Lecture 1

Reactor Neutrino Experiments and the Hunt for θ_{13} and CP Violation

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Present Knowledge for Neutrino Oscillation Parameters

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Unknown CP violation phase

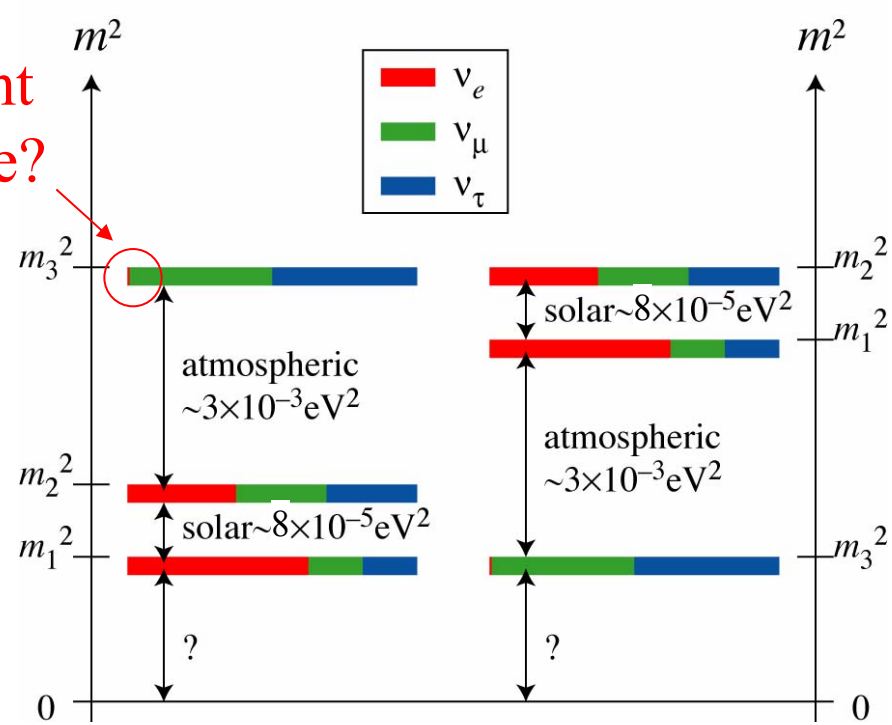
$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

Solar: $\theta_{12} \sim 30°$

$\sin^2 2\theta_{13} < 0.2$ at 90% CL (or $\theta_{13} < 13°$)

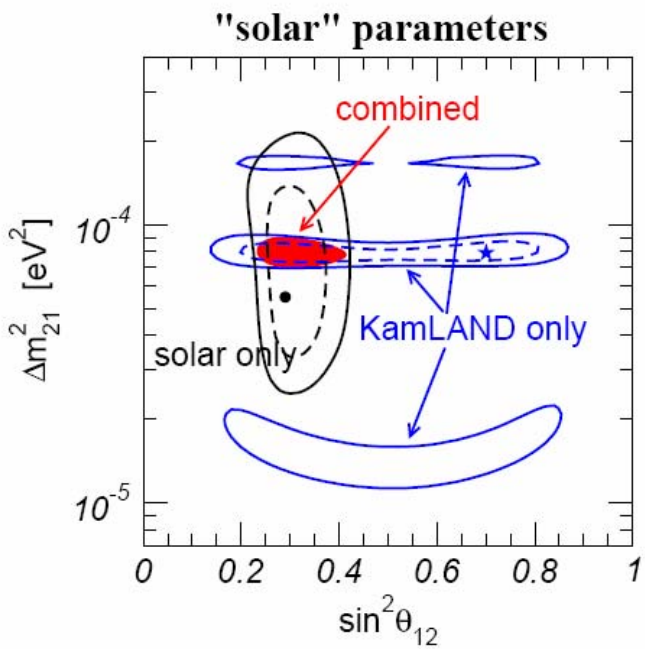
Atmospheric: $\theta_{23} \sim 45°$

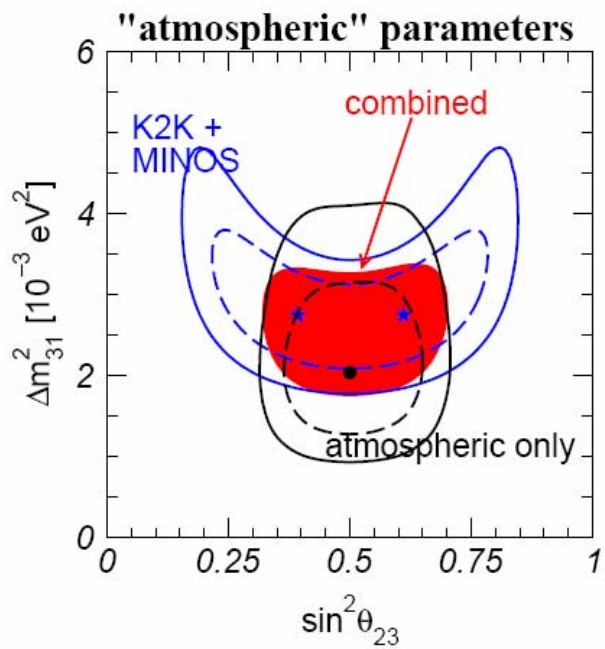
What is ν_e component of ν_3 mass eigenstate?

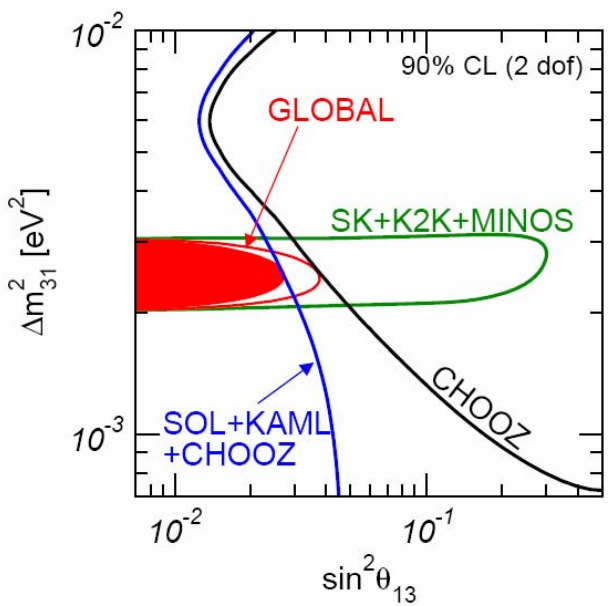


These two different mass schemes are called: ***Mass Hierarchy Problem***

Current Global Fits to Solar, Atmospheric, Accelerator, and Reactor Data







$$\sin^2\theta_{13} < \begin{cases} \text{90\% } (3\sigma) & \\ 0.027\ (0.058) & \text{CHOOZ+atm+LBL,} \\ 0.033\ (0.071) & \text{solar+KamLAND,} \\ 0.020\ (0.041) & \text{global data.} \end{cases}$$

Be careful, these are regions for $\sin^2\theta_{ij}$!!

$\mathbf{\sin^2\theta_{13}} = 0.02 \Rightarrow \mathbf{\sin^2 2\theta_{13}} = 0.08$

Cheat Sheet:

$U_{e3}^2 = \sin^2\theta_{13} \sim ½ \sin^2\theta_{\mu e} \sim 1/4 \sin^2 2\theta_{13}$

Experimental Methods to Measure θ_{13}

- Long-Baseline Accelerators: Appearance ($\nu_\mu \rightarrow \nu_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for appearance of ν_e or ν_τ in a pure ν_μ beam vs. L and E
    - Use near detector to measure background ν_e's (beam and misid)

NOνA:
$\langle E_\nu \rangle = 2.3$ GeV
L = 810 km

T2K:
$\langle E_\nu \rangle = 0.7$ GeV
L = 295 km

- Reactors: Disappearance ($\bar{\nu}_e \rightarrow \bar{\nu}_e$) at $\Delta m^2 \approx 2.5\times10^{-3}$ eV^2
  - Look for a change in ν_μ flux as a function of L and E
    - Look for a non- $1/r^2$ behavior of the ν_e rate
    - Use near detector to measure the un-oscillated flux

Double Chooz:
$\langle E_\nu \rangle = 3.5$ MeV
L = 1100 m

Long-Baseline Accelerator Appearance

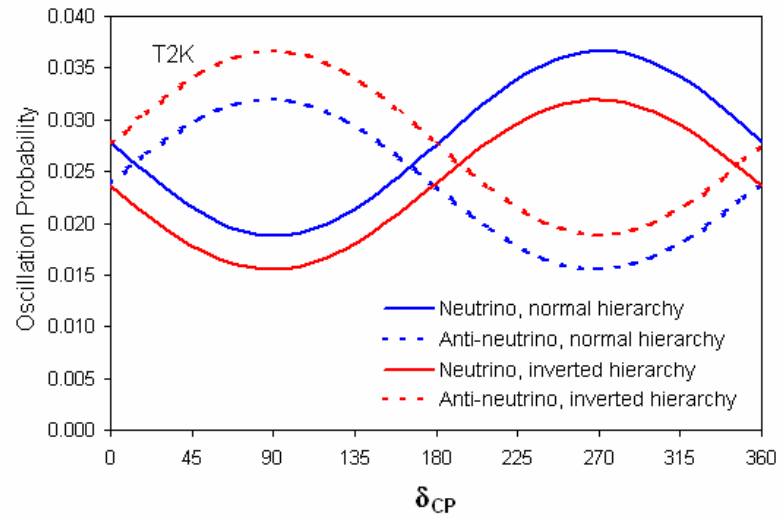
- Oscillation probability dependent not only on mixing angles but also:
  1. CP violation parameter (δ)
  2. Mass hierarchy (sign of Δm_{31}^2)
  3. Size of $\sin^2\theta_{23}$ (as opposed to the measured $\sin^2 2\theta_{23}$)

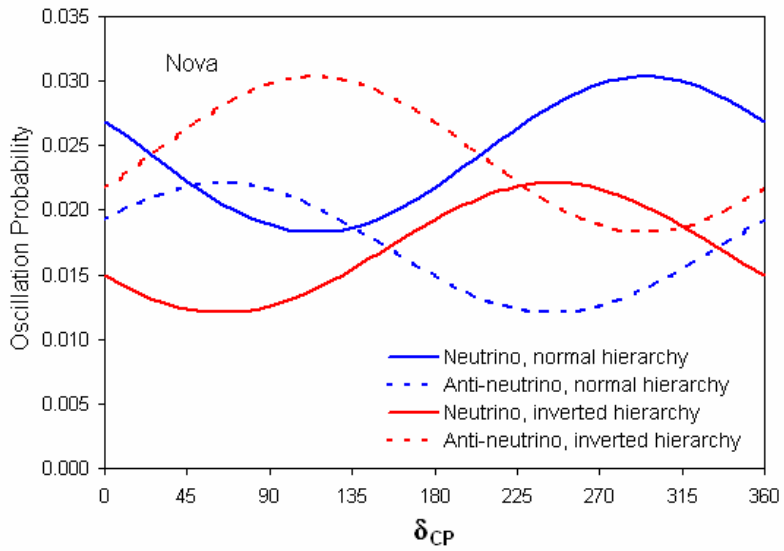
- These are both complications and an opportunity to measure these parameters
  - Use information from other oscillation measurements: reactors, solar/atmospheric/accelerator disappearance
  - Use combinations of appearance measurements for neutrinos and antinuetrinos at different baselines to determine CP δ and mass hierarchy

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

Oscillation probability vs δ_{CP} for Long-Baseline Appearance

($\Delta m^2 = 2.5\times10^{-3}$ eV^2 , $\sin^2 2\theta_{13} = 0.05$)





Blue: normal hierarchy

Red: inverted hierarchy

Solid: neutrino

Dashed: antineutrino

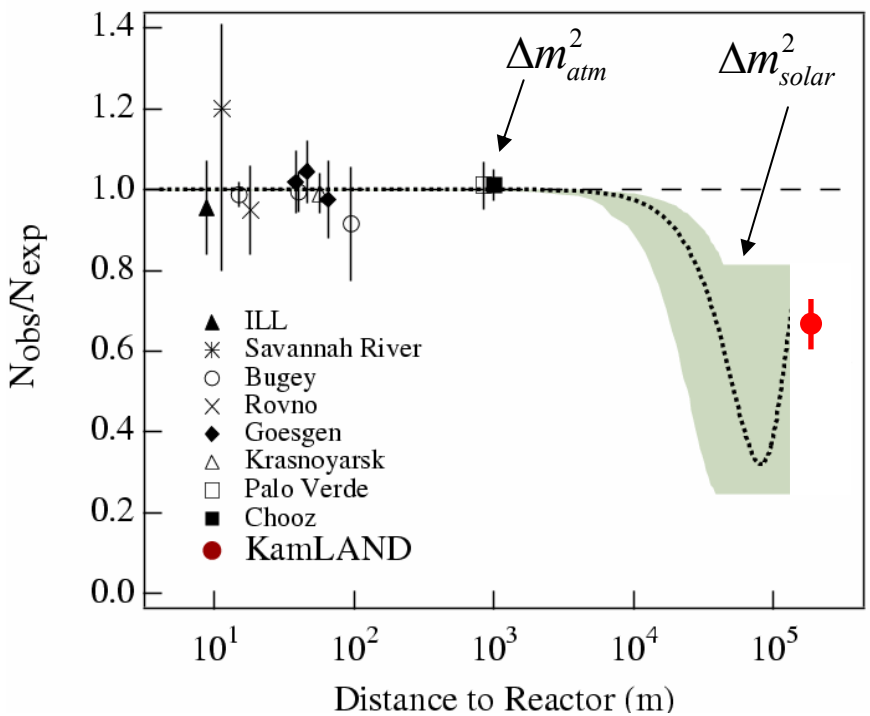
Reactor Disappearance Oscillation Probability

