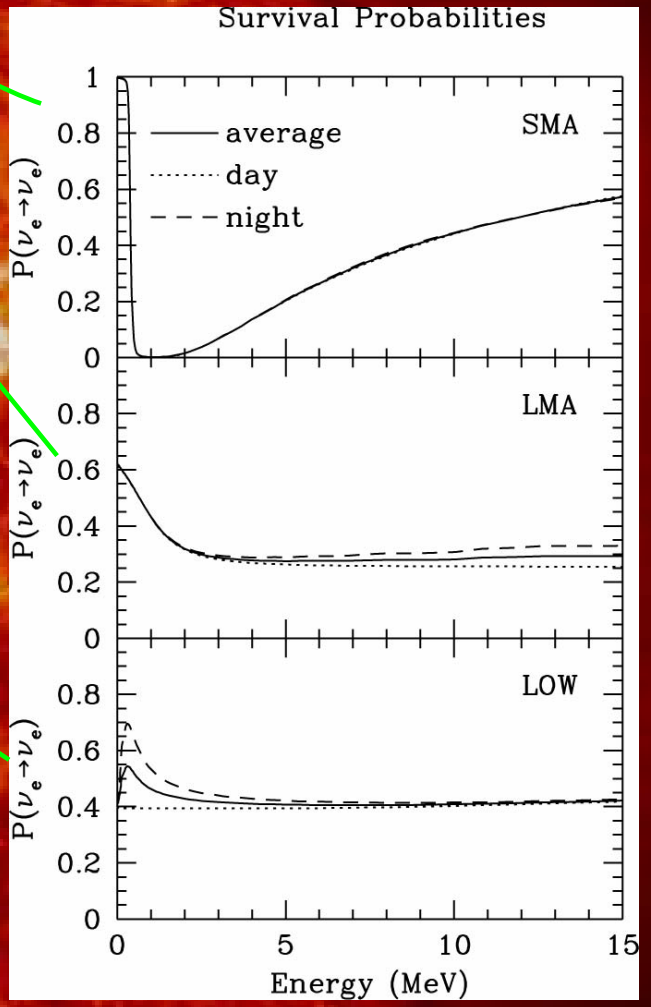
Matter Effects – the MSW effect





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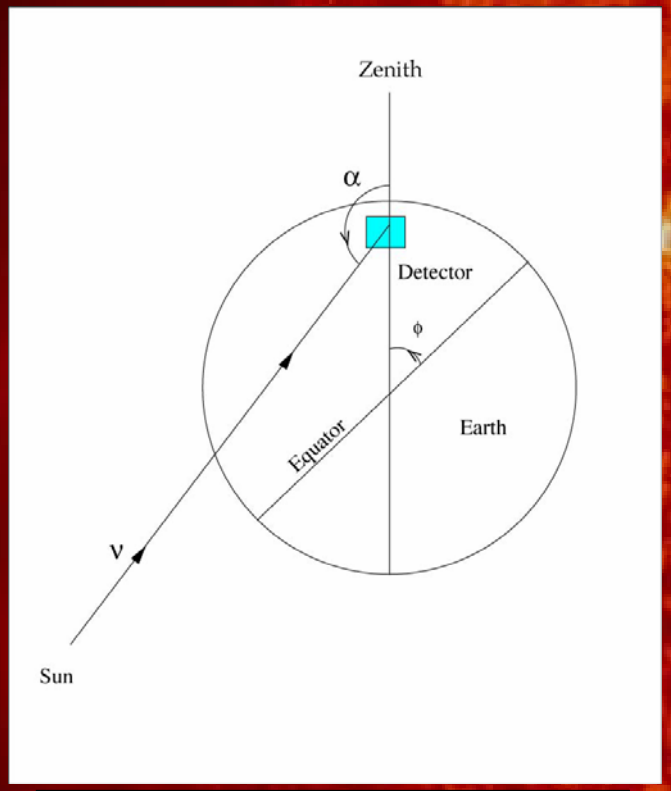
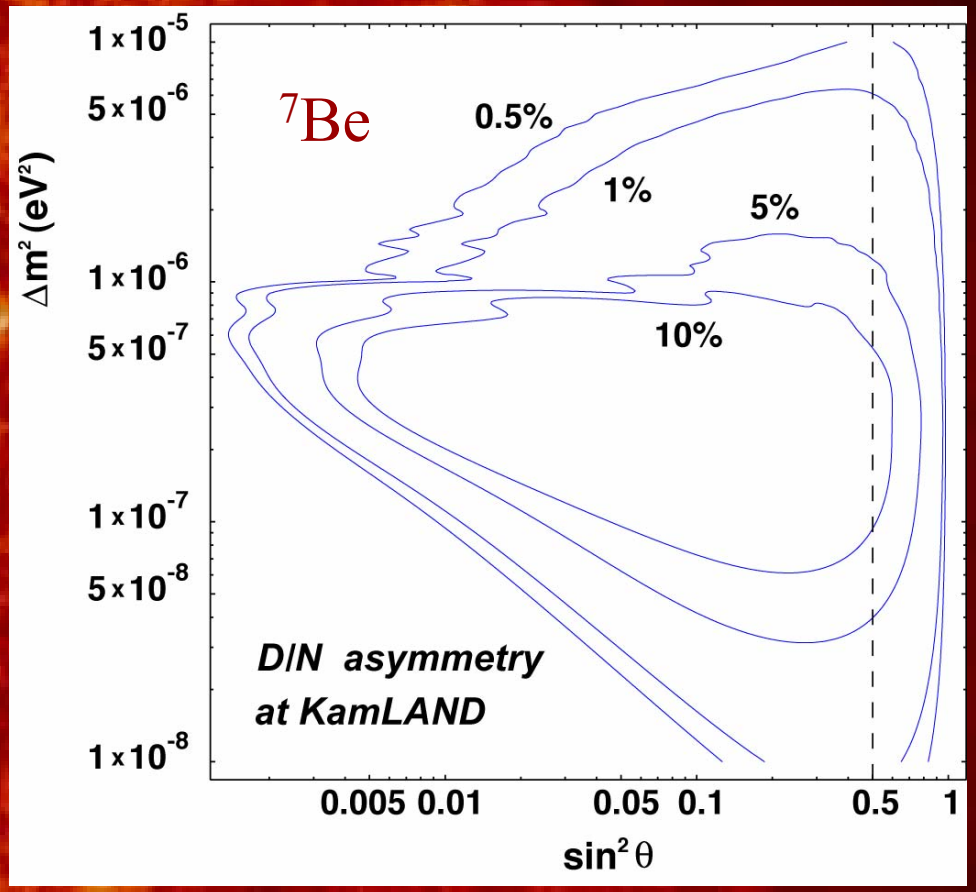
Matter Effects – the MSW effect

Day – Night Effect





$$\text{Asym} = \frac{N - D}{N + D}$$

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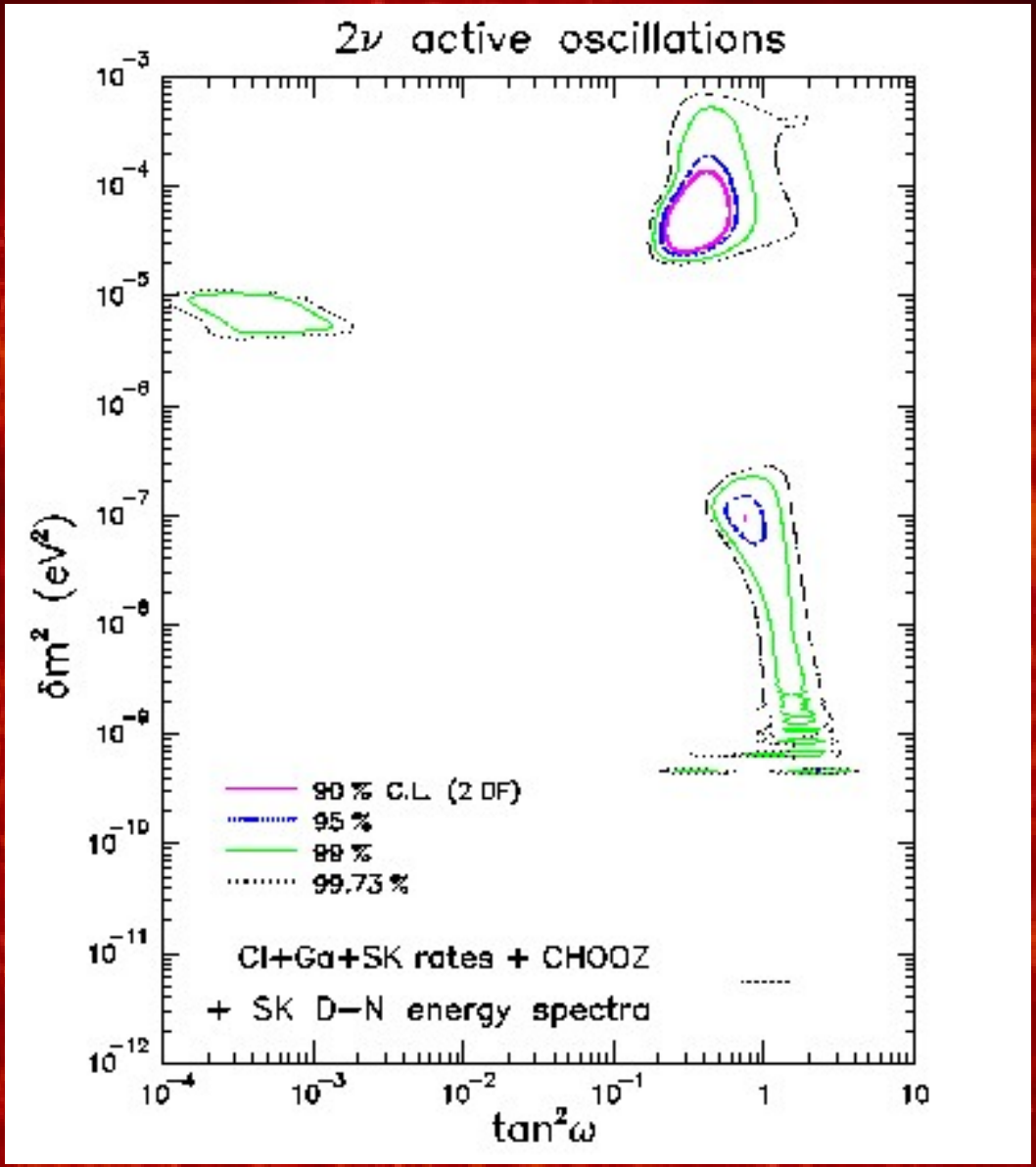
Which left us where?



But no smoking gun for oscillations….

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Solar..

SNO Collaboration

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Neutrinos

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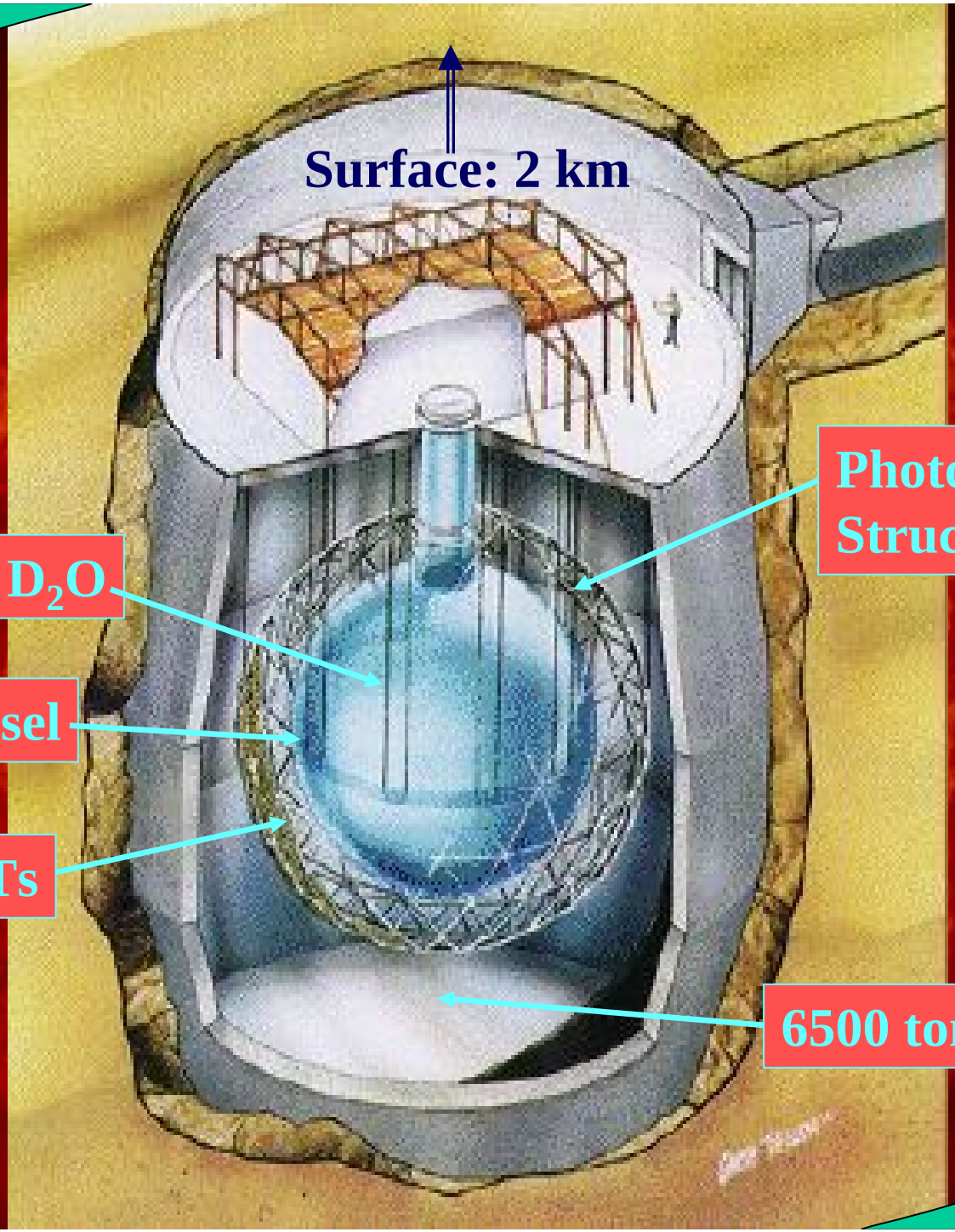
June 29, 2005

Solar..



Neutrinos

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Solar ν Interactions in SNO

Elastic Scattering (ES) $\nu_x + e^- \rightarrow \nu_x + e^-$

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

Charged Current (CC) $\nu_e + d \rightarrow p + p + e^-$

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

Neutral Current (NC) $\nu_x + d \rightarrow n + p + \nu_x$

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

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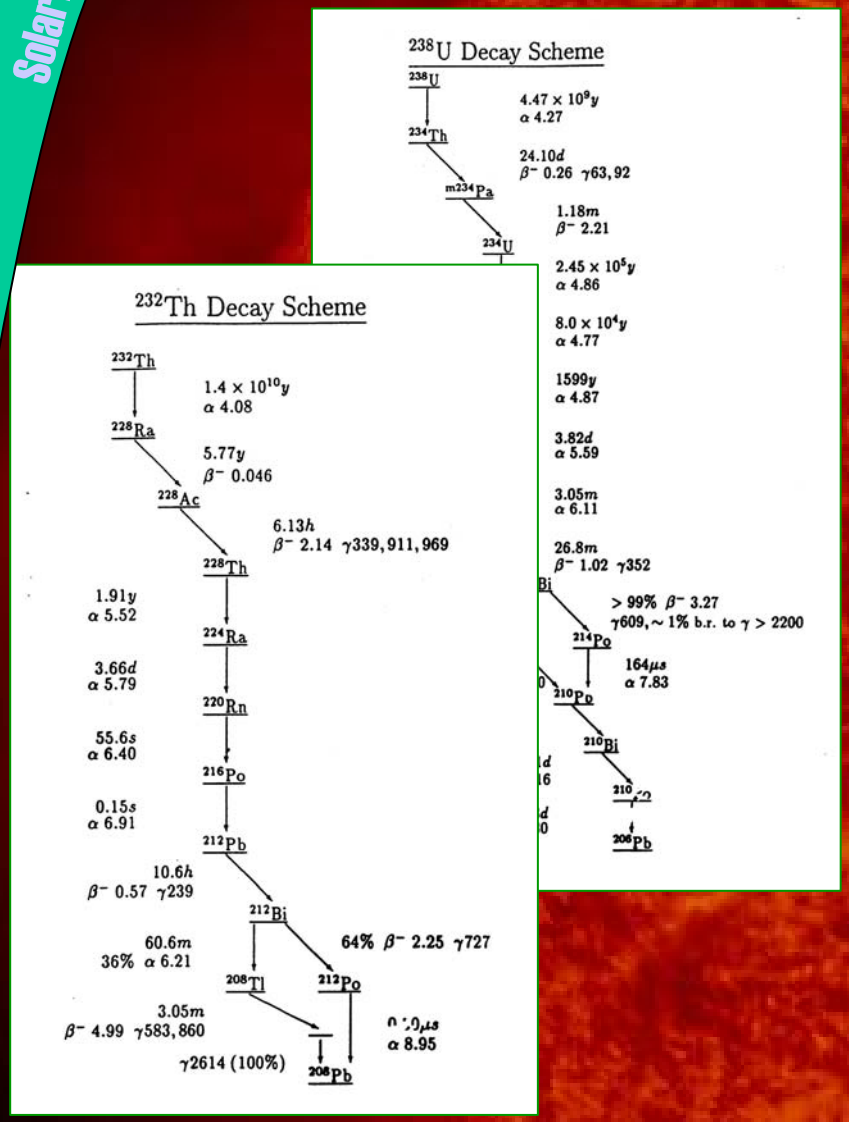
The enemy…..



