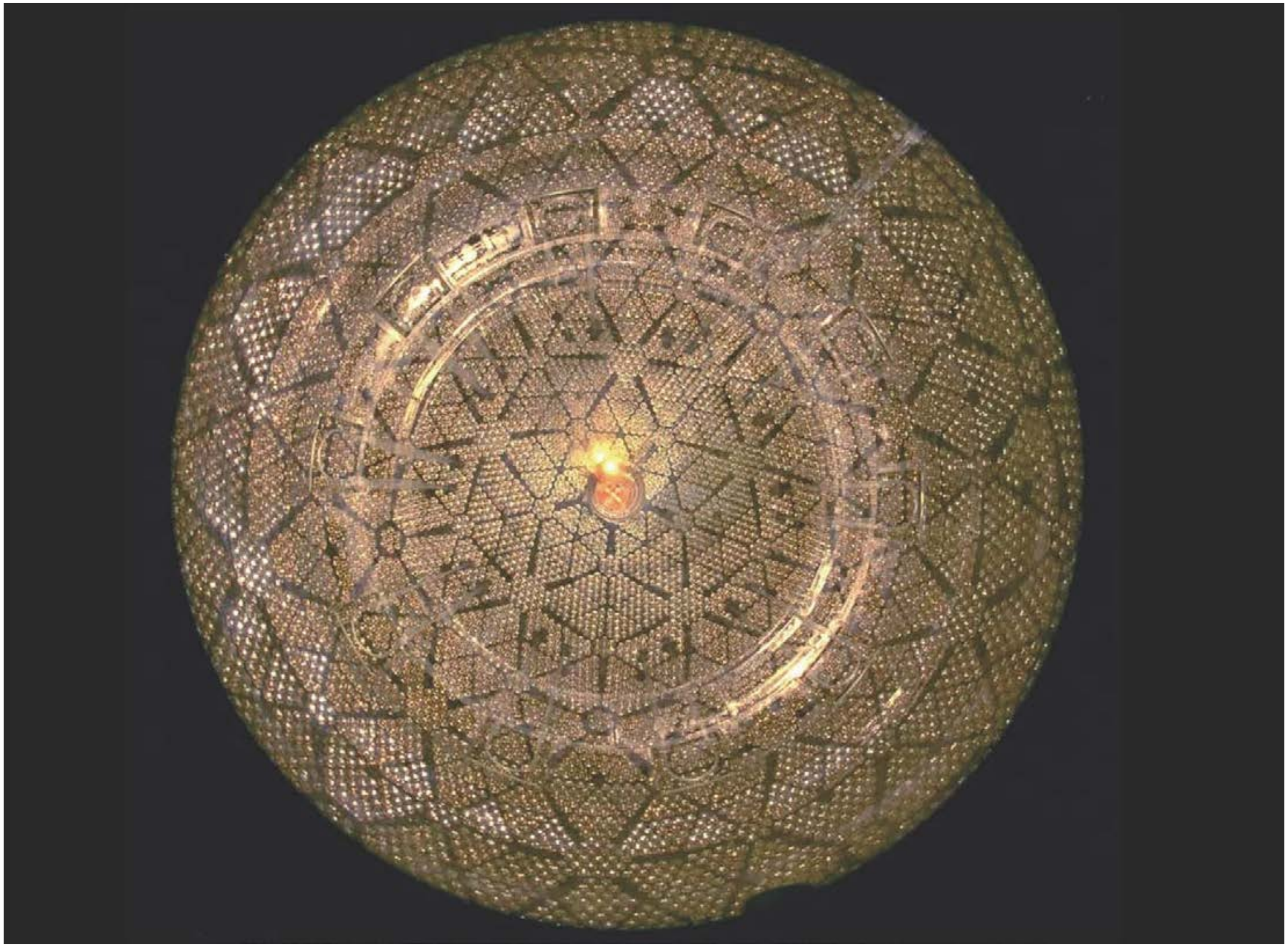
Bruno Pontecorvo and Solar Neutrinos



Art McDonald
Queen's University, Kingston, Canada and SNOLAB

Many Connections Between Bruno Pontecorvo, Solar Neutrinos And SNO

- **Science:**
  - **He proposed chlorine as a detection medium for reactor and solar neutrinos**
  - **Developed proportional counters – used by Davis and SNO ^{3}He detectors**
  - **Proposed neutrino oscillations**
  - **Proposed oscillations as the explanation for the solar neutrino problem**

NATIONAL RESEARCH COUNCIL OF CANADA

DIVISION OF ATOMIC ENERGY

INVERSE β PROCESS

by

B. Pontecorvo

Chalk River, Ontario

20 November, 1946

PD-205

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  - **One of the principal scientists developing the heavy water nuclear reactor**
    Therefore – Canadian reserves of heavy water available for SNO.

  - **He developed well logging with neutron sources**
    Main SNO calibration: 16N produced with a neutron source
    developed for well logging: invented by Pontecorvo

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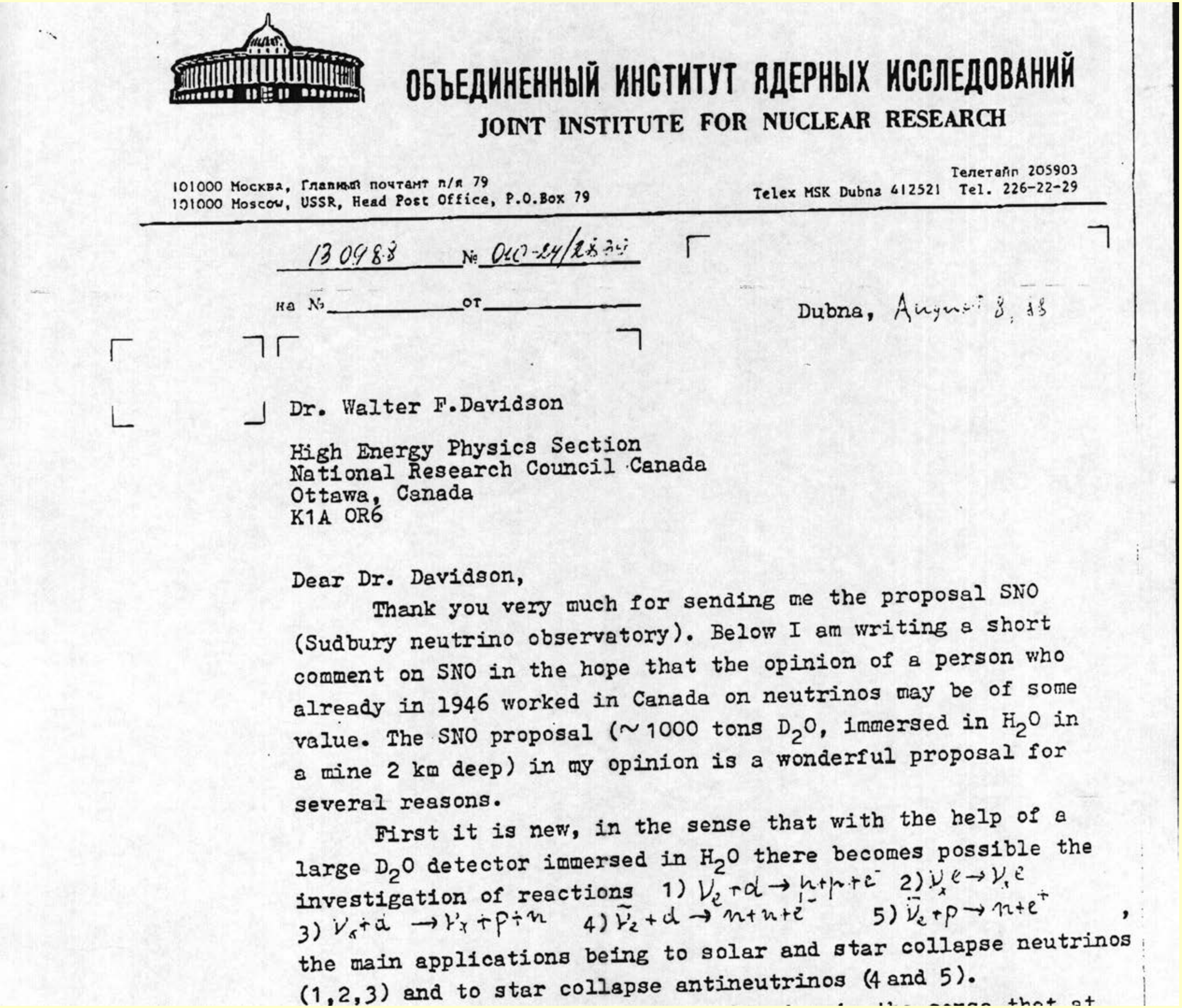
- International support:
  - An important letter of support at a critical time for SNO in 1988



ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
JOINT INSTITUTE FOR NUCLEAR RESEARCH

101000 Москва, Главный почтамт п/я 79
101000 Moscow, USSR, Head Post Office, P.O.Box 79

Телетайп 205903
Telex MSK Dubna 412521 Tel. 226-22-29

13.09.88 № 010-24/[illegible]

на № ______ от ______

Dubna, August 8, 88

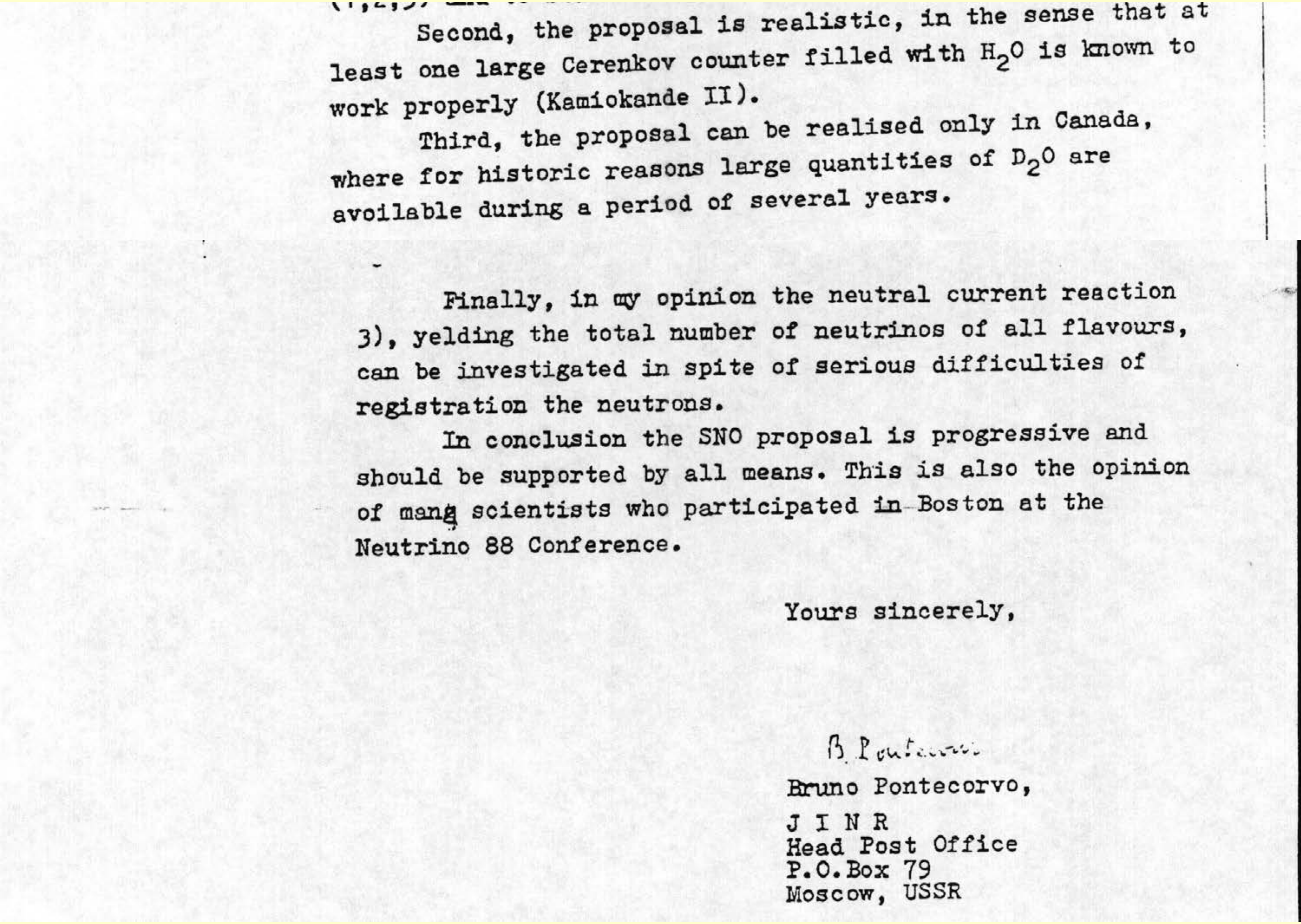
Dr. Walter F.Davidson

High Energy Physics Section
National Research Council Canada
Ottawa, Canada
K1A OR6

Dear Dr. Davidson,

Thank you very much for sending me the proposal SNO (Sudbury neutrino observatory). Below I am writing a short comment on SNO in the hope that the opinion of a person who already in 1946 worked in Canada on neutrinos may be of some value. The SNO proposal (~1000 tons D_2O, immersed in H_2O in a mine 2 km deep) in my opinion is a wonderful proposal for several reasons.

First it is new, in the sense that with the help of a large D_2O detector immersed in H_2O there becomes possible the investigation of reactions 1) $\nu_e + d \to p + p + e^-$ 2) $\nu_x e \to \nu_x e$ 3) $\nu_x + d \to \nu_x + p + n$ 4) $\tilde{\nu}_e + d \to n + n + e$ 5) $\bar{\nu}_e + p \to n + e^+$, the main applications being to solar and star collapse neutrinos (1,2,3) and to star collapse antineutrinos (4 and 5).



Second, the proposal is realistic, in the sense that at least one large Cerenkov counter filled with H_2O is known to work properly (Kamiokande II).

Third, the proposal can be realised only in Canada, where for historic reasons large quantities of D_2O are avoilable during a period of several years.

Finally, in my opinion the neutral current reaction 3), yelding the total number of neutrinos of all flavours, can be investigated in spite of serious difficulties of registration the neutrons.

In conclusion the SNO proposal is progressive and should be supported by all means. This is also the opinion of mang scientists who participated in Boston at the Neutrino 88 Conference.

Yours sincerely,

B. Pont

Bruno Pontecorvo,

J I N R
Head Post Office
P.O. Box 79
Moscow, USSR

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- **International support:**
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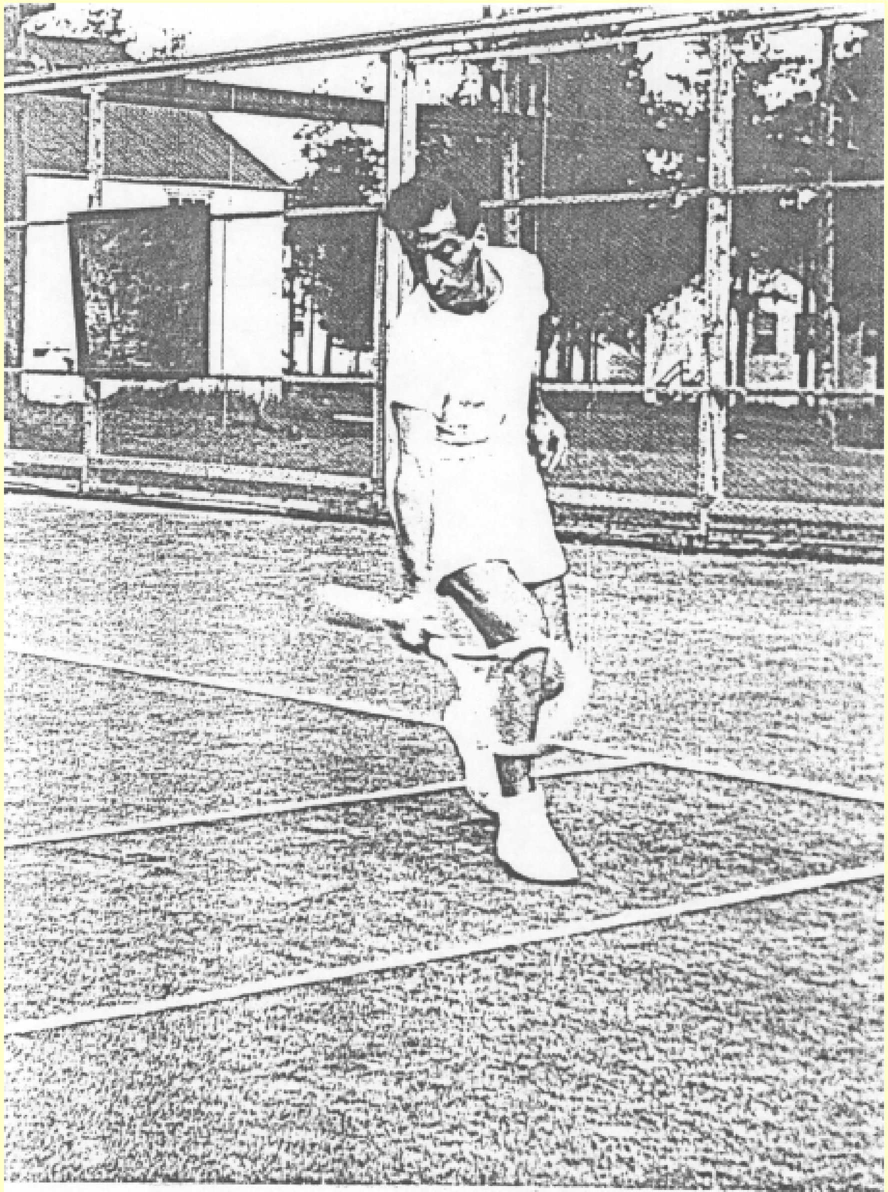
- **Personal:**
  - **My first 12 years of basic research were at Chalk River.**
  - **I knew many of Pontecorvo's Chalk River collaborators personally**
    - Hanna, Carmichael, Hincks, Sargeant.
  - **Bruno Pontecorvo and I played tennis on the same courts in Deep River**
    – 30 years separated in time and light years separated in ability!

