Reactor Neutrino Experiments - Lecture I

- The First 50 Years: From the Discovery of the Antineutrino to the First Observation of Antineutrino Disappearance -

Karsten M. Heeger

University of Wisconsin

http://neutrino.physics.wisc.edu

Outline

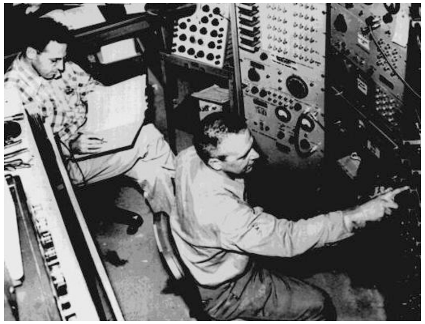
Lecture I - The First 50 Years: From The Discovery of the Antineutrino to the First Observation of Antineutrino Disappearance

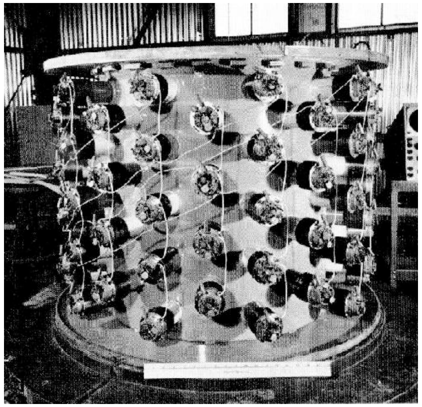
- Discovery of the Free Antineutrino
- The Reactor as an Antineutrino Source
- Detection of Antineutrinos
- Search for Neutrino Oscillation with Reactor Antineutrinos
- Observation of Reactor Antineutrino Disappearance at KamLAND
- Other Reactor Neutrino Experiments

Lecture II - Precision Oscillation Physics with Reactor Antineutrinos

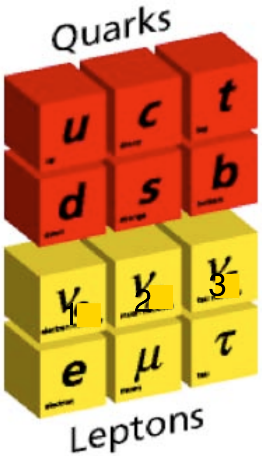
- Precision Measurement of Δm_{12}^2 at KamLAND
- Evidence for Oscillation of Reactor Antineutrinos at KamLAND
- Search for the Unknown Neutrino Mixing angle θ_{13}
- Future Opportunities: Precision Measurement of θ_{12}
- Applied Neutrino Physics: Reactor Monitoring with Antineutrinos

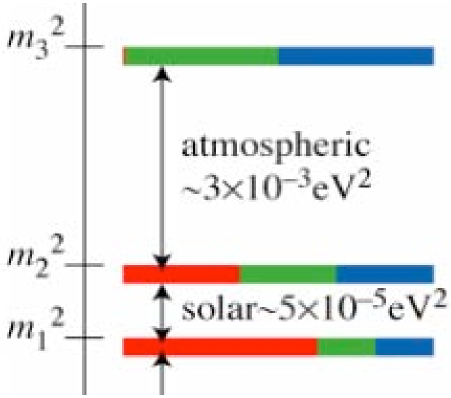
1956

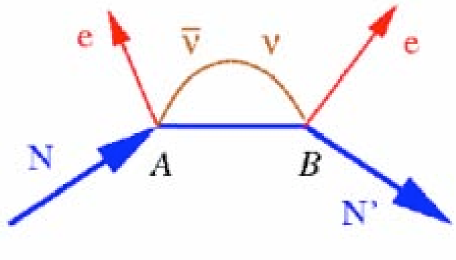


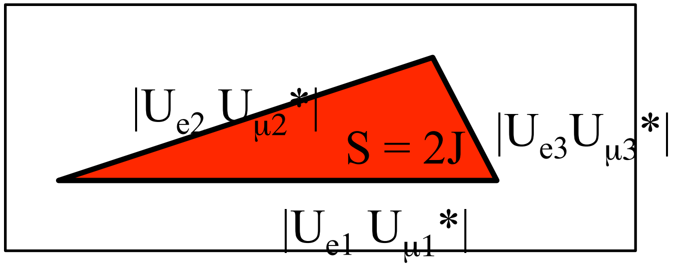


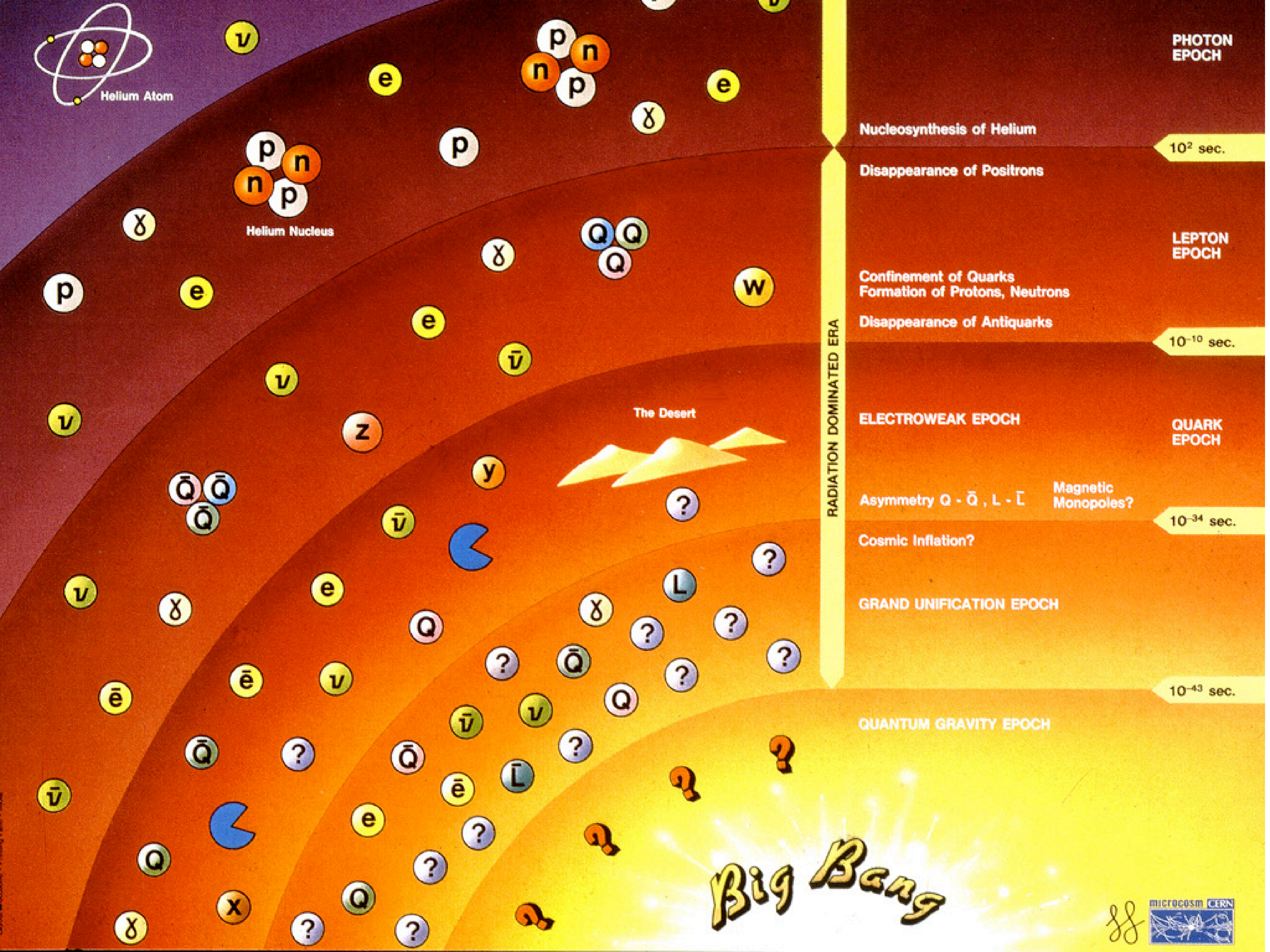
2006


Quarks
u
c
t
d
s
b
ν
1
ν
2
ν
3
e
μ
τ
Leptons


m_3^2
atmospheric
~3×10^{-3}eV^2
m_2^2
solar~5×10^{-5}eV^2
m_1^2


e
$\bar{\nu}$
ν
e
N
A
B
N'


$|U_{e2}\ U_{\mu2}{}^*|$
S = 2J
$|U_{e3}U_{\mu3}{}^*|$
$|U_{e1}\ U_{\mu1}{}^*|$



PHOTON EPOCH

Nucleosynthesis of Helium

10^{2} sec.

Disappearance of Positrons

LEPTON EPOCH

Confinement of Quarks
Formation of Protons, Neutrons

Disappearance of Antiquarks

10^{-10} sec.

ELECTROWEAK EPOCH

QUARK EPOCH

Asymmetry $Q - \bar{Q}$, $L - \bar{L}$

Magnetic Monopoles?

10^{-34} sec.

Cosmic Inflation?

GRAND UNIFICATION EPOCH

10^{-43} sec.

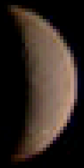
QUANTUM GRAVITY EPOCH

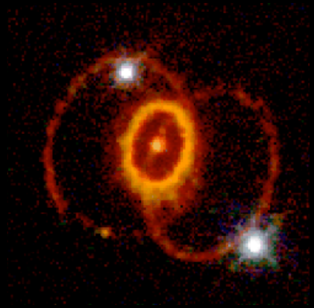
RADIATION DOMINATED ERA

Neutrinos from the Big Bang

~330 neutrinos per cm^3

0.5 proton per cm^3





Supernova Neutrinos

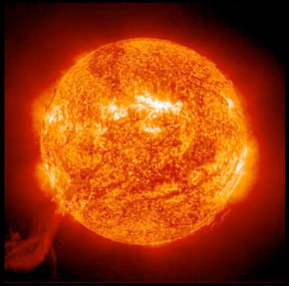
Atmospheric Neutrinos

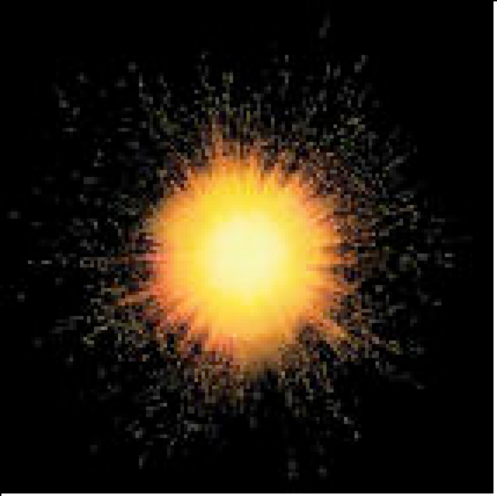
High Energy Cosmic Neutrinos

Geo Neutrinos

Accelerator&Reactor Neutrinos

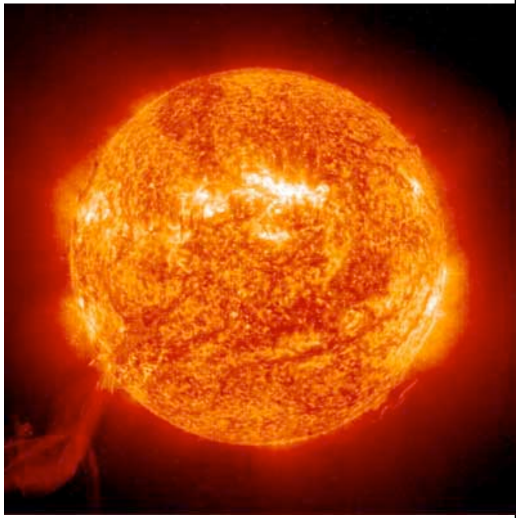
Solar Neutrinos





Neutrino Energies

Big-Bang neutrinos ~ 0.0004 eV



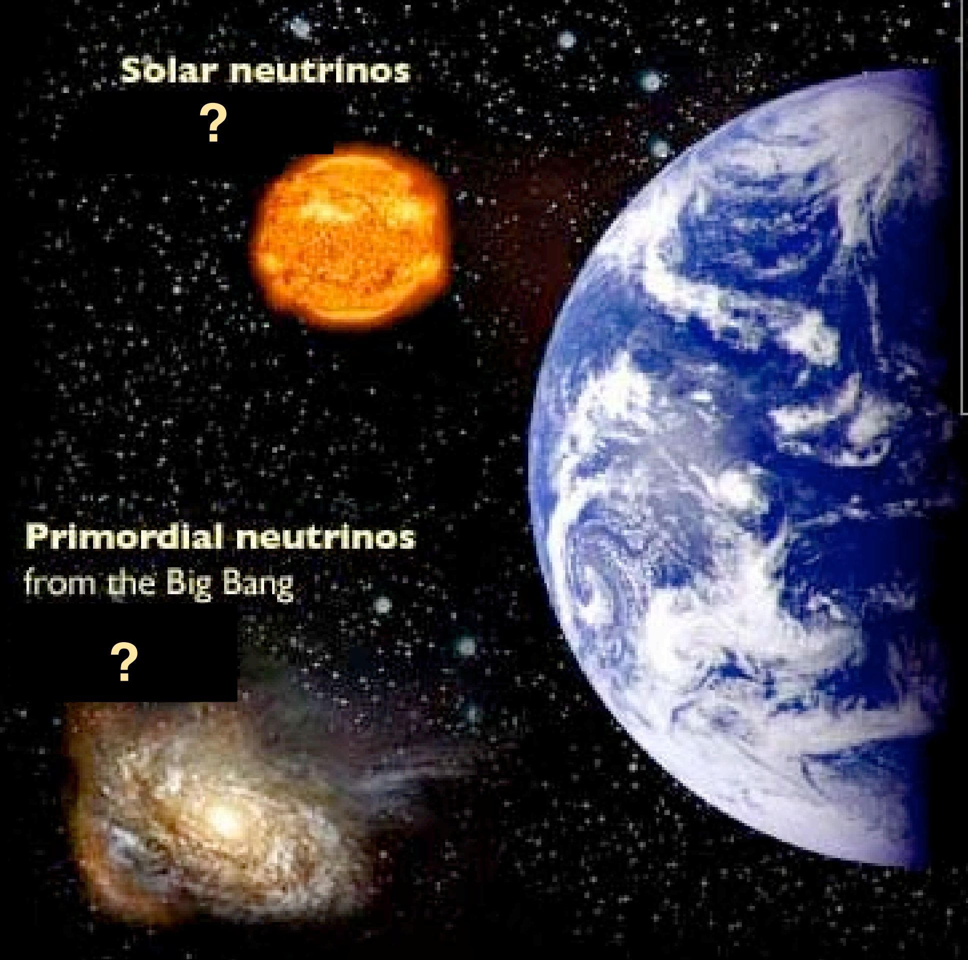
Neutrinos from the Sun < 20 MeV
depending of their origin.

Atmospheric neutrinos ~ GeV

Antineutrinos from nuclear reactors < 10.0 MeV

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

Neutrino Flux on Earth

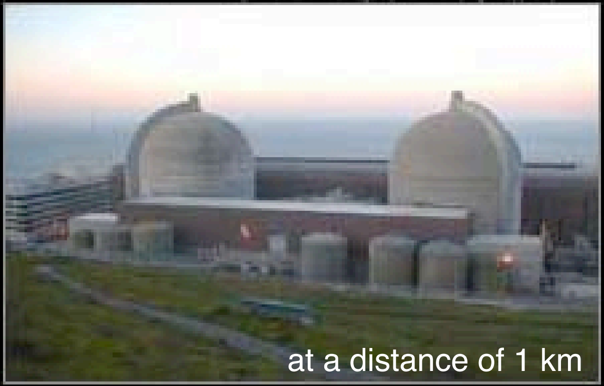


What produces the largest neutrino flux on Earth?

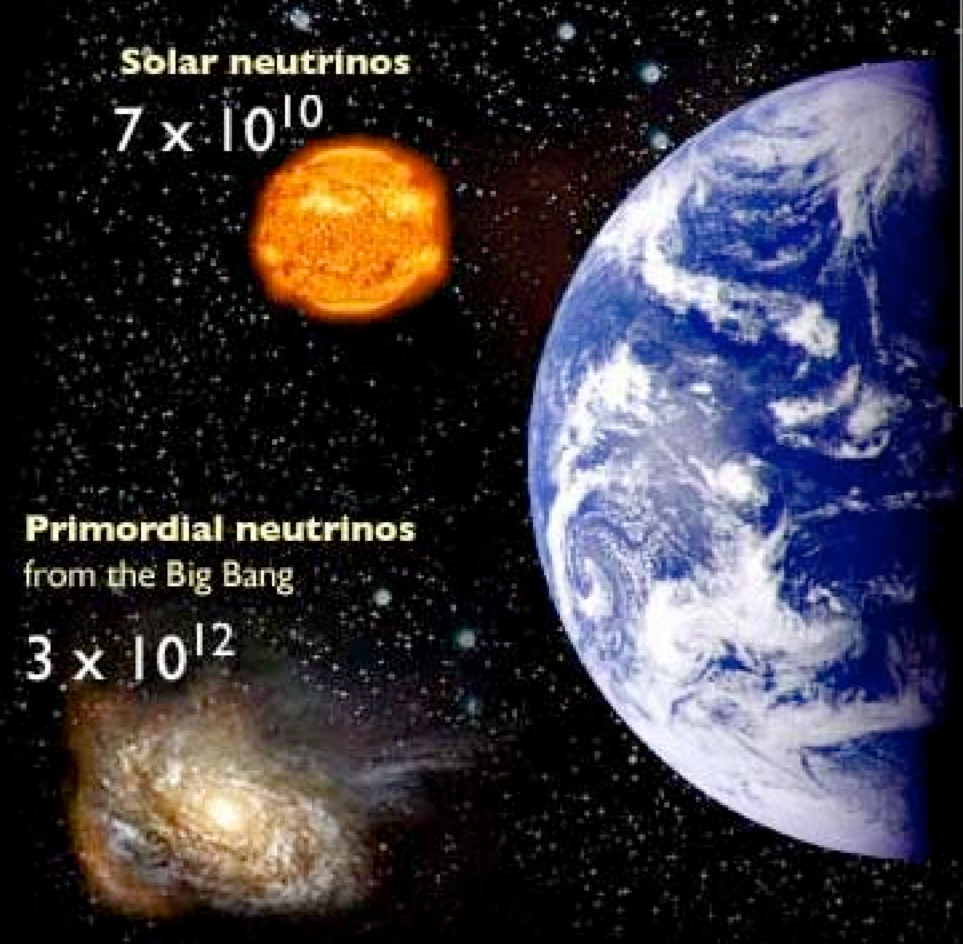
The Sun, the Big Bang, or a nuclear reactor?

Reactor neutrinos

?

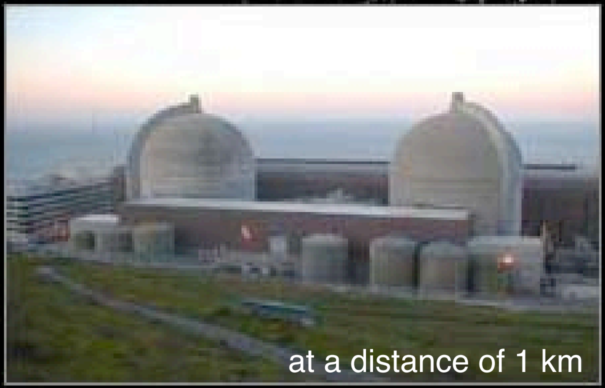

at a distance of 1 km

Neutrino Flux on Earth



What produces the largest neutrino flux on Earth?

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



at a distance of 1 km

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

1914

$$M_{parent}c^2 \Rightarrow E_{daughter} + E_{electron}$$

$$KE_{electron} = M_{parent}c^2 - M_{daughter}c^2 - m_{electron}c^2$$

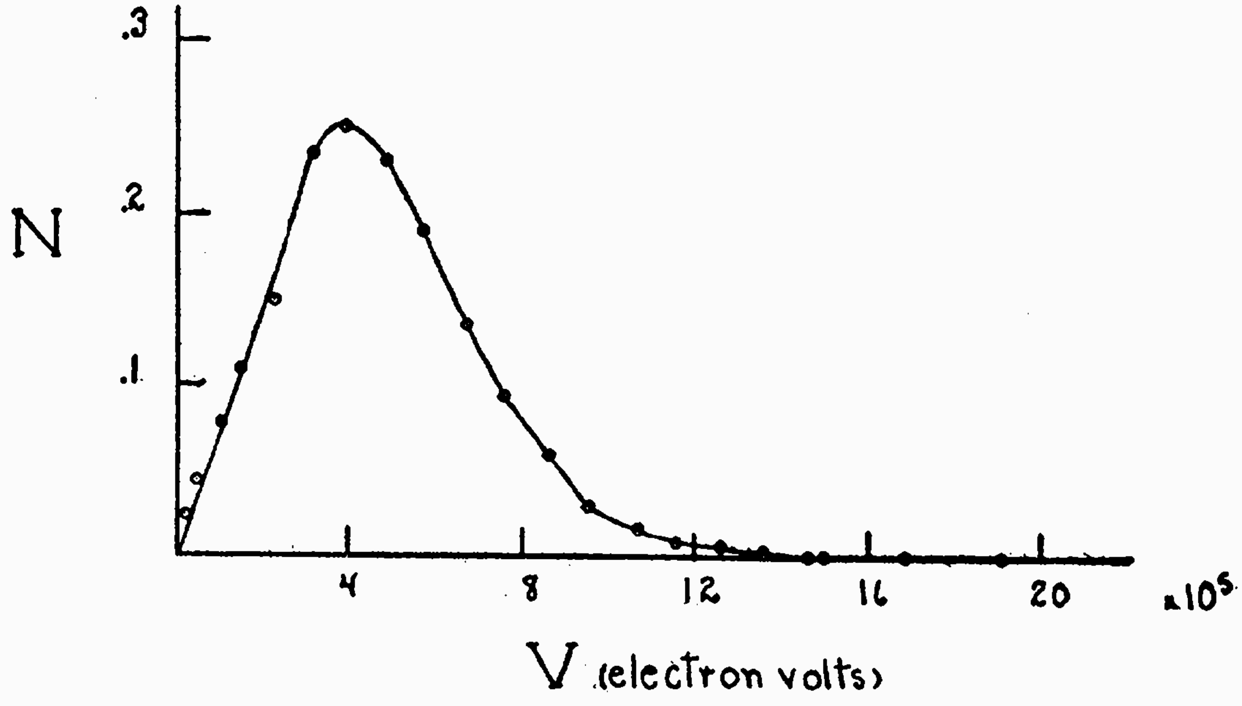
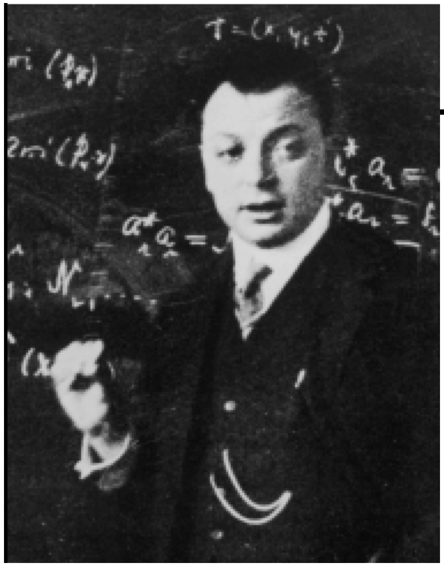
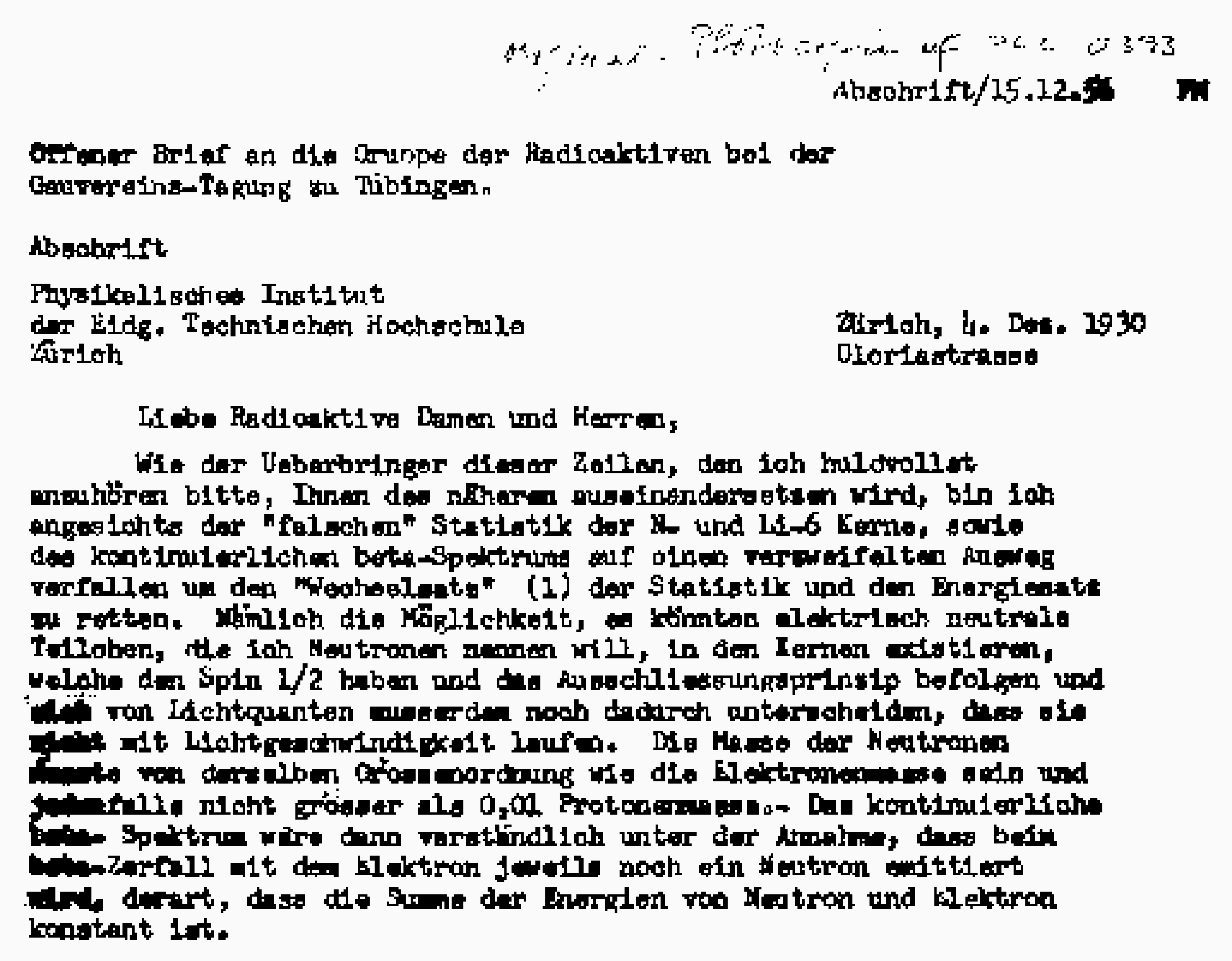


FIG. 5. Energy distribution curve of the beta-rays.



