The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2047-30

Workshop Towards Neutrino Technologies

13 - 17 July 2009

Reactor antineutrinos and control of nuclear reactors

Michel CRIBIER

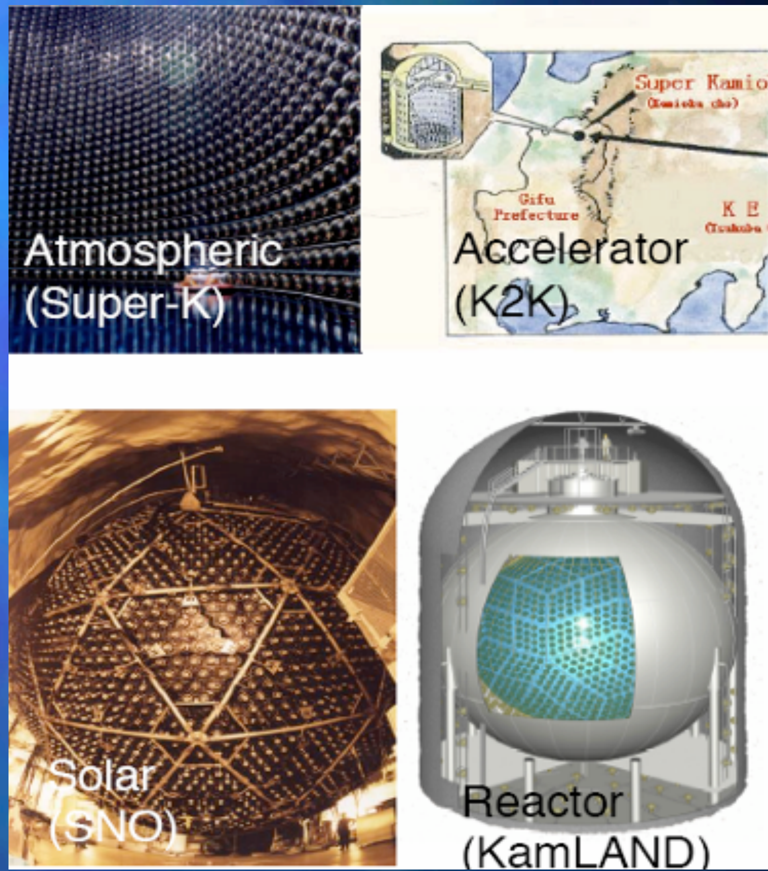
CEA-Dsm-Dapnia/Sphn
Cea-Saclay
F-91191 Gif-sur-Yvette, FRANCE

Antineutrinos and control of nuclear reactors

Michel Cribier
CEA/Saclay DSM/IRFU/SPP
& APC-Paris
mcribier@cea.fr

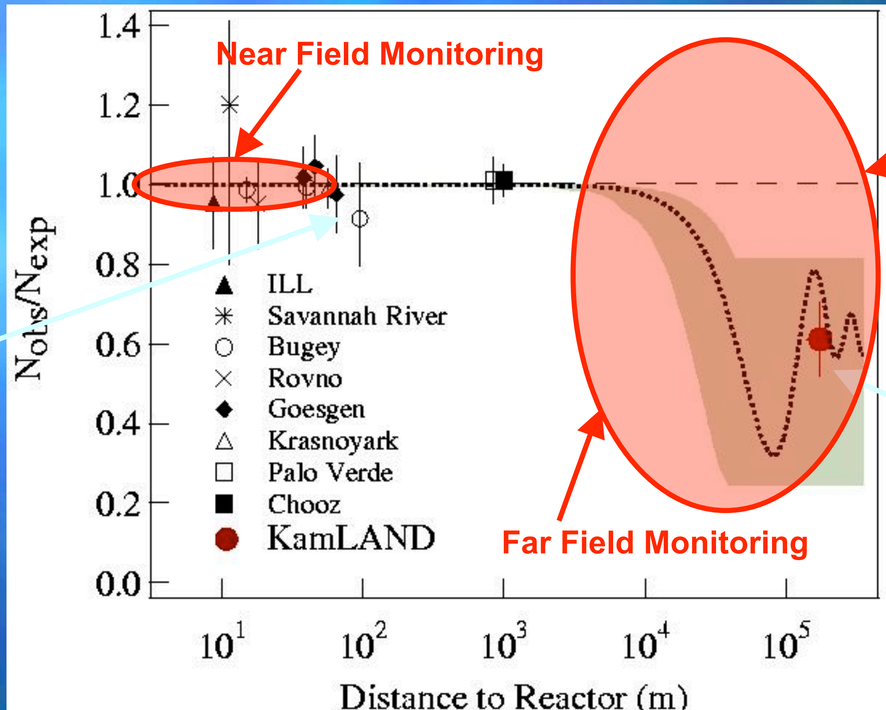
First evidence of physics beyond SM

- **Neutrino are massive**
- **Flavor oscillation $\nu_e \int \nu_\mu \int \nu_\tau$**
- **Neutrino are mainly understood**
- **Still to be measured**
  - **Absolute mass scale**
  - **Third underlying oscillation (θ_{13})**
  - **CP violation ?**
- **BUT TODAY Neutrinos are ENOUGH understood for the current applications in preparation**



The Breakthrough: neutrino oscillation

- **KamLAND sees remote reactors**
  - 1 kton monitoring 130 GWt of reactors
  - few events/week
  - 4% of signal from South Korea



Short shallow baseline
Reactor neutrino experiments

Geoneutrinos
Nuclear test explosion

KamLAND detector
At 2700 m.w.e. depth

KamLAND sees of neutrino oscillations of reactor antineutrinos @ 180 km
Confirmed by **K2K & MINOS**

IAEA

Nobel prize for peace in 2005

IAEA.org
International Atomic Energy Agency

- Safeguard activities :
  - Treaty of NonProliferation (and additional protocole) :
    - accepted (and unattended) controls
  - Detect Diversion from Civil Fuel Cycles to Weapons Programs of Fissile Material (Pu, enriched U)
  - Many places to control all around the world :
    - enrichment units, nuclear fuel factories, power and research reactors, reprocessing units, storage waste…
- Standard methods used
  - mostly checks of input/ouput declarations
  - sampling and analysis (γ-spectroscopy, isotopic content)
  - no direct Pu inventory made at the production place
- Seeking for new tools to perform future controls on increasing number of installations

IAEA: Standard Technology

- Safeguards are applied by the **IAEA** to verify the **correctness and completeness** of declarations made by States about the **exclusively peaceful use** of their nuclear material and activities and thereby reducing the risk of proliferation of nuclear weapons

- Many different PERFORMANT devices
  - Non Destructive Assay (NDA)
  - Containment and Surveillance (C/S): Containment verification, Seals, Cameras
  - Destructive Analysis (DA)
  - Environmental Sampling (ES)

- Already a device for monitoring power output of research reactor.

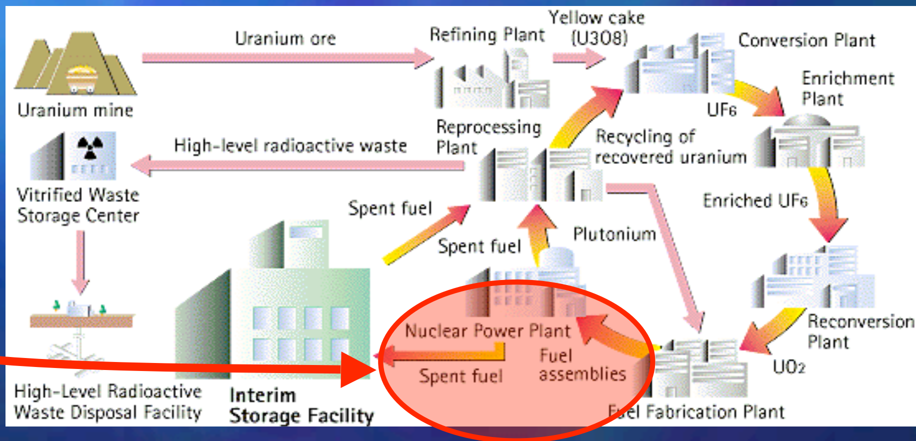
What ν could offer the Agency ?

- **Neutrinos** carries **DIRECT** information from nuclear fuel
- **Neutrinos CANNOT be hidden**. Not falsifiable !!!

- **CONTINUOUS Unattended Monitoring**

- Neutrinos can be used to monitor the thermal power
- Neutrinos provides already a ~50 kg sensitivity to Pu content – *in progress*

- **BUT ν-reactor monitoring addresses only a single step of the fuel cycle**



IAEA Constraints

- IAEA Detector Design Request:
  - ‘Small’ : 2.5 m footprint
  - Safe
  - Remote & Easy Operation by Inspectors
    - not trained as neutrino physicists
  - Reliable
  - “Relocatable”

- Challenges
  - Integration of detectors into the Safeguards Regime
  - Effort to Simplify the current Design while keeping detector performances
  - Monitoring of research reactors : modest power
  - Monitoring of Candu type reactors, Pebble bed modular reactors

- IAEA wishes, dreams ?
  - ground level detectors
  - easy mounting
  - sensitive to a “significant quantity” of Pu

Dialog IAEA Physicists

- December 2003
  - *Meeting to evaluate potential applicability of antineutrino detection technologies for safeguards purposes*
  - IAEA Novel Technologies Unit
  - 5 Physicists from US, Russia, France
- October 28-30, 2008
  - *Workshop on antineutrino detection for safeguards applications*
  - IAEA Division of Technical Support / Novel Technologies Unit
  - 19 Physicists from USA, Canada, Finland, Japan, France, Brazil, Netherland, EU
- Final report : soon ?