- In contrast, the reactor disappearance probability provides a straight forward method to measure $\sin^2 2\theta_{13}$ with no dependence on matter effect and CP violation
  - Only complication is associated with the atmospheric and solar Δm^2 interference terms which is small.

$$
\begin{aligned}
P_{\bar{\nu}_e \to \bar{\nu}_e} &= 1 - 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\
&- \frac{1}{2}\cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&+ 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}\left(\cos\left(\frac{\Delta m^2_{31} L}{2E} - \frac{\Delta m^2_{21} L}{2E}\right) - \cos\left(\frac{\Delta m^2_{31} L}{2E}\right)\right)
\end{aligned}
$$

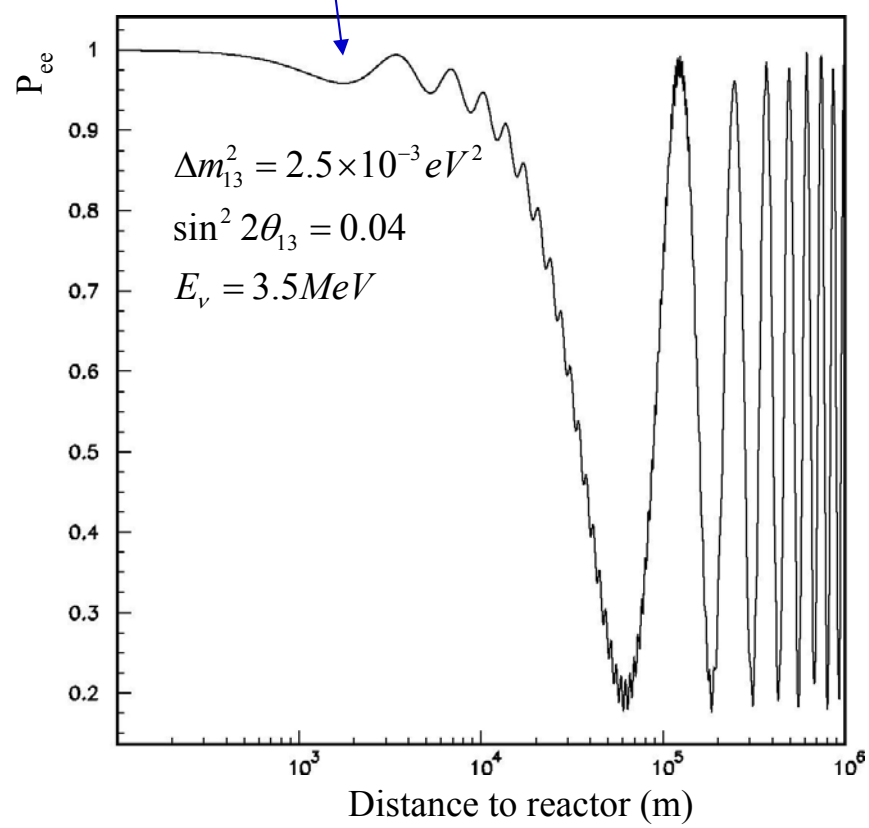
Reactor Measurements of $P(\bar{\nu}_e \to \bar{\nu}_e)$

Past measurements:



Future: Search for small oscillations at 1-2 km distance (corresponding to Δm^2_{atm}).

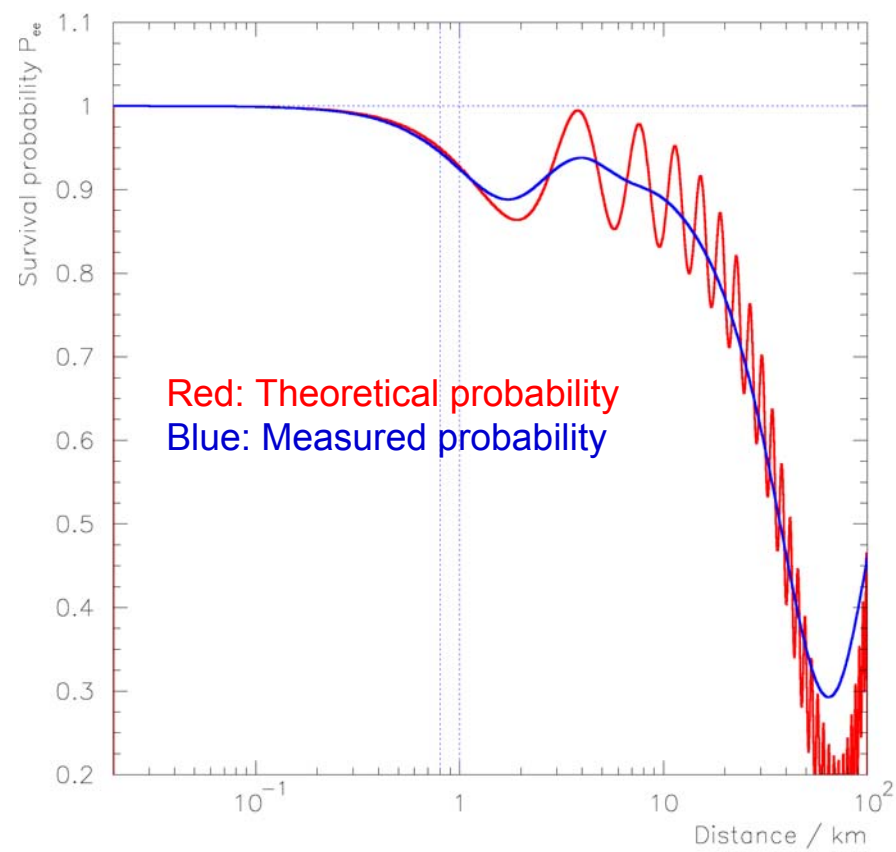
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx \underbrace{1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{13} L}{4E}} - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{12} L}{4E}$$



Experimental Resolution Effects

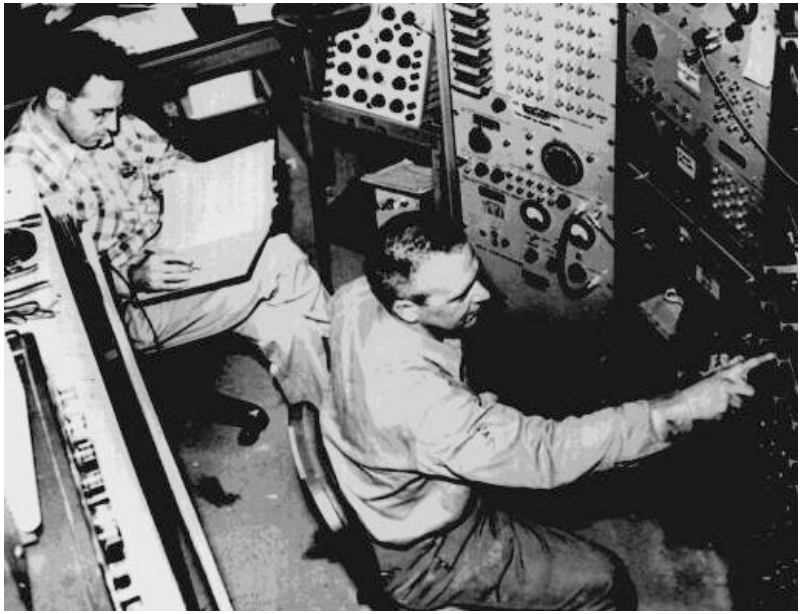
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$

- Oscillation probability is dependent on neutrino energy and distance from source-detector
- Oscillatory behavior is "washed" out by:
  - Finite energy resolution
    - Effectively integrate over the ~7-10 % uncertainty in the measured energy
  - Spread in distances from reactor
    - Reactor core size
    - Varying distances from multiple reactors



Reactor Neutrino Experiments

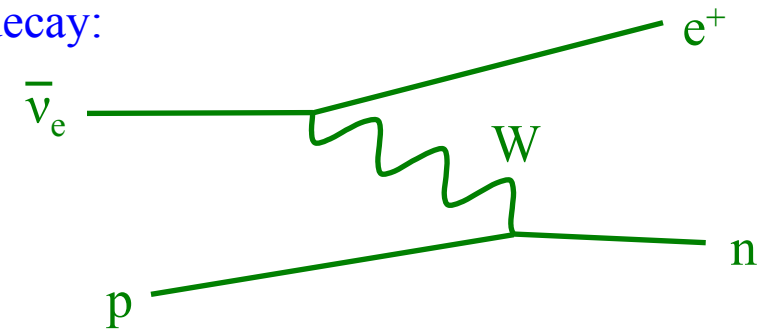
Long History of Reactor Neutrino Measurements



Reines and Cowan at the Savannah River Reactor

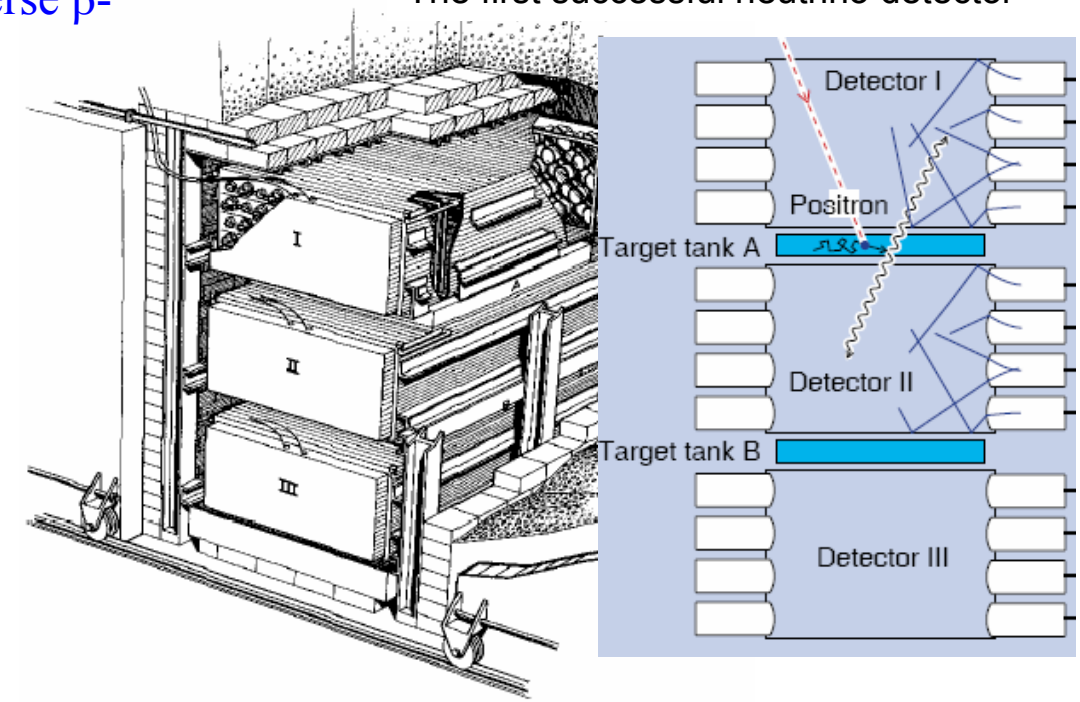
The original neutrino discovery experiment, by Reines and Cowan, used reactor anti-neutrinos…

The $\bar{\nu}_e$ interacts with a free proton via inverse β-decay:



Later the neutron captures giving a coincidence signal. Reines and Cowan used cadmium to capture the neutrons (modern exp. use Gadolinium)

The first successful neutrino detector



Nuclear Reactors as a Source of $\bar{\nu}_e$'s

Where are the reactor $\bar{\nu}_e$'s from?

- Typical modern nuclear power reactor has a thermal power of: P_{therm} = 3.8 GW
- About e=200 MeV / fission of energy is released in fission of ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu.
- The resulting fission rate, f, is thus: f = 1.2 ×10^{20} fissions/s
- At 6 $\bar{\nu}_e$ / fission the resulting yield is: 7.1 ×10^{20} / s.

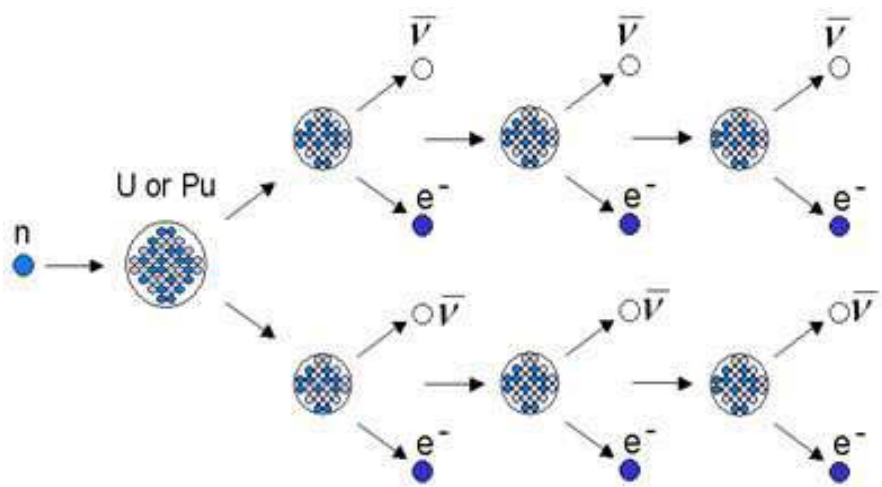
Example: ^{235}U fission

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

nuclei with most likely A from ^{235}U fission $\quad ^{94}_{40}Zr \quad ^{140}_{58}Ce$

→ on average 6 n have to β-decay to 6 p to reach stable matter.

