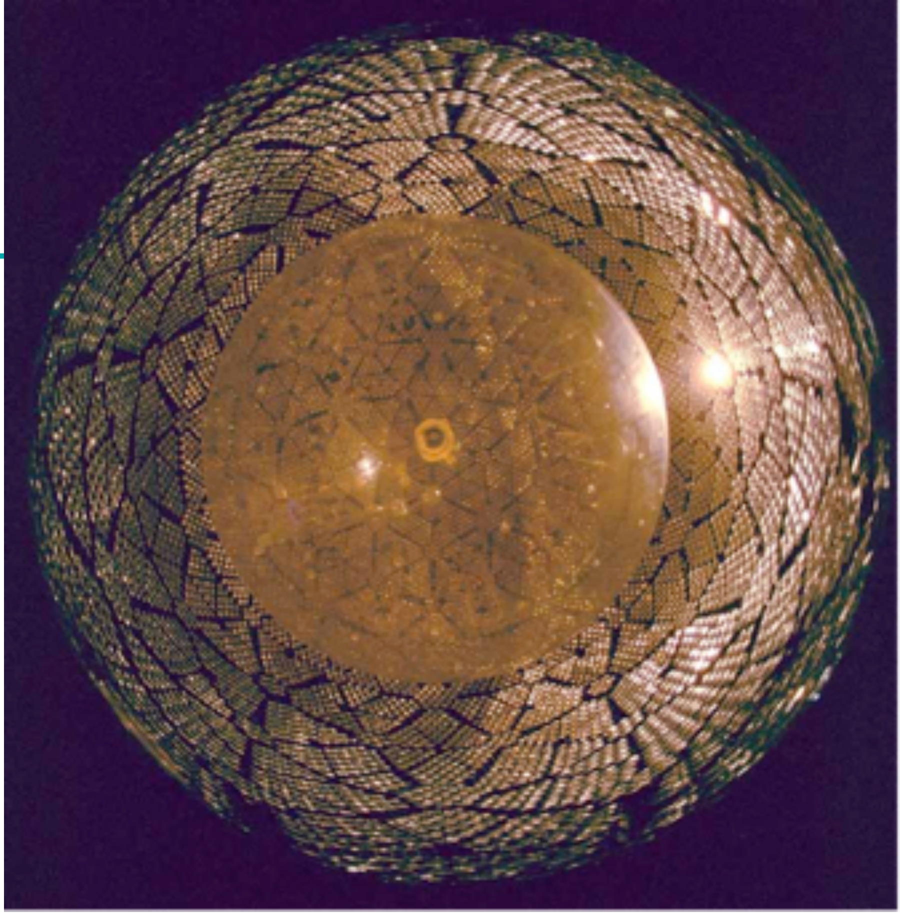
Results from the Sudbury Neutrino Observatory



David Waller for the SNO Collaboration
Carleton University, Ottawa, Canada
SLAC Summer Institute 2004

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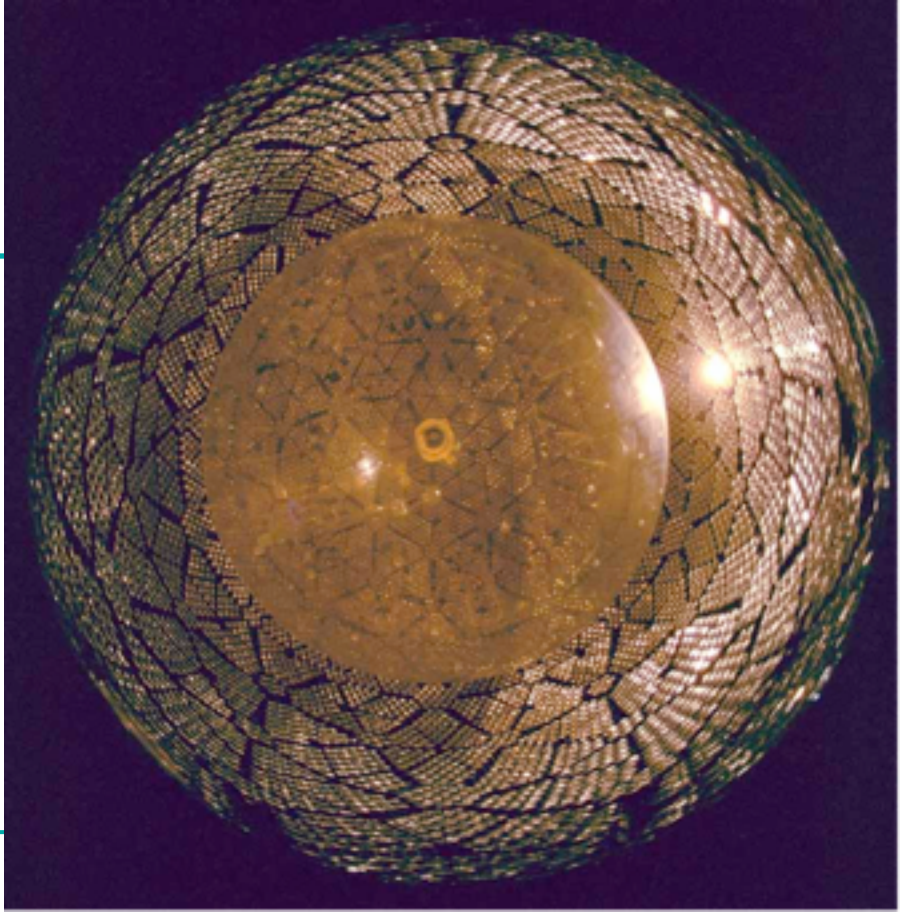

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Outline

- Introduction to SNO
- Previous solar neutrino results with D_2O
- Most recent solar neutrino result with D_2O + salt
- Non-solar neutrino results
- SNO's future
- Summary

Road map to talk…

- **Introduction to SNO** ←
- Previous solar neutrino results with D_2O
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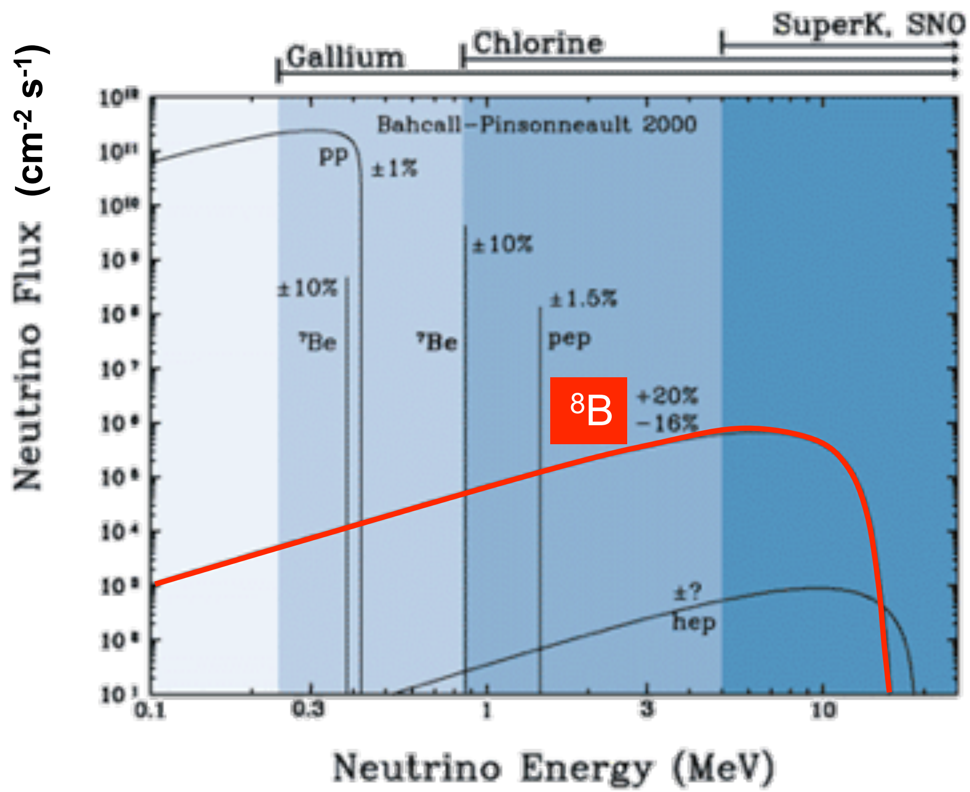
Purpose of SNO

- Resolve Solar Neutrino Problem (SNP): measured flux of ν from Sun is ~1/3 the predicted flux of Standard Solar Model.
  - Is Standard Solar Model wrong?
  - Do neutrinos oscillate from ν_e to ν_μ and/or ν_τ?
  - Something else happening (e.g. ν_e to sterile ν)?



- Observe ν from ^8B β-decay in Sun.

$$^8B \rightarrow {}^8Be + e^+ + \nu_e$$

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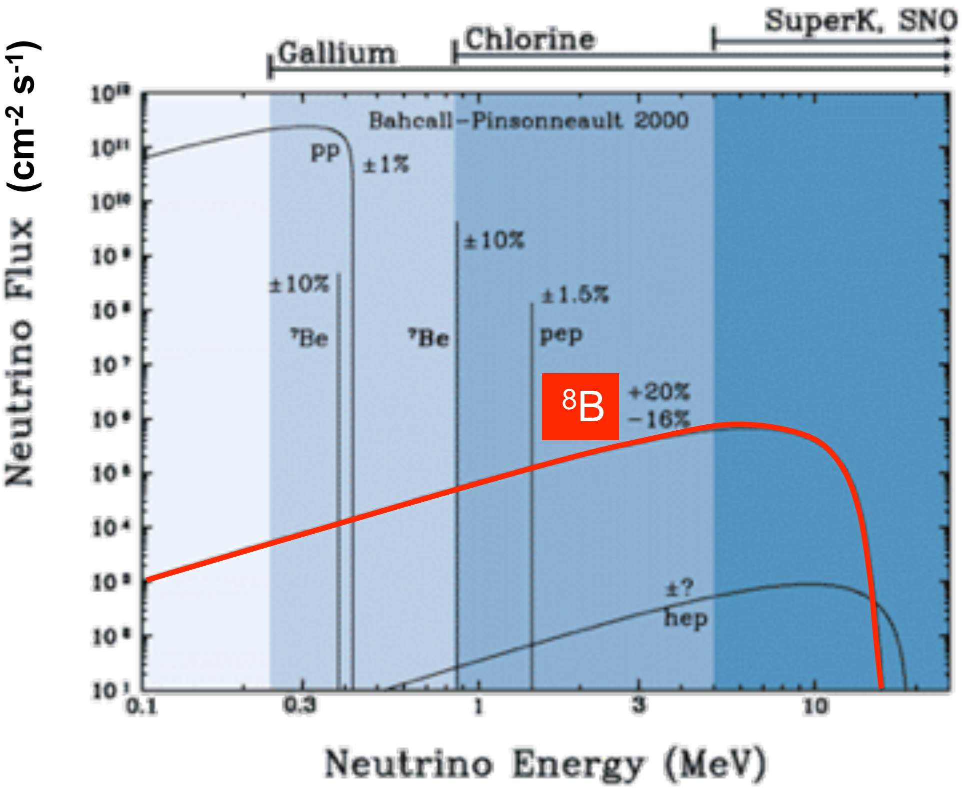

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- If Solar Neutrino Problem due to ν_e oscillation to ν_μ and/or ν_τ, SNO should provide direct evidence .
- SNO measures flux of ν_e and flux of $(\nu_e+\nu_\mu+\nu_\tau)$.
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Water Čerenkov expt's: Kamiokande, Super-K

Radiochemical expt's:
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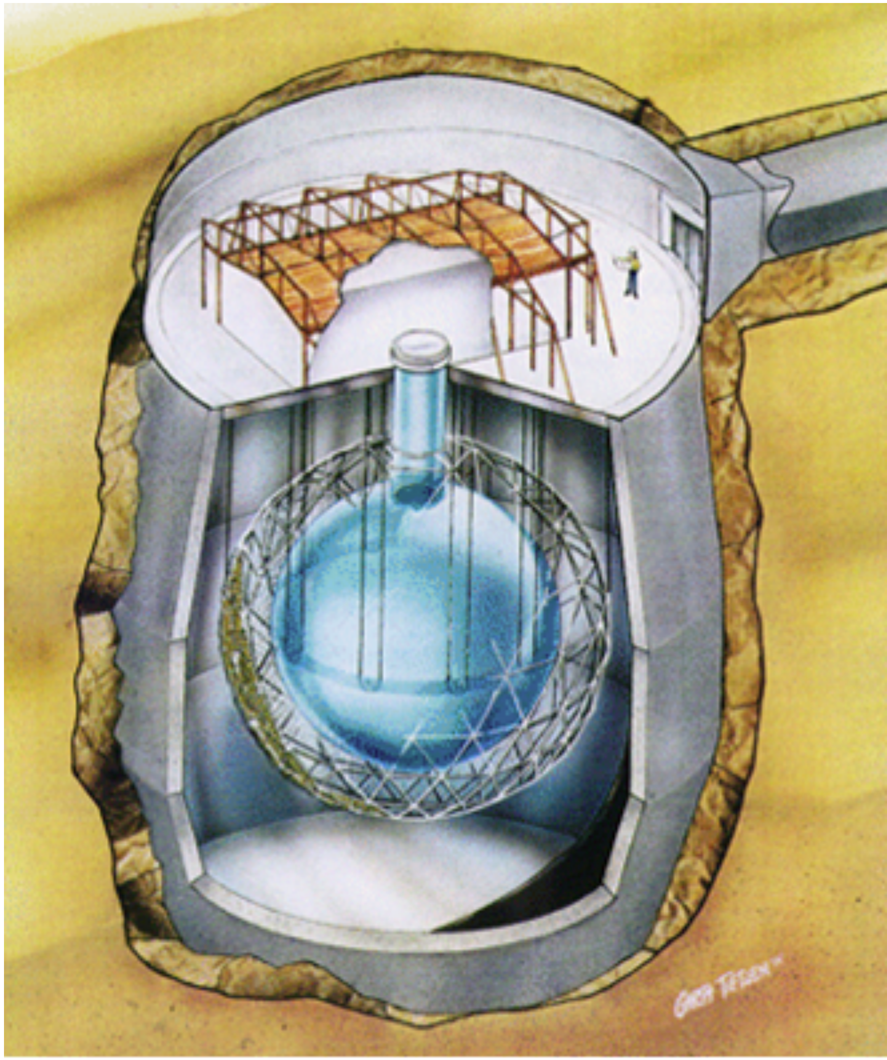
The SNO Detector

- 1,000 tonnes of D_2O.
- 6 m radius transparent acrylic vessel.
- 9,456 inward looking PMTs (with reflectors around PMTs have 54% geometrical acceptance).
- PMTs mounted on 9 m radius steel support structure.
- 7,000 tonnes of H_2O to support and shield D_2O.
- All materials carefully selected and tested to ensure minimal radioactive backgrounds (e.g. U, Th).



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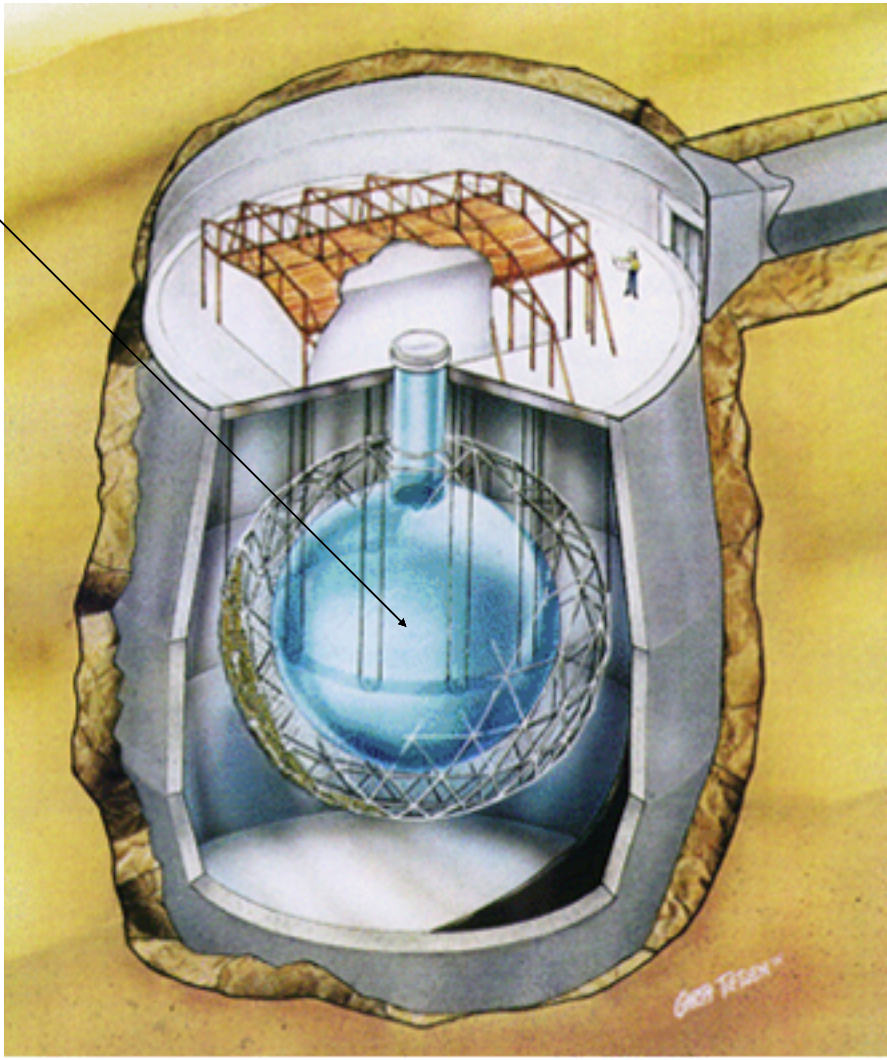

