Carleton UNIVERSITY

What can we learn about neutrinos at SNOLAB !?

Alain Bellerive

Canada Research Chair

Carleton University

www.snolab.ca

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

Outline

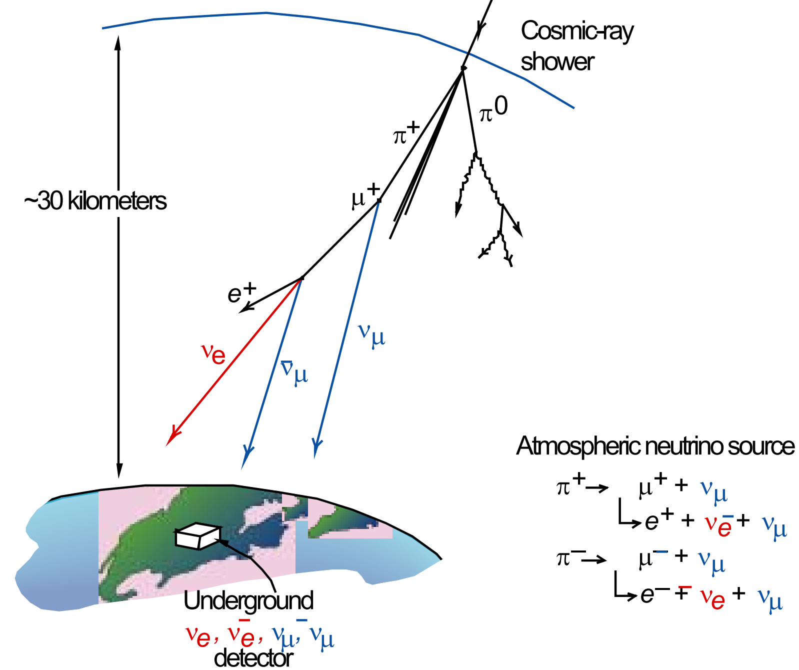
- Introduction & Neutrino Production in the Sun
- Solar Neutrino Problem
- Neutrino Oscillation and Matter Effects
- **Results from the Sudbury Neutrino Observatory**
- Constraints on Oscillation Parameters
- The Next Phase for SNO
- **Future Prospects at SNOLAB**
- A Proposal for Xenon Double Beta Decay Search
- Time Projection Chamber R&D
- Summary and Conclusion

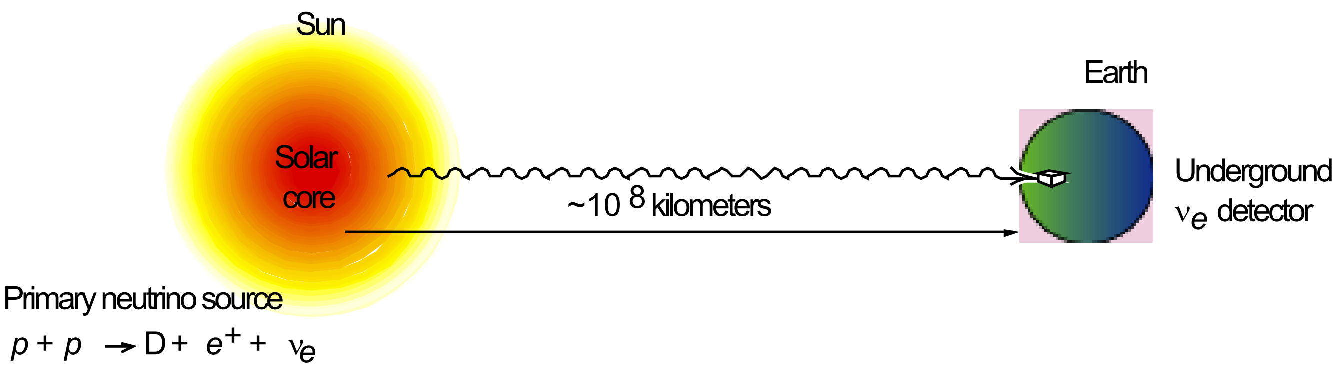
Evidence for Neutrino Oscillations

First evidence of neutrino oscillation

$$\frac{\nu_\mu}{\nu_e} \neq 2$$

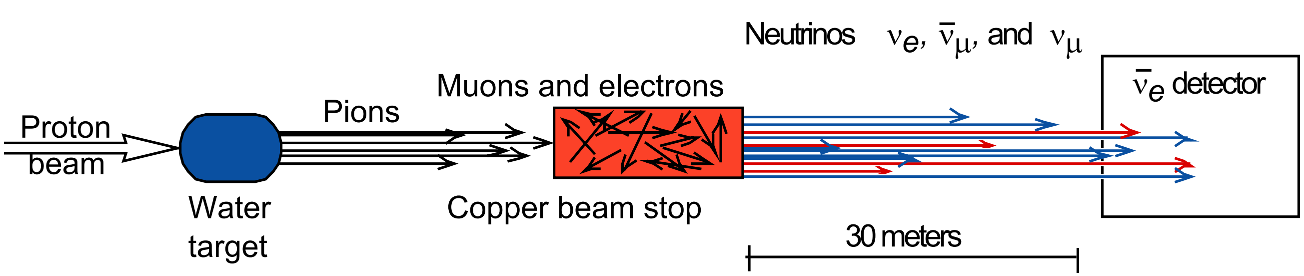
Atmospheric Neutrinos
high energies





Solar Neutrinos
low energies

Today's talk !!!



Neutrino Beams
and Reactors

Tunable energies and distances!

Macroscopic Properties of the Sun

Mean Distance from the Earth: 1.5×10^{11}m

Mass: 2×10^{30} kg

Radius: 6.96×10^{8} m

Luminosity: 3.8×10^{26} W

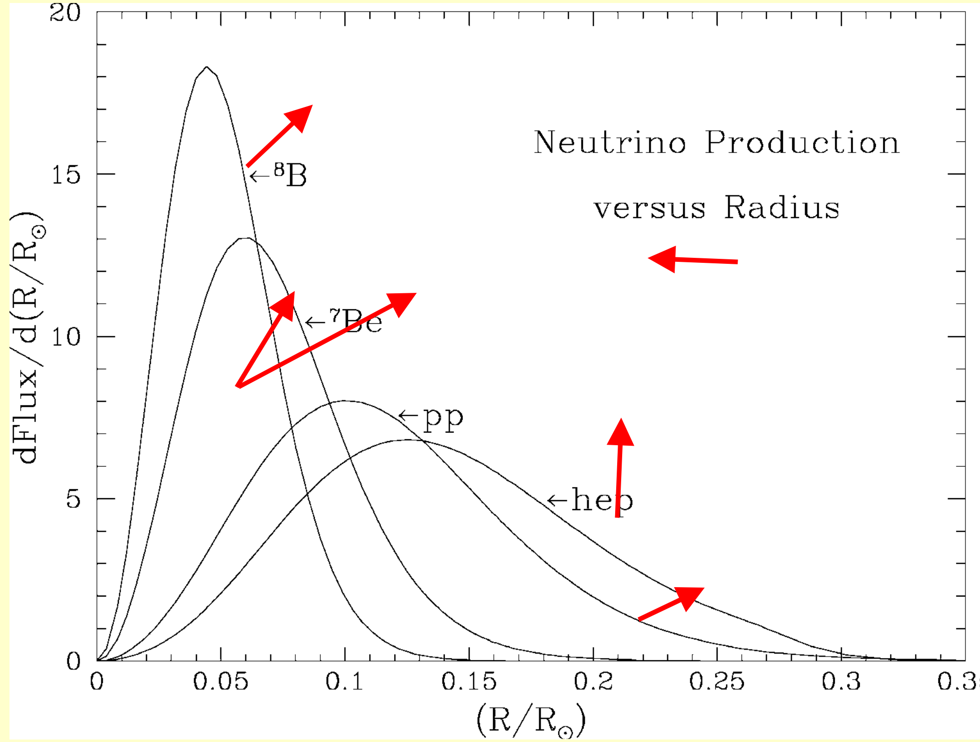
Neutrino flux: 6.5×10^{11} cm^{-2} s^{-1}

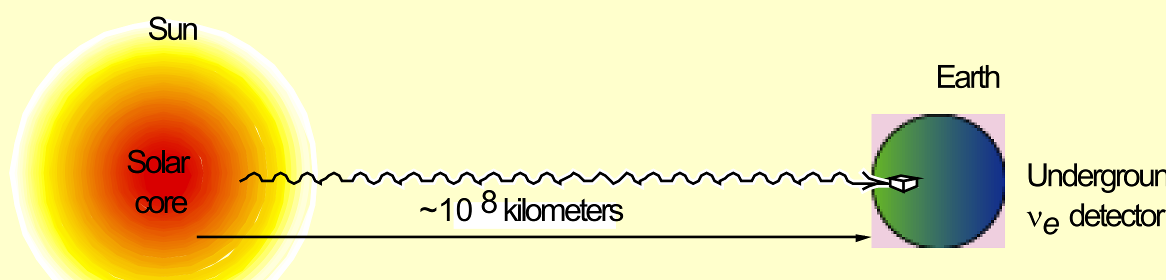
Neutrino Production in the Sun

Light Element Fusion Reactions

★ $p + p \rightarrow {}^{2}H + e^{+} + \nu_e$	99.75 %
★ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$	0.25 %
★ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$	~10^{-5} %
★ ${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$	15 %
★ ${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$	0.02 %

Neutrino Production Radius





Primary neutrino source

$p + p \rightarrow D + e^{+} + \nu_e$

Solar ν Flux Measurement Results

Experiment	Year	Detection Reaction	Ratio Exp/BP2000
Chlorine (127 t)	1970-1995	$^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Kamiokande (680t)	1986-1995	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.54 ± 0.08
SAGE (23 t)	1990-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.55 ± 0.05
Gallex + GNO (12 t)	1991-	$^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$	0.57 ± 0.05
SuperK (22kt)	1996-	$\nu_x + e^- \rightarrow \nu_x + e^-$	$0.451^{+0.017}_{-0.015}$

Chlorine – Gallium – Water experiments
have
different energy threshold

!!! The data suggest an energy dependence !!!

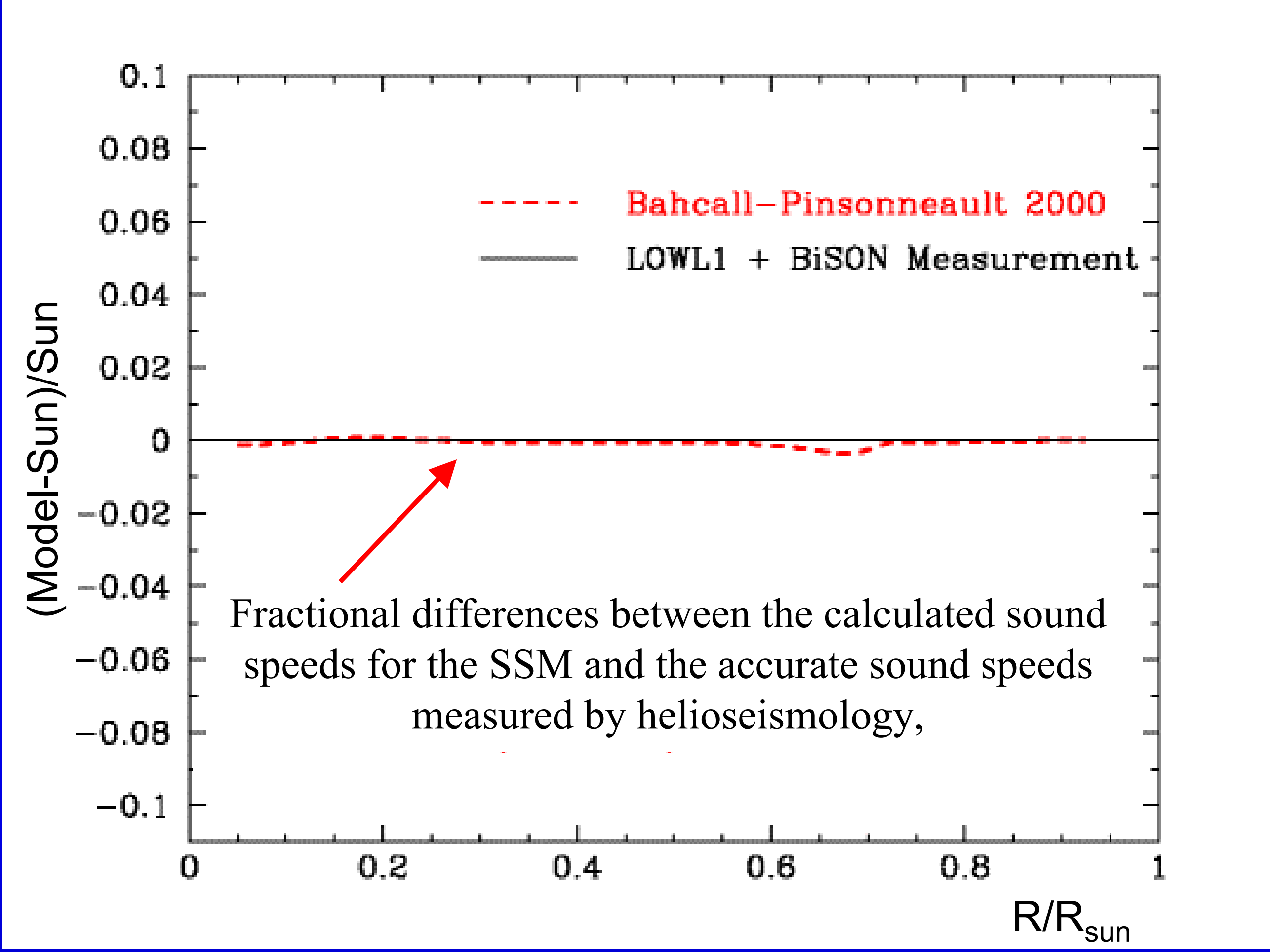
??? What could explain such a variation ???

Solar Neutrino Problem

- Historically the first culprit was assumed to be the method of determining the solar ν flux.
- In fact, the last 30 years showed that the SSM provides and accurate description of the macroscopic properties of our Sun.
- The mass, radius, shape, luminosity, age, chemical composition, and photon spectrum of the Sun are precisely determined and used as input parameters.
- Equation of state relates pressure and density; while the radiative opacity dictates photon transport.
- Experimental fusion cross sections used to determined the nuclear reaction rates.

Test of Standard Solar Model

SSM determines the present distribution of physical variables inside the Sun (like the core temperature and density), photon spectrum, the speed of sound, , and the neutrino fluxes.



Neutrino Mixing:

- As in the quark sector, it is possible to define a neutrino mixing matrix which relates the mass and weak eigenstates

Mixing Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

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

Solar Neutrino Oscillations

$P_{ee} = \sin^2(2\theta)\ \sin^2(1.27\Delta m^2\ L / E)$

- **Physics:**

  Δm^2 & $\sin(2\theta)$

- **Experiment:**

  Distance (L) & Energy (E)

$\Delta m^2 \equiv \Delta m^2_{12}$ and $\theta \equiv \theta_{12}$

3 Parameters !

$$\Delta m^2 = m_2^2 - m_1^2$$

$$\theta = \text{Mixing angle}$$

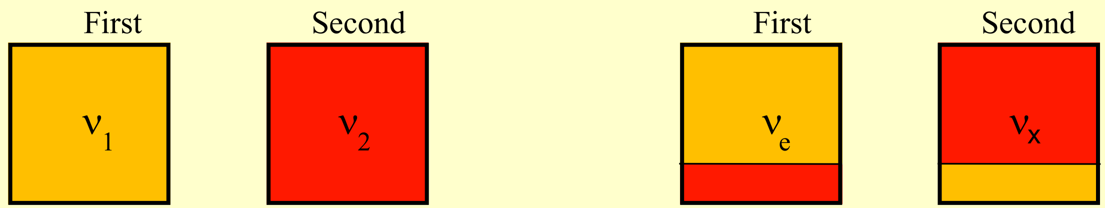
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The state evolves with time or distance

Neutrino Oscillations in matter

Neutrino States

Mass States **Weak States**



Time Evolution

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

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

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

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

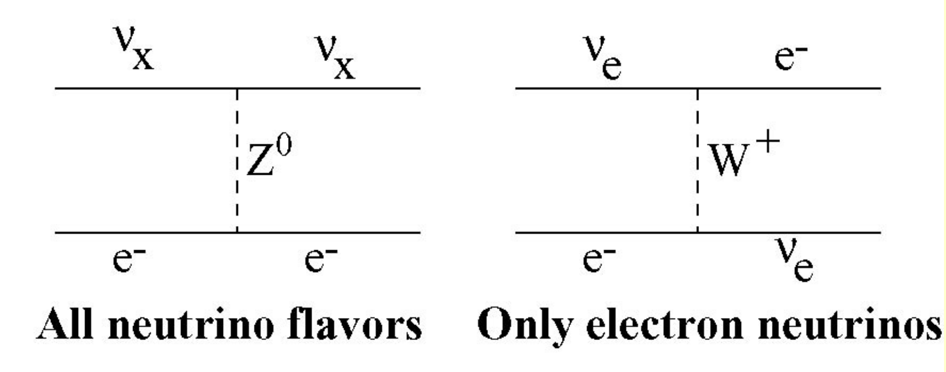
Matter-Enhanced Neutrino Oscillations

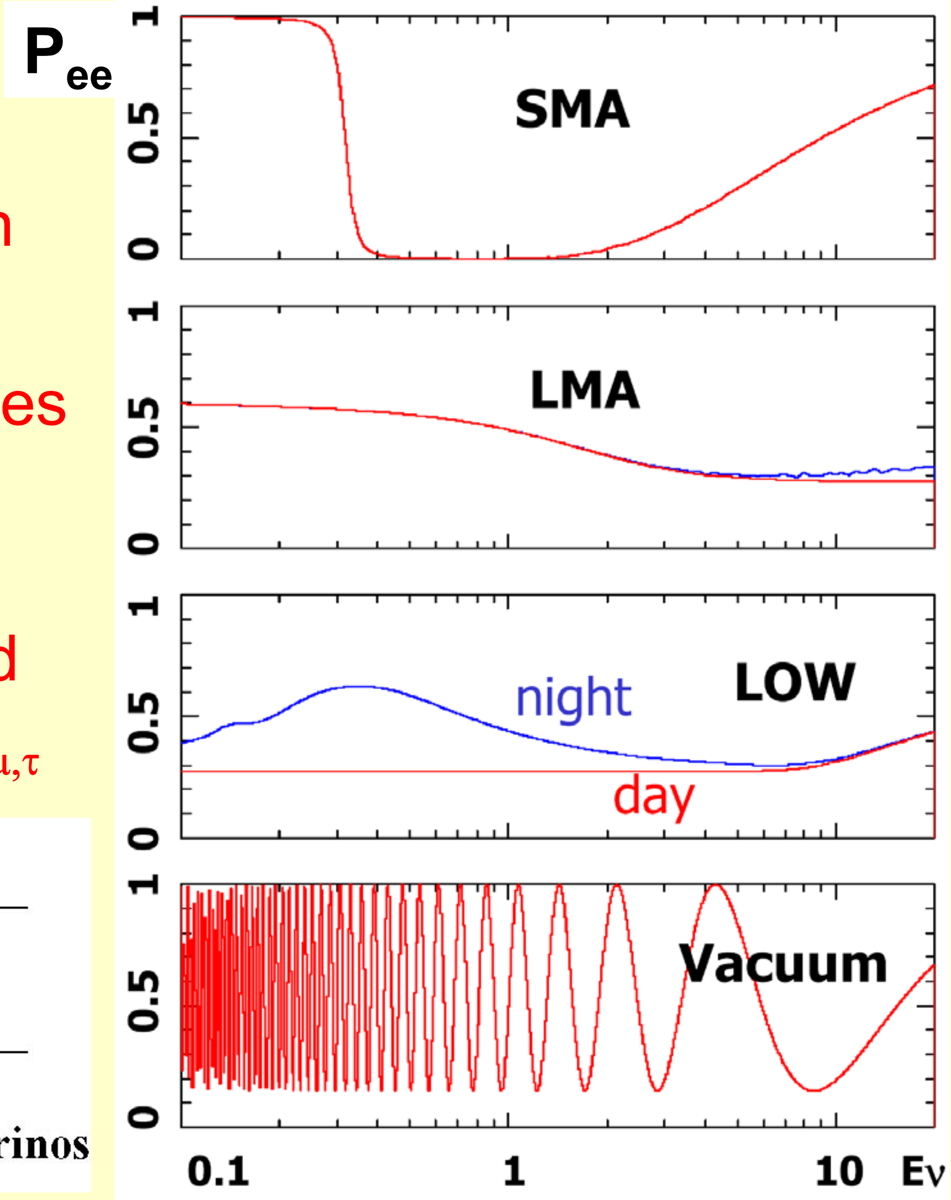
Neutrinos produced in weak state ν_e

$\Rightarrow$ High density of electrons in the Sun

$\Rightarrow$ Superposition of mass states $\nu_{1,2,3}$ changes through the MSW resonance effect

$\Rightarrow$ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$





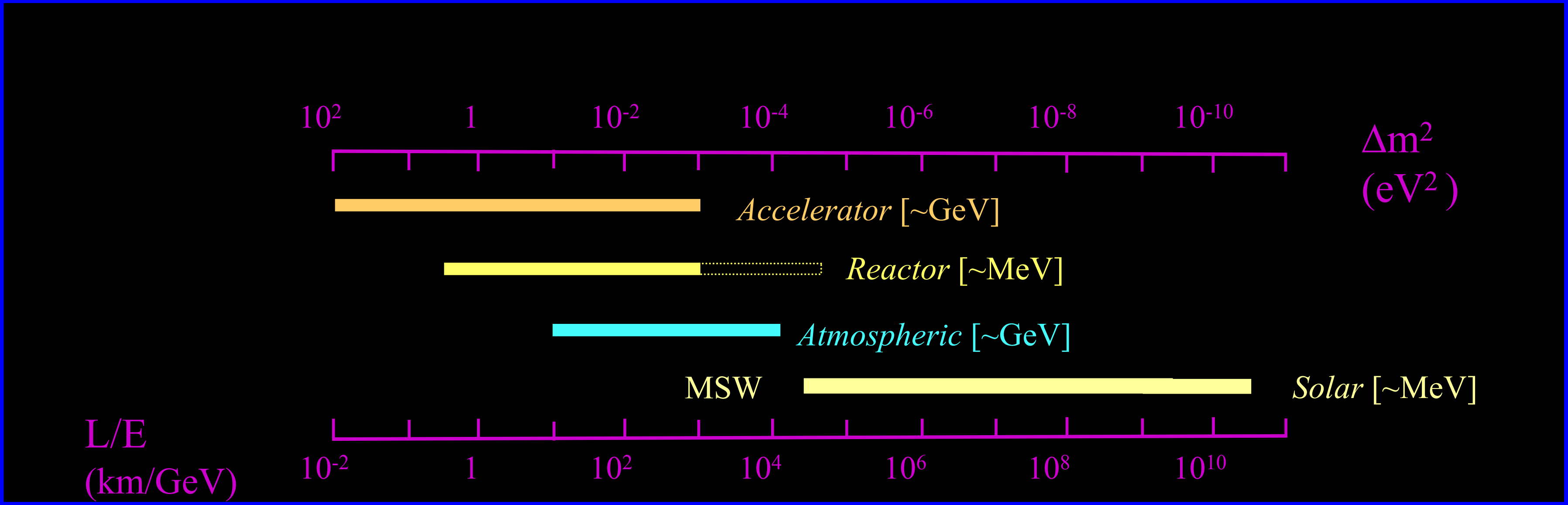
Sensitivity to ν oscillations

Vacuum Oscillations

- Different types of experiments sensitive to different aspects of oscillation space

MSW Oscillations

- For ν's in matter can acquire an effective mass through scattering, enhancing oscillations

