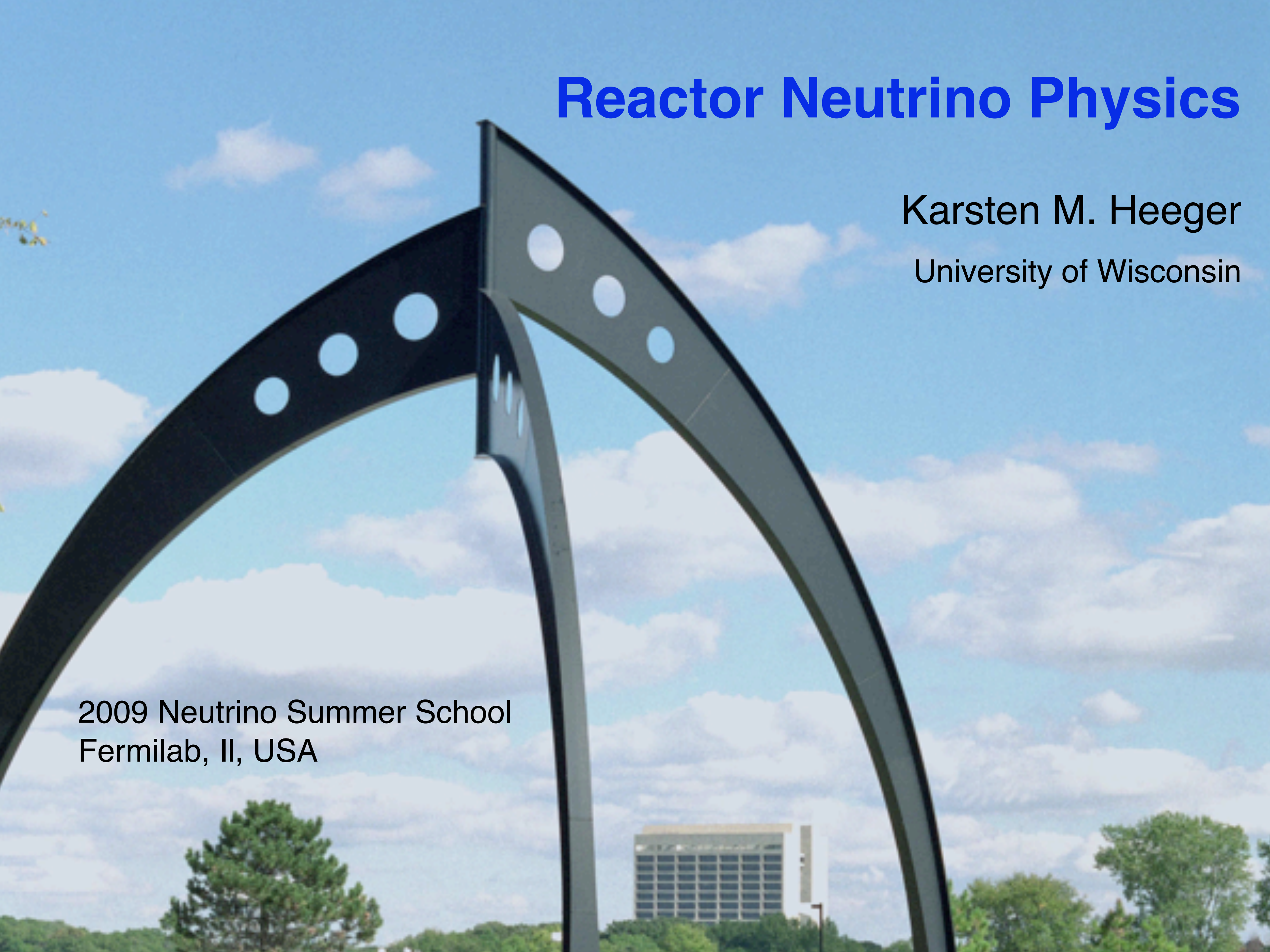


Reactor Neutrino Physics

Karsten M. Heeger

University of Wisconsin

2009 Neutrino Summer School
Fermilab, Il, USA

Outline

- Discovery of the Free Antineutrino

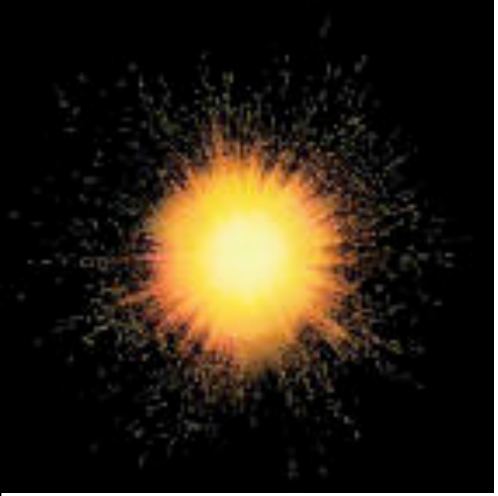
- Reactors as an Antineutrino Source

- Neutrino Oscillation Searches with Reactor Antineutrinos

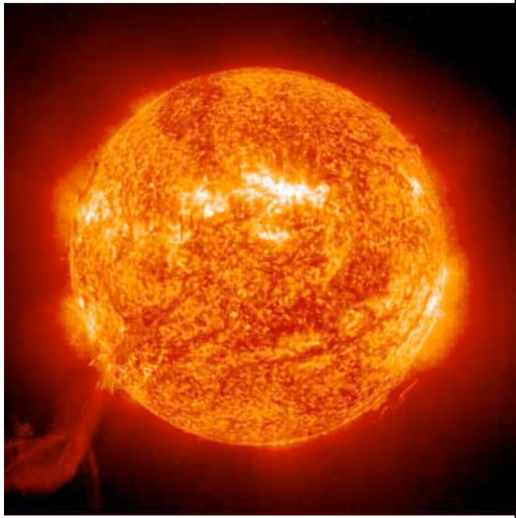
- Precision Oscillation Physics with Reactor $\overline{\nu}_e$

- Other Physics with Reactor $\overline{\nu}_e$

Neutrino Energies



Big-Bang neutrinos ~ 0.0004 eV



Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

Neutrinos from accelerators up to GeV (10^9 eV)

Neutrino Flux on Earth

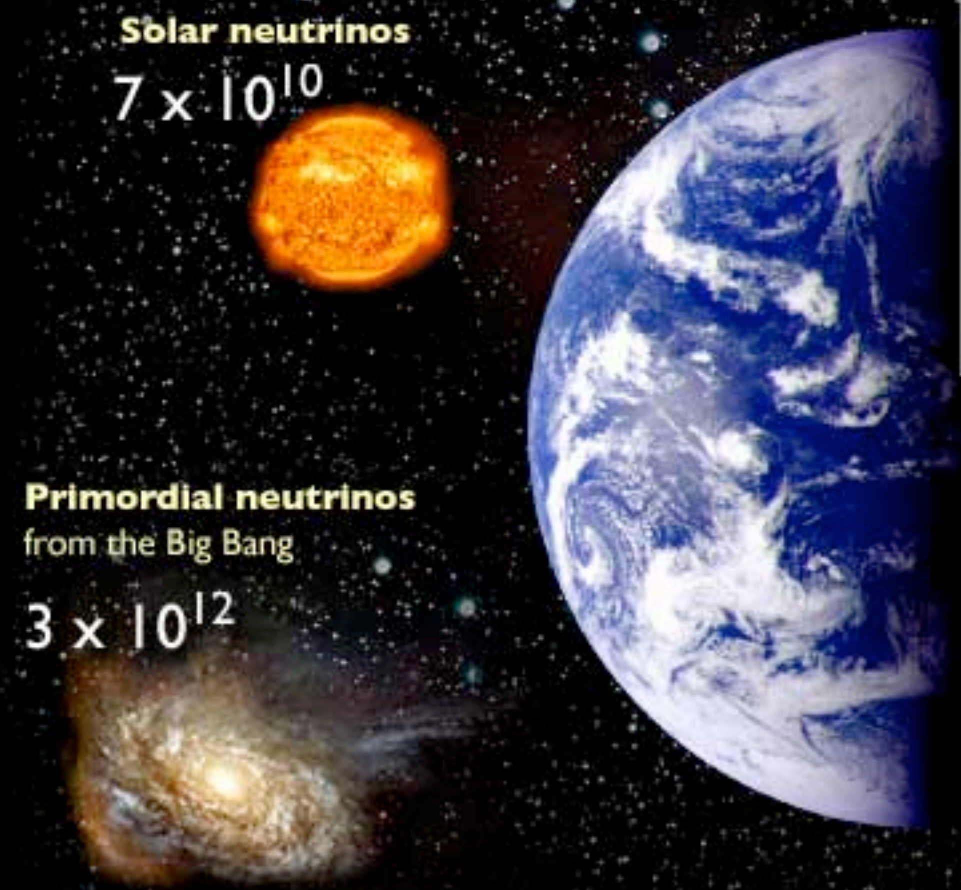
What produces the largest neutrino flux on Earth?

The Sun, the Big Bang, or a nuclear reactor?

Reactor neutrinos

?

Neutrino Flux on Earth



What produces the largest neutrino flux on Earth?

The Sun, the Big Bang, or a nuclear reactor?

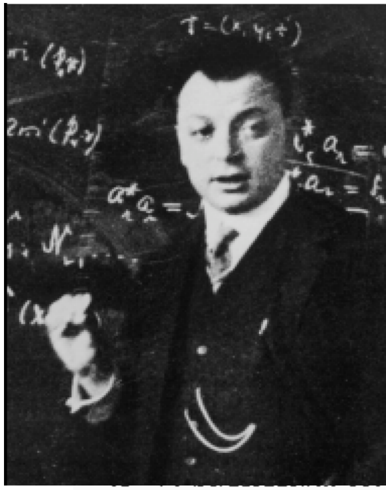
Reactor neutrinos

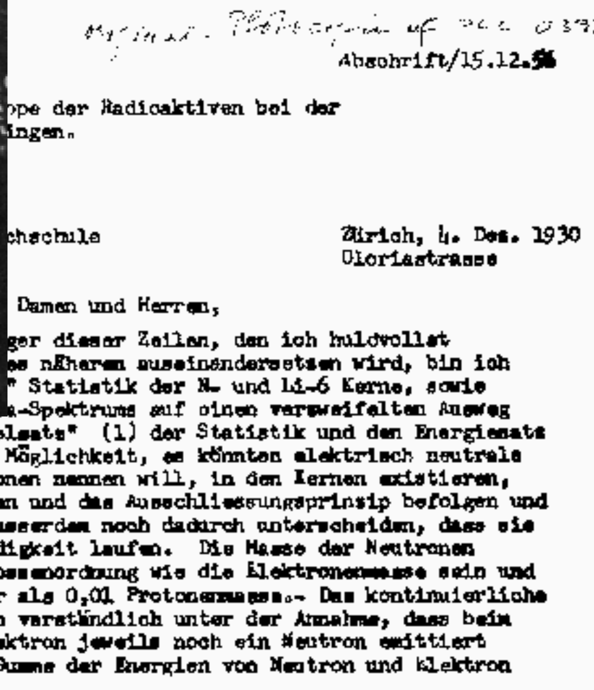
1×10^{10}

Discovery of the Free Antineutrino

History of the Neutrino

Pauli, 1930




Abschrift/15.12.56

...ppe der Radioaktiven bei der
...ingen.

...chschule

Zürich, 4. Dez. 1930
Gloriastrasse

...Damen und Herren,

...ger dieser Zeilen, den ich huldvollst
...s näheren auseinandersetzen wird, bin ich
...' Statistik der N- und Li-6 Kerne, sowie
...-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 Grossenordnung 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.

$N \rightarrow N' + e^-$ some nuclei emit electrons!

Chadwick, 1914

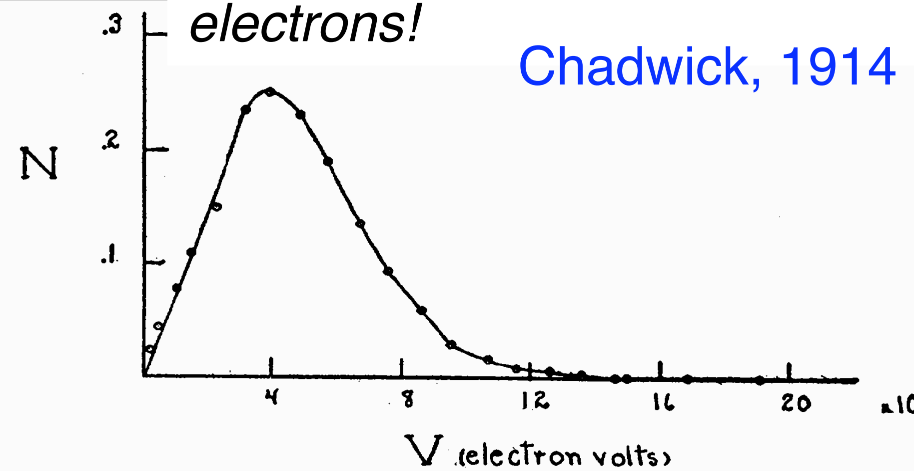
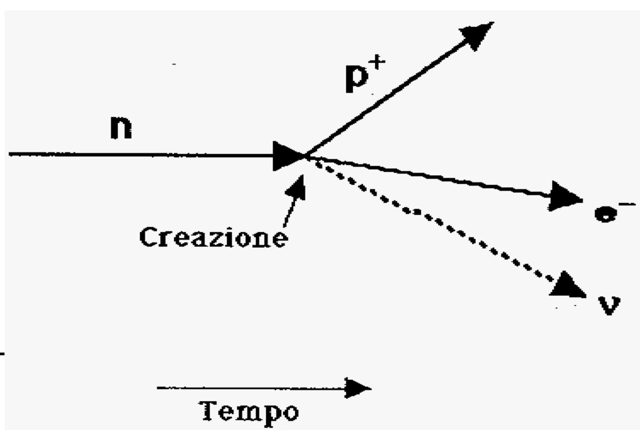
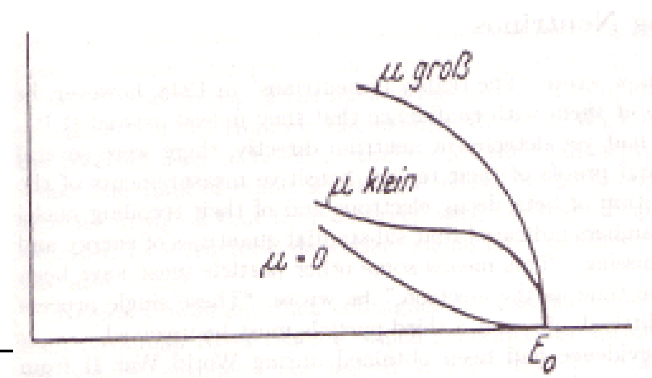


FIG. 5. Energy distribution curve of the beta-rays.

Fermi, 1934





Nuclear Reactors as a Neutrino Source

Бруно Понтекорво

Reactors are intense and pure sources of $\bar{\nu}_e$

B. Pontecorvo Natl.Res.Council Canada Rep. (1946) 205
Helv.Phys.Acta.Suppl. 3 (1950) 97

Good for systematic studies of neutrinos.

1953: Project Poltergeist

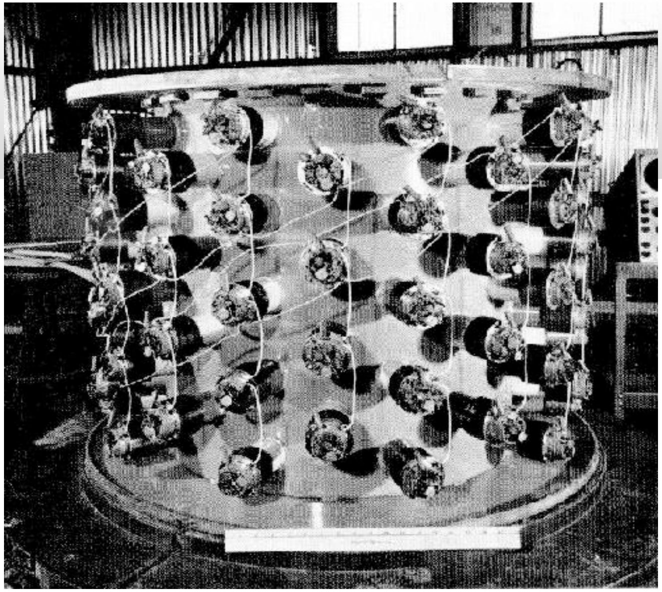
Experiment at Hanford

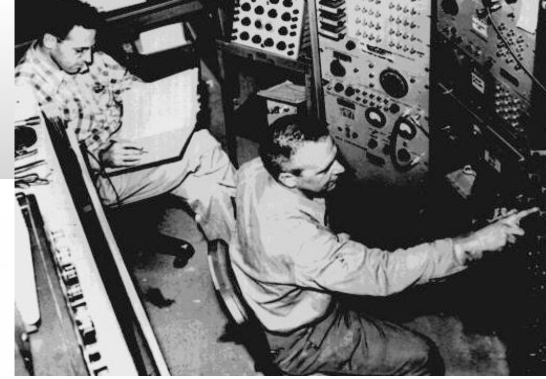
1956: First Direct Detection of the Antineutrino

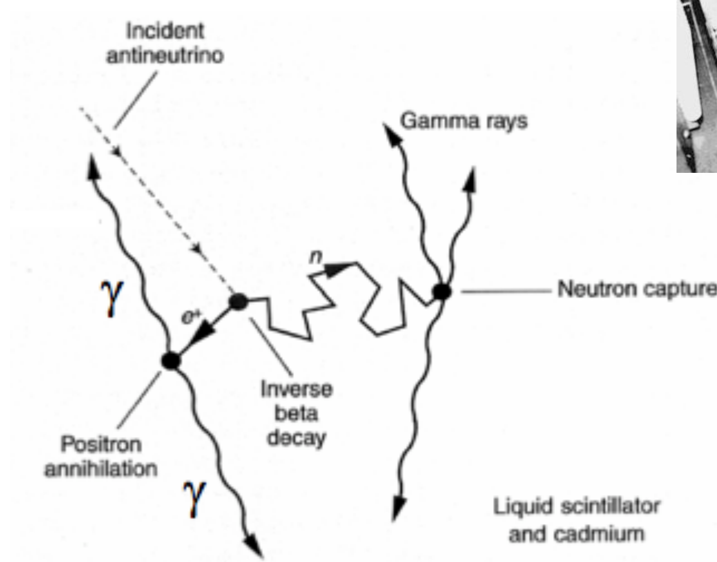
Clyde Cowan Jr.

Frederick Reines

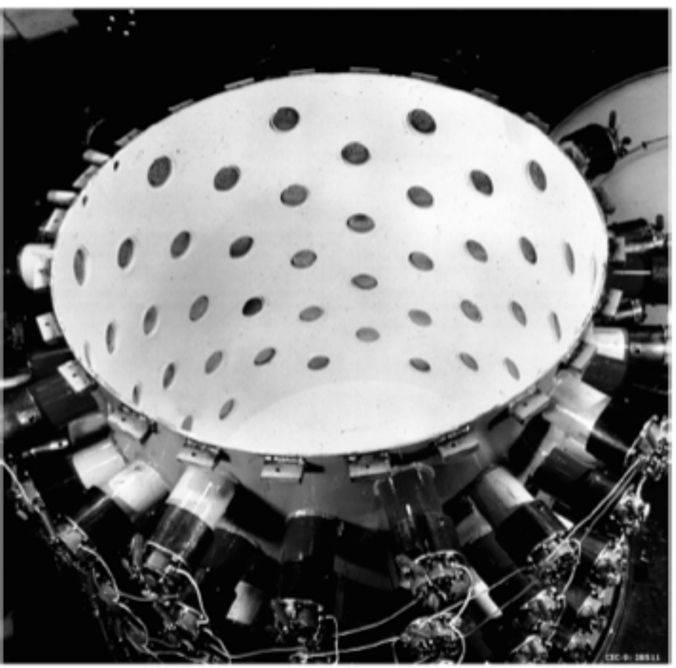
Hanford Experiment







300 liters of liquid scintillator loaded with cadmium



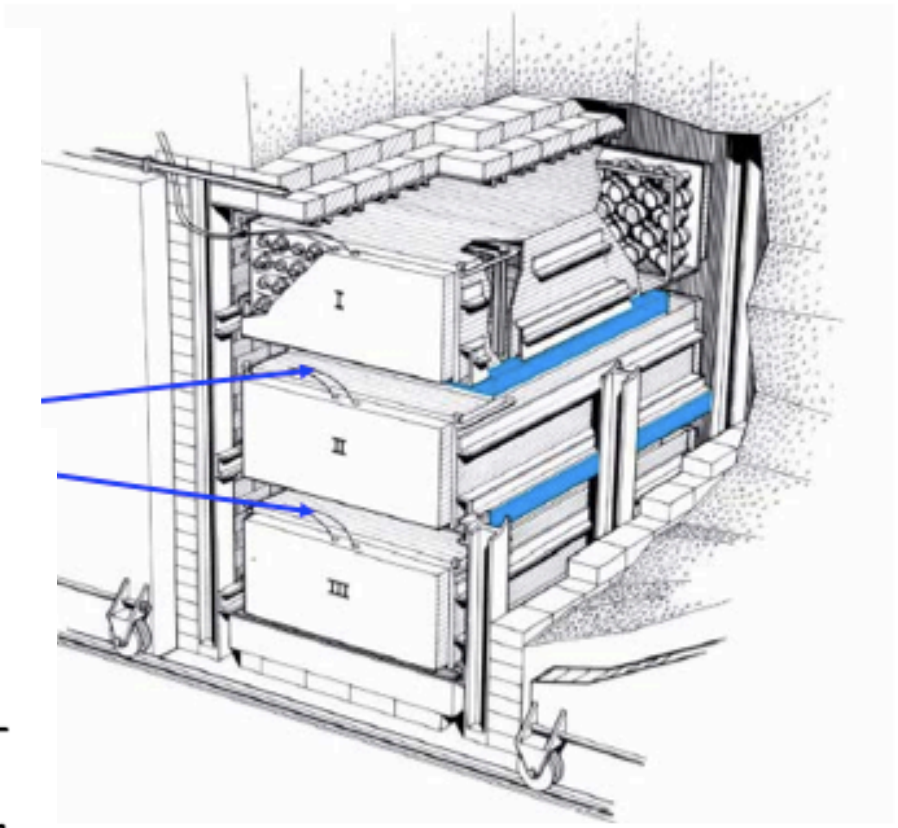
signal: delayed coincidence between positron and neutron capture on cadmium

high background (S/N ~ 1/20) made the experiment inconclusive

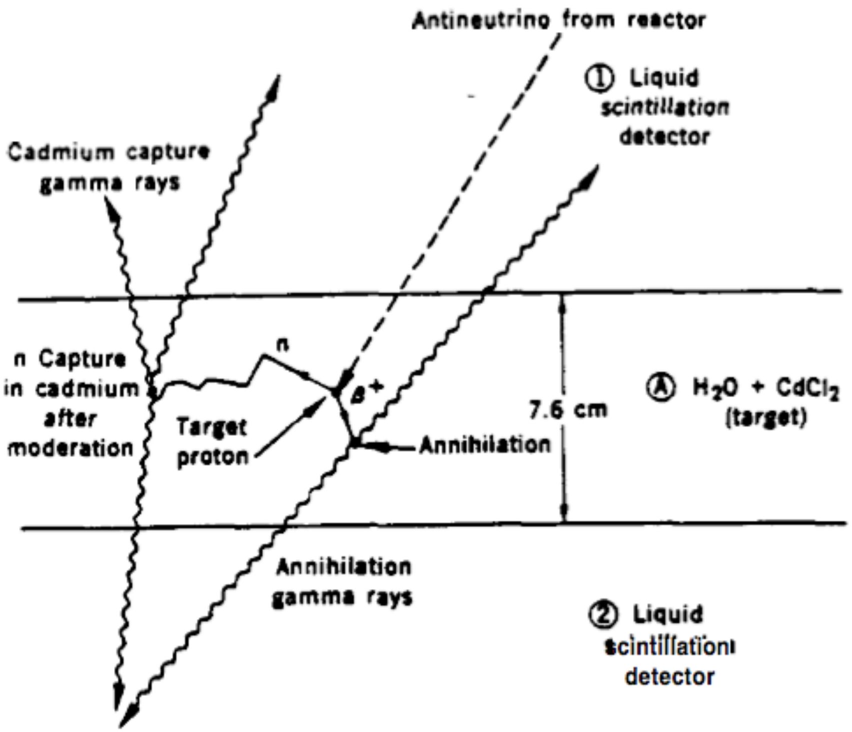
0.41+/- 0.20 events/minute

1956: Savannah River Experiment

tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

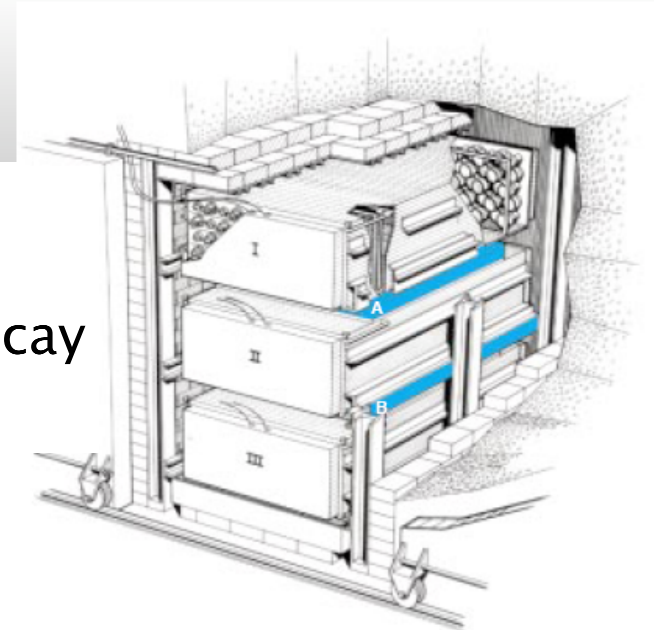


target tanks (blue) were filled with water+cadmium chloride



inverse beta decay would produce prompt and delayed signal in <u>neighboring</u> tanks

Observation of the Free Antineutrino



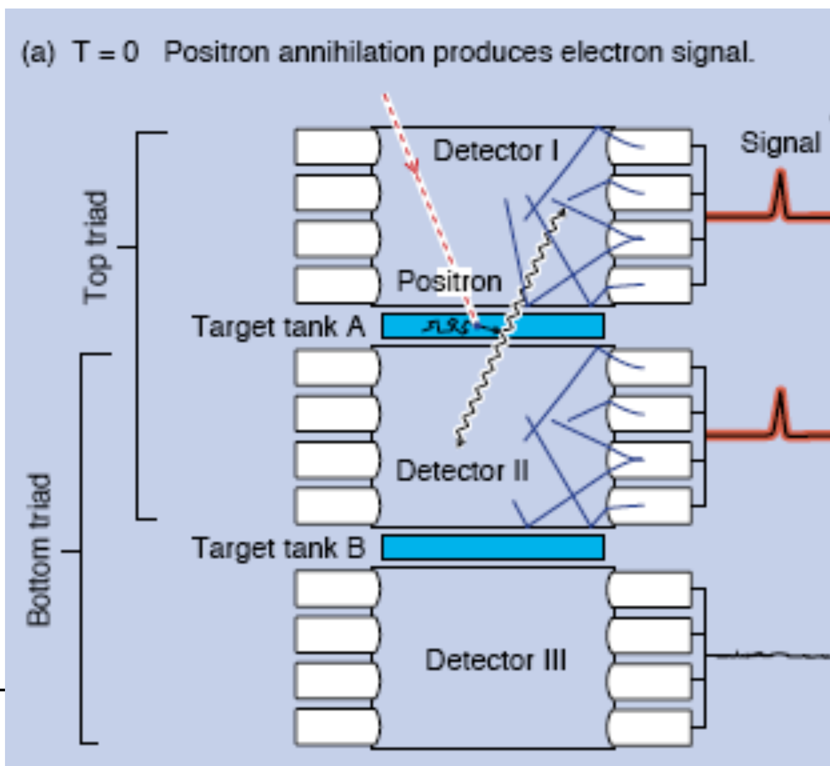
1959 The Savannah River Detector - A new design

Second version of Reines' experiment worked!

