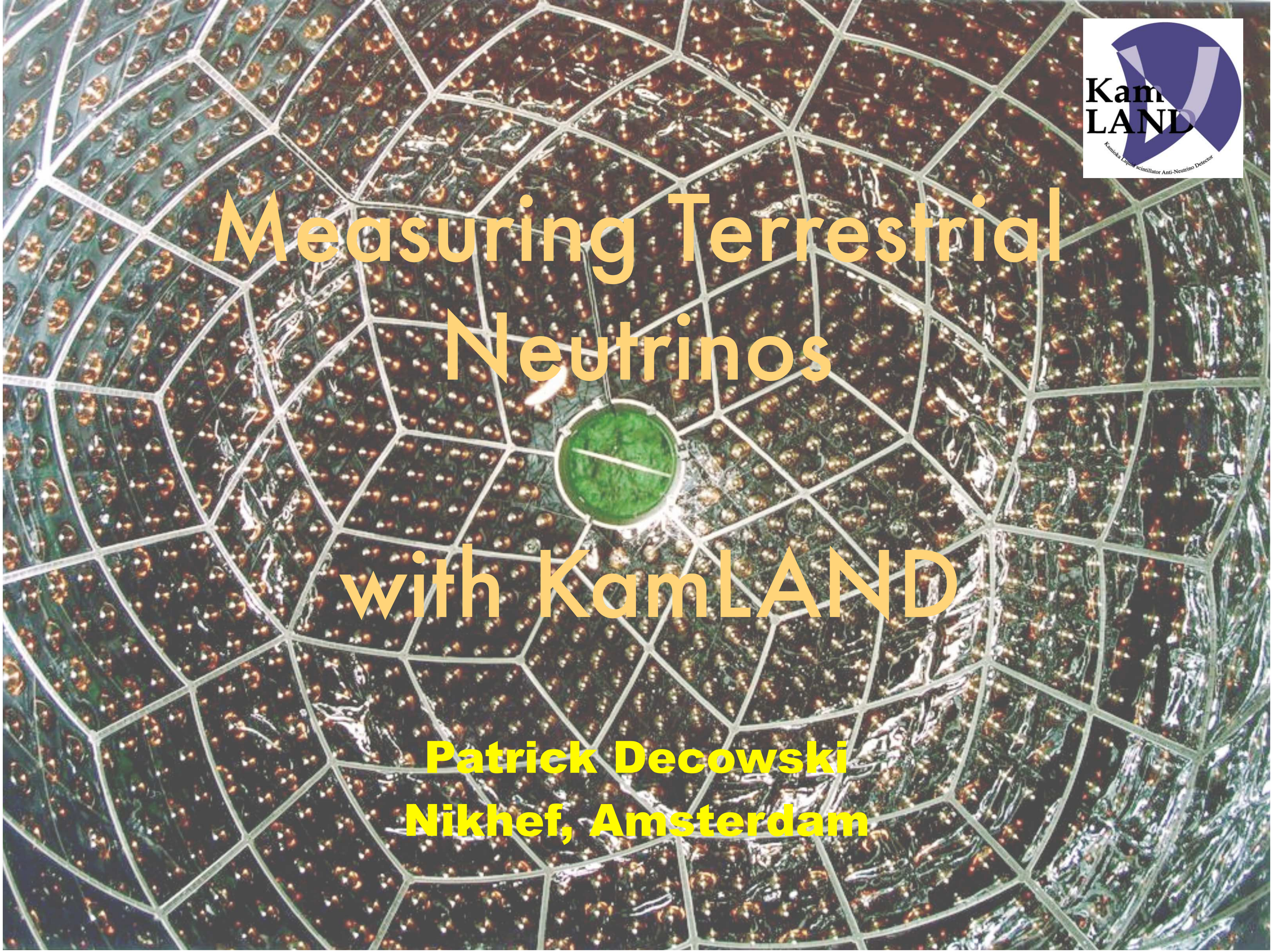


Measuring Terrestrial Neutrinos

with KamLAND

Patrick Decowski
Nikhef, Amsterdam

Neutrino Oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle; \qquad \alpha = e, \mu, \tau$$

$$|\nu_i(L)\rangle = e^{-i\frac{m_i^2 L}{2E}}|\nu_i(0)\rangle$$

3 ν flavor eigenstates

3 ν mass eigenstates

If there are only 2 neutrino generations:

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Probability that ν_e becomes ν_x after traveling a distance L:

$$\begin{aligned} P(\nu_e \rightarrow \nu_x) &= |\langle\nu_x(L)|\nu_e(0)\rangle|^2 \\ &= \left|(-\sin\theta\langle\nu_1(L)| + \cos\theta\langle\nu_2(L)|)|(\cos\theta|\nu_1(0)\rangle + \sin\theta|\nu_2(0)\rangle)\right|^2 \\ &= \cdots \\ &= \sin^2 2\theta \sin^2\left[\frac{(m_2^2 - m_1^2)L}{4E}\right] \end{aligned}$$

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2$$

Oscillation probability is given by the oscillation parameters θ en $\Delta m_{21}{}^2$

Neutrino Oscillation

In general not 2 ν, but 3 ν oscillation:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle; \qquad \alpha = e, \mu, \tau$$

where,

$$U_{MNSP} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric/accelerator } \nu} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_D} & 0 & c_{13} \end{pmatrix}}_{\text{reactor/accelerator } \nu} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar/reactor } \nu}$$

For the purposes of the rest of the talk:

- first consider two neutrino oscillation

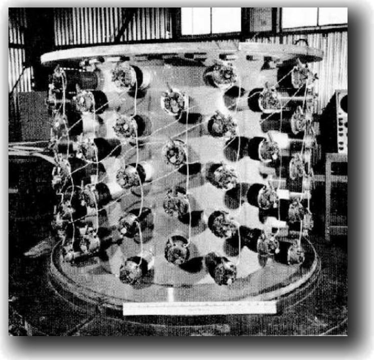
$$P(\nu_e \to \nu_x) = \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- then extend to three neutrino oscillation

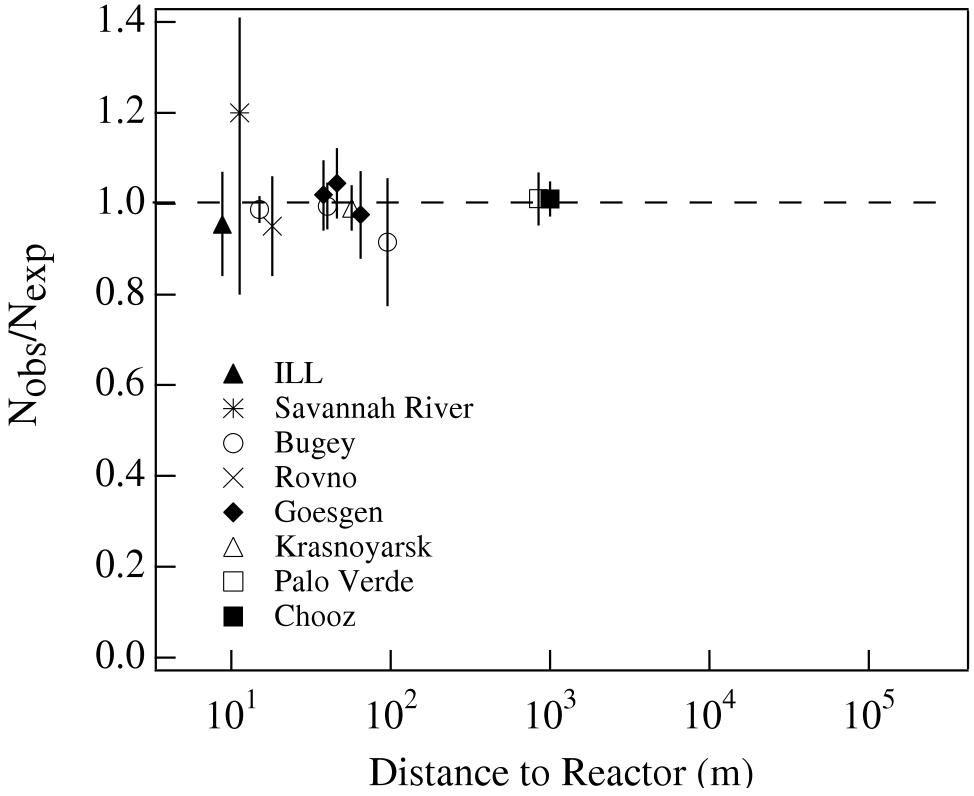
$$P(\nu_e \to \nu_x) \approx \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) + \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Oscillation searches with Reactors

Reactors have played an important role in the early history of neutrinos and in neutrino-oscillation searches: 1953 - Present



Project Poltergeist
(Reines & Cowan 1953)



- Many different experiments before 2002
  - Baselines up to 1km
  - No evidence for $\overline{\nu}_e$ disappearance

Patrick Decowski / Nikhef

About
Reactor Anti-Neutrinos

From the 1955 Movie with same title

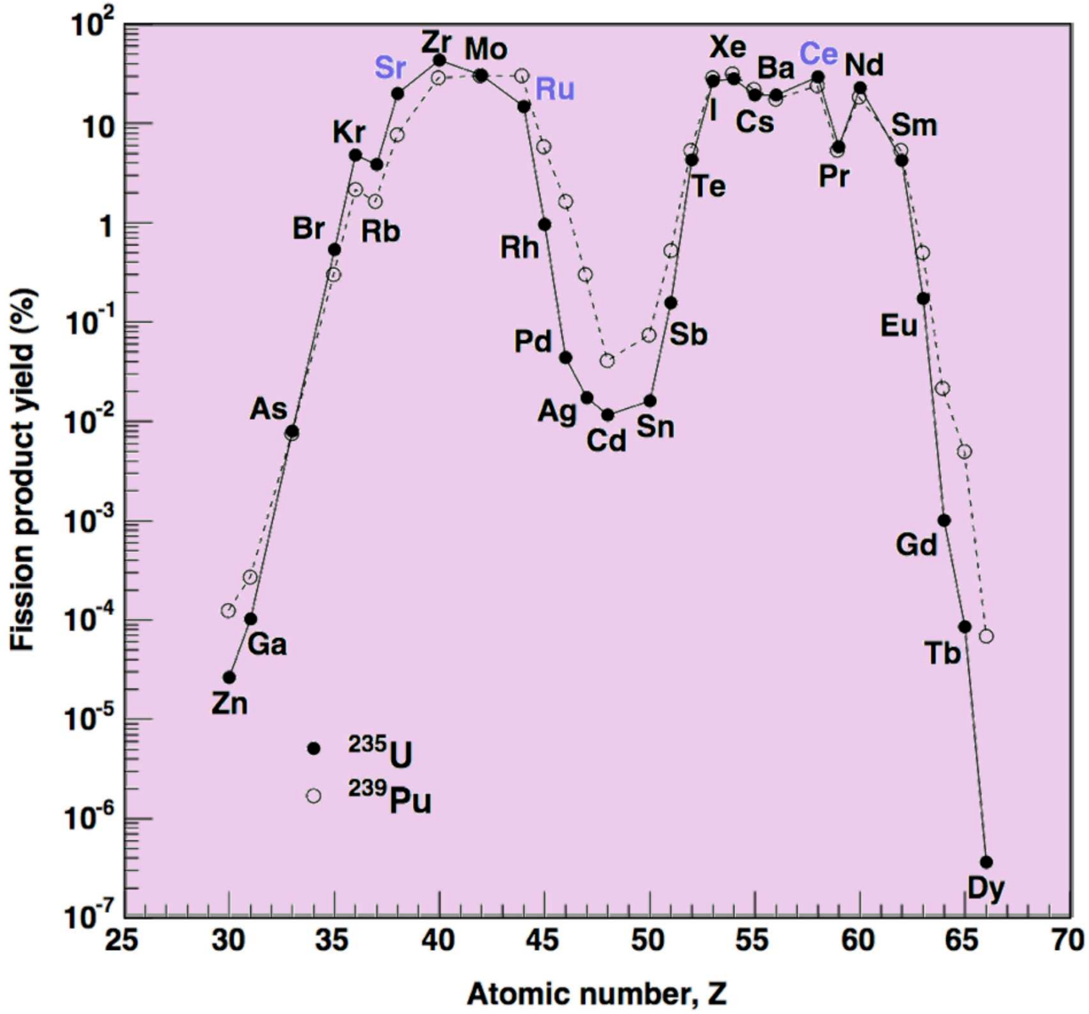
Reactor Anti-Neutrinos

$${}^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

The stable products most likely from Uranium fission:

$${}^{94}_{40}Zr \qquad {}^{140}_{58}Ce$$

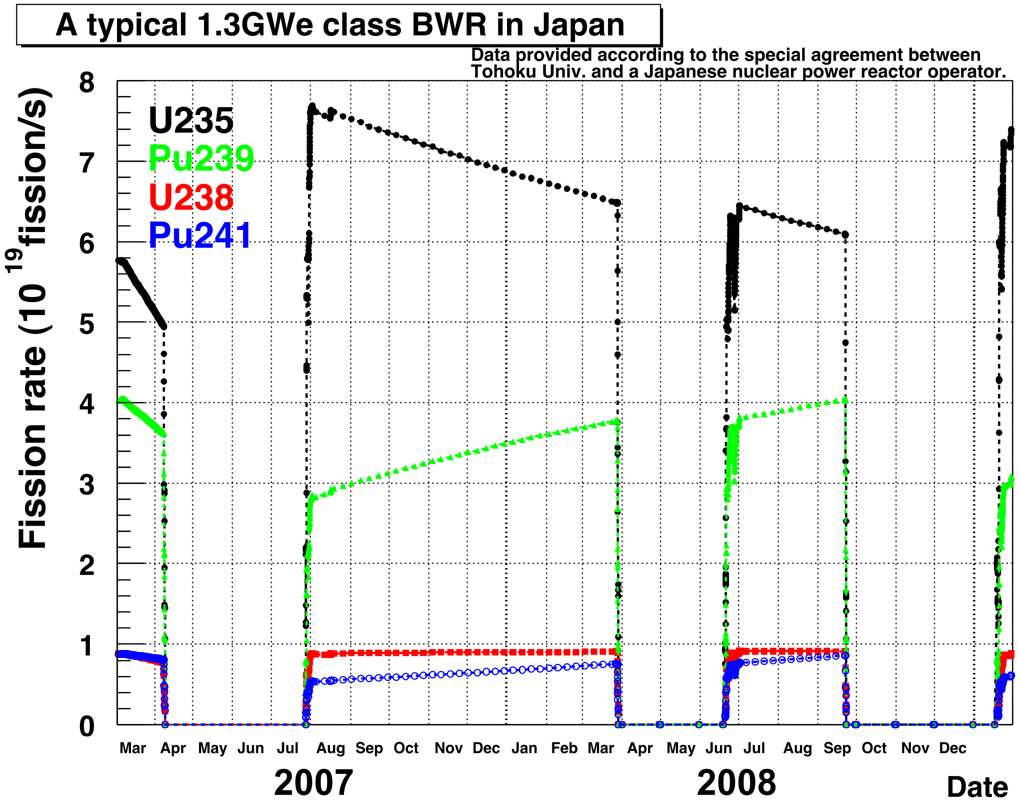
Together 98 protons and 136 neutrons



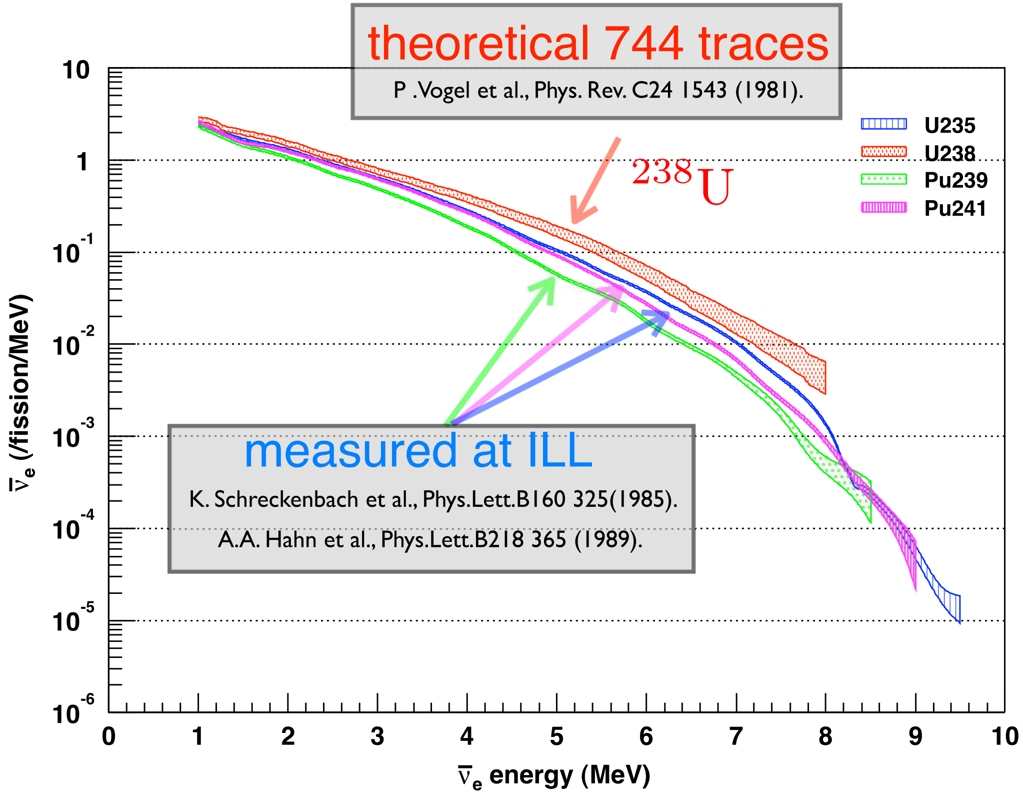
6 neutrons have to β-decay to reach stable matter, producing 6 $\overline{\nu}_e$ / fission

Calculating Neutrino Spectra

Only 4 isotopes relevant


A typical 1.3GWe class BWR in Japan

Data provided according to the special agreement between Tohoku Univ. and a Japanese nuclear power reactor operator.


theoretical 744 traces

P .Vogel et al., Phys. Rev. C24 1543 (1981).

measured at ILL

K. Schreckenbach et al., Phys.Lett.B160 325(1985).

A.A. Hahn et al., Phys.Lett.B218 365 (1989).

- Fission rates are provided by reactor companies
  - Chiefly function of thermal power
  - Weak function of inlet T: 10% → ~0.15% rate change

Anti-Neutrino Detection Method

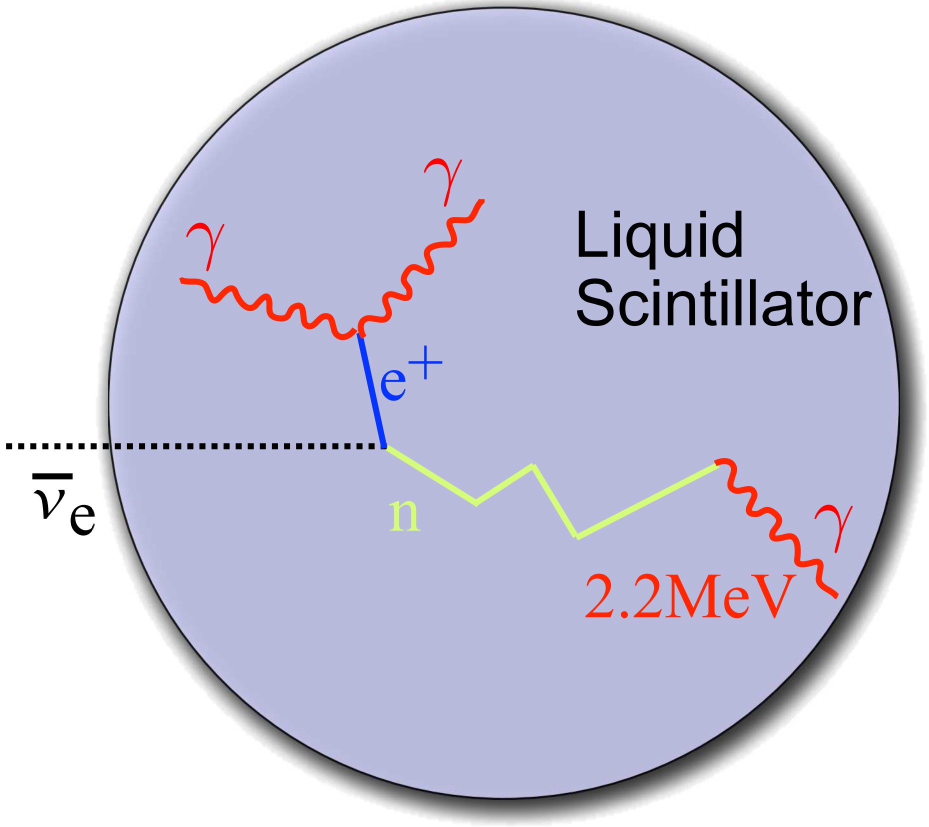
Inverse beta decay

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

$$\Big\downarrow \text{207 µs}$$

$$n + p \rightarrow d + \gamma$$

Scintillator is both target and detector



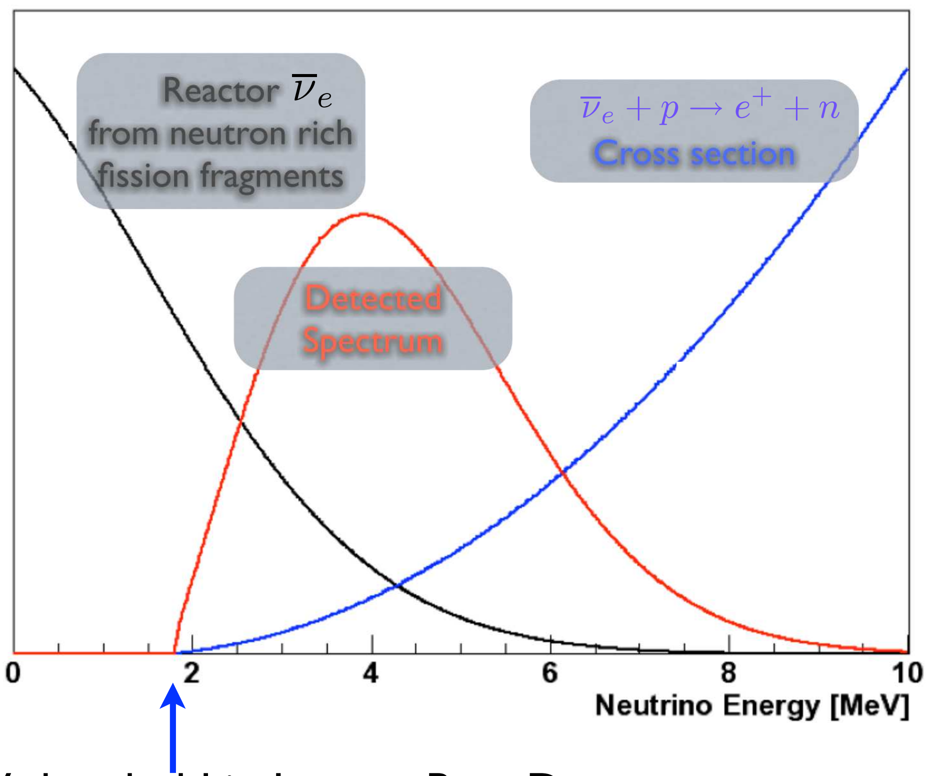
- Distinct two step process:
  - prompt event: positron

    $$E_{\overline{\nu}_e} \simeq E_{prompt} + 0.8MeV$$

  - delayed event: neutron capture after ~207µs
    - 2.2 MeV gamma

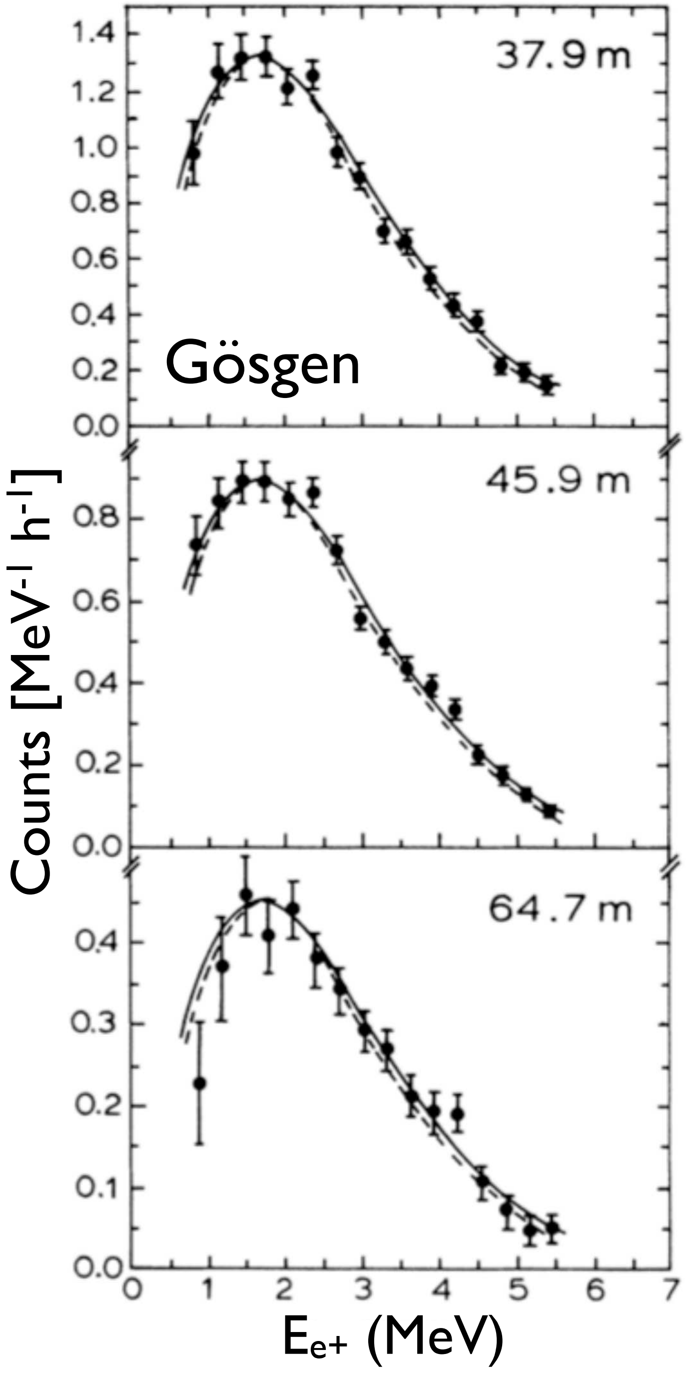
Delayed coincidence: good background rejection

Detected Reactor Spectrum



1.8MeV threshold in Inverse Beta Decay

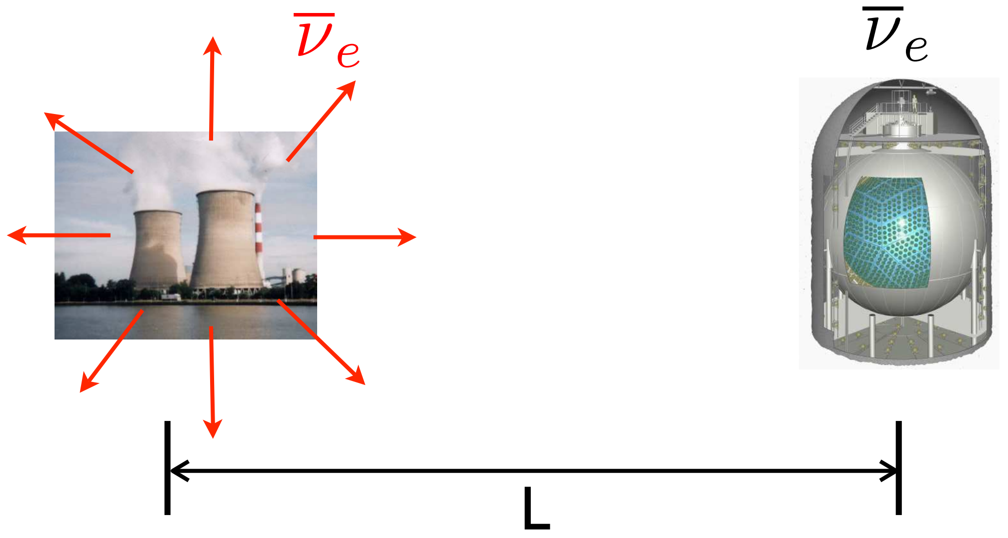
Zacek G. et al., Phys. Rev. D34, 2621 (1986).



