



# A reference worldwide model for antineutrinos from reactors

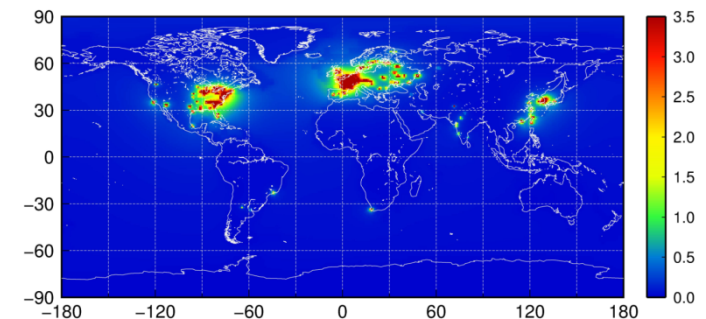
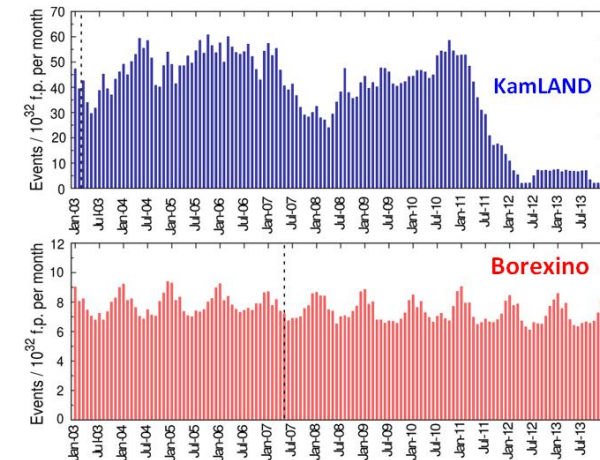
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University of Ferrara - INFN

In collaboration with Ivan Callegari, Giovanni Fiorentini, Fabio Mantovani, Barbara Ricci,  
Virginia Strati, and Gerti Xhixha (University of Ferrara-INFN)

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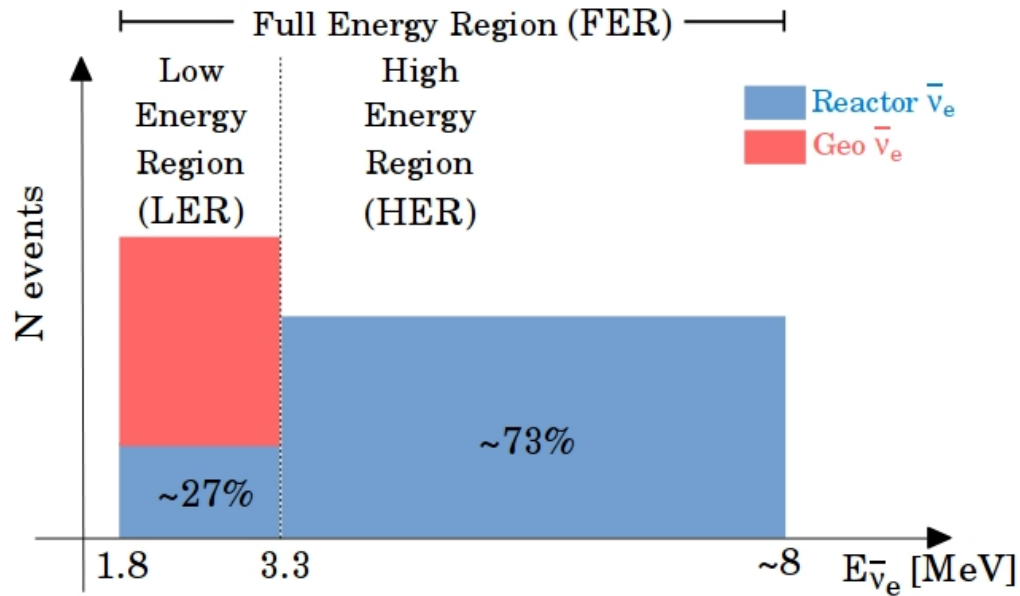
# Outline

- Why a reference model for reactor antineutrinos?
- Nuclear power plants: an overview of the worldwide reactor database
- Worldwide reactor signal calculation and Monte Carlo uncertainty propagation
- Some focuses: long-lived isotopes, spent nuclear fuels and research reactors
- Signal distance and temporal profiles
- Worldwide map of reactor signals
- Conclusions

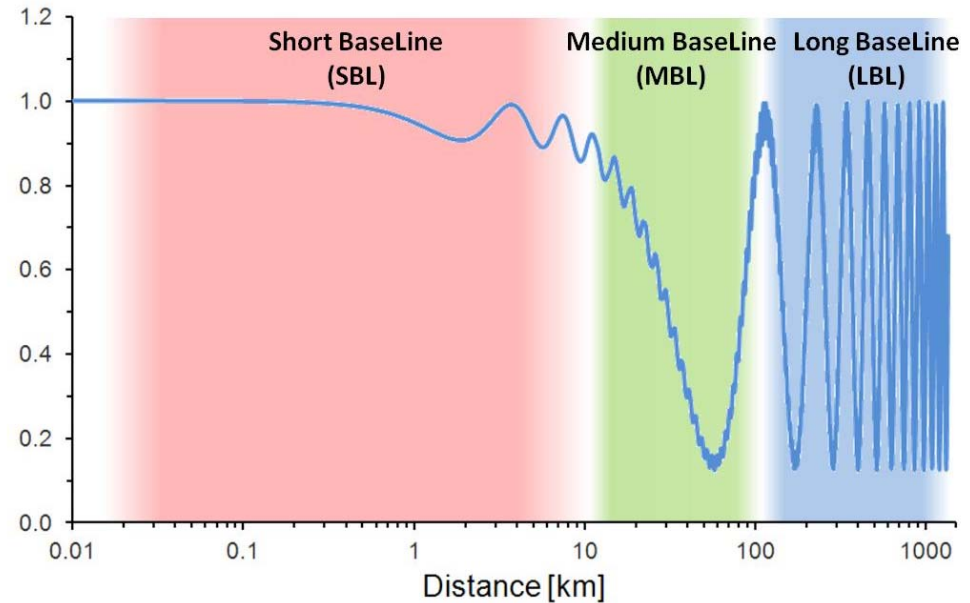


# Why a reference model for antineutrinos from reactors?

Reactor antineutrinos are the most severe source of **background for geoneutrino measurements**

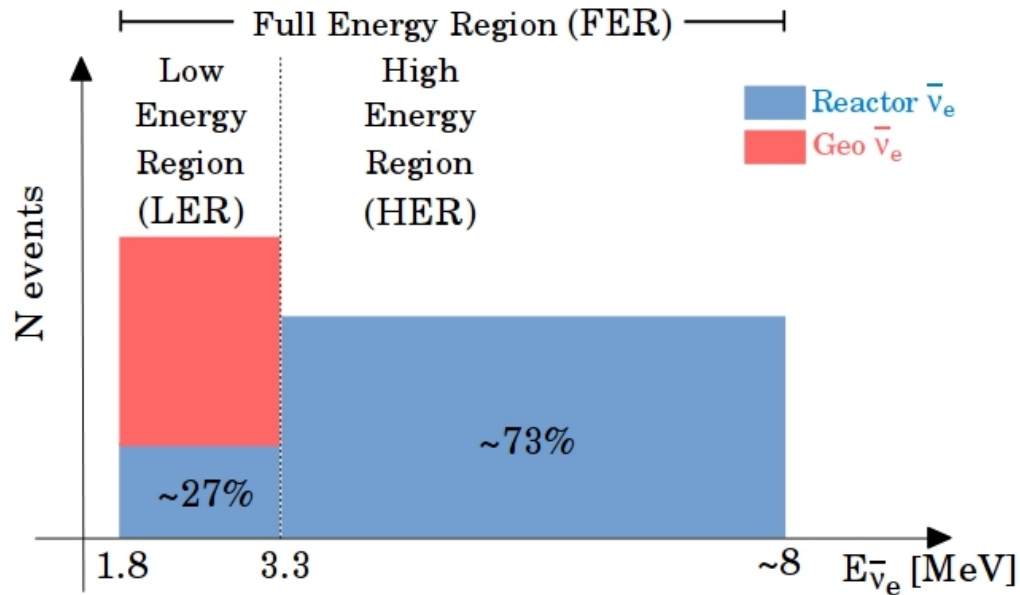


Liquid scintillation detectors: moving from the **Short BaseLine (SBL) (~1km)** and **Long BaseLine (LBL) era (~200 km)** towards the **Medium BaseLine (MBL) era (~50 km)**

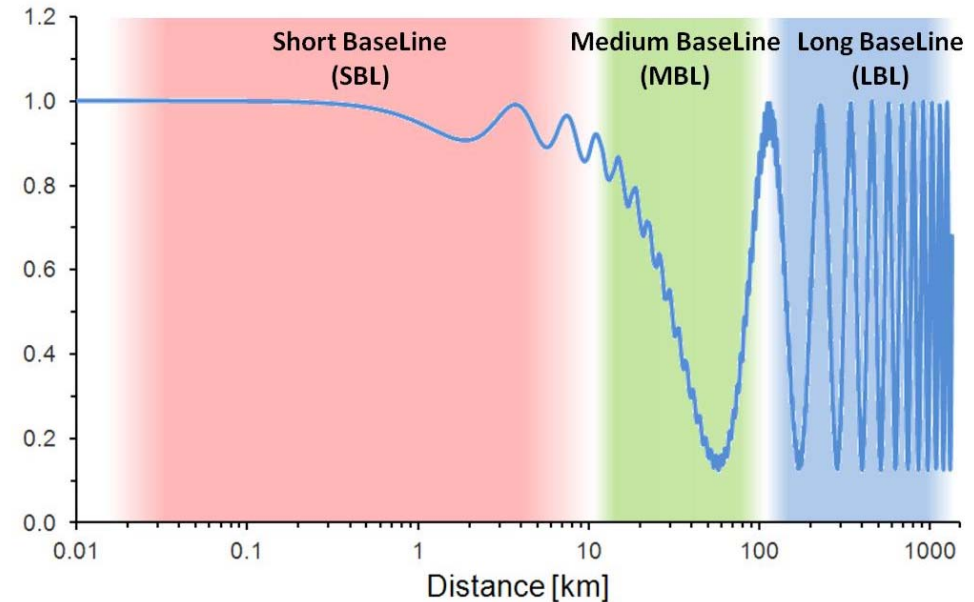


# Why a reference model for antineutrinos from reactors?

Reactor antineutrinos are the most severe source of **background for geoneutrino measurements**



Liquid scintillation detectors: moving from the **Short BaseLine (SBL)** ( $\sim 1\text{km}$ ) and **Long BaseLine (LBL)** era ( $\sim 200\text{ km}$ ) towards the **Medium BaseLine (MBL)** era ( $\sim 50\text{ km}$ )



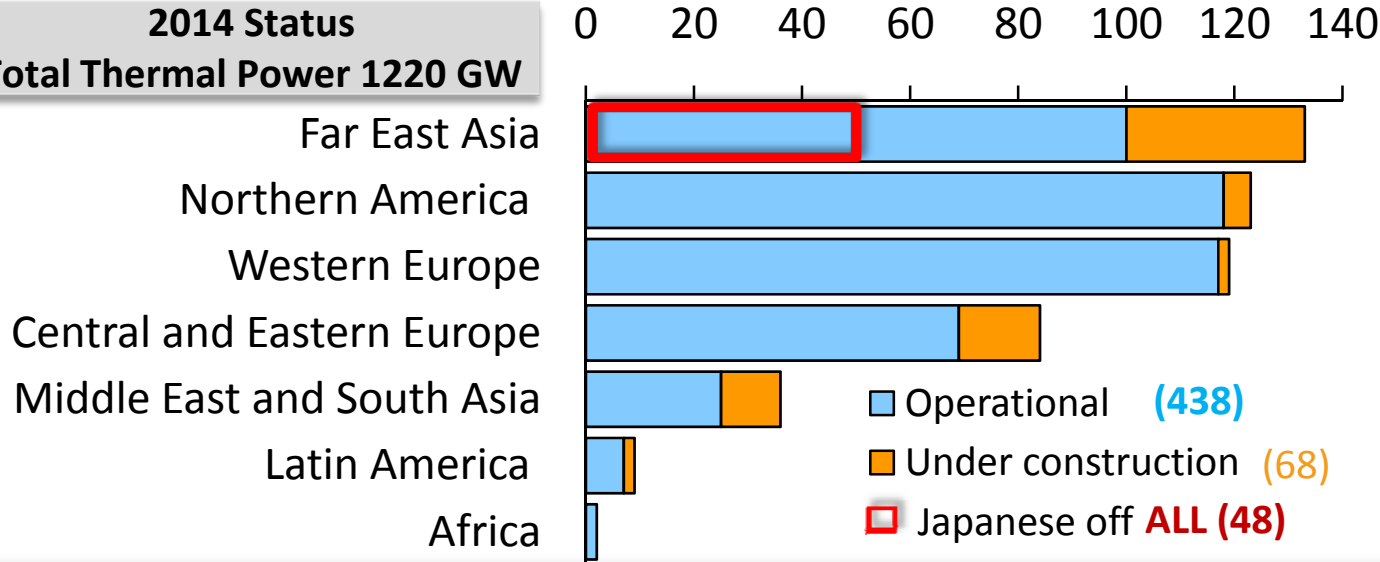
## Goal of the work

- provide on the base of reactors official data a **worldwide reference model required** for estimating the reactor signal for **LBL experiments**
- estimate the **signal uncertainty** starting from the uncertainties on individual inputs

