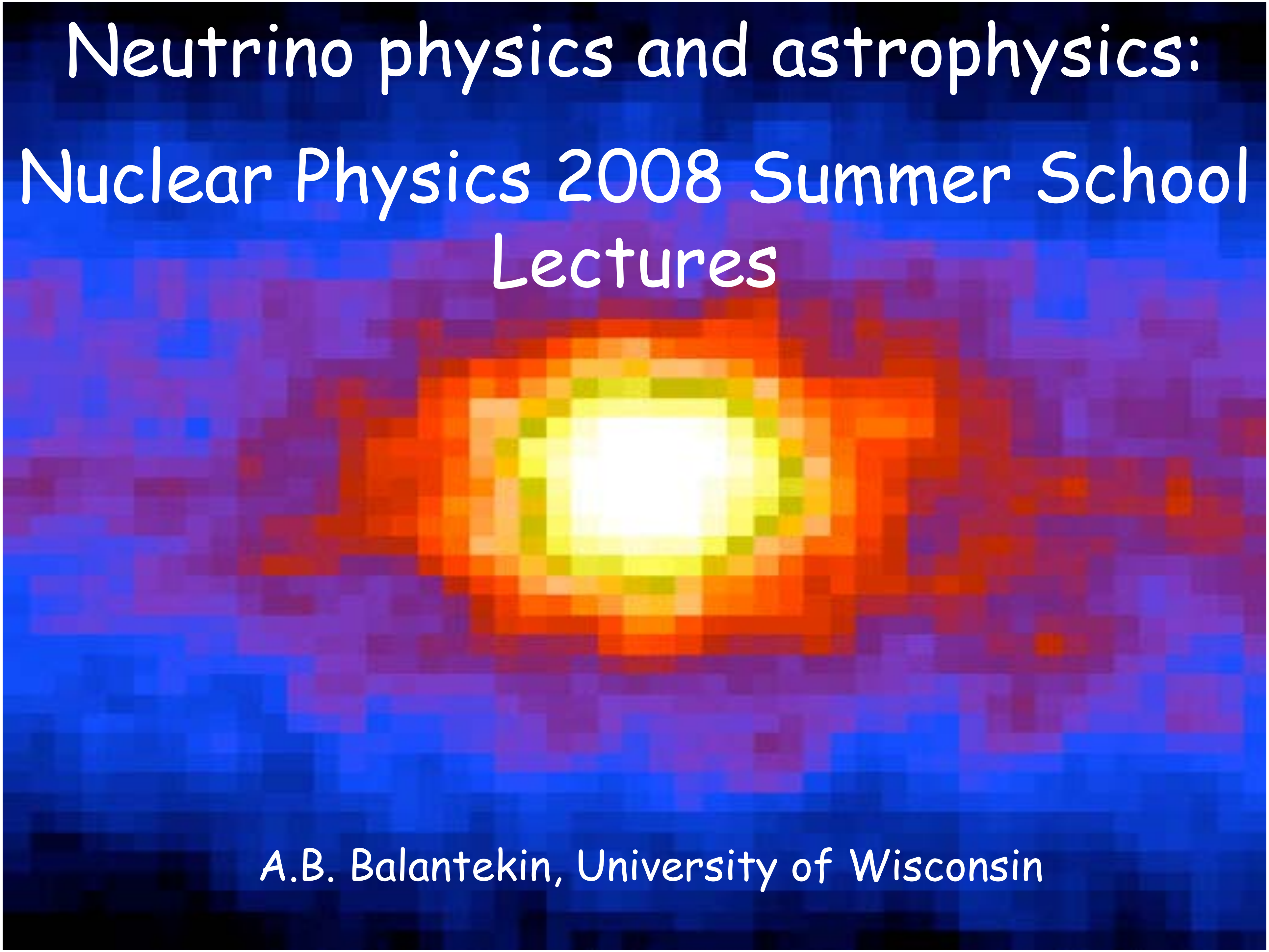
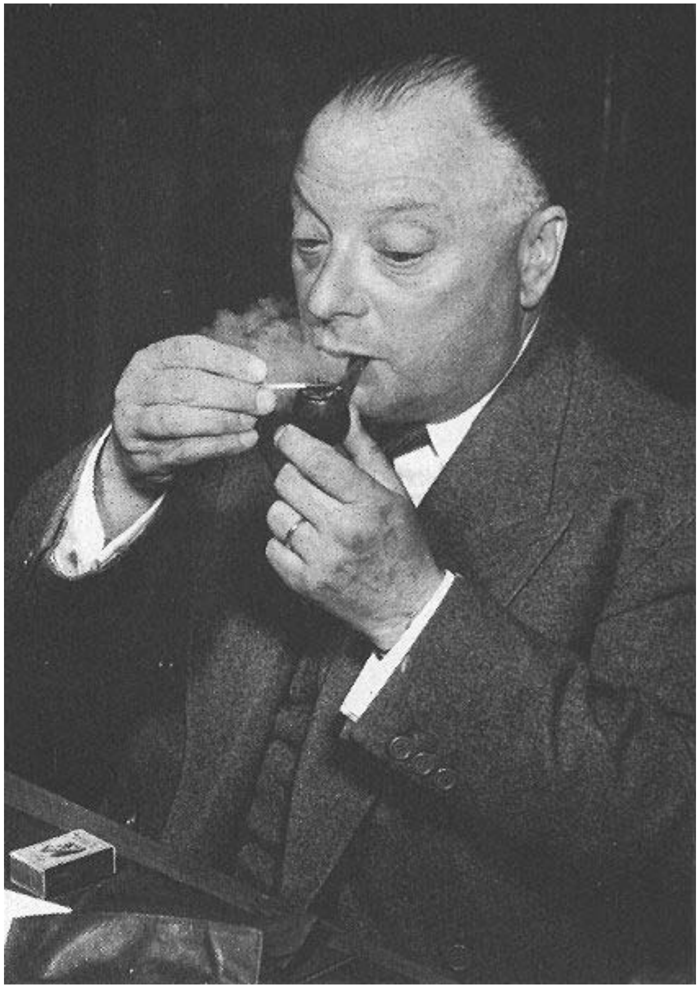


Neutrino physics and astrophysics:

Nuclear Physics 2008 Summer School Lectures

A.B. Balantekin, University of Wisconsin

Right now we are in the middle of twin revolutions in neutrino physics and astrophysics/cosmology …

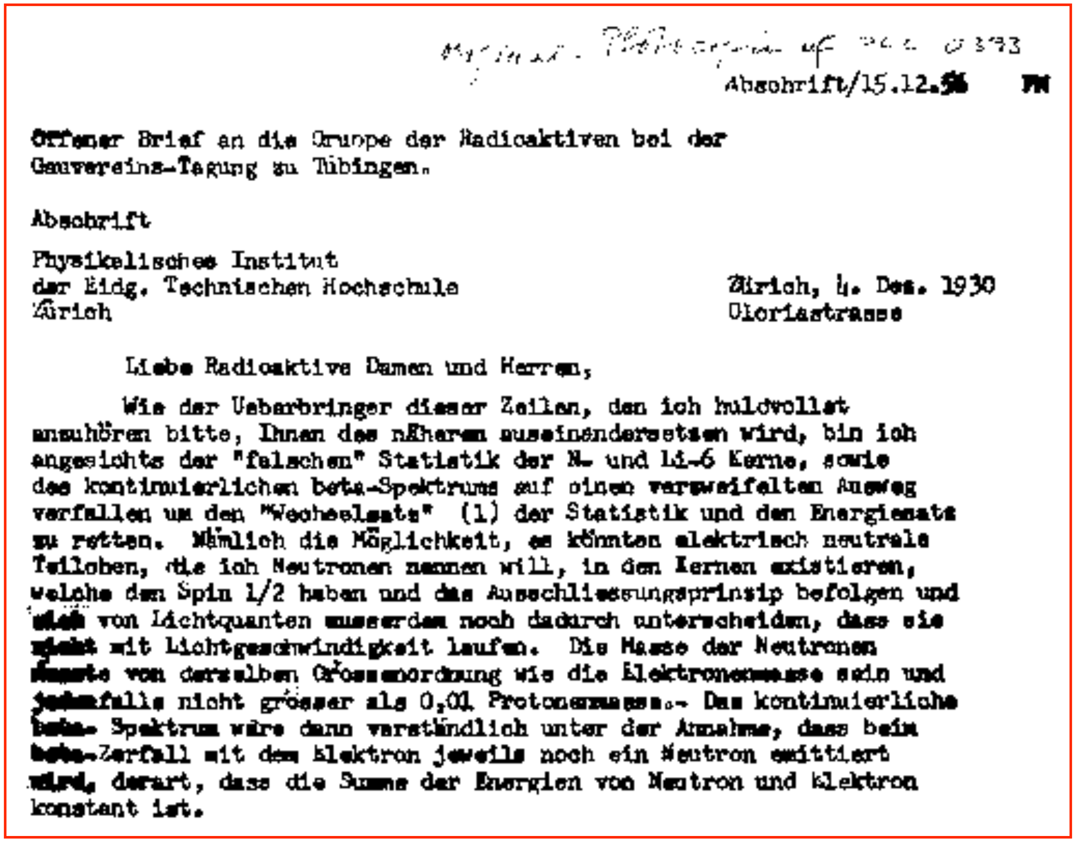


Wolfgang Pauli, father of neutrino and Pauli exclusion principle

Physicist goes to a ball

or

Mystery of Missing Energy



Original Photocopy of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Cosmic Gall
John Updike

Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed – you call
It wonderful; I call it crass.

Neutrino mass eigenstates are a combination of weak-interaction eigenstates: neutrinos mix!

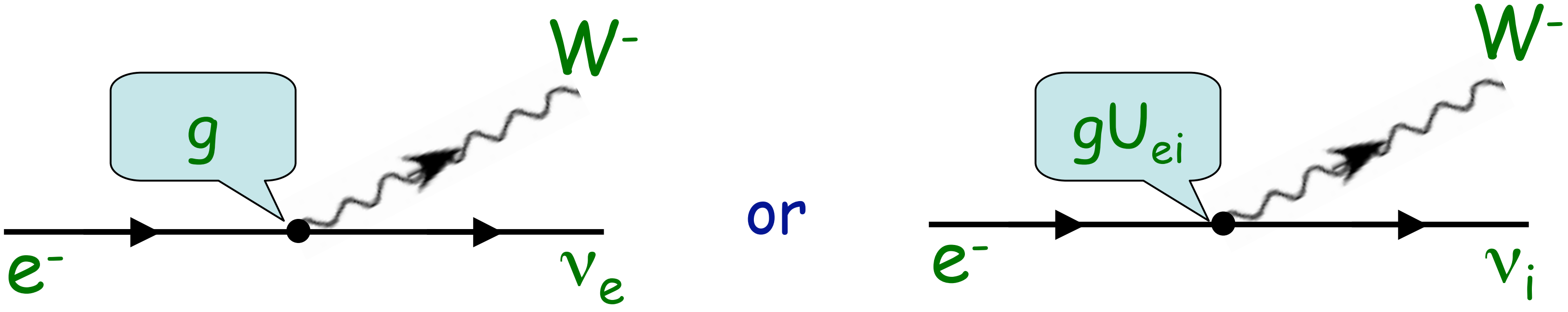
$$\nu_\alpha = \Sigma_i U_{\alpha i} \nu_i$$

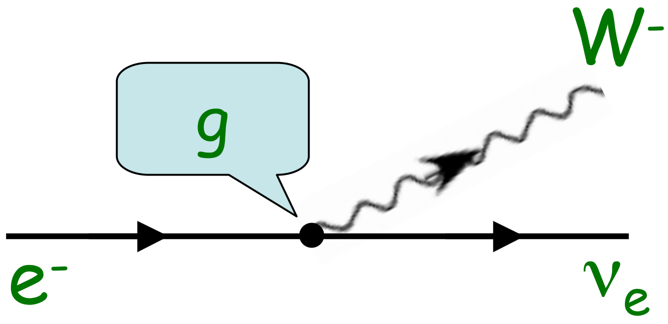
$\alpha = e, \mu, \tau$

$i = 1,2,3,..$

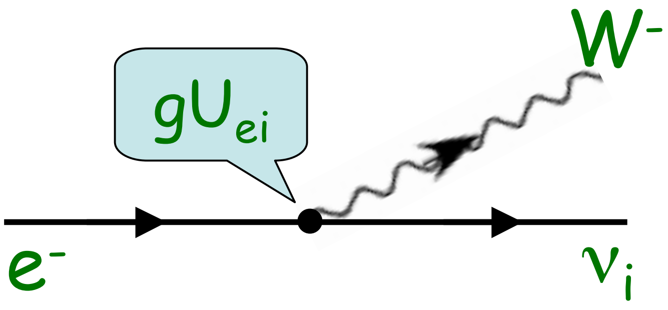
U is unitary: $U^\dagger U = UU^\dagger = 1$

If the neutrino mass were zero this would be nothing more than a change of basis in the Standard Model:





or



$$L_{SM} = -\frac{g}{\sqrt{2}}\sum_{\alpha=e,\mu,\tau}\left(\bar{\ell}_{L\alpha}\gamma^{\lambda}\nu_{L\alpha}W_{\lambda}{}^{-} + \bar{\nu}_{L\alpha}\gamma^{\lambda}\ell_{L\alpha}W_{\lambda}{}^{+}\right)$$

$$= -\frac{g}{\sqrt{2}}\sum_{\substack{\alpha=e,\mu,\tau\\ i=1,2,3}}\left(\bar{\ell}_{L\alpha}\gamma^{\lambda}U_{\alpha i}\nu_{Li}W_{\lambda}{}^{-} + \bar{\nu}_{Li}\gamma^{\lambda}U_{\alpha i}{}^{*}\ell_{L\alpha}W_{\lambda}{}^{+}\right)$$

Left-handed

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Reactor, long-baseline}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$$\times \underset{\text{Majorana phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$$\boxed{\begin{array}{l} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{array}}$$

When $\nu_i \to e^{i\phi}\,\nu_i$ then $U_{\alpha i} \to e^{i\phi}\,U_{\alpha i}$

When $\ell_\alpha \to e^{i\phi}\,\ell_\alpha$ then $U_{\alpha i} \to e^{-i\phi}\,U_{\alpha i}$

One can multiply any one row or any one column by the same phase by redefining the phases of the fields!

Except when the neutrino mass eigenstates are their own antiparticles ("Majorana neutrinos"):

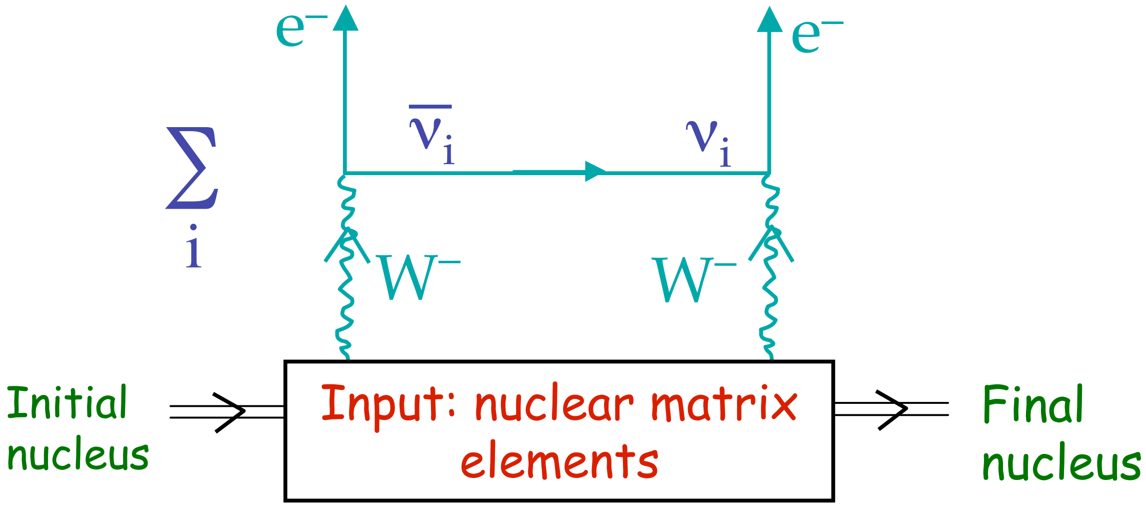
$$\nu_i = \nu_i^C = C\,\overline{\nu_i}^T$$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Only for Majorana neutrinos

Majorana nature of the neutrinos permit neutrinoless double beta decay:



Initial nucleus

Input: nuclear matrix elements

Final nucleus

- Symmetries, in particular weak isospin invariance, define the Standard Model.

- In the Standard Model, the left-handed and the right-handed components of the neutrino are treated differently: ν_L sits in an weak-isospin doublet ($I_W = 1/2$) together with the left-handed component of the associated charged lepton, whereas ν_R is an weak-isospin singlet ($I_W=0$).

- A mass term connects left- and right-handed components. The usual Dirac mass term is $L = m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$. But such a neutrino mass term breaks the weak-isospin symmetry, hence it is NOT permitted in the Standard Model.

- The right-handed component of the neutrino carries no weak isospin quantum numbers. This permits *Majorana neutrino mass* in the Standard Model if one only uses right-handed neutrinos.

Majorana mass term:

$$m_R \overline{\nu_R^{\,c}} \, \nu_R$$

- Such a mass term violates lepton number conservation since it implies that neutrinos are their antiparticles.
- It is permitted by the weak-isospin invariance of the Standard Model.
- Neutrino mass terms are not included in the fundamental Lagrangian of the Standard Model. They arise from new physics. Of course it is possible to write down an *effective* Lagrangian for the neutrino mass in terms of only the Standard Model fields if you give up renormalizability.

A note on dimensional counting

- Lagrangian, L, has dimensions of energy (or mass).
- $L = \int d^3x \, L \Rightarrow$ Lagrangian density, L, has dimensions of energy/volume or M^4.
- Define the scaling dimension of x, [x] to be -1 $\Rightarrow$ scaling dimension of momentum (or mass) is [m] = +1 (recall that $(p.x/\hbar)$ is dimensionless and we take $[\hbar]=0$).
- Clearly [L] = 4. This should be true for any Lagrangian density of any theory.
- Consider the mass term for fermions, $L_m = m\,\overline{\Psi}\Psi$. Then $[\overline{\Psi}\Psi] = 3$ or $[\Psi] = 3/2$.
- In the Standard Model the Higgs field vacuum expectation value gives the particle mass: $L = H\,\overline{\Psi}\Psi$. Hence [H] = 1.

Using the Standard Model degrees of freedom one can parameterize the neutrino mass by a dimension 5 operator. (Recall that $I_3^W = 1/2$ for the ν_L and -1/2 for H_{SM}).

$$L = X_{\alpha\beta} H_{SM} H_{SM} \overline{\nu_{L\alpha}{}^{c}} \nu_{L\beta} / \Lambda$$

$$v^2 X_{\alpha\beta} / \Lambda = U m_\nu^{\text{diagonal}} U^T$$

This term is not renormalizable!

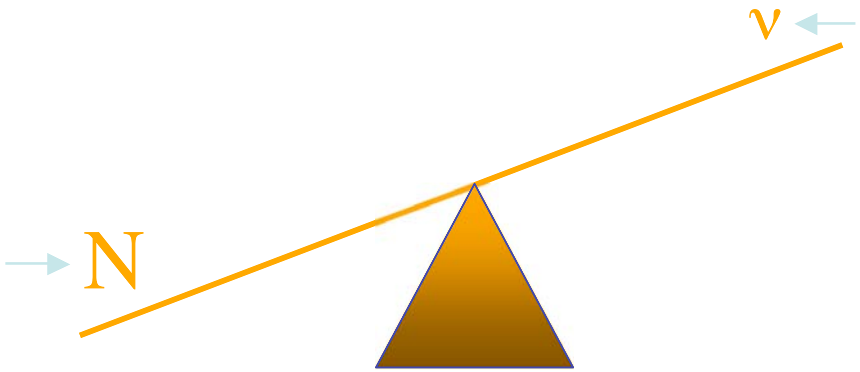
There are other ways to obtain neutrino mass:

$$L = H_{I=1} \overline{\nu_{L\alpha}{}^{c}} \, \nu_{L\beta}$$

Note: This Higgs is not in the Standard Model!

See-Saw Mechanism

$$\begin{pmatrix} 0 & h_\nu v \\ h_\nu v & M_R \end{pmatrix}$$



One of the most exciting discoveries in the physics during the last two decades was that neutrinos have mass!

This was achieved through the observation of neutrino oscillations!