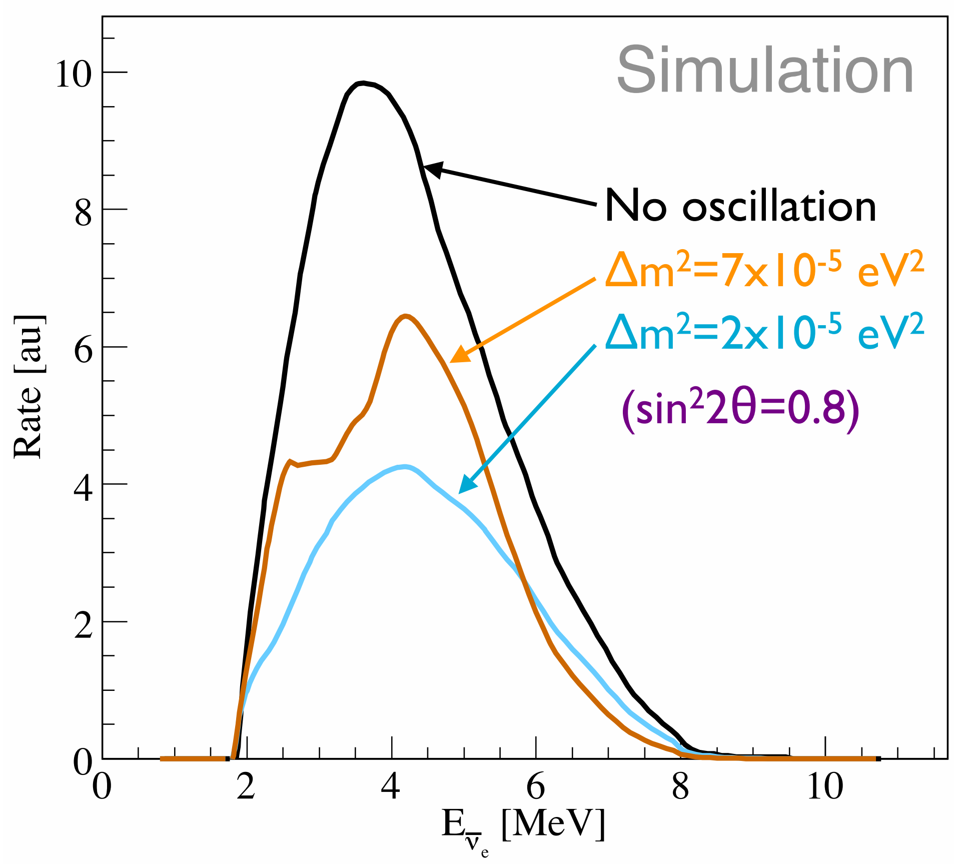
- In practice, only 1.5 neutrinos/fission detectable
- Calculated spectrum has been verified to 2% accuracy in past reactor experiments

No near detector necessary!

Reactors for Oscillation Studies



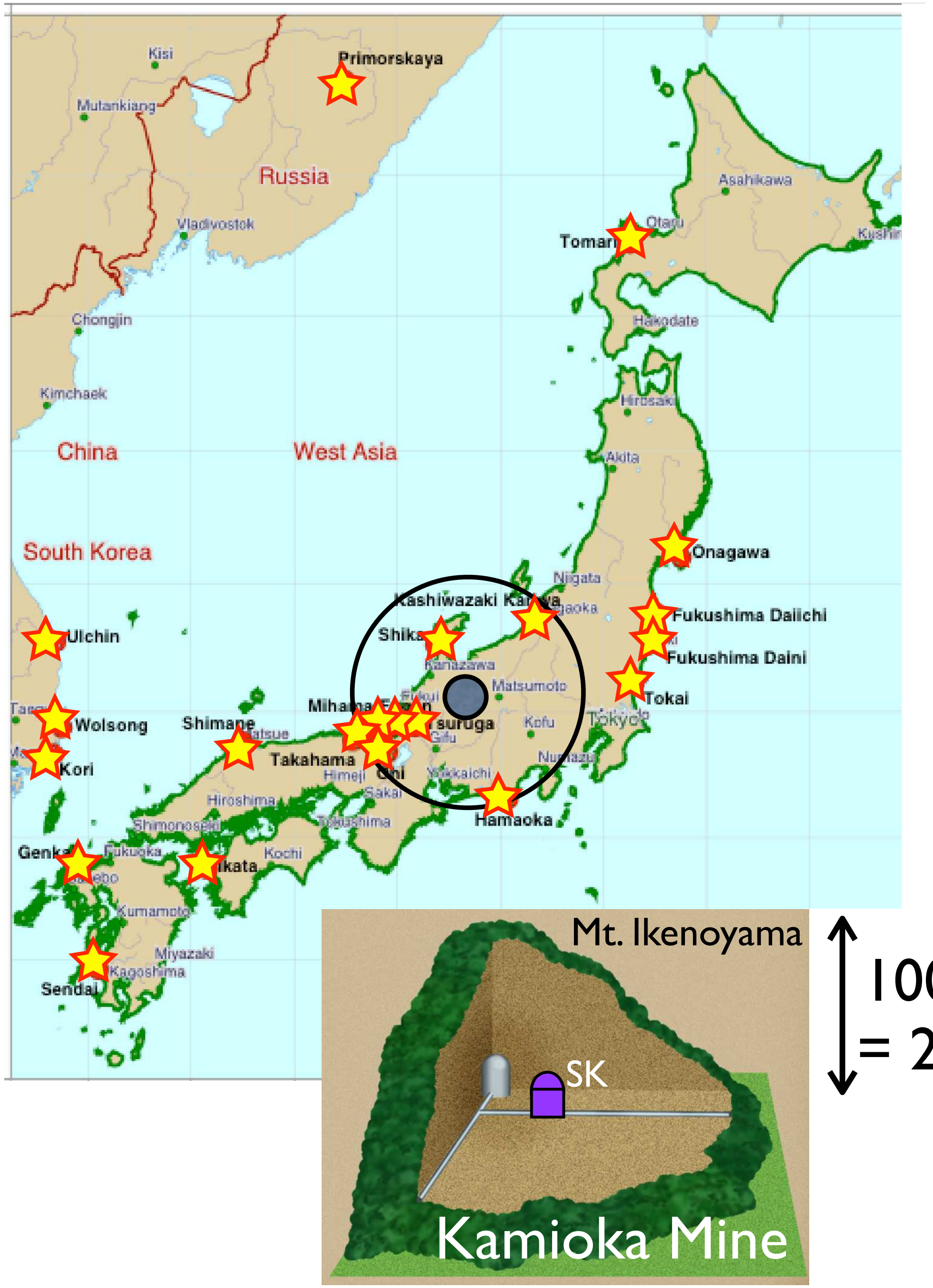
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$



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

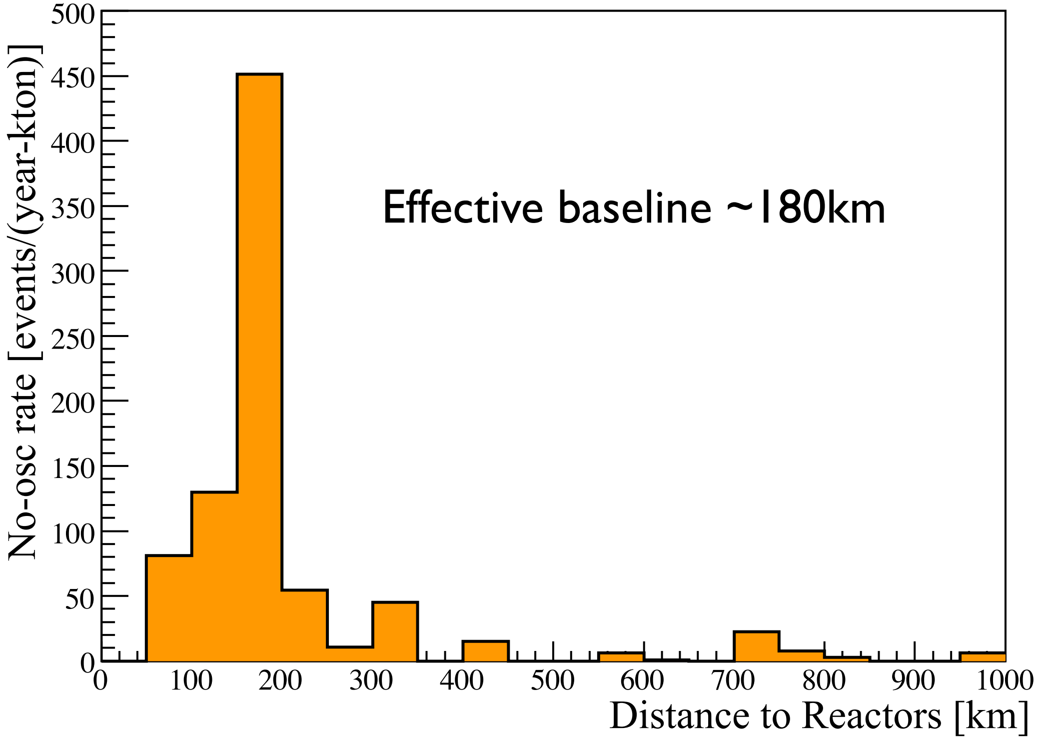
The KamLAND Experiment

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

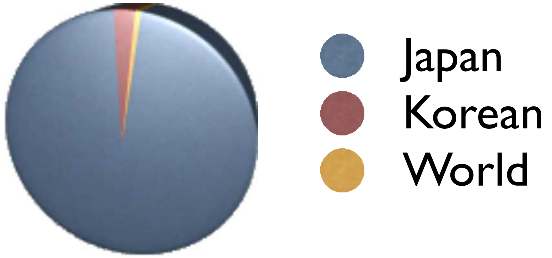


1000m rock = 2700 mwe

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



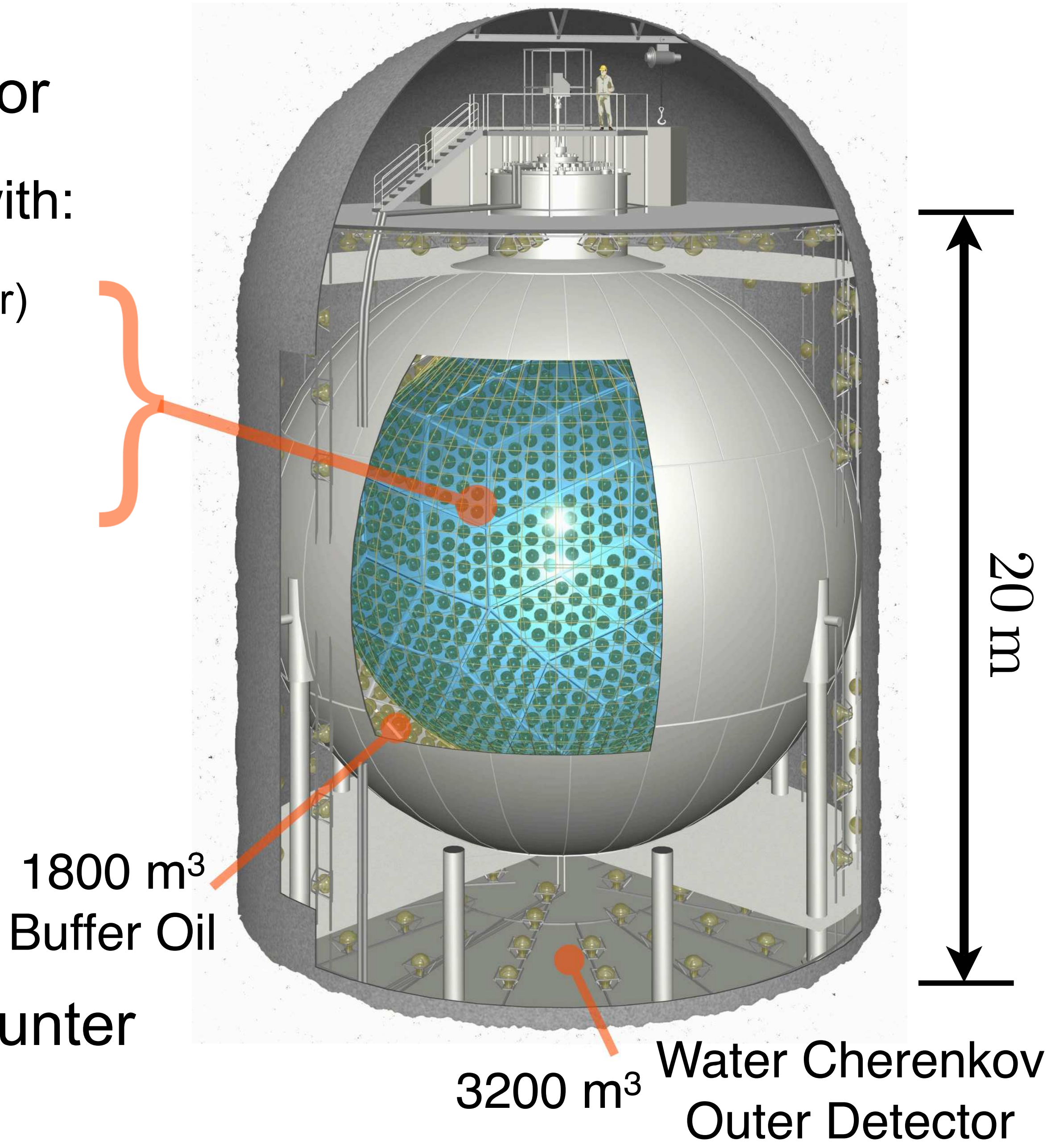
Reactor neutrino flux: ~6×10^6 cm^{-2}s^{-1}



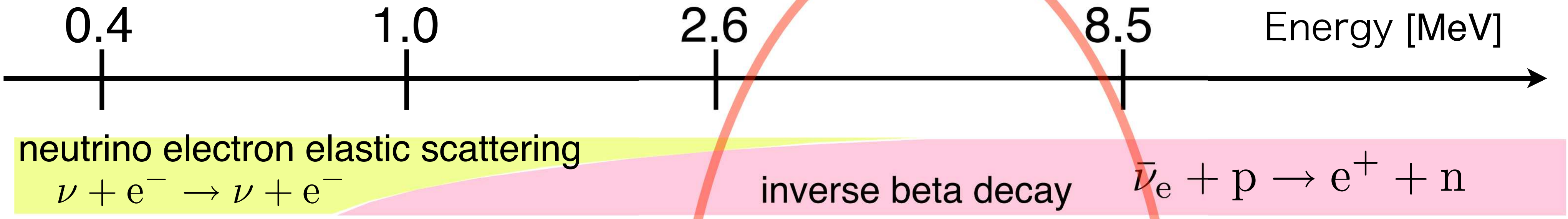
Patrick Decowski / Nikhef

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



KamLAND Physics Capabilities



neutrino electron elastic scattering

$\nu + e^- \rightarrow \nu + e^-$

inverse beta decay

$\bar{\nu}_e + p \rightarrow e^+ + n$

Neutrino Astrophysics

solar neutrino

Verification of SSM

Neutrino Geophysics

geo-neutrino

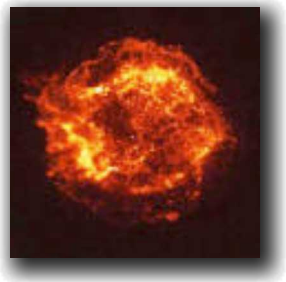
Study of earth heat model

Neutrino Physics

reactor neutrino

Precision measurement of oscillation parameters

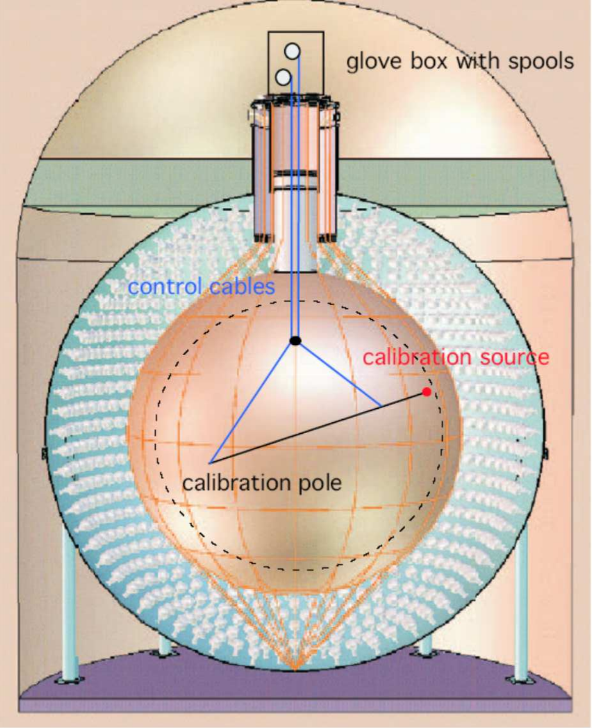
Neutrino Cosmology

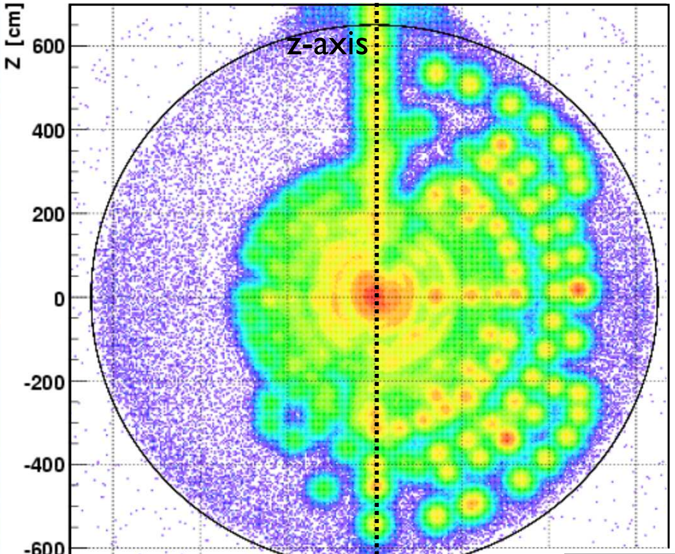


supernova, relic neutrino, solar anti-neutrinos etc.

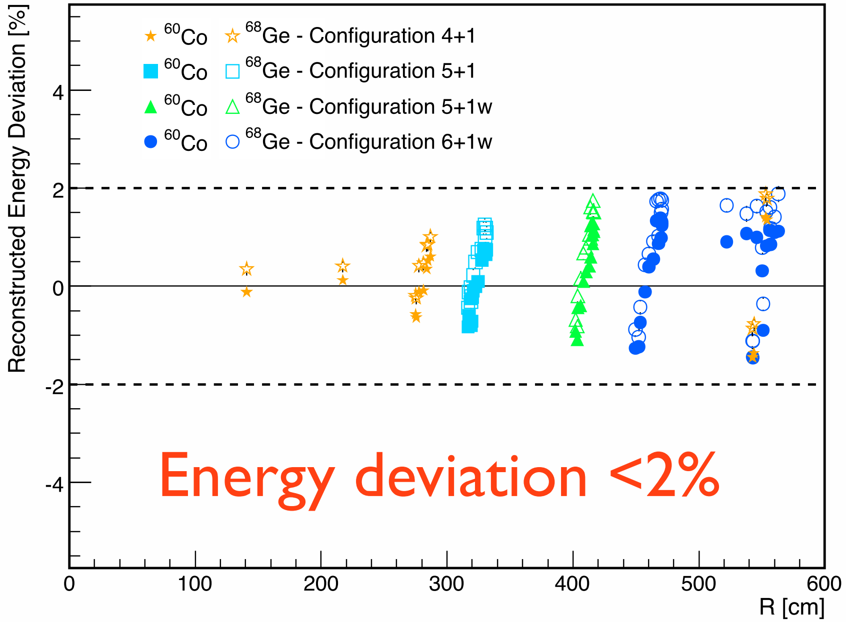
Verification of universe evolution, neutrino magnetic moment

Detector Characterization

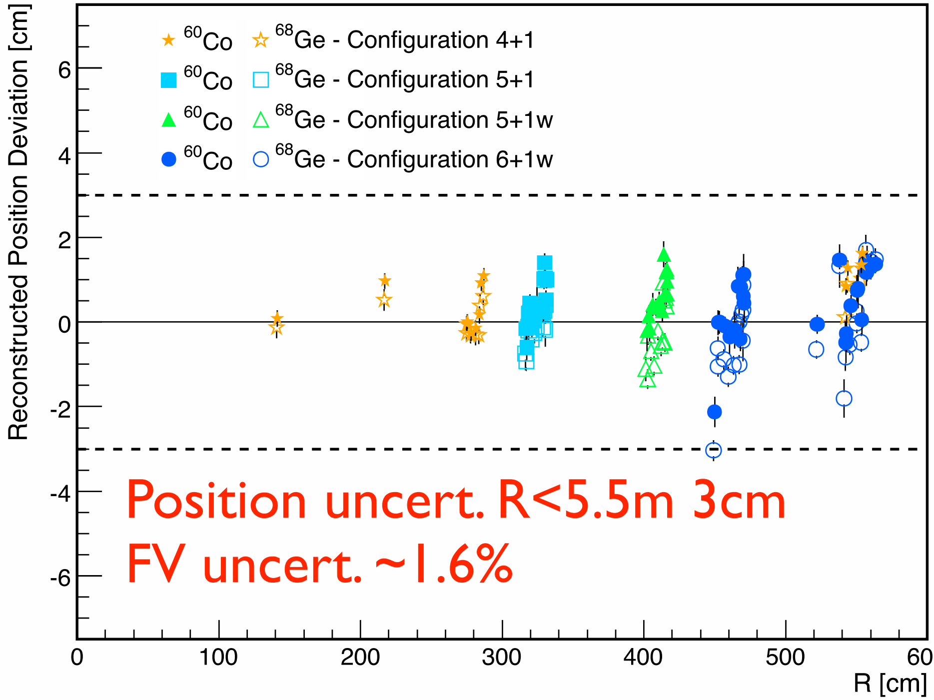




Range of radioactive sources (250keV to 6MeV):
^{203}Hg, ^{137}Cs, ^{68}Ge, ^{65}Zn, ^{60}Co, ^{241}Am^{9}Be, ^{210}Po^{13}C



Energy deviation <2%



Position uncert. R<5.5m 3cm

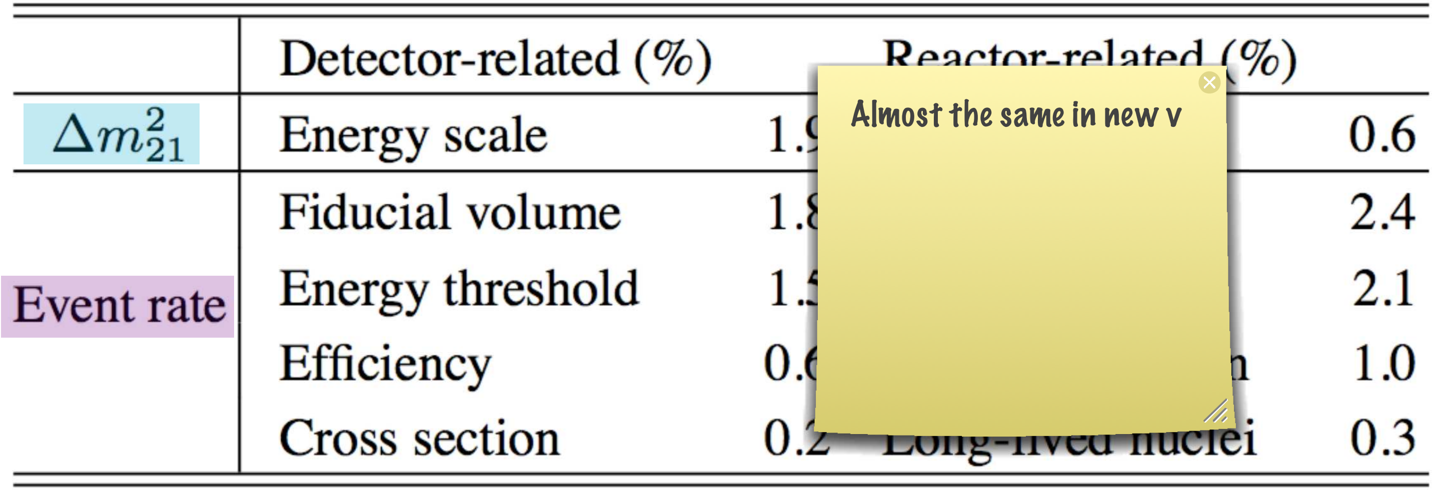
FV uncert. ~1.6%

Use ^{12}B/^{12}N spallation uniformity for 5.5m<R<6m

→ Total FV uncert R<6m: 1.8%

Systematic Uncertainties

Systematic uncertainties between Δm_{21}^2 and θ_{12} decouple to a large degree



	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	[illegible]	0.6
Event rate	Fiducial volume	1.8	[illegible]	2.4
	Energy threshold	1.5	[illegible]	2.1
	Efficiency	0.6	[illegible]n	1.0
	Cross section	0.2	Long-lived nuclei	0.3

