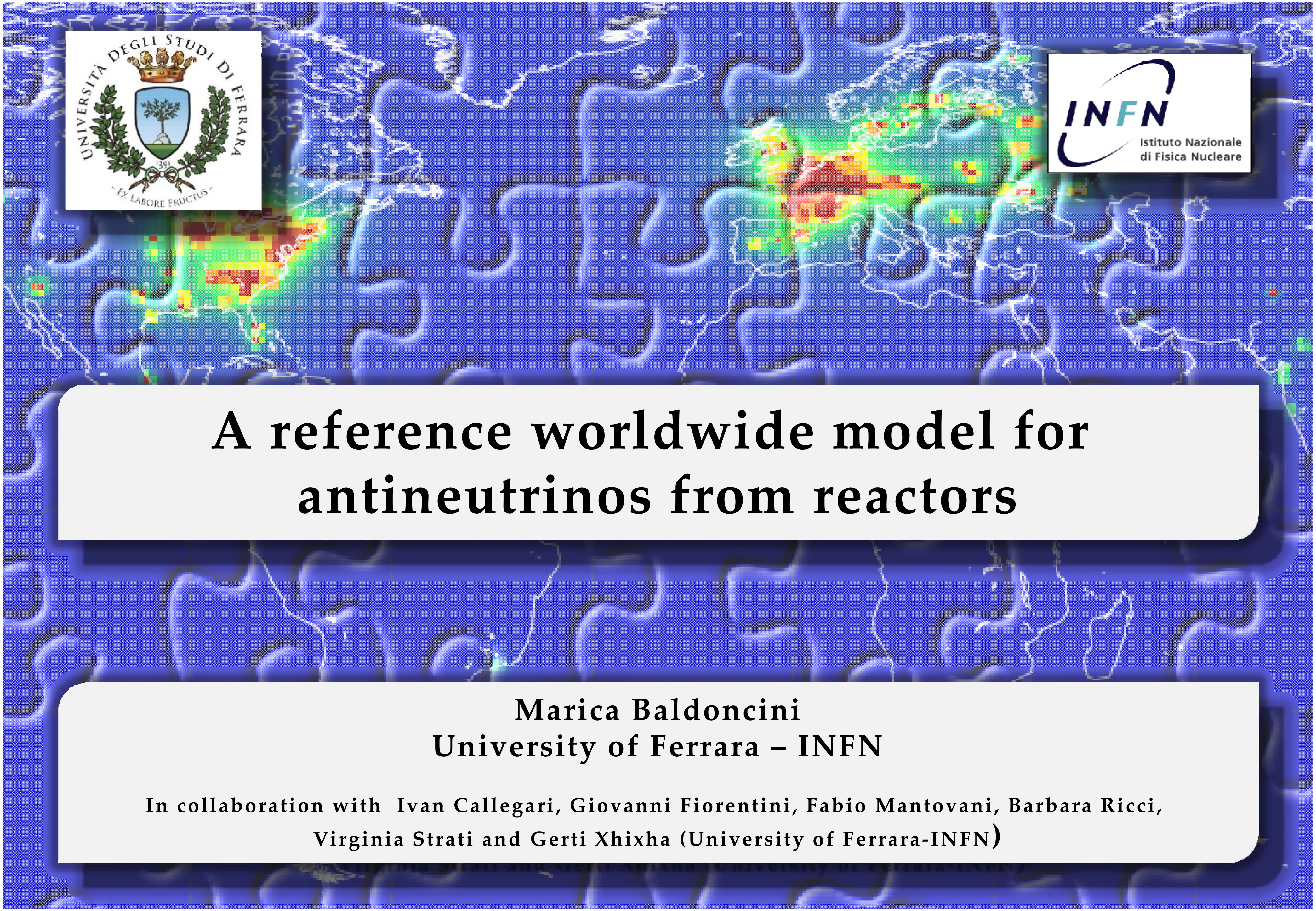

A reference worldwide model for antineutrinos from reactors

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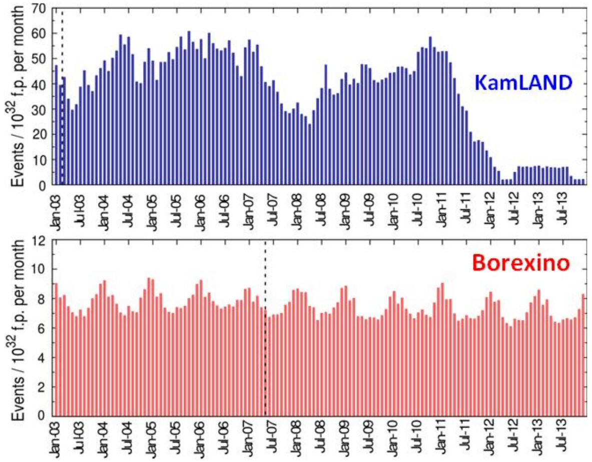
University of Ferrara – INFN

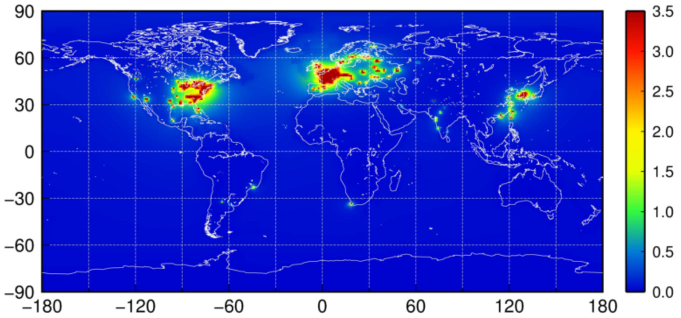
In collaboration with Ivan Callegari, Giovanni Fiorentini, Fabio Mantovani, Barbara Ricci,
Virginia Strati and Gerti Xhixha (University of Ferrara-INFN)

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, research reactors and reactor spectra
- Signal distance and temporal profiles
- Worldwide map of reactor signals
- Conclusions

Physical Review D
particles, fields, gravitation, and cosmology
arXiv:1411.6475v2

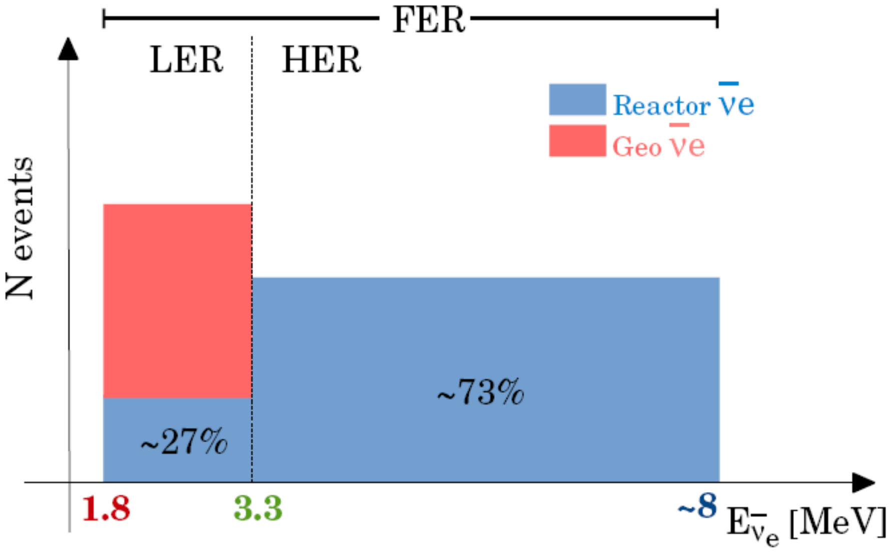




Reactor antineutrinos: a fundamental background for geoneutrino measurements

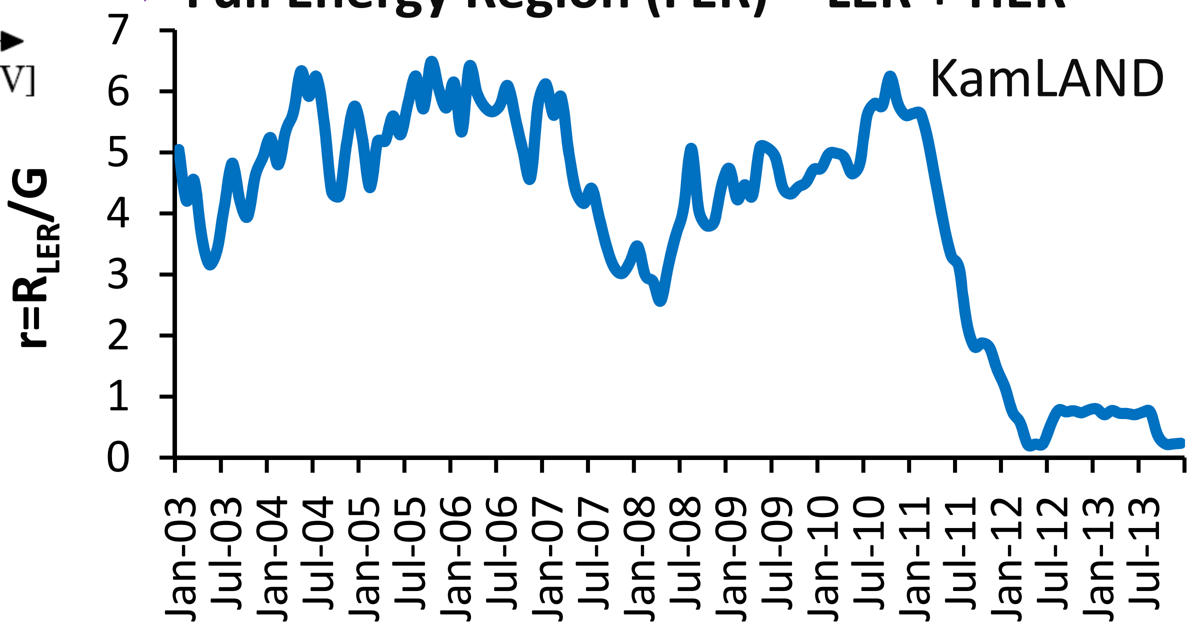
Inverse Beta Decay (**IBD**) Reaction

$$\overline{\nu}_e + p \rightarrow e^+ + n$$ ***- 1.806 MeV***

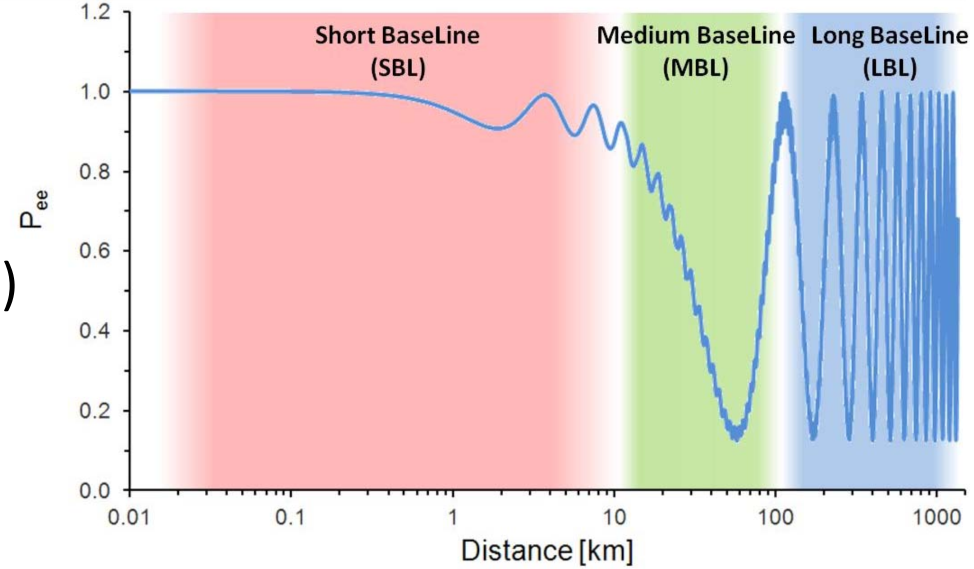


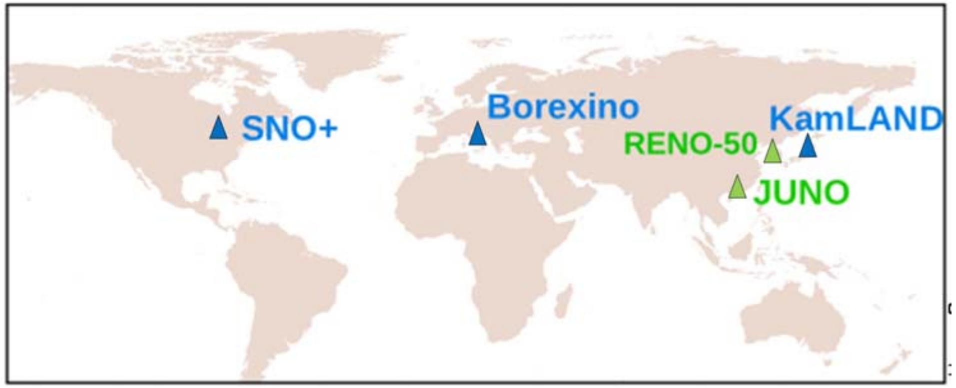
✓The ratio **r** between the reactor signal in the LER (**R**$_{\mathbf{LER}}$) and the geoneutrino signal (**G**) **changes in time** according to the different reactor operational conditions

- ✓**Low Energy Region (LER):** energy range starting at ***1.806 MeV*** (IBD threshold) and ending at ***3.3 MeV*** (end point of ^{214}Bi spectrum)
- ✓ **High Energy Region (HER)**: energy range starting at ***3.3 MeV*** and ending at ***8 MeV*** (end point of reactor spectrum)
- ✓ **Full Energy Region (FER) = LER + HER**



Why a reference model for antineutrinos from reactors?





