Solar Neutrino Experiments

It took more than 30 years to solve
the solar neutrino problem

But It may not be
completely resolved yet

This is the reason why we need
new experiments to measure solar
neutrinos

Solar Neutrinos

Big IF in 19th century: 'How does the sun shine?'

1854 H von Helmholtz

1862 L. Kelvin

proposed the source of the solar energy

→ gravitational contract

$\tau(\text{sun}) = (GM_\odot^2/R_\odot)/L_\odot \approx$ 30 million years

⟺ geological earth's lifetime of 4.6 billion years

⇩

Must WAIT: development of Nuclear Physics

1920 A. Eddington

recognized that the hydrogen burning into helium

→ produce 0.7% of mass energy

→ $\tau(\text{sun}) = (M_{\odot} c^2 \times 0.007 \times 0.1)/L_{\odot}$

$\approx$ 10 billion years

1938 C.F. von Weizsäker

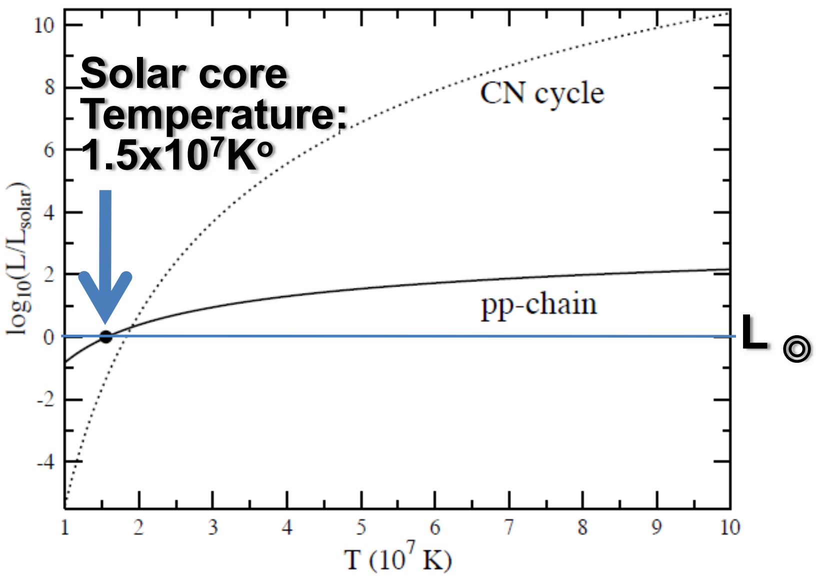
discovered CNO cycle (but not discussed in details)

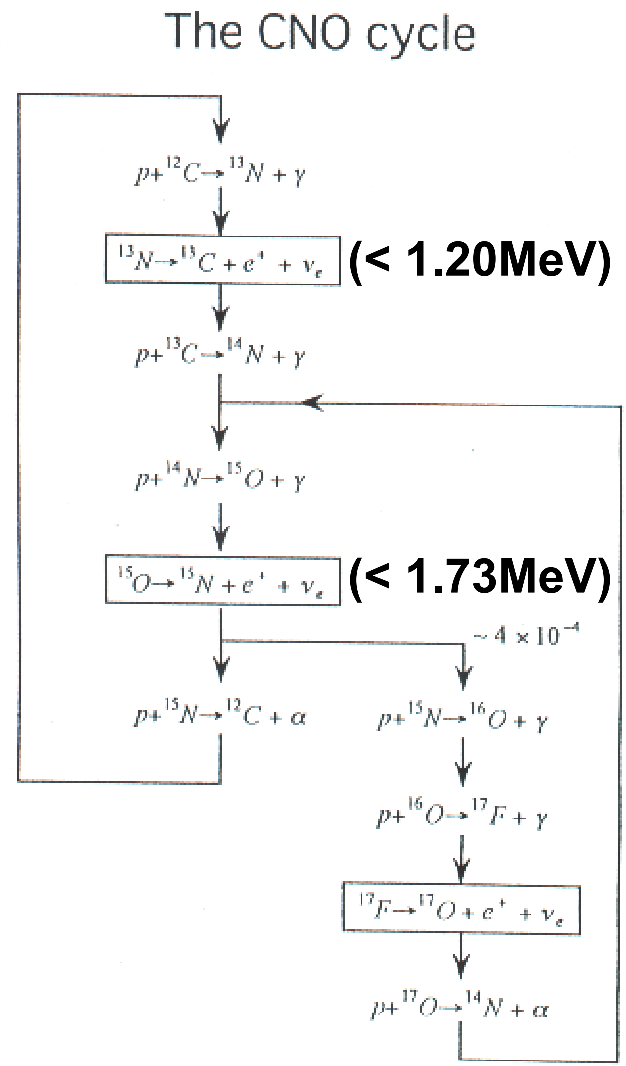
1939 H. Bethe

discovered pp-chain and described CNO cycle in details

pp-chain and CNO cycle

Astro-ph 0805.2013v1





Sun: pp-chain dominant

CNO: Hydrogen is burned using a carbon as a catalyst

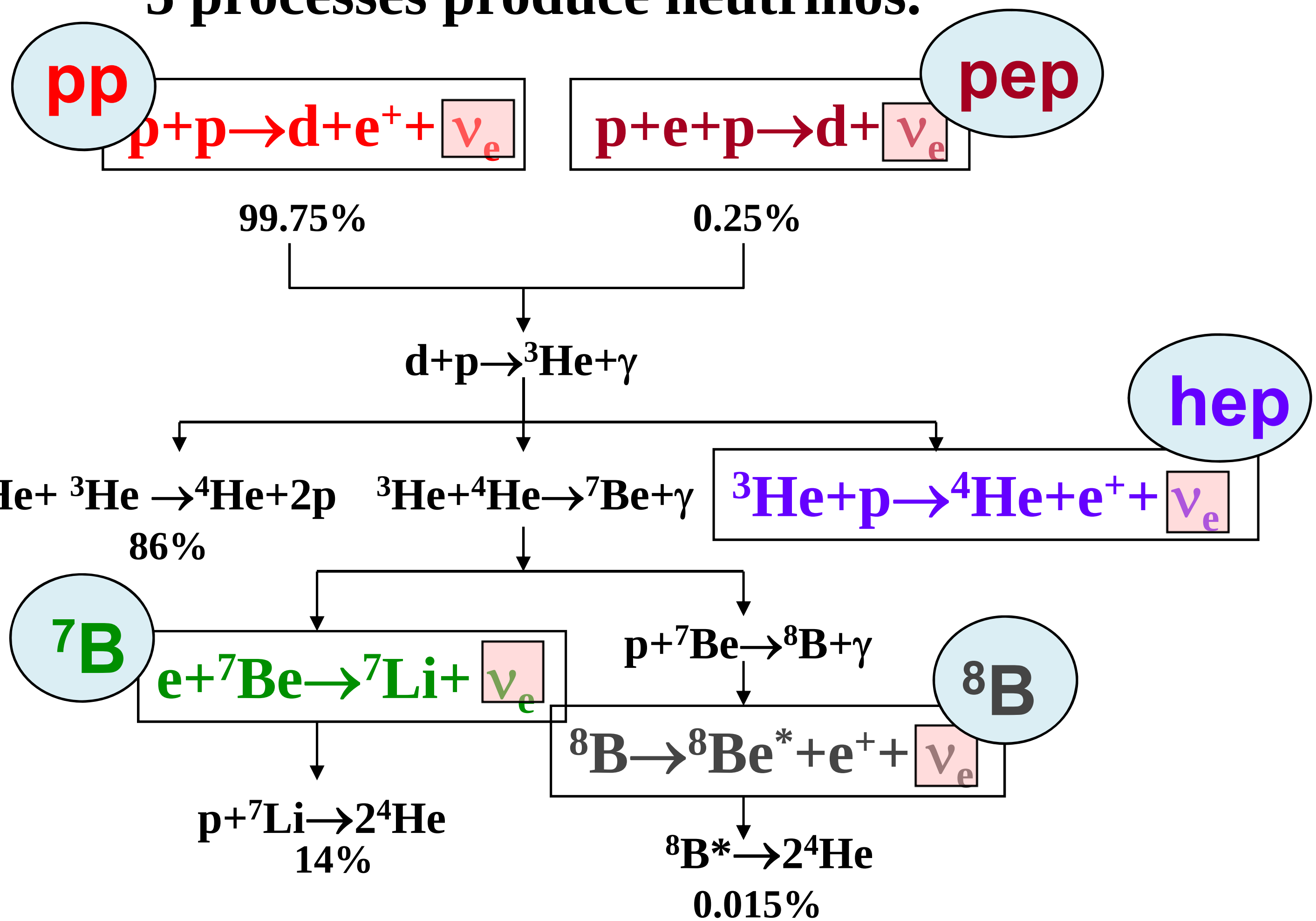
Relatively low energy neutrinos are produced

➔ SK/SNO cannot detect

pp-chain

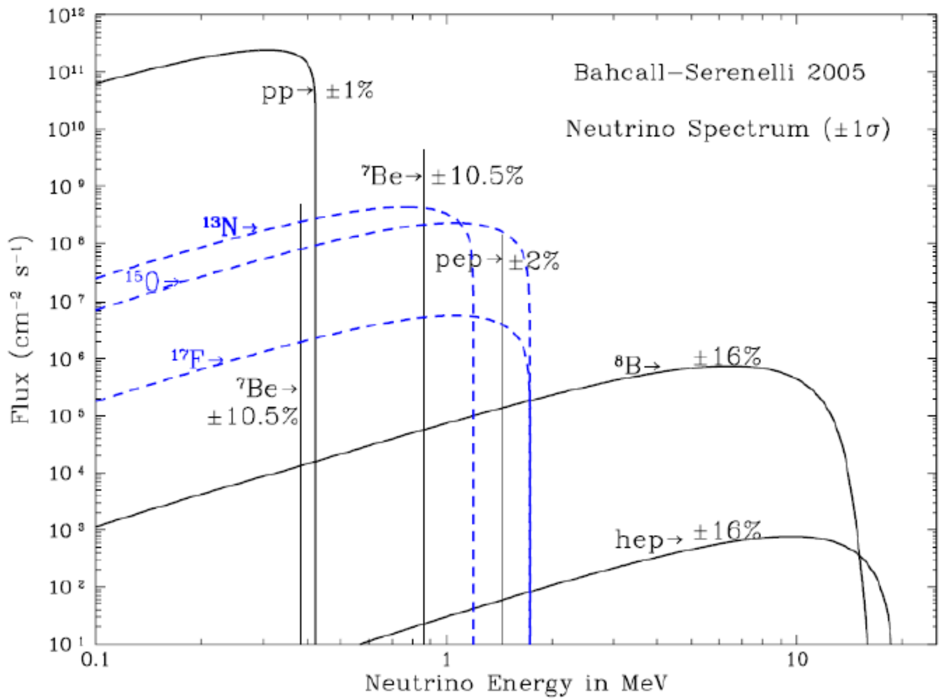
The dominant source of the sun's energy production.

5 processes produce neutrinos.



Detection of the ^8B neutrinos is a proof of pp-chain

Towards the solar ν measurements



Inside of the sun:

People realized neutrinos could probe inside (nuclear reaction) of the sun

1946 B.Pontecorvo

1949 L.Albarez

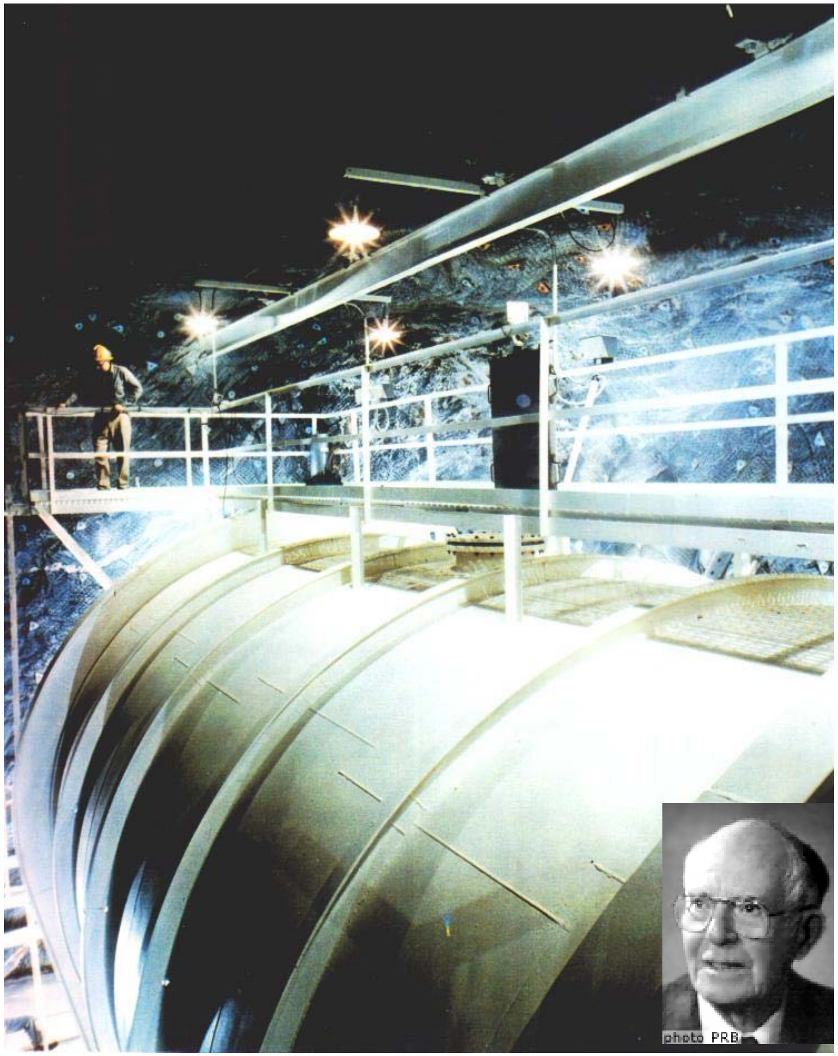
Idea of the detection of neutrinos through the process:

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

1964 R. Davis

proposed the Cl experiment at Homestake Mine, South Dakota

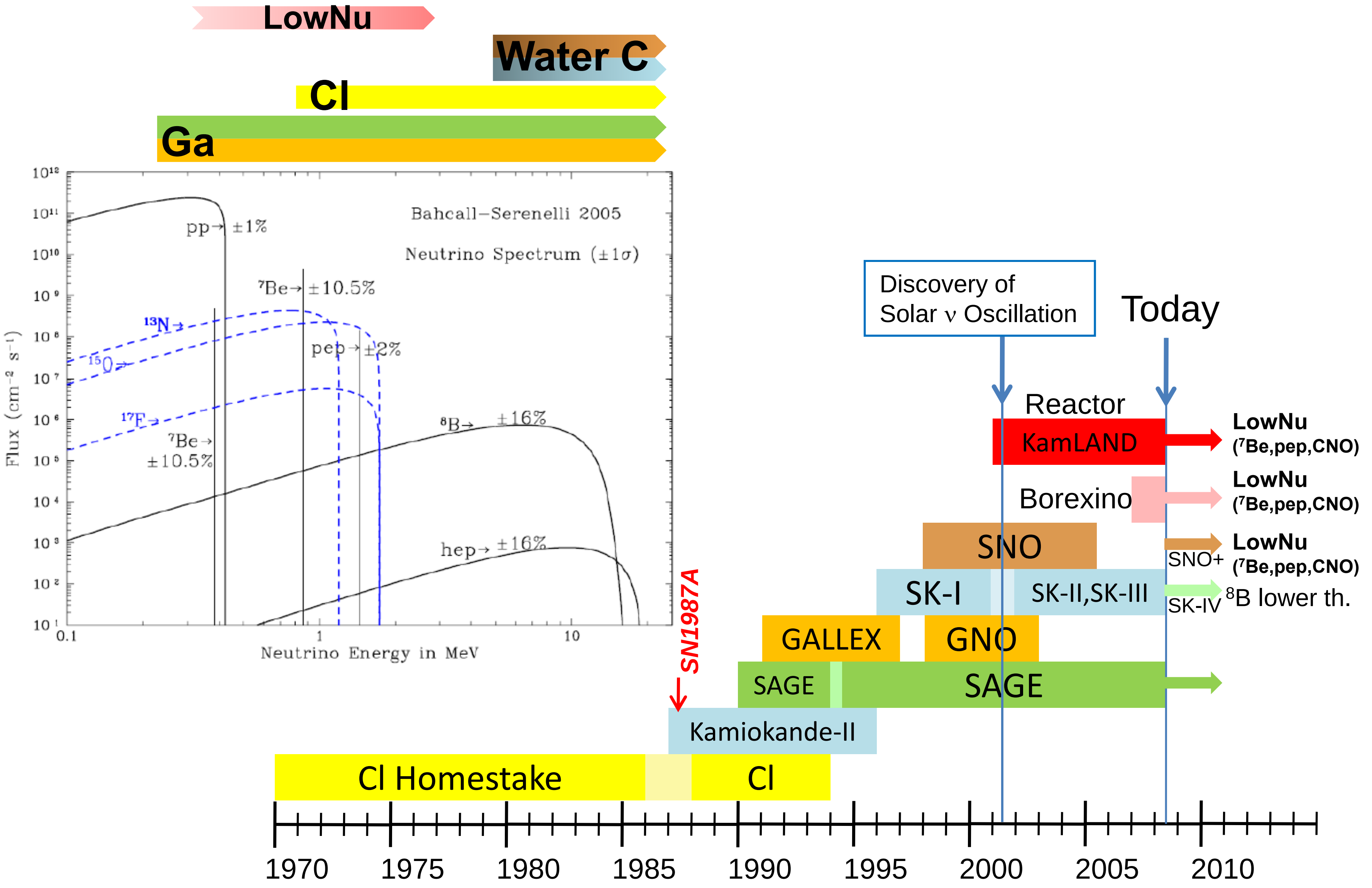
Pioneering experiment



- Homestake experiment by R. Davis
- Radiochemical Experiment
  - $\nu_e + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$ ($E_{th} > 817$ keV)
  - sensitive to CC interaction
  - Mostly detect ^{8}B and ^{7}Be neutrinos
  - 615 tons of perchloroethylene: C_2Cl_4
  - Extract and count Ar atoms every ~ 3 months
- Result:
  - R = data/SSM= 0.33±0.3

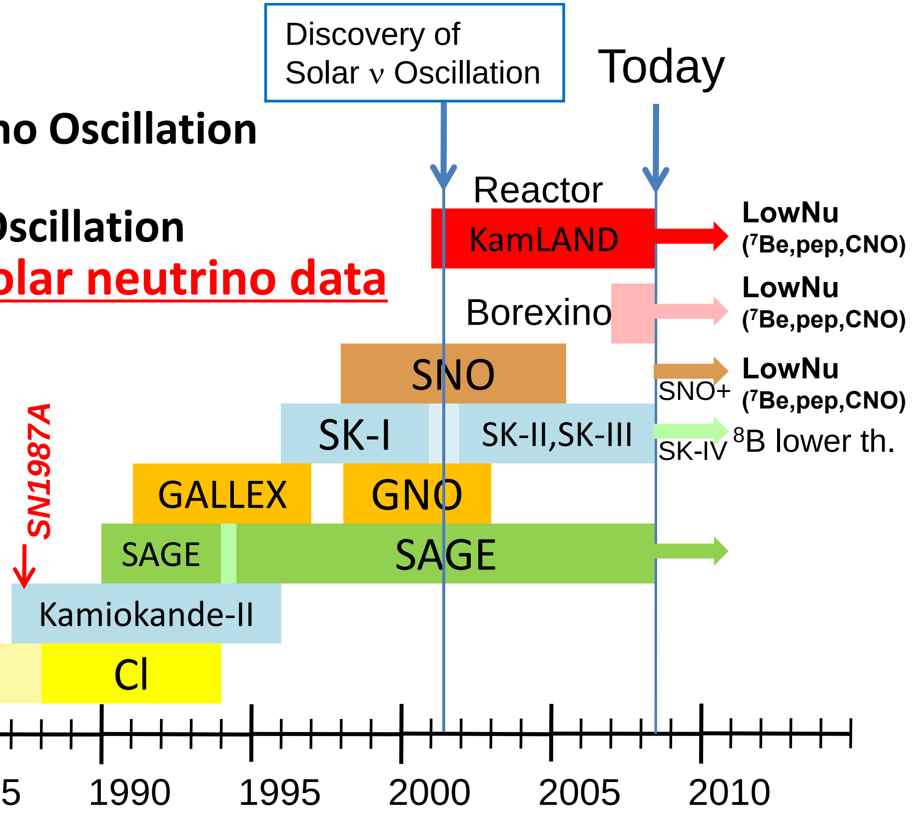
This deficit is known from early 70s (The solar neutrino problem)