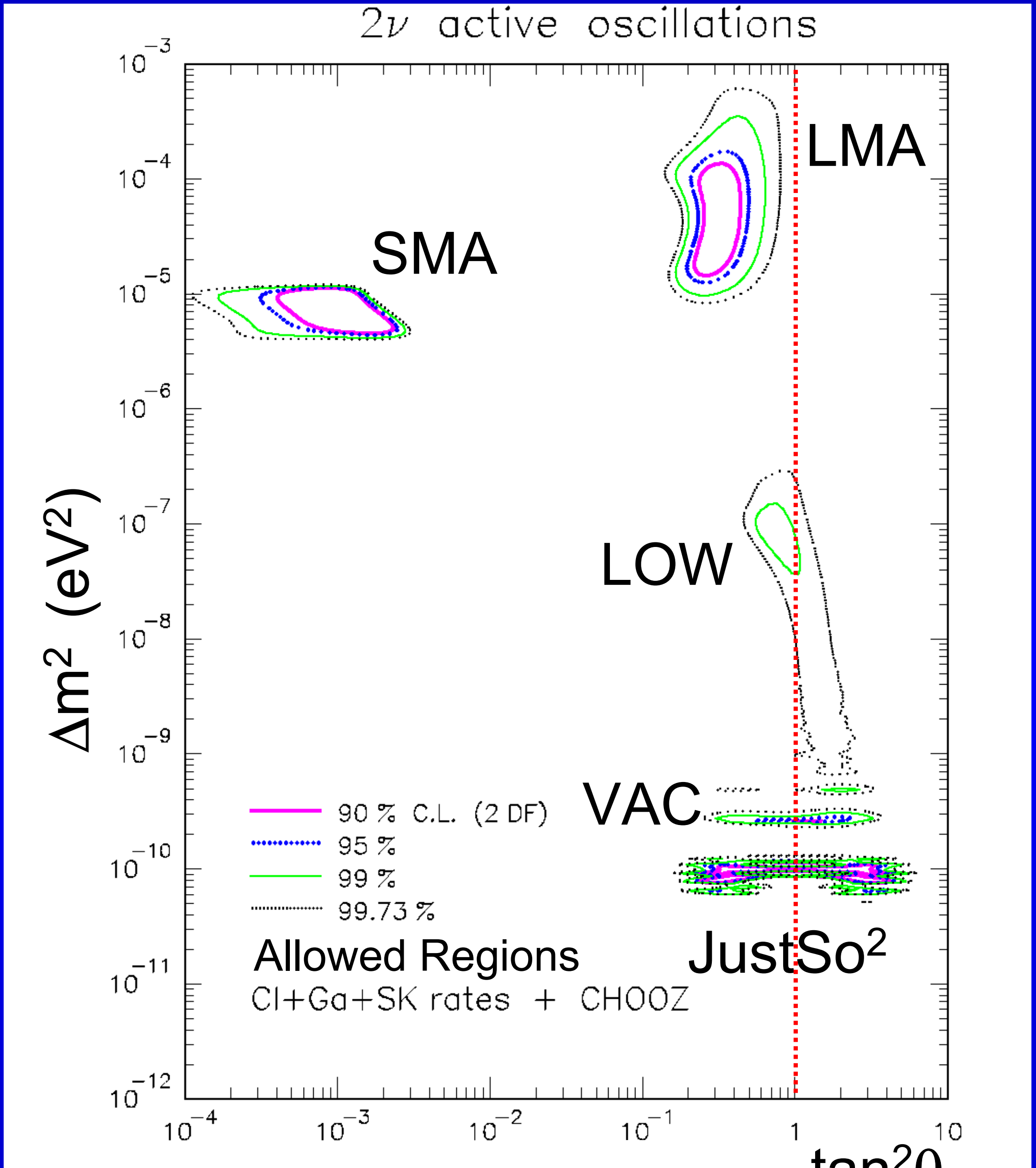


MSW = Mikheyev – Smirnov - Wolfenstein

Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO



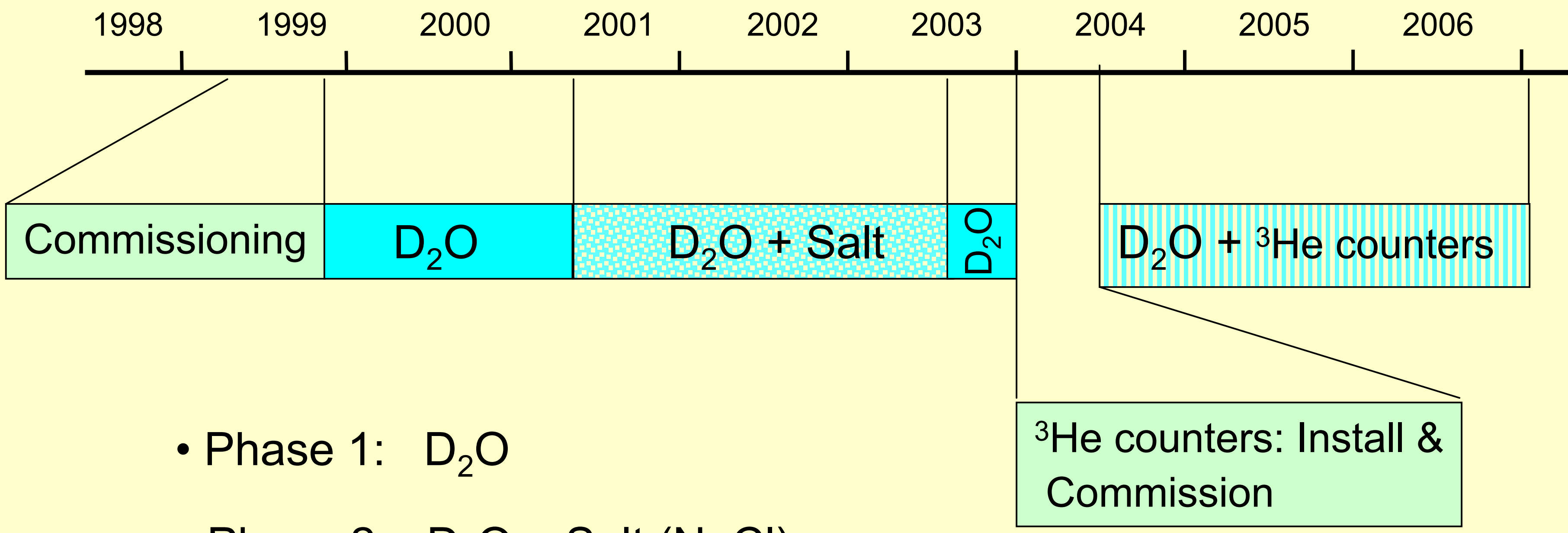
Phys.Rev. D64 (2001) 093007

Subury Neutrino Observatory

- Timeline
- Experimental Apparatus
- First Results from the D_20 Phase
- Most Recent Results from the Salt Phase NEW
- Outlook to the NCD Phase

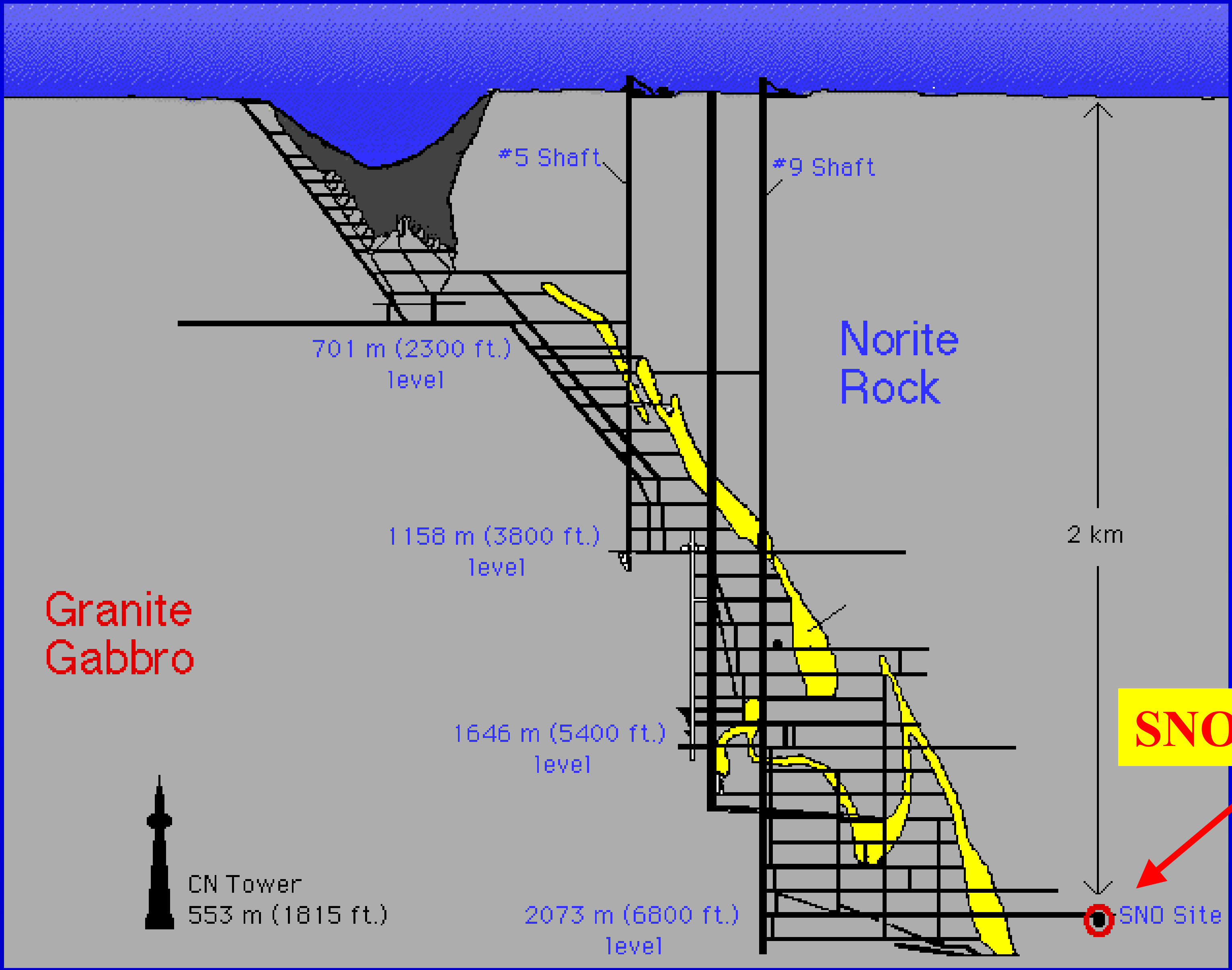
OVERAL PICTURE

SNO Timeline



- Phase 1: D_2O
- Phase 2: D_2O + Salt (NaCl)
- Phase 1a: D_2O
- Phase 3: D_2O + ^{3}He counters

Underground laboratory in Sudbury



NEW

SNOLAB

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

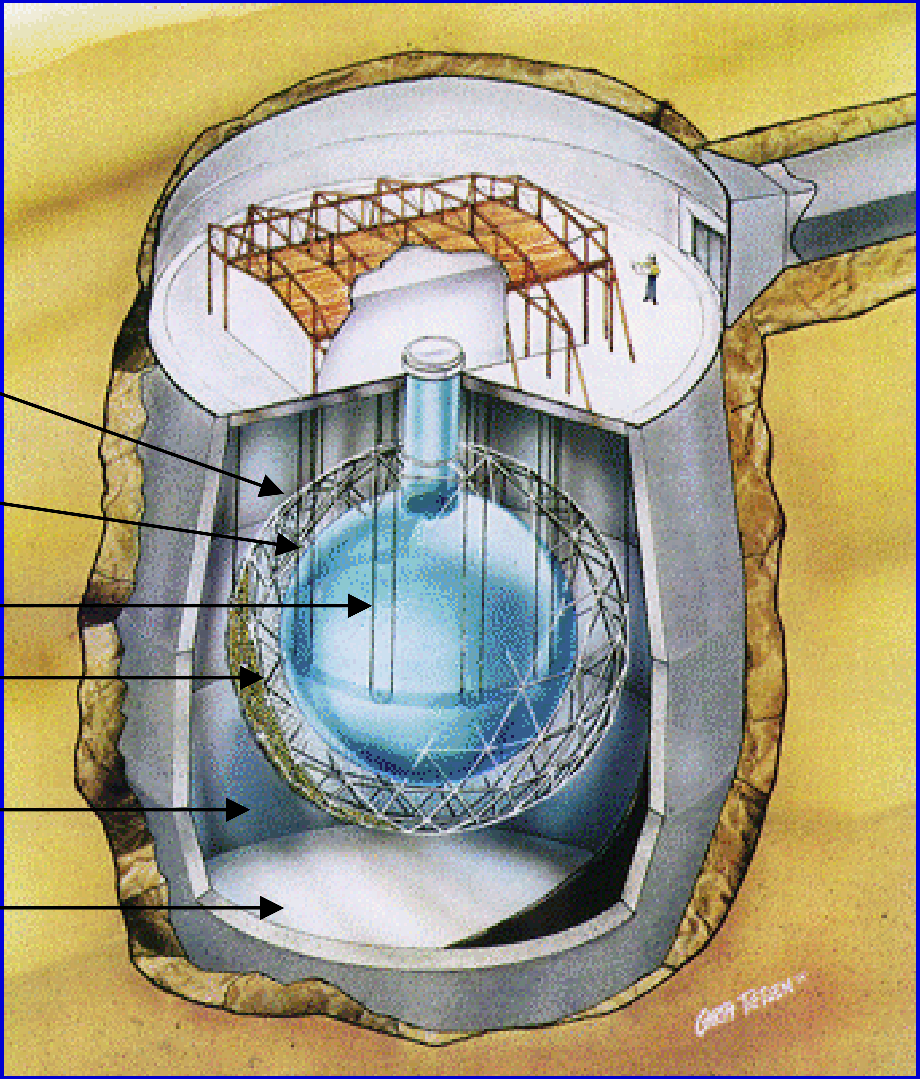
PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

Acrylic Vessel, 12 m diameter

1000 tonnes D_2O
1700 tonnes H_2O, Inner Shield

5300 tonnes H_2O, Outer Shield
Urylon Liner and Radon Seal

Energy Threshold = 5.511 MeV



Purpose of SNO

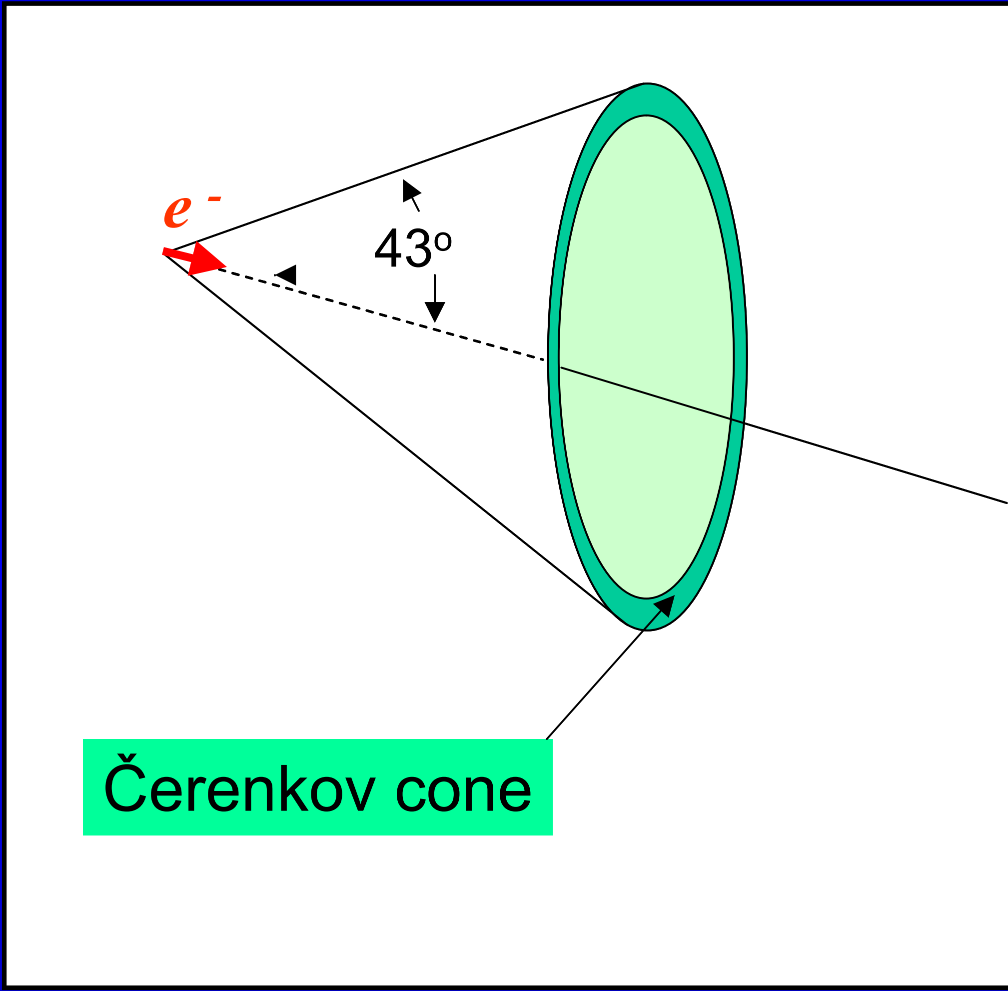
- If Solar Neutrino Problem due to ν_e flavour mixing to ν_μ and/or ν_τ, SNO should provide direct evidence .
- SNO measures flux of ν_e and flux of $(\nu_e+\nu_\mu+\nu_\tau)$.
- Previous expt's sensitive to only ν_e or mainly ν_e.

Water Čerenkov expt's:
Kamiokande, Super-K

Radiochemical expt's:
^{37}Cl at Homestake and
^{71}Ga at Gran Sasso/Baksan

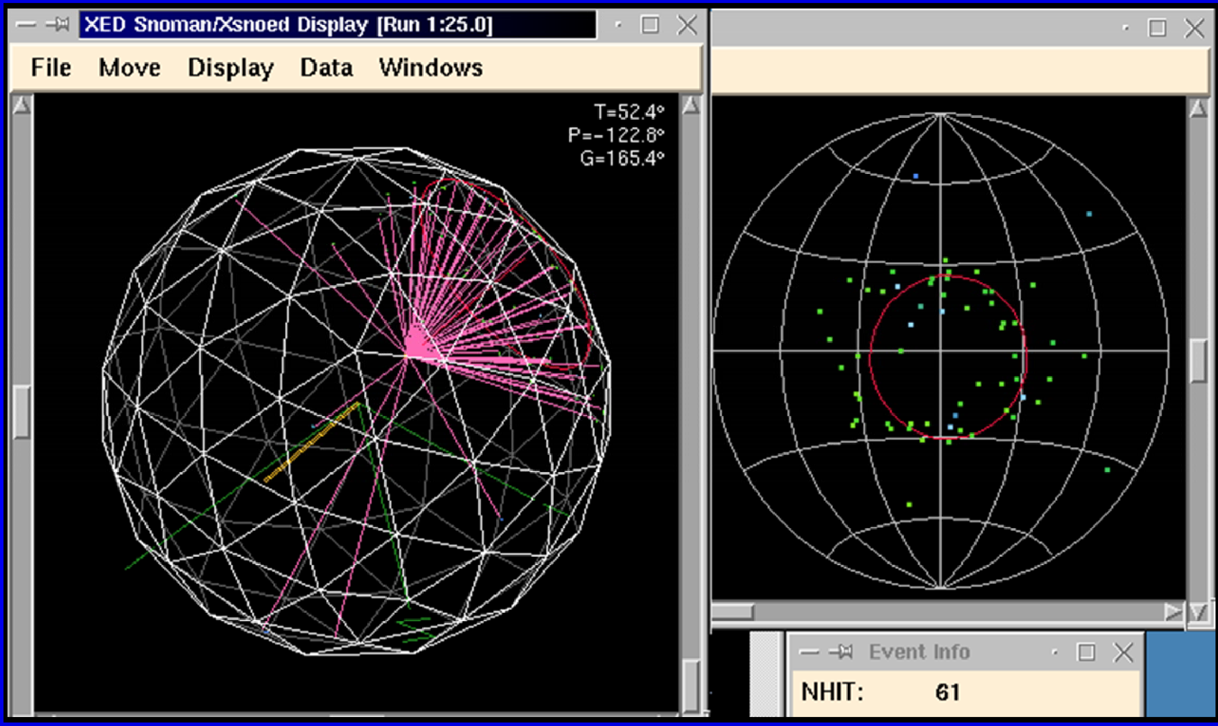
Neutrino detection in SNO

- PMTs detect Čerenkov photons from relativistic e^-:
  - e^- from CC or ES reaction
  - γ from n-capture (NC reaction) usually Compton-scatters e^- (pair production less likely).



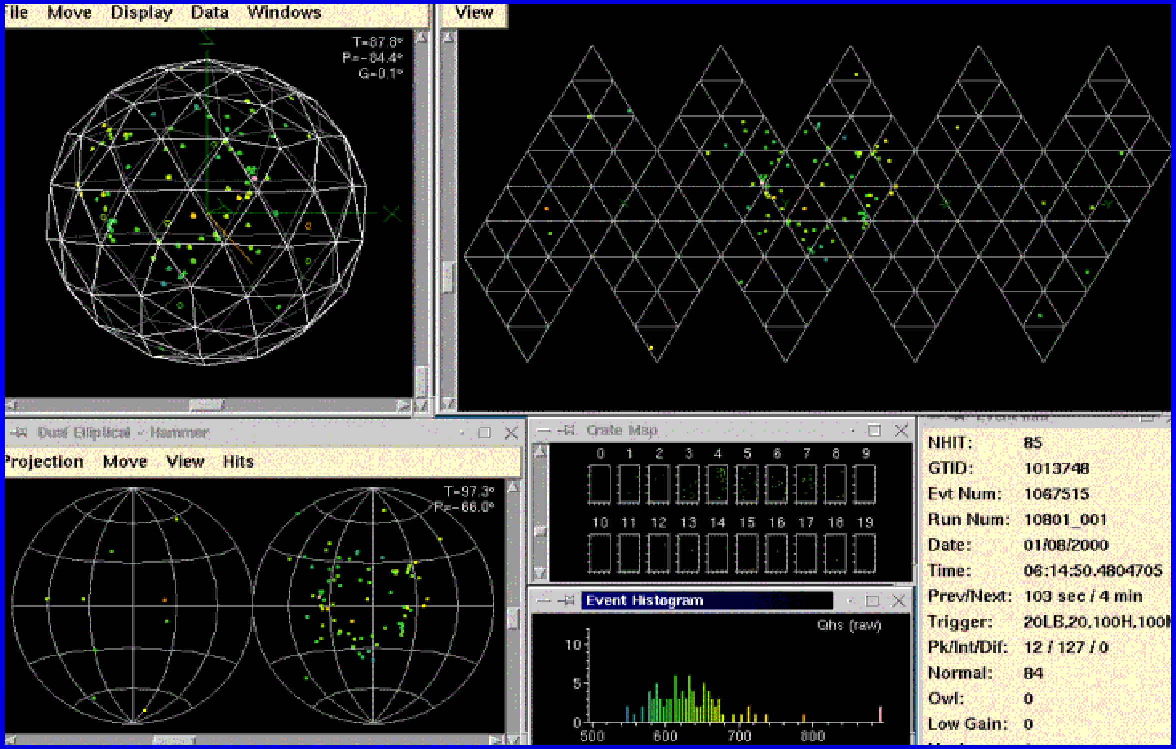
Neutrino detection in SNO

- Hit pattern from Čerenkov cone indicates physics event.
- PMT hit times and locations used to reconstruct e^- direction and location
- Number of PMT hits used to estimate electron energy.