✓ Nuclear power plants are the strongest man made antineutrino sources (**$L \sim 2 \times 10^{20}$ ν/sec** for **1 GW** thermal power)

✓ 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)**

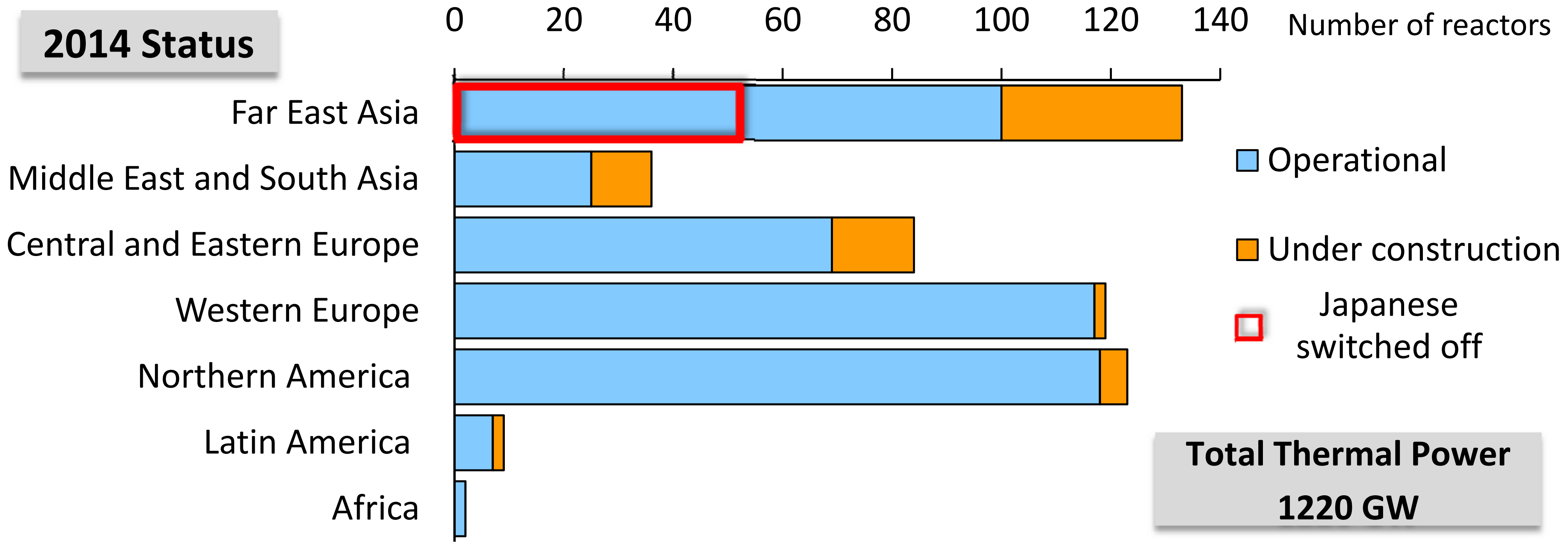
Goal of the work:

✓ provide on the base of reactors official data a **worldwide reference model required** for estimating the reactor signal for **LBL experiments**

✓ estimating **signal uncertainty** starting from the uncertainties on individual input quantities

Nuclear power plants in the world: geographical distribution

2014 Status



Total Thermal Power

1220 GW

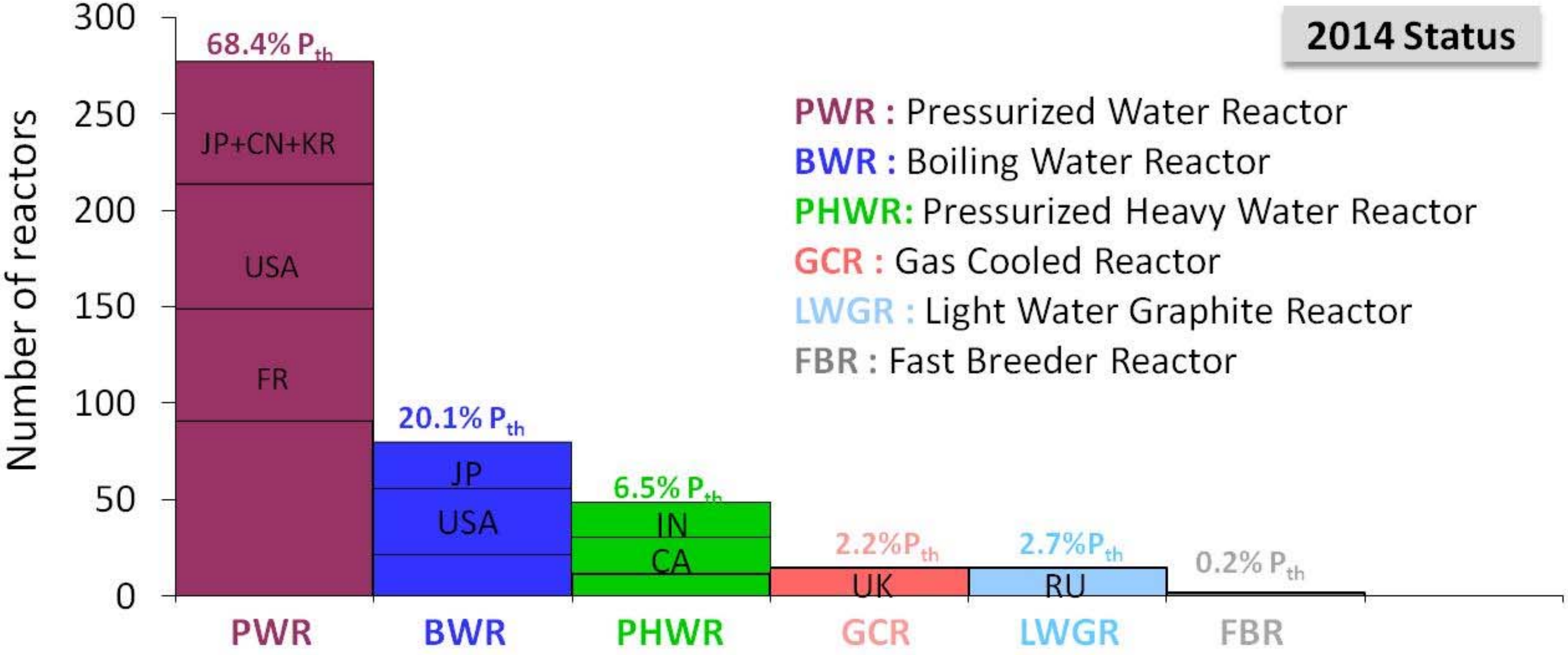
438 NUCLEAR POWER REACTORS IN OPERATION (**OR**)
ALL (48) OPERATIONAL JAPANESE CORES POWERED OFF FOR THE ENTIRE 2014
68 NUCLEAR POWER REACTORS UNDER CONSTRUCTION

✓Sharp **asymmetric geographical distribution**: only **2%** of ORs in **Southern Emisphere**

✓**Far East Asia**, **Western Europe** and **North America** host **25%** of the total ORs each

✓**40%** of **under construction** reactors in the world in **China** (~ 30 GW_{el})

Nuclear power plants in the world: reactor type distribution



The reactor technologies are not so relevant for studying antineutrinos as the **different fuel types**:

✓**PWR, BWR, LWGR** and **GCR**: **enriched uranium** with different enrichment levels (^{235}U ~ 2.2% for GCR and LWGR up to 5% for PWR and BWR)

✓**PHWR** (CANDU): **natural uranium** (^{235}U ~ 0.7%)

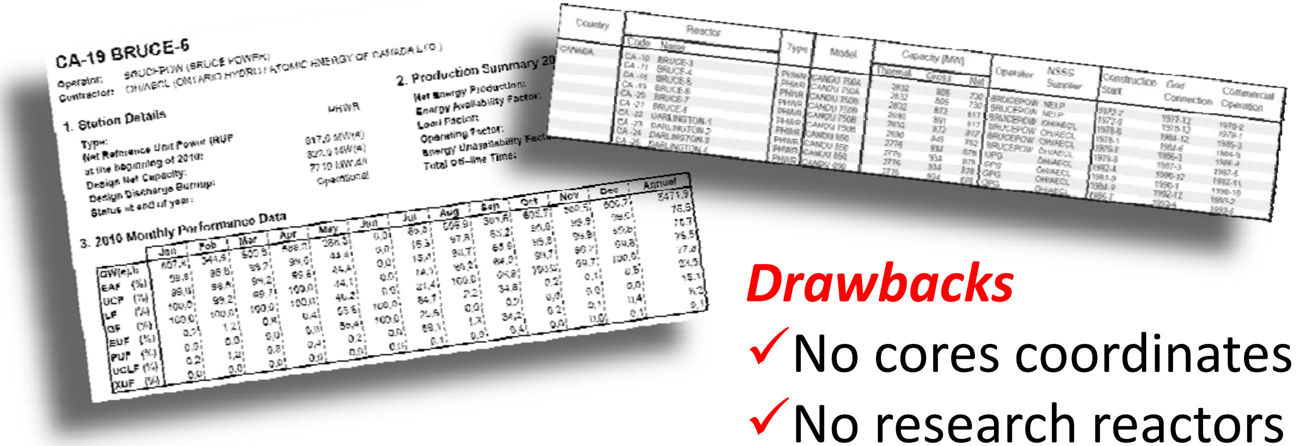
✓Few tens of reactors use Mixed Oxide fuels (**MOX**), a mixture of depleted U and Pu

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 [%]



CA-19 BRUCE-6

1. Station Details

2. Production Summary 20

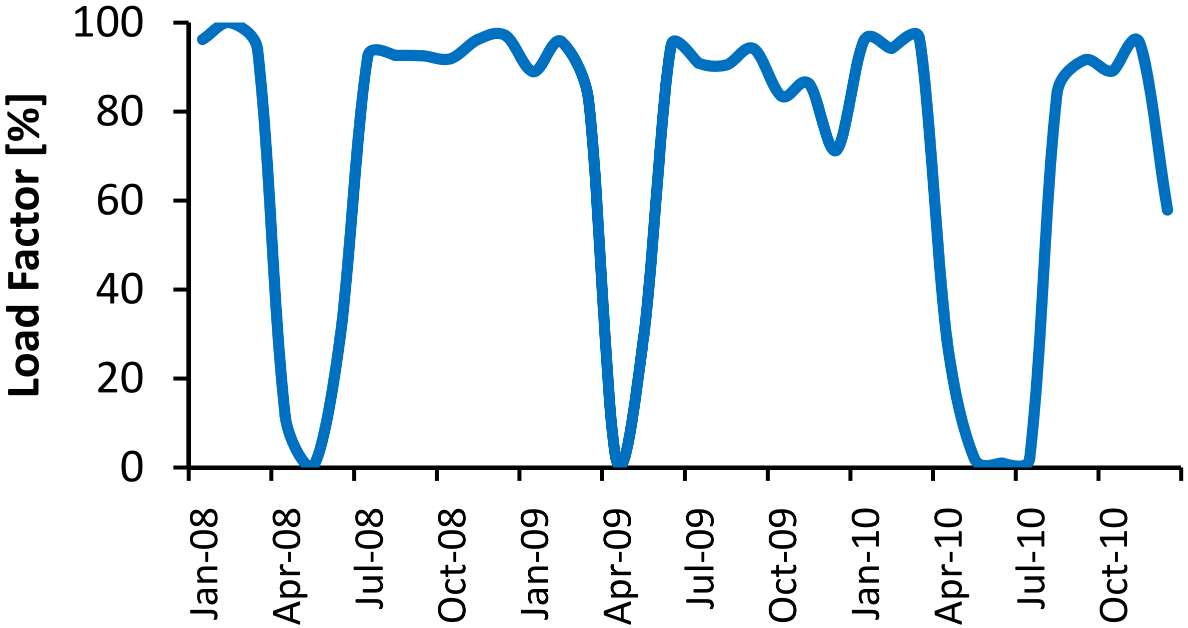
3. 2010 Monthly Performance Data

Country	Reactor Code	Reactor Name	Type	Model	Capacity (MW) Thermal	Gross	Net	Operator	NSSS Supplier	Construction Start	Grid Connection	Commercial Operation