Almost the same in new ν

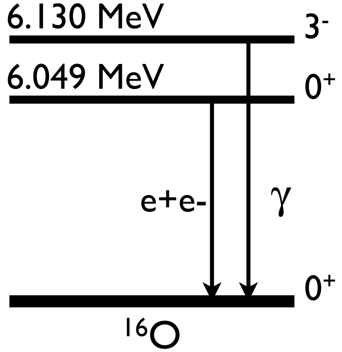
→ Sum: 2.0%

Primarily affecting θ_{12}
Sum: 4.1%

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

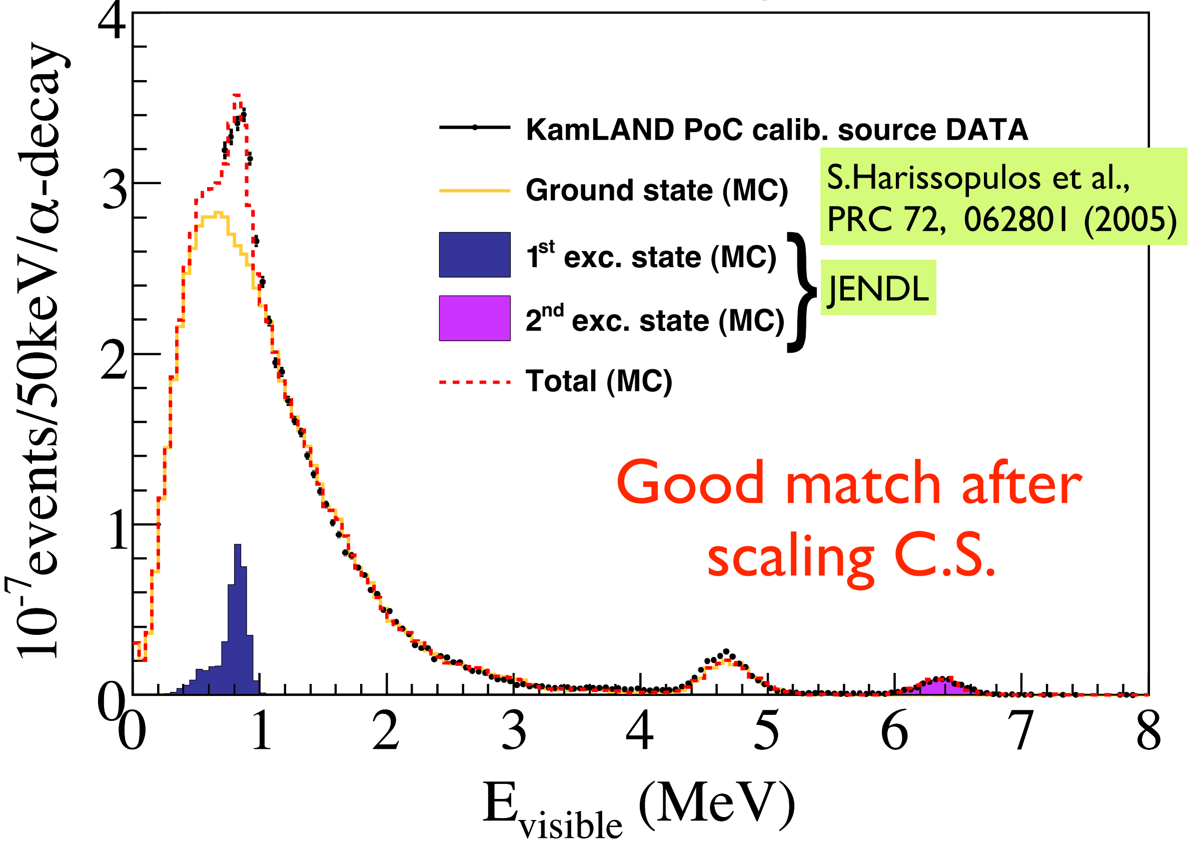
From ^{222}Rn chain: $^{210}Pb \xrightarrow{T_{1/2}=22yr} {}^{210}Bi \xrightarrow{5d} {}^{210}Po \xrightarrow{138d} {}^{206}Pb$

α, E=5.3MeV



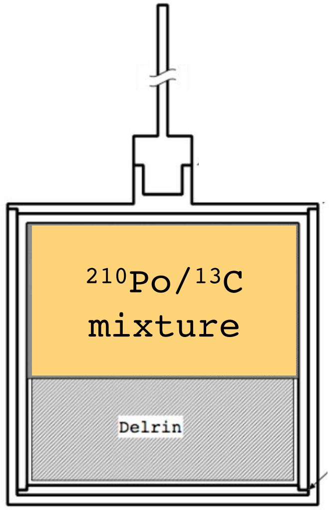
1.1% abundance of ^{13}C in LS → $\mathbf{^{13}C(\alpha,n)^{16}O}$

Cross sections tuned using detector MC



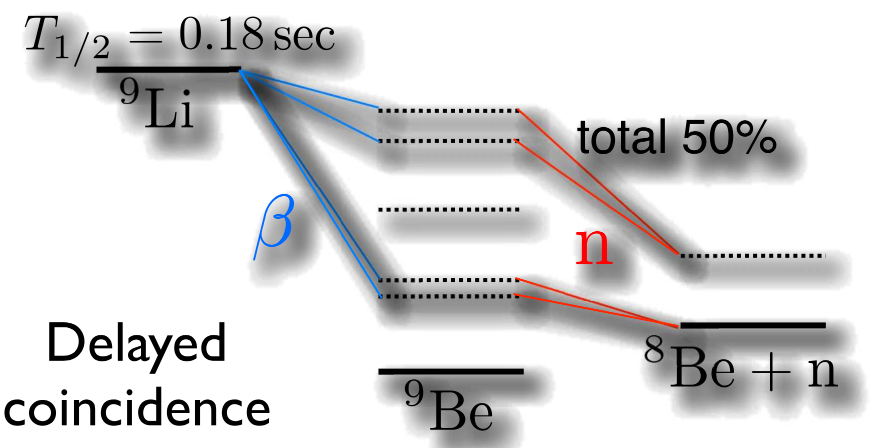
Good match after scaling C.S.

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

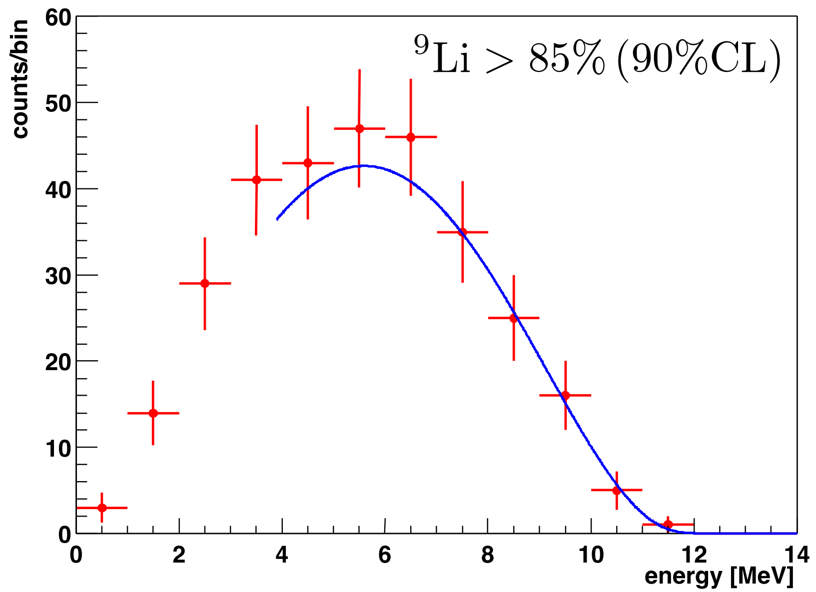


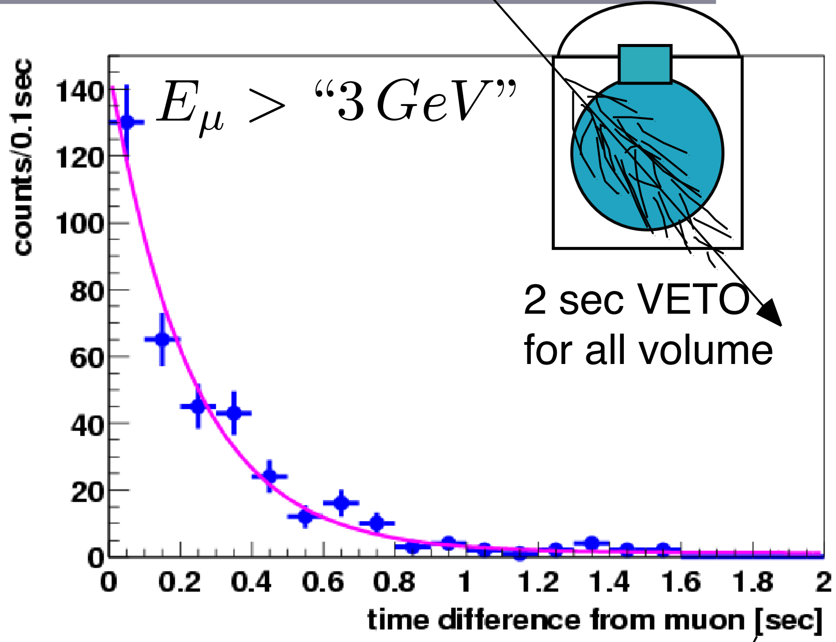
D.McKee et al., NIM A527, 272 (2008)

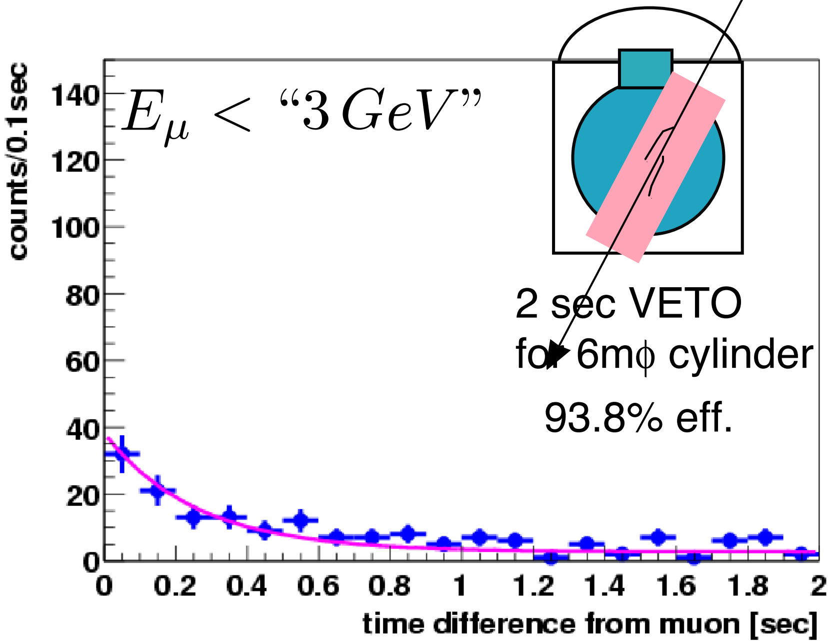
Muon Induced Spallation Events



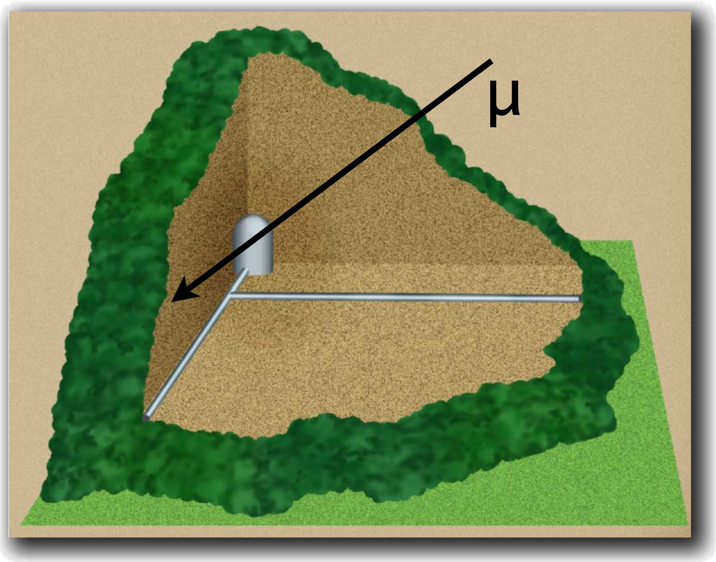
Delayed coincidence signature

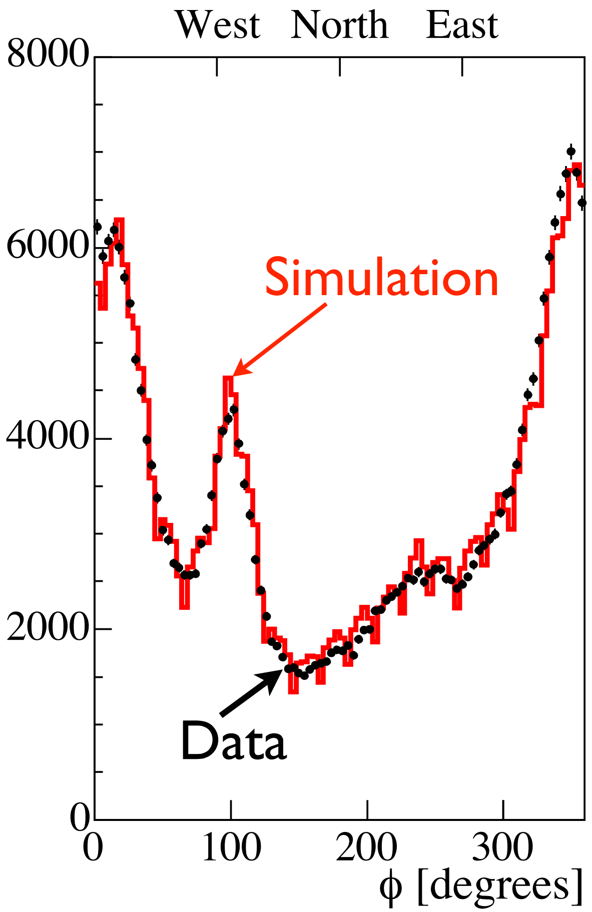


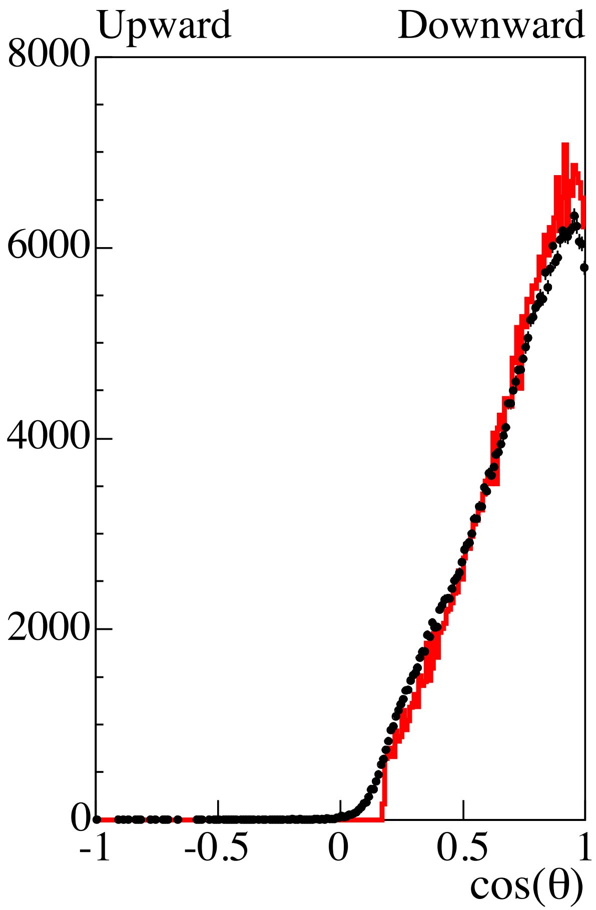




Muon Tracking Works





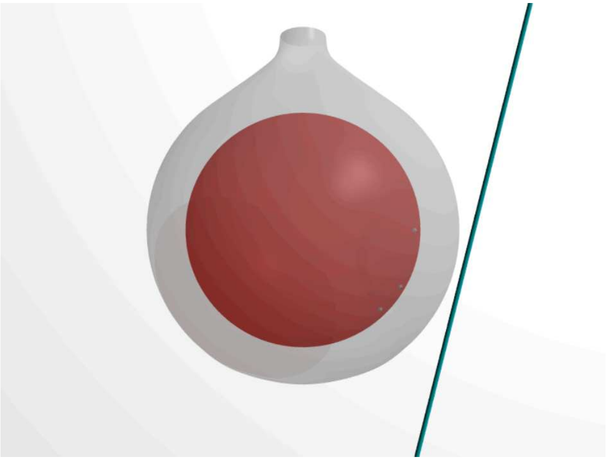


Comparison of tracking to simulation, including detailed mountain geometry

Dealing with muons

3 Typical scenarios of muons interacting in KamLAND

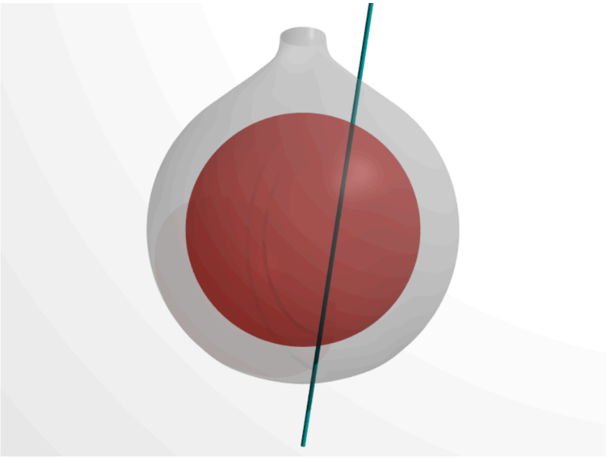
Muon outside LS



0 to 2 ms after muon outside LS:
veto entire volume.

>2 ms after muon outside LS:
all of fiducial volume is okay.

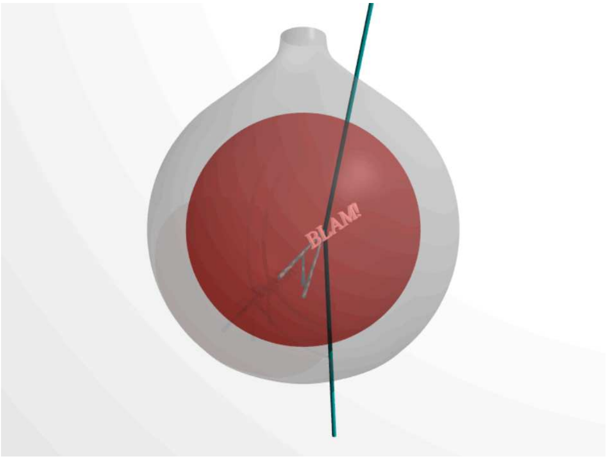
Muon in LS, little E deposited



0 to 2 ms after muon in LS:
veto entire volume

2 ms to 2 s after muon in LS:
veto events within 3 m of track

"Showering" Muon in LS



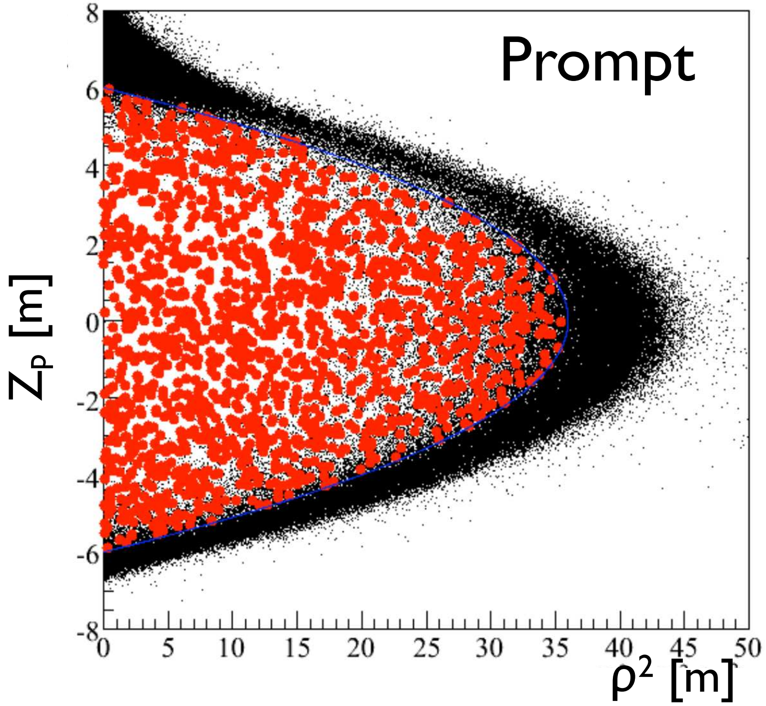
0 to 2 ms after shower in LS:
veto entire volume

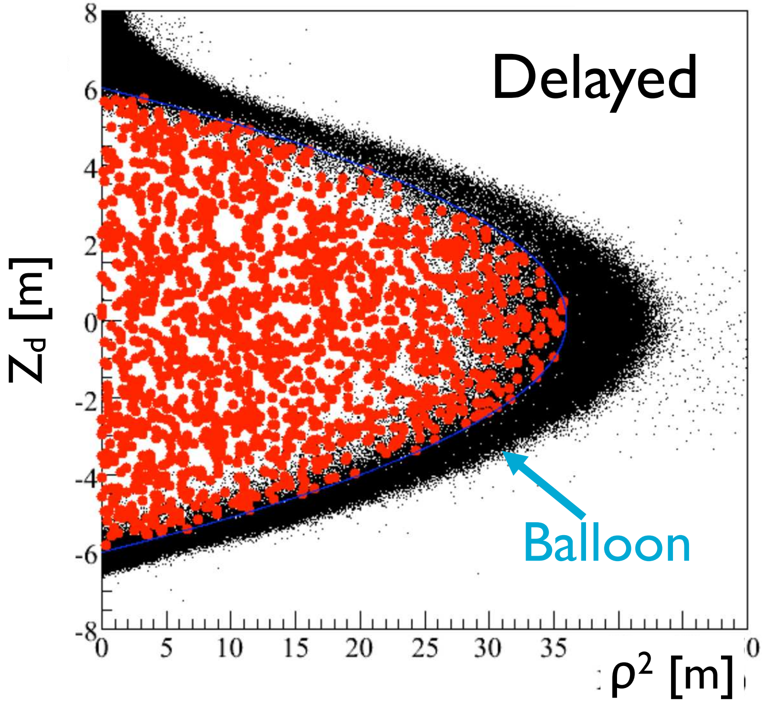
2 ms to 2 s after shower in LS:
also veto entire volume

Event Selection

- Inverse beta-decay selection:
  - $R_{prompt, delayed} < 6$ m
  - 0.9 MeV < E_{prompt} < 8.5 MeV
  - 1.8 MeV < $E_{delayed}$ < 2.6 MeV
  - $\Delta R < 2$m
  - 0.5 μs < ΔT < 1000 μs
  - L-ratio: Use event characteristics to limit effect of accidental backgrounds at high R

- Muon-induced spallation event cuts:
  - 2 ms veto after every μ
  - 2 s veto for showering/bad μ
  - 2 s veto in a R = 3m tube along track





Backgrounds

Background	Contribution
Accidentals	102.5 ± 0.1
^{9}Li/^{8}He	24.8 ± 1.6
Fast neutron & Atmospheric ν	<12.3
$^{13}C(\alpha,n)^{16}O_{gs}$, $np \rightarrow np$	171.7 ± 18.2
$^{13}C(\alpha,n)^{16}O_{gs}$, $^{12}C(n,n')^{12}C^{*}$ (4.4 MeV γ)	7.3 ± 0.8
$^{13}C(\alpha,n)^{16}O$ 1st exc. state (6.05 MeV $e^{+}e^{-}$)	15.9 ± 3.3
$^{13}C(\alpha,n)^{16}O$ 2nd exc. state (6.13 MeV γ)	3.7 ± 0.7
Total	325.9 ± 26.1

Accidental Coincidences

Cosmogenic

Background from ^{222}Rn chain

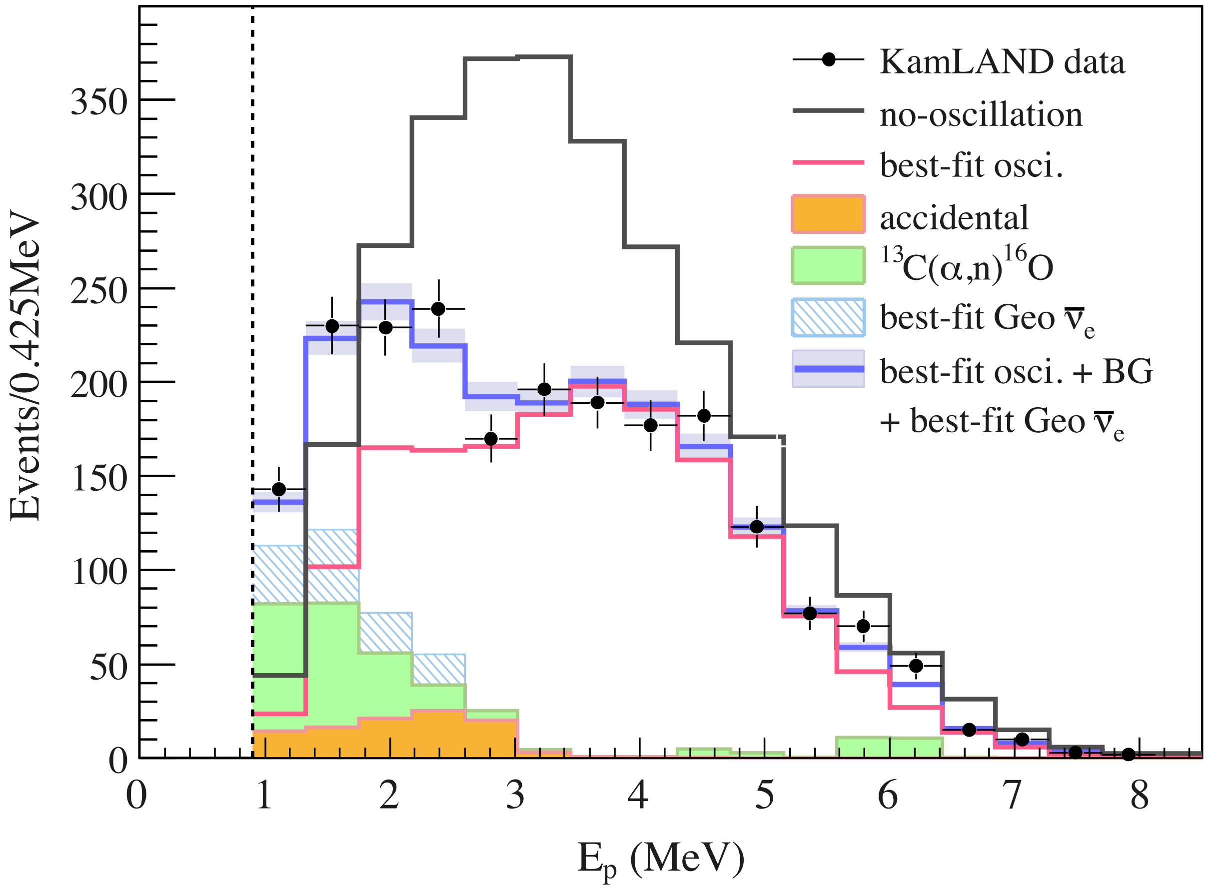
Geo-neutrinos are a background to the neutrino oscillation measurement

