48ème Ecole de Gif : La Physique Souterraine

Low Energy Neutrinos Underground Experiments

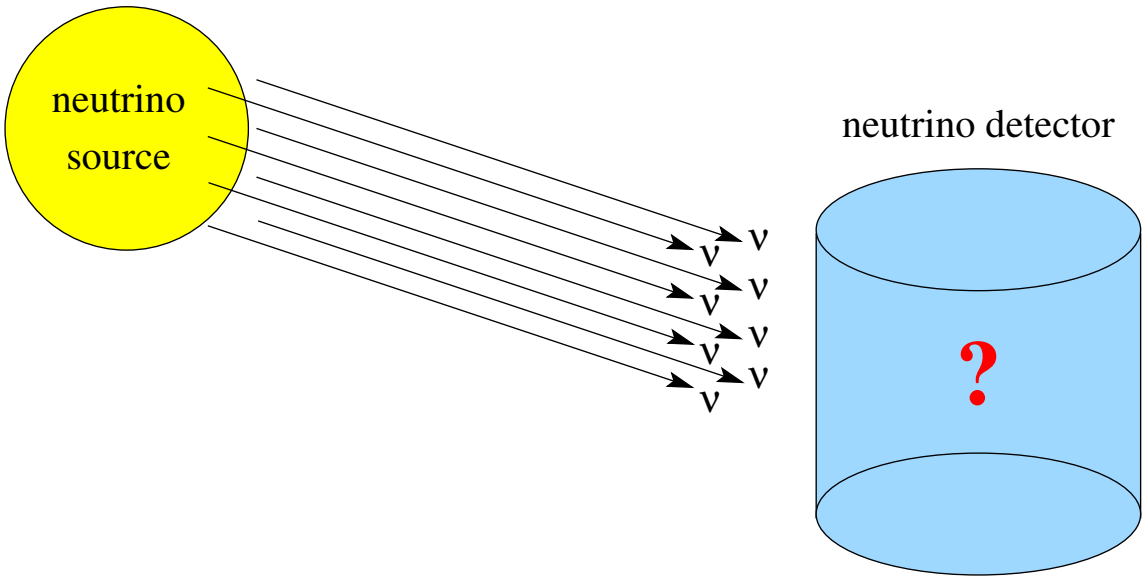
Mathieu BONGRAND

LAL Orsay

September, 2016

Neutrino Experiment

- To build a neutrino experiment, besides the phenoma we want to study, we need to define:
  - the expected number of neutrino events from a given source
  - how they would interact in our detector

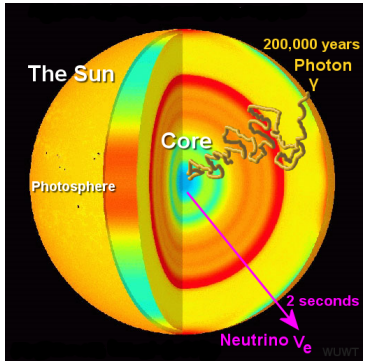


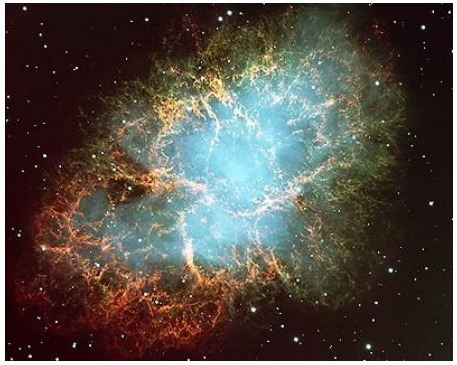
$$\mathrm{N}(E_\nu) = \phi_\nu(E_\nu) \ \cdot \ \sigma_\nu(E_\nu) \ \cdot \ \text{target}$$

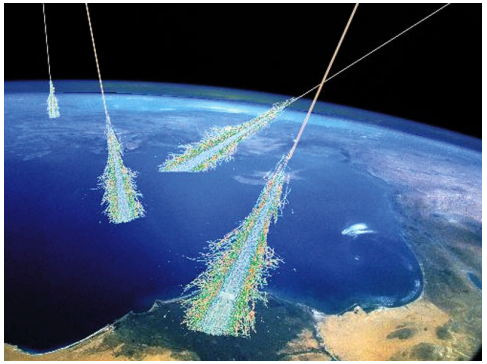
- The weak interaction neutrino cross-sections $\sigma_\nu(E_\nu)$ are tiny:
  - but $\sigma_\nu(E_\nu)$ increases with E_ν
  - we need intense neutrino sources (huge $\phi_\nu(E_\nu)$)
  - target detector has to be (very) large (few t $\rightarrow$ kt)

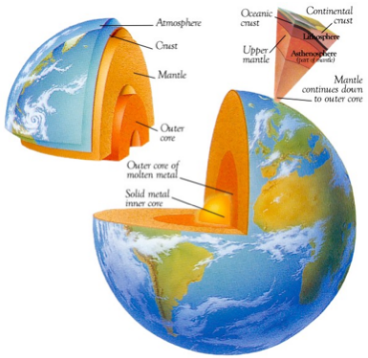
Neutrino Sources

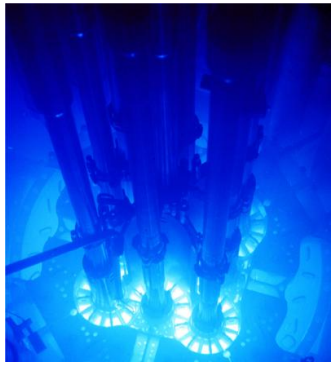
The neutrino is the 2nd most abundant particle in the Universe:
$\sim 300\ \nu_{relic}$ cm^{-3} (1st are the CMB photons)







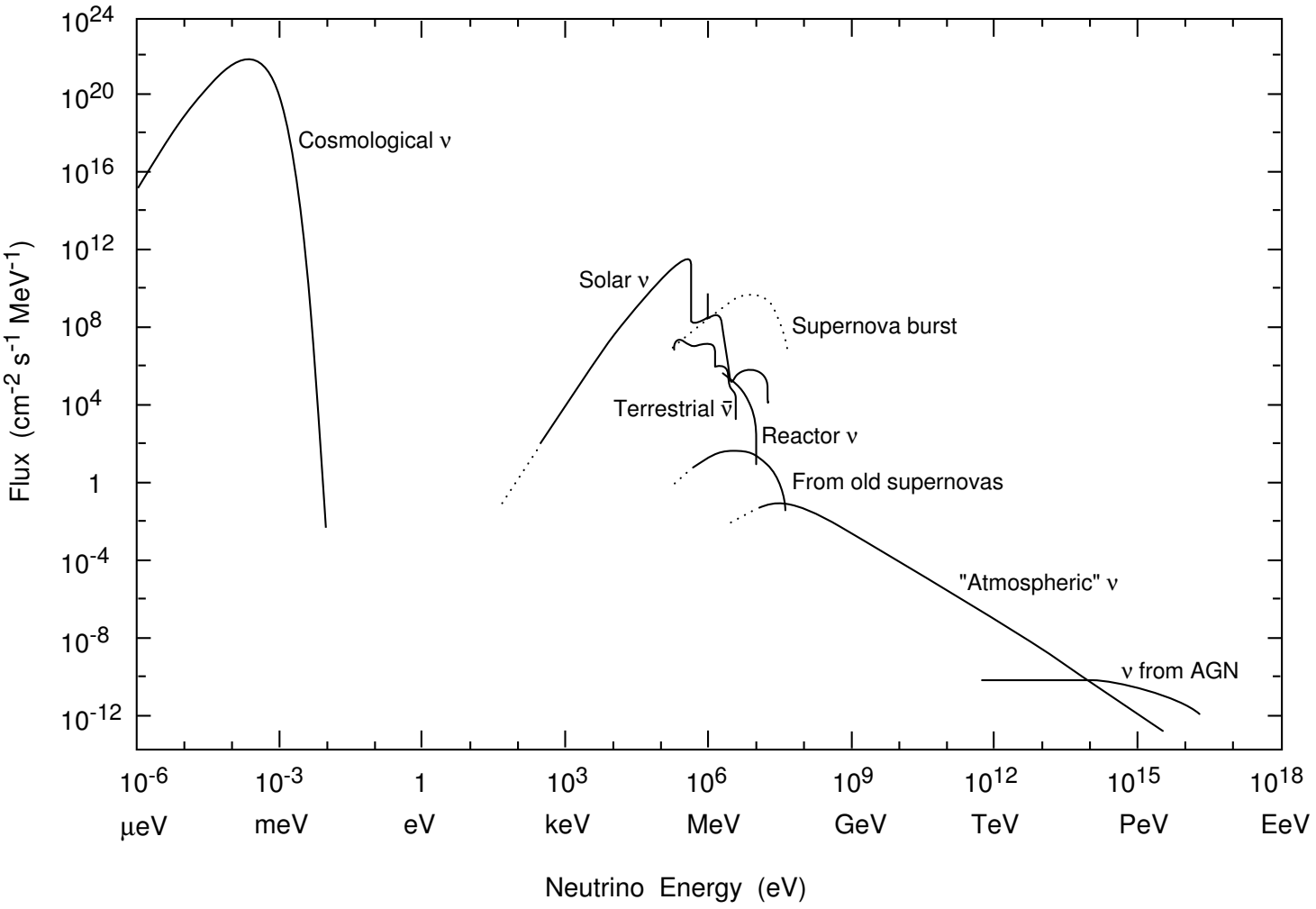




Neutrino Budget on Earth

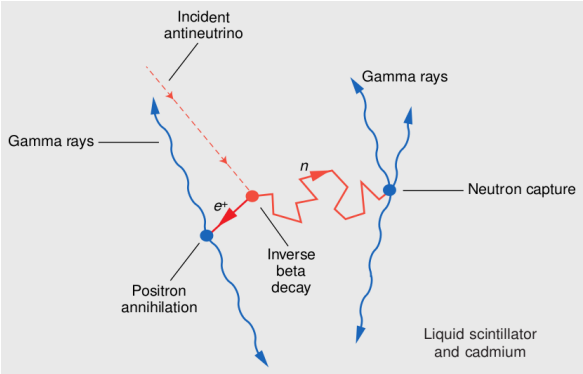
Sun	ν_e	1.5 10^8 km	continuous	6.5 10^{10} cm^{-2}s^{-1}
SN 1987A	$\overline{\nu}_e$	1.5 10^{18} km	$\sim$ 10 s	$\sim$ 5 10^8 cm^{-2}s^{-1}
Atmospheric	$\nu_{e\mu\tau}$ / $\overline{\nu}_{e\mu\tau}$	10-10 000 km	continuous	$\sim$ 1 cm^{-2}s^{-1}
Geoneutrinos	$\overline{\nu}_e$	0 - 6370 km	continuous	2.0 10^6 cm^{-2}s^{-1}
Reactor	$\overline{\nu}_e$	$\sim$1 km	continuous	1.0 10^{10} cm^{-2}s^{-1}
Accelerators	ν_μ / $\overline{\nu}_\mu$	200 - 800 km	pulsed	

Neutrino Fluxes and Energies on Earth

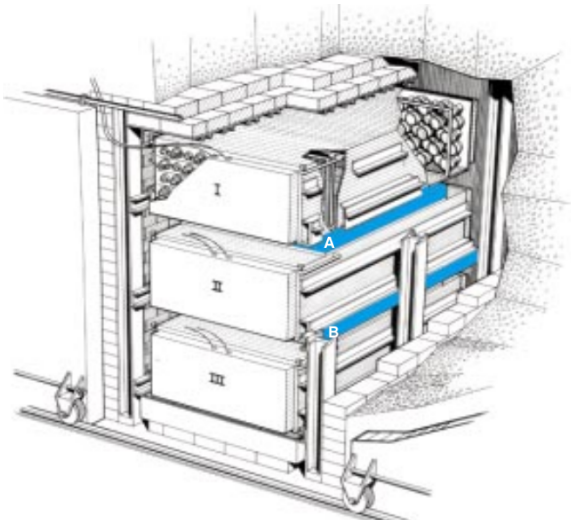


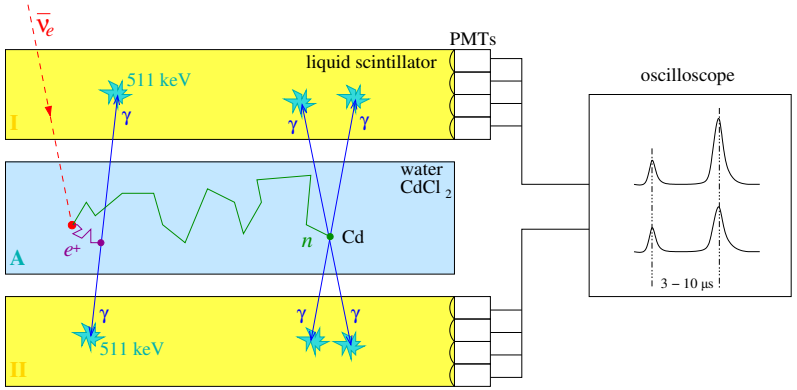
G. Giacomelli & M. Sioli, arXiv:hep-ex/0211035v1, 2002

The Discovery of the Neutrino



- 1934 - E. Fermi theory of β-decay
- 1934 - H. Bethe and R. Peierls understand that ν can invert the β-decay
- 1950's C. Cowan & F. Reines start the "Projet Poltergeist"
- delayed coincidence between e^+ annihilation and n radiative capture
- 1953 - First experiment at Hanford reactor not conclusive
- 1955 - Second experiment at Savannah River reactor



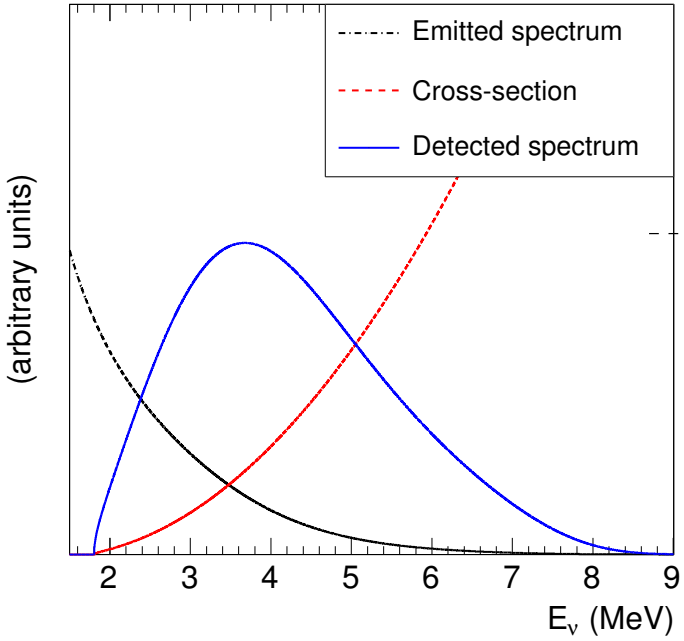


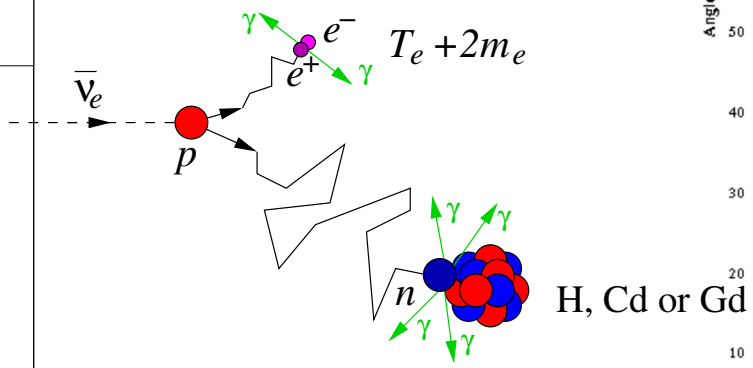
- 1956 - Discovery of the neutrino $\rightarrow$ telegram to Pauli

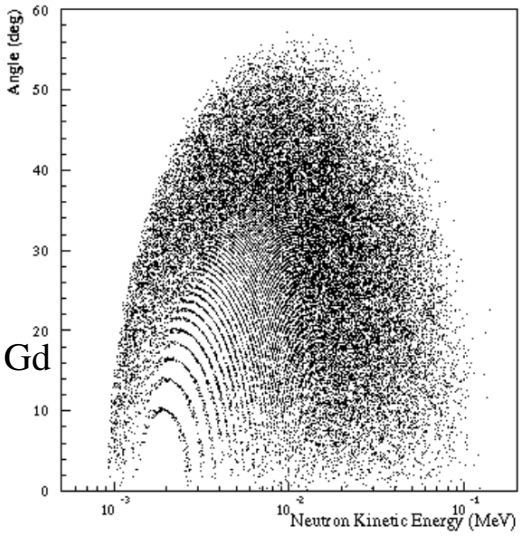
Inverse β-decay (IBD)

IBD still used for reactor and low energy $\overline{\nu}_e$ experiments:

- very low background thanks to the delayed coincidence
- the antineutrino is stopped and its energy is given by the energy of the positron: $E_{\overline{\nu}_e} = E_{e^+} + m_n - m_p$
- energy threshold: $E_{\overline{\nu}_e}^{min} = m_n - m_p + m_{e^+} = 1.8$ MeV
- incoming direction of the $\overline{\nu}_e$ with the forward boost of the n?





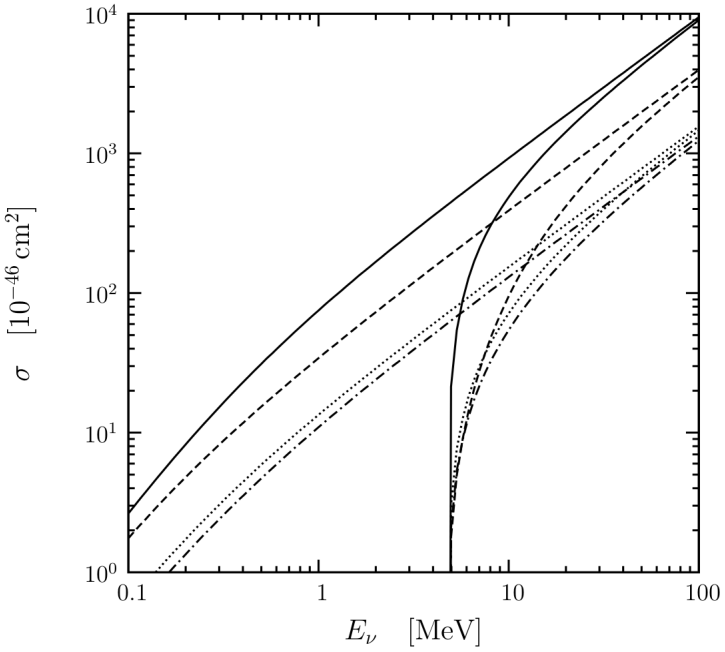


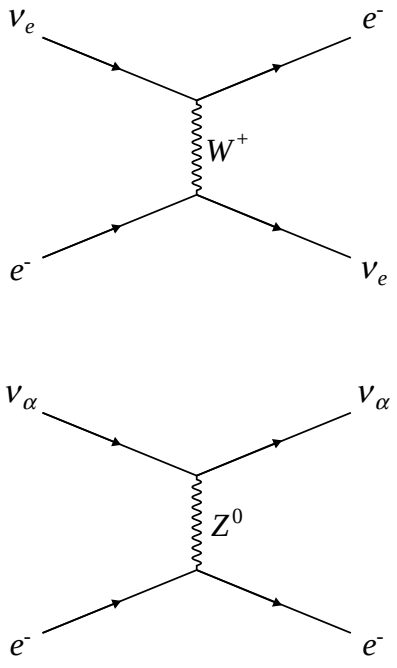
C. Bemporad, G. Gratta, P. Vogel, Rev. Mod. Phys. 74:297, 2002
M. Apollonio et al., Eur. Phys. J. C27:331-374, 2003

Neutrino-Electron Elastic Scattering (ES)

ES is used in most of the neutrino experiments (Solar, SN, atmospheric...): $\nu_\alpha\ e^- \to \nu_\alpha\ e^-$ or $\overline{\nu}_\alpha\ e^- \to \overline{\nu}_\alpha\ e^-$

- very well known cross sections increasing with E_ν
- sensitive to all the flavors of ν and $\overline{\nu}$
- $\sigma_{\nu_e} \simeq 2.4\ \sigma_{\overline{\nu}_e} \quad \sigma_{\nu_e} \simeq 6.2\ \sigma_{\nu_\mu \nu_\tau} \quad \sigma_{\nu_e} \simeq 7.1\ \sigma_{\overline{\nu}_\mu \overline{\nu}_\tau}$
- incoming ν direction is preserved in the e^- recoil: $E_e^2 \theta_e^2 < 2m_e$
- energy threshold due to detection technique





Legend: solid ν_e, dashed $\overline{\nu}_e$, dotted $\nu_{\mu,\tau}$, dash-dotted $\overline{\nu}_{\mu,\tau}$

C. Giunti & C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford, 2007

Neutrino-Nucleon Scattering

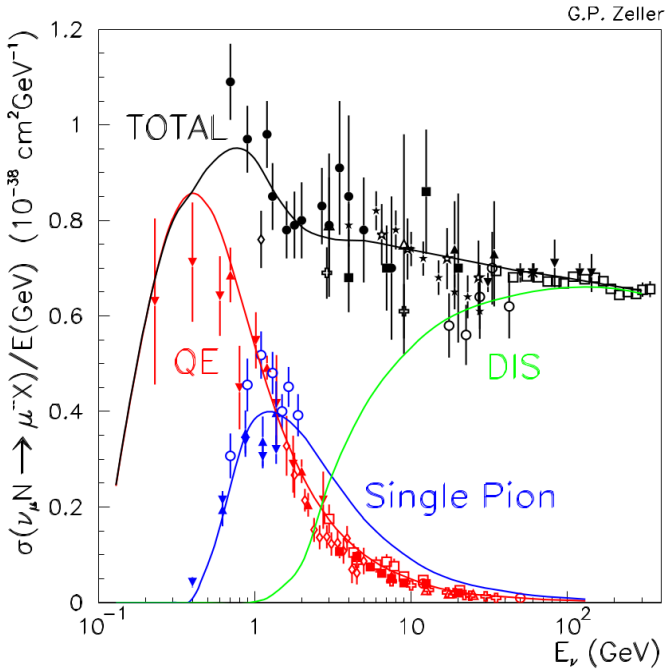
At higher neutrino energies the scattering occurs on nucleons:

$$\text{CC:} \quad \nu_\alpha \; N \to \alpha^- \; X \qquad \overline{\nu}_\alpha \; N \to \alpha^+ \; X$$
$$\text{NC:} \quad \nu_\alpha \; N \to \nu_\alpha \; X \qquad \overline{\nu}_\alpha \; N \to \overline{\nu}_\alpha \; X$$

$$\alpha = e, \mu, \tau \quad N = p, n \quad X = \text{hadrons}$$

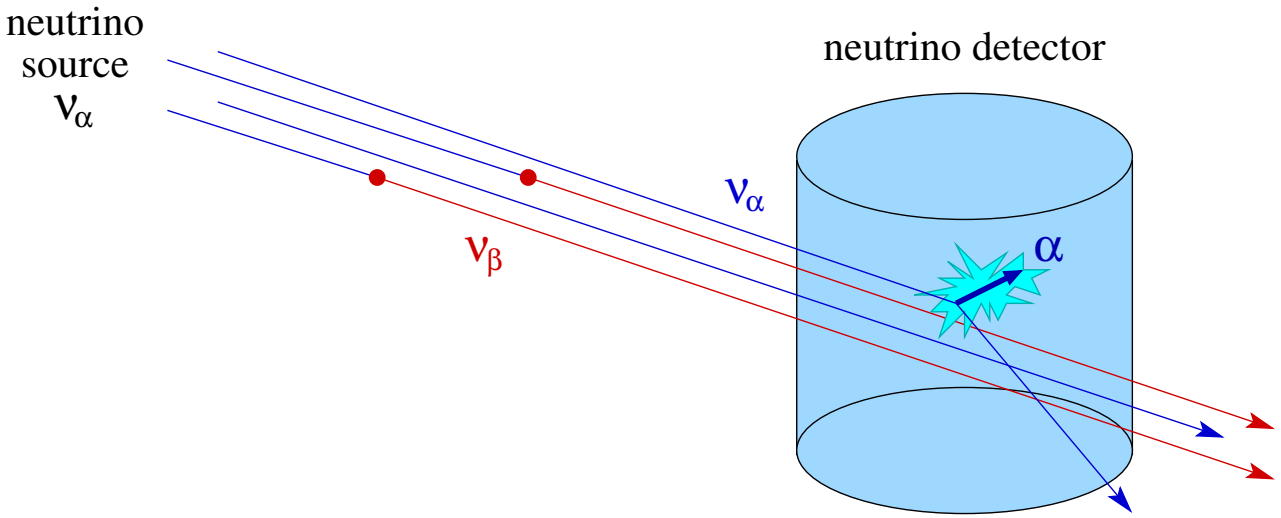
- In elastic or Quasi-Elastic (QE) scattering $X = p, n$
- Nuclear Resonance Production creates excited states $X = N^*$ or $\Delta \to p \; \pi^0 \; / \; n \; \pi^+$
- In Deep Inelastic Scattering (DIS) the nucleon is broken

