

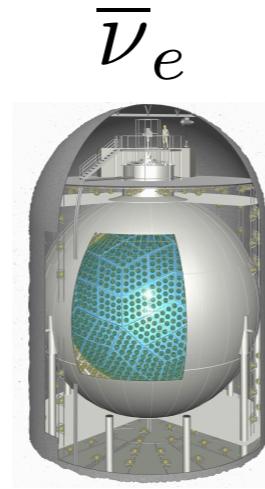
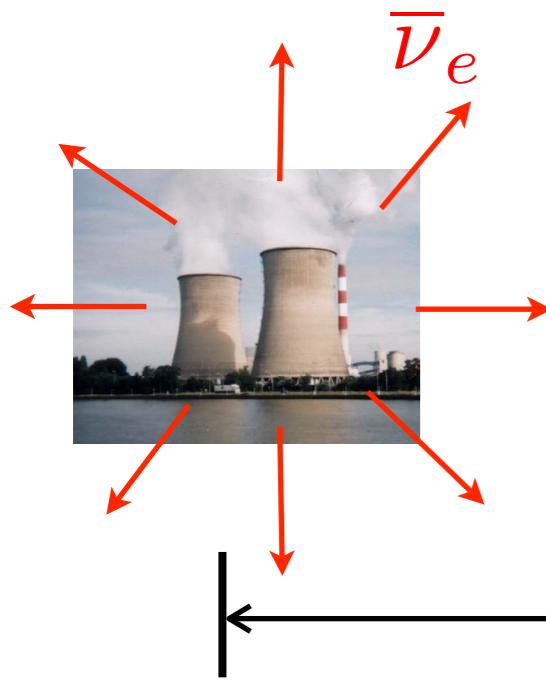
Measuring Terrestrial and Solar Neutrinos with KamLAND

Patrick Decowski
for the KamLAND Collaboration

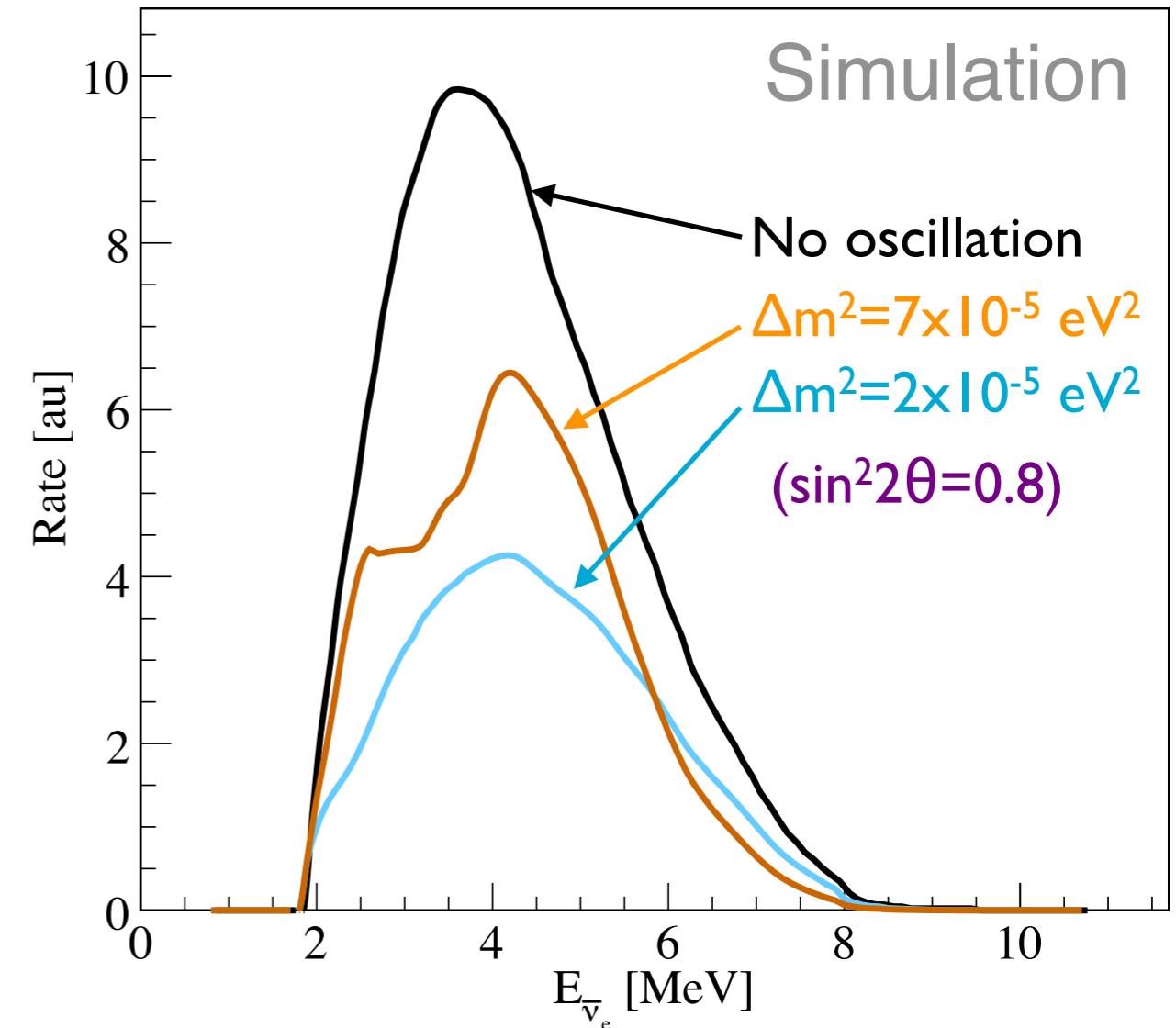
Nikhef, Amsterdam

Rencontres de Moriond EW 2010

Reactors for Oscillation Studies

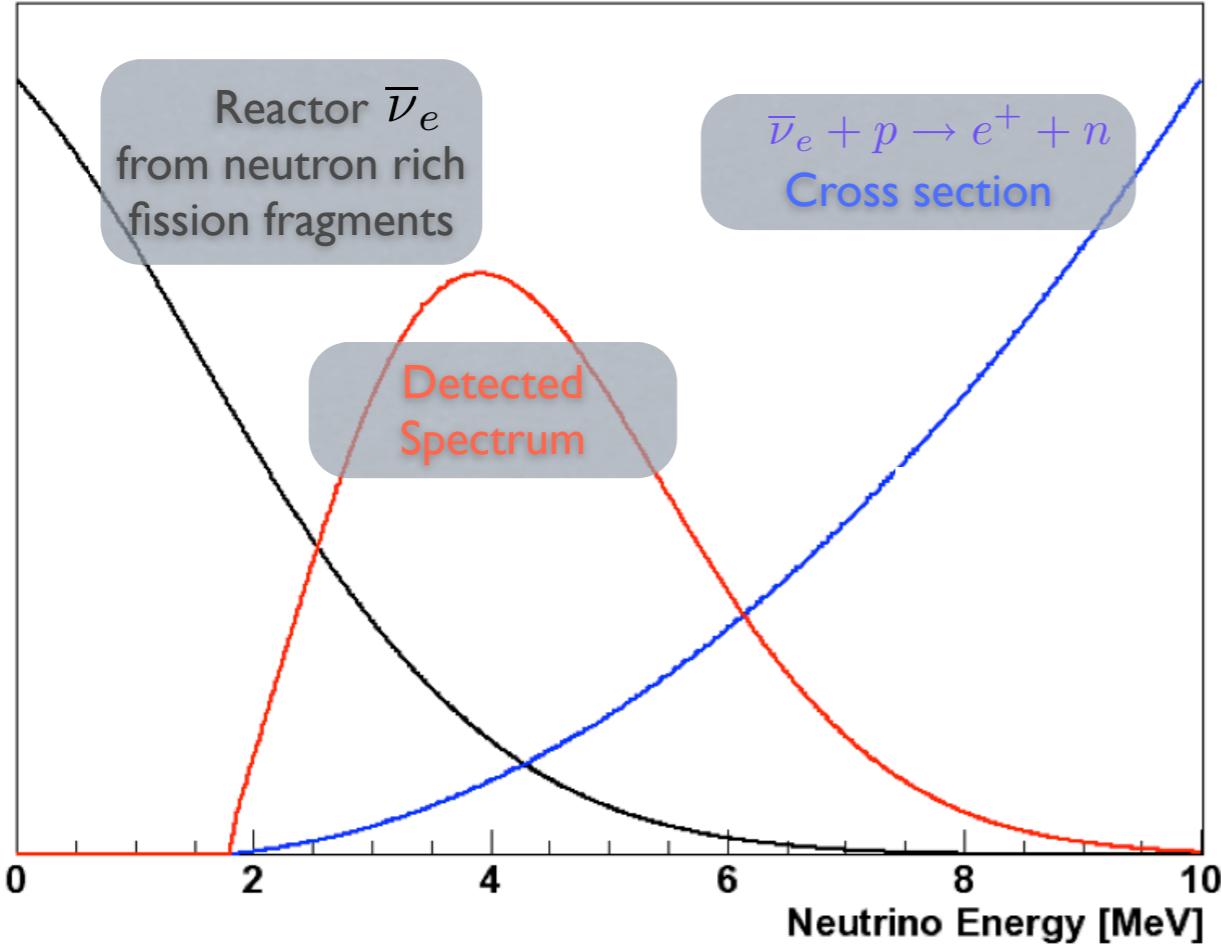


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2 L}{E}$$

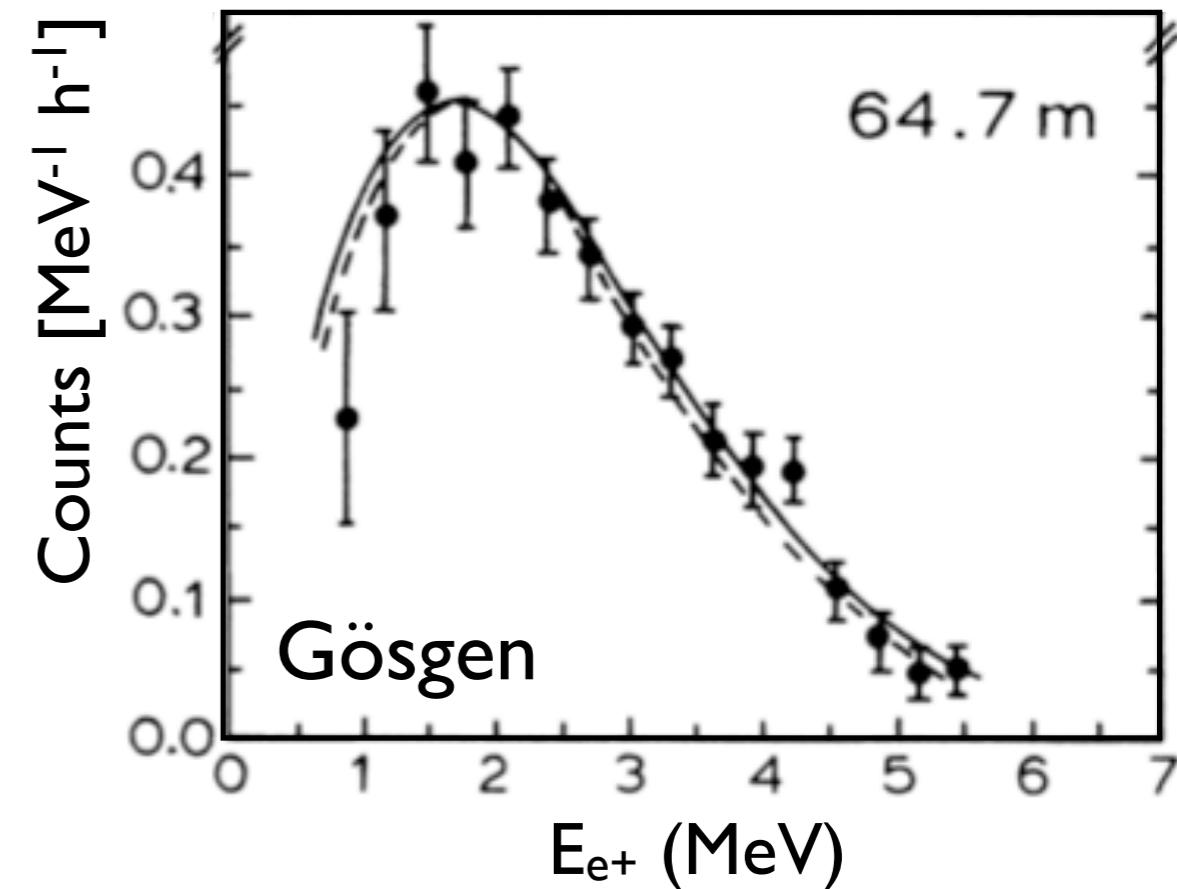


Neutrino oscillation changes the overall **normalization** and **shape** of the spectrum

Detected Reactor Spectrum



Zacek G. et al., Phys. Rev. D34, 2621 (1986).



- $\bar{\nu}_e$ produced in β -decay of fission products
 - Only ^{238}U , ^{235}U , ^{239}Pu , ^{241}Pu contribute significantly
- Fission rates are provided by reactor companies
 - Mainly function of thermal power
- Calculated spectrum has been verified to 2% accuracy in past reactor experiments

KamLAND detector

- 1 kton Scintillation Detector

- 6.5m radius balloon filled with:

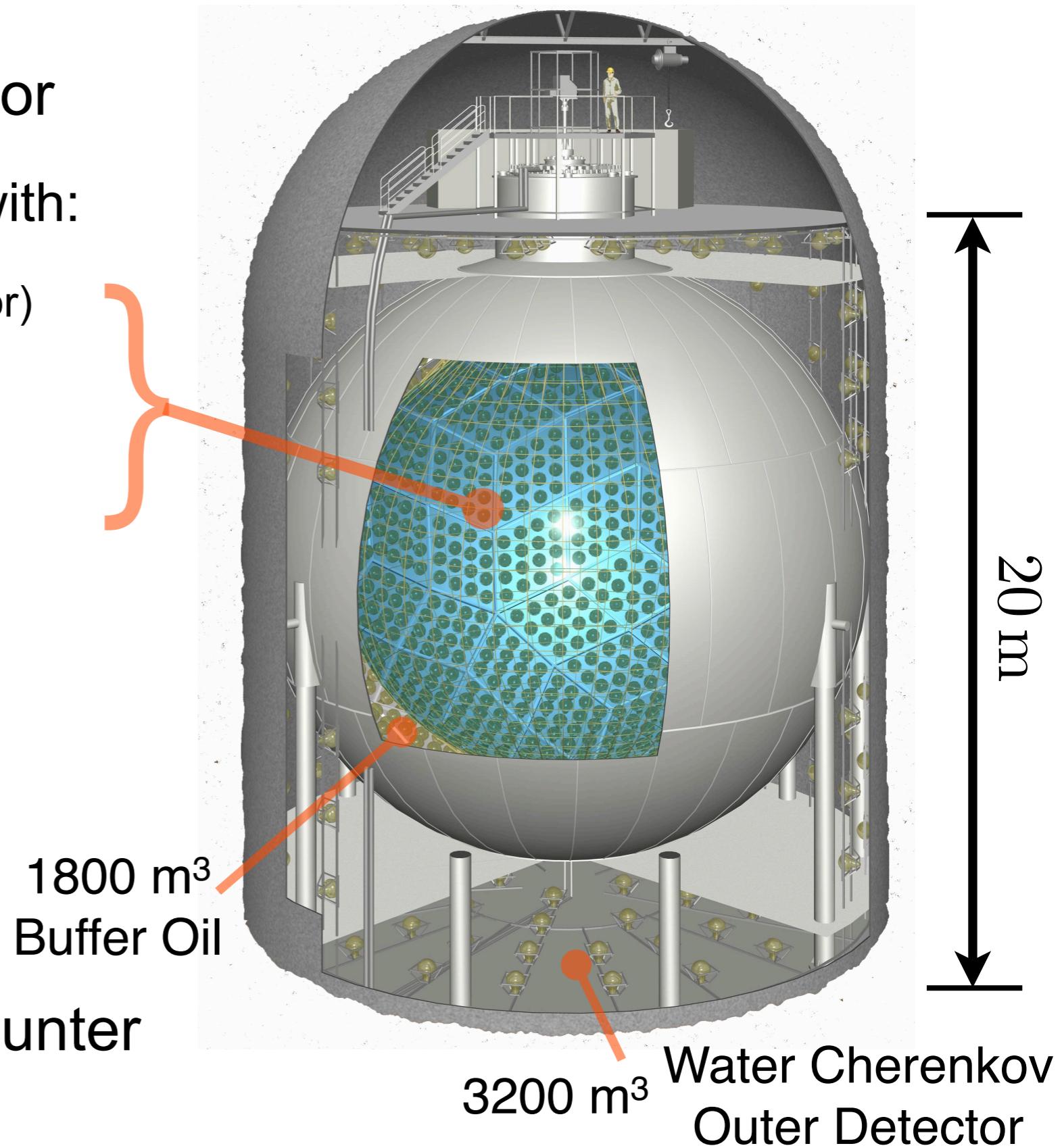
- 20% Pseudocumene (scintillator)
- 80% Dodecane (oil)
- PPO

