I. Solar Neutrino Experiments

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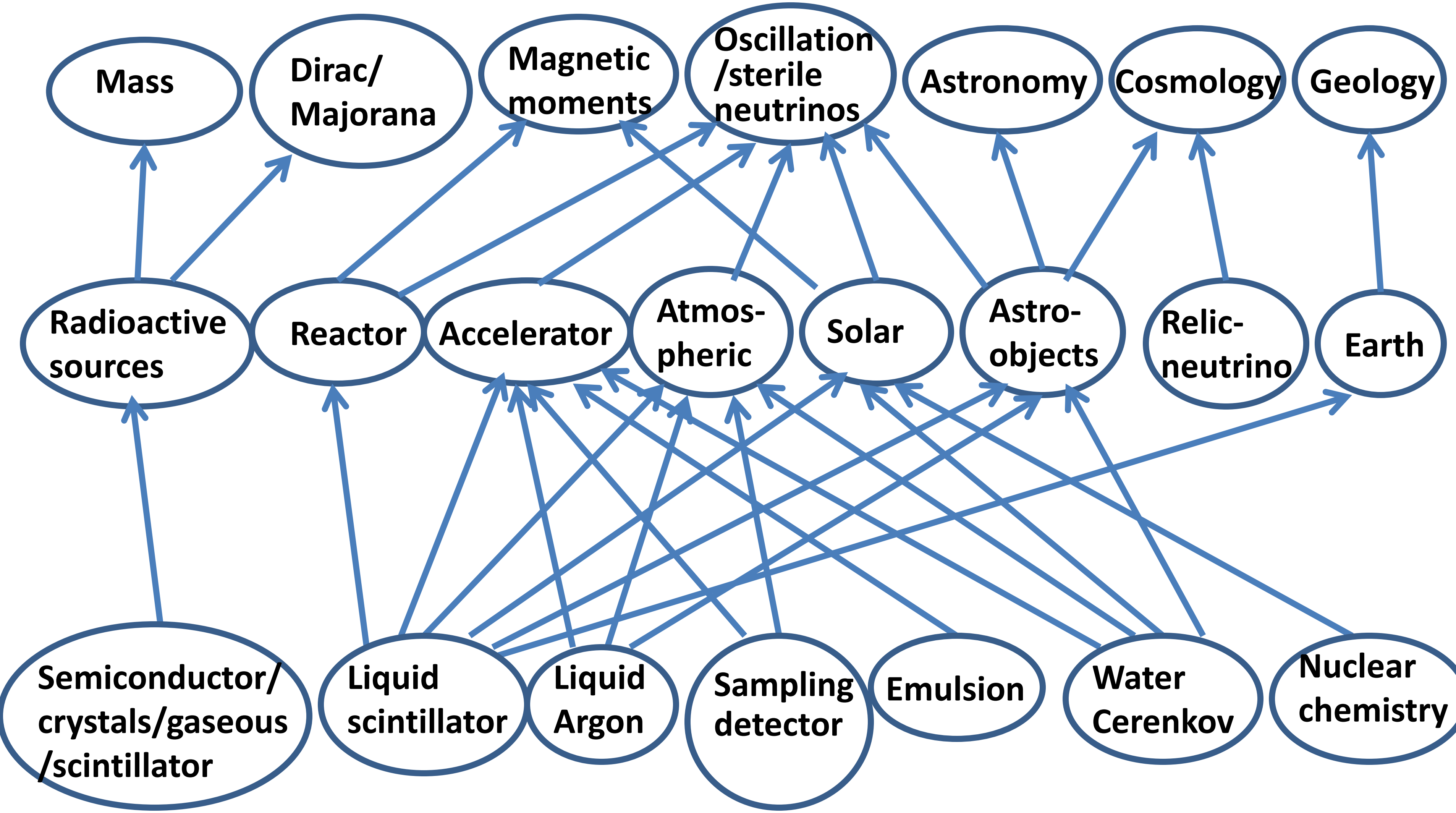
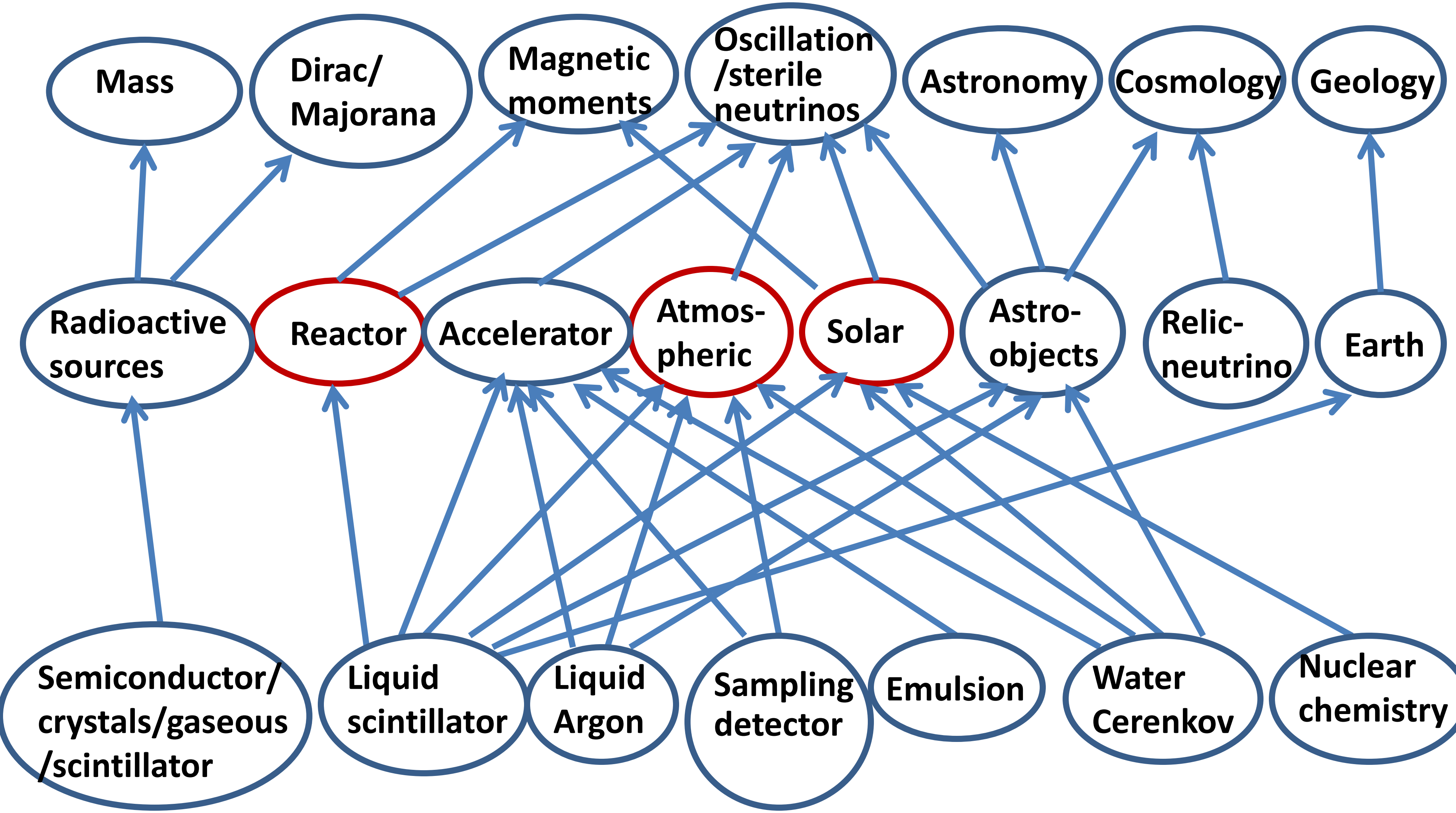
INSS 2014, St. Andrews

Neutrino industry

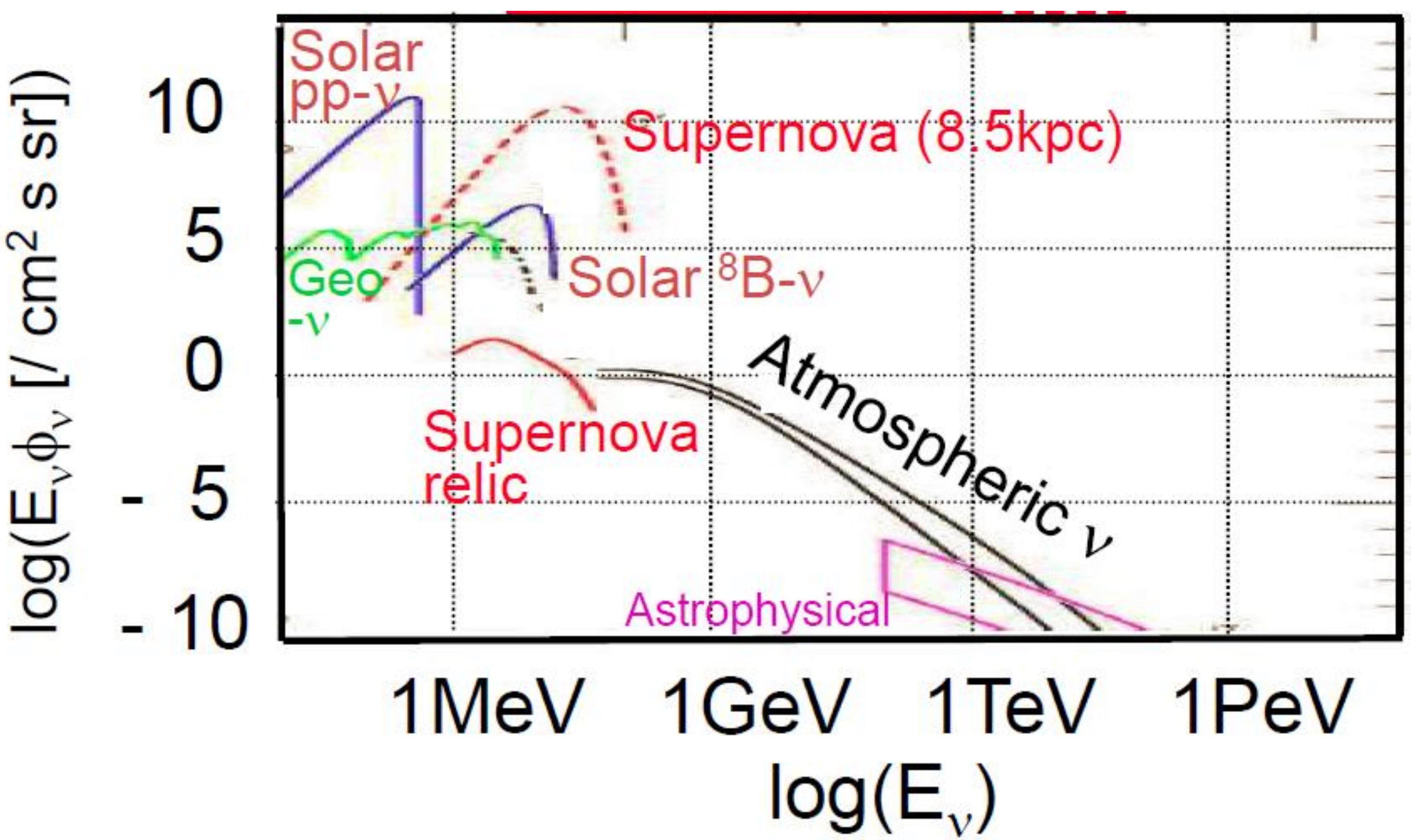
Neutrino Physics: Problems and Methods



Neutrino Physics： Problems and Methods



Neutrino Spectrum



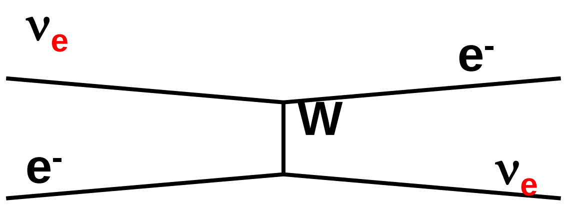
Neutrino Interactions with Matter

- Charge current interactions
  - $\nu_e + {}^{Z-1}A \rightarrow e^- + {}^{Z}A$
  - $\nu_e + p \rightarrow e^+ + n$

    } Low energy (~ MeV)
  - $\bar{\nu}_e + N \rightarrow N' + e^-$
  - $\nu_\mu + N \rightarrow N' + \mu^-$

    } High energy (~ GeV)
- Neutral current interactions(mostly backgrounds)
  - $\nu_\mu + N \rightarrow \nu_\mu + N' + x$
  - $\nu_e + N \rightarrow \nu_e + N' + x$
- Both
  - ν + e scattering

CC



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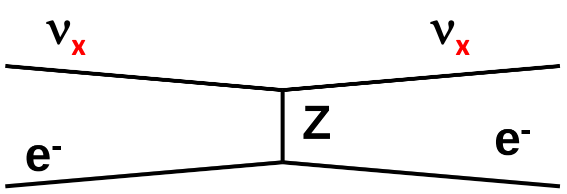
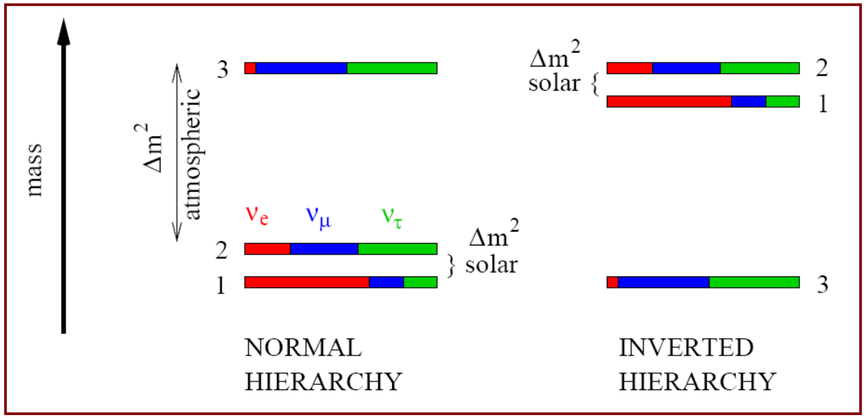


Characteristics of Neutrino Experiments

- Very strong neutrino sources
- Very large target mass
- Very low radioactive backgrounds
  - Sources: cosmic-rays, detector materials, environment
  - Method: underground, active & passive shielding, special materials selection and/or purification
  - Usual difficulties：
    - Large detector VS underground & low background
    - High resolution VS low background
    - Ultra low backgrounds：
      - Environmental： dust, air, water, shielding materials
      - Internal： Ge、CsI、LS、
      - Activation by cosmic-rays

Neutrino Oscillation Experiments

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



θ_{23} & ΔM^2_{32} | CP phase δ & θ_{13} | θ_{12} & ΔM^2_{21} | Majorana phase

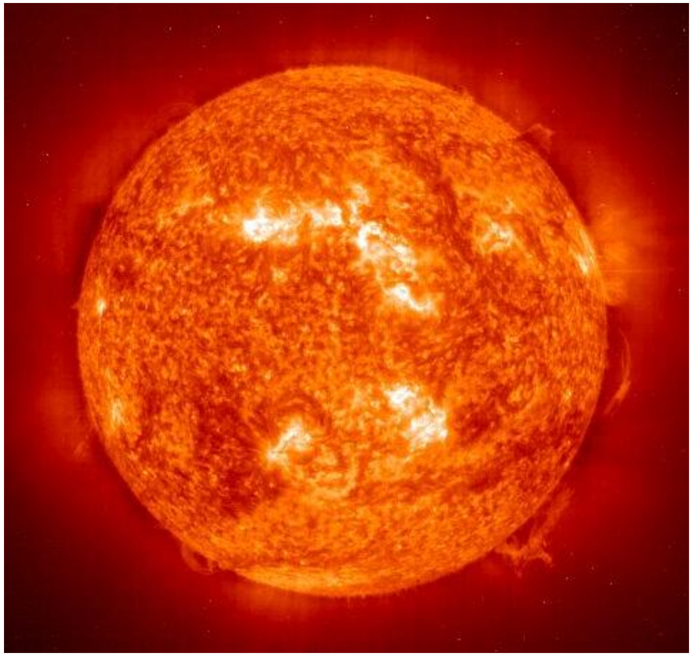
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric accelerator | **reactor accelerator** | **solar reactor** | **Double beta decays**

Solar neutrinos

Basic Facts of the Sun

- Mass 1.99 x 10^{30} kg
- Luminosity 3.842 x10^{33} erg/sec
- Radius 6.9598 x 10^{8} m
- Age 4.57 x 10^{9} years
- metals/hydrogen ratio: 0.0229
- Temperature :
  - Central: 15×10^{6} K(~ keV)
  - At surface: 6000 K
- Density at the center: 150gr/cc
- Central H abundance: 0.34



Where the energy comes from and how long it will last ?

Energy Production in Stars

Bethe 1939

pp chain

No neutrinos

CNO cycle

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than He^4 can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. INTRODUCTION

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, \qquad N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, \\ &N^{14}+H=O^{15}+\gamma, \qquad O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. \end{aligned} \quad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

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Detection of Solar Neutrinos

Bahcall, Davis 1964

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

The principal energy source for main-sequence stars like the sun is believed to be the fusion, in the deep interior of the star, of four protons to form an alpha particle.[1] The fusion reactions are thought to be initiated by the sequence $^{1}H(p, e^{+}\nu)^{2}H(p,\gamma)^{3}He$ and terminated by the following sequences: (i) $^{3}He(^{3}He, 2p)^{4}He$; (ii) $^{3}He(\alpha,\gamma)^{7}Be(e^{-}\nu)^{7}Li(p,\alpha)^{4}He$; and (iii) $^{3}He(\alpha,\gamma)^{7}Be(p,\gamma)^{8}B(e^{+}\nu)^{8}Be^{*}(\alpha)^{4}He$. No direct evidence for the existence of nuclear reactions in the interiors of stars has yet been obtained because the mean free path for photons emitted in the center of a star is typically less than 10^{-10} of the radius of the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

The most promising method[2] for detecting solar neutrinos is based upon the endothermic reaction ($Q = -0.81$ MeV) $^{37}Cl(\nu_{solar}, e^{-})^{37}Ar$, which was first discussed as a possible means of detecting neutrinos by Pontecorvo[3] and Alvarez.[4] In this note, we predict the number of absorptions of

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^{-})^{37}Ar$ induced us to place the apparatus previously described[1] in a mine and make a preliminary search. This experiment served to place an upper limit on the flux of extraterrestrial neutrinos. These results will be reported, and a discussion will be given of the possibility of extending the sensitivity of the method to a degree capable of measuring the solar neutrino flux calculated by Bahcall in the preceding paper.[2]

The apparatus consists of two 500-gallon tanks of perchlorethylene, C_2Cl_4, equipped with agitators and an auxiliary system for purging with helium. It is located in a limestone mine 2300 feet below the surface[3] (1800 meters of water equivalent shielding, m.w.e.). Initially the tanks were swept completely free of air argon by purging the tanks with a stream of helium gas. ^{36}Ar carrier (0.10 cm^3) was introduced and the tanks exposed for periods of four months or more to allow the 35-d ^{37}Ar activity to reach nearly the saturation value. Carrier argon along with any ^{37}Ar pro-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses the efficiencies mentioned, the upper limit of the neutrino capture rate in 1000 gallons of C_2Cl_4 is ≤ 0.5 per day or $\varphi\bar{\sigma} \leq 3\times10^{-34}$ sec^{-1} (^{37}Cl atom)$^{-1}$. From this value, Bahcall[2] has set an upper limit on the central temperature of the sun and other relevant information.