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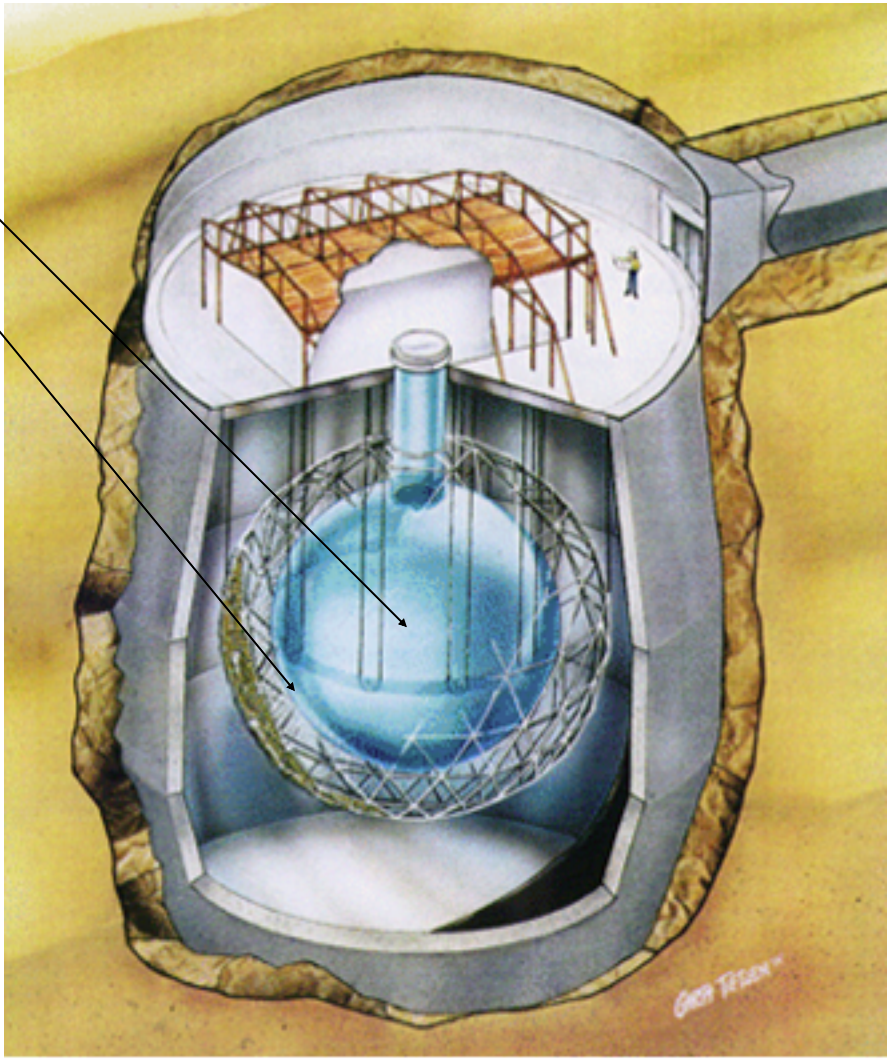

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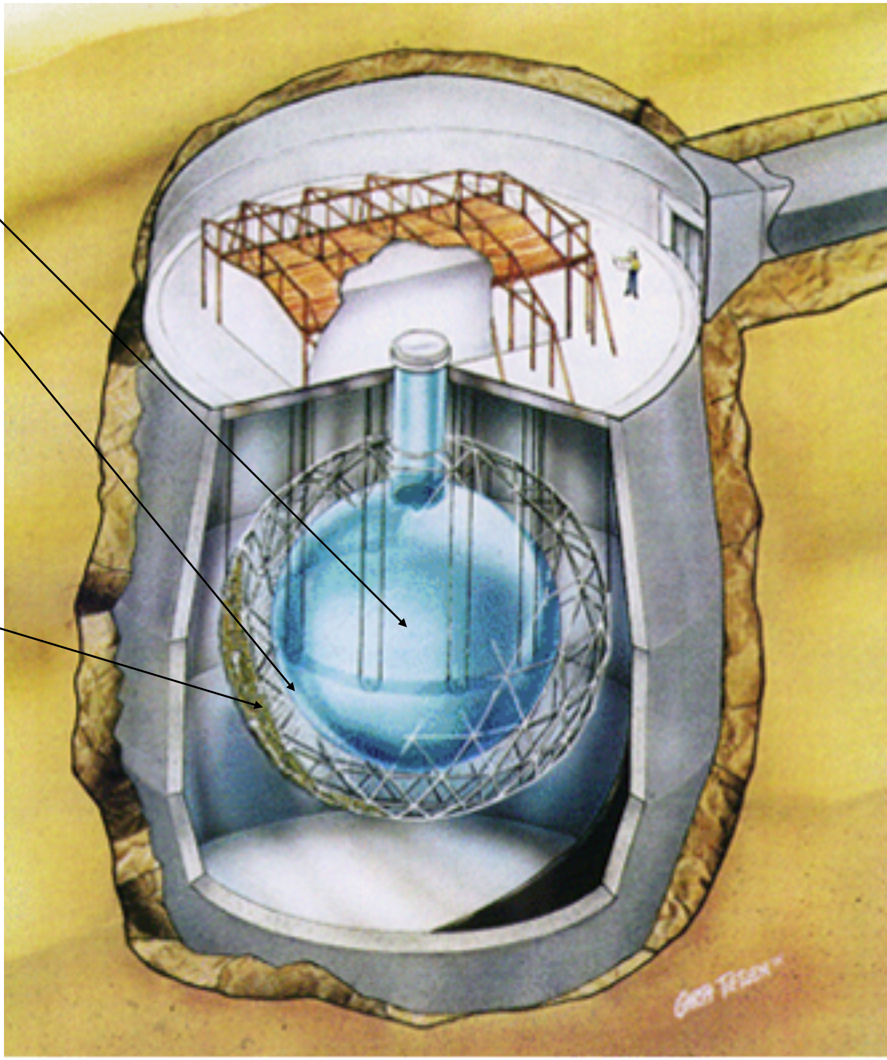

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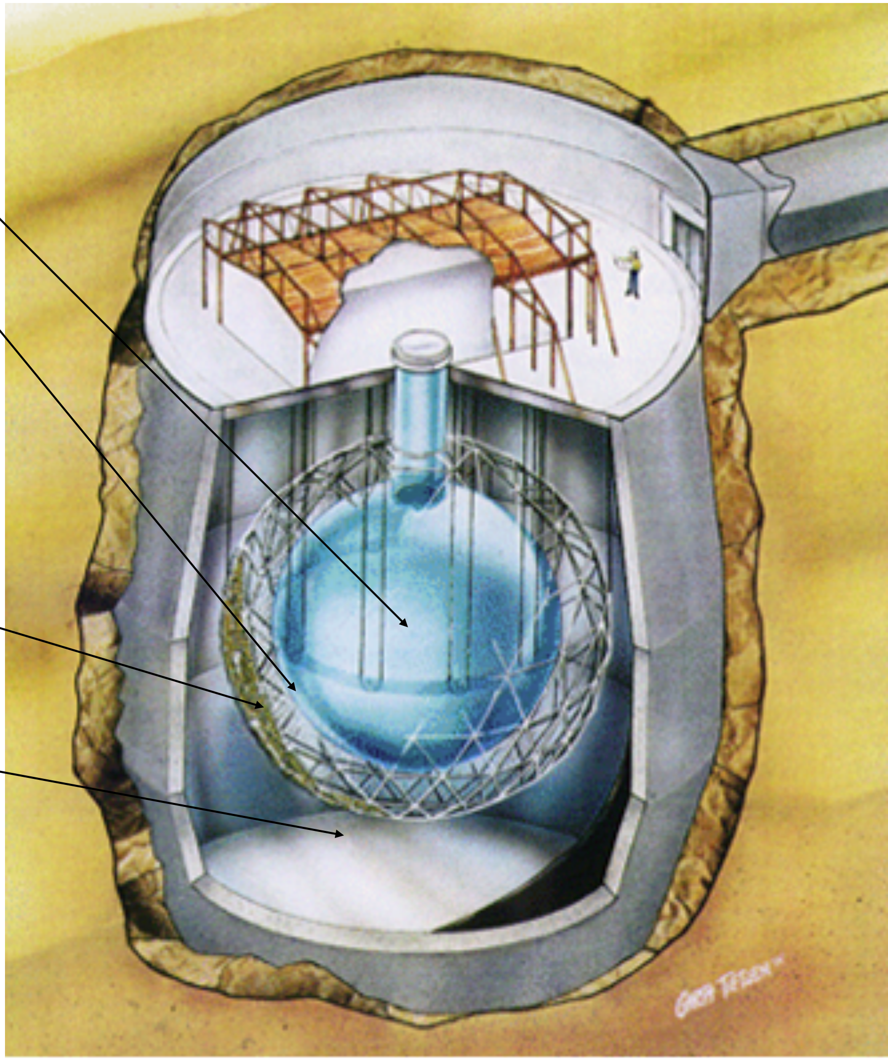
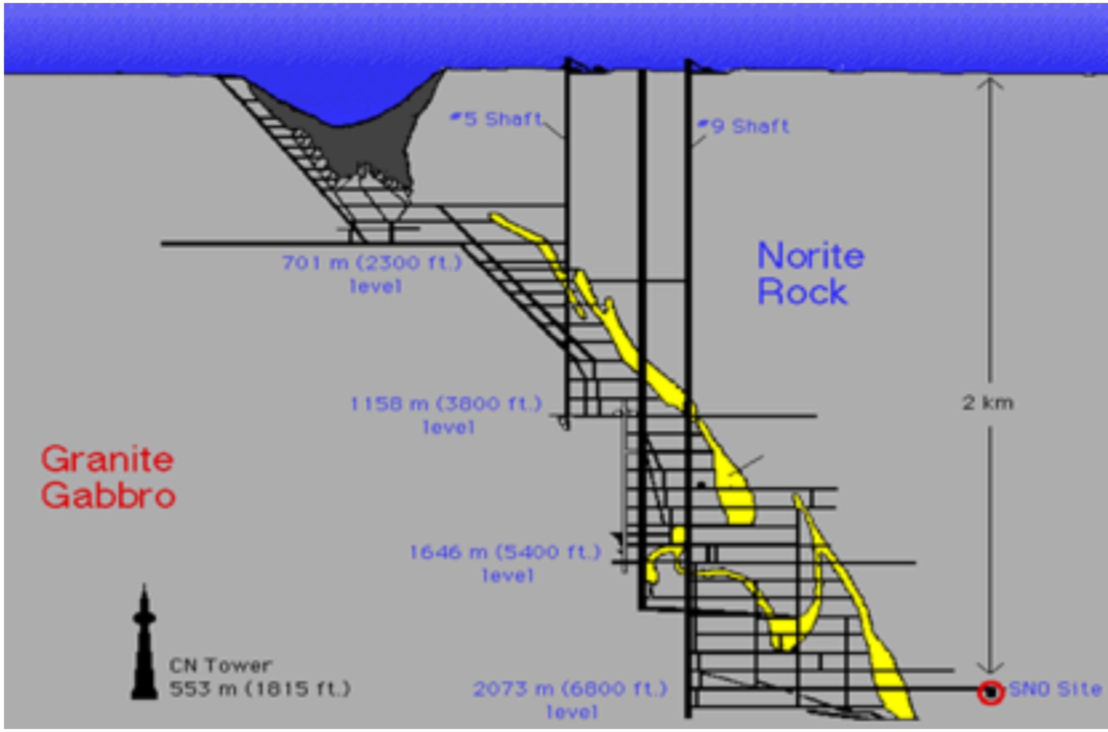
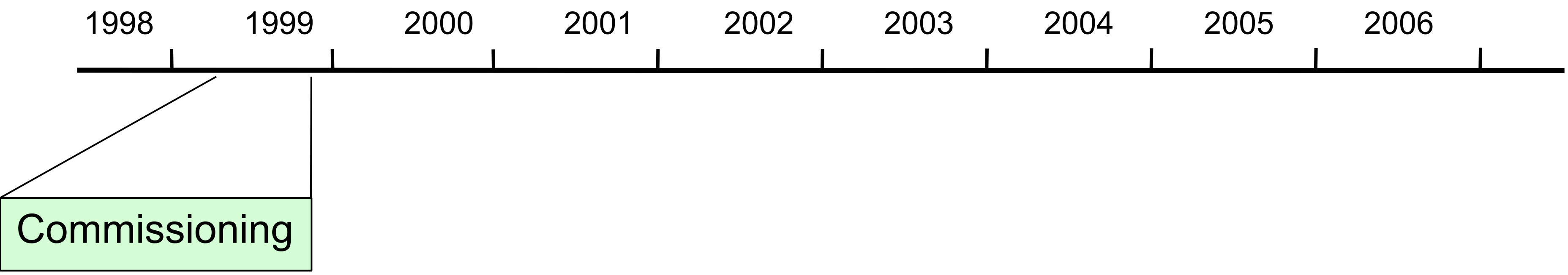


Location of SNO

- Located 2 km underground in active nickel mine near Sudbury, Canada
- Shielding from 2 km of rock reduces flux of cosmic ray muons to 70/day (>10^9/day on surface).
- Reduced cosmic ray background improves sensitivity to solar neutrinos.



SNO timeline



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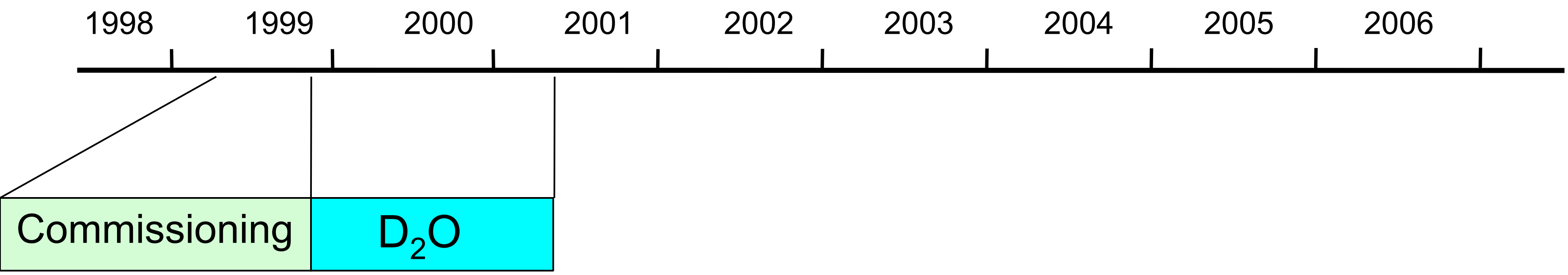
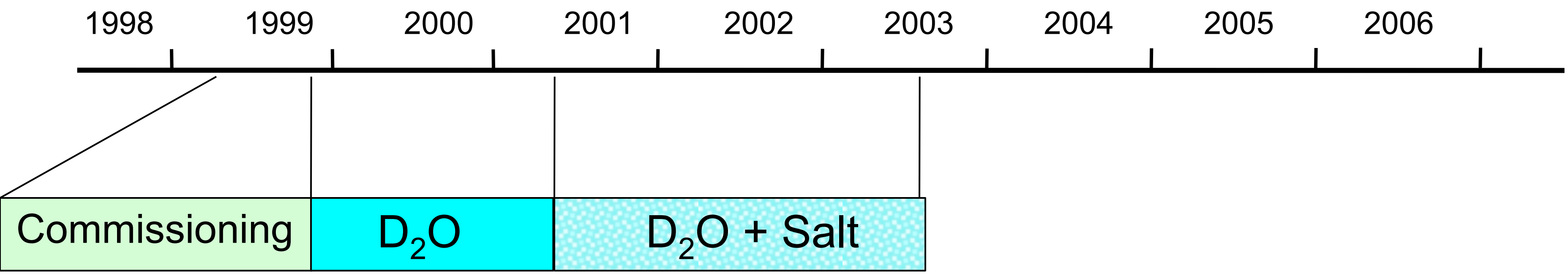


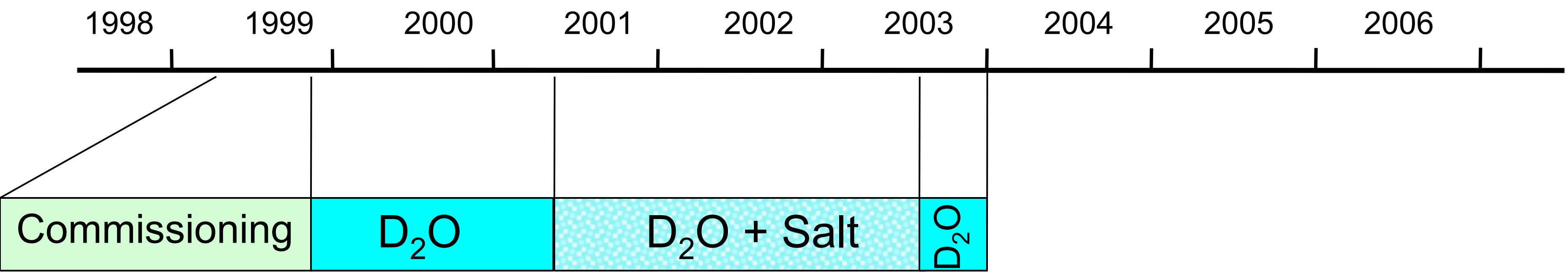
- Phase 1: D_2O

SNO timeline



- Phase 1: D_2O
- Phase 2: D_2O + Salt (NaCl)

SNO timeline



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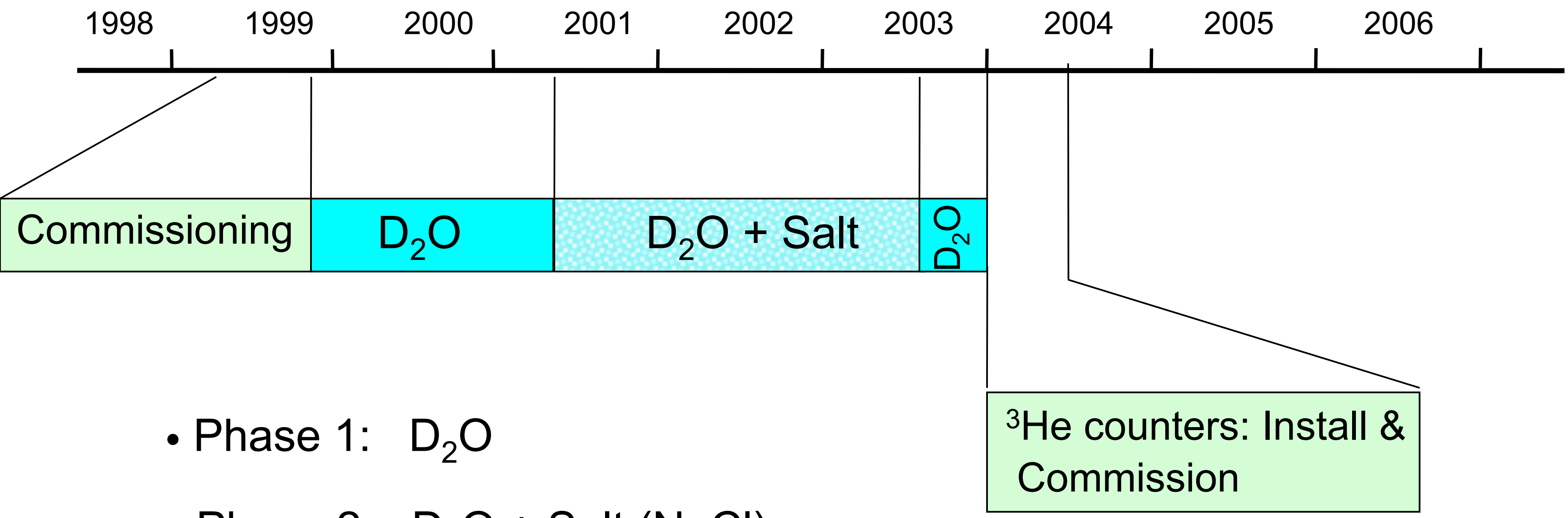

