



A reference worldwide model for antineutrinos from reactors

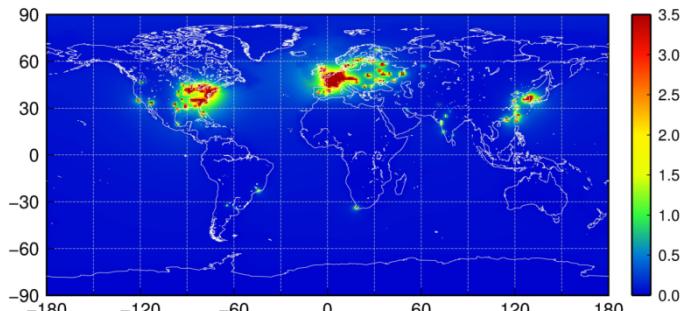
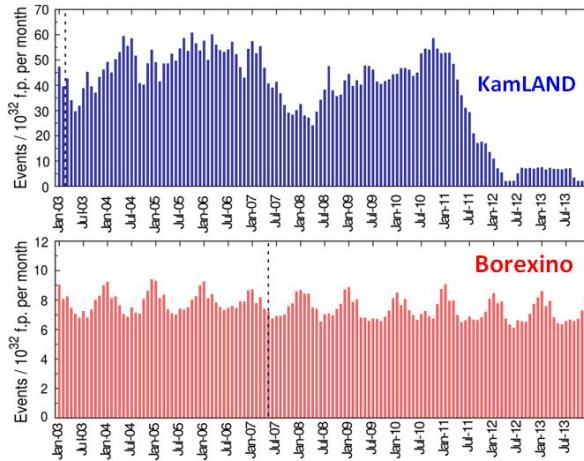
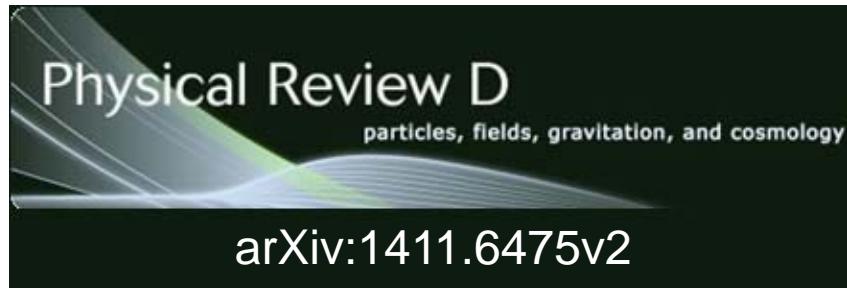
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In collaboration with Ivan Callegari, Giovanni Fiorentini, Fabio Mantovani, Barbara Ricci,
Virginia Strati and Gerti Xhixha (University of Ferrara-INFN)

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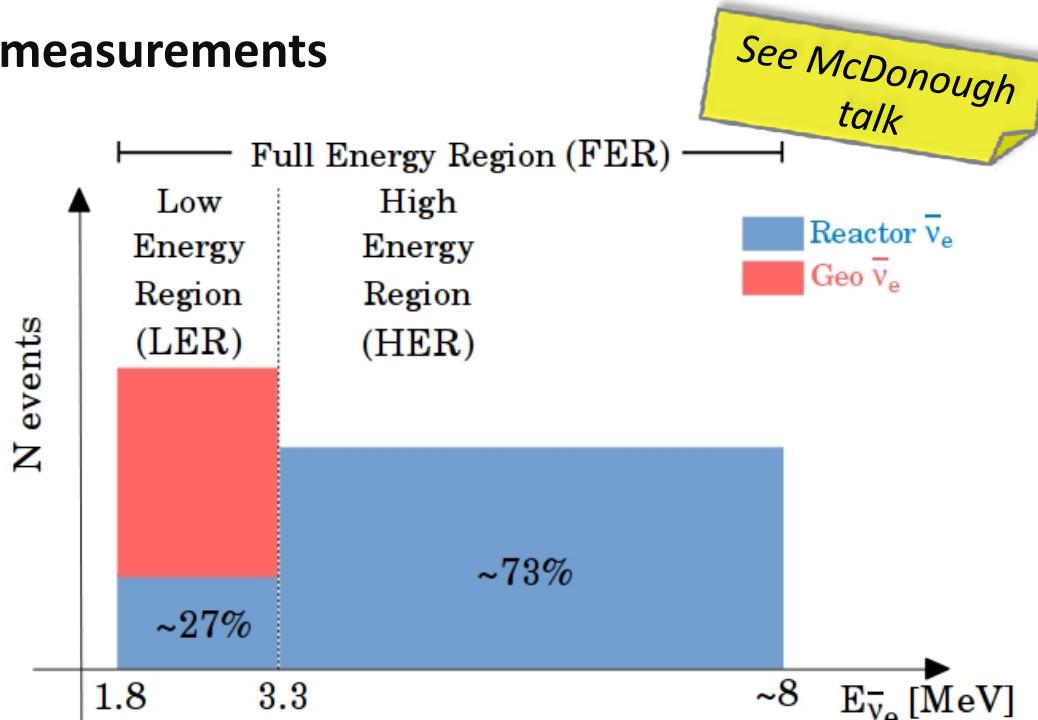
Outline

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

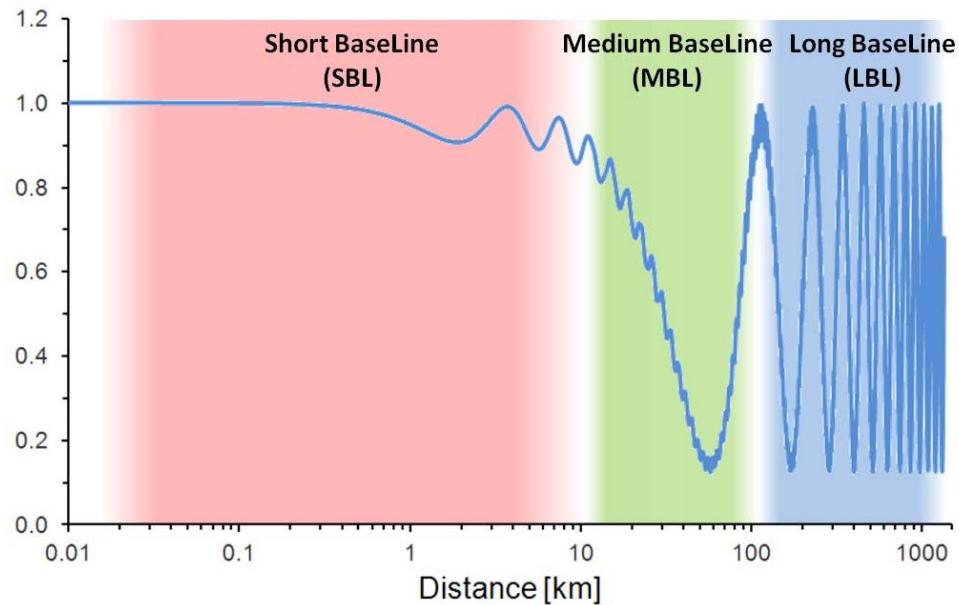


Why a reference model for antineutrinos from reactors?

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

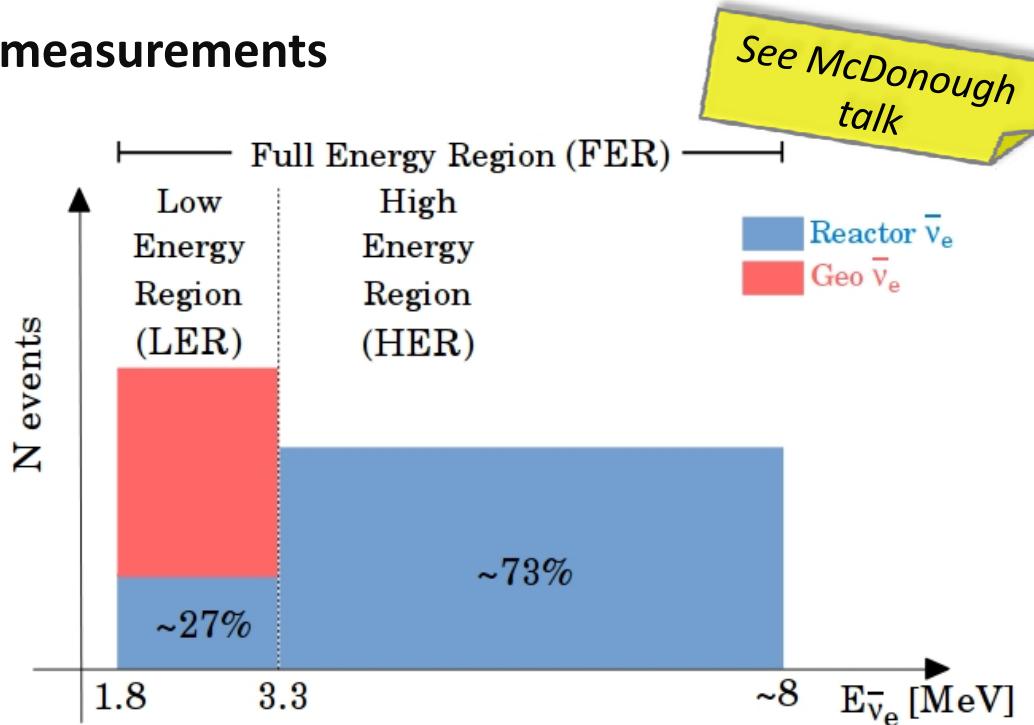


Liquid scintillation detectors: moving from the **Short BaseLine (SBL) (~1km)** and **Long BaseLine (LBL) era (~200 km)** towards the **Medium BaseLine (MBL) era (~50 km)**