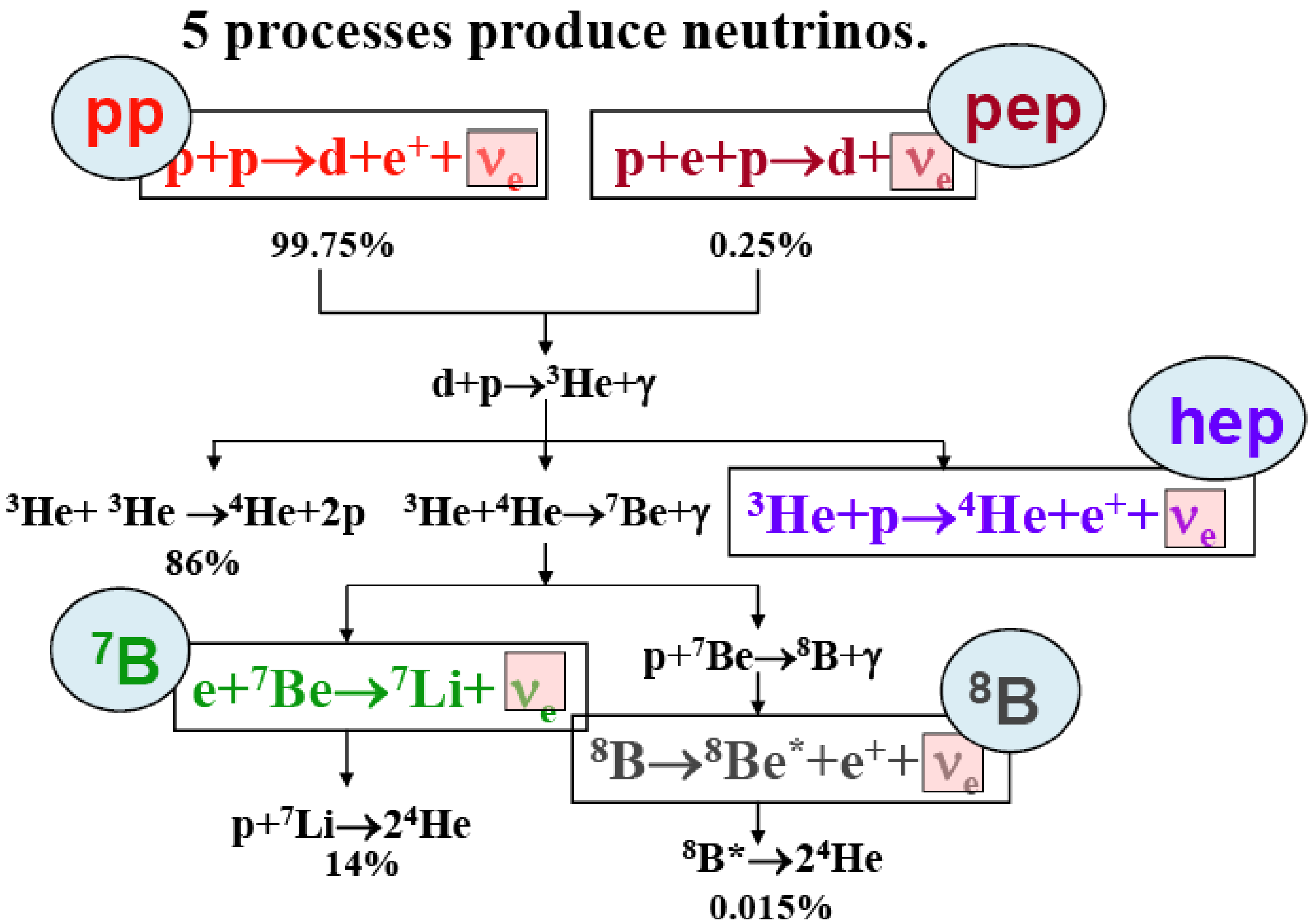
On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum\varphi_{\nu}(\text{solar})\,\sigma_{abs} = (4\pm2)\times10^{-35}\ \text{sec}^{-1}\ (^{37}\text{Cl atom})^{-1},$$

then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background. On the basis of experience

the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

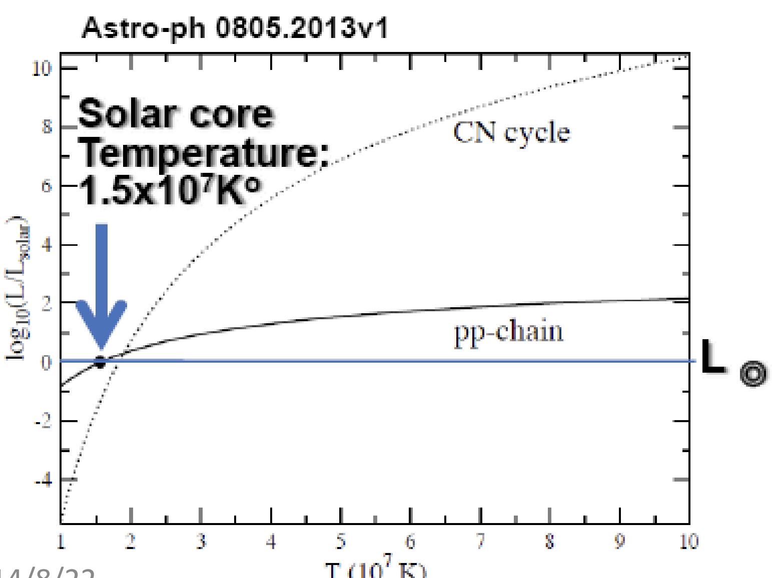
PP-chain

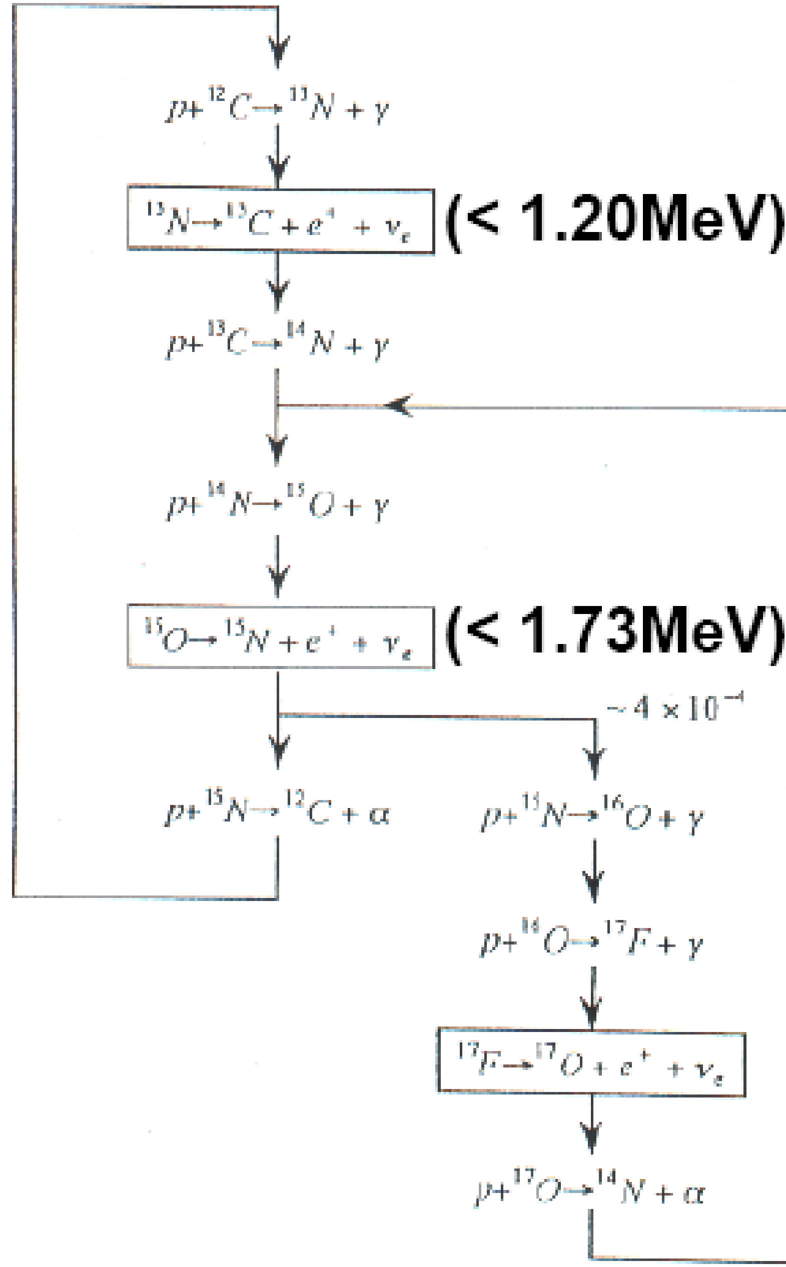


5 processes produce neutrinos.
pp
$p+p \rightarrow d+e^{+}+\nu_e$
pep
$p+e+p \rightarrow d+\nu_e$
99.75%
0.25%
$d+p \rightarrow {}^{3}He+\gamma$
hep
${}^{3}He+{}^{3}He \rightarrow {}^{4}He+2p$
86%
${}^{3}He+{}^{4}He \rightarrow {}^{7}Be+\gamma$
${}^{3}He+p \rightarrow {}^{4}He+e^{+}+\nu_e$
7B
$e+{}^{7}Be \rightarrow {}^{7}Li+\nu_e$
$p+{}^{7}Be \rightarrow {}^{8}B+\gamma$
8B
${}^{8}B \rightarrow {}^{8}Be^{*}+e^{+}+\nu_e$
$p+{}^{7}Li \rightarrow 2\,{}^{4}He$
14%
${}^{8}B^{*} \rightarrow 2\,{}^{4}He$
0.015%

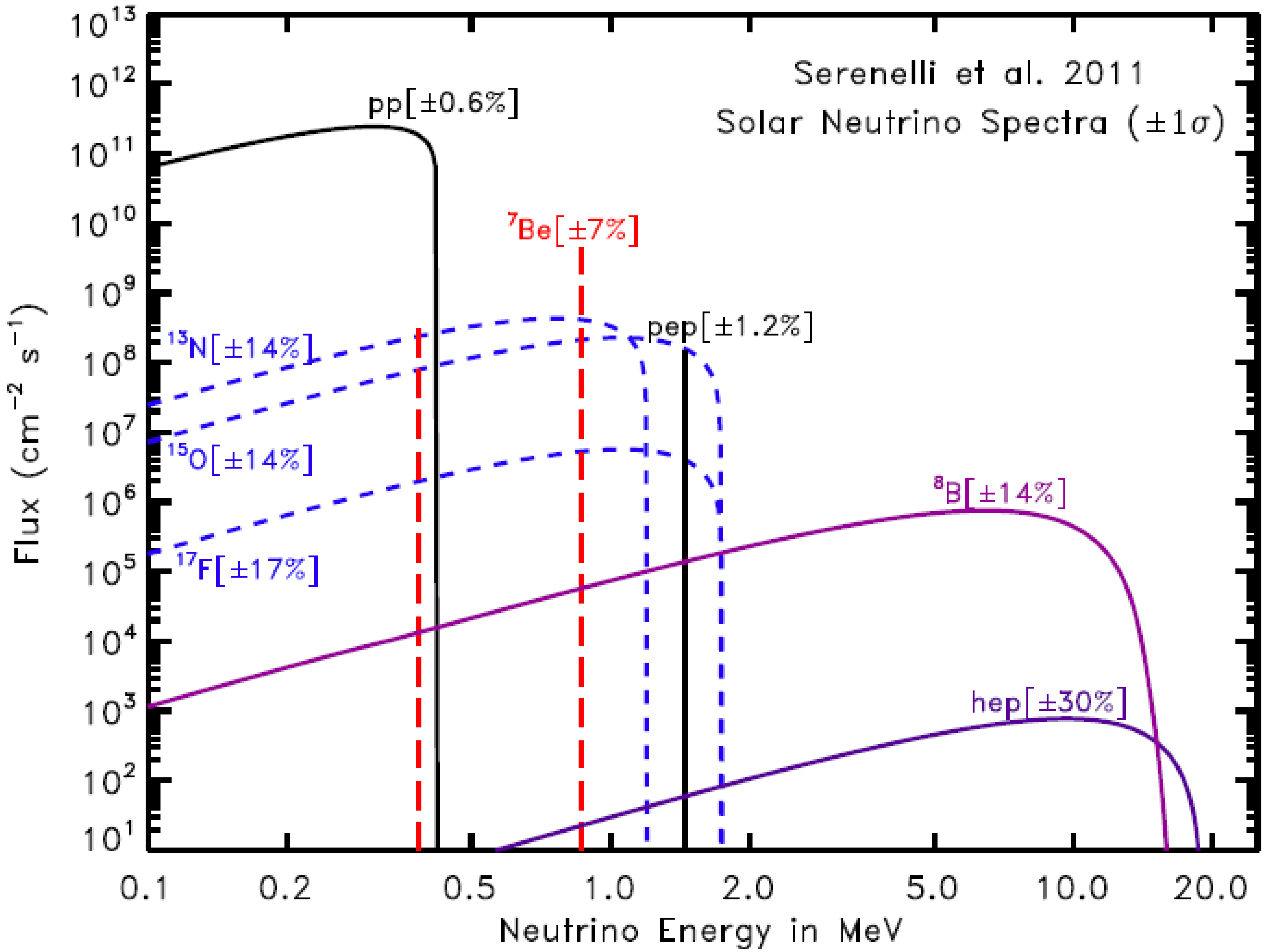
CNO cycle

- Relatively low energy neutrinos ➔ SK/SNO can not see them but Borexino could
- Only 1% solar energy now



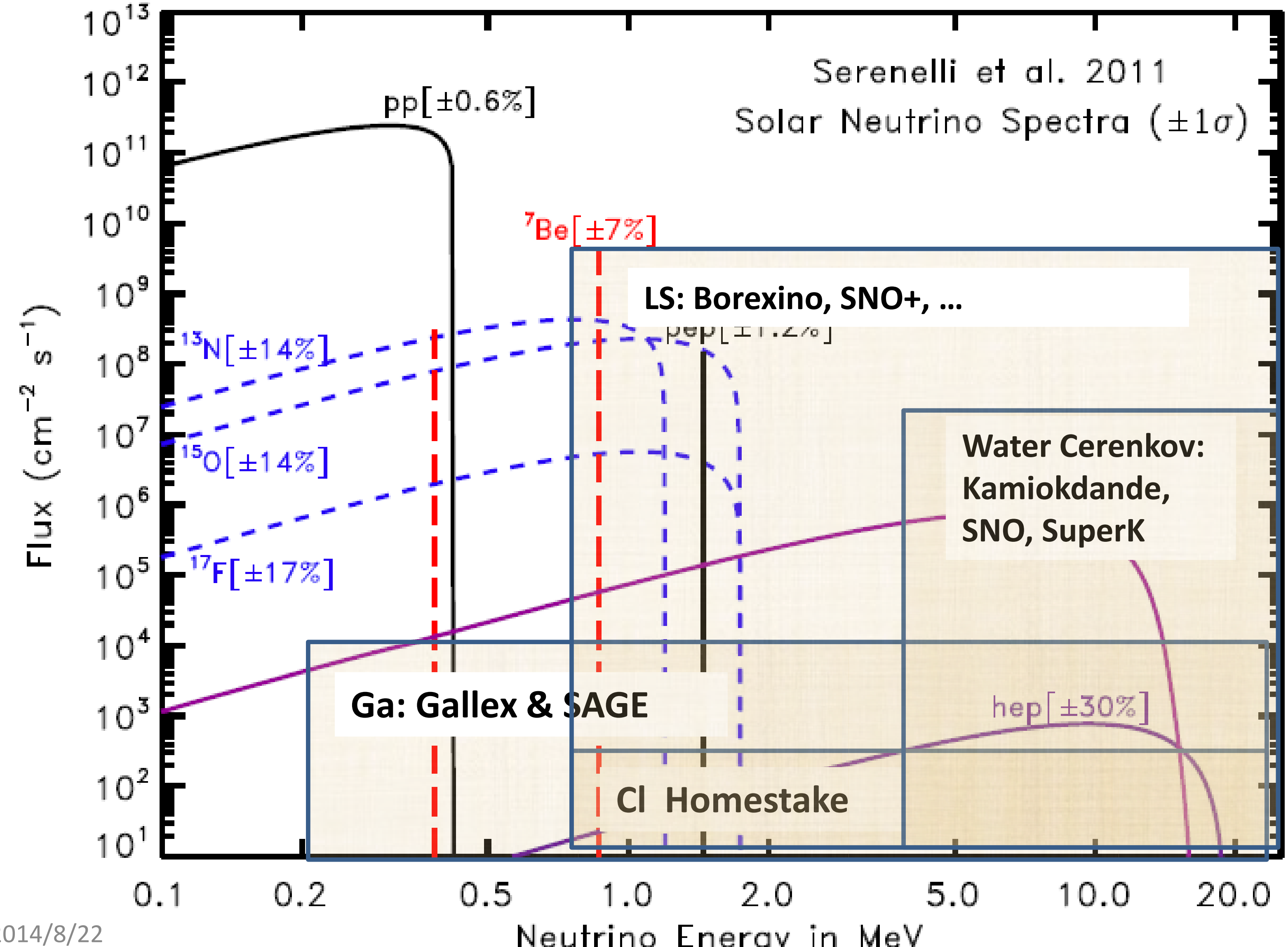


Solar Neutrino： PP-chain and CNO cycle



- PP-chain: mostly seen and dominant
- CNO: to be seen

Solar Neutrino Experiments

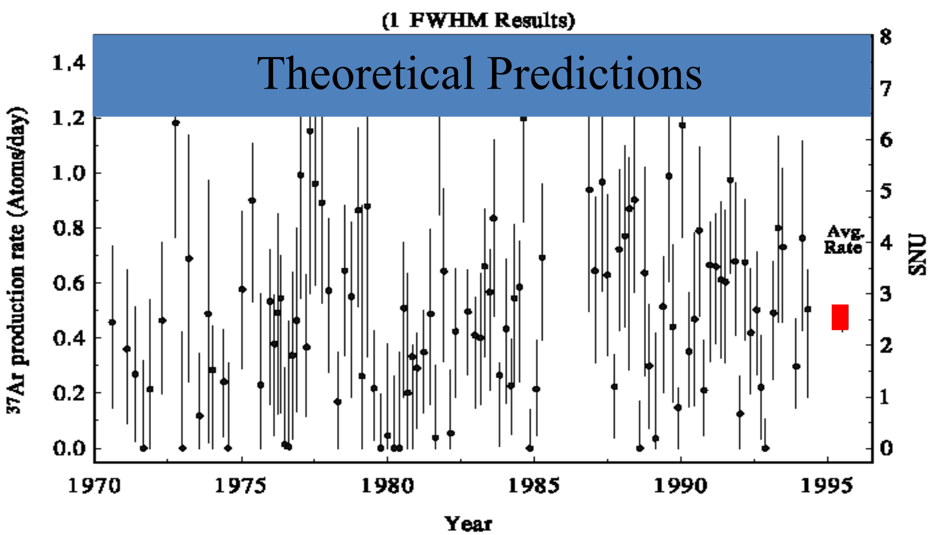


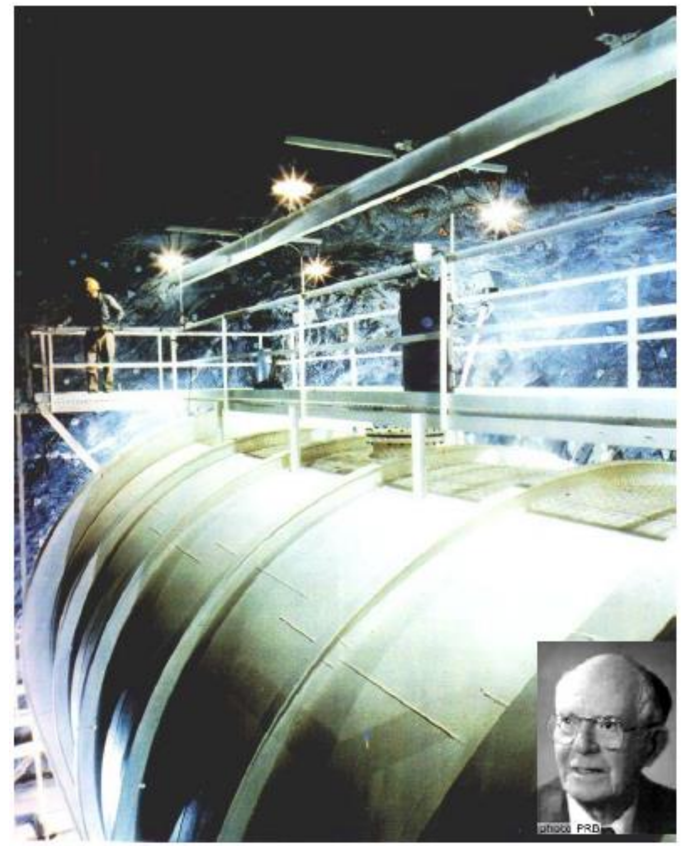
History of Solar Neutrinos

- **First indication of neutrino deficit by Homestake exp. (70's-90's)**
- **Confirmed by many Exp.s ➔ multiple solutions of θ_{12} & ΔM^2_{12}**
- **Solar neutrino oscillation established(00's):**
  - **SuperK: indication of LMA-MSW**
  - **SNO： missing ν_e appeared as $\nu_\mu+\nu_\tau$**
  - **KamLAND： determination of θ_{12} & ΔM^2_{12}**
  - **Standard Solar Model firmly established**
- **Current experiments:**
  - **Borexino**
  - **SuperKamiokande**
- **Future experiment:**
  - **XMASS, SNO+, … LENA, JUNO…**

Homestake Experiment

- 1949 L. Alvarez: neutrino detection by $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Real proposal by J. Bahcall & R. Davis
- Experiment by R. Davis since 1964
- 615t C_2Cl_4 , Overburden: 1500 m
- E_{th}>817 keV, sensitive to ^8B and ^7Be
- Extract and count ^{37}Ar every 3 months
- A total of ~2000 neutrinos over 30 years





R = data/SSM= 0.33±0.3

"Solar neutrino problem": Solar Model ? Experiment ? Neutrino oscillation ?