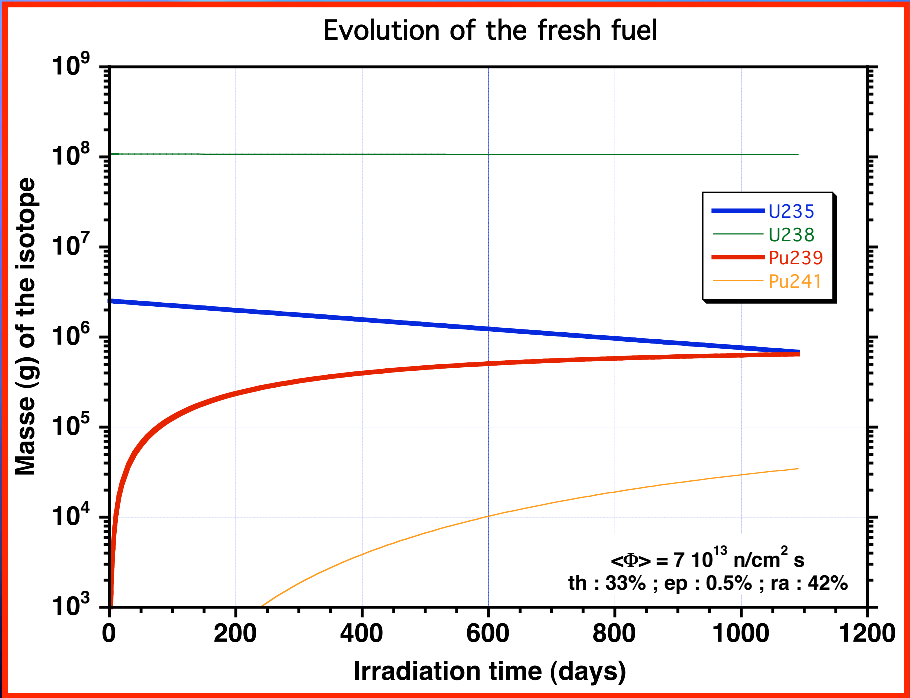
Recommendations issued by the Workshop

- It is recommended that the IAEA consider antineutrino detection and monitoring in its current R&D program for safeguarding bulk-process reactors
- It is recommended that the IAEA should also consider antineutrino monitoring in its Safeguards by Design approaches for power and fissile inventory monitoring of new and next generation reactors
- It is recommended that there should be further interaction between IAEA and the antineutrino research and development (R&D) community, including regular participation of IAEA safeguards departmental staff into international meetings
- It is recommended that IAEA safeguards departmental staff visit currently deployed and planned neutrino detection installations for safeguards applications
- It is recommended the IAEA work with experts to consider future reactor designs, using existing simulation codes for reactor evolution and detector response.

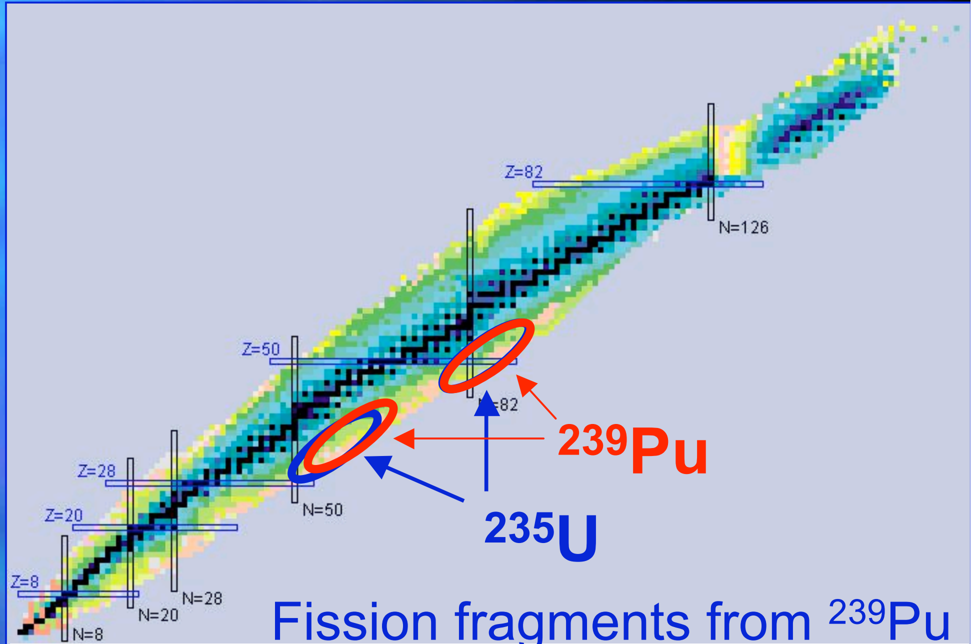
Physics basis allowing monitoring

Burn-up & Fission

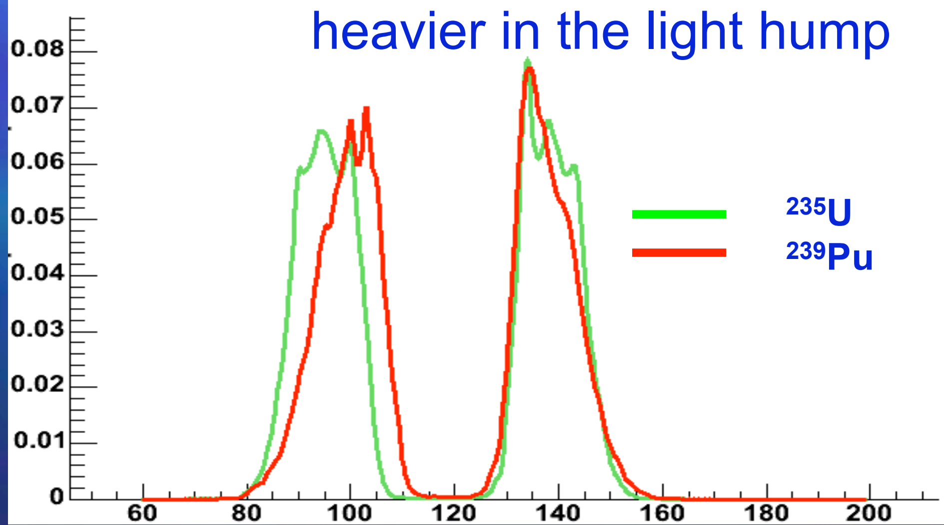
$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow{23\ min} {}^{239}_{93}Np \xrightarrow{2.3\ d} {}^{239}_{94}Pu$$