# Nuclear power plants in the world

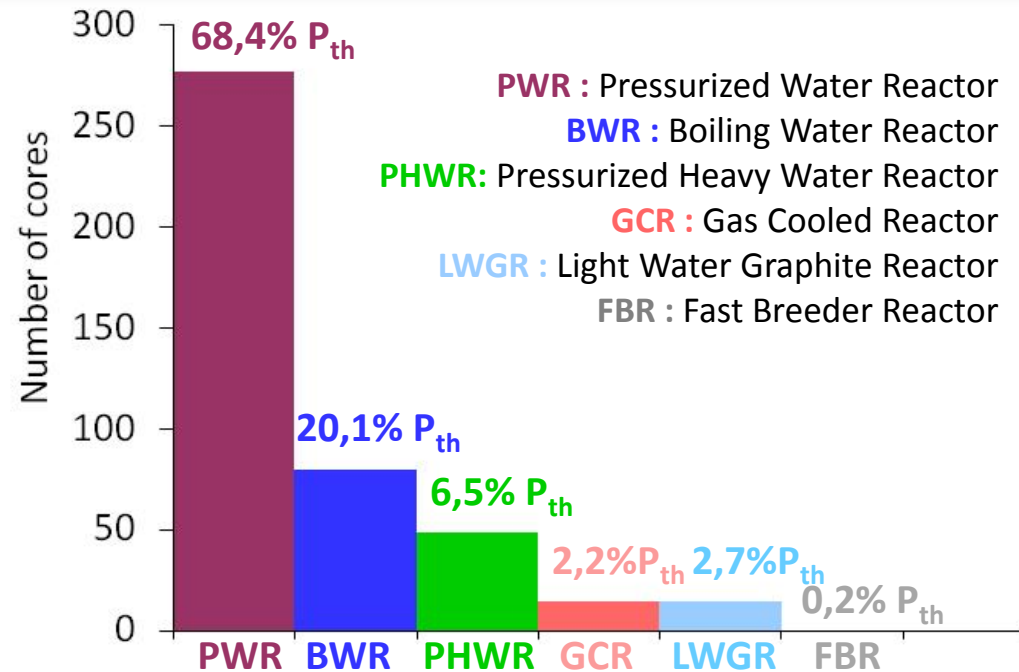
2014 Status

Total Thermal Power 1220 GW



- ✓ Far East Asia, Western Europe and North America host ~25% each
- ✓ 40% of under construction reactors in China (~ 30 GW<sub>el</sub>)

- ✓ PWR, BWR, LWGR and GCR: enriched uranium with different enrichment levels (from ~ 2.2% up to 5% <sup>235</sup>U)
- ✓ PHWR: natural uranium (~ 0.7% <sup>235</sup>U)
- ✓ Few tens of reactors use Mixed Oxide fuels (MOX), a mixture of depleted U and Pu



**PWR** : Pressurized Water Reactor  
**BWR** : Boiling Water Reactor  
**PHWR**: Pressurized Heavy Water Reactor  
**GCR** : Gas Cooled Reactor  
**LWGR** : Light Water Graphite Reactor  
**FBR** : Fast Breeder Reactor

# The Power Reactor Information System (PRIS) by the IAEA\*

**PRIS:** a database on commercial nuclear power reactors all over the world maintained by the International Atomic Energy Agency (IAEA)

## Used inputs

- ✓ Thermal Powers  $P_{th}$  [MW]
- ✓ Core type
- ✓ Use of MOX
- ✓ Monthly Load Factors

$$LF = 100 \times \frac{EG}{REG}$$

*EG* = net electrical energy produced

*REG* = reference energy generation

Typically **1 year** working at **~80% LF** and **~1 month off** for maintenance

## Drawbacks

- ✓ No cores coordinates
- ✓ No research reactors
- ✓ No unique database

**CA-19 BRUCE-6**  
 Operator: BRUCEPOWER (BRUCEPOWER)  
 Contractor: CHIAECL (CHIAECL HYDRO) / ATOMIC ENERGY OF CANADA (AEC)

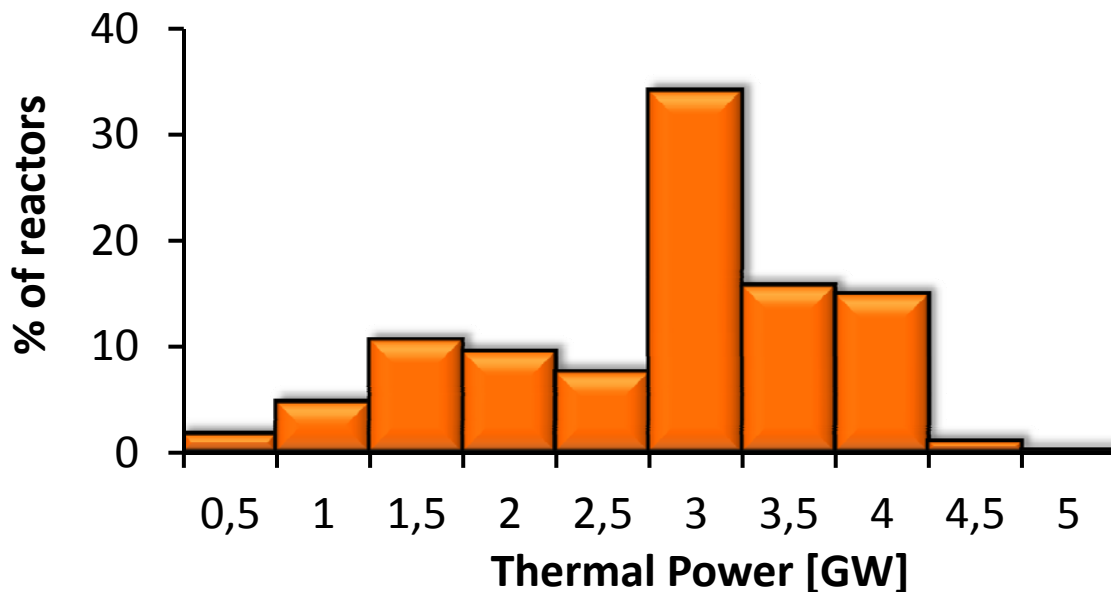
1. Station Details  
 Type: PHWR  
 Net Reference Unit Power (RUP) at the beginning of 2010: 517.0 MW(e)  
 Design Net Capacity: 522.0 MW(e)  
 Design discharge: 1710 MW (t)  
 Status at end of year: Operational

Country	Code	Name	Type	Model	Capacity [MW]			Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation
					Thermal	Core	Net					
CANADA	CA-10	BRUCE-3	PHWR	CANDU 750A	2832	805	730	BRUCEPOWER NELP		1972-3	1979-12	1978-2
	CA-11	BRUCE-4	PHWR	CANDU 750B	2832	805	730	BRUCEPOWER NELP		1972-3	1979-12	1978-2
	CA-18	BRUCE-5	PHWR	CANDU 750B	2832	805	730	BRUCEPOWER NELP		1972-3	1979-12	1978-2
	CA-20	BRUCE-6	PHWR	CANDU 750B	2832	805	730	BRUCEPOWER NELP		1972-3	1979-12	1978-2
	CA-21	BRUCE-7	PHWR	CANDU 750B	2832	805	730	BRUCEPOWER NELP		1972-3	1979-12	1978-2
	CA-22	DARLINGTON-1	PHWR	CANDU 750B	2690	872	817	BRUCEPOWER CHIAECL		1973-9	1979-12	1978-2
	CA-23	DARLINGTON-2	PHWR	CANDU 750B	2690	872	817	BRUCEPOWER CHIAECL		1973-9	1979-12	1978-2
	CA-24	DARLINGTON-3	PHWR	CANDU 750B	2690	872	817	BRUCEPOWER CHIAECL		1973-9	1979-12	1978-2
	CA-25	DARLINGTON-4	PHWR	CANDU 750B	2690	872	817	BRUCEPOWER CHIAECL		1973-9	1979-12	1978-2
				PHWR	CANDU 850	2776	934	878	OPG		1982-4	1987-3

3. 2010 Monthly Performance Data

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GW(e)h	607.0	514.9	505.7	482.2	289.3	0.0	52.0	07.9	25.9	95.1	95.1	8.1
EGP (%)	99.8	98.6	99.2	98.6	44.4	0.0	16.3	98.7	64.9	100.0	0.1	0.0
UCP (%)	100.0	100.0	100.0	100.0	44.4	0.0	14.1	98.2	65.9	100.0	0.1	0.0
CF (%)	0.2	1.2	0.0	0.0	55.2	0.0	21.4	2.2	34.0	0.2	0.1	0.4
PUF (%)	0.0	0.0	0.0	0.0	100.0	0.0	84.7	0.0	34.2	0.0	0.0	0.0
UCLF (%)	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0
KUF (%)												

~35% of commercial reactors has a  $P_{th} \sim 3\text{GW}$



\* <https://www.iaea.org/pris/>

# Nuclear reactors database at [www.fe.infn.it/antineutrino](http://www.fe.infn.it/antineutrino)

The web page [www.fe.infn.it/antineutrino](http://www.fe.infn.it/antineutrino) provides an **updated collection** of data about worldwide nuclear reactors for calculation of antineutrino signal

## 2003

- [Input database](#)
- [Numerical map](#)
- [Map](#)

## 2007

- [Input database](#)
- [Numerical map](#)
- [Map](#)

## 2011

- [Input database](#)
- [Numerical map](#)
- [Map](#)

## 2004

- [Input database](#)
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- [Map](#)

## 2008

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- [Map](#)

## 2012

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## 2005

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## 2009

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## 2013

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## 2006

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- [Map](#)

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- [Map](#)

## 2014

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# Reactor antineutrino signal calculation

The reactor antineutrino signal evaluation requires several ingredients for modeling the three antineutrino life stages:

- ✓ **production** at reactor cores
- ✓ **propagation** to the detector site
- ✓ **detection** in liquid scintillation detectors

## DETECTOR

- ◆  $\varepsilon = 100\%$  efficiency
- ◆  $\tau = 1$  year
- ◆  $N_p = 10^{32}$  free protons  
( $\sim 1$  kton liquid scintillator mass)

## $\bar{\nu}$ PHYSICS

- ◆  $P_{ee} = \nu_e$  oscillation survival probability
- ◆  $\sigma_{IBD}(E) =$  IBD cross section  
 $\bar{\nu}_e + p \rightarrow e^+ + n$  ( $E_{th} = 1.806$  MeV)

$$N_{TOT} = \varepsilon N_p \tau \sum_{k=1}^{N_{reactor}} \frac{P_i}{4\pi d_k^2} \langle LF_k \rangle \int dE_\nu \sum_{i=1}^4 \frac{p_i}{Q_i} \lambda_i(E_\nu) P_{ee}(E_\nu, d_k) \sigma_{IBD}(E_\nu)$$

[1 TNU = 1 event /  $10^{32}$  free protons / year]  $i = {}^{235}\text{U}, {}^{238}\text{U}, {}^{239}\text{Pu}, {}^{241}\text{Pu}$

## REACTOR

- ◆  $d_k =$  reactor distance
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- ◆  $LF =$  Load Factor
- ◆  $p_i =$  power fraction

## NUCLEAR

- ◆  $Q_i =$  energy released per fission
- ◆  $\lambda_i =$  reactor antineutrino spectrum

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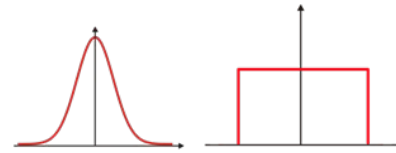
# Signal uncertainty via Monte Carlo sampling