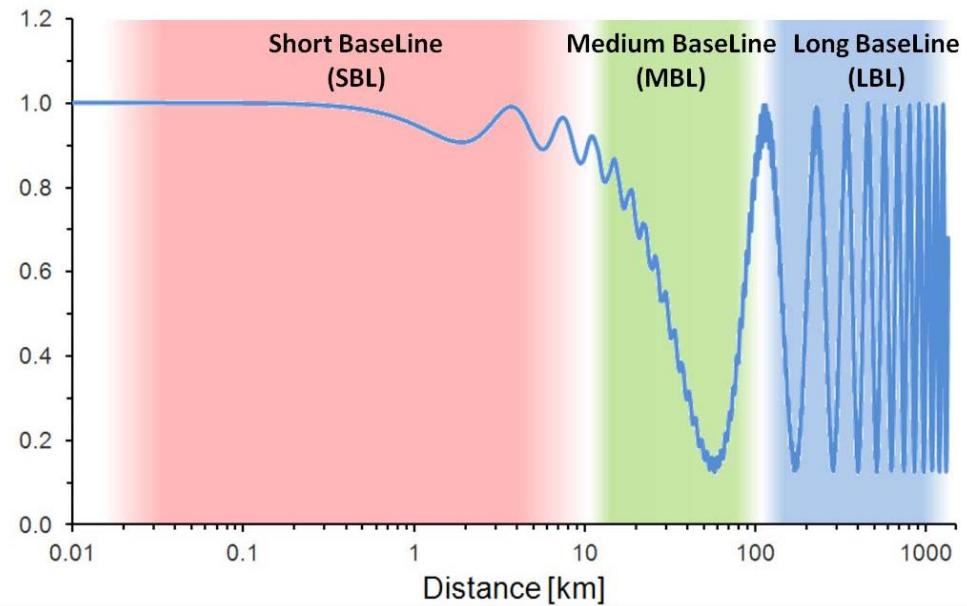


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Goal of the work

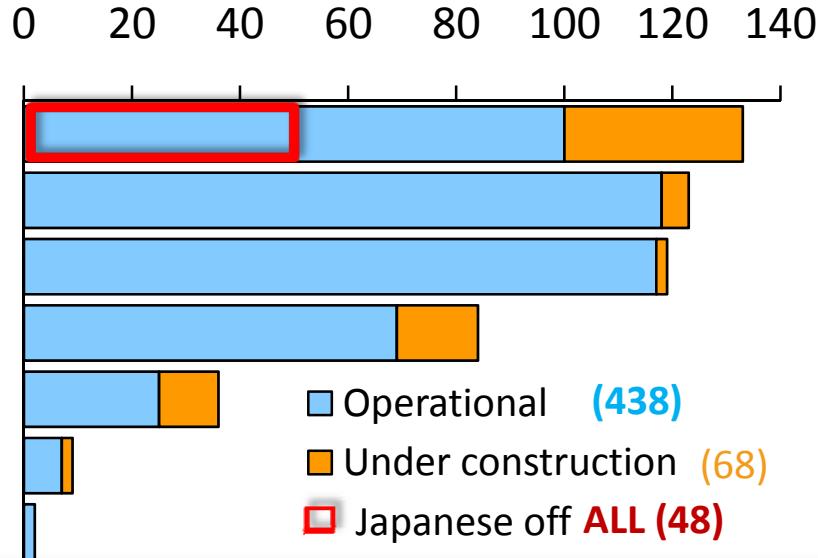
- provide on the base of reactors official data a **worldwide reference model required for estimating the reactor signal for LBL experiments**
- estimate the **signal uncertainty** starting from the uncertainties on individual inputs

Nuclear power plants in the world

2014 Status

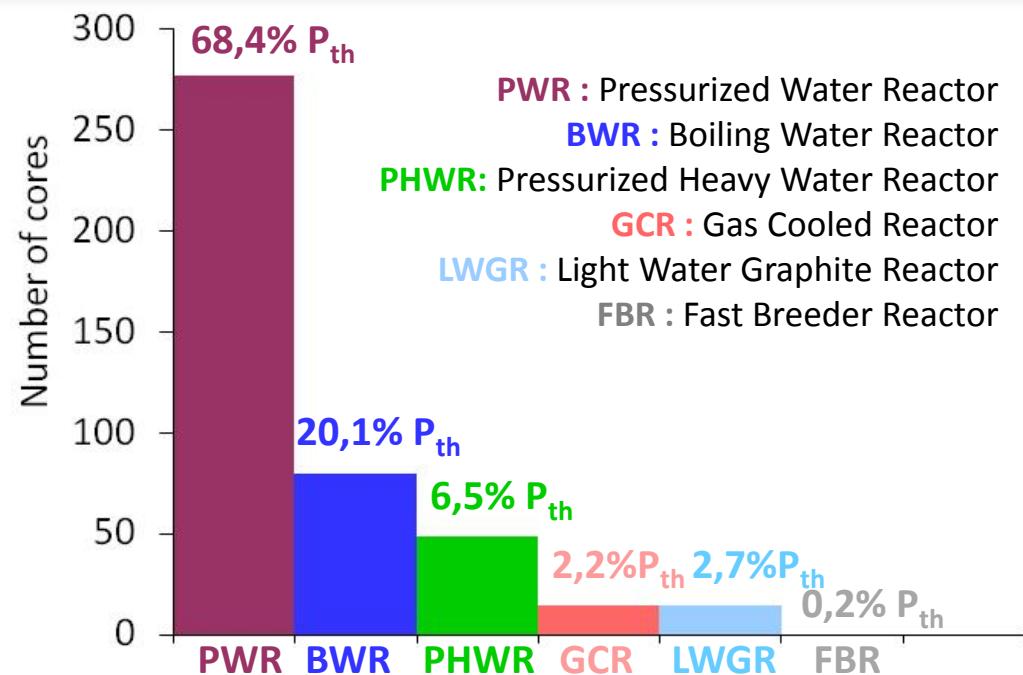
Total Thermal Power 1220 GW

- Far East Asia
- Northern America
- Western Europe
- Central and Eastern Europe
- Middle East and South Asia
- Latin America
- Africa



- ✓ Far East Asia, Western Europe and North America host ~25% each
- ✓ 40% of under construction reactors in China (~ 30 GW_{el})

- ✓ PWR, BWR, LWGR and GCR: enriched uranium with different enrichment levels (from ~ 2.2% up to 5% ²³⁵U)
- ✓ PHWR: natural uranium (~ 0.7% ²³⁵U)
- ✓ 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

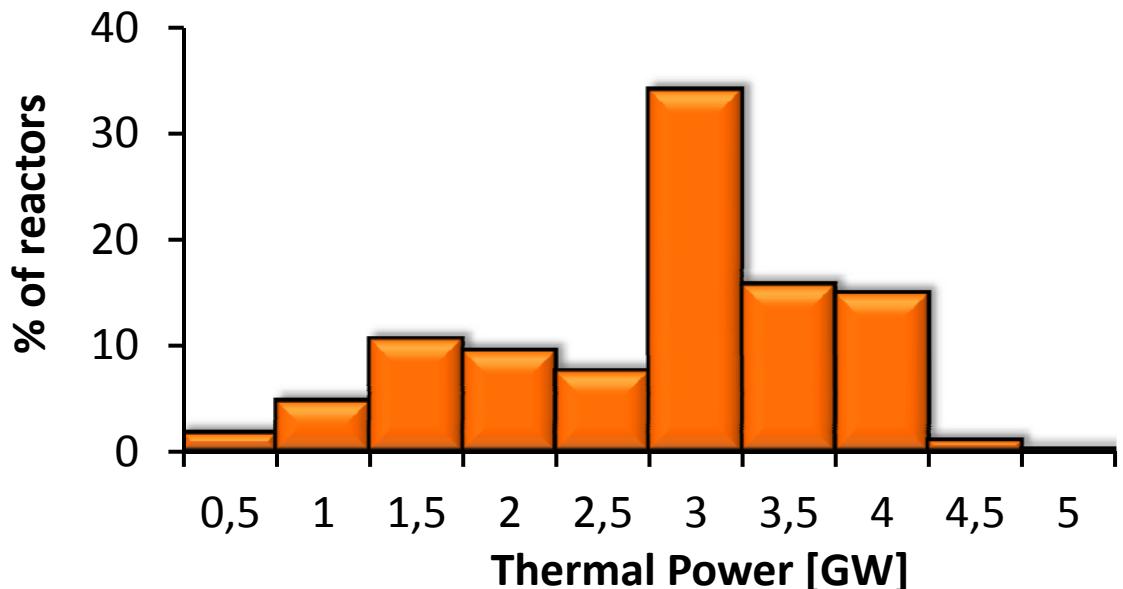
Drawbacks

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

The screenshot shows the PRIS database interface. At the top, it displays reactor details for CA-19 BRUCE-6, including operator (BRUCELLINK), contractor (CHABROL/ONTARIO HYDRO), and location (ATOMIC ENERGY OF CANADA LTD.). Below this, there are sections for 'Station Details' (Type: PHWR, Net Reference Unit Power: 817.0 MW(e), Design Net Capacity: 822.0 MW(e), Status at end of year: Operational), 'Country' (CANADA), 'Reactor' (CA-19 through CA-25), and 'Capacity [MW]' (Thermal, Gross, Net). A large table below lists monthly performance data for 2010, showing values for GW(h), EAP (%), LCF (%), LF (%), OF (%), PUP (%), UCLF (%), and KUF (%)) across the months of Jan to Jul.