Grow up of 239Pu
during operation

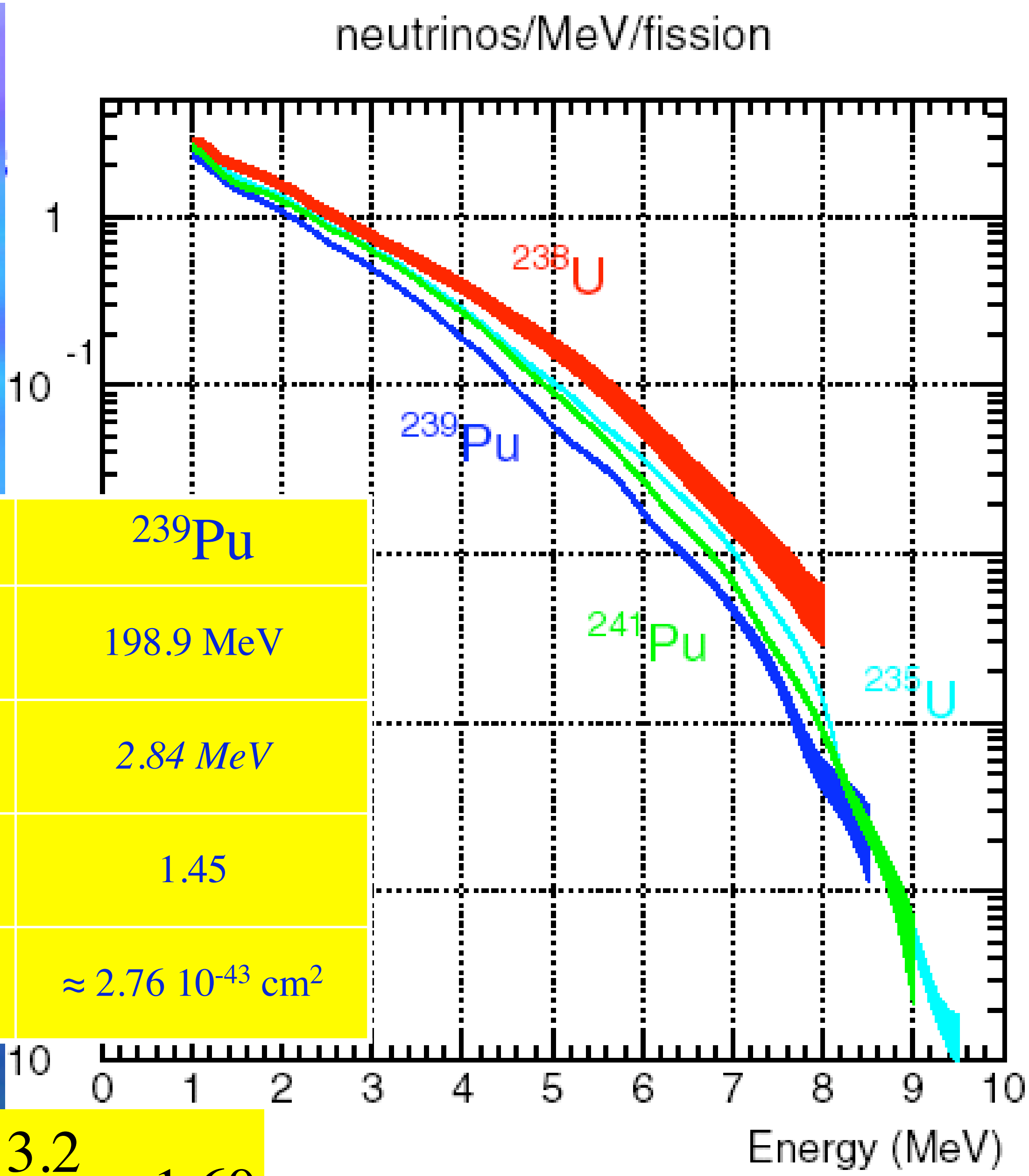


Fission fragments from ^{239}Pu heavier in the light hump



Fission & $\bar{\nu}$

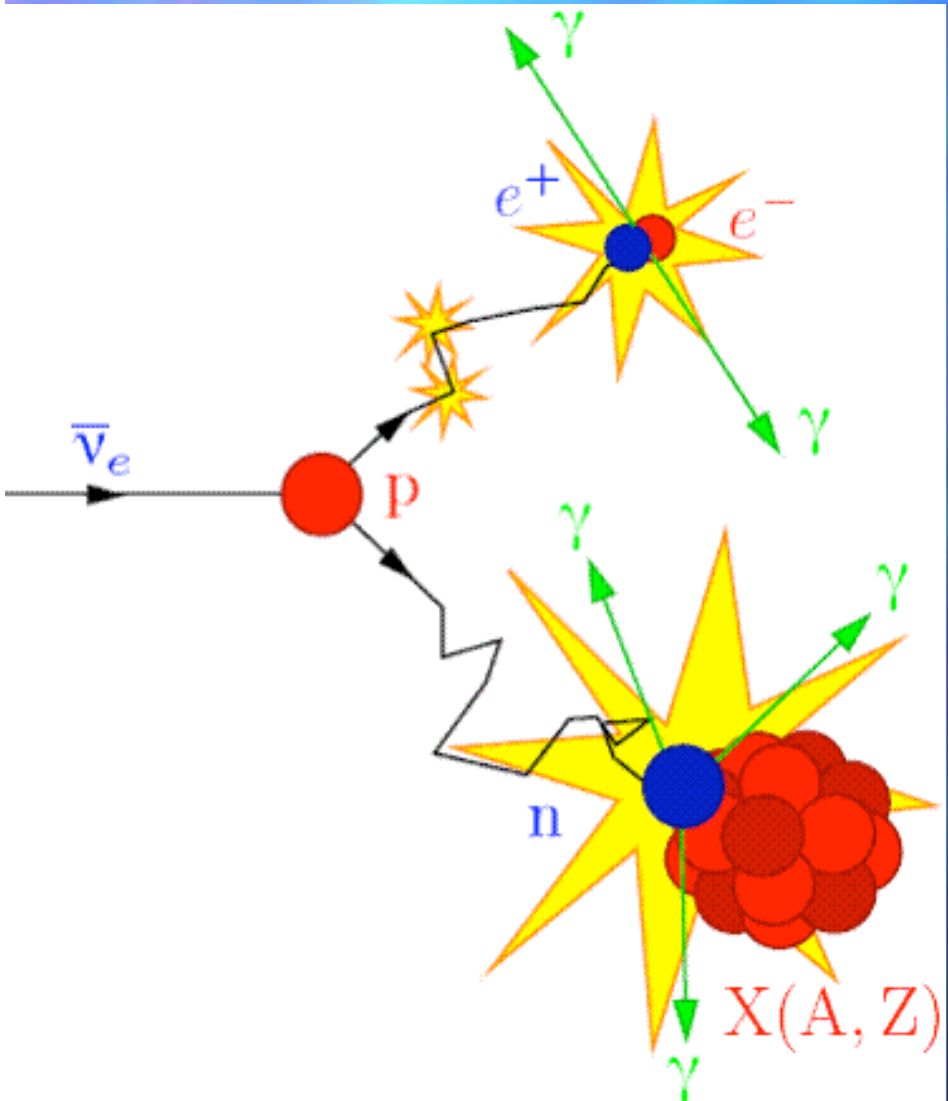
Fission products from ^{235}U or ^{239}Pu are different, hence ν are different



	^{235}U	^{239}Pu
released energy per fission	193.5 MeV	198.9 MeV
Mean energy of ν	*2.94 MeV*	*2.84 MeV*
ν per fission > 1.8 MeV	1.92	1.45
average inter. cross section	$\approx 3.2\ 10^{-43}$ cm^2	$\approx 2.76\ 10^{-43}$ cm^2

$$\frac{\#\,int\ ^{235}U}{\#\,int\ ^{239}Pu} = \frac{210.0}{201.7} \times \frac{1.92}{1.45} \times \frac{3.2}{2.76} = 1.60$$

Antineutrino detection



- **Beta inverse process**
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- Threshold @ 1.8 MeV
  - $\langle E_{\bar{\nu}} \rangle = 1.49 \rightarrow 2.94\,MeV$
  - $\langle N_{\bar{\nu}} \rangle = 5.98 \rightarrow 1.92$

An old idea

- Kurchatov's pioneers…

MEASURING NUCLEAR PLANT POWER OUTPUT
BY NEUTRINO DETECTION

V. A. Korovkin, S. A. Kodanev,
N. S. Panashchenko, D. A. Sokolov,
O. M. Solov'yanov, N. D. Tverdovskii,
A. D. Yarichin, S. N. Ketov, V. I. Kopeikin,
I. N. Machulin, L. A. Mikaélyan, and V. V. Sinev

  - experim. @ Rovno in 1986

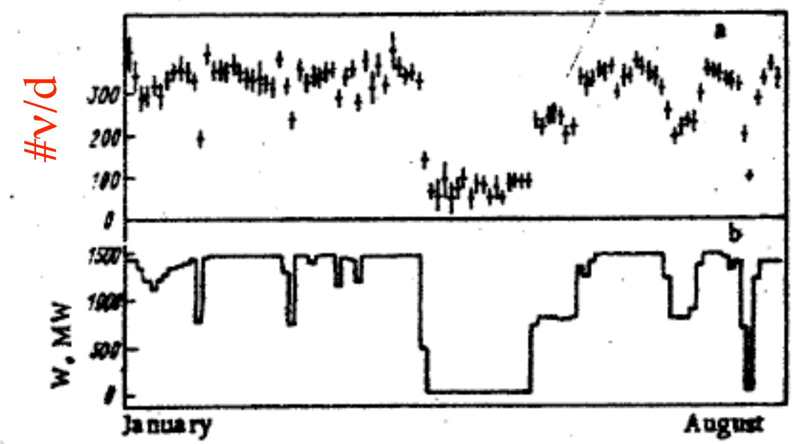
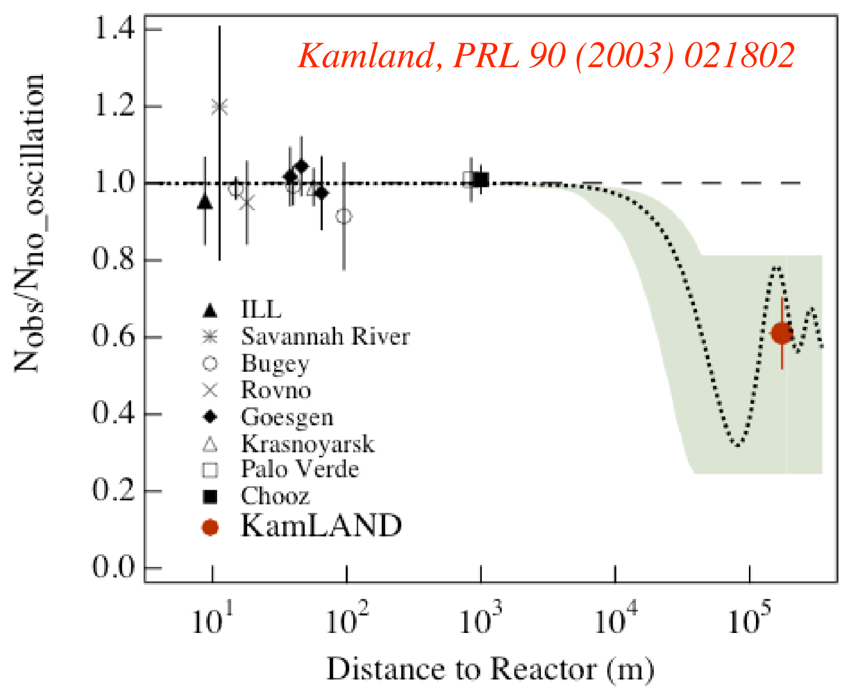


Fig. 2. Neutron instrumentation readings for January-August 1986 (a) and average daily reactor power based on data from thermal measurements (b).

