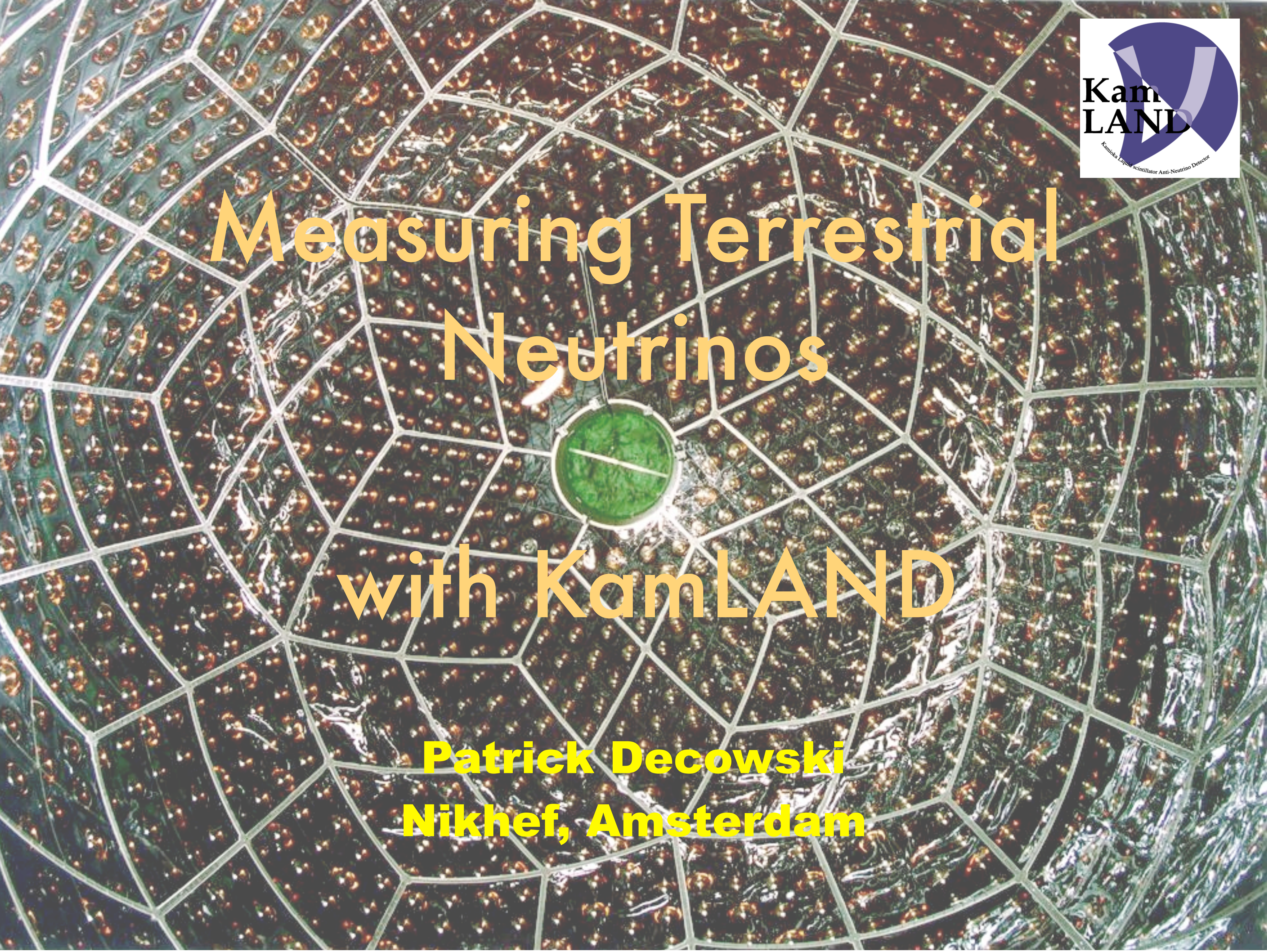


# Measuring Terrestrial Neutrinos with KamLAND

**Patrick Decowski**
**Nikhef, Amsterdam**

# Neutrino Oscillation

3 ν flavor eigenstates
3 ν mass eigenstates

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

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

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 $\nu_e$ becomes $\nu_x$ after traveling a distance L:

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

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

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

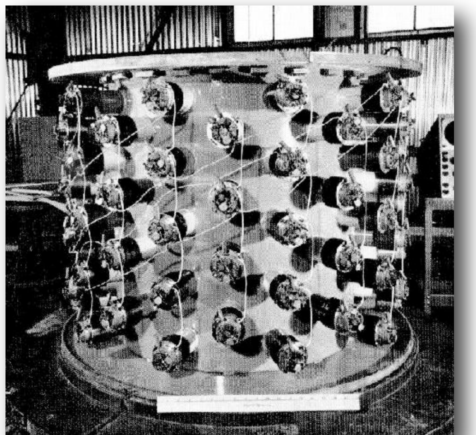
$$P(\nu_e \to \nu_x) = \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

- then extend to three neutrino oscillation

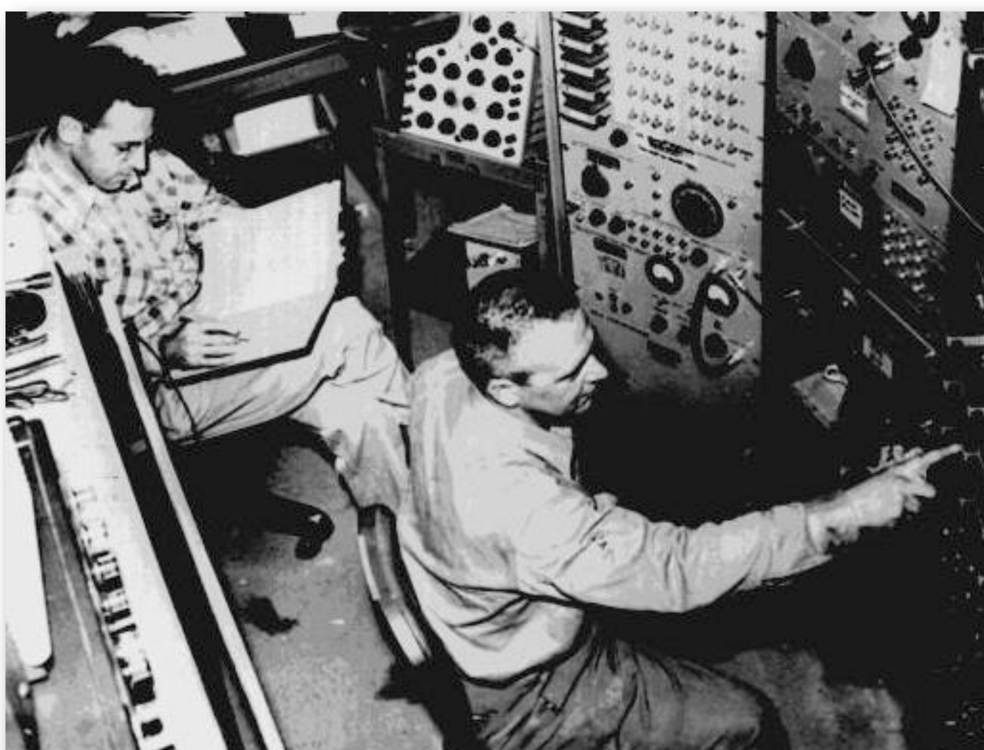
$$P(\nu_e \to \nu_x) \approx \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) + \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

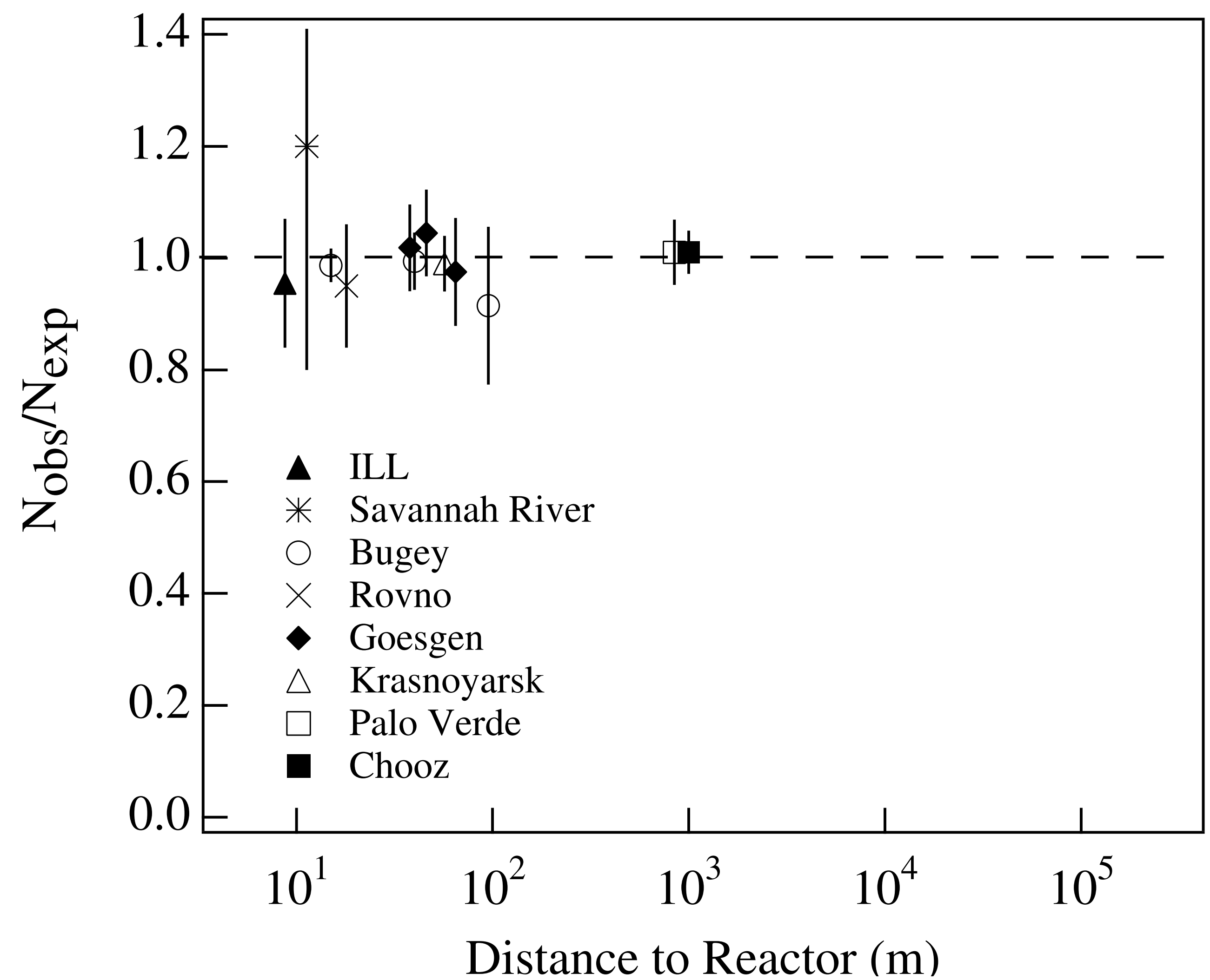
# Oscillation searches with Reactors

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

# About
# Reactor Anti-Neutrinos


From the 1955 Movie with same title

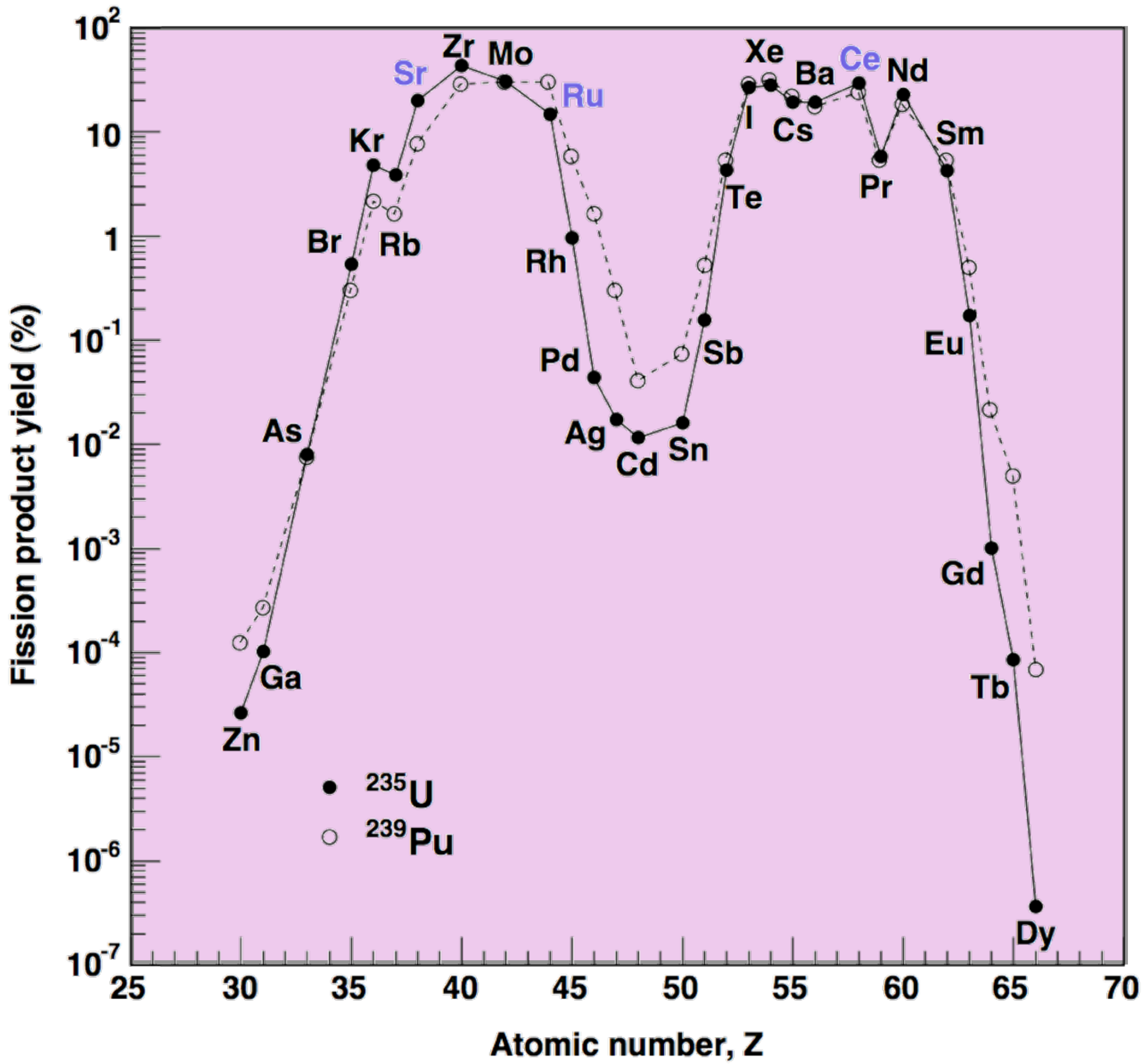
# Reactor Anti-Neutrinos

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

The stable products most likely from Uranium fission:

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

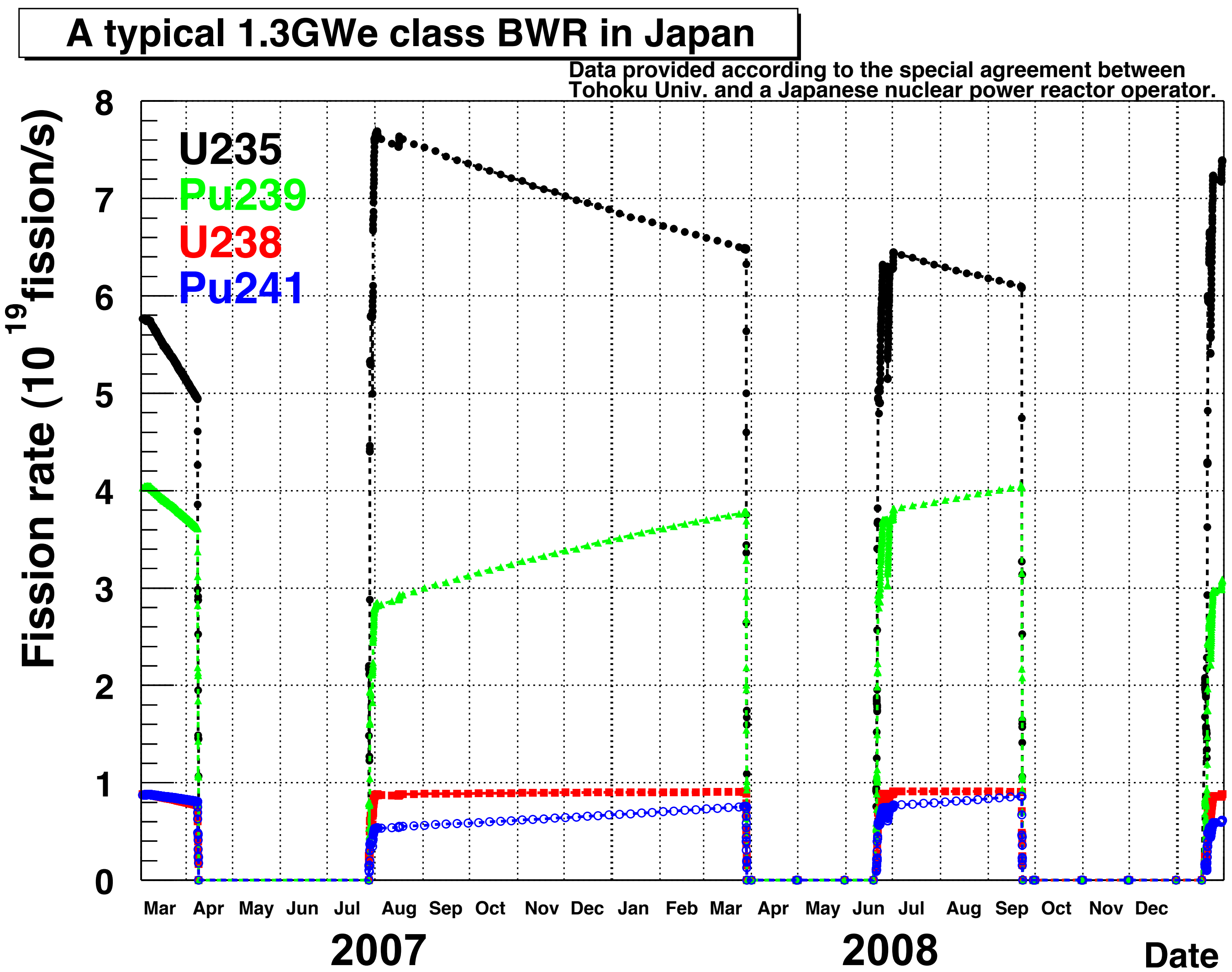
Together 98 protons and 136 neutrons

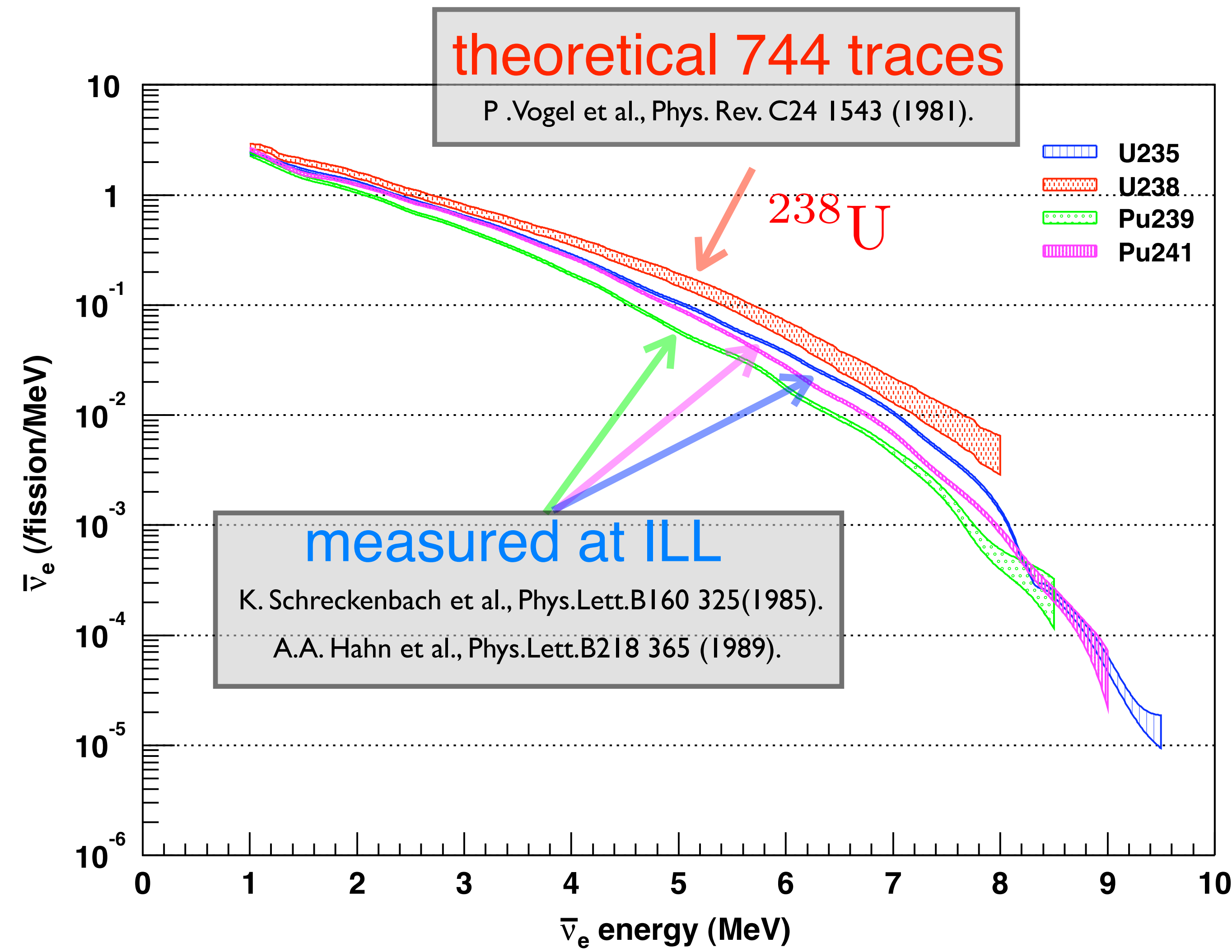



6 neutrons have to $\beta$-decay to reach stable matter, producing 6 $\overline{\nu}_e$ / fission

