Reactor anti-neutrinos in the world

B. Ricci, University and INFN, Ferrara

Neutrino Geoscience, LNGS 6-8 october 2010

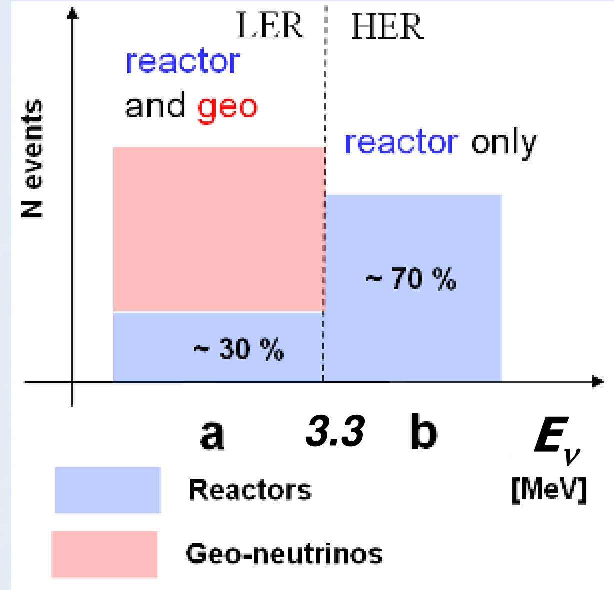
Outline:

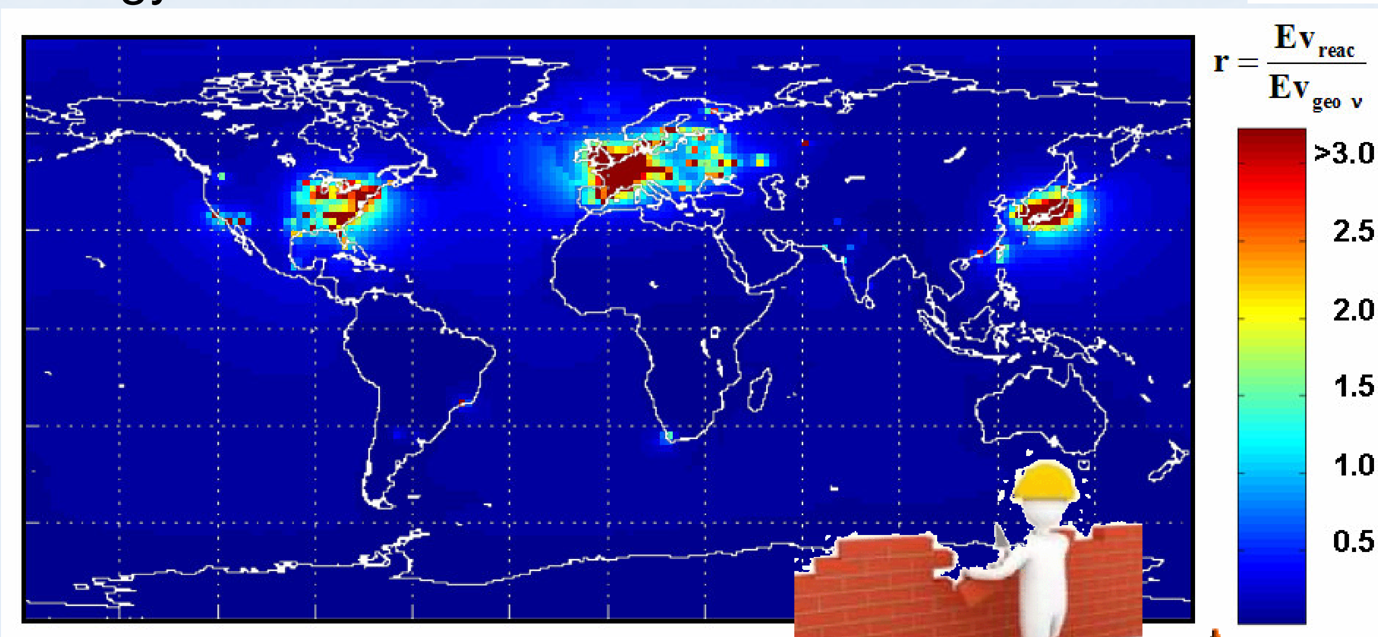
- why reactor anti-neutrinos ?
- reactors in the world
- signal calculation
- ingredients
- reactor signal for different sites
- annual variation of reactor signal
- conclusion

Work done with : Mantovani, Fiorentini, Chubakov (Univ. and INFN- Ferrara), Esposito (INFN-LNL), Vitali (Univ. Ferrara), Ludhova and Zavatarelli (Borexino coll), Lissia (INFN-Cagliari)

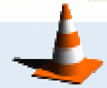
Reactor anti neutrinos and geo-neutrinos

- The **HER** has to be controlled by studying the different contributions from the nuclear reactors, if one wants to compare $Ev_{geo-\nu}$ and Ev_{react} in the **LER**.
- The 2006* map is based on 2000 IAEA database and considering all reactors at full power. The ratio r is referred to the geo-neutrino energy window.





	r
Kamioka	6.7
Sudbury	1.1
Gran Sasso	0.9
Pyhäsalmi	0.5
Baksan	0.2
Homestake	0.2
Hawaii	0.1
Curacao	0.1