SNO observables - event by event

PMT Information: Positions, Charges, Times



Event Reconstruction

Vertex, Direction, Energy, Isotropy

The SNO detector observes the following interactions:

CC **Charged Current**

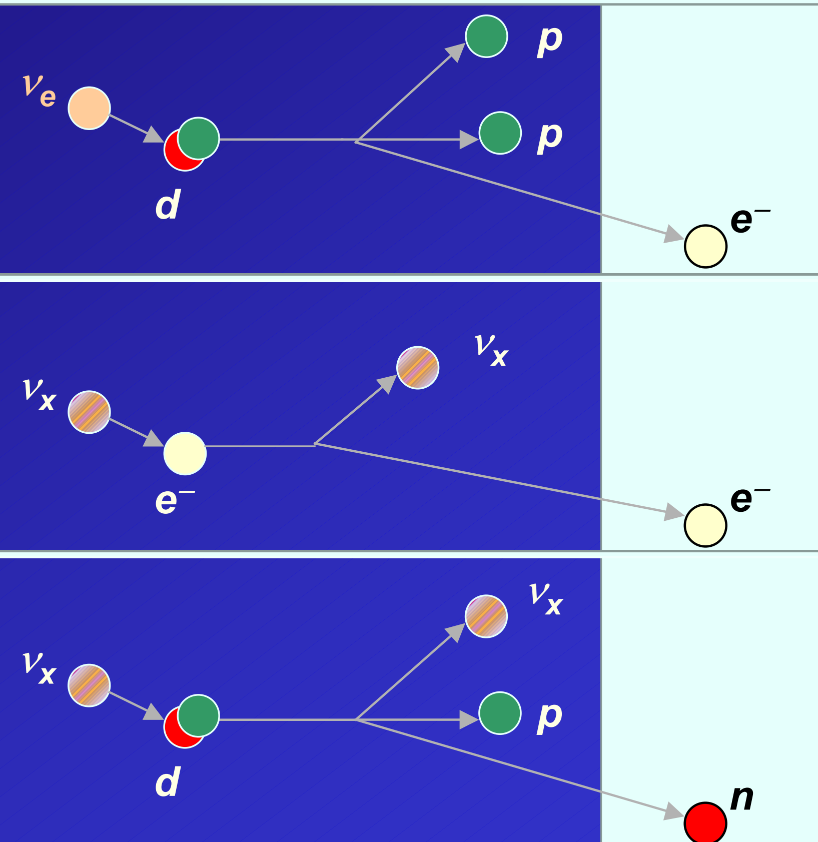
$\nu_e + d \rightarrow p + p + e^-$

ES **Elastic Scattering**

$\nu_x + e^- \rightarrow \nu_x + e^-$

NC **Neutral Current**

$\nu_x + d \rightarrow \nu_x + p + n$



Detected Particle

$x = e, \mu, \tau$

Neutrino Reactions in SNO

CC $\nu_e + d \rightarrow p + p + e^-$

Produces Cherenkov Light Cone in D_2O

- $Q = 1.445$ MeV
- good measurement of ν_e energy spectrum
- some directional info $\propto (1 - 1/3 \cos\theta)$
- ν_e only

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

n captures on deuteron ^2H or ^{35}Cl or ^3He

- $Q = 2.22$ MeV
- measures total ^8B ν flux from the Sun
- equal cross section for all ν types

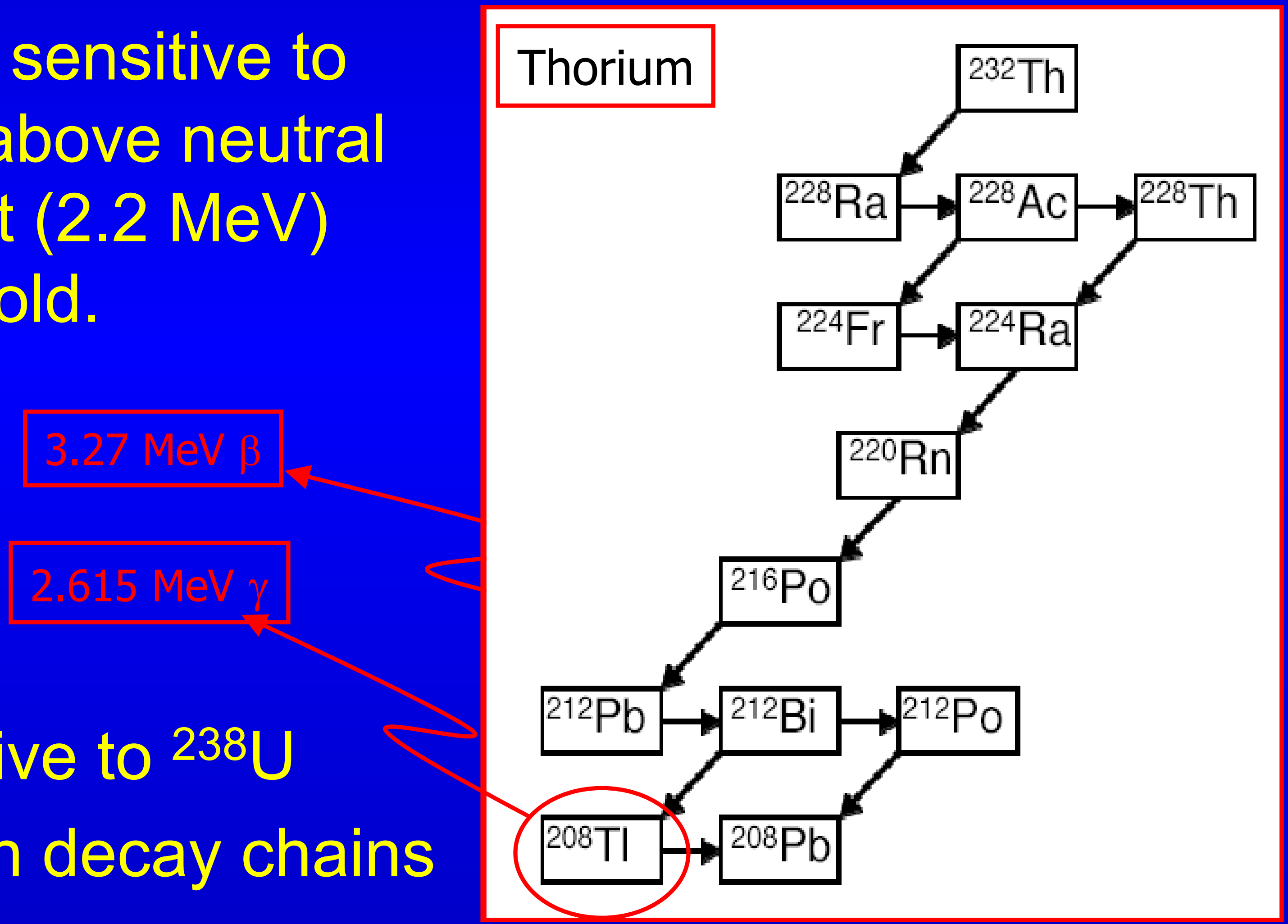
ES $\nu_x + e^- \rightarrow \nu_x + e^-$

Produces Cherenkov Light Cone in D_2O

- low statistics
- mainly sensitive to ν_e, some ν_μ and ν_τ
- strong directional sensitivity

An Ultraclean Environment

- Highly sensitive to any γ above neutral current (2.2 MeV) threshold.



- Sensitive to ^{238}U & ^{232}Th decay chains

Three Ways to Catch Neutrons!

$$\text{(NC)} \quad \nu_x + d \rightarrow \nu_x + p + n$$

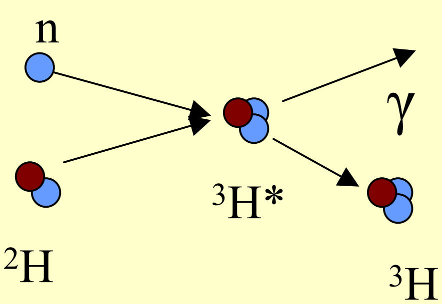
Pure D_2O

Nov. 99 - May 01

n captures on deuterium

$\sigma = 0.0005$b

6.2 MeV γ



PRL 87, 071301, 2001
PRL 89, 011301, 2002
PRL 89, 011302, 2002

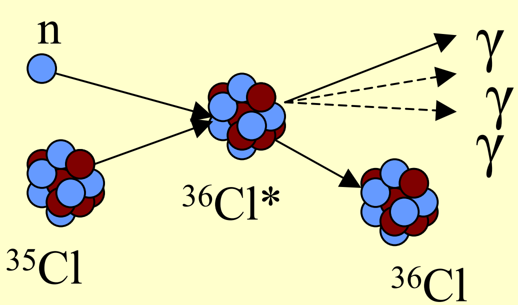
Salt

July 01 - Aug. 03

n captures on chlorine

$\sigma = 44$b

8.6 MeV multiple γ's



PRL 92, 181301, 2004
Submitted to PRC

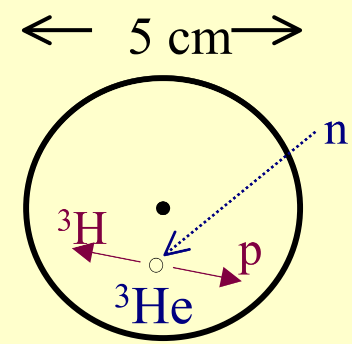
^{3}He

Summer 04 - Dec. 06

n captures on ^{3}He in discrete prop. counter array

$\sigma = 5330$b

0.764 MeV γ



$$n + {}^3He \rightarrow p + {}^3H$$

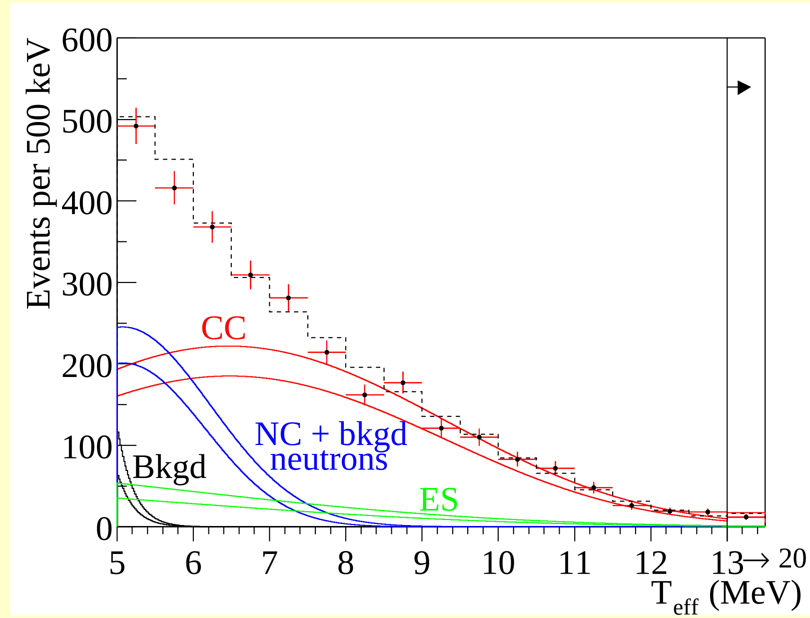
Subury Neutrino Observatory

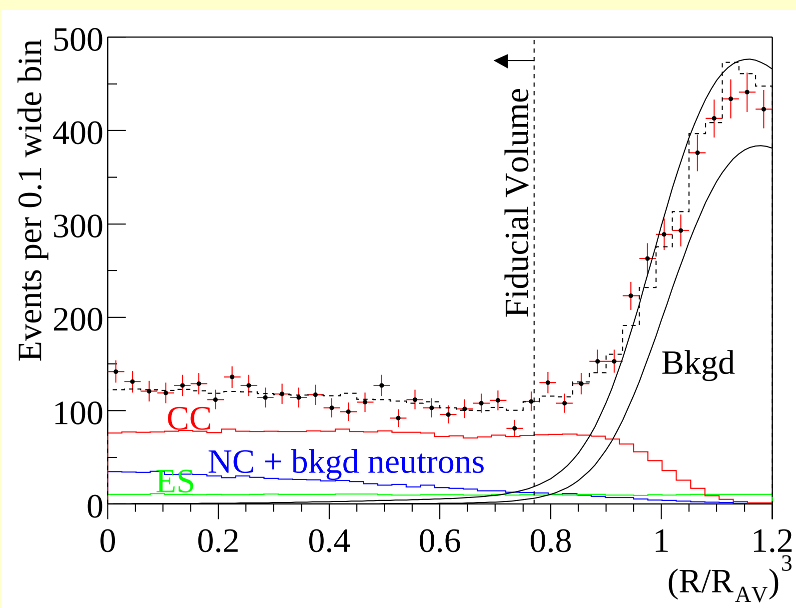
D_2O Results

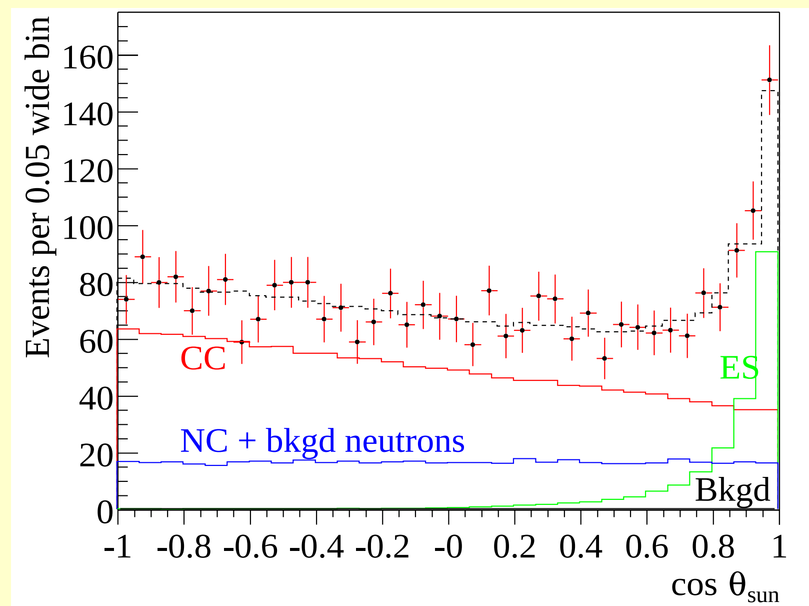
Shape Constrained Signal Extraction Results

#EVENTS

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







Shape Constrained Neutrino Fluxes

Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES} with E > 5.511 MeV

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

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

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

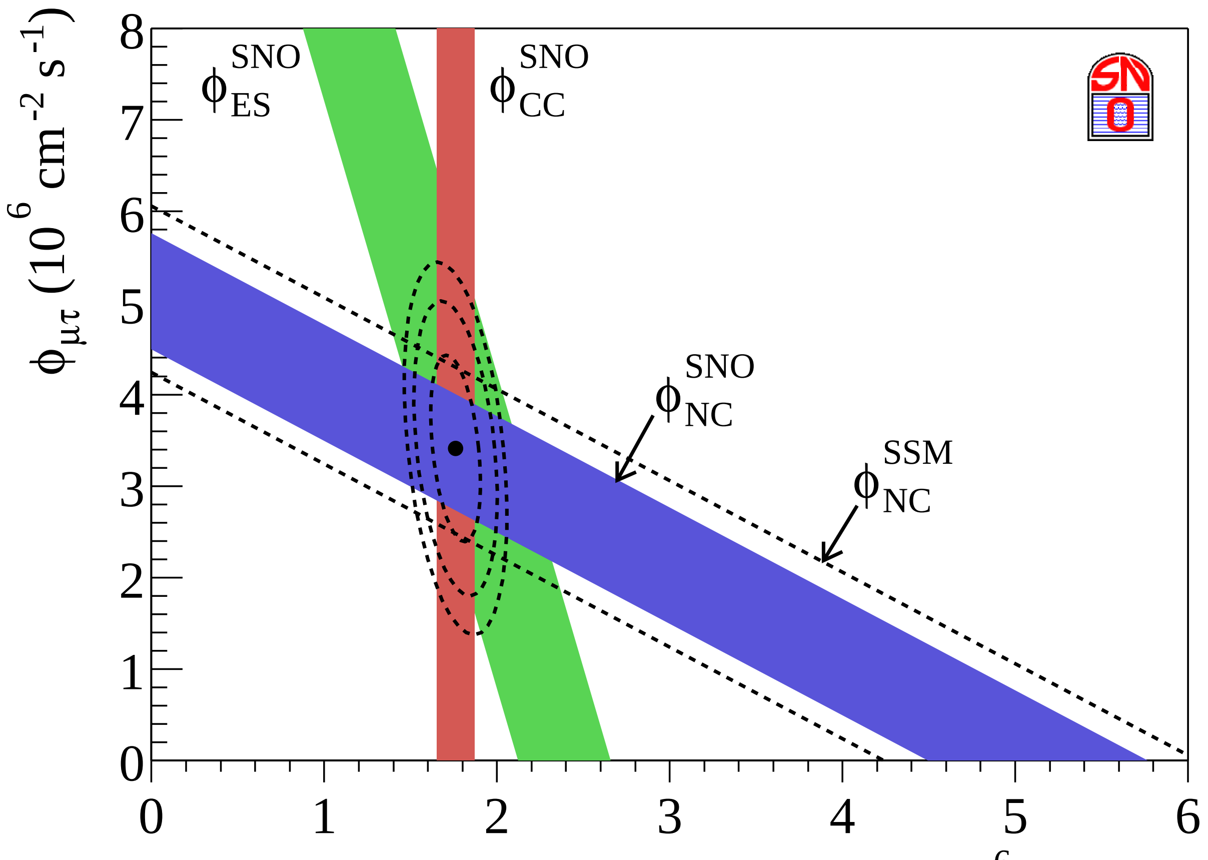
Signal Extraction in Φ_e, $\Phi_{\mu\tau}$

$$\Phi_e = 1.76^{+0.05}_{-0.05}\,(\text{stat.})\,^{+0.09}_{-0.09}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

$$\Phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}\,(\text{stat.})\,^{+0.48}_{-0.45}\,(\text{syst.})\ \text{x}10^6\ \text{cm}^{-2}\text{s}^{-1}$$

SNO NC in D_2O (April 2002)

~ 2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$



Phys. Rev. Lett. 89 (2002)

Flavor change at 5.3 σ level.

Sum of all the fluxes agrees with SSM.

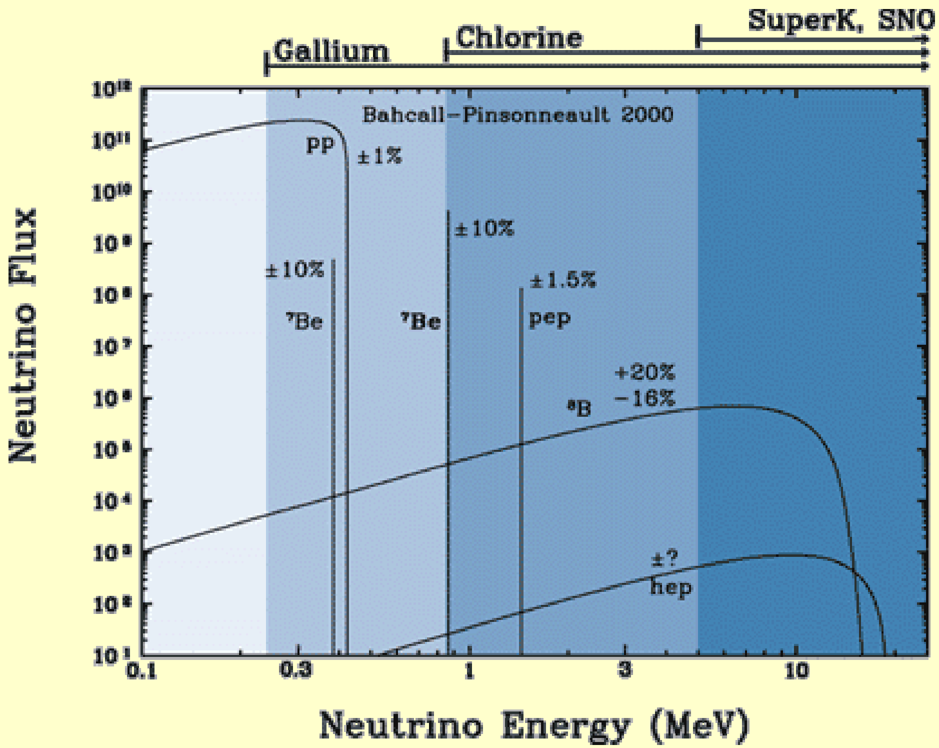
$$\Phi_{SSM} = 5.05^{+1.01}_{-0.81}$$

10^6 cm^{-2} s^{-1}

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

10^6 cm^{-2} s^{-1}

The Solar Neutrino Problem



Experiment	Exp/SSM
•SAGE+GALLEX/GNO	0.55
•Homestake	0.34
•Kamiokande+SuperK	0.47
•SNO CC (June 2001)	0.35
SNO NC (April 2002)	1.01

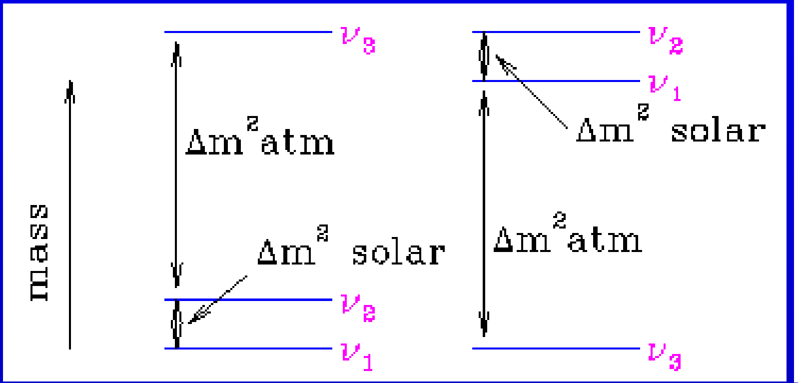
SNO CC vs NC implies flavor change, which can then explain other experimental results.

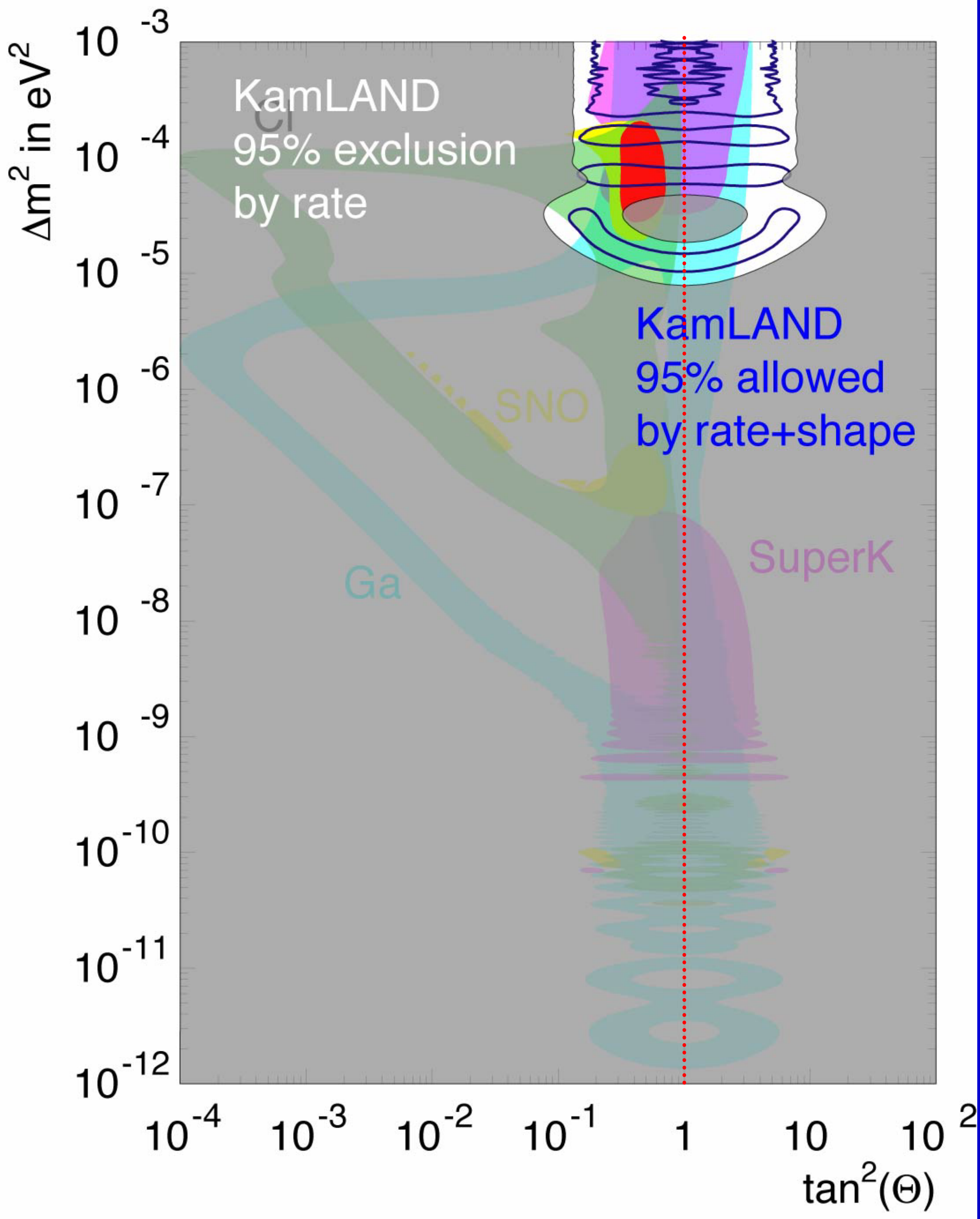
Progress in 2002 on the Solar Neutrino Problem