Wolfgang Pauli



[illegible] 0393

Abschrift/15.12.56 PM

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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

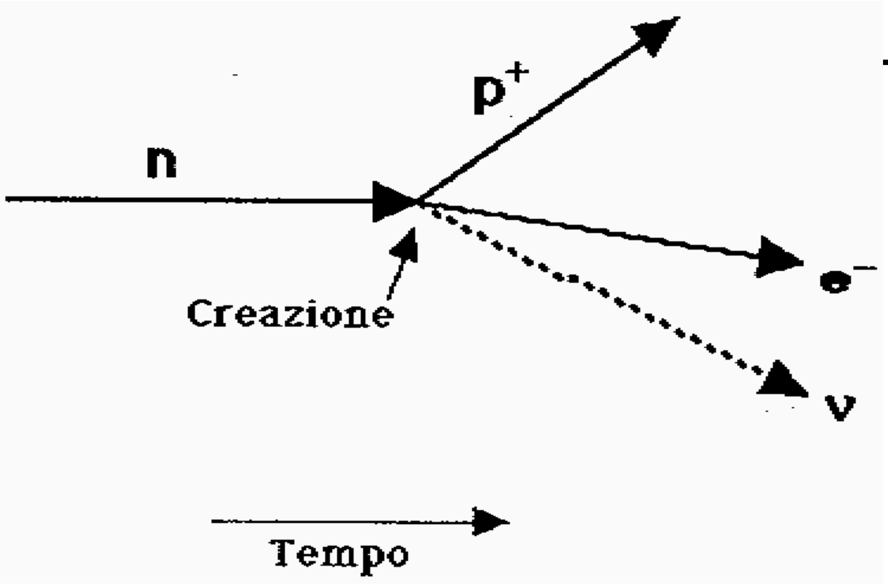
Liebe Radioaktive Damen und Herren,

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

Professor Pauli proposed that an undetectable particle shared the energy of beta decay with the emitted electron.

Enrico Fermi

Univ. of Chicago



Fermi's Theory of Beta Decay based on Pauli's Letter of Regrets

Experiment: $M_n c^2 \neq E_p + E_e$

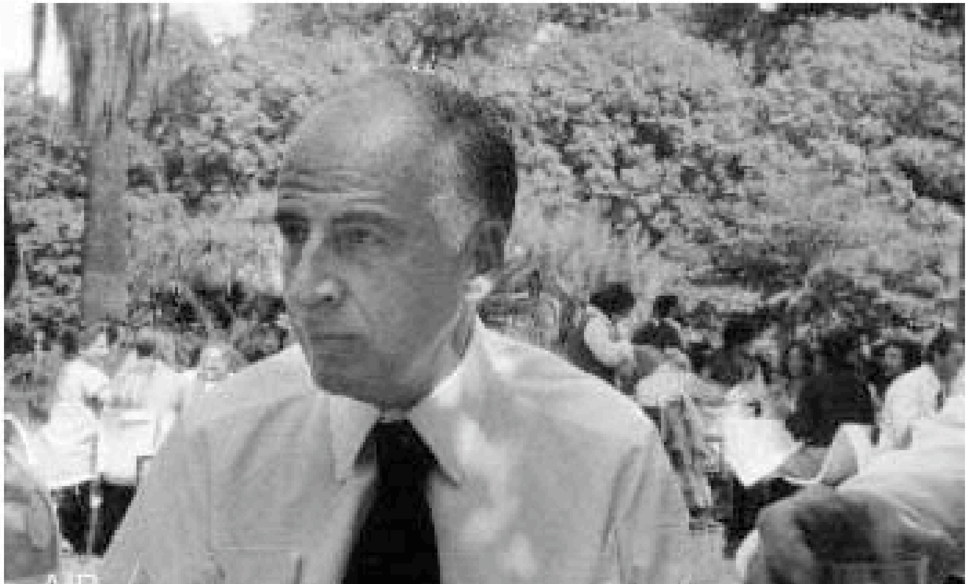
Conjecture: $M_n c^2 = E_p + E_e + E_\nu$

Consistency requires that E_ν is not observable!

Mr. Fermi's amazingly theory still stands (parity violation added in the 50s).

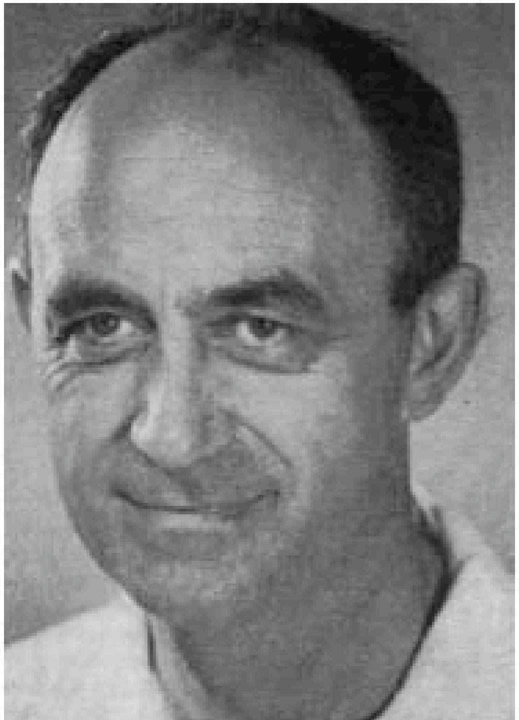
1949 IN COMO: Pontecorvo, (??), Fermi

Pontecorvo



Pauli

Fermi



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.

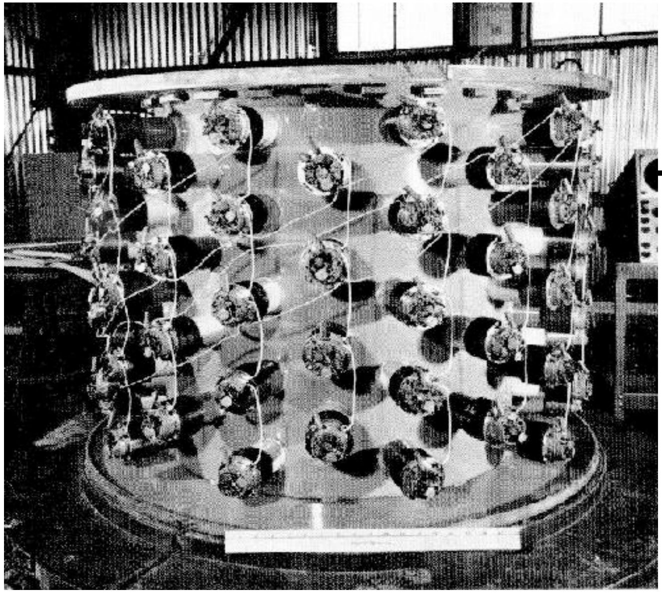
1956: First Direct Detection of the Antineutrino

Clyde Cowan Jr.

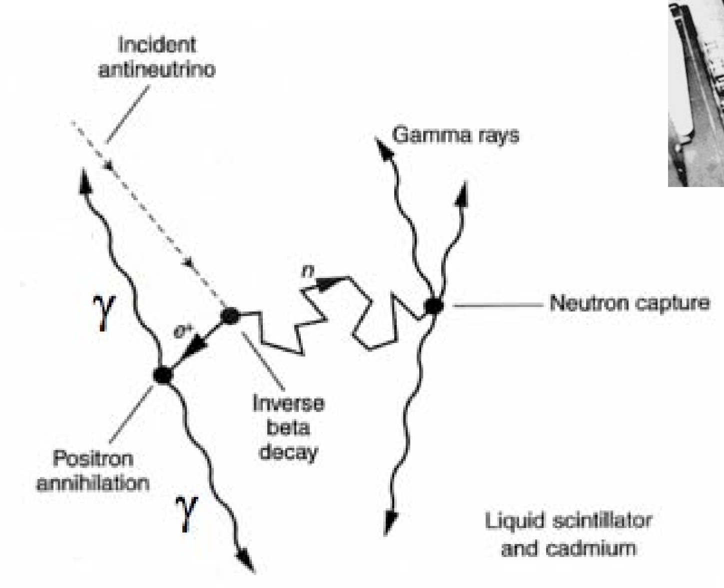
Frederick Reines

1953: Project Poltergeist

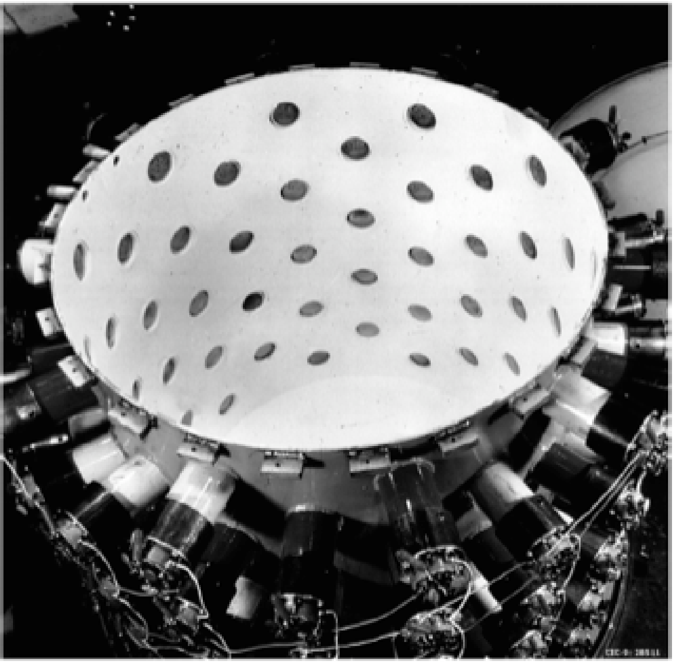
Experiment at Hanford



Hanford Experiment



300 liters of liquid scintillator loaded with cadmium



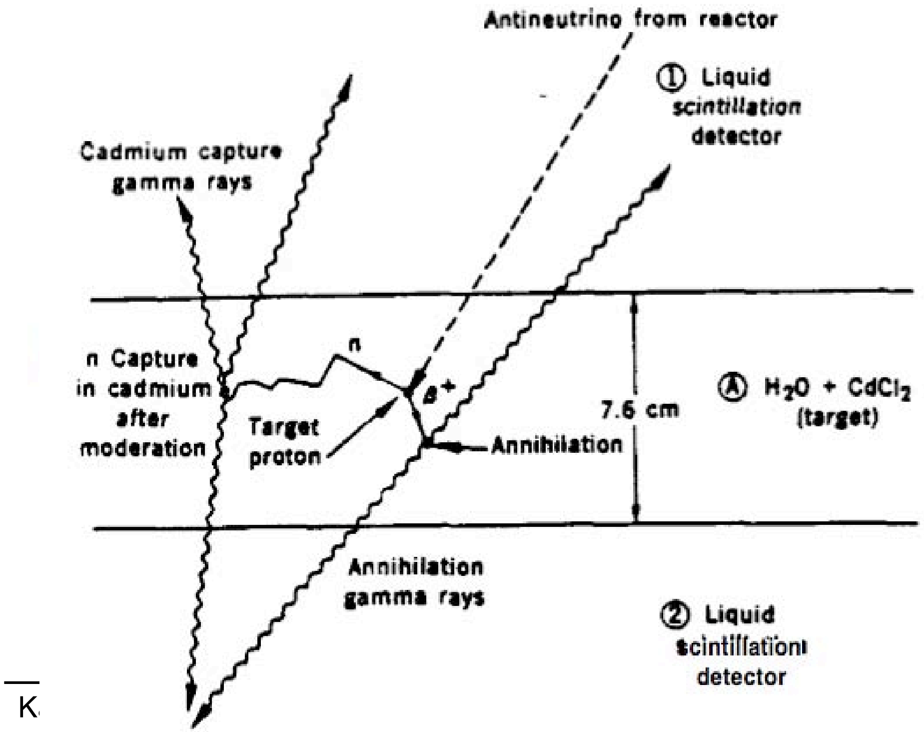
signal: delayed coincidence between positron (2-5 MeV) and neutron capture on cadmium (2-7 MeV)

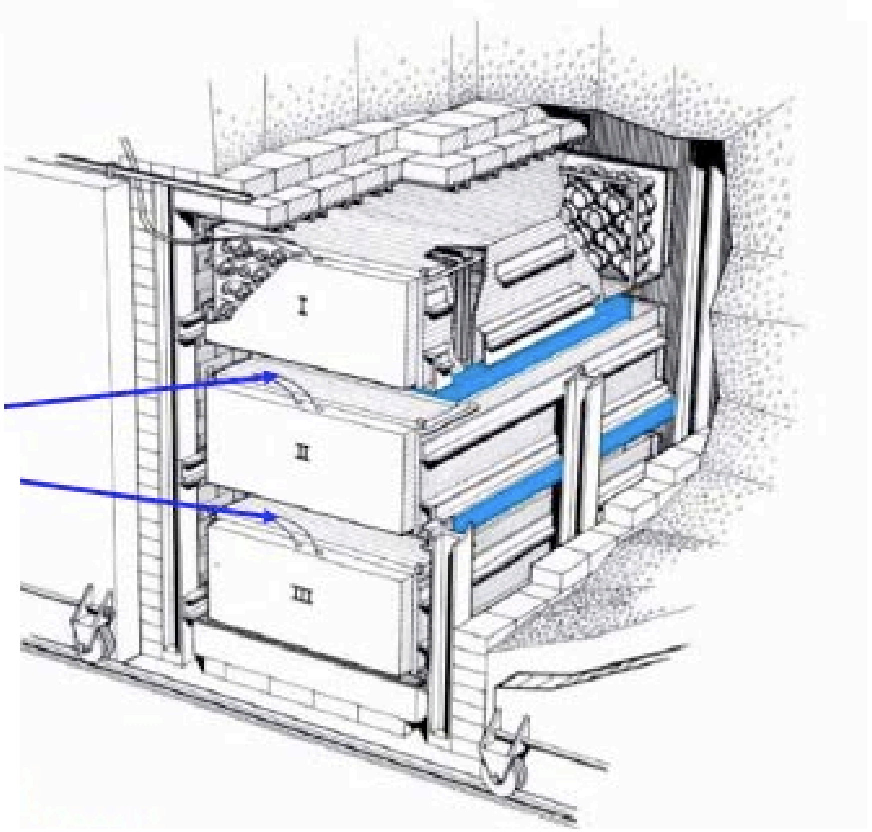
high background (S/N ~ 1/20) made the experiment inconclusive
0.41+/- 0.20 events/minute

1956: Savannah River Experiment

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

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

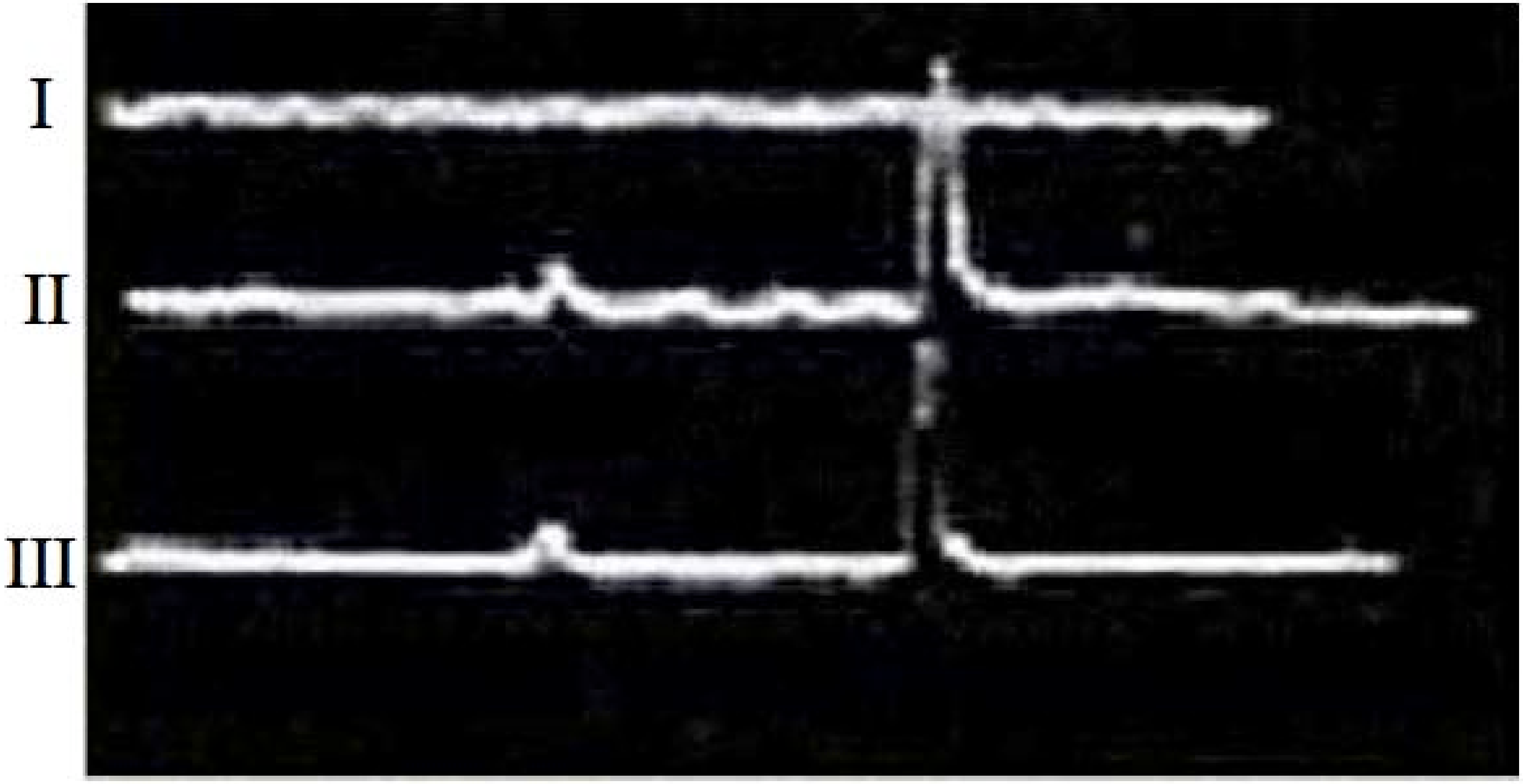




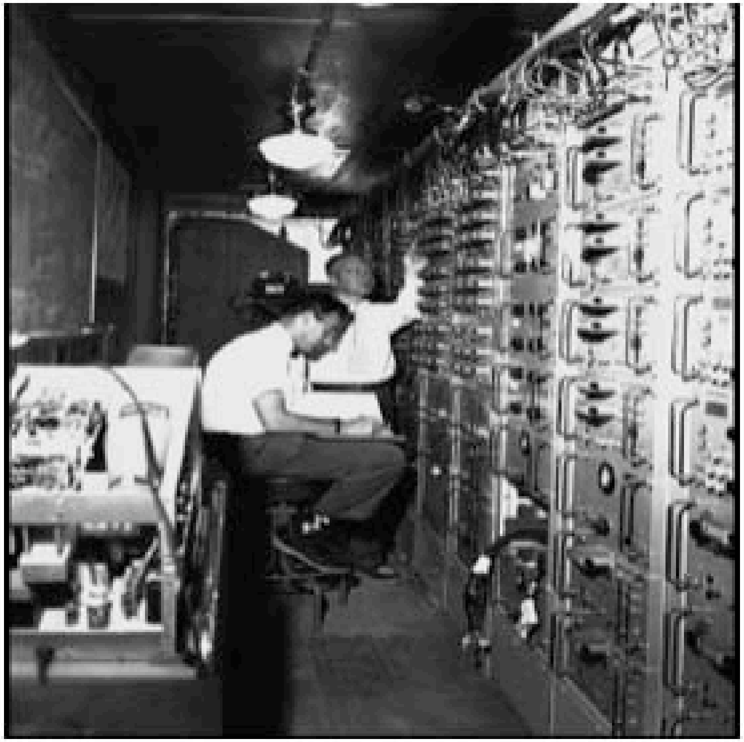
inverse beta decay would produce prompt and delayed signal in neighboring tanks

Oscilloscope Traces of Data

photographically recorded



1956: Savannah River Experiment



Electronics trailer

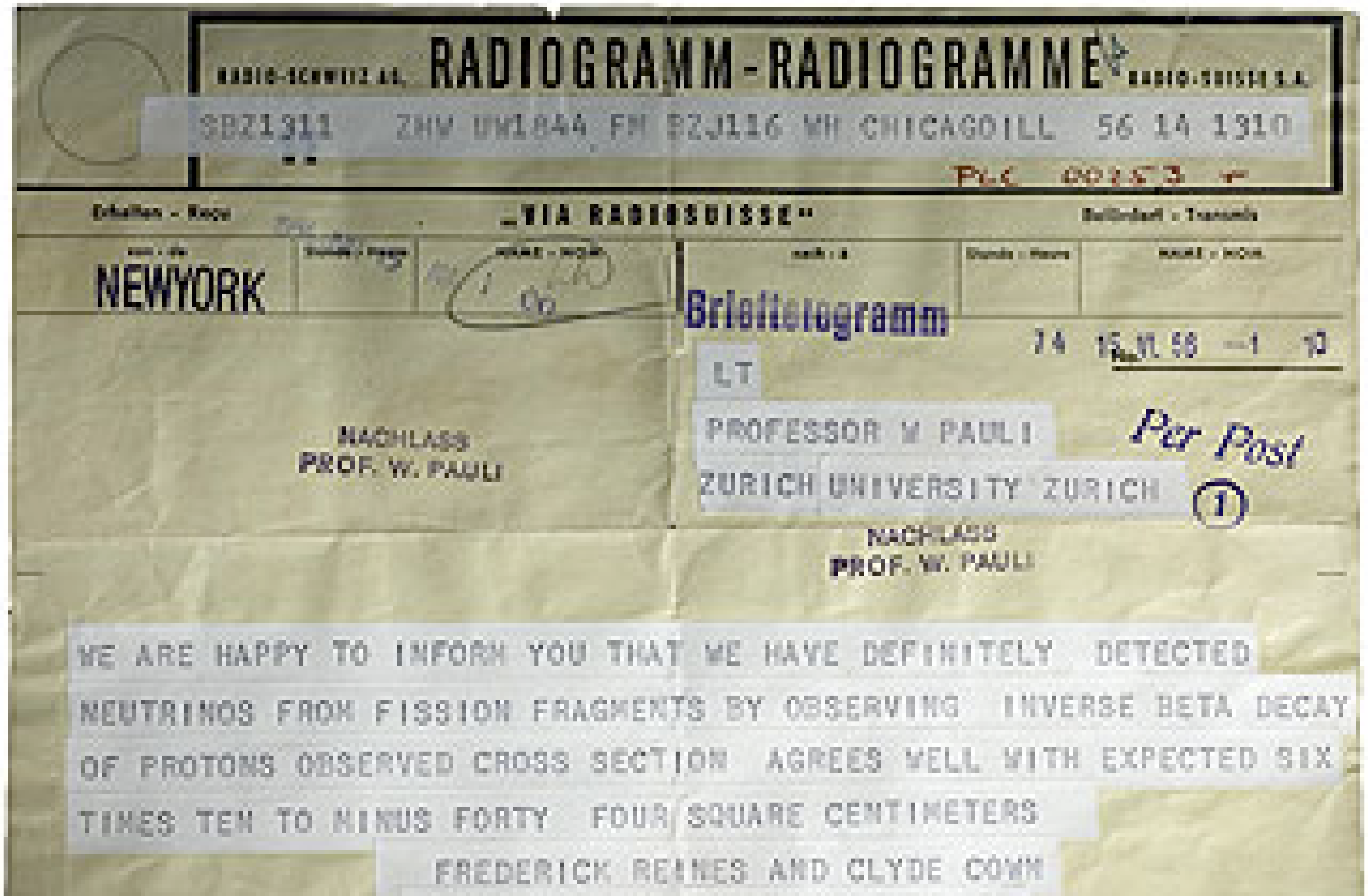
Shielding: 4 ft of soaked sawdust

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 A.G. **RADIOGRAMM-RADIOGRAMME** RADIO-SUISSE S.A.