- 34% PMT coverage

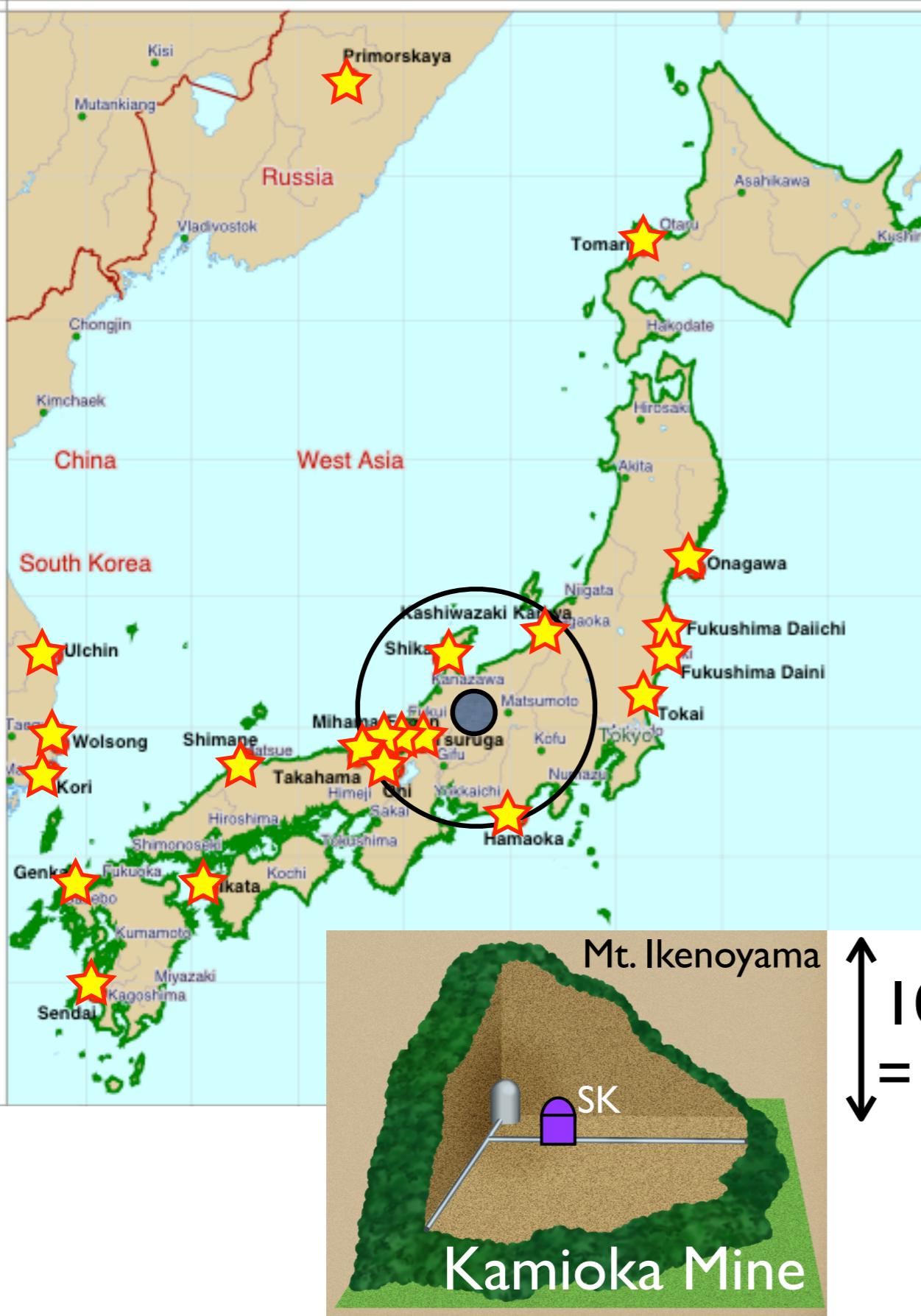
- ~1300 17" fast PMTs
- ~550 20" large PMTs

- Multi-hit electronics

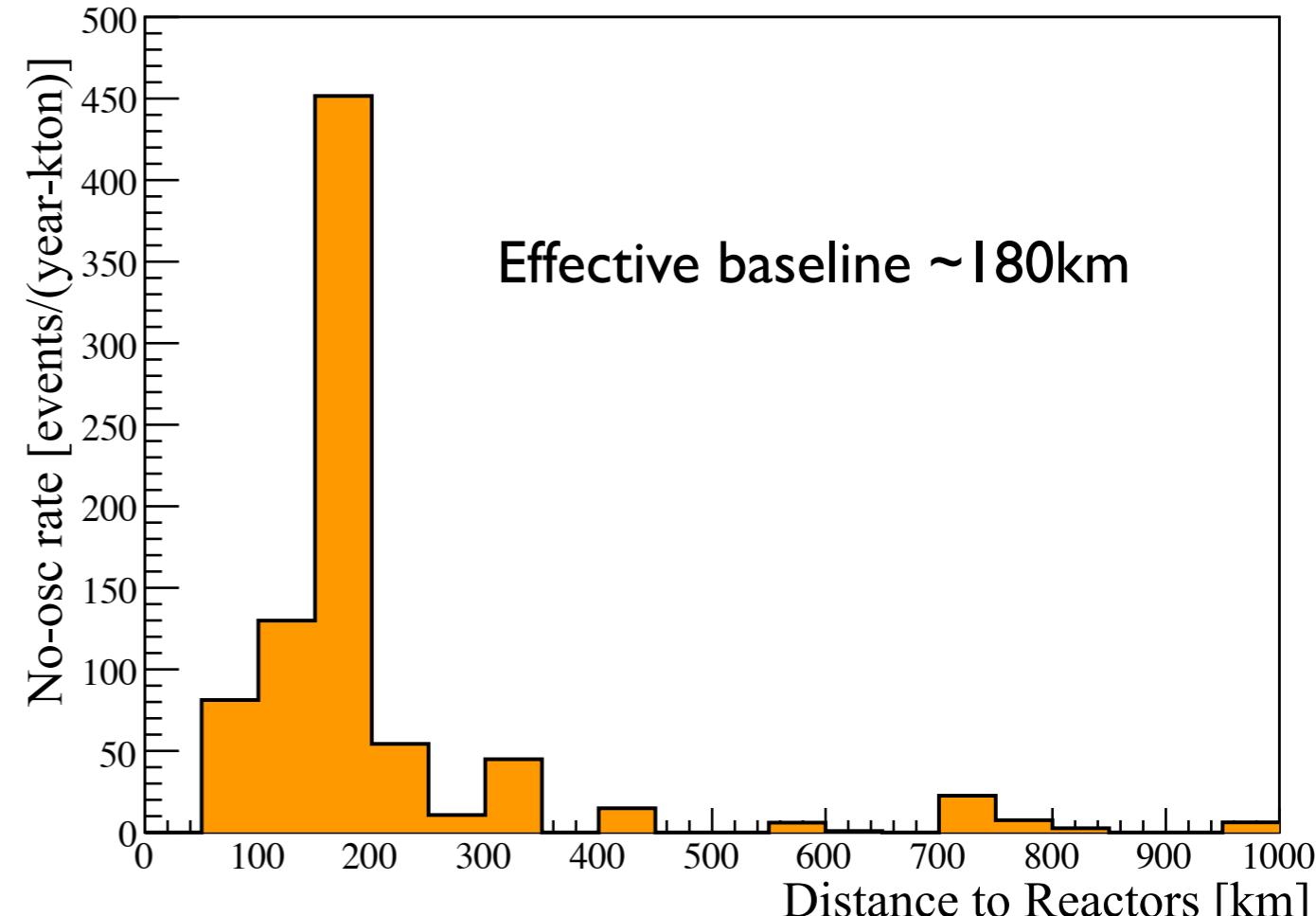
- Water Cherenkov veto counter



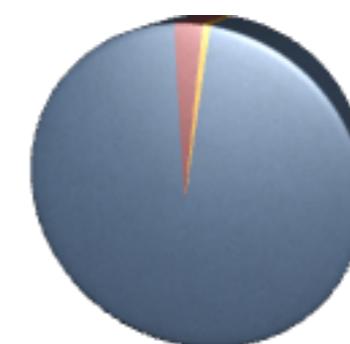
$\bar{\nu}_e$ from 55 Reactor Cores in Japan



70 GW (7% of world total) is generated
at 130-220 km distance from Kamioka



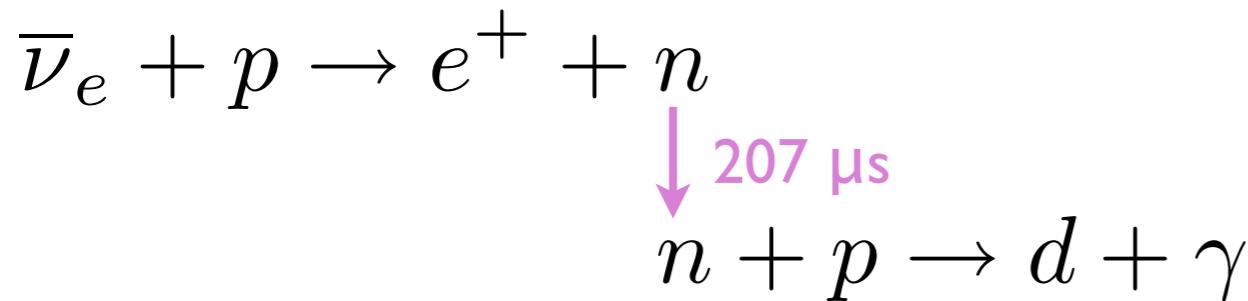
Reactor neutrino flux:
 $\sim 6 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$



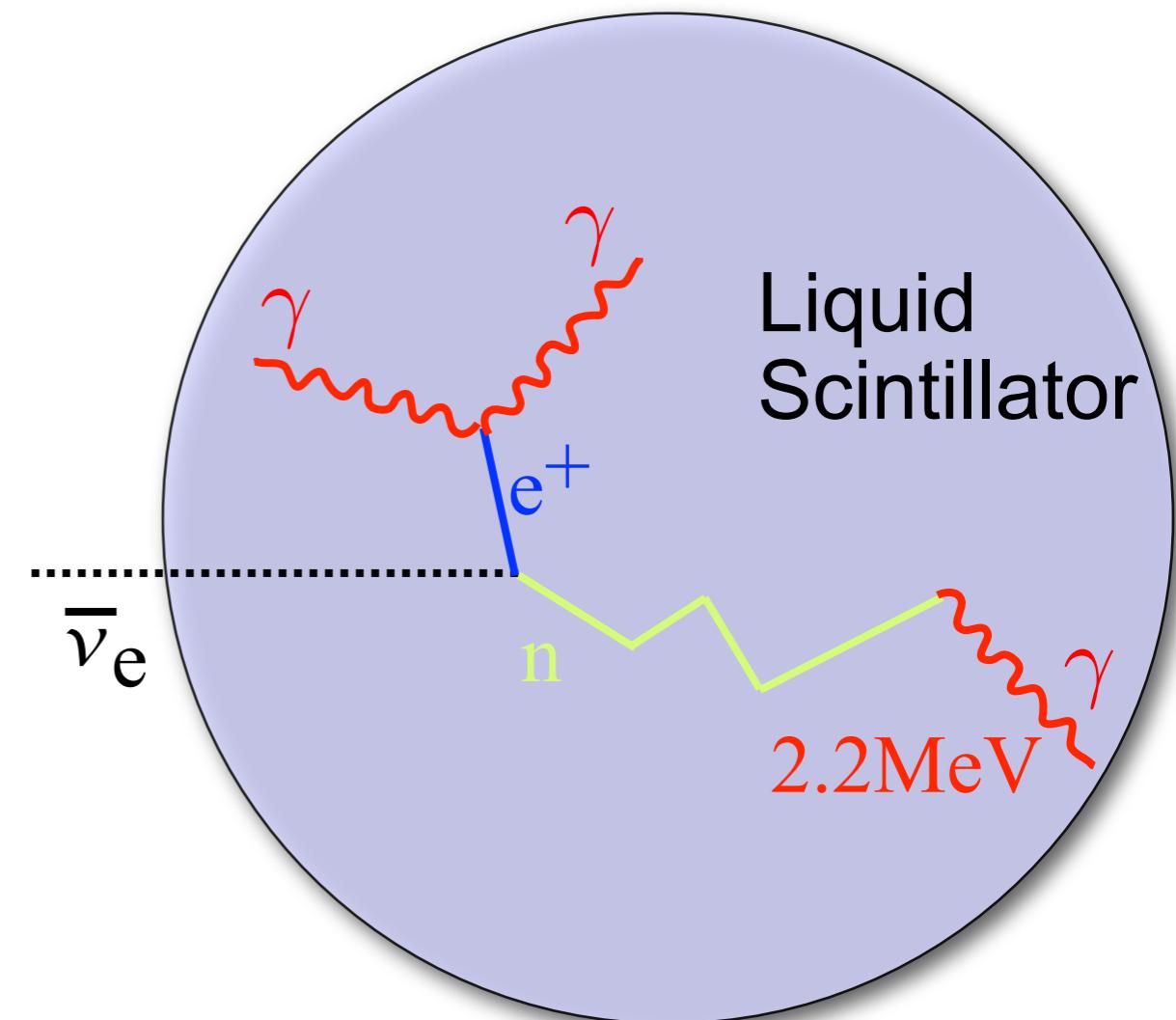
- Japan
- Korean
- World

Anti-Neutrino Detection Method

Inverse beta decay



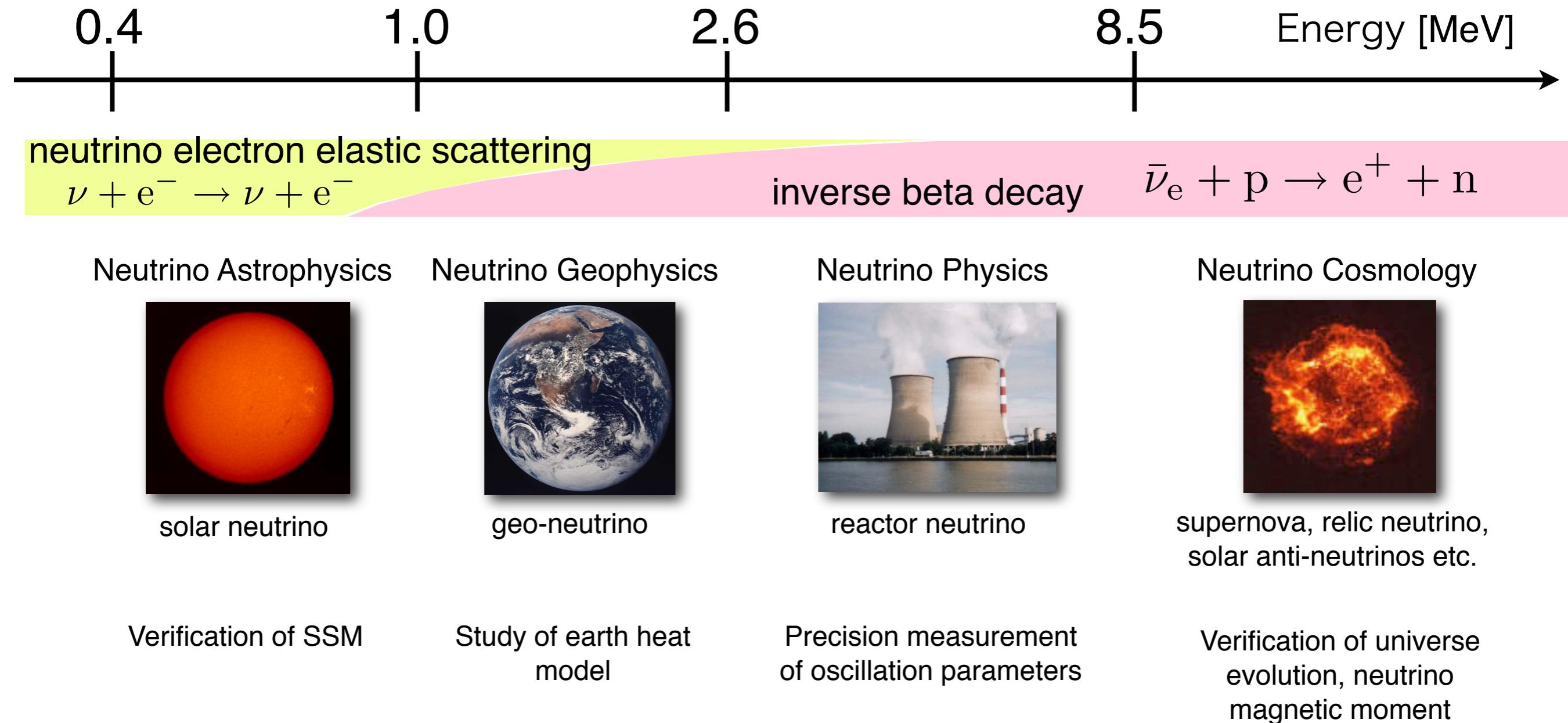
Scintillator is both target and detector



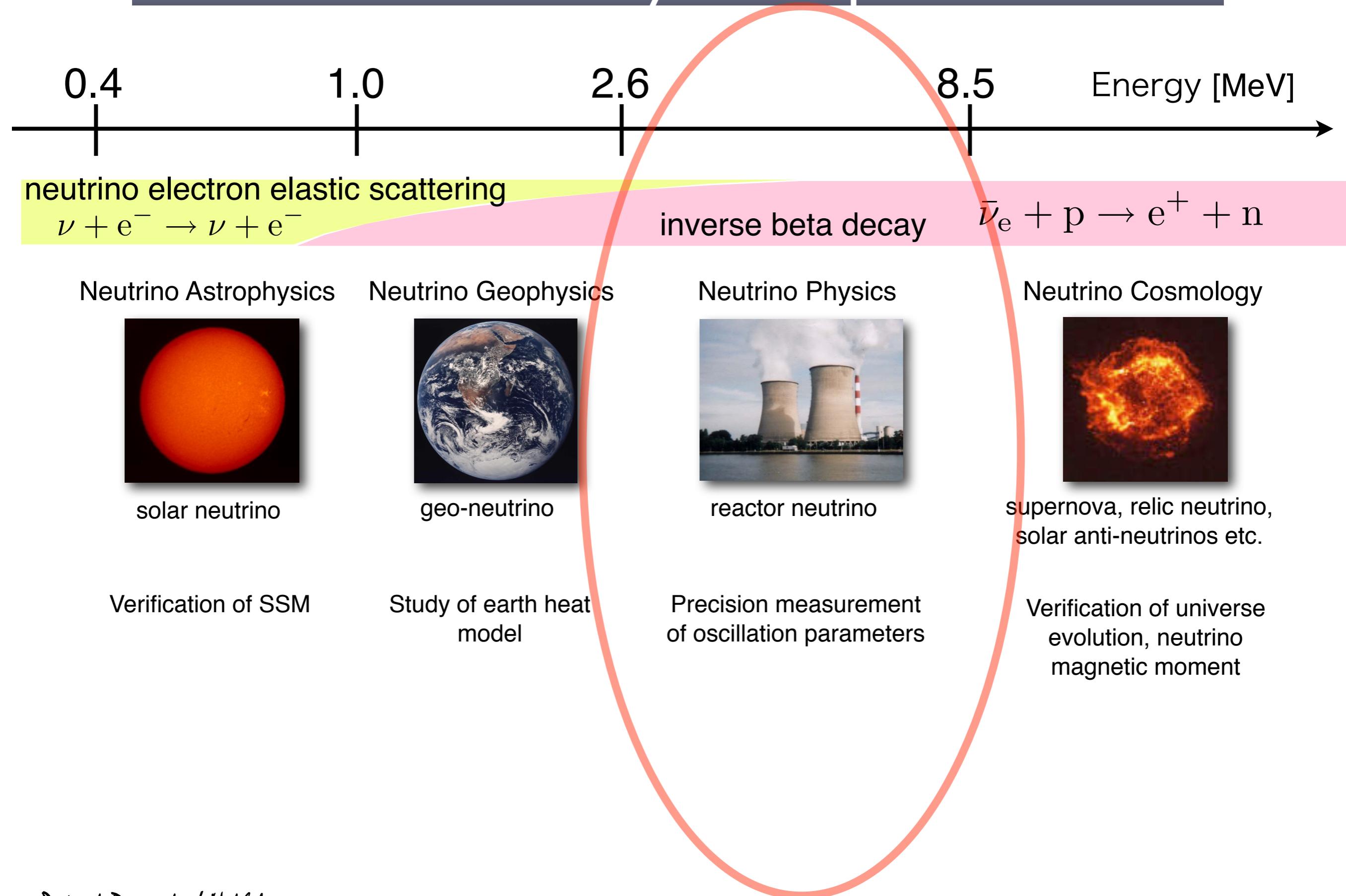
- Distinct two step process:
 - prompt event: positron
 - $E_{\bar{\nu}_e} \simeq E_{prompt} + 0.8 MeV$
- delayed event: neutron capture after $\sim 207 \mu s$
 - 2.2 MeV gamma