βs and γs from decays in these chains interfere with our signals at low energies

And worse, γs over 2.2 MeV cause $d + \gamma \rightarrow n + p$

Design called for:

D2O $< 10^{-15}$ gm/gm U/Th

H2O $< 10^{-14}$ gm/gm U/Th

Acrylic $< 10^{-12}$ gm/gm U/Th

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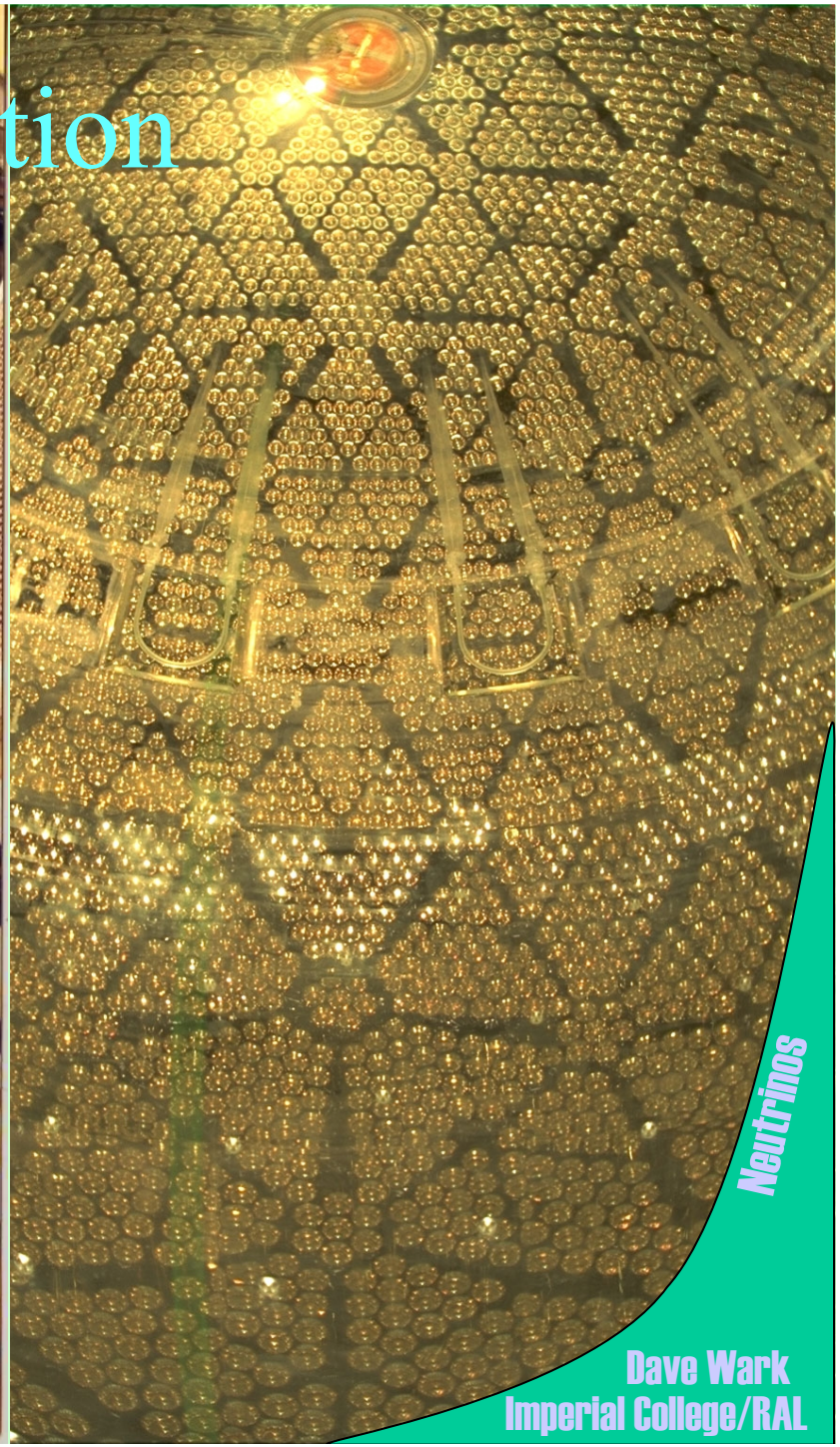
Construction



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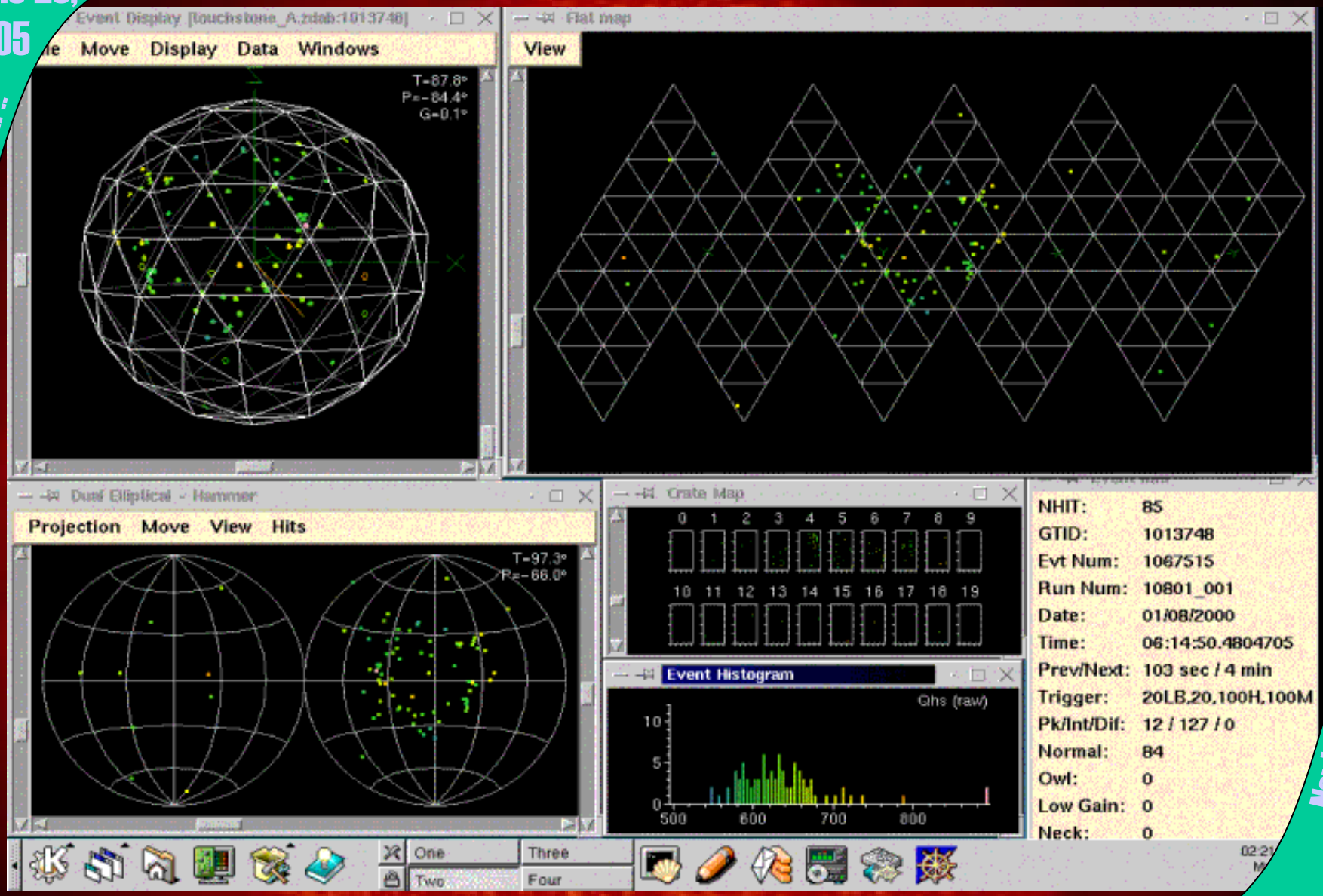
Solar ..



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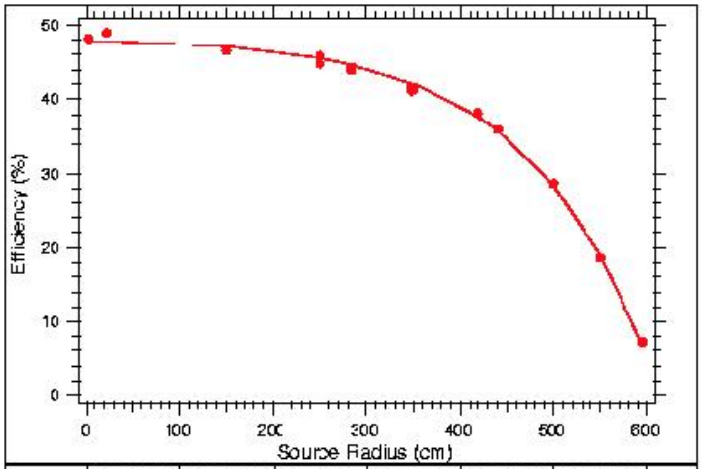
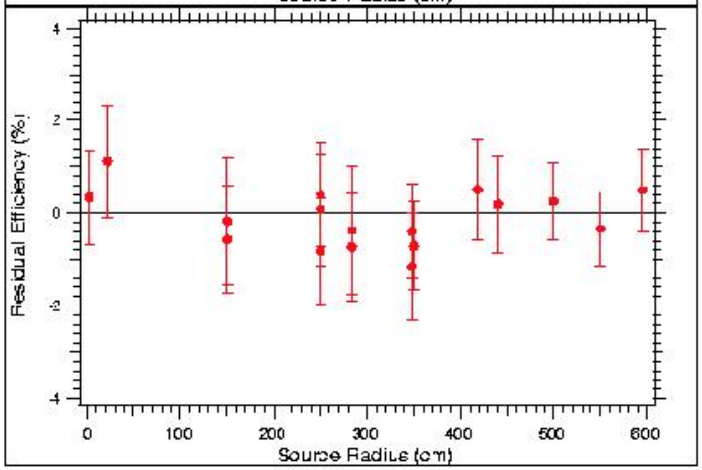
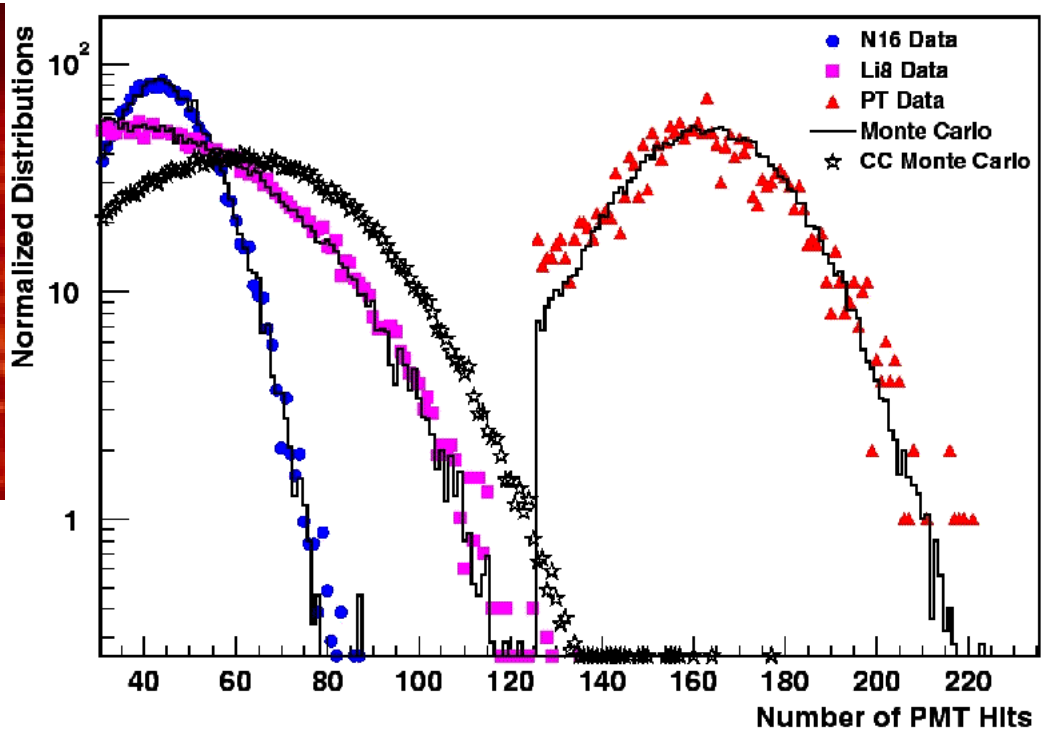
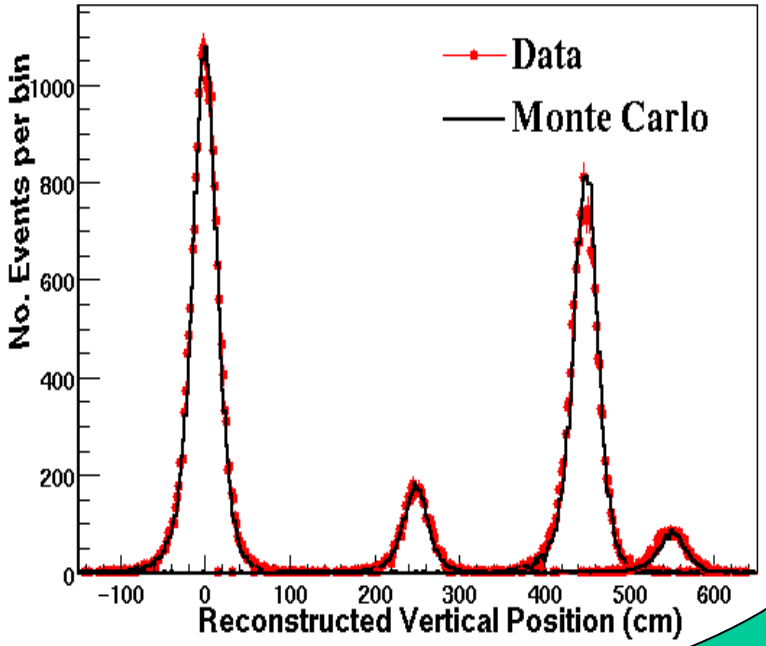
Calibrations:









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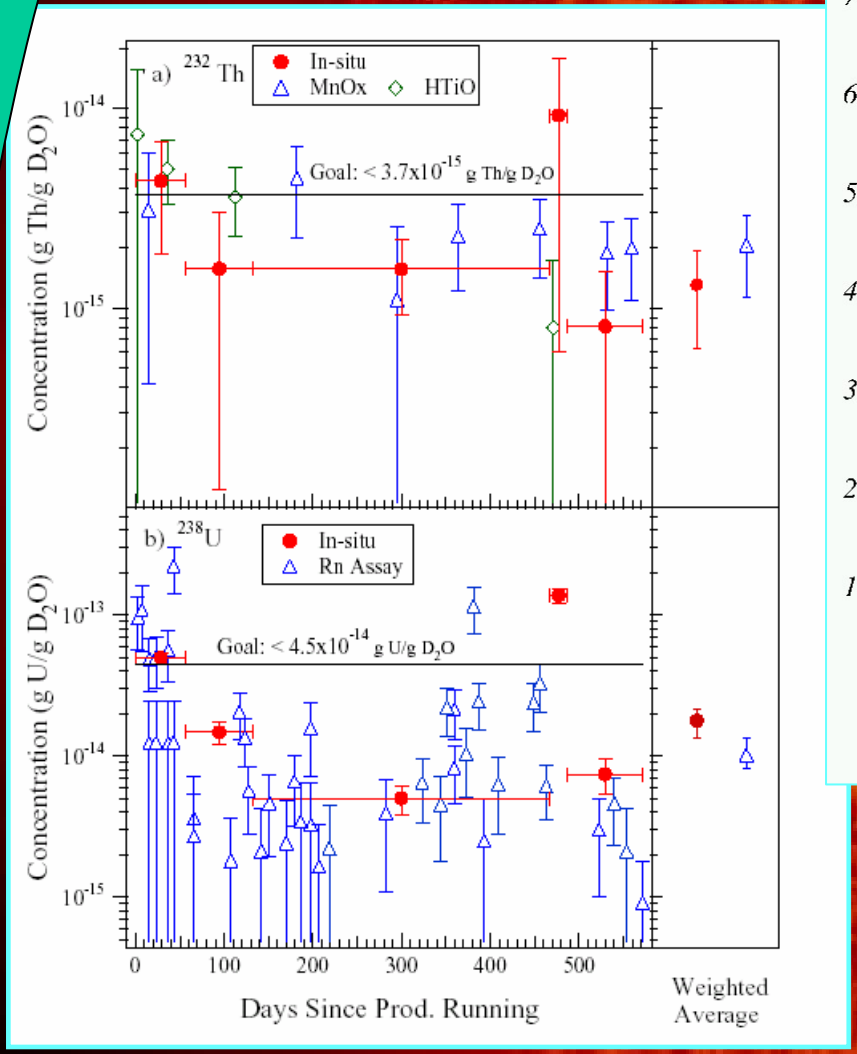
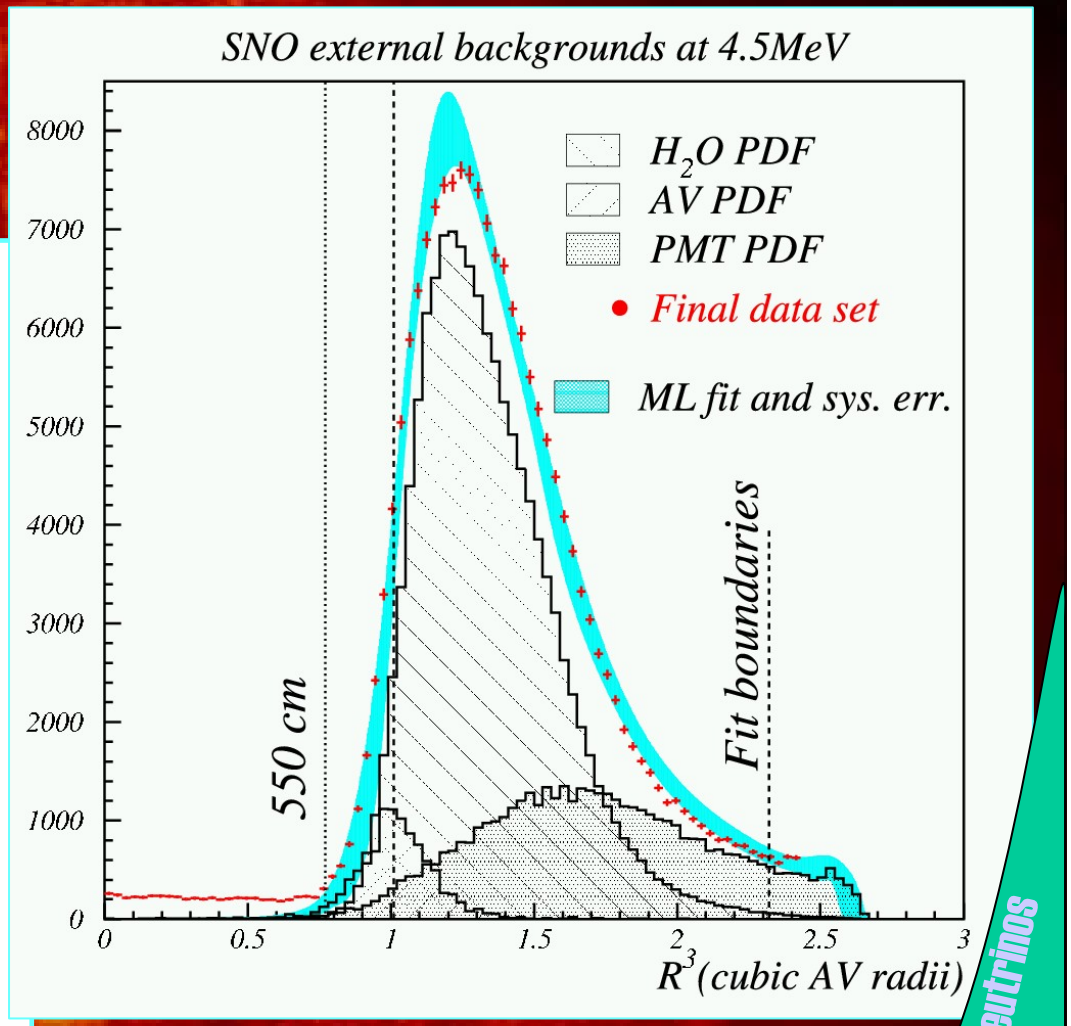
SNO Backgrounds