CA-19 BRUCE-6								
Operator: BRUCELLINK (HYDRO) ATOMIC ENERGY OF CANADA LTD.								
Contractor: CHABROL/ONTARIO HYDRO								
2. Reactor								
Country: CANADA								
3. 2010 Monthly Performance Data								
GW(h)	EAP (%)	LCF (%)	LF (%)	OF (%)	PUP (%)	UCLF (%)	KUF (%)	
Jan	607.0	54.9	59.8	59.2	100.0	44.1	0.0	0.0
Feb	604.9	55.8	59.2	59.0	100.0	44.4	0.0	0.0
Mar	594.1	44.2	59.2	59.0	100.0	44.4	0.0	0.0
Apr	592.0	100.0	59.2	58.4	100.0	46.2	0.0	0.0
May	582.1	100.0	59.2	58.4	100.0	46.2	0.0	0.0
Jun	582.1	100.0	59.2	58.4	100.0	46.2	0.0	0.0
Jul	582.1	100.0	59.2	58.4	100.0	46.2	0.0	0.0

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



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	2004	2005	2006
<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map
2007	2008	2009	2010
<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map
2011	2012	2013	2014
<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map	<ul style="list-style-type: none">• Input database• Numerical map• Map

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2003

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- Map

2004

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- Map

2005

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- Map

2006

Monthly Load Factors [%]

	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
P _{th} [MW]	1179	0,00	0,00	6,41	99,55	73,92	98,79	99,82	99,57	98,35	99,66	99,33

2007

- Input database
- Numerical map
- Map



	F-NAME	LAT [decimal°]	LONG [decimal°]	CORE TYPE	MOX	P _{th} [MW]	JAN	FEB	MAR	APR	MAY	JUNE	JULY	AUG	SEP	OCT	NOV	DEC
AN	ITUCHA-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
AM	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

2014

2014



- 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 **11 years** (2003 – 2014)

✓ **Direct implementation** thanks to standard file (ASCII, Excel)

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

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

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)

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

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

REACTOR

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

NUCLEAR

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

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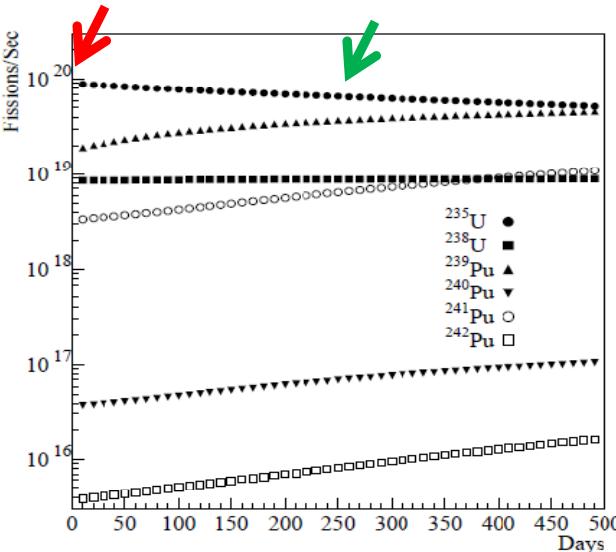
Fission fractions and power fractions collection

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

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	^{235}U	^{239}Pu	^{241}Pu	^{238}U	Reference
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	
		0.544	0.318	0.063	0.075	
		0.577	0.292	0.057	0.074	
f_i		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	
		0.560	0.300	0.080	0.060	
p_i		0.000	0.708	0.212	0.081	G. Bellini et al. (2010)
		0.543	0.411	0.024	0.022	G. Bellini et al. (2013)
MOX	p_i	0.560	0.300	0.080	0.060	G. Bellini et al. (2010)
PHWR	p_i	0.000	0.708	0.212	0.081	G. Bellini et al. (2010)
Natural Uranium	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

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 ($\delta m^2, \sin^2 \theta_{12}, \sin^2 \theta_{13}$)
- 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

<i>Input quantity</i>	<i>PDF</i>
ν oscillation ¹	δm^2 (eV) ² Gaussian $1\sigma = 3.4\%$
	$\sin^2 \theta_{12}$ Gaussian $1\sigma = 5.5\%$
	$\sin^2 \theta_{13}$ 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}
	f_{238U}
	f_{239Pu}
	f_{241Pu}
Thermal Power	P_{th} Gaussian $1\sigma = 2\%$
IBD cross section ³	σ_{IBD} Gaussian $1\sigma = 0.4\%$



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

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

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

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

Reactor and geoneutrino signal in 6 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}	5.3	2006
		18.3 ^{+0.6} _{-1.0}	0.6	2013
		7.4 ^{+0.2} _{-0.2}	0.2	2014
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
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
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 & Ohi 4 off

Yangjiang &
Taishan on
in 2020

Long Baseline experiments:
 $1\sigma \sim 4\%$ in LER

Signal uncertainty due to individual inputs

		<i>1σ on signal in FER [%]</i>		
<i>Input quantity</i>		<i>Borexino</i>	<i>KamLAND</i>	<i>SNO+</i>
ν <i>oscillation</i>	δm^2 (eV) ²	<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
<i>Energy per fission</i>	Q_{235U}	<0.1	<0.1	<0.1
	Q_{238U}			
	Q_{239Pu}			
	Q_{241Pu}			
<i>Fission fraction</i>	f_{235U}	0.1	0.5	<0.1
	f_{238U}			
	f_{239Pu}			
	f_{241Pu}			
<i>Thermal Power</i>	P_{th}	0.2	0.9	0.3
<i>IBD cross section</i>	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]	$Y_{235} [\%]$	$Y_{239} [\%]$
$^{93}\gamma$	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	$^{90}\gamma$	64.0 h	2.280	0.27	0.10

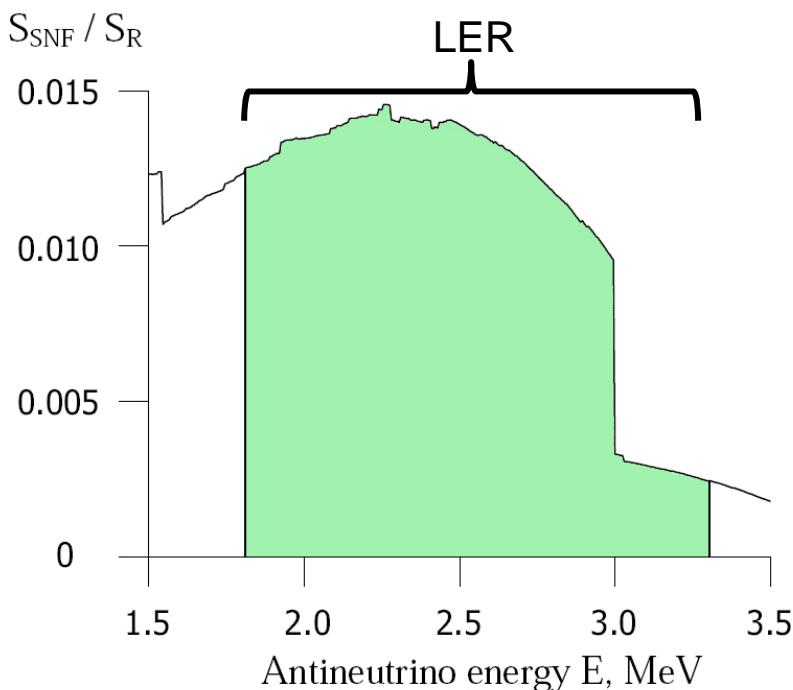
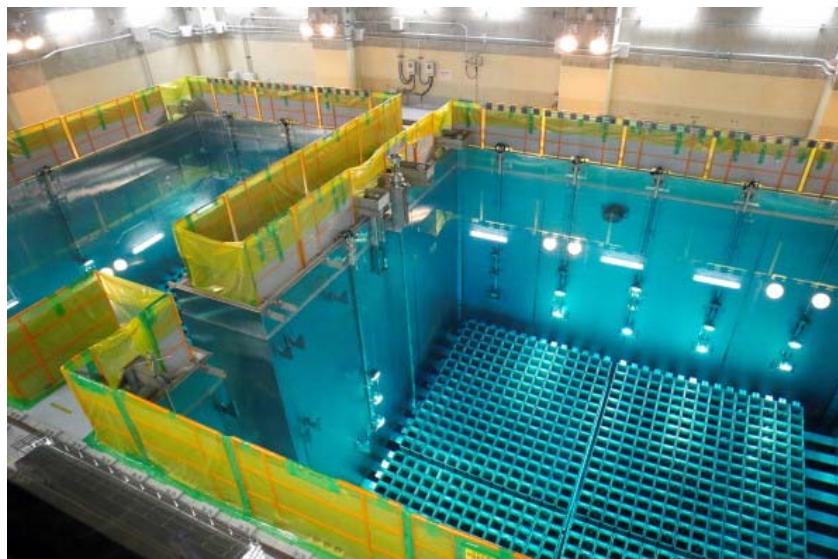
See Jaffke talk

- Fission fragments have **wide spread half-lives**, from fraction of seconds up to 10^{18} years
 - LLIs ($E_{\bar{\nu}_e}^{max} > 1.806$ 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
- $$\frac{\Delta R^{FER}}{R^{FER}} < 0.5\%$$

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

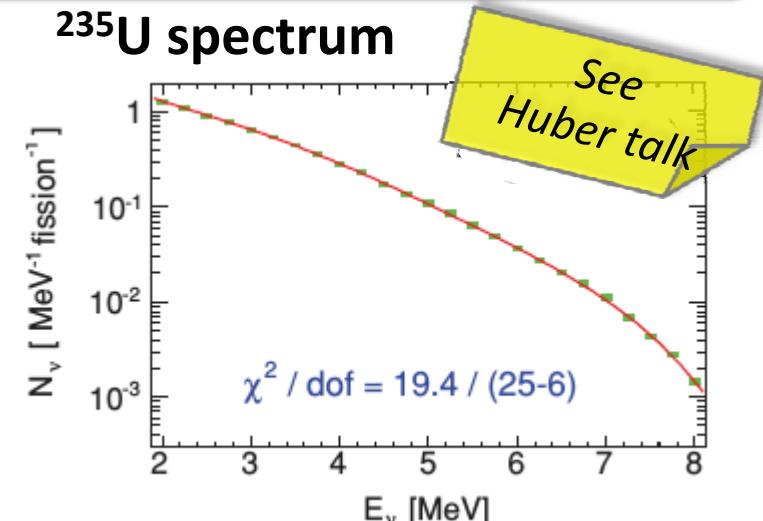
Signal increase due to the Spent Nuclear Fuels (SNFs)