First Tennis Champion at Chalk River – 1948
Bruno Pontecorvo



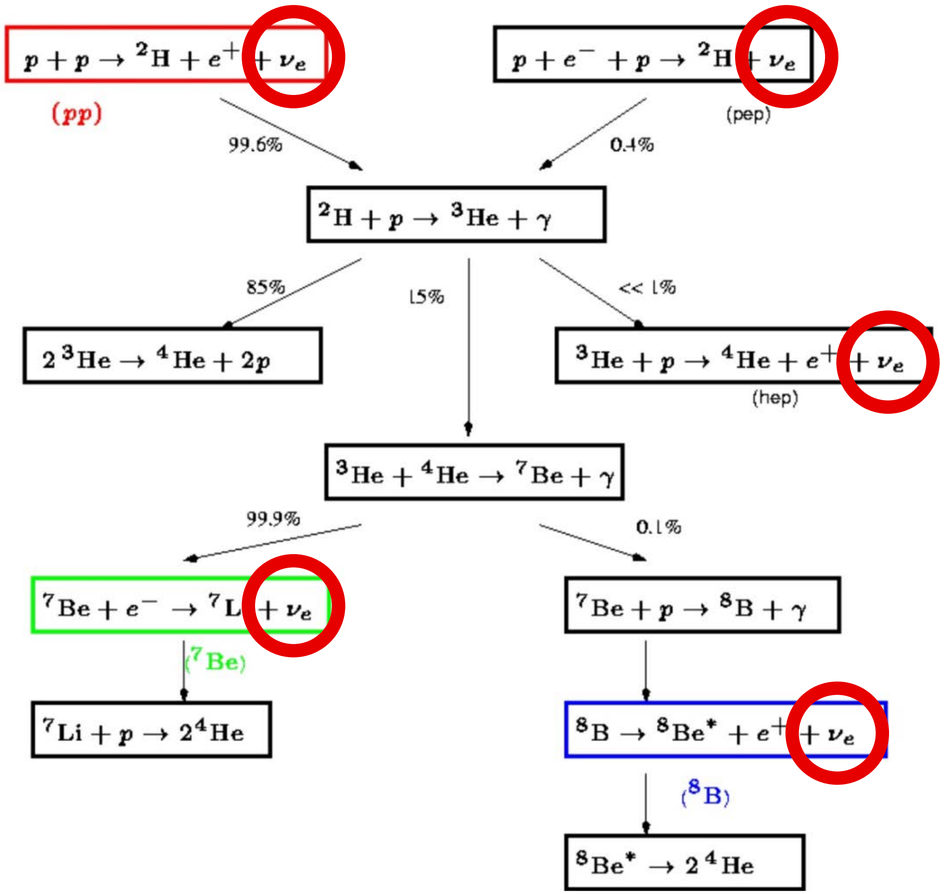
I was honored to meet
Bruno Pontecorvo
at Neutrino 1992
in Granada, Spain
and to provide a tour
of the SNO exhibit
at the Canadian Pavillion
at EXPO 1992 in Seville
and to have discussions about
his Canadian colleagues.

His science, his sense of
humour and his athletic ability
captivated me.

Today is a wonderful honor
for me to participate in a
Birthday celebration for such a
great scientist.

Solar Neutrinos

pp Chain



$p + p \rightarrow {}^2\mathrm{H} + e^+ + \nu_e$

(pp)

99.6%

$p + e^- + p \rightarrow {}^2\mathrm{H} + \nu_e$

(pep)

0.4%

${}^2\mathrm{H} + p \rightarrow {}^3\mathrm{He} + \gamma$

85%

15%

<< 1%

$2\,{}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2p$

${}^3\mathrm{He} + p \rightarrow {}^4\mathrm{He} + e^+ + \nu_e$

(hep)

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

99.9%

0.1%

${}^7\mathrm{Be} + e^- \rightarrow {}^7\mathrm{Li} + \nu_e$

(${}^7\mathrm{Be}$)

${}^7\mathrm{Li} + p \rightarrow 2\,{}^4\mathrm{He}$

${}^7\mathrm{Be} + p \rightarrow {}^8\mathrm{B} + \gamma$

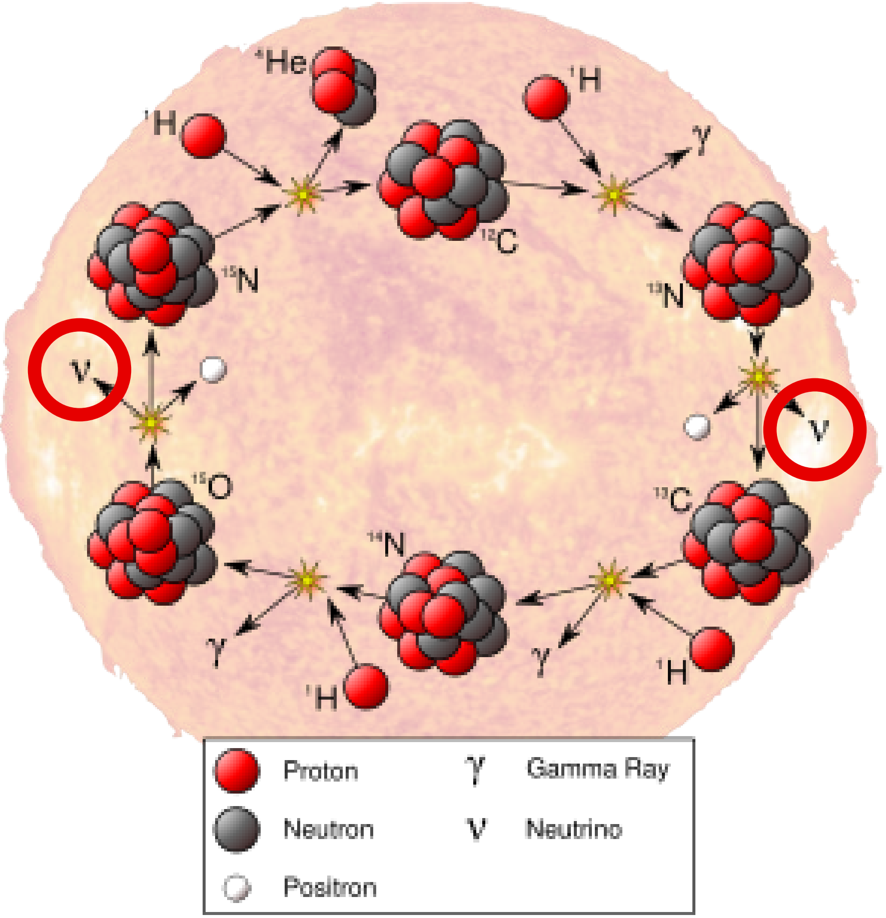
${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be}^* + e^+ + \nu_e$

(${}^8\mathrm{B}$)

${}^8\mathrm{Be}^* \rightarrow 2\,{}^4\mathrm{He}$

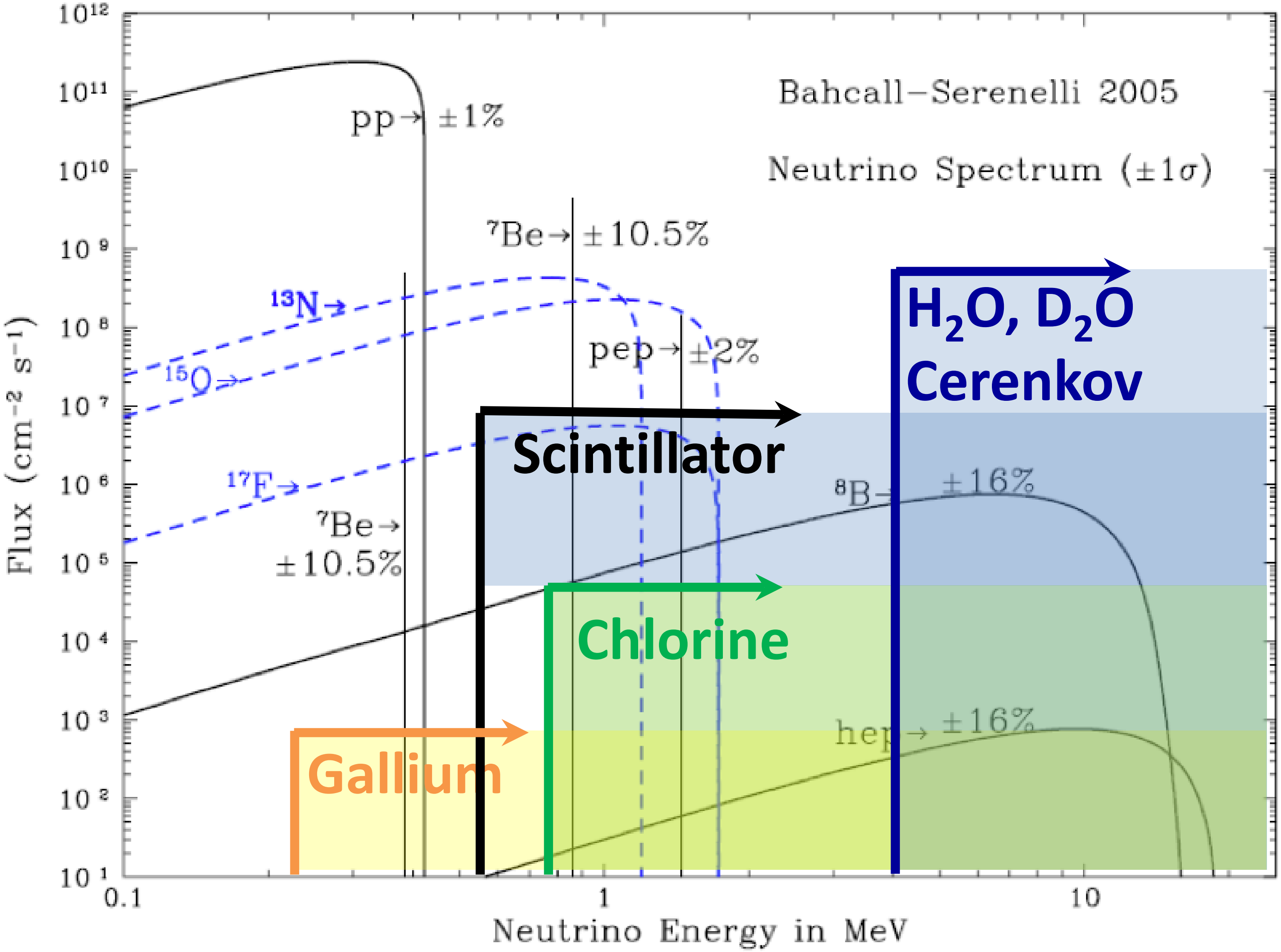
CNO Cycle

(contributes ~1% of solar energy)

