Status of Solar Neutrino Oscillations

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With many thanks to **Dave Wark -**
RAL/ University of Sussex and
Stephen Brice - Fermilab

The Solar Neutrino Problem

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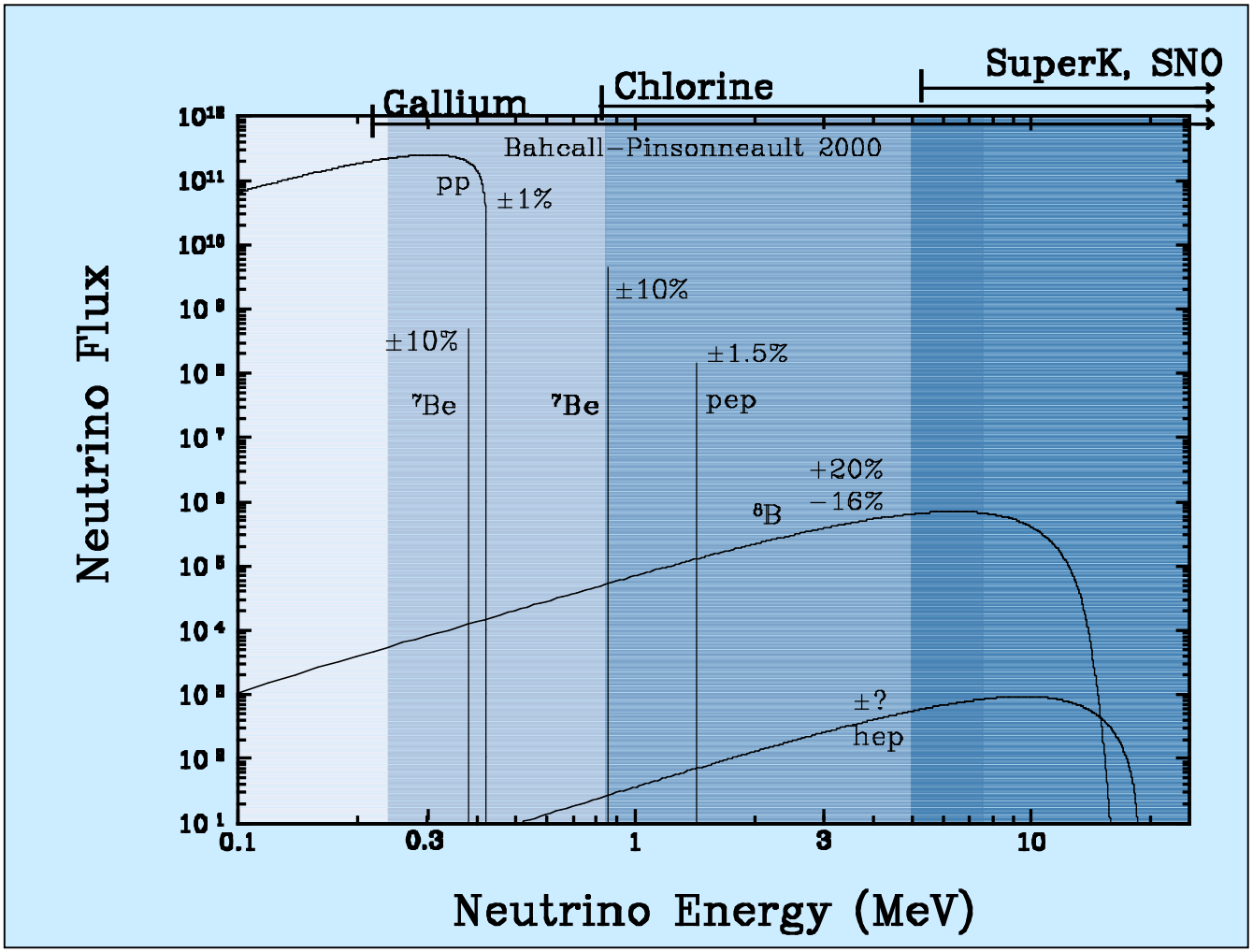
Next three plots adapted from http://www.sns.ias.edu/~jnb/



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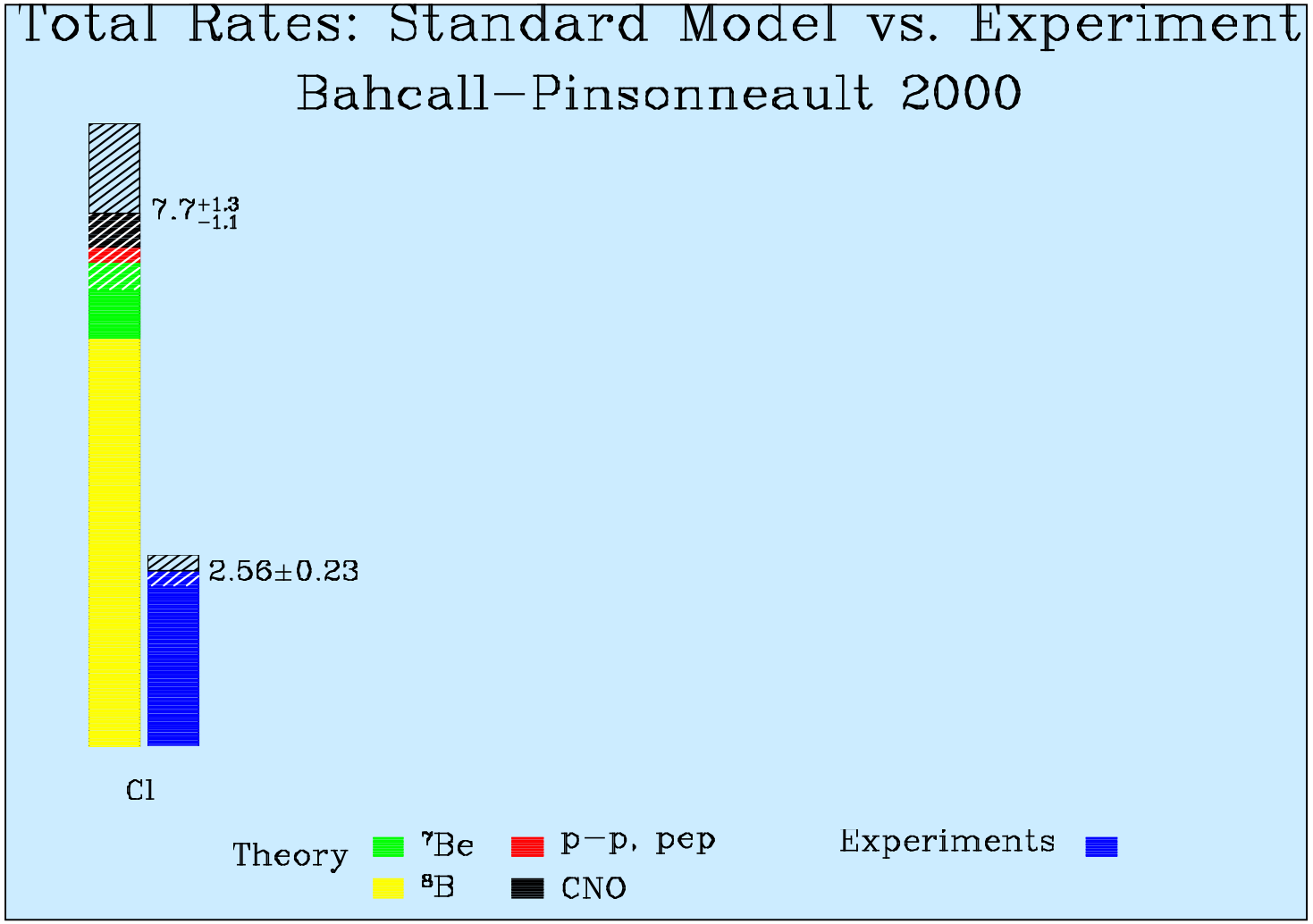

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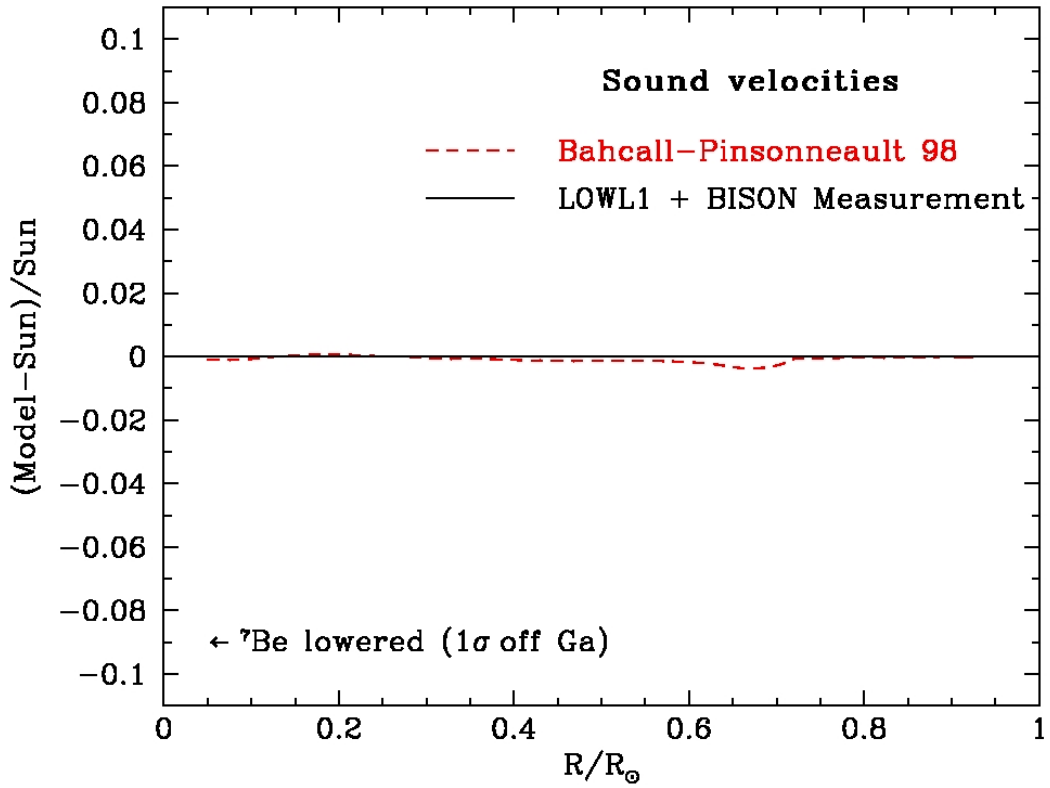