Correct knowledge of the differrent σ but improvements are coming



Neutrino Mixing & Oscillations

- Neutrino oscillations where though to solve the long-standing missing solar (R. Davis ∼1970) or atmospheric neutrinos (SK ∼2000):
  - experiments are generally sensitive to only one neutrino flavor
  - if a neutrino flavor change during its propagation from the source to the detector: the neutrino won't be detected



- Oscillations already observed in particle physics: $K^0 - \overline{K}^0$
  - occur when flavor eigenstates are not mass eigenstates
- **So neutrinos are massive particles!**
- In the late 1950s B. Pontecorvo started to study neutrino oscillations

Two Flavors Neutrino Oscillations

- Because of the neutrino mass splitting Δm_{ji}, the fixed neutrino energy E and baseline L: most of the experiments are only sensitive to the two flavor neutrino mixing (or an effective mixing)
- Much simpler to compute and to illustrate the oscillations
- Two flavors neutrino mixing parametrized by:
  - a single squared-mass difference: $\Delta m^2 = \Delta m^2_{ji} = m_j^2 - m_i^2$
  - a single mixing angle: $\theta \in [0, \pi/2]$

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\ \theta & \sin\ \theta \\ -\sin\ \theta & \cos\ \theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

- From this matrix we write the transition probability ($\alpha \neq \beta$):

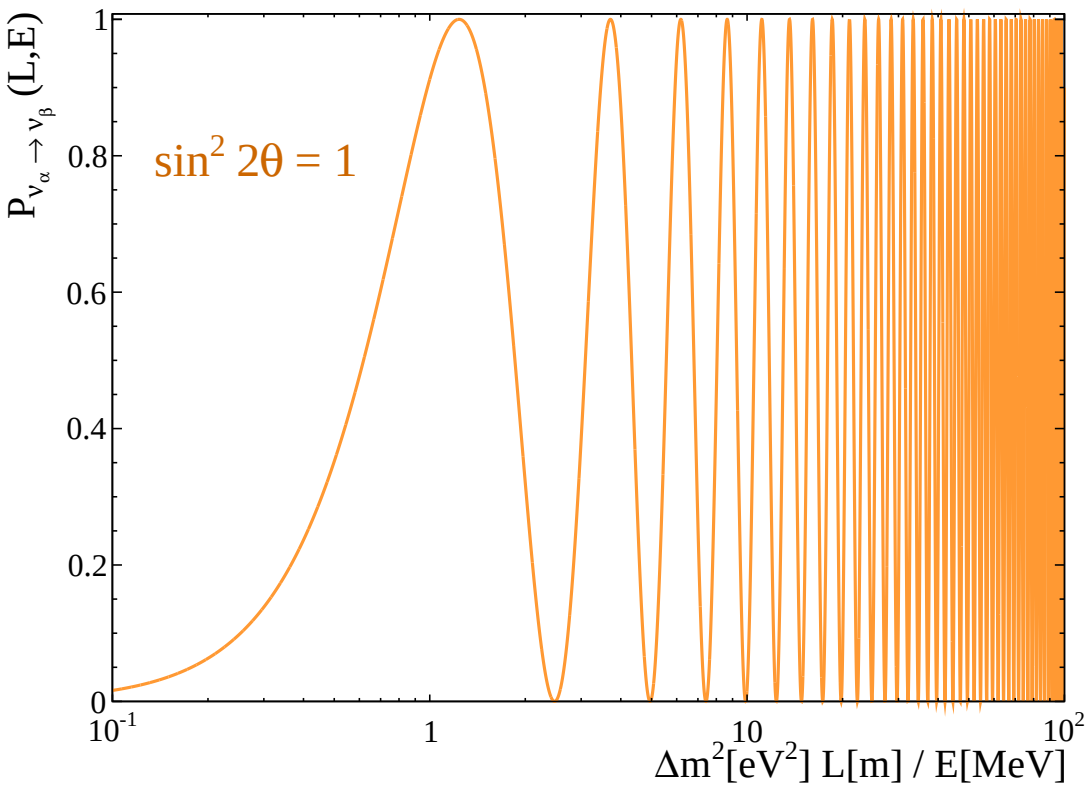
$$\begin{aligned} P_{\nu_\alpha \to \nu_\beta}(L, E) &= \frac{1}{2} \sin^2 2\theta \left[1 - \cos\left(\frac{\Delta m^2 L}{2E} \right) \right] \\ &= \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \end{aligned}$$

- The survival probability ($\alpha = \alpha$) is given by: $1 - P_{\nu_\alpha \to \nu_\beta}(L, E)$

Two Flavors Neutrino Oscillations Probability

- For experiments it is convenient to use:

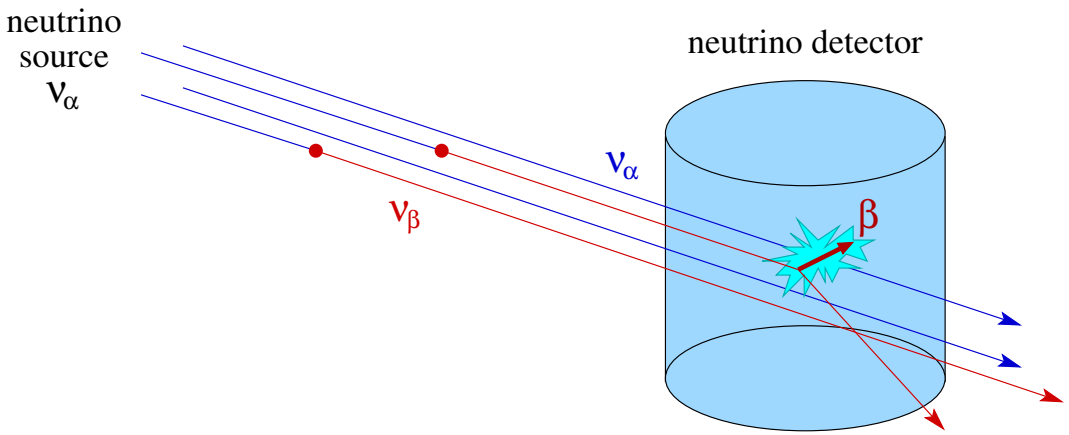
$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\theta \sin^2 \left(1.27 \, \frac{\Delta m^2 \, [eV^2] \; L \, [m]}{E \, [MeV]}\right)$$

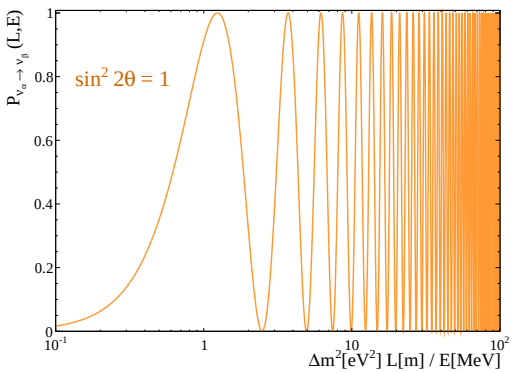


- The peak position gives the squared-mass difference Δm^2
- The peak amplitude gives the mixing angle θ

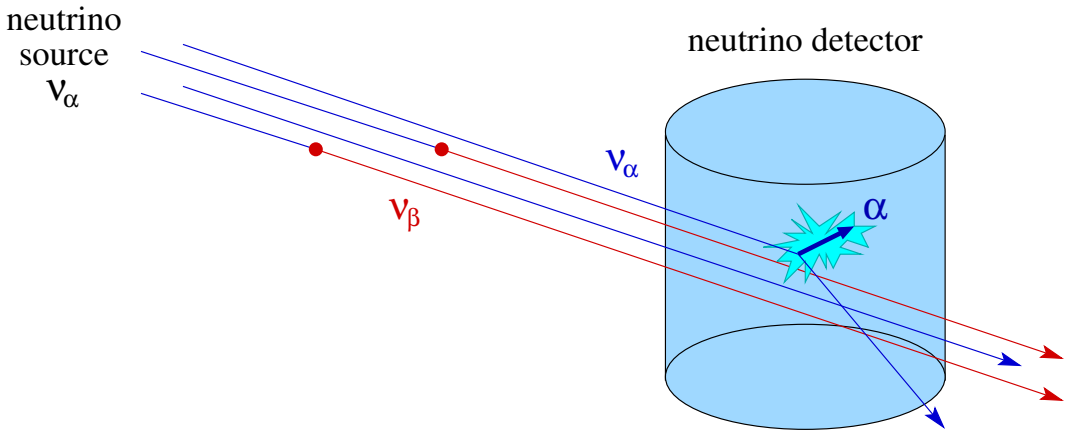
Two Kind of Oscillation Experiments

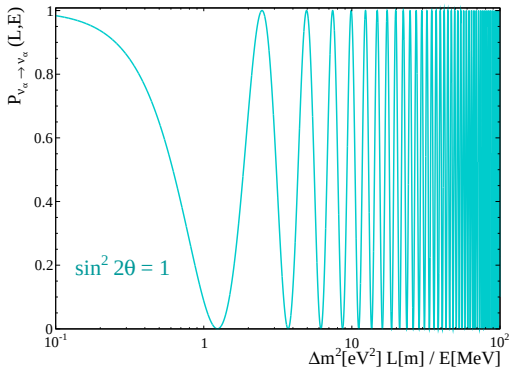
- Appearance experiment: transition probability $P_{\nu_\alpha \to \nu_\beta}(L, E)$





- Disappearance experiment: survival probability $P_{\nu_\alpha \to \nu_\alpha}(L, E)$





Three Flavors Neutrino Mixing

3×3 flavors neutrino mixing matrix *PMNS*
(similar to *CKM* mixing matrix for quarks):

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}\ e^{-i\delta} \\ -c_{23}s_{12} - s_{13}c_{12}s_{23}\ e^{+i\delta} & c_{23}c_{12} - s_{13}s_{12}s_{23}\ e^{+i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{12}c_{23}\ e^{+i\delta} & -s_{23}c_{12} - s_{13}s_{12}c_{23}\ e^{+i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Pontecorvo, Maki, Nakagawa & Sakata

Three flavors neutrino mixing parametrized by:

- 2 squared-mass difference: $\Delta m^2_{32},\ \Delta m^2_{21}$
- 3 mixing angles: $\theta_{12},\ \theta_{23},\ \theta_{13}$
- 1 CP violation phase: δ
- 2 Majorana phases: $\eta_1,\ \eta_2$?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & & s_{13}\ e^{-i\delta} \\ & 1 & \\ -s_{13}\ e^{i\delta} & & c_{13} \end{pmatrix}}_{\text{reactor/accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}}_{\text{solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

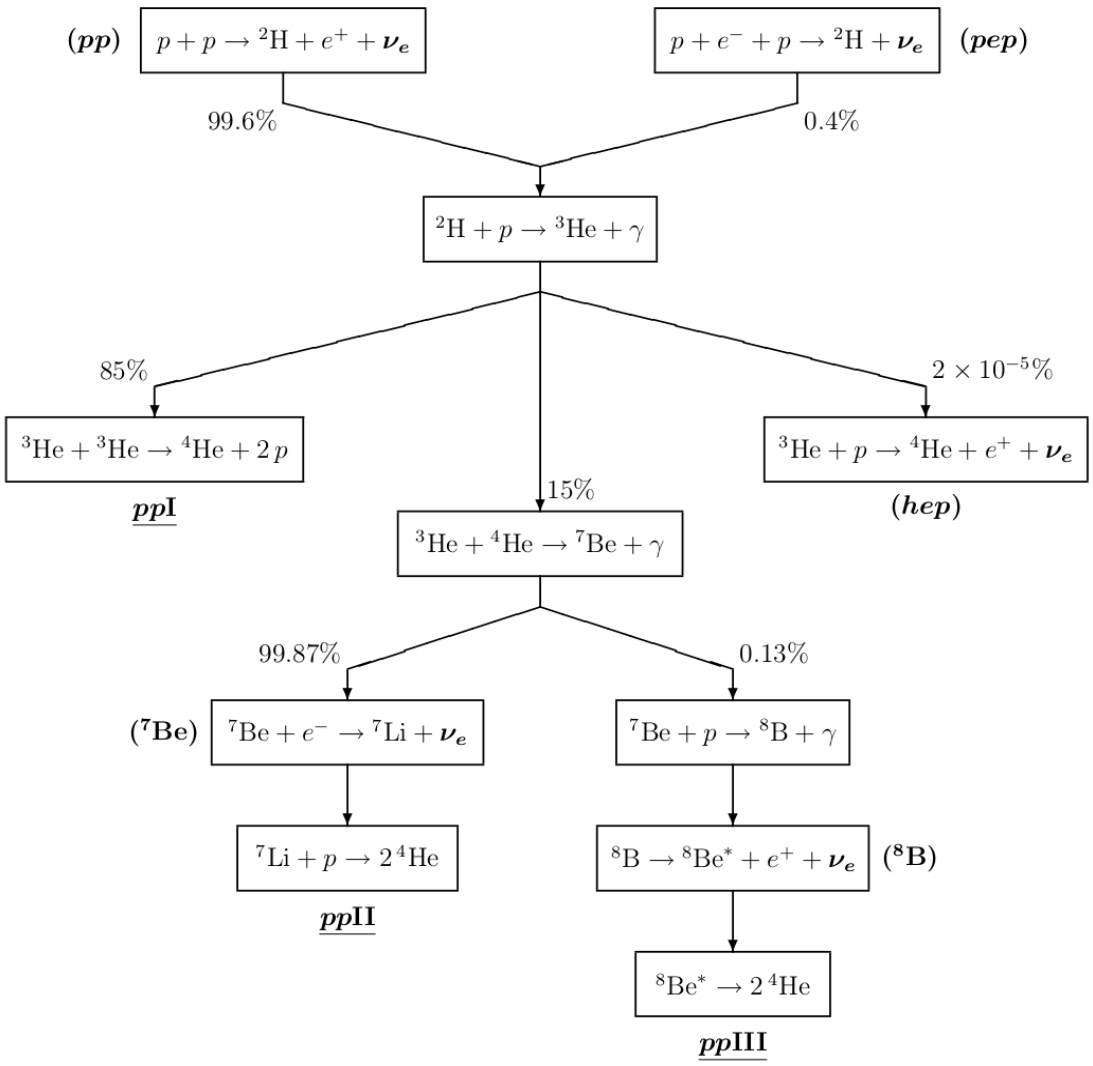
Solar Neutrinos

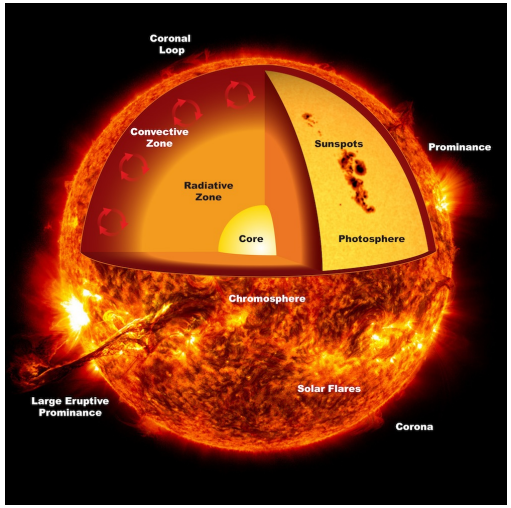
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\, e^{-i\delta} \\ & 1 & \\ -s_{13}\, e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

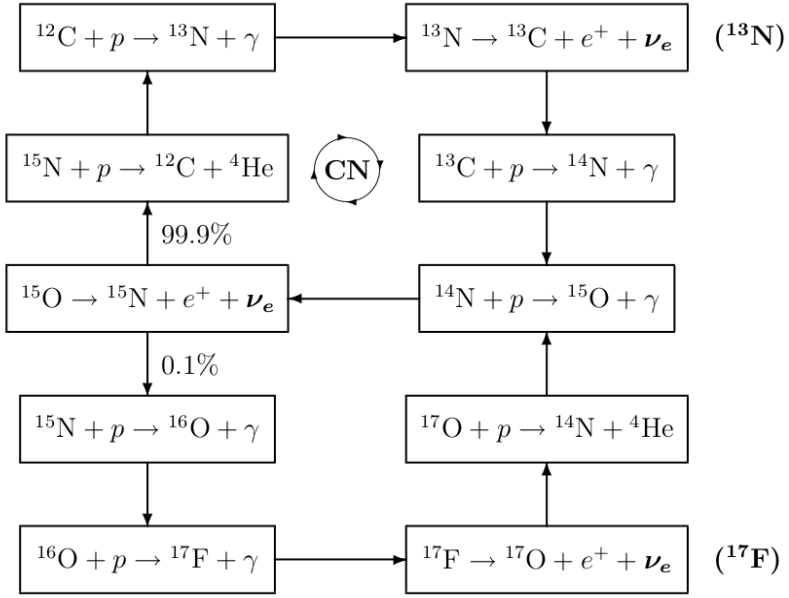
atmospheric reactor/accelerator solar

Solar Neutrinos Production

Solar neutrinos ν_e are produced in the core by nuclear fusion and neutrinos in the pp chain and the CNO cycles







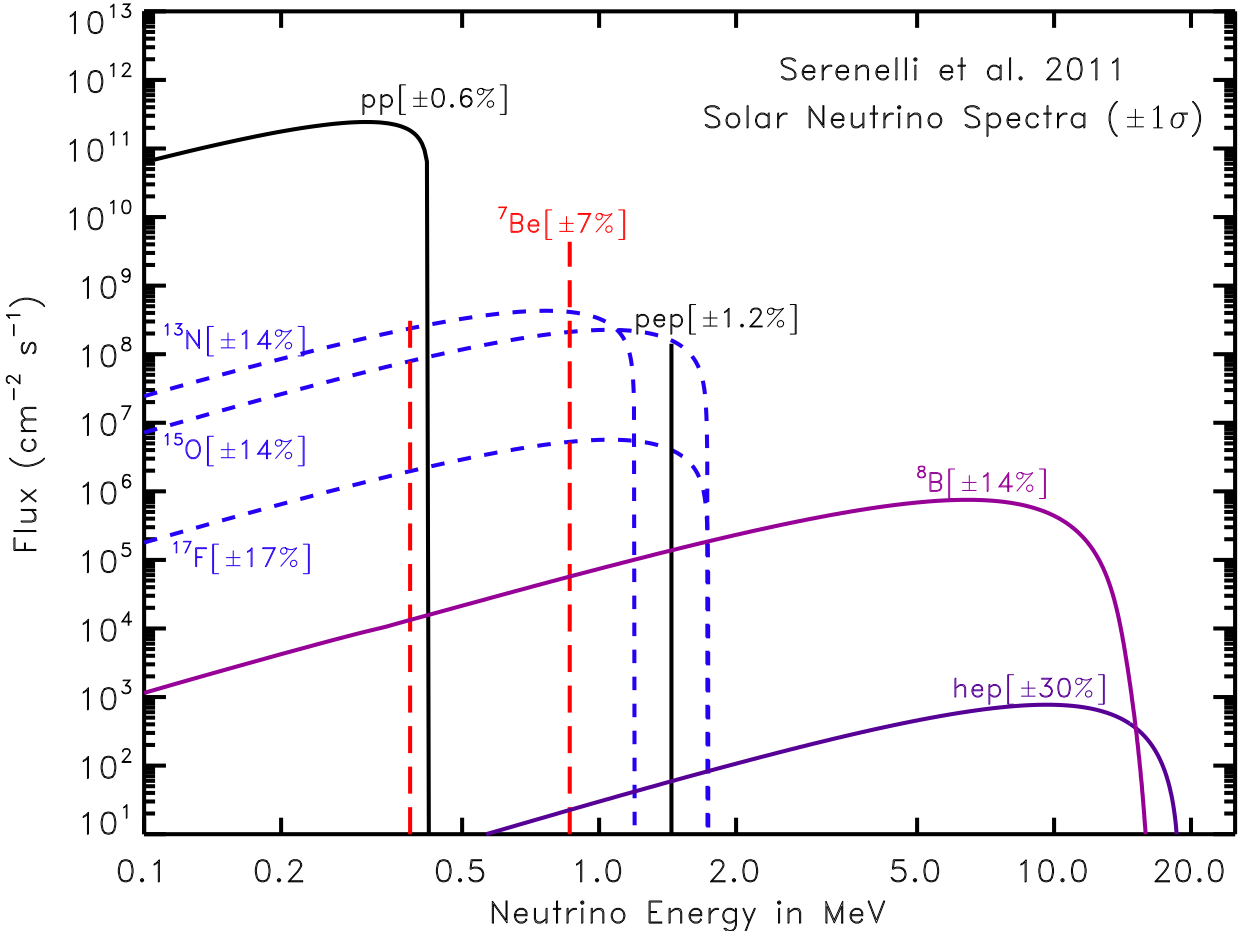
C. Giunti & C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford, 2007

Solar Neutrinos Spectrum

Predicted by J. Bahcall from the 1960's

^{7}Be and pep neutrinos have characteristic energy

pp, CNO, ^{8}B and hep have a continuous spectrum

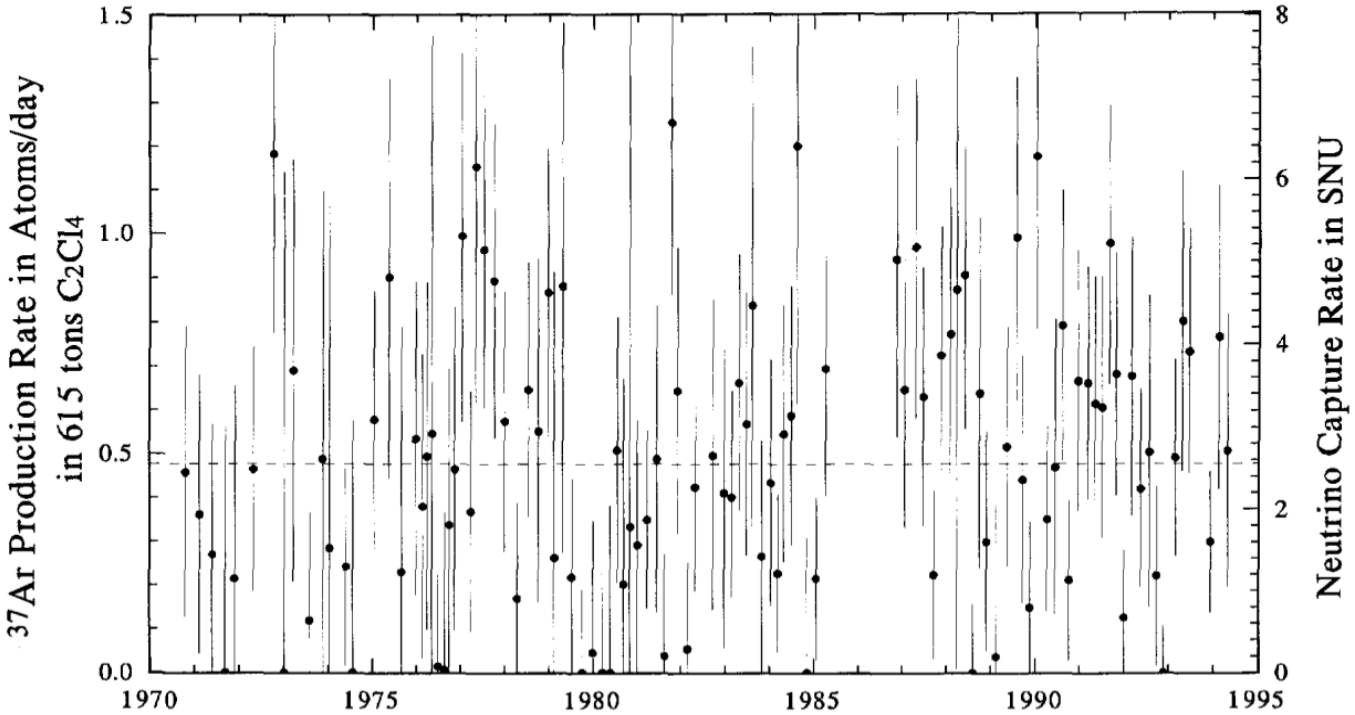


First Detection of the Solar Neutrinos

R. Davis built Chlorine experiment at Homestake (USA)

400 000 L of C_2Cl_4 from 1970 to 1994

$\nu_e \; {}^{37}_{17}\mathrm{Cl} \rightarrow e^- \; {}^{37}_{18}\mathrm{Ar}$ (threshold 814 keV)

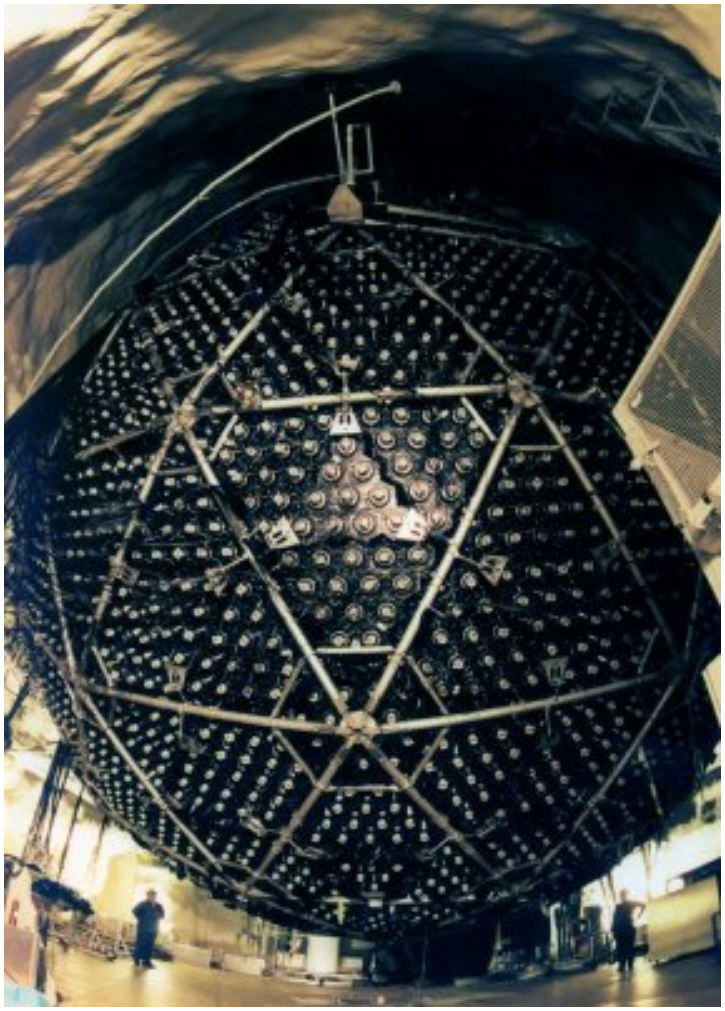


Only ∼30% of Bahcall's solar neutrino flux prediction

(Solar Neutrino Unit: 1 SNU = 10^{-36} capture/target atom/s)

The Sudbury Neutrino Observatory (SNO)

1 kt heavy water (D_2O) 12 m spherical Cherenkov detector at Creighton mine in Sudbury (Canada) under 6 000 m.w.e.