*Fiorentini et al - Earth Moon Planets - 2006

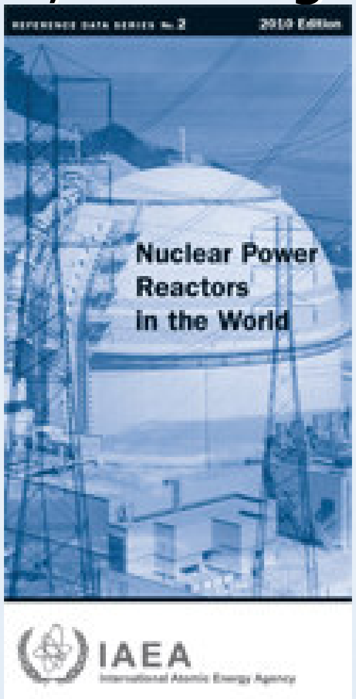
from Mantovani, Yokohama 2010

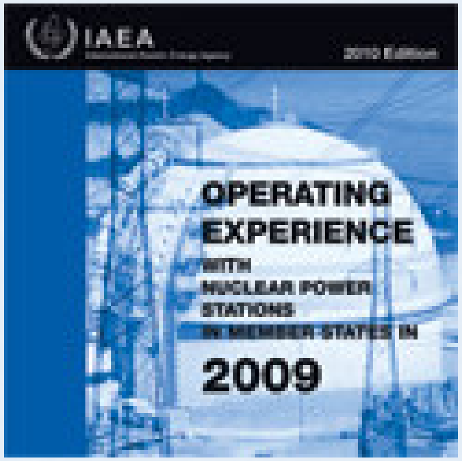
Data Source: IAEA files

- International Atomic Energy Agency

http://www.iaea.org/programmes/a2/

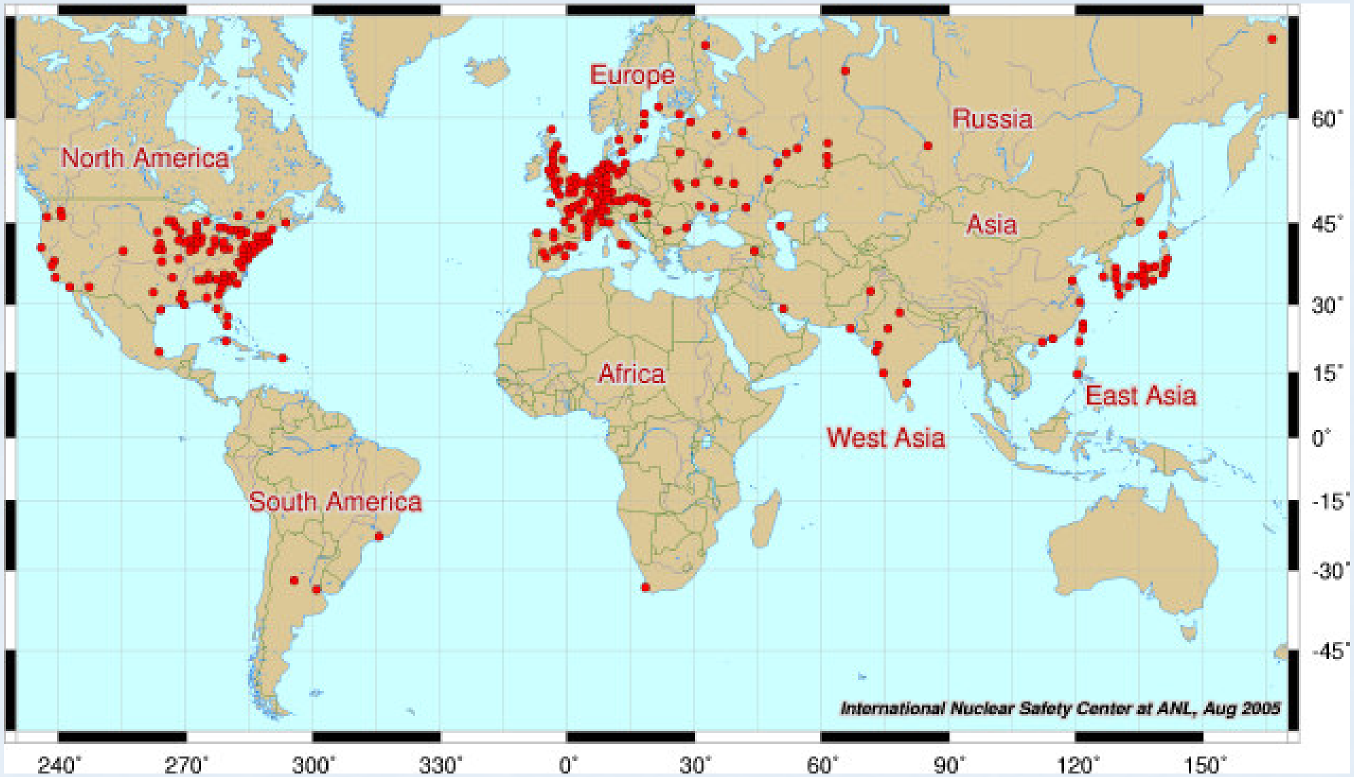
- On June, description and history of each core are published, reffering to previous year.





- Data on: thermal power, electrical capacity, electrical Load Factor, fuel enrichment…

Nuclear power plants in the world

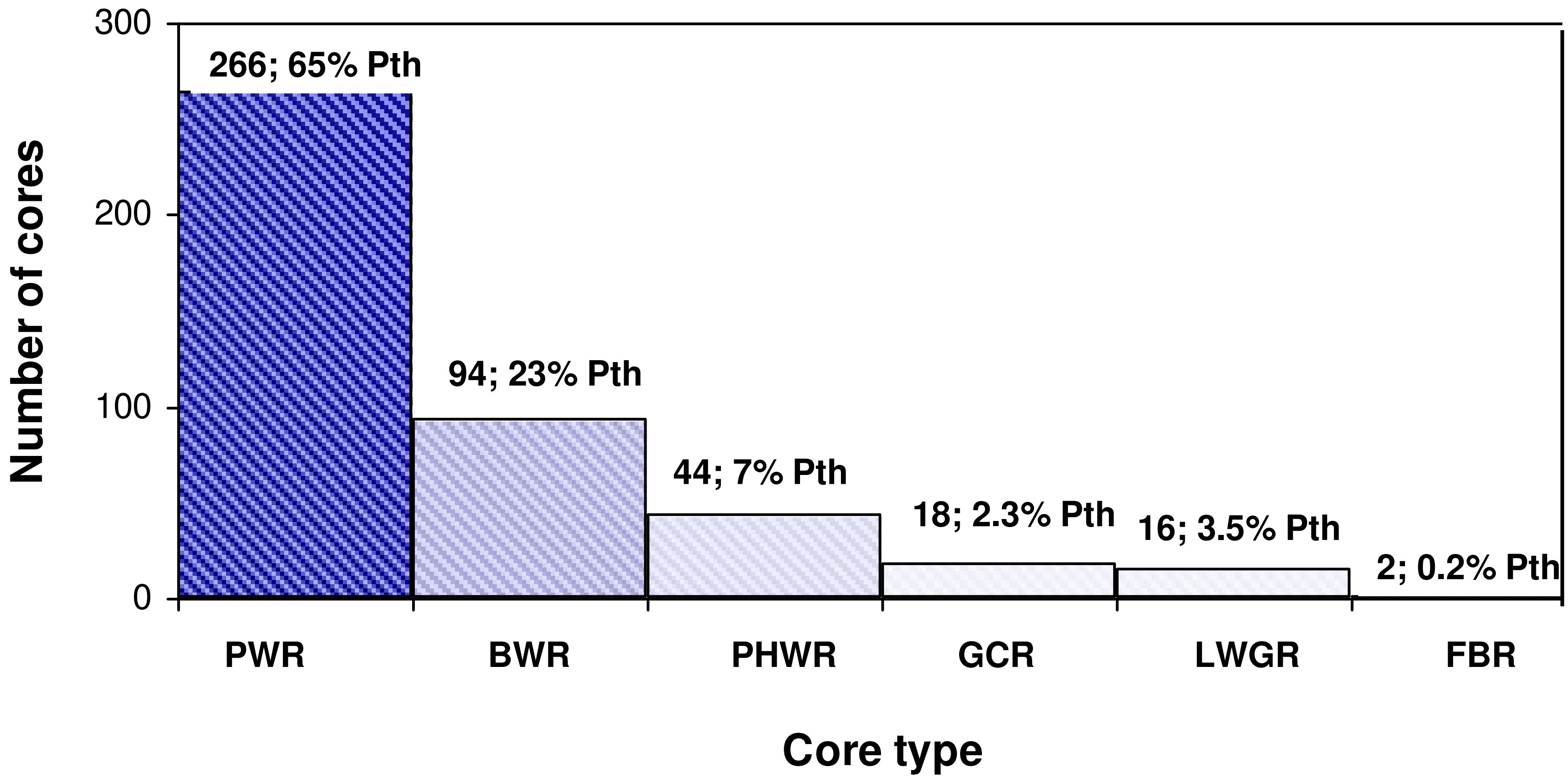


	#cores	Pth [GW]
Europe + Russia	197	519
North America	122	353
Japan+ Korea	76	201
Others	45	75
Total:	440	1148

- Mean thermal power for core: 2.6 GWth

at 31 Dec. 2009

Reactors by type



PWR	Pressurized (light) Water Reactor
BWR	Boiling Water Reactor
PHWR	Pressurized Heavy Water Reactor

GCR	Gas Cooled Reactor
LWGR	Light Water Graphite mod.
FBR	Fast Breeder Reactor

Signal calculation

DETECTOR
- ε=100% detection efficiency
- τ =1 year
- N_p=10^32

ν PHYSICS
- P_{ee} = survival probability
- $\sigma(E)$= cross section
  anti-ν_e +p -> e^+ +n
  E_{th}=1.806 MeV
  (calculation from Vissani and Strumia 2003)

$$N_{TOT} = \varepsilon\ N_p\ \tau\ \sum_{i=1}^{N_{reactor}} \frac{P_i}{4\pi d_i^2} < LF_i >_{2009} \int dE_\nu \sum_{k=1}^{Nfuel} \frac{p_k}{Q_k}\ \lambda_k(E_\nu) P_{ee}(E_\nu, d_i)\ \sigma(E_\nu)$$