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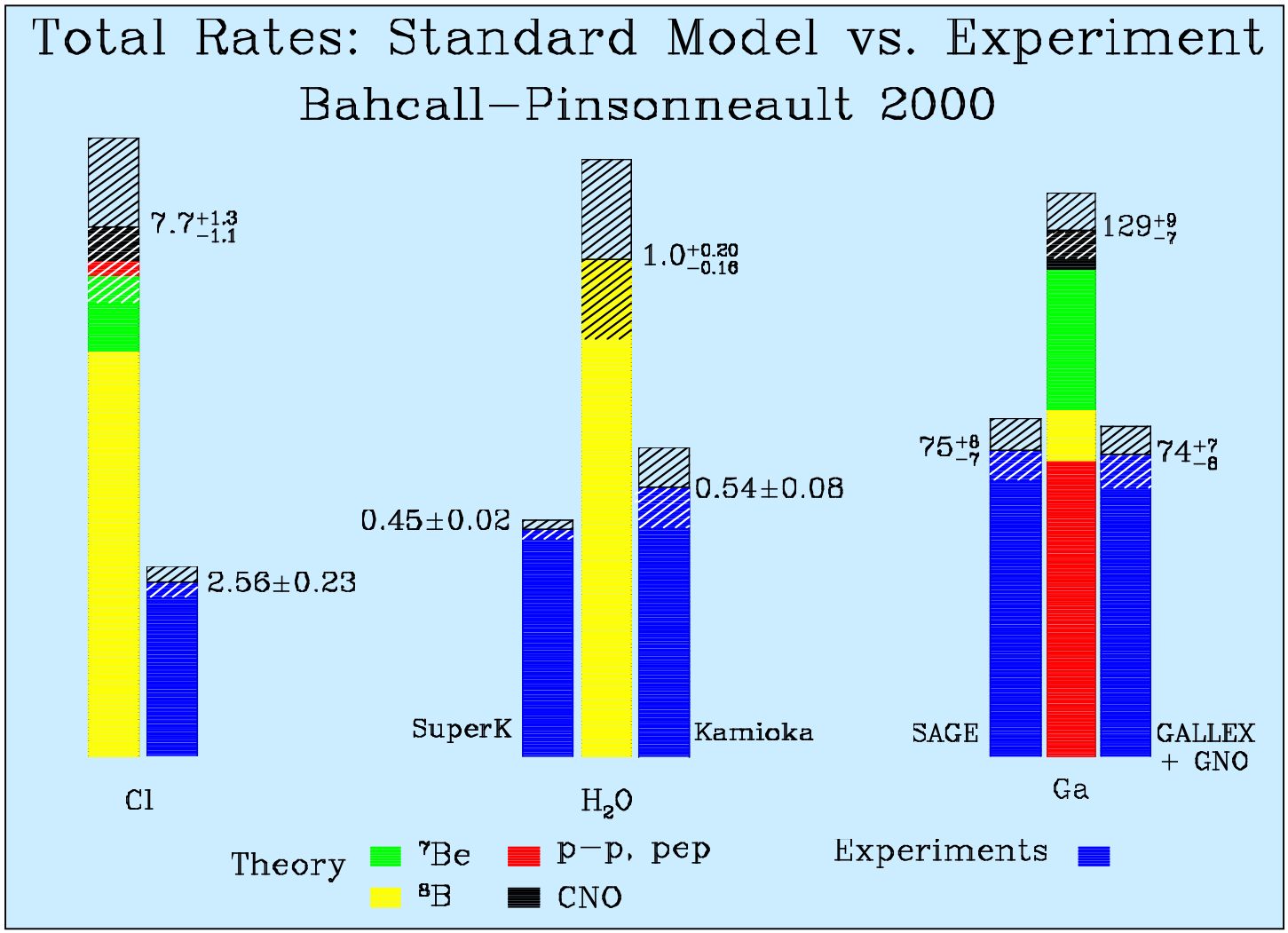

Neutrino Oscillations

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- Let us assume that neutrinos have (different) masses - Δm^2
- Let us assume that the mass eigenstates are not identical to the weak eigenstates
- If we consider 2 flavours the mixing is characterized by a single angle θ analogous to the Cabibbo angle in case of quarks

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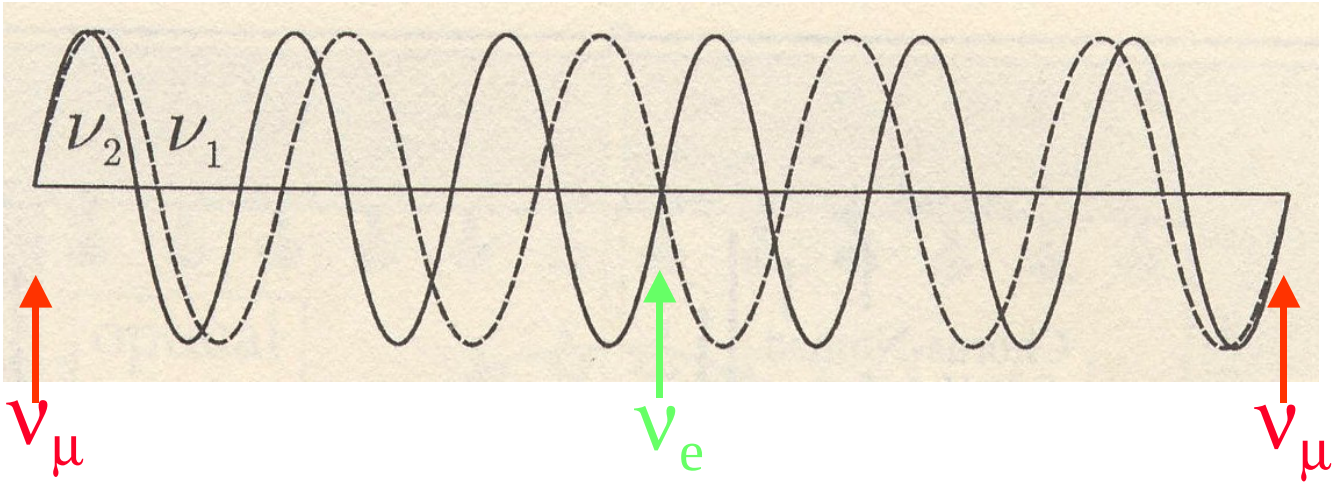
Neutrino Oscillations

- Recall that: $\psi_i(t) = \psi_i(0) e^{-iE_i t}$

- Consider $\theta = 45°$



Vacuum Oscillations

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- In general this leads to the disappearance of the original neutrino flavour

$$P(\nu_e \blacklozenge \nu_e) = 1 - \sin^2 2\theta \sin^2(1.27 \frac{m^2 L}{E})$$

- With the corresponding appearance of the "wrong" neutrino flavour

The MSW effect

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- ν_e have an extra diagram for scattering from electrons.
- gives ν_e an "effective mass" in matter.
- can lead to resonant enhancement of oscillations
  Ü the MSW effect

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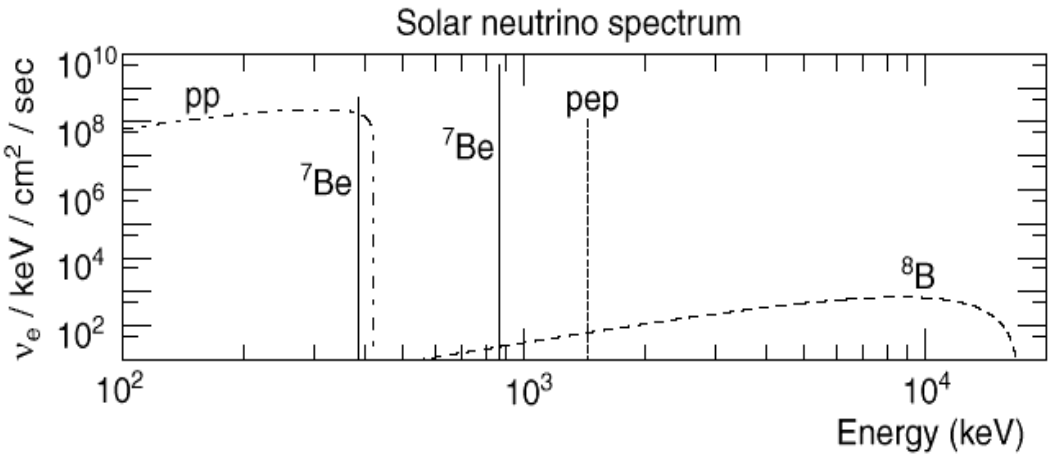
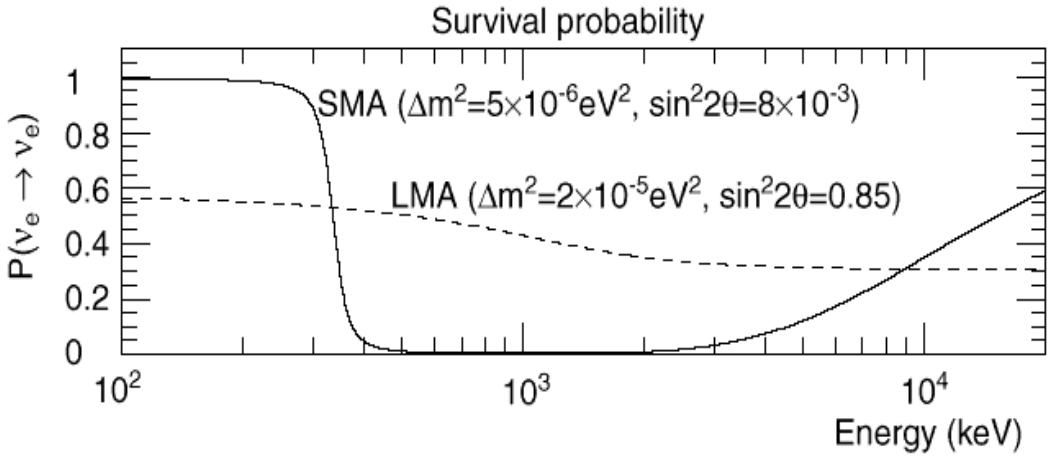
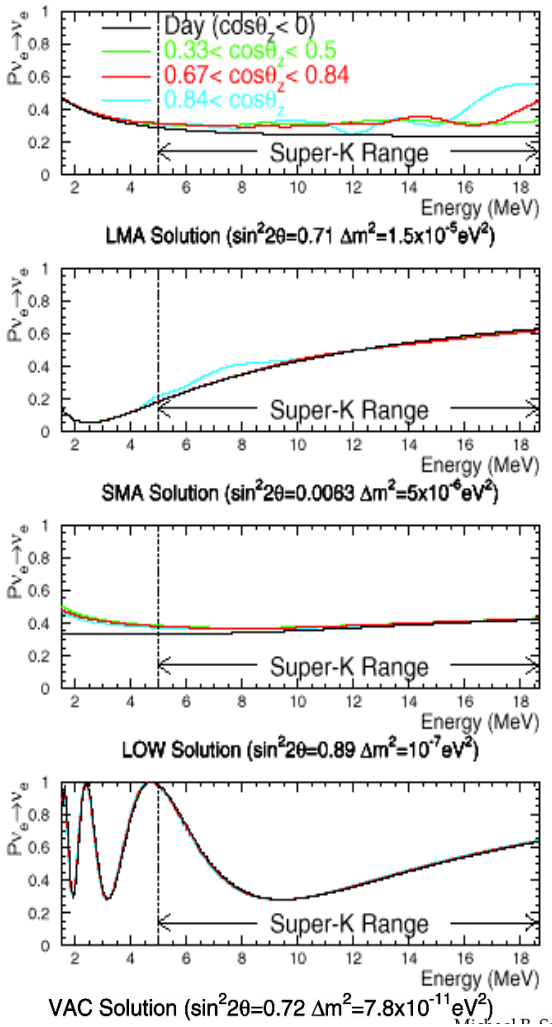
MSW effects on survival probabilities