# Calculating Neutrino Spectra

## Only 4 isotopes relevant




- 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

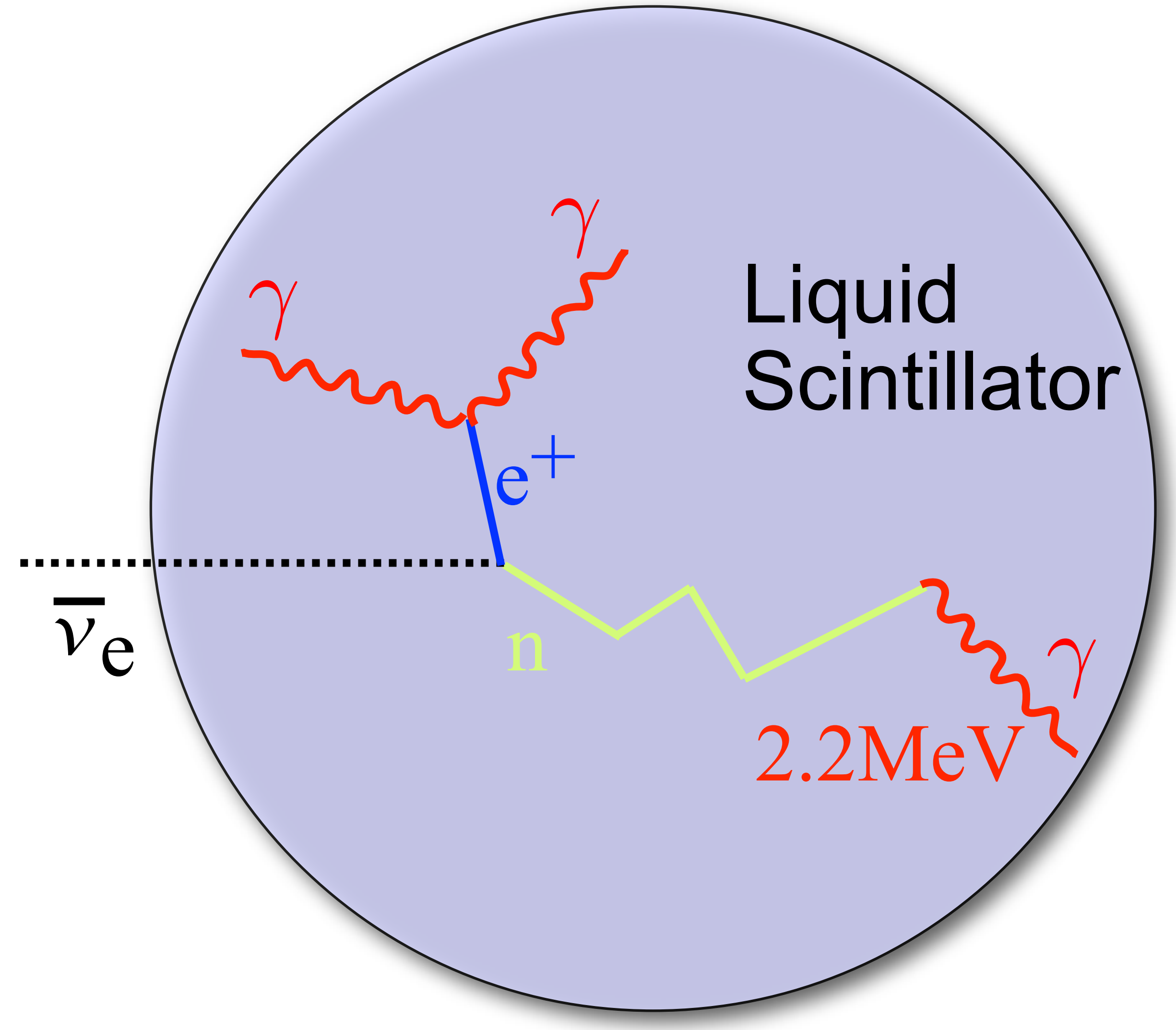
Inverse beta decay

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

↓ 207 μs

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

Scintillator is both target and detector



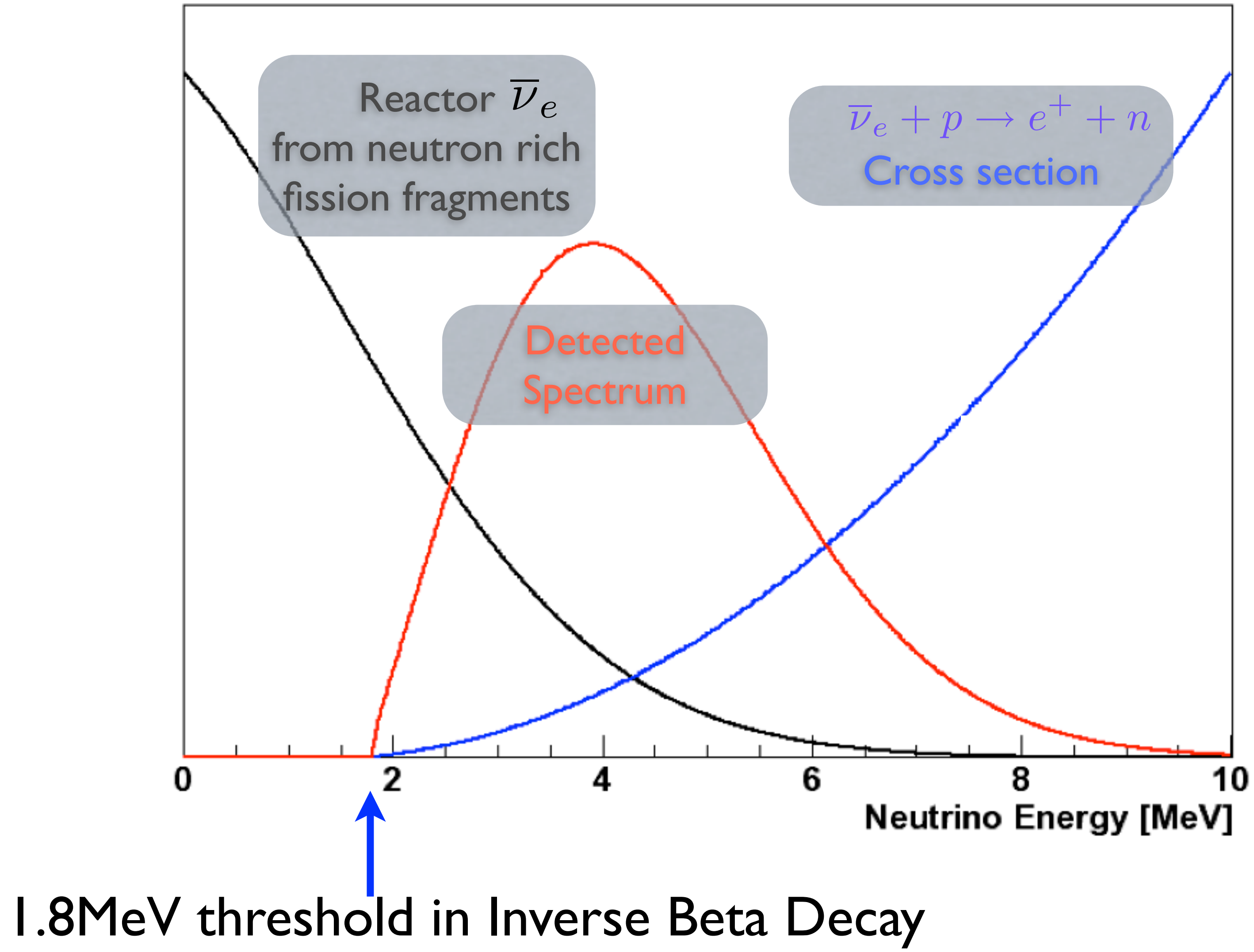

- Distinct two step process:
  - prompt event: positron

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

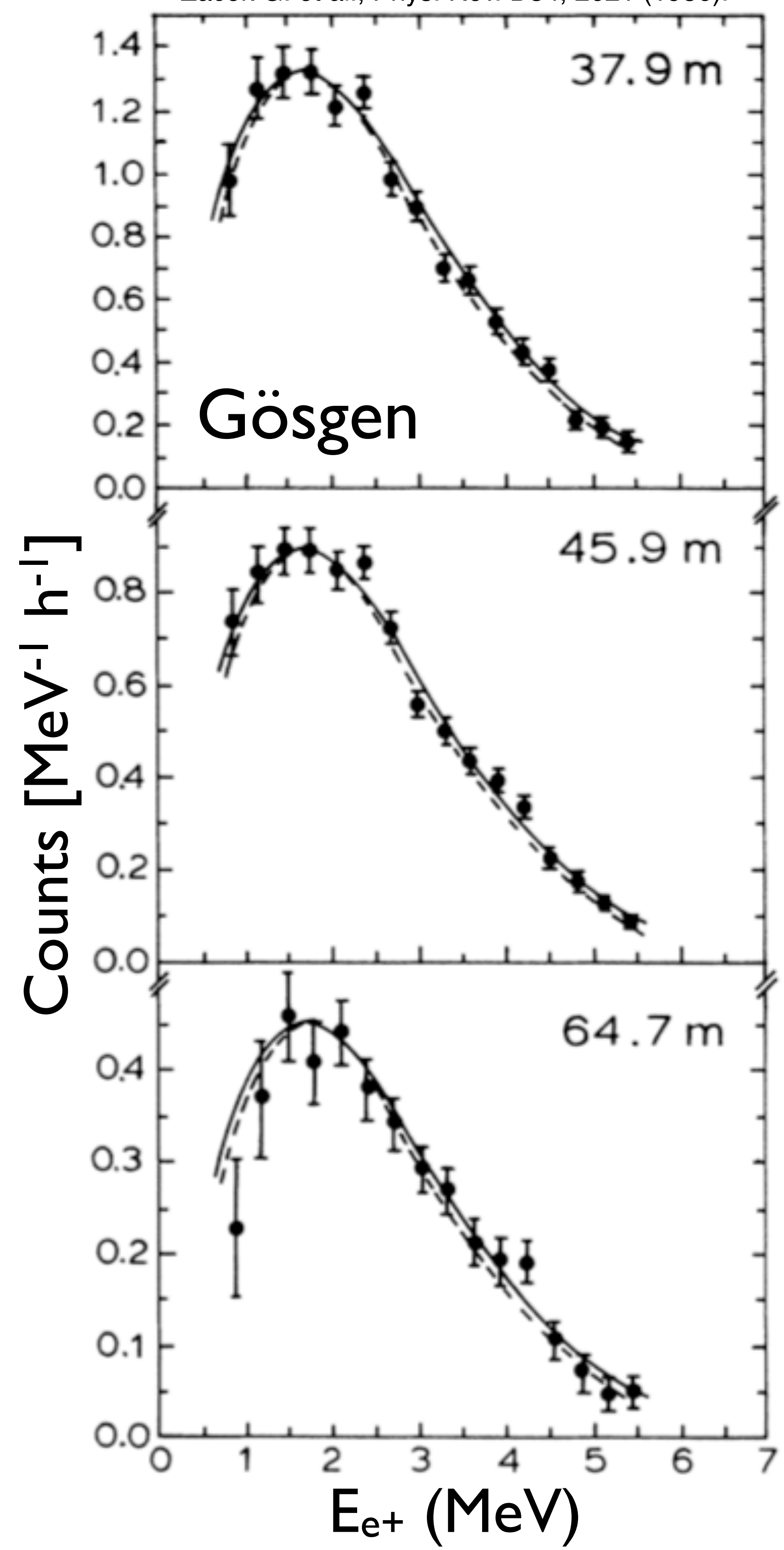
  - delayed event: neutron capture after ~207μs
    - 2.2 MeV gamma

Delayed coincidence: good background rejection

# Detected Reactor Spectrum



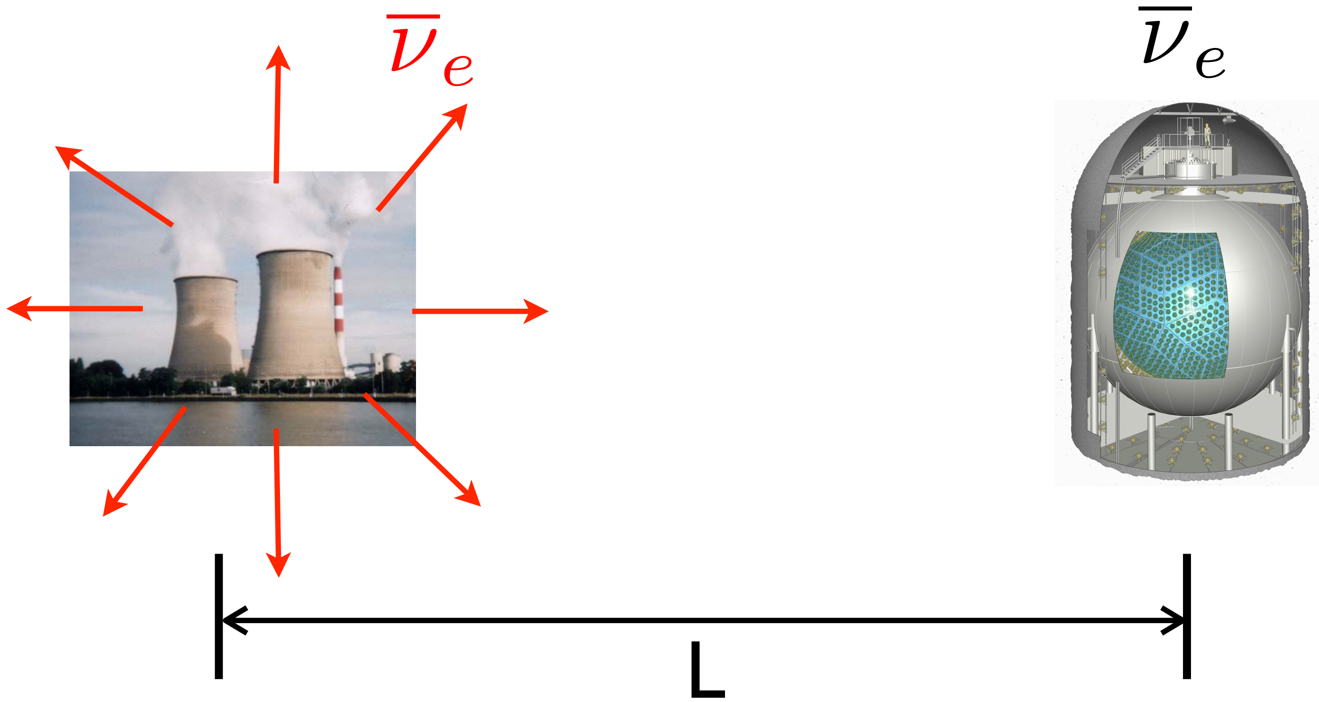

Zacek G. et al., Phys. Rev. D34, 2621 (1986).



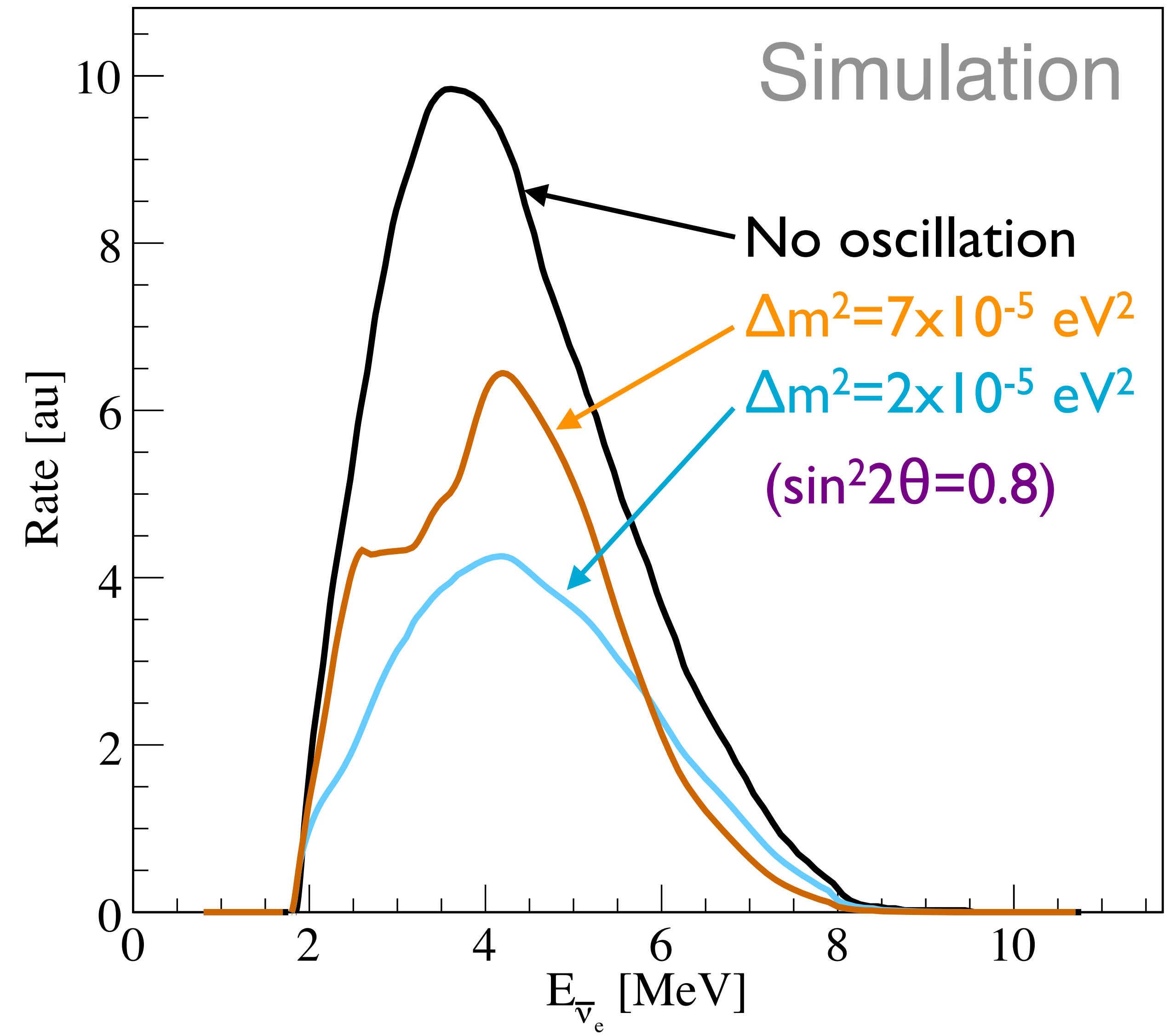

- In practice, only 1.5 neutrinos/fission detectable
- Calculated spectrum has been verified to 2% accuracy in past reactor experiments

No near detector necessary!