- 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 $\tau_{\text{SNF}} = 2.8 \text{ yr}$
- 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**



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}



- 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)

Antineutrino signal from Research Reactors (RRs)*

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

Russia

North America

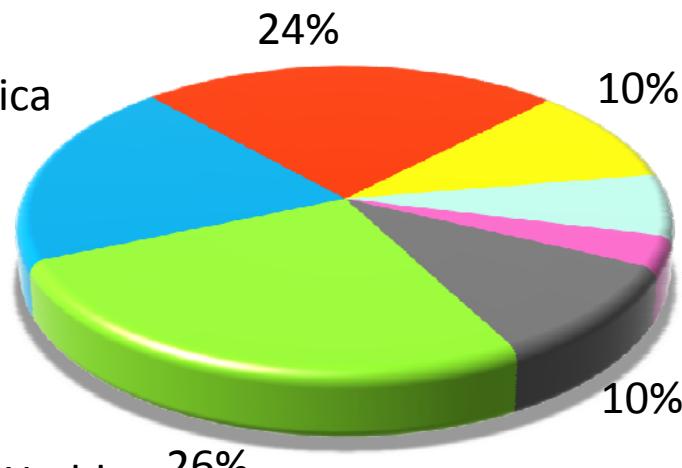
Europe

Asia

China

Japan

Rest of the World

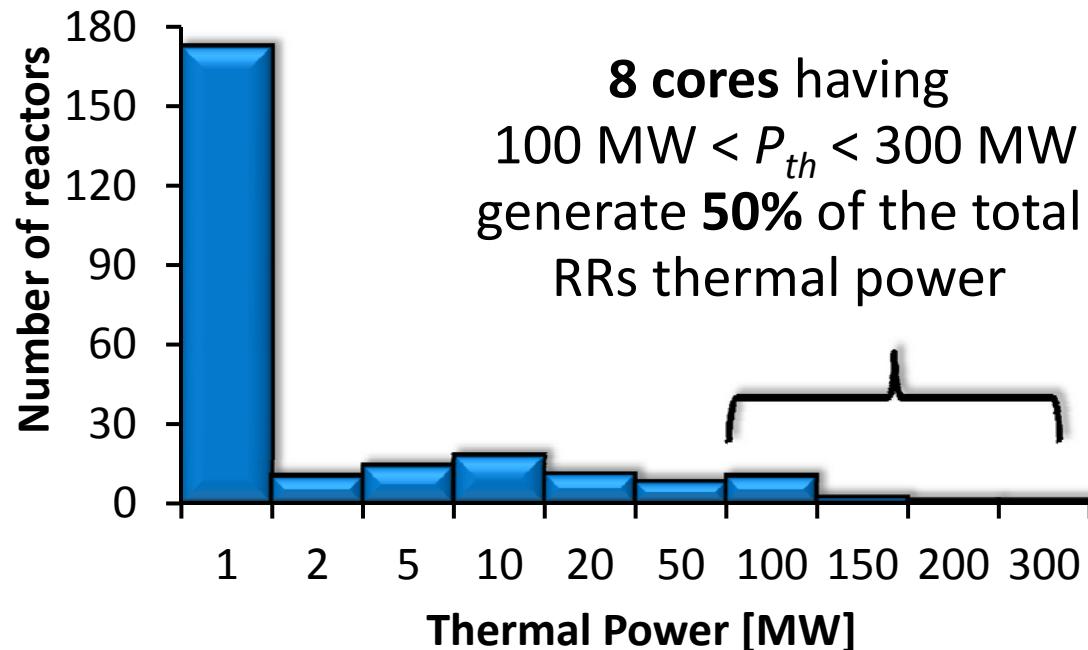


The 40 RRs accounting for 90% of the RRs thermal power and operating with a 80% annual LF give

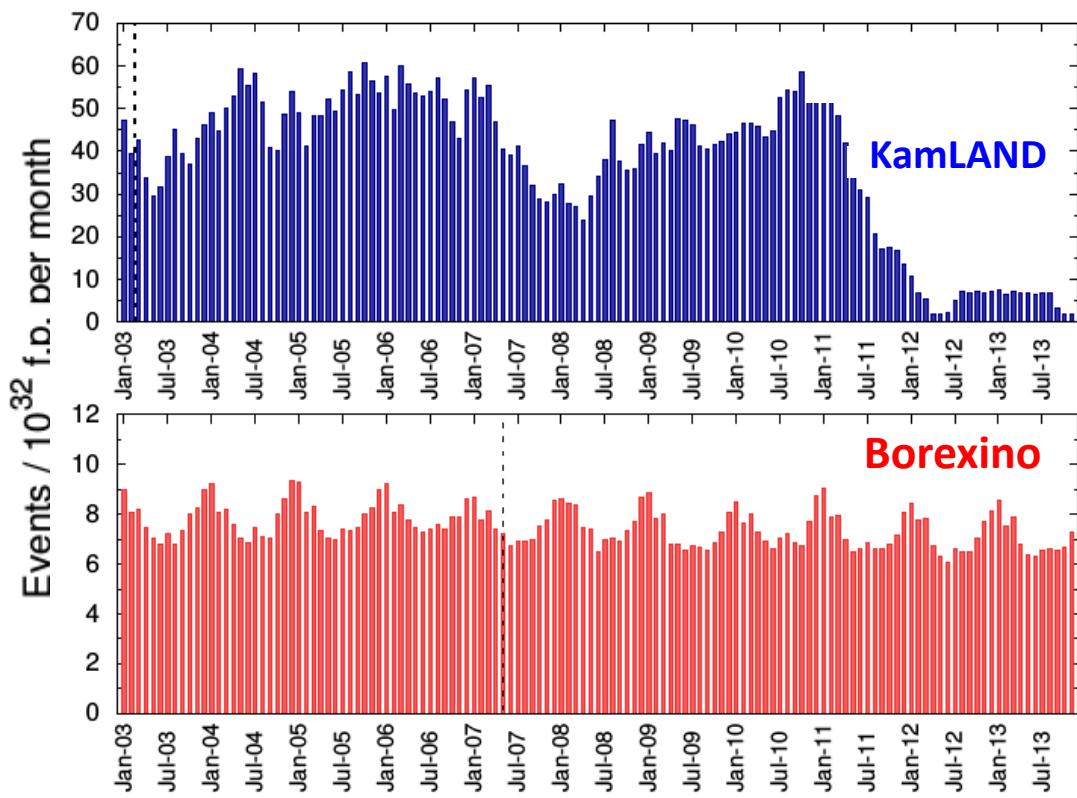
$$\frac{\Delta R^{FER}}{R^{FER}} < 0.2\%$$