Taken from the US KamLAND proposal







Taken from Micheal Smyth talk, Moriond 2001

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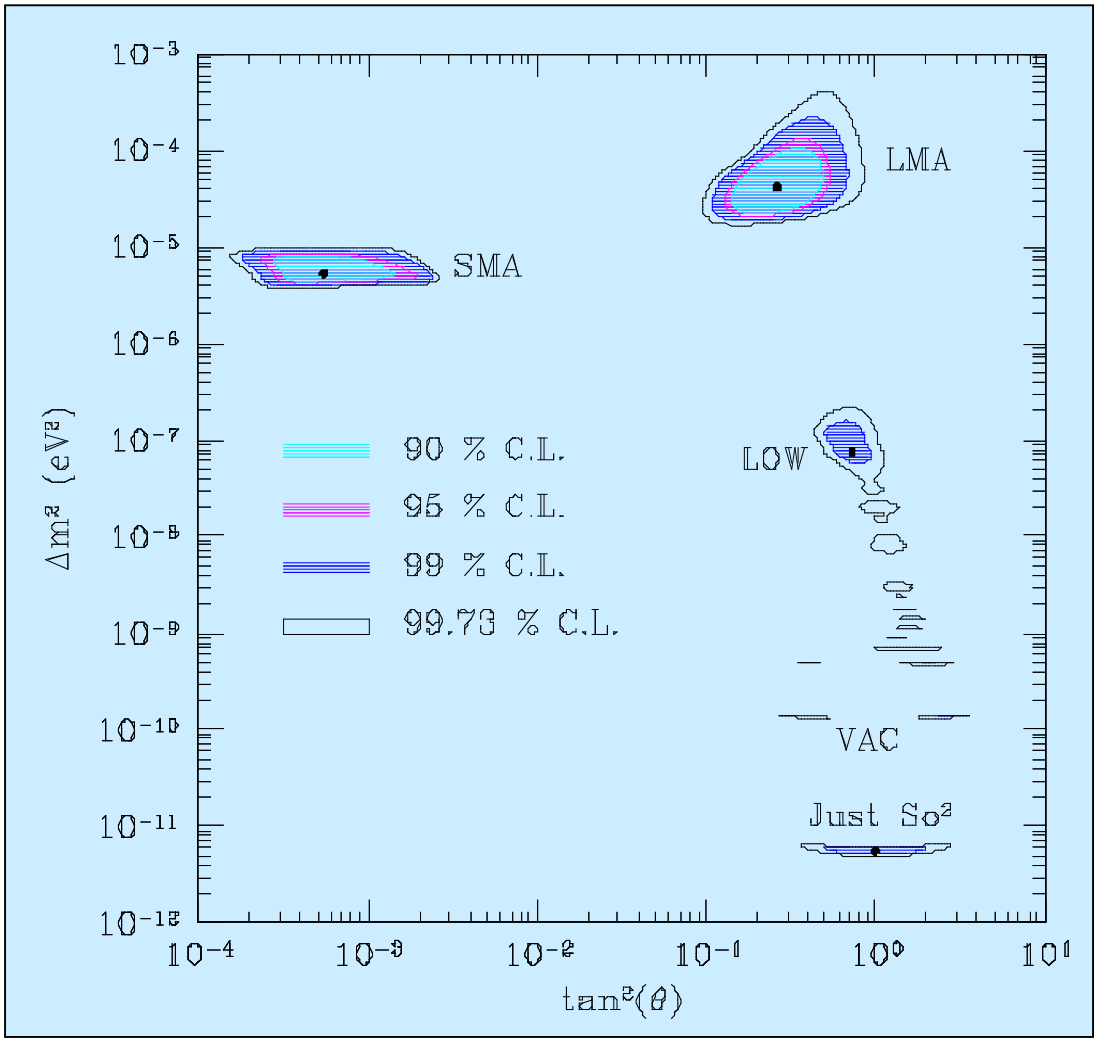
Global fit, ^{8}B Flux a free parameter

- Includes:
  - Rates:
    - » Homestake
    - » SAGE
    - » GALLEX/GNO
    - » Super-K
  - Super-K spectra
    - » day
    - » night



From Bahcall, Krastev, and Smirnov; hep-ph/0103179

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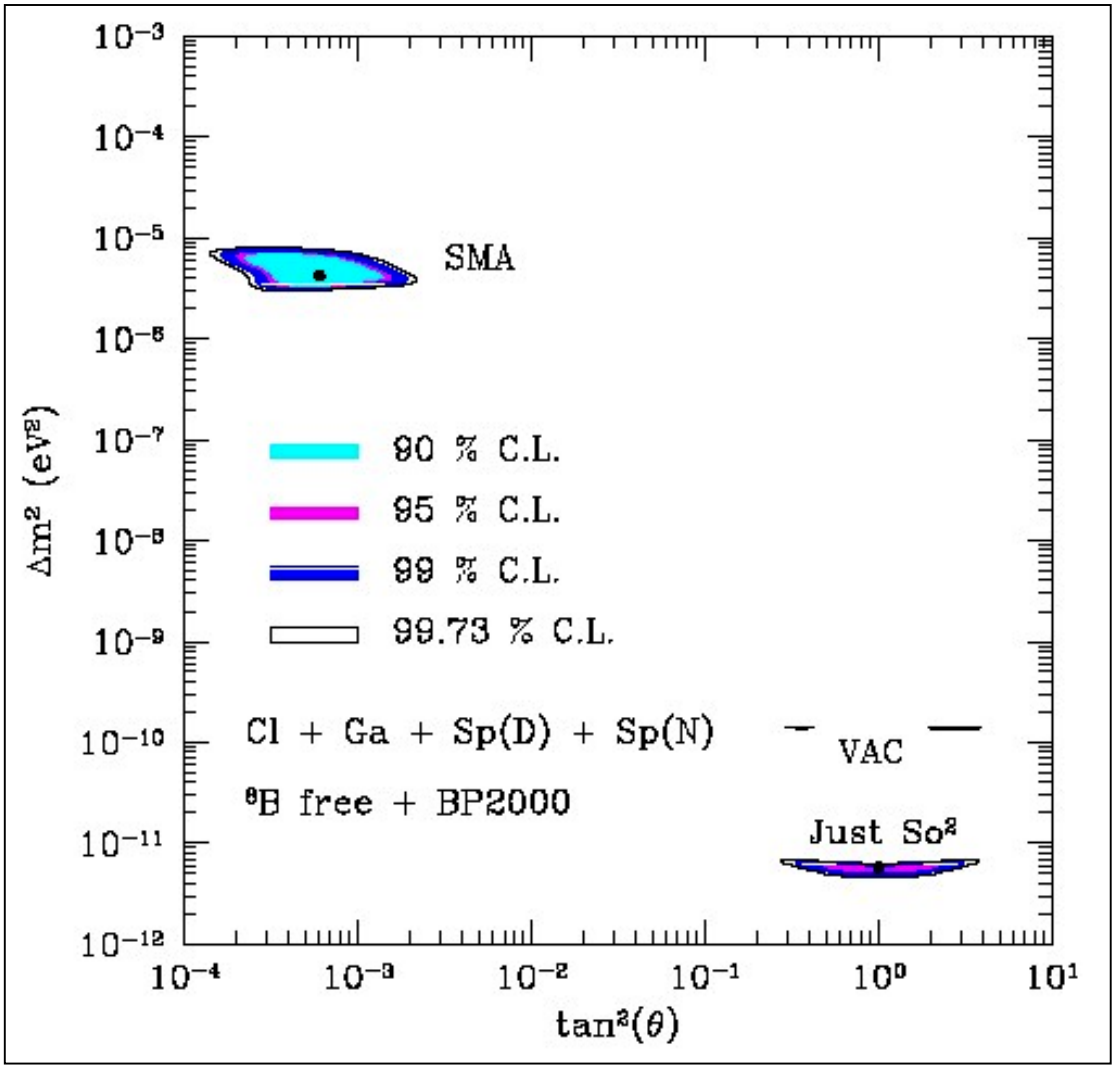
Sterile ν solutions

- Includes:
  - Rates:
    - » Homestake
    - » SAGE
    - » GALLEX/GNO
    - » Super-K
  - Super-K spectra
    - » day
    - » night



From Bahcall, Krastev, and Smirnov; hep-ph/0103179

Smoking guns?

- ν oscillations are consistent with the data, but are they the right explanation?
- Other models have been proposed - FCNC, extra dimensions, violations of the EP, neutrino decay, neutrino magnetic moments, etc….
- What would be proof for oscillations?

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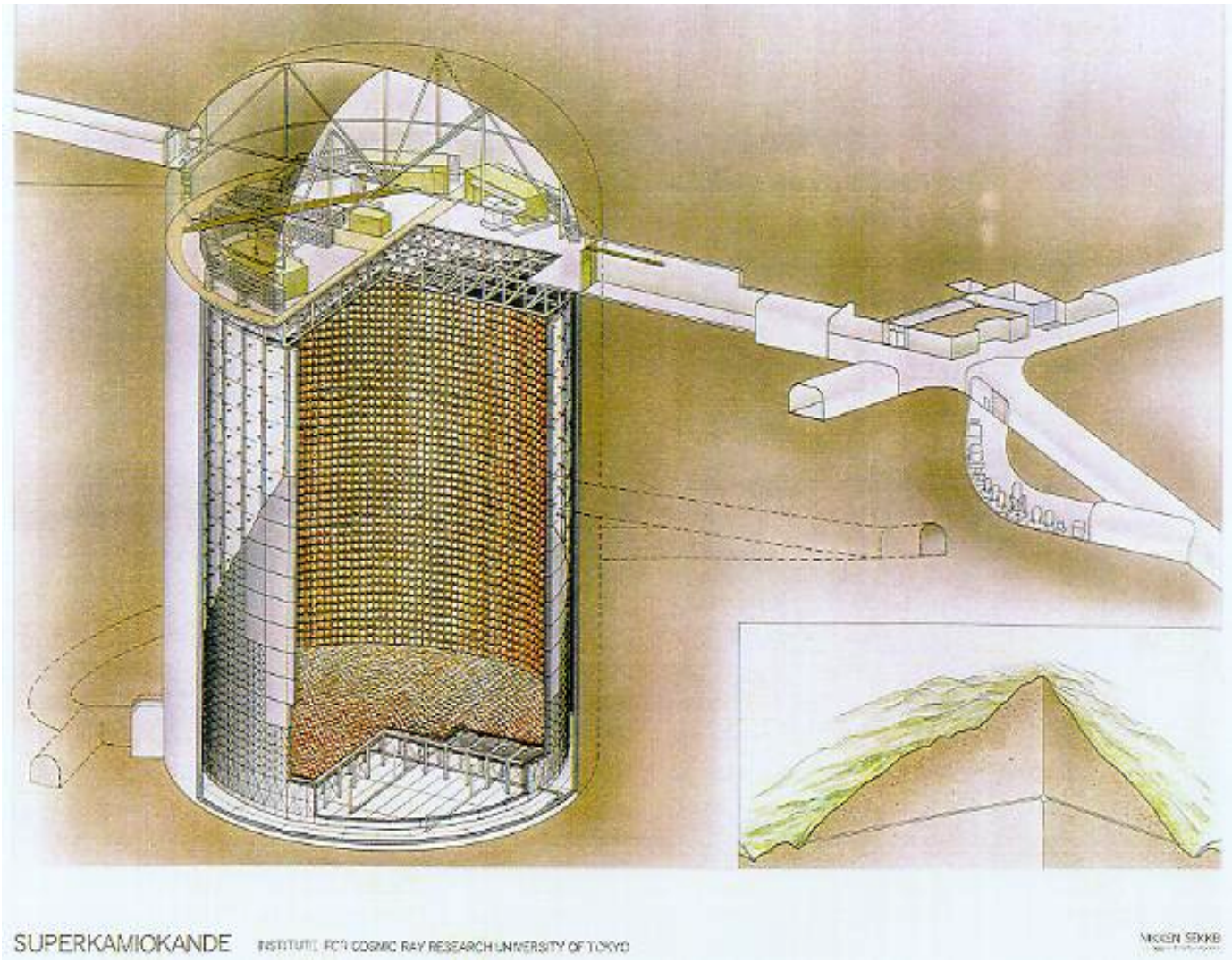
The Super-Kamiokande Detector



