# Non-Accelerator Neutrino Experiments

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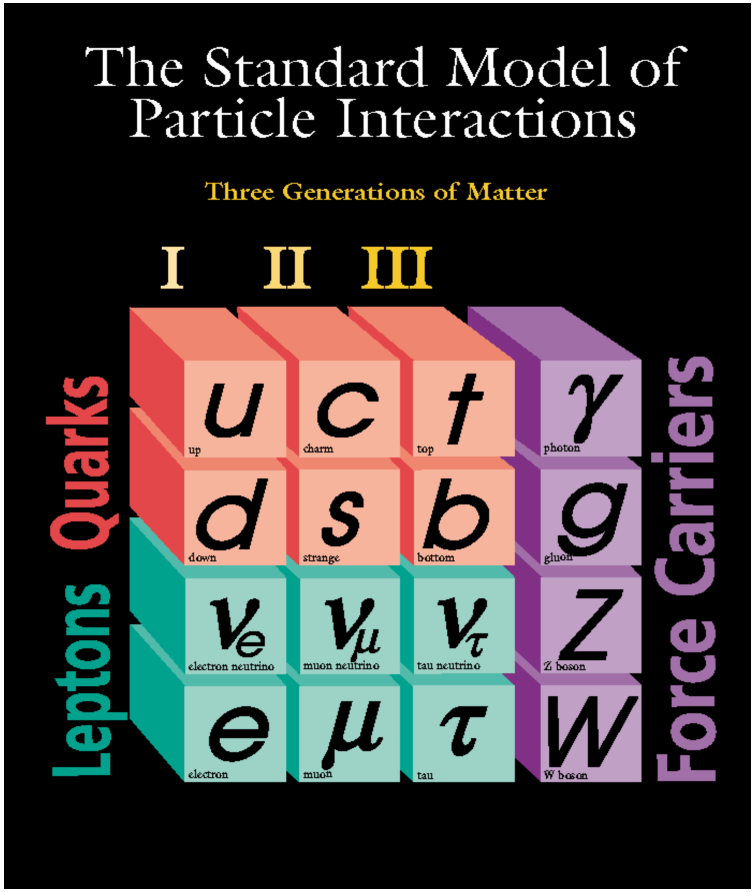
# Outline

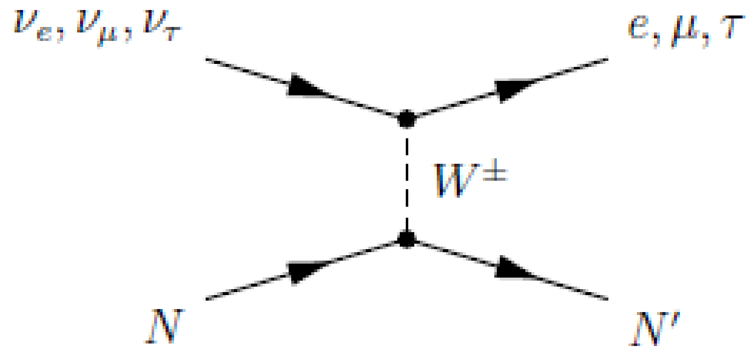
- Neutrinos in the Standard Model
- Neutrino Mixing and Oscillation
- Non-Accelerator Neutrino Sources
- Underground Neutrino Experiments
- Search for Non-Zero $\theta_{13}$
- Future Prospects

# Neutrinos in the Standard Model

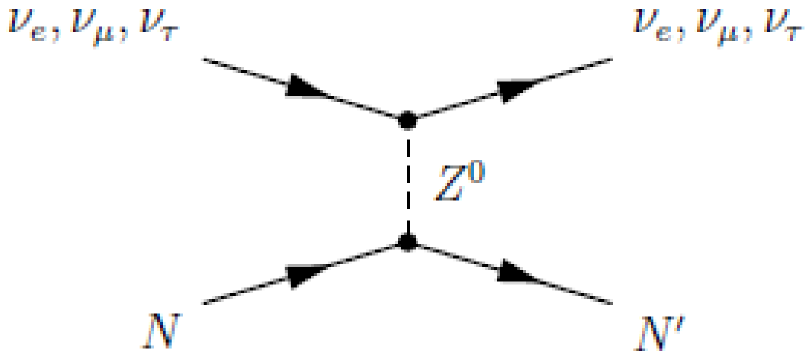
# Neutrinos in Standard Model




Neutrino interactions thru the weak charged current (**CC**) by exchanging a $W^{\pm}$ boson




and thru the weak neutral current (**NC**) by exchanging a $Z^0$ boson



# Dirac Equation

For spin -1/2 particles, the relativistic Dirac equation

$$\left(i\gamma^{\mu}\partial^{\mu} - m\right)\psi = 0$$

By defining two projection operators

$$P_L = \frac{1}{2}(1-\gamma_5), \quad P_R = \frac{1}{2}(1+\gamma_5)$$

Gives two chirality eignspinors

$$\psi_L = P_L\psi, \quad \psi_R = P_R\psi$$

Dirac equation can thus be expressed as

$$\left(i\frac{\partial}{\partial x^0} + i\sigma^i\frac{\partial}{\partial x^i}\right)\psi_R = m\gamma_0\psi_L, \quad \left(i\frac{\partial}{\partial x^0} - i\sigma^i\frac{\partial}{\partial x^i}\right)\psi_L = m\gamma_0\psi_R$$

Both equations decouple in the case of zero mass ($m$=0).

# Helicity & Chirality When $m$=0

**For massless spin -1/2 particle ($m$=0)**

$$i\frac{\partial}{\partial x^0}\psi_L = i\sigma^i\frac{\partial}{\partial x^i}\psi_L, \quad i\frac{\partial}{\partial x^0}\psi_R = -i\sigma^i\frac{\partial}{\partial x^i}\psi_R$$

**Identical to the Schrödinger equation in *p* space**

$$E\psi_{L,R} = \mp(\vec{\sigma}\cdot\vec{p})\psi_{L,R} \qquad i\frac{\partial}{\partial x^0} = i\frac{\partial}{\partial t} = E, \quad -i\frac{\partial}{\partial x^i} = p^i$$

**Since the definition of helicity is**

$$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{\sigma}|\cdot|\vec{p}|}$$

$$\psi_L \to H = \begin{cases} -1 & \text{particles} \\ +1 & \text{antiparticles} \end{cases} \qquad \psi_R \to H = \begin{cases} +1 & \text{particles} \\ -1 & \text{antiparticles} \end{cases}$$

**Chirality and helicity are identical in this case.**

# Case for a Particle with Mass

For massive spin -1/2 particle ($m \neq 0$), since

$$v < c$$

Lorentz boost to a new reference frame with a velocity $v_0$

$$v < v_0 < c, \quad \vec{v} \, // \, \vec{v}_0$$

In this new frame

$$\frac{\vec{p}}{|\vec{p}|} = -\frac{\vec{p}'}{|\vec{p}'|} \text{(due to Lorentz boost)}, \quad \frac{\vec{\sigma}}{|\vec{\sigma}|} = \frac{\vec{\sigma}'}{|\vec{\sigma}'|} \text{(given by nature)}$$

leading to a sign flip in helicity and chirality eignspinors

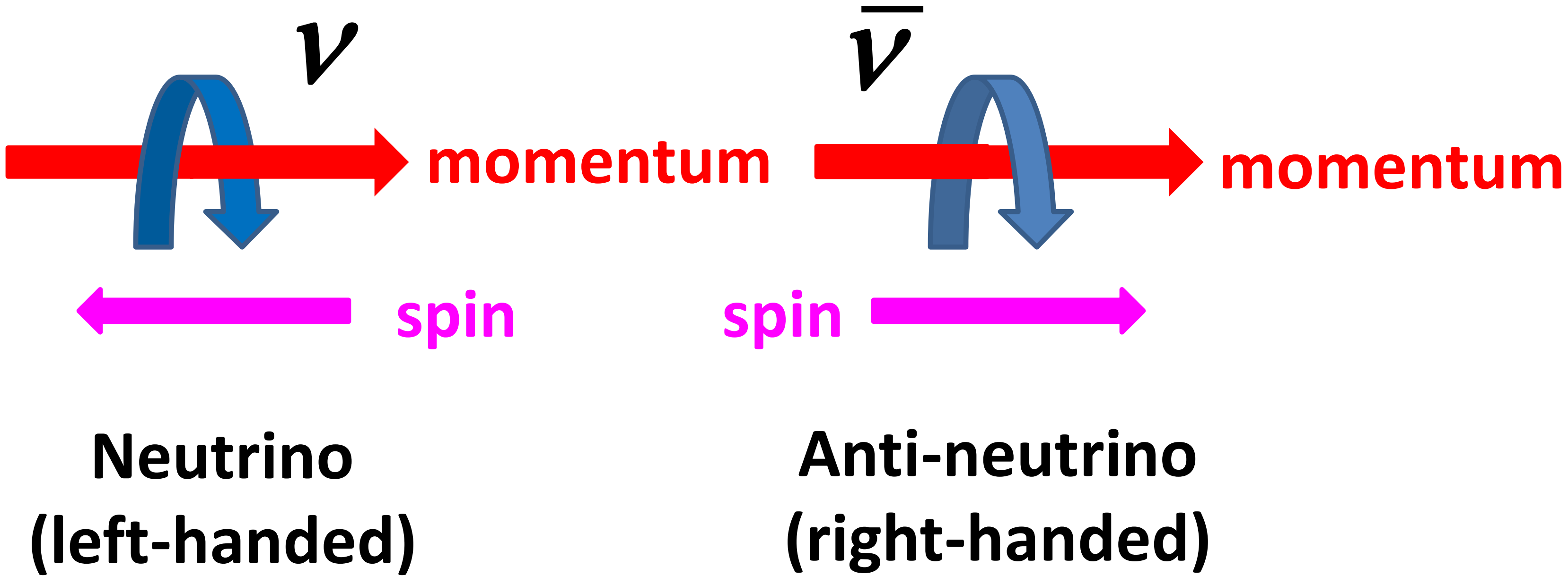
$$\psi_L \rightarrow \psi_R$$

no longer describe particles with fixed helicity and helicity is no longer a good conserved quantum number.

# Neutrinos and Anti-neutrinos

**If neutrinos are massless, then helicity is fixed**

$$H = \frac{\vec{p}\cdot\vec{\sigma}}{|\vec{p}|\cdot|\vec{\sigma}|} = \begin{cases} -1 & \text{Neutrinos (Left-handed)} \\ +1 & \text{Anti-neutrinos (Right-handed)} \end{cases}$$

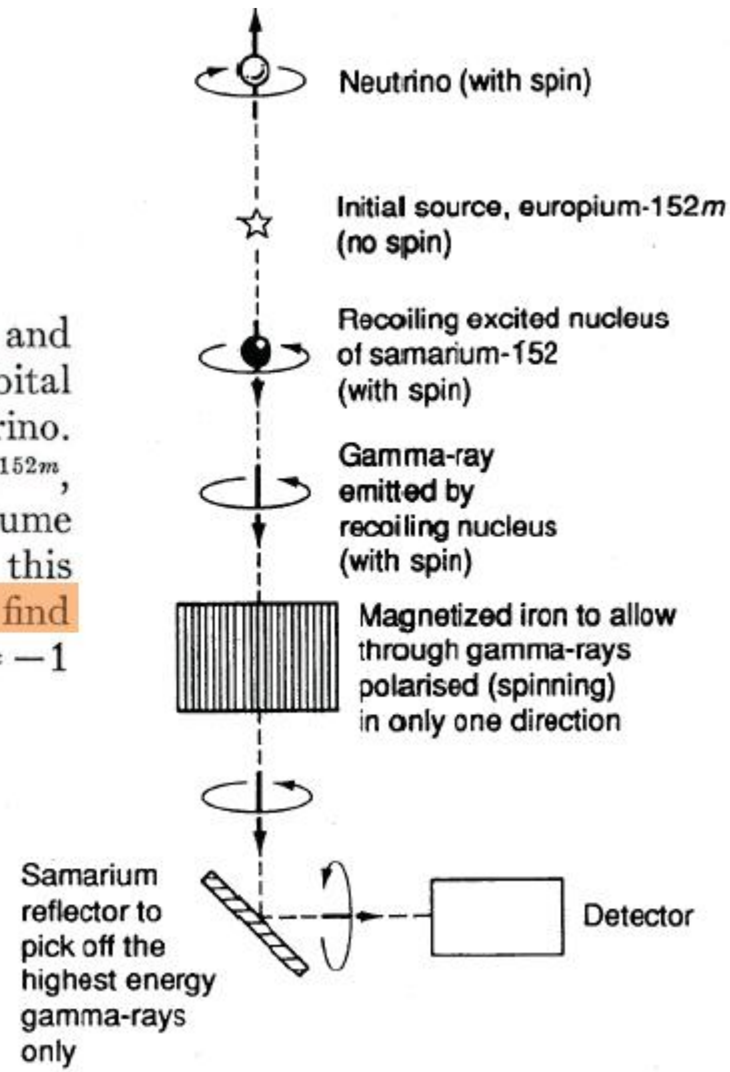


# Neutrinos Are Left-Handed

## Helicity of Neutrinos*

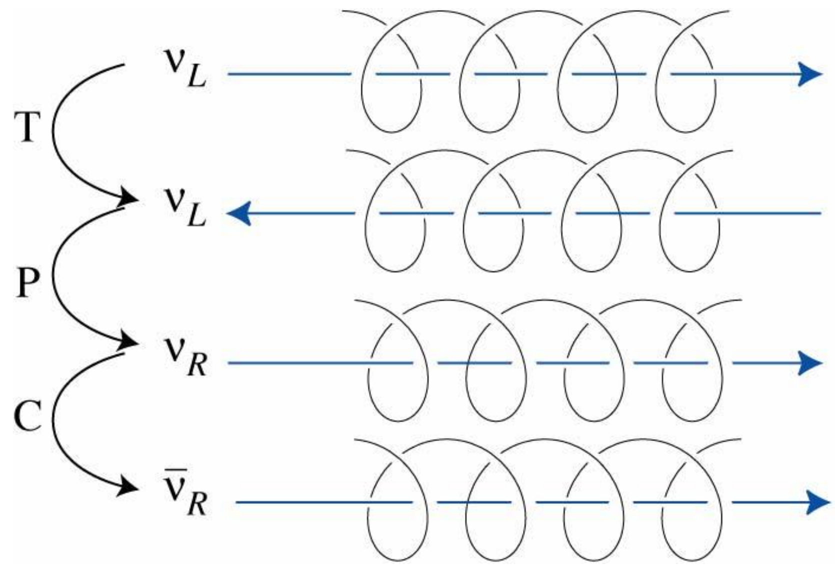
M. Goldhaber, L. Grodzins, and A. W. Sunyar
*Brookhaven National Laboratory, Upton, New York*
(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of $\gamma$ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with $Eu^{152m}$, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



# Neutrino Mass In SM

- **CPT** theorem in quantum field theory
  - **C**: interchange particles & anti-particles
  - **P**: parity
  - **T**: time-reversal




**Standard Model:** $\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L, \ \ell_R$

⇒ Charged lepton mass term

$$L_{m_\ell} = m_\ell \bar{\ell}_R \ell_L$$

Analogously, neutrino mass term

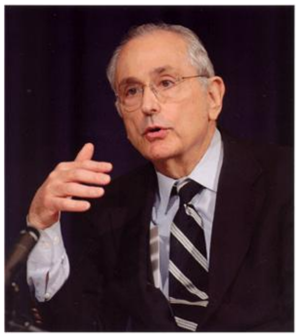
$$L_{m_\nu} = m_\nu \bar{\nu}_R \nu_L$$

✓ $\ell_R$ ⇒ $m_\ell \neq 0$

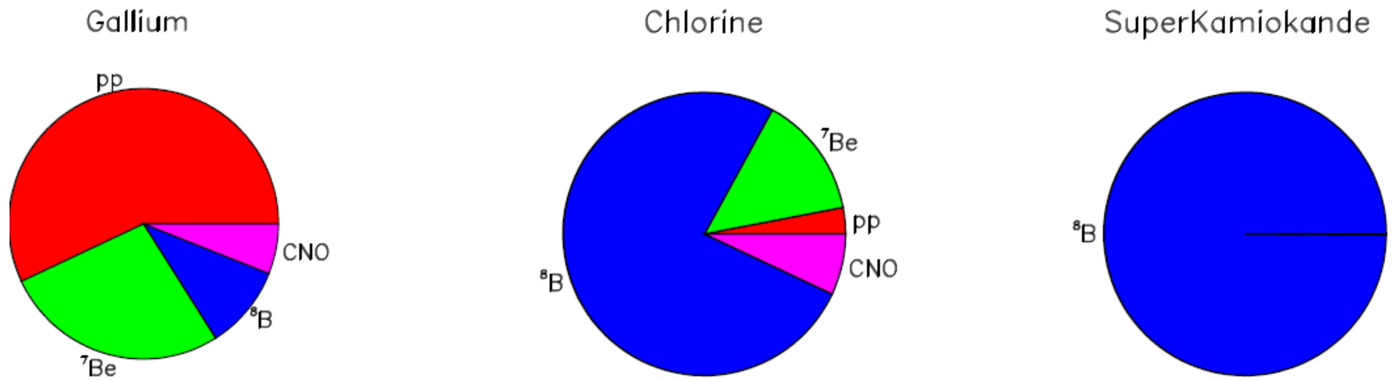
✗ $\nu_R$ ⇒ $m_\nu = 0$

# The Solar Neutrino Problem

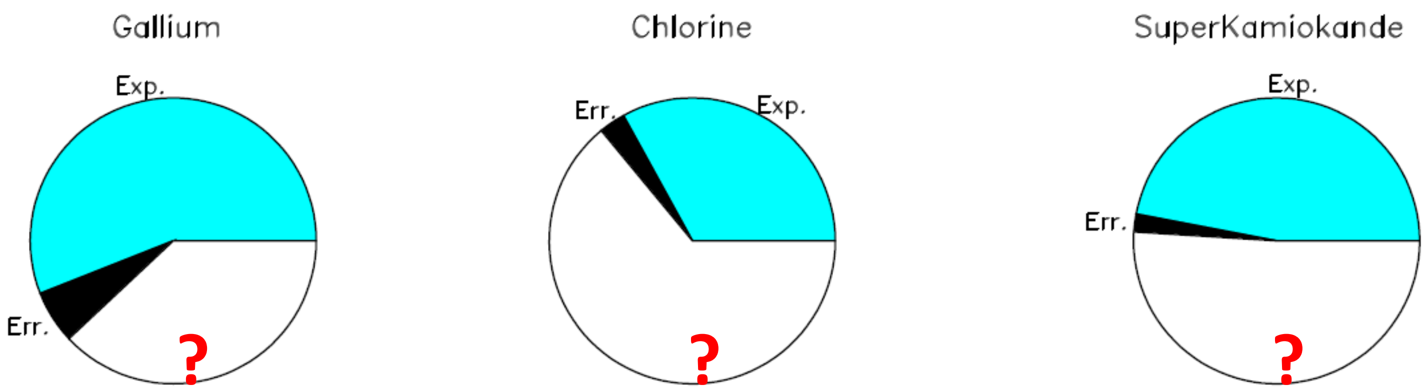
## Standard Solar Model (SSM):



John Bahcall

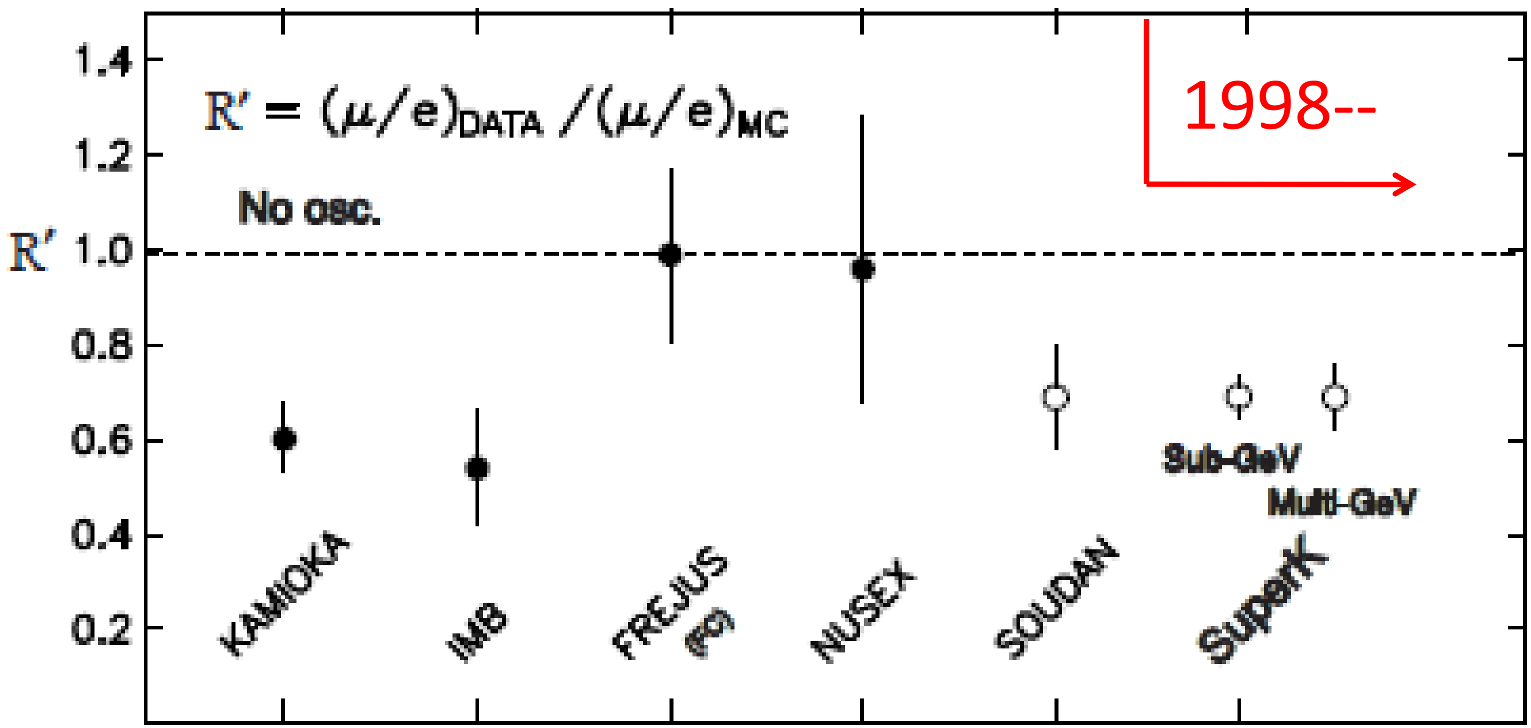



## Experiments (before 2001):




**Many suspicions on SSM and experiments**

# Atmospheric Neutrino Ratio



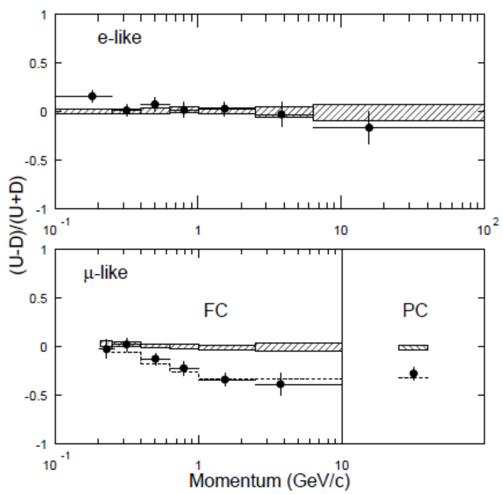

In early 1998, there are three observed hints of neutrino oscillation, and thus of neutrino mass. These hints are the behavior of solar neutrinos, the behavior of atmospheric neutrinos, and the results of the LSND experiment.