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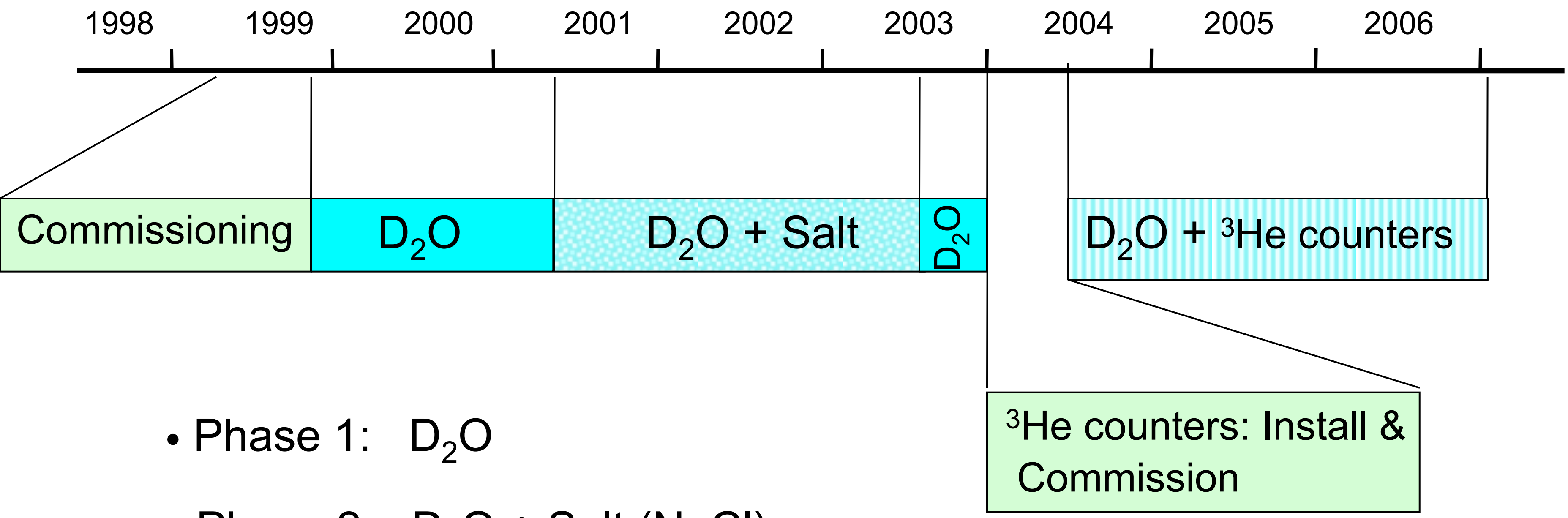
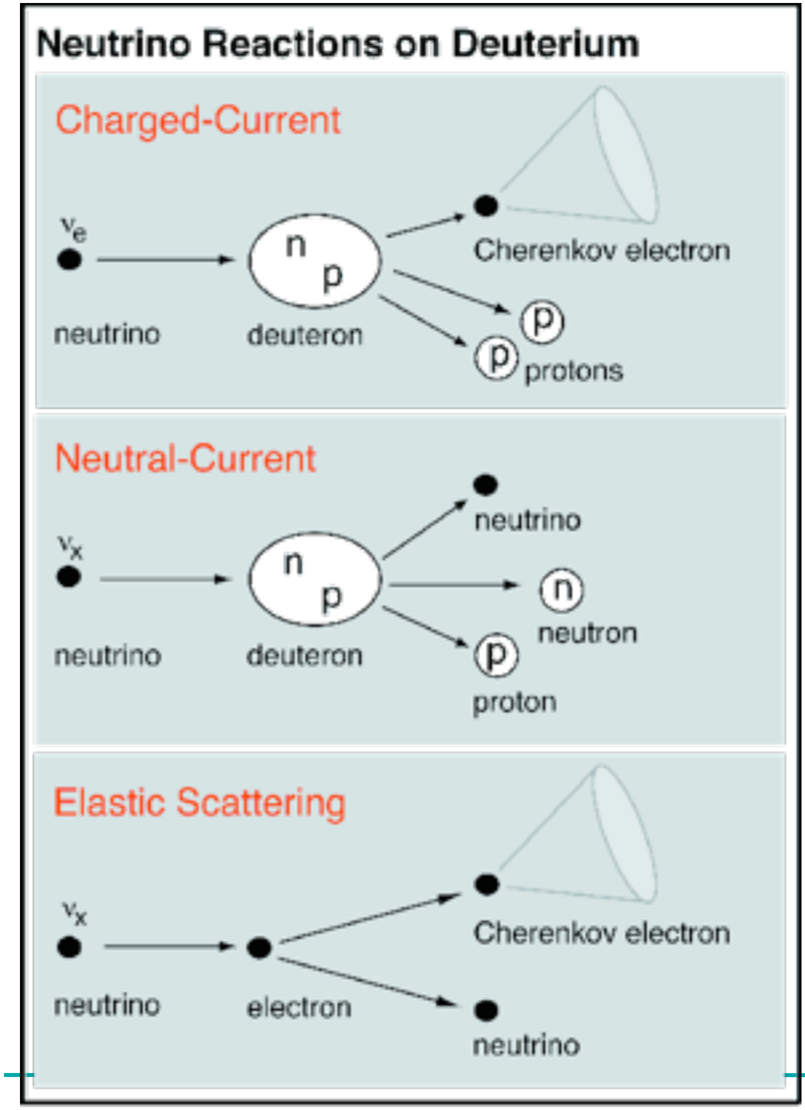


- Phase 1: D_2O
- Phase 2: D_2O + Salt (NaCl)
- Phase 1a: D_2O
- Phase 3: D_2O + ^{3}He counters

Neutrino reactions in SNO



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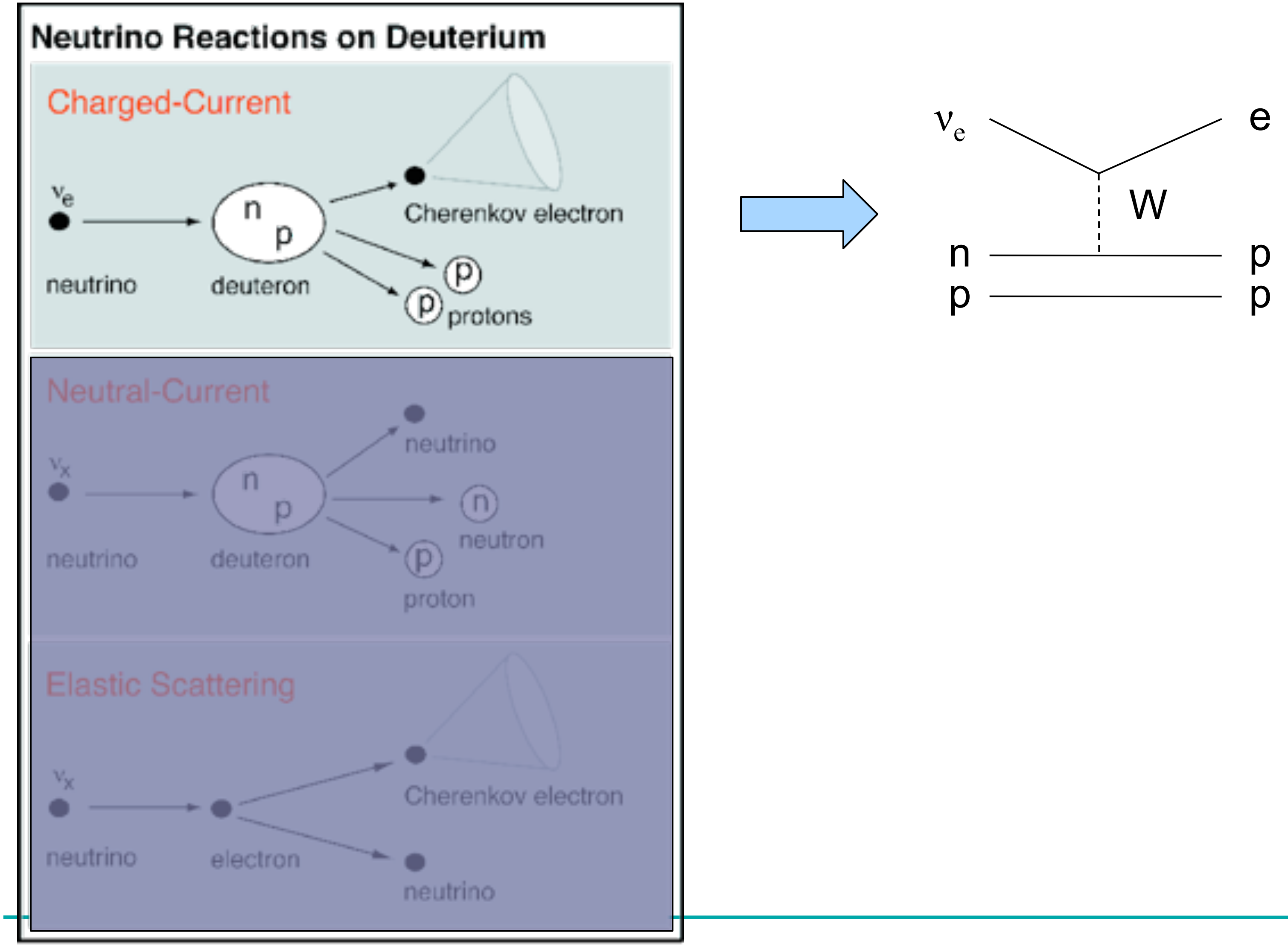

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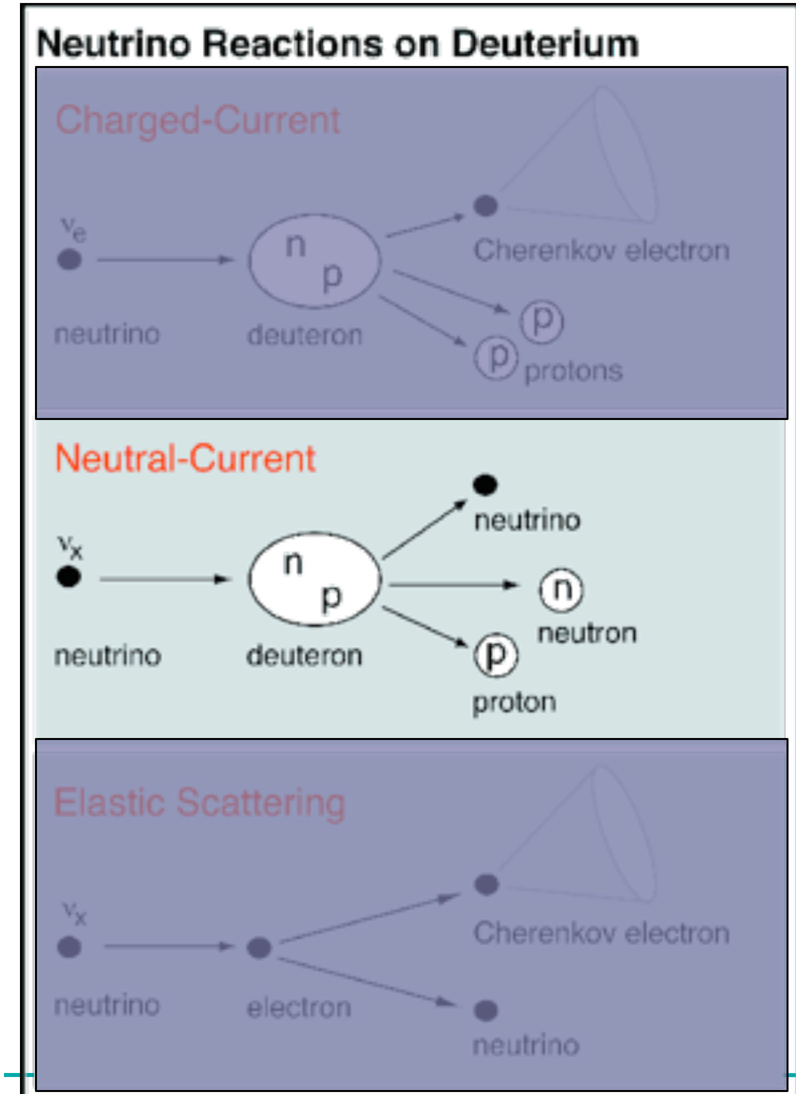

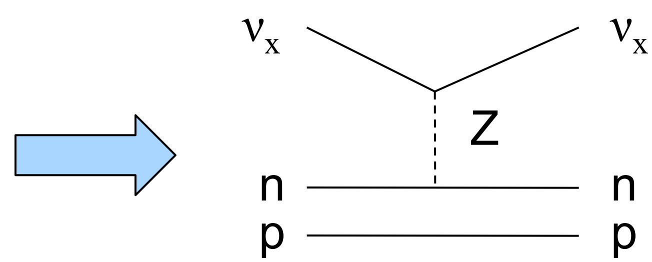

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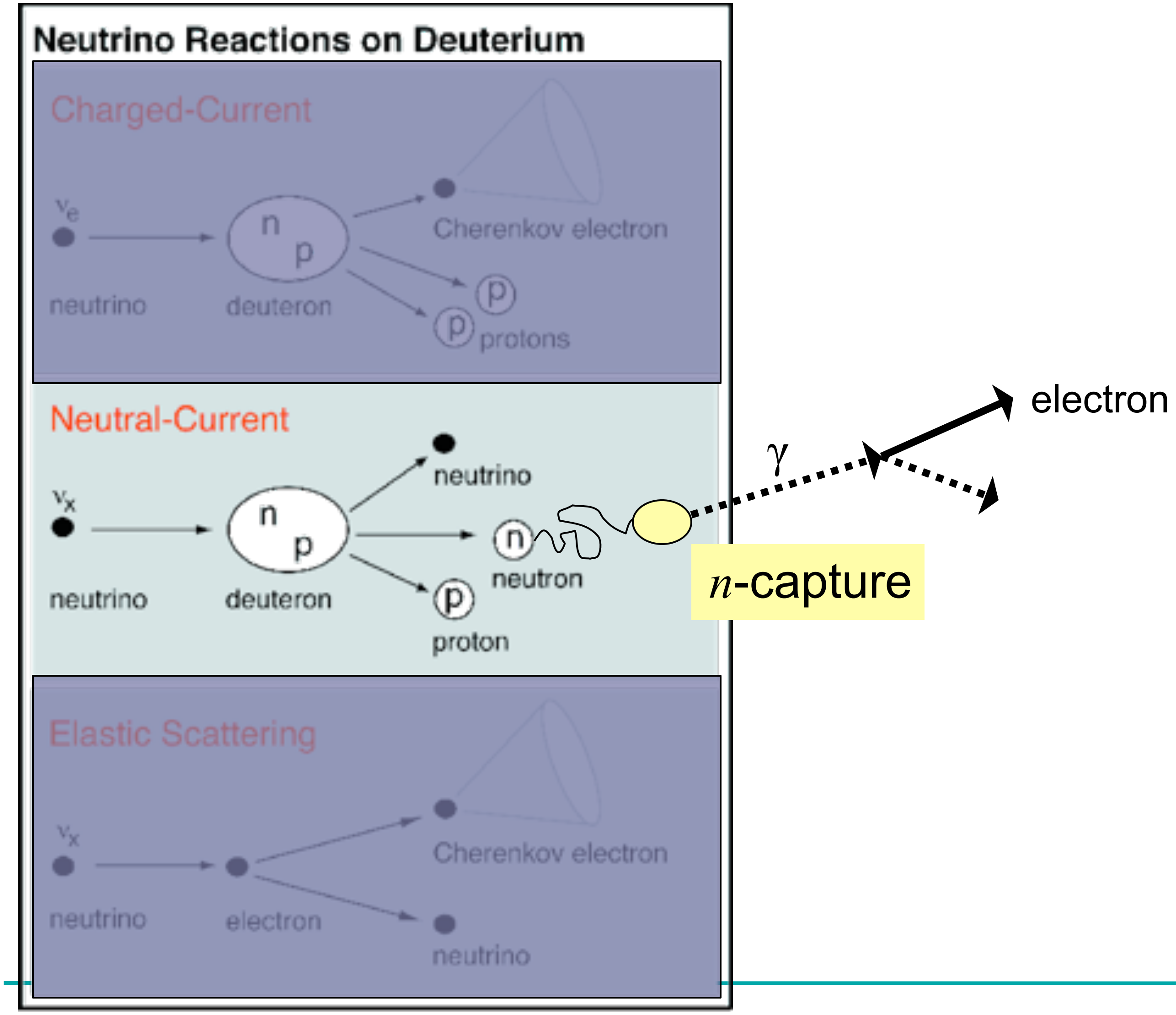