SNO Neutrino Detection

Heavy water (D_2O) allows neutrino detection through 3 reactions:

CC:	$\nu_e\ d \rightarrow p\ p\ e^-$	$E_\nu > 1.4$ MeV
NC:	$\nu_\alpha\ d \rightarrow p\ n\ \nu_\alpha$	$E_\nu > 2.2$ MeV
ES:	$\nu_\alpha\ e^- \rightarrow e^-\ \nu_\alpha$	$E_\nu > 5.5$ MeV

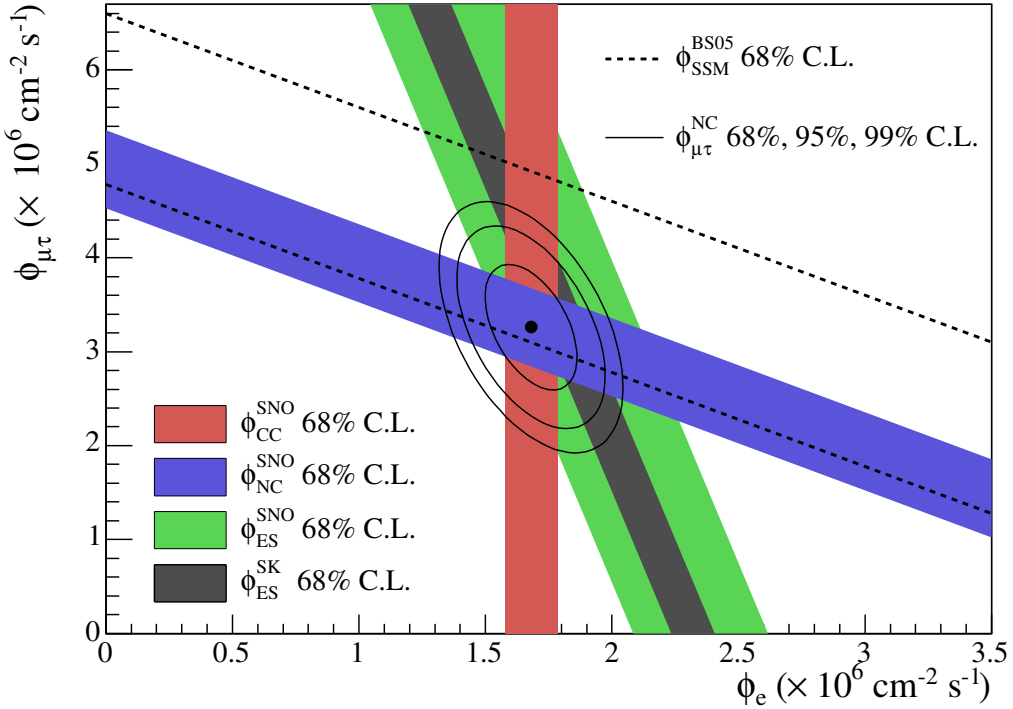
3 different phases for the n detection:

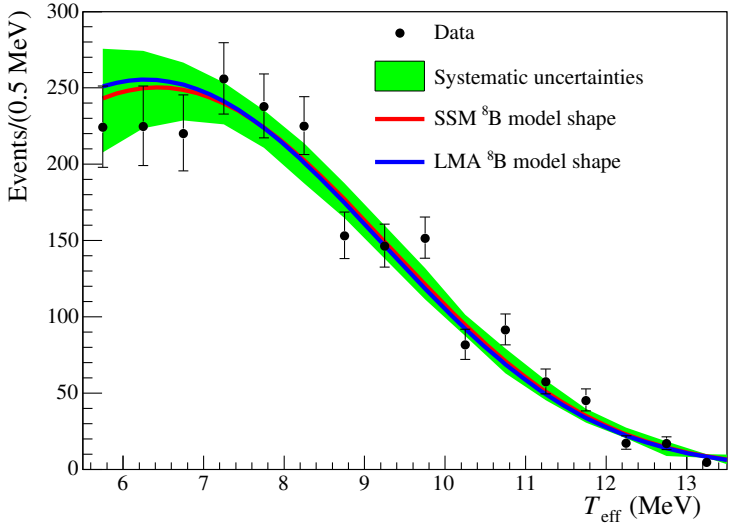
- 1999-2001: $n\ d \rightarrow^3$ H γ (6.3 MeV)
- 2001-2003: $n\ ^{35}$Cl $\rightarrow^{36}$ Cl γ (8.6 MeV)
- 2004-2006: ^{3}H proportional counters

SNO Main Result

Sensitive to all neutrino flavors and using 3 interactions SNO reconstructed the full solar neutrino flux and solved the 30 y problem

$$\phi_{ES} = 2.35 \pm 0.22 \pm 0.15 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$
$$\phi_{CC} = 1.68 \pm 0.06 \,^{+0.08}_{-0.09} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$
$$\phi_{NC} = 4.94 \pm 0.21 \,^{+0.38}_{-0.34} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$





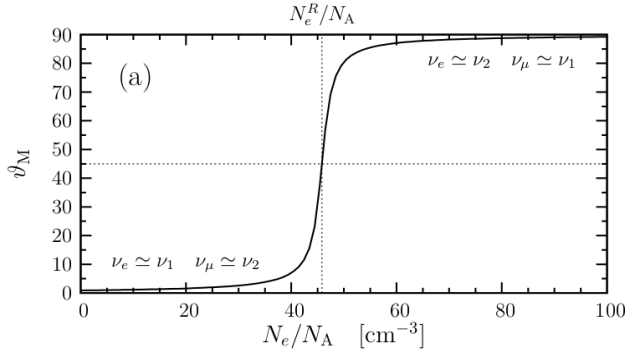
The Solar neutrino problem is due to $\nu_e \rightarrow \nu_{\mu\tau}$ oscillations

Phys. Rev. C72:055502, 2005

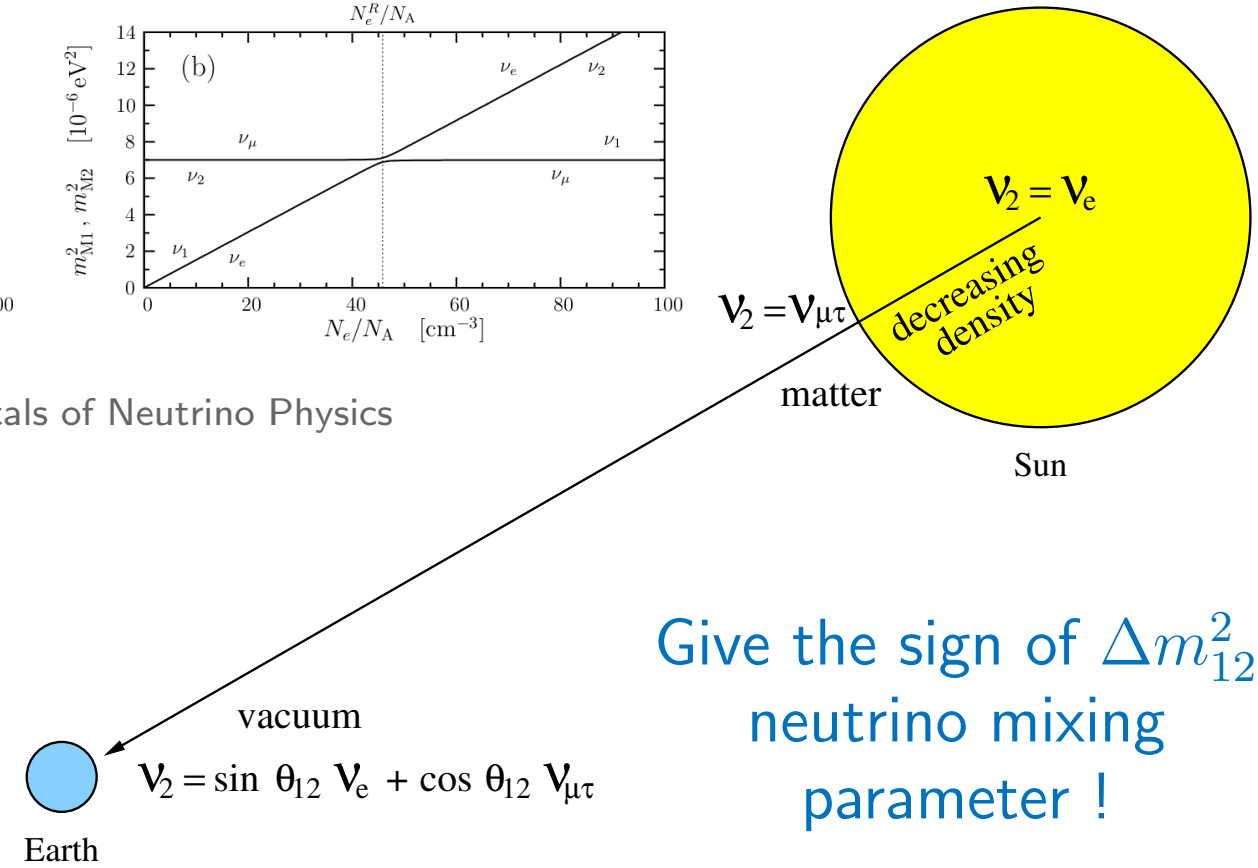
The MSW Effect

S. Mikheyev, A. Smirnov and L. Wolfenstein effect

$$\mathcal{H} = \frac{\Delta m^2_{21}}{4E}\begin{pmatrix} -\cos\ 2\theta_{12} & \sin\ 2\theta_{12} \\ \sin\ 2\theta_{12} & \cos\ 2\theta_{12} \end{pmatrix} + \sqrt{2}\,G_F N_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$



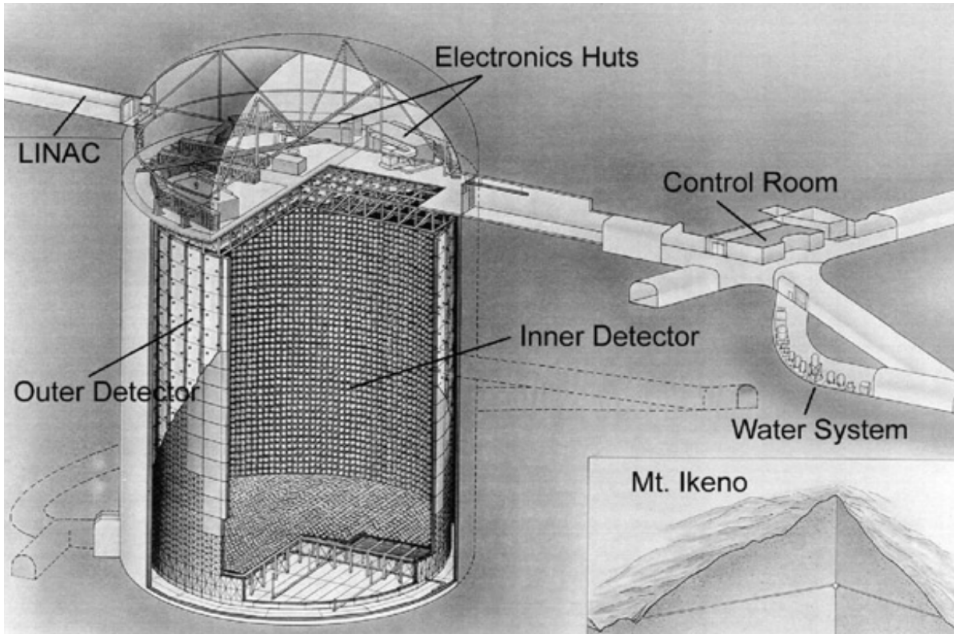
C. Giunti & C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford, 2007

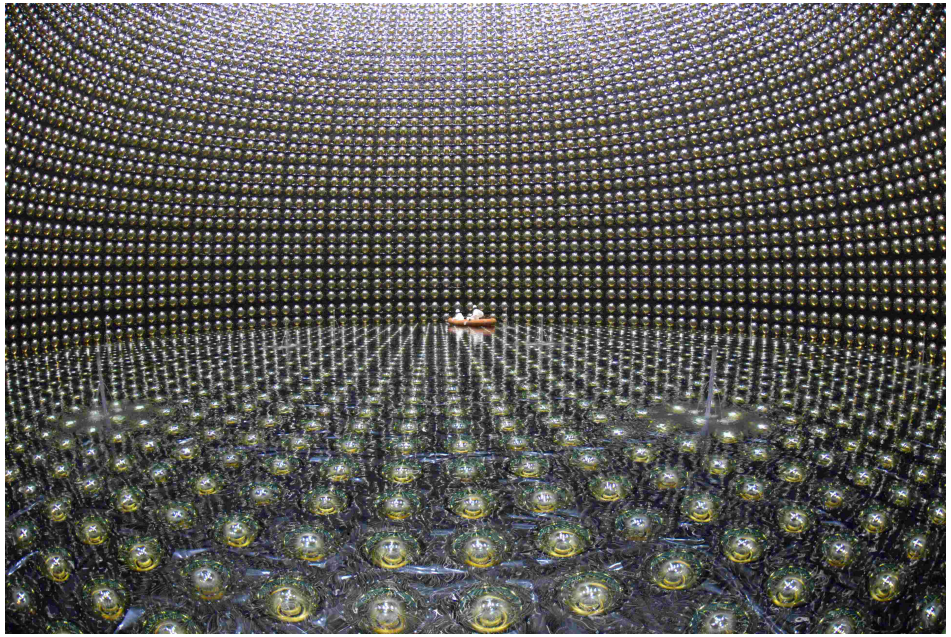


Give the sign of Δm^2_{12} neutrino mixing parameter !

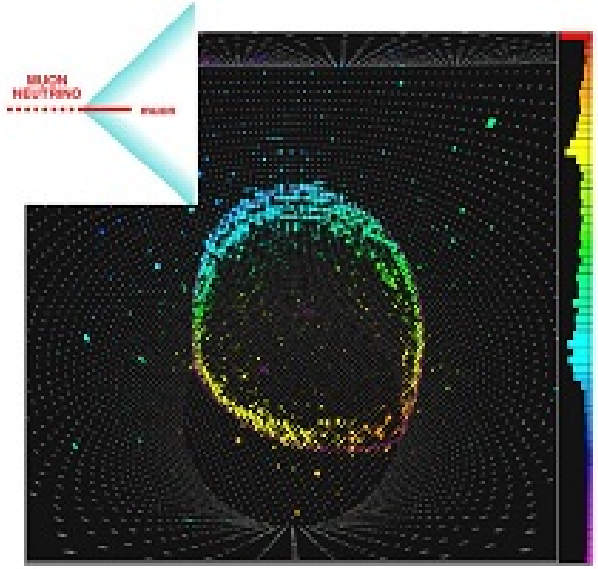
Super-Kamiokande Experiment

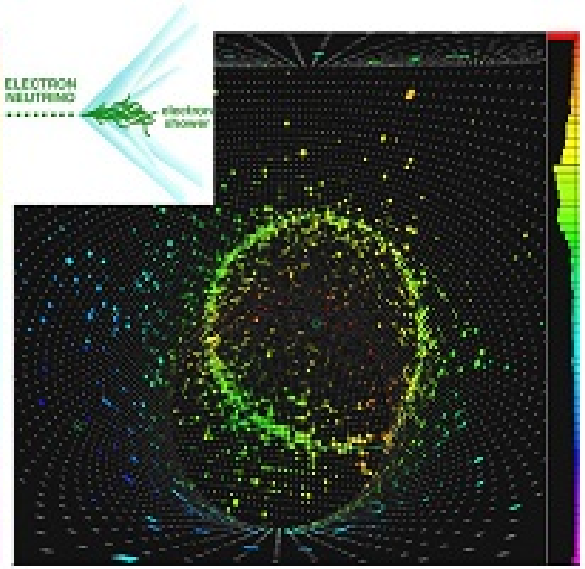
50 kt water Cherenkov - Kamioka in Japan - ∼13 000 PMTs 20”





$\nu_\mu \; N \to \mu \; X$

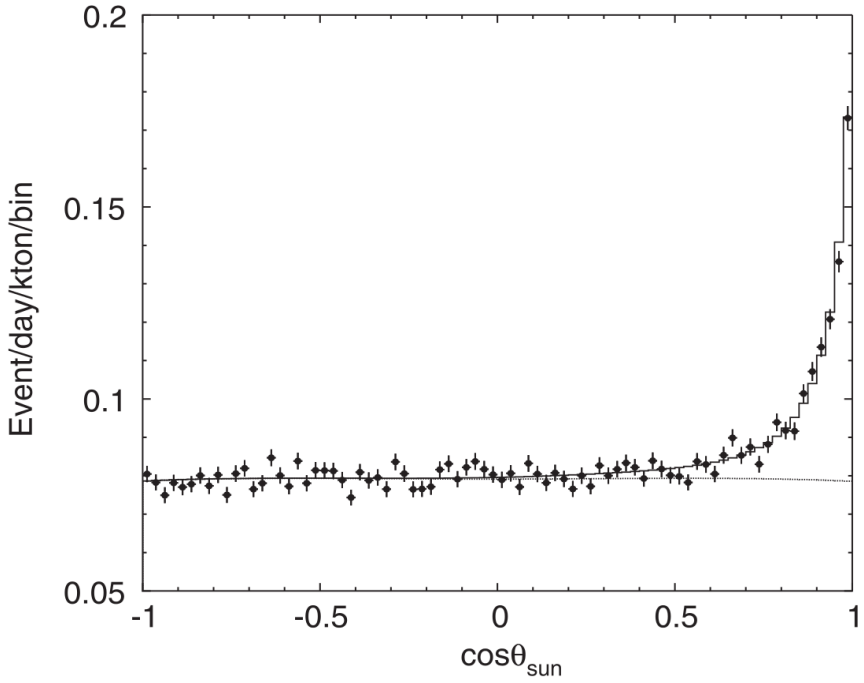


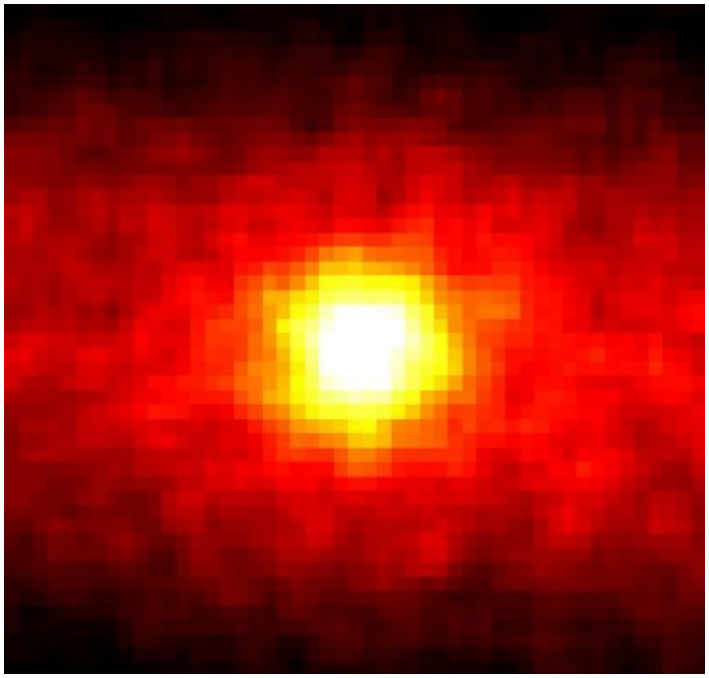


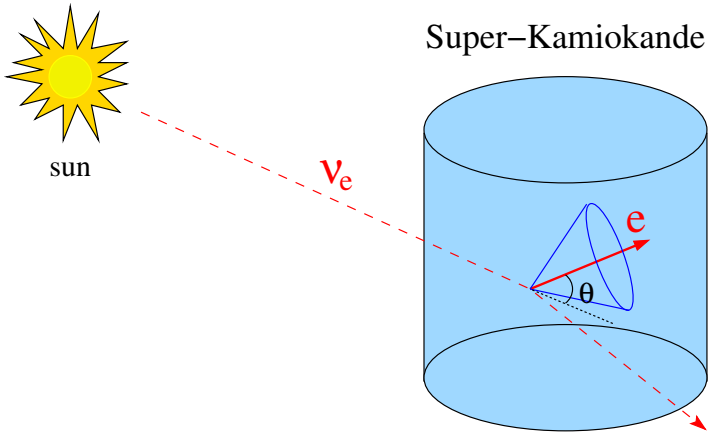
$\nu_\alpha \; e^- \to e^- \; \nu_\alpha$