SBZ1311 ZHW UW1644 FM B2J116 WH CHICAGOILL 56 14 1310

„VIA RADIOSUISSE"

NEWYORK

Brieftelegramm

15.VI.56

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

①

NACHLASS
PROF. W. PAULI

NACHLASS
PROF. W. PAULI

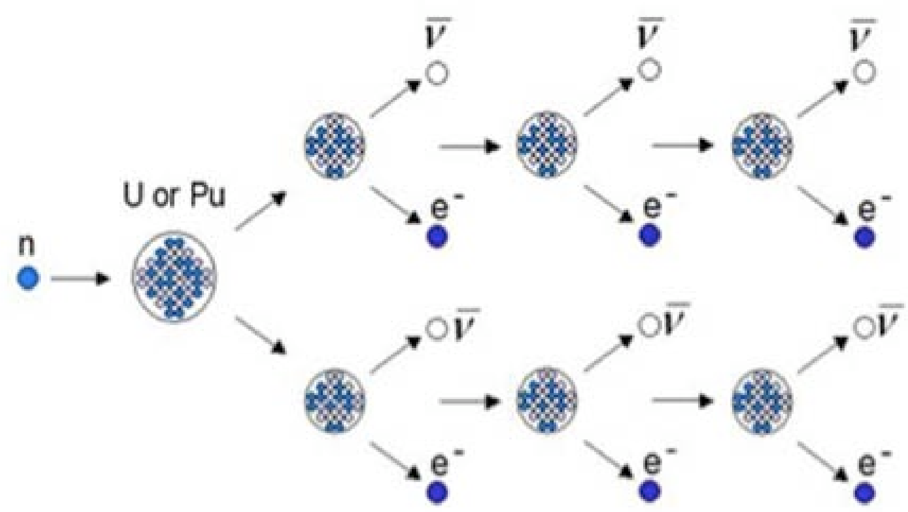
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

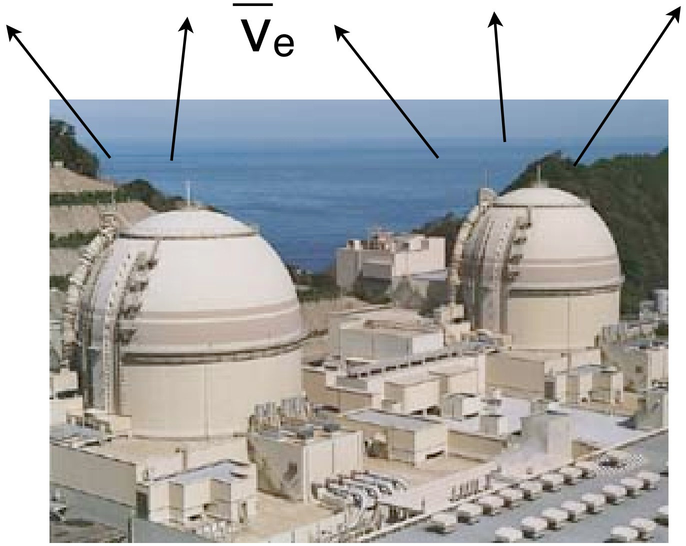
FREDERICK REINES AND CLYDE COWN

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

Reactors as Antineutrino Sources





U and Pu fission

- about 200MeV / fission is released
- fission rate is ~1.2×10^{20} fissions / sec

β^- decay of neutron rich fission fragments

reactors are copious, isotropic sources of $\bar{\nu}_e$

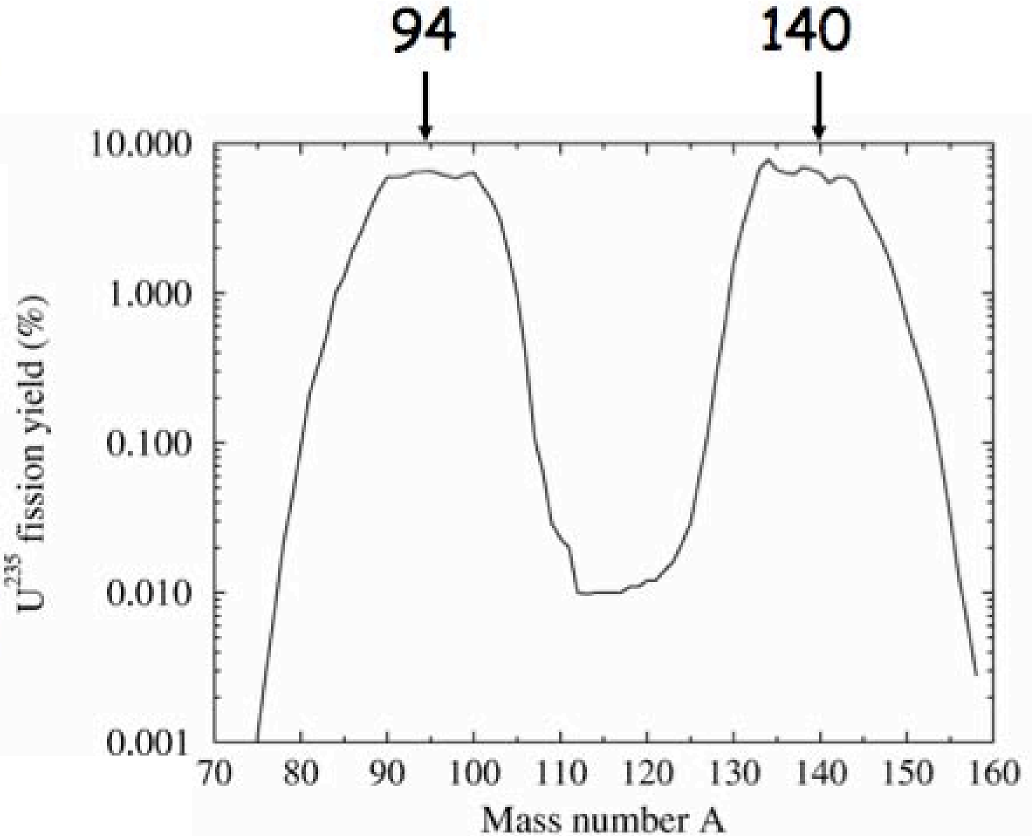
Example: ^{235}U Fission

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

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

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

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

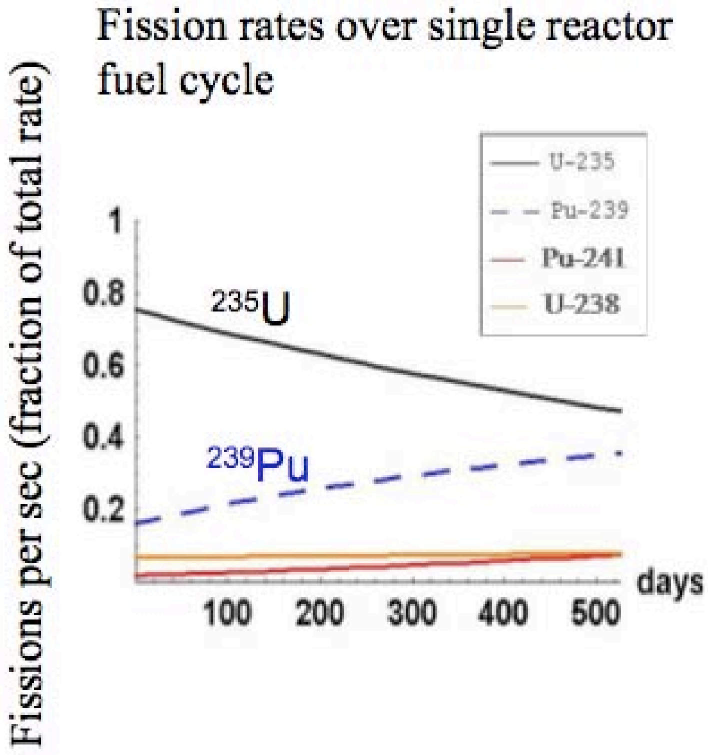


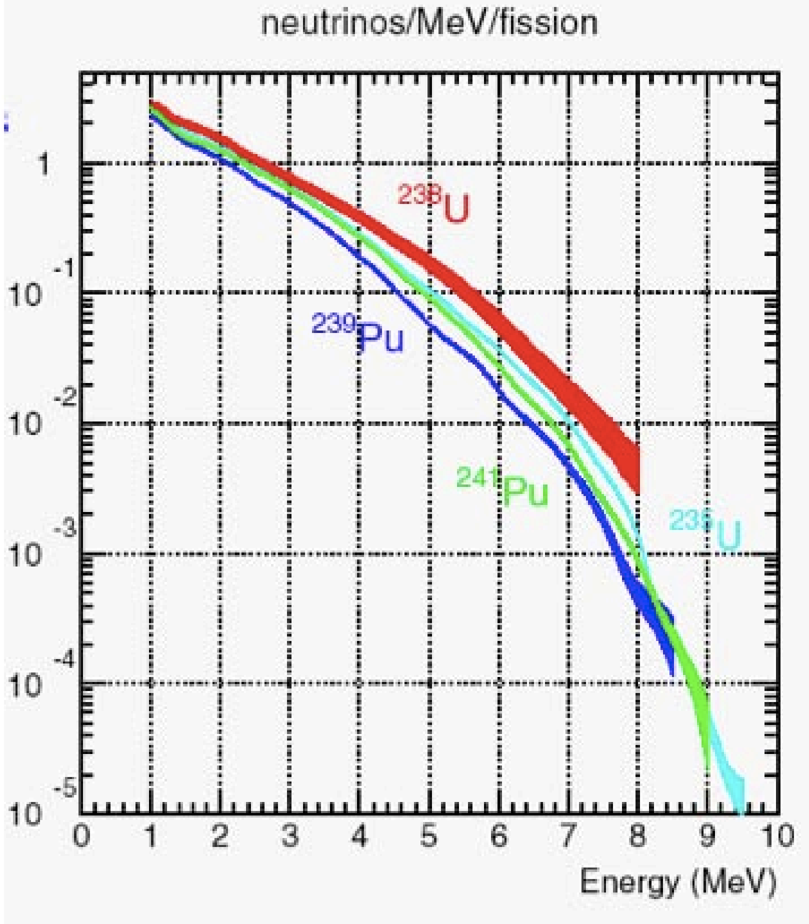
- on average 6n have to beta-decay to 6p to reach stable matter
- on average 1.5 are emitted with energy > 1.8 MeV

→ $\sim$ 200 MeV/fission and $\sim$6 $\bar{\nu}_e$ / fission implies that 3GW$_{th}$ reactor produces $\sim 6\times10^{20}$ $\bar{\nu}_e$ / sec.

Antineutrino Production in Nuclear Fuel

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


Fission rates over single reactor fuel cycle



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

from E. Blucher

Reactor Neutrino Flux and Spectrum

Prediction of the $\overline{\nu}_e$ Flux and Spectrum

> 99.9% of ν_e are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

~ 90% of ν_e are produced by fissions in ^{235}U, ^{239}Pu

Measurements

β^--spectra resulting from fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu has 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

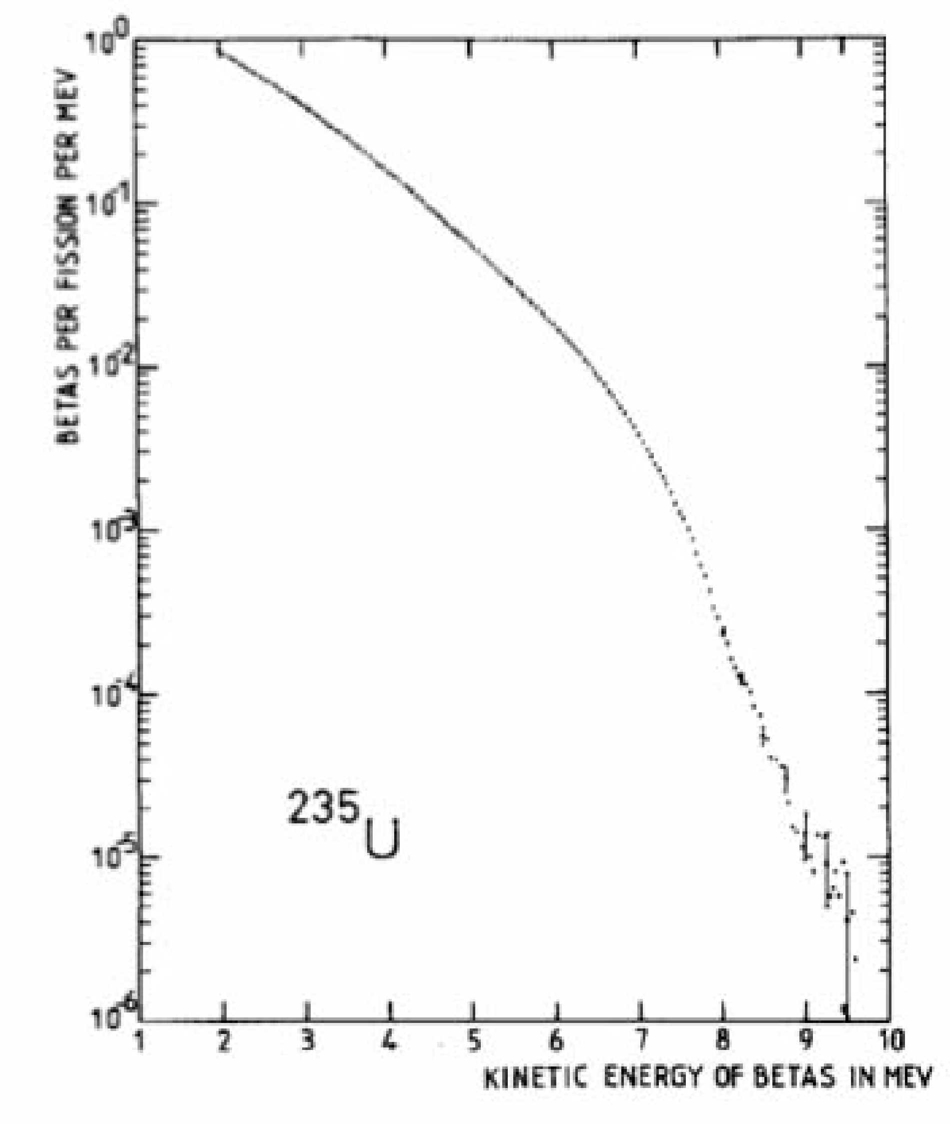
Calculations

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

→ determined from theory (+/-10%)

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

β Spectrum of ^{235}U Fission Products

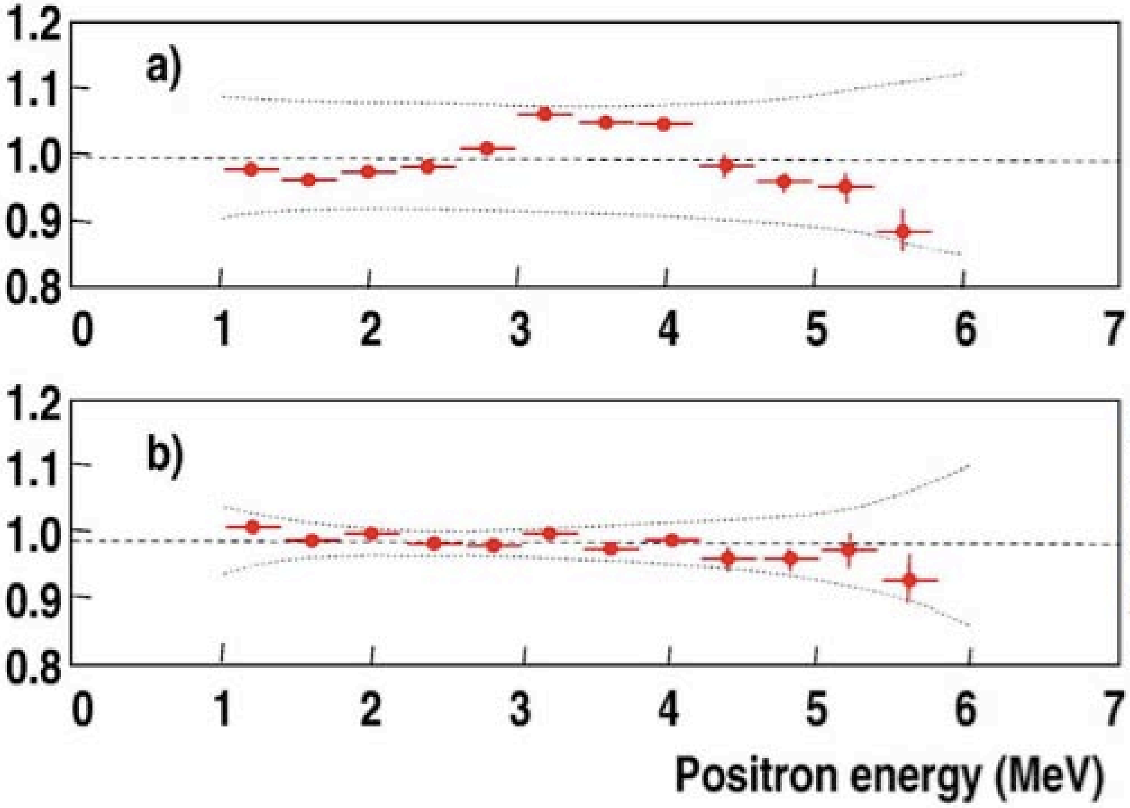


Schreckenbach et al.
PL160B 325 (1985)

Bugey Experiment

Derived ν Spectrum Checked Against Data

- β-spectra measured for ^{235}U, ^{239}Pu, ^{241}Pu. Converted into ν-spectra.
- theoretical calculations for ^{238}U

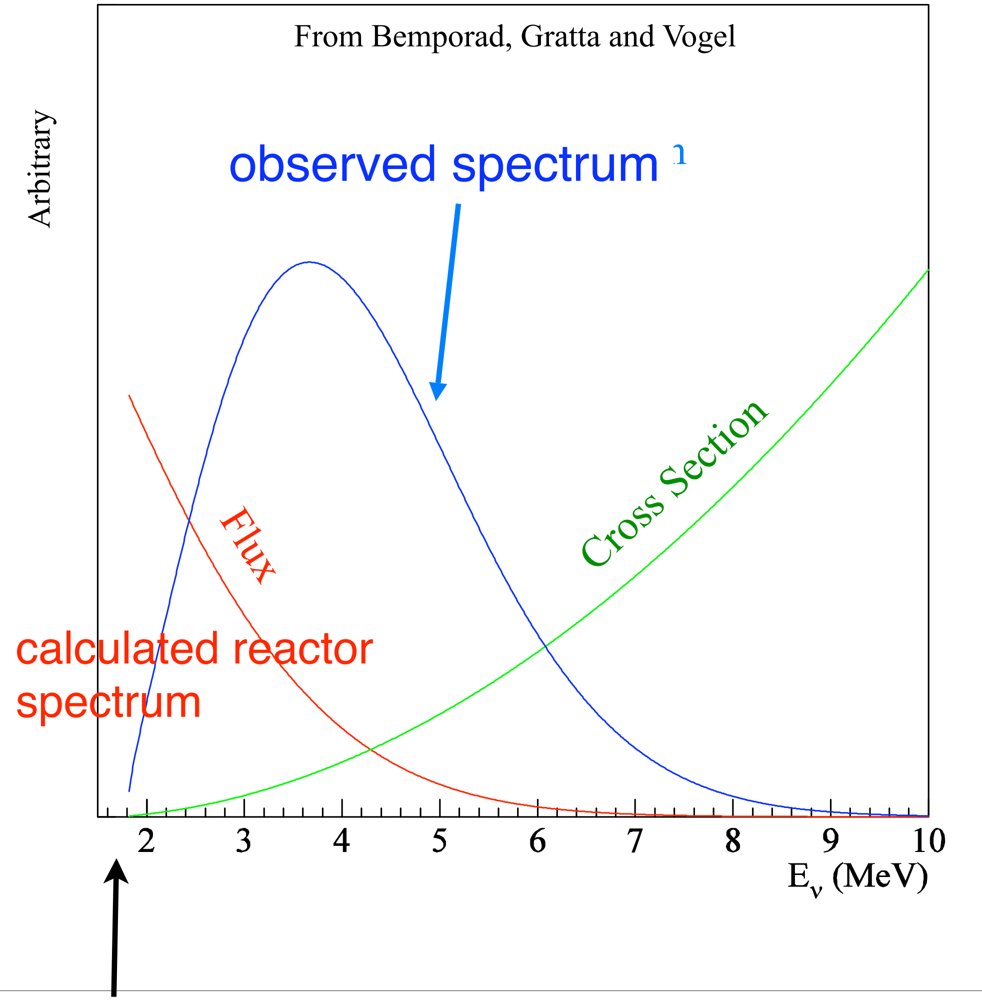


Bugey3/"first principle calculation"

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

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

$\overline{\nu}_e$ Spectrum



cross-section accurate to +/-0.2%

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

⇒only disappearance expts possible

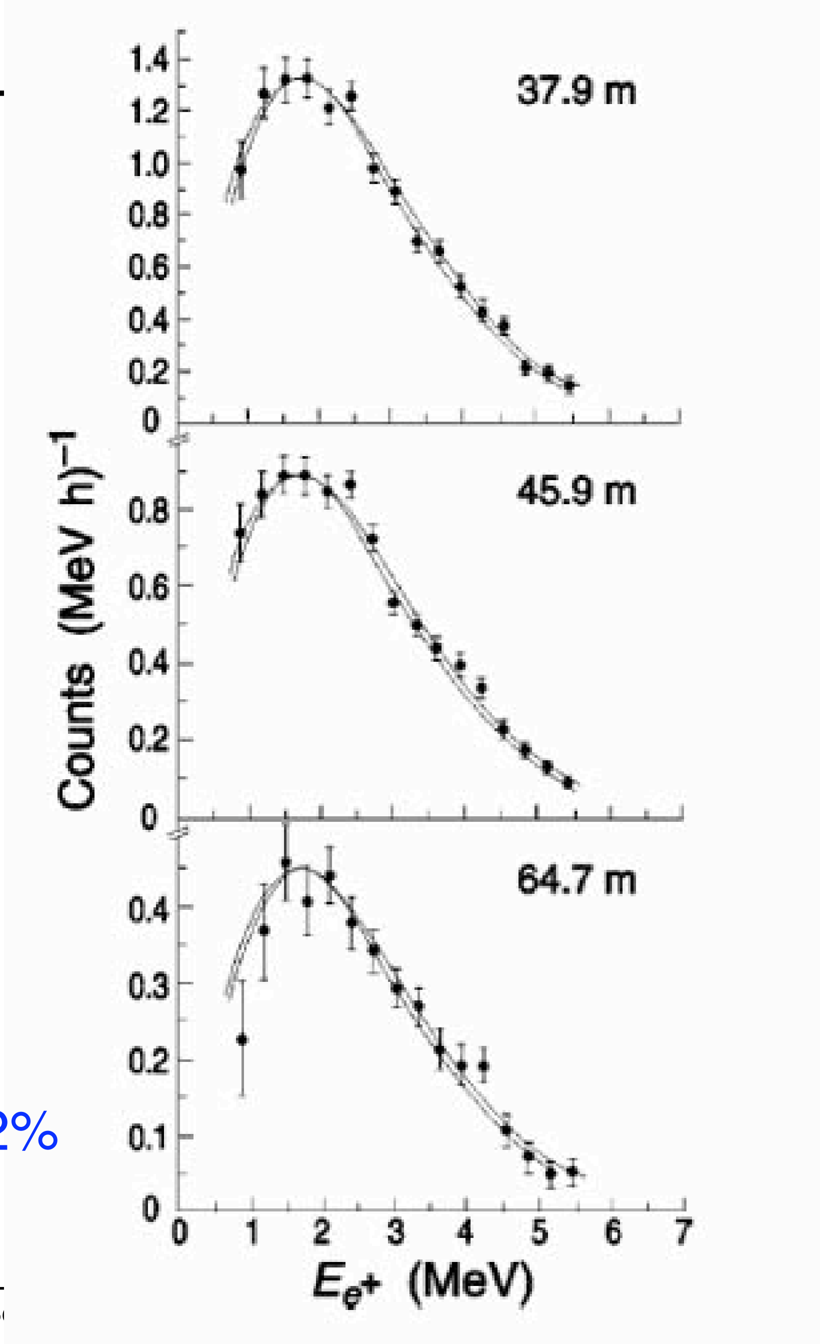
threshold: neutrinos with E < 1.8 MeV are not detected

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

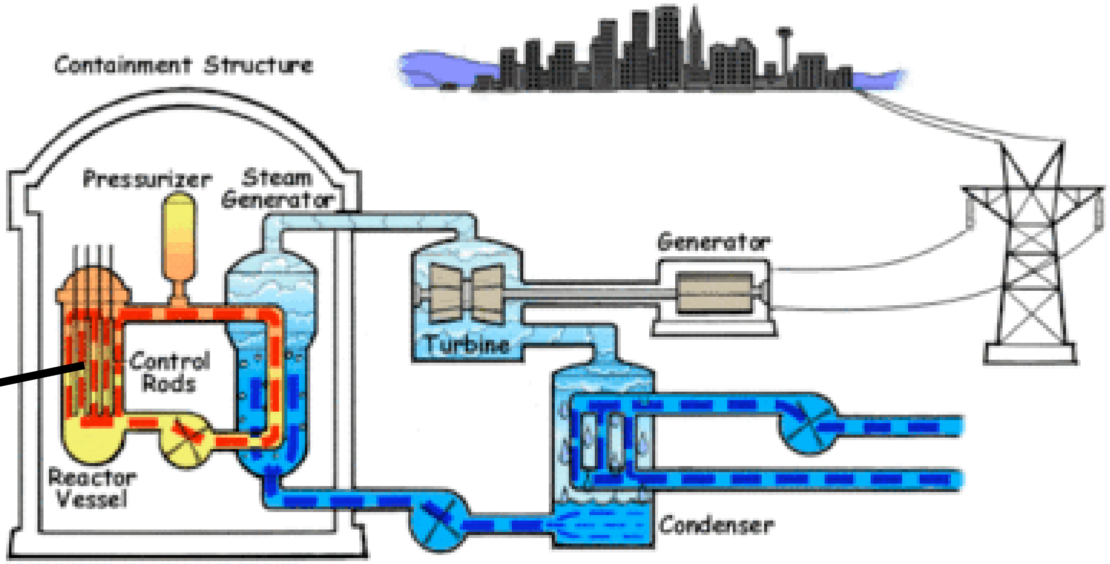


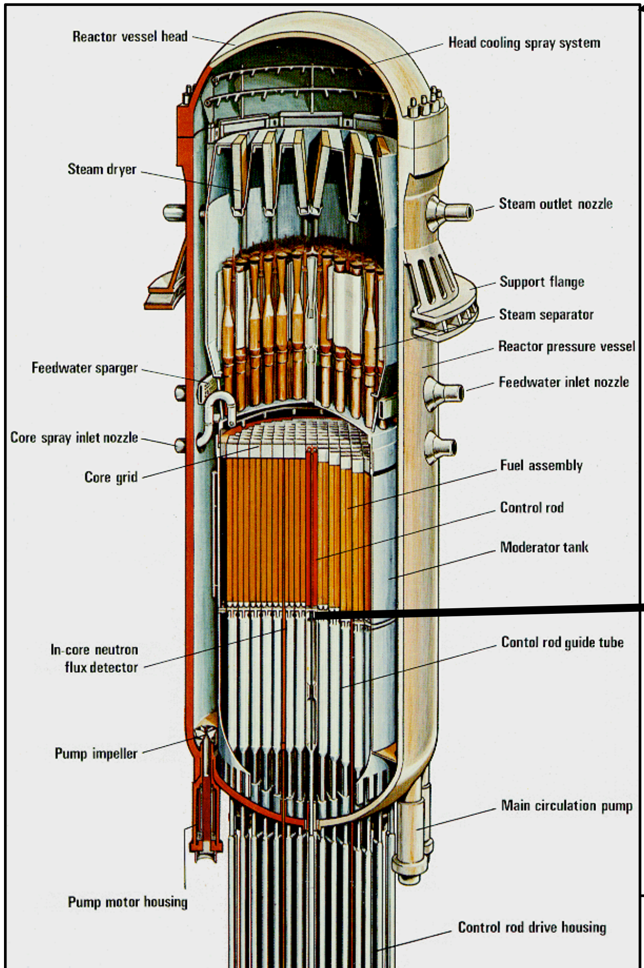
flux and energy spectrum agree to ~ 1-2%