Internal





External

Neutrinos

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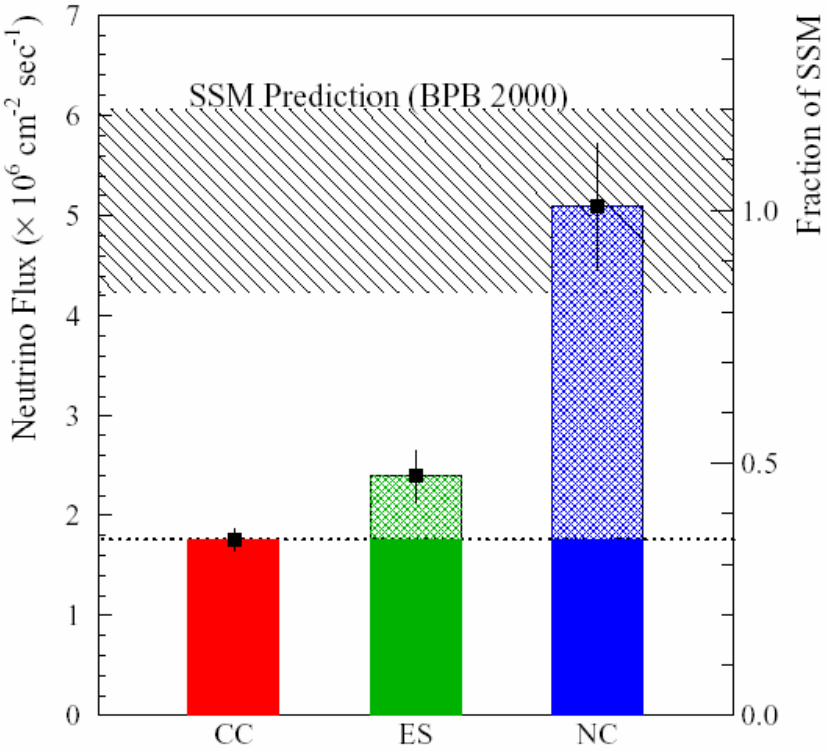
Measured SNO Fluxes

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!

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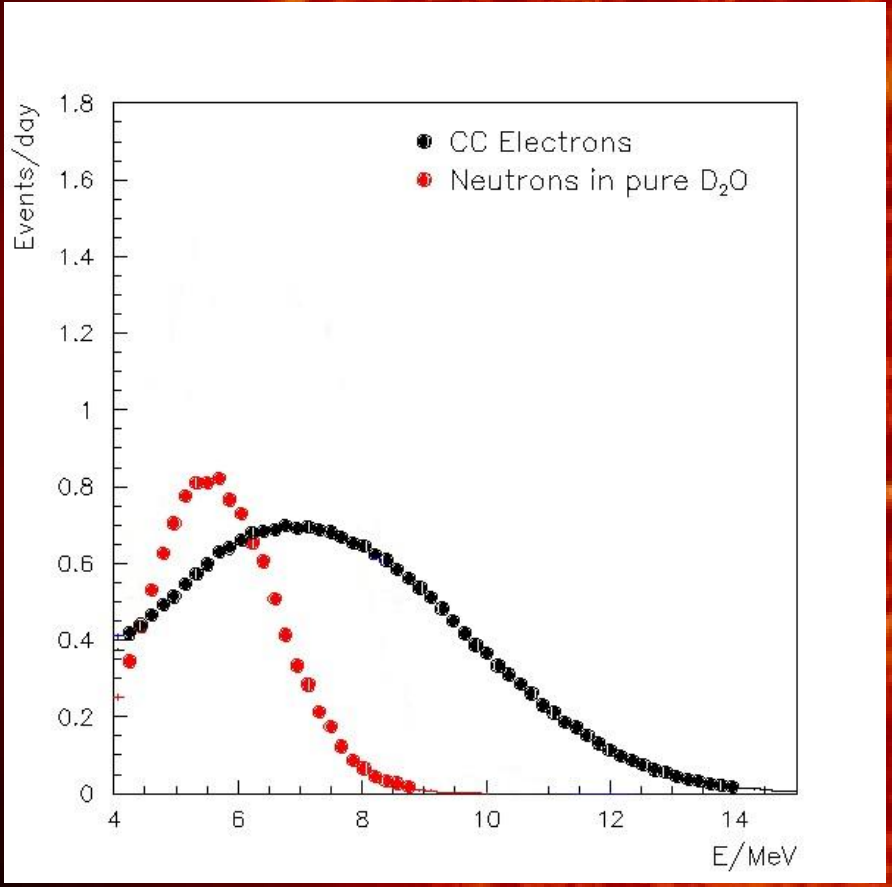
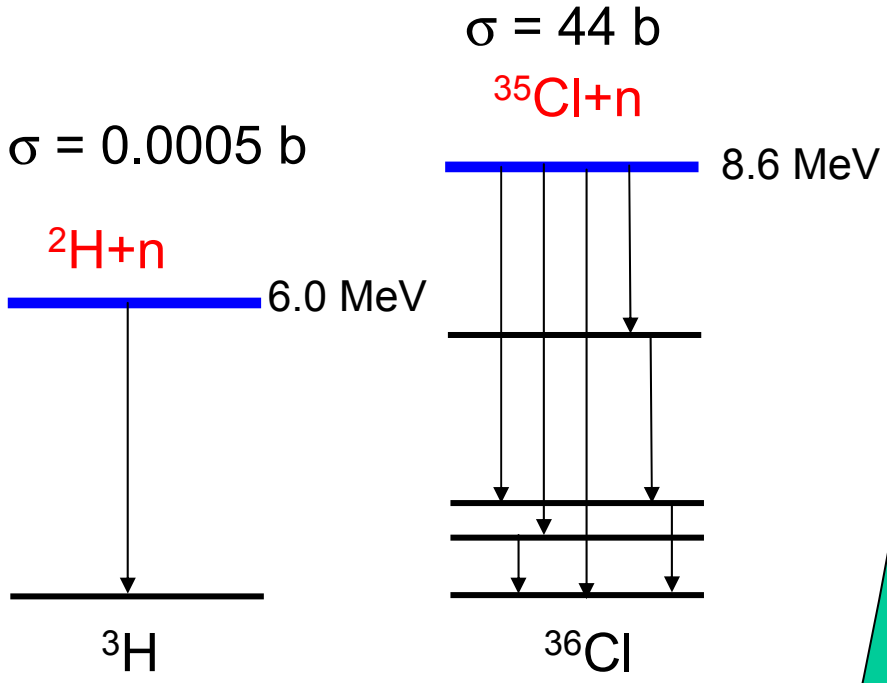
2 tons of NaCl added to D_2O on June 1, 2001





Neutrinos

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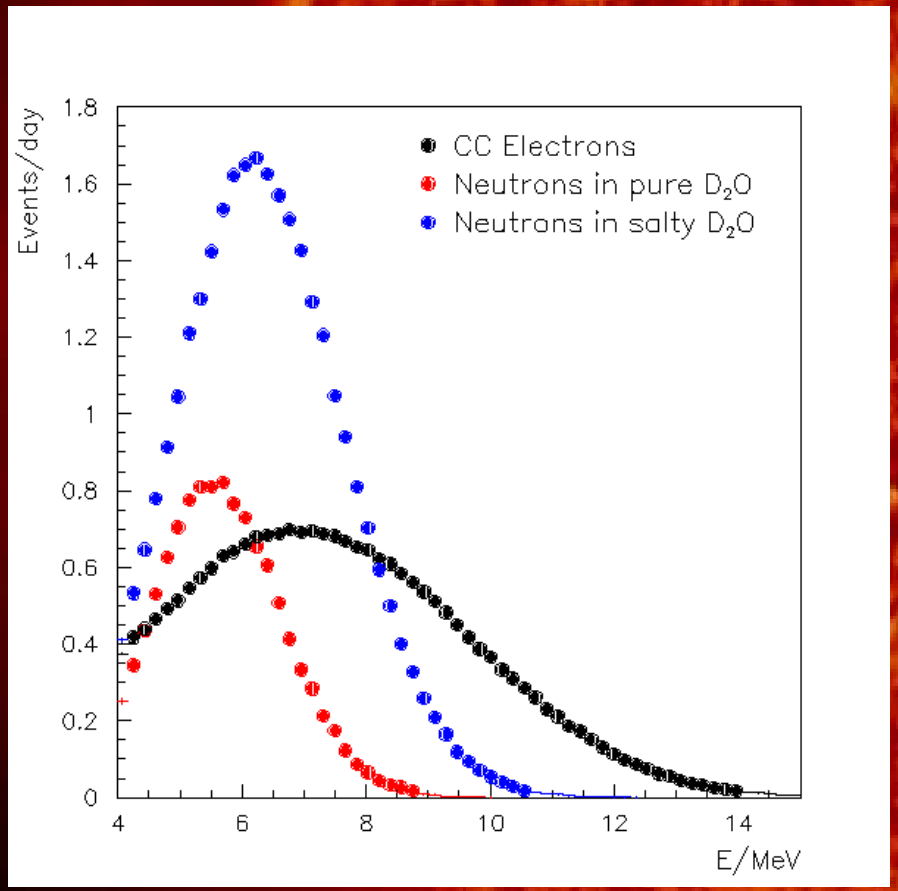

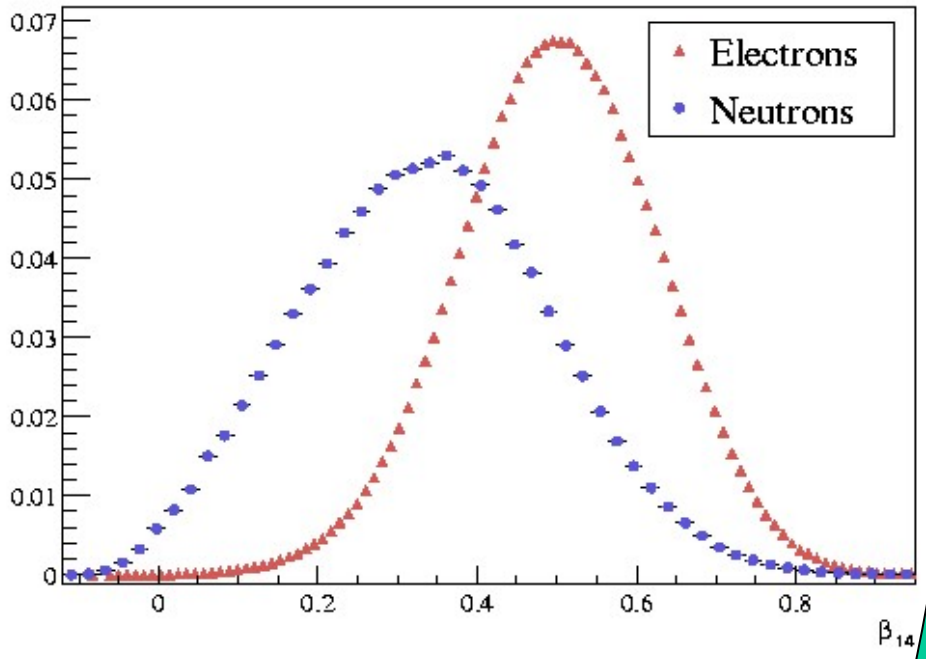

Figure 21: β_{14} for NC and electron MC.

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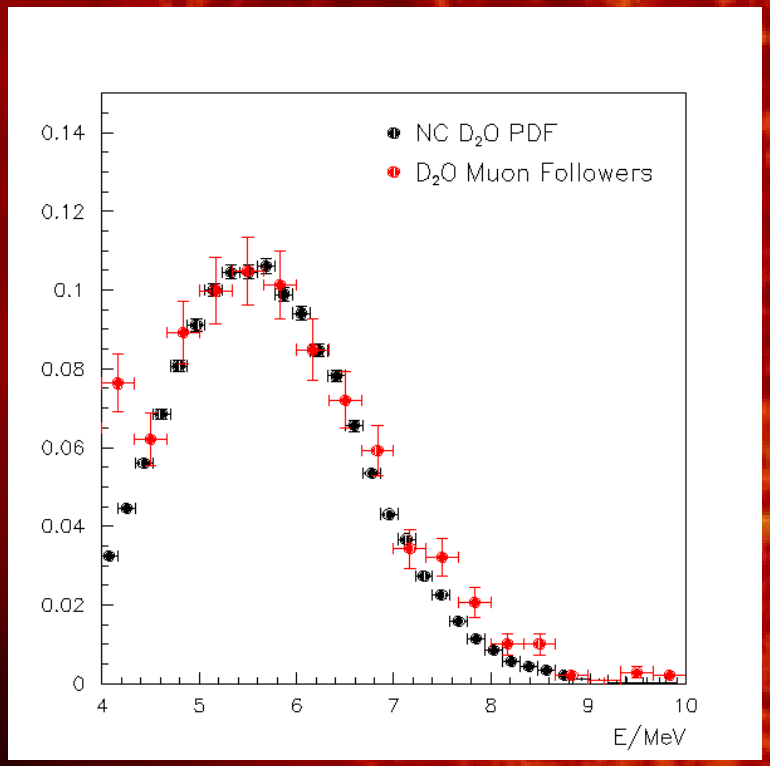
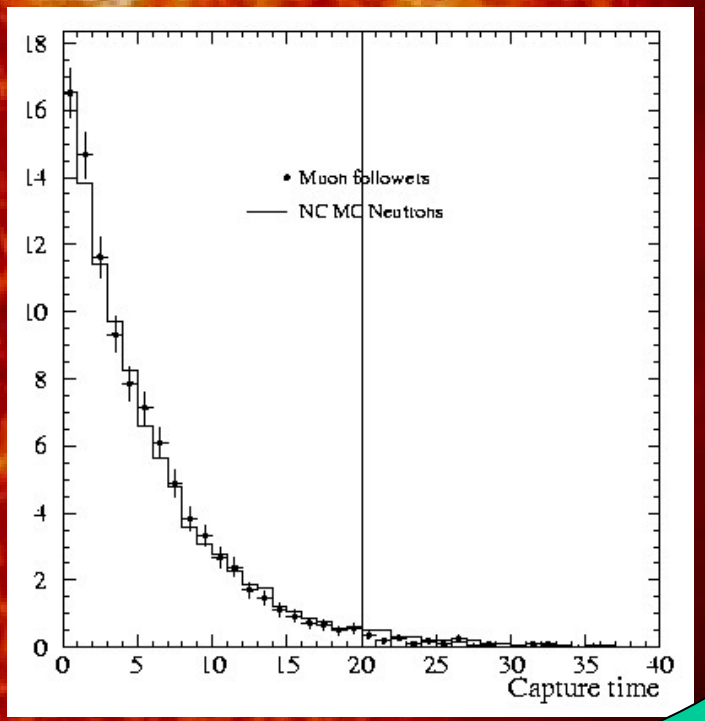
Blind Analysis Technique Used

- Unknown fraction of muon followers included in data set for analysis
- NC cross-section "spoiled" in Monte Carlo
- Data pre-scaled by unknown 80±10%