Using one geological model, which assumes 16TW of radiogenic heat from U+Th geo-neutrinos, expect 106 events

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

Energy Spectrum

From Mar 9, 2002 to November 4, 2009
2135 live days, 4126 ton-year exposure

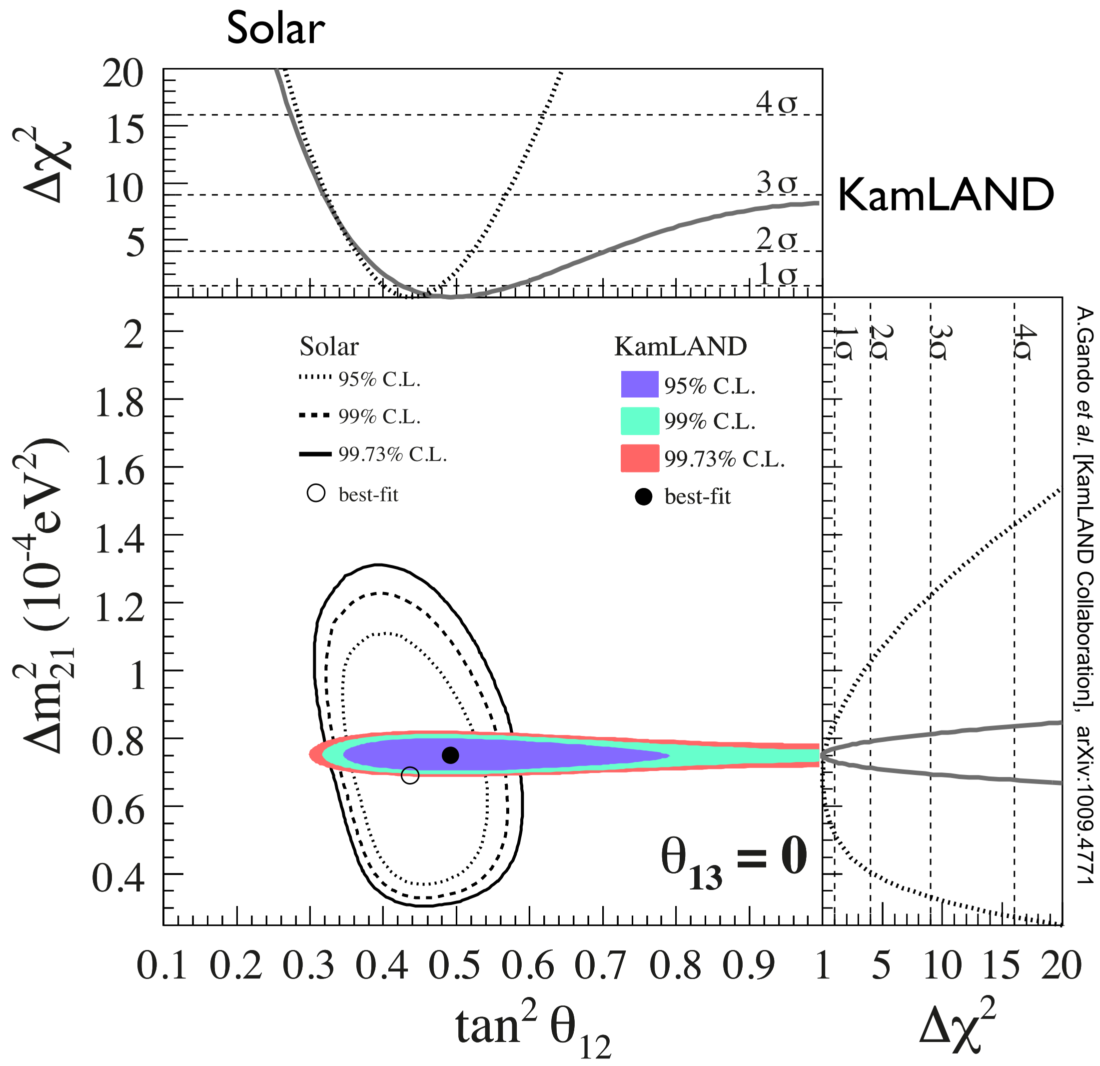


A.Gando *et al.* [KamLAND Collaboration], arXiv:1009.4771

Number of events:

no-osc expected	2879 ± 118
background	326 ± 26
observed	2106

Neutrino Oscillation Parameters



A.Gando *et al.* [KamLAND Collaboration], arXiv:1009.4771

KamLAND-only best-fit:

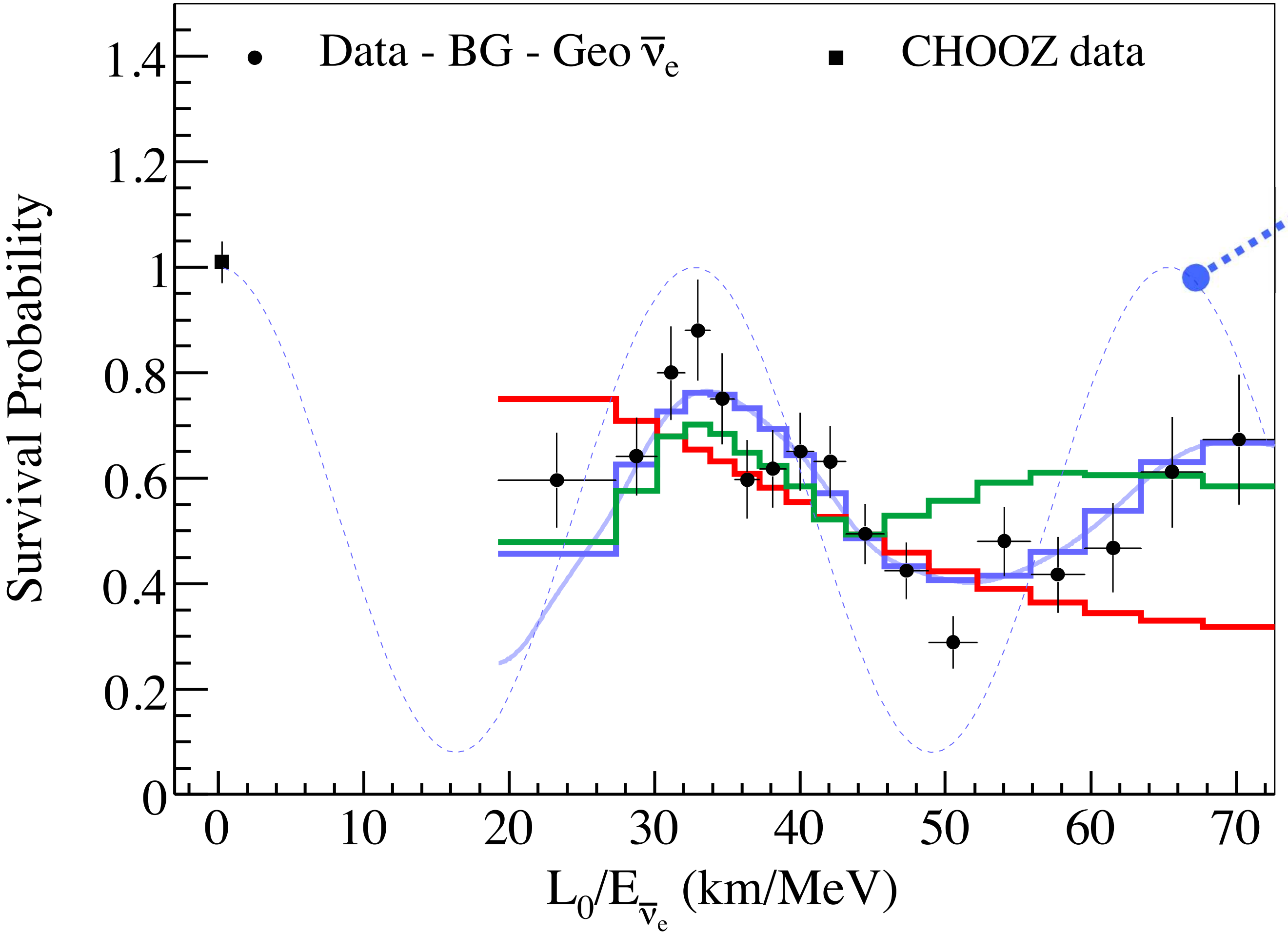
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.492^{+0.086}_{-0.067}$$

Solar Experiments are sensitive to θ_{12} (mainly SNO)

KamLAND is most sensitive to Δm^2_{21}

Illustration of Neutrino Oscillation



Oscillation pattern for a mono-energetic $\overline{\nu}_e$ at one baseline

LMA-1 (best fit)

LMA-2

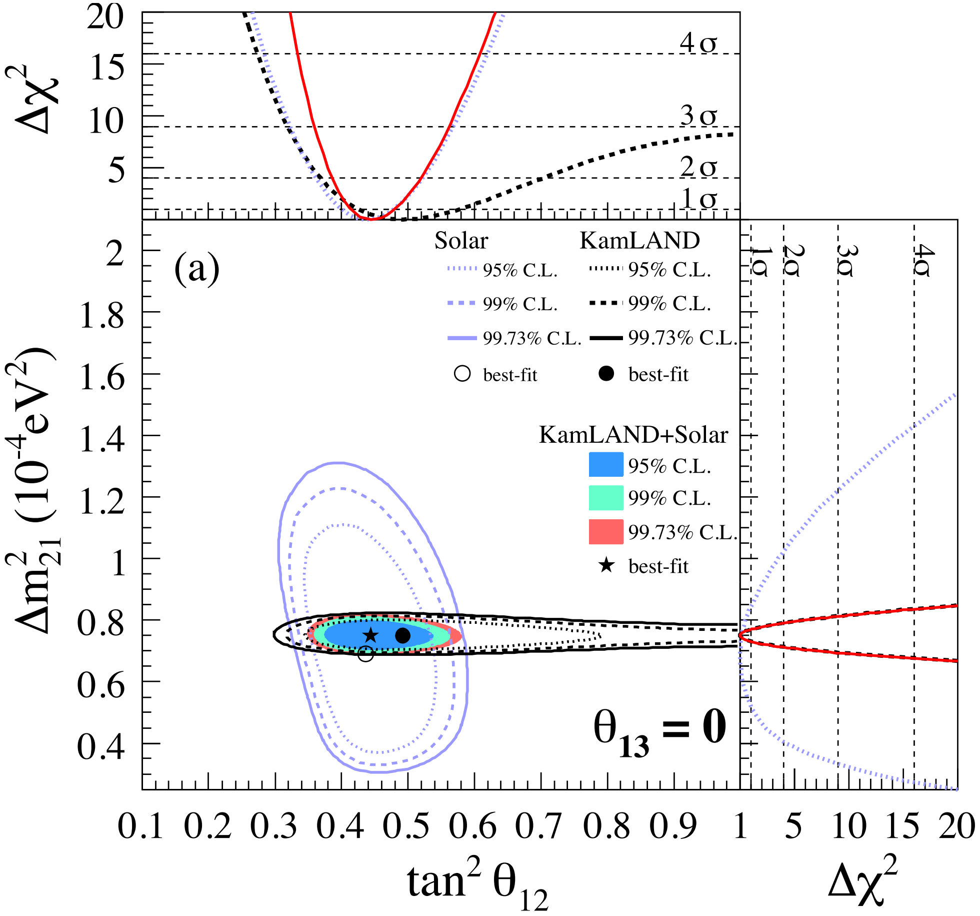
LMA-0

-fit oscillation
ounting for energy
trum and
tor distribution

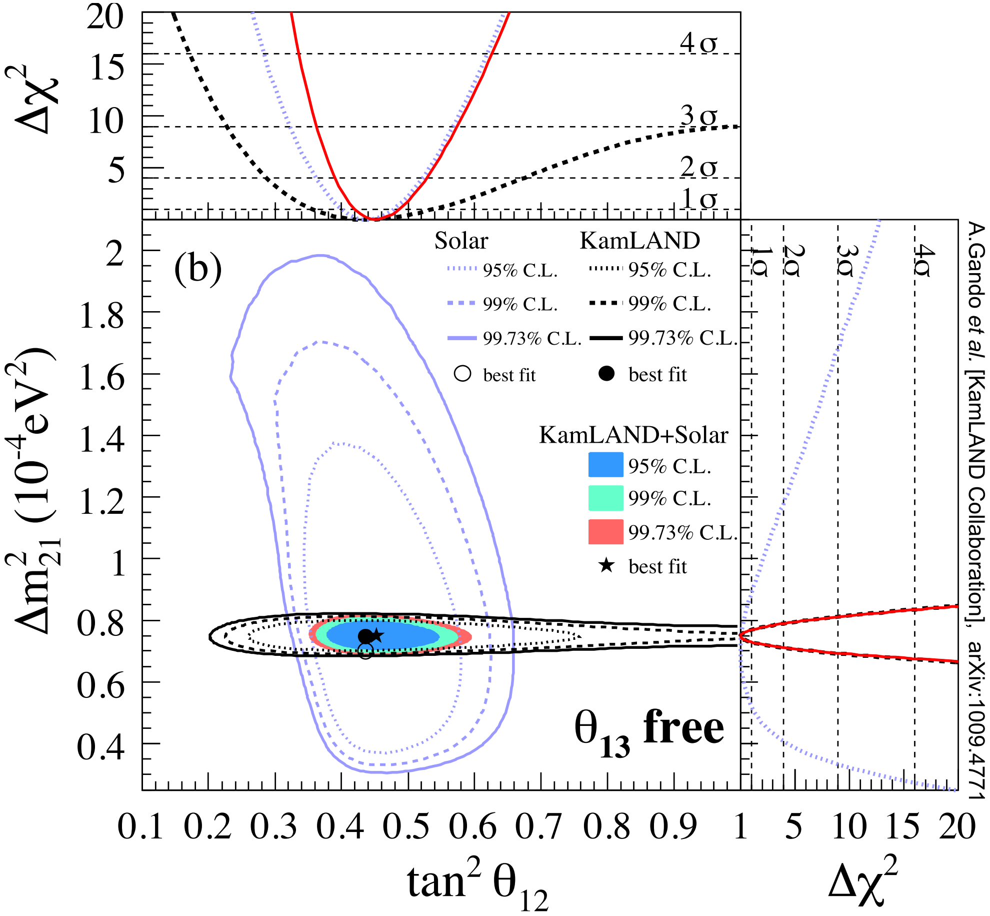
$$P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\Delta m^2}{4}\frac{L}{E})$$

3-flavor Oscillation

2-flavor oscillation



3-flavor oscillation



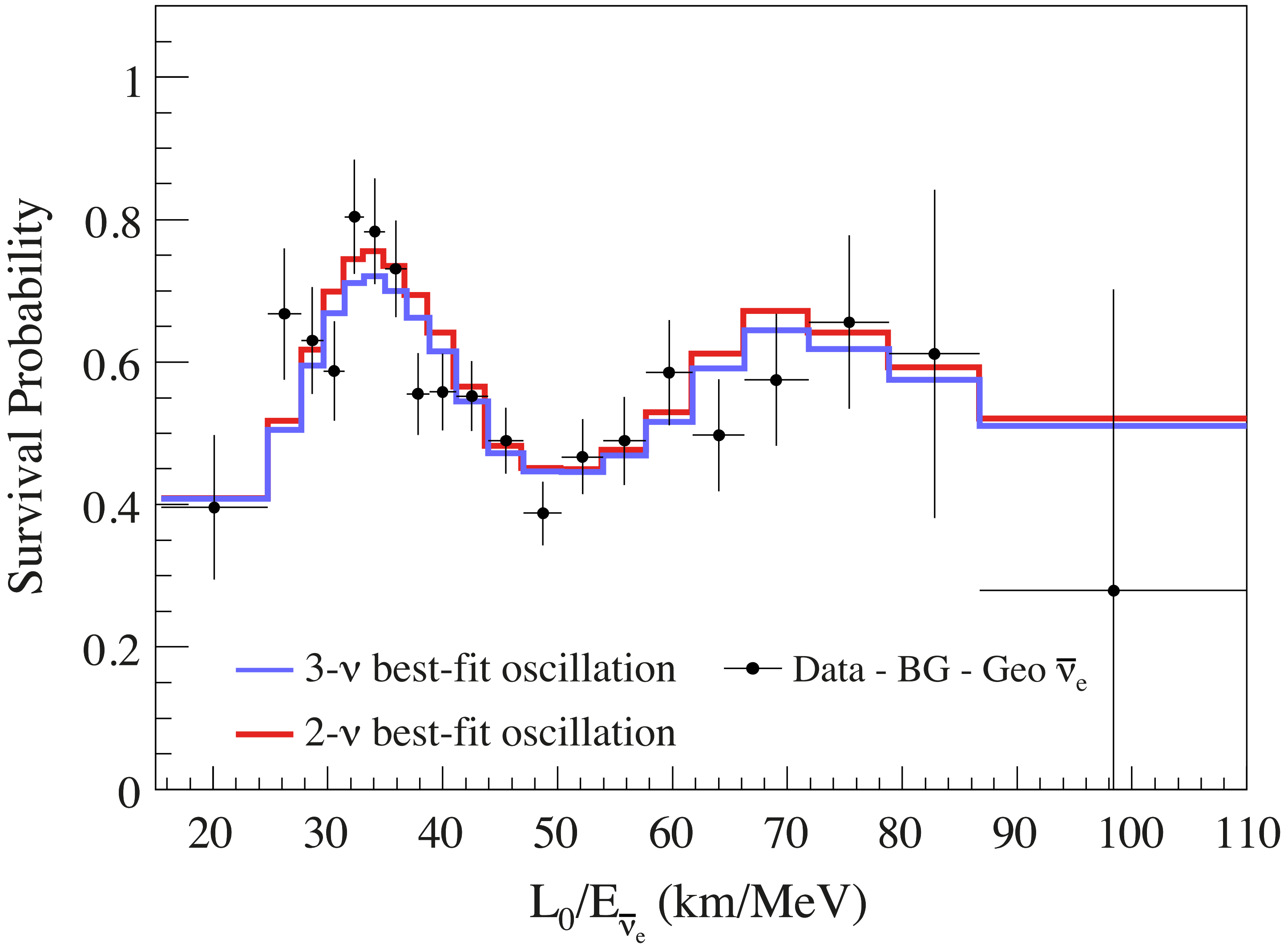
A.Gando *et al.* [KamLAND Collaboration], arXiv:1009.4771

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.444^{+0.036}_{-0.030}$$

↔

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$
$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

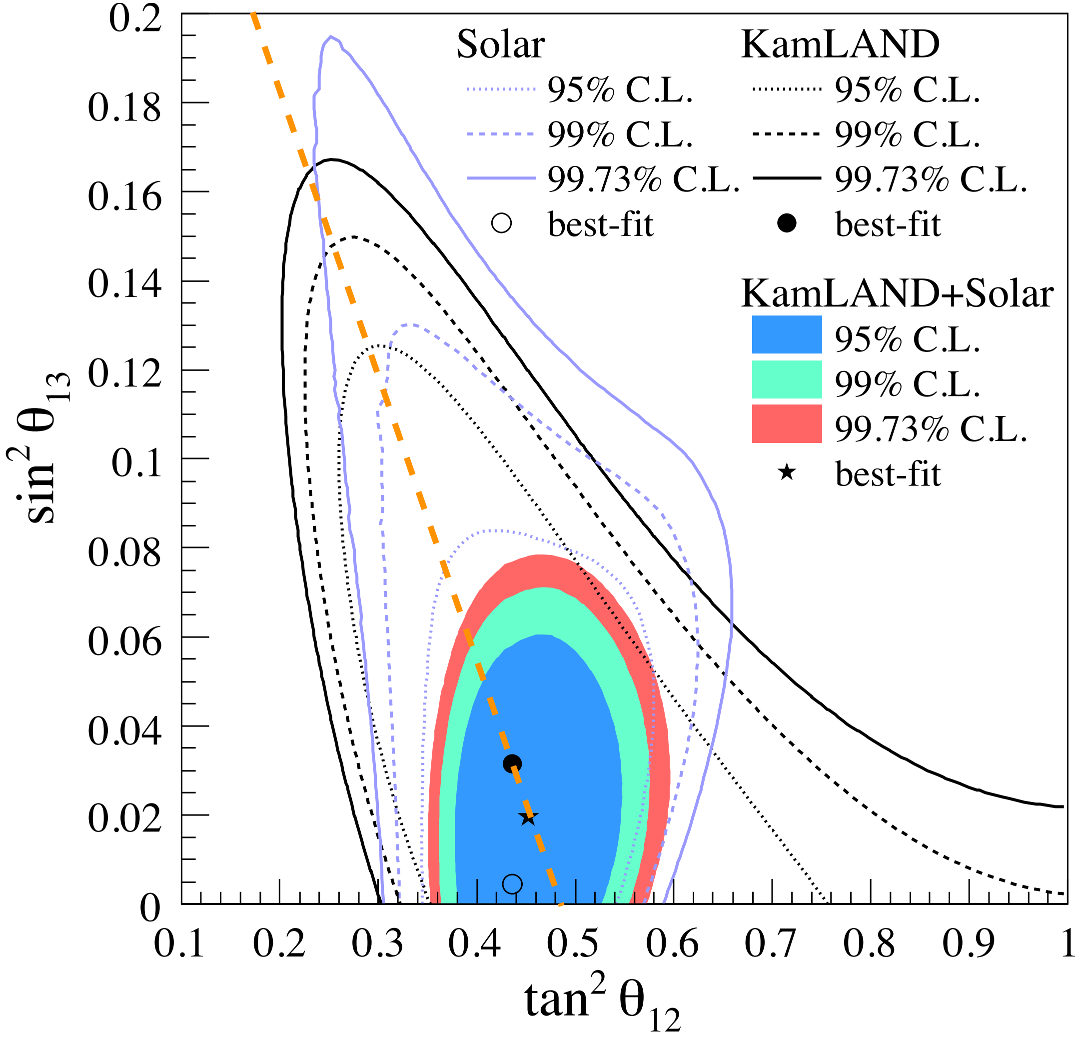
Effect of 3-nu Oscillation



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

Disentangling θ_{13}

KamLAND is not ideal for this measurement

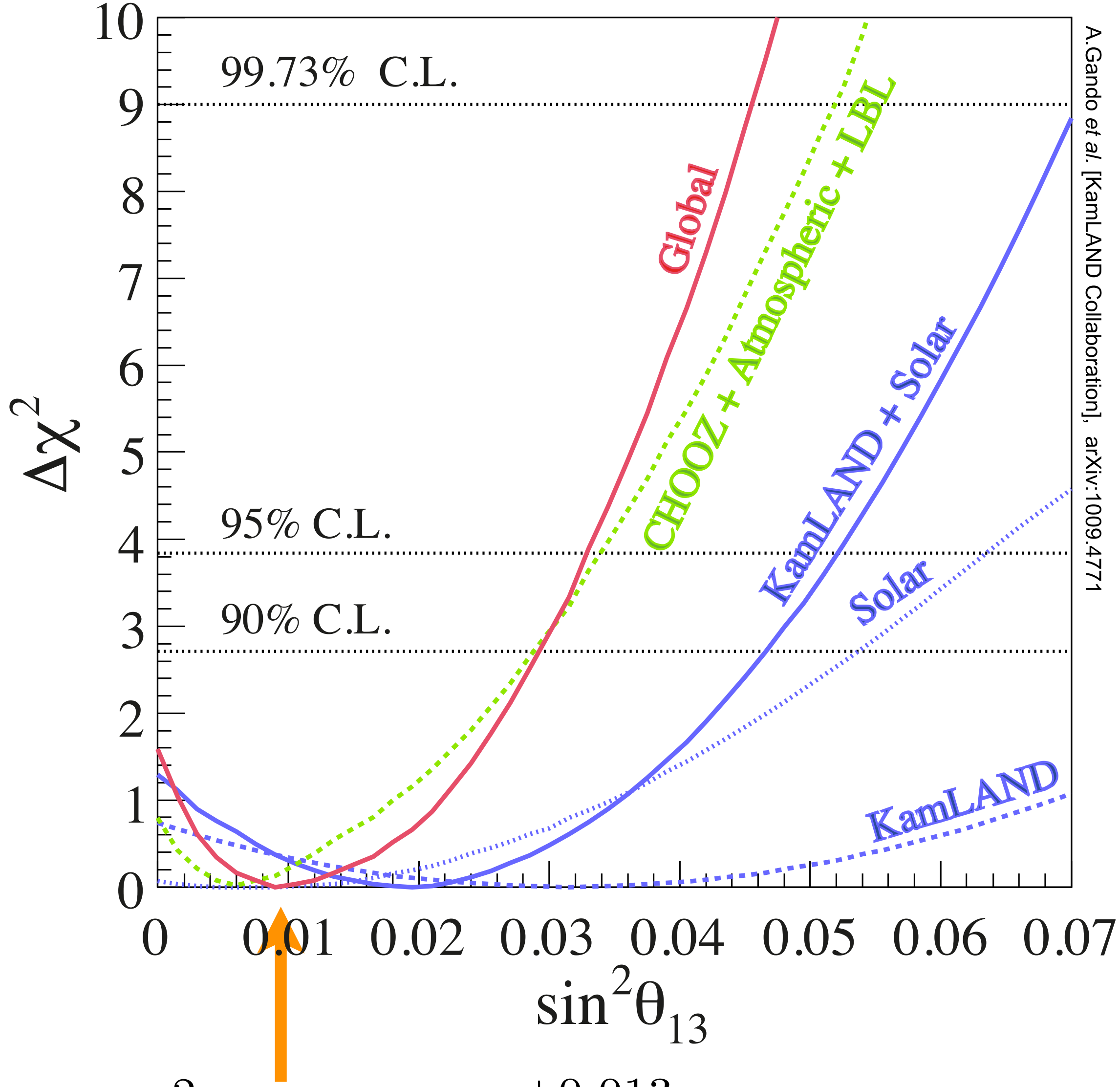


anti-correlation
θ_{12} and θ_{13}

A.Gando *et al.* [KamLAND Collaboration], arXiv:1009.4771

→ Global analysis with other experiments

Global fit of θ_{13}



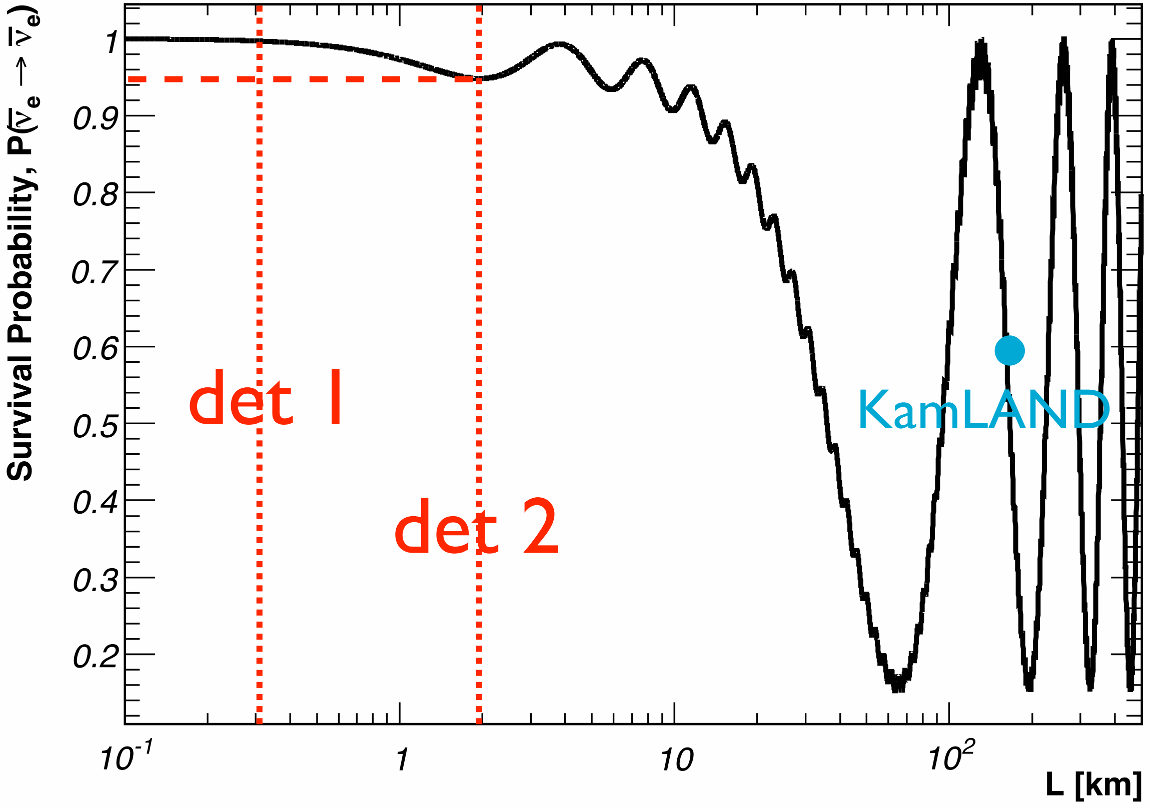
A.Gando *et al.* [KamLAND Collaboration], arXiv:1009.4771

