Systematic errors of reactor neutrino experiments

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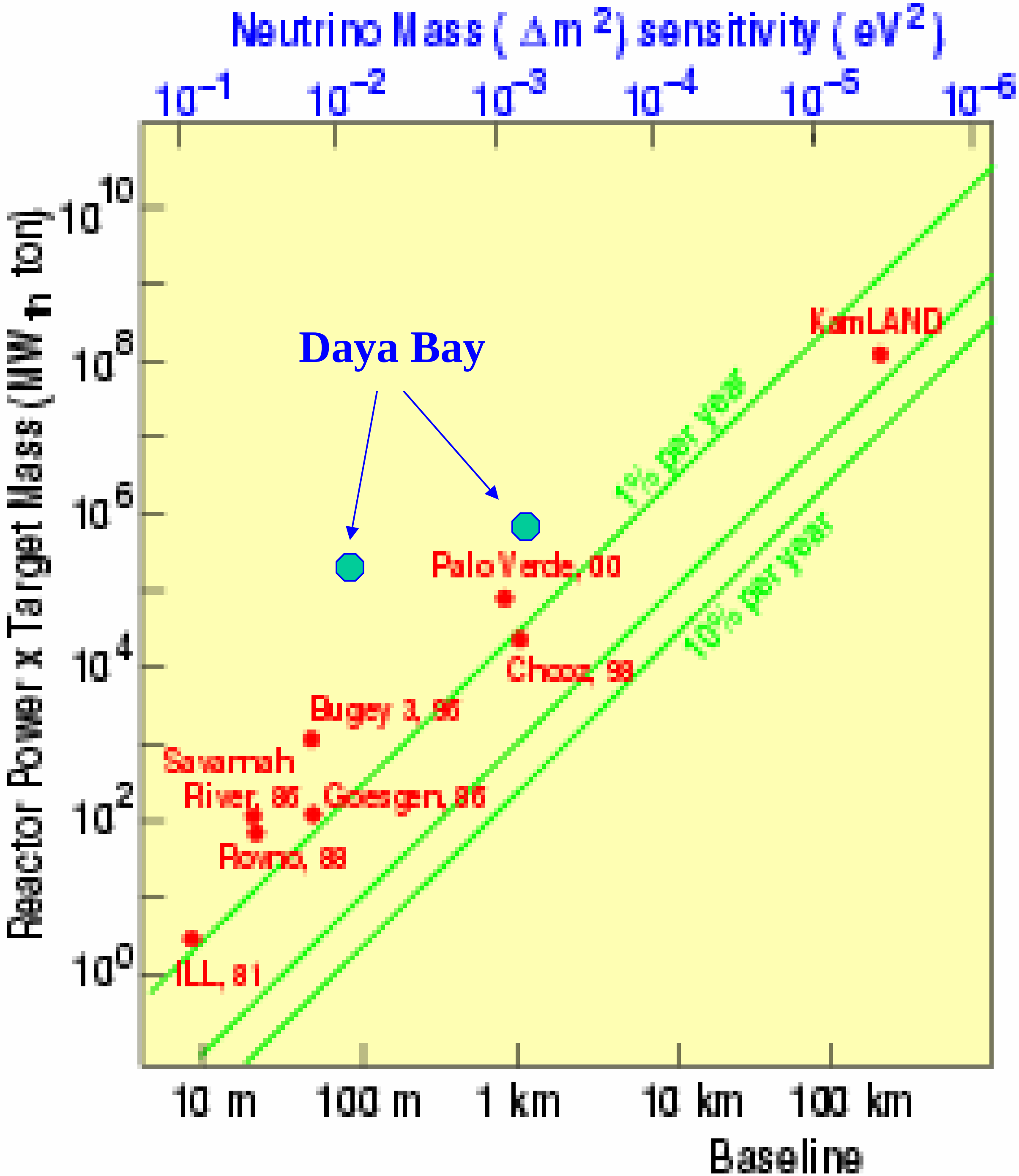


Neutrino Mass (Δm 2) sensitivity (eV 2)
10−1
10−2
10−3
10−4
10−5
10−6
Reactor Power x Target Mass (MW th ton)
10 10
10 8
10 6
10 4
10 2
10 0
Daya Bay
KamLAND
1% per year
10% per year
Palo Verde, 00
Chooz, 98
Bugey 3, 95
Savannah
River, 86
Goesgen, 86
Rovno, 88
ILL, 81
10 m
100 m
1 km
10 km
100 km
Baseline

Systematic errors

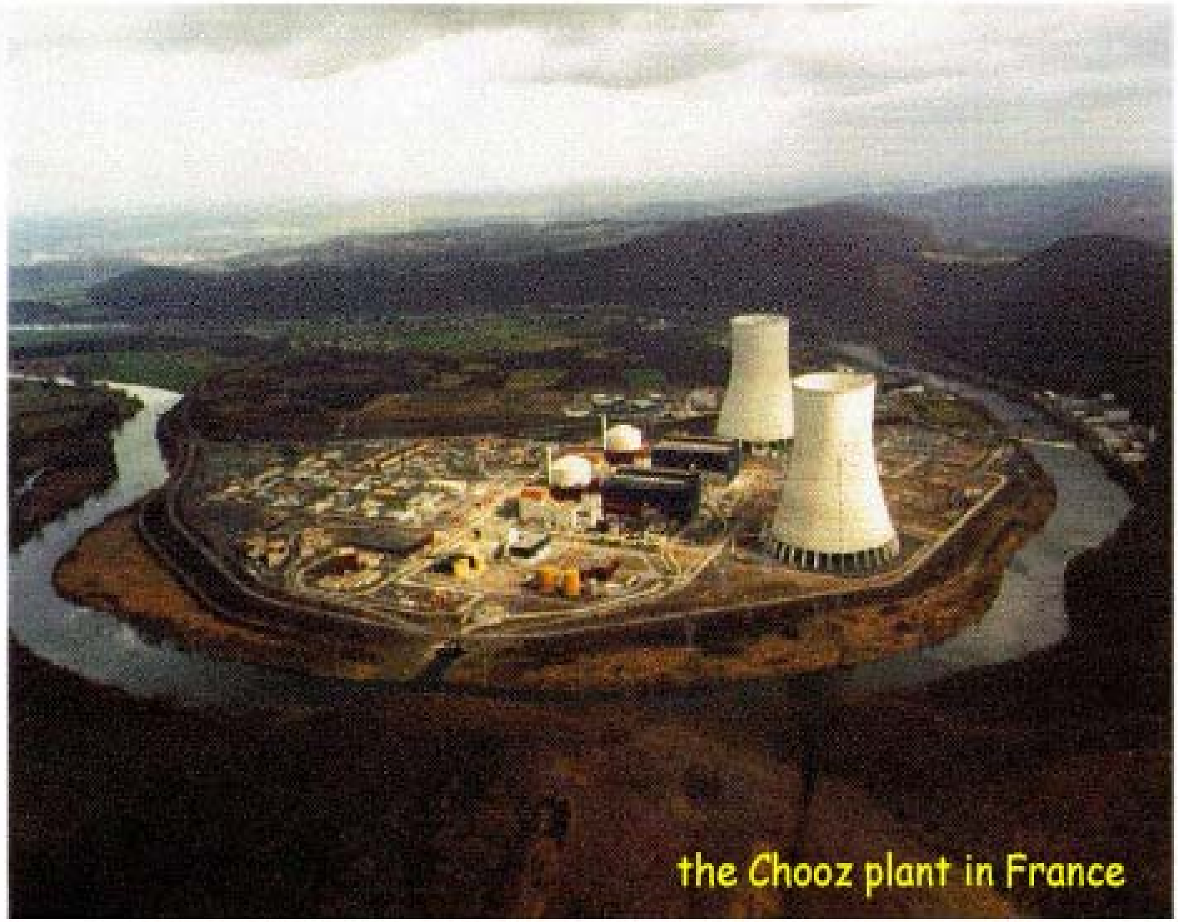
- Reactor related error
- Detector related error
- Background related error