Drawbacks

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

Typical duty cycle



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

EG = net electrical energy produced

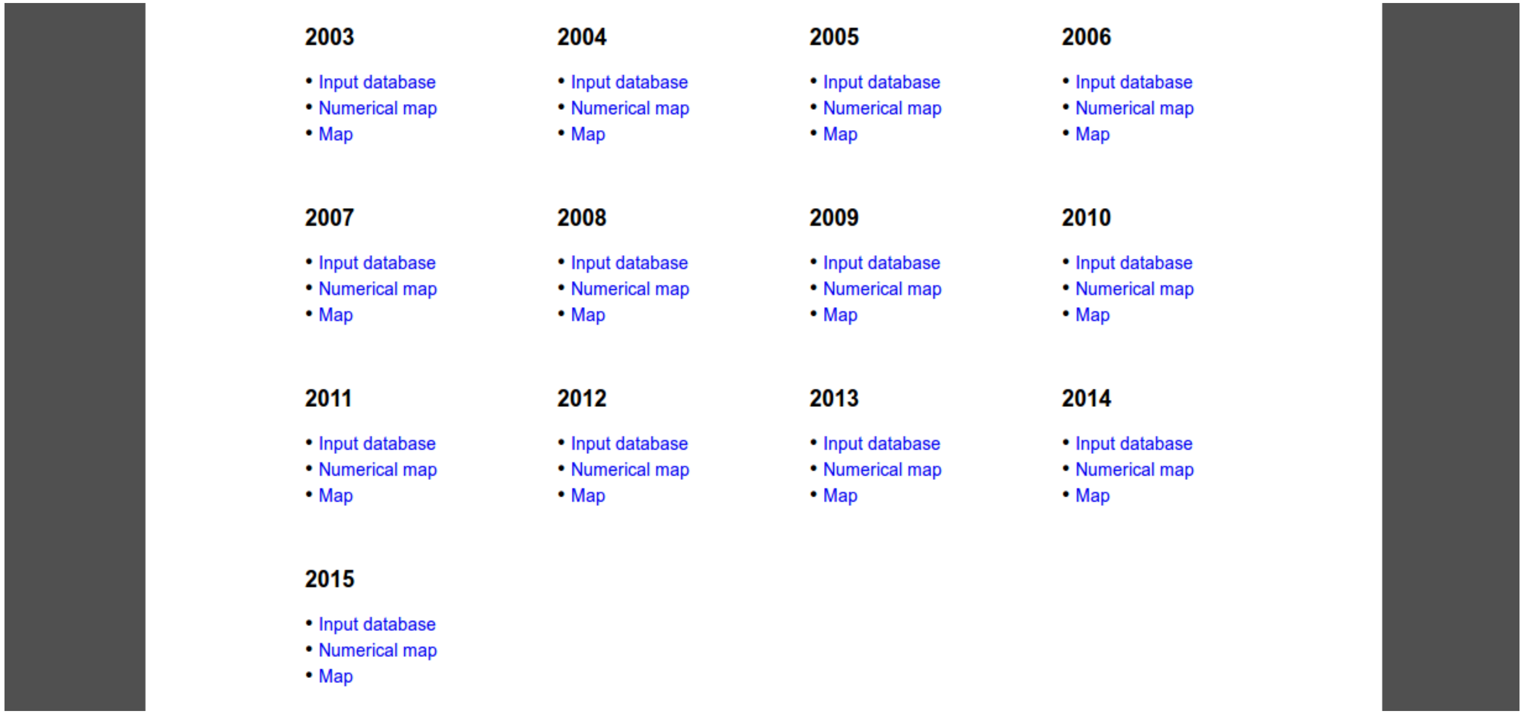
REG = reference energy generation

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

* https://www.iaea.org/pris/

Nuclear reactors database at www.fe.infn.it/antineutrino

The web page **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

2004

- Input database
- Numerical map
- Map

2005

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2006

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2007

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2008

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2010

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2011

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2012

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2013

- Input database
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2014

- Input database
- Numerical map
- Map

2015

- Input database
- Numerical map
- Map

Nuclear reactors database at www.fe.infn.it/antineutrino

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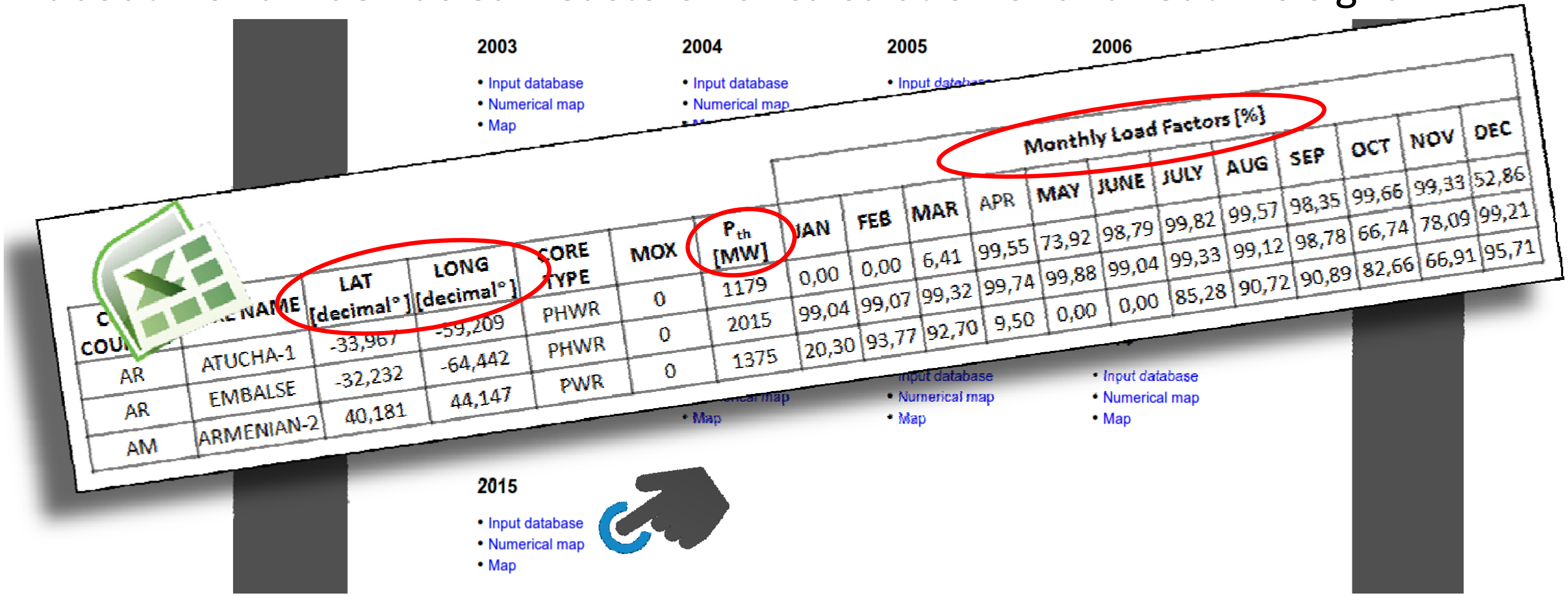


2003

- Input database
- Numerical map
- Map

2004

- Input database
- Numerical map

2005

- Input database

2006

C COU	NAME	LAT [decimal°]	LONG [decimal°]	CORE TYPE	MOX	P_{th} [MW]	Monthly Load Factors [%]											
							JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
AR	ATUCHA-1	-33,967	-59,209	PHWR	0	1179	0,00	0,00	6,41	99,55	73,92	98,79	99,82	99,57	98,35	99,66	99,33	52,86
AR	EMBALSE	-32,232	-64,442	PHWR	0	2015	99,04	99,07	99,32	99,74	99,88	99,04	99,33	99,12	98,78	66,74	78,09	99,21
AM	ARMENIAN-2	40,181	44,147	PWR	0	1375	20,30	93,77	92,70	9,50	0,00	0,00	85,28	90,72	90,89	82,66	66,91	95,71

- Input database
- Numerical map
- Map

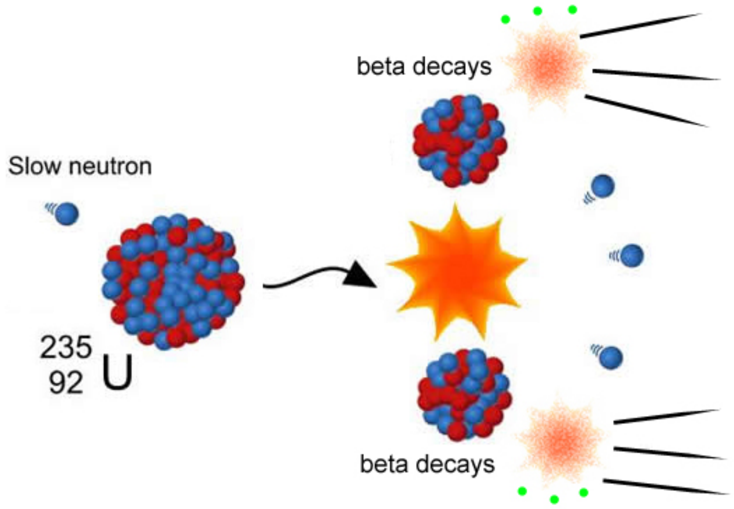
- Input database
- Numerical map
- Map

2015

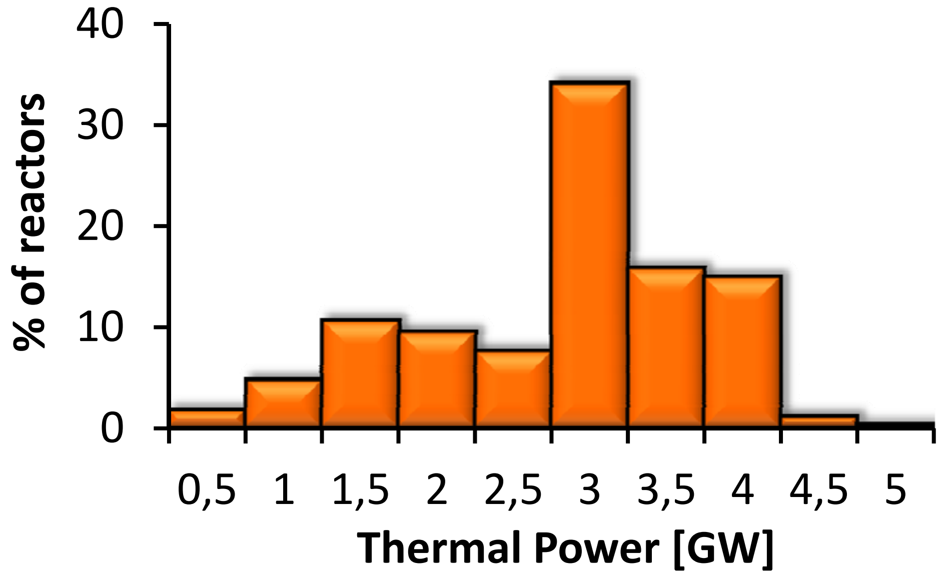
- Input database
- Numerical map
- Map

- ✓ **Global**: performance data of **all reactors in the world**
- ✓ **Monthly Load Factors** (%)
- ✓ **Public, official** and **free**
- ✓ **Latitude** and **longitude** of reactors
- ✓ **Multitemporal**: time lapse of **12 years** (2003 – 2015)
- ✓ **Direct implementation** thanks to standard file (ASCII, Excel)

Reactor thermal power and fission fractions



~35% of commercial reactors has a **P_{th} ~ 3GW**



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

A single fission process involves :

- the emission of **~ 6 antineutrinos**
- **~ 2 antineutrinos** above IBD threshold
- the production of **<Q> ~ 200 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 *ith* isotope

Q_i **=energy released in one fission** of the *ith* isotope [MeV/fission]

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

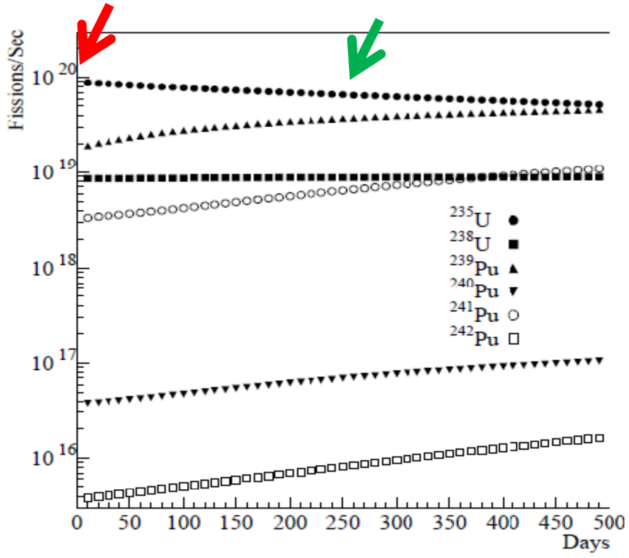
Fission fractions and power fractions collection

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

p_i is the **fraction of P_{th}** produced by the fission of the *ith* 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



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

Reactor Classes	Fractions	^{235}U	^{239}Pu	^{241}Pu	^{238}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	
		0.590	0.290	0.050	0.070	V. I. Kopeikin et al. (2004)
		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	0.022	0.024	G. Bellini et al. (2013)

Enriched Uranium

Mixed Oxide Fuel

Natural Uranium

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

- ◆ ε = 100% efficiency
- ◆ τ = 1 year
- ◆ $N_p = 10^{32}$ free protons

(~ 1kton liquid scintillator mass)

ν PHYSICS

- ◆ P_{ee} = ν_e oscillation survival probability
- ◆ $\sigma_{IBD}(E)$ = IBD cross section

$\bar{\nu}_e + p \rightarrow e^+ + n$ (E_{th} = 1.806 MeV)

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

[1 TNU = 1 event / 10^{32} free protons /year]

$i = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$

REACTOR

- ◆ d_k = reactor distance
- ◆ P_k = thermal power
- ◆ *LF* = Load Factor
- ◆ p_k = power fraction

NUCLEAR

- ◆ Q_i = energy released per fission
- ◆ λ_i = reactor antineutrino spectrum

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- P_k = thermal power
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NUCLEAR

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- λ_i = reactor antineutrino spectrum

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 ($\delta m^2, sen^2\theta_{12}, sen^2\theta_{13}$)
- IBD cross section (σ_{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***
ν oscillation[1]	δm^2 (eV)^2	Gaussian $1\sigma = 3.4$ %
	$sen^2\theta_{12}$	Gaussian $1\sigma = 5.5$ %
	$sen^2\theta_{13}$	Gaussian $1\sigma = 8.5$ %
Energy per fission[2]	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	f_{235U}	Flat
	f_{238U}	
	f_{239Pu}	
	f_{241Pu}	
Thermal Power	P_{th}	Gaussian $1\sigma = 2$ %
IBD cross section[3]	σ_{IBD}	Gaussian $1\sigma = 0.4$ %

Monte Carlo machinery

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

✓Uncertainty due solely to $\boldsymbol{X_i}$ obtained by **“freezing” all other inputs** sampling

[1] Capozzi et al.. Phys. Rev. D 89. 093018 (2014)

[2] Ma et al.. Phys. Rev. C 88. 014605 (2013)

[3] A. Strumia and F. Vissani. Phys. Lett. B 564. 42 (2003)

Reactor and geoneutrino signal in 6 experimental sites

Experiment	G [TNU]*	R_{LER} [TNU]	$r = R_{LER}/G$	Year
KamLAND	$31.5^{+4.9}_{-4.1}$	$168.5^{+5.7}_{-6.3}$	**5.4**	**2006**
		$18.3^{+0.6}_{-1.0}$	**0.6**	**2013**
		$7.4^{+0.2}_{-0.2}$	**0.2**	**2014**
JUNO	$39.7^{+6.5}_{-5.1}$	$26.0^{+2.2}_{-2.3}$	**0.7**	**2013**
		$354.5^{+44.5}_{-40.6}$	**8.9**	**2020**
Borexino	$40.3^{+7.3}_{-3.8}$	$22.2^{+0.6}_{-0.6}$	**0.6**	**2013**
SNO+	$45.4^{+7.5}_{-6.3}$	$47.8^{+1.7}_{-1.4}$	**1.1**	**2013**
RENO-50	$42.1^{+7.2}_{-5.9}$	$178.4^{+20.8}_{-19.6}$	**4.2**	**2013**
Hanohano	$12.0^{+0.7}_{-0.6}$	$0.9^{+0.02}_{-0.02}$	**0.1**	**2013**

Ohi 3 and Ohi 4 powered off

Yangjiang and Taishan will be powered on in 2020

Long Baseline experiments:
1σ ~ 4% in **LER**

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

Signal uncertainty due to individual inputs

		1σ on signal in FER [%]		
Input quantity		**Borexino**	**KamLAND**	**SNO+**
ν **oscillation**	δm^2 (eV)^2	<0.1	0.9	<0.1
	$sen^2\theta_{12}$	+2.4/-2.2	+2.1/-2.0	+2.4/-2.2
	$sen^2\theta_{13}$	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	σ_{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 σ_{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}Y	10.18 h	2.895	^{93}Zr	$1.61 \cdot 10^{6}$ yr	0.091	6.35	3.79
^{97}Zr	16.75 h	1.916	^{97}Nb	72.1 m	1.277	5.92	5.27
^{112}Pd	21.03 h	0.27	^{112}Ag	3.13 h	3.956	0.013	0.13
^{131m}Te	33.25 h	/	^{131}Te	25.0 m	2.085	0.09	0.20
^{132}Te	3.204 d	0.24	^{132}I	2.295 h	2.141	4.31	5.39
^{140}Ba	12.753 d	1.02	^{140}La	1.679 d	3.762	6.22	5.36
^{144}Ce	284.9 d	0.319	^{144}Pr	17.28 m	2.998	4.58	3.11
^{106}Ru	371.8 d	0.039	^{106}Rh	30.07 s	3.541	0.30	3.24
^{90}Sr	28.79 yr	0.546	^{90}Y	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** (***Ev_e^{max}* > 1.806 MeV** and **$\tau_{1/2}$ > 10h**) produce **spectral distortion** in the **LER**
- The LLIs having τ^{P} ~ yr are called **Spent Nuclear Fuels**

- Off-equilibrium correction to the reference spectra* gives

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

---

*T. A. Mueller et al.. Phys. Rev. C 83. 054615 (2011)

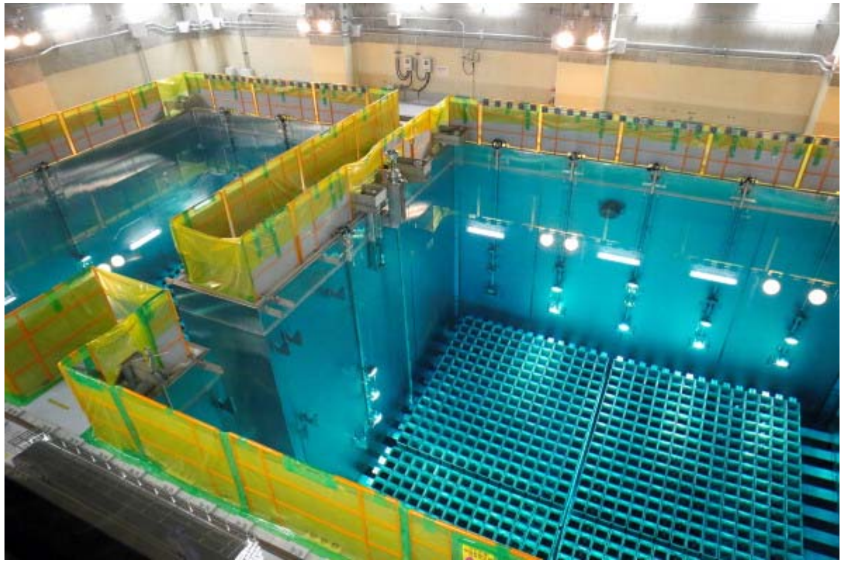
Signal increase due to the Spent Nuclear Fuels (SNFs)