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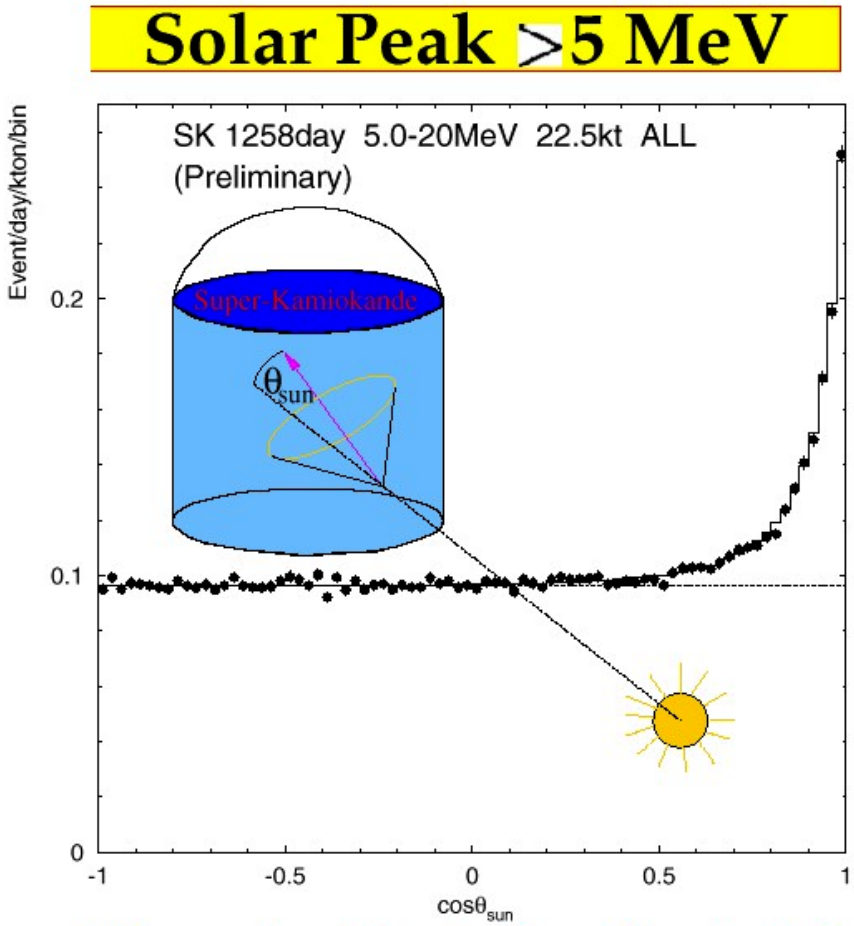
Super-K Elastic Scattering

Directly towards the Sun



Directly away from the Sun

SK reached its design threshold!

$$(0.451 \pm 0.005(\text{stat.})^{+0.016}_{-0.014}(\text{syst.})) \times \phi_{SSM}$$

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Smoking guns from solar ν? **Pre-SNO**

- **The appearance of the wrong-flavor neutrinos in the beam - not seen yet for solar neutrinos**
- **A variation of the rate with L/E**
  - **Spectral distortions**
  - **Seasonal variations**
- **Regeneration of neutrinos passing through the Earth.**

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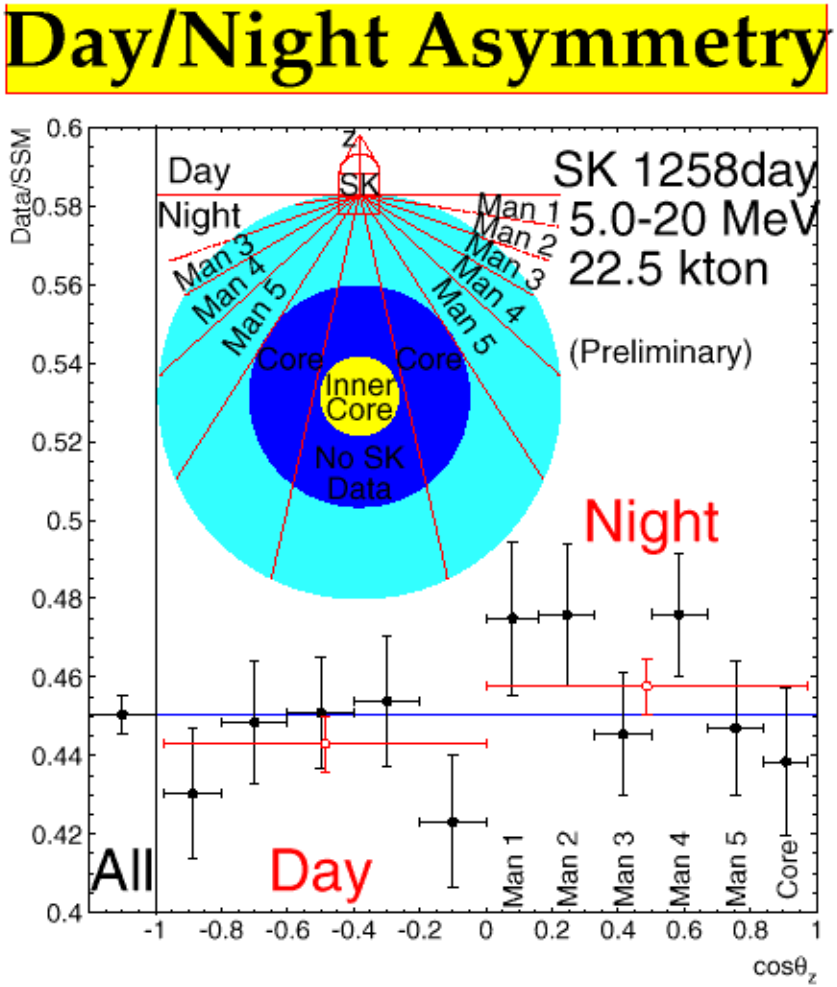
Day/Night variation in Super-K



$$\frac{D-N}{\frac{1}{2}(D+N)} = -0.033 \pm 0.022(\text{stat.})^{+0.013}_{-0.012}\,(\text{syst.})$$

Taken from Micheal SmyÕ talk, Moriond 2001

SNO

SNO Collaboration

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R.G. Allen, G. Buhler, **H.H. Chen***
University of California, Irvine
* Deceased

The SNO Detector

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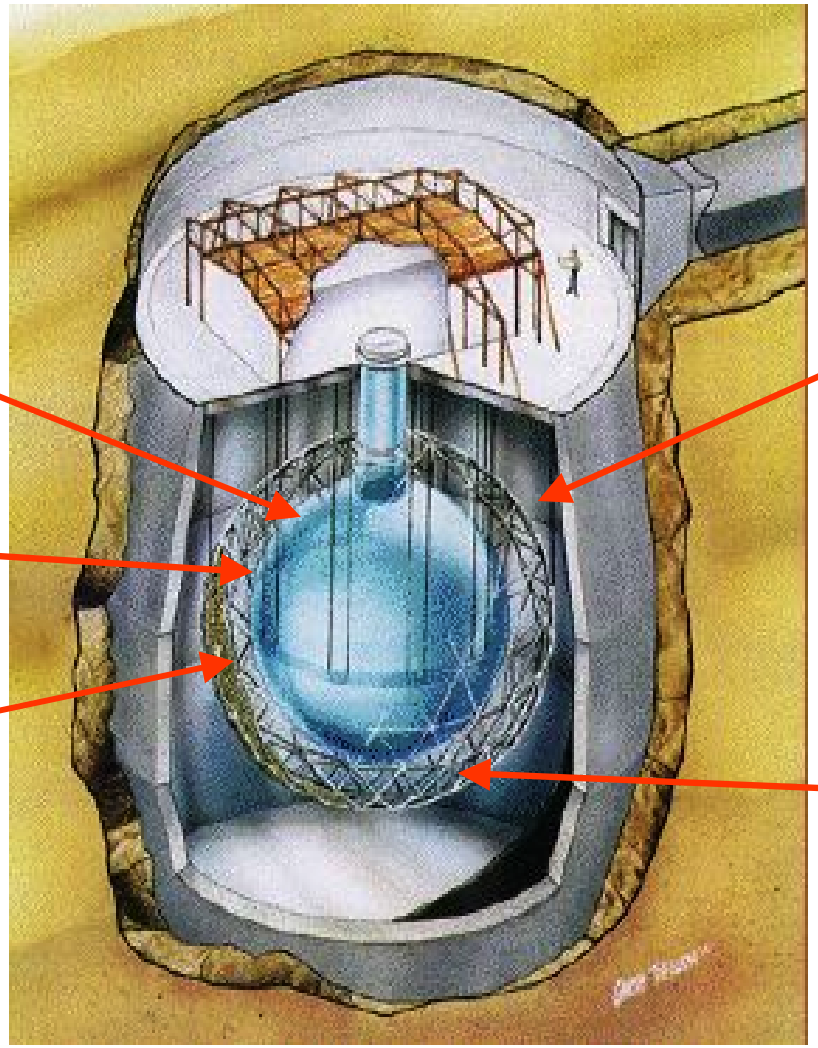

Surface: 2 km

1000 tons D_2O

Acrylic Vessel

10^4 8ÓPMTs

Phototube Support Structure (PSUP)

6500 tons H_2O

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ν Reactions in SNO

CC $\nu_e + d \Rightarrow p + p + e^-$ ⇐ ν_e only

-Good measurement of ν_e energy spectrum
-Weak directional sensitivity ∝ 1-1/3cos(θ)

NC $\nu_x + d \Rightarrow p + n + \nu_x$ ⇐ Equal cross section for all ν types

-Measure total ^{8}B ν flux from the sun.