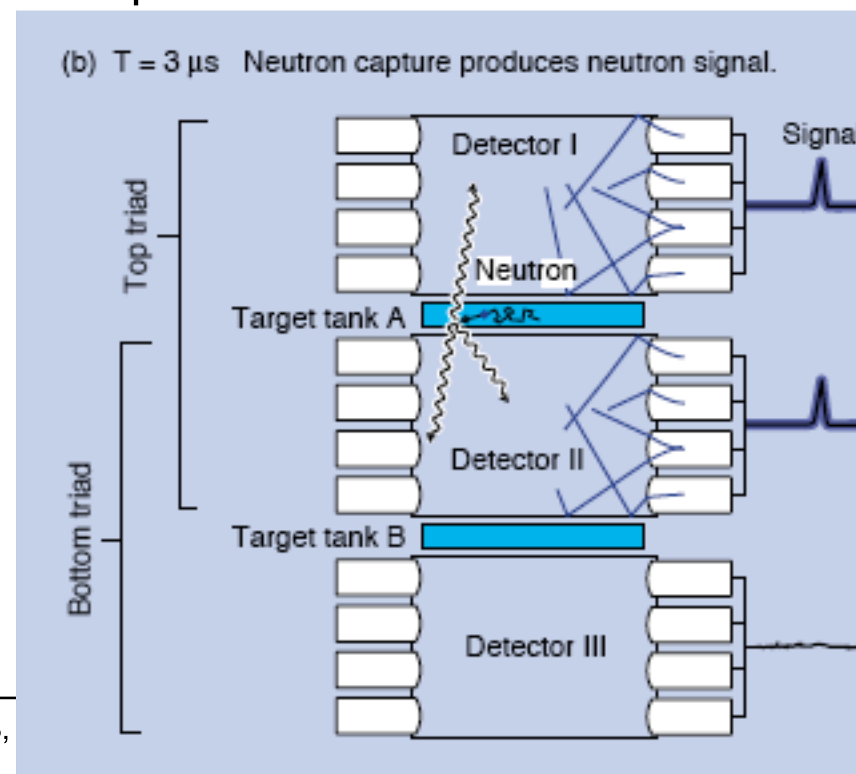
inverse beta decay

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

positron annihilation

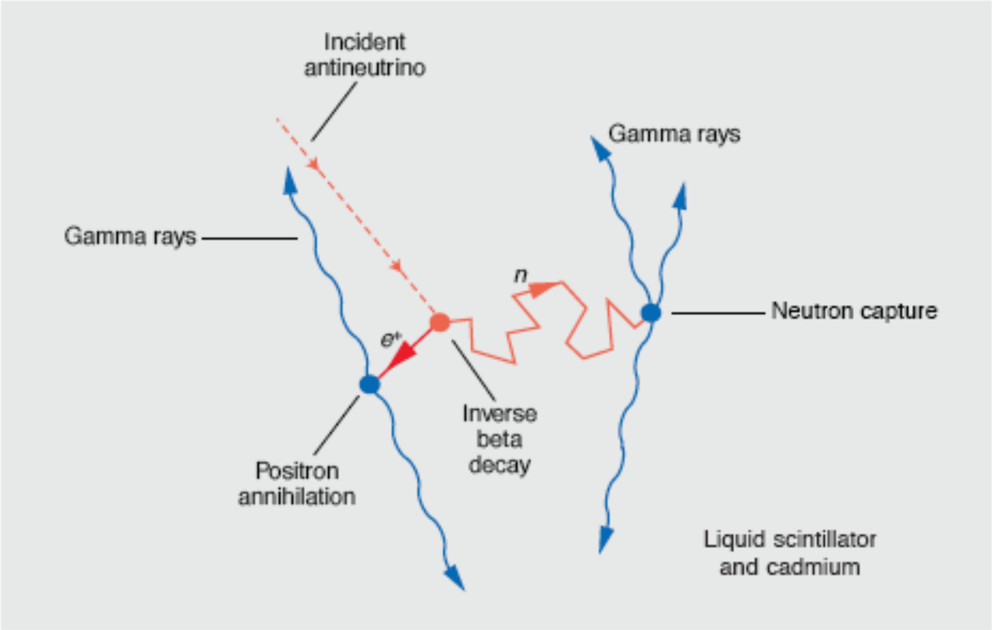


n capture



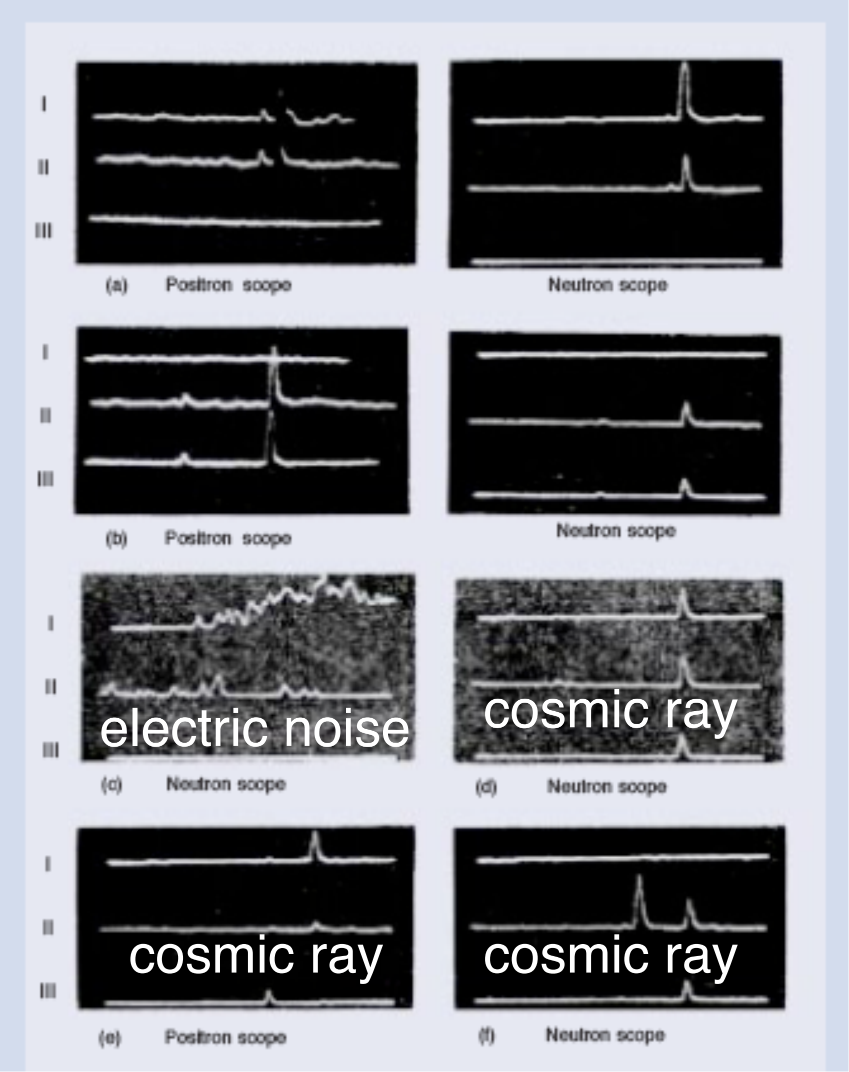
Reines-Cowan Experiment

coincidence event signature



signal/reactor independent background ~ 3:1

event signal



1956: Savannah River Experiment

Electronics trailer

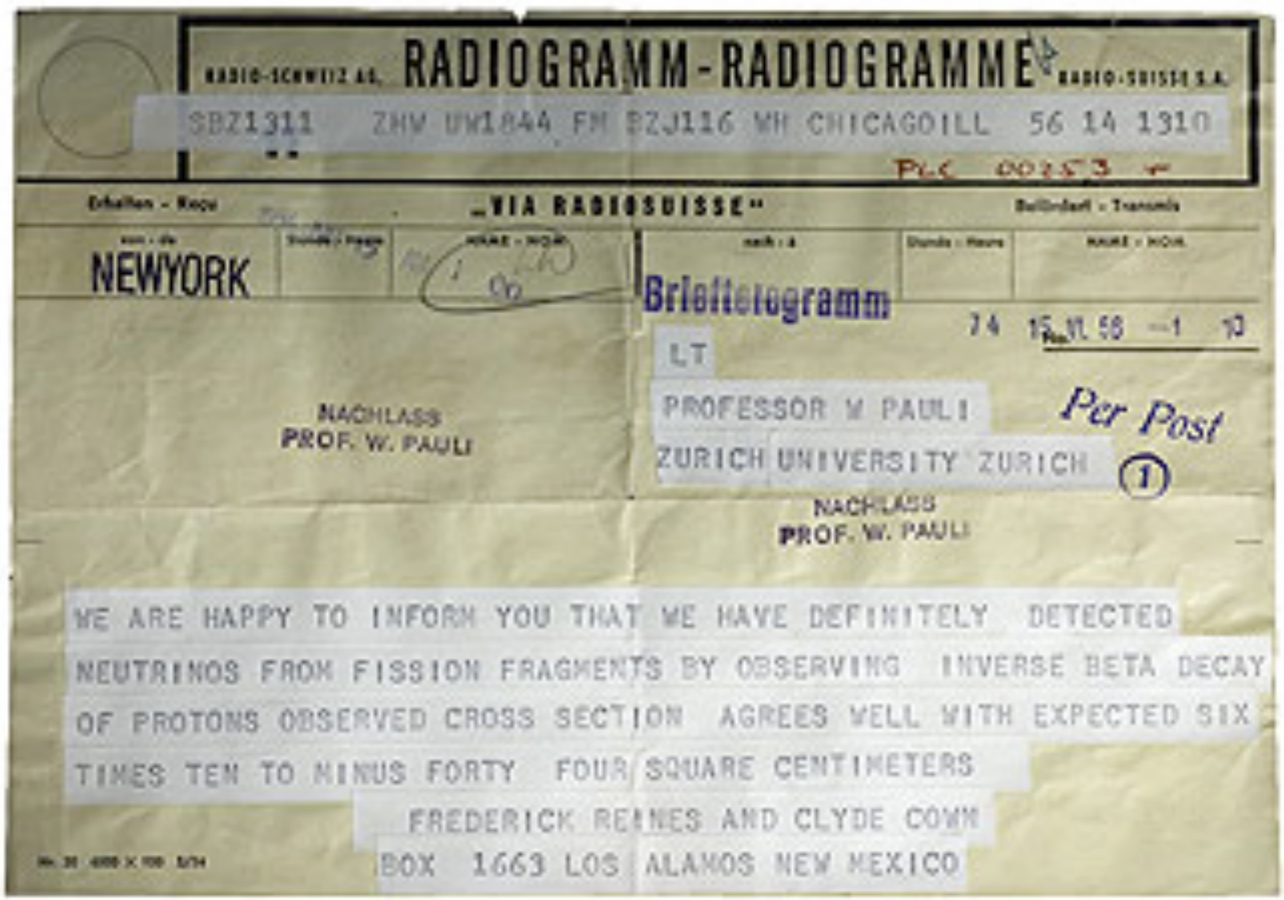
Shielding: 4 ft of soaked sawdust

1956: First Observation Observation of the Antineutrino

by April 1956, a reactor-dependent signal had been observed:

signal/reactor independent background ~ 3:1

in June 1956, they sent a telegram to Pauli



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHV UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS
PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN

BOX 1663 LOS ALAMOS NEW MEXICO

Following the first observation ....

- A Science article reported that the observed cross section was within 5% of the 6.3×10^{-44} cm^2 expected (although the predicted cross section has a 25% uncertainty).

- In 1959, following the discovery of parity violation in 1956, the theoretical cross section was increased by $\times2$ to $(10\pm1.7)\times10^{-44}$ cm^2

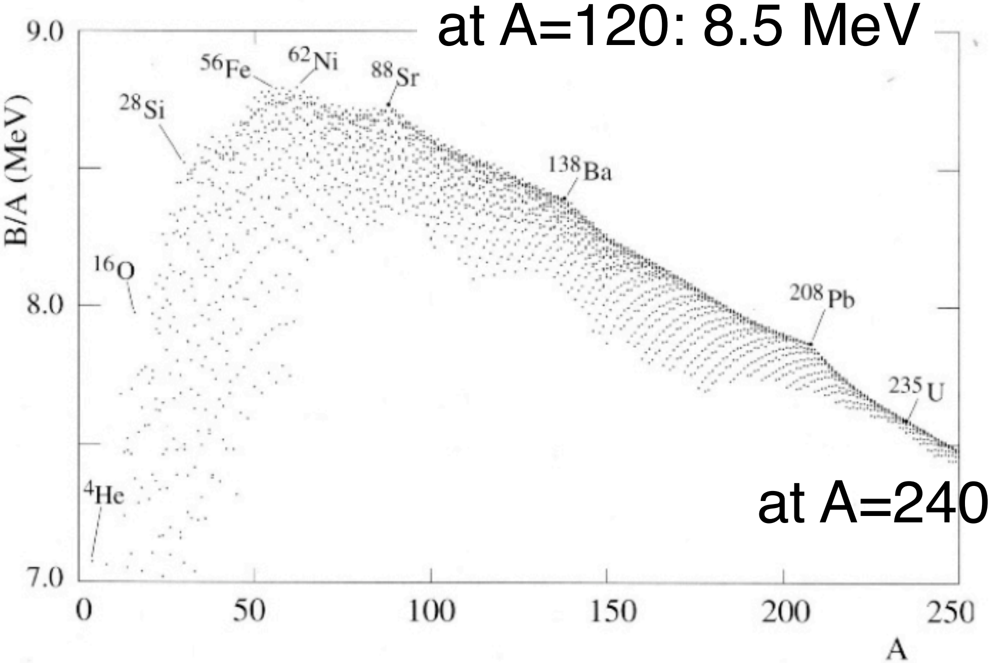
- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma = (12^{+7}_{-4})\times10^{-44}$ cm^2

Ref:
R.G. Arms, "Detecting the Neutrino", Physics in Perspectives, 3, 314 (2001)

Reactors as Antineutrino Source

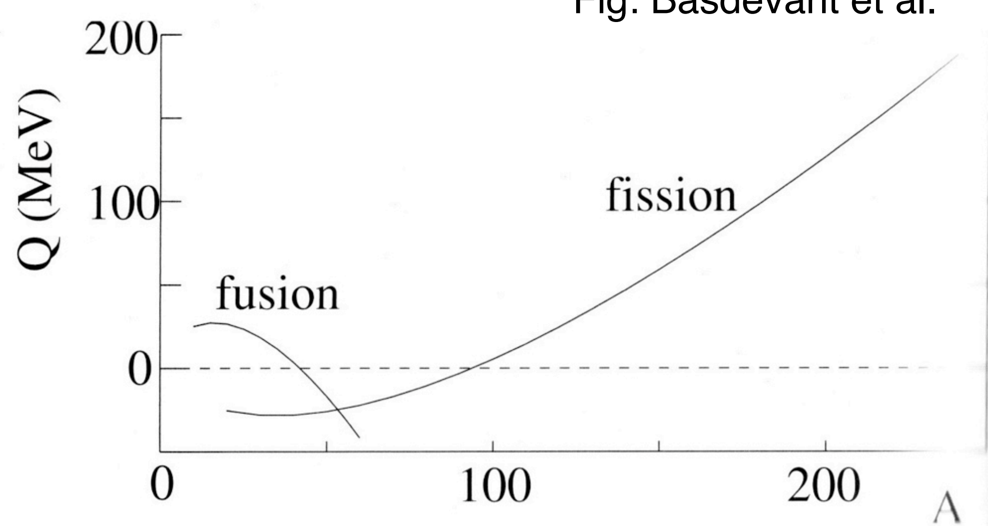
Energy Release in Fission and Self-Fusion

at A=120: 8.5 MeV



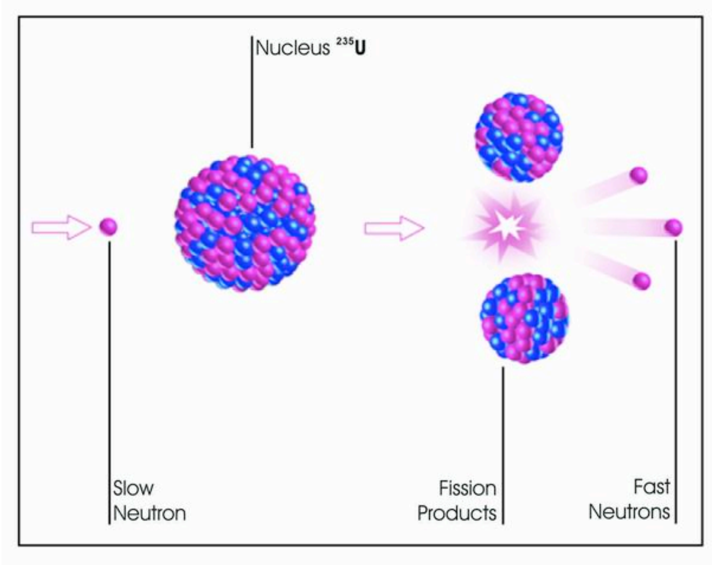
at A=240: 7.6 MeV

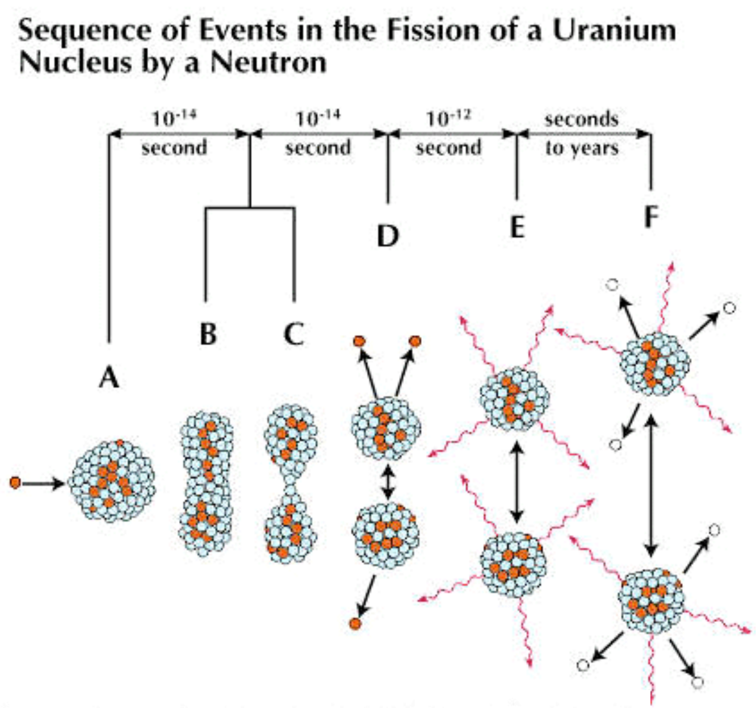
Fig: Basdevant et al.

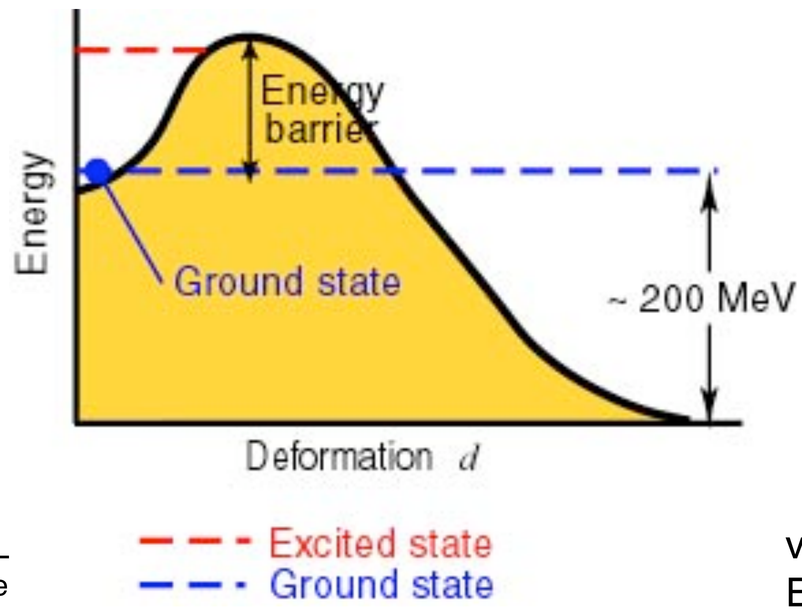


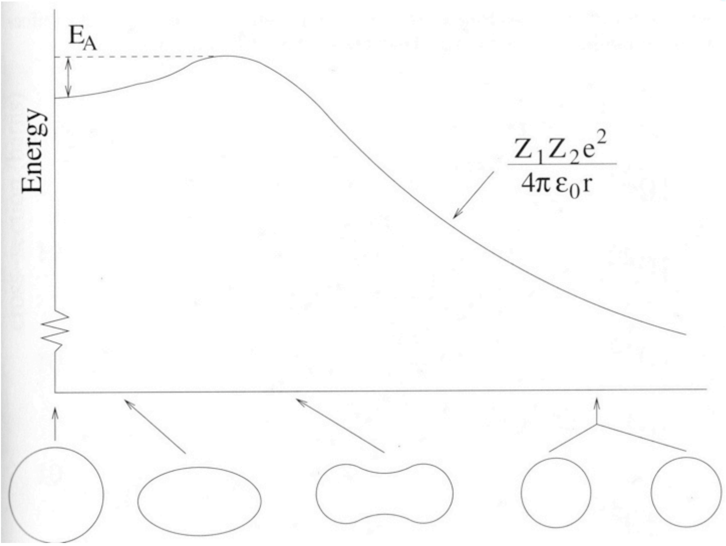
- only nuclei with 40 < A < 95 are stable against both fission and self-fusion
- Q_{fis} calculated for symmetric fission

Nuclear Deformation in Fission





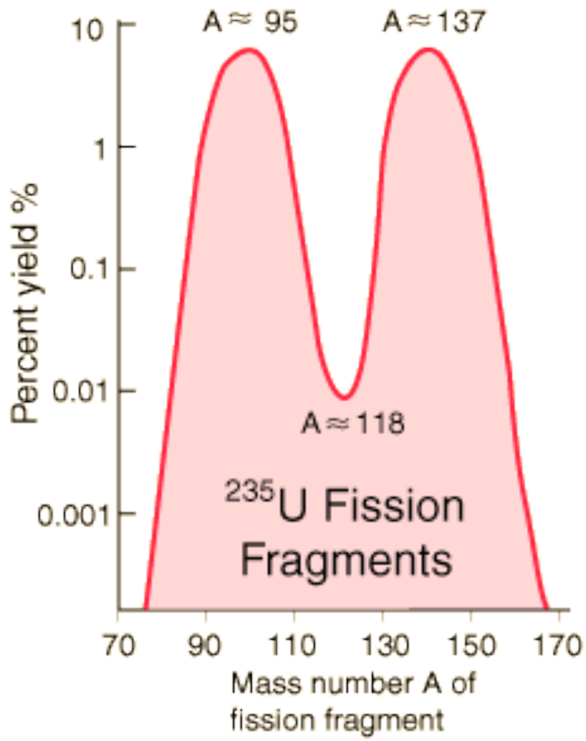


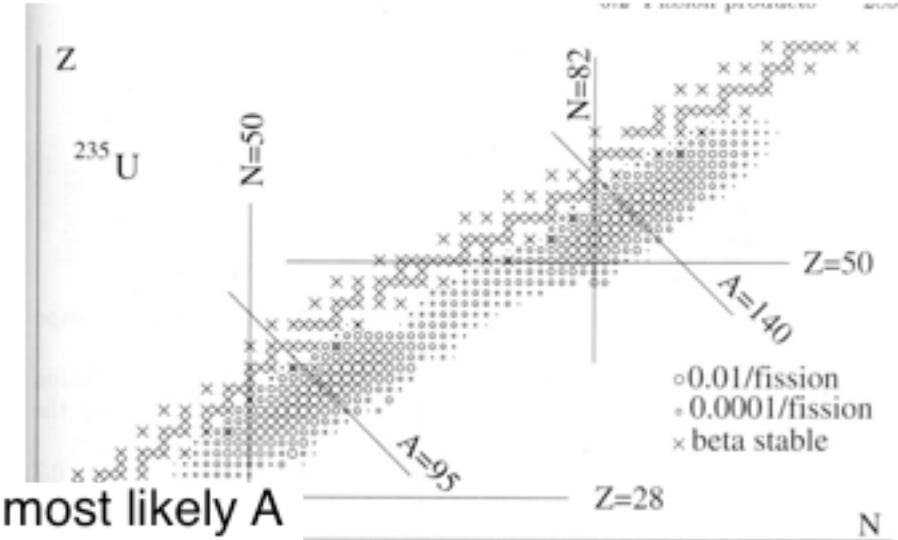


variation of energy as a function of distortion
E_A= fission barrier

Example: ^{235}U Fission

distribution of fission fragments





nuclei with most likely A from ^{235}U fission

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

together these have 98 p and 136 n while fission fragments (X_1+X_2) have 92 p and 144 n

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

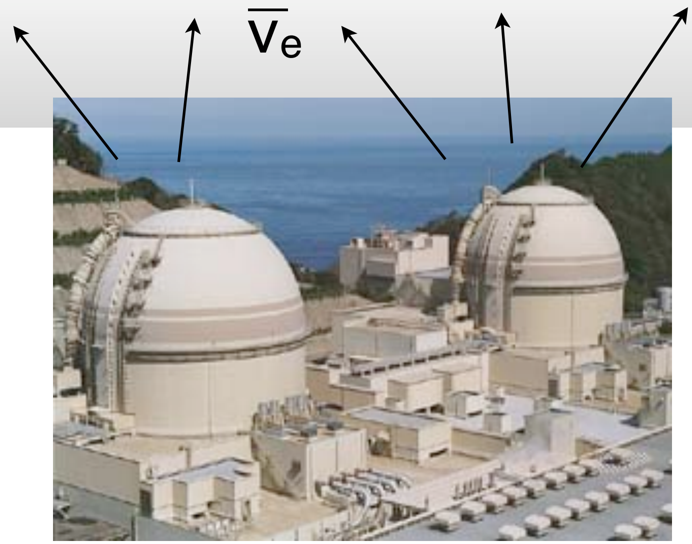
asymmetric fission into lighter and heavier nuclei

- on average 6n have to beta-decay to 6p to reach stable matter
- on average 1.5 are emitted with energy > 1.8 MeV

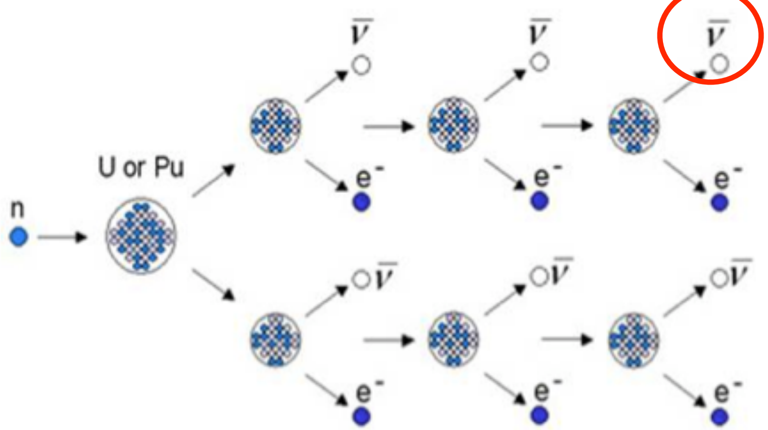
~ 200 MeV/fission and 6 $\overline{\nu}_e$/fission

3 GW_{th} reactor produces 6 x 10^{20} $\overline{\nu}_e$/sec

Reactors as Antineutrino Sources



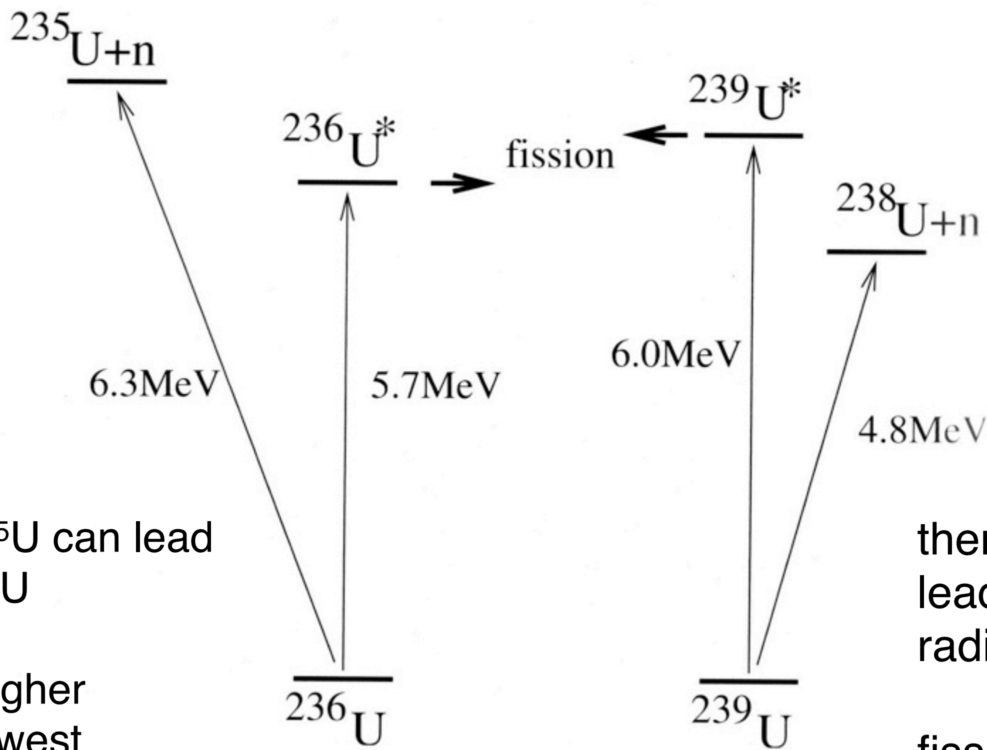
β^- decay of neutron rich fission fragments



energy per fission		MeV
Kinetic energy of fragments		165 ± 5
Energy of prompt photons		7 ± 1
Kinetic energy of neutrons		5 ± 0.5
Energy of β decay electrons		7 ± 1
Energy of β decay antineutrinos		10
Energy of γ decay photons		6 ± 1
	Total	200 ± 6

~ 200 MeV/fission and 6 $\overline{\nu}_e$/fission

Fission with thermal and fast neutrons



thermal n + ^{235}U can lead to fission of ^{236}U

n + ^{235}U has higher energy than lowest fissionable state

thermal n + ^{238}U does not lead to fission, only radiative capture

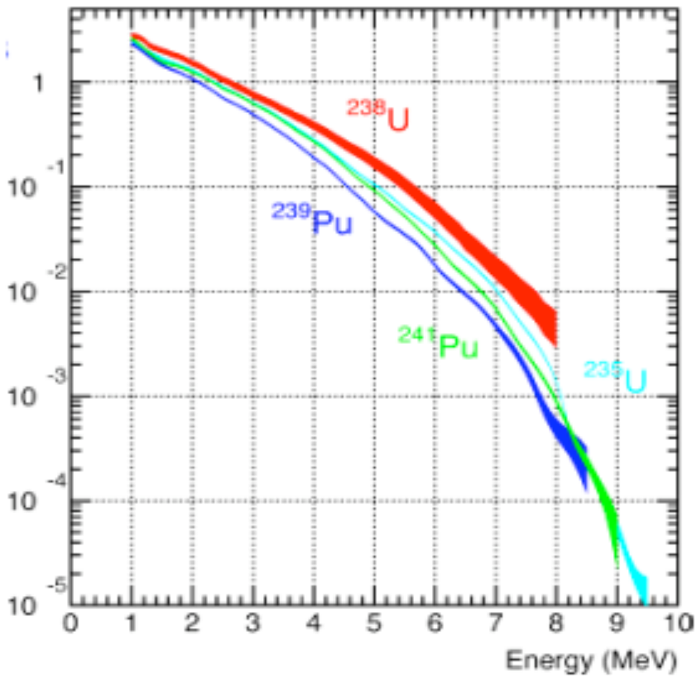
fission of ^{239}U requires addition of neutron with kinetic energy T_n=6-4.8=1.2 MeV

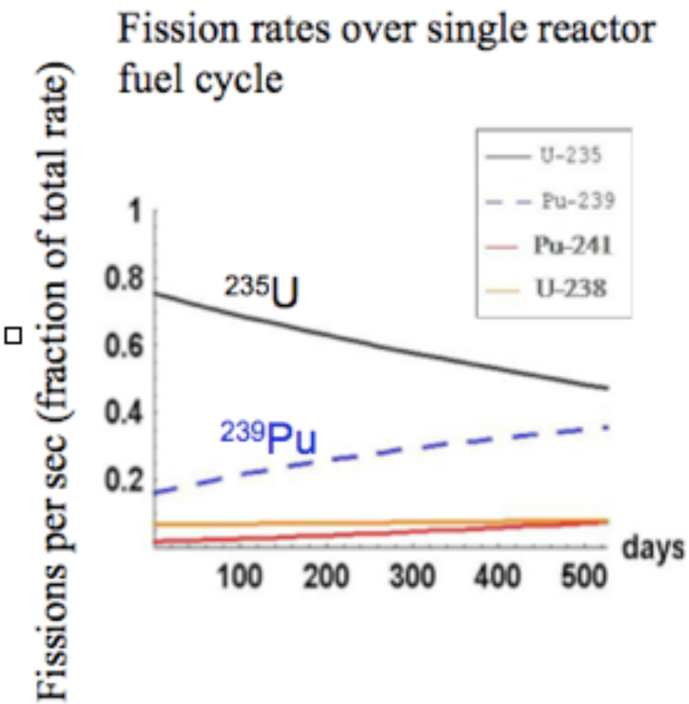
some nuclei require thermal neutrons for fission, others require fast neutrons

Antineutrino Production in Nuclear Fuel

> 99.9% of $\overline{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

~ 90% of $\overline{\nu}_e$ are produced by fissions in ^{235}U, ^{239}Pu

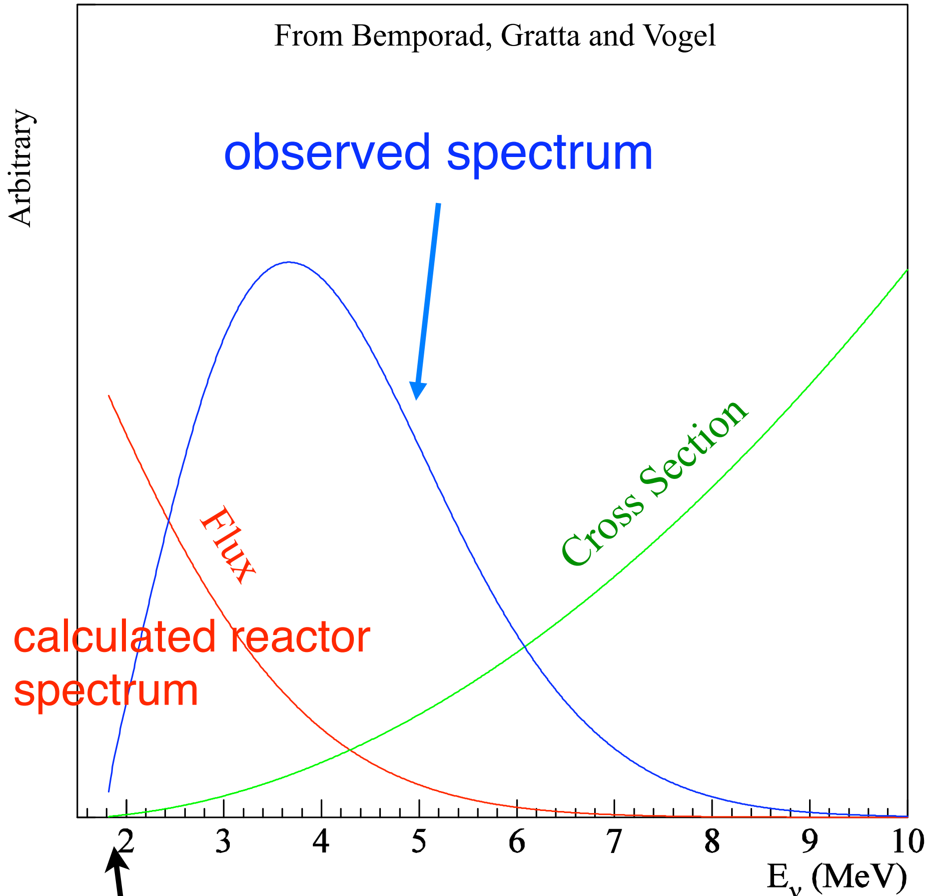




Plutonium breeding over fuel cycle (~250 kg) changes antineutrino rate (by 5-10%) and spectrum

typical fuel composition ^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570: 0.078: 0.0295: 0.057

$\overline{\nu}_e$ Spectrum



mean energy of $\overline{\nu}_e$: 3.6 MeV

⇒ only disappearance expts possible

cross-section accurate to +/-0.2%

rule of thumb:
~ 1 event per day per ton of LS
per GW_{th} at 1km

threshold: neutrinos with E < 1.8 MeV are not detected

only ~ 1.5 $\overline{\nu}_e$/fission can be detected

β-spectra and Fission Products

Measurements

β^--spectra resulting from fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu have been experimentally measured

(use thin layer of fissile material in beam of thermal neutrons, e.g. Schreckenbach et al., Hahn et al.)

