Reactor Neutrinos I

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Alushta, Ukraine

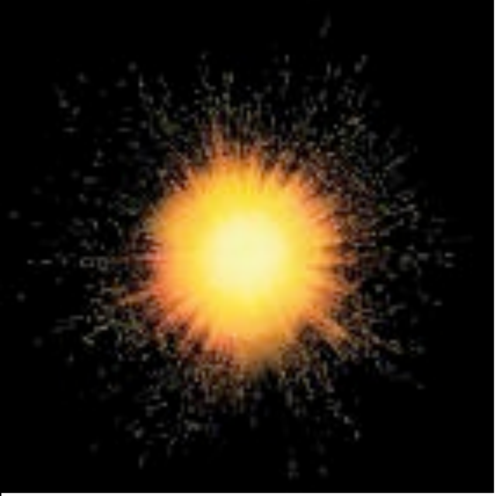
Outline

- Lecture 1
  - observation of the neutrino
  - reactors as an antineutrino source
  - prediction of the antineutrino flux from reactors
  - detection of reactor antineutrinos
  - oscillation searches with reactors
  - observation of reactor antineutrino disappearance at KamLAND
  - precision oscillation physics with reactor antineutrinos

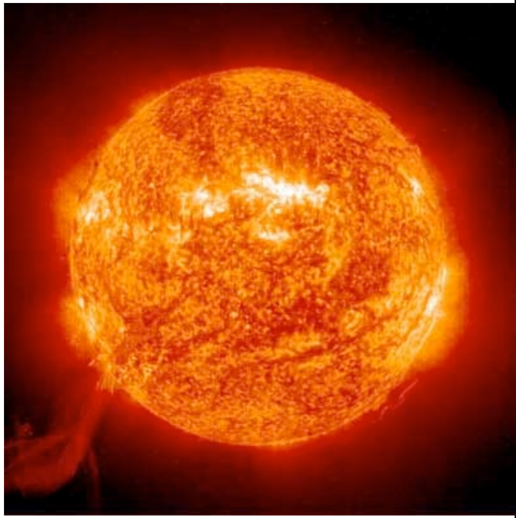
Outline

- Lecture 2
  - precision oscillation physics: theta13 and beyond
  - the reactor anomaly
  - future reactor experiments
    - θ_{12}
    - mass hierarchy
    - sterile neutrino searches
  - searches for new physics
    - magnetic moments
    - coherent scattering
    - NSI
  - experiments with antineutrino sources
  - applications of reactor antineutrinos: monitoring & communication

Neutrino Energies



Big-Bang neutrinos ~ 0.0004 eV

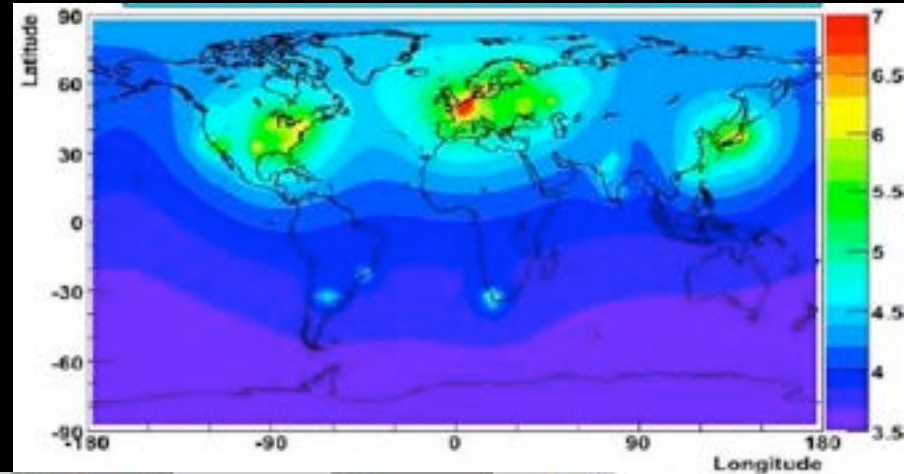


Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

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


Latitude
Longitude
90
60
30
0
-30
-60
-90
-180
-90
0
90
180
7
6.5
6
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5
4.5
4
3.5


Europe
Russia
North America
Asia
Africa
East Asia
West Asia
South America
International Nuclear Safety Center at ANL, Aug 2005
60°
45°
30°
15°
0°
-15°
-30°
-45°
240°
270°
300°
330°
0°
30°
60°
90°
120°
150°

Neutrino Flux on Earth

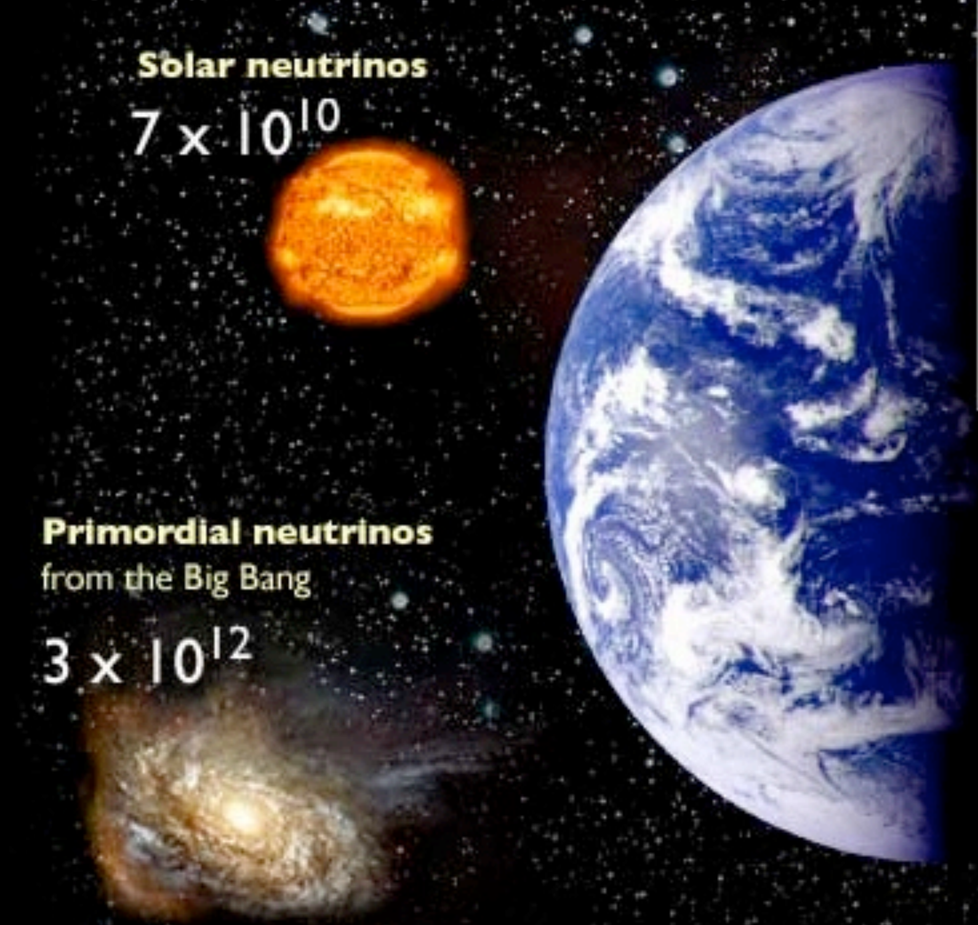
What produces the largest neutrino flux on Earth?

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

Reactor neutrinos

?

Neutrino Flux on Earth



What produces the largest neutrino flux on Earth?

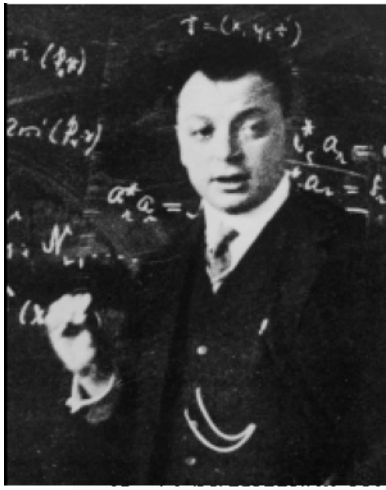
The Sun, the Big Bang, or a nuclear reactor?

Discovery of the Antineutrino

History of the Neutrino

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

Pauli, 1930



Abschrift/15.12.56

...pe der Radioaktiven bei der
...ingen.

...chschule

Zürich, 4. Des. 1930
Gloriastrasse

...Damen und Herren,

...ger dieser Zeilen, den ich huldvollst
...es 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.

Chadwick, 1914

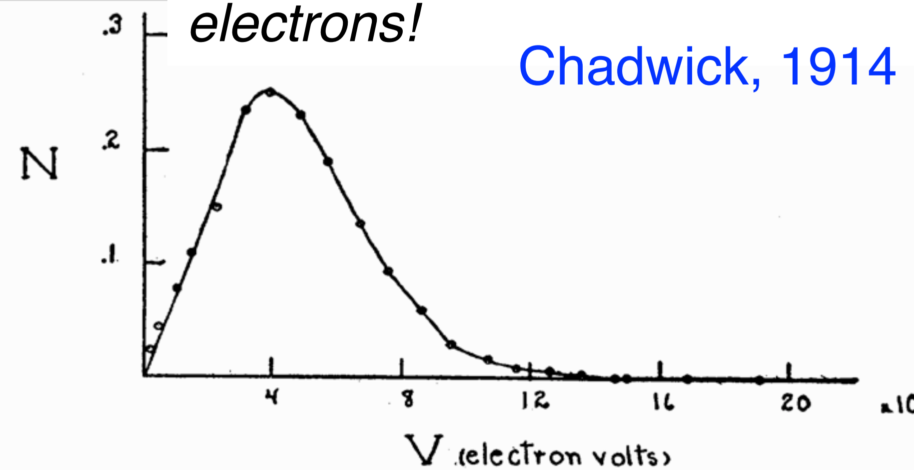
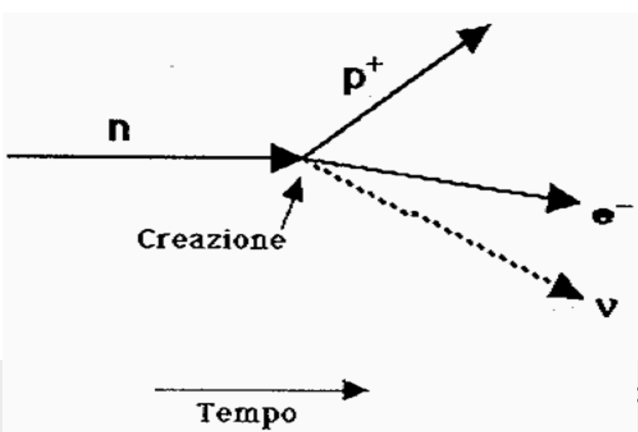
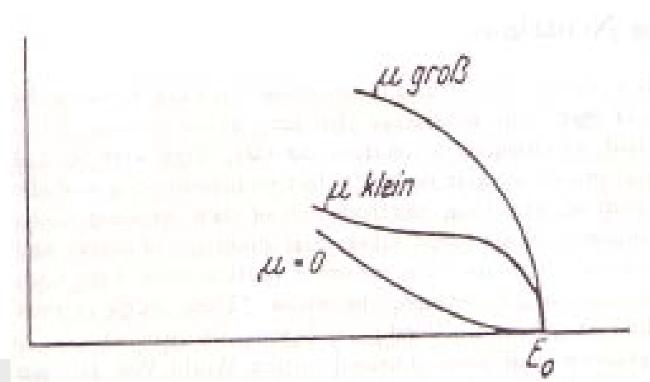


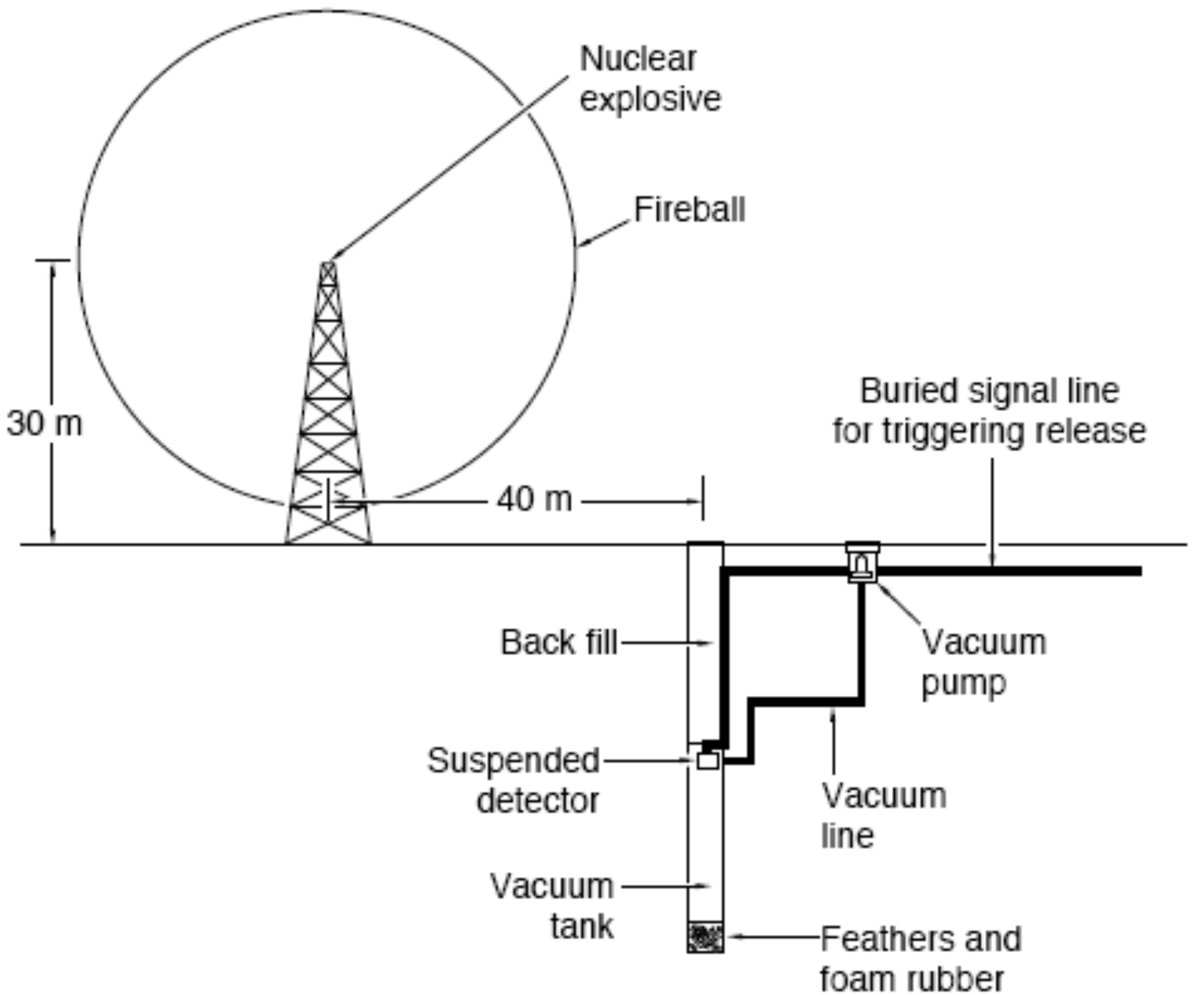
FIG. 5. Energy distribution curve of the beta-rays.

Fermi, 1934

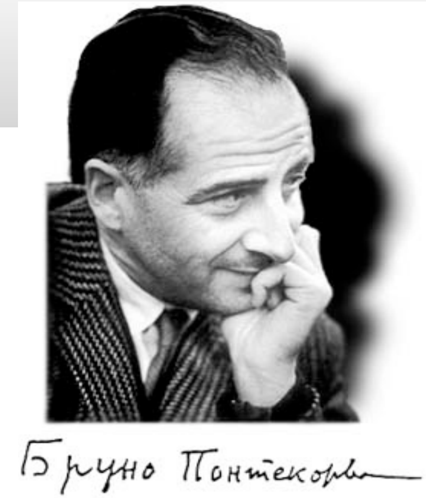




First Proposal For Direct Detection of Neutrino



Nuclear Reactors as a Neutrino Source

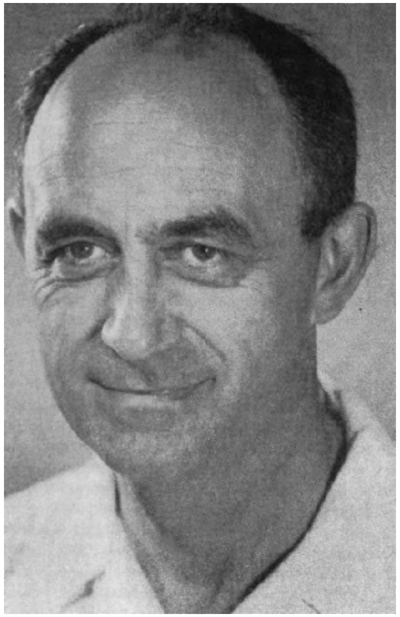


Reactors are intense and pure sources of $\bar{\nu}_e$

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

Good for systematic studies of neutrinos.

Enrico Fermi and the Neutrino



Enrico Fermi proposes "neutrino" as the name for Pauli's postulated particle.

He formulates a quantitative theory of weak particle interactions in which the neutrino plays an integral part.

THE UNIVERSITY OF CHICAGO
CHICAGO 37 · ILLINOIS
INSTITUTE FOR NUCLEAR STUDIES

October 8, 1952

Dr. Fred Reines
Los Alamos Scientific Laboratory
P.O. Box 1663
Los Alamos, New Mexico

Dear Fred:

Thank you for your letter of October 4th by Clyde Cowan and yourself. I was very much interested in your new plan for the detection of the neutrino. Certainly your new method should be much simpler to carry out and have the great advantage that the measurement can be repeated any number of times. I shall be very interested in seeing how your 10 cubic foot scintillation counter is going to work, but I do not know of any reason why it should not.

Good luck.

Sincerely yours,

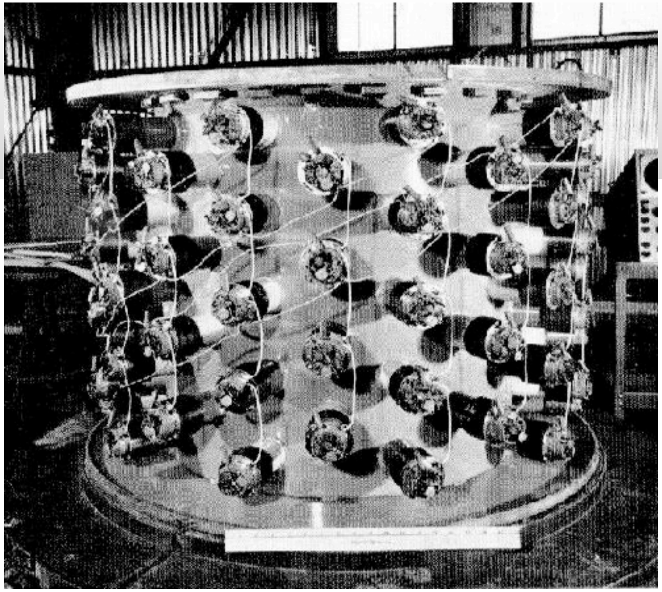
Enrico

Enrico Fermi

EF:vr

1953: Project Poltergeist

Experiment at Hanford



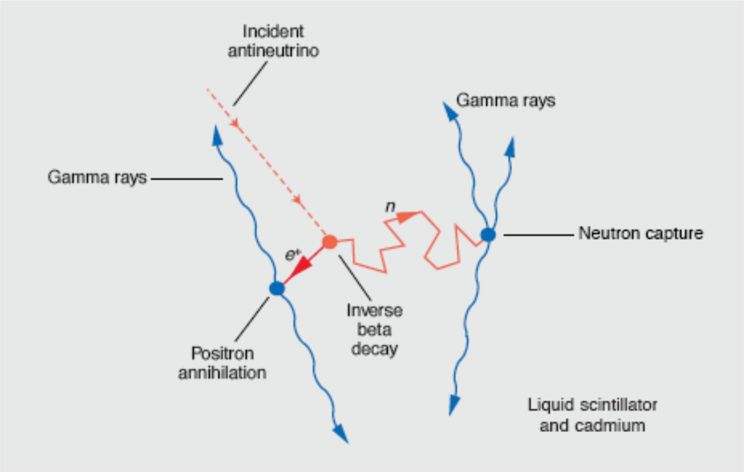
Hanford Experiment

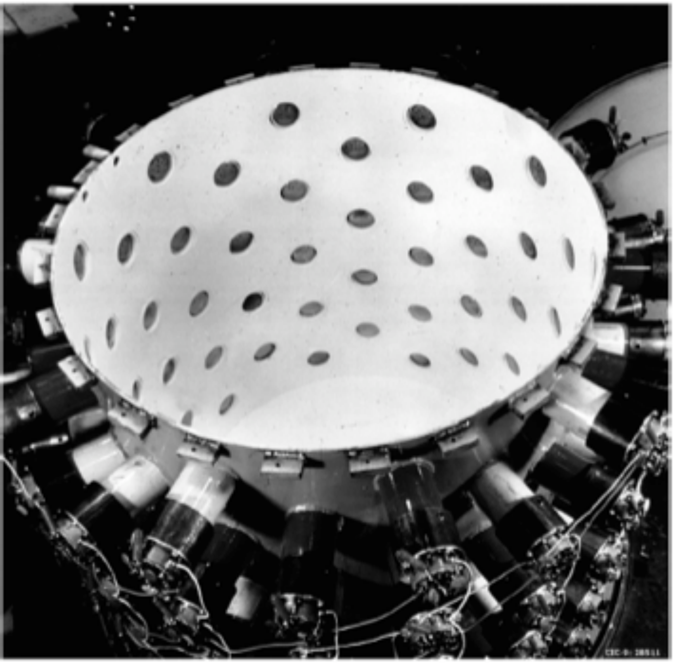
Reines, Cowan

inverse beta decay

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

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: First Direct Detection of the Antineutrino

Clyde Cowan Jr.

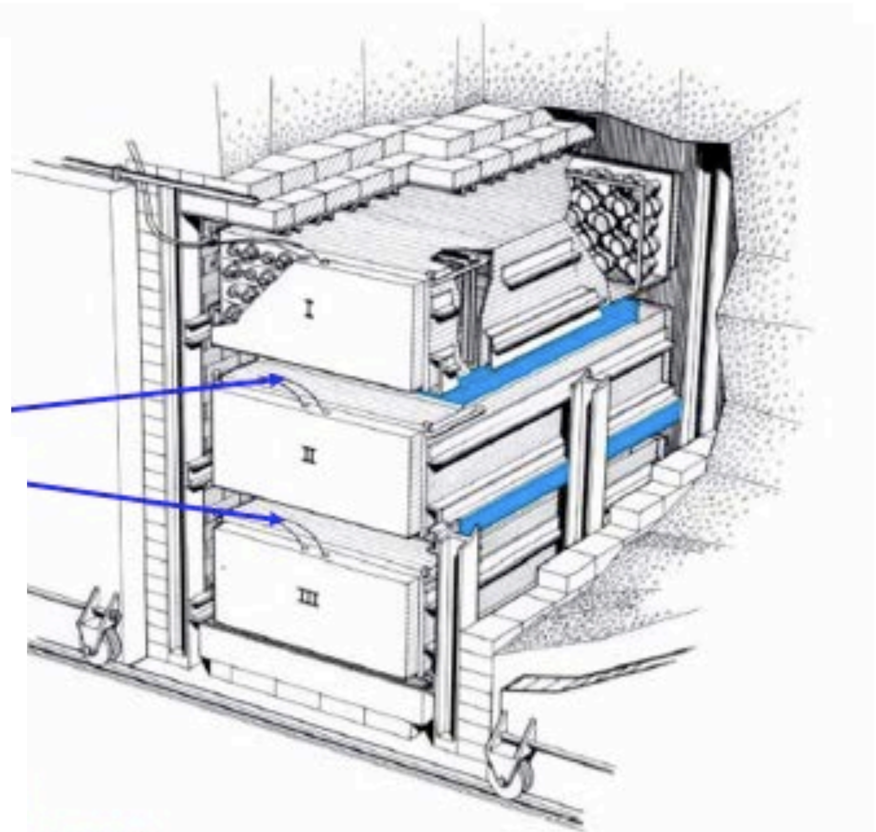
Frederick Reines

The Savannah River Detector

A new design (1959)

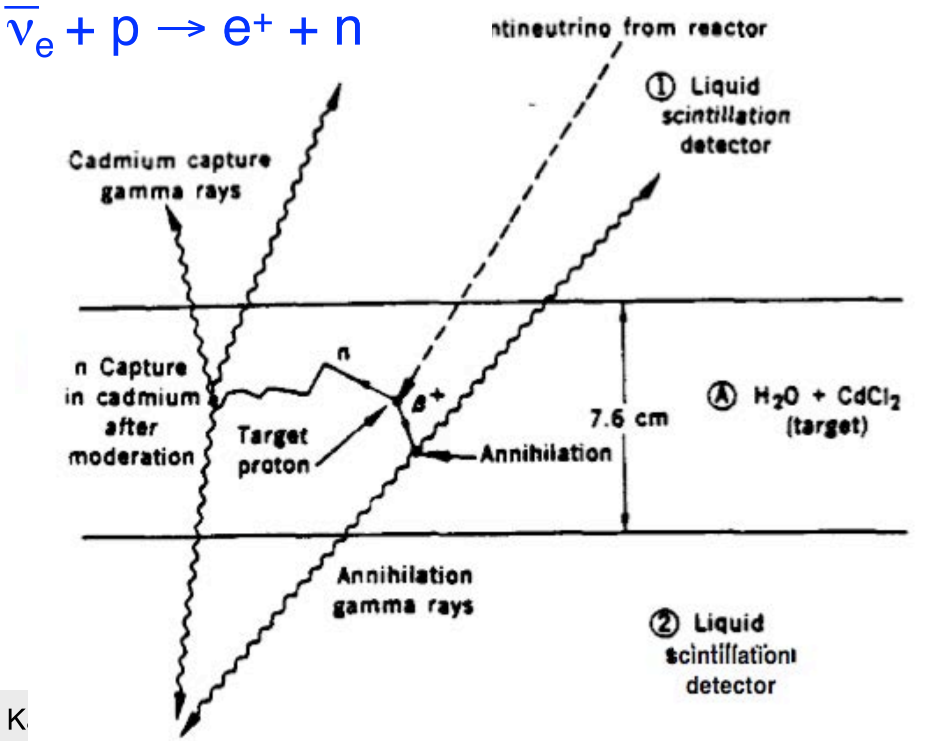
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