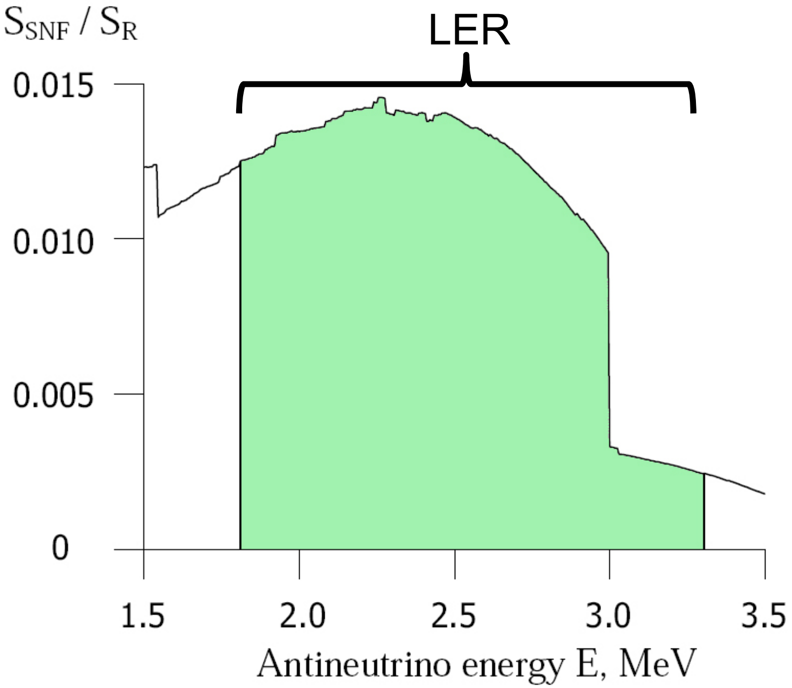
- A maintenance is typically scheduled **once a year** to **substitute 1/3 of the burnt fuel**

- SNFs are typically stored for **10 years** in **water pools** close to the reactor for cooling and shielding

- On the base of ^{235}U e ^{239}Pu normalized yields the mean life of SNFs is ***τ_{SNF}= 2.8 yr***

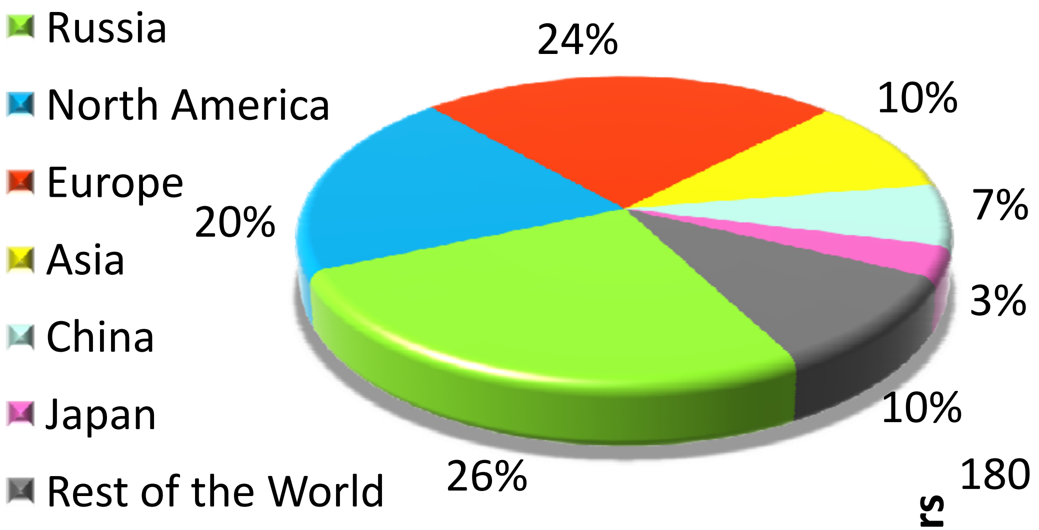
- Assuming that all SNF is accumulated for 10 years in the water pool close to each core the enhancement of the **antineutrino event rate** is **2.4%** in the **LER**





Antineutrino signal from Research Reactors (RRs)*

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

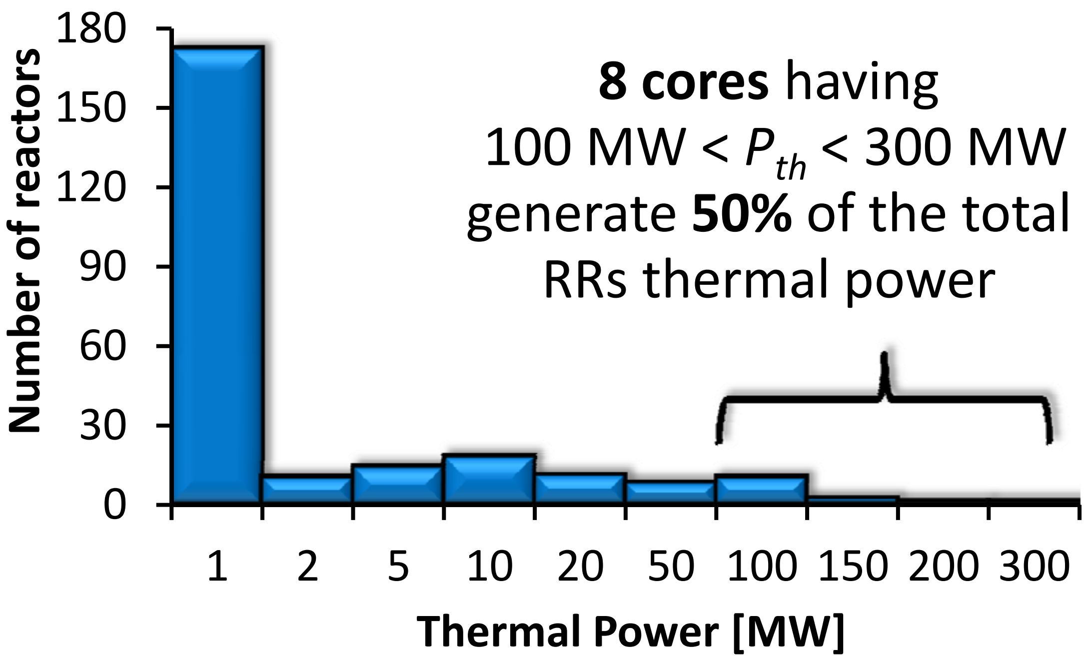


RRs employed for

- *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 RRs thermal power and operating with a 80% annual LF give

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

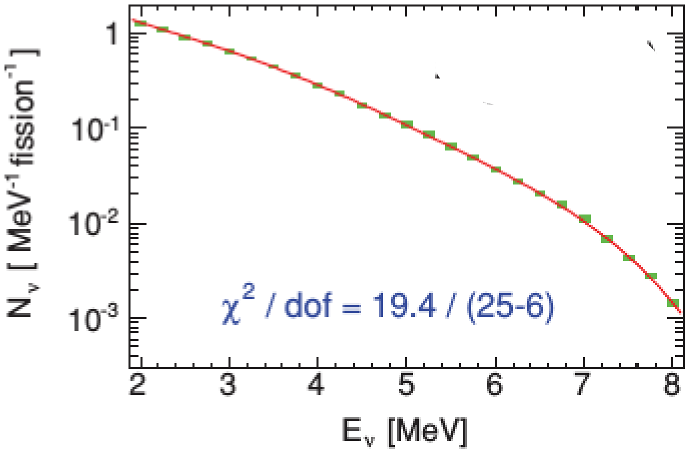


8 cores having 100 MW < P_{th} < 300 MW generate **50%** of the total RRs thermal power

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

Reactor spectra: impact on antineutrino signals

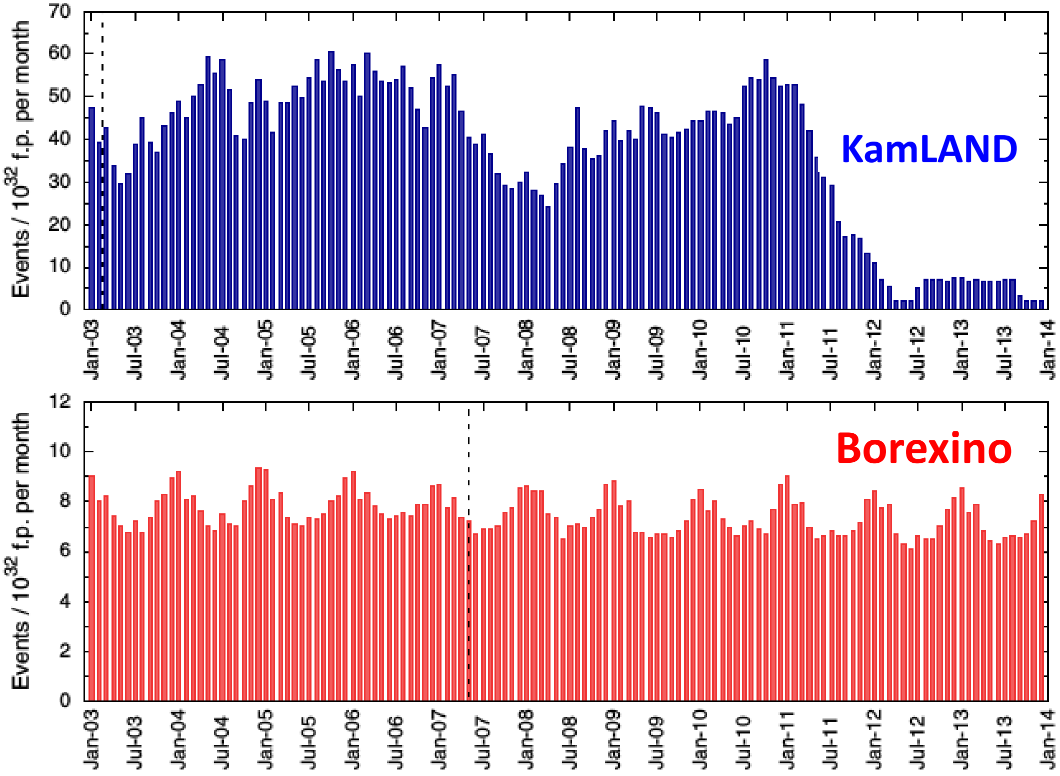
		R_{LER} [TNU]		
	Reactor spectra model	Borexino	KamLAND	SNO+
1989	P. Vogel	$22.1^{+0.6}_{-0.5}$	$18.3^{+0.6}_{-1.0}$	$47.2^{+1.7}_{-1.4}$
2004	P. Huber + ^{238}U from Mueller	$22.0^{+0.6}_{-0.5}$	$18.3^{+0.6}_{-1.0}$	$47.1^{+1.7}_{-1.4}$
2011	P. Huber et al. + ^{238}U from Mueller	$21.7^{+0.6}_{-0.5}$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



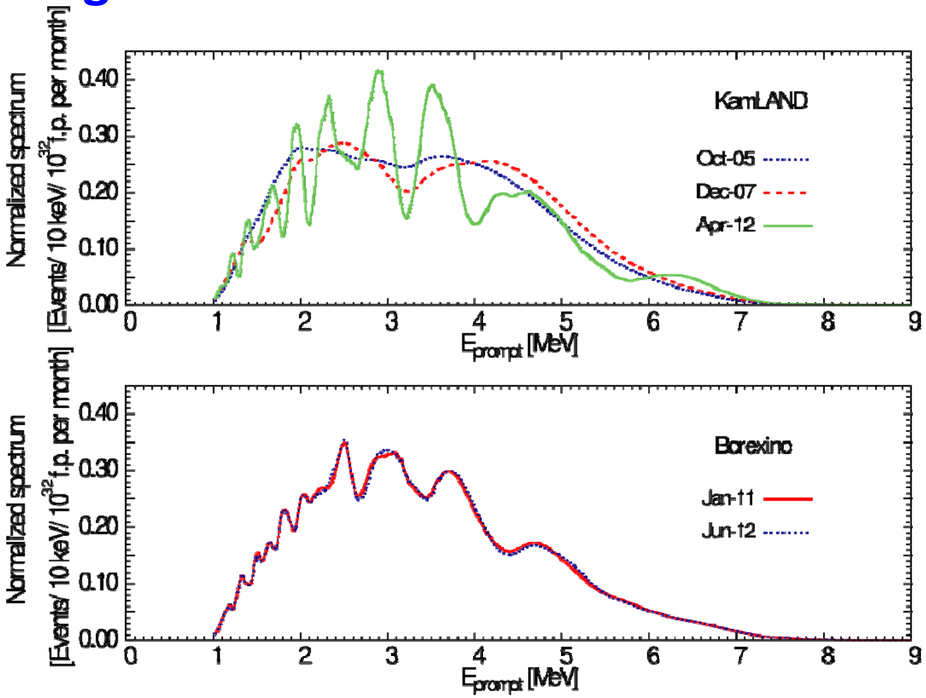
^{235}U spectrum

- **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 **1σ** uncertainty
- **Signal variability** is **reduced** between **recent parameterizations** (improvements in nuclear database inputs and in corrections to β shape)

Borexino and KamLAND signal time profiles

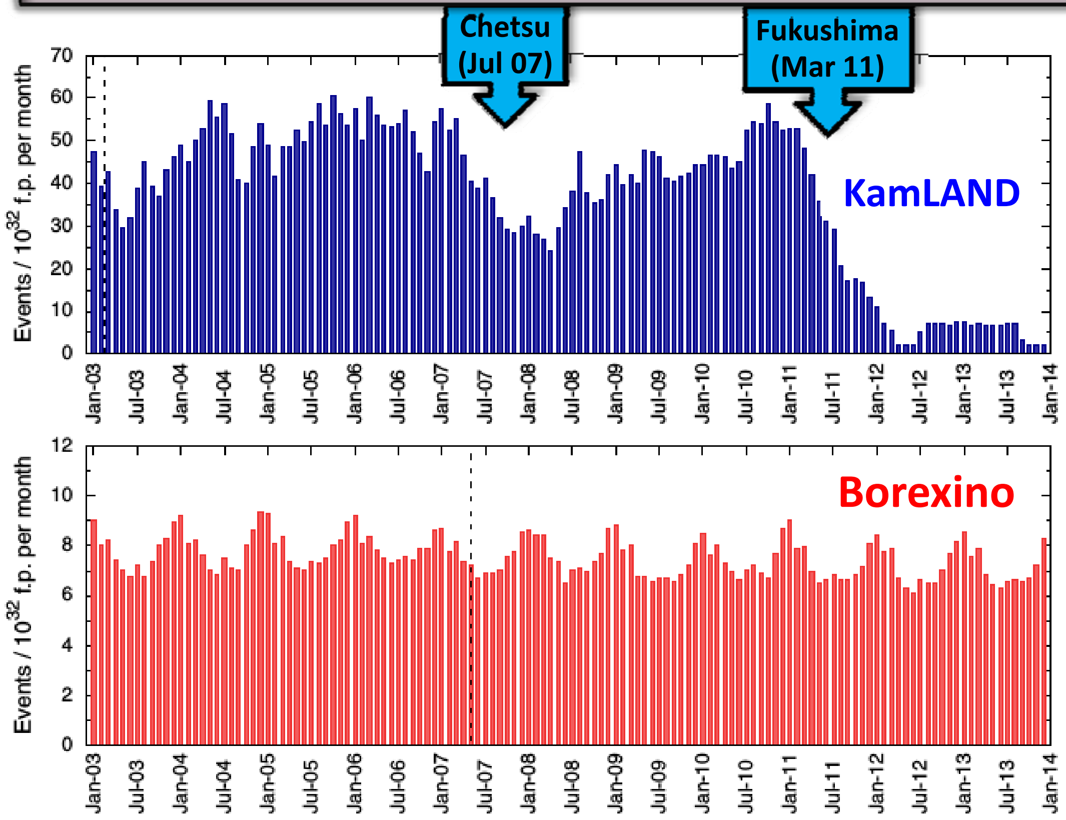


- ✓Signal time profile governed by the **Japanese nuclear industry** operational status
- ✓Shutdown of nuclear power plants concomitant to strong **earthquakes** manifestly visible
- ✓**Sensitive** to **operational conditions** of **single reactors**