March 2002

April 2002 with SNO

Dec 2002 with KamLAND





Subury Neutrino Observatory

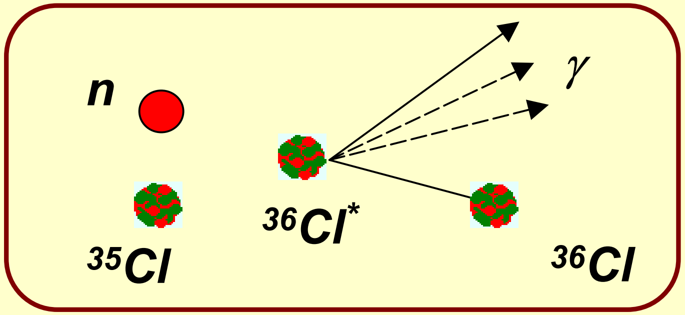
Salt Results

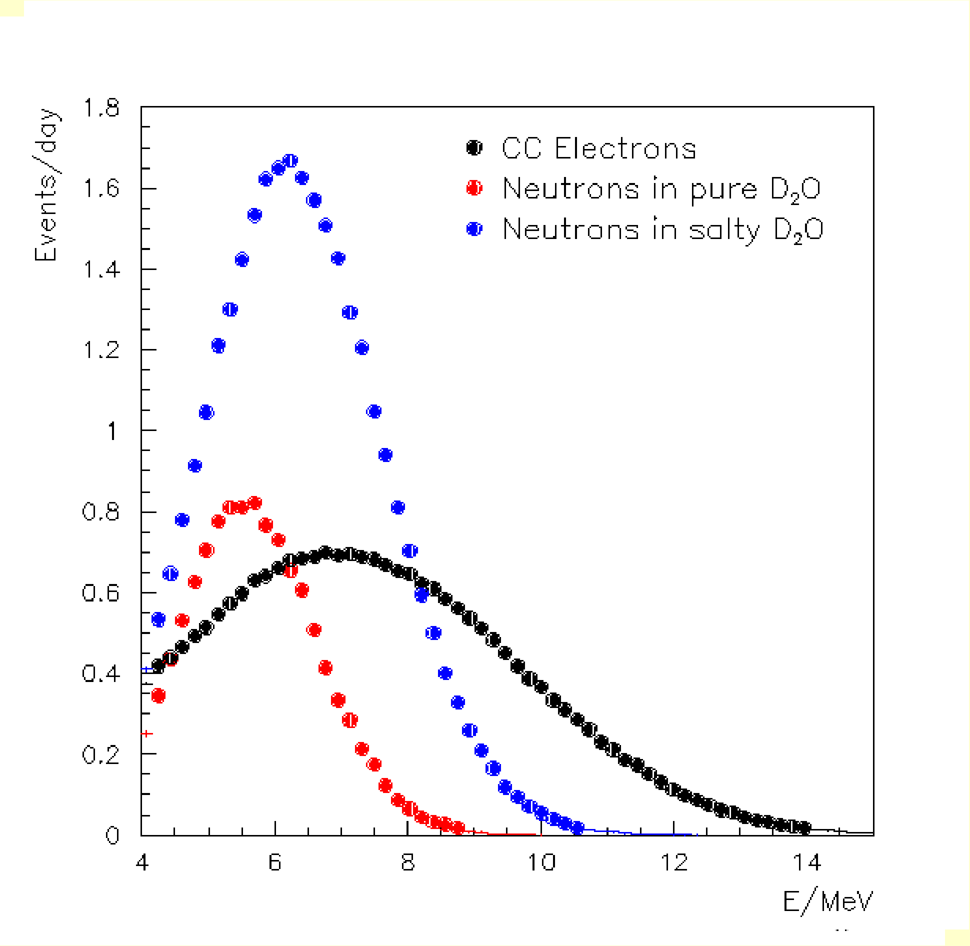
NEW

Nucl-exp / 0502021

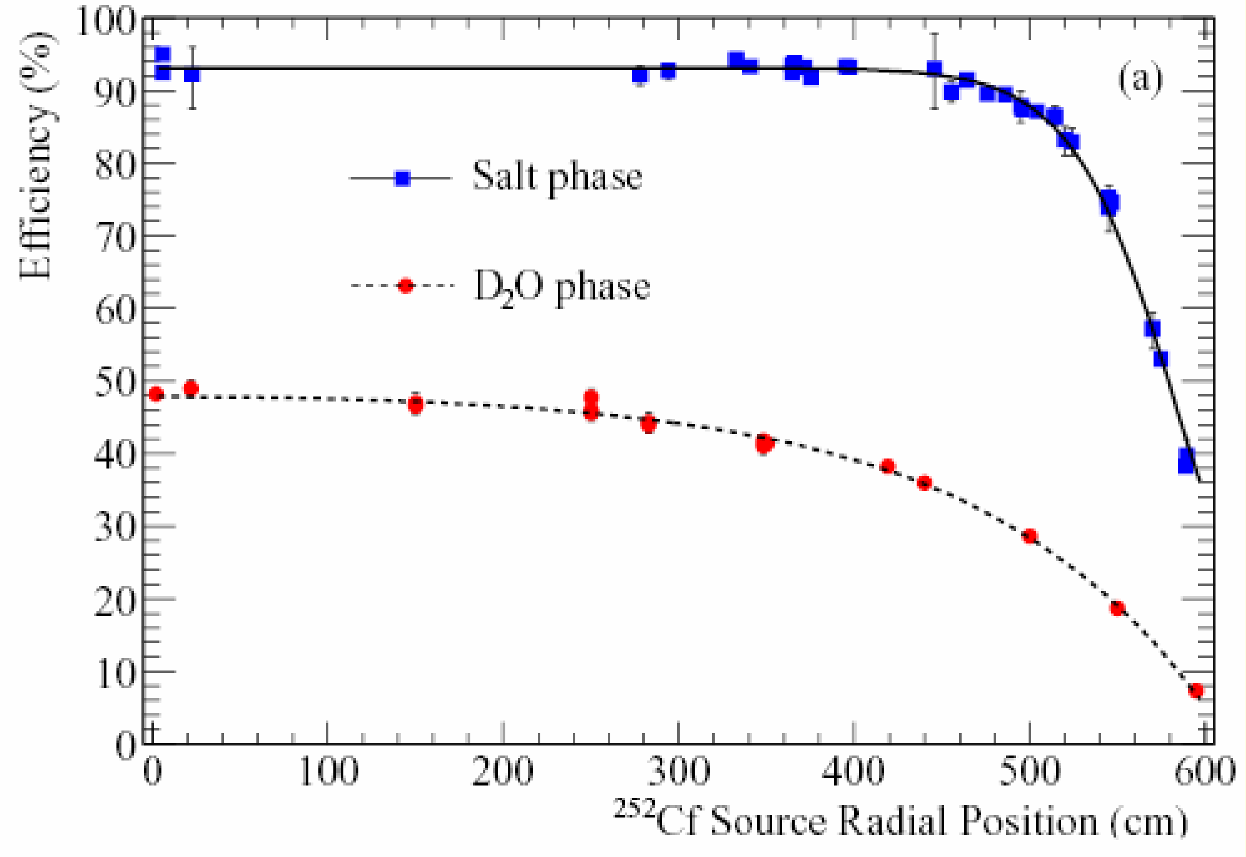
Advantages of Salt (original idea from Carleton)

- Neutrons capturing on ^{35}Cl provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.



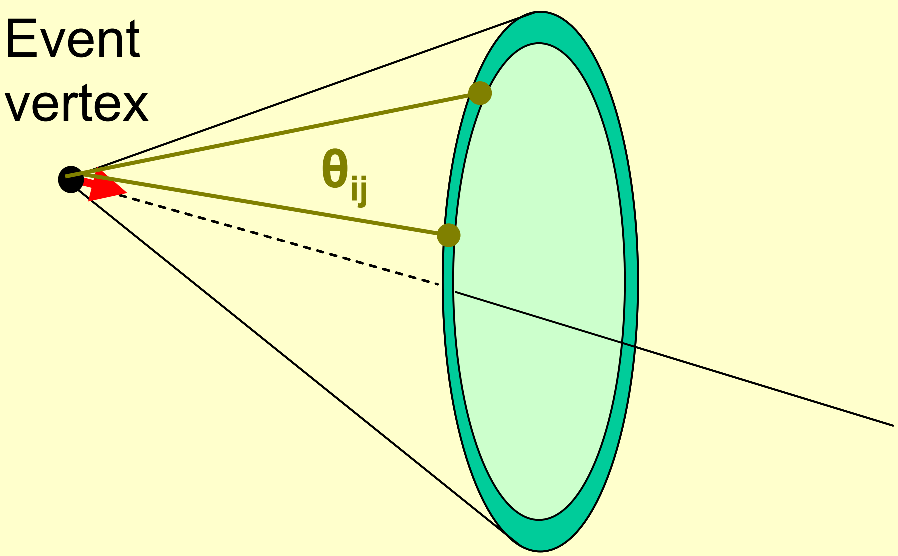


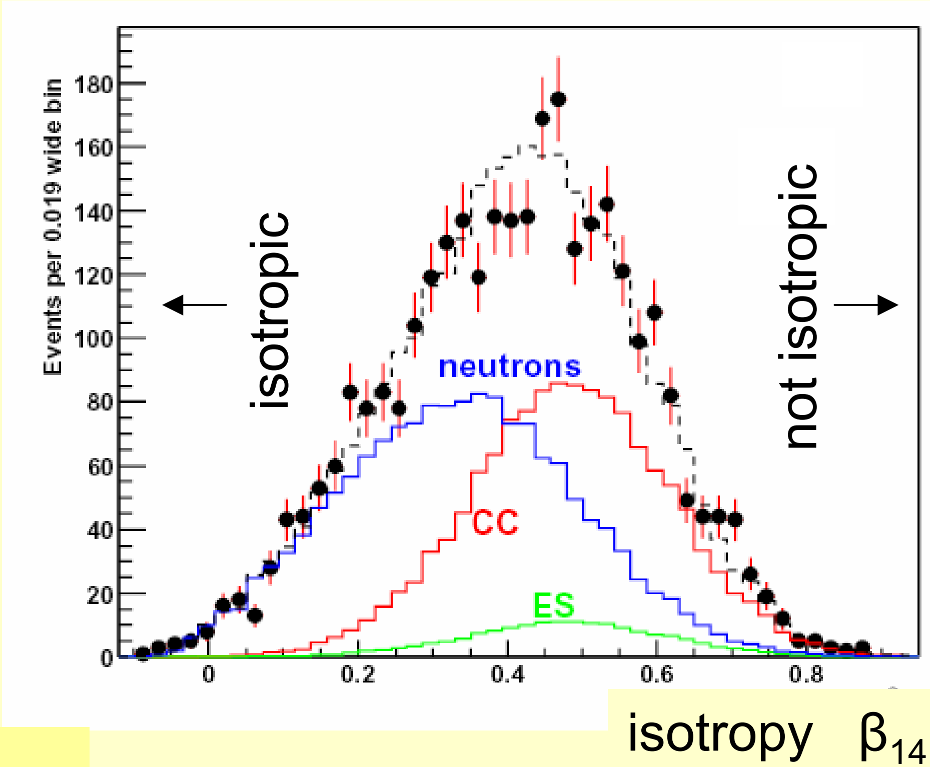
Advantages of salt: *n*-detection efficiency



With salt, higher E release from ***n***-capture and higher σ for ***n***-capture mean much higher NC detection efficiency.

Advantages of salt: event isotropy

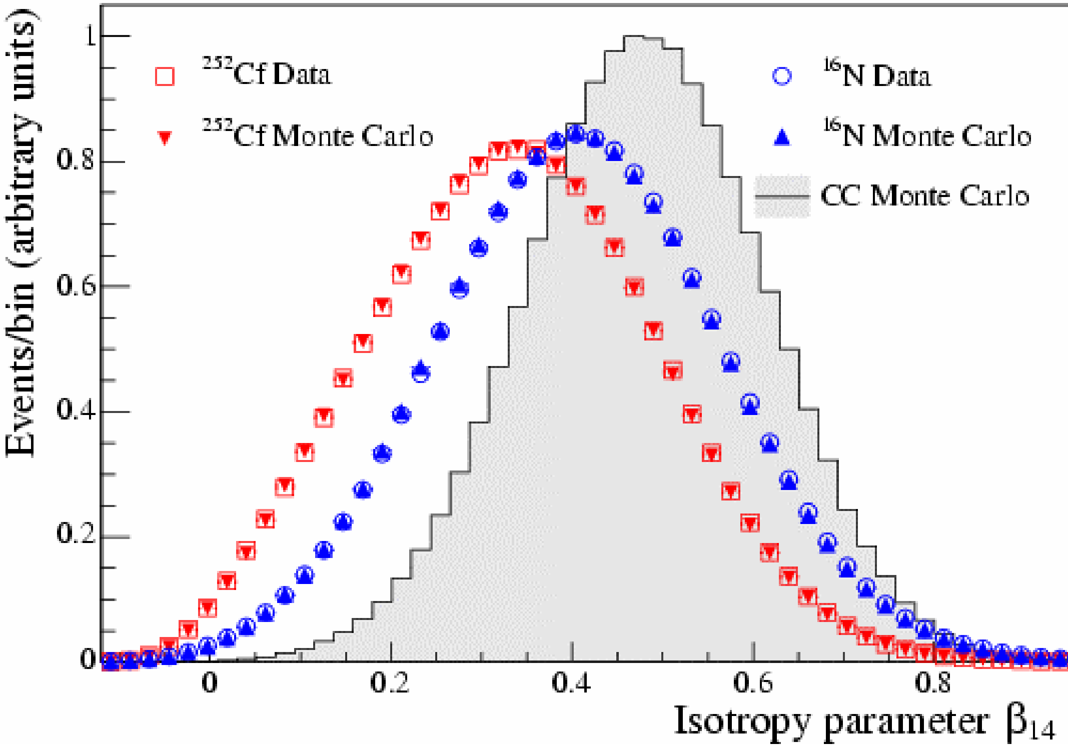


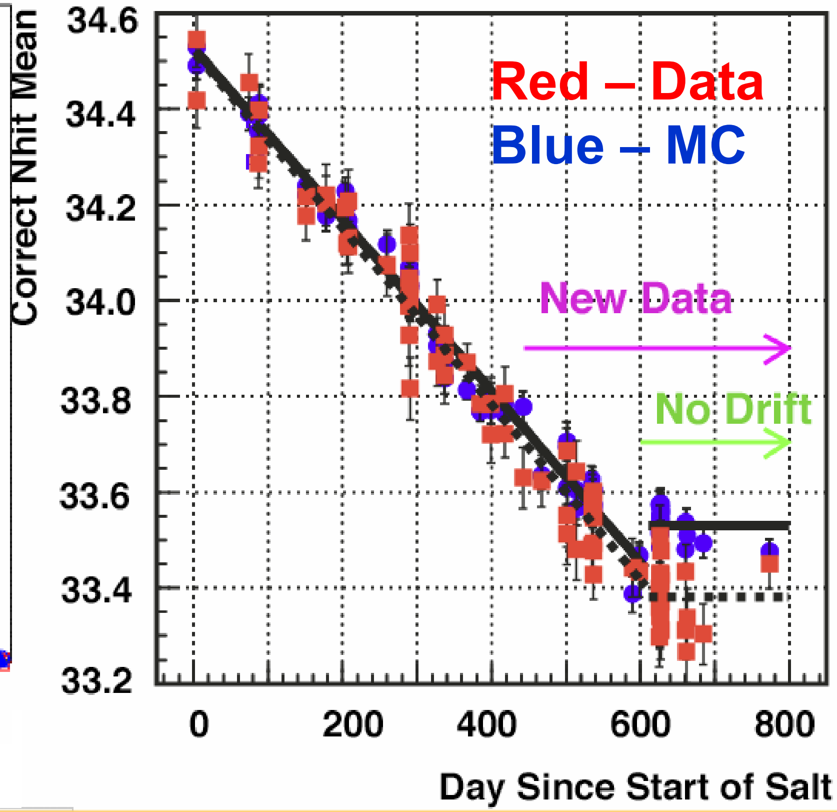


Isotropy variable, β_{14} , function of angles between each pair of hit PMTs (**θ_{ij}**) in event. (similar to *thrust* in collider physics)

β_{14} powerful discriminating variable between NC and CC/ES events.

Calibration of detector

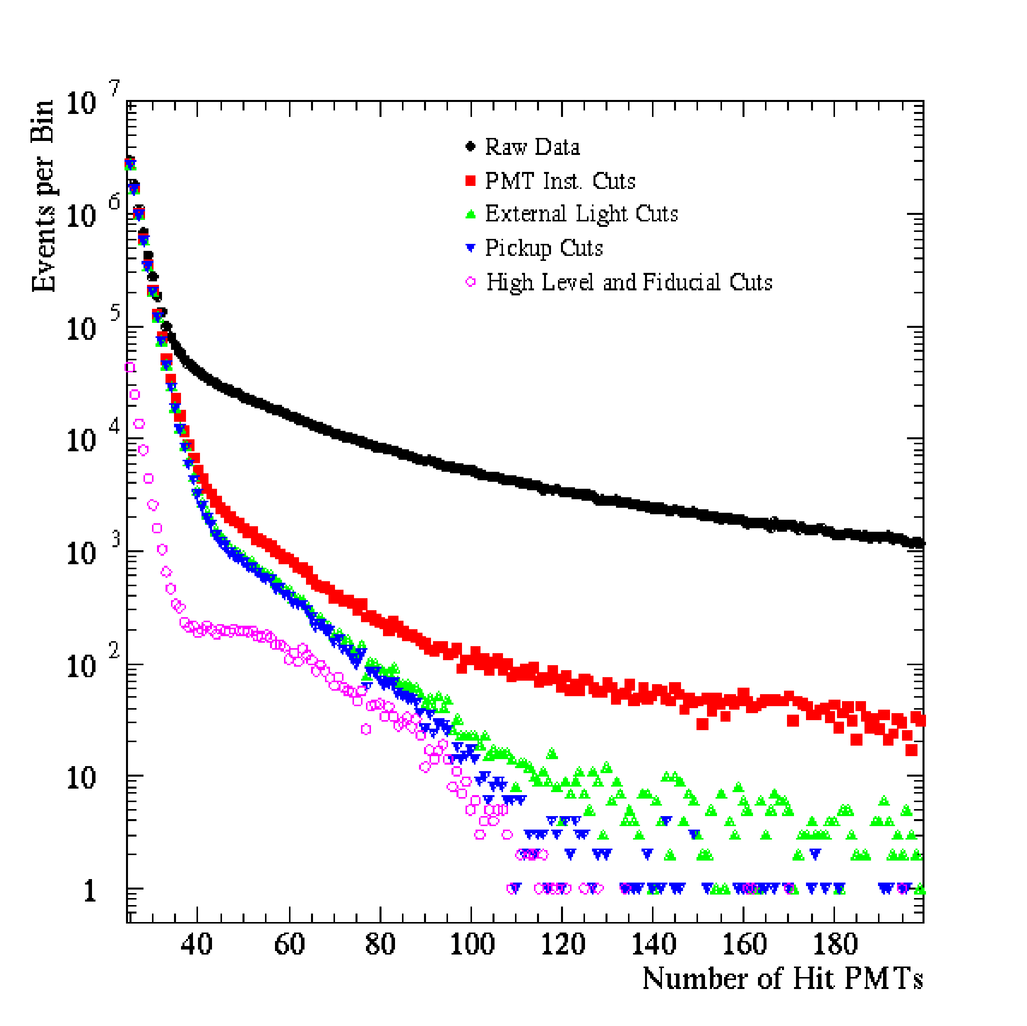




^{252}Cf (neutron) and ^{16}N (6 MeV γ) sources provide check of MC for β_{14}

^{16}N triggered γ -ray source calibrates energy response

Salt analysis: data set and data reduction



610,009,495 triggers

Instrumental background cuts

Cosmic ray muons + spallation products

Vtx reconstruction, PMT time and position disributions

Radius ≤ 550 cm, T ≥ 5.5 MeV

4722 events

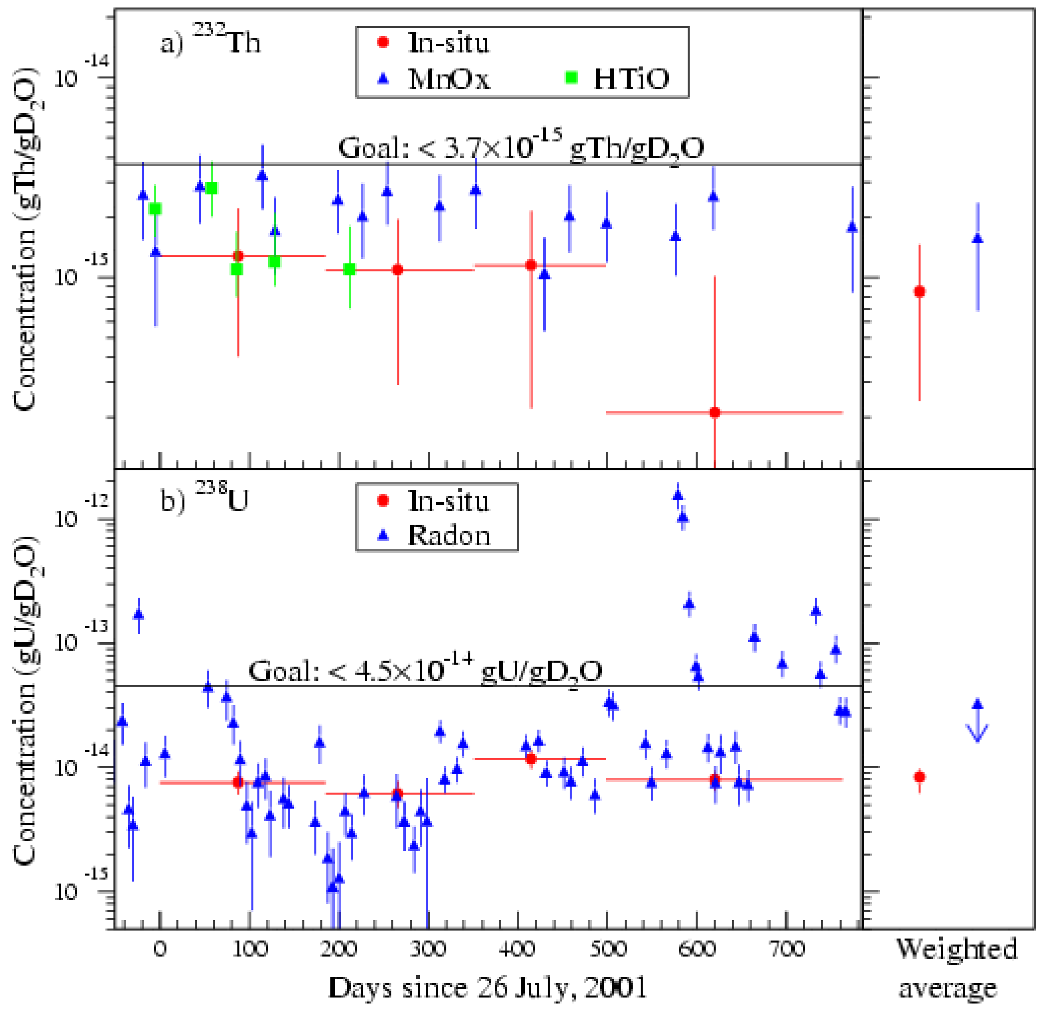
Radioactive backgrounds

- *Ex situ* measurements show Uranium and Thorium levels lower than goals

  ~ 1 background neutron/day

- *Ex situ* measurements consistent with *in situ* measurements

- *In situ* measurements more precise so used for solar neutrino analysis.