Neutrino Oscillations

$$\nu_e\,(t=0) = \cos\theta\ \nu_1 + \sin\theta\ \nu_2$$

$$\Downarrow$$

$$\nu_e\,(t) = \cos\theta\ \exp(iE_1t)\nu_1 + \sin\theta\ \exp\ (iE_2t)\nu_2$$

$$P(\nu_e \longrightarrow \nu_e) = |\nu_e(L)|^2$$

Phase Difference: $E_2 - E_1 \propto m_2{}^2 - m_1{}^2 = \delta m^2$

$$\begin{bmatrix} \Psi_e \\ \Psi_\mu \end{bmatrix} = \begin{bmatrix} \cos\theta_v & \sin\theta_v \\ -\sin\theta_v & \cos\theta_v \end{bmatrix} \begin{bmatrix} \Psi_1 \\ \Psi_2 \end{bmatrix},$$

$$i\hbar \frac{\partial}{\partial t} \begin{bmatrix} \Psi_e(t) \\ \Psi_\mu(t) \end{bmatrix}$$

$$= \frac{1}{4E} \begin{bmatrix} -\delta m^2 \cos 2\theta_v & \delta m^2 \sin 2\theta_v \\ \delta m^2 \sin 2\theta_v & \delta m^2 \cos 2\theta_v \end{bmatrix} \begin{bmatrix} \Psi_e(t) \\ \Psi_\mu(t) \end{bmatrix}$$

$$\delta m^2 = m_2^2 - m_1^2 \ \ (m_2 > m_1)$$

Appearance probability of the other flavor

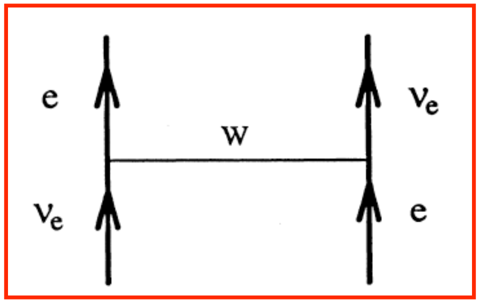
$$P = \sin^2 2\theta_v \sin^2[1.27\delta m^2(\mathrm{eV}^2) L/E(\mathrm{m/MeV})].$$

MSW effect

In vacuum: $E^2 = p^2 + m^2$

In a potential: $(E-\Phi)^2 = p^2 + m^2 \Rightarrow m_{eff}^2 = m^2 + 2E\Phi$

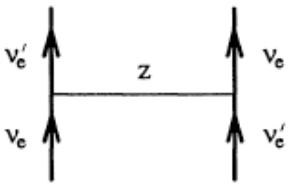
The potential is provided by the coherent forward scattering of ν_e's off the electrons in dense matter.

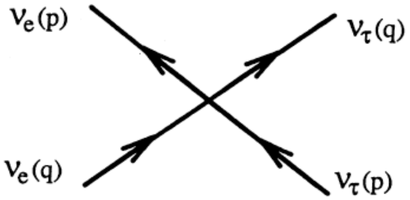


There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences *unless* we invoke a sterile neutrino.

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e \\ \psi_x\end{pmatrix} = \begin{pmatrix} -\frac{\delta m^2}{4p}\cos 2\theta + \frac{1}{\sqrt{2}}G_F N_e & \frac{\delta m^2}{4p}\sin 2\theta \\ \frac{\delta m^2}{4p}\sin 2\theta & \frac{\delta m^2}{4p}\cos 2\theta - \frac{1}{\sqrt{2}}G_F N_e \end{pmatrix}\begin{pmatrix}\psi_e \\ \psi_x\end{pmatrix}$$

If the neutrino density itself is also very high then one has to consider the effects of neutrinos scattering off other neutrinos. This is the case for a core-collapse supernova.





$$\boxed{i\frac{\partial}{\partial t}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix}=\frac{1}{2}\begin{pmatrix}A+B-\Delta\cos 2\theta & B_{e\mu}+\Delta\sin 2\theta\\ B_{\mu e}+\Delta\sin 2\theta & -A-B+\Delta\cos 2\theta\end{pmatrix}\begin{pmatrix}\psi_e\\ \psi_x\end{pmatrix}}$$

$$\Delta=\frac{\delta m^2}{2p},\qquad A=\sqrt{2}G_F N_e$$

$$\boxed{B=\sqrt{2}G_F\int dq(1-\cos\theta_{pq})\left[\left(|\psi_e(q,t)|^2-|\psi_x(q,t)|^2\right)\right]}$$

$$\boxed{B_{ex}=2\sqrt{2}G_F\int d^3q(1-\cos\theta_{pq})\left(\psi_e(q,t)\psi_\mu^*(q,t)\right)}$$

The most copious neutrino source for Earth is the Sun unless you are really close to a nuclear reactor!

Let us take a brief detour into this modest main sequence star.

Stellar Equilibrium

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p - \rho \nabla \phi$$

Equation of motion

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0$$

Equation of continuity

$$\nabla^2 \phi = 4\pi G \rho$$

Poisson's Equation

$$\frac{1}{p}\frac{Dp}{Dt} - \Gamma_1 \frac{1}{\rho}\frac{D\rho}{Dt} = \frac{\Gamma_3 - 1}{p}(\rho\epsilon - \nabla \cdot \mathbf{F})$$

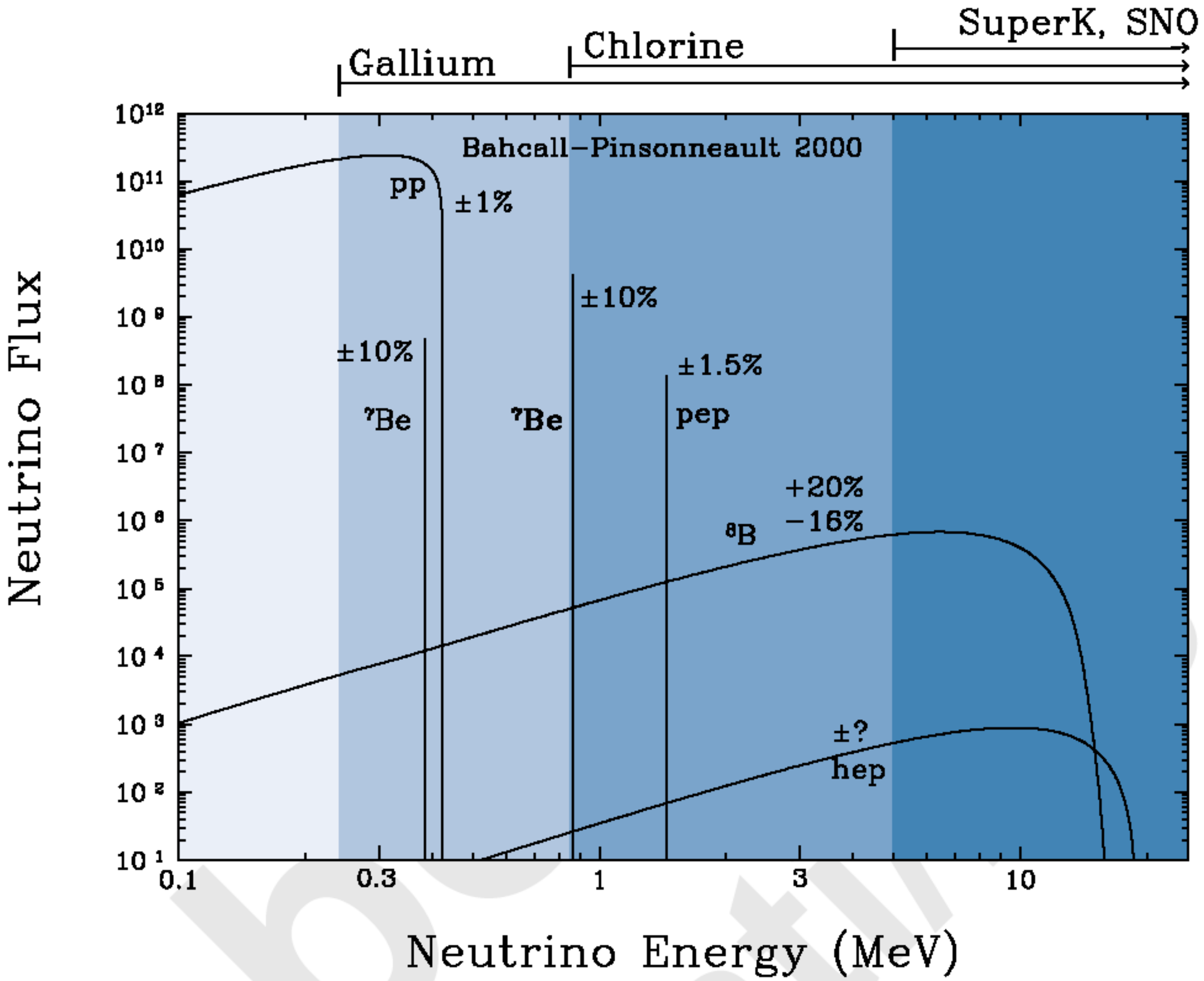
Energy Equation

$$\Gamma_1 = \left(\frac{\partial \log p}{\partial \log \rho}\right)_s, \Gamma_3 - 1 = \left(\frac{\partial \log T}{\partial \log \rho}\right)_s$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla$$

ε = Rate of nuclear energy generation

F = Energy flux



Continuous fluxes in /cm^2/s/MeV
Discrete fluxes in /cm^2/s

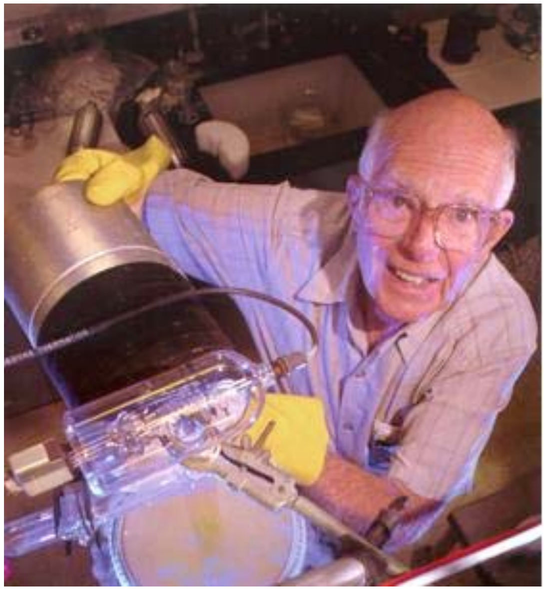
Solar neutrino experiments

- Radiochemical experiments: Measure integrated (over time and energy) count rate.
  1 SNU (solar neutrino unit) = 10^{-36} neutrinos captured per atom per second.

  Homestake (Cl), SAGE (Ga), Gallex (Ga), GNO (Ga)
- Real-time counting experiments: Measure the energy spectra in real time.

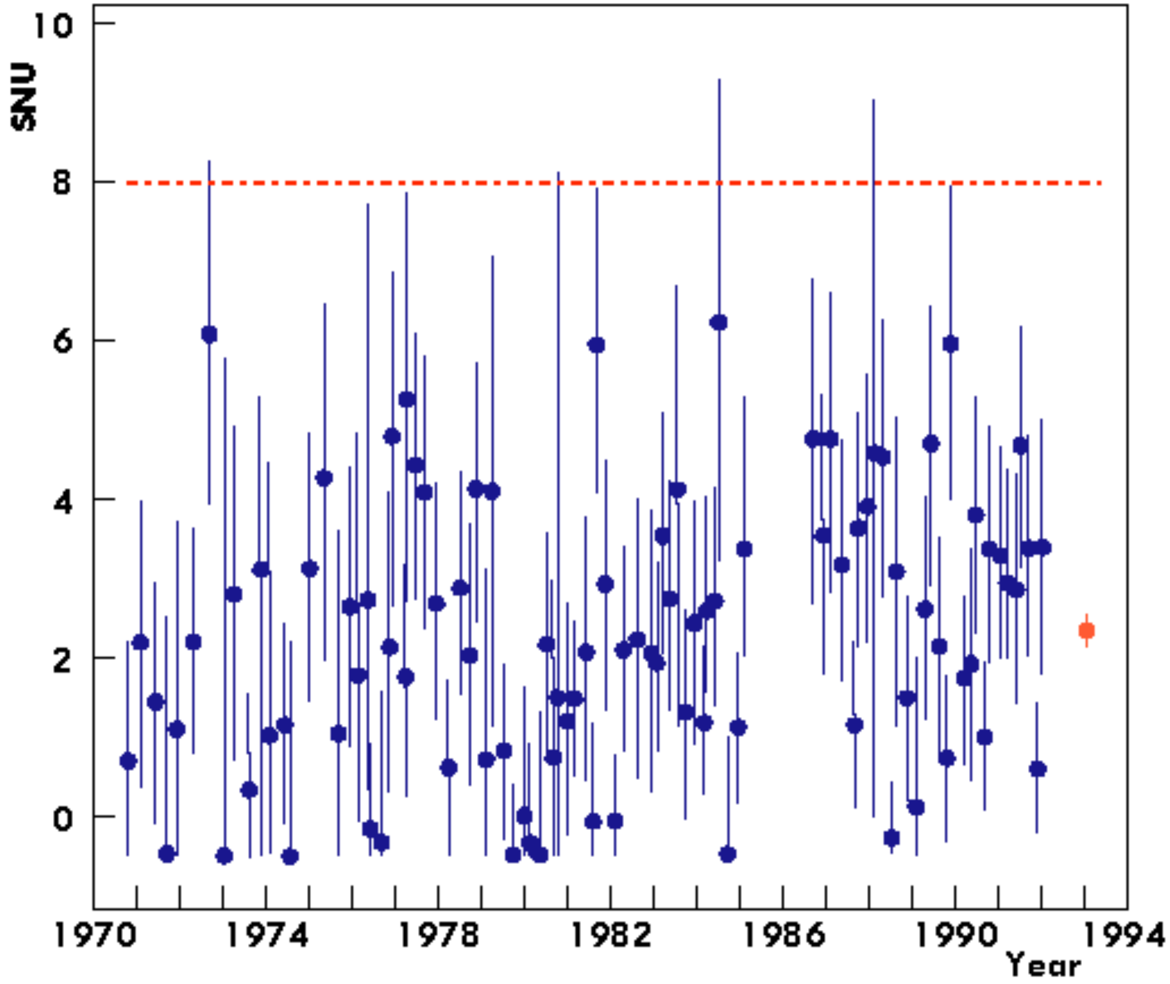
  Kamiokande, SuperKamiokande, SNO

Homestake Experiment



Then:

Homestake Count Rate



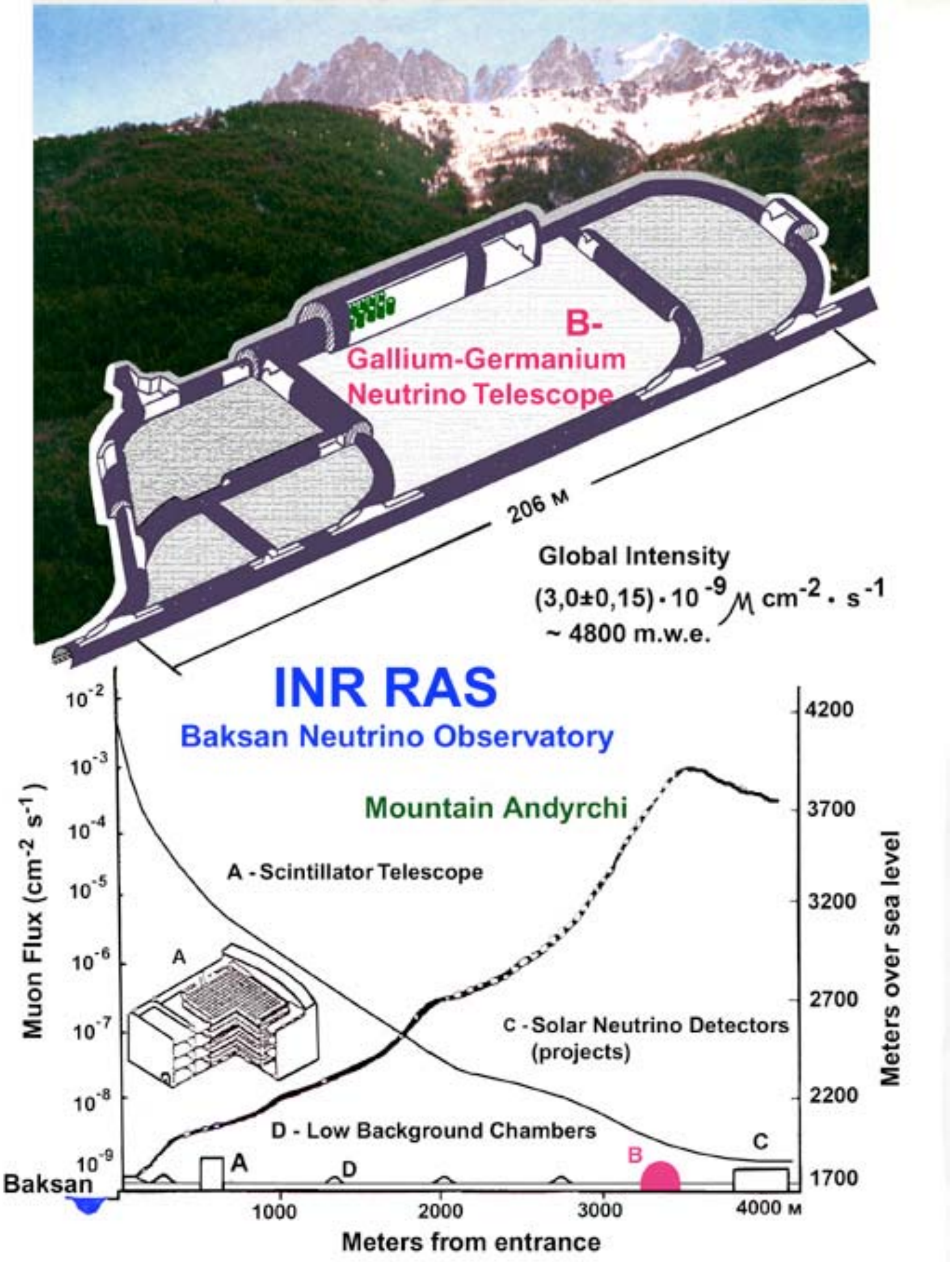
Those of us who believed the data thought that neutrino mixing angles are, like quark mixing angles, small for vacuum mixing, but, thanks to MSW, matter-enhanced oscillations do the reduction. Most people did not even believe the data.

SAGE Experiment

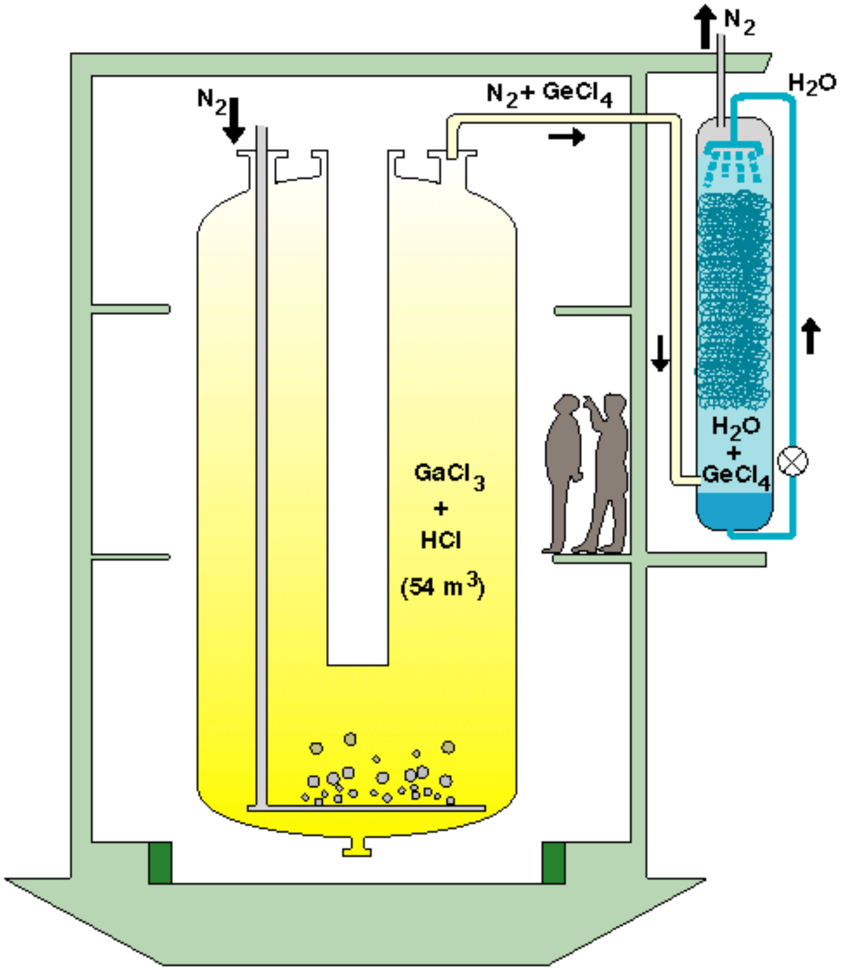
Mt. Andyrchi, Caucasus
Near Mt. Elbrus
Kabardino-Balkaria
Russia