→ on average 1.5 ν_e are emitted with energy > 1.8 MeV

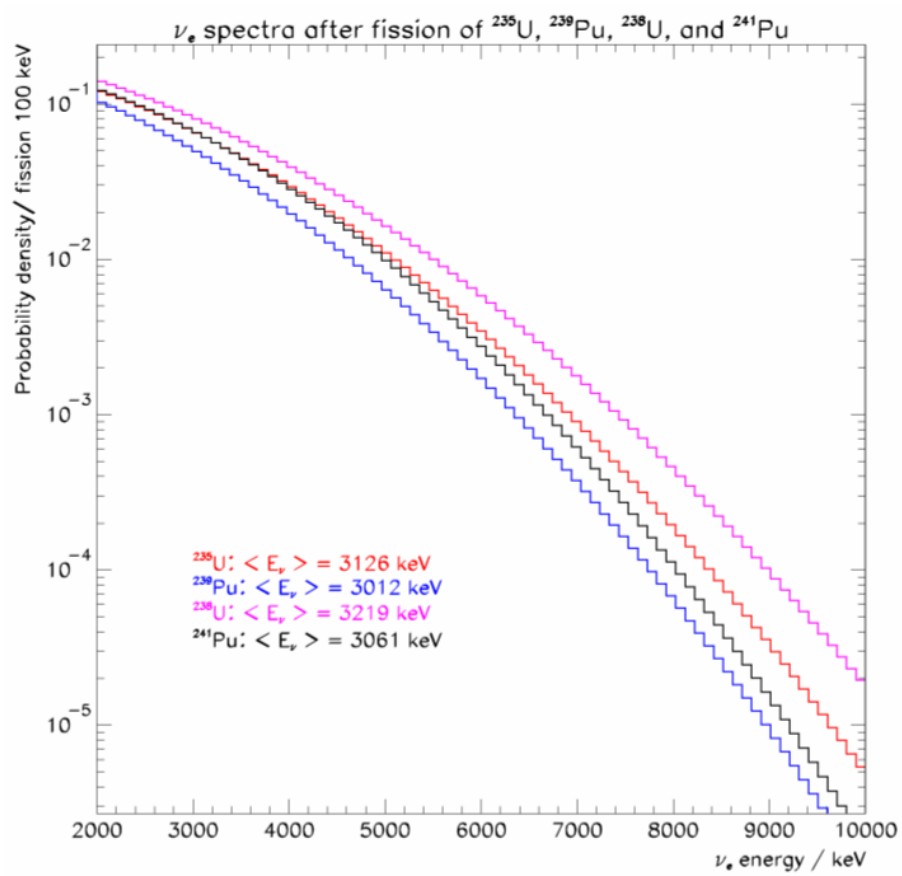


Reactor Neutrino Energy Spectrum Related to Measured Reactor Beta Spectrum

$$dN_e = p_e \cdot E_e \cdot (Q - E_\beta) \cdot F(Z, A) \quad dE_e$$

$$dN_\nu = \sqrt{(Q + m_e - E_\nu)^2 - m_e^2} \cdot (Q + m_e - E_\nu) \cdot E_\nu^2 \cdot F(Z, E_e) \quad dE_\nu$$

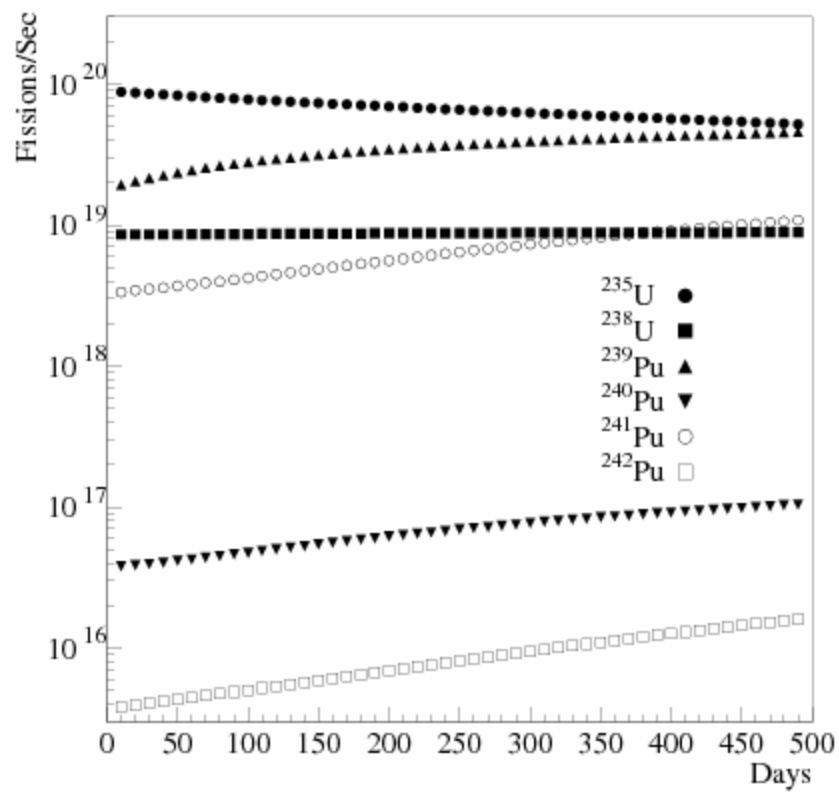
- β^- spectra resulting from fission of ^{235}U, ^{239}Pu, and ^{241}Pu has been experimentally measured
  - Can be converted into the $\bar{\nu}_e$–spectra.
    - K. Schreckenbach et al., Phys. Lett. B160 (1985);
    - A.A. Hahn et al., Phys. Lett. B218 (1989)
- ^{238}U beta spectra not available since fast fissions
  - Determined from theoretical calculation (±10%)
  - ^{238}U only 10% of rate



Burn-up Corrections

- Burn-up correction needed
  - The percentage of the different primary isotopes change with time
  - Different fuel components yield different spectra

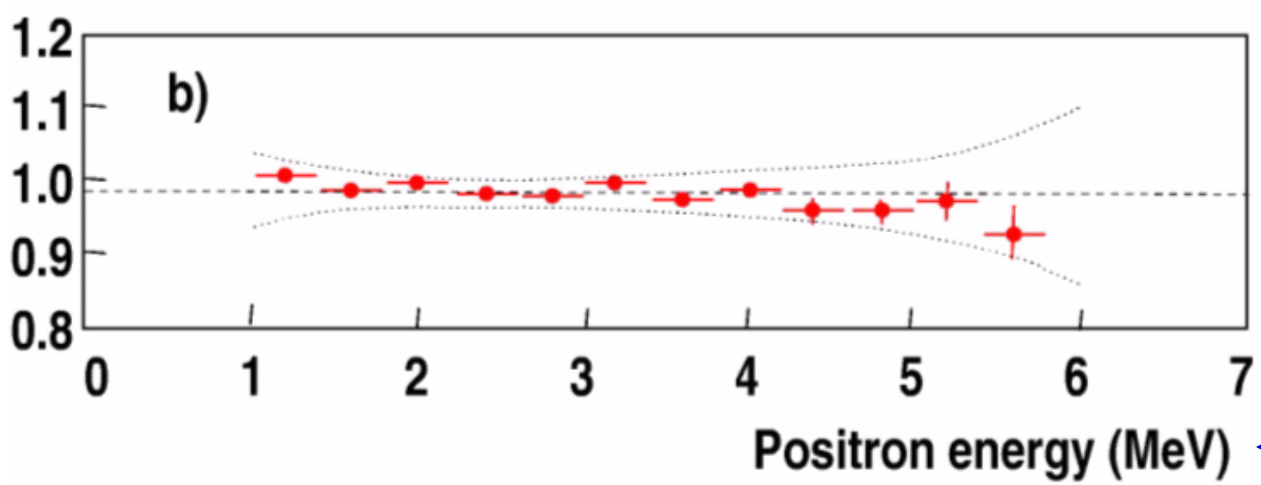
- Experiments receive information from reactor company who understand this very well
  - Use information to calculate a time dependent rate of neutrinos vs energy



Derived ν Spectrum Checked Against Data

β^- spectra measured for ^{235}U, $^{239,241}Pu$ at ILL. Converted into ν–spectra.
For ^{238}U theoretical calculation.

Most precise test: Bugey 3 (L=10–40 m, $1.5 \cdot 10^5$ $\bar{\nu}_e$–events.)
(Achkar et al., Phys. Lett. B374 (1996))



From ν interactions

Spectra derived from β–spectra. ±1.4% agreement.

Inverse Beta-Decay Kinematics

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

m_e=0.511 MeV
m_p=938.272 MeV
m_n=939.565 MeV

$$E_{thr} = \frac{(m_e + m_n)^2 - m_p^2}{2 \cdot m_p} \cdot c^2 \approx (m_e + m_n - m_p) \cdot c^2 = 1.806\,\text{MeV}$$

$$E_{\bar{\nu}} = E_\beta + \underbrace{m_e + m_n - m_p}_{\text{Threshold energy 1.805 MeV}} - \underbrace{O\left(\frac{E_{\bar{\nu}}^2}{m_n}\right)}_{\text{Neutron kinetic energy. Small 10-100 keV}}$$

A measurement of the outgoing positron energy gives the energy of the incoming neutrino!

Inverse Beta Decay Cross Section Known Very Accurately

$$\sigma_{tot}(E_e) \approx \underbrace{\frac{2\pi^2\hbar^3}{m_e^5 c^7 f \tau_n}}_{} \cdot \underbrace{p_e \cdot E_e}_{} \approx \frac{p_e \cdot E_e}{1\,MeV^2} \cdot 10^{-43}\ cm^2$$

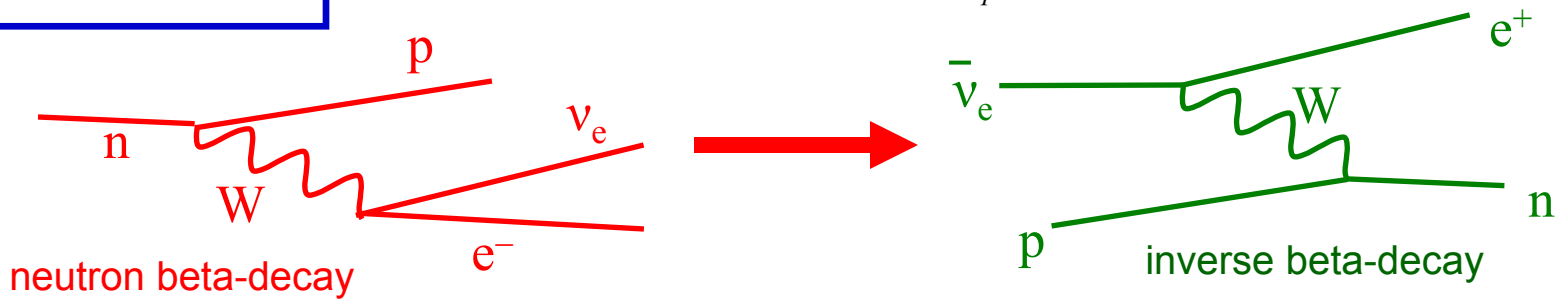
Squared matrix element, derived from decay of free neutron.

Phase space

In terms of neutrino energy

$$\sigma_{tot}(E_\nu) \approx \frac{2\pi^2\hbar^3}{m_e^5 c^7 f \tau_n} \cdot (E_{\bar{\nu}} - \Delta) \cdot \sqrt{(E_{\bar{\nu}} - \Delta)^2 - m_e^2}$$