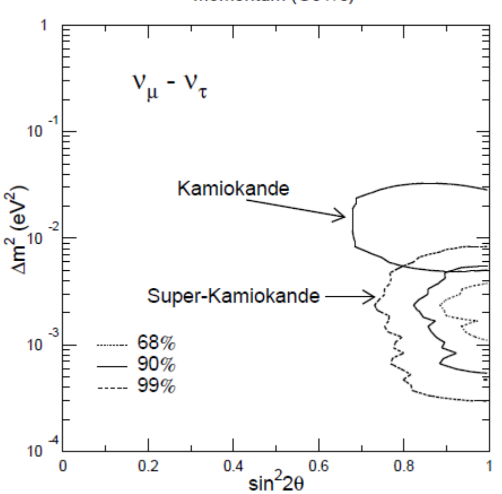
PDG1998

# Discovery of Neutrino Oscillation

PRL81, 1562 (1998)

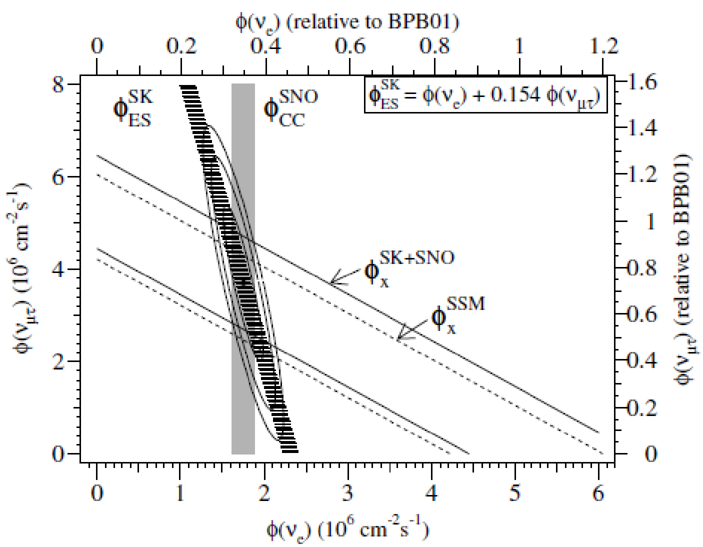
*Evidence for Oscillation of Atmospheric Neutrinos*



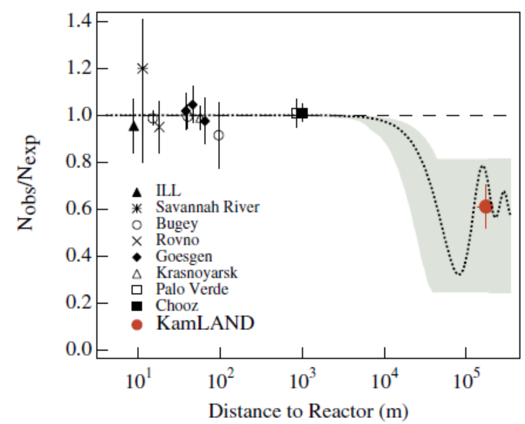

PRL87, 071301 (2001)

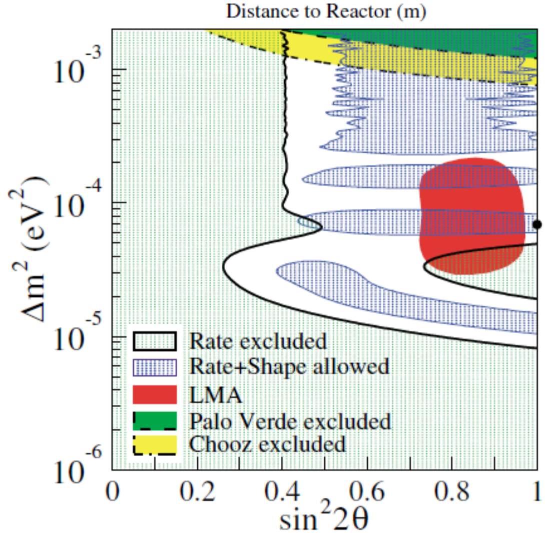
*Measurement of the Rate of $\nu_e + d \rightarrow p + p + e^-$ Interactions Produced by $^8B$ Solar Neutrinos at the Sudbury Neutrino Observatory*




PRL90, 021802 (2003)

*First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance*



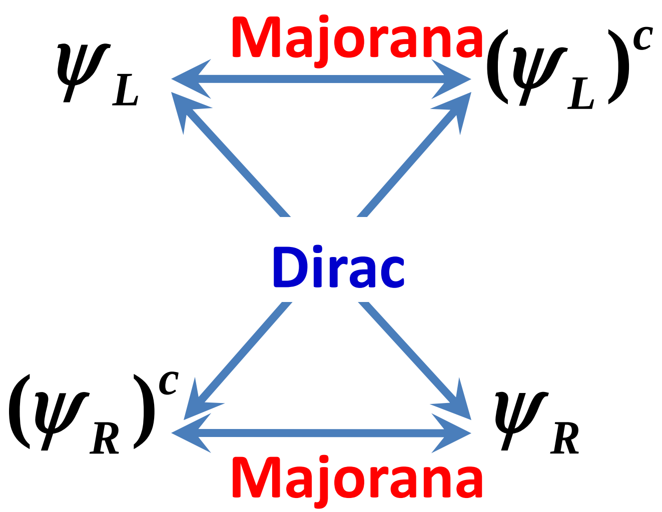



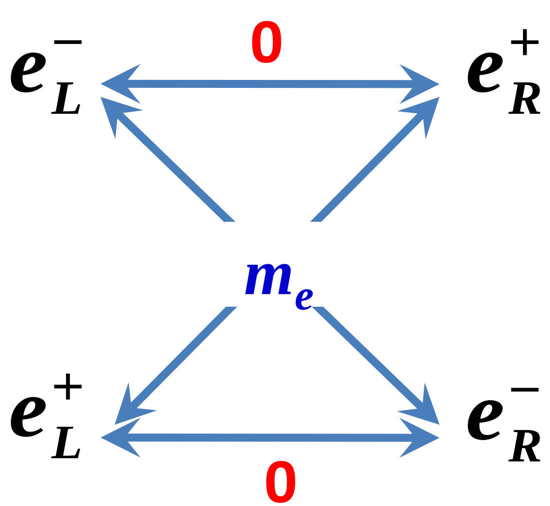
*"…I did not believe in neutrino oscillations, even after Davis' painstaking work and Bahcall's careful analysis: The oscillations were, I believed, uncalled for. Now, after the beautiful experiments which we shall hear about in the next few days, I have to surrender and accept neutrino oscillations as reality,…"* ---C.N. Yang , 2002, opening remarks on "**Neutrinos and Implications for Physics Beyond the Standard Model**"

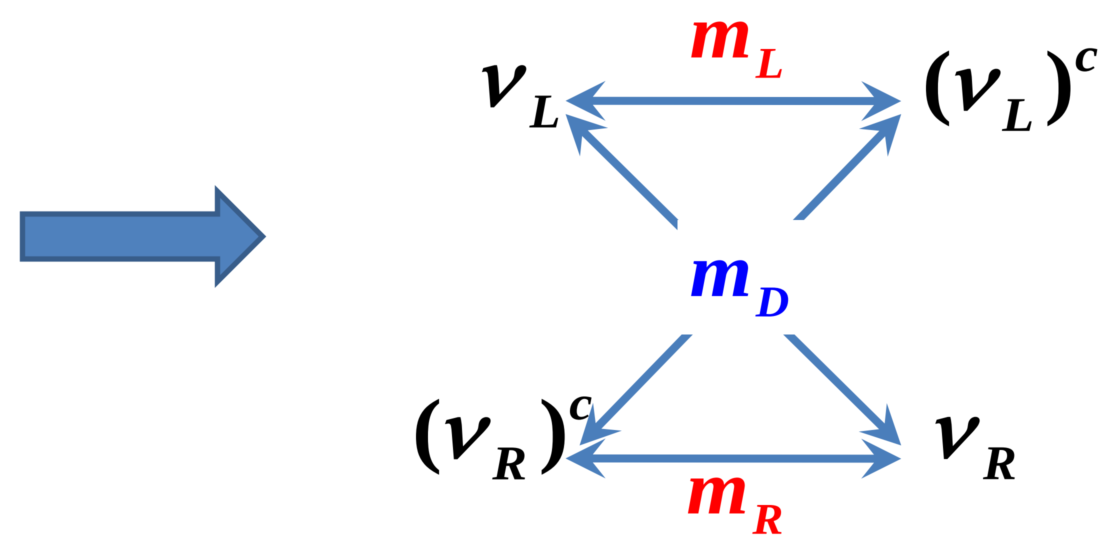
# Neutrino Mass, Mixing And Oscillation

# Stand Model Extension

- Massive neutrinos indicates new physics beyond SM.
- Minimum extension of SM is to allow $\nu_R$'s (Dirac masses) or **Lepton number violation** (Majorana masses) or both.



# Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

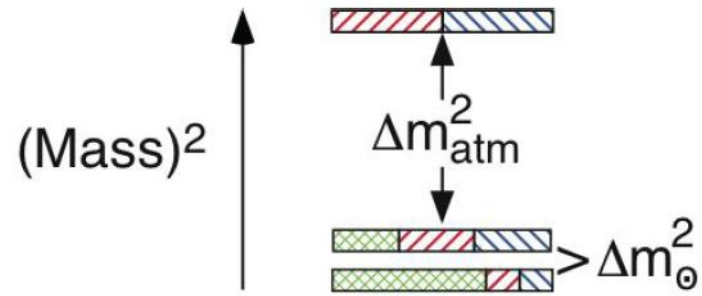
**Standard Model for leptons**

**Extension**

$$\Delta m^2_{12} = \Delta m^2_{\odot} << \Delta m^2_{atm} = |\Delta m^2_{32}| \approx |\Delta m^2_{31}|$$

**Pontecorvo**
**Maki**
**Nakagawa**
**Sakata**

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



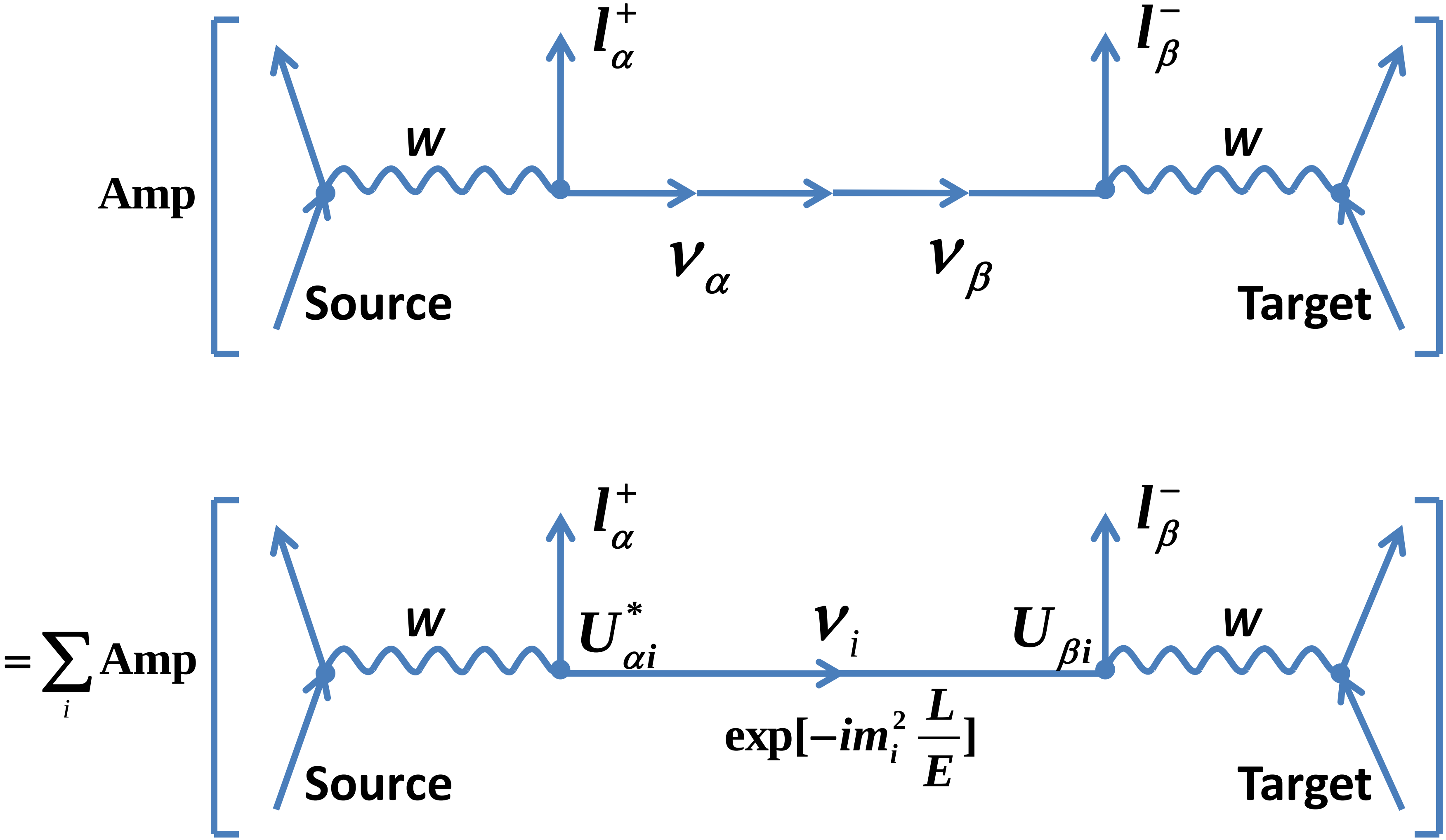

$$\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**Solar** **Reactor** **Atmospheric**

**Dirac phase $\delta$,**
**Majorana phases $\phi_1$, $\phi_2$**

**This extension introduces 3 masses + 3 angles + 1(3) phase(s) = 7(9) new parameters for SM**

# Neutrino Flavor Change In Vacuum



# Neutrino Oscillation

## Oscillation probability

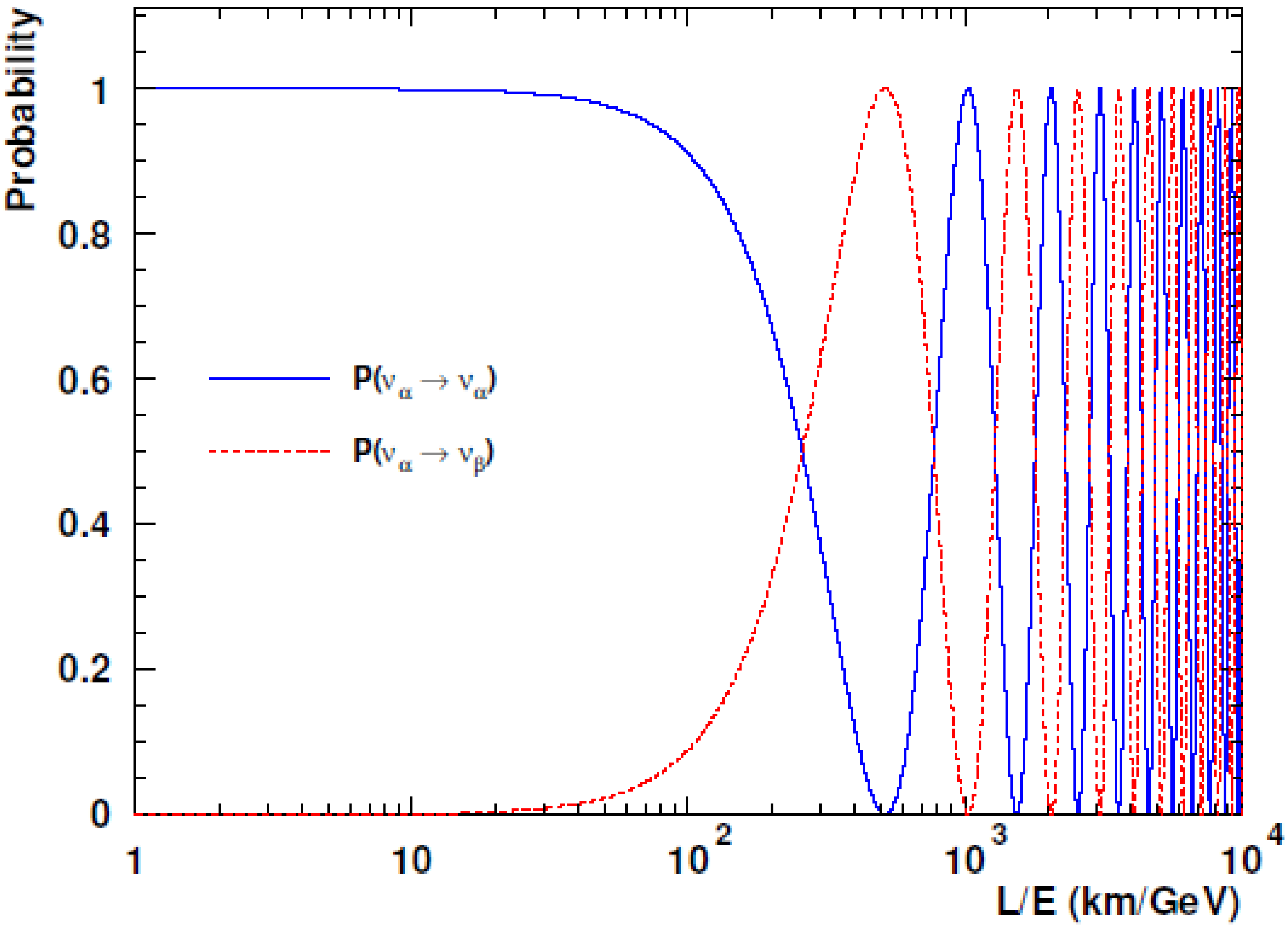
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27\, \Delta m^2_{ij}(L/E)] + 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin[2.54\, \Delta m^2_{ij}(L/E)]\,.$$

## Since one mass splitting is observed to be much bigger than the others, we can simply have

**Appearance:** $P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \sin^2 2\theta\, \sin^2[1.27\, \Delta m^2 (L/E)]$

**Disappearance:** $P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha) = 1 - \sin^2 2\theta\, \sin^2[1.27\, \Delta m^2 (L/E)]$

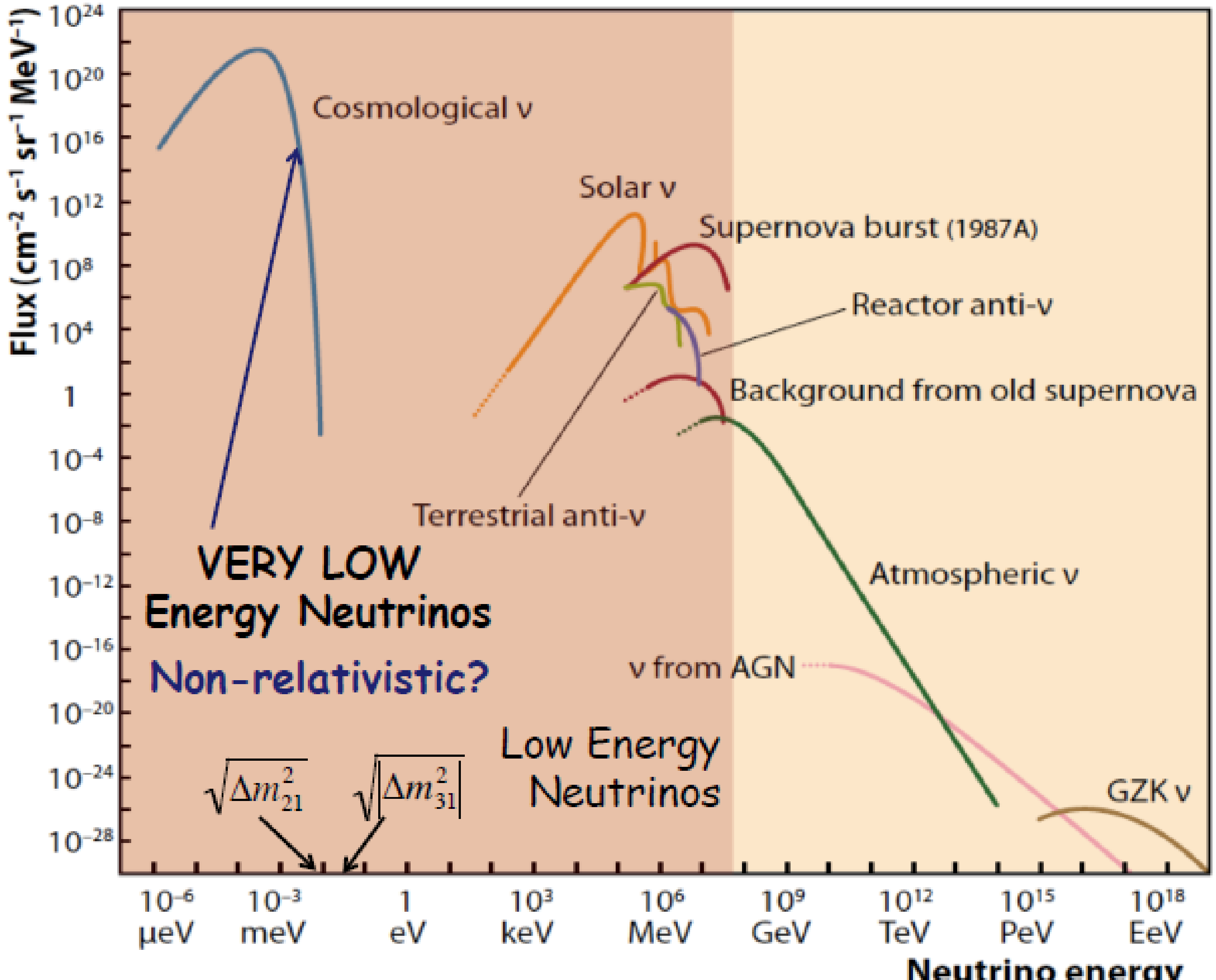
# Two-Flavor Neutrino Oscillation



# Non-Accelerator Neutrino Sources

# Non-Accelerator Neutrino Sources

Sergio Pastor, LowNu 2009



# Atmospheric Neutrinos

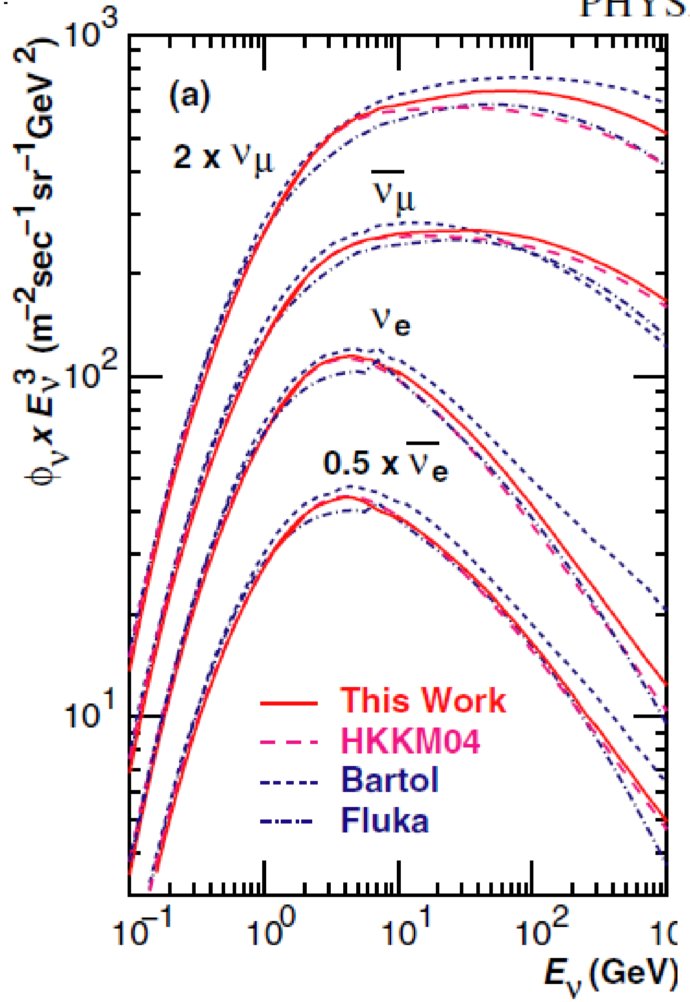
**Primary cosmic protons strikes atmosphere, producing pions , naively**

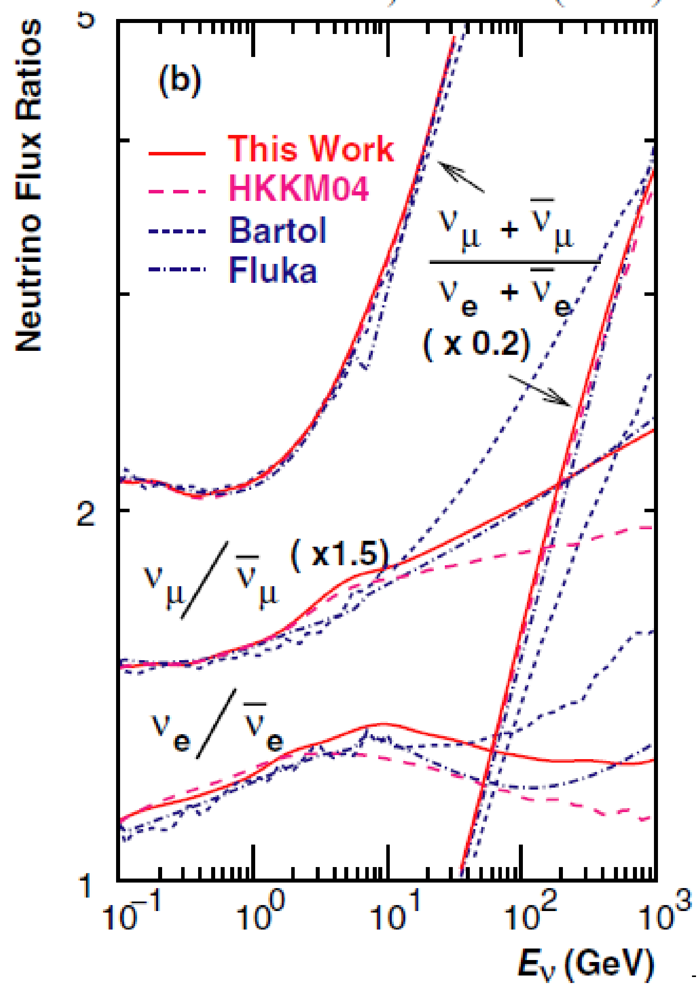
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$e^- + \bar{\nu}_e + \nu_\mu$$

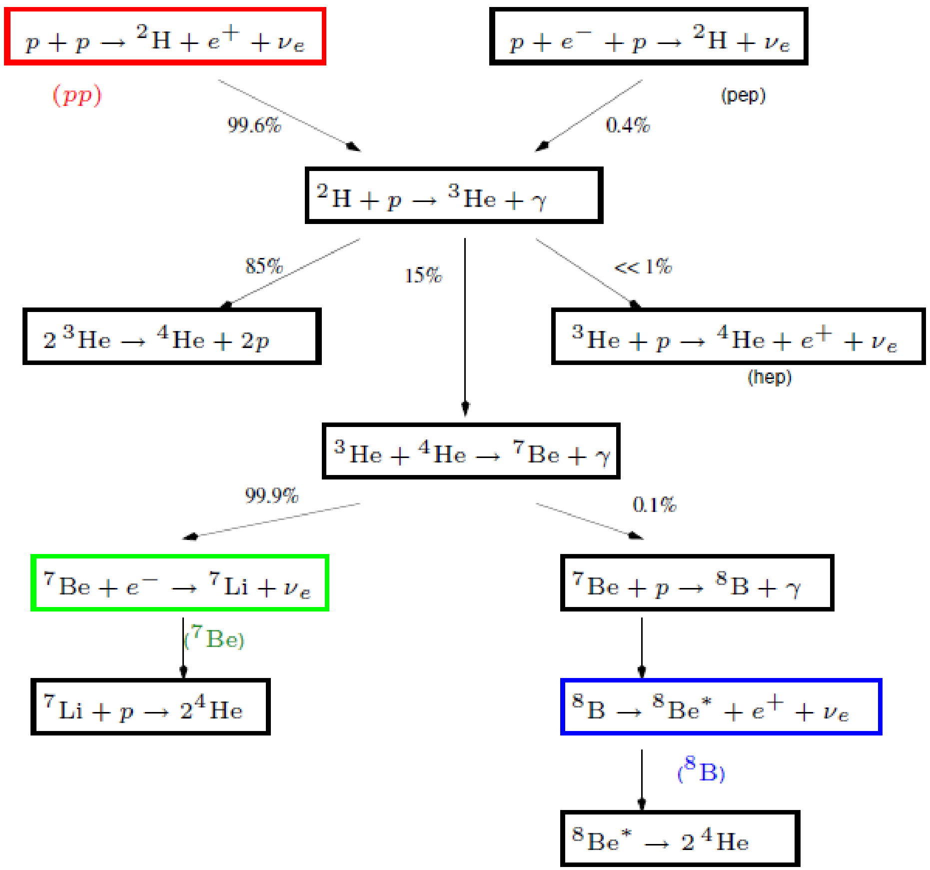
$$\frac{\Phi(\nu_\mu + \bar{\nu}_\mu)}{\Phi(\nu_e + \bar{\nu}_e)} \simeq 2$$