# Reactors for Oscillation Studies



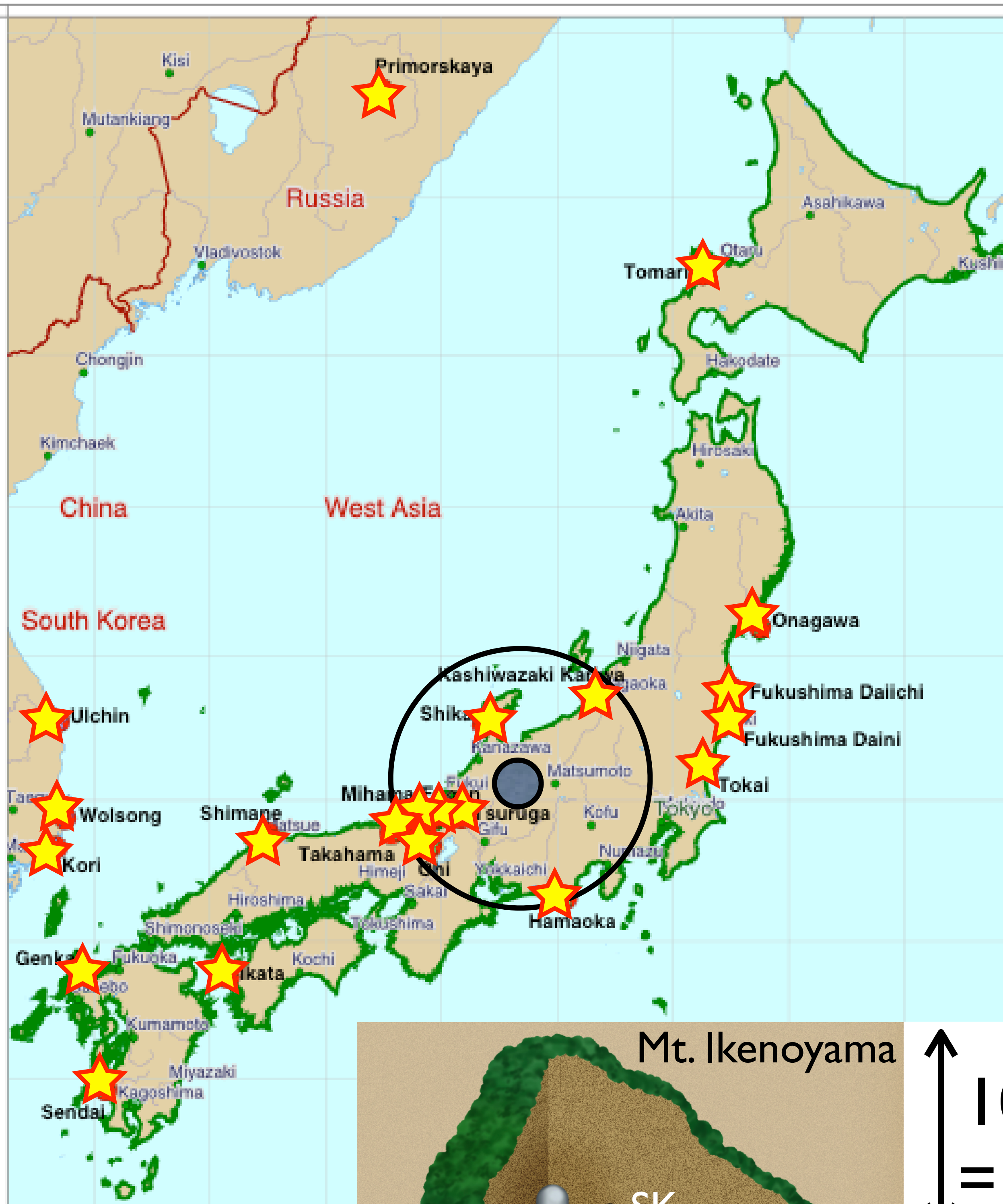

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$



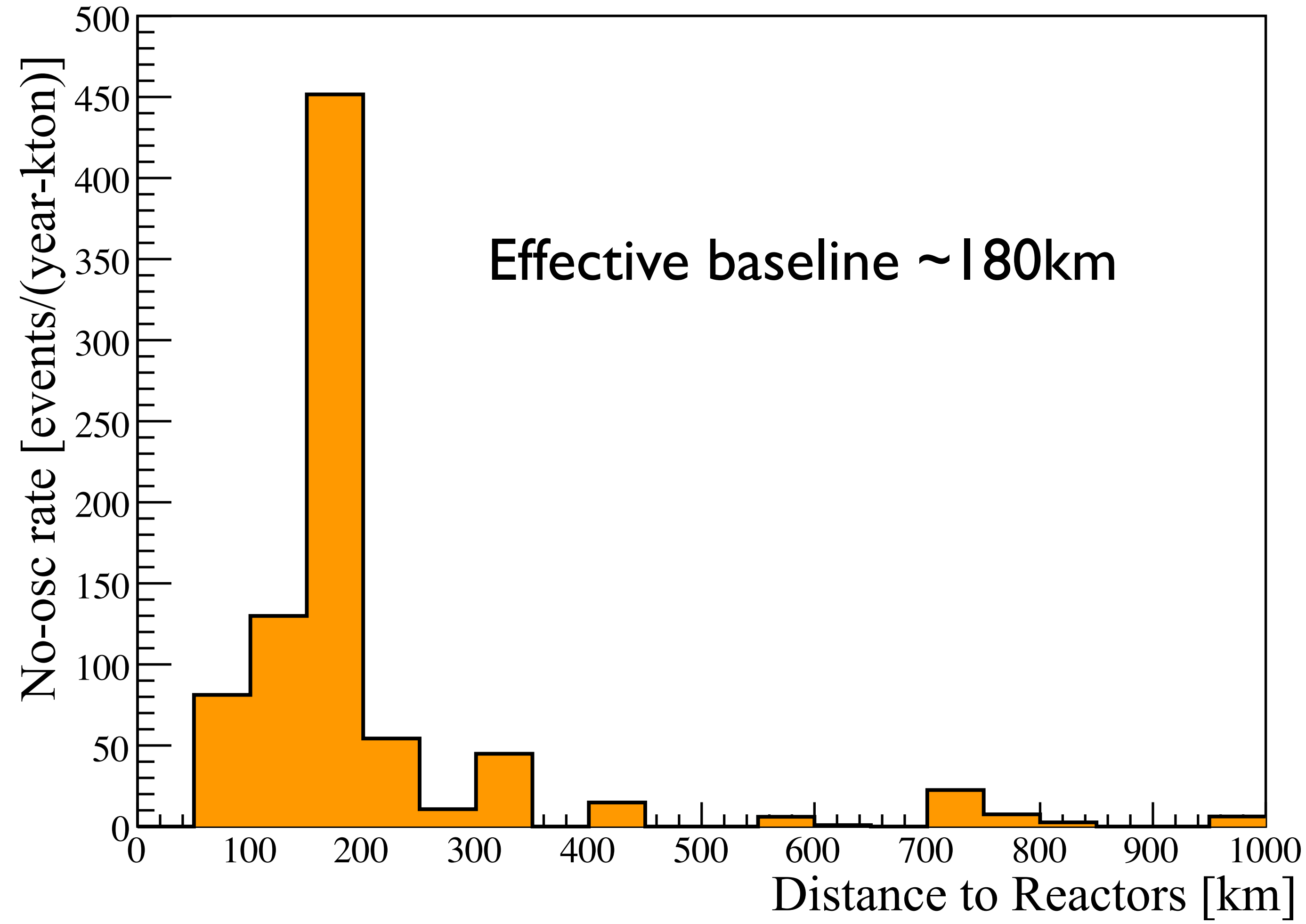

Neutrino oscillation changes the overall **normalization** and **shape** of the spectrum

# The KamLAND Experiment

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




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





1000m rock
= 2700 mwe

Reactor neutrino flux:
~$6 \times 10^6$ cm$^{-2}$s$^{-1}$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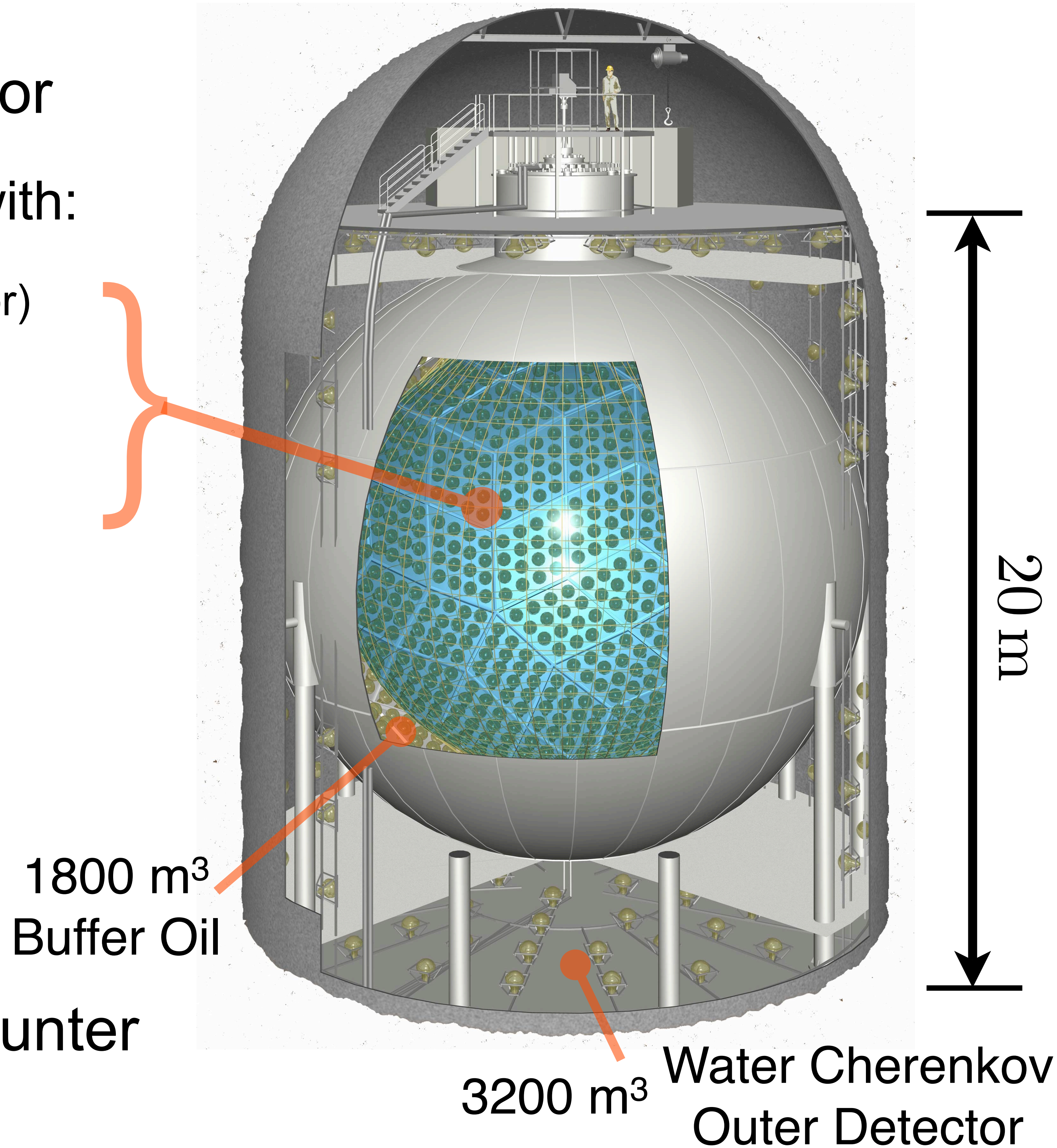
# KamLAND detector

- 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

0.4 | 1.0 | 2.6 | 8.5 | Energy [MeV]

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

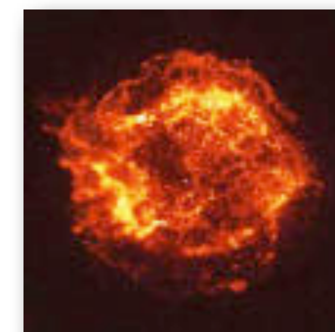
Study of earth heat model

**Neutrino Physics**

reactor neutrino

Precision measurement of oscillation parameters

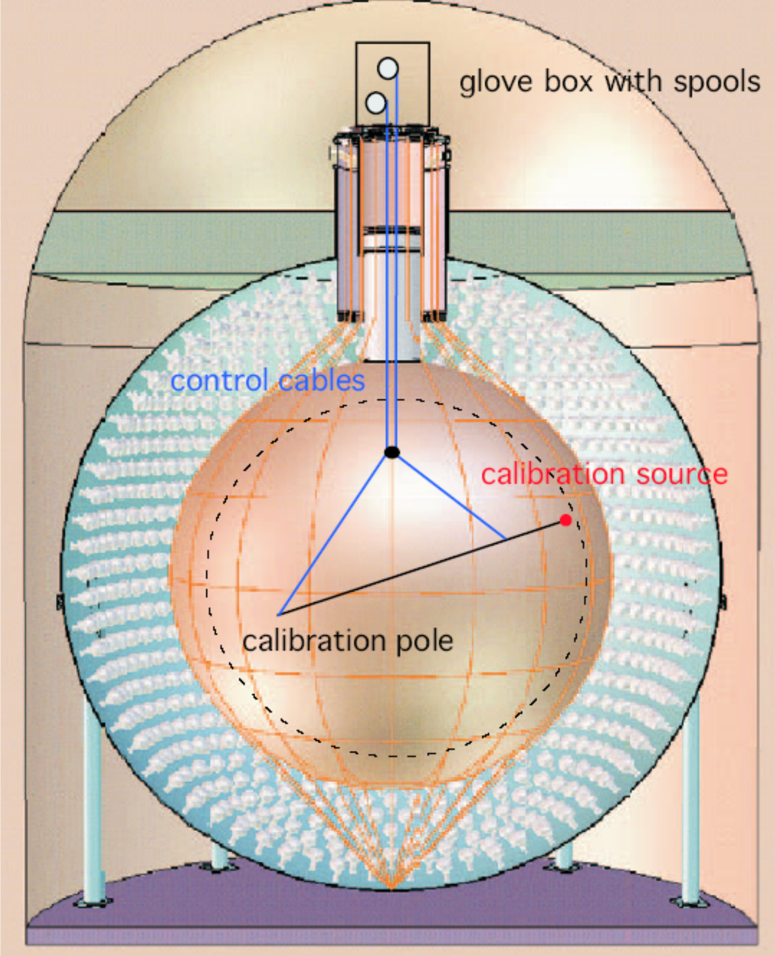
**Neutrino Cosmology**

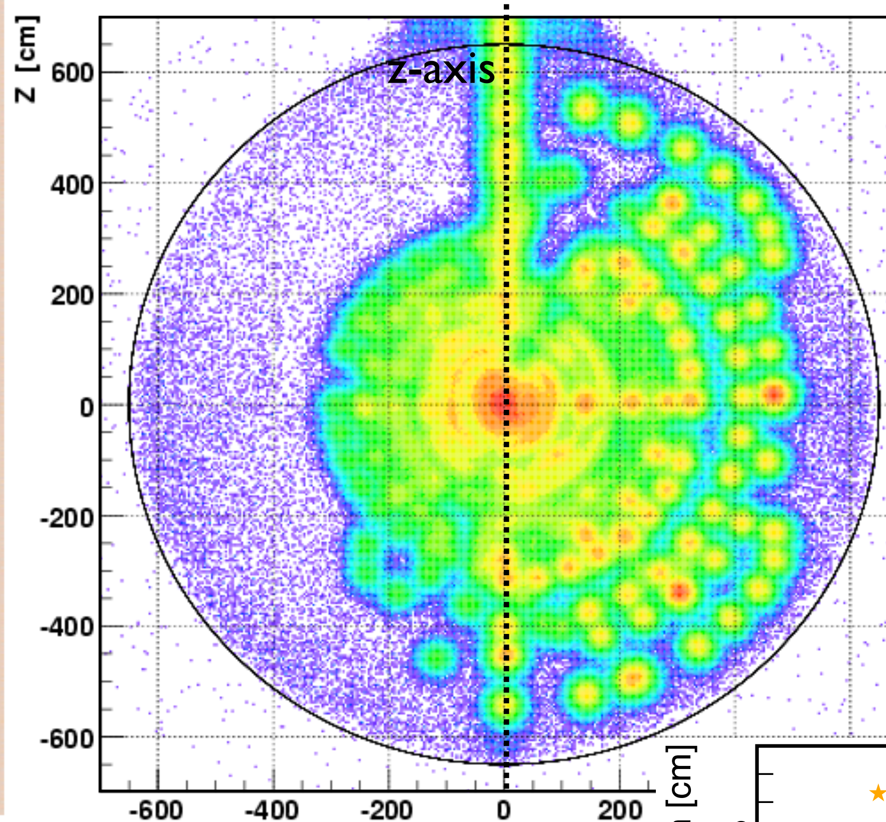


supernova, relic neutrino, solar anti-neutrinos etc.

