Workshop on the feasibility study of

the Daya Bay reactor neutrino experiment

Jan. 17-18, 2004 in IHEP, Beijing

Past Reactor Experiments (Some Lessons From History)

Stuart Freedman
University of California at Berkeley
and
Lawrence Berkeley National Laboratory

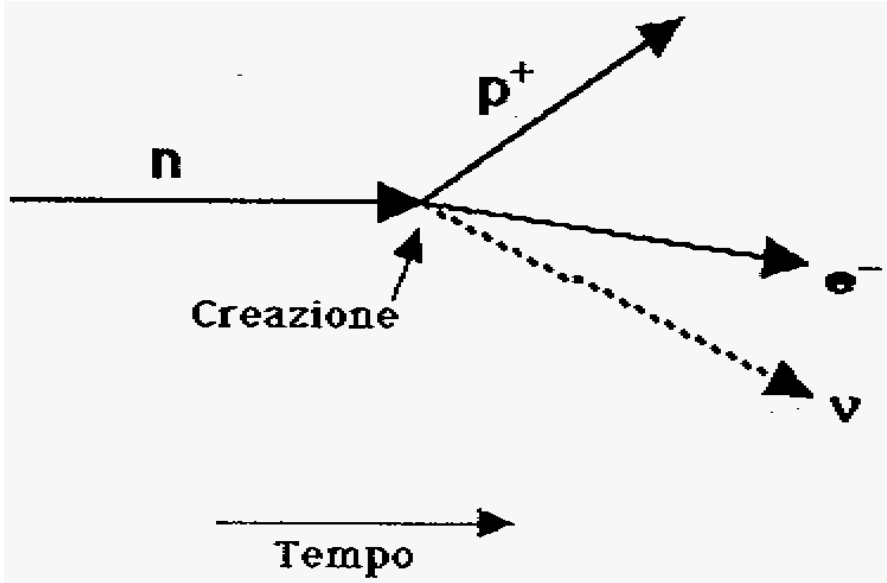
1953-1956

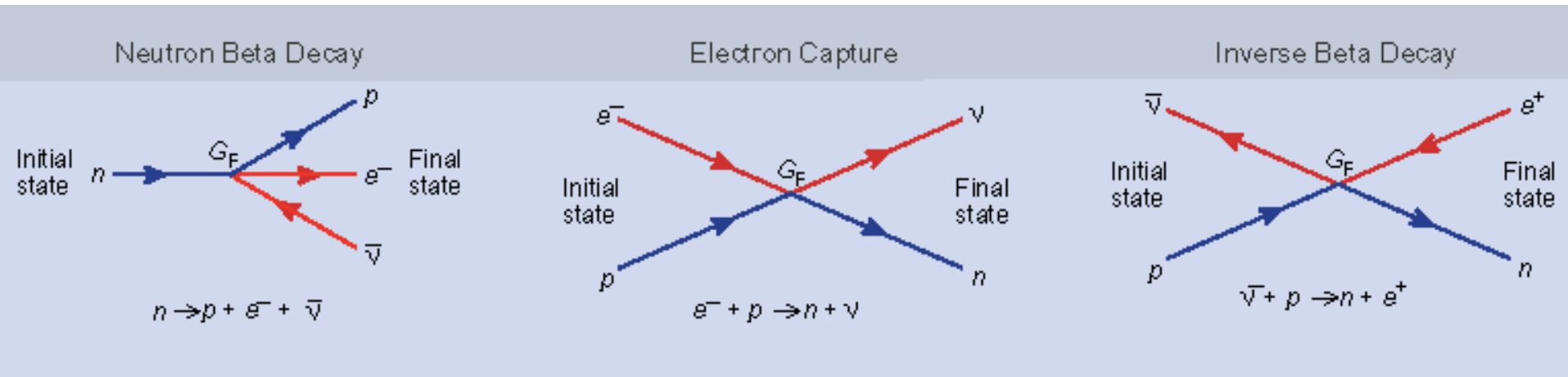
The Reines-Cowan Experiments

Detecting the Poltergeist

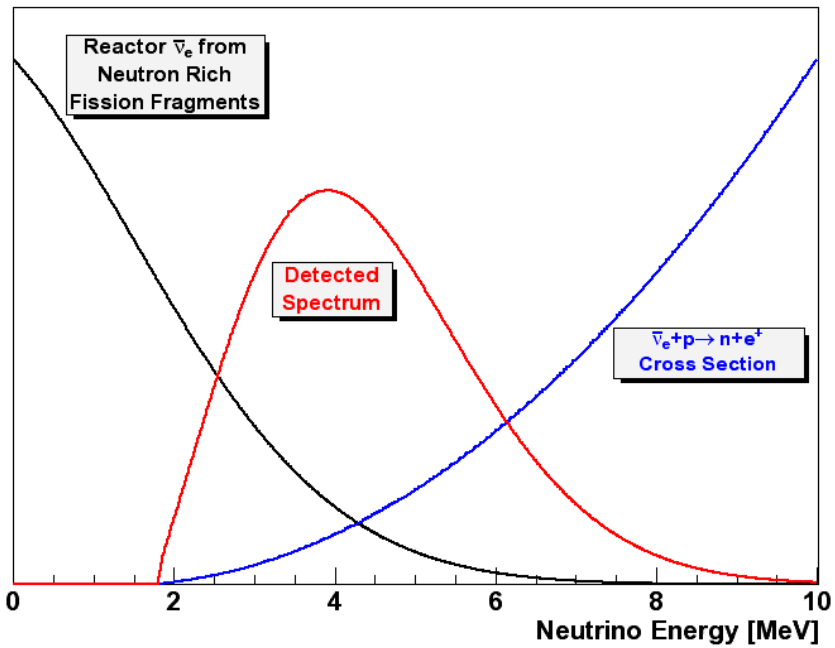
Hanford Team 1953

Enrico Fermi





Inverse Beta Decay Cross Section and Spectrum

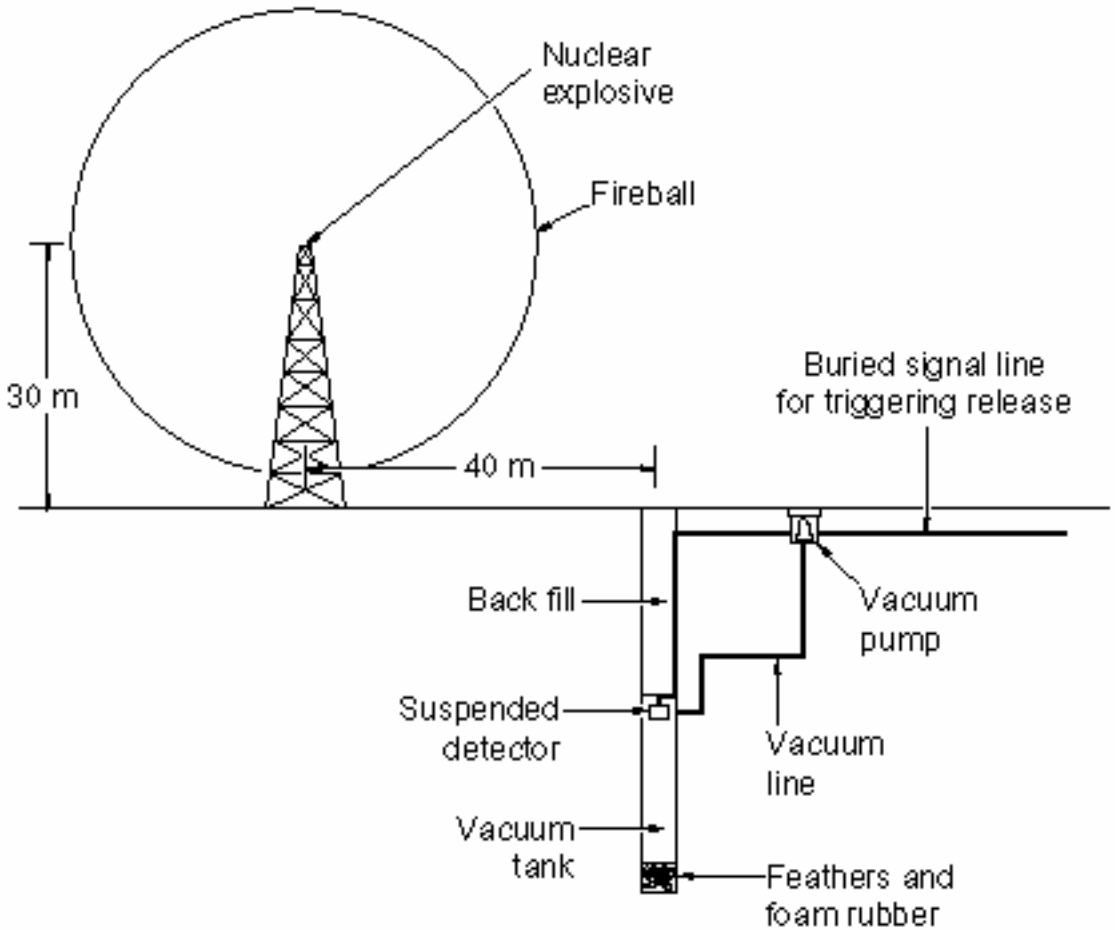


$$\sigma_{\text{tot}}^{(0)} = \sigma_0 (f^2 + 3g^2) E_e^{(0)} p_e^{(0)}$$

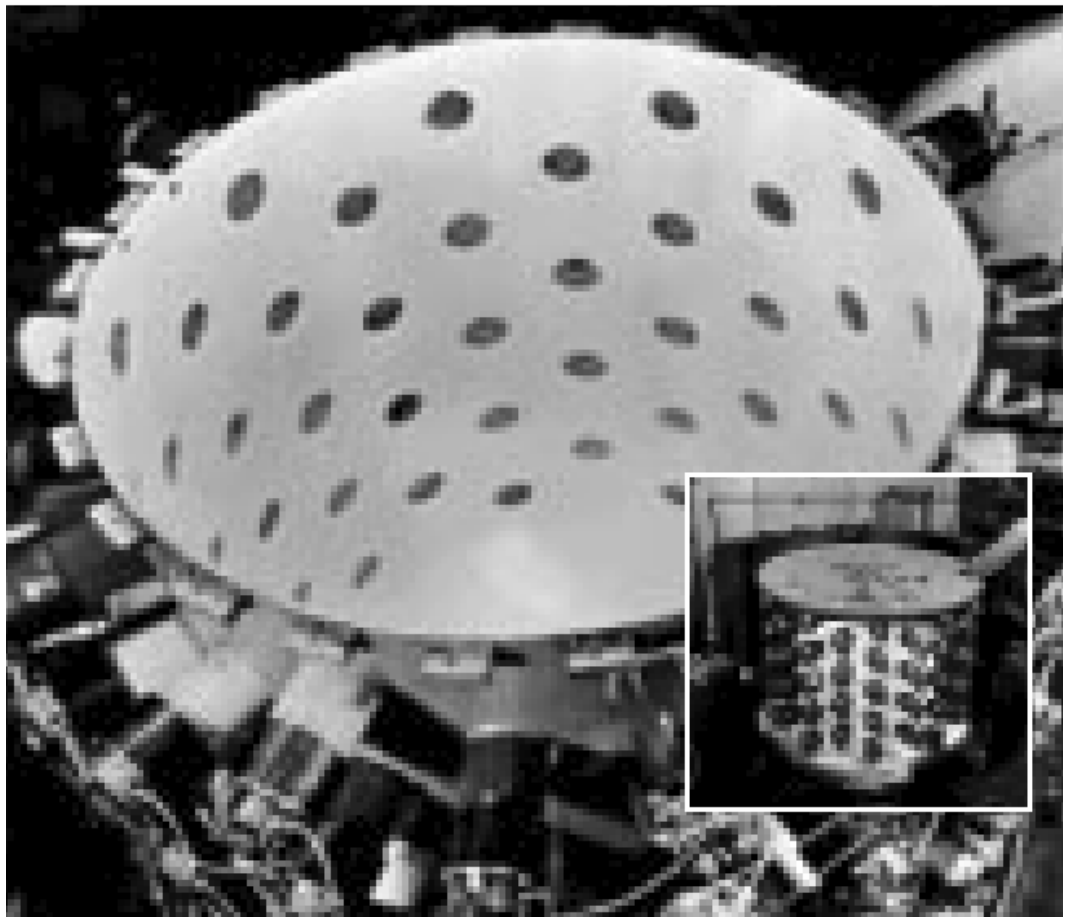
$$= 0.0952 \left(\frac{E_e^{(0)} p_e^{(0)}}{1\ \text{MeV}^2} \right) \times 10^{-42}\ \text{cm}^2$$

$$\sigma_0 = \frac{G_F^2 \cos^2 \theta_C}{\pi} (1 + \Delta_{inner}^R)$$

$$\sigma_{\text{tot}}^{(0)} = \frac{2\pi^2 / m_e^5}{f_{p.s.}^R \tau_n} E_e^{(0)} p_e^{(0)}$$