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



inverse beta decay

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



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

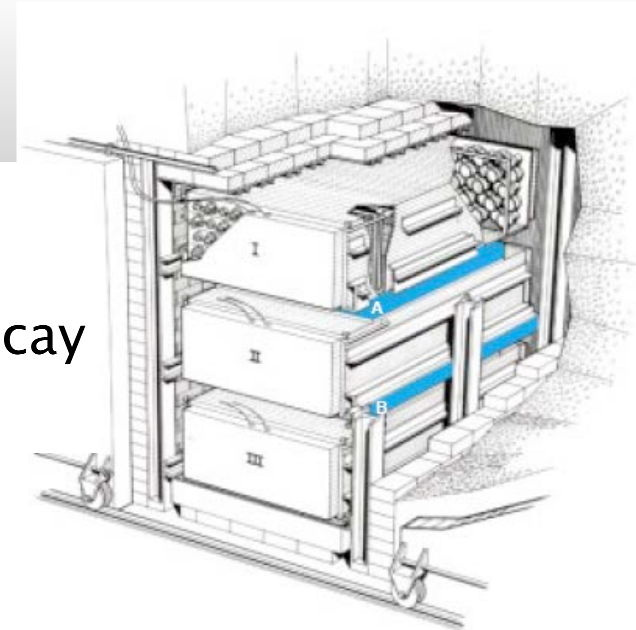
Observation of the Free Antineutrino

1959 The Savannah River Detector - A new design

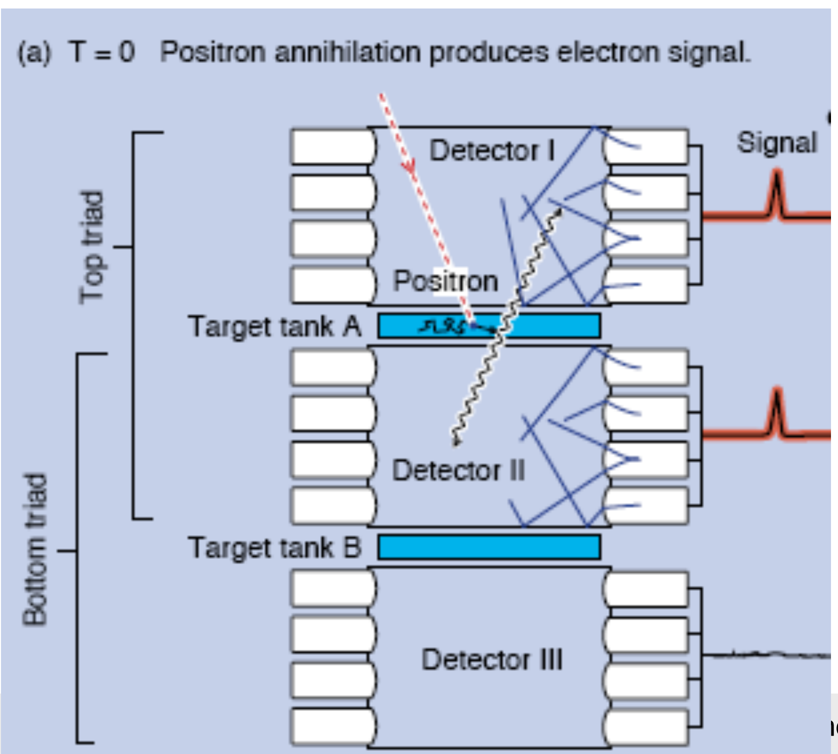
Second version of Reines' experiment worked!

inverse beta decay

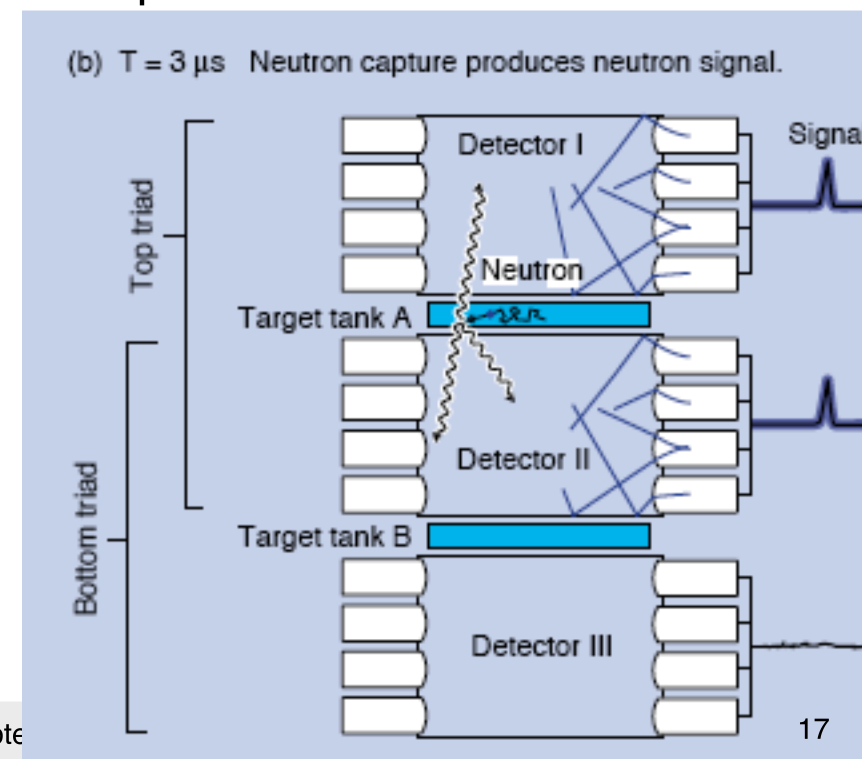
$\overline{\nu}_e + p \rightarrow e^+ + n$



positron annihilation



n capture



The Savannah River Detector

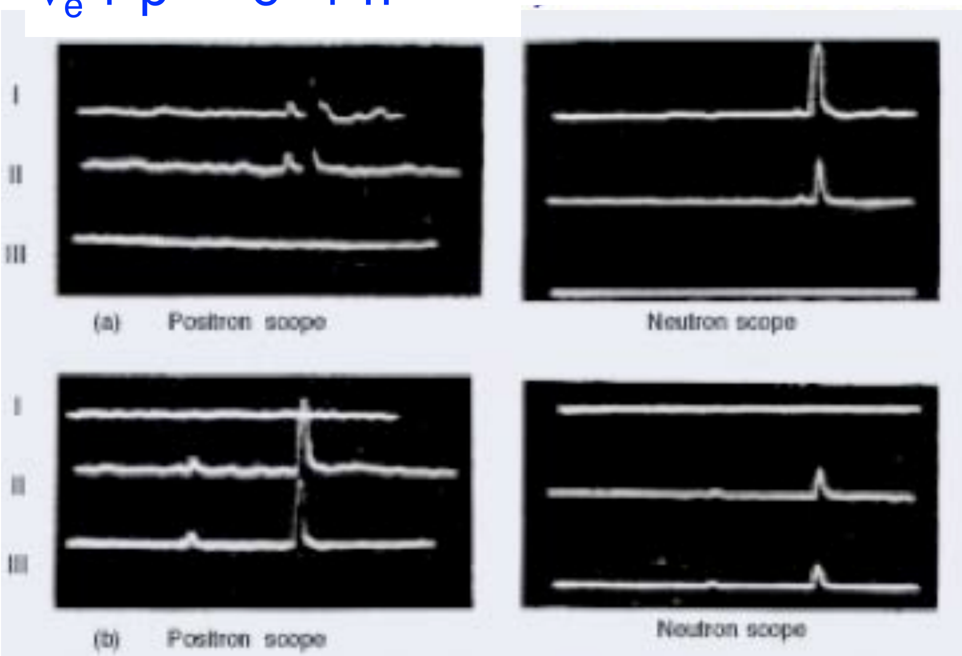
A new design (1959)

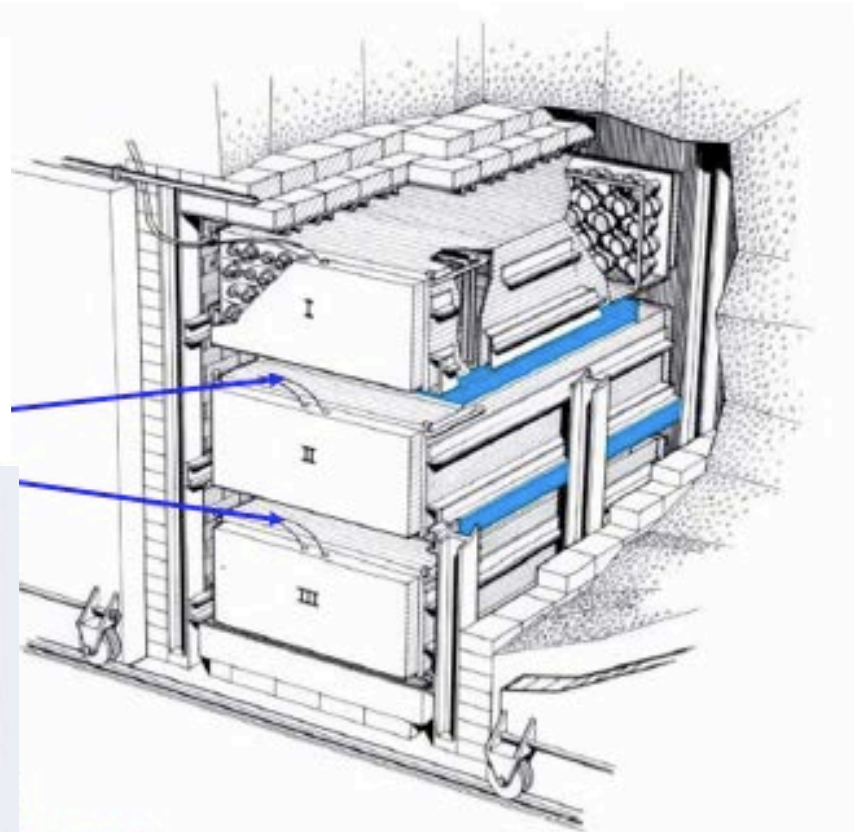
tanks I, II, and III were filled with liquid scintillator and instrumented with 5” PMTs

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

inverse beta decay

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





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

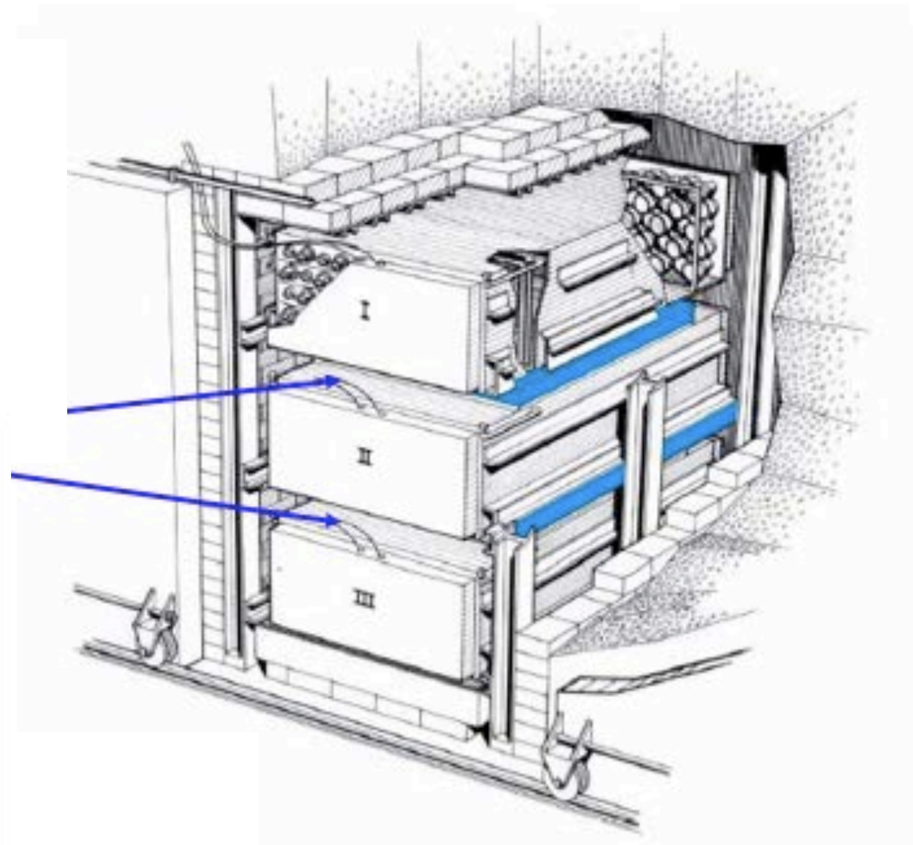
The Savannah River Detector

A new design (1959)

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

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

Shielding: 4 ft of soaked sawdust



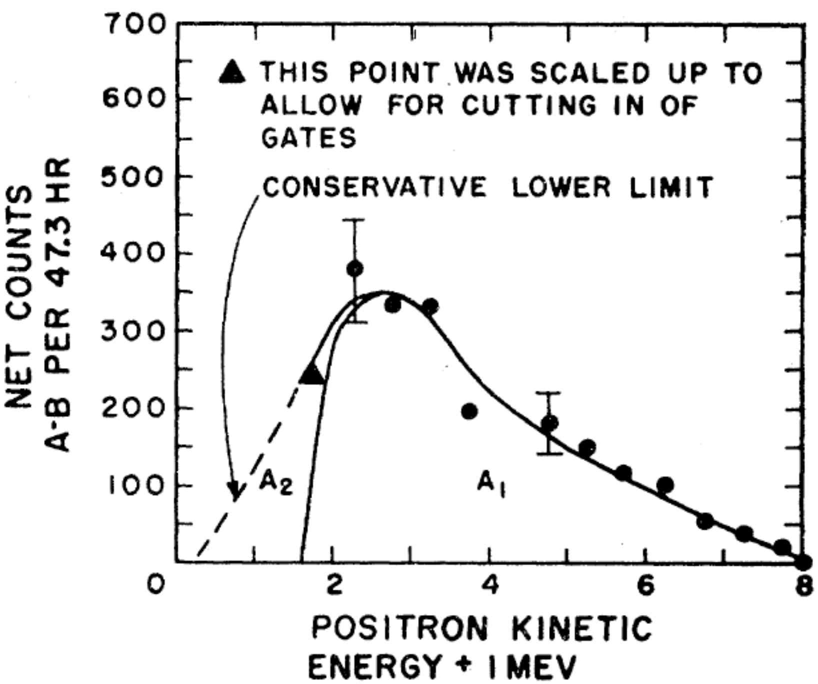
shielding and background reduction is important

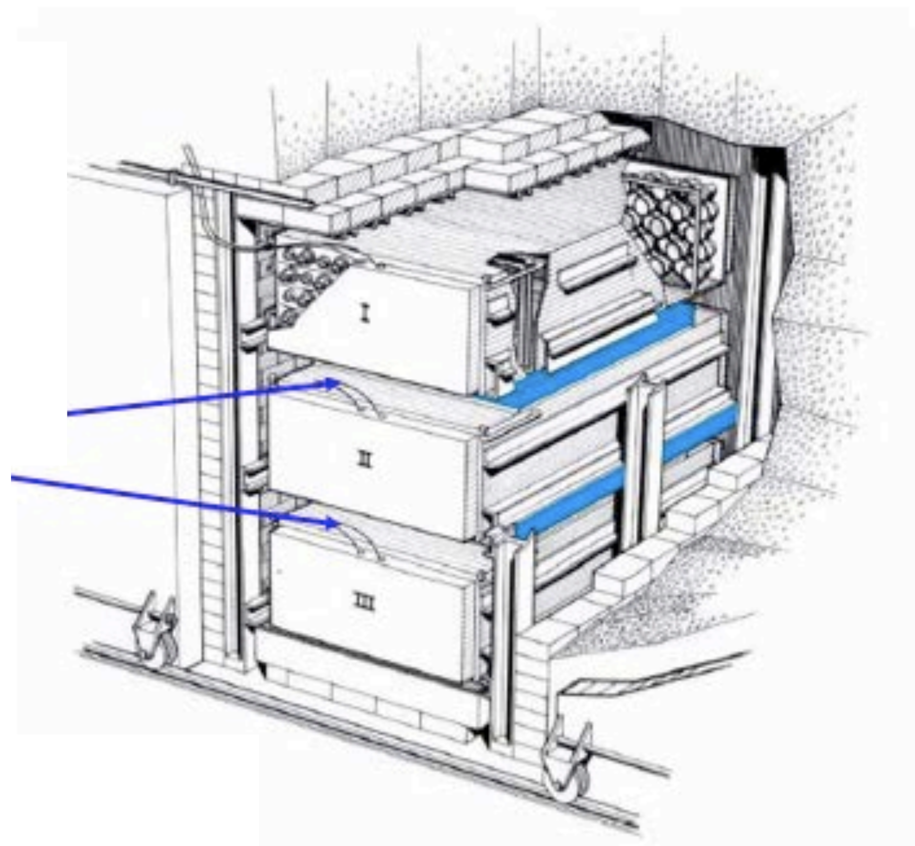
The Savannah River Detector

A new design (1959)

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

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





first reactor $\overline{\nu}_e$ spectrum

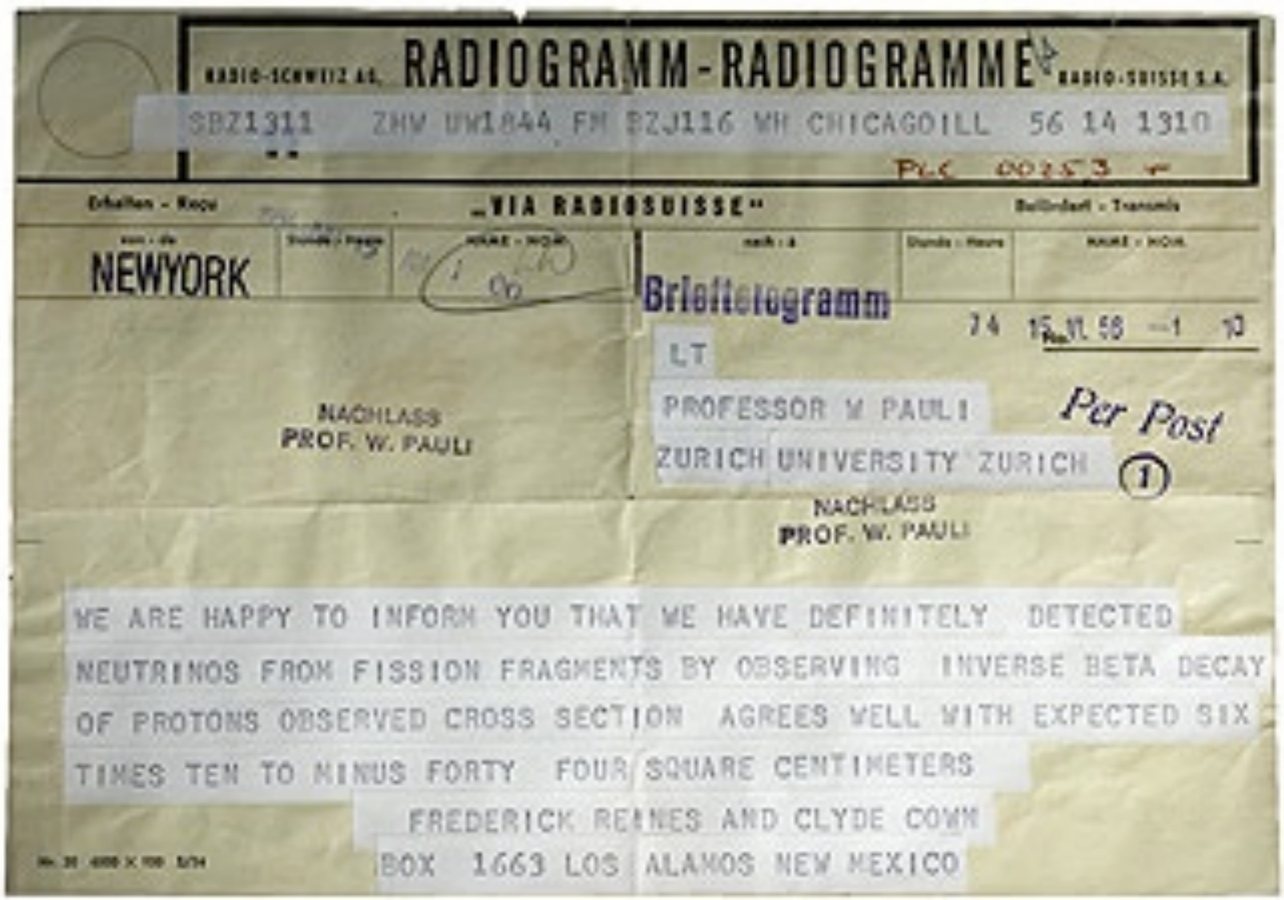
Reines, Cowan, Phys Rev 113, (1959)273

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 ZHW 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

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

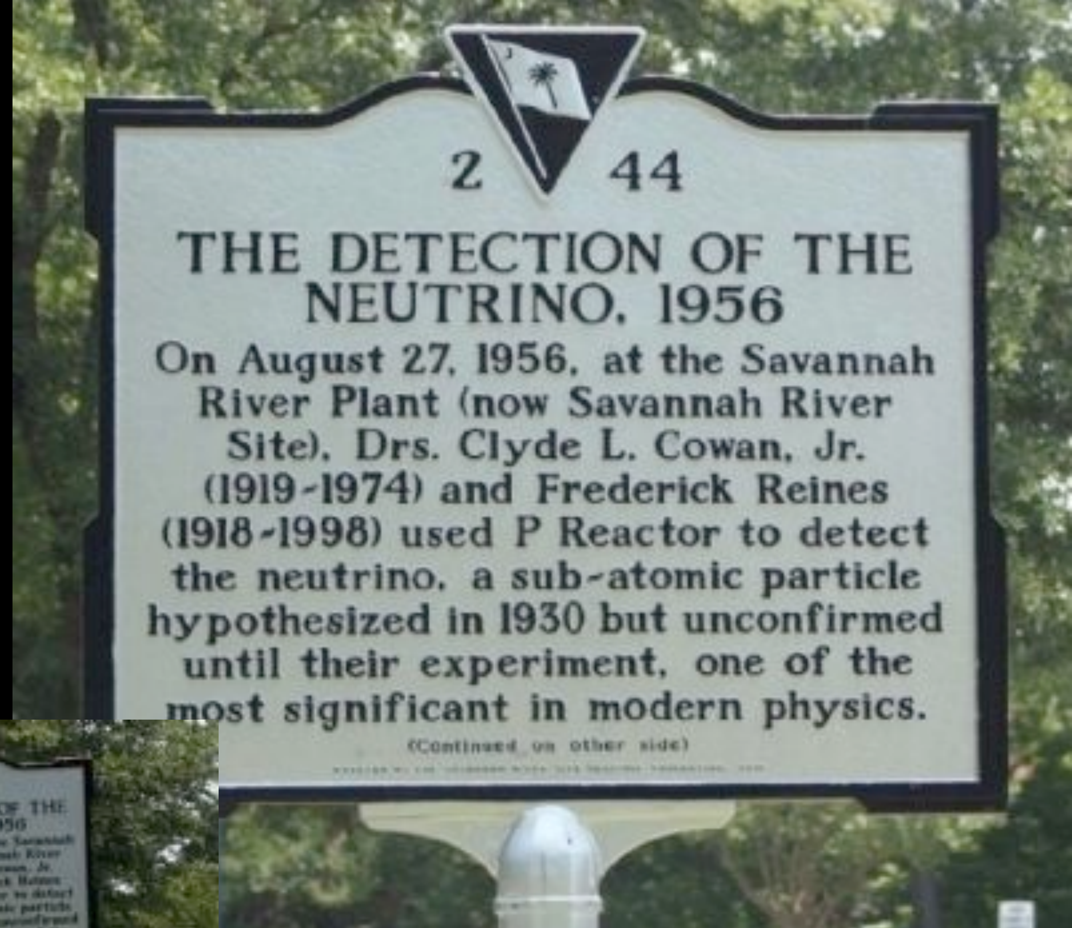
FREDERICK REINES AND CLYDE COWAN

BOX 1663 LOS ALAMOS NEW MEXICO

A Lesson from History

- 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 ×2 to $(10\pm1.7)\times10^{-44}$ cm^2
- In 1960, Reines and Cowan reported a reanalysis of the 1956 experiment and quoted $\sigma = (12^{+7}_{-4})\times10^{-44}\ \text{cm}^2$

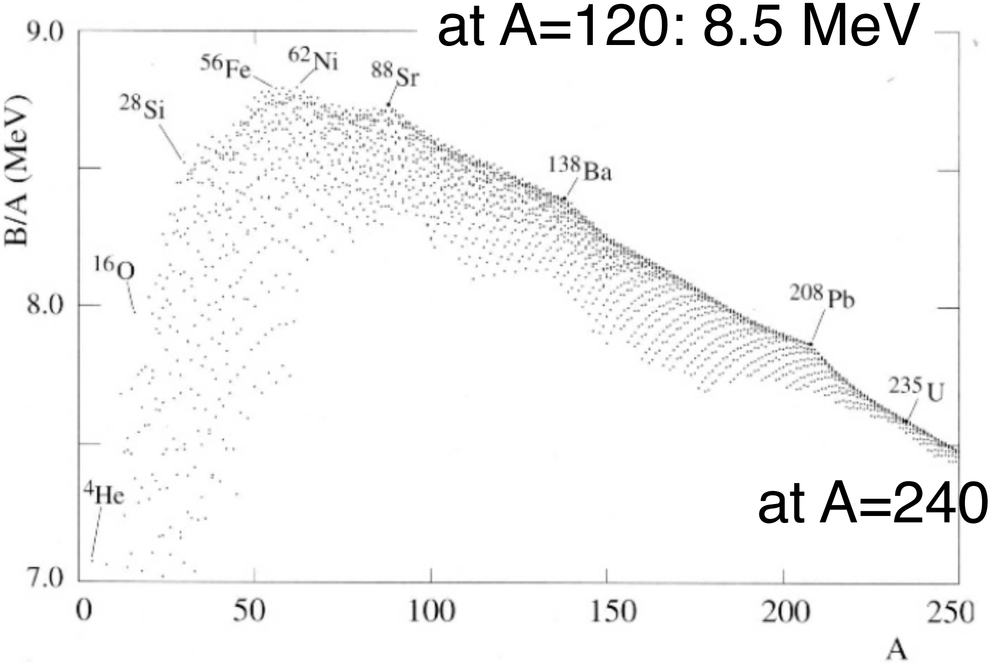
Ref:
R.G. Arms, "Detecting the Neutrino", Physics in Perspectives, 3, 314 (2001)


2 44
THE DETECTION OF THE NEUTRINO, 1956
On August 27, 1956, at the Savannah River Plant (now Savannah River Site), Drs. Clyde L. Cowan, Jr. (1919-1974) and Frederick Reines (1918-1998) used P Reactor to detect the neutrino, a sub-atomic particle hypothesized in 1930 but unconfirmed until their experiment, one of the most significant in modern physics.
(Continued on other side)