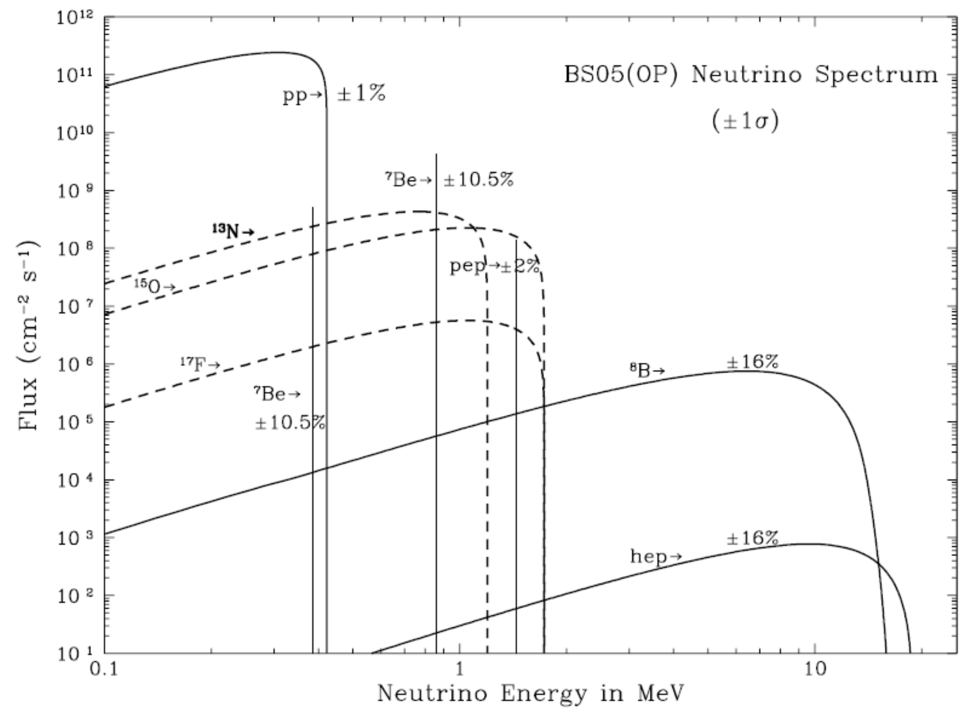
PHYSICAL REVIEW D **75**, 043006 (2007)



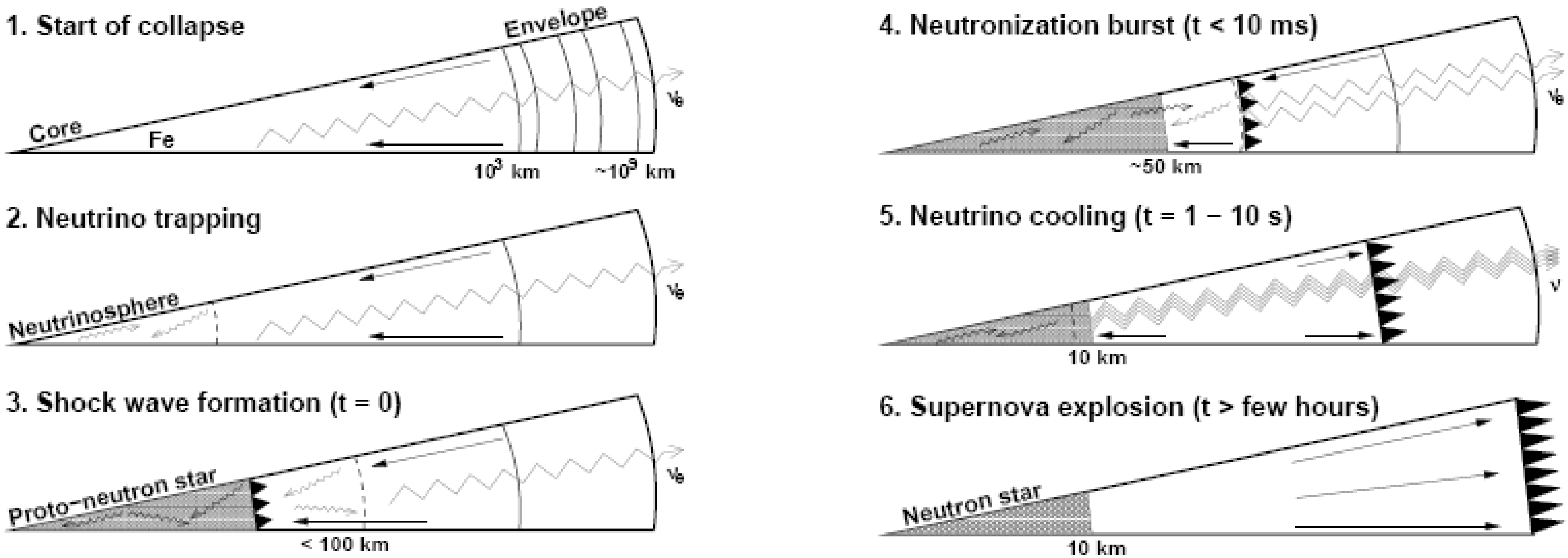
# Solar Neutrinos

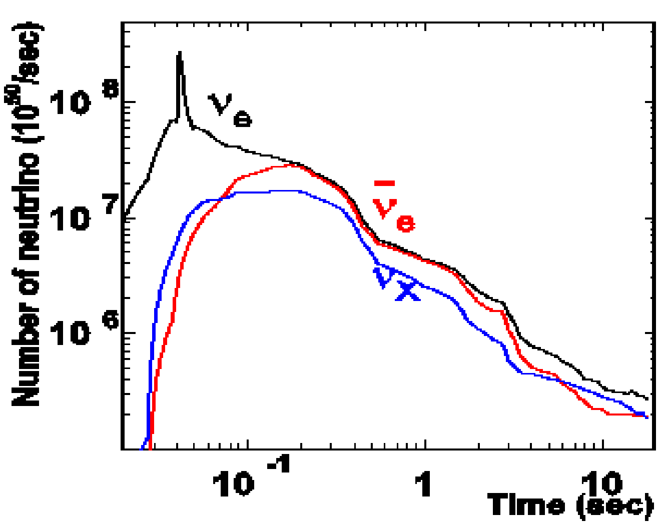


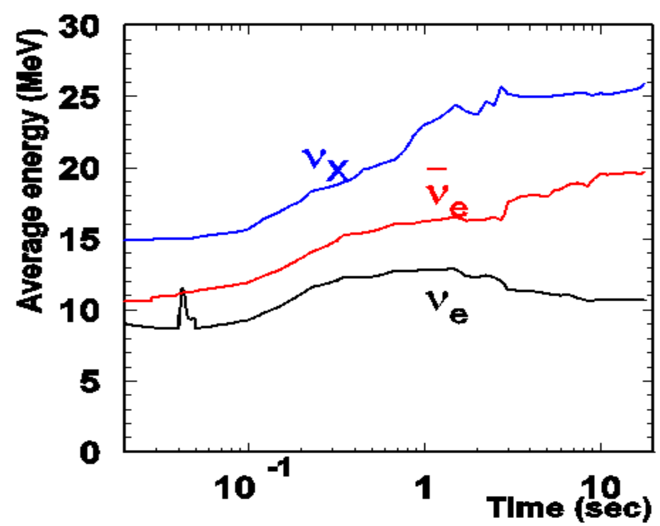




**The generated solar neutrinos are all $\nu_e$'s and, there is no $\bar{\nu}_e$ at all according to SSM.**

# Supernova Neutrinos



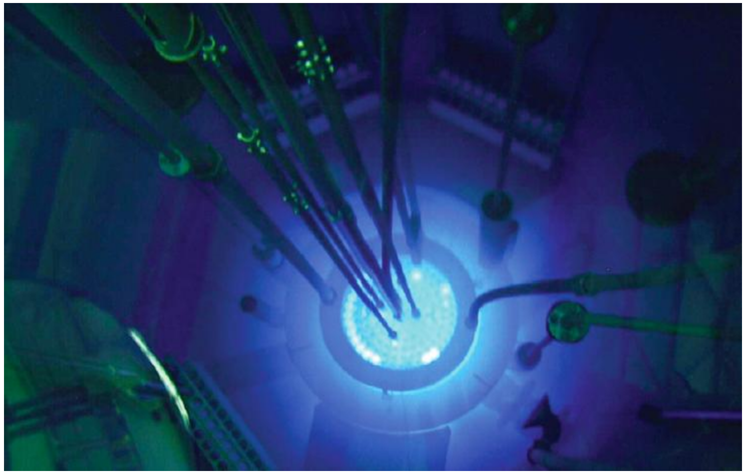



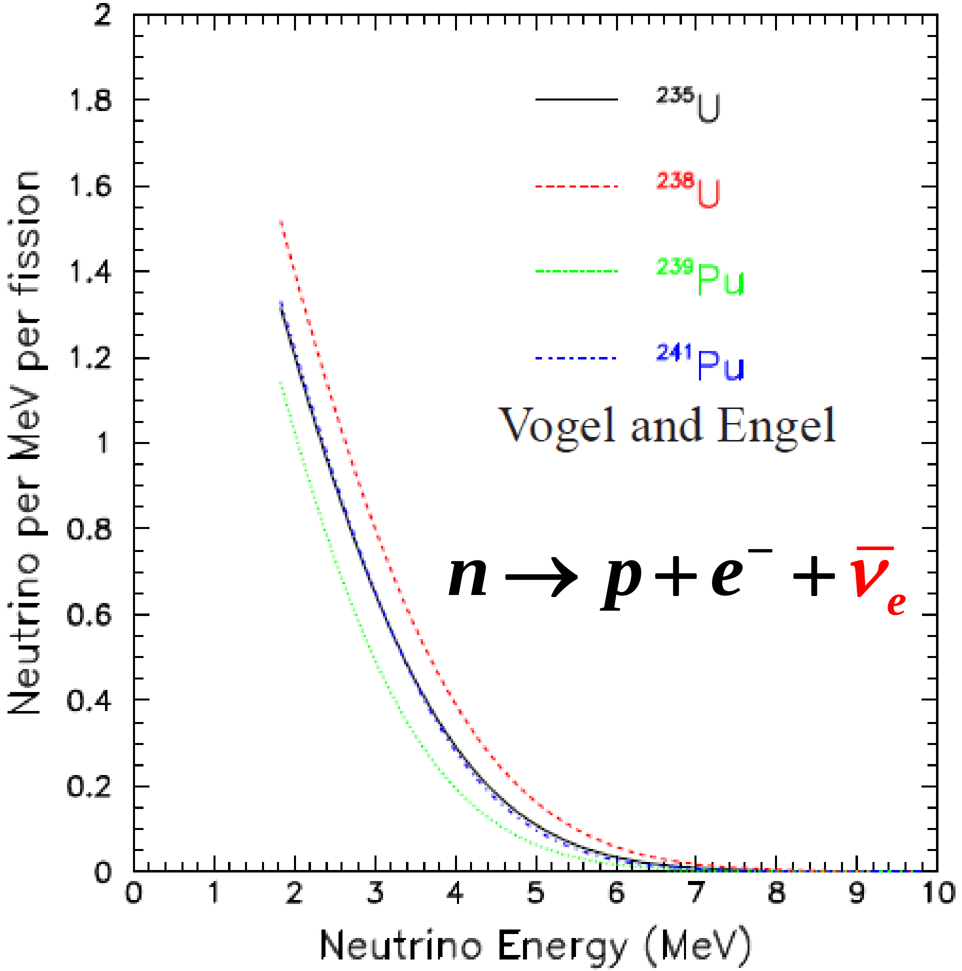

T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216(1998)

# Reactor Neutrinos

**Neutrinos from beta decays occurring inside the reactor.**

**A 1 $GW_{th}$ nuclear reactor can generate $2\times10^{20}$ $\bar{\nu}_e$'s/s**





# Sources Are Free


**It is true when not including the hidden charge.**

# Underground Neutrino Experiments

# How Easy to See a Neutrino?

**Take the solar neutrino experiment as an example,**

$$N_e = \sigma_{\nu e} \cdot \Phi_\nu \cdot N_{\text{target}}$$

**Since the solar neutrino flux on the Earth is**

$$\Phi_\nu \simeq 7\times 10^{10} / cm^2 / s, \quad \sigma_{\nu e} \sim 10^{-45} cm^2$$

**Assuming a 1kilo ton of water target gives**

$$N_{\text{target}} = (6\times 10^{23} molecules)\times(18 e^-)/molecule \times (10^3)^3 / 18$$

$$\sim 10^{32}$$

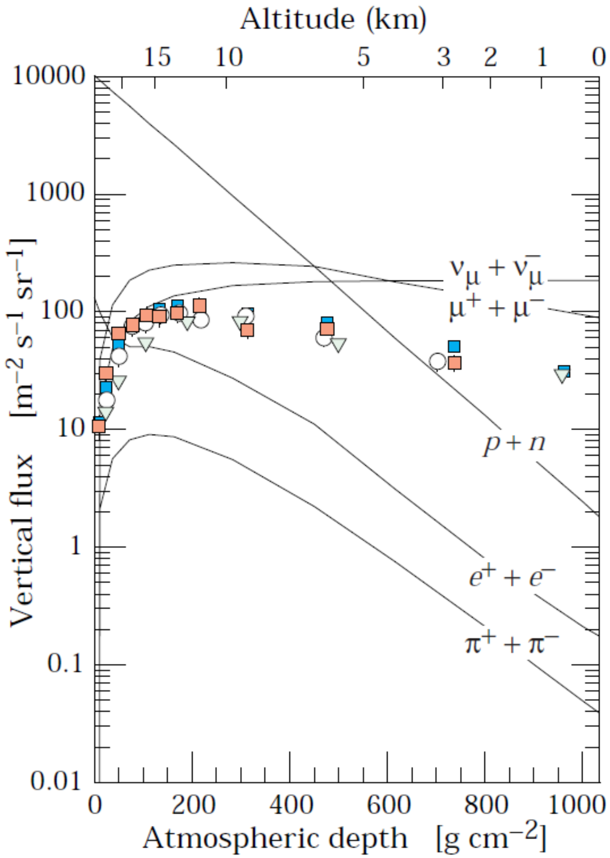
**Thus, the event rate is**

$$N_e \sim 0.01/s \quad or \quad 1000/day$$

# Why Do We Worry Cosmic Ray?

At sea level, the cosmic μ flux

$$\Phi_\mu \sim 1/cm^2/\min$$




That means in 1kilo ton water at sea level, the number of passing thru μ's is

$$\sim (10\times 100)^2 \times 1\min^{-1} = 1.7\times 10^4/s$$

These μ's can have reactions

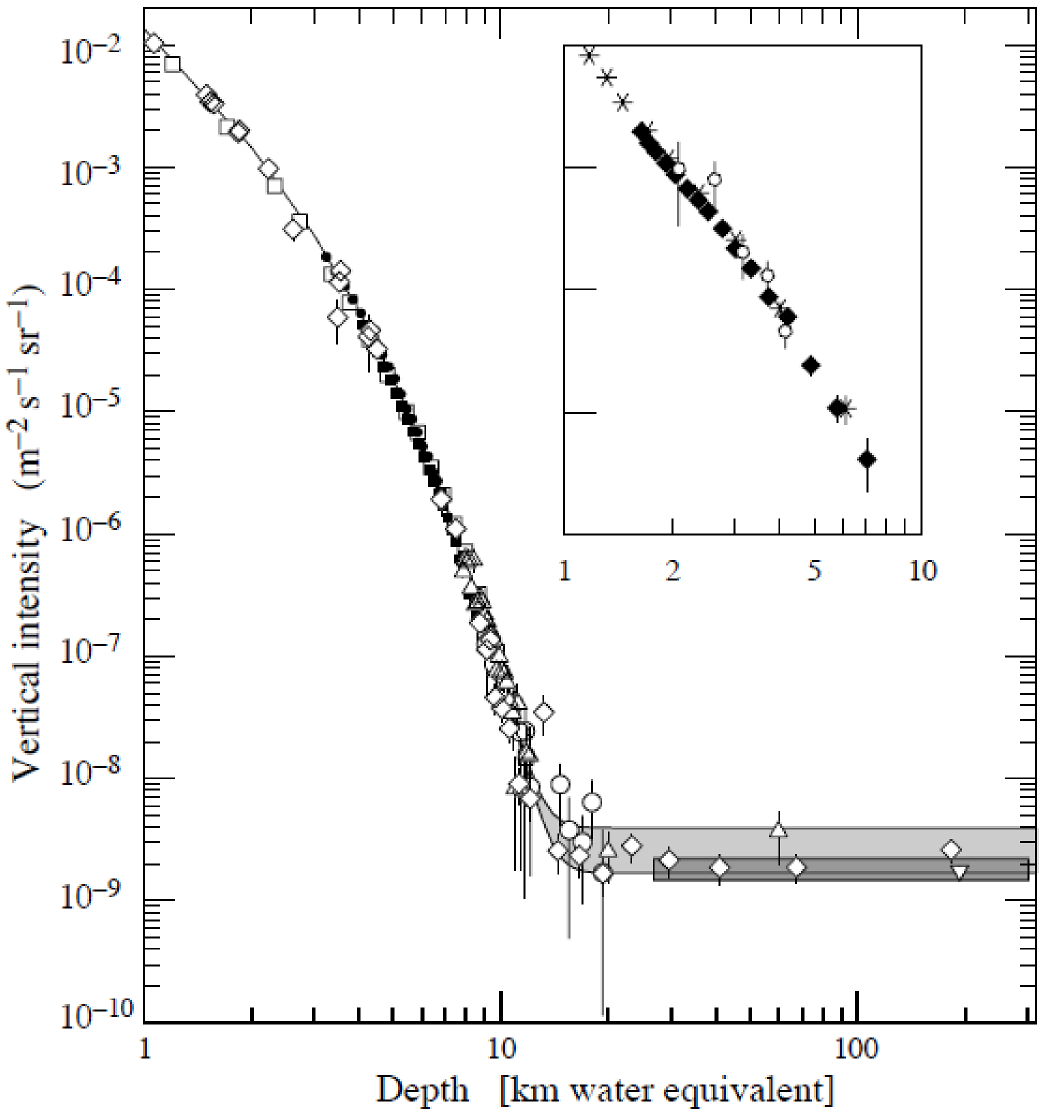
$$\mu^- + N \to \mu^- + N^+ + e^-$$

$$\mu^- + N \to n + X$$

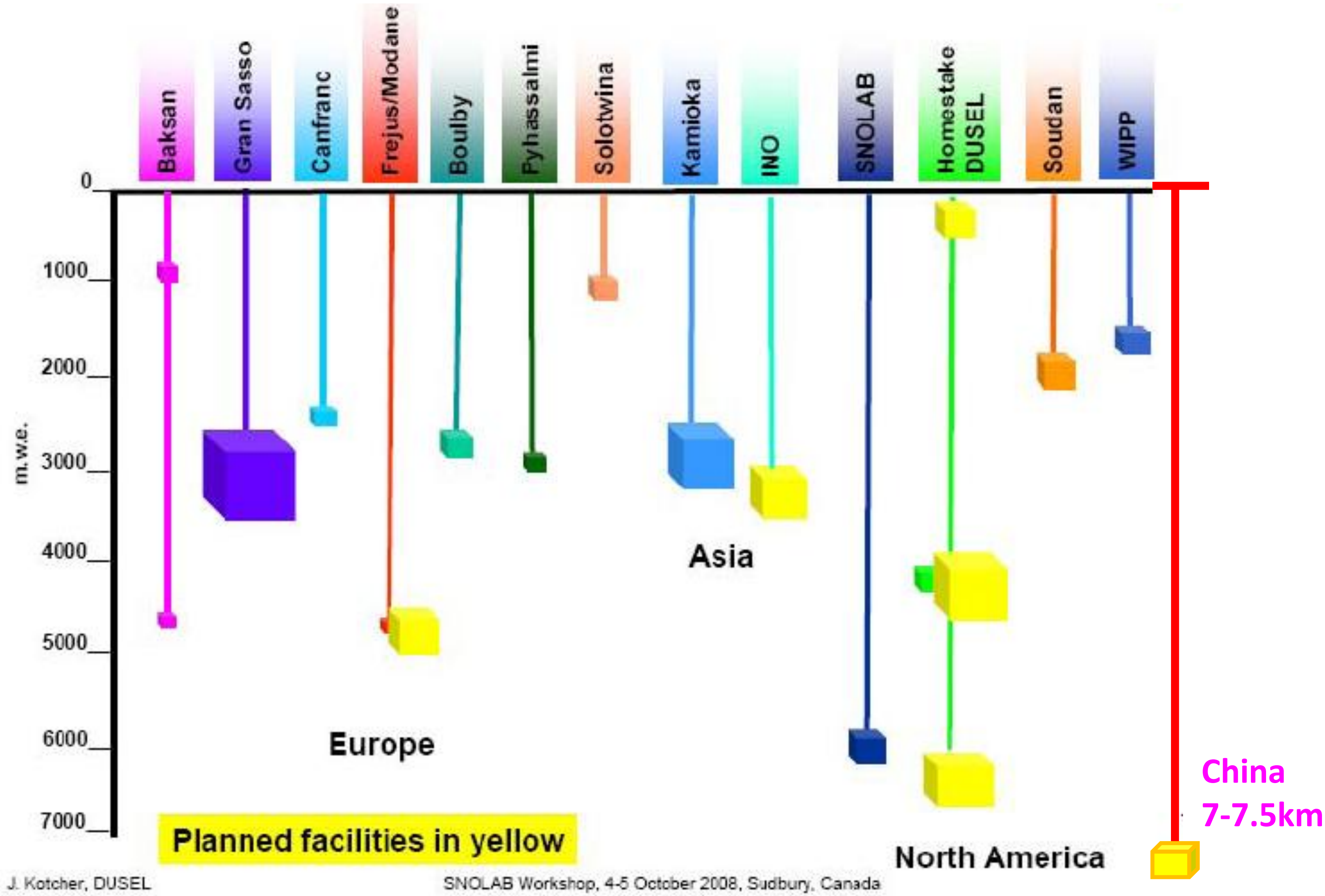
$$\mu^- + N \to N_1 + X, \quad N_1 \to N_2 + \beta + \bar{\nu}_e$$

Mimicking the neutrino reactions.