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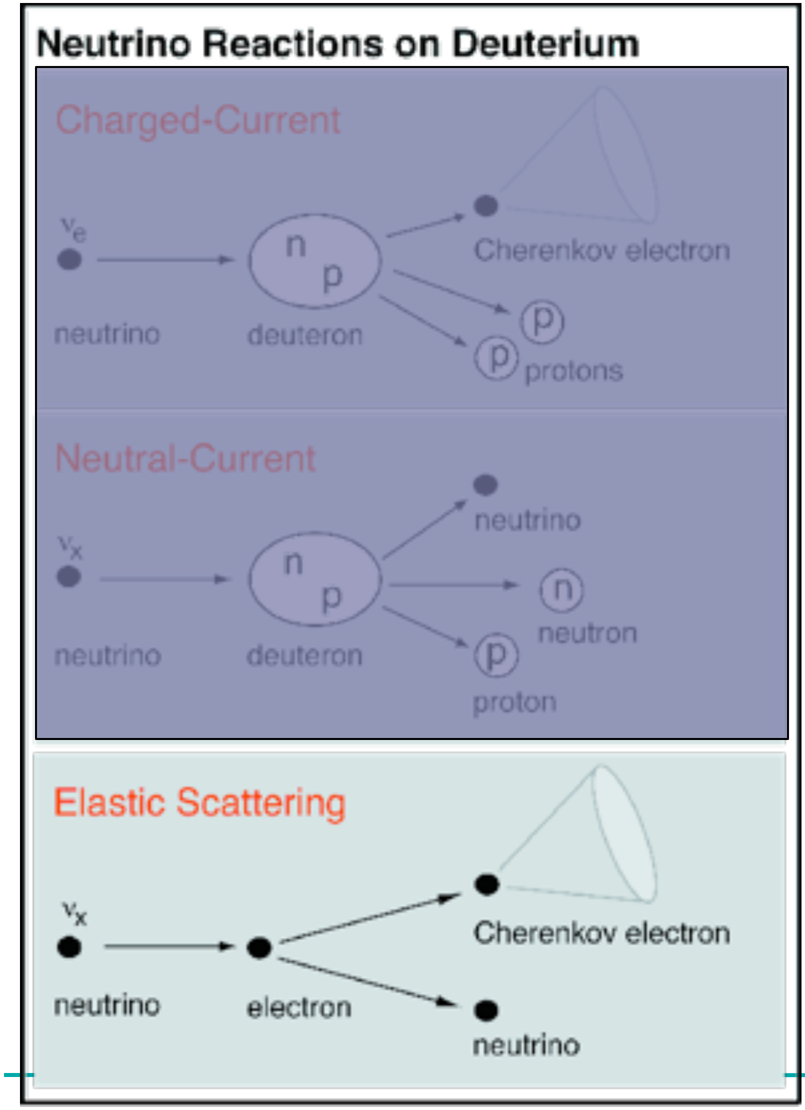
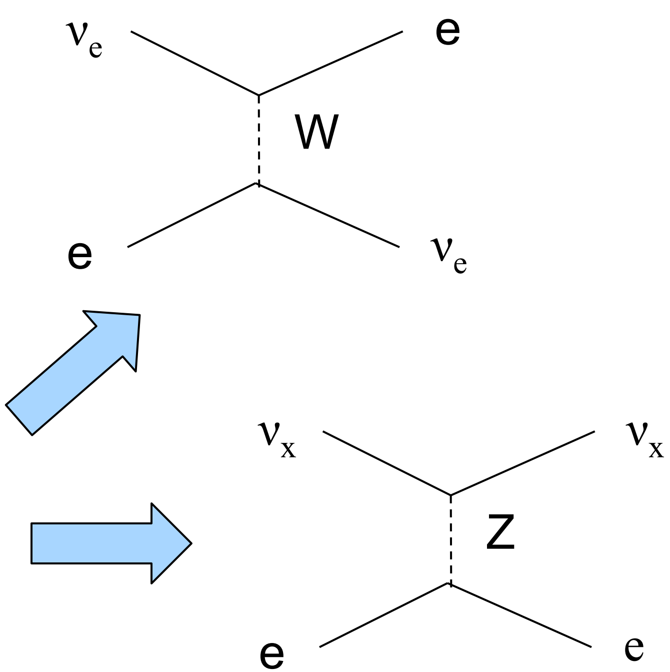
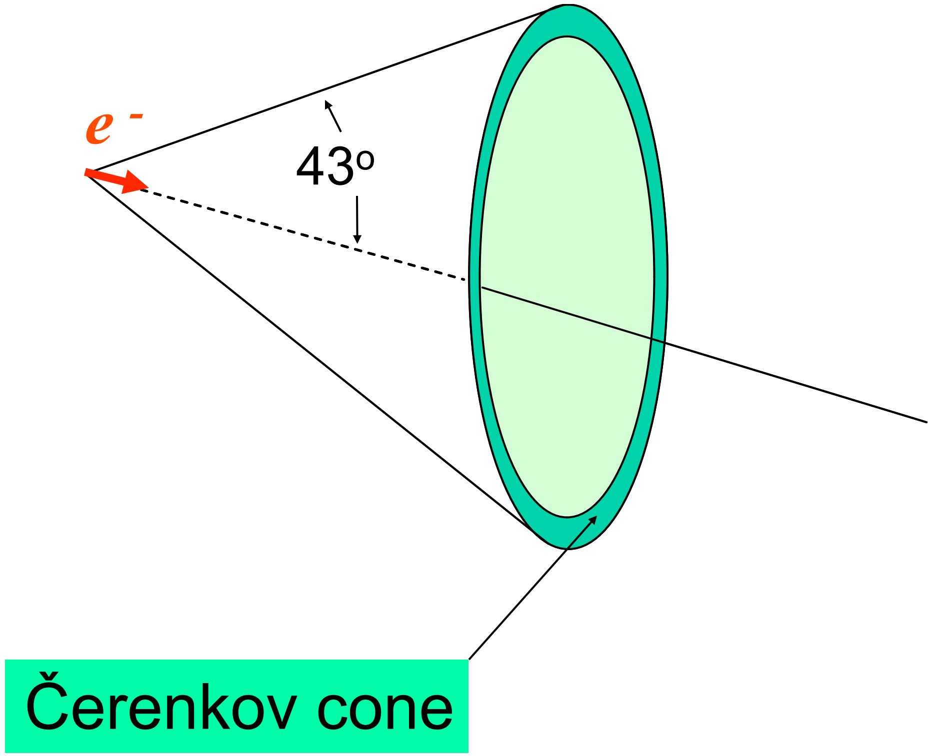


$\sigma_{ES}(\nu_e) = 6\ \sigma_{ES}(\nu_{\mu/\tau})$



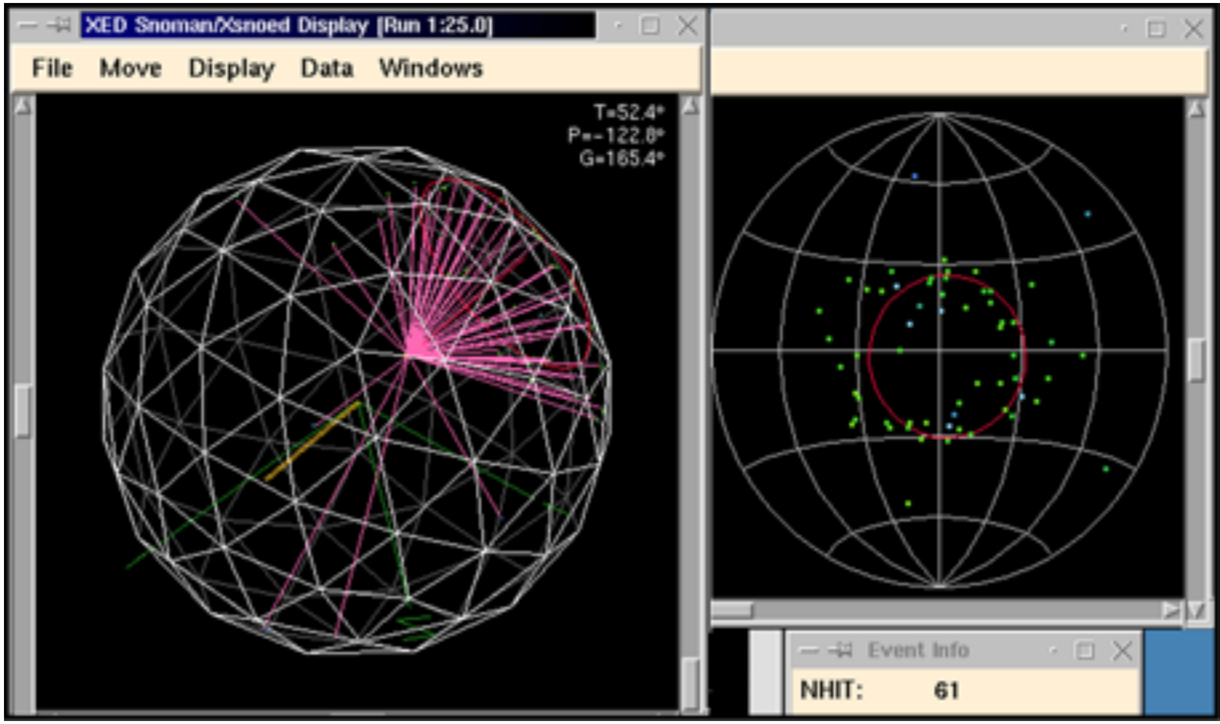
Neutrino detection in SNO

- 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).



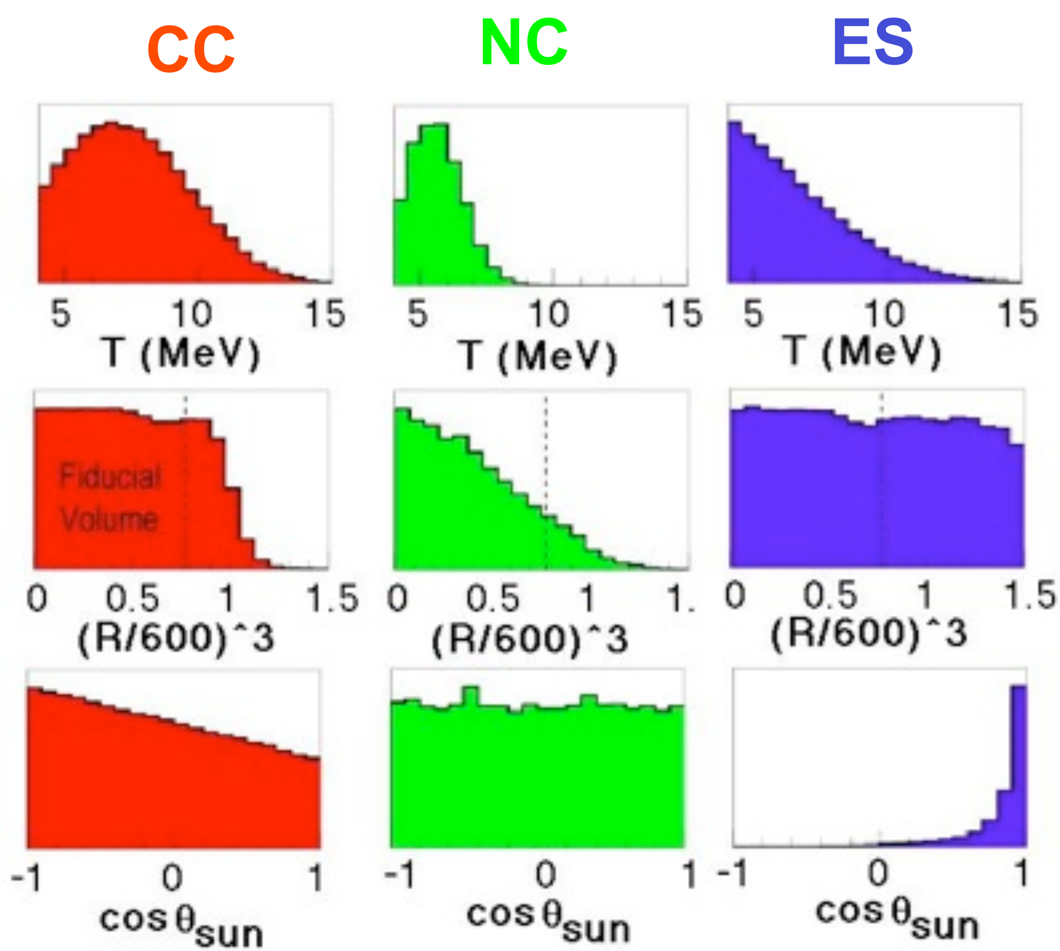
Neutrino detection in SNO

- 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.



Differentiating CC, ES and NC reactions

- Statistical separation based on several variables (e.g. during D_2O phase):
  - Electron kinetic energy, **T** (# of PMT hits)
  - Radial position of reconstructed vertex, **(R/600)^3** (volume-weighted)
  - Direction of electron w.r.t. Sun, $\mathbf{cos\ \theta_{sun}}$



Road map to talk…

- Introduction to SNO
- **Previous solar neutrino results with D_2O** ⟵
- Most recent solar neutrino result with D_2O + salt
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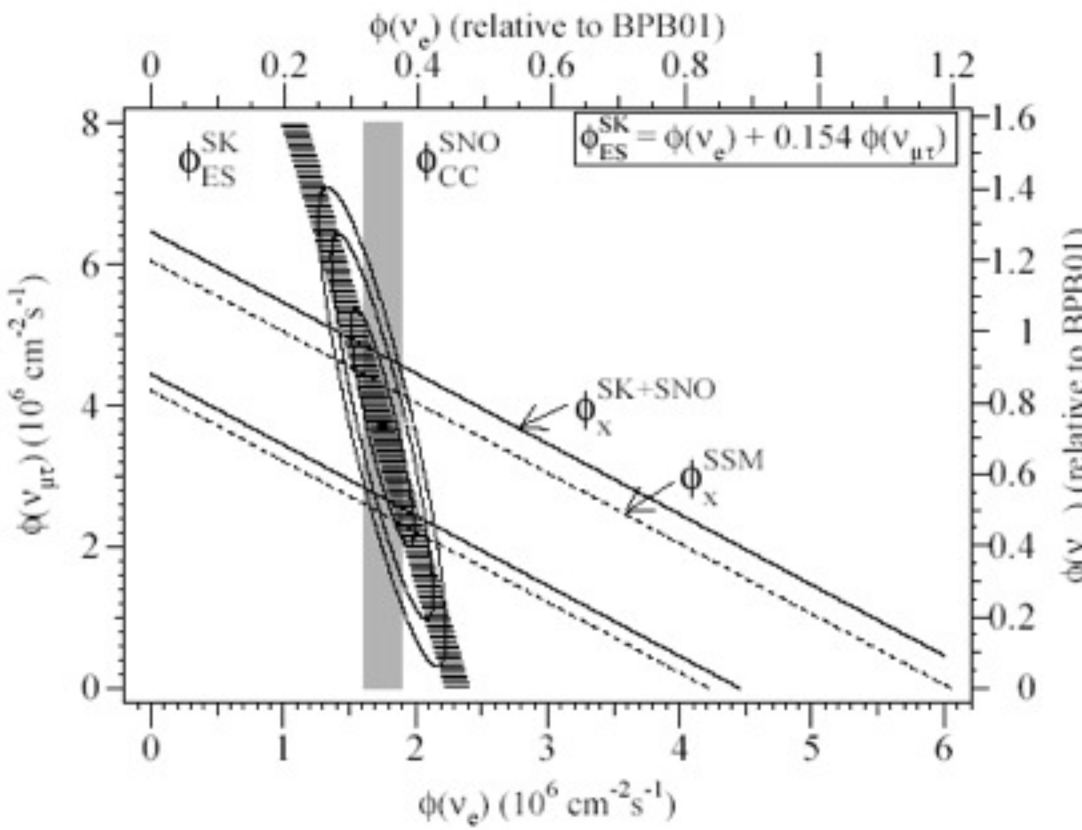
CC measurement with D_2O

- Measured CC reaction rate: $\phi_{CC} \equiv \phi(\nu_e)$
  - Can compare SNO's $\phi(\nu_e)$ to Super-K's $\phi(\nu_e)$ (assuming all ES interactions at Super-K due to ν_e)
  - 3.3 σ difference between $\phi(\nu_e)$'s .

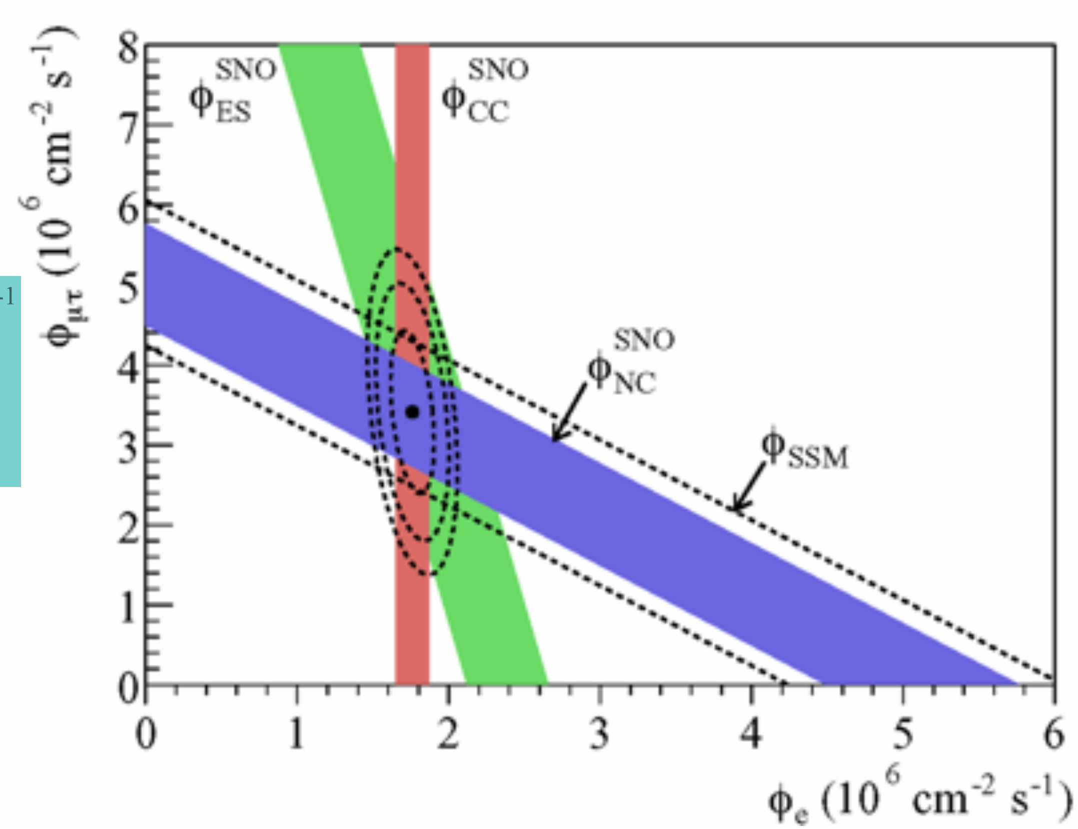


NC measurement with D_2O

- Measured NC reaction rate: $\phi_{NC} \equiv \phi(\nu_e+\nu_\mu+\nu_\tau)$

$$\phi_{CC} = (1.76^{+0.06}_{-0.05}(\text{stat}) \pm 0.09(\text{syst})) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

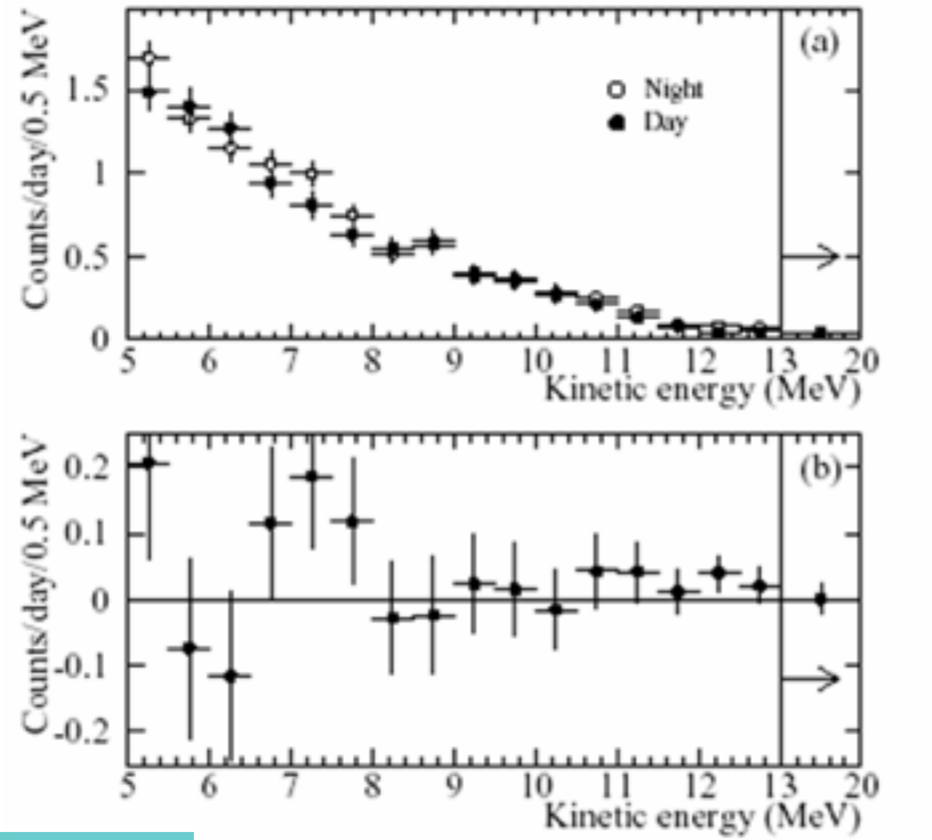
$$\phi_{NC} = (5.09^{+0.44}_{-0.43}(\text{stat})\ ^{+0.46}_{-0.43}(\text{syst})) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$



  - 5.3 σ signal for solar neutrino flavour mixing.
  - ϕ_{NC} consistent with SSM with neutrino flavour mixing.