Delayed coincidence: good background rejection

KamLAND Physics Capabilities



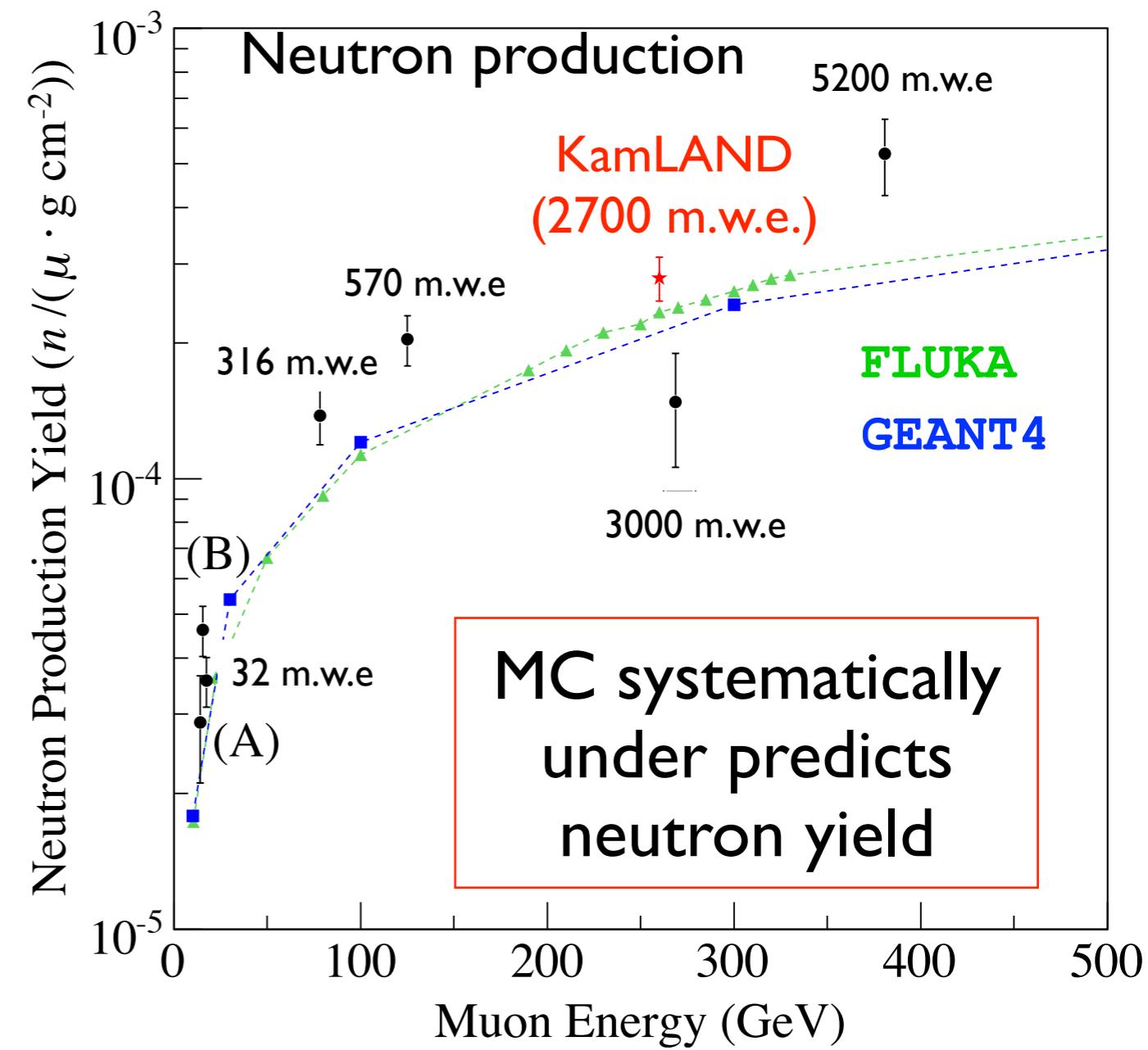
KamLAND Physics Capabilities



Neutron Production through Muon Spallation

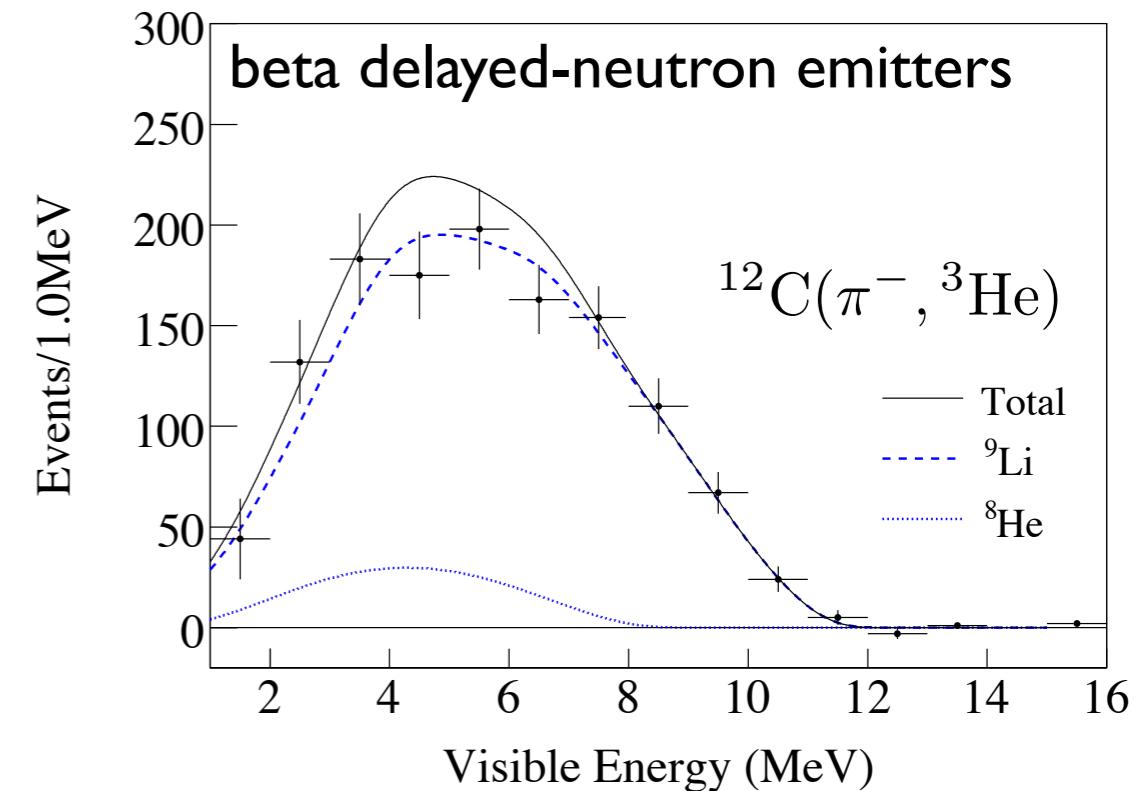
PRC 81, 025807 (2010) [arXiv:0907.0066].

- Detailed study of neutron and radioactive isotopes in muon-initiated spallation
- Important backgrounds for many low rate experiments
 - Dark Matter, $0\nu2\beta$, Neutrino...
- Comparison to two widely-used simulations:
 - FLUKA
 - GEANT4



Production of Radioactive Isotopes

Most radioactive spallation products are produced when the muon deposits a large amount of energy in the scintillator (“showering muons”)

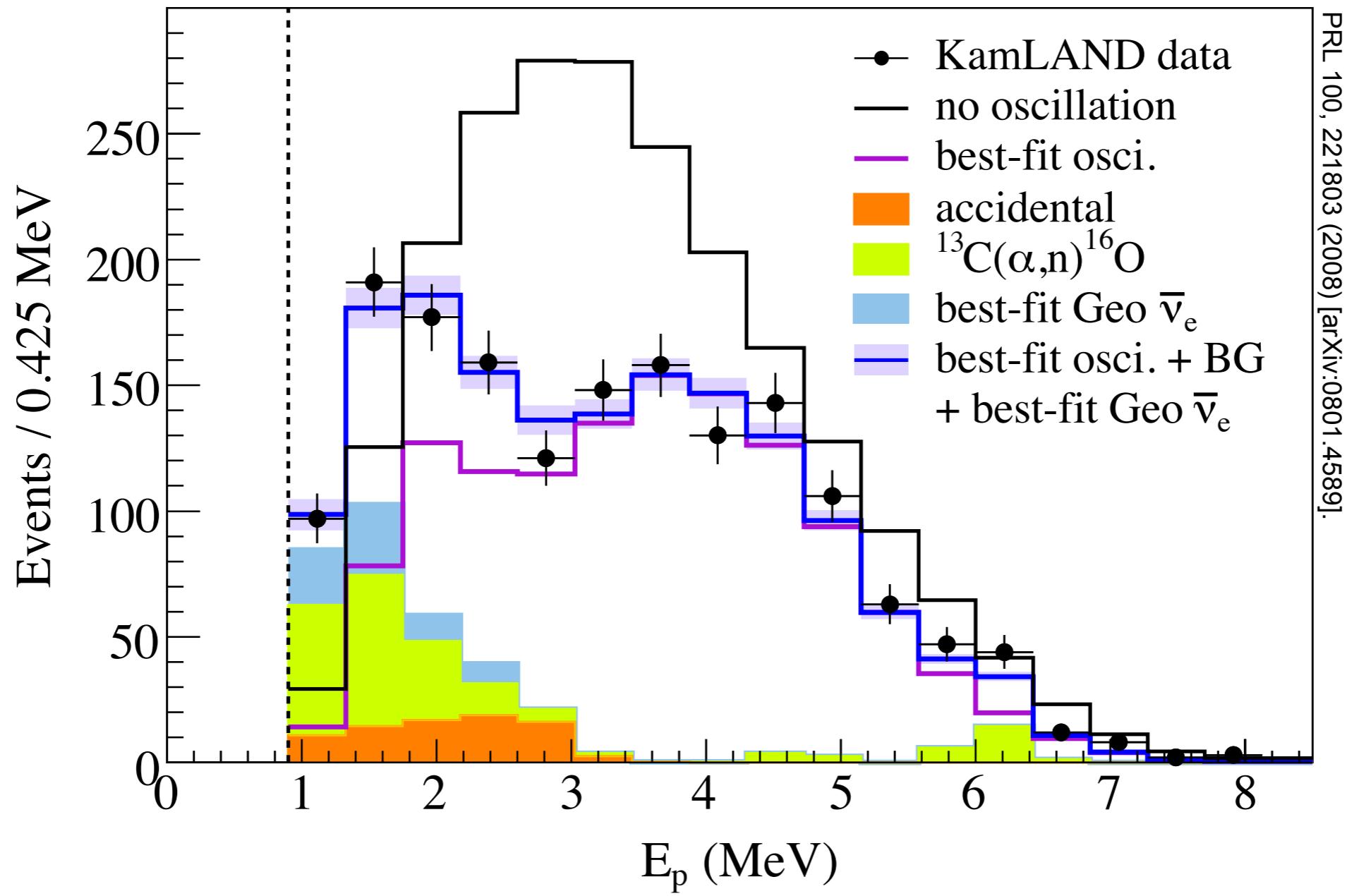


	Lifetime in KamLAND LS	Radiation Energy	Spallation Production Yield ($\times 10^{-7} (\mu \cdot (\text{g/cm}^2))^{-1}$)			Fraction from showering μ this measurement
			Hagner, <i>et al.</i>	FLUKA	KamLAND	
n	$207.5 \mu\text{s}$	$2.225 \text{ MeV} (\text{capt. } \gamma)$	—	2097 ± 13	2787 ± 311	$64 \pm 5\%$
${}^{12}\text{B}$	29.1 ms	$13.4 \text{ MeV} (\beta^-)$	—	27.8 ± 1.9	42.9 ± 3.3	$68 \pm 2\%$
${}^{12}\text{N}$	15.9 ms	$17.3 \text{ MeV} (\beta^+)$	—	0.77 ± 0.08	1.8 ± 0.4	$77 \pm 14\%$
${}^8\text{Li}$	1.21 s	$16.0 \text{ MeV} (\beta^- \alpha)$	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6	$65 \pm 17\%$
${}^8\text{B}$	1.11 s	$18.0 \text{ MeV} (\beta^+ \alpha)$	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4	$78 \pm 23\%$
${}^9\text{C}$	182.5 ms	$16.5 \text{ MeV} (\beta^+)$	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2	$91 \pm 32\%$
${}^8\text{He}$	171.7 ms	$10.7 \text{ MeV} (\beta^- \gamma n)$	$\} 1.0 \pm 0.3$	0.32 ± 0.05	0.7 ± 0.4	$76 \pm 45\%$
${}^9\text{Li}$	257.2 ms	$13.6 \text{ MeV} (\beta^- \gamma n)$		3.16 ± 0.25	2.2 ± 0.2	$77 \pm 6\%$
${}^{11}\text{C}$	29.4 min	$1.98 \text{ MeV} (\beta^+)$	421 ± 68	416 ± 27	866 ± 153	$62 \pm 10\%$
${}^{10}\text{C}$	27.8 s	$3.65 \text{ MeV} (\beta^+ \gamma)$	54 ± 12	19.1 ± 1.3	16.5 ± 1.9	$76 \pm 6\%$
${}^{11}\text{Be}$	19.9 s	$11.5 \text{ MeV} (\beta^-)$	< 1.1	0.84 ± 0.09	1.1 ± 0.2	$74 \pm 12\%$
${}^6\text{He}$	1.16 s	$3.51 \text{ MeV} (\beta^-)$	7.5 ± 1.5	12.08 ± 0.83	—	—
${}^7\text{Be}$	76.9 day	$0.478 \text{ MeV (EC } \gamma)$	107 ± 21	105.3 ± 6.9	—	—

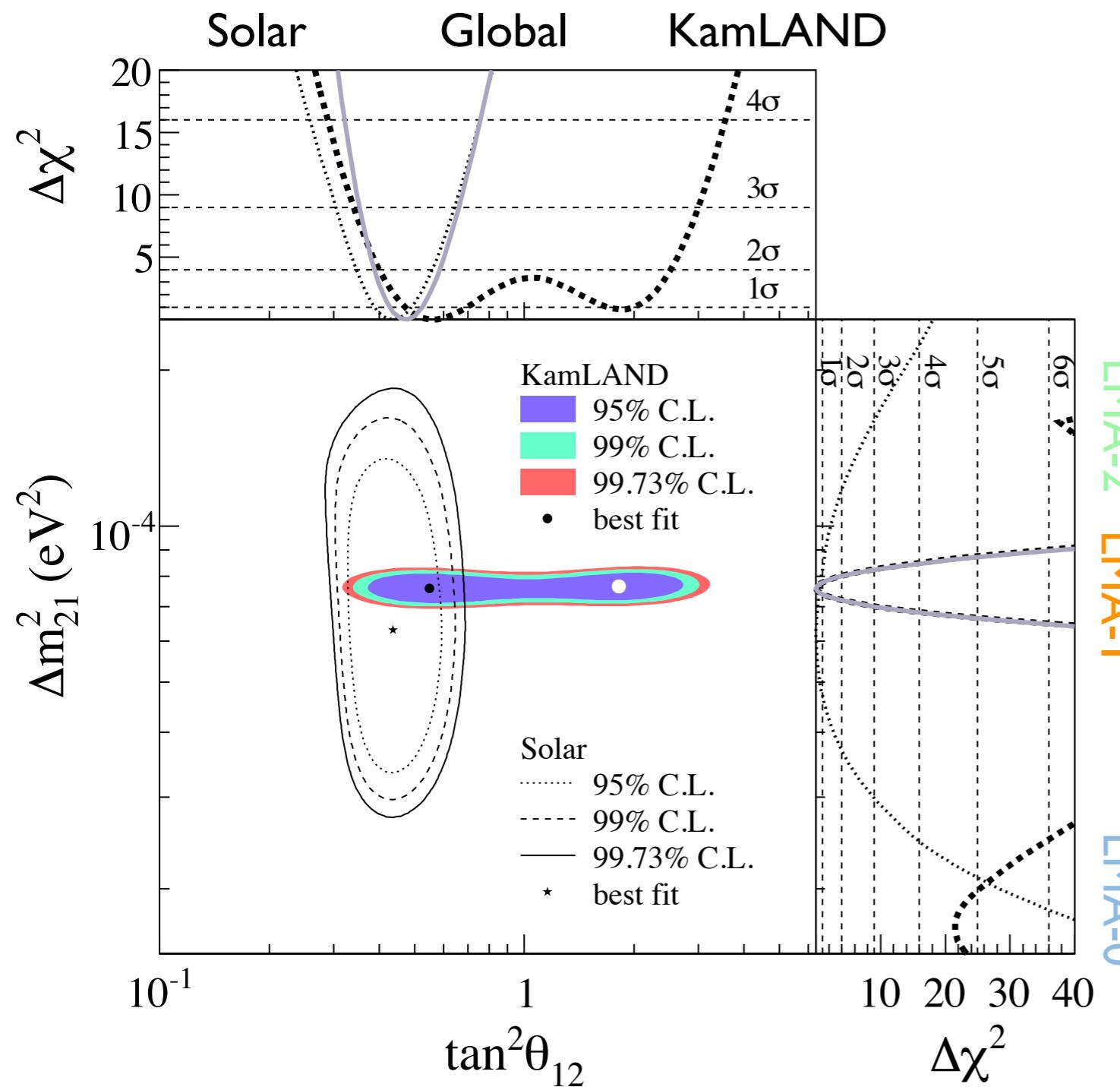
KamLAND Coll, PRC 81, 025807 (2010) [arXiv:0907.0066].