Neutrinos oscillate…

Now a known effect :

- Prob(ν_e-> ν_e) fnct of E_ν, L



No more unknown between emission and detection

Neutrino : a reliable tool

Reactors neutrinos

- **Particle physicists knows how to detect antineutrinos**
- **A detector : 2 tons target @ 25 meters from the core**
  - **~30000 neutrinos per day**
  - **operated remotely.**
- **Fuel evolution (burnup)**
  - **Reactor operation: 1 kg ^{235}U is burned & 0.2 kg $^{239,241}Pu$ produced**
  - **U and Pu have a slightly different rate/spectrum neutrino emission**
- **The neutrino count rate is a simple function of the thermal power:**

$$N_{\bar{\nu}} = \gamma(1+k)P_{th}$$

γ : reactor constant
k : burn up dependent

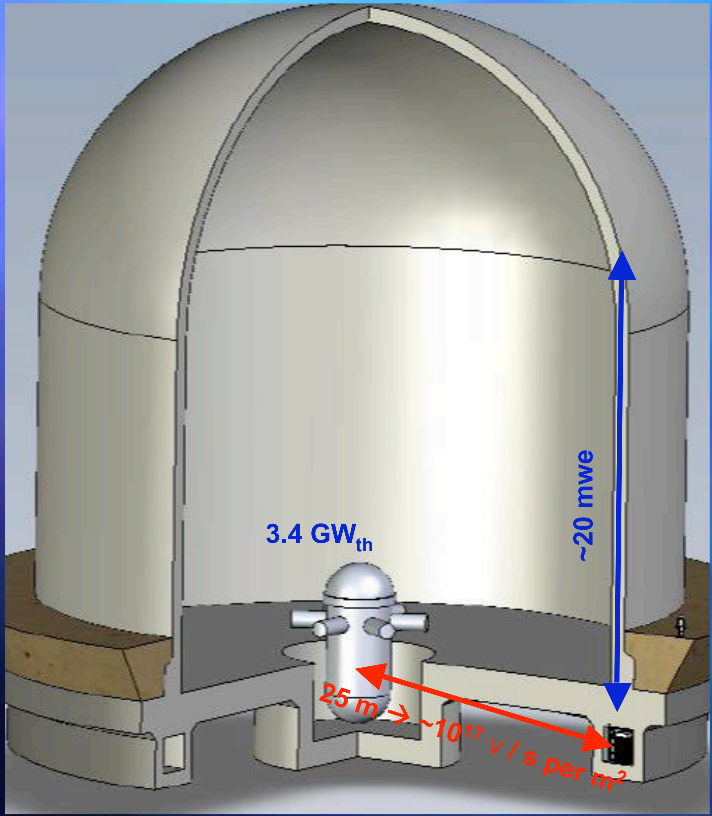
- **The neutrino energy spectrum is sensitive to the burnup**

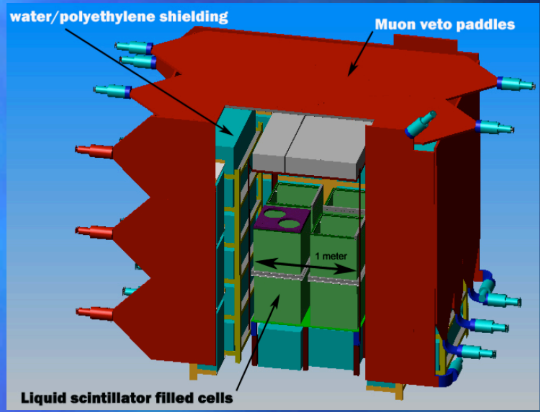
US effort

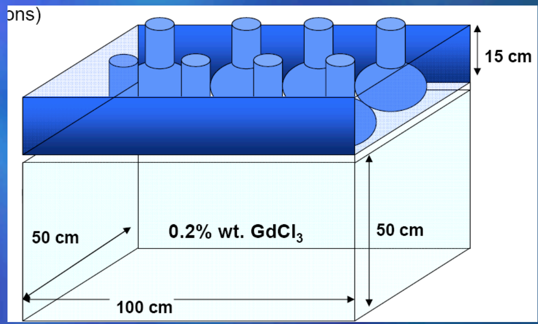
US efforts @ SONGS

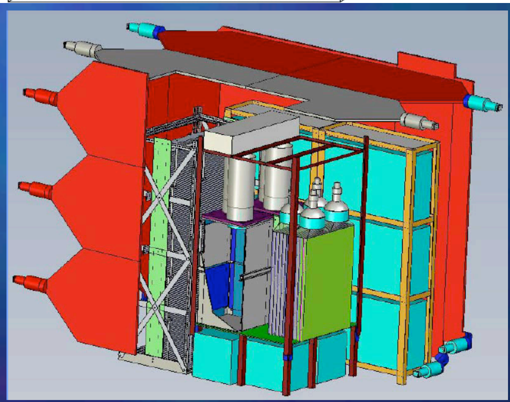
University of California Lawrence Livermore National Laboratory
Sandia National Laboratories

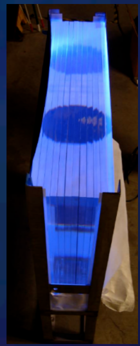
- The Strongest Worldwide Effort
  - Liquid Scintillator target
  - Plastic Scintillator target
  - Gd doped Water target



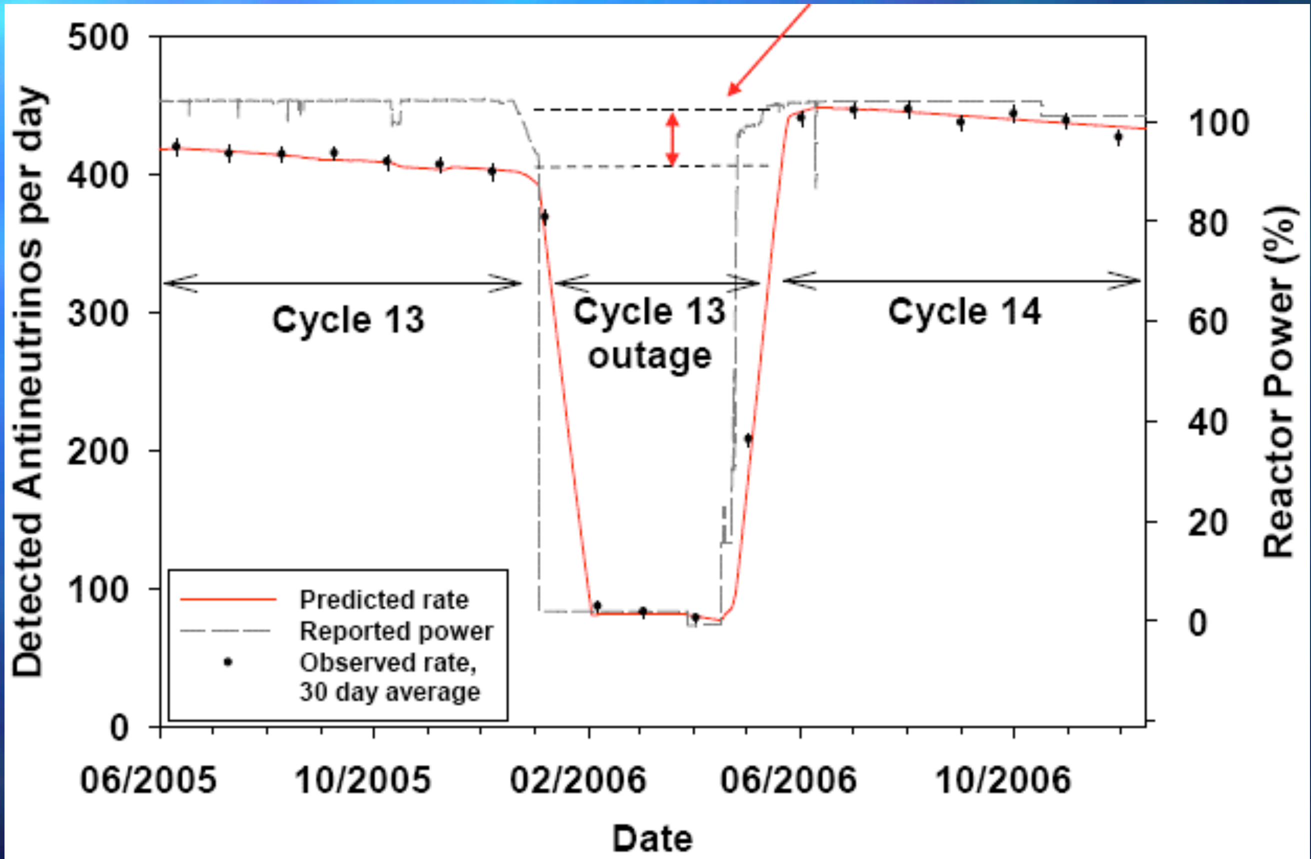




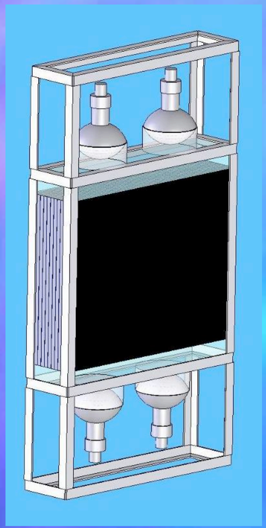




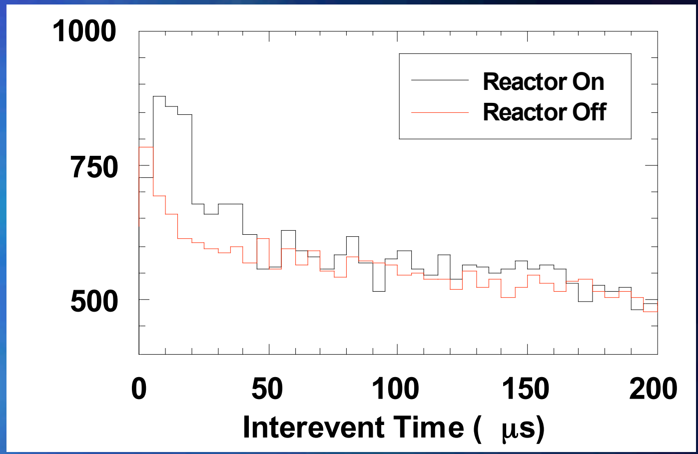
- Removal of 250 kg of ^{239}Pu followed by replacement with 1.5 tons of fresh ^{235}U fuel