More results from first phase (pure D_2O)

- Measured Night-Day rate asymmetry ($A^e_{N\text{-}D}$) and electron energy spectra for Night and Day.
- At Night, ν pass through Earth; CC and ES rates may increase due to matter enhanced mixing of ν_μ/ν_τ to ν_e.



$$A^e_{N-D} \equiv \frac{(\phi_N - \phi_D)}{(\phi_N + \phi_D)/2} = 0.140 \pm 0.063^{+0.015}_{-0.014}$$

$$A^e_{N-D} \equiv \frac{(\phi_N - \phi_D)}{(\phi_N + \phi_D)/2} = 0.070 \pm 0.049^{+0.013}_{-0.012}\,, \quad A_{NC} = 0$$

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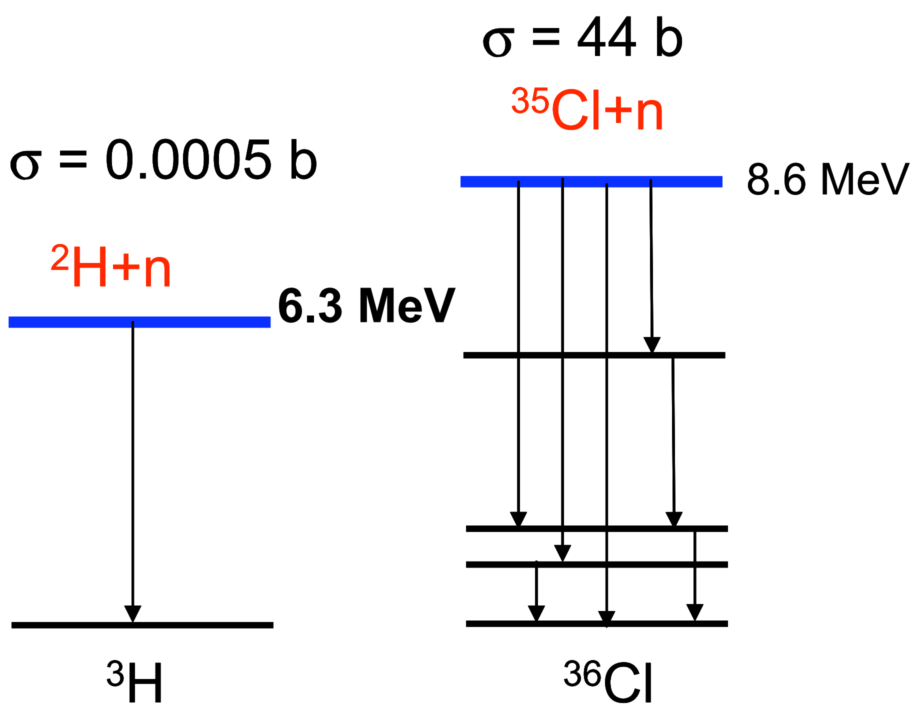
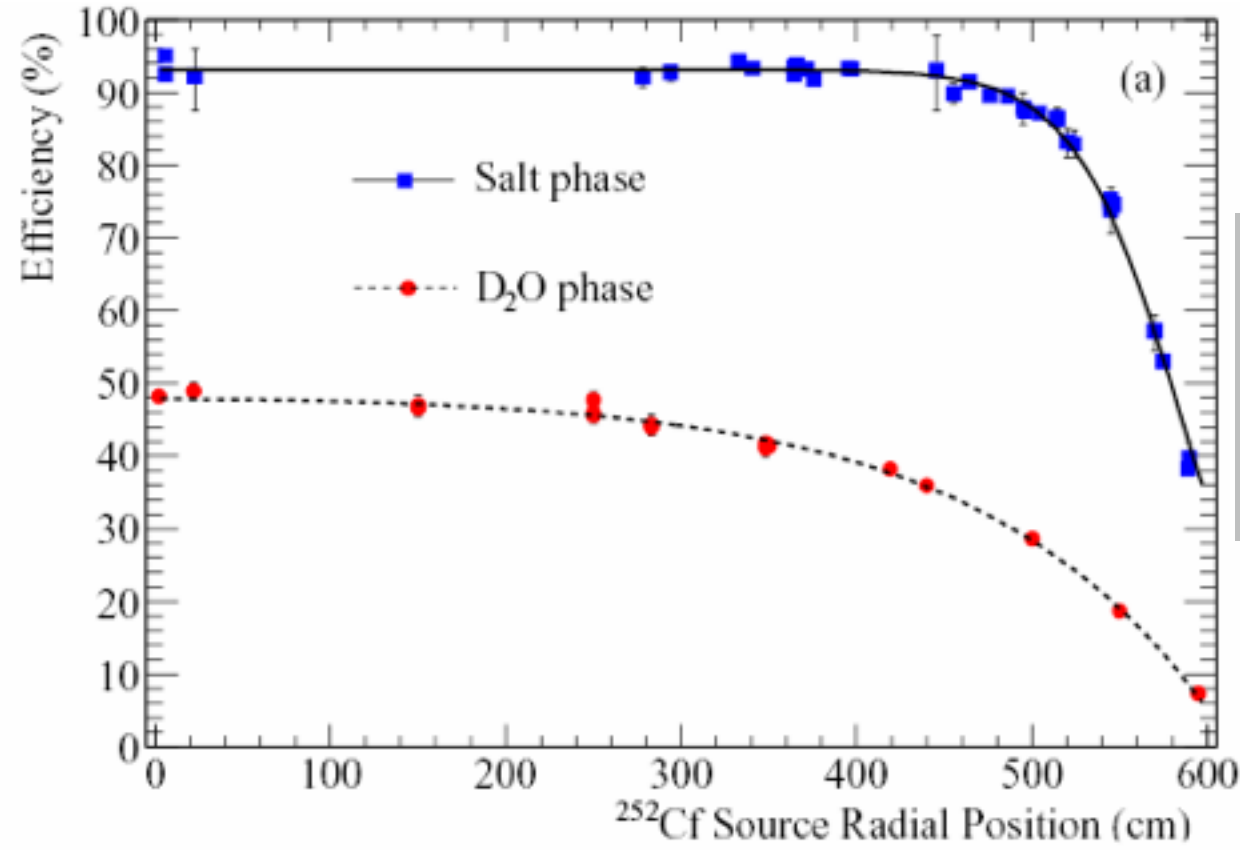
D_2O + Salt: why add salt?

- 2 tonnes of NaCl added.
- Change response to neutrons from NC reaction.
- Cl has larger σ than ^{2}H so *n*-capture efficiency improves.
- More energy released from ^{35}Cl +*n*.
  - Higher E event means more NC events above kinetic E threshold of analysis (5.5 MeV)
  - Multiple γ's → Č. photons from NC reaction more isotropic in detector (ES and CC produce single electron).

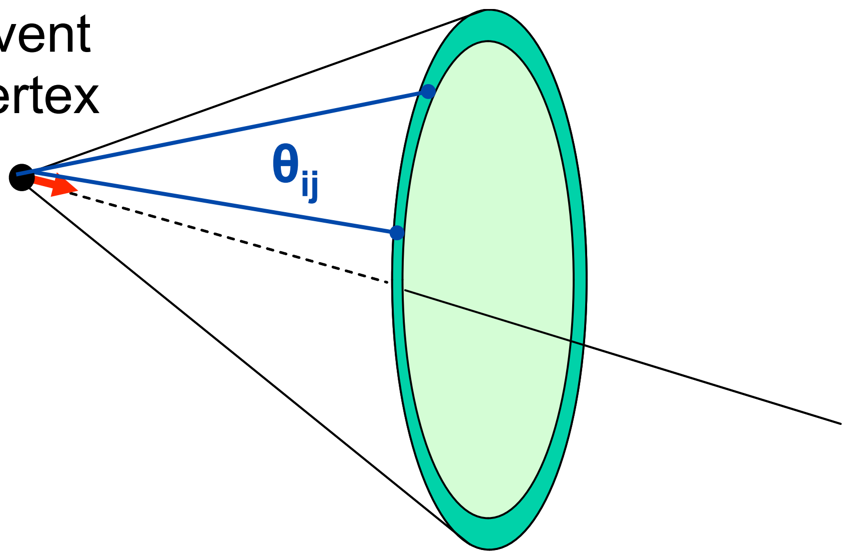


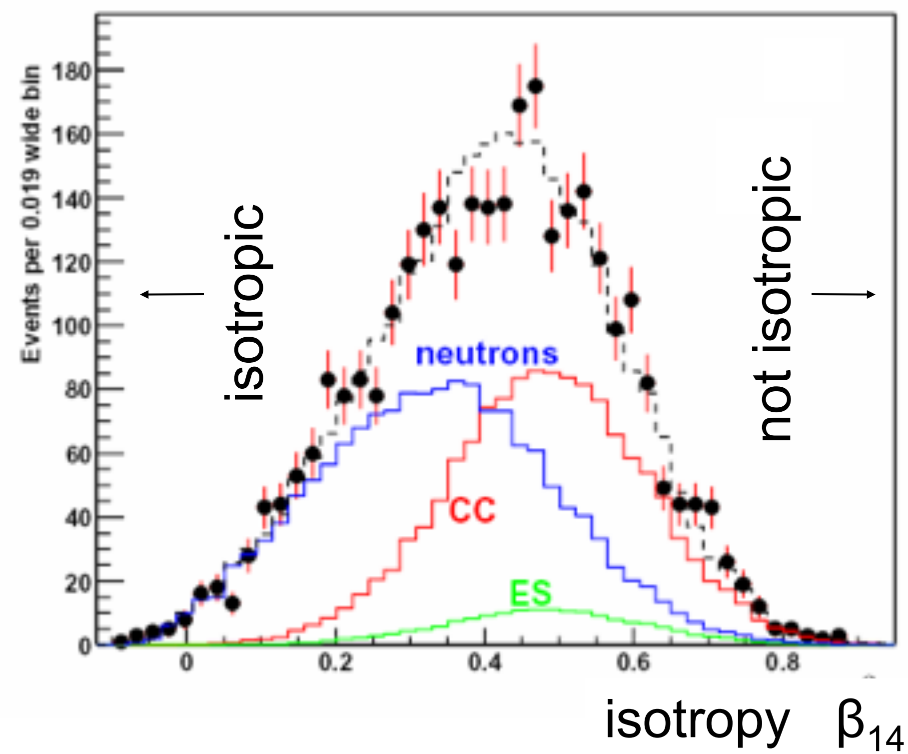
Advantages of salt: *n*-detection efficiency



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

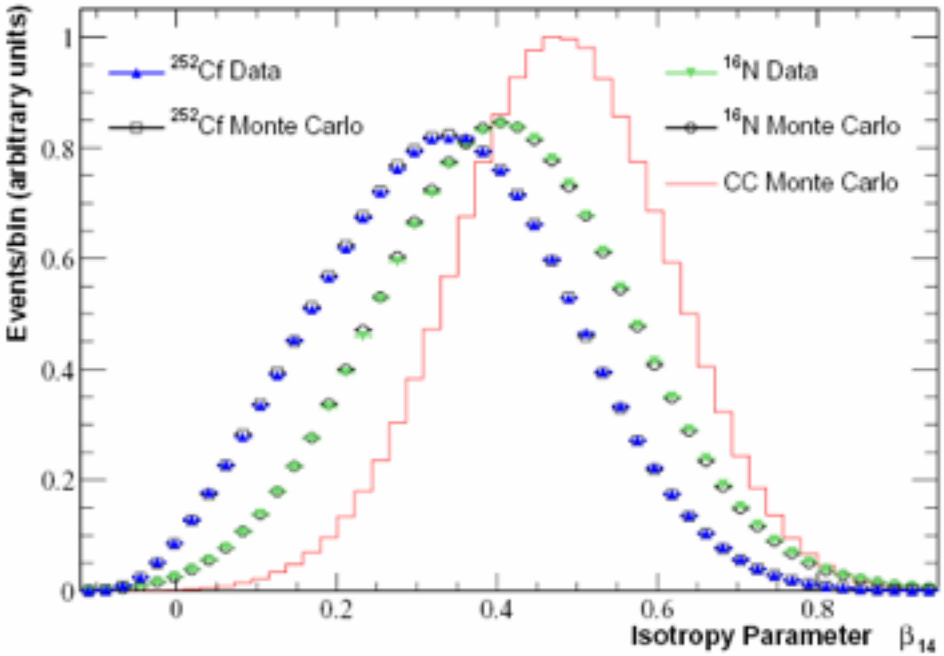


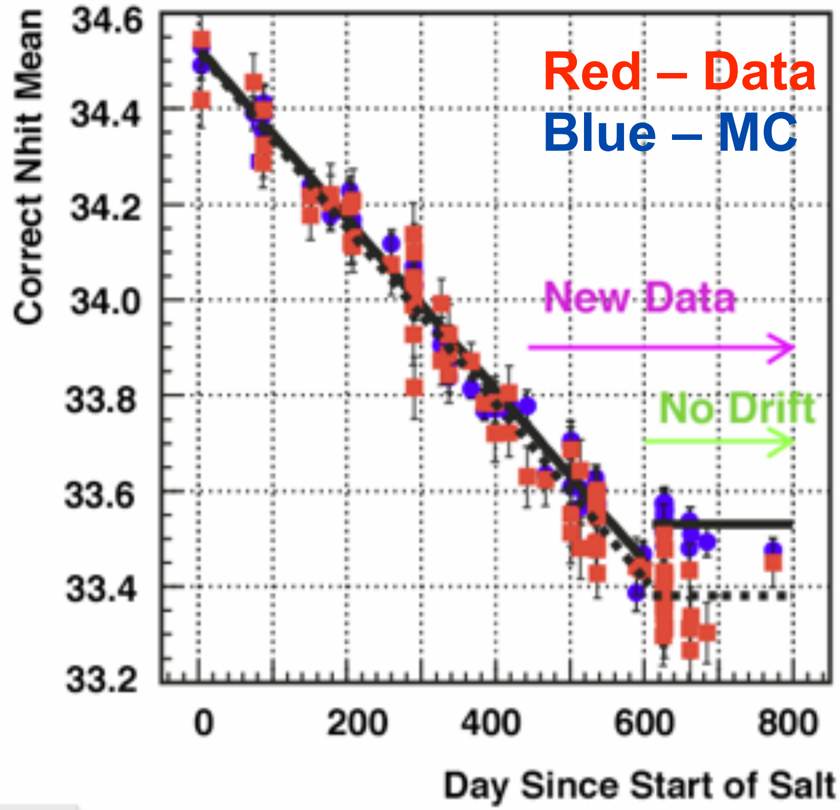


Isotropy variable, β_{14} , function of angles between each pair of hit PMTs (**θ_{ij}**) in event. (similar to *thrust* in collider physics)

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.

D_2O + Salt analysis: data set and data reduction

435,721,068 triggers

- Data recorded from July 2001 to October 2002 (2/3 of D_2O + salt data).

- 254.2 live days (detector maintenance and calibration during remaining time).

- Blind analysis performed
  - Analysis and cuts tuned with MC and "spoiled" subset of data.