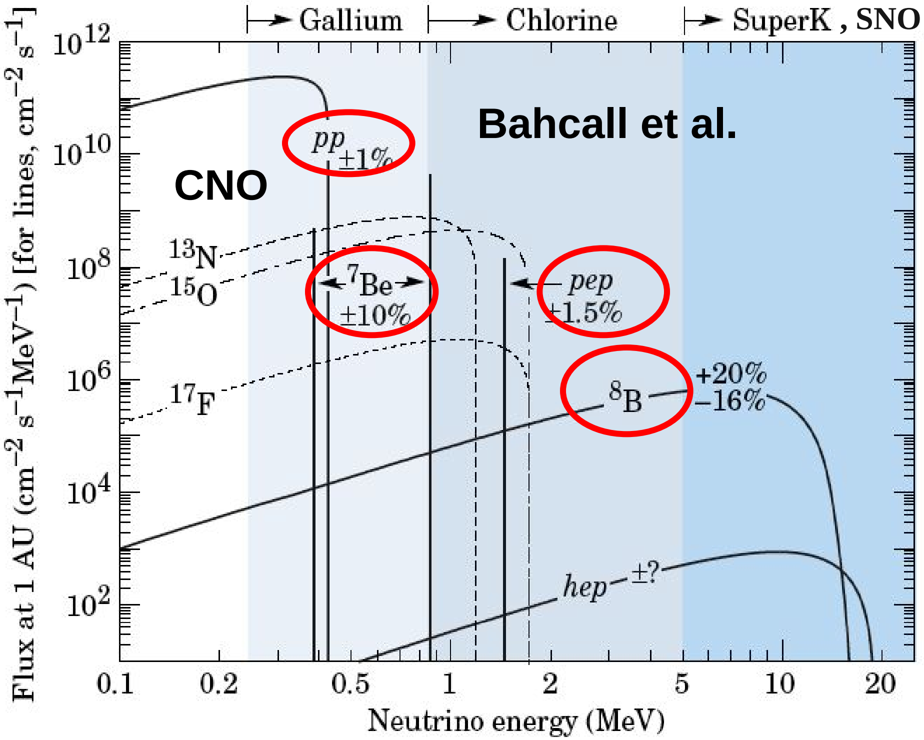


● Proton
● Neutron
○ Positron
γ Gamma Ray
ν Neutrino

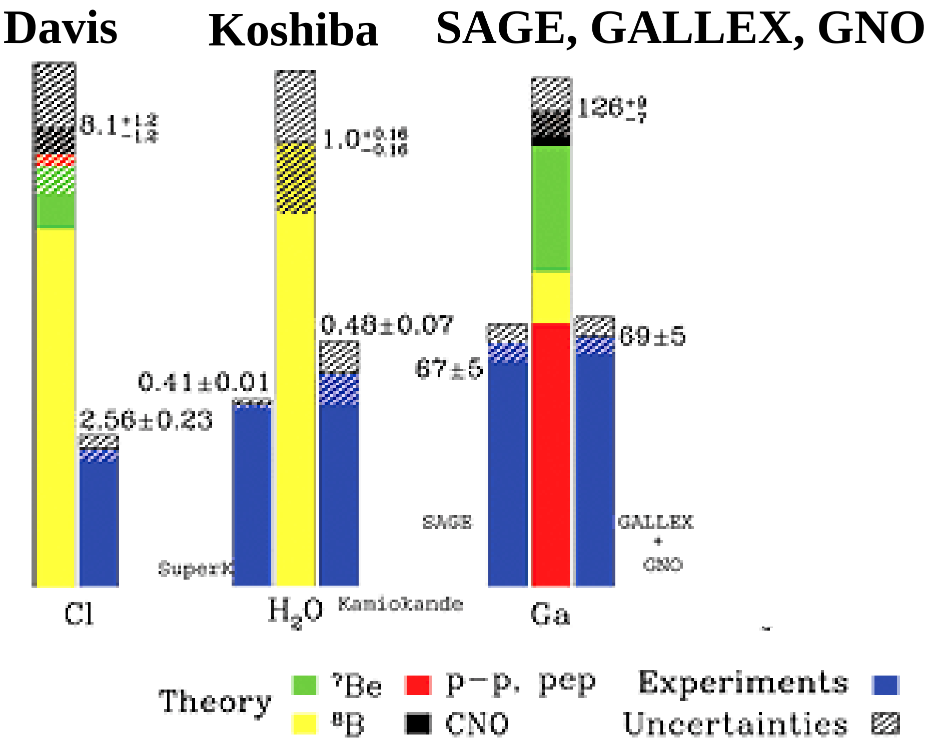
Solar ν Energy Spectra



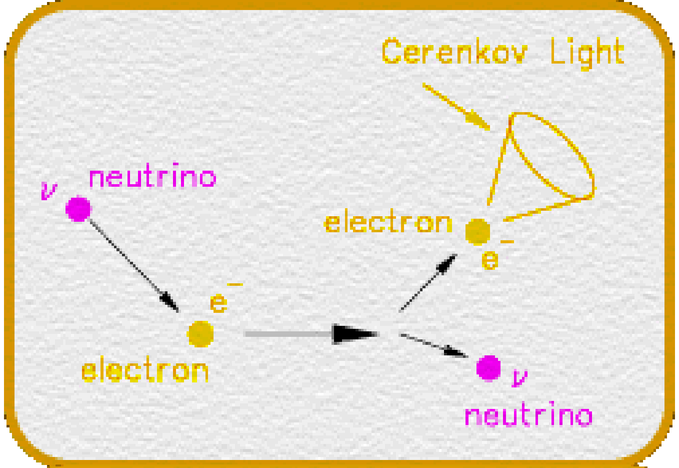
Solar Model Flux Calculations

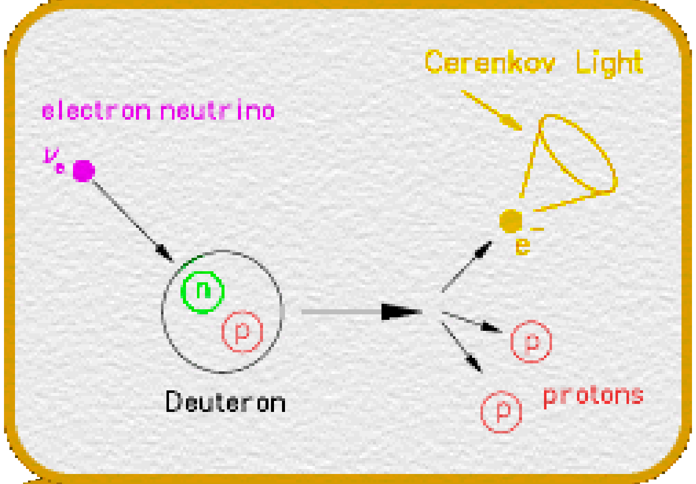


Pre-2001 Experiments Sensitive Mainly to Electron Neutrinos

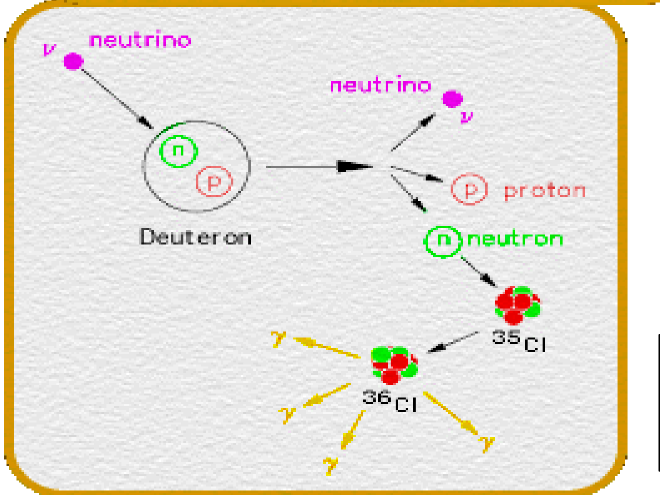


SNO used deuterium (D_2O) to observe separately ν_e and all neutrino types to determine if the low ν_e fluxes come from solar models or neutrino flavor change





D_2O



1) Neutrino Electron Elastic Scattering
86 % ν_e and 14% ν_μ , ν_τ
As observed by SuperKamiokande

First: SNO-SK comparison with lower sensitivity to ν_μ , ν_τ
First result: flavor change: 3.3 σ (2001)

2) Charged Current Interaction on Deuterium
100 % ν_e

Second: SNO-only comparison with high sensitivity to ν_μ , ν_τ
Second result: flavor change: 5.3 σ (2002)

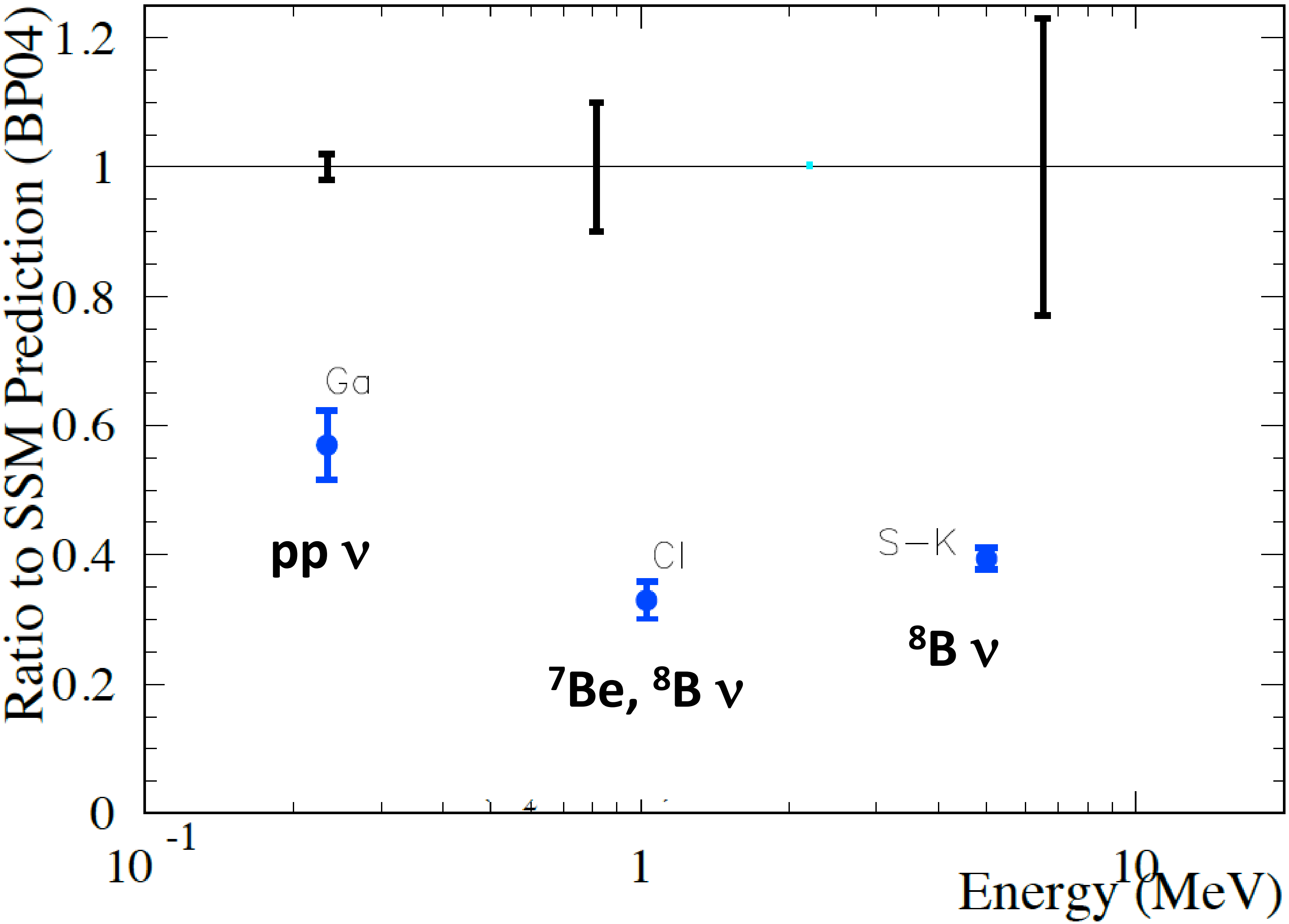
3) Neutral Current Interaction on Deuterium
Equal sensitivity for ν_e , ν_μ , ν_τ

Neutrons are detected by capture in 1) Deuterium, 2) Chlorine in dissolved salt and 3) ^{3}He in a detector array during the three phases of the experiment.

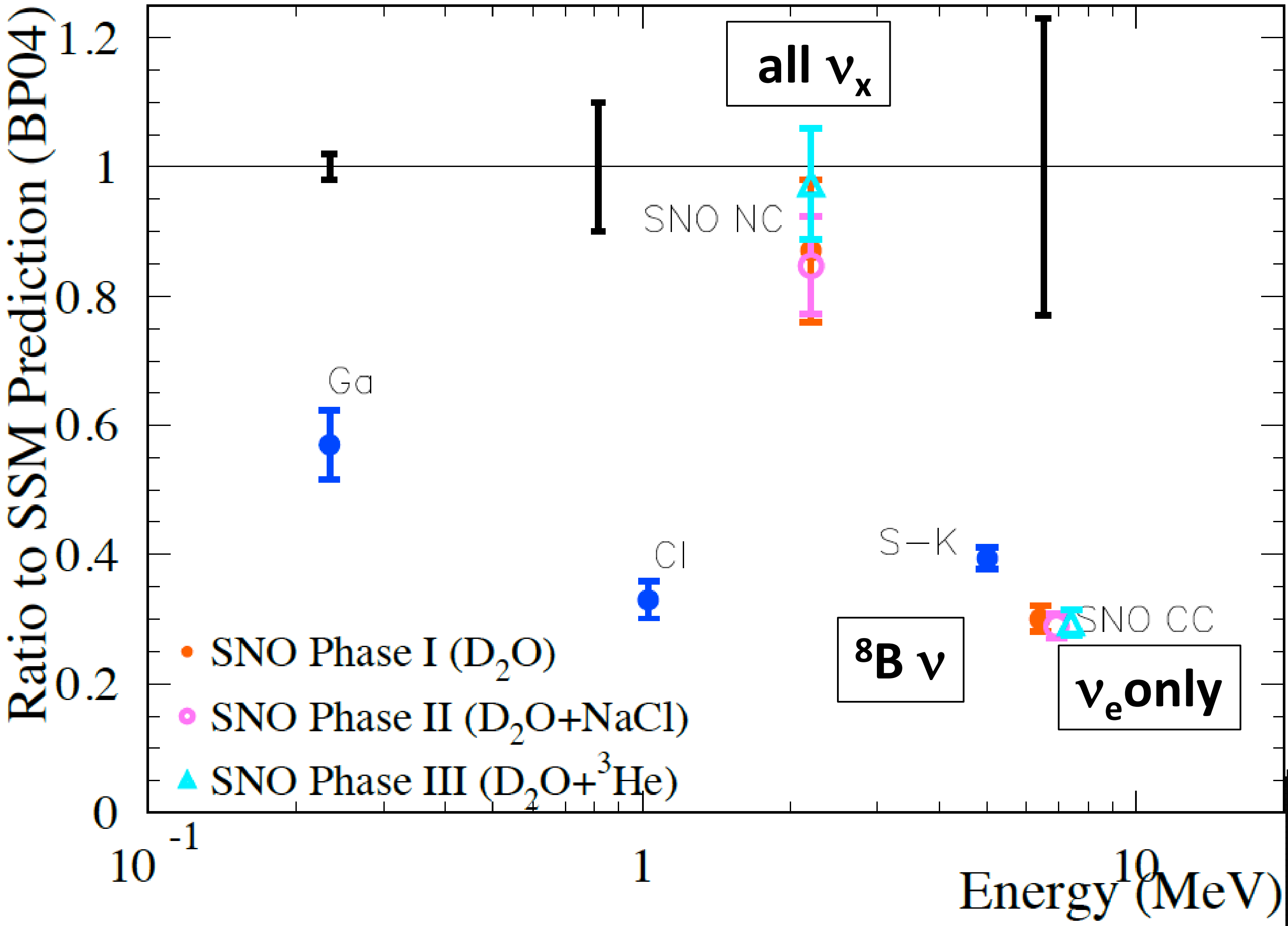
Gamma radioactivity must be very low to avoid neutron background from photodisintegration

Solar Neutrino Problem

Pre 2001



Solar Neutrino Problem Resolved



As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

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

For 3 Active neutrinos.

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

✓ ? ✓ ✓ ?

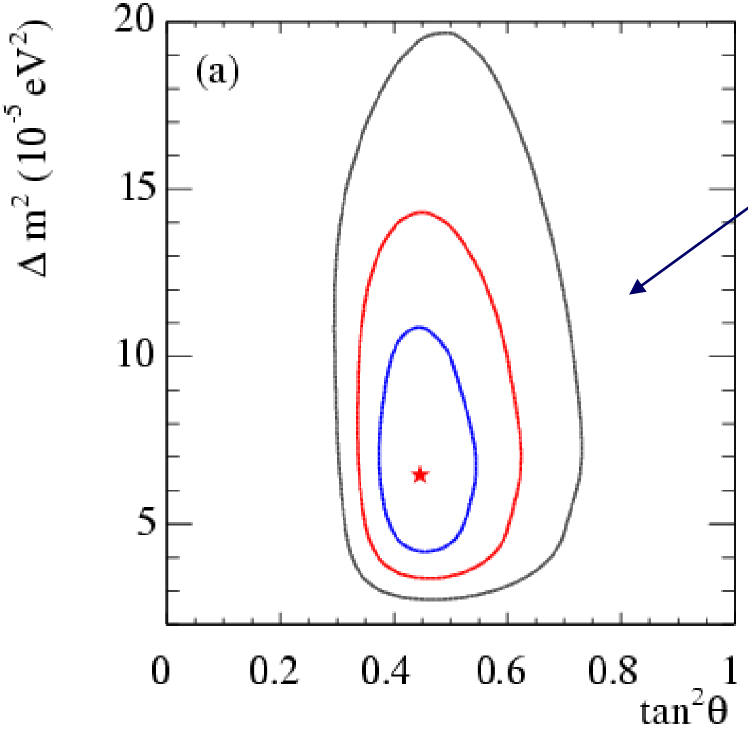
Atmospheric | **CP Violating Phase** | **Reactor, Accel.** | **Solar,Reactor** | **Majorana CP Phases**

✓ **Range defined for Δm_{12}, Δm_{23}**

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

For two neutrino oscillation in a vacuum: $P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2(1.27\frac{\Delta m^2 L}{E})$

In the dense matter in the sun or earth this can be changed due to the extra interactions of ν_e with electrons via W exchange (**Mikheyev-Smirnov-Wolfenstein (MSW) Effect**). Results can be distortion of the ν_e energy spectrum and/or day/night variations.



SOLAR ONLY

AFTER

SNO SALT

DATA

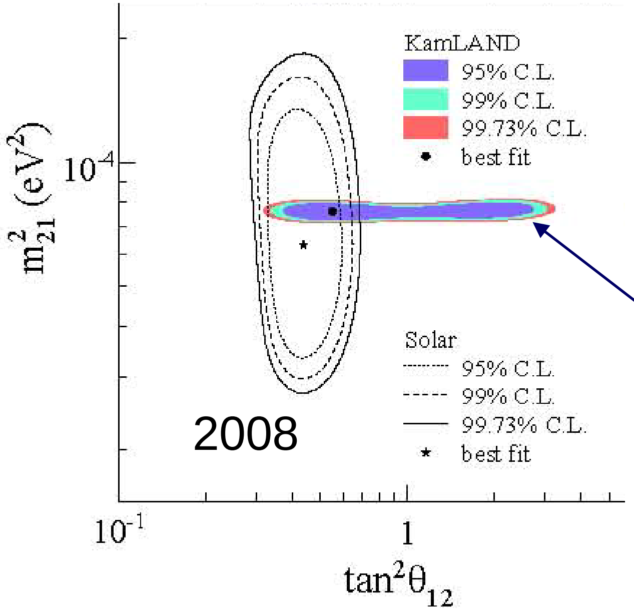
MSW: Large

Mixing Angle

(LMA) Region

- The solar results define the mass hierarchy ($m_2 > m_1$) through the Matter interaction (MSW)

- SNO: CC/NC flux defines $\tan^2 \theta_{12} < 1$ (ie Non - Maximal mixing) by more than 5 standard deviations

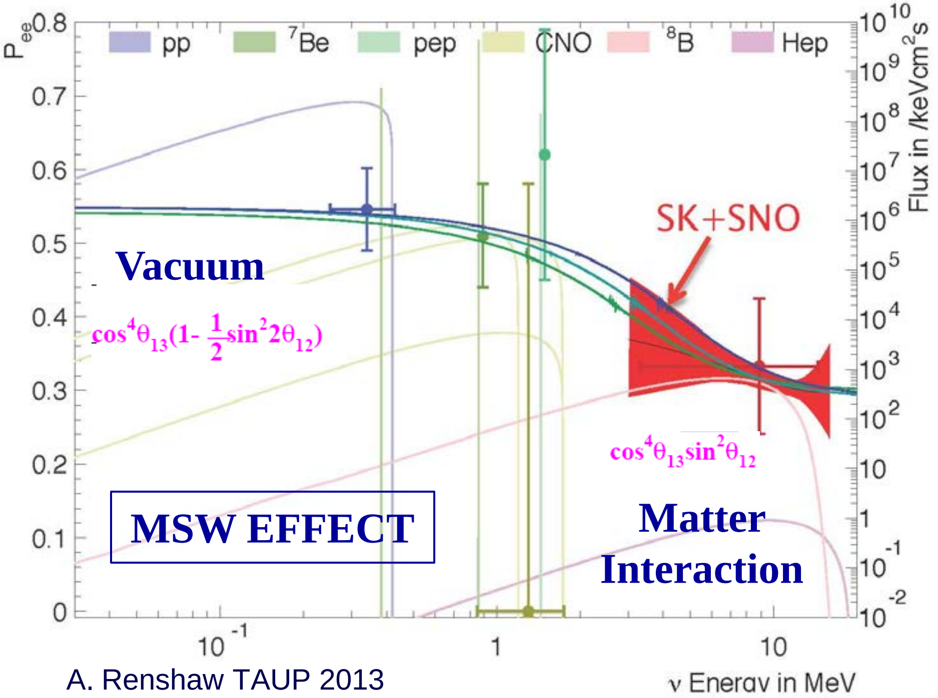


LMA for solar ν involves very small spectral distortion, small (~ 3 %) day-night asymmetry, as observed by SK, SNO