REACTOR
- d_i =reactor distance
- P_i=reference thermal power
- LF= Load Factor
- p_k= power fraction

NUC. PHYS.
- Q_k =energy released for fission
- λ_k =reactor anti-neutrino spectrum

K=235U, 238U, 239Pu , 241Pu

Effective Thermal Power

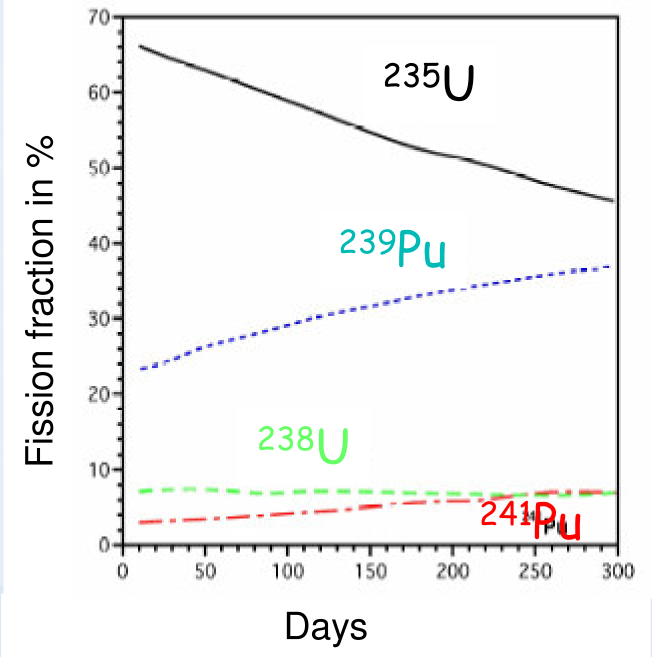
- From IAEA we have thermal capacity P_{th} and Load Factor
  (LF=electrical energy as measured at unit outlet terminals divided by net electrical energy which would have been supplied to the grid if the unit were operated continuously)
- From EDF we have the (measured) thermal power of French cores in 2008 [thank to D. Vignaud of Borexino coll. and E. Vrignaud from EDF]
- For each core we calculated: $LF_{th} = \frac{P^{EDF}_{thermal}}{P^{IAEA}_{thermal}}$ $\rho = \frac{LF_{th}}{LF_{IAEA}}$
- averaging on the cores: $< LF_{th} >_{cores} = 0.8 \pm 0.1$ $< \rho >_{cores} = 1.013 \pm 0.017$
- In addition, $P_{thermal}$ is measured with an accuracy of 2% (Djurcic et al. 2009)
- Conclusion: we assign an uncertainty of 2.4% at the "effective" thermal power (i.e. Pth * LF)

Power fractions (see Lasserre talk)

$$\frac{dN_k^{fis}}{dt} = P_{thermal}\frac{p_k}{Q_k}$$

- p_k=**fraction of power** which is produced by the k-th isotope: **K=235U, 238U, 239Pu , 241Pu**
- Depend on type of reactors and on time

	235U	239Pu	241Pu	238U
KamLand (average)	0.56	0.295	0.059	0.078
Chooz start*	0.66	0.24	0.02	0.08
Chooz stop	0.54	0.32	0.06	0.08
Russia**	0.556	0.326	0.047	0.071
Slovakia**	0.62	0.24	0.06	0.08
Mox Start* *	0	0.794	0.126	0.08
Mox Stop	0	0.636	0.284	0.08
Mox Medium	0	0.708	0.212	0.08



- We take : -Kamland average value (PWR+BWR reactors)

  -same power fractions for all cores in the world (+for 35 european cores, producing some 30% of the respective power with MOX fuel)
- By varying composition in the range of values available, the total signal changes of about 2%

*from G. Mention 2007 (thanks to Alimonti)

** from Private Comunication (thanks to Ludhova and Derbin)

Energy released for fission

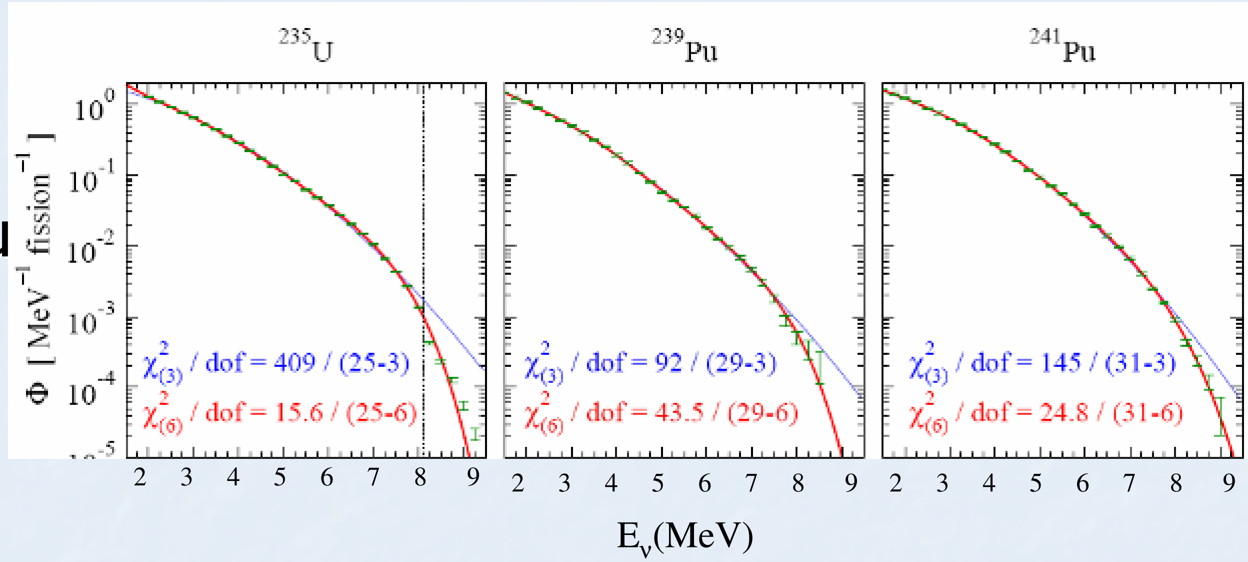
- For the four isotopes relevant in nuclear reactors (Apollonio et al 2003)
- The uncertainty on Q_k correspond to a variation of the calculate signal of about ± 0.3%

	# ν_e > 1.8 MeV	Q_k(MeV)
^{235}U	1.92	201.7 ± 0.6
^{238}U	2.38	205.0 ± 0.9
^{239}Pu	1.45	210.0 ± 0.9
^{241}Pu ,	1.83	212.4 ± 1.0

- Note: about 2 neutrinos, for each fission, have energy above the detection threshold.