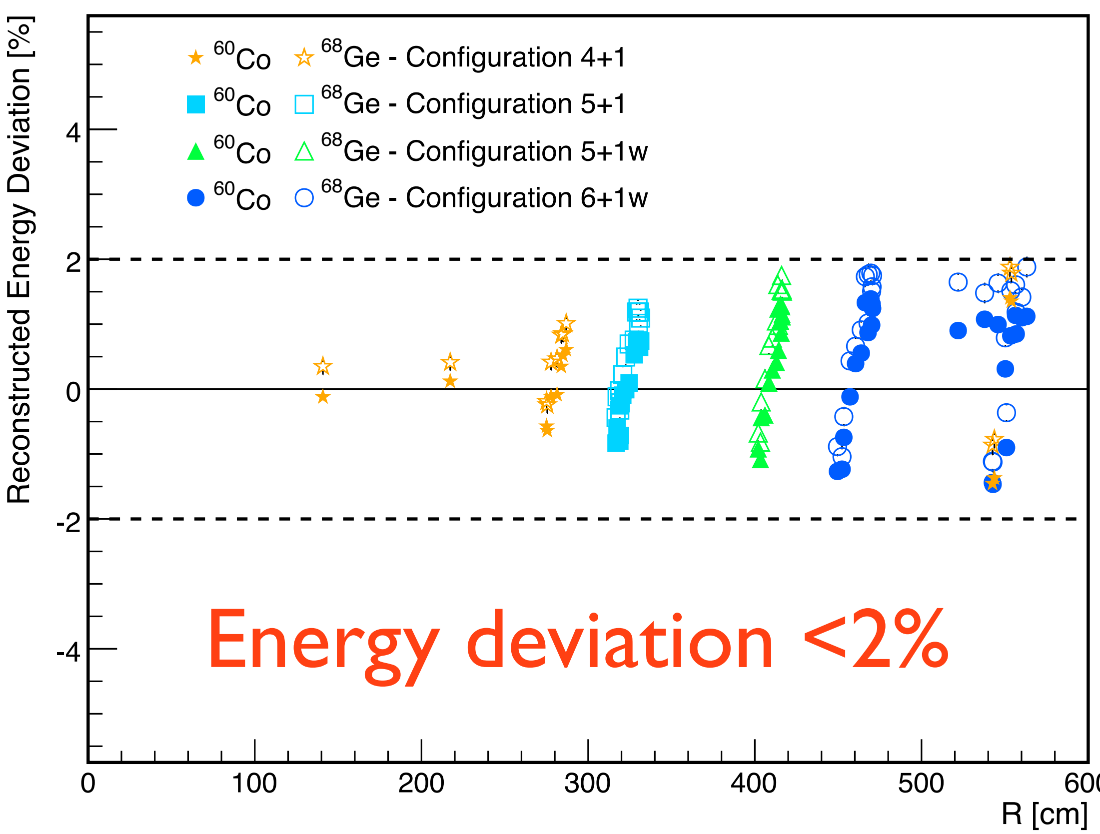
Verification of universe evolution, neutrino magnetic moment

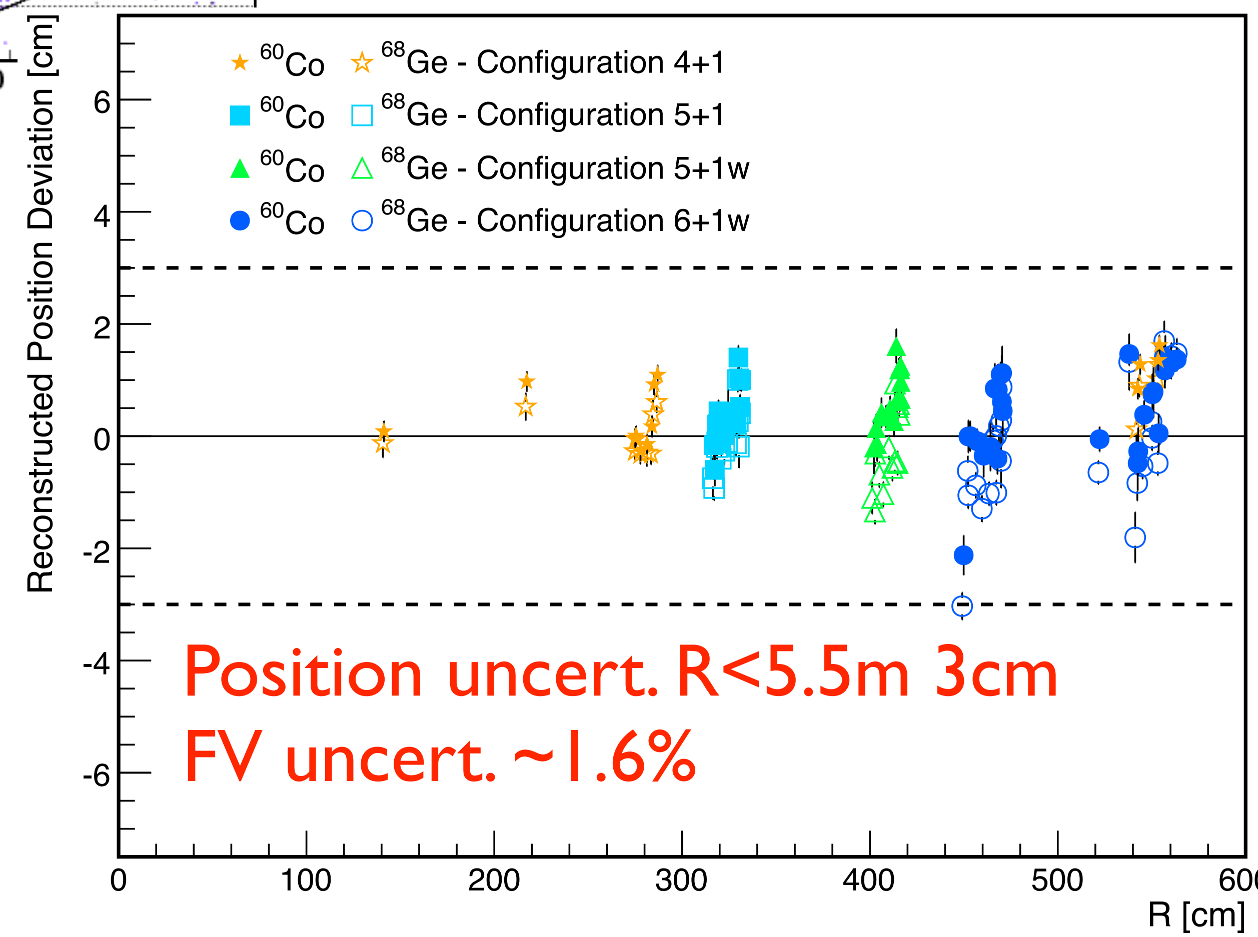
# Detector Characterization




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




Use $^{12}$B/$^{12}$N spallation uniformity for 5.5m<R<6m
→ Total FV uncert R<6m: 1.8%

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# Systematic Uncertainties

Systematic uncertainties between $\Delta m_{21}^2$ and $\theta_{12}$ decouple to a large degree

| | Detector-related (%) | | Reactor-related (%) | |
|---|---|---|---|---|
| $\Delta m^2_{21}$ | 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] | 1.0 |
| | Cross section | 0.2 | Long-lived nuclei | 0.3 |

Almost the same in new v

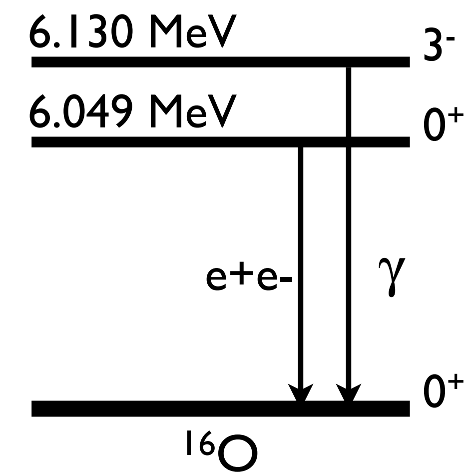
→ Sum: 2.0%

Primarily affecting $\theta_{12}$
Sum: 4.1%

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

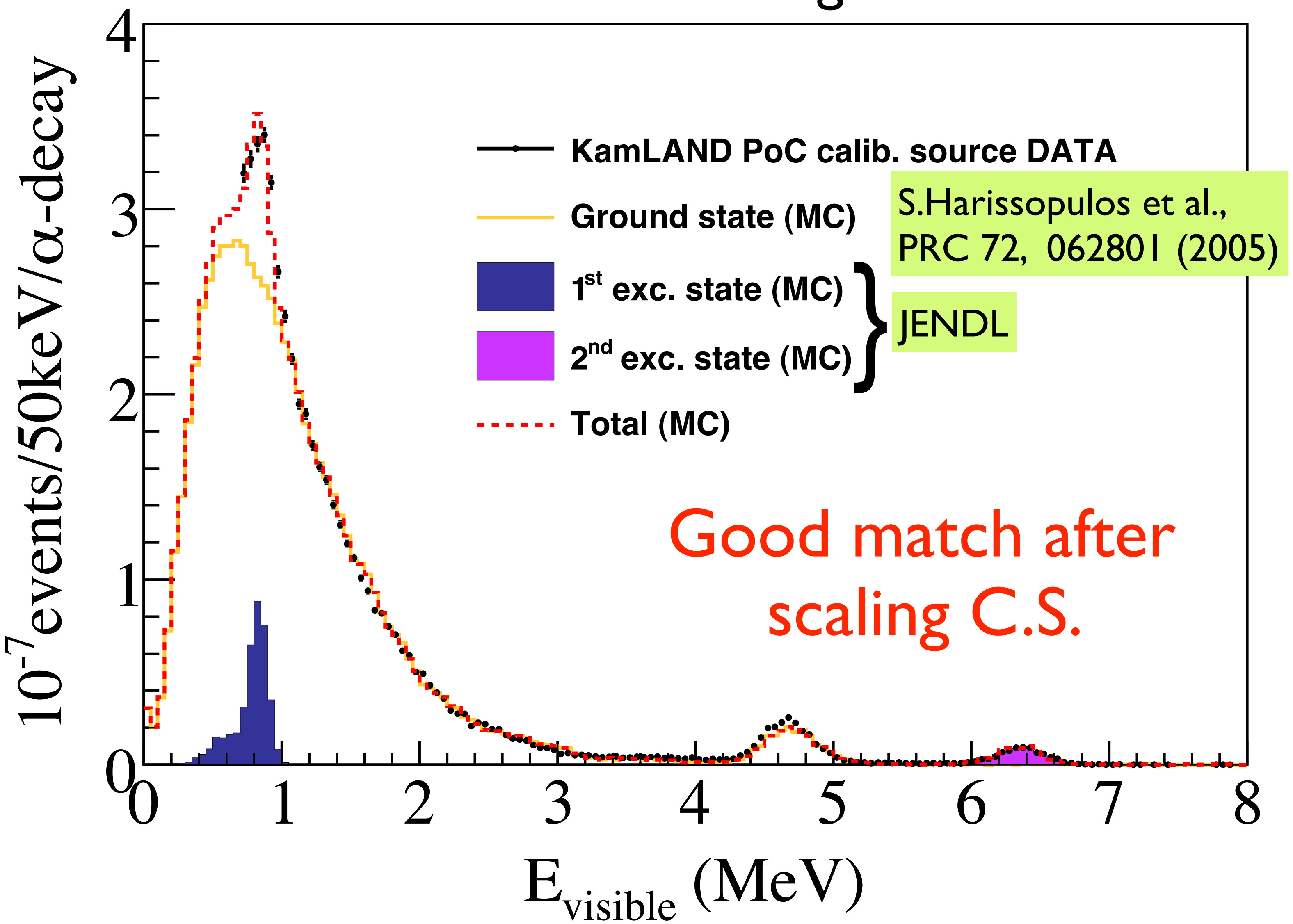
From $^{222}Rn$ chain: $^{210}Pb \xrightarrow{T_{1/2}=22yr} {}^{210}Bi \xrightarrow{5d} {}^{210}Po \xrightarrow{138d} {}^{206}Pb$

$\alpha$, E=5.3MeV

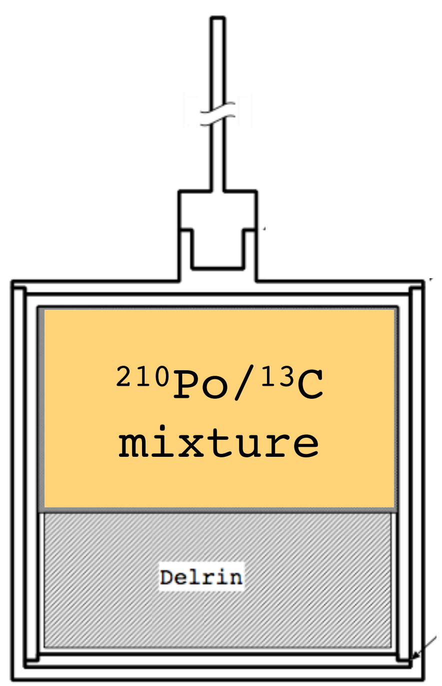



1.1% abundance of $^{13}C$ in LS → $\mathbf{^{13}C(\alpha,n)^{16}O}$

Cross sections tuned using detector MC

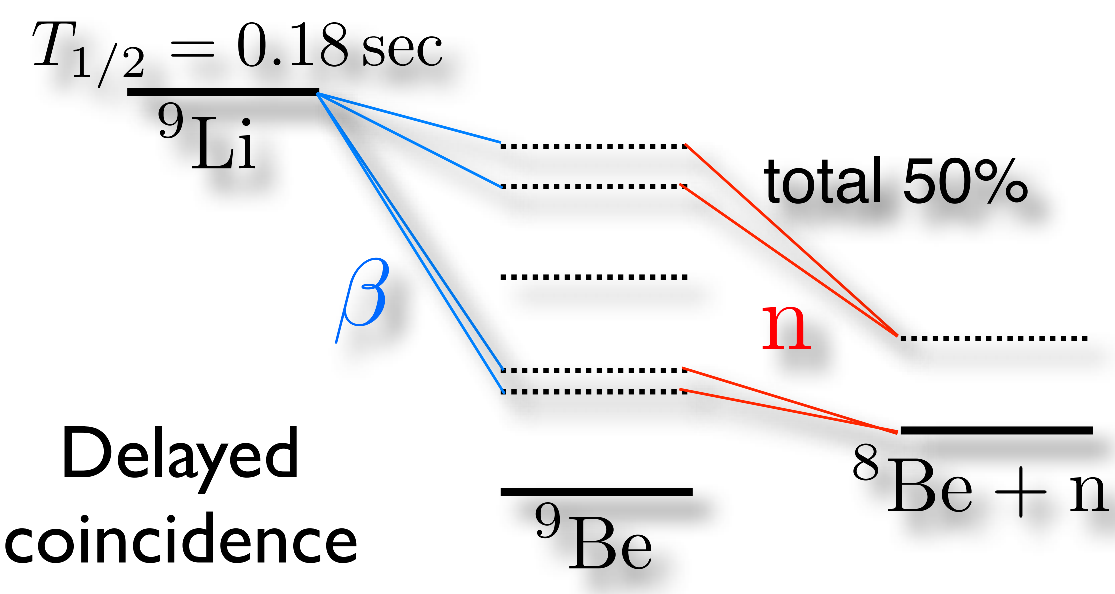



$^{210}Po^{13}C$ source deployed into the detector

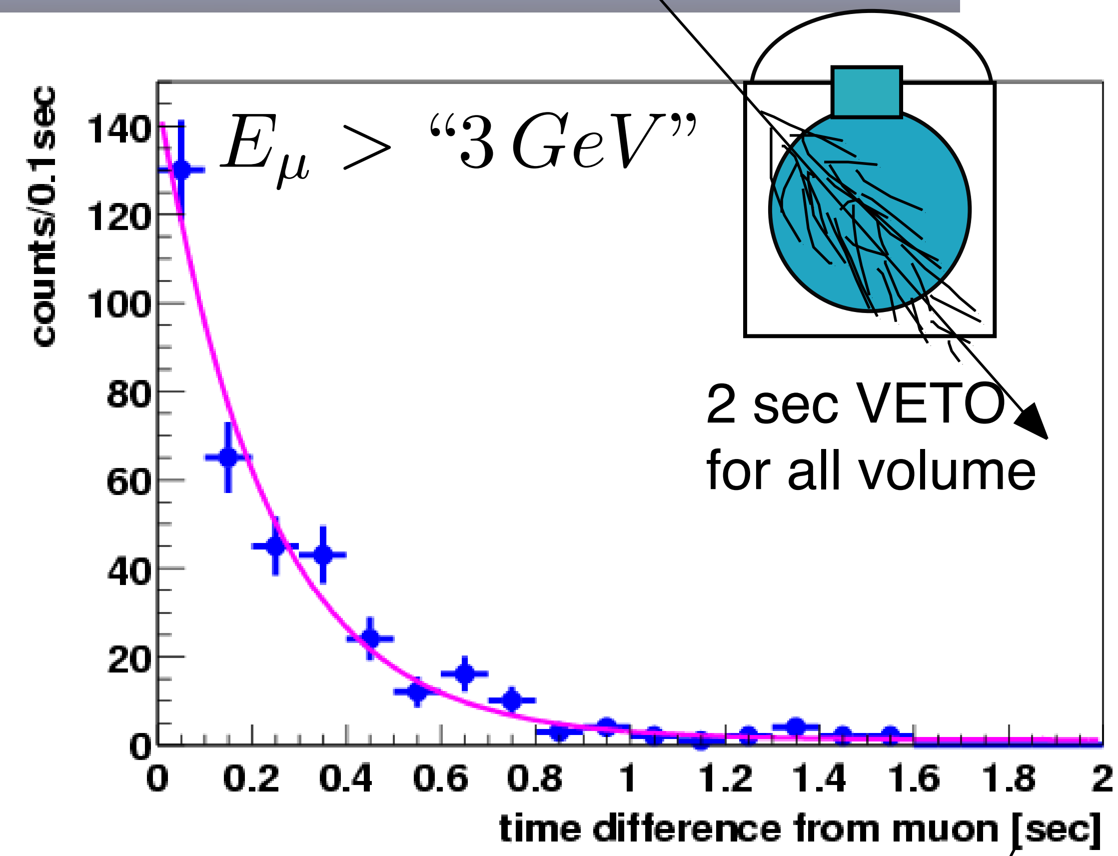


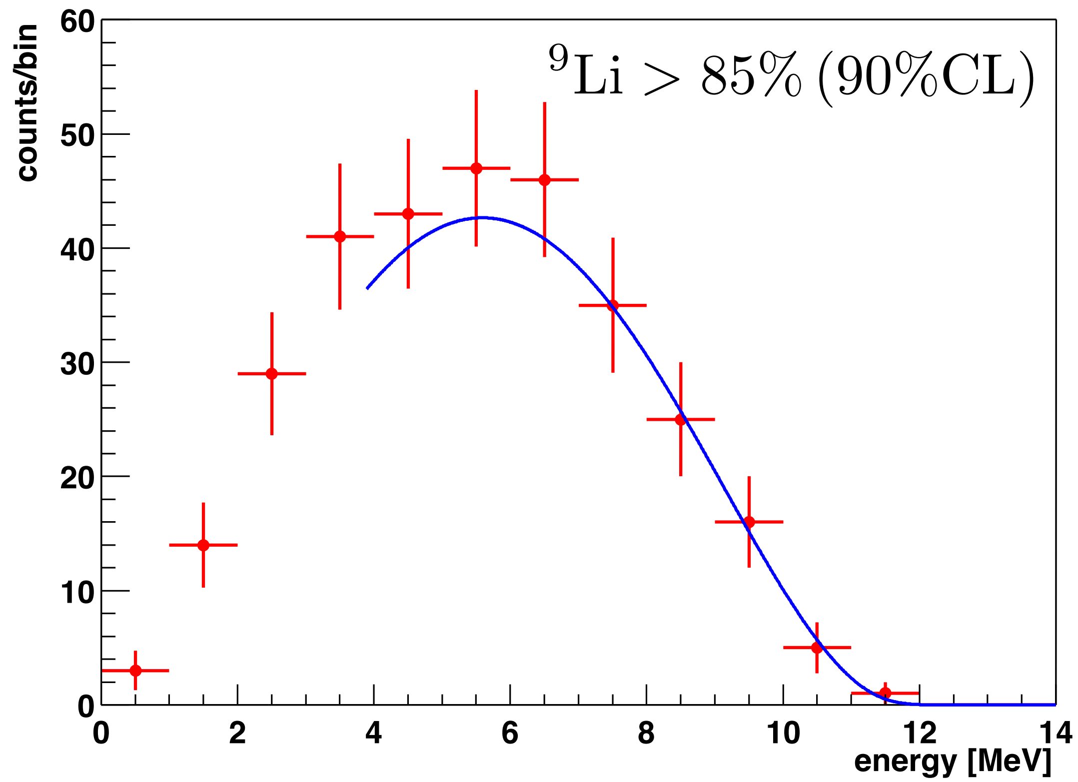

D.McKee et al., NIM A527, 272 (2008)