- ✓**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 and KamLAND signal time profiles



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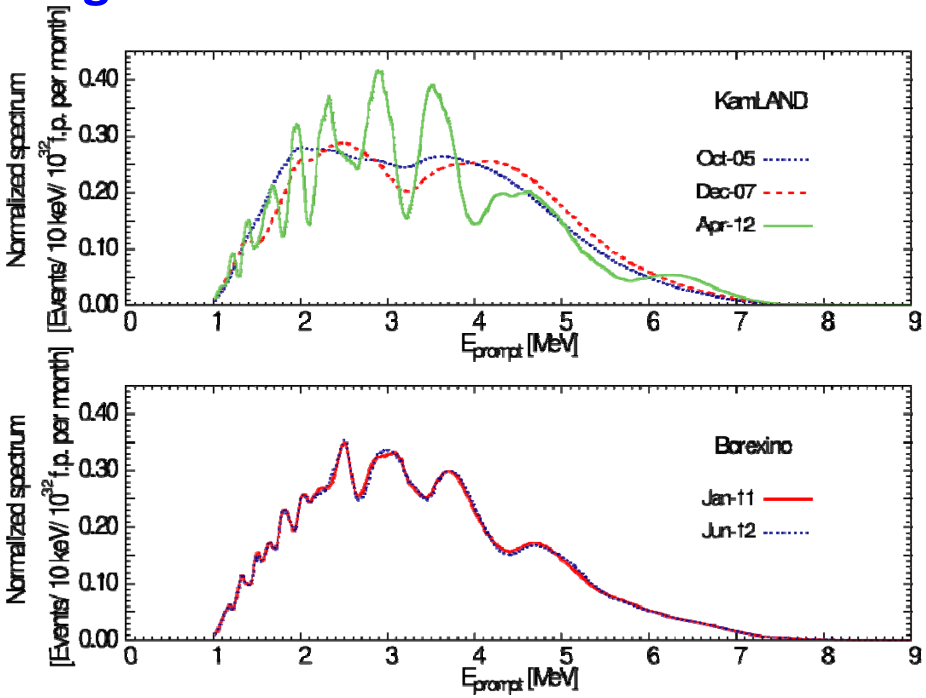

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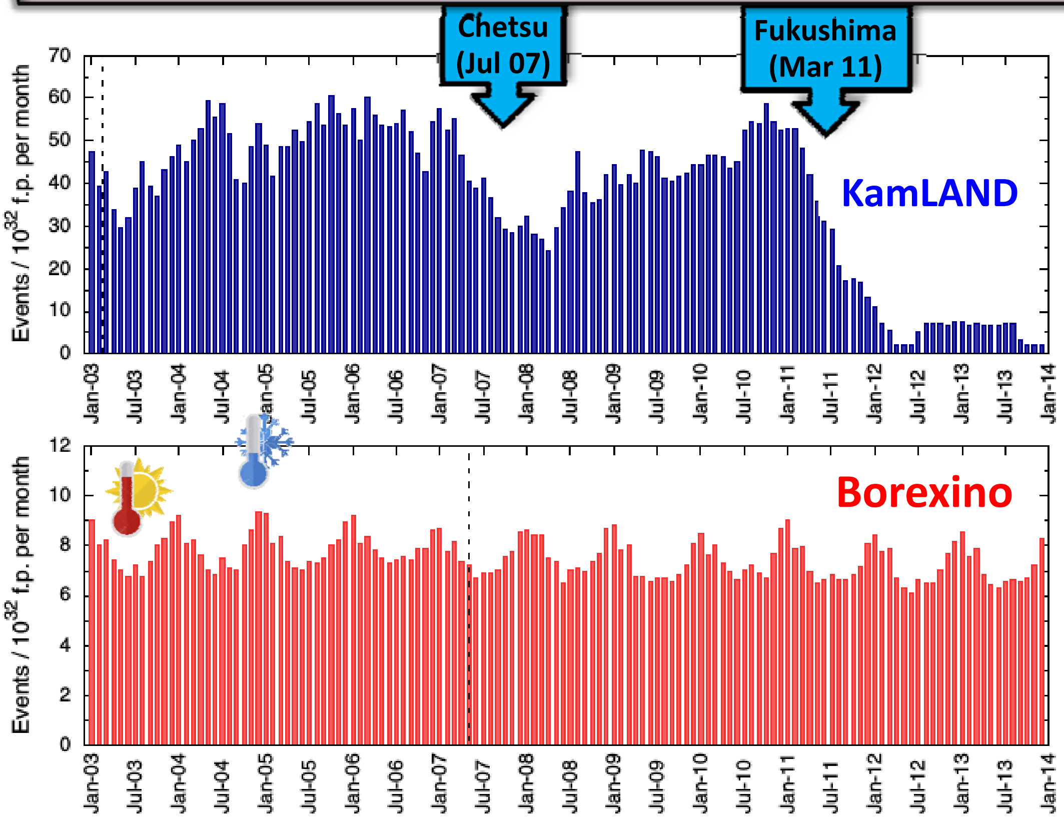

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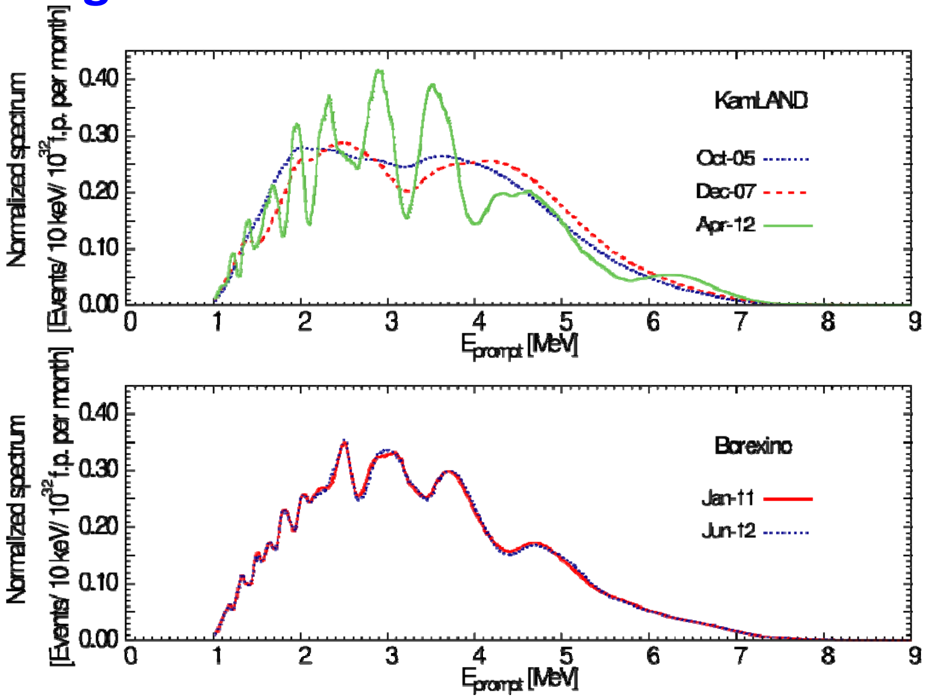

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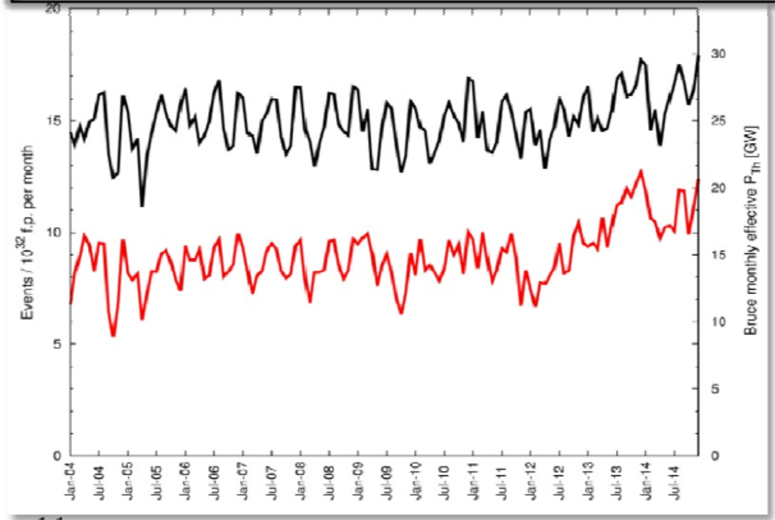
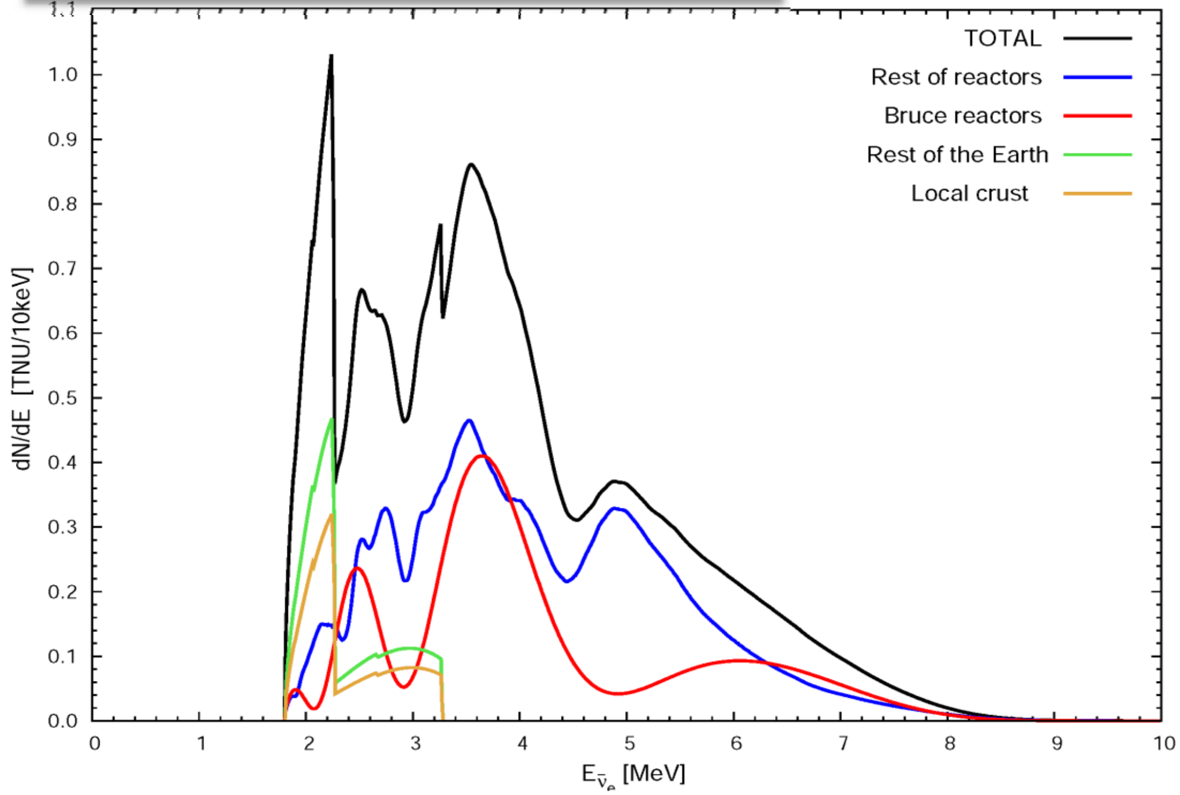
Reactor antineutrinos and geoneutrino at SNO+



- The temporal fluctuations (~10% at 1σ) of **reactor antineutrino signal** resembles the temporal profile of the Bruce Power Station effective thermal power.
- The geoneutrino signal of the Local Crust corresponds to ~ **50%** of the total crustal signal.