Backgrounds

Source	Average rate		Counts in data set
Neutrons generated inside D_2O:			
^2H photodisintegration [U, Th]			$91.3^{+30.4}_{-31.5}$
^2H photodisintegration [^{24}Na]			10.2 ± 2.5
n from fission [U]	0.43	n μg^{-1} U y^{-1}	0 ± 0
$^2H(\alpha,\alpha n)^1H$ [Th]	1.9	n μg^{-1} Th y^{-1}	0.93 ± 0.50
$^2H(\alpha,\alpha n)^1H$ [^{222}Rn]	0.80	n μg^{-1} U y^{-1}	2.89 ± 0.47
$^{17,18}O(\alpha,n)^{20,21}Ne$ [Th]	0.09	n μg^{-1} Th y^{-1}	0.03 ± 0.02
$^{17,18}O(\alpha,n)^{20,21}Ne$ [^{222}Rn]	0.20	n μg^{-1} U y^{-1}	0.72 ± 0.12
n from atmospheric ν			$15.8^{+21.3}_{-4.6}$
^{24}Na from muons	0.33	n y^{-1}	0.14 ± 0.14
muons in SNO	11240	n y^{-1}	≤ 1
muons in rock	0.14	n y^{-1}	0.08 ± 0.01
$\overline{\nu_e}$ "ccp"	0.03	n y^{-1}	0.01 ± 0.01
$\overline{\nu_e}$ "ccd"	1.43	n y^{-1}	0.6 ± 0.1
$\overline{\nu_e}$ "ncd"-reactor	3.24	n y^{-1}	1.4 ± 0.3
$\overline{\nu_e}$ "ncd"-terrestrial	1.2	n y^{-1}	0.5 ± 0.1
CNO ν	1.0	n y^{-1}	0.4 ± 0.4
Total internal-source neutrons			$125.1^{+37.3}_{-32.0}$
γ-rays generated uniformly inside D_2O:			
γ from fission [U]	0.04	γ μg^{-1} U y^{-1}	0 ± 0
γ from atmospheric ν			$3.2^{+4.6}_{-4.4}$
Total internal-source γ-rays			$3.2^{+4.6}_{-4.4}$
Decays of spallation products throughout D_2O:			
^{16}N following muons		^{16}N y^{-1}	< 1.3
Other spallation	1.2	^AZ y^{-1}	≤ 0.8
Cherenkov events from radioactivity inside D_2O:			
$\beta\gamma$ decays (U,Th,^{24}Na)			$3.6^{+1.0}_{-0.9}$
Backgrounds produced outside D_2O:			
Externally generated neutrons (from fit)			128.5 ± 42.4
$\beta\gamma$ decays (U, Th) in AV, H_2O, PMTs			< 18.5
Instrumental contamination			<3
Isotropic acrylic vessel events			< 6.55

U and Th: ~ 91 events

Recall: 4722 candidate events

Total Internal n: ~ 125 events

Fitted External n: ~ 129 events

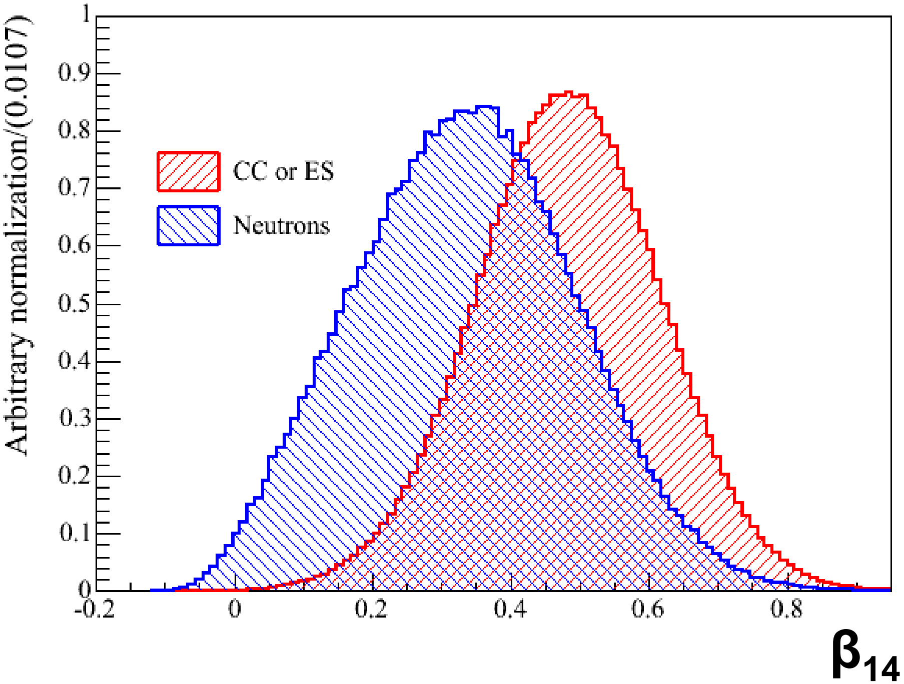
Measurement of CC, NC, ES events

- MC PDFs compared to data; extended unbinned ML fit used to estimate free parameters in fit.
- 3 (or 4) variables used to calculate likelihood PDFs:
  - Radial position of reconstructed vertex
  - Direction of electron w.r.t. Sun, $\cos\theta_{sun}$
  - Event isotropy, β_{14} (PMT hit pattern)
  - Electron kinetic energy (PMT hits) ***(optional)***
- Free parameters in fit:
  - number of NC, CC, ES signal events
  - "external neutron" background events

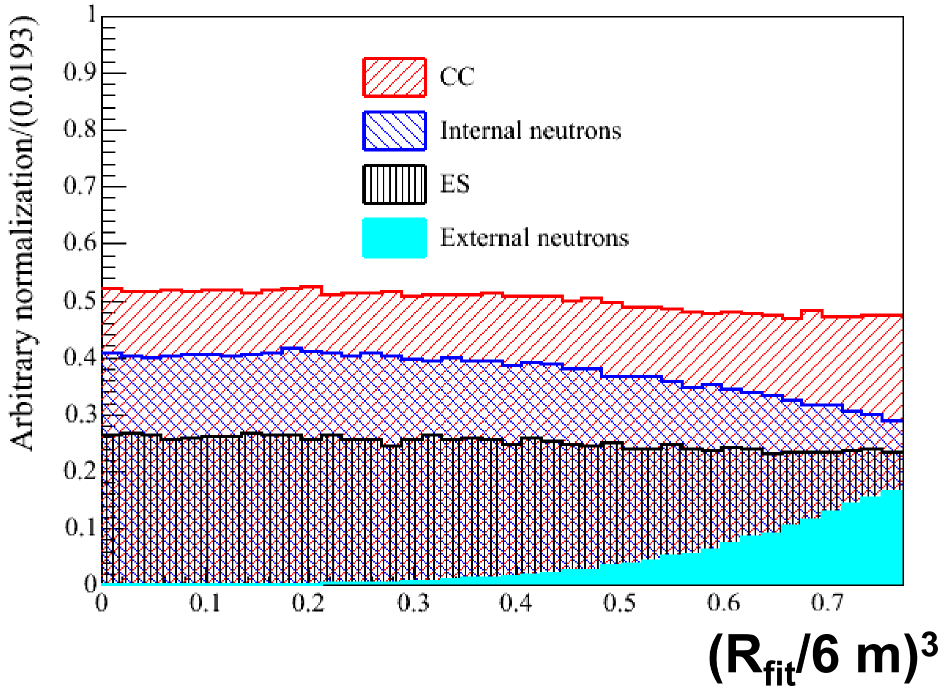
Matter enhanced oscillations change ES and CC spectra

PDFs for signals and backgrounds

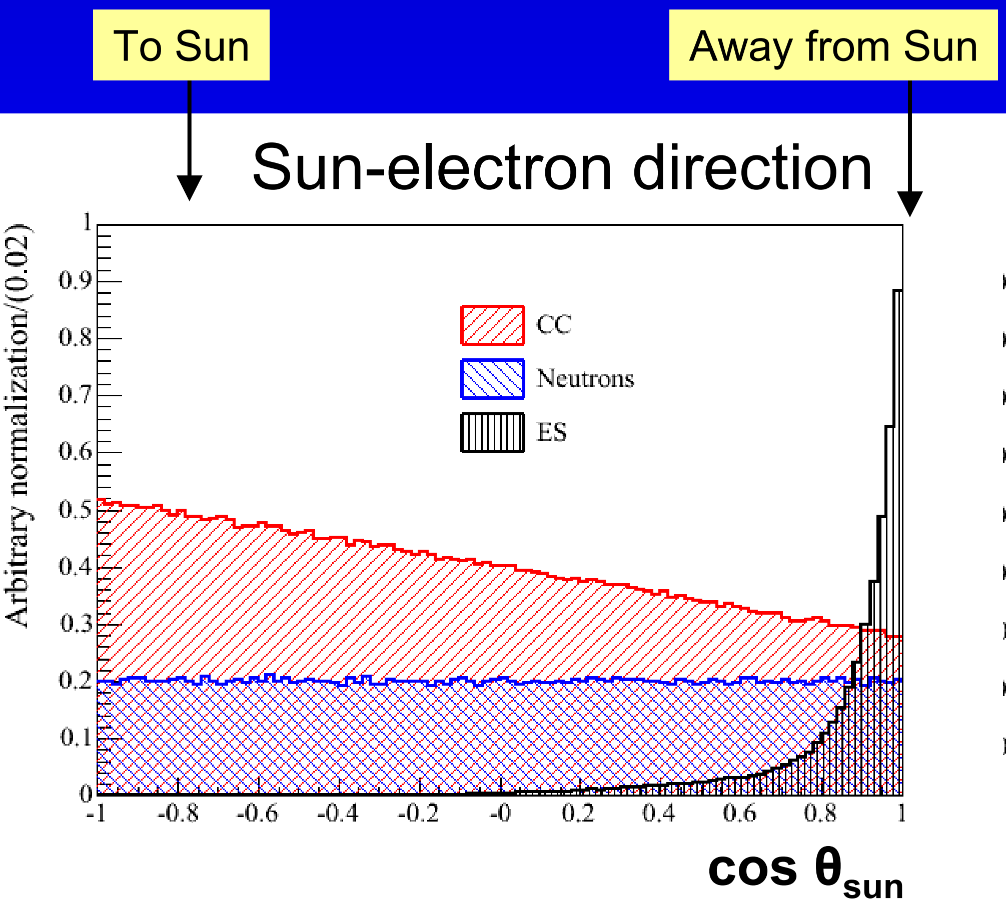
Isotropy

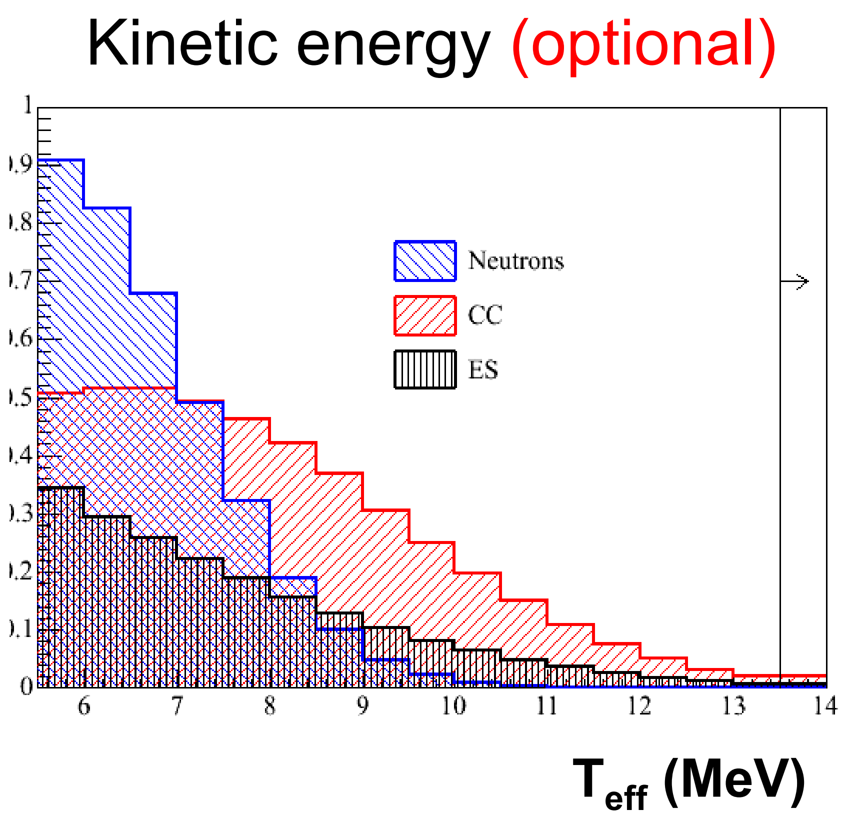


Radius of fitted vertex



PDFs for signals and backgrounds





Flux results from fits

Units for ϕ are 10^6 cm^{-2} s^{-1}

Energy spectrum of ^{8}B ν's constrained

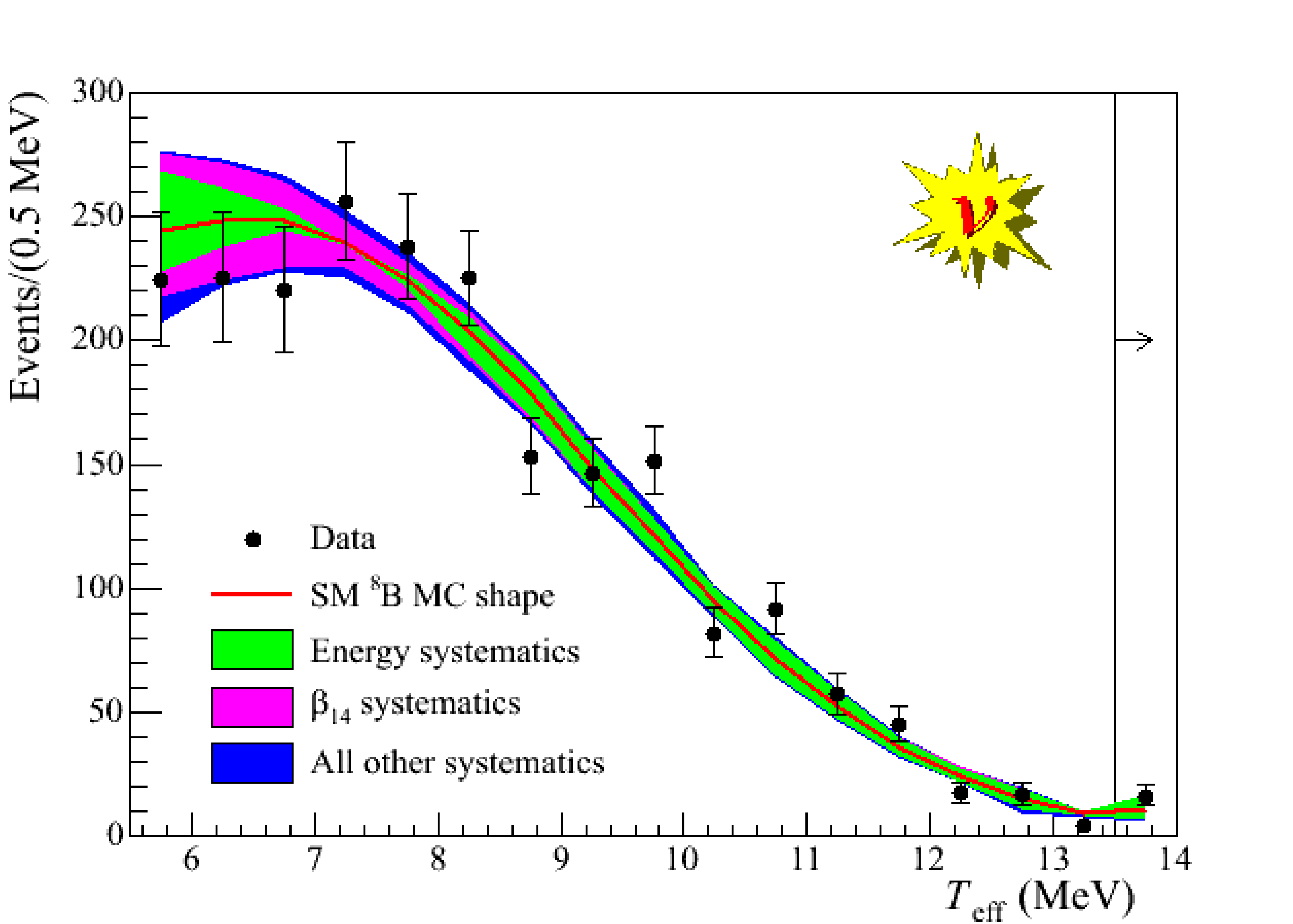
$$\phi_{CC}^{con} = 1.72^{+0.05}_{-0.05}(\text{stat})^{+0.11}_{-0.11}(\text{syst})$$
$$\phi_{ES}^{con} = 2.34^{+0.23}_{-0.23}(\text{stat})^{+0.15}_{-0.14}(\text{syst})$$
$$\phi_{NC}^{con} = 4.81^{+0.19}_{-0.19}(\text{stat})^{+0.28}_{-0.27}(\text{syst}),$$

Energy spectrum of ^{8}B ν's unconstrained (Energy not used in fit)

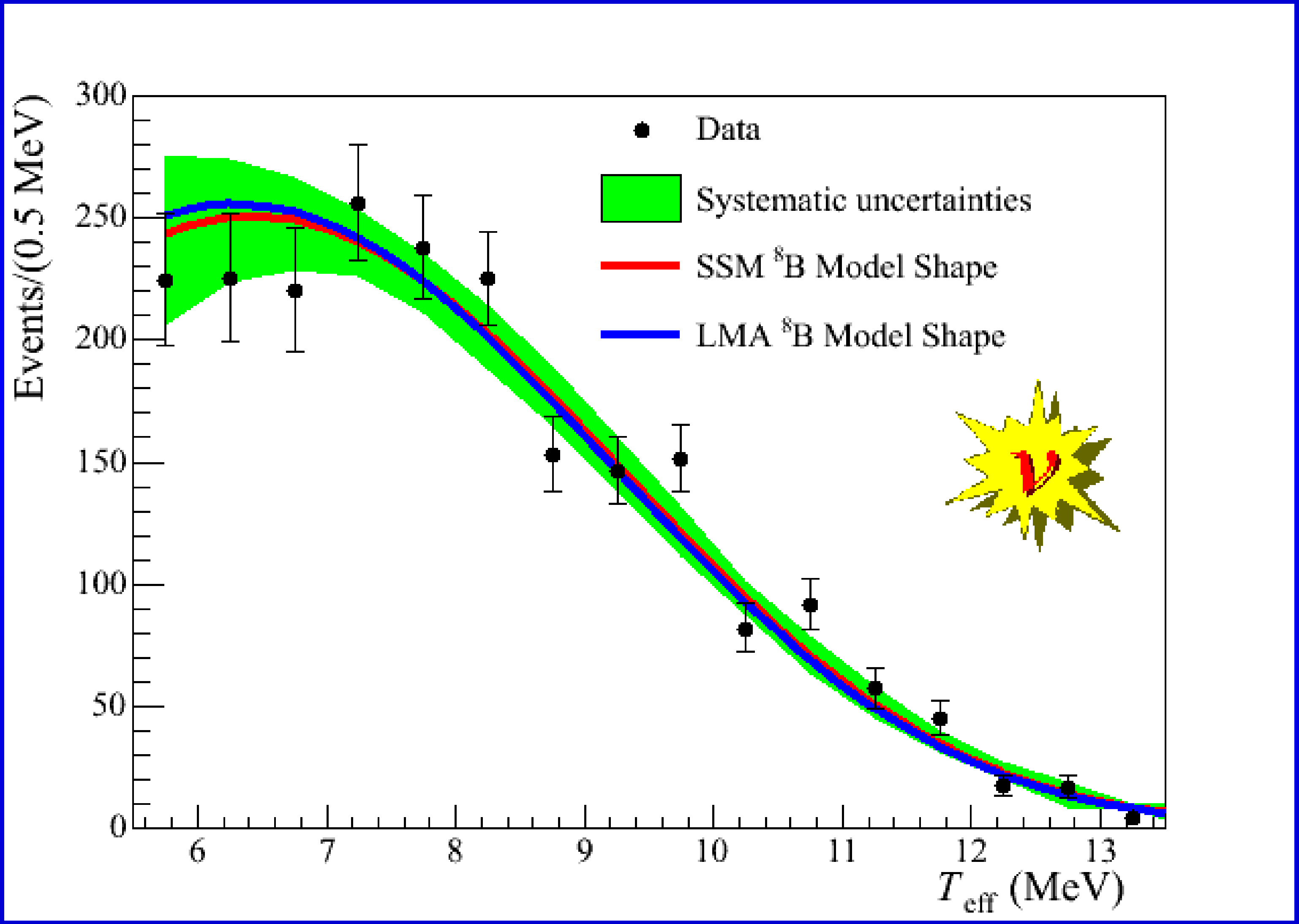
$$\phi_{CC}^{uncon} = 1.68^{+0.06}_{-0.06}(\text{stat})^{+0.08}_{-0.09}(\text{syst})$$
$$\phi_{ES}^{uncon} = 2.35^{+0.22}_{-0.22}(\text{stat})^{+0.15}_{-0.15}(\text{syst})$$
$$\phi_{NC}^{uncon} = 4.94^{+0.21}_{-0.21}(\text{stat})^{+0.38}_{-0.34}(\text{syst}),$$

Standard Solar Model (Bahcall, Pinsonneault 2004)	$\phi_{BP04} = 5.79 \pm 1.33$

Charged Current (CC=ν_e) Spectrum

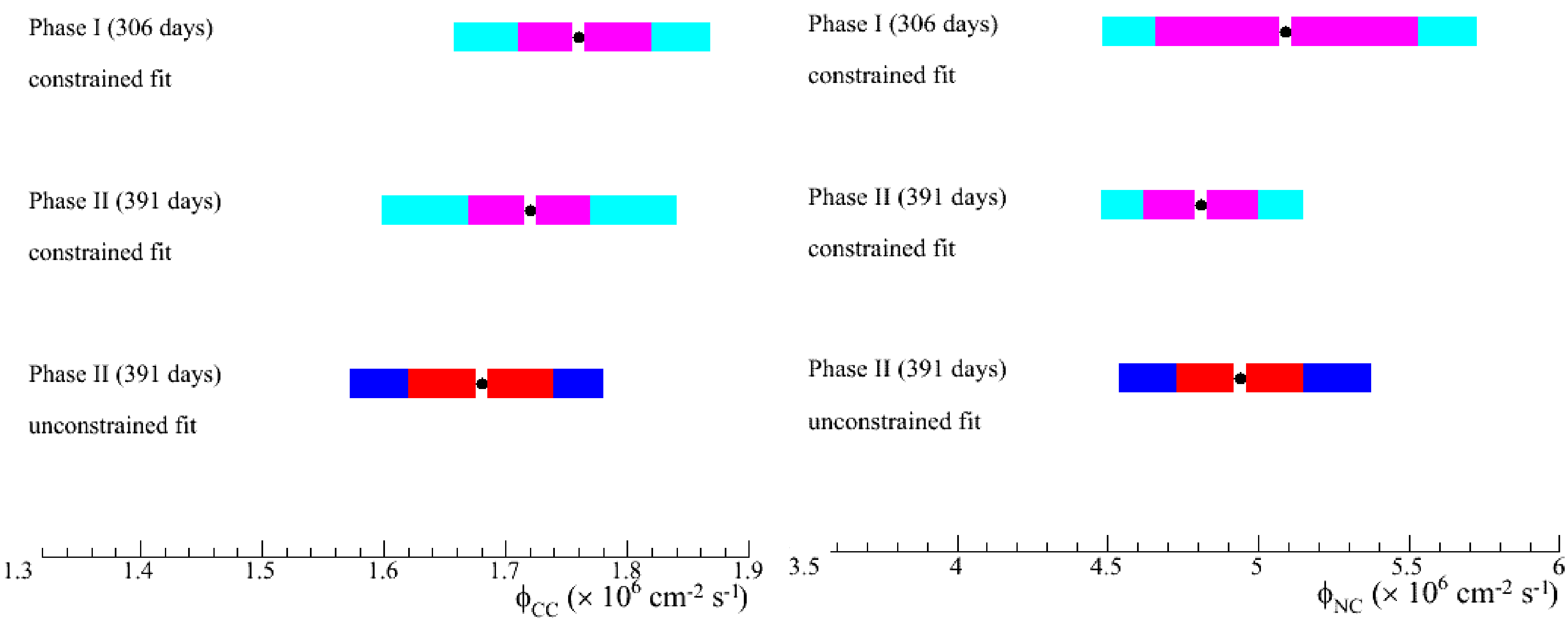


Charged Current ($CC=\nu_e$) Spectrum



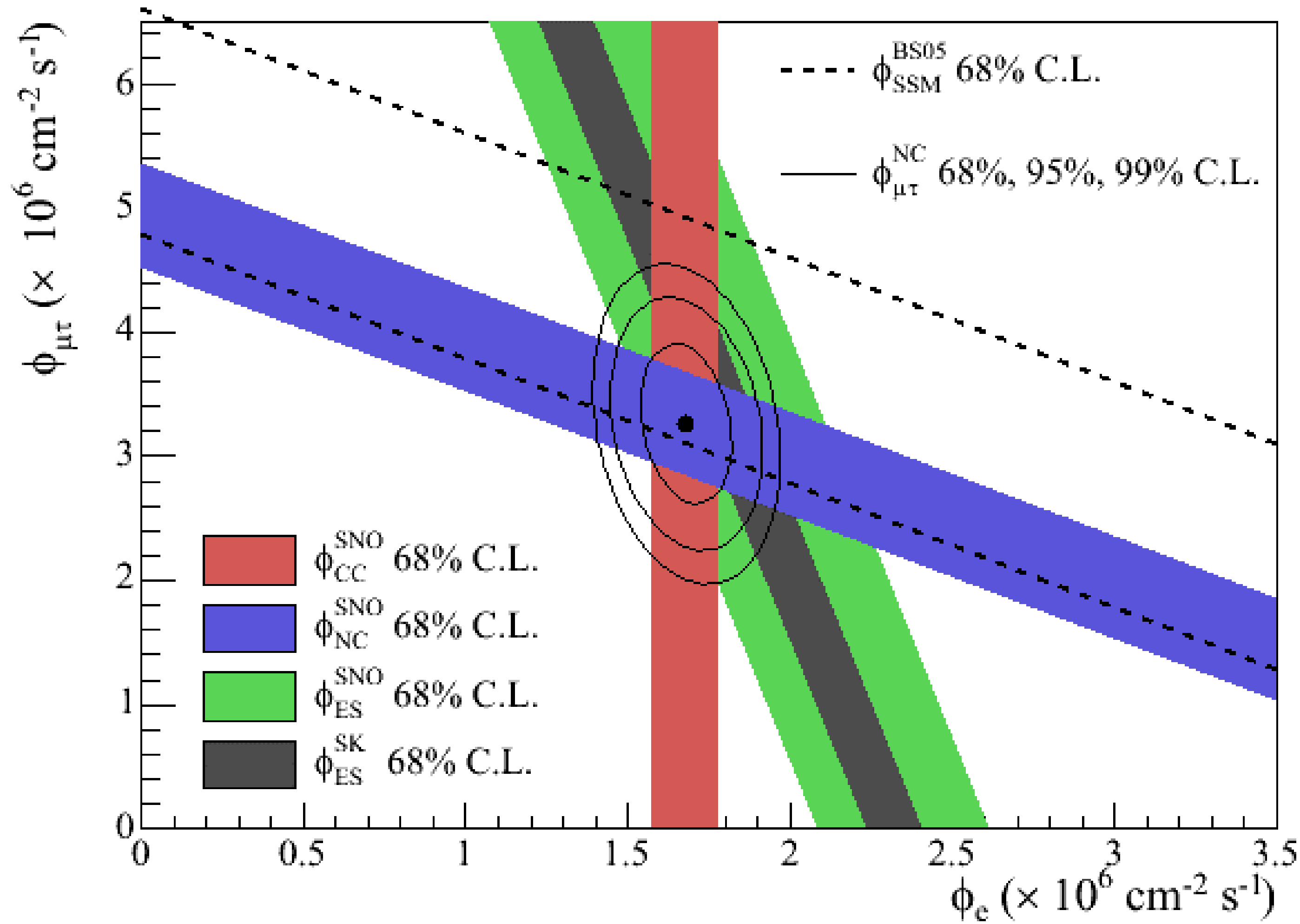
Comparison to previous results and SSM

More precise salt results confirm D_2O results



Comparison to previous results and SSM

More precise salt results confirm D_2O results



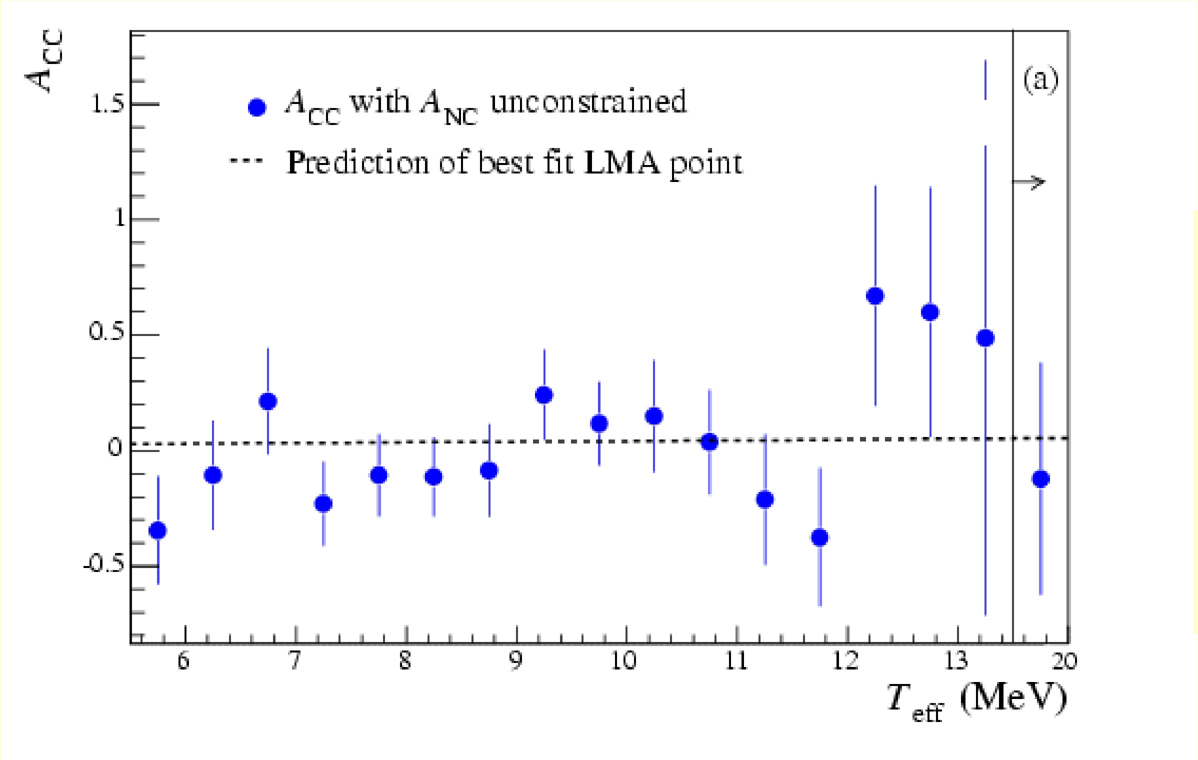
Day/Night Asymmetries

$$A_X = \frac{(\Phi_{night} - \Phi_{day})}{(\Phi_{night} + \Phi_{day})/2}$$

A_{CC}= -0.056 ± 0.074 (stat.) ± 0.051 (syst.)