→ can be converted to $\overline{\nu}_e$ spectra

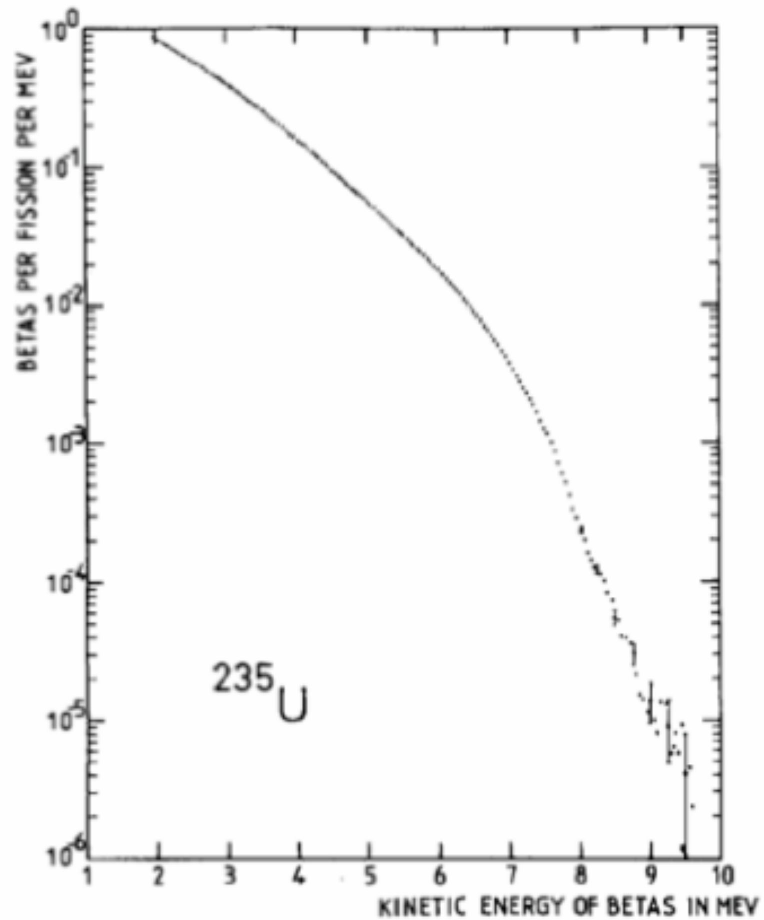
Calculations

^{238}U beta spectra not available since fast fissions

→ determined from theory (+/-10%)

(^{238}U is only 10% of rate)

Schreckenbach et a
PL160B 325 (1985)



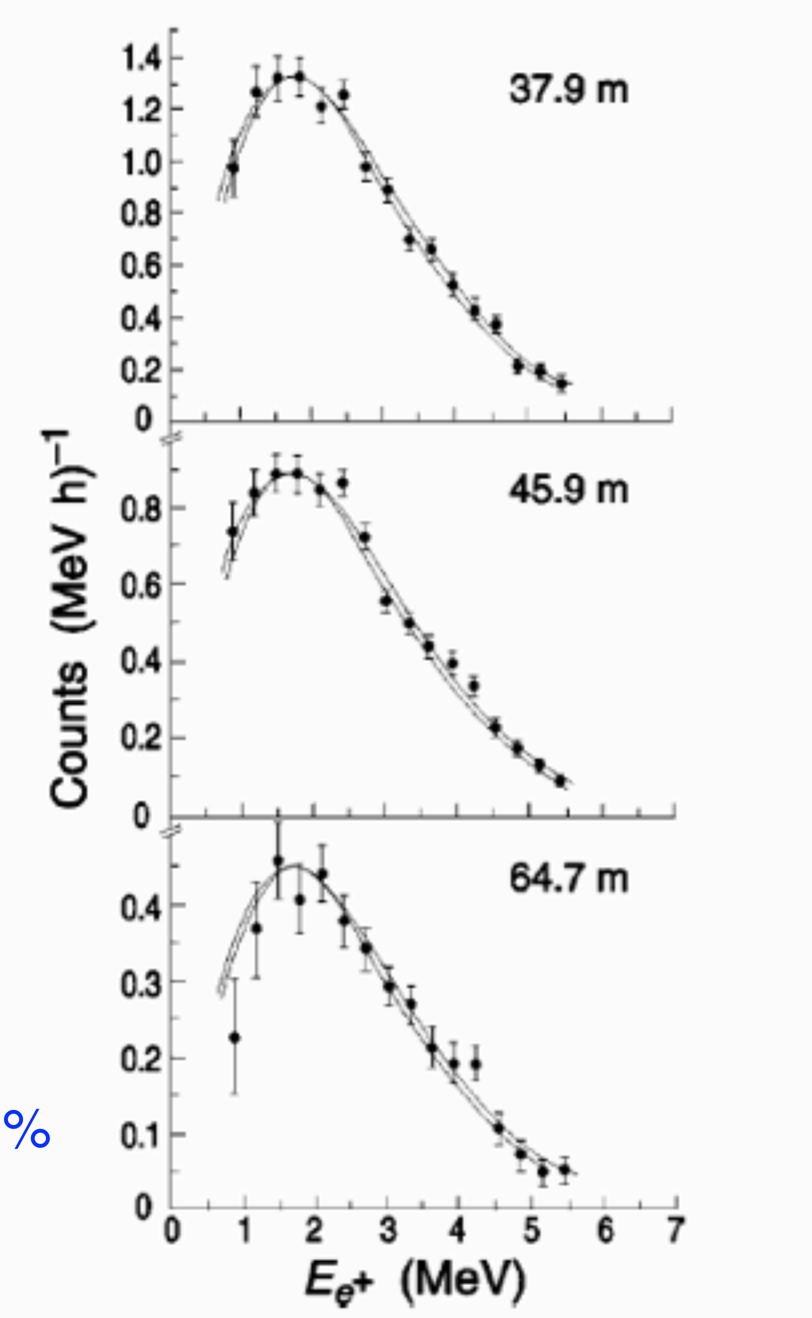
Goesgen Experiment

Comparison of Predicted Spectra to Observations

two curves are from fits to data and from predictions based on Schreckenbach et al.

3 baselines with one detector

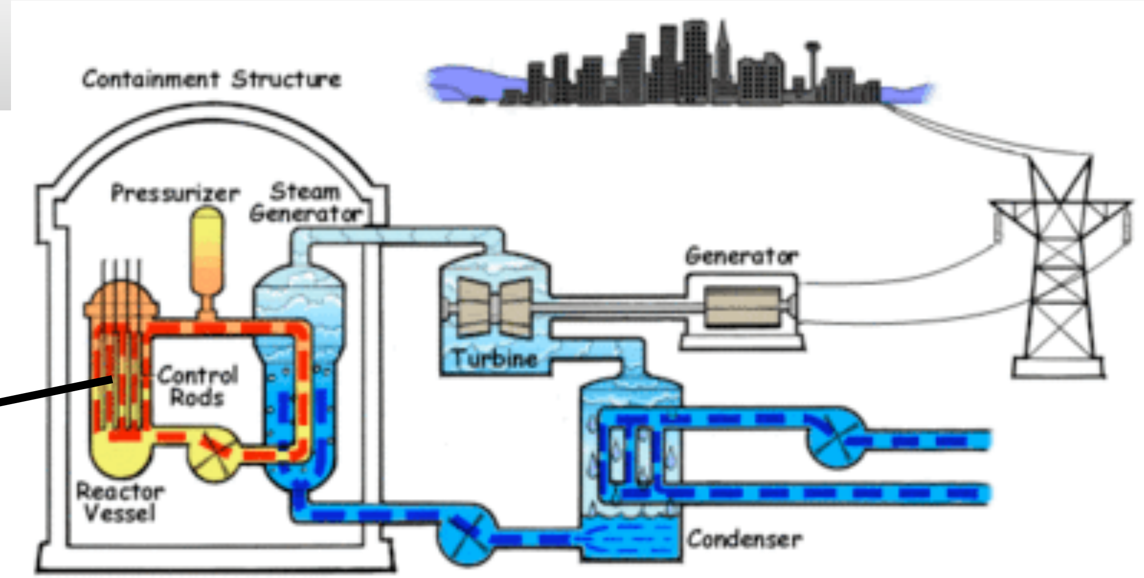
flux and energy spectrum agree to ~ 1-2%

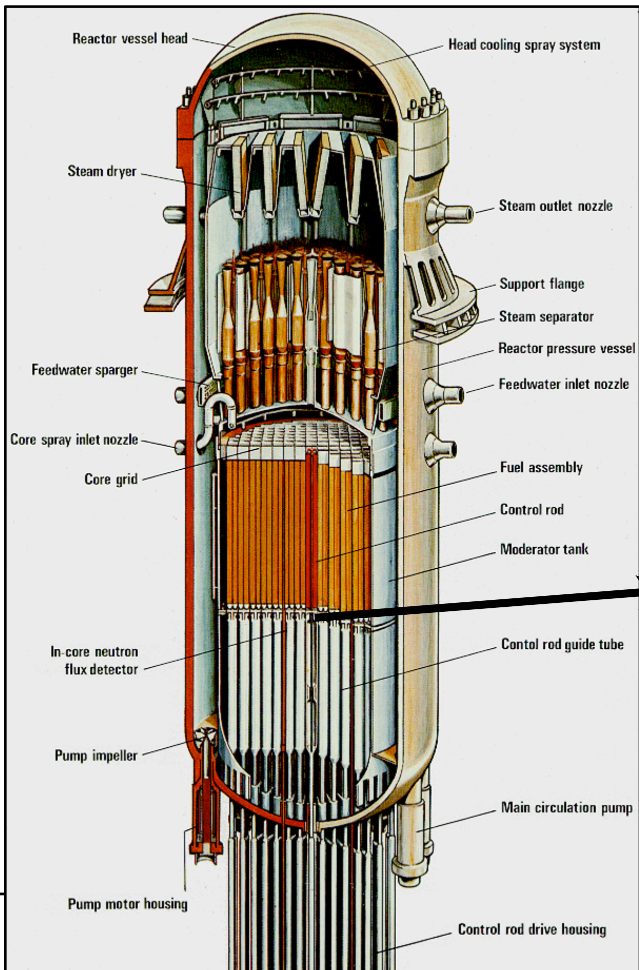


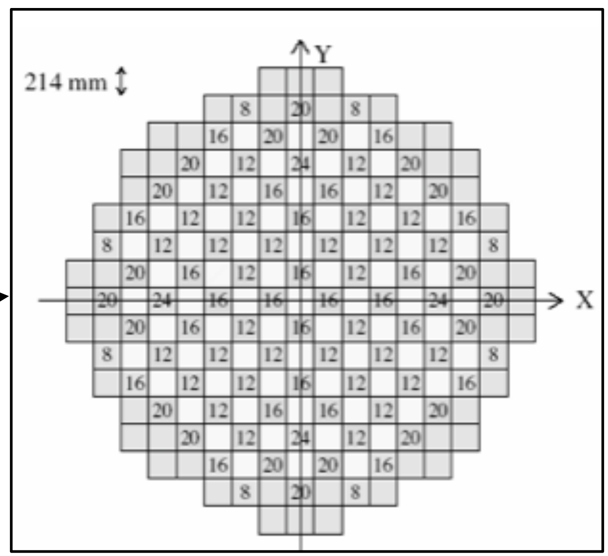
Nuclear Reactors

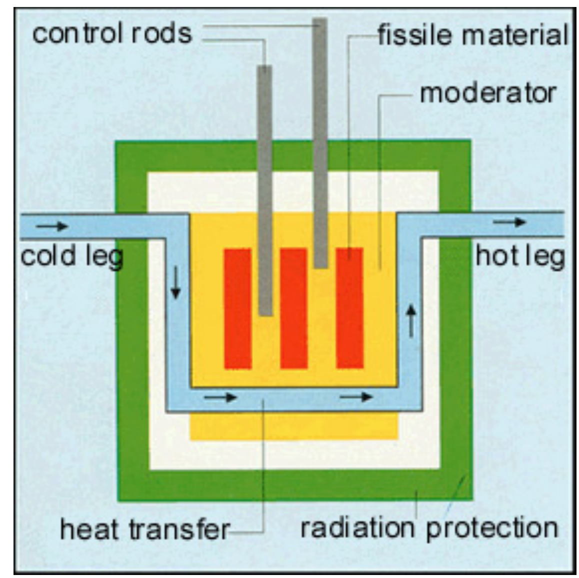
reactors are an extended neutrino source:

3-4m diameter, 4m high

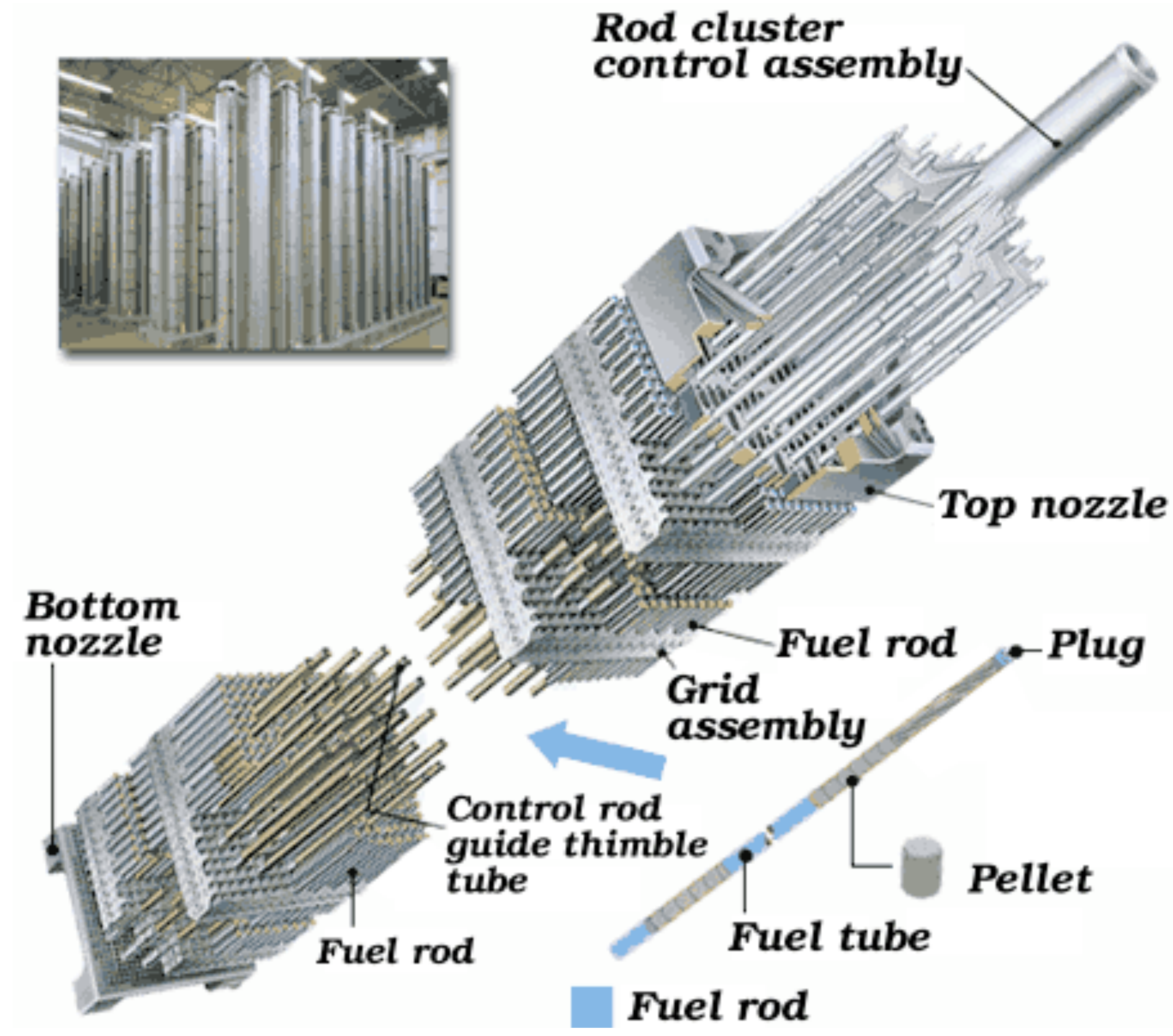








Fuel Element for a PWR Reactor



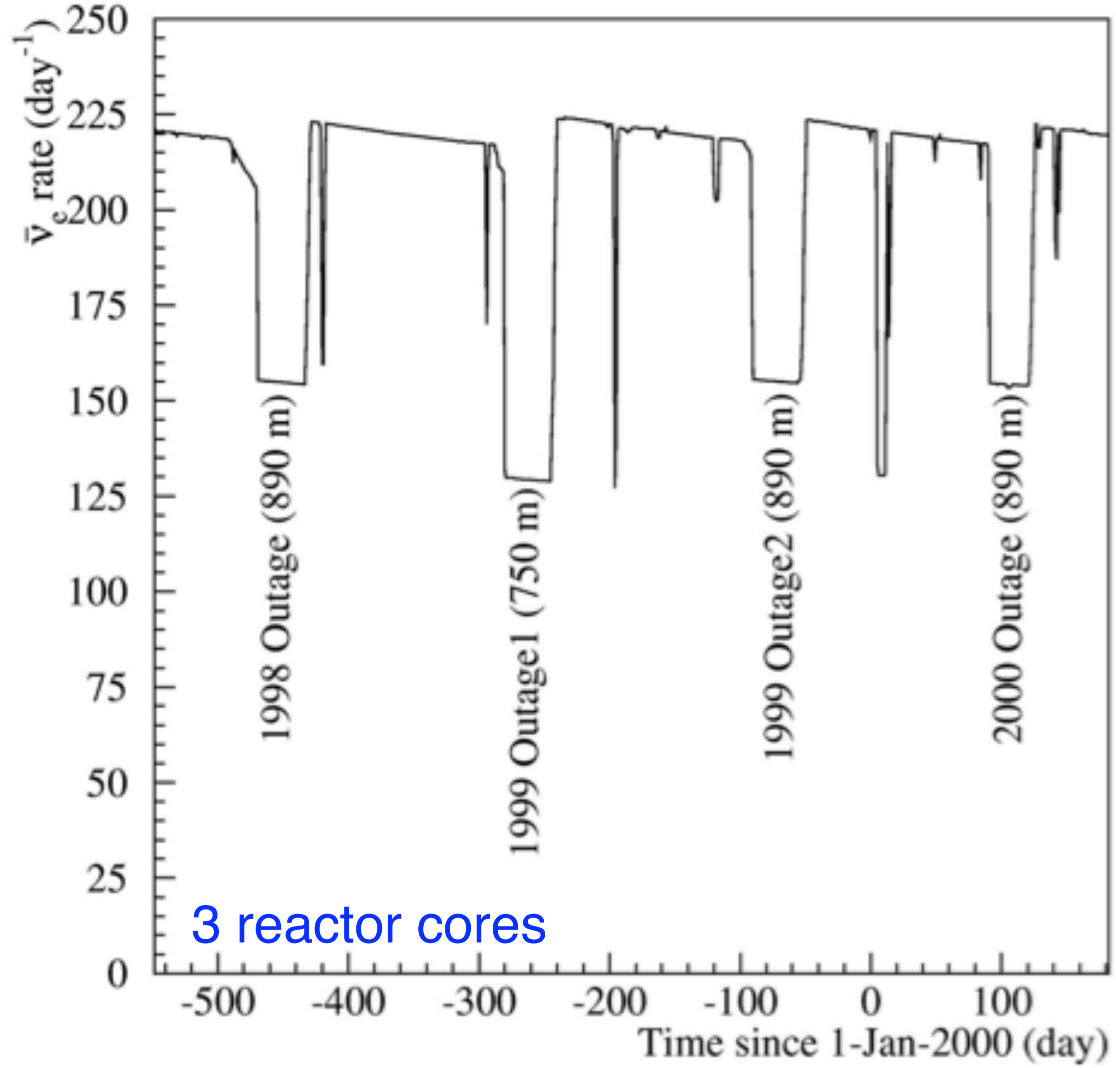
Reactor Refueling

$\overline{\nu}_e$ flux from reactor has time variation

3-6 week shutdown every 12-18 months

1/4-1/3 of fuel assemblies are replaced, remaining fuel repositioned

refueling at Palo Verde and predicted antineutrino rate



Build-Up of Fission Products & Burn-Up Corrections

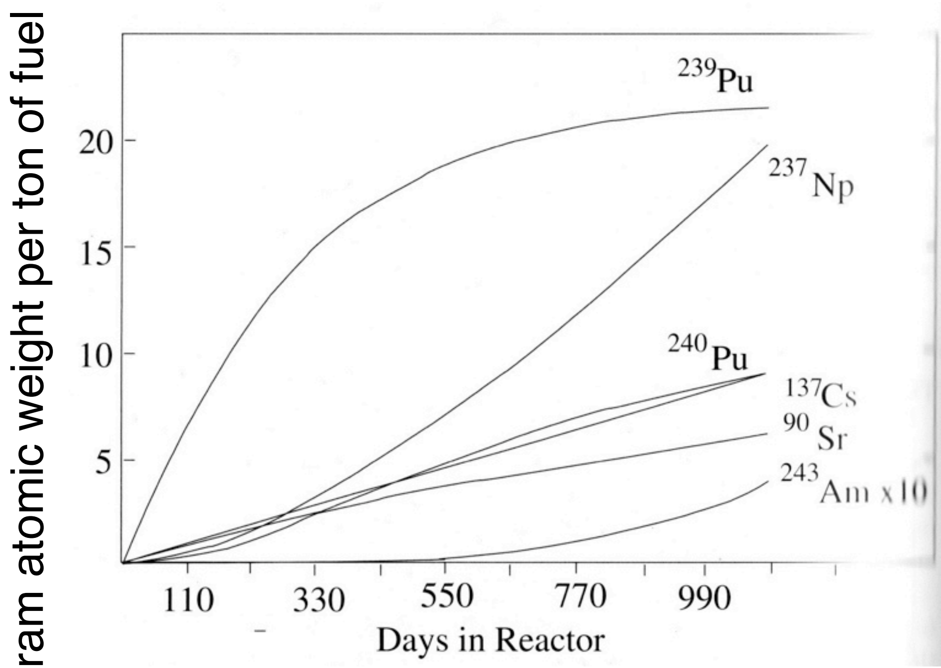
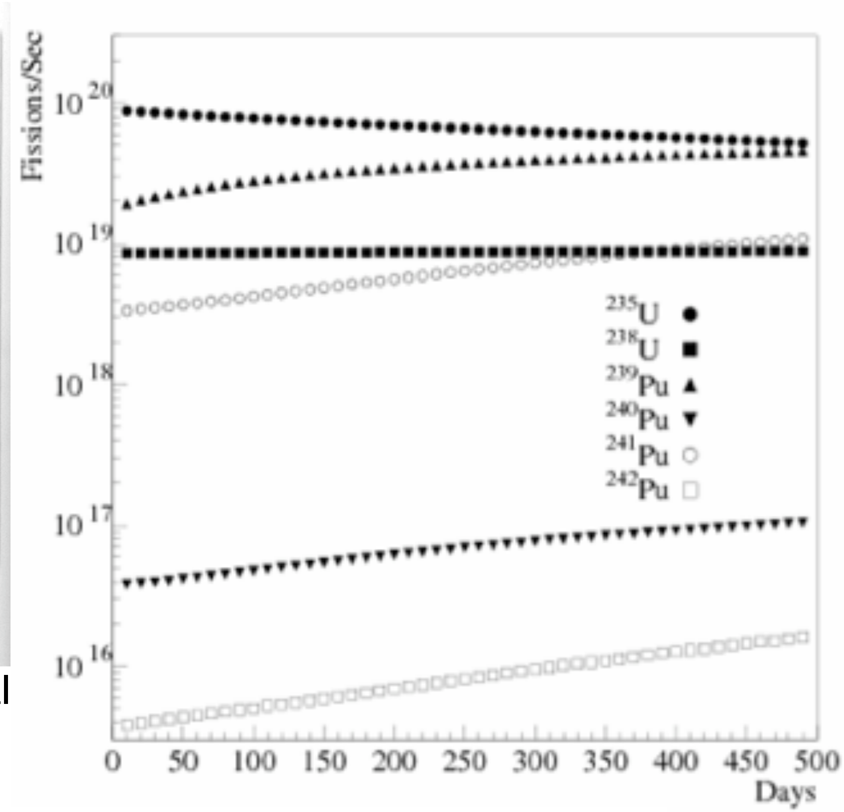


Fig: Basdevant et al



- 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

Neutrino Oscillation Searches with Reactor Antineutrinos

Oscillation Experiments with Reactors

experiments look for non-$1/r^2$ behavior of antineutrino interaction rate

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

for 3 active neutrinos, can study oscillation with two different oscillation length scales: Δm^2_{12}, Δm^2_{13}

$\Delta m^2_{12} \sim 8 \times 10^{-5}$ eV^2 → L ~ 1.8 km

$\Delta m^2_{13} \sim 2.5 \times 10^{-3}$ eV^2 → L ~ 60 km

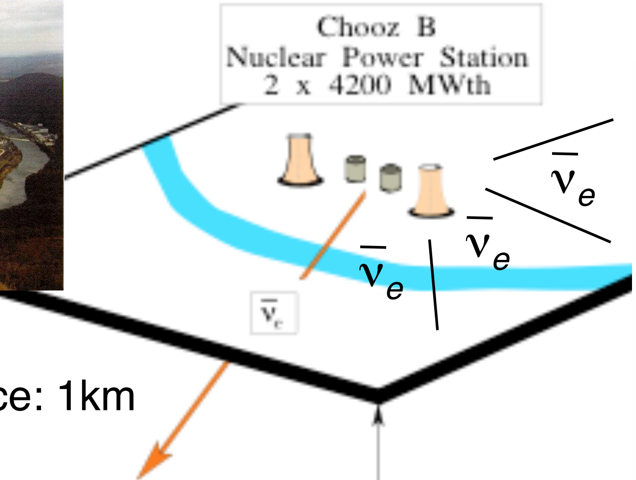
reactor appearance experiments?

Mean antineutrino energy is 3.6 MeV. Therefore, <u>only disappearance</u> experiments are possible.

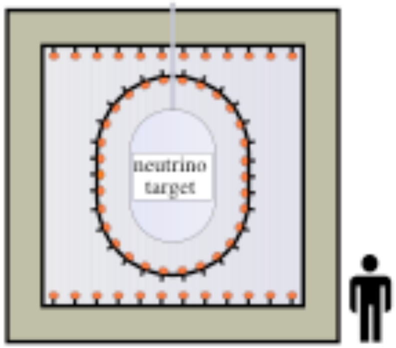
early oscillation experiments didn't know the length scales involved
early experiments tried to probe "atmospheric neutrino anomaly"

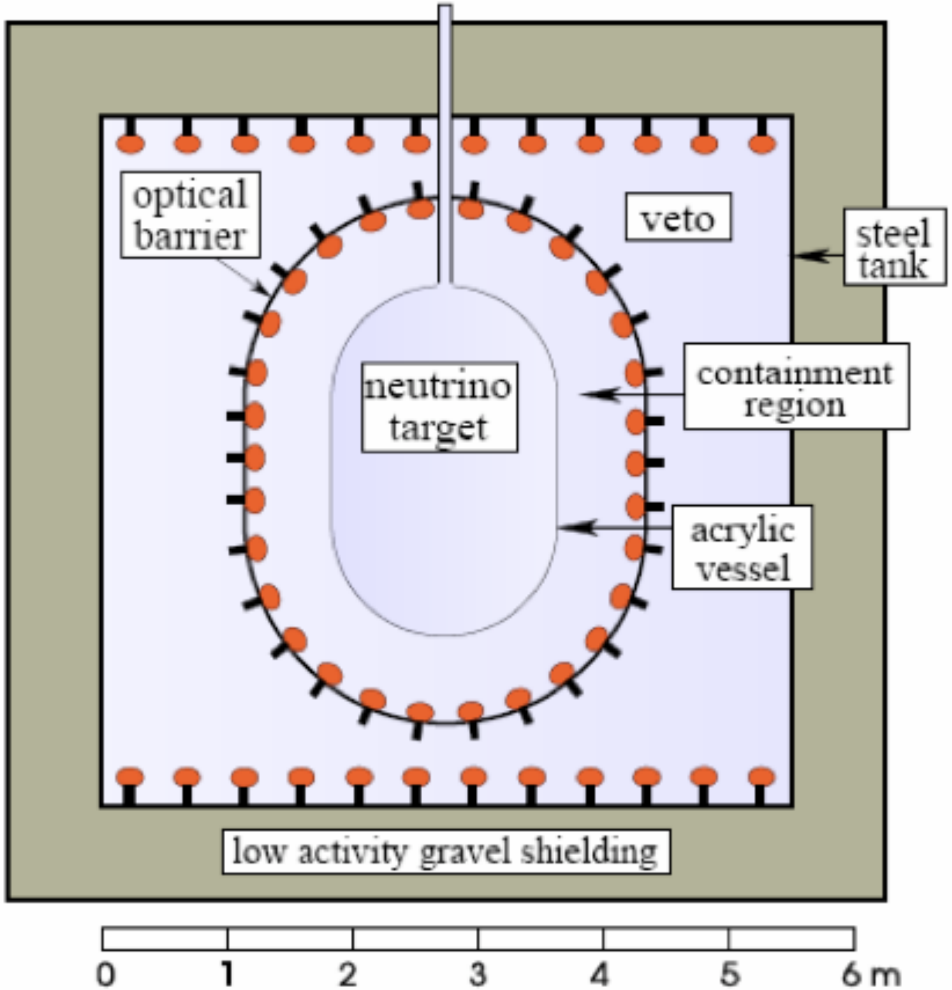
Neutrino Oscillation Search with Reactor Antineutrinos

Oscillation Searches at Chooz + Palo Verde: $\bar{\nu}_e \rightarrow \bar{\nu}_x$



Distance: 1km





Absolute measurement with 1 detector

detector size: several tons

Antineutrino Detection

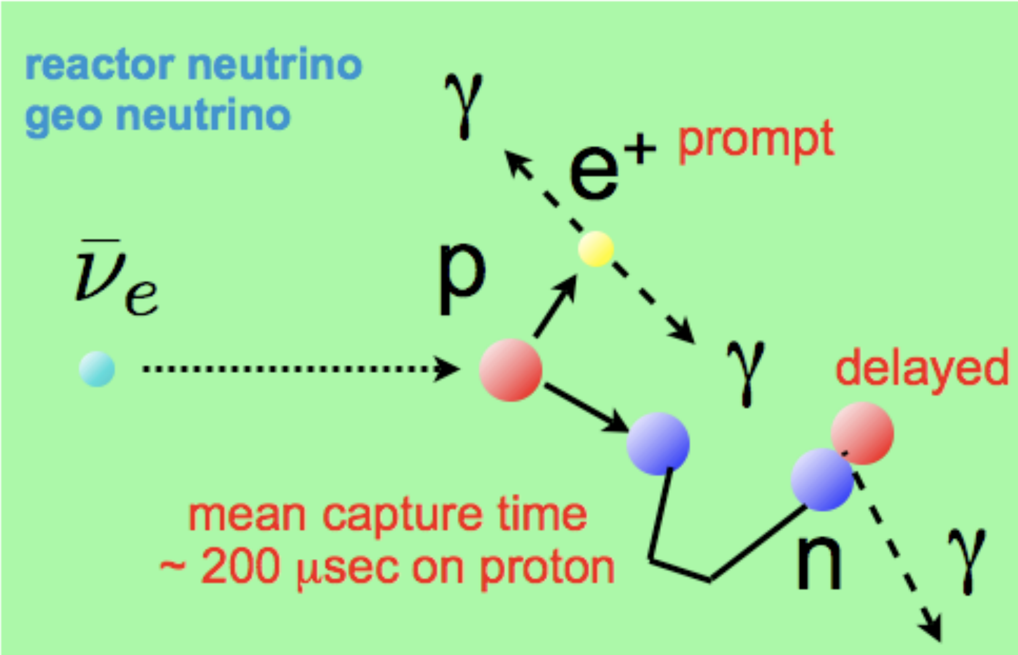
inverse beta decay

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

$$n + p \rightarrow D + \gamma \text{ (2.2 MeV)}$$

(delayed)

coincidence signature between prompt e^+ and delayed neutron capture on H, (or Cd, Gd)



anti-neutrino detection by inverse beta-decay

10-100 keV

1.805 MeV

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

other detection mechanisms:

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

$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

including E from e^+ annihilation, $E_{prompt} = E_{\bar{\nu}} - 0.8$ MeV

Backgrounds for Reactor Experiments

- Backgrounds to the e^+ - n coincidence signal

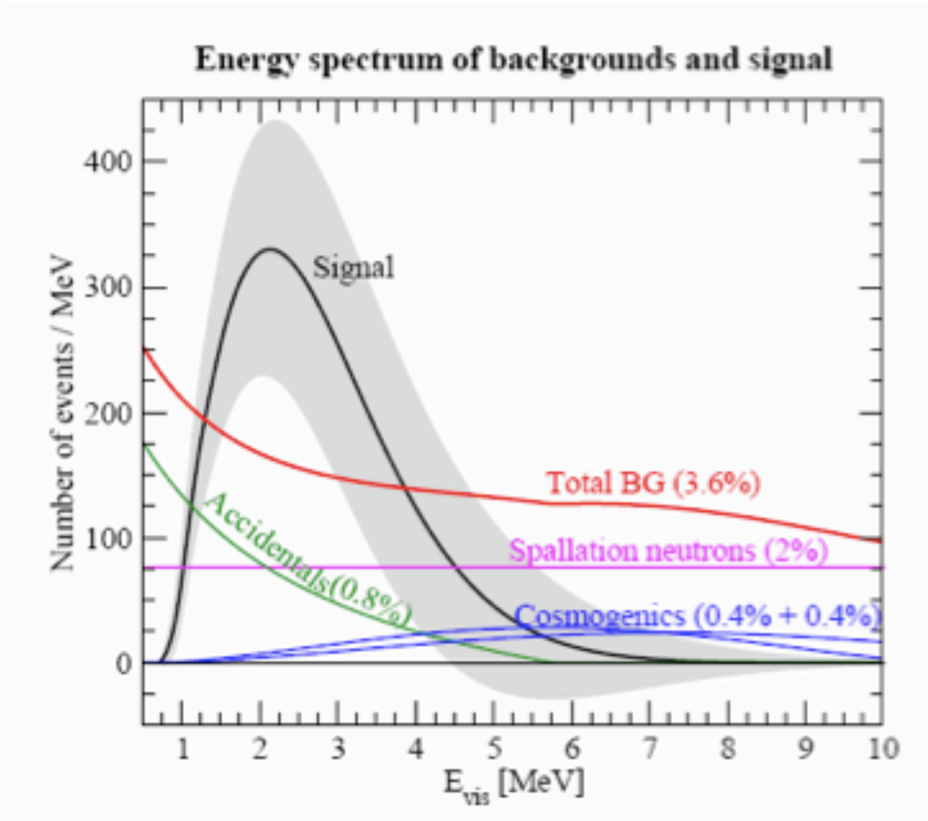
Uncorrelated Backgrounds

- 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)