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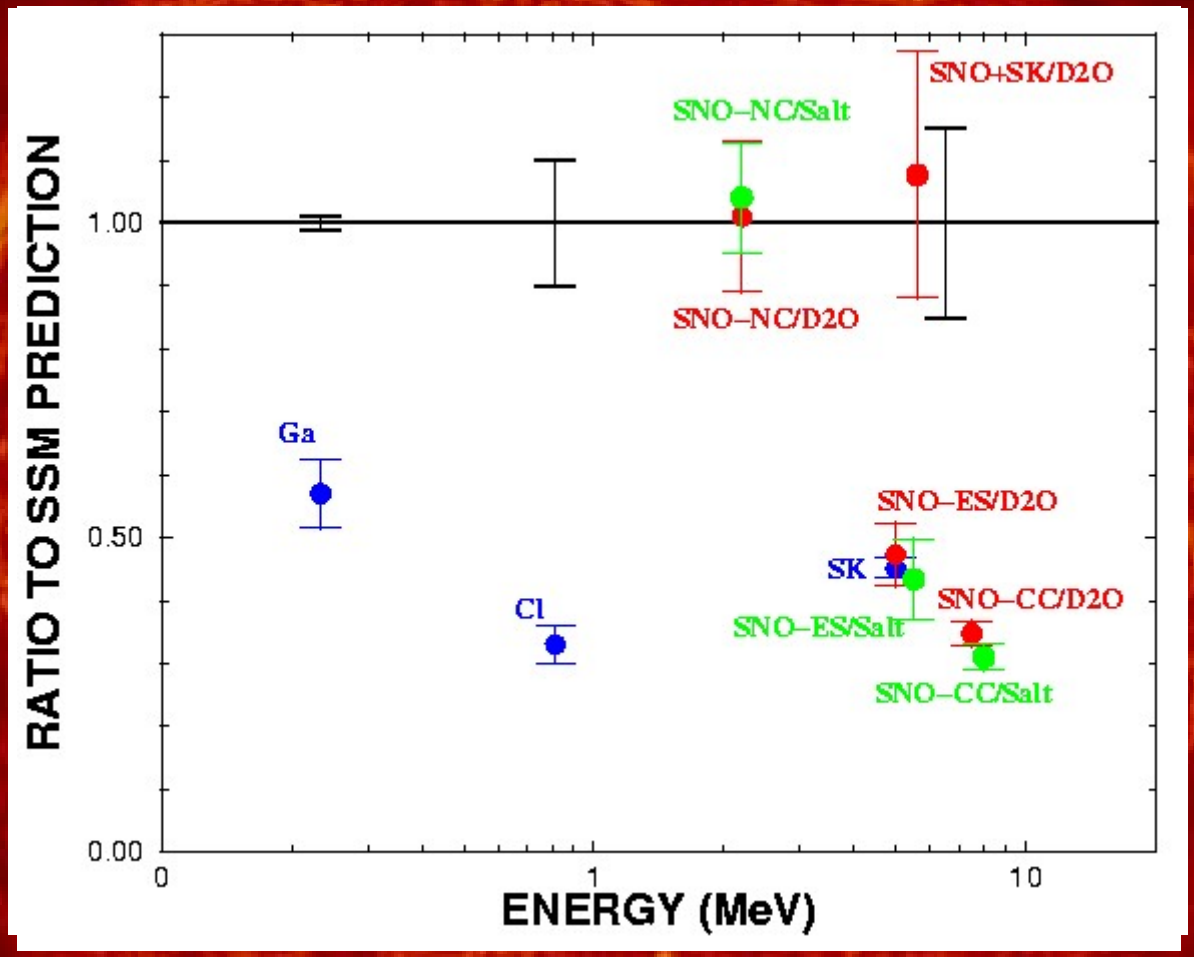
Comparison of pure D_2O and Salt results



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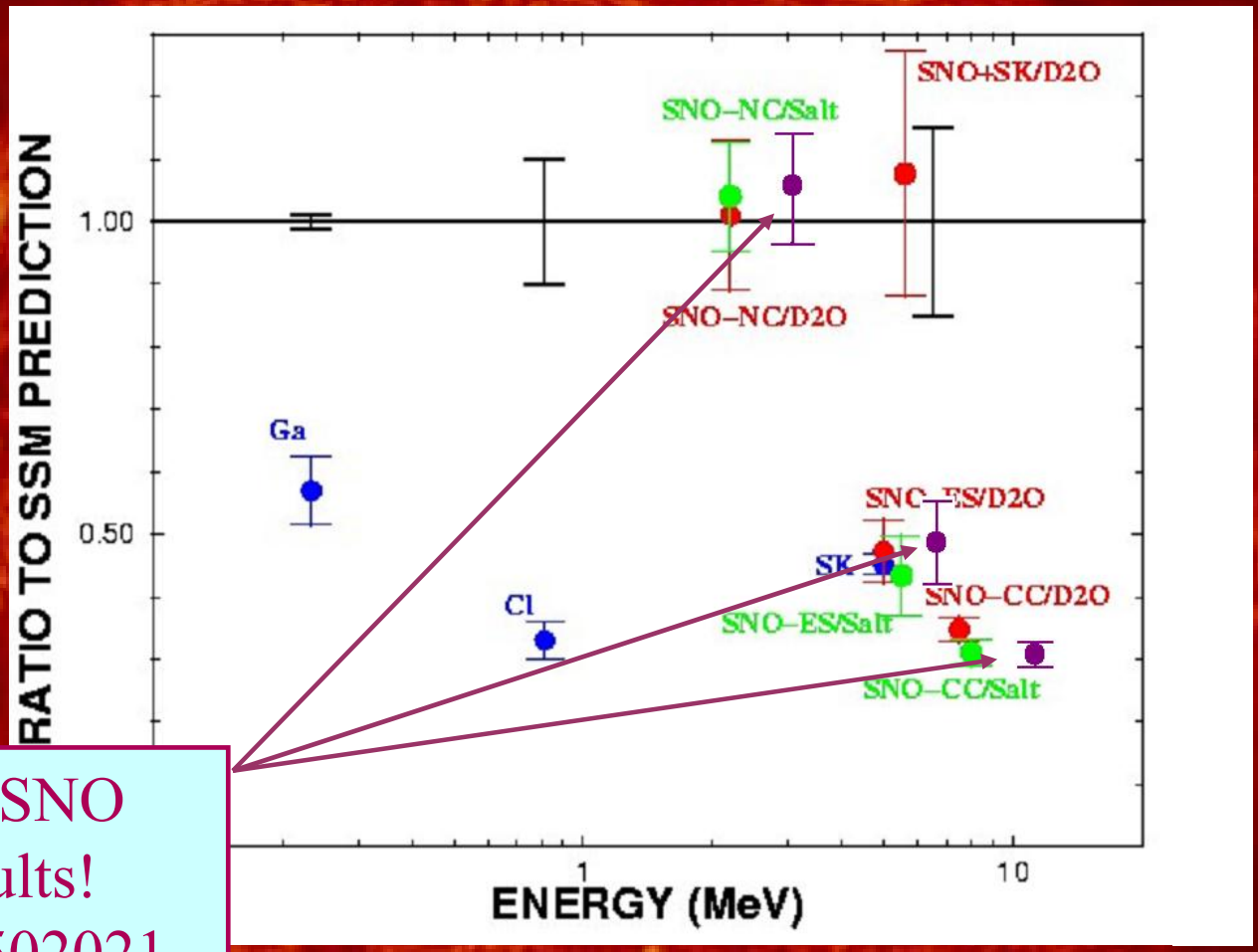

All new SNO salt results!
nucl-ex/0502021

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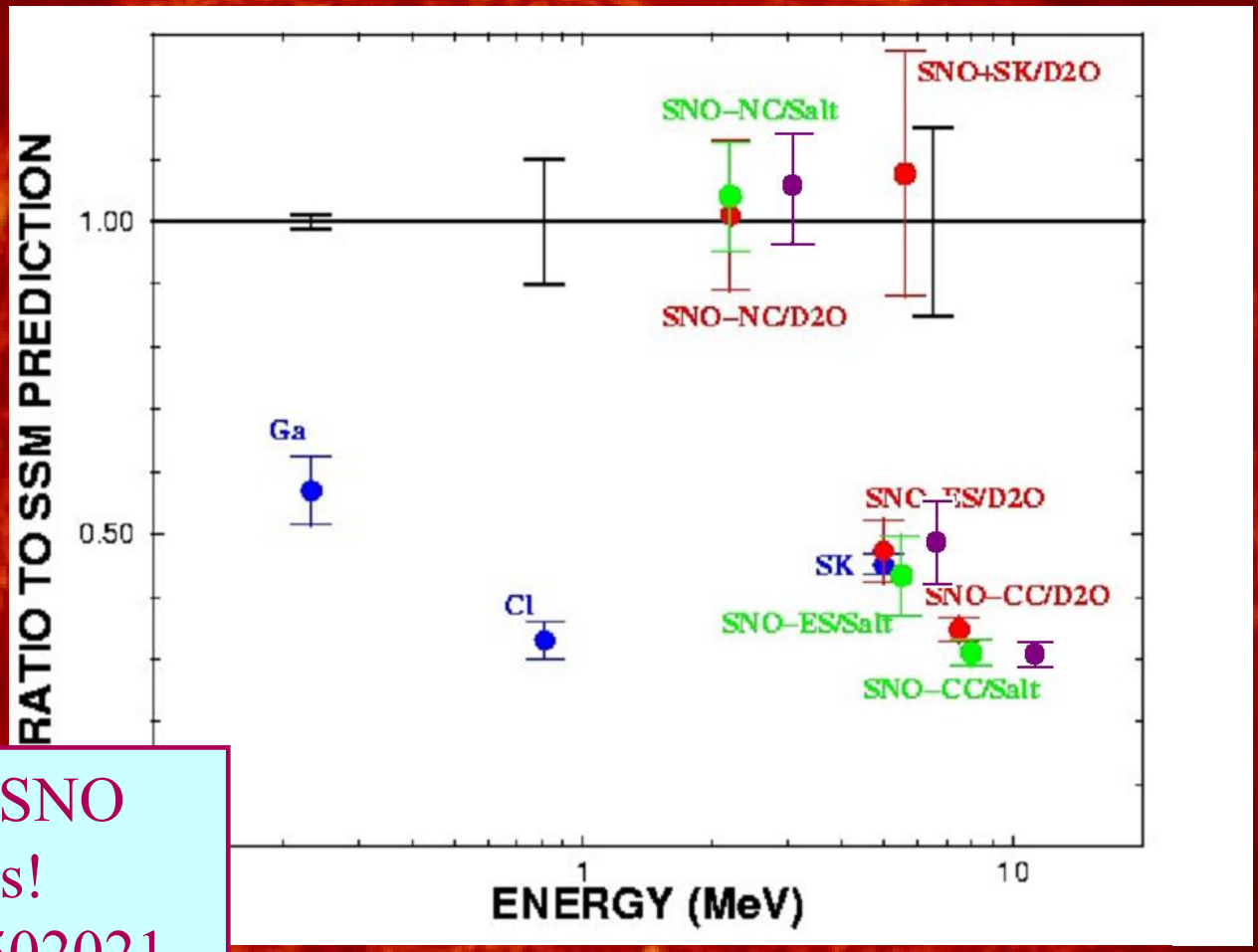
Comparison of pure D_2O and Salt results



All new SNO results!
nucl-ex/0502021

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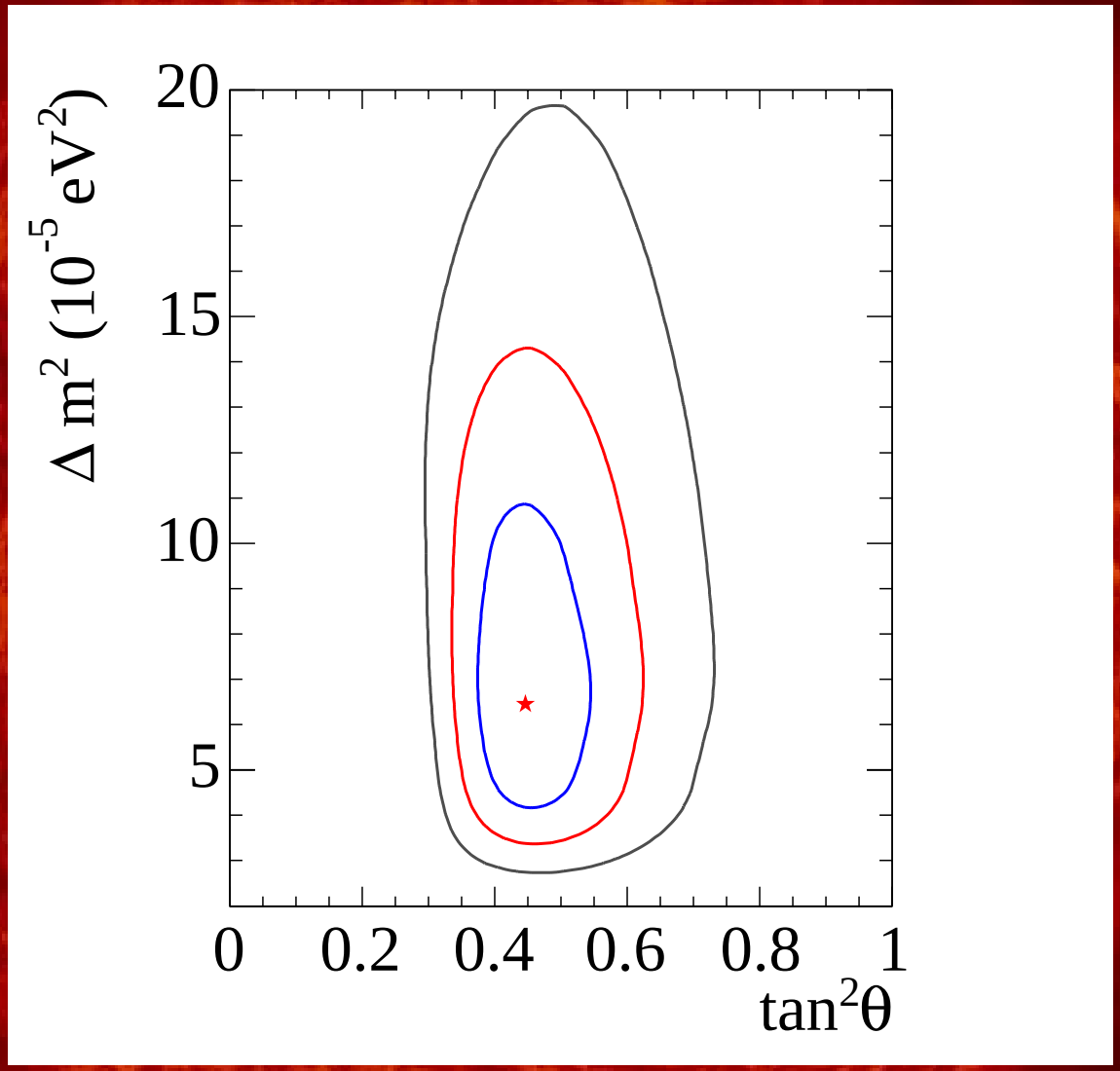
June 29, 2005

Solar...

Global Solar Analysis with 391-day salt data



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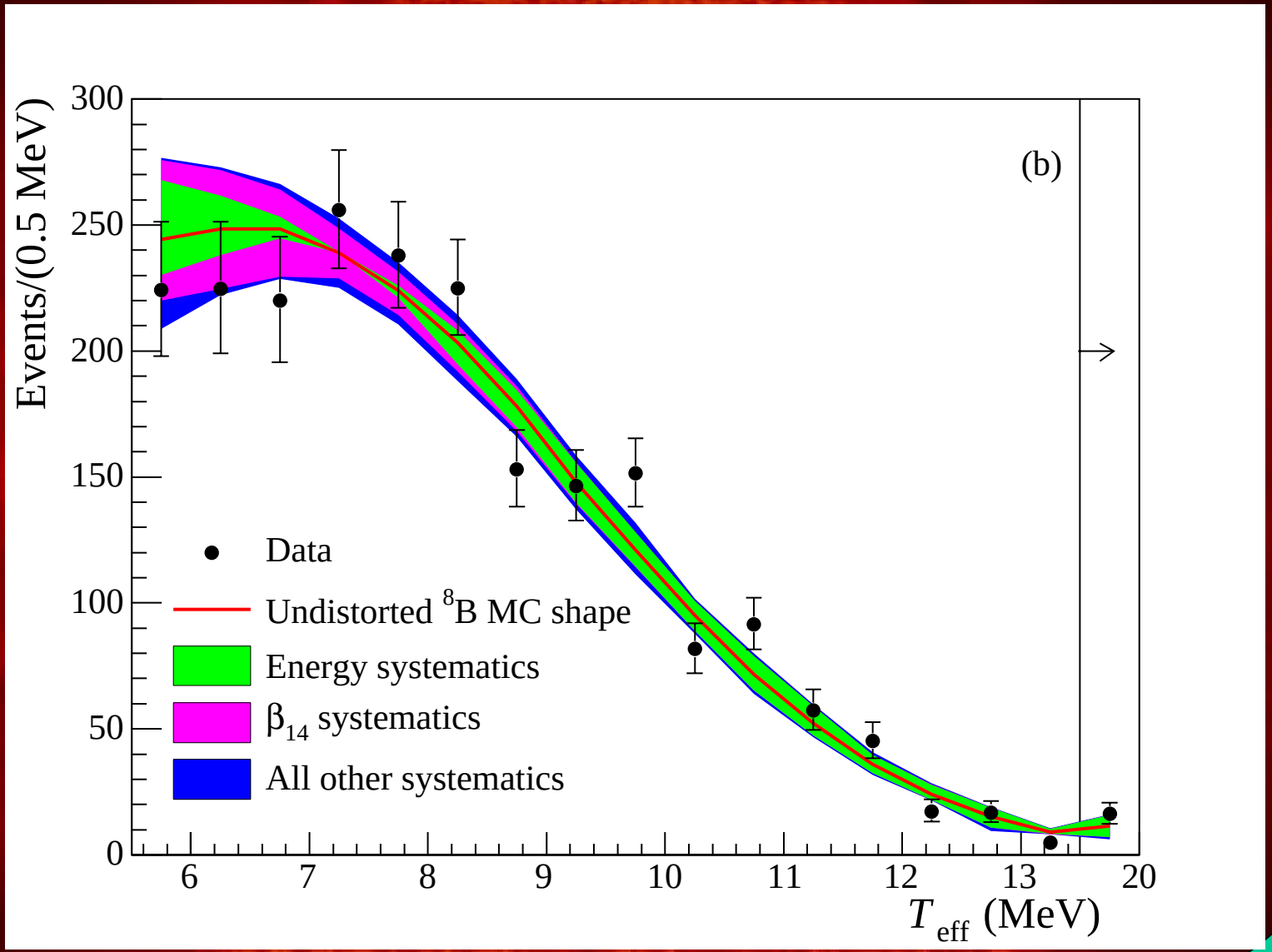
Systematic Error Bands