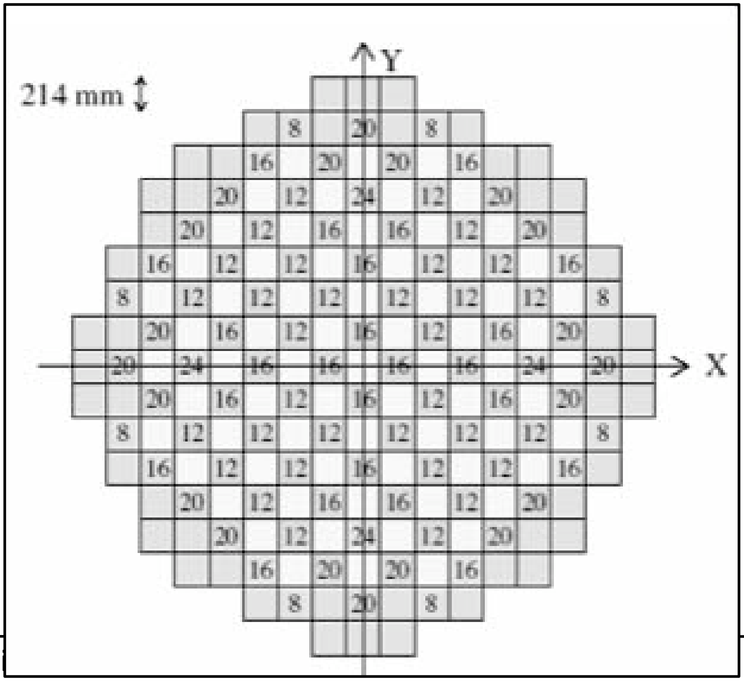
Nuclear Reactors

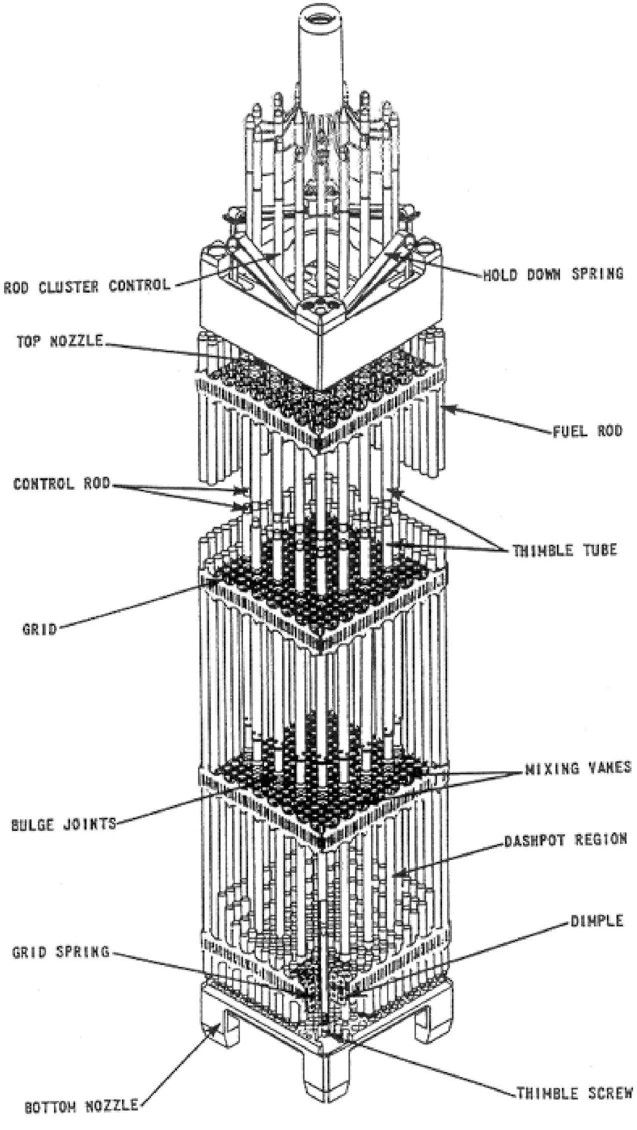
reactors are an extended neutrino source:

3-4m diameter, 4m high









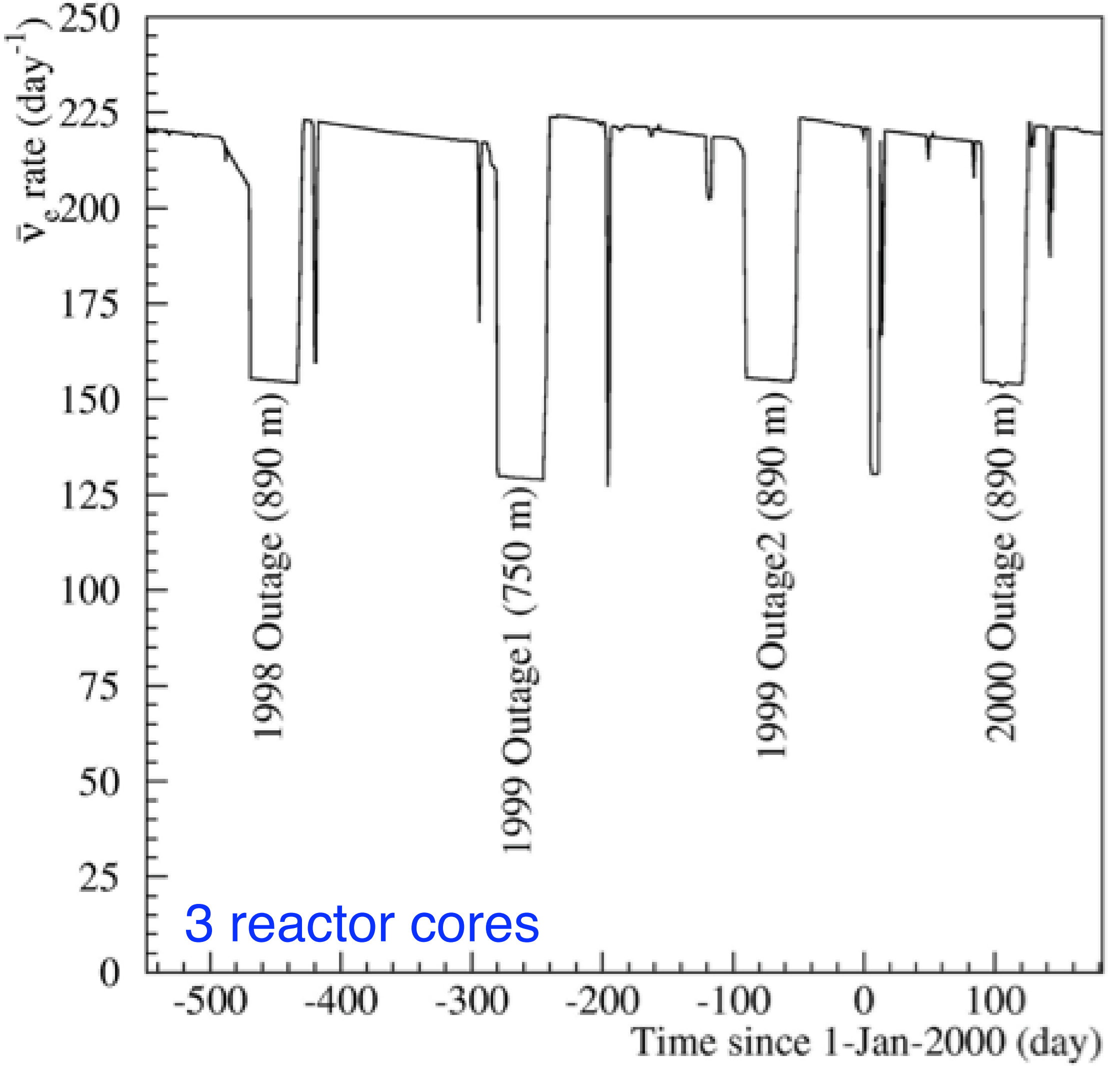
Reactor Fuel Assembly

Reactor Refueling

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

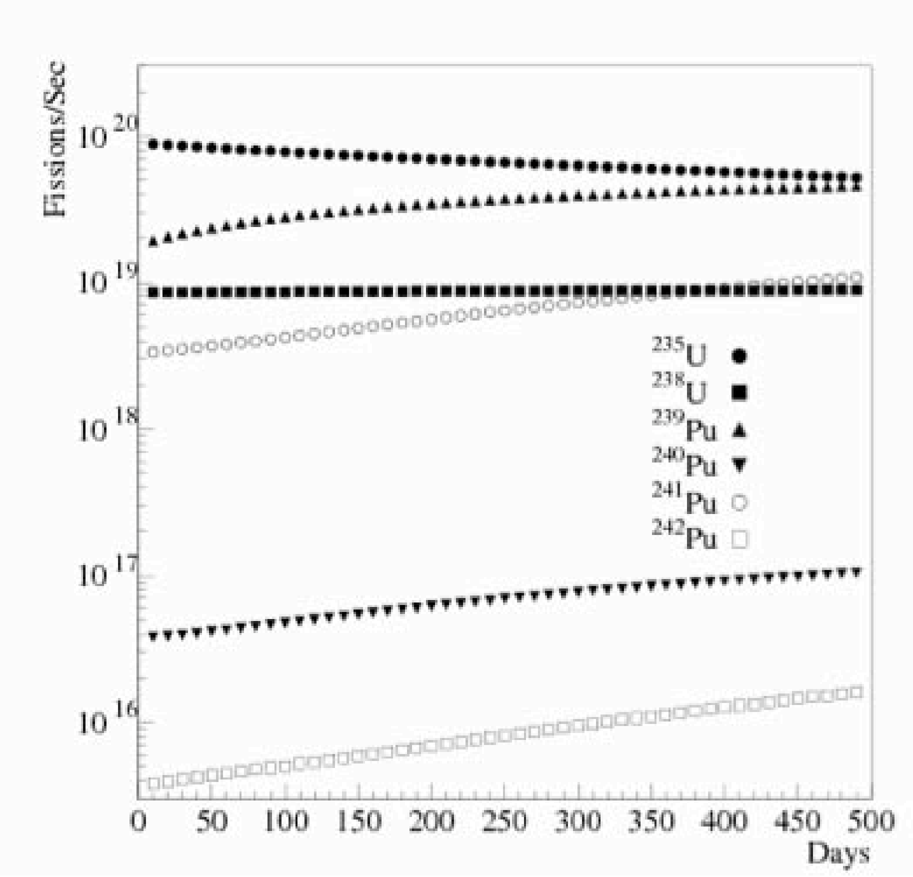


3 reactor cores

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

Burn-Up Corrections

- Burn-up correction needed
  - The percentage of the different primary isotopes change with time
  - Different fuel components yield different spectra
- Experiments receive information from reactor company who understand this very well
  - Use information to calculate a time dependent rate of neutrinos vs energy



Antineutrino Detection

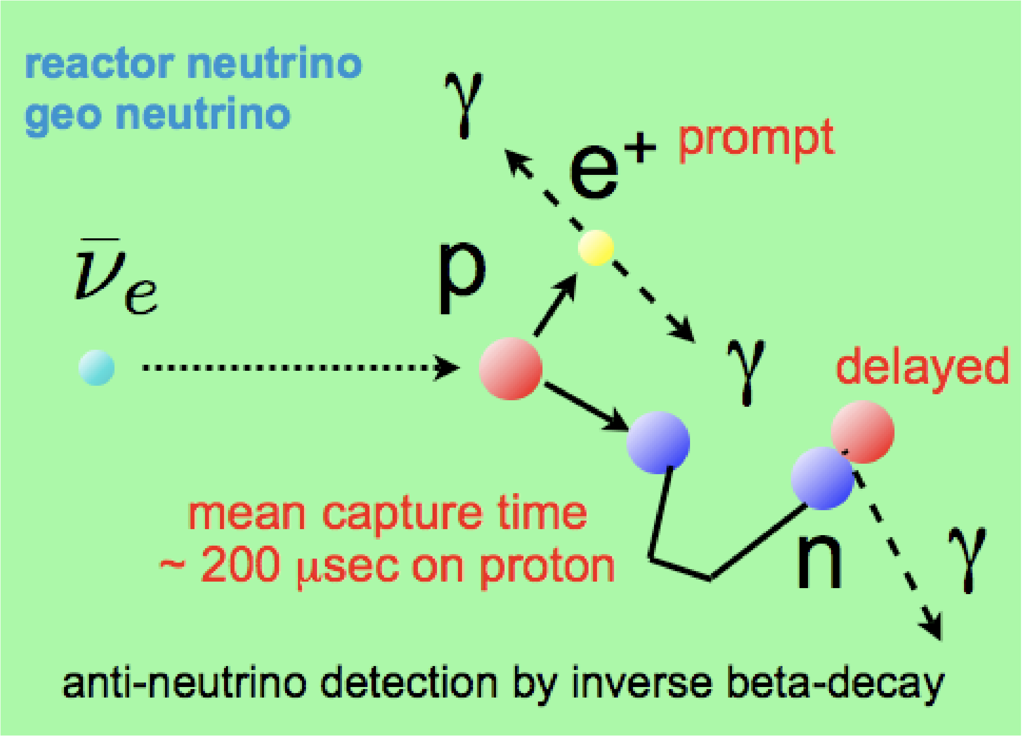
by inverse beta decay

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

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

(delayed)

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



anti-neutrino detection by inverse beta-decay

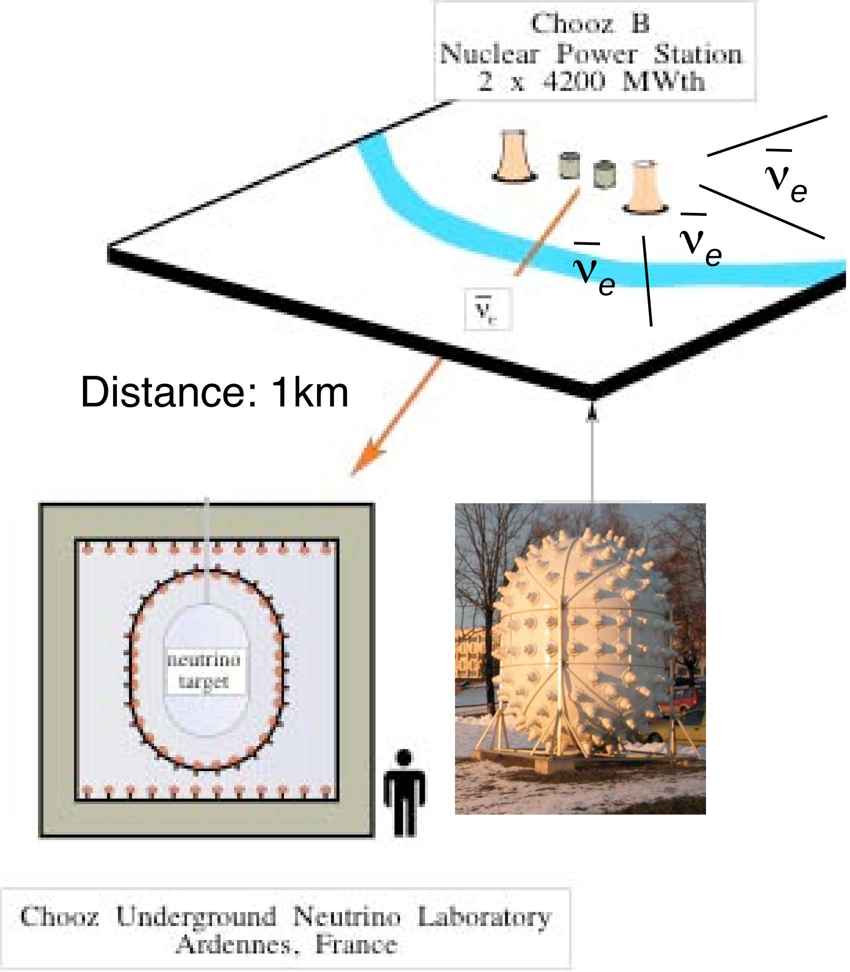
$$E_{\nu_e} \cong E_{e^+} + \overset{\text{10-100 keV}}{E_n} + \overbrace{(M_n - M_p) + m_{e^+}}^{\text{1.805 MeV}}$$

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

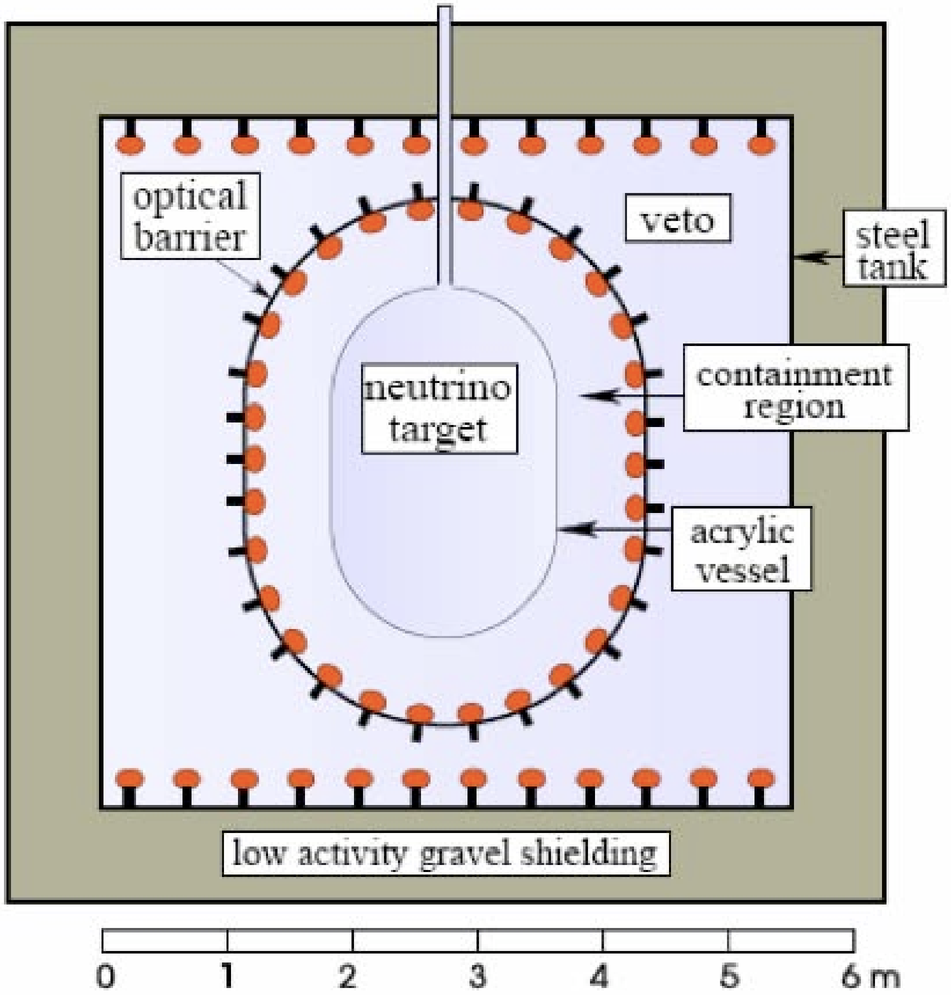
including E from e^+ annihilation, $E_{prompt} = E_\nu$ - 0.8 MeV

Neutrino Oscillation Search with Reactor Antineutrinos

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

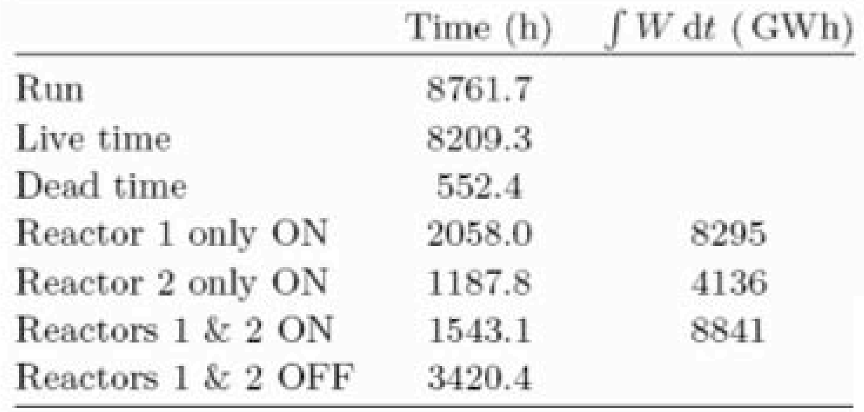


Distance: 1km



Chooz: Operation and Data Taking

Chooz data taking: April 97- July 98



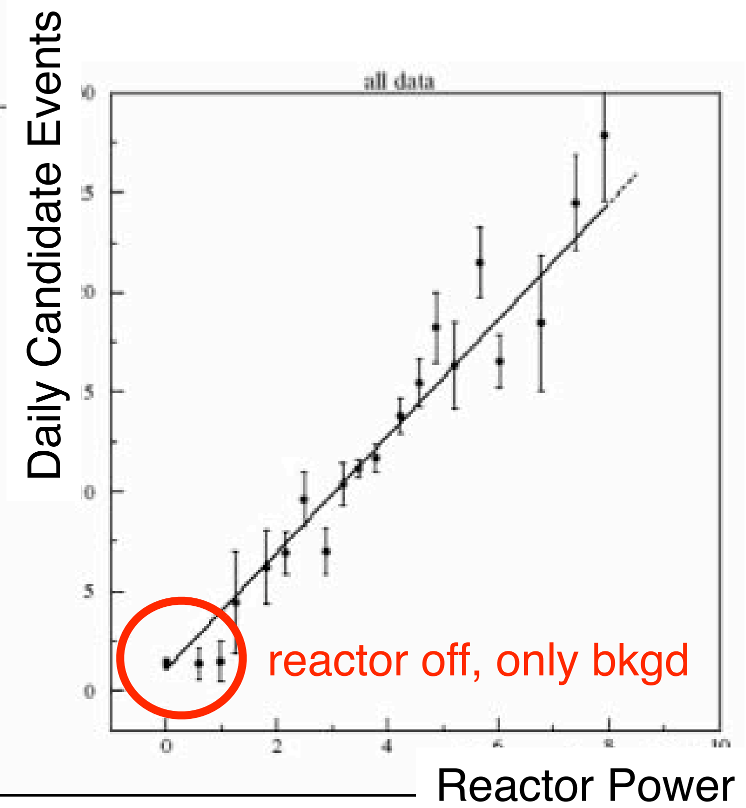
	Time (h)	$\int W\,dt$ (GWh)
Run	8761.7	
Live time	8209.3	
Dead time	552.4	
Reactor 1 only ON	2058.0	8295
Reactor 2 only ON	1187.8	4136
Reactors 1 & 2 ON	1543.1	8841
Reactors 1 & 2 OFF	3420.4	

~2.2 evts/day/ton with
0.2-0.4 bkg evts/day/ton

~total sample included
3600 ν events

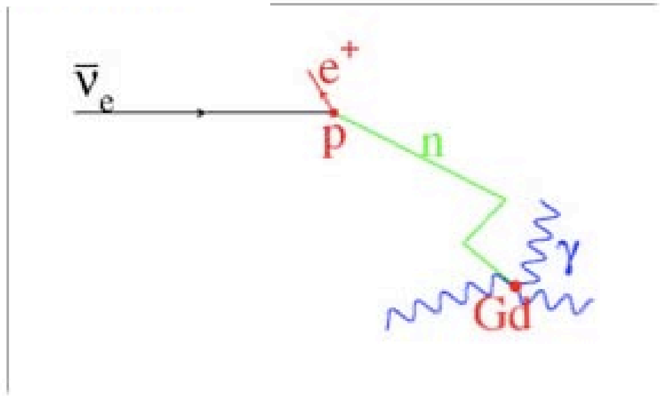
Chooz started data collection
before reactor began operating.

UNIQUE possibility to measure
backgrounds



Chooz: Signal and Correlated Background

Signal



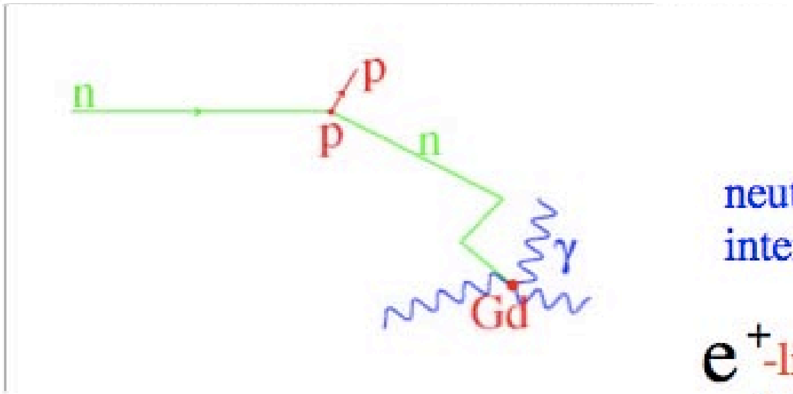
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$\Downarrow$$

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \sum_i \gamma$$

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

Correlated Background



neutrons from cosmic ray μ interaction in the rock

e^+-like signal faked by the proton recoil

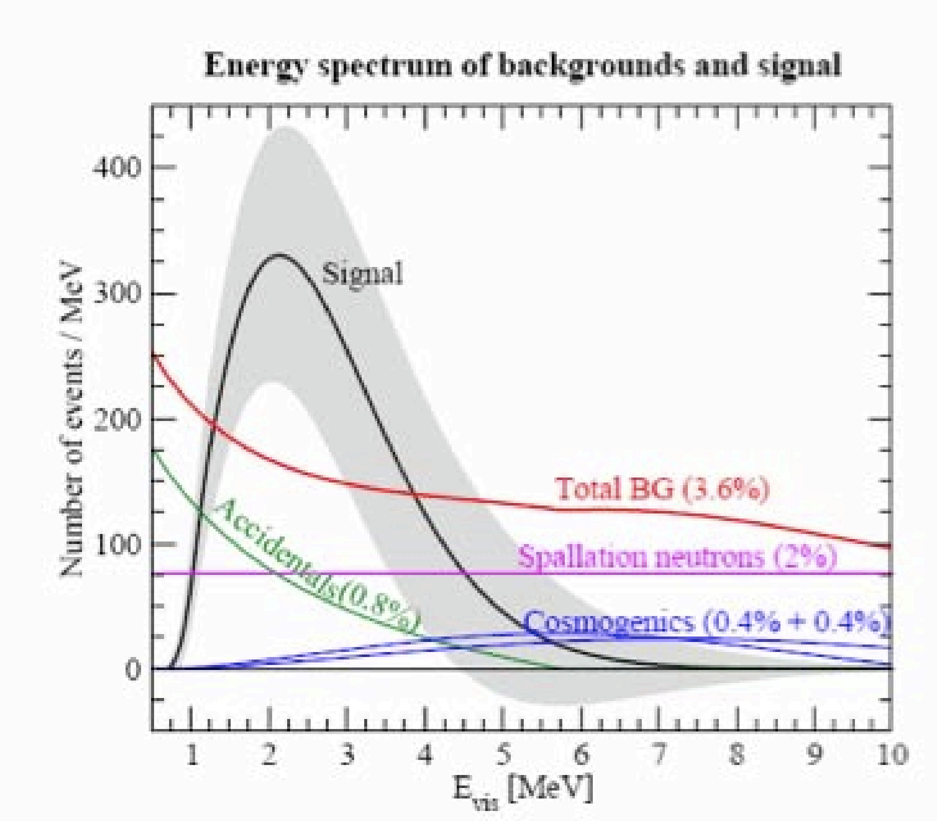
Backgrounds for Reactor Experiments

- 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)