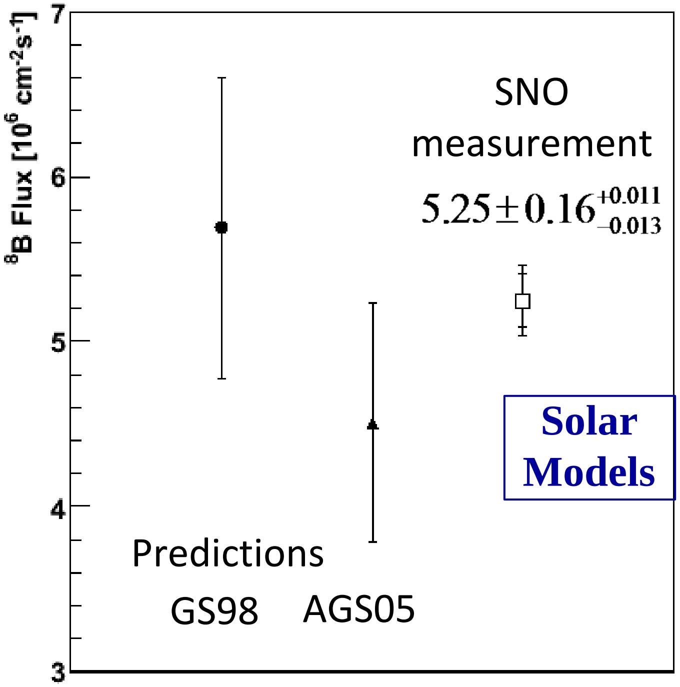
$$\mathrm{Asym}_{\mathrm{salt}\,+\,\mathrm{D_2O}} = 0.037 \pm 0.040$$

Good Agreement between SOLAR and KAMLAND (Reactor $\bar{\nu}$'s) confirms ν oscillation parameters, limits sterile neutrino flux

Advantages of Precision Measurements of Solar Neutrinos



A. Renshaw TAUP 2013



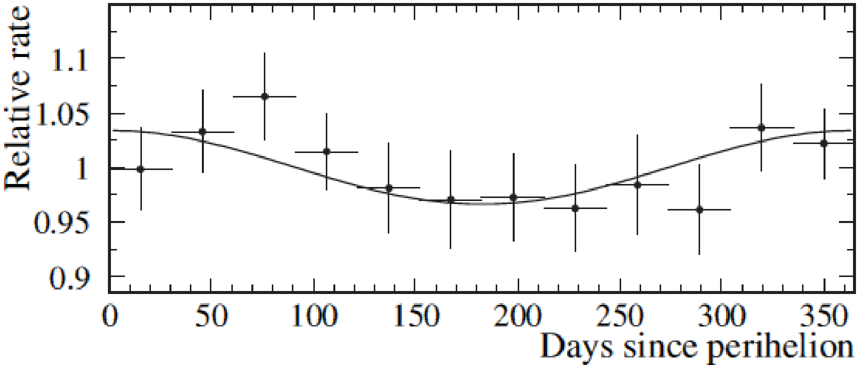
SNO plus Kamland gives a measure of θ_{13} in agreement with Daya Bay, Reno, T2K.

$$CC/NC = 0.317 \pm 0.016(stat) \pm 0.009(syst) = \underset{(\sim 1)}{\cos^4\theta_{13}}\,\sin^2\underset{\uparrow}{\theta_{12}}$$

With θ_{13} known, the SNO measurement of CC/NC defines θ_{12} accurately

Other SNO Solar Neutrino Results

Periodicity Paper: PRD72, 052010 (2005)
No variations between 1d and 10 years
Except for eccentricity of orbit

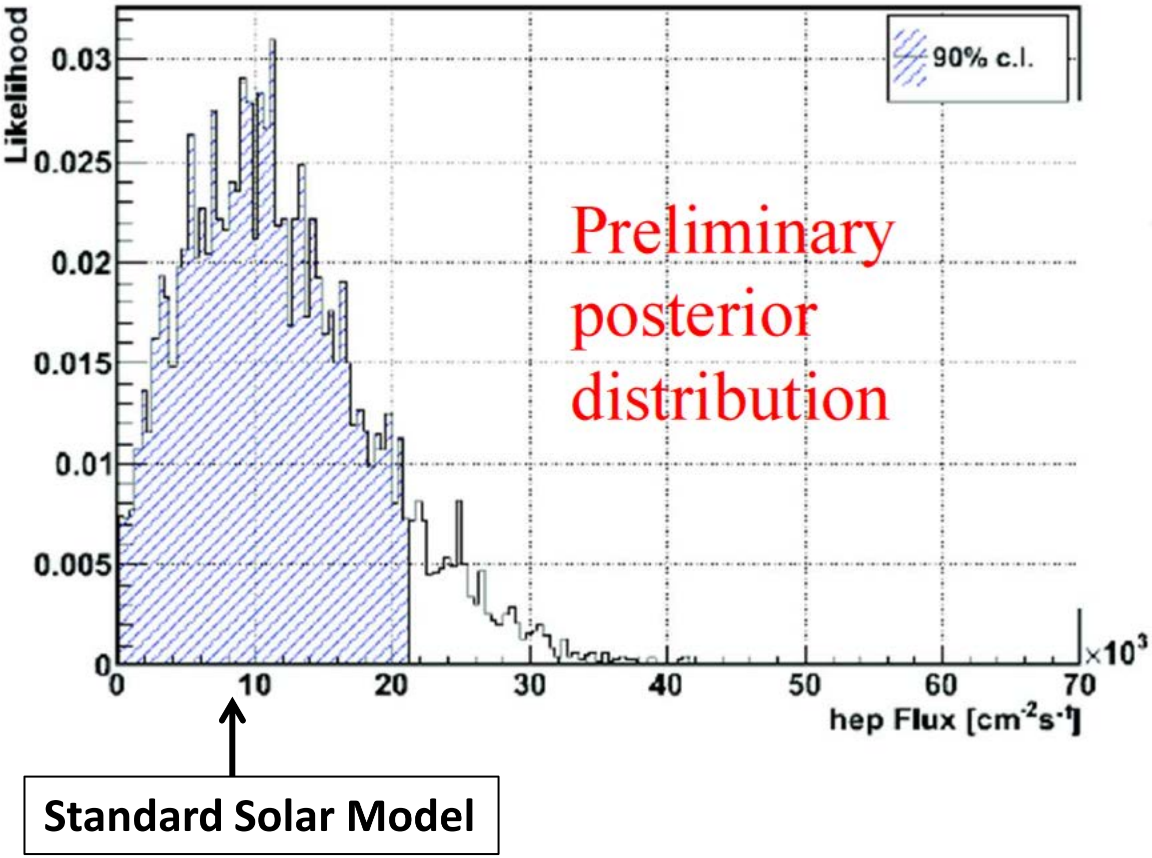


hep neutrino flux: Chris Howard SNO thesis, arXiv:0906.0040v1

Preliminary MCMC fit to all SNO data.

Limit of 22 x 10^3 cm^{-2}/s (90%)

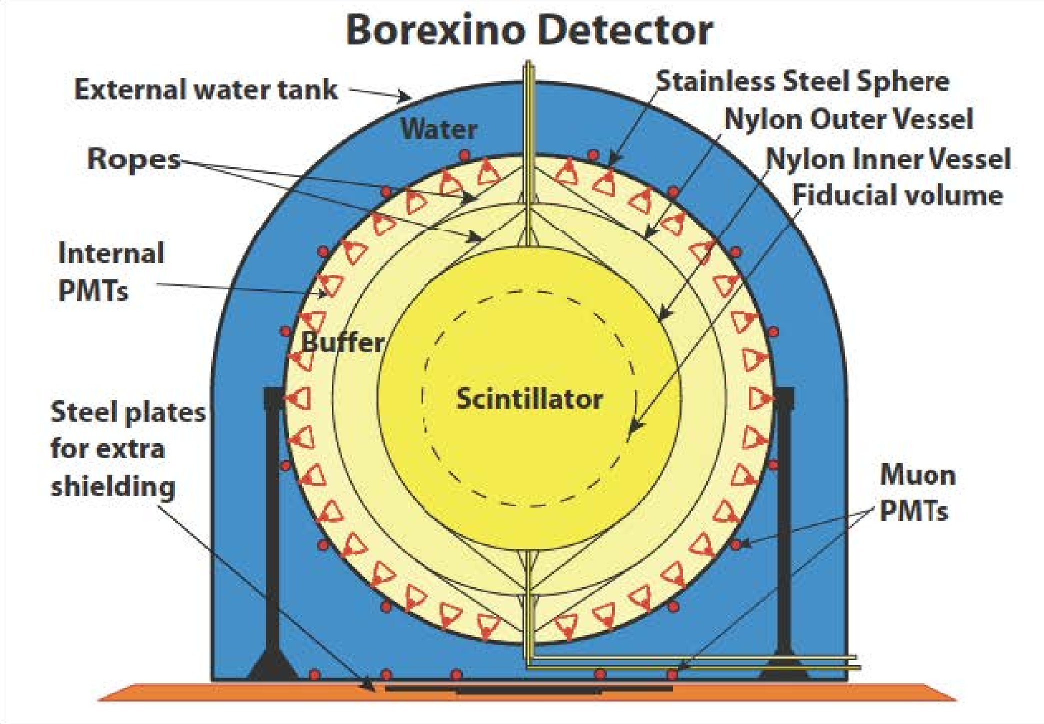
Consistent with
SSM: 8 x 10^3 cm^{-2}/s



Overview of the Borexino Detector

(Mostly Active Shielding)

- Shielding Against Ext. Backgnd.
  - Water: 2.25m
  - Buffer zones: 2.5 m
  - Outer scintillator zone: 1.25 m
- Main backgrounds: in Liq. Scint.
  - $^{14}C/^{12}C$
    - 10^{-18} g/g. cf. 10^{-11} g/g in air CO_2
  - U, Th impurities
  - ^{222}Rn daught (^{210}Pb, ^{210}Bi, ^{210}Po)
  - ^{85}Kr
- Light yield (2200 PMT's)
  - Detected: 500 p_e/MeV (~4%)
- Pulse shape discrimination.
  - Alpha-beta separation



Borexino Neutrino Measurements

Solar Neutrino rates (cpd/t)

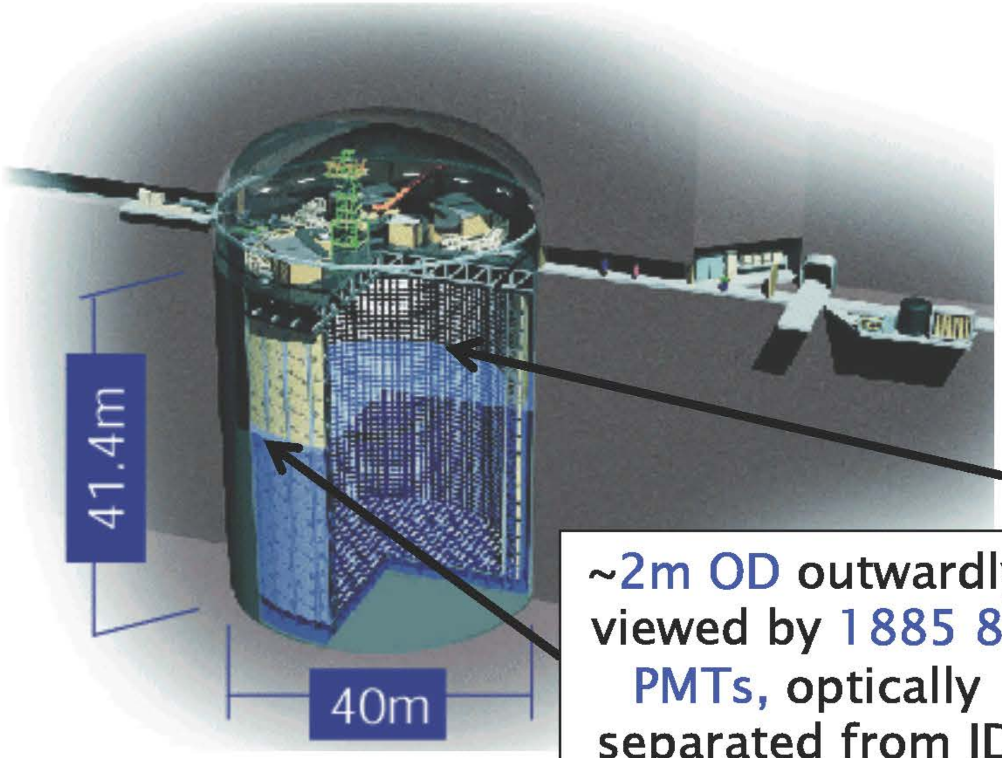
^{7}Be:	0.460 ± 0.023	Phys. Rev. Lett. 107 141302 (2011)
^{8}B:	0.0022 ± 0.0004	Phys. Rev. D 82, 033006 (2010)
pep:	0.031 ± 0.005	Phys. Rev,. Lett. 108, 051302 (2012)

Geo-neutrinos

- Total 14.3 ± 4.4 events Phys. Letts. B722, 295 (2013)

Super-Kamiokande

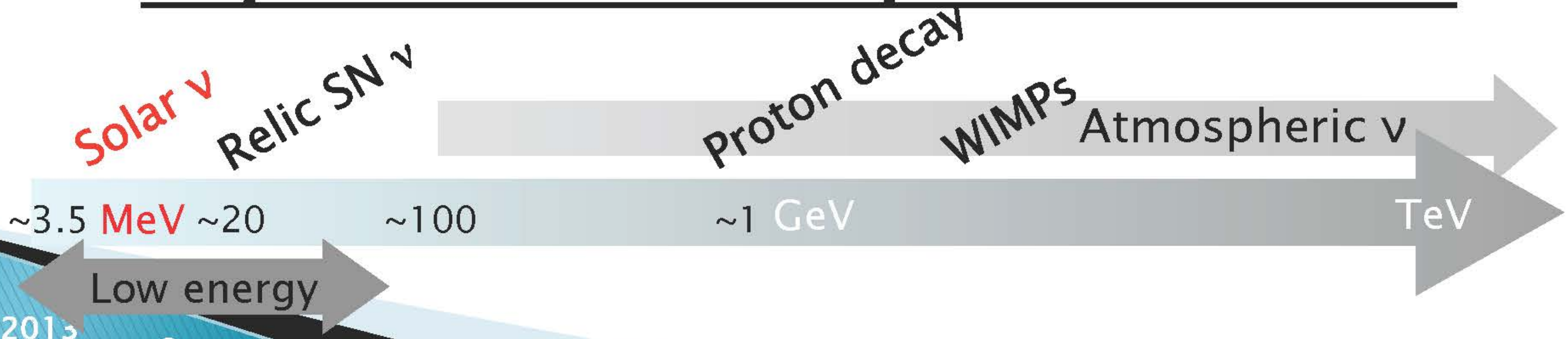
- 50 kton pure water Cherenkov detector
- 1 km (2700 mwe) underground



ID inwardly viewed by 11,129 20" PMTs (40% coverage, single photon sensitivity), 32kton->22.5kton FV