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Radius ≤ 550 cm, T ≥ 5.5 MeV

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Vtx reconstruction, PMT time and position disributions

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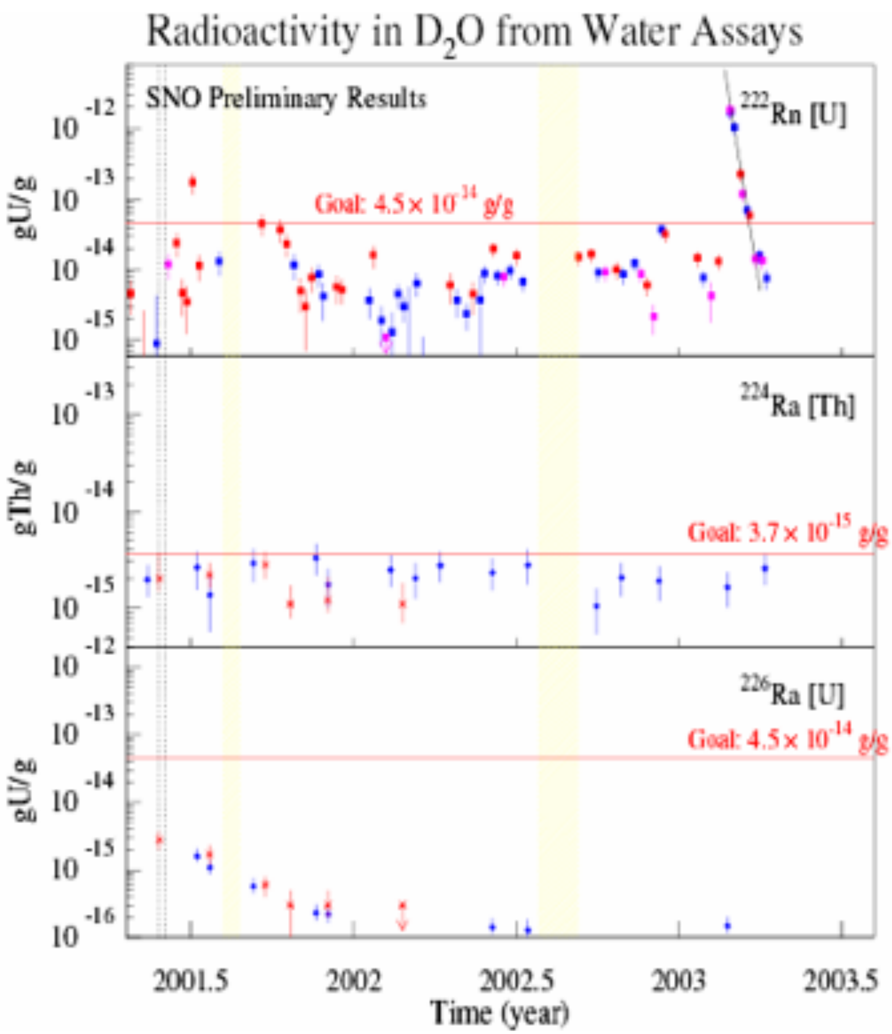
3055 events

Radioactive backgrounds

- *Ex situ* measurements show U and Th 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	Events
D_2O photodisintegration	$73.1^{+24.0}_{-23.5}$
$^2H(\alpha,\alpha)pn$	2.8 ± 0.7
$^{17,18}O(\alpha,n)$	1.4 ± 0.9
Fission, atmospheric ν (NC + sub-Cherenkov threshold CC)	23.0 ± 7.2
Terrestrial and reactor $\bar{\nu}$'s	2.3 ± 0.8
Neutrons from rock	≤ 1
^{24}Na activation	8.4 ± 2.3
n from CNO ν's	0.3 ± 0.3
Total internal neutron background	$111.3^{+25.3}_{-24.9}$
Internal γ (fission, atmospheric ν)	5.2 ± 1.3
^{16}N decays	< 2.5 (68% CL)
External-source neutrons (from fit)	$84.5^{+34.5}_{-33.6}$
Cherenkov events from $\beta - \gamma$ decays	< 14.7 (68% CL)
"AV events"	< 5.4 (68% CL)

U and Th

Recall: 3055 candidate 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)***

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Matter enhanced oscillations change ES and CC spectra

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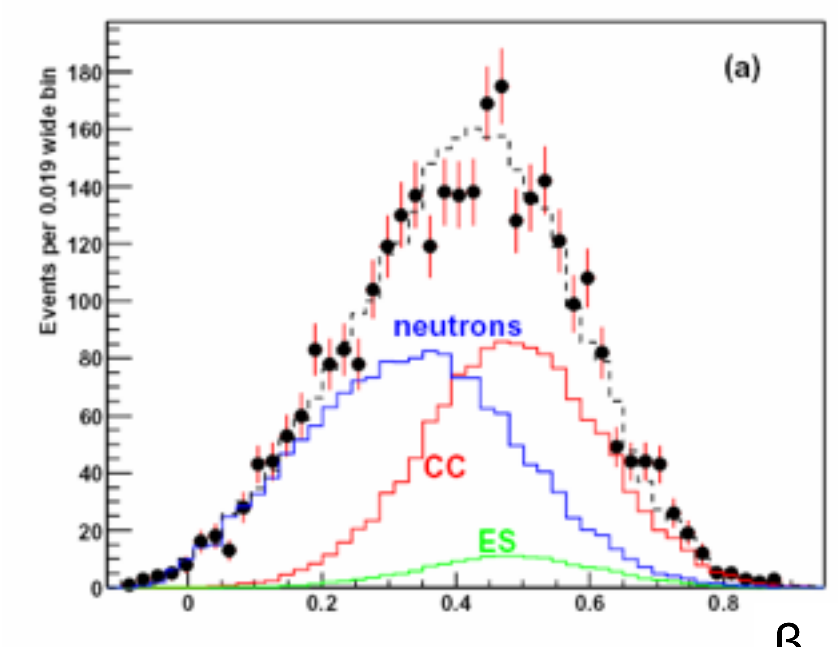
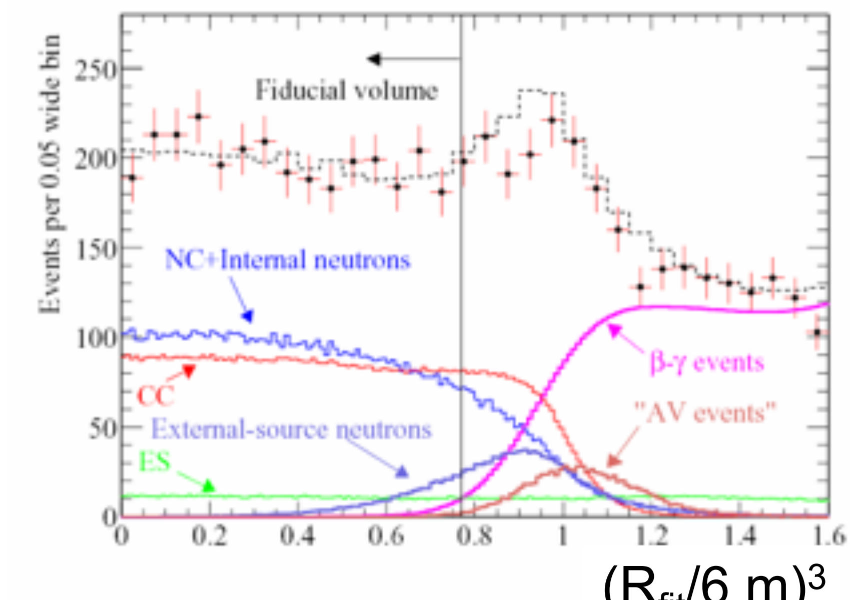
PDFs for signals and backgrounds

Isotropy



β_{14}

Radius of fitted vertex



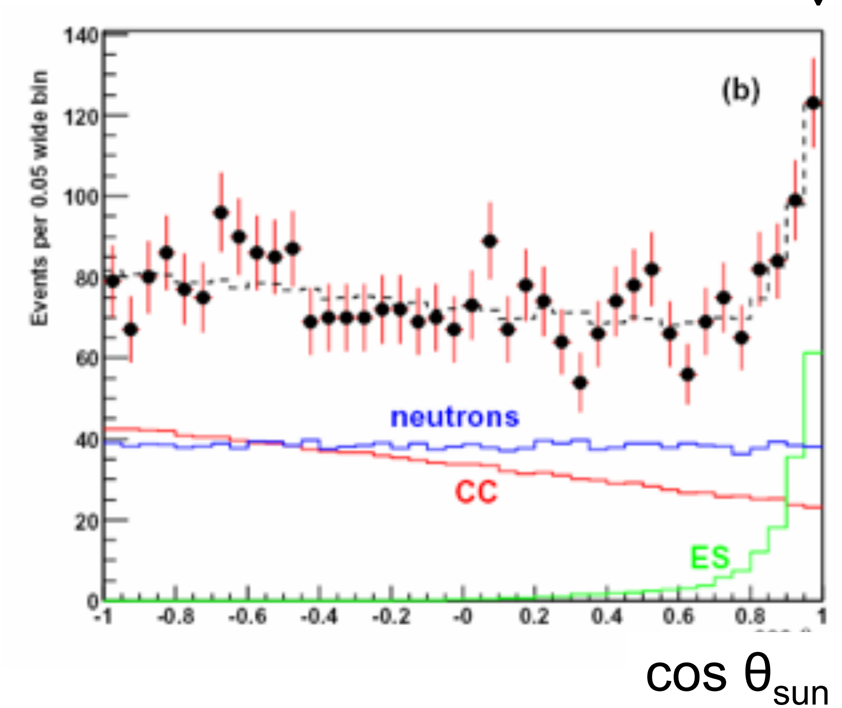
$(R_{fit}/6\ m)^3$

PDFs for signals and backgrounds

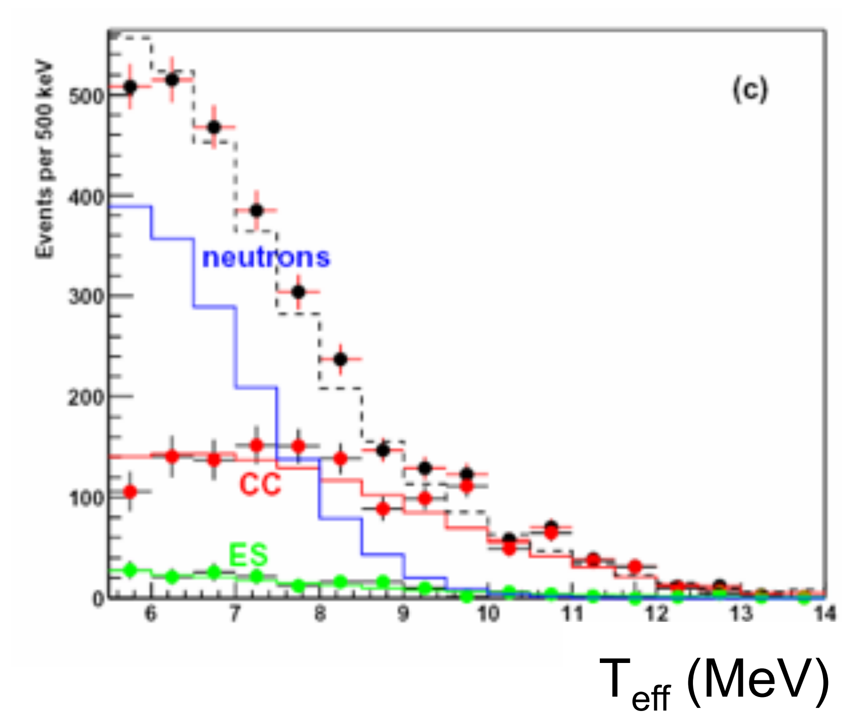
To Sun

Away from Sun

Sun-electron direction



Electron kinetic energy



Flux results from fit

Units for ϕ are 10^6 cm^{-2} s^{-1}

Energy spectrum of ^8B ν's constrained to Ortiz, *et al*. spectrum

$$\phi_{CC}^{SNO} = 1.70 \pm 0.07(\text{stat.})^{+0.09}_{-0.10}(\text{syst.})$$

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Standard Solar Model (Bahcall, Pinsonneault 2004)

$$\phi_{BP04} = 5.82 \pm 1.34$$

Systematic uncertainties

Source	NC uncert. (%)	CC uncert. (%)	ES uncert. (%)
Energy scale	-3.7,+3.6	-1.0,+1.1	±1.8
Energy resolution	±1.2	±0.1	±0.3
Energy non-linearity	±0.0	-0.0,+0.1	±0.0
Radial accuracy	-3.0,+3.5	-2.6,+2.5	-2.6,+2.9
Vertex resolution	±0.2	±0.0	±0.2
Angular resolution	±0.2	±0.2	±2.4
Isotropy mean †	-3.4,+3.1	-3.4,+2.6	-0.9,+1.1
Isotropy resolution	±0.6	±0.4	±0.2
Radial energy bias	-2.4,+1.9	±0.7	-1.3,+1.2
Vertex Z accuracy †	-0.2,+0.3	±0.1	±0.1
Internal background neutrons	-1.9,+1.8	±0.0	±0.0
Internal background γ's	±0.1	±0.1	±0.0
Neutron capture	-2.5,+2.7	±0.0	±0.0
Cherenkov backgrounds	-1.1,+0.0	-1.1,+0.0	±0.0
"AV events"	-0.4,+0.0	-0.4,+0.0	±0.0
Total experimental uncertainty	-7.3,+7.2	-4.6,+3.8	-4.3,+4.5
Cross section [13]	±1.1	±1.2	±0.5

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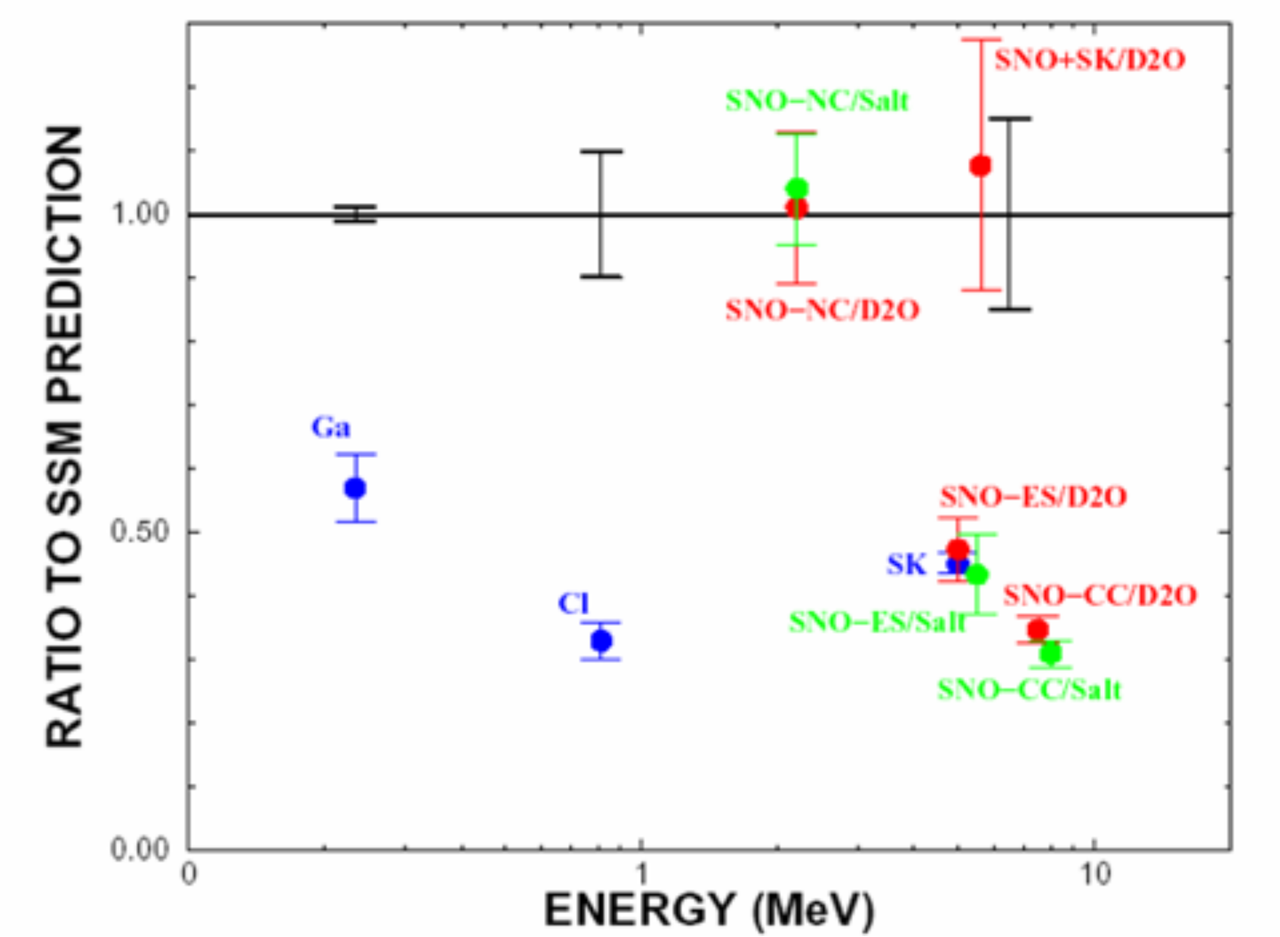
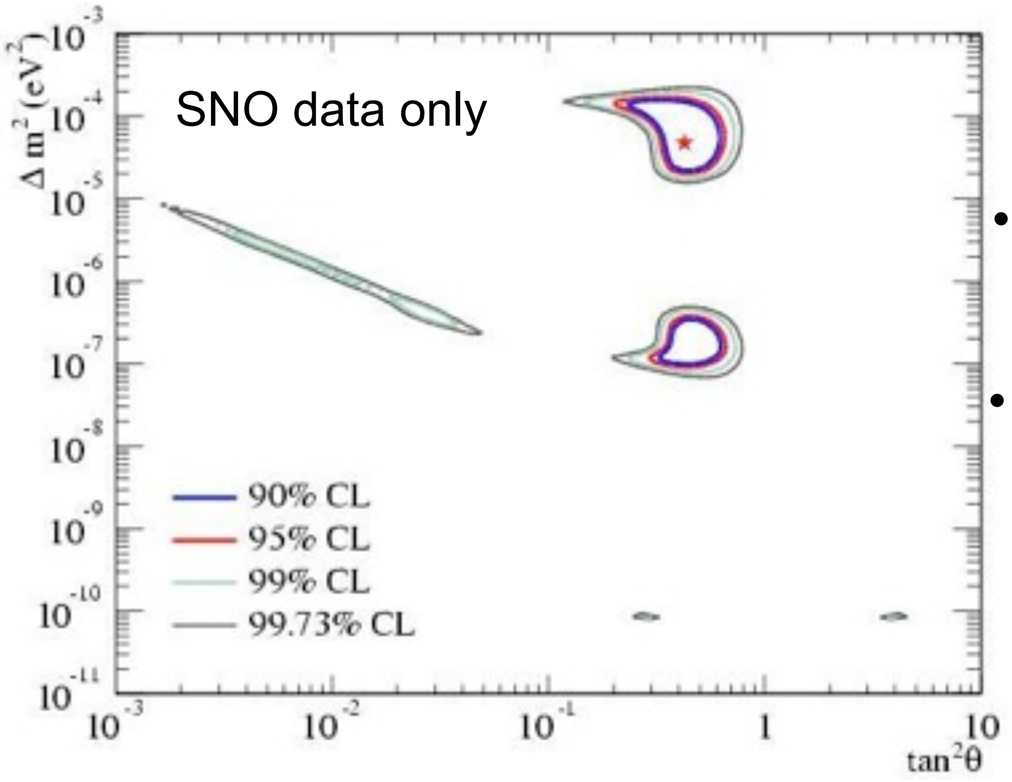
Comparison to previous results and SSM (BP2000)