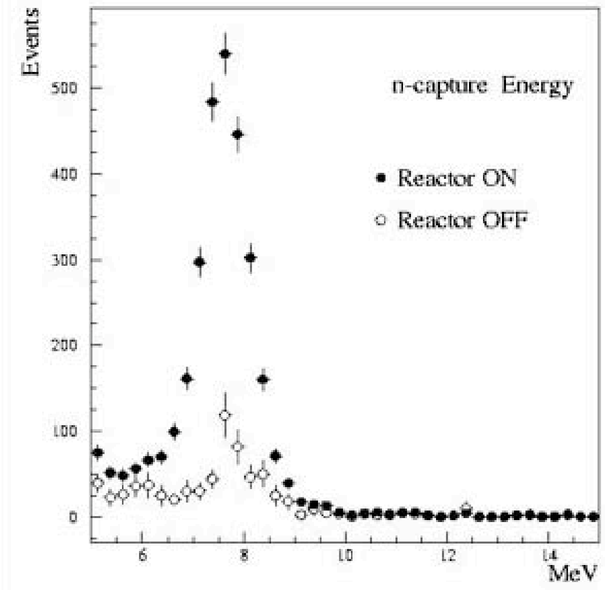


from M. Shaevitz

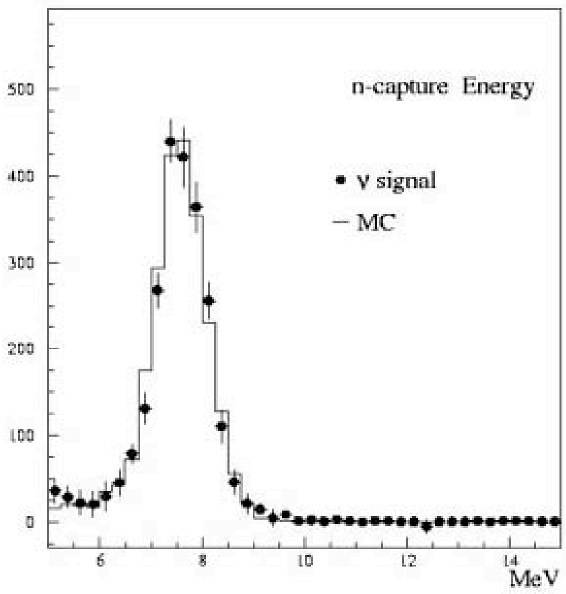
Chooz

Neutron Energy Spectra

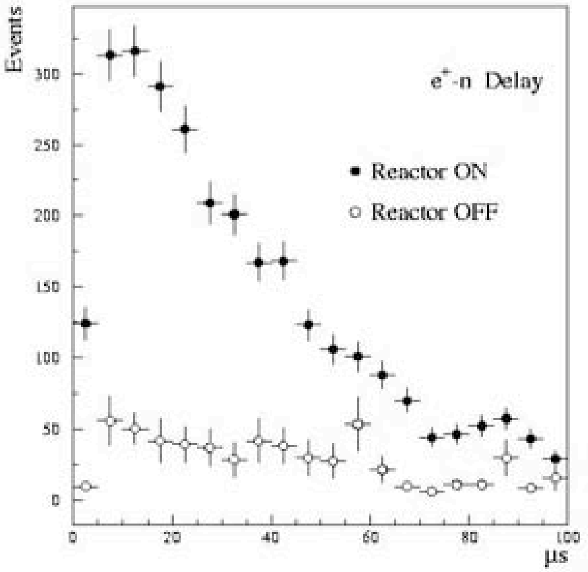
Reactor On/Off

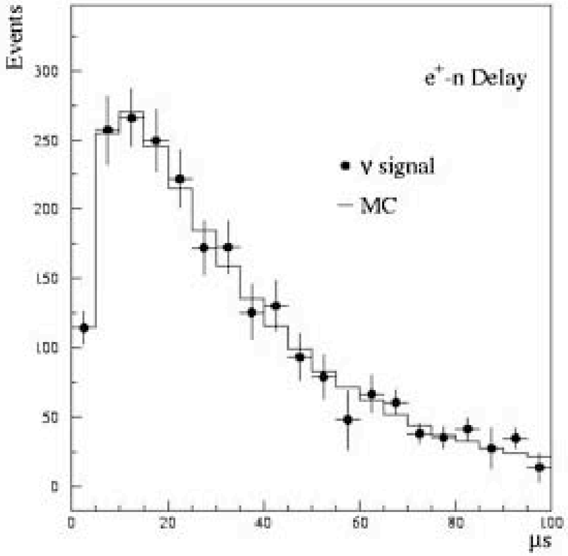


Signal vs MC



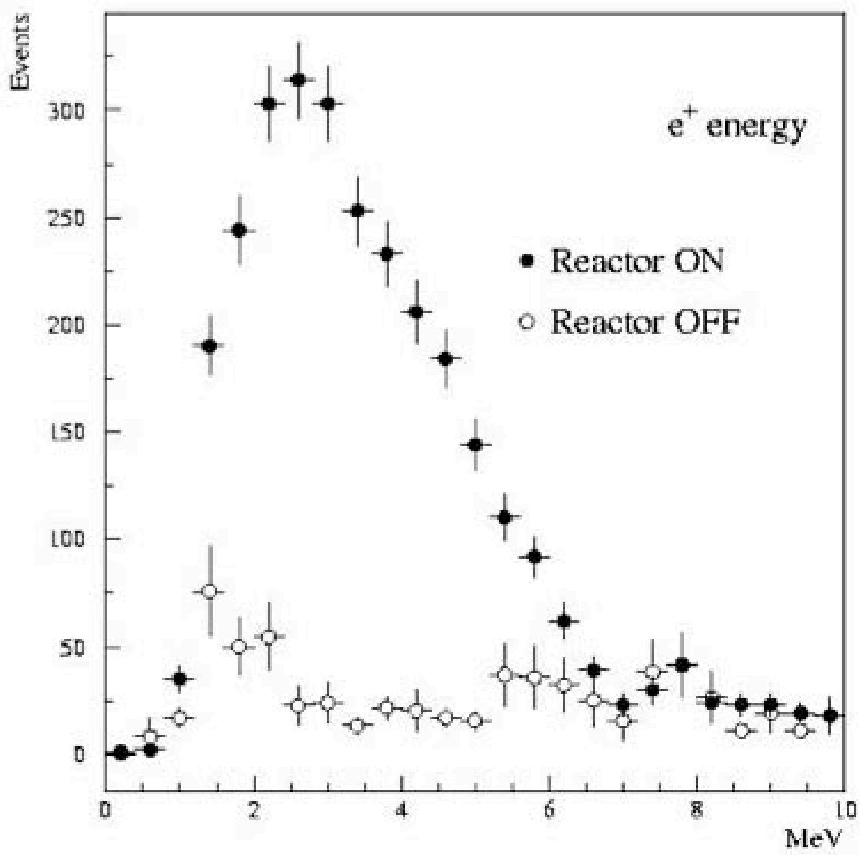
Neutron Delay Distribution



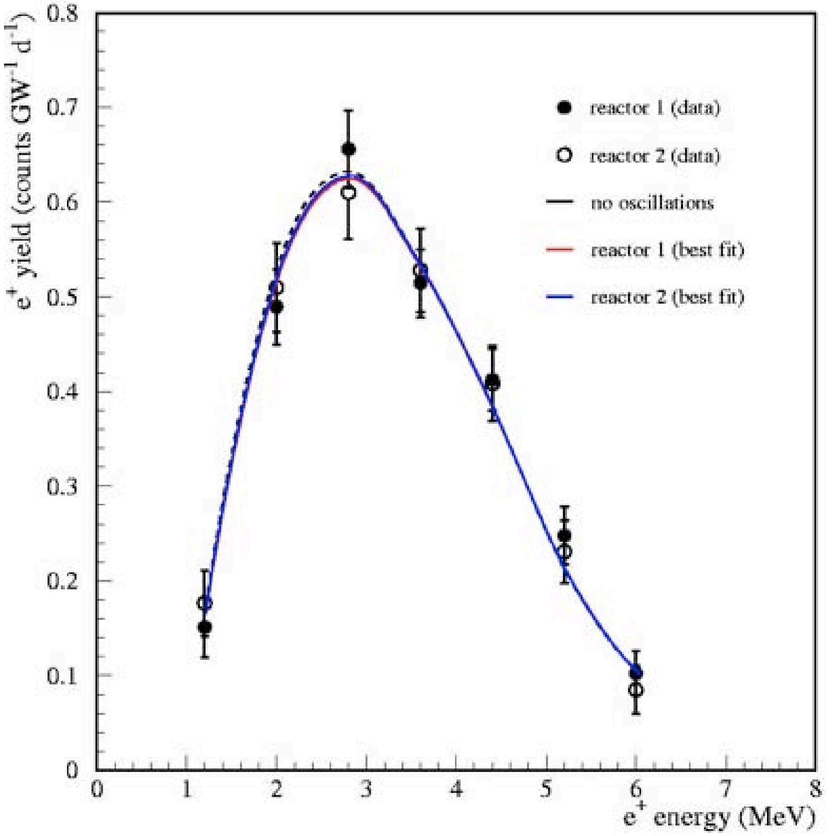


Chooz: Positron Spectrum

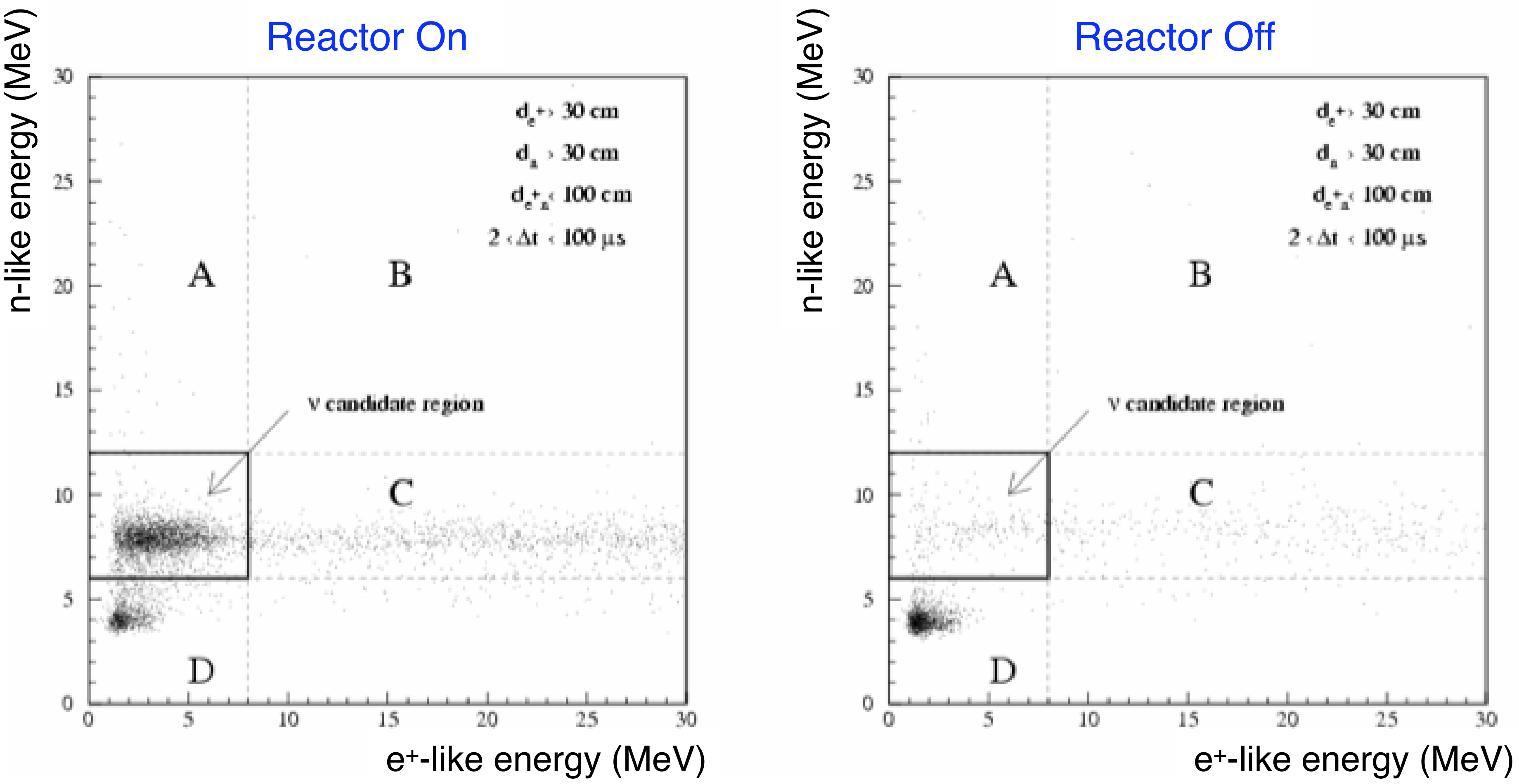
Reactor On/Off



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



Chooz: Reactor On/Off Data

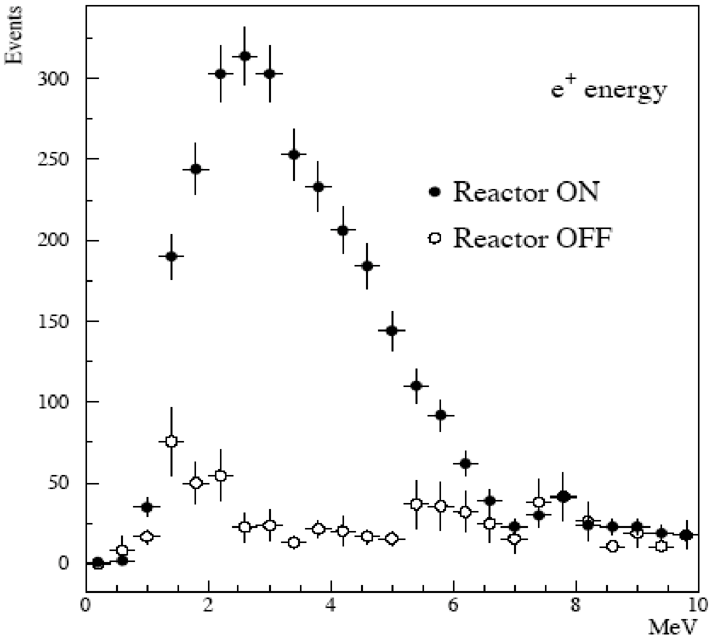


Chooz: Results

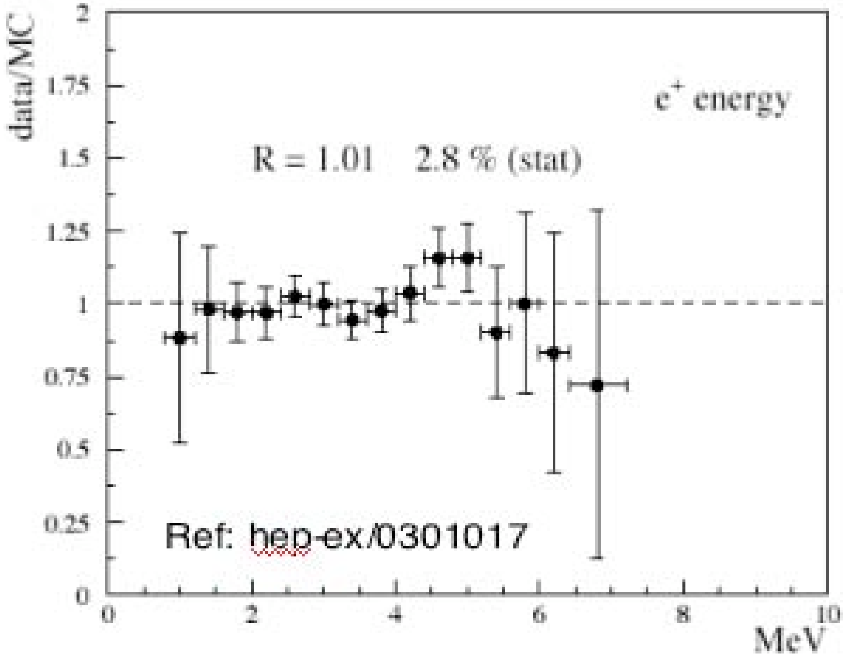
~3600 events in 335 days

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

2.7% uncertainty

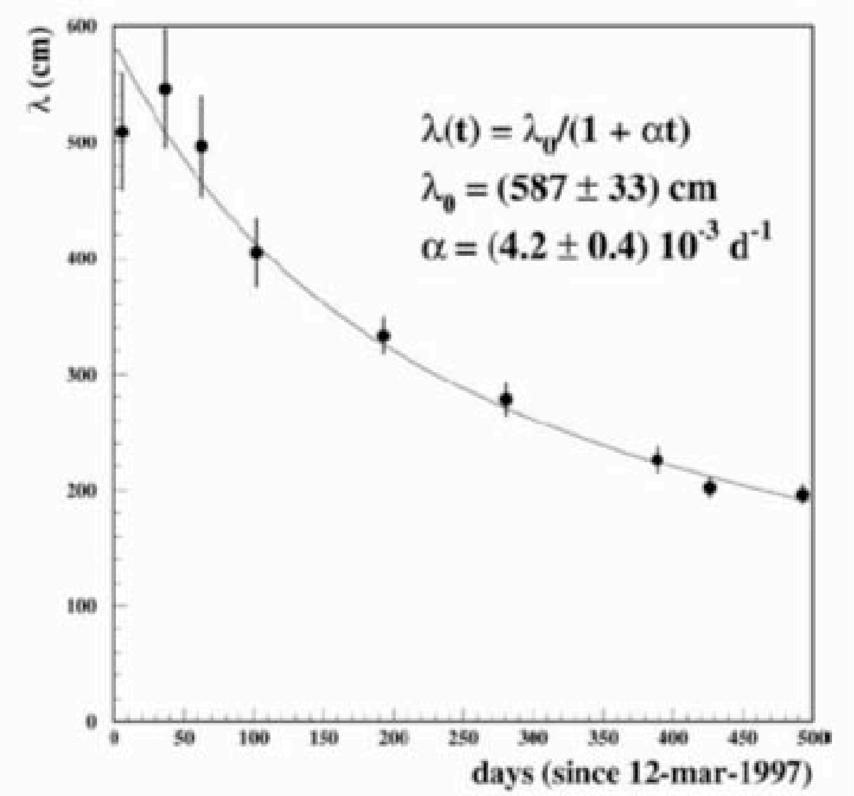


parameter	relative error (%)
reaction cross section (flux)	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%



Ref: hep-ex/0301017

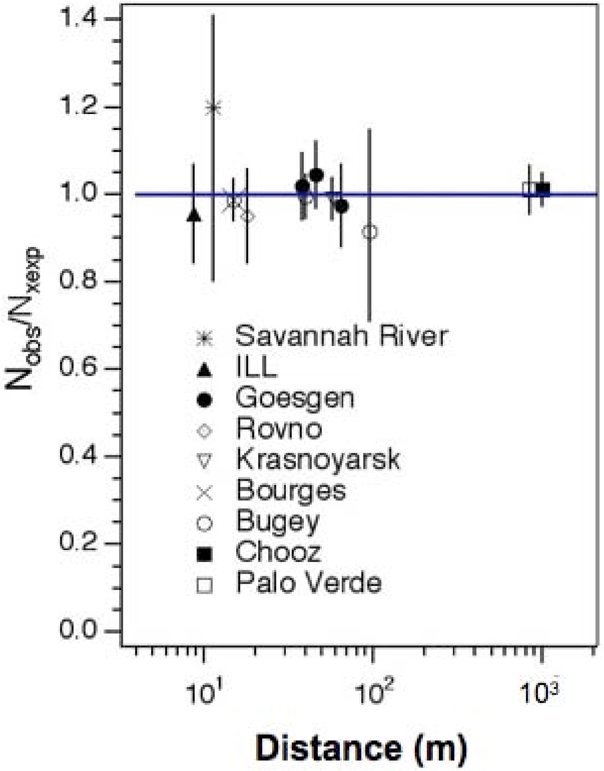
Chooz: Degradation of Scintillator



Attenuation degrades by ~0.4% per day.

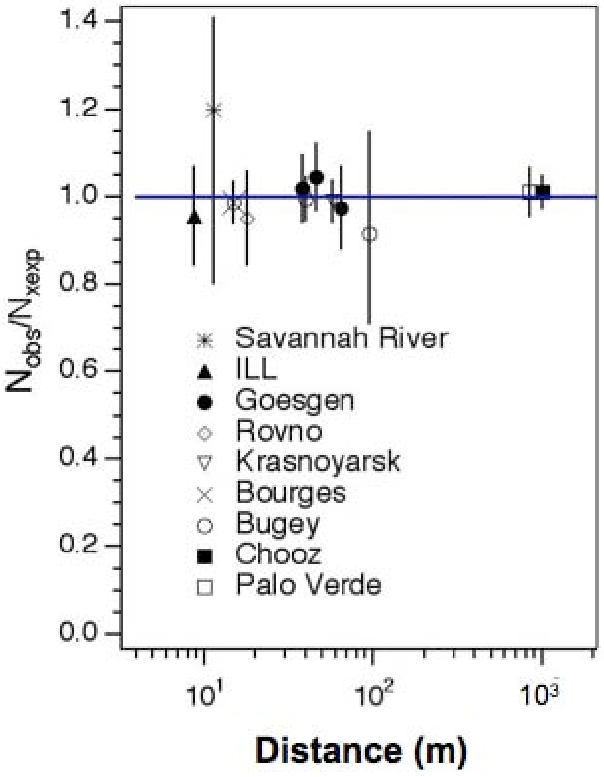
Reactor $\overline{\nu}_e$ Flux Measurements at Different Distances

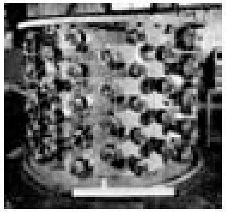
flux measurements at distances up to ~1km consistent with expectations



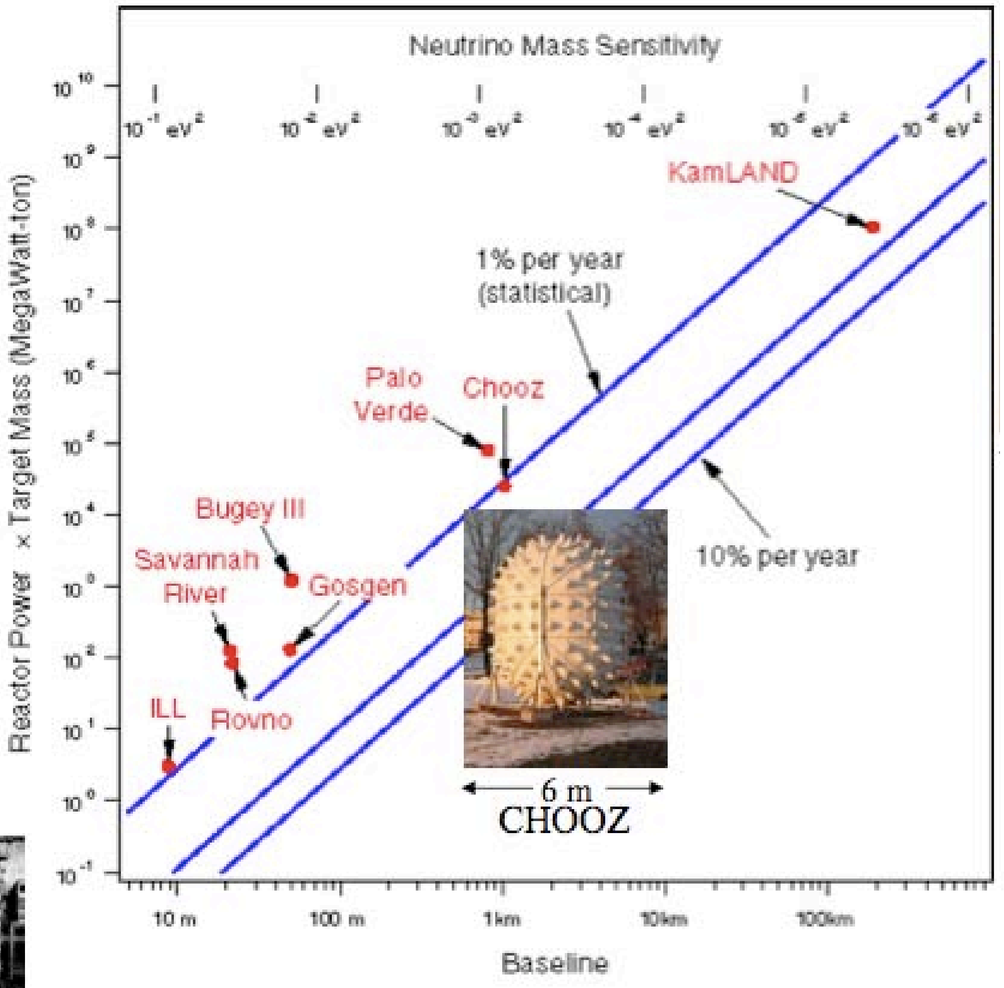
Reactor $\overline{\nu}_e$ Flux Measurements at Different Distances