RRs employed for

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

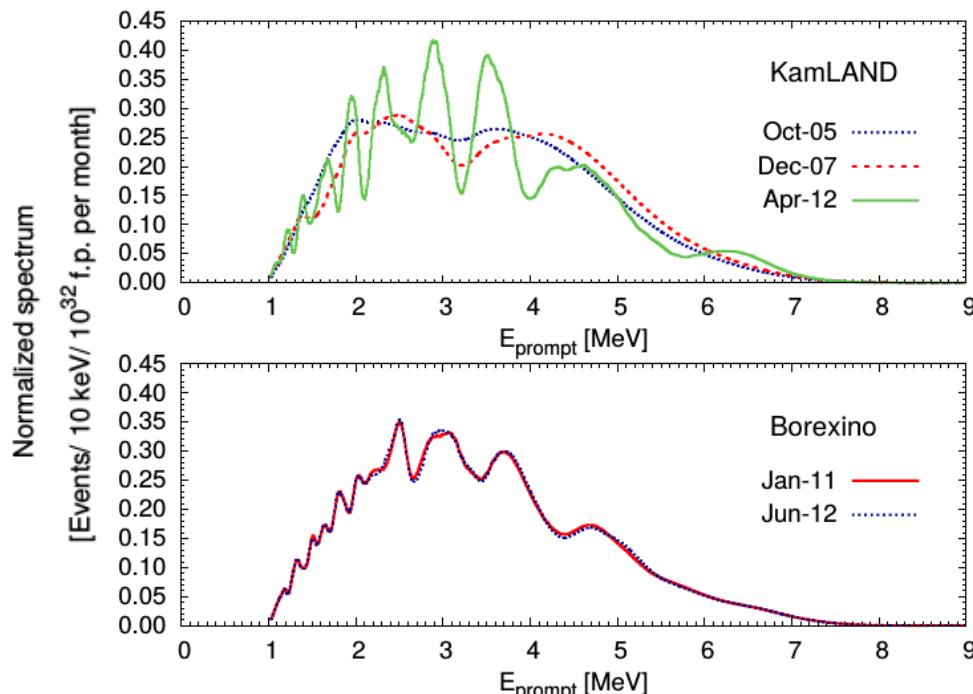


Borexino and KamLAND signal time profiles

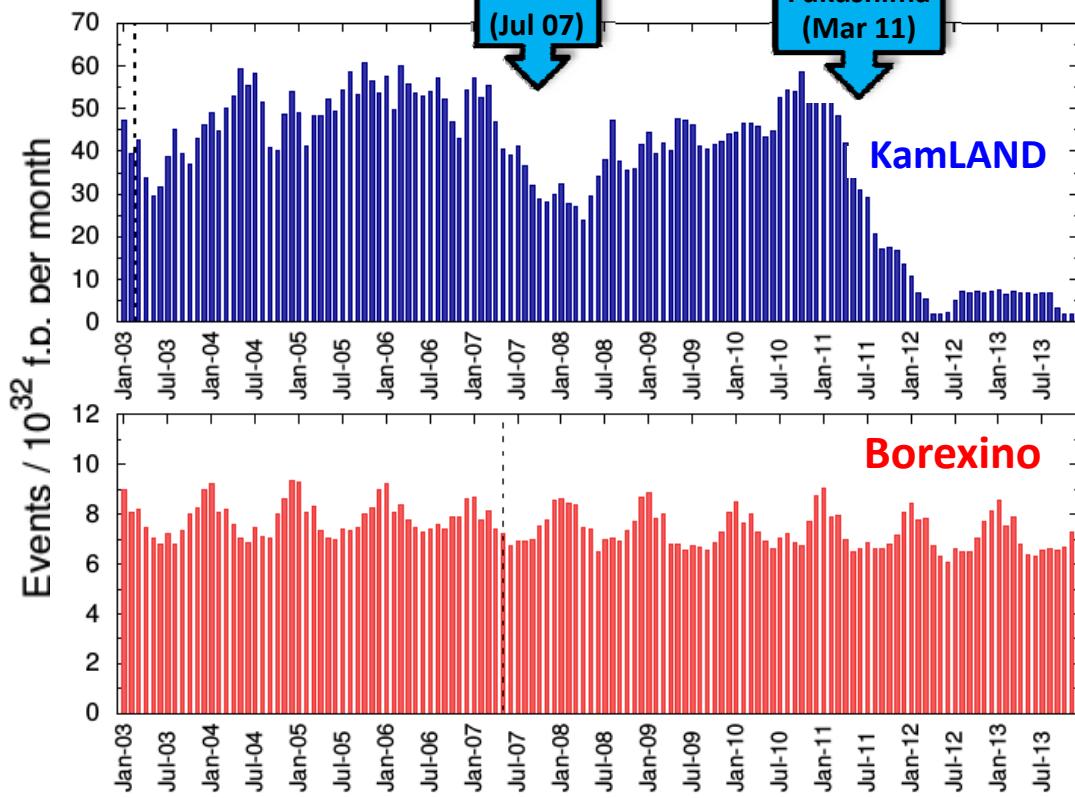


- ✓ **Seasonal signal variation** associated with the lower fall-spring electricity demand
- ✓ Relatively **insensitive** to **operational conditions** of **single reactors** since there are no close-by reactors dominating the antineutrino flux

- ✓ 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**

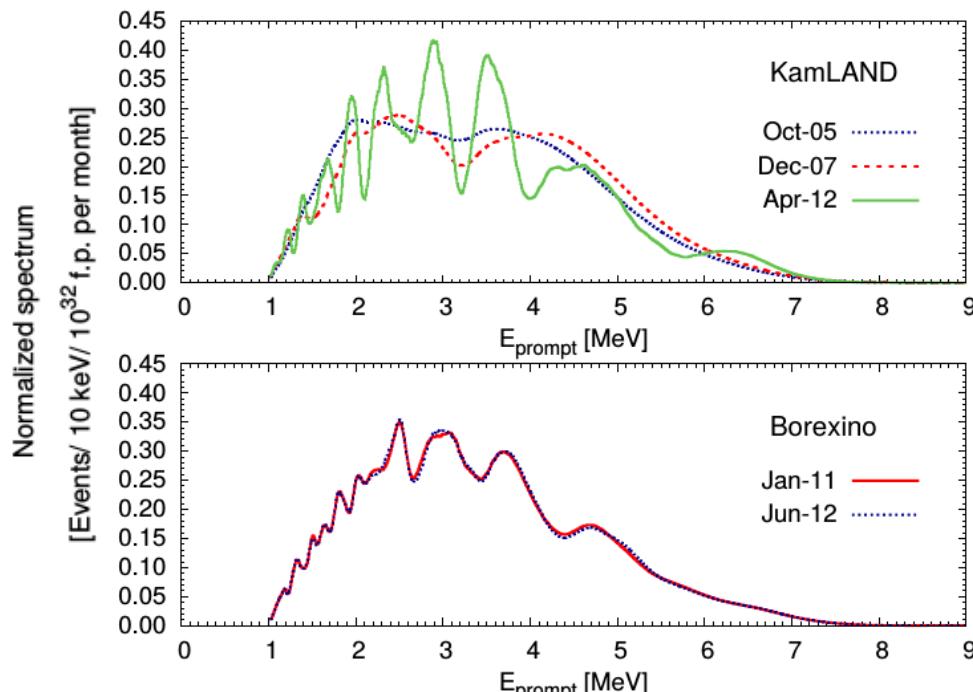


Borexino and KamLAND signal time profiles

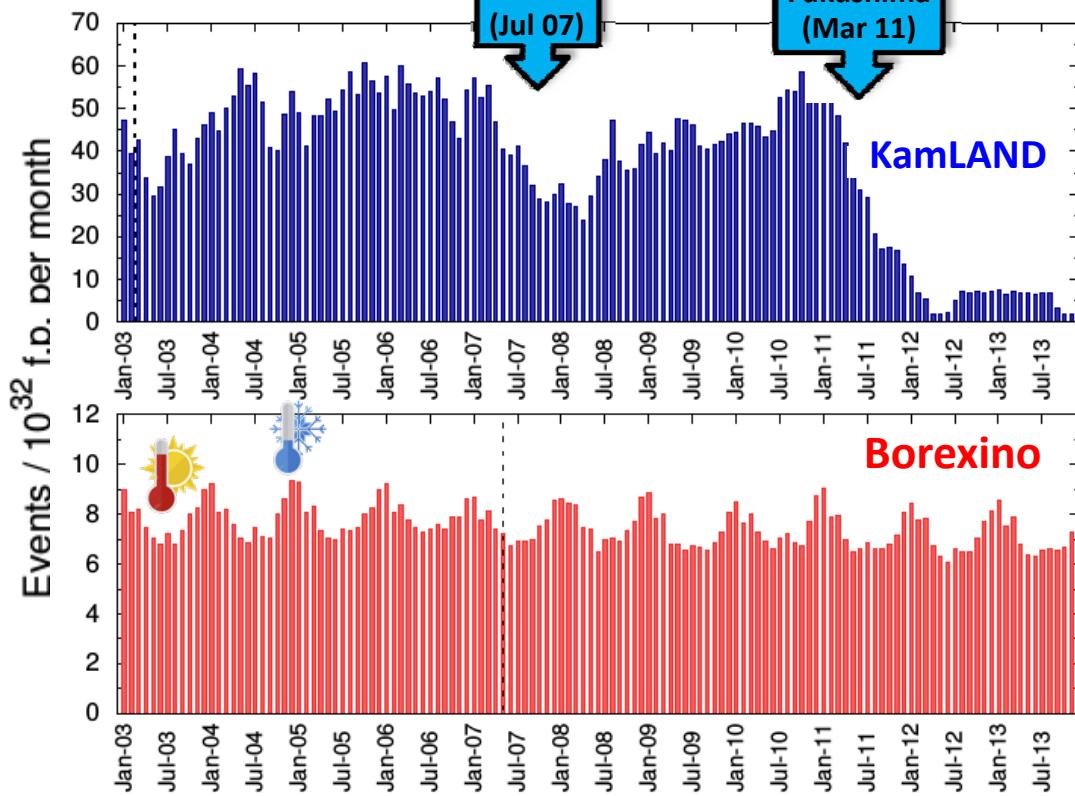


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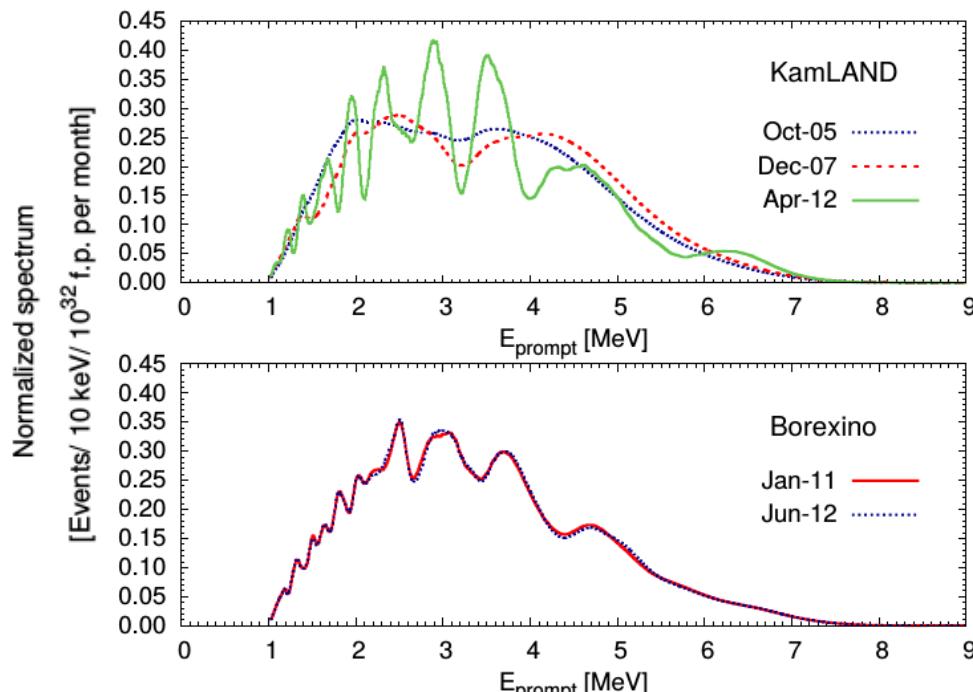