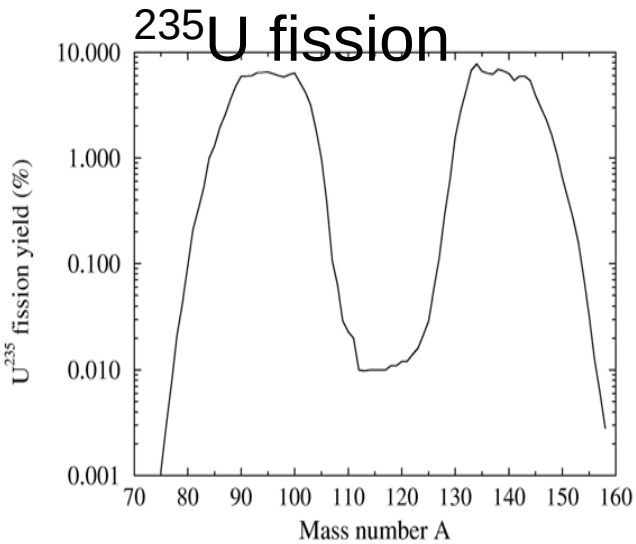


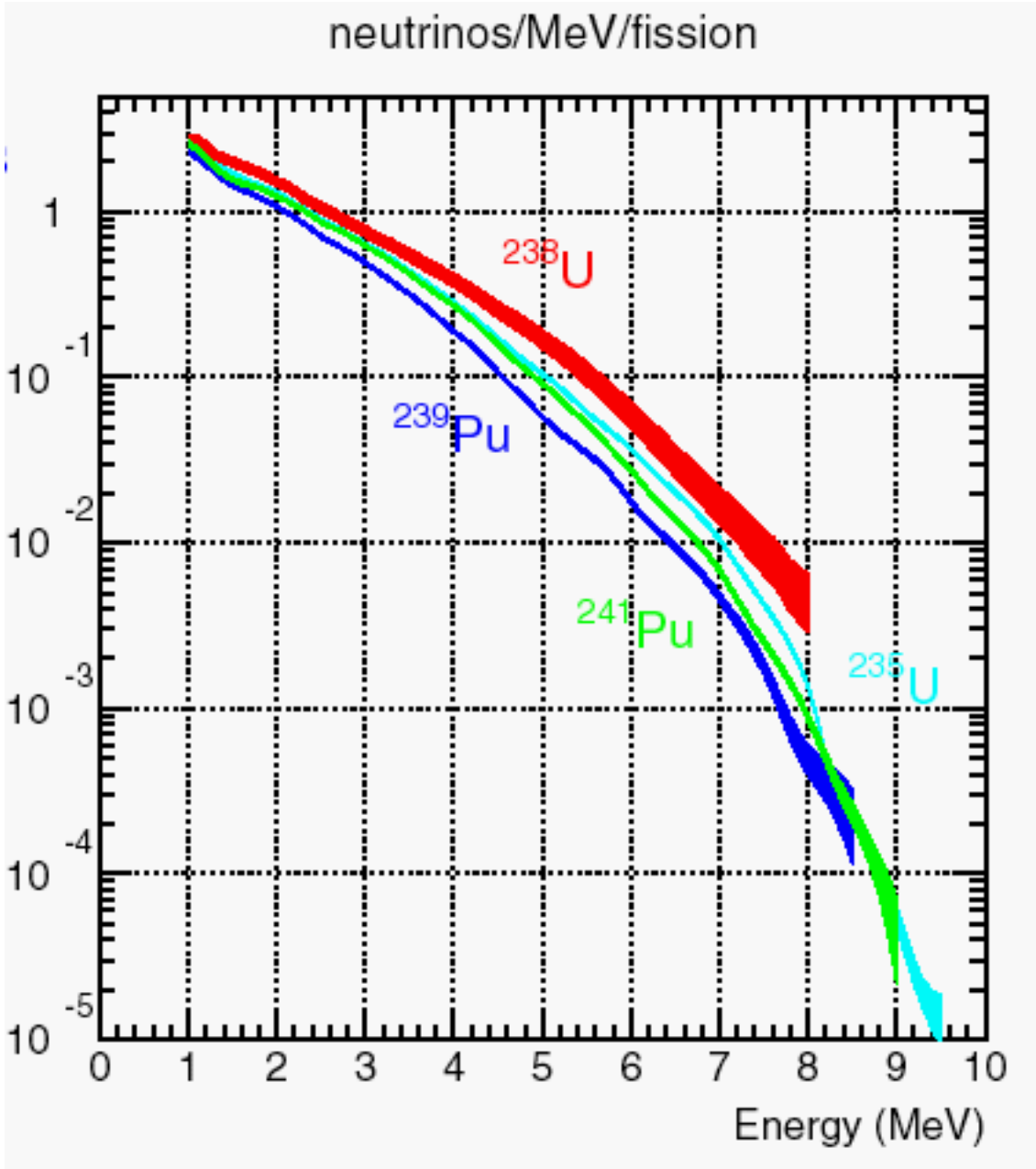
The first proposal for a neutrino experiment didn't use a reactor



Poltergeist: *the largest scintillator in the world*

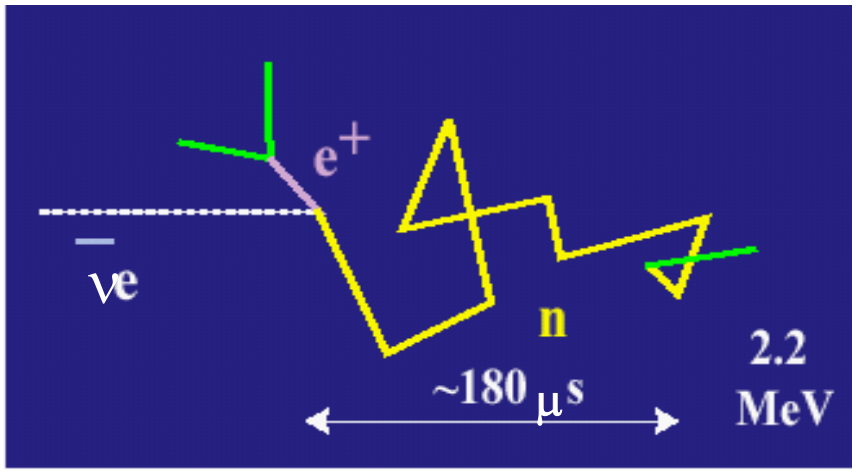
Neutrino Spectra from Principal Reactor Isotopes

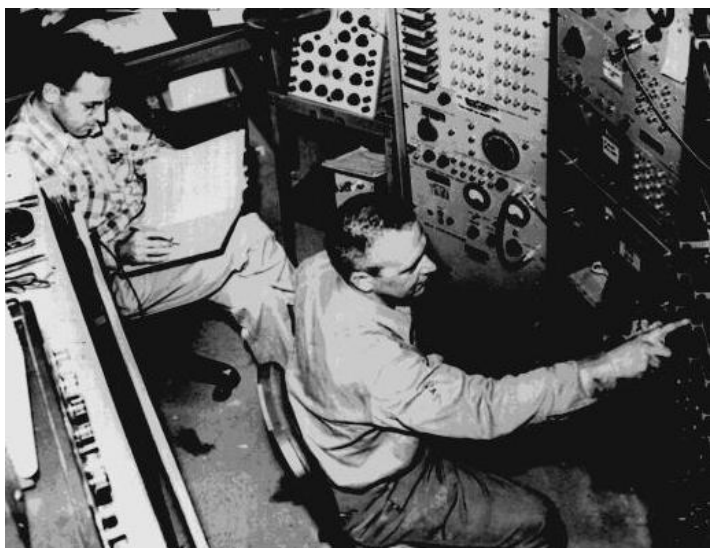


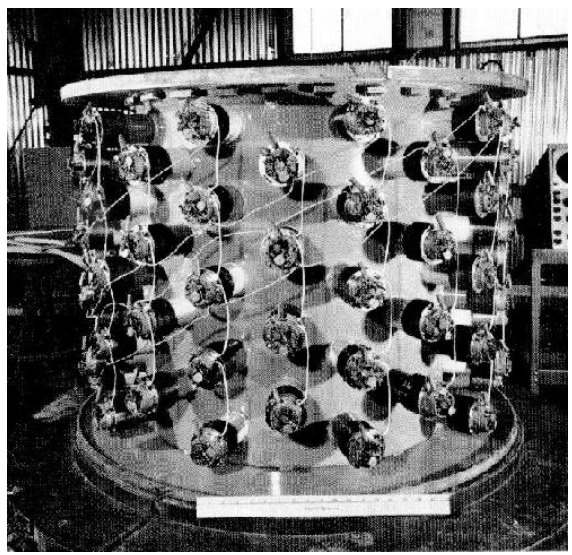


First Direct Detection of the Neutrino

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

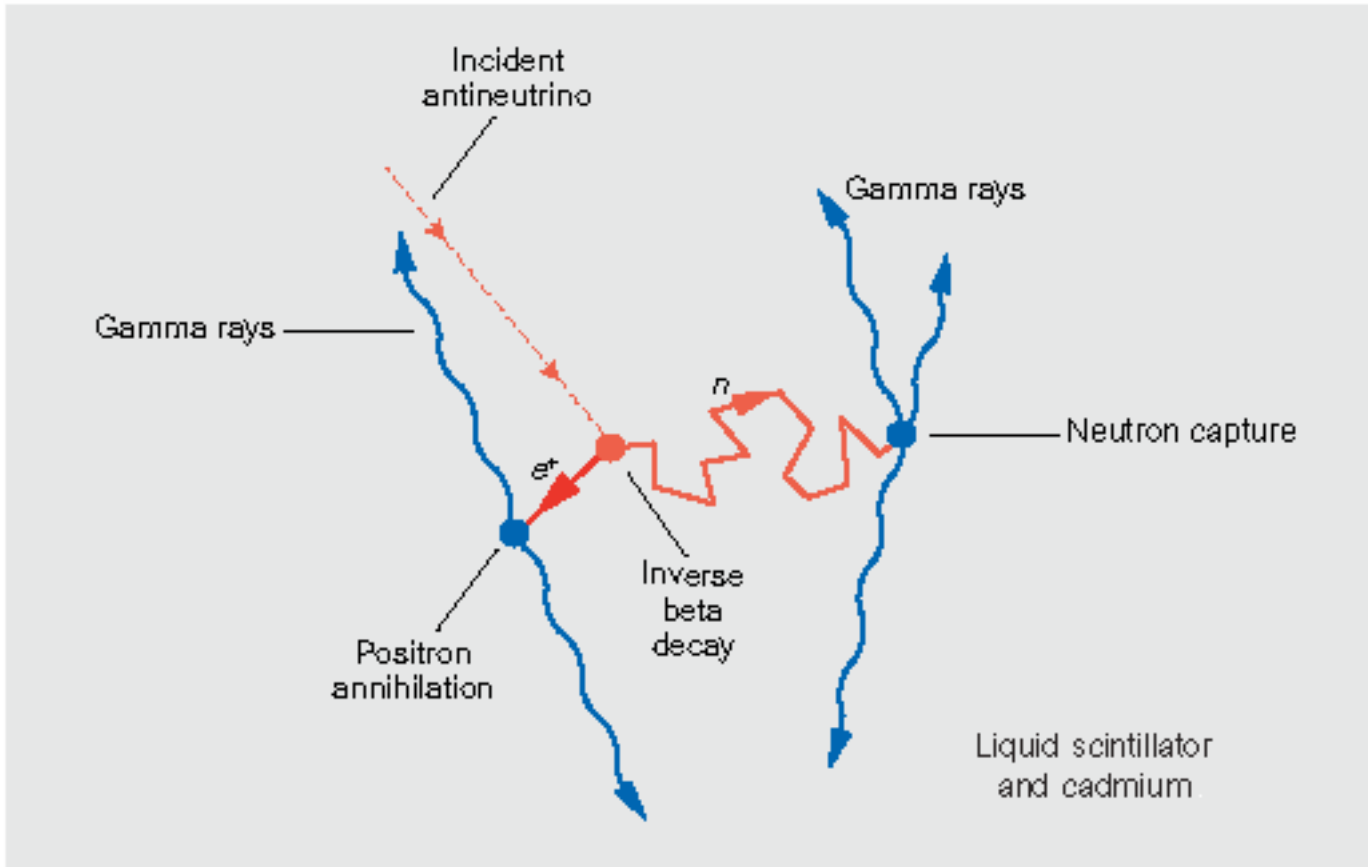


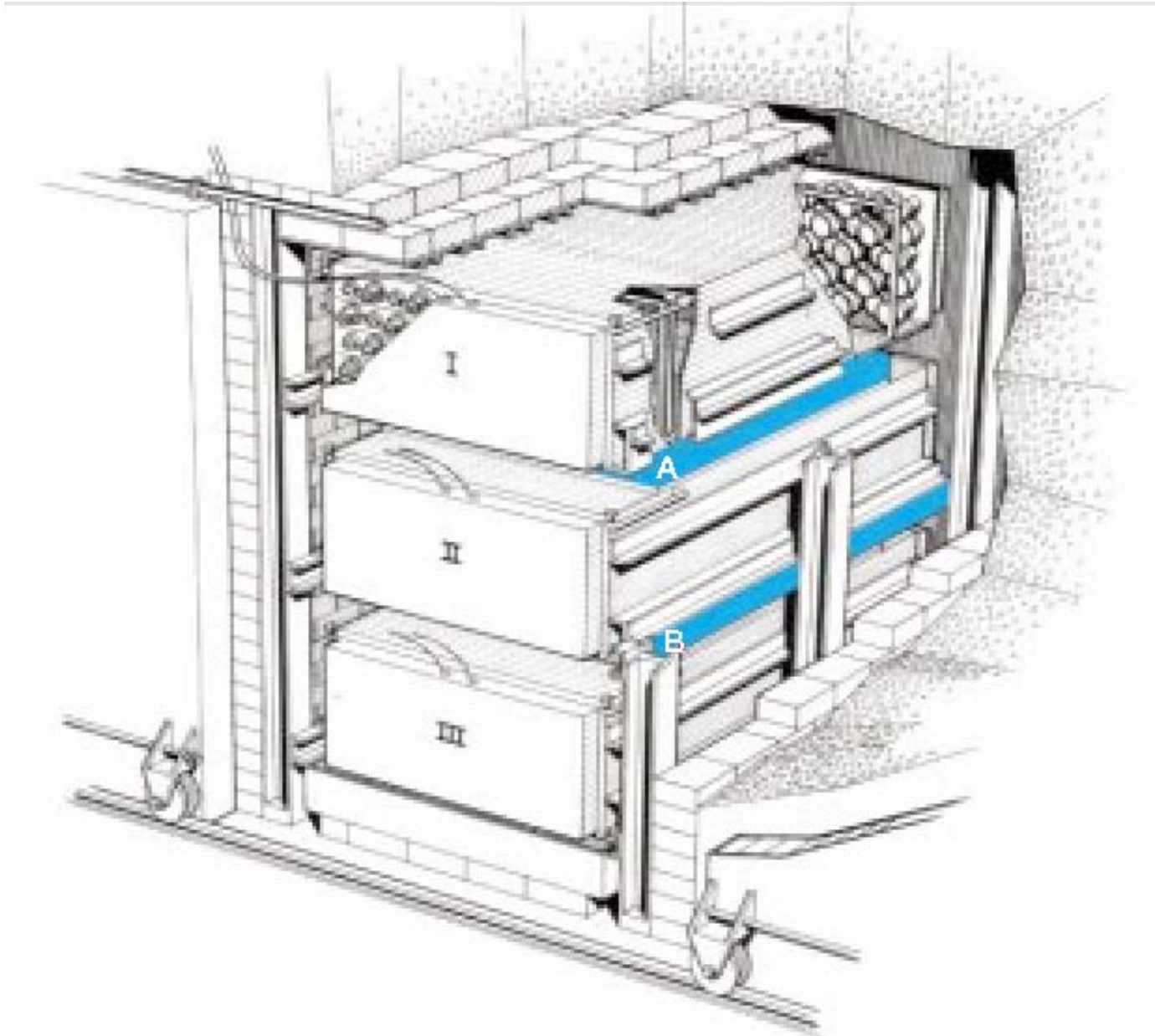


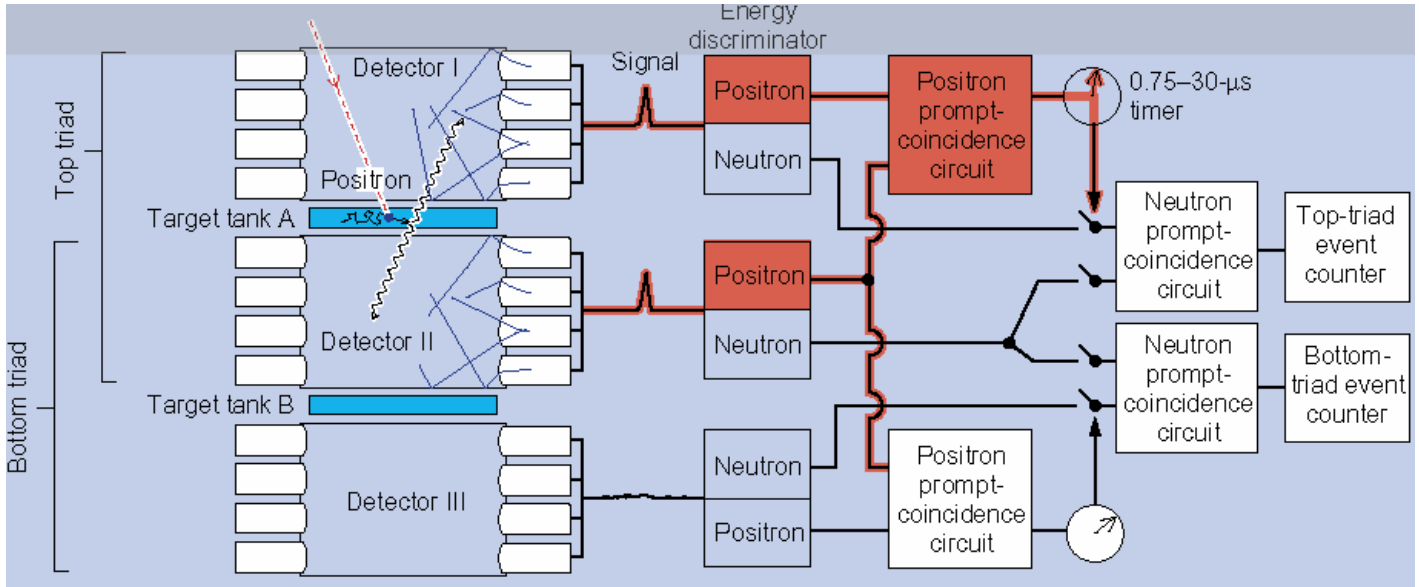


Backgrounds!