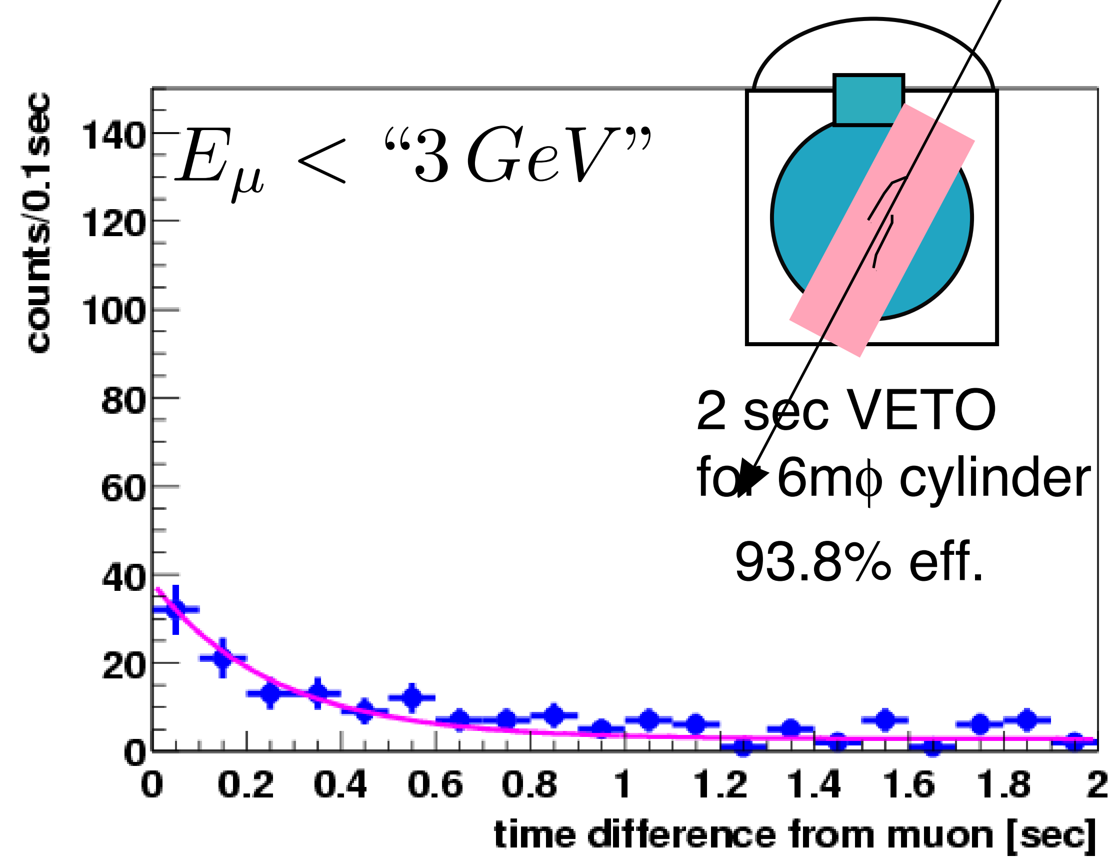
# Muon Induced Spallation Events



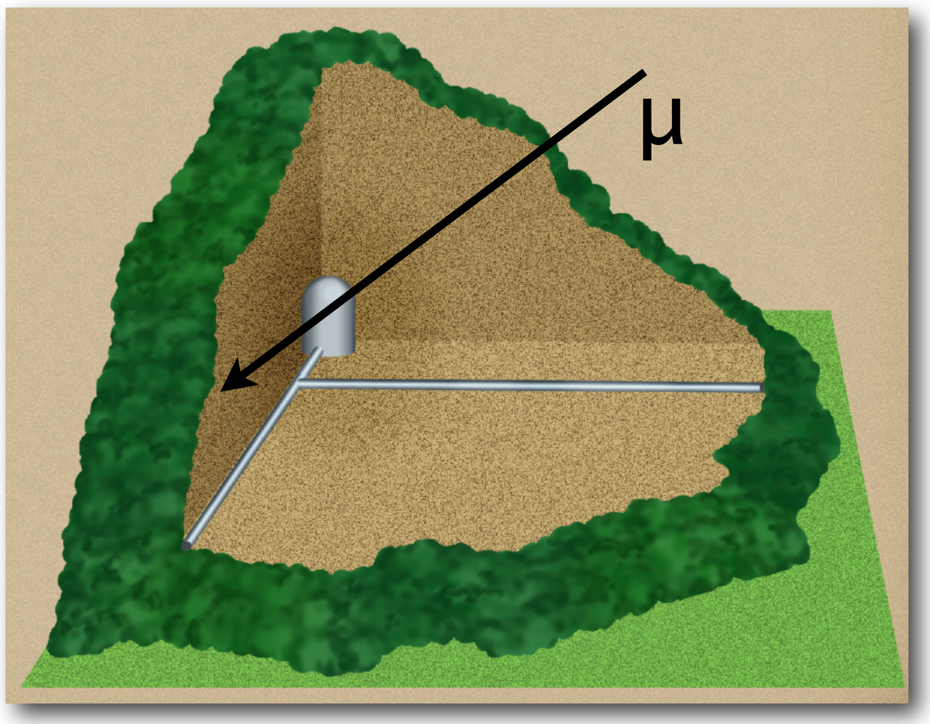

Delayed coincidence signature

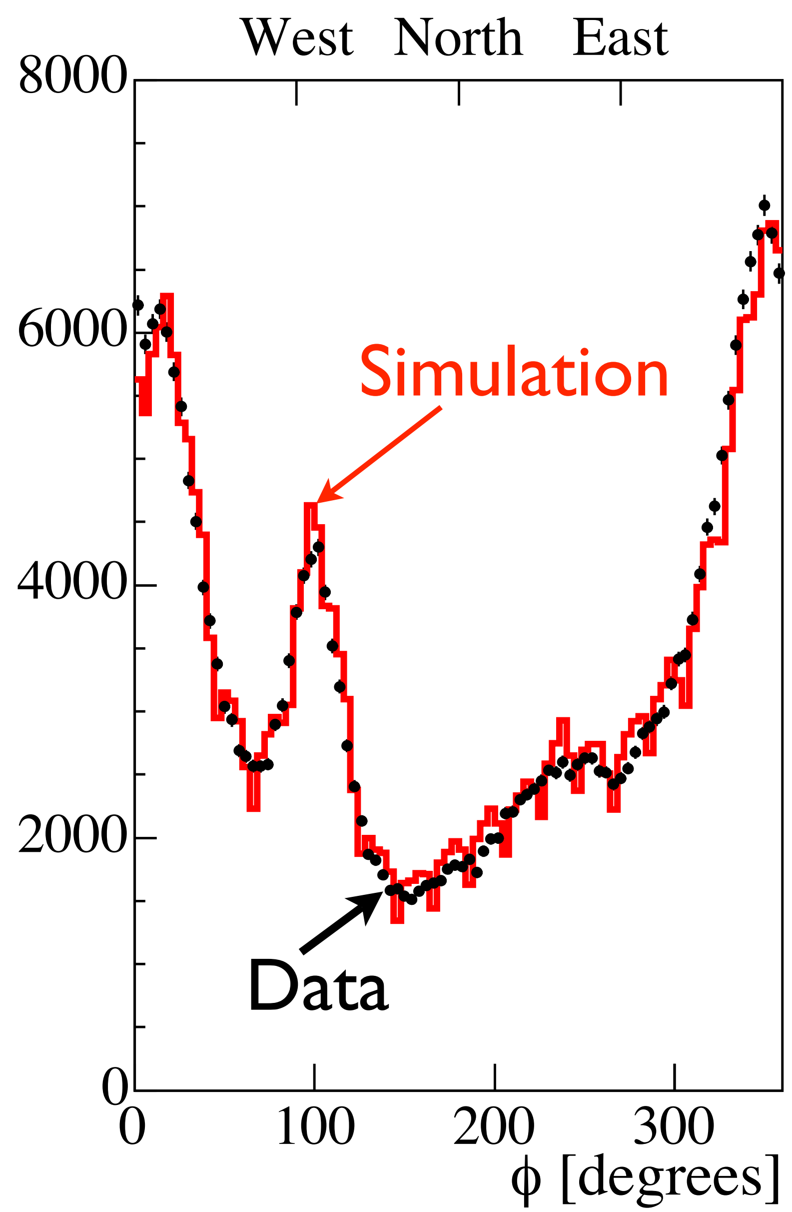


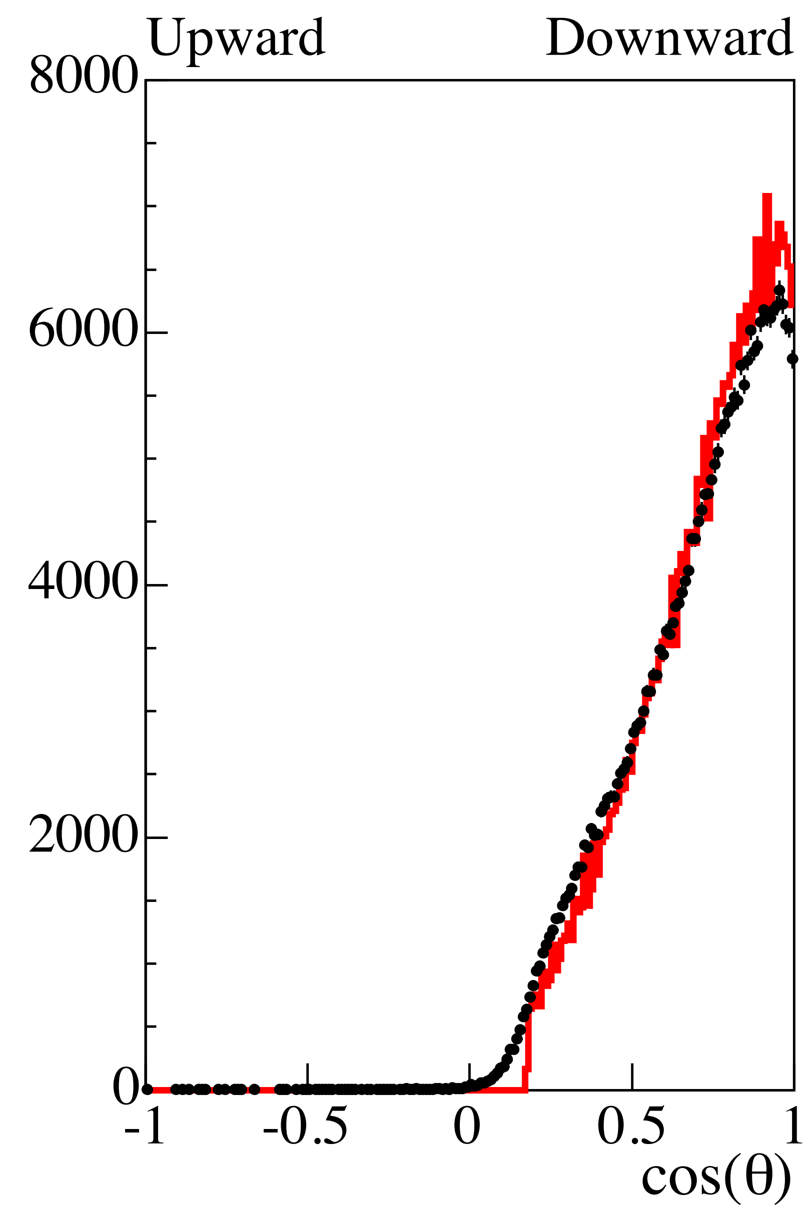



# Muon Tracking Works



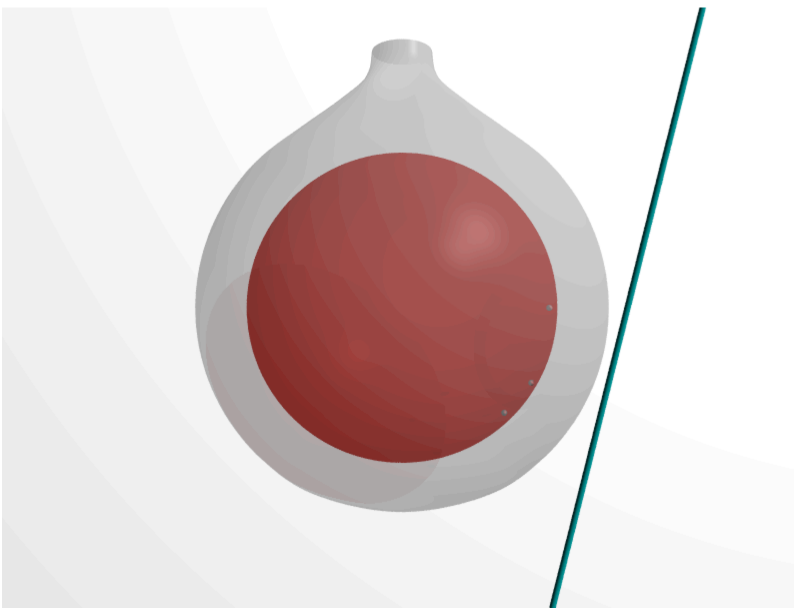




Comparison of tracking to simulation, including detailed mountain geometry

# Dealing with muons

## 3 Typical scenarios of muons interacting in KamLAND

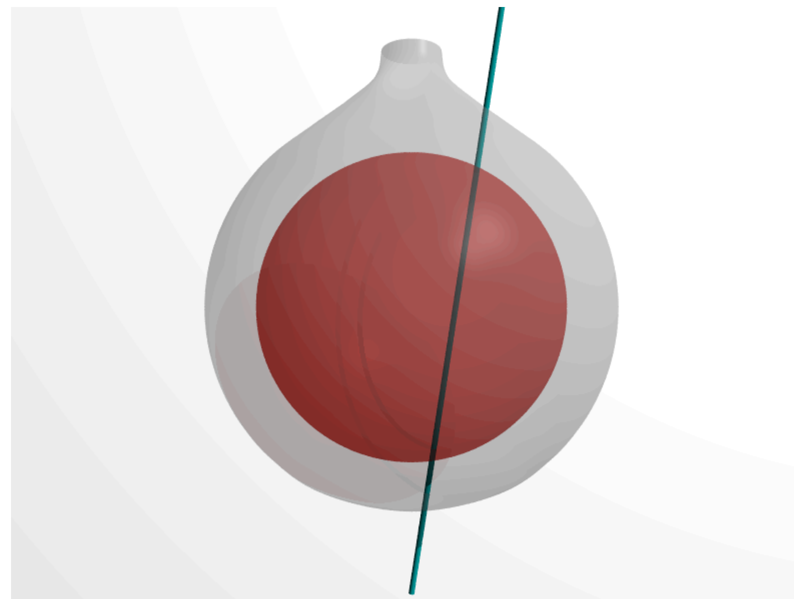
### Muon outside LS



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

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

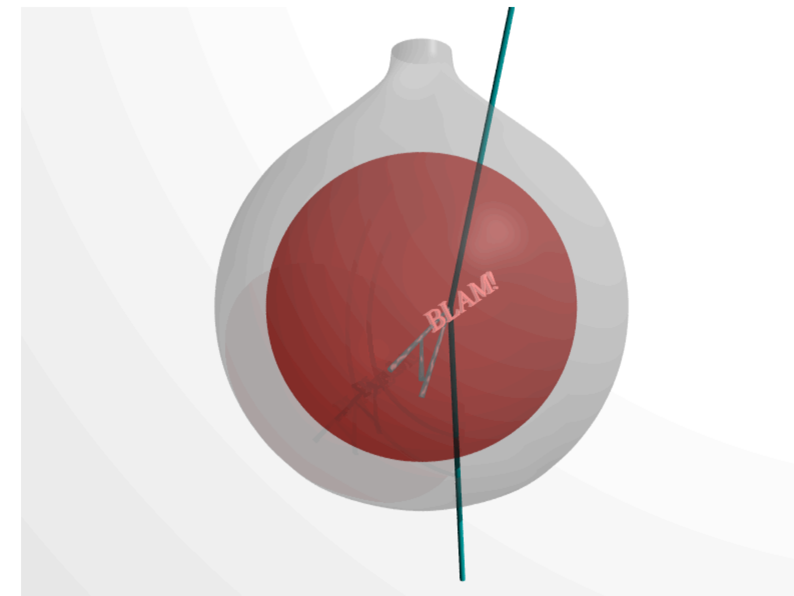
### Muon in LS, little E deposited



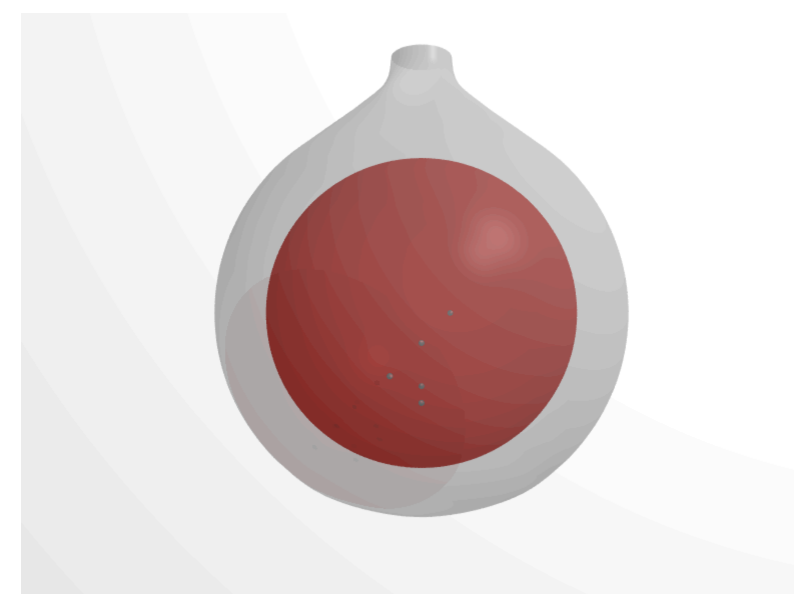
0 to 2 ms after muon in LS:
veto entire volume