Reactor: Source of neutrinos

$$200 MeV / fission$$

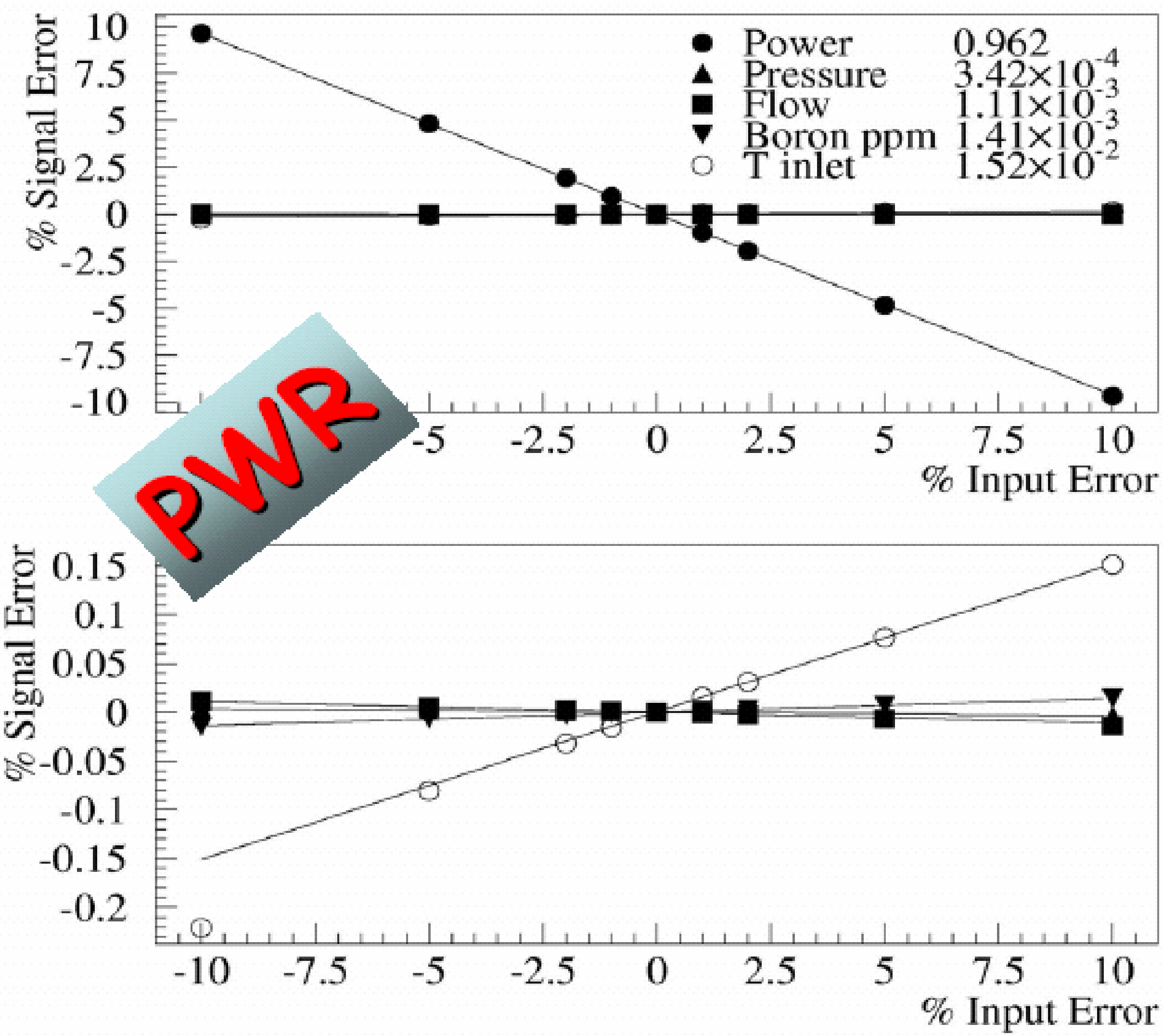
$$6\bar{\nu}_e / fission$$

A typical large power reactor produces 3 $GW_{thermal}$ and $6 \cdot 10^{20}$ antineutrinos/s



Systematic Error: Power

The 200 MeV/fission part:



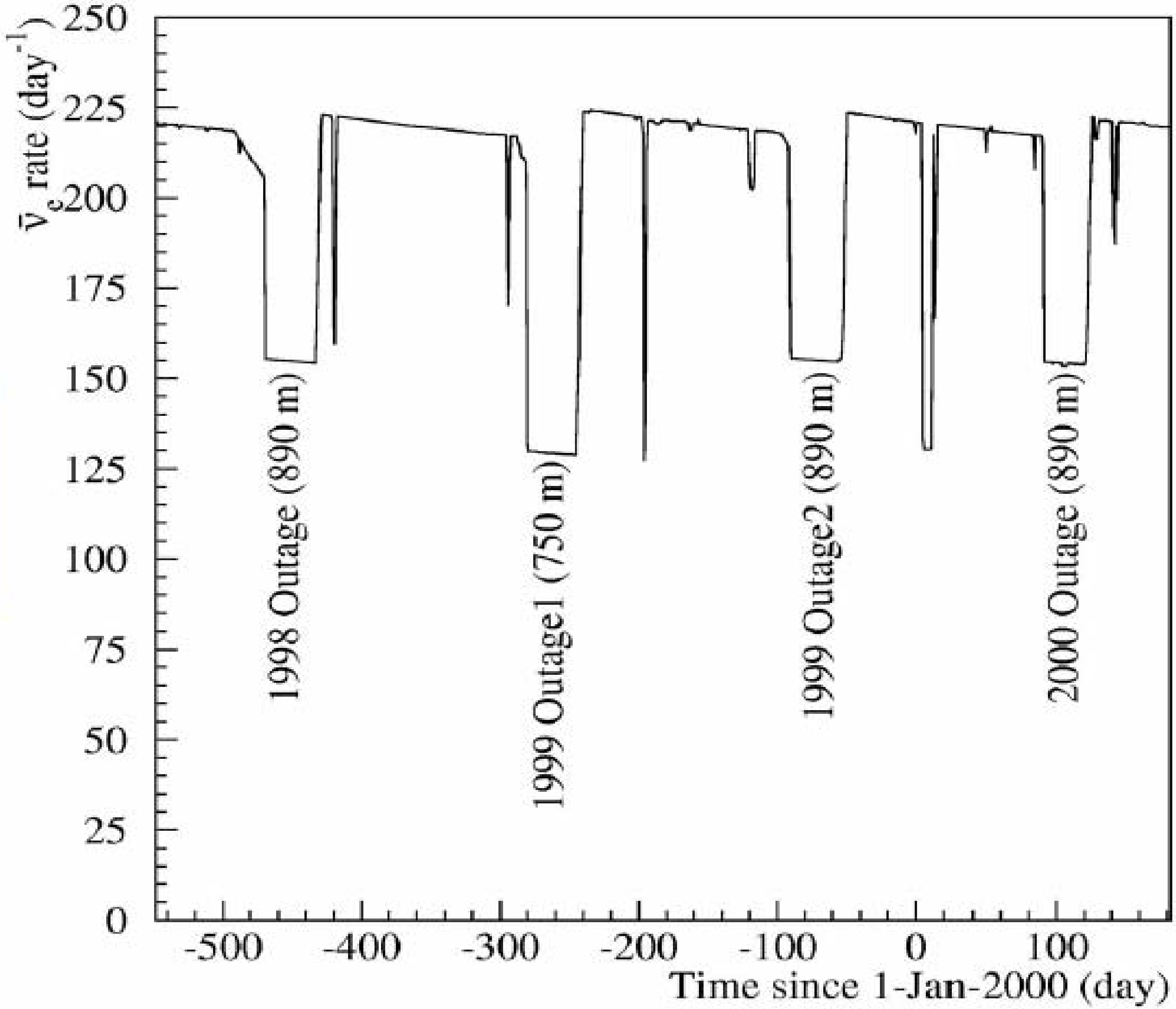
Thermal power is routinely measured by the reactor operator in order to adjust the reactor to the highest licensed power