The investigated sources of uncertainty are:

- Thermal Powers ( $P_{th}$ )
- Fission Fractions ( $f_i$ )
- Energy released per fission ( $Q_i$ )
- Oscillation parameters ( $\delta m^2, \text{sen}^2 \theta_{12}, \text{sen}^2 \theta_{13}$ )
- IBD cross section ( $\sigma_{IBD}$ )

In principle there is some correlation among these inputs, which are however affected by **enrichment level** and **burn up stage**: both info are **unknown** in our global database

Input quantity	PDF	
$\nu$ oscillation <sup>1</sup>	$\delta m^2$ (eV) <sup>2</sup> Gaussian $1\sigma = 3.4\%$	
	$\text{sen}^2 \theta_{12}$ Gaussian $1\sigma = 5.5\%$	
	$\text{sen}^2 \theta_{13}$ Gaussian $1\sigma = 8.5\%$	
Energy per fission <sup>2</sup>	$Q_{235U}$ Gaussian $1\sigma = 0.1\%$	
	$Q_{238U}$ Gaussian $1\sigma = 0.3\%$	
	$Q_{239Pu}$ Gaussian $1\sigma = 0.2\%$	
	$Q_{241Pu}$ Gaussian $1\sigma = 0.2\%$	
Fission fraction	Extraction among 22 equally probable sets of $f_i$ taken from literature	
		$f_{235U}$
		$f_{238U}$
		$f_{241Pu}$
Thermal Power	$P_{th}$ Gaussian $1\sigma = 2\%$	
IBD cross section <sup>3</sup>	$\sigma_{IBD}$ Gaussian $1\sigma = 0.4\%$	



**Monte Carlo machinery**

Uncertainty on signal obtained via a **Monte Carlo sampling** of each input according to its **Probability Density Function (PDF)**

<sup>1</sup>Capozzi et al.. Phys. Rev. D 89. 093018 (2014)

<sup>2</sup> Ma et al.. Phys. Rev. C 88. 014605 (2013)

<sup>3</sup>A. Strumia and F. Vissani. Phys. Lett. B 564. 42 (2003)

# Reactor and geoneutrino signal in 6 sites

Experiment	G [TNU]*	R <sub>LER</sub> [TNU]	r = R <sub>LER</sub> /G	Year
KamLAND	31.5 <sup>+4.9</sup> <sub>-4.1</sub>	168.5 <sup>+5.7</sup> <sub>-6.3</sub>	5.3	2006
		18.3 <sup>+0.6</sup> <sub>-1.0</sub>	0.6	2013
		7.4 <sup>+0.2</sup> <sub>-0.2</sub>	0.2	2014
JUNO	39.7 <sup>+6.5</sup> <sub>-5.1</sub>	26.0 <sup>+2.2</sup> <sub>-2.3</sub>	0.7	2013
		354.5 <sup>+44.5</sup> <sub>-40.6</sub>	8.9	2020
Borexino	40.3 <sup>+7.3</sup> <sub>-3.8</sub>	22.2 <sup>+0.6</sup> <sub>-0.6</sub>	0.6	2013
SNO+	45.4 <sup>+7.5</sup> <sub>-6.3</sub>	47.8 <sup>+1.7</sup> <sub>-1.4</sub>	1.1	2013
RENO-50	42.1 <sup>+7.2</sup> <sub>-5.9</sub>	178.4 <sup>+20.8</sup> <sub>-19.6</sub>	4.2	2013
Hawaii	12.0 <sup>+0.7</sup> <sub>-0.6</sub>	0.9 <sup>+0.02</sup> <sub>-0.02</sub>	0.1	2013

Ohi 3 & Ohi 4  
off

Yangjiang &  
Taishan on  
in 2020

See Wurm talk

See Ianni  
& Ludhova talk

See Maneira talk

See Seo talk

Long Baseline experiments:  
1σ ~ 4% in LER

\*Y. Huang et al., Geochemistry, Geophysics, Geosystems 14, 2003 (2013)

# Signal uncertainty due to individual inputs

Input quantity		$1\sigma$ on signal in FER [%]		
		Borexino	KamLAND	SNO+
$\nu$ oscillation	$\delta m^2$ (eV) <sup>2</sup>	<0.1	0.9	<0.1
	$\sin^2 \theta_{12}$	+2.4/-2.2	+2.1/-2.0	+2.4/-2.2
	$\sin^2 \theta_{13}$	0.4	0.4	0.4
Energy per fission	$Q_{235U}$	<0.1	<0.1	<0.1
	$Q_{238U}$			
	$Q_{239Pu}$			
	$Q_{241Pu}$			
Fission fraction	$f_{235U}$	0.1	0.5	<0.1
	$f_{238U}$			
	$f_{239Pu}$			
	$f_{241Pu}$			
Thermal Power	$P_{th}$	0.2	0.9	0.3
IBD cross section	$\sigma_{IBD}$	<0.1	<0.1	<0.1

- ✓ Reactor signal uncertainty dominated by  $\sin^2(\vartheta_{12})$
- ✓ Results are **time dependent** (2013 status) and **site dependent**
- ✓ Signal uncertainty due to  $P_{th}$  reflects the **signal amount generated by single reactors** (for KamLAND 60% of the signal originated by 2 cores)
- ✓ Eventual correlation of reactor operational info act on <1% uncertainties
- ✓ **Negligible** (<0.1%) uncertainty from  $Q_i$  and  $\sigma_{IBD}$

# Signal increase due to the Long Lived Isotopes (LLIs)

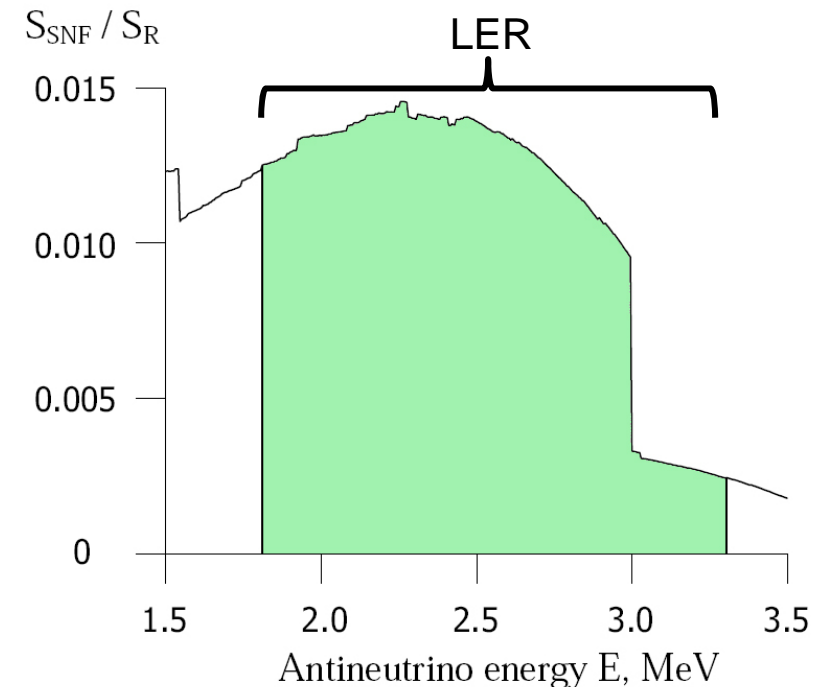
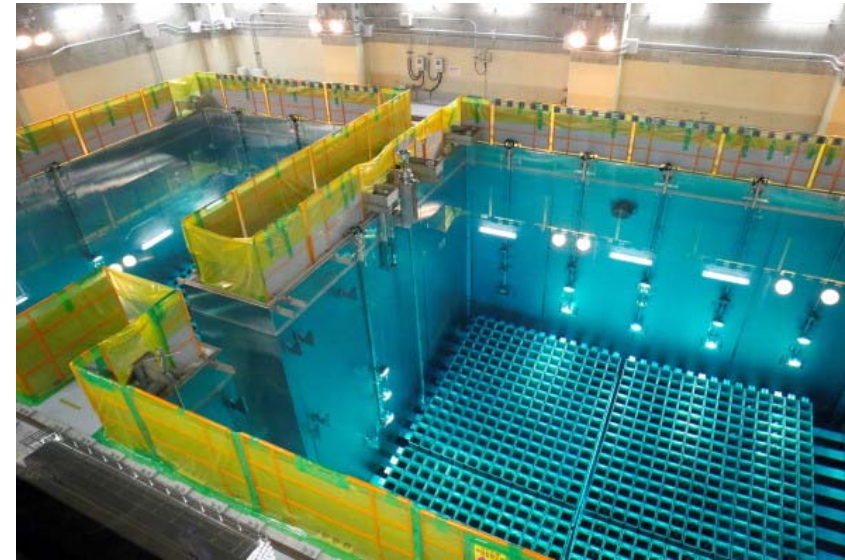
$P$	$\tau_{1/2}^P$	$E_{\bar{\nu}_e}^{max P}$ [MeV]	$D$	$\tau_{1/2}^D$	$E_{\bar{\nu}_e}^{max D}$ [MeV]	$Y_{235}$ [%]	$Y_{239}$ [%]
$^{93}\gamma$	10.18 h	2.895	$^{93}\text{Zr}$	$1.61 \cdot 10^6$ yr	0.091	6.35	3.79
$^{97}\text{Zr}$	16.75 h	1.916	$^{97}\text{Nb}$	72.1 m	1.277	5.92	5.27
$^{112}\text{Pd}$	21.03 h	0.27	$^{112}\text{Ag}$	3.13 h	3.956	0.013	0.13
$^{131m}\text{Te}$	33.25 h	/	$^{131}\text{Te}$	25.0 m	2.085	0.09	0.20
$^{132}\text{Te}$	3.204 d	0.24	$^{132}\text{I}$	2.295 h	2.141	4.31	5.39
$^{140}\text{Ba}$	12.753 d	1.02	$^{140}\text{La}$	1.679 d	3.762	6.22	5.36
$^{144}\text{Ce}$	284.9 d	0.319	$^{144}\text{Pr}$	17.28 m	2.998	4.58	3.11
$^{106}\text{Ru}$	371.8 d	0.039	$^{106}\text{Rh}$	30.07 s	3.541	0.30	3.24
$^{90}\text{Sr}$	28.79 yr	0.546	$^{90}\gamma$	64.0 h	2.280	0.27	0.10

- Fission fragments have **wide spread half-lives**, from fraction of seconds up to  $10^{18}$  years
- **LLIs** ( $E_{\nu_e}^{max} > 1.806$  MeV and  $\tau_{1/2} > 10$ h) produce **spectral distortion** in the **LER**
- The LLIs having  $\tau^P \sim$  yr are called **Spent Nuclear Fuels (SNFs)**
- Off-equilibrium correction to the reference spectra\* gives

$$\frac{\Delta R^{FER}}{R^{FER}} < 0.5\%$$

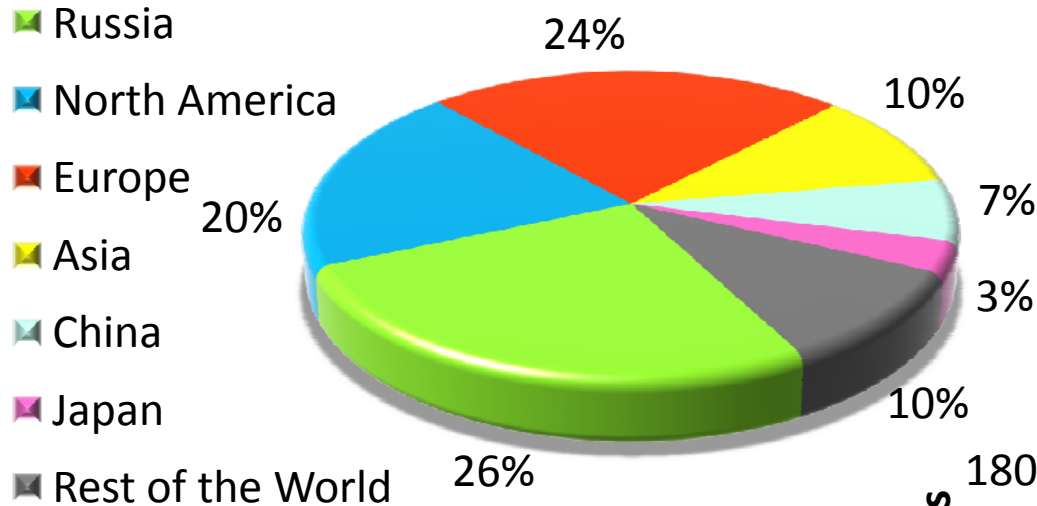
# Signal increase due to the Spent Nuclear Fuels (SNFs)