Reactors as Antineutrino Source

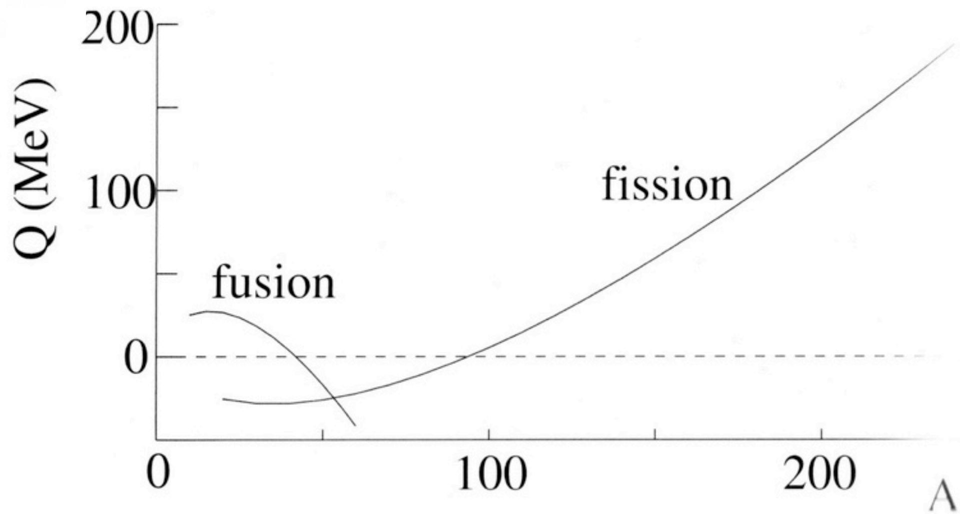
Energy Release in Fission and Self-Fusion

at A=120: 8.5 MeV



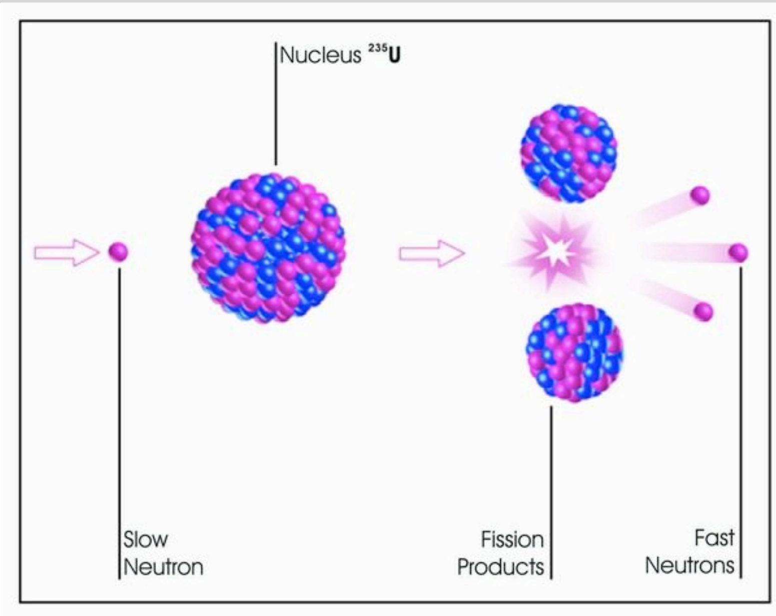
at A=240: 7.6 MeV

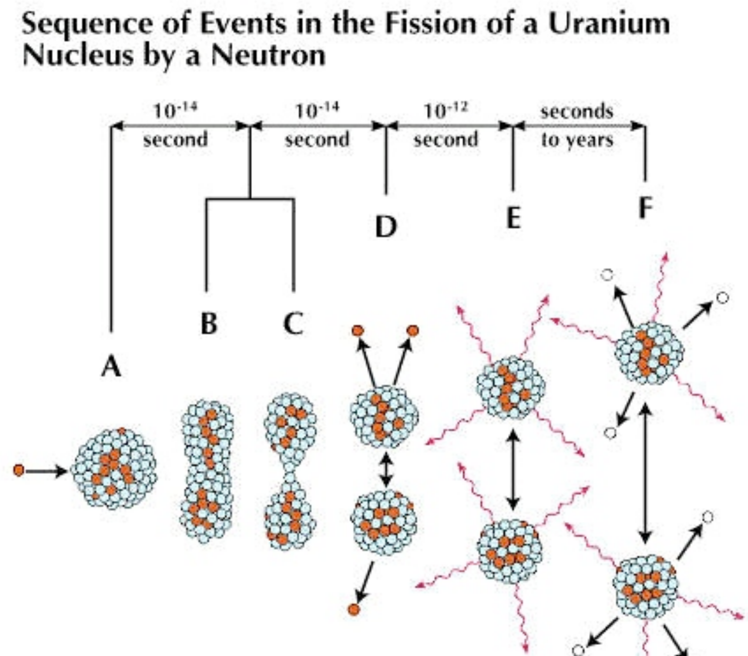
Fig: Basdevant et al.



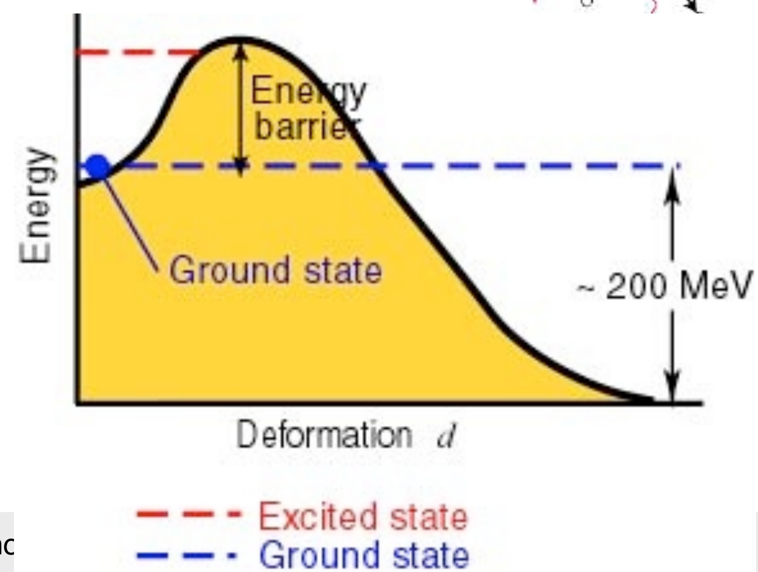
- only nuclei with $40 < A < 95$ are stable against both fission and self-fusion
- Q_{fis} calculated for symmetric fission

Fission and Nuclear Deformation





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

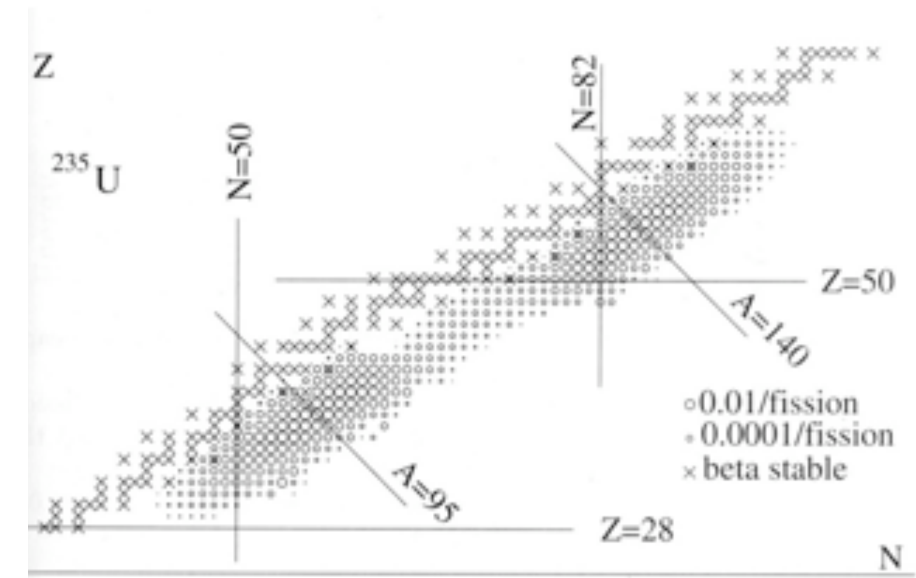


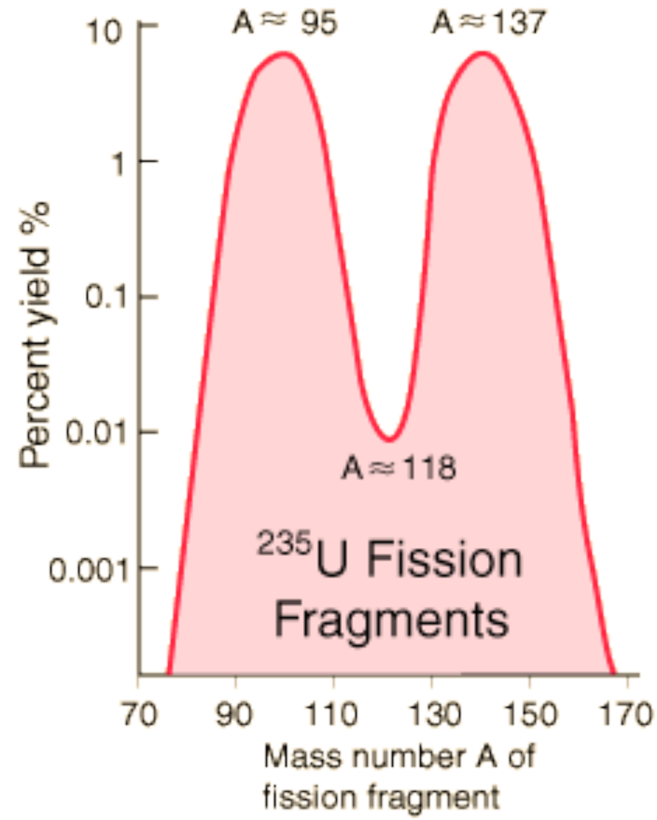
^{235}U Fission

distribution of fission fragments

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

asymmetric fission into lighter





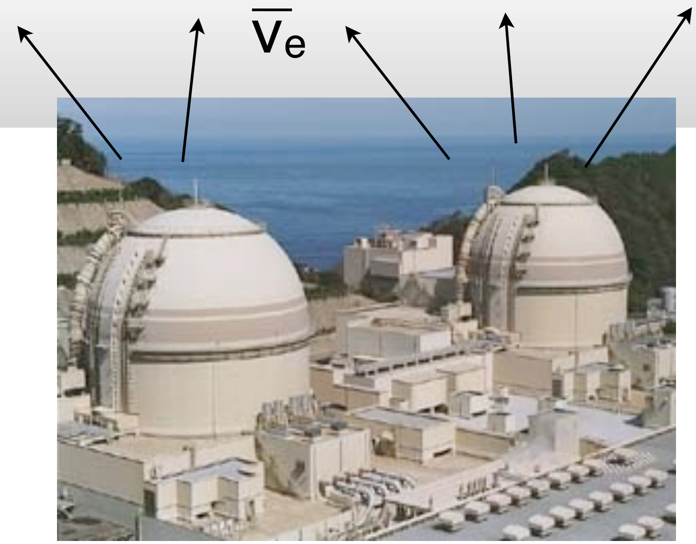
nuclei with most likely A from ^{235}U fission

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

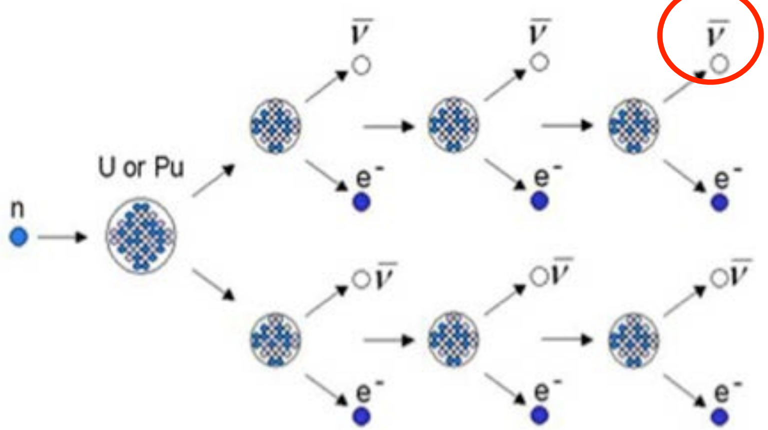
together these have 98 p and 136 n while fission fragments (X_1+X_2) have 92 p and 144 n

on average 6n have to beta-decay to 6p to reach stable matter → $\overline{\nu_e}$

Reactors as Antineutrino Sources



β^- decay of neutron rich fission fragments



pure source of $\overline{\nu}_e$

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

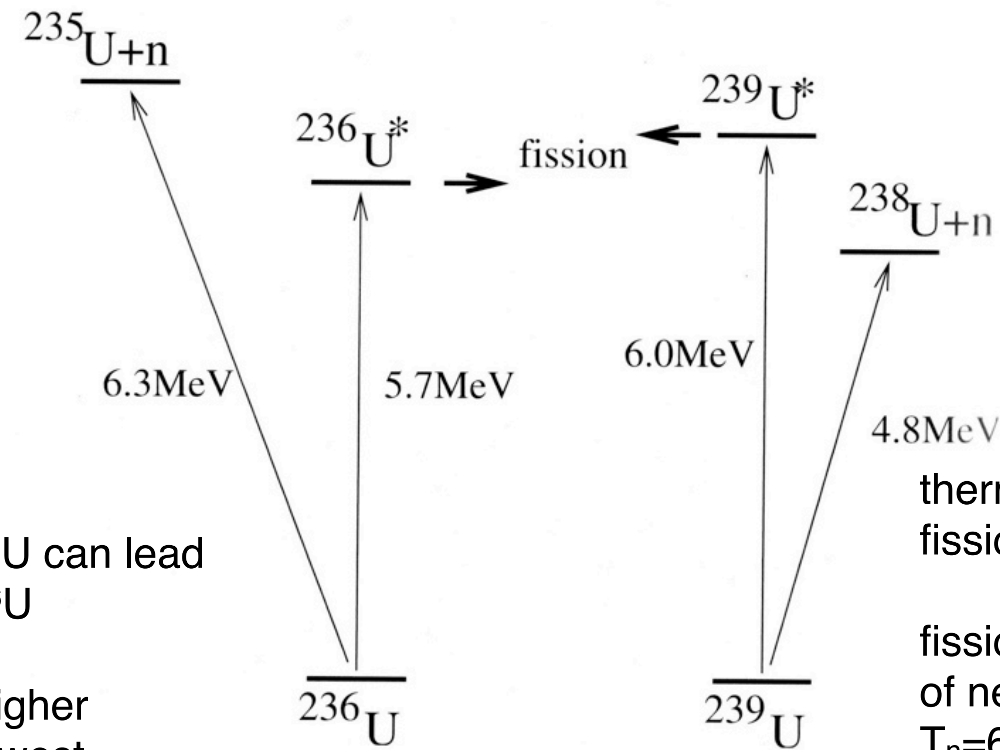
some energy taken away by neutrinos, neutrons etc

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

3 GWth reactor produces ~6x10^{20} $\overline{\nu}_e$/sec

Fission with thermal and fast neutrons

^{235}U



^{238}U

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

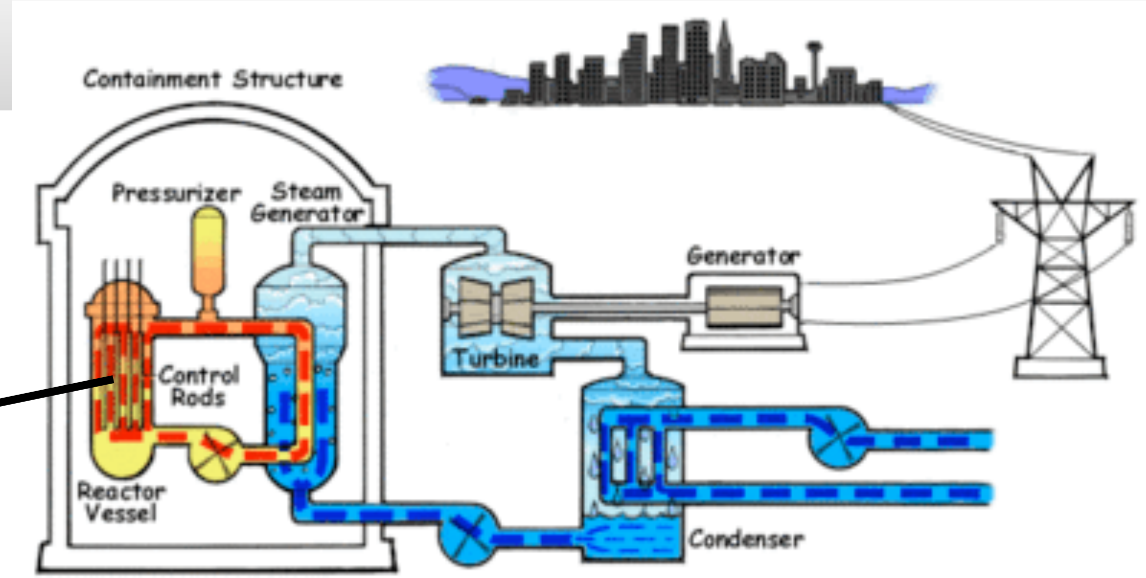
Nuclei which are used most easily as fuel (fission rapidly by thermal neutron capture):
^{233}U, ^{235}U, ^{239}Pu

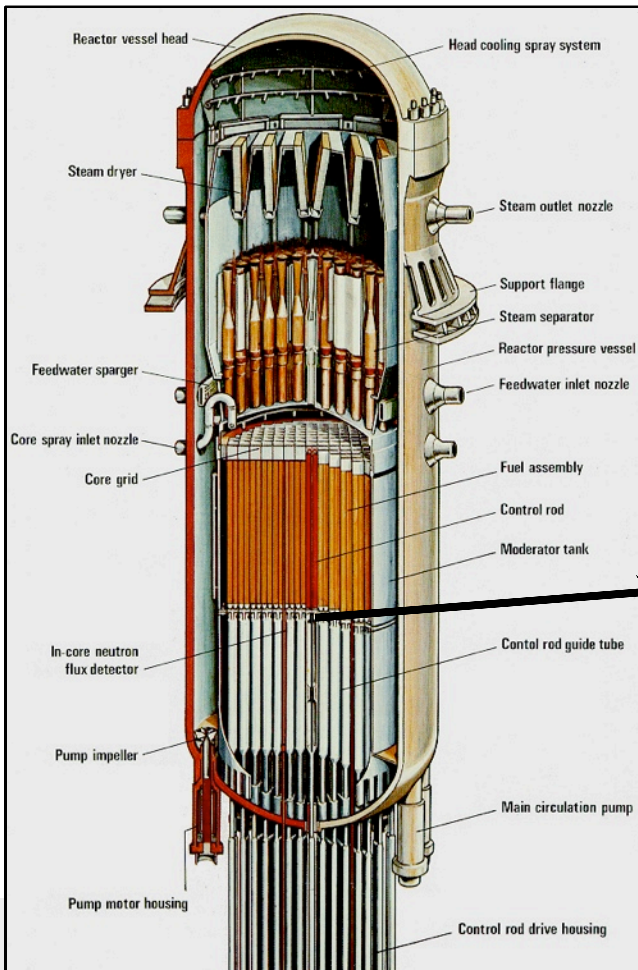
reactors which burn ^{239}Pu and which contains ^{238}U can produce more Pu than it needs → breeder reactor

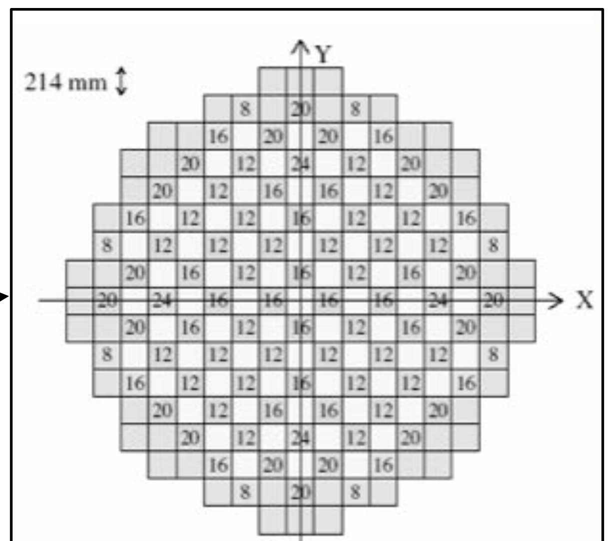
Nuclear Reactors

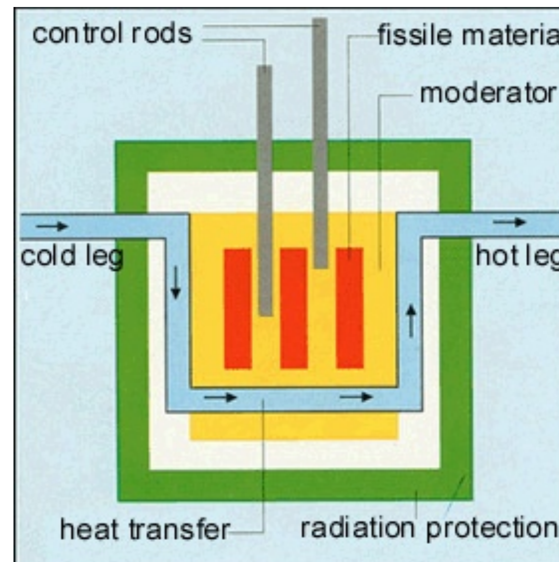
reactors are an extended neutrino source:

3-4m diameter, 4m high

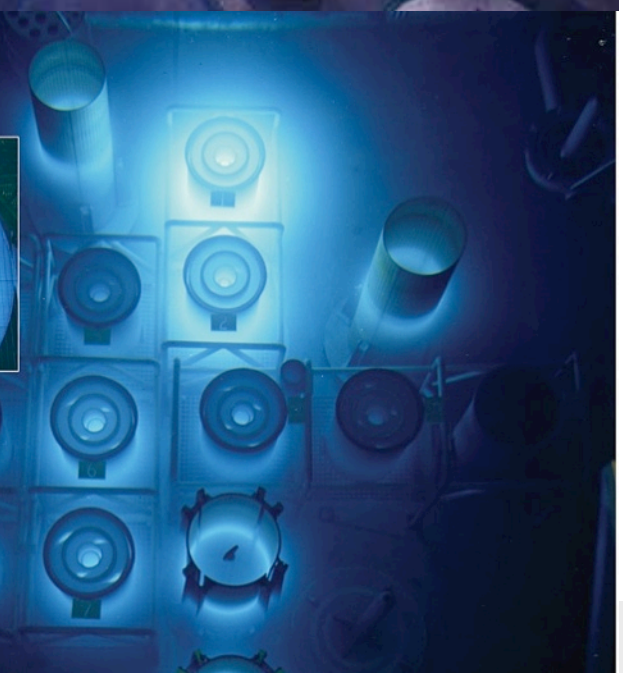


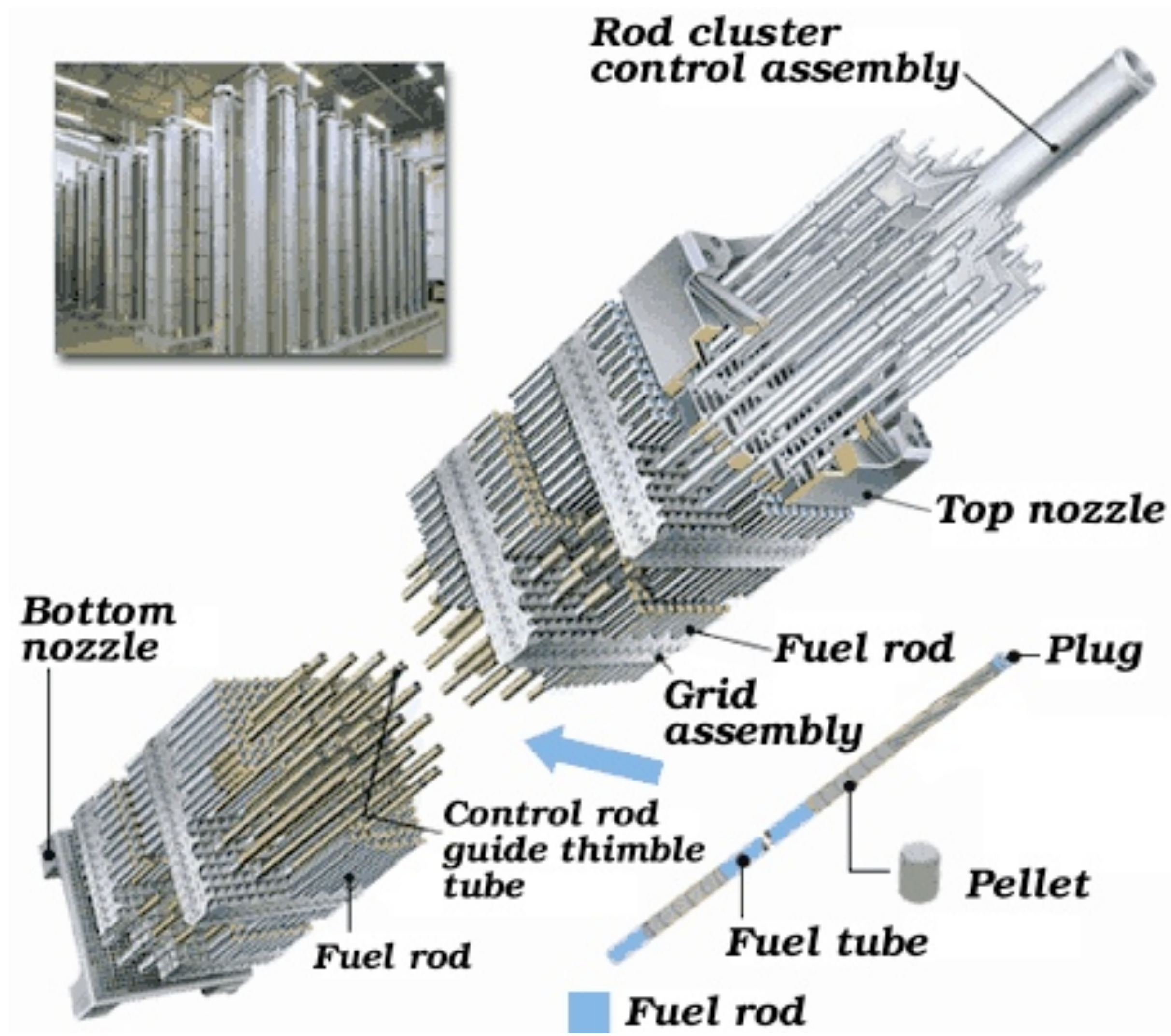






Fuel Element for a PWR Reactor





Reactor Antineutrinos

Source

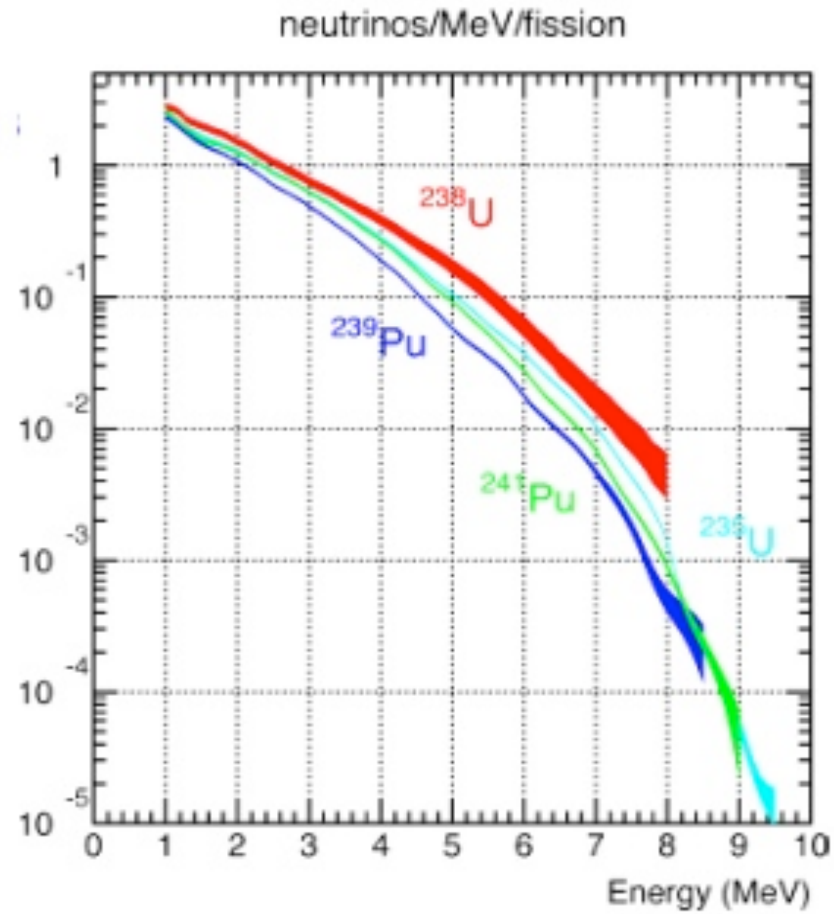
$\bar{\nu}_e$ from β-decays

of n-rich fission products

pure $\bar{\nu}_e$ source

typical fuel composition

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



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

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

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

Build-Up of Fission Products & Burn-Up Corrections

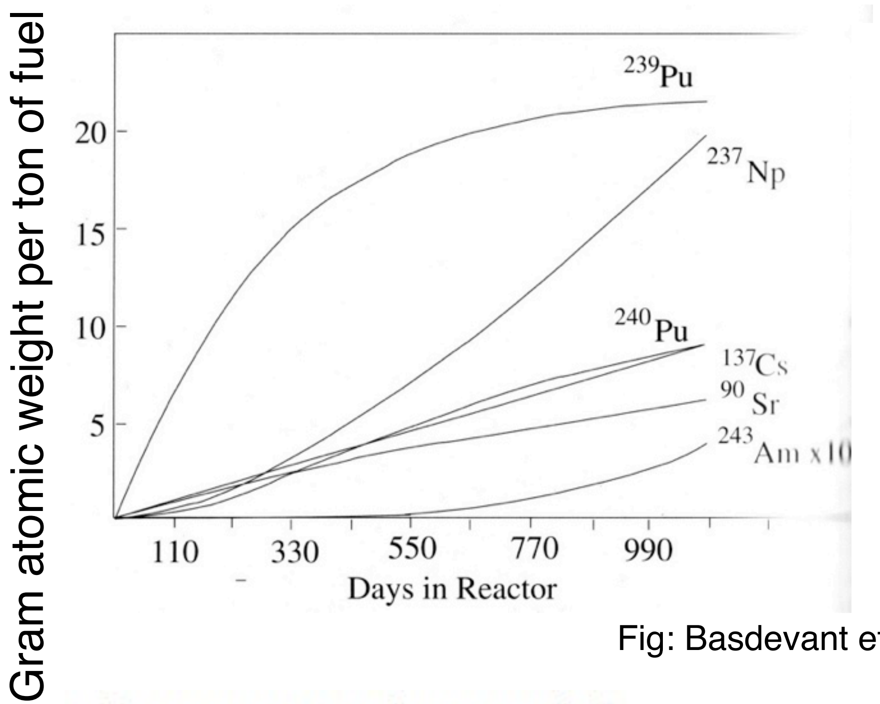
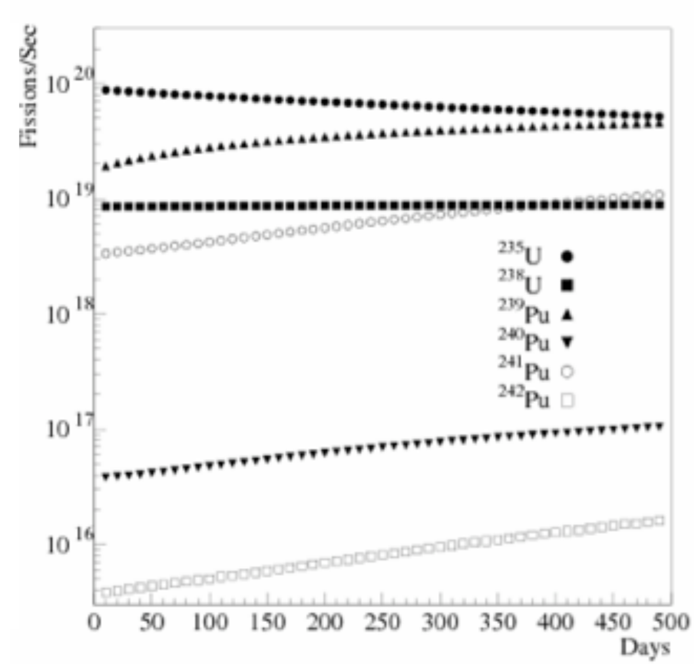


Fig: Basdevant et al.



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

isotope uncertainties of 4-6% for most
0.1% for ^{238}U, correlated

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

~5% isotope uncertainty yields
~0.5% uncertainty in neutrino flux

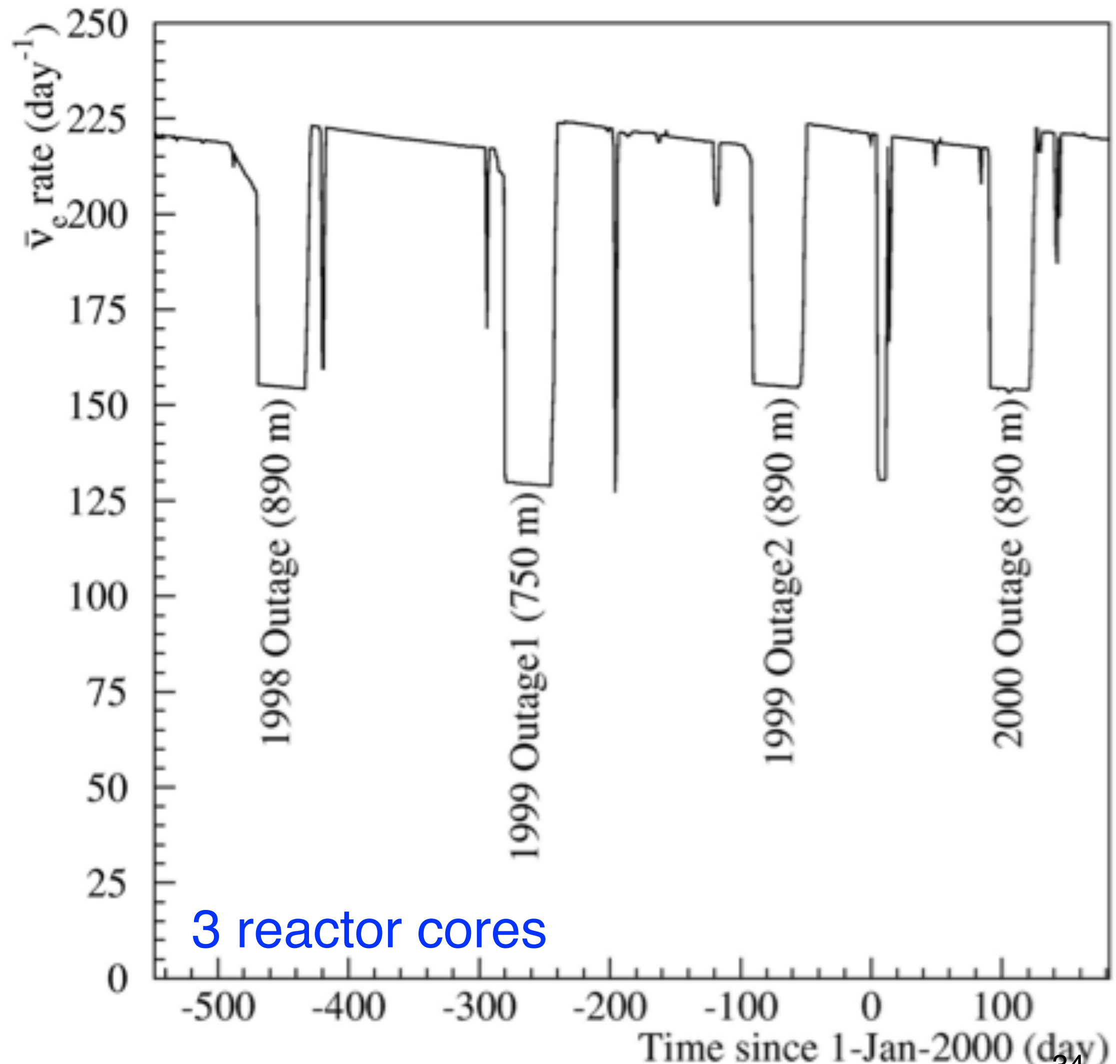
Reactor Refueling and Time Variation

$\overline{\nu}_e$ 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 reactors and predicted antineutrino rate



Thermal Power → Fission → Antineutrinos

1. Power Measurement

most accurate measurement is
secondary heat balance method
offline,
done weekly,
uncertainty ~0.5-0.7%

Origin of uncertainty	Contribution [MWth]	Relative fraction [%] of the 17.2 MWth
Discharge coefficient	15.33	79.57
Differential pressure	6.33	13.57
Steam gen. inlet temp.	2.81	2.68
Primary input	2.00	1.35
Others uncertainties	2.98	3.00
Uncertainty at 95% C.L.	4250±17.2 MW (0.40%)	

2. Core Simulation

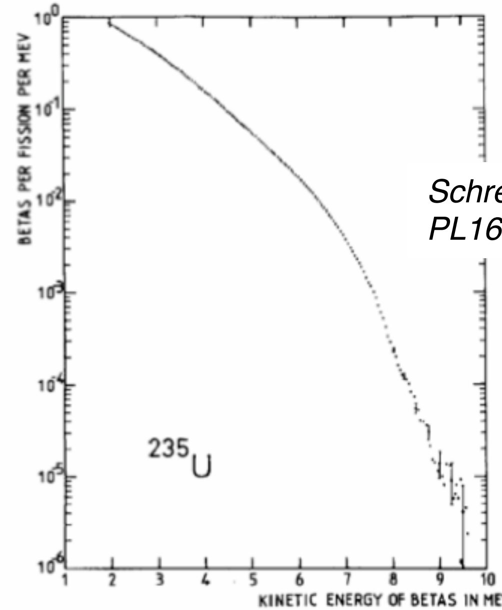
fission fraction of fuel isotopes are obtained by core simulation

3. Energy release per fission in MeV

Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65

4. Neutrino Spectra

Fission Products, β-spectra, $\bar{\nu}$



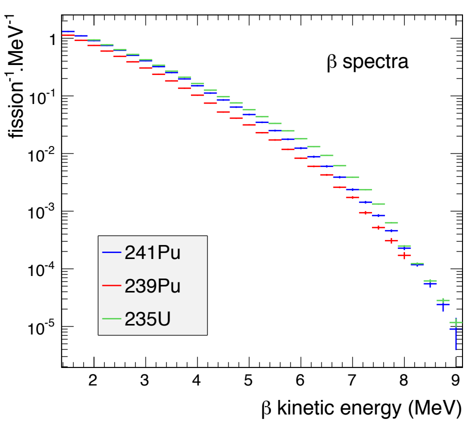
Schreckenbach et al. PL160B 325 (1985)

Measurements

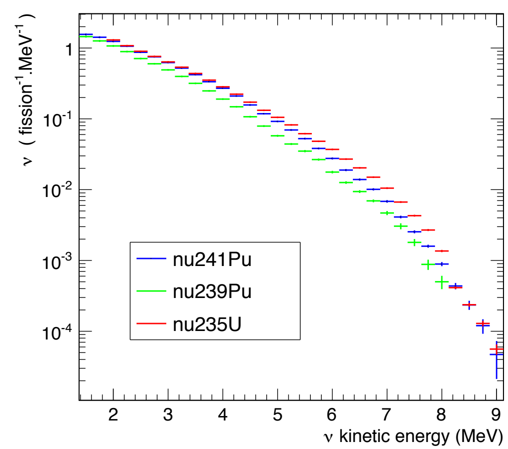
- β^--spectra resulting from fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu have been experimentally measured
- use thin layer of fissile material in beam of thermal neutrons, e.g. Schreckenbach et al., Hahn et al.
- can be converted to $\bar{\nu}_e$ spectra

reference spectra from ILL over last 25 years

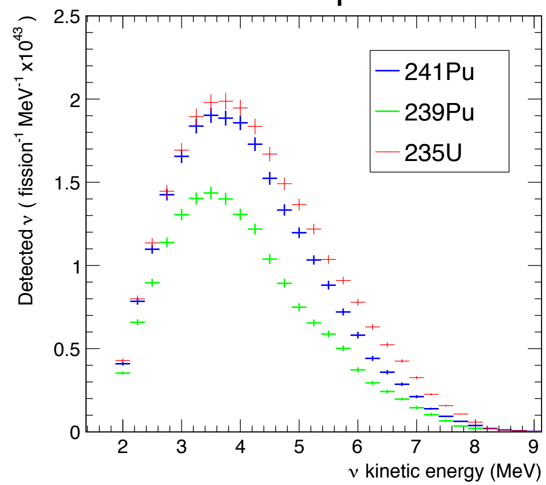
β-spectra



emitted $\bar{\nu}$-spectra



detected $\bar{\nu}$-spectra



Calculations

^{238}U beta spectra not available, fast neutrons required for fission
→ determined from theory (+/-10%), contributes 7-10% of fissions in a PWR

Neutrino Flux Predictions

Reactor data

Thermal power, δP_{th} <1%

Reactor evolution codes

Fraction of fissions from isotope k, $\delta\alpha_k$=few %

$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases

E released per fissions of isotope k, δE_k≈0.3%

ν spectrum per fission

$S_k(E)$ = Σ all fission products

$S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branches of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

Theory of β-decay

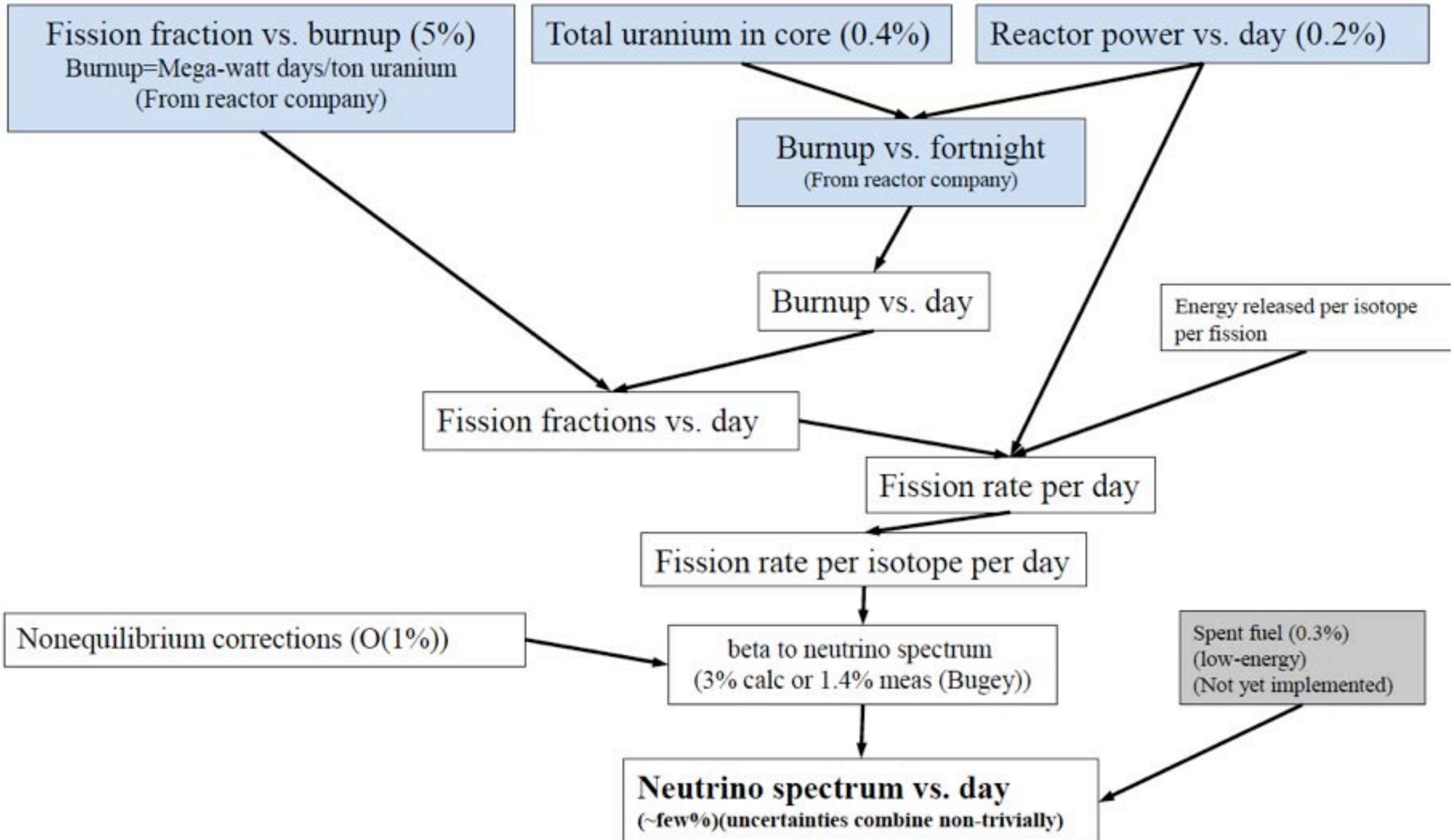
$$S^b_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta^b_{fp} = G_{\nu(QED)} + L_{0(coulomb\ size)} + C_{(weak\ size)} + S_{(screening)} + \delta_{WM\ (weak\ magnetism)}$$

Ref: Lhuillier

Neutrino Flux Predictions



Ref: Lewis

Goesgen Experiment (1986)

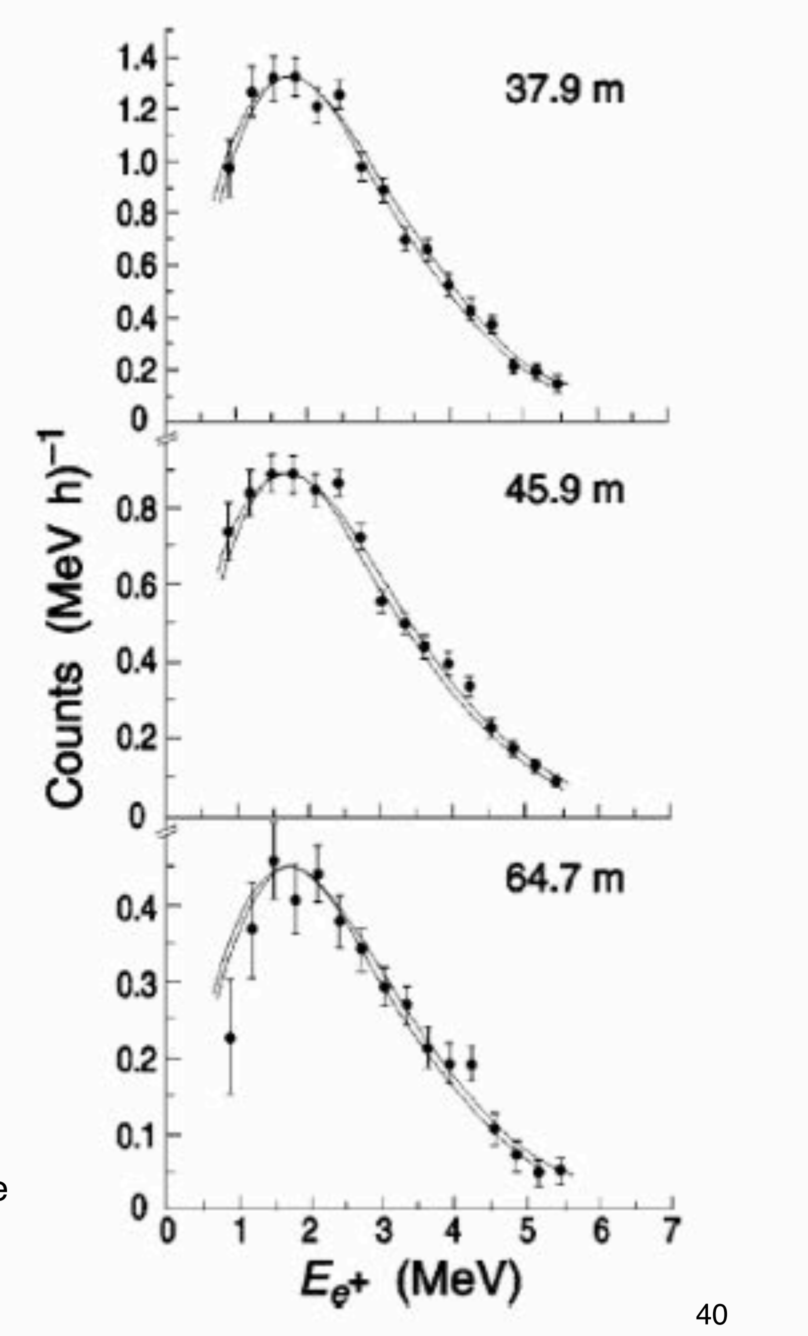
Comparison of Predicted Spectra to Observations

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%

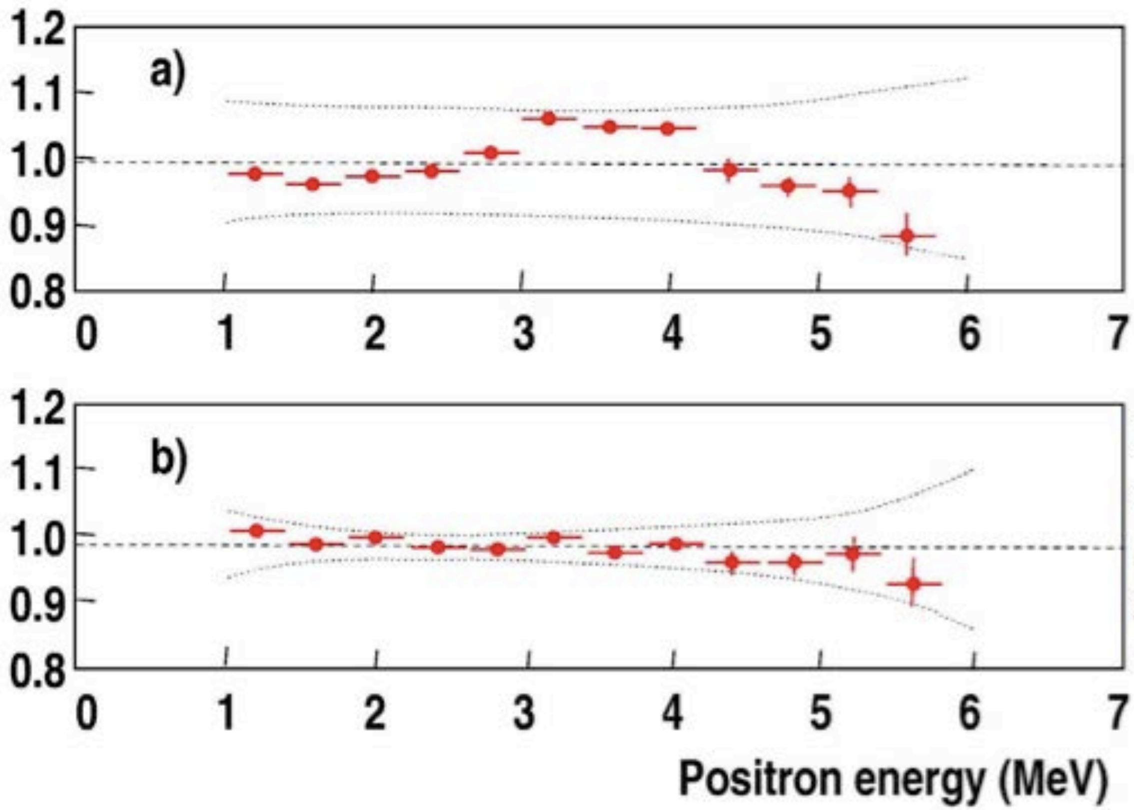
reactors are a “well-calibrated” source of $\overline{\nu}_e$



Bugey Experiment (1996)

Check $\overline{\nu}$ Spectrum Against Data

Measured $\overline{\nu}_e$ spectrum shape and normalization agreed with calculated predictions to ~10% and with converted electron spectra even better



Bugey3/"first principle calculation"

Calculation only
Klapdor and Metzinger, 1982

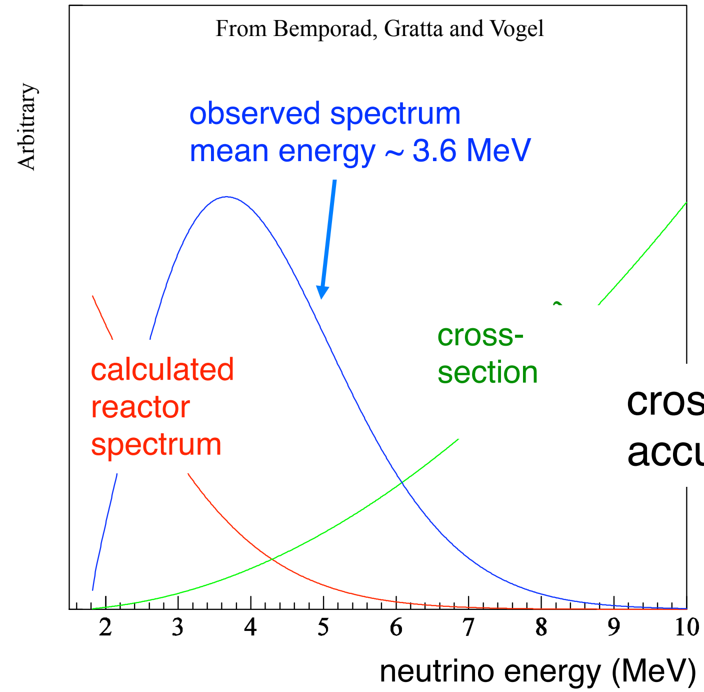
Bugey3/"best prediction" *(uses β^- spectra where possible and calculation for ^{238}U)*