$$\Delta = m_n - m_p$$

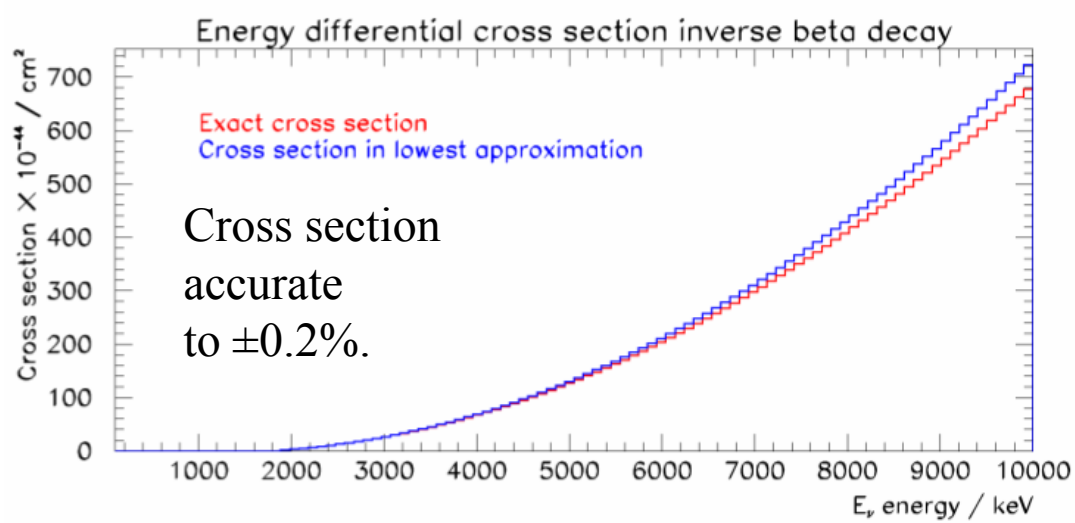


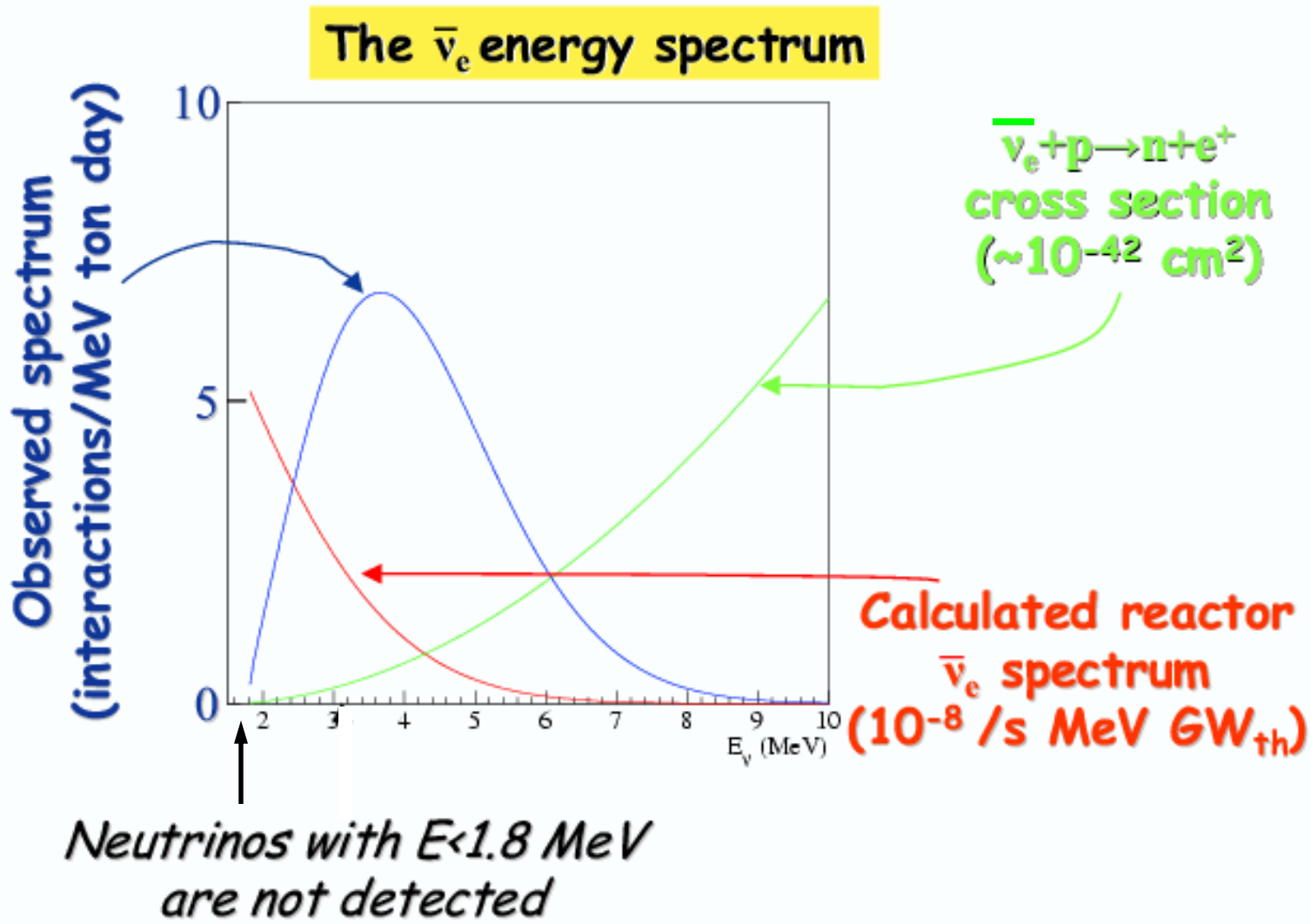
neutron beta-decay

τ_n = 885.7 ± 0.8 s (0.1%)

For precise cross section:
- Radiative corrections
- Weak magnetism correction
- Neutron recoil correction

Vogel & Beacom,
Phys. Rev. D60 (1999)




The $\bar{\nu}_e$ energy spectrum
Observed spectrum
(interactions/MeV ton day)
10
5
0
2
3
4
5
6
7
8
9
10
E_ν (MeV)
$\bar{\nu}_e + p \rightarrow n + e^+$
cross section
($\sim 10^{-42}$ cm^2)
Calculated reactor
$\bar{\nu}_e$ spectrum
(10^{-8} /s MeV GW$_{th}$)
Neutrinos with E<1.8 MeV
are not detected

Comparison of Prediction to Goesgen Observation

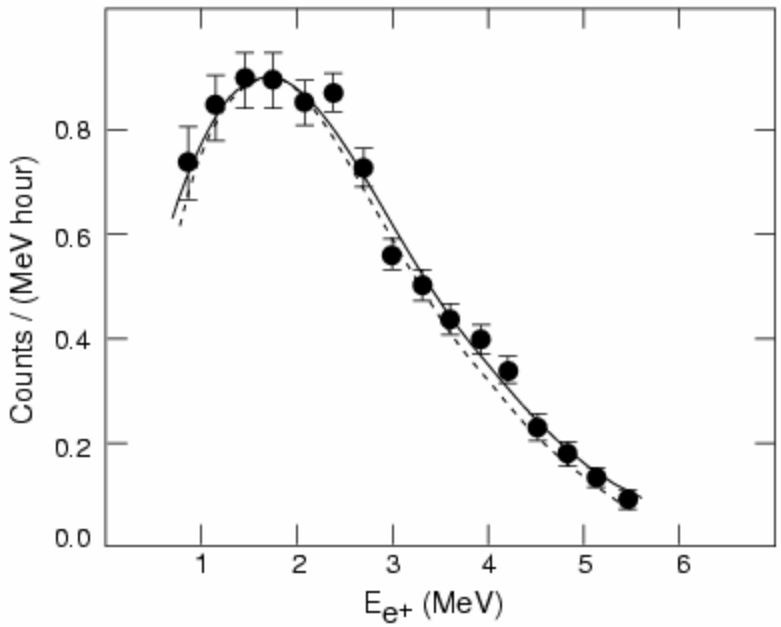


Figure 5: Positron spectrum measured at 45.9 m from the core of the Gösgen reactor [36]. Data points are obtained after background subtraction, errors are statistical only. The solid curve is a fit to the data assuming no oscillations. The dashed curve is derived independently by β-spectroscopy.

Flux and Energy Spectrum → ~1-2 %

Summary for Reactor Neutrino Fluxes and Event Rates

Flux and energy distribution of reactor anti-neutrinos is well understood to within ±1.5%.

Flux and spectral models have been tested in independent ways using:

- β–spectroscopy
- direct anti–neutrino detection
- isotopic analysis of fuel elements

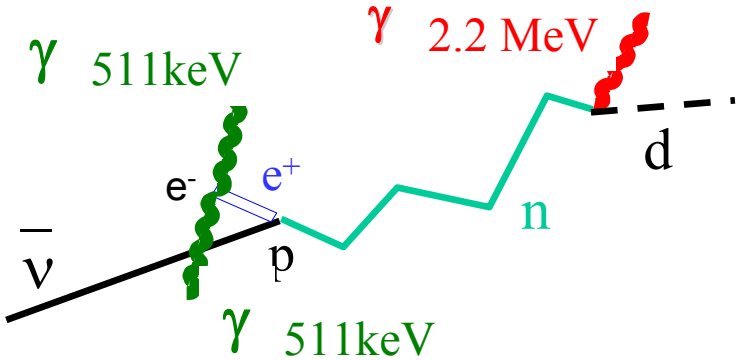
Reactors are a well understood source of $\bar{\nu}_e$ and can be used as a precision tool for physics measurements

Signal and Major Neutron Background

Coincidence signal: detect

- Prompt: e^+ annihilation
  → $E_\nu = E_{prompt} + E_n + 0.8$ MeV
- Delayed: **n** capture 180 μs capture time
  - capture on proton → d
  or - capture on Gd → Gd* → γ's

SIGNAL

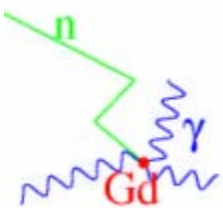


$$\bar{\nu}_e + p \rightarrow n + e^+$$

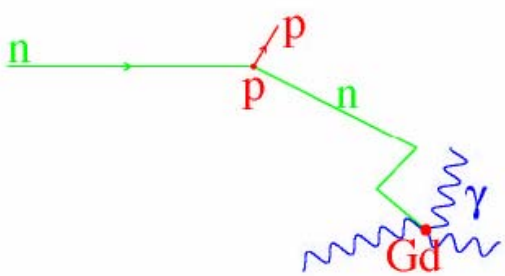
$$\Downarrow$$

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \sum \gamma_i$$

$$\sum_i E_{\gamma_i} \cong 8 \text{ MeV}$$



CORRELATED BACKGROUND



neutrons from cosmic ray μ interaction in the rock

e^+-like signal faked by the proton recoil

Backgrounds for Reactor Disappearance Exp's

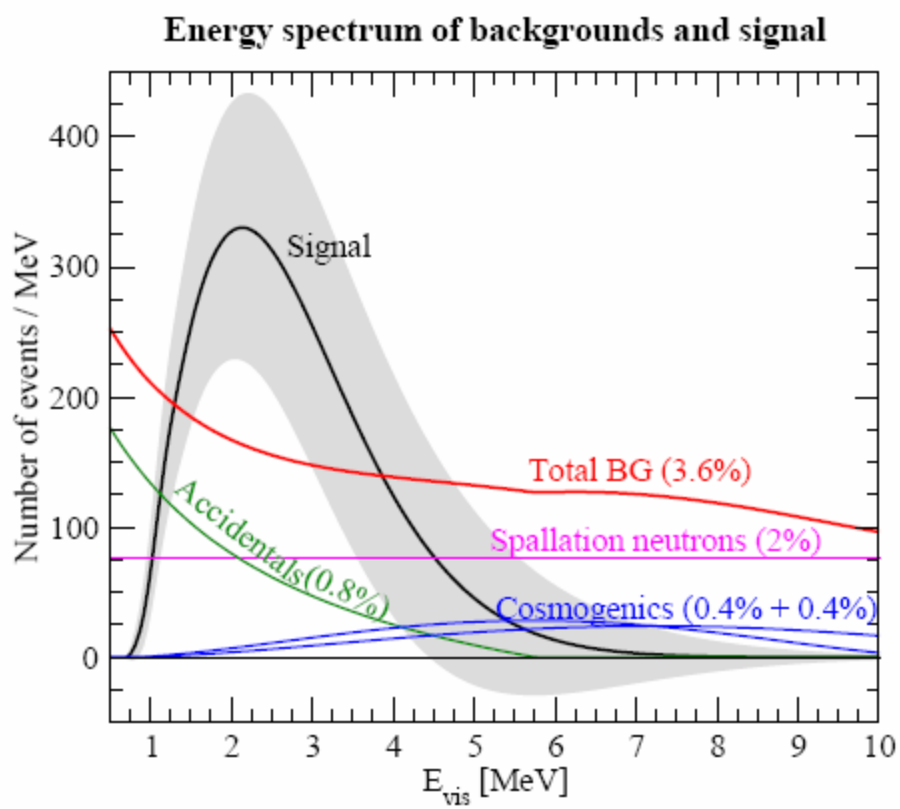
- Backgrounds to the e^+ - n coincidence signal

  Uncorrelated Backgrounds
  - ambient radioactivity
  - accidentals
  - cosmogenic neutrons

  Correlated Backgrounds
  - cosmic rays induce neutrons in the surrounding rock and buffer region of the detector
  - cosmogenic radioactive nuclei that emit delayed neutrons in the detector

    eg. ^{8}He (T1/2=119ms)

    ^{9}Li (T1/2=178ms)