INR RAS

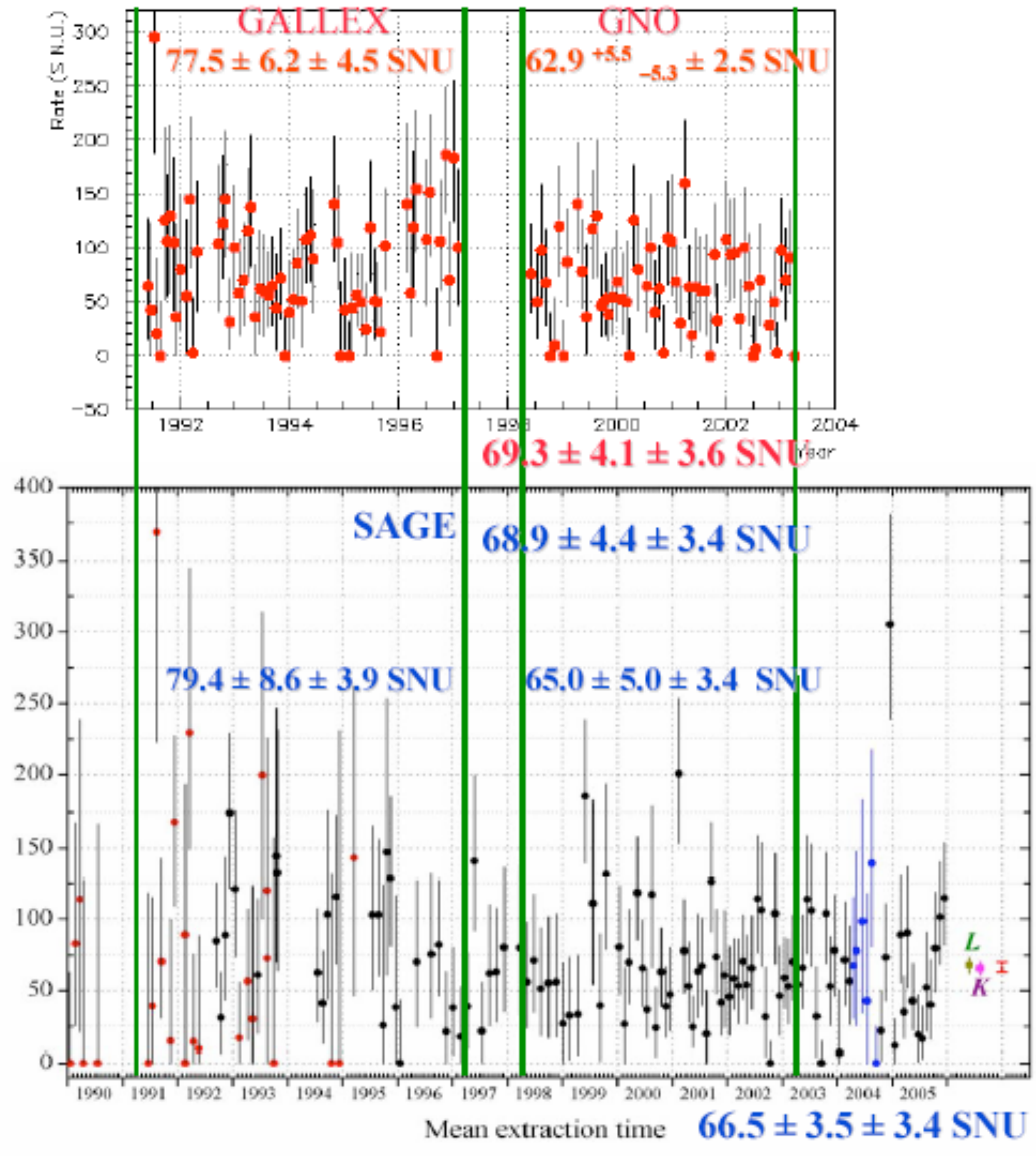
Baksan Neutrino Observatory



Gallex and GNO

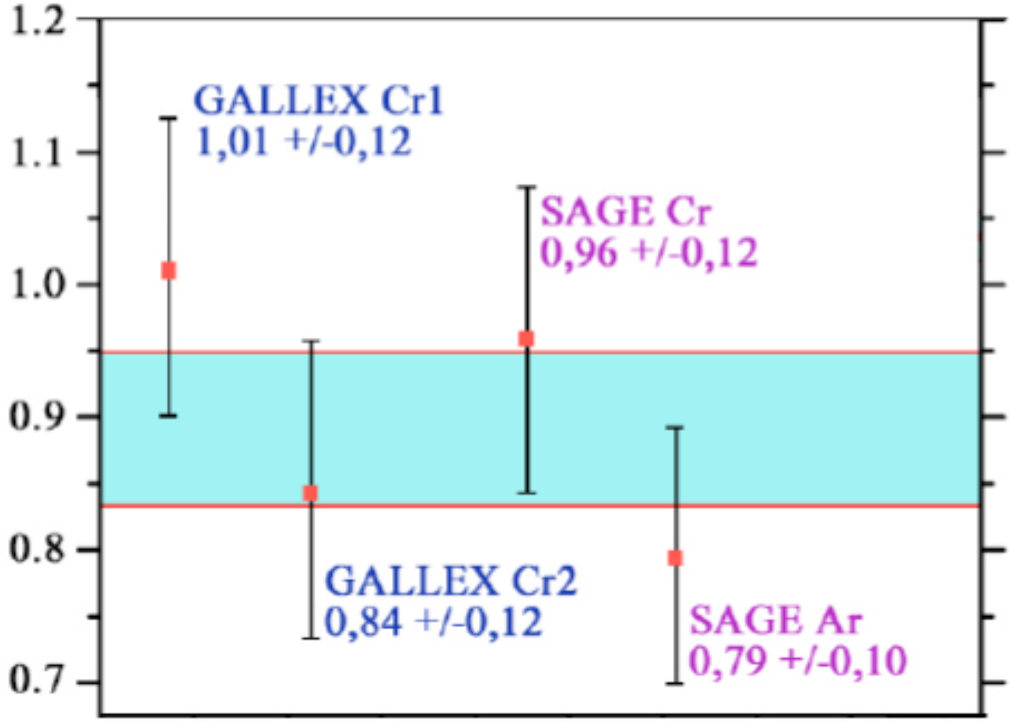


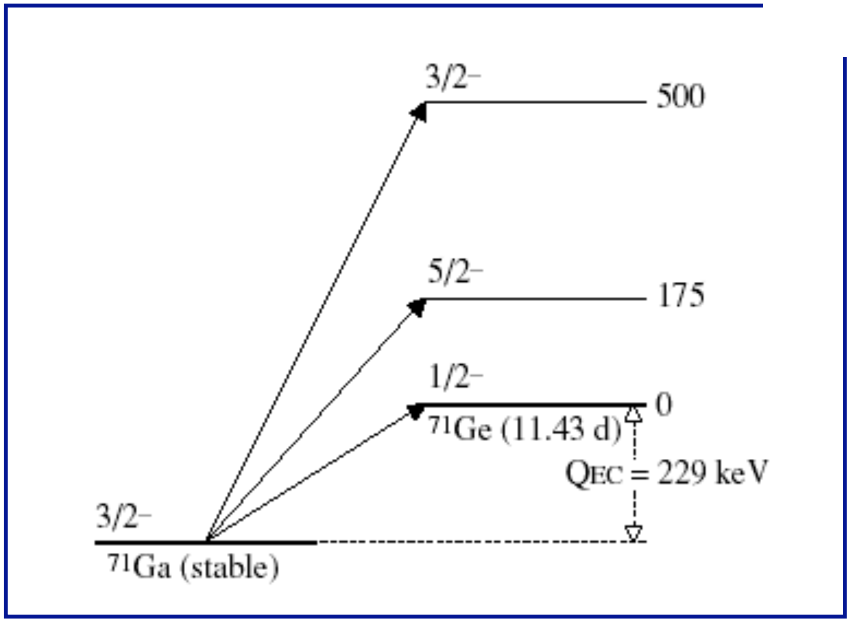
Now:



Adopted from Gavrin

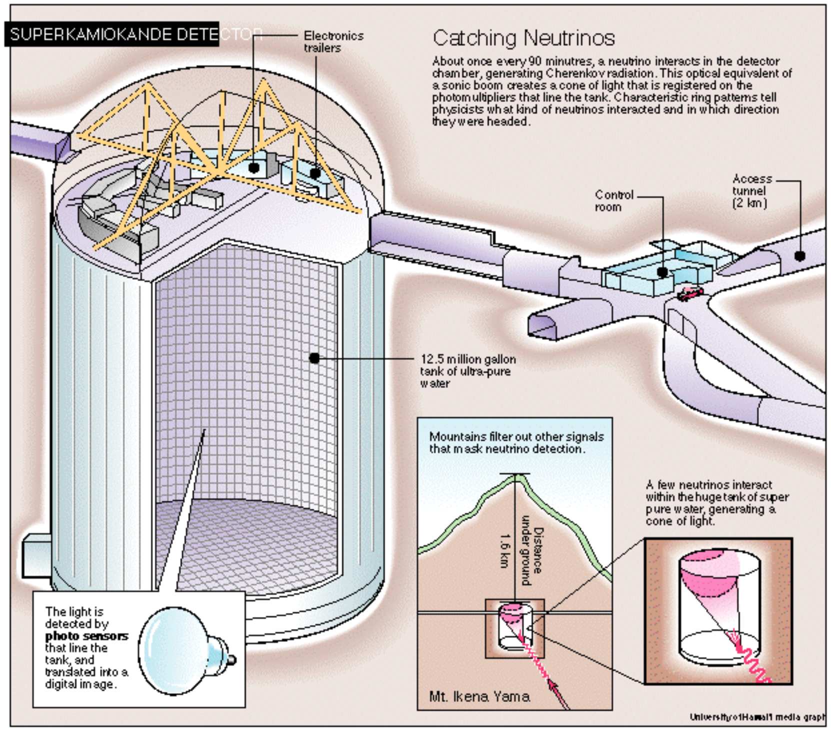
What are the Ga source experiments telling us?





Ground state cross-section is fixed from the beta-decay (via detailed balance). Correction is due to the excited states, which contribute little to the solar neutrino capture rate.

SuperKamiokande Detector



Catching Neutrinos

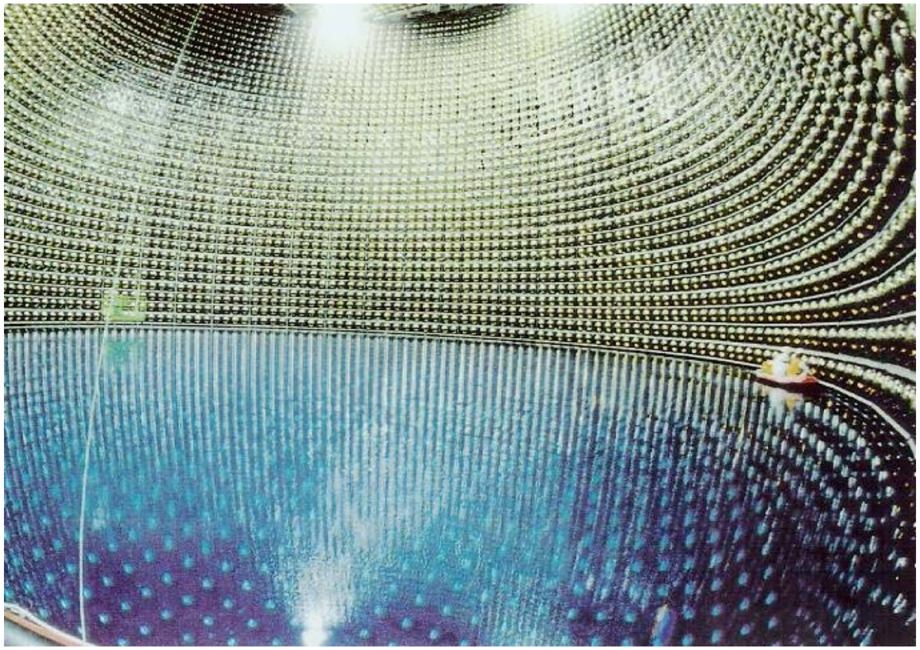
About once every 90 minutres, a neutrino interacts in the detector chamber, generating Cherenkov radiation. This optical equivalent of a sonic boom creates a cone of light that is registered on the photomultipliers that line the tank. Characteristic ring patterns tell physicists what kind of neutrinos interacted and in which direction they were headed.

Mountains filter out other signals that mask neutrino detection.

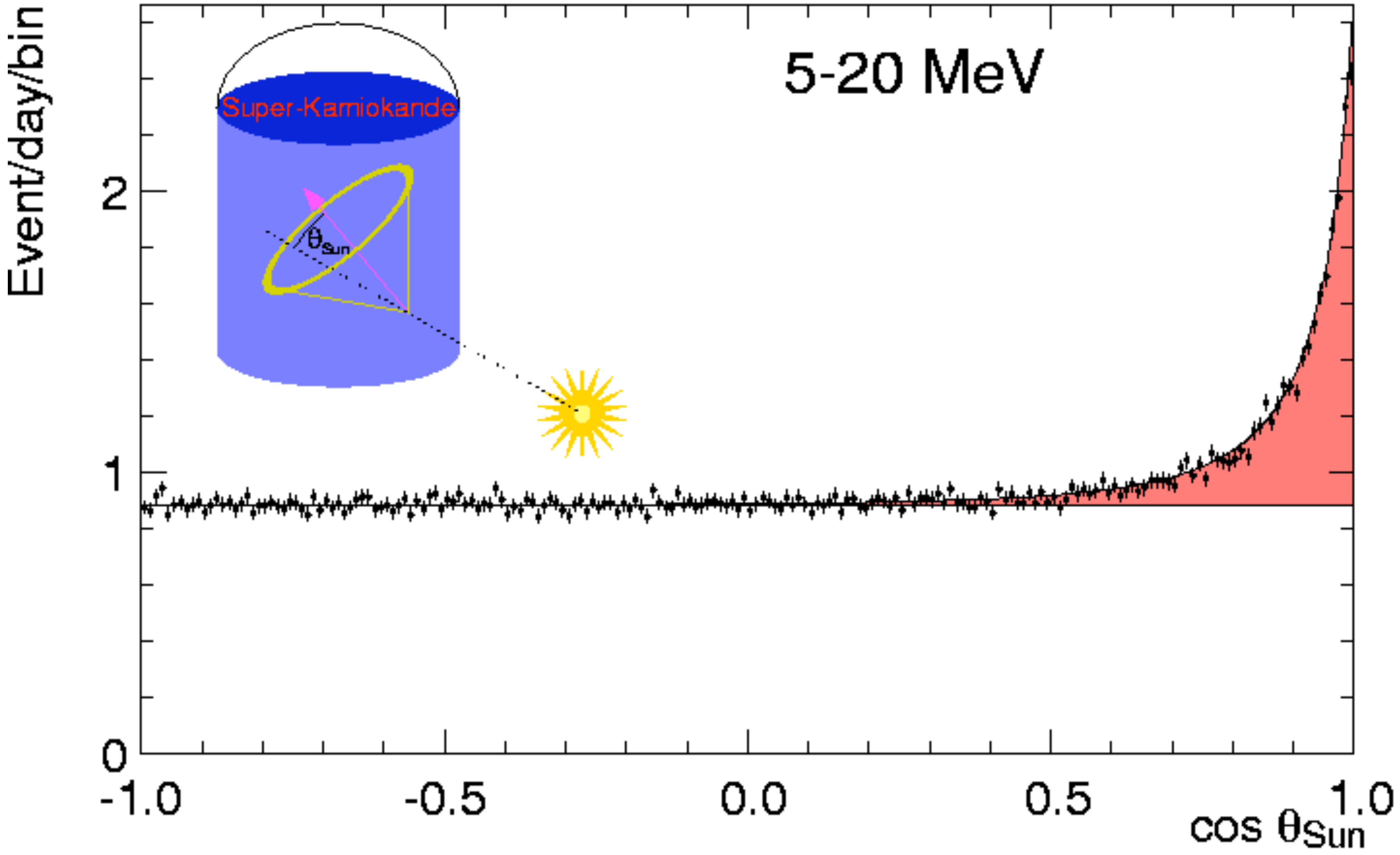
A few neutrinos interact within the huge tank of super pure water, generating a cone of light.

The light is detected by **photo sensors** that line the tank, and translated into a digital image.

University of Hawaii media graph



SuperKamiokande-I ^8B solar ν's



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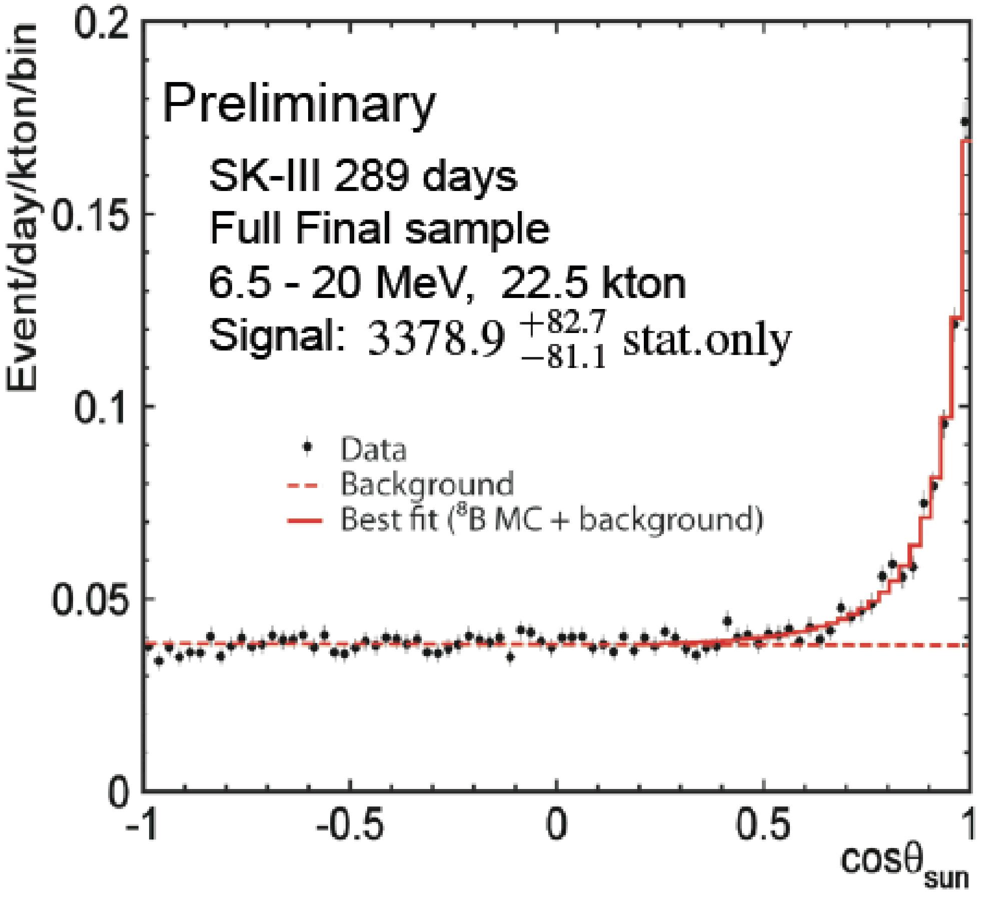
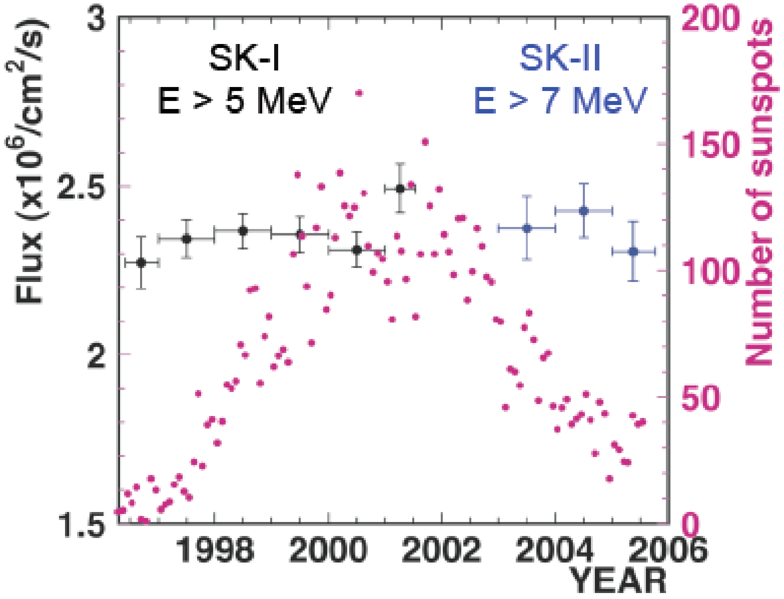
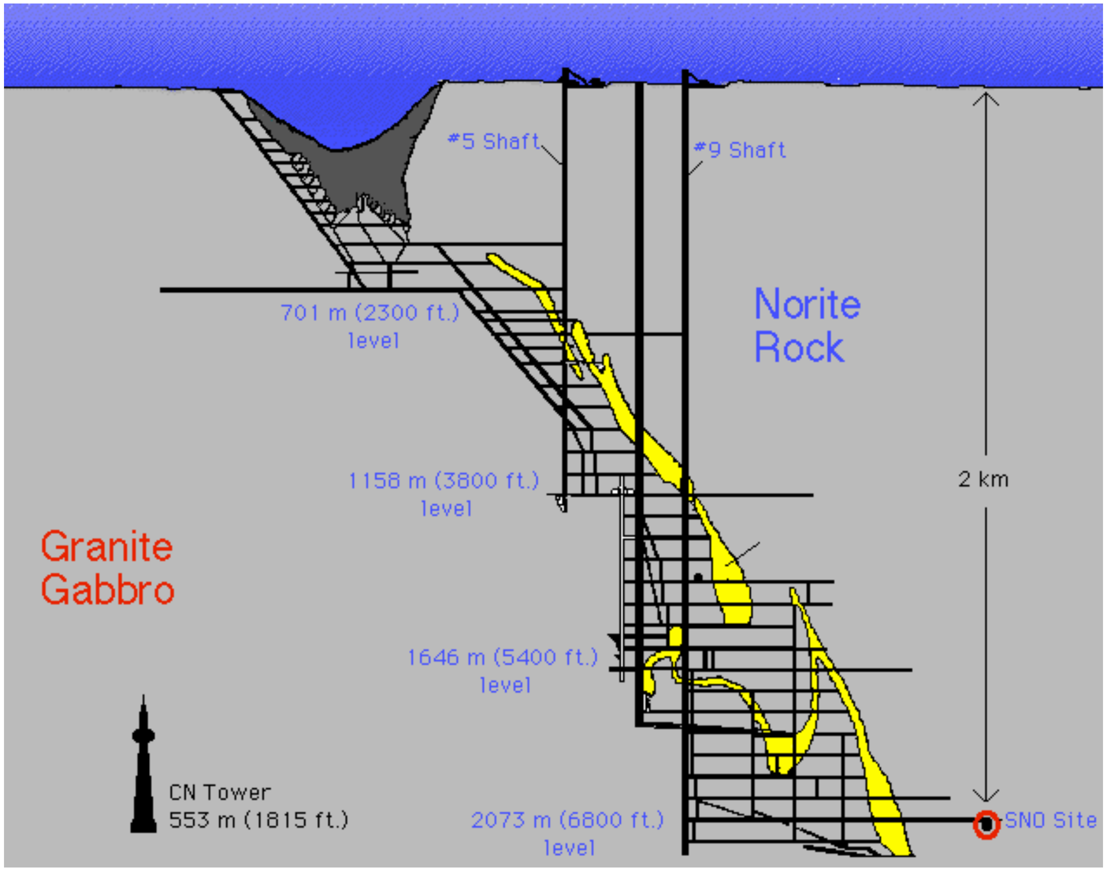