Energy Spectrum

1491 live days (2002-2007), 2881 ton-year exposure
observe 1609 candidates with 276.1 ± 23.5 background events



Neutrino Oscillation Parameters



2-nu analysis:

Best-fit light-side:

$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5} \text{ eV}^2$$

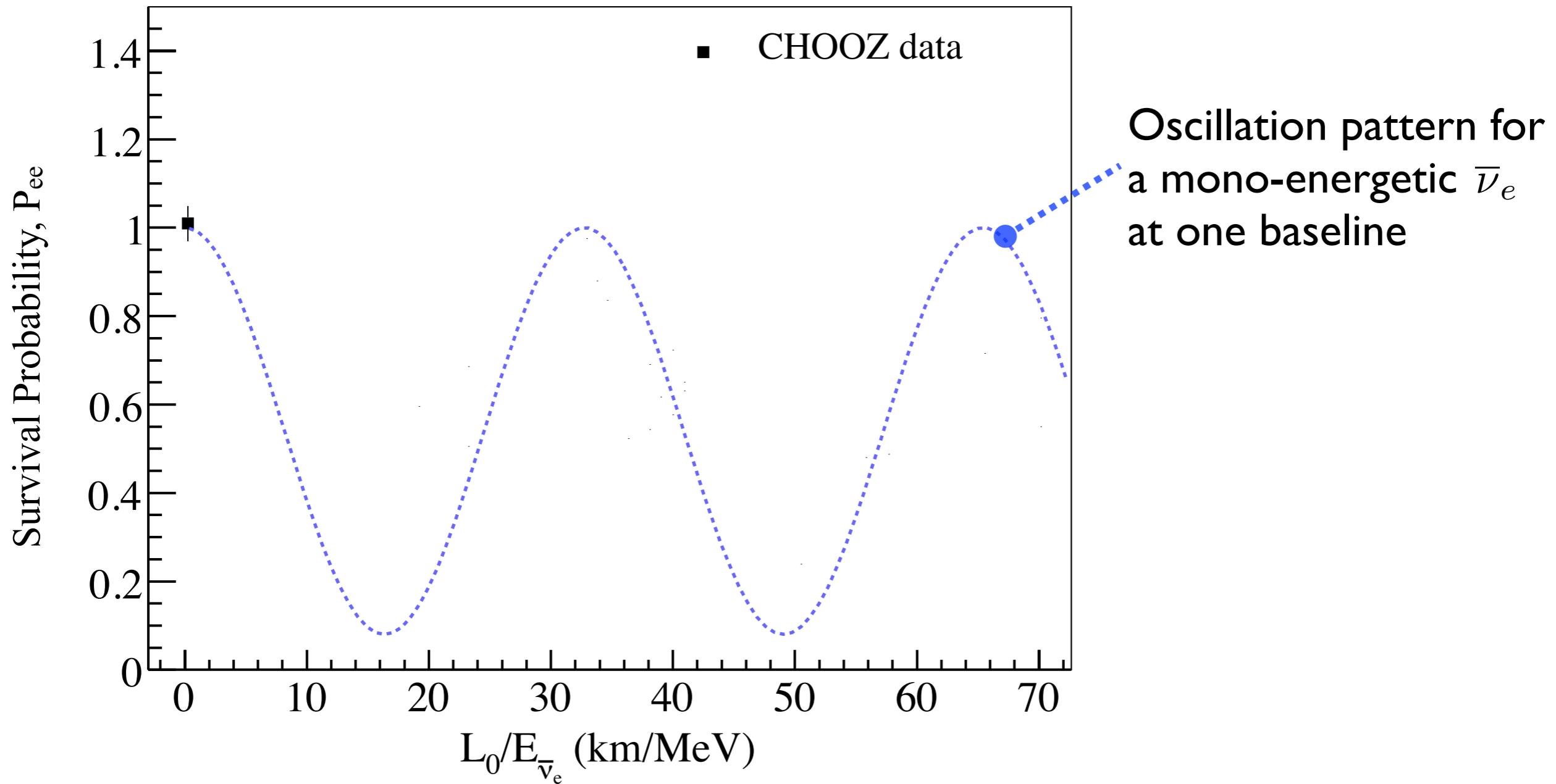
$$\tan^2 \theta = 0.56^{+0.14}_{-0.09}$$

Best-fit dark-side:

$$\Delta m^2 = 7.64 \times 10^{-5} \text{ eV}^2$$

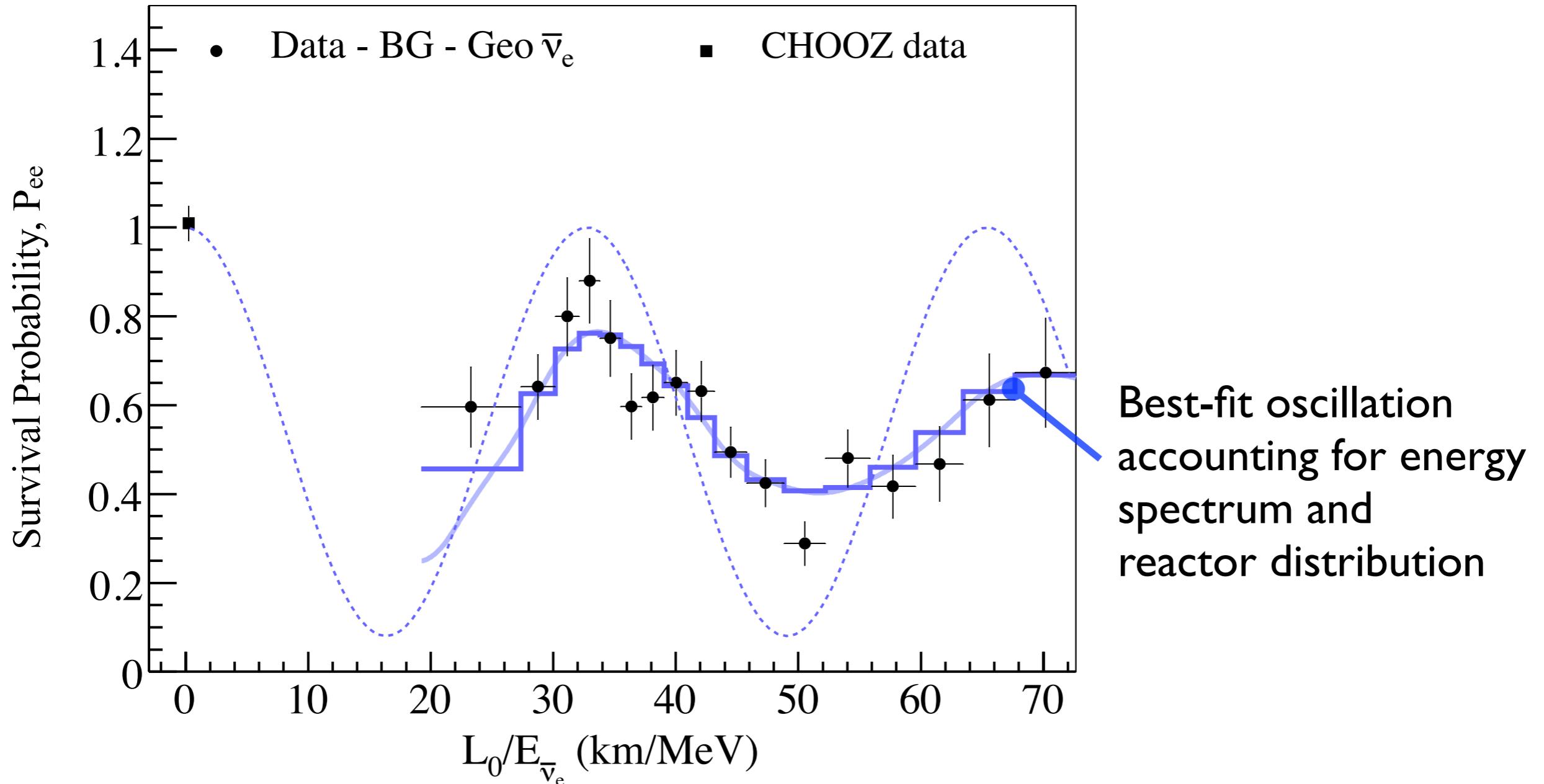
$$\tan^2 \theta = 1.84$$

Illustration of Neutrino Oscillation



$$P_{ee} = 1 - \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4} \frac{L}{E} \right)$$

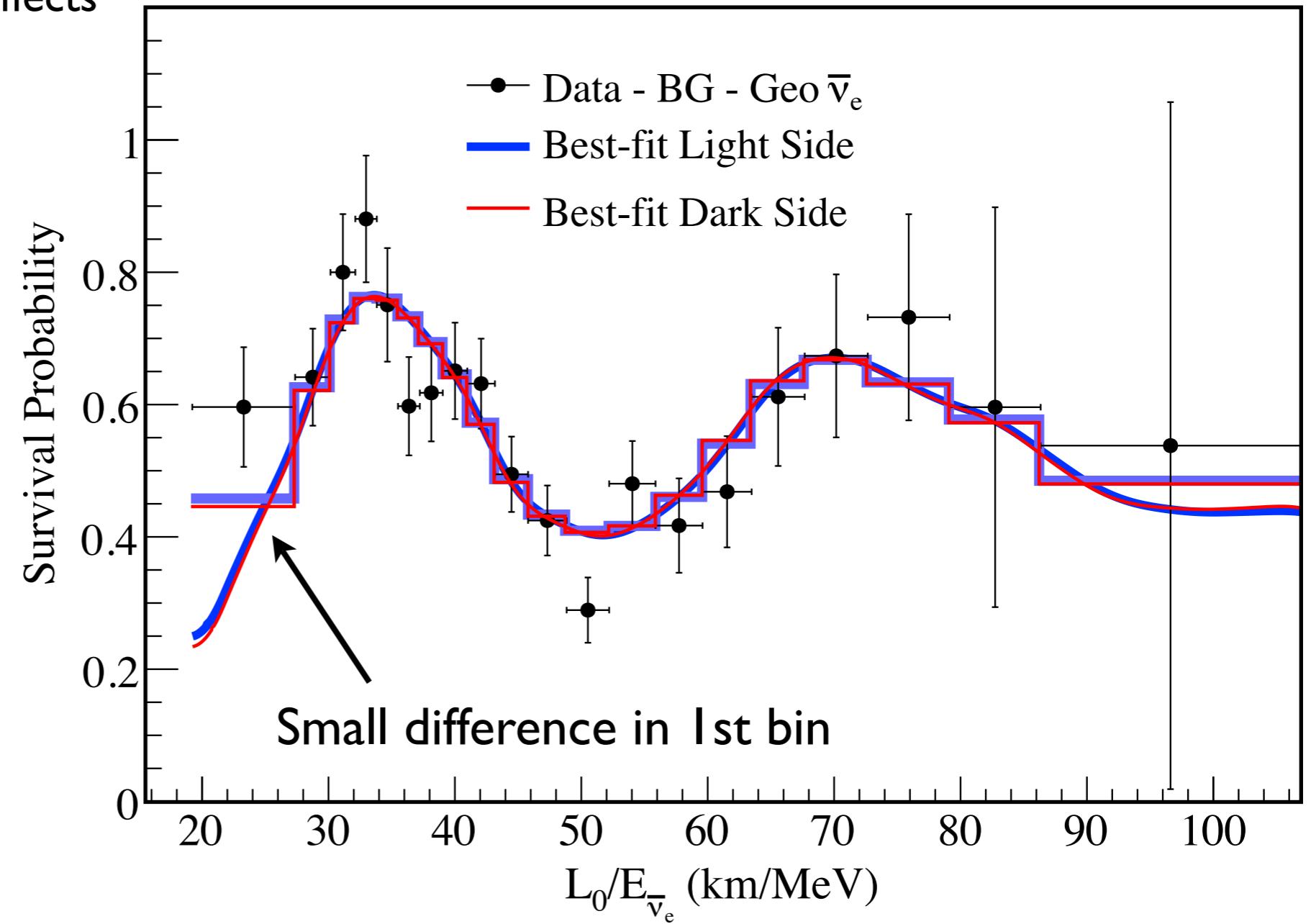
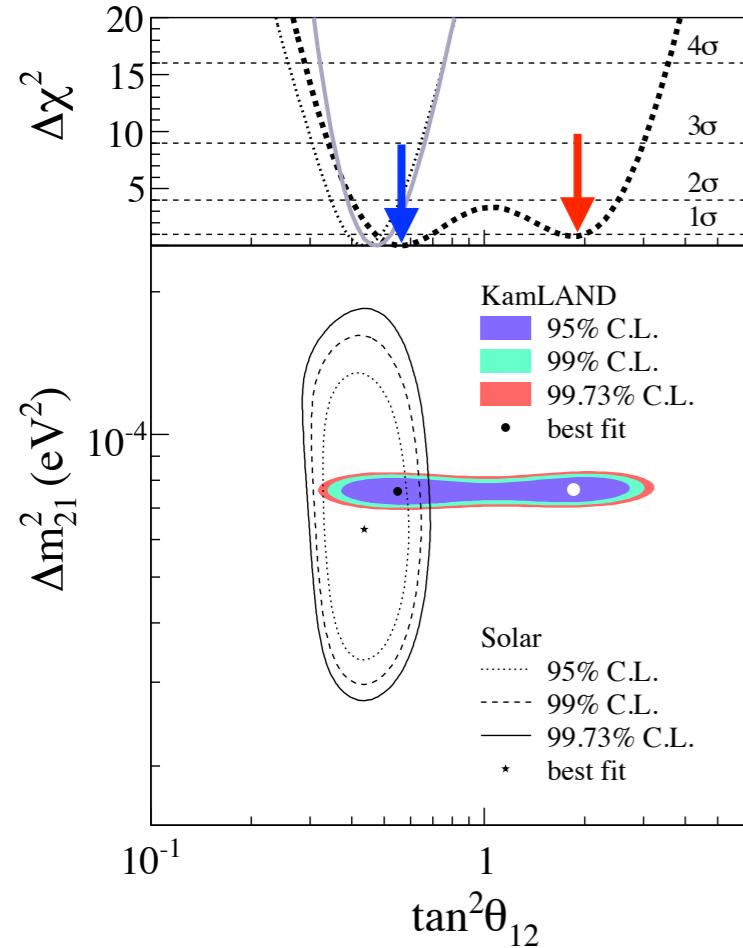
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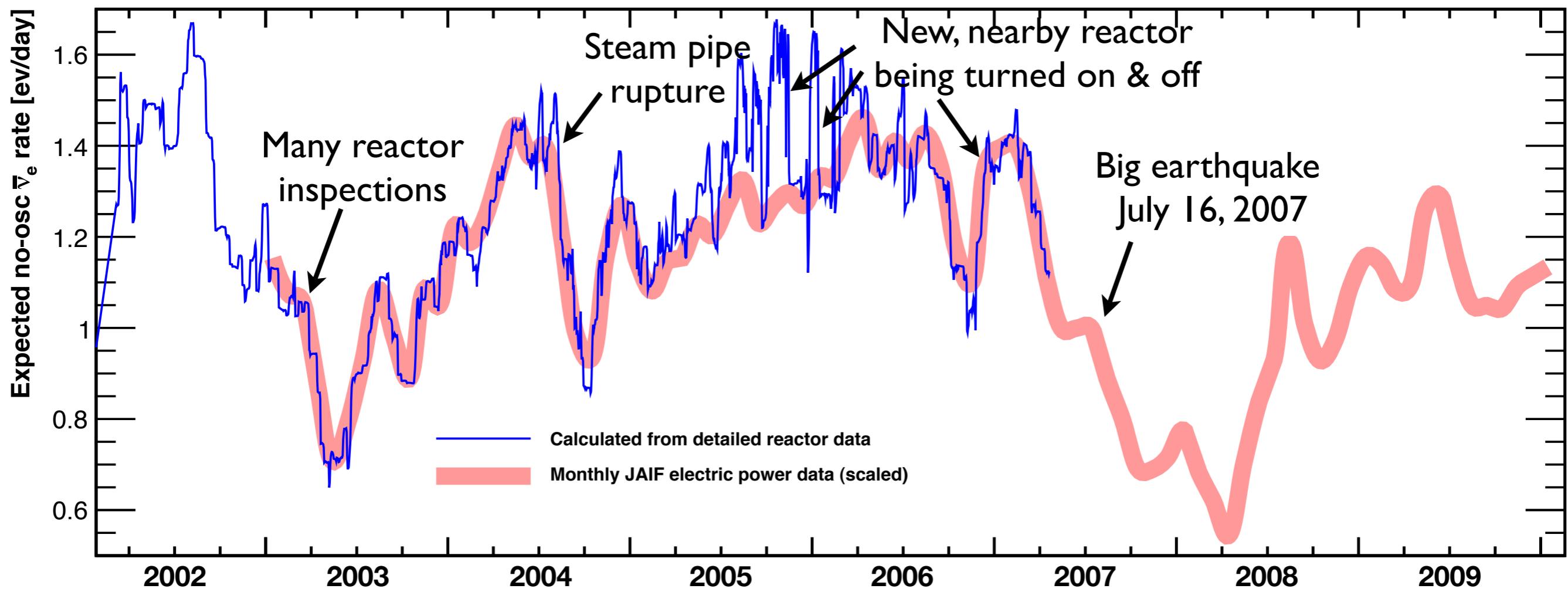
Best-fit Light and Dark Side