ES $\nu_x + e^- \Rightarrow \nu_x + e^-$ ⇐ All ν types but enhanced sensitivity to ν_e

-Low Statistics
-Strong directional sensitivity

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SNO run sequence

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

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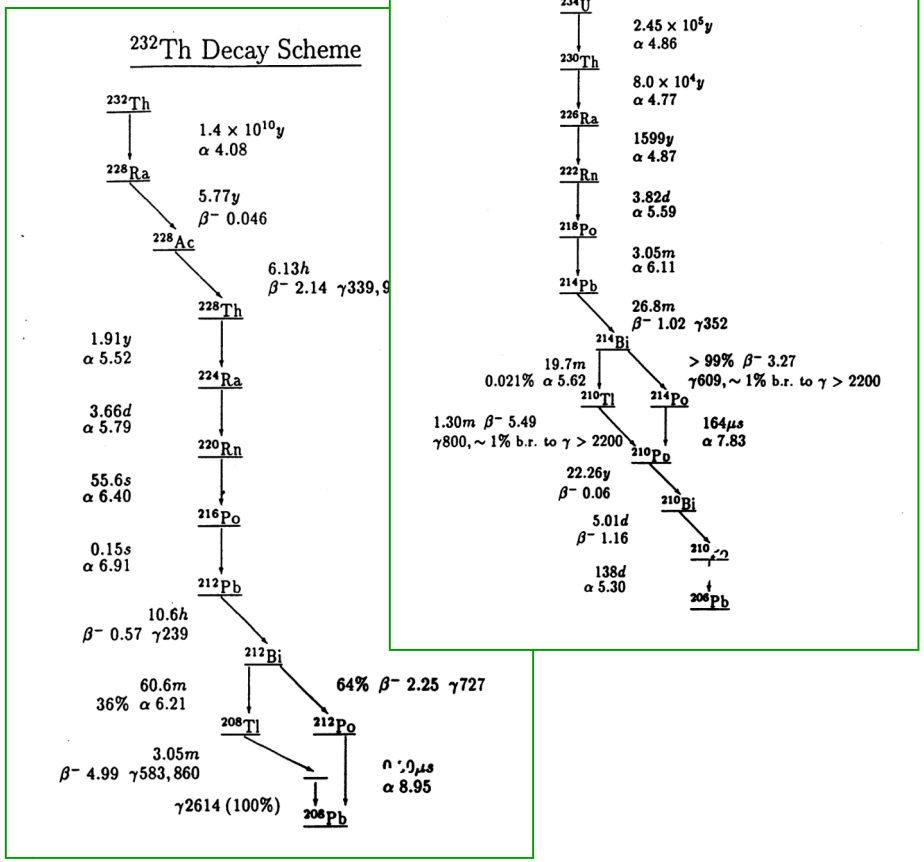
The enemy…..



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:

D_2O $< 10^{-15}$ gm/gm U/Th

H_2O $< 10^{-14}$ gm/gm U/Th

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

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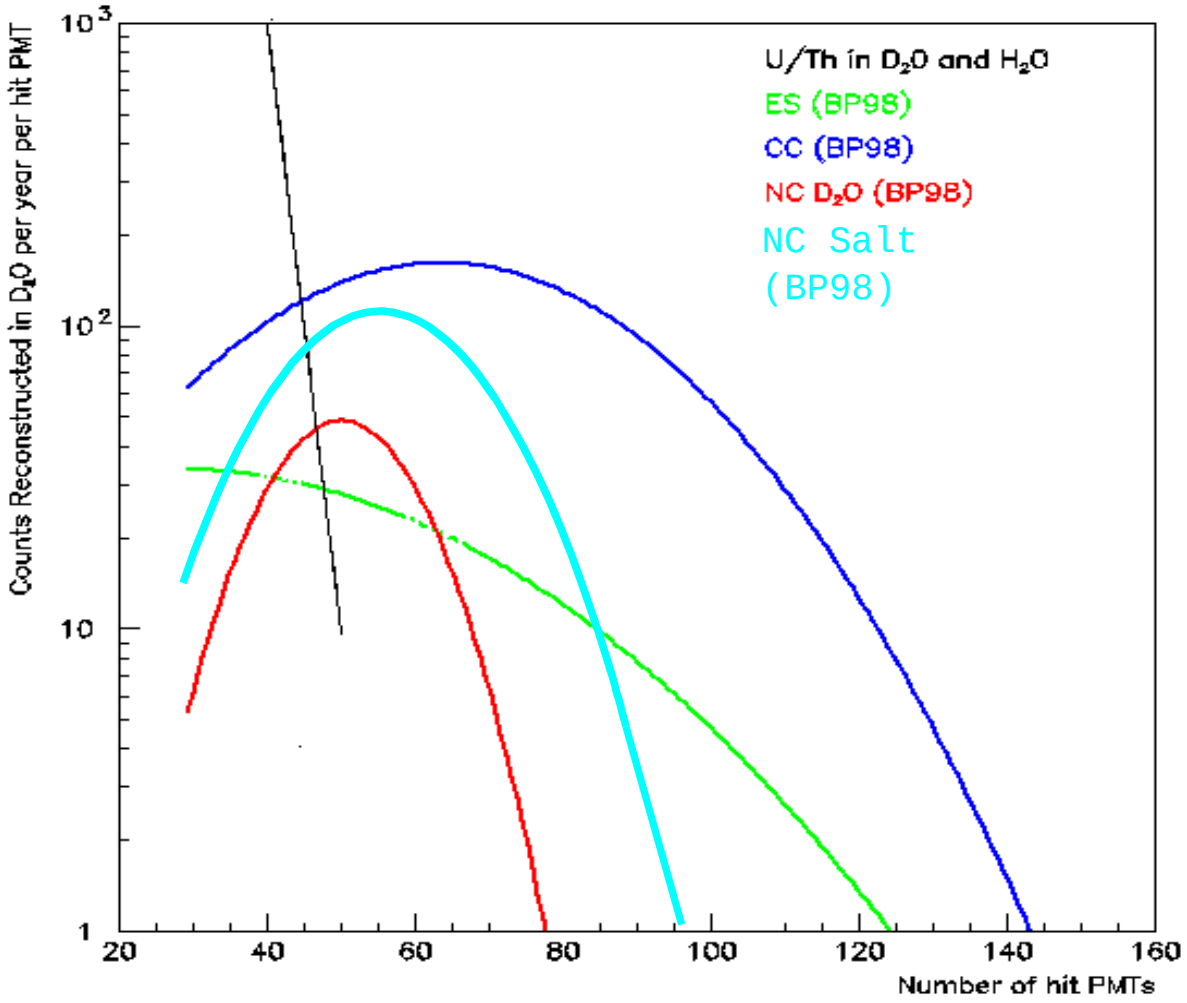
Signals in SNO



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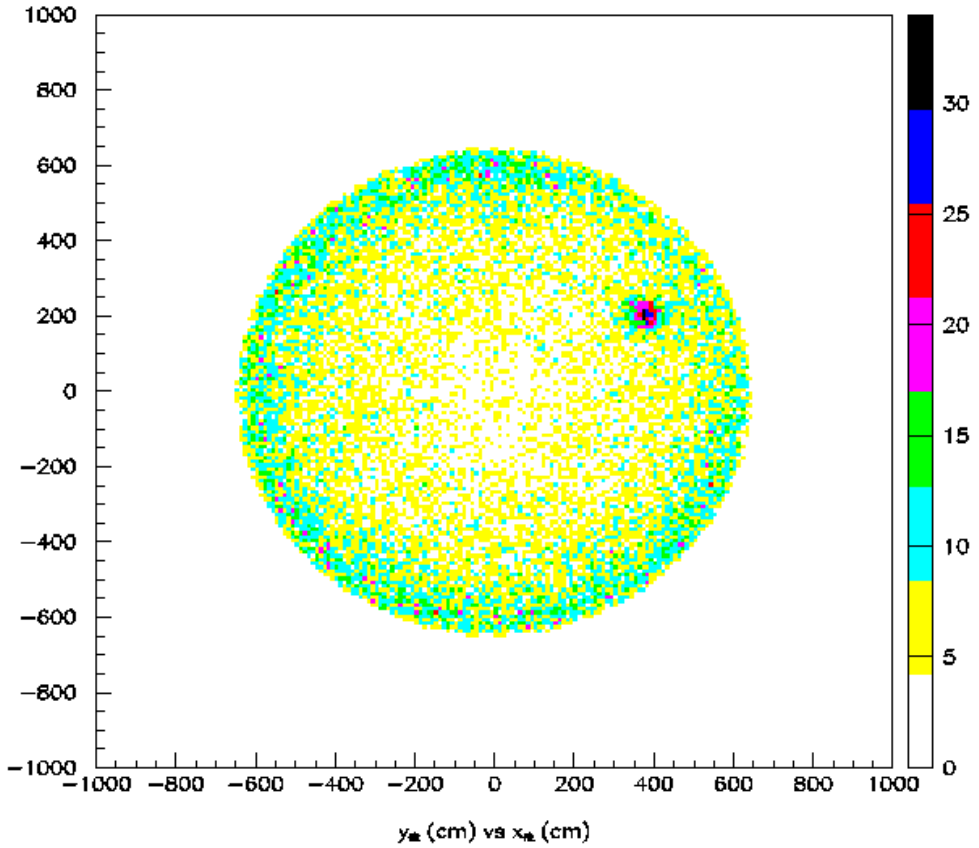
Acrylic Vessel Assay

- Every piece sampled and tested
- Sample bonds tested
- Direct Assay by Cherenkov light