Confirmation by GALLEX & SAGE

- **Proposed by V.A. Kuzmin and G.T. Zatsepin in 1966**

$$\nu_e + {}^{71}Ga \rightarrow e + {}^{71}Ge$$

  - $E_{th} > 230keV$
  - Attempt to measure pp-neutrinos

- **SAGE in Baksan (1990~):**
  - **60t Metallic Ga**
- **GALLEX in Gran SASSO(1991~)**
  - **60t GaCl3**

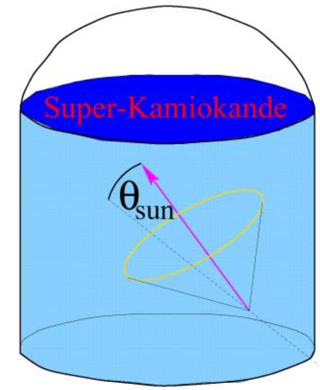
SAGE Site

Chemical extraction of ^{71}Ge

R=0.52±0.07 (SAGE)
R=0.59±0.06 (Gallex)

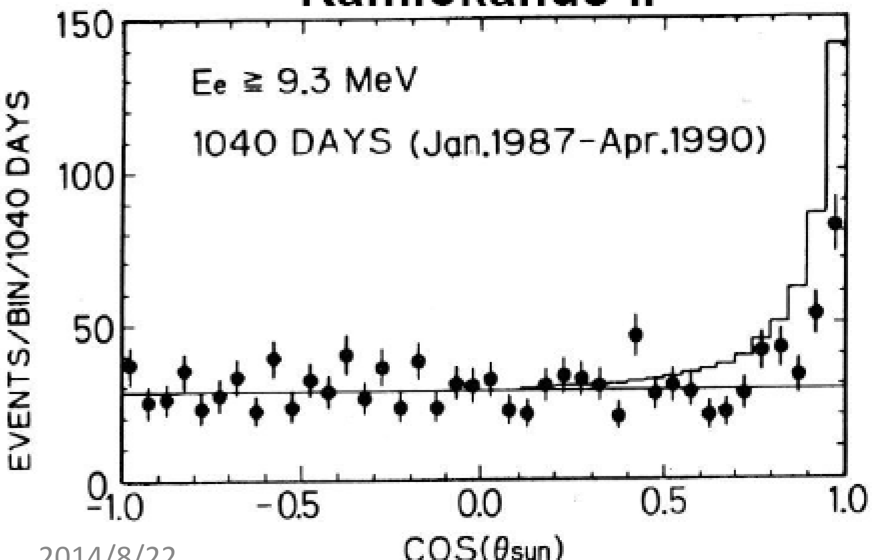
Confirmation by Kamiokande & IMB

- **Kamiokande**
  - 4500t (680t fid.) water
  - $\nu_e + e \rightarrow \nu_e + e$
  - E_{th}=7 MeV(only ^8B)
  - Directional
  - Evidence of ^8B neutrinos

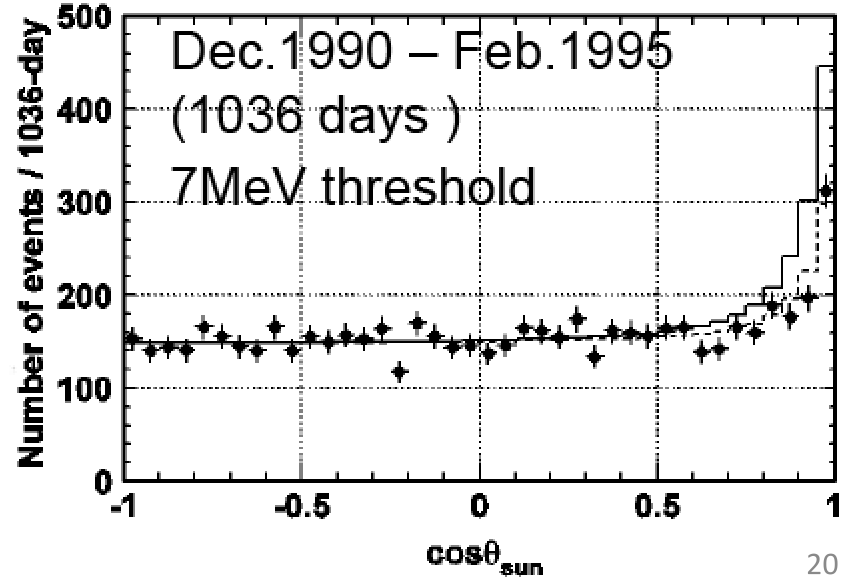


$$\frac{\text{Data}}{\text{SSM}} = 0.55 \pm 0.04 \pm 0.07$$

Kamiokande-II

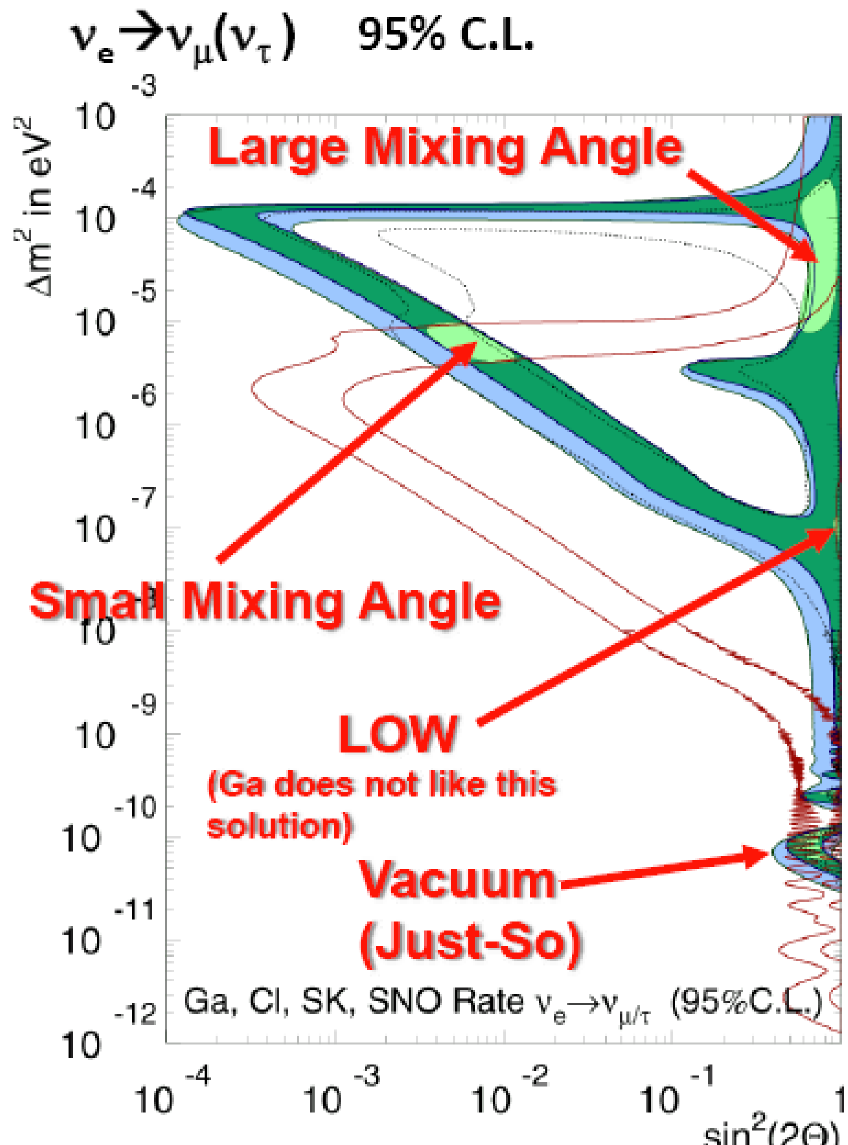


Kamiokande-III



Problems:

- These R's gave four possible solutions to neutrino oscillation
- Standard Solar models (SSM) reliable ?

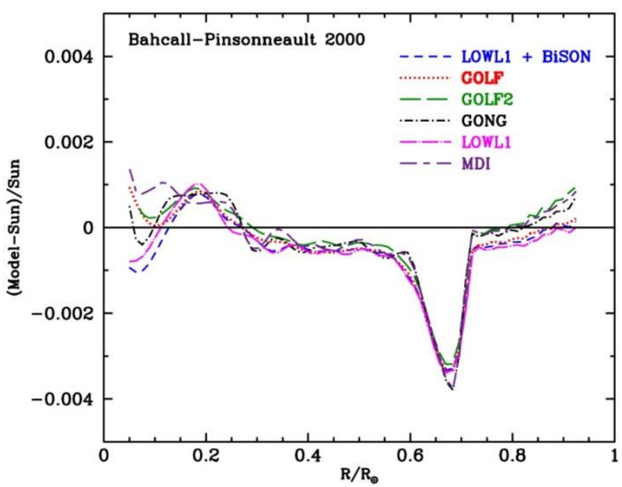


Success of the Standard Solar Model

- Input parameters: mass, age
- Quantities to match: luminosity, radius, metals/hydrogen ratio
- Free parameters: mixing length, chemical composition

- Construct a 1 $M_\odot$ initial model with X_{ini}, Z_{ini}, ($Y_{ini} = 1 - X_{ini} - Z_{ini}$) and a_{MLT}
- evolve it for the solar age $t_\odot$
- match $(Z/X)_\odot$, $L_\odot$ and $R_\odot$ to better than one part in 10^5

- Output: neutrino fluxes, chemical & electron/neutron profile, density & sound speed, helium abundance at surface, …



One example:

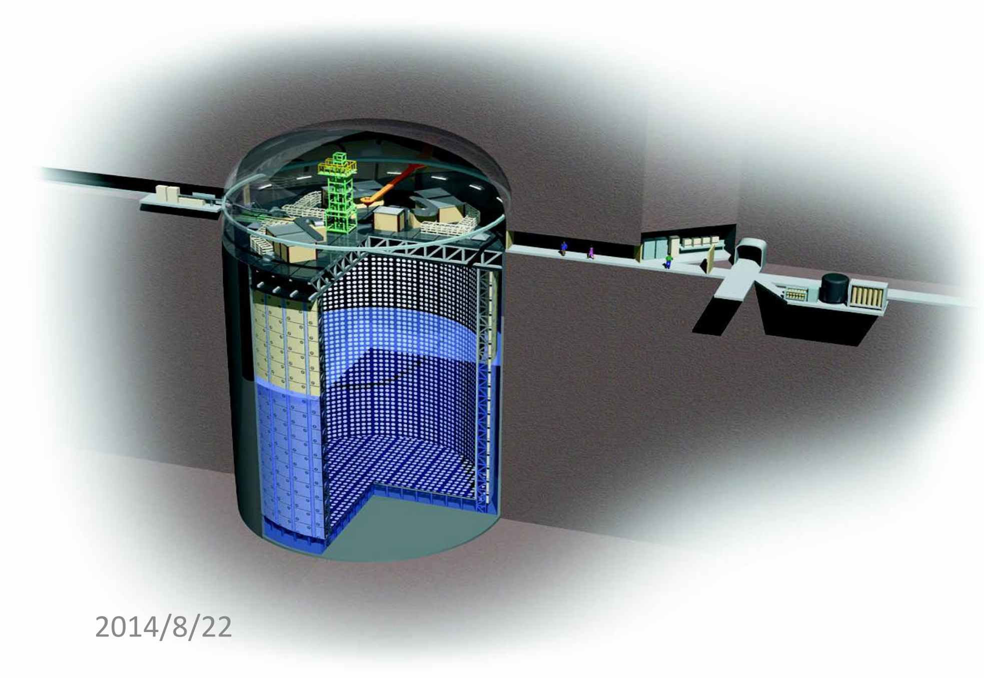
Relative sound-speed difference between observation (through helioseismological model) and standard solar model

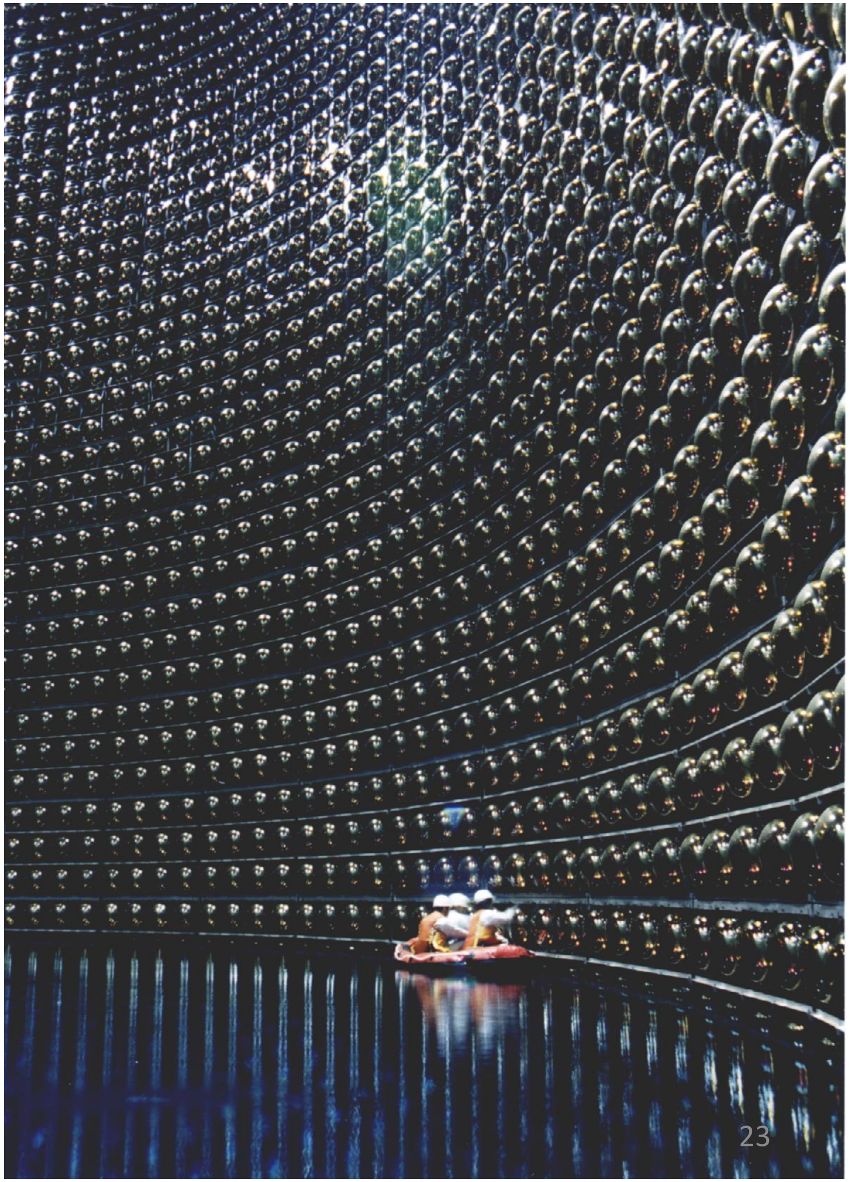
Better than 0.5% !!

Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

SuperKamiokande Experiment

- 50 kt water water Cereknov detector; 22.5 kt fiducial volume
- 40 m diameter and ~ 50 m high
- Operational since May 31st, 1996

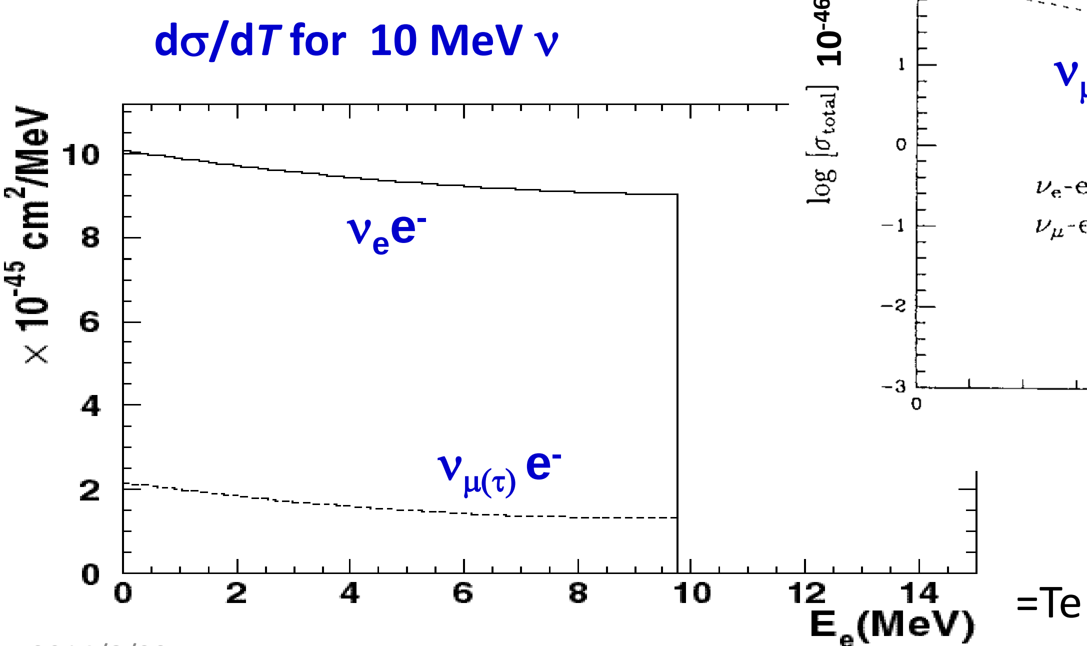


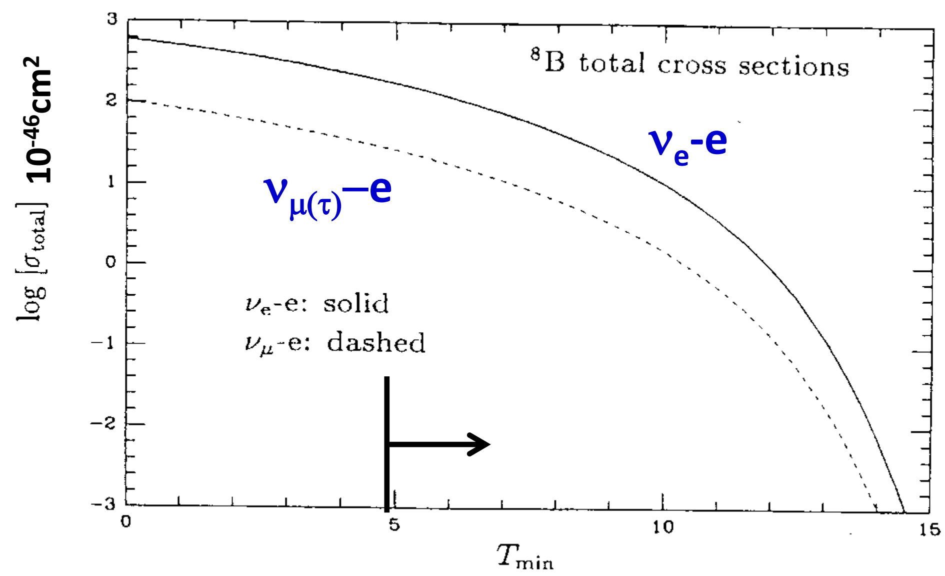


Solar Neutrino detection at SuperK

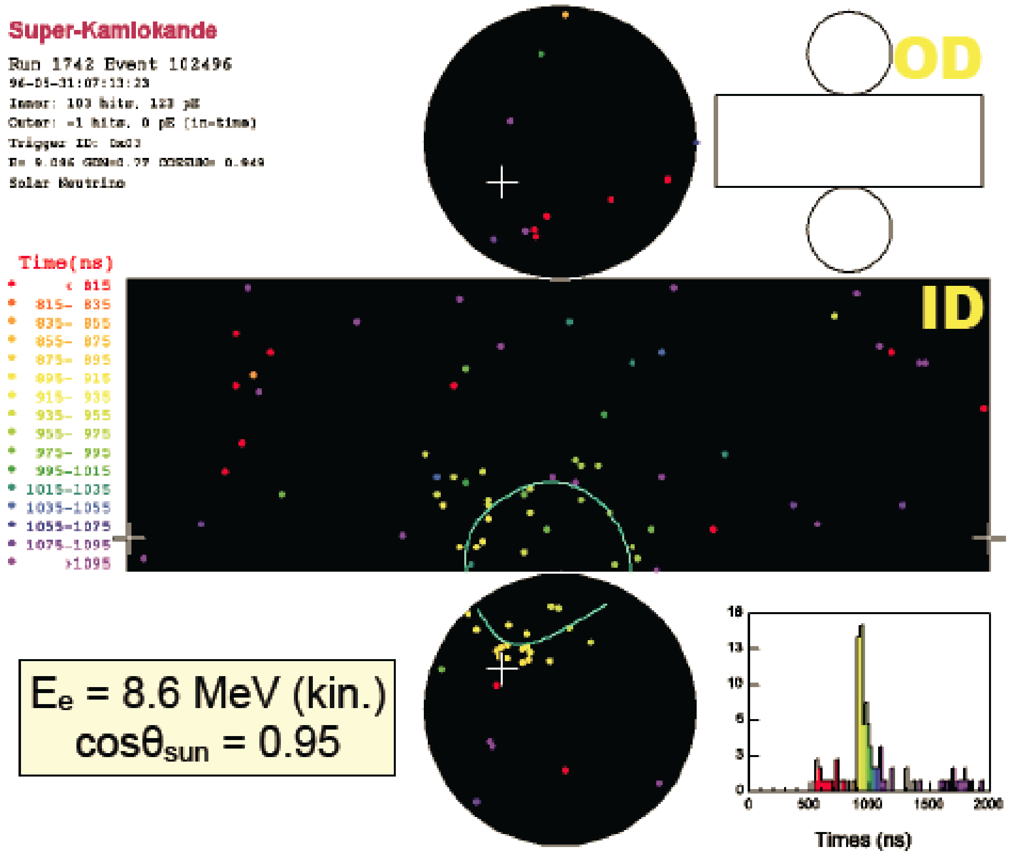
- Neutrino interactions

$$\frac{d\sigma}{dT_e} = \frac{2G_F{}^2 m_e{}^2}{\pi}\left[g_L{}^2 + g_R{}^2\left(1-\frac{T_e}{E_\nu}\right)^2 - g_L g_R \frac{m_e T_e}{E_\nu{}^2}\right]$$