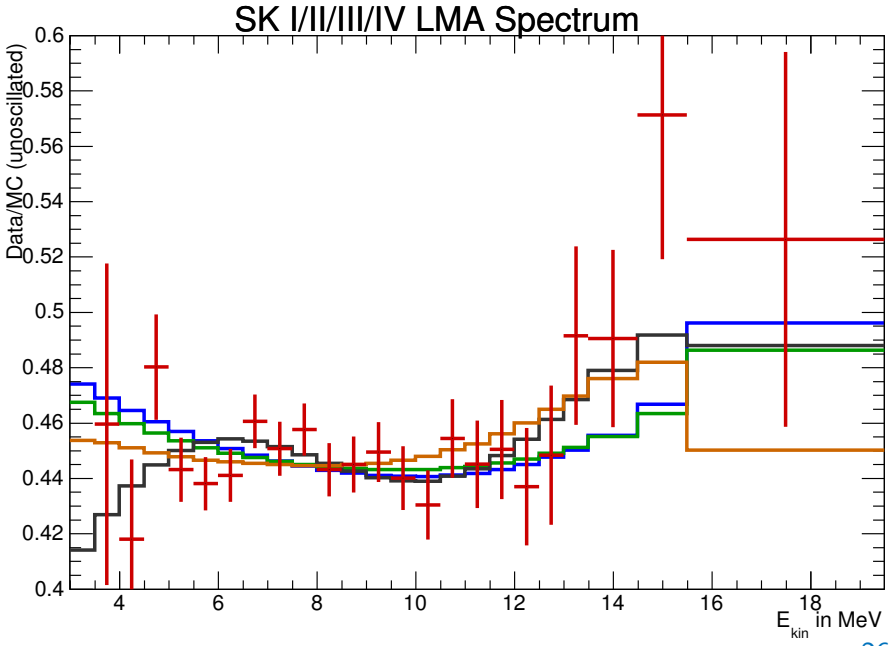
$\nu_e \; N \to e^- \; X$

Super-Kamiokande Solar Neutrinos





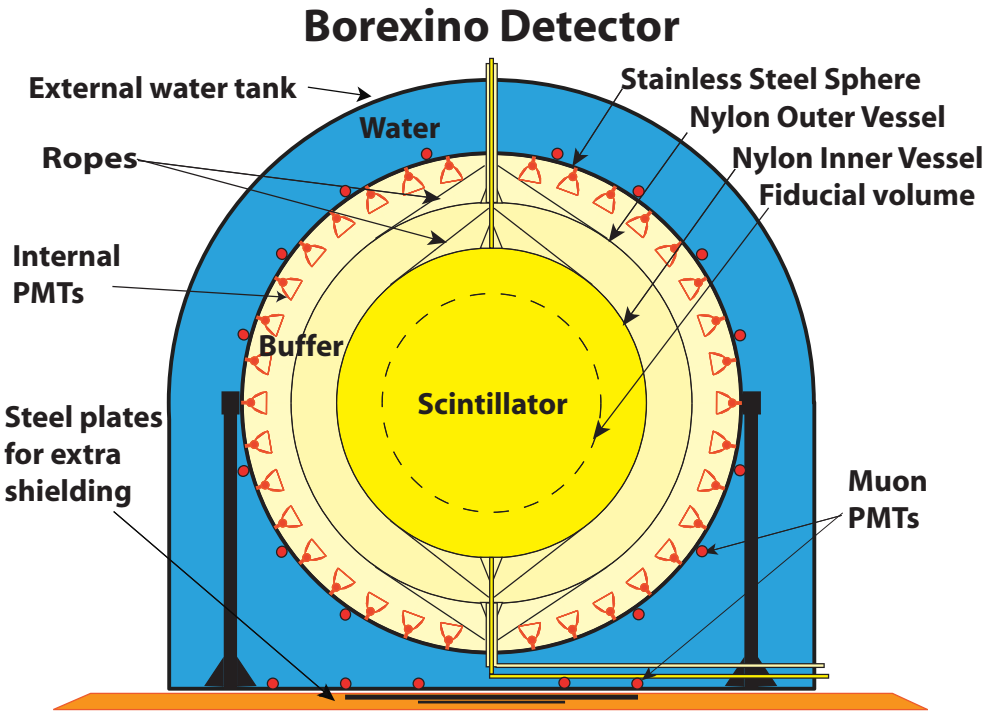


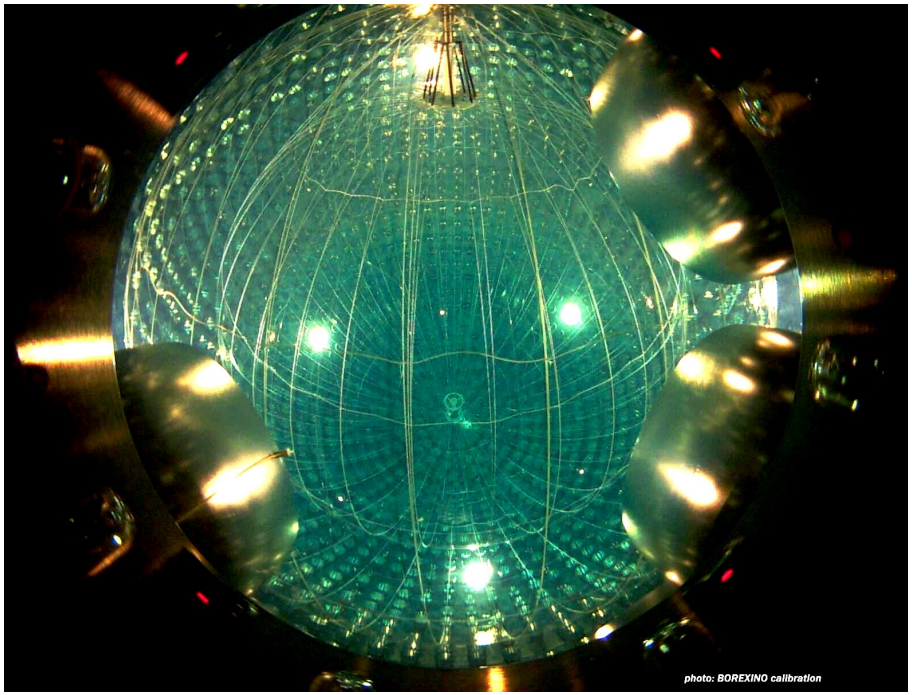


Phys. Rev. D 78, 032002, 2008 & arXiv:1606.07538

Borexino

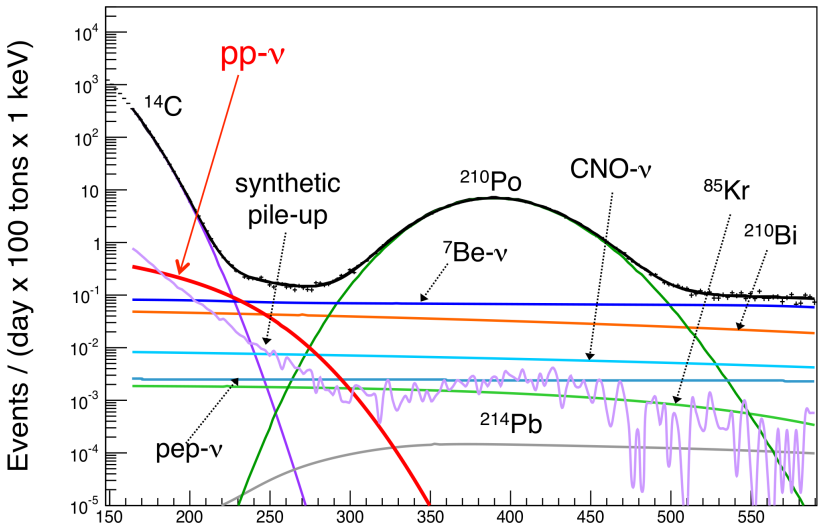
300 t liquid scintillator target at LNGS - ∼2200 PMTs - 500 PE/MeV
$\nu_\alpha\ e^- \rightarrow \nu_\alpha\ e^-$ detection is identical to β and γ backgrounds
$\rightarrow$ extremly low background detector





Borexino Solar Neutrinos Results

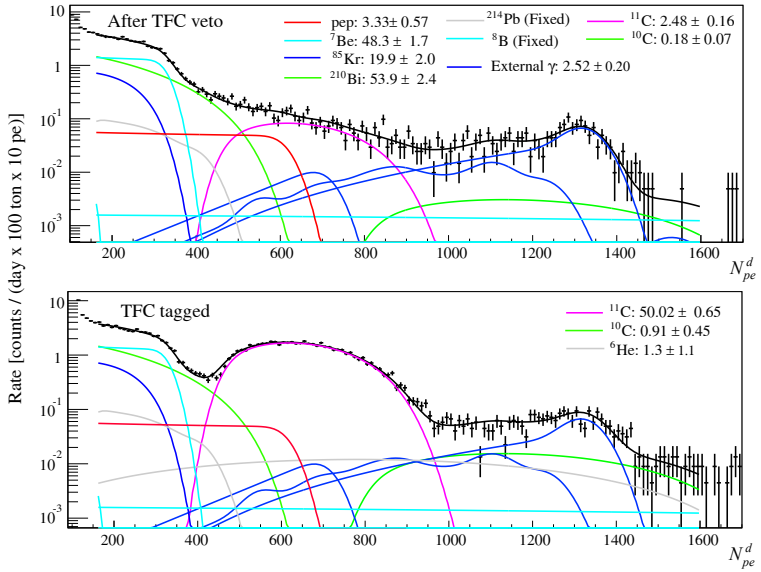
Very low background and low threshold experiment ~150 keV
First detections of ^{7}Be, pep and pp neutrinos - limits on CNO

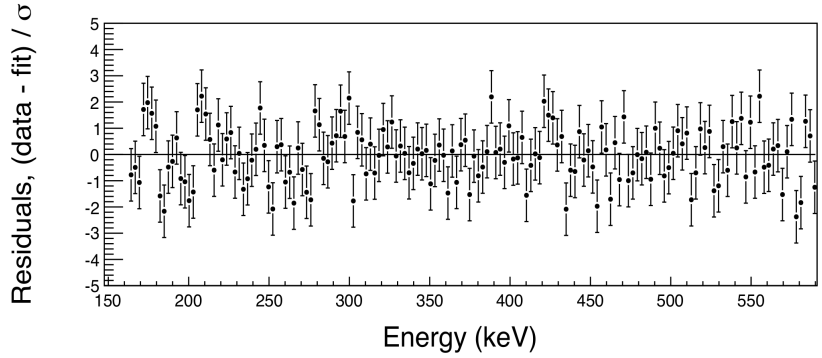


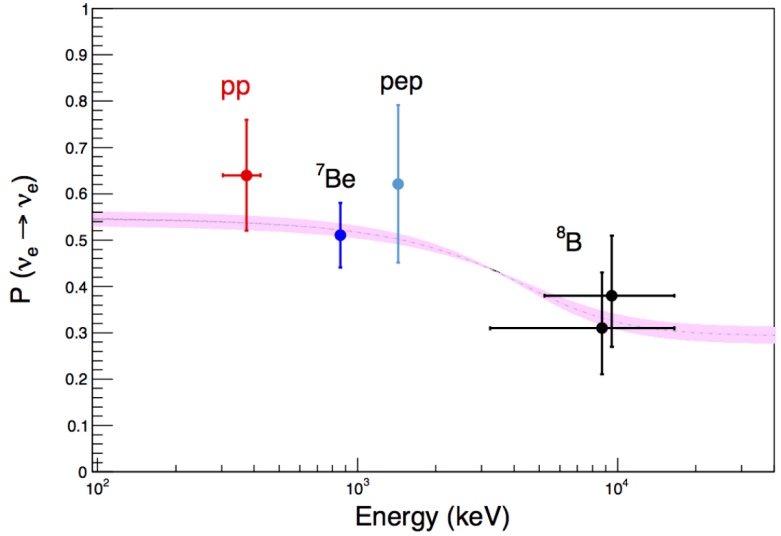
χ^2/d.o.f = 172.3/147

- pp ν: 144 ± 13 (free)
- ^{7}Be ν: 46.2 ± 2.1 (constrained)
- pep ν: 2.8 (fixed)
- CNO ν: 5.36 (fixed)
- ^{214}Pb: 0.06 (fixed)
- ^{210}Po: 583 ± 2 (free)
- ^{14}C: 39.8 ± 0.9 (constrained)
- Pile-up: 321 ± 7 (constrained)
- ^{210}Bi: 27 ± 8 (free)
- ^{85}Kr: 1 ± 9 (free)

Fit range: 165-590 keV





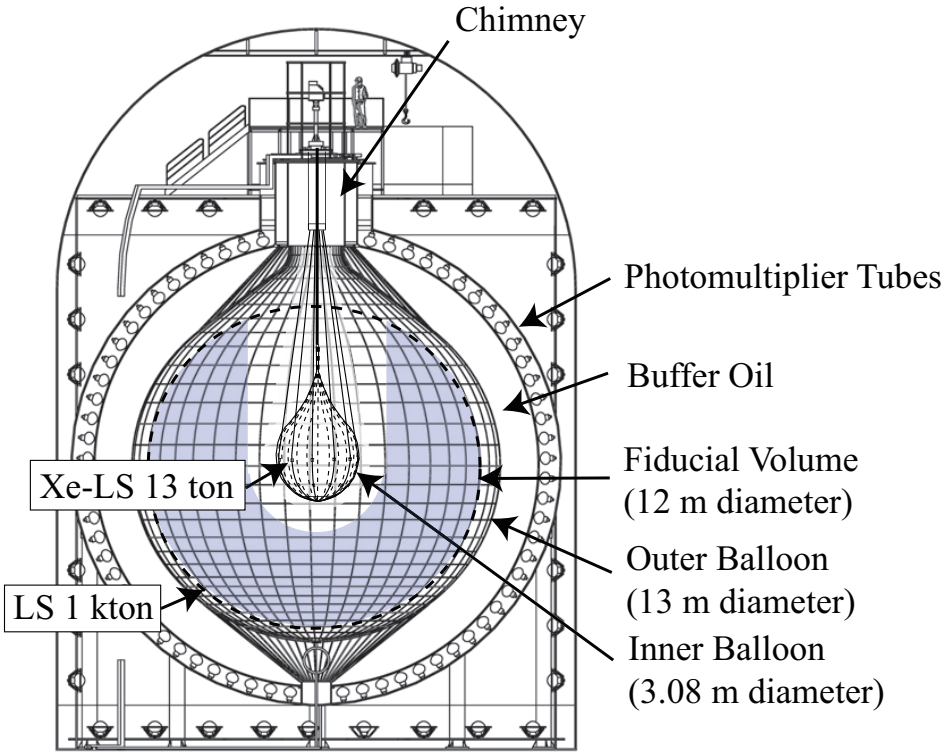


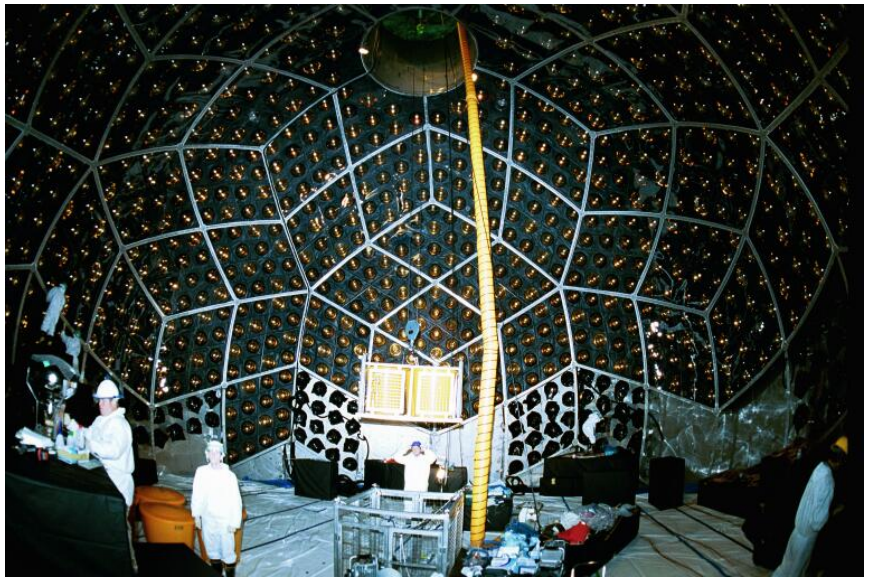
arXiv:1308.0443 & arXiv:1507.02432

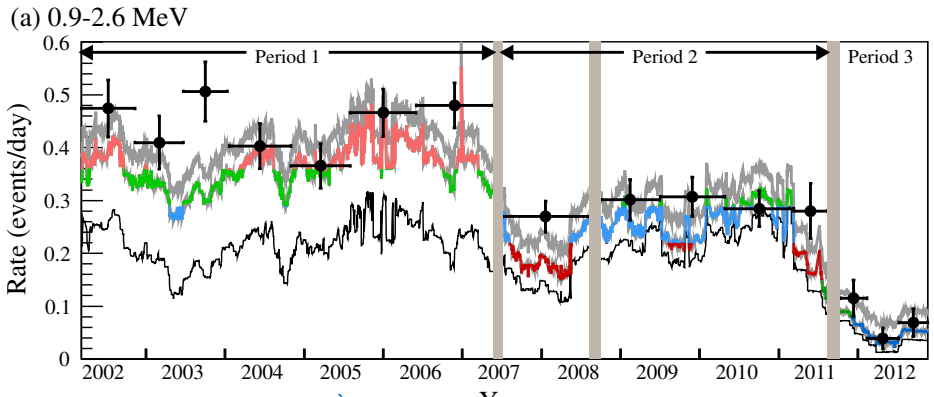
KamLAND

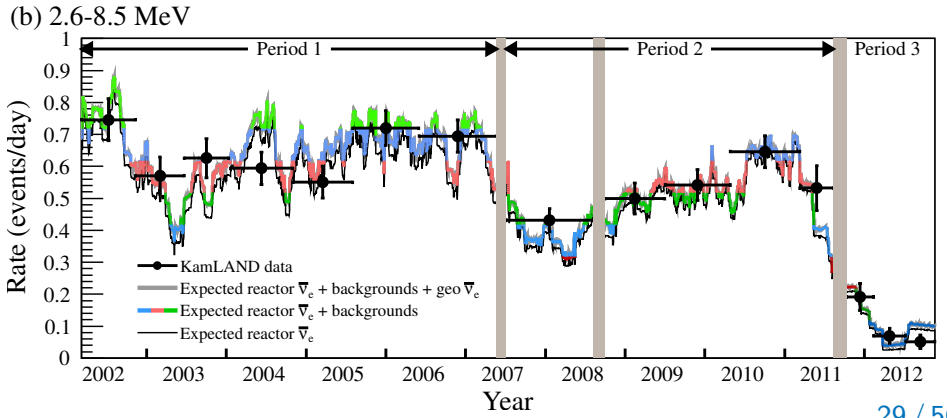
Antineutrino reactor experiment sensitive to solar oscillation parameters

$\overline{\nu}_e$: $\langle E_\nu \rangle \sim$ 3 MeV - $L \sim \langle 180 \rangle$ km





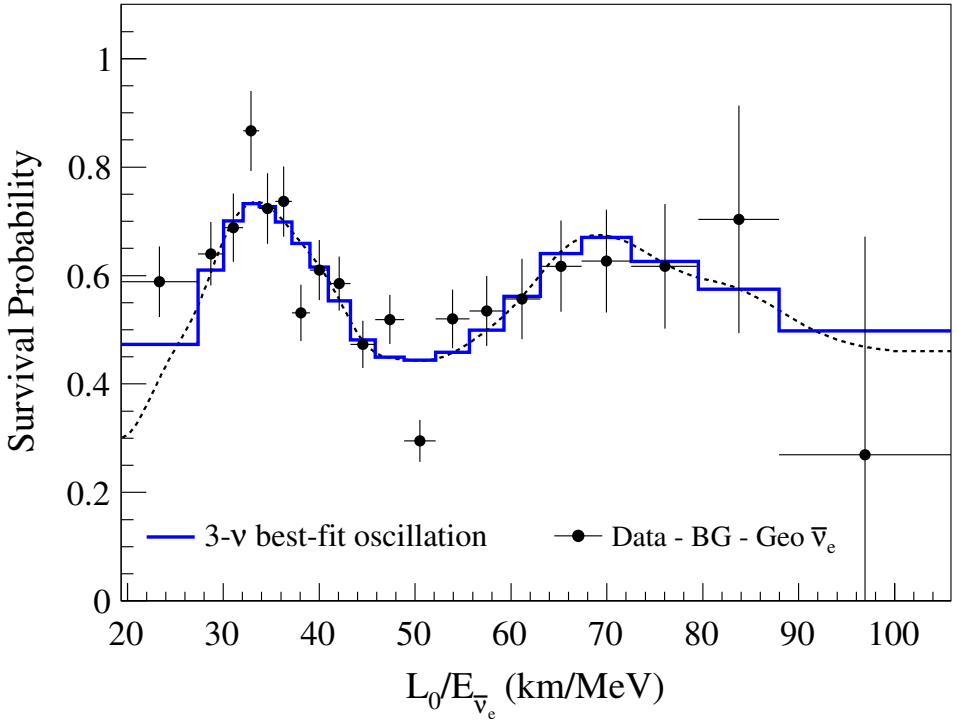


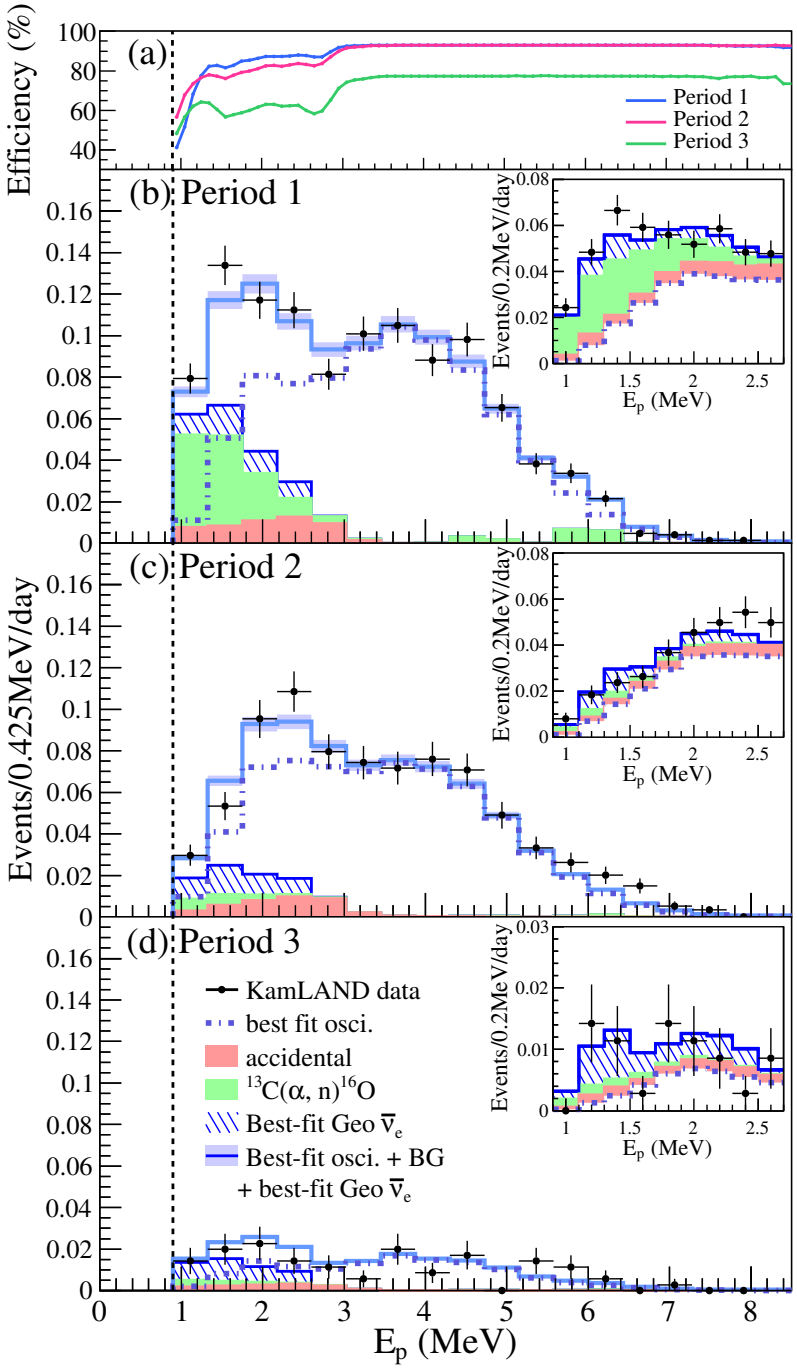


KamLAND Solar Results

Reactor antineutrinos oscillation disappearance spectrum: $\overline{\nu}_e \rightarrow \overline{\nu}_\alpha$

$$P_{ee}^{3\nu} = \cos^4\theta_{13} \times [1 - \sin^2 2\theta_{12\,M} \sin^2\left(\frac{\Delta m_{21}{}^2_M L}{4E_\nu}\right)] + \sin^4\theta_{13}$$