AV well below (~1/10) the target level of 2 ppt U/Th



ÒBerkeley BlobÓ
9^{+20}_{-5} m 3 µg ÒThÓ

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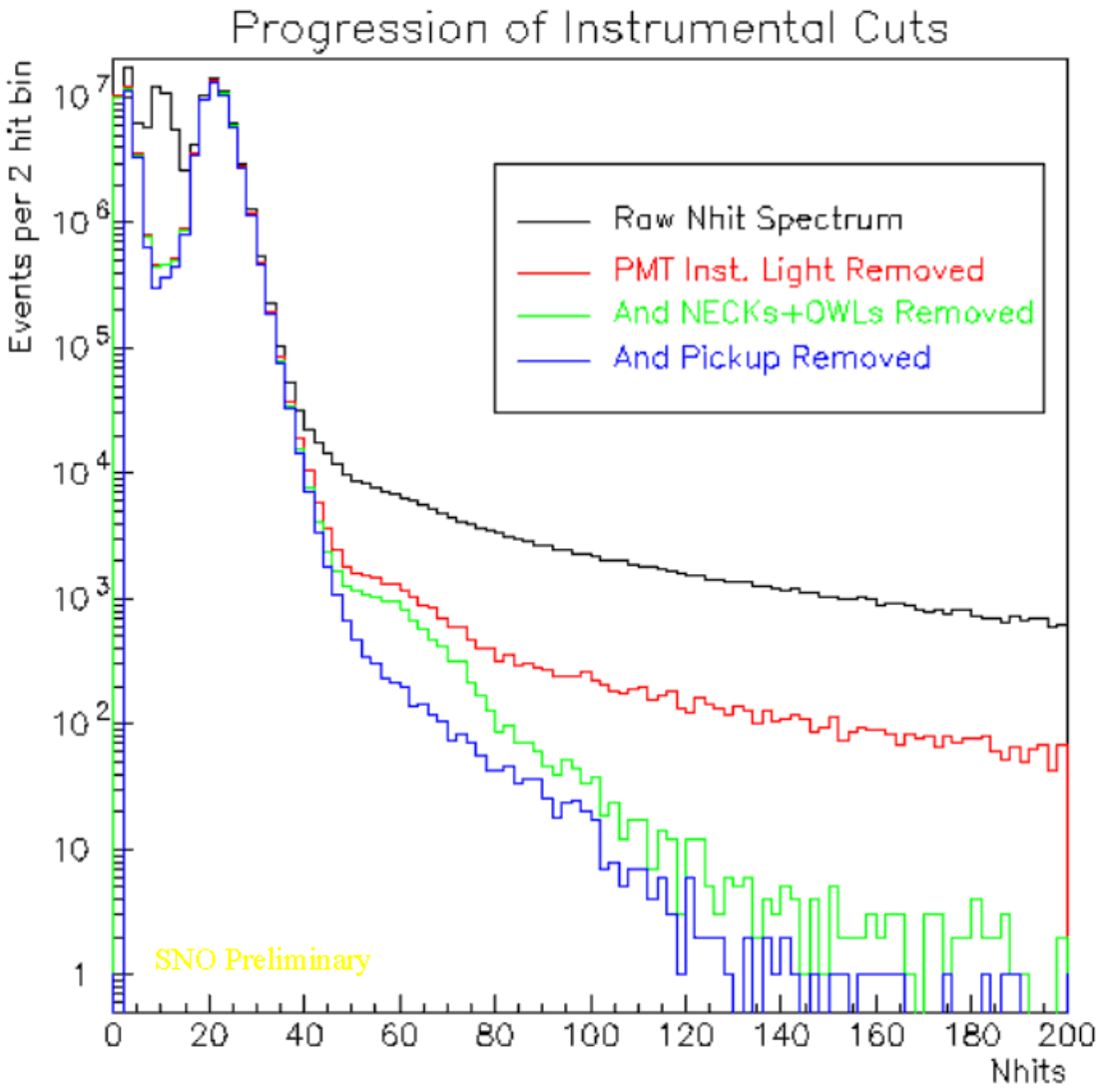
Instrumental Background Cuts



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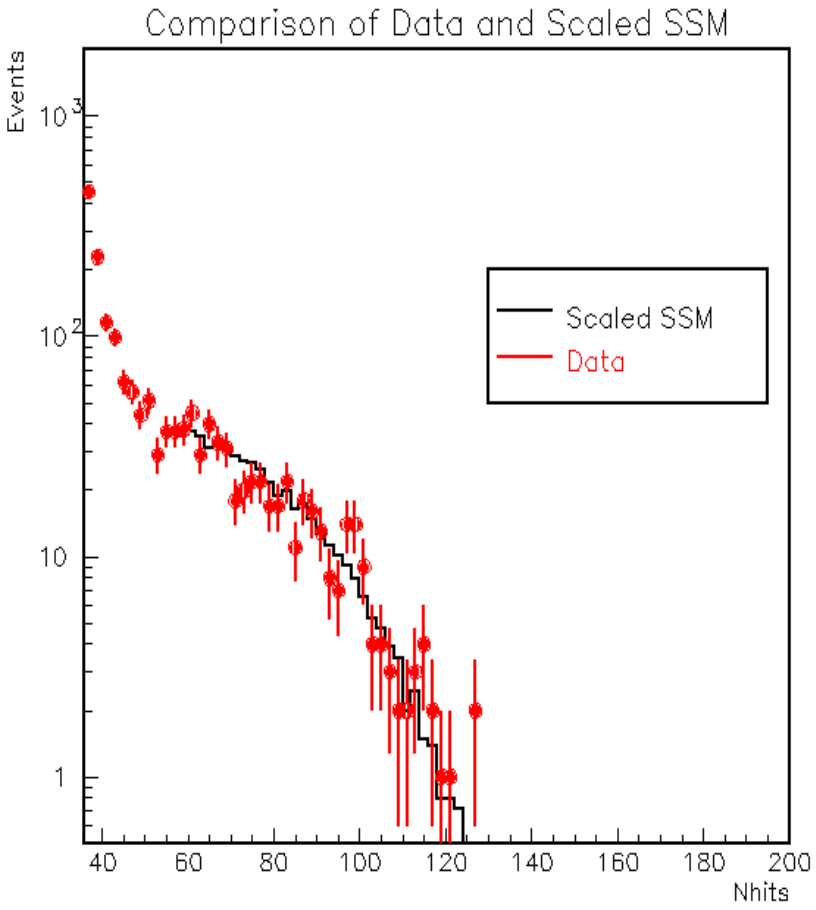
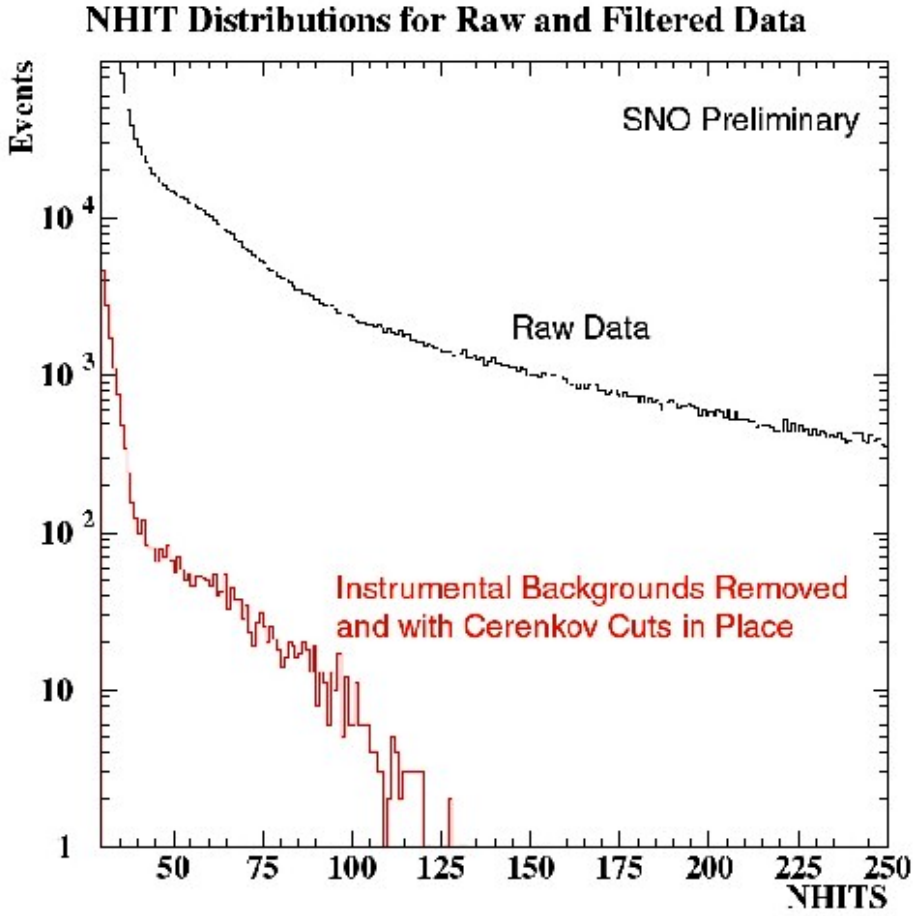
Solar Neutrino Spectrum





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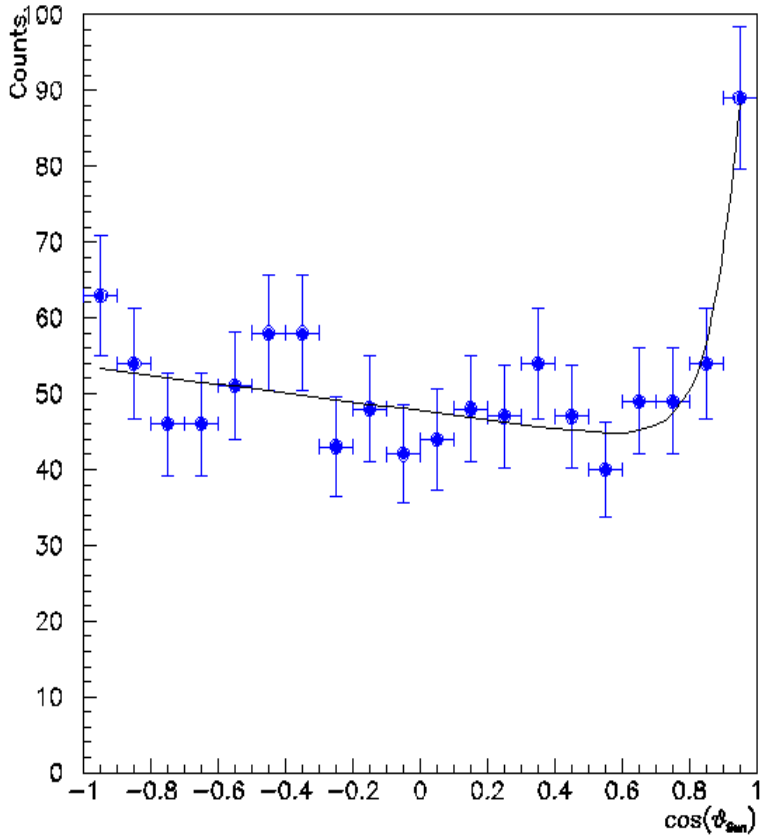
SNO $\cos(\theta)_{sun}$ distribution



Electron Angle with respect to the direction from the Sun

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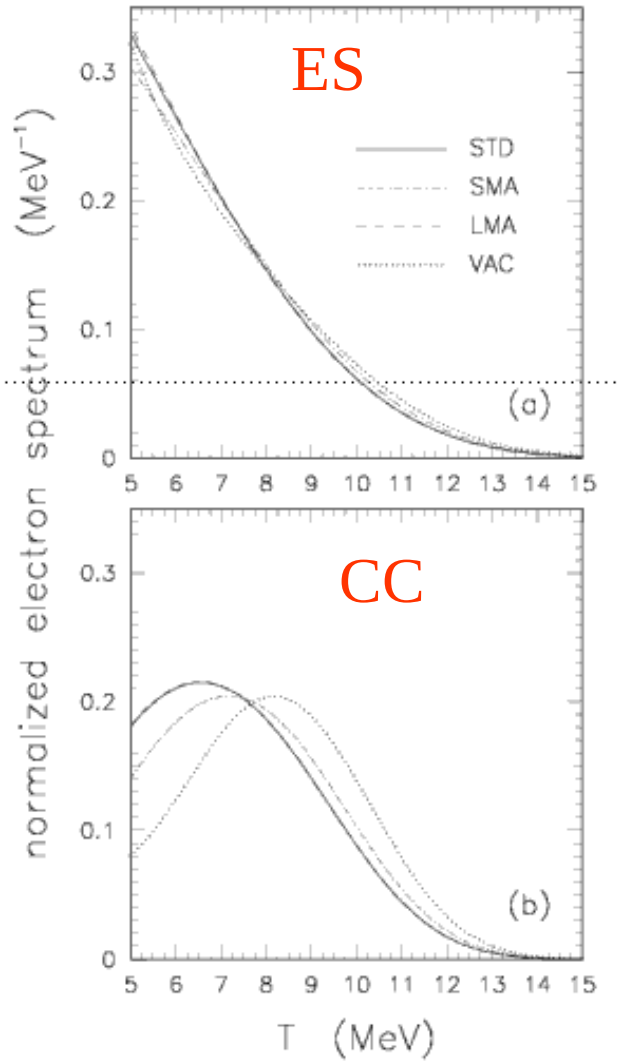
Smoking Guns in SNO - 1

Charged-current spectrum is more sensitive to shape distortions!