Economics push the error on this to 0.6-0.7%

Reactor thermal power

Known to <1%

Power history for the 3-unit Palo Verde plant

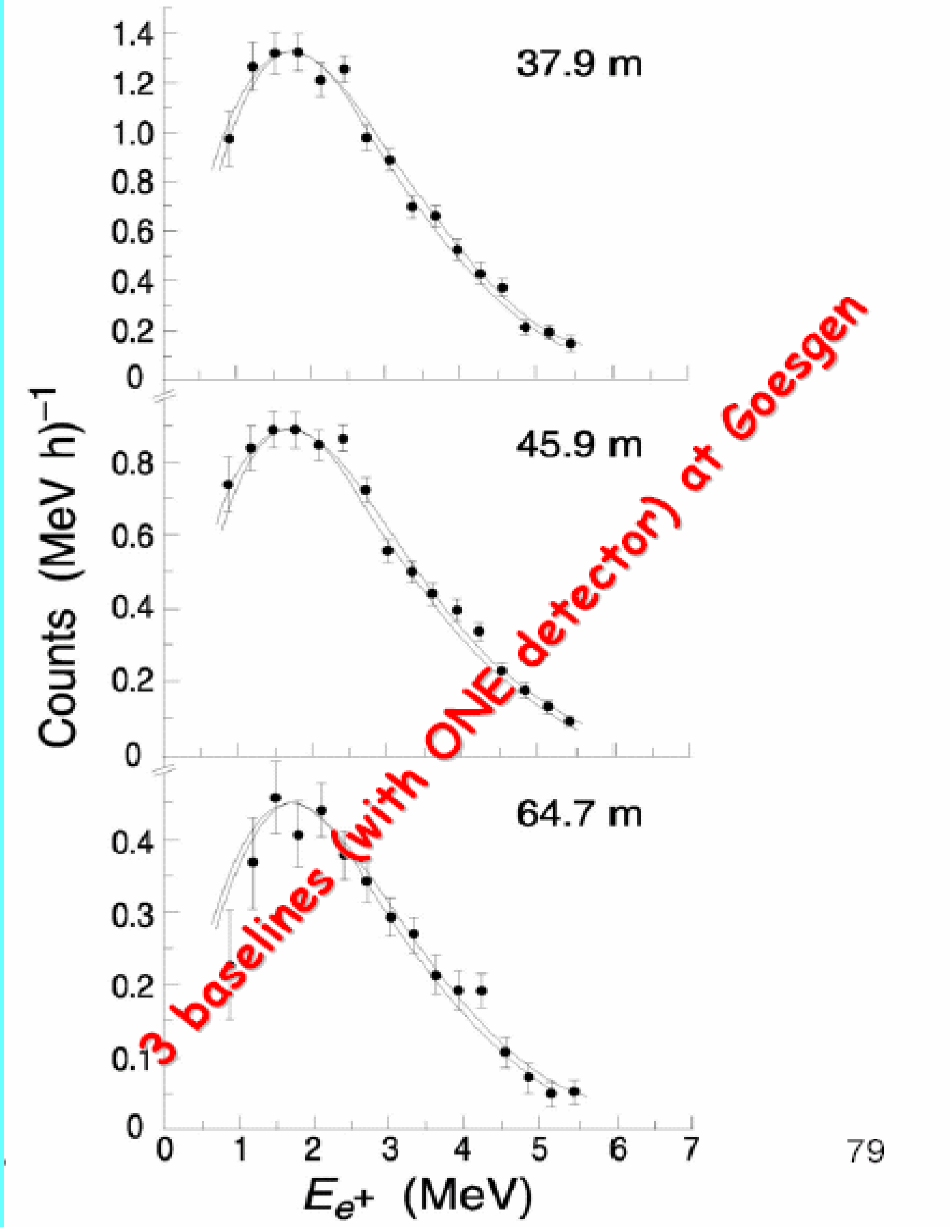


Prediction of reactor neutrino spectrum

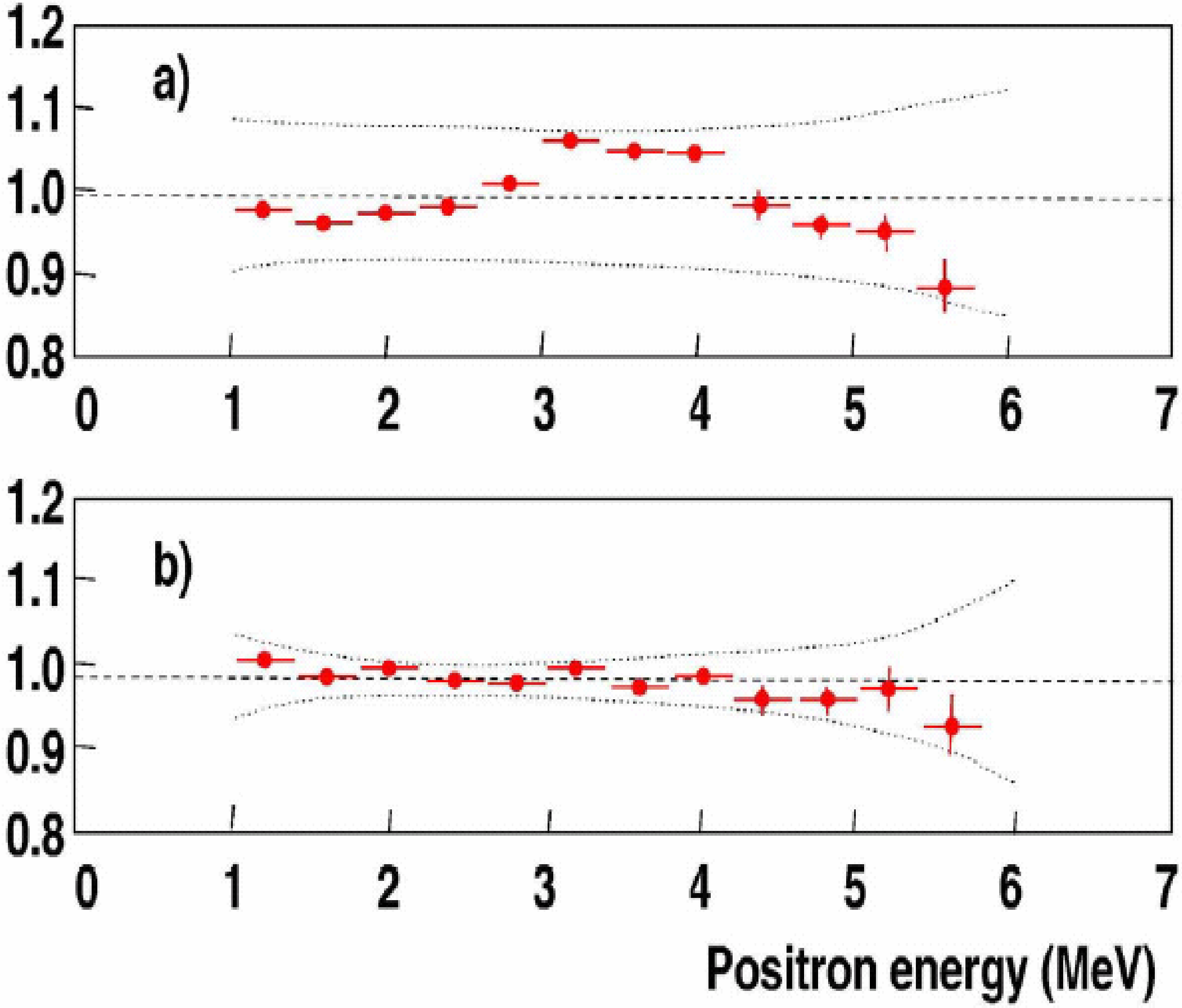
- **Three ways to obtain reactor neutrino spectrum:**
  - **Direct measurement**
  - **First principle calculation**
  - **Sum up neutrino spectra from ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U**