- A maintenance is typically scheduled **once a year** to **substitute 1/3 of the burnt fuel**
- SNFs are typically stored for **10 years** in **water pools** close to the reactor for cooling and shielding
- On the base of  $^{235}\text{U}$  e  $^{239}\text{Pu}$  normalized yields the mean life of SNFs is  $\tau_{SNF} = 2.8 \text{ yr}$
- Assuming that all SNF is accumulated for 10 years in the water pool close to each core the enhancement of the **antineutrino event rate** is **2.4%** in the **LER**



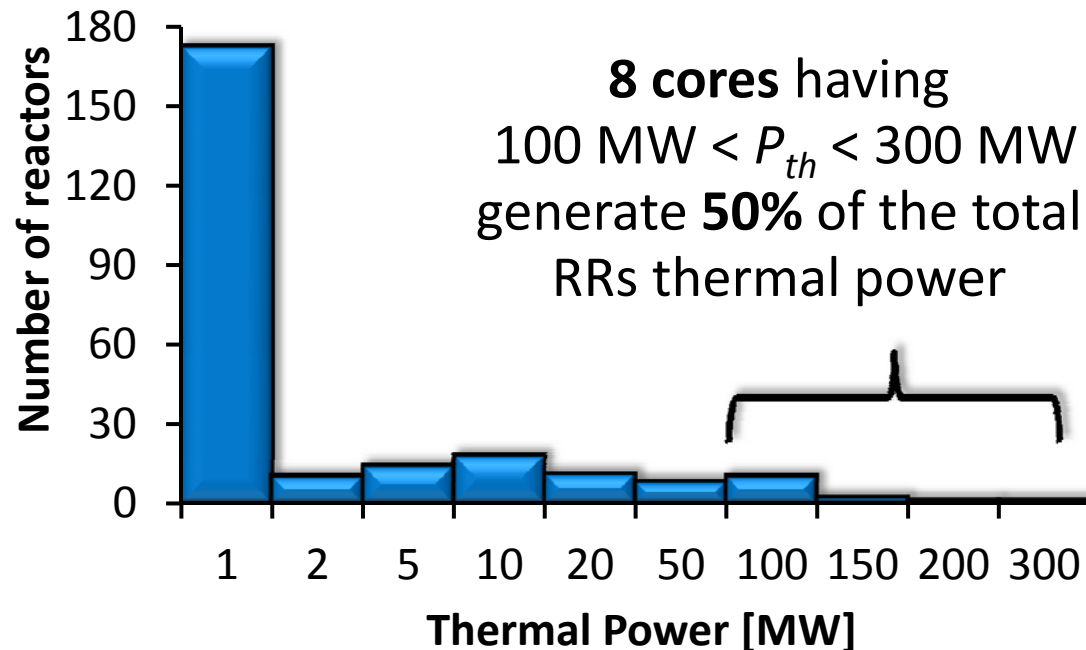
# Antineutrino signal from Research Reactors (RRs)\*

247 RRs around the world / Total  $P_{th} = 2.2 \text{ GW}$  (0.2% of commercial reactors  $P_{th}$ )



RRs employed for

- *neutron beam generation* (production of radioisotopes, neutron scattering experiments, etc)
- *R&D for nuclear energy research*
- *teaching/training purposes*

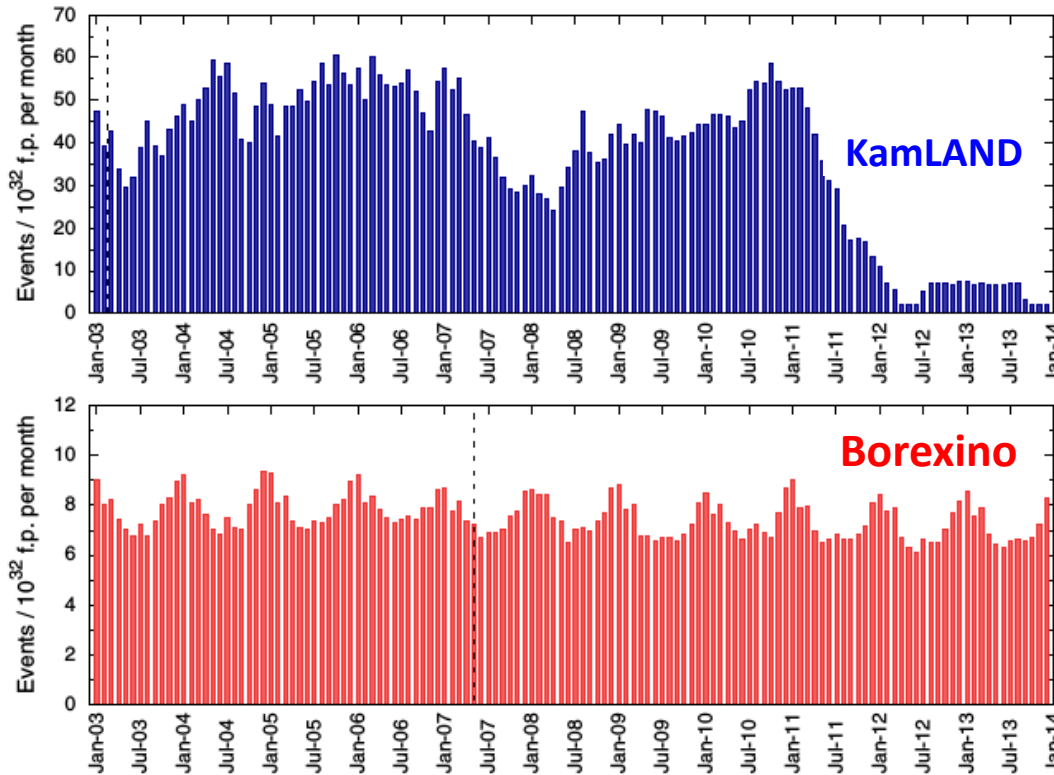


The 40 RRs accounting for 90% of the RR thermal power and operating with a 80% annual LF give

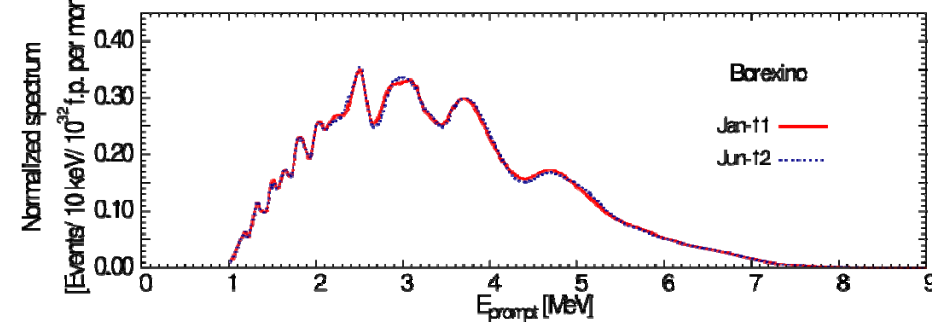
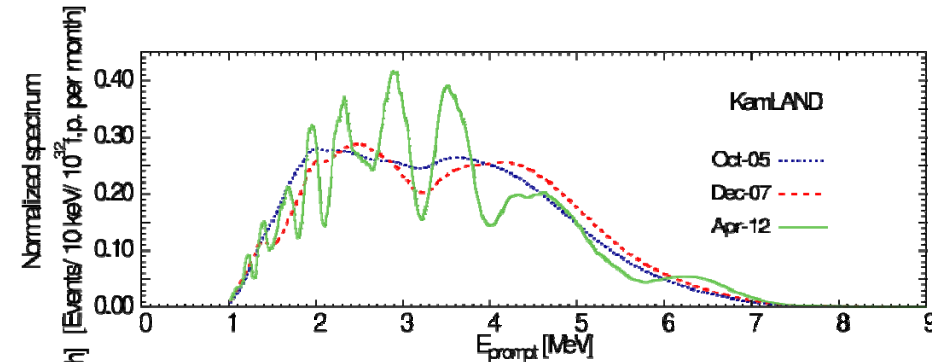
$$\frac{\Delta R_{FER}}{R_{FER}} < 0.2\%$$

\*<http://nucleus.iaea.org/RRDB/RR/ReactorSearch.aspx?filter=0>

# Borexino and KamLAND signal time profiles

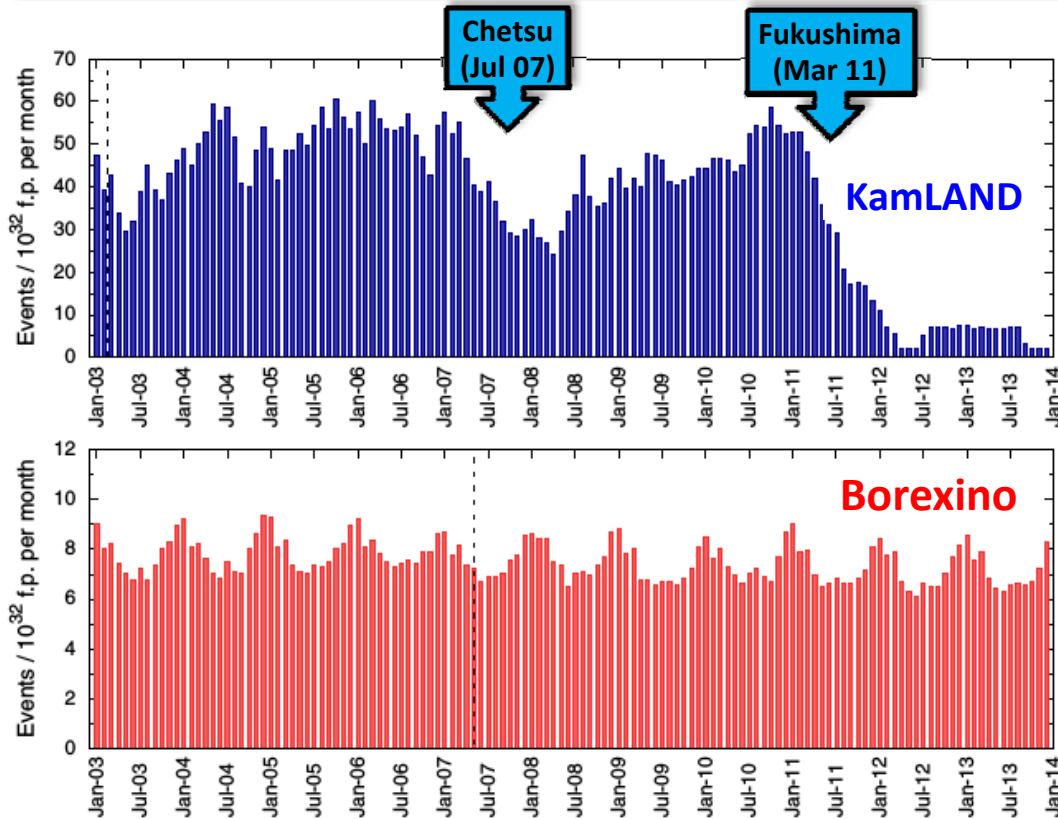


- ✓ Signal time profile governed by the **Japanese nuclear industry** operational status
- ✓ Shutdown of nuclear power plants concomitant to strong **earthquakes** manifestly visible
- ✓ **Sensitive** to **operational conditions** of **single reactors**

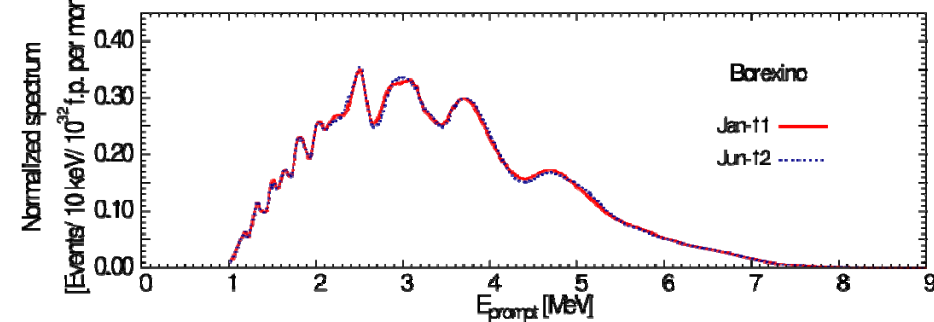
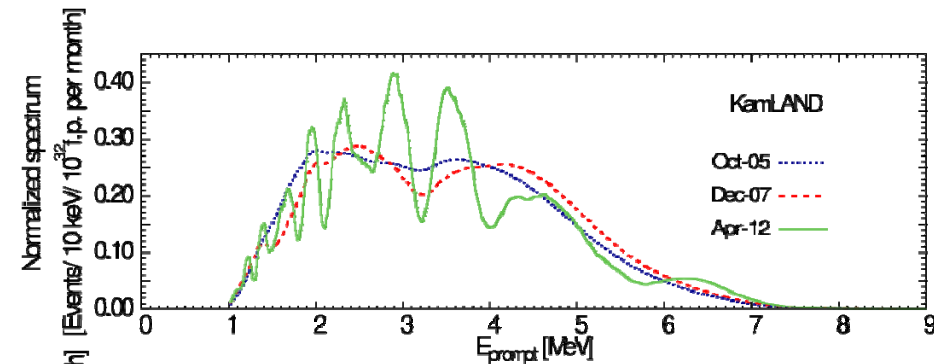