Solar Neutrino Problem(SNP) and Solar Neutrino Experiments



Solar Neutrino Problem(SNP) and Solar Neutrino Experiments

- **Before Super-K (Radiochemical + Kamiokande)**
  - **Cl, Ga, Kamiokande**
    ➔ Indication of the oscillation
    ➔ Not-conclusive
- **Super-K**
  - **Aim to find flux independent evidence**
    ➔ Small effect
- **SNO**
  - **SNO CC+SK ES ➔ Evidence of Neutrino Oscillation (flux independent)**
  - **➔ SNO CC+SNO NC ➔ strengthen the Oscillation**
- **1 parameter region (LMA)🡐 w/ all solar neutrino data**
- **KamLAND (reactor ν)**
  - **Confirmation of LMA**
  - **Precise determination of Δm^2**
- **Borexino (Low energy ν)**
  - **Start of new era**



Radiochemical + Kamiokande (befor Super-K)

1) Cl Experiment

← explaines as 1st solar ν experiment

2) Ga Experiment (SAGE & GALLEX)

- SAGE in Baksan (1990~)
  60tons Metallic Ga
- GALLEX/GNO in GranSasso (1991~)
  60tons $GaCl_3$

1966 V.A.Kuzmin and G.T.Zatsepin

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

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

SAGE Site

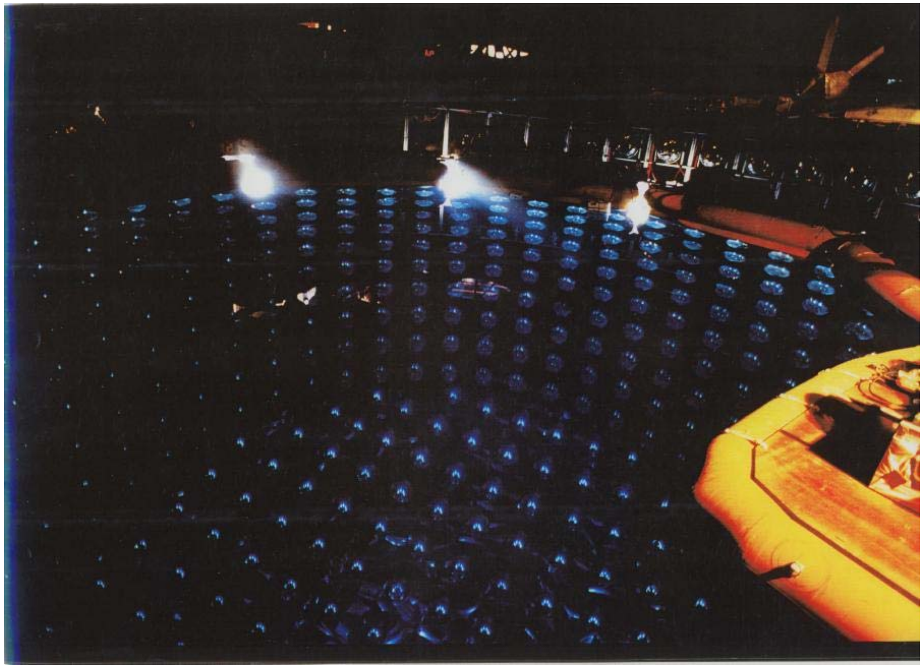
R=0.52±0.07 (SAGE)
R=0.59±0.06 (Gallex)

Radiochemical + Kamiokande (before Super-K)

3) Kamiokande

- **4,500 tons (680 tons fid.) Water Cherenkov Detector**
- **$\nu_e + e^- \rightarrow \nu_e + e^-$ (H_2O); CC+NC**
- **E_{th} = 7MeV (only ^8B)**
- **Directionality, Energy, Time**

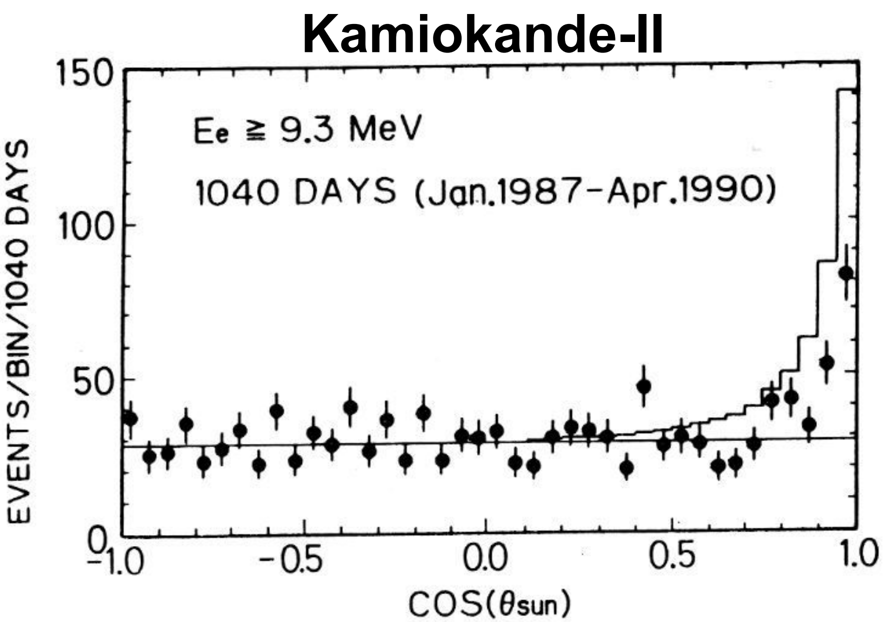
- **Direct (directional) evidence of solar neutrinos**
- **First direct evidence of the existence of ^8B neutrinos**
  - **First evidence of neutrinos from pp-chain**

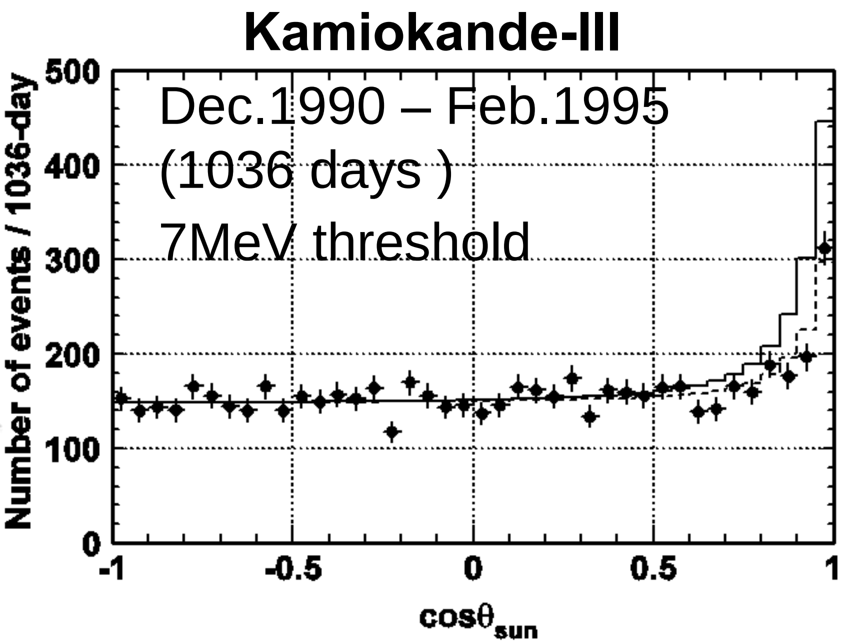


R=0.55±0.08 (Kamiokande)

Solar neutrinos by Kamiokande

Directional solar ^{8}B neutrino observation



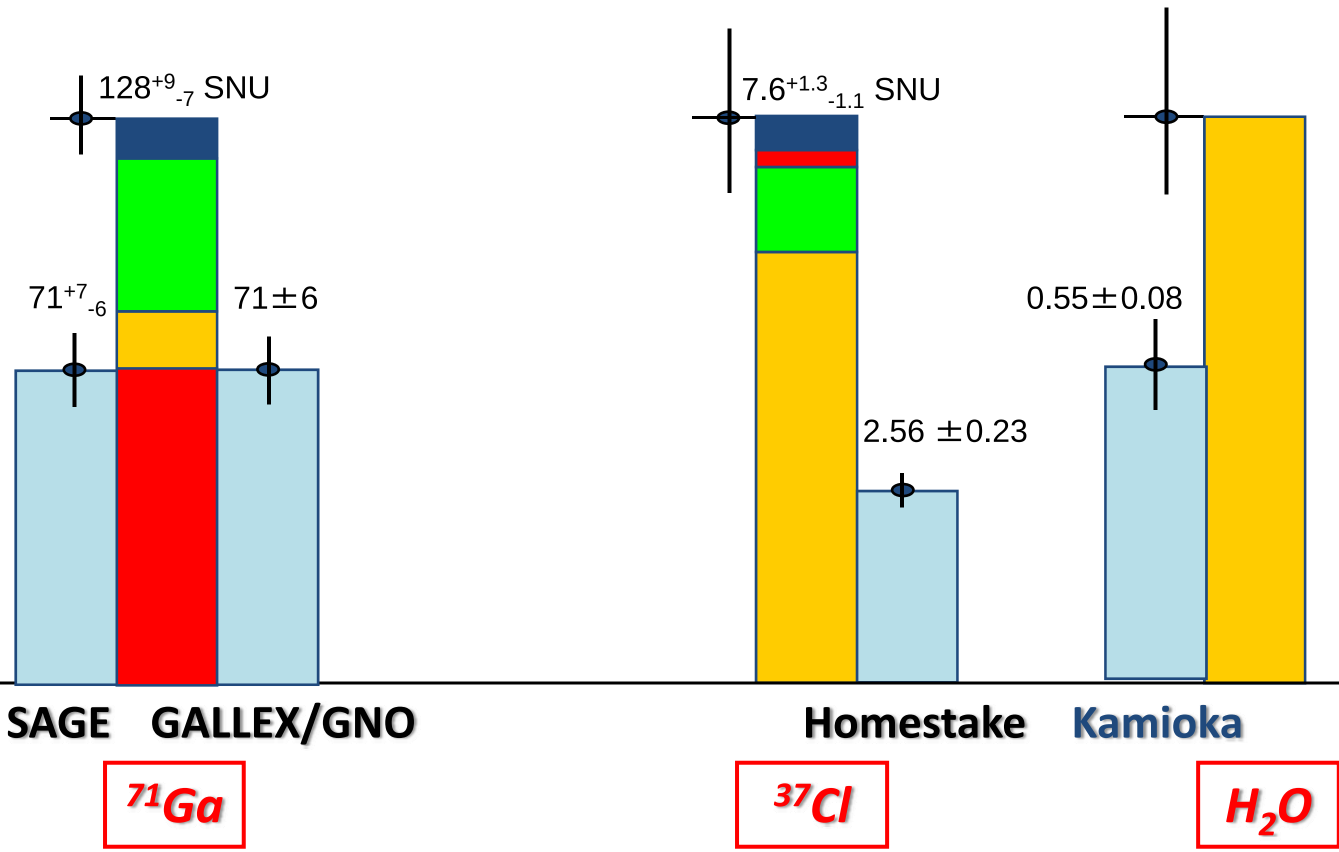


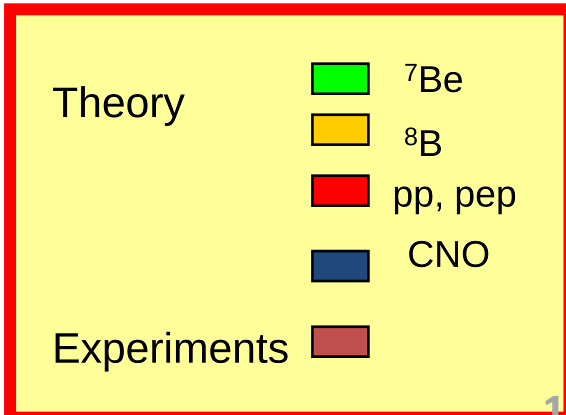
~600 events in total

^{8}B flux : 2.80 ± 0.19 ± 0.33 [x 10^{6} /cm^{2}/sec]

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

Solar neutrino flux measurements



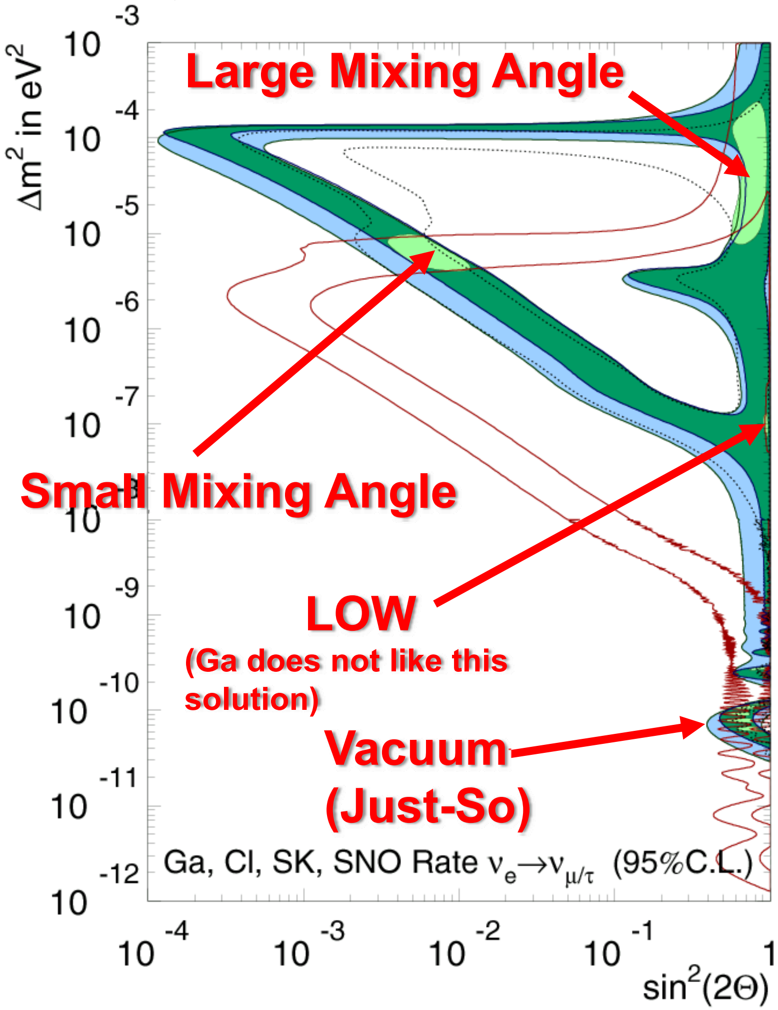


Early '90s

The results of these 4 experiments gave us four allowed regions under the oscillation hypothesis based on the expected flux calculated by the standard solar model.

Flux (Rate)-global analysis (a guide for the solution)

$\nu_e \rightarrow \nu_\mu(\nu_\tau)$ 95% C.L.



$$\tan^2 2\theta_m = \frac{\tan^2 2\theta_V}{1-(2p\sqrt{2}_F n_e)/(\delta m^2 \cos 2\theta_V)}$$

= 0

Resonance condition
Adiabatic transition

$\delta m^2 \leq 1.6\times10^{-4}\ eV^2$
for 10 MeV

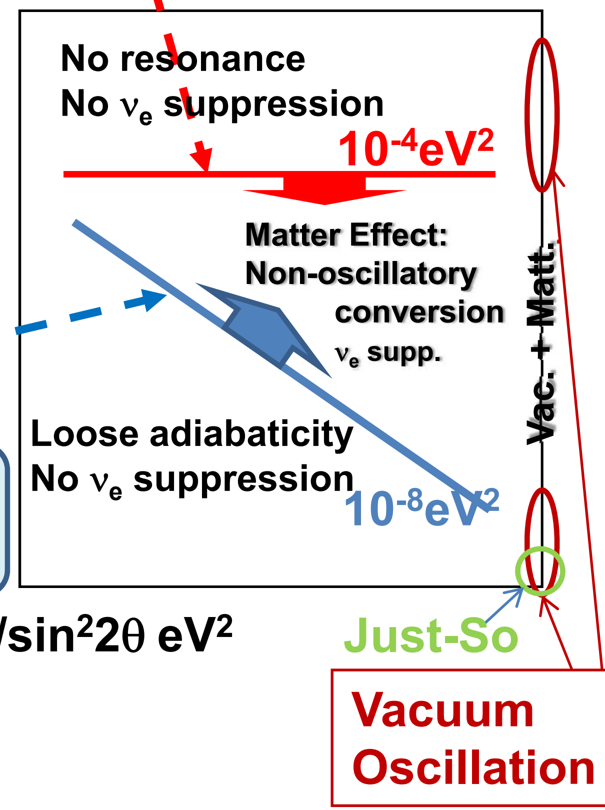
MSW

Failure of the adiabatic condition

$$\frac{\delta m^2}{2E_\nu}\,\frac{\sin^2 2\theta}{\cos^2 2\theta} \geq \left|\frac{1}{n_e}\frac{dn_e}{dr}\right|$$

$\delta m^2 \geq 6.3\times10^{-8}\cos^2 2\theta/\sin^2 2\theta\ eV^2$

for 10 MeV



These results are not conclusive

Reason

- Flux ('Standard' Solar Model) dependent
- 4 solutions

➔ Need flux (SSM) independent evidence

Solar Neutrino Measurement in Super-Kamiokande (SK)

Aim of SK solar ν

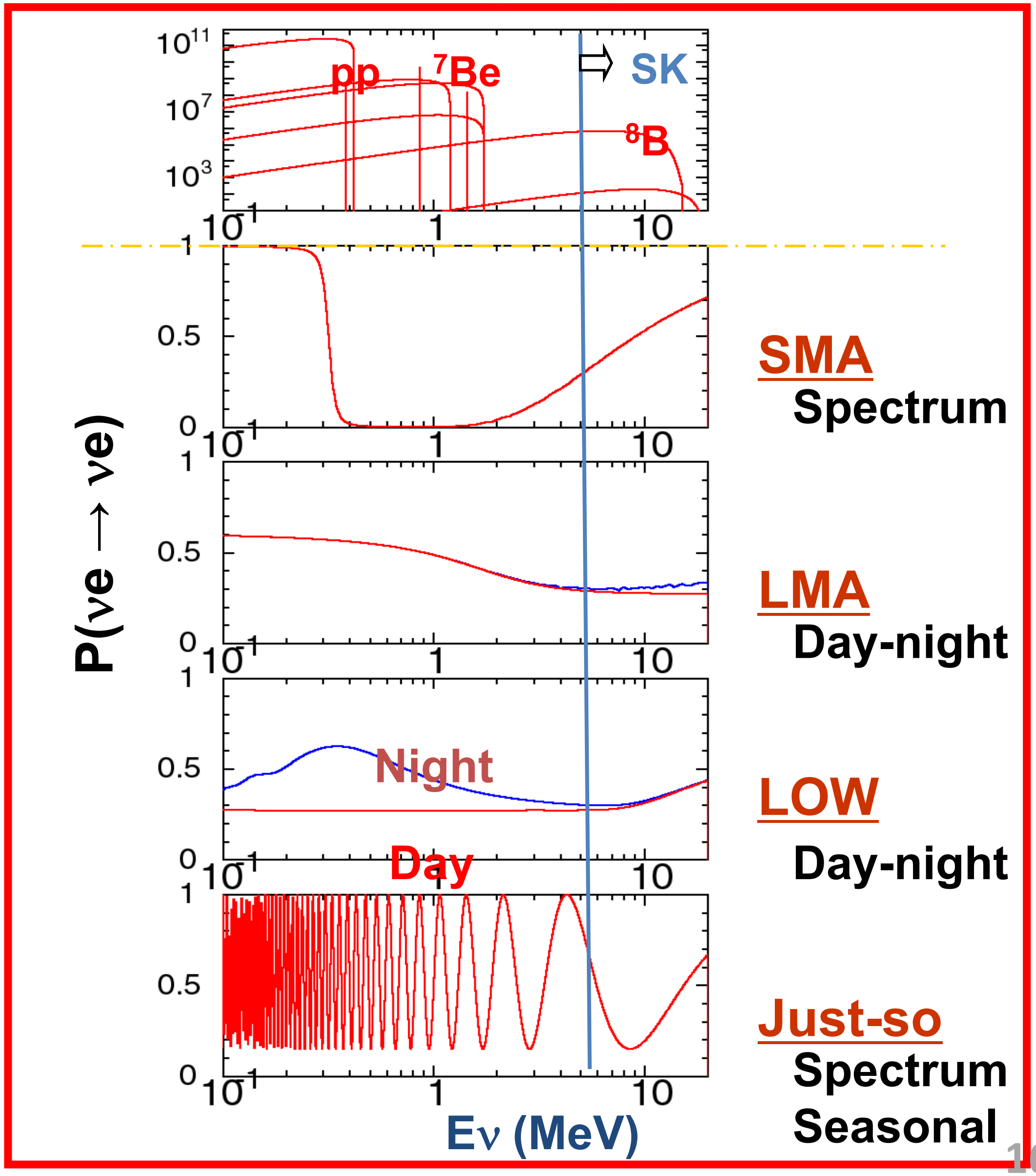
Search for

flux independent evidence:

- spectrum distortion
- time variations

  day night flux difference

  seasonal variation



Characteristics of the Super-Kaminokande Solar neutrino measurements

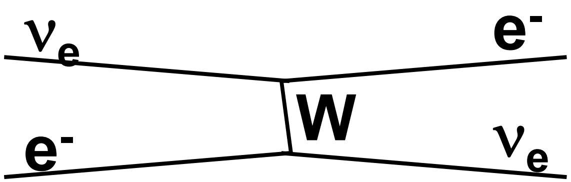
Energy
Direction
Time

Requirement for ASTRONOMY

Super-Kamiokande satisfies these requirments through $\nu + e \rightarrow \nu + e$ scattering

$\nu + e \rightarrow \nu + e$ scattering

- Well known cross sections



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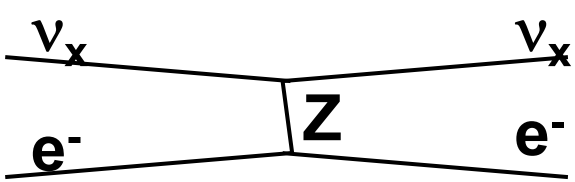
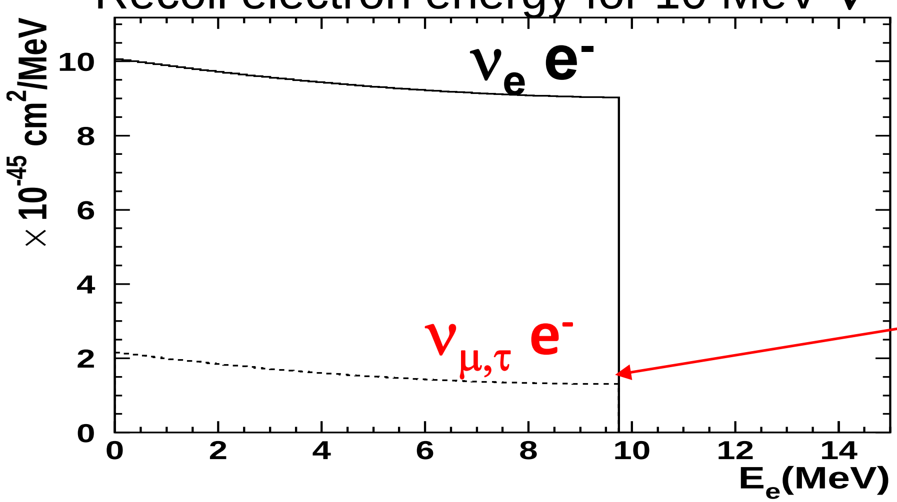


$$\frac{d\sigma}{dT} = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2(1 - T/E_\nu)^2 - g_L g_R m_e T/E_\nu^2\right]$$

$\nu_e e$:	$g_L = ½ + \sin^2\theta_W$	; $g_R = \sin^2\theta_W$
$\bar{\nu}_e e$:	$g_L = \sin^2\theta_W$	; $g_R = ½ + \sin^2\theta_W$
$\nu_{\mu,\tau} e$:	$g_L = -½ + \sin^2\theta_W$	; $g_R = \sin^2\theta_W$
$\bar{\nu}_{\mu,\tau} e$:	$g_L = \sin^2\theta_W$	; $g_R = -½ + \sin^2\theta_W$

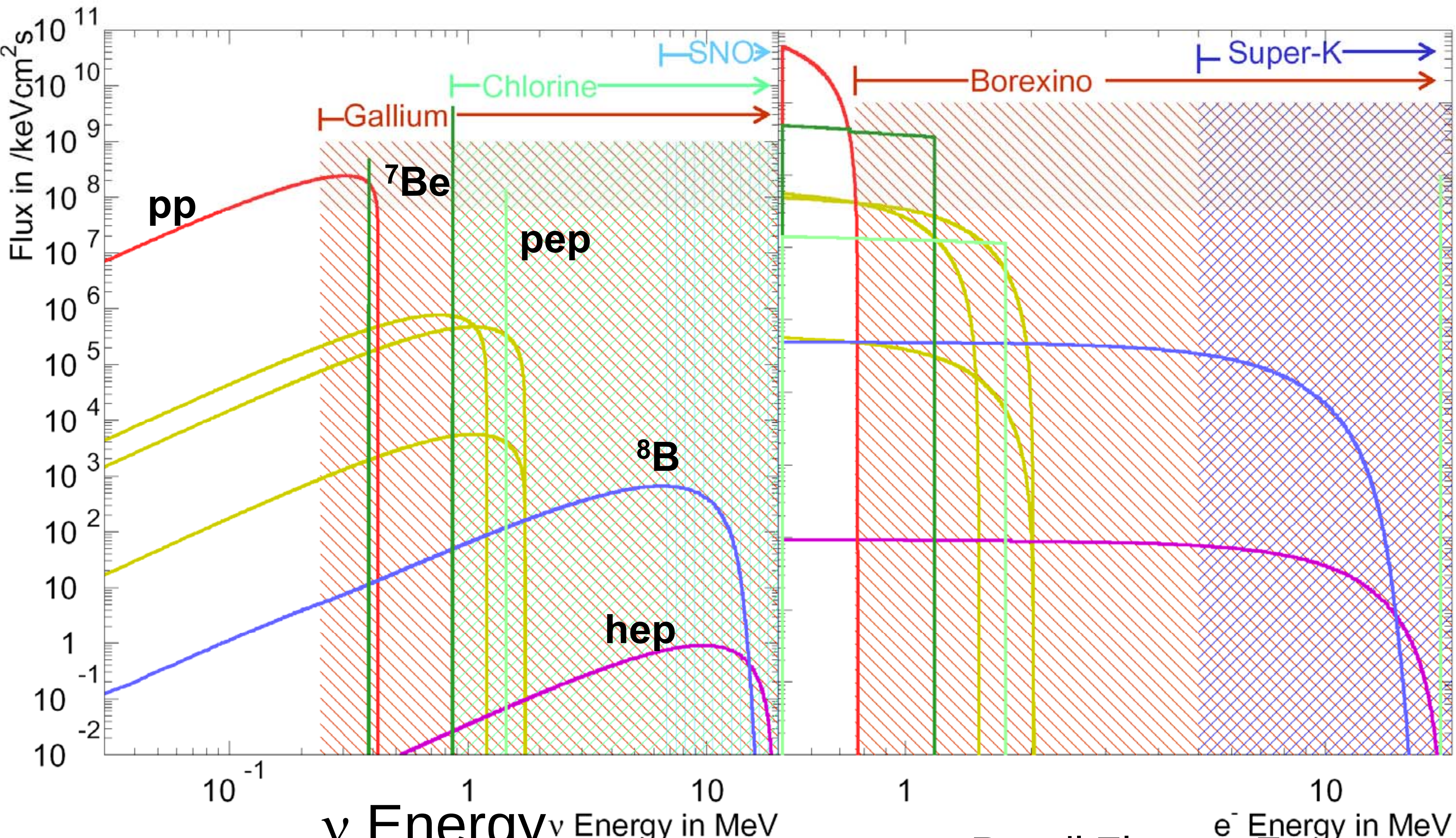
Recoil electron energy for 10 MeV ν



Sensitive to $\nu_{\mu,\tau}$
as well as ν_e
though with reduced sensitivity

$\sigma(\nu_{\mu,\tau} e^-) / \sigma(\nu_e e^-) = \sim 0.15$

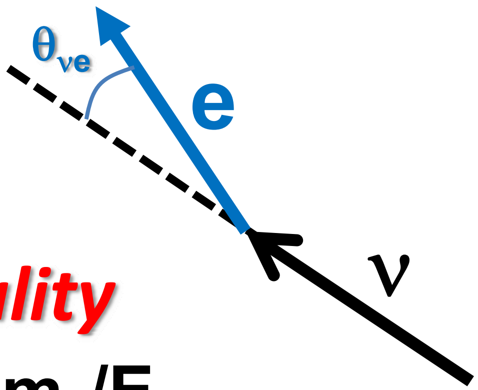
Solar ν Spectrum

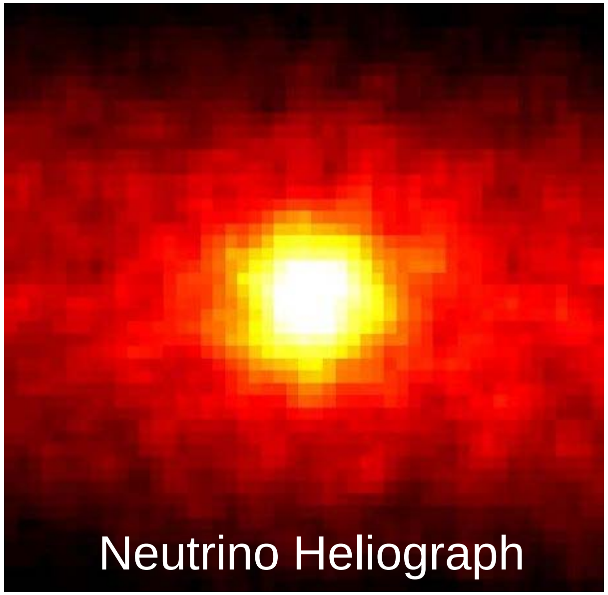


ν Energy

Recoil Electron Energy
for $\nu_e + e \rightarrow \nu_e + e$

Direction of Electron



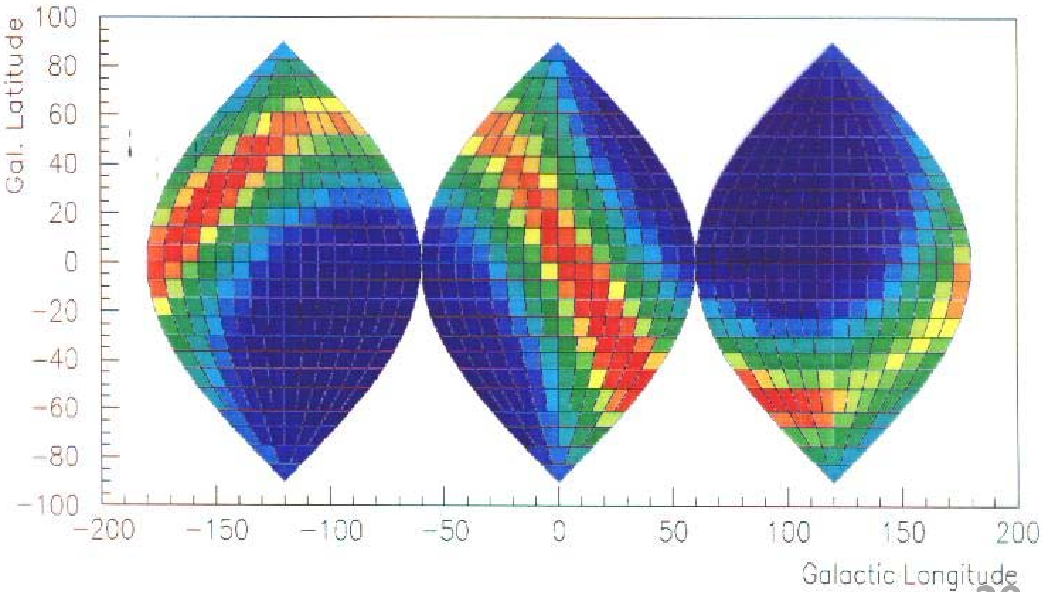


Directionality

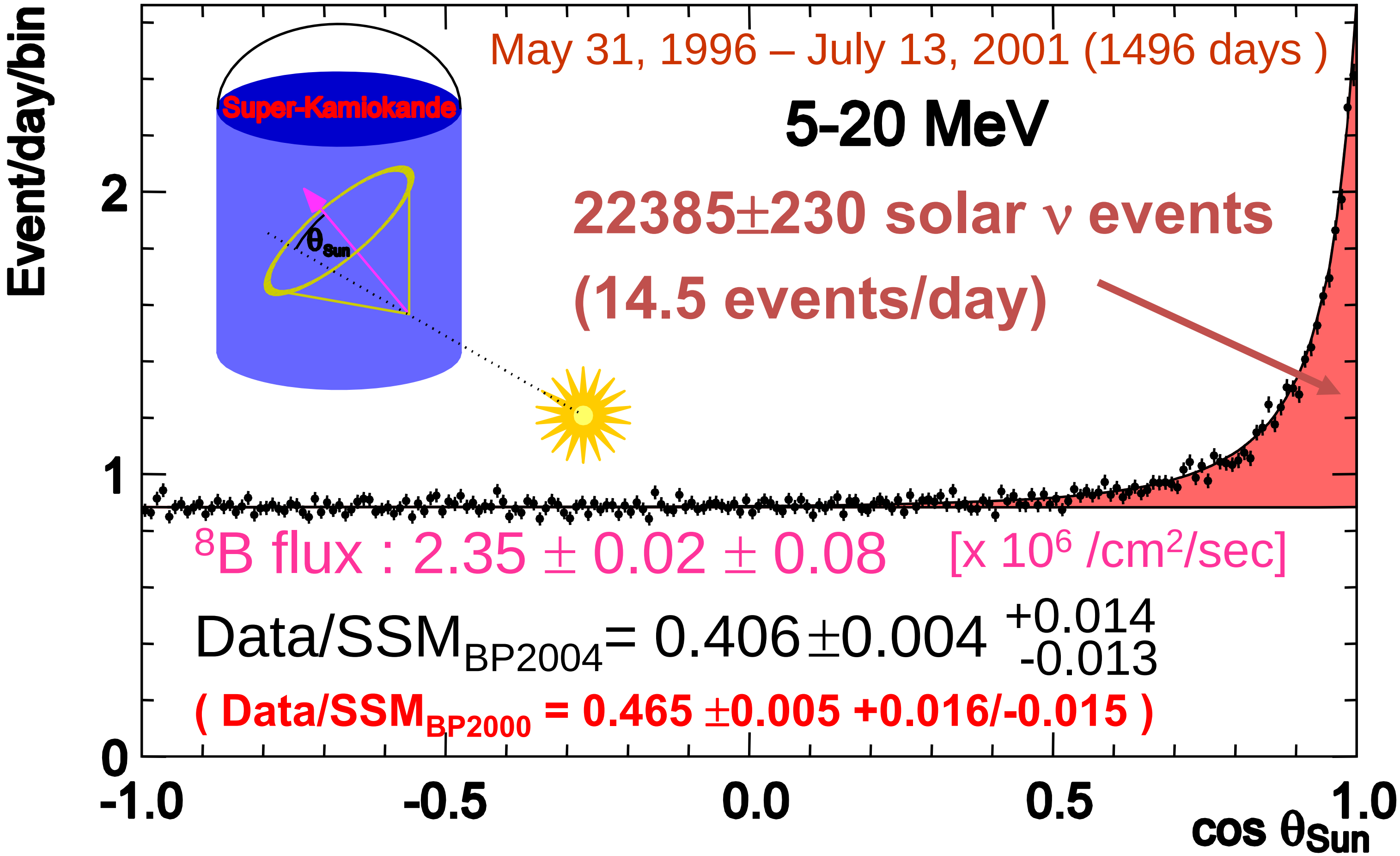
- $\theta_{\nu e}^2 < 2m_e/E$
  Forward scattering
  18.6 deg @10 MeV

Angular resolution

- **Multiple Scattering**
  ~26 deg @10 MeV



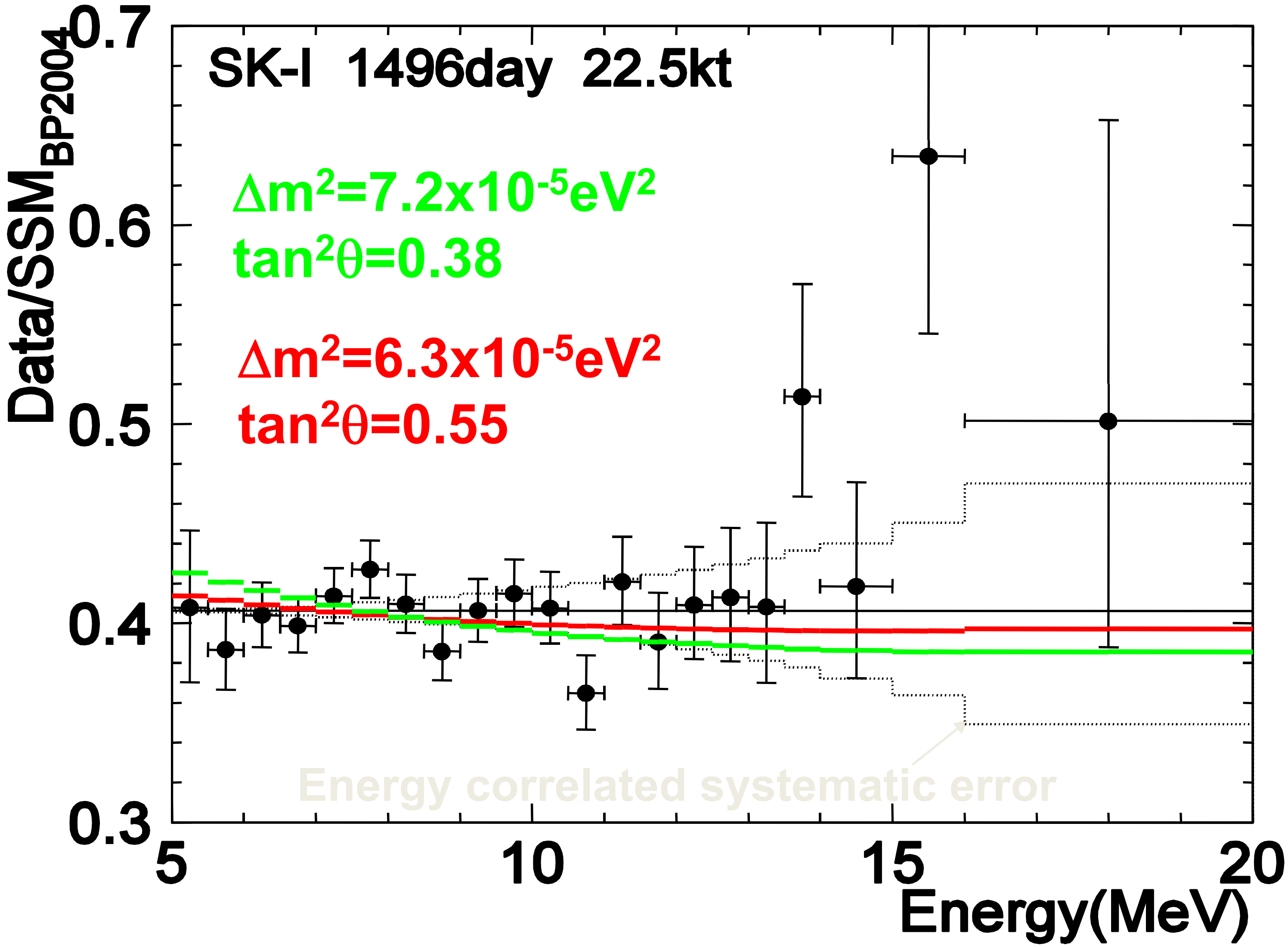
Super-Kamiokande-I solar neutrino data



16,700: e-type solar neutrinos (from SNO)

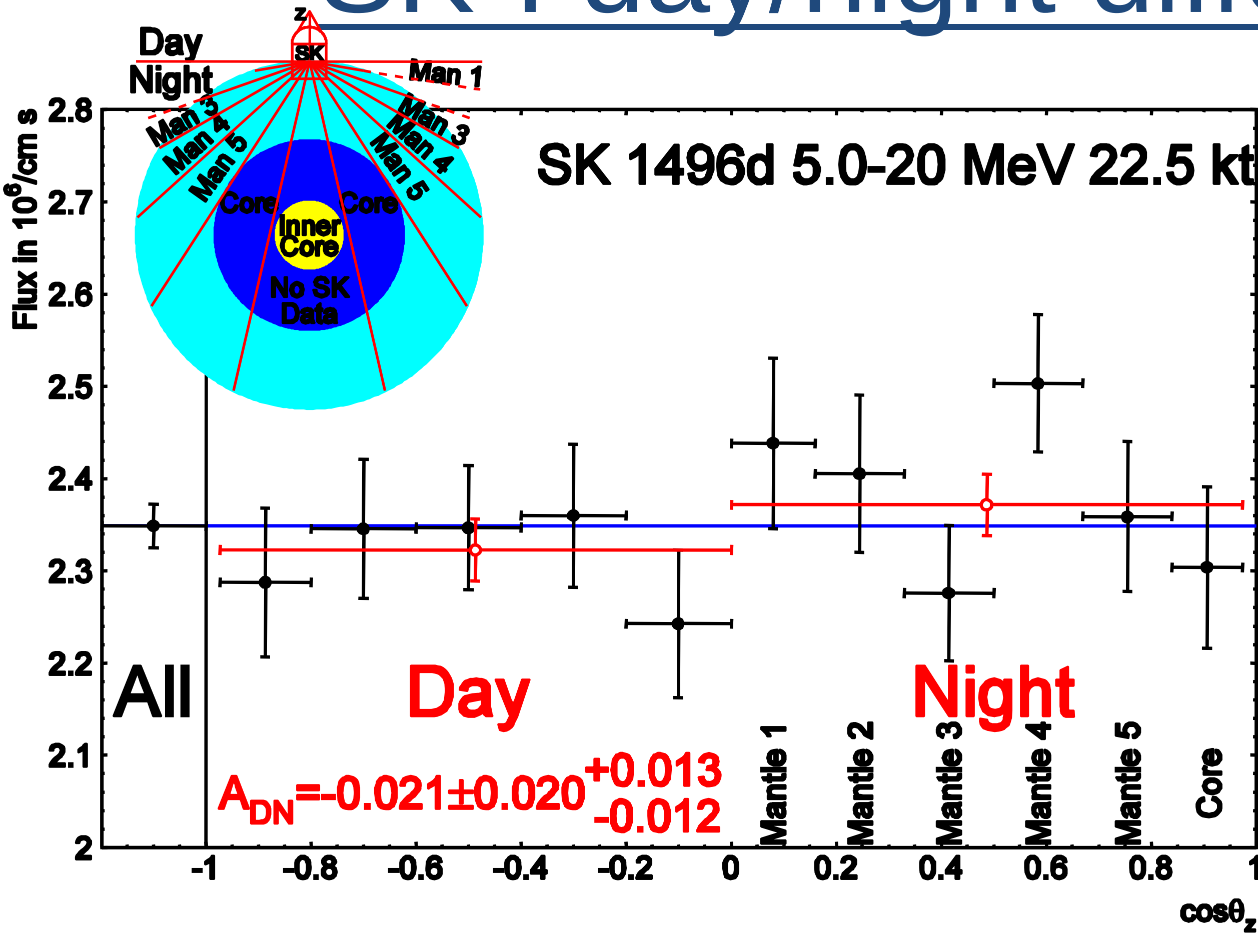
About 5,700 μ/τ type solar neutrinos in Super-K

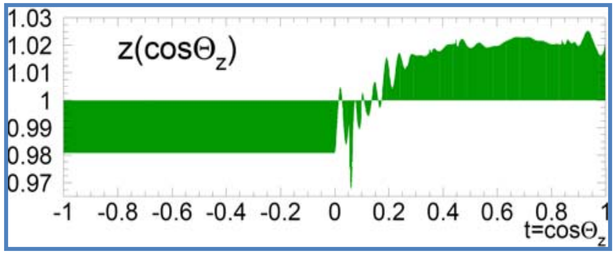
Energy spectrum of SK-I



χ^2(flat)=20.2/20 (44.3% C.L.): Consistent with no distortion!