Geoneutrinos signal[1](TNU)

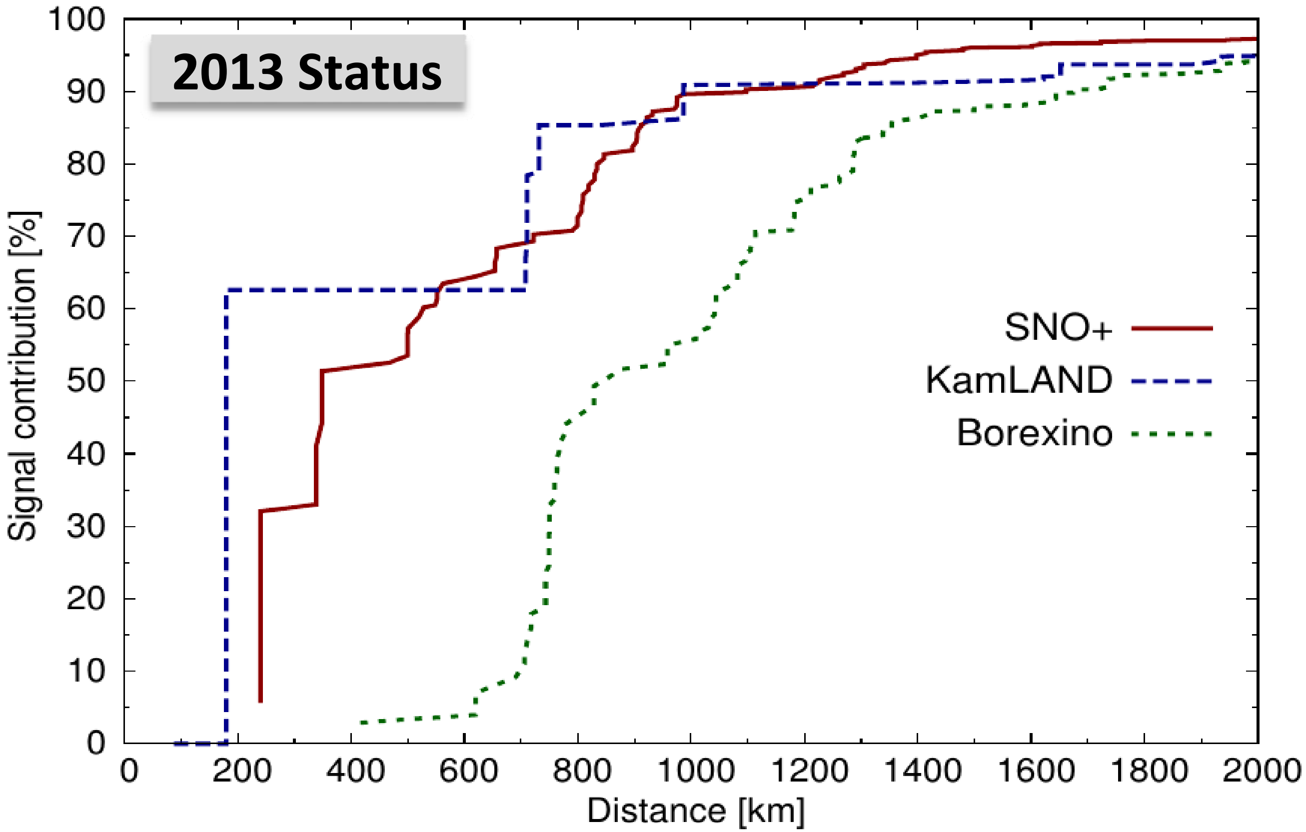
Local Crust	$15.6^{+5.3}_{-3.4}$
Rest of the Crust	$15.1^{+2.8}_{-2.4}$
Cont. Lithos. mantle	$2.1^{+2.9}_{-1.2}$
Mantle	**9**
TOTAL	40^{+6}_{-4}

Reactor antineutrinos signal[2] (TNU)

	LER	FER
Bruce reactors	$17.3^{+1.0}_{-0.7}$	$73.7^{+2.0}_{-1.8}$
Rest of reactors	$31.2^{+0.9}_{-0.8}$	$118.9^{+2.8}_{-2.6}$
TOTAL	$48.5^{+1.8}_{-1.5}$	$192.6^{+4.7}_{-4.4}$

1 - Huang et al. 2014 Geoch. Geoph. Geosys.
2 - Baldoncini et al. 2016 TAUP Proceedings

Borexino, KamLAND and SNO+ signal distance profiles



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

✓**1st** is **~60%** at **180 km** (Japanese Ohi3 and Ohi4)

✓**2nd** is **~85%** at **730 km** (Japanese plus East coast South Korean)

✓**3rd** is **~90%** at **990 km** (Japanese plus all South Korean)

SNO+ profile has **2 major discontinuities**

✓ **1st** is **~32%** at **~240 km** (Canadian Bruce)

✓ **2nd** is **~50%** at **~350 km** (Canadian Pickering and Darlington)

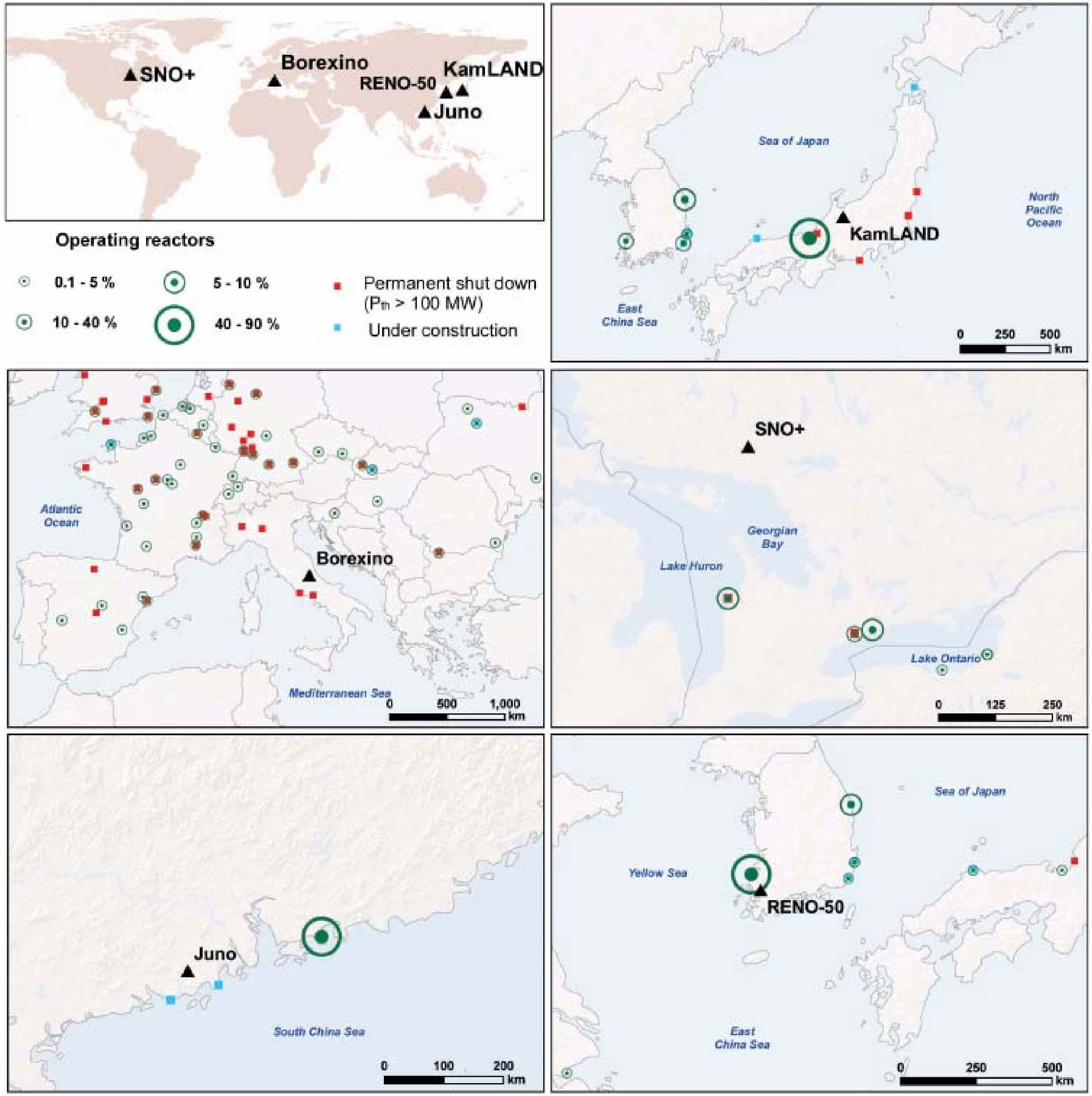
✓For **d > 500km** the profile **levels out** (USA stations)

BX 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



- ✓ **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

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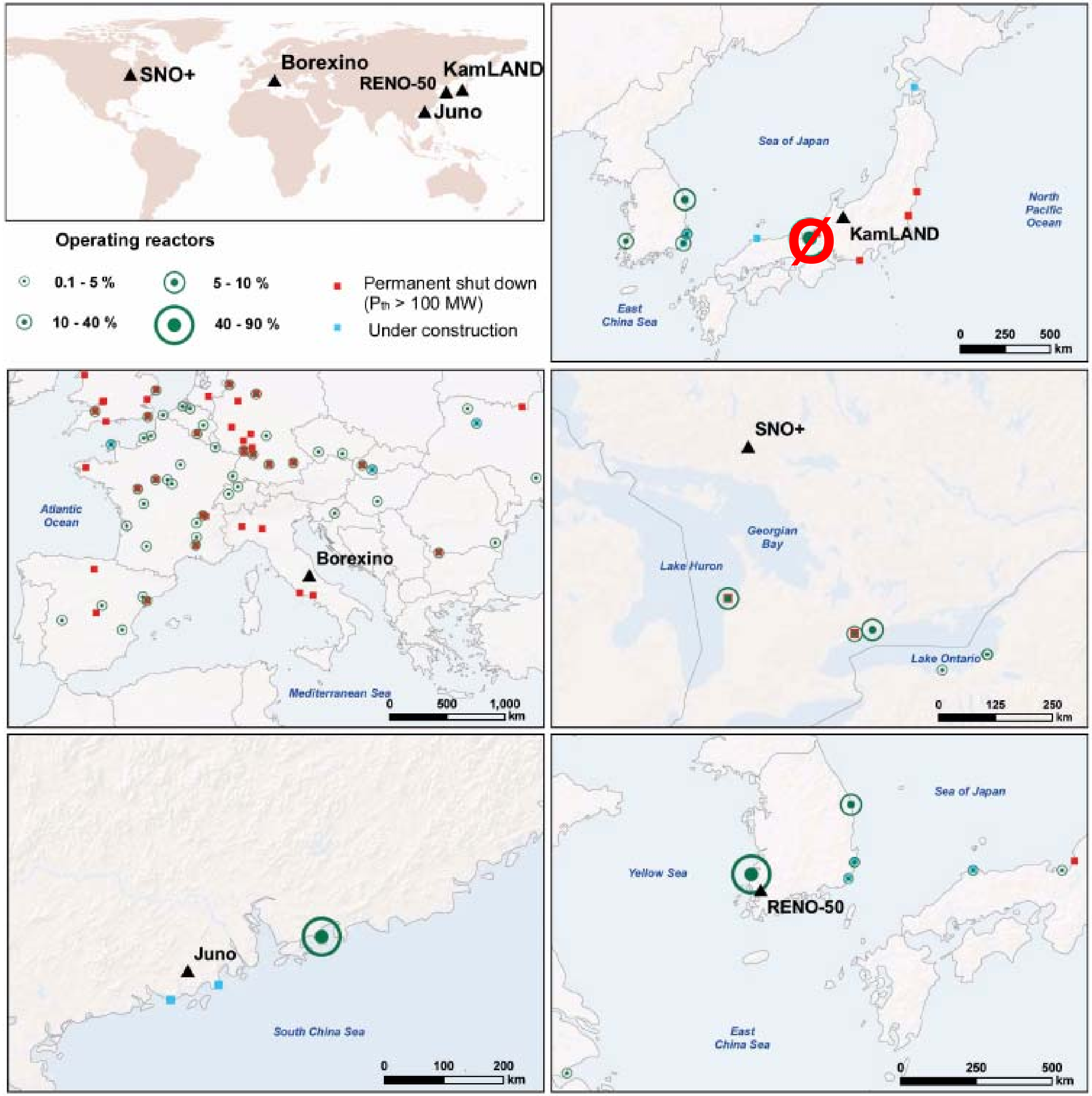

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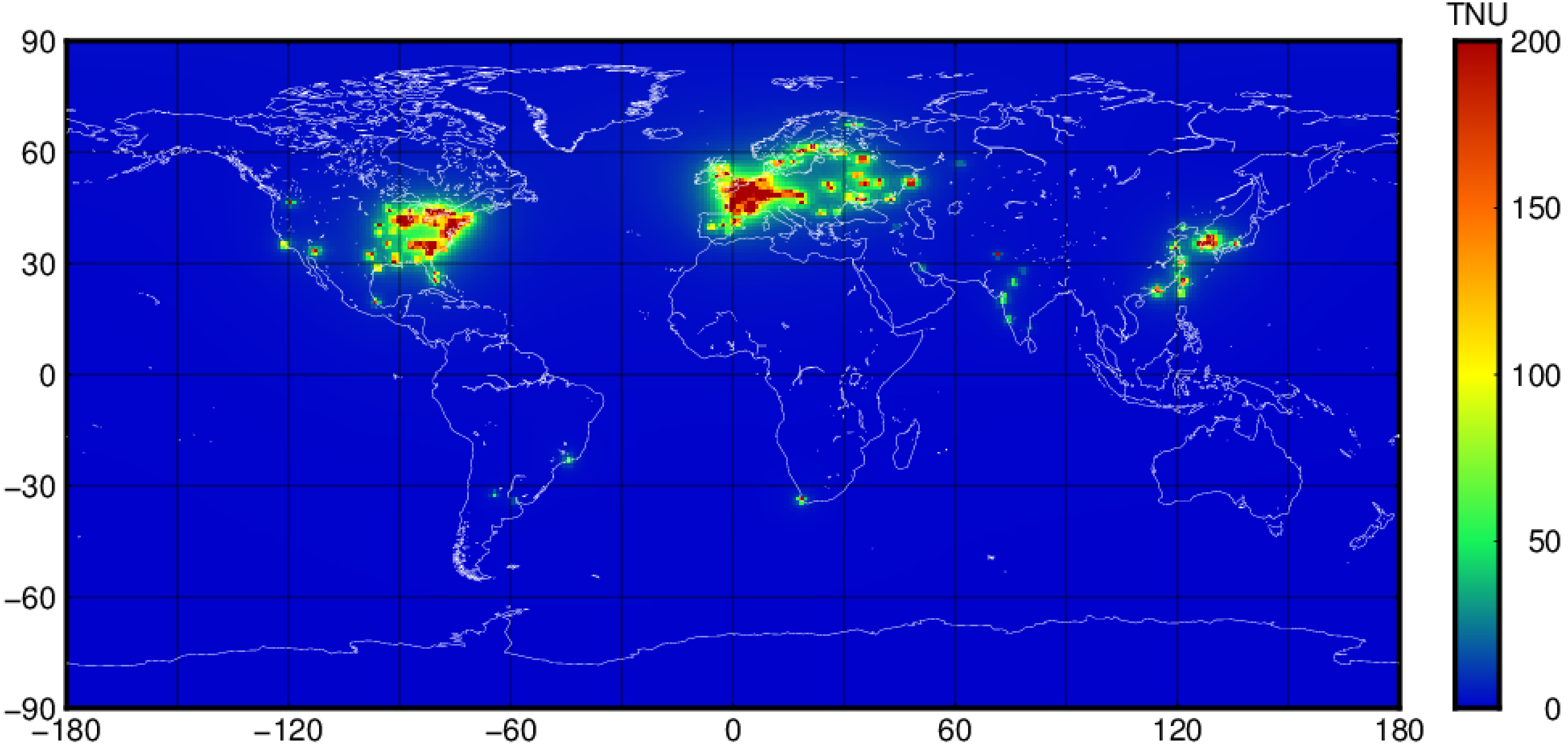
A World Map of Reactor Antineutrino Signal

1◦ x 1◦ Map of the worldwide predicted reactor antineutrino **signal in the LER** originated by nuclear power plants working with **2013** operating performance