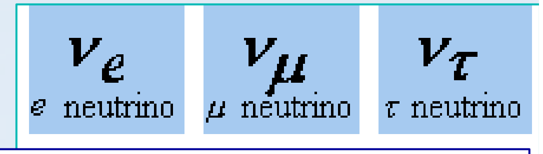
Anti-nu spectrum (see Lasserre talk)

- 235U, 239Pu, 241Pu from polynomial fit of exp.tal data (Huber & Schwetz 2004)
- 238U from calculation of Vogel and Hendel 1989
- Uncertainty in the spectrum is quoted to be about 2.5% (schrekenbach et al 1985, Hahn et al 1989, Vogel et al 1981…)



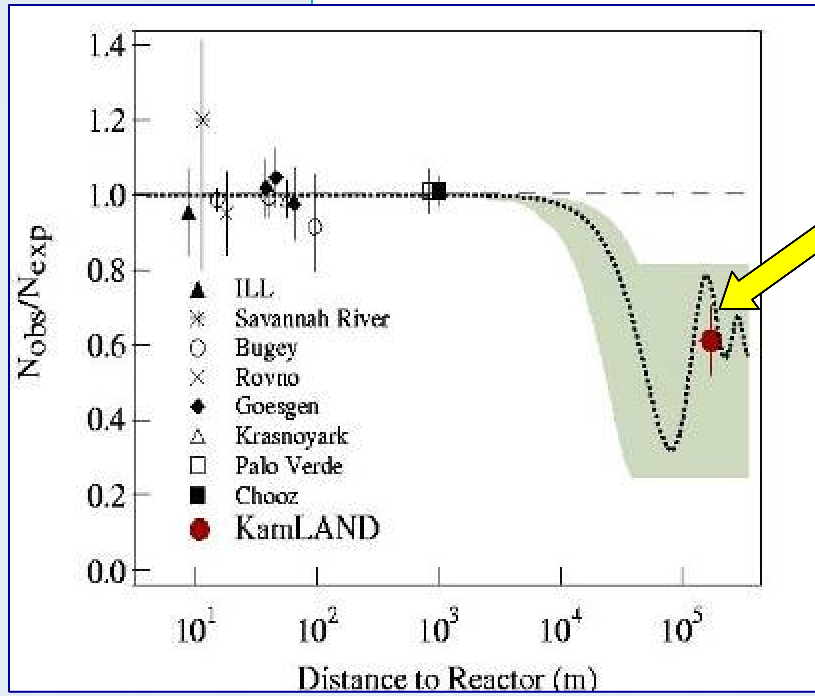
pol. coeff	235U	239Pu	241Pu	238U
a0	3.519	2.560	1.487	0.976
a1	-3.517	-2.654	-1.038	-0.162
a2	1.595	1.256	0.413	-0.079
a3	-0.417	-0.362	-0.142	0.000
a4	0.050	0.045	0.019	0.000
a5	-0.002	-0.002	-0.001	0.000

Neutrino oscillation
(see. Ianni and Lasserre talk)



- During the travel source-detector the flavour of the particle can change.
- The survival probability is given by:

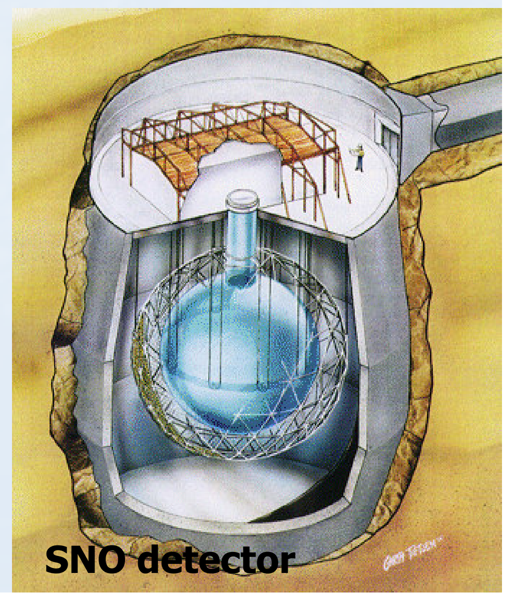
$$P_{ee} = 1 - \sin^2 2\theta_{12} \sin^2 \left[\frac{1,27\Delta m_{12}{}^2 (eV^2) L(km)}{E(GeV)} \right]$$



- Neutrinos oscillation has been observed both for anti neutrinos from reactors and for solar neutrinos, finding:

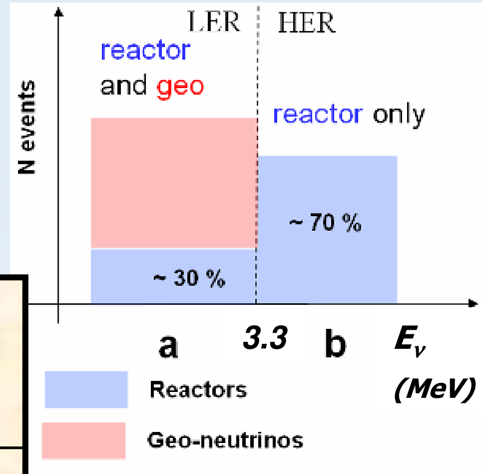
$$\boxed{\Delta m^2_{12} = 7.65^{+0.23}_{-0.20} \times 10^{-5} eV^2} \qquad \boxed{\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}}\ *$$

- The error on mixing angle, reflect in an uncertainty on reactor signal of about 2.5%, Δm^2 error gives smaller contribution



*Schwetz,Tortola and Valle 2010

Reactor anti-nu Predictions



	R LER [TNU]	R HER [TNU]	R TOTAL [TNU]
KAMIOKA	152±6.5	65.3 ± 3.2	527±26
FREJUS	133±6.9	374.4 ± 19.2	567±26
SUDBURY	44.3±2.2	139.5 ± 6.9	184±9.0
GRAN SASSO	23.1±1.1	26.2 ± 1.3	88.7±4.3
PYHASALMI	18.1±0.8	21.5 ± 1.1	71.7±3.5
BAKSAN	9.33±0.44	53.6 ± 2.6	35.5±1.7
DUSEL	8.40±0.38	7.5 ± 0.4	32.1±1.6
HAWAII	1.06±0.05	3.0 ± 0.1	4.04±0.19
CURACAO	2.65±0.12	23.7 ± 1.2	10.2±0.5

- 2009 IAEA data
- no spent fuel
- 100% efficiency
- Vacuum oscillation

- Estimated uncertainties in predicted signals are of the order of 4-5%, due to mixing angle, antiν spectrum, power fraction and effective thermal power