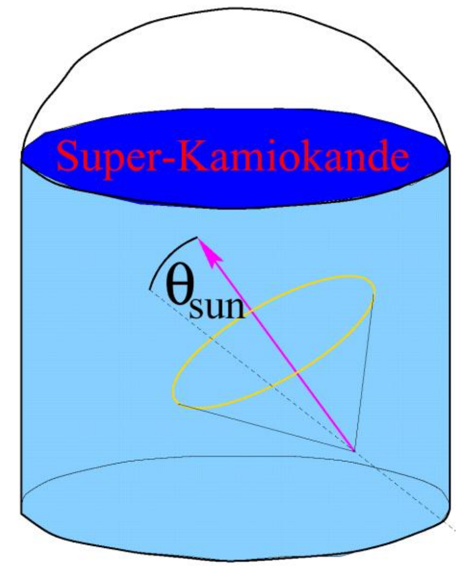


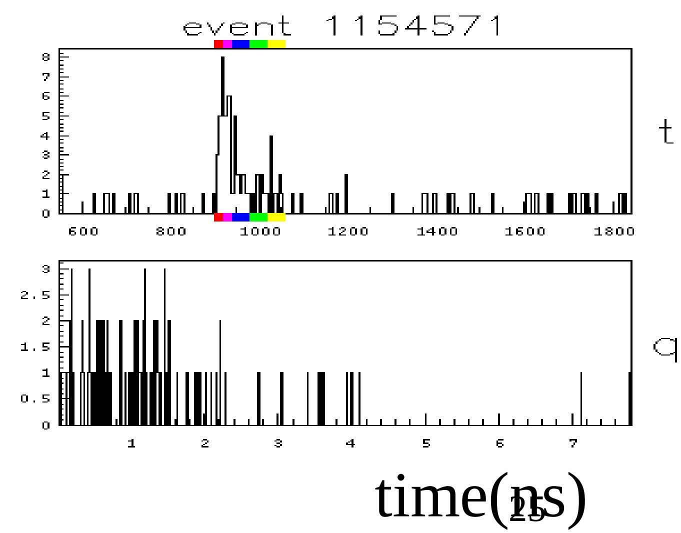


Signal: Electrons Scattered by Neutrinos



E_e = 8.6 MeV (kin.)
$\cos\theta_{sun}$ = 0.95

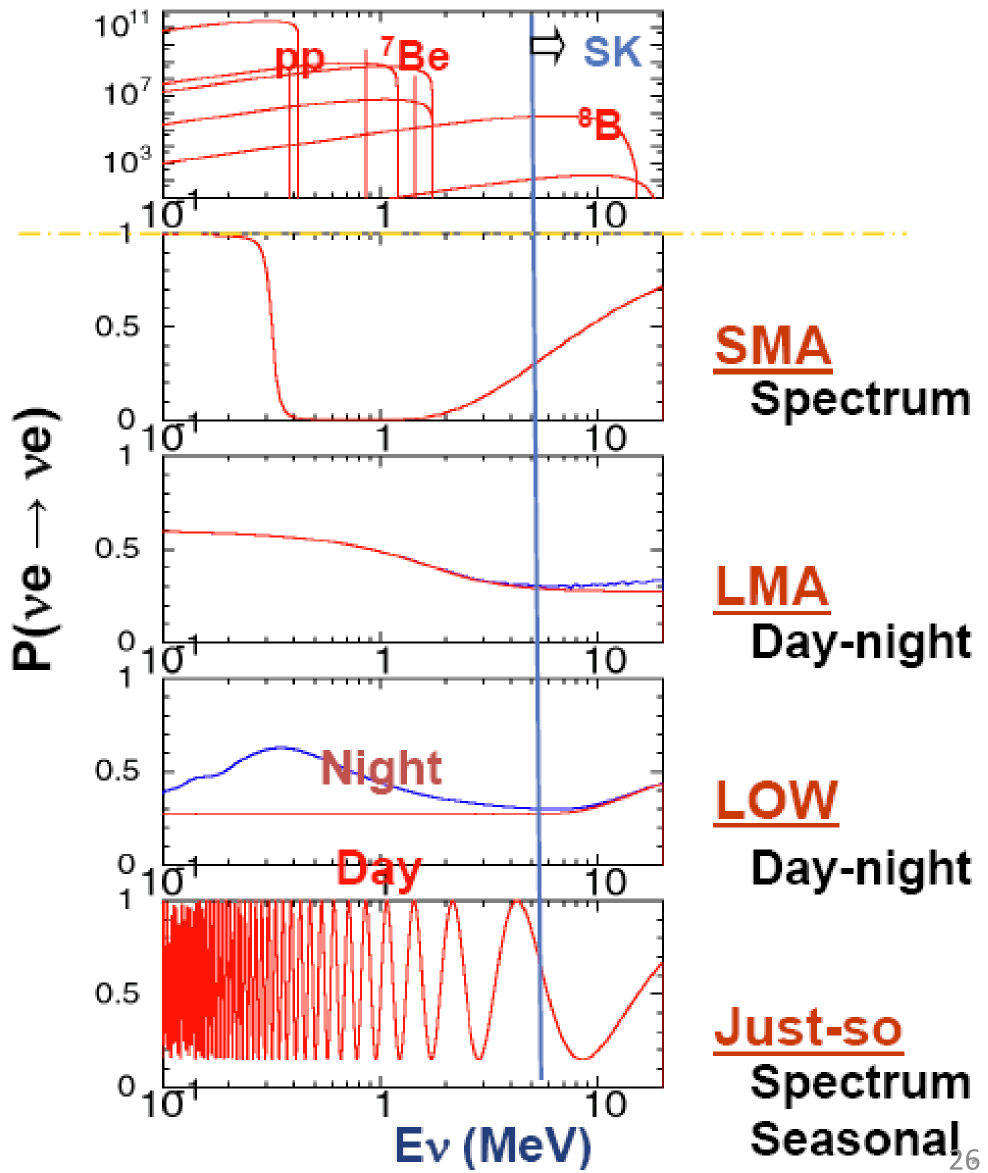




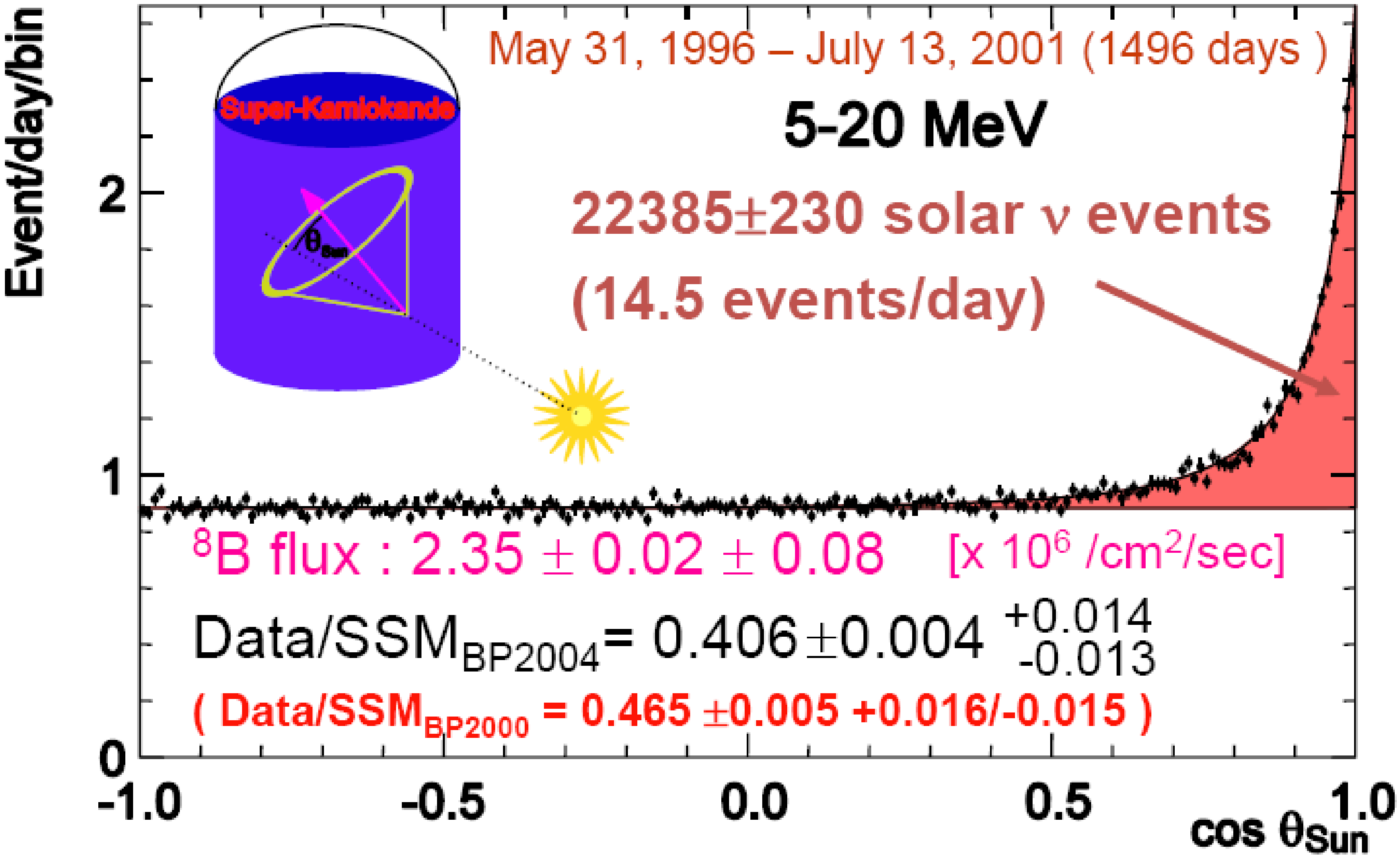
- Timing information ➔ vertex
- Ring pattern ➔ direction
- PMT hits ➔ energy

What SuperK can do ?

- **Flux independent analysis:**
  - Day-night effects
  - Seasonal variation
  - Spectrum distortion



SuperK Results(SK-I)

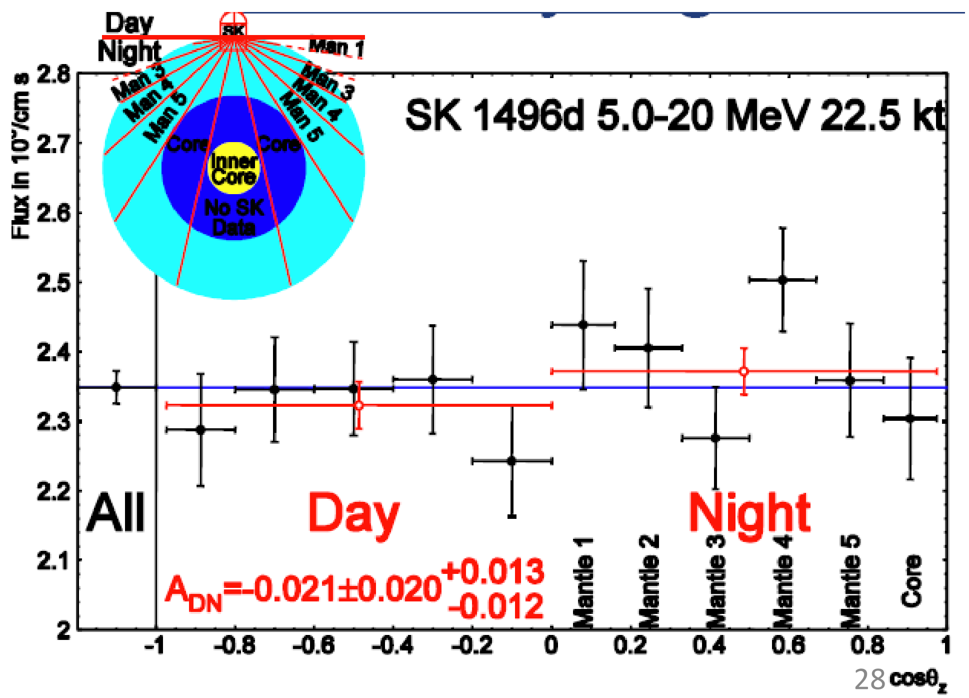


SuperK results

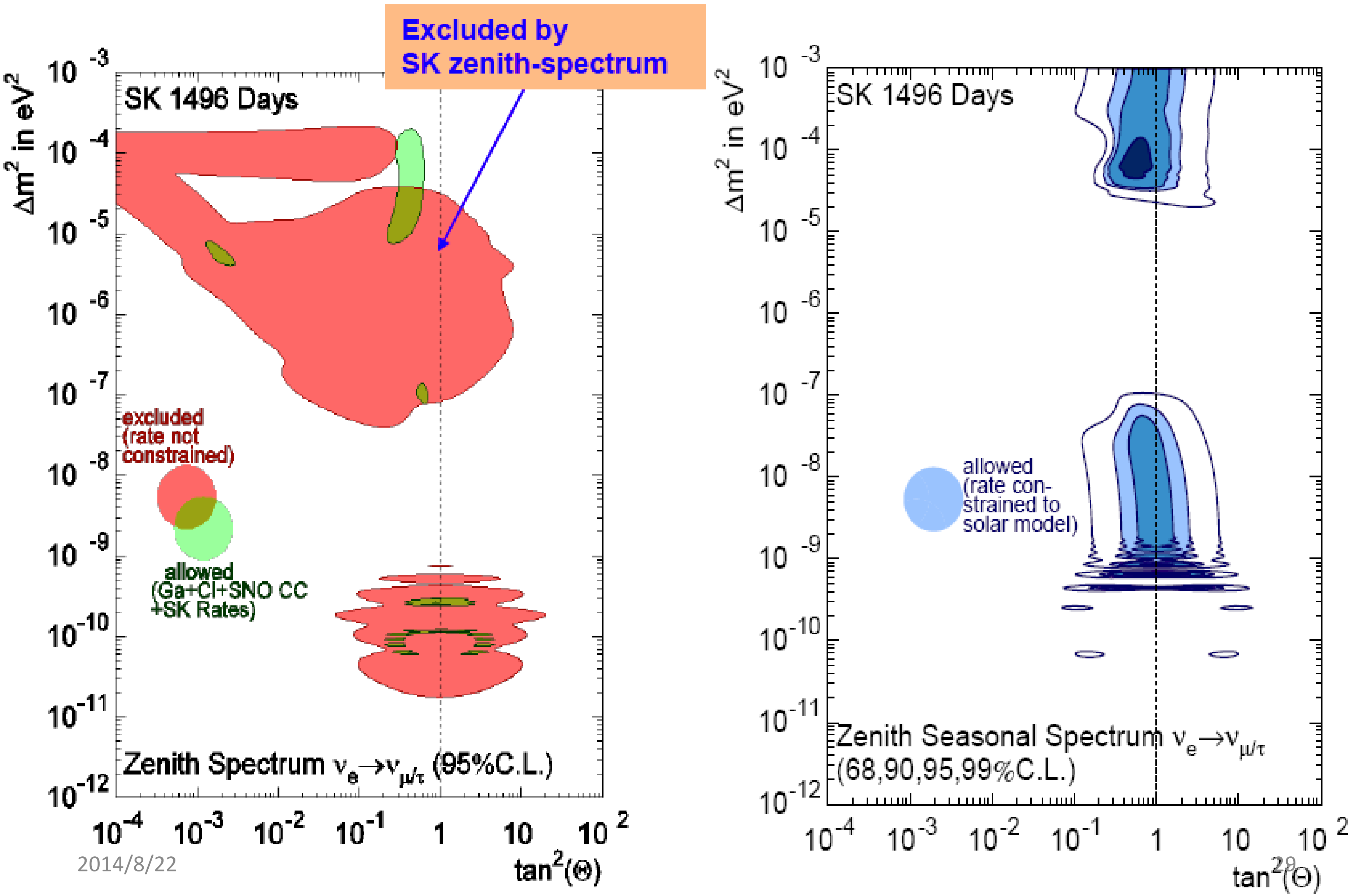
- No sizable day/night effect
- No sizable seasonable effect
- No sizable spectrum distortion

Disfavor SMA & VO solution

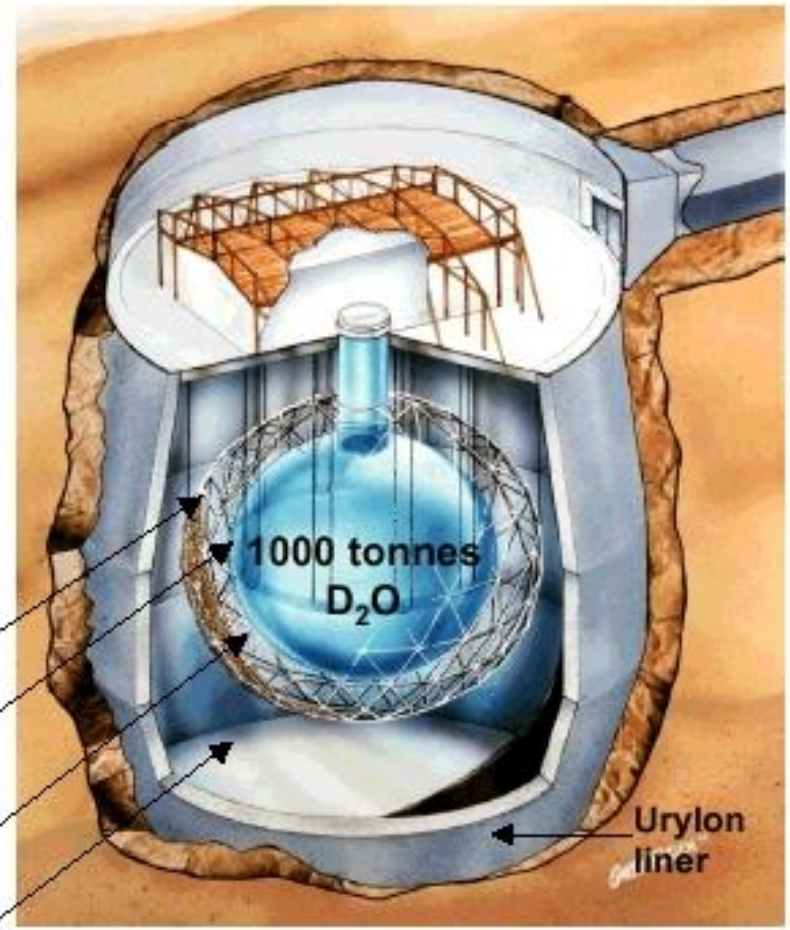
Mixing angle is large !