Beta calibrated
Schreckenbach, 1985
Hahn, 1989

spectra derived from β-spectra: +/-1.4% agreement

Detection and Studies of Reactor Antineutrinos

Reactor Antineutrinos



Detection **inverse β-decay**

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

cross-section accurate to +/-0.2%

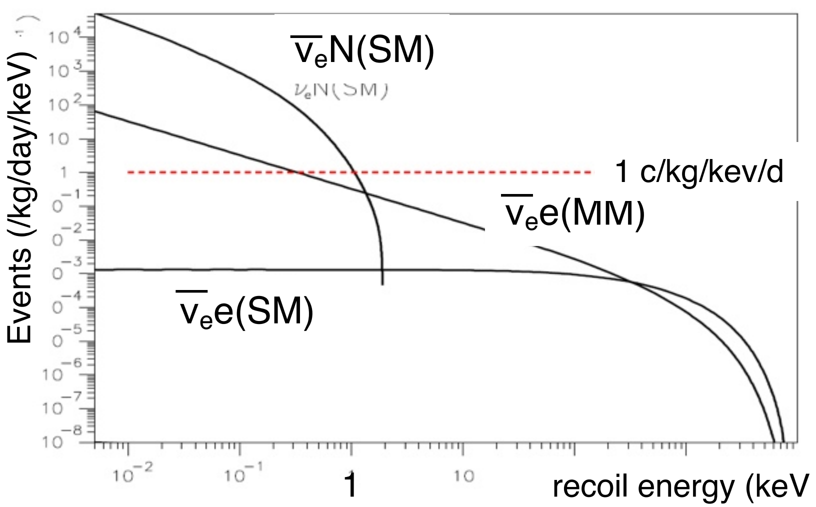
observable **rate** and energy **spectrum**

only disappearance experiments possible

neutrinos with E < 1.8 MeV are not detected

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

$\bar{\nu}_e$ scattering



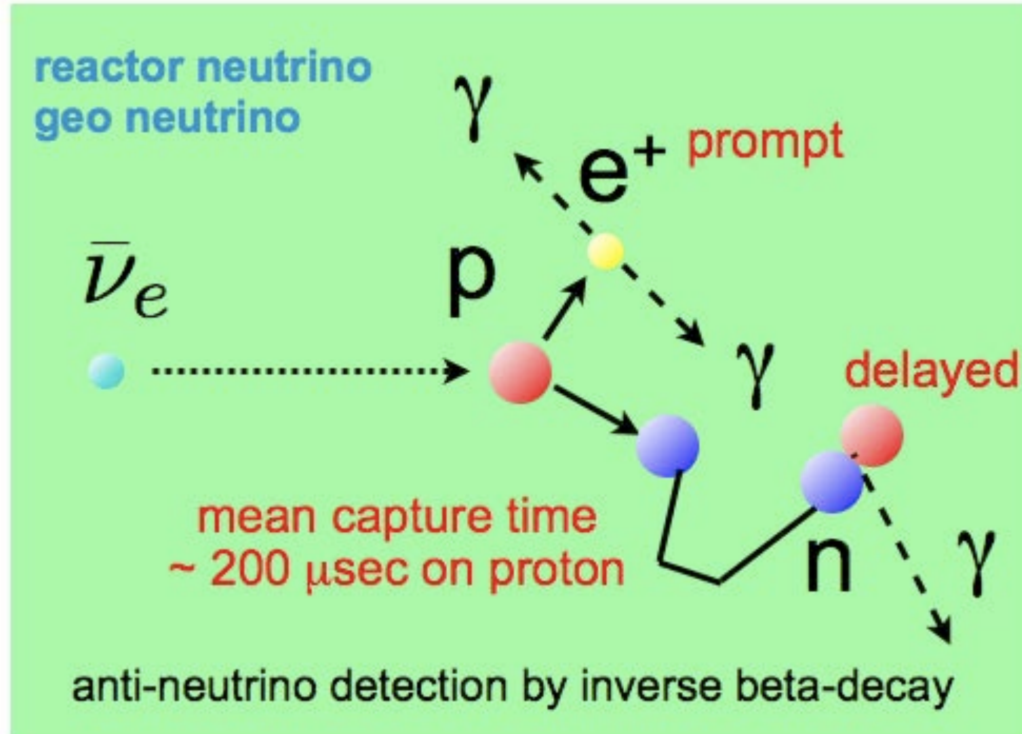
Antineutrino Detection

inverse beta decay

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

$n + p \rightarrow D + \gamma$ (2.2 MeV)
(delayed)

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



1.805 MeV

10-100 keV

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

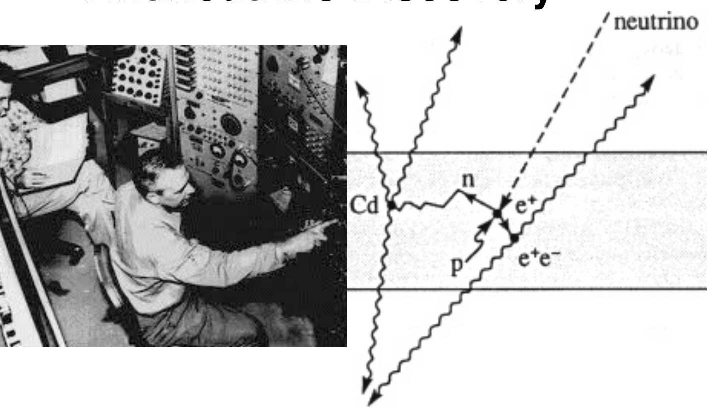
other detection mechanisms:
$\bar{\nu}_e + d \rightarrow e^+ + n + n$
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

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

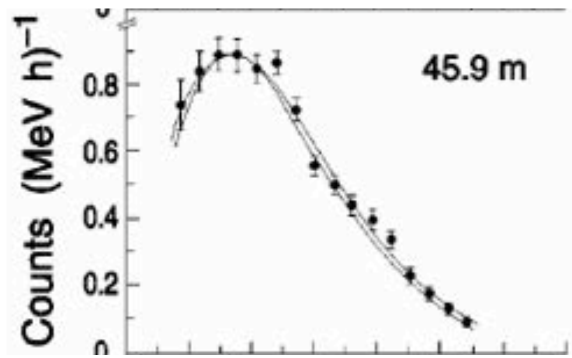
Physics with Reactor $\overline{\nu}_e$

Discoveries and Precision Measurements of Neutrino Properties

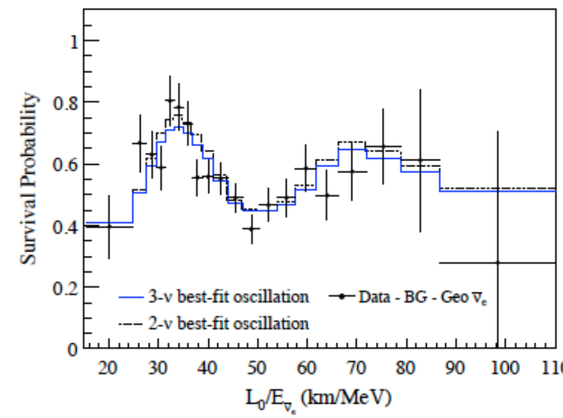
Antineutrino Discovery



Reactor $\overline{\nu}_e$ Spectra

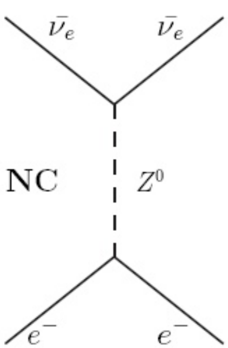


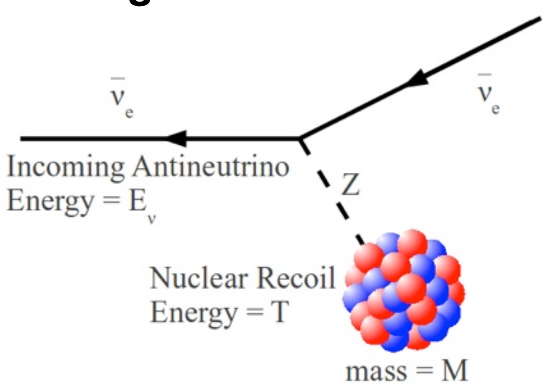
$\overline{\nu}_e$ Oscillations



Searches for New Physics

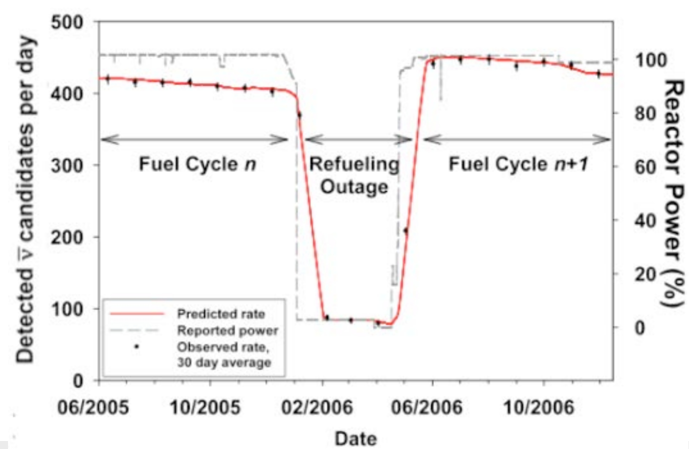
neutrino magnetic moment and **coherent scattering** searches





Reactor Monitoring and Application

fuel burnup and isotopic composition



Neutrino Oscillation Searches with Reactor Antineutrinos

Neutrino Oscillation

neutrino flavor change occurs if neutrinos have mass and leptons mix

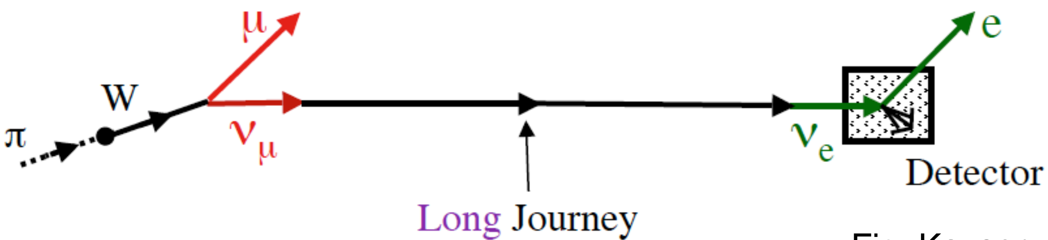
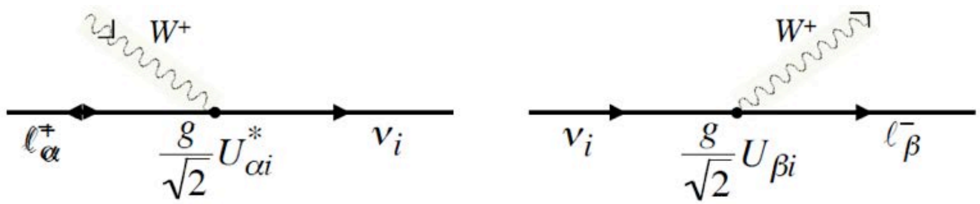


Fig: Kayser

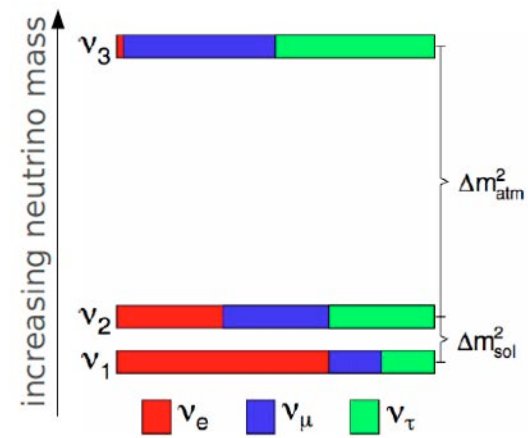
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

mixing matrix



$$U = \begin{array}{c} \\ e \\ \mu \\ \tau \end{array}\begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \end{array}$$

mass eigenstates

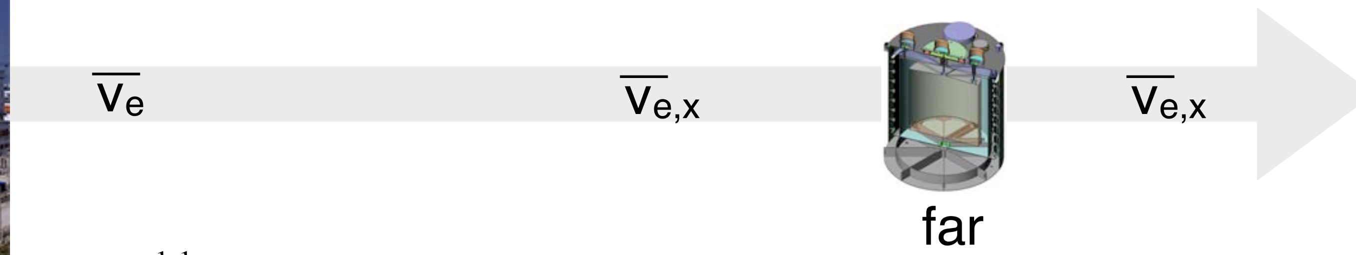


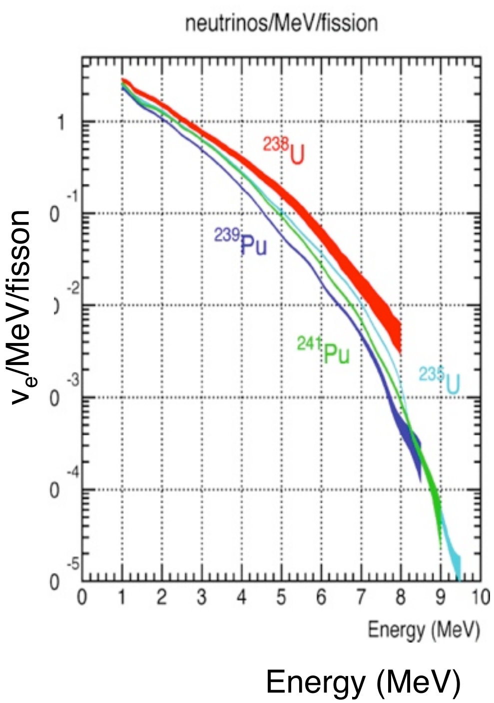
Experiments study flavor conversion as a function of energy, distance and determine mixing angle and mass splitting

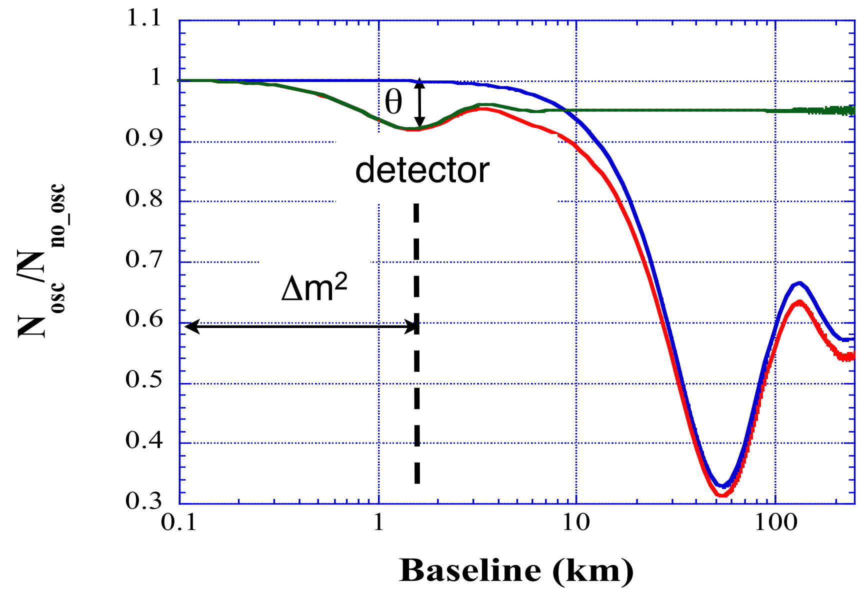
2-neutrino case, vacuum

$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

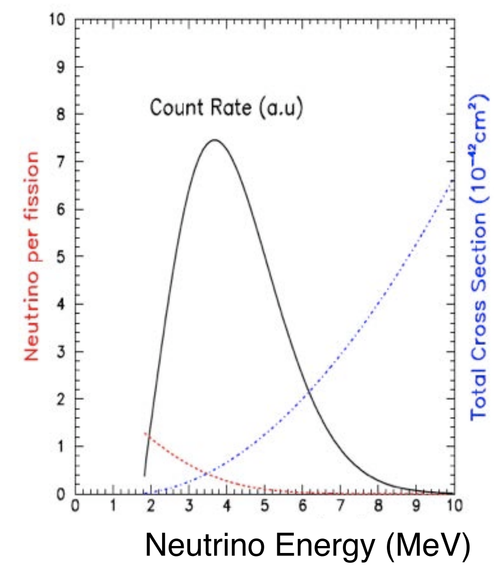
Reactor Neutrino Oscillation Experiments







$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{32}^2 L}{4E}$$



Oscillation Experiments with Reactors

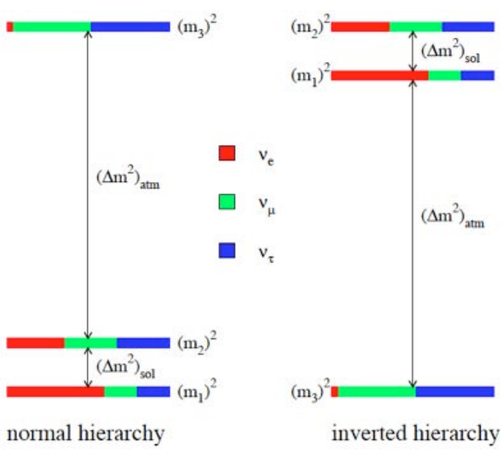
Measure (non)-1/r² behavior of $\overline{\nu}_e$ interaction rate

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

L/E → Δm^2

amplitude of oscillation → θ

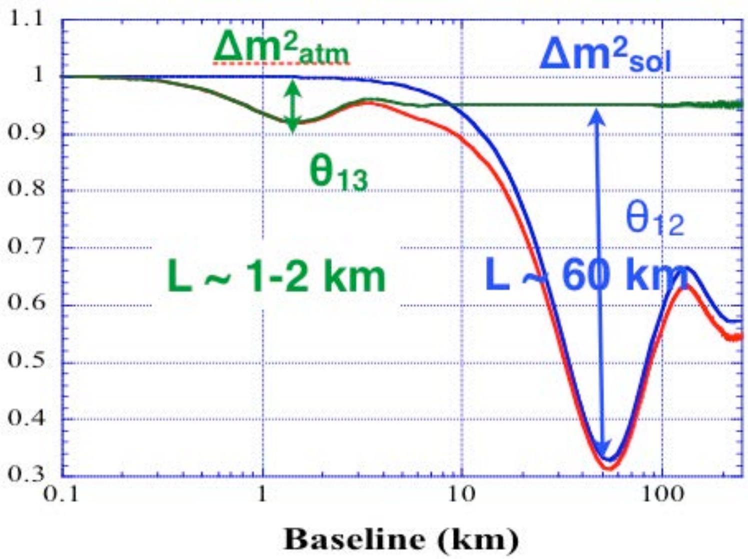
for 3 active ν, two different oscillation length scales: Δm^2_{12}, Δm^2_{23}



$\Delta m^2_{12} \sim 7.6 \times 10^{-5}\ \mathrm{eV}^2$

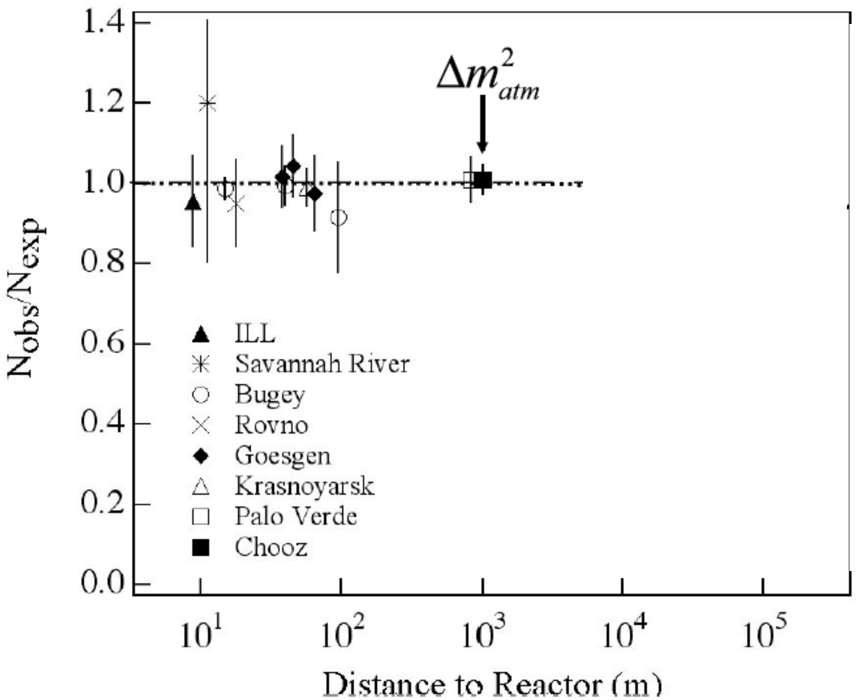
$\Delta m^2_{23} \sim 2.4 \times 10^{-3}\ \mathrm{eV}^2$

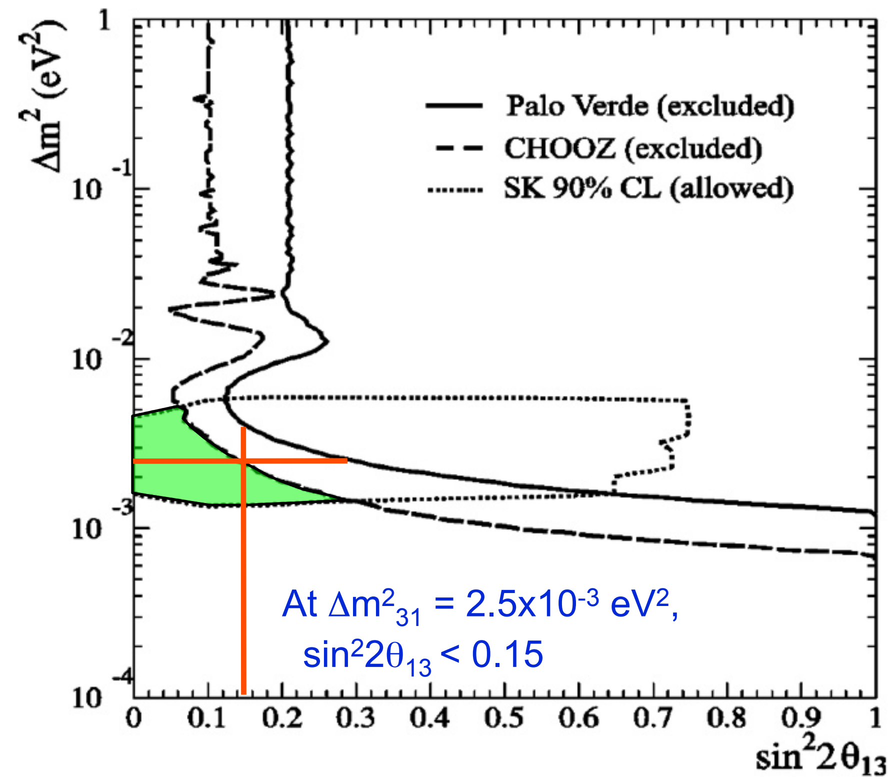
$\Delta m^2_{23} \approx \Delta m^2_{13}$



Search for Neutrino Oscillations at Reactors

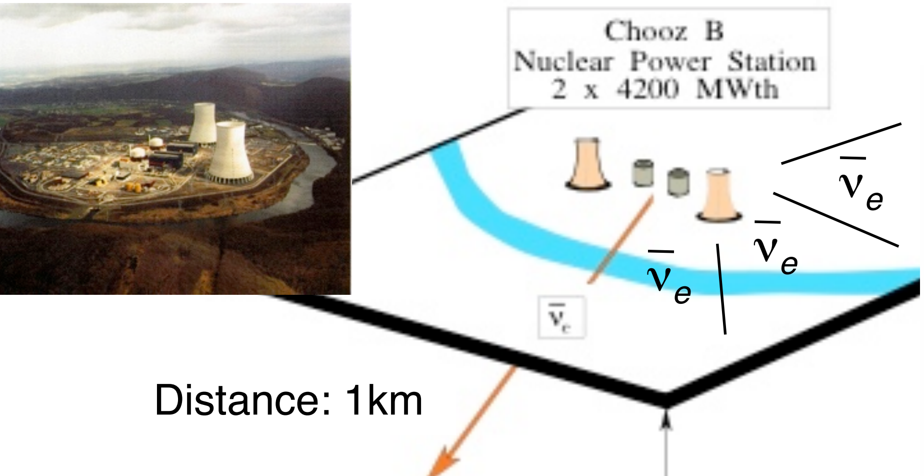
early experiments tried to probe "atmospheric neutrino anomaly"
early oscillation experiments didn't know the length scales involved



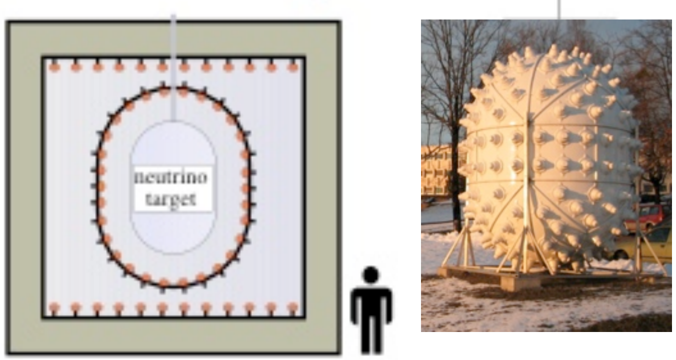


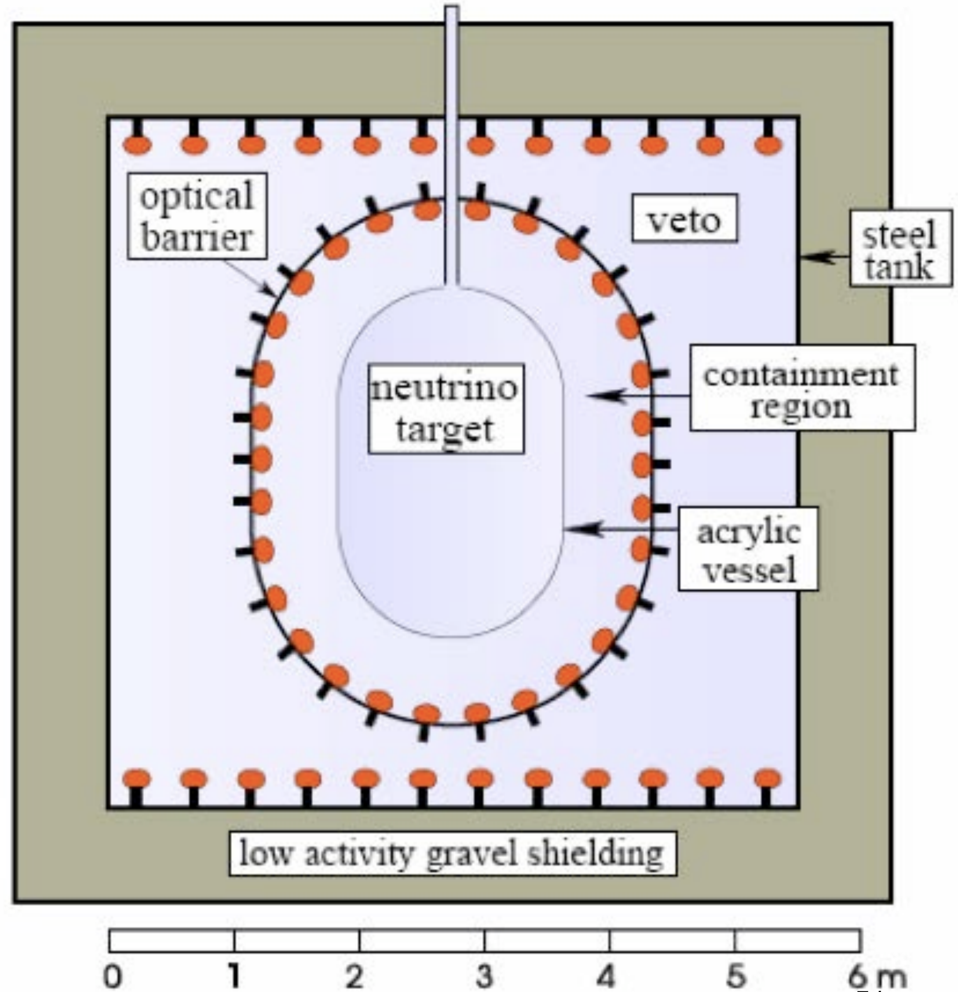
Neutrino Oscillation Search with Reactor Antineutrinos