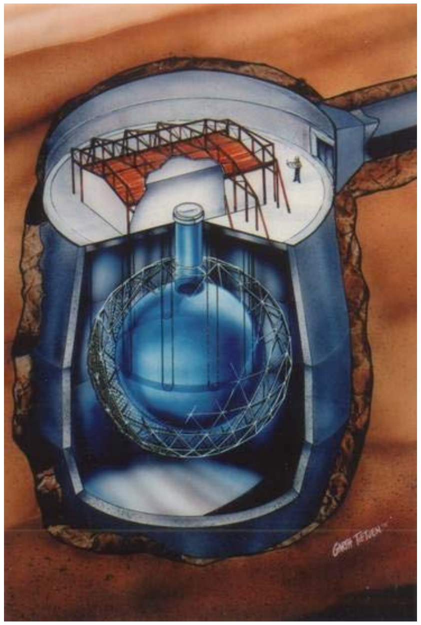
Correlation with Solar Activity



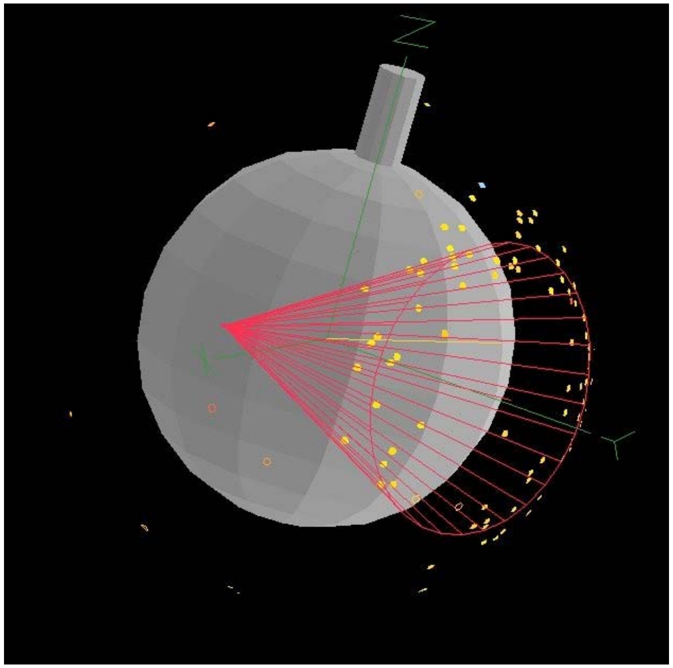
No correlation with solar cycle minima or maximum seen

Sudbury Neutrino Observatory





Sudbury Neutrino Observatory

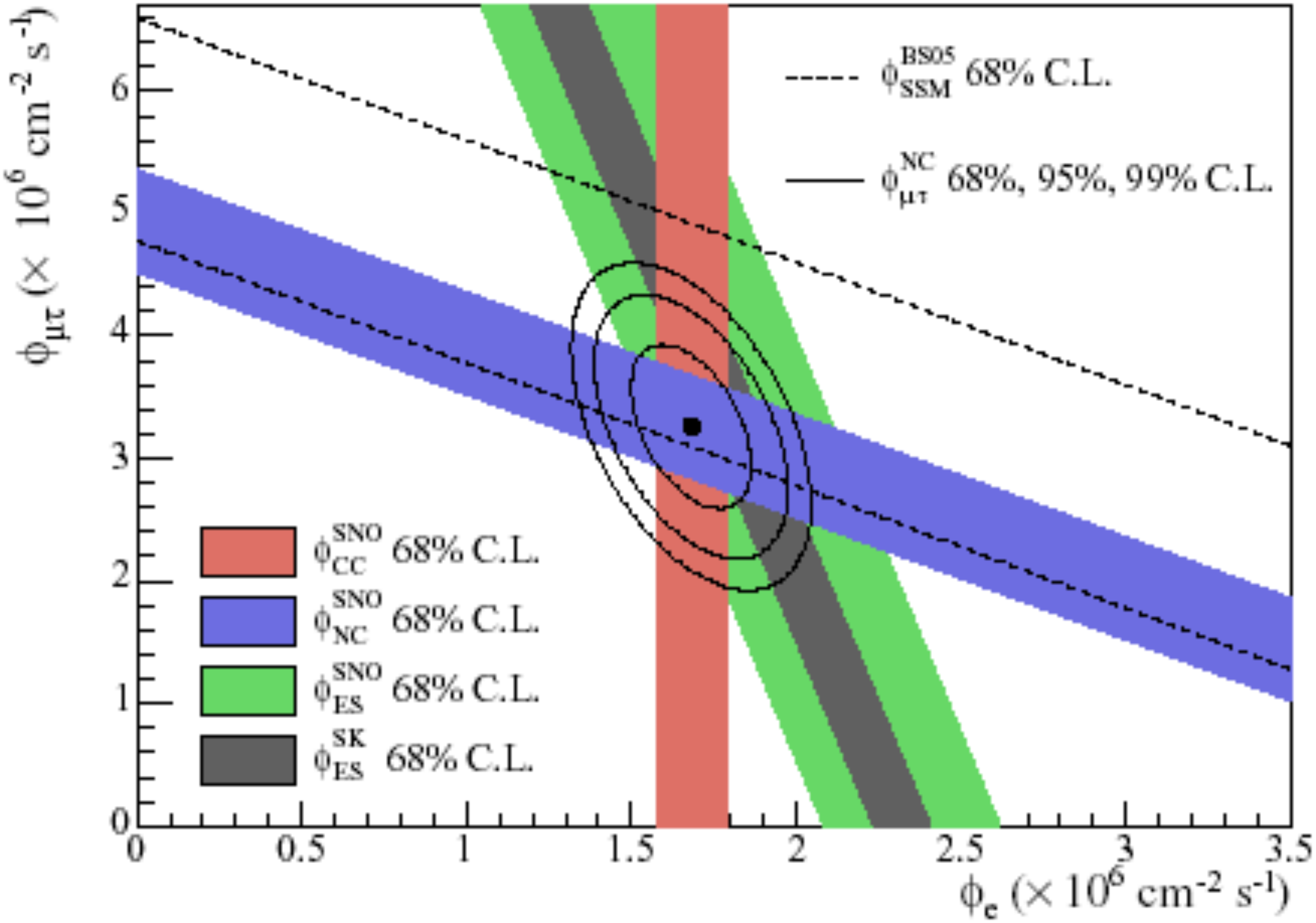


$\nu_e + d \rightarrow p + p + e^-$ CC

$\nu_e + e \rightarrow \nu_e + e$ ES

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

SNO



ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times$ 10^6 cm^{-2} s^{-1})
ϕ_e ($\times$ 10^6 cm^{-2} s^{-1})
0
1
2
3
4
5
6
0
0.5
1
1.5
2
2.5
3
3.5

Preliminary

Fluxes

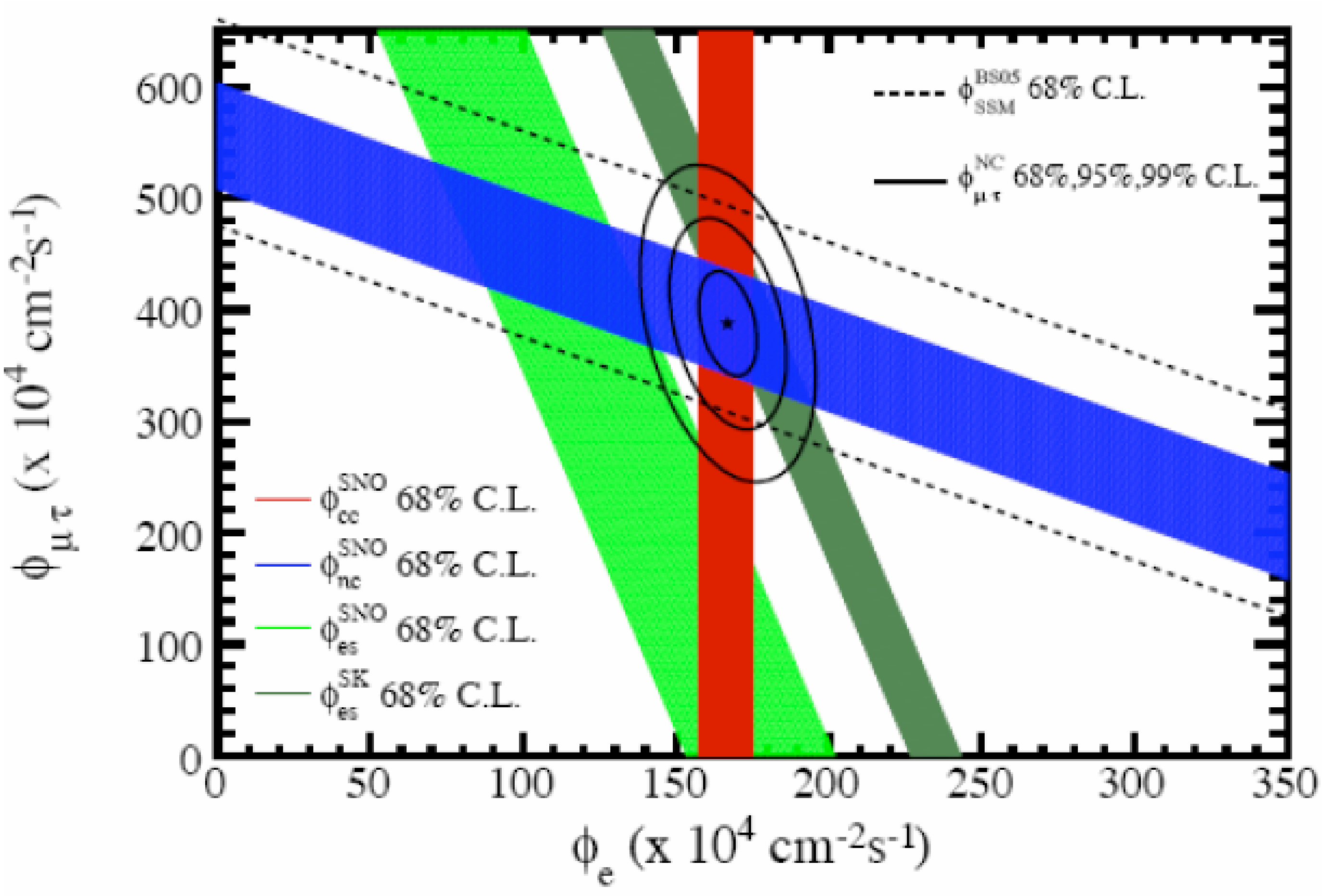
(10^4 cm^{-2} s^{-1})

ν_e: 167(9)

ν_{ES}: 177(26)

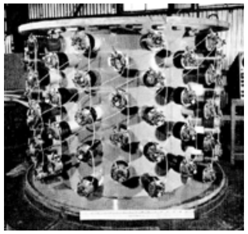
ν_{total}: 554(48)

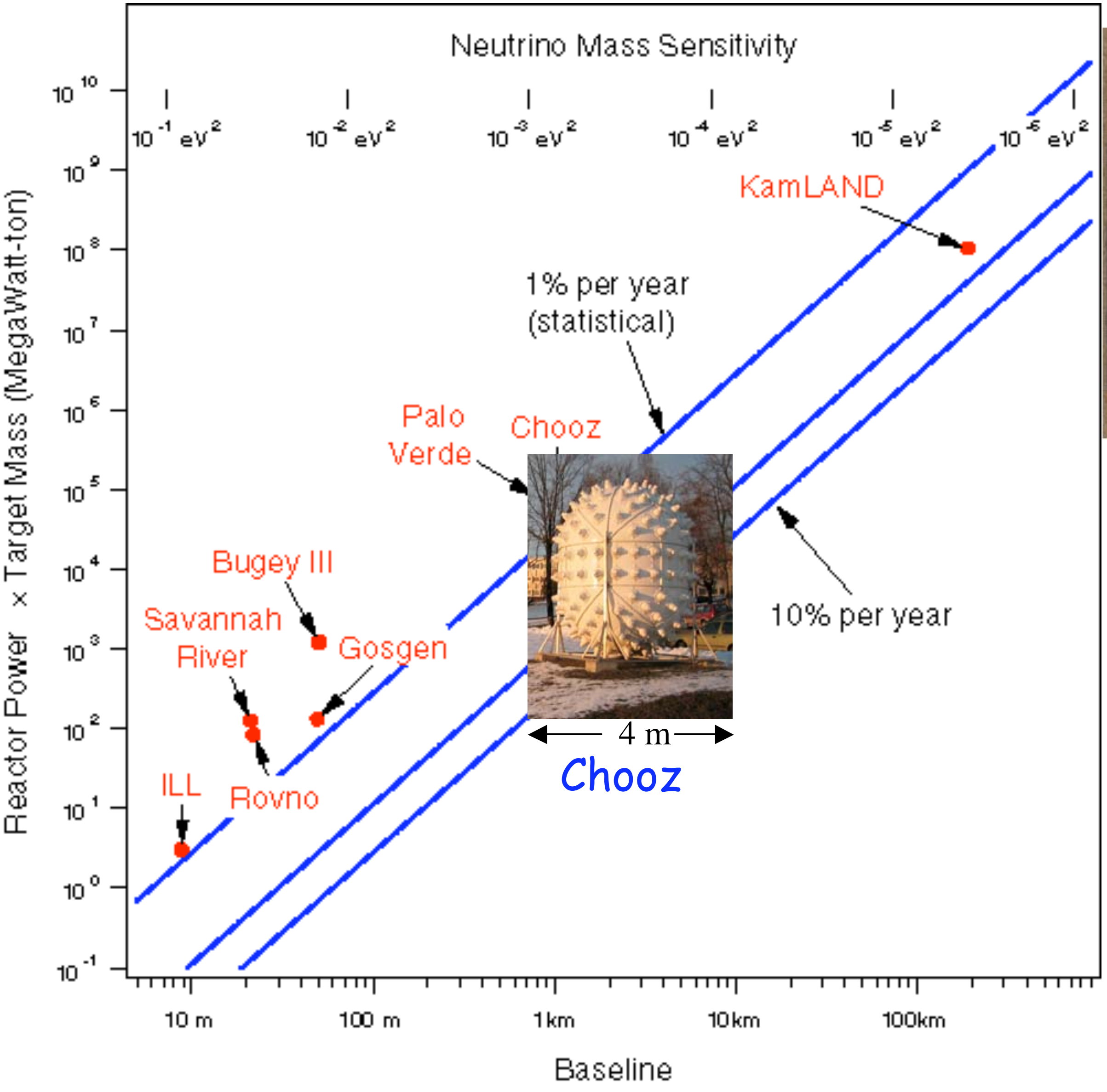
ν_{SSM}: 569(91)

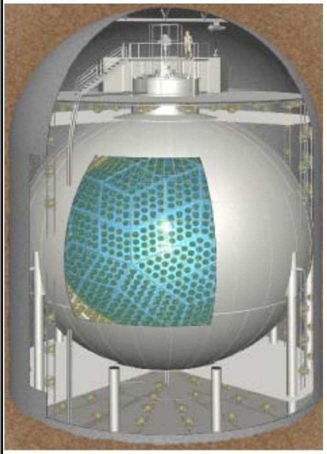


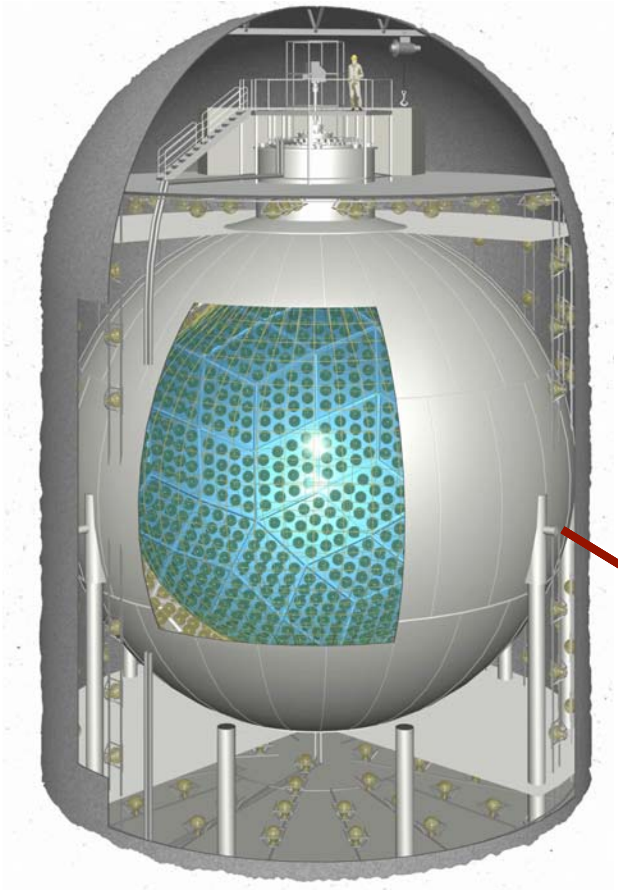
From NEUTRINO 2008 presentation

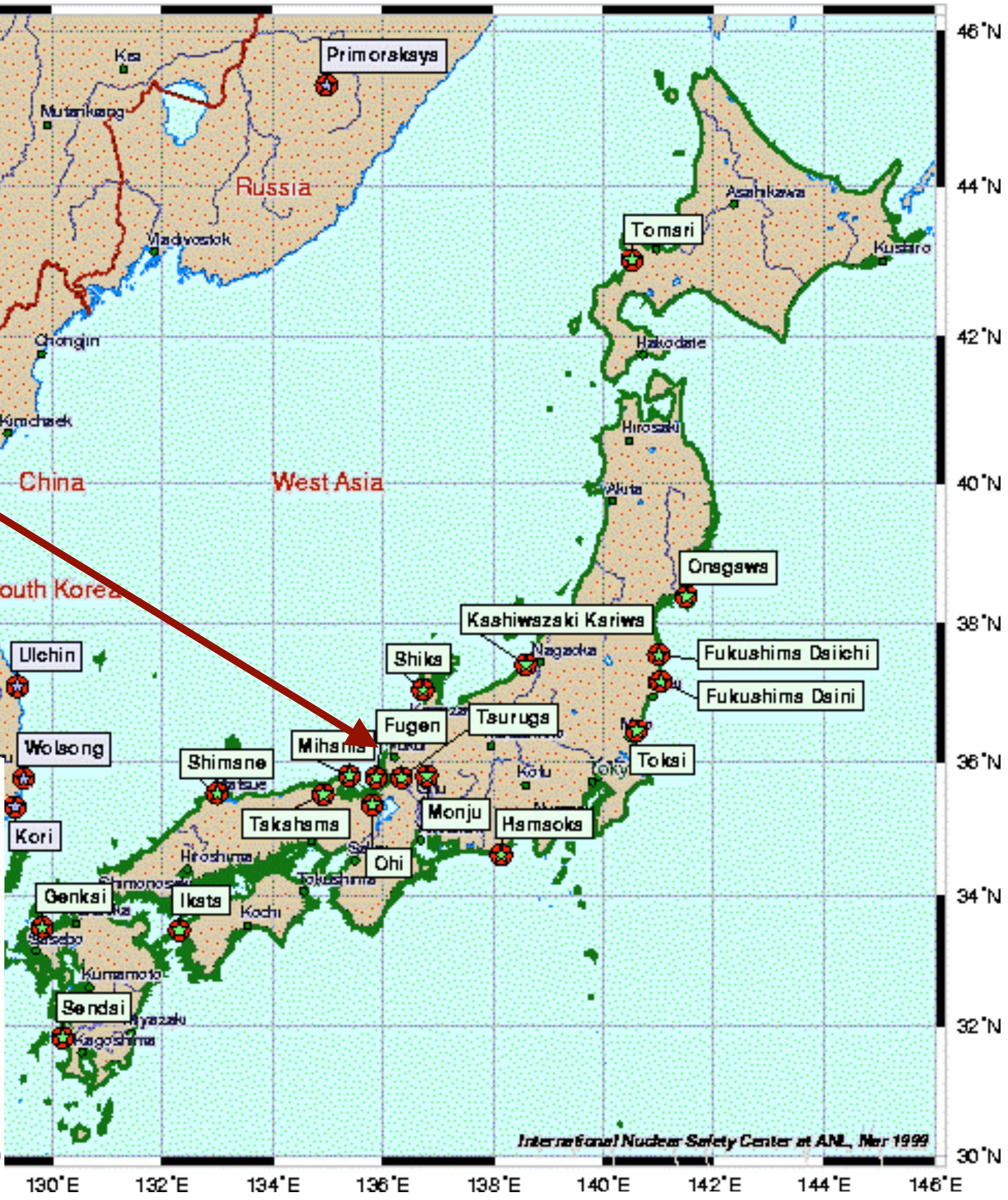
Long Baseline Reactor Neutrino Experiments