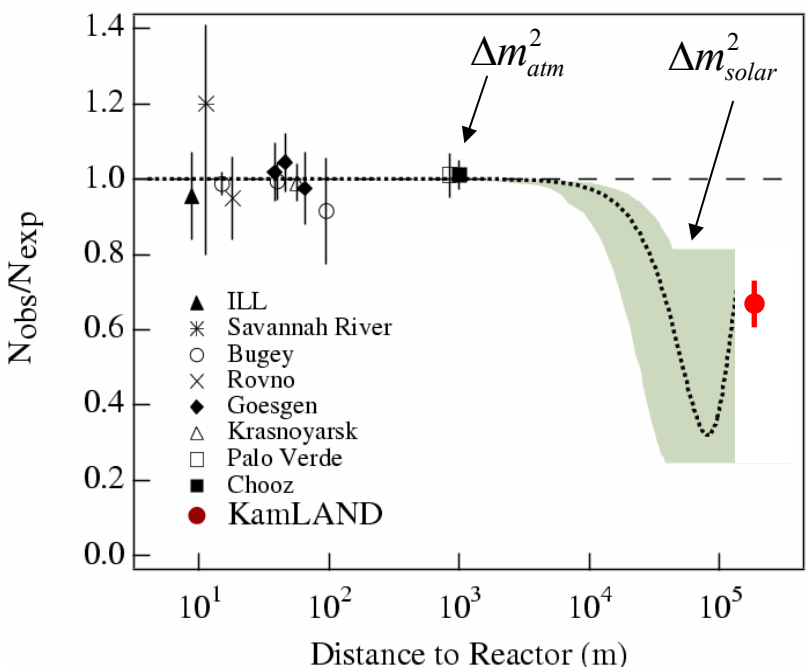
Reactor Neutrino Experiments

Past and Present Reactor Experiments

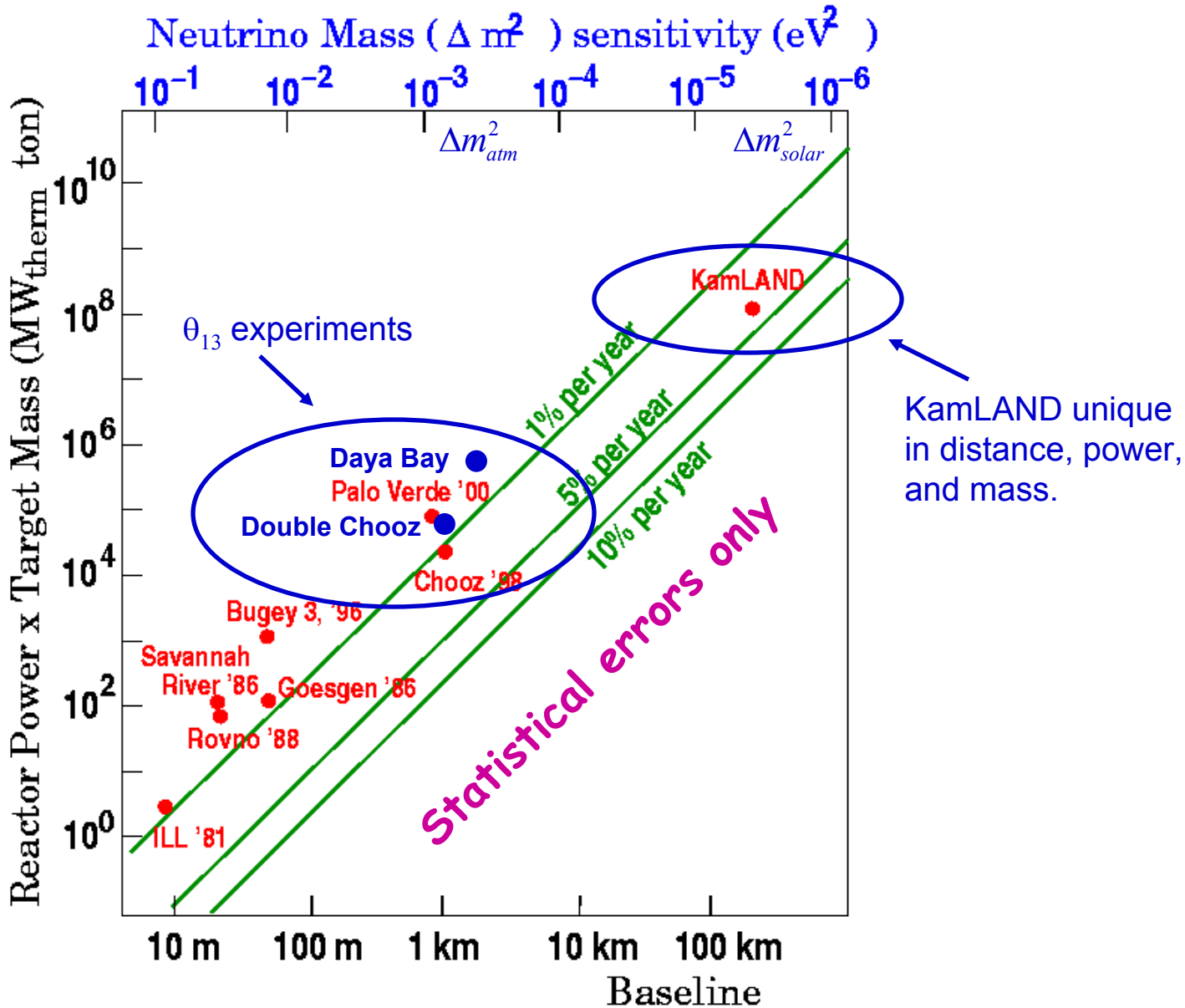
- Solar neutrino Δm^2 region
  - Kamland experiment $\Leftarrow$ single detector, multiple reactors

- Single detector experiments probing $\Delta m^2 \geq \Delta m_{atm}^2$
  - CHOOZ and Palo Verde $\Leftarrow$ single detector exp's at Δm_{atm}^2
  - Other experiments probe higher Δm^2 (ILL, Savanah River,Bugey,Goesgen,Rovno,Krasnoyarsk)

- New multi-detector experiments optimized for $\Delta m^2 = \Delta m_{atm}^2$
  - Double Chooz
  - Daya Bay
  - Plus possibly Reno and Angra

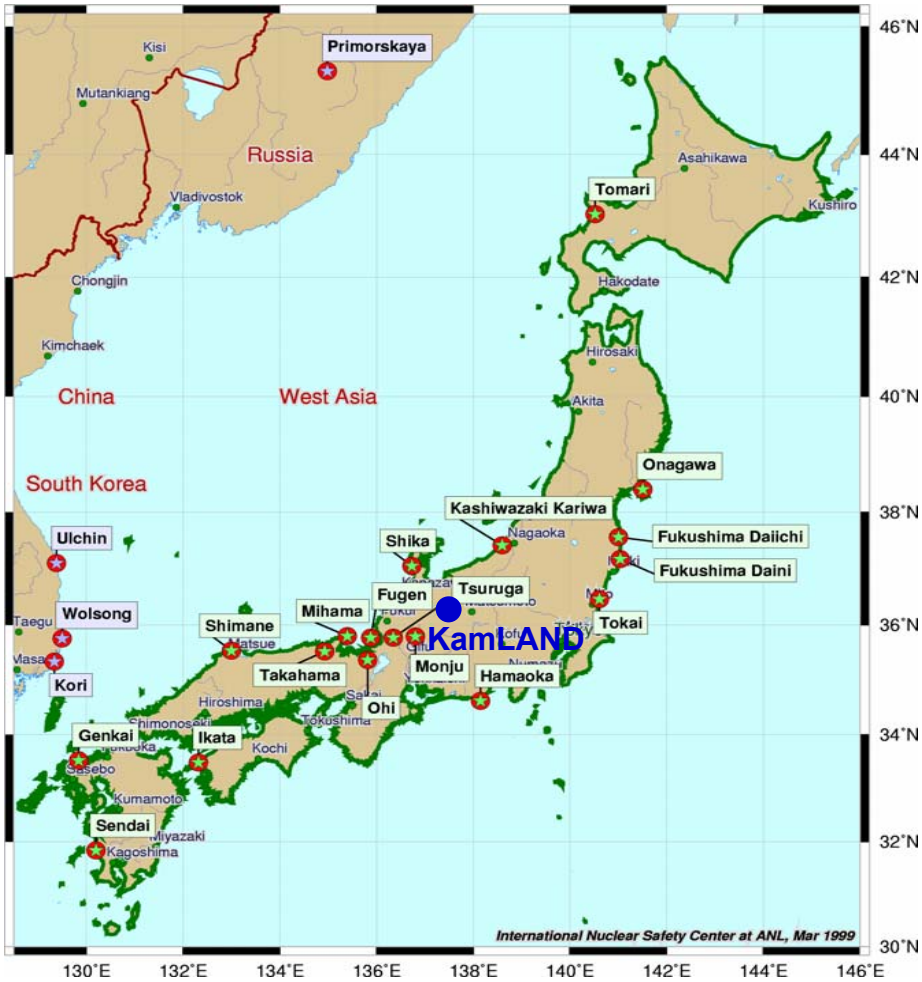


Event Rate (power x mass) vs Distance



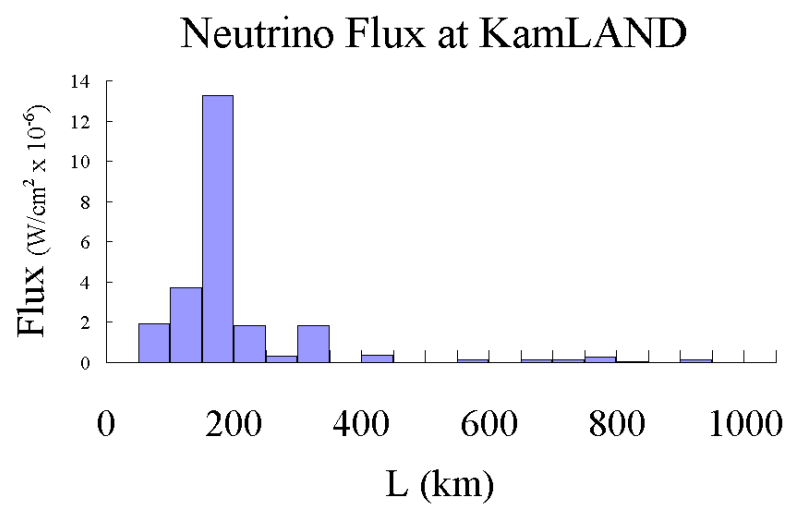
KamLAND Experiment

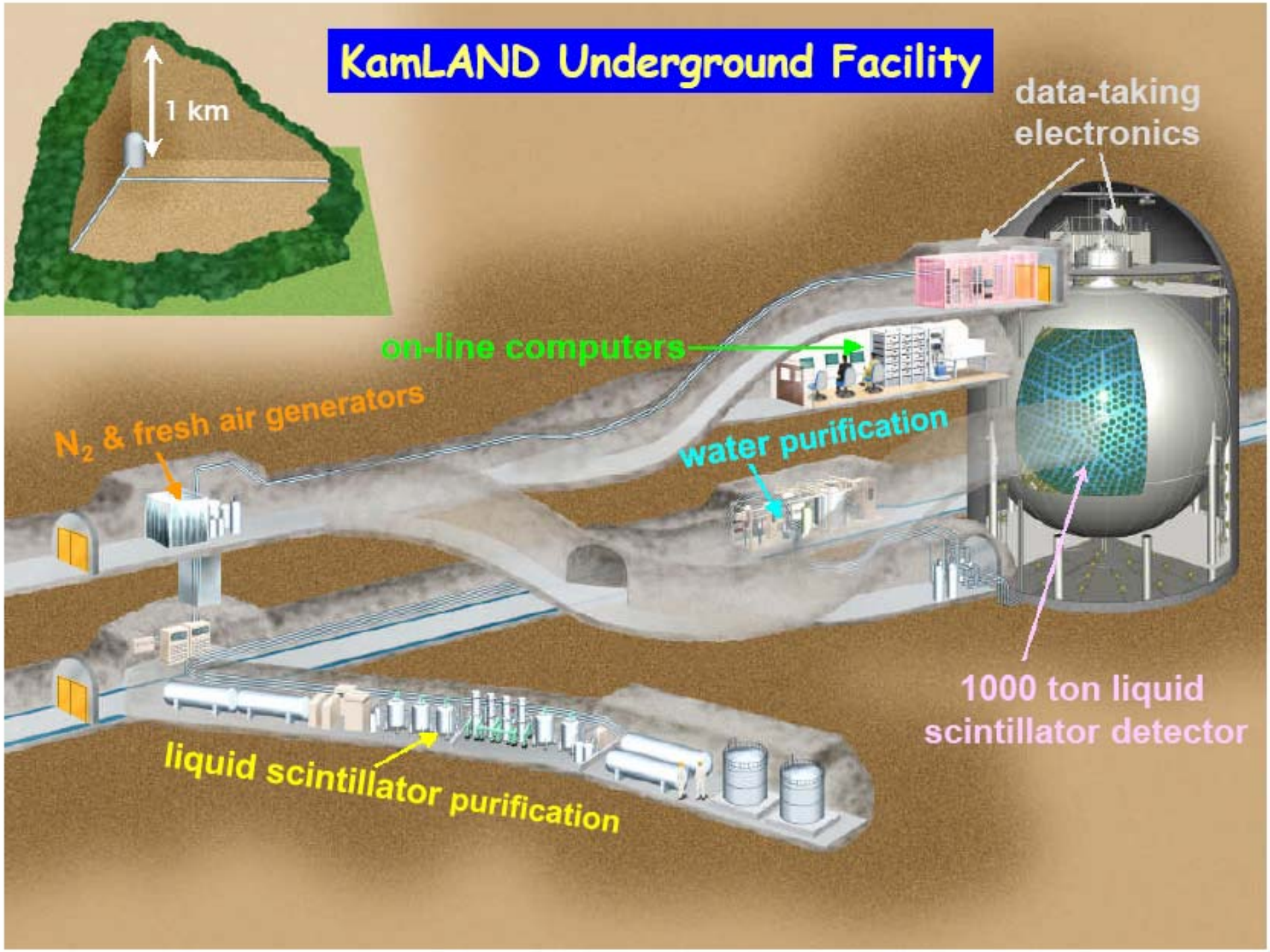
KamLAND Reactor Neutrino Exp



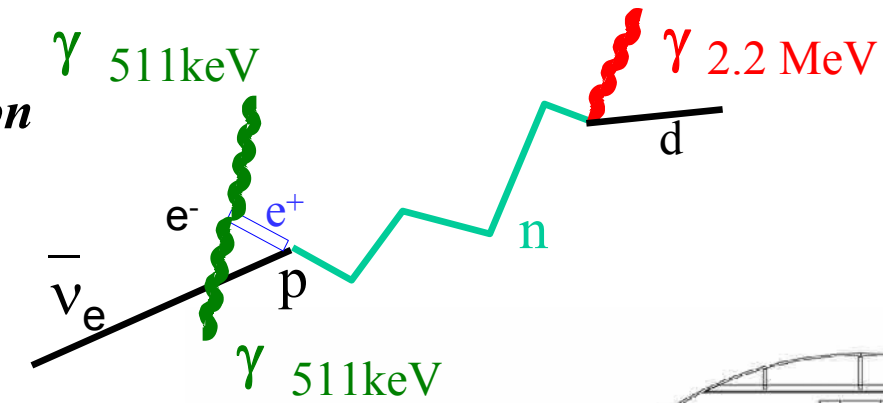
KamLAND uses all the Japanese reactors as a long-baseline source (60 GW)

- Fairly tight baseline spread (85.3% of flux 140 km < L < 344 km)