SK-I day/night difference





$$A_{DN} = \frac{(\text{Day-Night})}{(\text{Day+Night})/2}$$

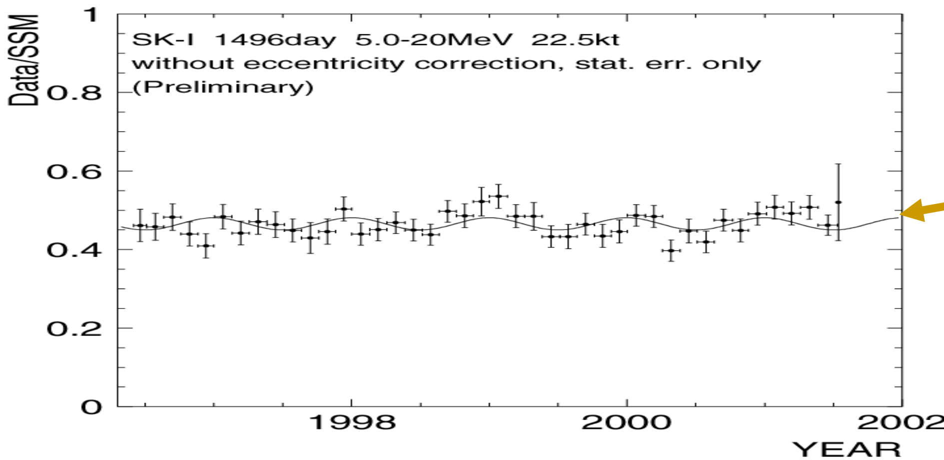
No sizable Day/Night effect

Day-Night Flux difference

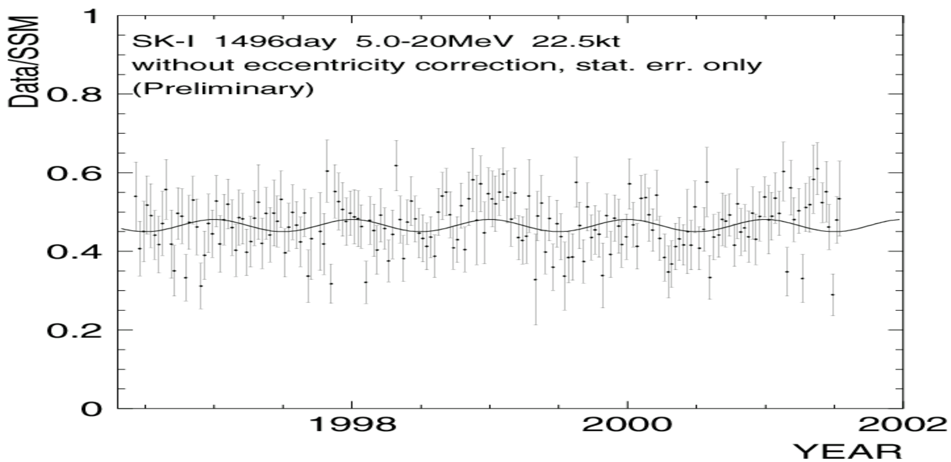
$\phi(^8B)_{day} = 2.32 \pm 0.03 \pm ^{0.08}_{0.07}$ $\phi(^8B)_{night} = 2.37 \pm 0.03 \pm 0.08$

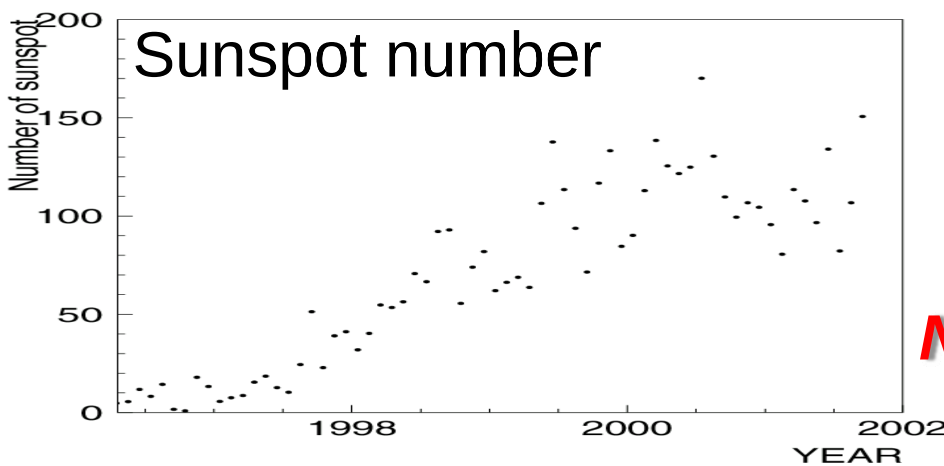
$$\frac{D-N}{(D+N)/2} = -(0.021 \pm 0.020 \pm ^{0.013}_{0.012})$$

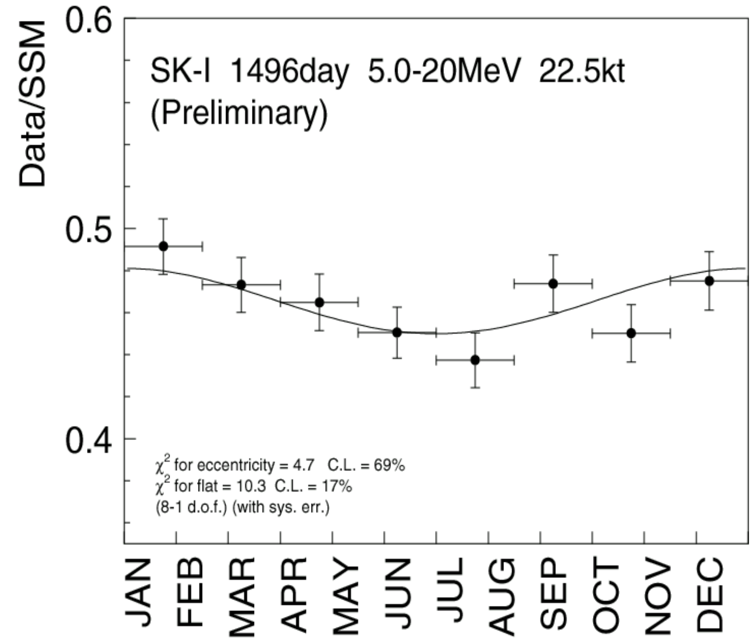
Flux and time variations



Eccentricity (7% annual variation)







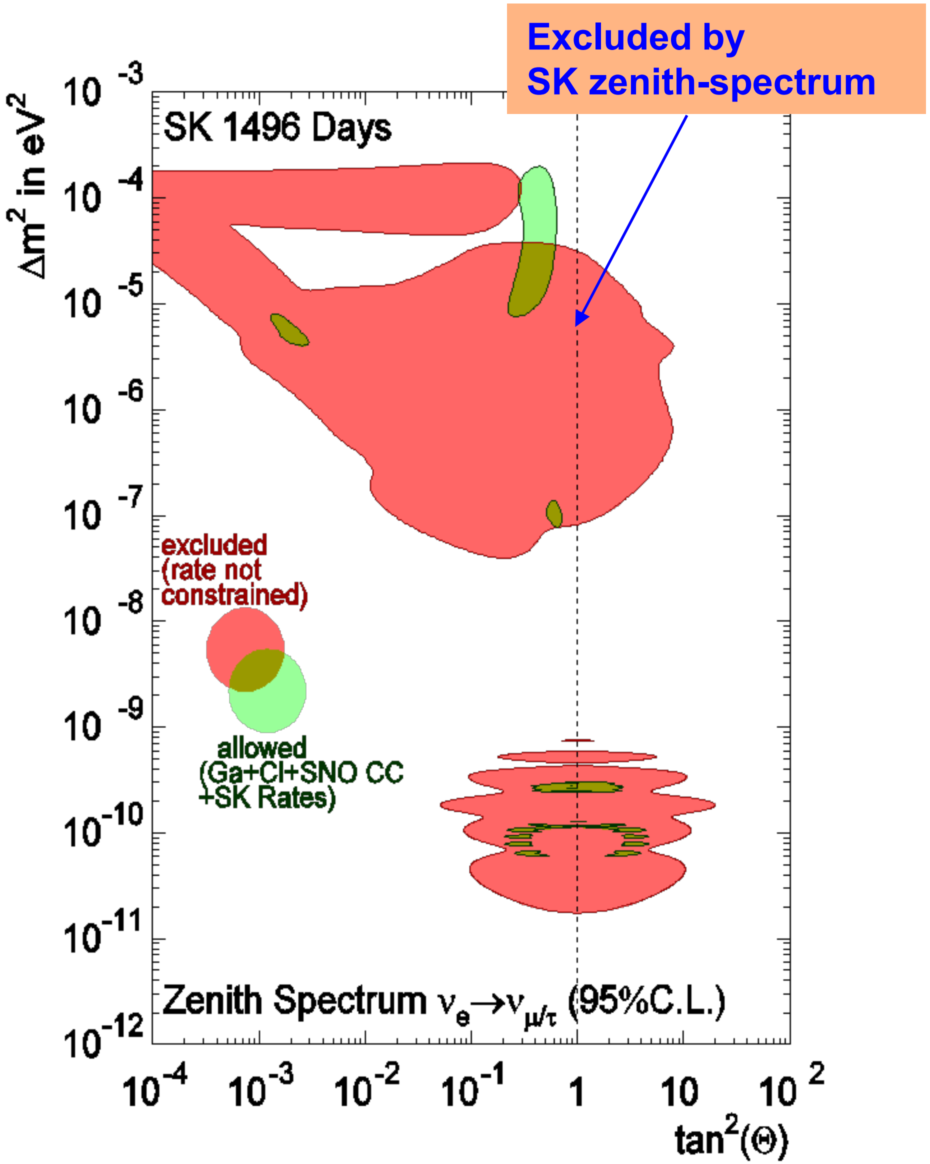
χ^2 = 4.7 / 7dof (69%) for eccentricity
χ^2 = 10.3 / 7dof (17%) for flat
$\Delta\chi^2 = 5.6$

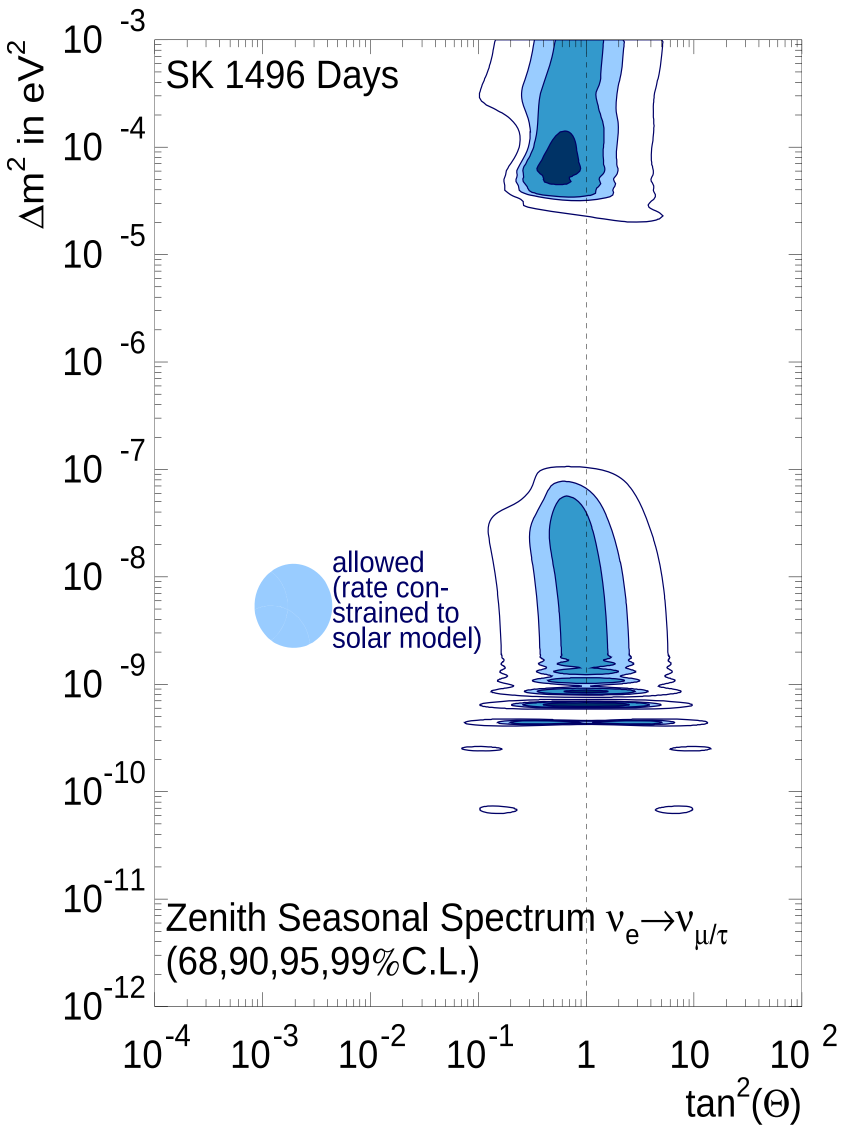
No seasonal or yearly variations

Small effect, but strong constraint

- LMA
  → Small energy distortion
  → Small day/night effect
  → No other time variations
  ➔ unlucky for Super-K
- But by the non-observation of those effects, SK provided strong constraint on the parameters (in 2000)
  - Disfavored SMA and VO(JustSo)
  - Suggested that the mixing angle is large

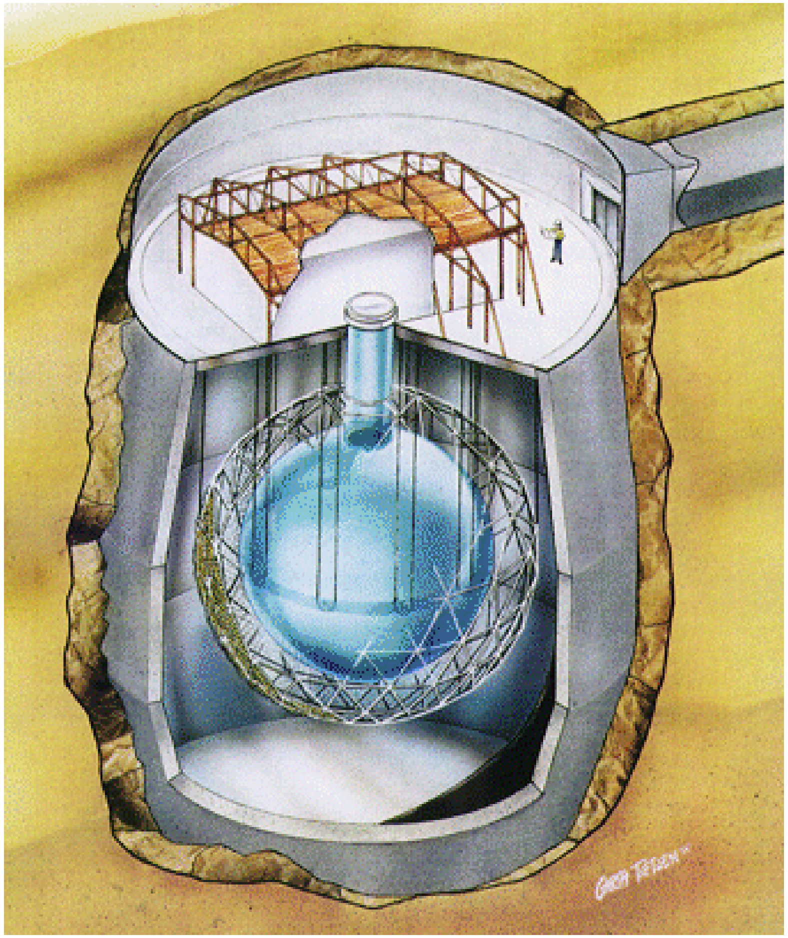
SK select large mixing





SNO (Sudbury Neutrino Observatory)

6000 mwe overburden



- 1000 tons D_2O
  - 12m Diameter Acrylic Vssel
- 1700 tons H_2O Inner Shield
- 9500 PMTs, 60% coverage
- Outer Shield H_2O
  - 5300 tons

SNO (Sudbury Neutrino Observatory)

Electron scattering (ES)

$\nu + e^- \rightarrow \nu + e^-$

ν_e and (ν_μ, ν_τ)x~0.15

Charged Current (CC)

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

sensitive only to ν_e

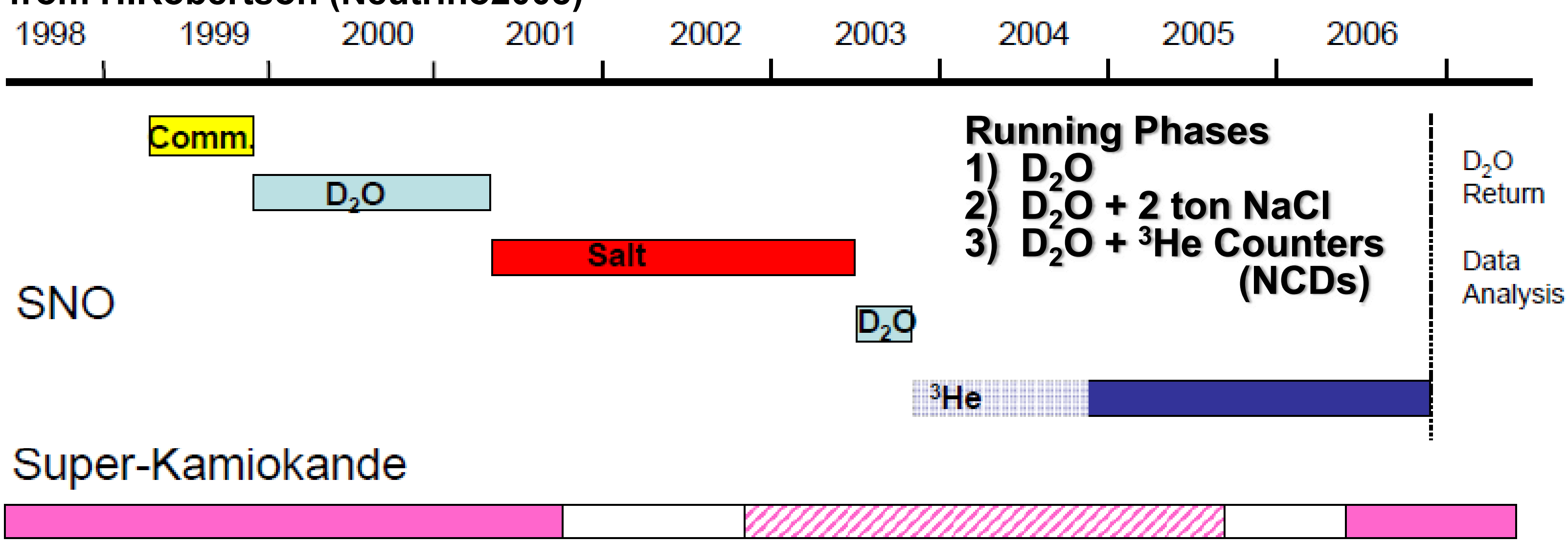
Neutral current interaction (NC)