1TNU = 1 event /10^32 protons / yr

Comparison with geo-neutrino signal

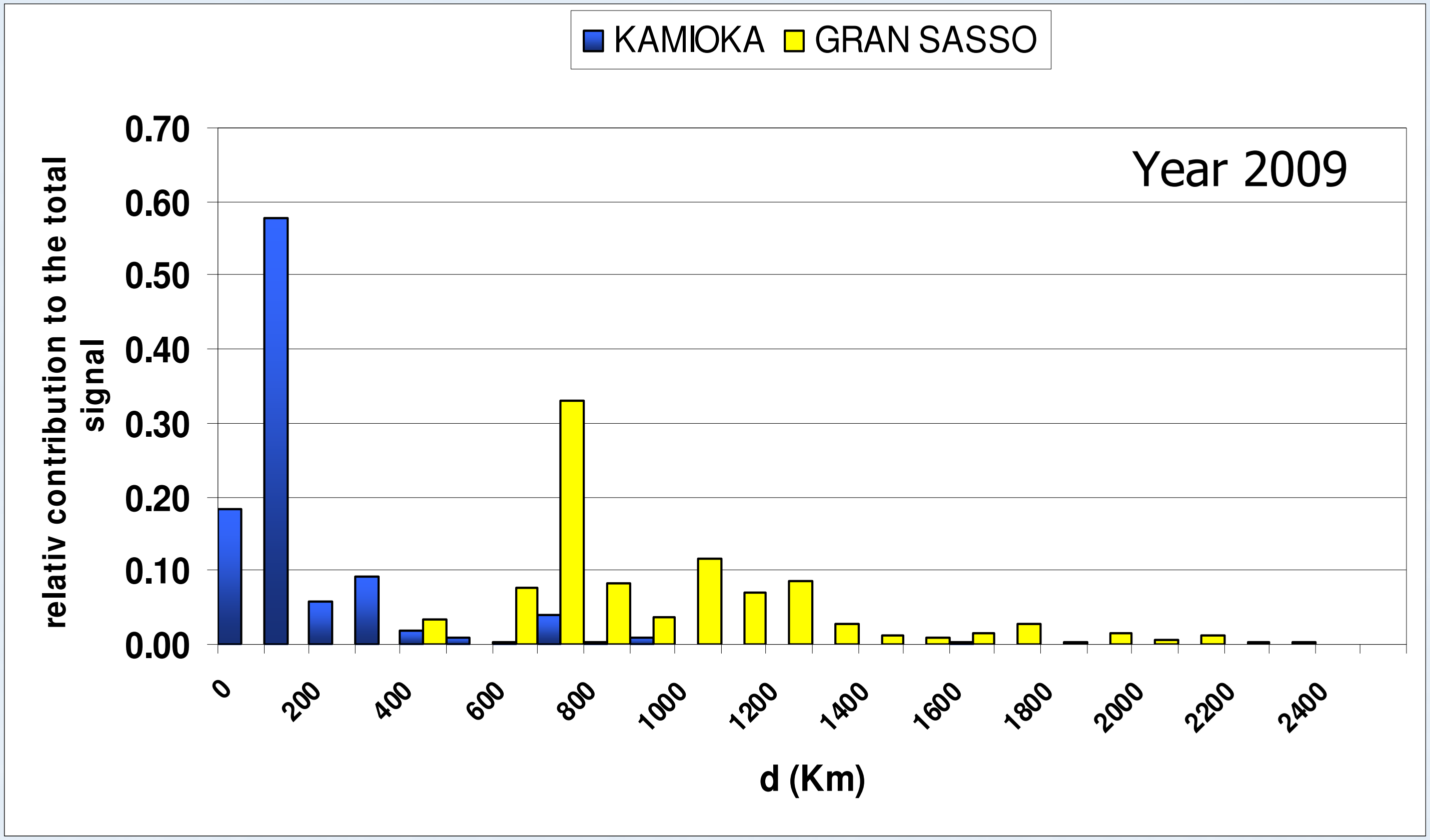
	R LER [TNU]	Geo ν (G)* [TNU]	ΔG	r= R_{LER}/G
KAMIOKA	152 (1±5%)	34.5	14	4.4
FREJUS	133 "	43.1	13	3.2
SUDBURY	44.3 "	50.8	9.7	0.87
GRAN SASSO	23.1 "	40.7	8.0	0.57
PYHASALMI	18.1 "	51.5	8.3	0.35
BAKSAN	9.33 "	50.8	7.7	0.18
DUSEL	8.40 "	52.6	7.8	0.16
HAWAII	1.06 "	12.5	3.7	0.085
CURACAO	2.65 "	32.5	5.9	0.082

- ΔG represents the limiting statistical error on the geo-neutrino signal which might be achieved with a detector with an effective exposure of 10^32 proton yr

$$\Delta G = \sqrt{G + R_{LER}}$$

*Fiorentini et al Phys. Rep. 2007

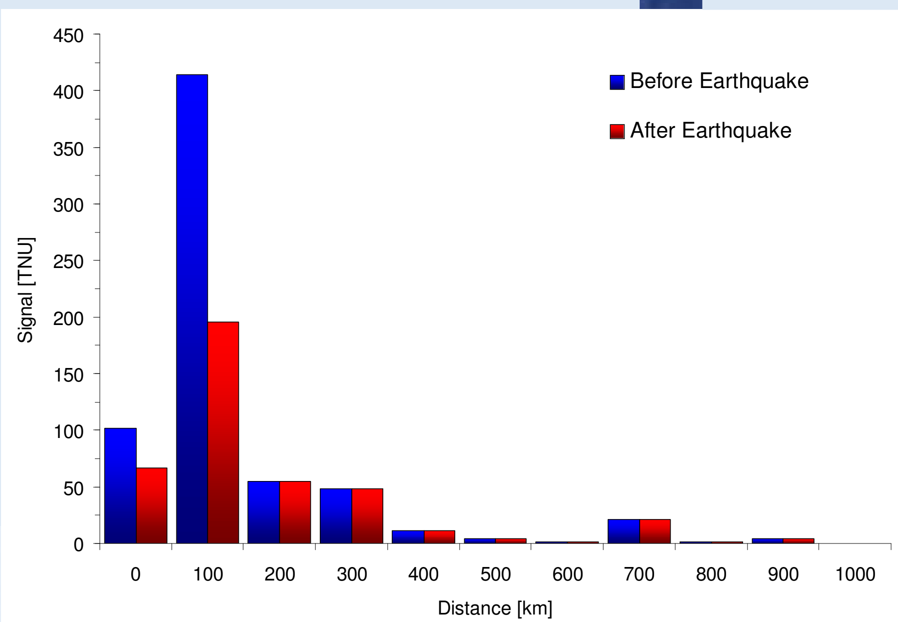
GRAN SASSO vs KAMIOKA



- For Gran Sasso, the nearest core contributes with 3% to the total signal
- Kamioka is mainly sensitive to the nearest cores (less than 200 Km)…as well known…

Consequences of 2007 Japan earthquake

- March 2007: earthquake hit Shika (2 cores)
- July 2007:earthquake hit Kashiwazaki (7 cores)