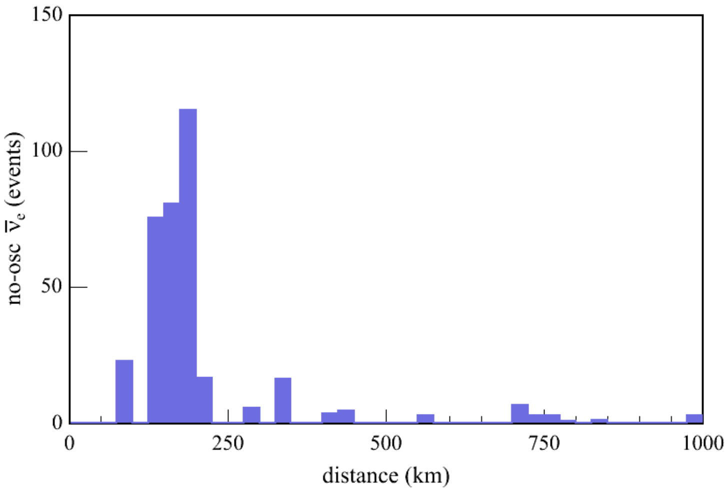


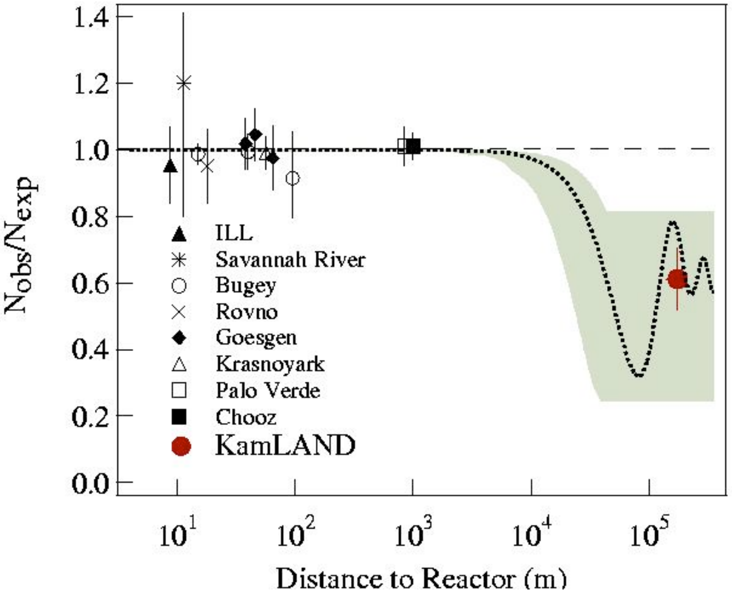






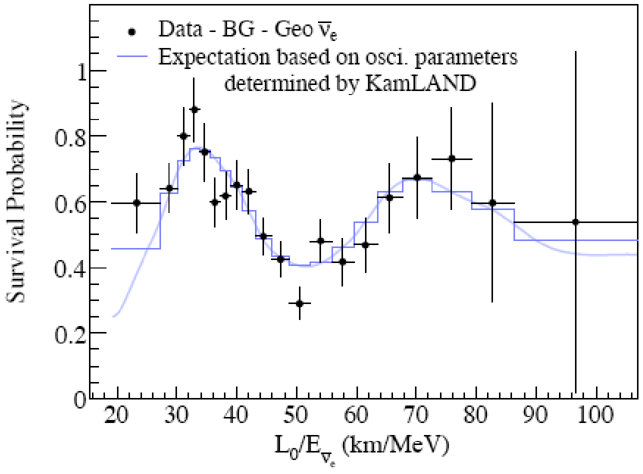

Primorskaya
Kfa
Mutankang
Russia
Vladivostok
Chongjin
Kimchaek
China
West Asia
South Korea
Tomari
Asahikawa
Kushiro
Hakodate
Hirosaki
Akita
Onagawa
Kashiwazaki Kariwa
Nagaoka
Shika
Fukushima Daiichi
Fukushima Daini
Ulchin
Wolsong
Kori
Fugen
Tsuruga
Mihama
Shimane
Matsue
Takahama
Monju
Hamaoka
Ohi
Tokai
Kofu
Tokyo
Hiroshima
Shimonoseki
Tokushima
Kochi
Genkai
Ikata
Sasebo
Kumamoto
Sendai
Miyazaki
Kagoshima
International Nuclear Safety Center at ANL, Mar 1999
46°N
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
130°E
132°E
134°E
136°E
138°E
140°E
142°E
144°E
146°E

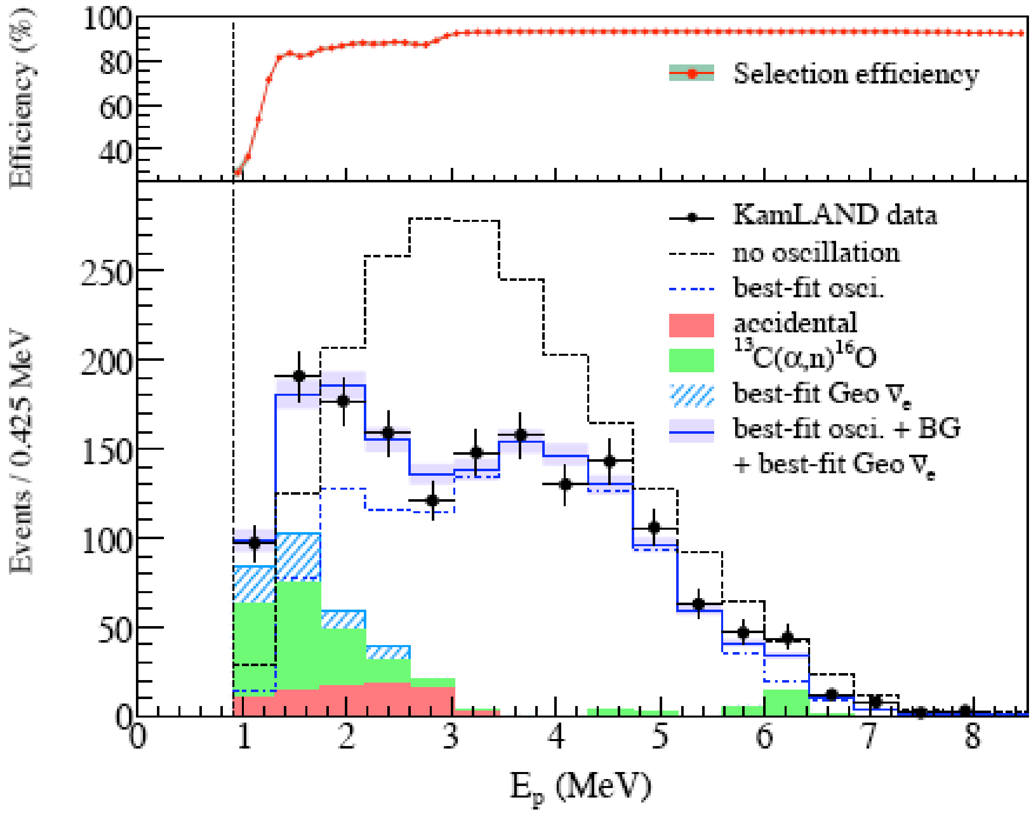

150
100
50
0
no-osc $\overline{\nu}_e$ (events)
0
250
500
750
1000
distance (km)



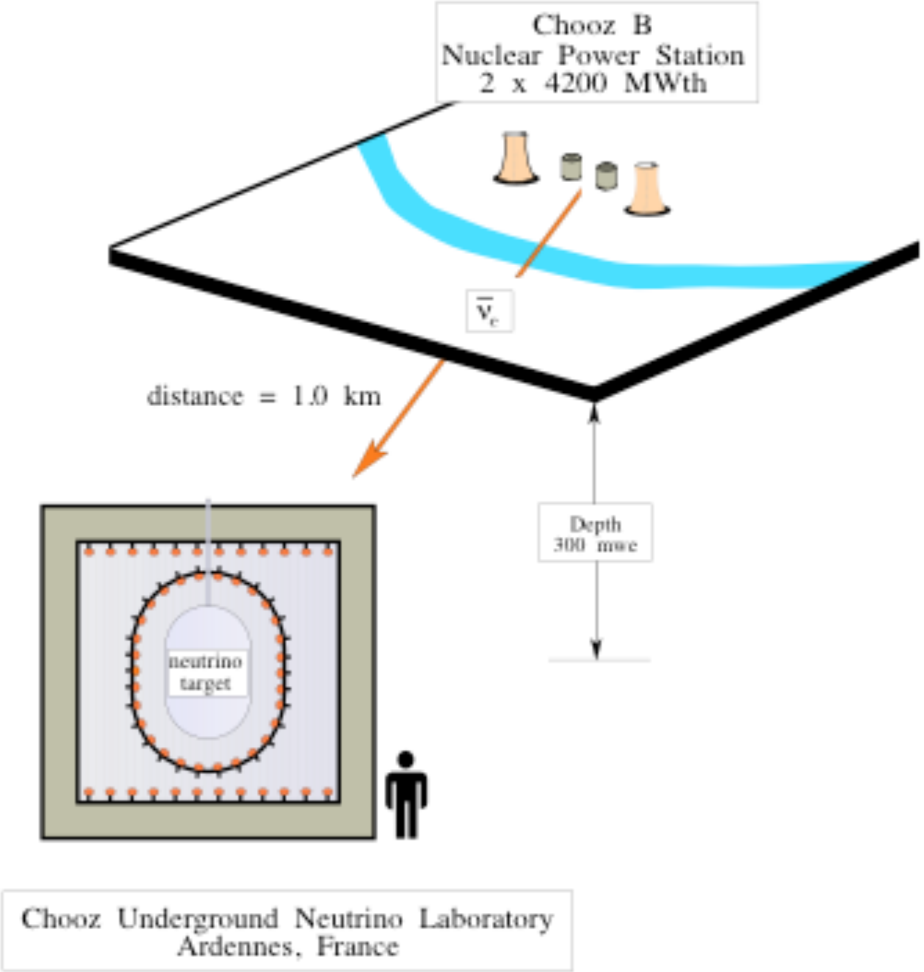
KamLAND

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

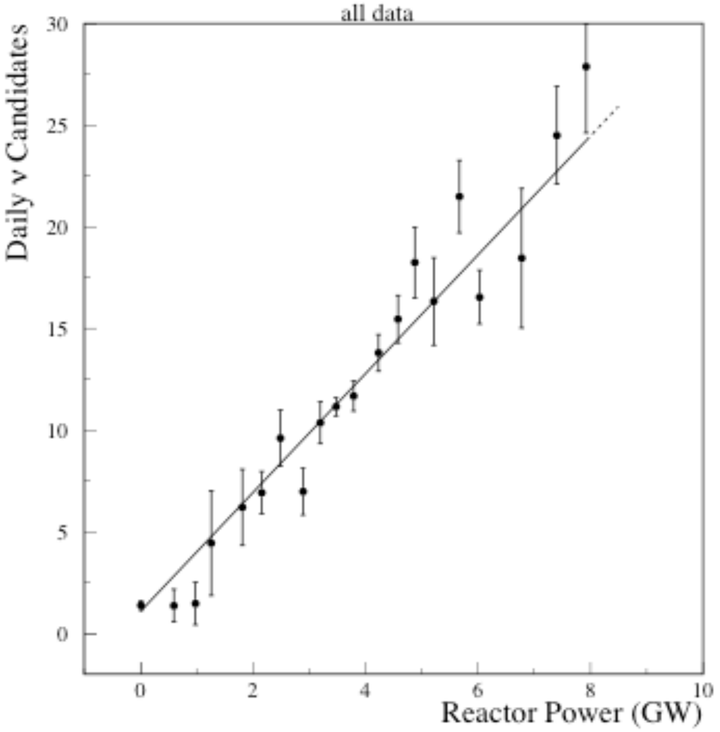


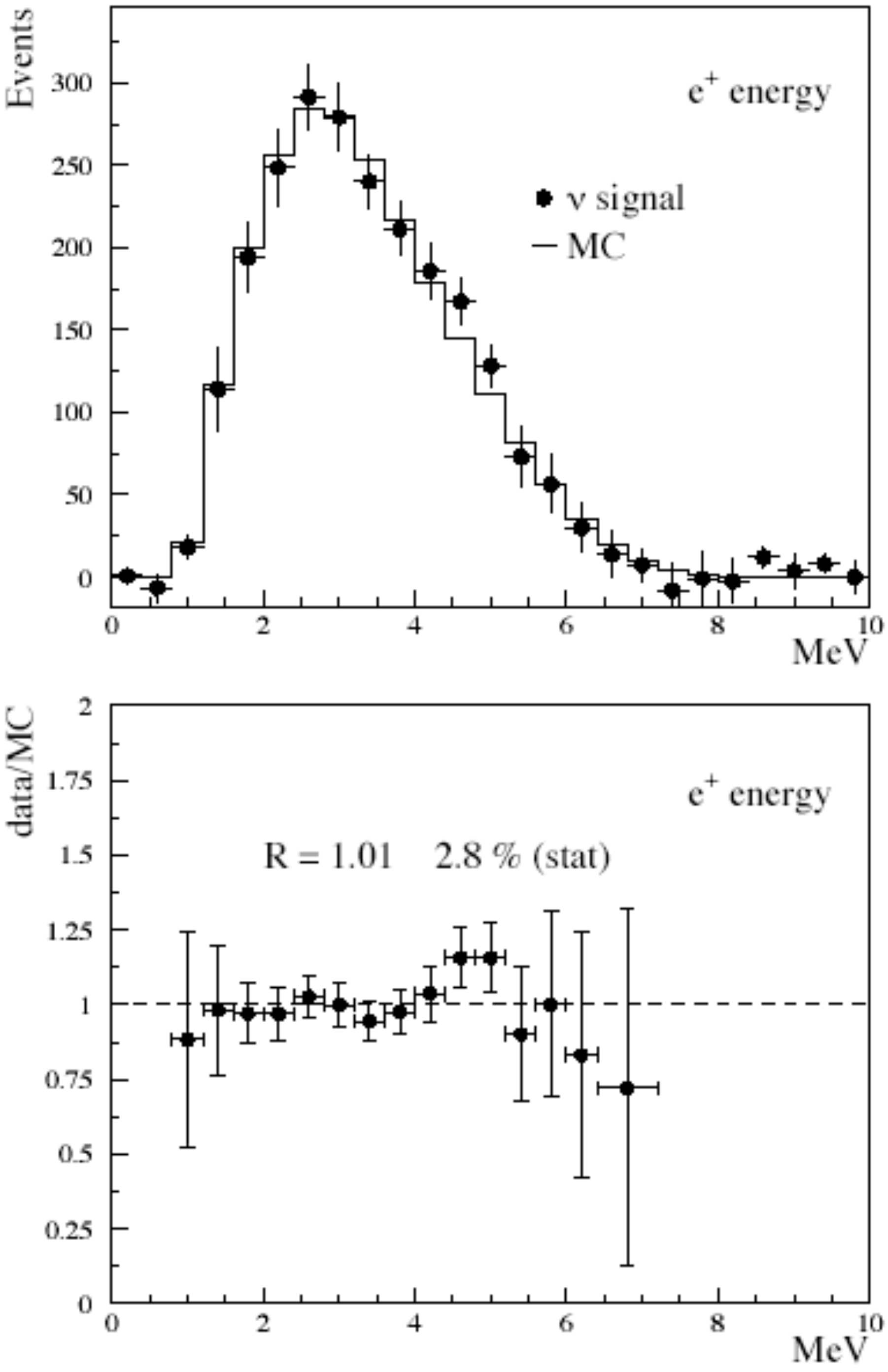


CHOOZ

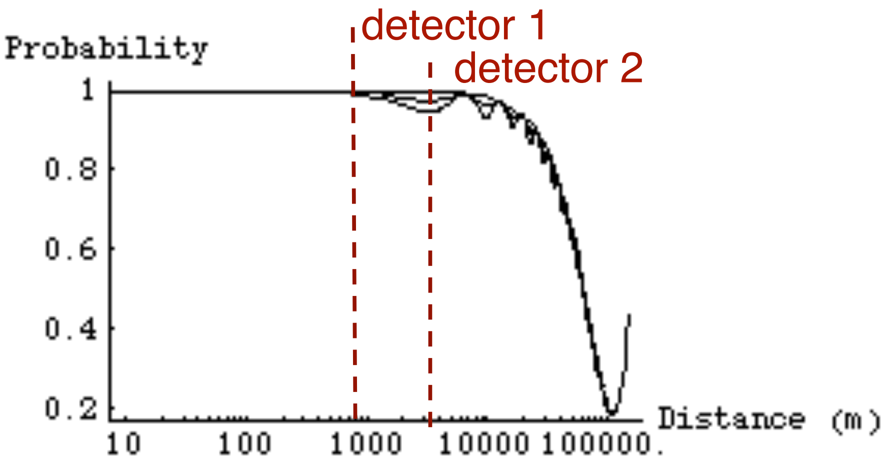

Chooz B
Nuclear Power Station
2 x 4200 MWth
$\bar{\nu}_e$
distance = 1.0 km
Depth
300 mwe
neutrino
target
Chooz Underground Neutrino Laboratory
Ardennes, France

CHOOZ

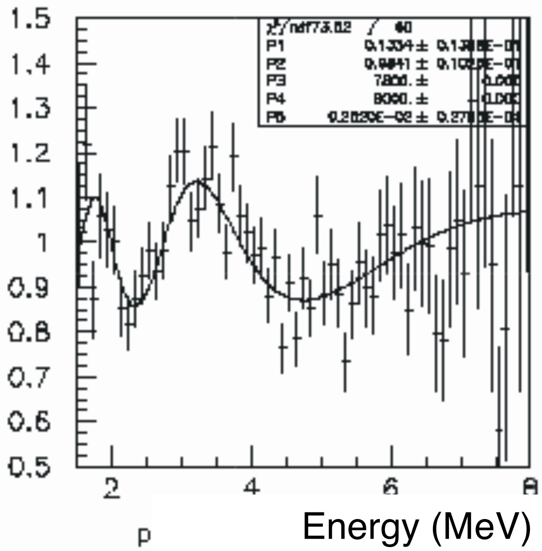

all data
Daily ν Candidates
30
25
20
15
10
5
0
0
2
4
6
8
10
Reactor Power (GW)


Events
300
250
200
150
100
50
0
e+ energy
ν signal
MC
0
2
4
6
8
10
MeV
data/MC
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0
e+ energy
R = 1.01   2.8 % (stat)
0
2
4
6
8
10
MeV

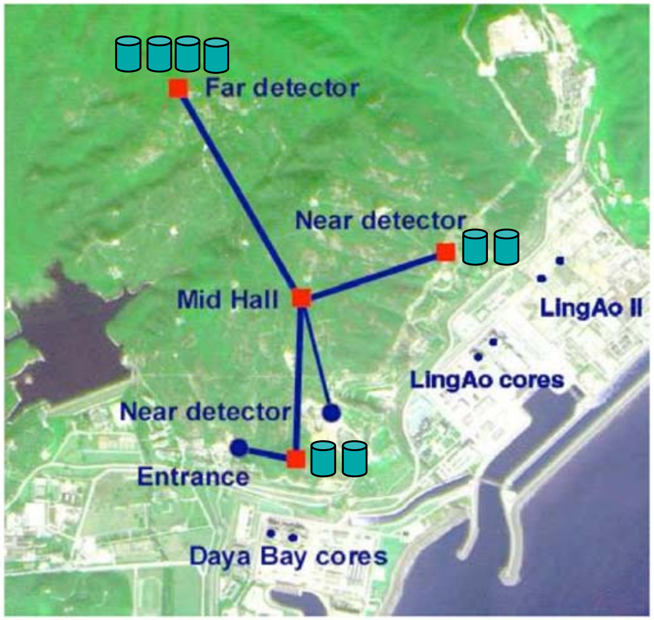
Two-Detector Reactor Experiment to measure θ_{13}



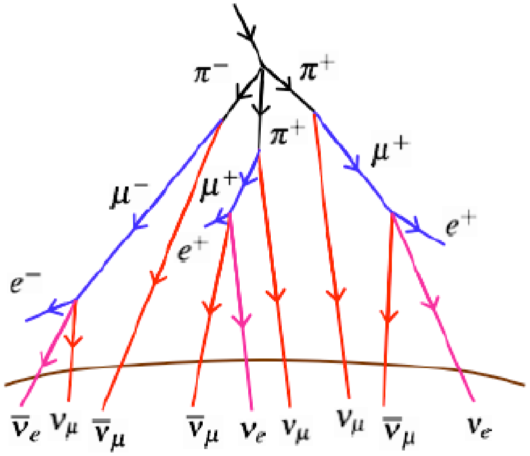
Spectral Ratio

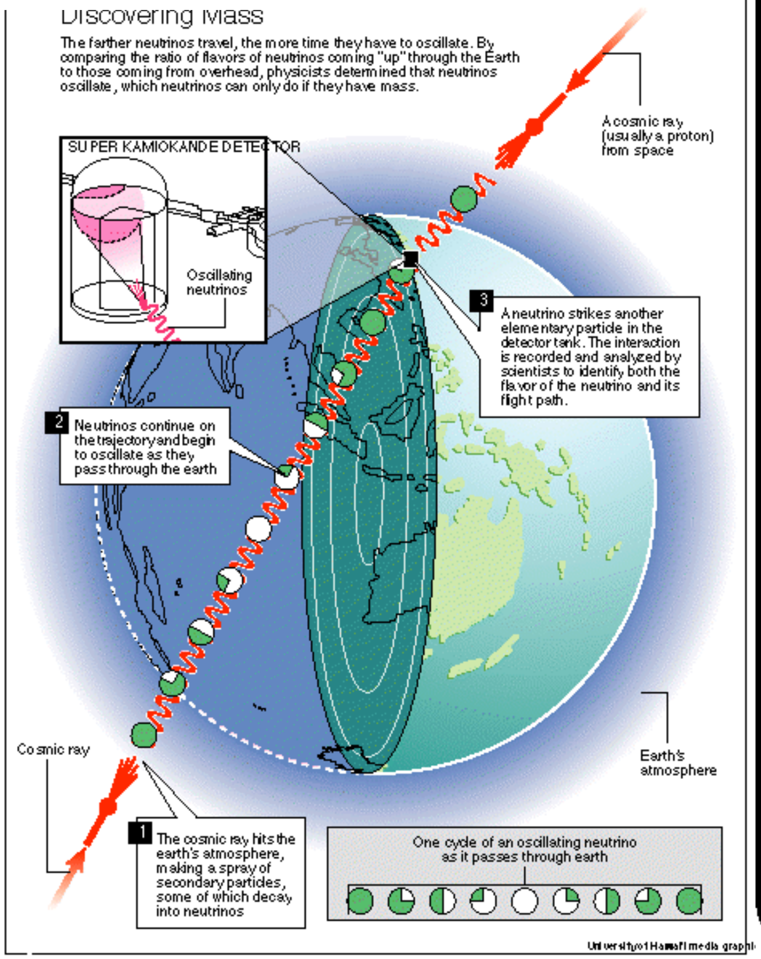


Daya Bay Reactor Experiment, China



Atmospheric Neutrinos




Discovering Mass

The farther neutrinos travel, the more time they have to oscillate. By comparing the ratio of flavors of neutrinos coming "up" through the Earth to those coming from overhead, physicists determined that neutrinos oscillate, which neutrinos can only do if they have mass.