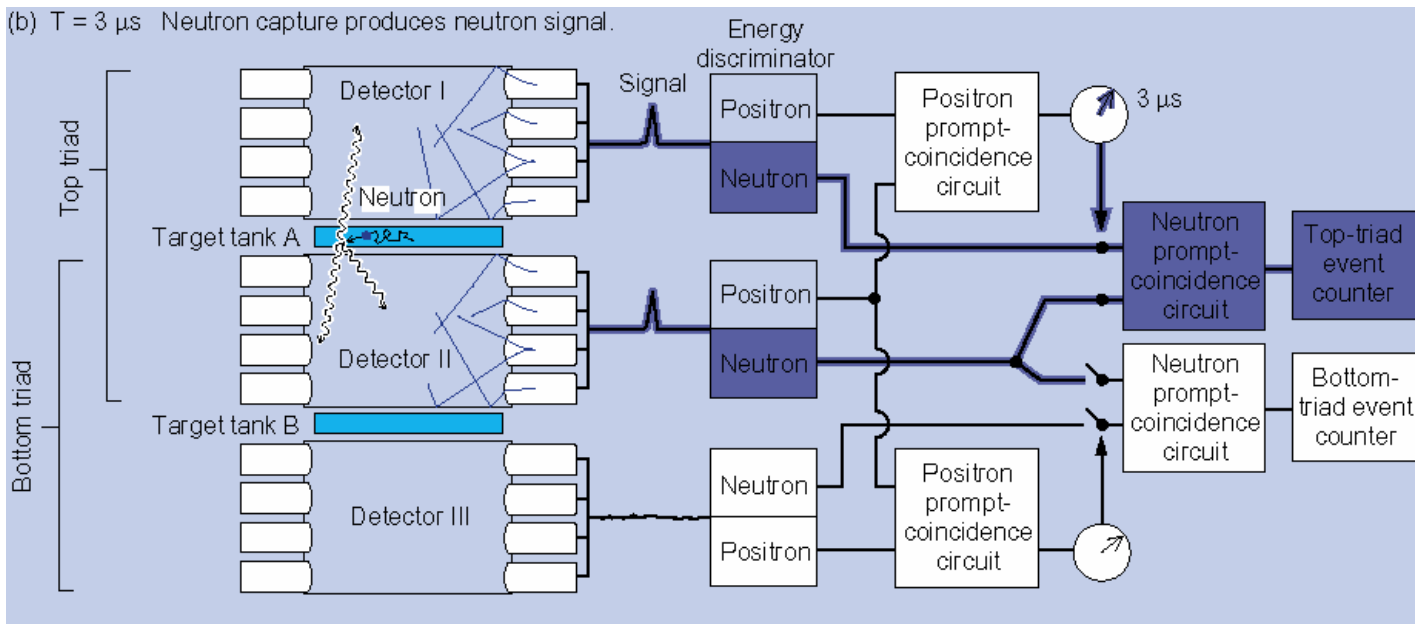
Savannah Team 1955

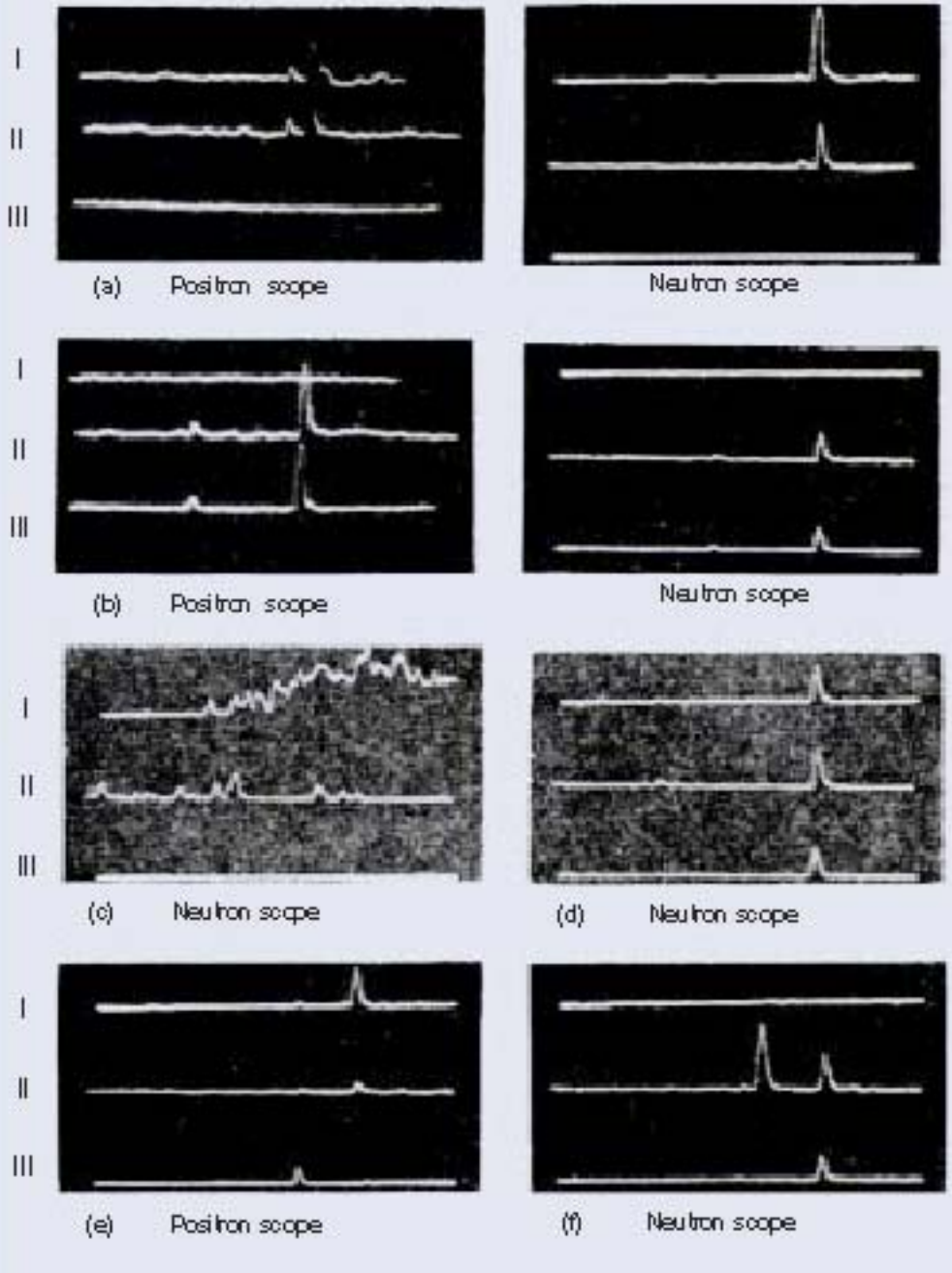

Incident
antineutrino
Gamma rays
Gamma rays
n
Neutron capture
e+
Inverse
beta
decay
Positron
annihilation
Liquid scintillator
and cadmium

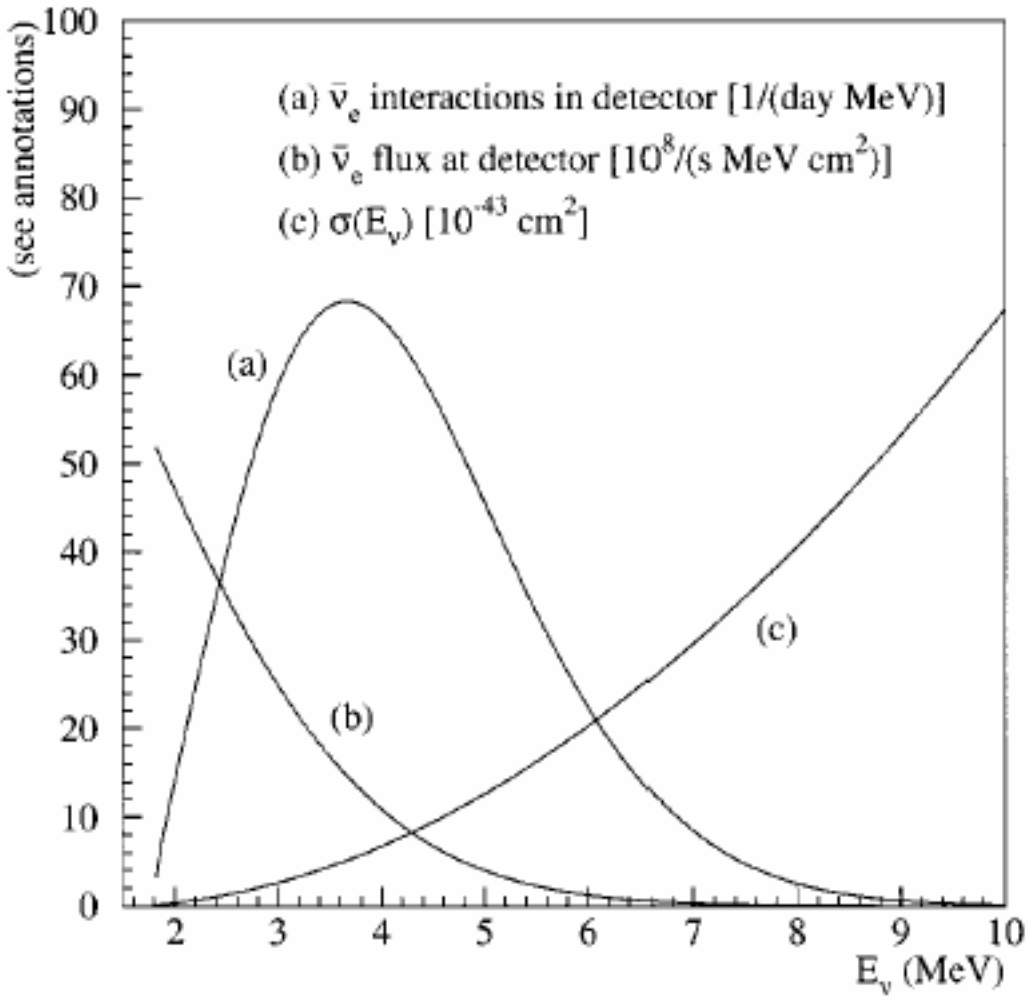

I
II
III
A
B

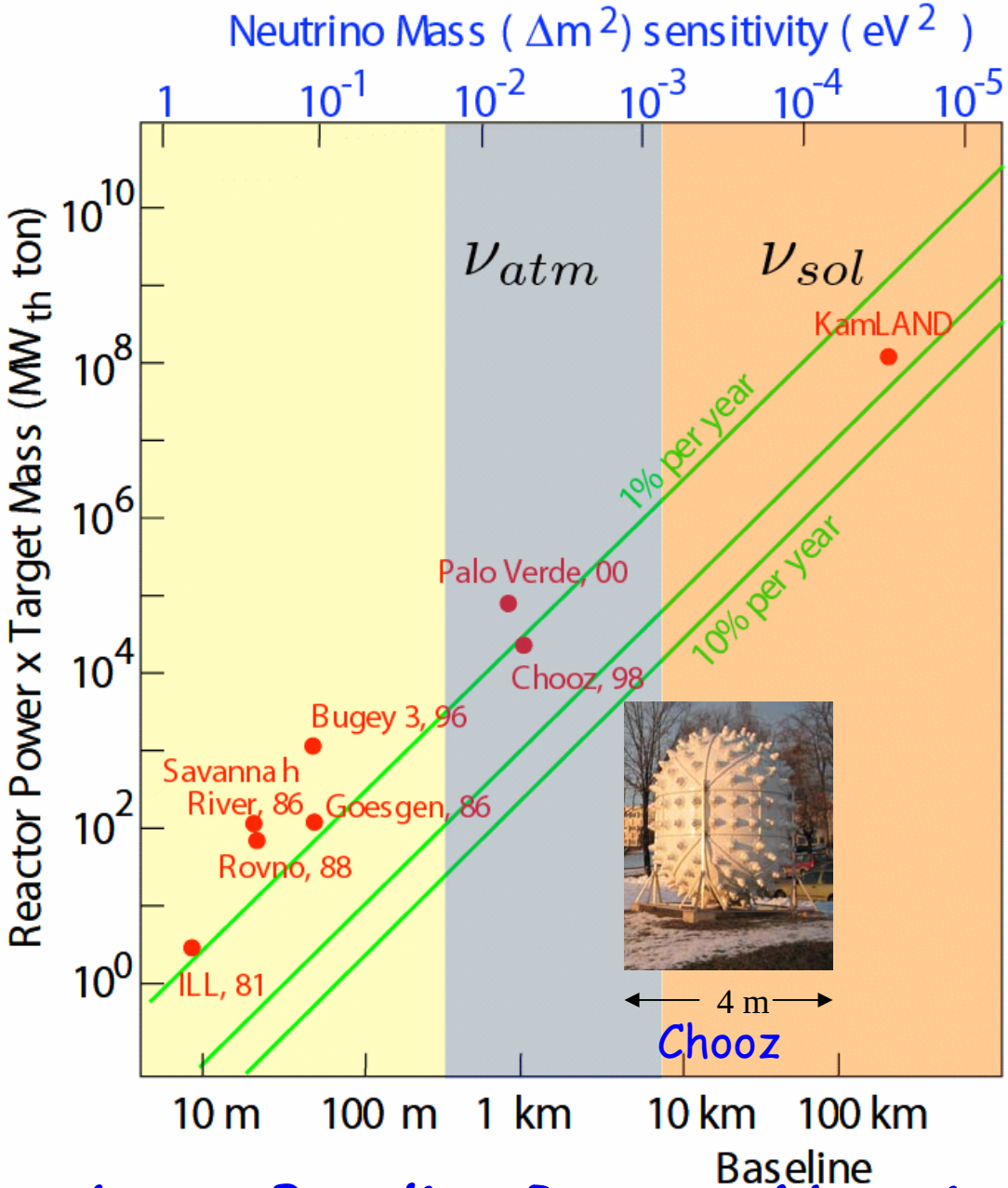


(b) T = 3 μs Neutron capture produces neutron signal.