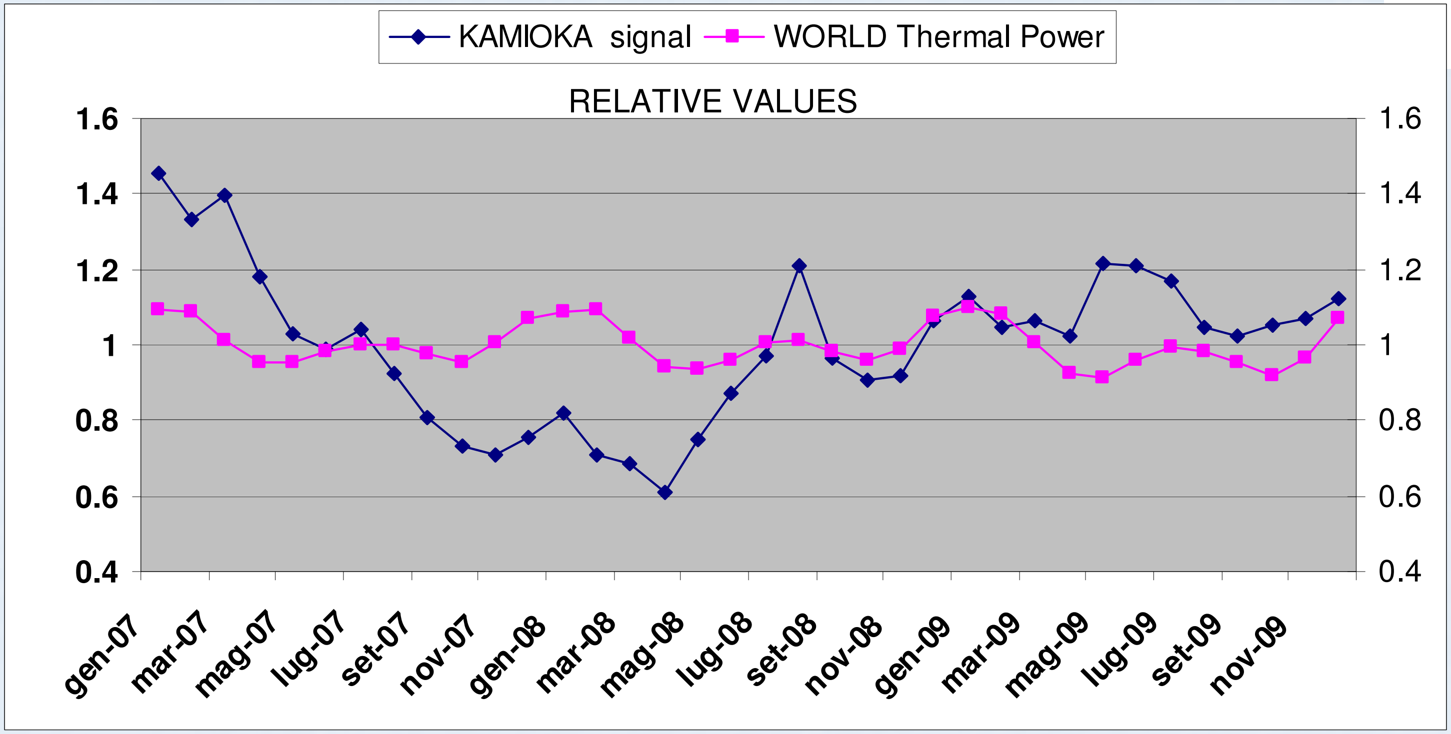


$$\frac{S_{\text{After E.}}}{S_{\text{Before E.}}} \sim 0.62$$

from Mantovani, Yokohama 2010

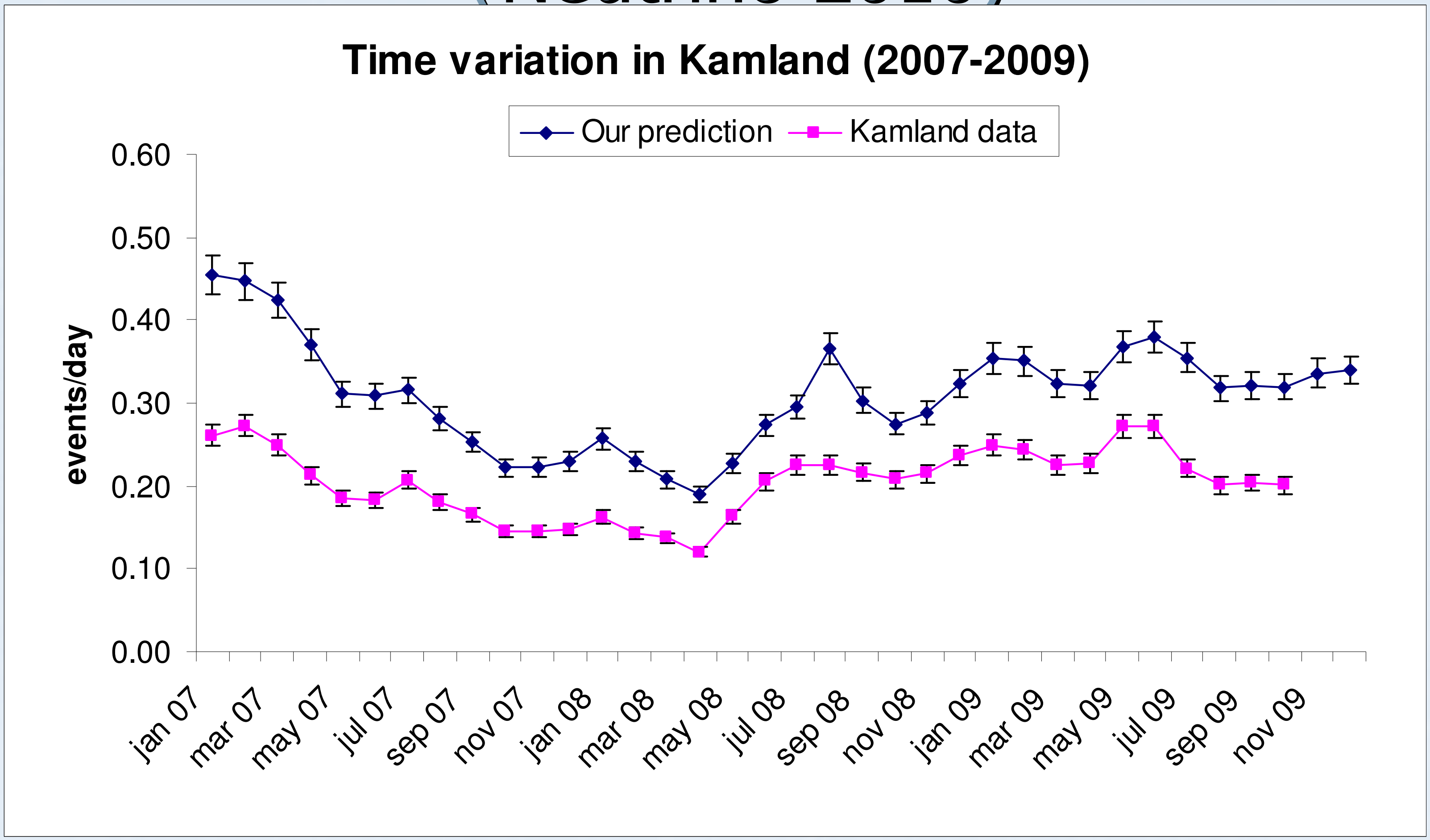
Time variation

- we know from IAEA data the (electrical) Load Factor month by month ⇒ we can study the time modulation of the predicted signals.



- At Kamioka site, for a detector of 10^32 protons, we expect a mean value of 40 events in 1 month
- The monthly averaged valued of the total thermal power in the world is 910 GW

Kamland data on expected reactor events (Neutrino 2010)