$$\sin^2\theta_{13} = 0.009^{+0.013}_{-0.007}$$

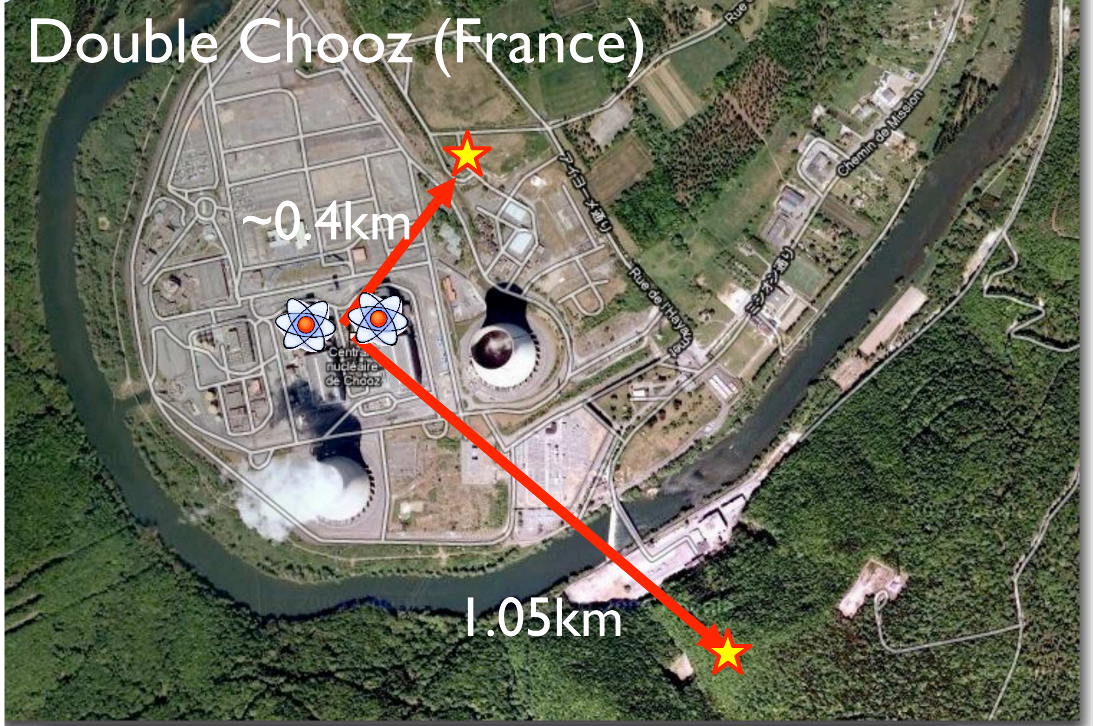
Non-zero θ_{13} excluded at 79% C.L.

High Precision Measurement of θ₁₃

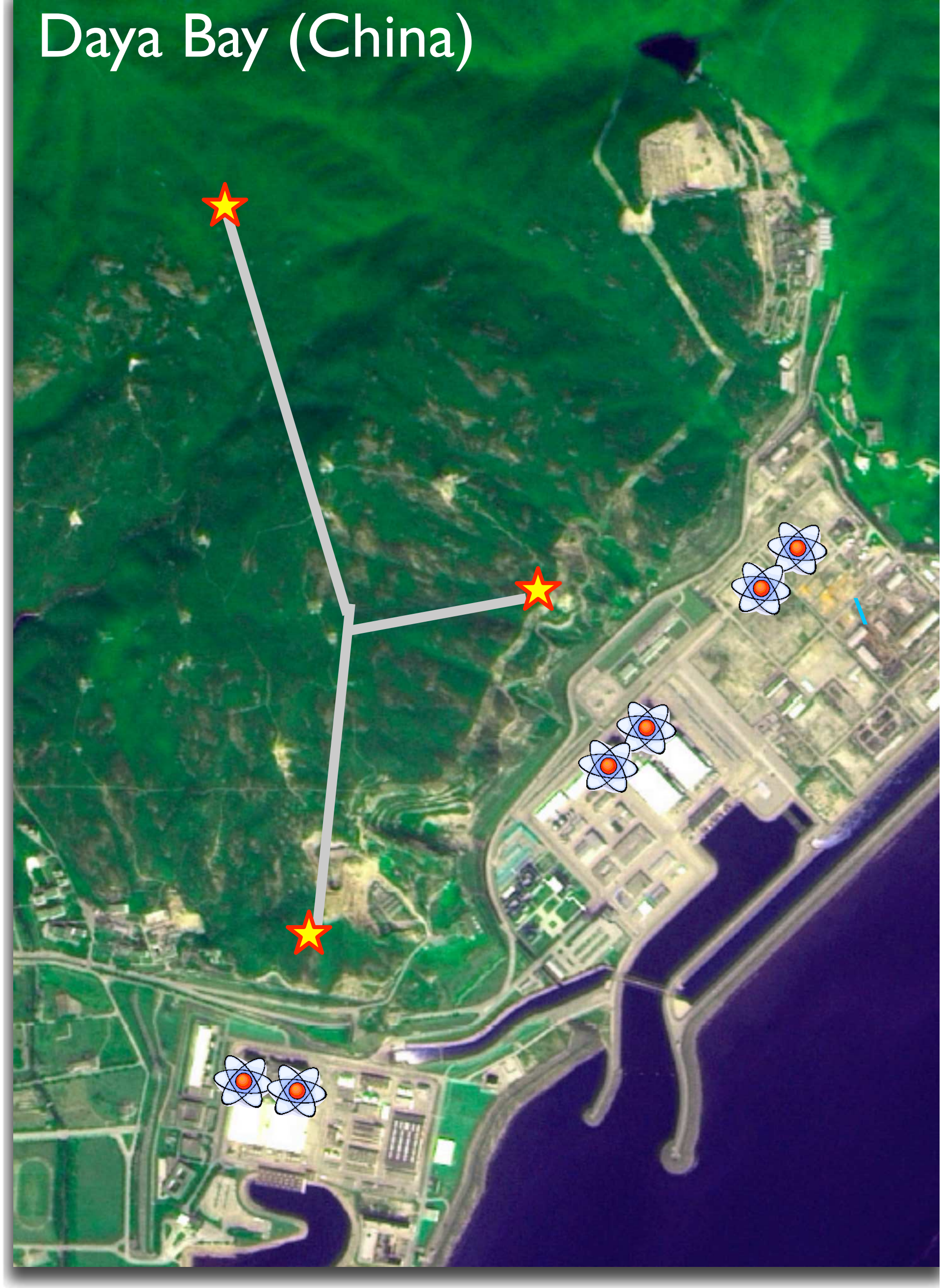
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



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


Double Chooz (France)
~0.4km
1.05km
Centrale nucléaire de Chooz
Chemin de Mission
Rue de l'Hayeux


Yellow Sea
Near Detector
Reactors
RENO (South Korea)
1 km
Far Detector


Daya Bay (China)

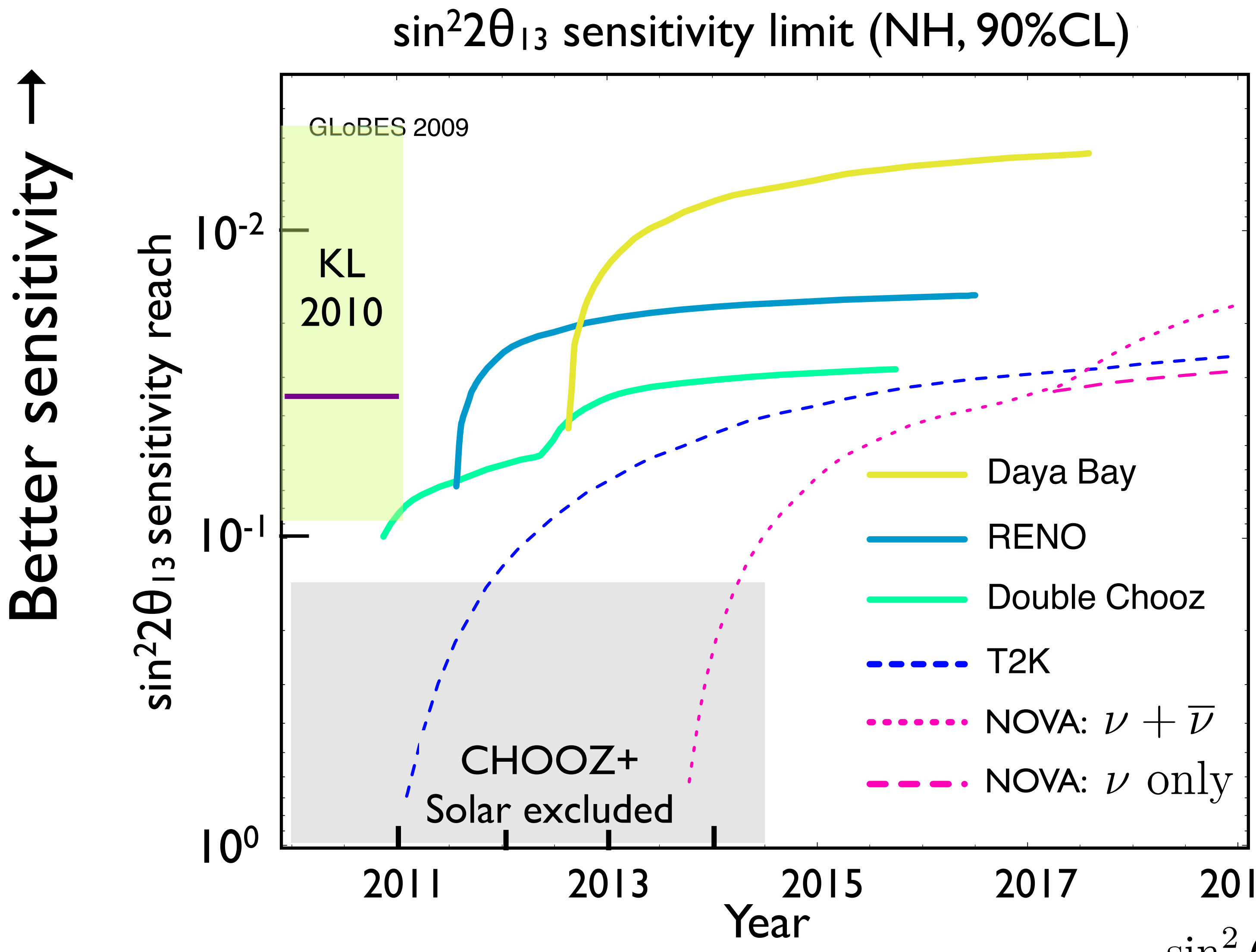
Future Reactor θ_{13} Experiments

	Power (GW_{th})	Mass (Tons)	Distance to Reactor		Syst. Uncert. (%)	Est. Start (in Dec'10)
			Near (m)	Far (m)		
Double Chooz	8.5	2x10	400	1050	0.6	Dec 2010
Daya Bay	17.4	8x20	363 481	1985 1613	0.4/0.2 base/optm	mid 2011
RENO	16.4	2x16	290	1380	0.5	April 2011

Typical neutrino event rates:

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

Sensitivity Limits



Modified from P.Huber *et al.*, JHEP 0911:044 (2009).

$$\sin^2\theta_{13} \approx \frac{1}{4}\sin^2 2\theta_{13}$$

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

Geoneutrino Results

nature 436, 441–602 28 July 2005 www.nature.com/nature nature outlook: India no.7050 npg

28 July 2005 | www.nature.com/nature | $10

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

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Gene signature for metastasis

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Everything has a fingerprint

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EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

$10.00US $12.99CAN

Deconstructing Earth

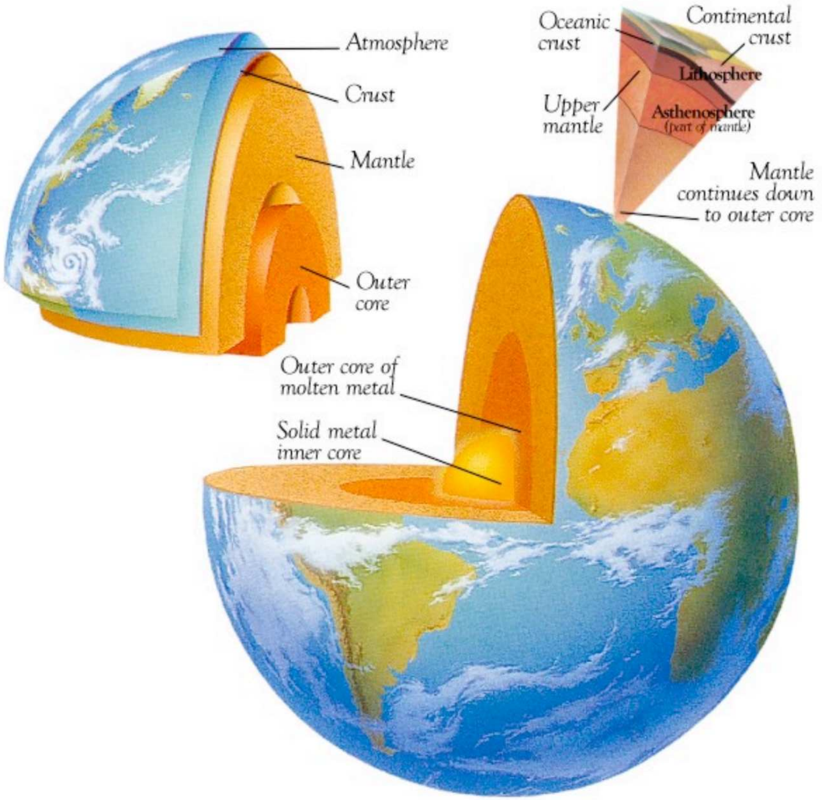
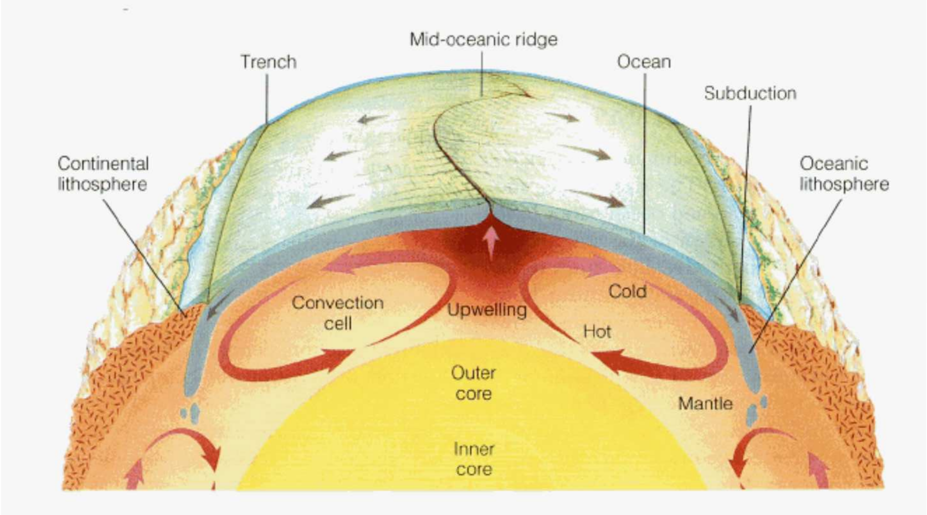


Image by C. Rose and D. Kindersley

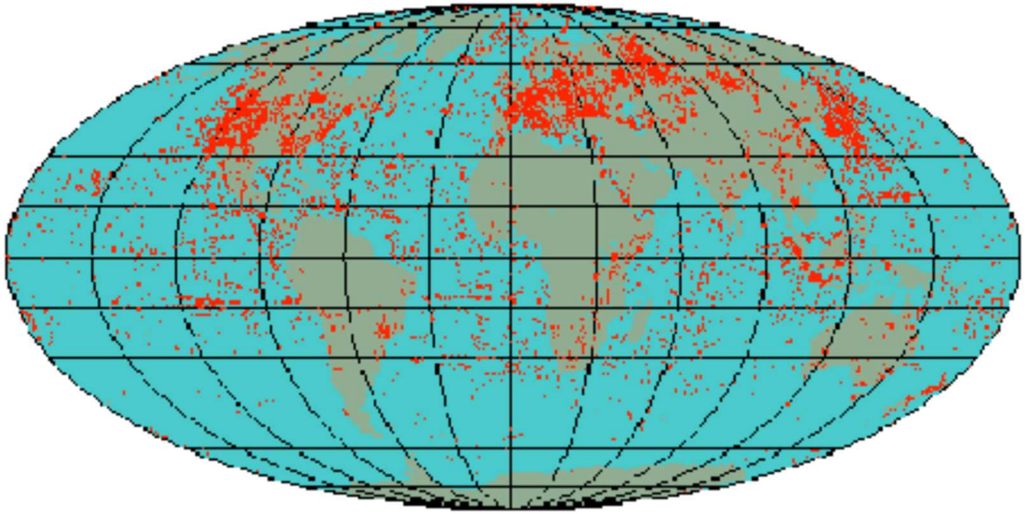


- Earth is subdivided into basic regions:
  - Inner Core
  - Outer Core
  - Lower Mantle
  - Upper Mantle
  - Continental / Oceanic crust
- These regions are solid except for the outer core
- Oceanic crust is made at mid-oceanic ridge and recycled at continental trenches

Where does the energy for convections, plate tectonics, etc. come from?

Earth's Heat Flow

Bore hole locations:



Heat Flow:

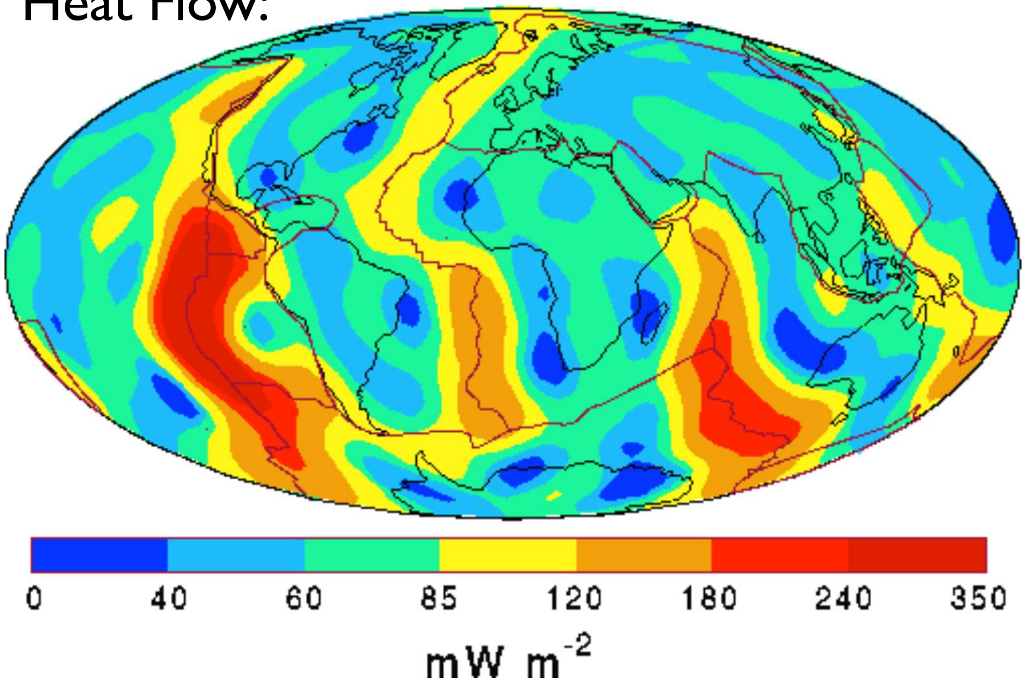


Image from Pollack et al.

- Based on bore holes measuring conductive heat flow (need temp. grad. and conductivity)
  - Total heat flow: 46 ± 3TW
  - 30-32TW measured, then extrapolated to account for ocean surface
  - Average heat flux: 87 mW/m^2
- Where does this heat come from?

Radiogenic Heat

How much do radioactive decays contribute to heat?