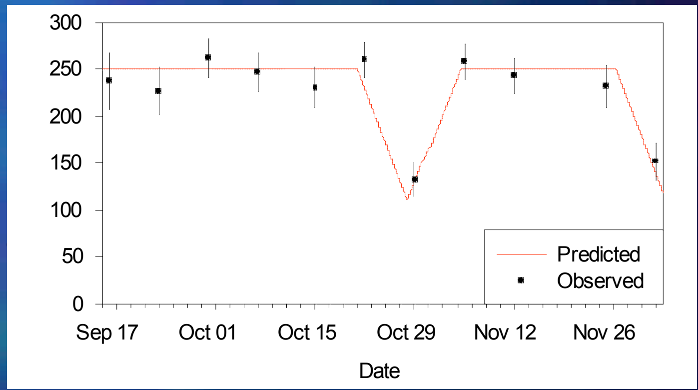


US Effort: SANDS-Plastic scintillators



- Several important advantages over the LS that it replaces in a commercial reactor environment
  - Non-flammable, non-hazardous, and no possibility of liquid spillage
  - Near complete preassembly possible
  - The device clearly observes reactor antineutrinos, i.e. can monitor reactor state
  - R&D ongoing

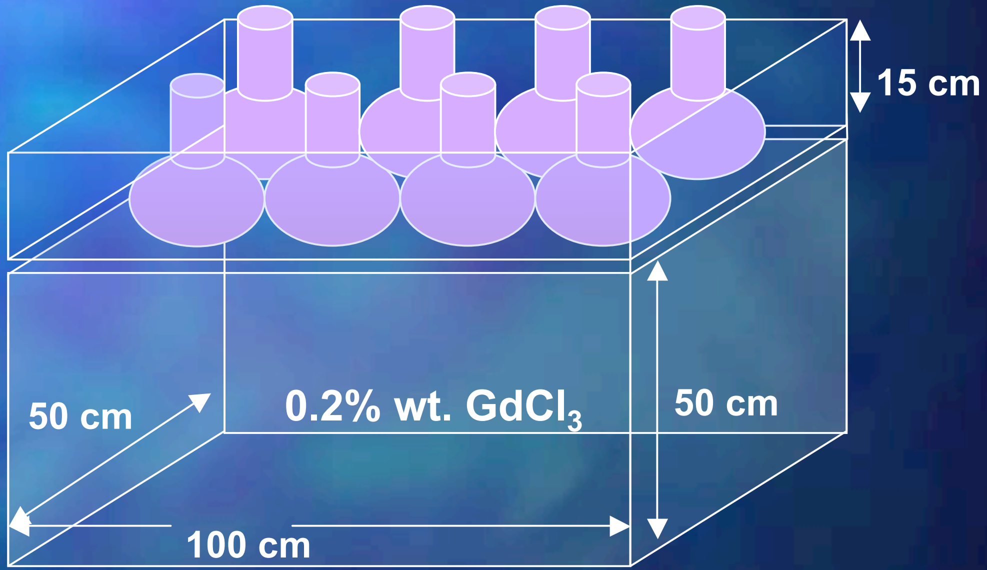




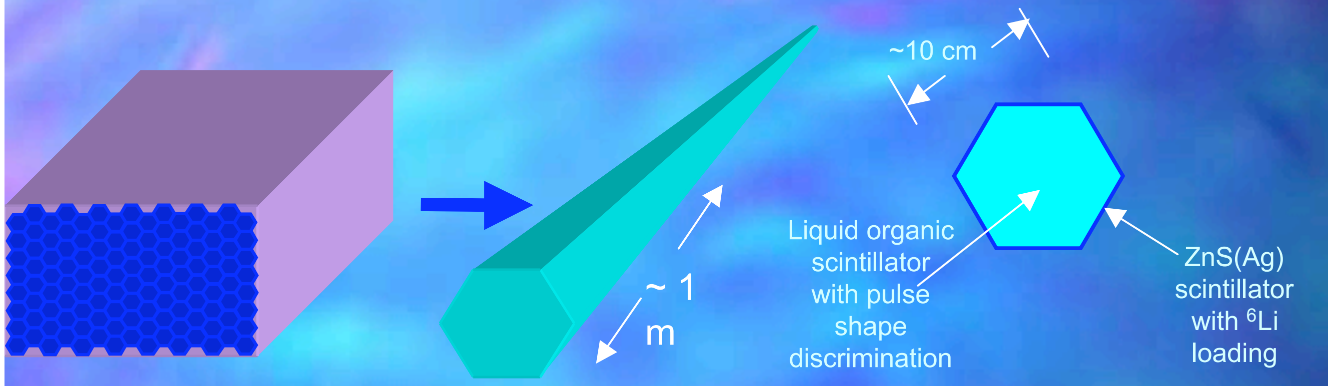
US Effort: SANDS-Water

- Important Water transparancy measurement: Is GADZOOK Dead?

- Detector prototype running at SONGS
  - No shielding ! Calibration Data
  - How well could this detector see reactor neutrinos?



Segmented Detectors

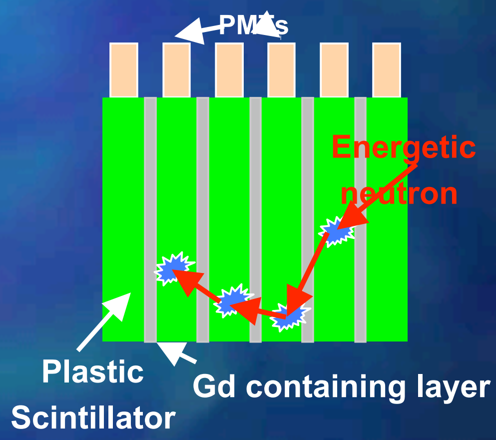


Neutrino signature

- Positron → single cell
- Neutron → Bright ZnS pulse in two adjacent cells about ~10 ms after e^{+}

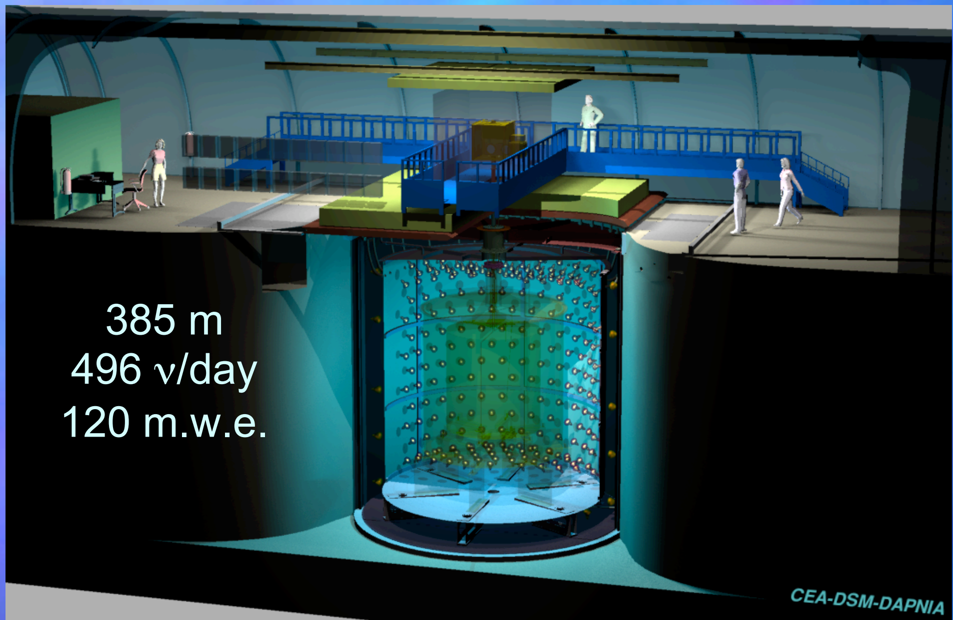
- Segmented detectors
- New R&D on highly segmented detector with ^{6}LiF:ZnS(Ag)
- No Quenching

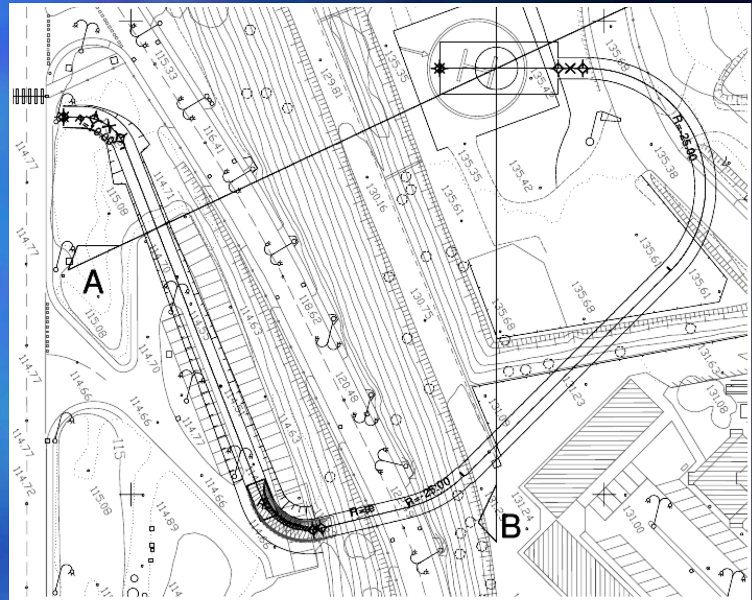
- Background rejection
  - Fast neutrons → PSD
  - Muons induced
  - …
- A way to ground level detectors ? Worst a try !!!