    ^{235}U, ^{239}Pu, ^{241}Pu from their measured β spectra

    ^{238}U(10%) from calculation (10%)
- **They all agree well within 3%**



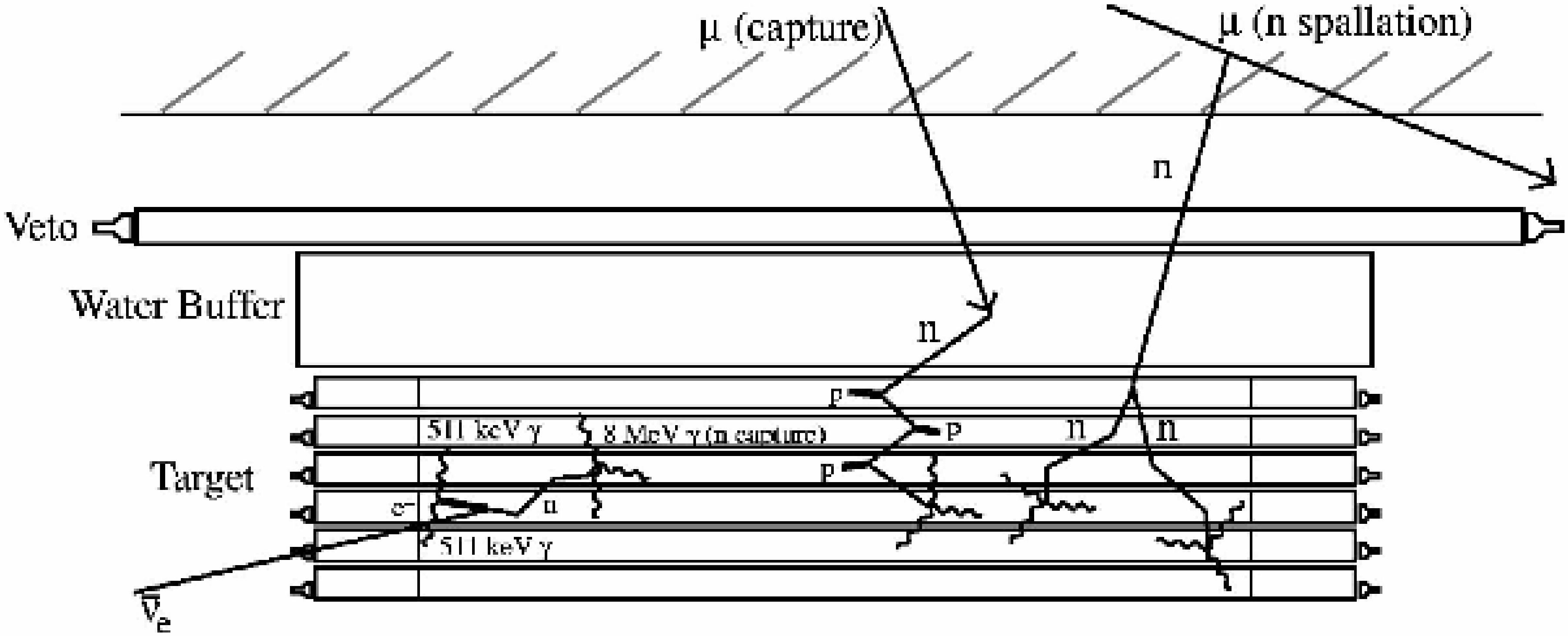
Total error on neutrino spectrum



Bugey3/"first principle calculation"

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

Background - Correlated



Background - Uncorrelated: environmental radioactivity

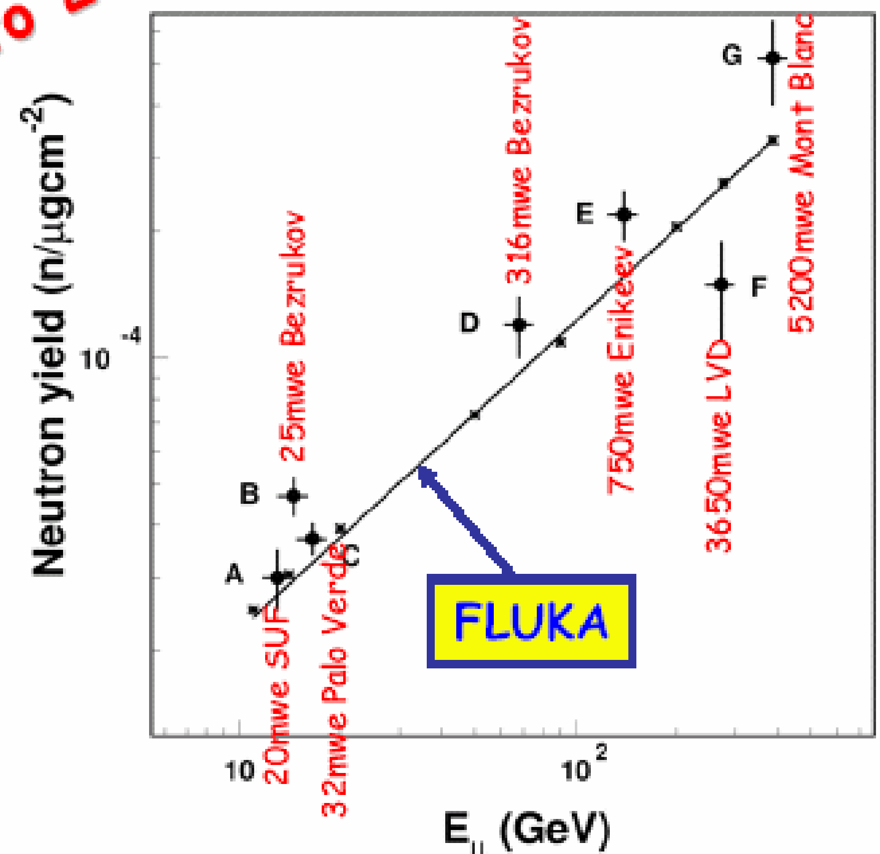
n-production from μ quite well studied at Palo Verde, high energy spectrum and vetoed events can be used to predict background in the interesting region