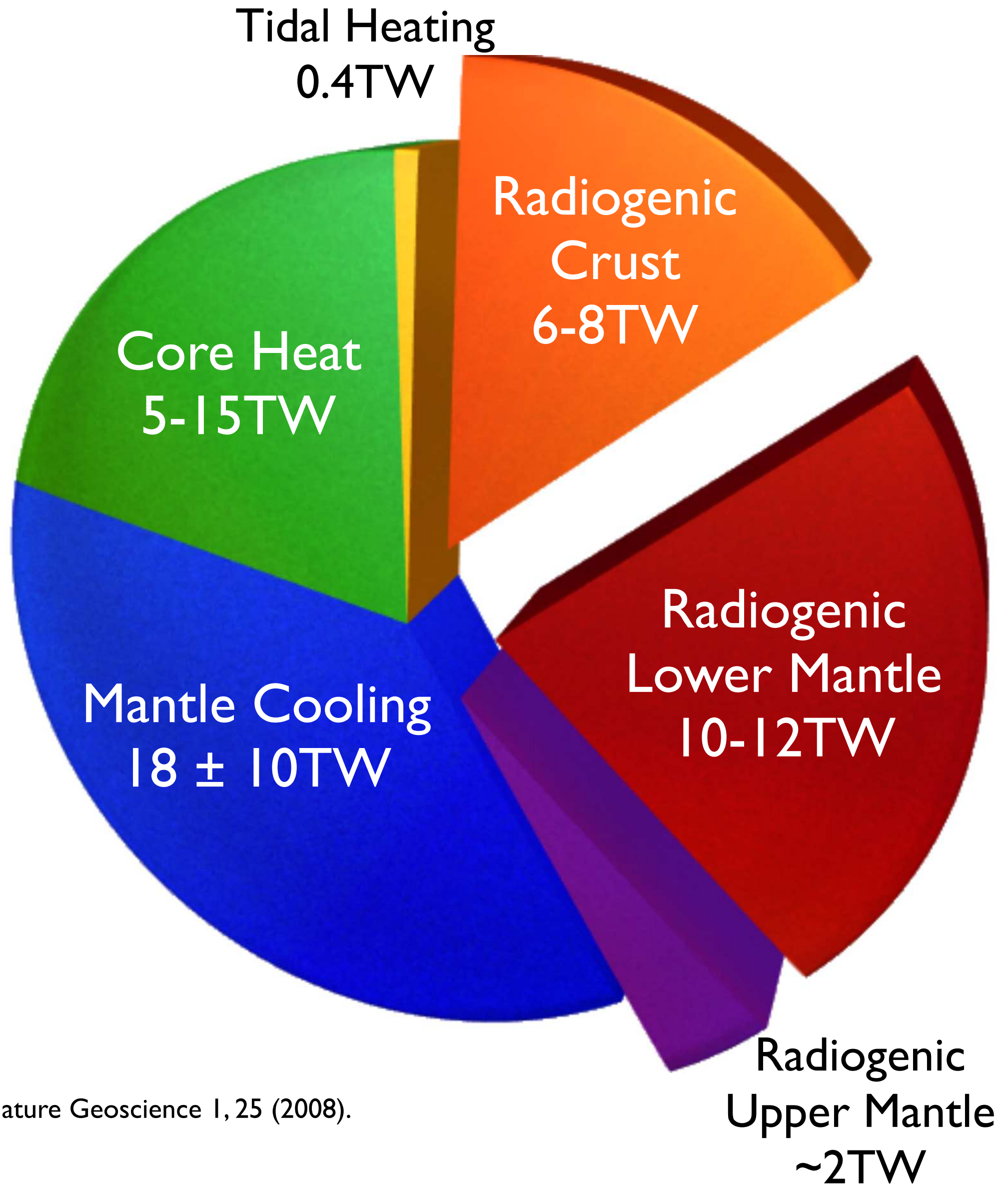
- Abundances of elements in Carbonaceous Chondritic meteorites are similar to those in the solar photosphere
- Composition of Earth should be similar to these chondrites
- These chondrites contain U-238, Th-232 and K-40 and therefore there should be similar concentrations in the Earth
- From these meteorites, we know the Th/U mass ratio to be ~3.9
- U, Th and K decay and in one reference model:
  - Uranium and Thorium account for 8TW each
  - Potassium is 3-4TW

} Total radioactive power: ~20TW

- “Differentiation”, e.g. for U-238:

Core	<<1 ng/g
Mantle	~10 ng/g
Continental Crust	~1000 ng/g

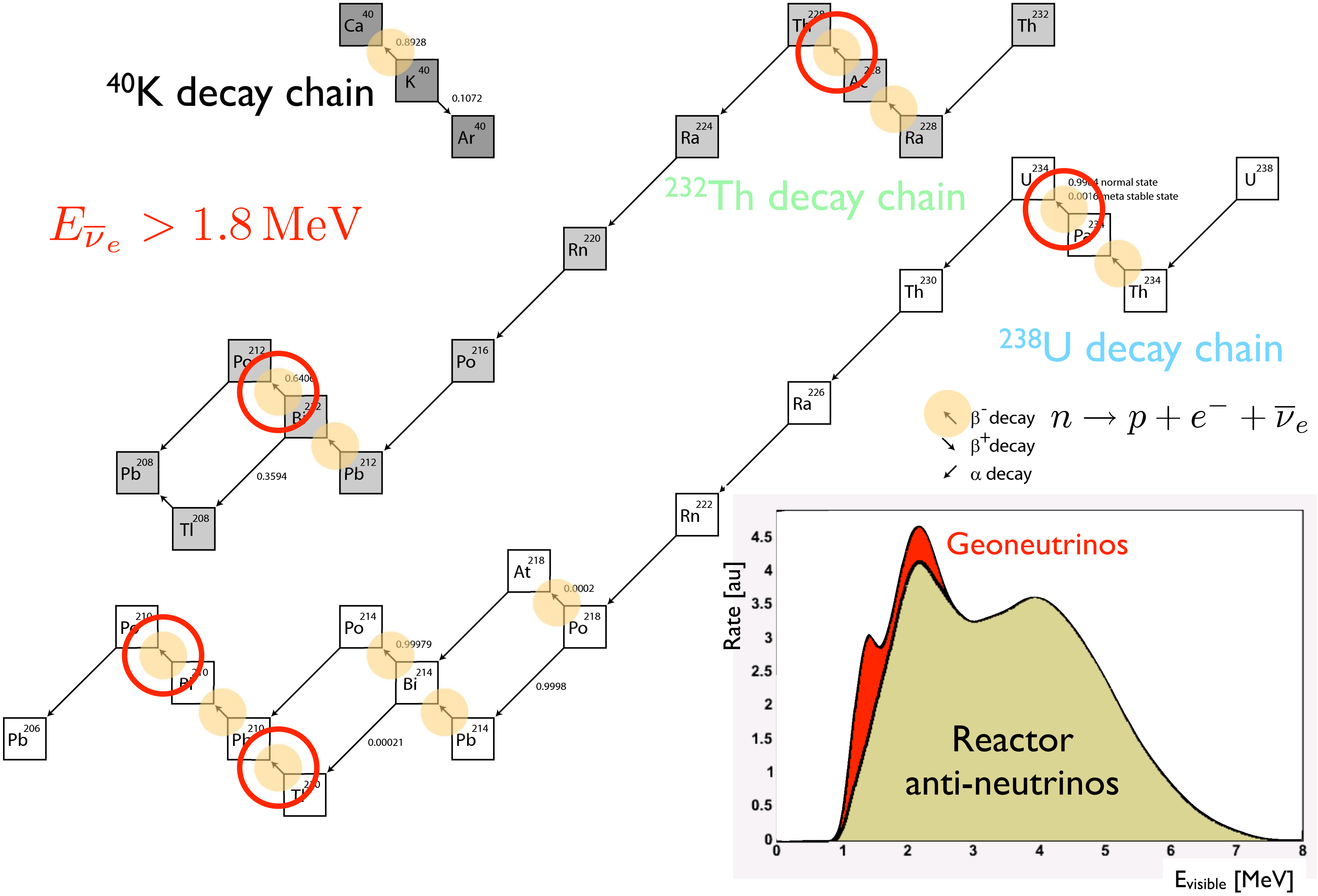
Where does the 46 ± 3 TW come from?



Estimate of
Radiogenic Heat:
20 ± 3 TW

T.Lay *et al.*, Nature Geoscience 1, 25 (2008).

Producing Geoneutrinos



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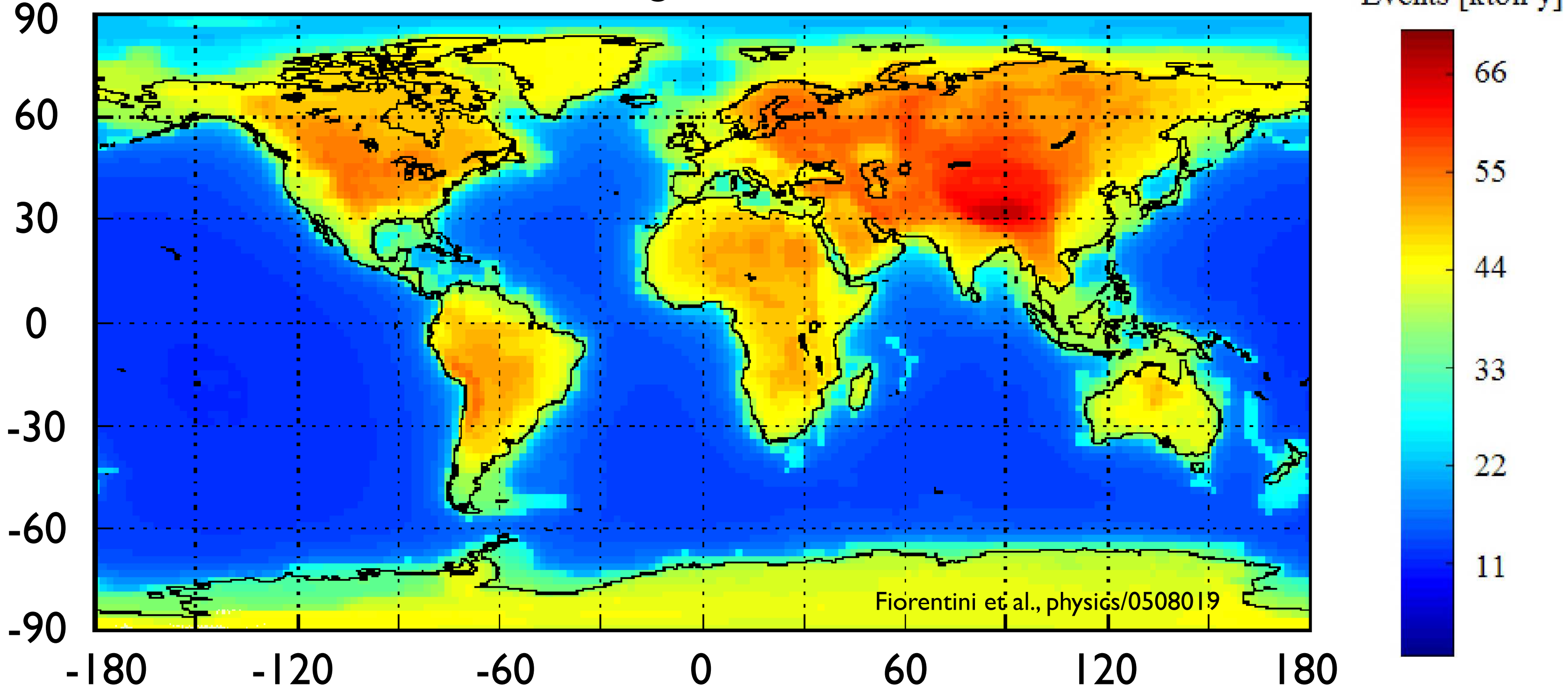
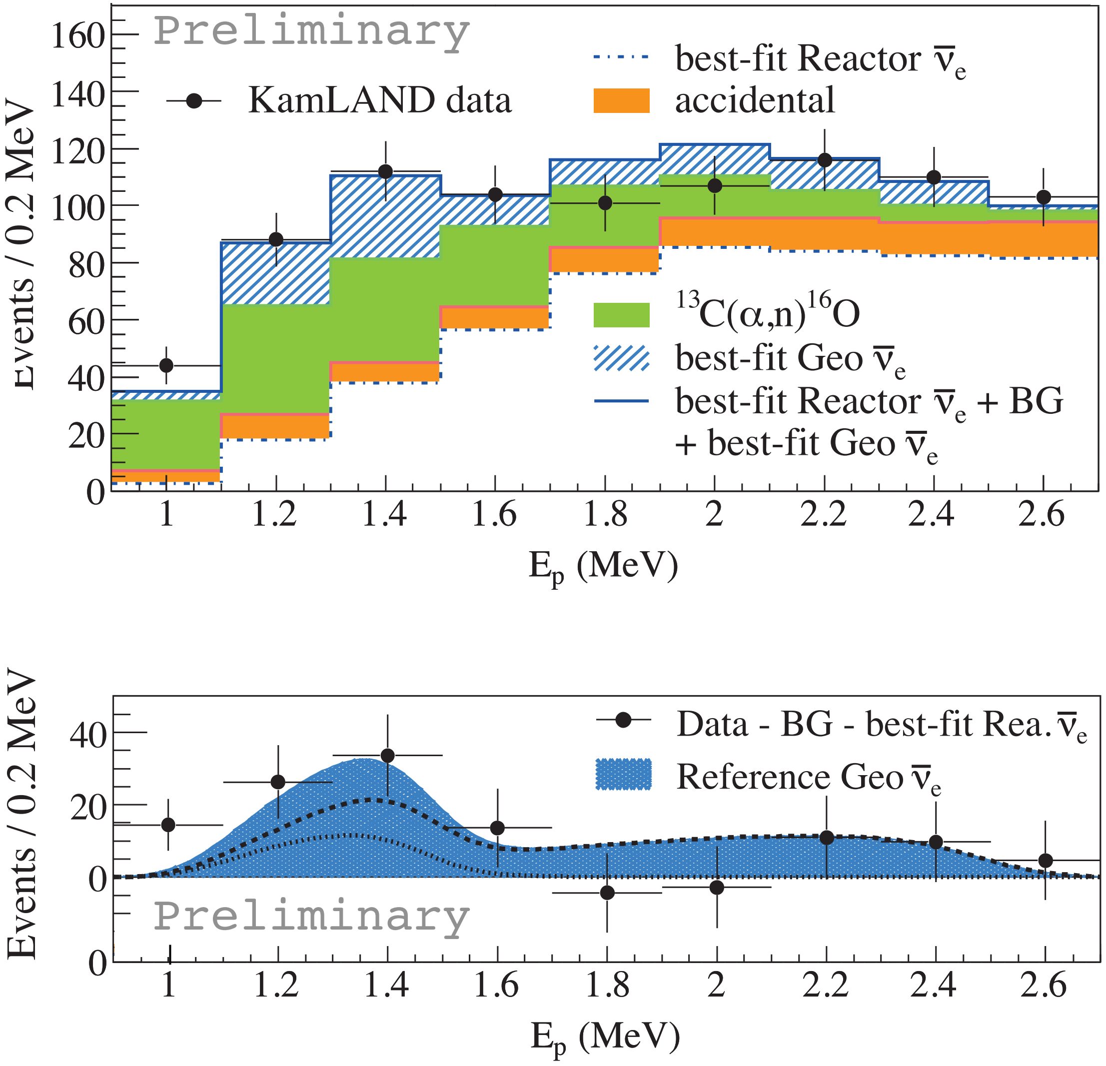
Reference Model


Predicted geoneutrino flux

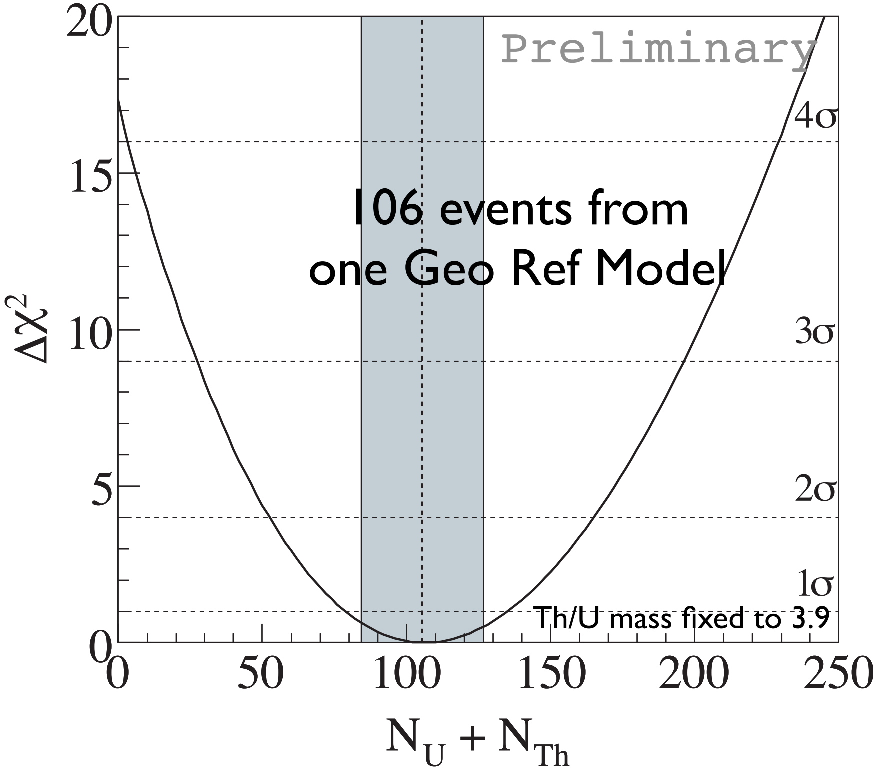
Fiorentini et al., physics/0508019

Sun shines in neutrinos - the Earth in anti-neutrinos

Indications from KamLAND...



111 ± 44 events in 4126 ton-year

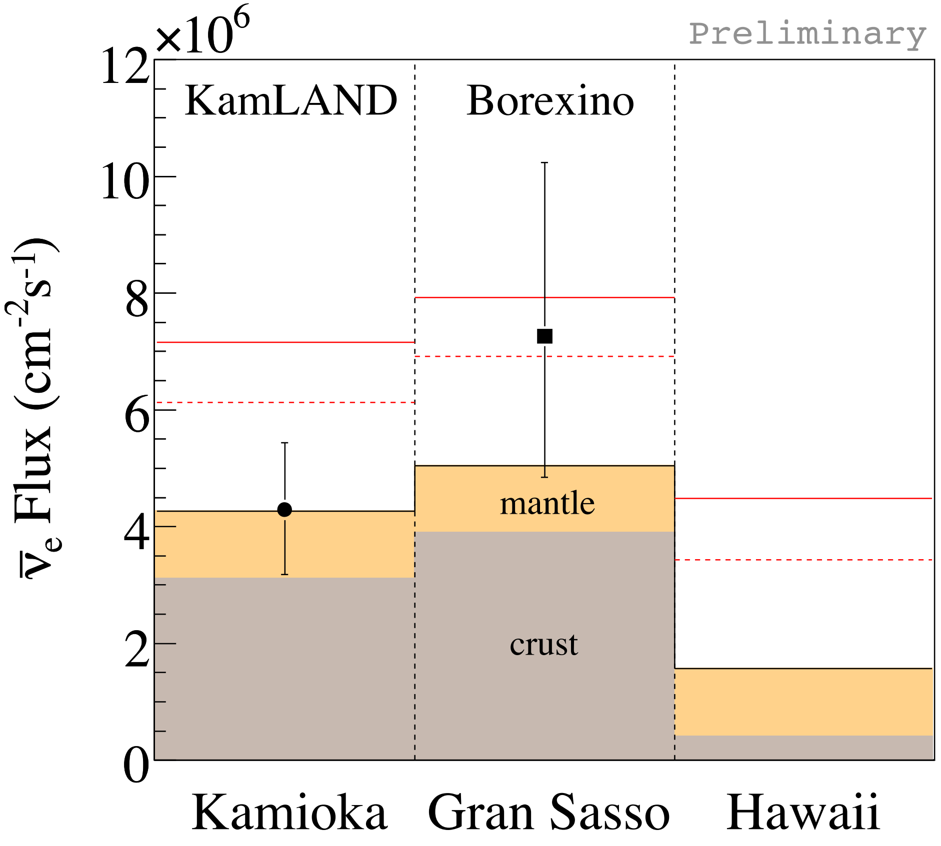


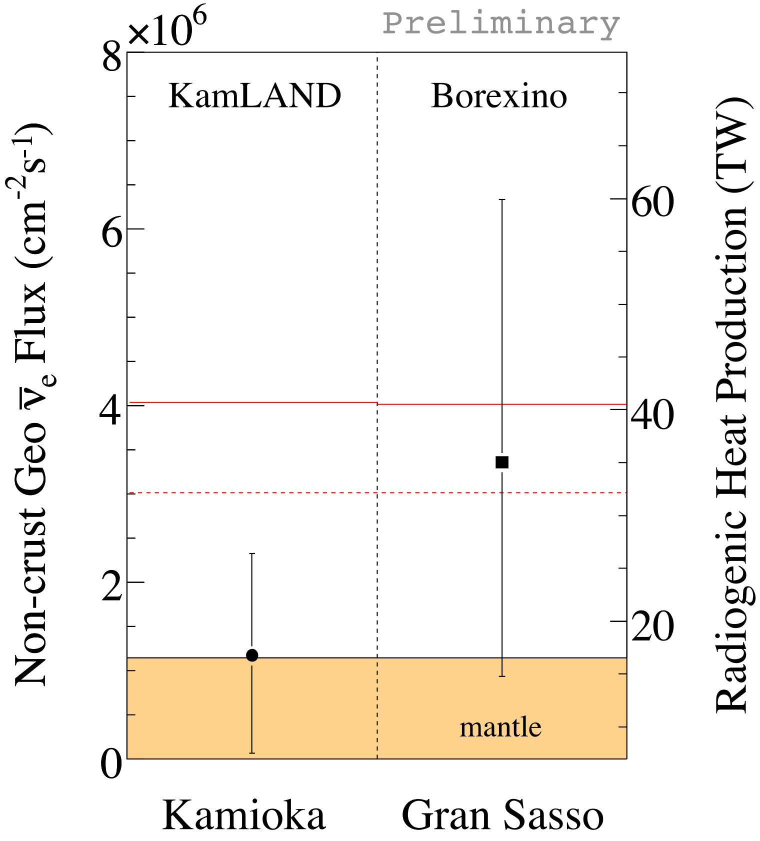
106 events from one Geo Ref Model

Recent report from Borexino: $9.9^{+4.1}_{-3.4}$ events in 253 ton-yr [Phys.Lett.B687:299-304,2010]

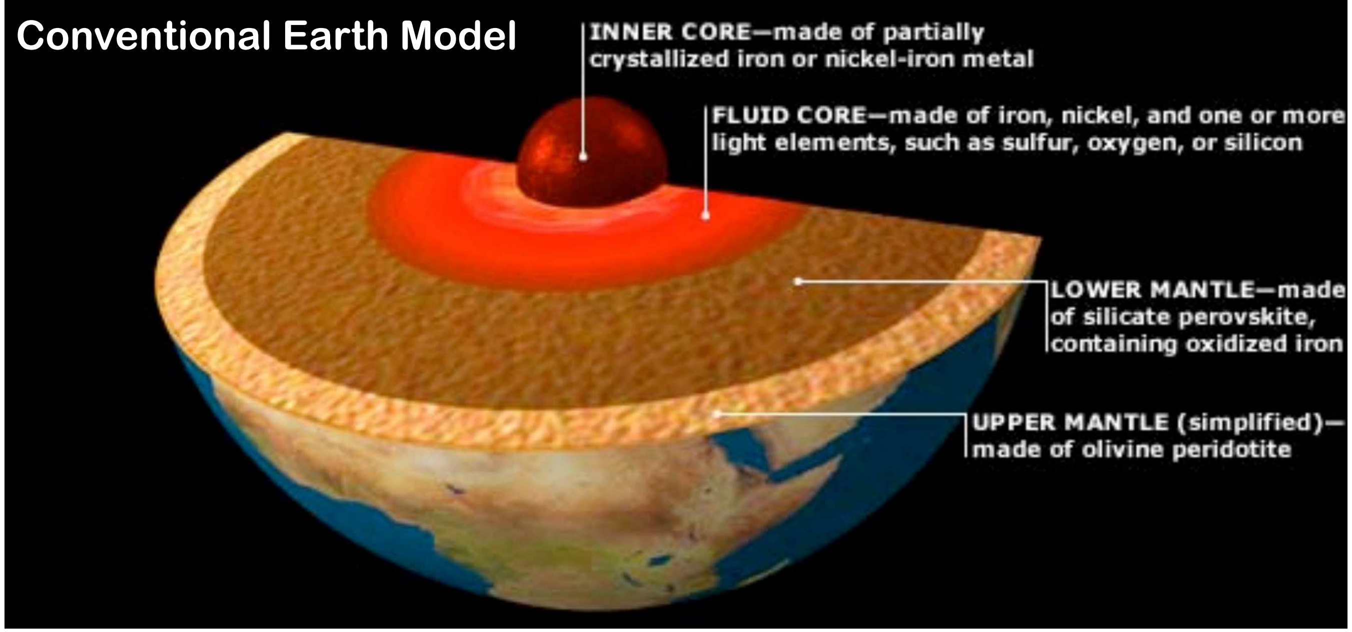
Multi-site Measurements of Geo-νs

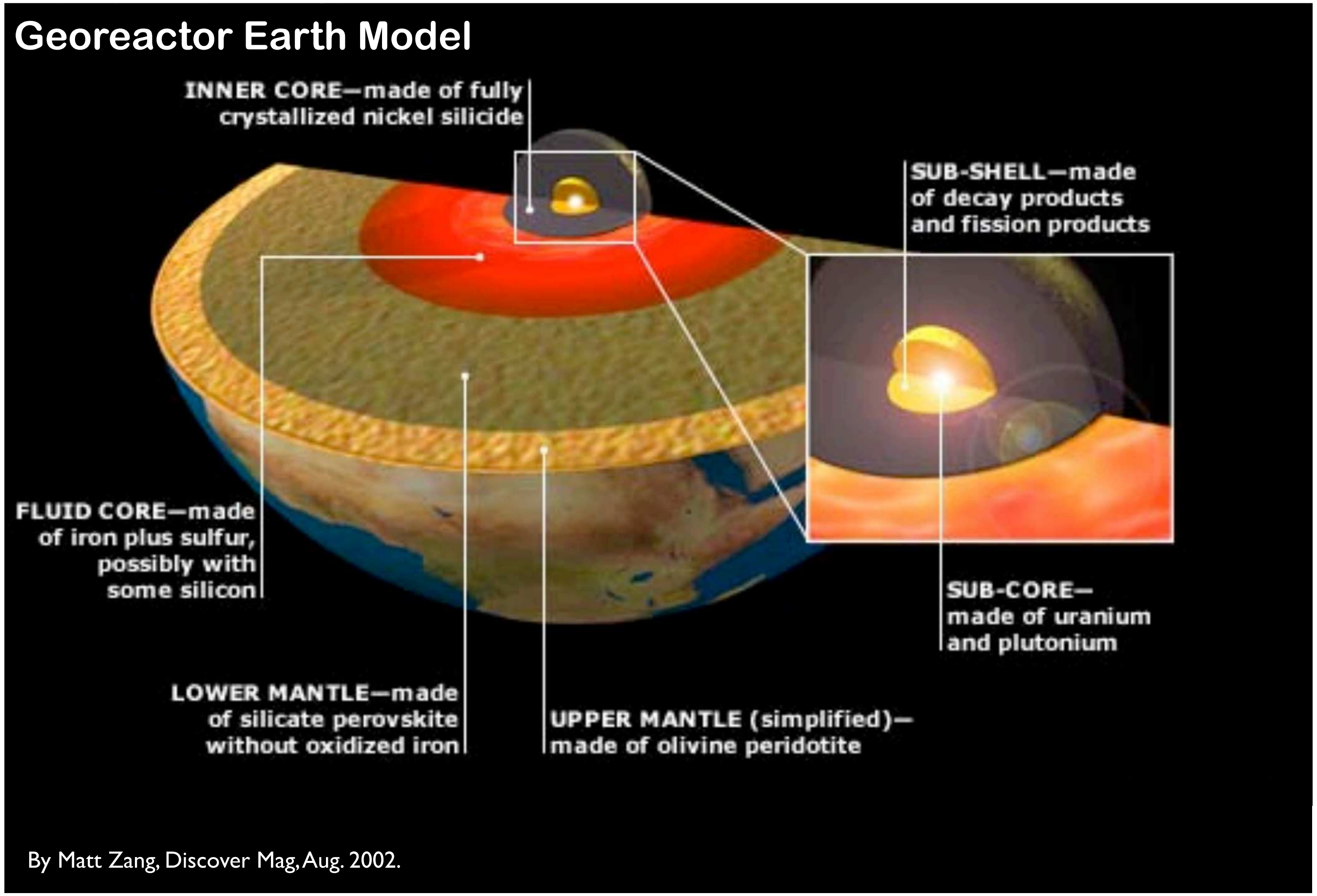
Crust contribution varies locally: multi-site measurements





Start to probe various models for radiogenic heat production



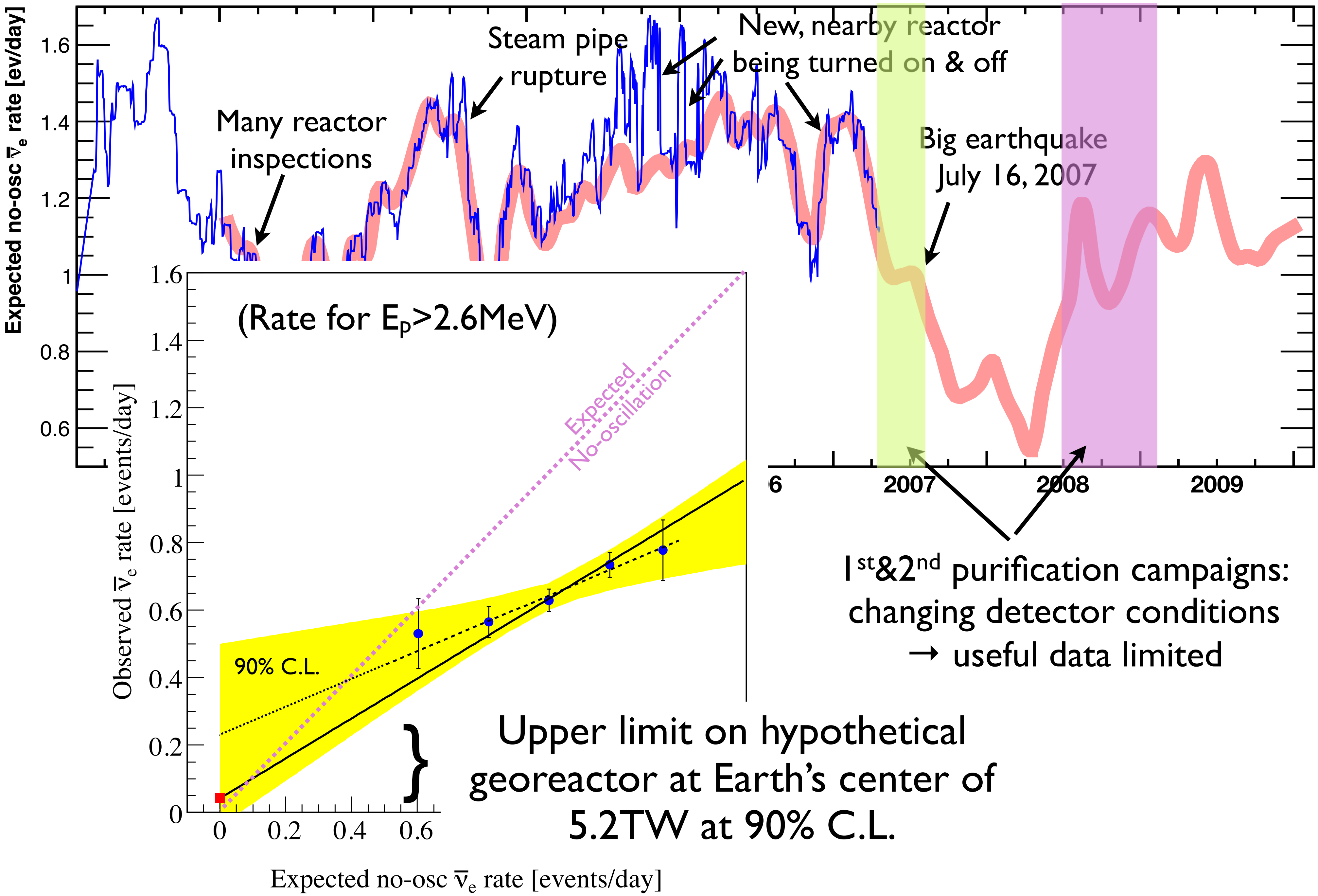


By Matt Zang, Discover Mag, Aug. 2002.