Analysis includes Earth matter effects



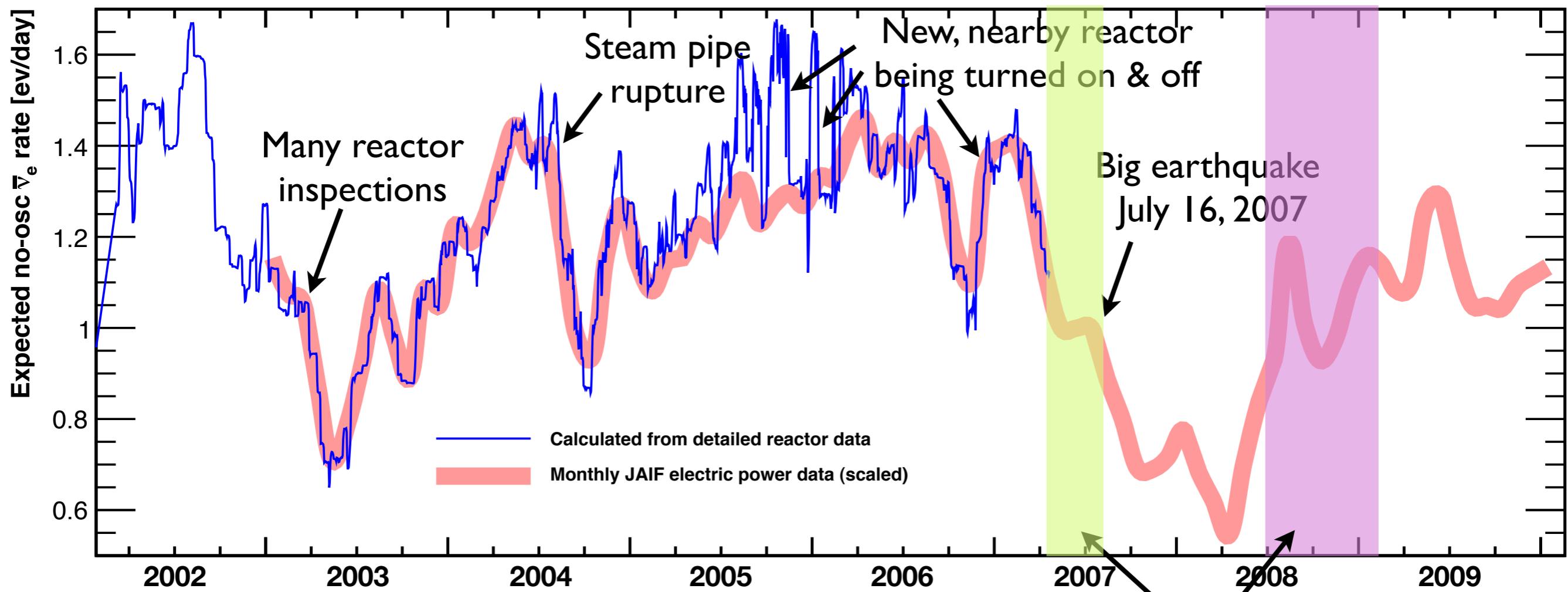
Difference in best-fit on the light and dark side is very small

Reactor Signal Changes with Time



Detailed operational records
from all 55 reactors in Japan

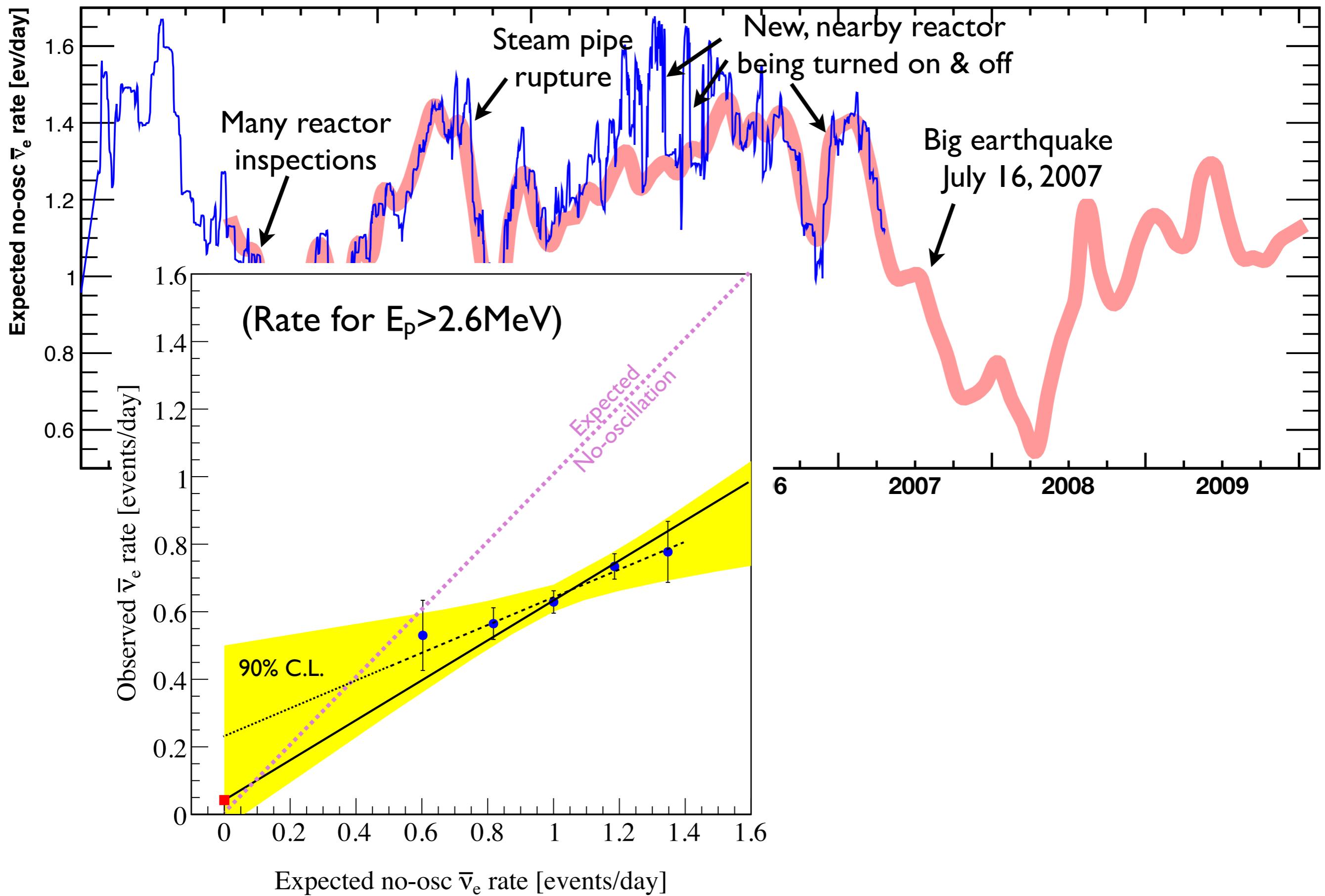
Reactor Signal Changes with Time



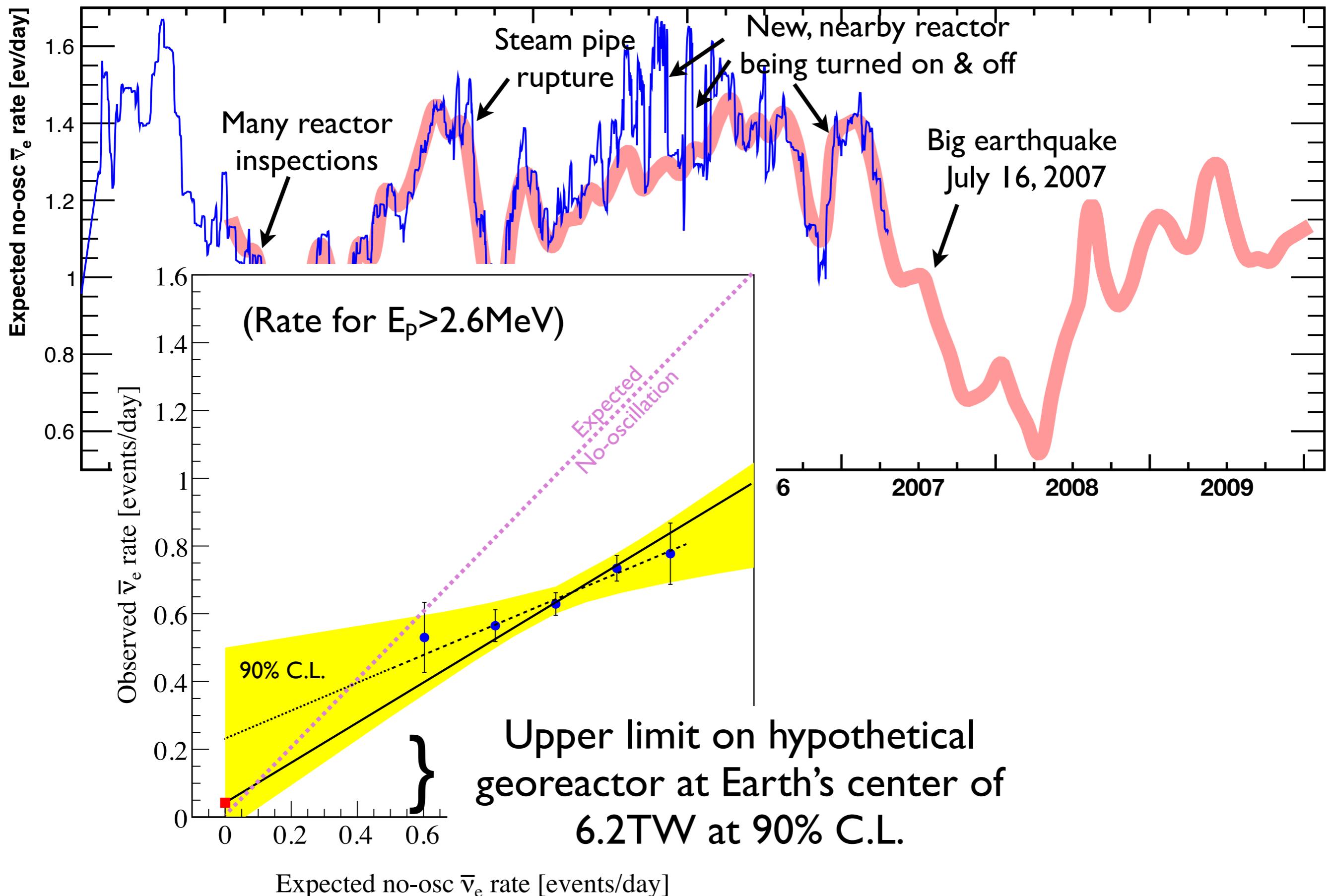
Detailed operational records
from all 55 reactors in Japan

1st&2nd purification campaigns:
changing detector conditions
→ useful data limited

Reactor Signal Changes with Time



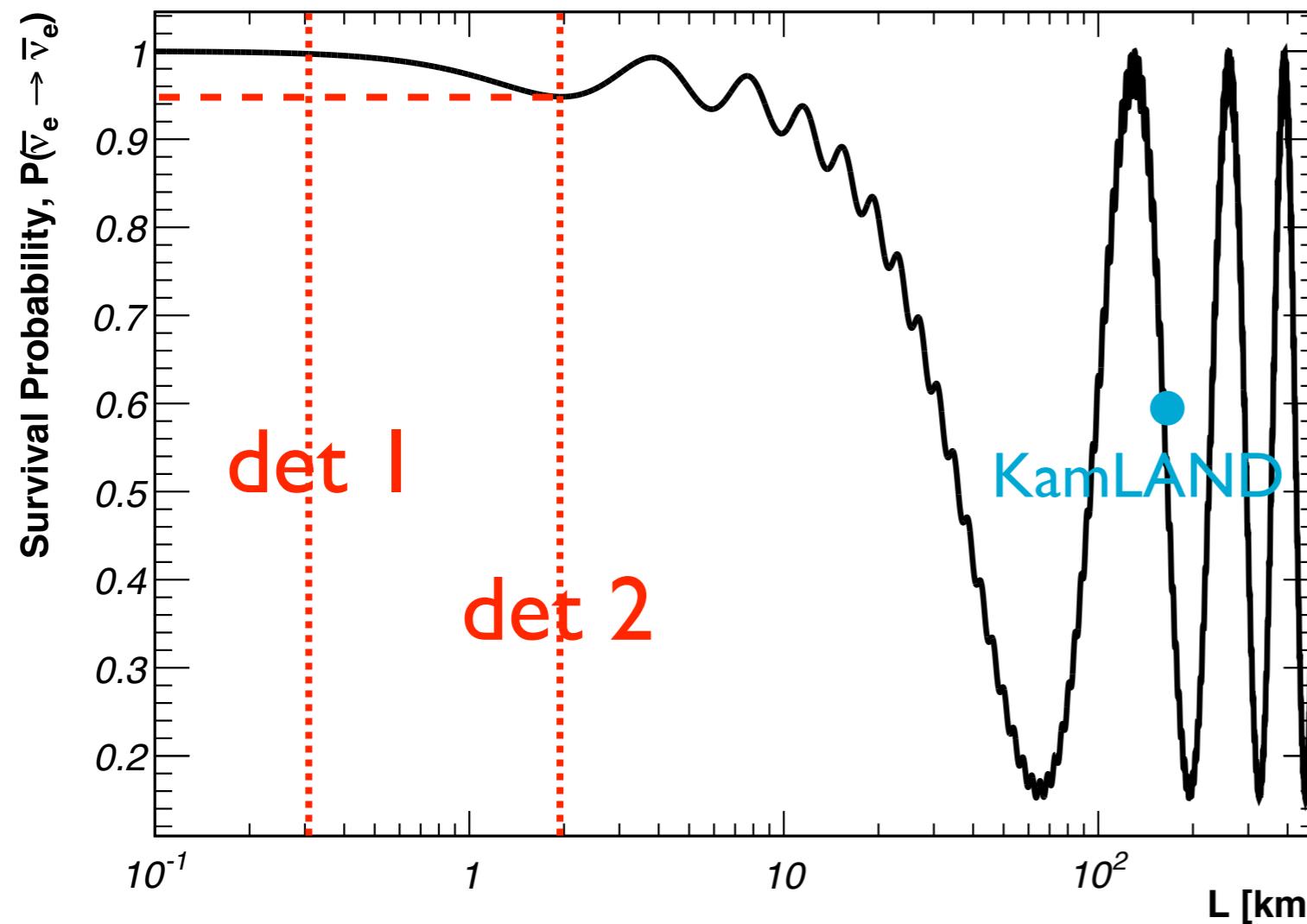
Reactor Signal Changes with Time



High Precision Measurement of θ_{13}

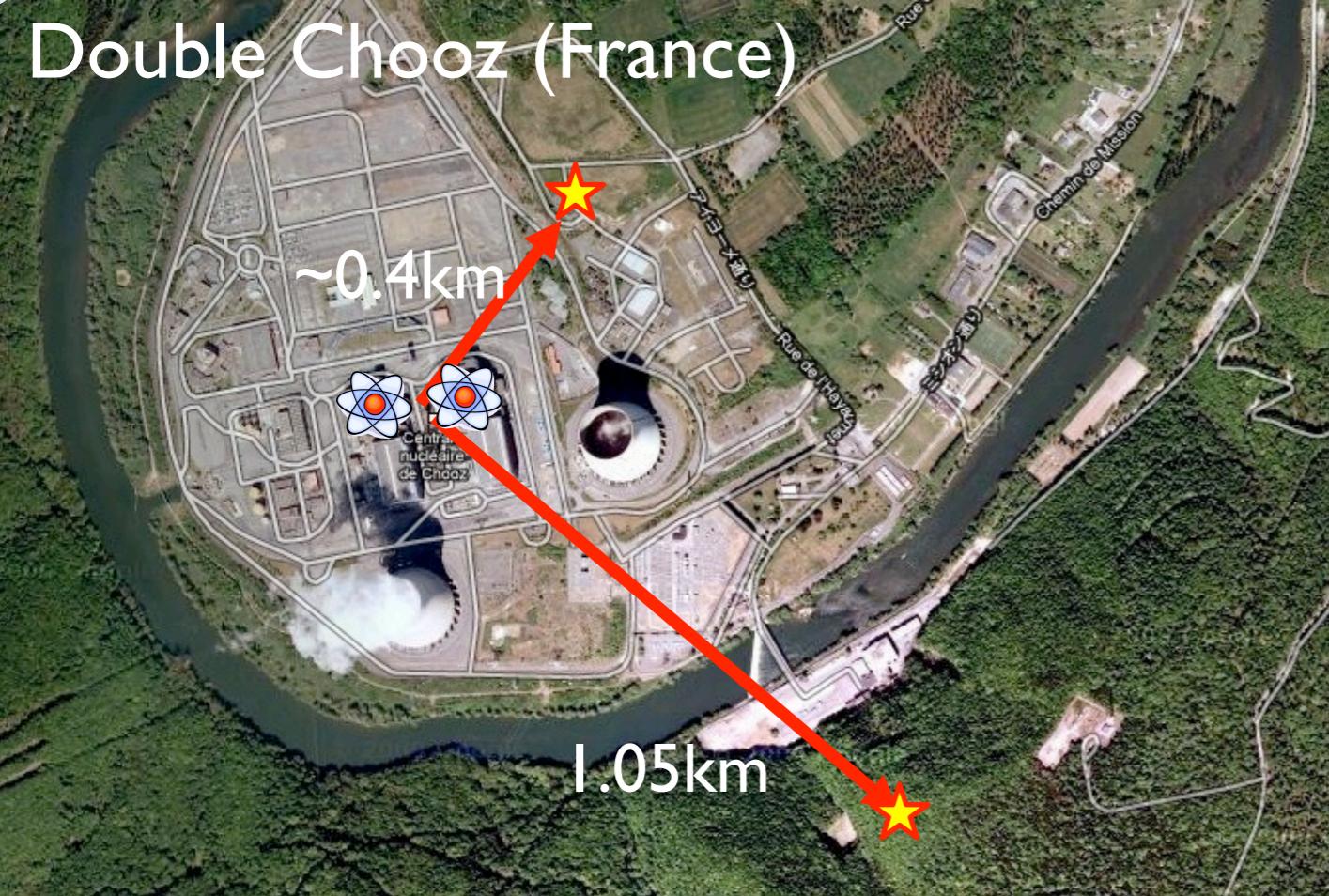
What about θ_{13} ? Current limits: $\sin^2 2\theta_{13} < 0.17$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E} \right)$$