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

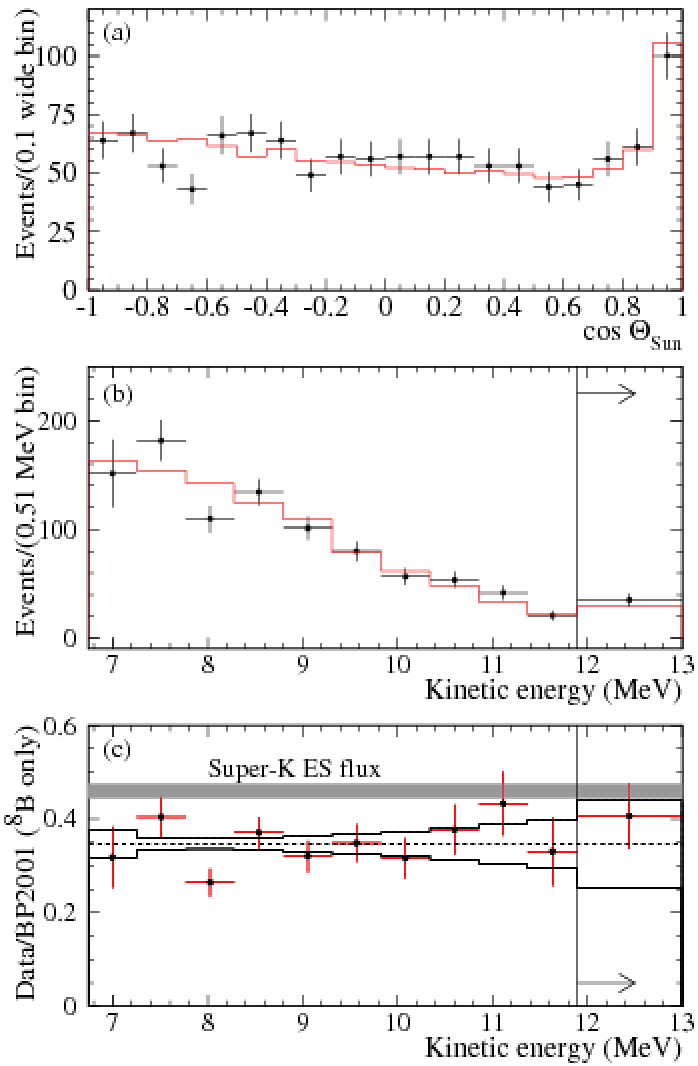
1) $n + d \rightarrow t + 6.25$ MeV γ
2) $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$ MeV $\sum\gamma$
3) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV

sensitive to all neutrinos

from H.Robertson (Neutrino2008)



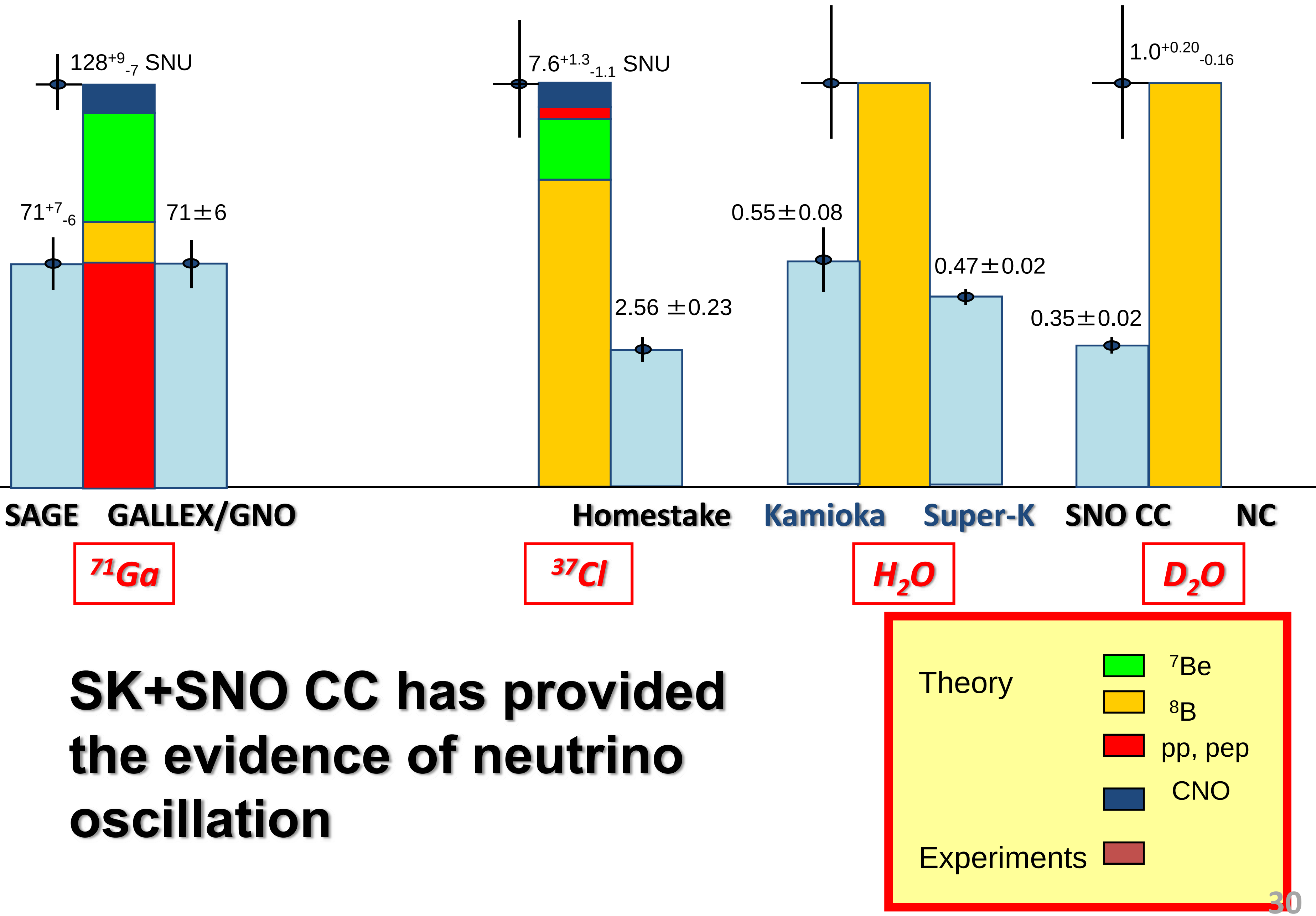
Phase I Charged Current Results and Evidence for Neutrino Oscillation[23]



$$\phi_{ES}(\nu_e) = 2.39 \pm 0.34(\text{stat.})^{+0.16}_{-0.14}(\text{sys.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

$$\phi_{cc}(\nu_e) = 1.75 \pm 0.07(\text{stat.})^{+0.12}_{-0.11}(\text{sys.}) \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$$

Solar neutrino flux measurements



SK+SNO CC has provided the evidence of neutrino oscillation

Discovery of Solar Neutrino Oscillation

- **SK (ES) +SNO（CC) in June 2001**

ν_e produced in the sun

Prediction from SSM

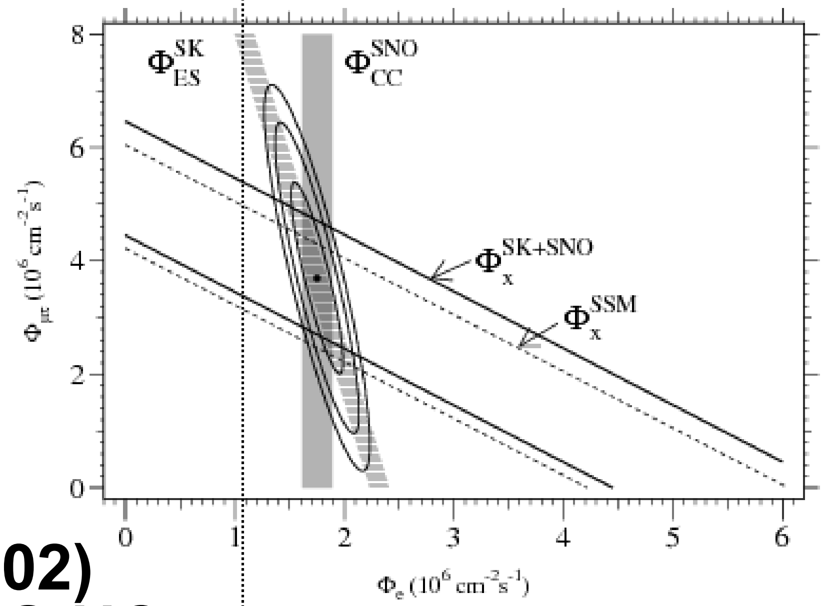
ν_e + (ν_μ,ν_τ)x0.15

SK 46.5 %

SNO CC 35 %

SK break down 35% from ν_e,remaining from ν_μ,ν_τ

Total ν flux 5.7±0.9 [x10^6/cm^2/s]



Evidence of Neutrino Oscillation

Existence of $\nu_{\mu,\tau}$ components in the solar neutrinos measured at earth.

(in 2002)
SNO NC 5.1±0.6 [x10^6/cm^2/s]

SNO Neutral Current Measurements

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

1) $n + d \rightarrow t + 6.25$ MeV γ

2) $n + {}^{35}Cl \rightarrow {}^{36}Cl + 8.6$ MeV $\sum\gamma$ (~2000 kg of NaCl)

3) $n + {}^{3}He \rightarrow p + t + 0.76$ MeV

^{3}He NCD

- 36 strings of ^{3}He and
  4 strings of ^{4}He counters on a 1m x1m grid.
- Capture efficiency ~ 21%