A_{NC}= 0.042 ± 0.086(stat.) ± 0.067 (syst.)

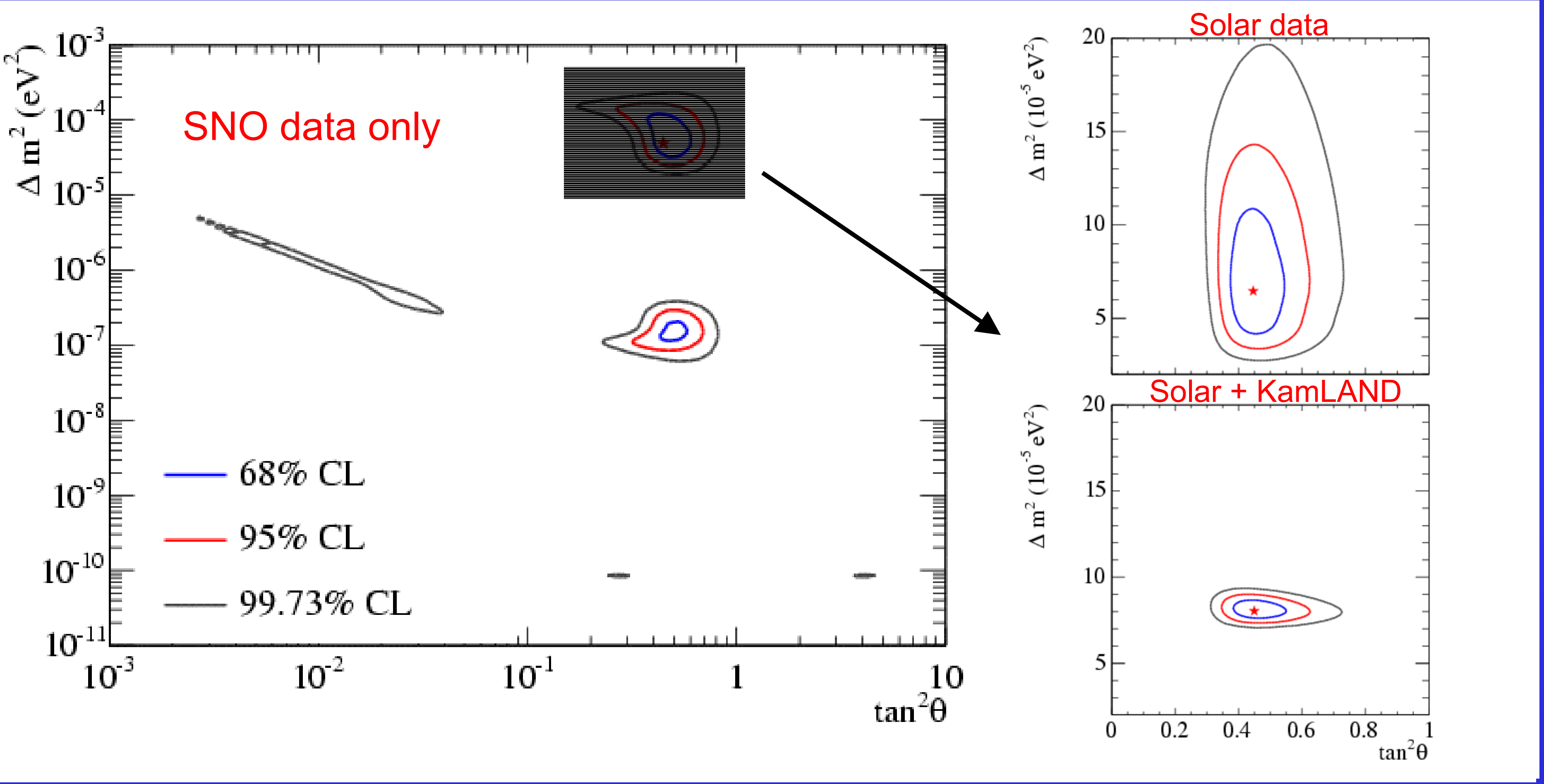
A_{ES}= 0.146 ± 0.198(stat.) ± 0.032 (syst.)



A_{CC} and A_{NC} are correlated (ρ = -0.532)

In standard neutrino oscillations, A_{NC} should be zero…

SNO: Results Phase II: neutrino oscillation parameters



Ratio of CC/NC fluxes gives $P(\nu_e \rightarrow \nu_e)$

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$$

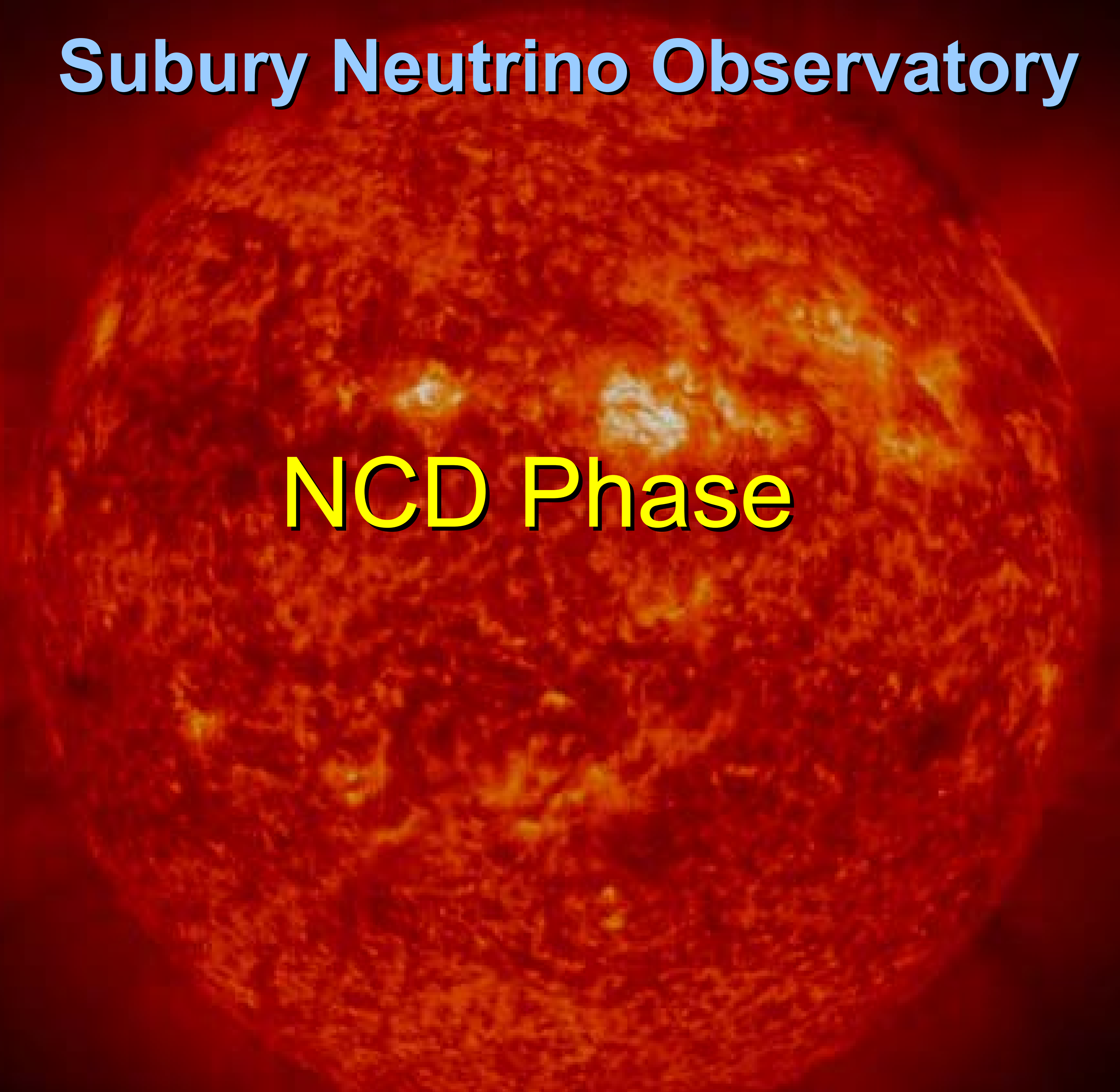
Interpretation of salt flux results: neutrino oscillation parameters

1-D projections of oscillation parameters give marginal uncertainties on $\tan^2\theta$ and Δm^2

Oscillation analysis	Δm^2 (10^{-5} eV^2)	$\tan^2\theta$
SNO-only	$5.0^{+6.2}_{-1.8}$	$0.45^{+0.11}_{-0.10}$
Global solar	$6.5^{+4.4}_{-2.3}$	$0.45^{+0.09}_{-0.08}$
Solar plus KamLAND	$8.0^{+0.6}_{-0.4}$	$0.45^{+0.09}_{-0.07}$

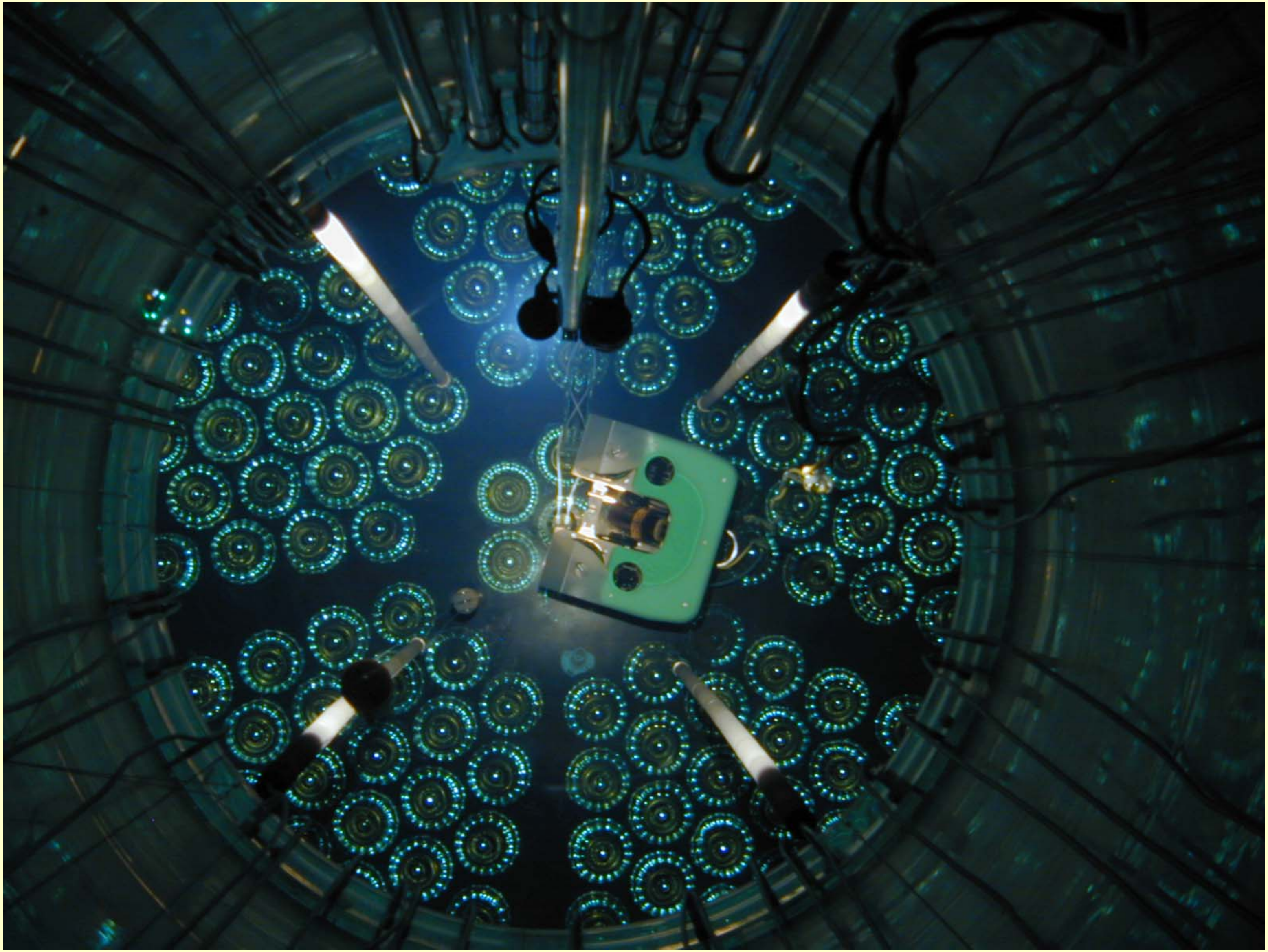
Maximal mixing ($\tan^2\theta = 1$) excluded at ~ 6 σ

Subury Neutrino Observatory



NCD Phase

NCD Deployment



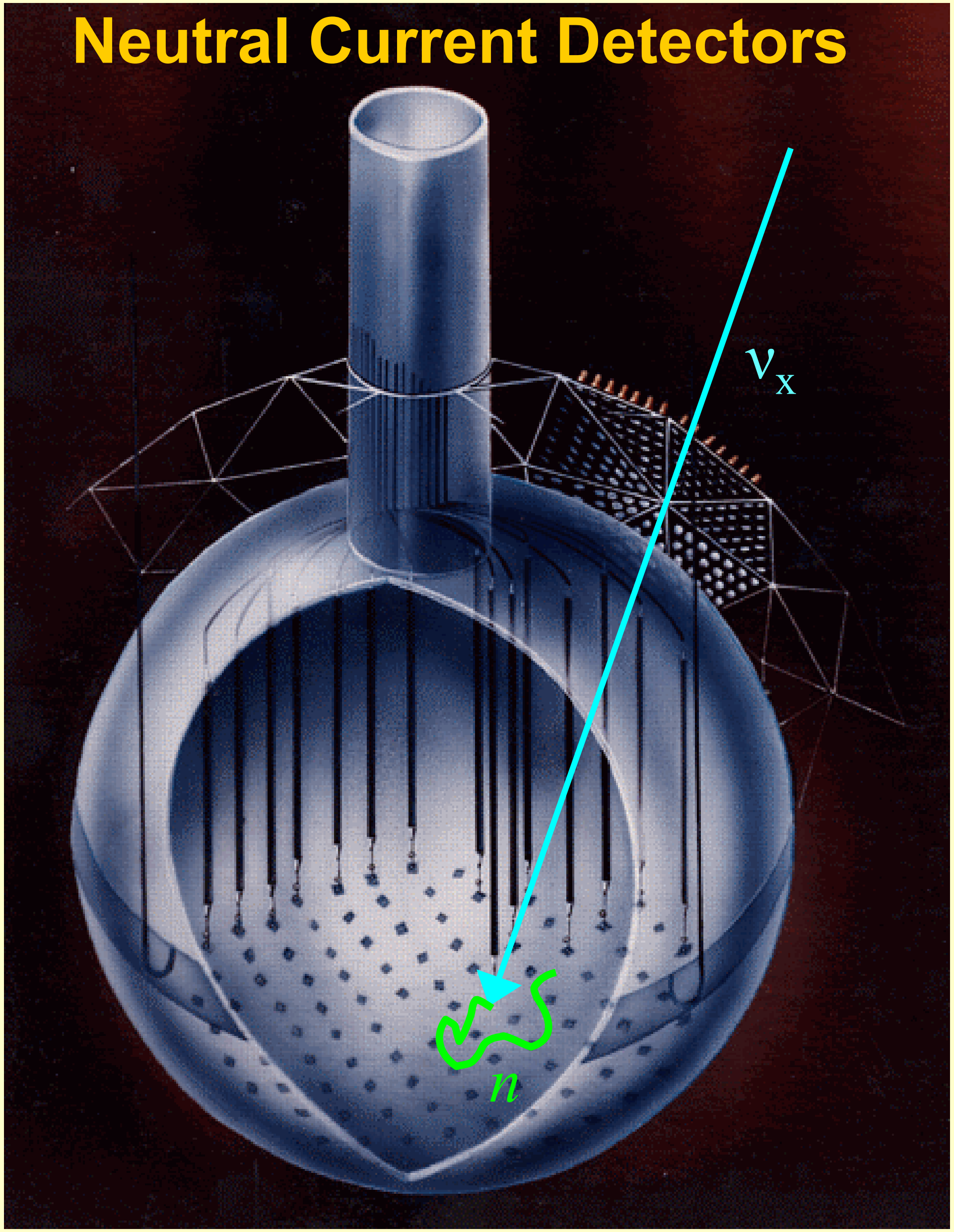
SNO NCD Phase

NC

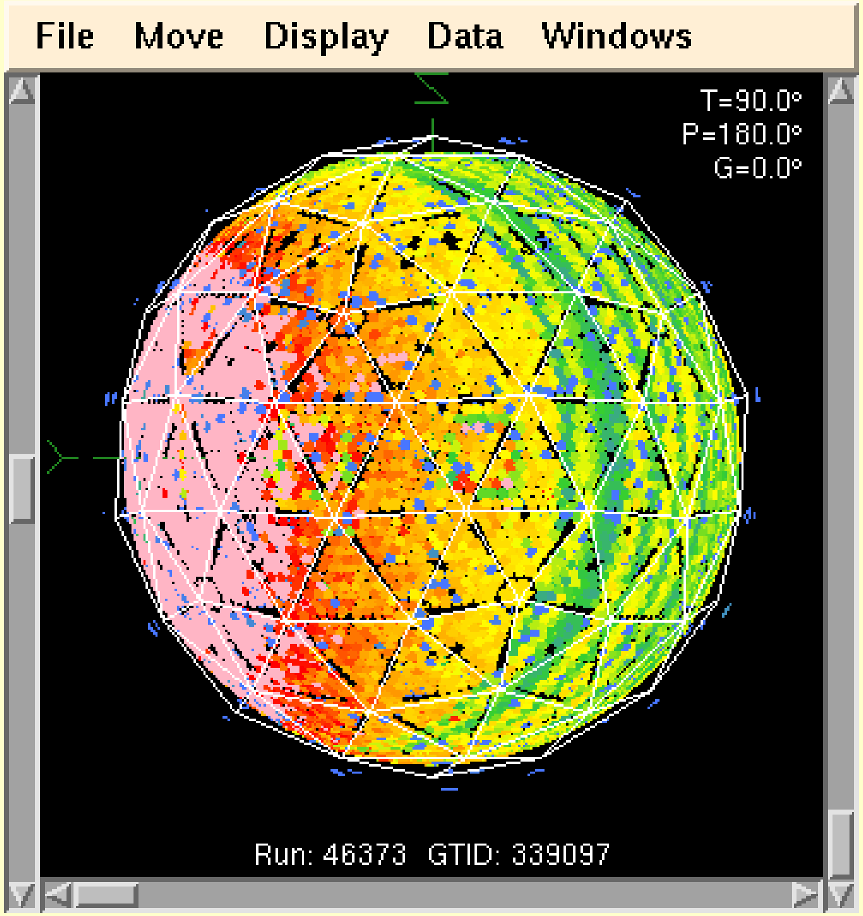
$$\nu_x + d \rightarrow p + n + \nu_x$$

$$n + {}^3\mathrm{He} \rightarrow p + t$$

- Event by event separation
- Break the correlation between NC & CC events
- Measure in separate data streams NC & CC events
- Different systematic errors than neutron capture on NaCl
- Commissioning Fall 04 (now!)



Optical Calibration: LIVE !!!!!



NCD Phase - Advantage of ^{3}He counters

	Correlation Coefficient		
	D_2O	Salt	^{3}He
CC,NC	-0.950	-0.521	~0
NC,ES	-0.297	-0.064	~0
CC,ES	-0.208	-0.156	~ -0.2

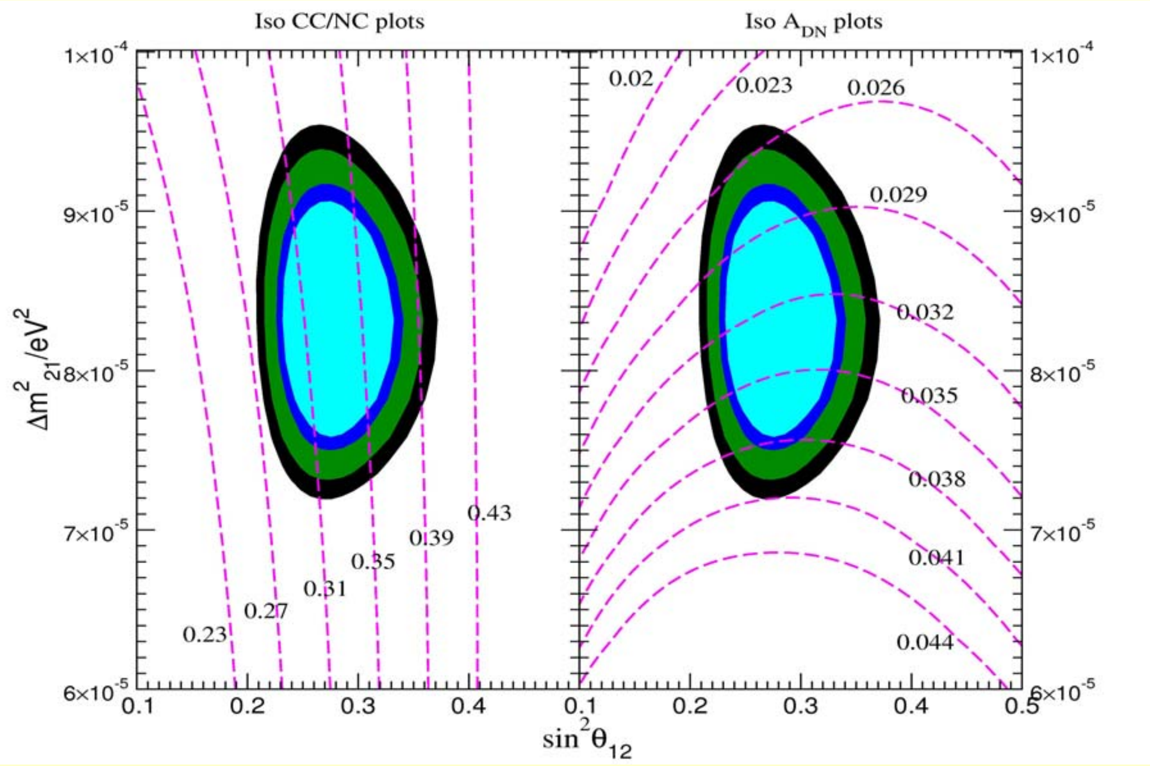
- Reduction in anti-correlation between NC and CC will help to reduce uncertainty in CC/NC ratio.
- Smaller uncertainty in CC/NC ratio means smaller uncertainty in $\tan^2\theta$.
- Best CC spectrum from D2O with NC constrained by NCD and overall consistency with Salt

What SNO might tell us in the future…

The Ultimate D2o + Salt + NCD Analysis !