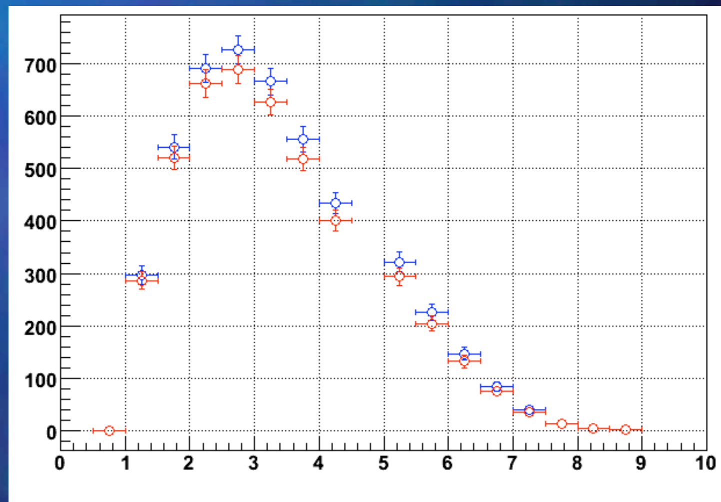
French effort

French Effort: Double Chooz Near





- ❖ Very well measured spectrum
- ❖ 2 extreme fixed fuel compositions
- ❖ ^{235}U=0.66 ^{239}Pu=0.24 ^{238}U=0.08 ^{241}Pu=0.02
- ❖ ^{235}U=0.47 ^{239}Pu=0.37 ^{238}U=0.08 ^{241}Pu=0.08



- ❖ Kolmogorov-Smirnov Test on Burn-up:
- ❖ H_0: the two “burn-up” induce identical spectra
- ❖ → Rate and shape: $P_{KS} = 1.8 \times 10^{-2}$

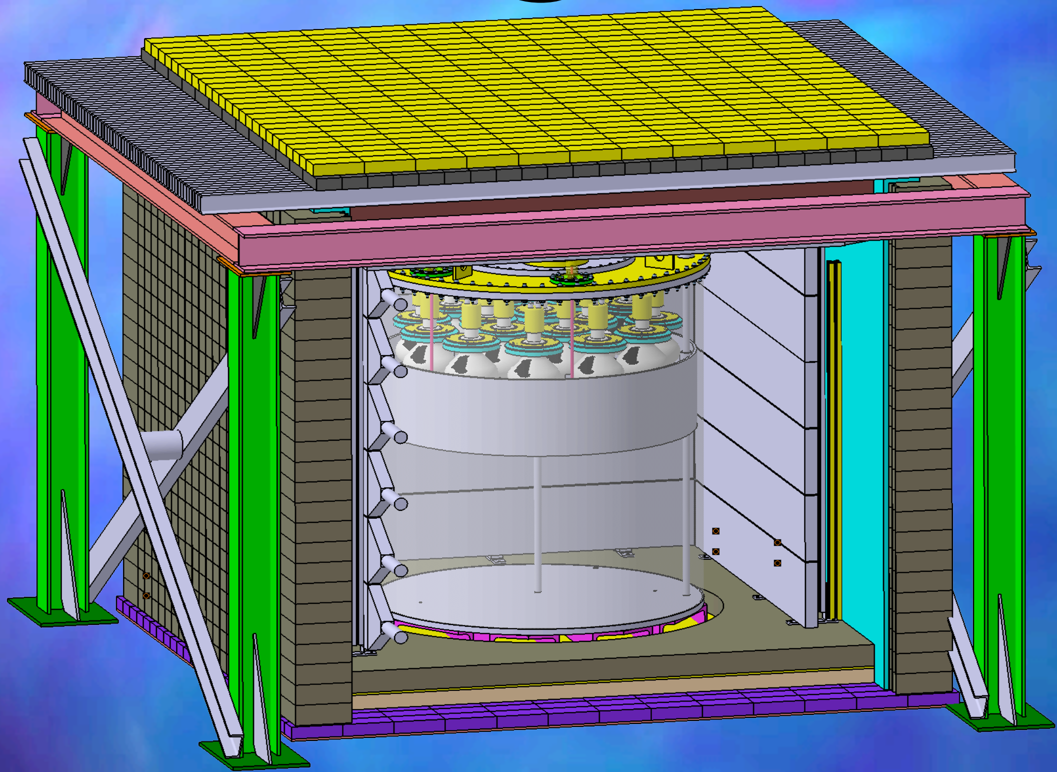
Nucifer

17 PMT's

1.8 m^3 Gd-LS

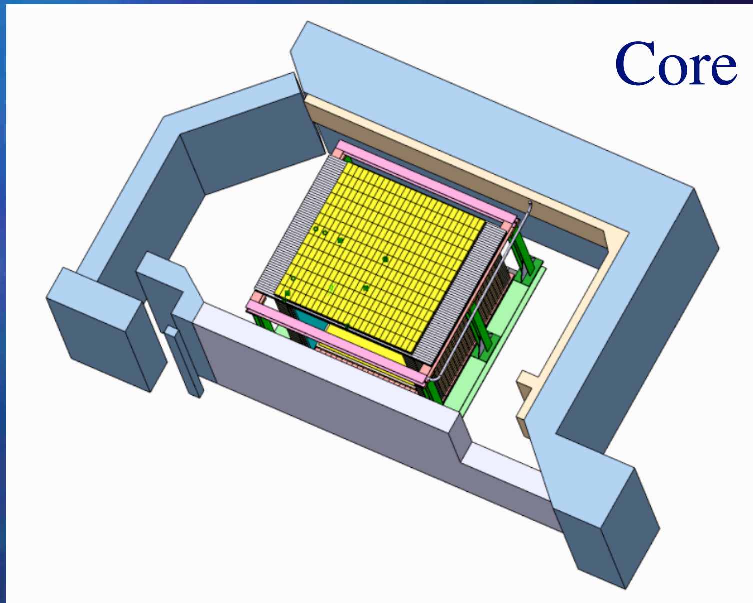
Under assembly

Nucifer @ Osiris



70 MW research reactor
@ Saclay
Position @ 5-6 m from core

≈ 40 ν evt/h



To be re-mounted
in dec. 2009
Feb. 2010 : reactor ON
March-Sept : OFF

Backgrounds @ Osiris

	γ on Nucifer E>1.5 MeV	μ att. factor	n_{th} ($cm^{-2}.s^{-1}$)	n_{fast} ($cm^{-2}.s^{-1}$)
Osiris Off	5 kHz	2.7	1.2 10^{-4}	2.3 10^{-4}
Osiris On	5 MHz	2.7	1. 10^{-3}	2.3 10^{-4}
ILL On	500 kHz?	?	0.3	?

- 10 cm Pb
- 15 cm CH_2
  (2.5 boré + 10 + 2.5 boré)
- Muon veto
- 10 cm Pb on wall facing the core

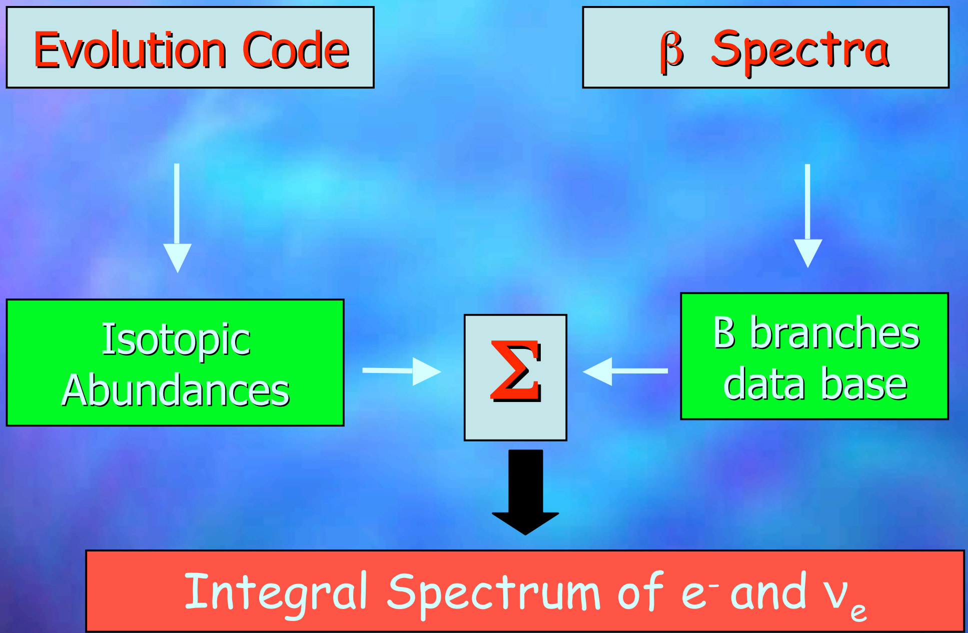
S/B_{acc} = 1/2.5
S/B_{corr} = 1/30

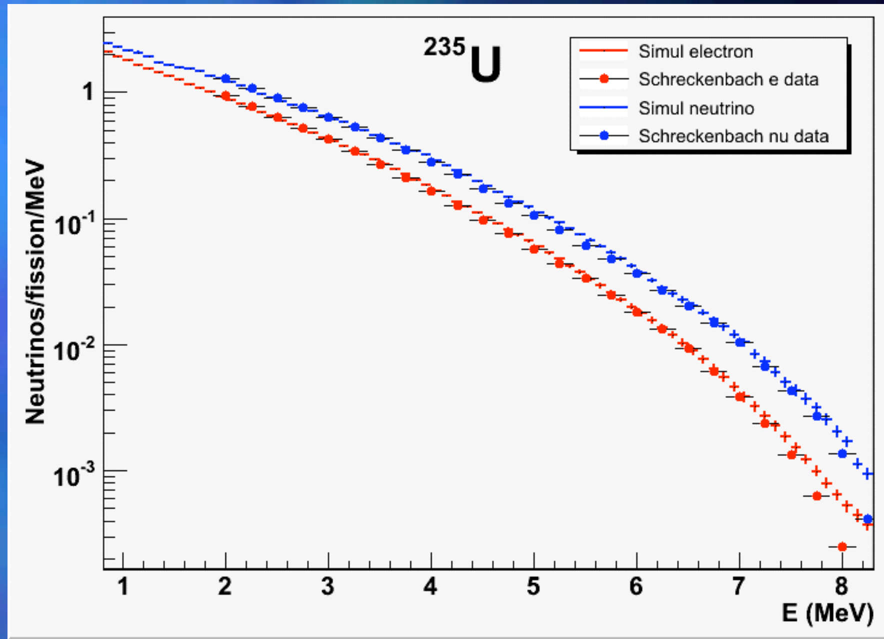
Sensitivity ?