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





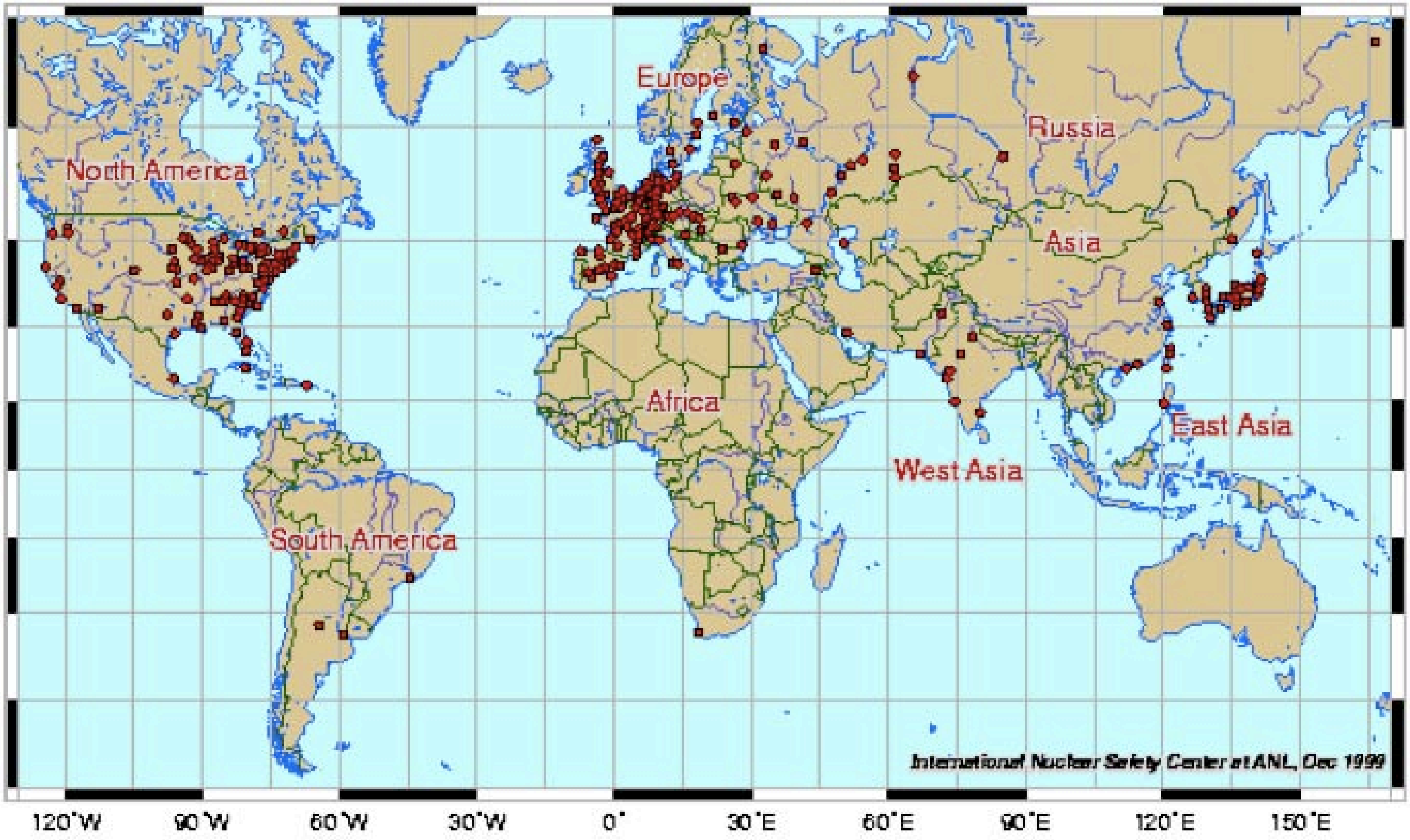
Poltergeist



Nuclear Reactors in the World

Longer baselines for reactor antineutrino flux measurements require

- large $\overline{\nu}_e$ source
- large detectors
- deep experimental site



International Nuclear Safety Center at ANL, Dec 1999

K

Measurement of Reactor Antineutrinos in KamLAND

Japanese Reactors


Kashiwazaki

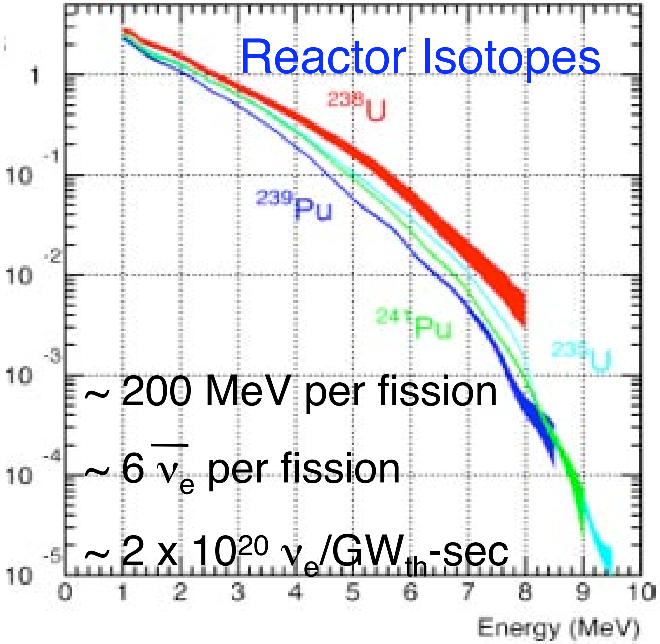

Takahama


Ohi

53 reactors


Japan

Reactor Isotopes



~ 200 MeV per fission

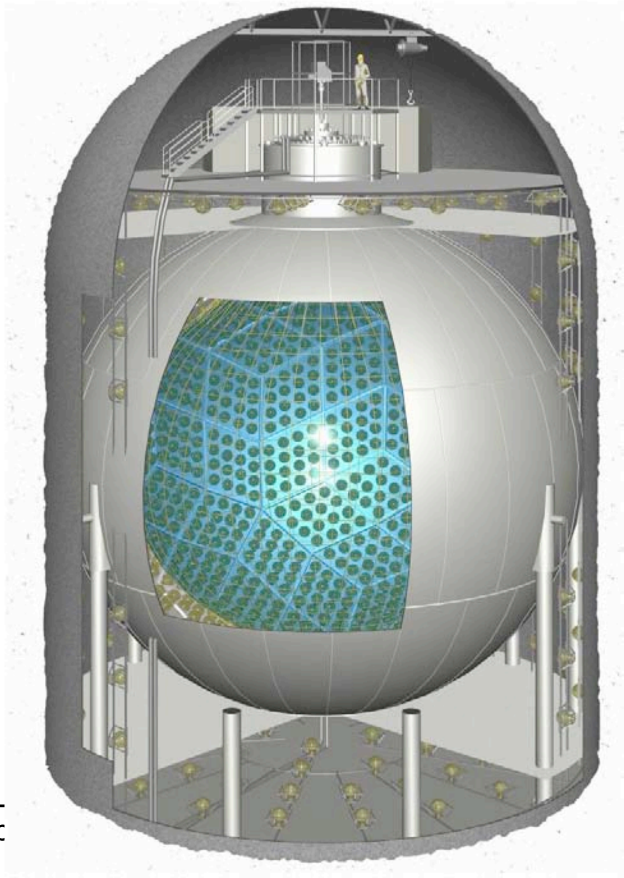
~ 6 $\bar{\nu}_e$ per fission

~ 2 x 10^{20} ν_e/GW$_{th}$-sec

reactor $\bar{\nu}$ flux ~ 6x10^6/cm^2/sec

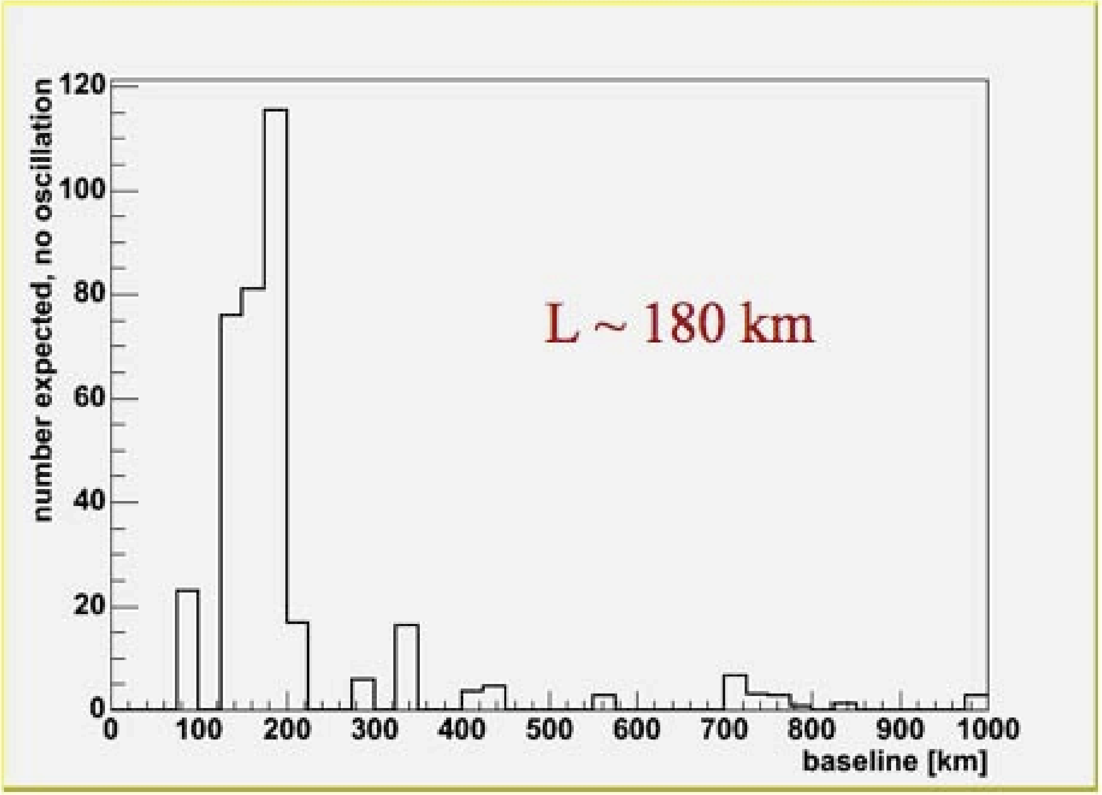
Anti-Neutrino Detection
through inverse β-decay

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



Baseline Distribution at KamLAND

A limited range of baselines contributes to the flux of antineutrinos at KamLAND

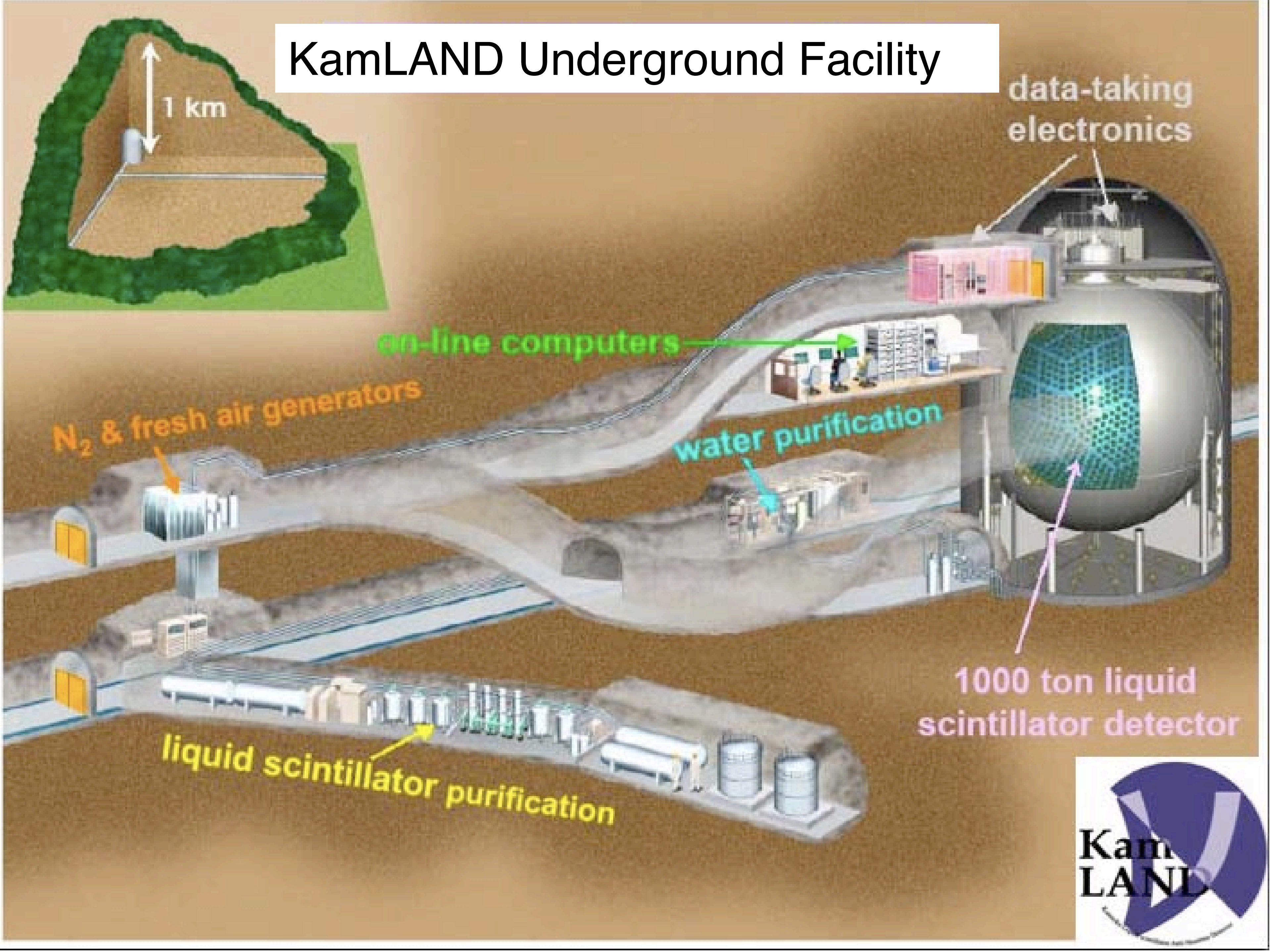


Korean reactors:
3.4±0.3%

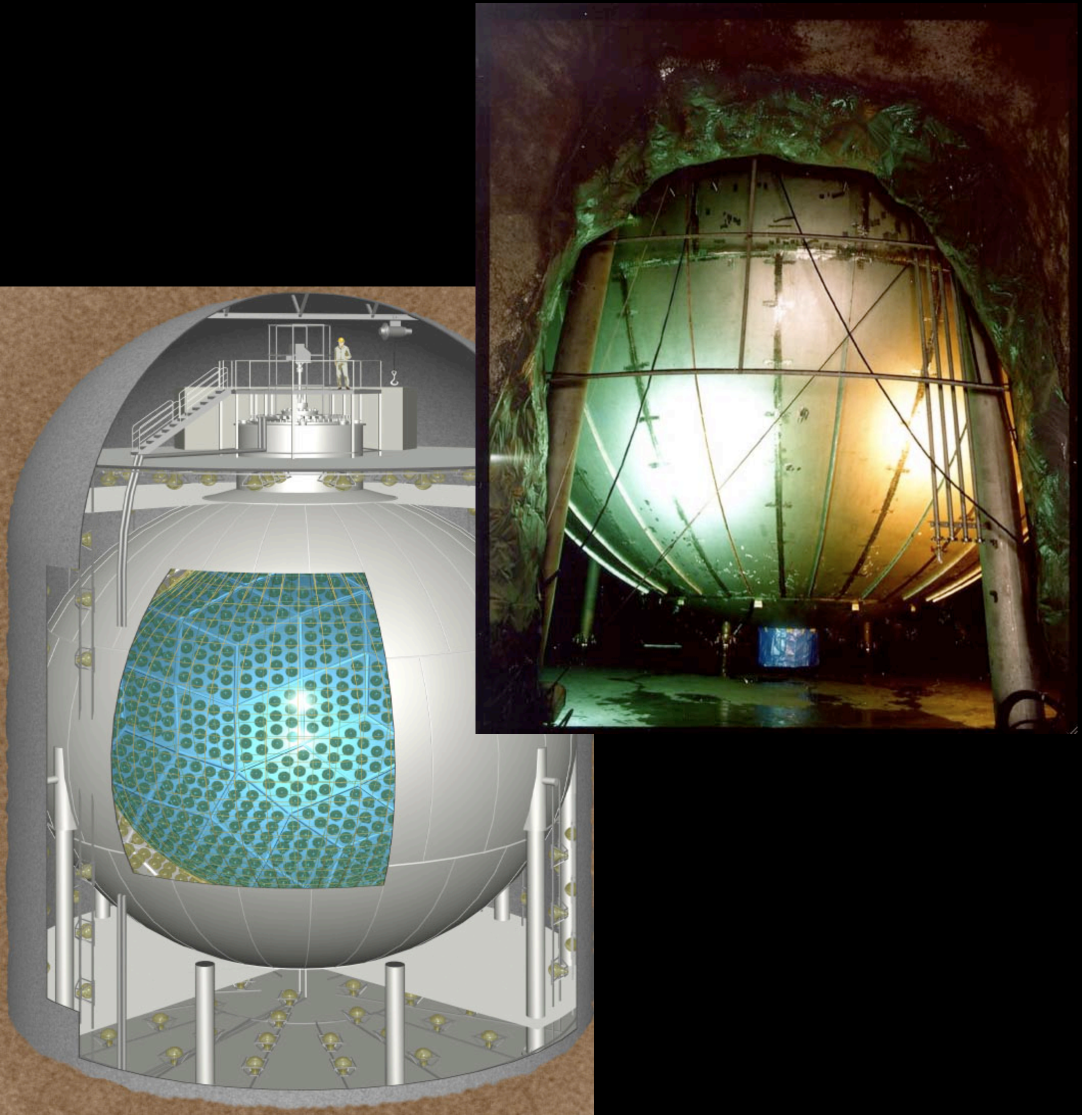
Rest of the world
+JP research reactors:
1.1±0.5%

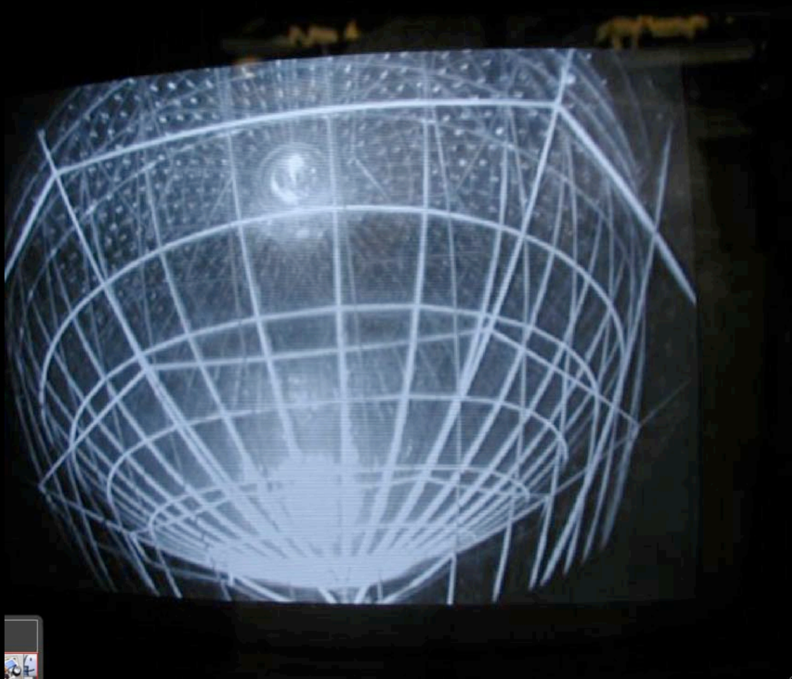
Japanese spent fuel:
0.04±0.02%

KamLAND Underground Facility

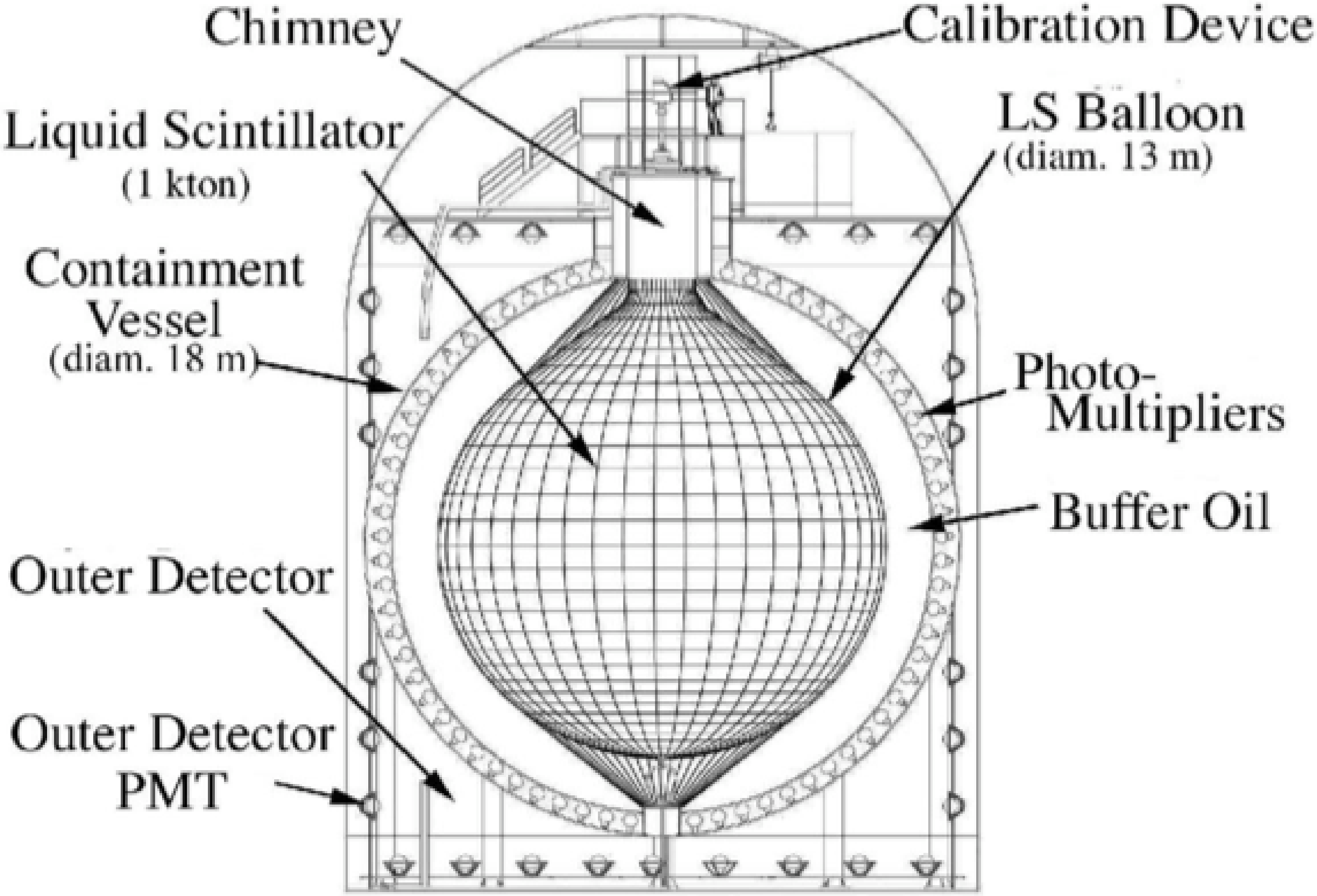


Going Underground to Detect Neutrinos

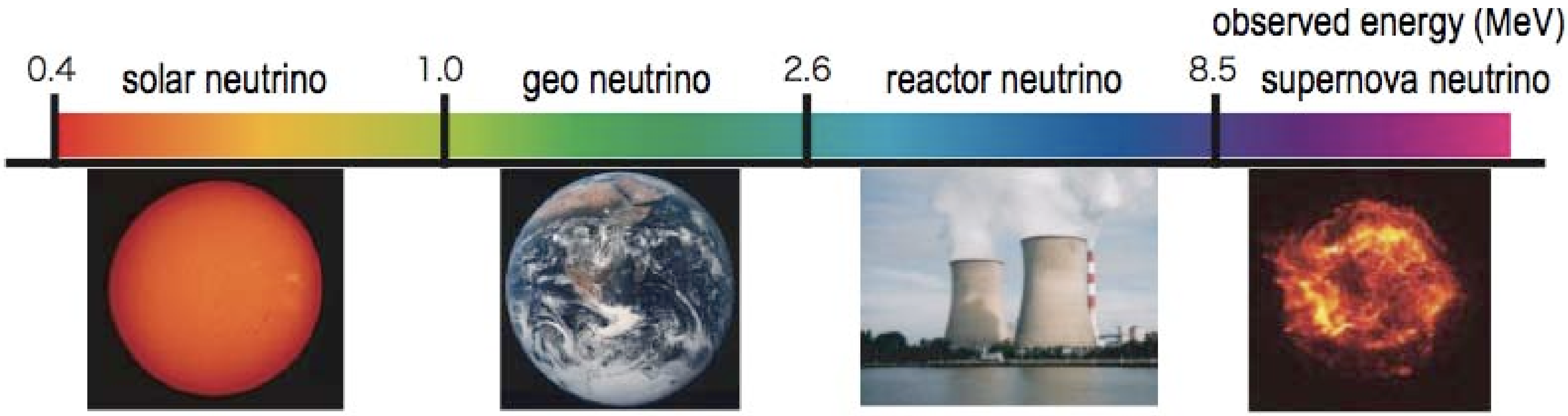


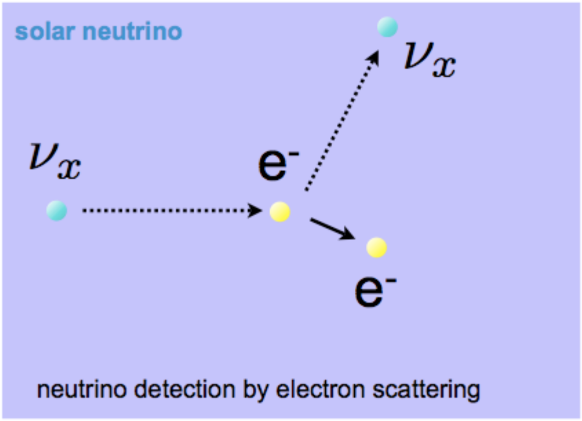


KamLAND Detector

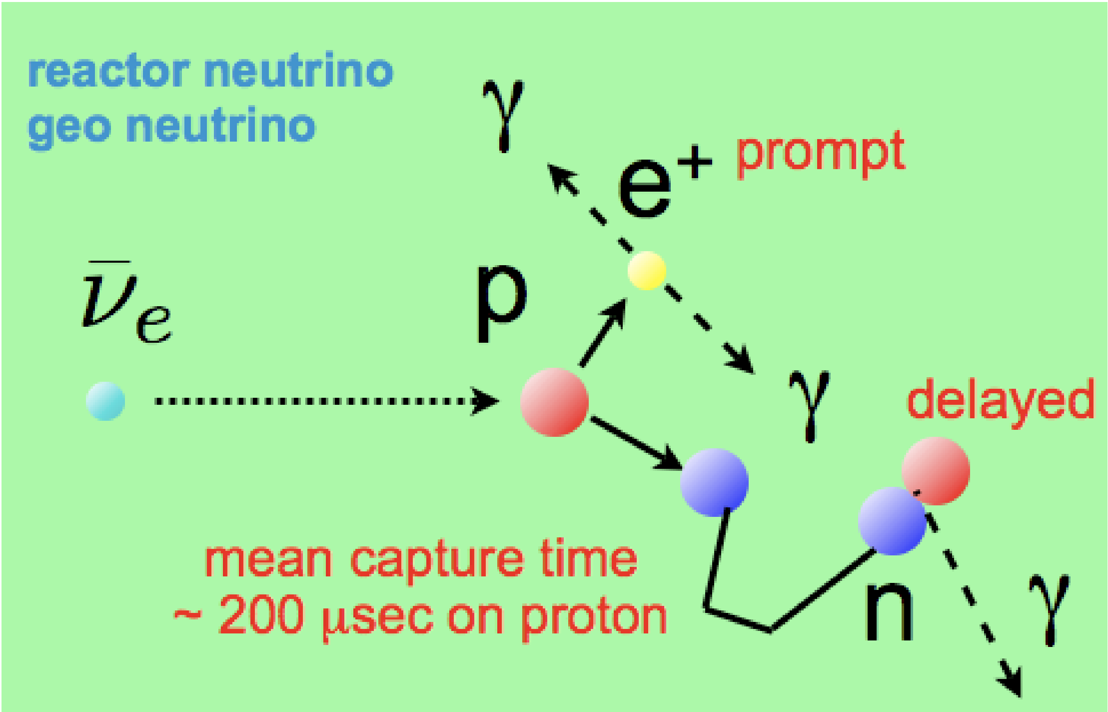


Detecting (Anti)Neutrinos in KamLAND



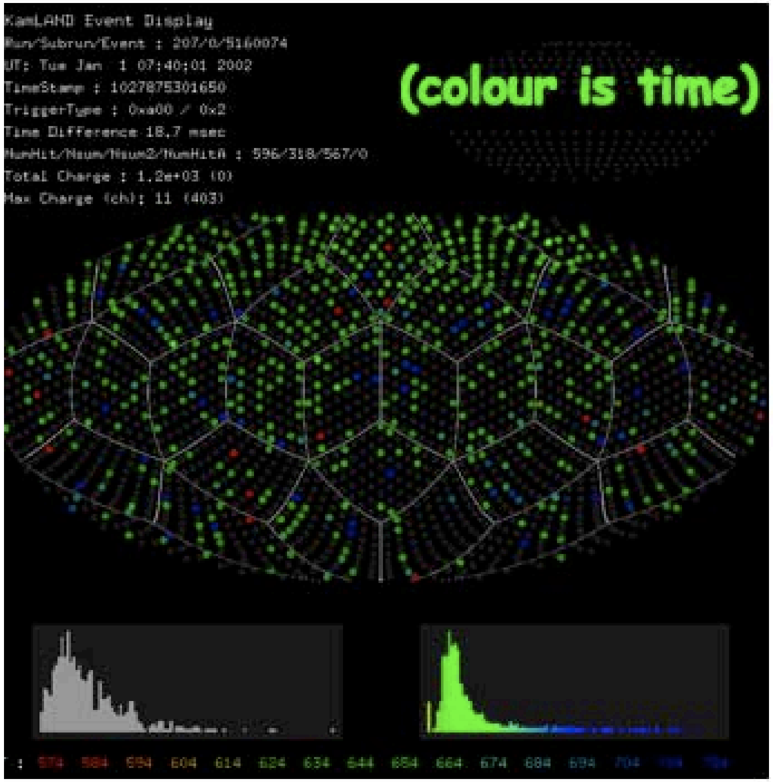


neutrino detection by electron scattering

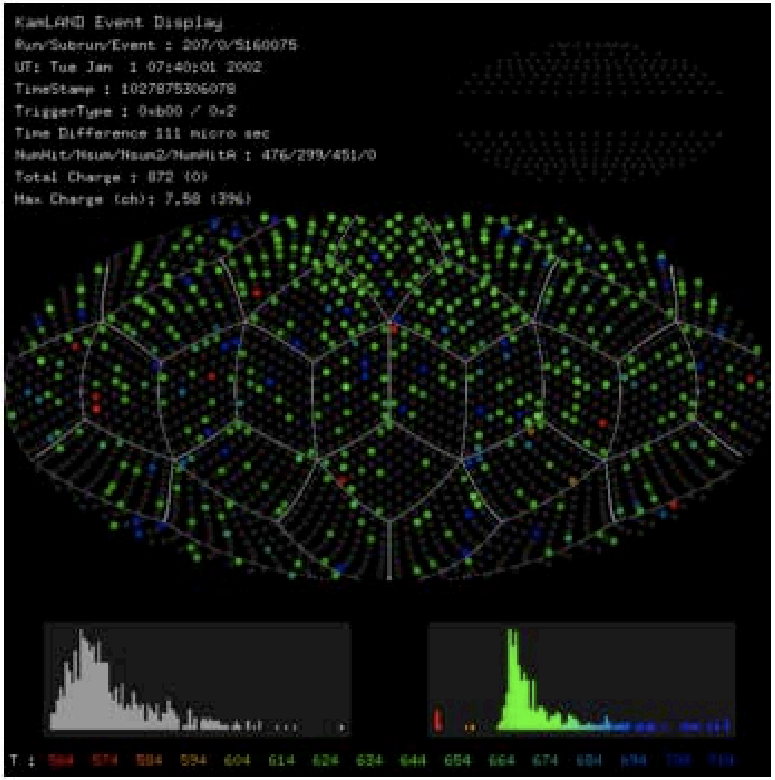


anti-neutrino detection by inverse beta-decay

Antineutrino Candidate Event



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160074
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875301650
TriggerType : 0xa00 / 0x2
Time Difference 18.7 msec
NumHit/Nsum/Nsum2/NumHitA : 596/318/567/0
Total Charge : 1.2e+03 (0)
Max Charge (ch): 11 (403)
```