~2m OD outwardly viewed by 1885 8" PMTs, optically separated from ID

Physics studies at Super-Kamiokande

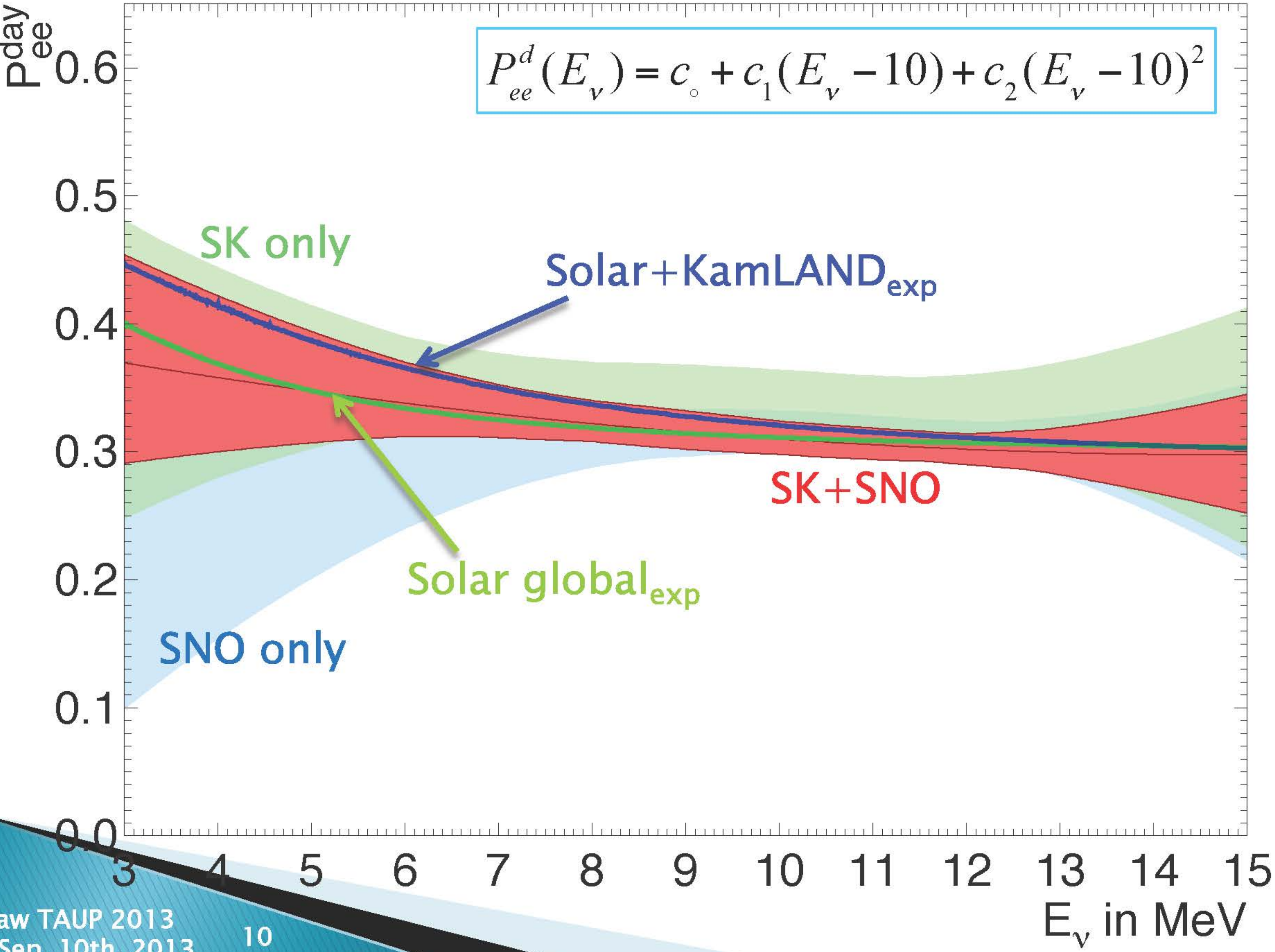


Solar ν
Relic SN ν
Proton decay
WIMPs
Atmospheric ν

~3.5 MeV ~20 ~100 ~1 GeV TeV

Low energy

Allowed Survival Probability $P_{ee}(E_\nu)$


$$P_{ee}^{d}(E_\nu) = c_\circ + c_1(E_\nu - 10) + c_2(E_\nu - 10)^2$$

SK Day/Night Asymmetry

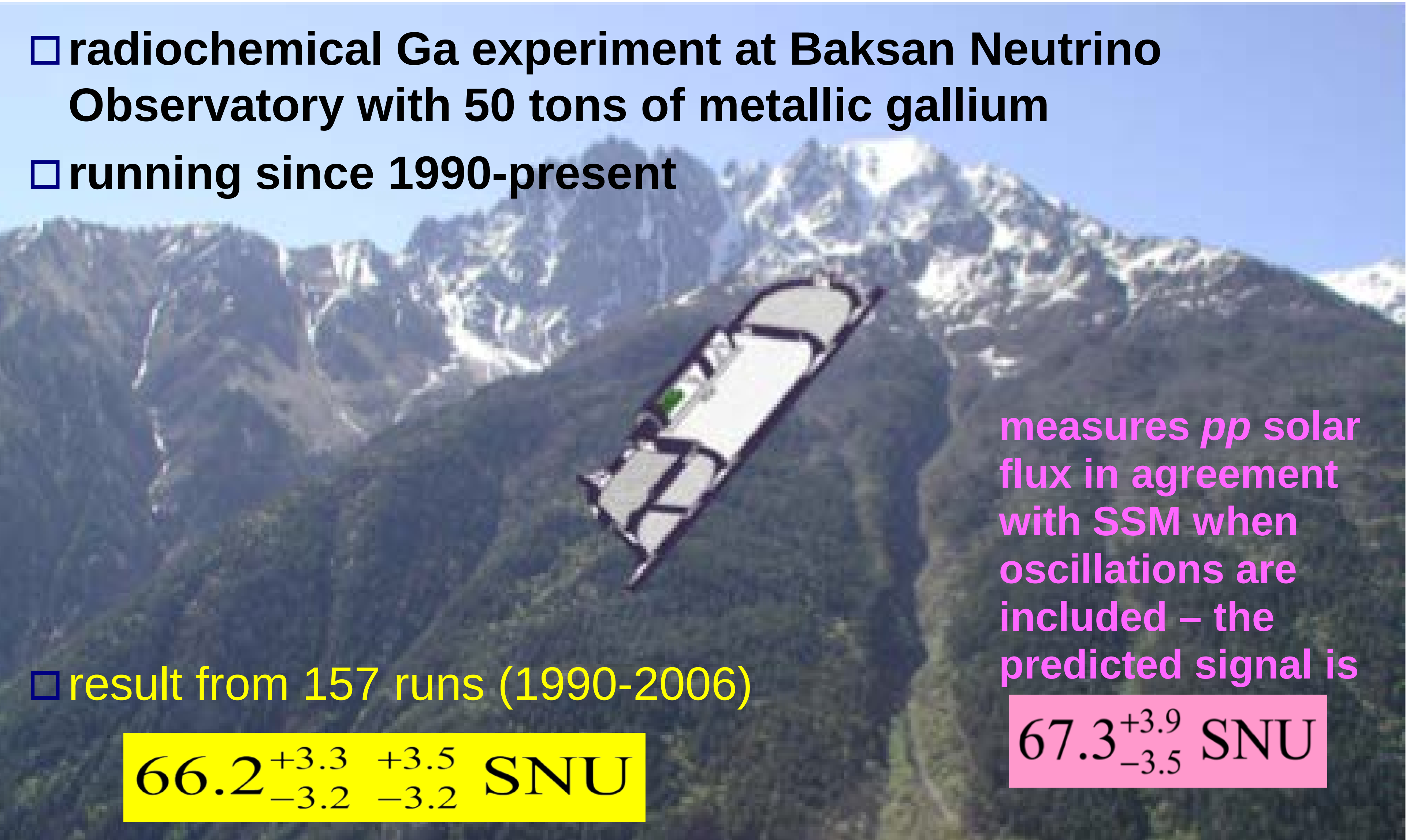
$\Delta m_{21}^2 = 4.9 \times 10^{-5}\ \mathrm{eV}^2$ $\sin^2\theta_{12} = 0.314$ $\sin^2\theta_{13} = 0.025$

	Straight Asymmetry	Ampfit
SK-I	-2.1±2.0±1.3%	-2.0±1.7±1.0%
SK-II	-5.5±4.2±3.7%	-4.3±3.8±1.0%
SK-III	-5.9±3.2±1.3%	-4.3±2.7±0.7%
SK-IV	-5.3±2.0±1.4%	-3.4±1.8±0.6%
SK-I/II/III/IV	-4.2±1.2±0.8%	-3.2±1.0±0.5%

Day/Night asymmetry deviates from zero by 2.8 or 2.7 σ

- First significant indication for the solar neutrino day/night effect
- This is a “direct” indication for matter enhanced neutrino oscillation

SAGE – Russian American Gallium Experiment



- **radiochemical Ga experiment at Baksan Neutrino Observatory with 50 tons of metallic gallium**
- **running since 1990-present**

measures *pp* solar flux in agreement with SSM when oscillations are included – the predicted signal is

$$67.3^{+3.9}_{-3.5}\ \text{SNU}$$

- result from 157 runs (1990-2006)

$$66.2^{+3.3}_{-3.2}\ {}^{+3.5}_{-3.2}\ \text{SNU}$$

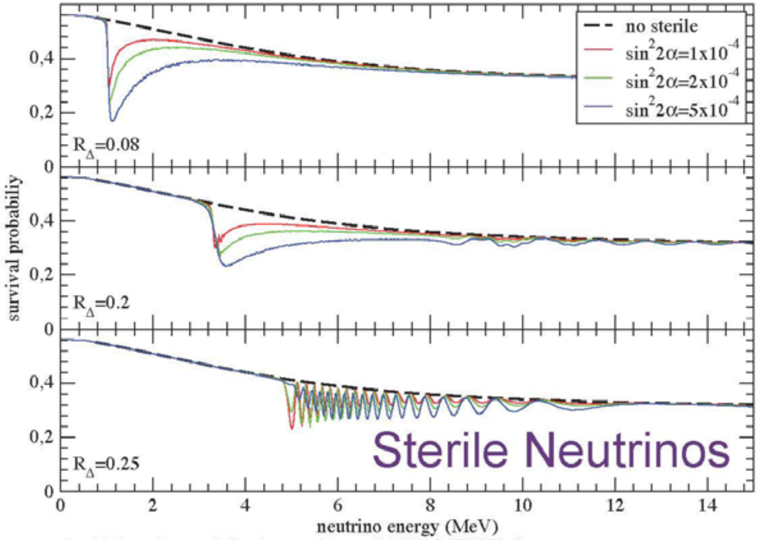
Future Solar Neutrino Experiments (Beyond those already in operation)

pep/CNO	Medium	Status
SNO+	780 kg LAB Liq scintillator	Construction, start 2014
Kamland-2	780 lb Liq Scintillator	Following KamLAND-Zen

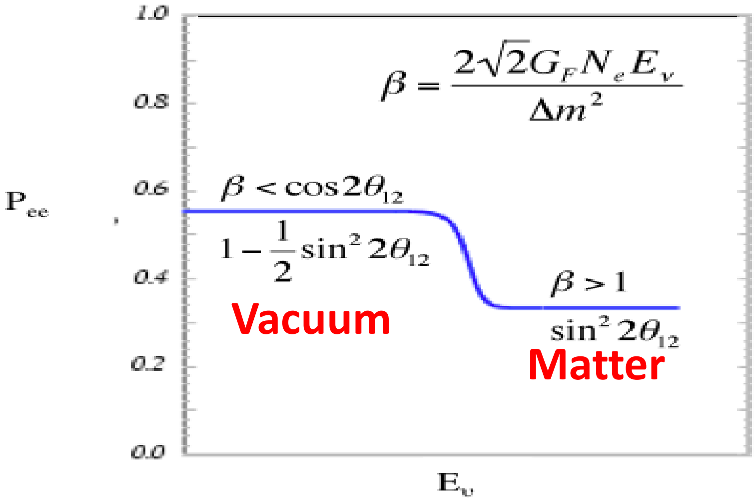
For pp, ^{7}Be neutrinos, measuring CC plus ES could extract electron and total neutrino fluxes

pp via ES		
XMASS	20 tons Liq Xe	835 kg since 2010 for $\beta\beta$
CLEAN	50 tons Liq Ne	MiniClean (500 kg) start 2013
pp, ^{7}Be via CC		
LENS	10 tons ^{115}In	μLENS under development
MOON	3 tons ^{100}Mo	R&D in progress
IPNOS	^{115}In	R&D in progress
MEGAPROJECTS	Threshold defines: ^{8}B + ?	
HyperK, MEMPHYS	Megaton Water Cerenkov	
LBNE, GLACIER	50 to 100 kTon Liquid Ar	
LENA	50 kTon Liq Scintillator	

New Physics at the Vacuum-Matter Transition?

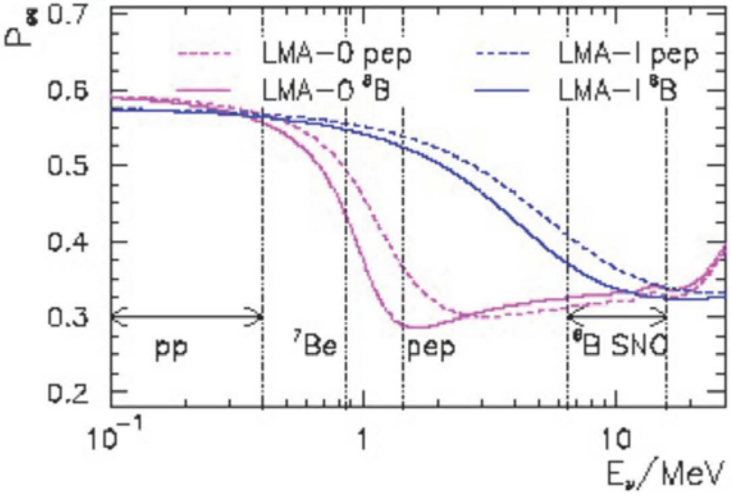


de Holanda and Smirnov, hep-ph/1012.5627v2

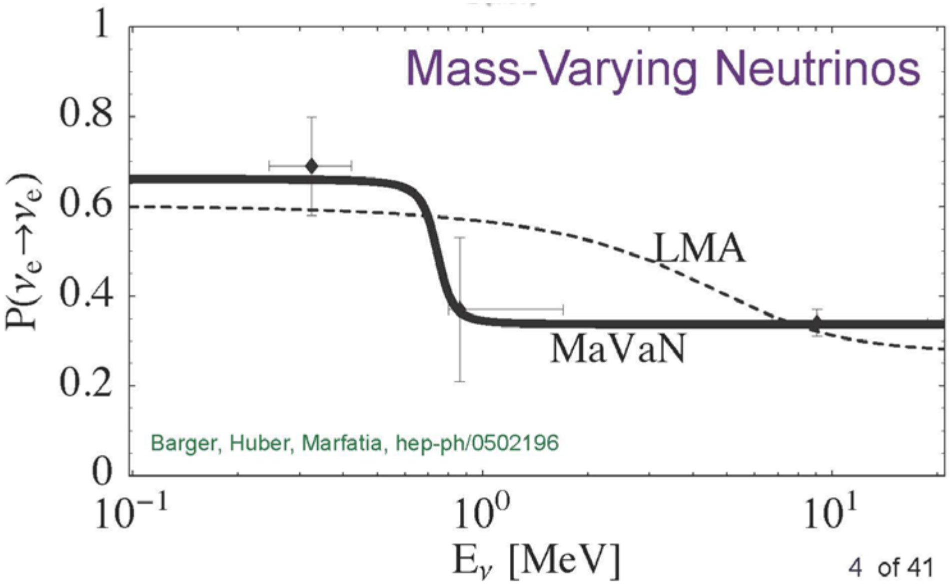


hep-ph/0305159

P_{ee} curve with non-standard interactions



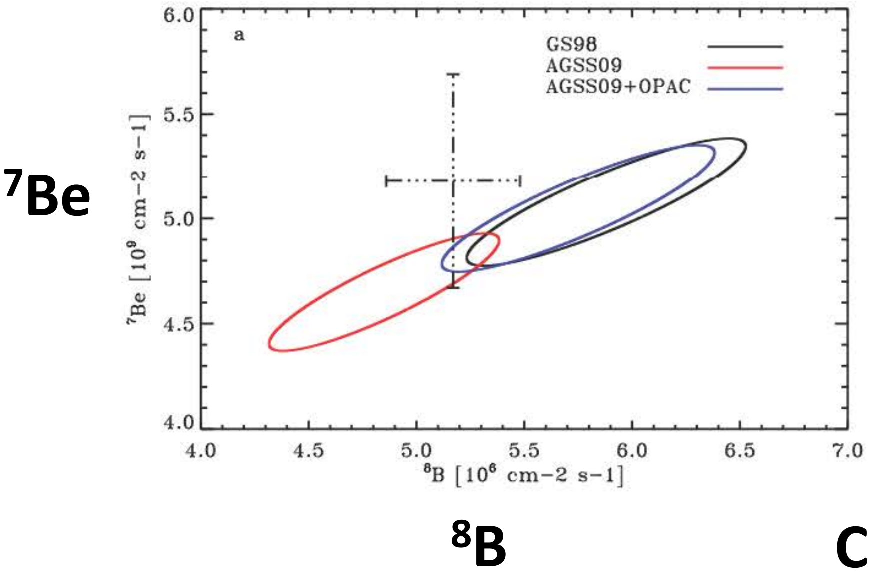
from Friedland, Lunardini, Peña-Garay, hep-ph/0402266



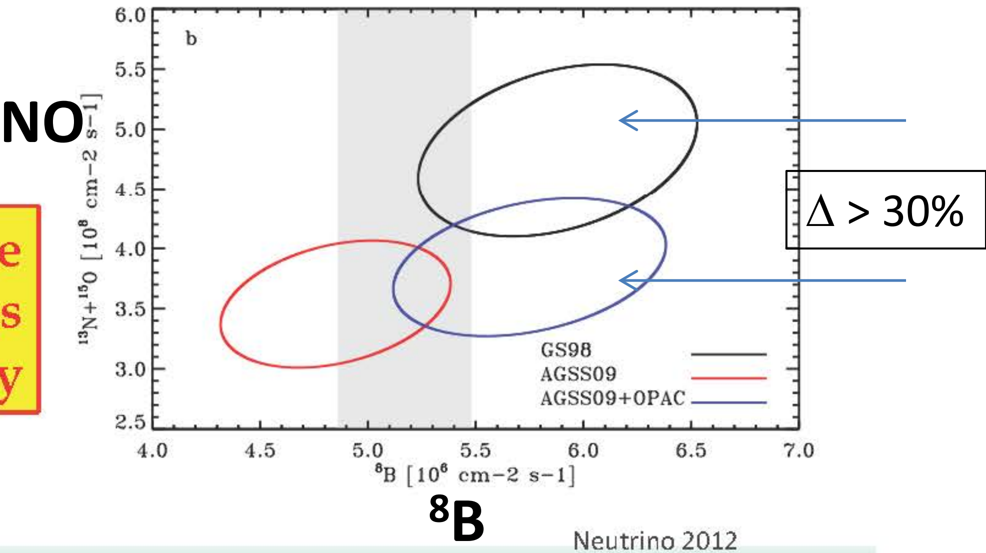
Barger, Huber, Marfatia, hep-ph/0502196

Serenneli

WHY Φ(CNO)?