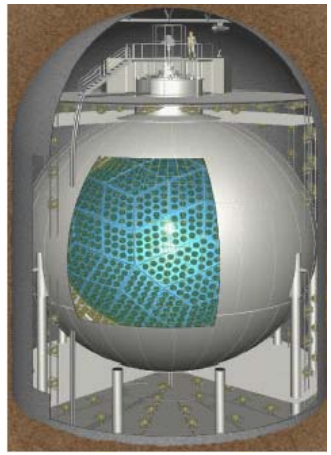

I
II
III
(a) Positron scope
Neutron scope
I
II
III
(b) Positron scope
Neutron scope
I
II
III
(c) Neutron scope
(d) Neutron scope
I
II
III
(e) Positron scope
(f) Neutron scope


(see annotations)
100
90
80
70
60
50
40
30
20
10
0
2
3
4
5
6
7
8
9
10
E_ν (MeV)
(a) $\bar{\nu}_e$ interactions in detector [1/(day MeV)]
(b) $\bar{\nu}_e$ flux at detector [10^8/(s MeV cm^2)]
(c) $\sigma(E_\nu)$ [10^{-43} cm^2]
(a)
(b)
(c)



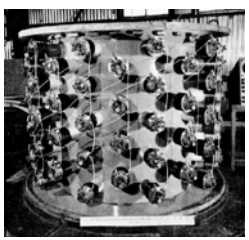
4 m

Chooz



20 m

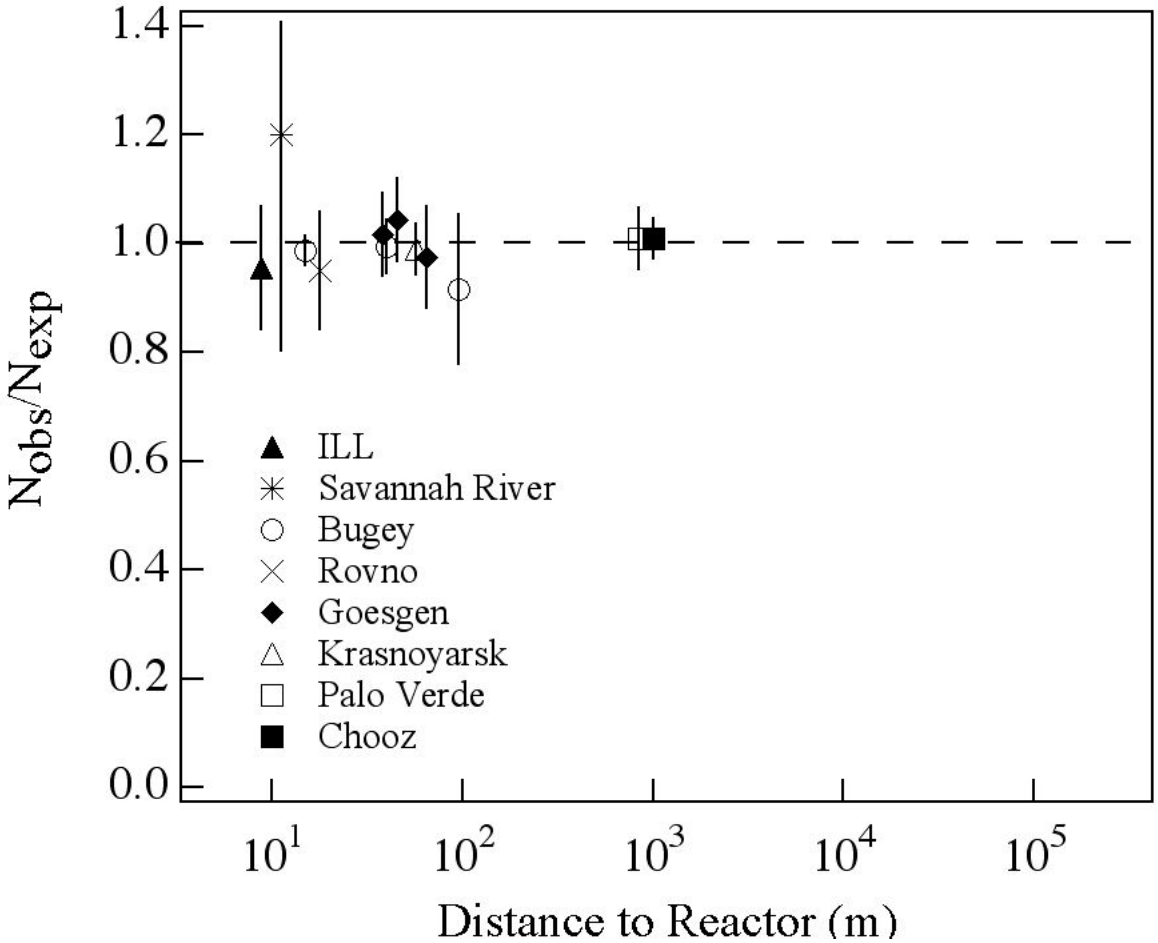
KamLAND



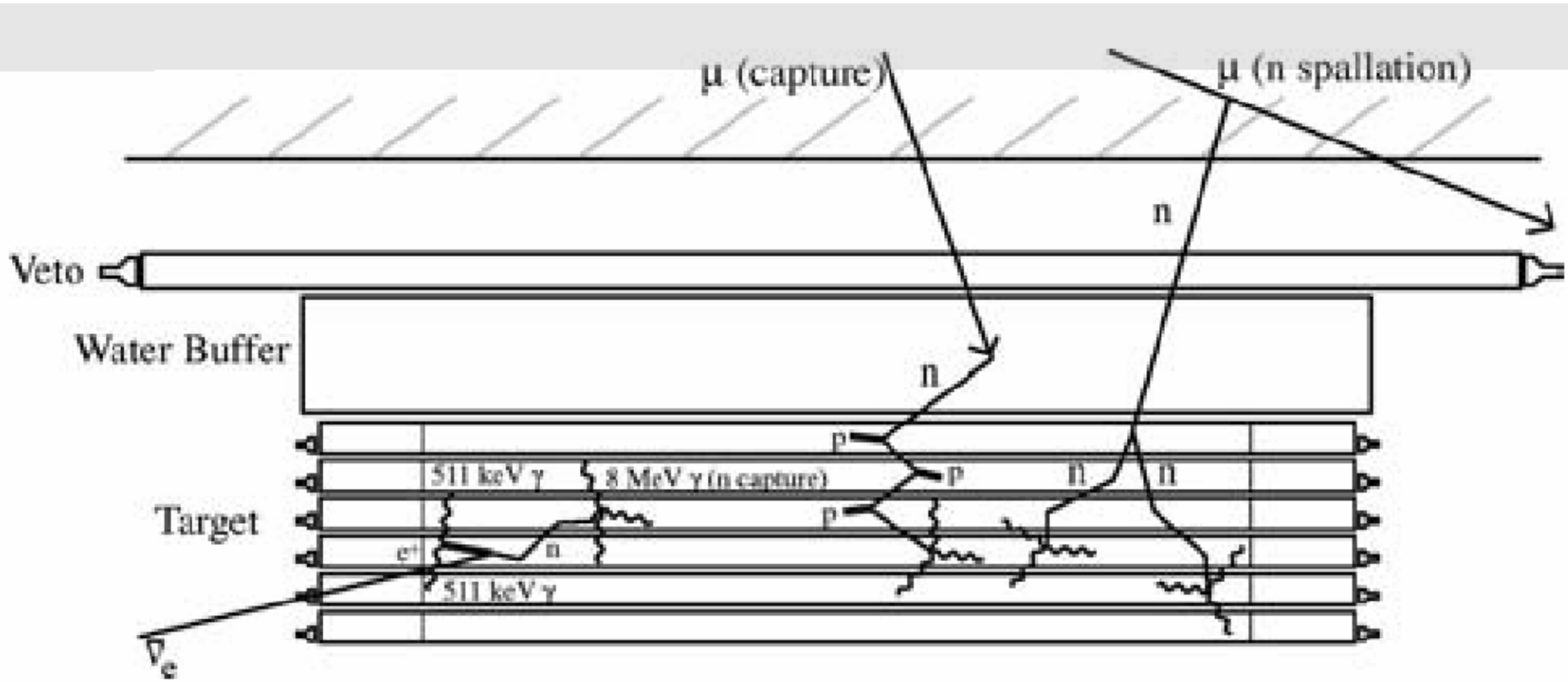
1m

Poltergeist

Long Baseline Reactor Neutrino Experiments


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N_{obs}/N_{exp}
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)

Correlated Backgrounds from External Neutrons

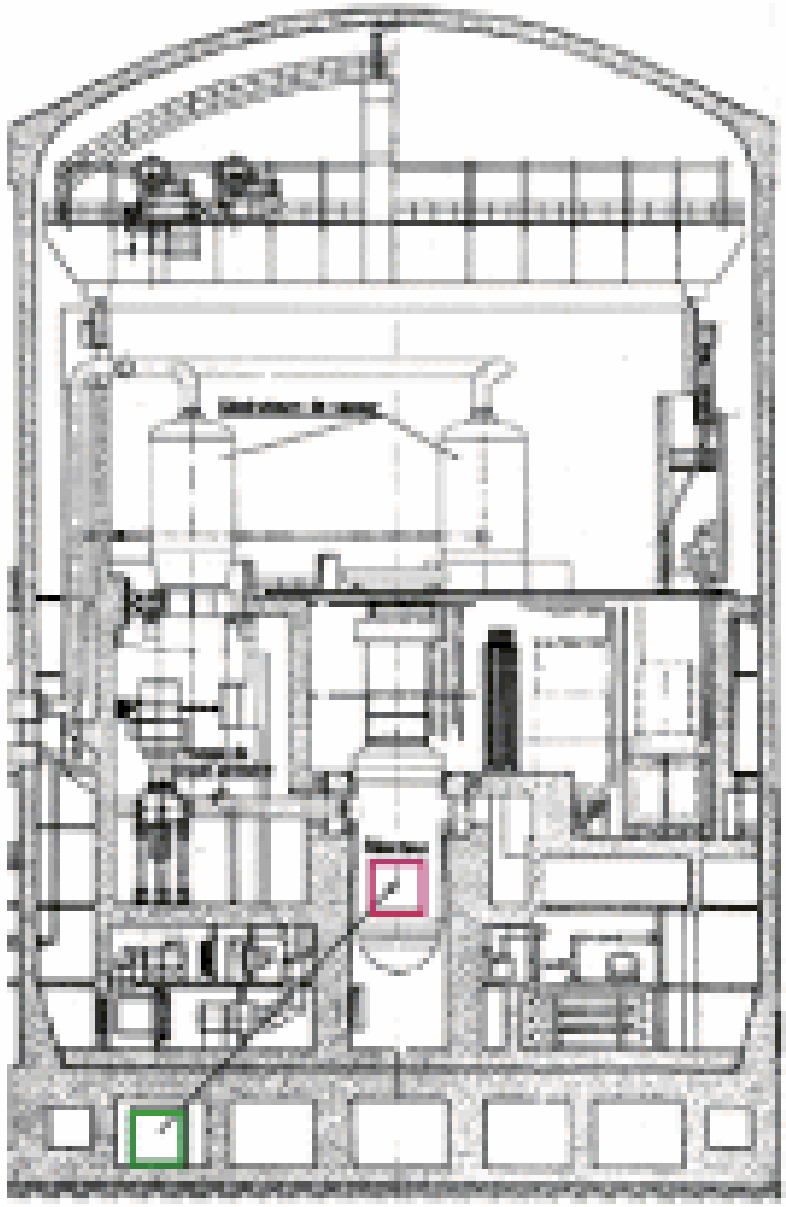


Palo Verde

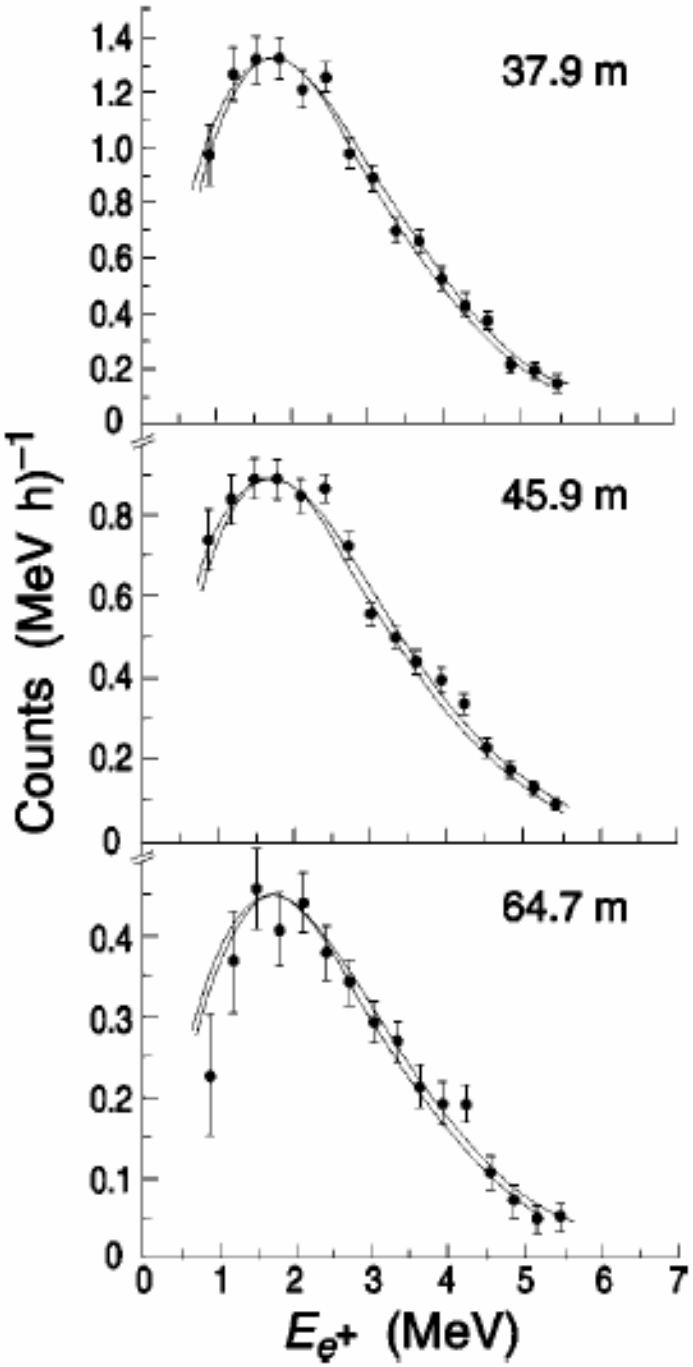
Spallation Produced Radio-Isotopes in Liquid Scintillator