SK select large mixing



SNO Experiment



Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 μ day^{-1})

Nucl. Inst. and Meth. A449, p172 (2000)

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^{8}B decay via the neutral-curent reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.

Neutrino Detection in SNO

Charged-Current (CC)

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

$E_e \sim E_\nu$, ~isotropic

$\Rightarrow \nu_e$

Neutral-Current (NC)

$\nu_x + d \longrightarrow \nu_x + n + p$

$n + d \rightarrow t + \gamma$, E_g = 6.25 MeV

$\nu_x = \nu_e + \nu_\mu + \nu_\tau \Leftarrow$

Elastic Scattering (ES)

$\nu_x + e^- \longrightarrow \nu_x + e^-$

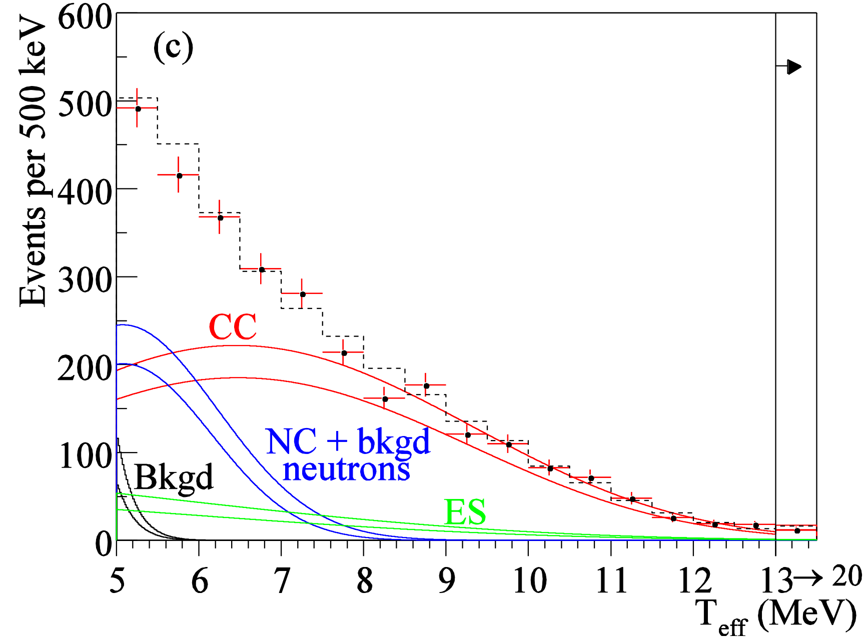
Forward Peaking

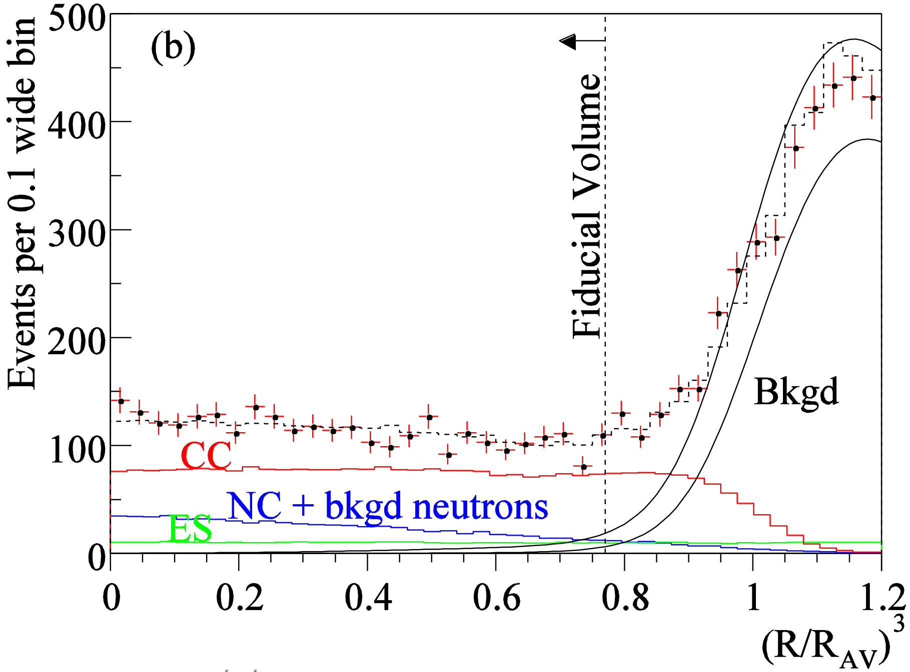
$\Rightarrow \nu_x = \nu_e + (\nu_\mu + \nu_\tau)/6$

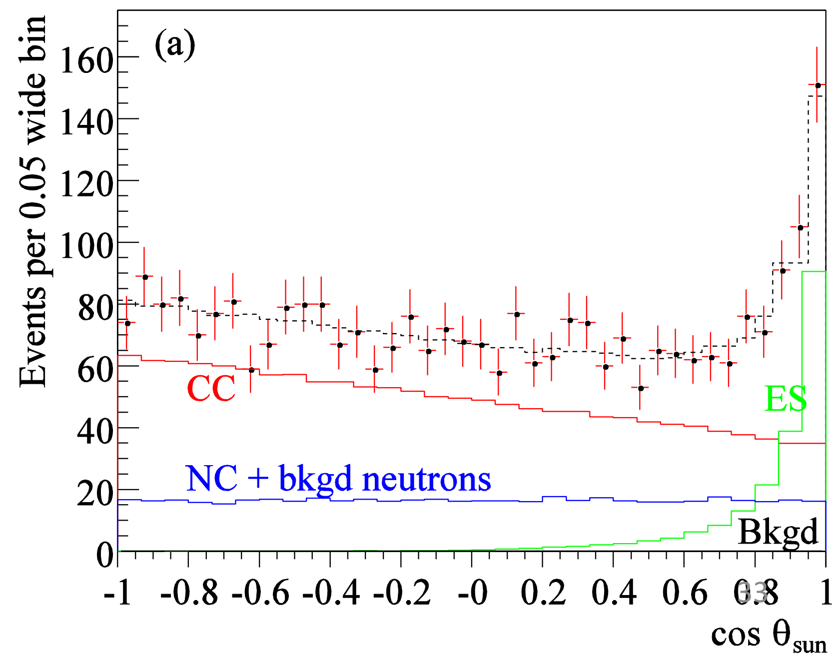
Shape Constrained Signal Extraction Results

#EVENTS

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

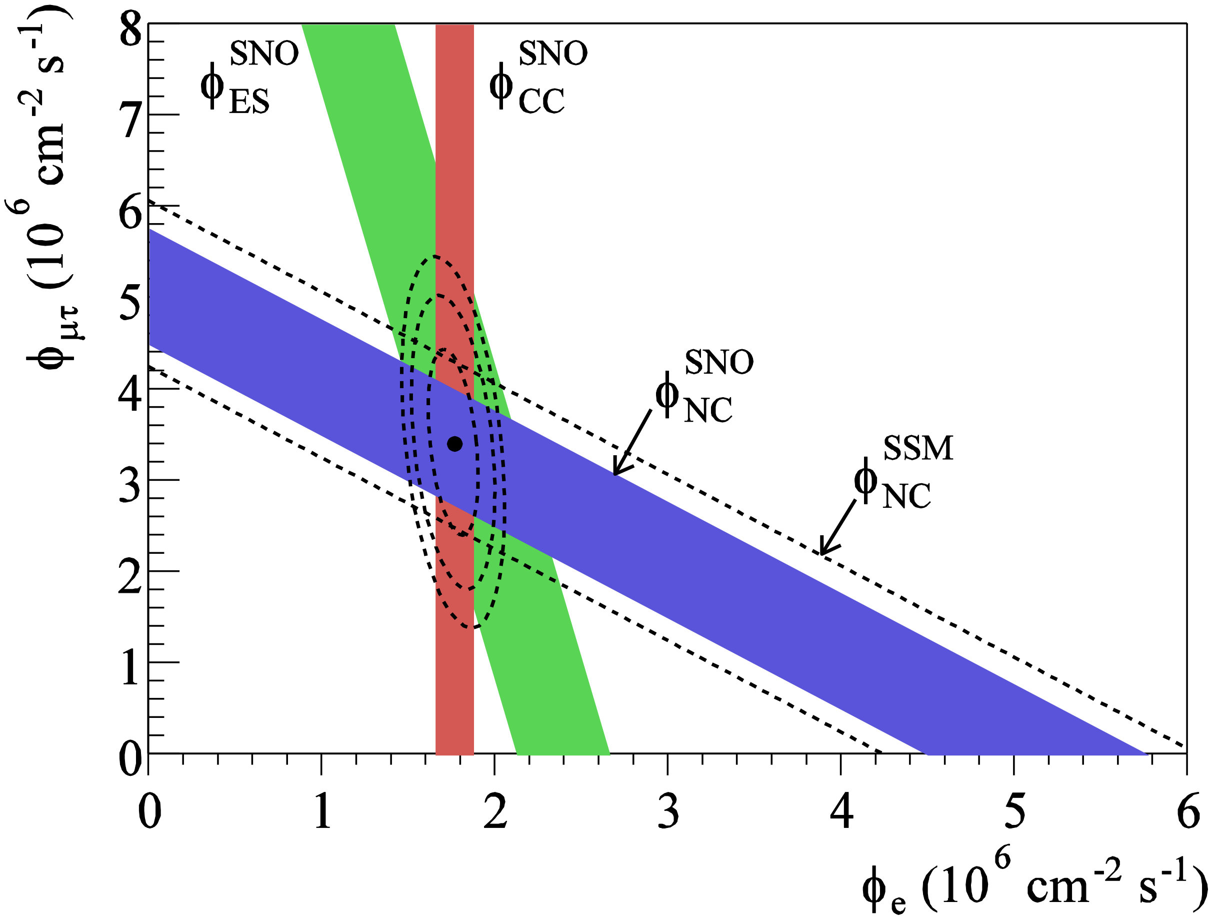






SNO observation: $\nu_{\mu\tau}$ Flux

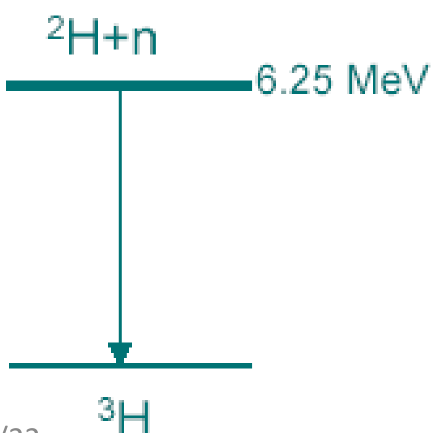
$\Phi_{ssm} = 5.05 \,^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09 \,^{+0.44}_{-0.43} \,^{+0.46}_{-0.43}$

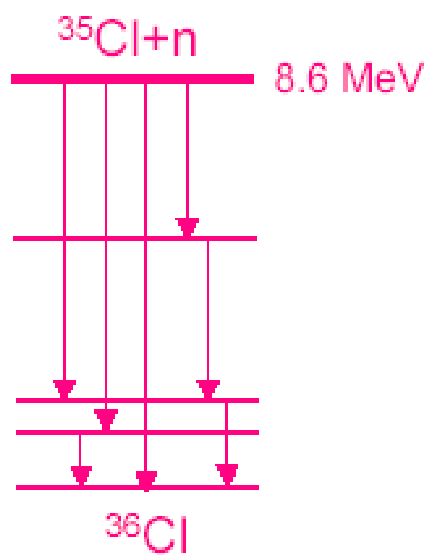


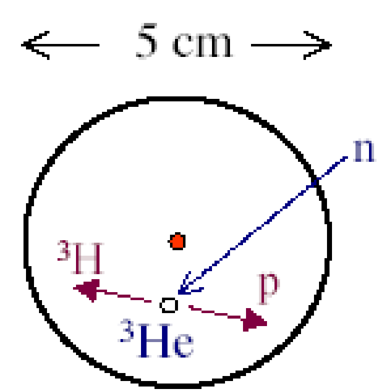
Strong evidence of flavor change ν's

Three neutron detection methods

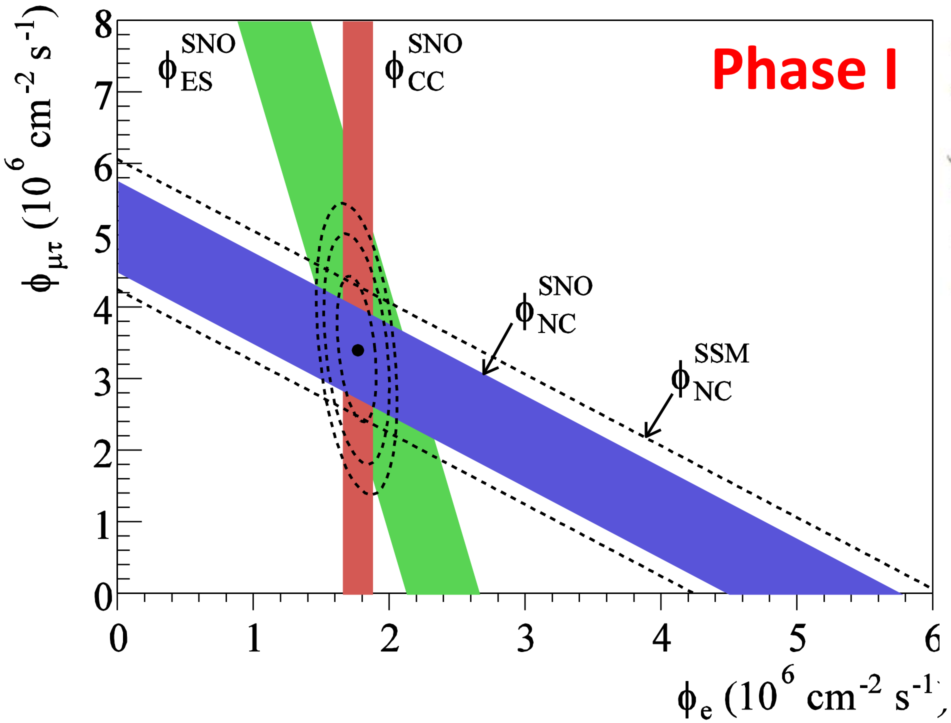
Phase I (D_2O)	Phase II (salt)	Phase III (^3He)
Nov. 99 - May 01	July 01 - Sep. 03	Summer 04 - Dec. 06
n captures on $^2H(n, \gamma)^3H$ σ = 0.0005 b Observe 6.25 MeV γ PMT array readout Good CC	2 t NaCl. n captures on $^{35}Cl(n, \gamma)^{36}Cl$ σ = 44 b Observe multiple γ's PMT array readout Enhanced NC	40 proportional counters $^3He(n, p)^3H$ σ = 5330 b Observe p and ^3H PC independent readout Event by Event Det.