Changing opacity recovers also $\Phi(^8B)$ & $\Phi(^7Be)$

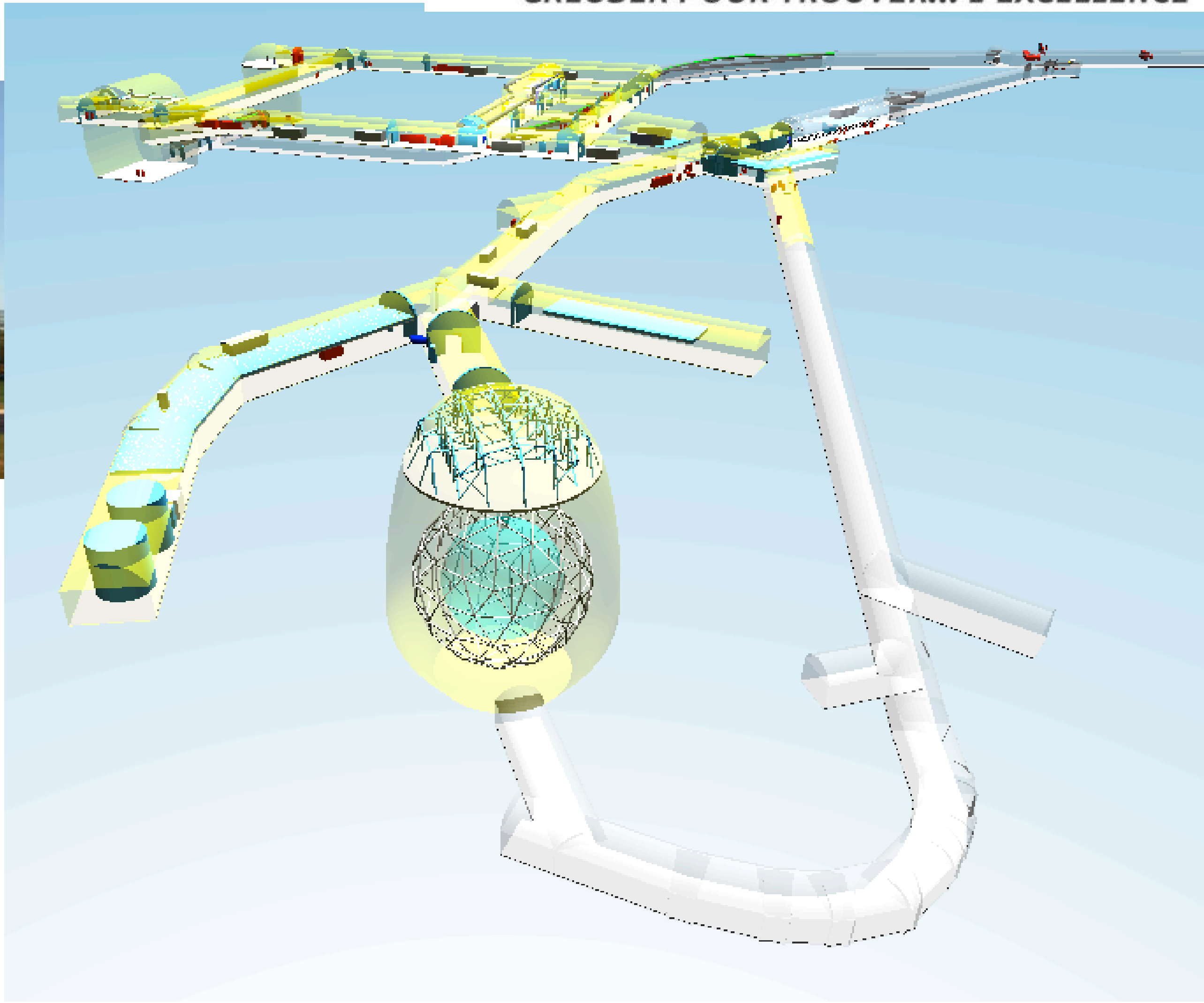


CNO fluxes can break the degeneracy between abundances and radiative opacity

SNO+

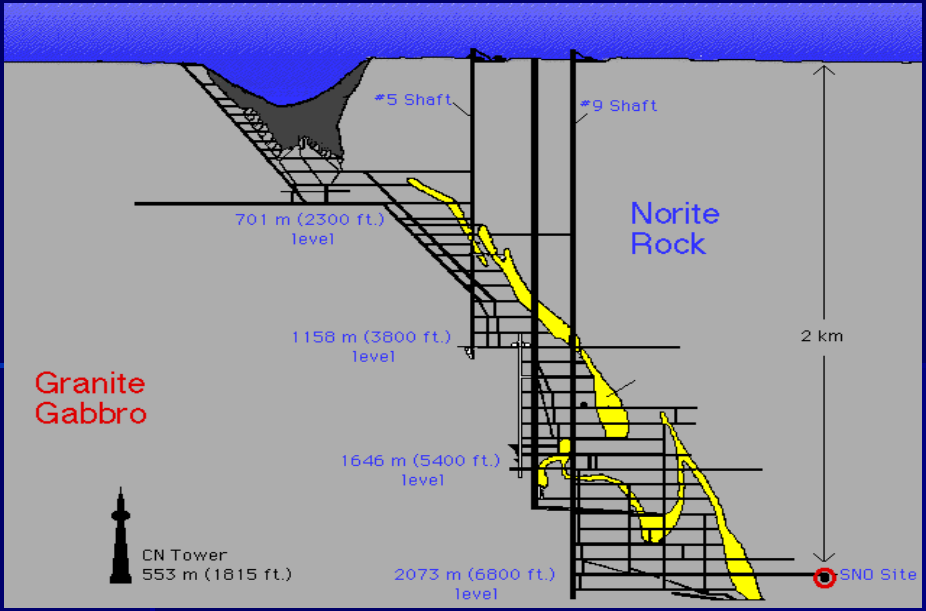
SNOLAB

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



SNOLAB in Sudbury, Ontario, Canada

Depth, 2 km, Class 2000 Cleanliness throughout the lab. 3 times the excavated volume of SNO, space for > 5 additional expts



~~1000 tonnes D_2O~~ → **780 tonnes liquid Scintillator (LAB)**

12 m diameter Acrylic Vessel

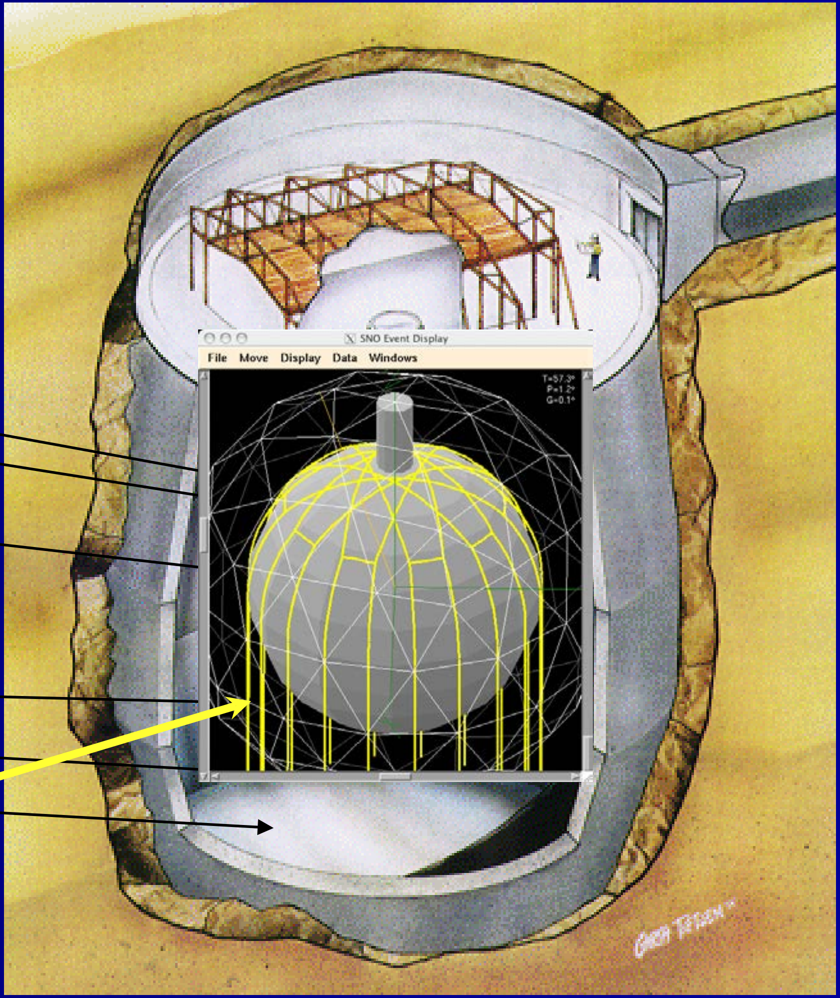
18 m diameter support structure; 9500 PMTs

(~60% photocathode coverage)

1700 tonnes inner shielding H_2O
5300 tonnes outer shielding H_2O
Urylon liner radon seal

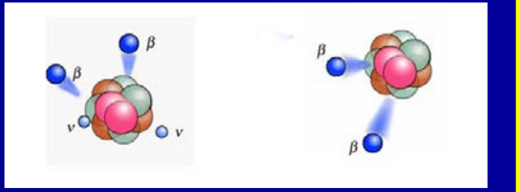
hold down rope net

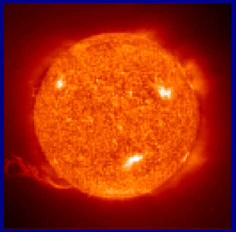
depth: 2092 m (~6010 m.w.e.) ~70 muons/day

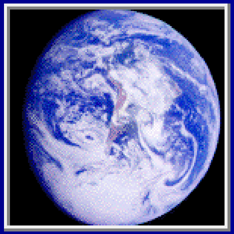


SNO+ Physics Program

- search for neutrino-less double beta decay: > 800 kg of ^{130}Te
- neutrino physics
  - –solar neutrinos
  - –geo antineutrinos
  - –reactor antineutrinos
  - –supernova neutrinos



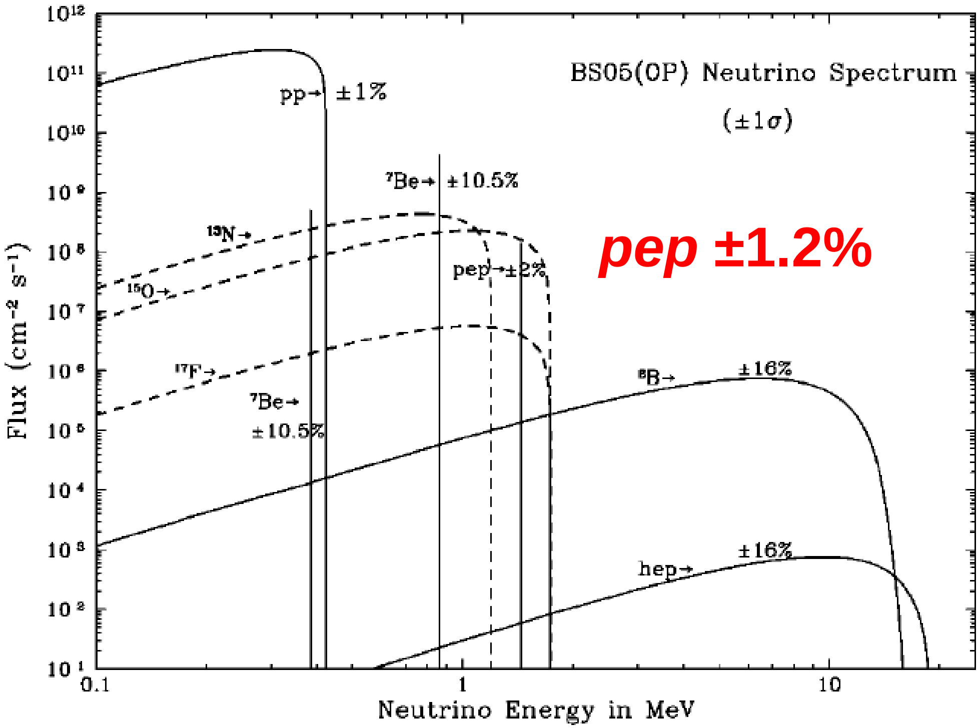




SNO+ Physics Goals

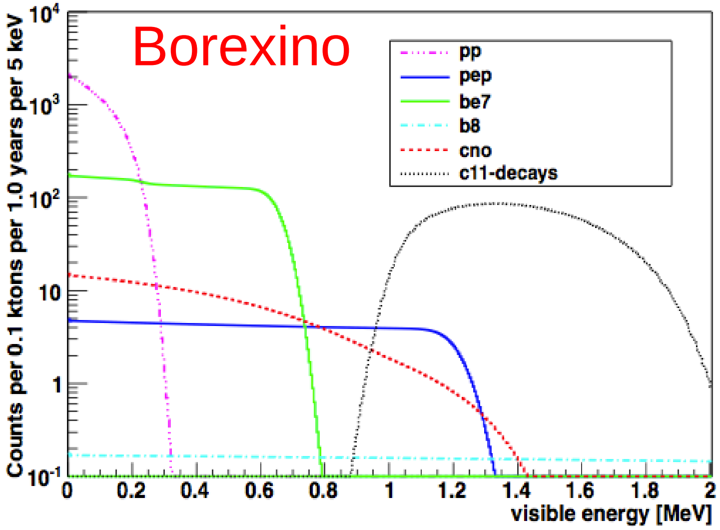
SNO+

- will detect pep solar neutrinos without cosmogenic ^{11}C background (in Borexino and KamLAND)
  - $R = \Phi P_{ee} \sigma$
  - known flux, known cross section
  - thus measurement probes the neutrino survival probability with few% precision