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

### "Showering" Muon in LS



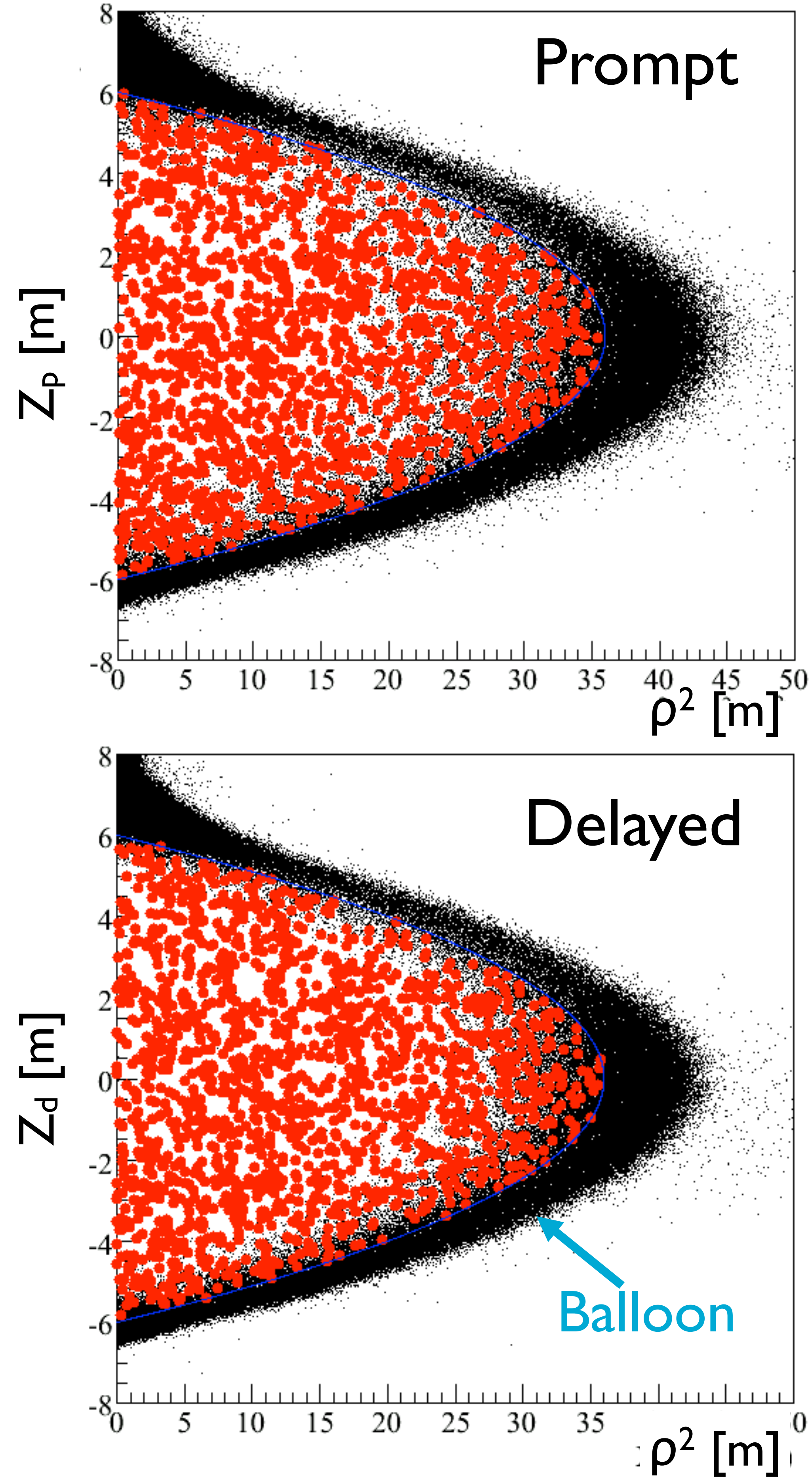

0 to 2 ms after shower in LS:
veto entire volume



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 < $\Delta T$ < 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 | $102.5 \pm 0.1$ |
| $^{9}\mathrm{Li}/^{8}\mathrm{He}$ | $24.8 \pm 1.6$ |
| Fast neutron & Atmospheric $\nu$ | $<12.3$ |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}_{gs}$, $\mathrm{np} \rightarrow \mathrm{np}$ | $171.7 \pm 18.2$ |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}_{gs}$, $^{12}\mathrm{C}(\mathrm{n},\mathrm{n}')^{12}\mathrm{C}^{*}$ (4.4 MeV $\gamma$) | $7.3 \pm 0.8$ |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ 1st exc. state (6.05 MeV $e^{+}e^{-}$) | $15.9 \pm 3.3$ |
| $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ 2nd exc. state (6.13 MeV $\gamma$) | $3.7 \pm 0.7$ |
| Total | $325.9 \pm 26.1$ |

→ Accidental Coincidences

Cosmogenic

Background from $^{222}$Rn chain

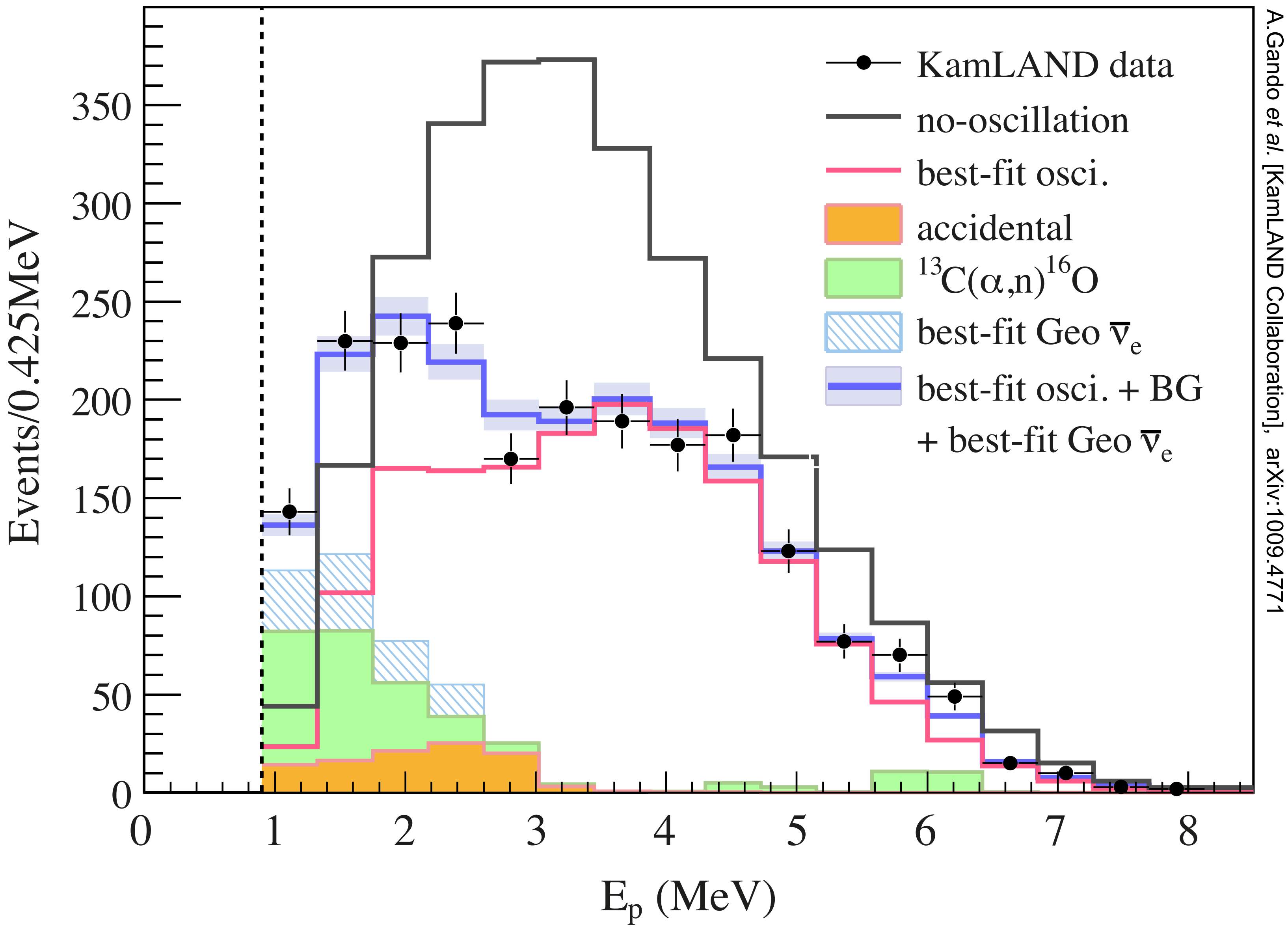
**Geo-neutrinos** are a background to the neutrino oscillation measurement

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

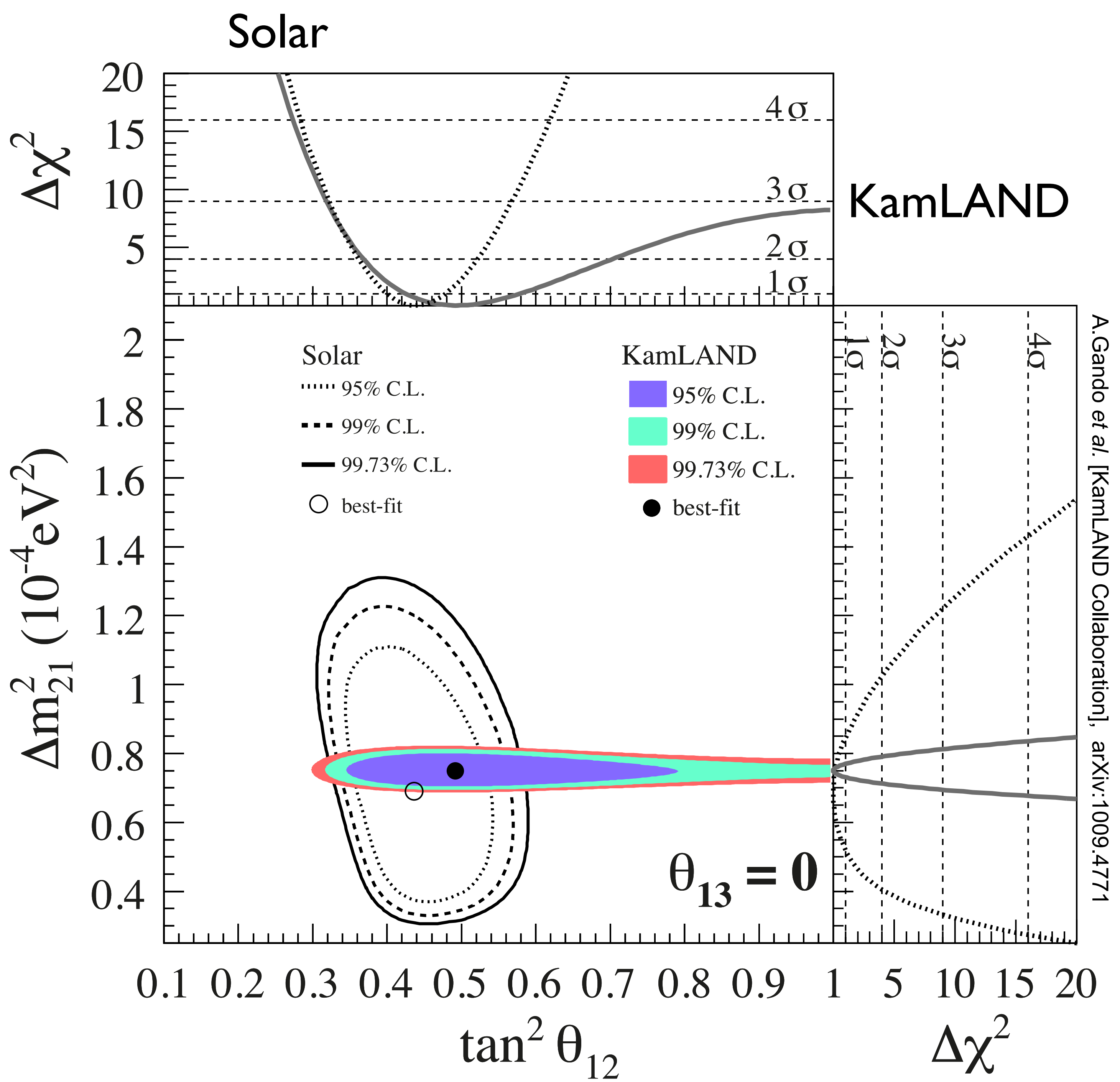



Number of events:

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

Patrick Decowski / Nikhef

# Neutrino Oscillation Parameters




**KamLAND-only best-fit:**

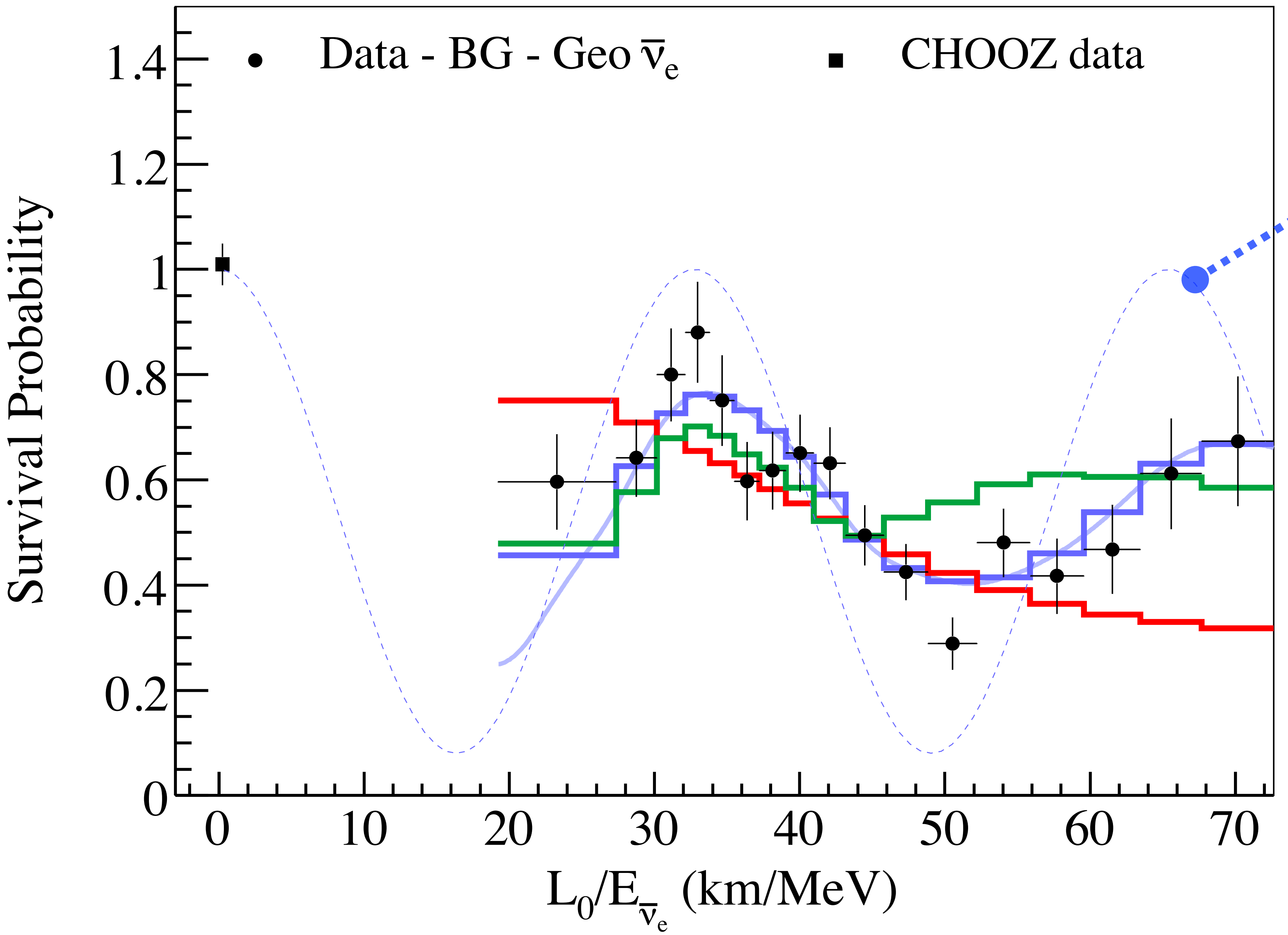
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$

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

Solar Experiments are sensitive to $\theta_{12}$ (mainly SNO)

KamLAND is most sensitive to $\Delta m^2_{21}$

# Illustration of Neutrino Oscillation




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

LMA-1 (best fit)

LMA-2

LMA-0

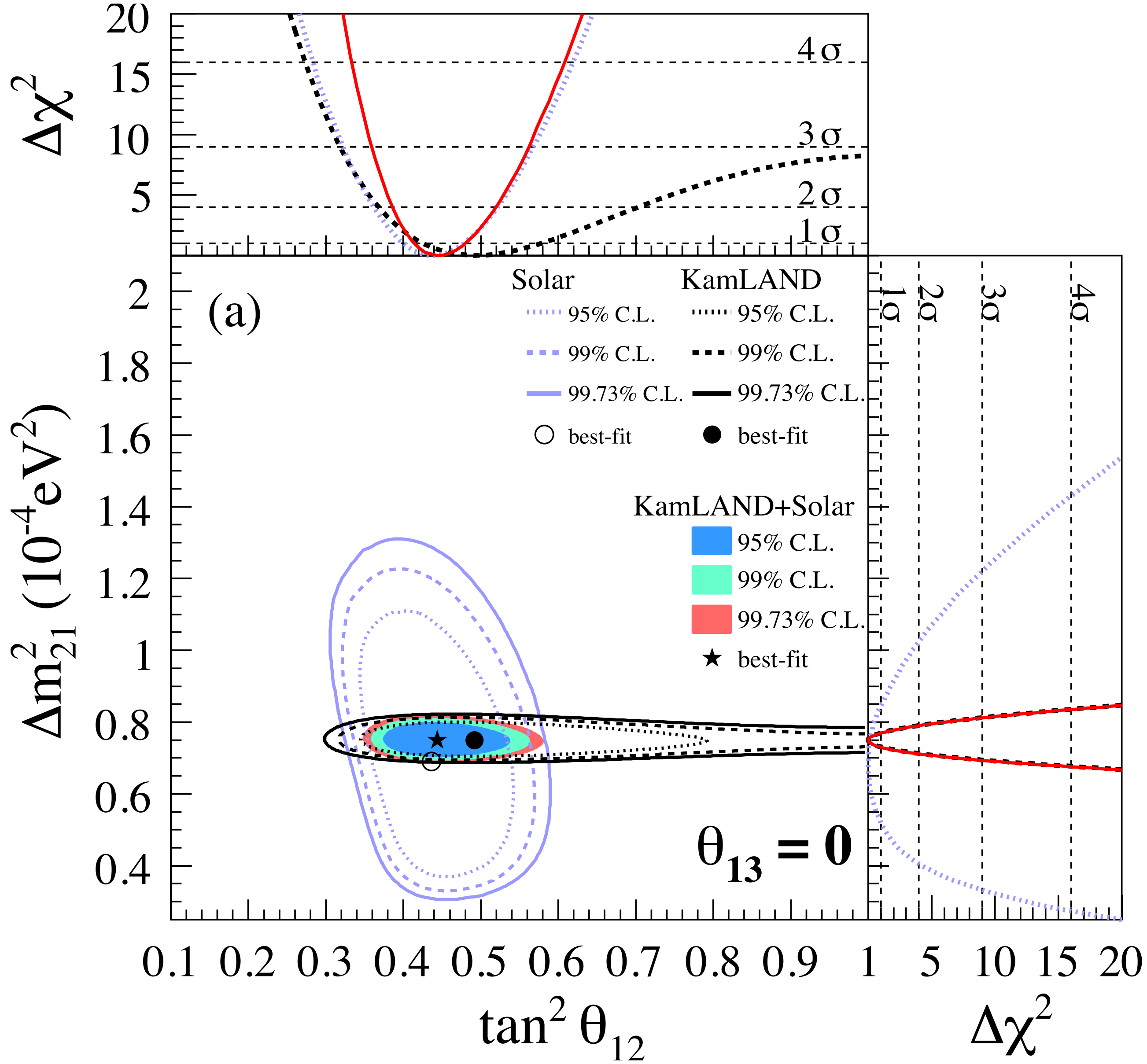
-fit oscillation
ounting for energy
trum and
tor distribution