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



Distance: 1km





Absolute measurement with 1 detector

detector size: several tons

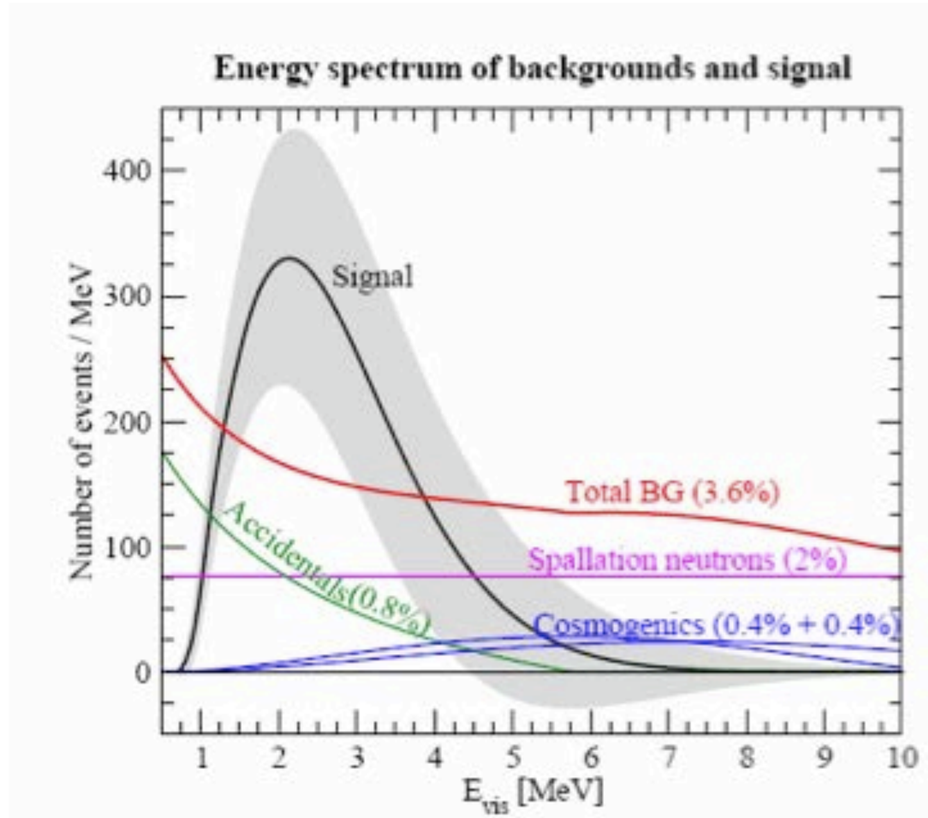
Backgrounds for Reactor Experiments

- 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)

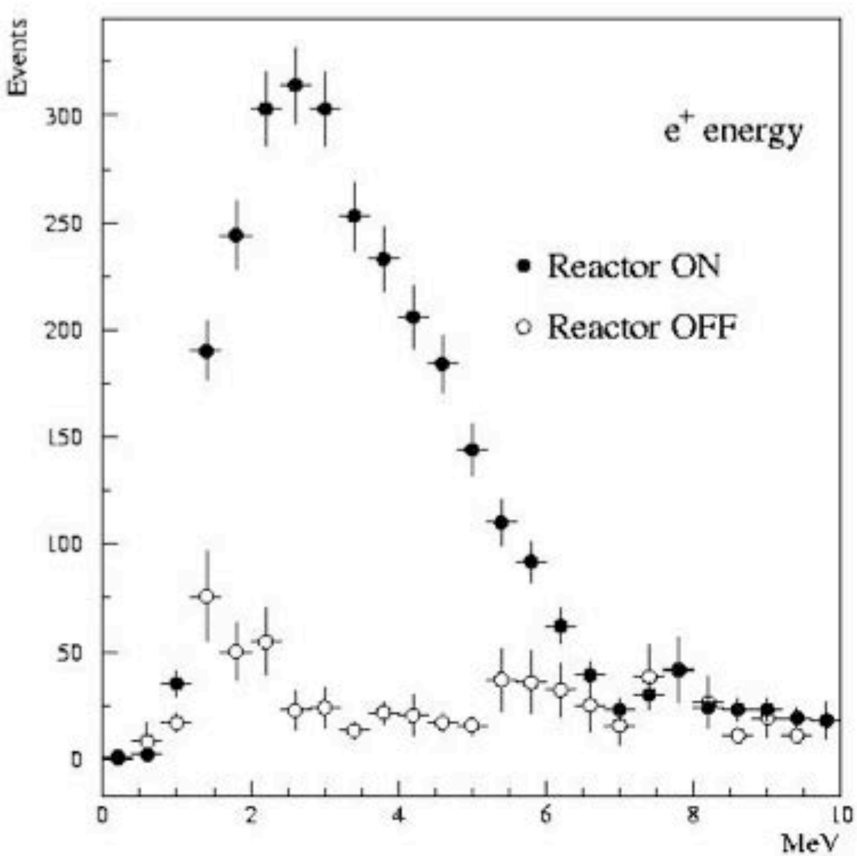


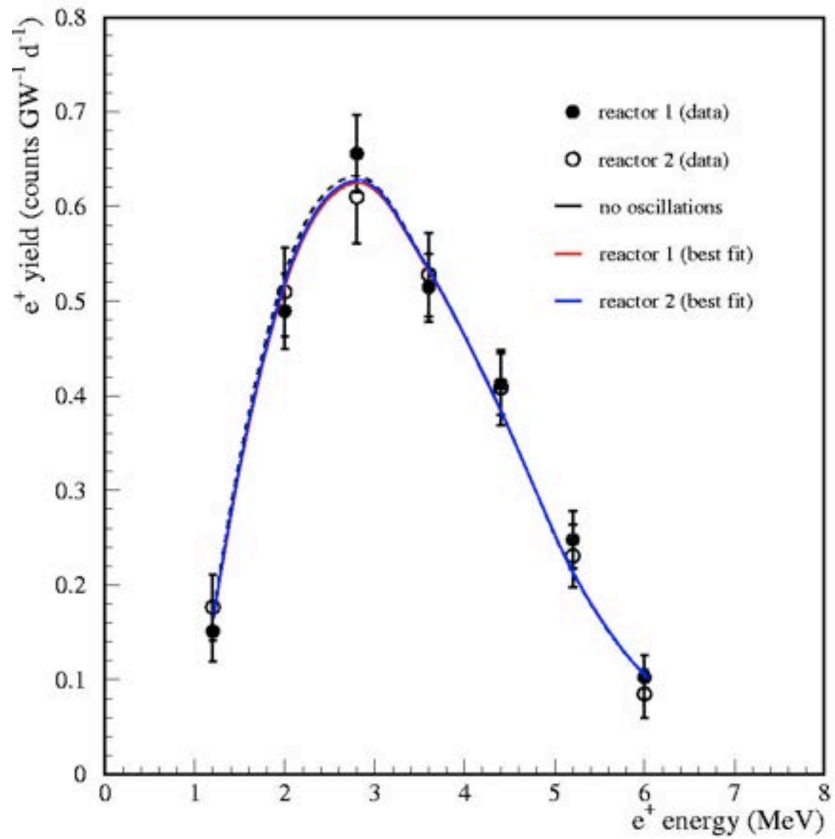
from M. Shaevitz

Chooz: Positron Spectrum

Reactor On/Off

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





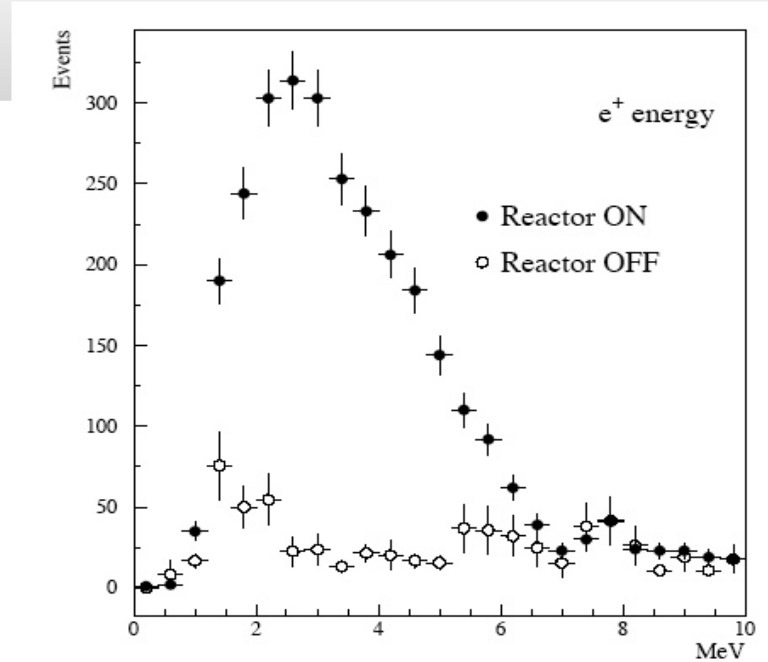
Chooz: Results

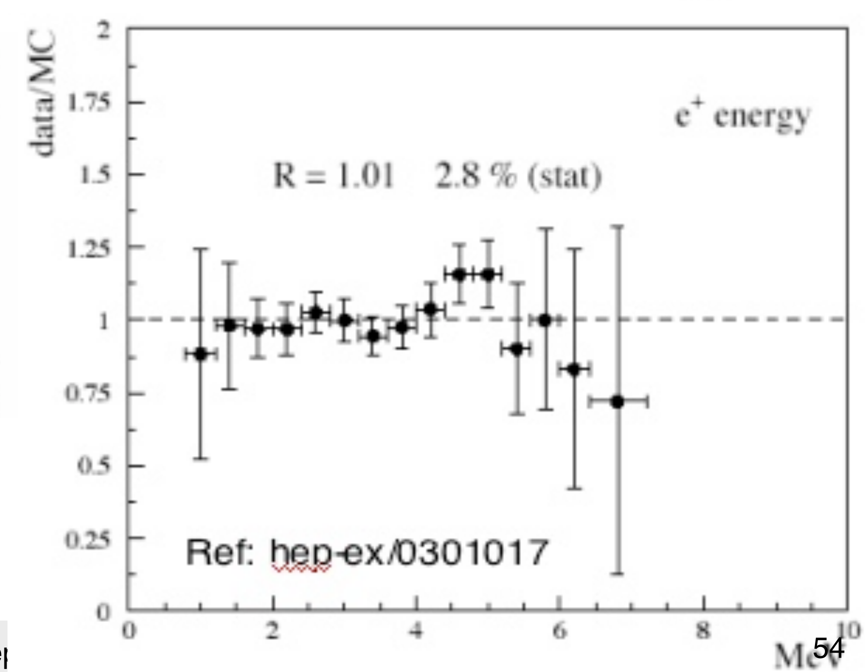
~3600 events in 335 days

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

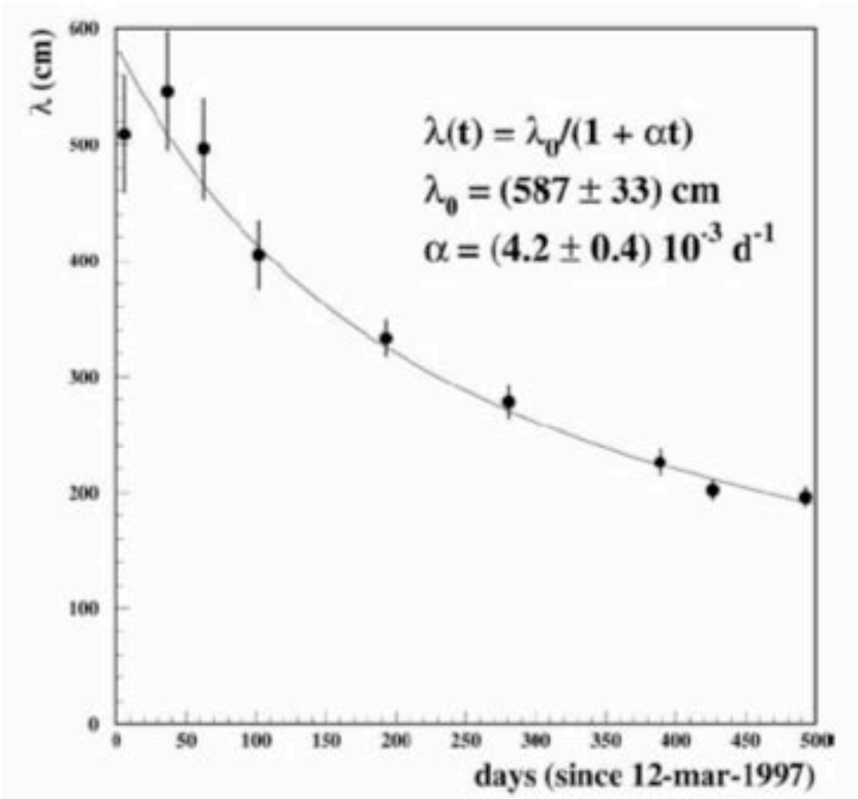
2.7% uncertainty

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%



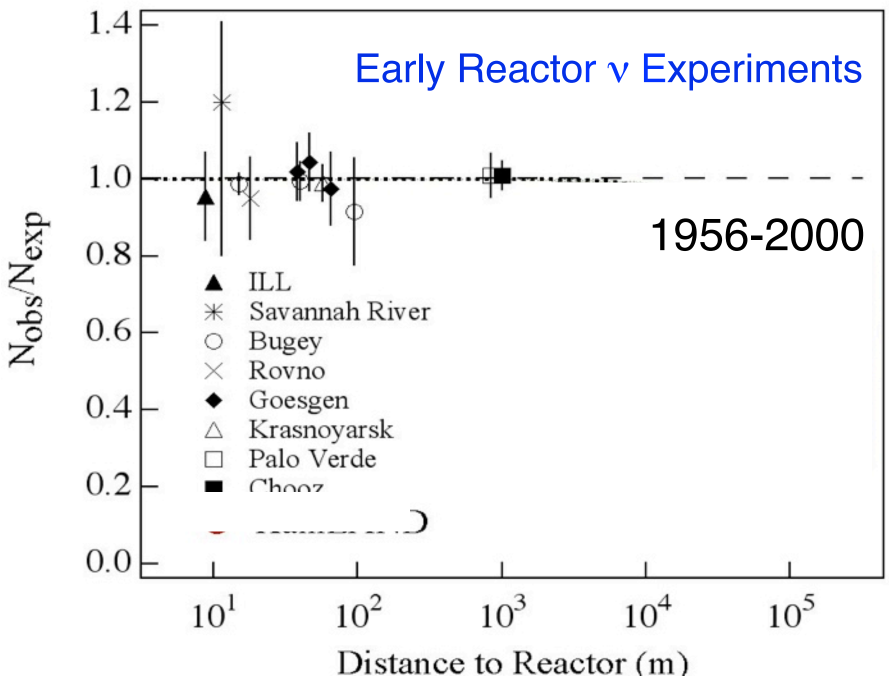


Chooz: Degradation of Scintillator

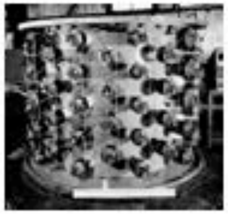


Attenuation degrades by ~0.4% per day.

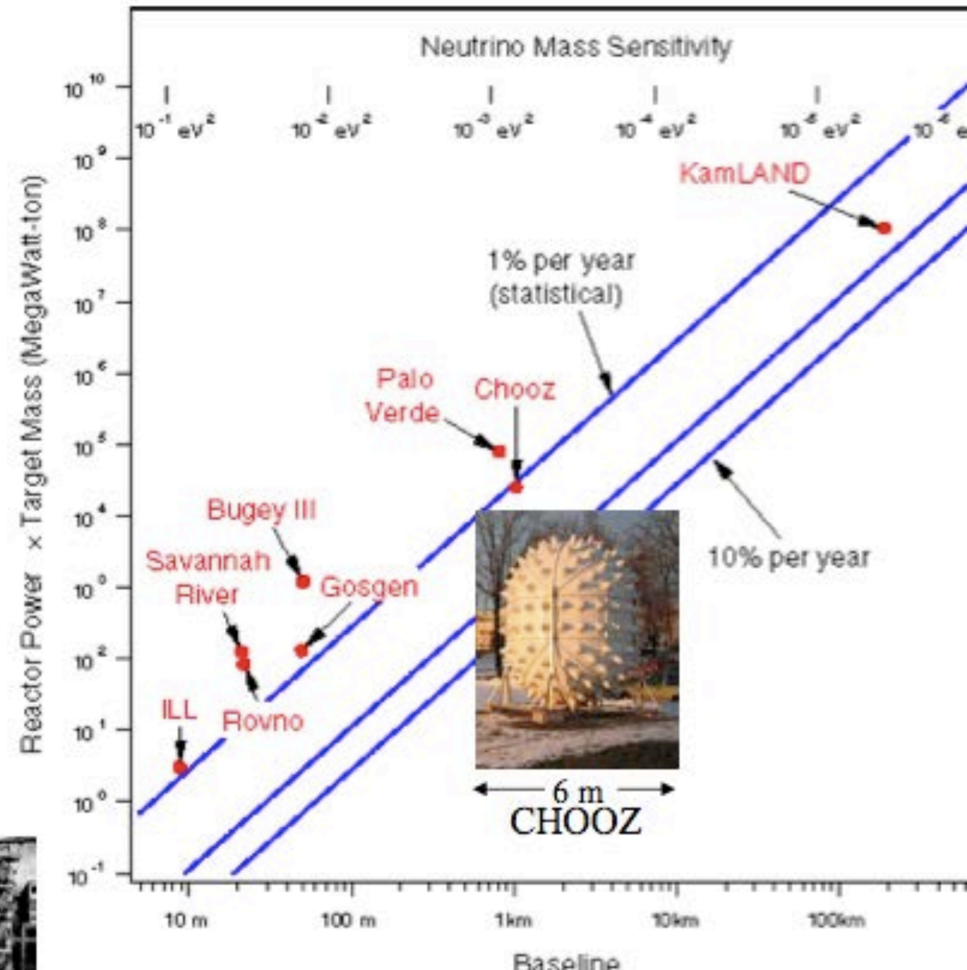
Reactor $\bar{\nu}_e$ Flux Measurements at Different Distances



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

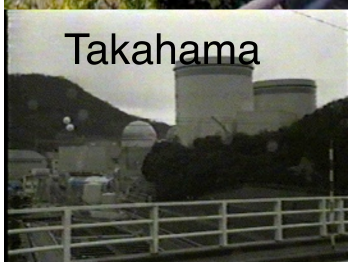


1m
Poltergeist



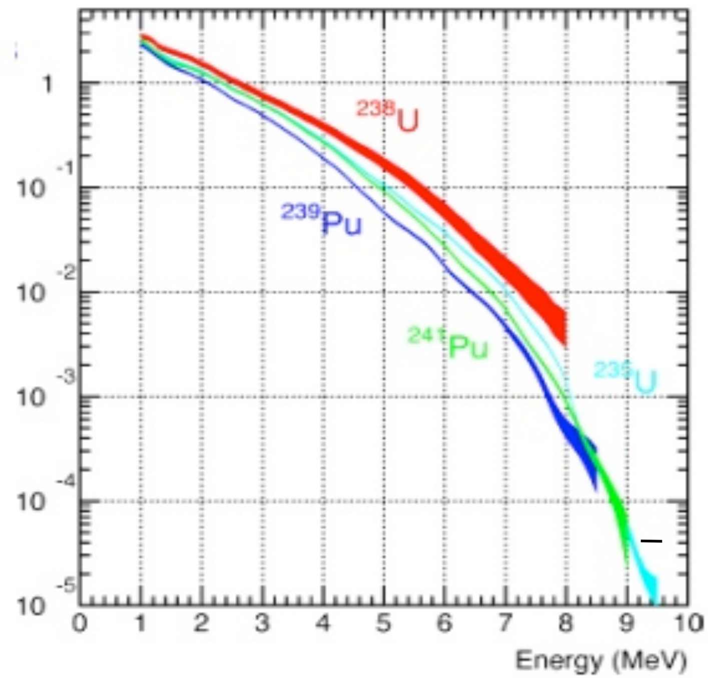
Reactor Antineutrinos in Japan

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 $10^6/cm^2/sec$

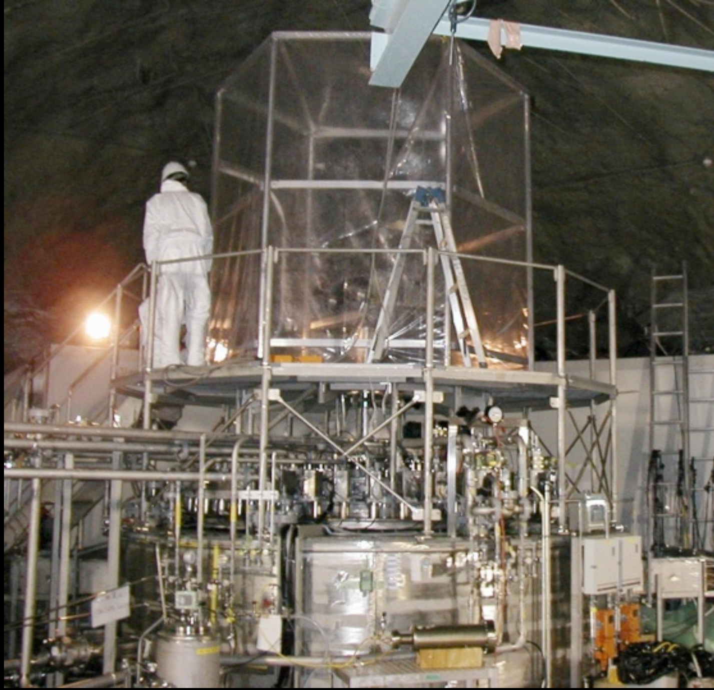
KamLAND Antineutrino Detector

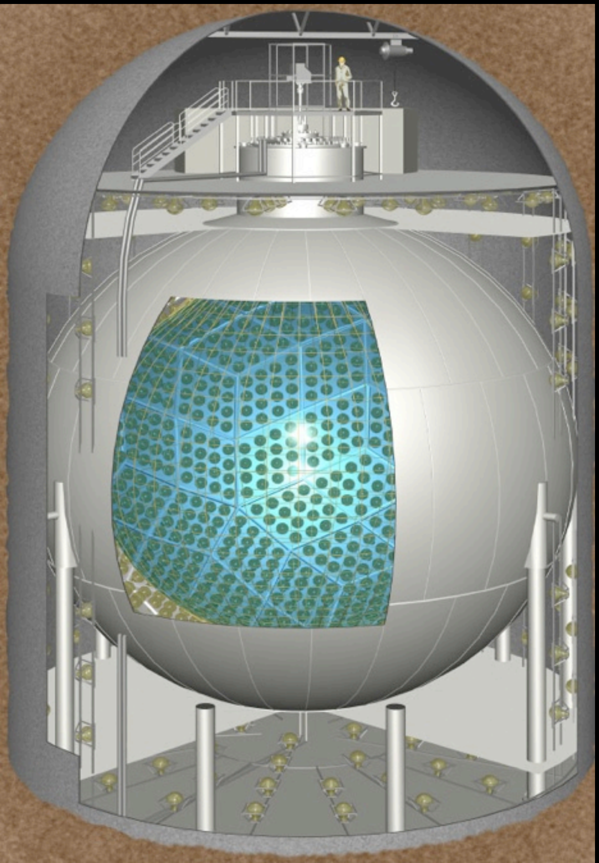
$\overline{\nu}_e + p \rightarrow e^+ + n$

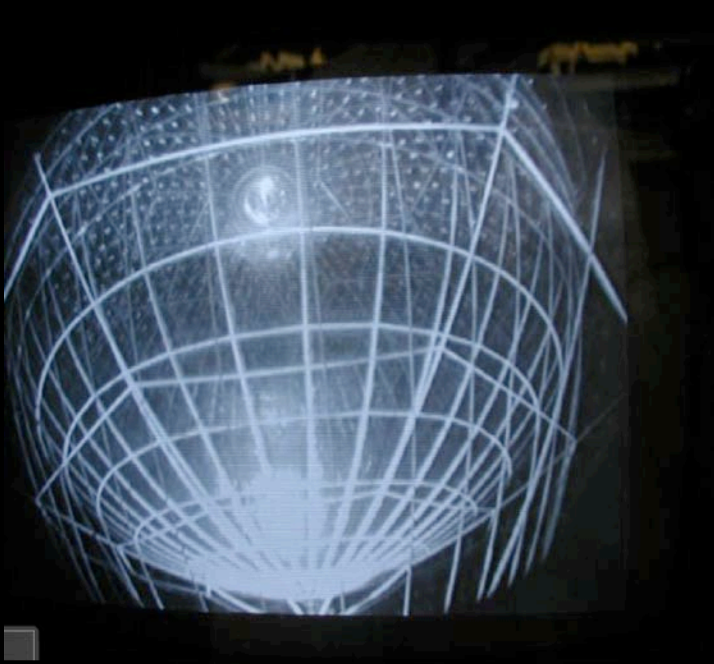
$$E_{\overline{\nu}_e} \simeq E_p + \overline{E}_n + 0.8\,\mathrm{MeV},$$

through inverse β-decay

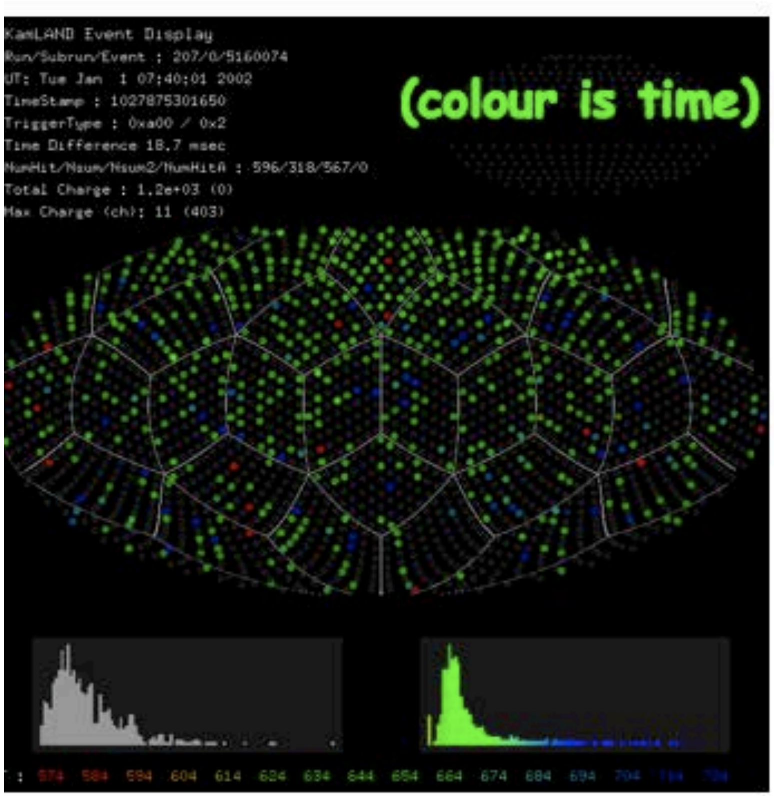
liquid scintillator target:
- proton rich > 10^{31} protons
- good light yield