	Isotope	**$t_{1/2}$**	**E_{max}** (MeV)	**Background**
β^-	^{12}B	0.02 s	13.4	Uncorrelated
	^{11}Be	13.80 s	11.5	Uncorrelated
	^{11}Li	**0.09 s**	**20.8**	**Correlated**
	^{9}Li	**0.18 s**	**13.6**	**Correlated**
	^{8}Li	0.84 s	16.0	Uncorrelated
	^{8}He	**0.12 s**	**10.6**	**Correlated**
	^{6}He	0.81 s	3.5	Uncorrelated
β^+, EC	**^{11}C**	**20.38 m**	**0.96**	**Uncorrelated**
	^{10}C	19.30 s	1.9	Uncorrelated
	^{9}C	0.13 s	16.0	Uncorrelated
	^{8}B	0.77 s	13.7	Uncorrelated
	^{7}Be	53.3 d	0.48	Uncorrelated

Bugey

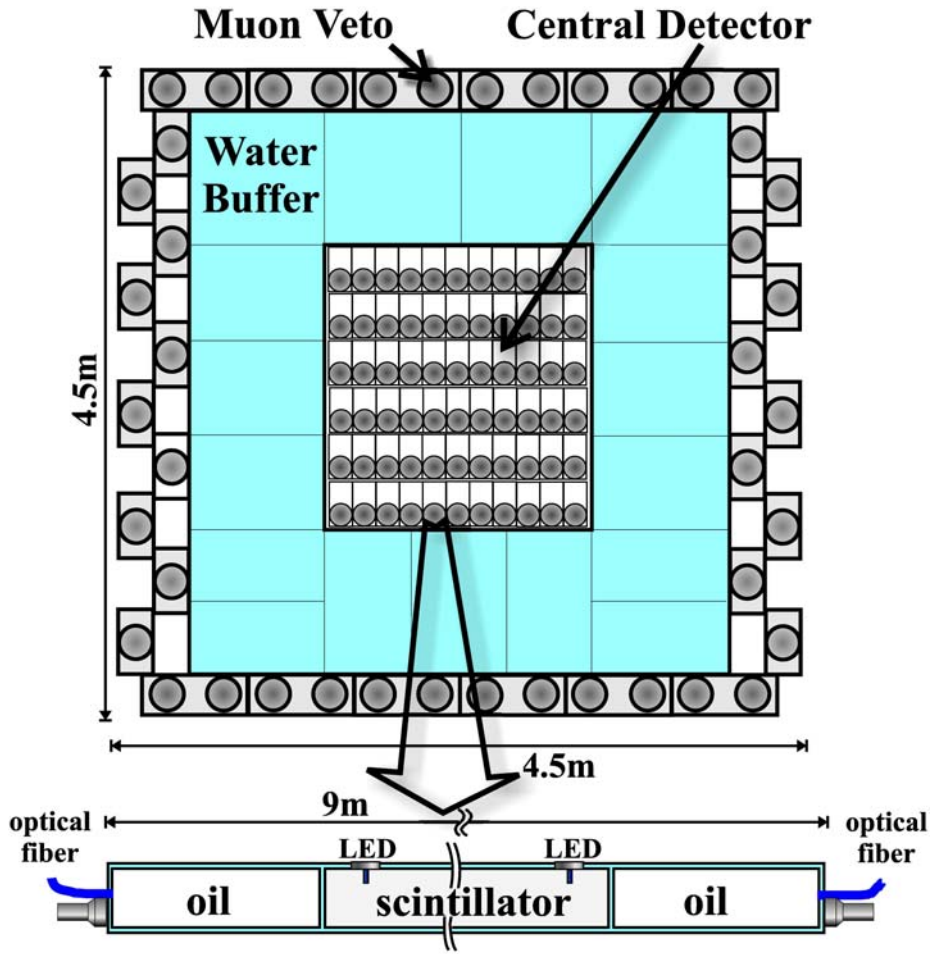


Le bâtiment réacteur



Gosgen

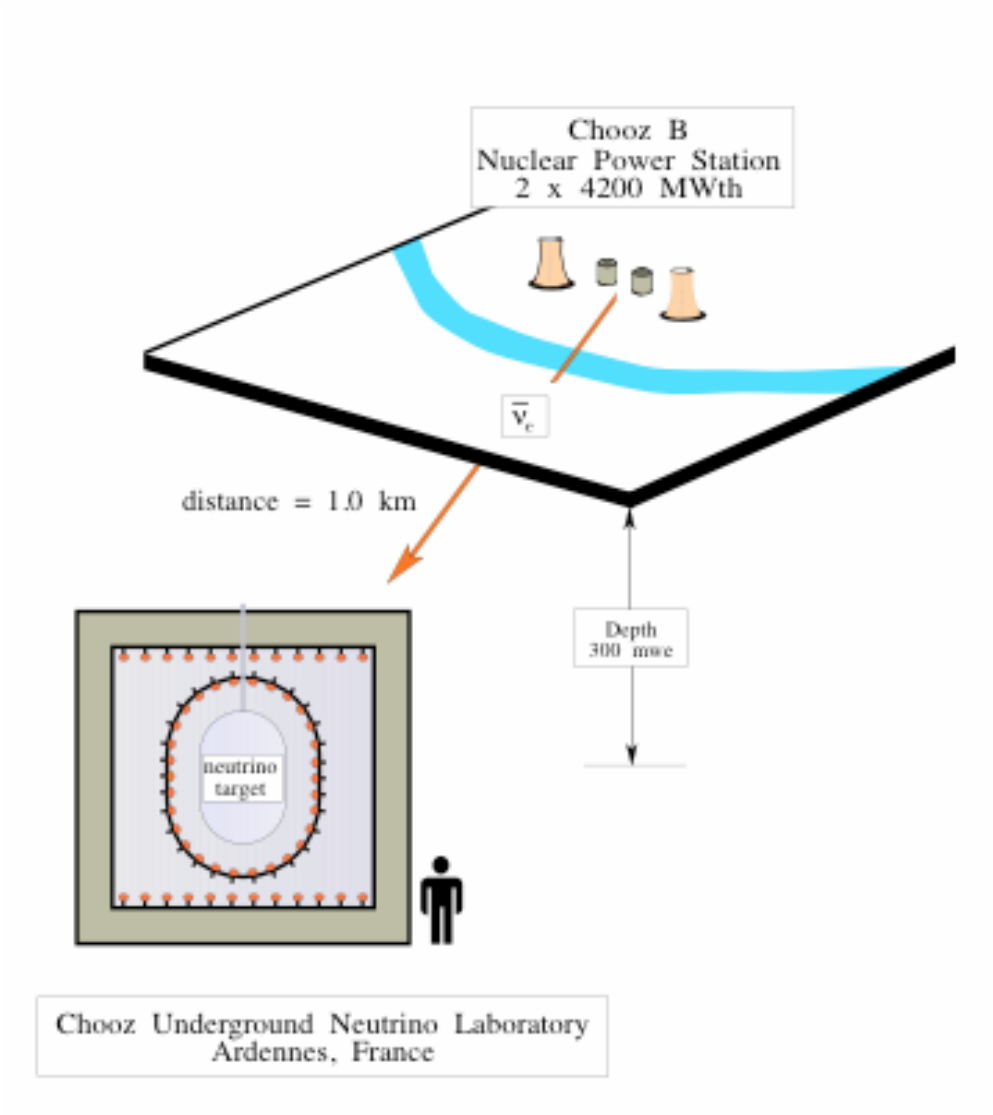
- 32 mwe
- 12 ton, Gd loaded, scintillating target
- 3 reactors: 11.6 GW
- Baselines 890 m and 750 m
- Expected rate of ~50 evts/day



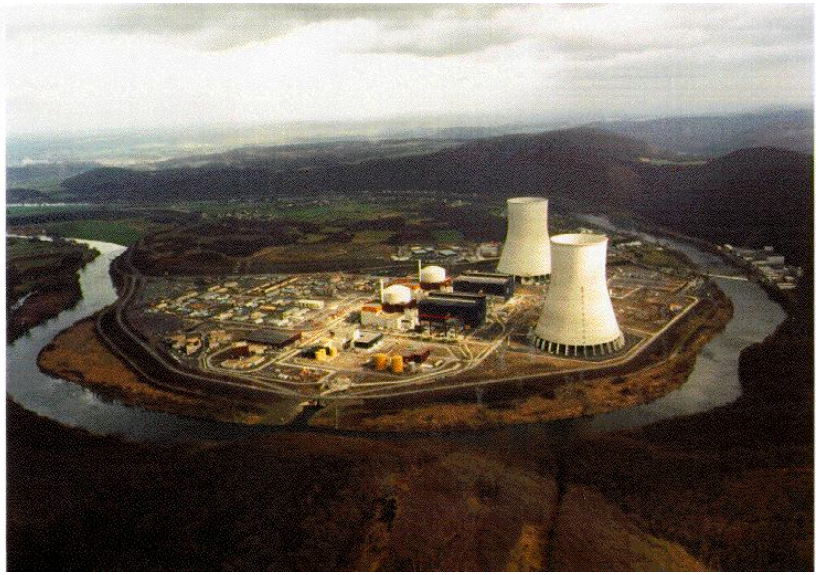
Palo Verde

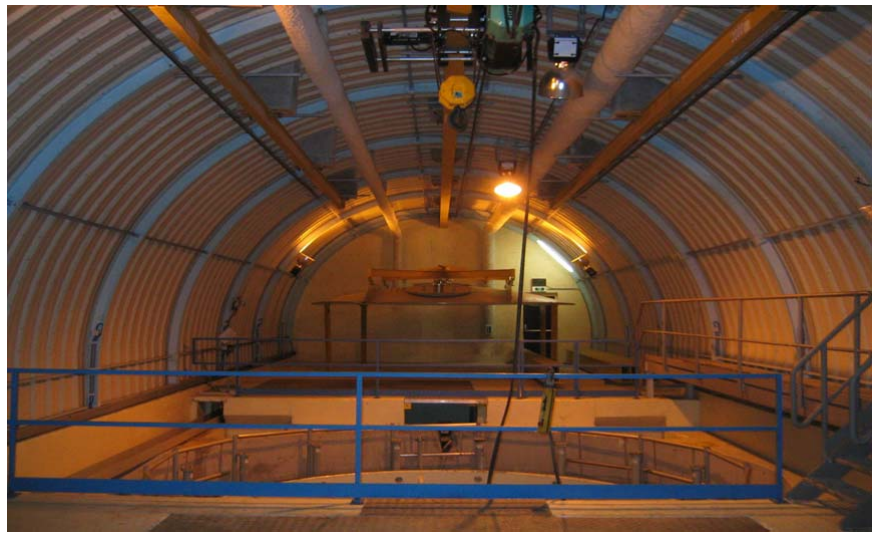
Palo Verde

Chooz

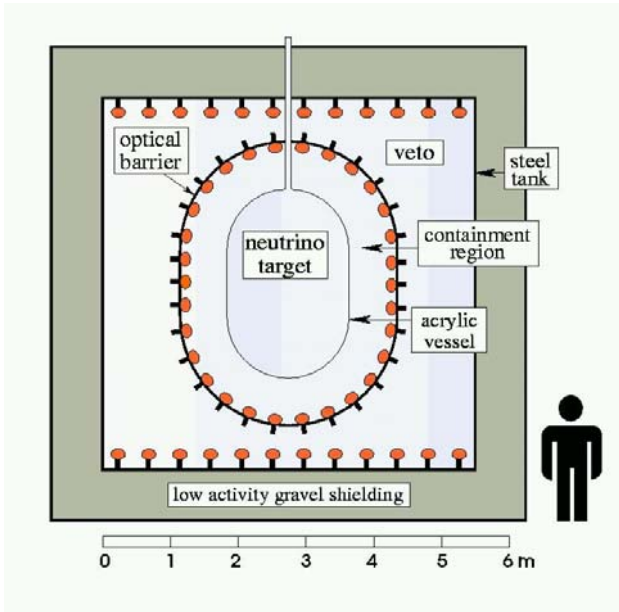

Chooz B
Nuclear Power Station
2 x 4200 MWth
$\bar{\nu}_e$
distance = 1.0 km
Depth
300 mwe
neutrino
target
Chooz Underground Neutrino Laboratory
Ardennes, France