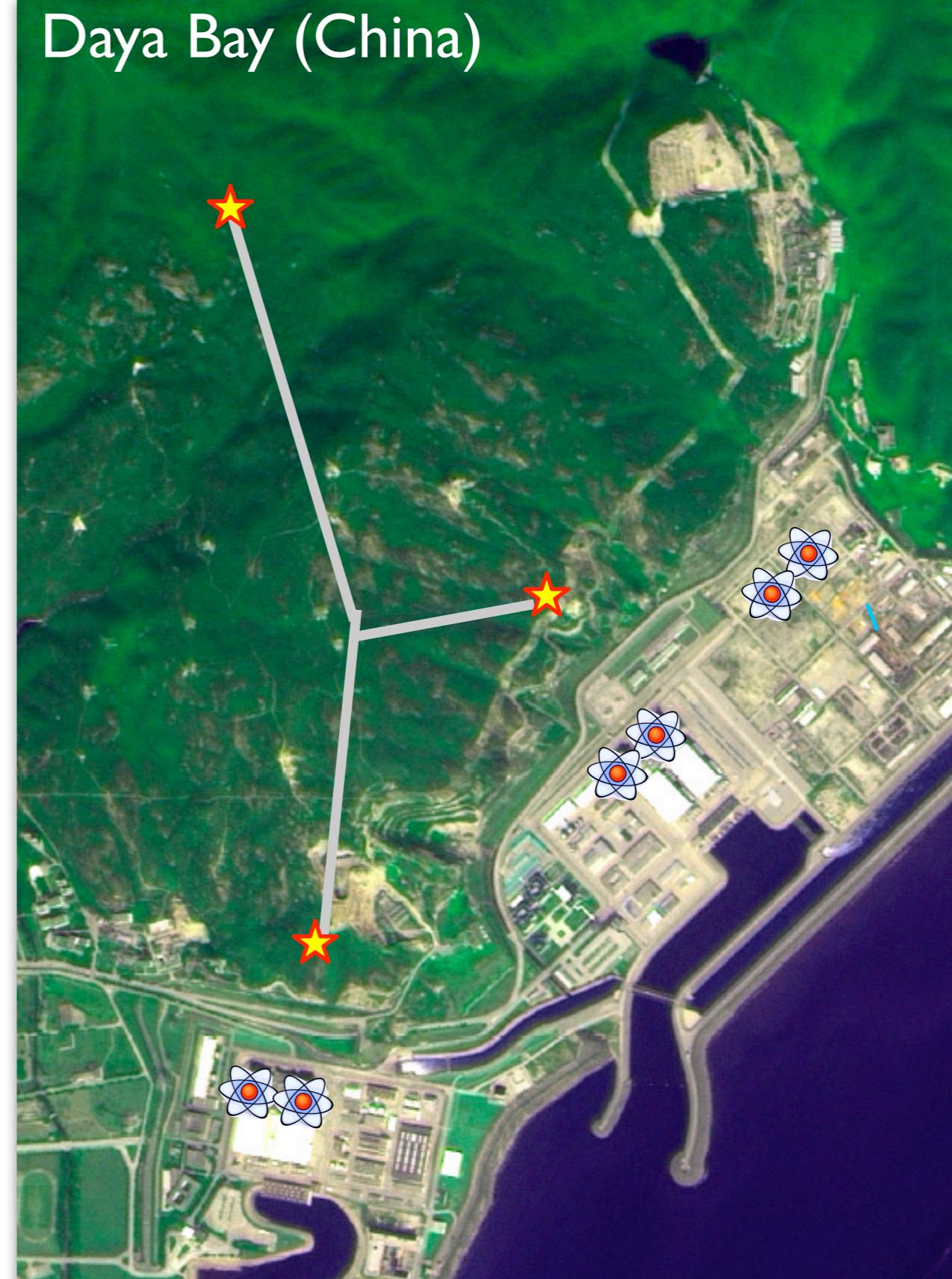


High precision measurement: use two detectors to cancel systematics:
< 1% measurements

Double Chooz (France)



Daya Bay (China)



RENO (South Korea)



Future Reactor θ_{13} Experiments

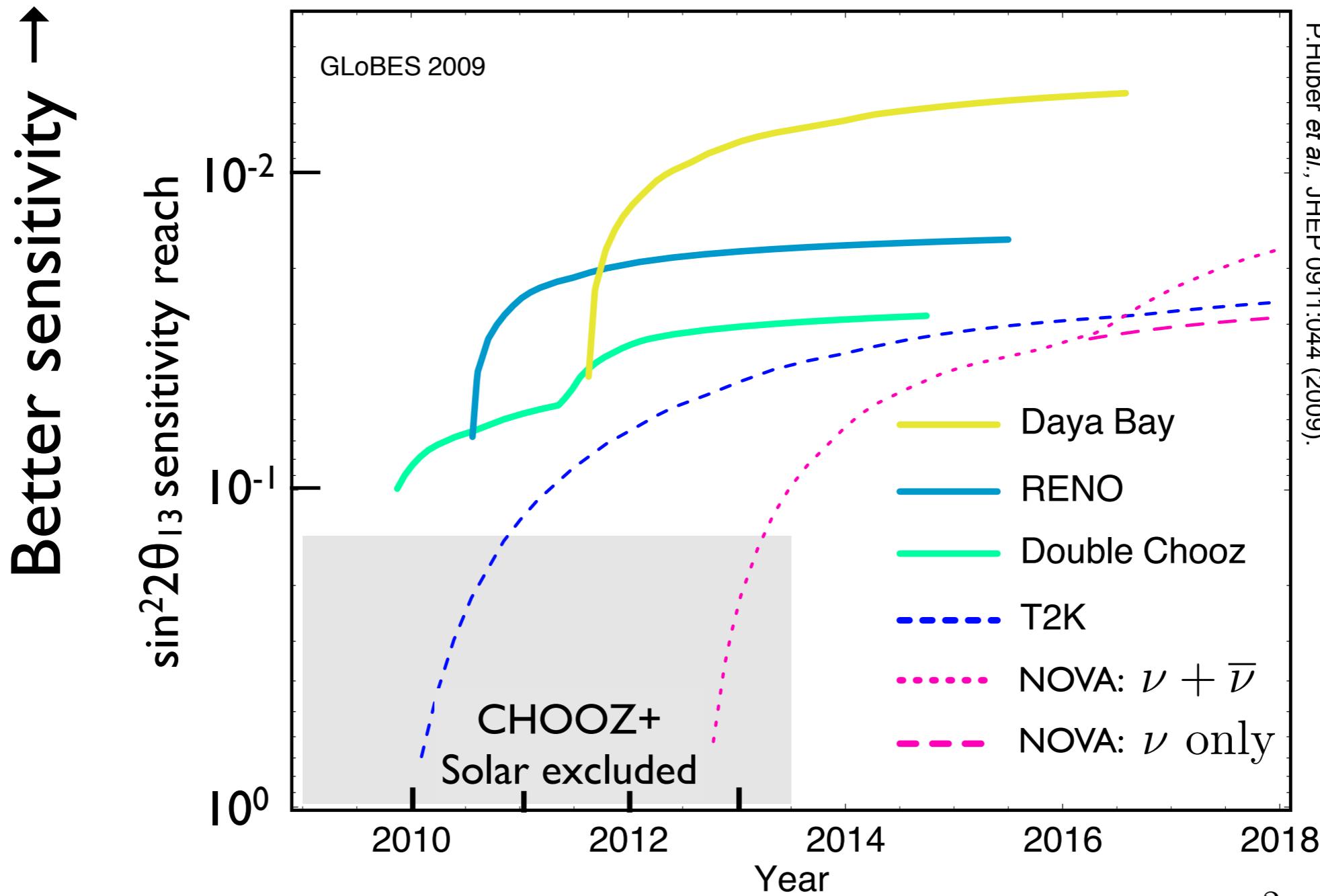
	Power (GW _{th})	Mass (Tons)	Distance to Reactor		Syst. Uncert. (%)	Est. Start (in Feb'10)
			Near (m)	Far (m)		
Double Chooz	8.5	2x10	400	1050	0.6	mid 2010
Daya Bay	17.4	8x20	363 481	1985 1613	0.4/0.2 base/optm	end 2010
RENO	16.4	2x16	290	1380	0.5	mid 2010

Typical event rates:

Near	hundreds/day
Far	tens/day
KamLAND	0.5/day

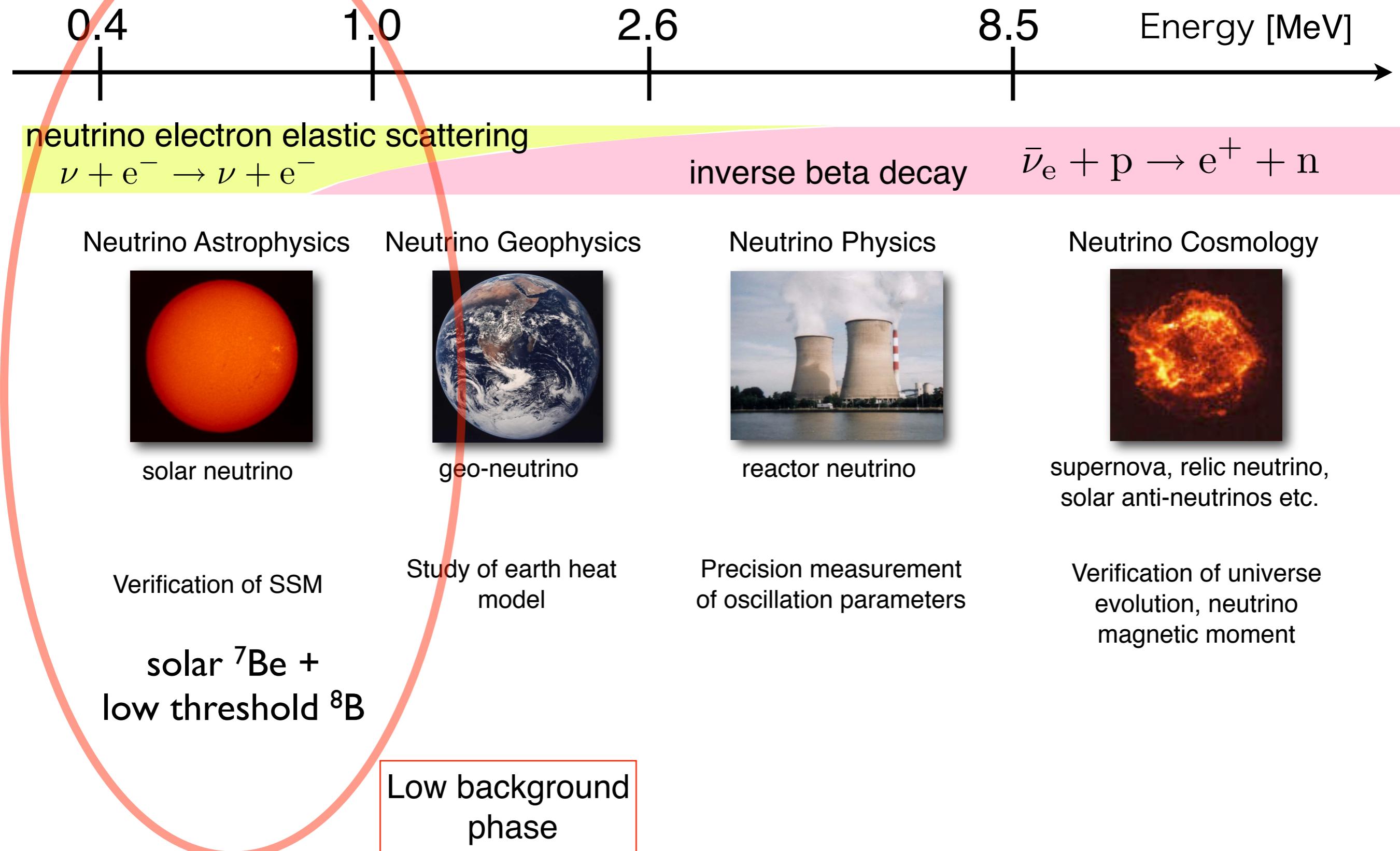
Sensitivity Limits

$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90%CL)



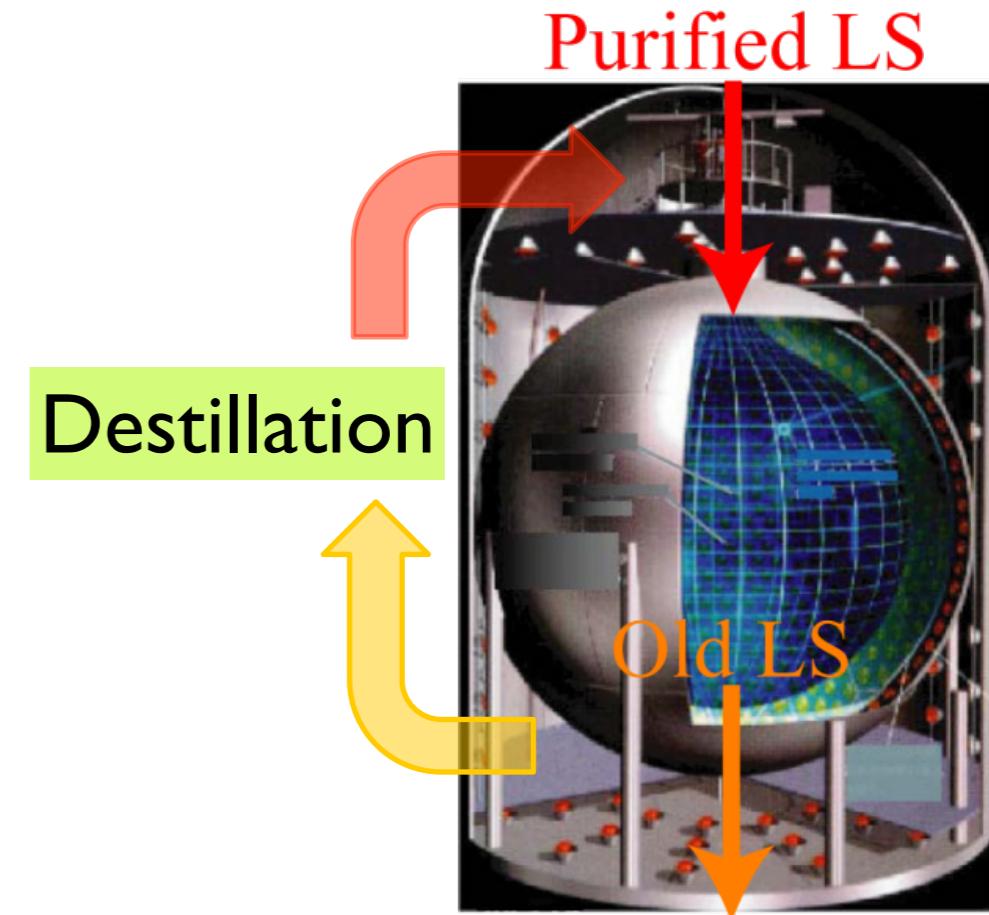
Reactor experiments will find or put best limit on θ_{13}

KamLAND Physics Capabilities

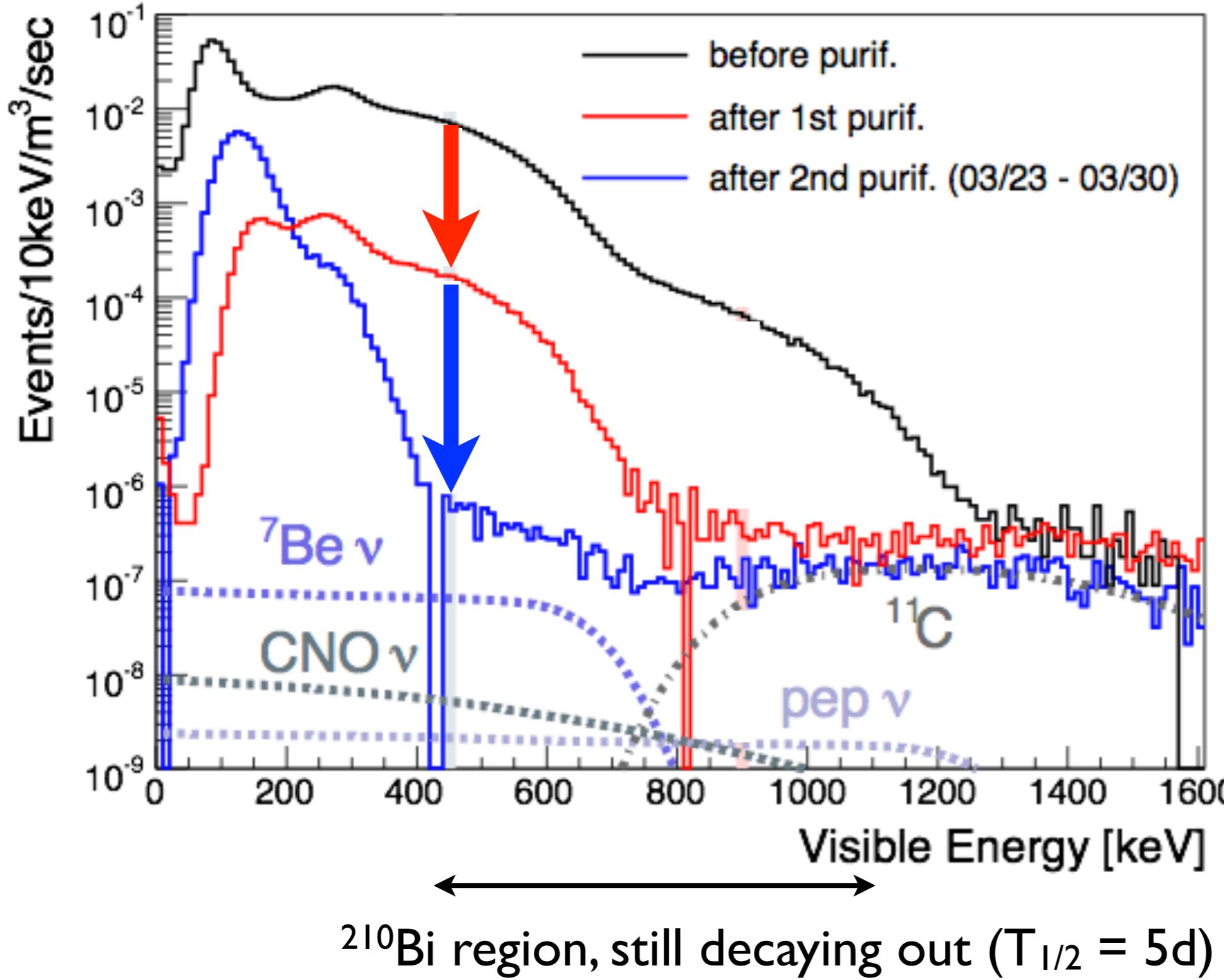


Scintillator Purification

- Large background
 - ^7Be : ^{85}Kr , ^{210}Bi , ^{210}Po
 - ^8B : ^{208}TI
- Industrial-scale distillation system
 - 1st run: Apr 17 - Aug 1, 2007
 - $V_{\text{purified}} = 1700 \text{ m}^3$
 - 2nd run: Jun 19, 2008 - Feb 9, 2009
 - $V_{\text{purified}} = 4900 \text{ m}^3$
- Noticed changes in optical properties of LS during purification