1 The cosmic ray hits the earth's atmosphere, making a spray of secondary particles, some of which decay into neutrinos

2 Neutrinos continue on the trajectory and begin to oscillate as they pass through the earth

3 A neutrino strikes another elementary particle in the detector tank. The interaction is recorded and analyzed by scientists to identify both the flavor of the neutrino and its flight path.

University of Hawaii media graphic

ATMOSPHERIC NEUTRINOS

$$\text{Cosmic Rays} + \text{O},\text{N} \rightarrow \pi^\pm(K^\pm)$$

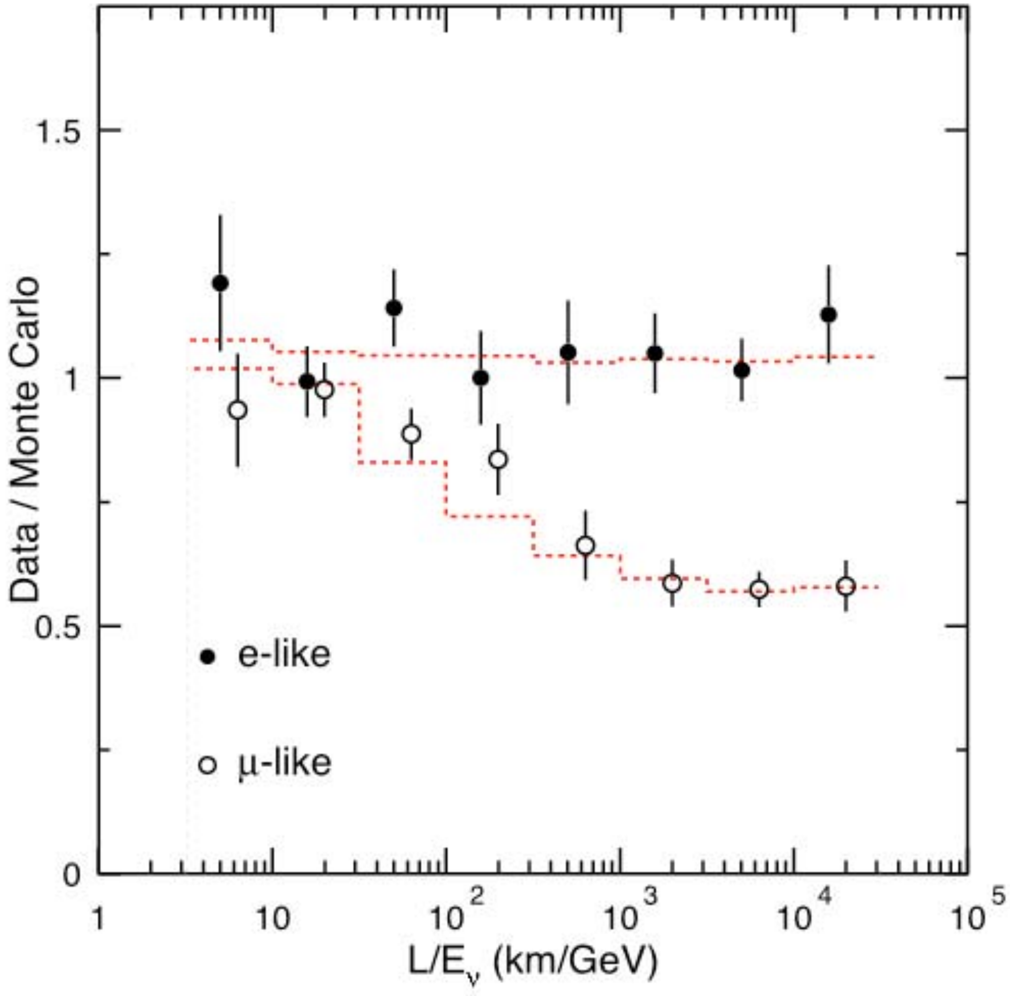
$$\begin{aligned} \pi^\pm(K^\pm) &\rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu), \\ \mu^\pm &\rightarrow e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu). \end{aligned}$$

$$r = (\nu_e + \overline{\nu}_e)/(\nu_\mu + \overline{\nu}_\mu) \sim 0.5$$

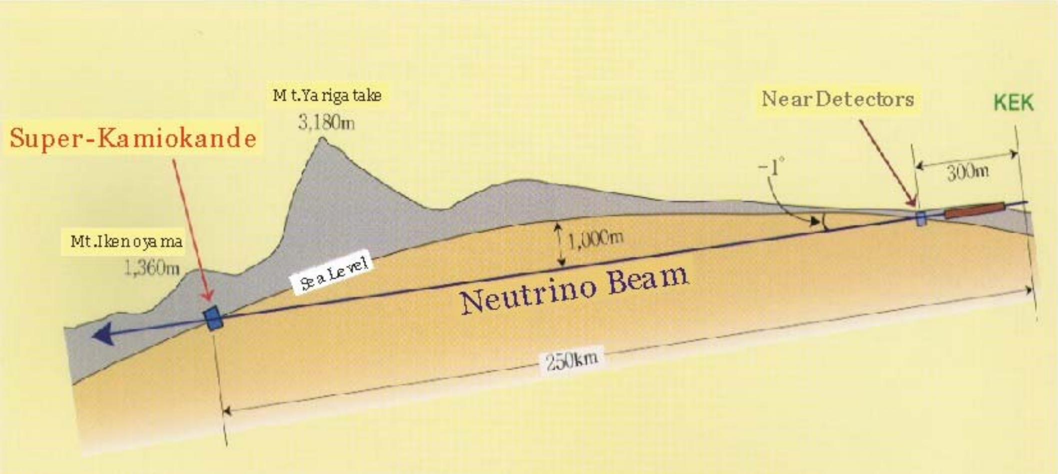
Including the effects of muon polarization $r \sim 0.45$.

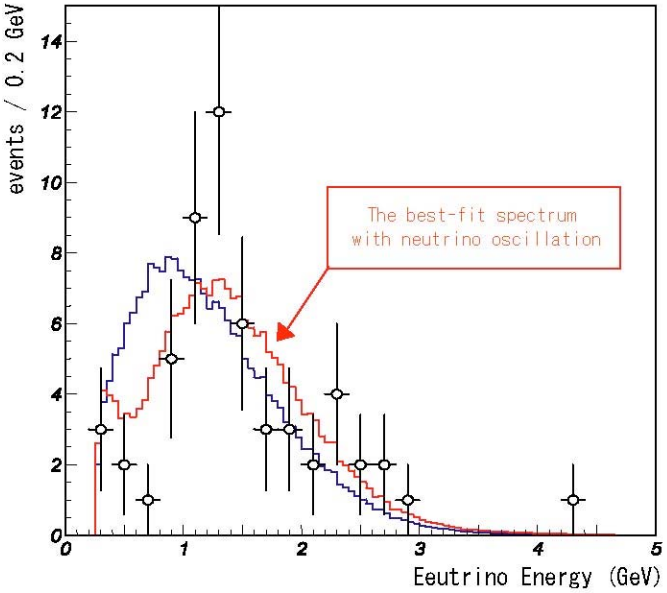
$$R = \frac{(\nu_\mu/\nu_e)_{\text{data}}}{(\nu_\mu/\nu_e)_{\text{MonteCarlo}}}$$

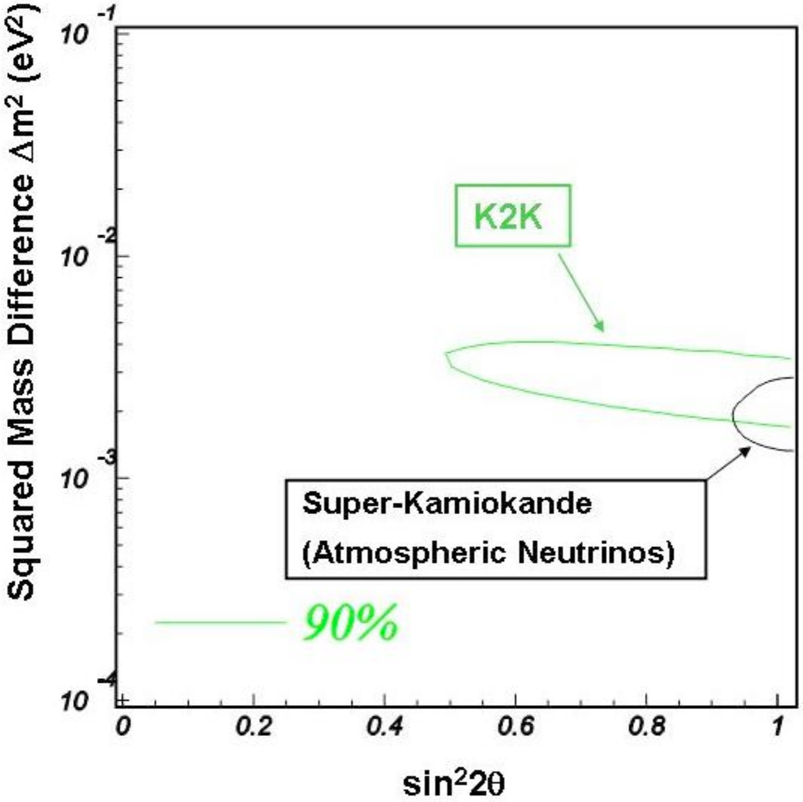
Atmospheric Neutrino Oscillations

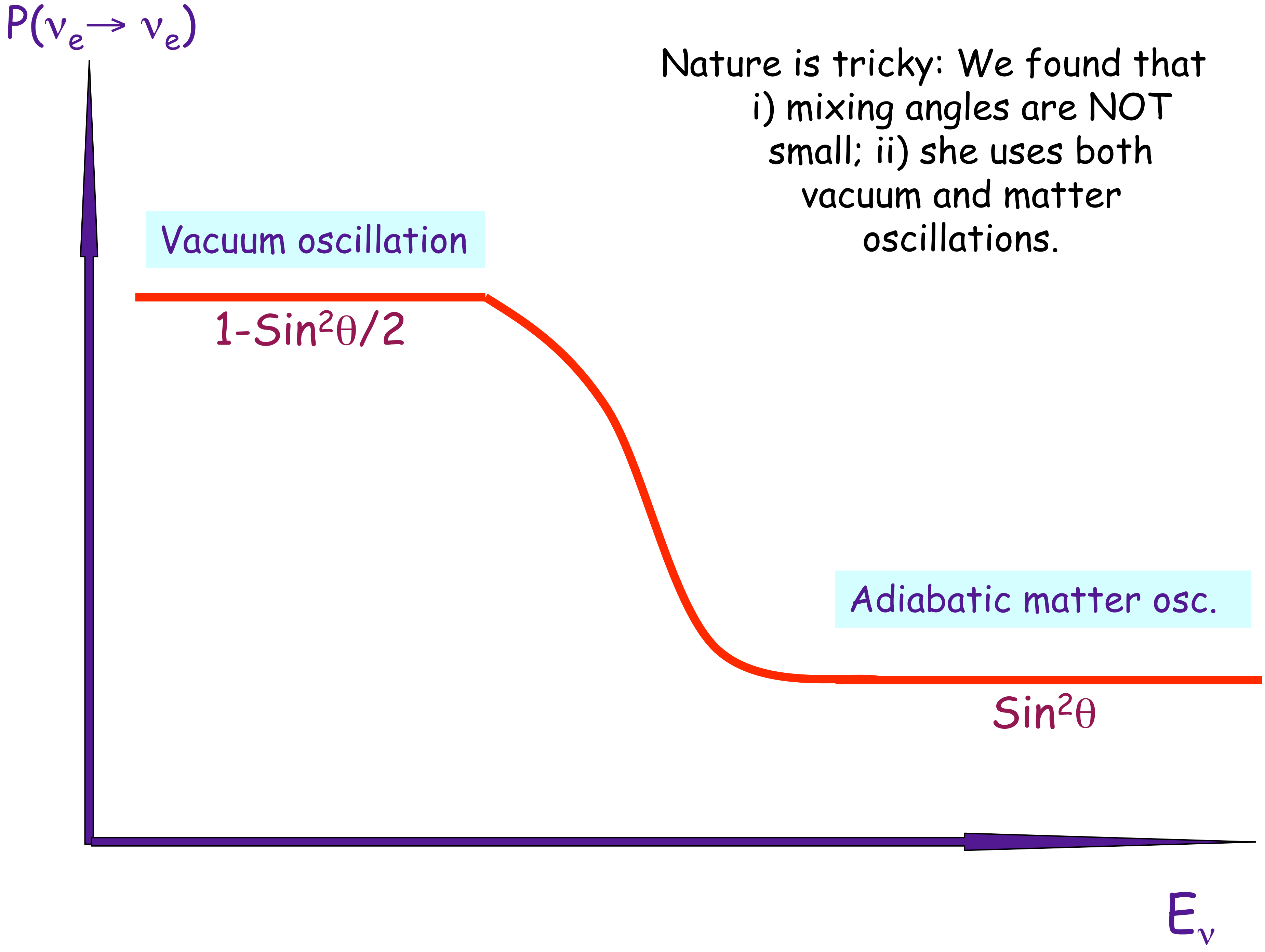


K2K to SuperKamioka









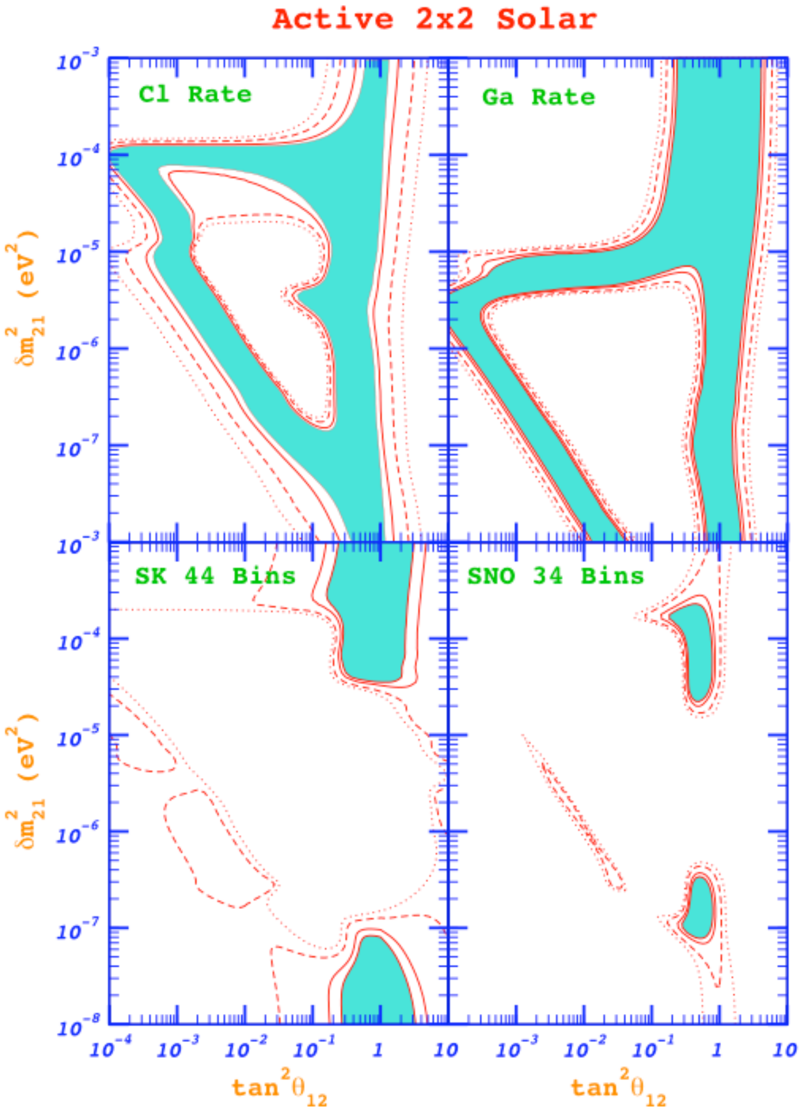
Nature is tricky: We found that i) mixing angles are NOT small; ii) she uses both vacuum and matter oscillations.