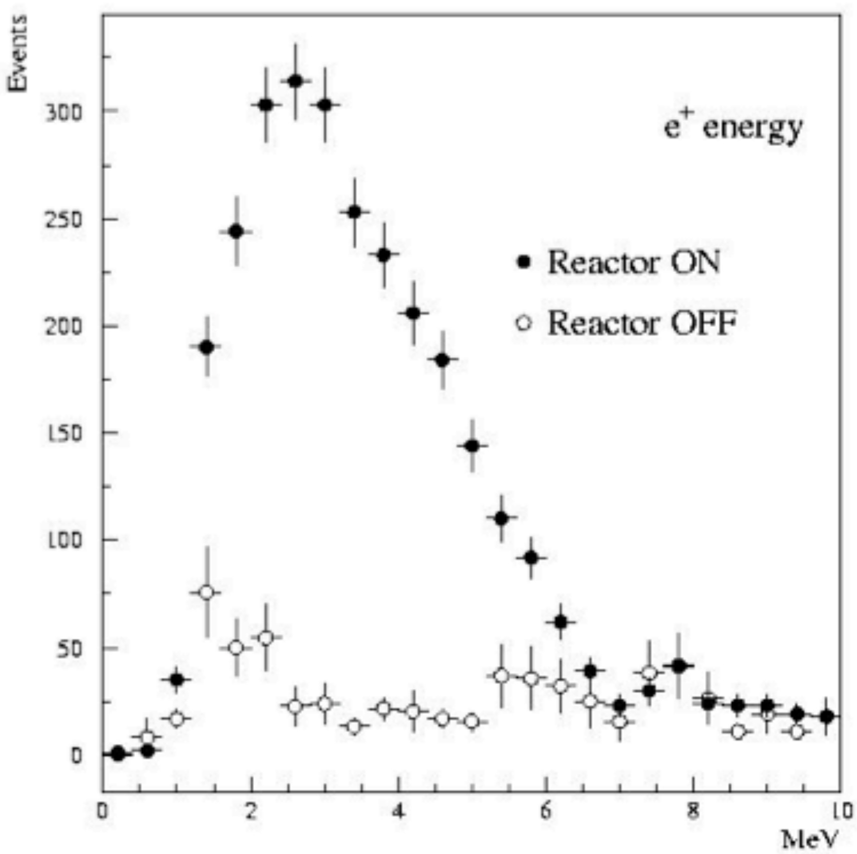


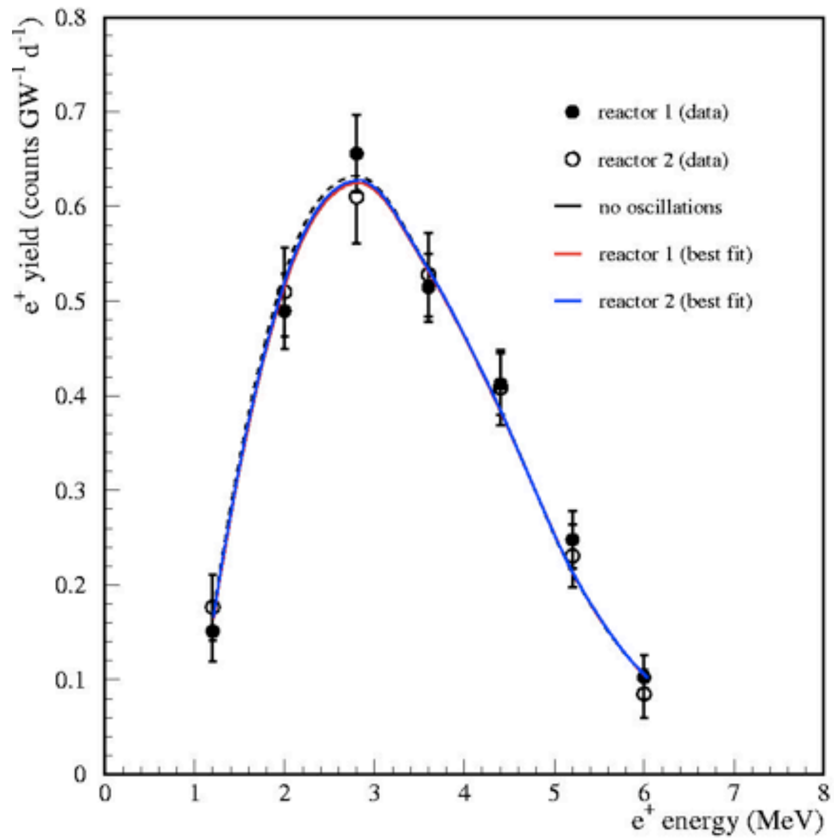
from M. Shaevitz

Chooz: Positron Spectrum

Reactor On/Off

- Positron Yields for Reactors I+II
- Fit to Spectrum
- Comparison to Expected Yield for No Oscillation





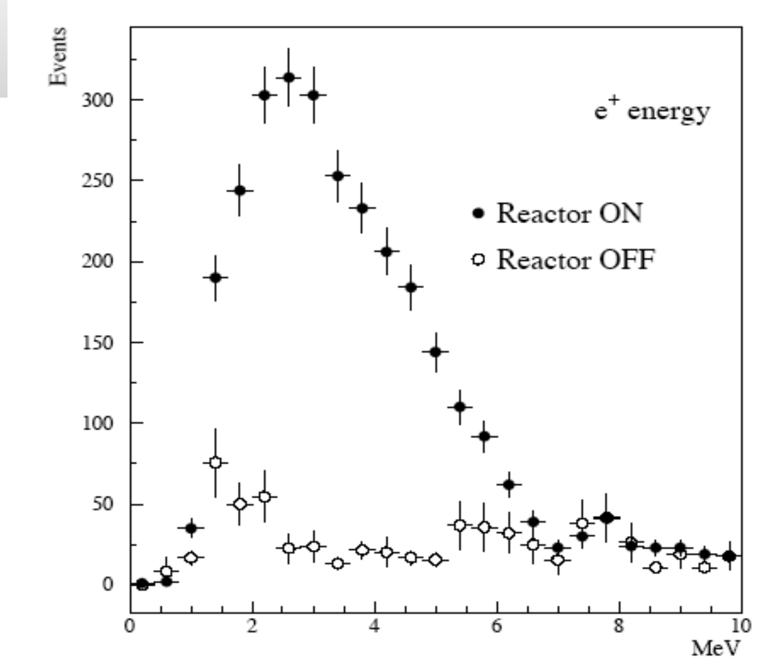
Chooz: Results

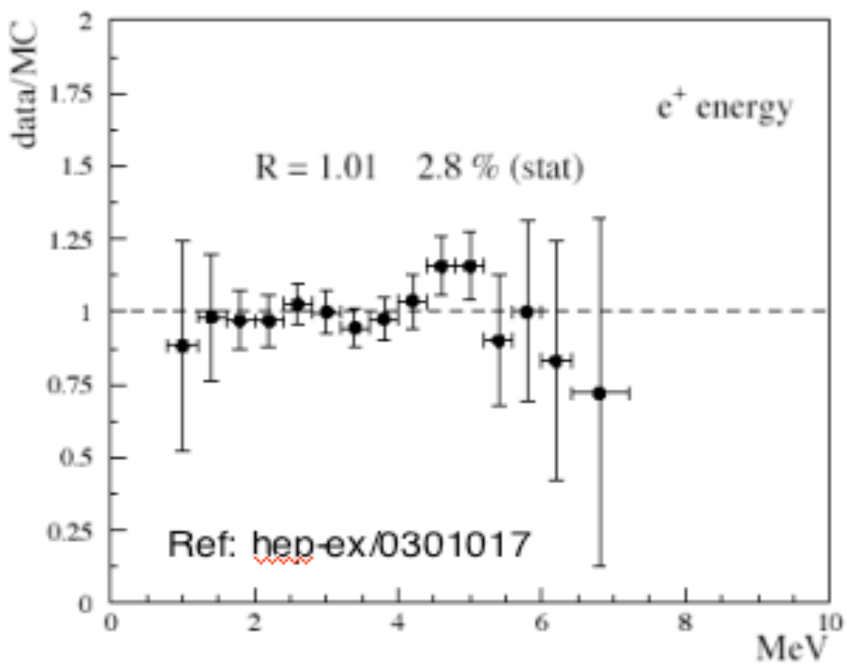
~3600 events in 335 days

~2.2 events/day/ton
with 0.2-0.4 bkgd events/day/ton

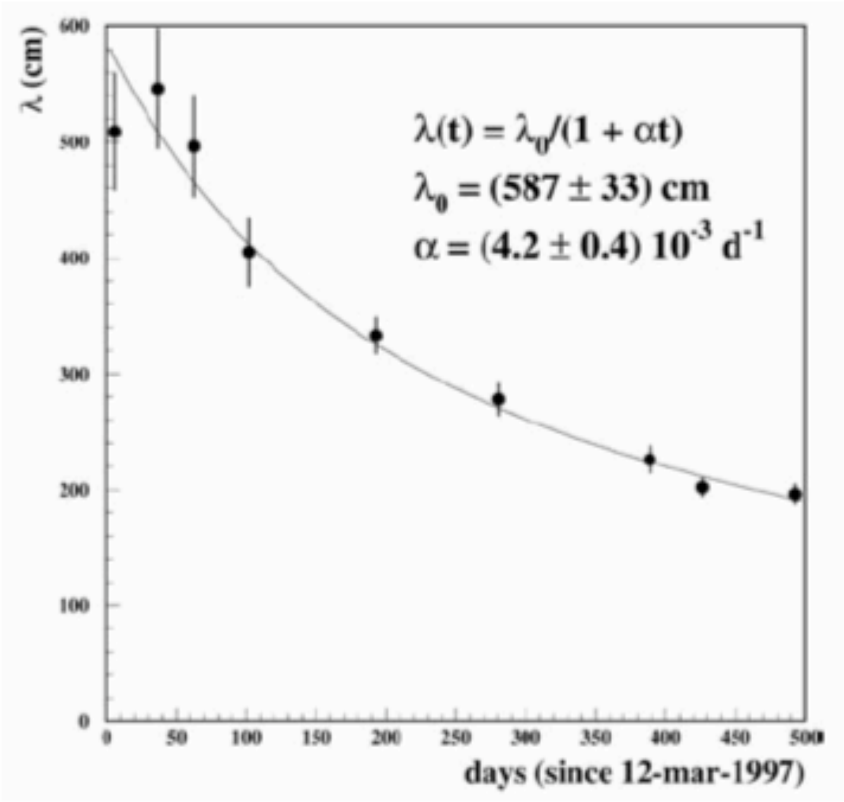
2.7% uncertainty

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%



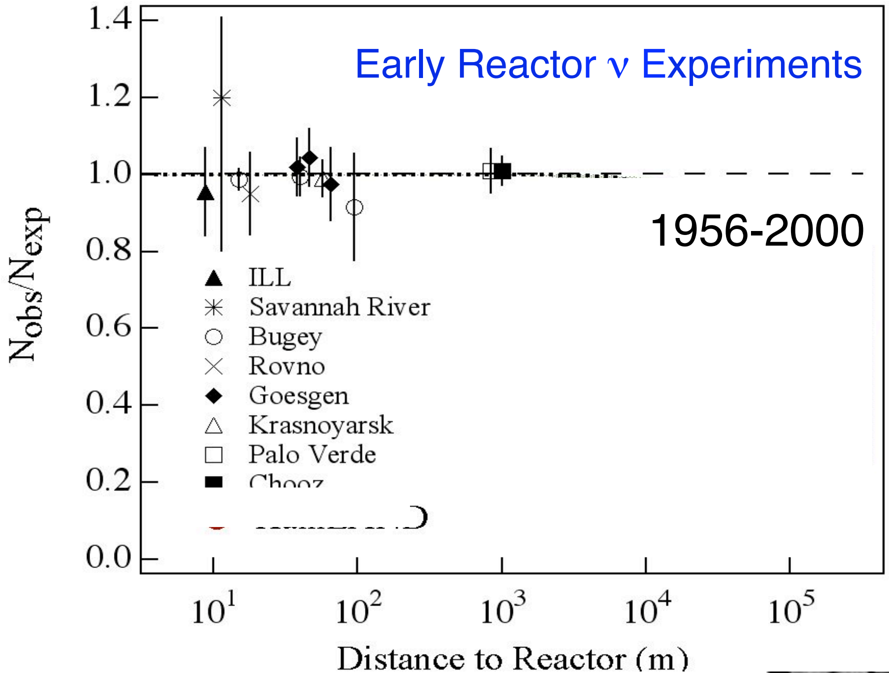


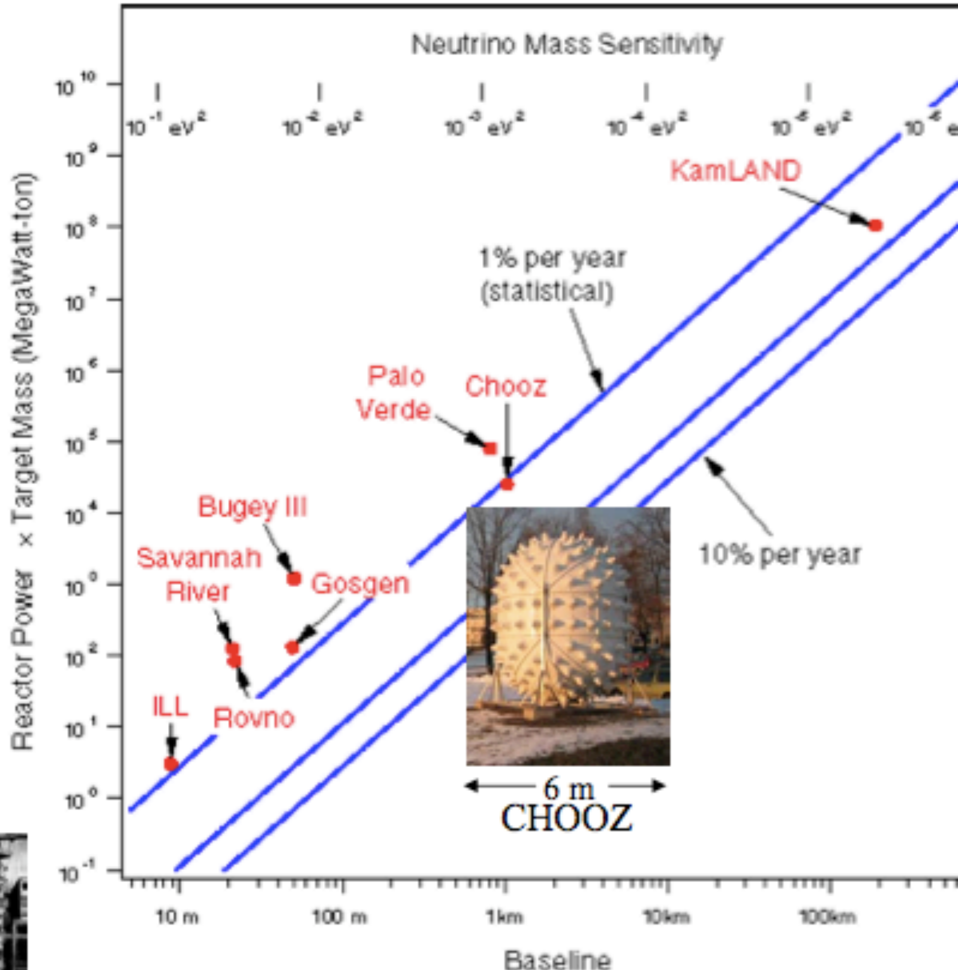
Chooz: Degradation of Scintillator



Attenuation degrades by ~0.4% per day.

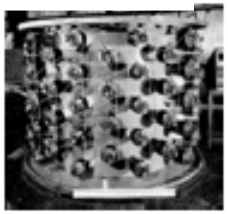
Reactor $\bar{\nu}_e$ Flux Measurements at Different Distances





6 m
CHOOZ

flux measurements at distances up to ~1km consistent with expectations



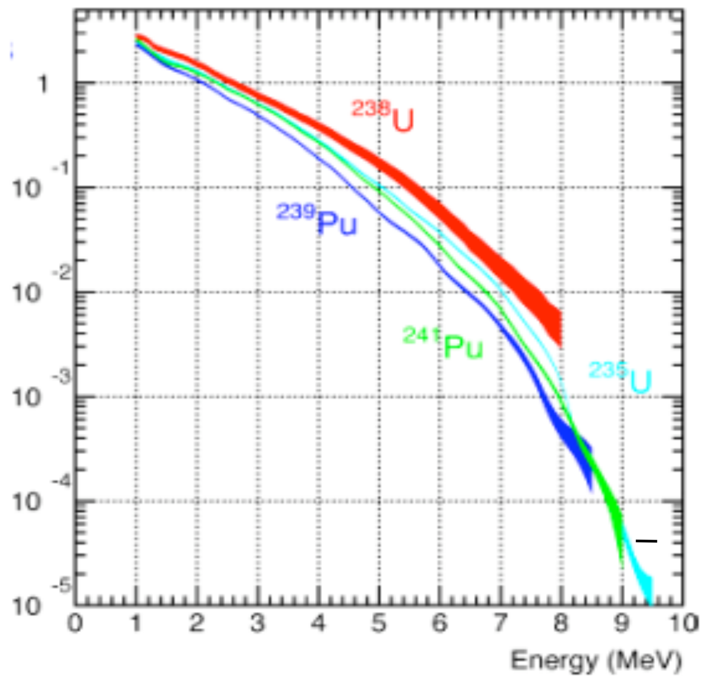
1m
Poltergeist

Reactor Antineutrinos in Japan

Japanese Reactors

55 reactors

Reactor Antineutrinos



^{235}U:^{238}U:^{239}Pu:^{241}Pu = 0.570: 0.078: 0.0295: 0.057

~ 200 MeV per fission

~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} $\bar{\nu}_e$/GW_{th}-sec

reactor $\bar{\nu}$ flux ~ 6 x 10^6/cm^2/sec

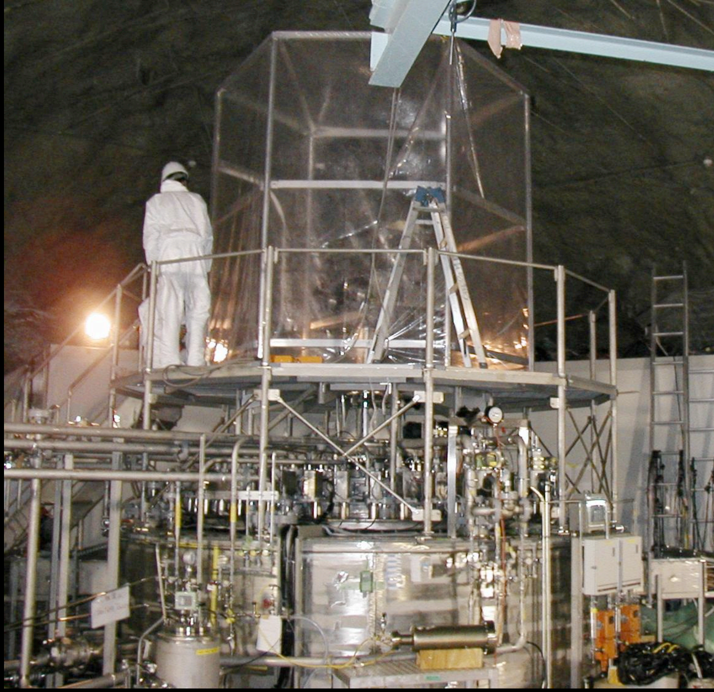
KamLAND Antineutrino Detector

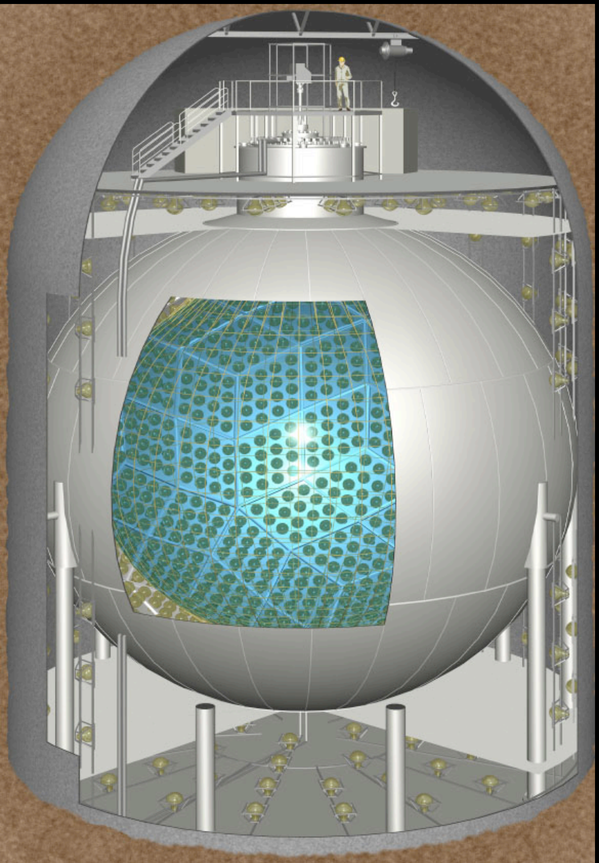
$\overline{\nu}_e + p \rightarrow e^+ + n$

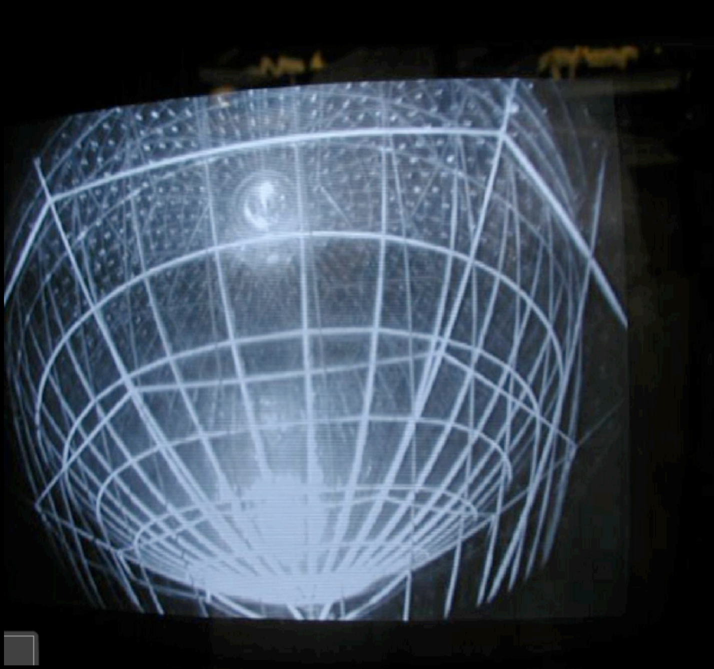
$$E_{\overline{\nu}_e} \simeq E_p + \overline{E}_n + 0.8\,\mathrm{MeV},$$

through inverse β-decay

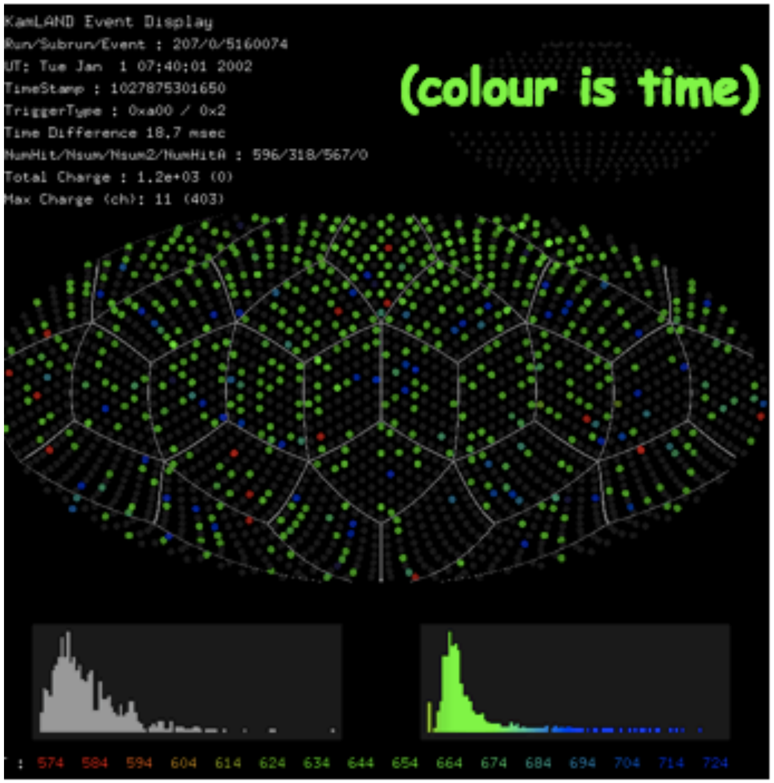
liquid scintillator target:
- proton rich > 10^{31} protons
- good light yield

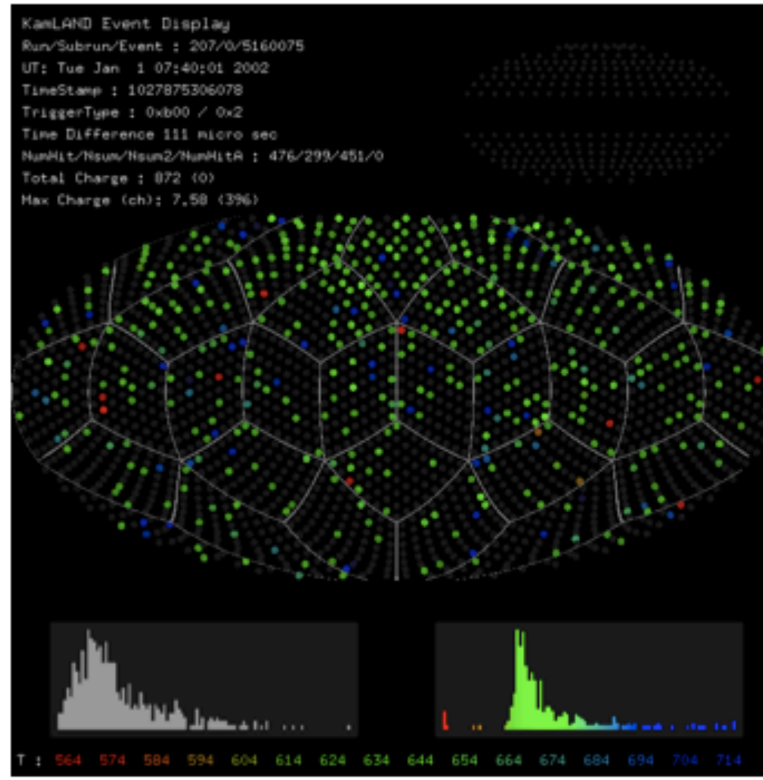






Antineutrino Candidate Event





Prompt Signal
E = 3.20 MeV

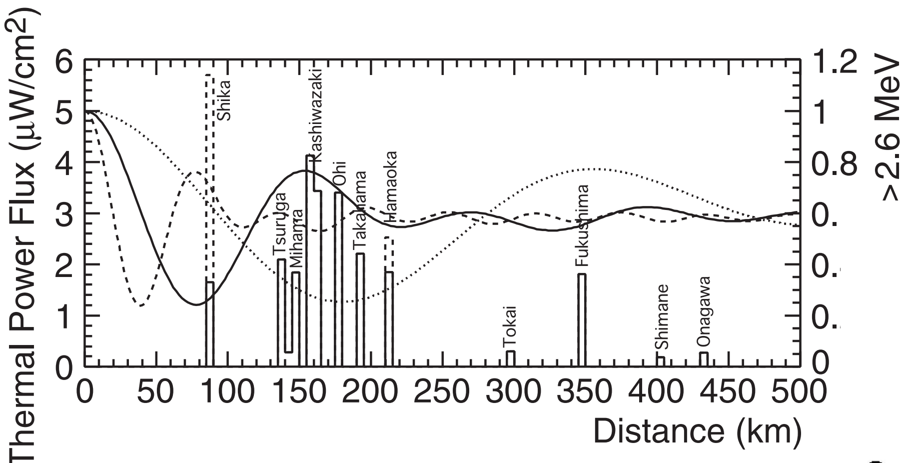
$\Delta t = 111$ ms
$\Delta R = 34$ cm

Delayed Signal
E = 2.22 MeV

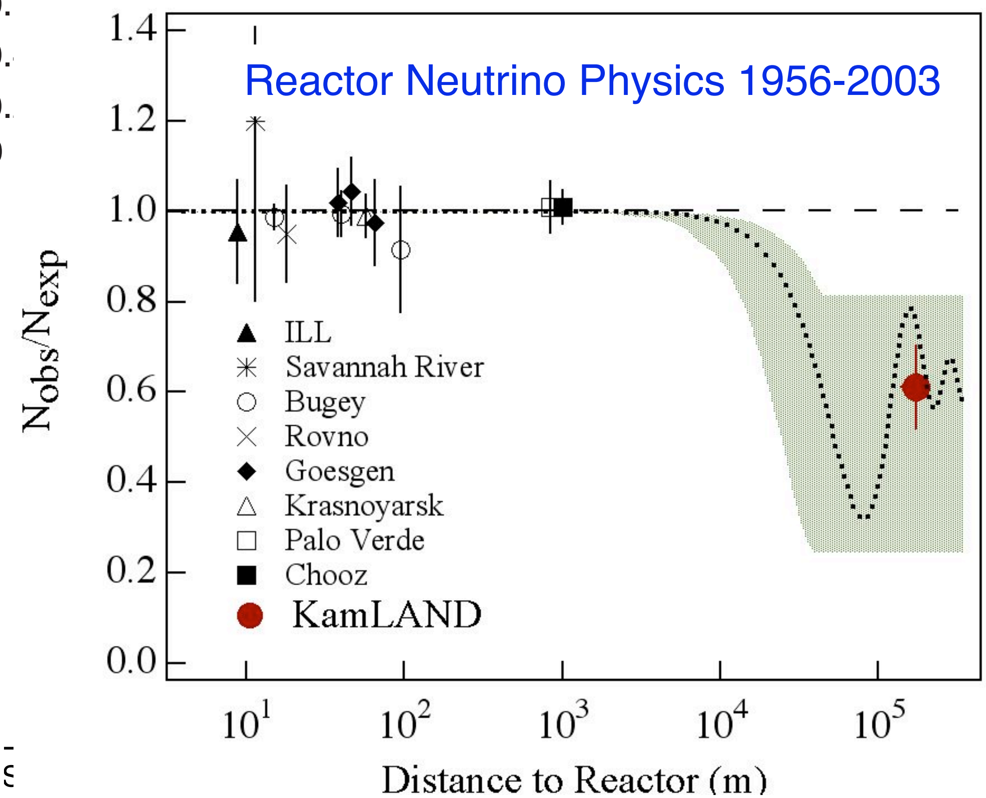
First Evidence for Reactor $\overline{\nu}_e$ Disappaerance

KamLAND 2003

mean, flux-weighted reactor distance ~ 180km



Japan

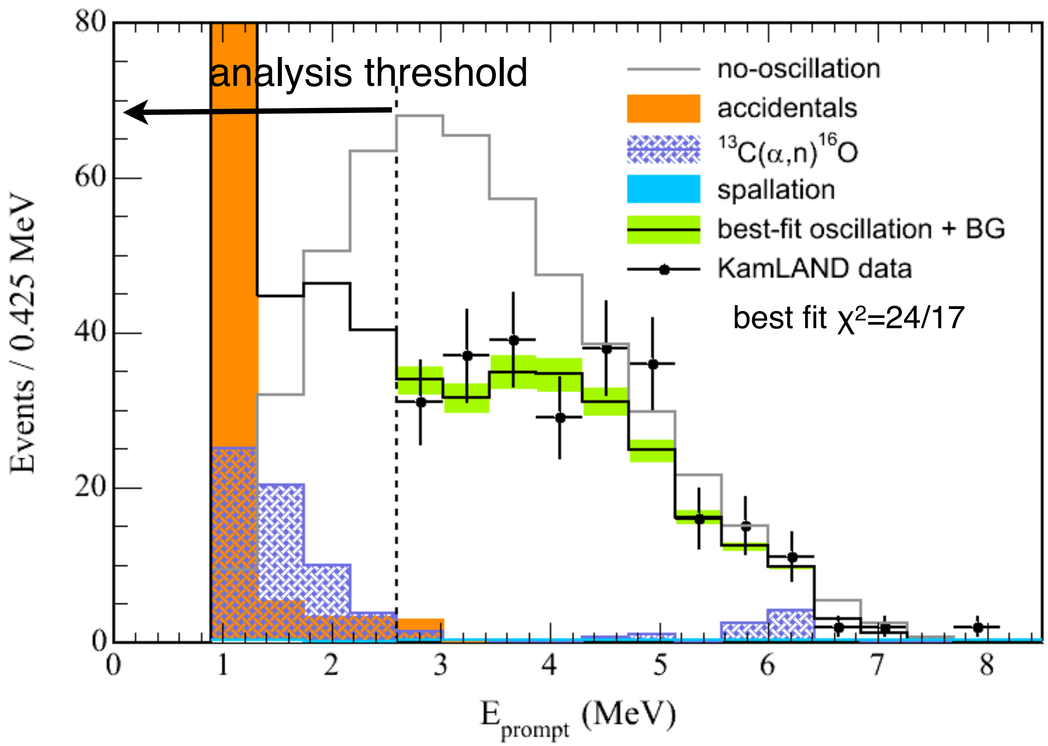


PRL 90:021802 (2003)

Observed $\overline{\nu}_e$	54 events
No-Oscillation events	86.8 ± 5.6
Background	1 ± 1 events
Livetime:	162.1 ton-yr

Evidence of Spectral Distortion

KamLAND 2004



hep-ex/0406035 (2004)

Observed $\bar{\nu}_e$	258 events
No-Oscillation	365.2 ± 23.7 (syst.)
Background	17.8 ± 7.3 events
Livetime:	766.3 ton-yr

fiducial volume syst.: 4.7%
total systematics = 6.5%

$^{210}\mathrm{Pb} \longrightarrow {}^{210}\mathrm{Bi} \longrightarrow {}^{210}\mathrm{Po} \xrightarrow{138\mathrm{d},\ \alpha} {}^{206}\mathrm{Pb}$

$\longrightarrow {}^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ $(\sim 10^{-7})$

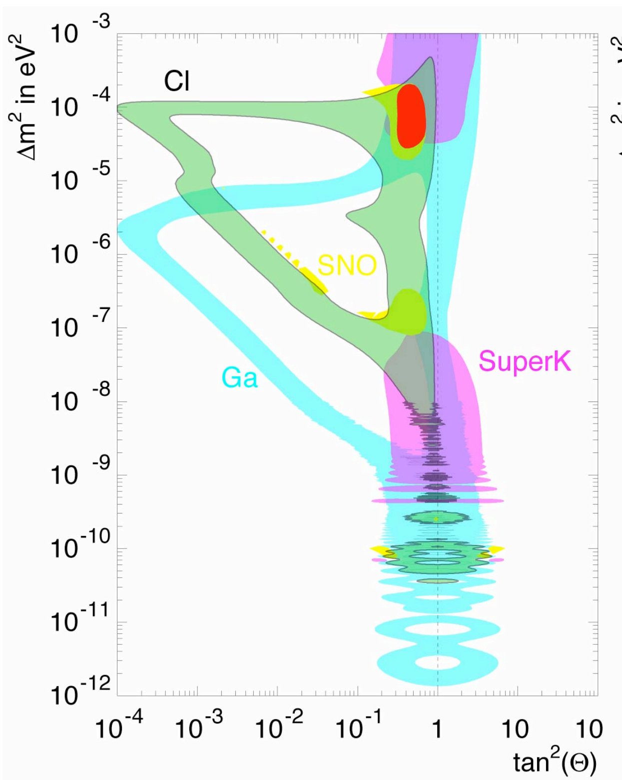
^{222}Rn decay chain introduced in the LS during assembly

Spectral Distortions: A unique signature of neutrino oscillation!