M. Fallot et al.
D. Lhuillier et al.

Simulation Effort in France

Ab Initio **simulation of the ν spectrum evolution from all fission products**



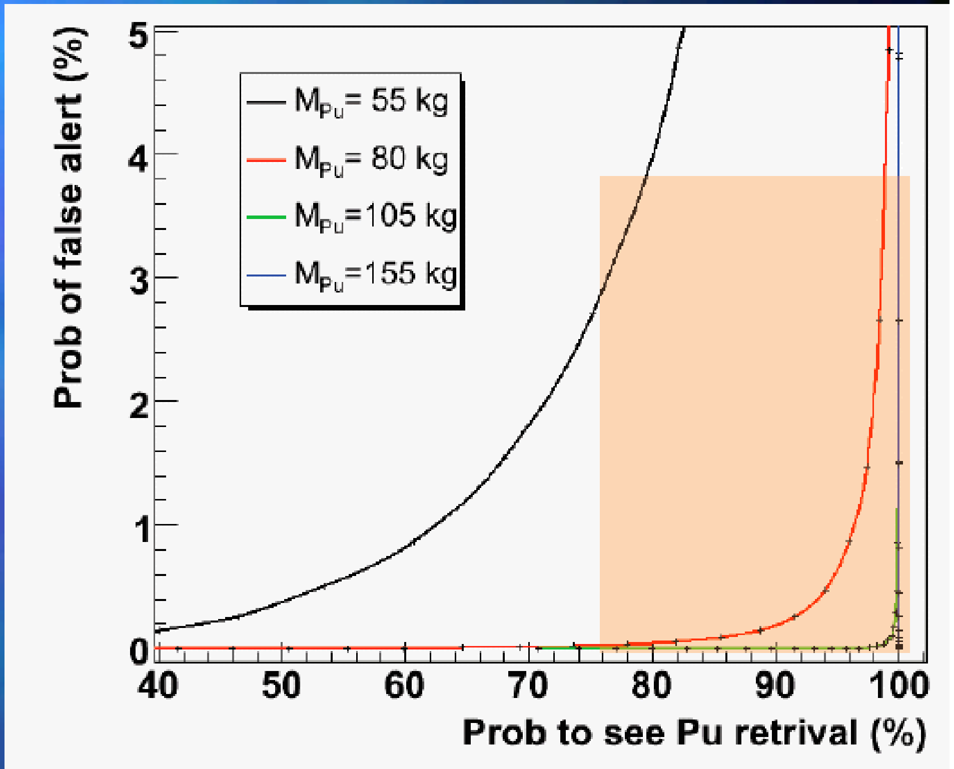


- **Good agreement with Schreckenbach data**
- **Towards a reliable absolute normalisation**
- **Good understanding of the errors**

→ **Towards application to test diversion scenario**

Sensitivity to ^{239}Pu

- χ^2 test on shape
- Study 2 x 16 days
- Retrieval of 55 kg of ^{239}Pu
  - seen @ 75% CL
  - 4% false alarm
- 80 kg observed certainly

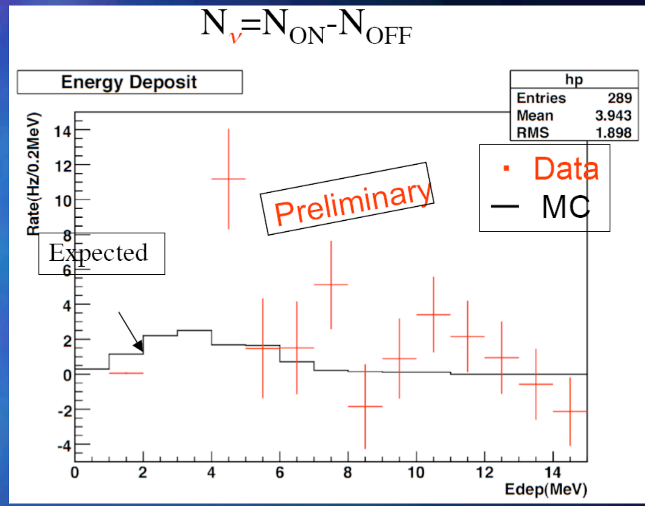


D.Lhuillier, A. Porta, T. Mueller

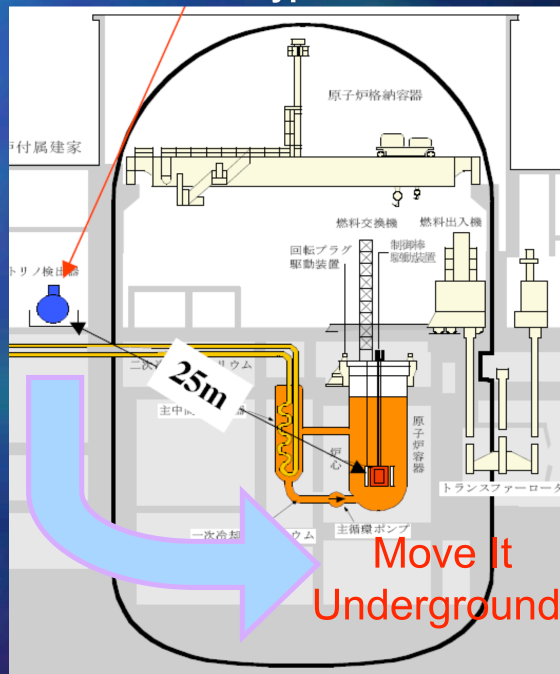
Others efforts

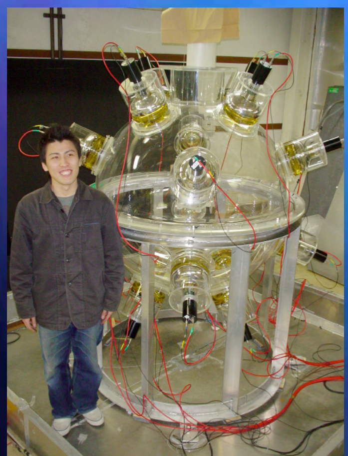
Japanese Effort: Kaska

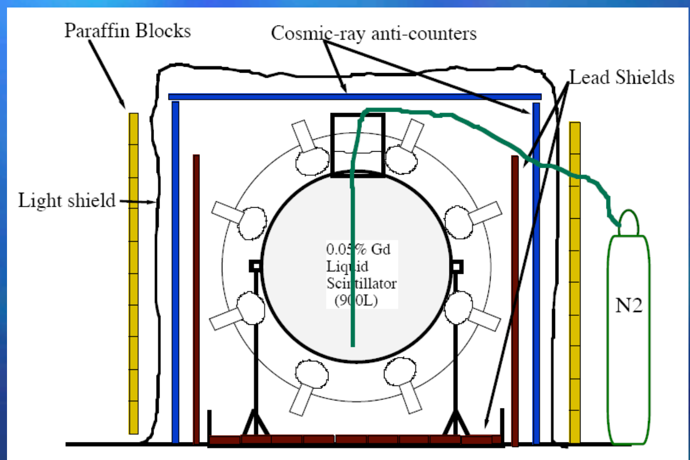
- FIRST Trial of Neutrino Detection from Joyo Fast Research Reactor
- Fast Breeder Research Reactor (Pu rich)
  - P_{th}=140 MW
  - Frequent ON/OFF
  - L~25m
  - ~150 ν *p−>e⁺ n* reaction/day
- KASKA detector prototype
- Positive Signal ?
- Ground level detector



KASKA Prototype

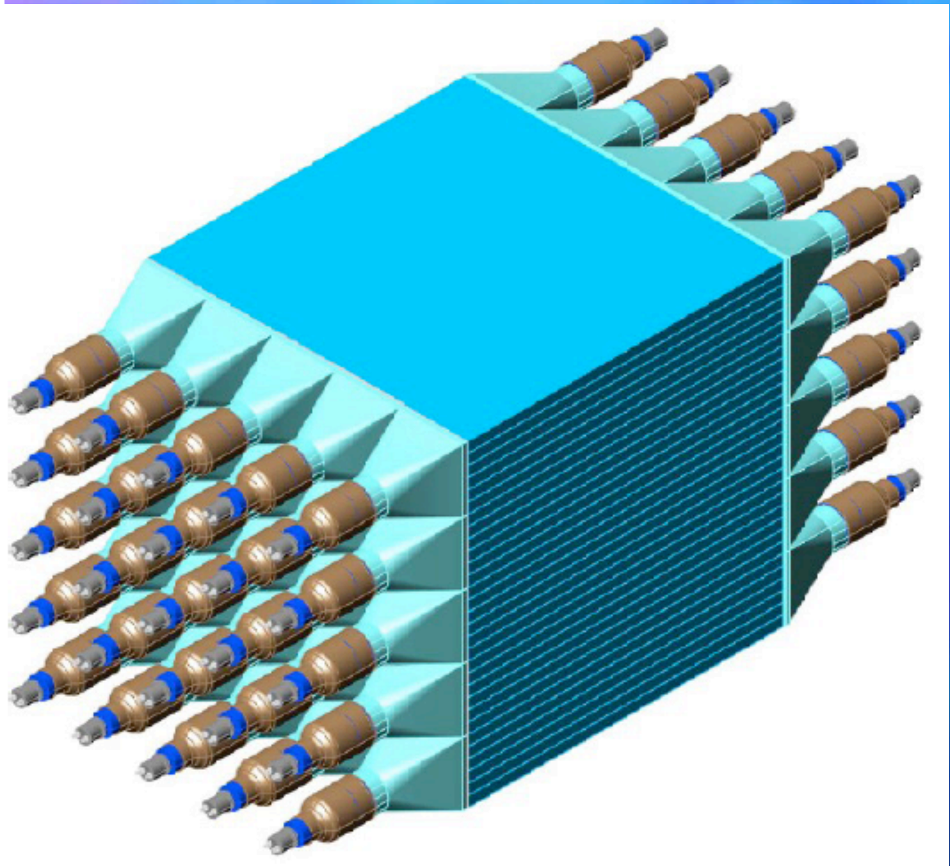






Brazil : Angra

During that time…
…in Italy



- CORMORAD
  - *M. Battiglieri et al.*
  - Segmented plastic scintillator
  - Mylar-Gd foils
  - Developped in cooperation with industry (Ansaldo)