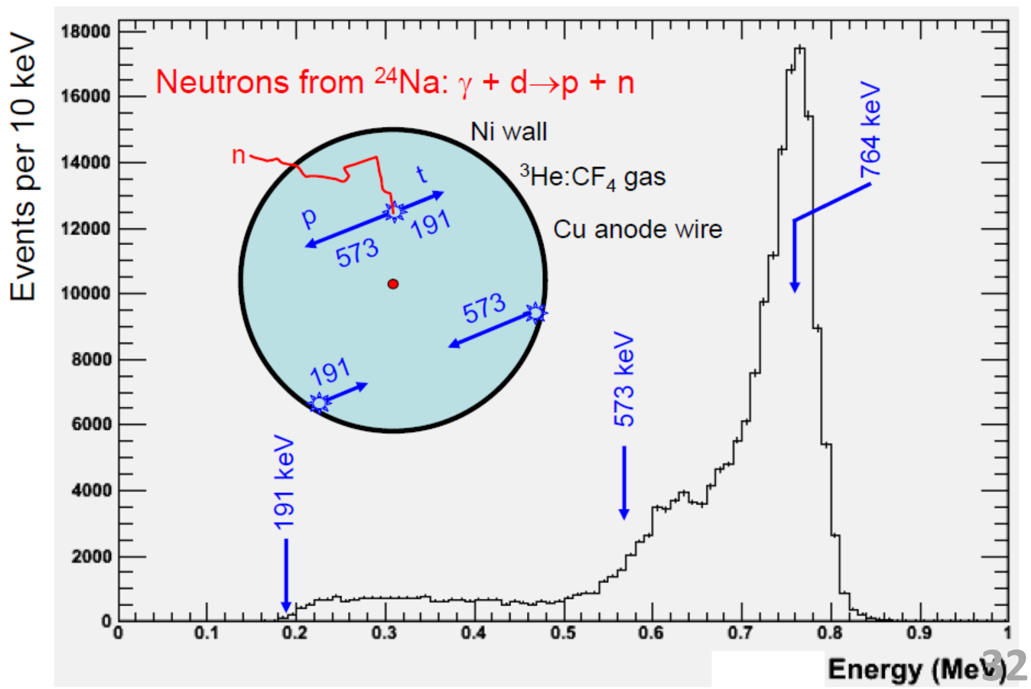
Advantage

- Separate signal paths: CC and NC
- Reduction of 6.25 MeV gamma

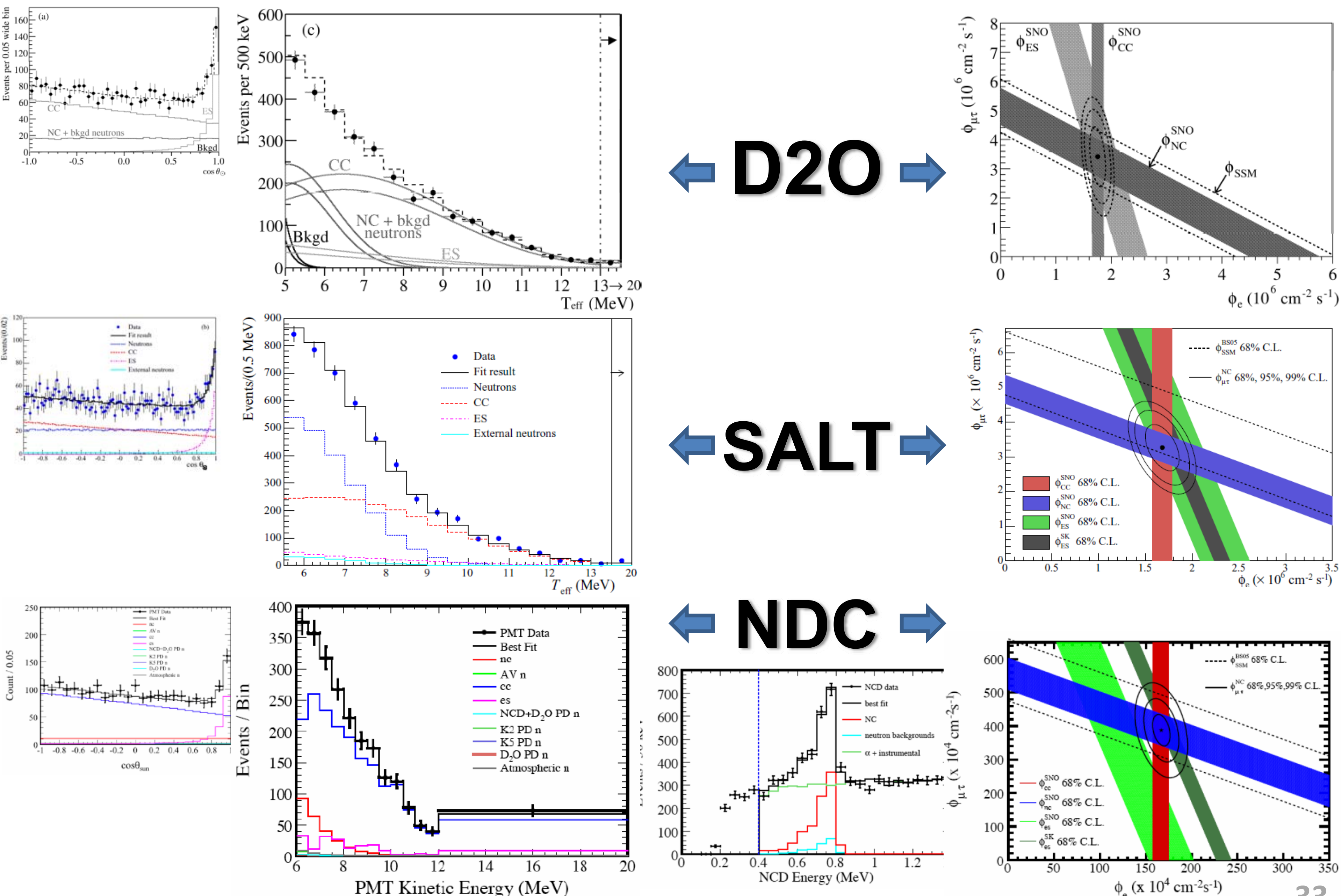
Difficulties

- Low signal rate: ~1000 n/year
- Ultra-low BG materials needed
- Light loss

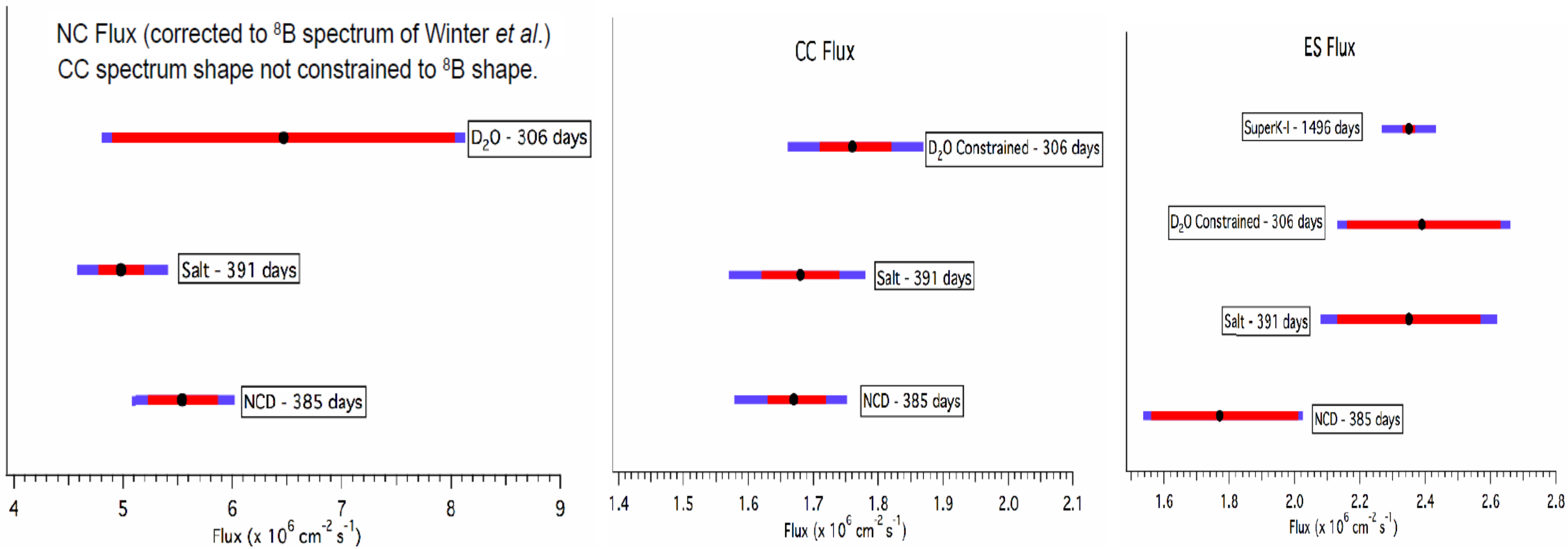
Energy Spectrum



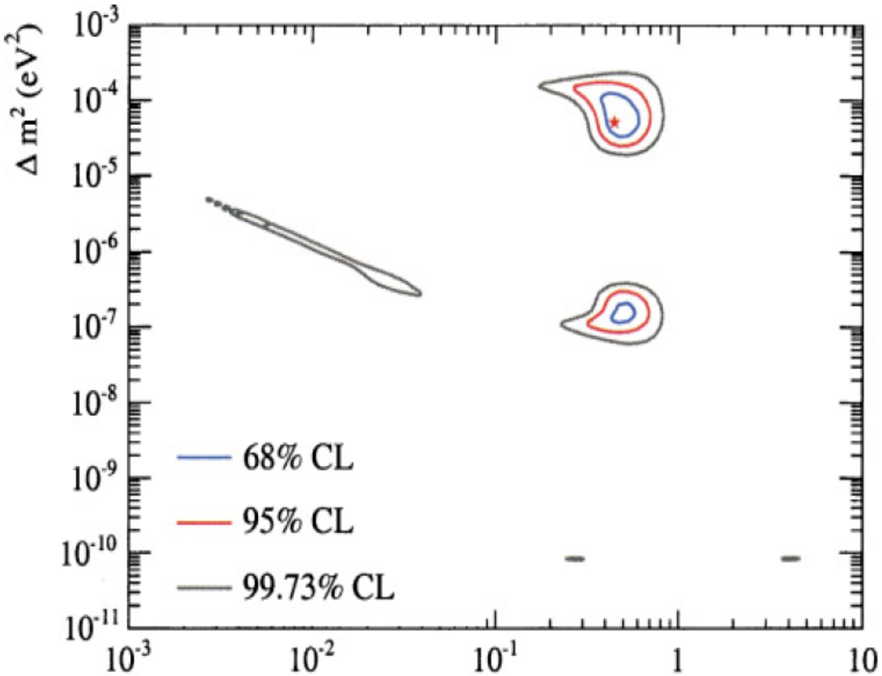
SNO Neutral Current Measurements



SNO Phase II and Phase III

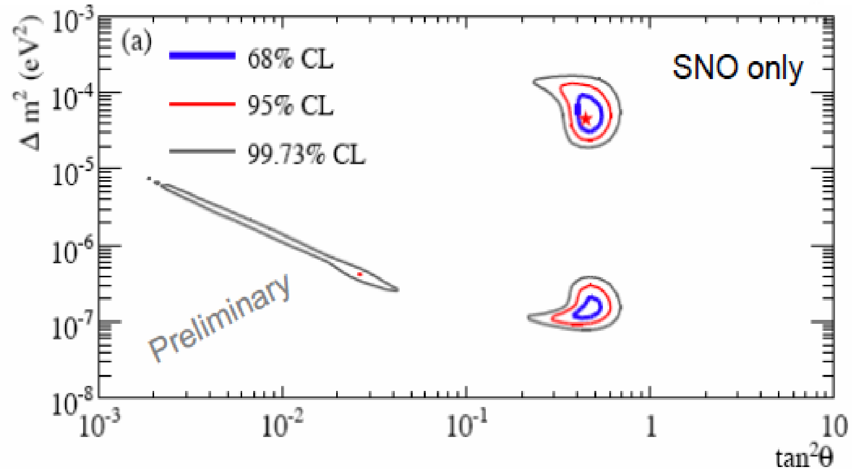


SNO Only Results



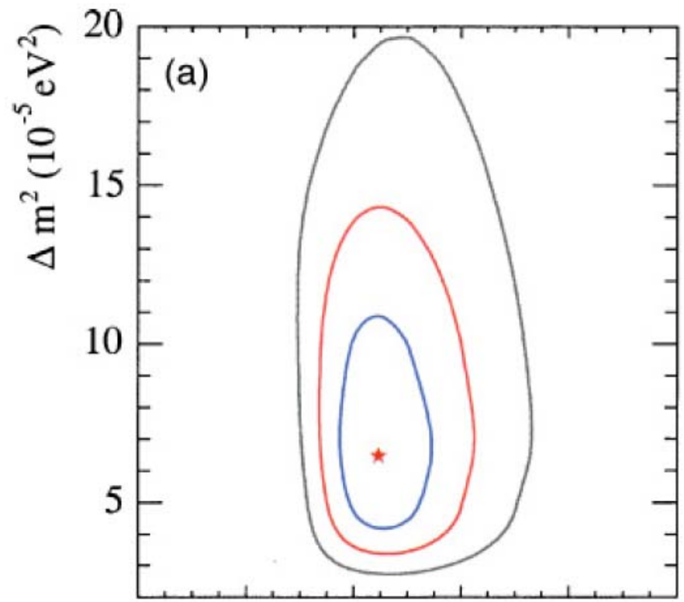
Phase I+II

- We need other solar neutrino experiments to single out the solution

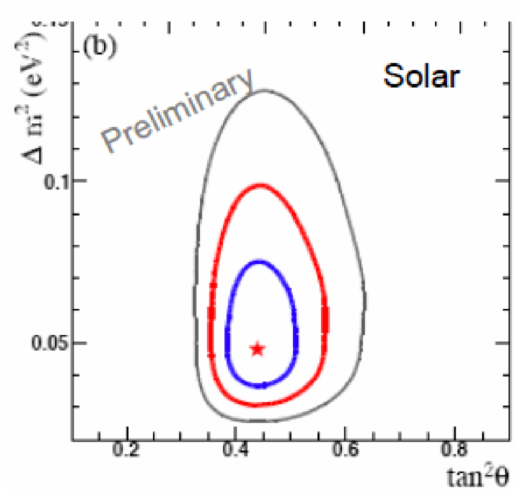


Phase I+II+III

Solar Neutriono Results

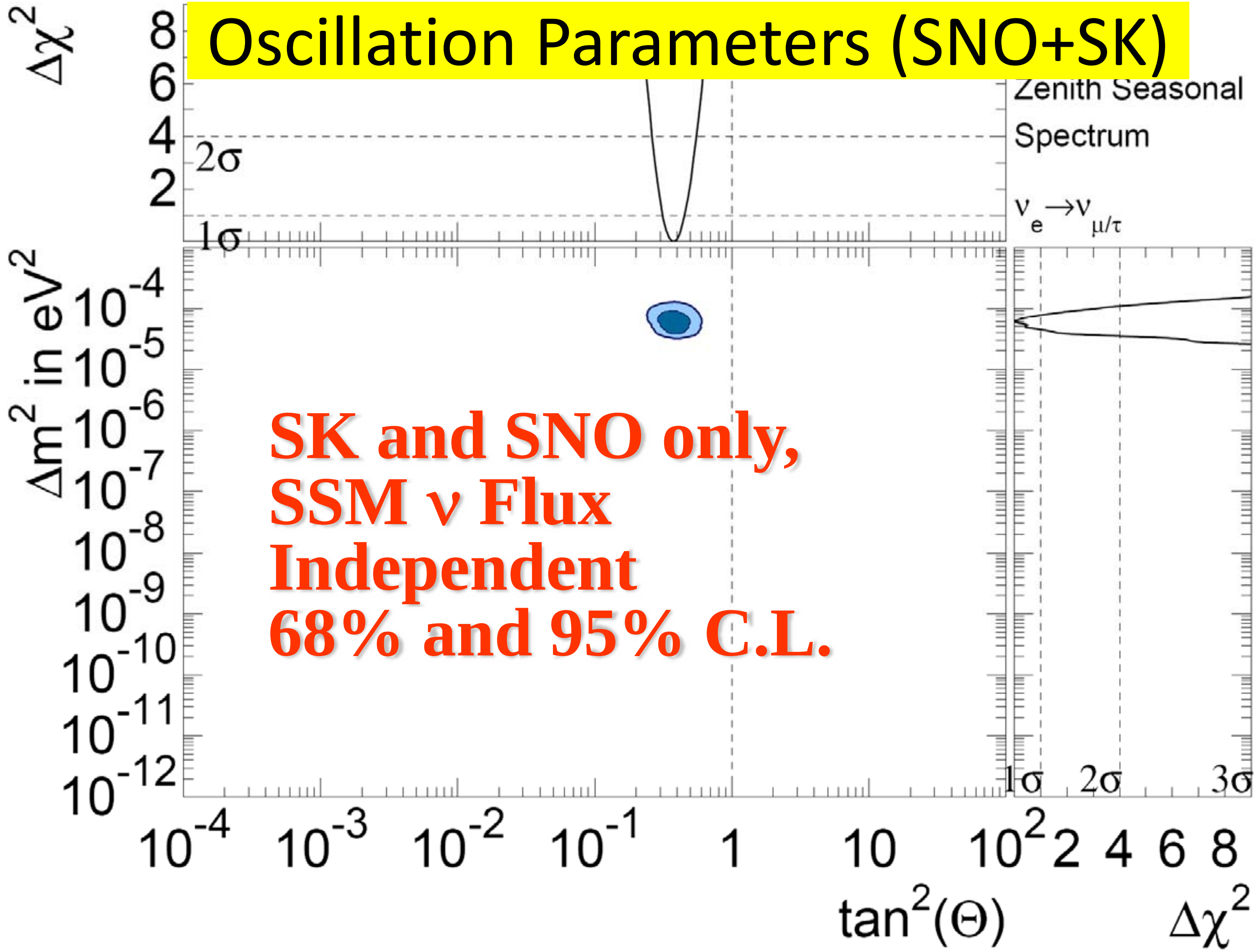


Phase I+II



Phase I+II+III

Oscillation Parameters (SNO+SK)



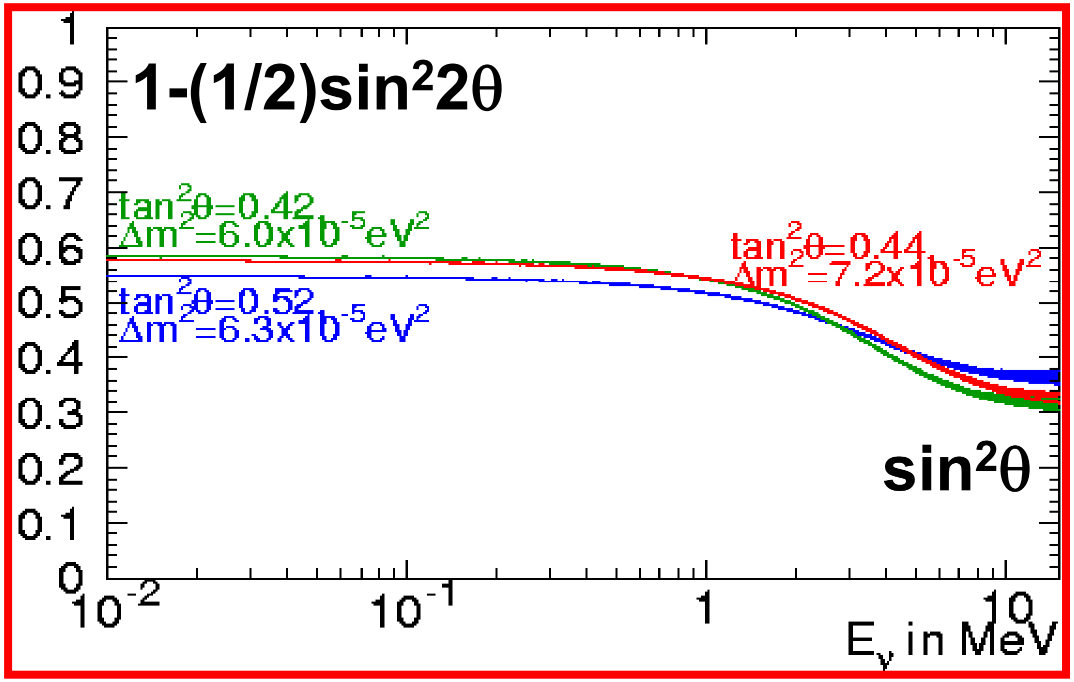
SK and SNO only,
SSM ν Flux
Independent
68% and 95% C.L.

SK+SNO (Salt) best
($\tan^2\theta=0.38$, $\Delta m^2=6.0\times10^{-5} eV^2$)

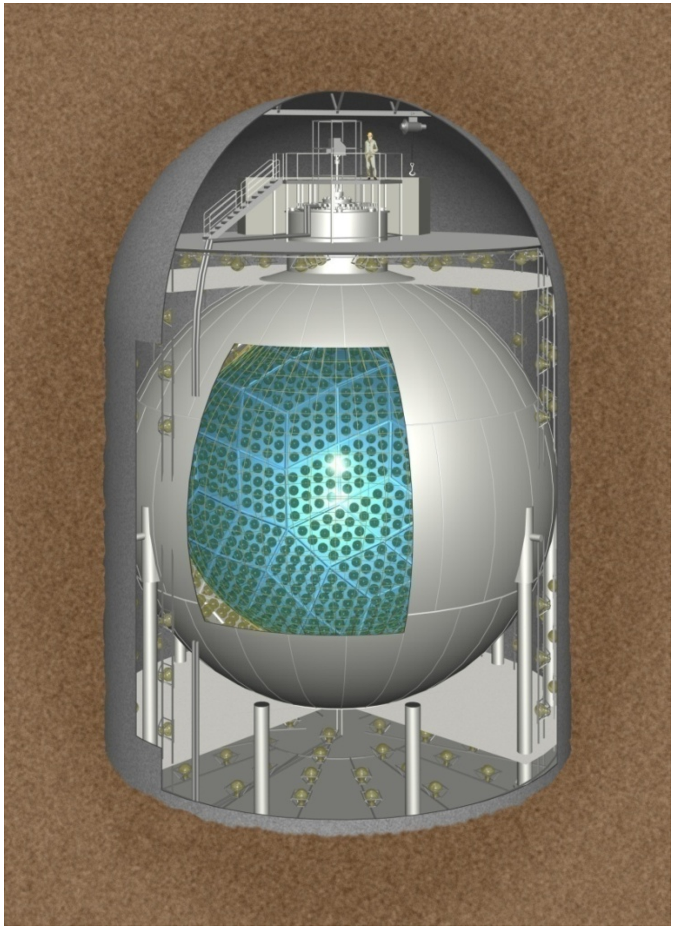
Large Mixing Angle Solution

- **In the sun (for LMA solutions)**
  - **Low energy ν below ~1 MeV, never pass the resonance:**
    - $\theta_m \rightarrow \theta_V$ (E <1 MeV) ➔ $P=1-(1/2)\sin^2 2\theta$
  - **Eν > 1 MeV: adiabatic**

    $P=\cos^2\theta\cos^2\theta_m+\sin^2\theta\sin^2\theta_m$:
    - $\theta_m \rightarrow \pi/2$ ➔ $P=\sin^2\theta$



KamLAND



Long Baseline Reactor Experiment

1 kton liq. scint. (target and detector)

1,280 17“ PMTs; 550 20” PMTs

→ 34% coverage

Water Cherenkov Veto Counter

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$207\mu s$ ↳ $+ p \rightarrow \gamma$ (2.2MeV)

Prompt event: e^+

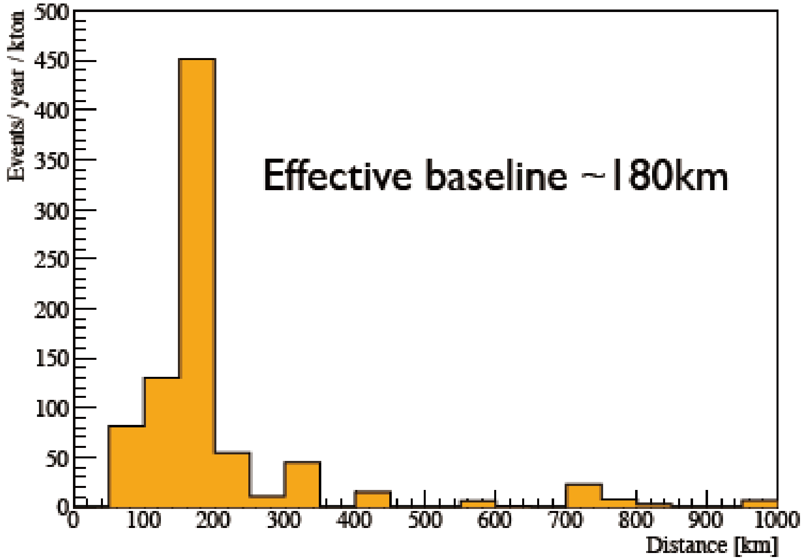
$E\nu_e = Ee^+ + 0.8$ MeV

Delayed event: neutron capture

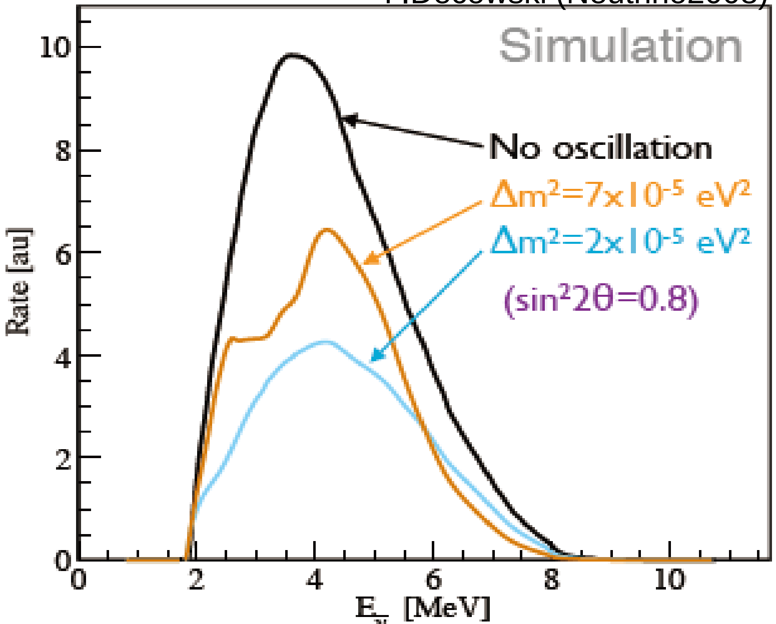
2.2 MeV γ

Reactor Neutrinos

- ***70GW of Commercial Nuclear Power (7% of the world) is generated between 130 and 220 km from Kamioka***



P.Decowski (Neutrino2008)

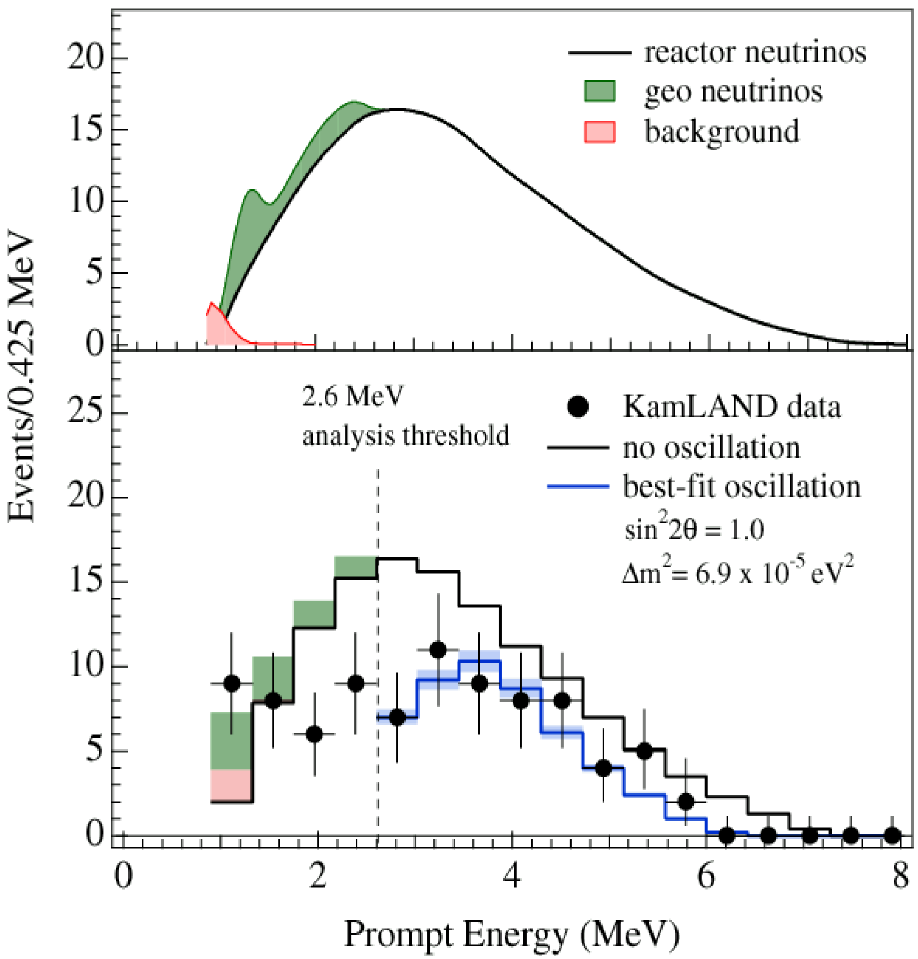


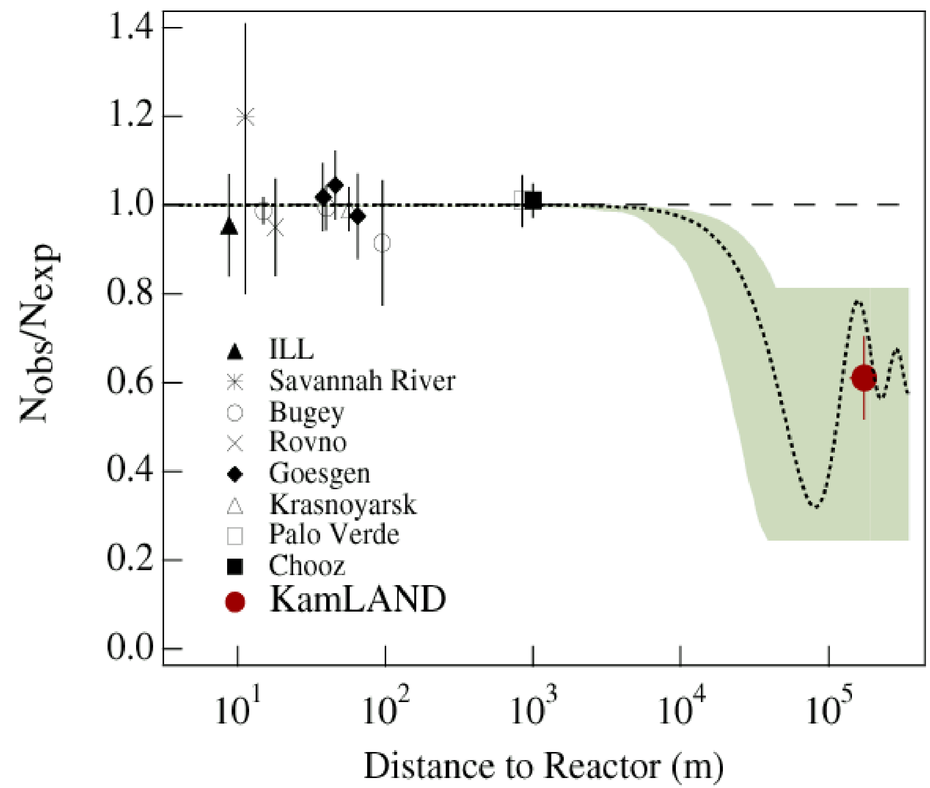
<L> ~ 180km

<Eν> ~ 5 MeV

$\Delta m^2 > 3x10^{-5}eV^2$
(sensitivity)