- ✓ **Seasonal signal variation** associated with the lower fall-spring electricity demand
- ✓ Relatively **insensitive** to **operational conditions** of **single reactors** since there are no close-by reactors dominating the antineutrino flux

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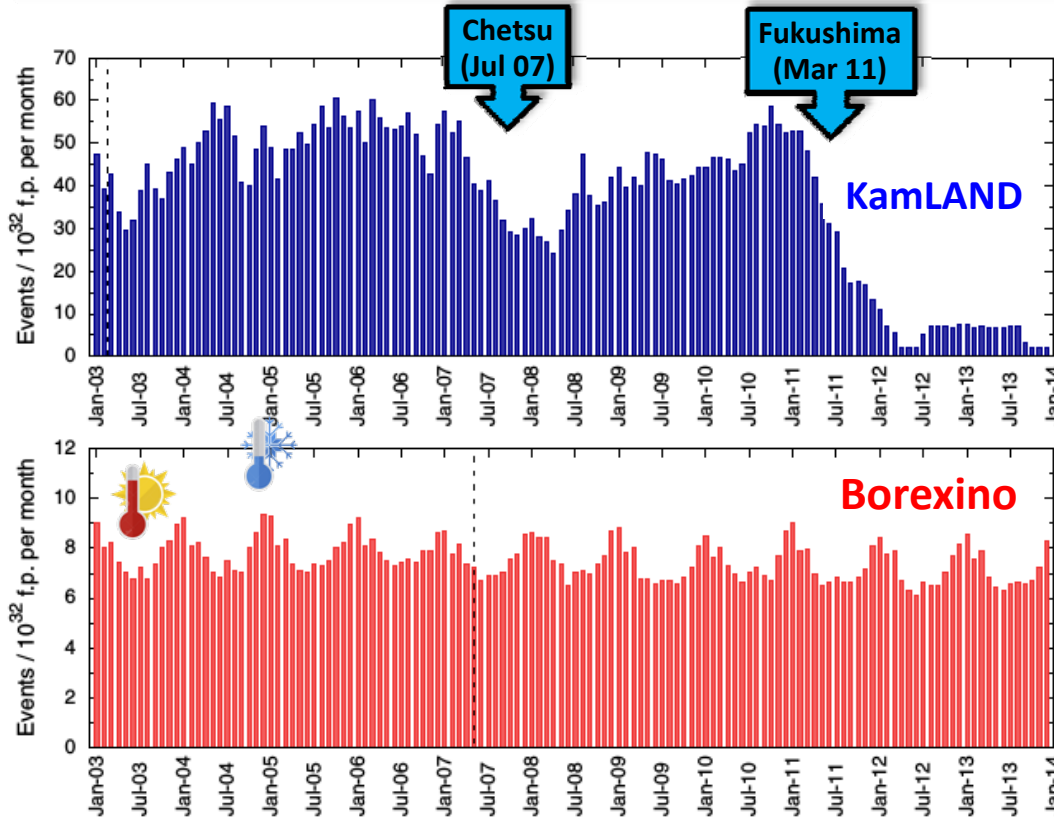


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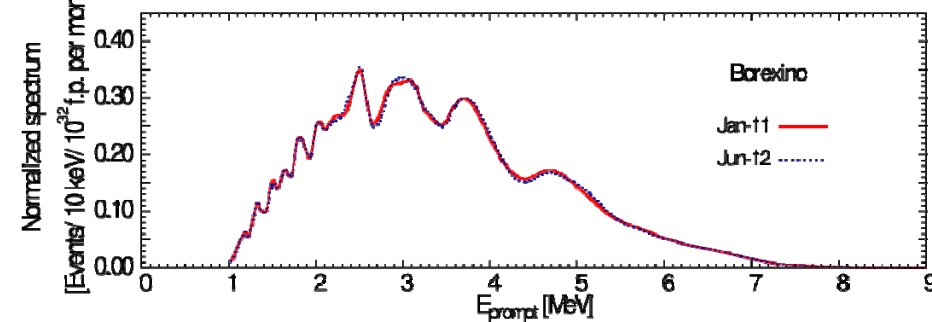
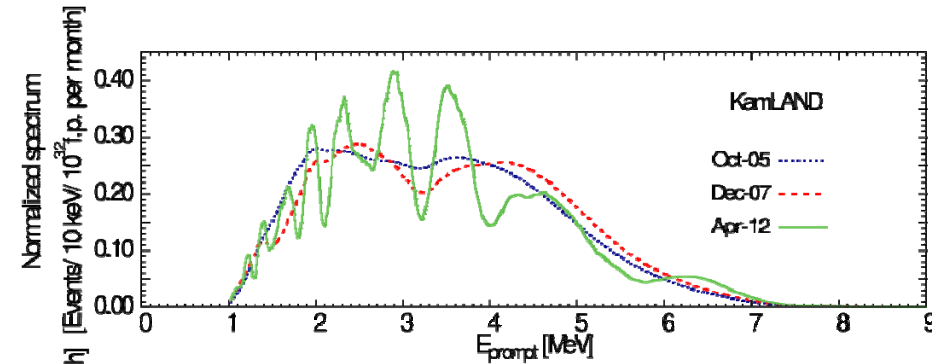


- ✓ **Seasonal signal variation** associated with the lower fall-spring electricity demand
- ✓ Relatively **insensitive** to **operational conditions** of **single reactors** since there are no close-by reactors dominating the antineutrino flux

# Borexino and KamLAND signal time profiles

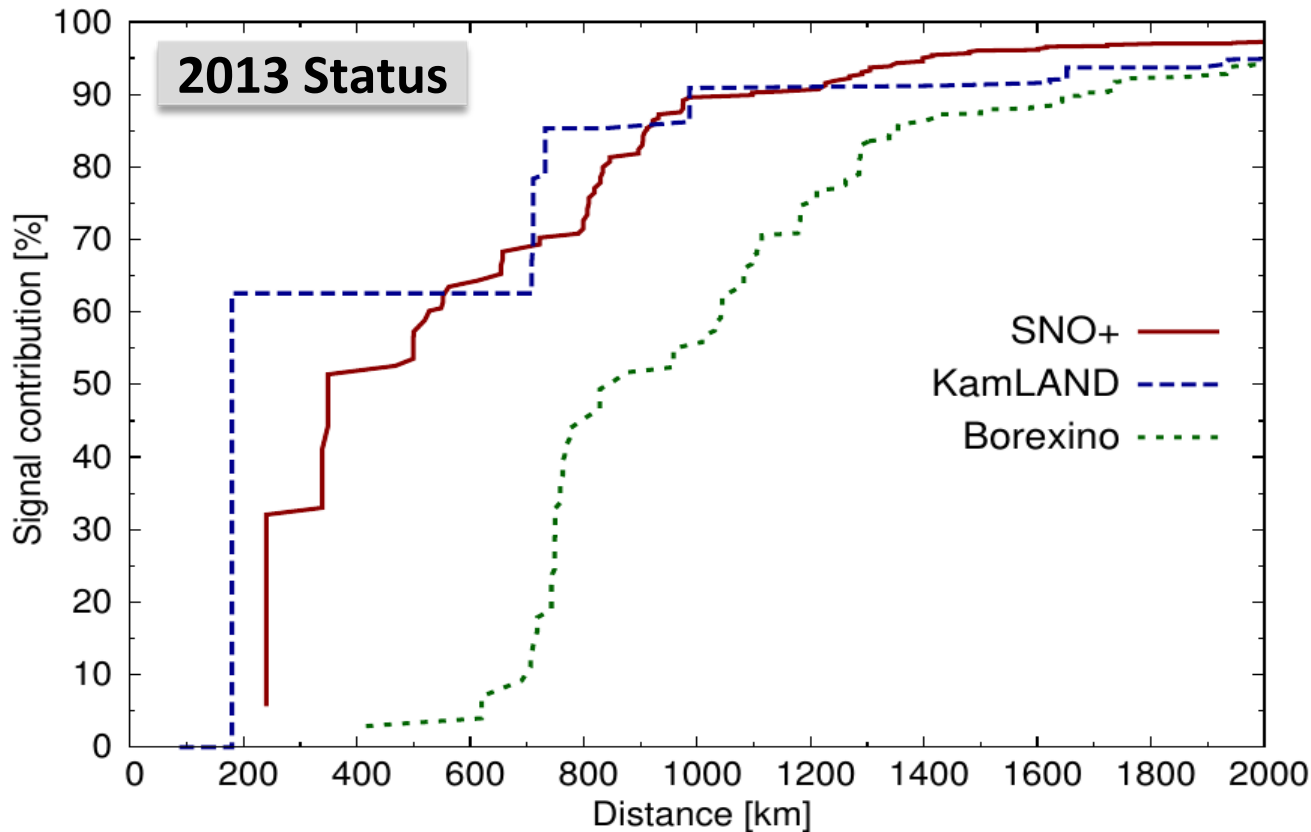


- ✓ Signal time profile governed by the **Japanese nuclear industry** operational status
- ✓ Shutdown of nuclear power plants concomitant to strong **earthquakes** manifestly visible
- ✓ **Sensitive** to **operational conditions** of **single reactors**



- ✓ **Seasonal signal variation** associated with the lower fall-spring electricity demand
- ✓ Relatively **insensitive** to **operational conditions** of **single reactors** since there are no close-by reactors dominating the antineutrino flux

# Borexino, KamLAND and SNO+ signal distance profiles



**KamLAND step-like** profile  
with **3 major discontinuities**

- ✓ **1<sup>st</sup>** is **~60%** at **180 km**  
(Japanese Ohi3 and Ohi4)
- ✓ **2<sup>nd</sup>** is **~85%** at **730 km**  
(Japanese plus East coast  
South Korean)
- ✓ **3<sup>rd</sup>** is **~90%** at **990 km**  
(Japanese plus all South  
Korean)

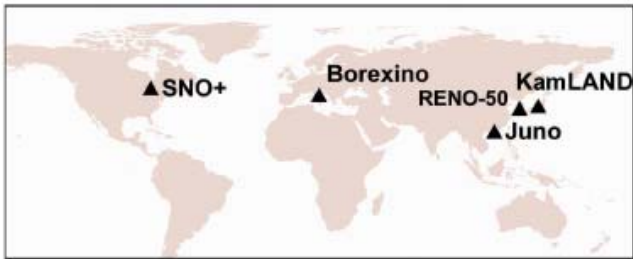
**SNO+** profile has **2 major discontinuities**

- ✓ **1<sup>st</sup>** is **~32%** at **~240 km** (Canadian Bruce)
- ✓ **2<sup>nd</sup>** is **~50%** at **~350 km** (Canadian Pickering  
and Darlington)
- ✓ For **d > 500km** the profile **levels out** (USA  
stations)

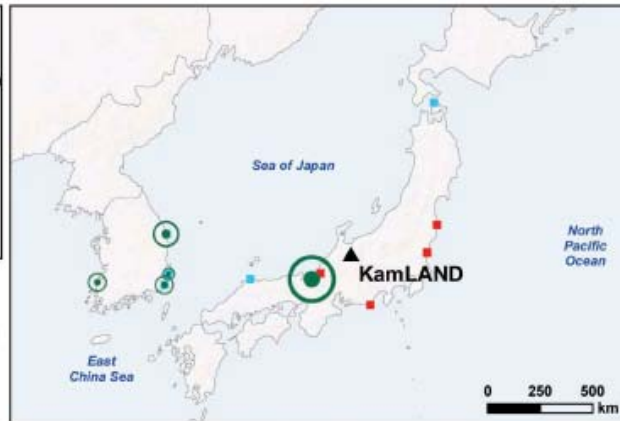
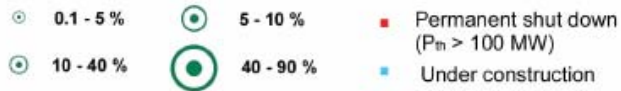
**Borexino** profile is **smooth**