# How To Reduce μ Background?



# Underground Labs

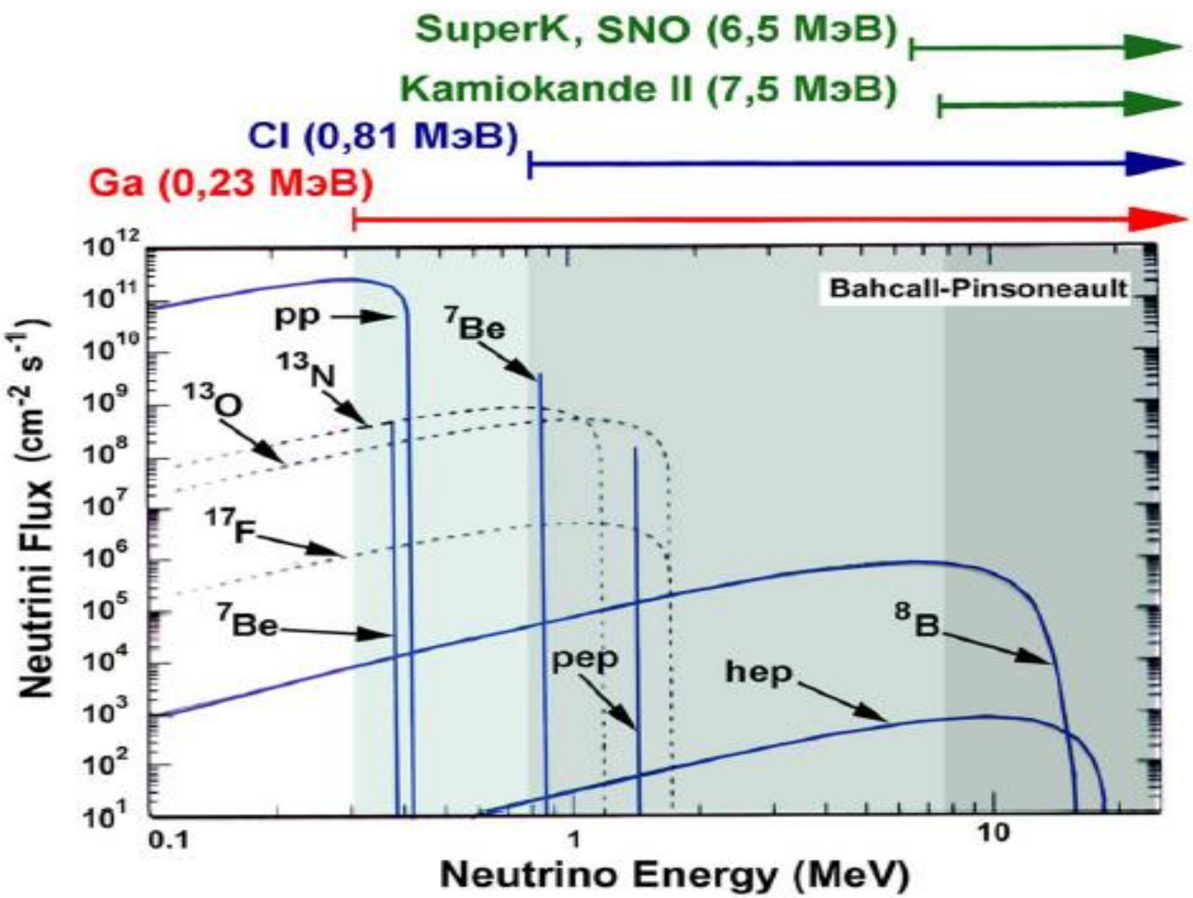


# Solar ν Experiments

✓Radiochemical expts
- Homestake (Cl)
- Gallex/GNO (Ga)
- Sage (Ga)

✓Č expts
- Kamiokande ($H_2O$)
- Super-K ($H_2O$)
- SNO ($D_2O$)

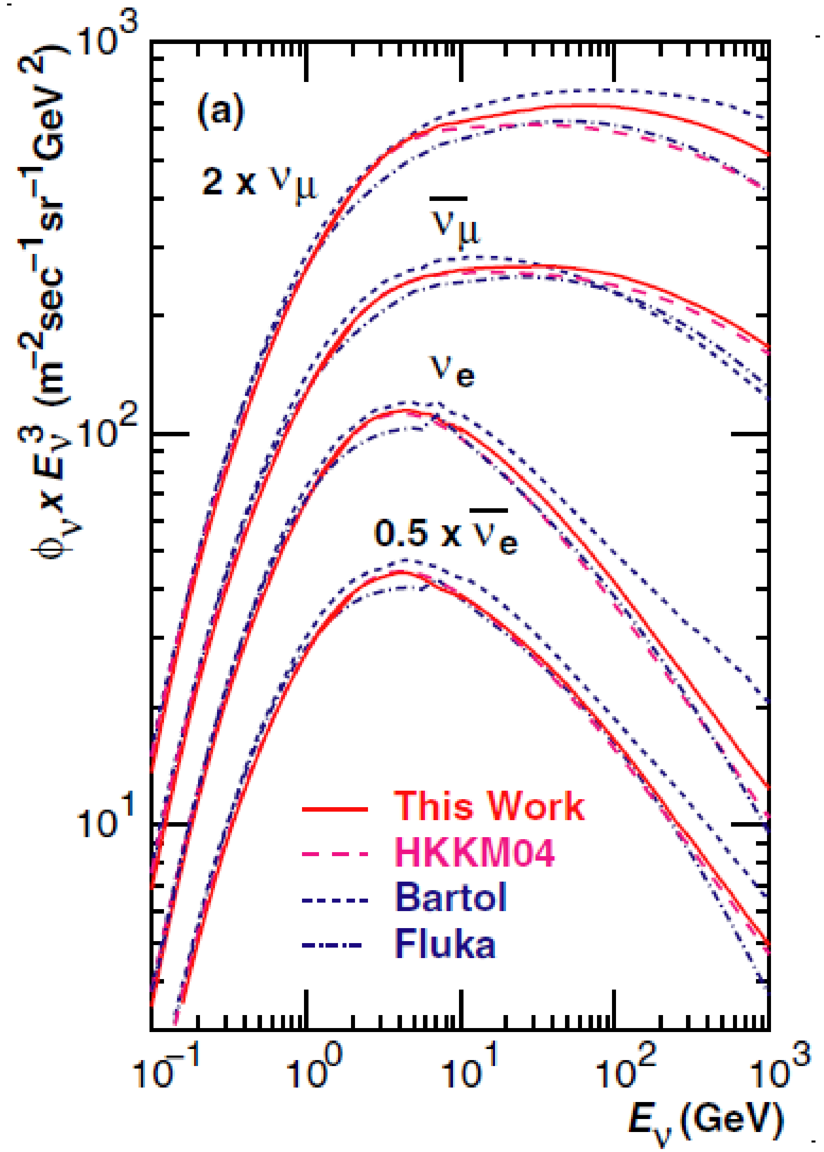
✓Scintilator expts
- Borexino
- KamLAND (?)



# Atmospheric ν Experiments

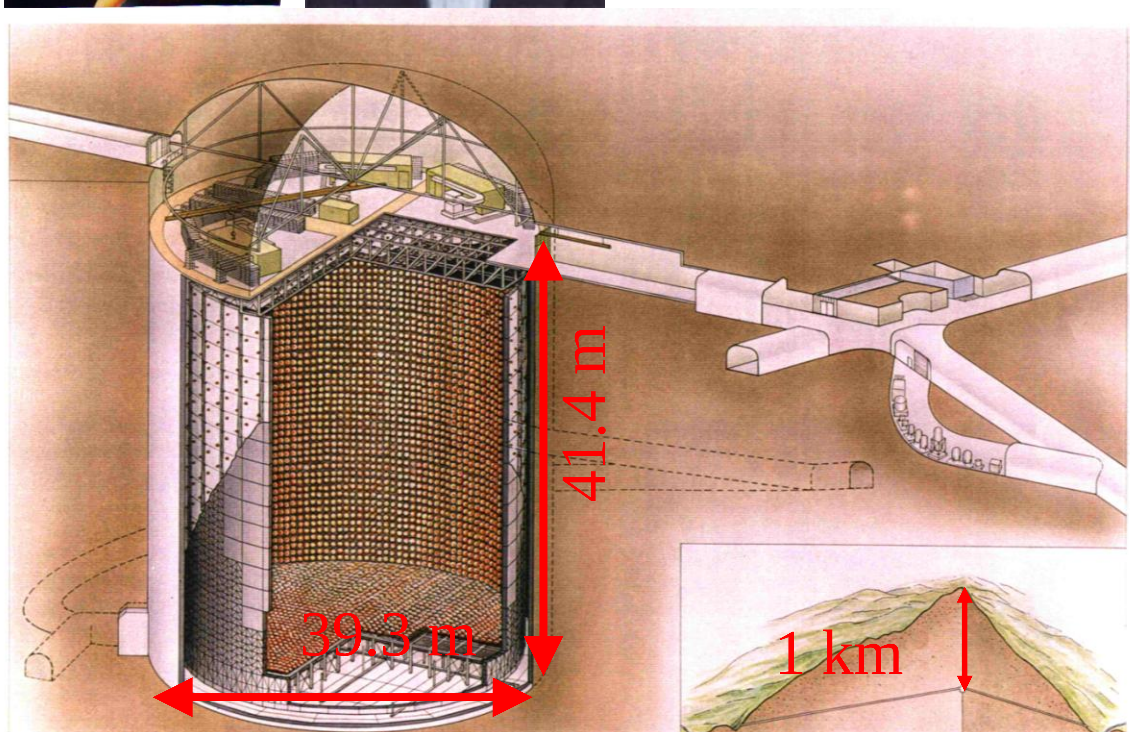
✓ Water Č experiments
- Kamiokande (1000ton)
- IMB (3300ton)
- Super-K (22.5kton)

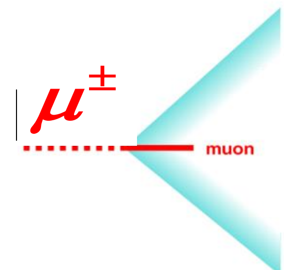
✓ Tracking Calorimeter
- Nusex (130ton iron)
- Frejus (700ton iron)
- Soudan (1000ton iron)

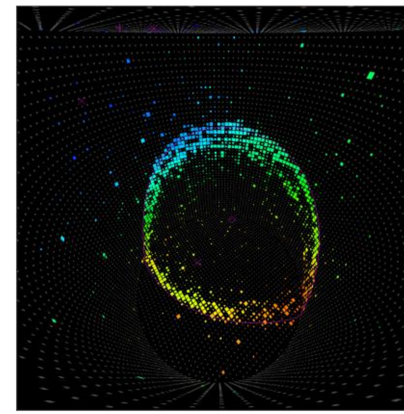


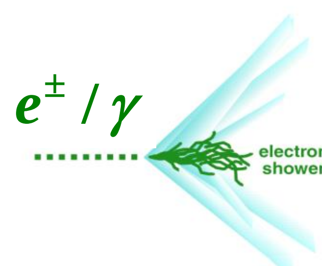
# Super Kamiokande Experiment

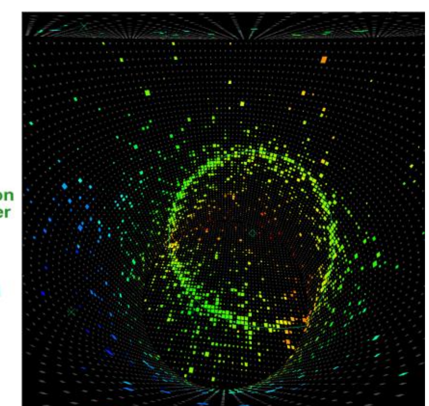
**A 50k tons water Č detector located at 1k m underground**



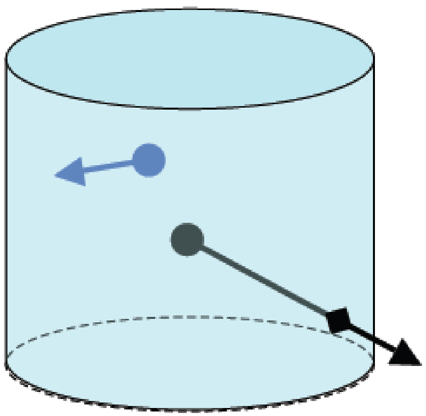





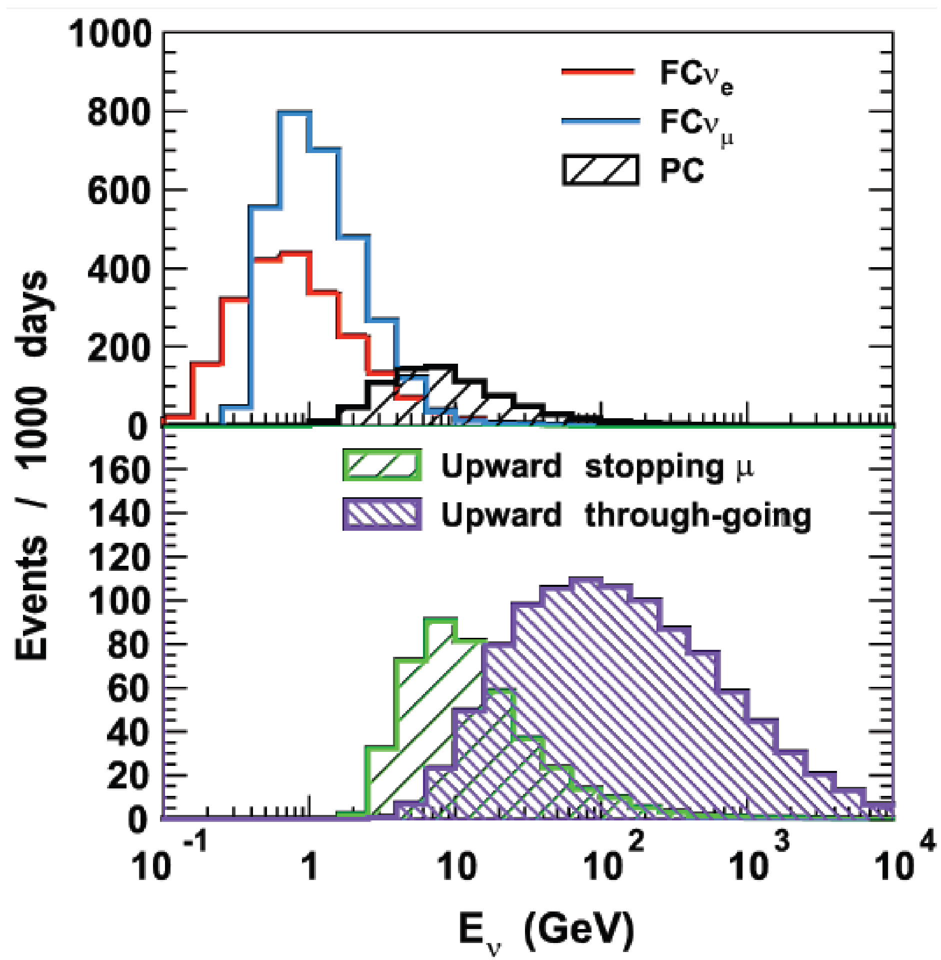



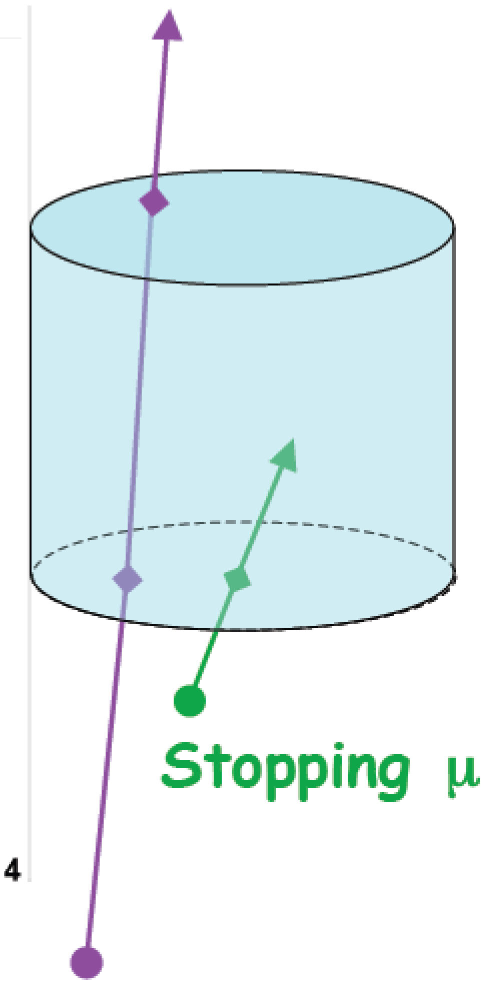
# Event Classification @ SK

Fully Contained (FC)

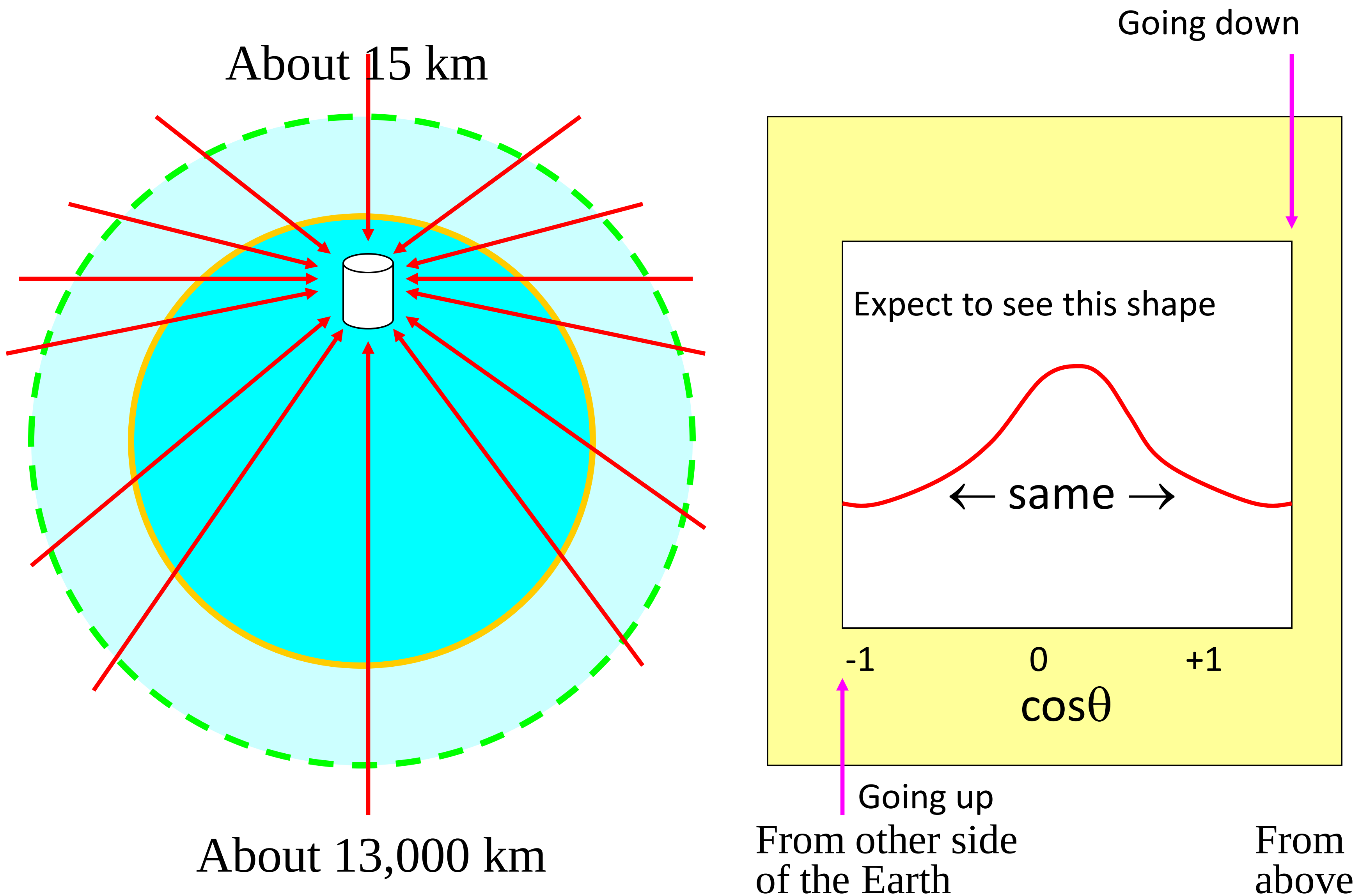


Partially Contained (PC)



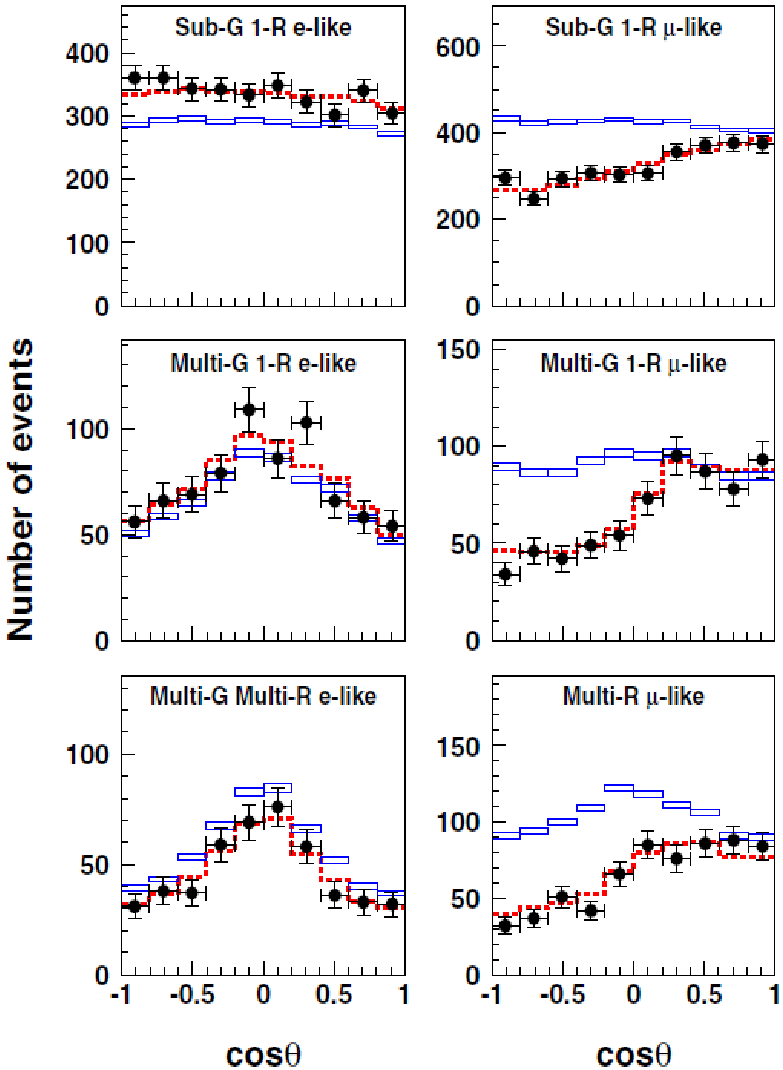



# Expected Flux Distribution



# Zenith Angle Distributions

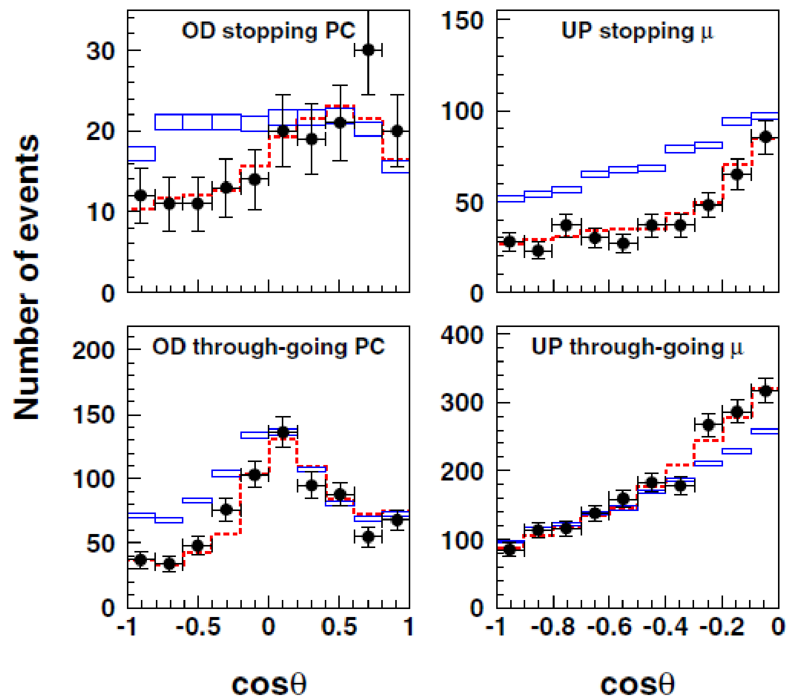
PHYSICAL REVIEW D **74**, 032002 (2006)




**Data**

**MC with no oscillation**

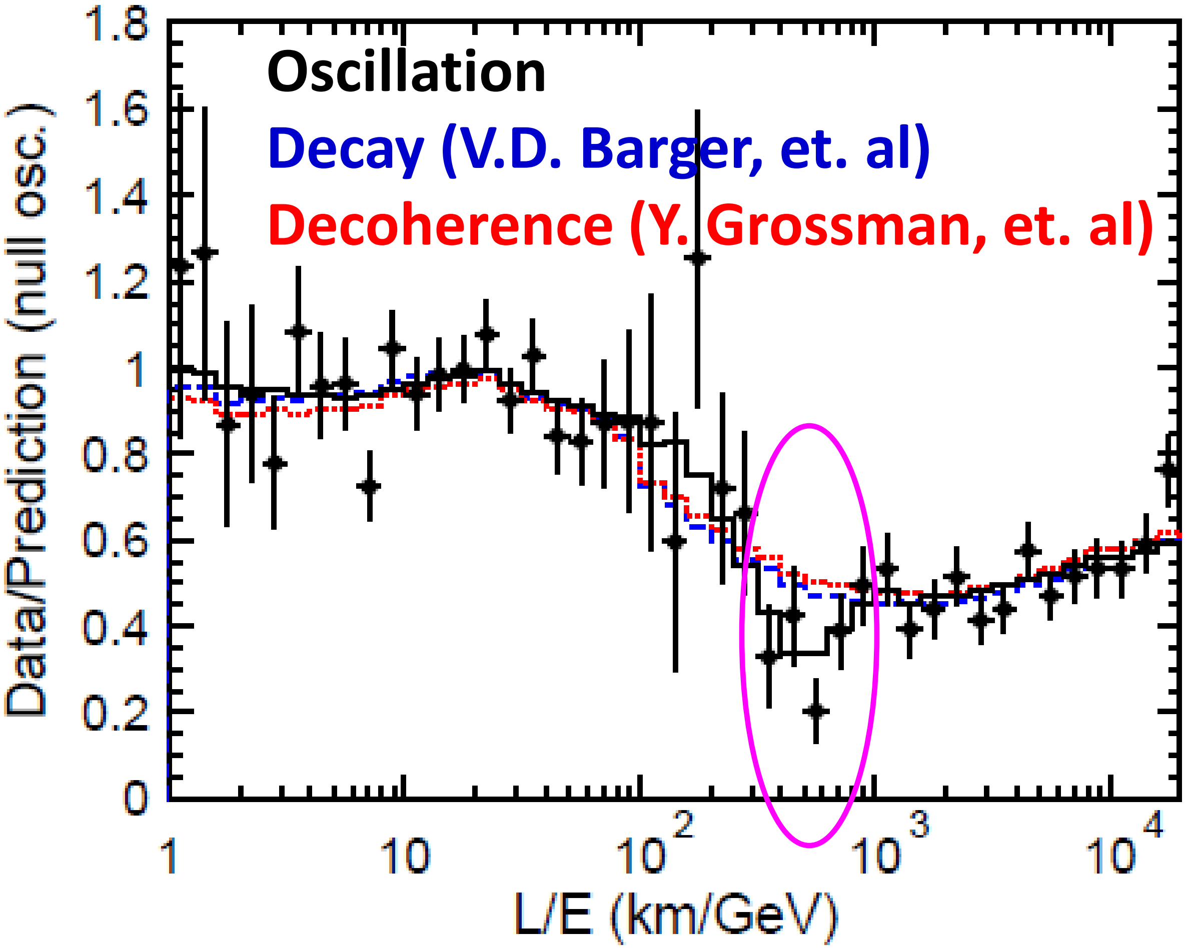
**MC with best-fit oscillation**




- **Less deviation for $\nu_e$**
- **Large deviation for $\nu_\mu$**

# Oscillation Signature

**Neutrino oscillation should have a signature of the survival probability varying with L/E**




**Alternative models are ruled out at ~5σ level**

Phys.Rev.Lett.93:101801,2004

# Tau Neutrino Appearance

**If the deviation is due to**

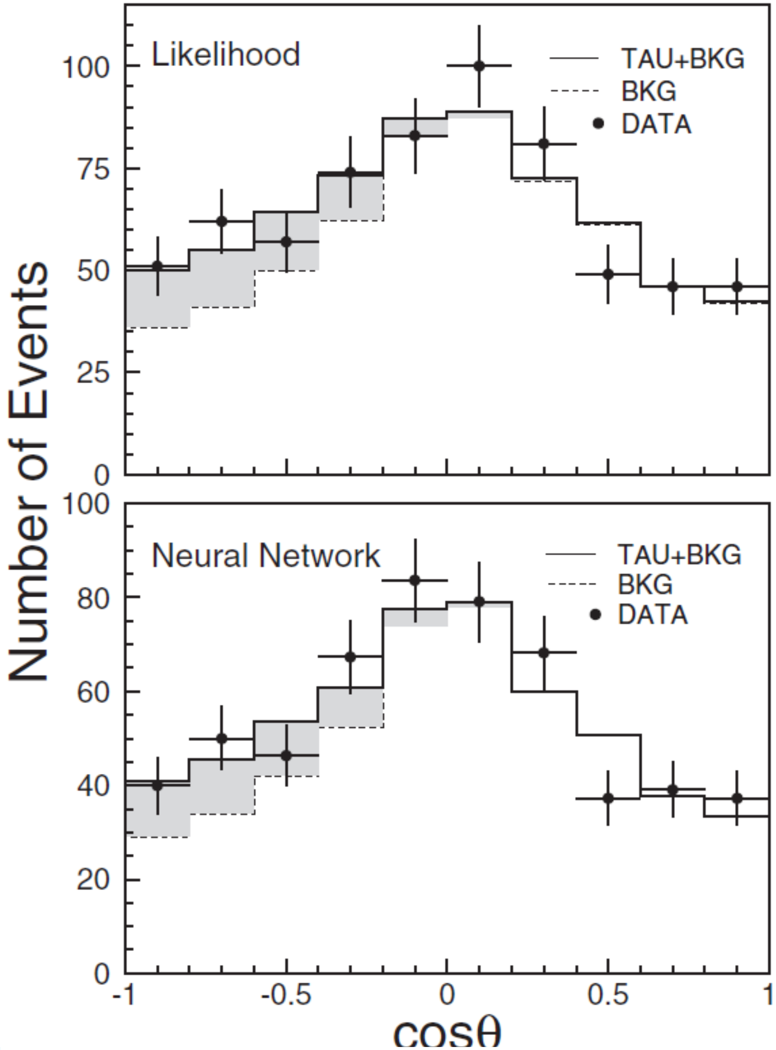
$$\nu_\mu \rightarrow \nu_\tau$$

**Then $\nu_\tau$ appearance should be observed. However, in CC there is a threshold issue**

$$E_{\nu_\tau}^{th} = \max(0, m_\tau \frac{m_{N'}}{m_N} + \frac{m_\tau^2 + m_{N'}^2 - m_N^2}{2m_N})$$

$$E_{\bar{\nu}_\tau}^{th} = 3460.7\,\text{MeV}, E_{\nu_\tau}^{th} = 3455.5\,\text{MeV}$$