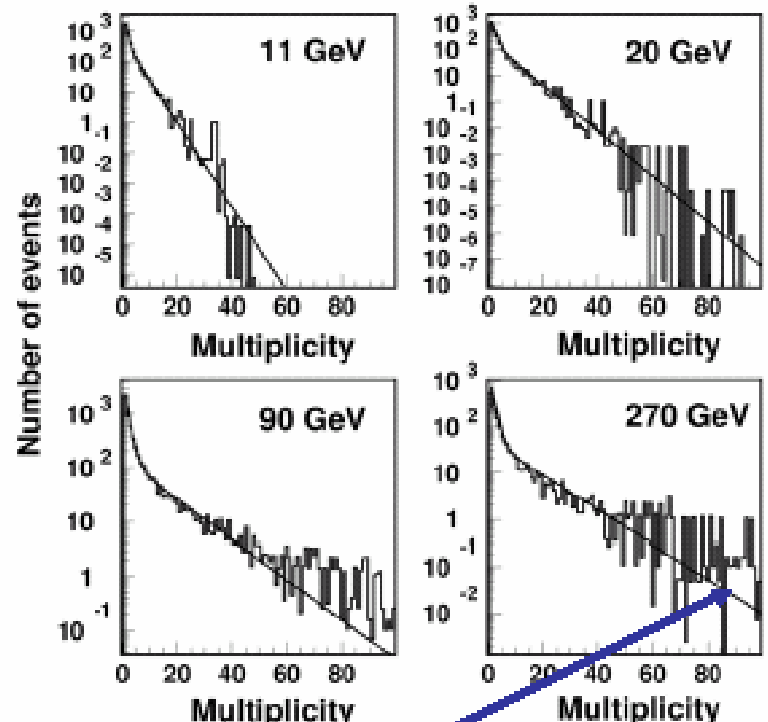
Measurement of bkgnd to 20% appears possible

- Y-F.Wang, L.Miller, GG; Phys. Rev. D 62, 013012 (2000)
- F.Boehm et al., Phys. Rev. D 62, 092005 (2000)

FLUKA is quite accurate for most variables

- Y-F.Wang et al., Phys. Rev. D 64, 013012 (2001)





Parametrization based on FLUKA

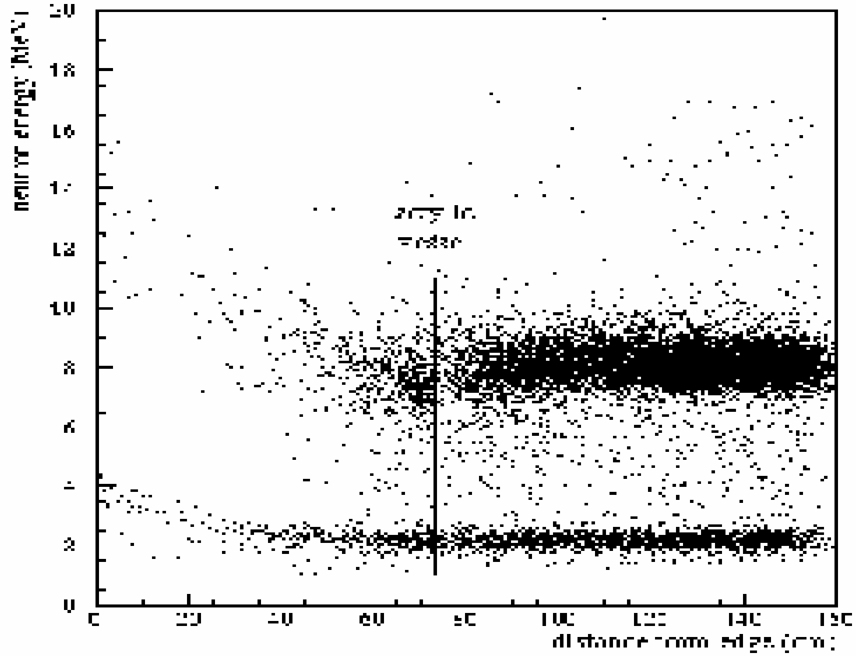
Table 6
Muon-induced background rates in BOREXINO, calculated for different energy regions that are relevant for solar neutrino physics[a]

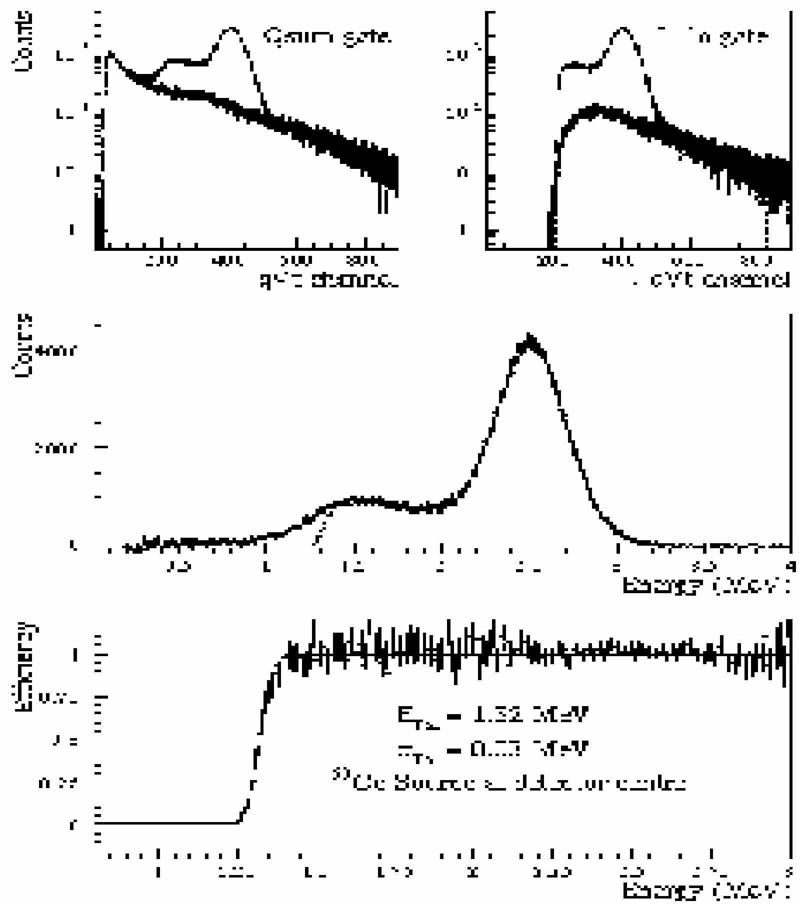
Isotopes	Muon-induced background rates in BOREXINO given in counts/(day × 100 tons) for the different energy regions			
	Full energy range	$250 < E < 800$ keV ^{7}Be-ν region	$0.8 < E < 1.4$ MeV pep-ν region	$2.8 < E < 5.5$ MeV ^{8}B-ν region
^{11}C	14.55 ± 1.49	0	7.36 ± 0.75	0
^{7}Be	0.34 ± 0.04	0.34 ± 0.04	0	0
^{11}Be	<0.034	$<4.3 \times 10^{-4}$	$<1.0 \times 10^{-4}$	<0.01
^{10}C	1.95 ± 0.21	0	0	0.56 ± 0.06
^{8}Li	0.070 ± 0.017	$(2.5 \pm 0.6) \times 10^{-4}$	$(8.0 \pm 2.0) \times 10^{-4}$	0.020 ± 0.005
^{6}He	0.26 ± 0.03	0.040 ± 0.004	0.07 ± 0.01	0.011 ± 0.001
^{8}B	0.11 ± 0.02	0	$(3.3 \pm 0.6) \times 10^{-5}$	0.020 ± 0.004
^{9}C	0.077 ± 0.025	0	0	0.016 ± 0.005
^{9}Li + ^{8}He	0.034 ± 0.007	$<6.8 \times 10^{-4}$	$<1.0 \times 10^{-3}$	<0.014

[a] The rates are given in counts/day normalized to 100 tons of target mass.