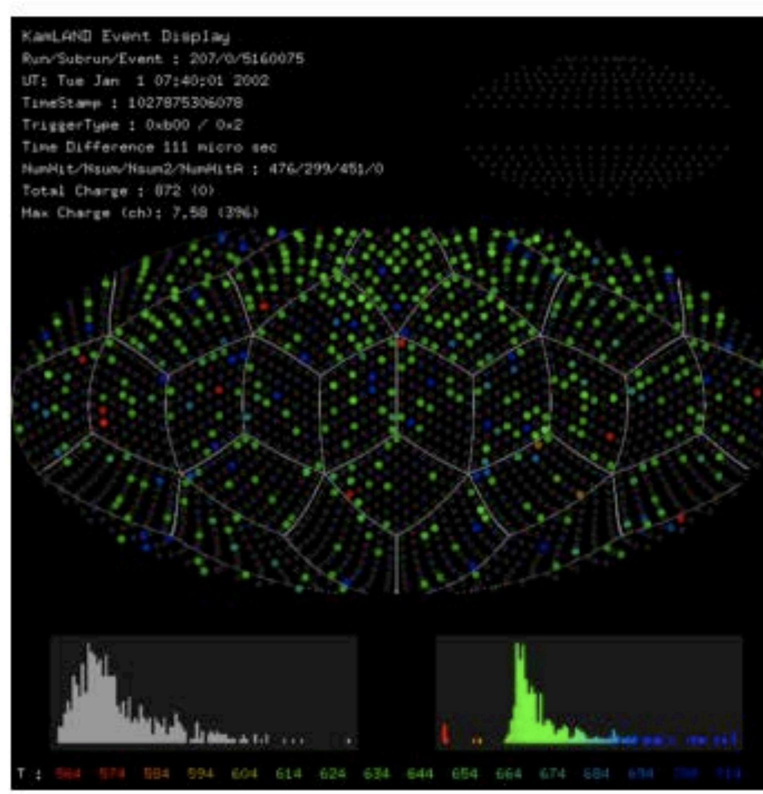






Antineutrino Candidate Event





Prompt Signal
E = 3.20 MeV

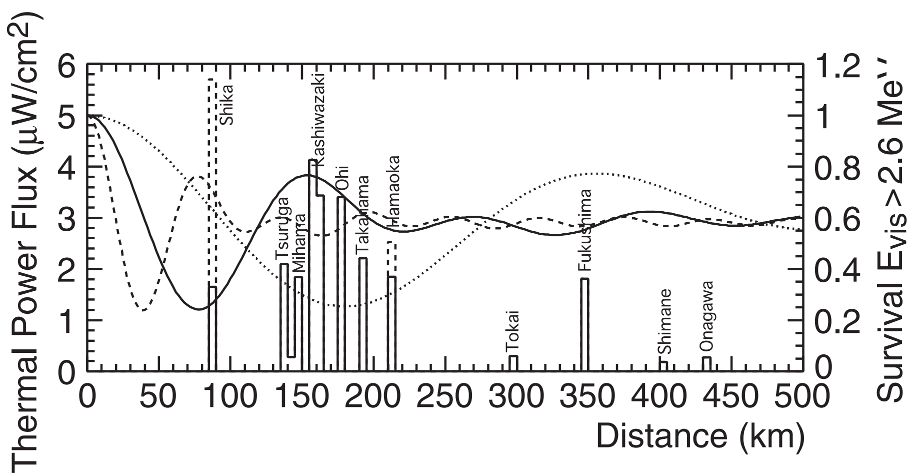
$\Delta t = 111$ ms
$\Delta R = 34$ cm

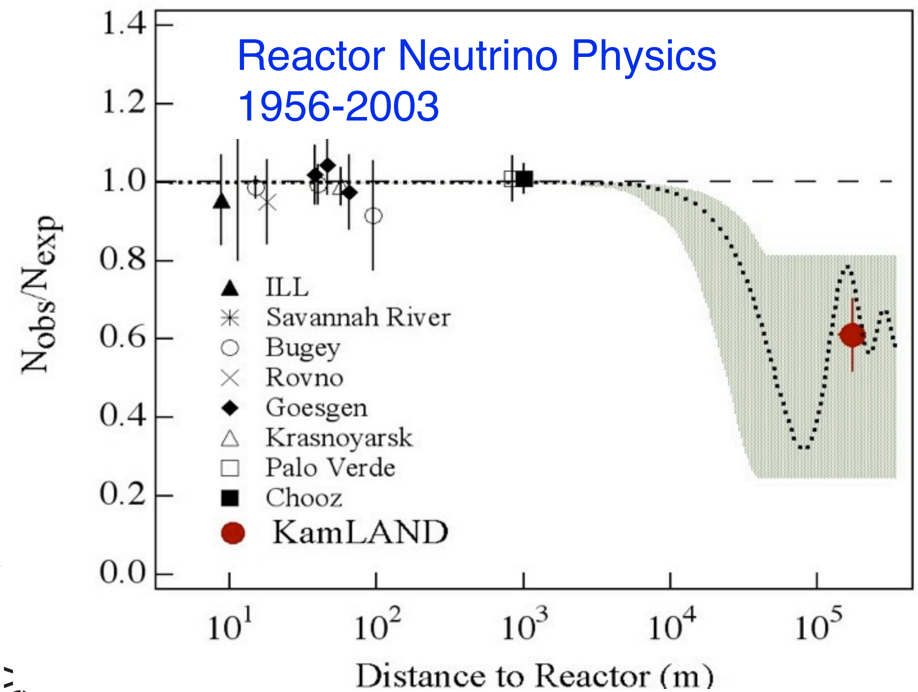
Delayed Signal
E = 2.22 MeV

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

KamLAND 2003

mean, flux-weighted reactor distance ~ 180km



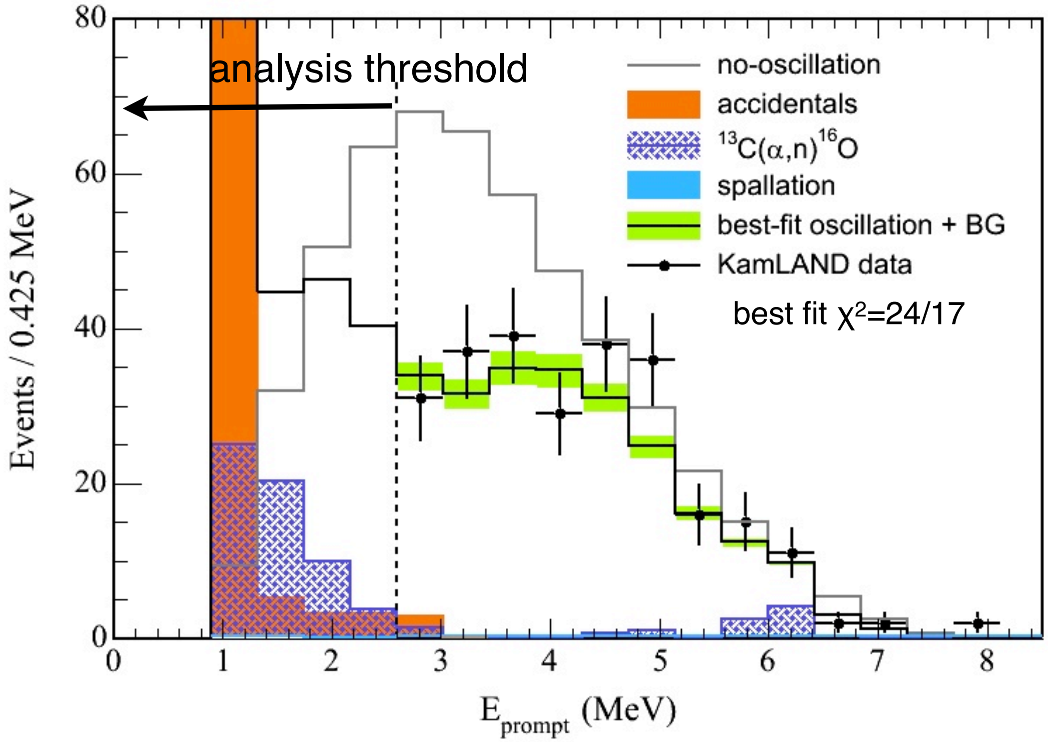


Observed $\overline{\nu}_e$	54 events
No-Oscillation events	86.8 ± 5.6
Background	1 ± 1 events
Livetime:	162.1 ton-yr

PRL 90:021802 (2003)

Evidence of Spectral Distortion

KamLAND 2004



Observed $\overline{\nu}_e$	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%

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

$\hookrightarrow {}^{13}C(\alpha,n){}^{16}O$ (~10^{-7})

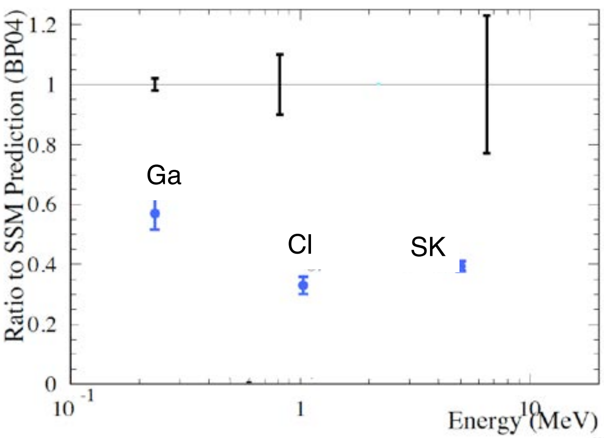
^{222}Rn decay chain introduced in the LS during assembly

Spectral Distortions: A unique signature of neutrino oscillation!

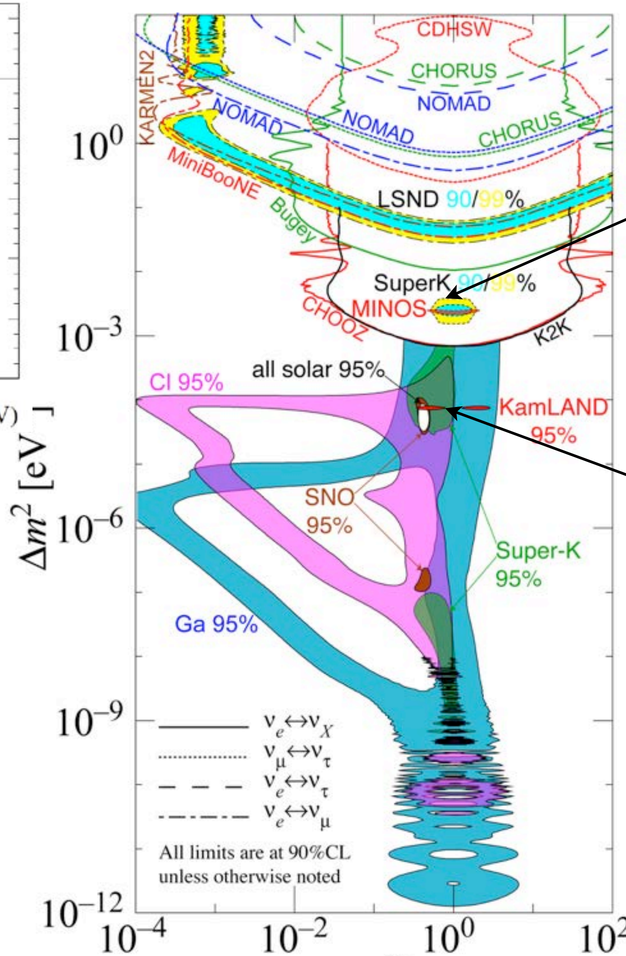
Simple, rescaled reactor spectrum is excluded at 99.6% CL(χ^2=37.3/18)

Measuring Neutrino Oscillation Parameters

solar neutrino problem



oscillation searches



atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

θ_{12}, Δm^2_{12}

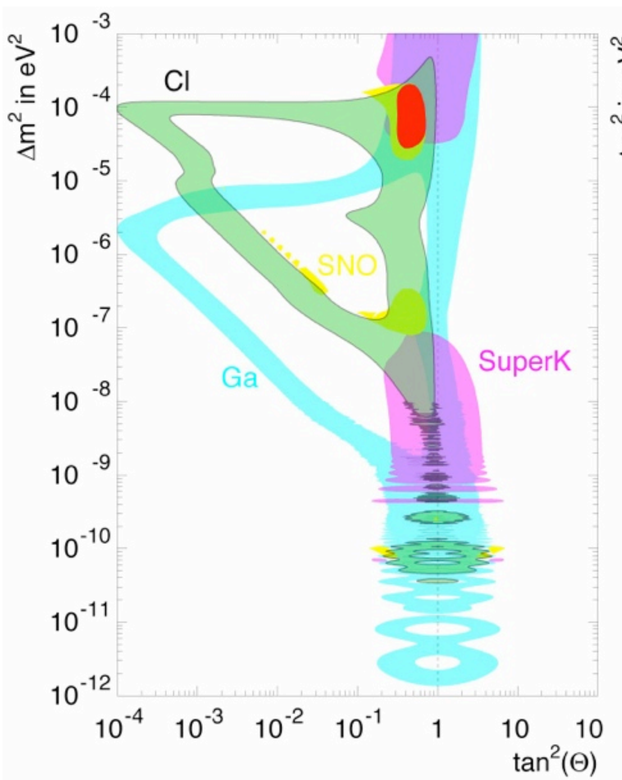
1960-1990

1990-2000

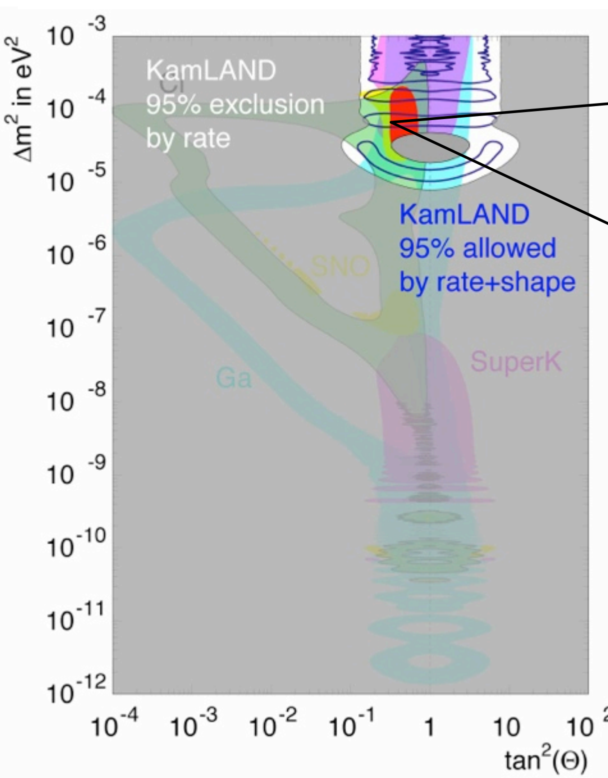
2000 - Present

Measuring Neutrino Oscillation Parameters

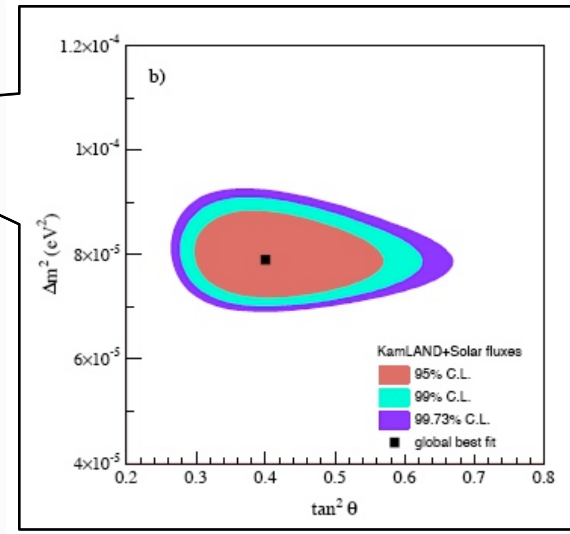
Solar Neutrinos



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

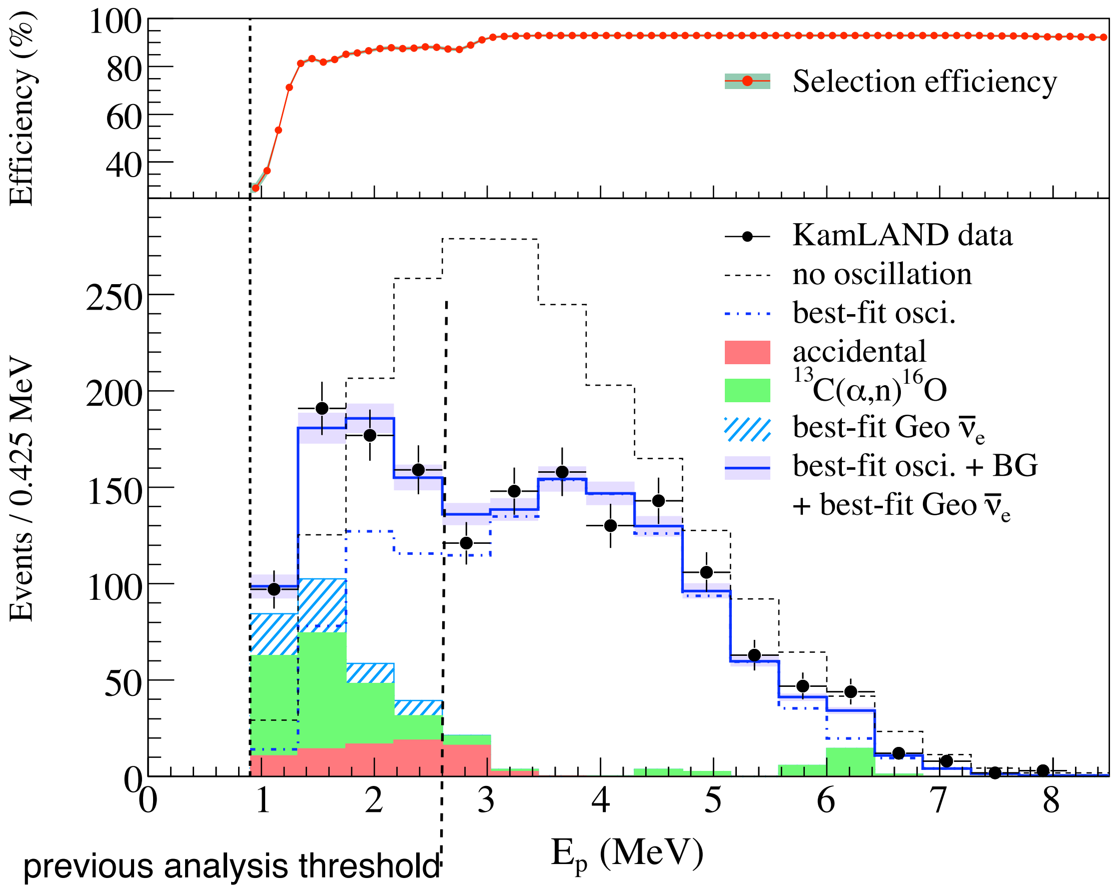
Beginning of precision neutrino physics

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

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.

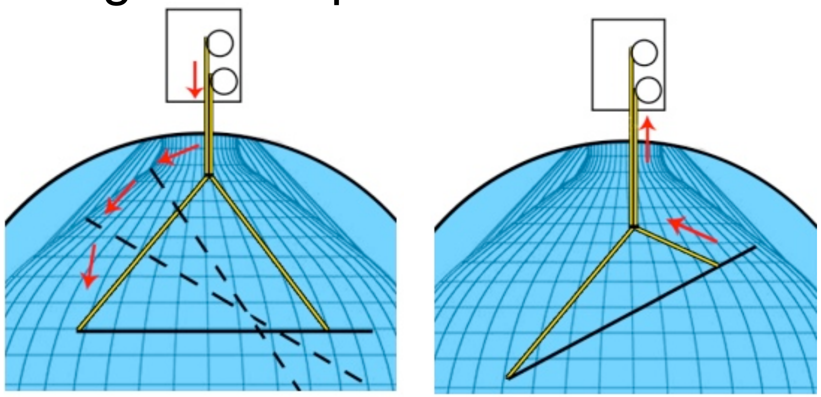
Background	Contribution
Accidentals	80.5 ± 0.1
^{9}Li/^{8}He	13.6 ± 1.0
Fast neutron & Atmospheric ν	<9.0
^{13}C(α,n)^{16}O G.S.	157.2 ± 17.3
^{13}C(α,n)^{16}O ^{12}C(n,nγ)^{12}C (4.4 MeV γ)	6.1 ± 0.7
^{13}C(α,n)^{16}O 1st exc. state (6.05 MeV e^+e^-)	15.2 ± 3.5
^{13}C(α,n)^{16}O 2nd exc. state (6.13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

significantly reduced

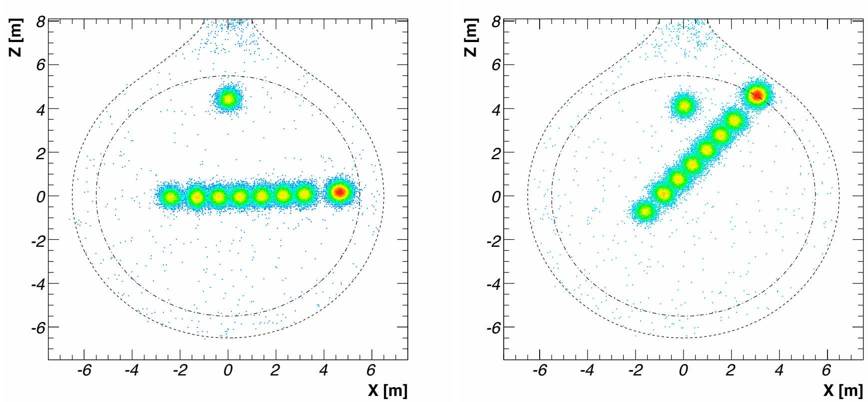
(number of events)

4π Full-Volume Calibration

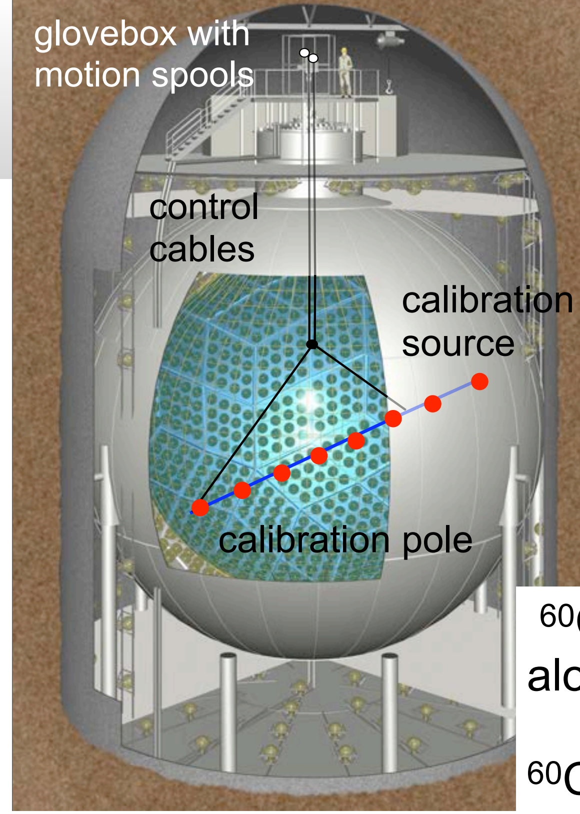
Design Concept



Calibration Data

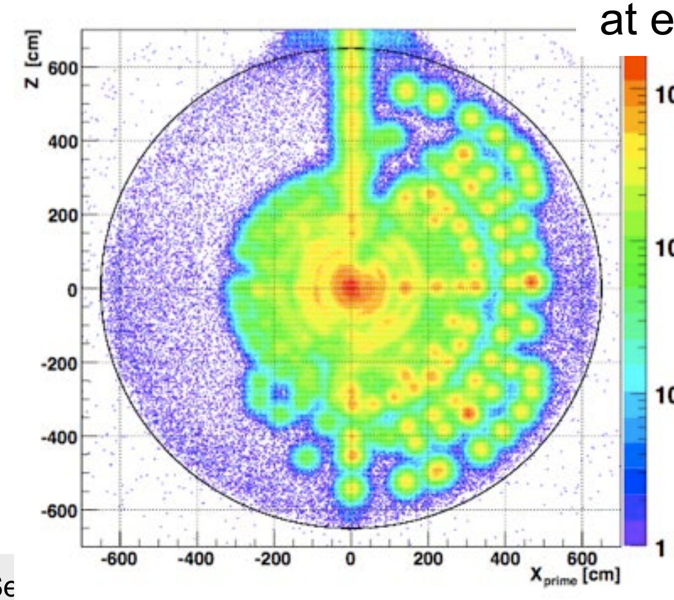


Vertex distribution of $^{60}Co/^{68}Ge$ composite source in 4π calibration runs.