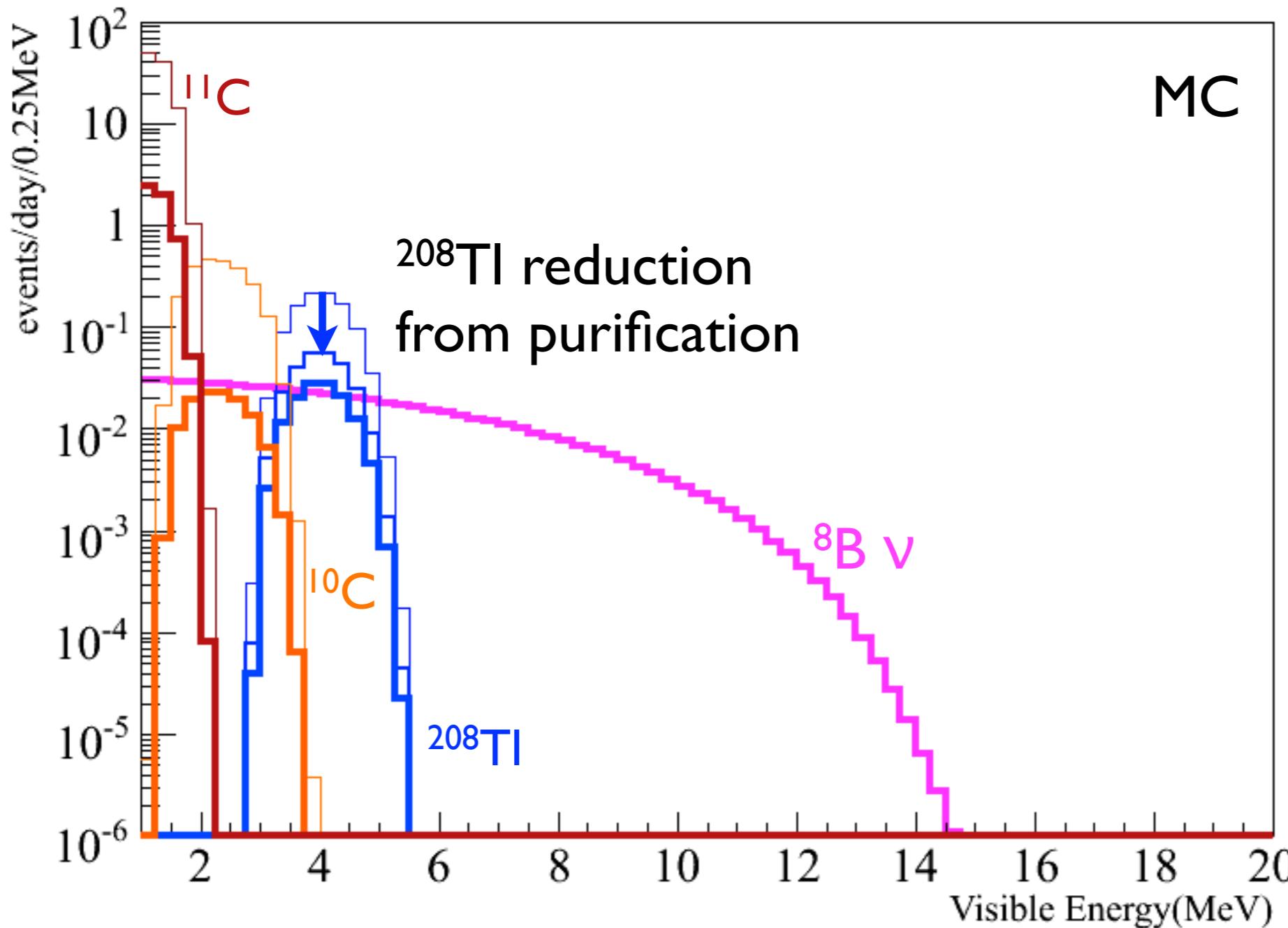
Result of purification



Only 7 days of data,
shortly after end of
purification

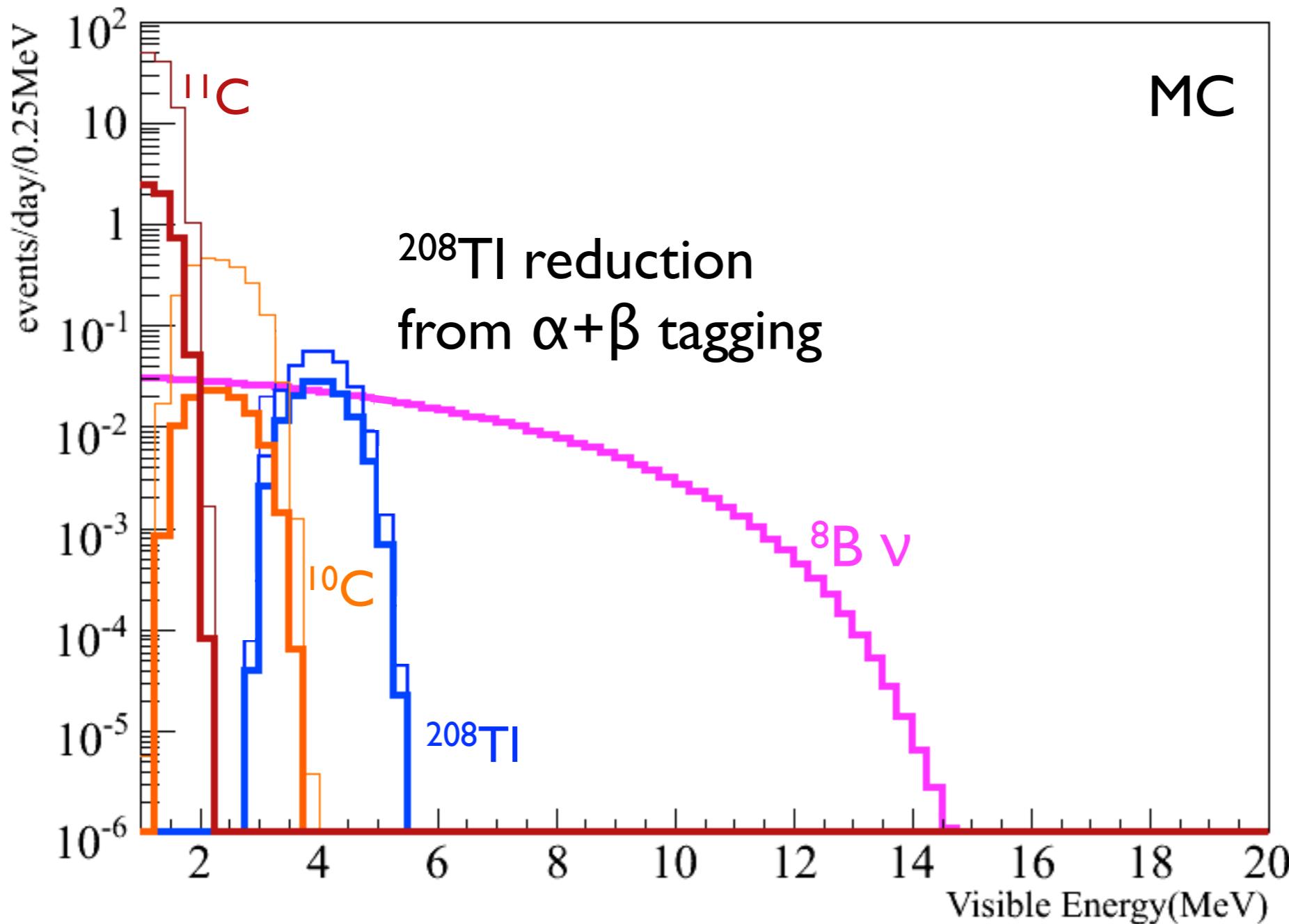
Large reduction of
backgrounds

Low-threshold solar ${}^8\text{B}$ measurement



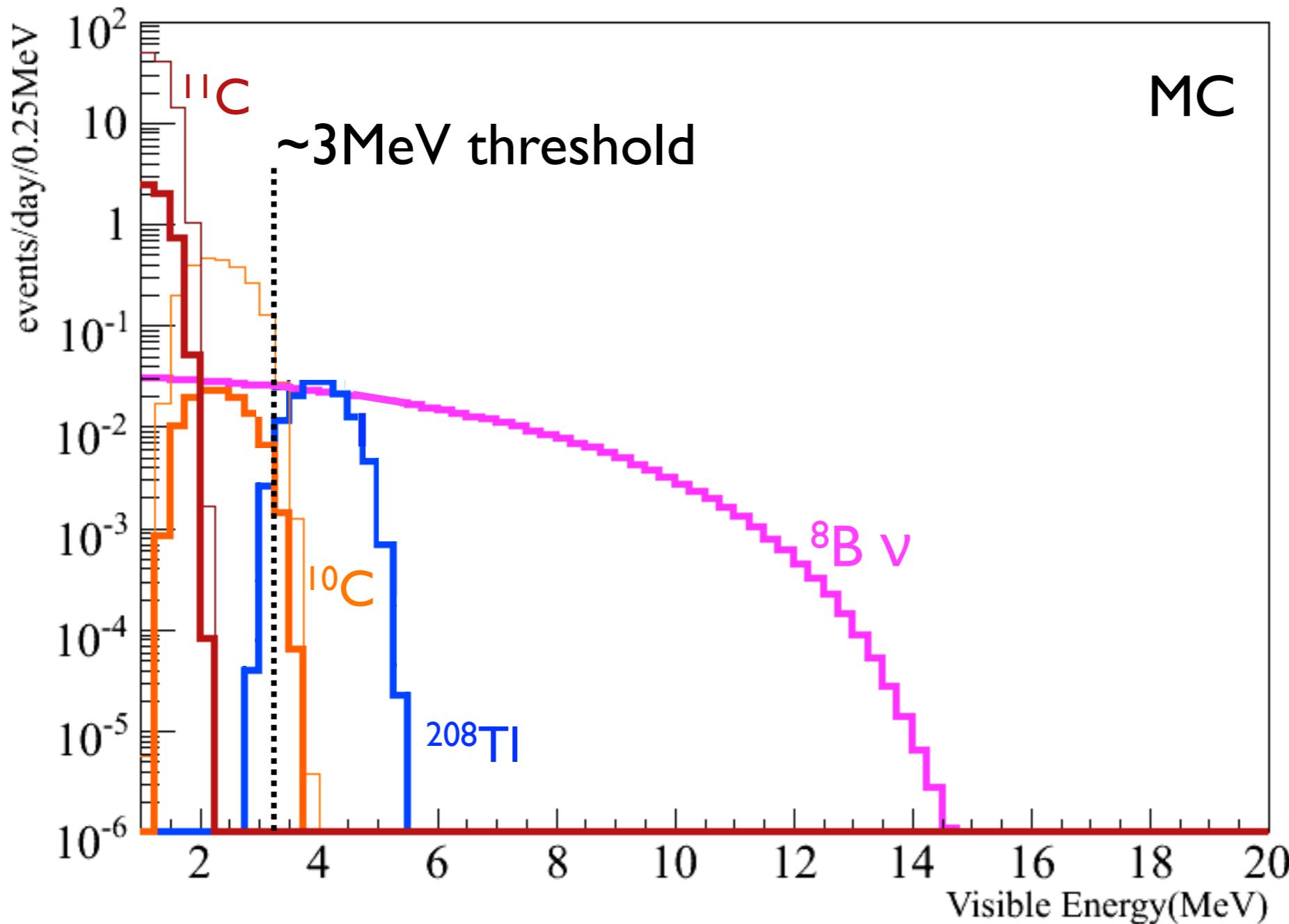
(Main background for geo-neutrino measurement removed)

Low-threshold solar ${}^8\text{B}$ measurement



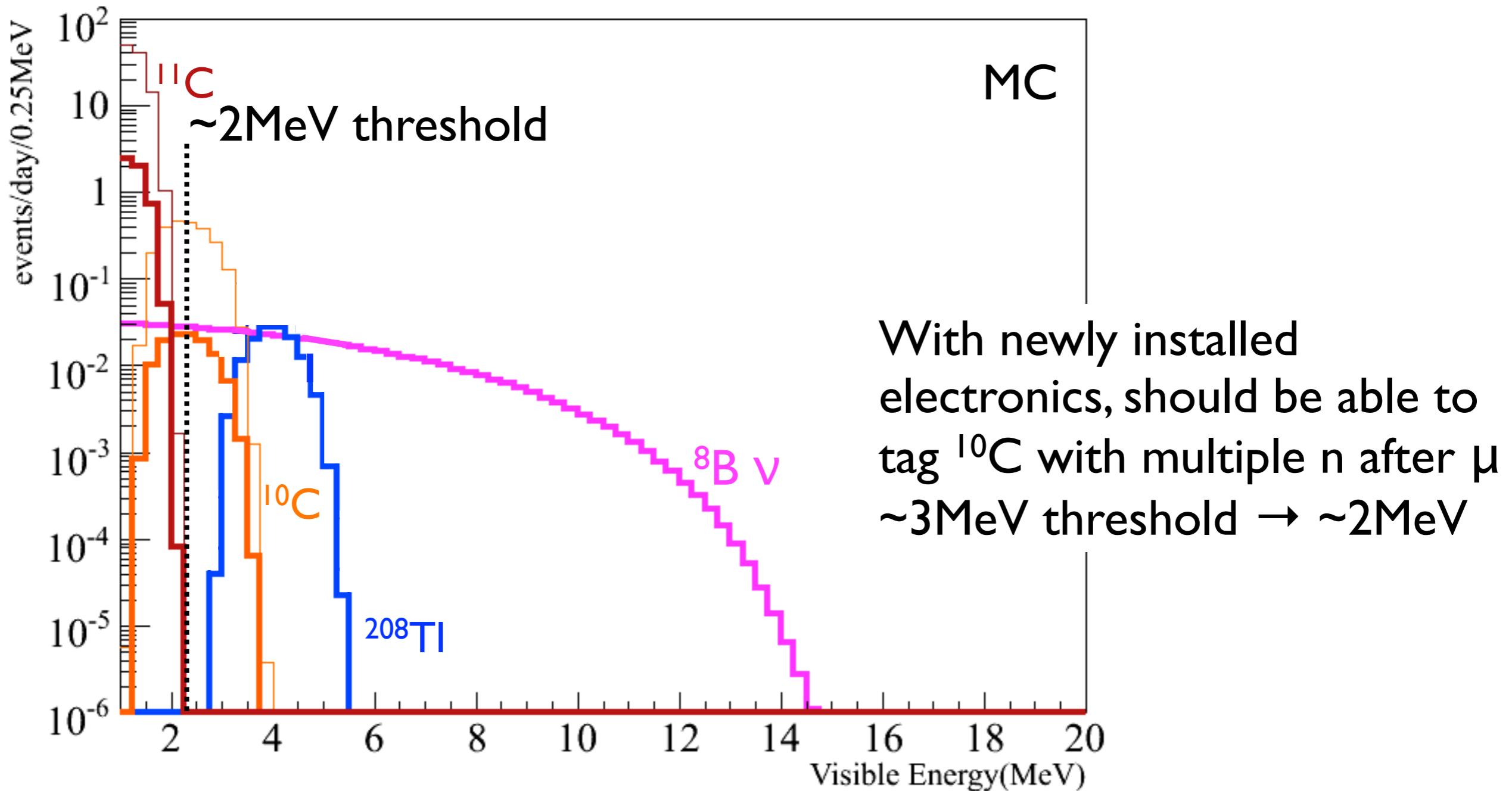
(Main background for geo-neutrino measurement removed)

Low-threshold solar ${}^8\text{B}$ measurement



(Main background for geo-neutrino measurement removed)