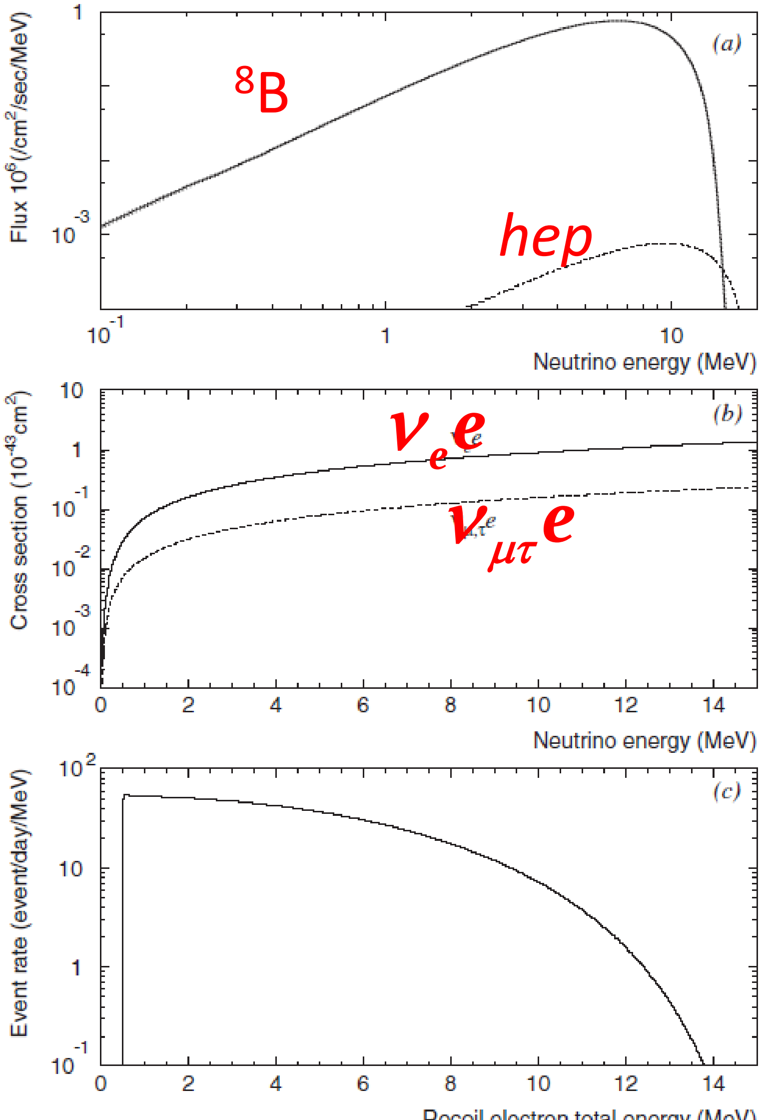
**and a short lifetime of τ, complicating the analysis.**

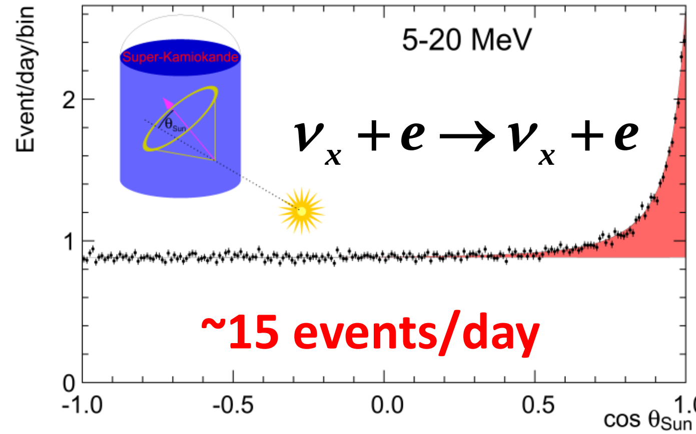



PRL 97, 171801 (2006)

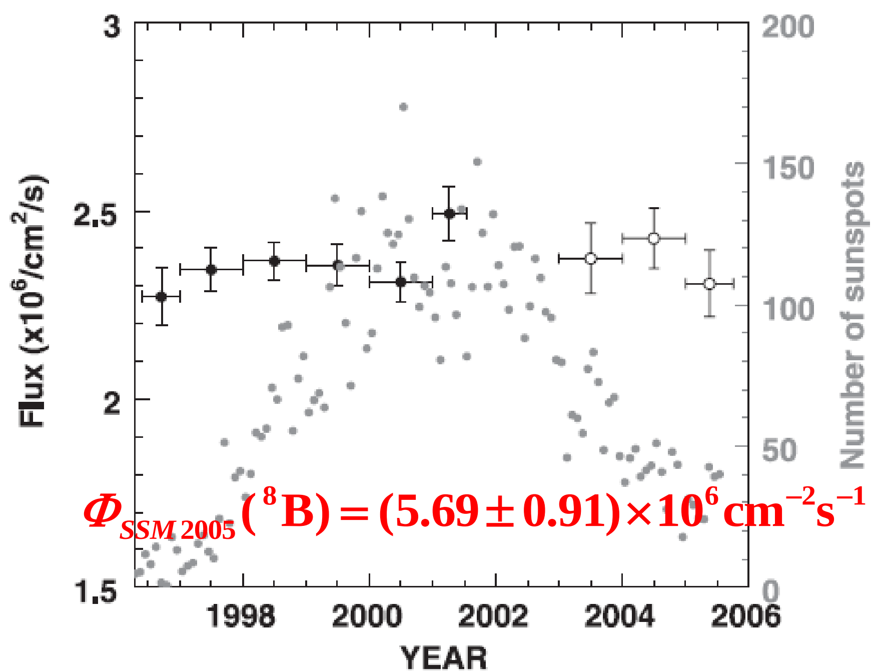
The hypothesis of no tau neutrino appearance is disfavored by 2.4 sigma.

# Solar Neutrino Flux



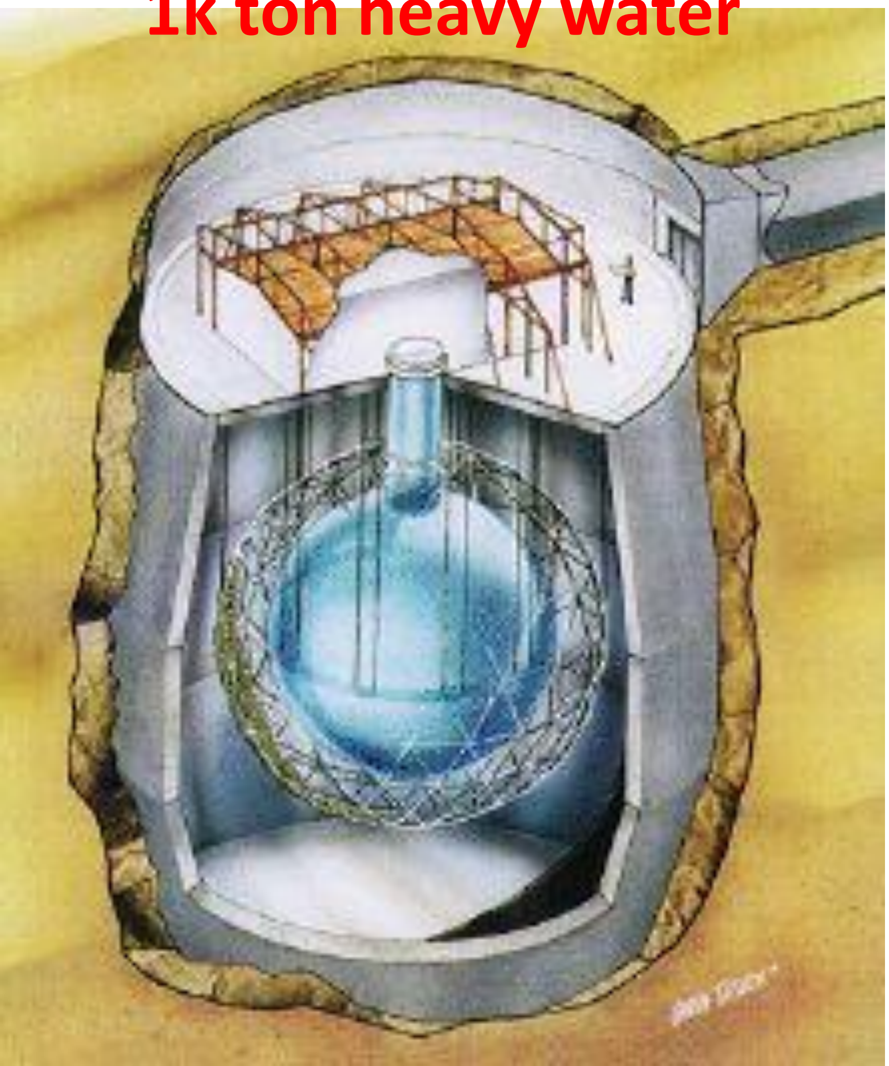

PHYSICAL REVIEW D 78, 032002 (2008)

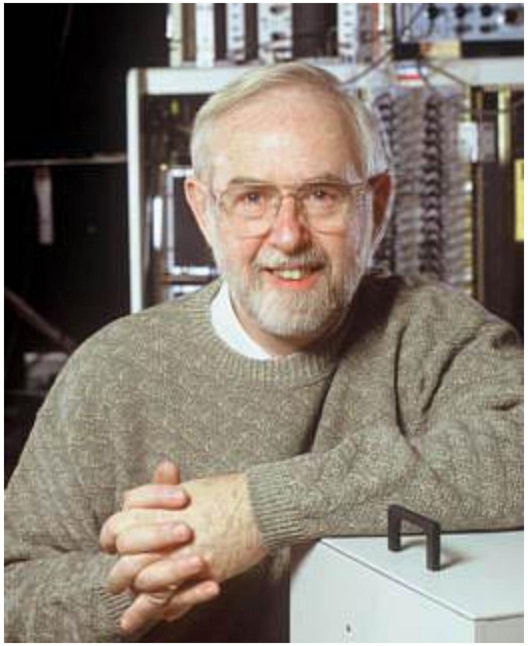



$$\Phi_{SSM\,2005}(^{8}\mathrm{B}) = (5.69 \pm 0.91) \times 10^{6}\,\mathrm{cm^{-2}s^{-1}}$$

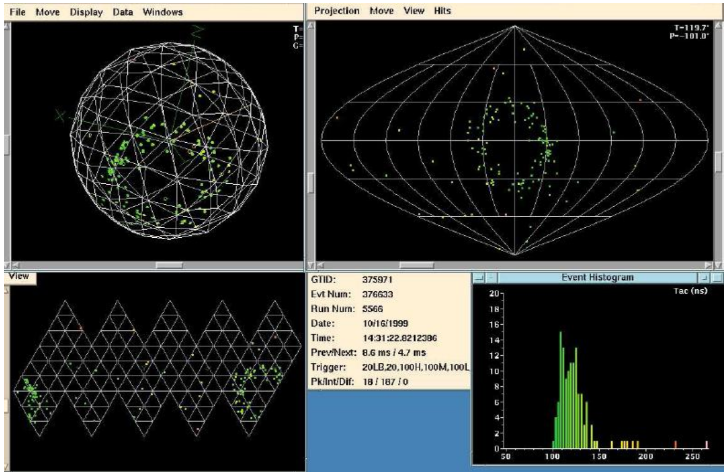
# SNO Experiment

**2092m to Surface**
**1k ton heavy water**

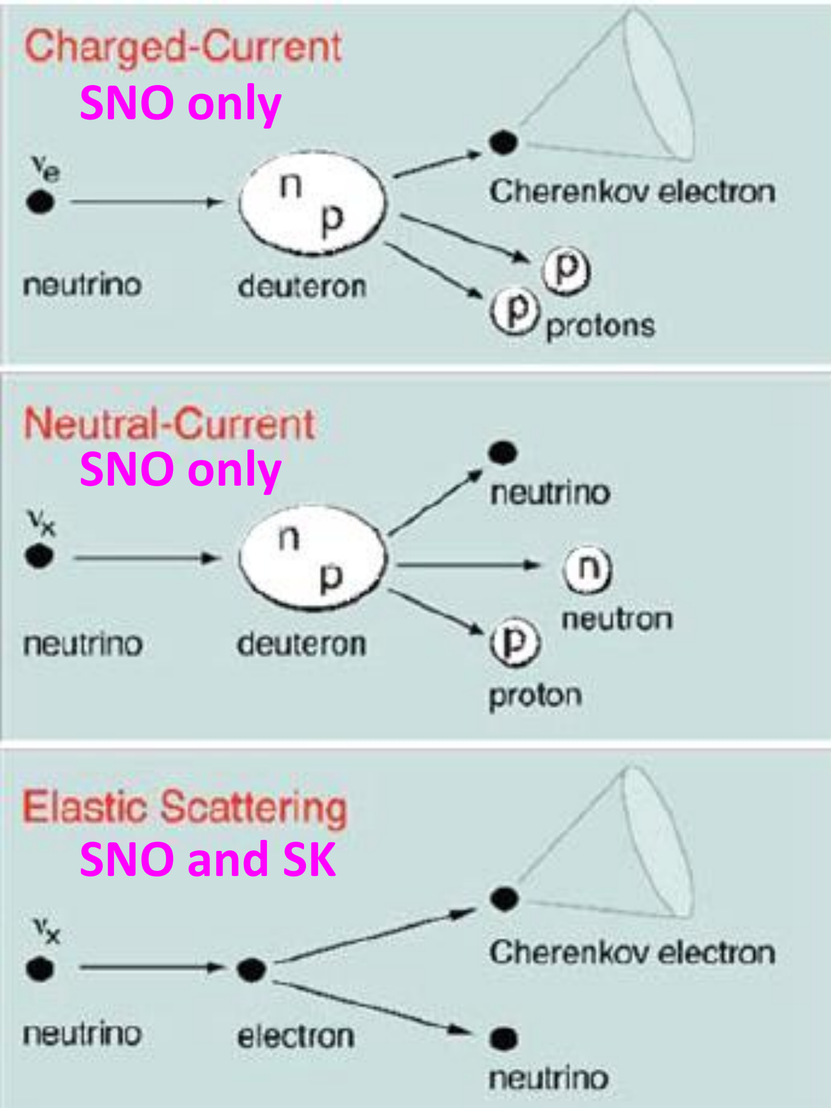


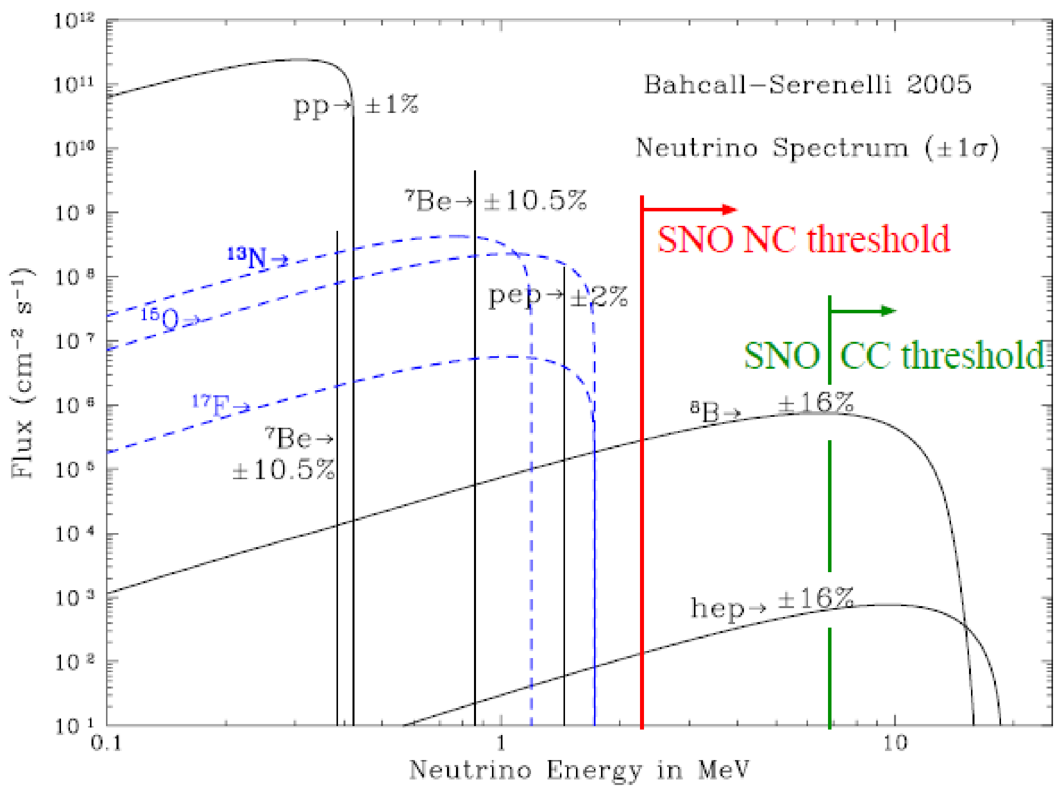


Arthur B. McDonald

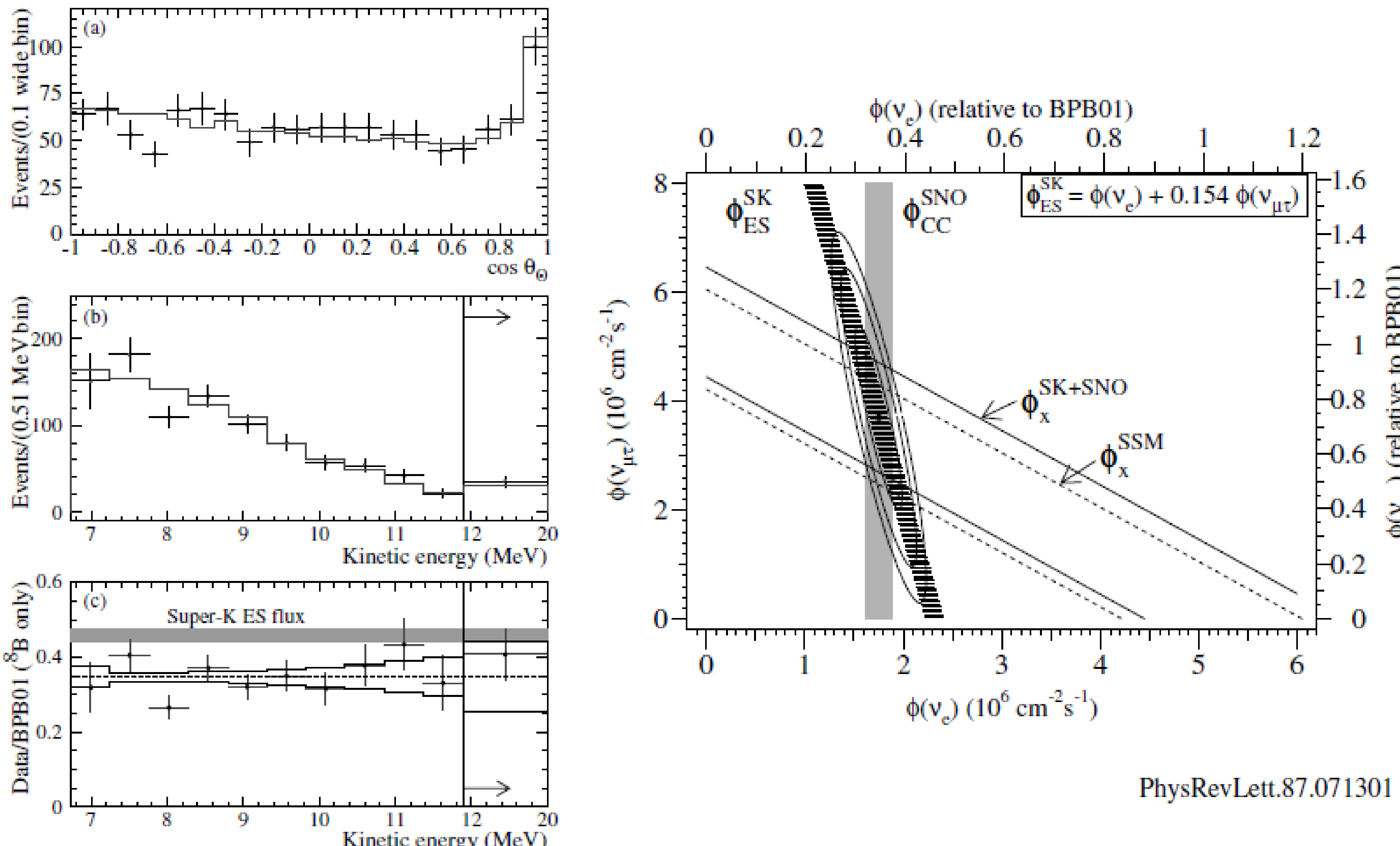


# Solar Neutrinos Interactions



# First Result from SNO




PhysRevLett.87.071301

**Good agreement between the measurement and the SSM.**

# Three Phases Of SNO

**Efficient detection of the neutrons produced via the NC plays a key role in measuring the solar neutrinos.**

| D$_2$O Phase | Salt Phase | NCD Phase |
|---|---|---|
| (pure D$_2$0) | (D$_2$O + 0.2% NaCl) | ($^3$He counters) |
| Nov 1999 - May 2001 | July 2001 - Sept 2003 | Dec 2004 - Dec 2006 |
| $n + d \rightarrow t + \gamma$ | $n + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \gamma$'s | $n + {}^{3}\mathrm{He} \rightarrow p + t$ |
| $(\sigma = 0.0005\, b)$ | $(\sigma = 44\, b)$ | $(\sigma = 5330\, b)$ |
| Detect a Compton-scattered electron from a 6.25 MeV $\gamma$ | Detect Compton-scattered electrons from multiple $\gamma$'s totalling 8.6 MeV | Detect 764 keV of ionization from the charged particles in $^3$He proportional counters |

S. Oser

# Final Answer from SNO

PRL **101**, 111301 (2008)

$$\phi_{CC}^{SNO} = 1.67^{+0.05}_{-0.04}(\text{stat})^{+0.07}_{-0.08}(\text{syst})$$

$$\phi_{ES}^{SNO} = 1.77^{+0.24}_{-0.21}(\text{stat})^{+0.09}_{-0.10}(\text{syst})$$

$$\phi_{NC}^{SNO} = 5.54^{+0.33}_{-0.31}(\text{stat})^{+0.36}_{-0.34}(\text{syst})$$