- ✓ Signal **spread out** over the European  
countries
- ✓ Closest power station at **415 km**  
(Slovenia) gives the major fraction of  
the signal (**~3%**)

# A live reference model



Operating reactors

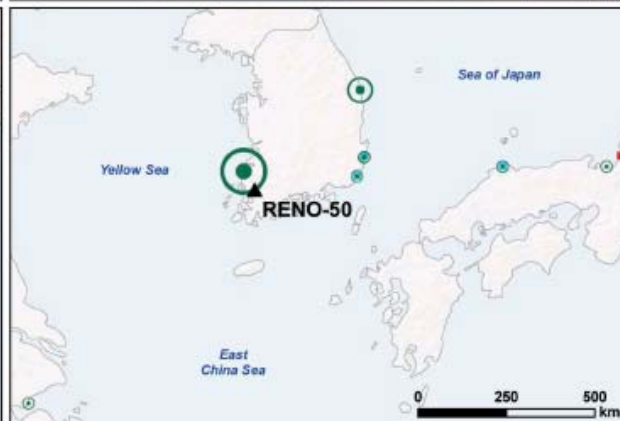
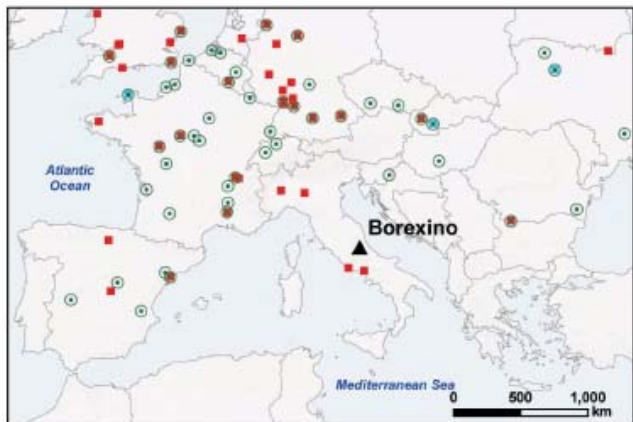


✓ **Borexino:** ~50% of the signal from a  $10^3$  km radius by ~50 reactors. **Single core temporal profile is not relevant.**

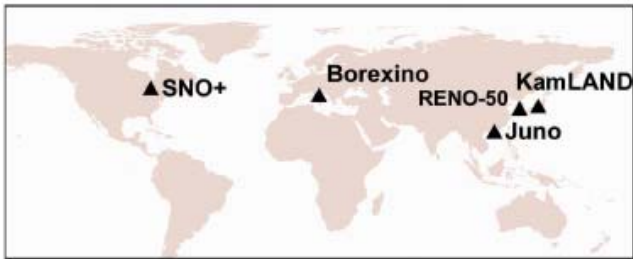
✓ **KamLAND:** in 2013 few Japanese cores give high signal contribution, but in **2014 all powerd off.**

✓ **JUNO:** in 2013 **Guangdong** and **Ling Ao** gave 90% of the signal. After **2020** their contribution will be **6%.**

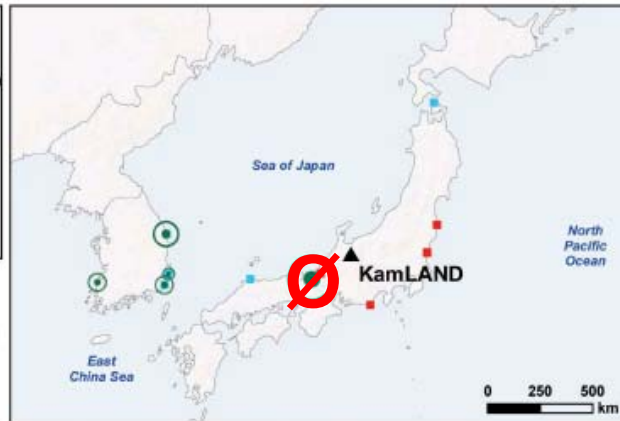
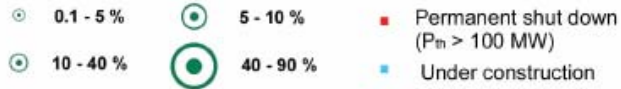
✓ **RENO-50:** **90%** of the signal from close **South Korean** reactors (55% from YongWang and 35% from Ulchin power stations)



# A live reference model



Operating reactors

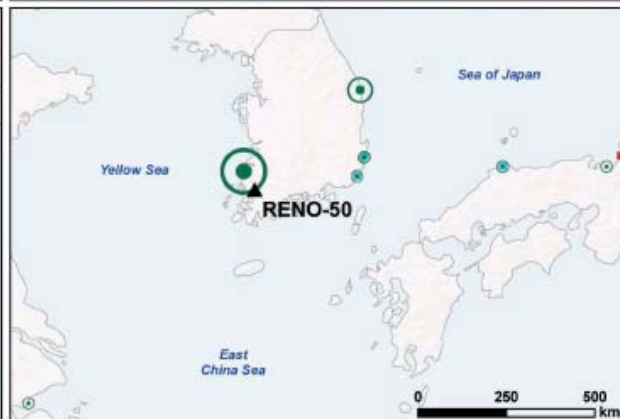
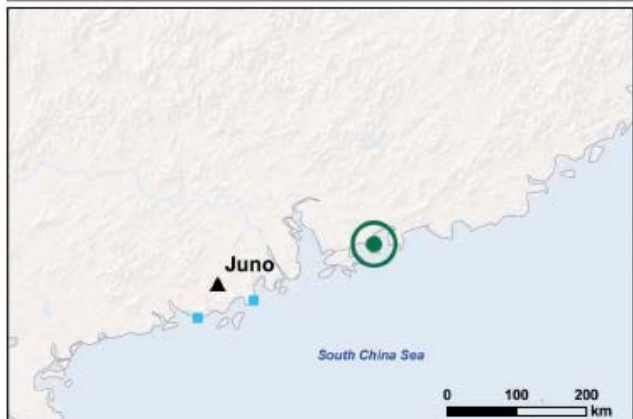
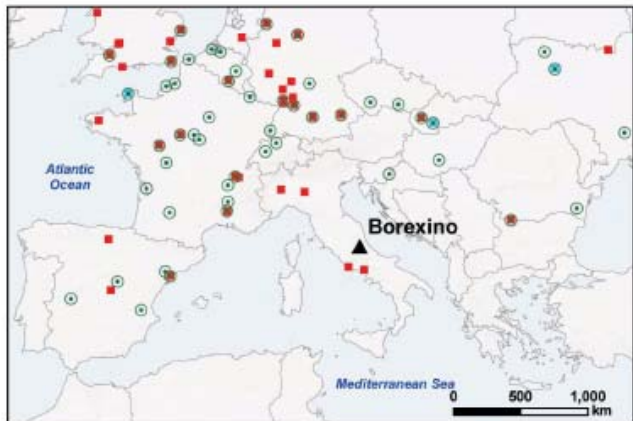


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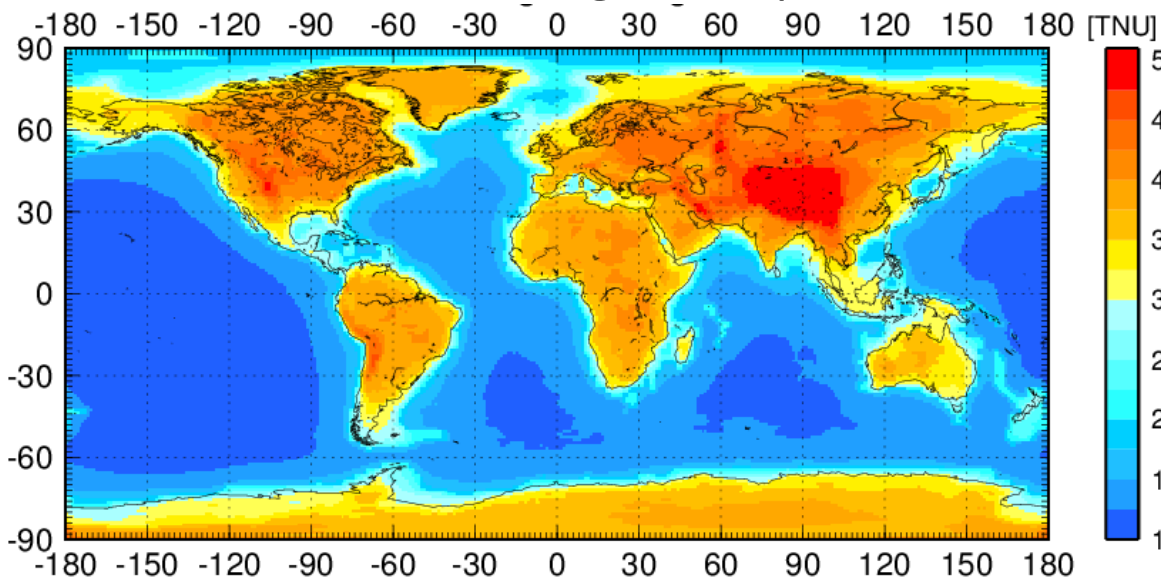
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✓ **RENO-50**: **90%** of the signal from close **South Korean** reactors (55% from YongWang and 35% from Ulchin power stations)



# Geoneutrinos and reactor antineutrinos across the world

Geov signal map

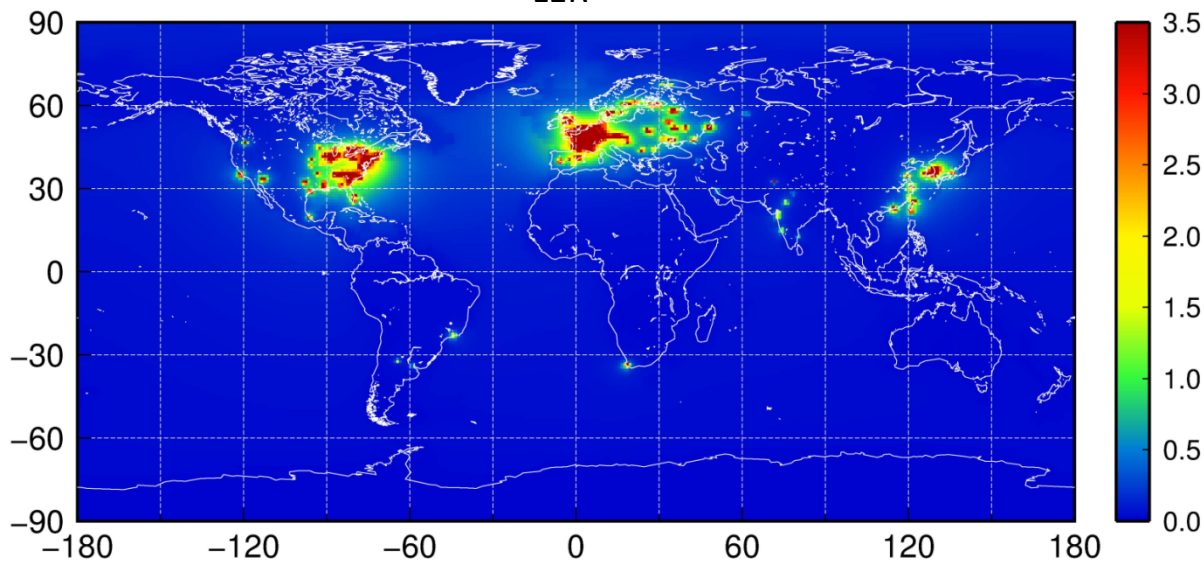


✓ The **geoneutrino signal** is **constant** and it has a **continental distribution**

✓ The **reactor signal** changes in **time** and has a **highly asymmetrical distribution** with respect to the equator