Underground Vault for Chooz

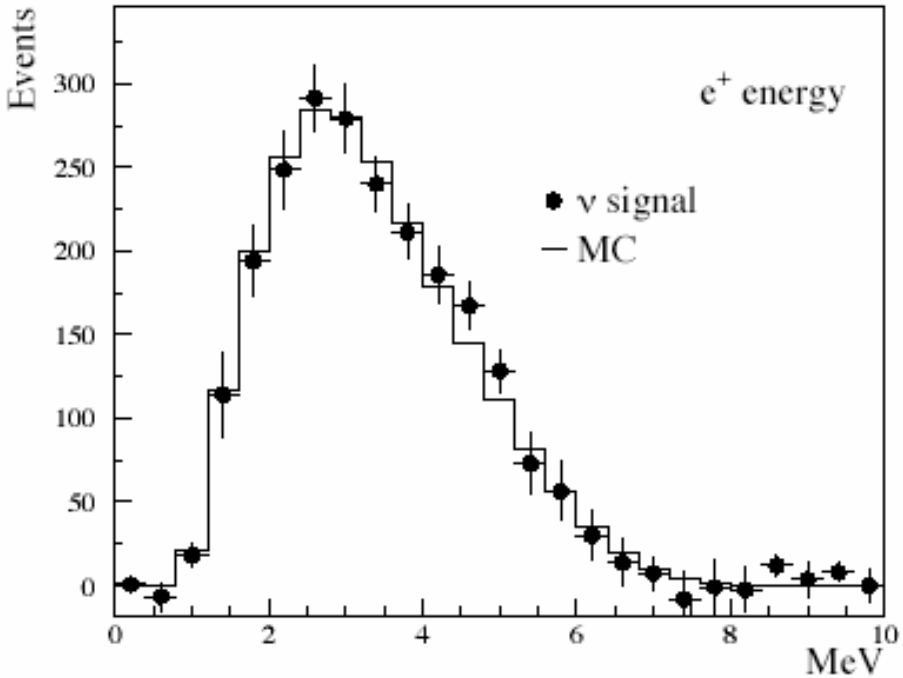


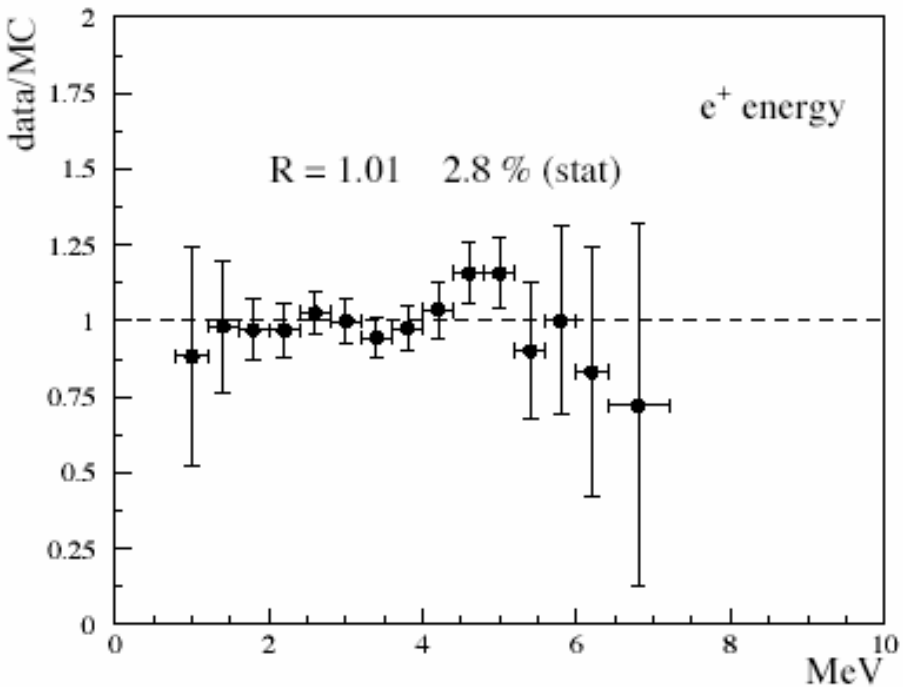


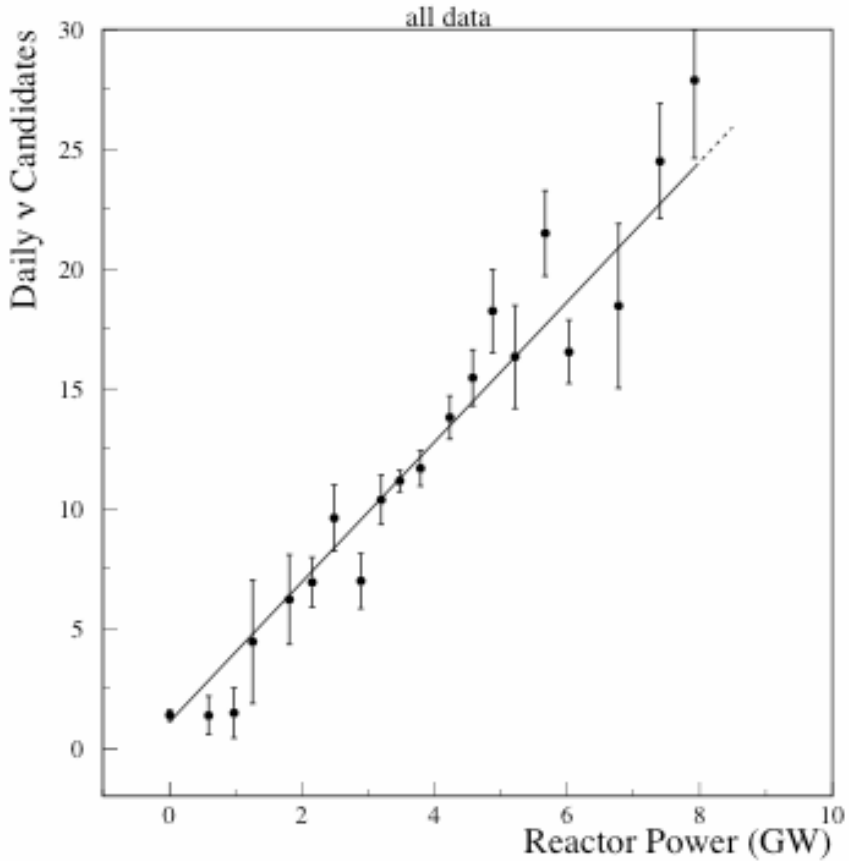
- **5 ton, Gd loaded, scintillating target**
- **300 mwe**
- **2 reactors: 8.5 GW_l**
- **Baselines 1115 m and 998 m**
- **Expected ~25 evts/day**

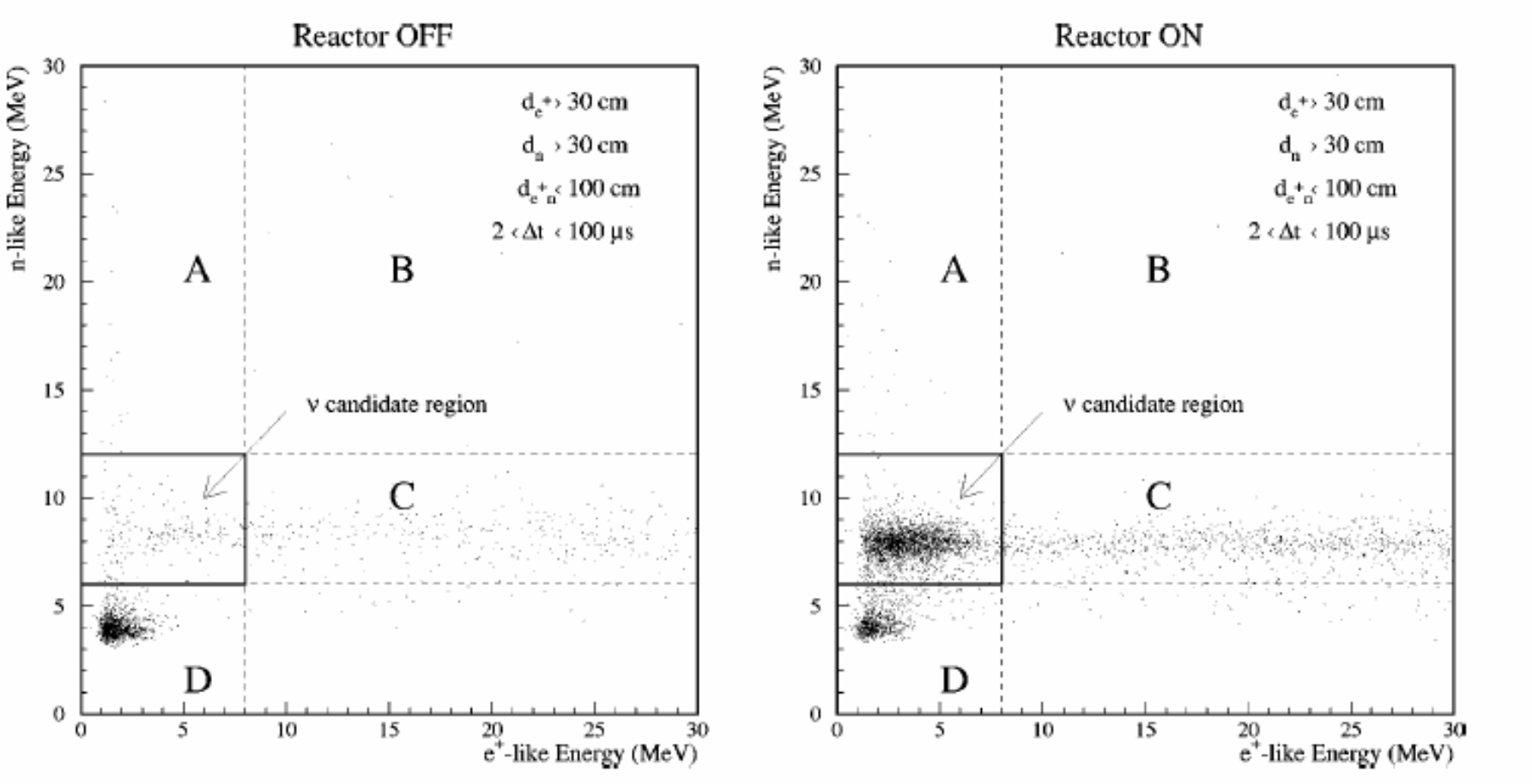


CHOOZ


Events
e+ energy
ν signal
MC
MeV


data/MC
e+ energy
R = 1.01 2.8 % (stat)
MeV

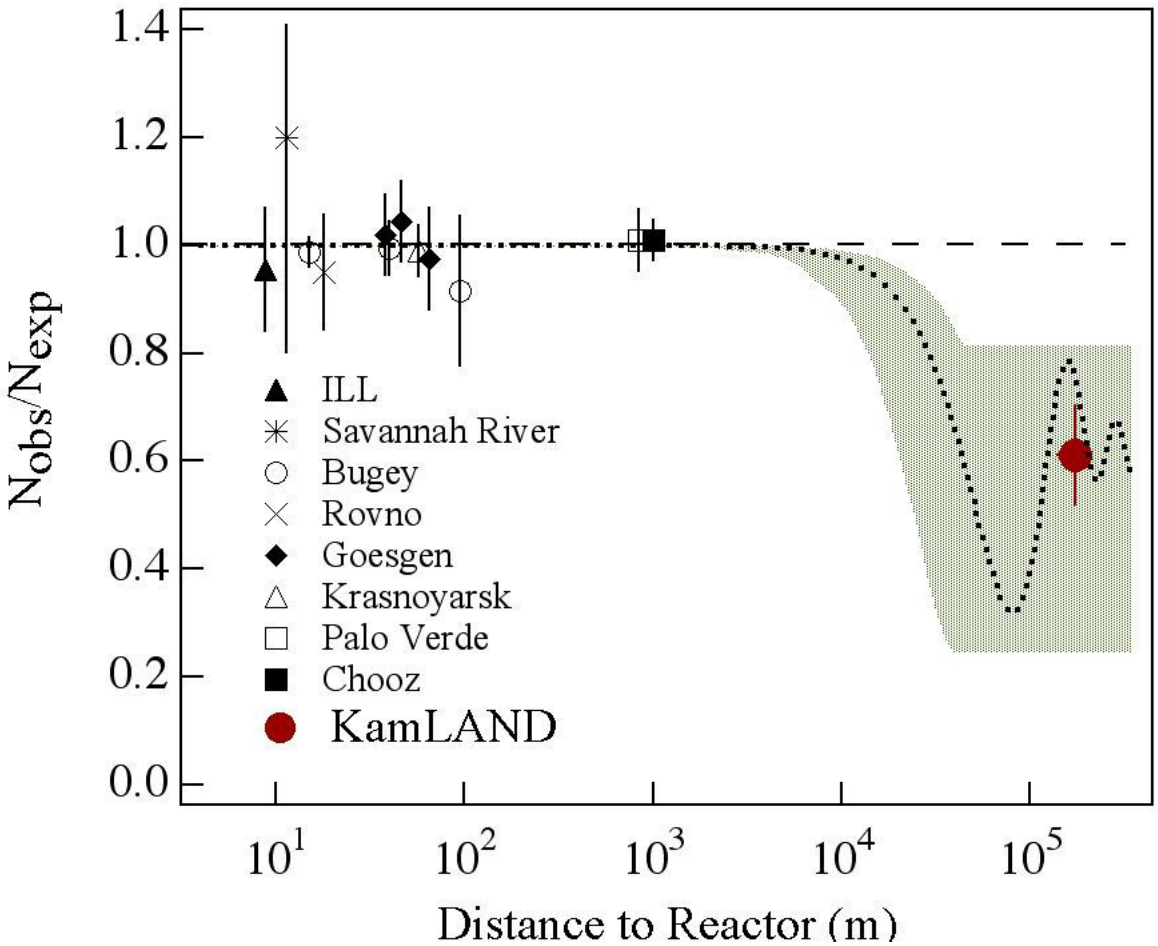

all data
Daily ν Candidates
Reactor Power (GW)

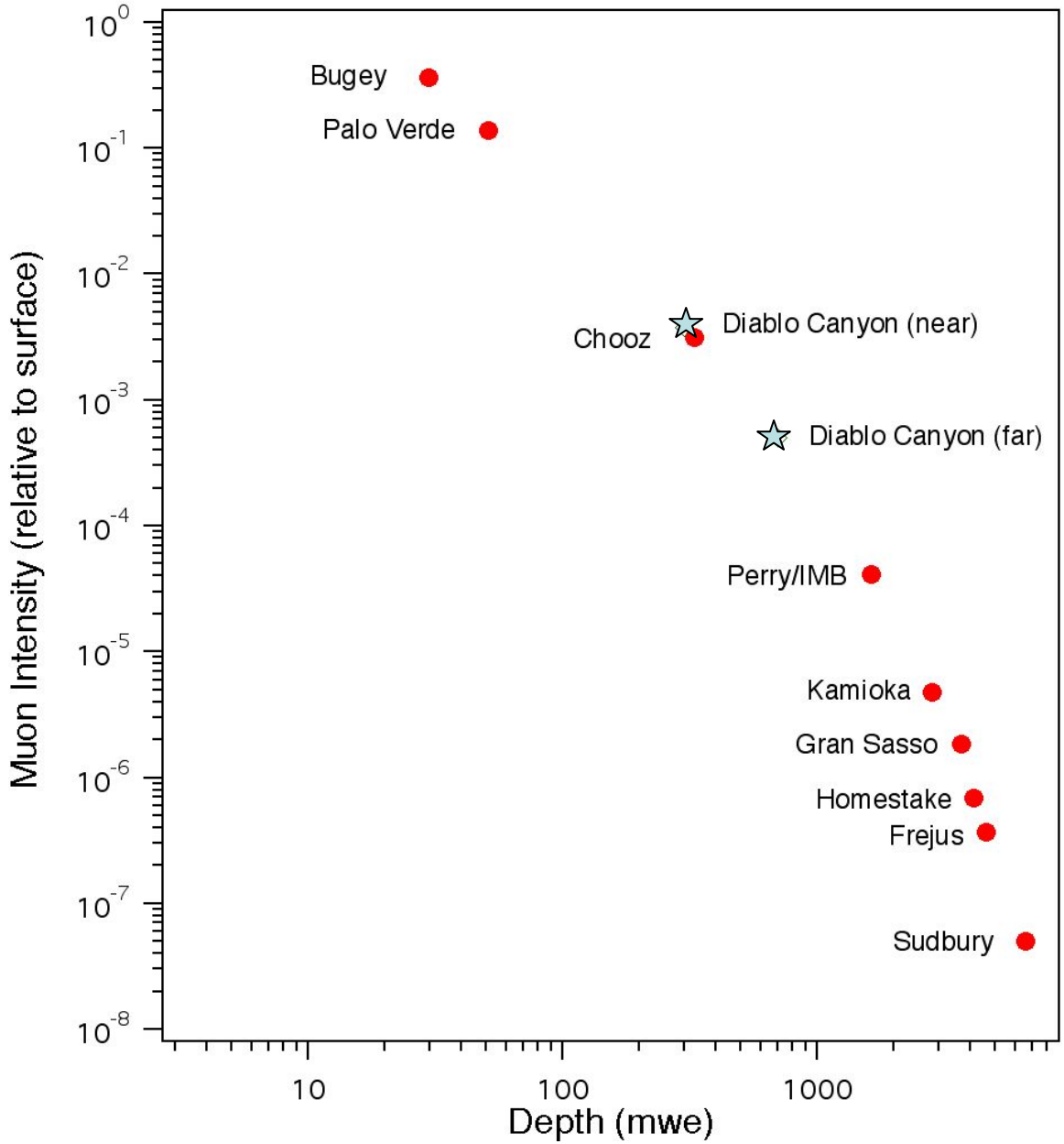

Reactor OFF
Reactor ON
n-like Energy (MeV)
e+-like Energy (MeV)
d_e+ > 30 cm
d_n > 30 cm
d_e+_n < 100 cm
2 < Δt < 100 μs
A
B
C
D
ν candidate region
0
5
10
15
20
25
30

Chooz

Table 10. Contributions to the overall systematic uncertainty on the absolute normalization factor.