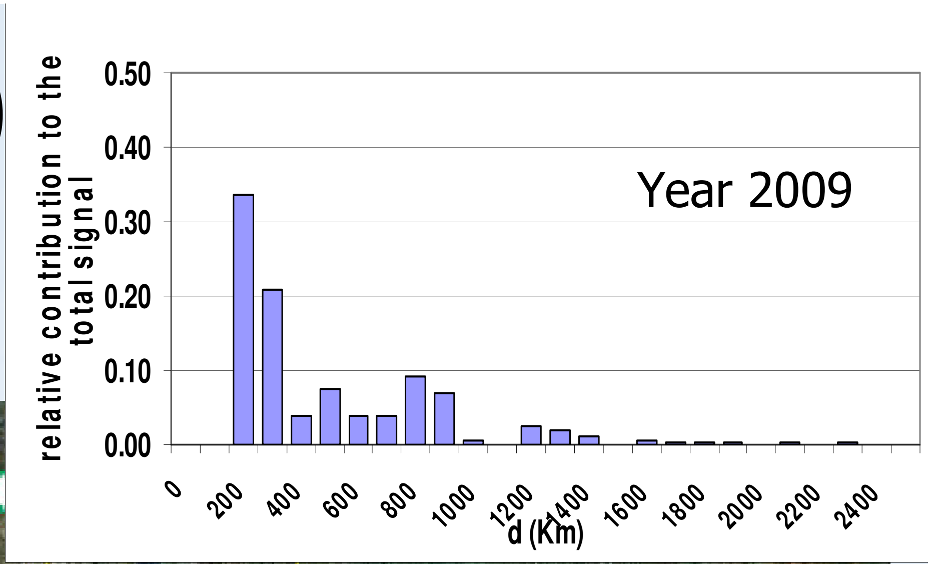


- We use: N_p=3.46 x10^31, eff.=0.687

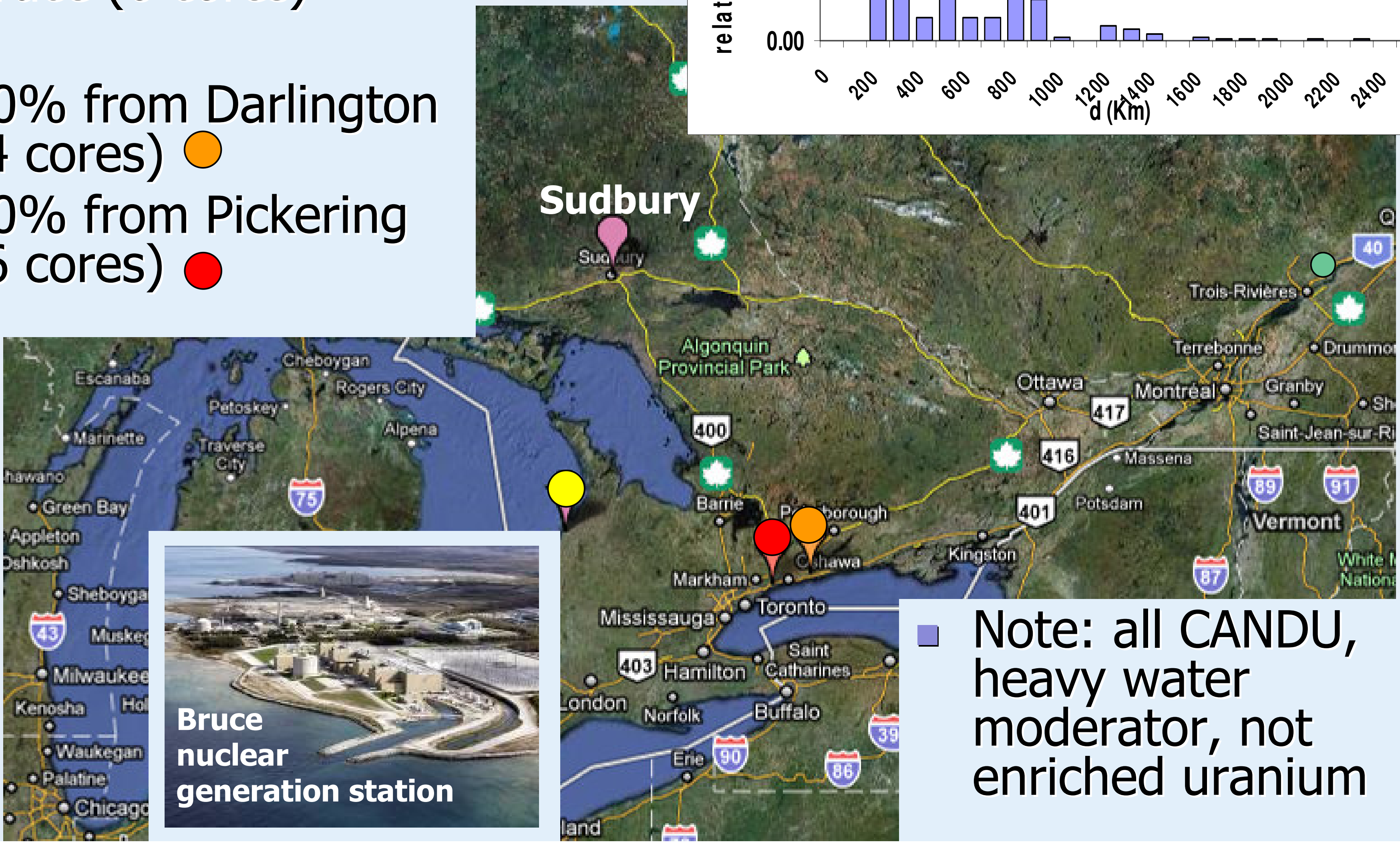
(from KamLand coll. Nature 2005)

- Note: uncertainties about 5%

Sudbury (r=0.9)

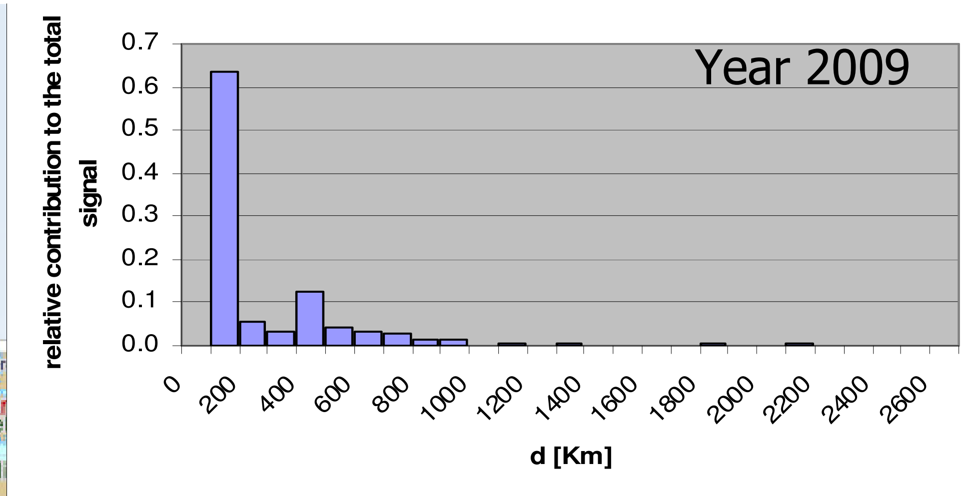


- About 1/3 of the total signal comes from Bruce (6 cores)
- 10% from Darlington (4 cores)
- 10% from Pickering (6 cores)



- Note: all CANDU, heavy water moderator, not enriched uranium

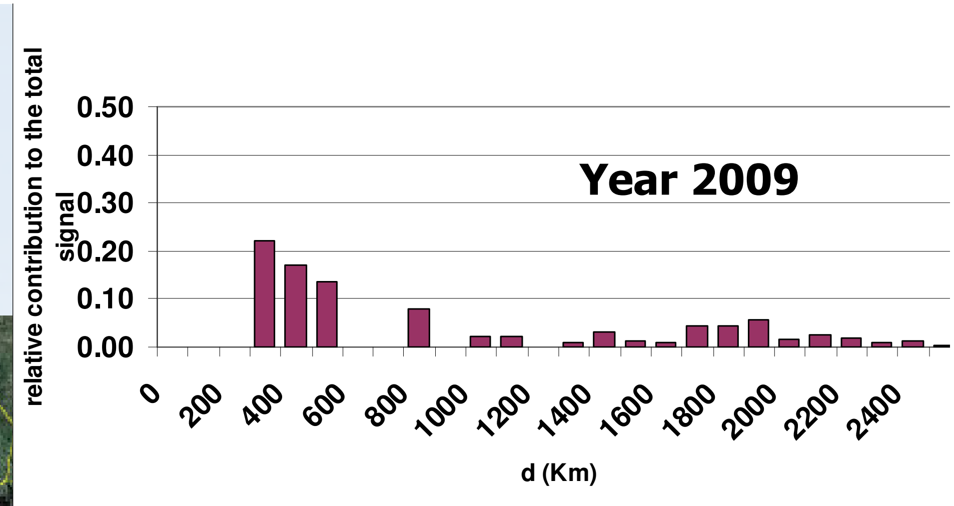
FREJUS (r= 3)