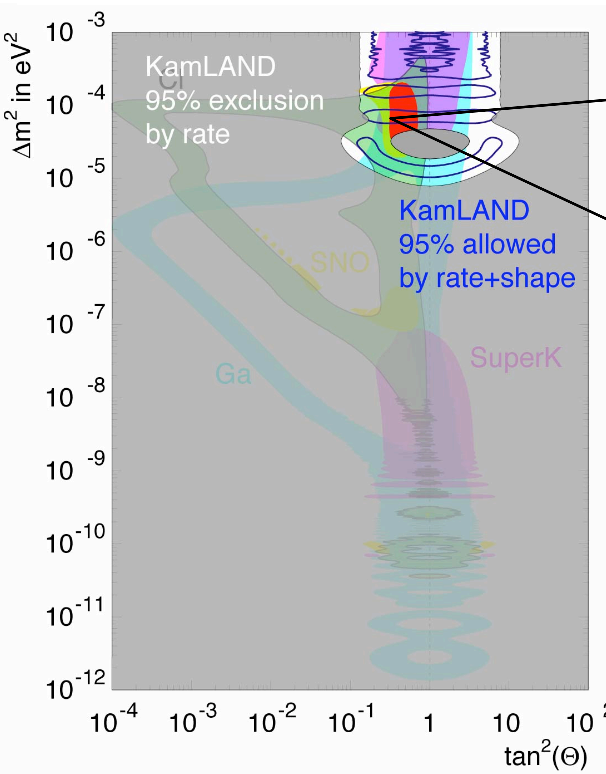
Simple, rescaled reactor spectrum is excluded at 99.6% CL(χ^2=37.3/18)

Measuring Neutrino Oscillation Parameters

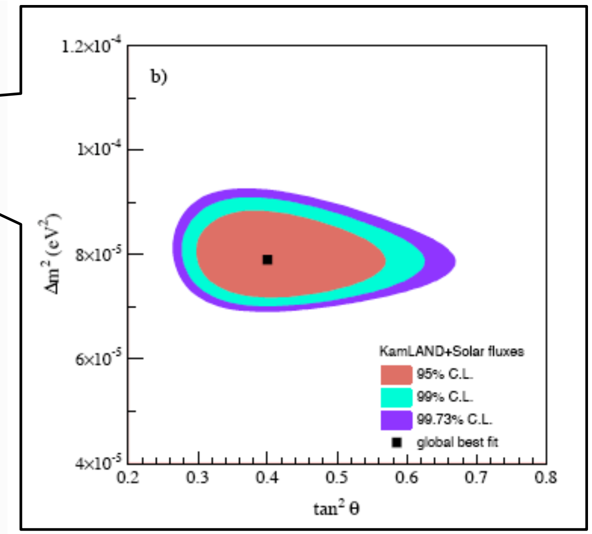
Solar Neutrinos



Solar Neutrinos
+ KamLAND 2003
($\bar{\nu}_e$ rate)



Solar Neutrinos
+ KamLAND 2004
($\bar{\nu}_e$ rate+spectrum)



Agreement between oscillation parameters for $\bar{\nu}$ and ν

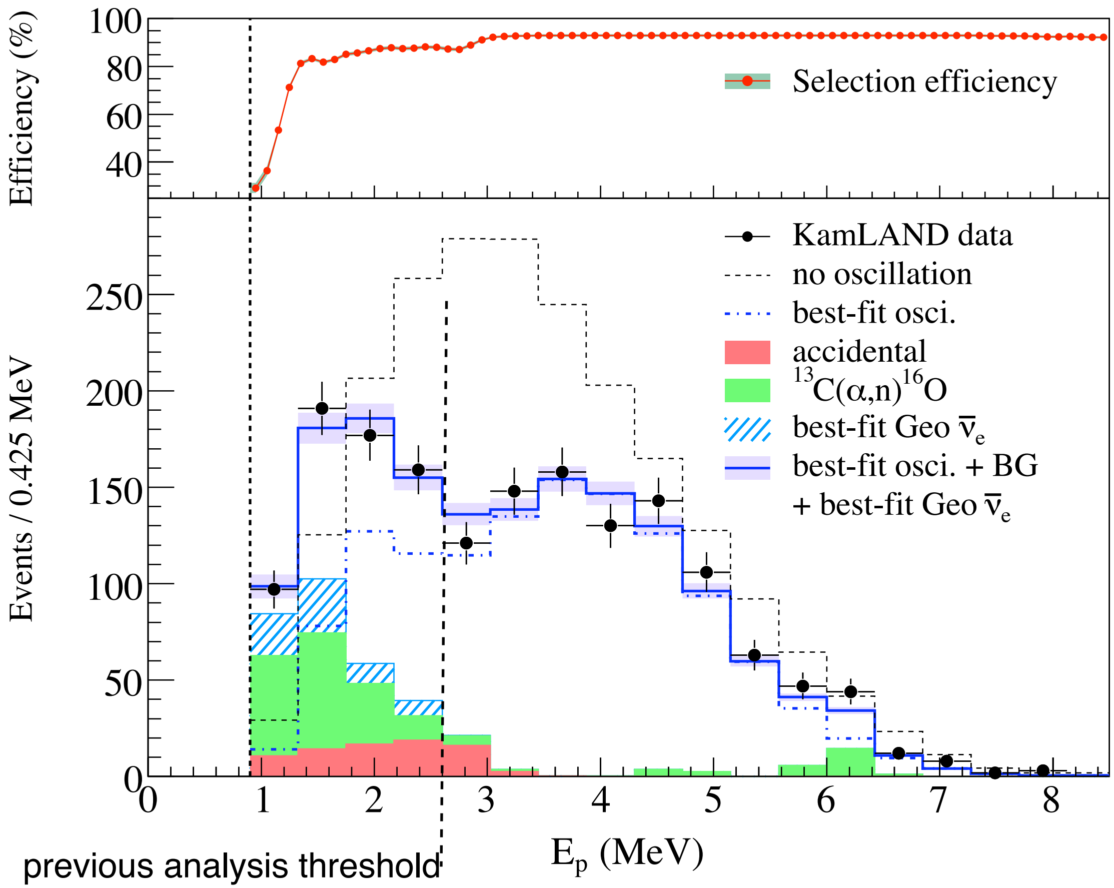
Beginning of precision neutrino physics

Precision Oscillation Physics with Reactor Neutrinos

Evidence of Spectral Distortion

KamLAND 2008

Prompt event energy spectrum for $\overline{\nu}_e$



number of events

expected

(no-oscillation): 2179 ± 89 (syst)

observed: 1609

bkgd: 276 ± 23.5

significance of disappearance

(with 2.6 MeV threshold): 8.5σ

no-osc χ^2/ndf=63.9/17

significance of distortion: > 5σ

best-fit χ^2/ndf=21/16 (18% C.L.)

- unbinned likelihood fit (rate+shape+time)
- 2-flavor oscillation analysis with w/Earth matter effects
- geo-neutrino U,Th amplitude is a free parameter

Systematic Uncertainties and Backgrounds

KamLAND
Kamioka Liquid scintillator Anti-Neutrino Detector

Systematic Uncertainties

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\overline{\nu}_e$-spectra [7]	0.6
Event rate	Fiducial volume	1.8	$\overline{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3

fiducial volume systematics reduced from 4.7% → 1.8%

total systematics: 4.1%

Estimated Backgrounds

TABLE II: Estimated backgrounds after selection efficiencies.

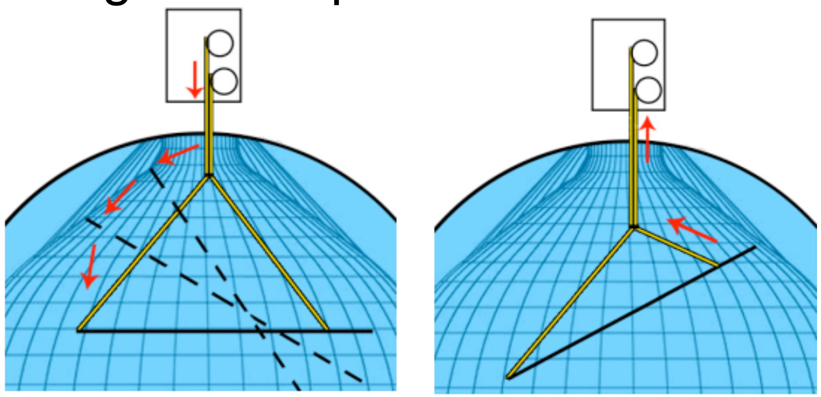
Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
^{13}C$(\alpha$,n$)^{16}$O G.S.	157.2 ± 17.3
^{13}C$(\alpha$,n$)^{16}$O ^{12}C(n,n$\gamma)^{12}$C (4.4 MeV γ)	6.1 ± 0.7
^{13}C$(\alpha$,n$)^{16}$O 1st exc. state (6.05 MeV e$^+$e$^-$)	15.2 ± 3.5
^{13}C$(\alpha$,n$)^{16}$O 2nd exc. state (6.13 MeV γ)	3.5 ± 0.2
Total	276.1 ± 23.5

significantly reduced

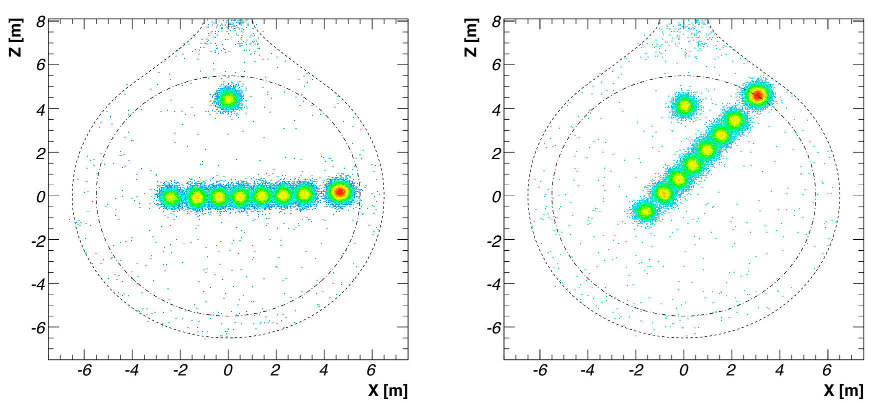
(number of events)

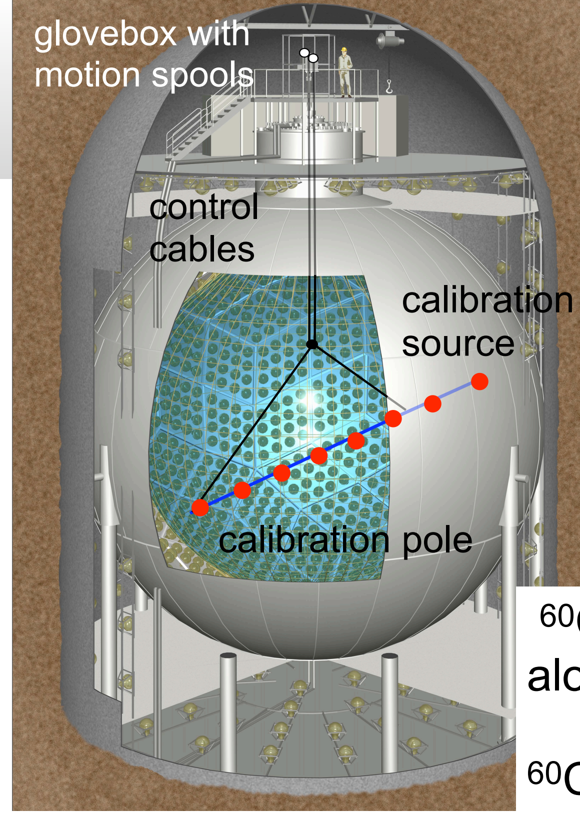
4π Full-Volume Calibration

Design Concept



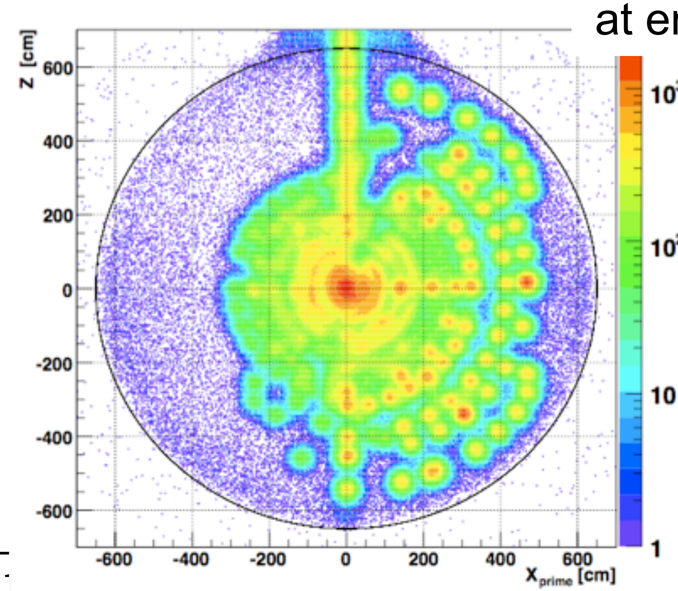
Calibration Data





^{60}Co sources along pole

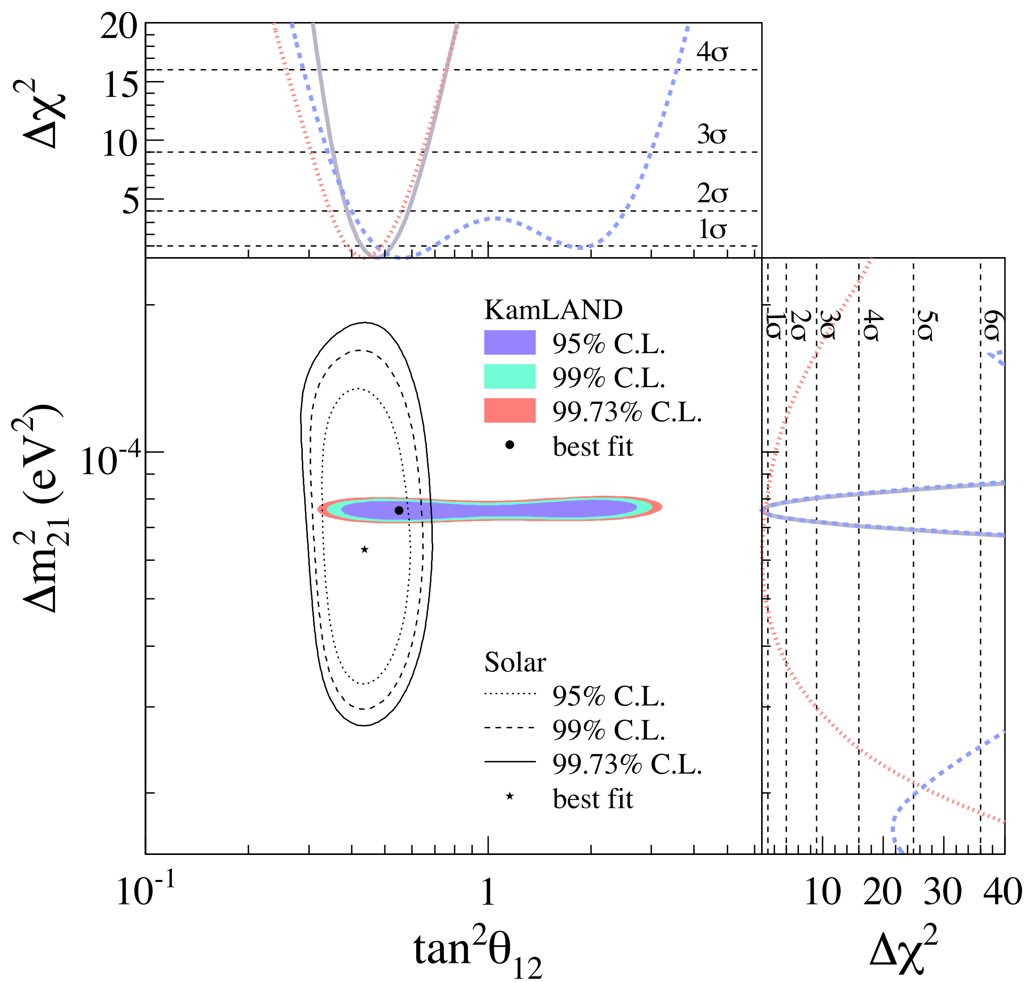
^{60}Co/^{68}Ge source at end



Vertex distribution of ^{60}Co/^{68}Ge composite source in 4π calibration runs.

Oscillation Parameters

Rate-Shape-Time Analysis



KamLAND only

$\tan^2\Theta = 0.56\ ^{+0.14}_{-0.09}$

$\Delta m^2 = 7.58\ ^{+0.21}_{-0.21}\ \times 10^{-5}\ \mathrm{eV}^2$

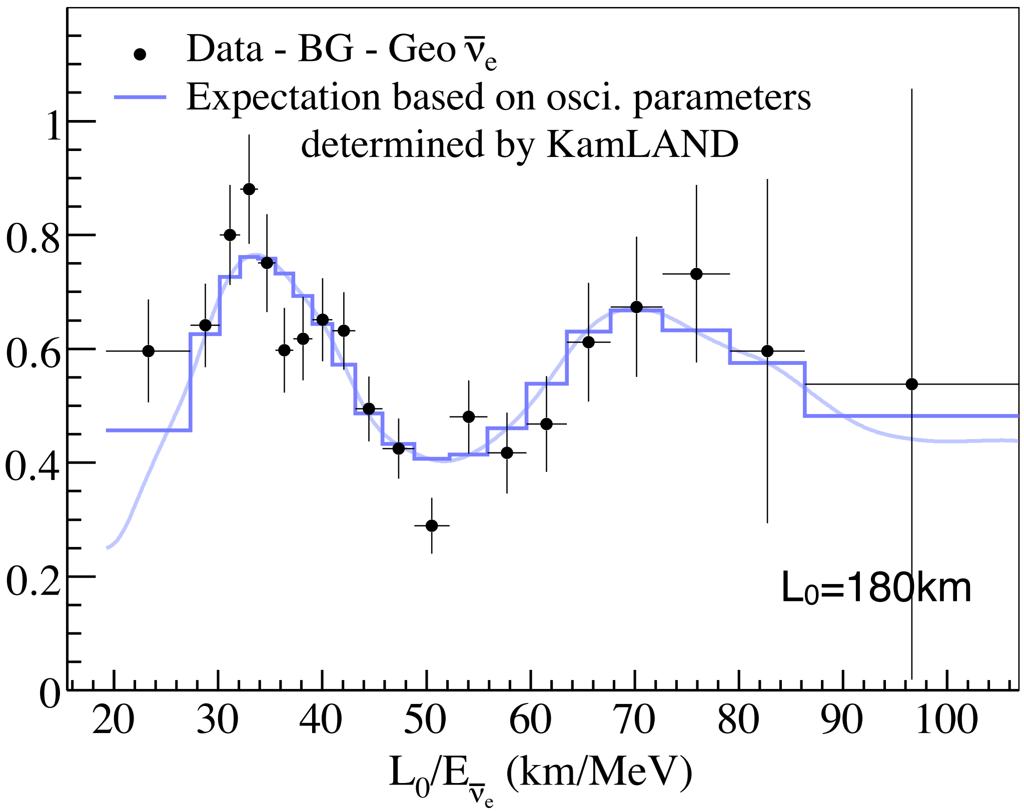
KamLAND+solar

(combined under assumption of CPT invariance)

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

$\Delta m^2 = 7.59\ ^{+0.21}_{-0.21}\ \times 10^{-5}\ \mathrm{eV}^2$

L/E Dependence



oscillation $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$

decay $P_{ee} = (\cos^2\theta + \sin^2\theta \exp(-\frac{m_2}{2\tau}\frac{L}{E}))^2$

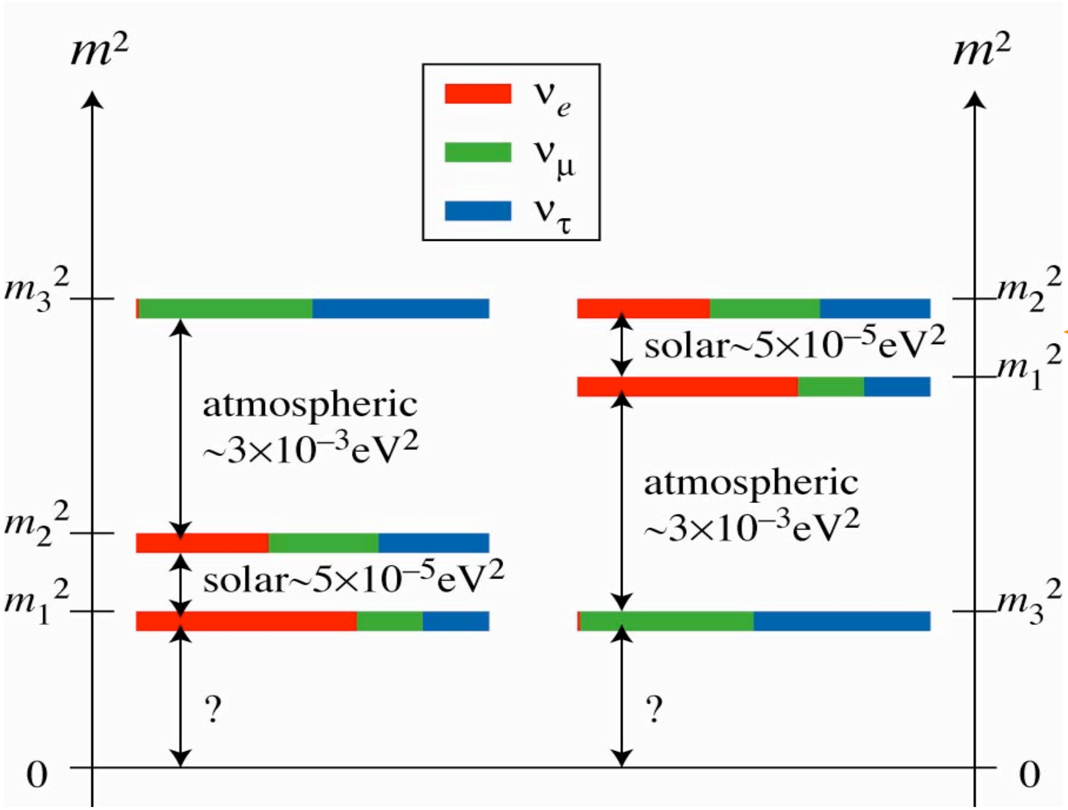
ecoherence $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta(1 - \exp(-\gamma\frac{L}{E}))$

Solar neutrino problem solved!

1970-1995	first identified by Ray Davis (missing solar ν_e)
2002-2007	SNO observes neutrino flavor change, finds evidence for neutrino mass
2003-2008	KamLAND demonstrates ν oscillation, precision measurement of θ, Δm^2

What we know...

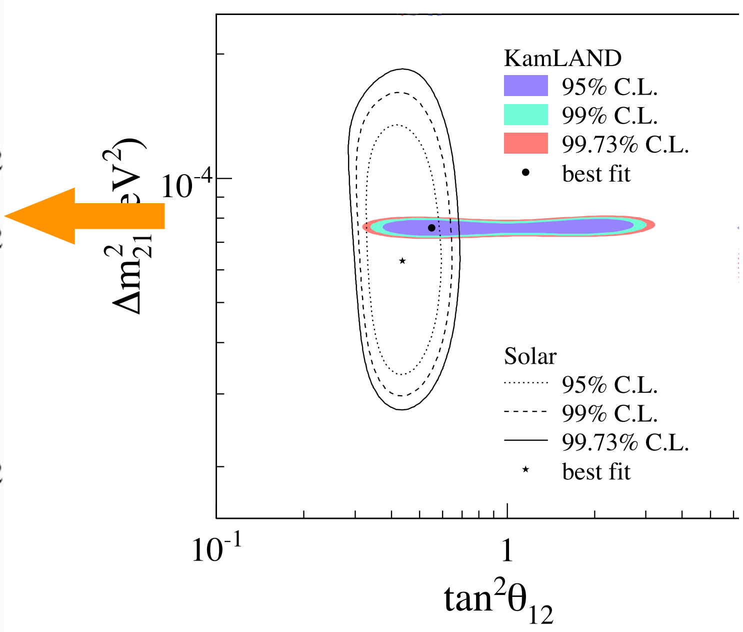
Neutrino Mass Splitting



normal

inverted

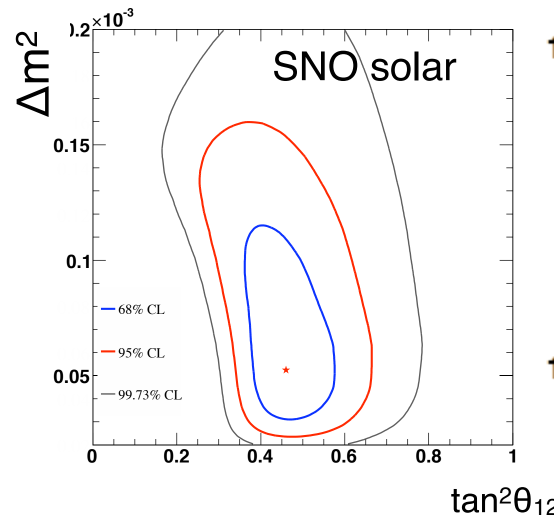
KamLAND 2008

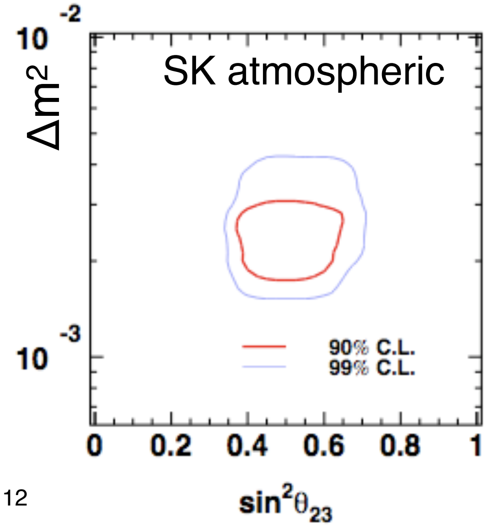


- KamLAND provides most precise value of Δm_{12}^2 (~2.8%)

What we know...

Neutrino Mixing Angles





$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

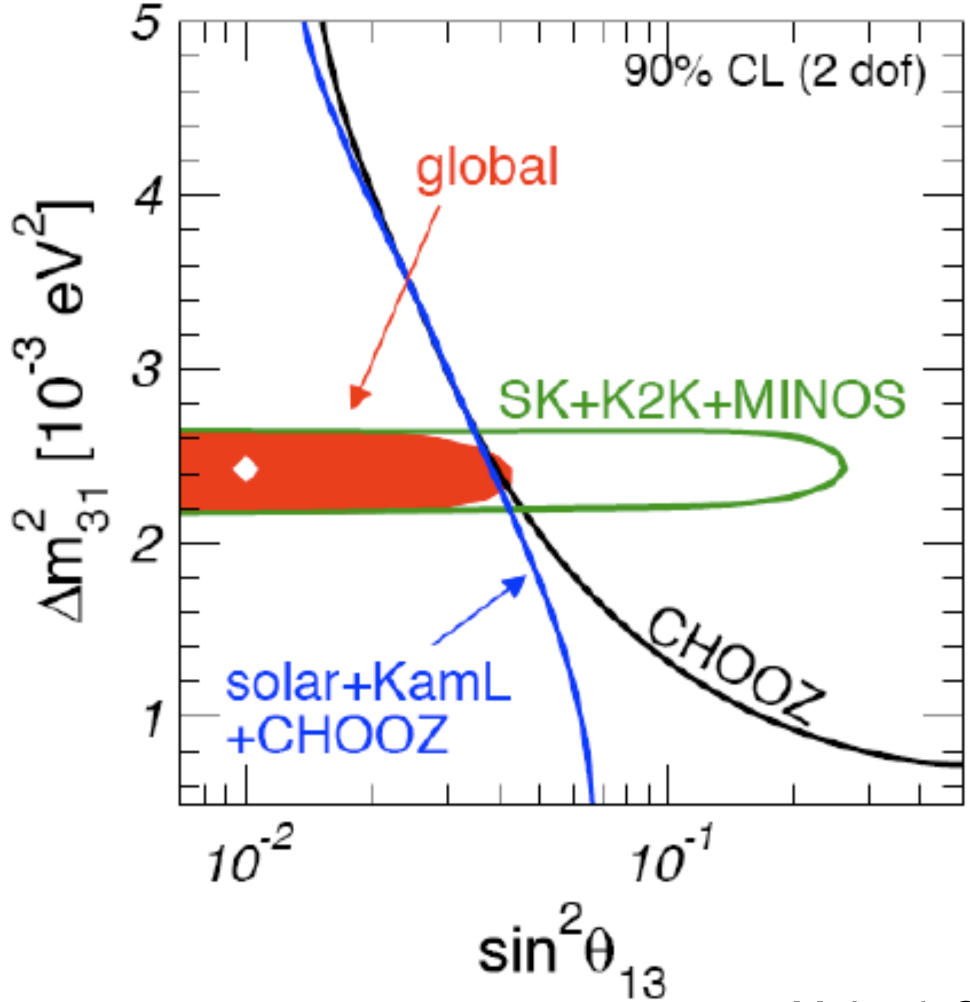
atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$

$\theta_{23} = \sim 45°$ — maximal?