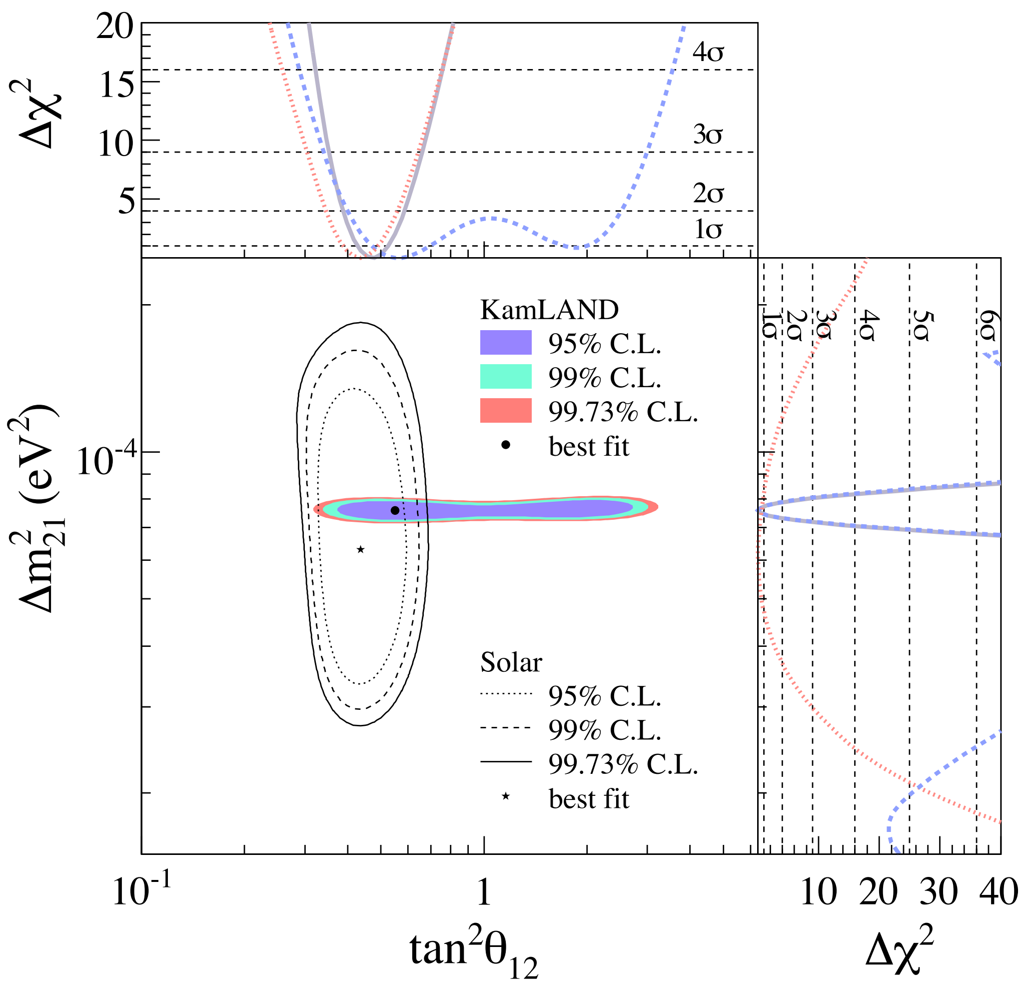
^{60}Co sources along pole

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



Oscillation Parameters

Rate-Shape-Time Analysis



KamLAND only

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

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

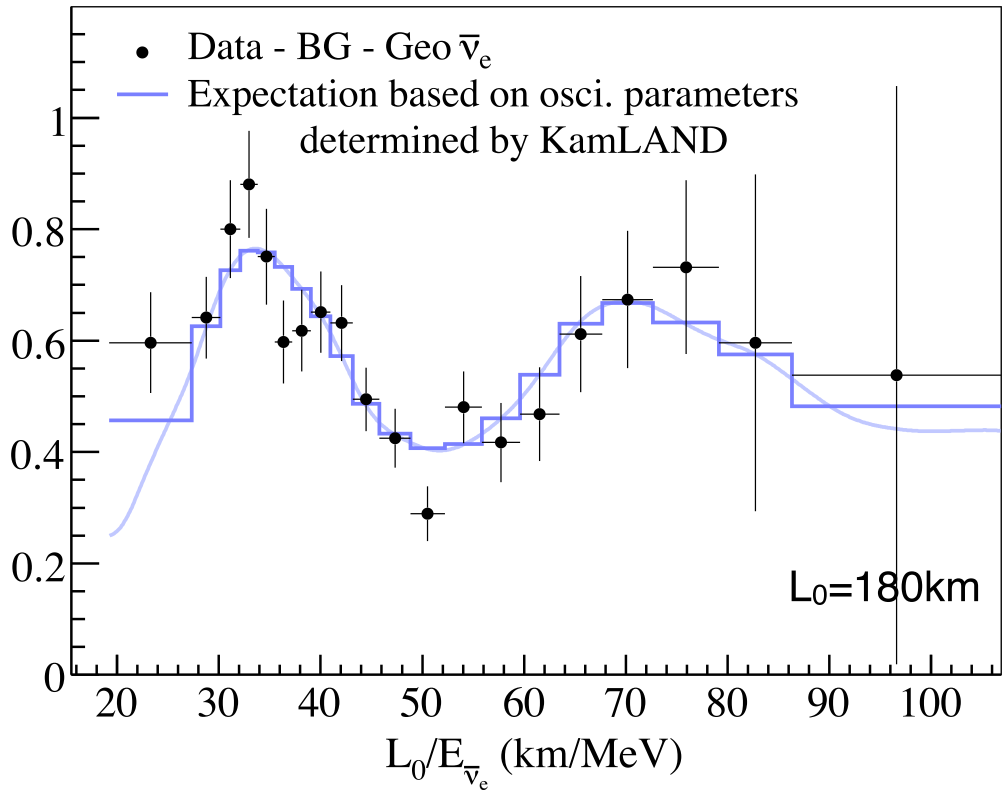
KamLAND+solar

(combined under assumption of CPT invariance)

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

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

KamLAND L/E Dependence



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

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

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

Solar neutrino problem solved!

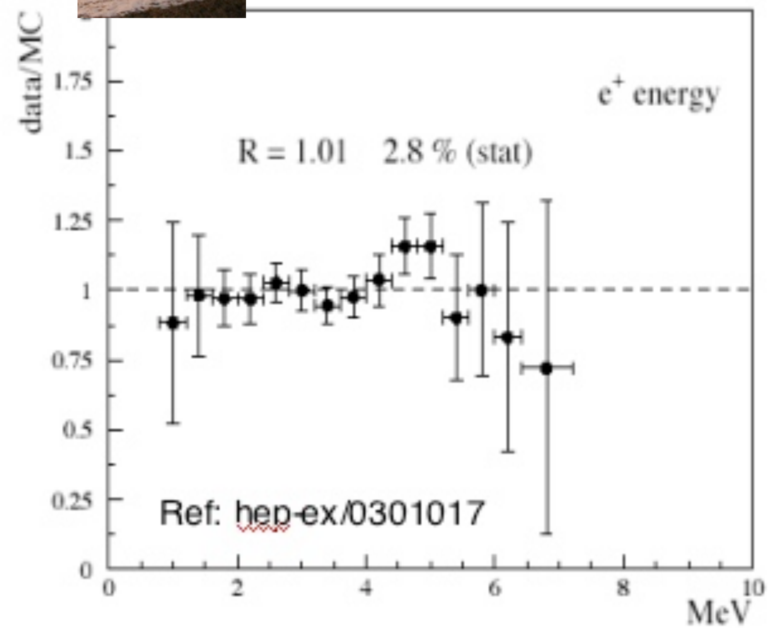
1970-1995 first identified by Ray Davis (missing solar ν_e)

2002-2007 SNO observes neutrino flavor change, finds evidence for neutrino mass

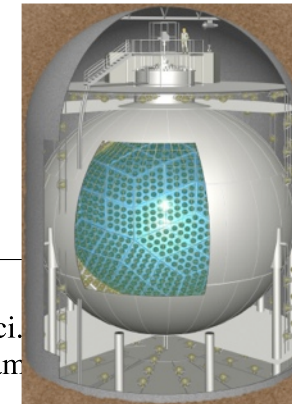
2003-2008 KamLAND demonstrates ν oscillation, precision measurement of θ, Δm^2

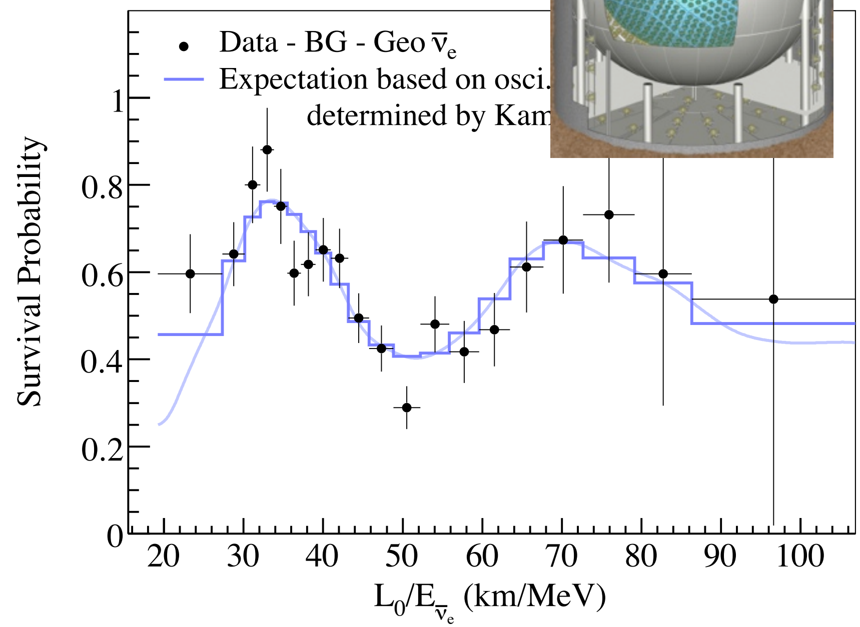
Pathway Towards Discovery

baseline: 1 km
size: 5 ton



180 km
1000 ton

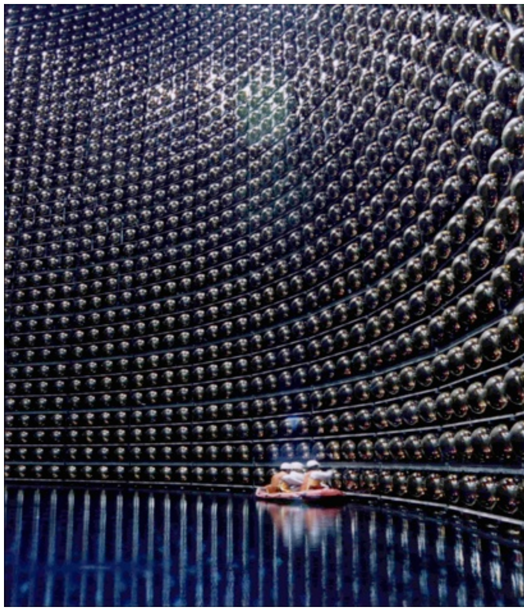




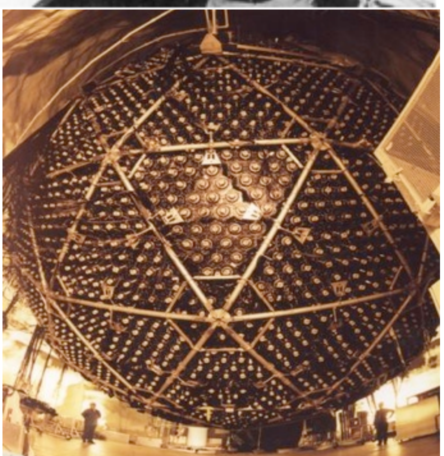
- Take big steps
- Don't always trust "theoretical" guidance
- A little bit of luck

Neutrino Discoveries - A Success Story

1968 Ray Davis detects 1/3 of expected solar neutrinos.
(Nobel prize in 2002)



1998 SuperK reports evidence for oscillation of atmospheric neutrinos.



2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor $\bar{\nu}_e$

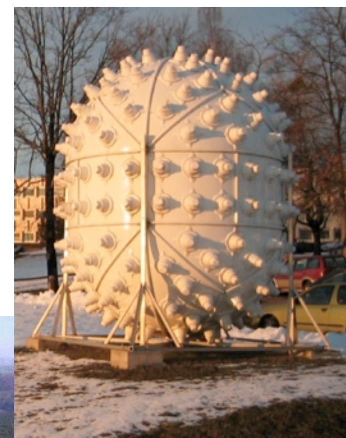
55 years of liquid scintillator detectors
A story of varying baselines...

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

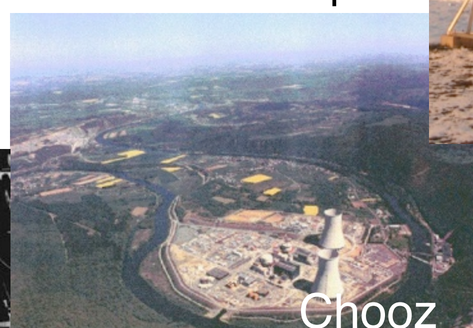
2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

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



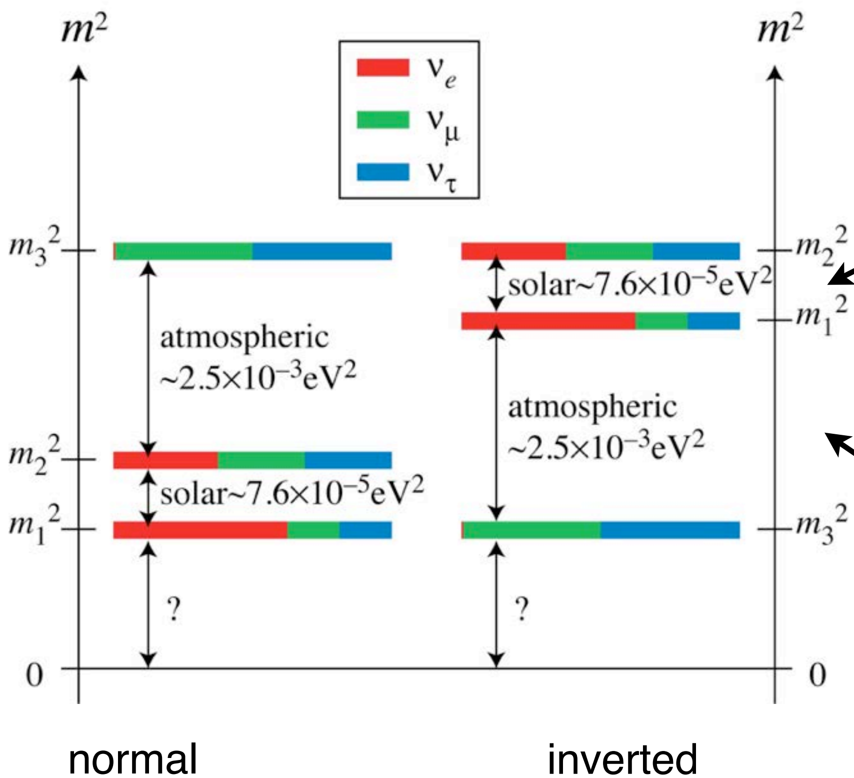
1956 - First observation of (anti)neutrinos



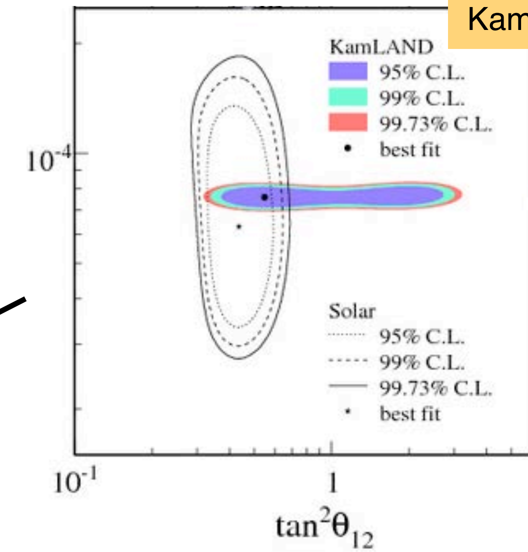
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

Measurement of Fundamental Parameters

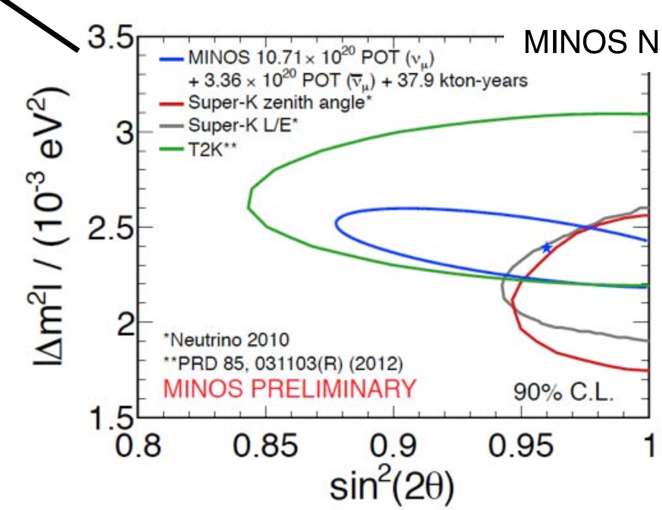
Mass Splittings



KamLAND 2010



MINOS Nu2012



KamLAND has measured Δm_{12}^2 to ~2.8%

Neutrino Oscillation

Mixing Angles

$$P_{i\to i} = \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L}{E}\right)$$

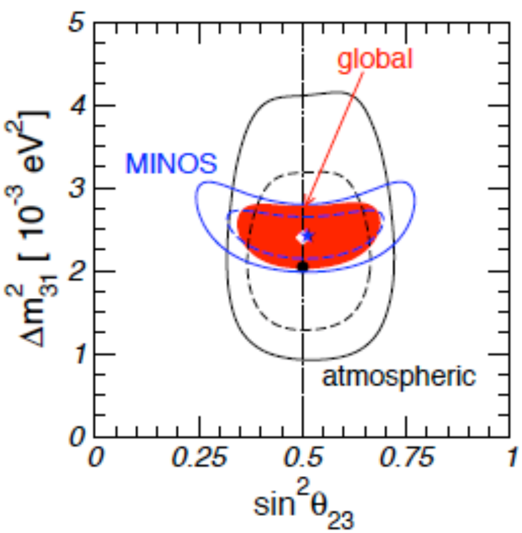
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

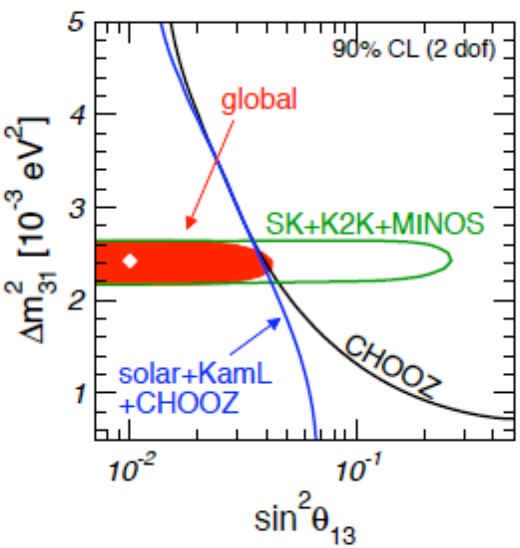
U_{MNSP} Matrix

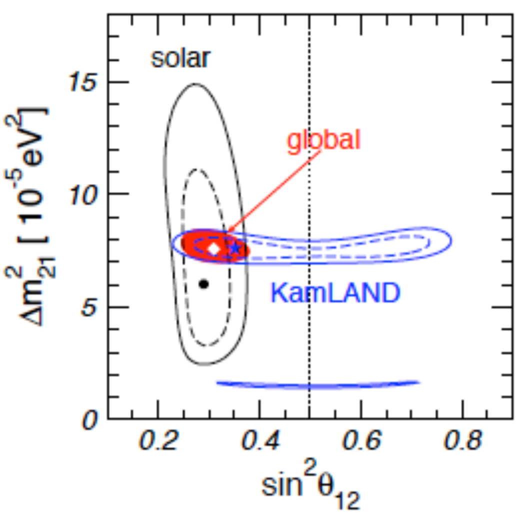
Maki, Nakagawa, Sakata, Pontecorvo

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

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

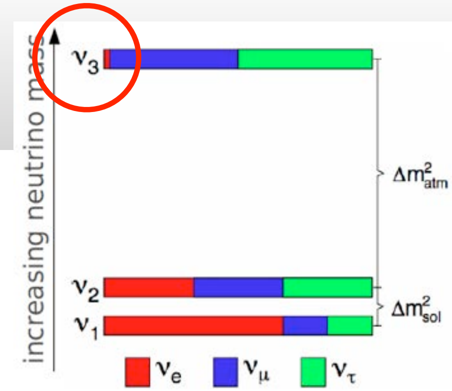






Schwetz et al
arXiv:0808.2016
updated as of 2010

Neutrino Oscillation - Before 2011



Mixing Angles

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atmospheric, K2K | reactor and accelerator | SNO, solar SK, KamLAND | 0νββ

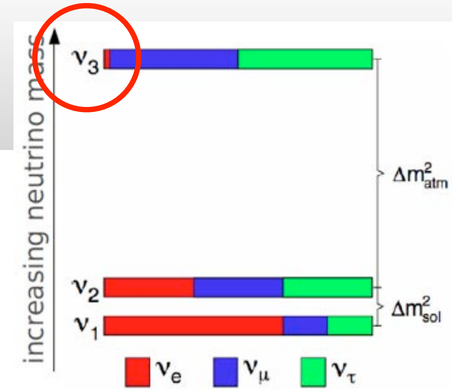
$\sin^2\theta_{23}$ | $\sin^2\theta_{13}$ | $\sin^2\theta_{12}$

$0.50^{+0.07}_{-0.06}$ | small? zero? | $0.318^{+0.019}_{-0.016}$

maximal?

large, but not maximal!

Neutrino Oscillation - Before 2011



Mixing Angles

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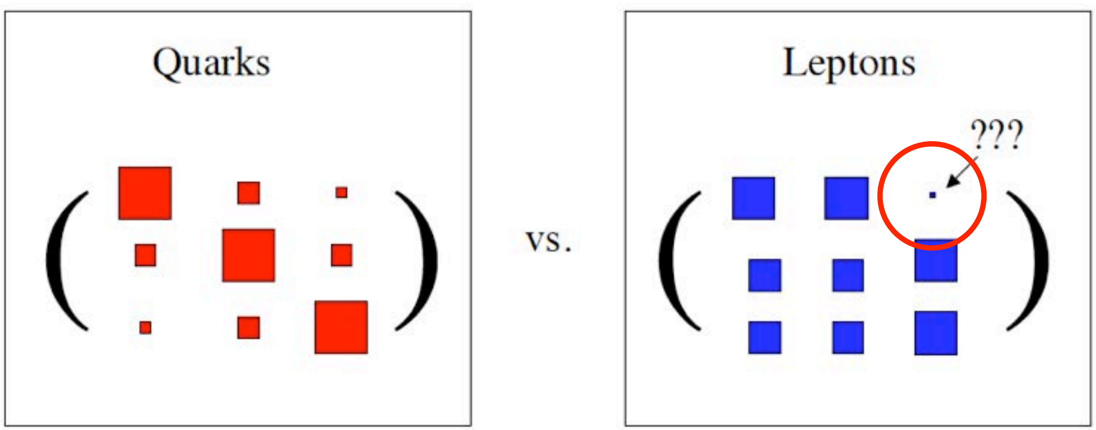
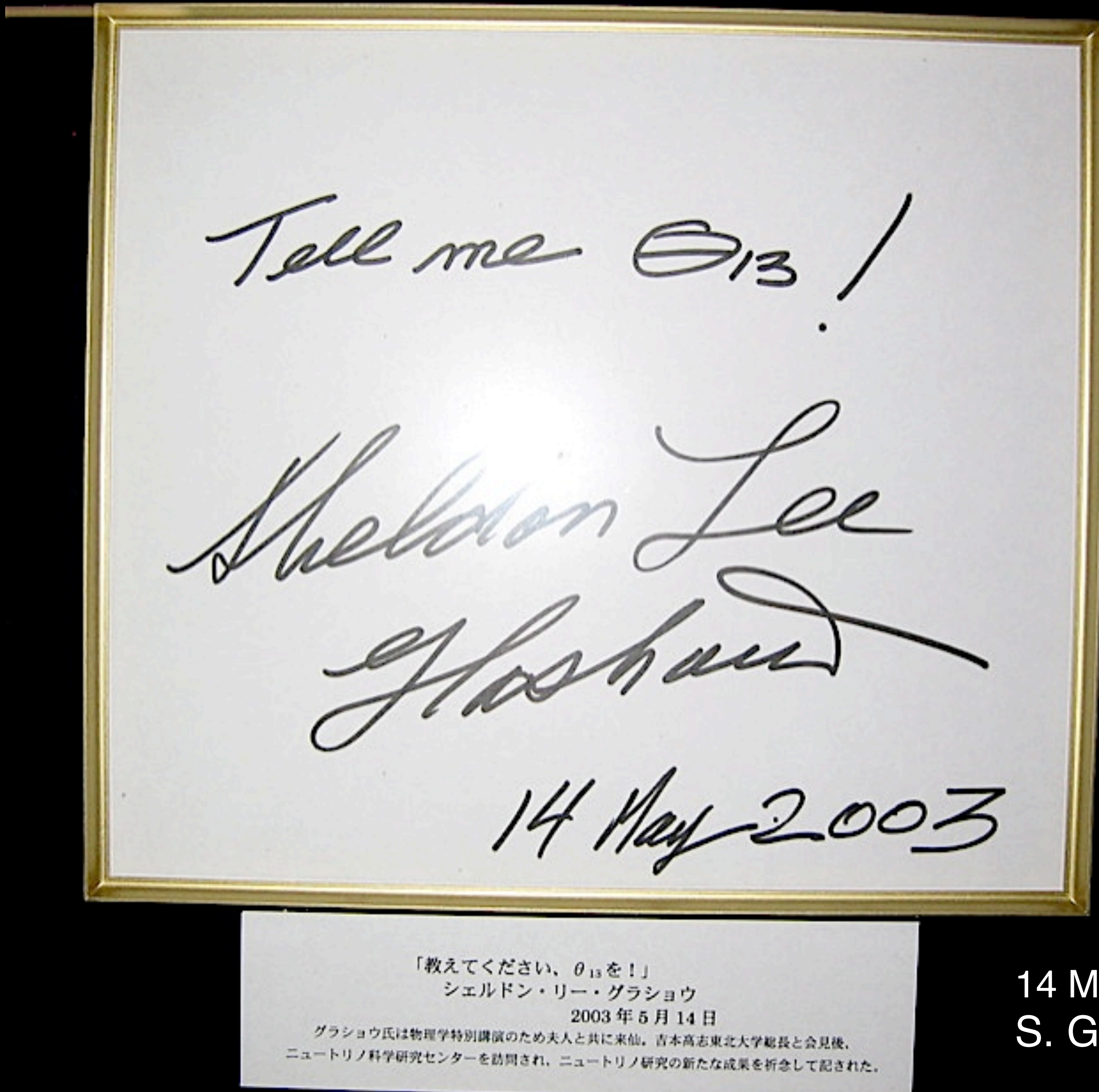
atmospheric, K2K — reactor and accelerator — SNO, solar SK, KamLAND — $0\nu\beta\beta$





14 May 2003
S. Glashow