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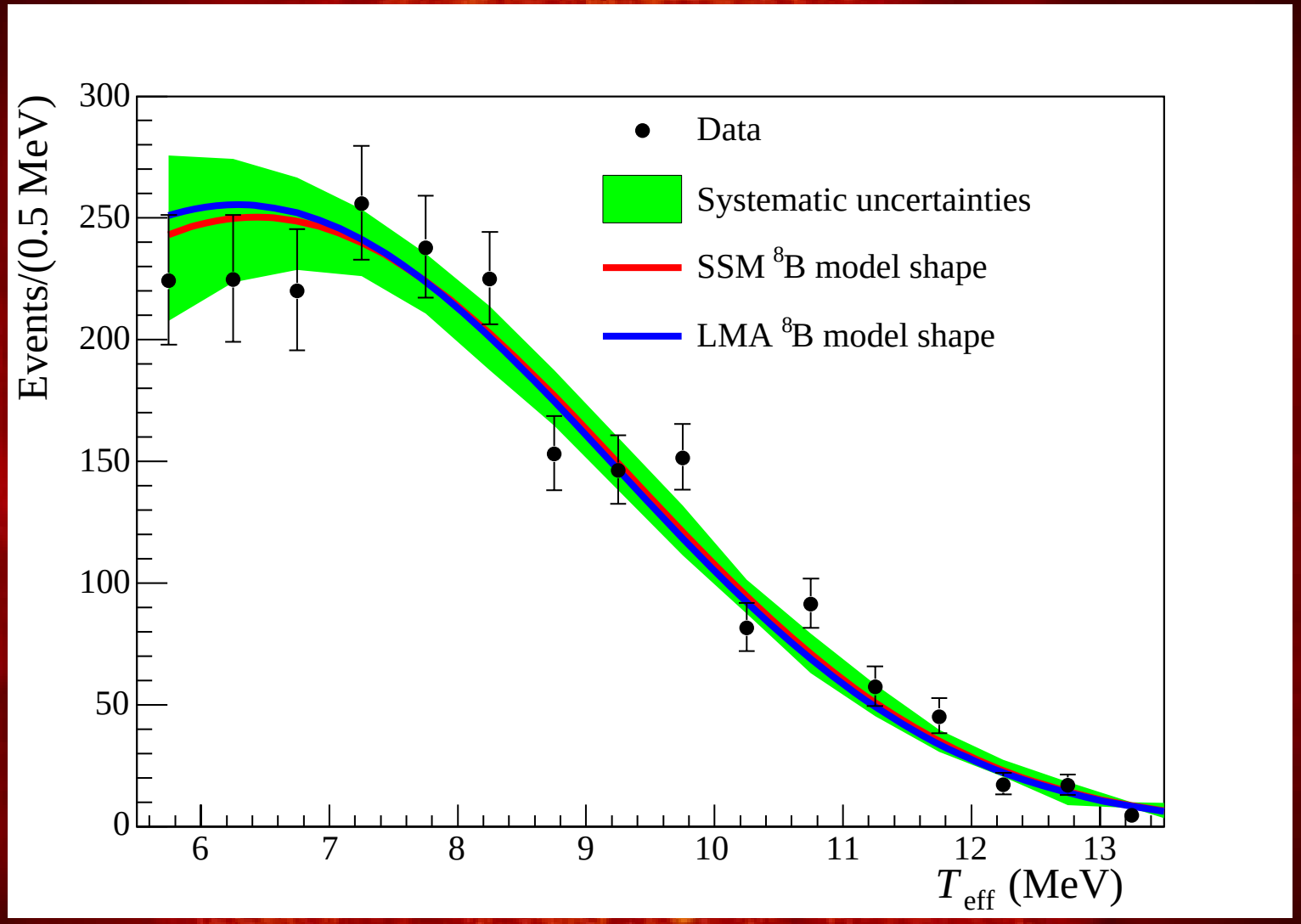
LMA Shape Distortion



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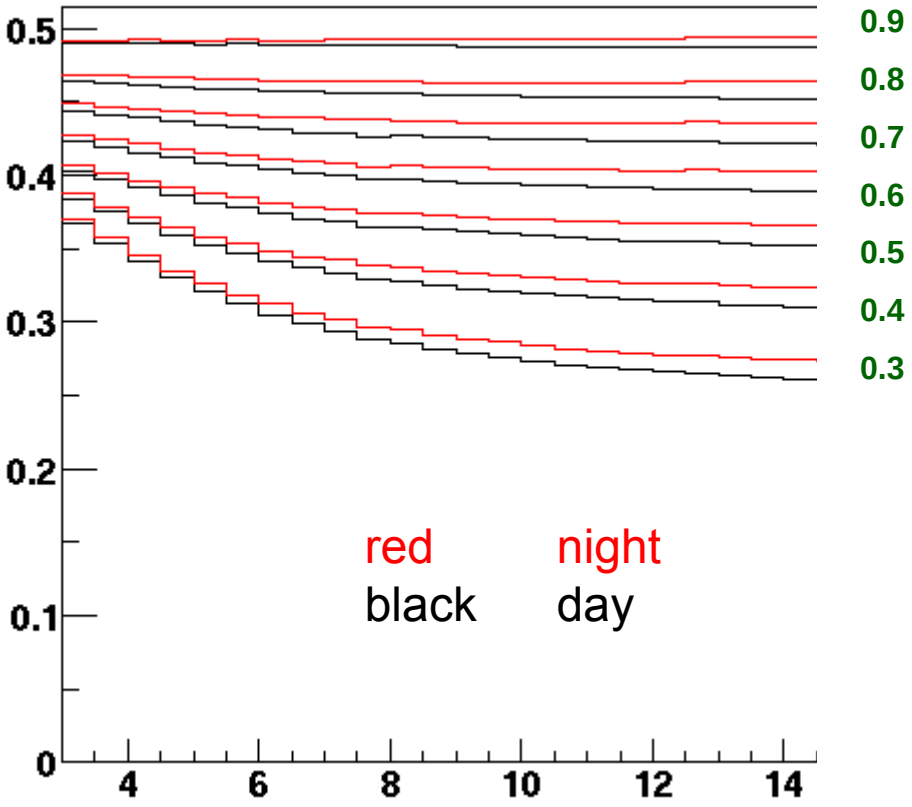
Expected Day/Night Shape Distortion

CC Spectral Shape



$\tan^2\theta$

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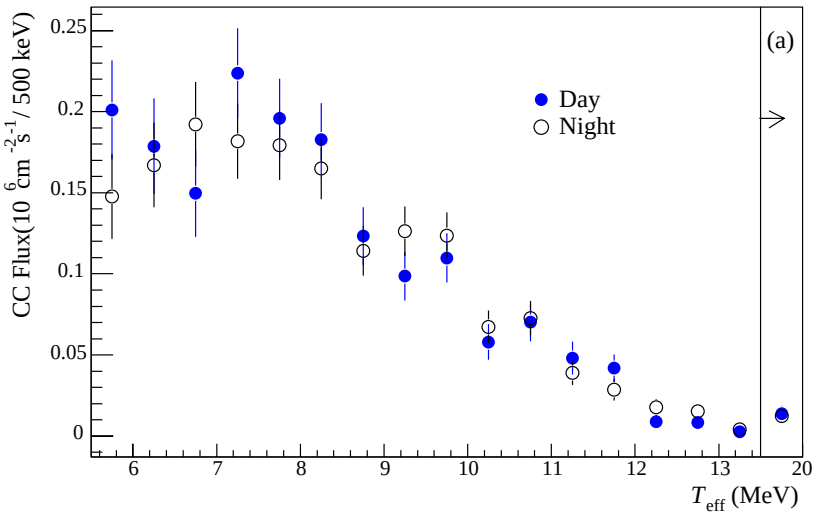
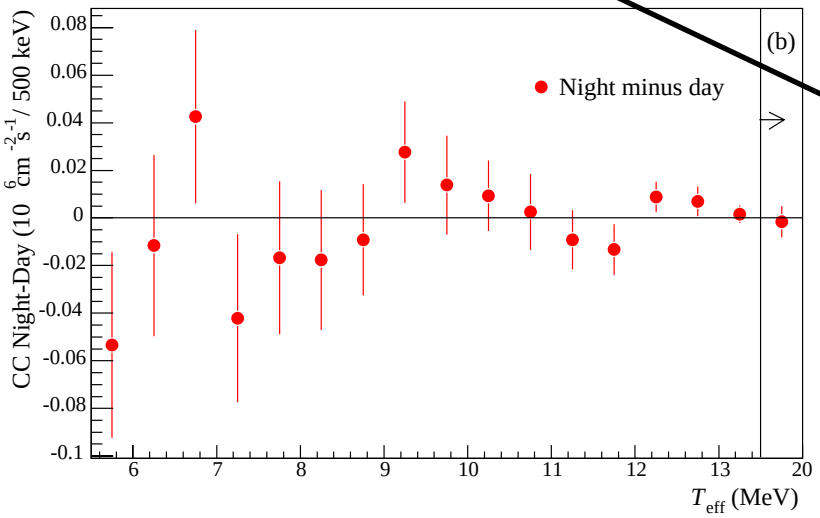
Imperial College/RAL

IoP ½ Day
June 29, 2005

New Salt Day-Night Analysis





- raw event rate:

	Events	Rate (day^{-1})
Day	2134	12.09 ± 0.26
Night	2588	12.04 ± 0.24

- day and night fluxes:

Signal	Day flux	Night flux	A
CC	1.73 ± 0.09 ± 0.10	1.64 ± 0.08 ± 0.09	−0.056 ± 0.074 ± 0.053
NC	4.81 ± 0.31 ± 0.39	5.02 ± 0.29 ± 0.41	0.042 ± 0.086 ± 0.072
ES	2.17 ± 0.34 ± 0.14	2.52 ± 0.32 ± 0.16	0.146 ± 0.198 ± 0.033

- $A_{NC} = 0$ applied:

Signal	Day flux	Night flux	A
CC	1.73 ± 0.09 ± 0.10	1.64 ± 0.08 ± 0.09	−0.056 ± 0.074 ± 0.053
NC	4.81 ± 0.31 ± 0.39	5.02 ± 0.29 ± 0.41	0.042 ± 0.086 ± 0.072
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above in units 10^{6} cm^{-2} s^{-1}

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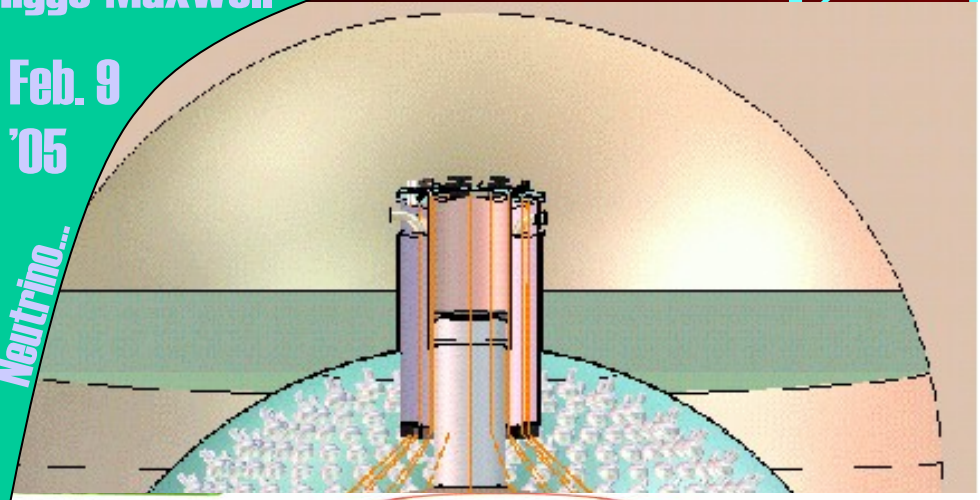
Higgs-Maxwell

Feb. 9 '05

Neutrino...

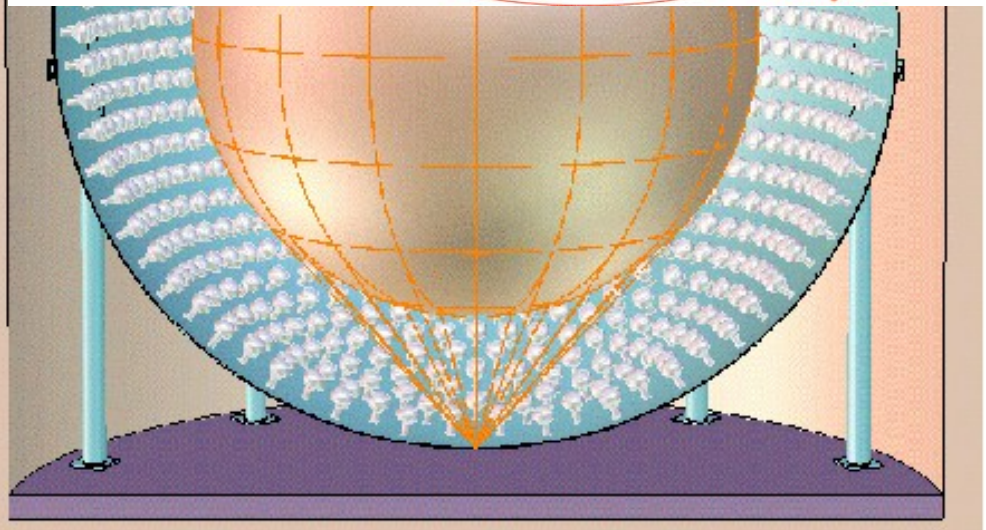


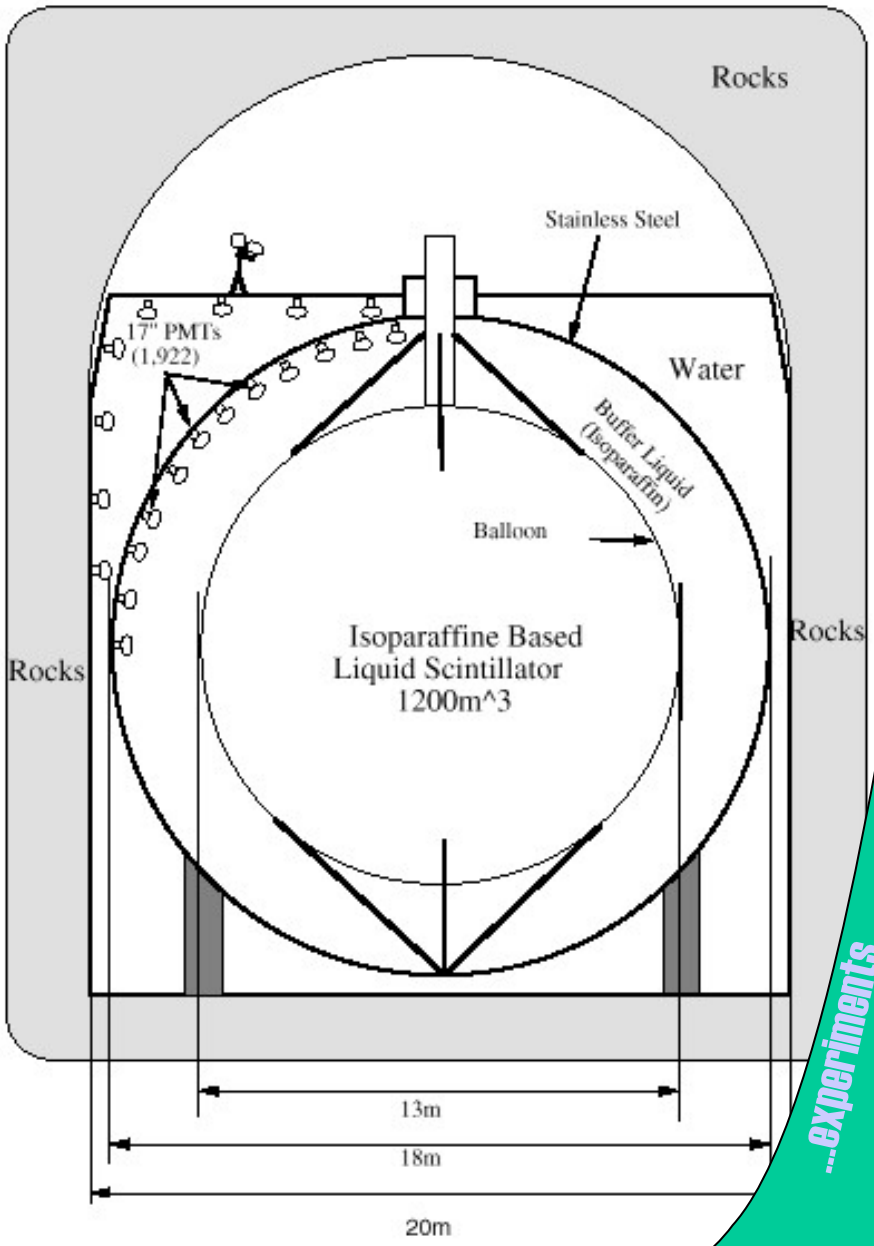
$\bar{\nu}_e\ p \rightarrow e^+ n$ (E_ν >1.8MeV)

$e^+e^- \rightarrow 2\gamma$ (0.51MeV) "Prompt" (=E_ν −0.77MeV)

180μs

$np \rightarrow d\gamma$(2.2MeV) "Delayed"