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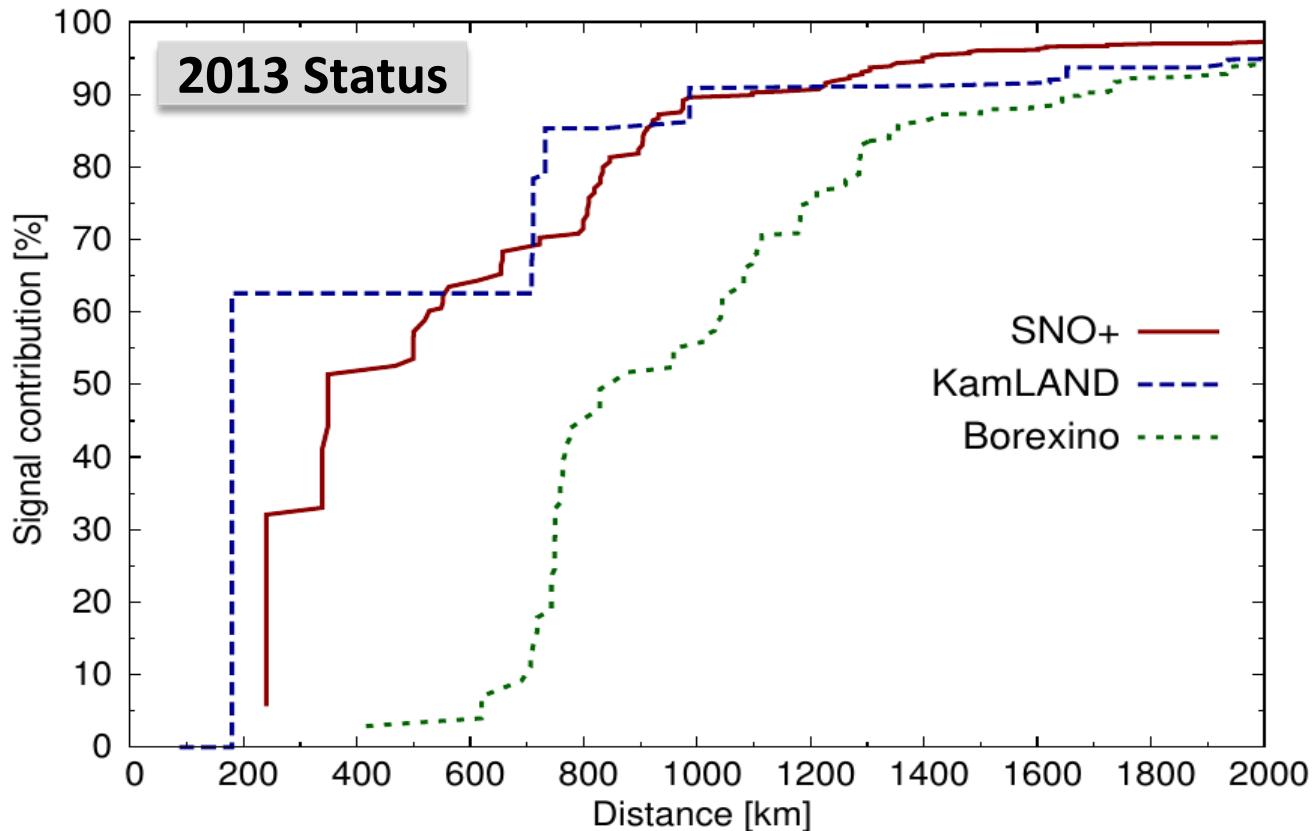


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Borexino, KamLAND and SNO+ signal distance profiles



KamLAND 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)

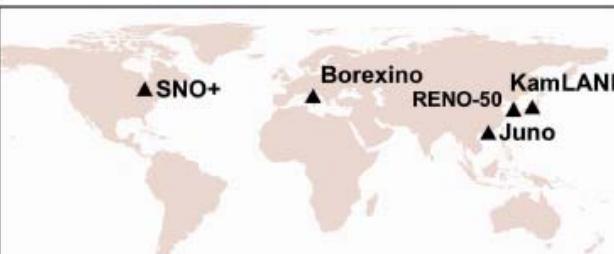
SNO+ profile has 2 major discontinuities

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

Borexino profile is **smooth**

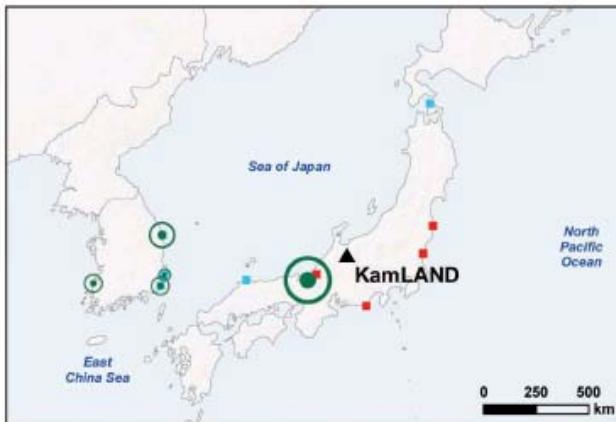
- ✓ Signal **spread out** over the European countries
- ✓ Closest power station at **415 km** (Slovenia) gives the major fraction of the signal (~3%)

A live reference model



Operating reactors

- 0.1 - 5 %
- 5 - 10 %
- 10 - 40 %
- 40 - 90 %
- Permanent shut down ($P_{th} > 100$ MW)
- Under construction

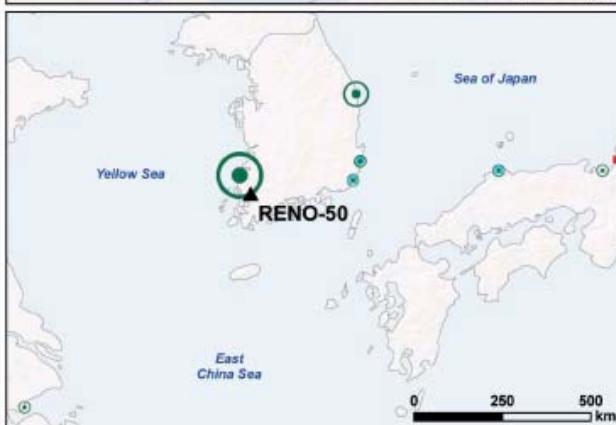
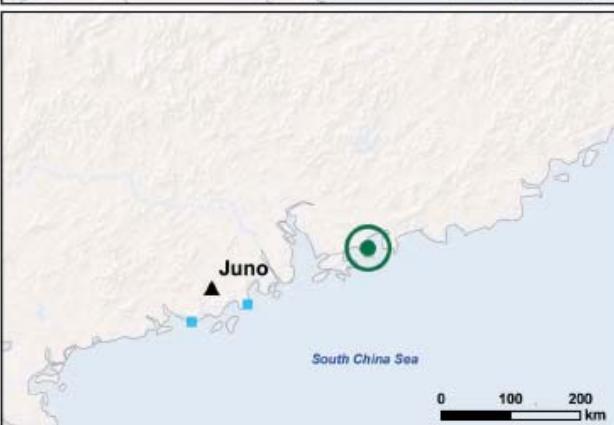
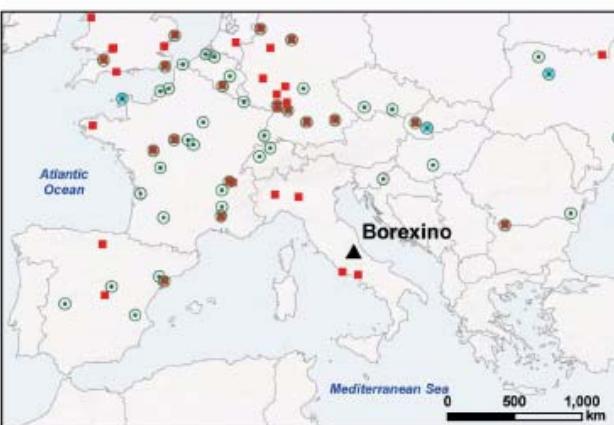


✓ **Borexino:** ~50% of the signal from a 10^3 km radius by ~50 reactors. **Single core temporal profile is not relevant.**