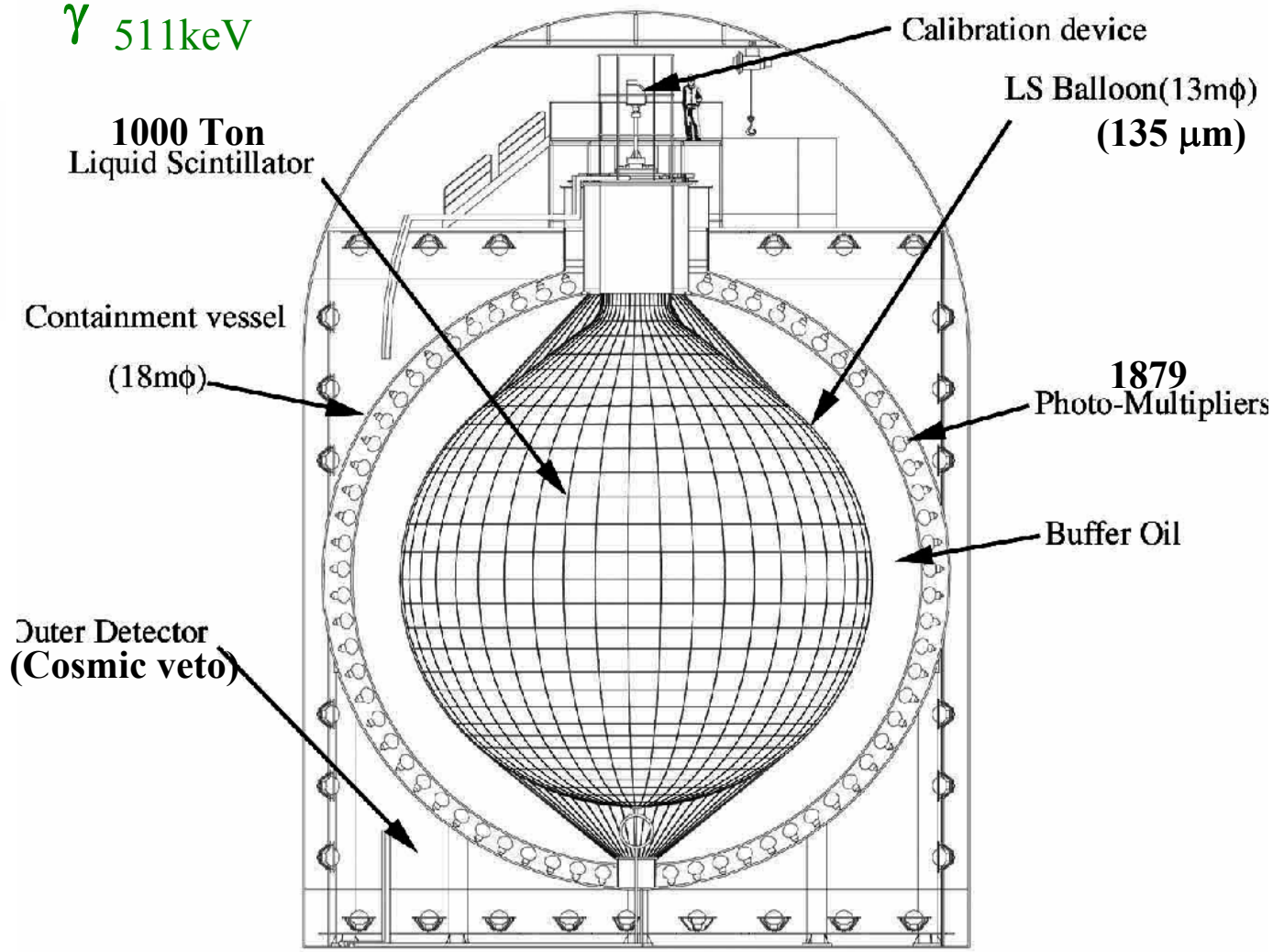



KamLAND Underground Facility
1 km
data-taking electronics
on-line computers
N_2 & fresh air generators
water purification
1000 ton liquid scintillator detector
liquid scintillator purification

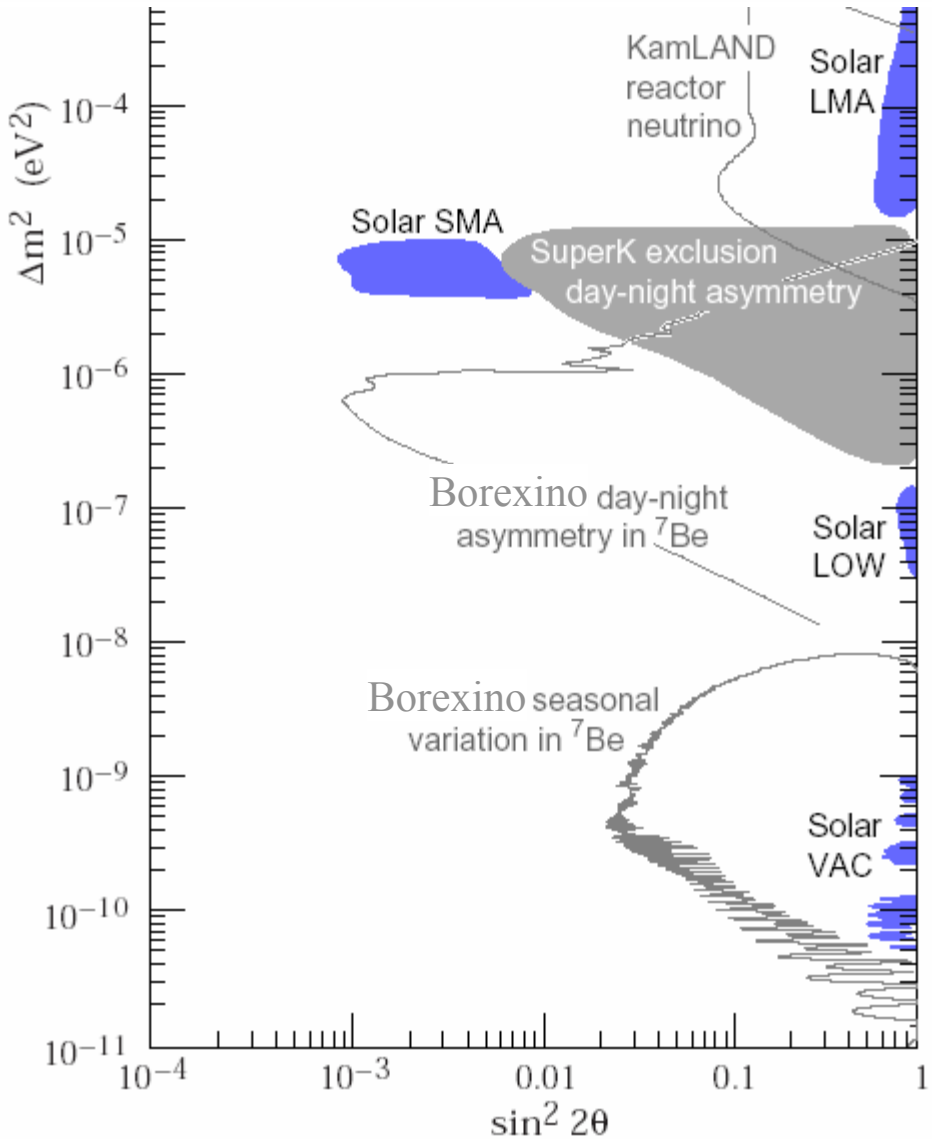
e^+ plus neutron delayed coincidence



KamLAND Detector



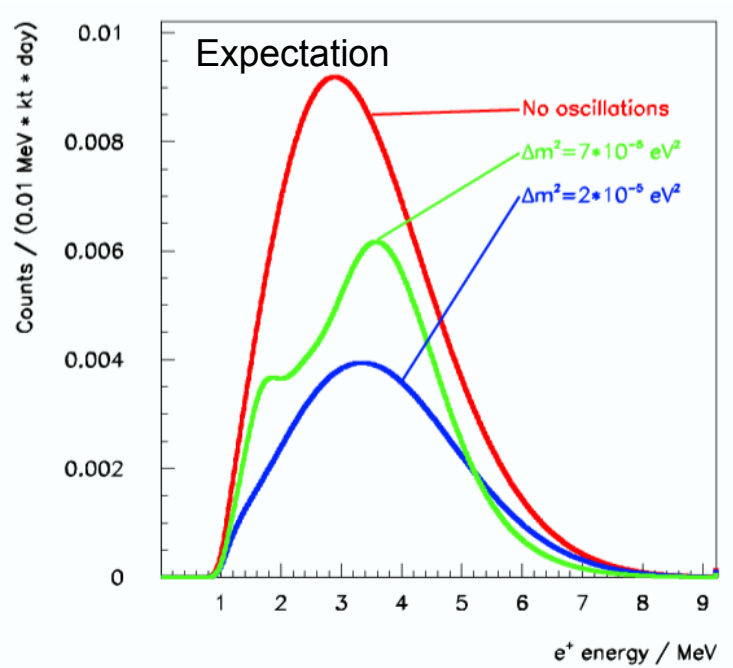
KamLAND Only Sensitive to Large Mixing Angle (LMA) Region

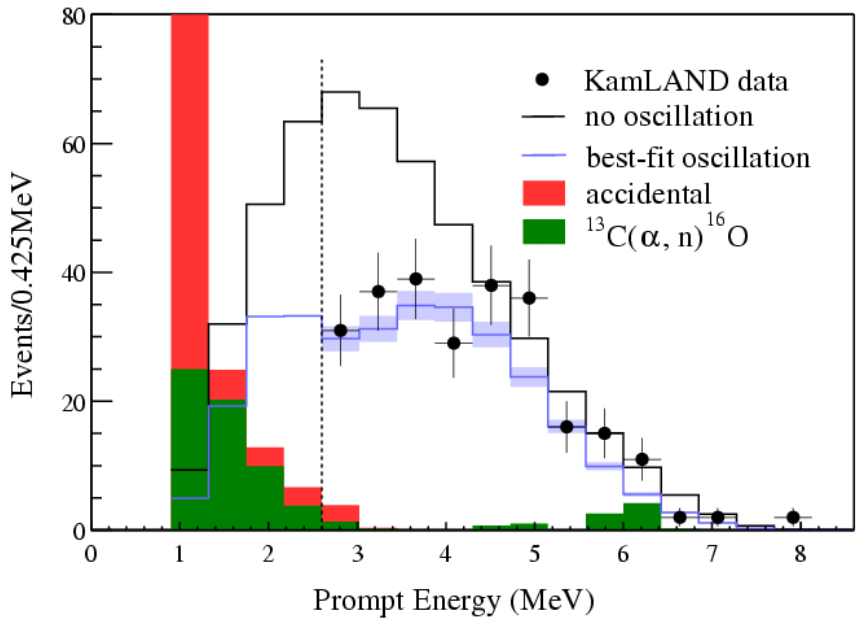


KamLAND was the key experiment that would break the degeneracy with respect to the different allowed regions for solar neutrino oscillations.

- If KamLAND doesn't see a signal, then LMA is gone
- If KamLAND sees a signal, then Solar Δm^2 would be precisely determined

KamLAND Results





Observed: 258 events
No-oscillation: 365.2 ± 23.7 events
Background: 17.6 ± 7.2 events

$(N_{obs} - N_{bkgnd})/N_{no\text{-}osc}$ =
0.658 ± 0.044 (stat) ± 0.047 (syst)
(99.998 % CL signal)

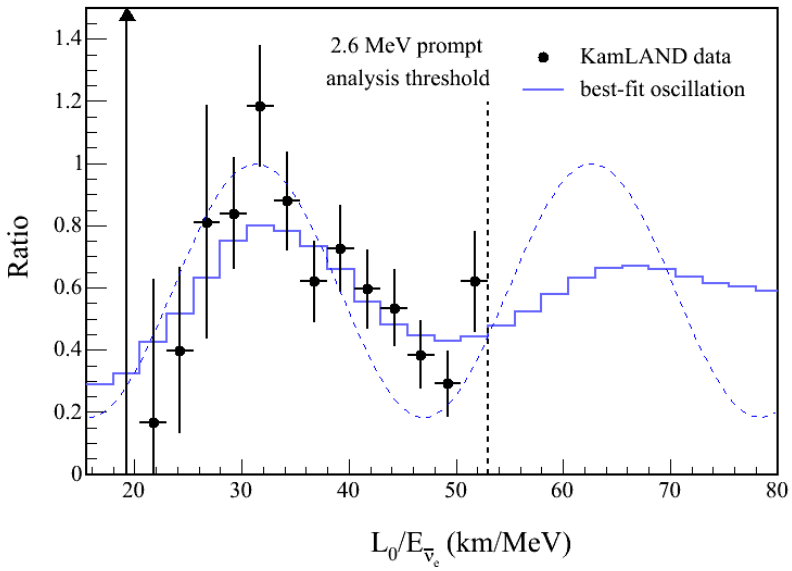
Neutrino Oscillation Interpretation

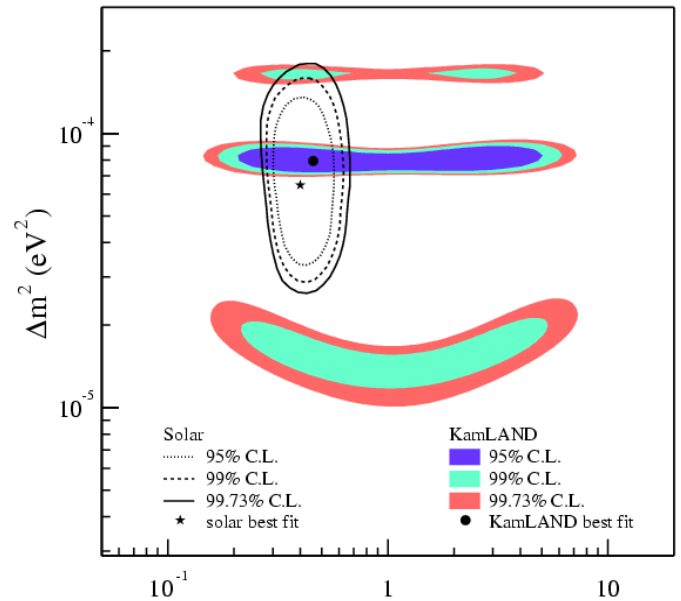
Distribution has L/E behavior expected for neutrino oscillations