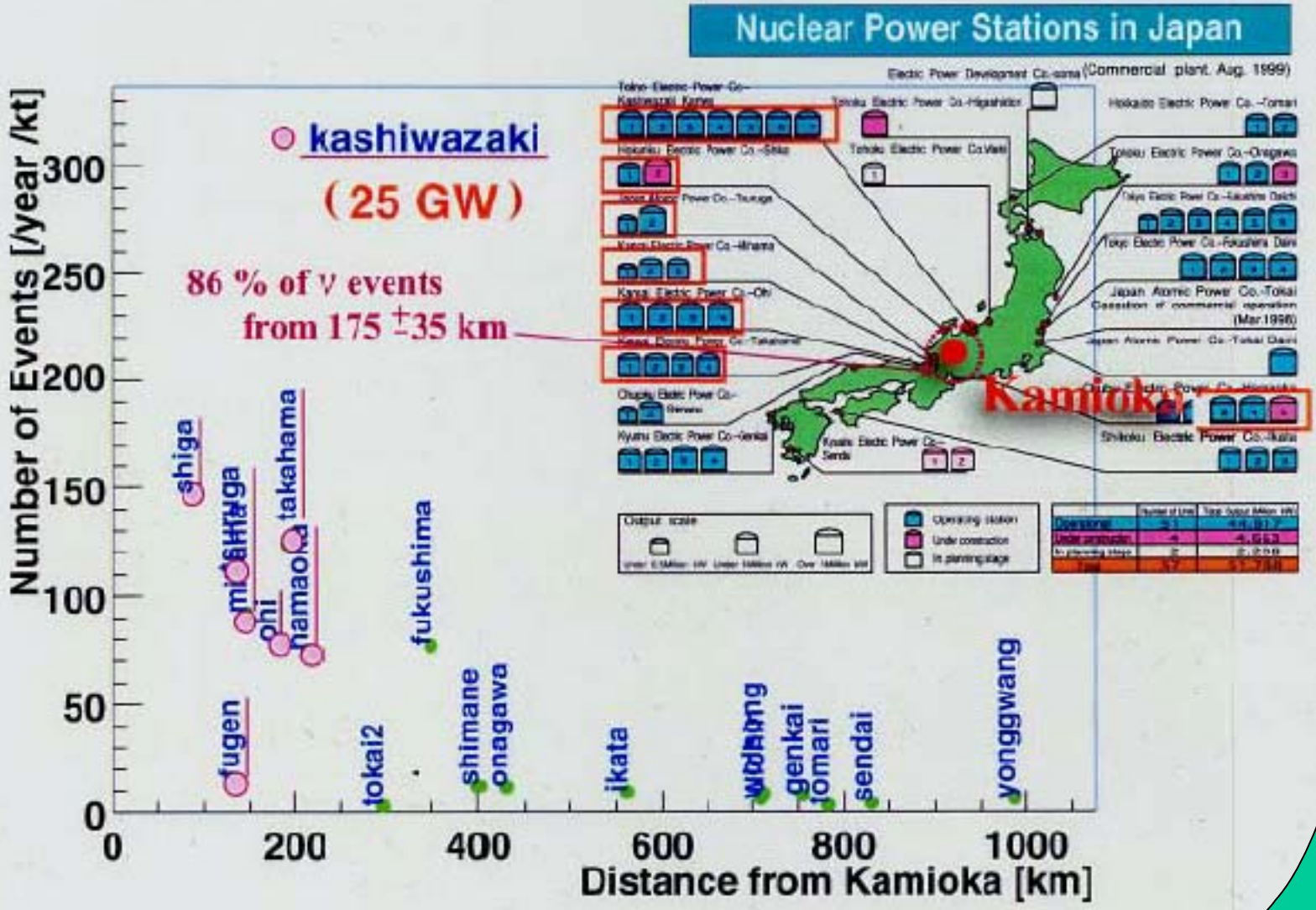




...experiments

Dave Wark
University of Sussex/RAL

Power Plant Reactors and Event Rate



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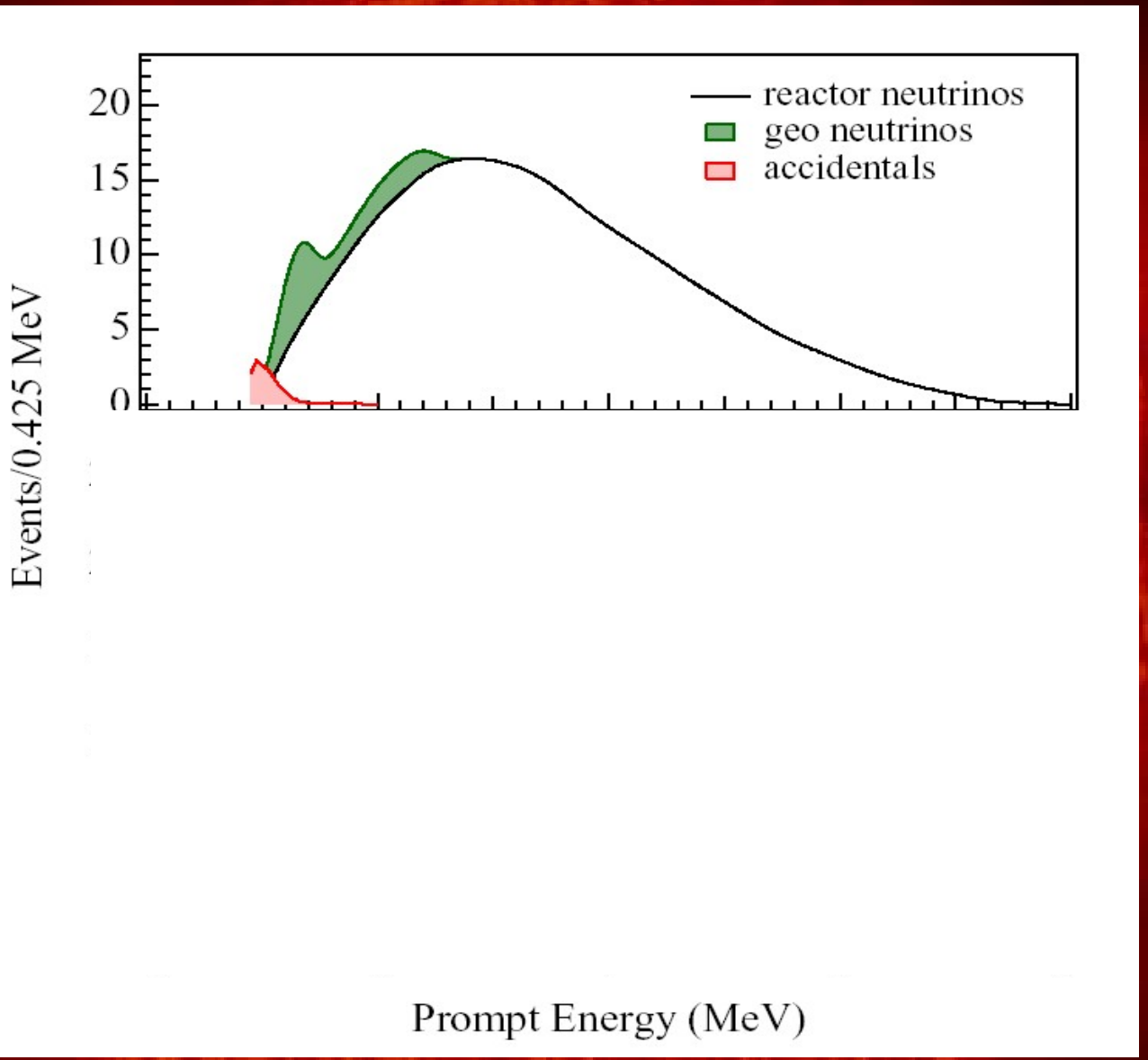
1st KamLAND Results …



K. Eguchi et al., hep-ex/0212021

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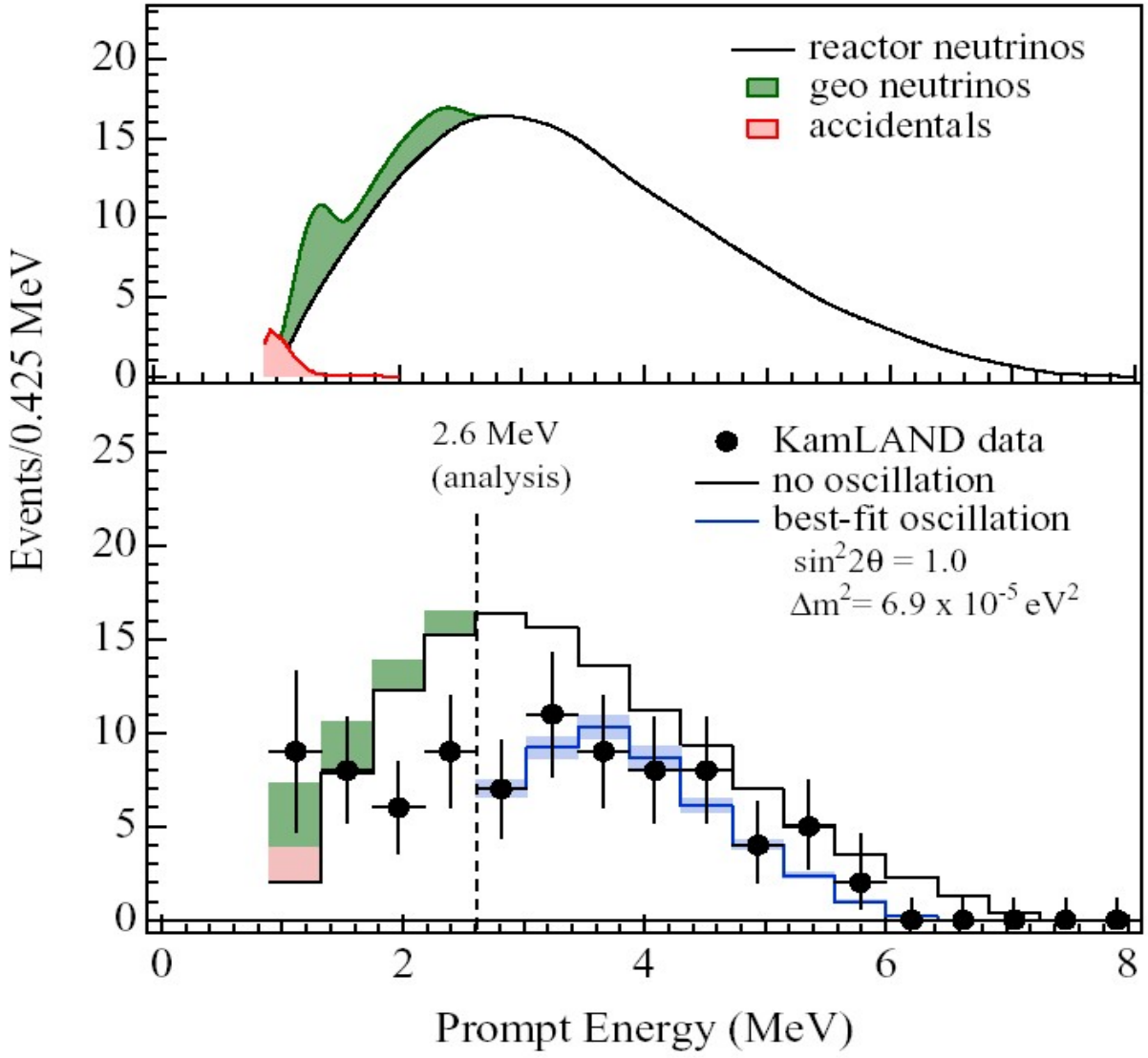
1st KamLAND Results …



K. Eguchi et al., hep-ex/0212021

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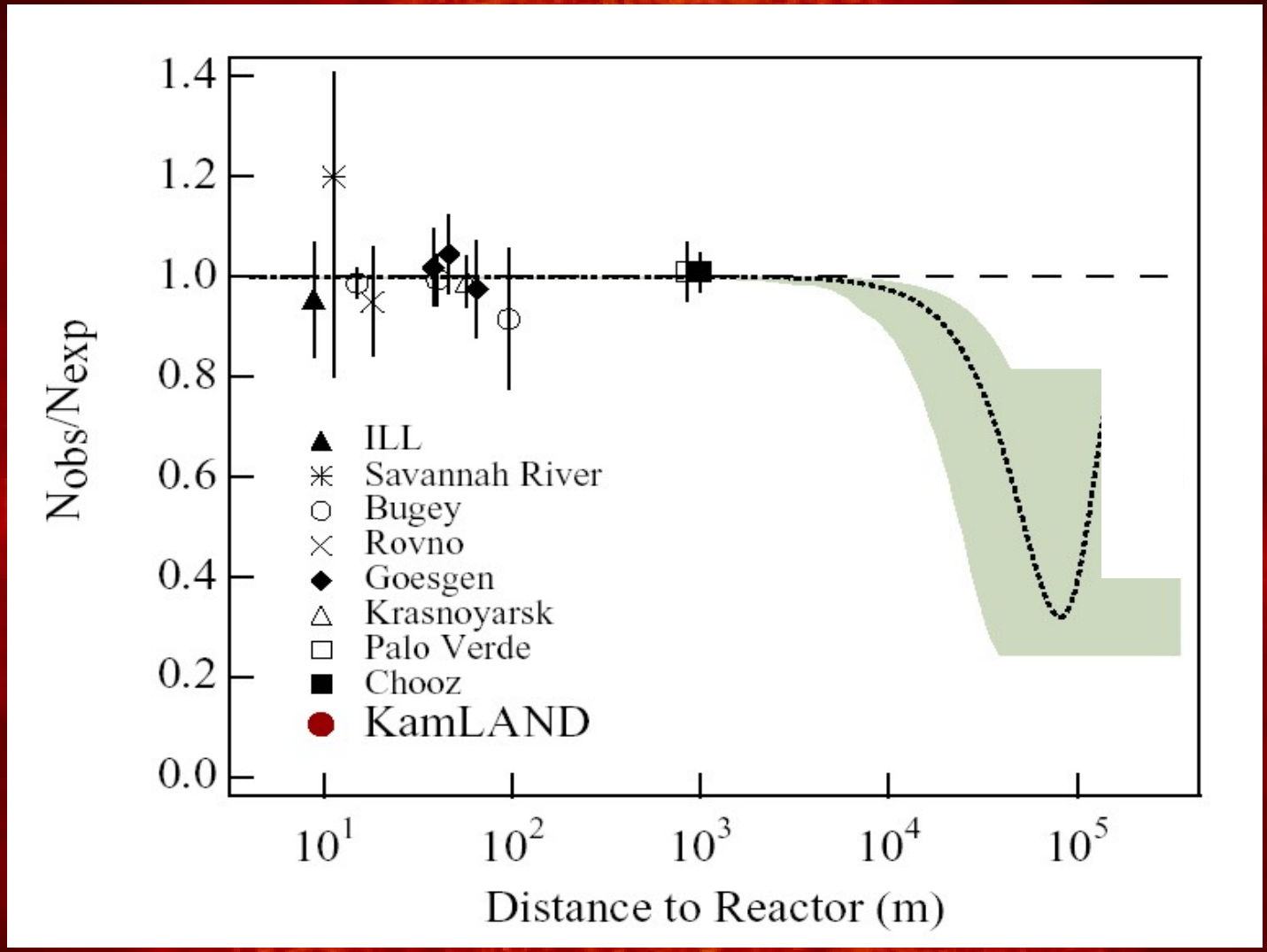
What does this mean about solar ν?



Observed/Expected = 0.611 ± 0.085(stat.) ± 0.041(syst.)

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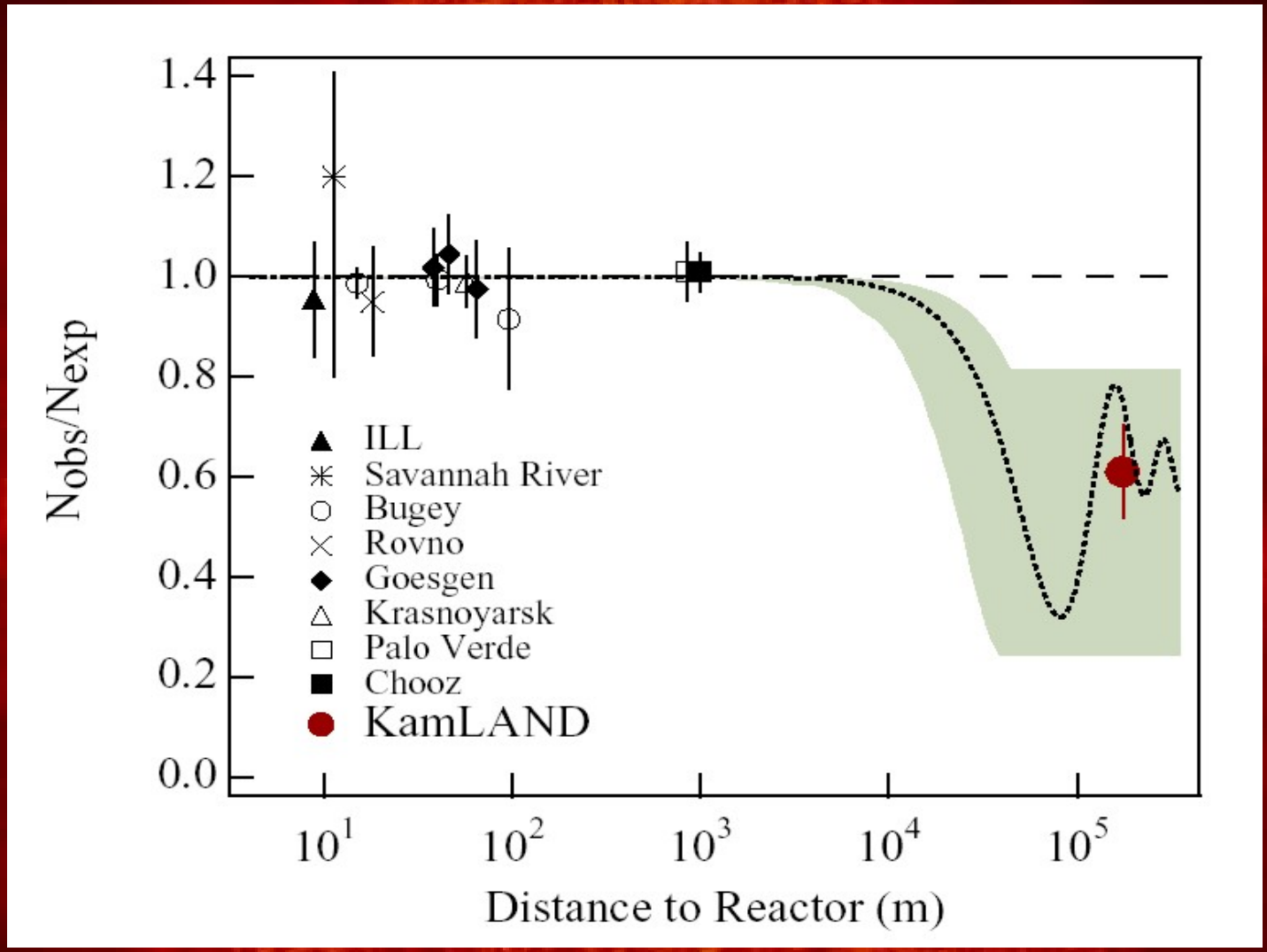
Imperial College/RAL

What does this mean about solar ν?



Observed/Expected = 0.611 ± 0.085(stat.) ± 0.041(syst.)