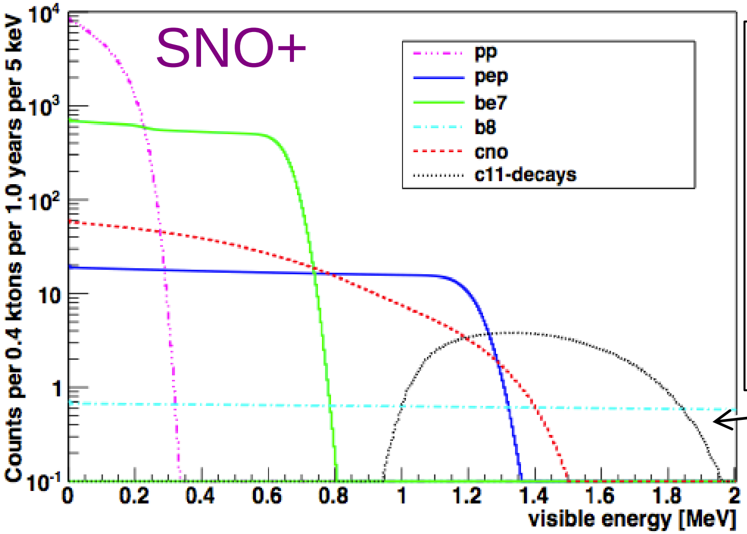


pep ±1.2%

Analytically generated spectra with 5%/√E resolution

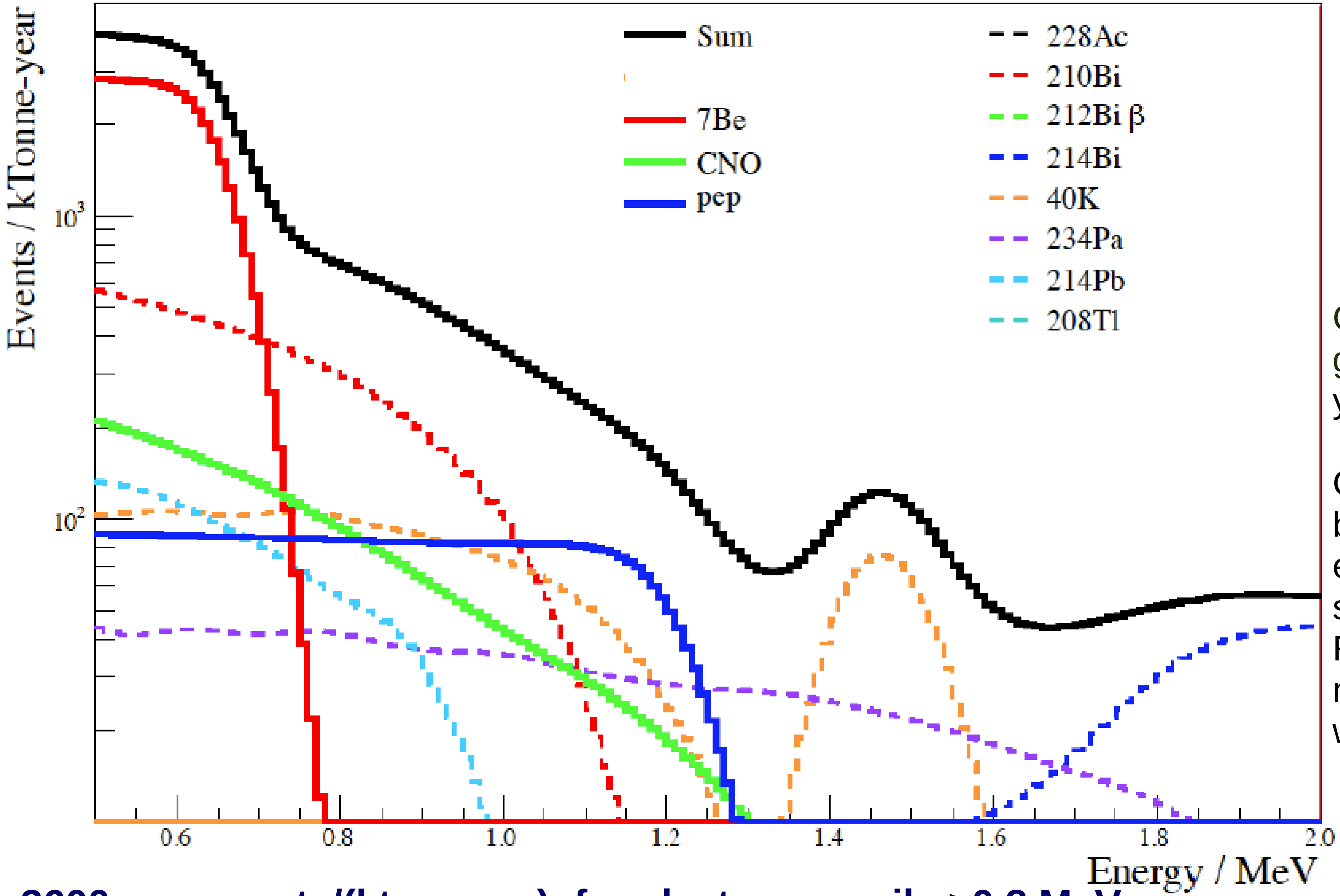


Analytically generated spectra with 5%/√E resolution



^{11}C background can be cut further using muon tracks.

SNO+ pep and CNO Solar Neutrino Signals

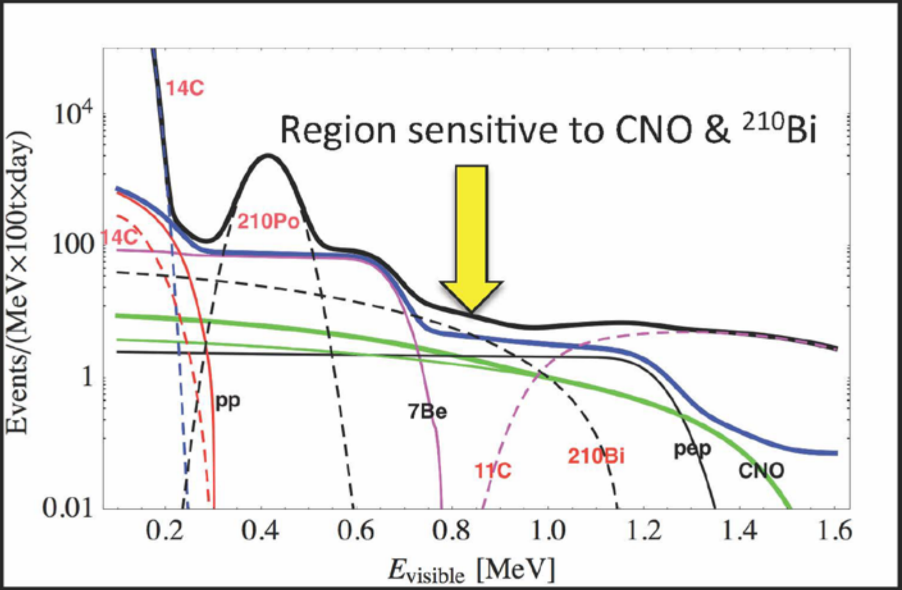


CNO measurement goal: ±10% after 3 years.

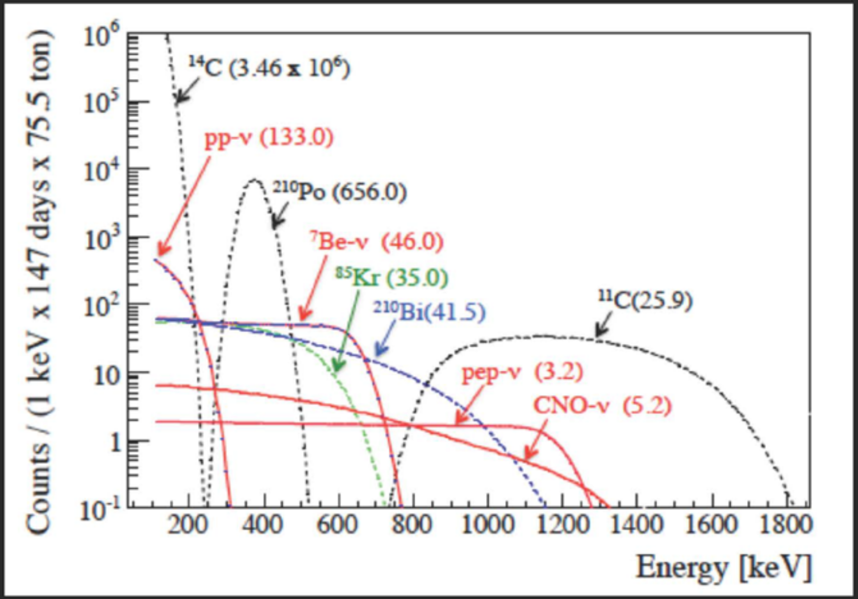
Control of ^{210} Bi background is essential through strong control of Rn, Pb, use of metal scavengers, water extraction.

3600 *pep* events/(kton·year), for electron recoils >0.8 MeV
goal: <u>±5% total uncertainty</u> after 3 years (including systematic and SSM)

Backgrounds before & after Water Extraction + N_2 Stripping


Region sensitive to CNO & ^{210}Bi

After re-purification 2012-2013
(with ^{11}C cuts)

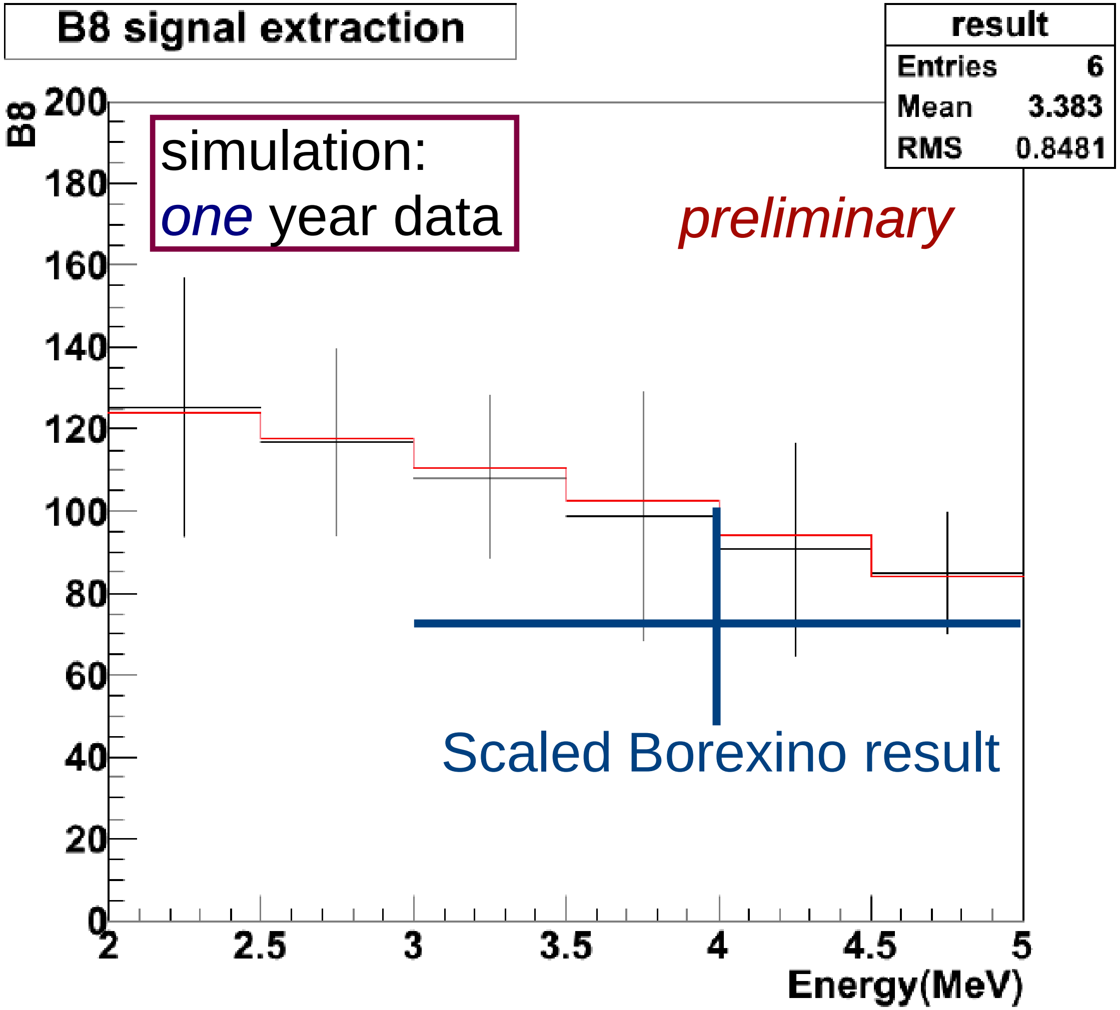


Before re-purification 2008-2010
Without ^{11}C cuts. See arXiv1308.0443v1.

Calaprice: Borexino

SNO+ Low Energy ^{8}B Solar Neutrinos

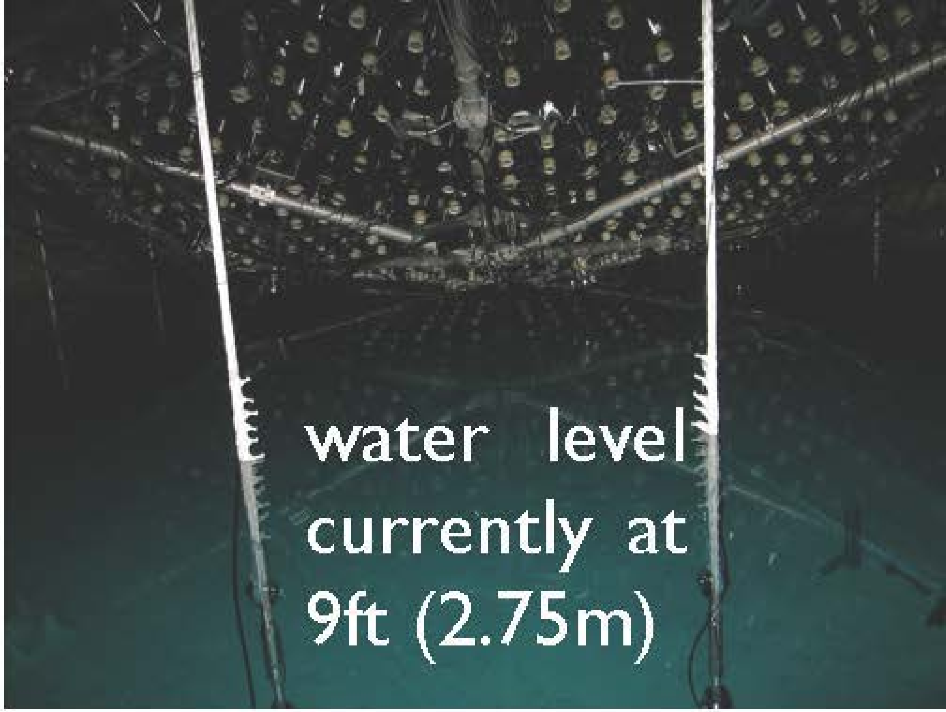
- ☐ simulation of SNO+ extracted ^{8}B solar neutrino signal using constraint on ^{214}Bi from the Bi-Po delayed coincidence
- ☐ SNO+ detects ^{8}B solar neutrinos with neutrino-electron elastic scattering



simulation:
one year data

preliminary

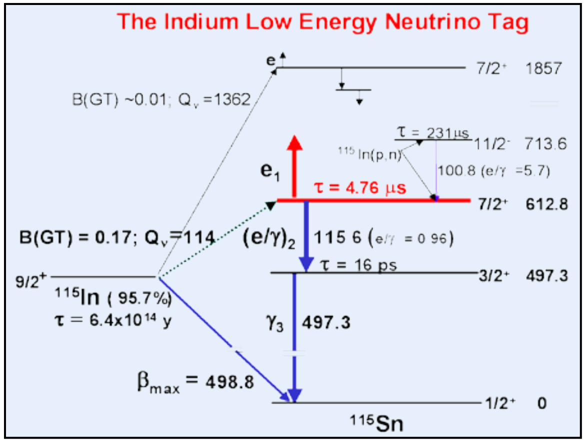
Scaled Borexino result



SNO+ Schedule

- Acrylic Vessel Hold Down Net installed
- New SNO+ Electronics and DAQ installed and tested (air-fill data)
- Water fill detector commissioning starting end of 2013
- Scintillator fill mid 2014 run for a few months
- Addition of Te to the scintillator and Double Beta decay measurements: Late 2014
- Solar neutrino measurements after Te removed.

LENS

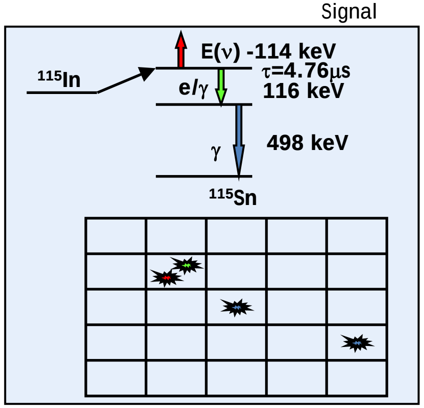


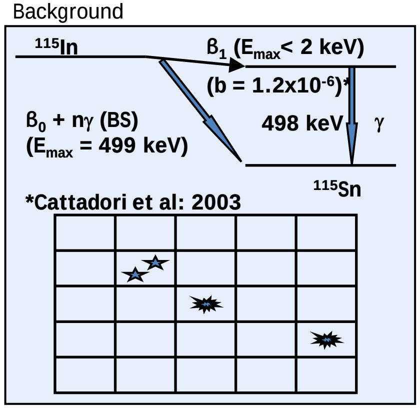
$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau = 4.76\,\mu s)} + {}^{115}Sn$$

- Low threshold = 115 keV (access to 95.5% of the pp-ν continum 0-420keV)
- Directly measures neutrino energy
  $E_\nu = E_e + Q$ (115 keV)
- Typical target mass 10t Indium (96% ^{115}In)
- Principal challenge:background from ^{115}In beta decay ($\tau_{1/2} = 6.4 \times 10^{14}$ years, $E_{endpoint}$ ~ 499 keV) (but this only affects p-p neutrinos)

→ 10 tons In → 8×10^{13} decays/year compared to 400 ν_{pp} events/year

Indium β⁻-Background Discrimination



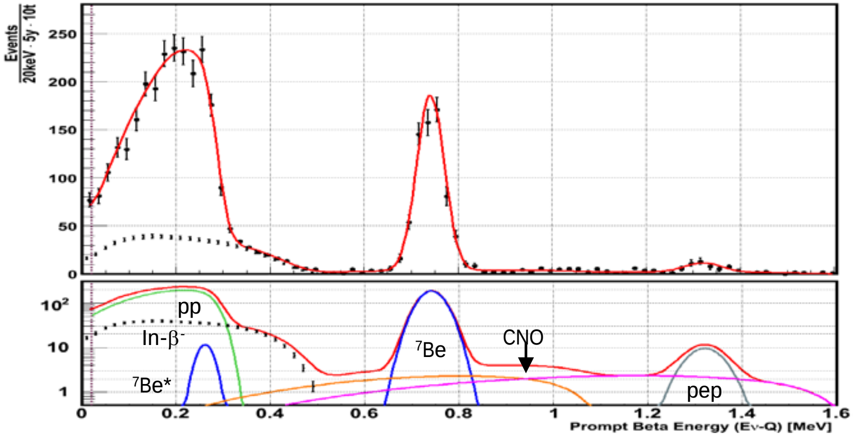


Signal Signature:

Prompt e⁻ (✸)
followed by
low energy (e⁻/γ) (✸)
and
Compton-scattered γ (✸)

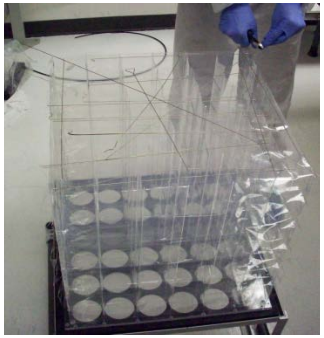
Background:
Random time and space coincidence between two β-decays (✸);
Extended shower (☆) can be created by:
- a) 498 keV γ from decay to excited state;
- b) Bremsstrahlungs γ-rays created by β;
- c) Random coincidence (~10 ns) of more β-decays;

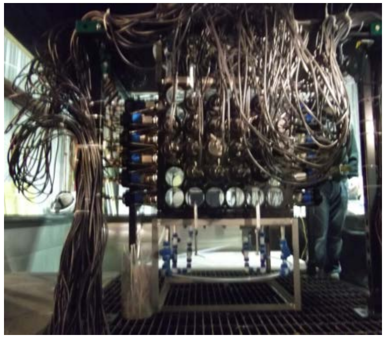
Or any combination of a), b) and c).