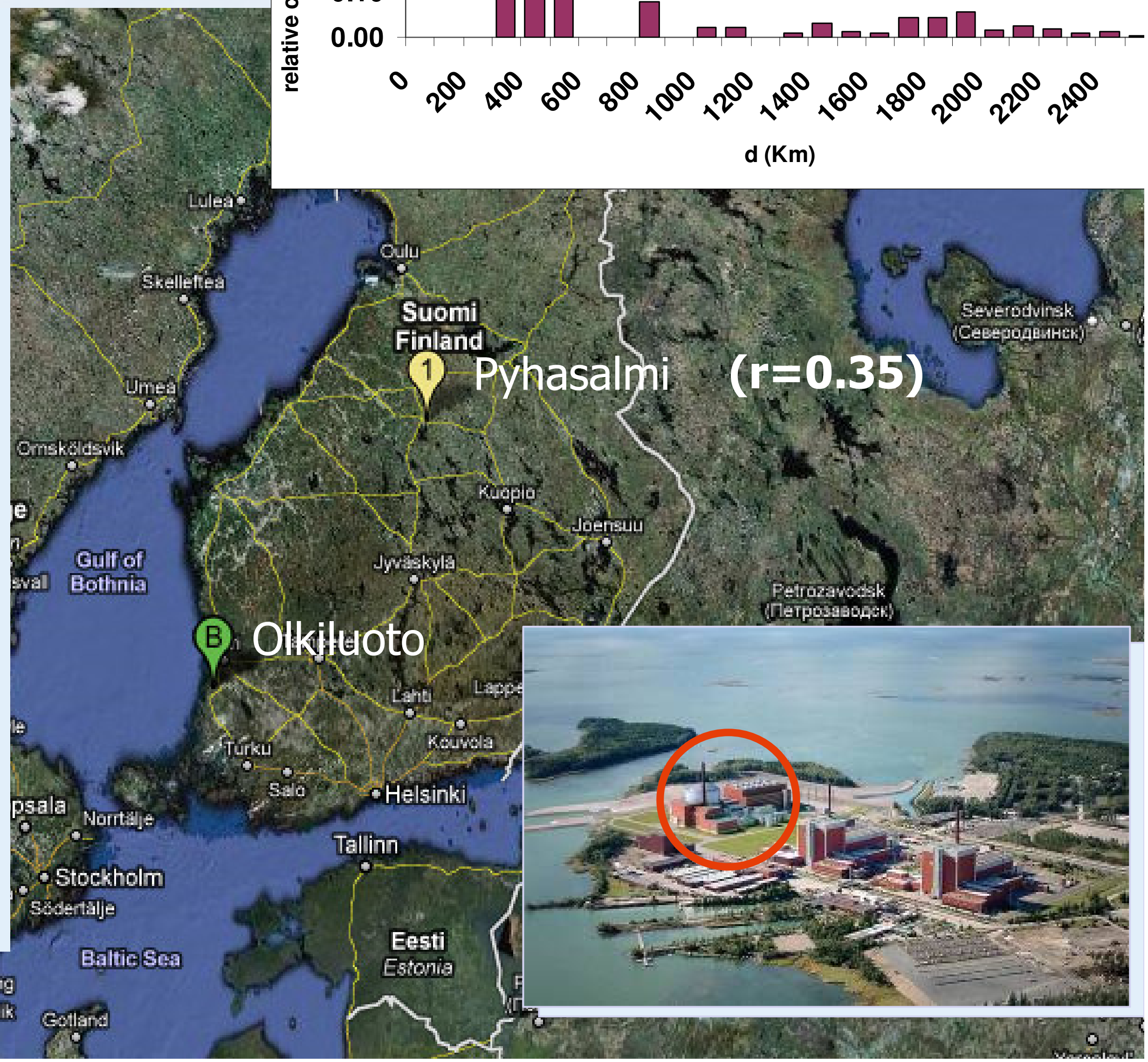


- Situation similar to Kamioka
- Near to French and Switzerland cores

New reactors in Finland ?

- Olkiluoto 3: ~4300 MWth, start 2013(?)
- Olkiluoto 4: ~4300 MWth approved July 2010
- With both, signal at Phyasalmi increases of 10%
- ....but not only new cores...





Spent fuel

- Contribution of the anti-ν emitted from the stored irradiated fuel
- KamLand coll. quotes +2.4 %
- In Chooz is at most +1.5%
- Note: spent fuel contributes mainly at low energy region
- Problems: location of spent fuel and total amount

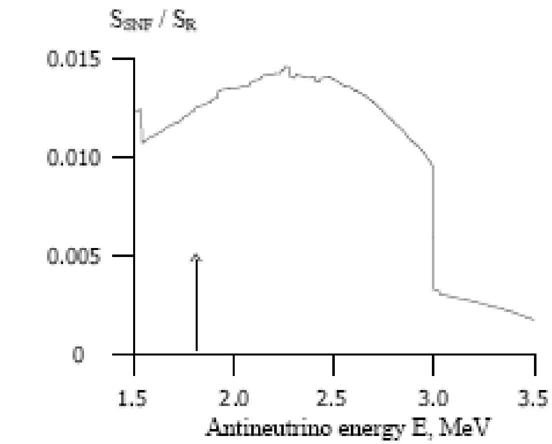
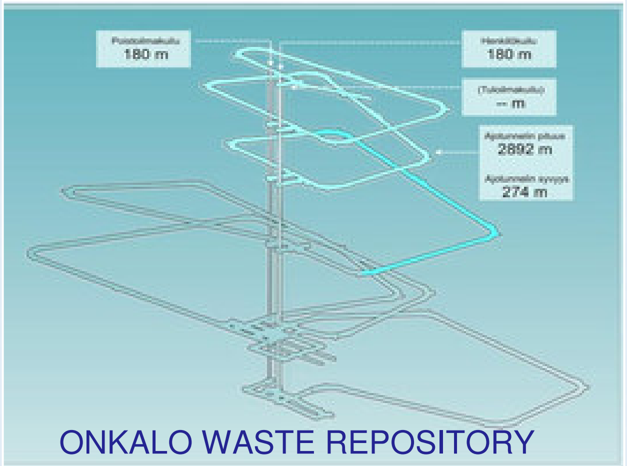


Fig. 1. Time-averaged ratio of spent fuel $\tilde{\nu}_e$ spectrum S_{SNF} to the reactor $\tilde{\nu}_e$ spectrum S_R above the inverse beta-decay reaction threshold (1.8 MeV)

Kopeikin et al 2004



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Conclusion

- We update reactor signal for different sites, interesting for geo-neutrino studies.

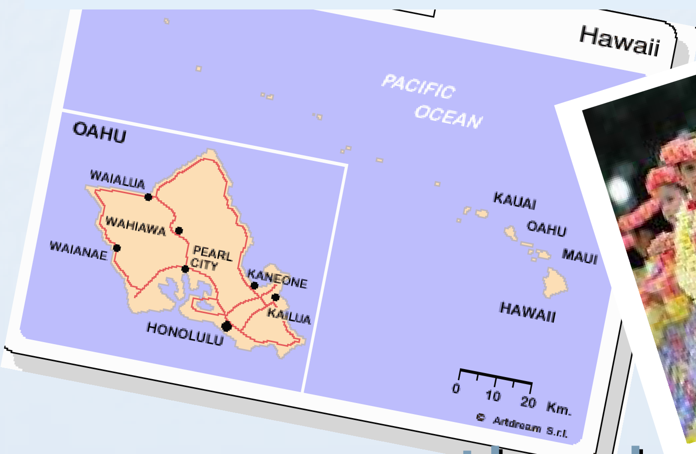
- We are able to following the time variation of the predicted signal along a period of 3 years (2007 – 2009)

- Open question:
  - matter effect in neutrino oscillation (≤ 1%...)
  - contribution of the spent fuel
  - power fraction change with time and with type core (CANDU for SNO)

BUT…..

The "true" conclusion

- let's go to unique sites:
- far from reactors
- where interesting (scientific) discoveries can occur…



thank you for your attention !