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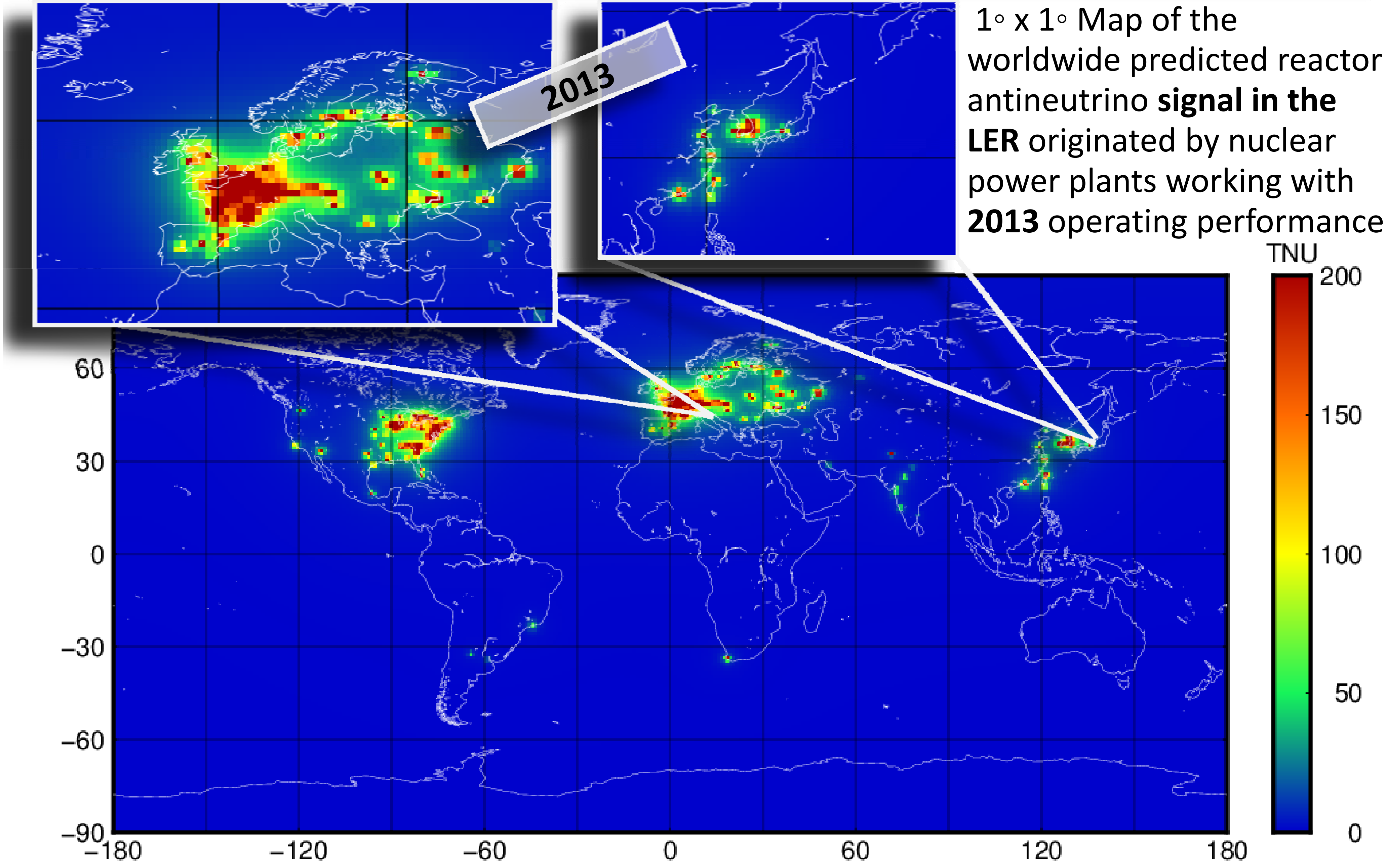

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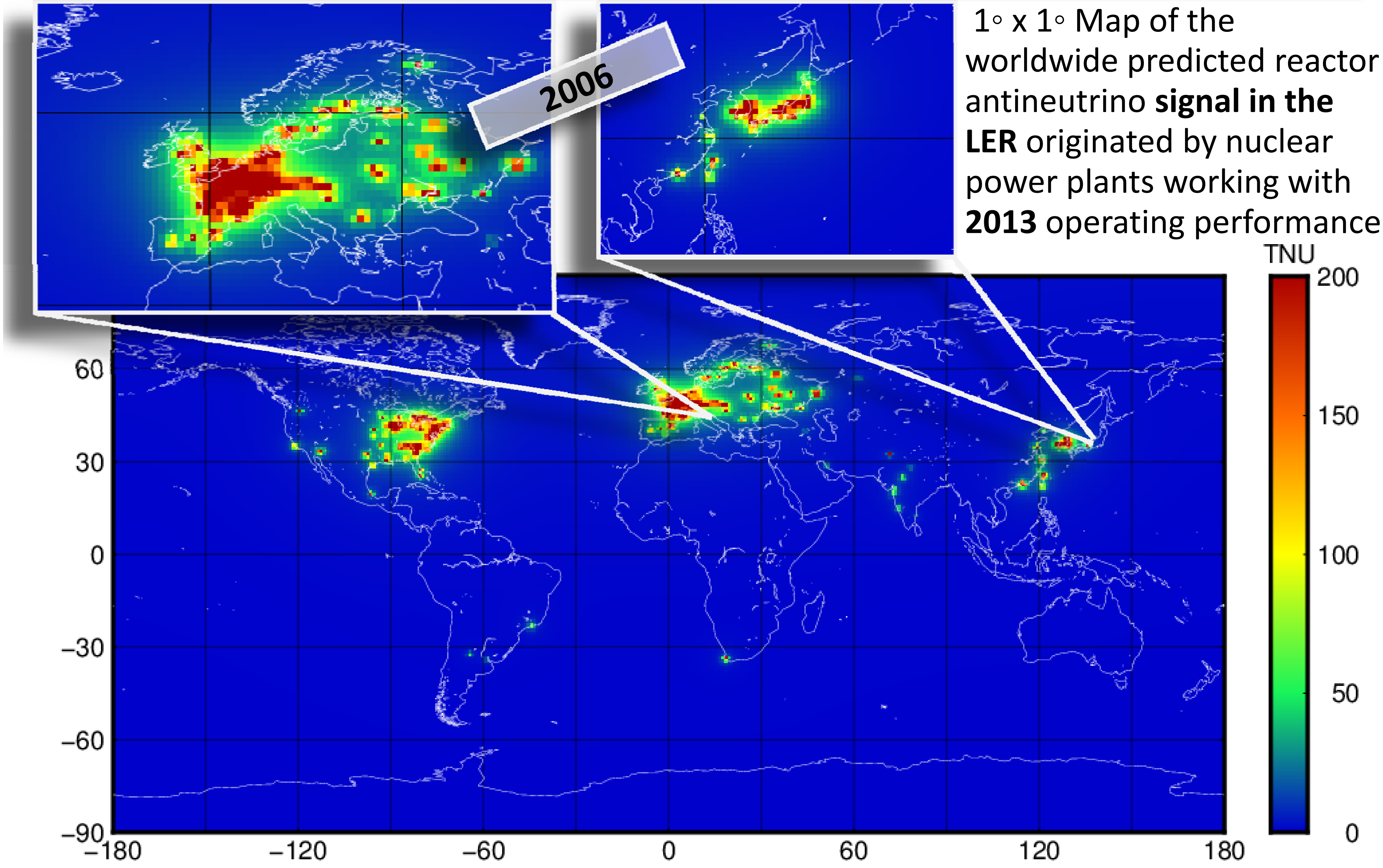

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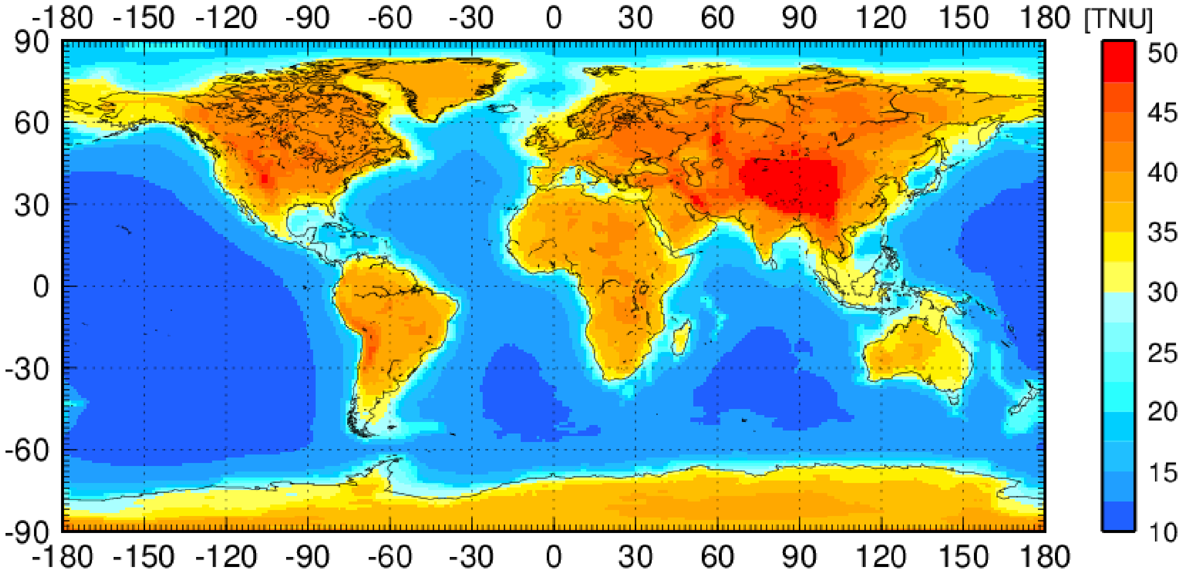
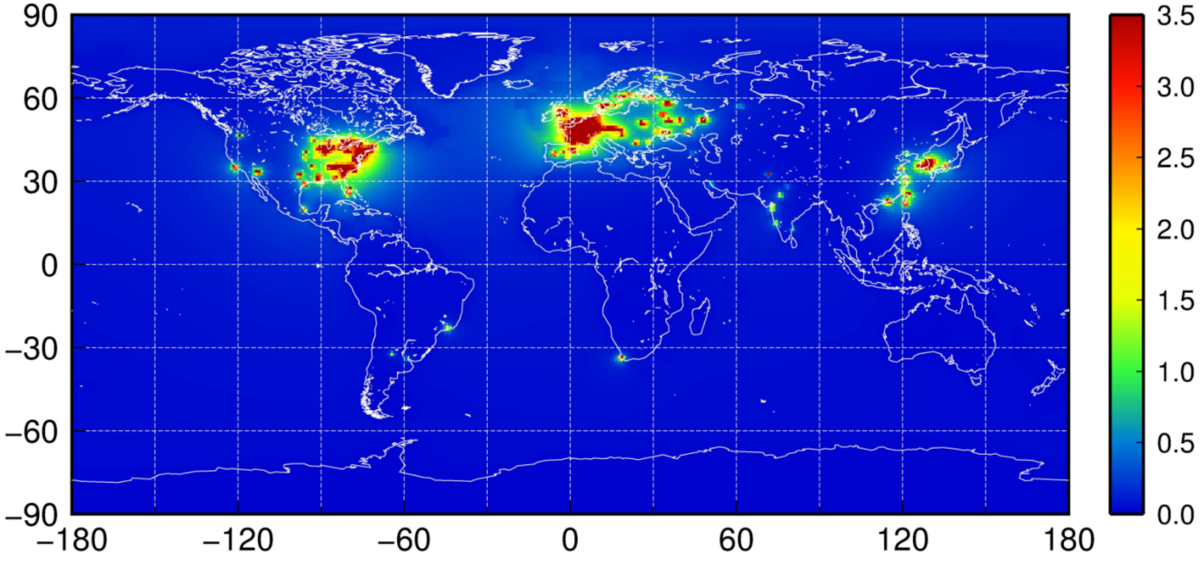
Where to look for mantle geoneutrinos…

Geoν signal map



r = R_{LER}/G 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

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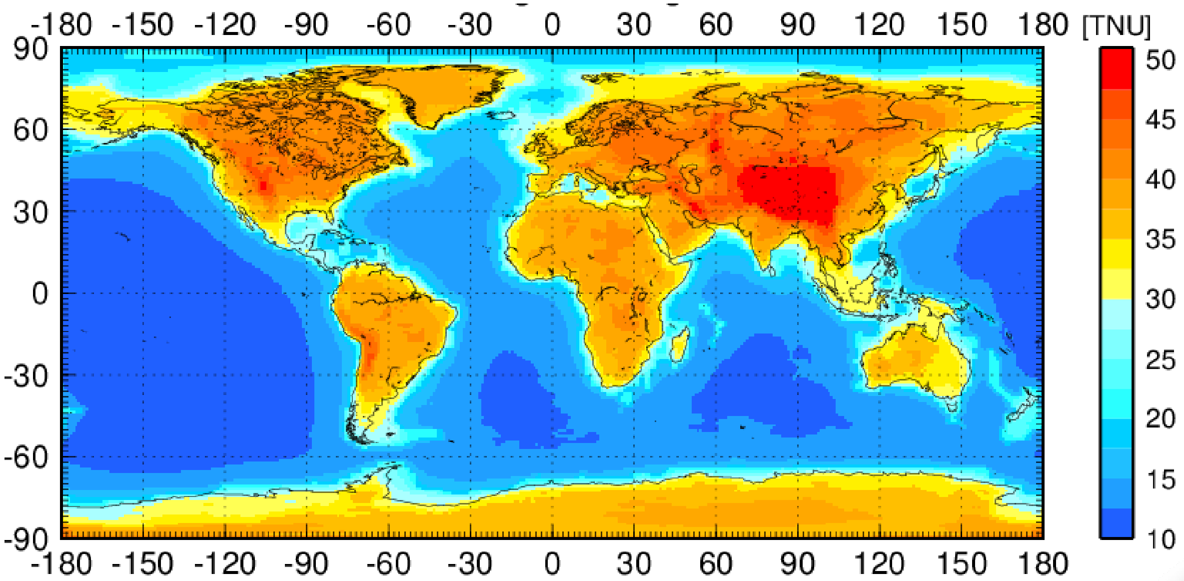
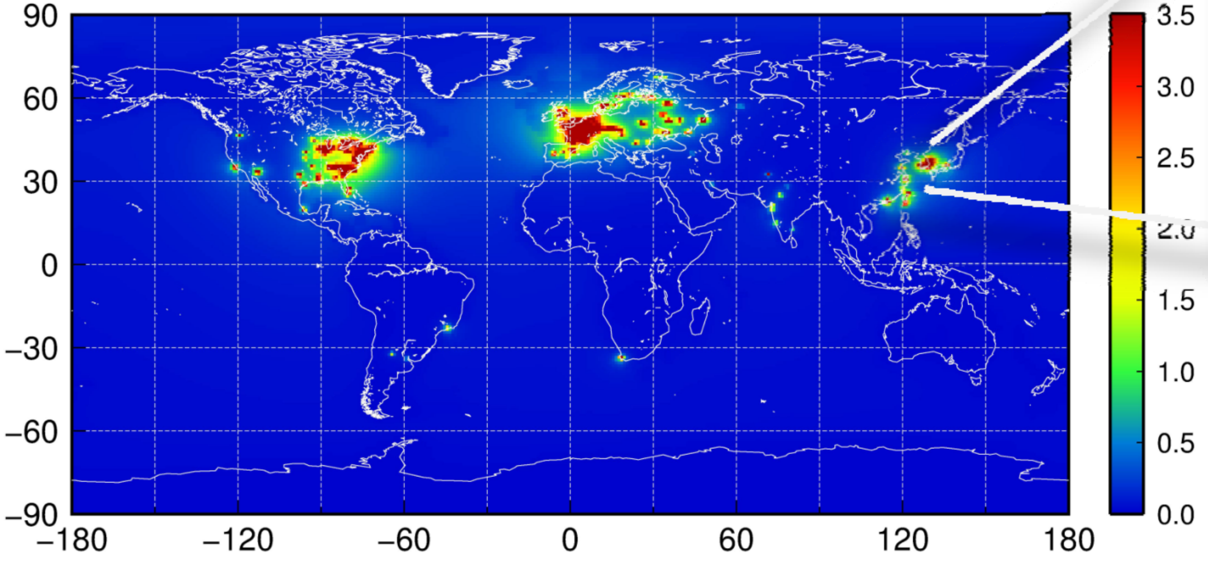