```
KamLAND Event Display
Run/Subrun/Event : 207/0/5160075
UT: Tue Jan  1 07:40:01 2002
TimeStamp : 1027875306078
TriggerType : 0xb00 / 0x2
Time Difference 111 micro sec
NumHit/Nsum/Nsum2/NumHitA : 476/299/451/0
Total Charge : 872 (0)
Max Charge (ch): 7.58 (396)
```

Prompt Signal
E = 3.20 MeV

Δt = 111 ms
ΔR = 34 cm

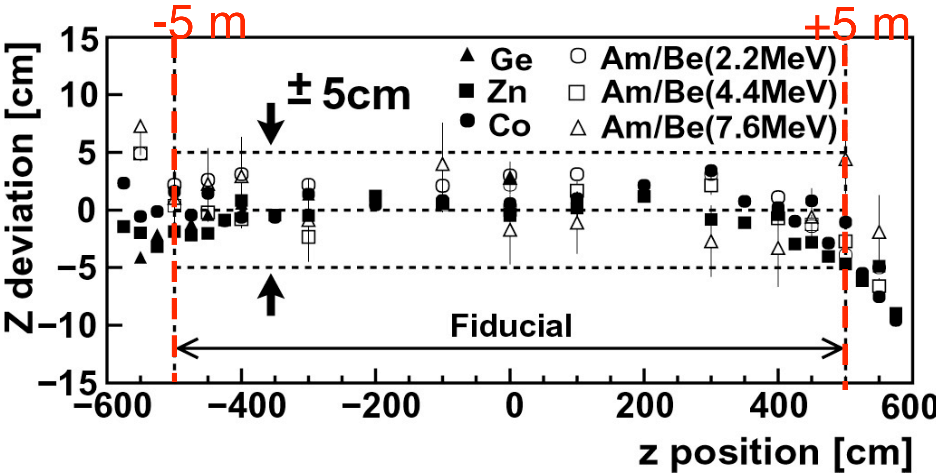
Delayed Signal
E = 2.22 MeV

KamLAND

KamLAND z-axis Calibration

Routine Calibration Sources

^{68}Ge	e^+	2 x 0.511 MeV
^{65}Zn	γ	1.116 MeV
^{60}Co	γ	2.506 MeV
AmBe	γ, n	2.22, 4.44, and 7.65 MeV
Laser and LEDs		



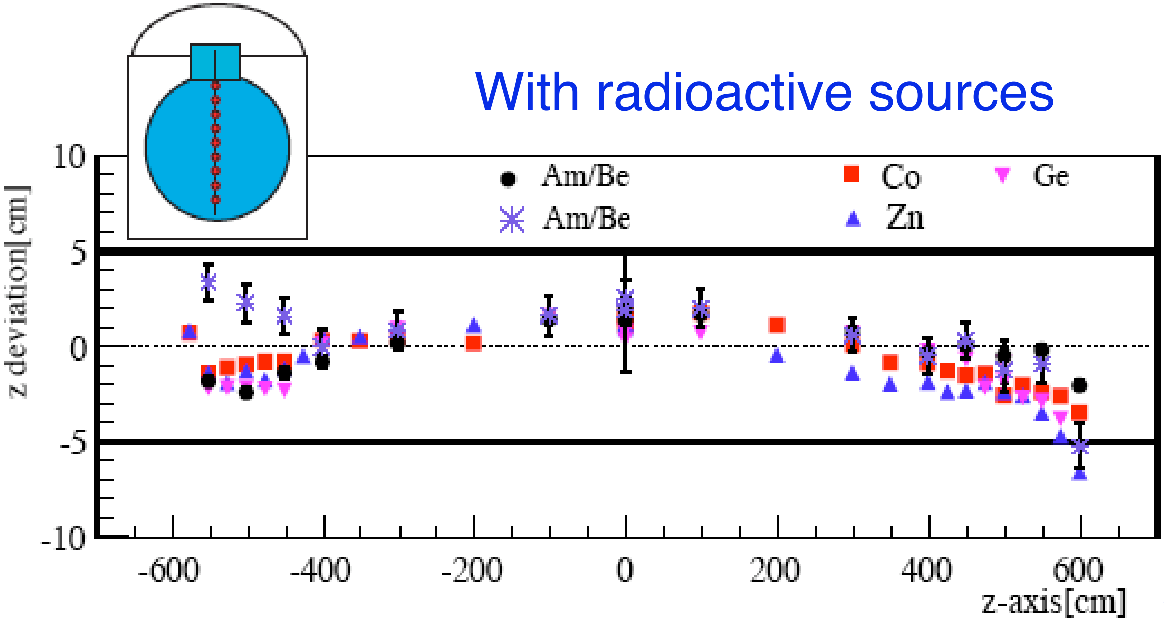
^{60}Co: 1.173+1.333 MeV in the detector

σ = 6.2% / $\sqrt{E}$

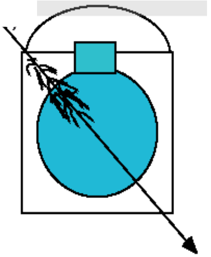
light yield: 239 p.e./MeV

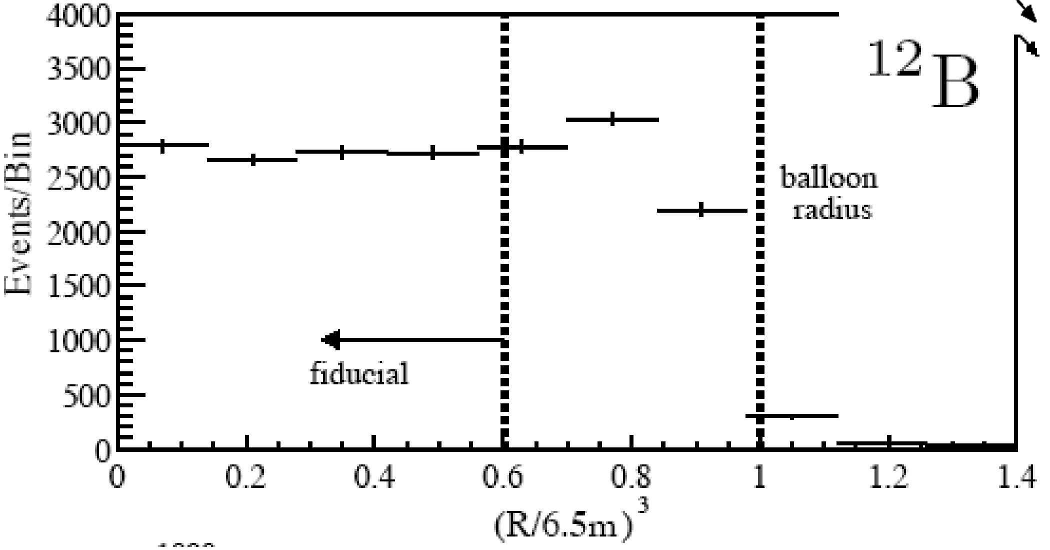
Fiducial Volume Determination

With radioactive sources



With muon spallation



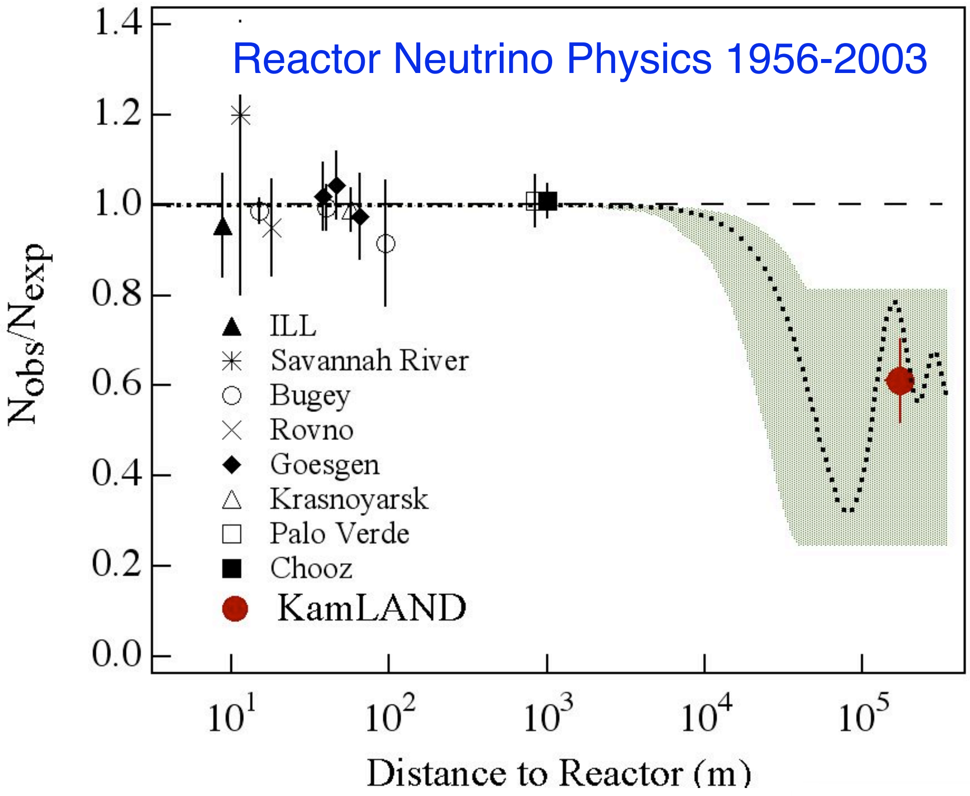


Fiducial/Total Volume Ratios

Geometrical	0.595 ± 0.013
^{12}B β-decays	0.607 ± 0.006
p(n,γ)d	0.587 ± 0.013
^{9}Li relative	< 2.7%

KamLAND volume error: 4.7%

KamLAND in 2003:
First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance



PRL 90:021802 (2003)

Observed ν_e	54 events
No-Oscillation events	86.8 ± 5.6
Background	1 ± 1 events
Livetime:	162.1 ton-yr

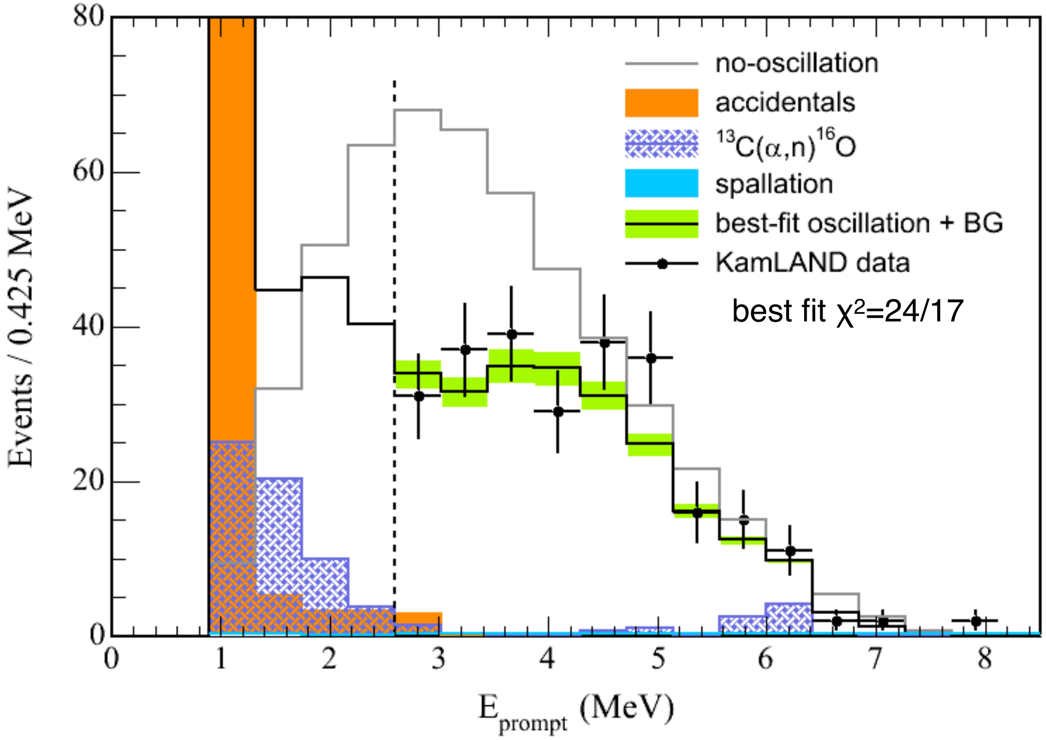
50 Years of Reactor Neutrino Physics

1953 First reactor neutrino experiment

1956 *“Detection of Free Antineutrino”,*Reines and Cowa
→ Nobel Prize in 1995

2003 KamLAND’s observation of ν_e disappearance

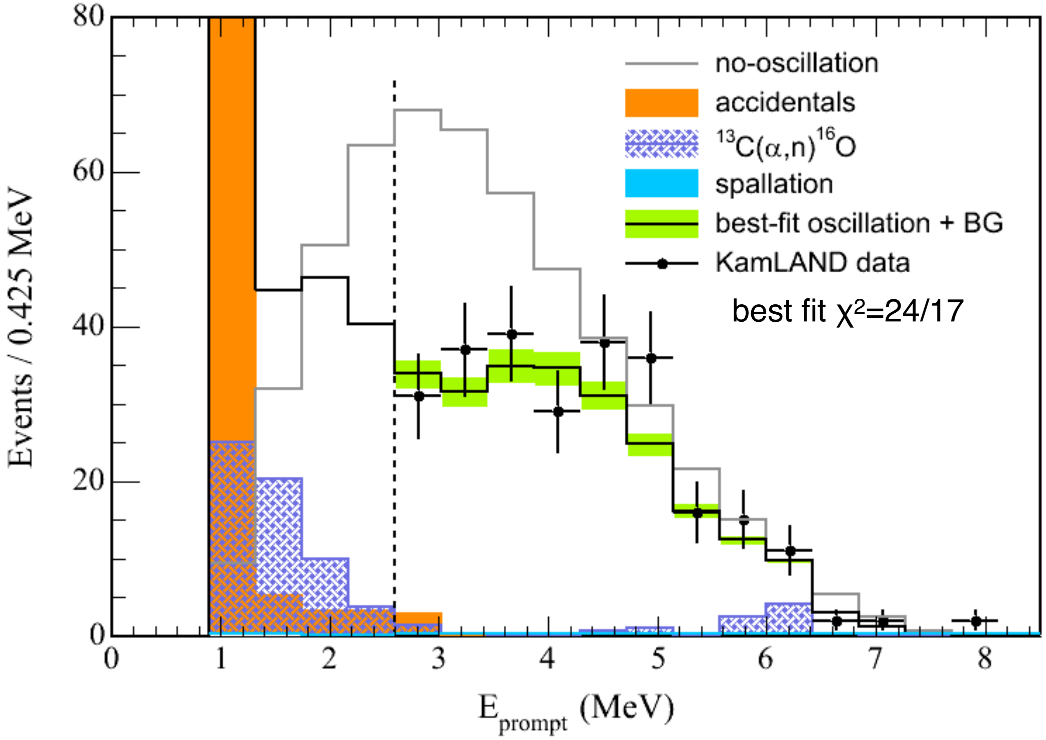
KamLAND in 2004:
Evidence of Spectral Distortion in Energy Spectrum



hep-ex/0406035 (2004)

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

KamLAND in 2004:
Evidence of Spectral Distortion in Energy Spectrum



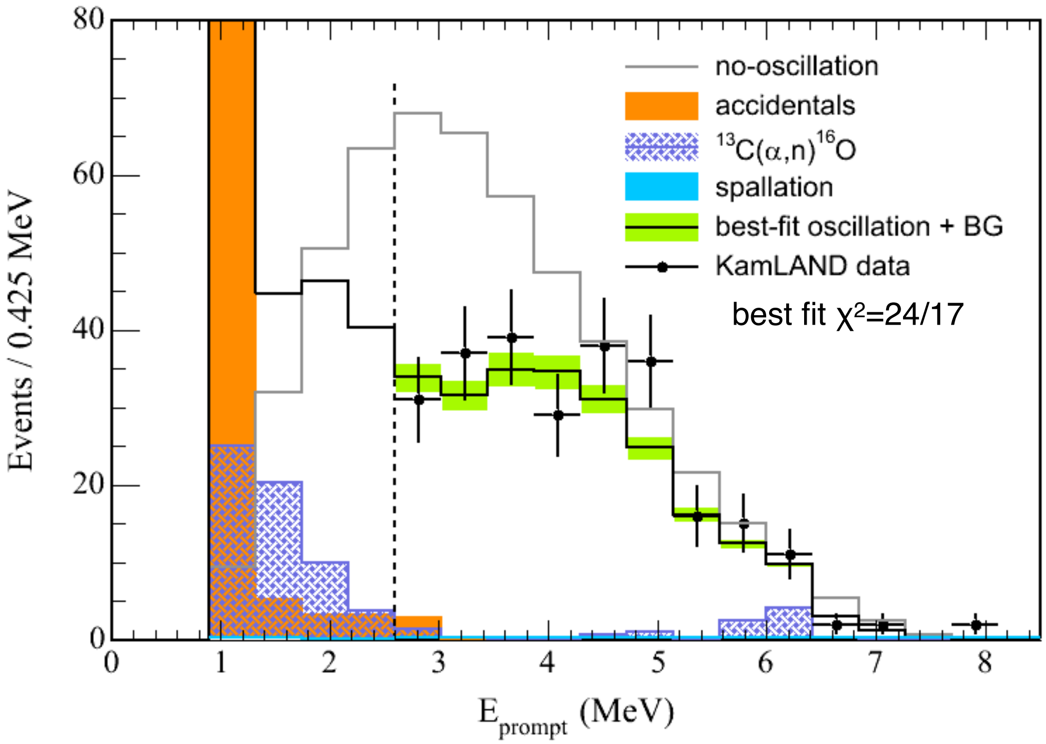
hep-ex/0406035 (2004)

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

Spectral Distortions: A unique signature of neutrino oscillation!

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

KamLAND in 2004:
Evidence of Spectral Distortion in Energy Spectrum



hep-ex/0406035 (2004)

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

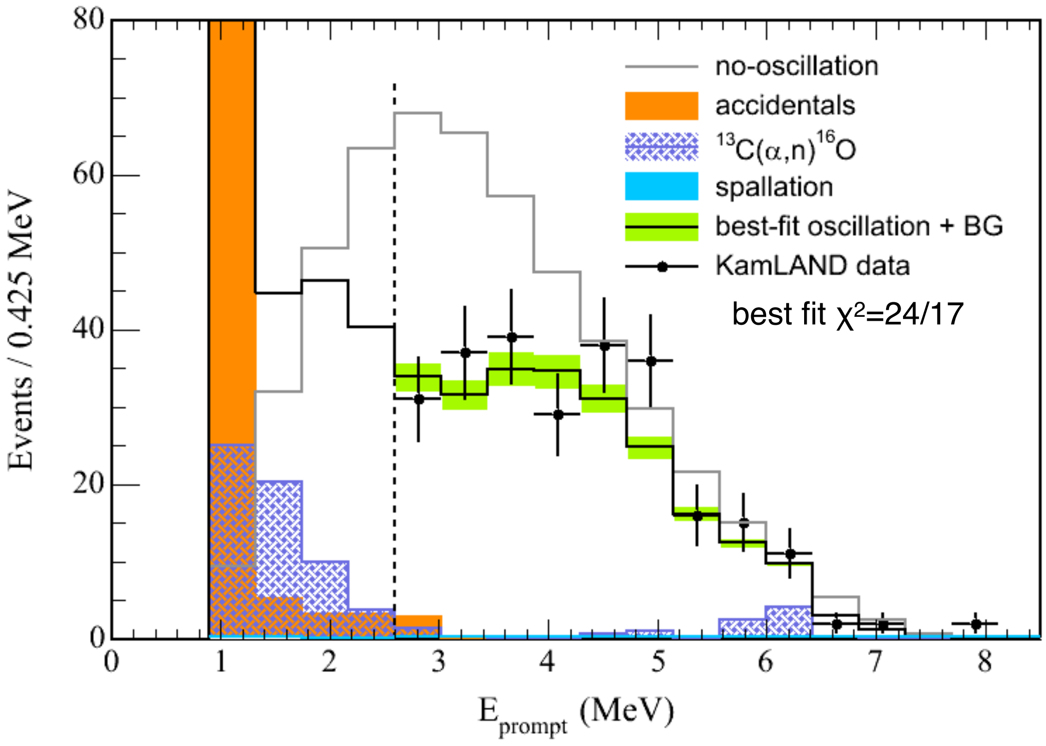
$$^{210}Pb \longrightarrow {}^{210}Bi \longrightarrow {}^{210}Po \xrightarrow{138d,\ \alpha} {}^{206}Pb$$

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

Spectral Distortions: A unique signature of neutrino oscillation!

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

KamLAND in 2004:
Evidence of Spectral Distortion in Energy Spectrum



hep-ex/0406035 (2004)

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

Future

Reduce ^{210}Pb, lower analysis threshold.

Reduce systematic error with improved calibrations.

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

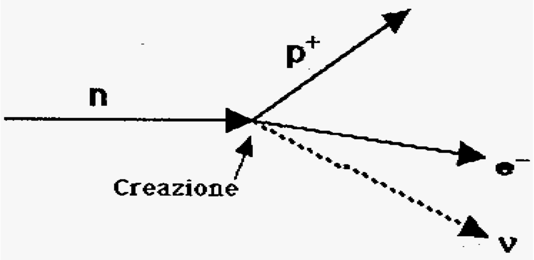
$$\longrightarrow {}^{13}C(\alpha,n)^{16}O \quad (\sim 10^{-7})$$

Spectral Distortions: A unique signature of neutrino oscillation!

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

Neutrino Oscillation

Fermi, 1934



Neutrino States

Mass States

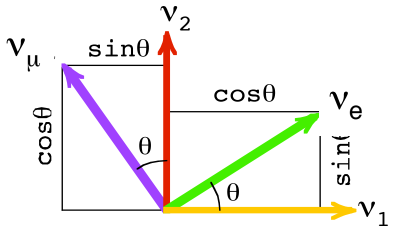
First

Second

Weak States

First

Second

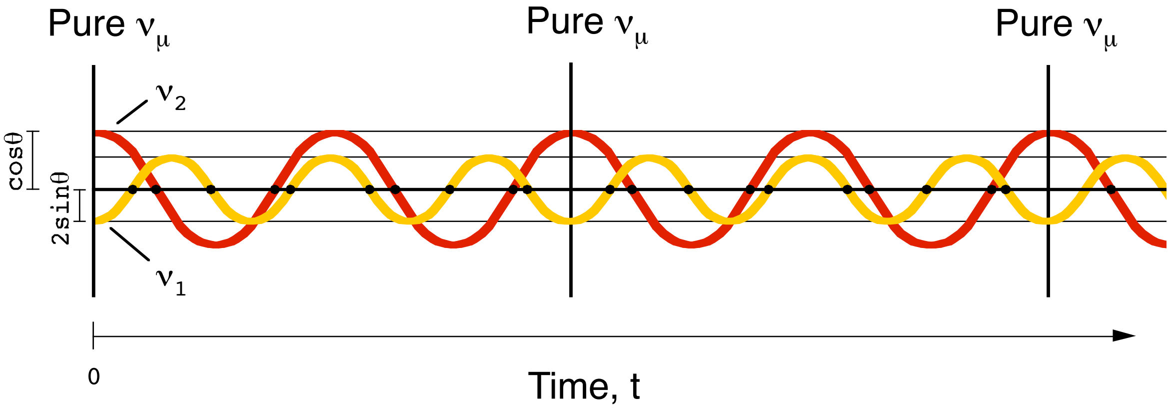


$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{bmatrix}\cos\theta & \sin\theta\\ 2\sin\theta & \cos\theta\end{bmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Time Evolution

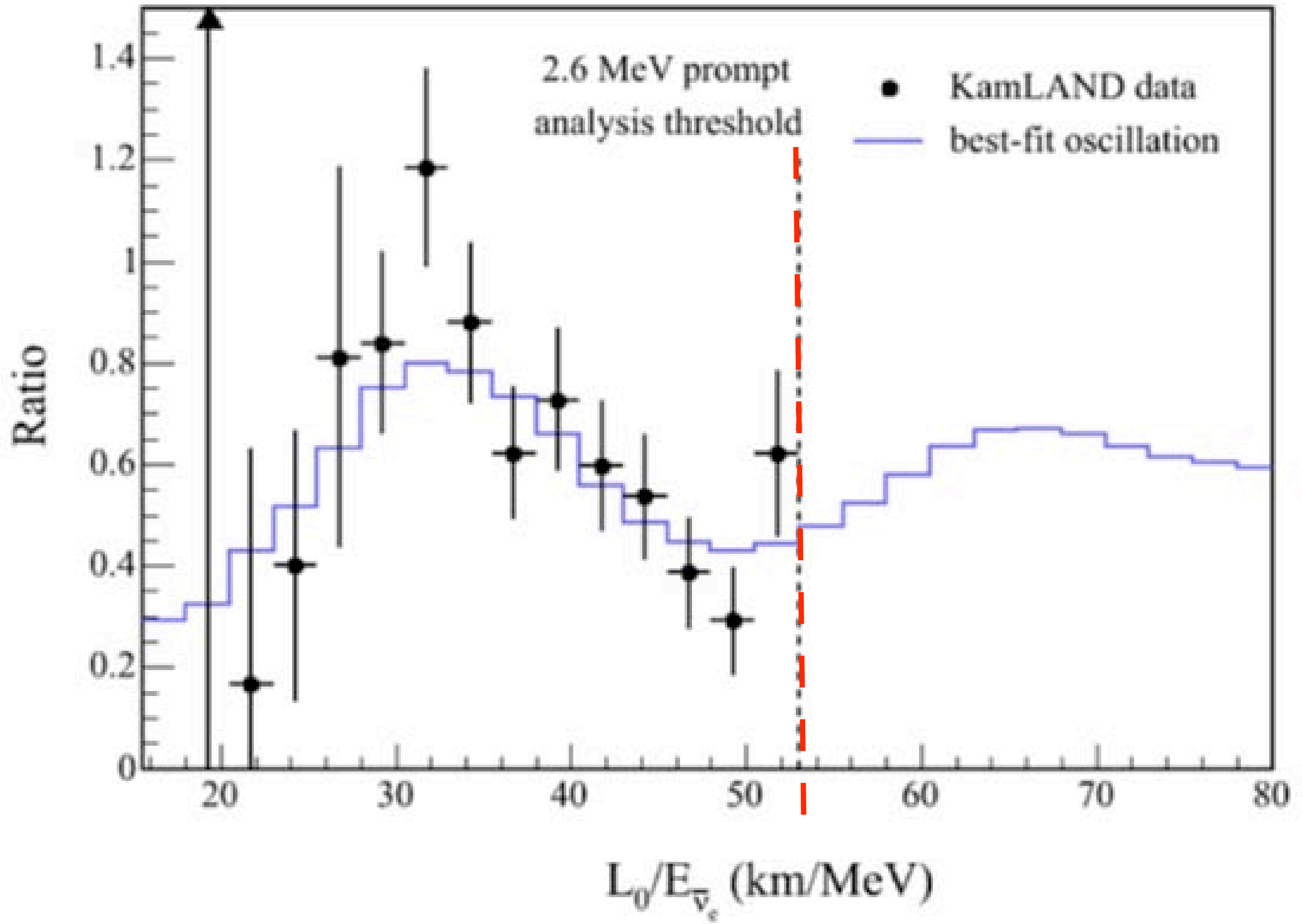
Бруно Понтекорво

Pontecorvo, 1968



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

KamLAND 2004 Data



L_0=180 km

KamLAND - Systematic Uncertainties

E > 2.6 MeV

	%
Fiducial volume	4.7
Energy threshold	2.3
Efficiency of cuts	1.6
Live time	0.06
Reactor power	2.1