$\theta_{13} = ?$

$\theta_{12} \sim 32°$ — large, but not maximal!

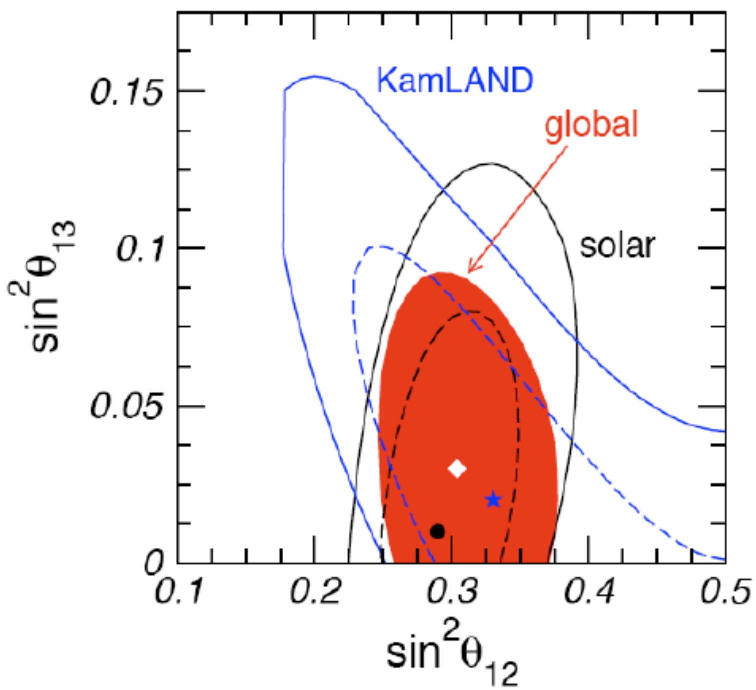
Current Knowledge of θ_{13}: Experimental Bounds



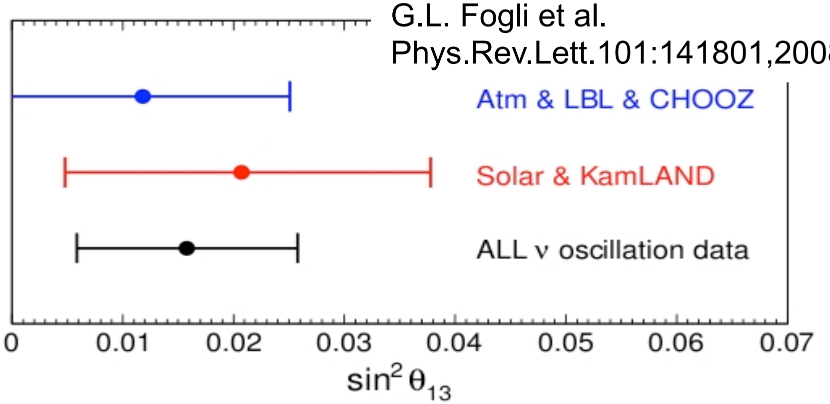
Maltoni, Schwetz, arXiv:0812.3161v1

Current Knowledge of θ_{13}: Experiment & Theory

Global Fit



G.L. Fogli et al.
Phys.Rev.Lett.101:141801,2008



Theory

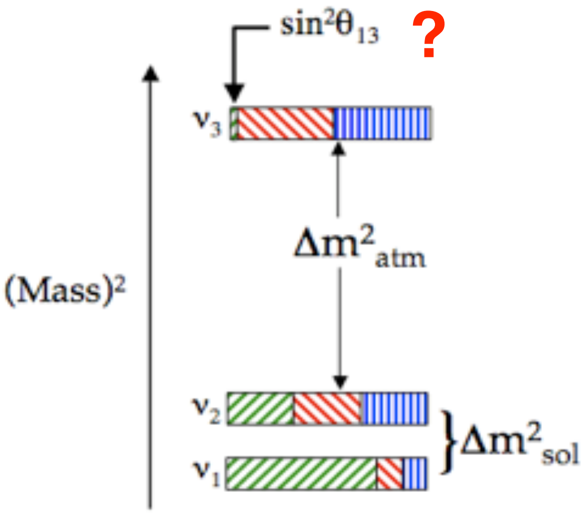
Model(s)	Refs.	$\sin^2 2\theta_{13}$
Minimal SO(10)	[22]	0.13
Orbifold SO(10)	[23]	0.04
SO(10) + Flavor symmetry	[24]	$1.2 \cdot 10^{-6}$
	[25]	$7.8 \cdot 10^{-4}$
	[26–28]	0.01 .. 0.04
	[29–31]	0.09 .. 0.18
SO(10) + Texture	[32]	$4 \cdot 10^{-4}$ .. 0.01
	[33]	0.04
$SU(2)_L \times SU(2)_R \times SU(4)_c$	[34]	0.09
Flavor symmetries	[35–37]	0
	[38–40]	$\lesssim 0.004$
	[41–43]	10^{-4} .. 0.02
	[40, 44–47]	0.04 .. 0.15
Textures	[48]	$4 \cdot 10^{-4}$ .. 0.01
	[49–52]	0.03 .. 0.15
3 × 2 see-saw	[53]	0.04
	[54] (n.h.)	0.02
	(i.h.)	$> 1.6 \cdot 10^{-4}$
Anarchy	[55]	> 0.04
Renormalization group enhancement	[56]	0.03 .. 0.04
M-Theory model	[57]	10^{-4}

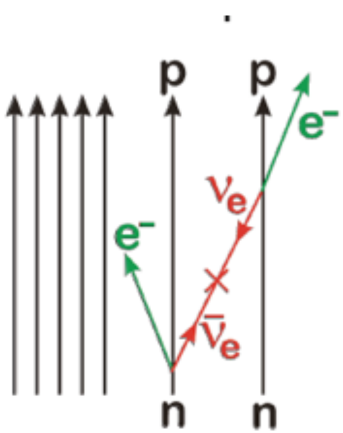
we don't know θ_{13} ...

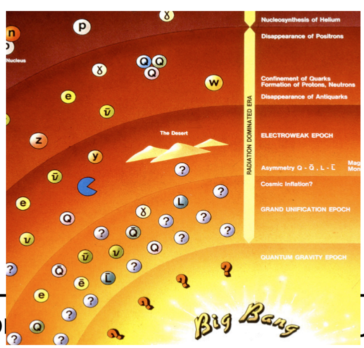
Ref: FNAL proton driver report, hep-ex/0509019

Open Questions

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23}$$
$$\sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$







Questions

Is there μ–τ symmetry in neutrino mixing?

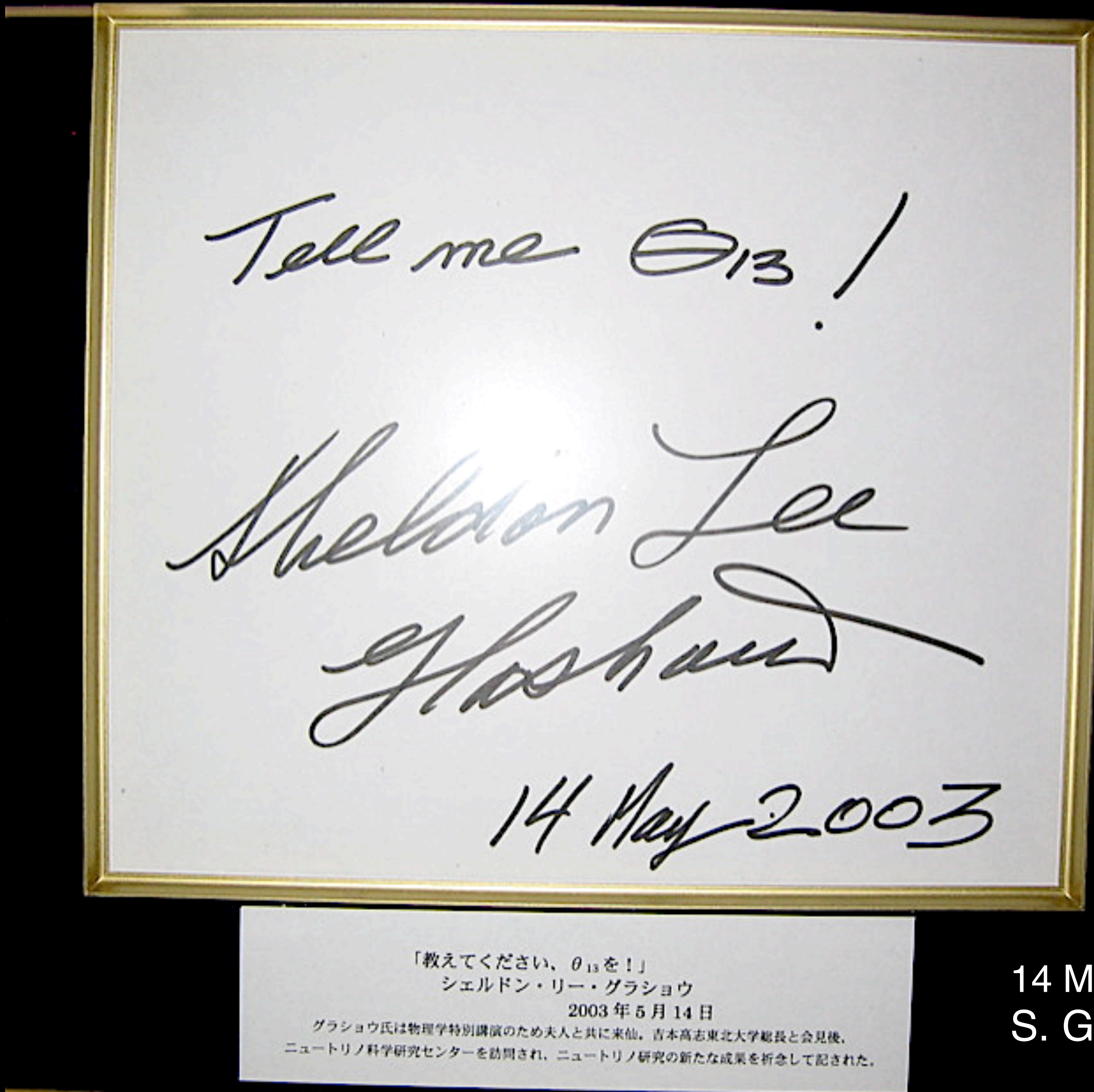
Is there leptonic CPV?

What is mass hierarchy?

Do neutrinos have Majorana mass?

What is the absolute mass scale?

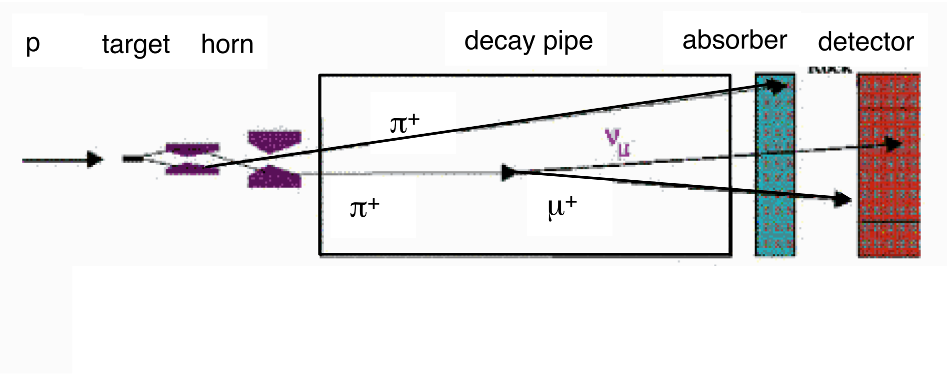
What is the role of neutrinos in the Universe?



14 May 2003
S. Glashow

Reactor and Accelerator Experiments

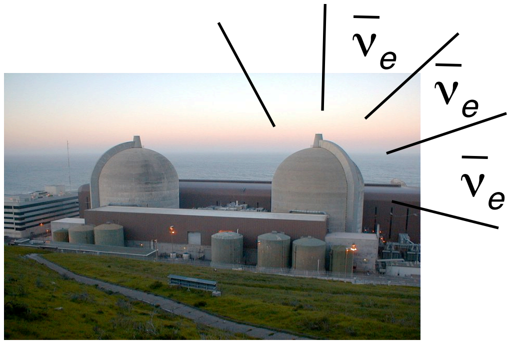
Method 1: Accelerator Experiments



$$P_{\mu e} \approx \sin^2 2\theta_{13} \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{31}{}^2 L}{4E_\nu} + \ldots$$

- appearance experiment $\nu_\mu \rightarrow \nu_e$
- measurement of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ yields θ_{13}, δ_{CP}
- baseline *O(100 -1000 km),* matter effects present

Method 2: Reactor Neutrino Oscillation Experiment



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

- disappearance experiment $\overline{\nu}_e \rightarrow \overline{\nu}_e$
- look for rate deviations from $1/r^2$ and spectral distortions
- observation of oscillation signature with 2 or multiple detectors
- baseline *O(1 km),* no matter effects

Reactor and Accelerator Experiments

reactor **($\bar{\nu}_e$ disappearance)**

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

- Clean measurement of θ_{13}
- No matter effects

mass hierarchy

CP violation

matter

accelerator **(ν_e appearance)**

$$\begin{aligned} P(\nu_\mu \to \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin\Delta_{31}[\cos\Delta_{32}\cos\delta - \sin\Delta_{32}\sin\delta]\sin\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta]\sin^2\Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)\frac{aL}{4E_\nu}\sin\Delta_{31}\left[\cos\Delta_{32} - \frac{\sin\Delta_{31}}{\Delta_{31}}\right] . \end{aligned}$$

- $\sin^2 2\theta_{13}$ is missing key parameter for any measurement of δ_{CP}

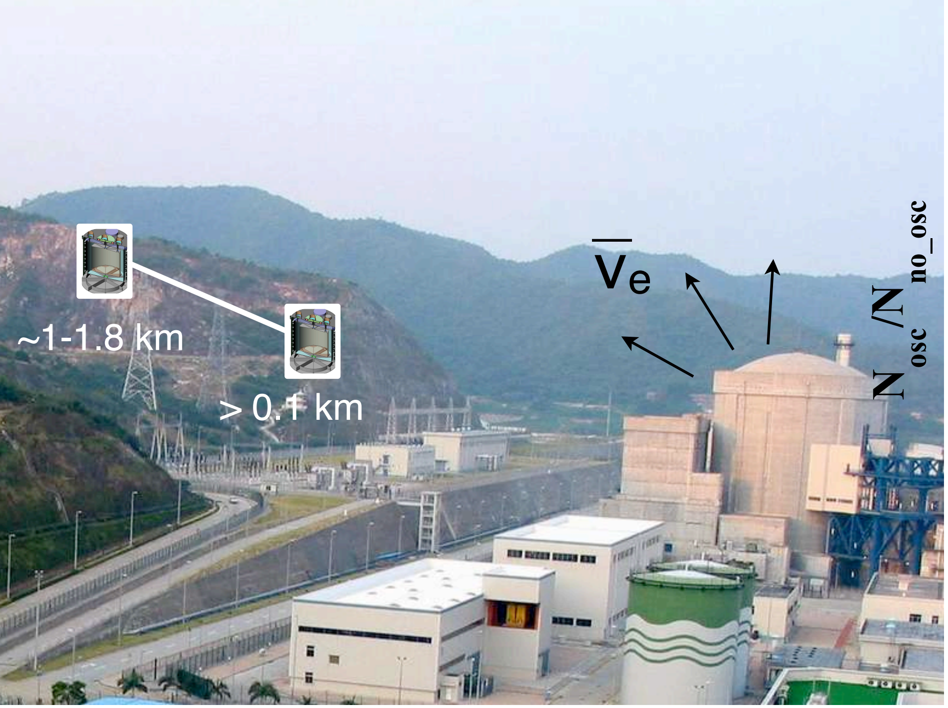
Precision Measurement of Mixing with Reactor $\overline{\nu}$

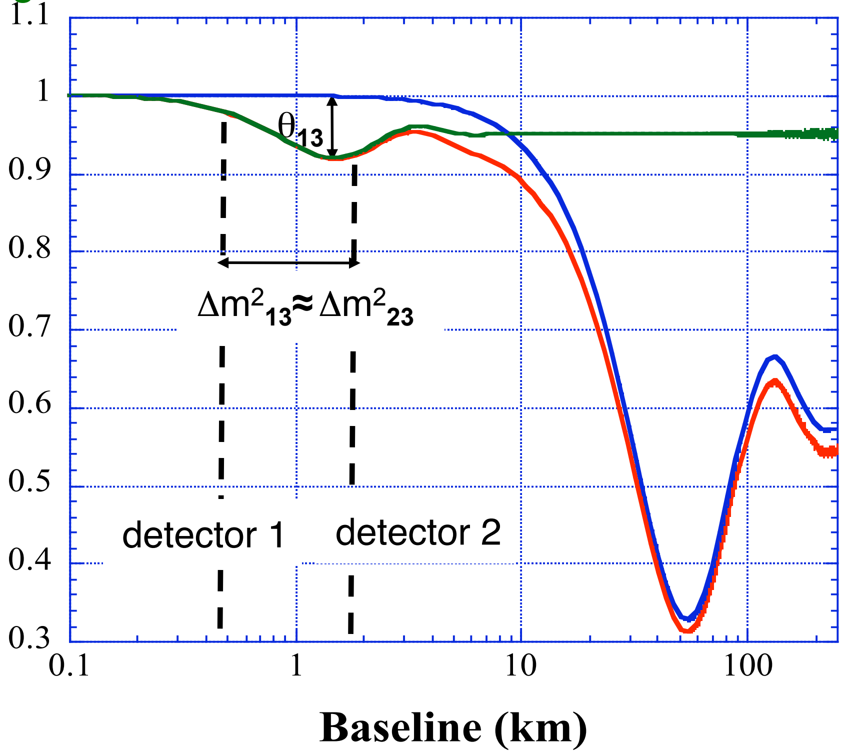
Search for θ_{13} in new oscillation experiment with <u>multiple detectors</u>

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

Small-amplitude oscillation due to θ_{13} integrated over E

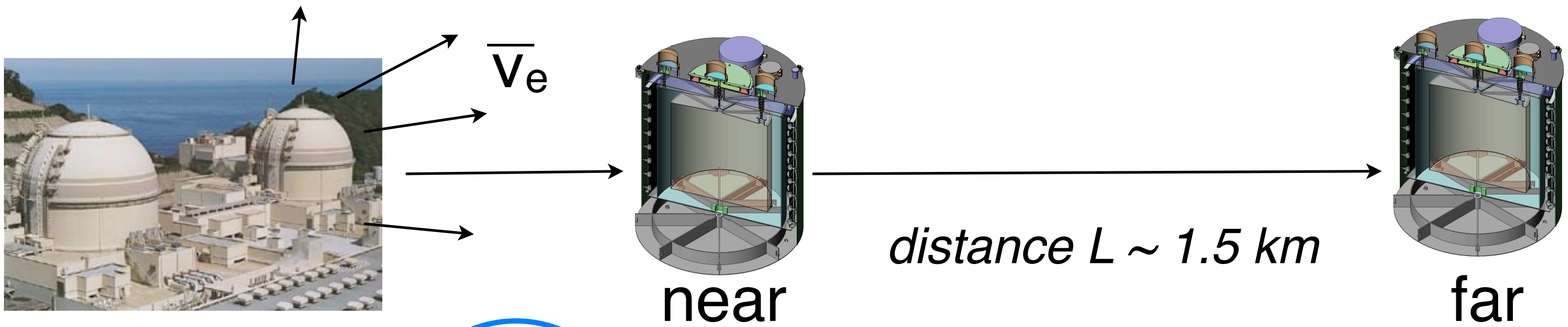
Large-amplitude oscillation due to θ_{12}





Concept of Reactor θ_{13} Experiments

Measure ratio of interaction rates in multiple detectors



$$\frac{N_{\mathrm{f}}}{N_{\mathrm{n}}} = \left(\frac{N_{\mathrm{p,f}}}{N_{\mathrm{p,n}}}\right)\left(\frac{L_{\mathrm{n}}}{L_{\mathrm{f}}}\right)^2\left(\frac{\epsilon_{\mathrm{f}}}{\epsilon_{\mathrm{n}}}\right)\left[\frac{P_{\mathrm{sur}}(E, L_{\mathrm{f}})}{P_{\mathrm{sur}}(E, L_{\mathrm{n}})}\right]$$

Measured Ratio of Rates

Detector Mass Ratio, H/C

mass measurement

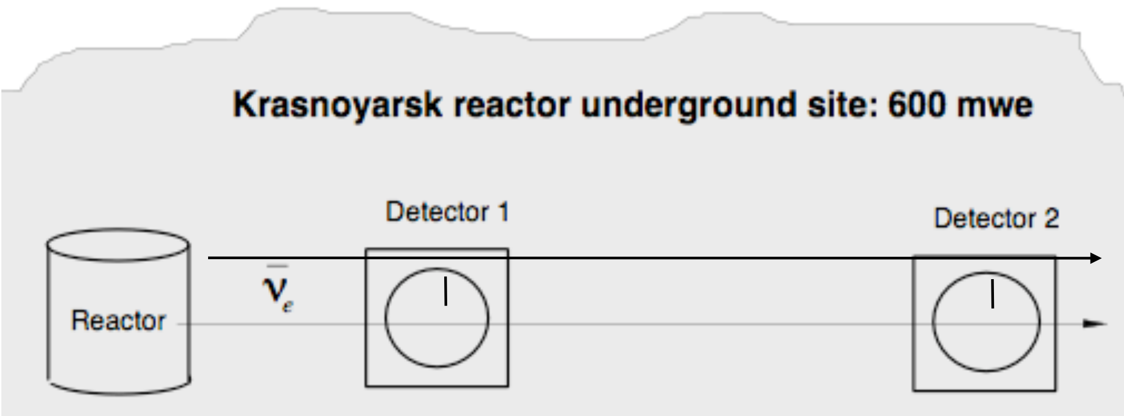
Detector Efficiency Ratio

calibration

$\sin^2 2\theta_{13}$

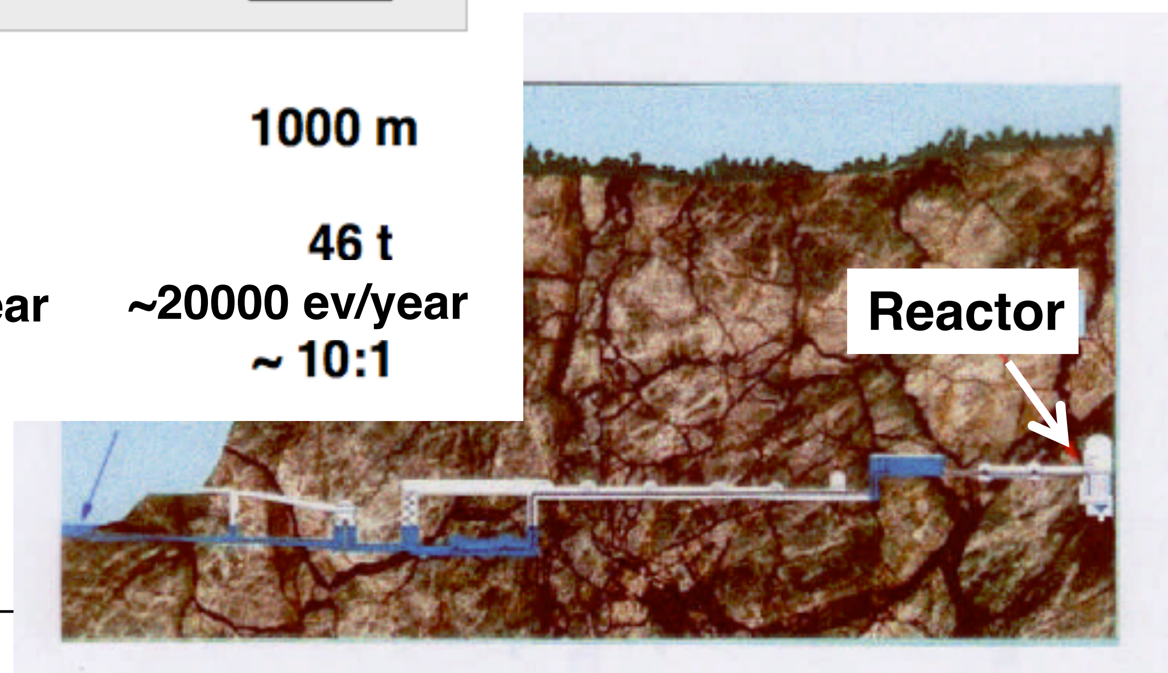
Reactor θ_{13} Experiment at Krasnoyarsk, Russia

Original Idea: First proposed at Neutrino2000



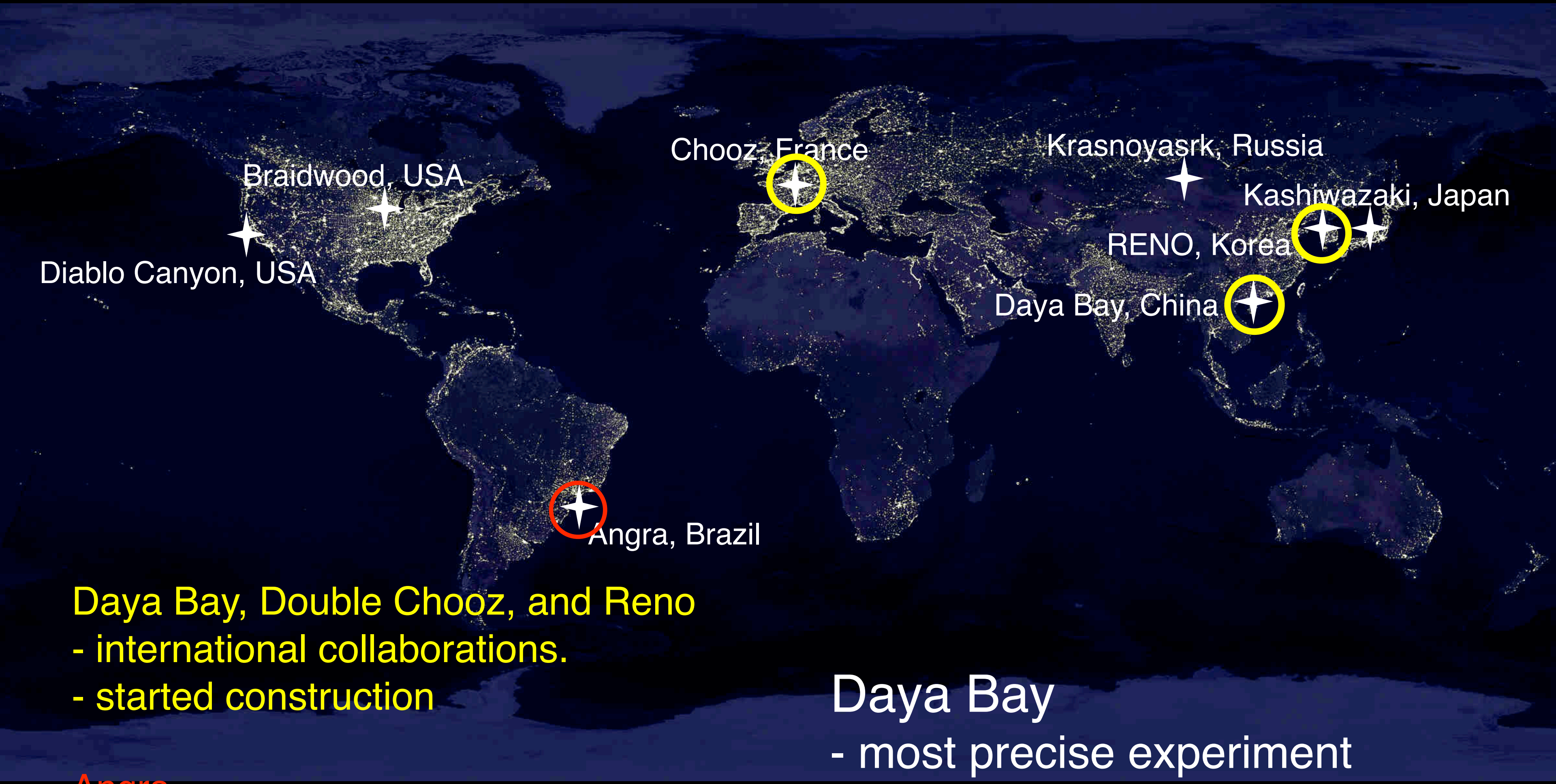
	115 m	1000 m
Target:	46 t	46 t
Rate:	~1.5 x 10^6 ev/year	~20000 ev/year
S:B	>>1	~ 10:1

Krasnoyarsk
- underground reactor
- detector locations determined by infrastructure



Ref: Marteyamov et al, hep-ex/0211070

World of Proposed Reactor θ_{13} Neutrino Experiments



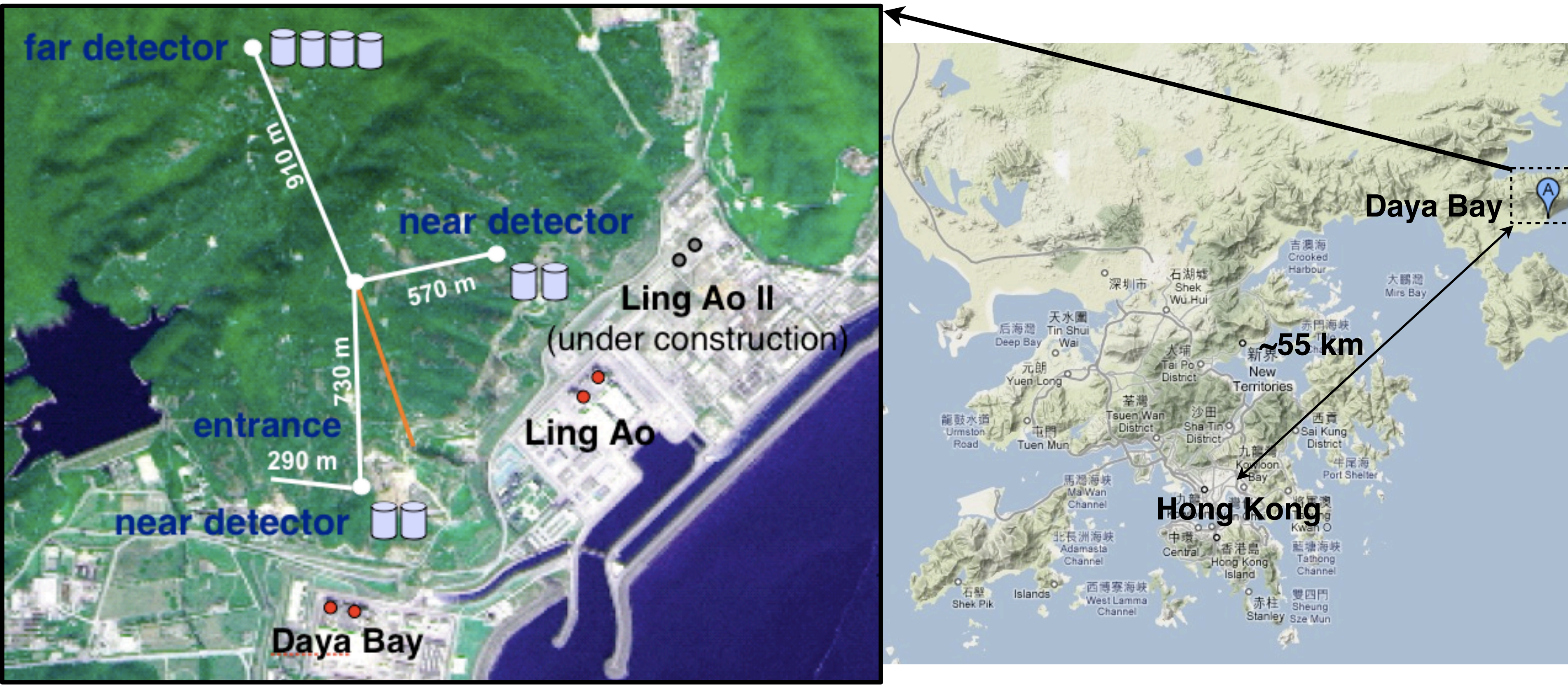
Daya Bay, Double Chooz, and Reno
- international collaborations.
- started construction

Angra
- R&D
- nuclear proliferation studies

Daya Bay
- most precise experiment
- only experiment to reach sensitivity of $\sin^2 2\theta_{13} < 0.01$