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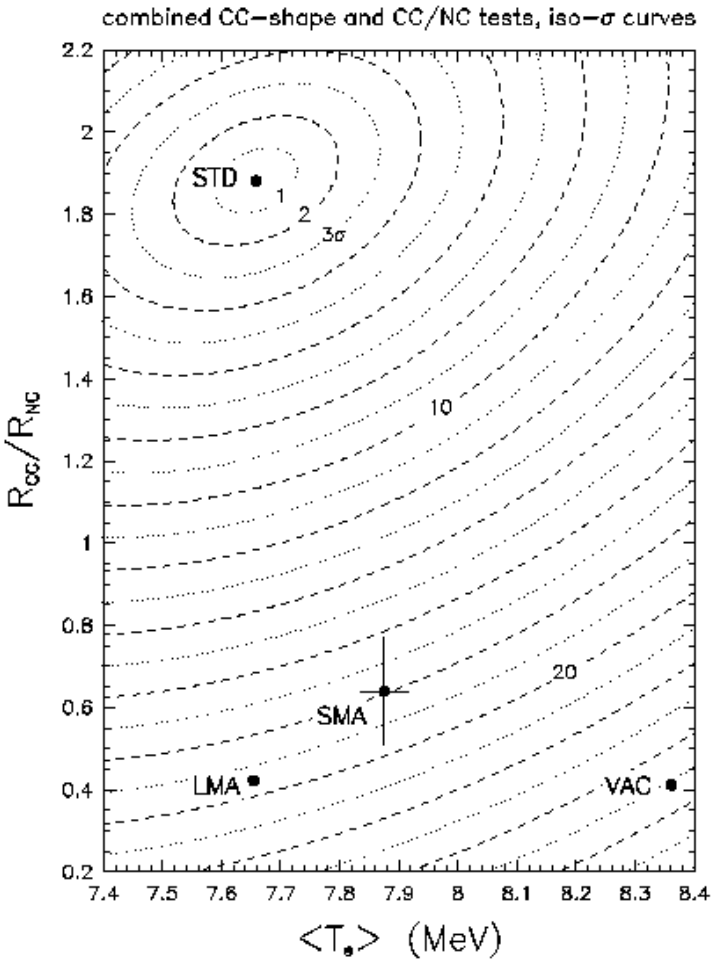
Smoking Guns in SNO - 2

Charged-Current to Neutral Current ratio is a direct signature for oscillations

$$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}$$



Bahcall etal., Phys. Rev. D **54**, 5147 (1996)

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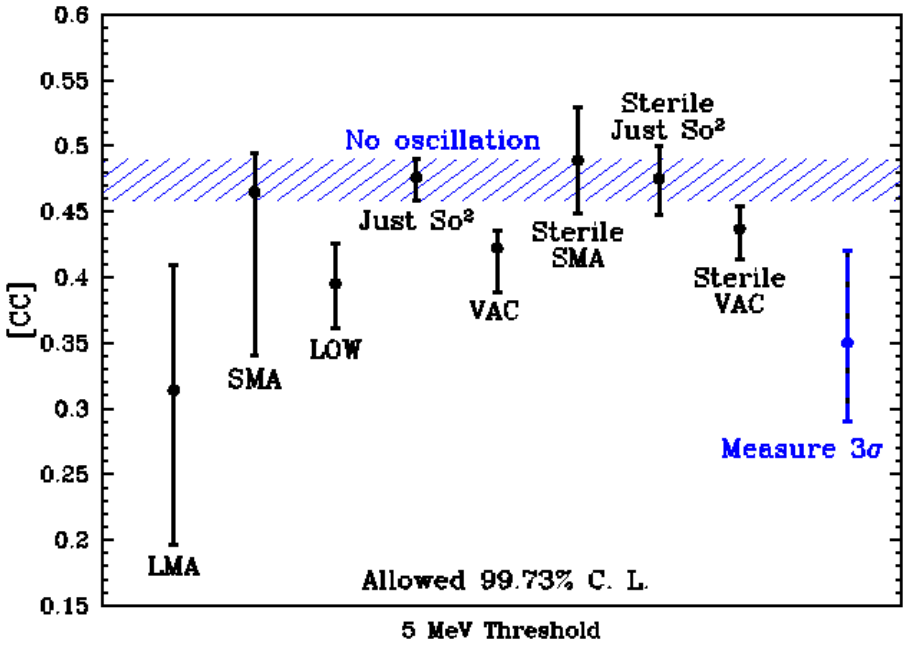
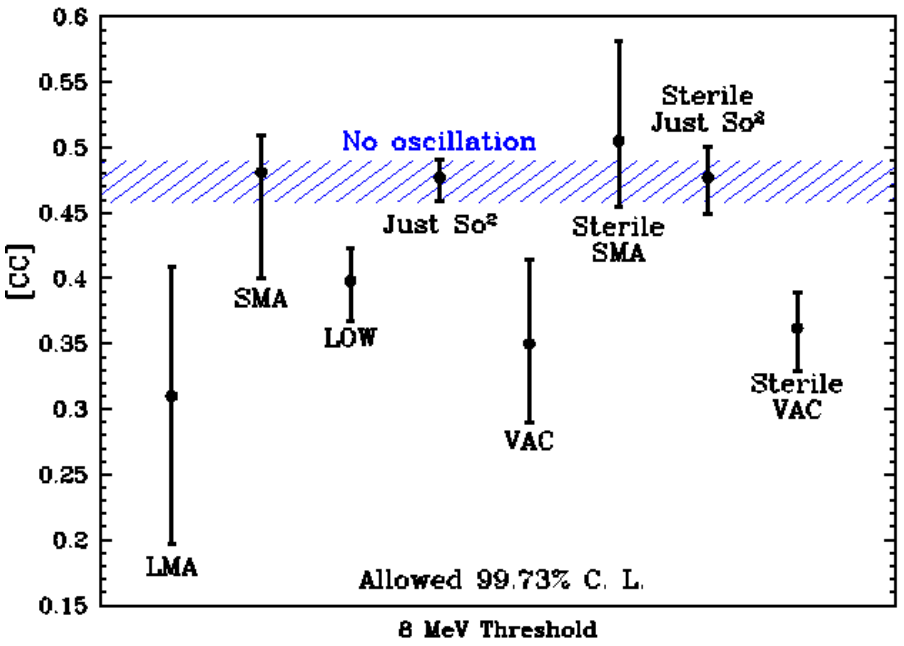
Smoking Guns in SNO - 3





CC/ES Could also show significant effects!

$$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.14(\nu_\mu + \nu_\tau)}$$

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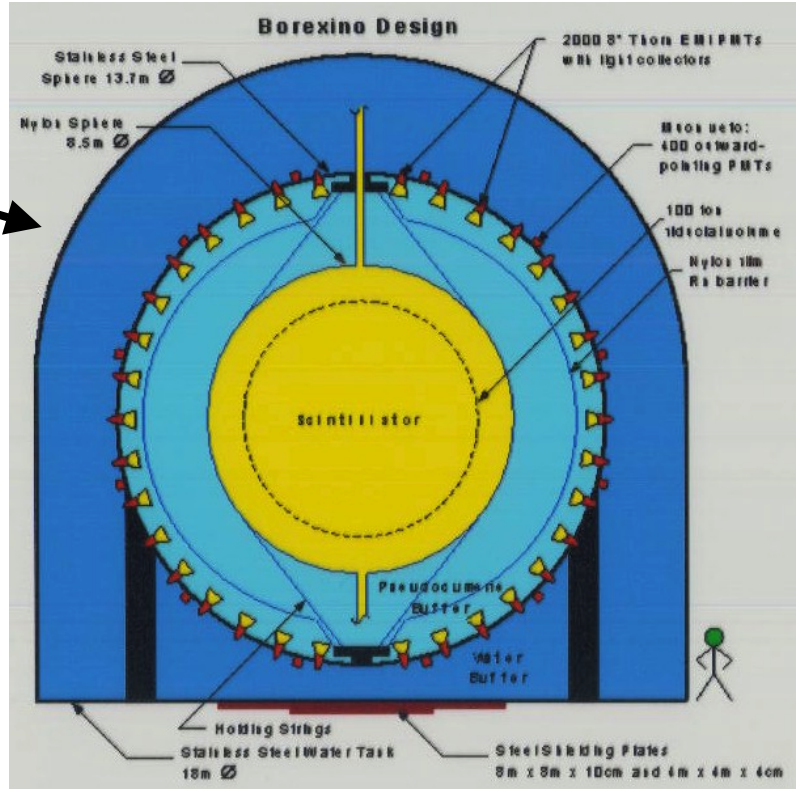
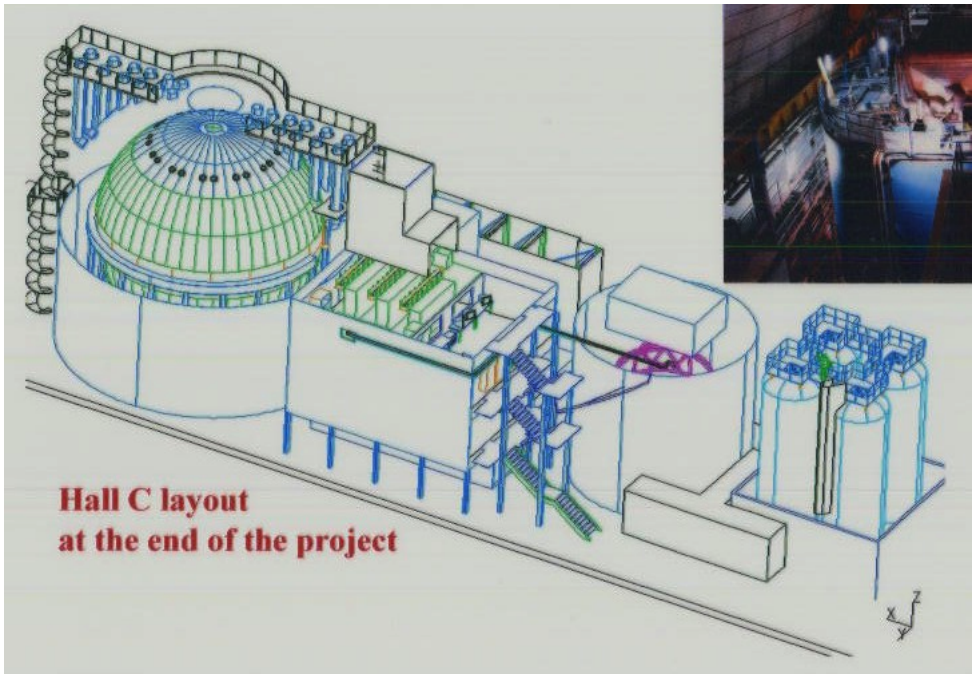
Borexino