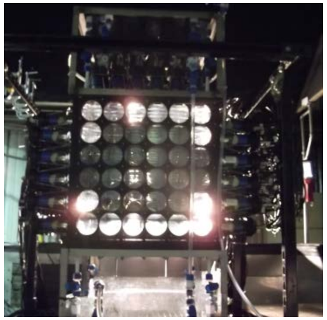


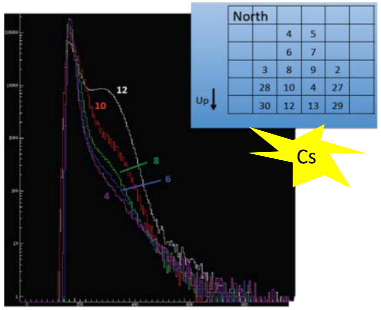
μLENS

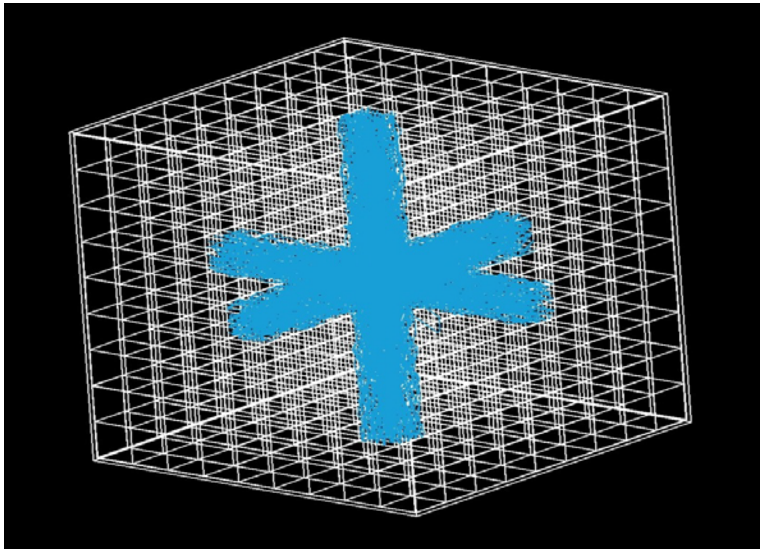
- μLENS Scintillation Lattice Construction
  - 3-D grid made of thin FEP-Teflon
  - Filled with Linear-Alkylbenzene+fluors
- West face of μLENS partially instrumented
- Light channeling from west to east
- Initial μLENS source (^{137}Cs) run
- Layout of μLENS at KURF

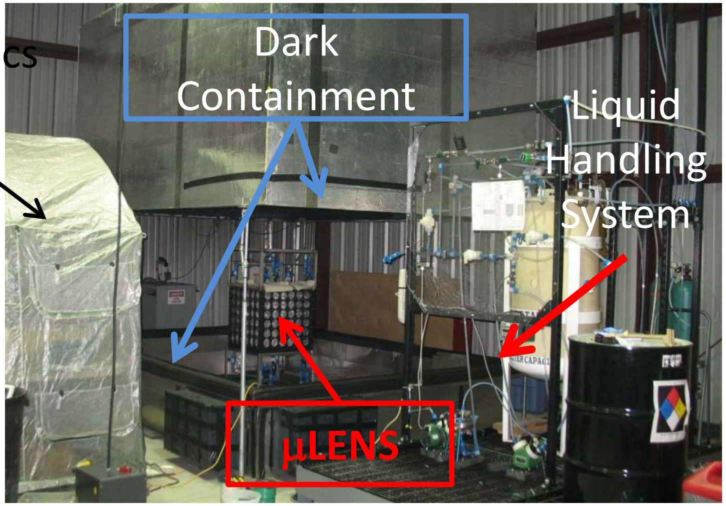












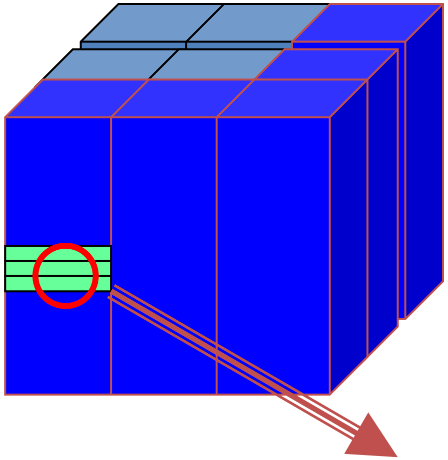
Electronics Tent

Dark Containment

Liquid Handling System

μLENS

MOON * OSAKA CTU FNAL JINR LANL UNC TU UW VNIIEF



Multilayer PL/NaI plates and PL fiber planes with thin ^{100}Mo source film for solar ν and ββ .

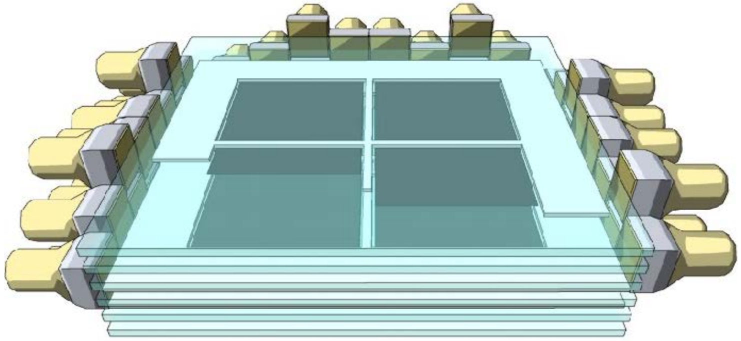
A. Low Q=0.17 MeV, large CC of 680 & 220 SNU for pp & ^{7}Be-ν by using measured B(GT).

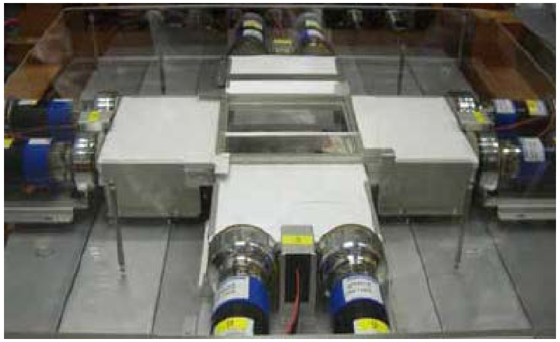
B. Real time studies of inverse β rays in delayed coincidence with the β decays from ^{100}Tc.

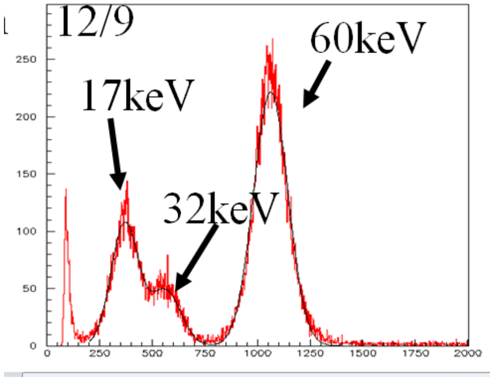
R&D

Multi PL plates, 15 mm thick
ΔE/E σ = 3.8 % at 1 MeV

Multi NaI plates, each 5 mm thick
ΔE/E σ = 2.6 % at 1 MeV **





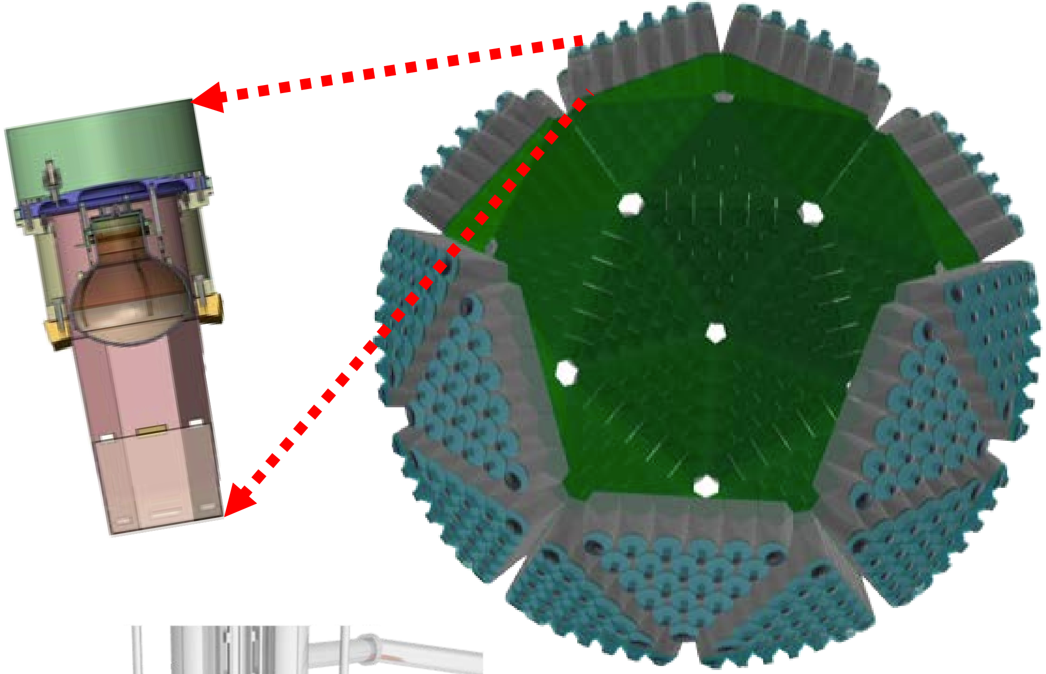


***H. Ejiri, Progress Particle Nucl. Phys. 64 (2010) 249**
****K. Fushimi et al., J. phys. Conference Series, 203 0120064**

Noble Liquid
pp Neutrino via Elastic Scattering

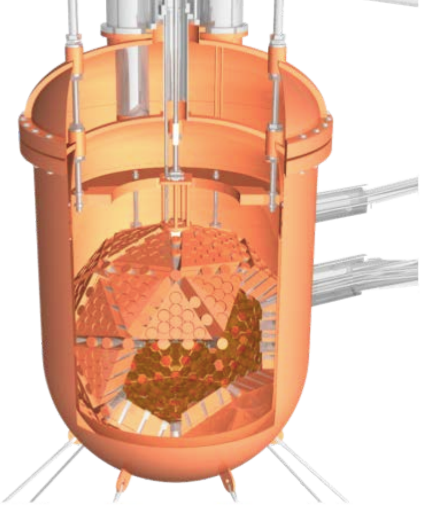
CLEAN:
50-T scale Ne for pp neutrinos

No intrinsic backgrounds for Ne
27K: most contaminants freeze out
Currently constructing MiniClean
At 500 kg for Dark Matter with Ar/Ne



XMASS:
20T goal: For pp, requires depletion of ^{136}Xe by factor of 100 to reduce 2-ν double beta decay background

835kg LXe running since 2010 for neutrino-less Double Beta Decay.
Presently being refurbished.



Solar neutrinos in LENA

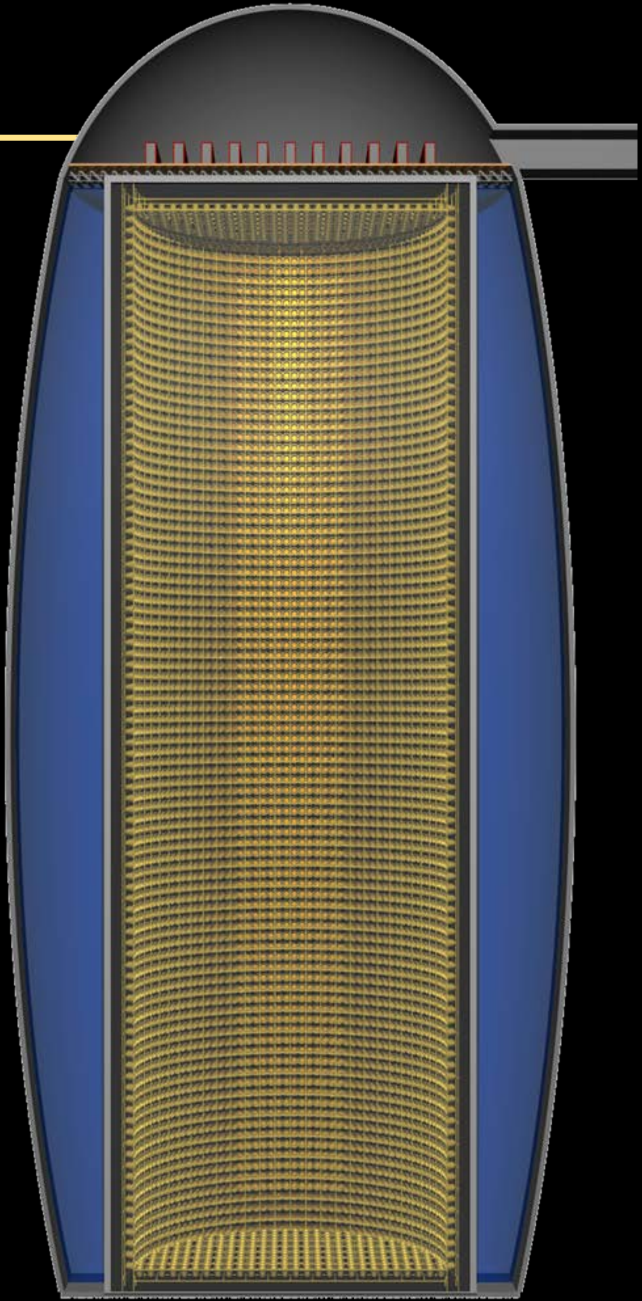
- fiducial volume for solar νs: 30-35 ktons
- ~30% of the cosmogenic bg in Borexino

Particle and astrophysics programme

- oscillations in vacuum-matter transition
  → search non-standard interactions etc.
- neutrino → antineutrino conversion
- solar metallicity
- contribution of CNO cycle
- time modulations in the solar ν flux
  → helioseismic g-modes, ... ?

Neutrino detection

- νe-scattering:
  10^4 cpd ^{7}Be, 3×10^2 cpd pep/CNO ...
- CC-interaction of ν_e on ^{13}C:
  ~10^3 cpa of ^{8}B, E>2.2 MeV



LENA: 4000 mwe, 50000 tons

arXiv:1104.5620

Future Solar Neutrino Experiments (Beyond those already in operation)

pep/CNO	Medium	Status
SNO+	780 kg LAB Liq scintillator	Construction, start 2014
Kamland-2	780 lb Liq Scintillator	Following KamLAND-Zen

For pp, ^{7}Be neutrinos, measuring CC plus ES could extract electron and total neutrino fluxes

pp via ES		
XMASS	20 tons Liq Xe	835 kg since 2010 for ββ
CLEAN	50 tons Liq Ne	MiniClean (500 kg) start 2013
pp, ^{7}Be via CC		
LENS	10 tons ^{115}In	μLENS under development
MOON	3 tons ^{100}Mo	R&D in progress
IPNOS	^{115}In	R&D in progress
MEGAPROJECTS	**Threshold defines: ^{8}B + ?**	
HyperK, MEMPHYS	Megaton Water Cerenkov	
LBNE, GLACIER	50 to 100 kTon Liquid Ar	
LENA	50 kTon Liq Scintillator	