- Georeactor definitely not mainstream theory
- Primarily motivated by the observation that the ^{3}He/^{4}He high at some volcanic plumes
- Oklo natural reactor 2 Gy ago (^{235}U/^{238}U ratio)
- 10-15 km nuclear core
- 3-10TW of heat output
- Should produce anti-neutrinos according to reactor spectrum

5-15% of 'manmade' reactor spectrum at KamLAND

Reactor Signal Changes with Time



Many reactor inspections

Steam pipe rupture

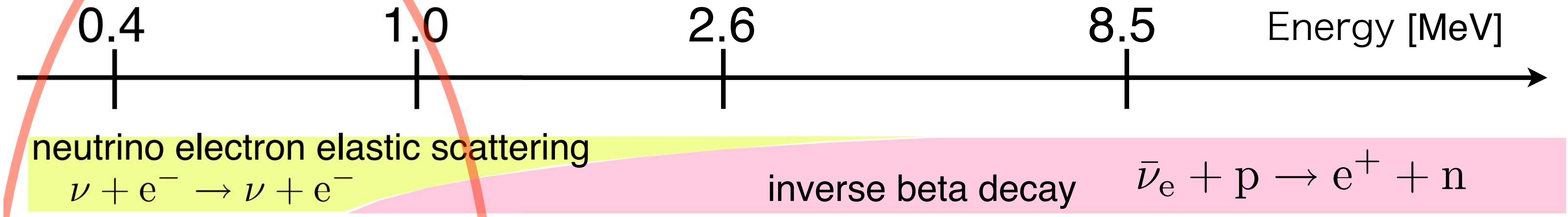
New, nearby reactor being turned on & off

Big earthquake July 16, 2007

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

Upper limit on hypothetical georeactor at Earth's center of 5.2TW at 90% C.L.

KamLAND Physics Capabilities



neutrino electron elastic scattering $\nu + e^- \rightarrow \nu + e^-$

inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

Neutrino Astrophysics

solar neutrino

Verification of SSM

Neutrino Geophysics

geo-neutrino

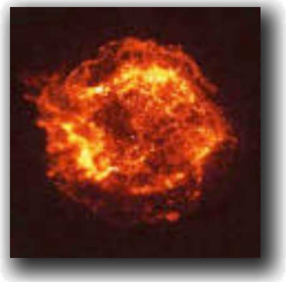
Study of earth heat model

Neutrino Physics

reactor neutrino

Precision measurement of oscillation parameters

Neutrino Cosmology

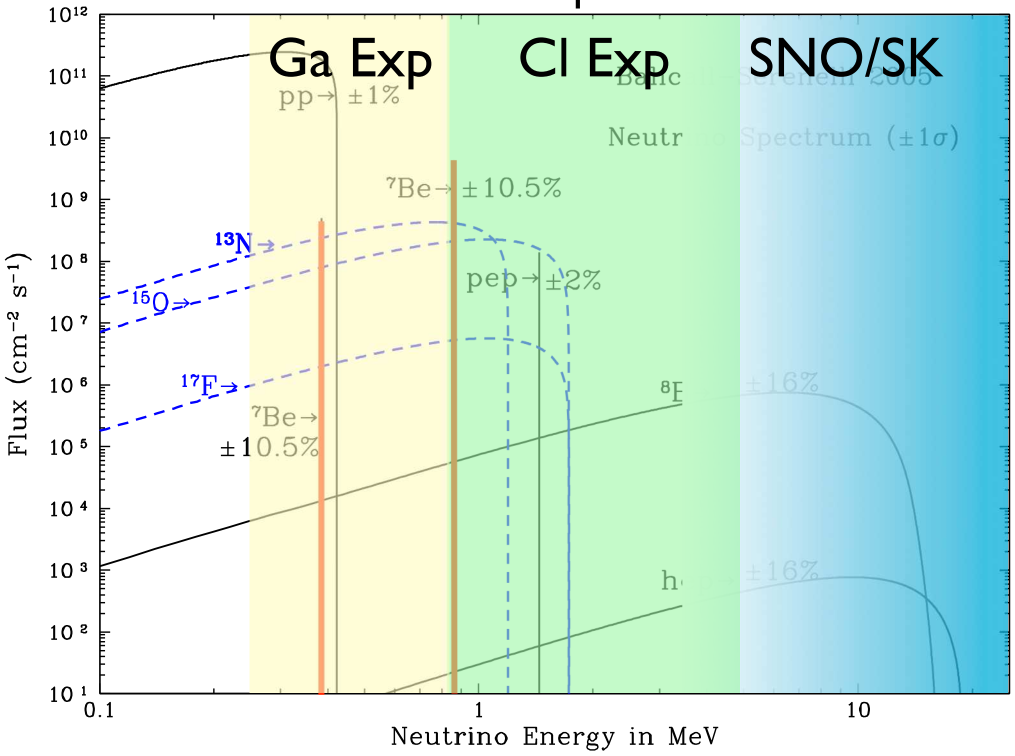


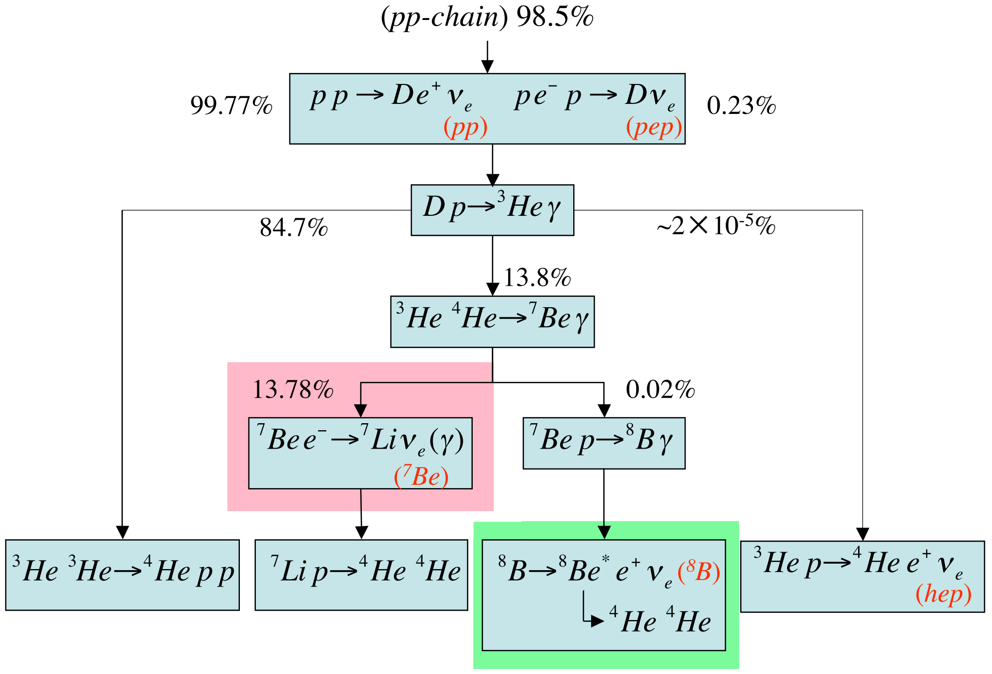
supernova, relic neutrino, solar anti-neutrinos etc.

Verification of universe evolution, neutrino magnetic moment

Testing Standard Solar Model

Solar Neutrino Spectrum





(pp-chain) 98.5%

99.77% $p\,p \rightarrow D e^+ \nu_e$ (pp)

$p e^- p \rightarrow D \nu_e$ (pep) 0.23%

$D\,p \rightarrow {}^3He\,\gamma$

84.7% $^3He\,{}^3He \rightarrow {}^4He\,p\,p$

13.8% $^3He\,{}^4He \rightarrow {}^7Be\,\gamma$

13.78% $^7Be\,e^- \rightarrow {}^7Li\,\nu_e(\gamma)$ (7Be)

$^7Li\,p \rightarrow {}^4He\,{}^4He$

0.02% $^7Be\,p \rightarrow {}^8B\,\gamma$

$^8B \rightarrow {}^8Be^*\,e^+\,\nu_e$ (8B) $\rightarrow {}^4He\,{}^4He$

~2×10⁻⁵% $^3He\,p \rightarrow {}^4He\,e^+\,\nu_e$ (hep)

^{7}Be ~14% ^{8}B ~0.02%

- Use neutrinos to understand the Sun
  - Neutrinos emerge from the Sun in 2sec - photons take 40000 years
- Test the Standard Solar Model (SSM)
  - General confirmation of SSM exists

Patrick Decowski / Nikhef

Solar Measurements

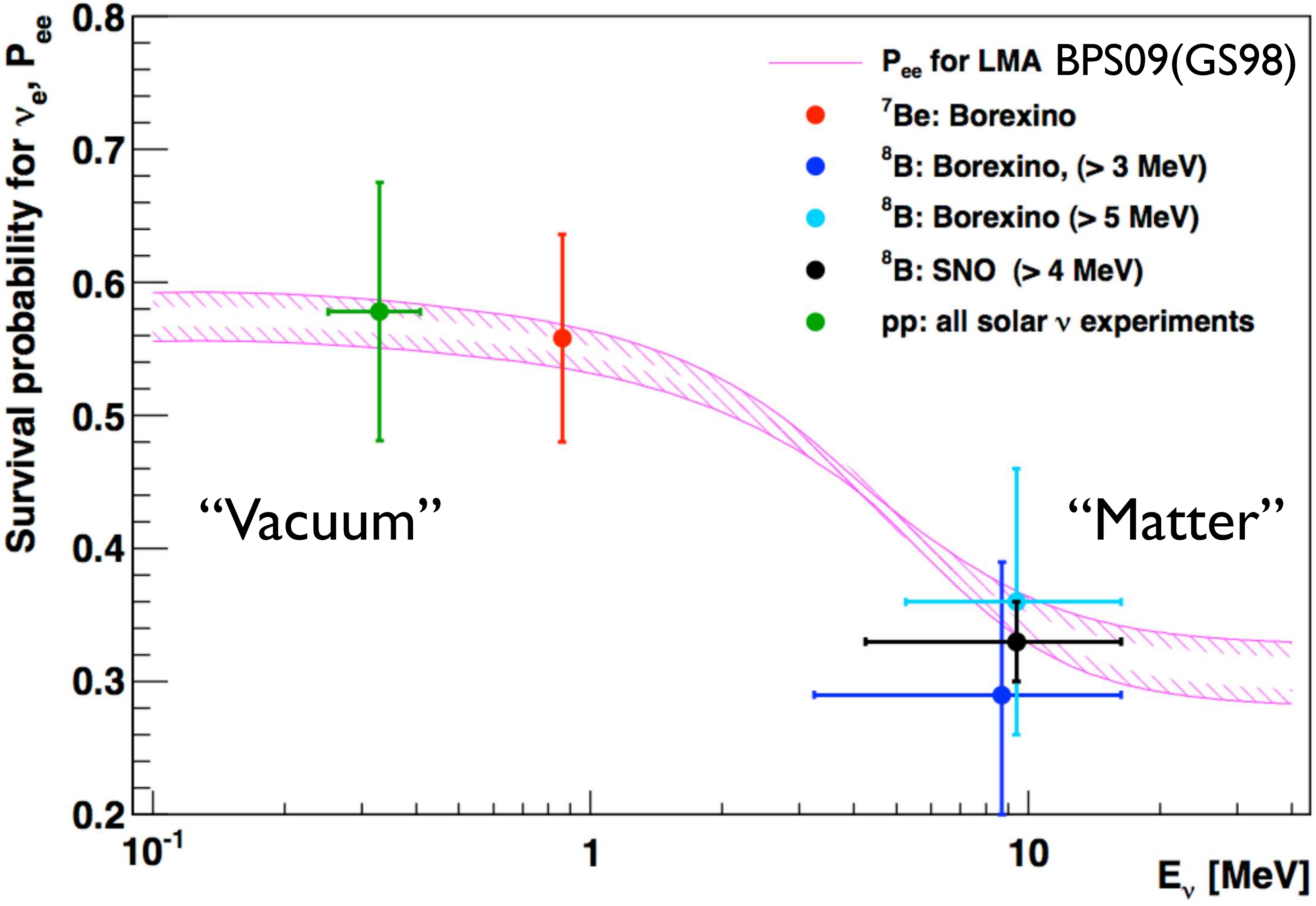
- Precision measurements: detailed comparisons between measurements and models
- Accurate measurement of pp(1%) and ^{7}Be(5%) neutrinos allows the calculation of neutrino-inferred solar luminosity to ~1%:

neutrinos:
photons:

$$\frac{\mathcal{L}_\nu^{\rm inf}}{\mathcal{L}_\odot} = 1.4^{+0.2}_{-0.3} \overset{?}{=} 1.00$$

Probability Transition Region

Solar neutrino survival probability

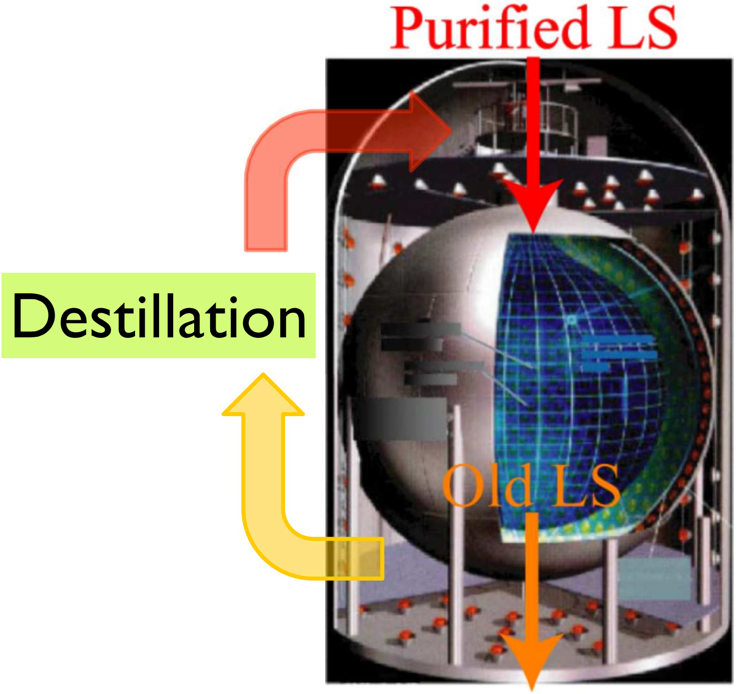


G.Bellini *et al.* [Borexino Collaboration], arXiv:0808.2868v3

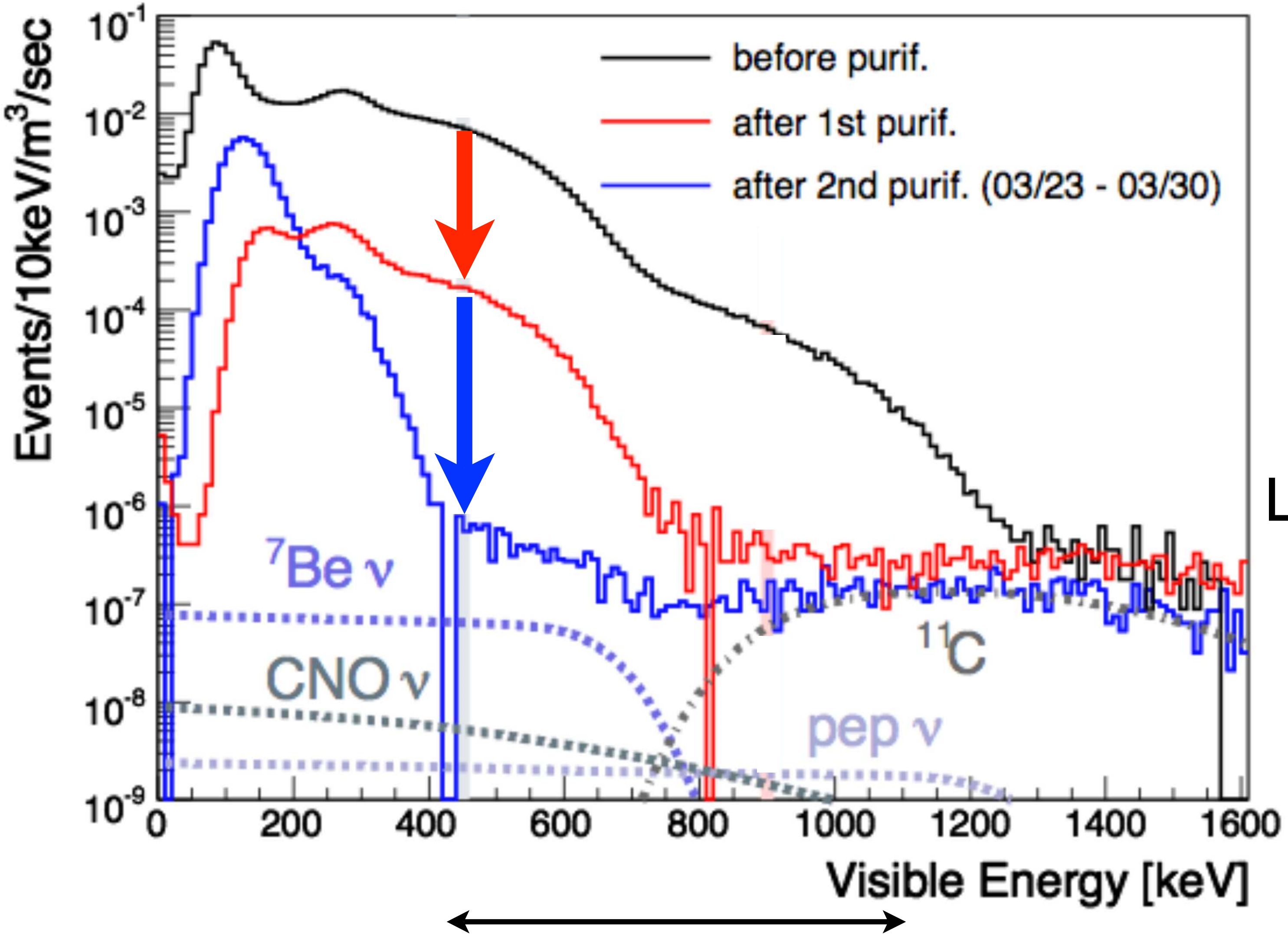
Current experiments are probing the interesting region from "vacuum oscillations" to "matter oscillations" in the Sun

Scintillator Purification

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



Result of purifcation

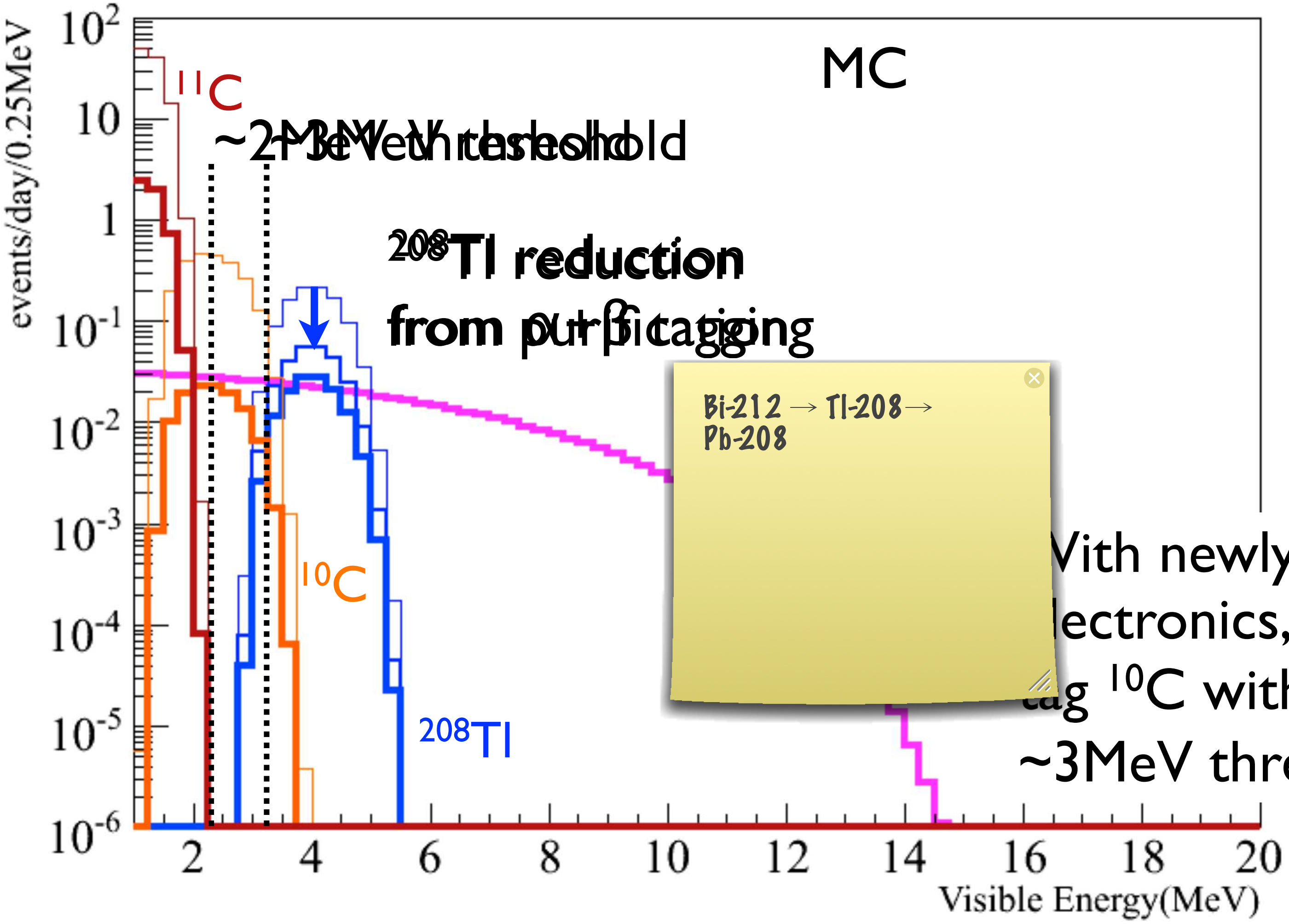


^{210}Bi region, still decaying out ($T_{1/2}$ = 5d)