ES in 300t superclean scintillator target





Under Construction, data taking end 2001

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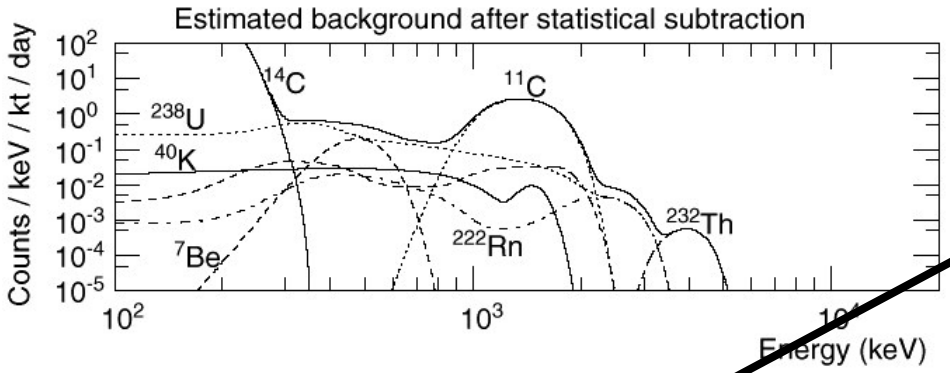
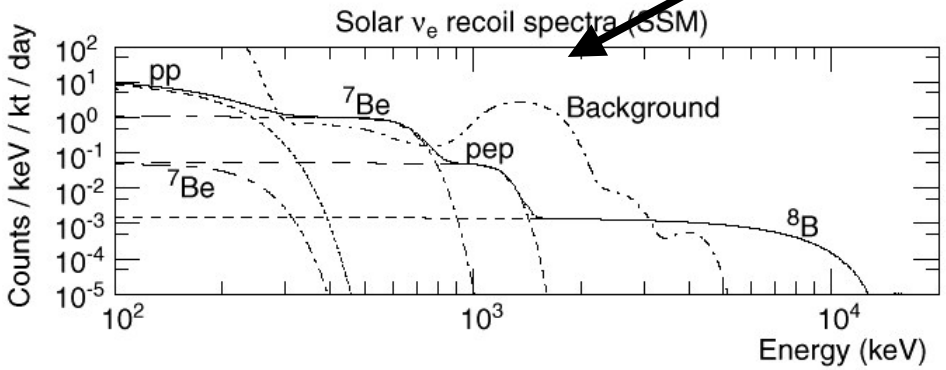
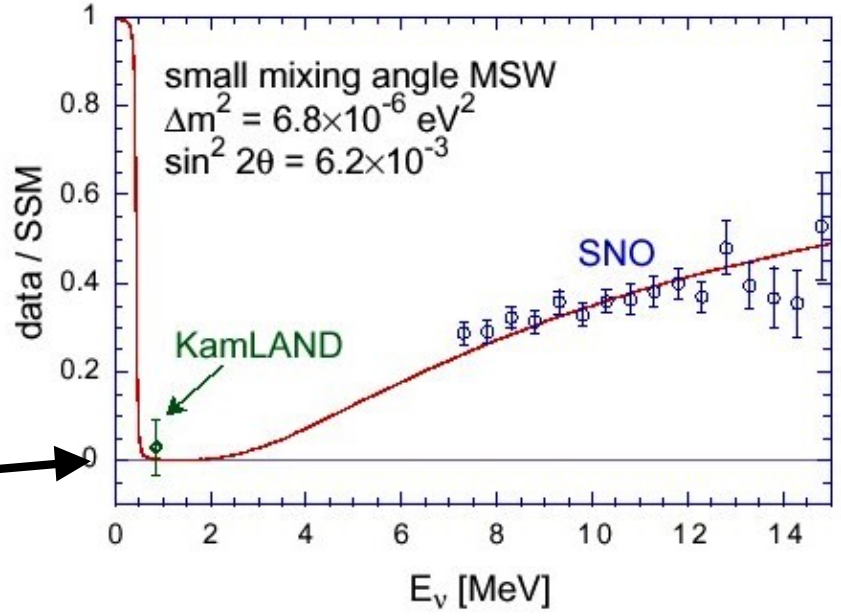
Signals and Backgrounds



Background suppression is challenging!



Signal suppression is promising!



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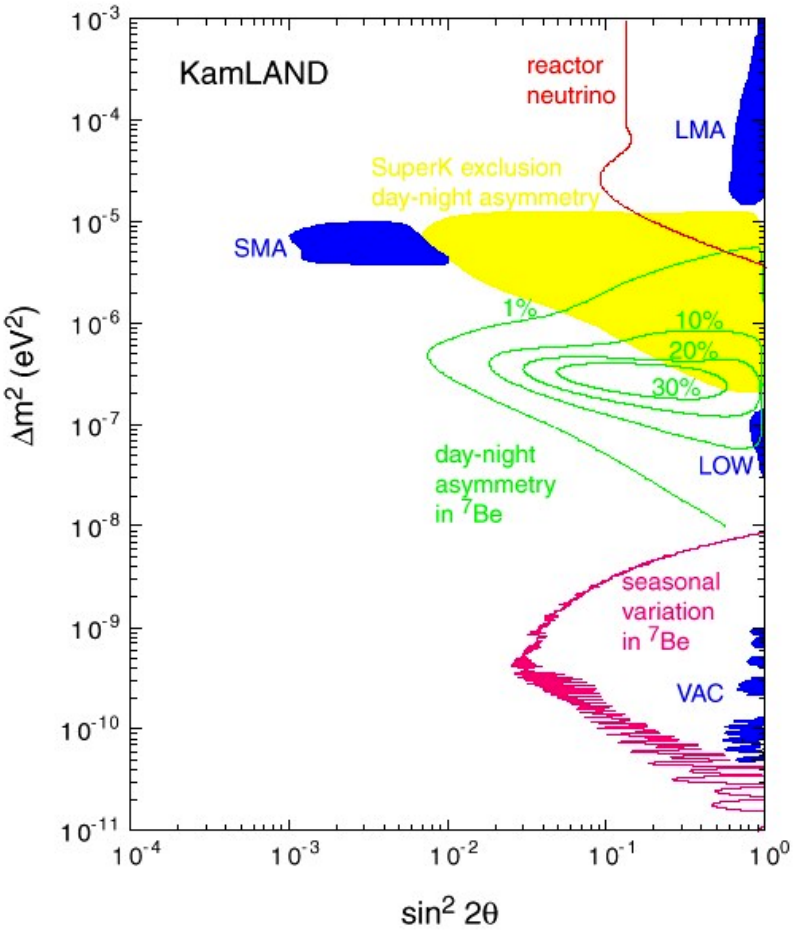
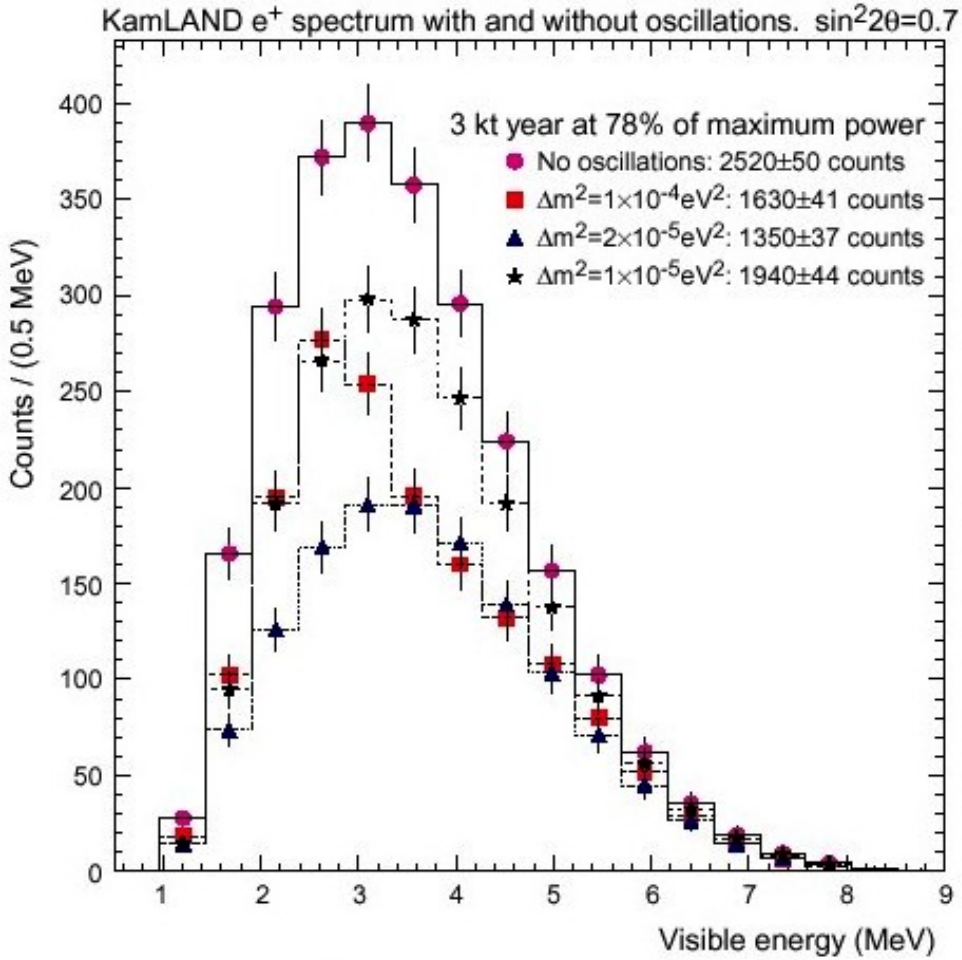
Oscillation Sensitivity





Reactor ν disappearance

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Conclusions

- Neutrino Oscillations very strongly indicated.
- A real Solar ν smoking gun from SNO collaboration.
- We live in interesting times……