5t 0.1% Gd-loaded scintillators

Shielding:
300 MWE
2 m scintillator +
0.14m Fe
1km baseline
Signal: ~30/day
Eff. : ~70%
BK:
corr. 1/day
uncorr. 0.5/day





Position cut

Energy cut

Systematics

sources	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
total	2.7

Closer look -- Detection efficiency

Table 6. Summary of the neutrino detection efficiencies.

selection	ϵ(%)	rel. error (%)
positron energy*	97.8	0.8
positron-geode distance	99.9	0.1
neutron capture	84.6	1.0
capture energy containment	94.6	0.4
neutron-geode distance	99.5	0.1
neutron delay	93.7	0.4
positron-neutron distance	98.4	0.3
neutron multiplicity*	97.4	0.5
combined*	69.8	1.5

*average values

Experience gained

- **Not stable Gd-loaded scintillator ($\lambda \sim$ 5–2m)**
- **PMT directly in contact with scintillator → too high uncorr. Background → too high E_{th}(1.32 MeV)**
- **Good shielding → low background**
- **Homogeneous detector → Gd peak at 8 MeV**
- **2m scintillator shielding gives a neutron reduction of $0.8*10^6$.**

12t 0.1% Gd-loaded scintillators

Shielding:

32 MWE /1m water

0.9 km baseline

Signal: ~20/day

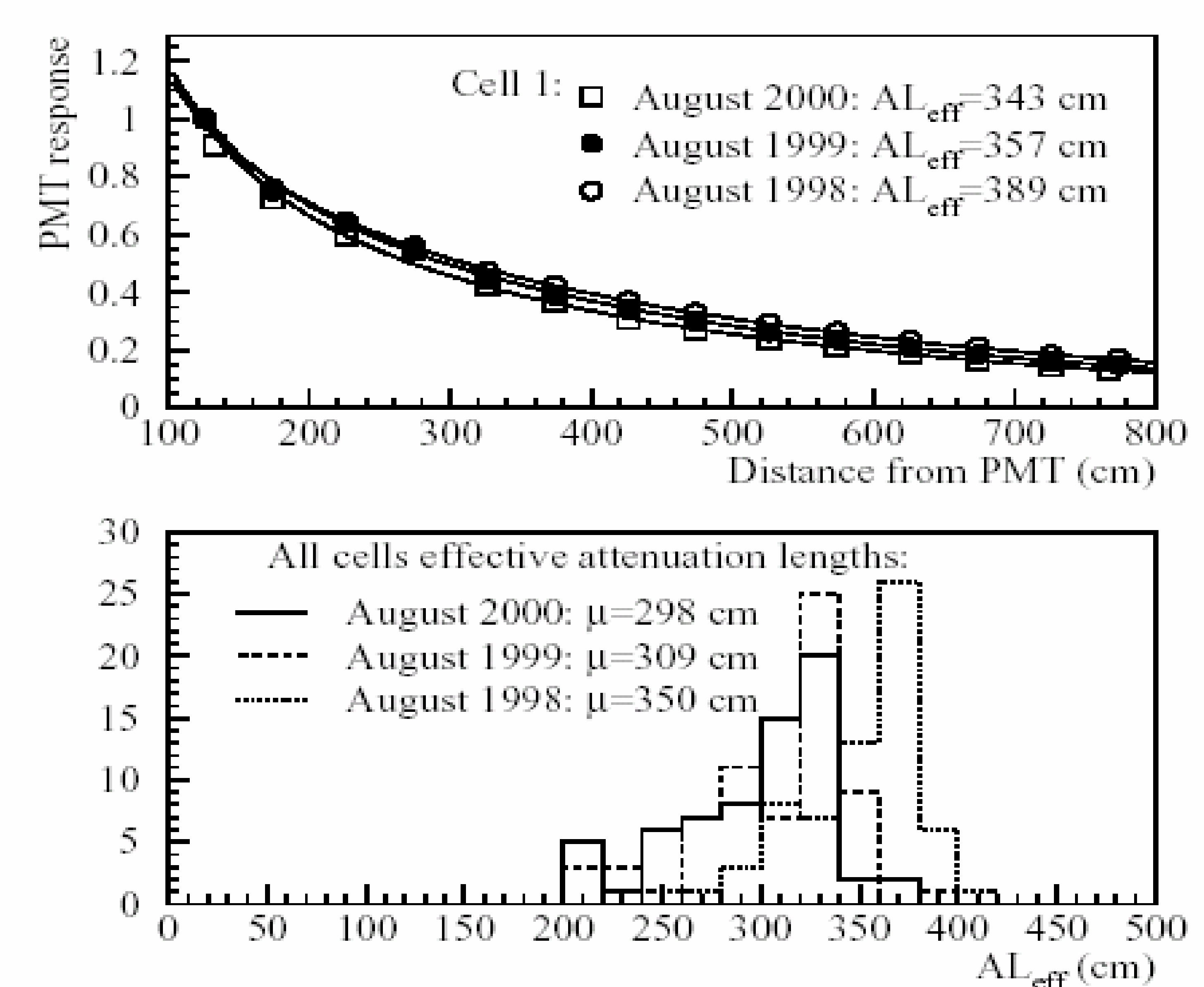
Eff. ~ 10%

BK:

corr.: ~ 15/day

uncorr. ~ 7/day

Very stable Gd-loaded liquid scintillator



Systematics

Sources	power method	Swap method
e+ trigger efficiency	2.0	2.0
n trigger efficiency	2.1	2.1
ν flux prediction	2.1	2.1
ν selection cuts	4.5	2.1
Background variation	2.1	N/A
$(1-\varepsilon_1)\ B_{pn}$	N/A	3.3
Total	6.1	5.3

Error on ν selection cuts obtained from multi-variable analysis

Experience gained

- **Good Gd-loaded scintillator($\lambda \sim 11$m)**
- **Not enough shielding → too high corr./uncorr. Background**
- **Segmentation makes Gd capture peak <6MeV → too high uncorr. Background**
- **Rn may enter the detector, problem ?**
- **Veto eff. is not high enough(97.5%)**
- **Swap method to measure/cancel backgrounds → key to success**
- **1m water shielding gives a neutron reduction of 10^6 (lower energy, complicated event pattern).**

KamLAND

1000t scintillators

Shielding:

3000 MWE/3m Water

180 km baseline

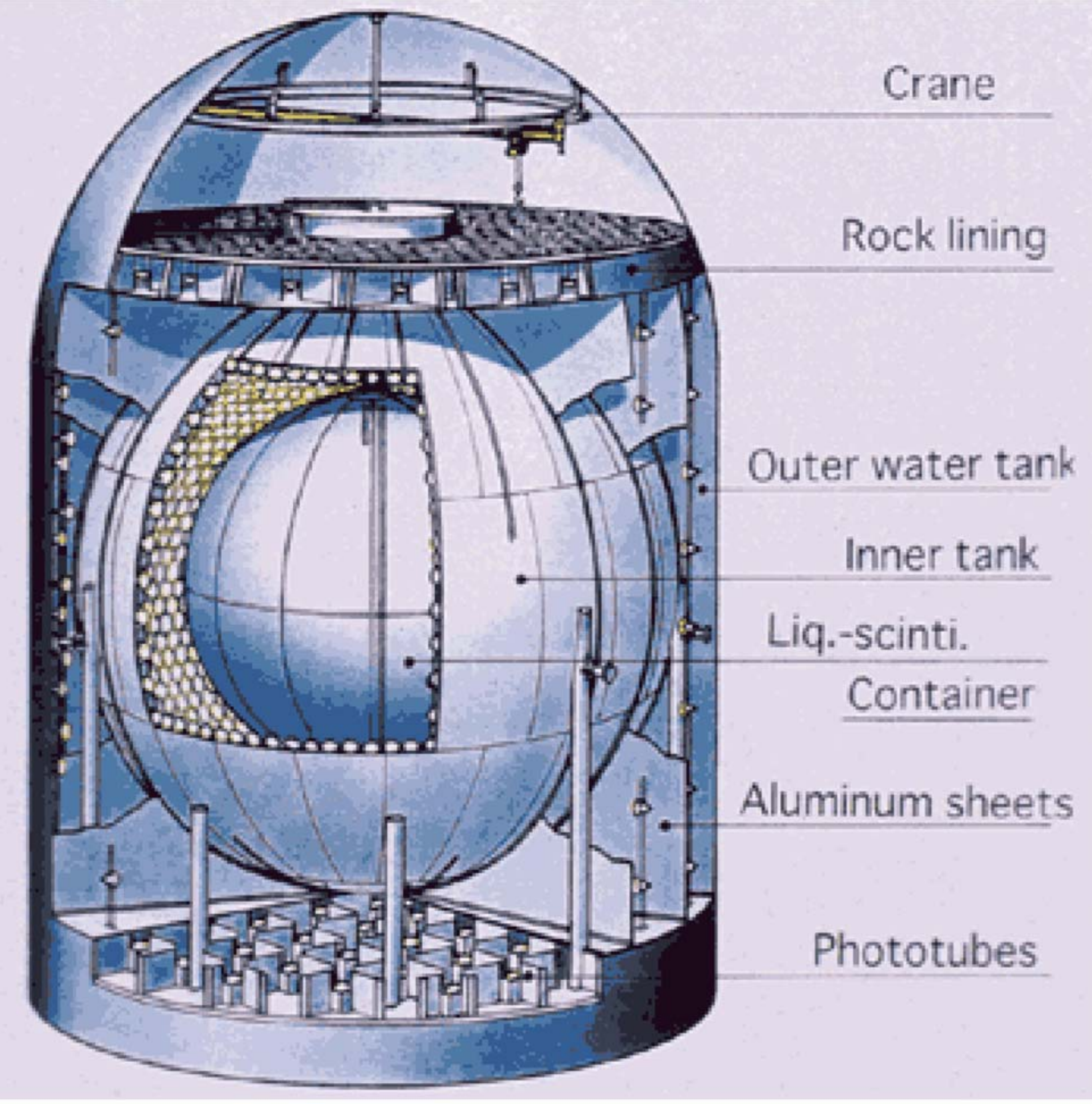
Signal: ~0.5/day

Eff. ~40%

BK:

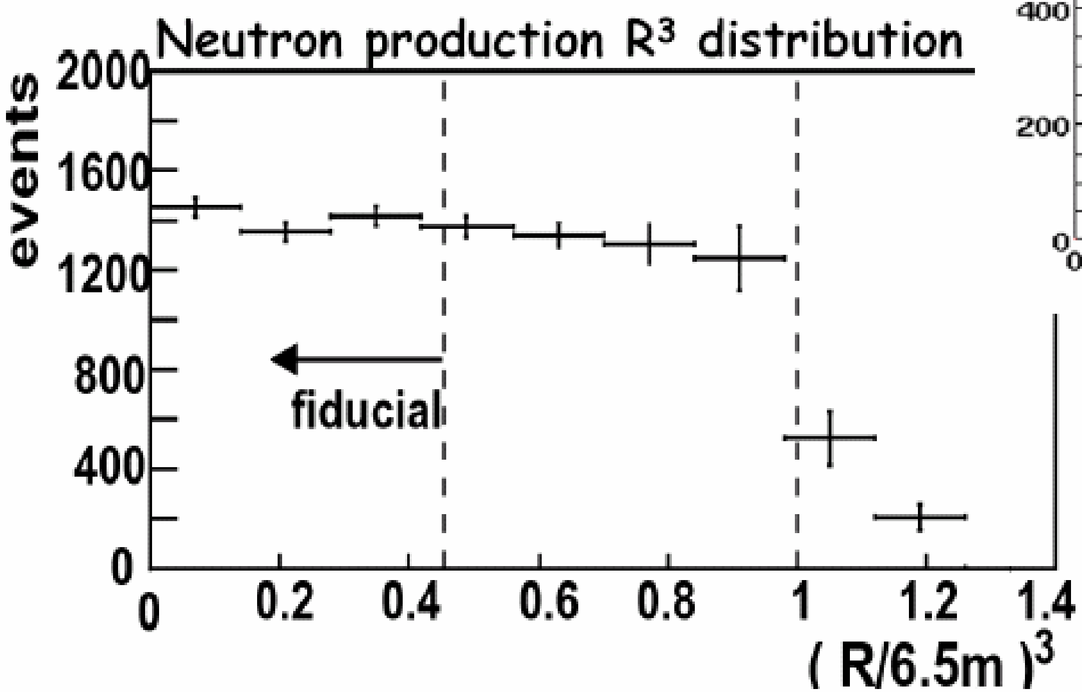
corr.: ~0.001/day

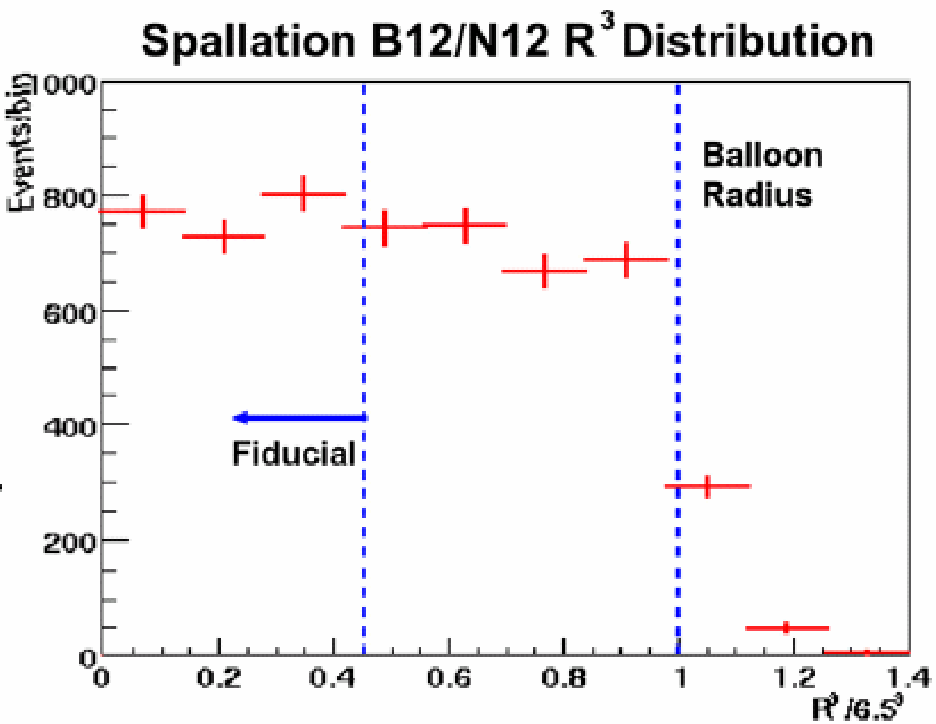
uncorr. ~0.01/day



Large error on fiducial volume

$R_{fid} = 6.5\ m$
$R_{fid} = 5\ m$
$\Delta V_{fid}/V_{fid} = 4.6\ \%$





Fiducial mass 408 ton (out of 1000)