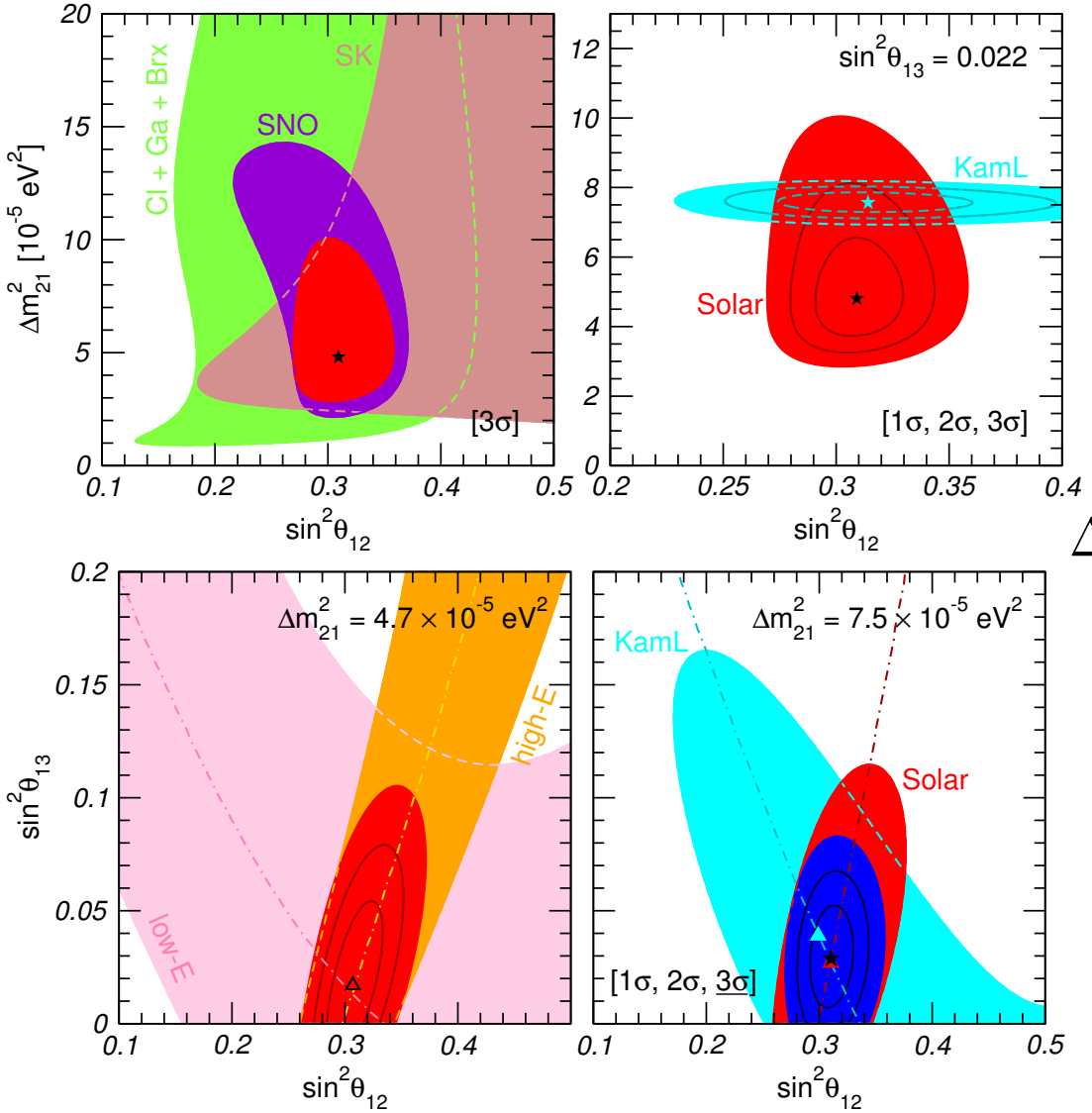




Phys. Rev. D83:052002, 2011 & arXiv:1303.4667

Solar Neutrinos Global Fit

$\theta_{13} \neq 0$ reduced the solar and KamLAND θ_{12} tension
However a small tension remain in Δm_{21}



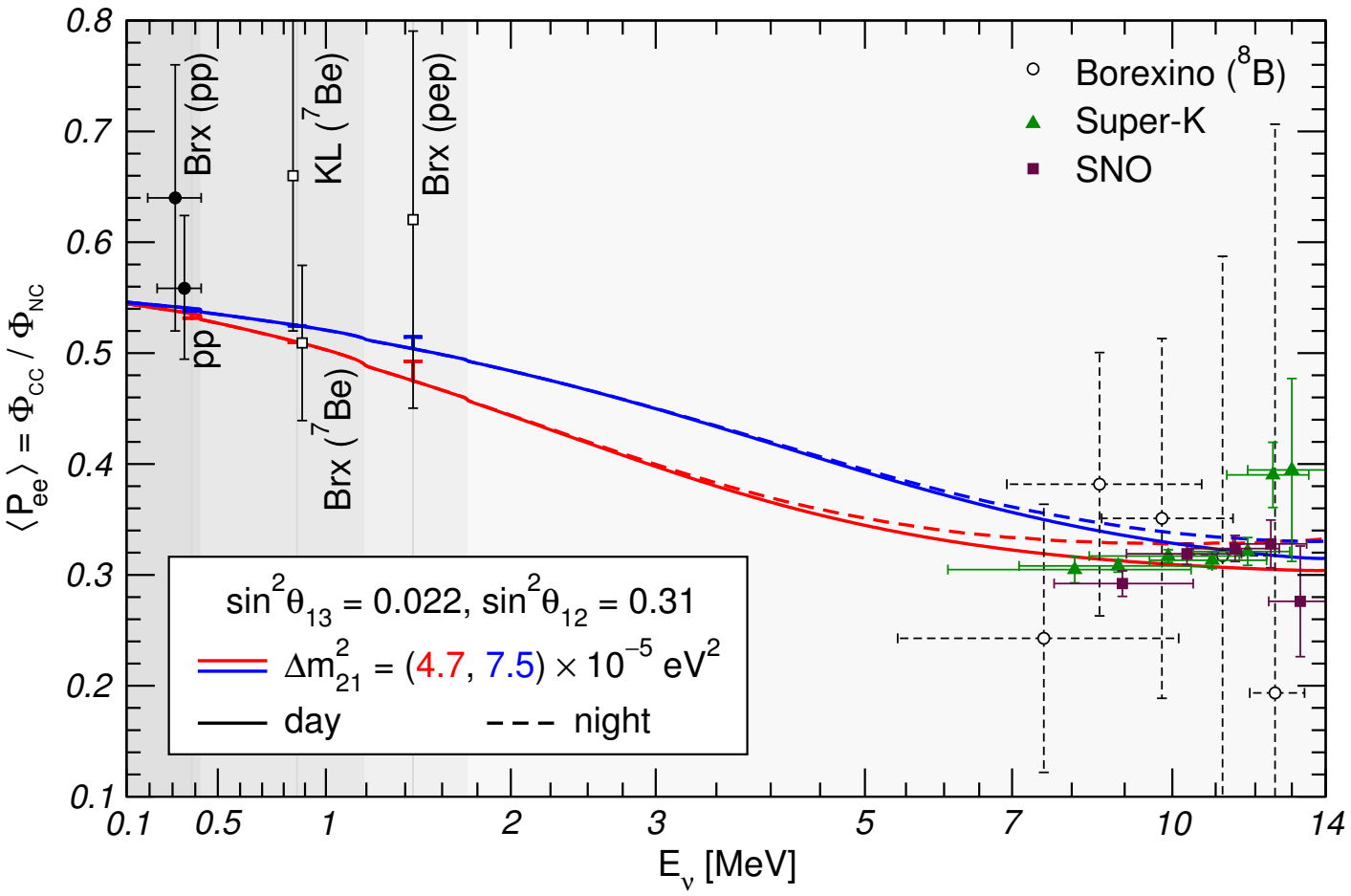
PDG values:

$$\sin^2 2\theta_{12} = 0.846 \pm 0.021$$

$$\Delta m^2_{12} = (7.53 \pm 0.18)\ 10^{-5}\ \text{eV}^2$$

Transition between MSW and vacuum solar ν oscillations

At low energy: $P_{ee} \rightarrow P_{ee}^{vac}$ and matter effects dominate at high energy
Intermediate region is where MSW resonance takes place
This region transition is determined by Δm^2_{21}



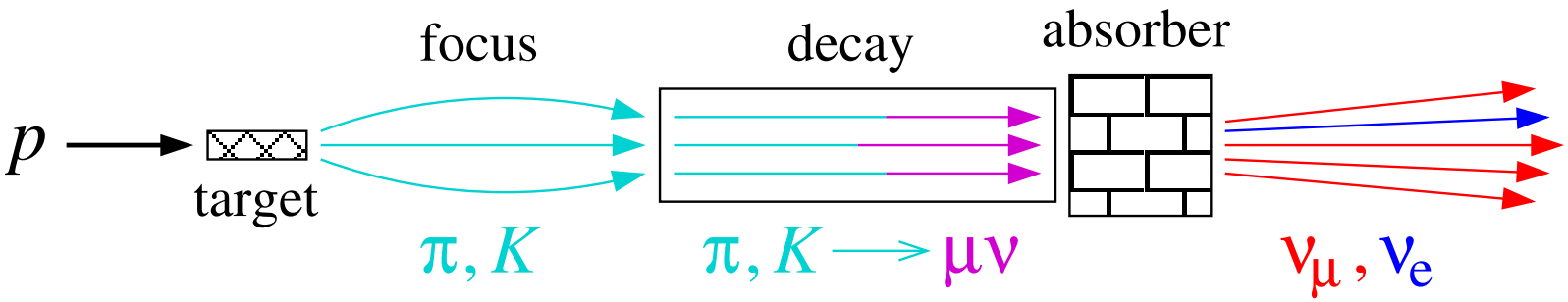
Eur. Phys. J. A 52 (2016) 87 & arXiv:1507.05287

Atmospheric Neutrinos

Started with atmospheric neutrinos measurements but is now dominated by accelerator neutrino beam experiments (MINOS, T2K, Noνa...)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\, e^{-i\delta} \\ & 1 & \\ -s_{13}\, e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

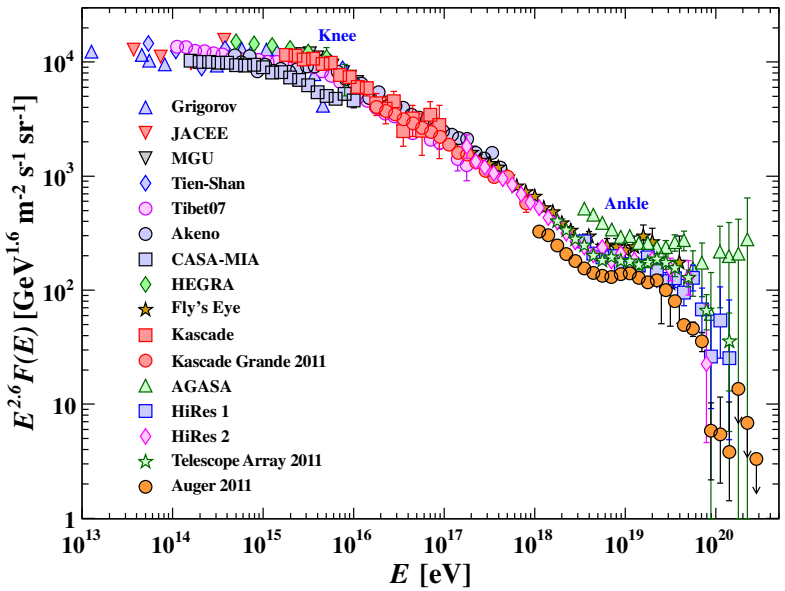
atmospheric reactor/accelerator solar

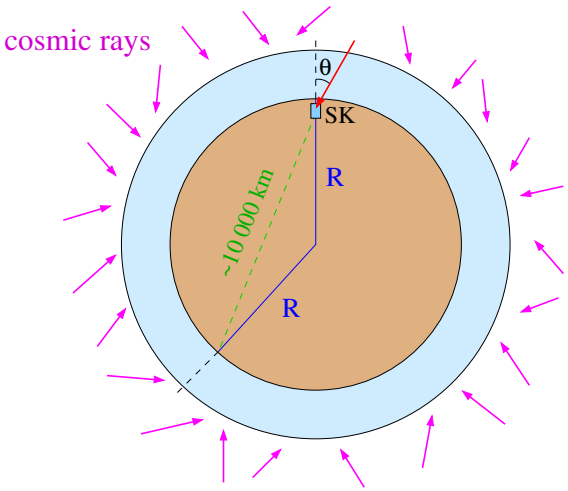


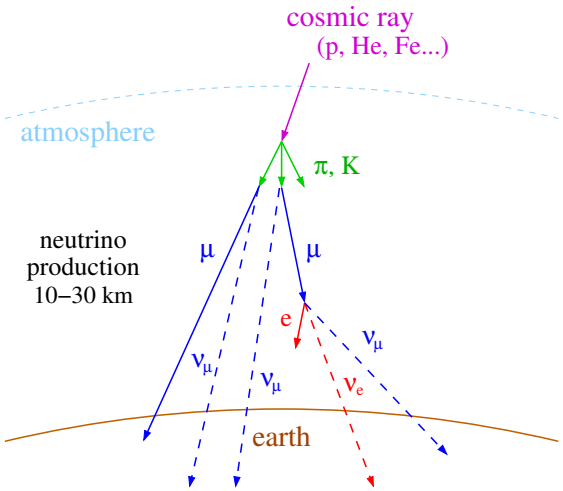
Atmospheric Neutrinos

1912 - V. F. Hess discovers the cosmic rays in his balloon

During 100 years intensively studied





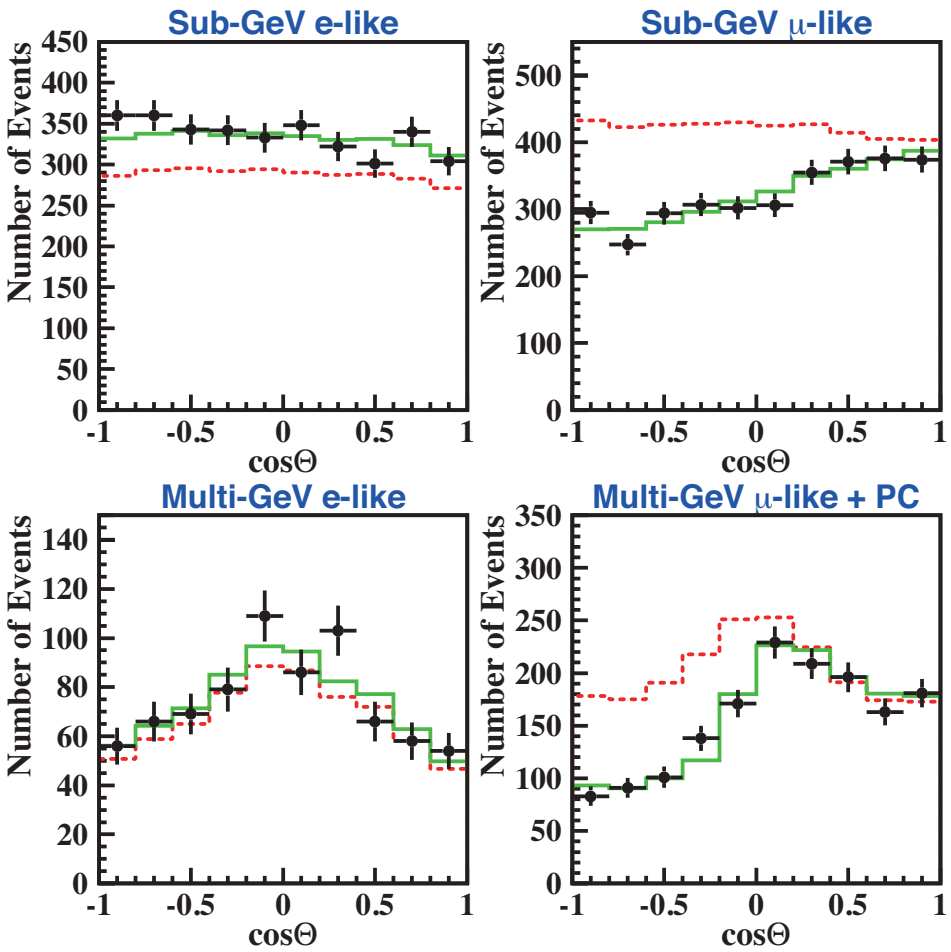


The ratio between ν_e and ν_μ events is well known from the cosmic rays interacting in the atmosphere

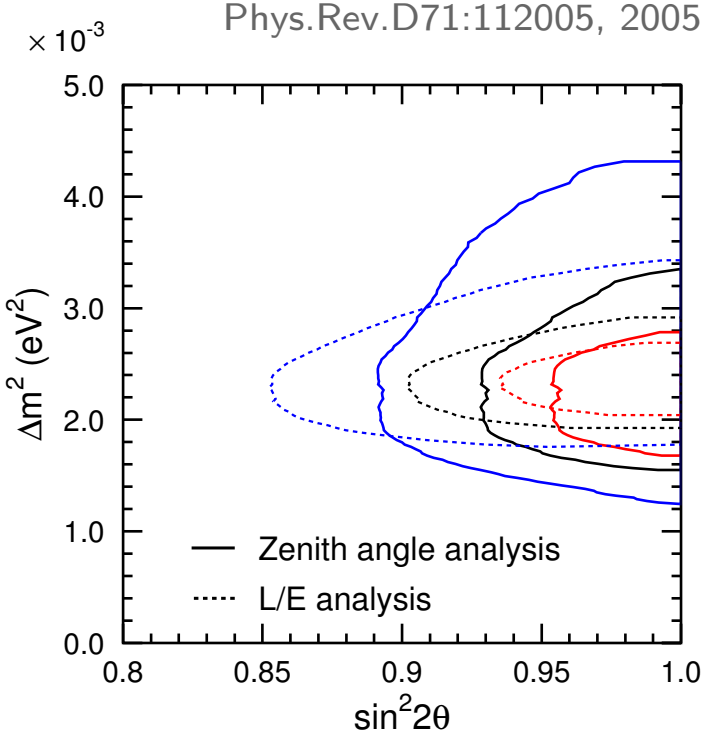
$$R = \frac{\phi(\nu_\mu + \overline{\nu}_\mu)}{\phi(\nu_e + \overline{\nu}_e)} \quad R \simeq 2 \text{ for } E_\nu < 1 \text{ GeV and } R > 2 \text{ for } E_\nu > 1 \text{ GeV}$$

Super-Kamiokande Atmospheric Neutrinos

Super-Kamiokande also found an anomaly between the predicted ratio between ν_e and ν_μ events



Phys.Rev.D71:112005, 2005



PDG values:

$$\sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018}$$

$$|\Delta m^2_{32}| = (2.42 \pm 0.06)\ 10^{-3}\ \text{eV}^2$$

Upward going ν_μ $(\cos\theta < 0)$ oscillated into ν_τ but not ν_e

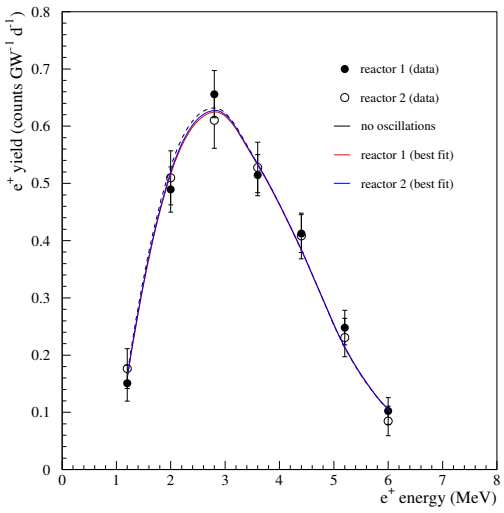
Reactor Neutrinos

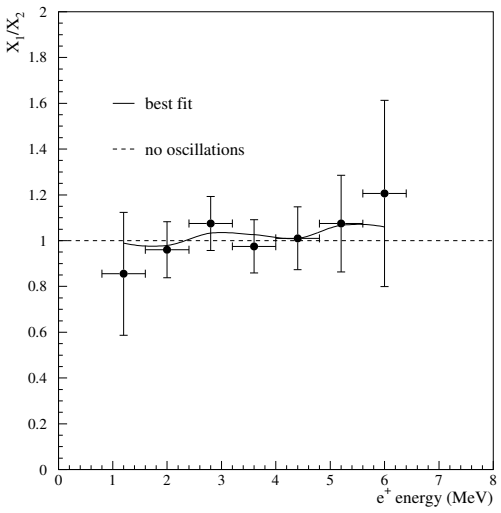
KamLAND is a reactor neutrino experiment at long baseline measuring solar neutrino oscillations

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & & \\ & c_{23} & s_{23}\\ & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & & s_{13}\,e^{-i\delta}\\ & 1 & \\ -s_{13}\,e^{i\delta} & & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

atmospheric reactor/accelerator solar

θ_{13} mixing angle was limited by Chooz (1997-1998) limit $\sin^2 2\theta_{13} < 0.17$





Eur.Phys.J.C27:331-374,2003
arXiv:0301017

Important for the search of CP violation (δ phase)

3 new generation reactor experiments looking for very low θ_{13}: Double Chooz, Daya-Bay & RENO

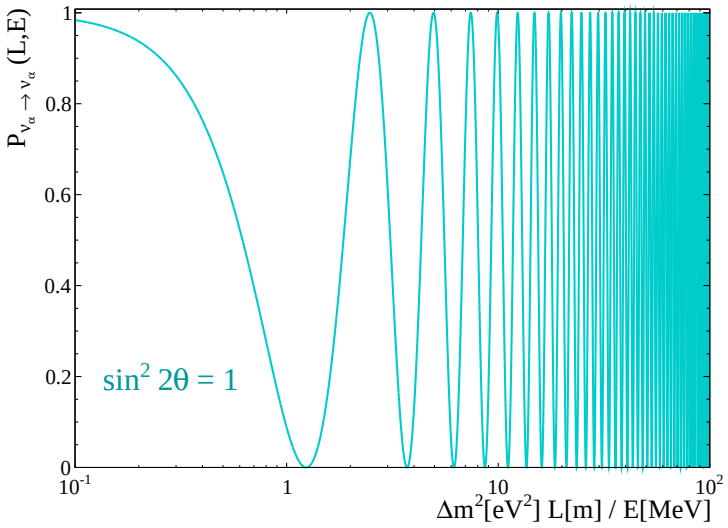
Reactor Neutrino Experiments

Multidetector experiments to cancel neutrino flux systematics:

- near detector measure the non oscillated neutrino flux
- far detector measure the amplitude of the oscillation

Given atmospheric results on Δm_{31} : $\sim$1 km baseline is needed to measure θ_{13}

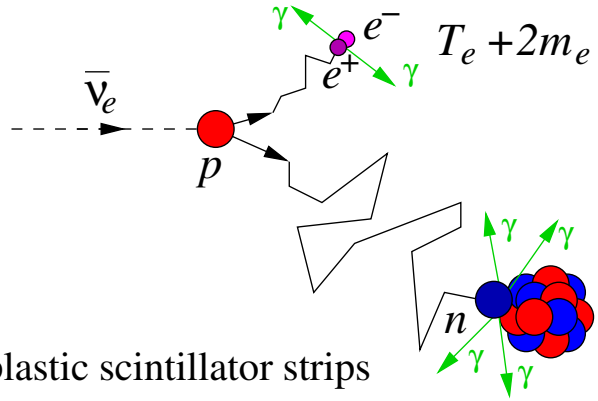
$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

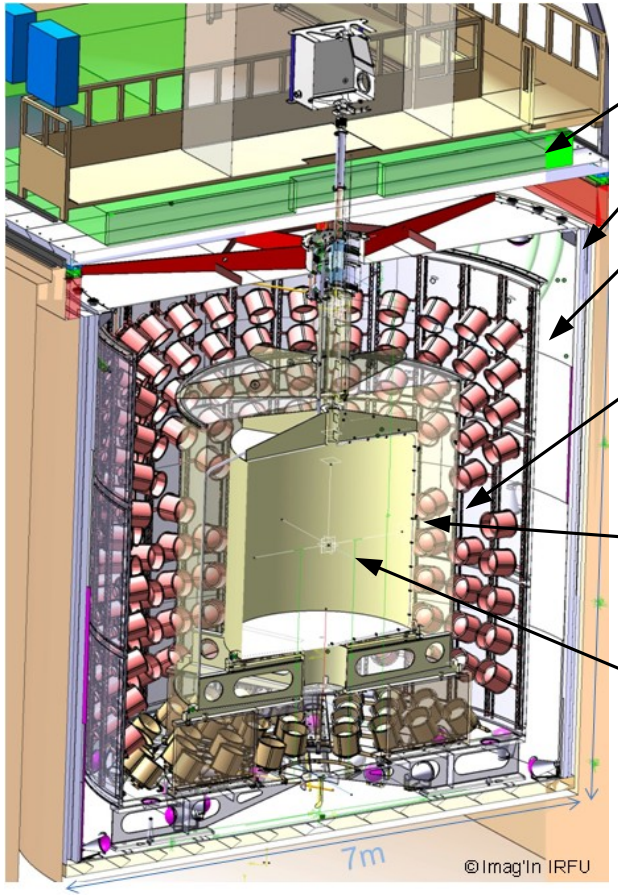


Double Chooz Detector Example

Shalow depth underground laboratories (<1000 m.w.e.)