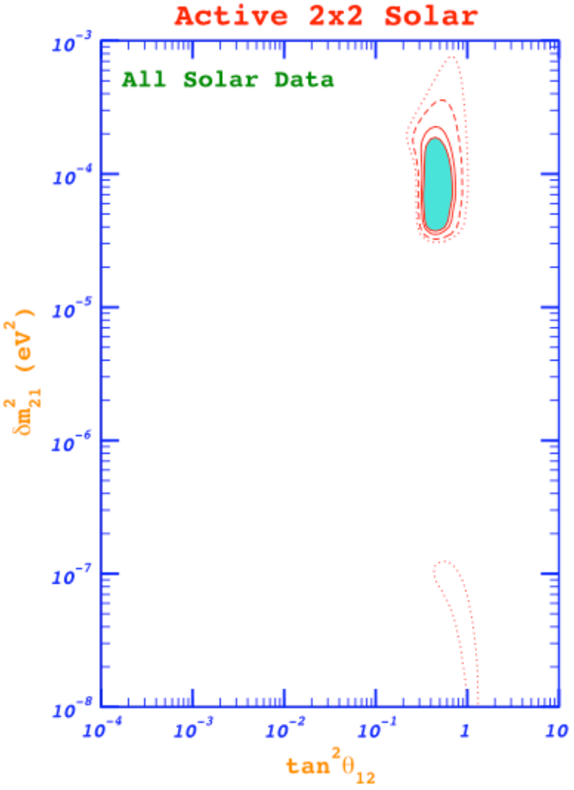
Typically solar neutrino analyses assume that ν_e mixes with a combination of ν_μ and ν_τ. This is exact only when θ_{13} is zero. When θ_{13} is non-zero, but small we can use

$$\boxed{\begin{aligned} P_{3x3}(\nu_e \rightarrow \nu_e) = \mathrm{Cos}^4\theta_{13}\, P_{2X2}(\nu_e \rightarrow \nu_e \text{ calc. with } \mathrm{Cos}^2\theta_{13} N_e) \\ + \mathrm{Sin}^4\,\theta_{13} \end{aligned}}$$

This works both for vacuum and matter oscillations…

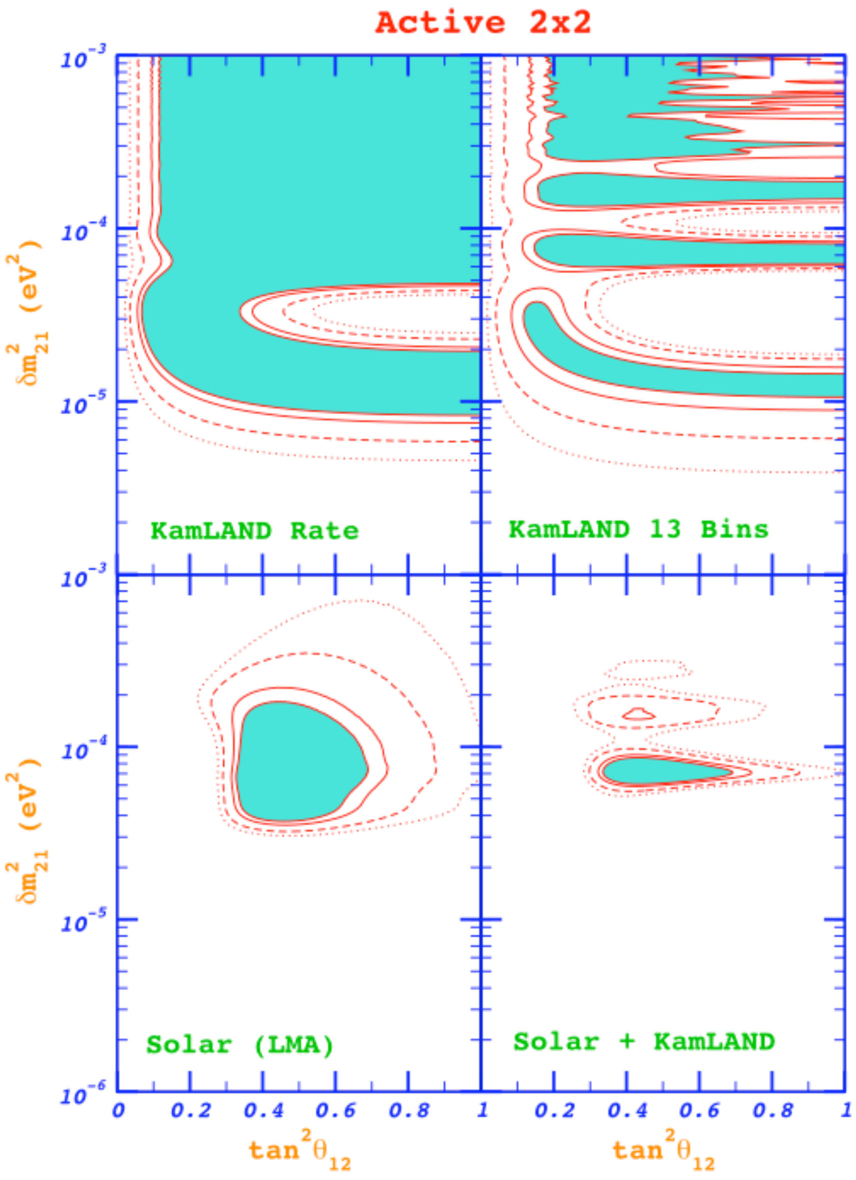
A global analysis of the solar neutrino data

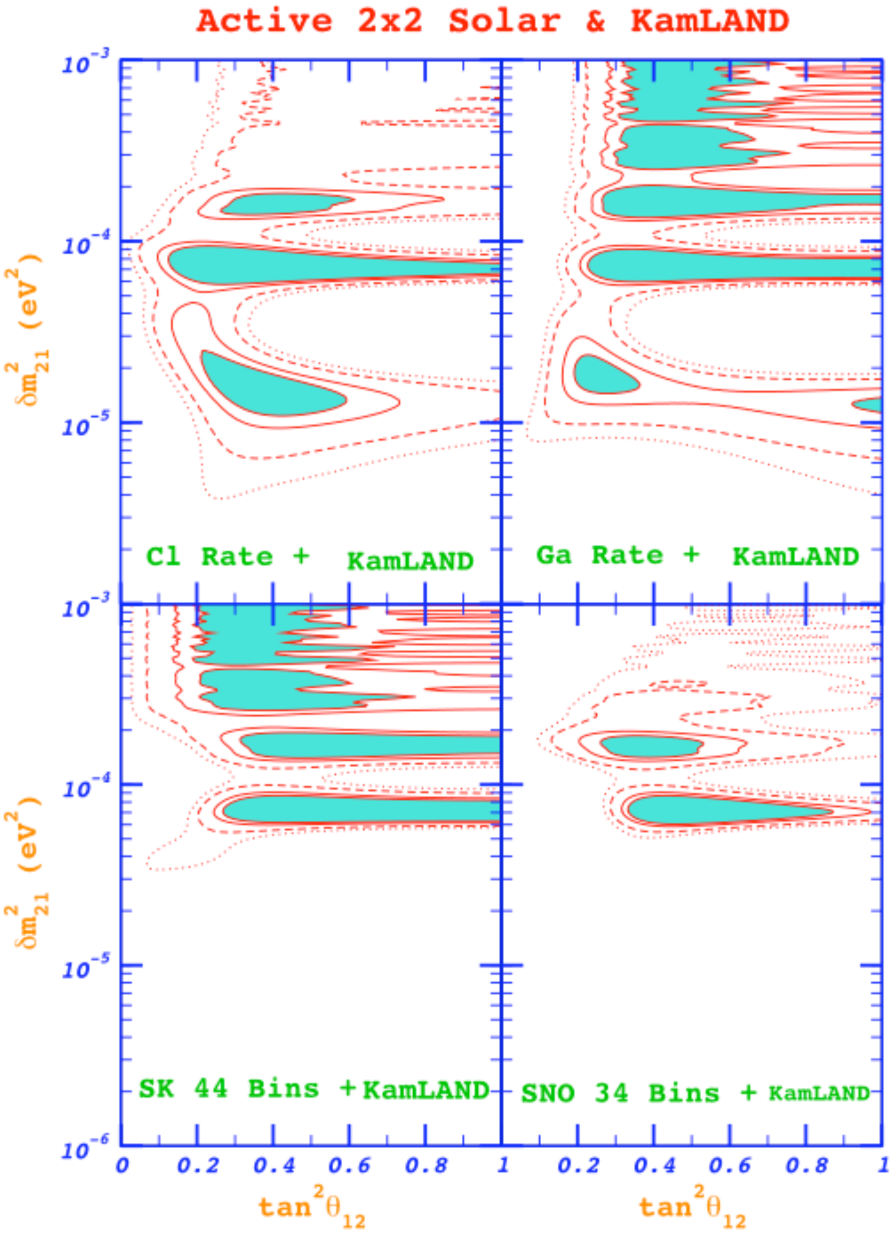




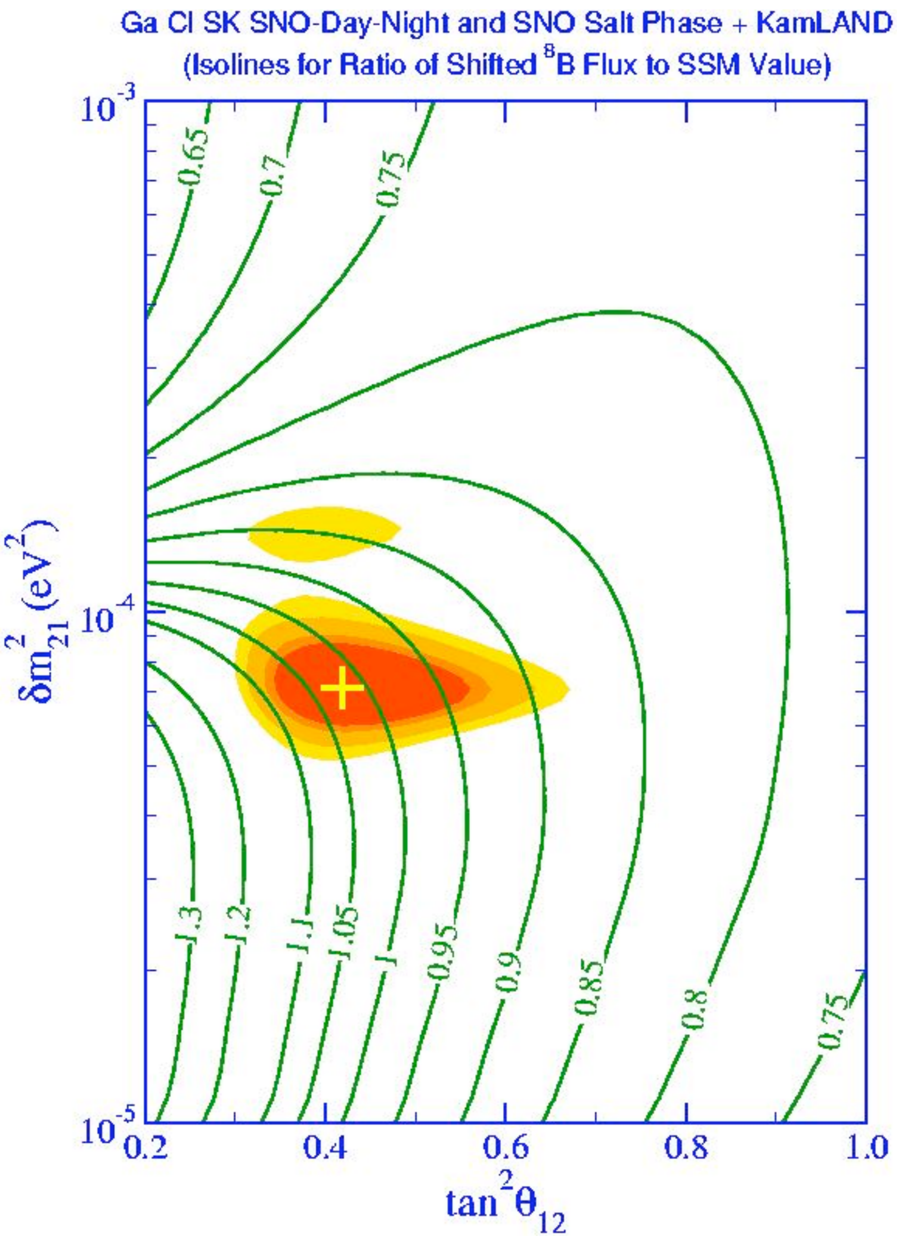
Balantekin & Yuksel, J. Phys. G 29, 665 (2003).

Solar + KamLAND Global Analysis

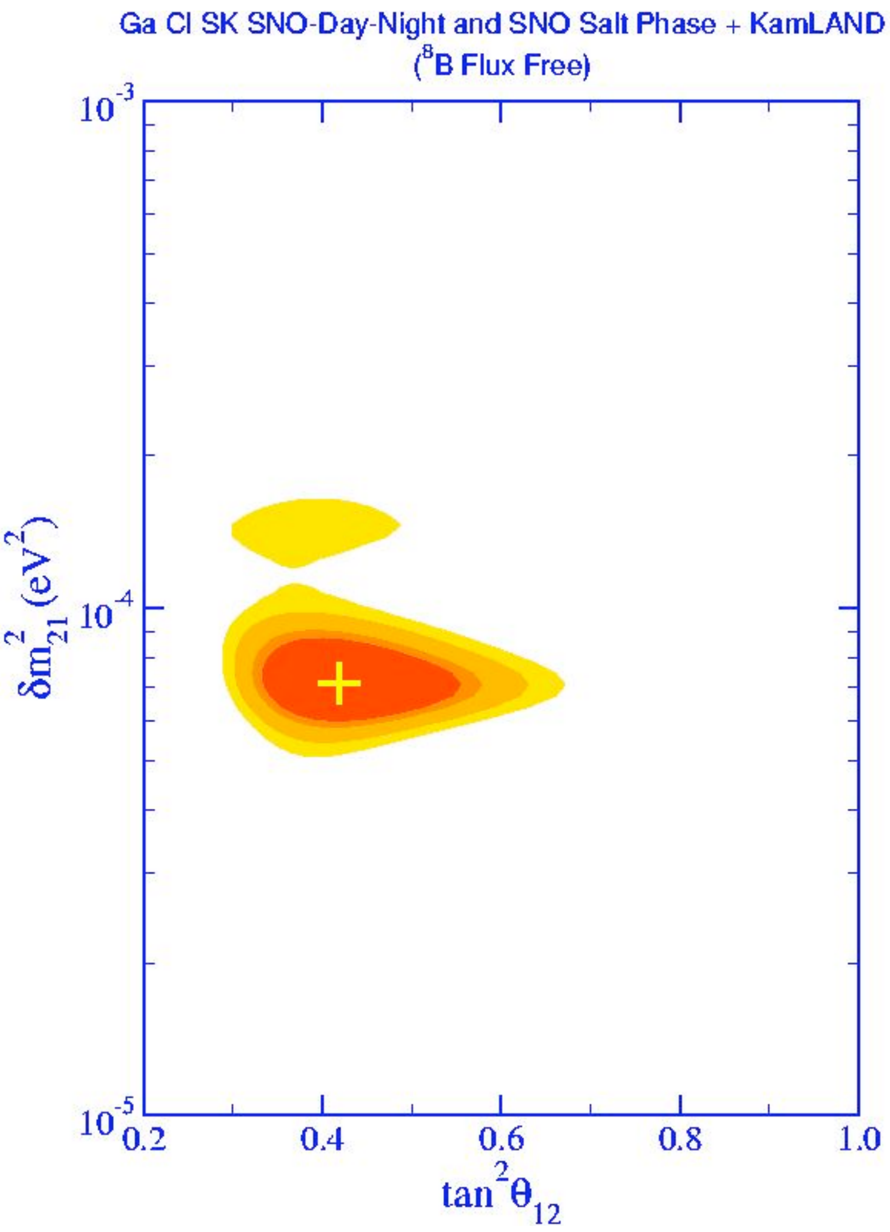




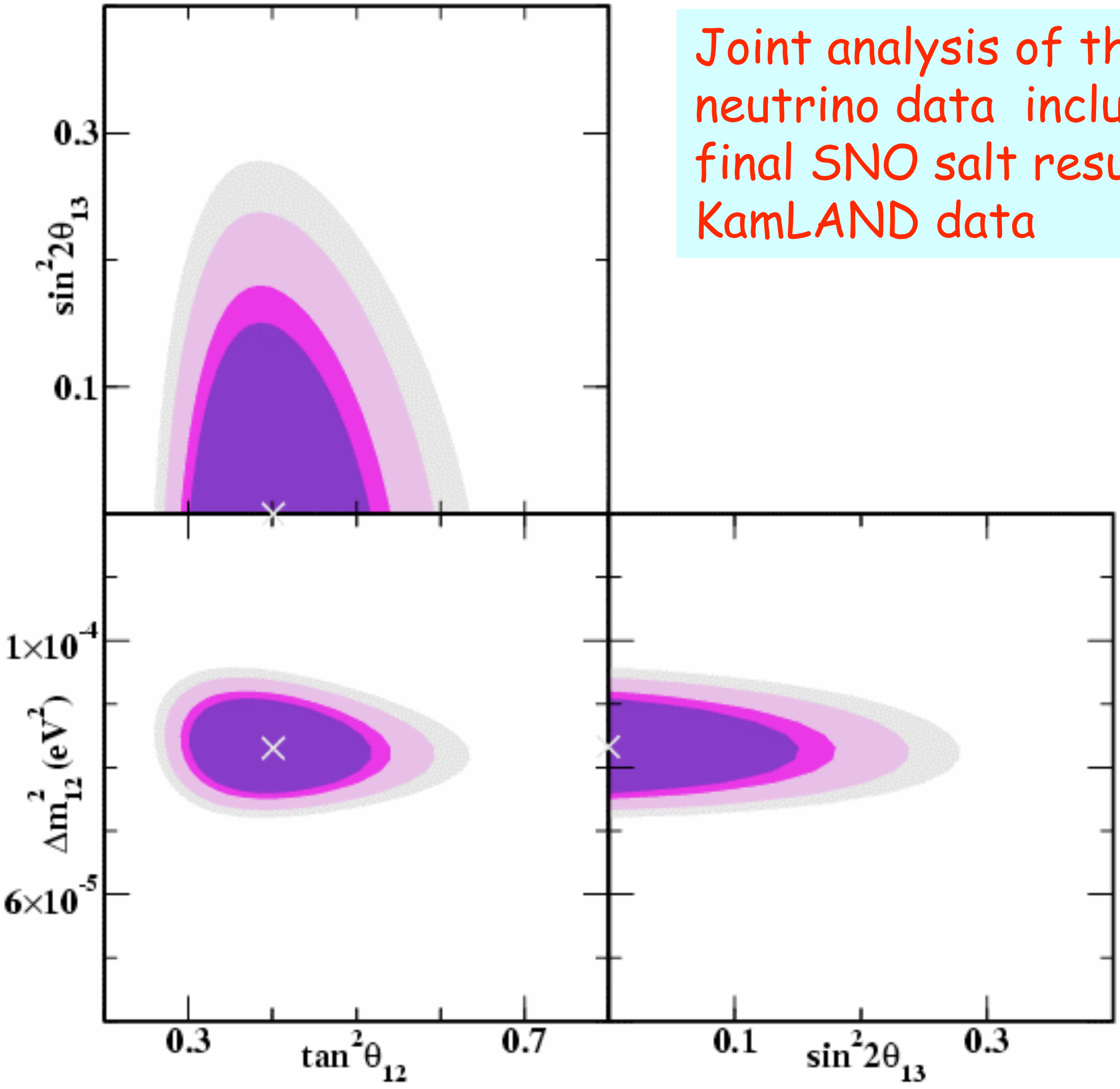
SNO first Salt Results , Balantekin and Yuksel, PRD 68, 113002 (2003)



Ga Cl SK SNO-Day-Night and SNO Salt Phase + KamLAND
(Isolines for Ratio of Shifted ^{8}B Flux to SSM Value)



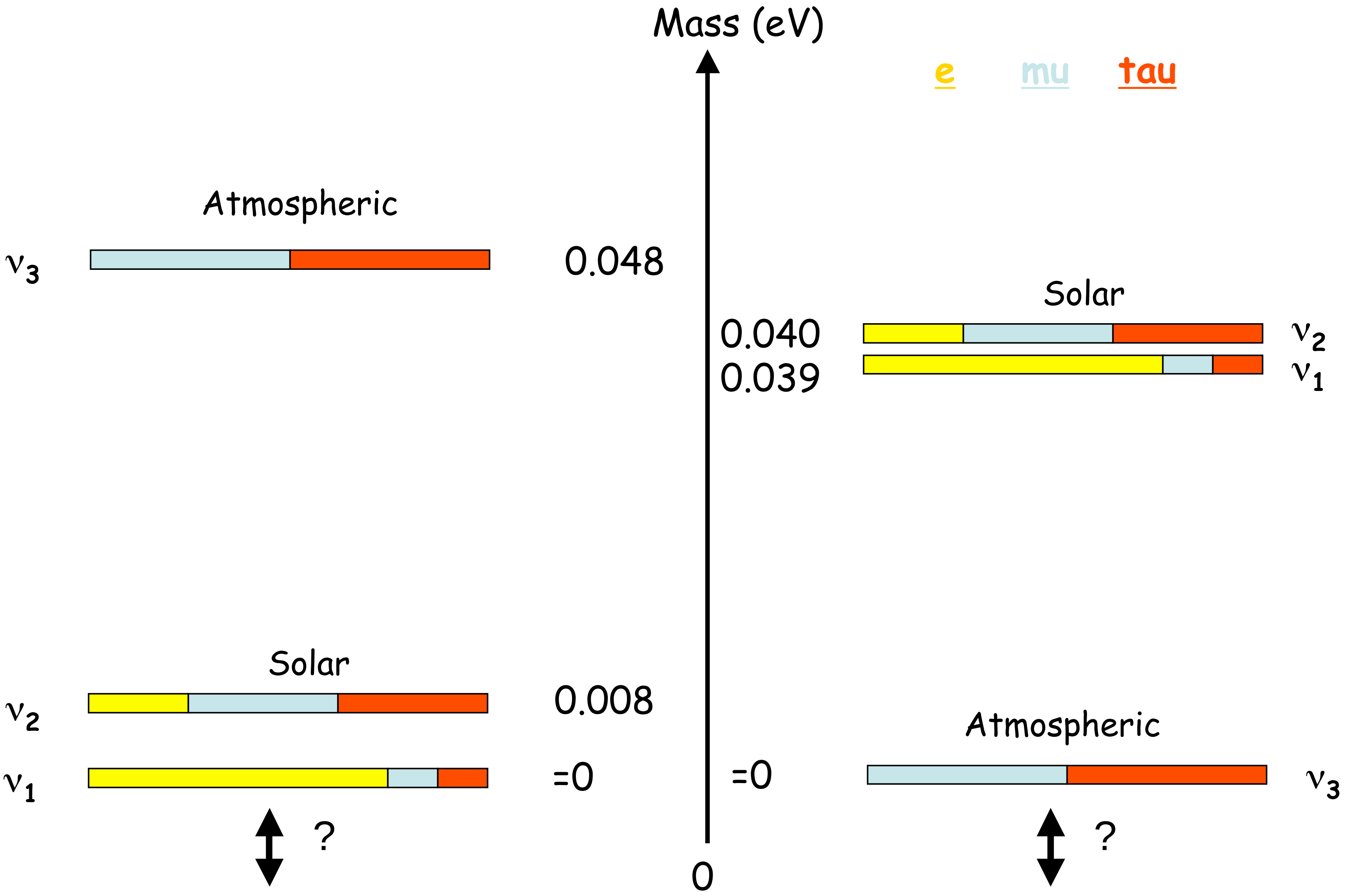
Ga Cl SK SNO-Day-Night and SNO Salt Phase + KamLAND
(^{8}B Flux Free)