New challenges

- Surface detectors
  - Some ideas like segmented detectors
  - More sophisticated => more costly
  - Bigger detectors : veto, shielding
  - Worst a try…
- Directionality
  - Already some measurement (Chooz, Rovno)
  - Modest precision ≈ 20-30 °
  - Use of Li-doped scintillators ?
- Compact detectors
  - Coherent detectors : a good idea ? Not sure
  - Not yet seen at lab level

Distant survey

Clandestine nuclear reactor

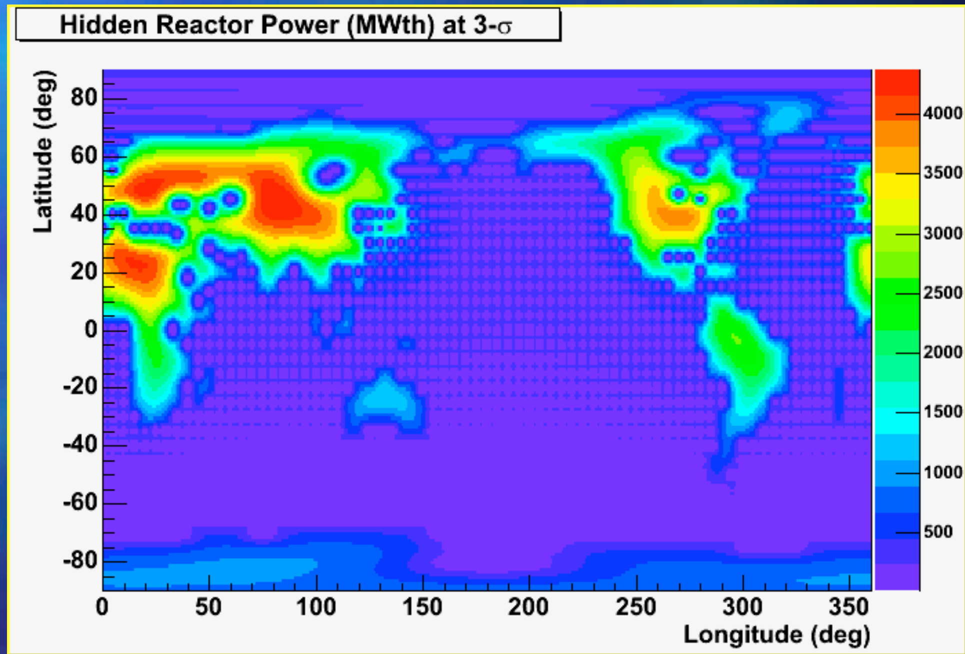
- **Monitor a country without cooperation?**
- **Neutrino rate:**

$$450\ events \times \left(\frac{100\ km}{D}\right)^2 \times \left(\frac{P}{10\ MW}\right) \times \left(\frac{1}{1\ Megaton\ water}\right) \times \left(\frac{t}{1\ year}\right)$$

- **Challenge: Mega Ton Scale water-based antineutrino detectors**
- **Prohibitive PMT cost**
  - **Invent low-cost 'wallpaper' photodetectors**
- **Hope: discover and exploit coherent neutrino scattering**

Remote survey

- Movable (non-nuclear) submarine
  - ≈ 50 000 m^3
- Count at 3 positions :
  - Signal ≈ (P_{th} ???)/ R^2
  - Triangulation
- Detection of underground clandestine reactor

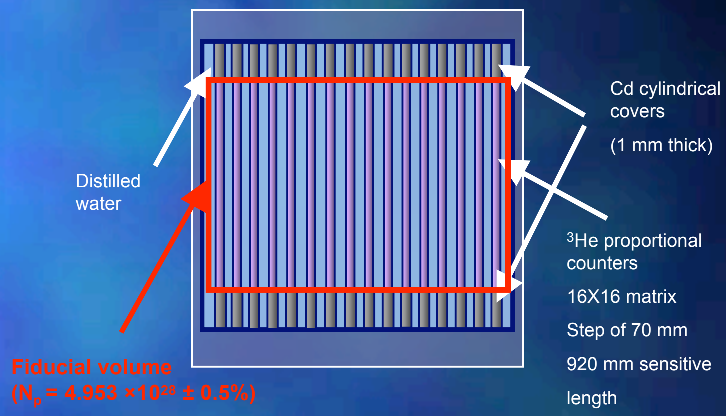


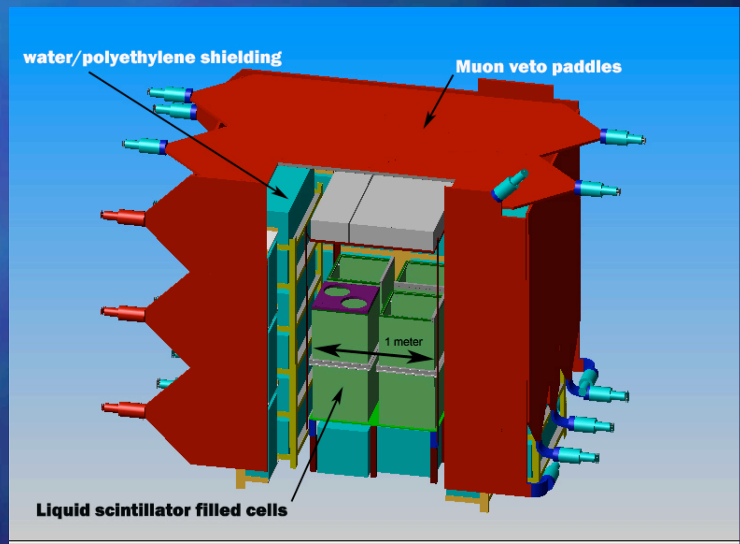
Global survey
10 Mtons units
≈ 1000 units in ocean
J. Learned at Neutrino'04

Thermal power with neutrinos

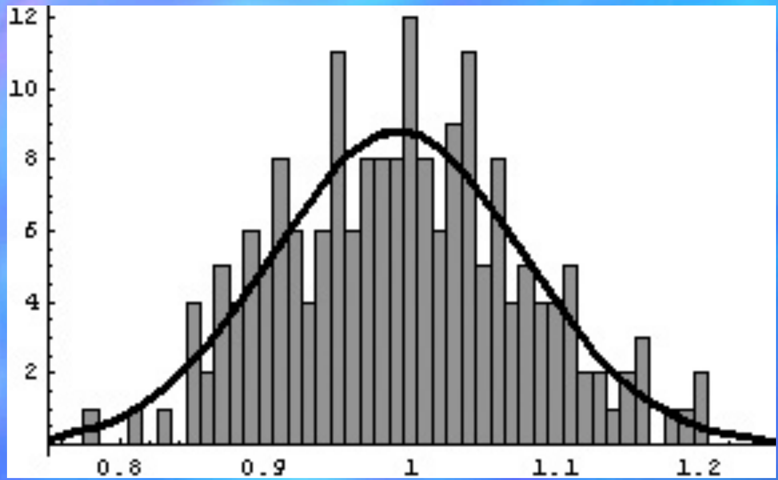
$$N_{\bar{\nu}} = \gamma\, P_{th} \times \left[1 + k(t)\right]$$

- Absolute precision 3% achievable
- More accurate calibration might be possible at research reactors
- % level monitoring
  - In few days @ GWt_{th} reactors
  - System. errors complementary to standard procedures
- Unique opportunity of cross calibration of different cores
- Which technique?



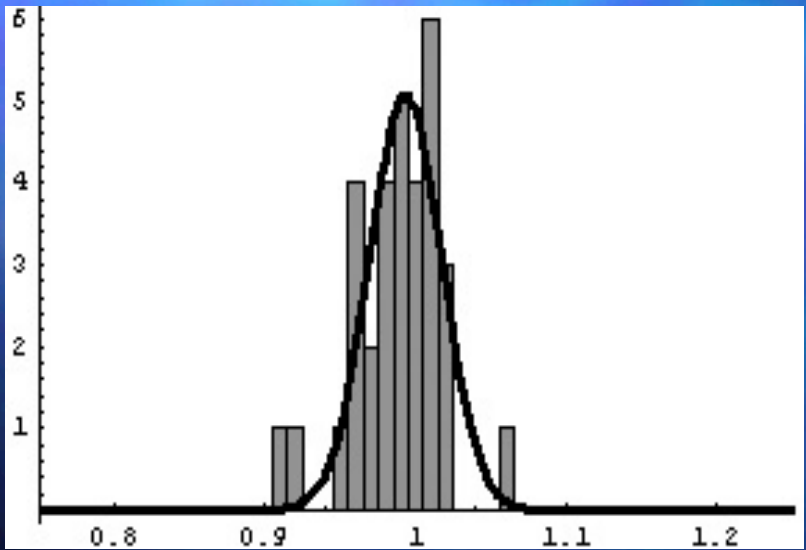


Thermal power : SANDS Data



Daily average

8 % relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)



Weekly average

3% relative uncertainty
in thermal power estimate
(normalized to 30 day avg.)

Conclusion

- The 1st application of neutrino
  - A peaceful one : a tool to reinforce controls of nonproliferation
- A world wide effort
  - Discussions with IAEA
  - Already many options studied in different countries
- A challenging developments
  - Sensitivity
  - Directionality
  - Ground surface deployment
  - But also small, simple, robust, easy to install…

Neutrinos for Peace