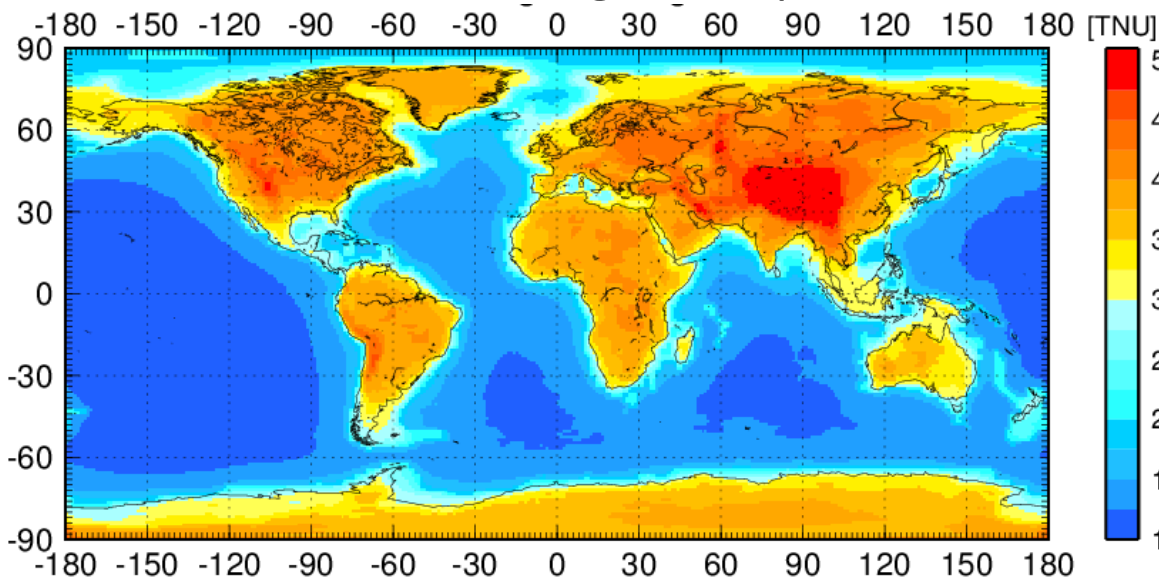
✓ The ratios  $r = R_{\text{LER}}/G$  are **time dependent**

$r = R_{\text{LER}}/G$  map



# Geoneutrinos and reactor antineutrinos across the world

Geov signal map

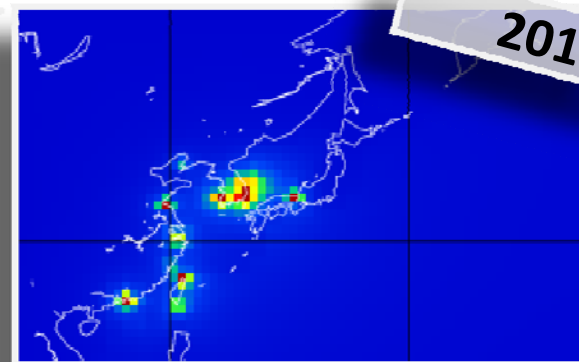
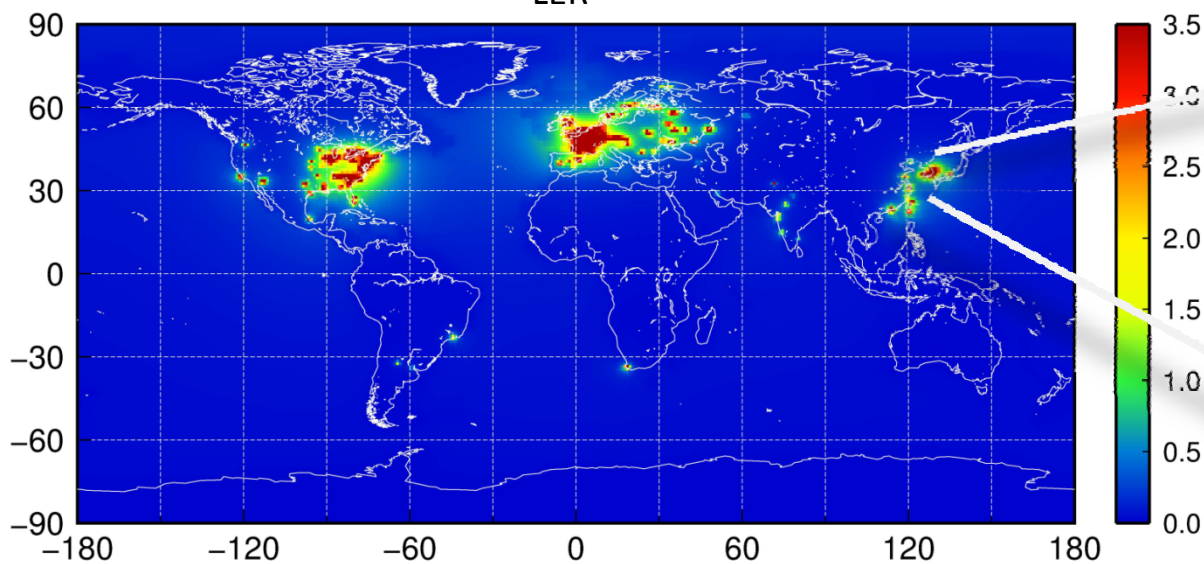


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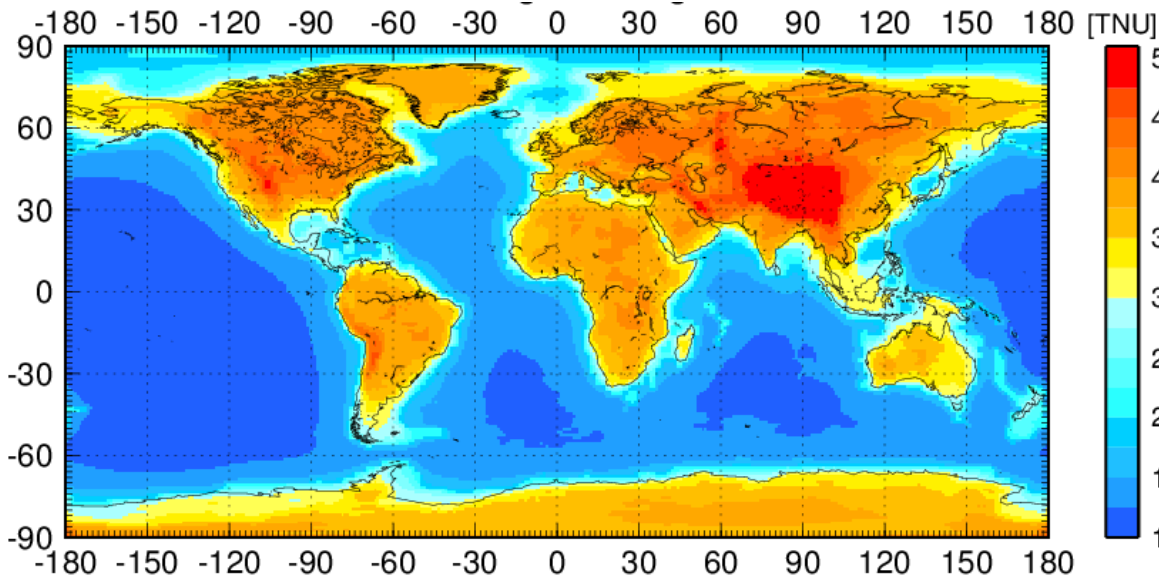
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# Geoneutrinos and reactor antineutrinos across the world

Geov signal map

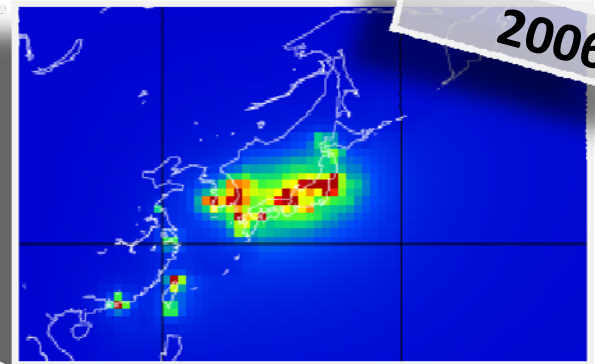
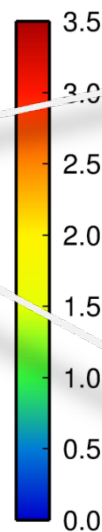
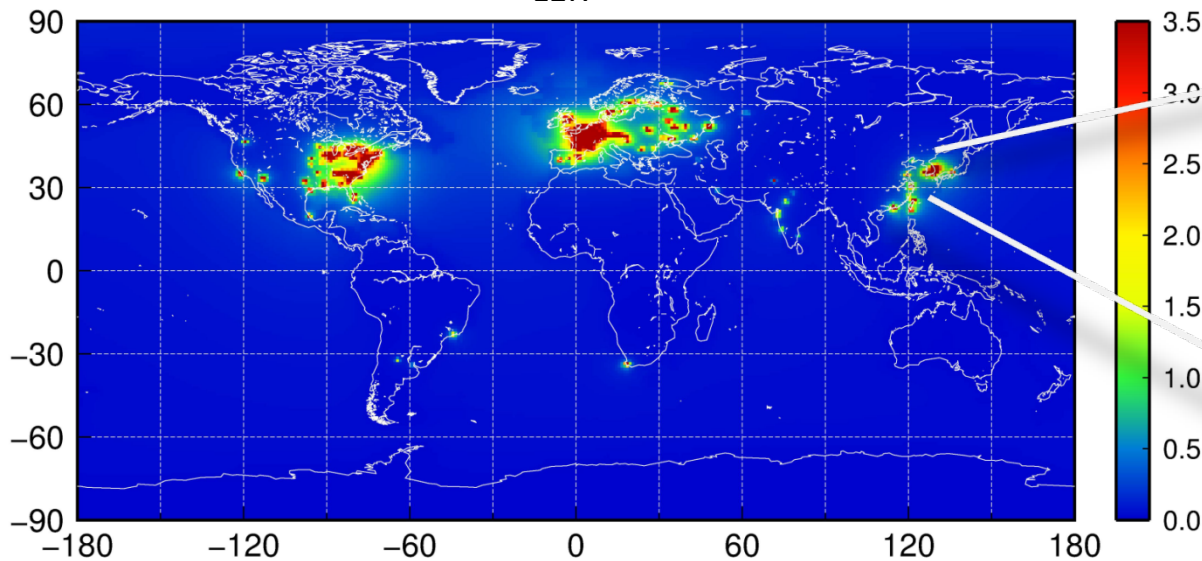


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$r = R_{\text{LER}}/G$  map



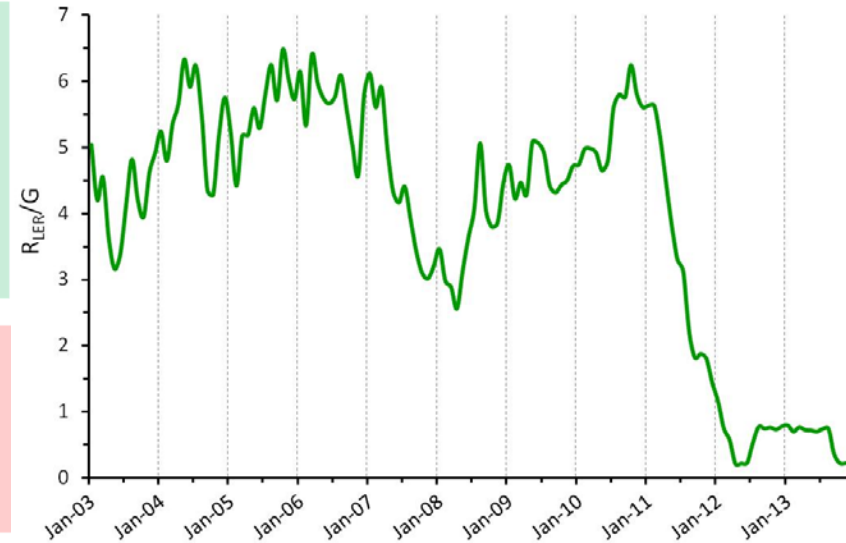
# Conclusions

From [www.fe.infn.it/antineutrino](http://www.fe.infn.it/antineutrino) everybody can freely download a **multitemporal, updated** and **ready-to-use database** for calculating the antineutrino signal from worldwide reactors



A **worldwide reference model for antineutrino from reactors** is a relevant benchmark for geoneutrino science: the profile of  $R_{\text{LER}}/G$  and the relative contribution of each core change in time

From the standard data of IAEA the reactor antineutrino signal at LBL experiments can be studied with a  $1\sigma$  uncertainty of  **$\sim 4\%$**  in the LER



The uncertainty on the signal in the FER is dominated for LBL experiments by  $\sin^2(\vartheta_{12})$ , which provides an uncertainty of  **$\sim 2.2\%$**

**RRs** and **SNFs** give a systematic enhancement of the commercial reactor signal: the signal increase due to **RRs** is  **$< 0.2\%$** , while **SNFs** stored in water pools increase the antineutrino event rate in the **LER** of  **$\sim 2.4\%$**