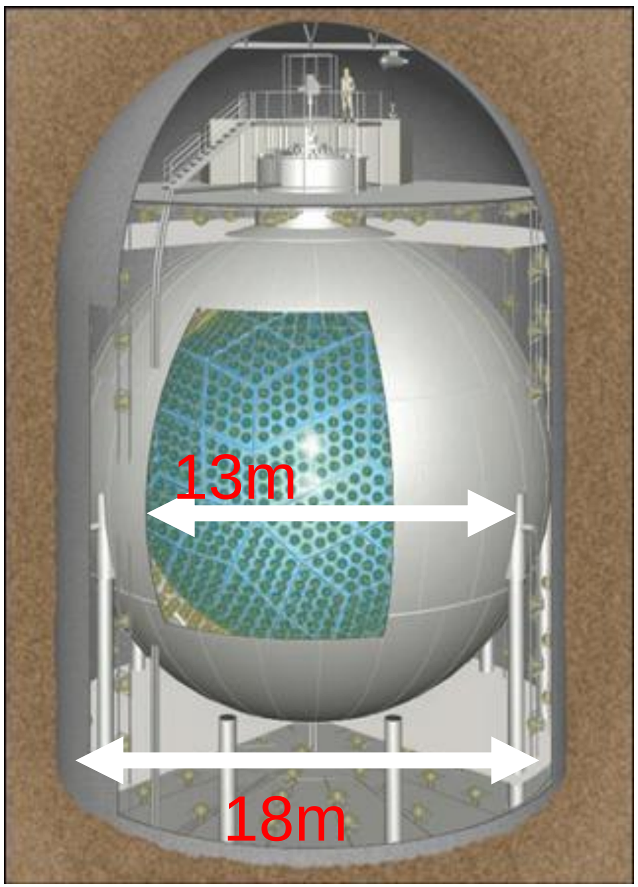
$$\frac{\phi_{CC}^{SNO}}{\phi_{NC}^{SNO}} = 0.301 \pm 0.033(\text{total})$$

$$\Phi_{SSM\,2005}(^{8}\mathrm{B}) = (5.69 \pm 0.91) \times 10^{6}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

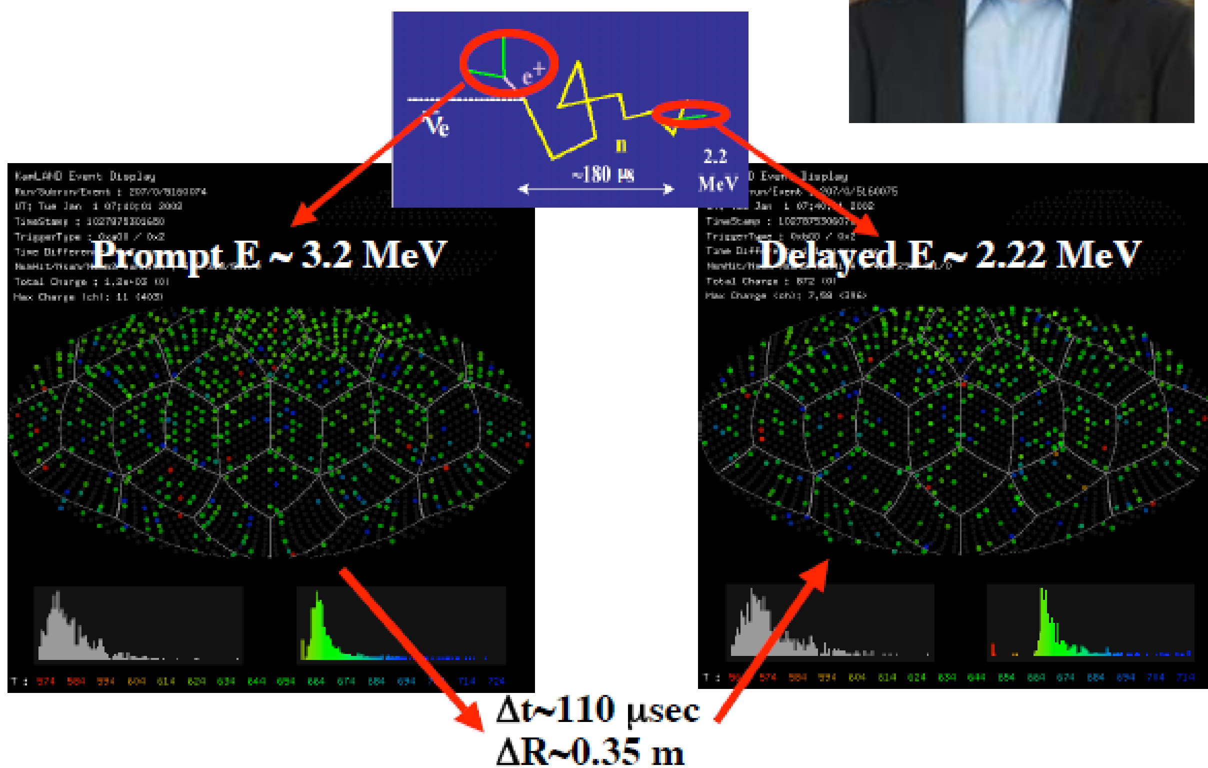
J. N. Bahcall, A. M. Serenelli, and S. Basu, Astrophys. J. **621**, L85 (2005).

# KamLAND Experiment

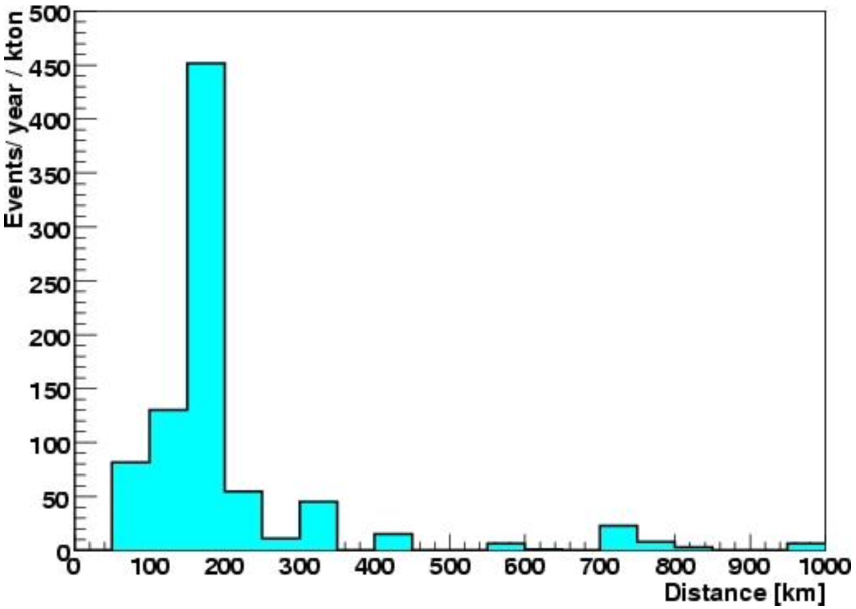
## Observation of the reactor neutrino disappearance at L/E value where the solar neutrino effect occurs




Located at Kamioka, using 1k ton liquid scintillator as the target.



# Reactor Neutrinos at KamLAND

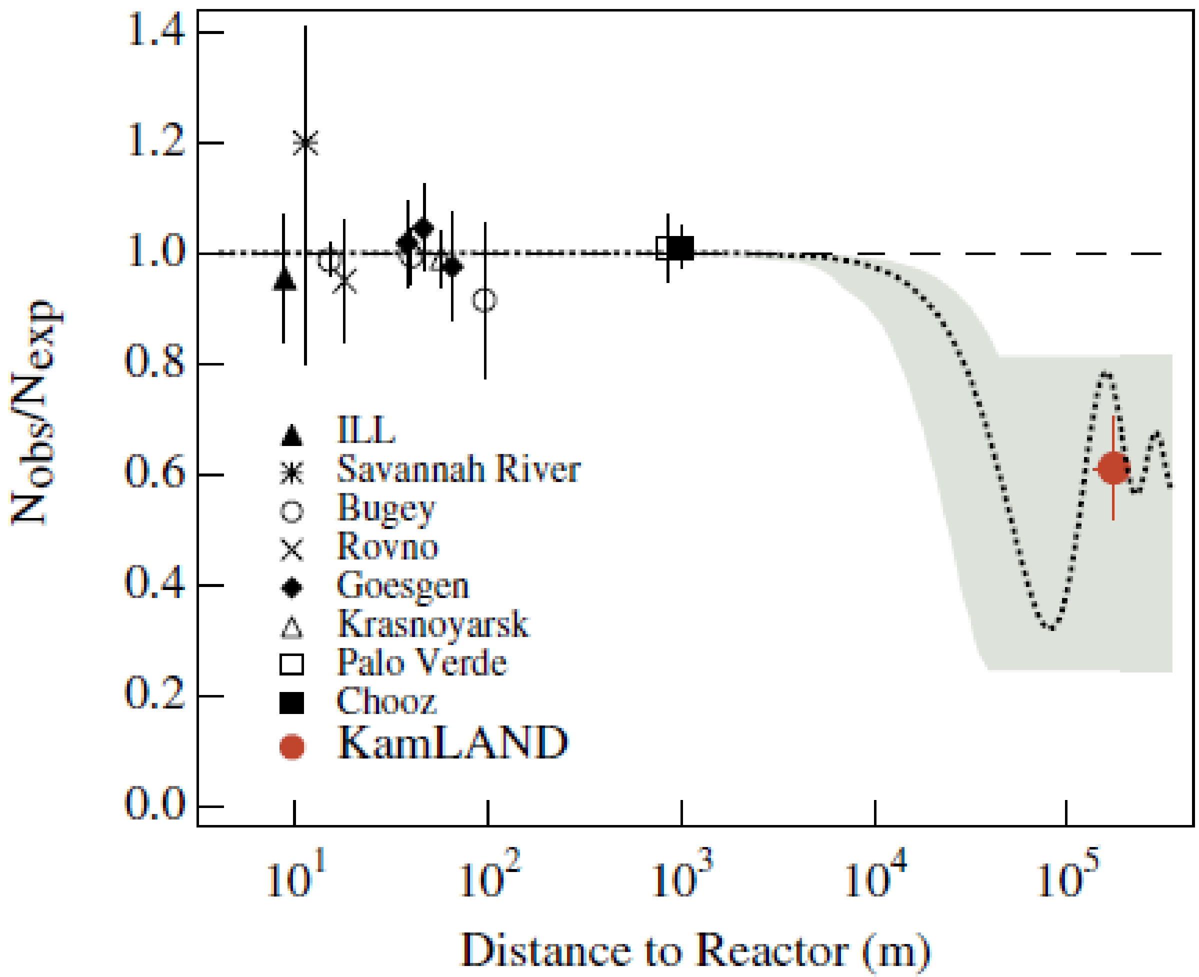




**Japan reactors 94~97%**

**Korea reactors 3 ~ 5%**

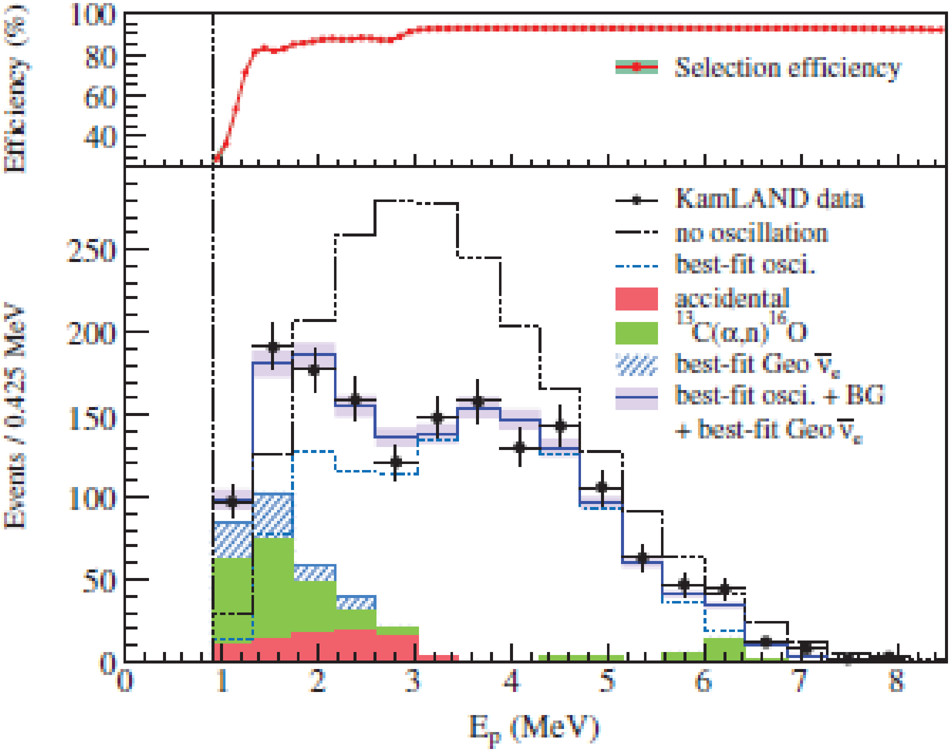
**world reactors ~ 0.5%**

# First Result From KamLAND

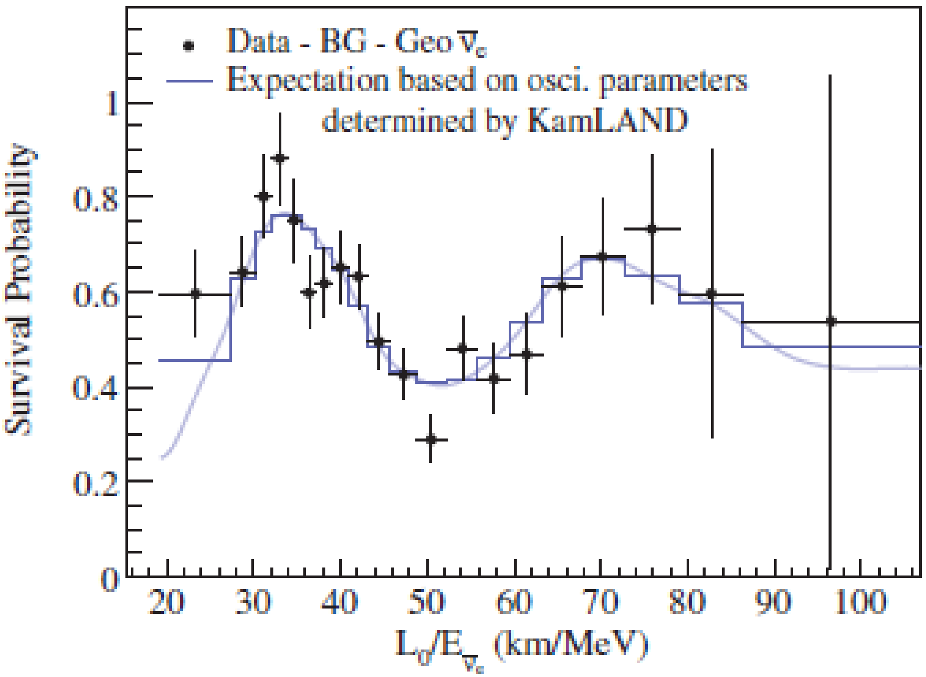



PhysRevLett.90.021802

# Latest Results From KamLAND



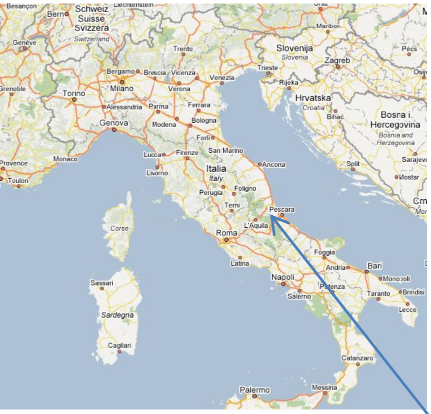

PRL 100, 221803 (2008)

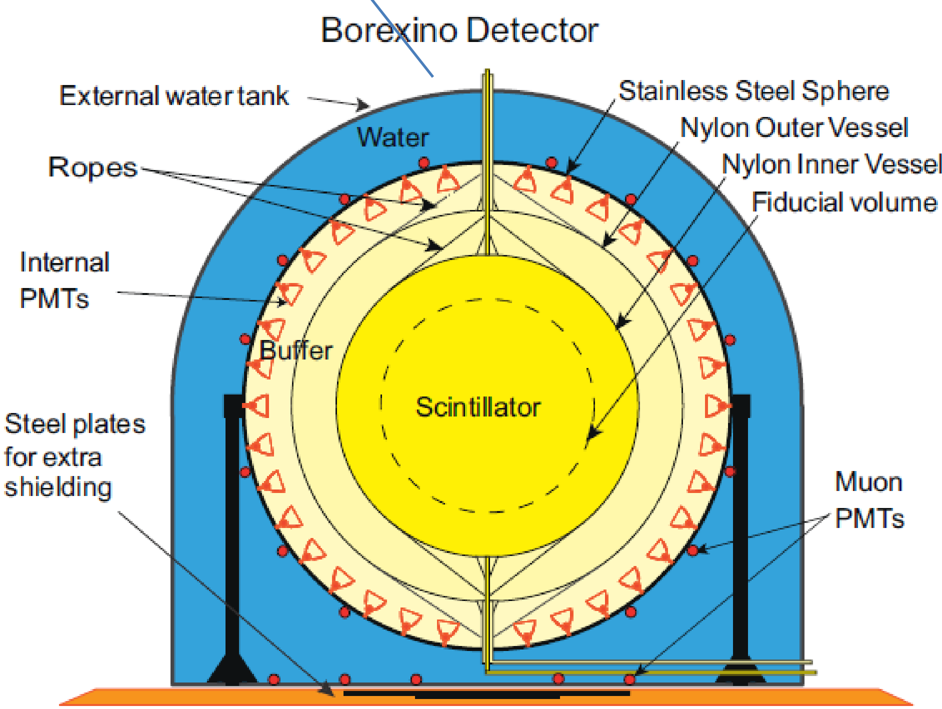


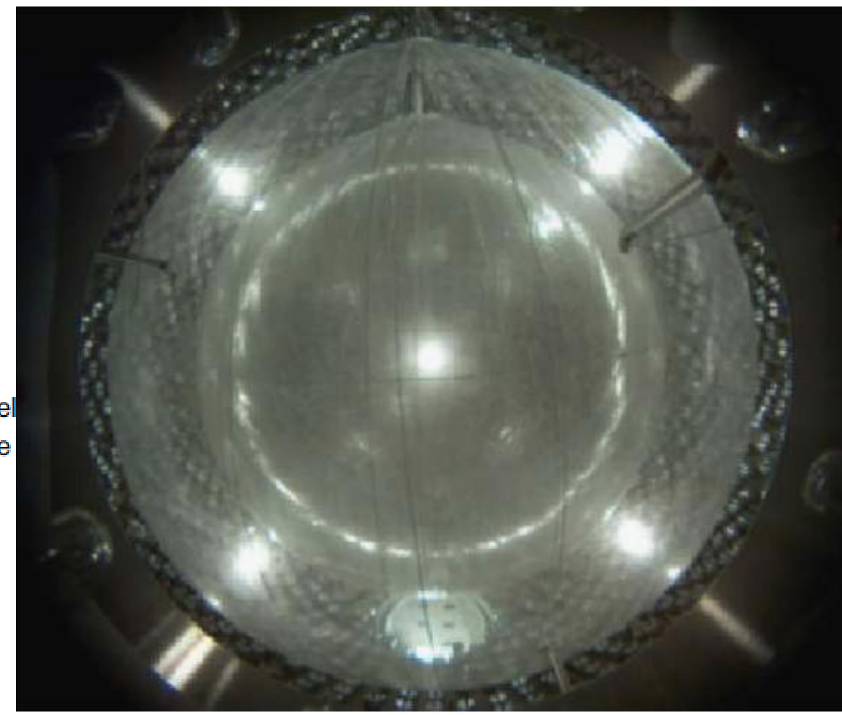

$$\Delta m^2_{21} = 7.58^{+0.14}_{-0.13}(\text{stat})^{+0.15}_{-0.15}(\text{syst})\times 10^{-5}\,\text{eV}^2$$

$$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(\text{stat})^{+0.10}_{-0.06}(\text{syst})$$

# Borexino Experiment

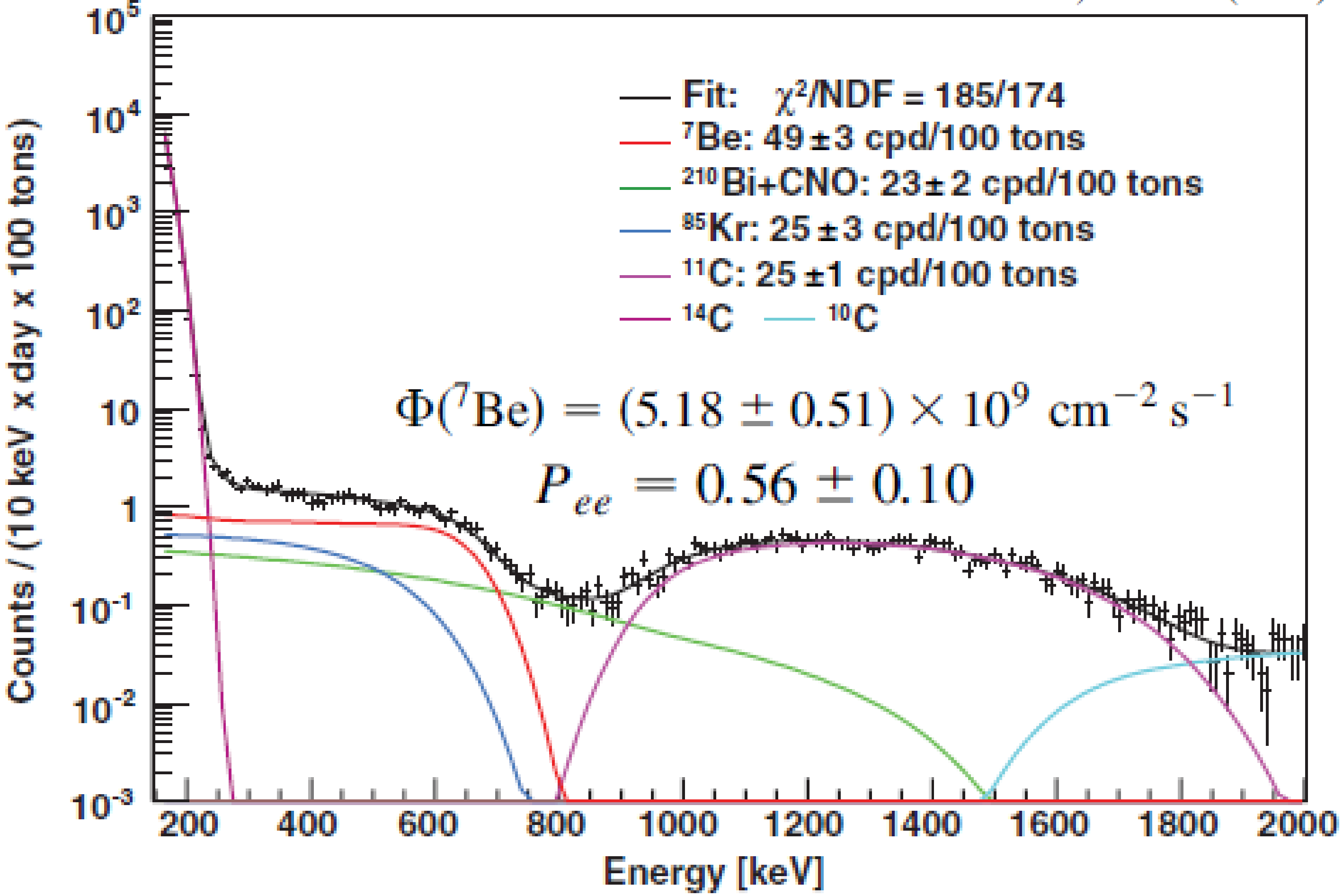


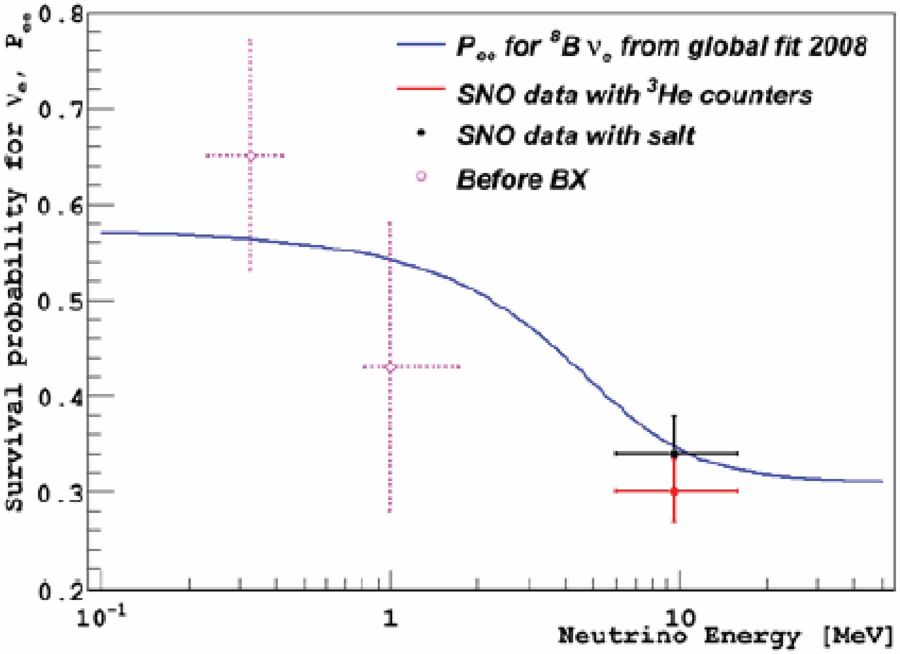



# $^{7}$Be Solar Neutrino Measurement

PRL **101**, 091302 (2008)

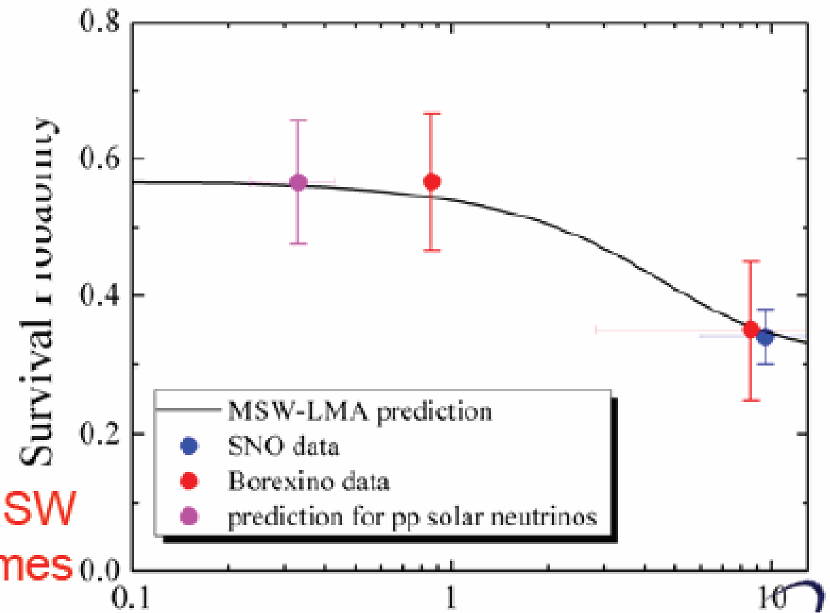


# Impact from Borexino




Before Borexino

After Borexino




Striking first confirmation of the predicted MSW transition between vacuum and matter regimes

# Comparison With Solar Models

- **Borexino measurement:** PRL **101**, 091302 (2008)

  **49 ± 3(stat) ± 4 (syst) cpd/ 100ton**
- **High metallicity Solar model MSW/LMA:**

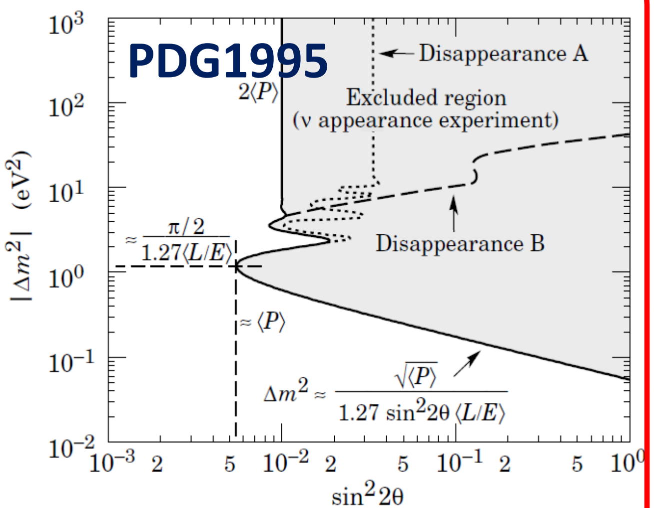
  **48 ± 4 cpd / 100ton**
- **Low metallicity Solar model , MSW/LMA**

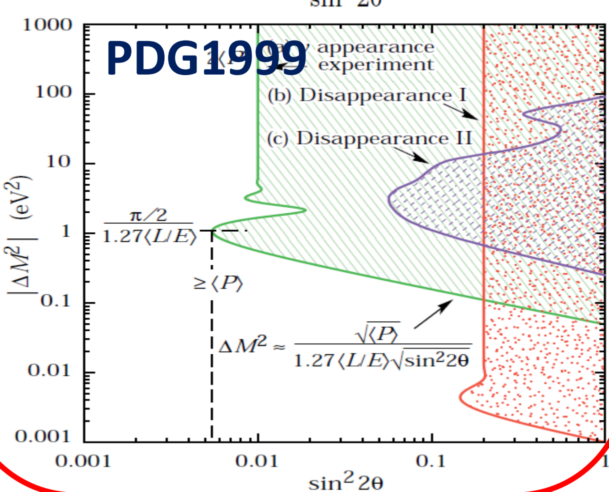
  **44 ± 4 cpd / 100ton**
- **High metallicity Solar model, nonoscillating neutrino** (inconsistent with measurement at the 4 σ C.L.)