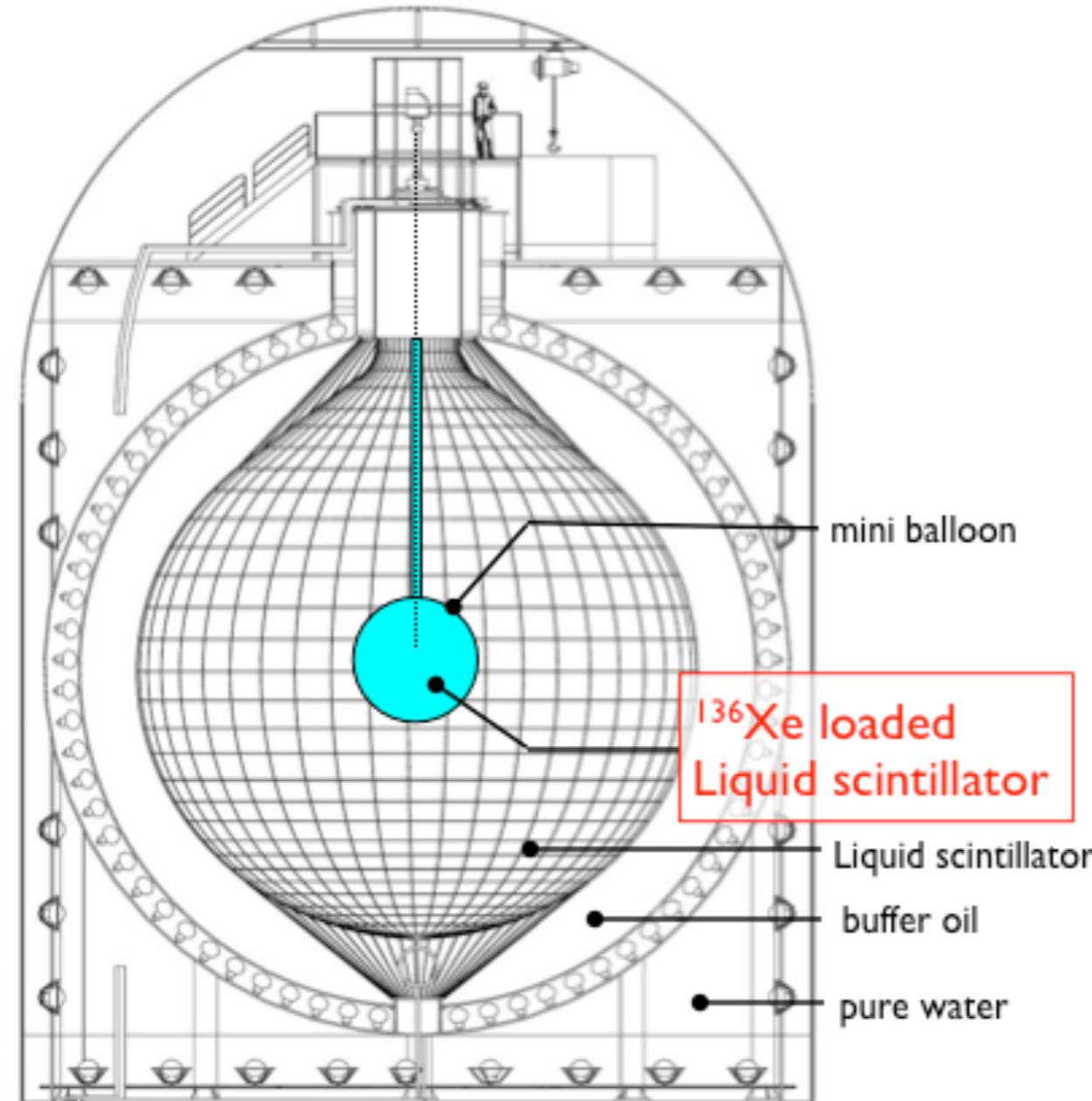
Low-threshold solar ${}^8\text{B}$ measurement



(Main background for geo-neutrino measurement removed)

KamLAND 0v2 β

400kg of ^{136}Xe
in secondary balloon



Japanese collaborators have secured funding for KamLAND 0v2 β
End of KamLAND as-we-know-it in April 2011

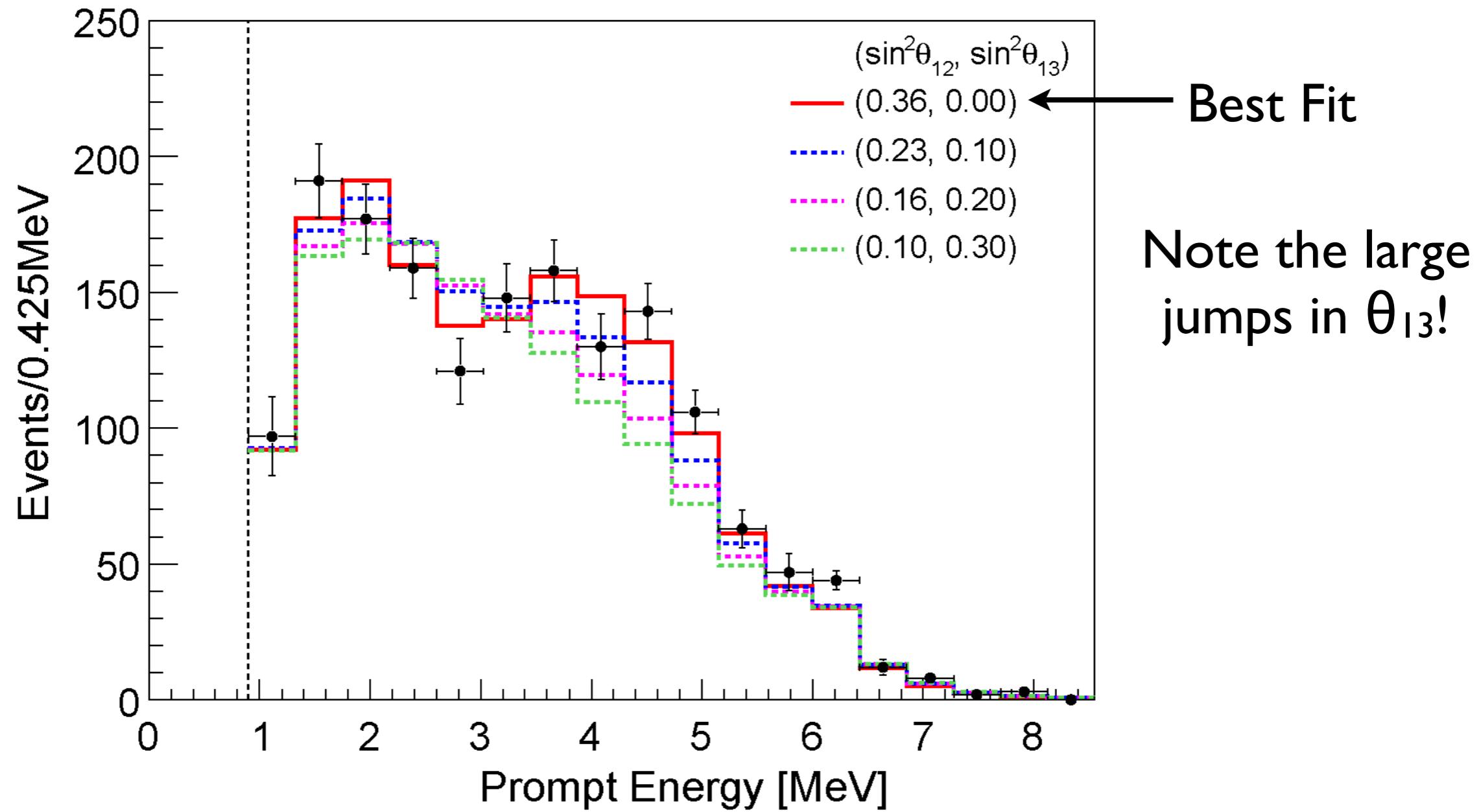
Conclusions

- KamLAND
 - Precision measurement of neutrino parameters
 - 2 more years of data acquired, 1 more year to come. Work on reduction of syst. uncert.
 - Low background phase
 - Detection of ${}^7\text{Be}$ and low-threshold ${}^8\text{B}$ solar neutrinos
 - Data taking ongoing
 - Due to lower backgrounds, (much) improved geo-neutrino measurement
 - In April 2011, KamLAND will morph:
 - Become a $0\nu 2\beta$ experiment with 400kg of ${}^{136}\text{Xe}$
- Three precision θ_{13} reactor experiments getting ready
 - First results expected mid 2011 !

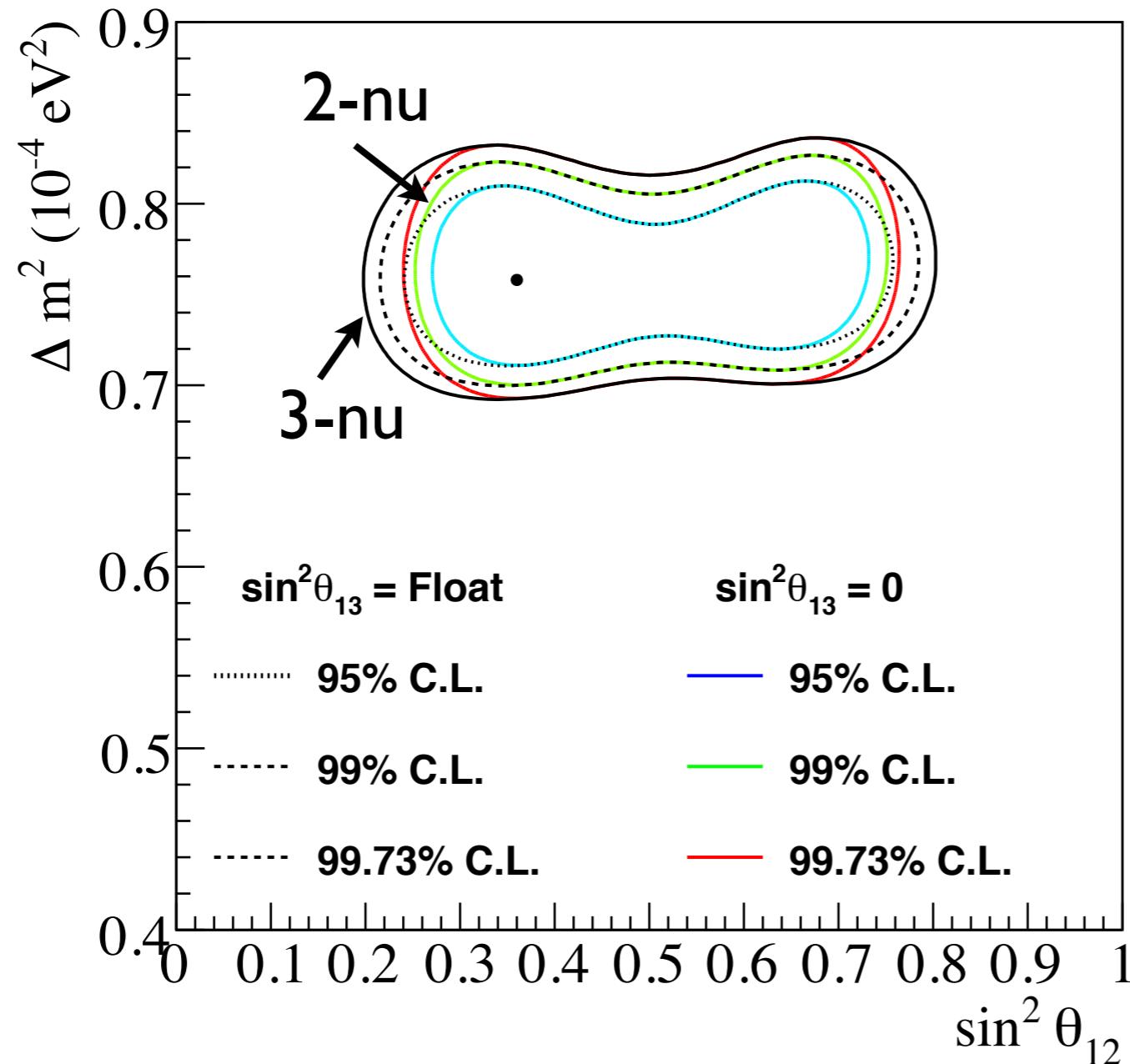
Backup Slides

KamLAND θ_{13} Sensitivity

KL2008 Result fit for $\sin^2\theta_{12}$ for different $\sin^2\theta_{13}$



3-flavor Analysis



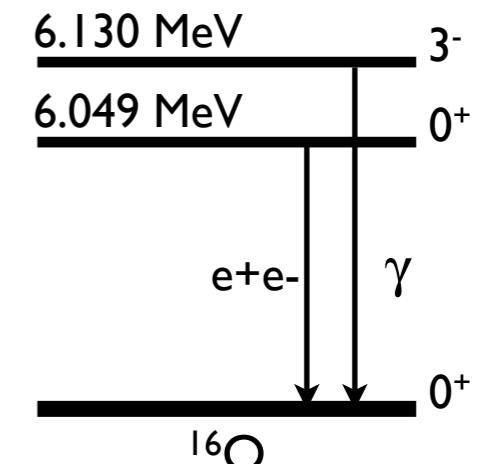
Best-fit value does
not change in 3-nu
analysis

KamLAND has very little sensitivity to θ_{13}
 Δm^2 stays the same in 3-flavor analysis

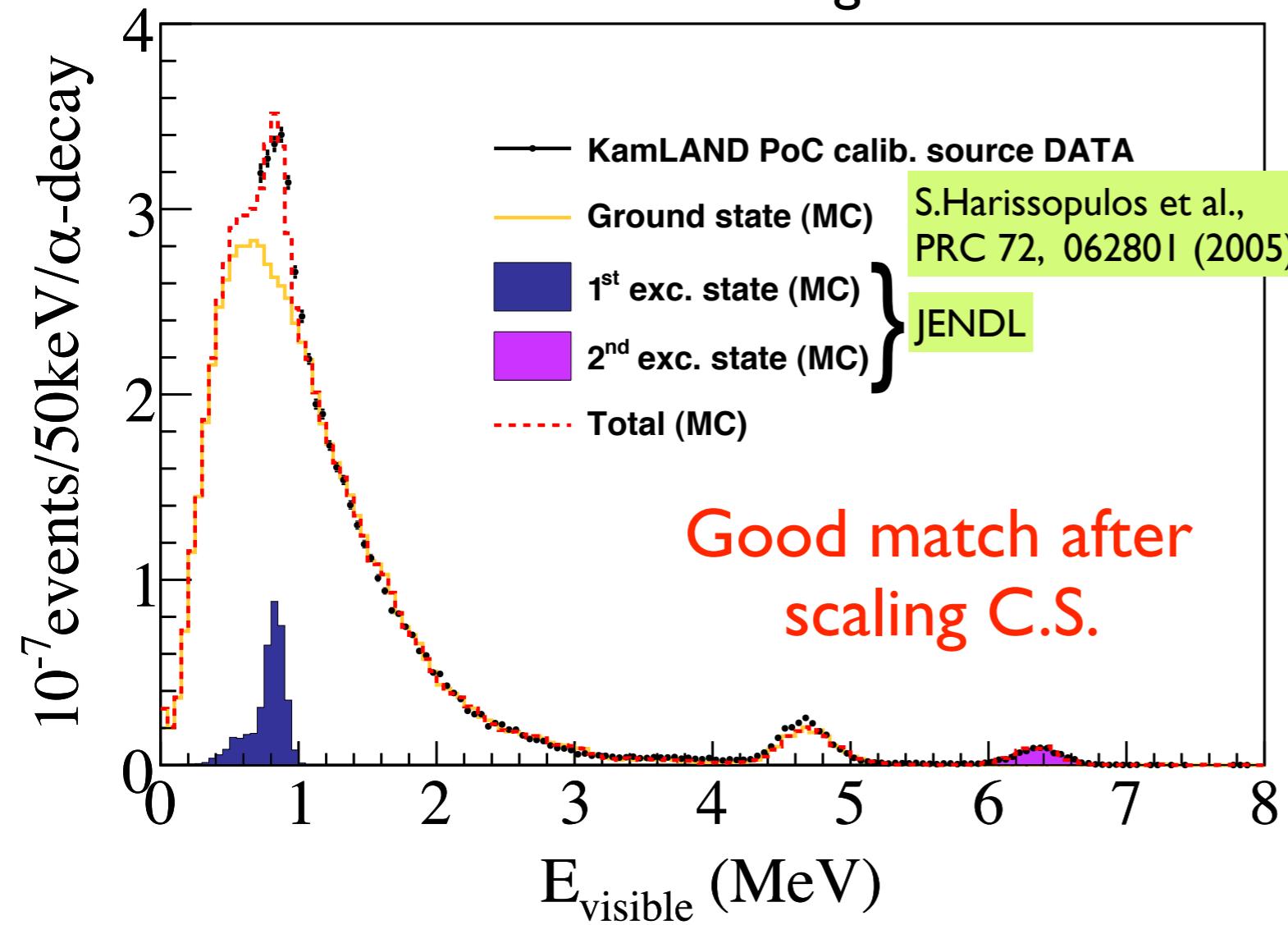
Dominant BG: $^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$

From $T_{1/2}=22\text{yr}$ 5d 138d
 ^{222}Rn chain: $^{210}\text{Pb} \rightarrow ^{210}\text{Bi} \rightarrow ^{210}\text{Po} \rightarrow ^{206}\text{Pb}$
 $\alpha, E=5.3\text{MeV}$

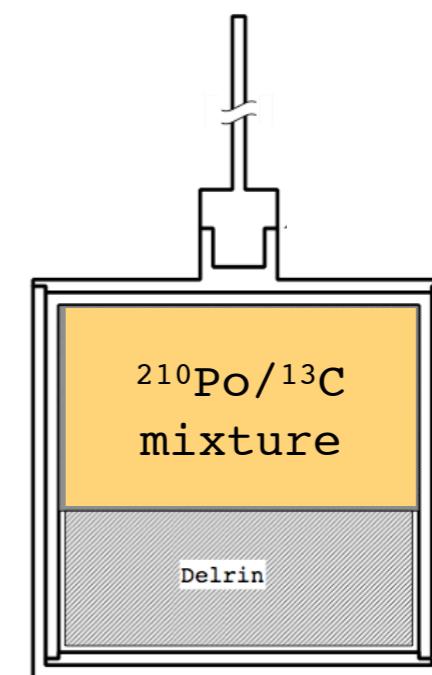
1.1% abundance of ^{13}C in LS $\rightarrow ^{13}\text{C}(\alpha, \text{n})^{16}\text{O}$



Cross sections tuned using detector MC



$^{210}\text{Po}^{13}\text{C}$ source deployed into the detector



D.McKee et al., NIM A527, 272 (2008)

Backgrounds

Background	Contribution	
Accidentals	80.5 ± 0.1	 Accidental Coincidences
$^9\text{Li}/^8\text{He}$	13.6 ± 1.0	 Cosmogenic
Fast neutron & Atmospheric ν	<9.0	
$^{13}\text{C}(\alpha, n)^{16}\text{O}_{gs}$, $\text{np} \rightarrow \text{np}$	157.2 ± 17.3	
$^{13}\text{C}(\alpha, n)^{16}\text{O}_{gs}$, $^{12}\text{C}(n, n')^{12}\text{C}^*$ (4.4 MeV γ)	6.1 ± 0.7	
$^{13}\text{C}(\alpha, n)^{16}\text{O}$ 1 st exc. state (6.05 MeV $e^+ e^-$)	15.2 ± 3.5	
$^{13}\text{C}(\alpha, n)^{16}\text{O}$ 2 nd exc. state (6.13 MeV γ)	3.5 ± 0.2	
Total excluding geo-neutrino	276.1 ± 23.5	

Geo-neutrinos are a background to the neutrino oscillation measurement

Using one geological model, which assumes 16TW of radiogenic heat from U+Th geo-neutrinos, expect 69.7 events

However, analysis is done by simultaneously fitting geo- and reactor neutrinos !