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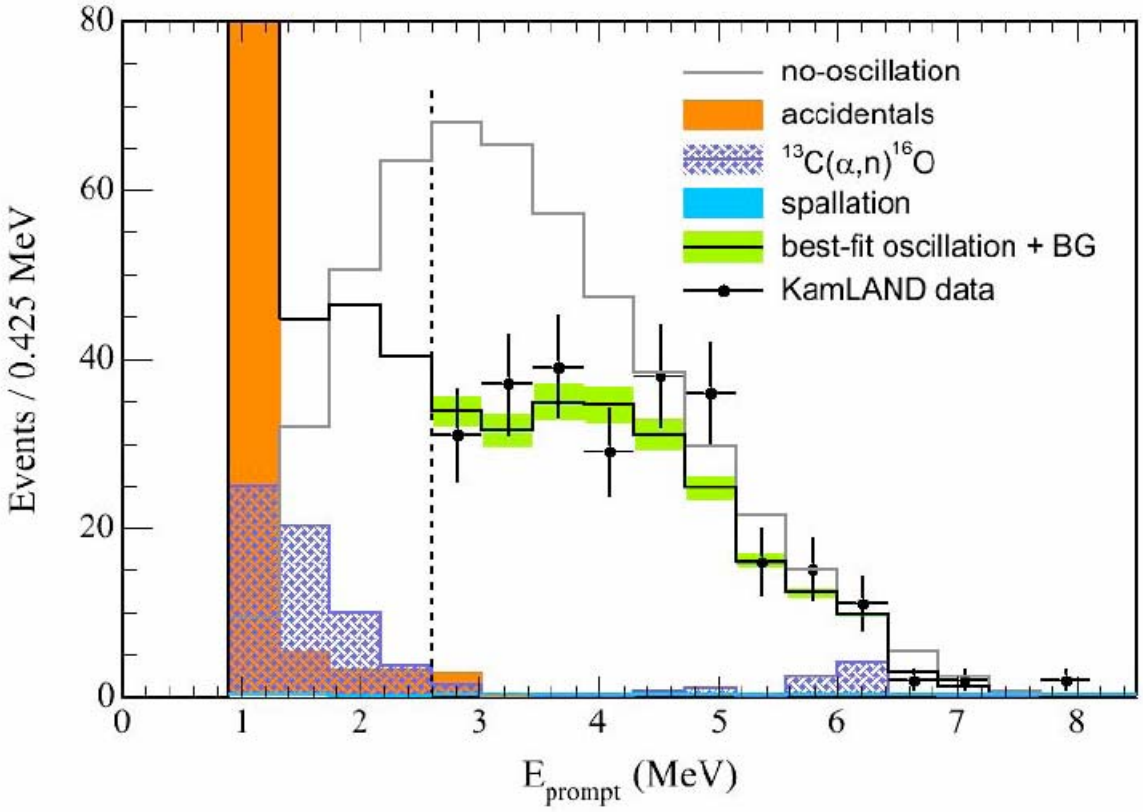
Newer KamLAND Results …



Best-fit oscillation:

$\tan^2\theta = 0.46$

$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5} eV^2$

A fit to a simple rescaled reactor spectrum is excluded at 99.6% CL

KamLAND Collab, Phys. Rev. Lett 94 081802 (2005)

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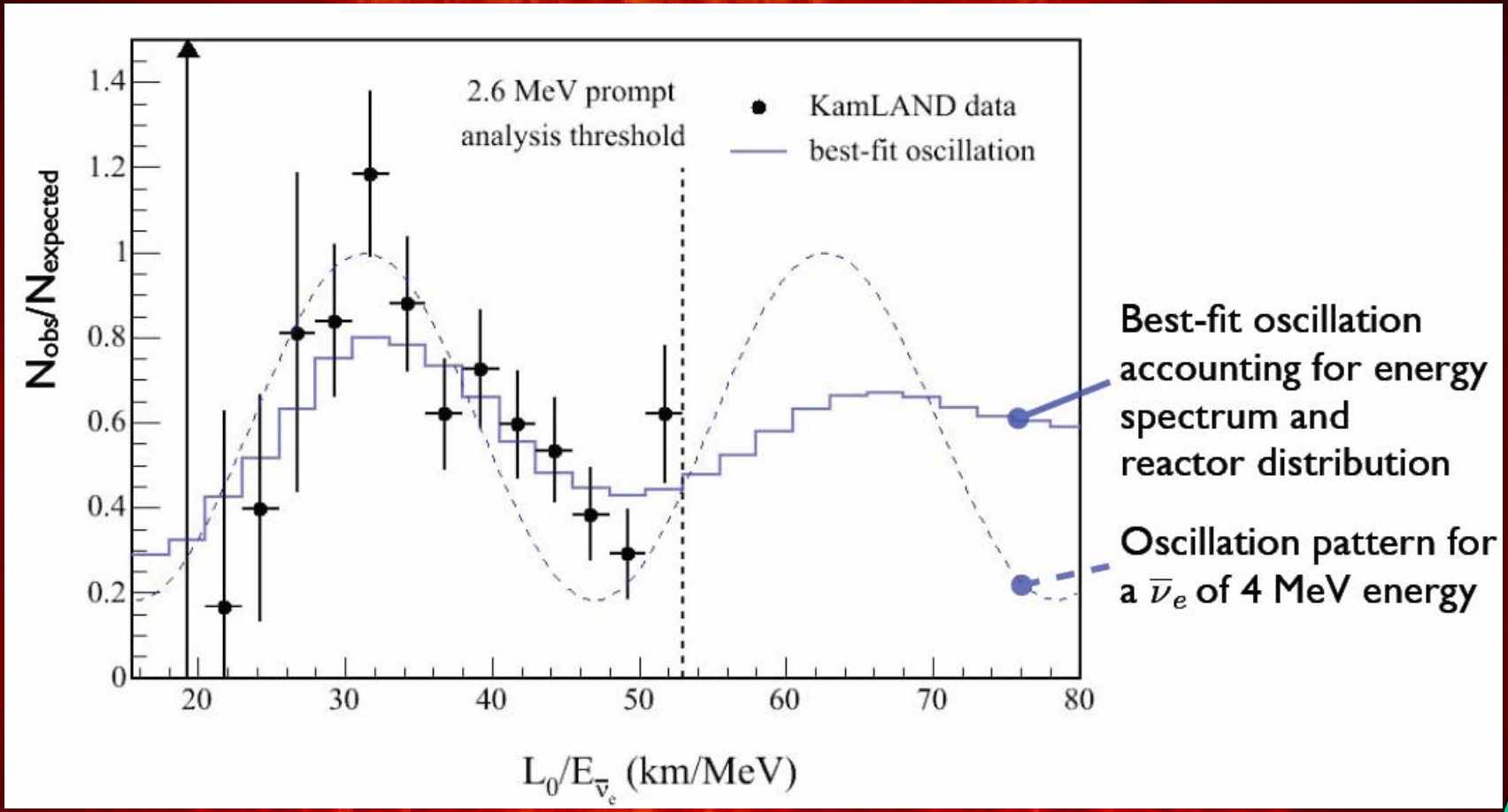
Newer KamLAND Results …



KamLAND Collab, Phys. Rev. Lett 94 081802 (2005)

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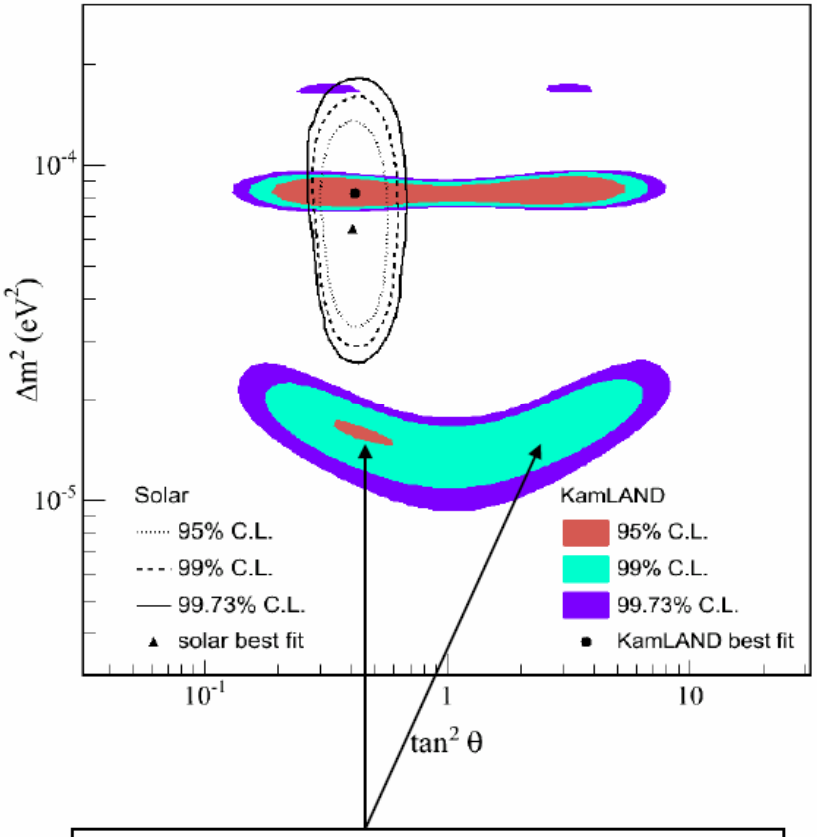
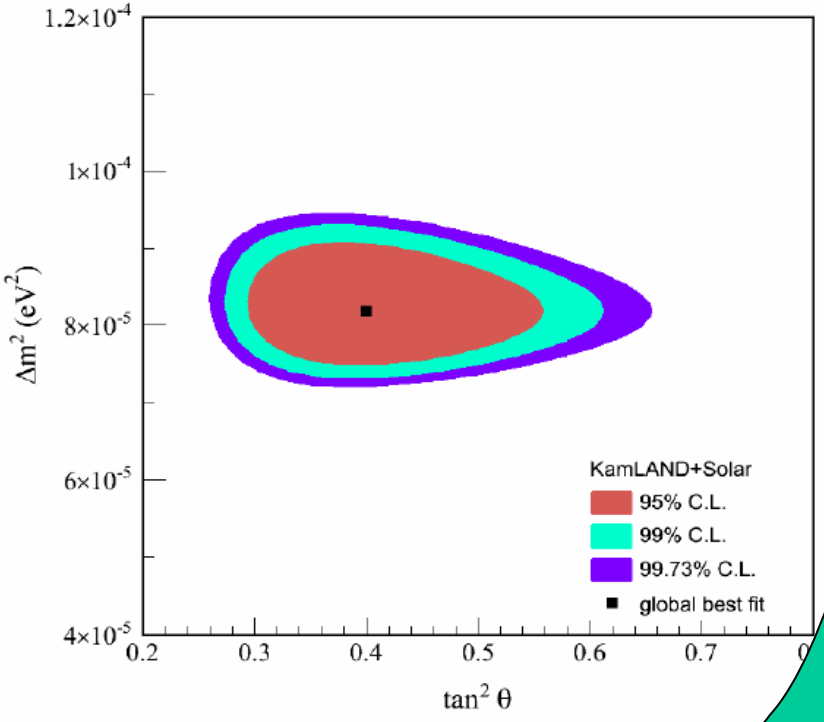
Combined solar ν - KamLAND 2-flavor analysis

$$\Delta m^2_{12} = 8.2^{+0.6}_{-0.5} \times 10^{-5}\, eV^2$$

$$\tan^2\theta_{12} = 0.40^{+0.09}_{-0.07}$$



Includes (small) matter effects



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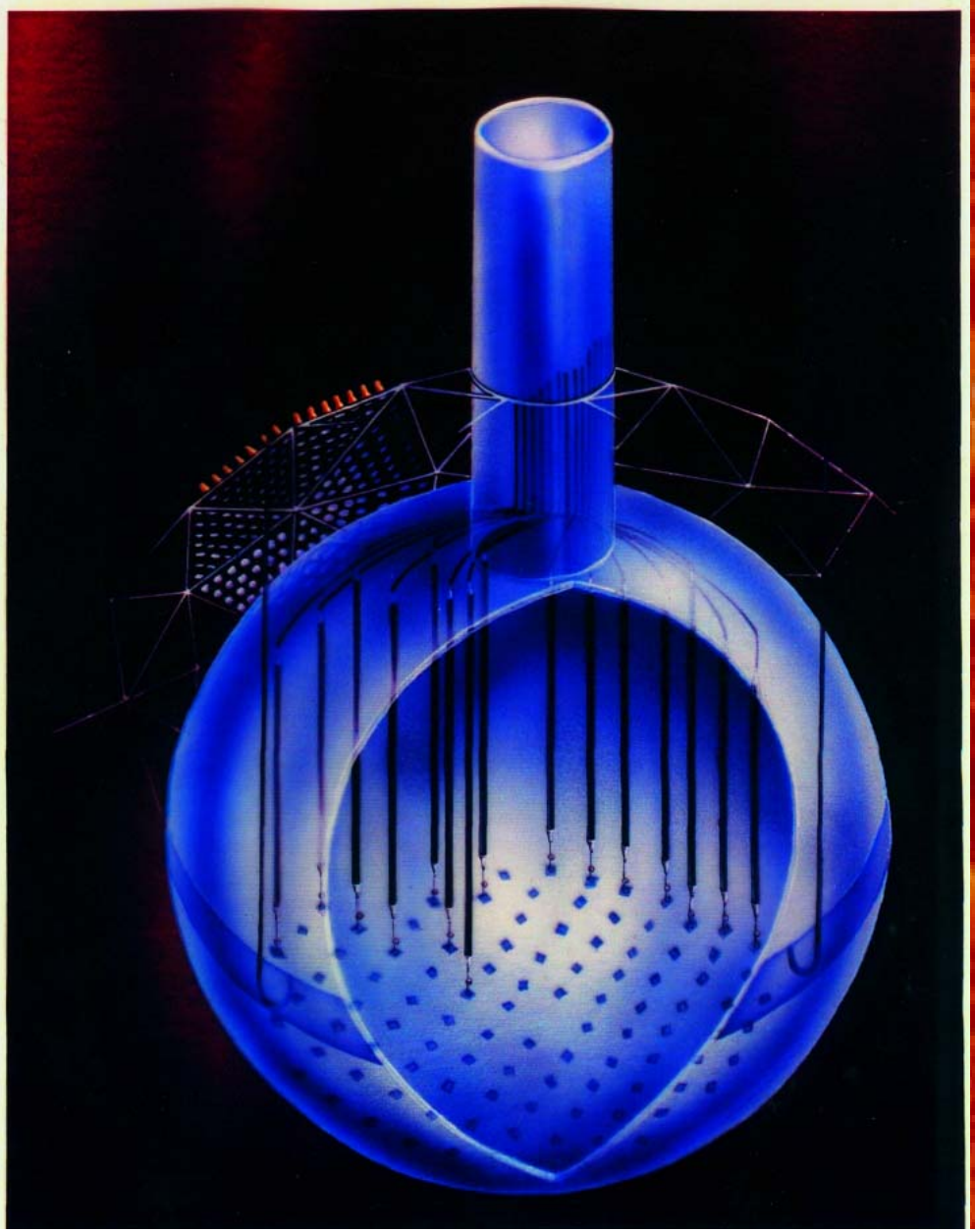
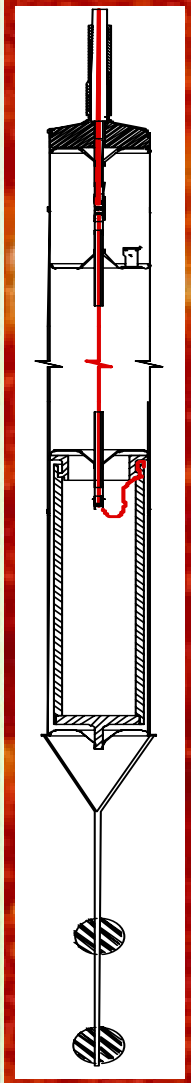
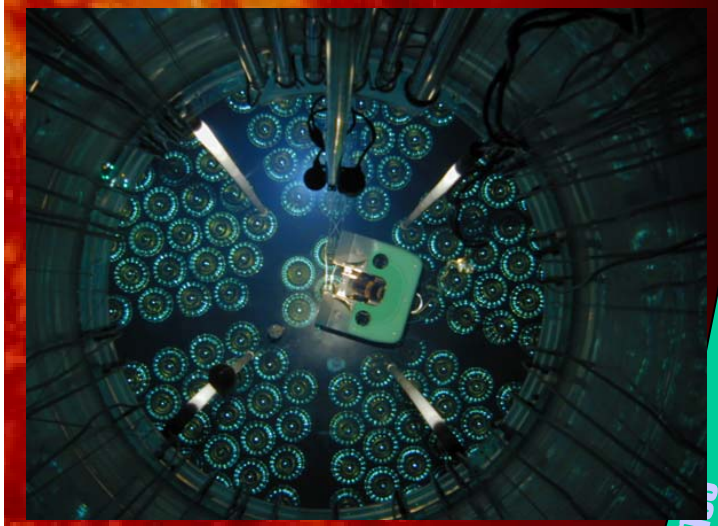
The Future - SNO



Now taking solar neutrino data…





Data taking ends next year.