Only 7days of data, shortly after end of purification

Large reduction of backgrounds

Low-threshold solar ^{8}B measurement



~2MeV threshold

~3MeV threshold

^{208}Tl reduction

from purification

from α+β tagging

Bi-212 → Tl-208→
Pb-208

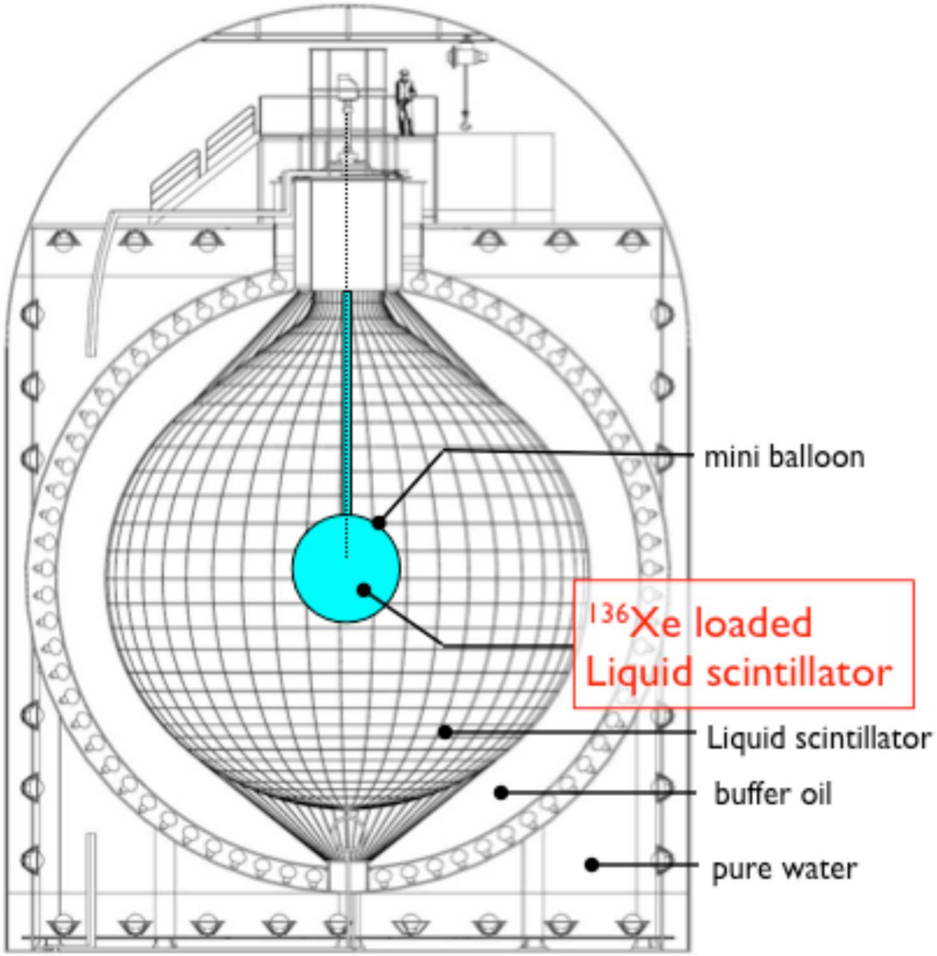
Vith newly installed
lectronics, should be able to
ag ^{10}C with multiple n after μ

~3MeV threshold → ~2MeV

(Main background for geo-neutrino measurement removed)

KamLAND Future: 0ν2β

400kg of ^{136}Xe
in secondary balloon



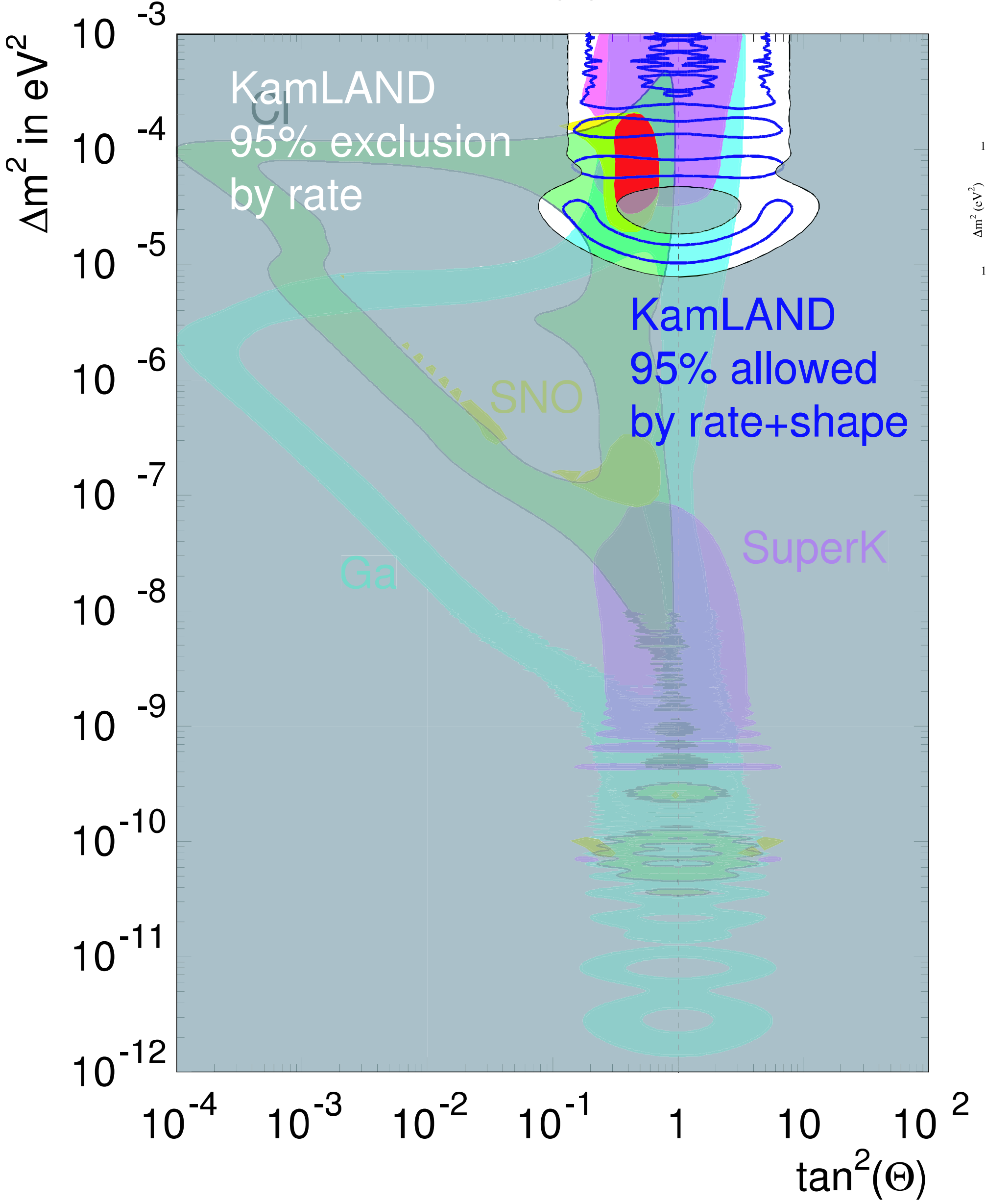
Japanese collaborators have secured funding for KamLAND 0ν2β
End of KamLAND as-we-know-it in April 2011

Summary

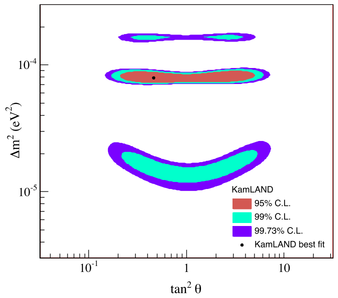
- Era of precision measurements of neutrino oscillation parameters
  - Hard to further improve Δm_{12}^2
  - Next goal: θ_{13} to better than 1%
- Start of answering geological questions with neutrino science
- KamLAND's low background phase running
  - Solar ^{7}Be and low energy threshold ^{8}B neutrinos
  - Due to lower backgrounds, (much) improved geo-neutrino measurement
- KamLAND's future: neutrinoless double beta-decay
  - 400kg of ^{136}Xe

Precision Neutrino Measurements

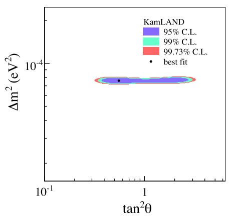
KL 2002



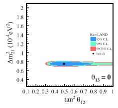
KL 2004



KL 2008

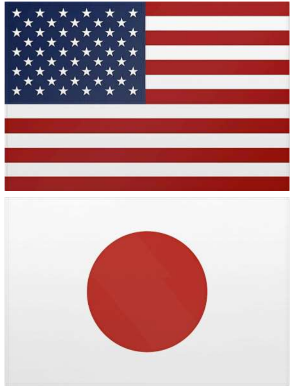


KL 2010



Neutrino Oscillation:
A precision measurement!

KamLAND Collaboration



S. Abe,[1] T. Ebihara,[1] S. Enomoto,[1] K. Furuno,[1] Y. Gando,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1] Y. Kibe,[1] Y. Kishimoto,[1] M. Koga,[1] A. Kozlov,[1] Y. Minekawa,[1] T. Mitsui,[1] K. Nakajima,[1,*] K. Nakajima,[1] K. Nakamura,[1] M. Nakamura,[1] K. Owada,[1] I. Shimizu,[1] Y. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] Y. Takemoto,[1] K. Tamae,[1] A. Terashima,[1] H. Watanabe,[1] E. Yonezawa,[1] S. Yoshida,[1] J. Busenitz,[2] T. Classen,[2] C. Grant,[2] G. Keefer,[2] D.S. Leonard,[2] D. McKee,[2] A. Piepke,[2] M.P. Decowski,[3] J.A. Detwiler,[3] S.J. Freedman,[3] B.K. Fujikawa,[3] F. Gray,[3,†] E. Guardincerri,[3] L. Hsu,[3,‡] R. Kadel,[3] C. Lendvai,[3] K.-B. Luk,[3] H. Murayama,[3] T. O'Donnell,[3] H.M. Steiner,[3] L.A. Winslow,[3] D.A. Dwyer,[4] C. Jillings,[4,§] C. Mauger,[4] R.D. McKeown,[4] P. Vogel,[4] C. Zhang,[4] B.E. Berger,[5] C.E. Lane,[6] J. Maricic,[6] T. Miletic,[6] M. Batygov,[7] J.G. Learned,[7] S. Matsuno,[7] S. Pakvasa,[7] J. Foster,[8] G.A. Horton-Smith,[8] A. Tang,[8] S. Dazeley,[9,¶] K.E. Downum,[10] G. Gratta,[10] K. Tolich,[10] W. Bugg,[11] Y. Efremenko,[11] Y. Kamyshkov,[11] O. Perevozchikov,[11] H.J. Karwowski,[12] D.M. Markoff,[12] W. Tornow,[12] K.M. Heeger,[13] F. Piquemal,[14] and J.-S. Ricol[14]

(The KamLAND Collaboration)

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Backup Slides

Can KamLAND Detect a Nuclear Test?

North Korea tested a nuclear device in Oct 2006 and May 2009: can KamLAND detect a test of a nuclear weapon?

- Assume a test of a Hiroshima size bomb (~15kton TNT) or ~10 kg of fissile material
  - Larger bombs are detectable by other means
- Further assume:
  - All material is fully fissioned
  - Distance is ~1000km from KamL
  - Typical 3GW (thermal) reactor has a few tons of fissile material burned up in a cycle of ~18months → 10kg/day

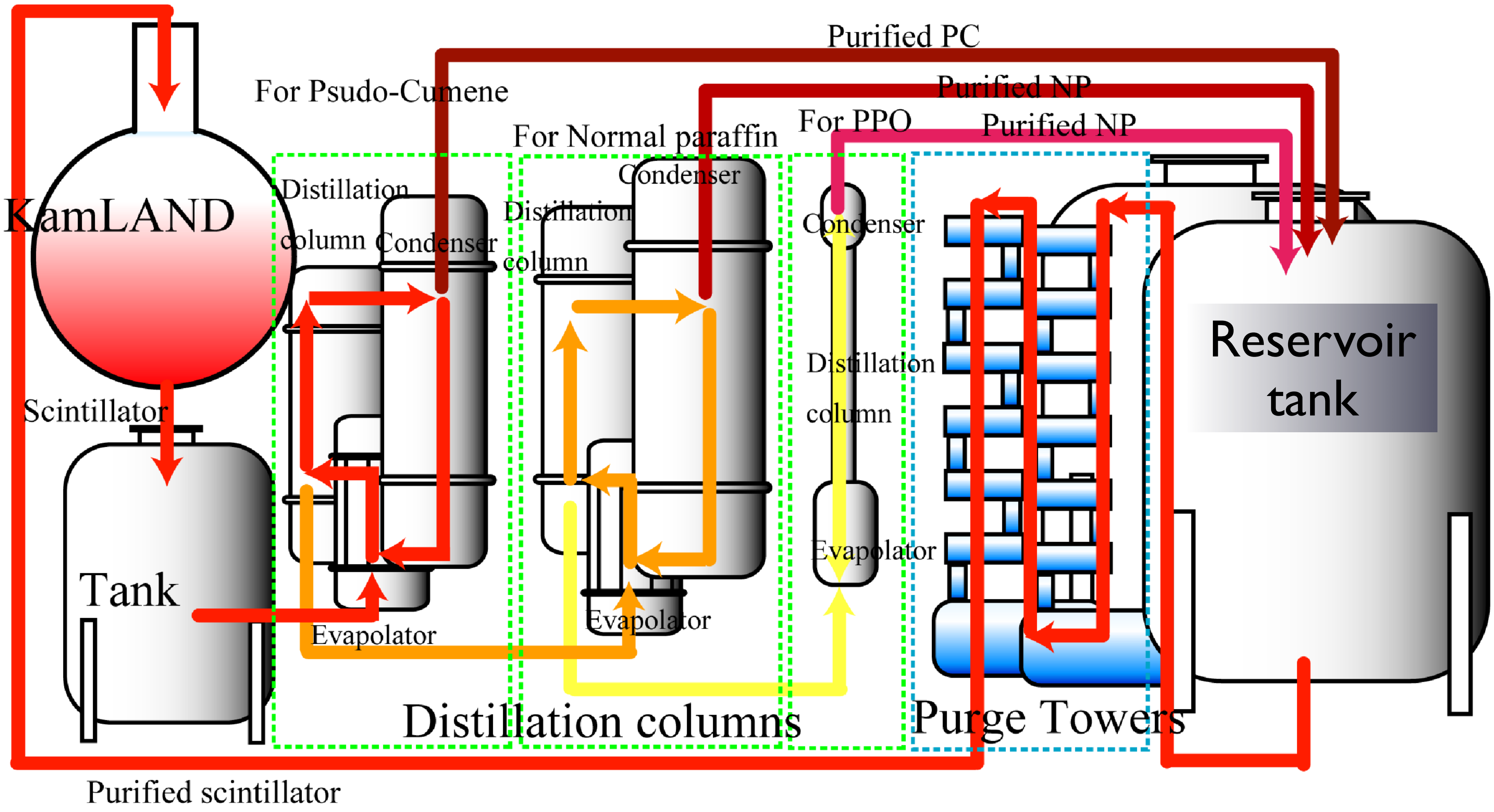
-May 2006 bomb was <1kton
-Oct 2009 was 2-4 kton

Both were plutonium

- KamLAND measures anti-neutrinos from 55 ~3GW$_{th}$ reactors, at a rate of ~1 anti-neutrino/day at avg. distance of ~200km

A small nuclear device will generate <0.001 of an additional anti-neutrino event in KamLAND

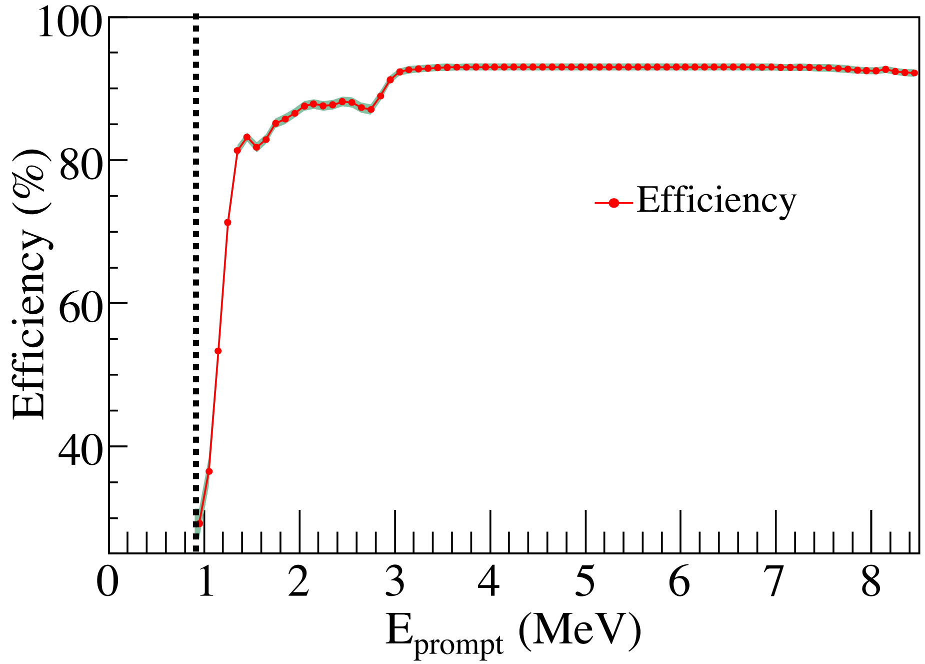
Low Background Phase



Liquid Scintillator from KamLAND is distilled into PC, MO and PPO, remixed and purged with N_2

L-selector: Signal/Accidentals Discrimination

Use prompt-delayed event characteristics to distinguish Accidental BG from Signal



Generate Accidentals PDF from DATA (random pairs):

$$f_{acc}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$$

Generate Signal PDF from MC (no-osc spectrum):

$$f_{\overline{\nu}_e}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$$

L-selector (calculated EbE):

$$L = \frac{f_{\overline{\nu}_e}}{f_{\overline{\nu}_e} + f_{acc}}$$

Establish L-selector cuts for different E_p bins, where FOM is maximal

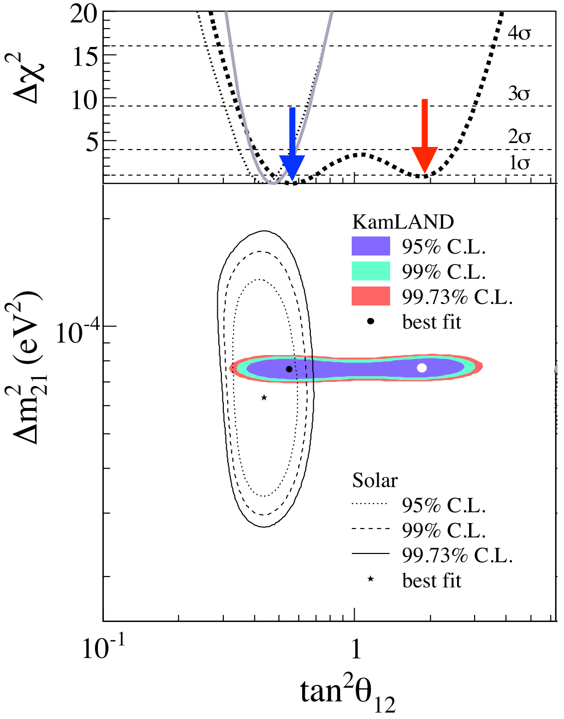
$$FOM = \frac{S}{\sqrt{S + B_{acc}}} \longrightarrow L_{cut} \qquad (E_p \text{ bins of } 0.1\text{MeV})$$

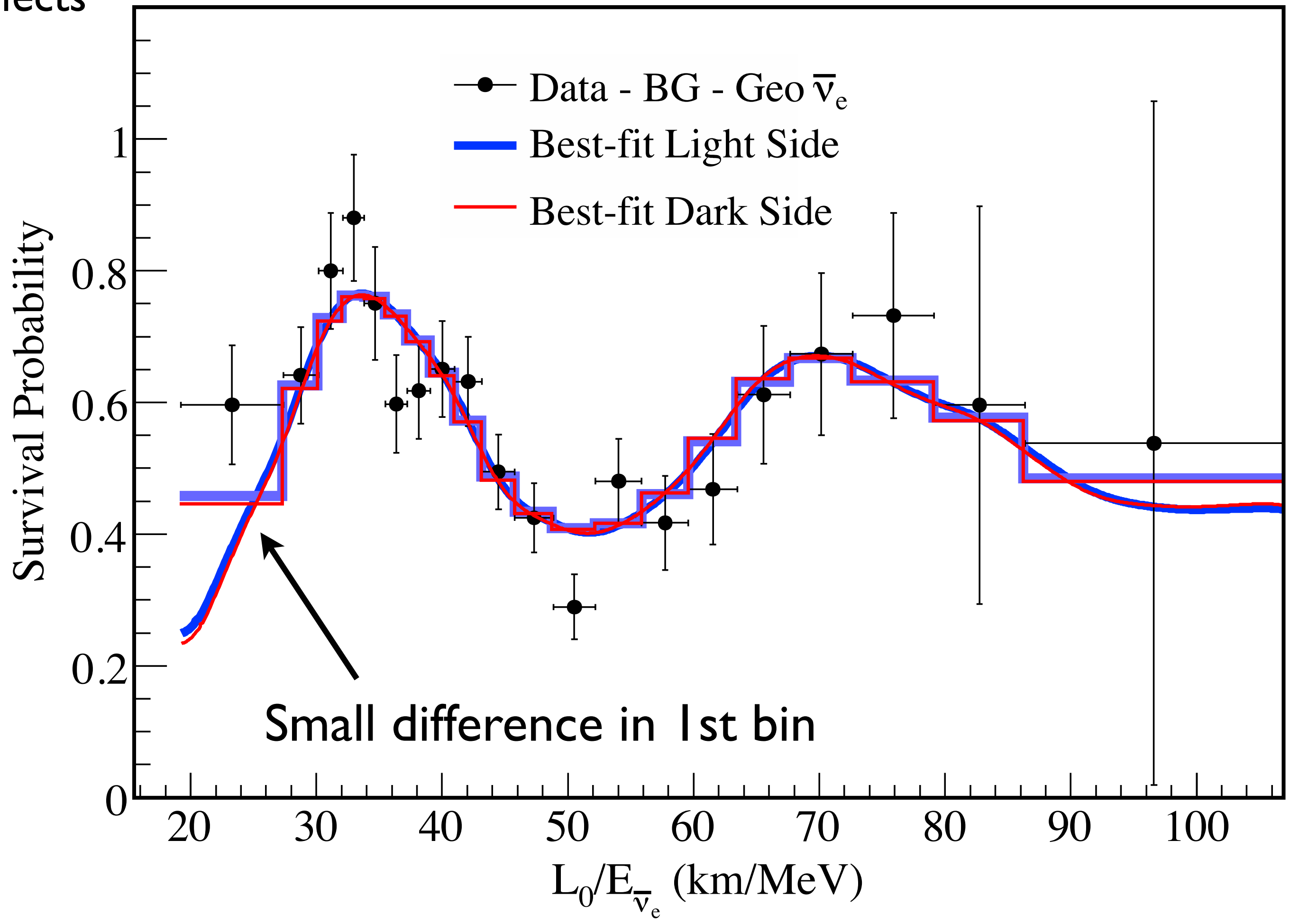
If for candidate event pair $L > L_{cut}$ → anti-neutrino

Efficiency for E_p>~3MeV as expected from spatial cuts alone

Best-fit Light and Dark Side

Analysis includes Earth matter effects



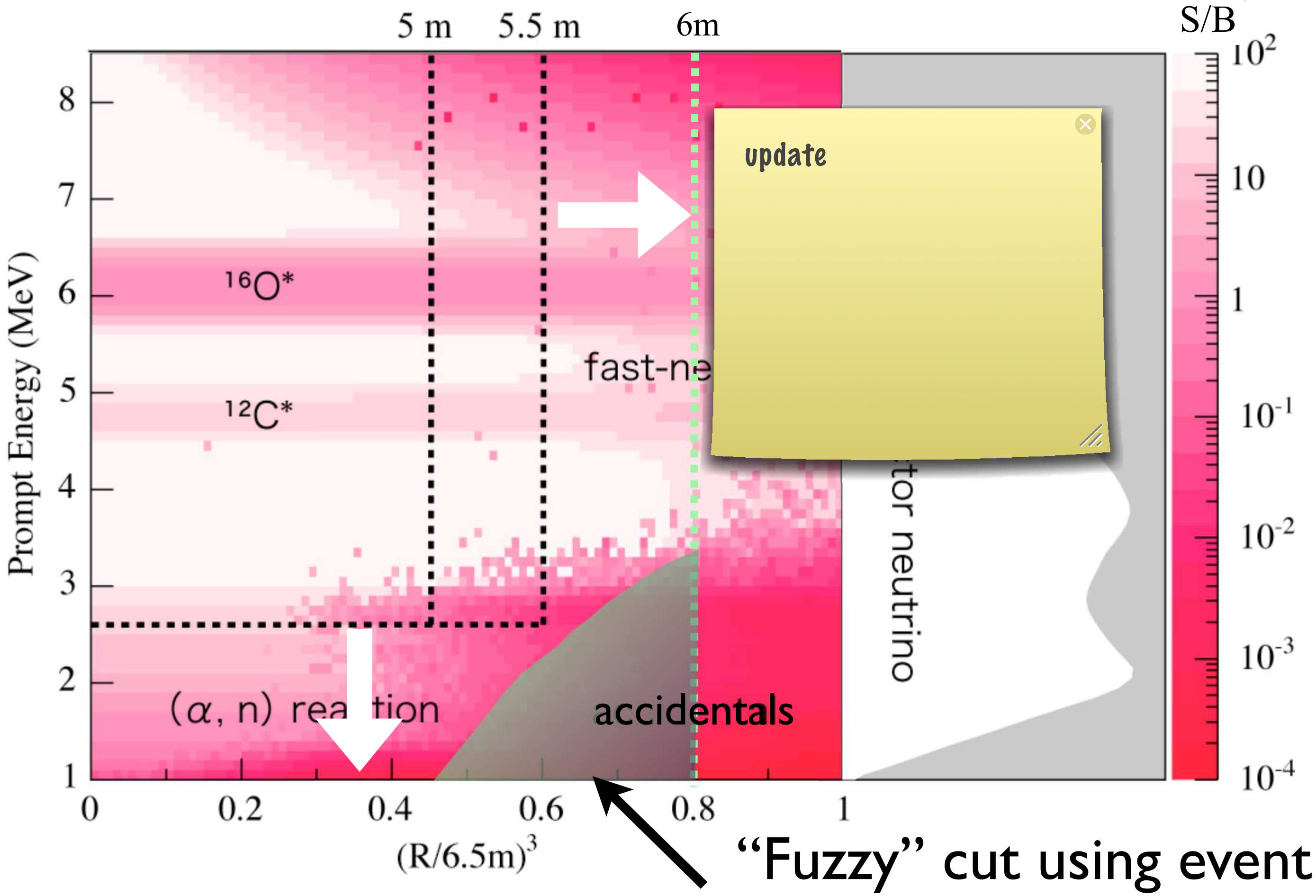


Small difference in 1st bin

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

Analysis Improvements

	Max Radius(m)	Lifetime(days)	Exposure(ton-yr)	Exposure Increase
KL2002	5	145	162	1x
KL2004	5.5	515	766	4.7x
KL2008	6	1491	2881	17.8x



Energy threshold from 2.6MeV → 1.0MeV (Inverse Beta Decay threshold)

“Fuzzy” cut using event characteristics to distinguish signal from accidentals

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