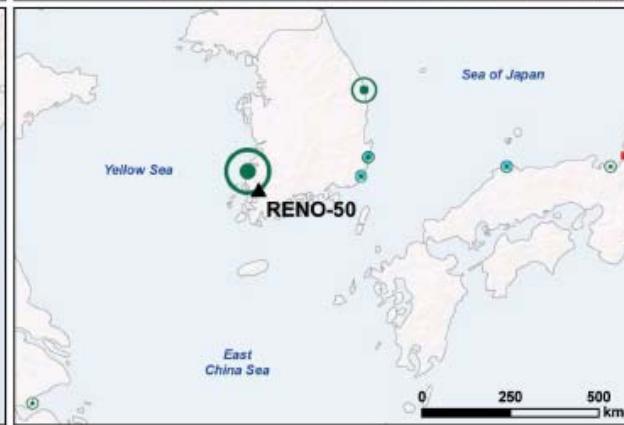
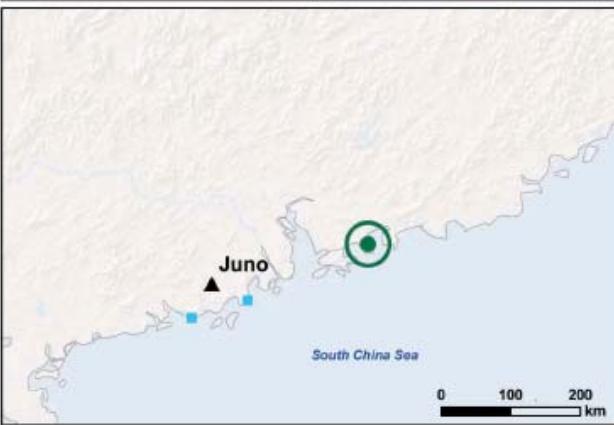
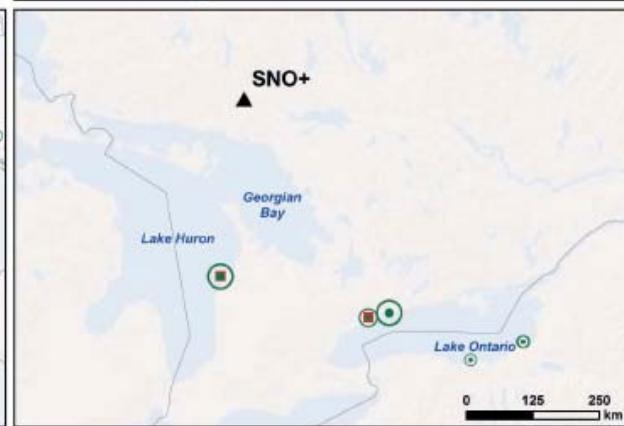
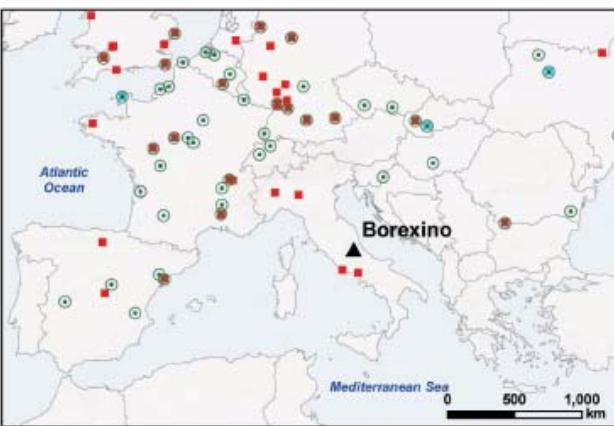
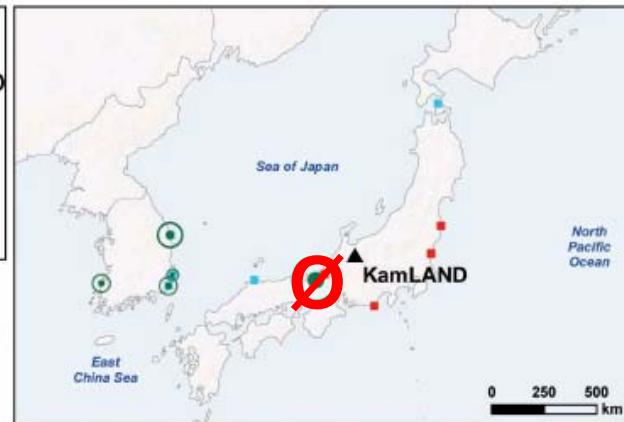
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✓ **JUNO:** in 2013 **Guangdong** and **Ling Ao** gave 90% of the signal. After **2020** their contribution will be **6%**.

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



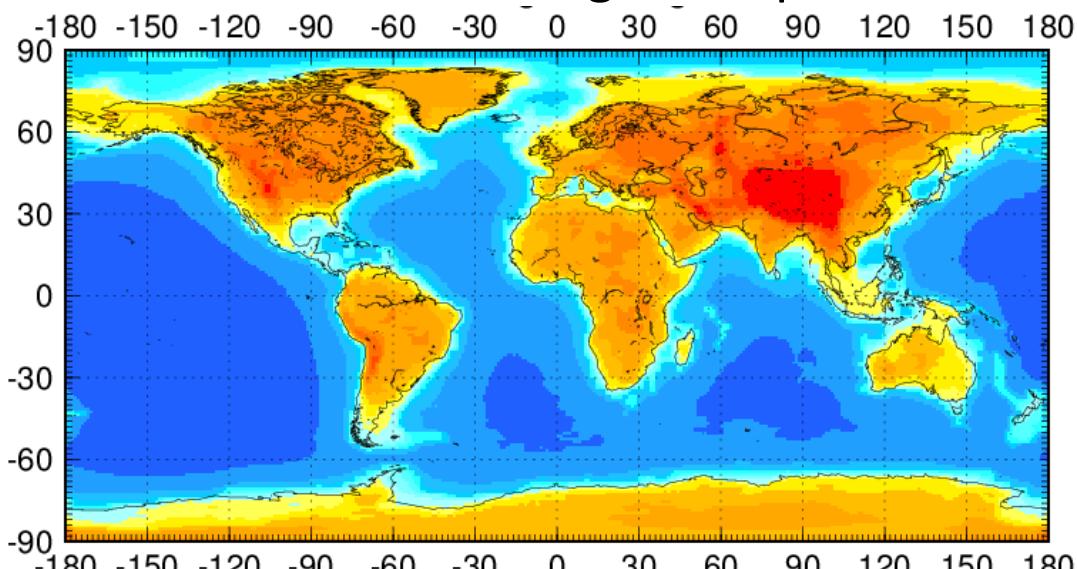
A live reference model



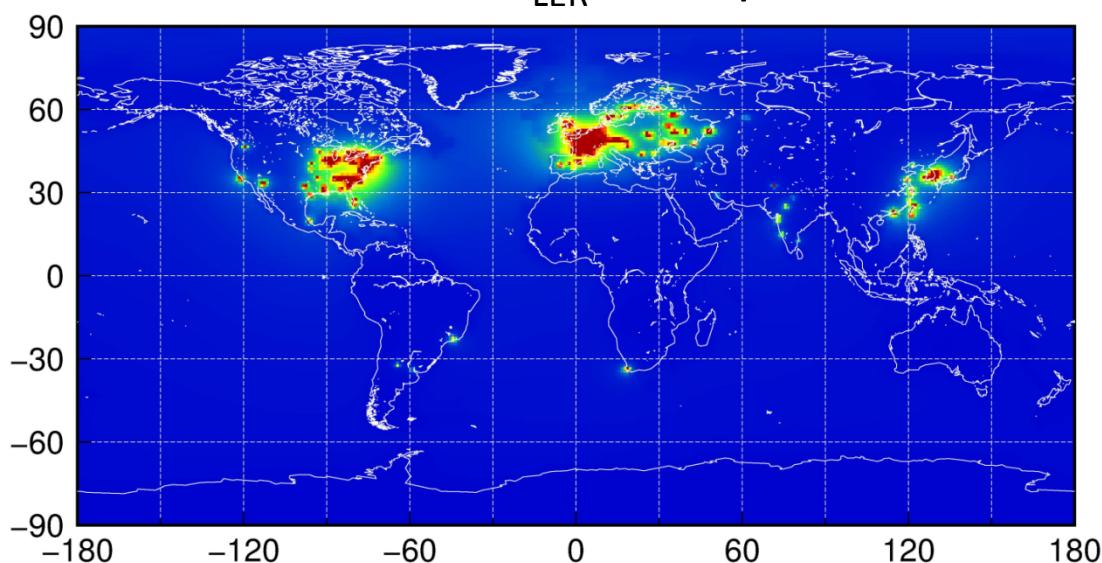
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Geoneutrinos and reactor antineutrinos across the world

Geov signal map



$r = R_{LER}/G$ map



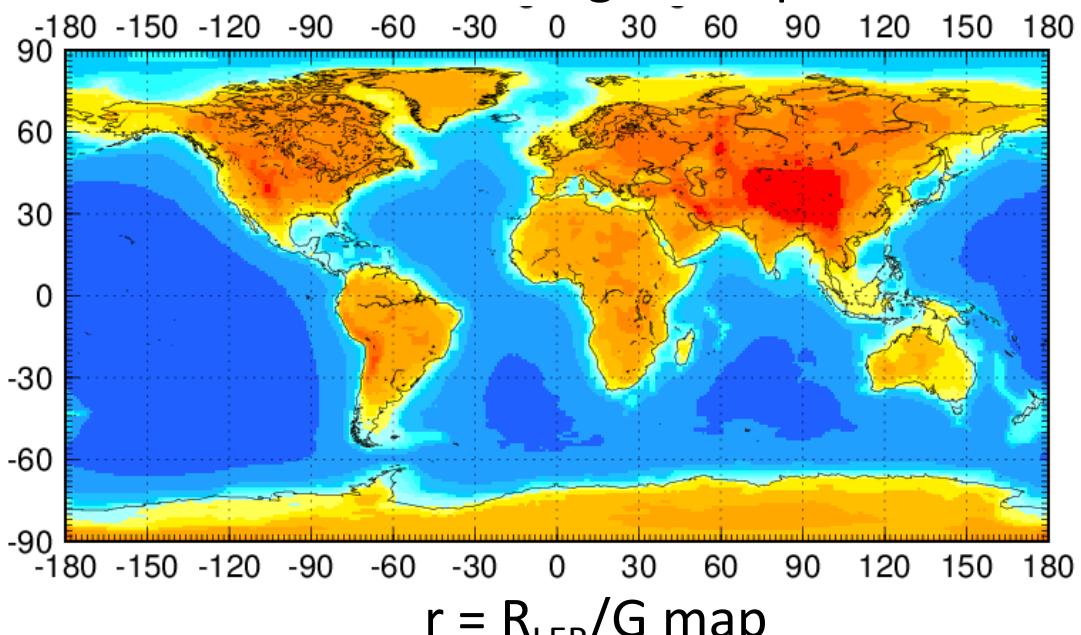
✓ The **geoneutrino signal is constant** and it has a **continental distribution**