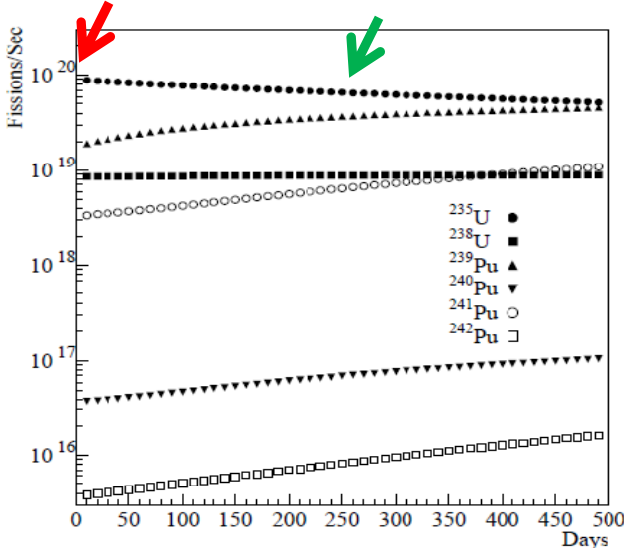
# Fission fractions and power fractions collection

$$p_i = \frac{f_i Q_i}{\sum_{i=1}^4 f_i Q_i}$$

$p_i$  is the fraction of  $P_{th}$  produced by the fission of the  $i$ th isotope

$$\frac{dN_i^{fiss}}{dt} = LF \cdot P_{th} \frac{p_i}{Q_i}$$

Extensive collection of different sets of fission/power fractions from literature



Reactor Classes	Fractions	<sup>235</sup> U	<sup>239</sup> Pu	<sup>241</sup> Pu	<sup>238</sup> U	Reference	
PWR BWR LWGR GCR	$f_i$	0.538	0.328	0.056	0.078	G. Mention et al. (2011)	
		0.614	0.274	0.038	0.074		
		0.620	0.274	0.042	0.074		
		0.584	0.298	0.050	0.068		
		0.543	0.329	0.058	0.070		
		0.607	0.277	0.042	0.074		
		0.603	0.276	0.045	0.076		
		0.606	0.277	0.043	0.074		
		0.557	0.313	0.054	0.076		
		0.606	0.274	0.046	0.074		
		0.488	0.359	0.067	0.087		Y. Abe et al. (2012)
		0.580	0.292	0.054	0.074		Z. Djurcic et al. (2009)
		0.544	0.318	0.063	0.075		
		0.577	0.292	0.057	0.074		V. I. Kopeikin et al. (2004)
		0.590	0.290	0.050	0.070		
		0.570	0.295	0.057	0.078		S. Abe et al. (2008)
		0.568	0.297	0.057	0.078		K. Eguchi et al. (2003)
		0.563	0.301	0.057	0.079		T. Araki et al. (2005)
		0.650	0.240	0.040	0.070		V. I. Kopeikin (2012)
	0.560	0.310	0.060	0.070			
0.480	0.370	0.080	0.070				
	$p_i$	0.560	0.300	0.080	0.060	G. Bellini et al. (2010)	
MOX	$p_i$	0.000	0.708	0.212	0.081	G. Bellini et al. (2010)	
PHWR	$p_i$	0.543	0.411	0.024	0.022	G. Bellini et al. (2013)	

The values reported in the table depend on **enrichment** and **burn up stage** of the core

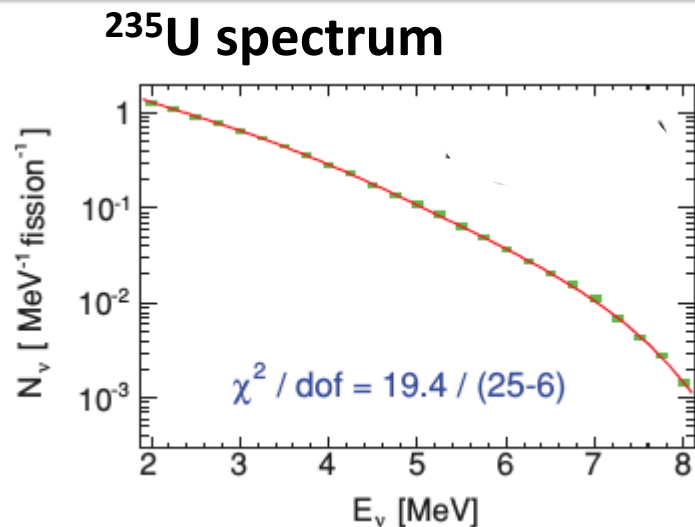
Enriched Uranium

Mixed Oxide Fuel

Natural Uranium

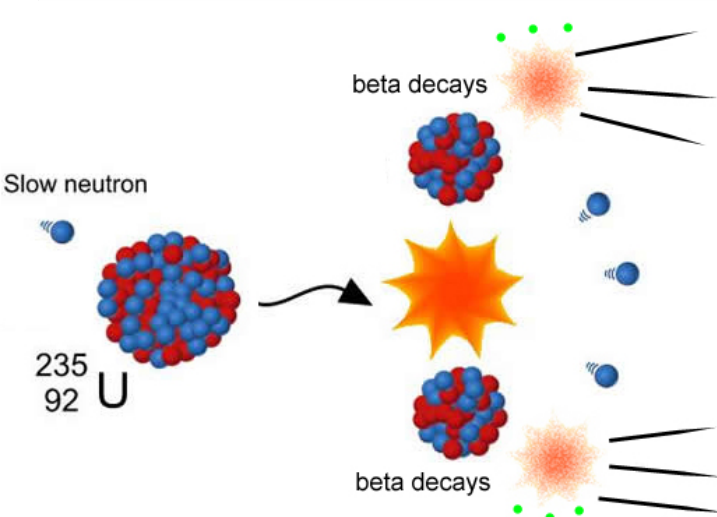
# Reactor spectra: impact on antineutrino signals

	Reactor spectra model	$R_{\text{LER}}$ [TNU]		
		Borexino	KamLAND	SNO+
1989	P. Vogel	$22.1^{+0.6}_{-0.5}$	$18.3^{+0.6}_{-1.0}$	$47.2^{+1.7}_{-1.4}$
2004	P. Huber + $^{238}\text{U}$ from Mueller	$22.0^{+0.6}_{-0.5}$	$18.3^{+0.6}_{-1.0}$	$47.1^{+1.7}_{-1.4}$
2011	P. Huber et al. + $^{238}\text{U}$ from Mueller	$21.7^{+0.6}_{-0.5}$	$18.0^{+0.6}_{-1.0}$	$46.3^{+1.7}_{-1.4}$
2011	Mueller et al.	$21.6^{+0.5}_{-0.6}$	$17.9^{+0.6}_{-1.0}$	$46.0^{+1.7}_{-1.4}$



- **Recent strong effort** in improving the determination of reactor antineutrino spectra with different methods (ab-initio, conversion, mixed)
- Using different spectra has the **same effect** for **all sites**
- Different spectra can give a max signal variation of **~2.5%**, undistinguishable with respect to  **$1\sigma$**  uncertainty
- **Signal variability** is **reduced** between **recent parameterizations** (improvements in nuclear database inputs and in corrections to  $\beta$  shape)

# Reactor thermal power and fission fractions



~35% of commercial reactors has a  $P_{th} \sim 3\text{GW}$

$^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$  give > 99% of the fissions

A single fission process involves :

- the emission of ~ 6 antineutrinos
- ~ 2 antineutrinos above IBD threshold
- the production of  $\langle Q \rangle \sim 200\text{ MeV}$

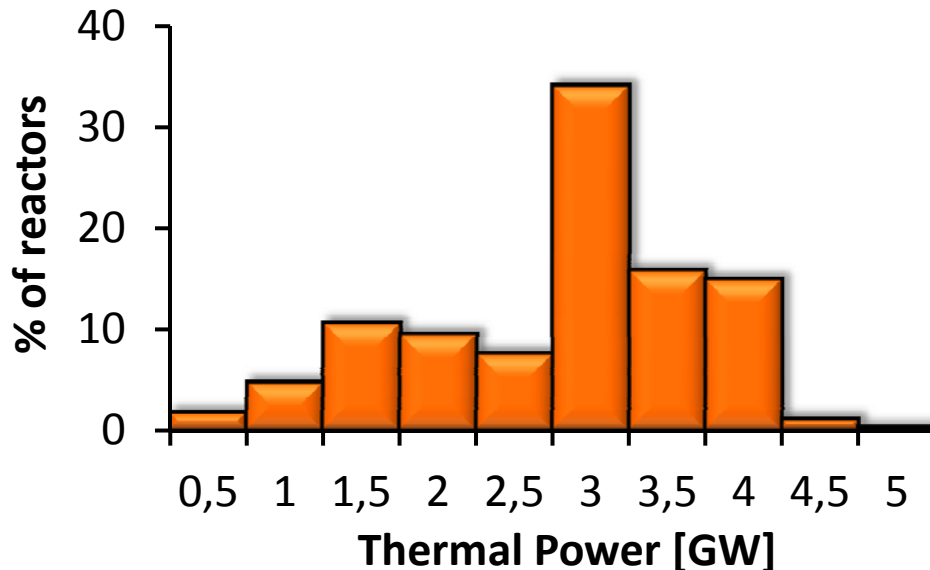
$$P_{th} = R \sum_{i=1}^4 f_i Q_i$$

$R$  = total fission rate [fissions/sec]

$f_i$  = relative fission yield, i.e the fraction of fissions produced by the  $i$ th isotope

$Q_i$  = energy released in one fission of the  $i$ th isotope [MeV/fission]

Fissile isotope	$Q_i$ [MeV/fission]
$^{235}\text{U}$	$202.36 \pm 0.26$
$^{238}\text{U}$	$205.99 \pm 0.52$
$^{239}\text{Pu}$	$211.12 \pm 0.34$
$^{241}\text{Pu}$	$214.26 \pm 0.33$



# Thermal power uncertainty

The total signal is:

$$S = \epsilon N_p \tau \sum_{r=1}^{N_{react}} \frac{P_r}{4\pi L_r^2} \langle LF \rangle_r \times \int dE_{\bar{\nu}_e} \sum_{i=1}^4 \frac{p_i}{Q_i} \phi_i(E_{\bar{\nu}_e}) \sigma(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}, \hat{\theta}, L_r) \quad (1)$$

which can be rewritten as:

$$S = \sum_{r=1}^{N_{react}} P_r A_r \quad (2)$$

where  $P_r$  is the thermal power of the r-core with uncertainty  $\Delta P_r$  and  $A_r$  all the rest.

The relative error on the signal S is:

$$\frac{\Delta S}{S} = \frac{\sqrt{\sum_r (\Delta P_r A_r)^2}}{S} \quad (3)$$

$$= \sqrt{\sum_r \left( \frac{A_r P_r}{S} \frac{\Delta P_r}{P_r} \right)^2} \quad (4)$$

$$= \sqrt{\sum_r (C_r)^2 \left( \frac{\Delta P_r}{P_r} \right)^2} \quad (5)$$

where  $C_r = (A_r P_r)/S$  is relative contribution of the r-core to the total signal.

# Spent Nuclear Fuel contribution

0.6% increase in unoscillated IBD event rate in the FER for  $M_{SNF} = M_{reactor}^*$

$$\begin{aligned}\tau_{1/2}^{SNF} &= \sum_{i=^{144}\text{Ce}, ^{106}\text{Ru}, ^{90}\text{Sr}} k_i \tau_{1/2}^i, \\ k_i &= \sum_{l=^{235}\text{U}, ^{239}\text{Pu}} f_l \bar{Y}_l^i,\end{aligned}\quad (14)$$

where  $\tau_{1/2}^i$  is the half-life of the  $i$ th SNF species,  $f_l$  is the fission fraction (normalized to unity) for the  $l$ th fissioning isotope, and  $\bar{Y}_l^i$  is the production yield, with the normalization constraint  $\sum_l \bar{Y}_l^i = 1$ .

Mean life of SNF  $\tau_{SNF} = \mathbf{2.8 \text{ yr}}$  on the base of  $^{235}\text{U}$  e  $^{239}\text{Pu}$  normalized yields

Enhancement of the unoscillated IBD event rate due to the SNFs in the FER

$$\Delta N_{IBD}^{FER} = \sum_{n=0}^T \frac{1}{3} * 0.6 * \exp\left(-\frac{n}{\tau_{SNF}}\right)$$

For a storage time  $T = 10 \text{ yr}$

$$\Delta N_{IBD}^{LER} = 2.4\%$$