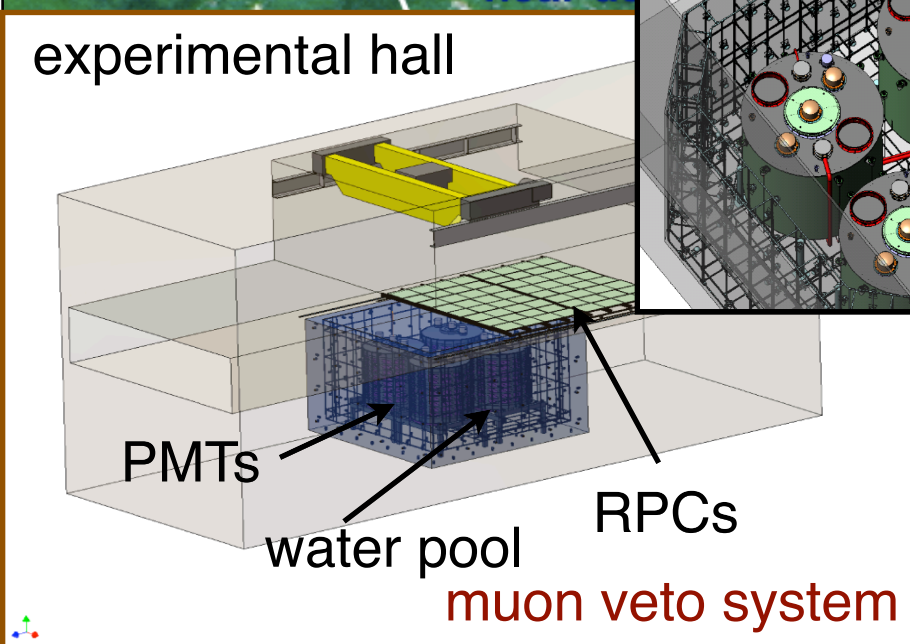
Daya Bay, China

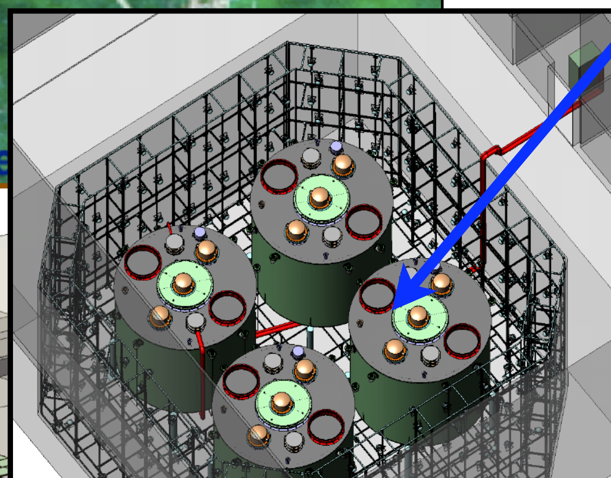
http://dayawane.ihep.ac.cn/

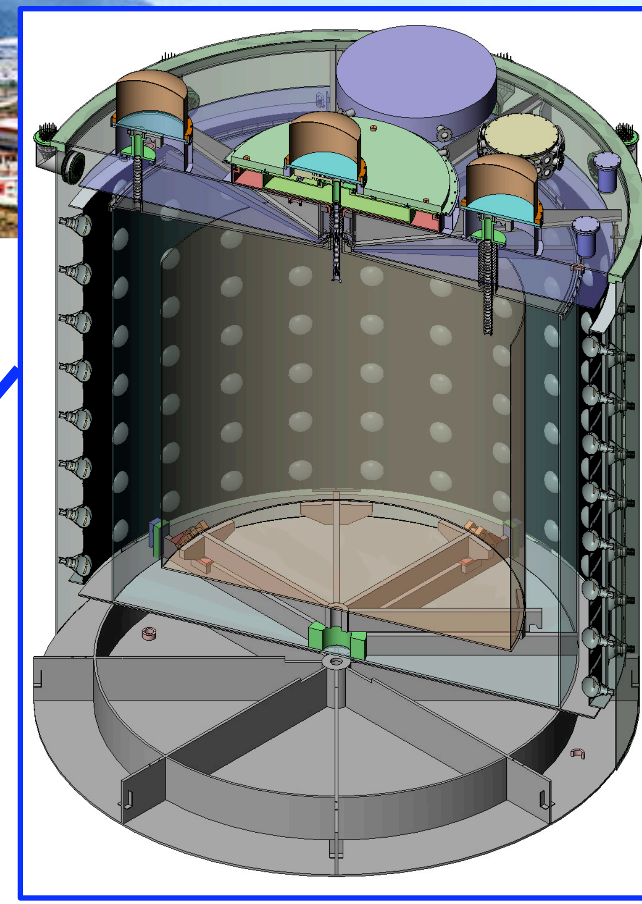


Daya Bay, China

http://dayawane.ihep.ac.cn/





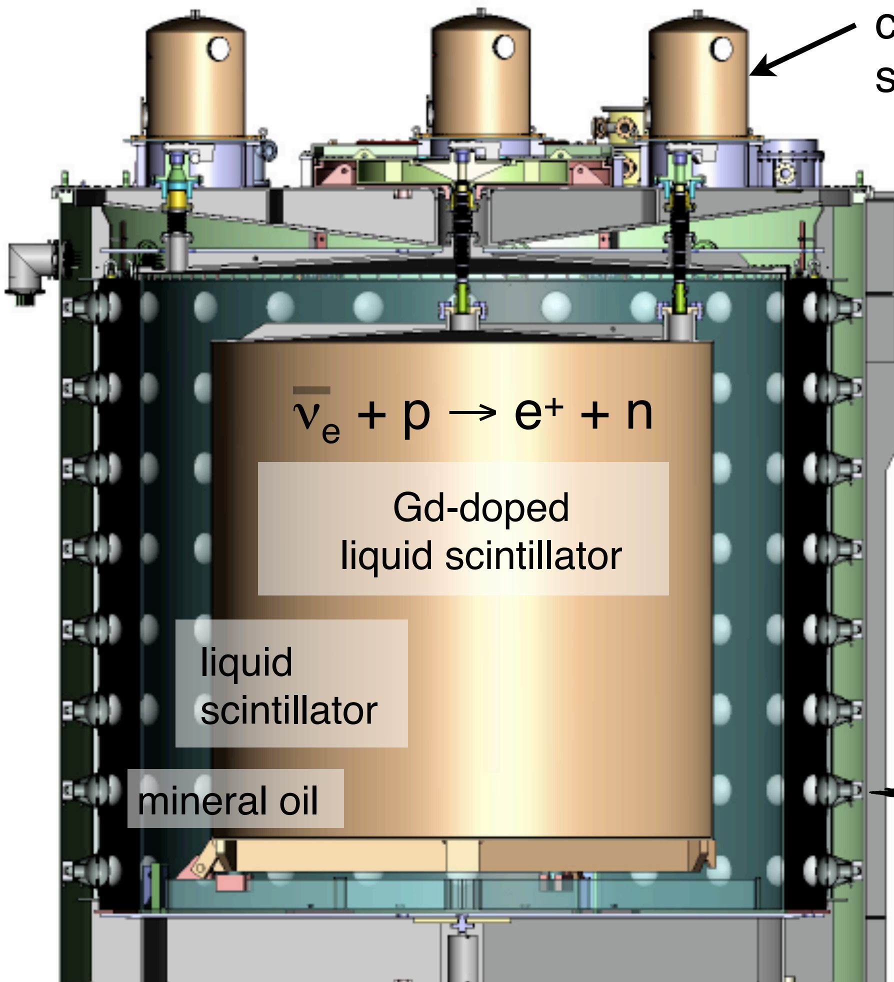


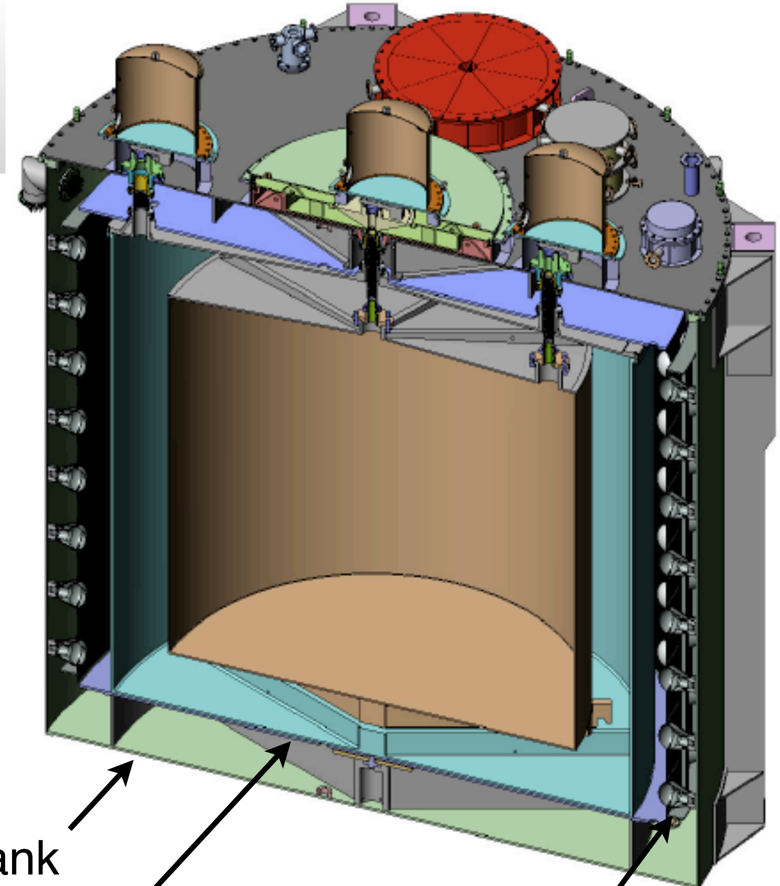
antineutrino detectors

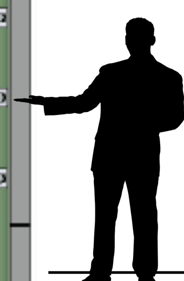
multiple detectors per site
cross-check efficiency

Daya Bay Antineutrino Detectors

- 8 “identical”, 3-zone detectors
- no position reconstruction, no fiducial cut



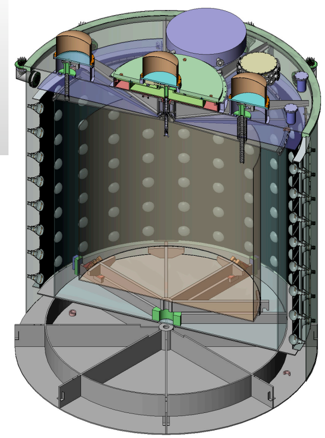




target mass:	20t per detector
detector mass:	~ 110t
photosensors:	192 PMTs
energy resolution:	12%/√E

Antineutrino Detection

Signal and Event Rates



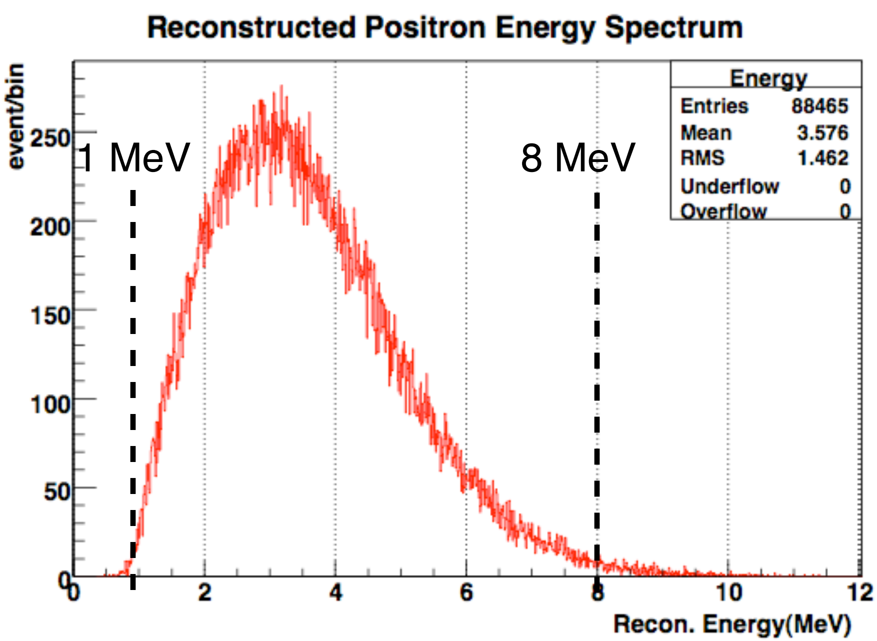
Daya Bay near site 840
Ling Ao near site 760
Far site 90
events/day per 20 ton module

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

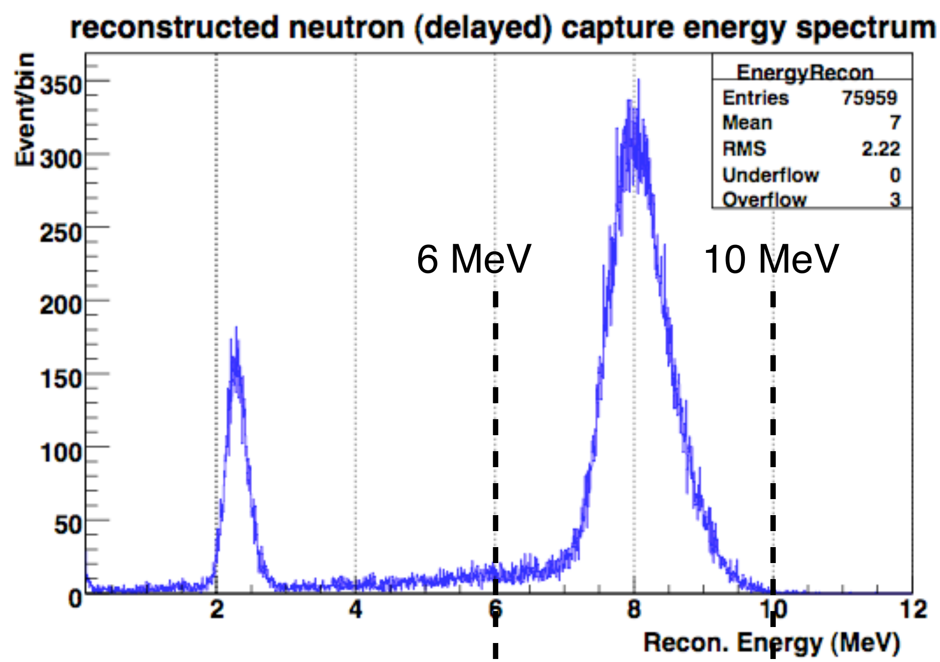
0.3 b $\mapsto$ $+ p \rightarrow D + \gamma$ (2.2 MeV) (delayed)

49,000 b $\mapsto$ $+ Gd \rightarrow Gd^* \rightarrow Gd + \gamma$'s (8 MeV) (delayed)

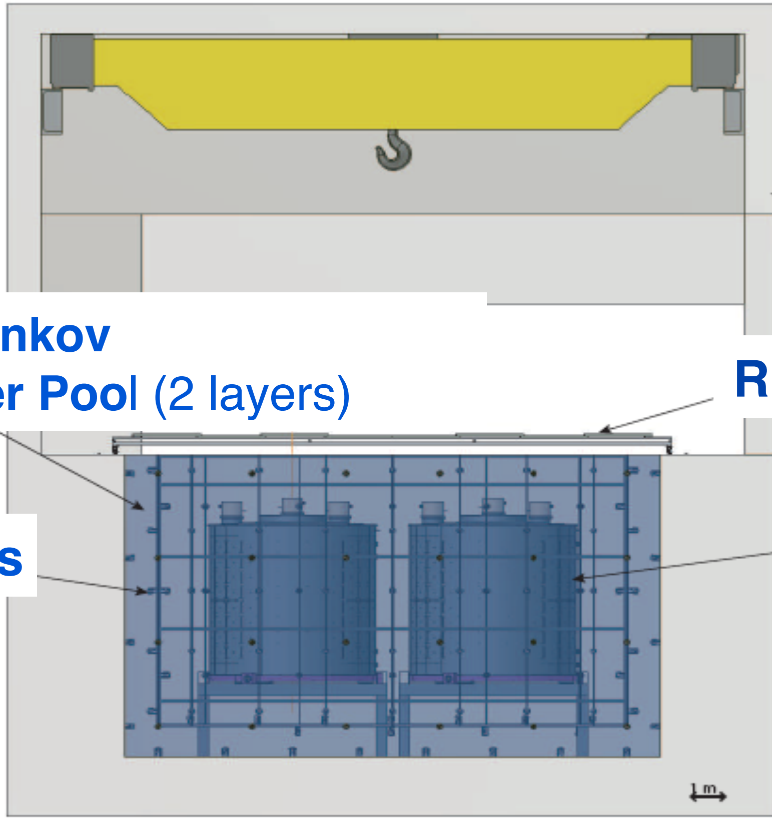
Prompt Energy Signal

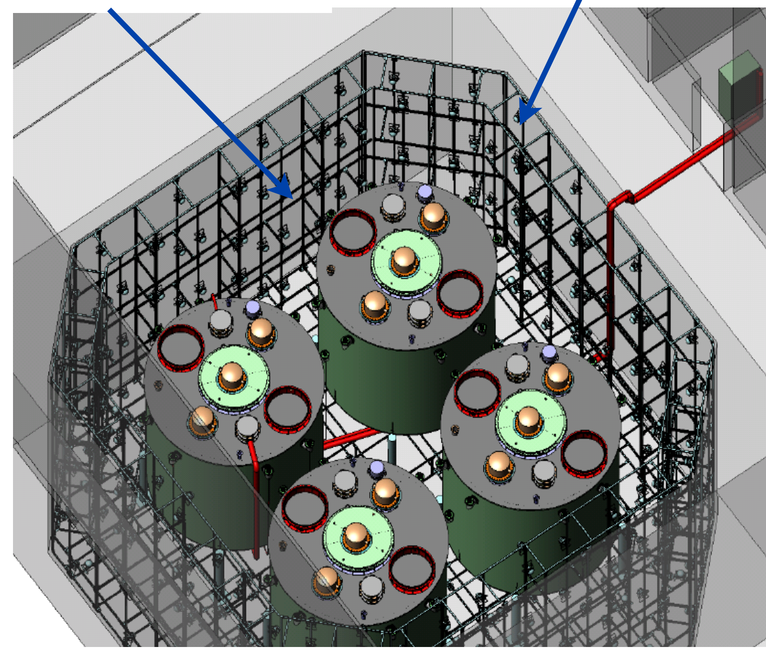


Delayed Energy Signal



Muon Veto System





RPCs: muon detect efficiency 98.6% and ~0.5m spatial resolution.
Two-layer water pool: 962 PMTs, >2.5m water shield for neutron background, ~0.5m spatial resolution

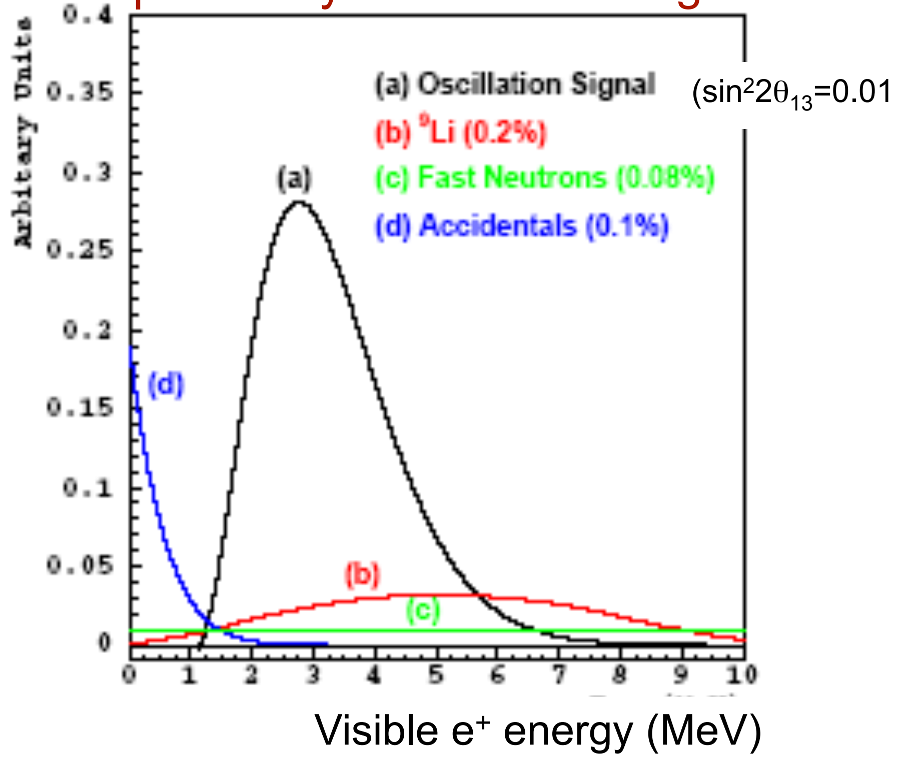
Daya Bay veto system provides a combined muon detection efficiency > 99.5%.

Background Sources

1. **Natural Radioactivity**: PMT glass, steel, rock, radon in the air, etc
2. **Slow and fast neutrons** produced in rock & shield by cosmic muons
3. **Muon-induced cosmogenic isotopes:** $^{8}He/^{9}Li$ which can β-n decay

- Cross section measured at CERN (Hagner et. al.)
- Can be measured in-situ, even for near detectors with muon rate ~ 10 Hz:

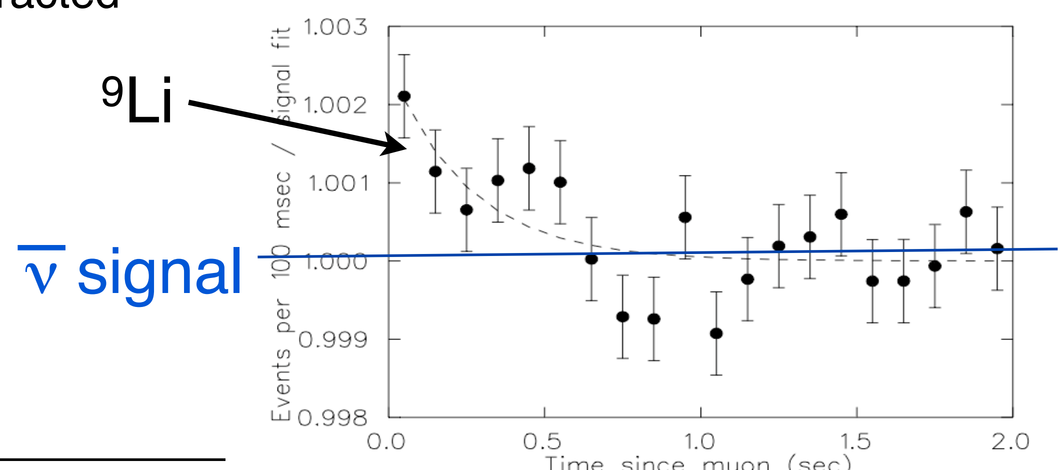
β-n decay of ^{9}Li mimics signal

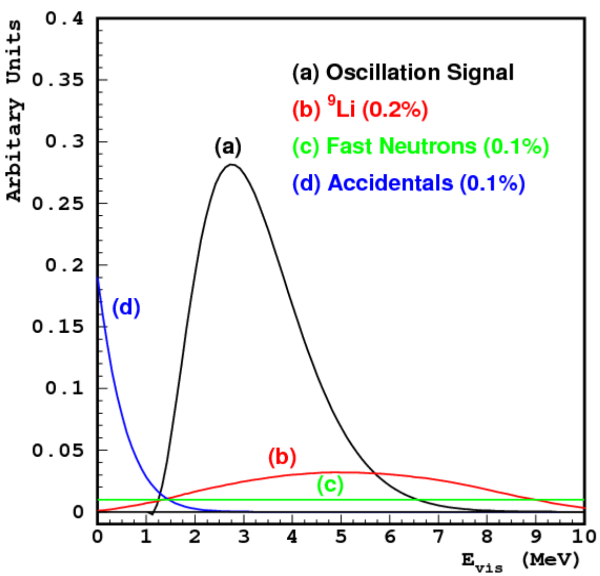


Daya Bay Background Summary

	DYB site	LA site	far site
Antineutrino rate (/day/module)	840	760	90
Natural radiation (Hz)	<50	<50	<50
Single neutron (/day/module)	18	12	1.5
β-emission isotopes (/day/module)	210	141	14.6
Accidental/Signal	<0.2%	<0.2%	<0.1%
Fast neutron/Signal	0.1%	0.1%	0.1%
^{8}He^{9}Li/Signal	0.3%	0.2%	0.2%

backgrounds from beta-delayed neutron emission isotopes ^{8}He and ^{9}Li will have to be measured and subtracted





Systematic Uncertainties

Detector-Related Uncertainties

Absolute measurement **Relative measurement**

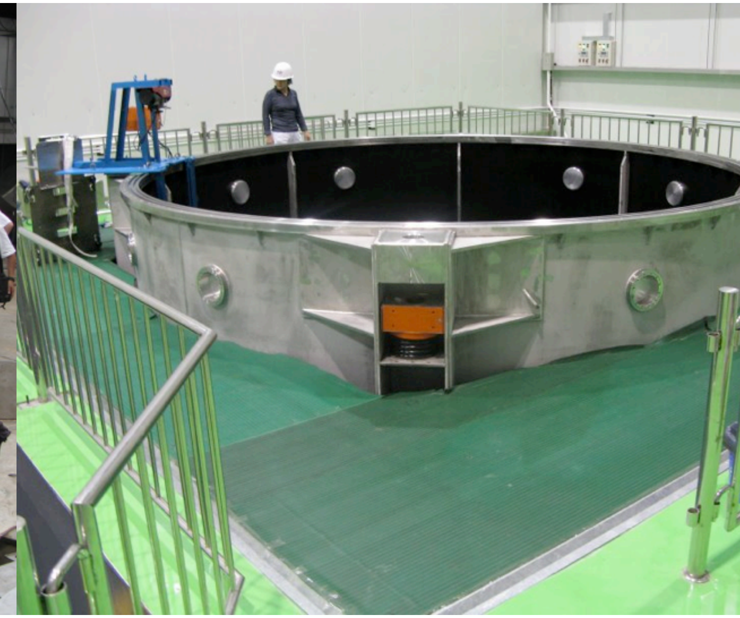
Source of uncertainty		Chooz (*absolute*)	Daya Bay (*relative*) Baseline	Goal	Goal w/Swapping
# protons		0.8	0.3	0.1	0.006
Detector Efficiency	Energy cuts	0.8	0.2	0.1	0.1
	Position cuts	0.32	0.0	0.0	0.0
	Time cuts	0.4	0.1	0.03	0.03
	H/Gd ratio	1.0	0.1	0.1	0.0
	n multiplicity	0.5	0.05	0.05	0.05
	Trigger	0	0.01	0.01	0.01
	Live time	0	<0.01	<0.01	<0.01
Total detector-related uncertainty		1.7%	0.38%	0.18%	0.12%

Ref: Daya Bay TDR

O(0.2-0.3%) precision for relative measurement between detectors at near and far sites

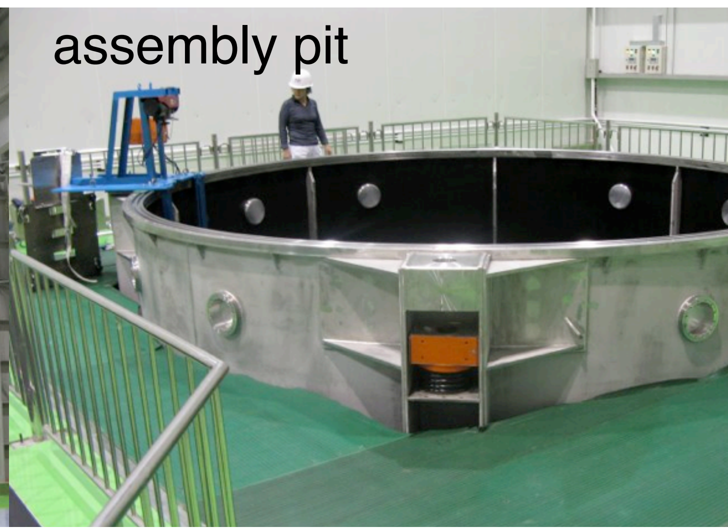
Fabrication and Delivery of Detector Components

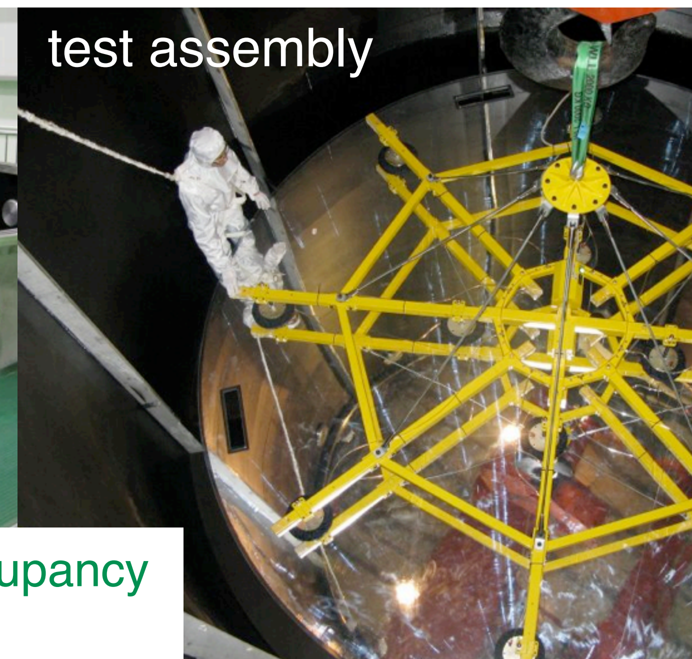
detector tank



acrylic target vessels

Detector Assembly at the Daya Bay Power Plant





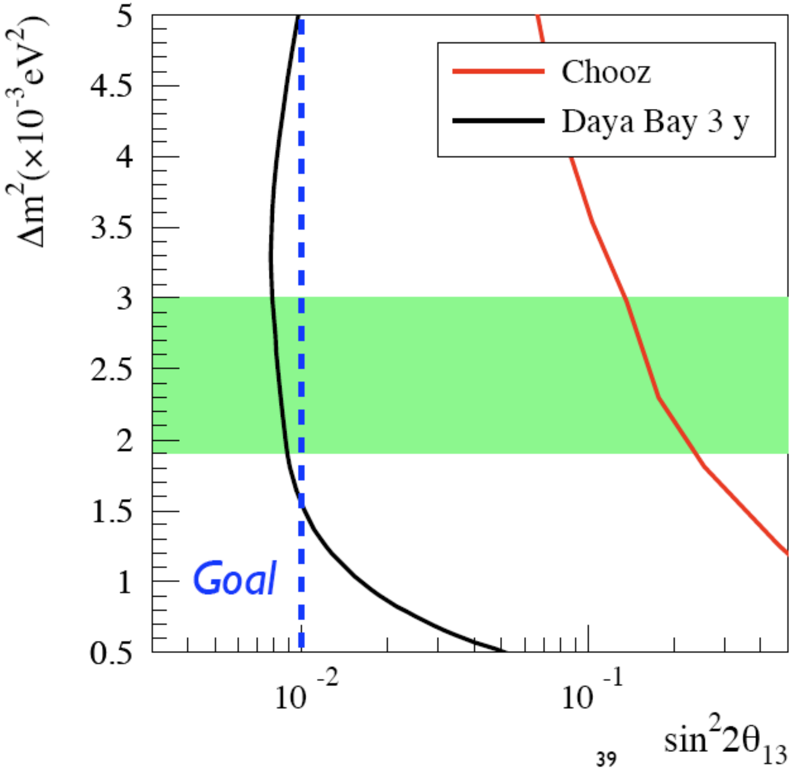
March 2009: Assembly building occupancy

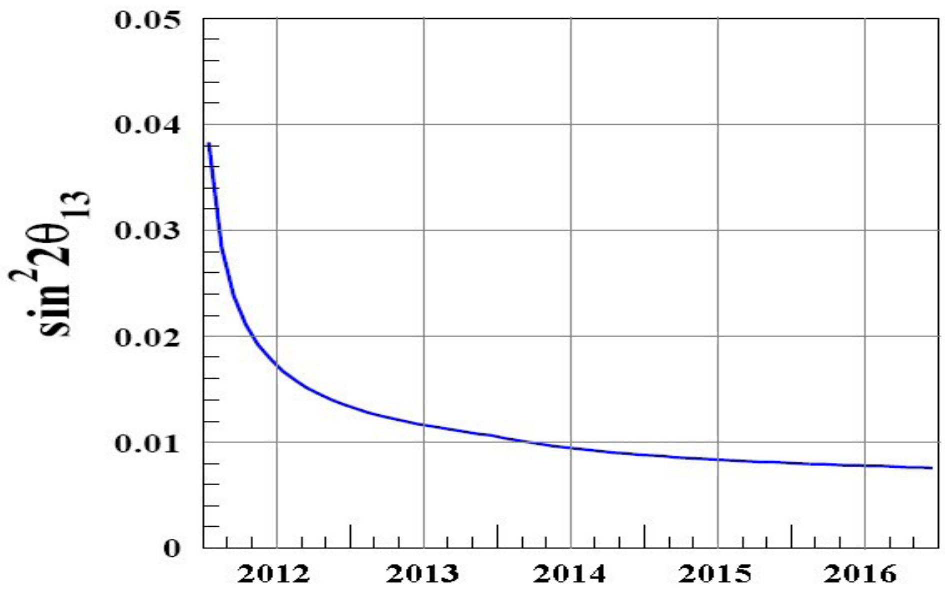
Fall 2009: Near Hall occupancy

Sensitivity of Daya Bay

Daya Bay Sensitivity to $\sin^2 2\theta_{13}$

$\sin^2 2\theta_{13}$ < 0.01 @ 90% CL
in 3 years of data taking



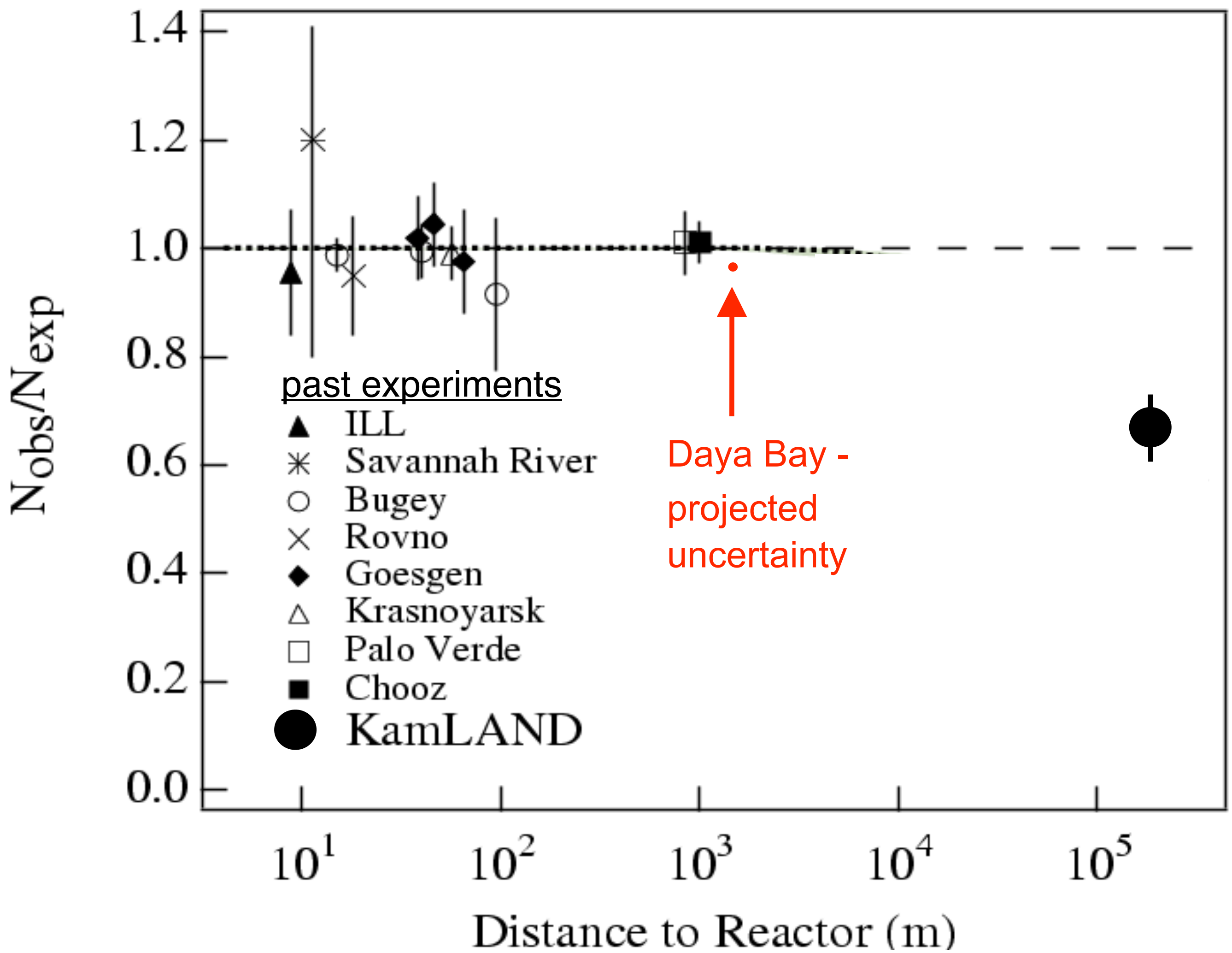


2008-2011 experiment construction
2010 start data taking with near site
2011 start data taking with full experiment