8 t Gd-LS $\overline{\nu}_e$ target





Outer veto: plastic scintillator strips

Shielding: 15 cm of steal

Inner veto:
90 m^3 of liquid scintillator & 78 PMTs
[40% LAB, 60 % Tetradecane, PPO, Bis-MSB]

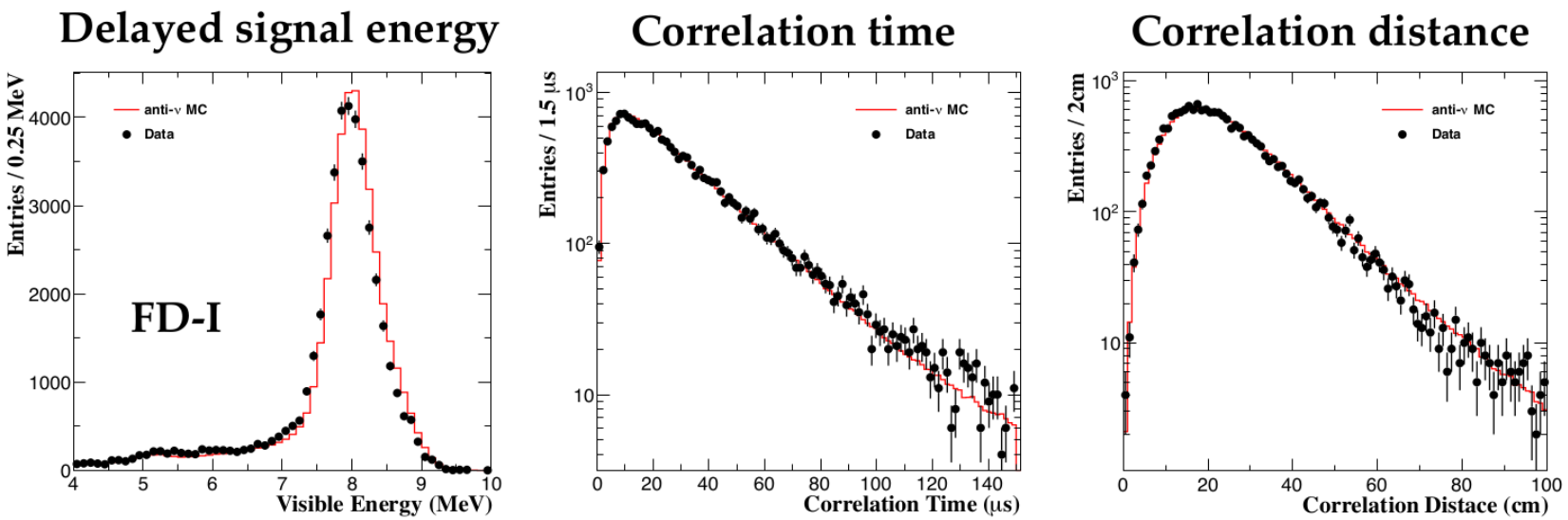
Buffer:
110 m^3 of non scintillating mineral oil & 390 PMTs
[30% Tetradecane, 70% Oil]

Gamma catcher:
22.3 m^3 of liquid scintillator
[46% Dodecane, 50% Oil, 4% PXE, PPO, Bis-MSB]

Neutrino target:
10.3 m^3 of liquid scintillator doped with 0.1 g/L of Gd
[80% Dodecane, 20% PXE, PPO, Bis-MSB, Gd]

IBD Selection and Backgrounds in DC

Matsubara ICHEP 2016

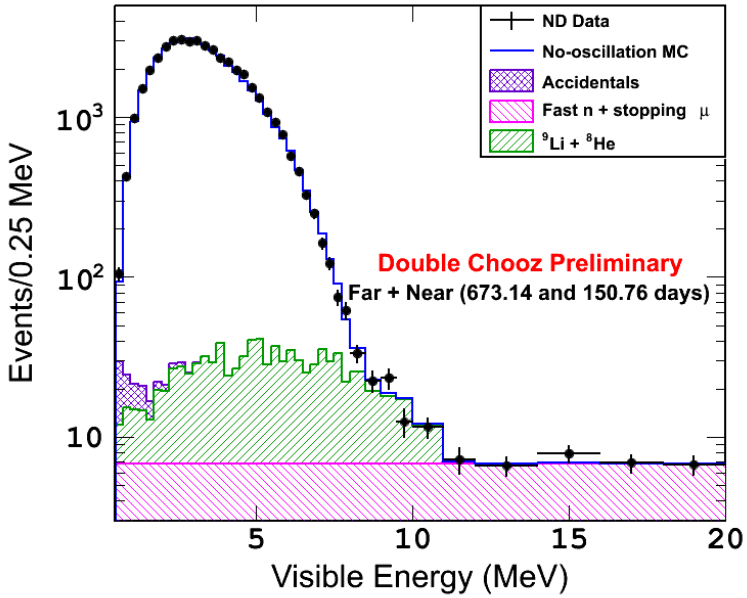


Signal:

- prompt e^+ and delayed n-capture
- rate: ∼40 in far and ∼300 IBD/d in near

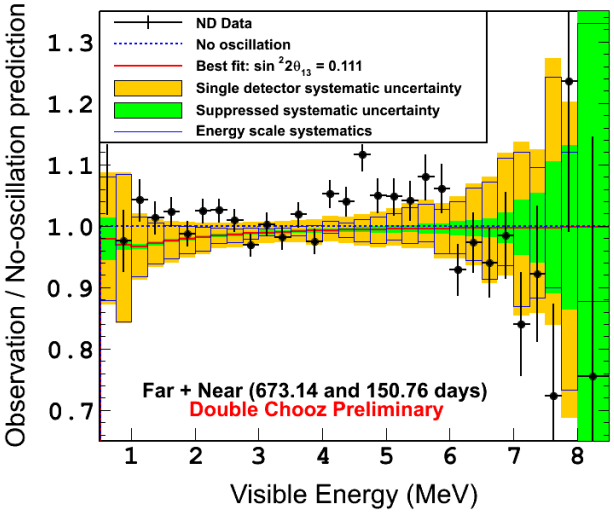
Backgrounds:

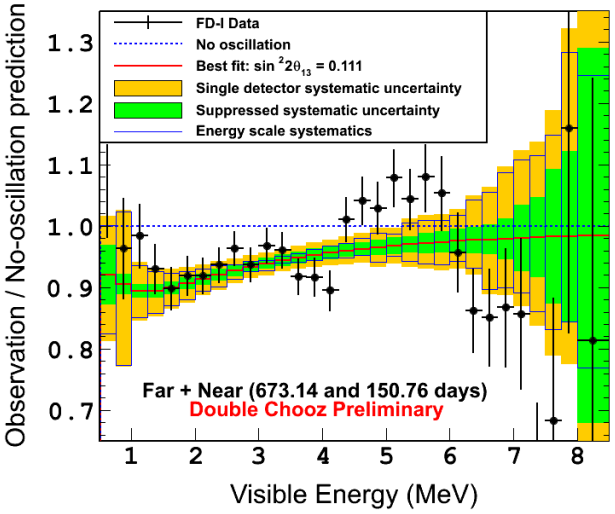
- accidental: $\gamma + n$
- fast-n: p-recoil + n-capture
- stopping μ: $\mu \rightarrow e\ \nu_e\ \nu_\mu$
- (β,n) emitters: ^{9}Li & ^{8}B
- rate: ∼1 in far and ∼10 in near bkg/d

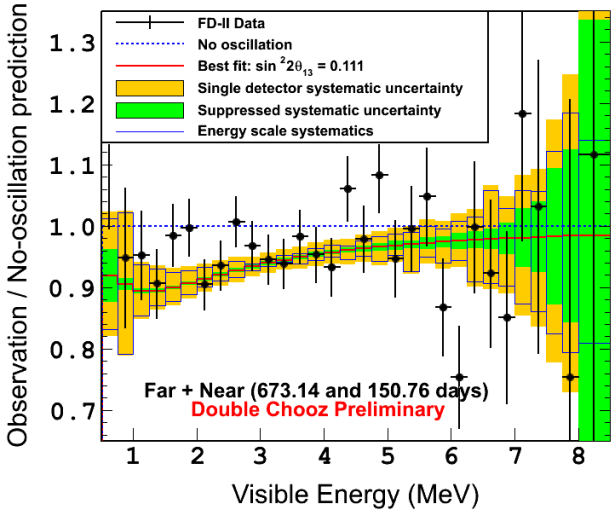


Oscillation result in DC

Matsubara ICHEP 2016

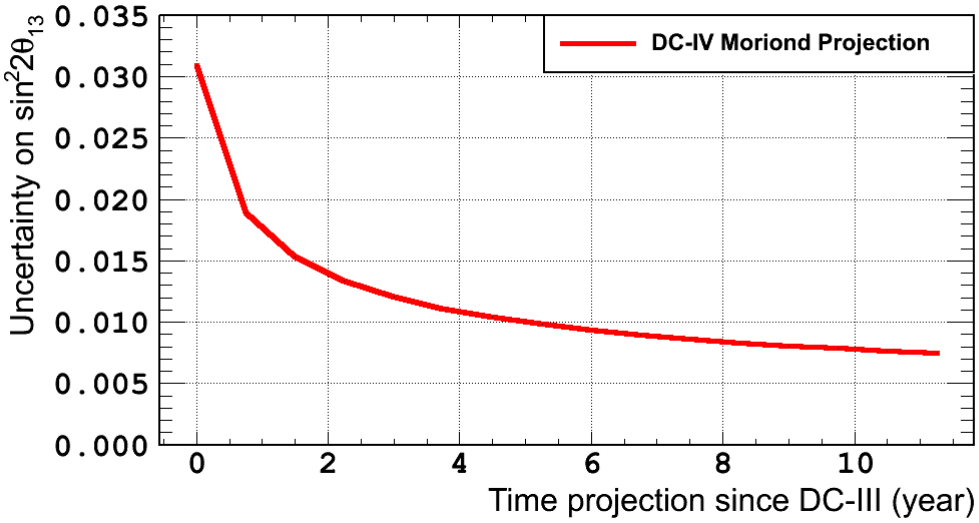




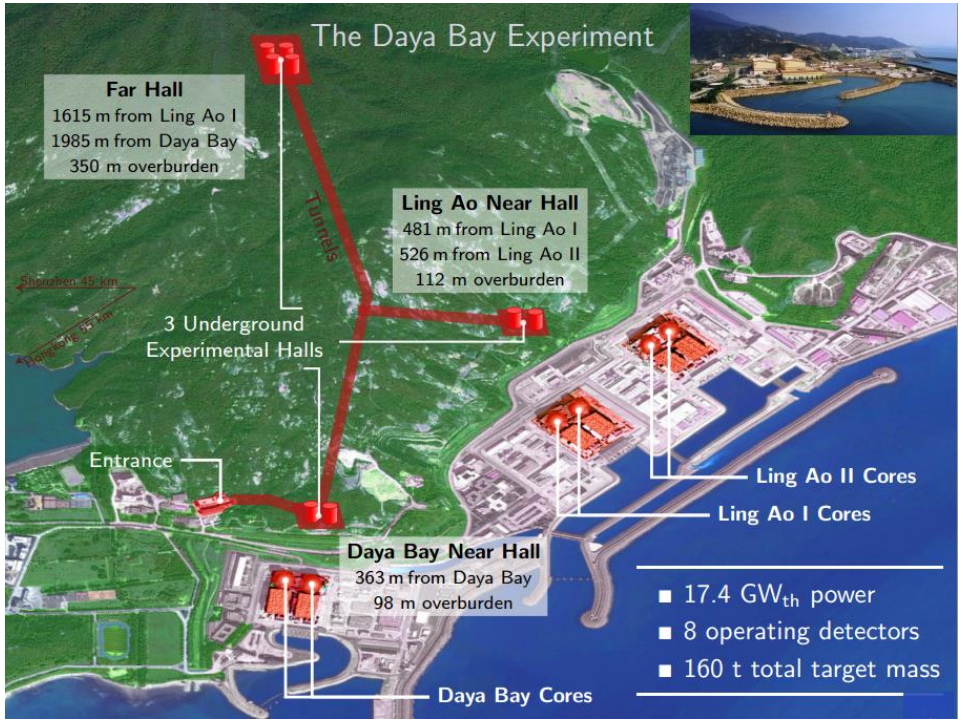


Best-fit: $\sin^2 2\theta_{13} = 0.111 \pm 0.018$ ($\chi^2/\text{dof} = 128.8/120$)
Non-zero θ_{13} observation at 5.8 σ C.L.

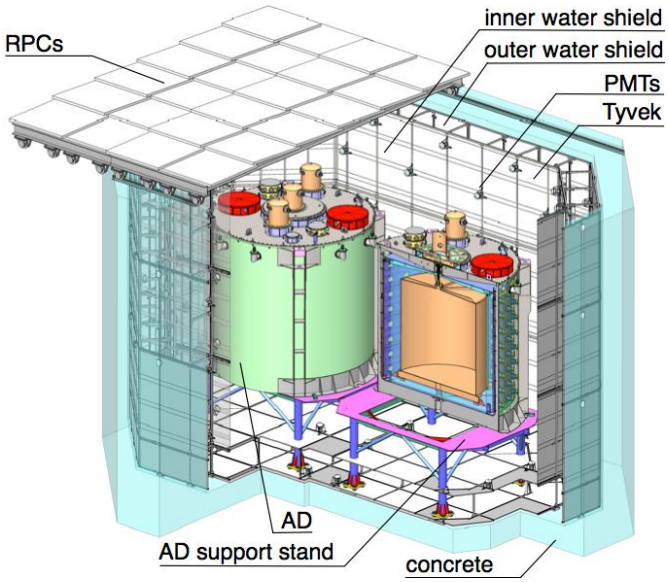
Prospects:
Improving systematics to 0.01
Increasing statistics including γ-catcher n-captures on H