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

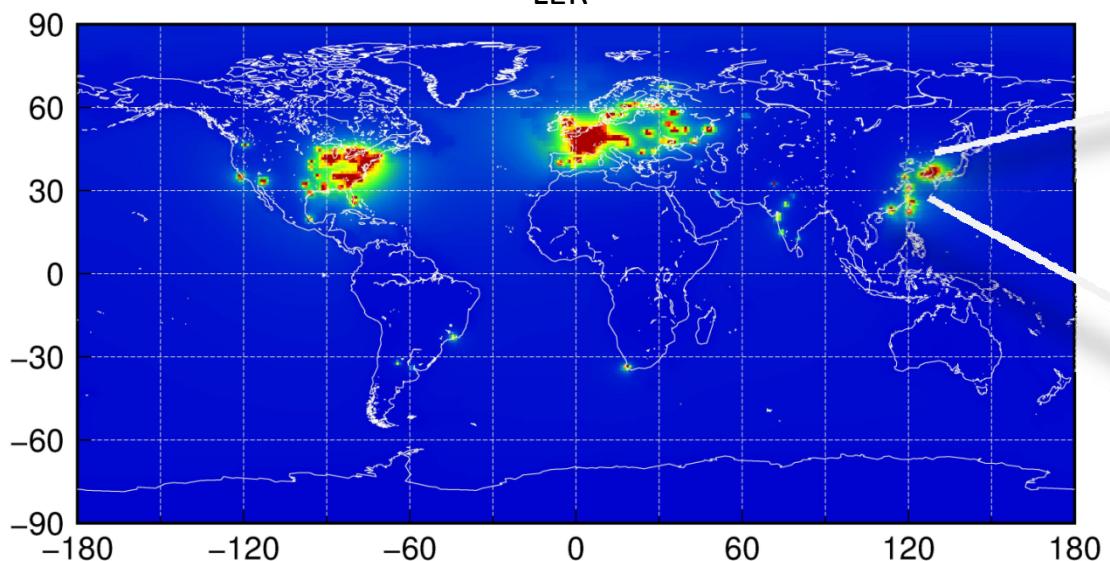
✓ The ratios $r = R_{LER}/G$ are **time dependent**

Geoneutrinos and reactor antineutrinos across the world

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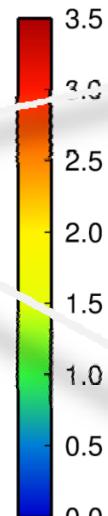
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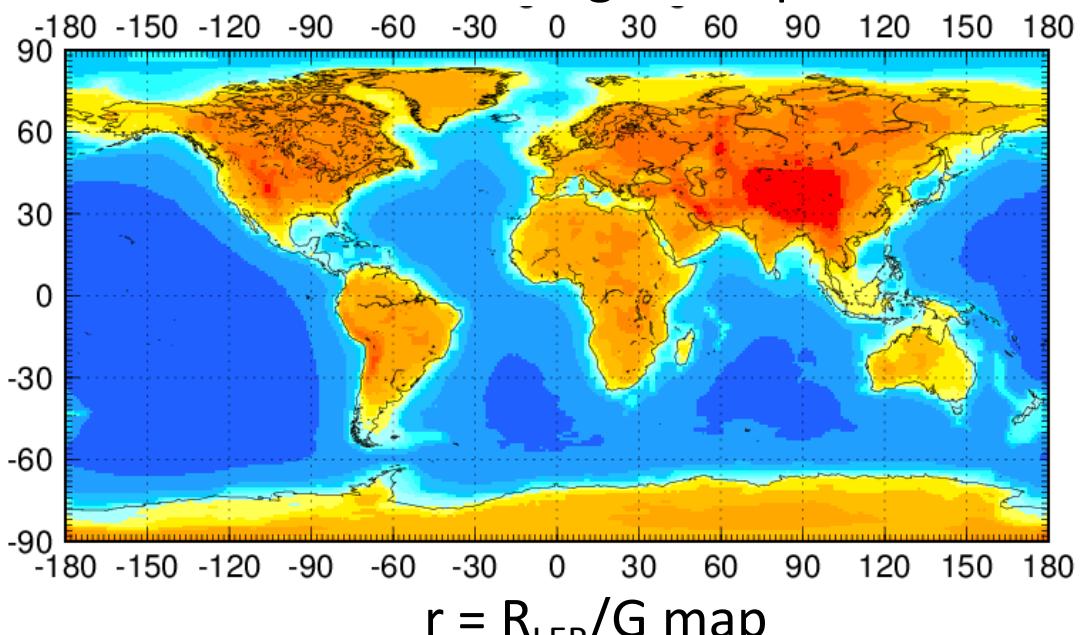
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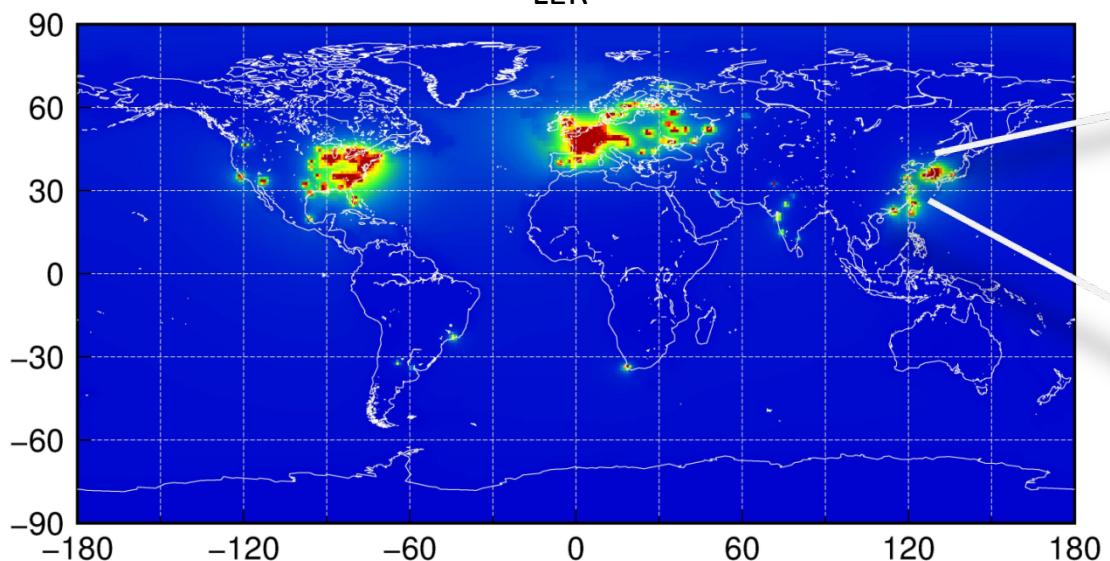


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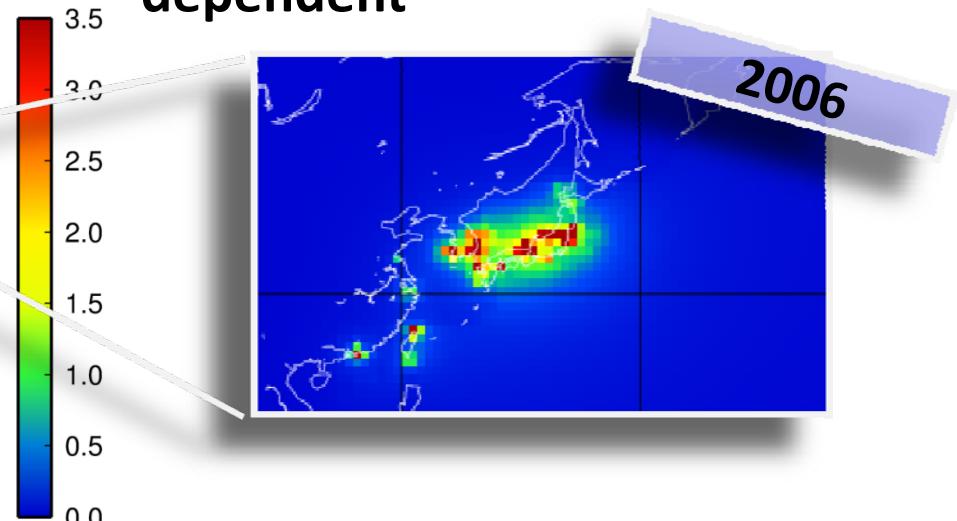
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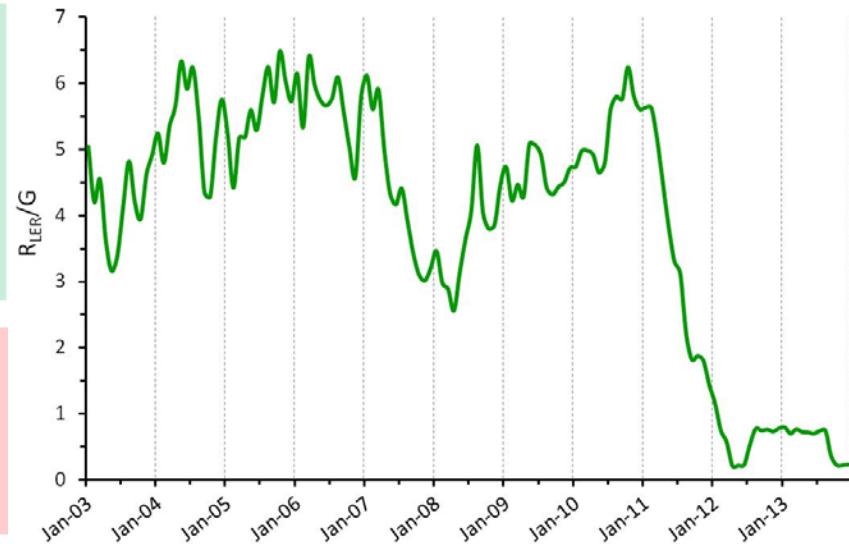


Conclusions

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



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 $\sim 4\%$ 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 $\sim 2.4\%$