Fuel composition	1.0
$\bar{\nu}_e$ spectra	2.5
cross section	0.2
Total uncertainty	6.5 %

KamLAND - Systematic Uncertainties

E > 2.6 MeV

	%	
Fiducial volume	4.7	
Energy threshold	2.3	
Efficiency of cuts	1.6	
Live time	0.06	
Reactor power	2.1	*given by reactor company, difficult to improve on*
Fuel composition	1.0	
$\bar{\nu}_e$ spectra	2.5	*theoretical, model-dependent*
cross section	0.2	
Total uncertainty	6.5 %	

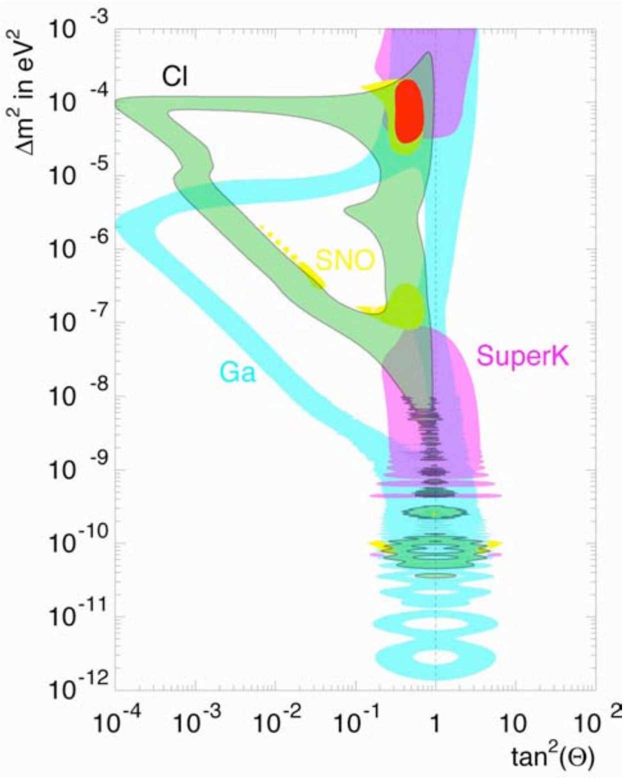
KamLAND - Systematic Uncertainties

E > 2.6 MeV

	%	
Fiducial volume	4.7	volume calibration
Energy threshold	2.3	energy calibration or analysis w/out threshold
Efficiency of cuts	1.6	
Live time	0.06	
Reactor power	2.1	*given by reactor company, difficult to improve on*
Fuel composition	1.0	
$\bar{\nu}_e$ spectra	2.5	*theoretical, model-dependent*
cross section	0.2	
Total uncertainty	6.5 %	

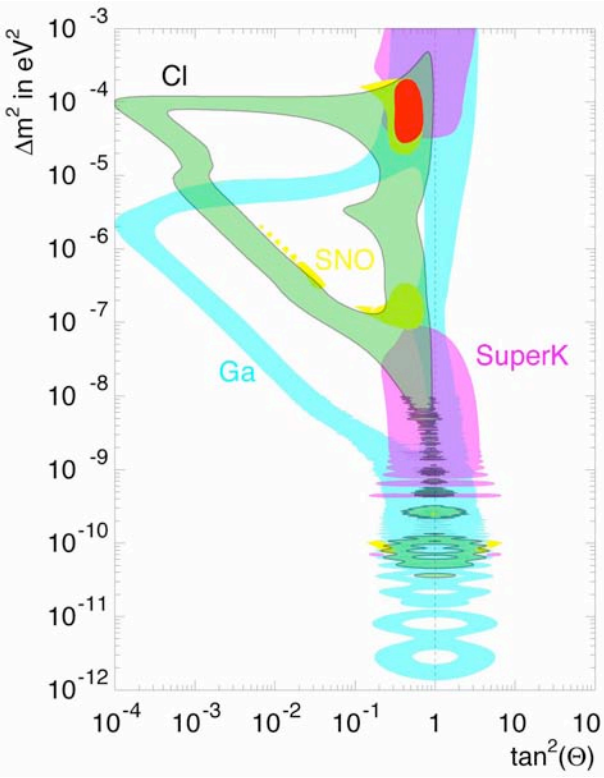
Measuring Neutrino Oscillation Parameters

Solar Neutrinos

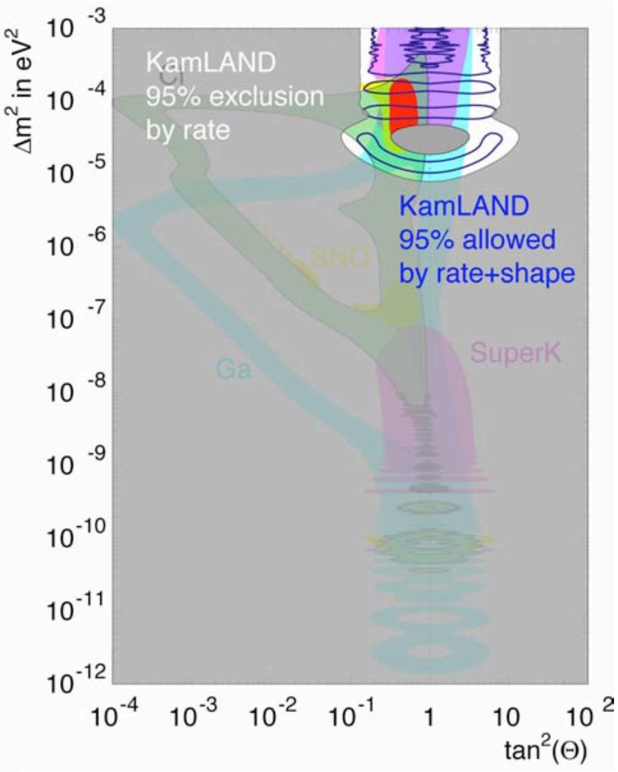


Measuring Neutrino Oscillation Parameters

Solar Neutrinos



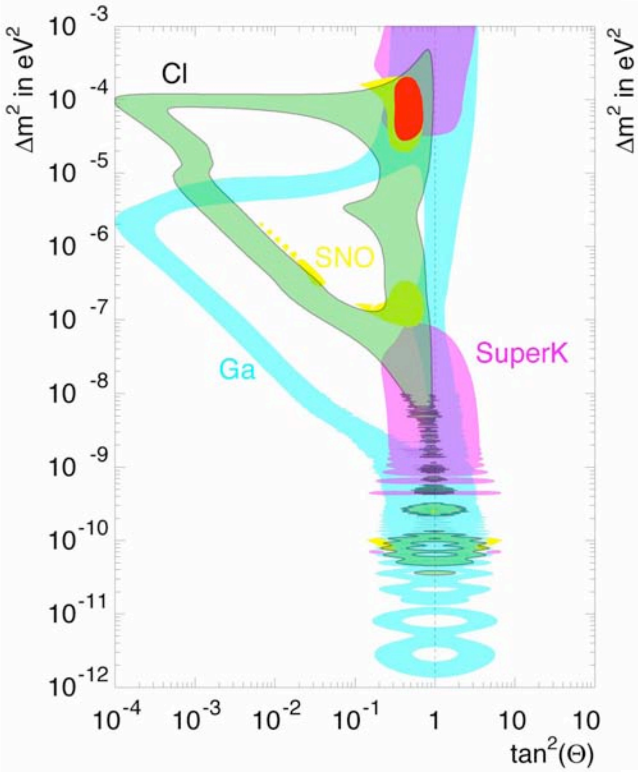
Solar Neutrinos
+ KamLAND 2003
($\bar{\nu}_e$ rate)



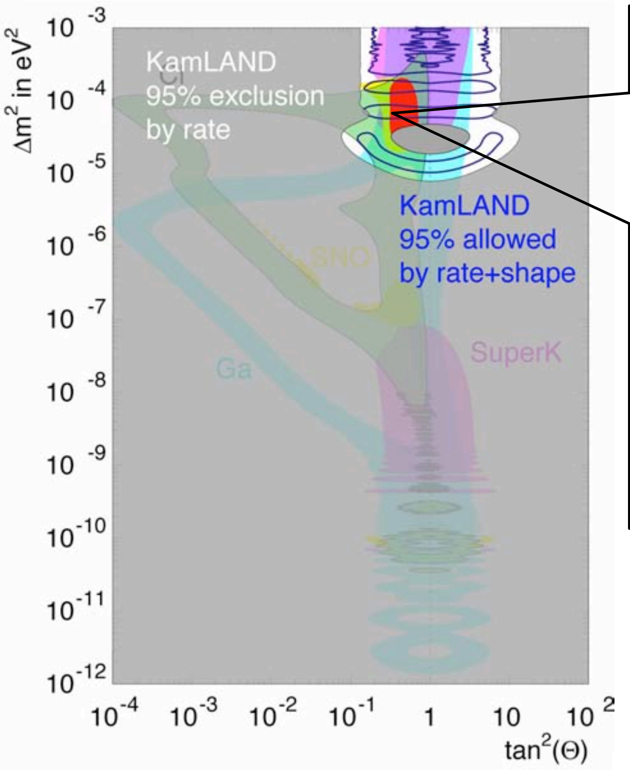
Agreement between oscillation parameters for $\bar{\nu}$ and ν

Measuring Neutrino Oscillation Parameters

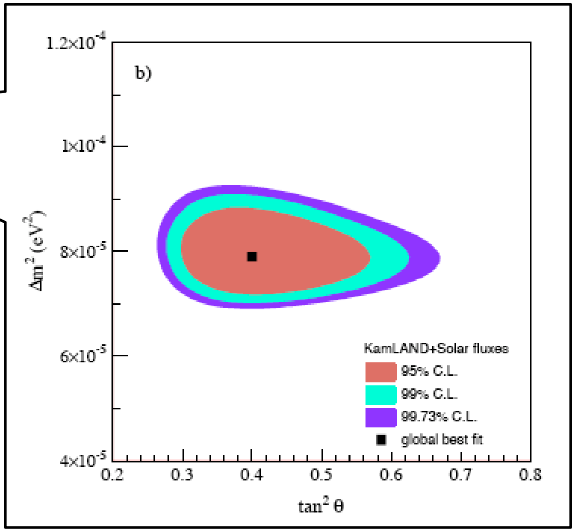
Solar Neutrinos



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



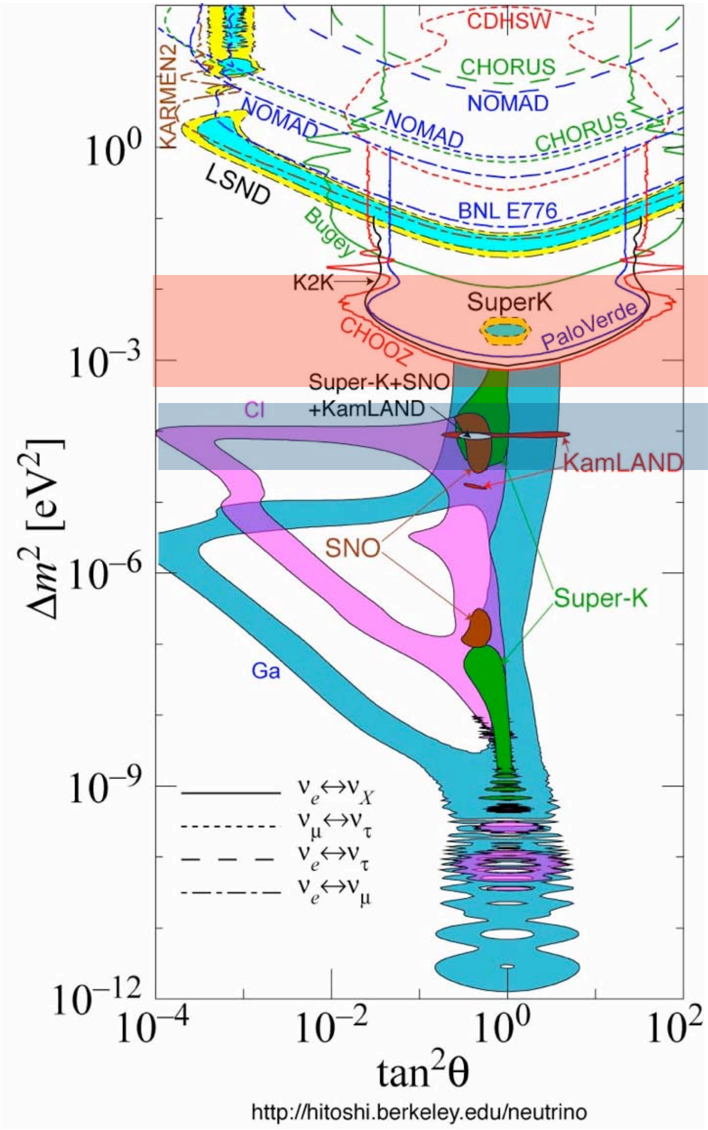
Solar Neutrinos
+ KamLAND 2004
($\bar{\nu}_e$ rate+spectrum)



Precision neutrino physics

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

Discovery Era in Neutrino Physics: 1998 - Present

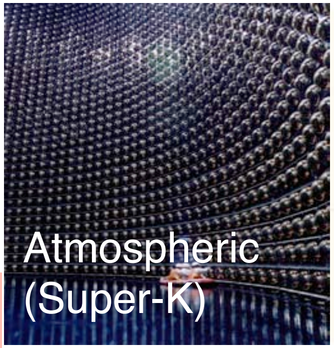


http://hitoshi.berkeley.edu/neutrino

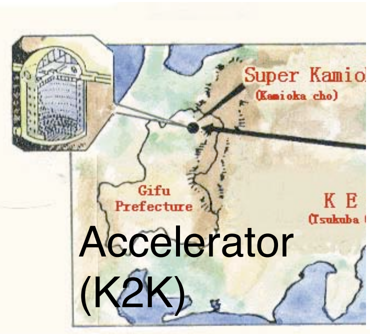
$\nu_\mu \Rightarrow \nu_\tau$

$\nu_e \Rightarrow \nu_{\mu,\tau}$

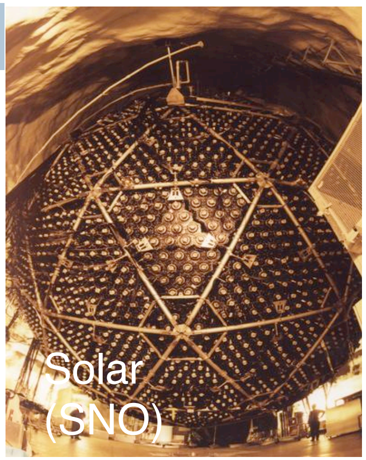
Δm_{ij}^2 measured
and confirmed.



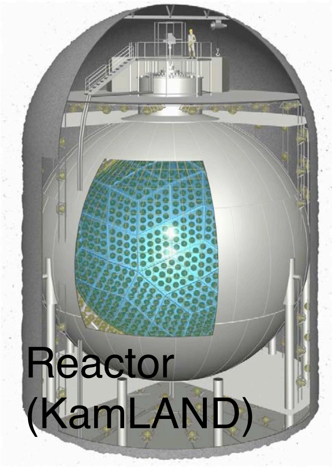
Atmospheric
(Super-K)



Accelerator
(K2K)



Solar
(SNO)



Reactor
(KamLAND)

SK: zenith angle dependence of atm ν_μ
SNO: solar ν_e flavor transformation
KamLAND: reactor $\bar{\nu}_e$ disappearance

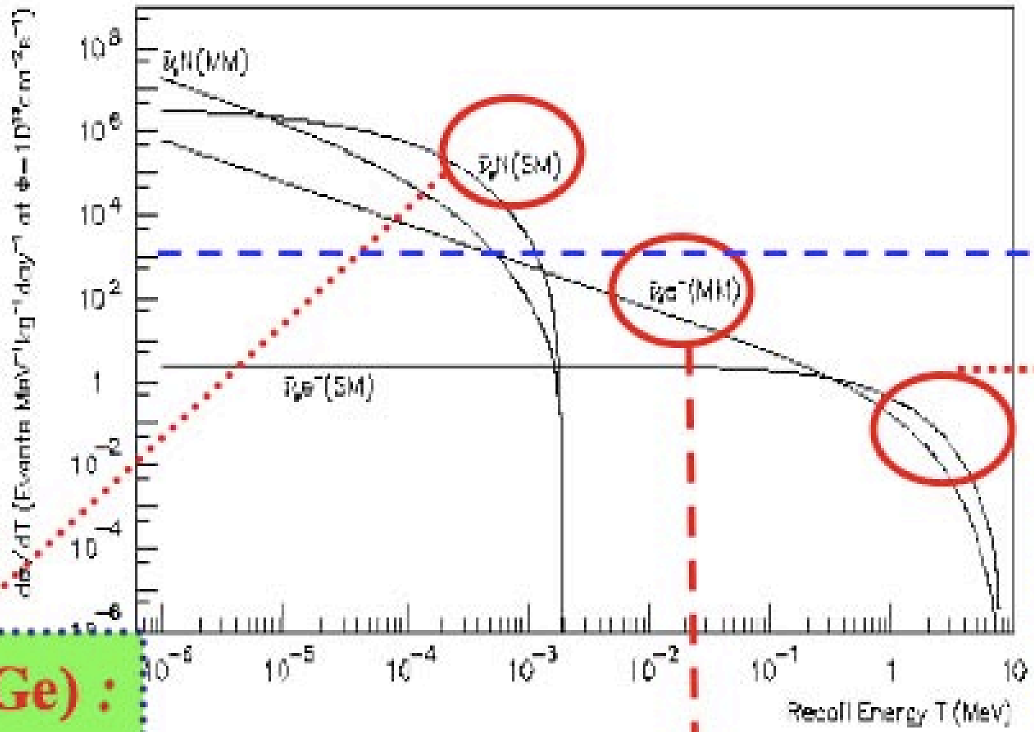
Other Reactor Neutrino Physics: Texono

- TEXONO Collaboration – Academia Sinica-based and run, with groups from China, Turkey & India, close partnership with KIMS group in Korea.
- Facilities – Kuo-Sheng Reactor Neutrino Laboratory in Taiwan; YangYang Underground Laboratory in South Korea.
- Program – Low Energy Neutrino and Astroparticle (Dark Matter) Physics. Neutrino Magnetic Moments, Neutrino Radiative Decays, Axions

from Jun Cao, Lepton/Photon

Reactor Neutrino Interaction Cross-Sections

quality ← **Detector requirements** → **mass**



Bkg level at O(10 keV)~ 1 counts / kg-keV-day

R&D (ULEGe) :

- **Coh. (νN)**
- **T < 1 keV**

Results (HPGe):

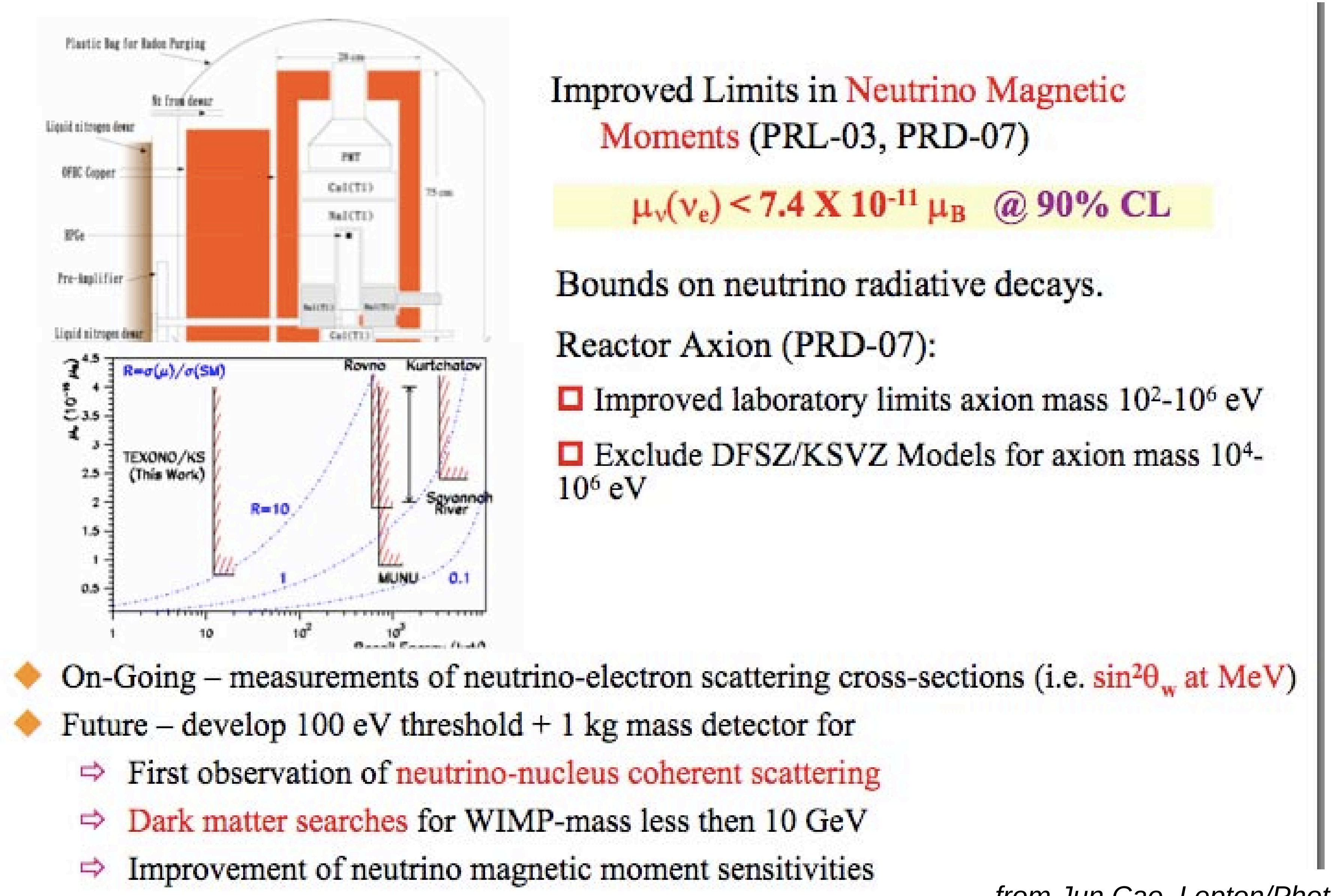
- **$\mu_\nu(\nu_e)$**
- **T ~ 1-100 keV**

On-Going Data Taking & Analysis [CsI(Tl)] :

- **SM σ(νe)**
- **T > 2 MeV**

from Jun Cao, Lepton/Photon

Texono 2007 Highlights



Improved Limits in Neutrino Magnetic Moments (PRL-03, PRD-07)

$\mu_\nu(\nu_e) < 7.4 \text{ X } 10^{-11}\ \mu_B$ @ 90% CL

Bounds on neutrino radiative decays.

Reactor Axion (PRD-07):

- ☐ Improved laboratory limits axion mass 10^2-10^6 eV
- ☐ Exclude DFSZ/KSVZ Models for axion mass 10^4-10^6 eV

- On-Going – measurements of neutrino-electron scattering cross-sections (i.e. $\sin^2\theta_w$ at MeV)
- Future – develop 100 eV threshold + 1 kg mass detector for
  - ⇨ First observation of neutrino-nucleus coherent scattering
  - ⇨ Dark matter searches for WIMP-mass less then 10 GeV
  - ⇨ Improvement of neutrino magnetic moment sensitivities

from Jun Cao, Lepton/Photon