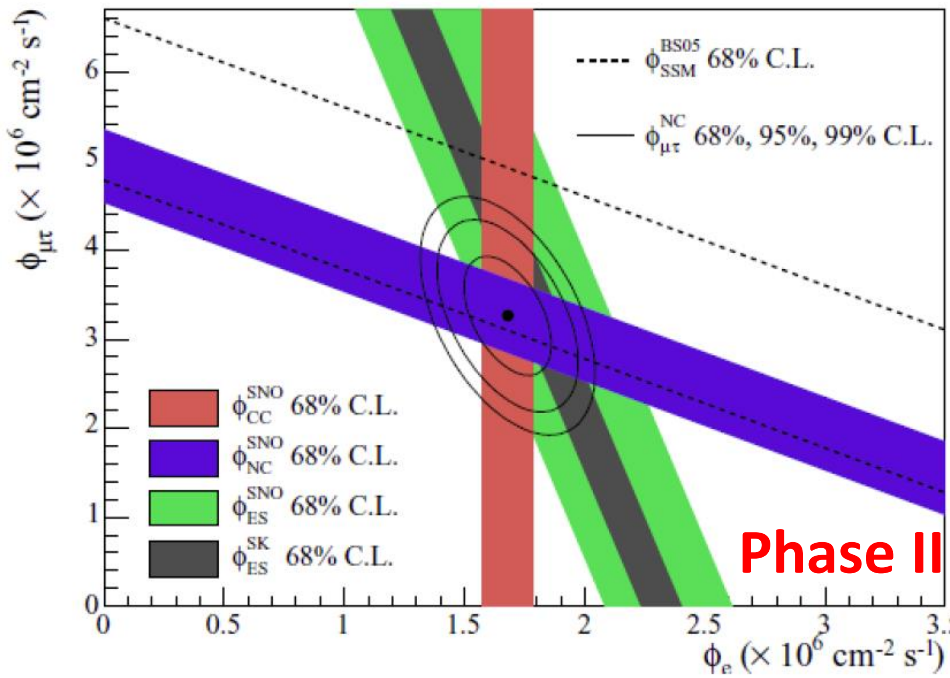


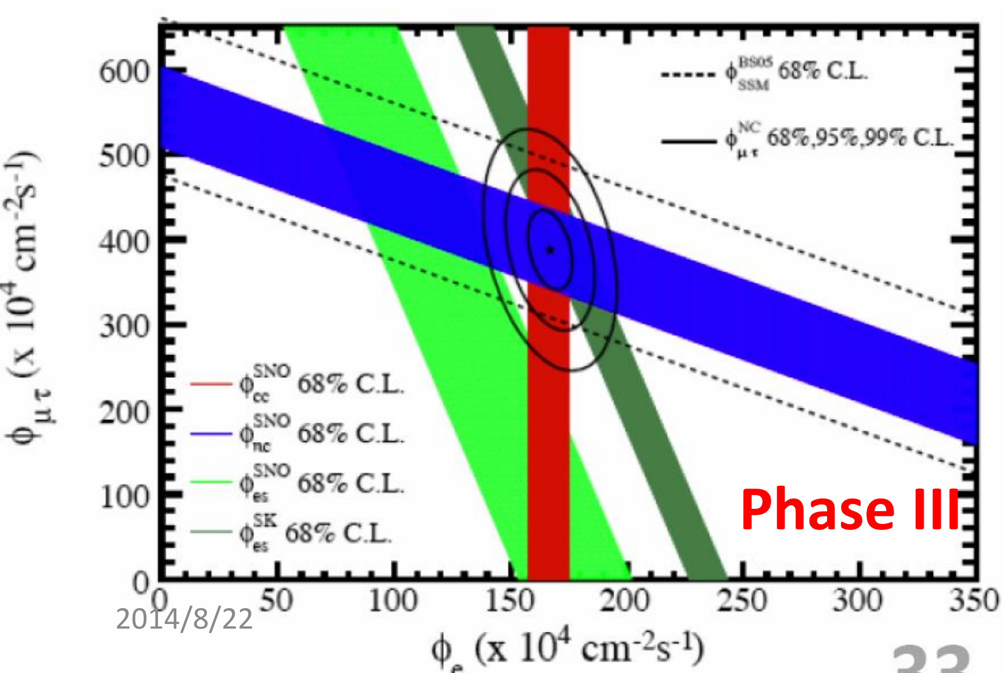




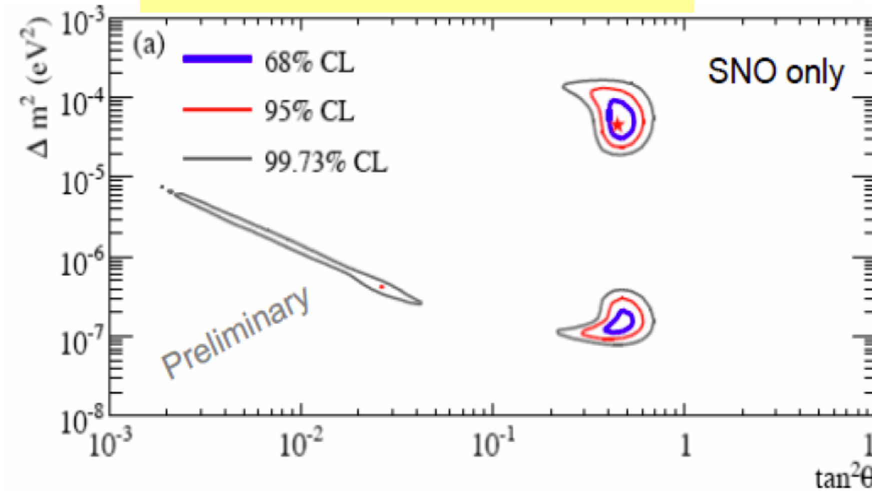
$n + {}^3He \rightarrow p + {}^3H$



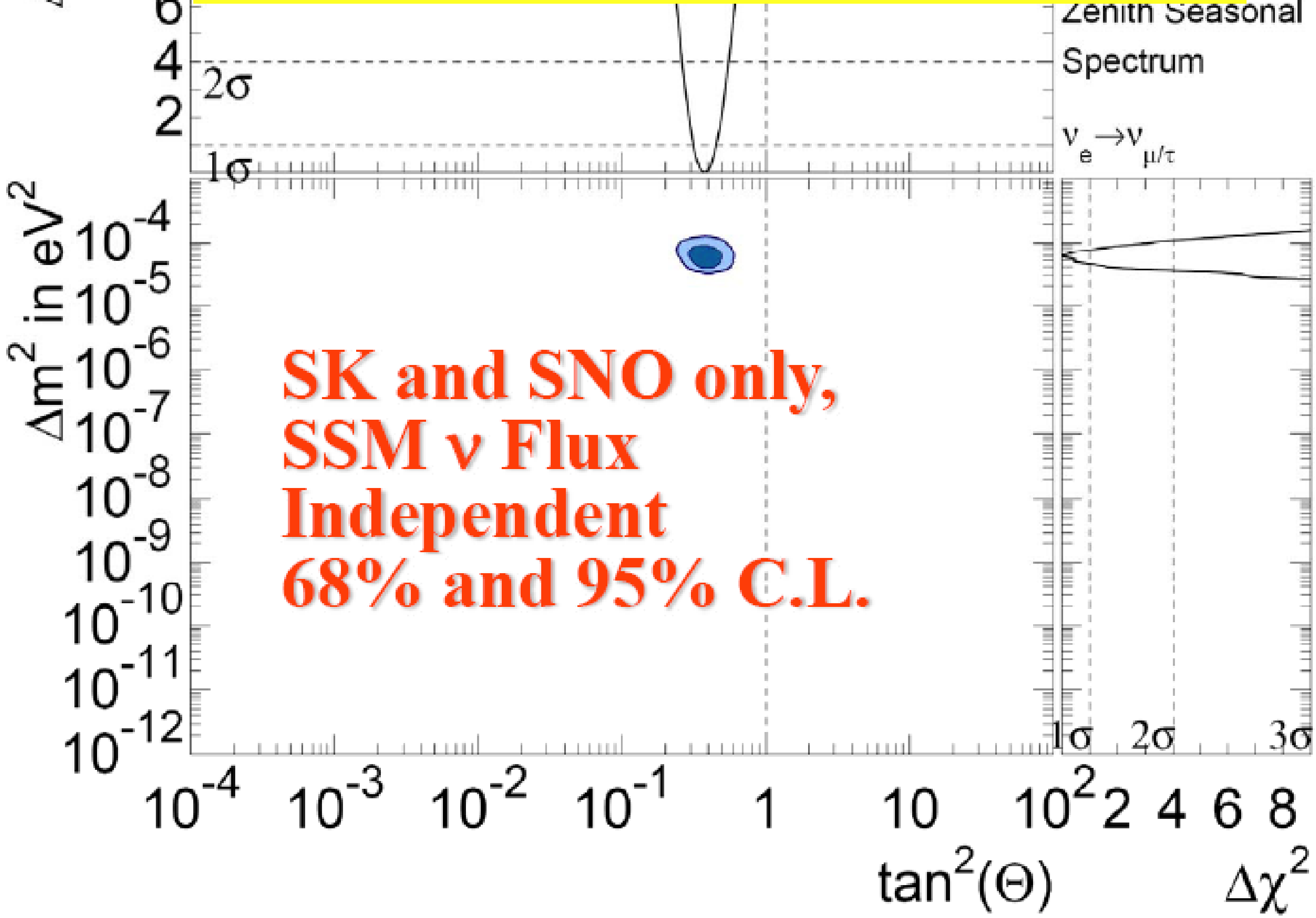




SNO only, Phase I+II+III



Oscillation Parameters (SNO+SK)



SK+SNO (Salt) best

($\tan^2\theta$=0.38, Δm^2=6.0x10^{-5}eV^2)

KamLAND

1000t scintillators

Shielding:

3000 MWE/3m Water

180 km baseline

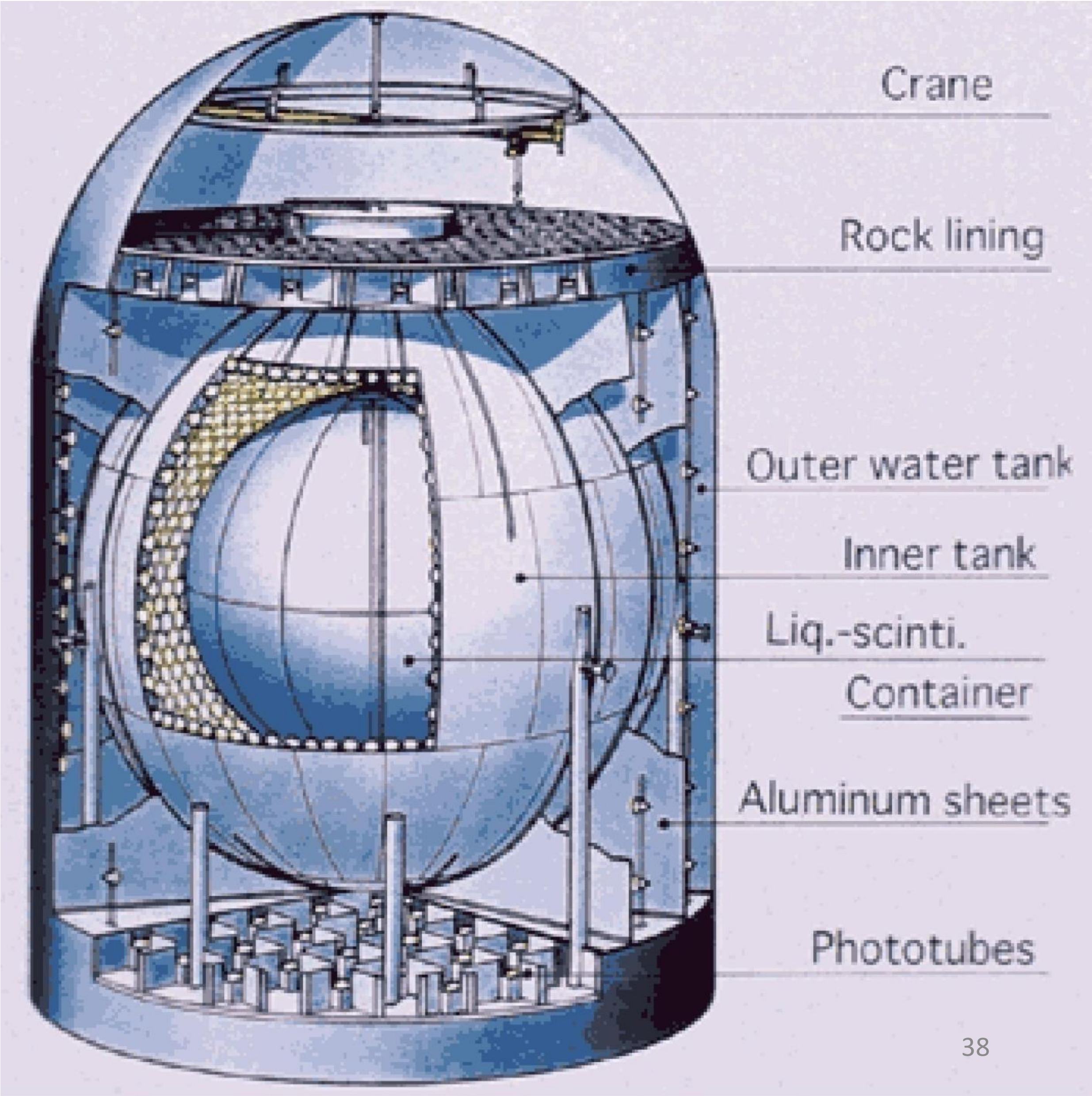
Signal: ~0.5/day

Eff. ~40%

BK:

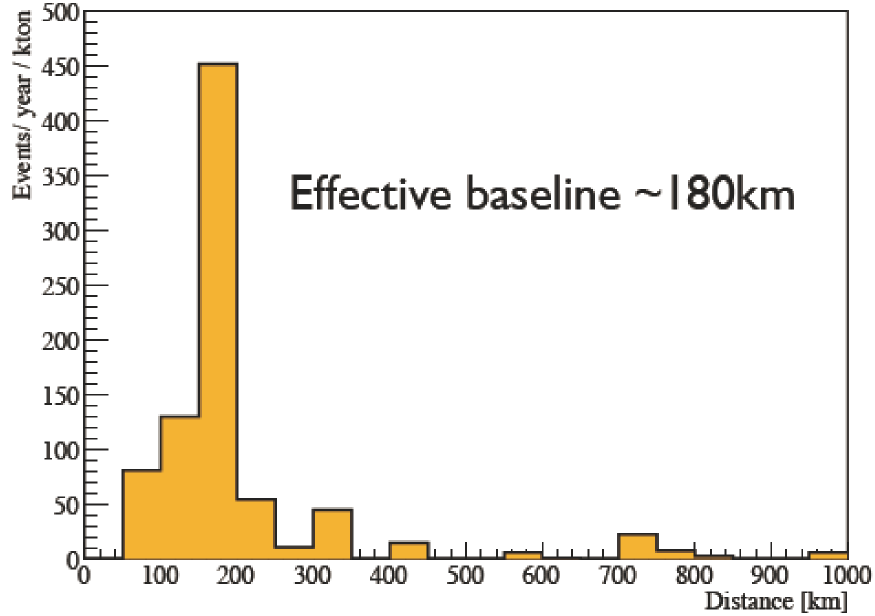
corr.: ~0.001/day

uncorr. ~0.01/day



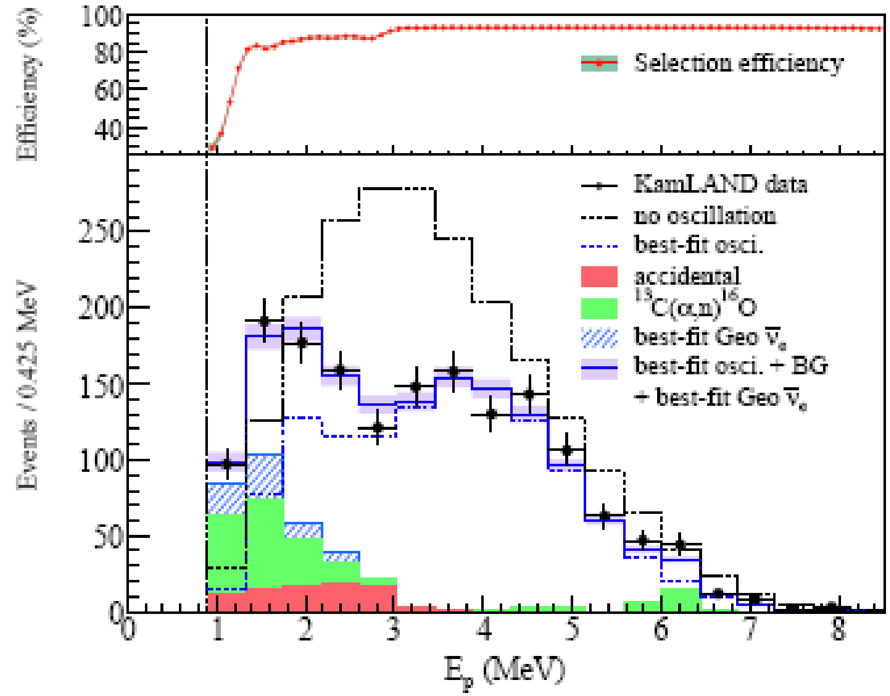
Neutrino Reactors nearby Kamioka

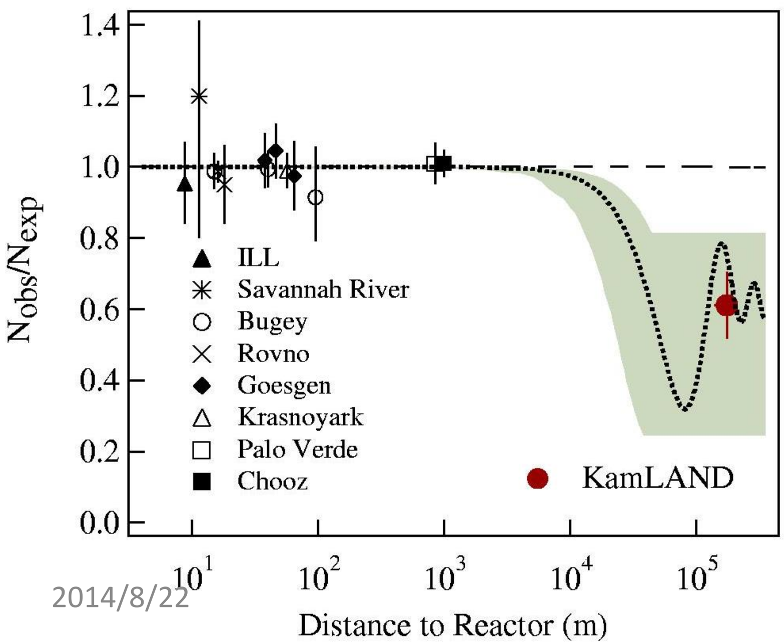
70 GW (7% of world total) is generated at 130-220 km distance from Kamioka