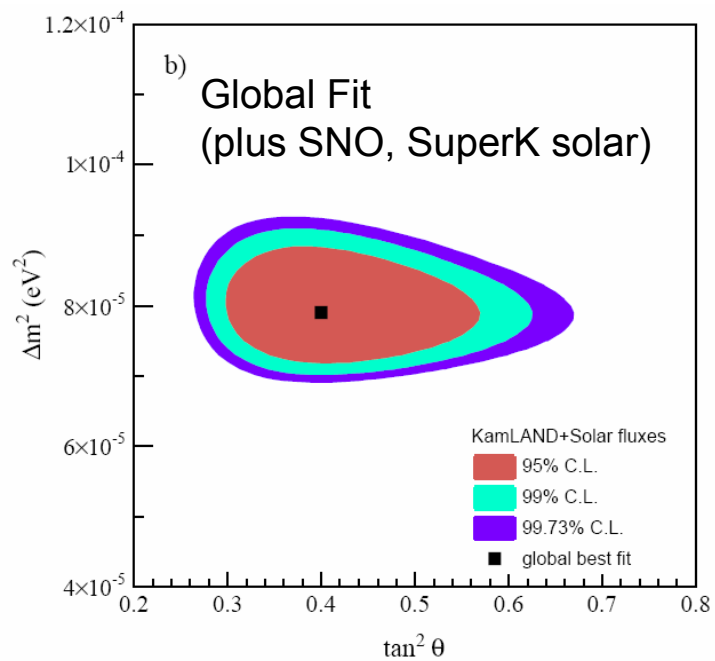
⇒ **KamLAND best fit :**

$\Delta m^2 = 7.9 \times 10^{-5}\ eV^2$

$\tan^2\theta = 0.45$







$\Delta m^2 = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ eV^2$

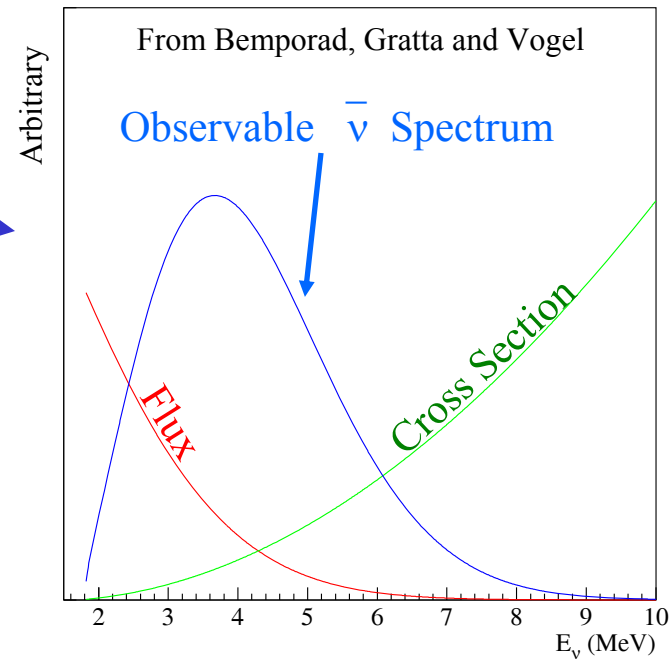
$\tan^2\theta = 0.40^{+0.10}_{-0.07}$

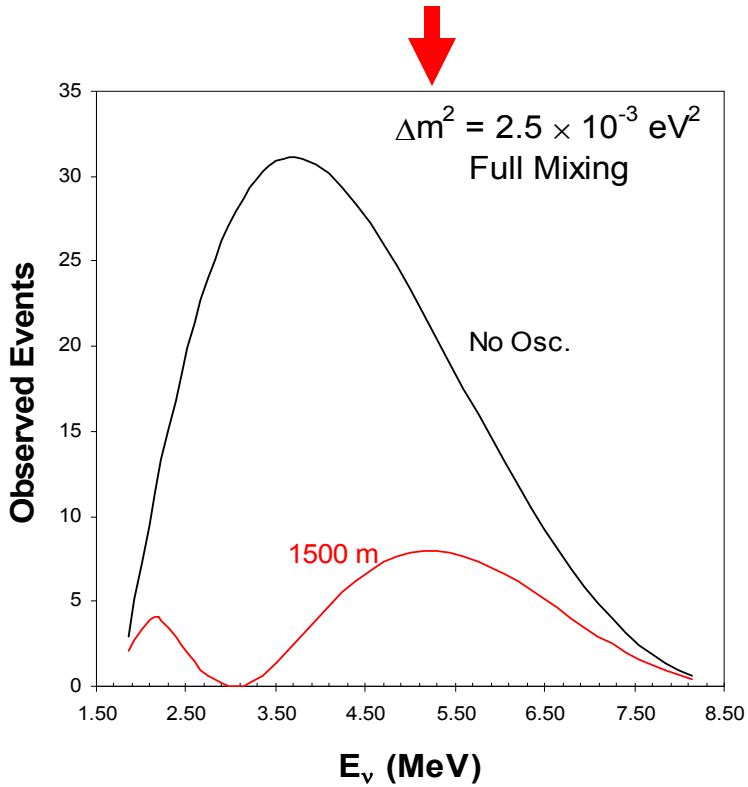
$(\sin^2 2\theta_{12} = 0.82^{+0.07}_{-0.07})$

Previous theta13 experiments

Reactor Measurements of θ_{13}

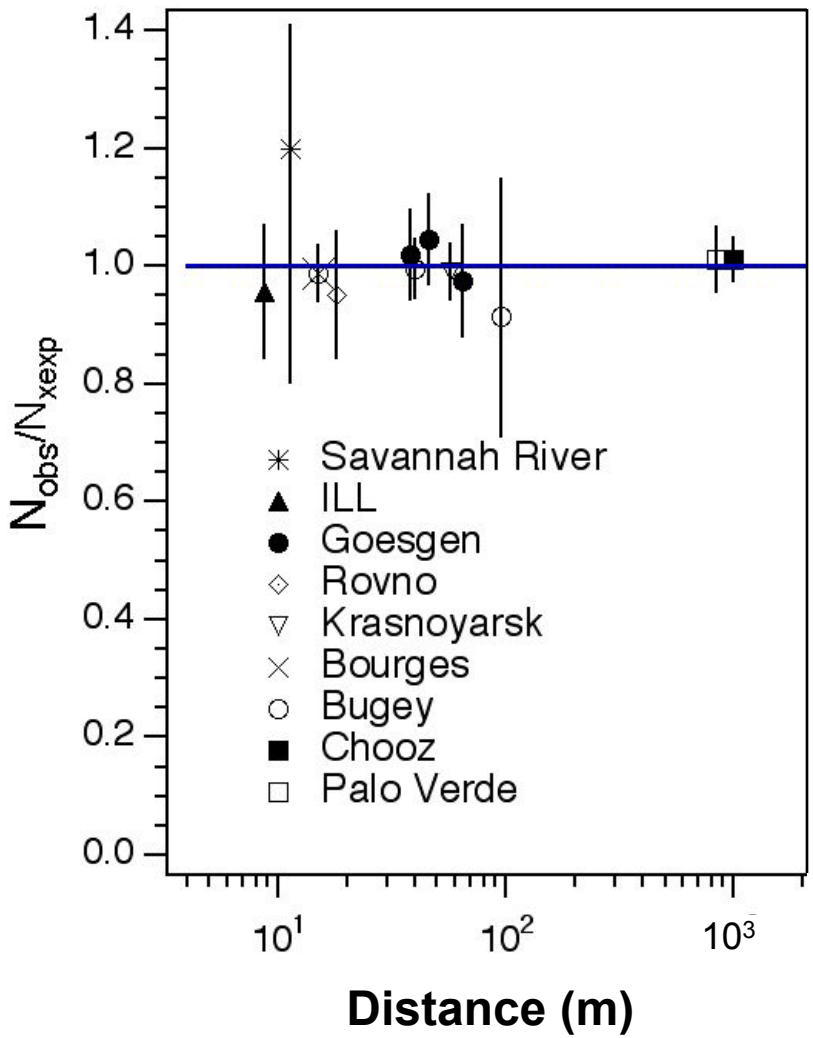
- Nuclear reactors are very intense sources of $\bar{\nu}_e$ with a well understood spectrum
  - 3 GW → 6×10^{20} $\bar{\nu}_e$/s
    700 events / yr / ton at 1500 m away
  - Reactor spectrum peaks at ~3.7 MeV
  - Oscillation Max. for $\Delta m^2=2.5\times10^{-3}$ eV^2 at L near 1500 m

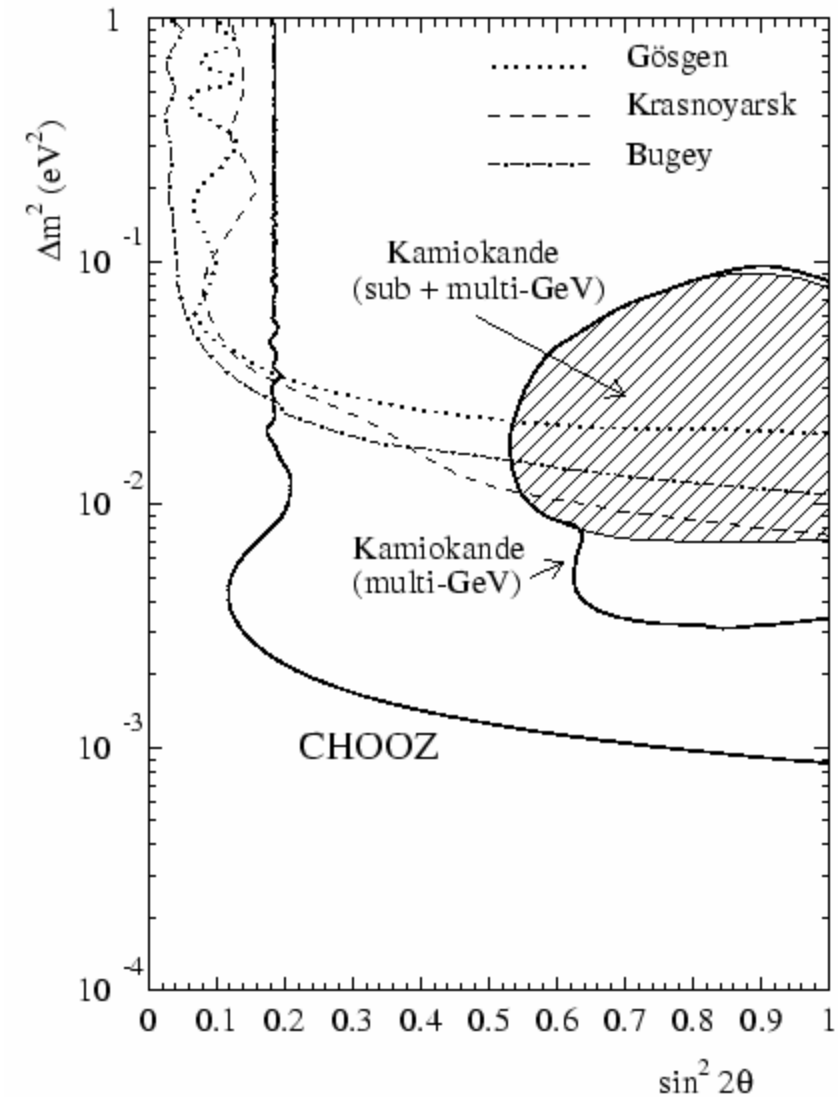




- Disappearance Measurement:
  Look for small rate deviation from $1/r^2$ measured at near and far baselines
  - Counting Experiment
    - Compare events in near and far detector
  - Energy Shape Experiment
    - Compare energy spectrum in near and far detector