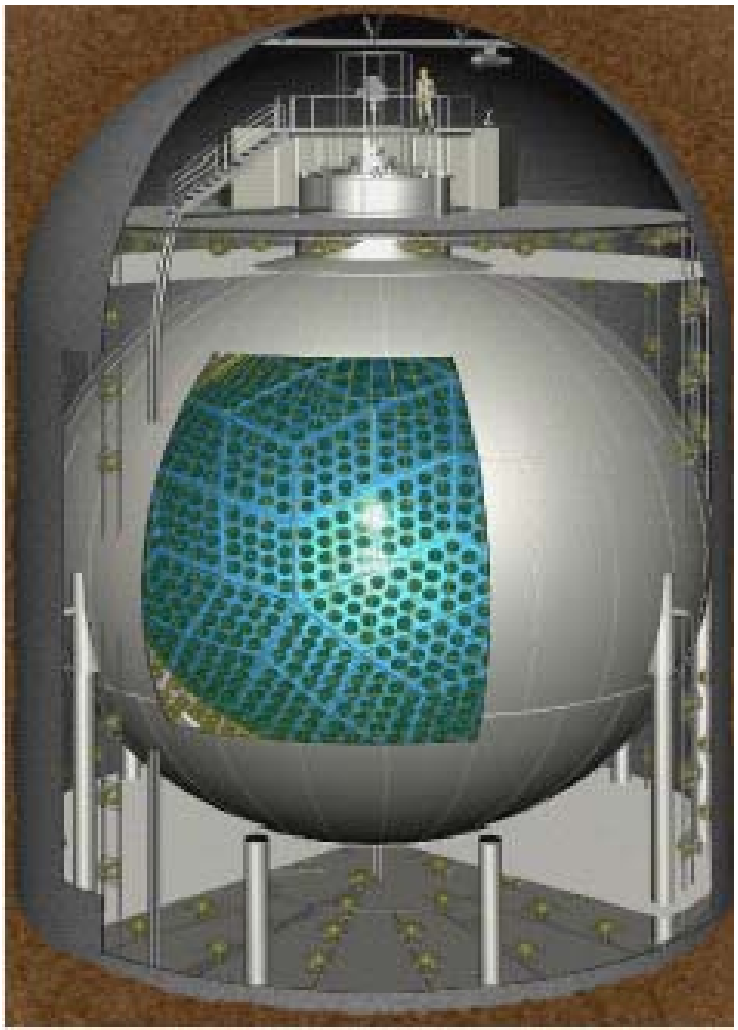
parameter	relative error (%)
reaction cross section	1.9%
number of protons	0.8%
detection efficiency	1.5%
reactor power	0.7%
energy released per fission	0.6%
combined	2.7%


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
N_{obs}/N_{exp}
ILL
Savannah River
Bugey
Rovno
Goesgen
Krasnoyarsk
Palo Verde
Chooz
KamLAND
10^1
10^2
10^3
10^4
10^5
Distance to Reactor (m)


Muon Intensity (relative to surface)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
Bugey
Palo Verde
Chooz
Diablo Canyon (near)
Diablo Canyon (far)
Perry/IMB
Kamioka
Gran Sasso
Homestake
Frejus
Sudbury
10
100
1000
Depth (mwe)

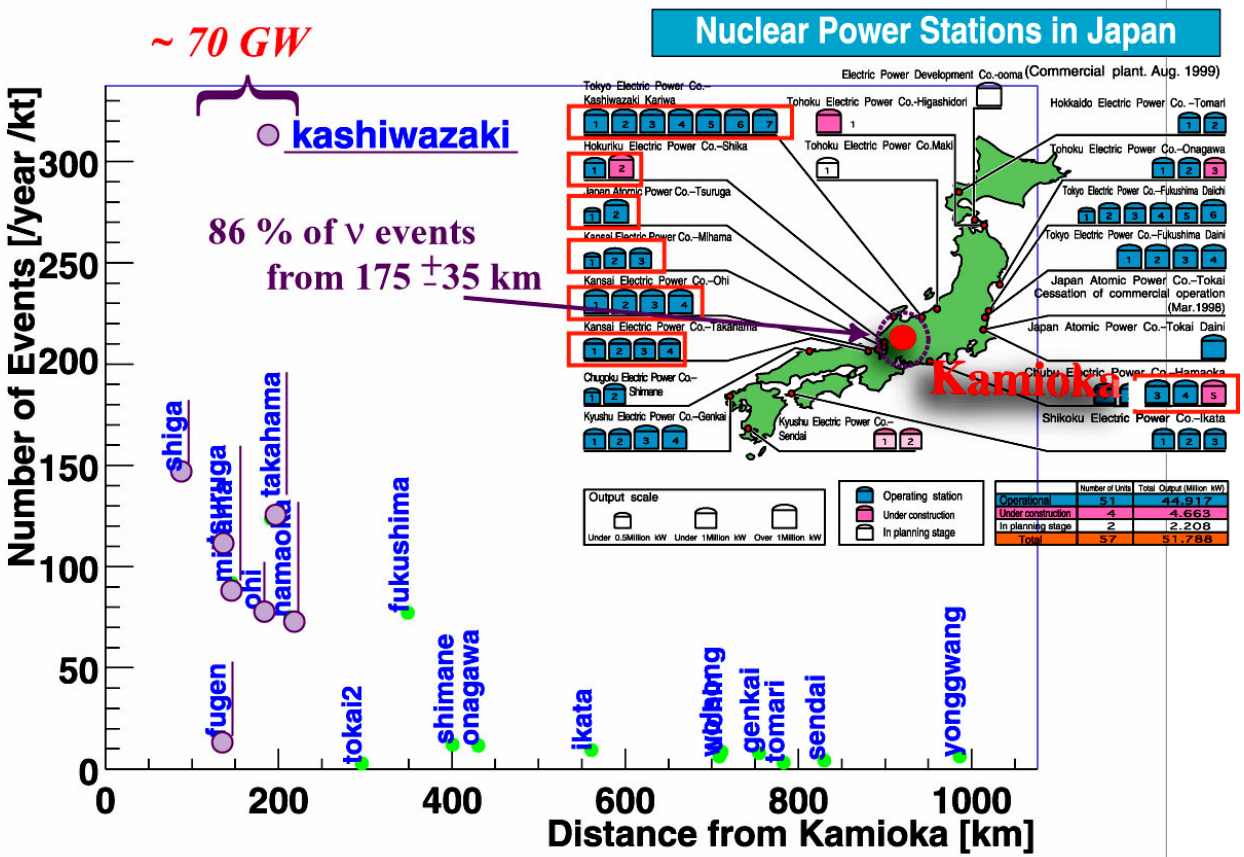
KamLAND

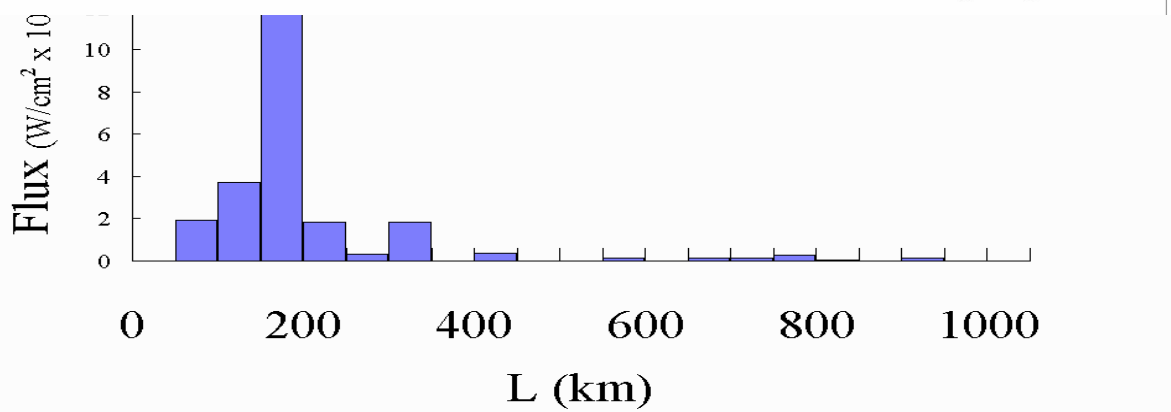
Kamioka Liquid-Scintillator Anti-Neutrino Detector