KamLAND 1st Results





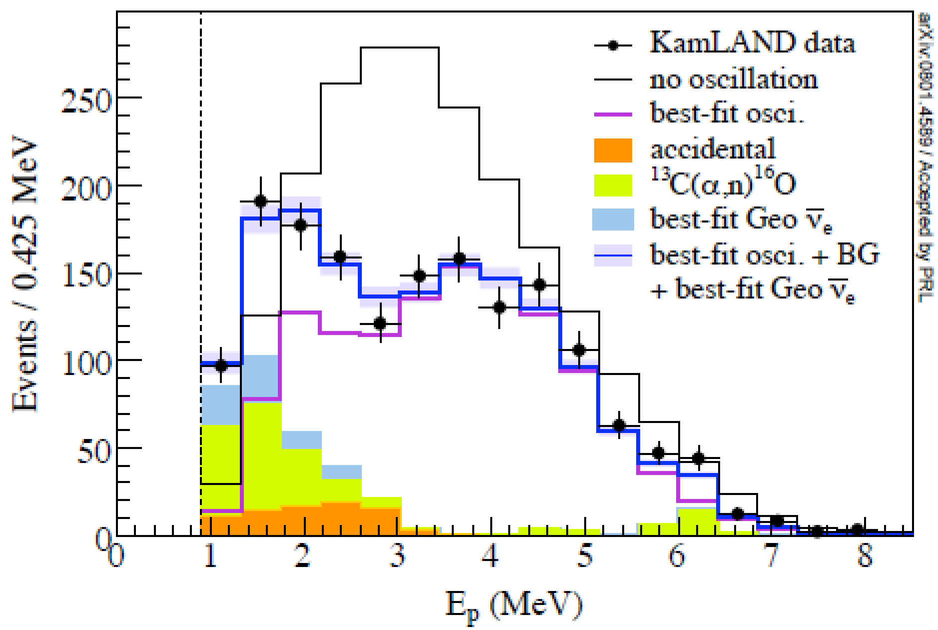
141.1 days
Observe 54 events
Expects 86.8 ±5.6 events

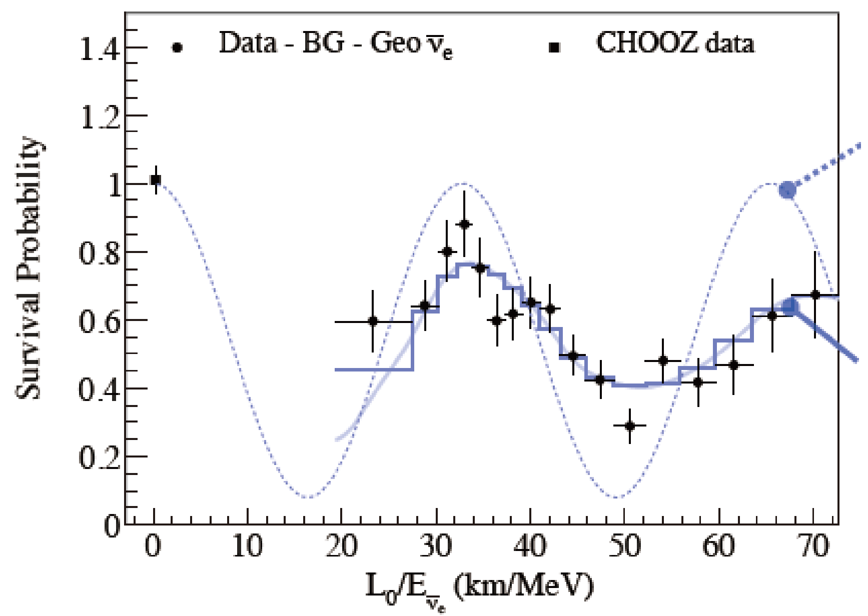
Ratio = 0.661±0.085 ±0.041

Latest Results from KamLAND

	Max Radius (m)	Liivetime(days)	Exposure (ton･yr)
KL2002	5	145	162
KL2004	5.5	515	766
KL2007	6	1492	2881

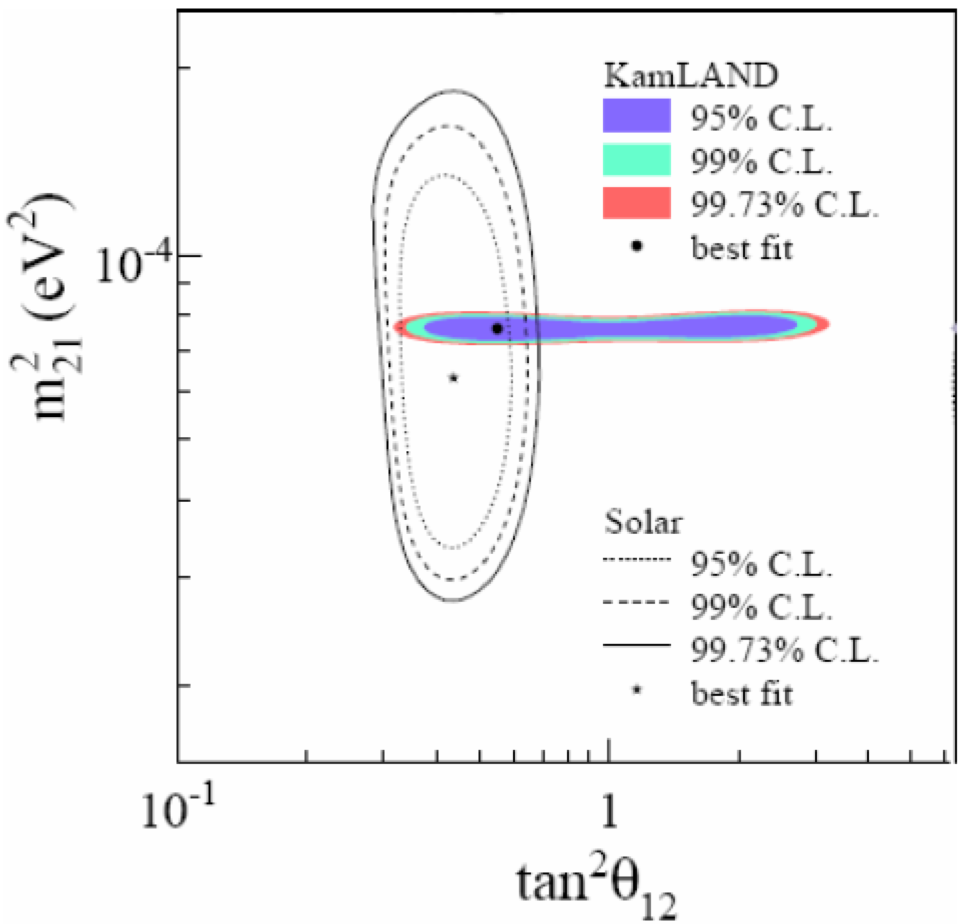
No oscillation spectrum: excluded at 5.1σ



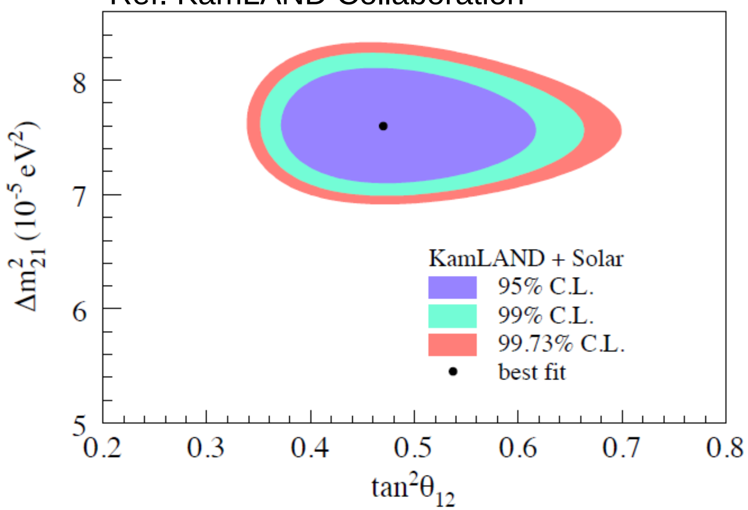


Precise Determination of the Large Mixing Angle Solution

Ref. KamLAND Collaboration



Ref. KamLAND Collaboration



Best fit:

Solar + KamLAND(2008)

$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

$\Delta m^2 = 7.59 \pm 0.21$ eV^2

Solar ν vs KamLAND

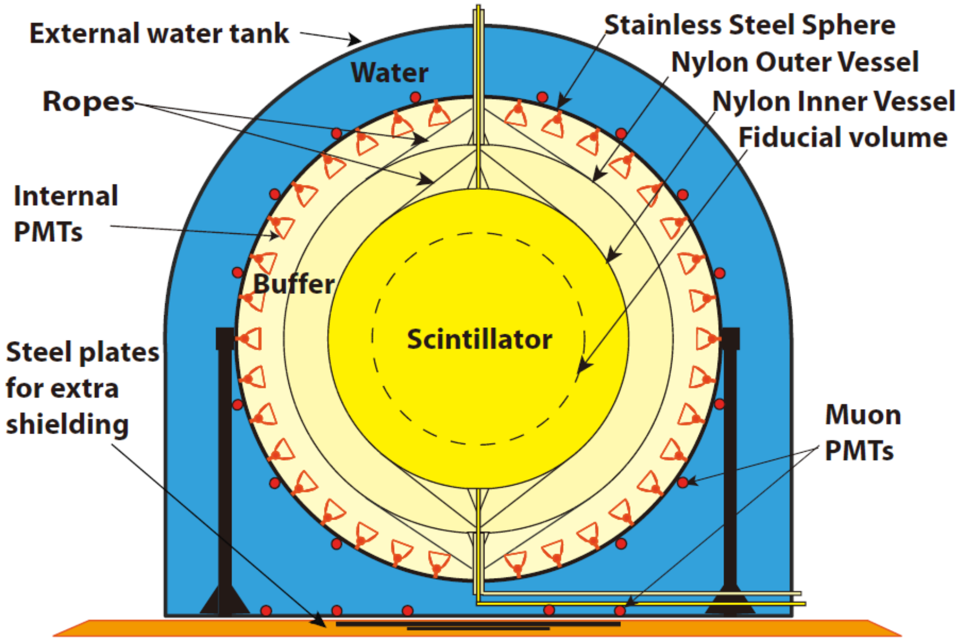
$$\begin{matrix} \Delta m^2 sol \\ \tan^2\theta sol \end{matrix} \sim \begin{matrix} \Delta m^2 KL \\ \tan^2\theta KL \end{matrix}$$

- **Caution about the difference**

Solar neutrinos	KamLAND
ν_e	$\bar{\nu}_e$
Adiabatic conversion; matter effect (SK,SNO) ~ Vacuum (pp-ν, ^{7}Be-ν)	Vacuum oscillation
Very Long Base-line	Relatively Short-base line
No phase information	Phase is crucial
Strong magnetic fields in the sun	No magnetic fields

Borexino

Located at 3800 mwe depth



Use various techniques to reduce backgrounds

1. Low BG nylon fabrication in a low Rn room
2. Rapid transport to avoid cosmo-genic prod.
3. Underground purification plant
4. Gas stripping of scintillator

etc…..

- Use ν+e → ν+e
  - Detect scintillation light by PMTs
  - No directionality
- 278 tons liq. scintillator in Nylon Balloon (r=4.25m)
- Shielded by buffer liquid and water
- Buffer liquid: 890 tons (r=6.75m)
- Outer Nylon Barrier aginst Rn form PMsT
- 2214 PMTs see scintillator
- 2100 tons of water in a cylindrical dome

Purpose

- Test of LMA, especially to explore the vacuum matter transition region
- Look for new physics
  - MaVAN, NSI,,,,,
- Test metallicity of the sun

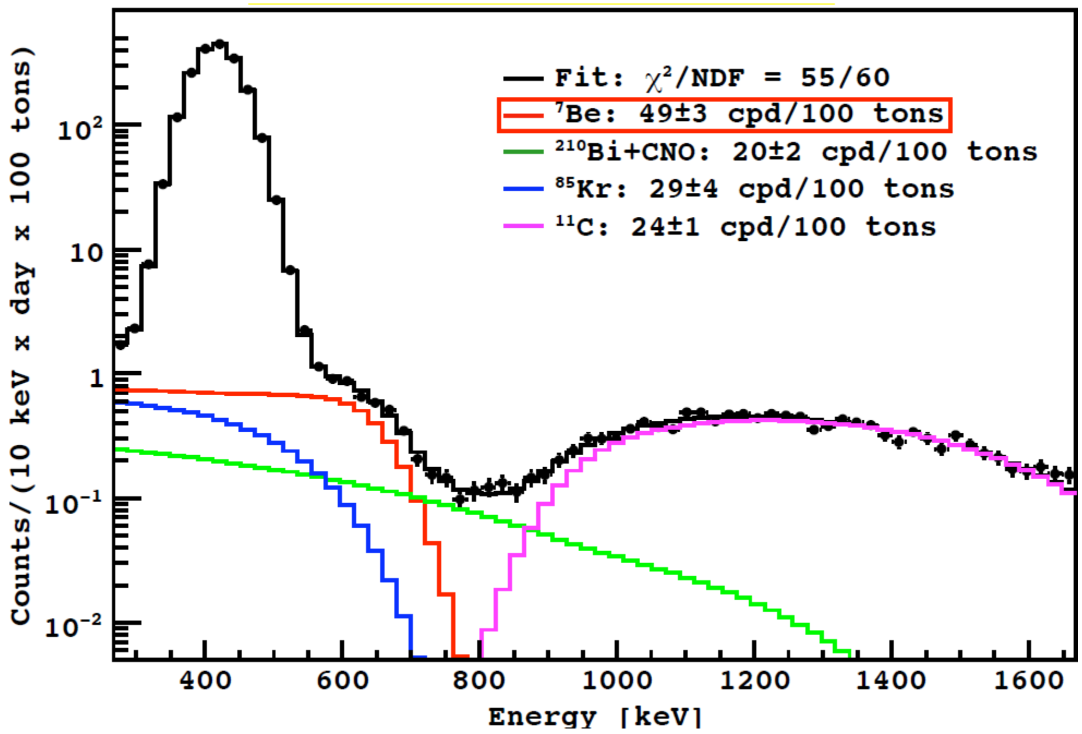
  ← CNO

192days Borexino Results

- **Detected:**
49±3(stat.)±4(syst.) (cpd/100ton)

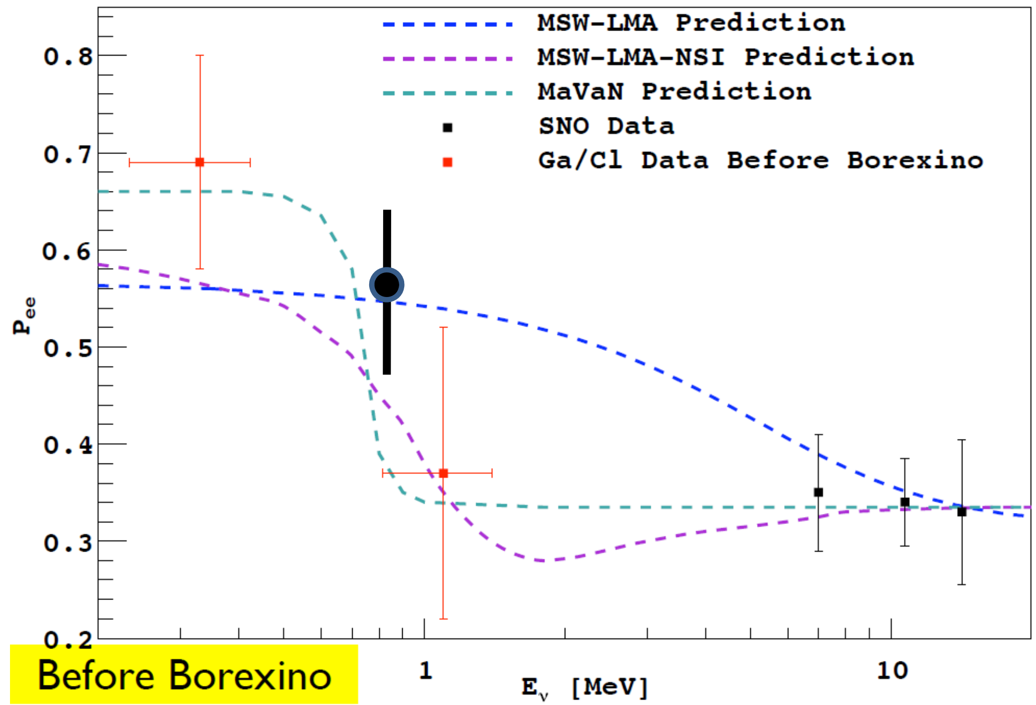
- **No Oscillation**
75±4 cpd/100tons (cpd/100ton)

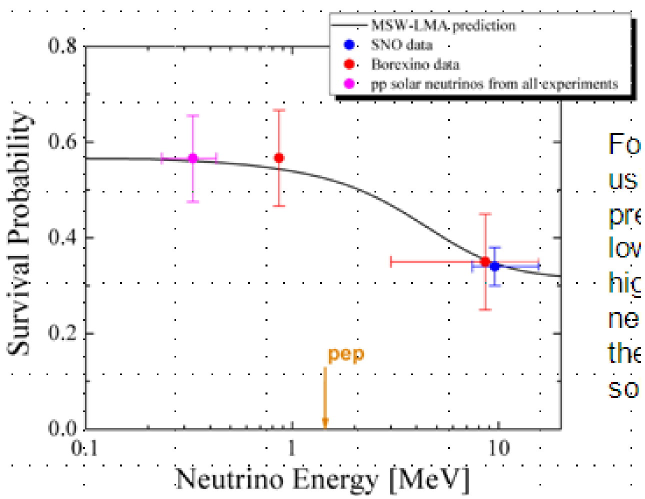
- **LMA**
48±14cpd/100tons (cpd/100ton)



192days Borexino Results

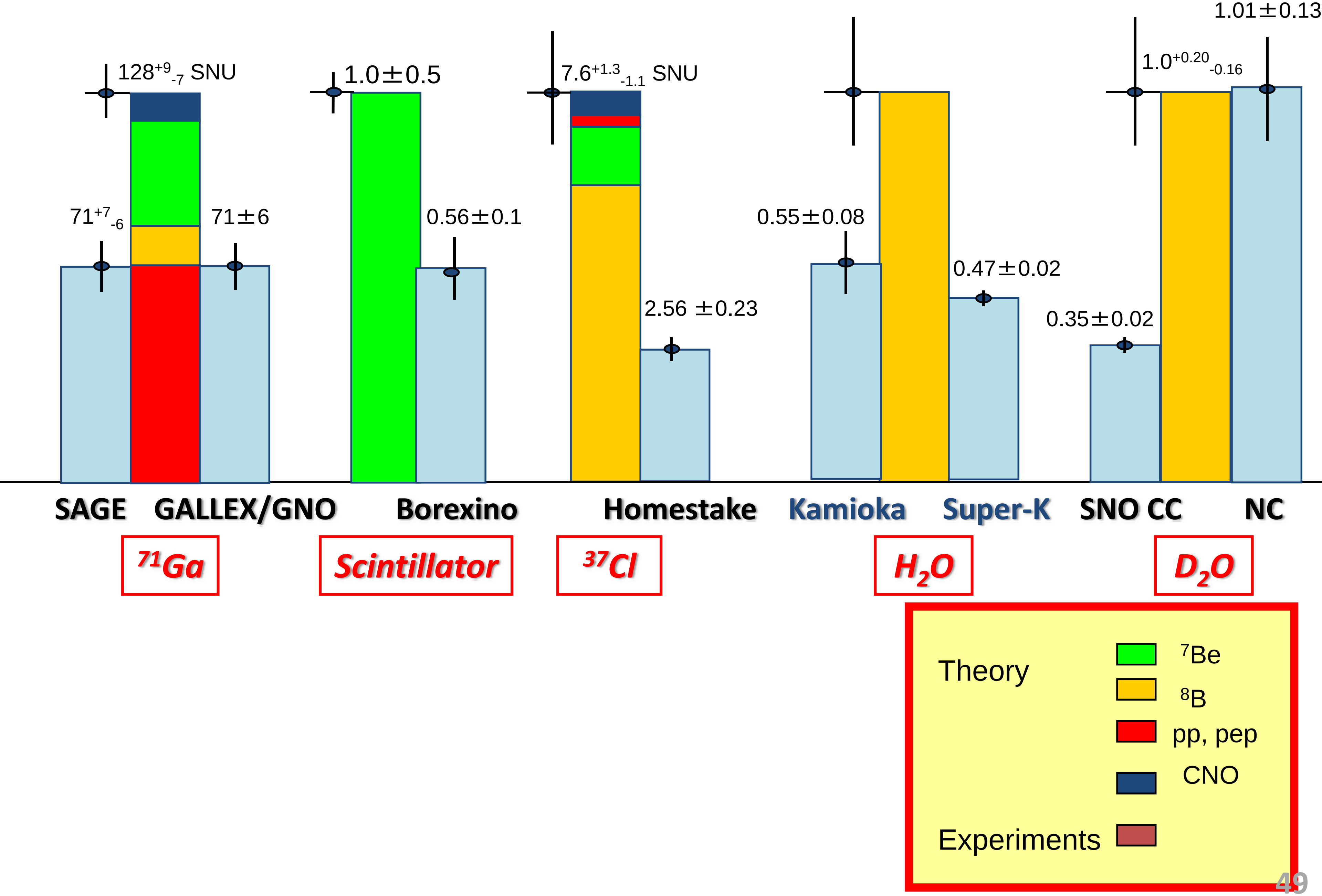
- $\phi(^7Be) = 5.08 \pm 0.25 \times 10^9\ cm^{-2}s^{-1}$
- $P_{ee}(^7Be) = 0.56 \pm 0.08$