$r = R_{LER}/G$ map



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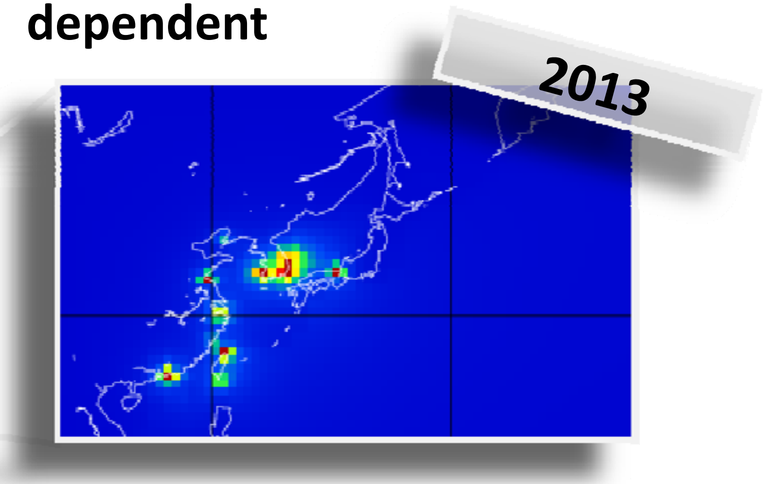

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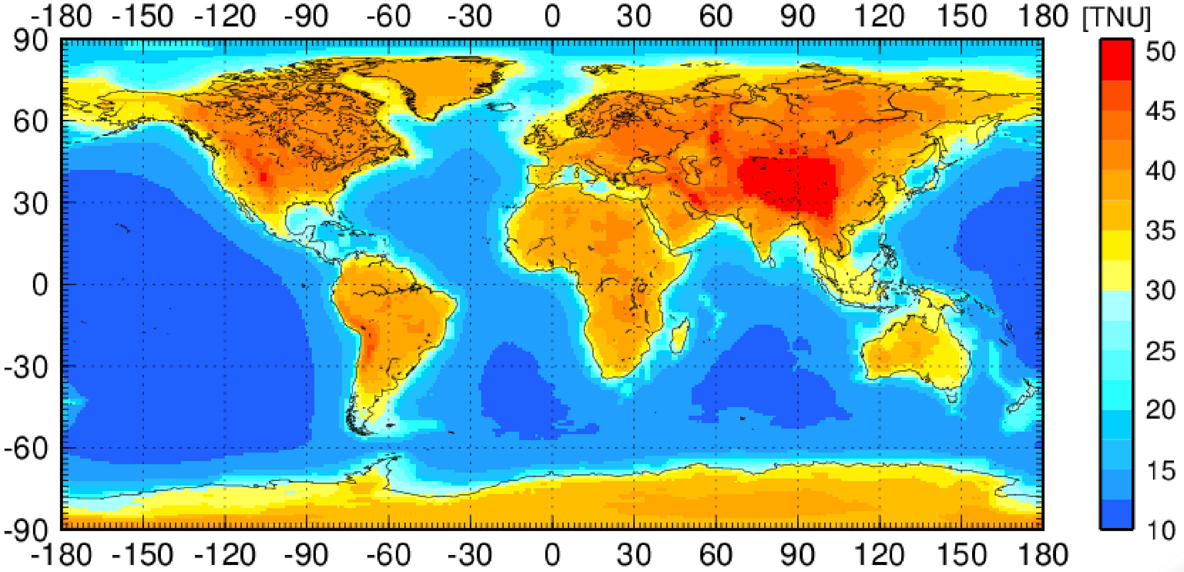

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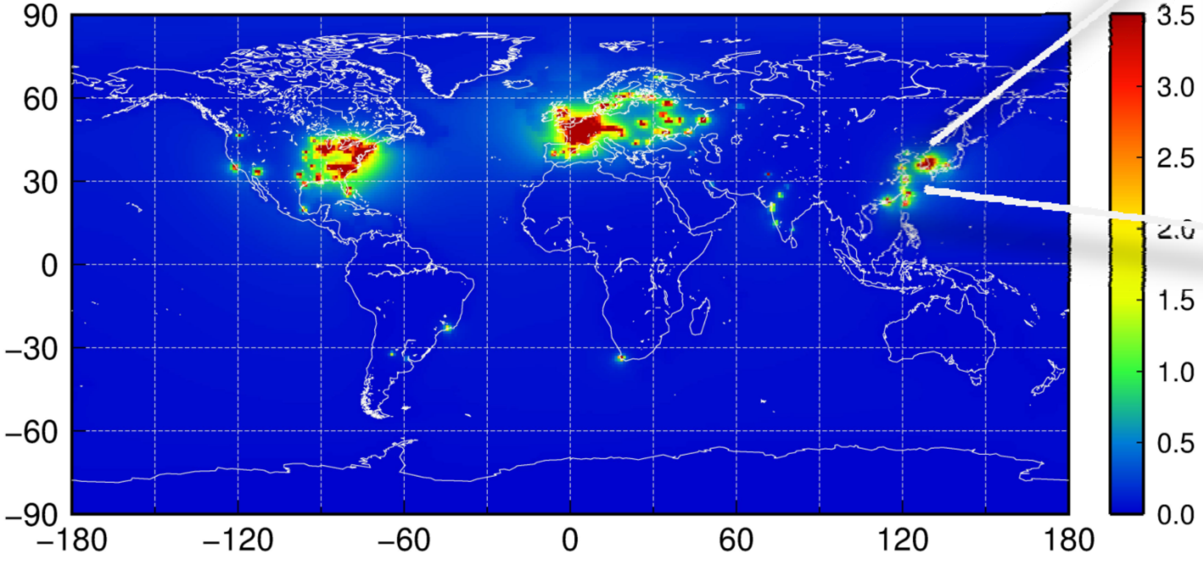

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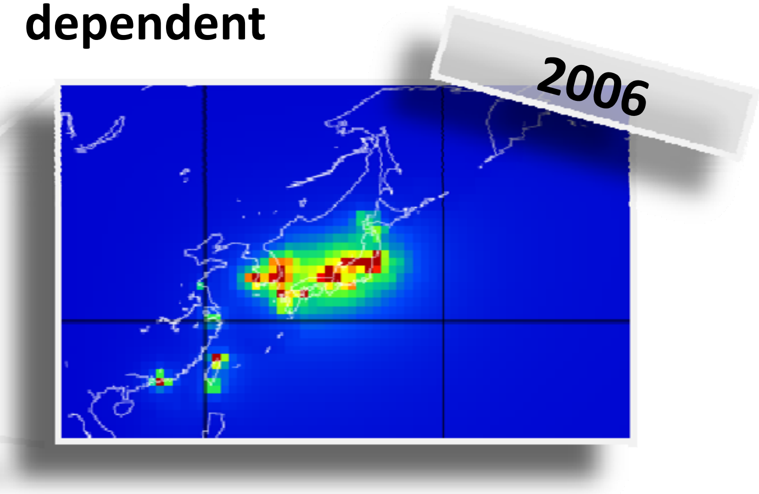

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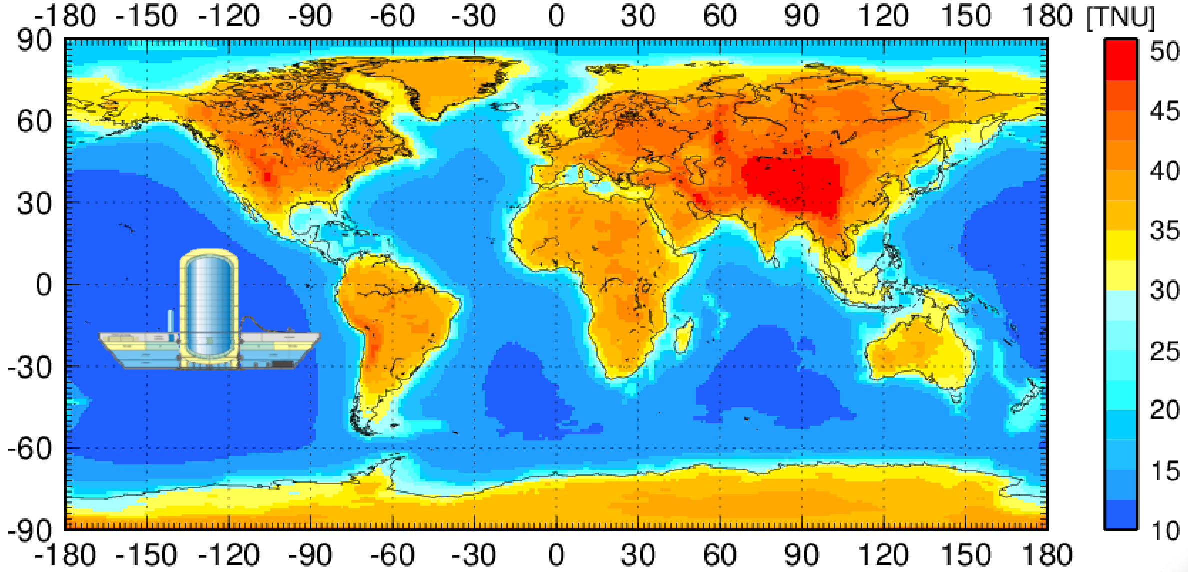

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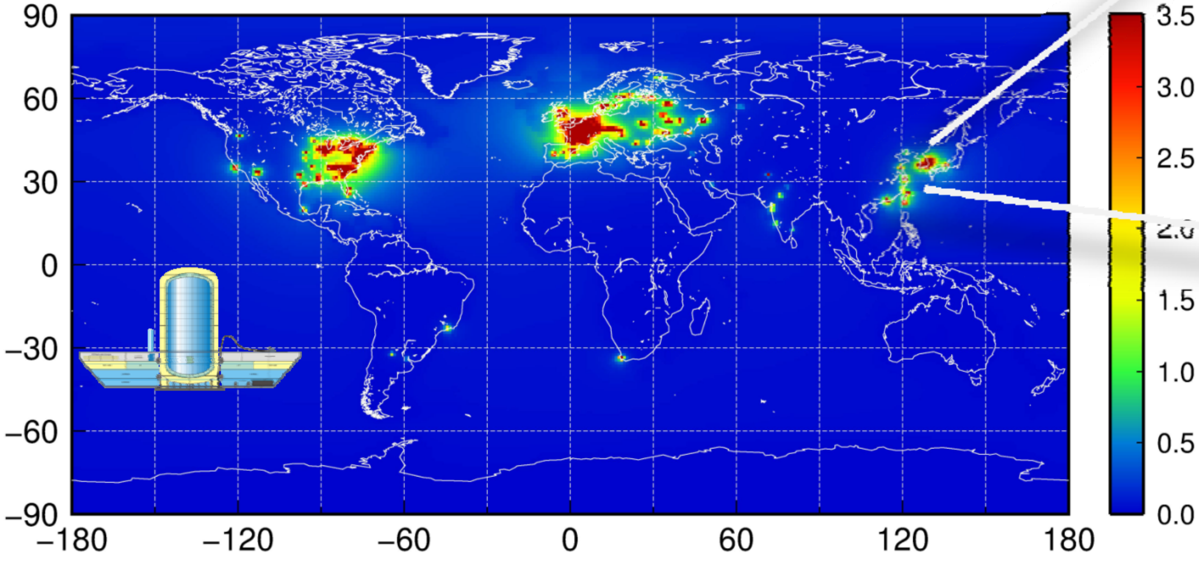

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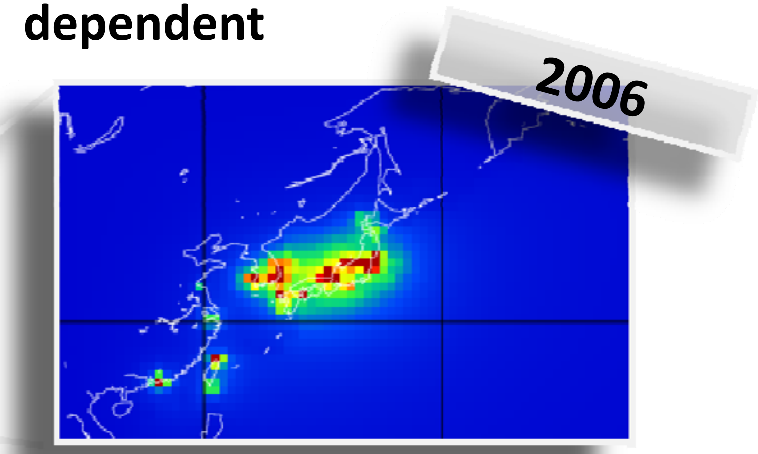


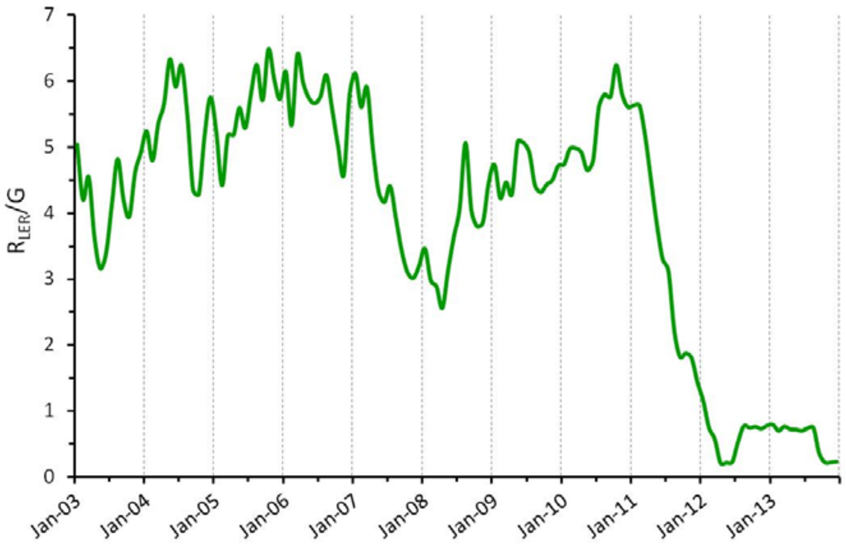
- A **deep ocean antineutrino detector** far from reactors and from the continental crust will potentially observe **mantle geoneutrinos**

Conclusions

From **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

DOWNLOAD

A **worldwide reference model for antineutrino from reactors** is a relevant benchmark for geoneutrino science: the profile of R_{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 **1σ** uncertainty of ~**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 **~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 **~2.4%**