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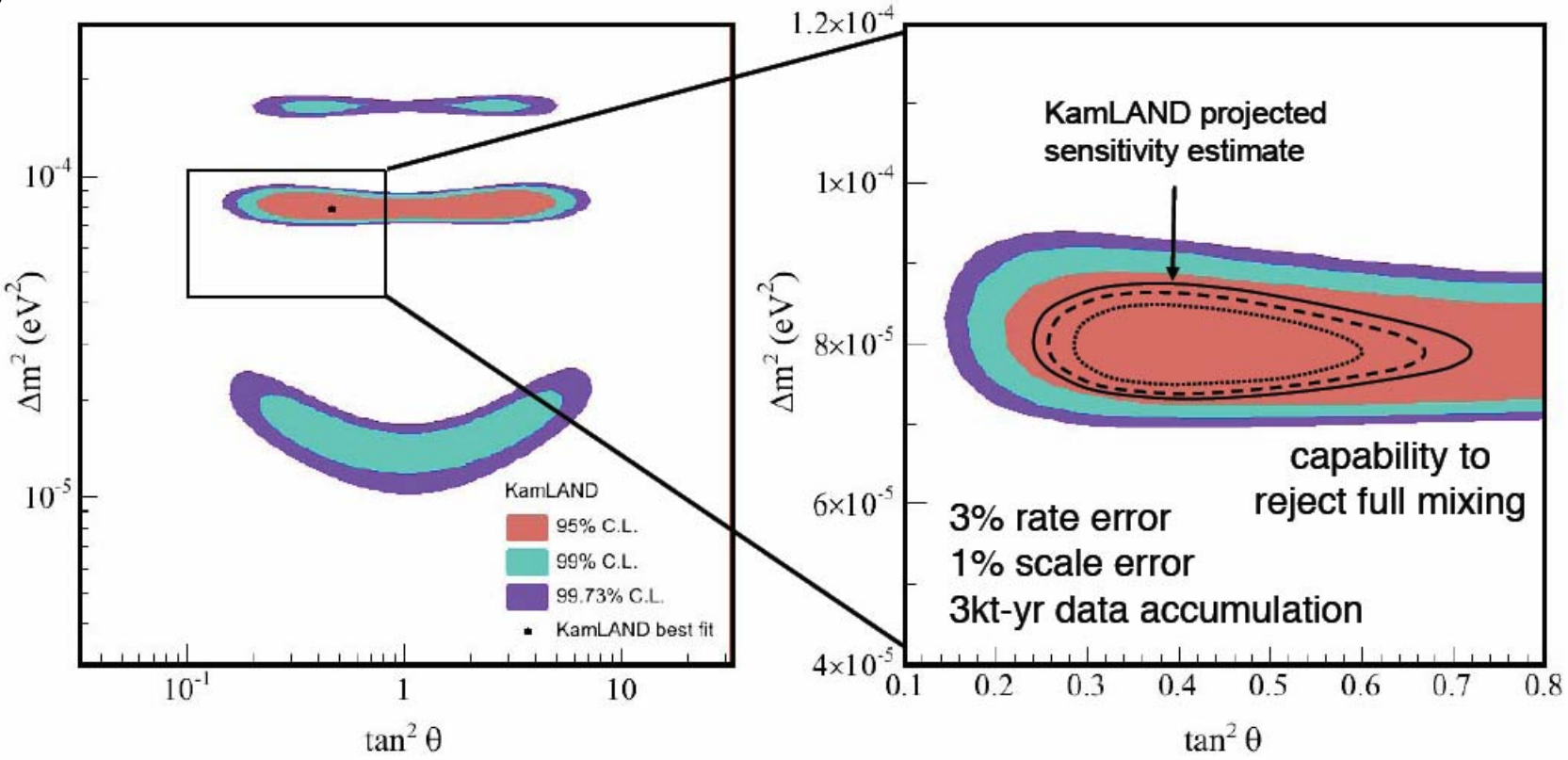
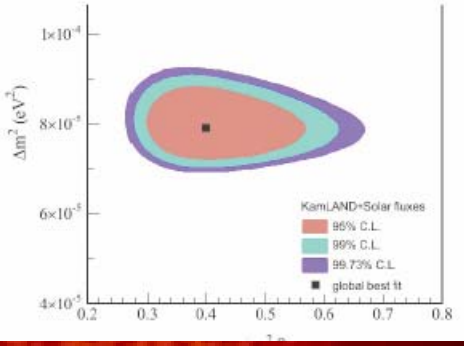
KamLAND Future Sensitivity



Mixing angle determination comparable with current solar data



Patrick Decowski / UC Berkeley

Dave Wark
Imperial College/RAL

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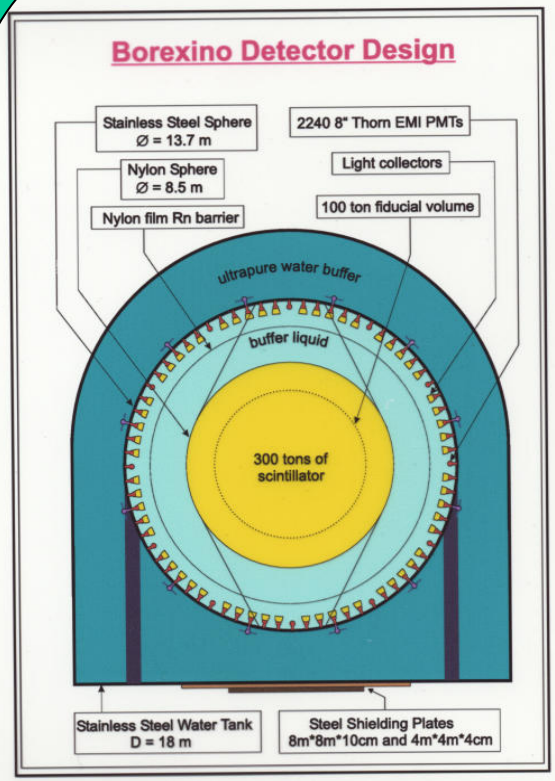
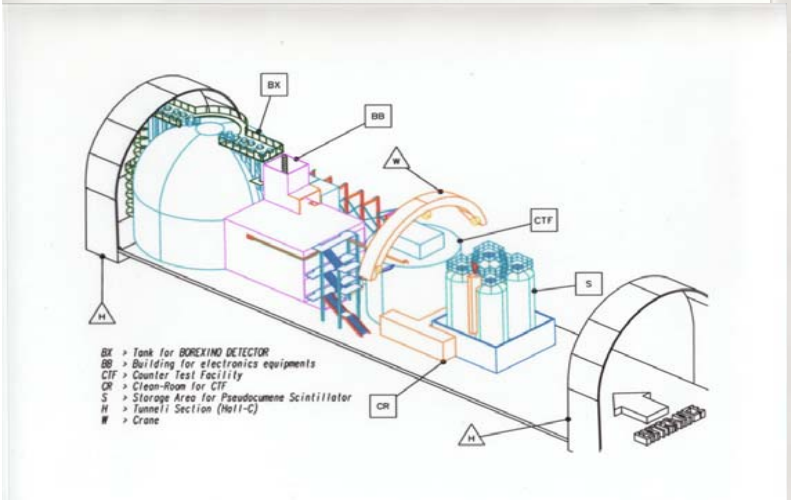
June 29, 2005

Solar ..

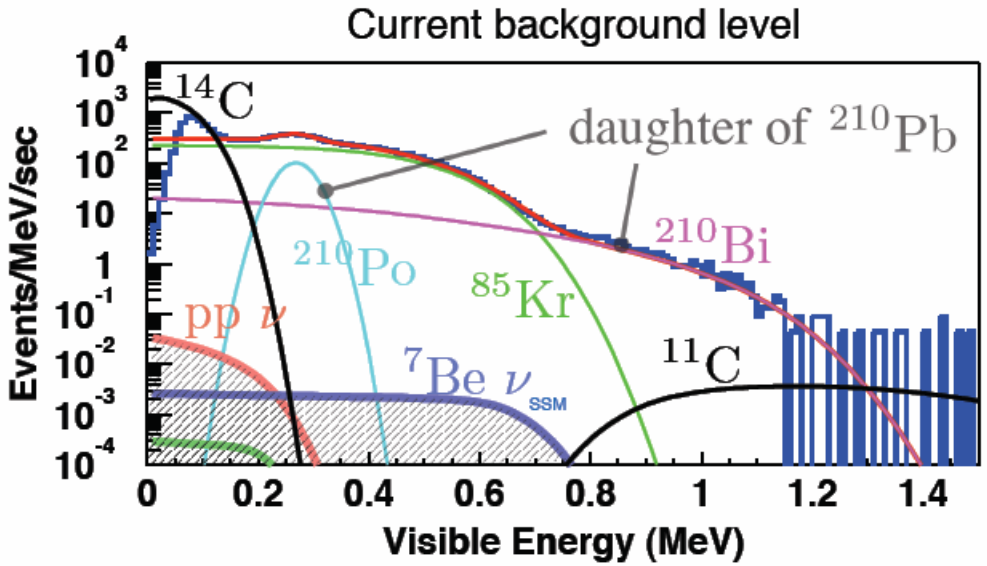
Borexino Detector Design





Neutrinos

Dave Wark
Imperial College/RAL



Background	Current Level	Goal
^{238}U(by Bi-Po)	3.5×10^{-18}g/g	OK
^{238}U(by ^{234}Pa)	O(10^{-15}g/g)	10^{-18}g/g
^{232}Th (by Bi-Po)	5.2×10^{-17}g/g	OK
^{40}K	2.7×10^{-16}g/g	$< 10^{-18}$g/g
^{210}Pb	$\sim 10^{-20}$g/g	5×10^{-25}g/g $\sim 1\mu$Bq/m^3
^{85}Kr, ^{39}Ar	^{85}Kr =0.7Bq/m^3	1μBq/m^3
^{222}Rn (after purification)	^{238}U $= 3.5 \times 10^{-18}$g/g $= 3.3 \times 10^{-8}$Bq/m^3	OK (1μBq/m^3)
^{222}Rn (during purification)		1mBq/m^3 ^{210}Pb $= 0.5\mu$Bq/m^3 after decay

Purification level:

$$\frac{1}{10^{4\sim5}}$$

$$\frac{1}{10^{\sim6}}$$

Patrick Decowski / UC Berkeley

Dave Wark
Imperial College/RAL

Low-E solar neutrinos

- Now that we have those annoying neutrino oscillations sorted out, we can get back to using neutrinos to study the core of the sun.
- Total neutrino flux measured by SNO already constrains non-standard solar physics.
- Producing high-statistics, real time measurements of the lower energy solar ν would allow:
  - Verification of the transition from vacuum $\rightarrow$ MSW oscillations
  - Better constraint on oscillations parameters, in particular, θ_{12}
  - Solar neutrino spectroscopy allows strong tests of solar models
  - Observation of CNO neutrinos would produce first direct experimental test of the main nucleosynthesis reaction in the Universe
- Many experiments proposed – LENS, HERON, CLEAN, SNO++,….

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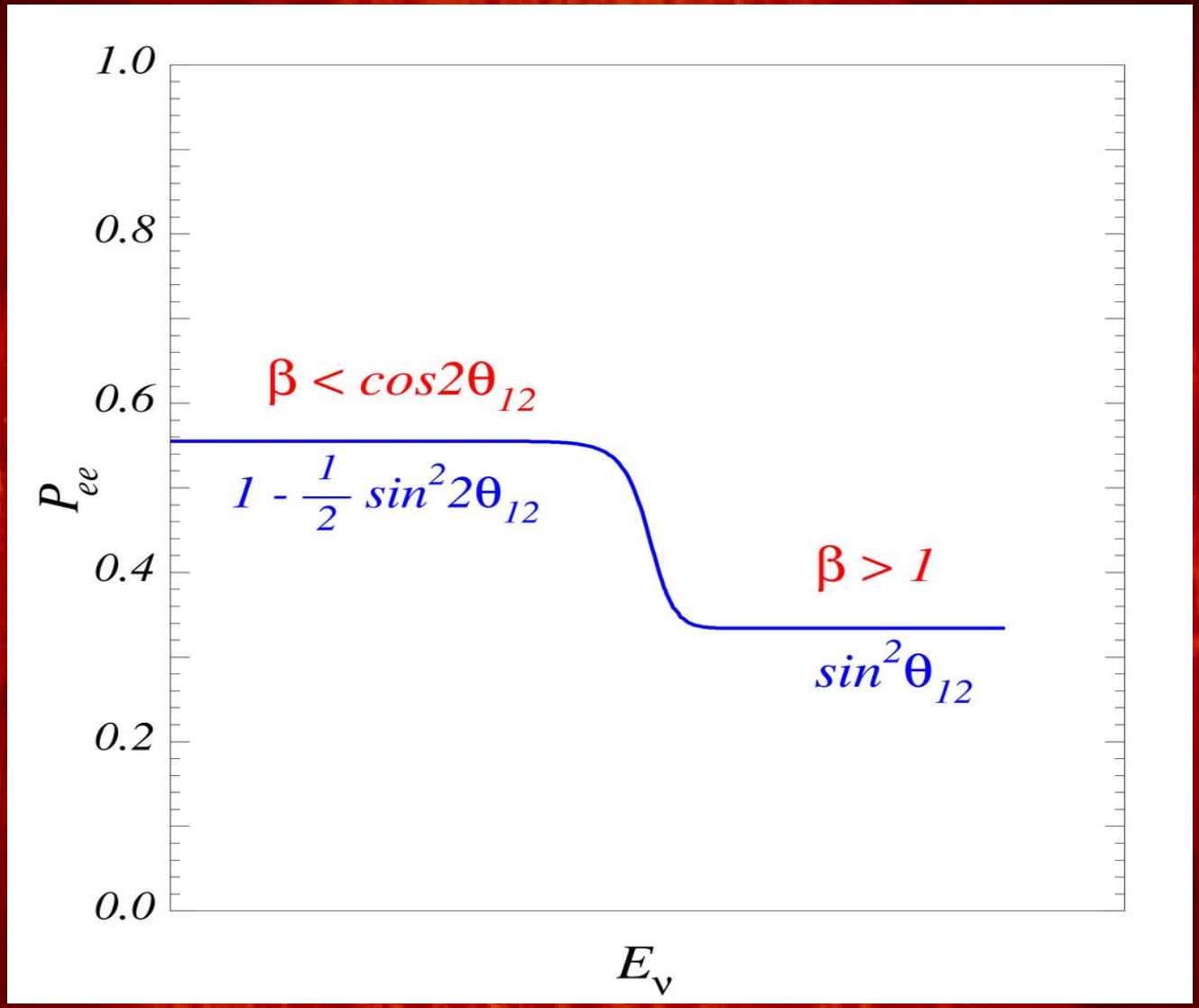
Imperial College/RAL

IoP ½ Day
June 29, 2005

Solar ..



Neutrinos

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- Many experiments proposed – LENS, HERON, CLEAN, SNO++,….

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Conclusions

- *Solar neutrinos provided the first evidence for what was subsequently confirmed as physics beyond the Standard Model.*
- *Arguably after the gallium experiments the default model was neutrino oscillations.*
- *(Super-K then confirmed that neutrinos have mass)*
- *SNO confirmed that neutrinos change flavour.*
- *KamLAND confirmed that neutrinos oscillate.*
- *Future solar neutrino experiments may provide further tests of MSW oscillations and valuable insights into stellar physics.*

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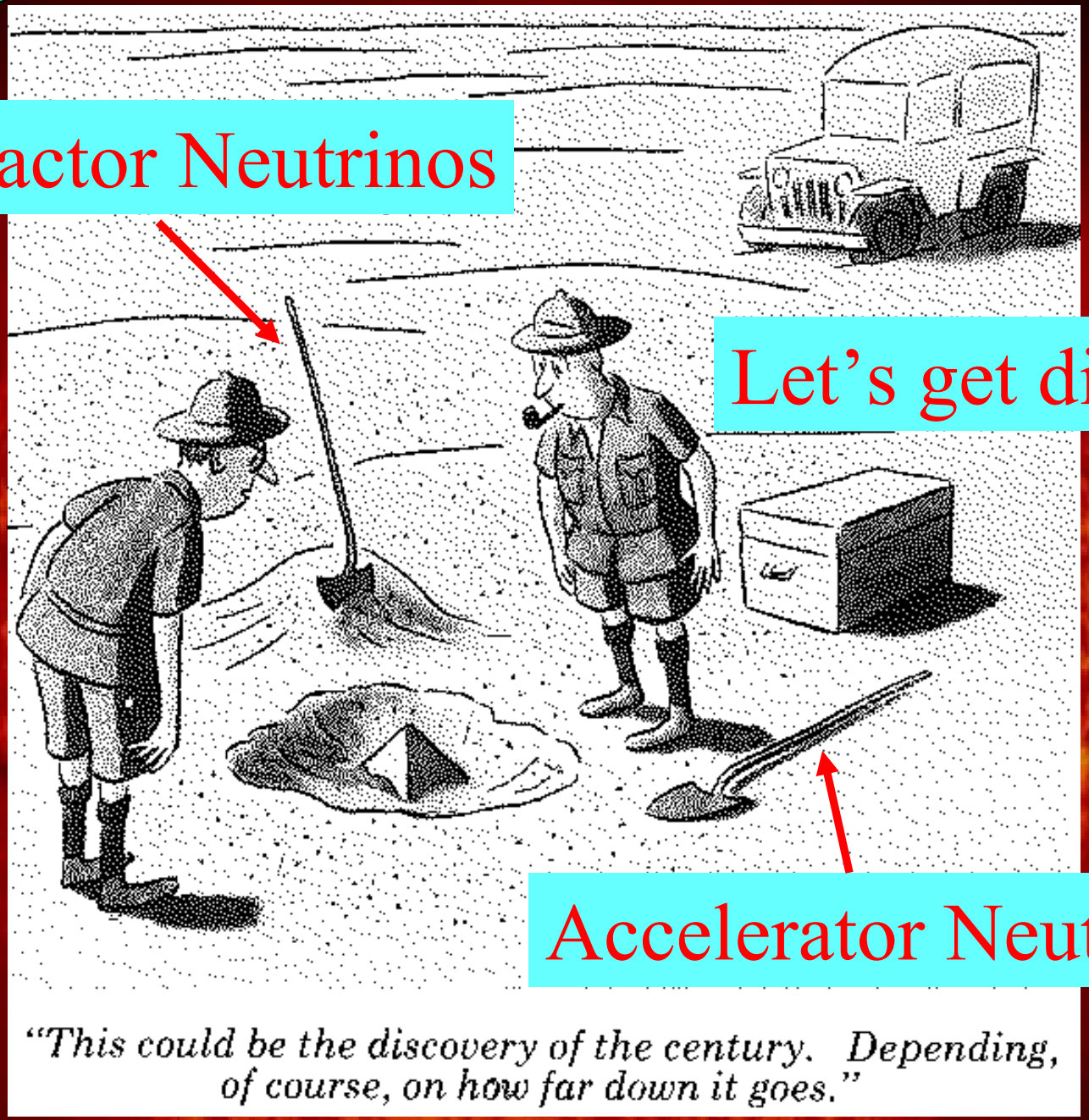
Solar..

Reactor Neutrinos



Neutrinos

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