  **74 ± 4 cpd / 100ton**

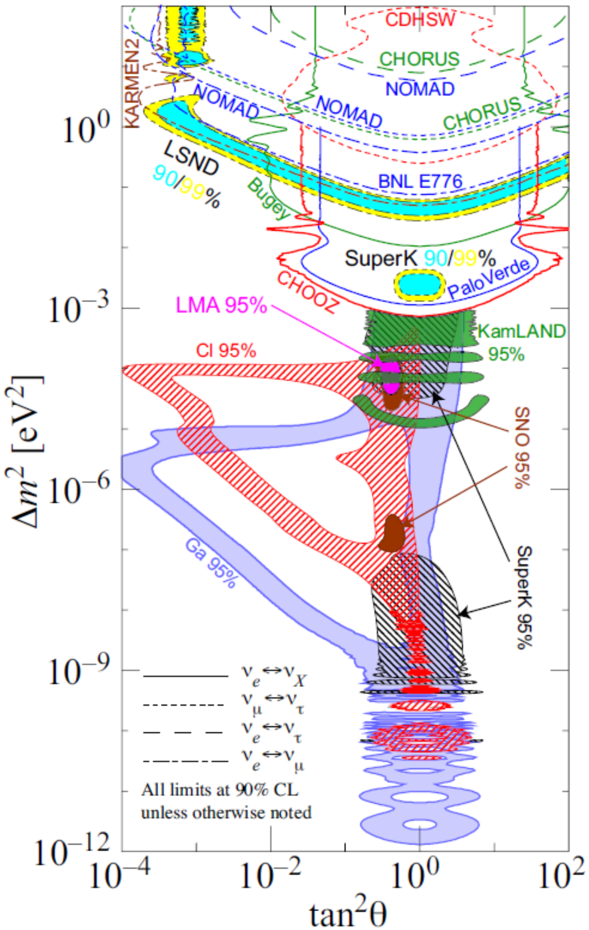
# Achievement on Mass Splitting and Mixing Measurements

## Dark Age

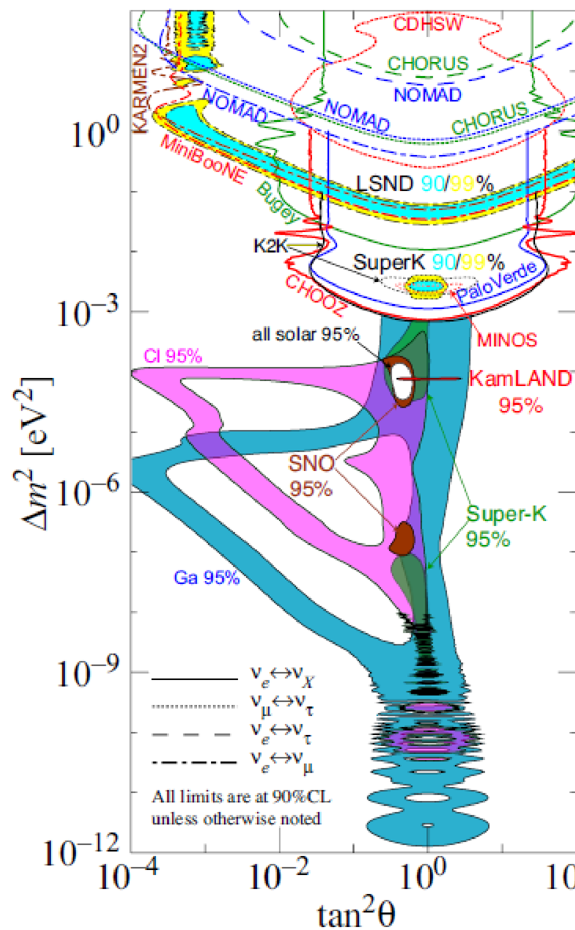



## PDG2004

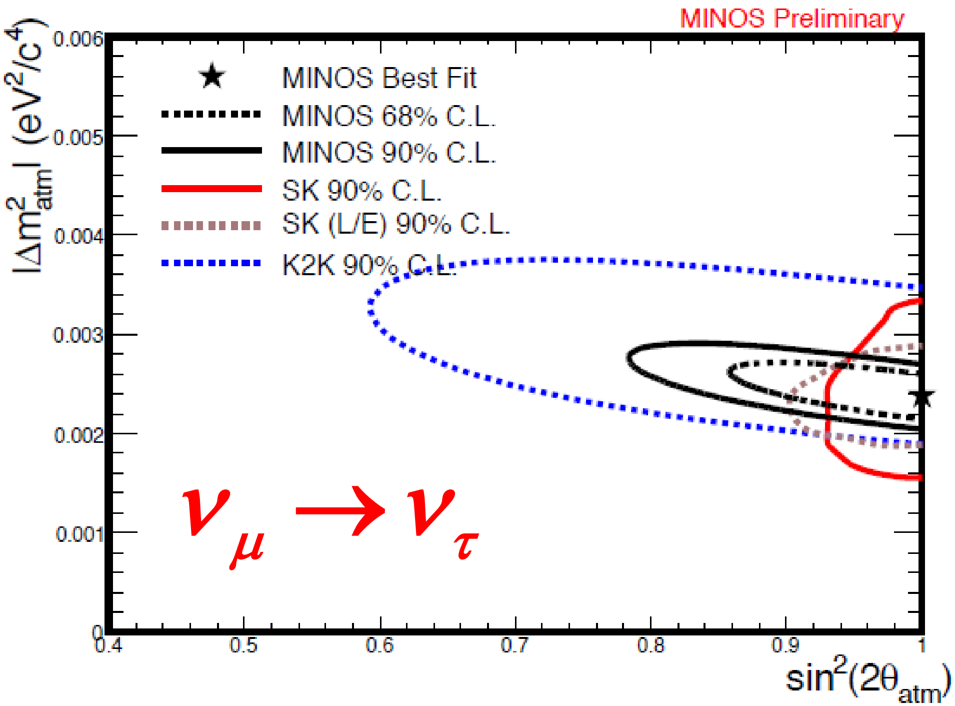


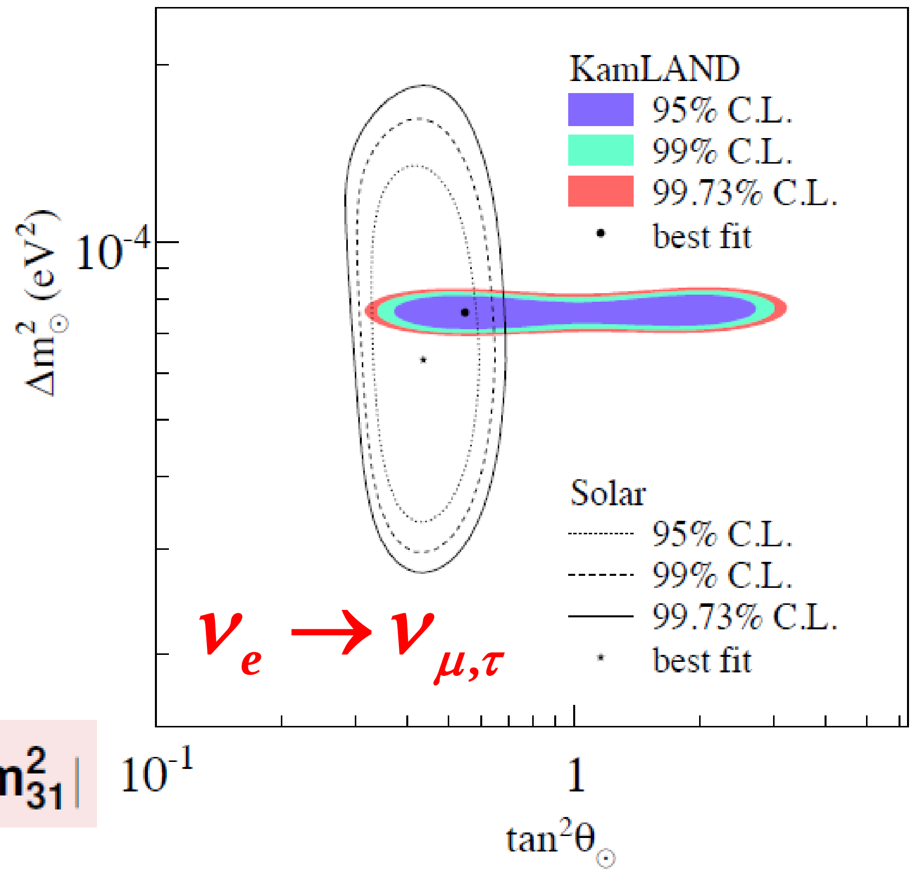

## PDG2008




$$\Delta m^2 : \Delta m^2_\odot \text{ or } \Delta m^2_{atm} \text{ or } \Delta m_{LSND};\ \theta : \theta_\odot \text{ or } \theta_{atm} \text{ or } \theta_{LSND}$$

# Do We Fully Understand Neutrino Oscillation Now?




$$\Delta m^2_{12} = \Delta m^2_\odot << \Delta m^2_{atm} = |\Delta m^2_{32}| \approx |\Delta m^2_{31}|$$

$$\theta_{13} = ?$$

$$\theta_\odot = \theta_{12}, \quad \theta_{atm} \approx \theta_{23}$$

$$m_1 < m_2 < m_3 \quad \text{or} \quad m_3 < m_1 < m_2\ ?$$

# Search For Non-Zero $\theta_{13}$ In Non-Accelerator Neutrino Experiments

# Why Is It So Important?

**Since $\theta_{13}$ is the gateway of CP violation in lepton sector!**

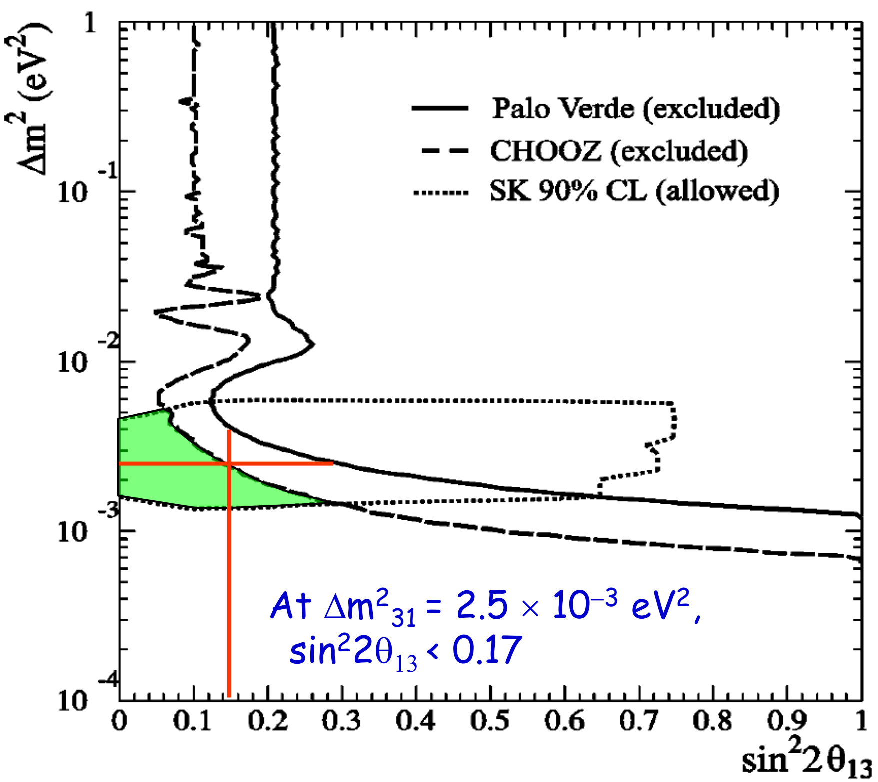
$$\begin{pmatrix} \\ \end{pmatrix}\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{12} \end{pmatrix}\begin{pmatrix} \\ \end{pmatrix}\begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

**CP violation parameters:**

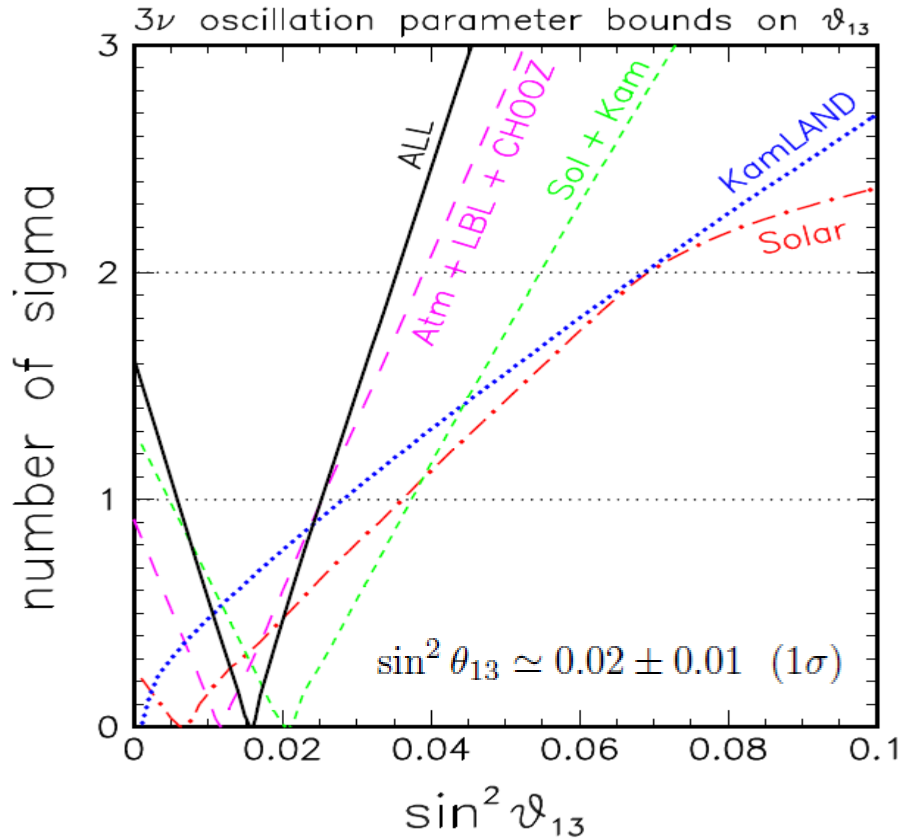
**Majorana phases $\phi_1$, $\phi_2$ (very hard)**
**Dirac phase $\delta$ (may be accessible thru accelerator neutrino experiment provided that $\sin\theta_{13}$ is not so small)**

# Current knowledge on $\theta_{13}$

**Direct search (PRD 62, 072002)**

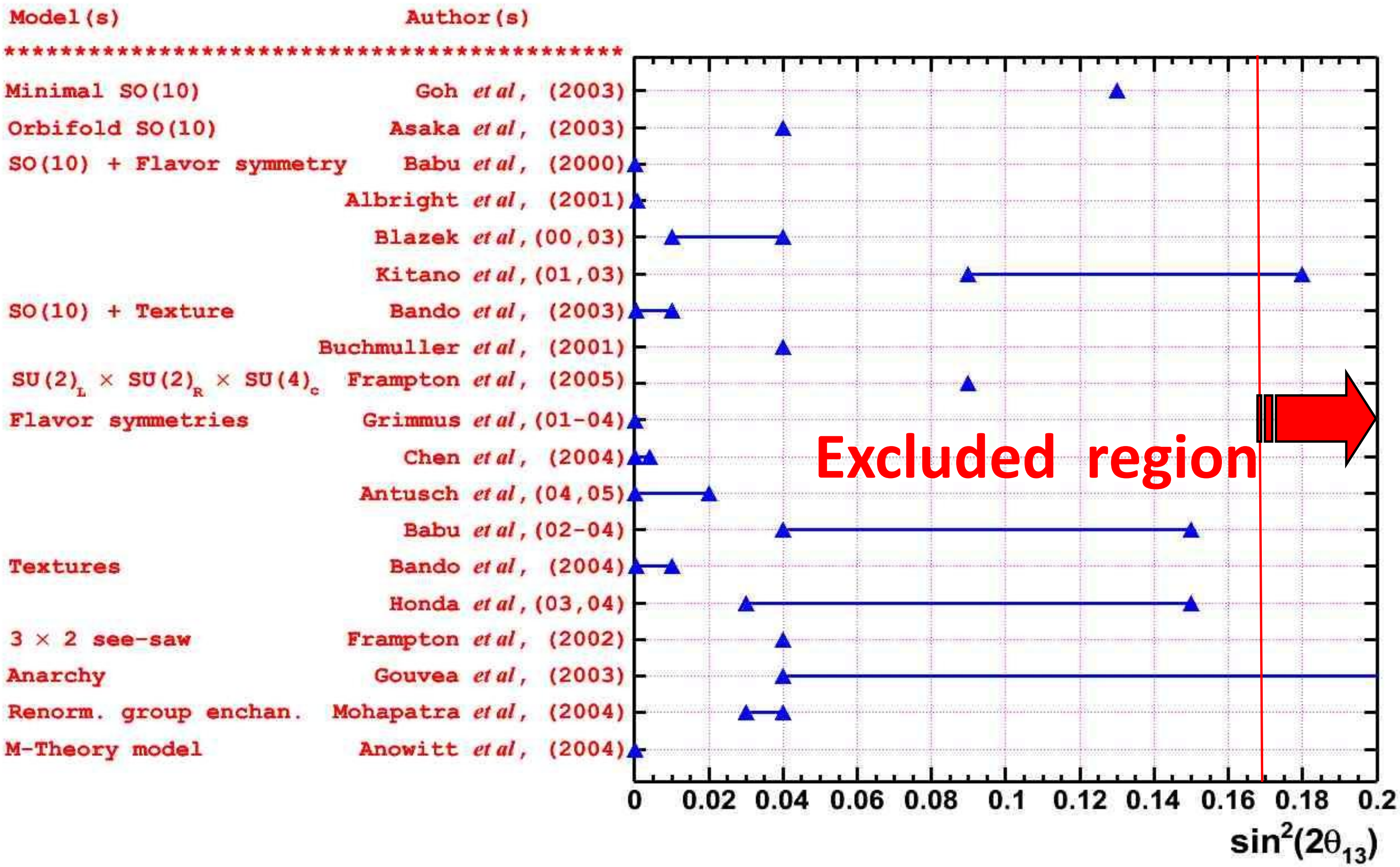



**Global fit (hep-ph/0905.3549)**




**A small $\theta_{13}$(e.g. $\sin^2 2\theta_{13}<0.01$) would make future experimental searches for CP violation become a kind of "Mission: Impossible".**

# Theoretical predictions for $\theta_{13}$

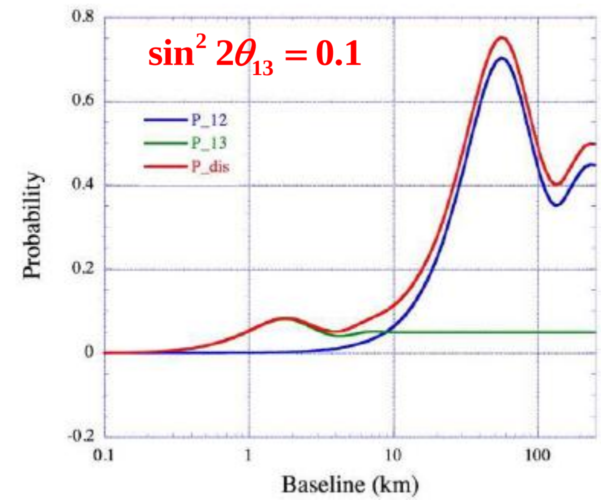



**A precise $\theta_{13}$ measurement is helpful in understanding the physics beyond the Standard Model.**

# How to measure $\theta_{13}$?

## ➢Disappearance searches at reactors:

$$P_{dis} = P_{12} + P_{13} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(1.267\cdot\Delta m^2_{21}\cdot\frac{L}{E})$$
$$+\cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{31}\cdot\frac{L}{E})$$
$$+\sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(1.267\cdot\Delta m^2_{32}\cdot\frac{L}{E})$$




## ➢Appearance searches at accelerators:

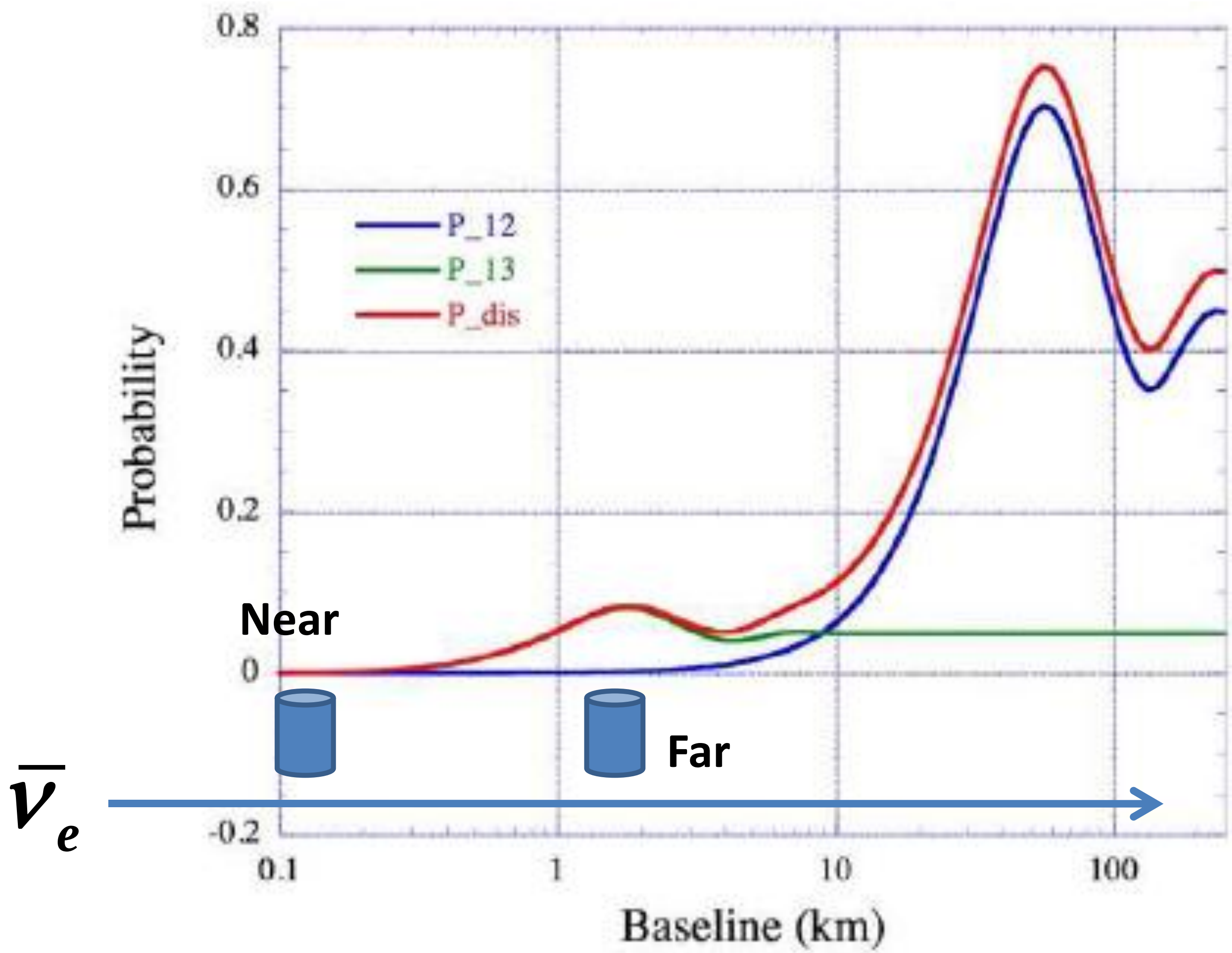
$$P_{app} \approx \sin^2\theta_{23}\sin^2\theta_{13}\sin^2(1.267\Delta m^2_{23}\frac{L}{E}) + \cos^2\theta_{23}\sin^2\theta_{12}\sin^2(1.267\Delta m^2_{12}\frac{L}{E})$$
$$-A(\rho)\cos^2\theta_{13}\sin\theta_{13}\sin\delta$$