nominal running period: 3 years

Ratio of Measured to Expected $\overline{\nu}_e$ Flux

Expected precision in Daya Bay to reach $\sin^2 2\theta_{13} < 0.01$

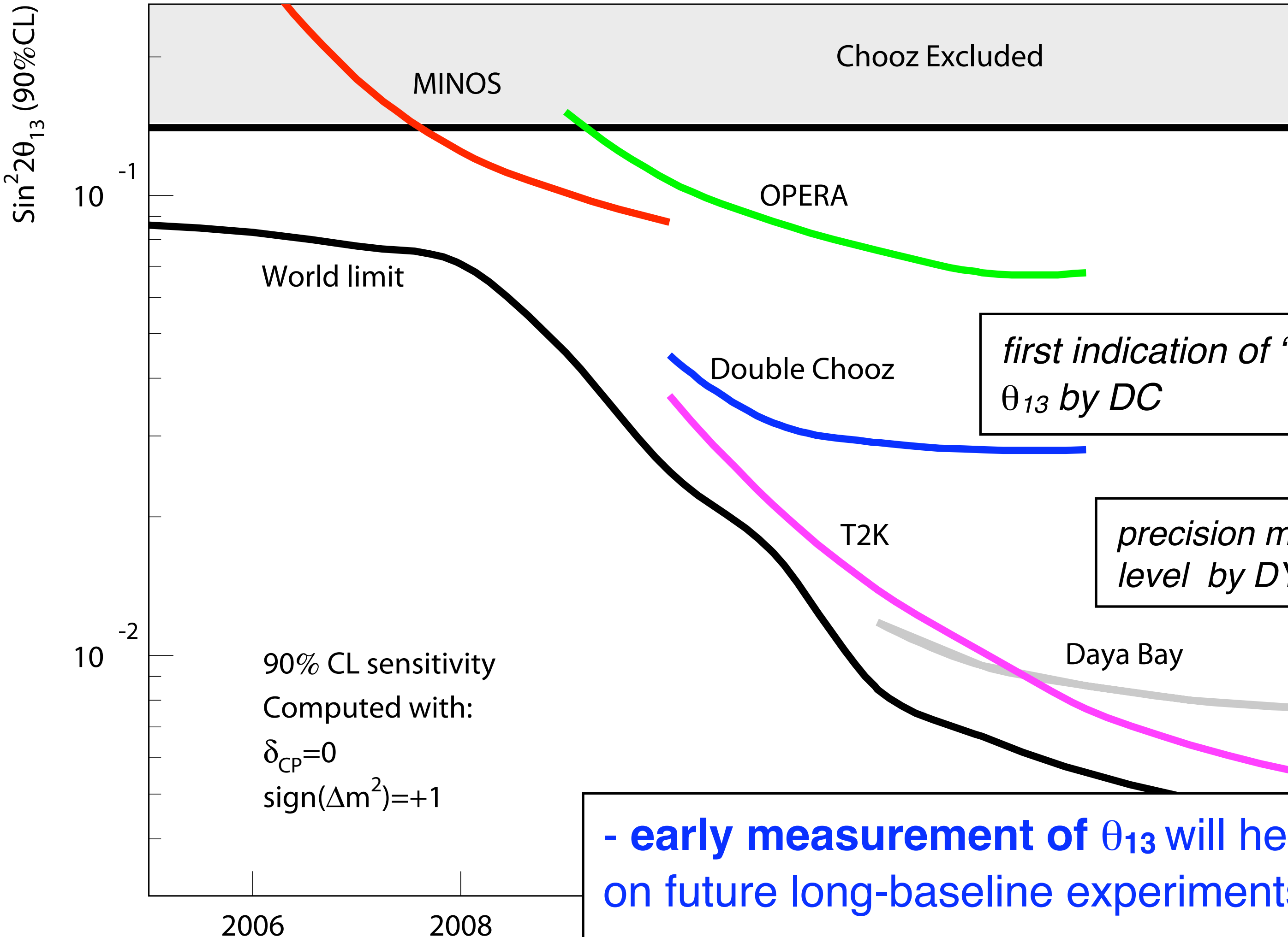


past reactor experiments
= 1 detector

next generation of experiments
> 2 detectors

Future of Neutrino Oscillation Experiments

Fig: M. Mezzetto



first indication of "largish" θ_{13} by DC

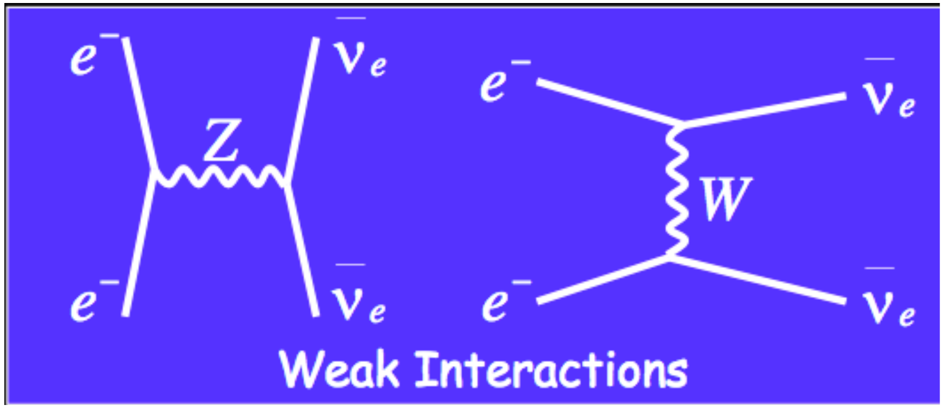
precision measurement at 1% level by DYB

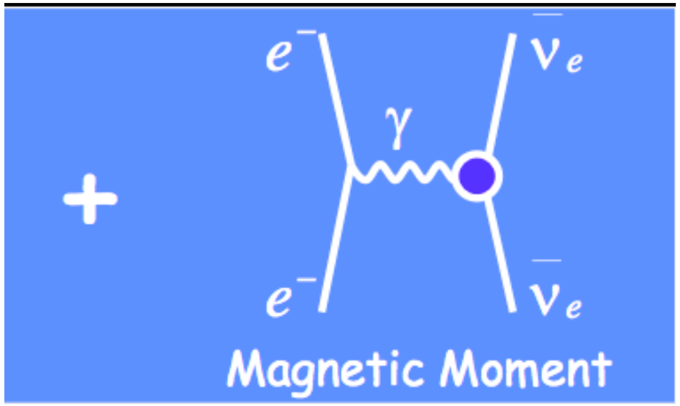
- **early measurement of** θ_{13} will help make decision on future long-baseline experiments

- **precision measurement of** θ_{13} useful for combined analysis with T2K and NoVA, 2σ hint for ~~CP~~ possible?

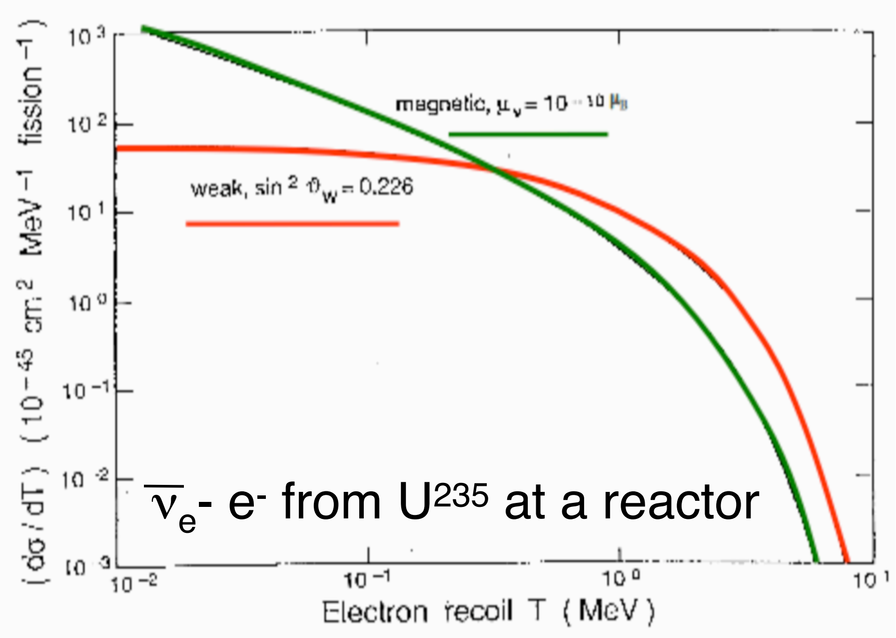
Other Physics with Reactor Antineutrinos

What about a Neutrino Magnetic Moment?





$$\frac{d\sigma}{dT_e} = weak\,\text{int} + \frac{\pi\alpha^2\mu_\nu^{\ 2}}{m_e^{\ 2}}\left(\frac{1}{T_e} - \frac{1}{E_\nu}\right)$$



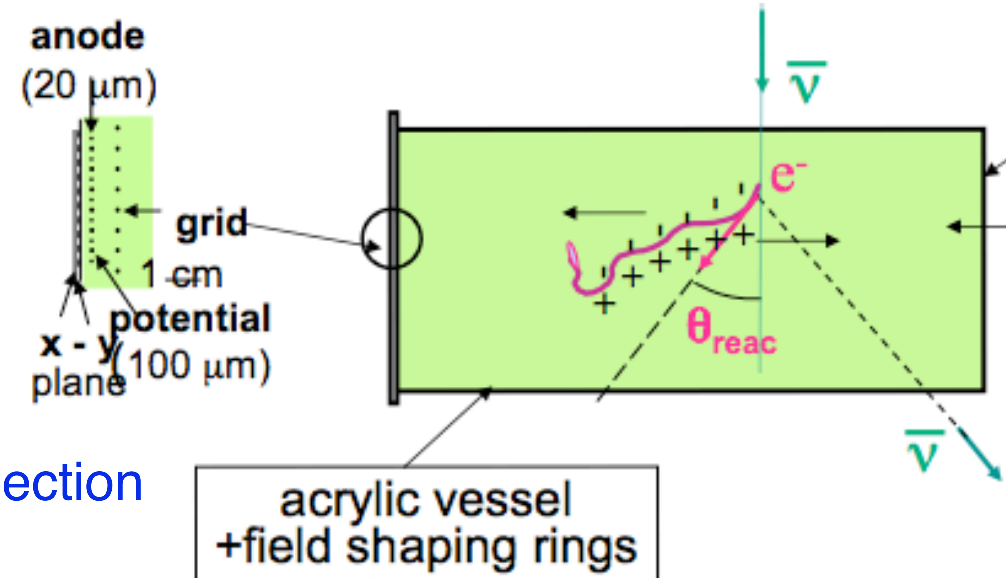
Electron Recoil T (MeV)

Reactor Experiments

UC Irvine	$\mu_\nu^{reac} < 2\text{-}4 \times 10^{-10}\ \mu_B$
Kurchatov	$\mu_\nu^{reac} < 2.4 \times 10^{-10}\ \mu_B$
Rovno	$\mu_\nu^{reac} < 1.9 \times 10^{-10}\ \mu_B$
MUNU	$\mu_\nu^{reac} < 1.0 \times 10^{-10}\ \mu_B$

Low Electron Recoil Energy Experiment

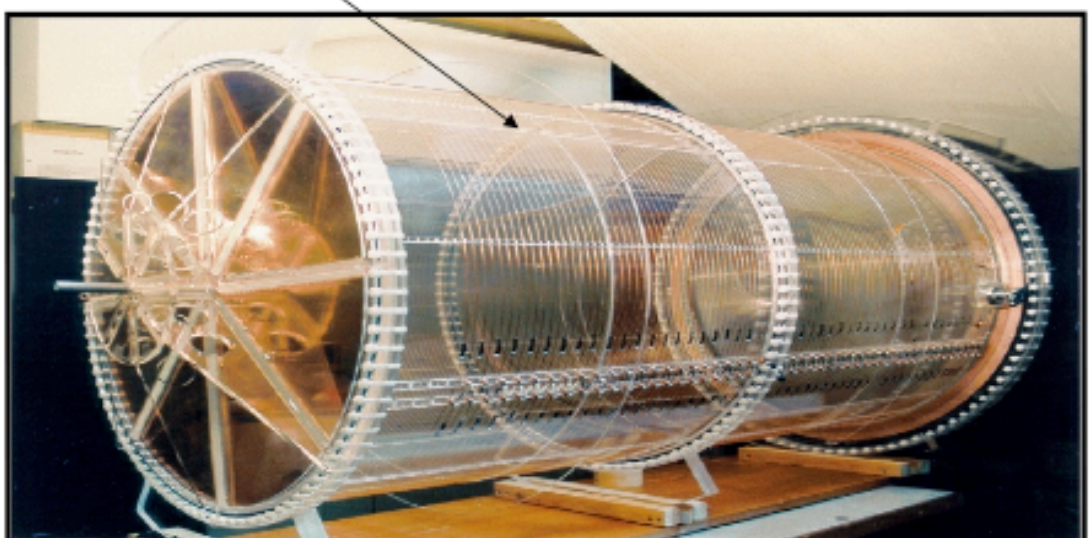
Experiment at Nuclear Reactors (low energy source of $\overline{\nu}_e$)



3bar CF_4 gas

High density, relatively low Z, good drifting properties

Time Projection Chamber



V=1 m^3

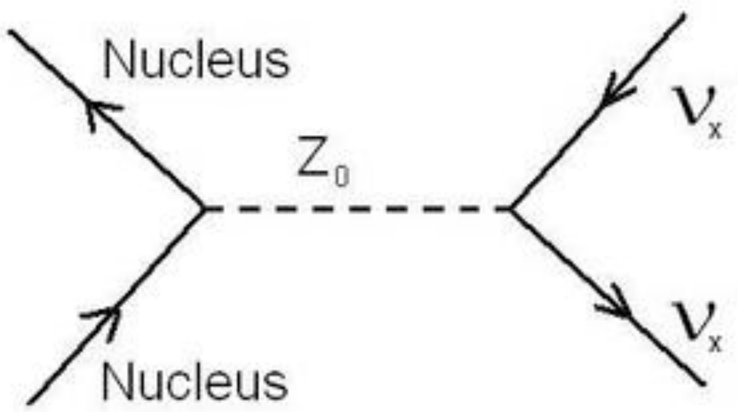
L=1.6 m

D=0.9 cm

L =160 cm

Φ = 90 cm

Coherent Neutrino Scattering



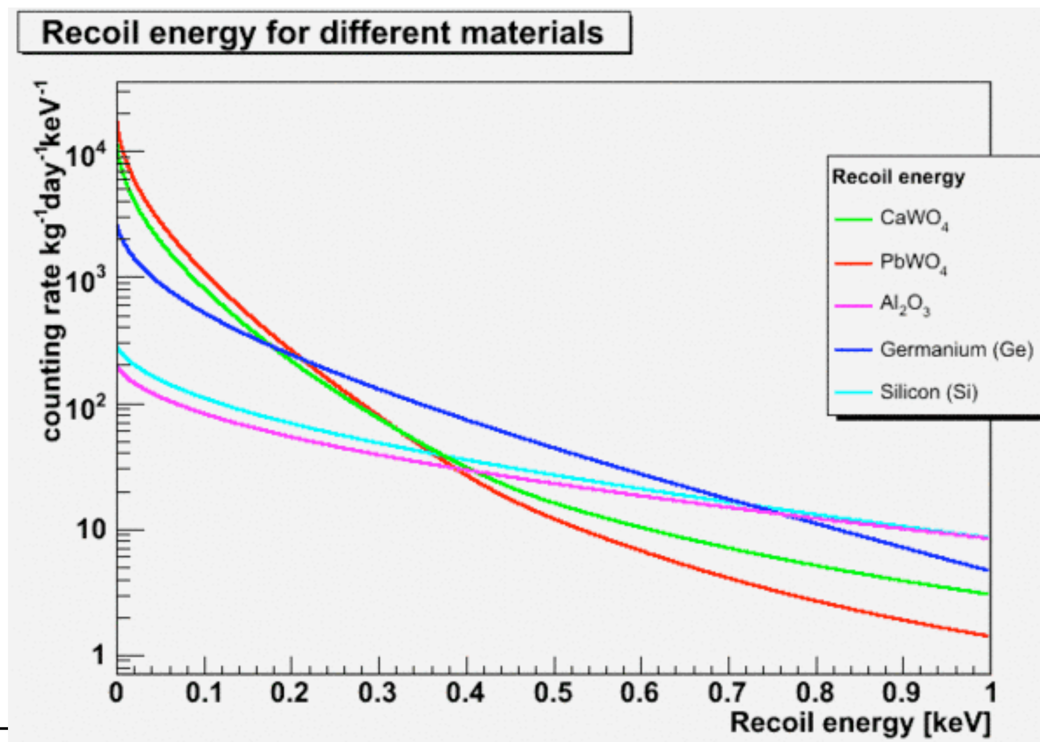
$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}\left[Z\left(4\sin^2\theta_W - 1\right) + N\right]^2 E_\nu^2\,(1+\cos\theta)$$

neutral current process at low neutrino energies of about 1- 50 MeV

At low momentum transfers, a neutrino of any flavor scatters off a nucleus, neutrino interacts simultaneously with all nucleons

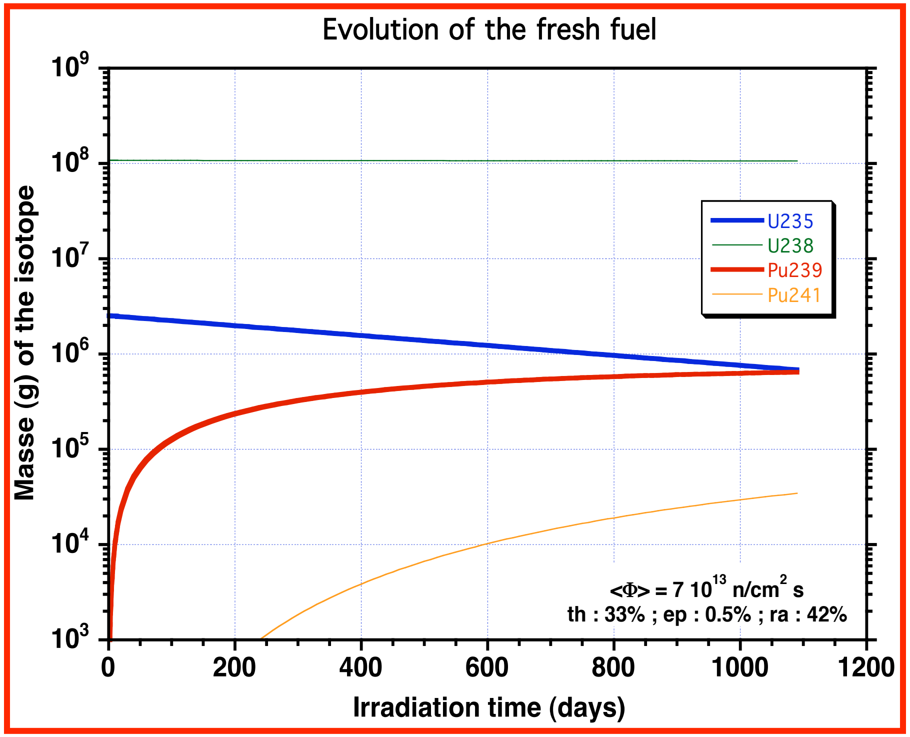
cross section for CNNS is very large compared to other neutrino cross sections.

momentum transfer is still tiny

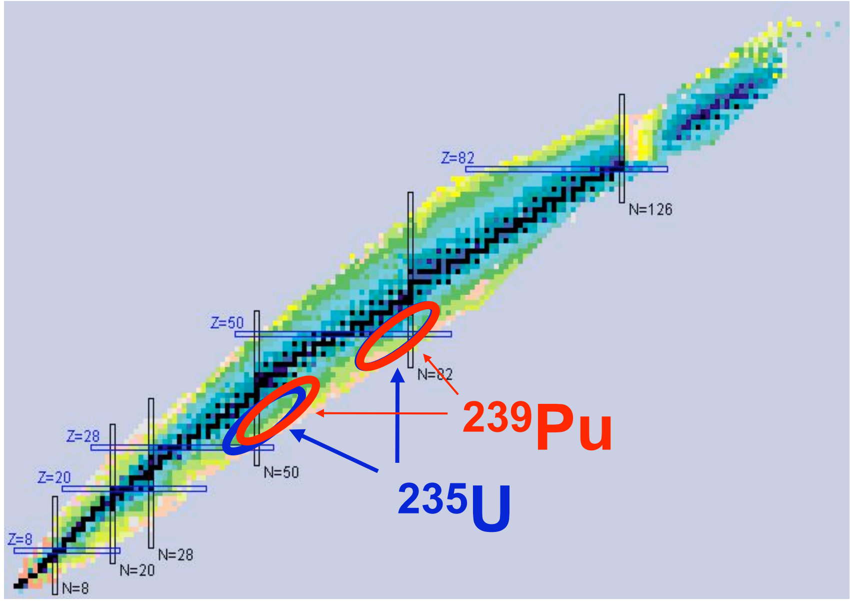


Applied Neutrino Physics: Reactor Monitoring

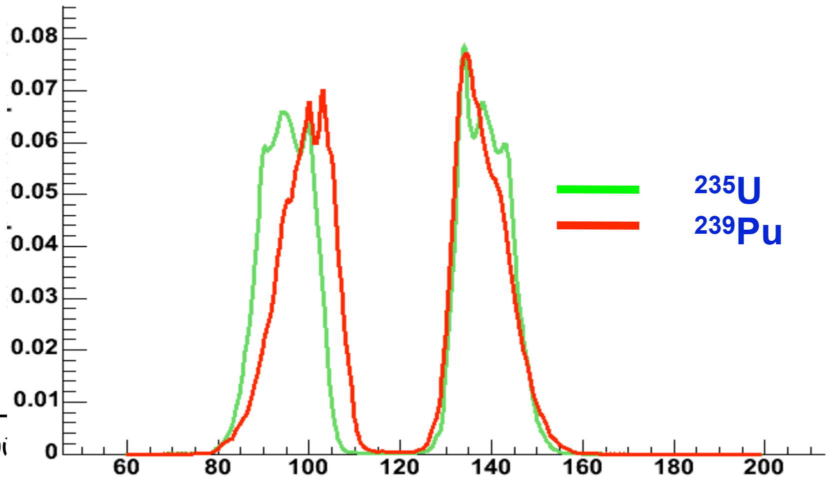
$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow{23\ min} {}^{239}_{93}Np \xrightarrow{2.3\ d} {}^{239}_{94}Pu$$



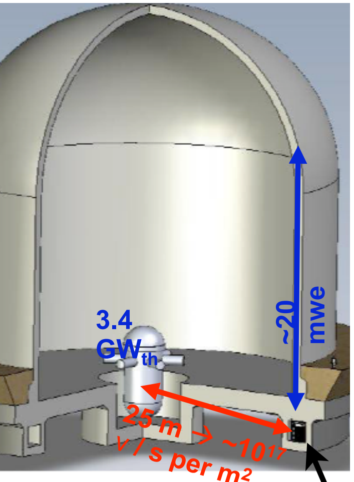
fraction of ^{239}Pu increases during reactor operation

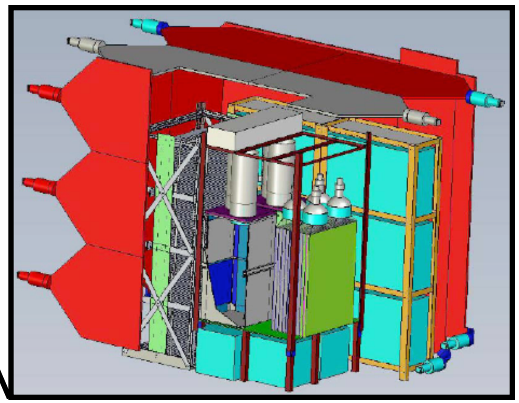


Fission fragments from ^{239}Pu heavier in the light hump



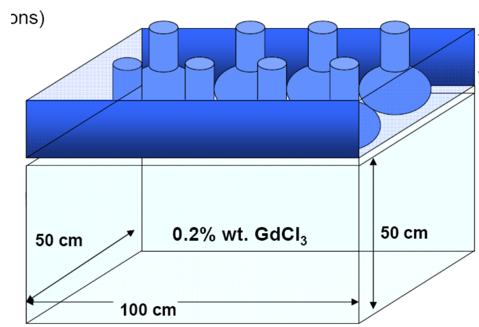
Reactor Monitoring in US

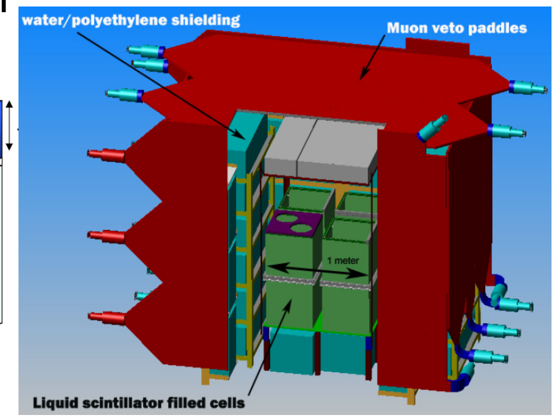




Targets under consideration

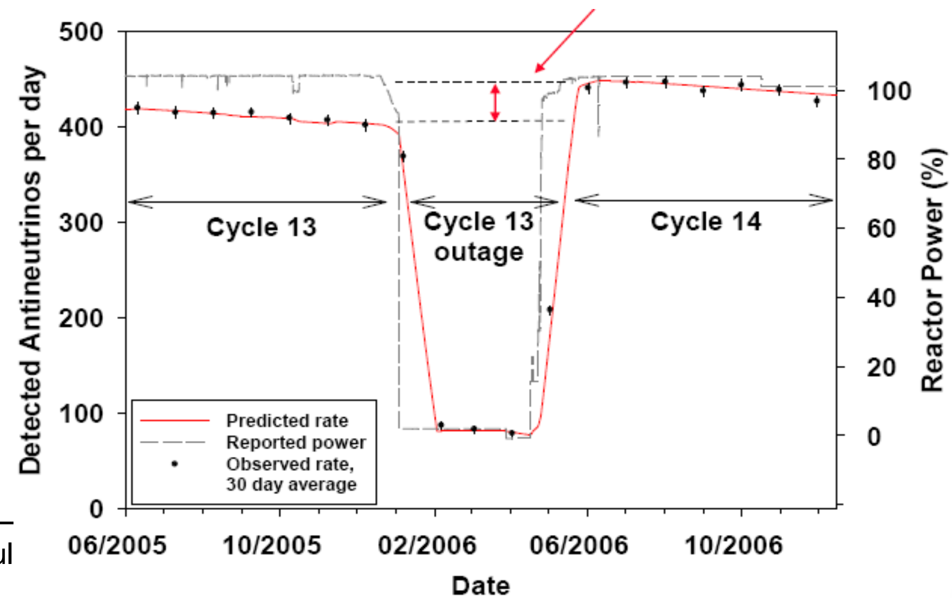
Liquid Scintillator
Plastic Scintillator
Gd-doped Water





Removal of 250 kg of ^{239}Pu followed by replacement with 1.5 tons of fresh ^{235}U fuel

thermal power with neutrinos? - 3% precision achievable



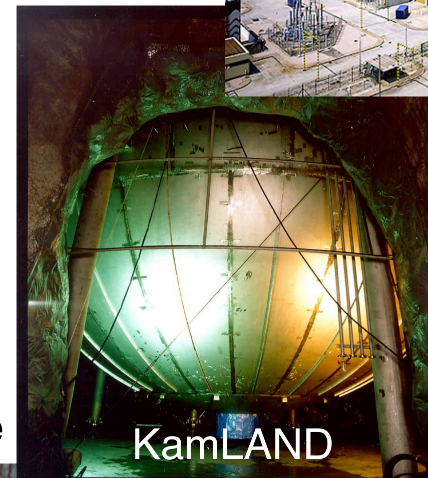
Neutrino Physics at Reactors

Next - Discovery and precision measurement of θ_{13}

2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

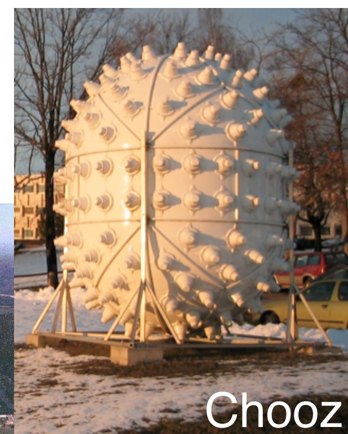
2004 - Evidence for spectral distortion

2003 - First observation of reactor antineutrino disappearance

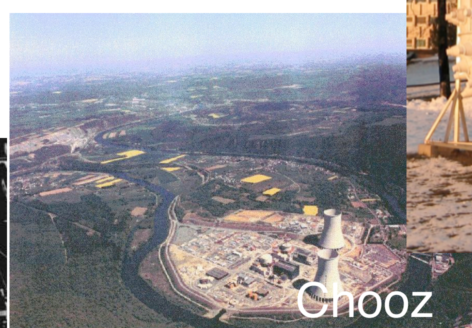


1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe



1956 - First observation of (anti)neutrinos



Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France