@NOW2008
ArXiv 0808,2868
Start to see ^8B neutrinos

Solar neutrino flux measurements



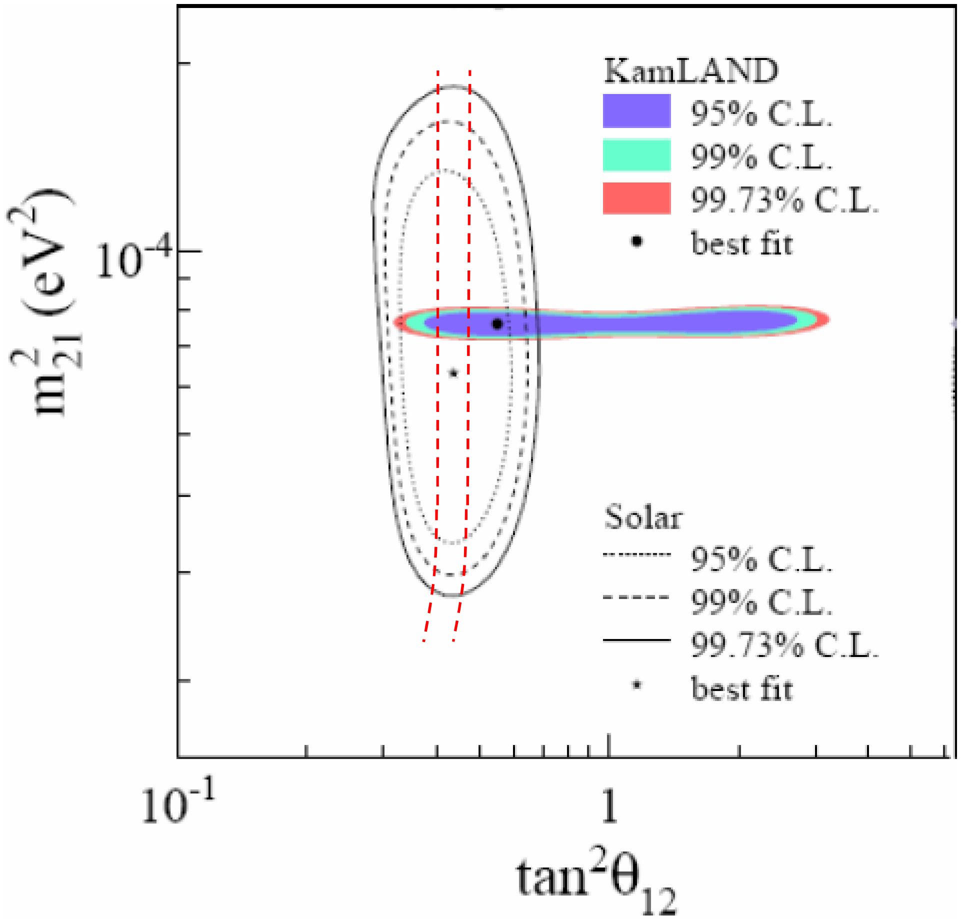
Future (What is missing)

- **Precise test of LMA**
  - **Low energy neutrinos (pp, 7Be, pep)**
    - **Cl Problem**

      ← Borexino, KamLAND, SNO+, XMASS
  - **upturn and continuous measurement of lower side of ^{8}B**
    - **Borexino**
    - **Super-K**
- **Precise determination of oscillation parameters**
  - **Δm^2 ← KamLAND**
  - **θ ← pp, precise Day/Night (^{8}B) → XMASS (pp)**
- **Test of solar metallicity**
  - **CNO , NC**
    - **Borexino, KamLAND, SNO+**
- **Solar vs KamLAND (Reactor)**
  - **CPT ?,?,?**
- **Look for new Physics**

$\tan\theta_{12}$ improvement

Xmass 5yrs for pp-neutrinos

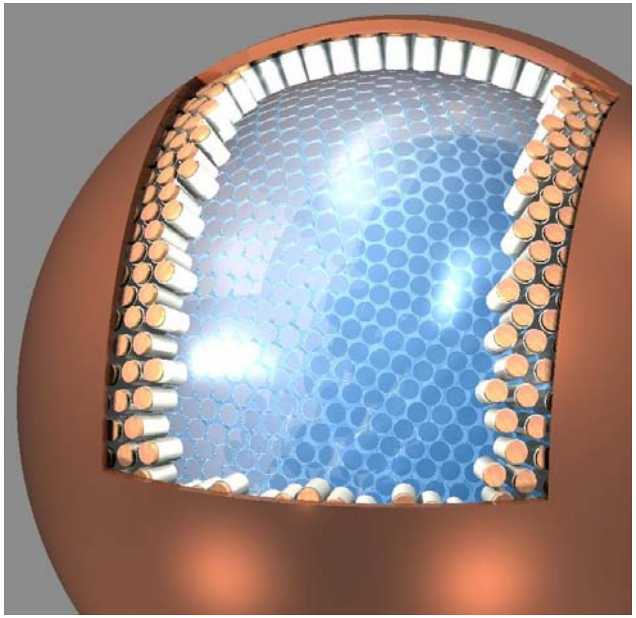


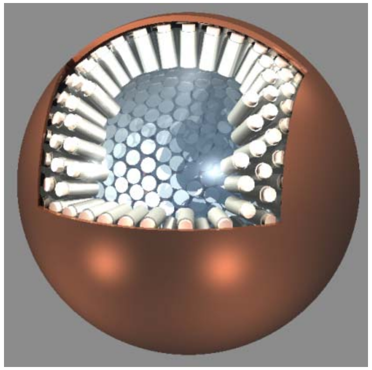
Statistical error and SSM prediction error

➔ 1%

➔ pp neutrino can determine θ_{12} very accurately

XMASS





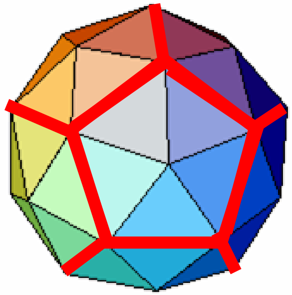
Ref: Y. Suzuki et al., hep-ph/0008296, (2000).

- ***Multi-purpose astro-partcle and neutrino experiment***
  - **10 ton fiducial mass**
    (2.5 m in diameter (24 tons))
    - **Dark Matter**
    - **Solar pp-neutrinos** $\nu+e \rightarrow \nu+e$
    - **Double beta decay** $^{136}Xe \rightarrow ^{136}Ba+2e$
- ***First phase:***
  - **100kg fiducial mass**
    (0.8 m in diameter (850kg))
    - **Dark Matter**

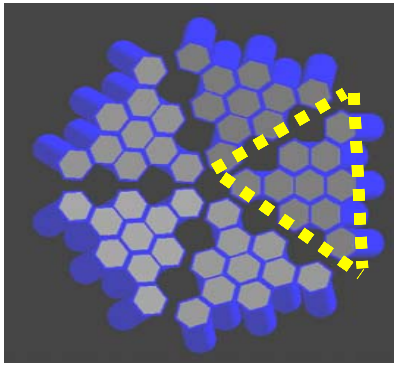
Why liquid xenon

- **Large photon yield (~42 photons/keV ~ NaI(Tl))**
  Low threshold
- **High density (~3 g/cm^3)**
  Compact detector (10 ton: sphere with diameter of ~2m)
- **Large Z (=54)**
  Shielding effect by itself (self-shield) is large.
- Purification (distillation)
- No long life radioactive isotope
- Scintillation wavelength (175 nm, detected directly by PMT)
- Free from Carbon

→ We can achieve low energy threshold and low background.



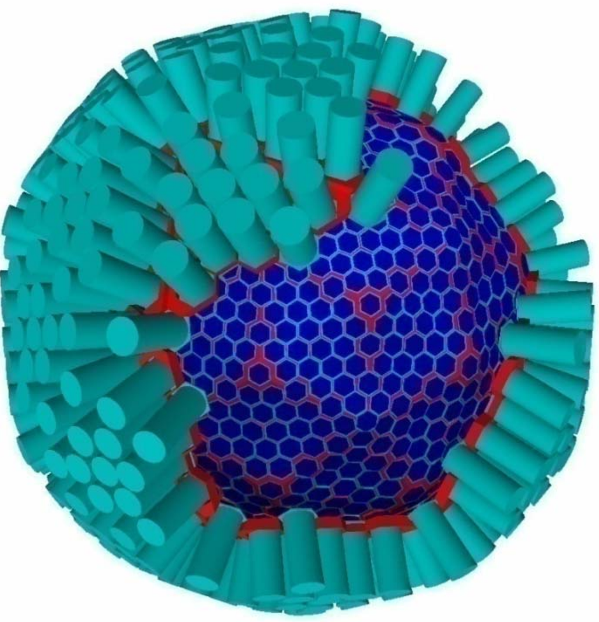
Phase I detector



- **Single phase liq. Xe**
- **Pentakis-dodecahedron**

  ← 12 pentagonal pyramids

  Each pyramid ← 5 triangles
- **Radius: 39~42 cm**
- **642 Hex. PMT immersed in liq. Xe**
- **PMT photo-cathode coverage: 64%**
- **Inner mass of Xenon: 857kg (~3g/cm^3)**



Aim, Signal and Backgrounds

Aim:

– **10^{-4} dru (ev/kg/keV/day)** *before any PSD applied*

➔ **10^{-45}cm^2 SI for ~100GeV WIMPs**

For the signal detection

– **Low threshold: ~ 5 keV or less**

🡐 8 pe /keV (64% photo-cov.)

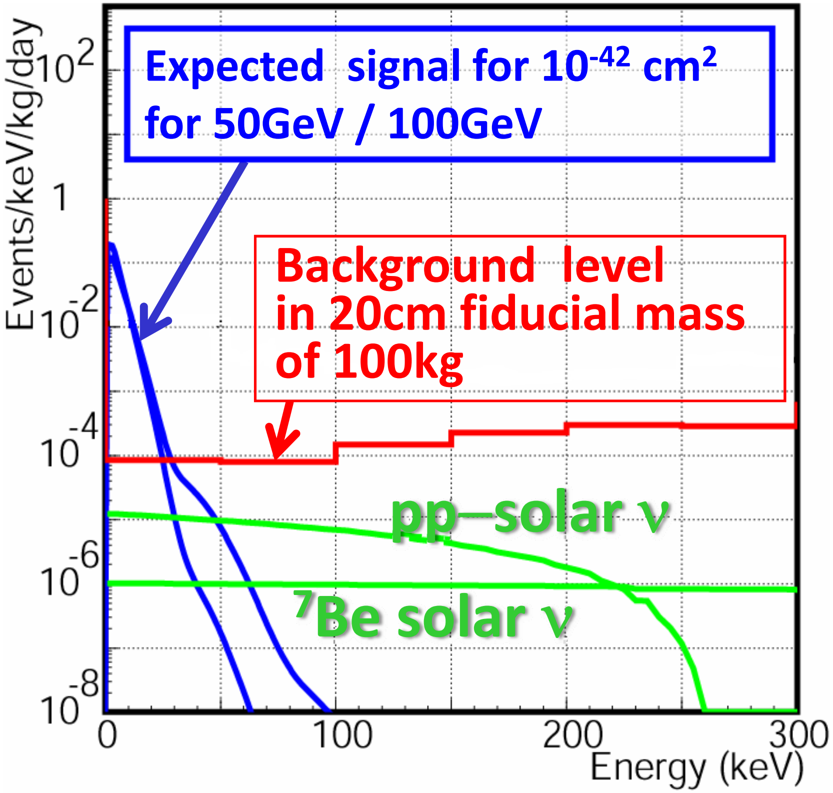
– **Large fiducial volume: 100kg or more**

20cmϕ: 100kg

(20cm self-shield)

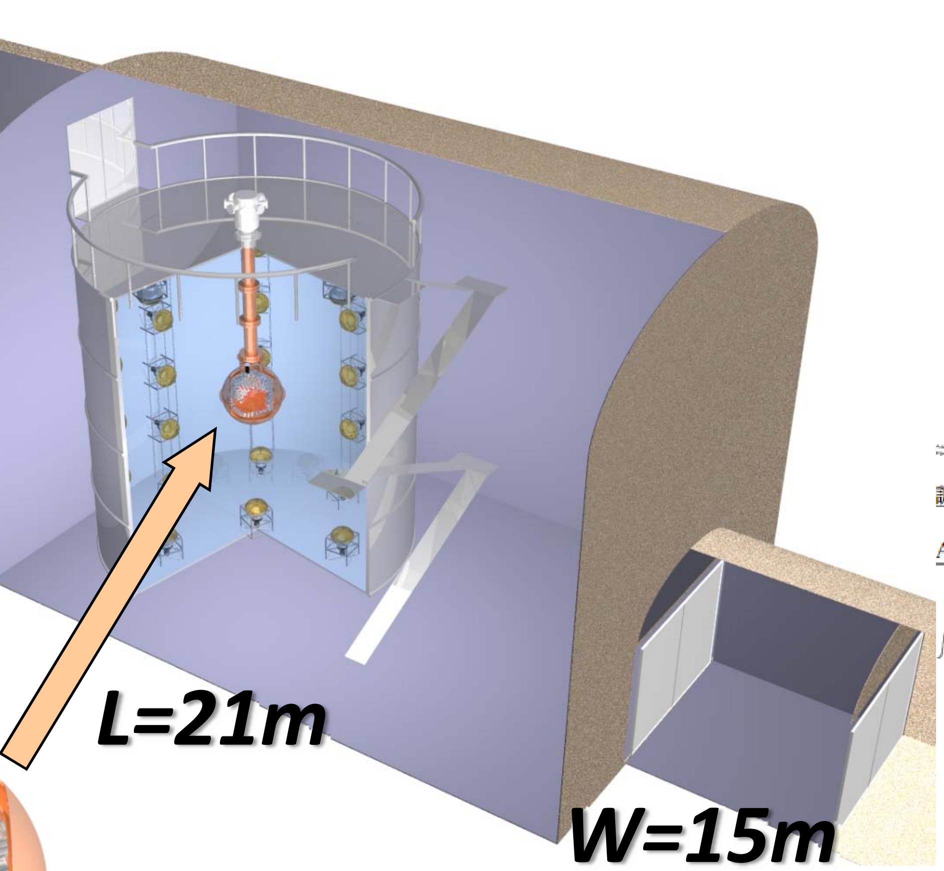
25cmϕ: 200kg

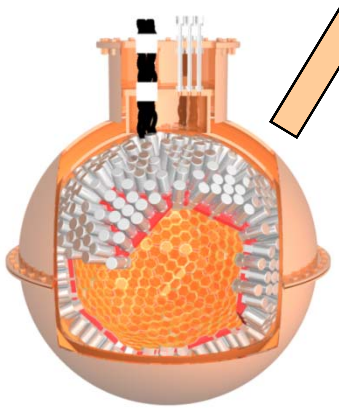
(15cm self-shield)

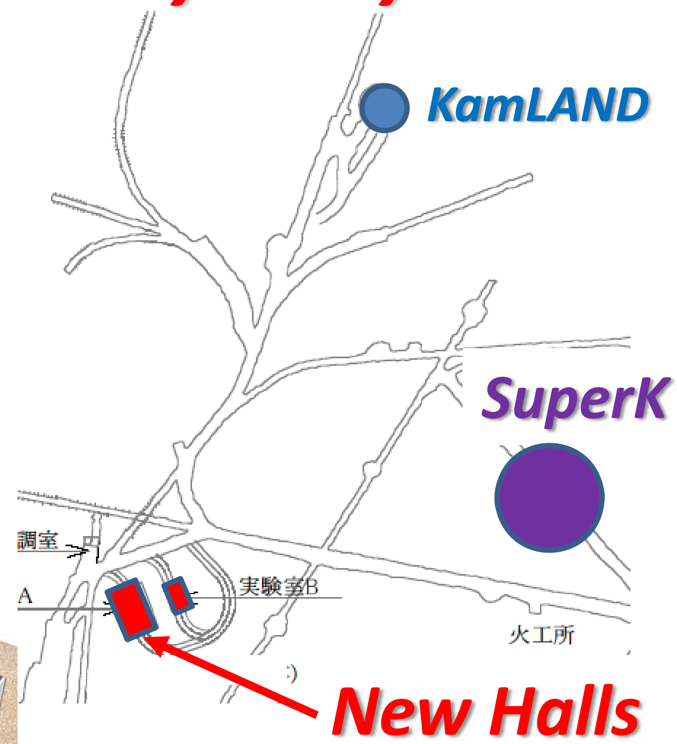


New Experimental Hall

Cavity was completed in February this year



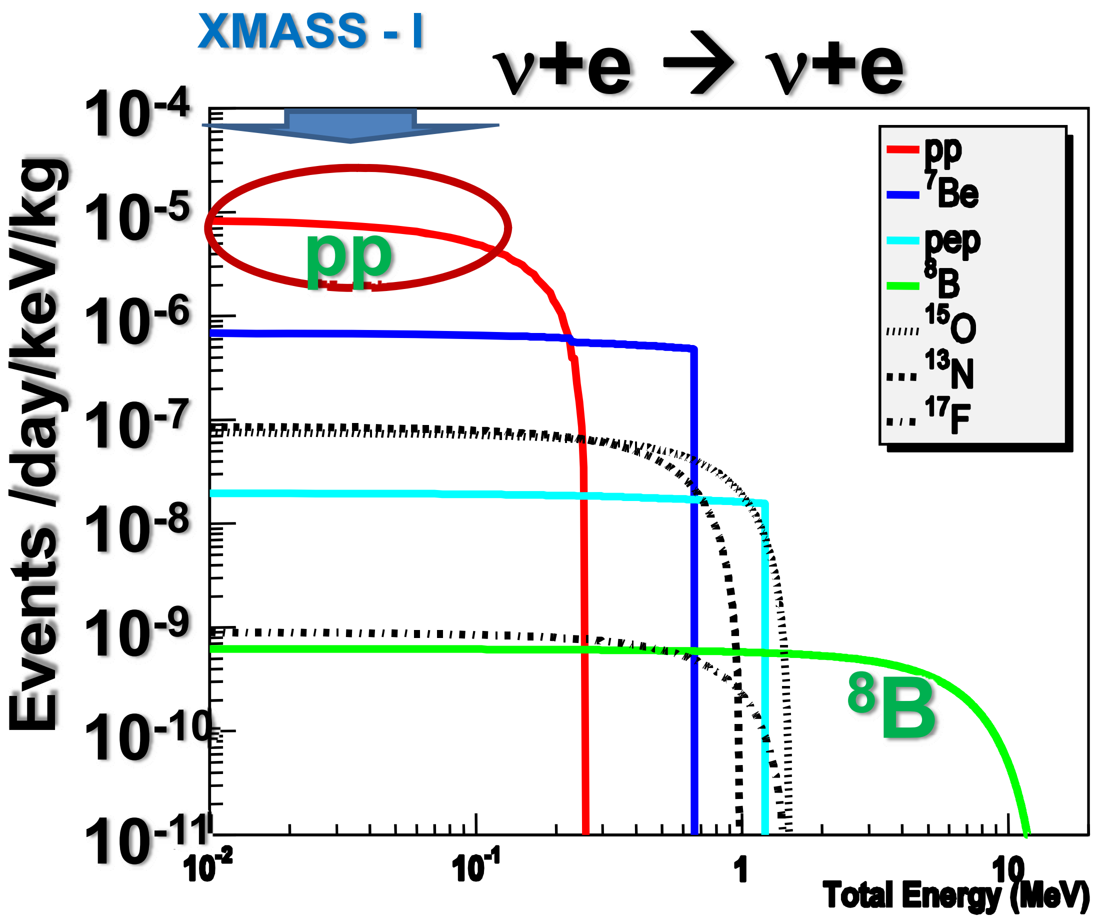




Water tank will be constructed by next February

New Experimental Hall

Signals



- pp-solar neutrinos:
  ➔ ~10^{-5} dru @ <100keV

To see pp neutrinos
➔ BG should be lower than
< 10^{-5} dru level

- We will be in <10^{-4} dru region for XMASS Phase I:

We will be seeing solar pp-neutrinos relatively soon !!
But need 10 tons of Xenon

Summary

- Need more precise measurements of both solar neutrinos and KamLAND, which may provide a further confirmation of LMA and may lead us to the sub-leading phenomena beyond the standard scenario of LMA.

おしまい