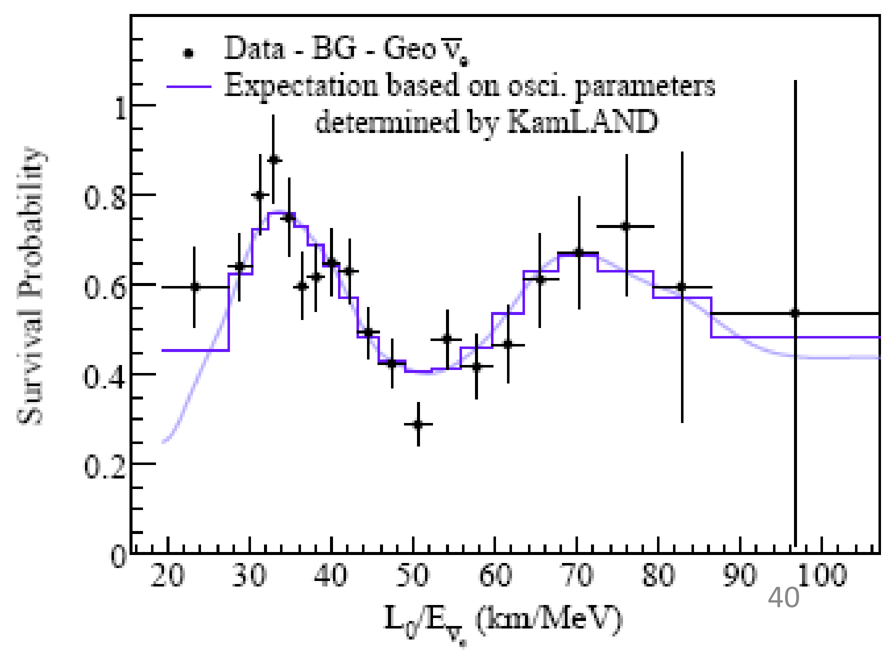


Oscillation signal

- Rate
- Energy spectrum
- L/E plot

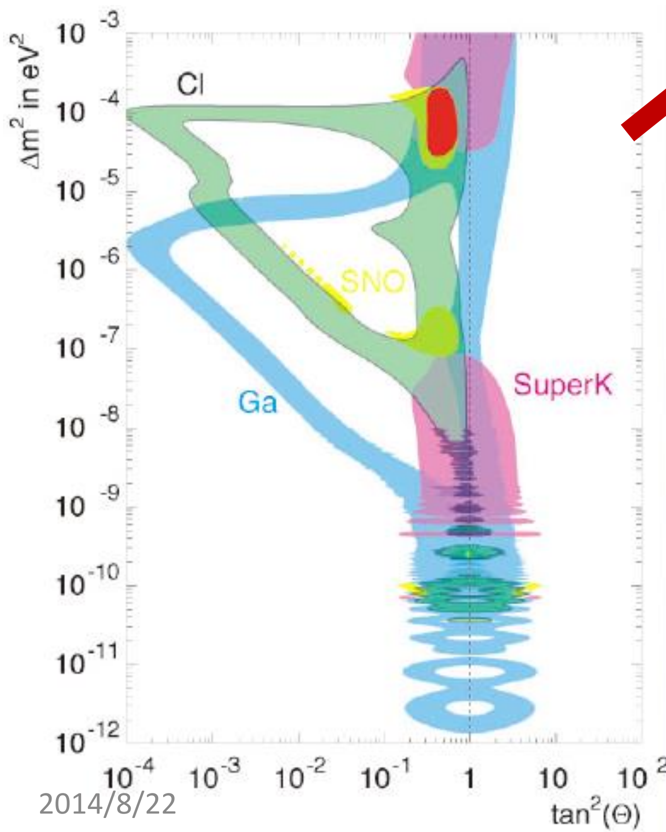


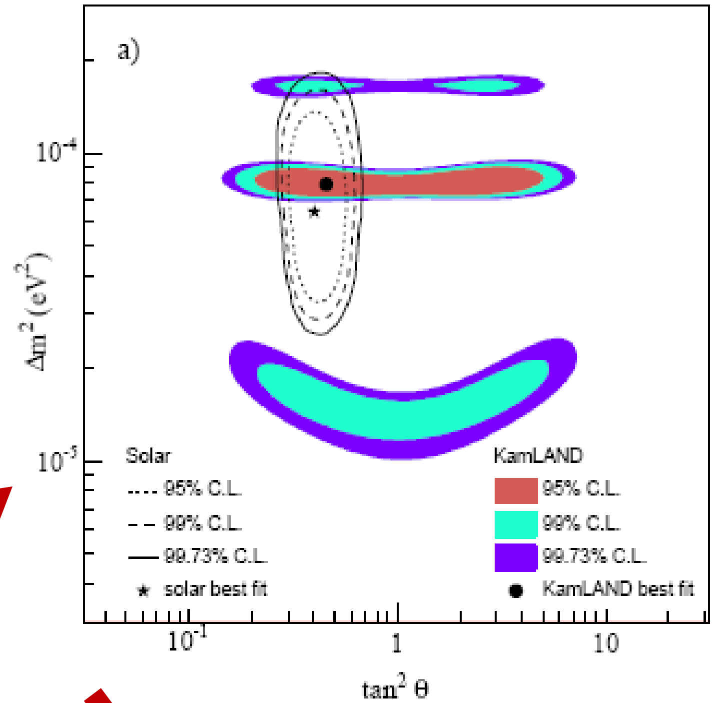


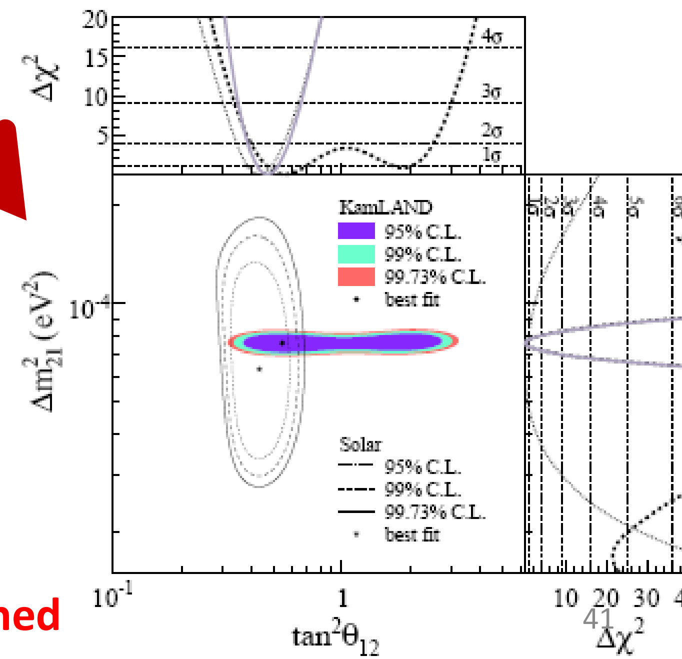


KamLAND Results

- PRL90(2003)021802
- PRL94(2005)081801
- PRL100(2008)221803

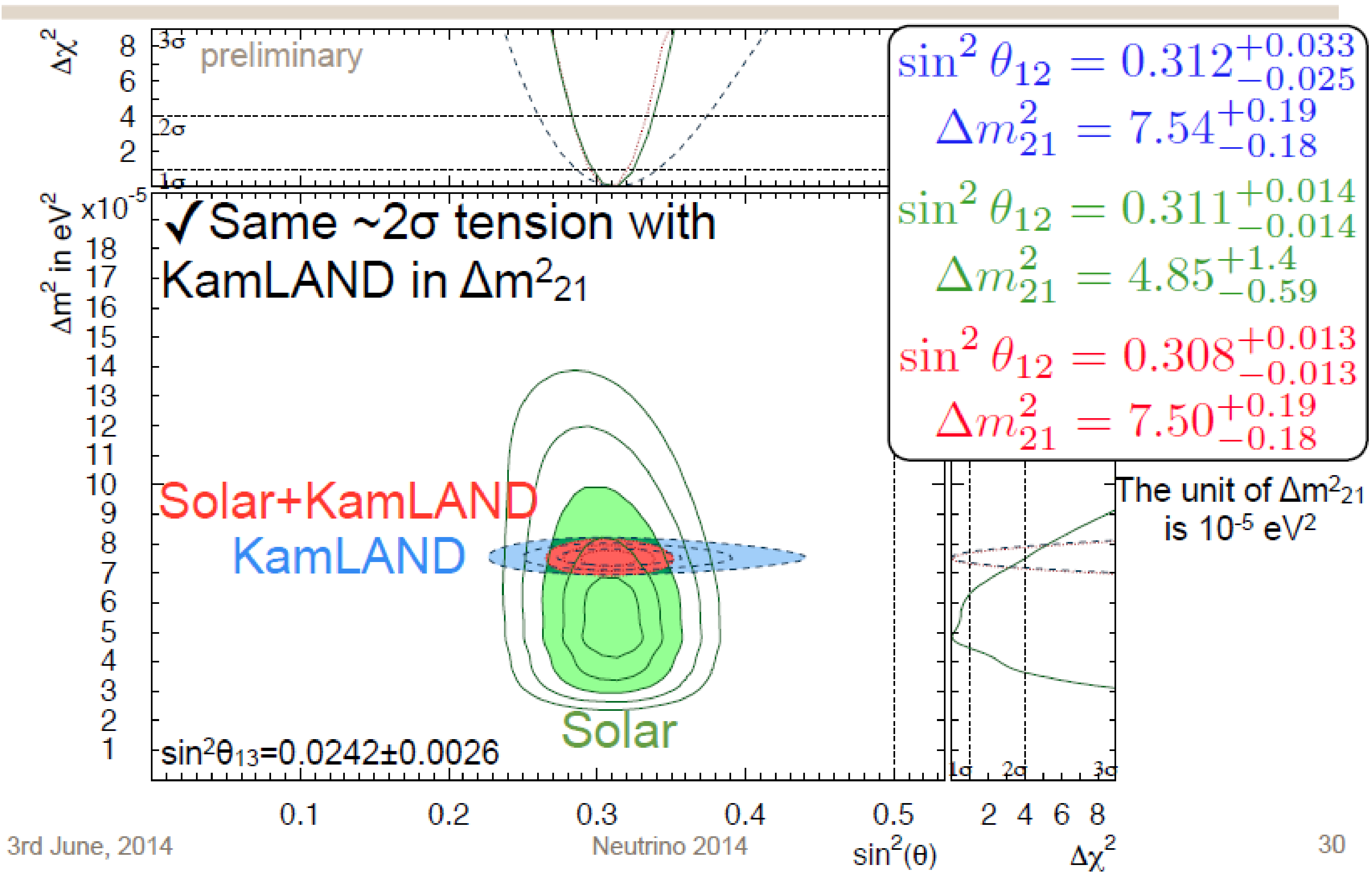






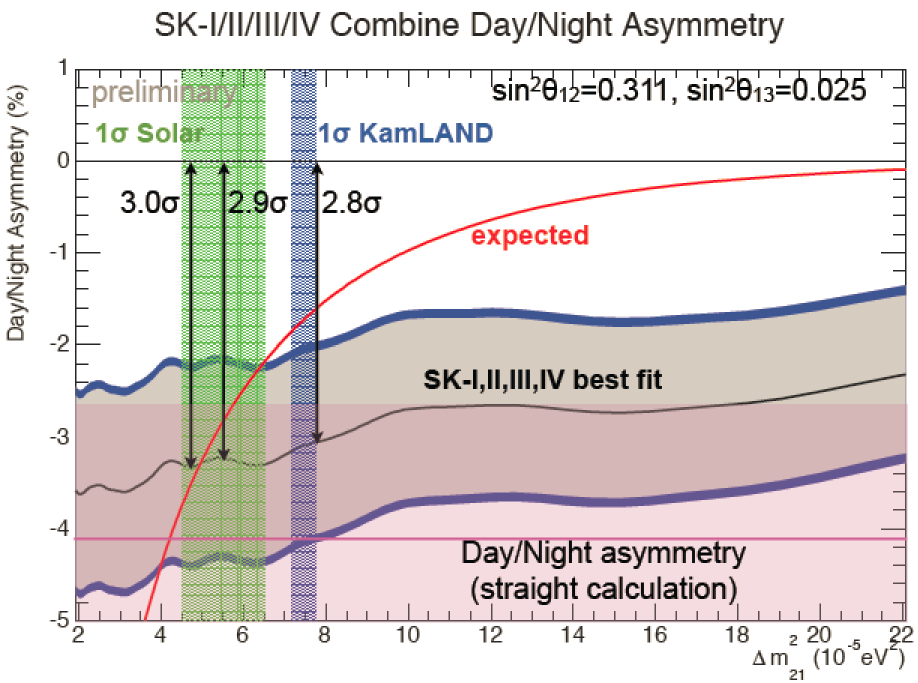
LMA firmly established

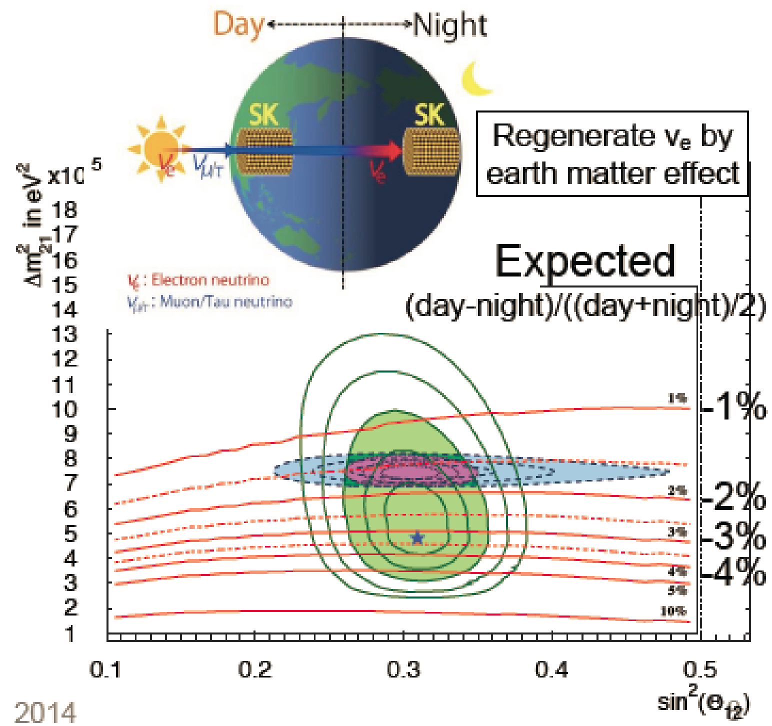
Final Results

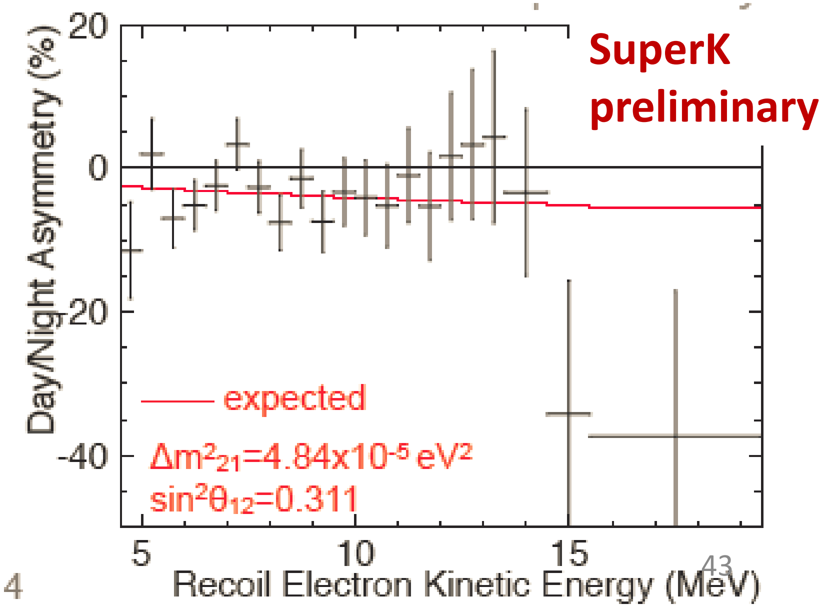


New： Day-Night Effect

- **Day-Night neutrino flux asymmetry is an indication of the regeneration of ν_e as they travel through earth matter(earth matter effect)**
- **A ~ 2.8 σ asymmetry is observed.**
- **In agreement with expectation (1 σ tension)**



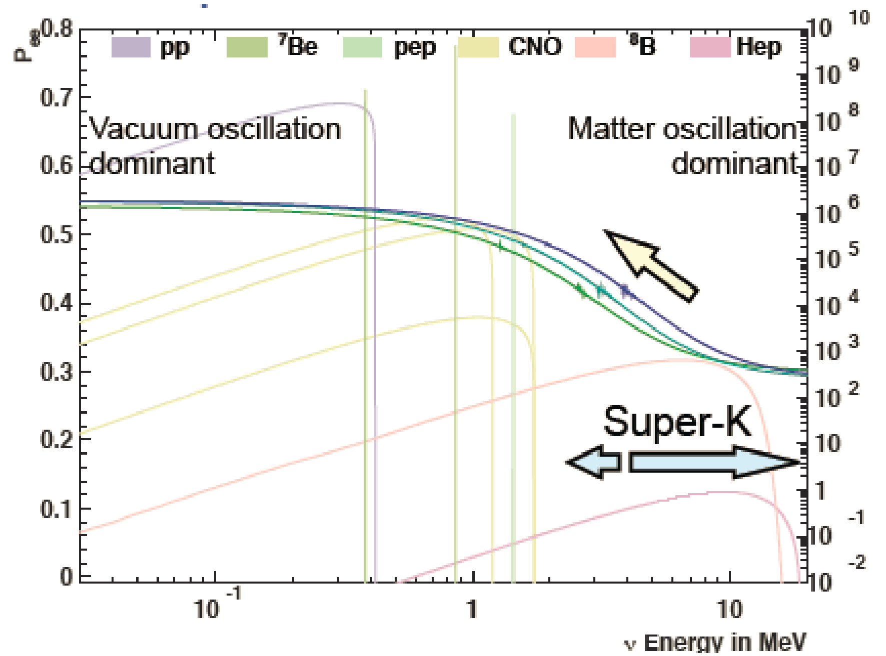


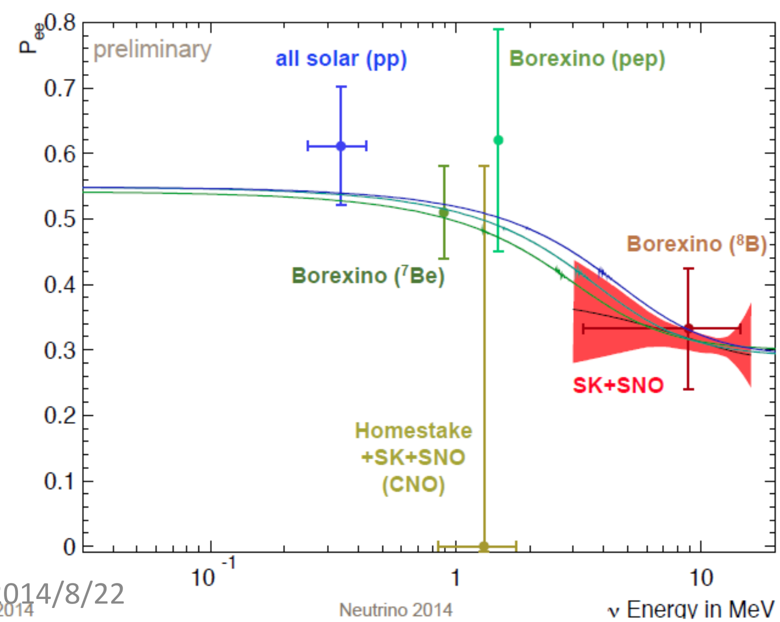


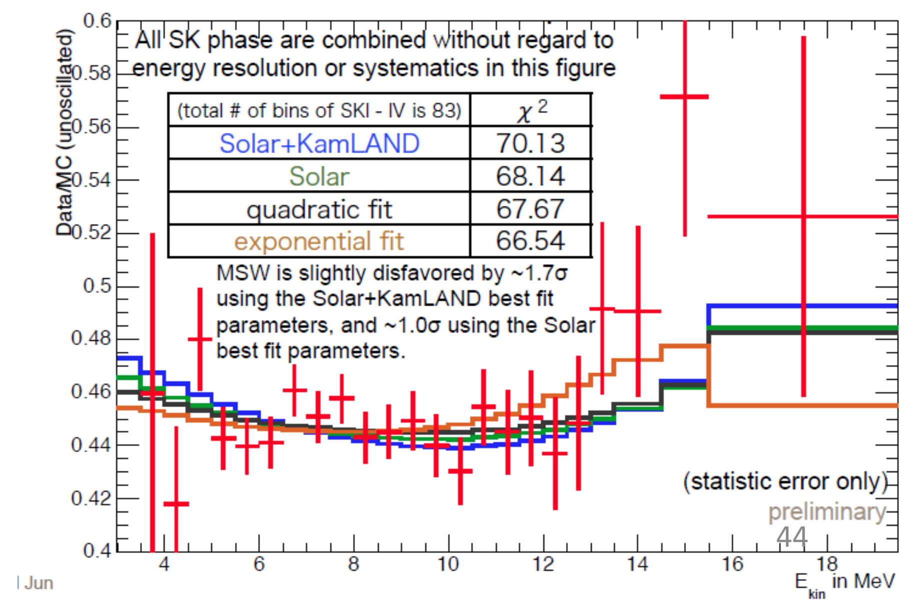
Phys.Rev.Lett. 112 (2014) 091805

New： Spectrum Distortion

- Spectrum “upturn” is an indication of MSW effect in the sun (solar matter effect)
- MSW is disfavored by SuperK at 1.7 σ
- SuperK and SNO are complementary to constrain the shape. MSW is consistent with all the data at 1 σ



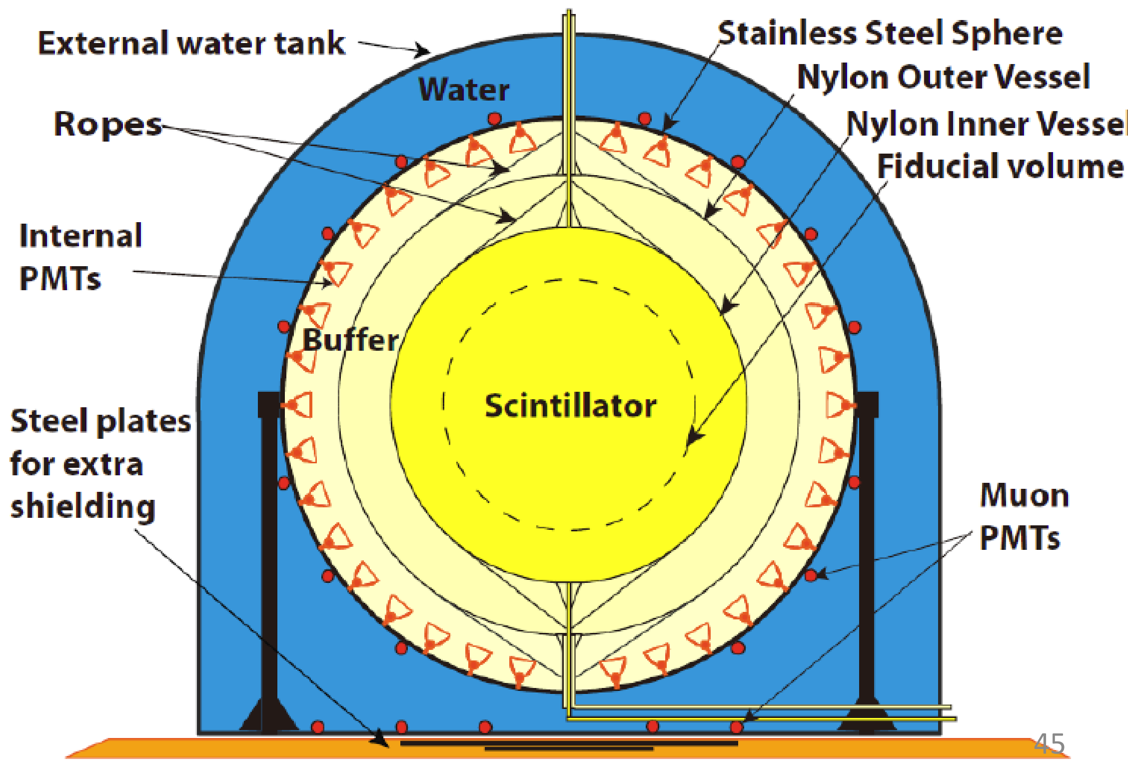




Borexino

- Overburden: 3800 MWE
- Extremely low background
- Use $\nu_e + e \rightarrow \nu_e + e$
  - Scintillation light 500 PE/MeV
  - No directionality
  - Threshold: 60 keV for pp neutrinos(not yet)

Target liq. Scint.: 270t
Fiducal volume: 100 t
Buffer liq.: 890t
No. of PMT: 2214
Balloon: 150 μm Nylon