➢**Reactor experiments provide a clean environment to measure $\theta_{13}$.**
➢**Accelerator experiments give access to both $\theta_{13}$ and $\delta$ values.**

# How to Reach 1% Precision?

- **Increase statistics:**
  - **Need intensive neutrino flux from powerful nuclear reactors**
  - **Utilize larger target mass, hence larger detectors**
- **Reduce systematic uncertainties:**
  - **Reactor-related:**
    - **Optimize baseline for best sensitivity and smaller residual errors**
    - **Near and far detectors to minimize reactor-related errors**
  - **Detector-related:**
    - **Use "Identical" pairs of detectors to do *relative* measurement**
    - **Comprehensive program in calibration/monitoring of detectors**
    - **Interchange near and far detectors (optional)**
  - **Background-related**
    - **Go deeper to reduce cosmic-induced backgrounds**
    - **Enough active and passive shielding**

# The Detector Place Selection



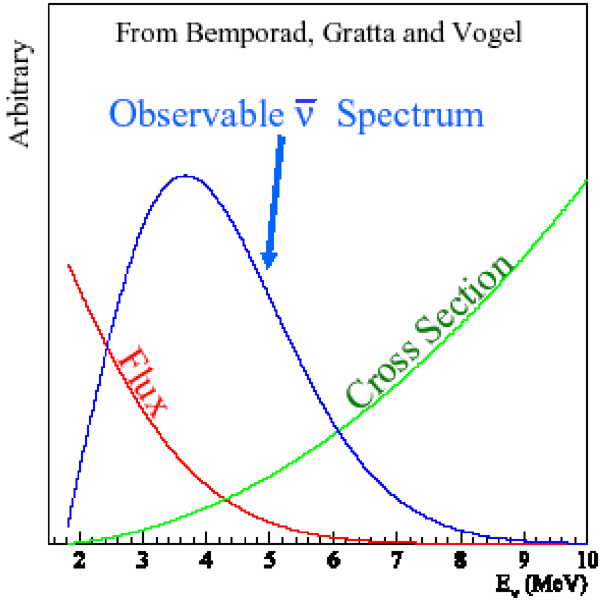
# Signature of A Signal

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

Prompt signal: $e^+ + e^- \rightarrow 2\gamma's$ $(E_{e^+} > 2m_e = 1.022\text{MeV})$

Delayed signal: $n + Gd \rightarrow Gd' + \gamma's$ $(\sum E_\gamma \sim 8\text{MeV},\ \tau_0 \sim 28\mu s)$

Delayed signal: $n + p \rightarrow d + \gamma$ $(E_\gamma = 2.2\text{MeV},\ \tau_0 \sim 180\mu s)$

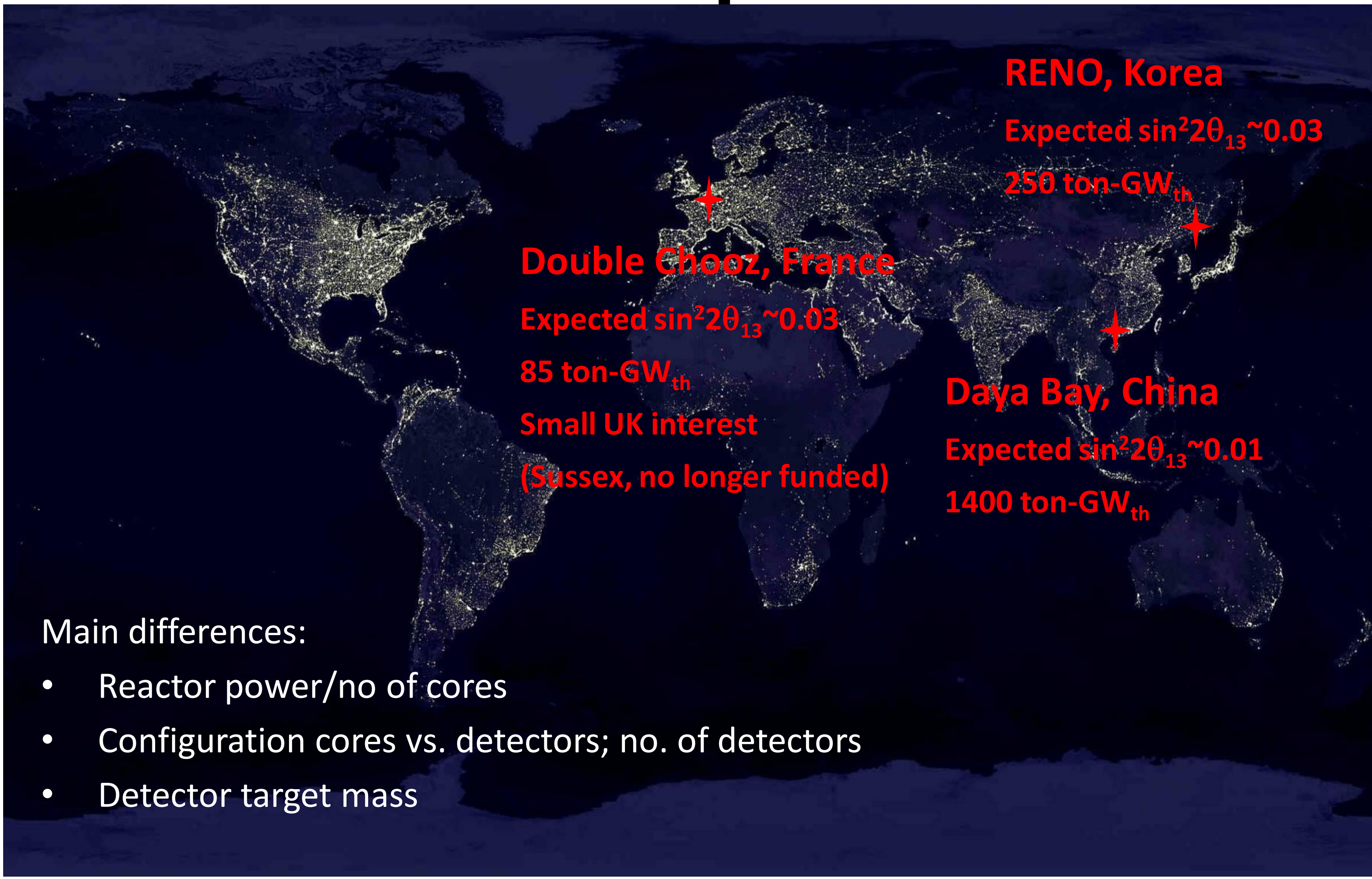



**Threshold=1.8 MeV**

***Neutrino energy:***

$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

# Reactor Experiments




Main differences:

- Reactor power/no of cores
- Configuration cores vs. detectors; no. of detectors
- Detector target mass

# Status and Expected Milestones

## Double Chooz

- 2009
- ND hall + tunnel construction begins
- 2010 — FD ready for data-taking
- 2011
- $\sin^2 2\theta_{13} \sim 0.06$
- ND ready for data-taking
- 2012
- 2013
- 2014 — $\sin^2 2\theta_{13} \sim 0.03$

**Near :** 500/day
**Far :** 50/day

## RENO

- N and F tunnels completed
- 2009
- ND and FD commissioning
- ND and FD ready for data-taking
- 2010
- 2011
- 2012
- 2013 — $\sin^2 2\theta_{13} \sim 0.03$ ???
- 2014

**Near :** 1,280/day
**Far :** 114/day

## Daya Bay

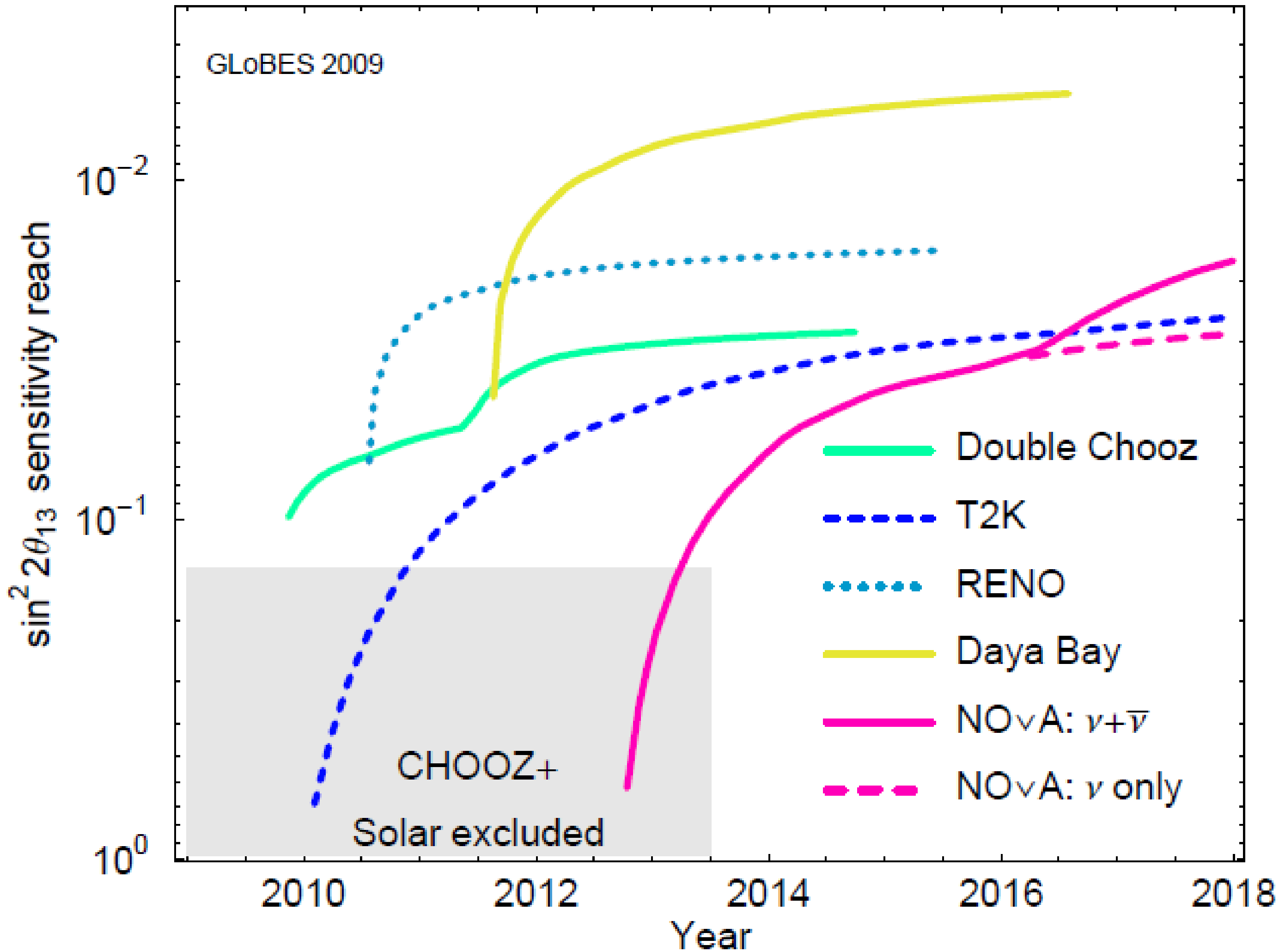
- 2009 — Near Hall occupancy
- First detector complete; start dry run
- 2010 — Near Hall ready for data-taking
- 2011 — Far Hall ready for data-taking; Ling Ao Hall ready a bit earlier
- 2012
- 2013
- 2014 — $\sin^2 2\theta_{13} \sim 0.01$

**Near :** 1,680/day (DYB)
1,480/day (LA)
**Far :** 360/day

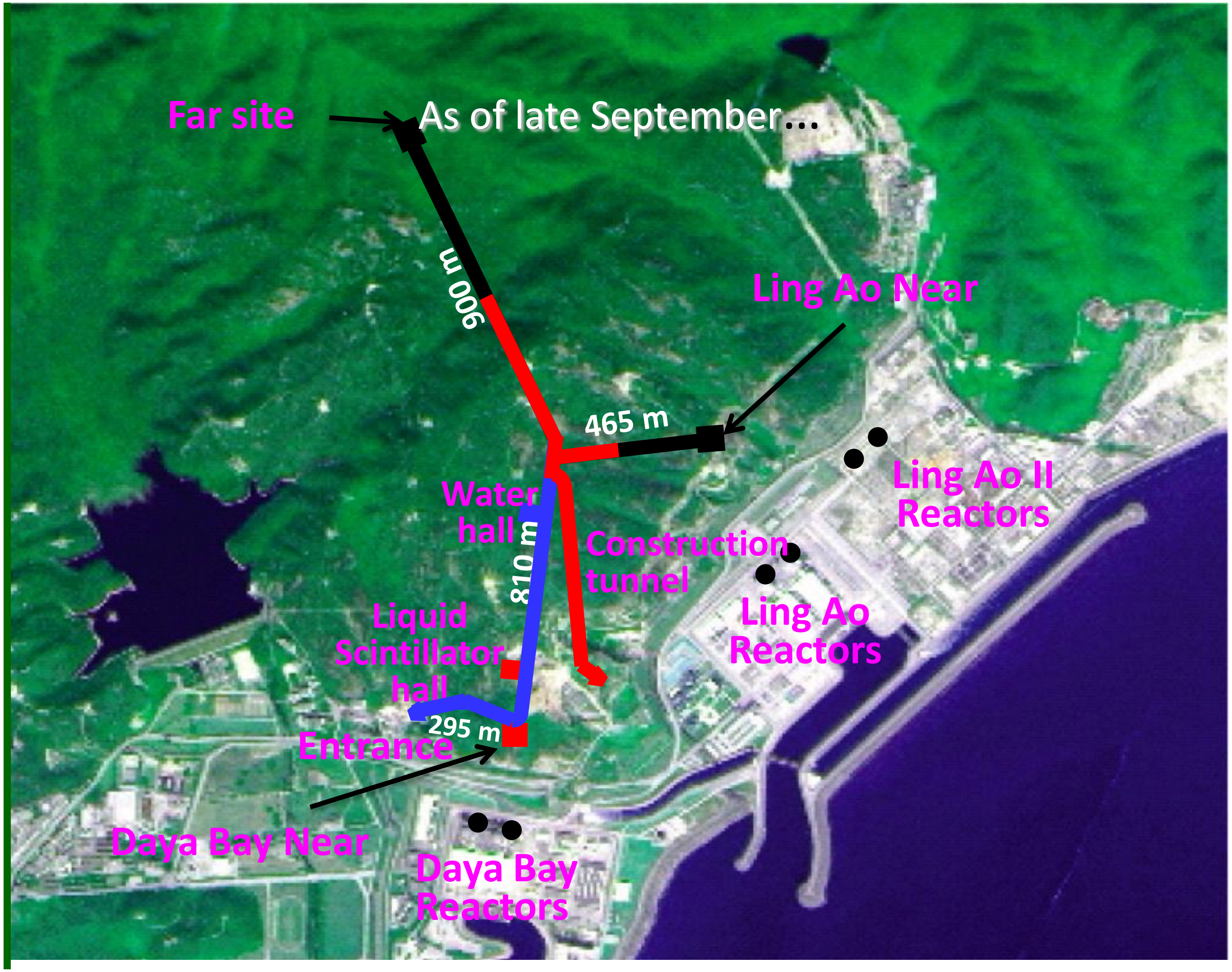
Elisabeth Falk

# Expected Sensitivities

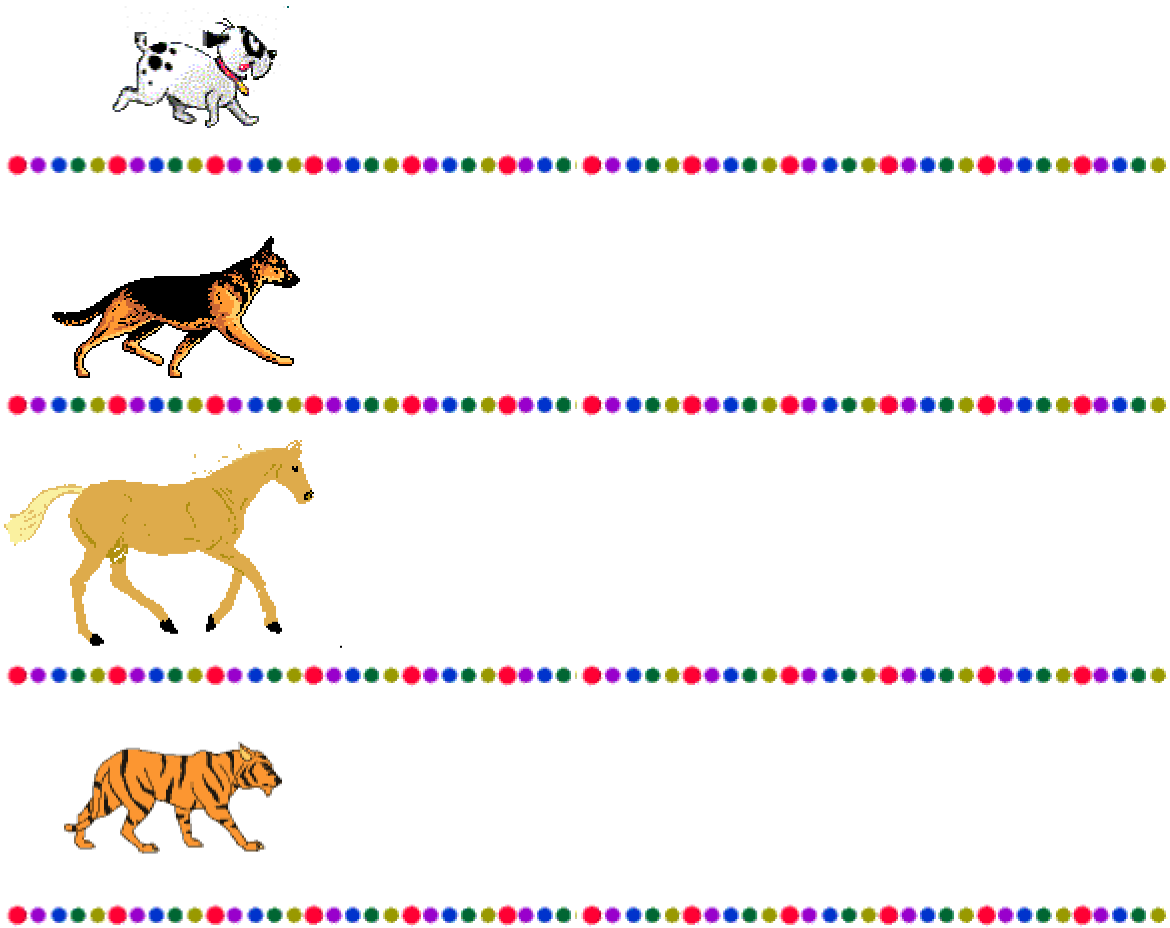
$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90% CL) Huber et al. arXiv:0907.1896



# DayaBay Civil Construction



# Waiting for $\theta_{13}$



**Double-Chooz, DayaBay, RENO, T2K, …**

**Which one will win the game?**

It is about 11 years since the discovery of neutrino mass. Still, in spite of enormous efforts of many theoreticians and experimentalists the "Physics behind neutrino mass" has not been identified. It should be some "New physics" beyond the Standard Model. It can be the old "new physics" invented many years ago and studied in details theoretically. It can be new "New physics" proposed recently, or something we have not thought about.

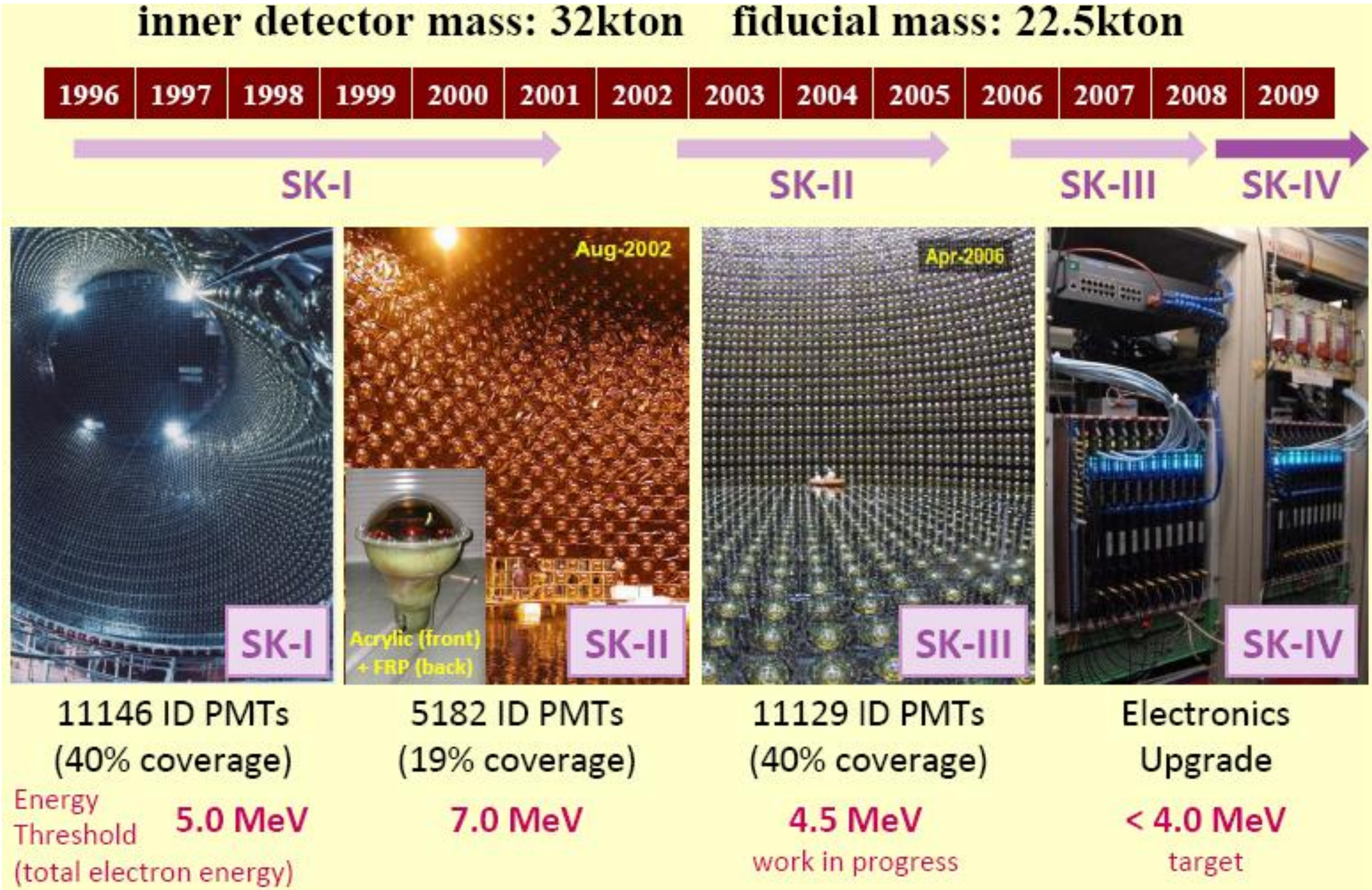
A. YU. SMIRNOV

# Future Prospects for Non-Accelerator Neutrino Experiments

# Work-To-Do and Remaining Issues

- Precise measurements of $\Delta(m_{23})^2$ and $(\sin 2\theta_{23})^2$ (atmospheric neutrino experiments)
- Solar neutrino oscillation in the transition phase between vacuum effect and matter effect (solar neutrino experiments)
- Measurement of $\theta_{13}$ (reactor experiments)
- CP violation and mass hierarchy (need to collaborate with accelerator experiments)

# Atmospheric ν Future Prospect



# Solar Neutrino Future Prospects

- Borexino
- Super-Kamiokande IV
- SAGE
- KamLAND
- LENS
- SNO+
- CELAN
- MOON
- XMASS

# Reactor Neutrino Future Prospects

- For $\theta_{13}$
  - ✓ Double-CHOOZ
  - ✓ DayaBay
  - ✓ RENO
- For $\theta_{12}$
  - ◆ DayaBay II (60km)?

# Summary

- Compelling evidences for neutrino oscillation from
  - Atmospheric neutrino experiments
  - Solar neutrino experiments
  - Reactor antineutrino experiment
  - Accelerator neutrino experiments (yesterday lecture)
- Neutrino oscillation indicates new physics (NP) beyond the Standard Model, but we still don't know what NP is yet.
- Measuring non-zero $\theta_{13}$ is the priority task for non-accelerator neutrino experiments.