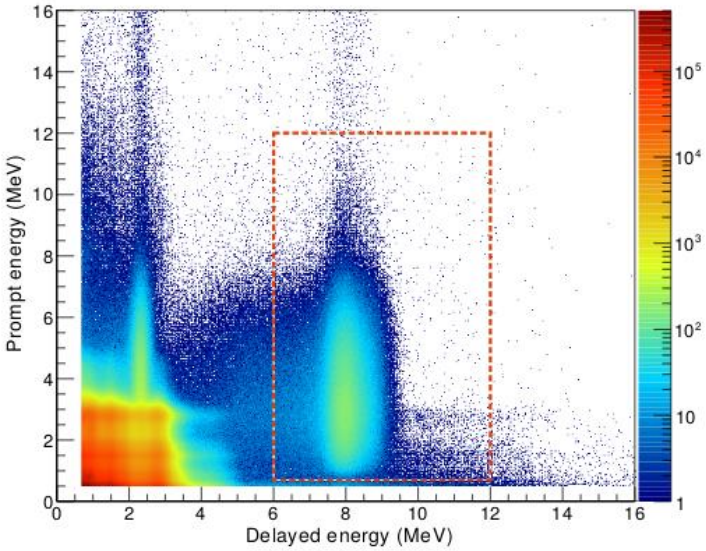


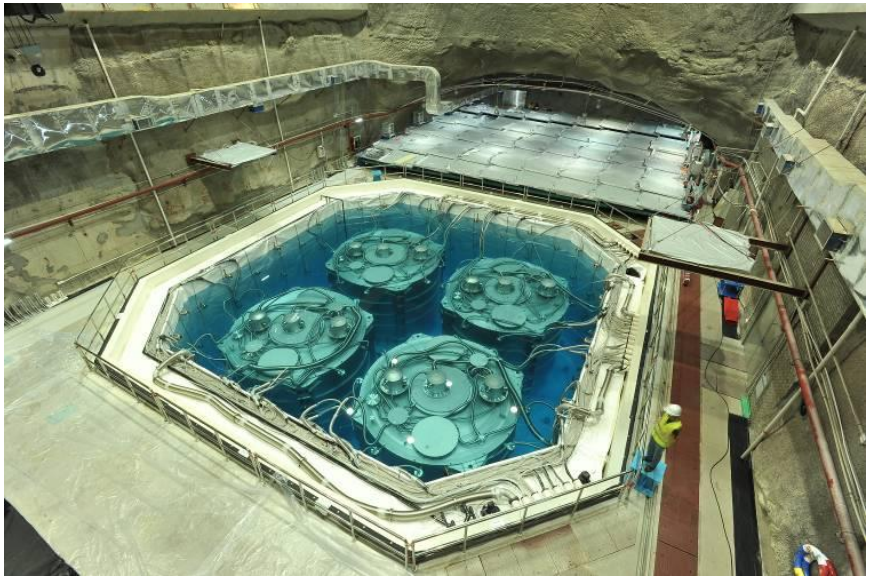
Daya Bay Experiment



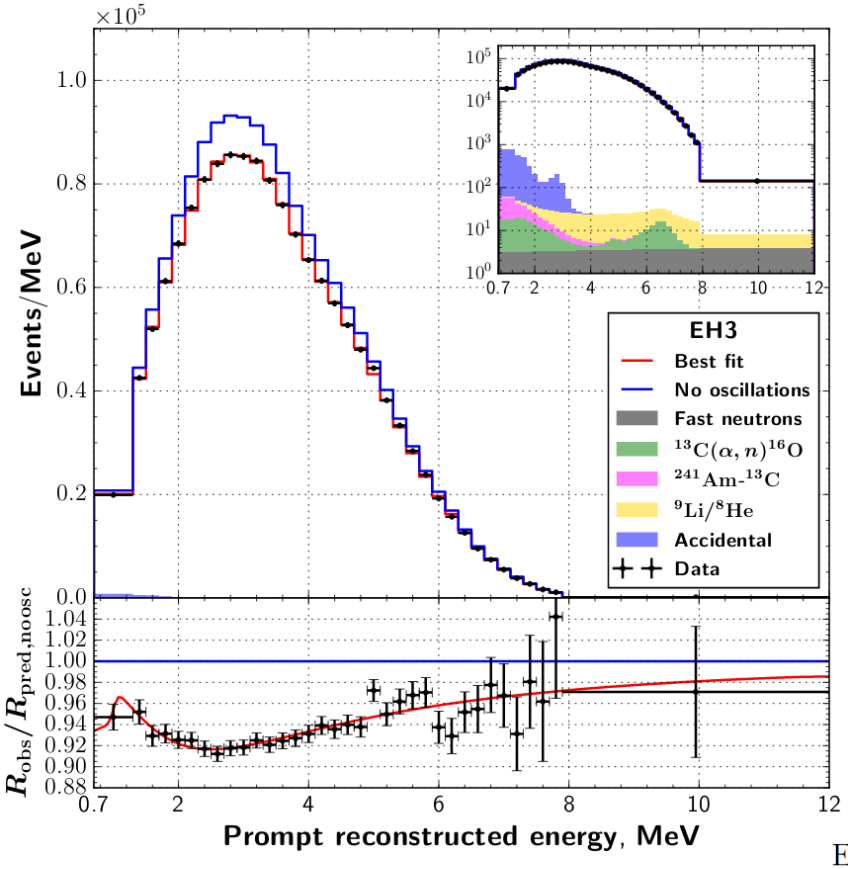
20 t Gd-LS $\overline{\nu}_e$ target

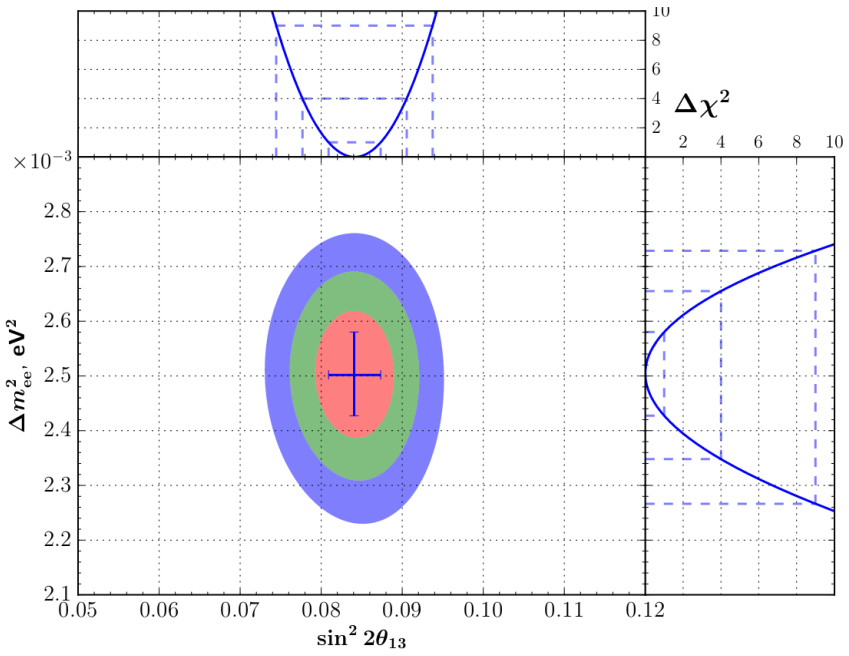






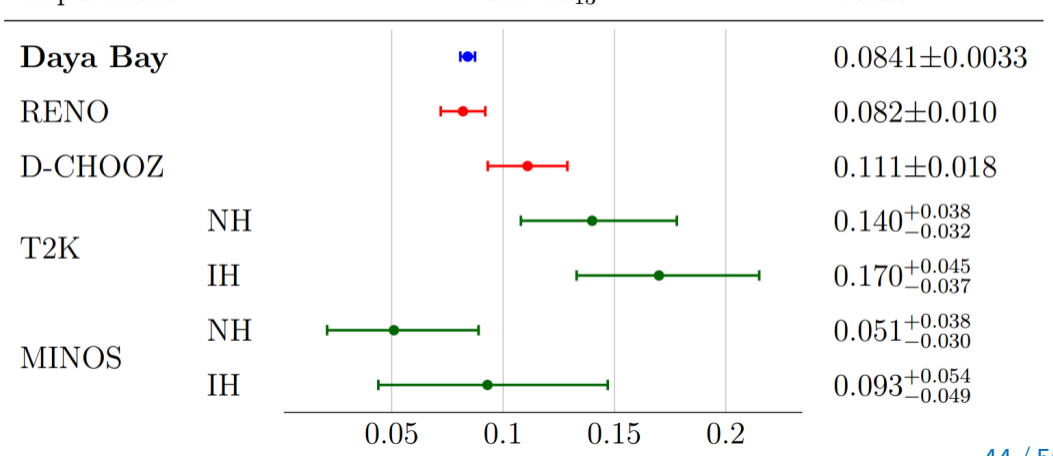
Daya Bay θ_{13} Result





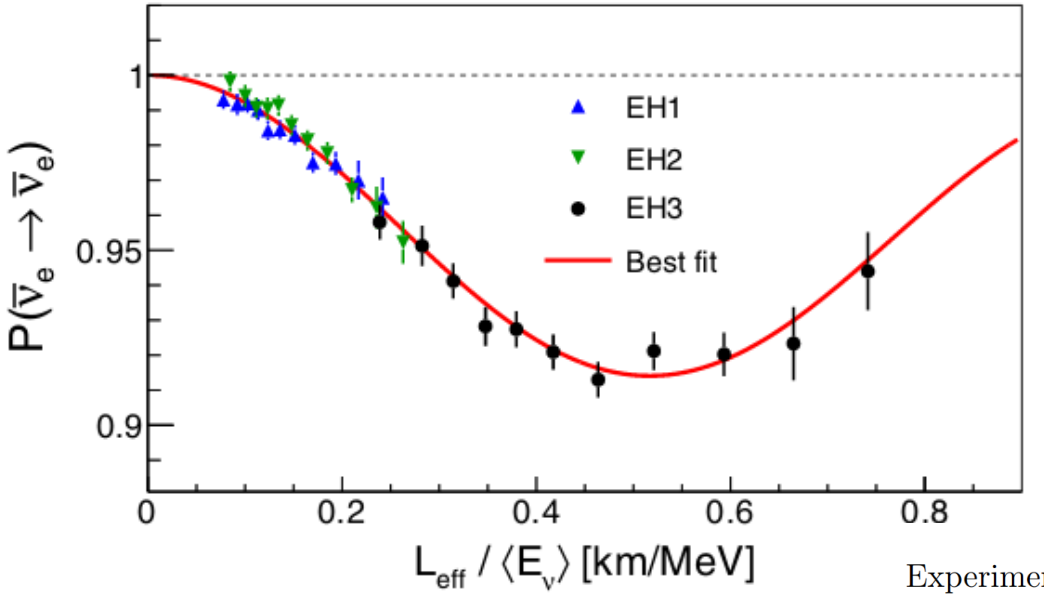
$\sim 2.6 \times 10^6$ IBD in near hall

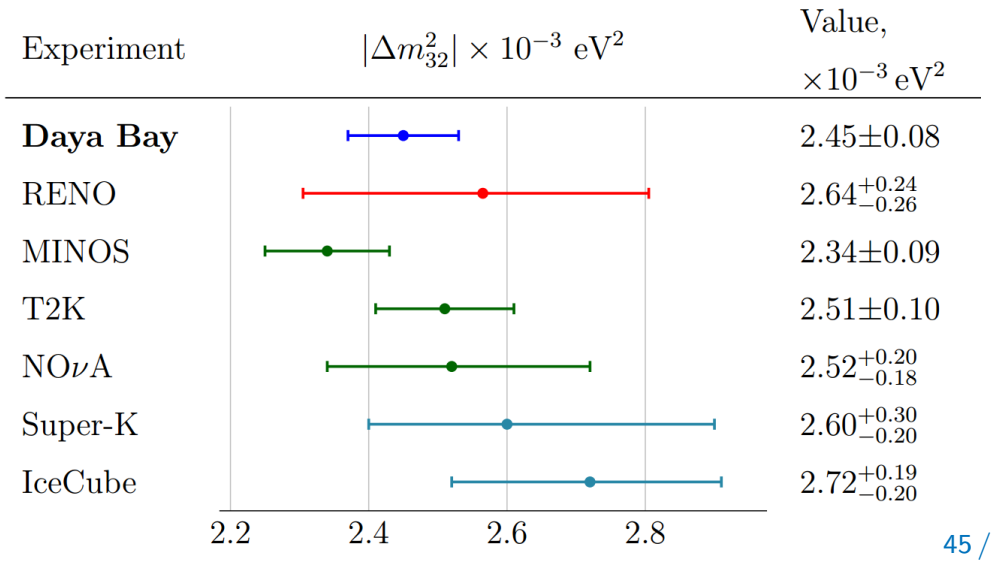
$\sim 300 \times 10^3$ IBD in far hall



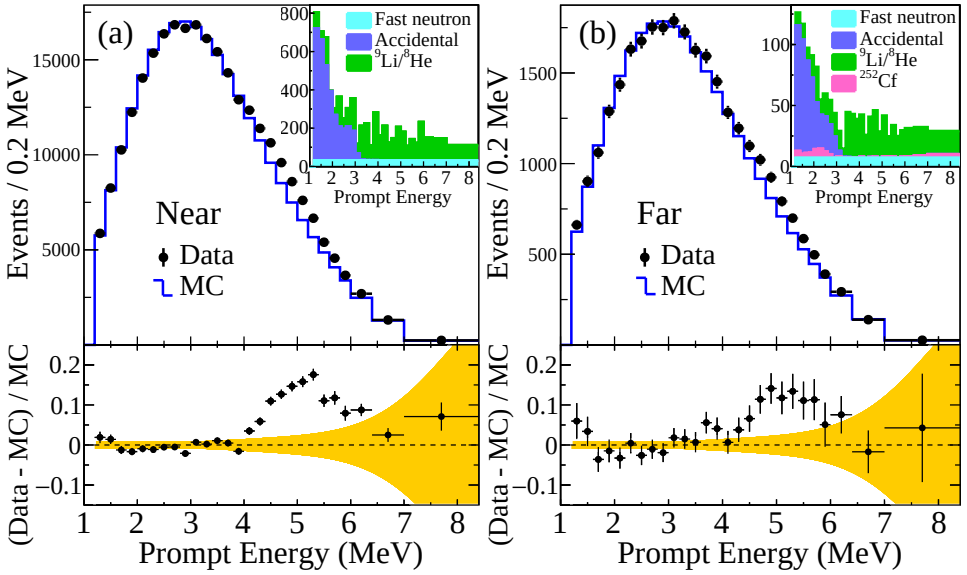
Daya Bay Δm^2_{13} Result

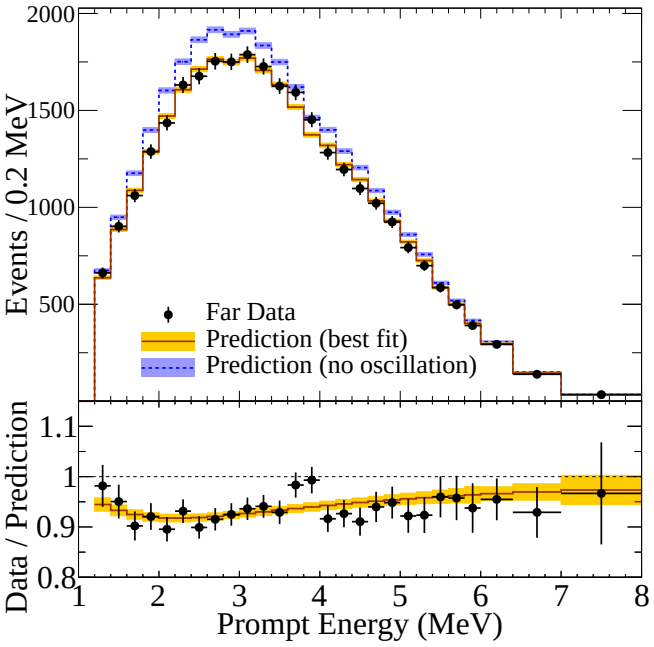
Thanks to multi-reactors and multi-detectors configuration
Daya Bay can provide the most precise measurement of Δm^2_{13}
(previously know from atmospheric & accelerators)

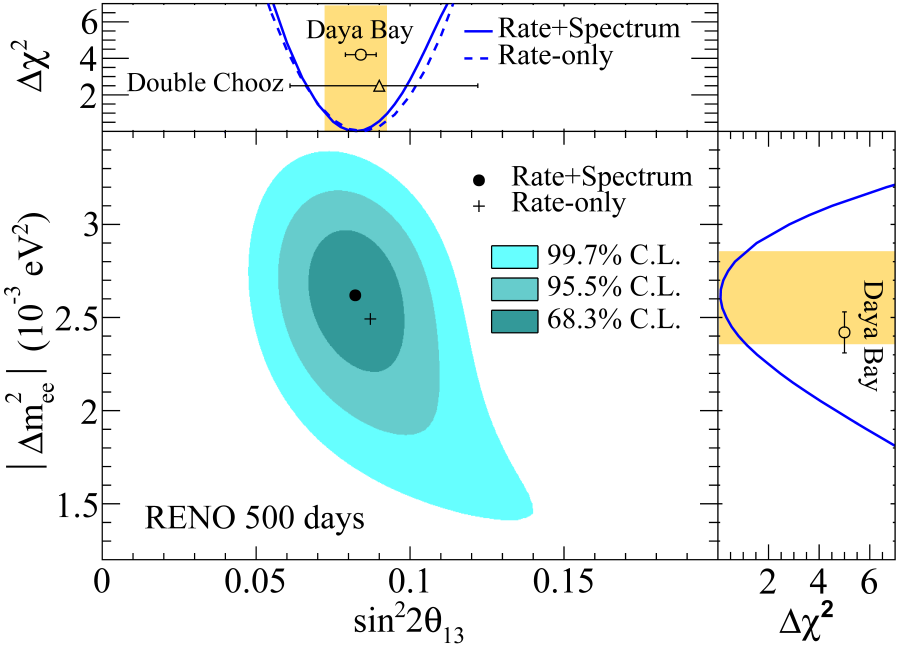




Similar Results from RENO Experiment in Korea







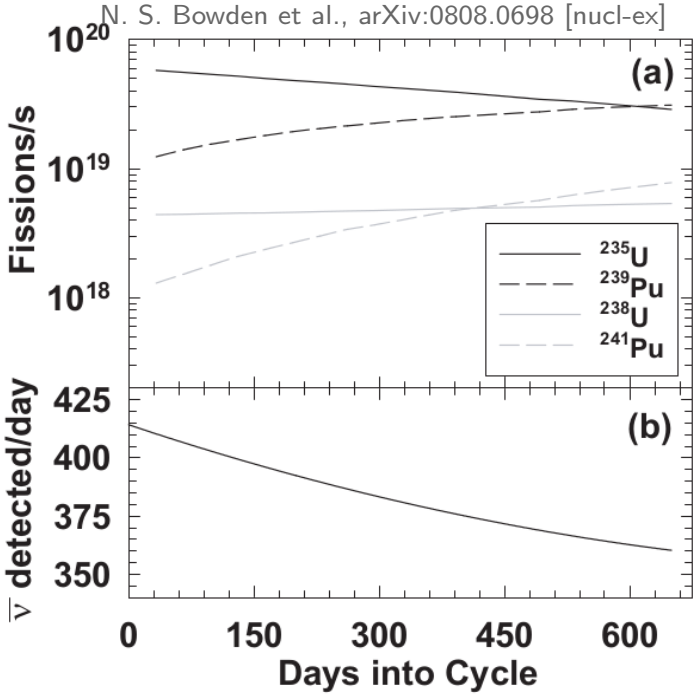
Phys. Rev. Lett. 116, 211801 (2016) - arXiv:1511.05849

Anti-neutrino energy spectrum reevalutation

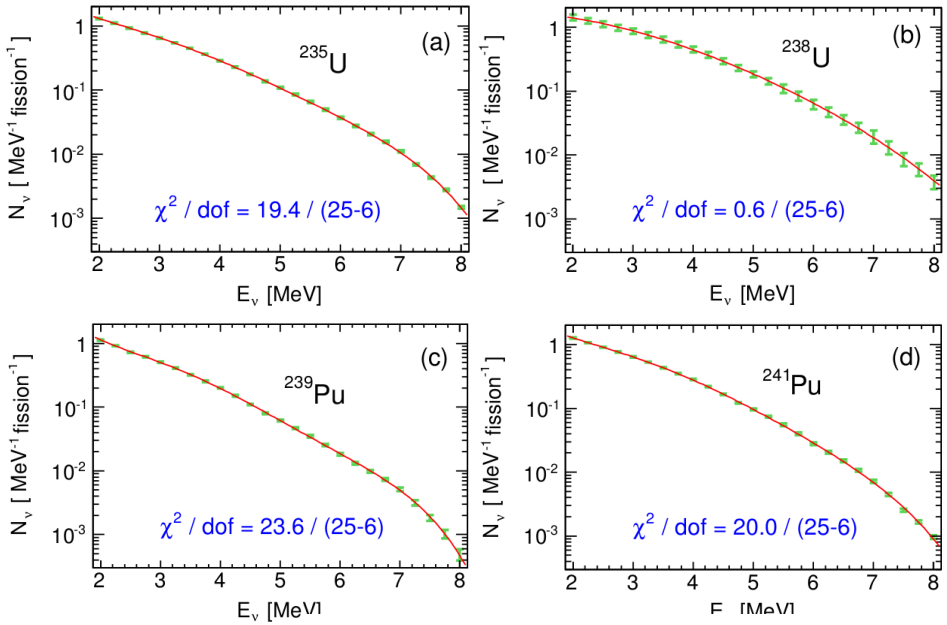
Nuclear reactors are huge isotropic source of neutrinos

- 200 MeV and 6 $\overline{\nu}_e$ per fission
- short lived β-emitters $\rightarrow$ follow the thermal power
- $\sim 2\ 10^{20}\ \overline{\nu}_e\ \mathrm{s}^{-1}\mathrm{GW}_{\mathrm{th}}^{-1}$

N. S. Bowden et al., arXiv:0808.0698 [nucl-ex]



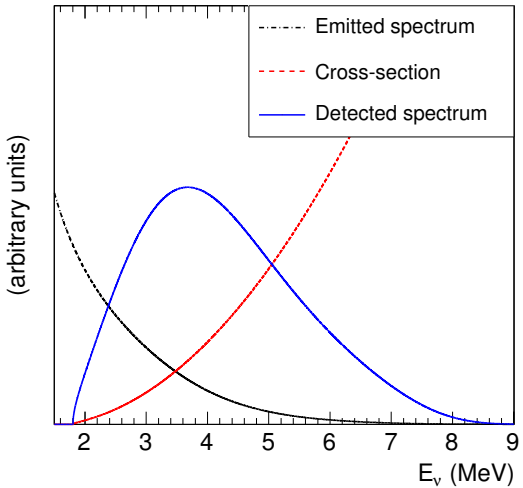
T. Mueller et al., Phys. Rev. C 83, 054615, 2011



+3.5% new conversion of ILL β spectra: $\nearrow \phi_{\overline{\nu}_e}$

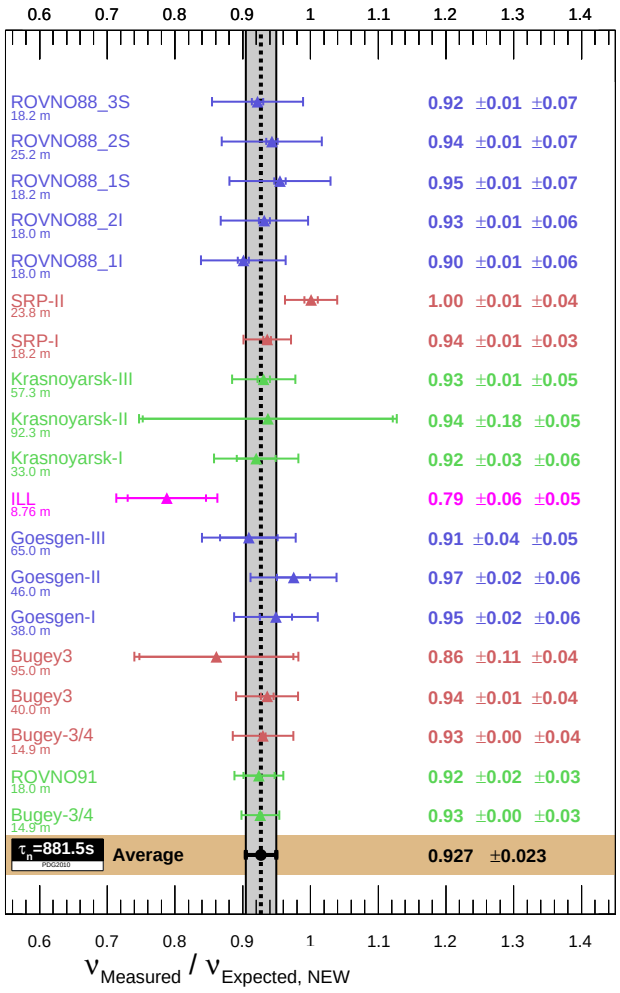
+1.5% off-equilibrium (long-lived isotopes): $\nearrow \phi_{\overline{\nu}_e}$

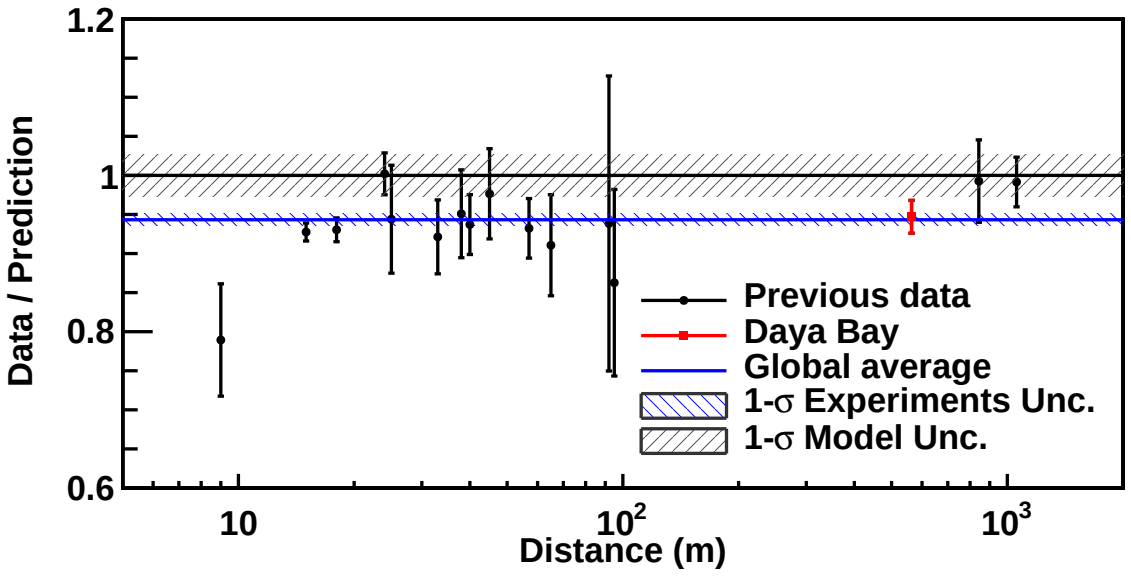
+1.5% neutron live-time τ_n (880±1 s): $\nearrow \sigma_{\mathrm{IBD}}$



Reactor anti-neutrino anomaly

This reevalutation of the anti-neutrinos reactor spectrum for reactor experiments → ∼ 6.5 % deficit in short baseline experiments



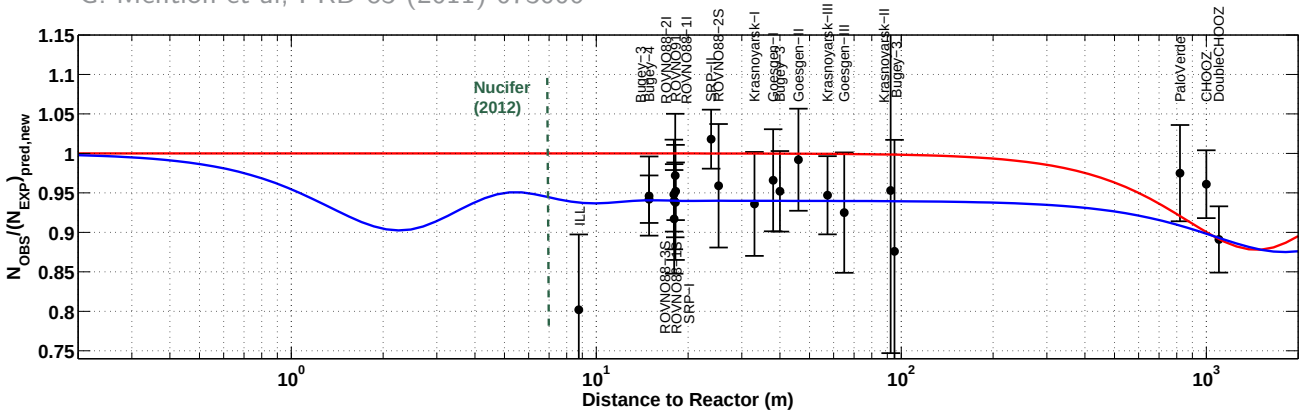


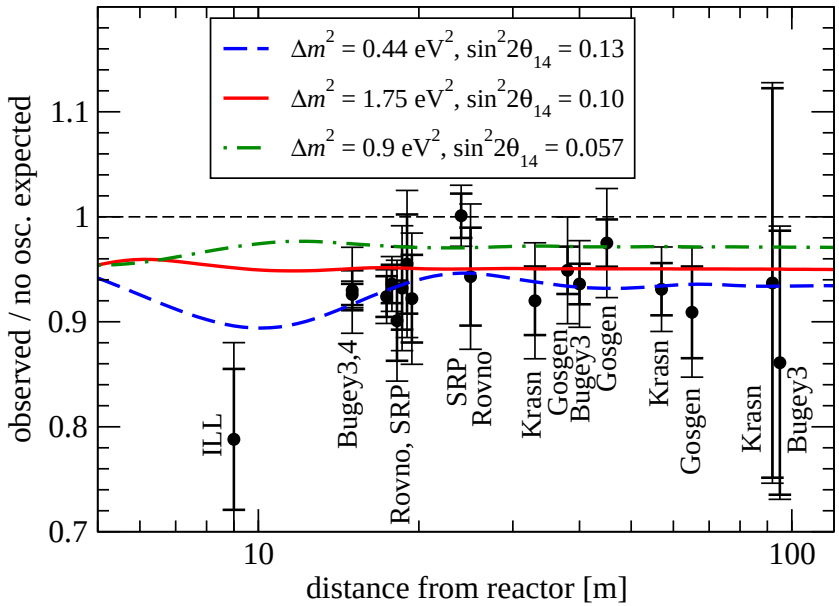
G. Mention et al, PRD 83 (2011) 073006
K. N. Abazajian et al., arXiv:1204.5379
F. P. An et al., Phys. Rev. Lett. 116, 061801 (2016)

Possible explanation: the sterile neutrino ν_s

Sterile(s) neutrino(s) neutral lepton not sensitive to weak interaction:
SM right-handed singlet which can have in principle any mass
Can couple to active neutrinos throught Lagrangian mass term

G. Mention et al, PRD 83 (2011) 073006



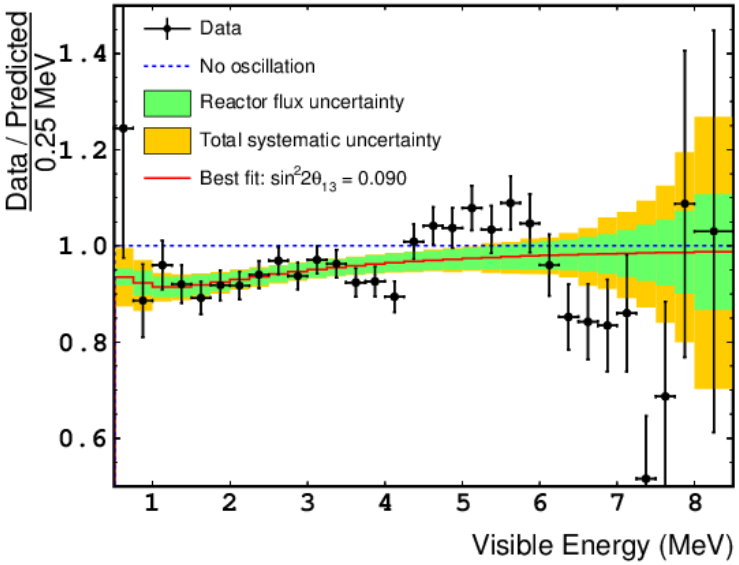


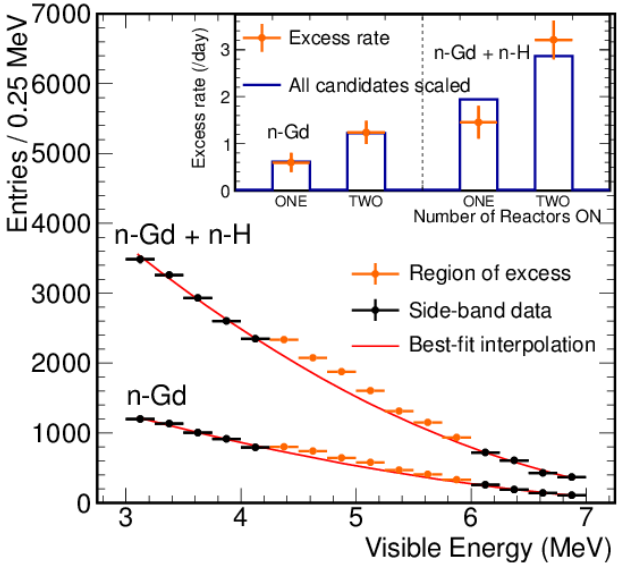
J. Kopp et al., JHEP 1305:050, 2013

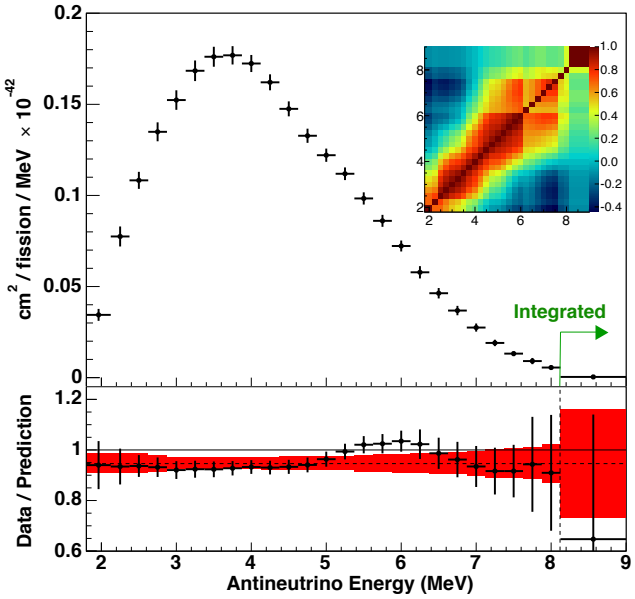
Distortion of anti-neutrino spectrum "5 MeV bump"