Salt phase 254 day results provide independent measurement of ^{8}B solar neutrino flux, demonstrate flavor conversion to >7σ, and improve MSW parameter measurements.

Current Oscillation Picture:



Goal for Final SNO
(D_2O + salt + NCD)

Results from full 391 days of salt data <u>soon</u>!

Includes day-night and spectrum.

^{3}He phase underway, for event-by-event NC discrimination…and even better physics!

CC/NC ratio to 7%

D/N asymmetry to 3% abs. uncertainty

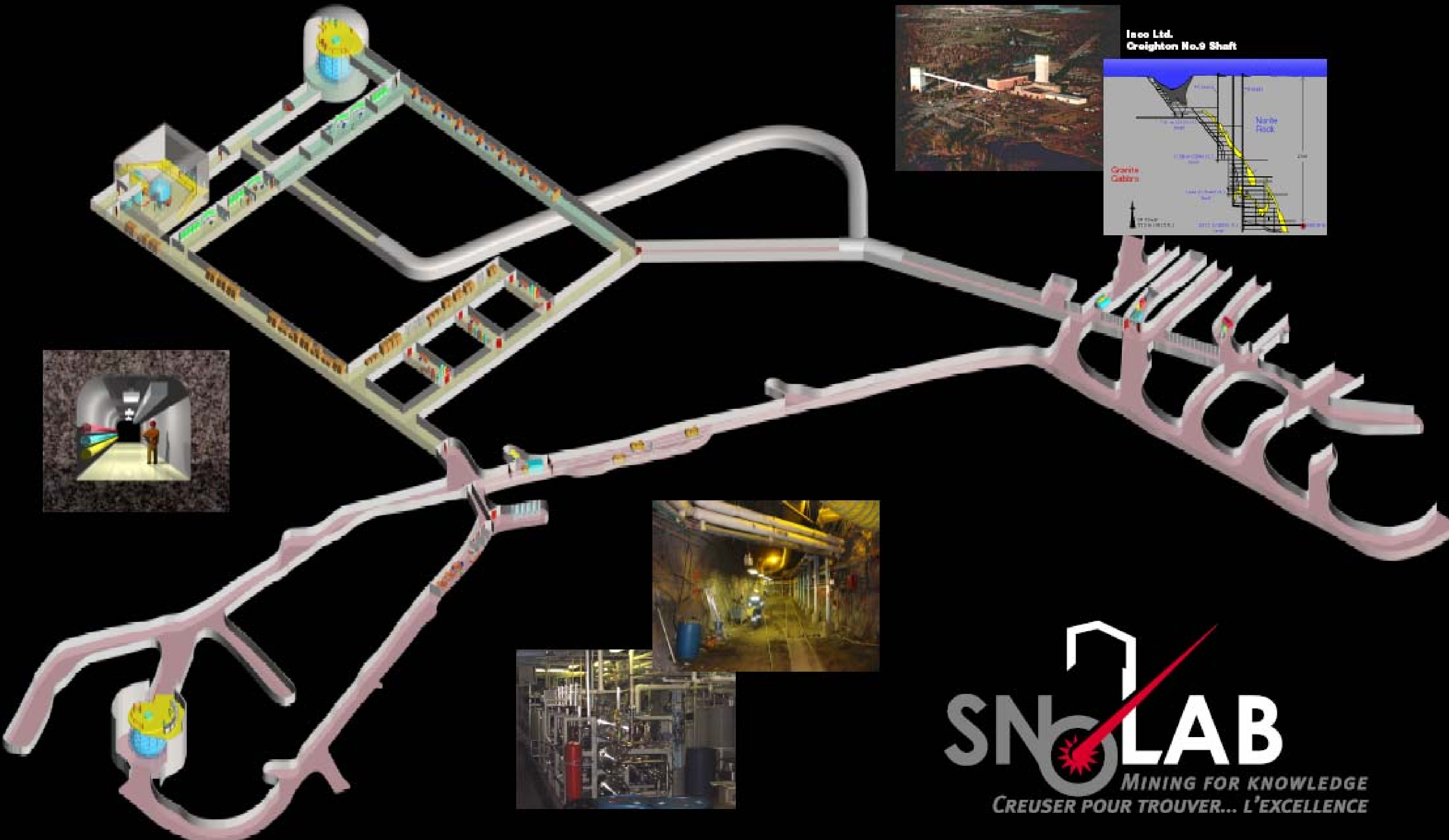
hep-ph/0406328

SNOLAB

EXO

A Proposal for Double Beta Decay Search

- Absolute Majorana Neutrino Mass Scale
- Why Xenon?
- Prototype at WIMP
- Time Projection Chamber R&D



SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER… L'EXCELLENCE

Deep: 2092 m underground $\Rightarrow$ 85 $\mu/m^2/y$

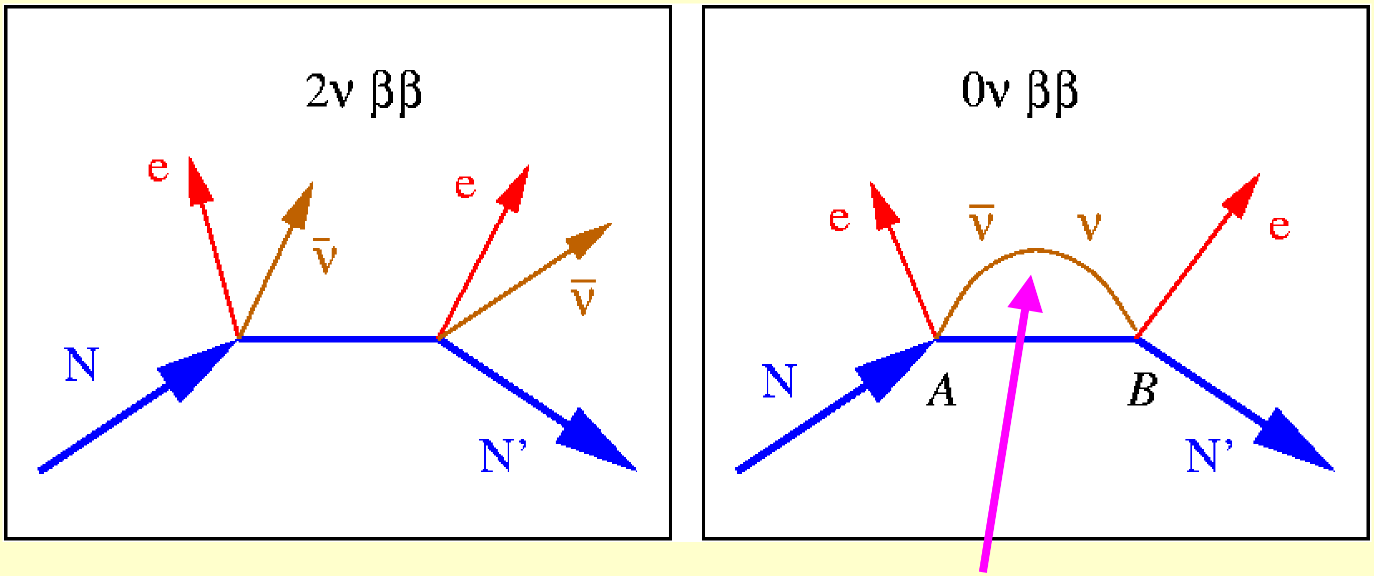
Carleton UNIVERSITY

Carleton
UNIVERSITY

There are two varieties of ββ decay

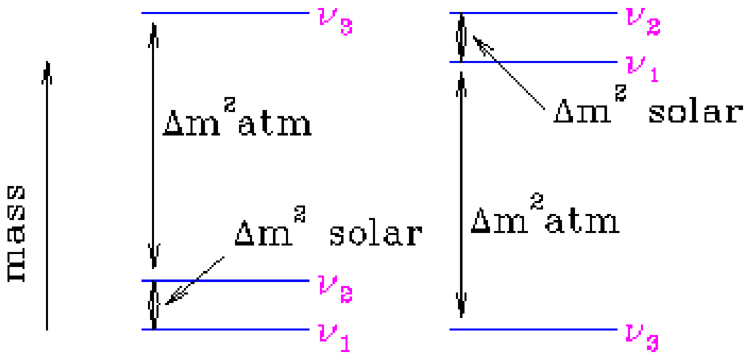
2ν mode: a conventional 2nd order process in nuclear physics

0ν mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$ Since helicity has to "flip"
- $\nu = \bar{\nu}$



Several new particles can take the place of the virtual ν

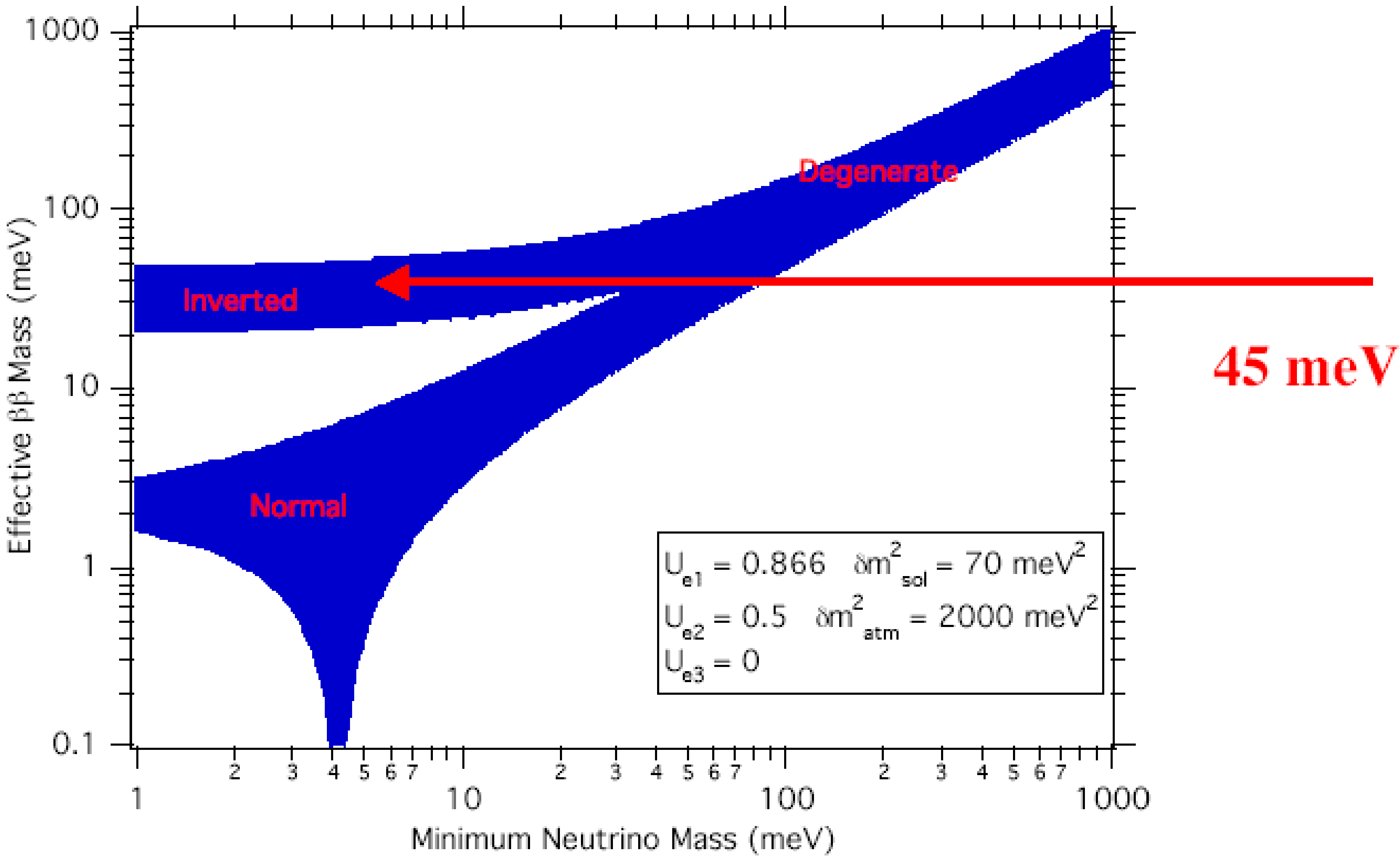
But 0νββ decay always implies new physics



Effective Majorana ν mass

($\varepsilon_i = \pm 1$ if CP is conserved)

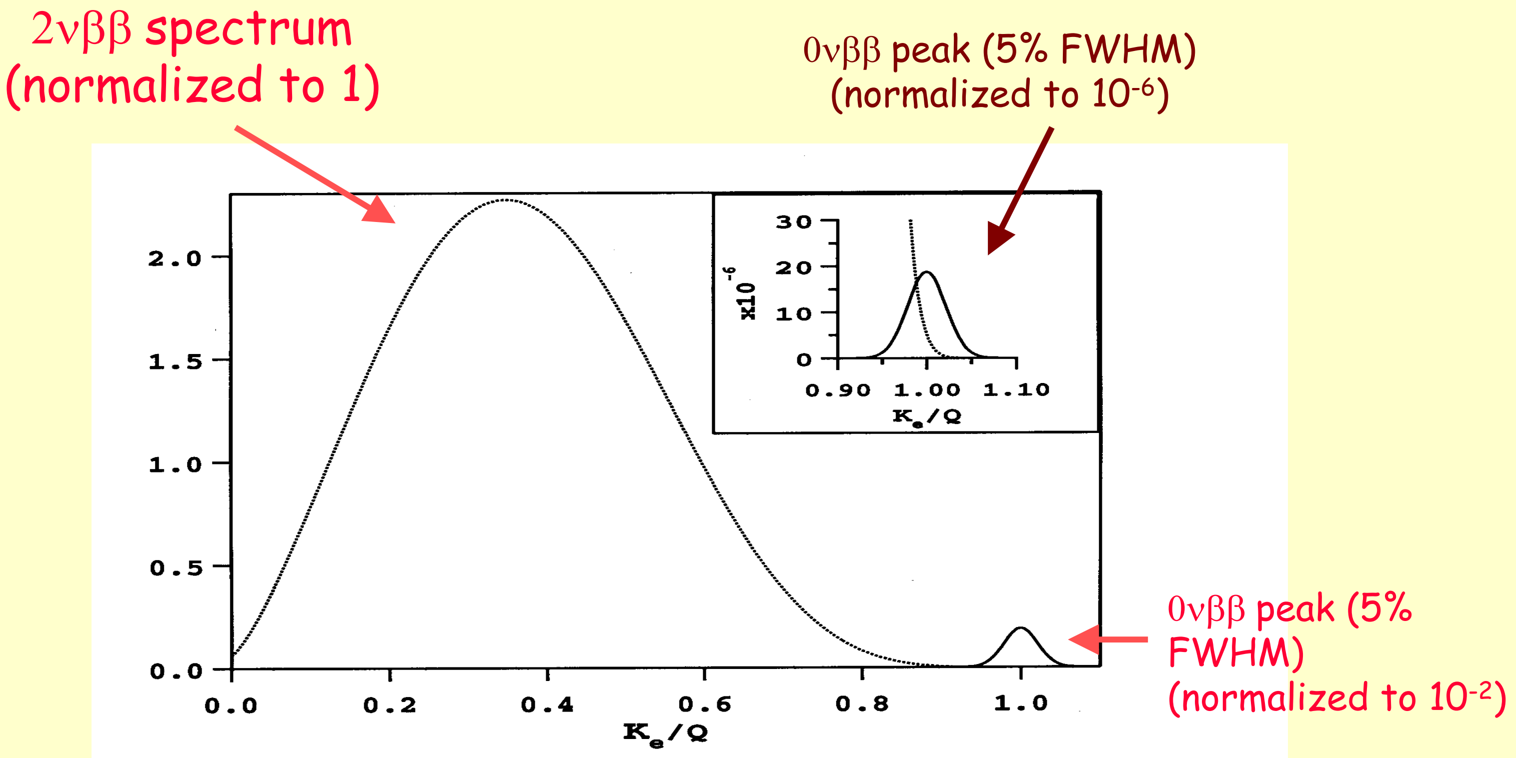
$$\langle m_\nu \rangle = \left| \sum_{i=1}^{3} U_{e,i}^2 m_i \ \varepsilon_i \right|$$



Xe is ideal for a large experiment

- No need to grow crystals
- Can be re-purified during the experiment
- No long lived Xe isotopes to activate
- Can be easily transferred from one detector to another if new technologies become available
- Noble gas: easy(er) to purify
- ^{136}Xe enrichment easier and safer:
  - noble gas (no chemistry involved)
  - centrifuge feed rate in gram/s, all mass useful
  - centrifuge efficiency ~ Δm. For Xe 4.7 amu

Background due to the Standard Model $2\nu\beta\beta$ decay



Summed electron energy in units of the kinematic endpoint (Q)

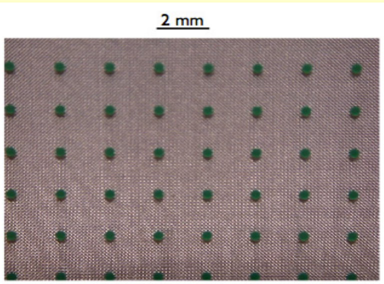
from S.R. Elliott and P. Vogel, Ann.Rev.Nucl.Part.Sci. **52** (2002) 115.

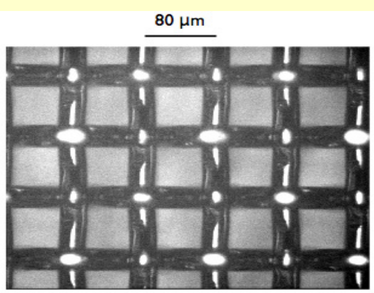
<u>The only effective tool here is energy resolution</u>

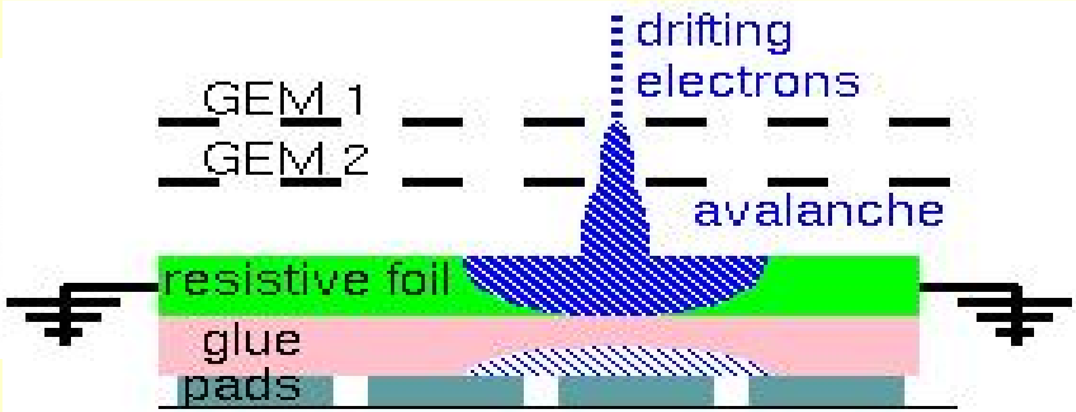
Energy Resolution

- For a 2.5 MeV electron the lower limit on the relative resolution from statistical fluctuations alone corresponds to FWHM energy resolution $\Delta E/E \approx 0.3\%$ [Fano limit]
- Hope to obtain an energy resolution after the full reconstruction of an event of $\Delta E/E \approx 1\%$ [competitive with Germanium detector]

Micropattern Detectors for TPC



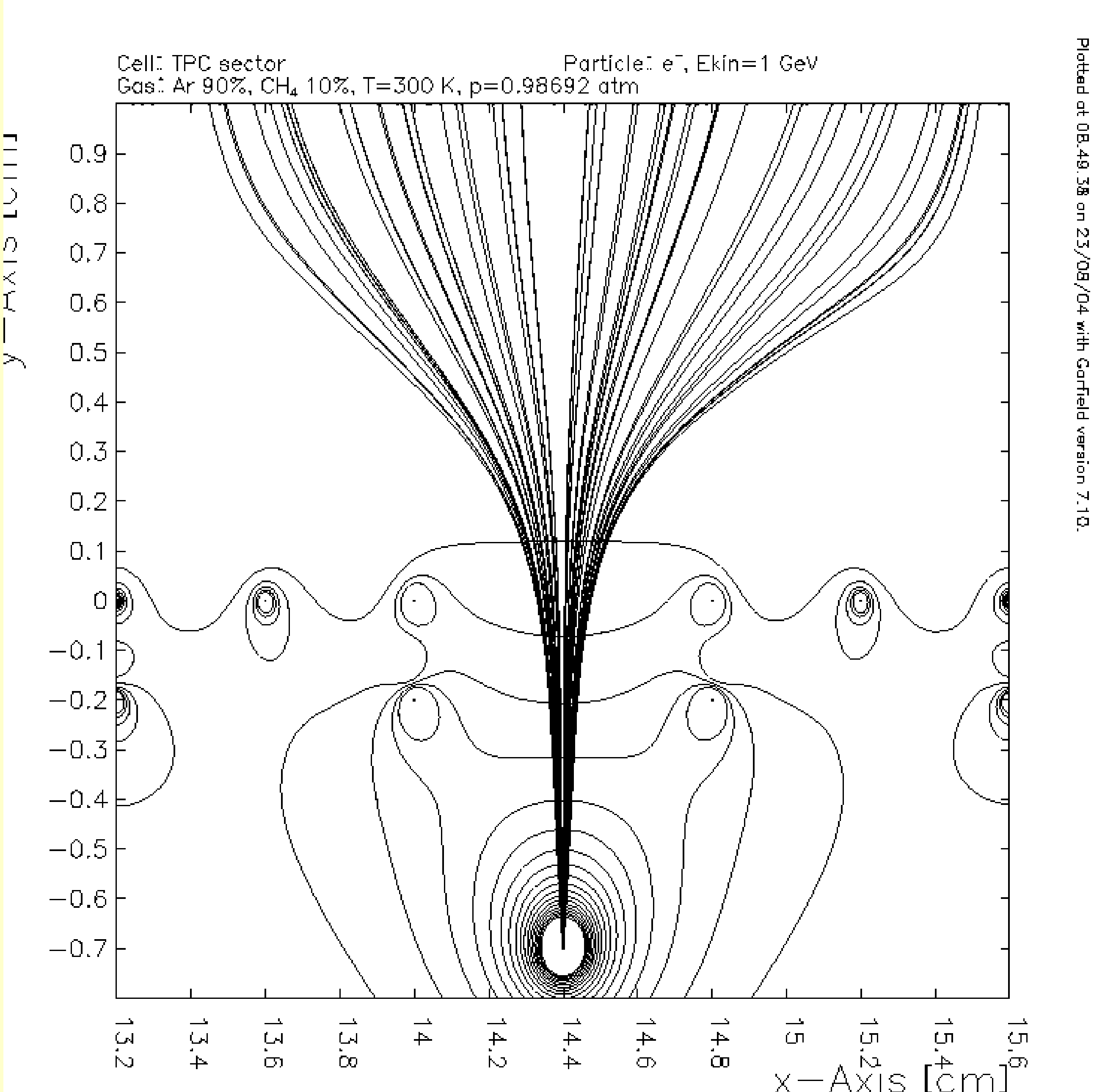




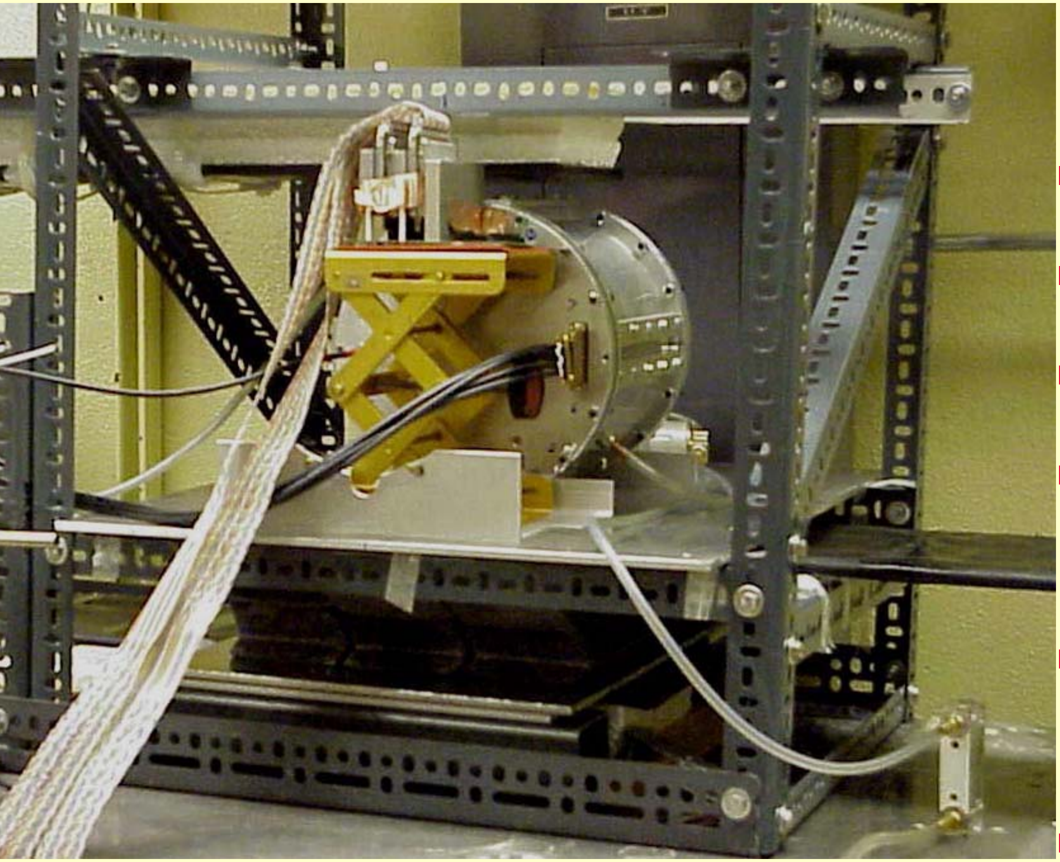
Best energy resolution amongst gas proportional detectors with electron transmission close to 100% through the anode mesh