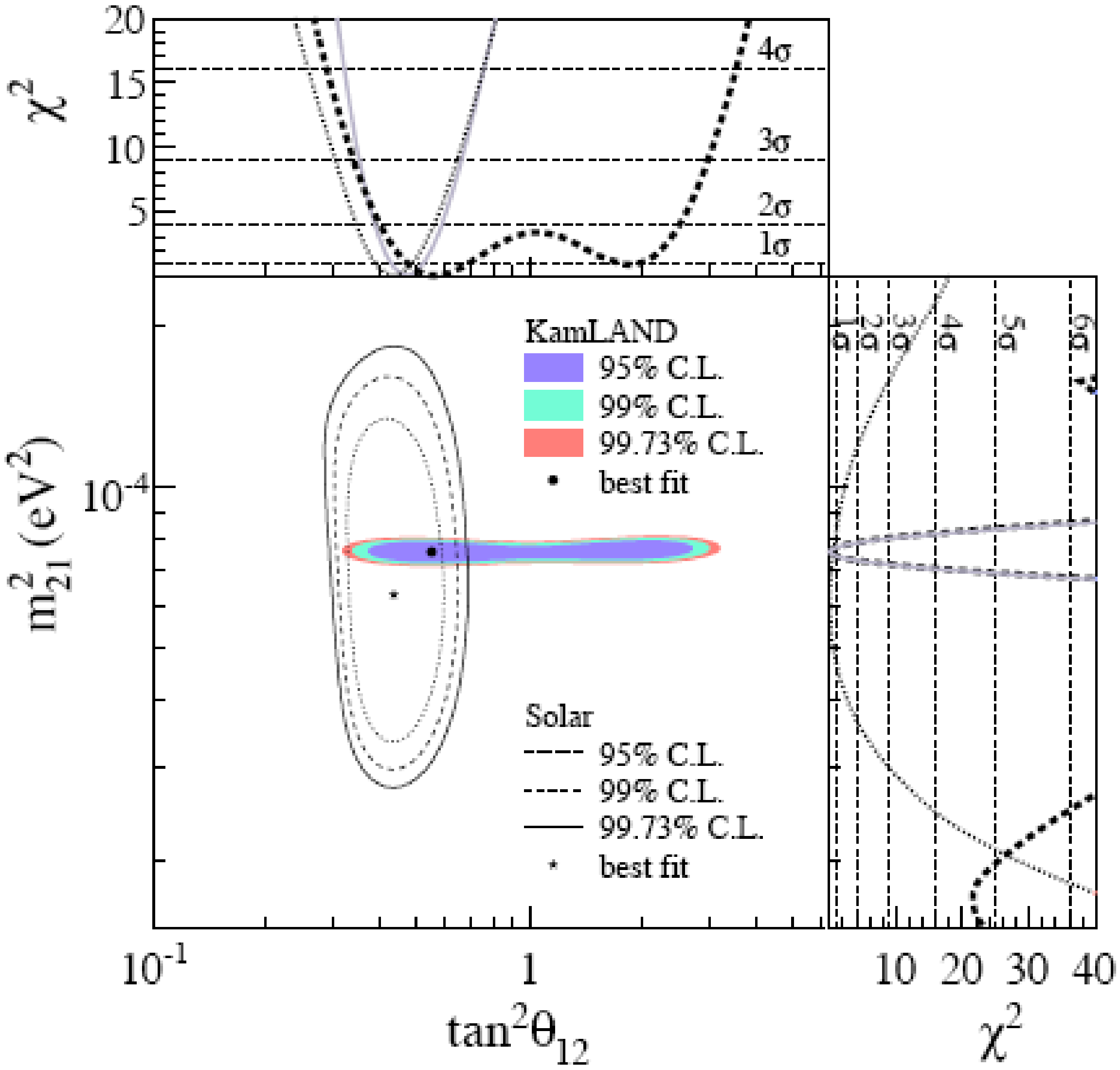


Joint analysis of the solar neutrino data including final SNO salt results and KamLAND data

Balantekin, et al., PLB 613, 61 (2005)

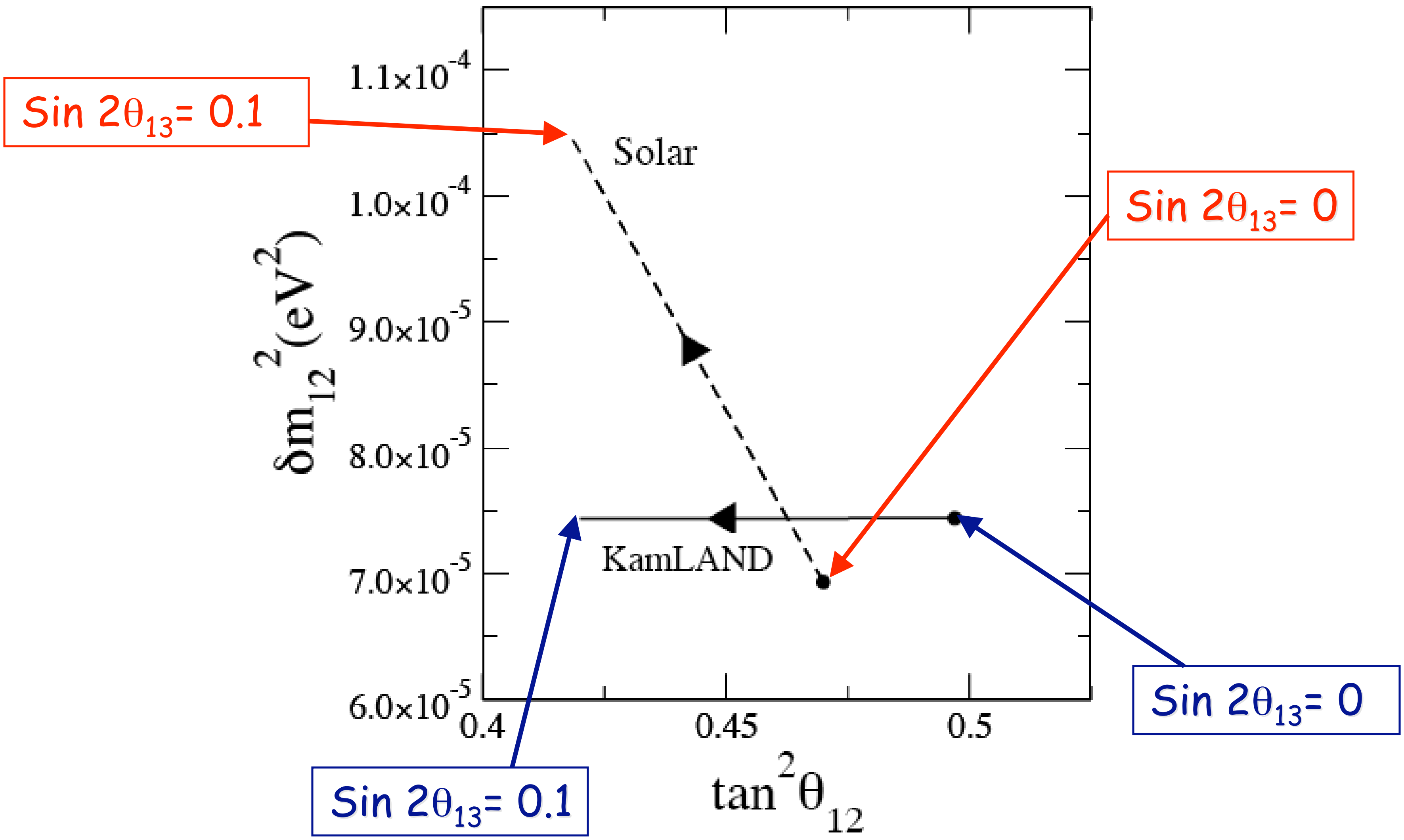
Neutrino Masses and Flavor Content





KamLAND and solar best fit values are not the same!
CPT-violation? Other new physics?

….or is it simply ignoring θ_{13} ?

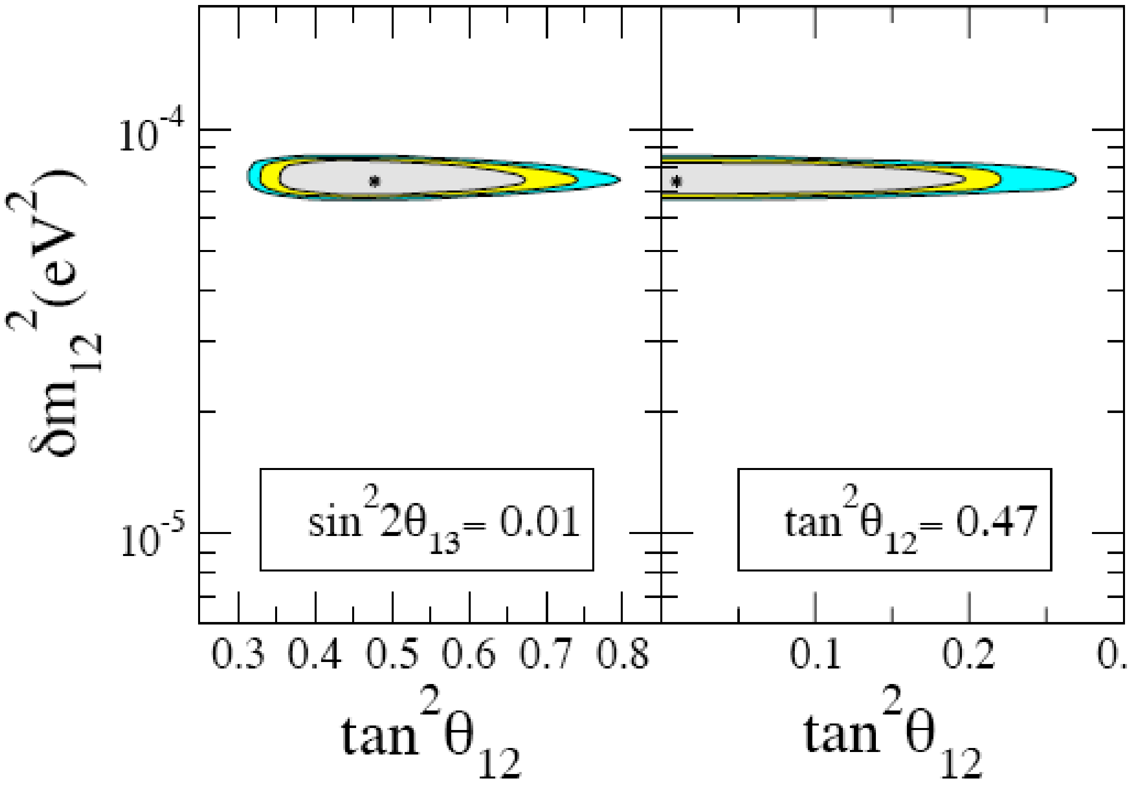


$\sin 2\theta_{13}= 0.1$

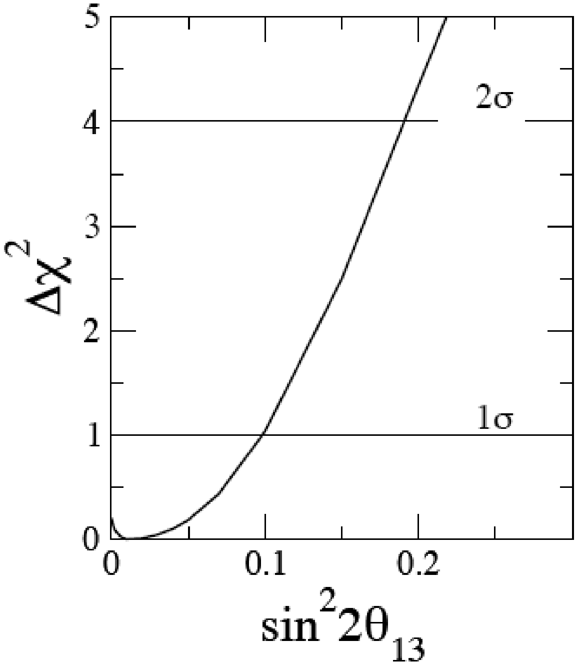
$\sin 2\theta_{13}= 0$

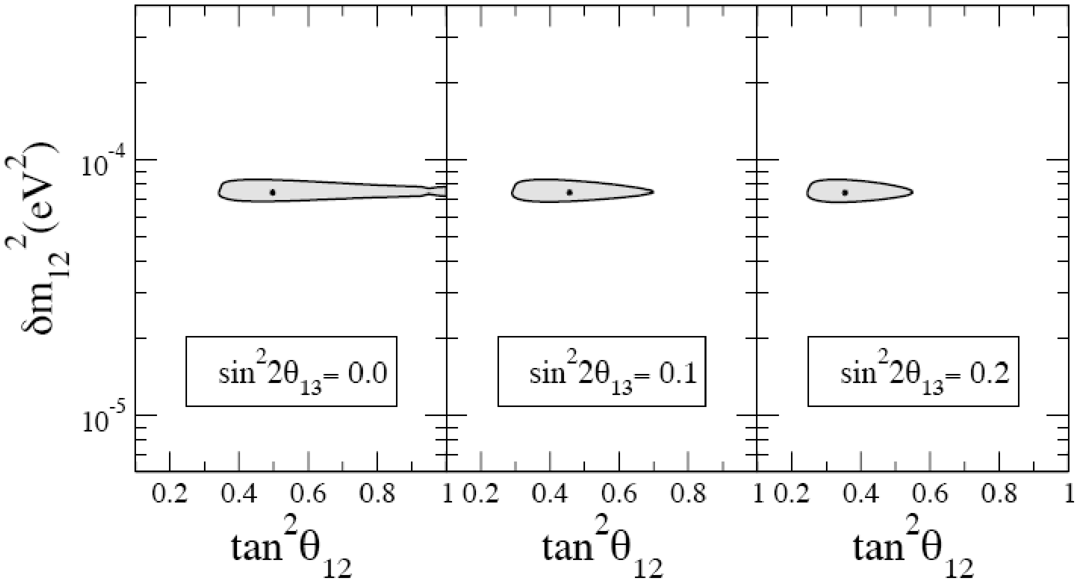
$\sin 2\theta_{13}= 0$

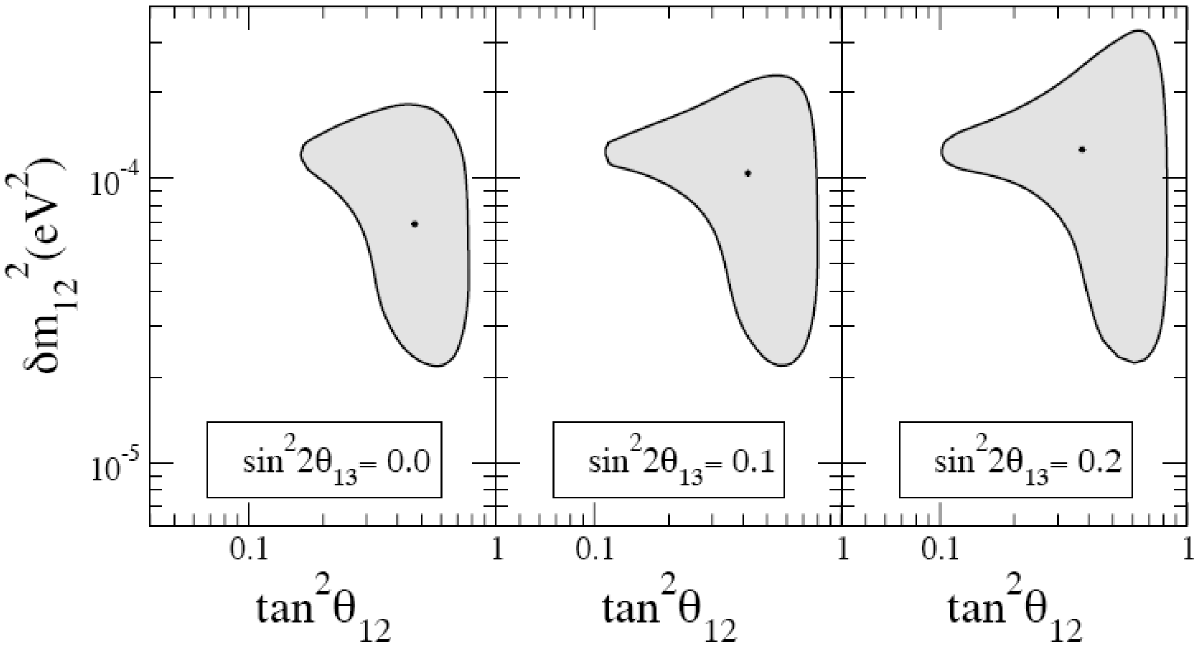
$\sin 2\theta_{13}= 0.1$



A.B. Balantekin, D. Yilmaz,
arXiv:0804.3345



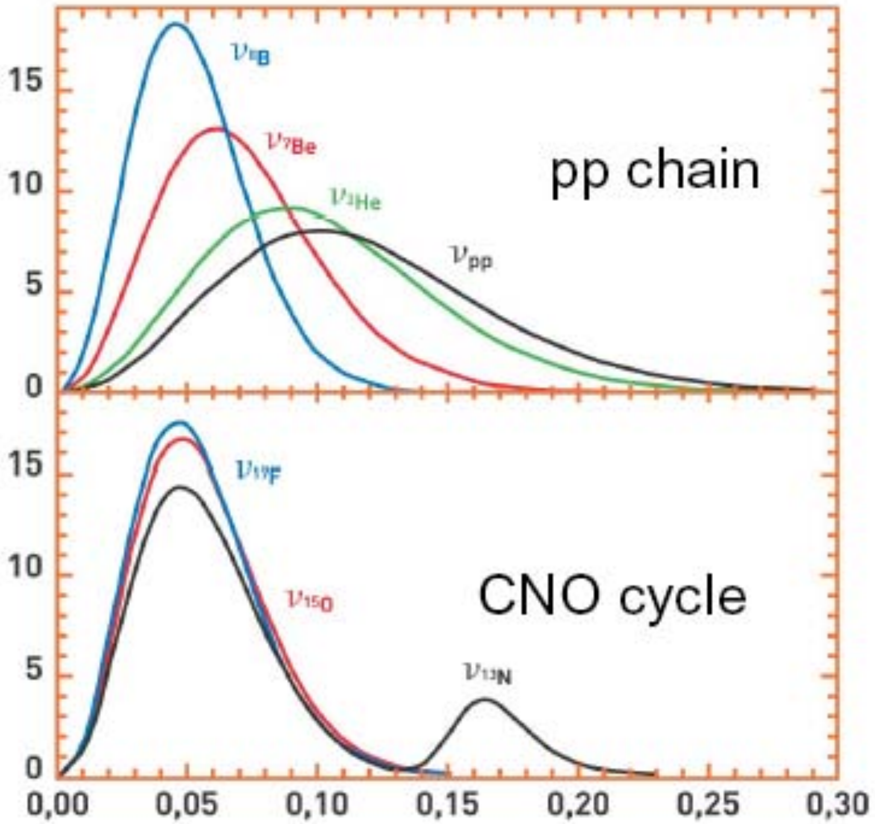

δm_12^2(eV^2)
10^-4
10^-5
sin^2 2θ_13 = 0.0
sin^2 2θ_13 = 0.1
sin^2 2θ_13 = 0.2
0.2
0.4
0.6
0.8
1
tan^2θ_12

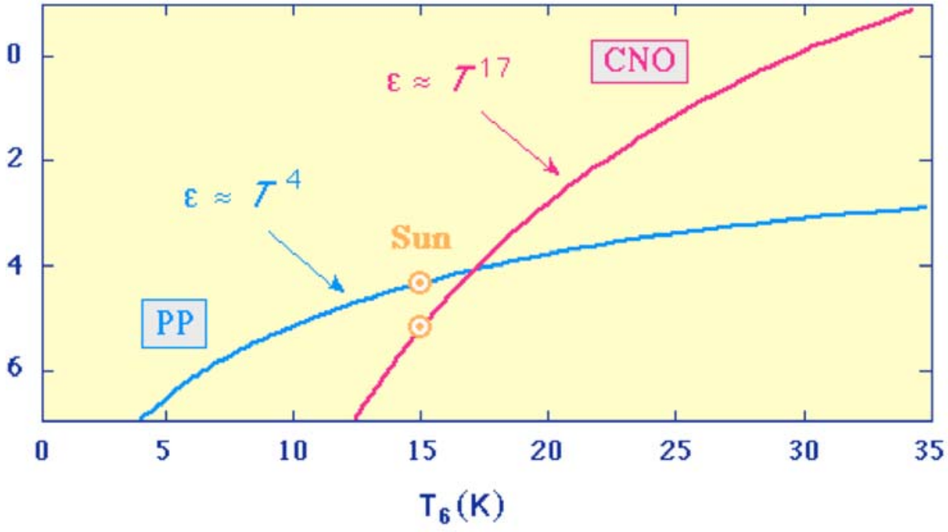

δm_12^2(eV^2)
10^-4
10^-5
sin^2 2θ_13 = 0.0
sin^2 2θ_13 = 0.1
sin^2 2θ_13 = 0.2
0.1
1
tan^2θ_12

Are nuclear fusion reactions the only source of solar energy? To answer this question we need to accurately measure solar neutrino luminosity!

- This is a crucial test of energy generation during the main stage of stellar evolution.
- It is a test independent of the detailed dynamics of the solar models.
- It requires pp, pep, ^{7}Be, and CNO neutrino fluxes.
- Present uncertainty is very big, but a few percent of accuracy is within reach.

How much does the CNO cycle contribute in the Sun?





In SSM CNO cycle contribute about 0.8% of the neutrino flux. Data are consistent with this. A more precise measurement of the CNO contribution will provide a test of SSM.