Systematic errors

Systematic errors	E>0.9 MeV	E>2.6 MeV
Total LS mass	2.13	2.13
Fiducial mass ratio	4.03	4.03
Energy threshold	--	2.13
Efficiency of cuts	2.06	2.06
Live time	0.07	0.07
Reactor power	2.05	2.05
Fuel composition	1.0	1.0
Time lag	0.28	0.28
ν spectra	2.25	2.48
Cross section	0.2	0.2
Total	6.0	6.4

Experience gained

- Very good shielding
- Balloon not good → target mass not well defined
- Light transport in scintillator unknown → particularly bad for Large detectors → large error on position reconstruction
- Background from 8He/9Li
- Not good enough veto tracking system
- 3m water shielding gives a neutron reduction of $>13*10^6$(high energy).

Three main types of errors:

reactor related(3%)

background related(0.5-4%)

detector related(3%)

How to reduce these errors ?

Can we do better than 1% ???

Systematic error comparison

		Chooz	Palo Verde	KamLAND
Reactor power		0.7	0.7	2.05
Reactor fuel/ν spectra		2.0	2.0	2.7
ν cross section		0.3	0.2	0.2
No. of protons	H/C ratio	0.8	0.8	1.7
	Mass	-	-	2.1
Efficiency	Energy cuts	0.89	2.1	0.26
	Position cuts	0.32		3.5
	Time cuts	0.4		0.
	P/Gd ratio	1.0		-
	n multiplicity	0.5		-
background	correlated	0.3	3.3	1.8
	uncorrelated	0.3	1.8	0.1
Trigger		0	2.9	0
livetime		0	0.2	0.2

Important point to have small systematic error

- Energy threshold less than 0.9 MeV
- Homogeneous detector
- Scintillator mass well determined
- Target scintillator all from one batch, mixing procedures well controlled
- Not too large detector
- Comprehensive calibration program
- Background well controlled ➔ good shielding
- Be able to measure everything(Veto ineff., background, energy/position bias, …)
- A lot of unforeseen effects will occur when looking at 0.1% level

Reactor related error

- Use two detectors, far/near to cancel reactor related errors and some of detector/background related errors
- For one/two reactors, cancellation is exact
- For multiple reactors, cancellation is NOT exact
  - Multiple near detectors may be needed
  - Only uncorrelated errors contribute to final errors
  - Optimum positions to have minimum errors, typically 0.1-0.2%

➔ see J. Cao’s talk

Background related error

- Just to have enough shielding
- How much is enough ?
  - Uncorrelated backgrounds: U/Th/K MC
  - Correlated backgrounds:

    Y.F. Wang et al., PRD64(2001)0013012

    T. Hagner et al., Astroparticle Phys. 14(2000) 33

Background - correlated

- **Cosmic-muon-induced neutrons:**
  - **B/S < 0.005 → 1/day @ ~1km**
  - **Can be measured by veto tagging, accuracy<20%**
  - **Veto rate < 1KHz, 2-3 layers RPC(1600-2400 m^2) ?**
  - **Methods:**
    - **Overburden > 100 MWE**
    - **Active Veto, ineff. < 0.5%, known <0.2%**
  - **Three scenarios:**

	100 MWE	300 MWE	1000 MWE
muon rate/m^2 (Hz)	4	0.4	0.02
n rate in rock/m^3 (/day)	11000	1600	160
reduction required (10^6)	9.2	1.4	0.14
Shielding (water equivalent) (m)	2.5m	2.1m	1.5m

Other correlated backgrounds

- β-neutron instable isotopes from cosmic μ
  - $^{8}He/^{9}Li$, Br(n) = 12%/48%, ^{9}Li dominant
  - Production rates = $f_{\mu} \cdot N_A \cdot \sigma \cdot Br$

	100 MWE	300 MWE	1000 MWE
Average E_{μ} (GeV)	36	64	160
muon rate/m^2 (Hz)	4	0.4	0.02
Cross section (μb)	0.61	0.94	1.86
$^{8}He/^{9}Li$ (1/day/module)	3.4	0.53	0.053

  - Depth > 300 MWE, best 1000 MWE

Background - Uncorrelated

- **B/S < 0.05 ➔ < 8/day @ far site**
- **Can be measured by swap method, precision ~ √B/s=2.5%/day**
- **single rate @ 0.9MeV < 50Hz**

  $2 \cdot R_{\gamma} \cdot R_{n} \cdot \tau < 0.04$/day/module

- **Methods:**
  - **Low activity glass for PMT, > 0.5m oil shielding (dominant!)**
  - **3 MWE shielding, low activity sand/aggregate or Fe ?**
  - **Rn concentration < 20 Bq/m^3, N_2 flushing ?**
  - **(U, Th, K) in Scintillator < 10^{-13} g/g, clean Gd**
  - **All mechanical structure made of low activity materials**
  - **Calibration gadget made of clean materials such as Teflon, …**
  - **Clean everywhere, no dust, no …**

Systematic error comparison

		Chooz	Palo Verde	KamLAND	Cancel ?
Reactor power		0.7	0.7	2.05	<0.1%
Reactor fuel/ν spectra		2.0	2.0	2.7	
ν cross section		0.3	0.2	0.2	0
No. of protons	H/C ratio	0.8	0.8	1.7	0
	Mass	-	-	2.1	<0.1
Efficiency	Energy cuts	0.89	2.1	0.26	0.2
	Position cuts	0.32		3.5	0.2
	Time cuts	0.4		0.	0.1
	P/Gd ratio	1.0		-	0
	n multiplicity	0.5		-	<0.1
background	correlated	0.3	3.3	1.8	<0.1
	uncorrelated	0.3	1.8	0.1	<0.1
Trigger		0	2.9	0	<0.1
livetime		0	0.2	0.2	<0.1

Possibly best systematic errors

- Reactor < 0.1%
- Background < 0.2%
- Energy cut ~ 0.2%
- Position cut ~ 0.2%
- Time cut < 0.1%
- Livetime ~ 0.1%
- Other unexpected <0.2%
- Total < 0.5%

Further reduction of systematic errors: multiple modules

- **Smaller modules have less unknowns**
- **Multiple handling to control systematic errors**
- **Easy construction**
- **Easy movable detector**
- **Scalable**
- **Easy to correct mistakes**

Summary

- **Systematic errors from reactor well under controll: Near vs Far**
- **Errors from backgrounds: just need "enough" shielding**
- **Errors from detector: can be controlled to 0.5% level if the detector carefully designed**

θ_{13} experiment at 0.5% level is possible !

Let's do it !!!