Electrostatic analysis looking at field uniformity

TPC Simulation



R&D Effort



Track reconstruction with charge dispersion on resistive anode and resolution study

TPC

- New Initiative at Carleton
- Time Projection Chamber
- Application for EXO
- Overlap with detector development for the ILC
- World consensus to build a new $e^+ e^-$ linear collider (LC)
- Detectors capable of precision measurements

Conclusion

- **SNO provided direct evidence of flavor conversion of solar ν_e's**
- **SNO (d2o+salt+ncd) will provide the ultimate measurment of the total (NC) solar ν_x flux**
- **Real-time data do not show large energy distortion nor time-like asymmetry**
- **Matter Effect explains the energy dependence of solar oscillation**
- **Large mixing angle (LMA) solutions are favored**
- **Solar Neutrino Problem is now an industry for precise measurements of neutrino oscillation parameters – SNO (d2o+salt+NCD) Ultimate NC**

Implications and Outlook

- **Solar neutrinos demonstrate that <u>neutrinos have mass</u> and the minimum SM is incomplete**
  - **Unlike the quark sector where the CKM mixing angles are small, the lepton sector exhibits large mixing**
  - **The ν masses and mixing may play significant roles in determining structure formation in the early universe as well as supernovae dynamics and the creation of matter**
- **The coming decade will be exciting for neutrino physics helping delineate the *New* Standard Model that will include neutrino masses and mixing**
  - **Precision measurements of the leptonic mixing matrix**
  - **Determination of neutrino masses (*e.g.* EXO)**
  - **Investigation of lepton sector CP and CPT properties**

Goals of SNOLAB

Measure and Study the Low-Energy Solar Neutrino Spectrum in Real Time

Determine the Absolute Mass Scale, Mixing Pattern, and Character of Neutrinos

Determine the Dark Matter Content of the Universe

➔ Ultra-Low Background
➔ Deep and Clean

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

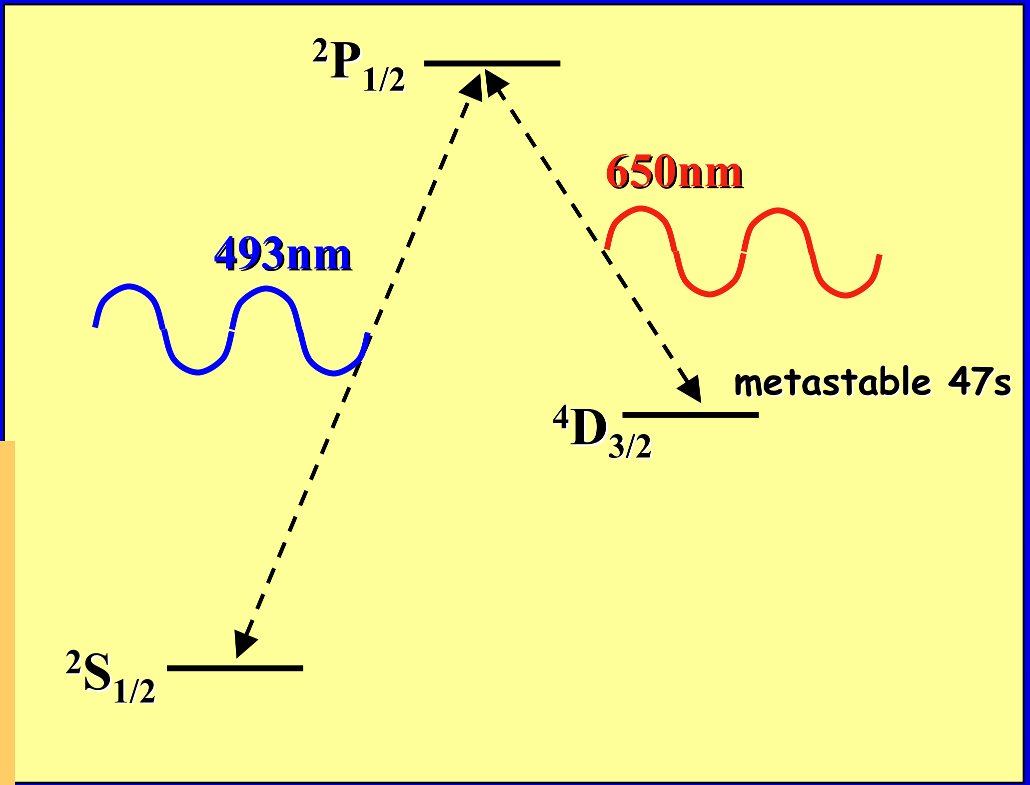
A (probably incomplete) list of the different ideas discussed by various groups

Experiment	Nucleus	Detector	$T^{0\nu}$ (y)	< m_ν > eV
CUORE	^{130}Te	.77 t of TeO_2 bolometers (nat)	7×10^{26}	.014-.091
EXO	^{136}Xe	10 t Xe TPC + Ba tagging	1×10^{28}	.013-.037
GENIUS	^{76}Ge	1 t Ge diodes in LN	1×10^{28}	.013-.050
Majorana	^{76}Ge	1 t Ge diodes	4×10^{27}	.021-.070
MOON	^{100}Mo	34 t nat.Mo sheets/plastic sc.	1×10^{27}	.014-.057
DCBA	^{150}Nd	20 kg Nd-tracking	2×10^{25}	.035-.055
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator	$> 10^{26}$	.053-.24
COBRA	^{116}Cd, ^{130}Te	10 kg of CdTe semiconductors	1×10^{24}	.5-2.
Candles	^{48}Ca	Tons of CaF_2 in liq. scint.	1×10^{26}	.15-.26
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scint in liq scint	2×10^{26}	.038-.172
Xmass	^{136}Xe	1 t of liquid Xe	3×10^{26}	.086-.252

Note that the sensitivity numbers are somewhat arbitrary, as they depend on the author's guesstimate of the background levels they will achieve

Xe offers a qualitatively new tool against background: $^{136}Xe \rightarrow {}^{136}Ba^{++} e^- e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)

Ba^+ system best studied
(Neuhauser, Hohenstatt,
Toshek, Dehmelt 1980)
Very specific signature
"shelving"
Single ions can be detected
from a photon rate of 10^7/s



- Important additional constraint
- Huge background reduction

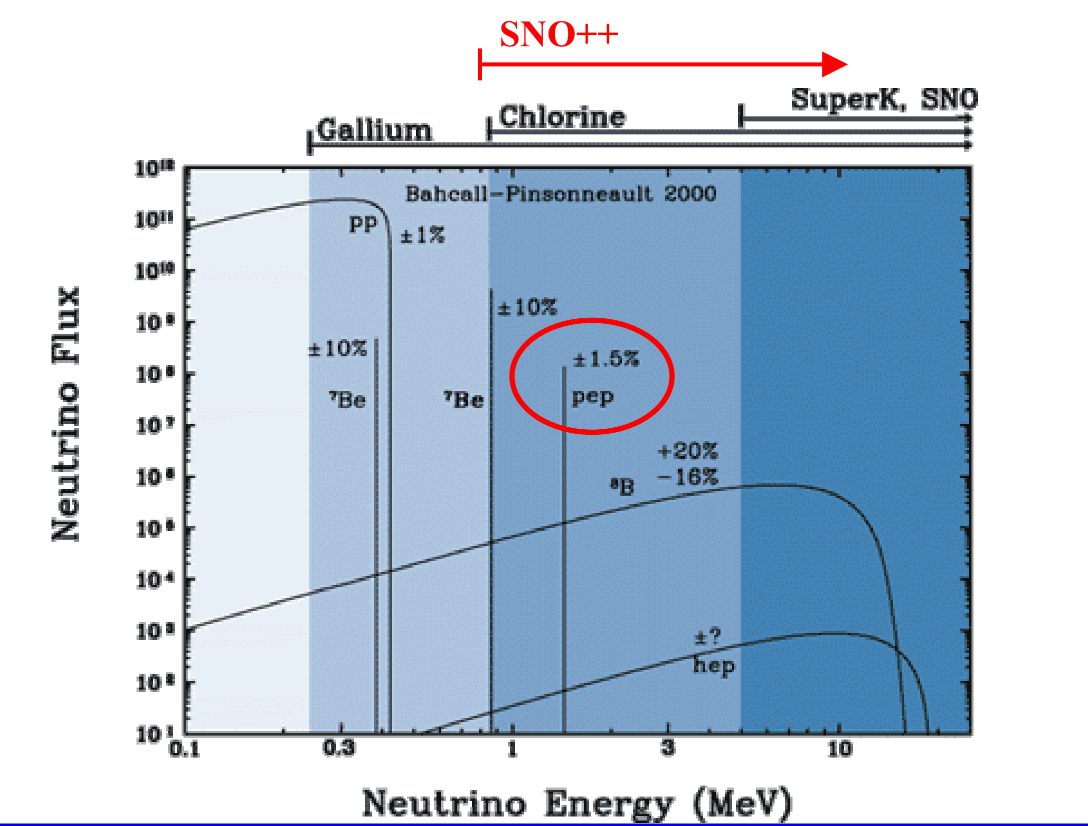
Outline

Scientific Program

- **Low Energy Neutrinos**
  - Sudbury Neutrino Observatory (SNO)
  - SNO++ (upgrade with liquid scintillator)
- **Search for Cold Dark Matter**
  - Picasso
- **Investigation of Double-Beta Decay**
  - Majorana
  - Enriched Xenon Observatory (EXO)
- **Summary**

SNO++: Fill with Liquid Scintillator

Physics program: *pep* neutrinos



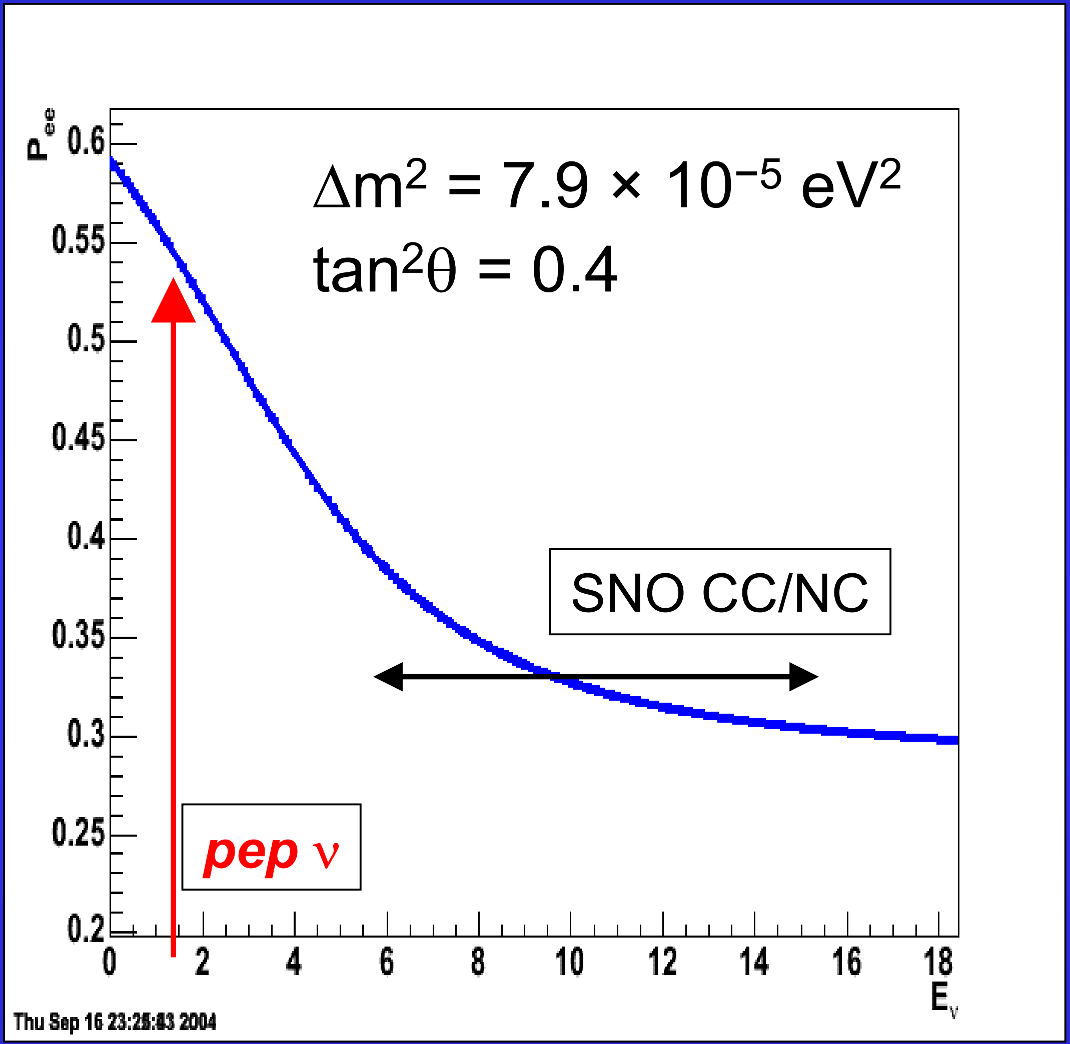
SNO++: Survival Probability

pep flux:

Uncertainty ±1.5%

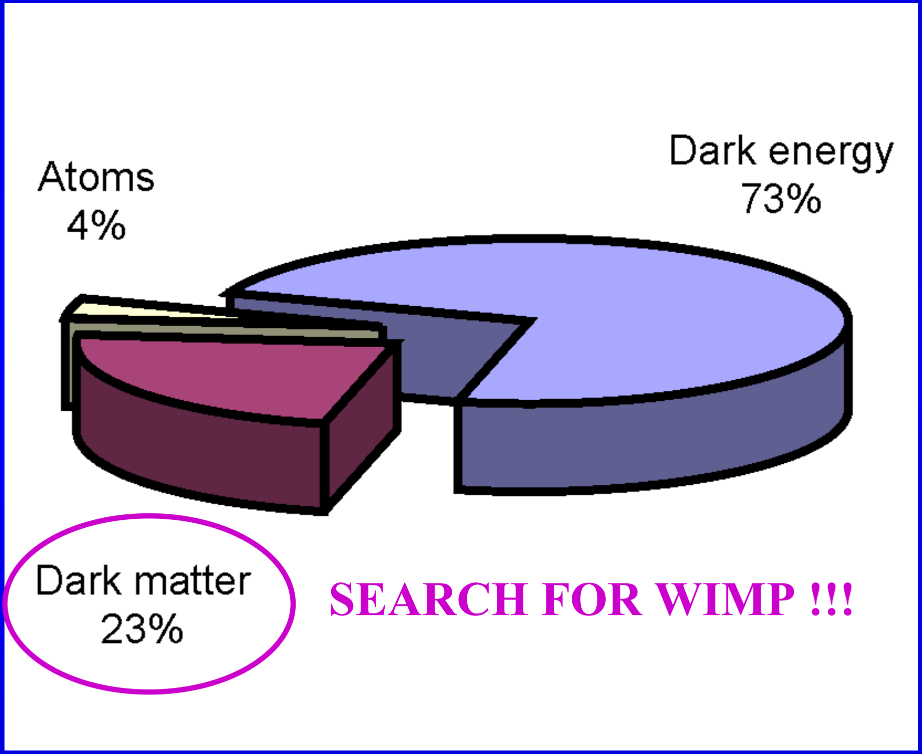
Allows precision test of the Solar Standard Model & the LMA matter enhanced oscillation scenario

Real-time low energy ν's experiments are the ultimate probe of the Sun



SNOLAB: The Cosmic Connections

Energy budget of Universe



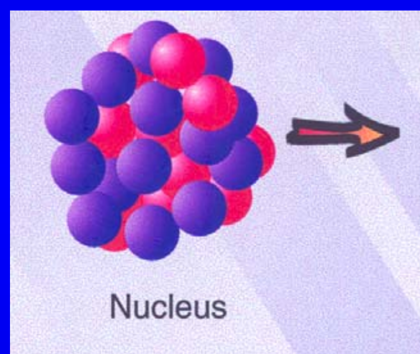
96% is a mystery!

Neutralino Interaction with Matter

Spin independent interaction – scalar coupling

⇒ heavy nuclei

$M_{WIMP} \sim 100$ GeV



$M_{Recoil} < 100$ keV

➔ Require Low-E Threshold
➔ Require Large Target Mass with Ultra-Low Background

Neutralino Interaction with Matter

Spin dependent interaction – axial coupling λ

Picasso

- Small freon droplets in polymerized gel at room T° droplets overheat
- A particle hit vaporizes the droplet:
  - phase transition event
  - an acoustic shock wave detected with piezoelectric transducers

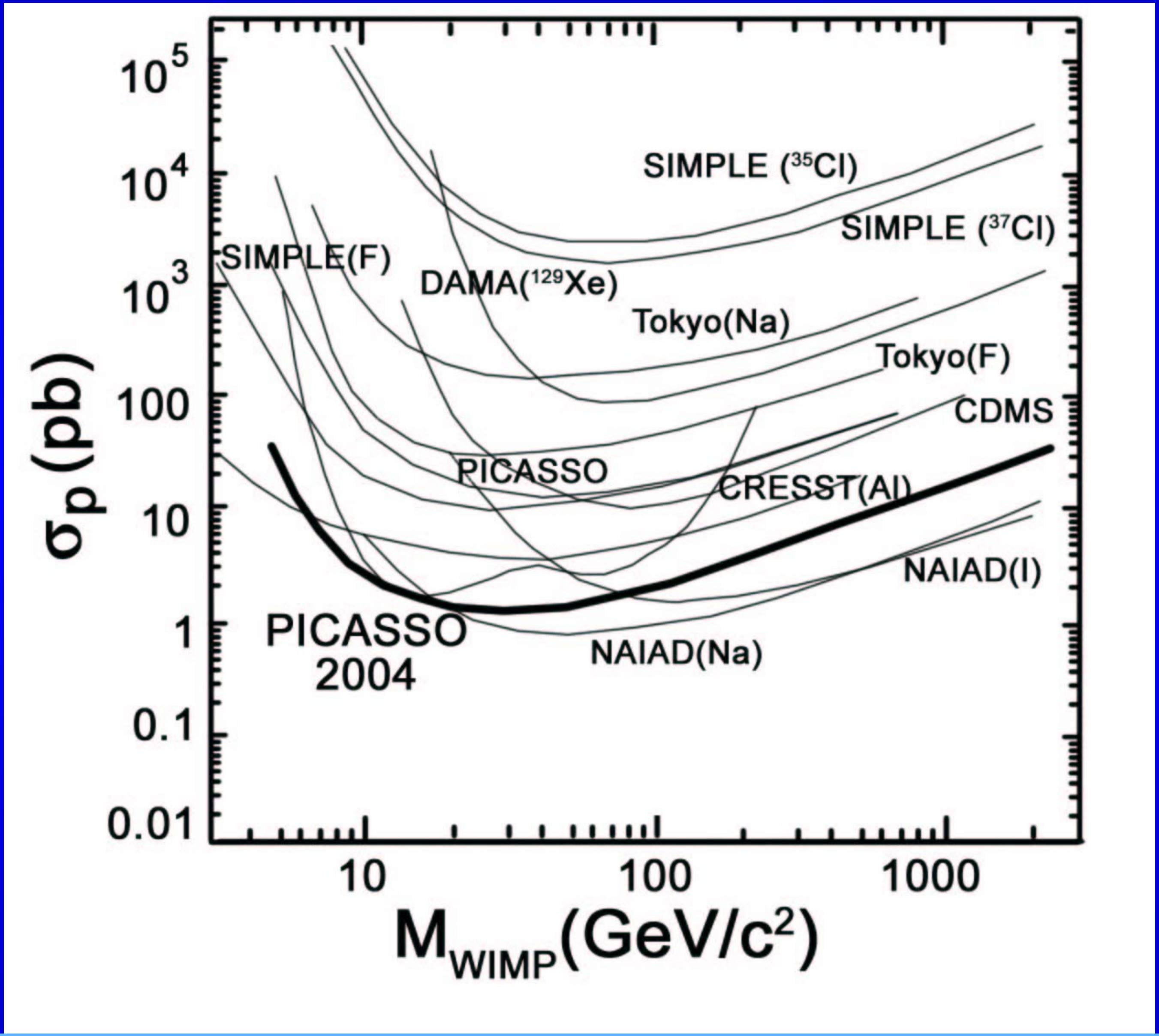
Target nuclei

Isotope	Spin	Unpaired	λ^2
^{7}Li	3/2	p	0.11
^{19}F	1/2	p	0.863
^{23}Na	3/2	p	0.011
^{29}Si	1/2	n	0.084
^{73}Ge	9/2	n	0.0026
^{127}I	5/2	p	0.0026
^{131}Xe	3/2	n	0.0147

Picasso at SNOLAB

Remotely controled from Montréal

Improved Spin Dependent Limits from the PICASSO Dark Matter Search Experiment
hep-ex/0502028



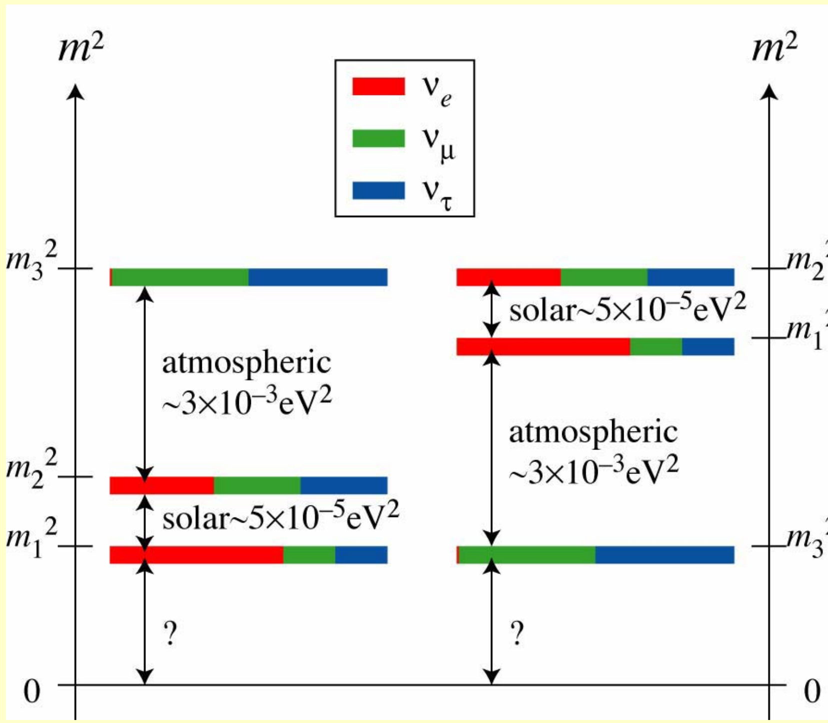
Yet, we still do not know: - the neutrino mass scale
- the choice of mass hierarchy

~2.8 eV

From tritium endpoint (Maintz and Troitsk)

~0.3 eV

From 0νββ if ν is Majorana



23 eV

Time of flight from SN1987A (PDG 2002)

~1 eV

From WMAP

Investigation of ββ decay

These *experimental* problems take a central place in the future of Particle Physics