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

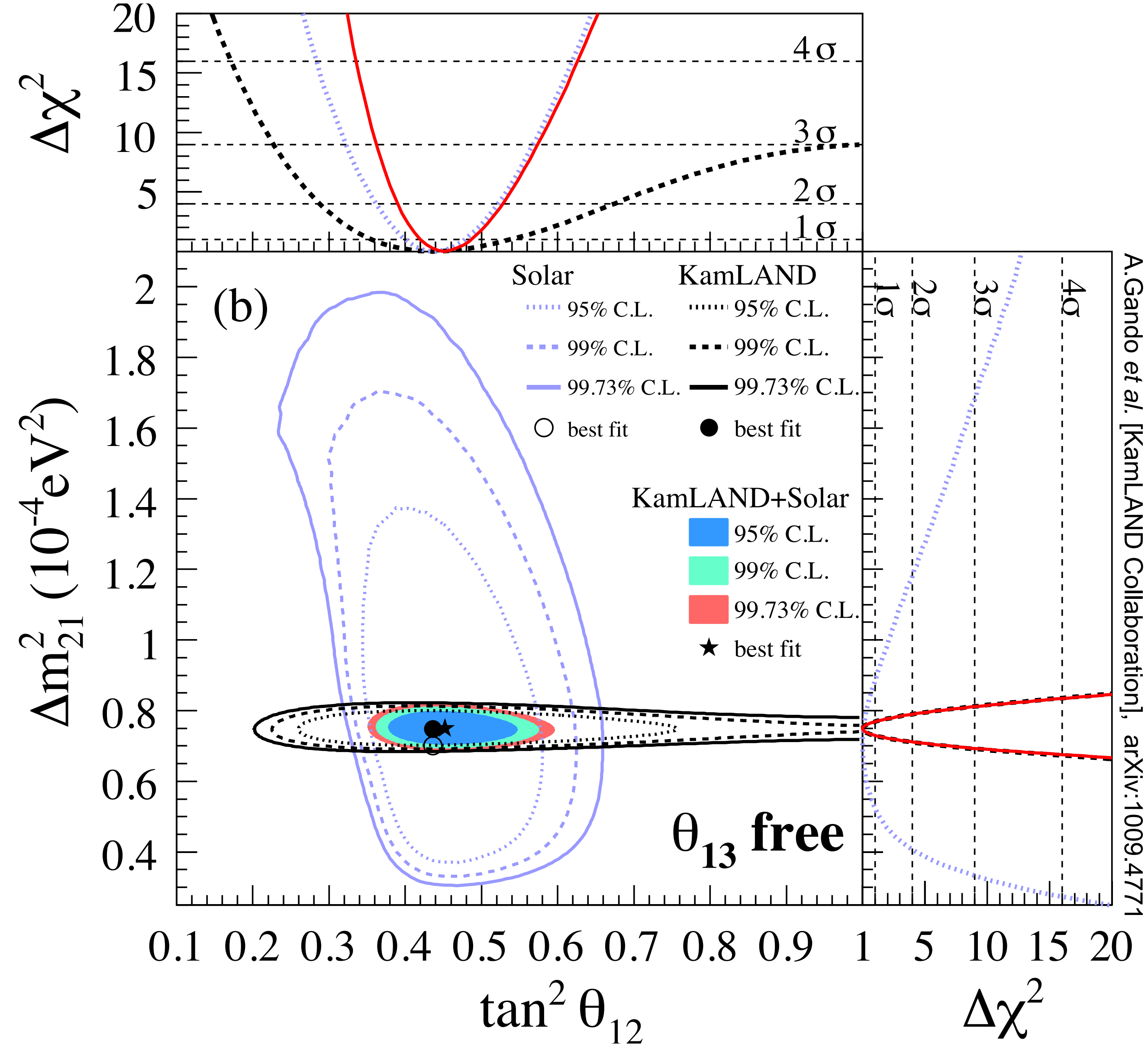
Patrick Decowski / Nikhef

# 3-flavor Oscillation

## 2-flavor oscillation



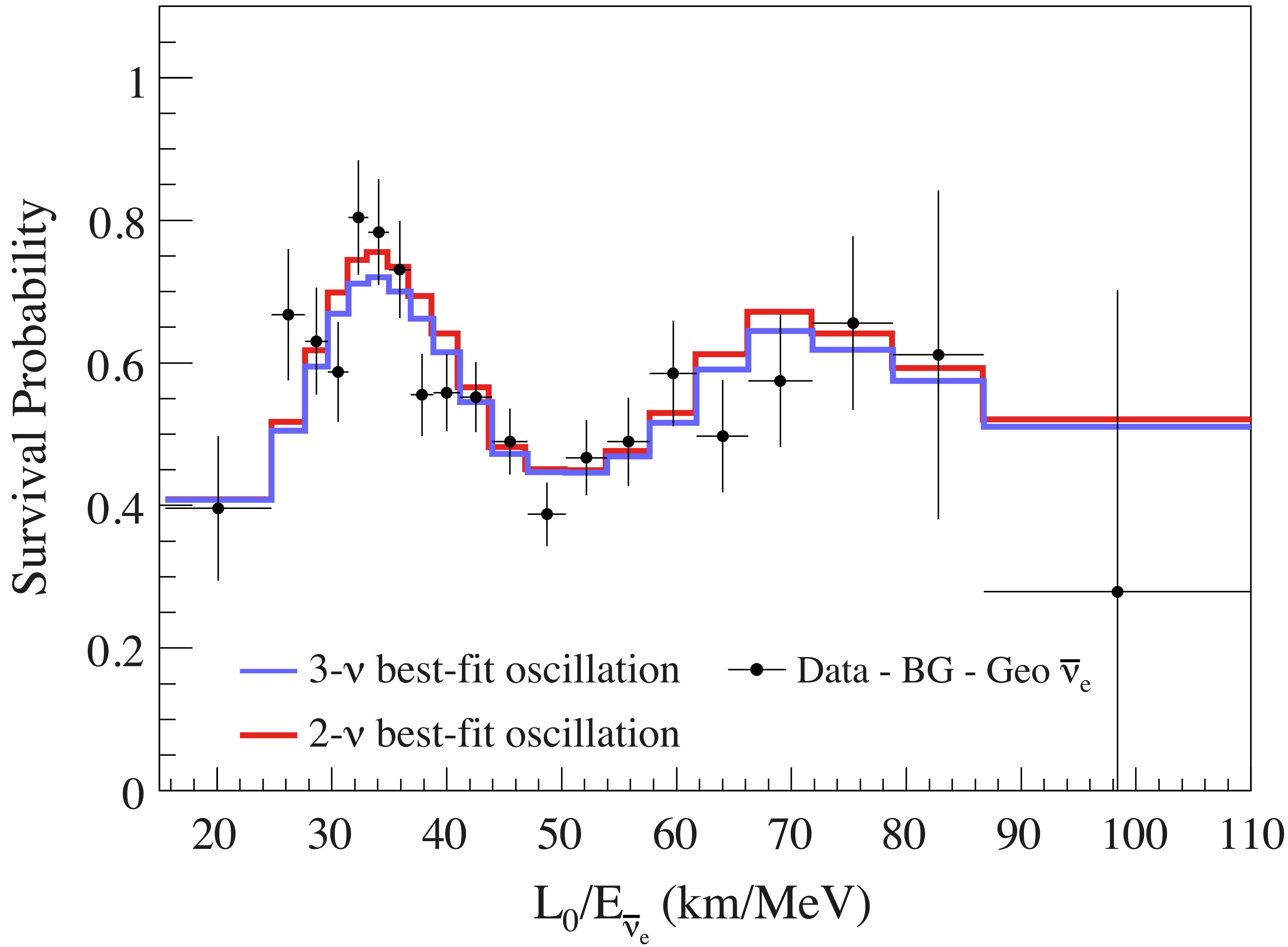

## 3-flavor oscillation




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

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

# Effect of 3-nu Oscillation

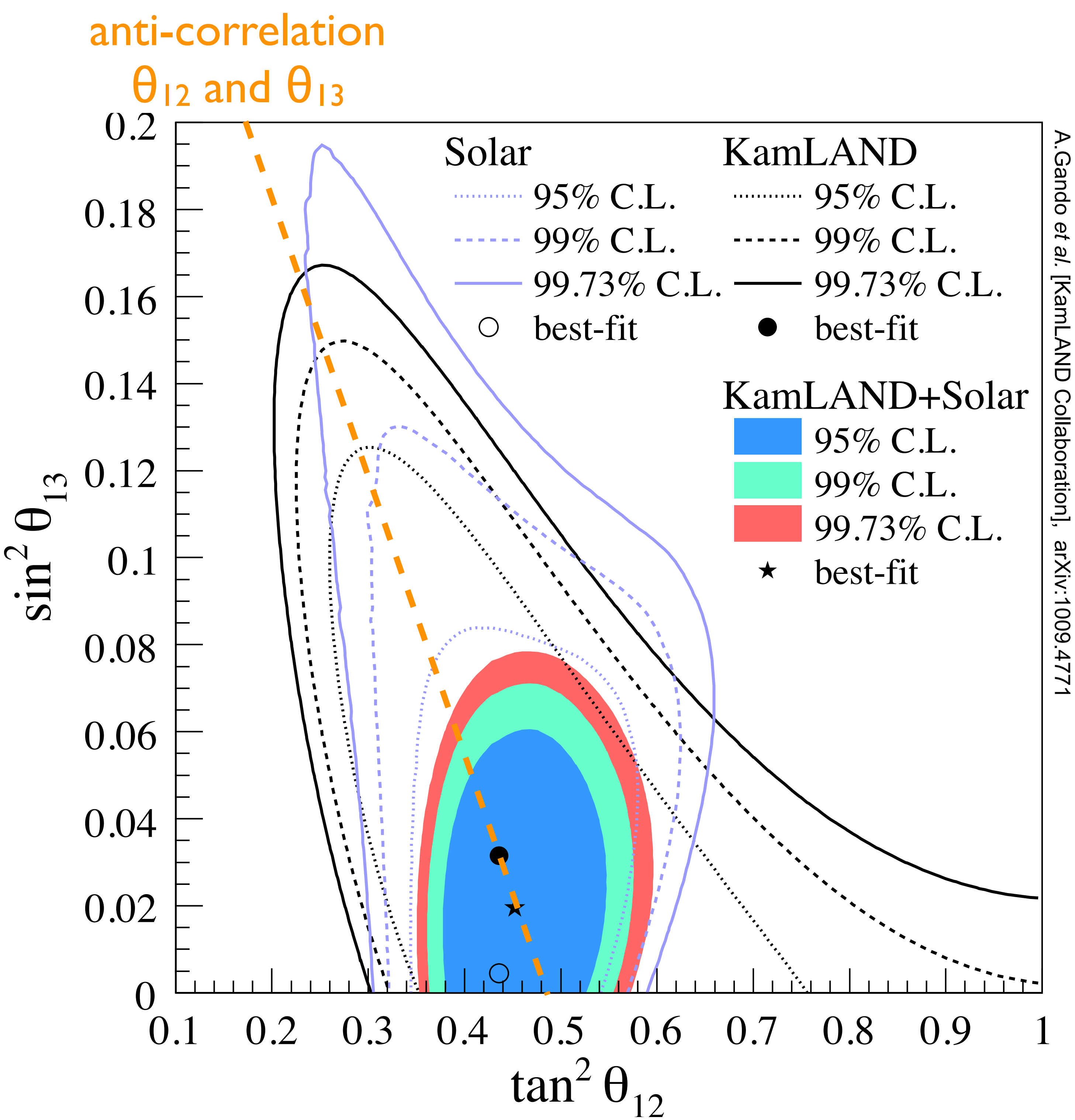



$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Patrick Decowski / Nikhef

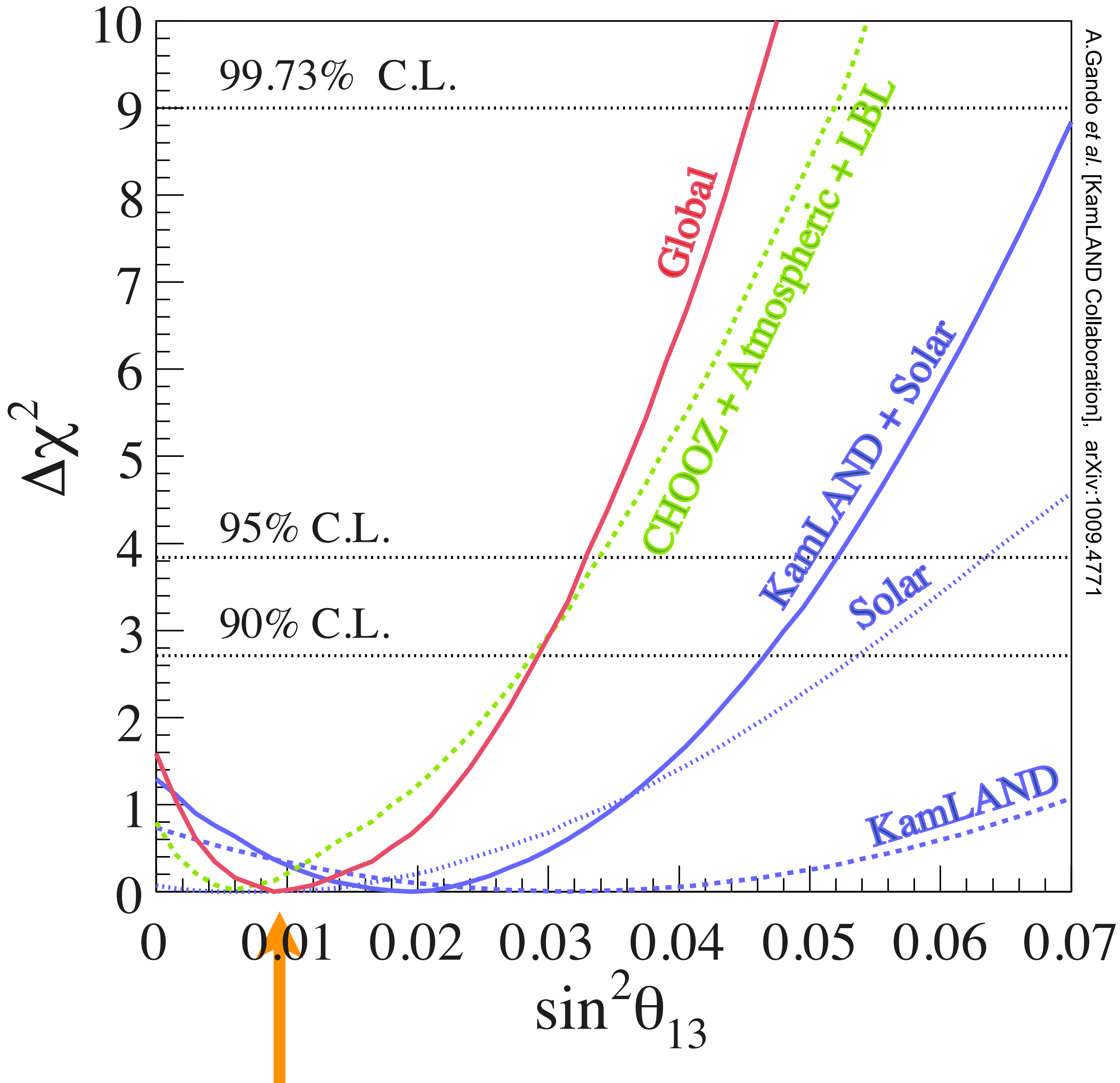
# Disentangling $\theta_{13}$

KamLAND is not ideal for this measurement




→ Global analysis with other experiments

# Global fit of $\theta_{13}$



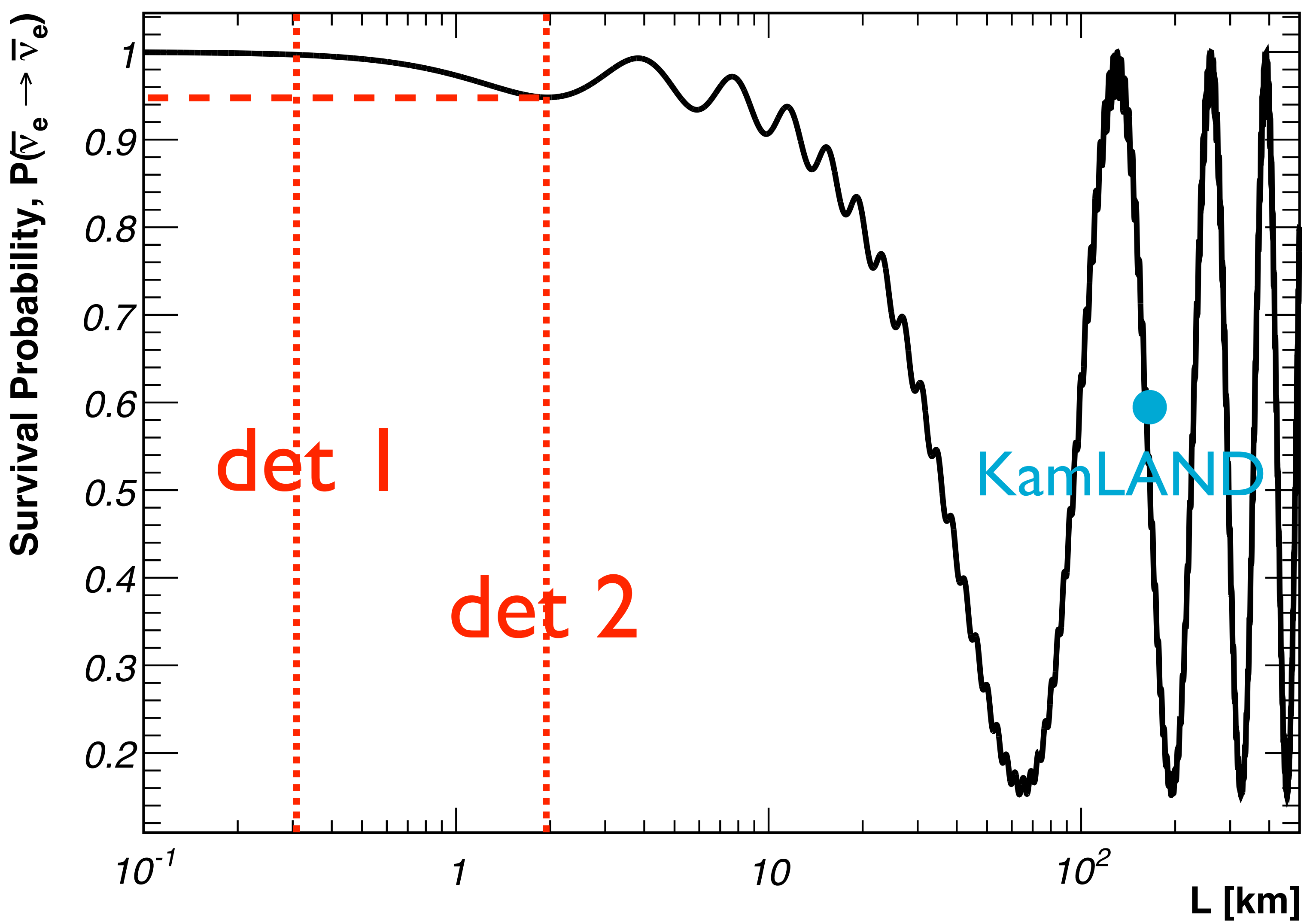

$$\sin^2\theta_{13} = 0.009^{+0.013}_{-0.007}$$

Non-zero $\theta_{13}$ excluded at 79% C.L.