Previous Early Oscillation Searches

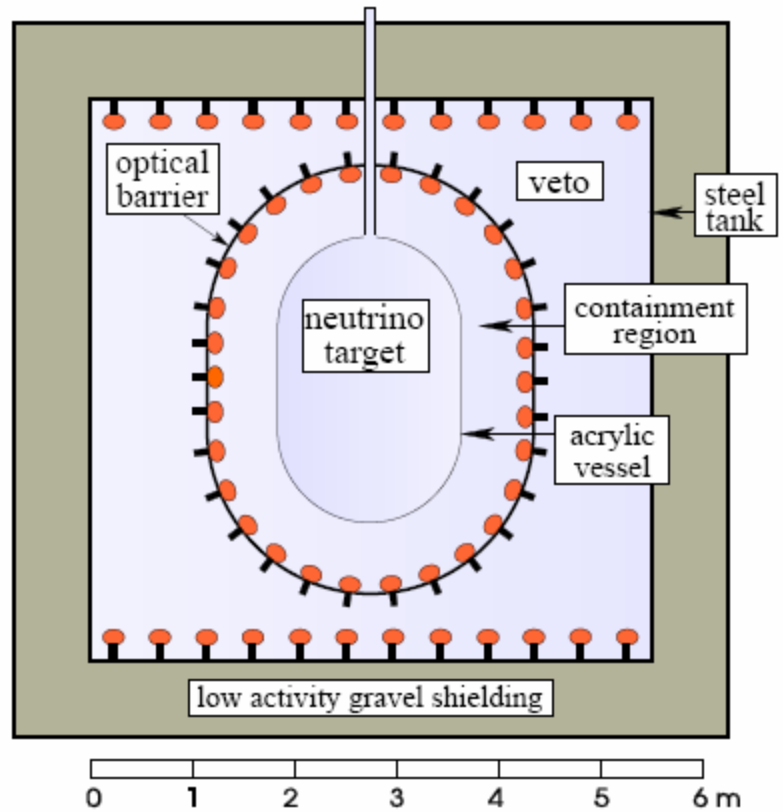




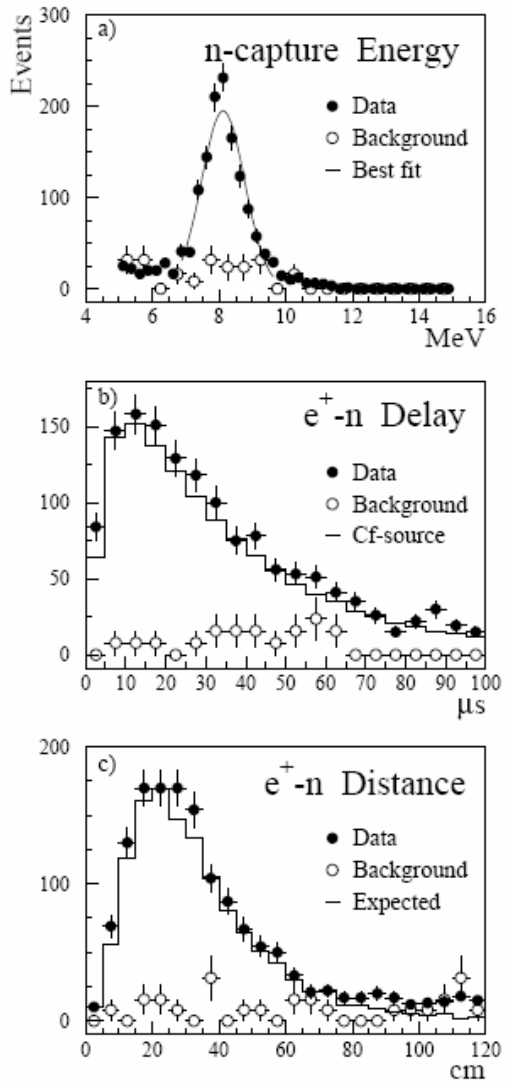
CHOOZ Reactor Experiment

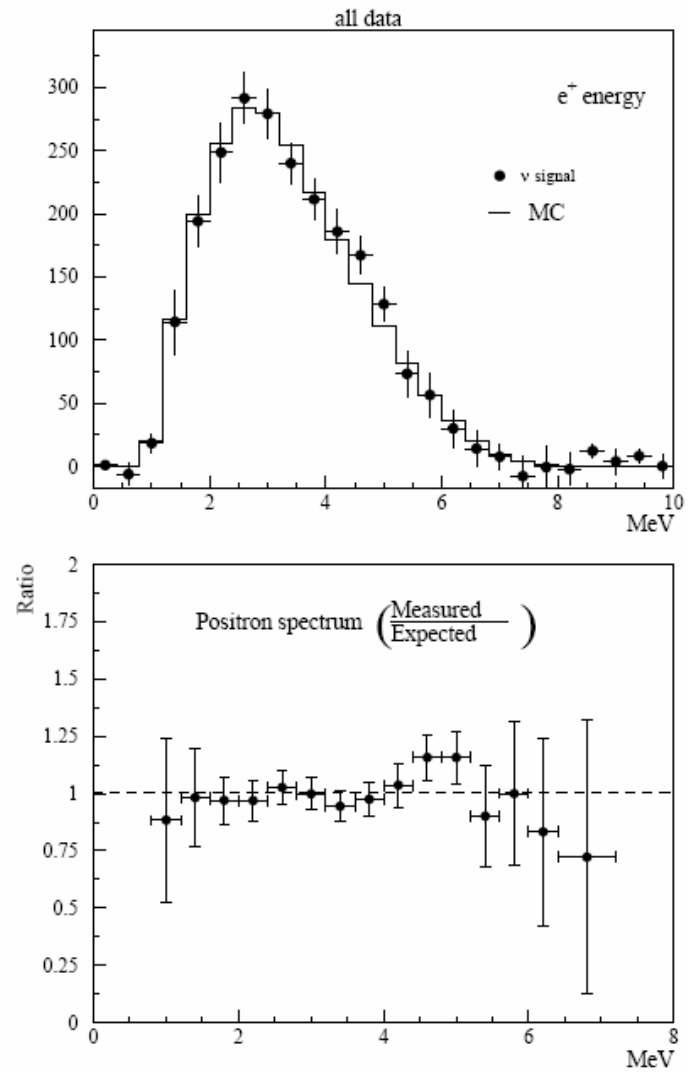
- CHOOZ Experiment probed this region
  - One detector experiments
    - Major systematic associated with reactor flux
  - Detectors used liquid scintillator with gadolinium and buffer zones for background reduction
  - Shielding:
    - CHOOZ: 300 mwe
  - Fiducial mass:
    - CHOOZ: 5 tons @ 1km, 5.7 GW
      - ~2.2 evts/day/ton with 0.2-0.4 bkgnd evts/day/ton
      - ~3600 $\bar{\nu}$ events

parameter	relative error (%)
reaction cross section (flux)	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%



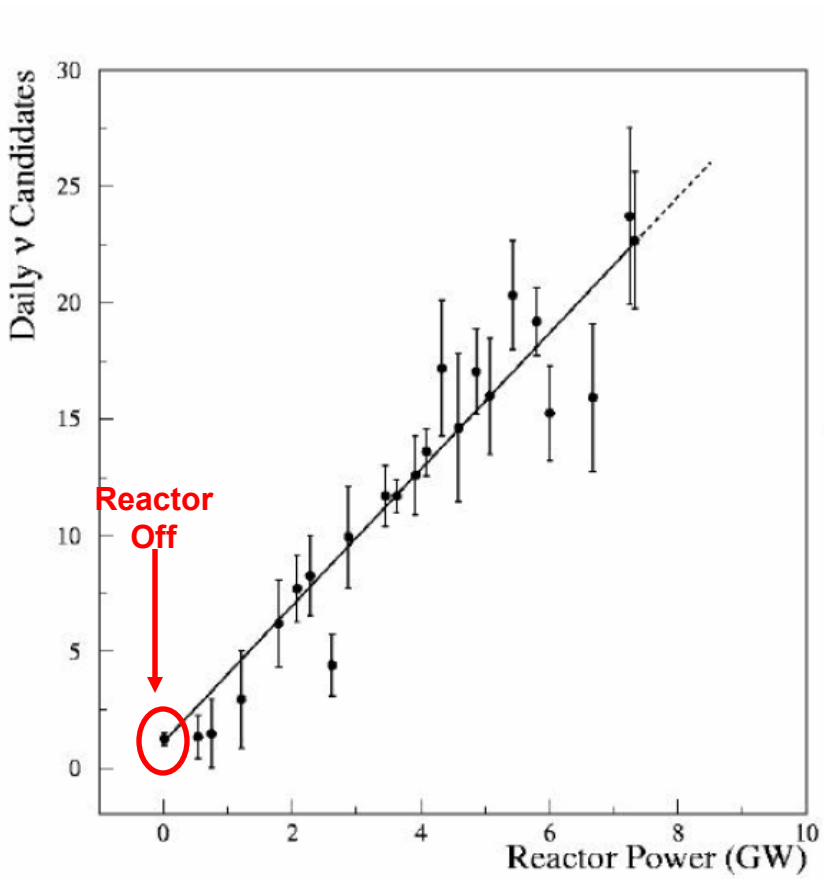
Comparison of Data and Predictions

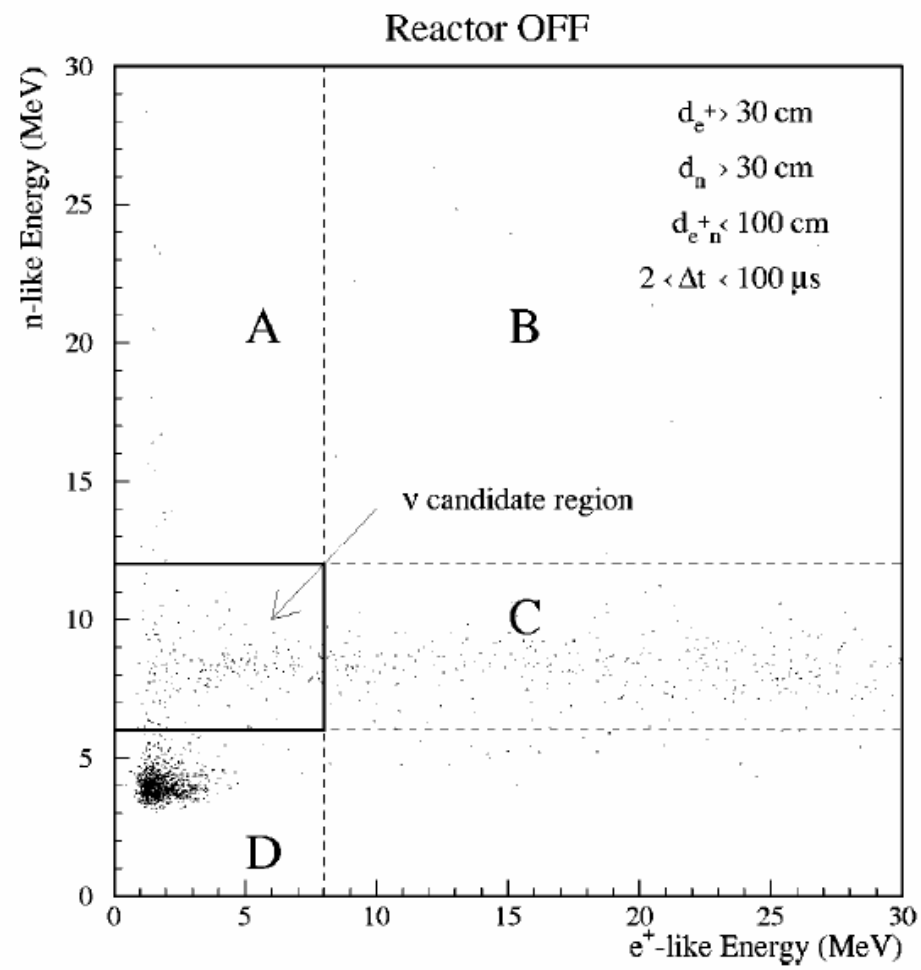


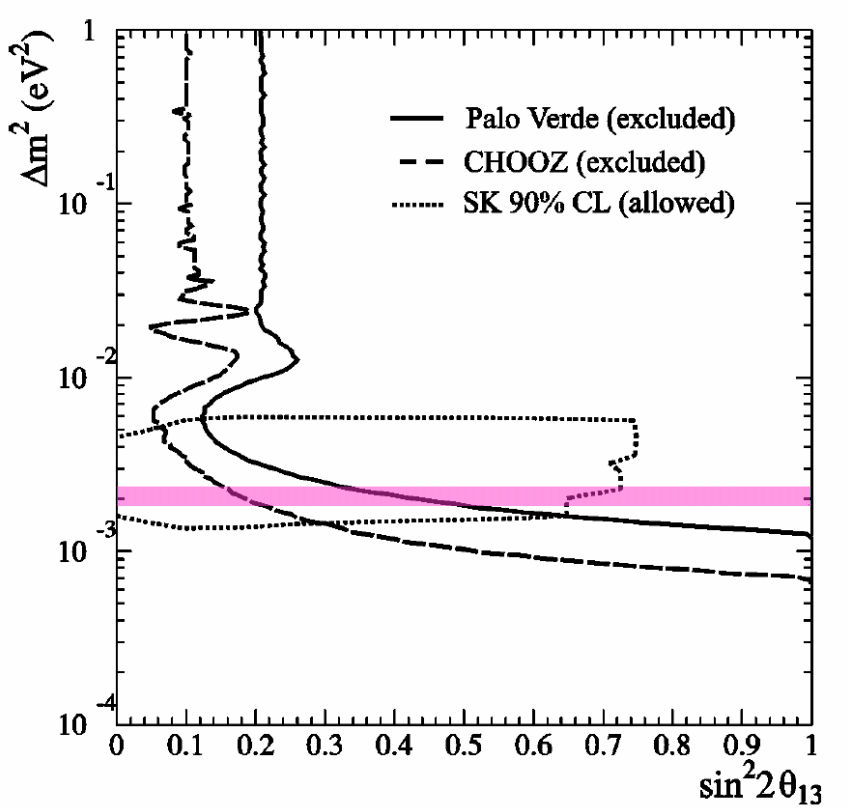
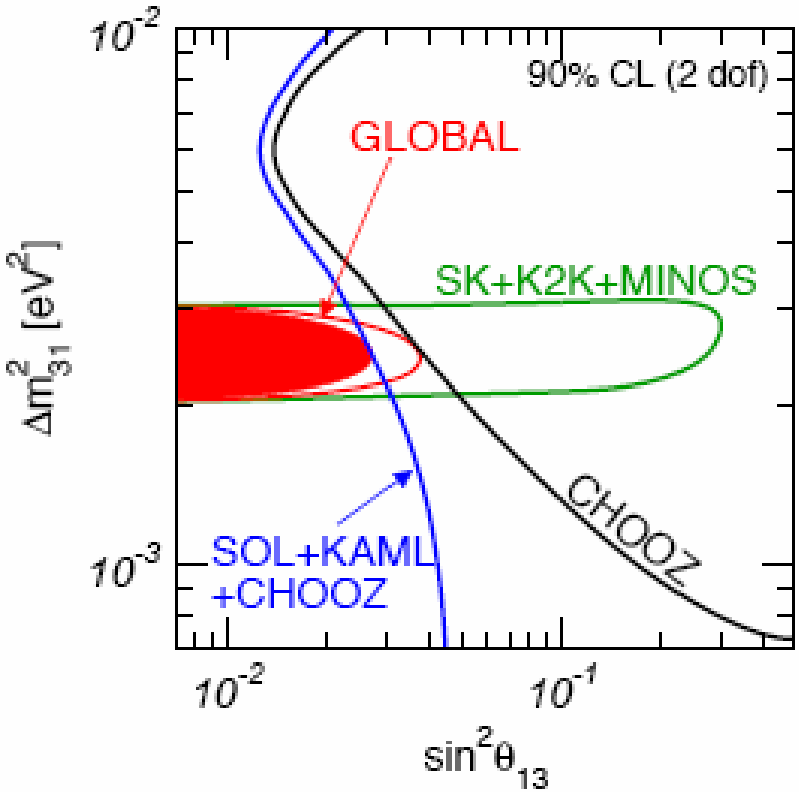


CHOOZ Reactor Off and On Data

CHOOZ had the unique opportunity to measure background rates before the reactors turned on!





Current Limits on $\sin^2\theta_{13}$

Best current limit from:
CHOOZ (single detector experiment)
$\sin^2(2\theta_{13})<0.2$
$(\sin^2(\theta_{13})<0.05)$