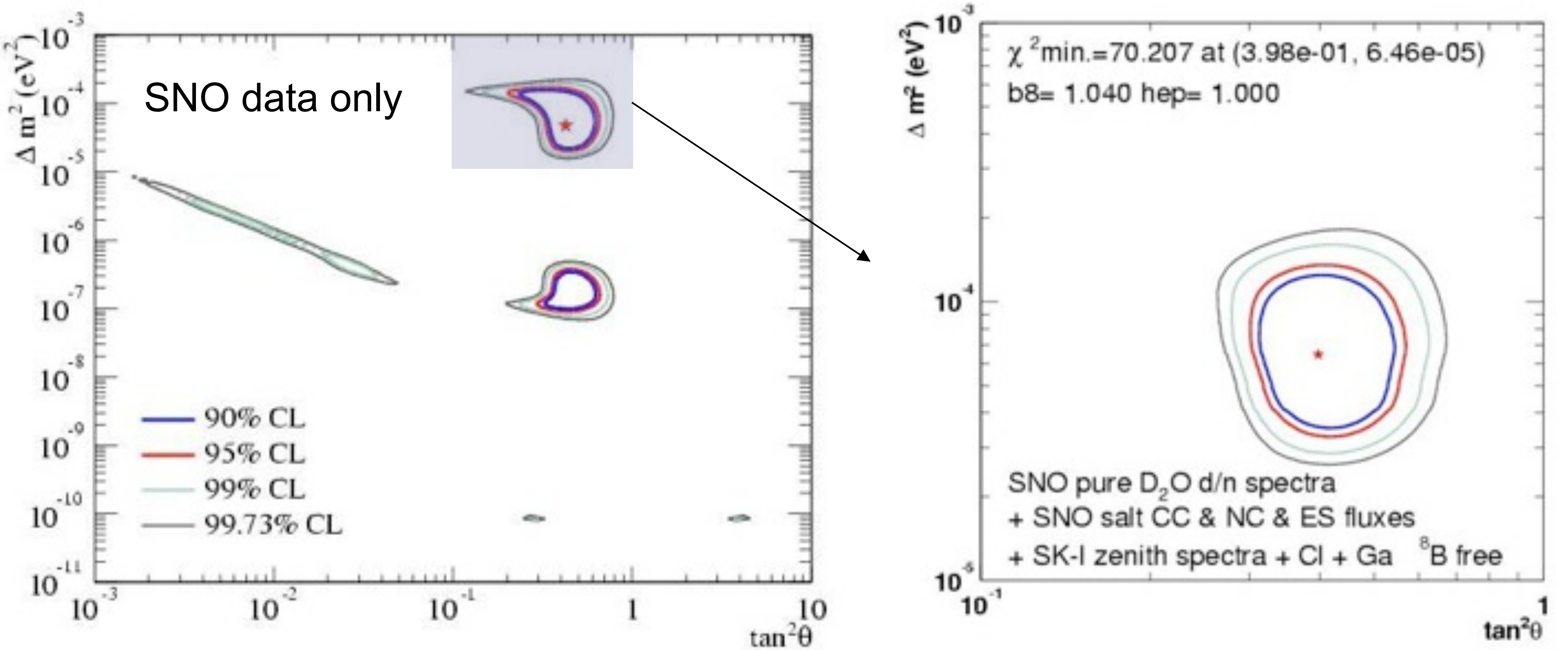
More precise salt results confirm D_2O results.

Interpretation of salt flux results: neutrino oscillation parameters

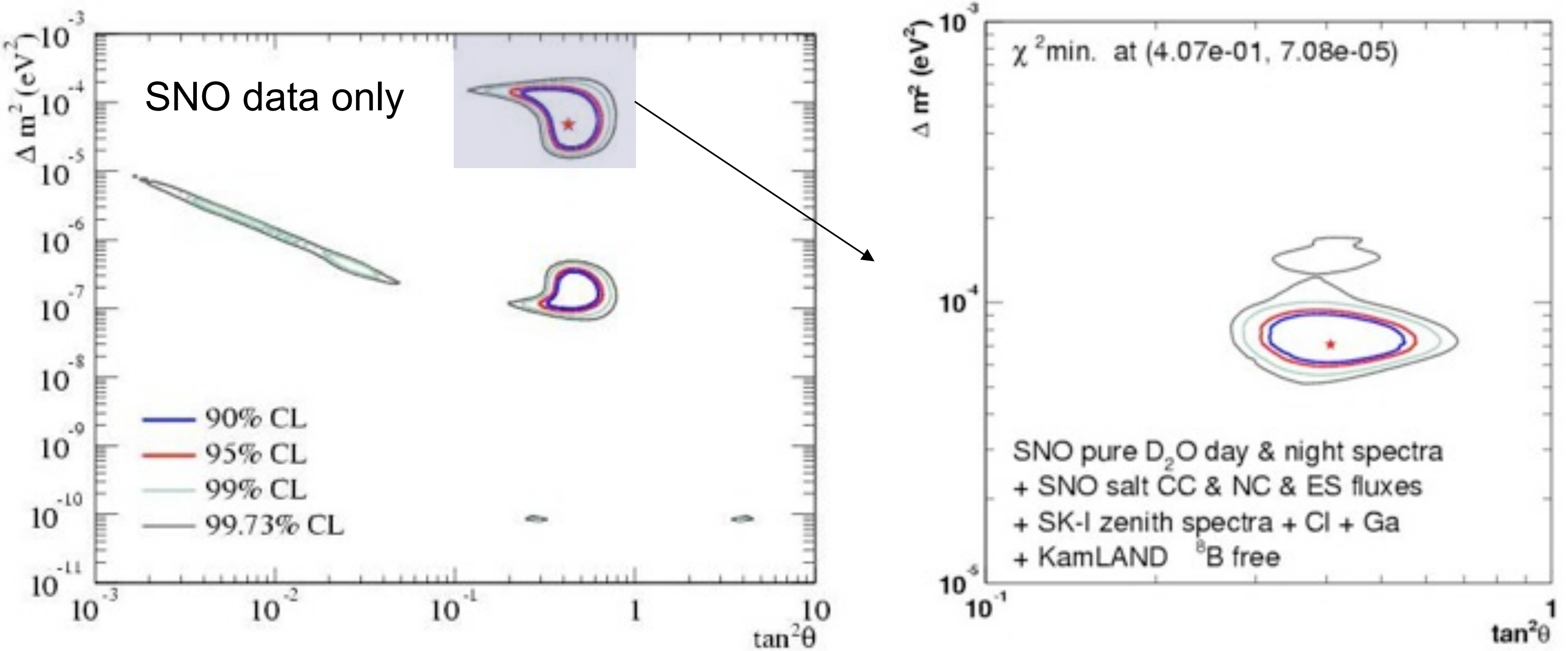


- Ratio of CC/NC fluxes gives $P(\nu_e \rightarrow \nu_e)$
- $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)$

Interpretation of salt flux results: neutrino oscillation parameters

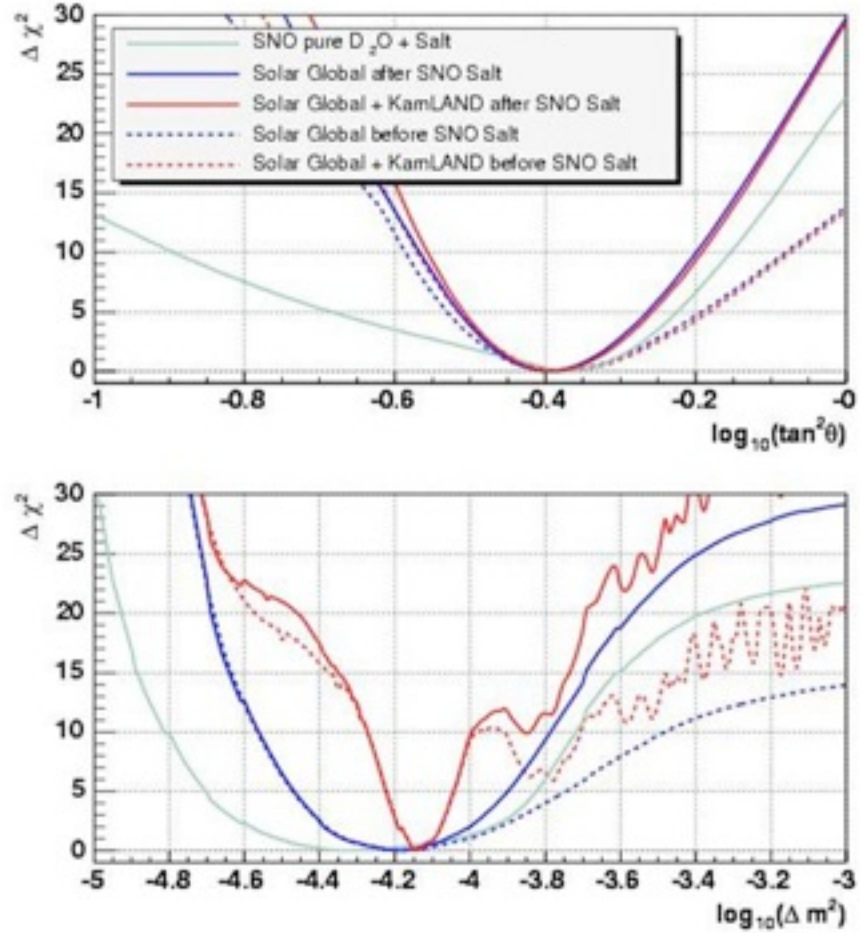


Interpretation of salt flux results: neutrino oscillation parameters



Interpretation of salt flux results: neutrino oscillation parameters

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



$\theta = 32.5^{+1.7}_{-1.6}$ degrees

Maximal mixing (θ = 45 degrees) excluded at 5.4 σ.

$\Delta m^2 = (7.1^{+1.0}_{-0.3}) \times 10^{-5}\ eV^2$

Road map to talk…

- Introduction to SNO
- Previous solar neutrino results with D_2O
- Most recent solar neutrino result with D_2O + salt
- **Non-solar neutrino results**
- SNO's future
- Summary

Recent non-solar ν SNO results

Nucleon Decay

.

- "Invisible" decay of n and p (e.g. $N \to 3\,\nu$) from ^{16}O produces γ-ray of 6→7 MeV.
- In SNO, γ-ray of 6→7 MeV looks like n-capture.
- Compare n-capture rates in SNO Phases 1 and 2 (different n-efficiences) to set limit on τ_{inv} of p and n.

$\tau_{inv}^{p} > 2.1 \times 10^{29}$ years, 90% CL

$\tau_{inv}^{n} > 1.9 \times 10^{29}$ years, 90% CL

$\bar{\nu}_e$ search

- Solar ν_e might convert to $\bar{\nu}_e$ via Spin Flavour Precession or ν_e decay.
- Look for 2- or 3-fold coincidences from

$$\bar{\nu}_e + d \to n + n + e^+$$

- 2 candidate coincidences (one 2-fold, one 3-fold) in Phase 1.
- $1.68^{+0.93}_{-0.45}$ background expected (mainly ν)

$\text{Prob}(\nu_e \to \bar{\nu}_e) < 0.81\%$, 90% CL

Road map to talk…

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- **SNO's future** ←
- Summary

Future of SNO: ^{3}He counters

- Detect neutrons from NC interactions via

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

- ^{3}He-filled proportional tubes detect recoiling p and ^{3}H.
- 40 ^{3}He-filled proportional tubes in 1m grid (398 m total length).
- $\sigma(n + {}^3\mathrm{He}) = 10^7\,\sigma(n + {}^2\mathrm{H})$
- Event-by-event identification of NC interactions (no correlation with CC rate like in earlier phases).

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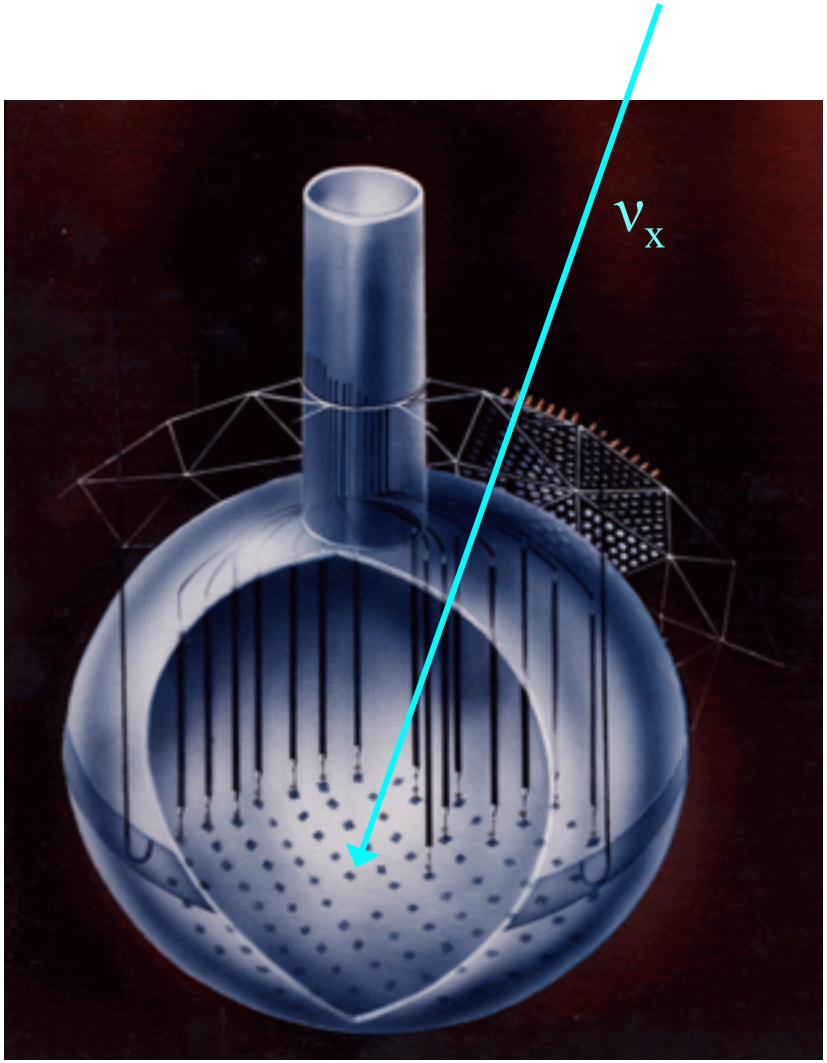

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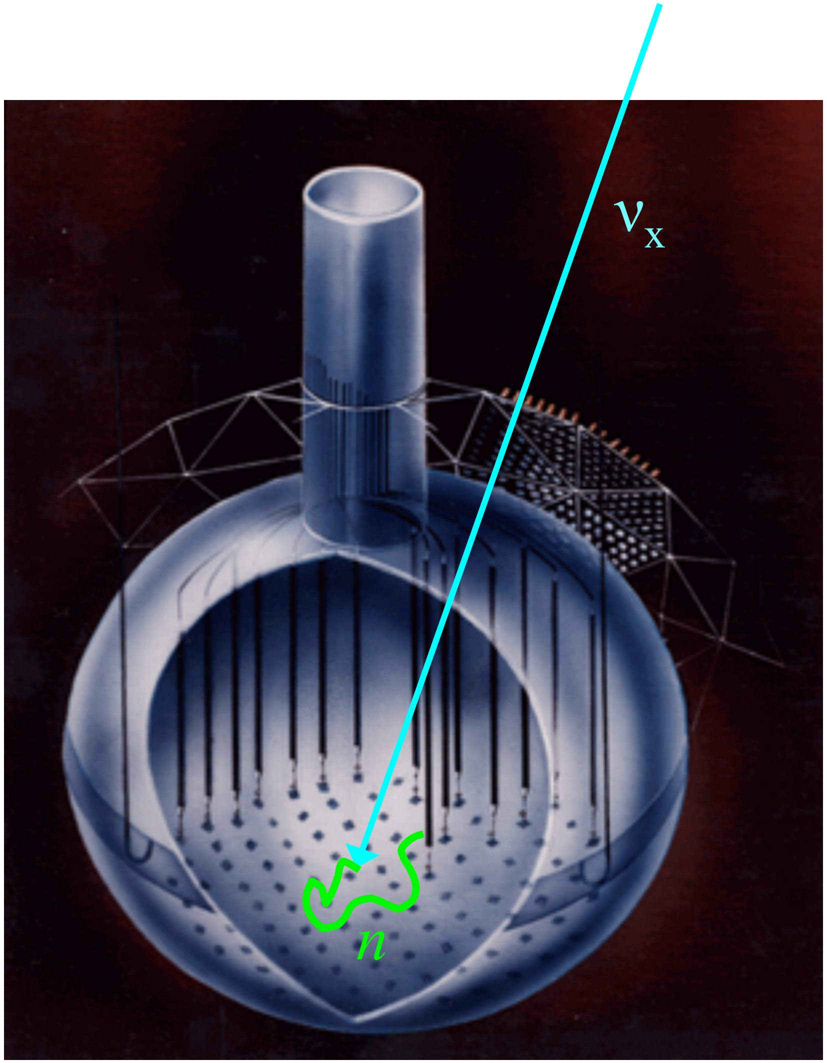
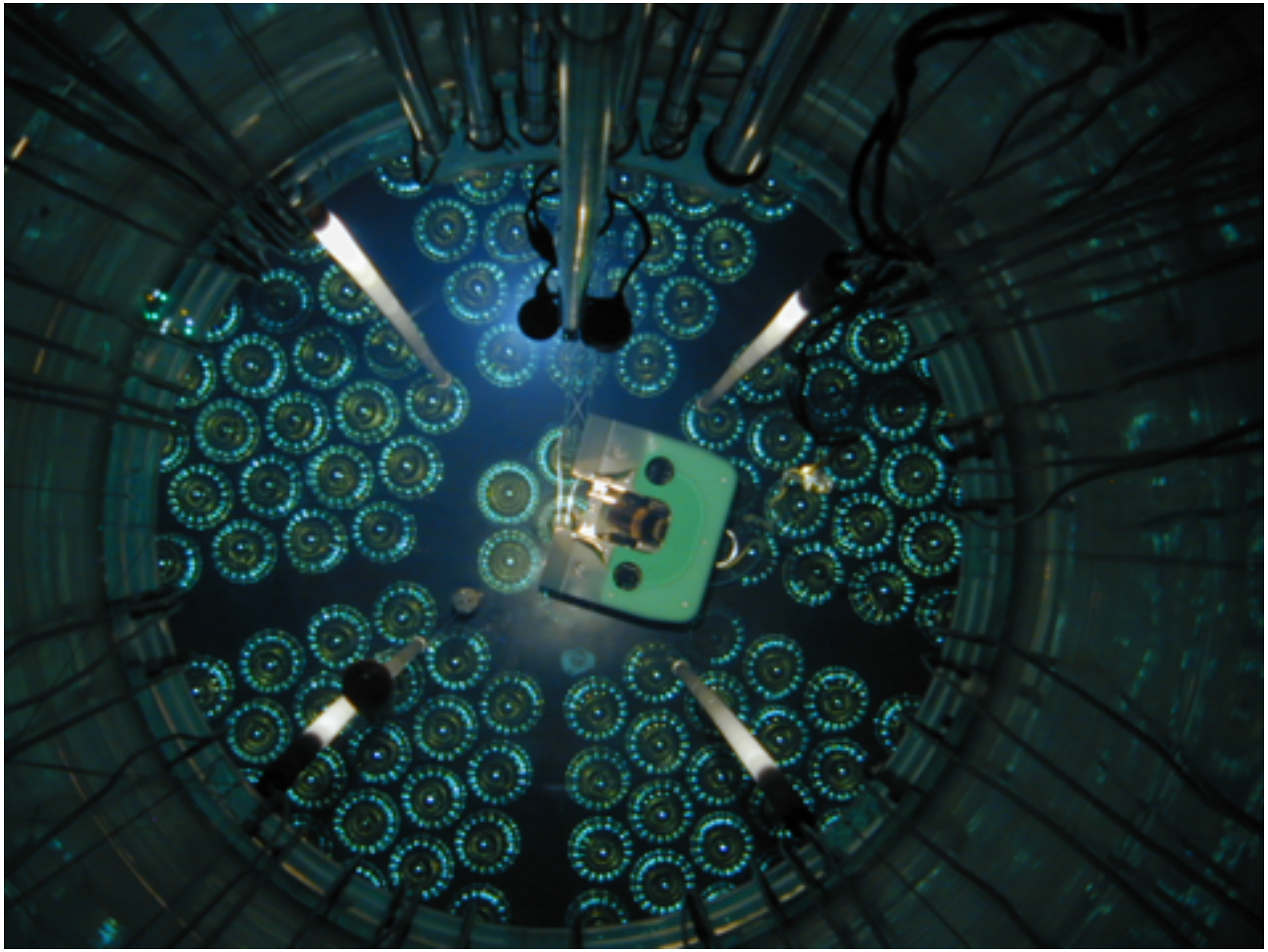