Operational since 2007

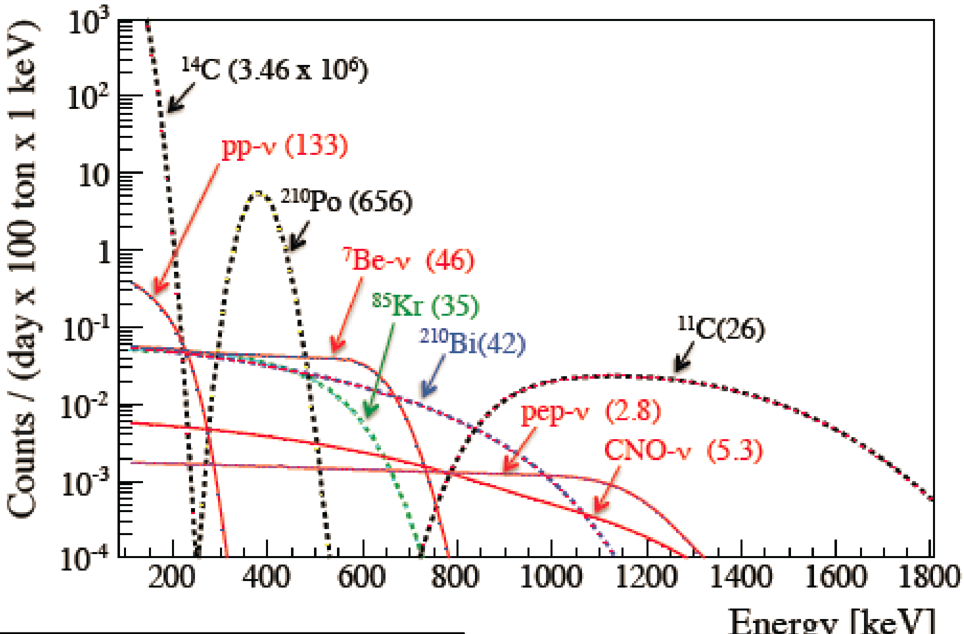
The Cleanest Neutrino Experiment

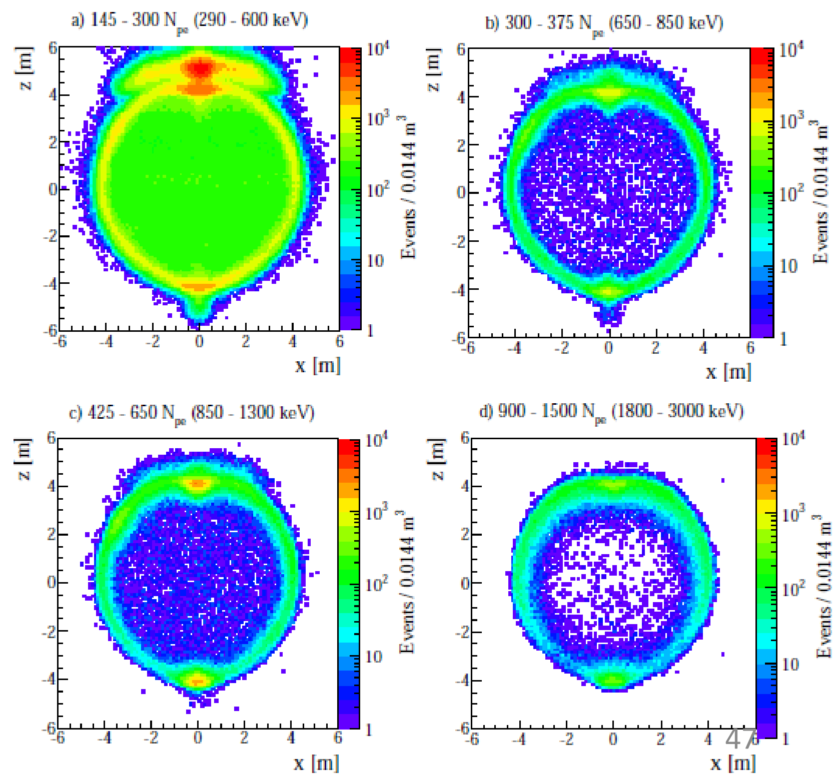
Radio-Isotope		Concentration or Flux		Strategy for Reduction		Final in phase I
Name	**Source**	**Typical**	**Required**	**Hardware**	**Software**	
μ	cosmic	~ 200 s^{-1} m^{-2} @ sea level	<$10^{-10}$$s^{-1}$ m^{-2}	underground water detector	Cerenkov PS analysis	< 10^{-10} eff. > 0.99992
γ	rock			water	fid. vol.	negligible
γ	PMTs, SSS			buffer	fid. vol.	negligible
^{14}C	intrinsic PC	~10^{-12} g/g	~10^{-18} g/g	selection	threshold	2.7 x10^{-18} $^{14}C/^{12}C$
^{238}U ^{232}Th	dust, metallic	10^{-5}-10^{-6} g/g	<10^{-16} g/g	distillation, W.E., filtration, mat. selection, cleanliness	tagging, α/β	$5.35 \pm 0.5\times10^{-18}$ $3.8 \pm 0.8 \times 10^{-18}$ g/g
^{7}Be	cosmogenic	~3 10^{-2} Bq/t	<10^{-6} Bq/t	distillation	--	not seen
^{40}K	dust, PPO	~2. 10^{-6} g/g (dust)	<10^{-18} g/g	distillation, W.E.	--	not seen
^{210}Po	surface cont. from ^{222}Rn		<1 c/d/t	distillation, W.E., filtration, cleanliness	fit	May '07: 70 c/d/t Jan '10: ~1 c/d/t
^{222}Rn	emanation from materials, rock	10 Bq/l air, water 100-1000 Bq rock	<10 cpd 100 t	N_2 stripping cleanliness	tagging, α/β	<1 cpd 100 t
^{39}Ar	air, cosmogenic	17 mBq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	<< ^{85}Kr
^{85}Kr	air, nuclear weapons	~ 1 Bq/m^3 (air)	< 1 cpd 100 t	N_2 stripping	fit	30 ± 5 cpd/100 t

Fighting with Backgrounds

- Material selection & purification
- Cleaning and washing
- Gas tight and ultrapure N_2 flushing
- Underground material storage and usage

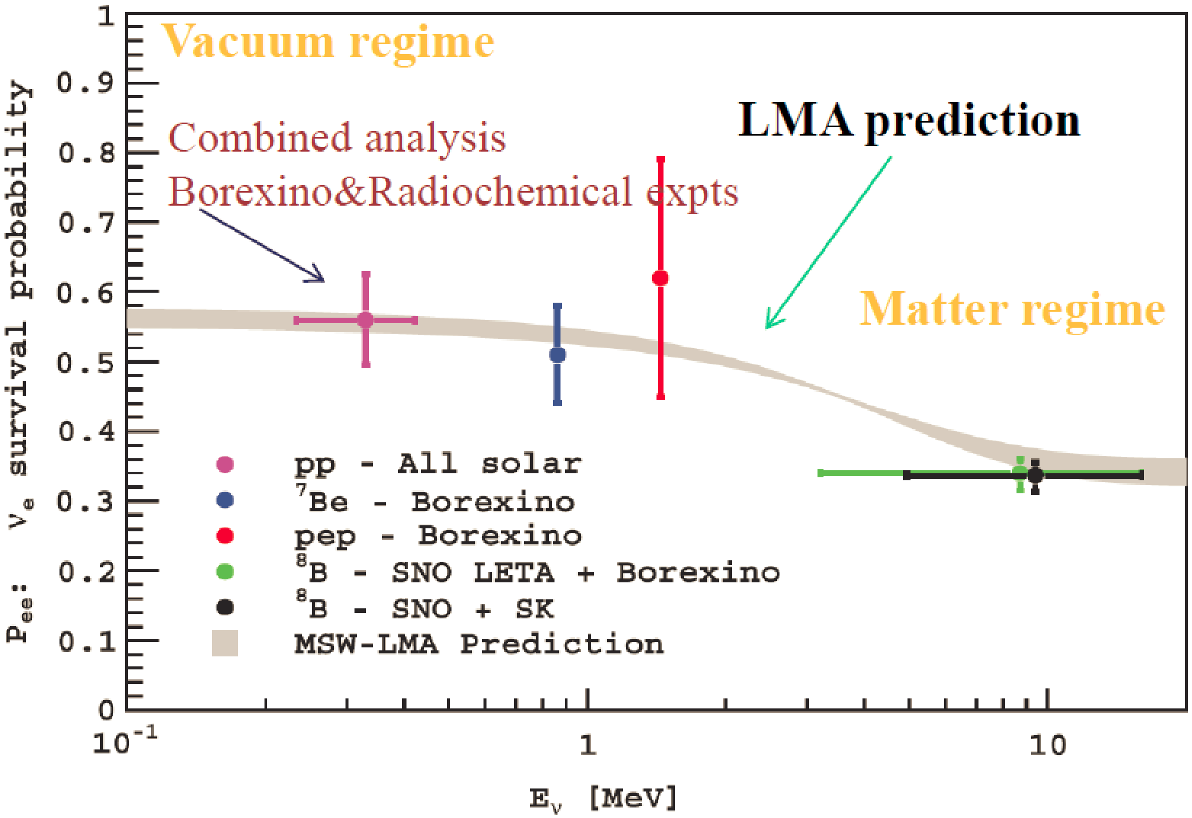
- Active tagging
- Energy threshold
- Vertex cut
- Timing & Chain reactions
- Spectrum fitting and subtraction





PRD 89(2014) 112007

Confirmation of the Solar Model and the Neutrino Oscillation



Ranucci @ neutrino 2014

- Accomplished:
  - ^{7}Be flux
  - ^{8}B flux down to 3 MeV
  - pep flux & limit on CNO
- Future:
  - pp neutrinos
  - CNO

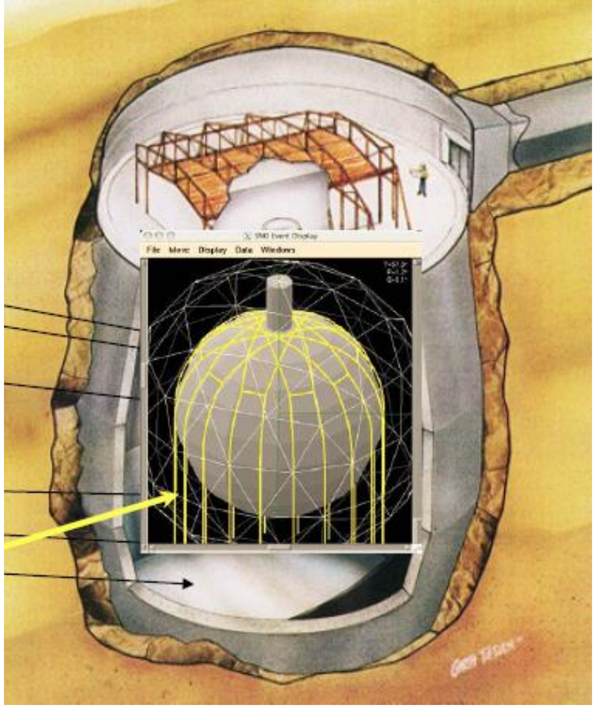
Future

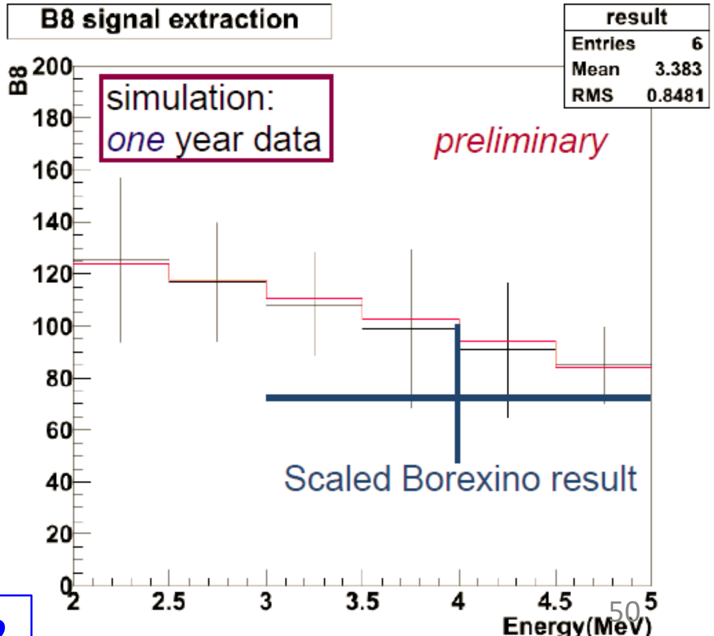
- Better oscillation measurements
  - Seasonal variations
  - Spectrum distortion
  - Day-night effect
- Non-standard interactions
  - Flavor changing NC
  - Sterile neutrinos
  - Mass varying neutrinos
- Solar physics:
  - Understand the stellar formation by measuring the metallicity of the Sun’s core
    - Precision 8B flux
    - CNO flux

- SuperK
- Borexino
- SNO+
- XMASS
- JUNO
- HyperK
- LENA
- ...

SNO+

- **Construction almost finished, to be operational soon**
  - 780t liquid scintillator(LAB-based)
  - 9500 PMTs
  - Water shielding
  - Hold down rope net on the 12 m diameter Acrylic vessel
- **Physics:**
  - Solar neutrinos
    - Better measurement of pep & ^{8}B neutrinos
    - Look for CNO neutrinos
  - Geoneutrinos
  - Supernova neutrinos
  - Double beta decays

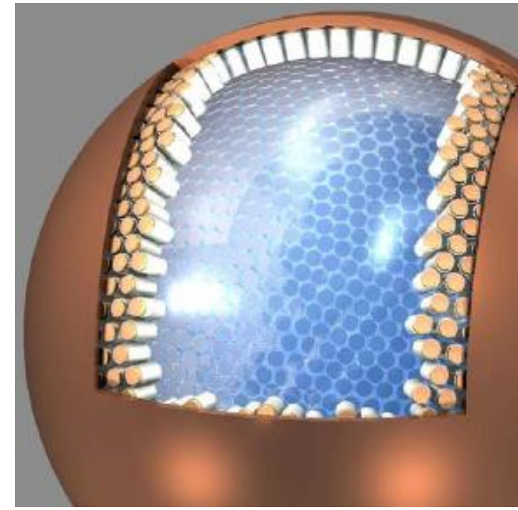


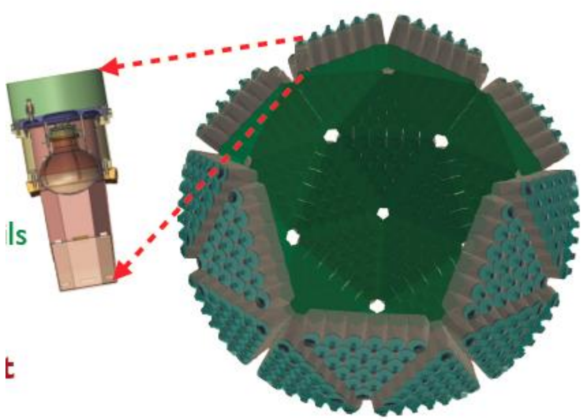


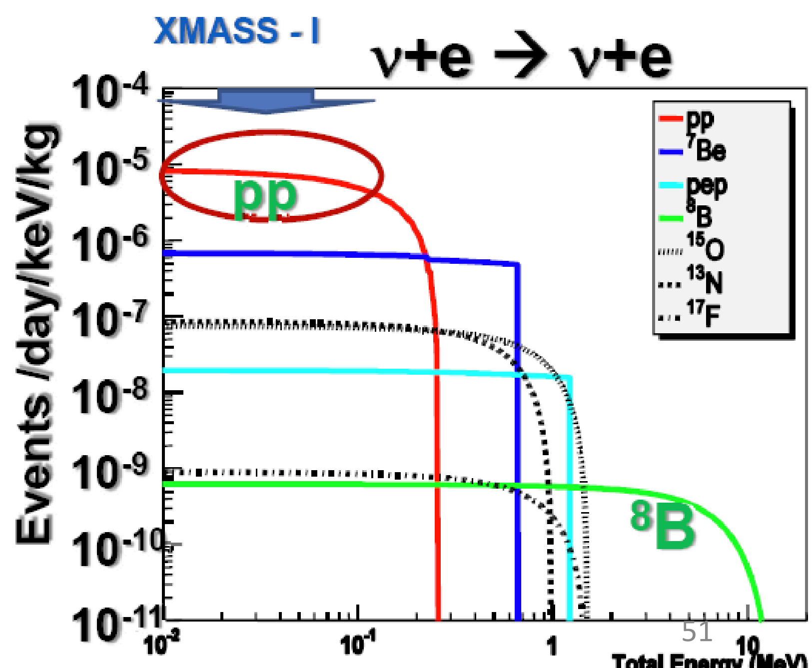
McDonald@Neutrino'12

Noble Liquid: XMASS, LZ & CLEAN

- **Why ?**
  - Good for Dark matter searches, double beta decays & Solar pp neutrinos
  - low background: PSD/purification
- **XMASS: 24t Liquid Xe detector(R=1.25m)**
  - Phase I(operational)
    - 0.85t, R=0.4m, fiducial mass=0.1t
- **LZ: 7t Liquid Xe detector**
  - Initial phase: LUX
    - 0.37t, operational
- **CLEAN: 50 t liquid Neon**





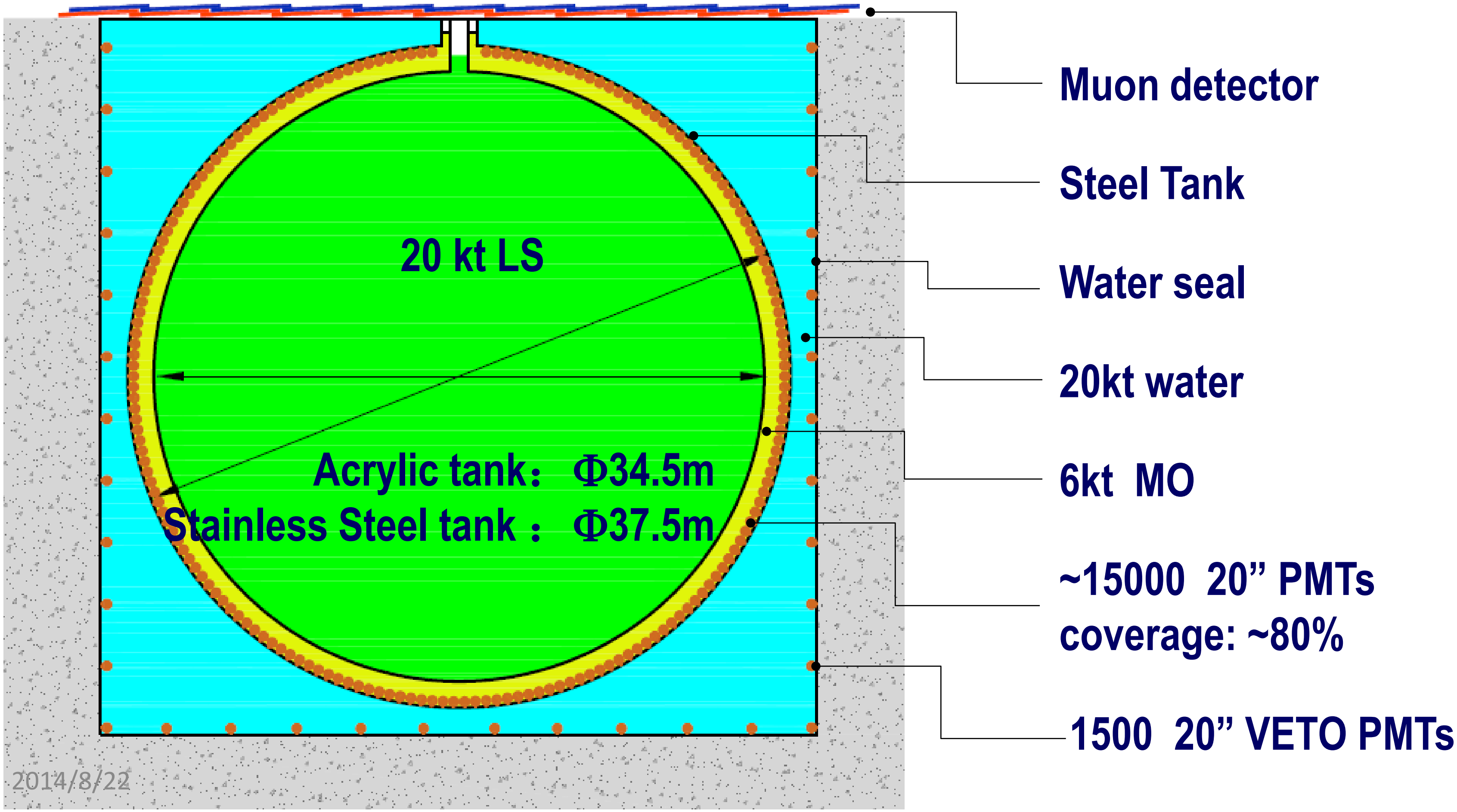


Future experiment: LENA

arXiv:1104.5620

- **The detector:**
  - 50 kt liquid scintillator(LAB)
  - 30,000 12” PMT with Winston cone, 30% coverage
  - Water Veto with 4000 8” PMT
- **Physics**
  - Solar neutrinos
    - CNO neutrinos for solar metallicity
  - Burst Supernova neutrinos
  - Diffused Supernova neutrinos
  - Geo-neutrinos
  - Short baseline neutrino oscillation experiment using radioactive sources: sterile neutrinos

JUNO



- See more in the Reactor neutrino section

Summary

- Solar neutrinos gave us the first hint of the neutrino oscillation
- Neutrino mixing parameters, θ_{12} and $\Delta M^2{}_{21}$, are determined by the SuperK, SNO and KamLAND experiments
- Approved the Standard Solar Model
- More to learn
- More experiments in the future