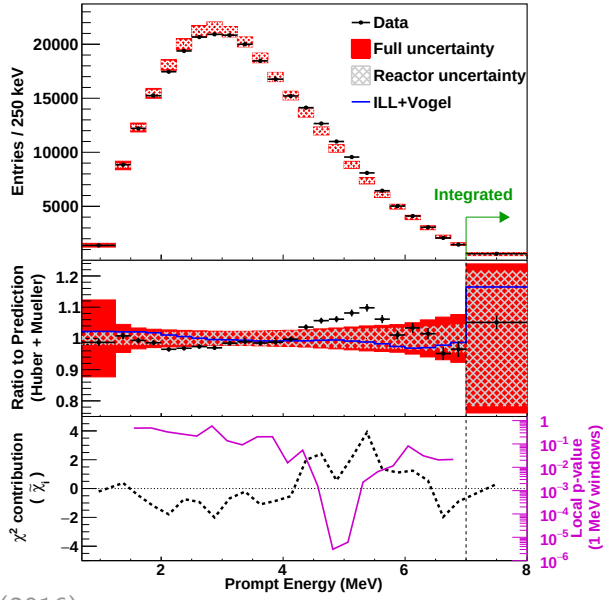
All 3 θ_{13} reactor experiments observes an excess between 4 and 6 MeV

Y. Abe et al., JHEP 10 (2014) 086







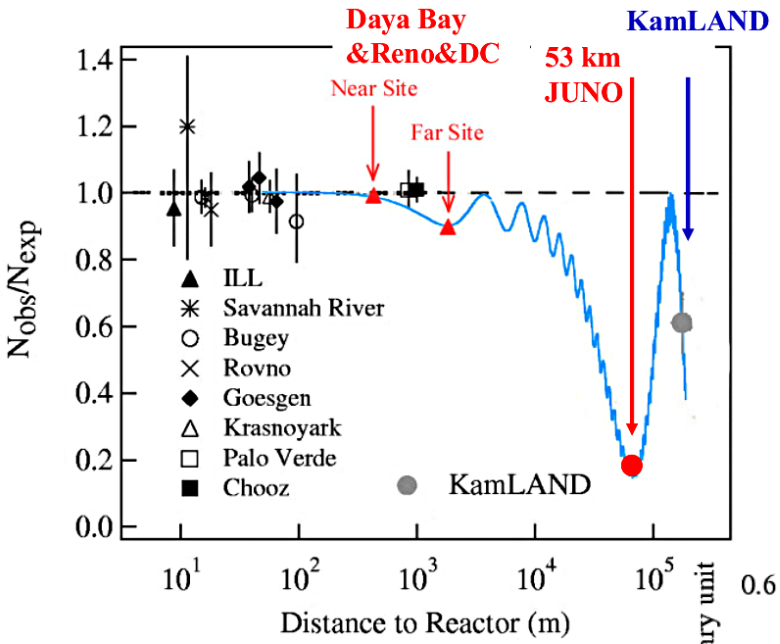


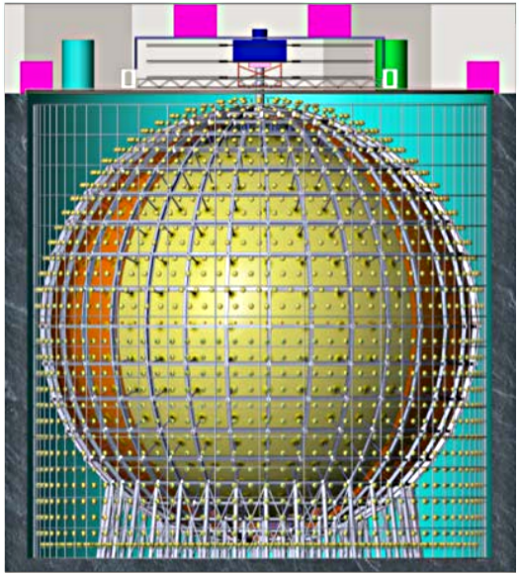
F. P. An et al., Phys. Rev. Lett. 116, 061801 (2016)

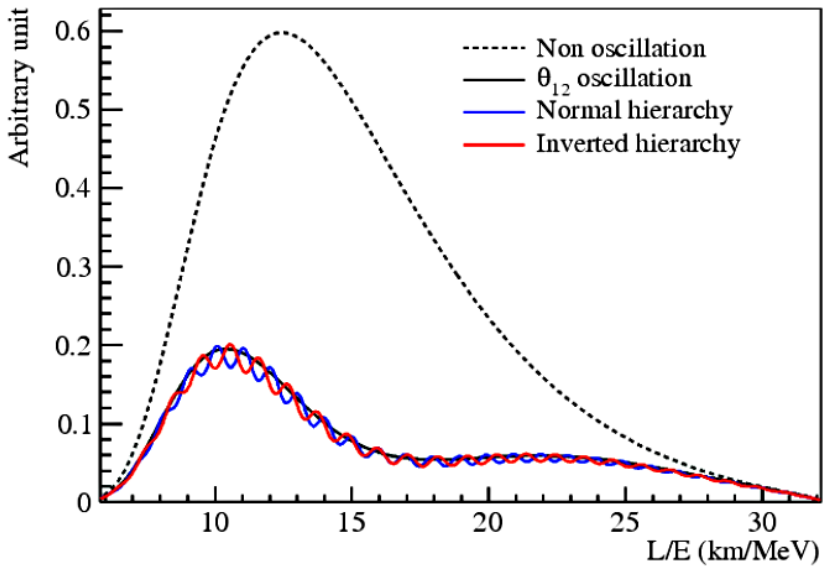
Mass Hierarchy with JUNO

arXiv:1507.05613
Ranucci Neutrino 2016

20 kt LS detector in China 3% energy resolution
Reactor experiment at 53 km for reactors with $\sim$ 2100 m.w.e.
Wide neutrino physics program







Summary of Neutrino Oscillation measurements

The three flavor $e,\ \mu,\ \tau$ neutrino mixing in the PMNS 3×3 matrix describes well the measurements

Solar: $\nu_e \to \nu_{\mu\tau}$

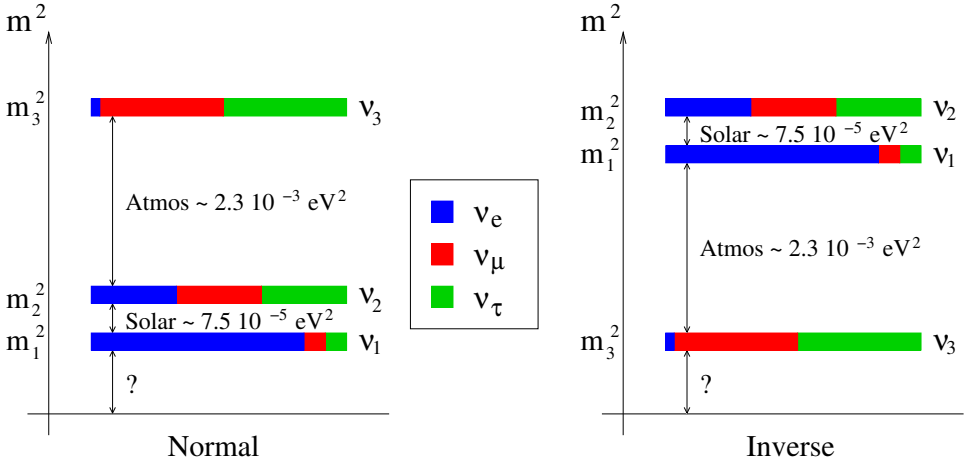
$$\sin^2 2\theta_{12} = 0.846 \pm 0.021$$
$$\Delta m^2_{12} = (7.53 \pm 0.18)\ 10^{-5}\ \text{eV}^2$$

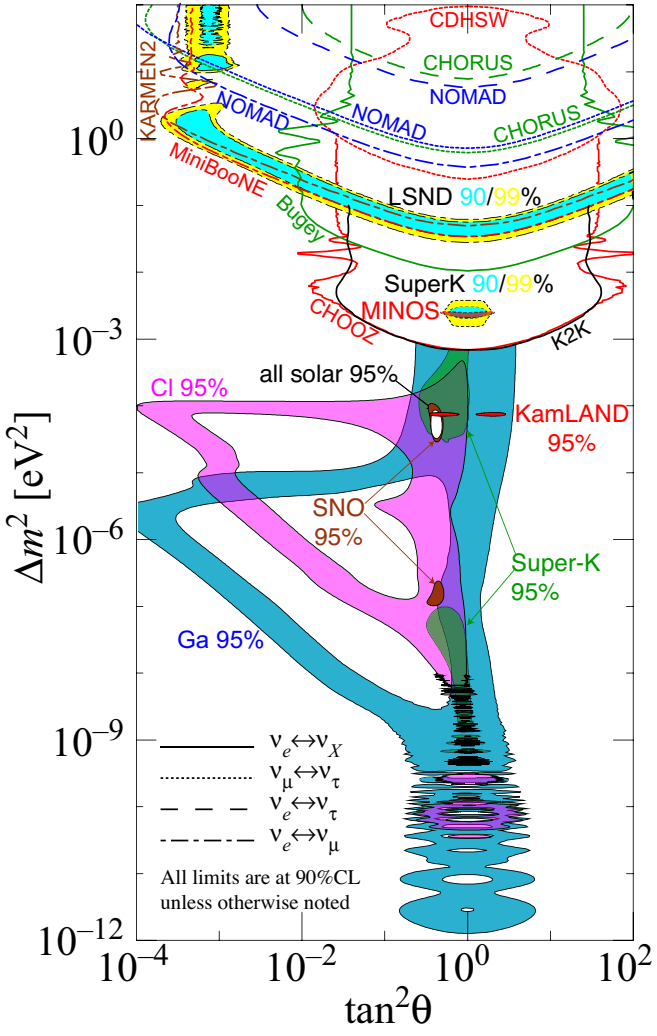
Atmospheric: $\nu_\mu \to \nu_\tau$

$$\sin^2 2\theta_{23} = 0.999^{+0.001}_{-0.018}$$
$$|\Delta m^2_{32}| = (2.42 \pm 0.06)\ 10^{-3}\ \text{eV}^2$$

Reactors: $\nu_e \to \nu_x$ or $\nu_\mu \to \nu_e$

$$\sin^2 2\theta_{13} = 0.085 \pm 0.005$$





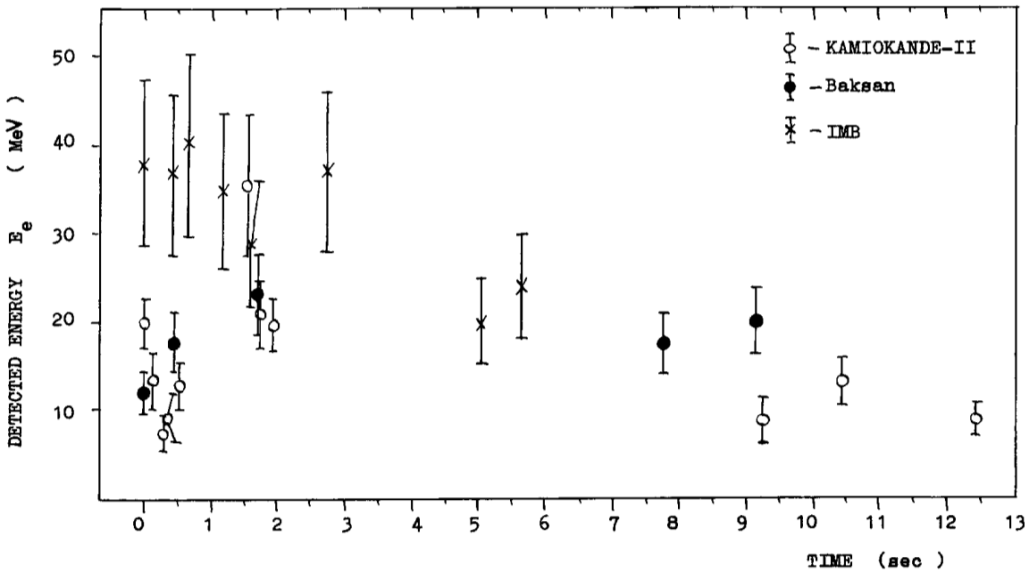
PDG 2014/2016

We still don't know absolute mass scale, mass hierarchy and $\delta_{\mathcal{CP}}$

Supernova Neutrinos

Supernova neutrinos detection is crucial for astrophysics models
Neutrinos from the supernova SN 1987A have been detected:

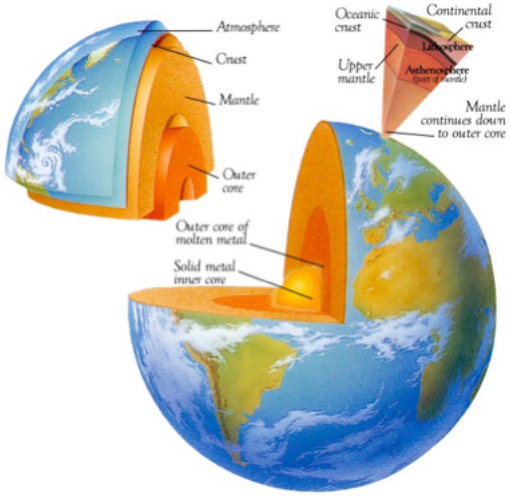
- 3 experiments Baksan 0.2 kt, Kamiokande 2.1 kt & IMB 6.8 kt
- in coincidence within a $\sim$ 10 s burst
- 25 $\overline{\nu}_e$ events with an average energy of 12.5 MeV
- total number of neutrinos emitted $\sim$ 8 10^{57}
- energy released $\sim$ 2 10^{53} erg (90 %) in agreement with models



Actual experiments are ready for the next supernova
Addition of Gd for radiative neutron capture in Super-Kamiokande

Physics Letters B 205, 209-214, 1988

Geoneutrinos in KamLAND

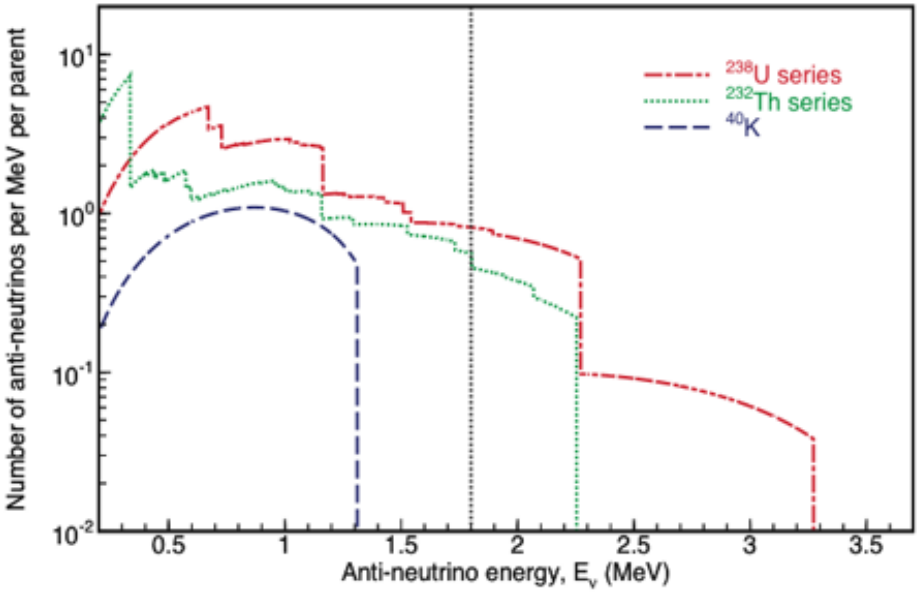


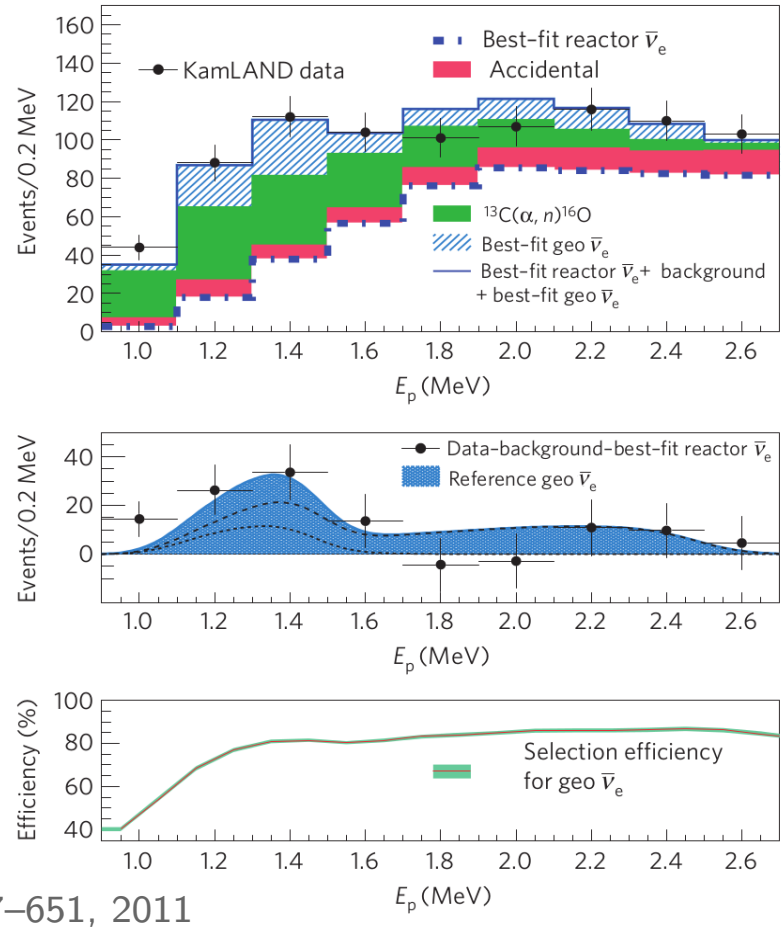
Half Earth's heat is due to natural radioactivity:

- total heat ~47±2 TW
- ^{238}U ~8 TW, ^{232}Th ~8 TW and ^{40}K ~4 TW

2005 KamLAND reported the 1st detection of geoneutrinos ($\overline{\nu}_e$)

Update in 2011 after Kashiwazaki–Kariwa shutdown
106^{+29}_{-28} geoneutrino events



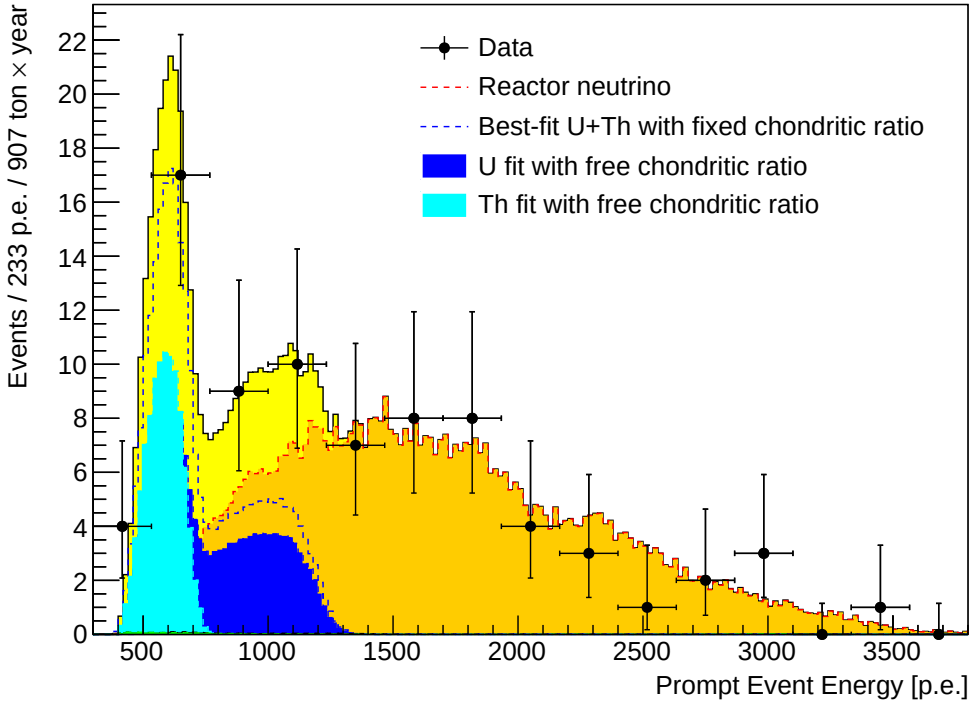


Nature Geoscience 4, 647–651, 2011

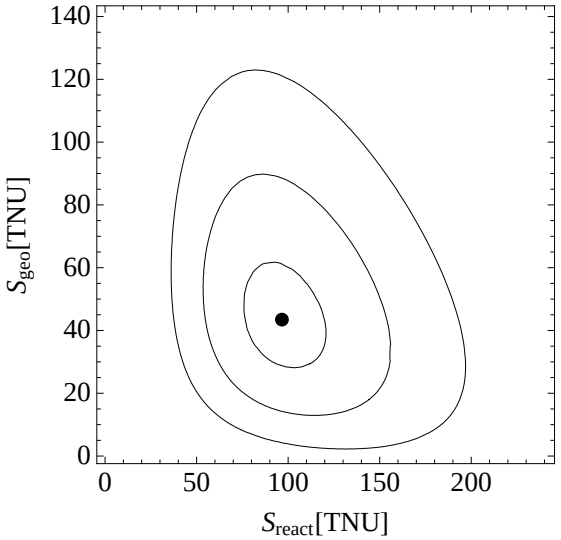
Geoneutrinos in Borexino

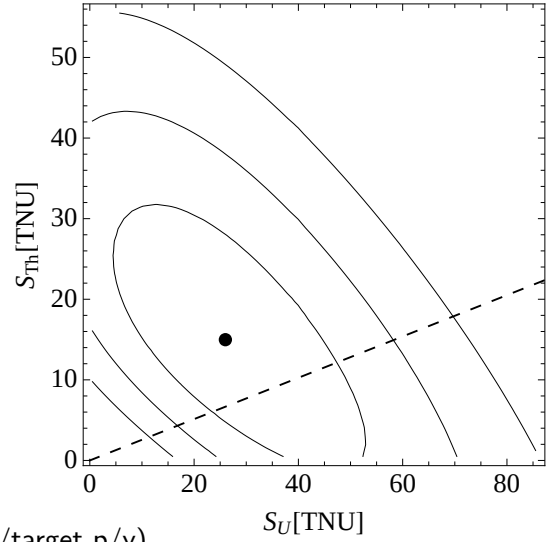
arXiv:1506.04610

Borexino also detected geoneutrinos and presented an update in 2015
Less $\overline{\nu}_e$ reactor background
Radiogenic heat production for U and Th
$\in$ 23-36 TW



$$23.7\ ^{+6.5}_{-5.7}(stat)\ ^{+0.9}_{-0.6}(sys)$$
geo-neutrino events





(Terrestrial Neutrino Unit: 1 TNU = 10^{-32} event/target p/y)