Advantage of ^{3}He counters

	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 $\tan^2\theta$.

Installation of ^3He counters complete! Commissioning in progress.



Summary

- SNO has completed data-taking for first two phases (D_2O and D_2O +Salt).
- Results from first two phases give convincing evidence of solar neutrino flavour change (first direct evidence of ν_e flavour change!).
  - ν_e has non-zero mass.
- Solar Neutrino Problem resolved after 30+ years (SSM correct!).
- Searches for "invisible" nucleon decay and electron anti-neutrinos have set interesting new limits.
- Last phase with ^{3}He proportional counters has begun.

SNO Collaboration

Carleton University
Laurentian University
Queen's University
TRIUMF
University of British Columbia
University of Guelph

Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
University of Pennsylvania
University of Texas at Austin
University of Washington

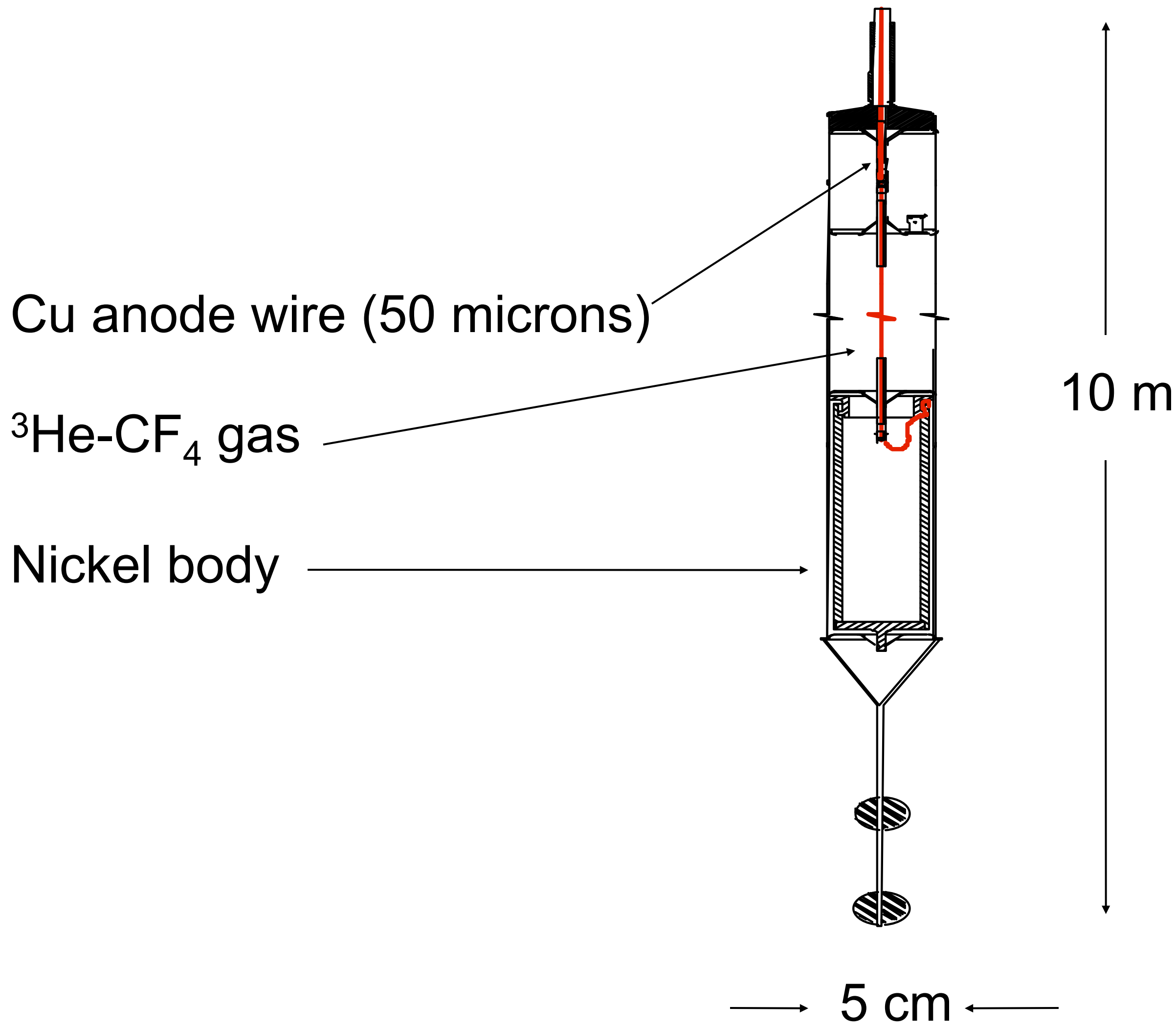
Oxford University
Rutherford Laboratory
University of Sussex

References

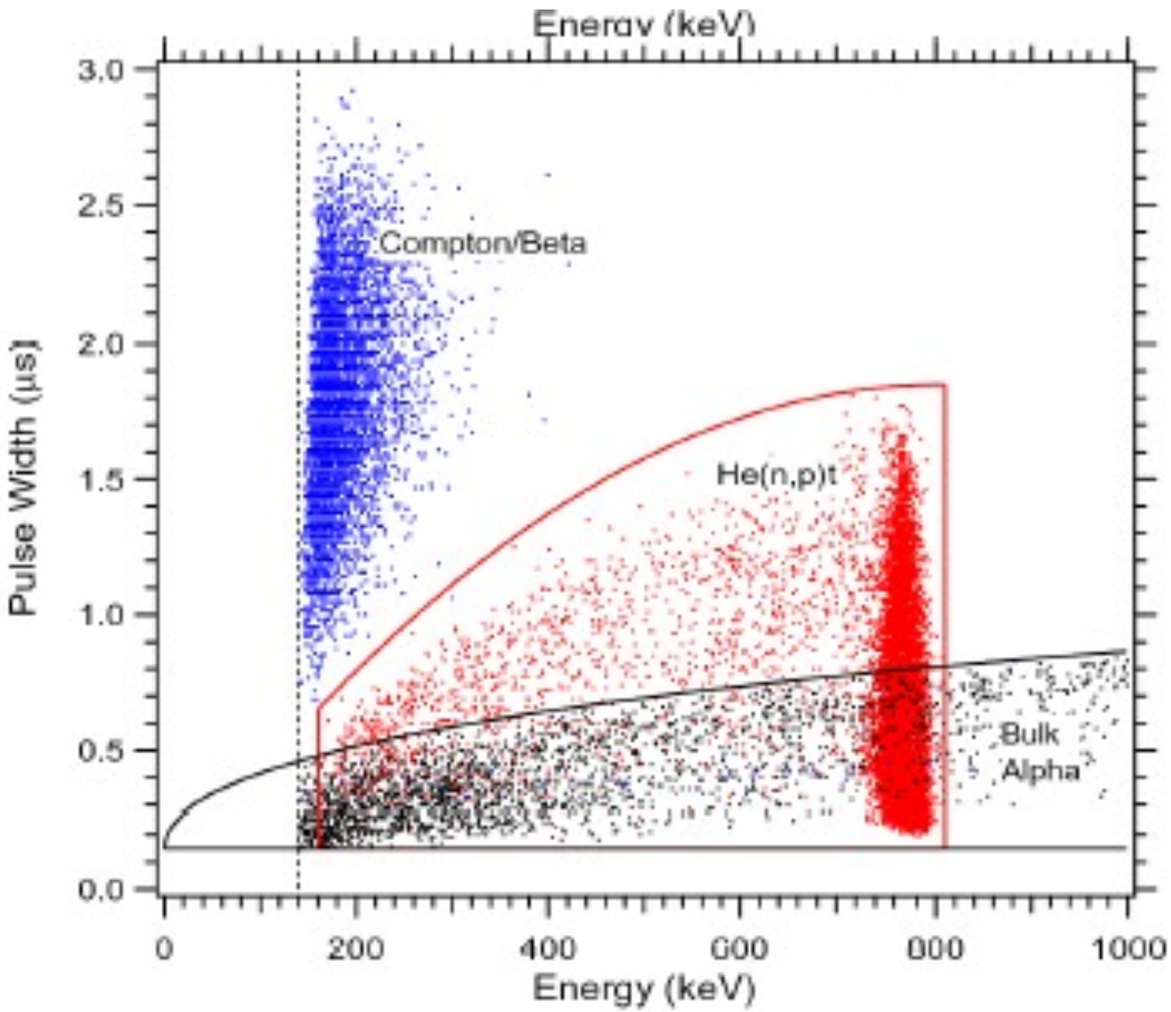
- SNO detector details:
  Nucl.Instrum.Meth.A449:172-207,2000, **nucl-ex/9910016**
- CC flux in D2O:
  Phys.Rev.Lett.87:071301,2001, **nucl-ex/0106015**
- NC flux in D2O:
  Phys.Rev.Lett.89:011301,2002, **nucl-ex/0204008**
- Night-Day Asymmetry in D2O:
  Phys.Rev.Lett.89:011302,2002, **nucl-ex/0204009**
- NC in in D2O+Salt:
  Phys.Rev.Lett.92:181301,2004, **nucl-ex/0309004**
- Nucleon Decay:
  Phys.Rev.Lett.92:102004,2004, **hep-ex/0310030**
- Anti-neutrino Search:

Extra slides…

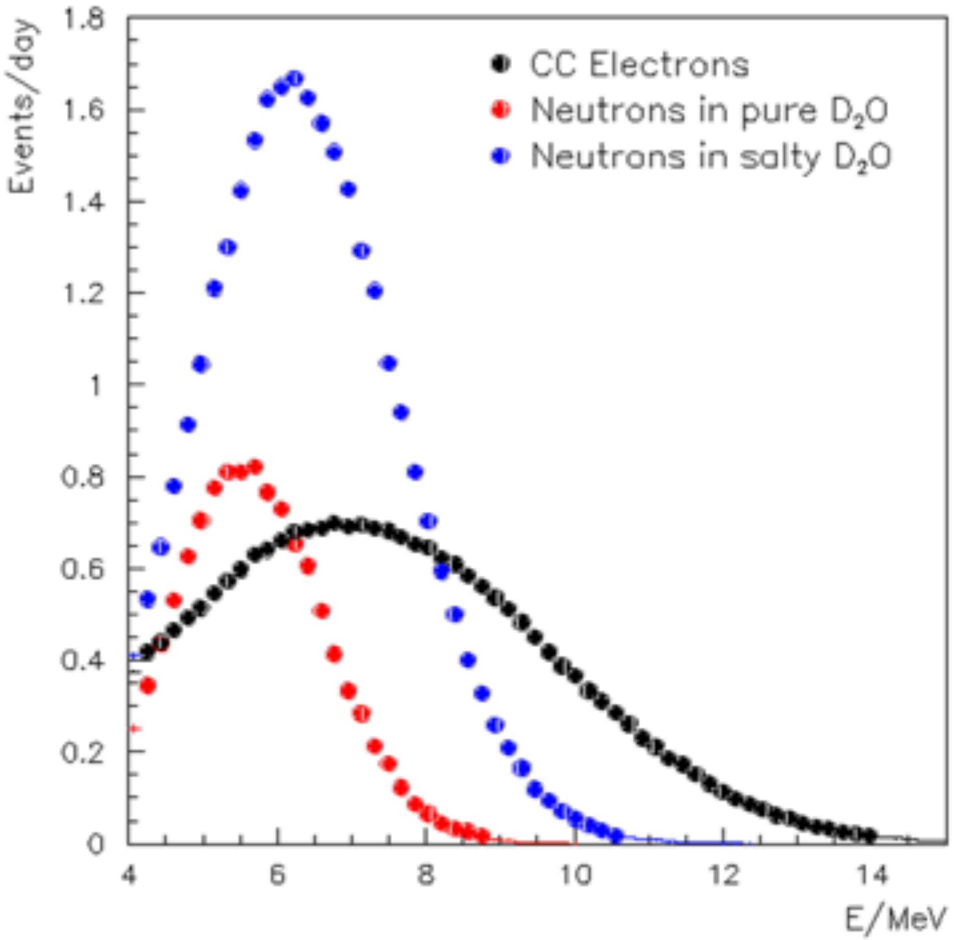
^3He proportional counters



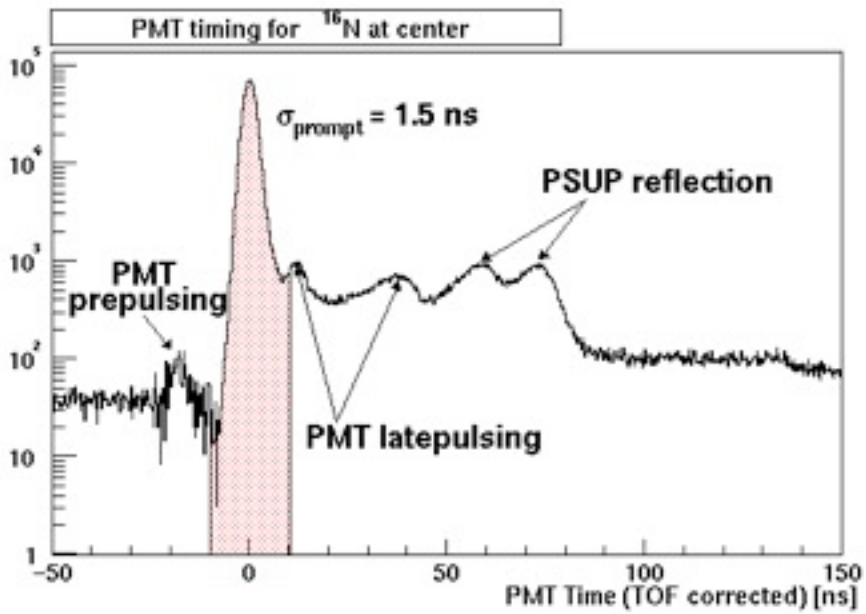
^{3}He proportional counters

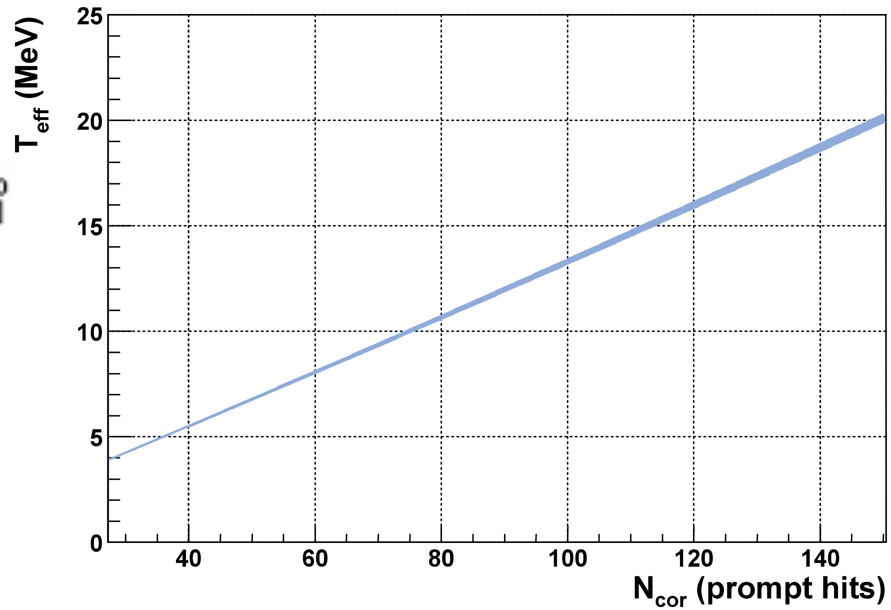


Advantage of adding salt to D_2O



PMT timing and T_{eff} vs. NHIT





Ex-situ

- Ion exchange (^{224}Ra, ^{226}Ra)
- Membrane Degassing (^{222}Rn)

count daughter product decays

In-situ

- Low energy data analysis
- Separate ^{208}Tl & ^{214}Bi