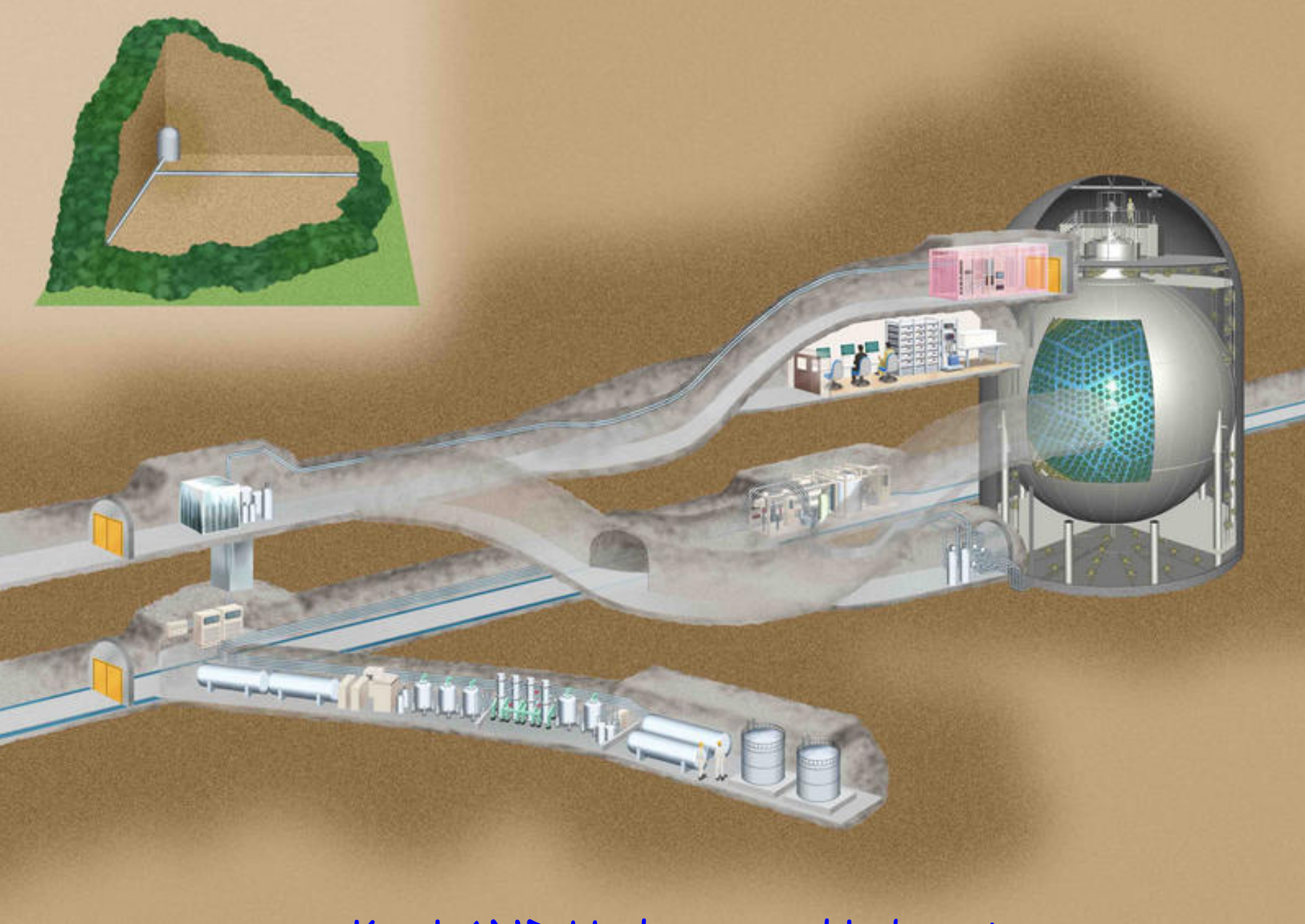


20 % of world nuclear power

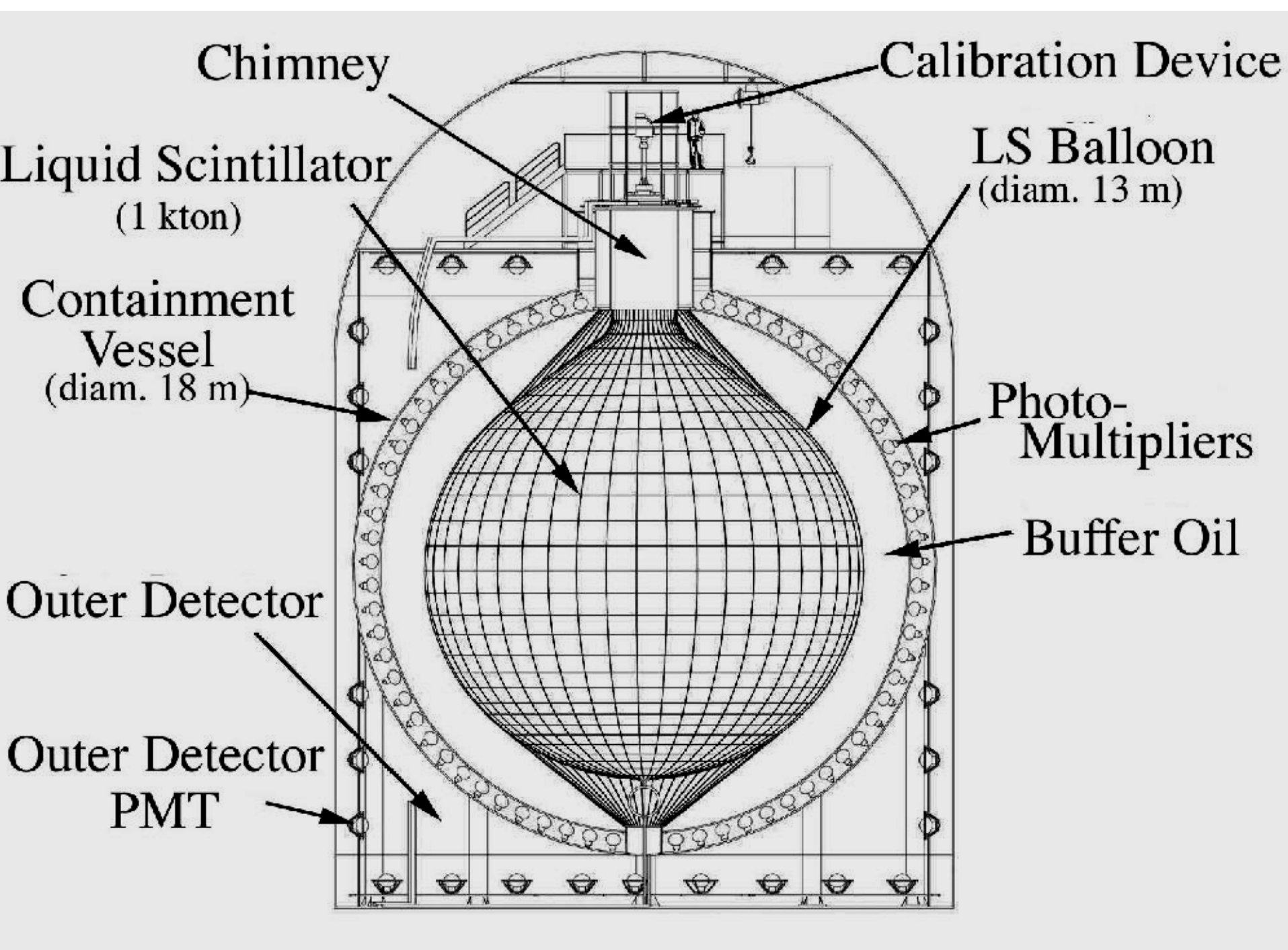
~ 70 GW

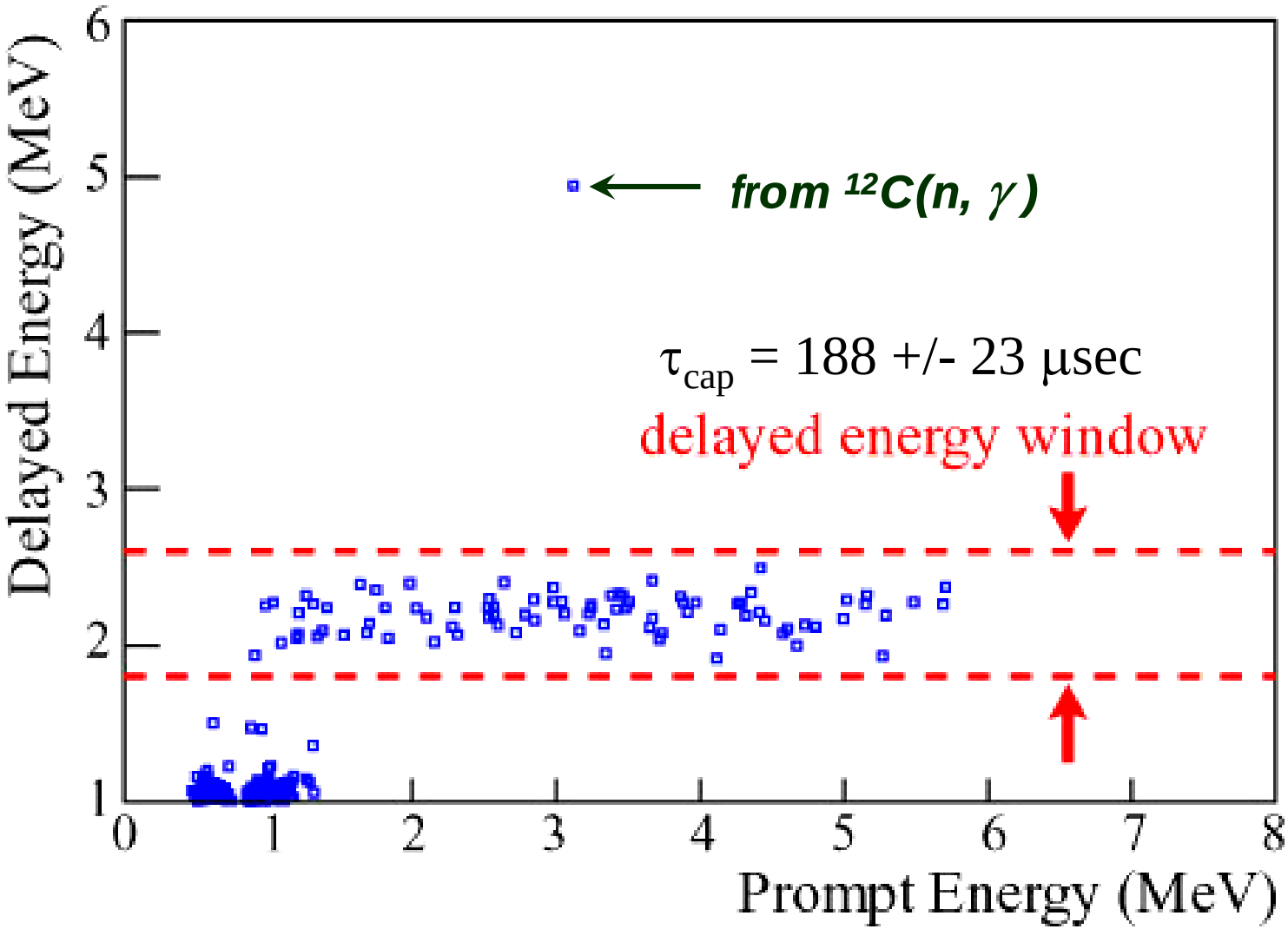


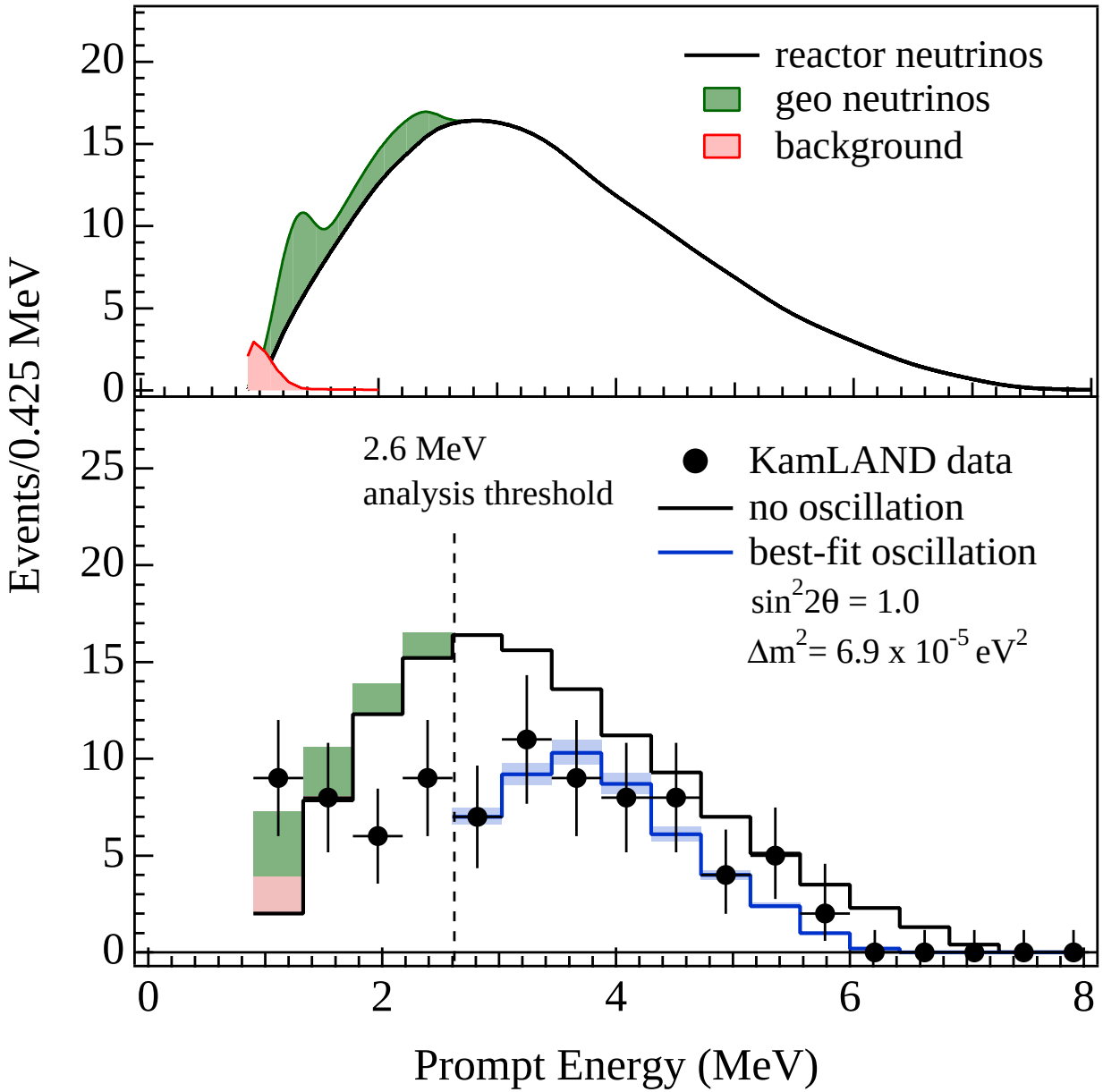




KamLAND Underground Laboratory


Chimney
Calibration Device
Liquid Scintillator
(1 kton)
LS Balloon
(diam. 13 m)
Containment
Vessel
(diam. 18 m)
Photo-
Multipliers
Buffer Oil
Outer Detector
Outer Detector
PMT

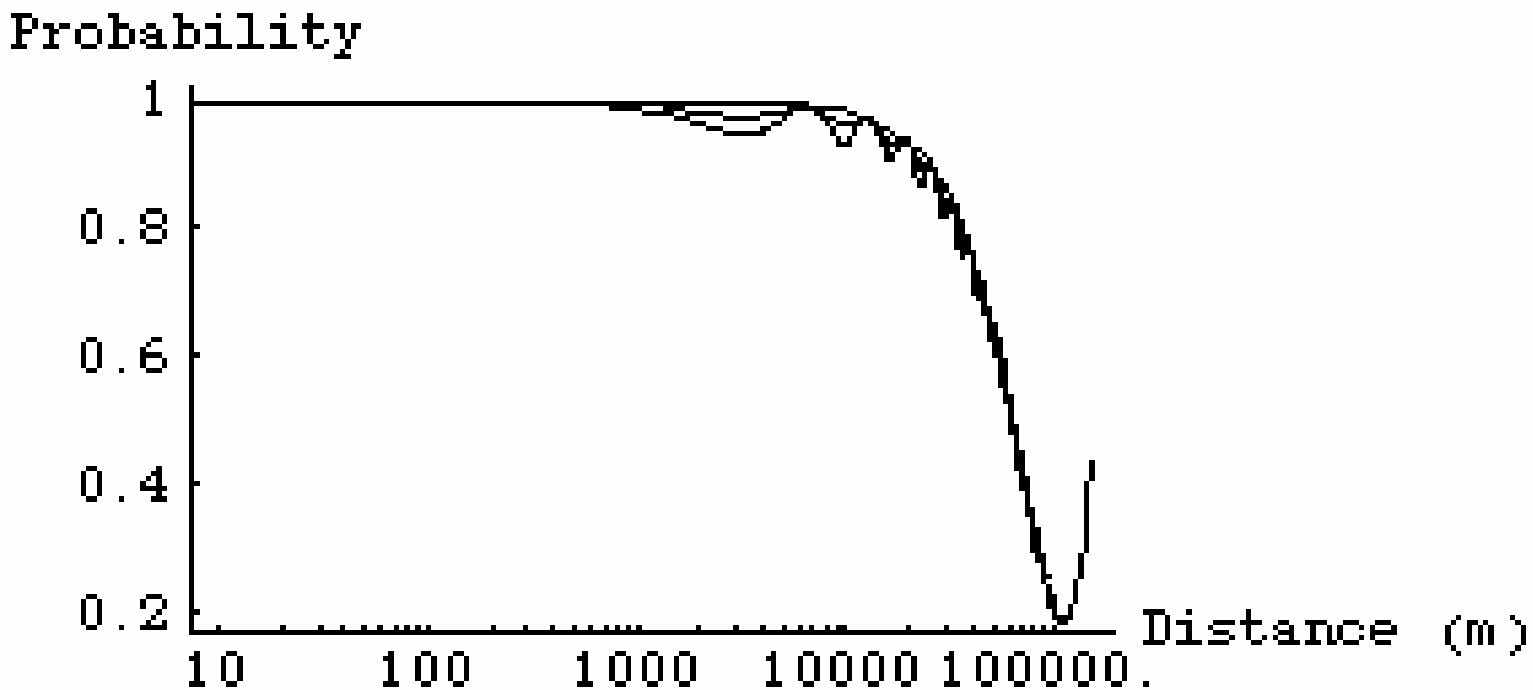

Delayed Energy (MeV)
Prompt Energy (MeV)
from $^{12}C(n, \gamma)$
τ_{cap} = 188 +/- 23 μsec
delayed energy window
0
1
2
3
4
5
6
7
8


reactor neutrinos
geo neutrinos
background
2.6 MeV
analysis threshold
KamLAND data
no oscillation
best-fit oscillation
sin²2θ = 1.0
Δm²= 6.9 x 10⁻⁵ eV²
Events/0.425 MeV
Prompt Energy (MeV)
0
5
10
15
20
25
0
2
4
6
8

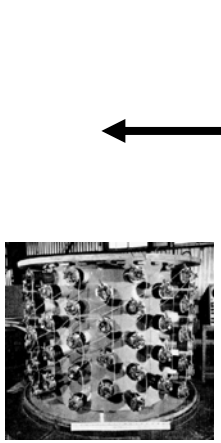
Systematic Uncertainties

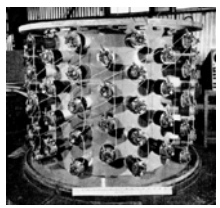
E > 2.6 MeV

	%
Total LS mass	2.1
Fiducial mass ratio	4.1
Energy threshold	2.1
Tagging efficiency	2.1
Live time	0.07
Reactor power	2.0
Fuel composition	1.0
Time lag	0.28
$\bar{\nu}_e$ spectra	2.5
Cross section	0.2
Total uncertainty	6.4 %


Probability
1
0.8
0.6
0.4
0.2
10
100
1000
10000
100000.
Distance (m)

Experimental Design



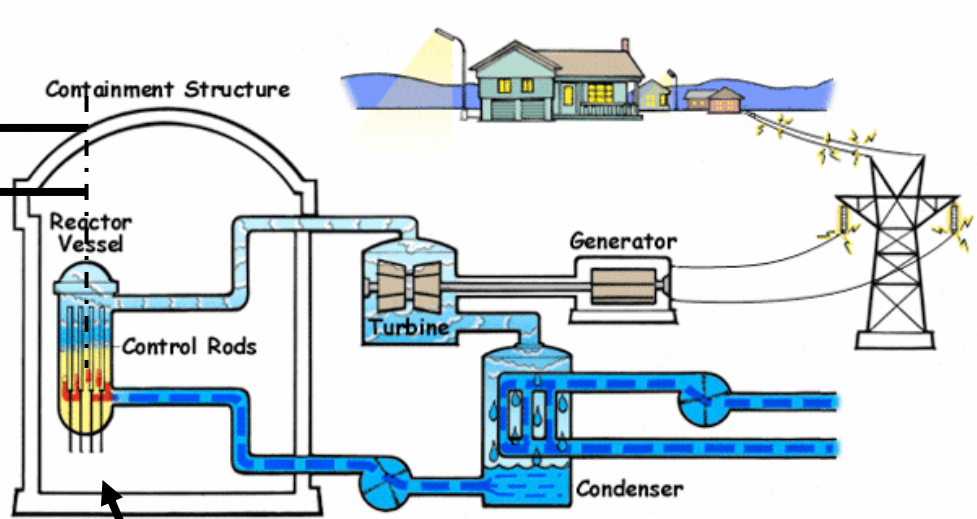


d_2

d_1

Detector 2

Detector 1



Reactor

Reactor θ_{13}

QuickTime?and a TIFF (Uncompressed) decompressor are needed to see this picture.

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