Patrick Decowski / Nikhef

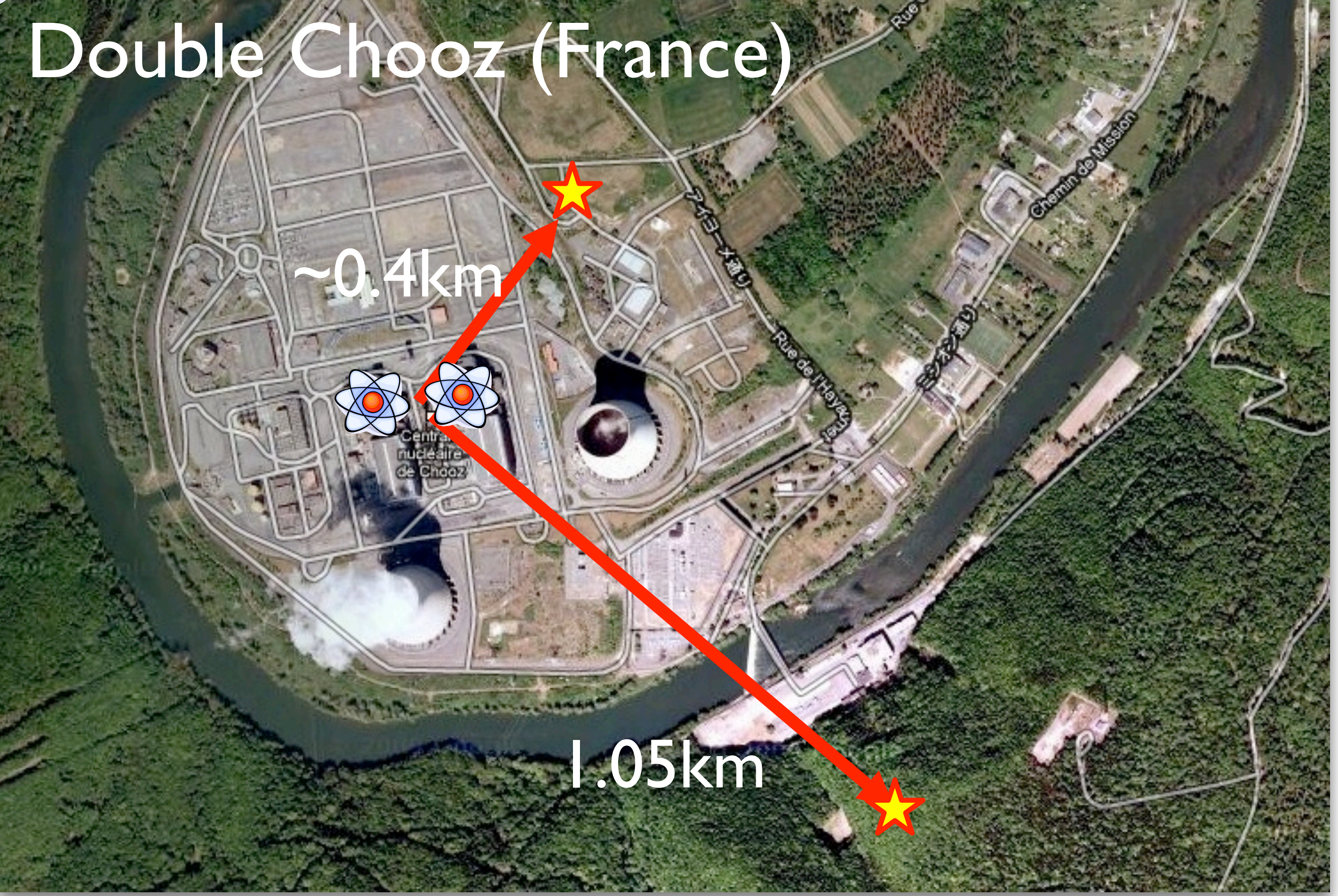
# High Precision Measurement of θ13

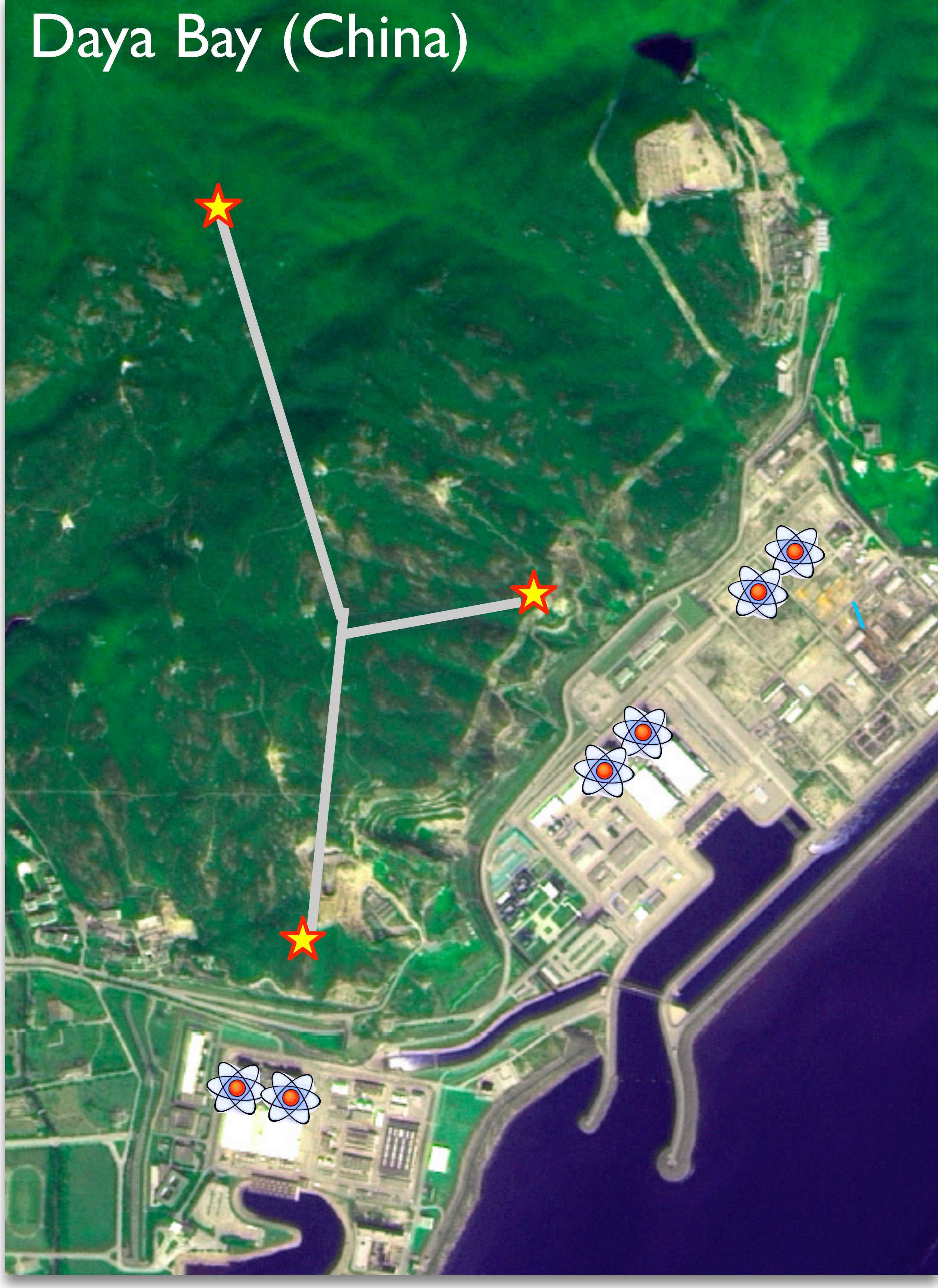
$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$





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


Double Chooz (France)
~0.4km
1.05km


Daya Bay (China)


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

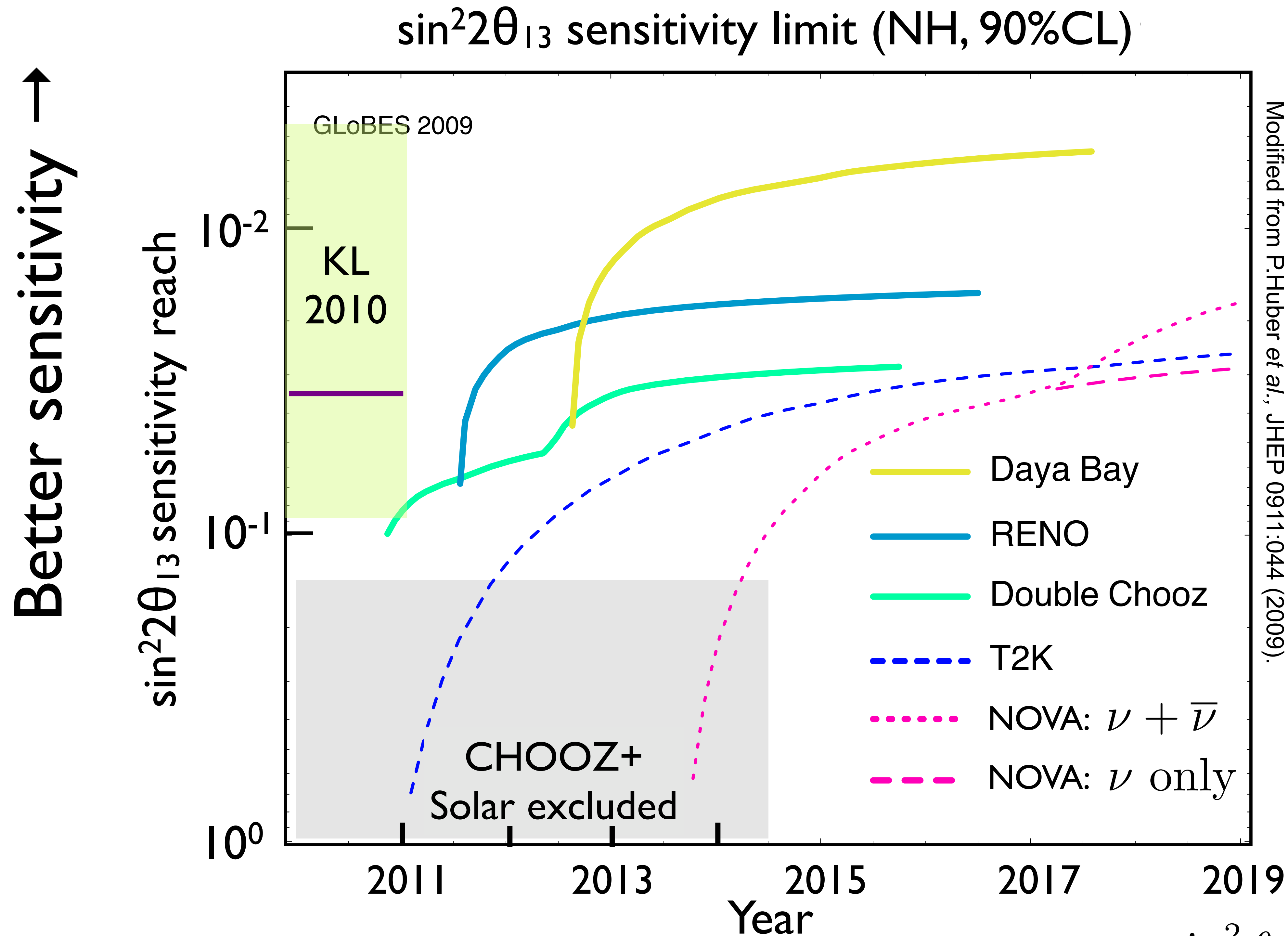
# Future Reactor $\theta_{13}$ Experiments

| | 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<br>481 | 1985<br>1613 | 0.4/0.2<br>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




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

Reactor experiments will find or put best limit on $\theta_{13}$

# Geoneutrino Results

# Deconstructing Earth

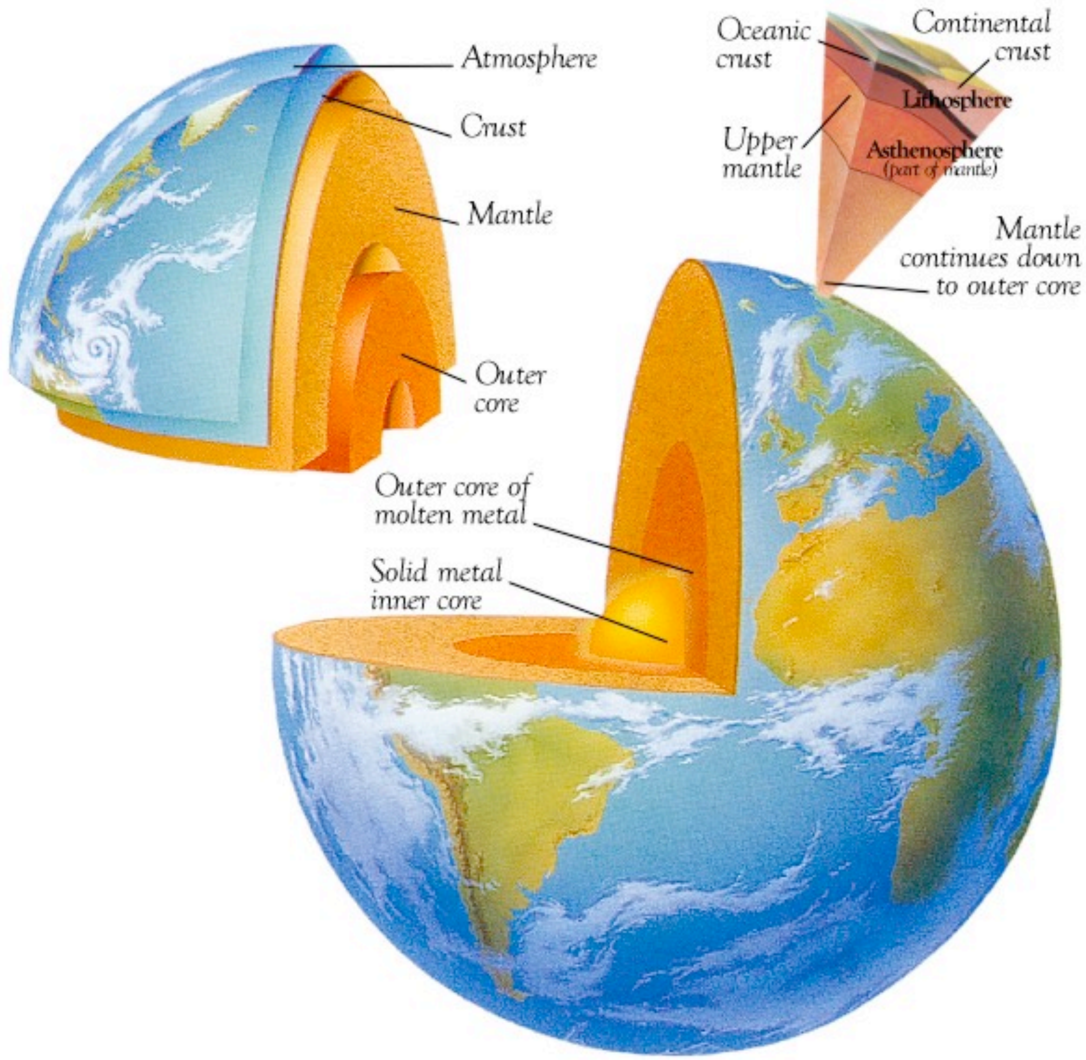
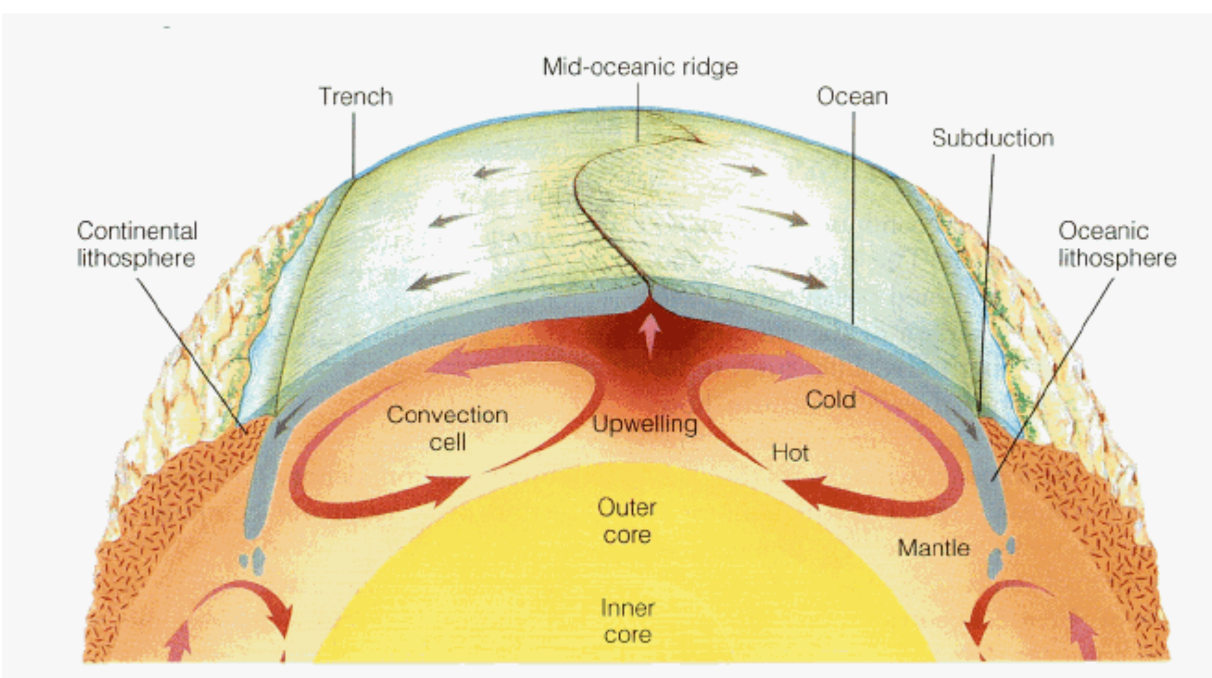



Image by C. Rose and D. Kindersley

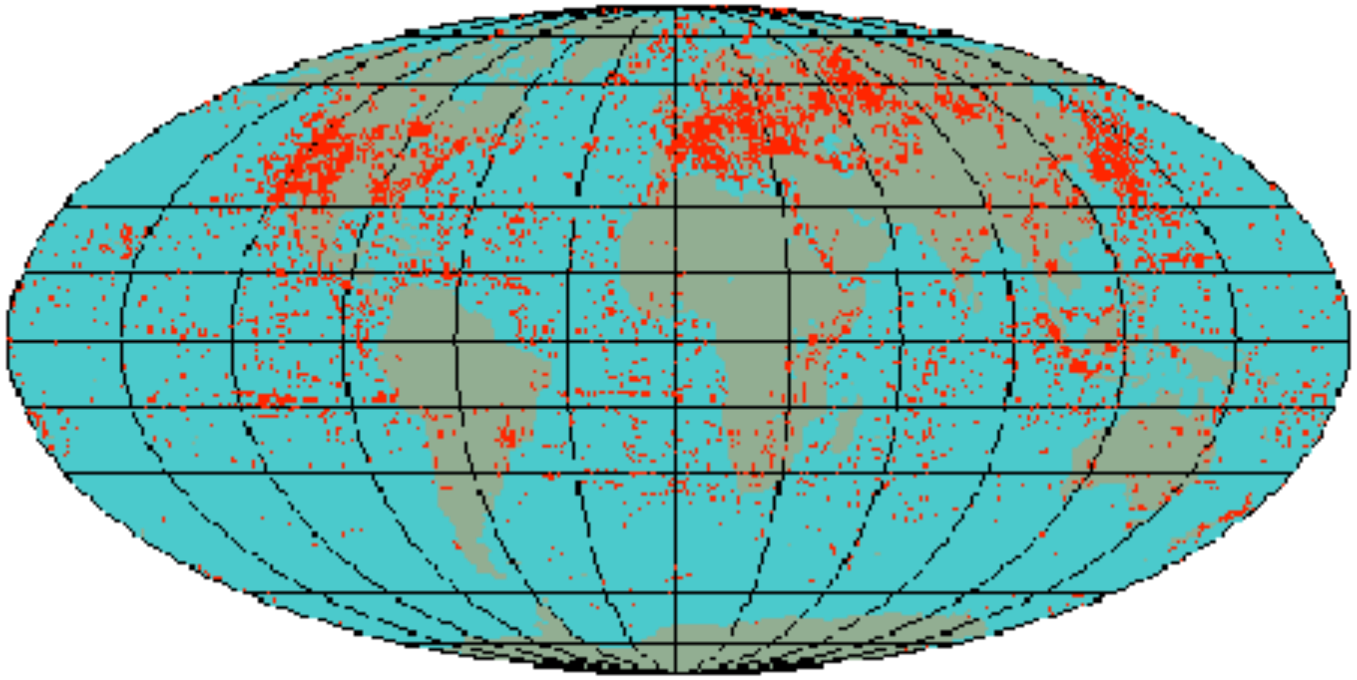



- Earth is subdivided into basic regions:
  - Inner Core
  - Outer Core
  - Lower Mantle
  - Upper Mantle
  - Continental / Oceanic crust
- These regions are solid except for the outer core
- Oceanic crust is made at mid-oceanic ridge and recycled at continental trenches

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

# Earth's Heat Flow

Bore hole locations:



Heat Flow:

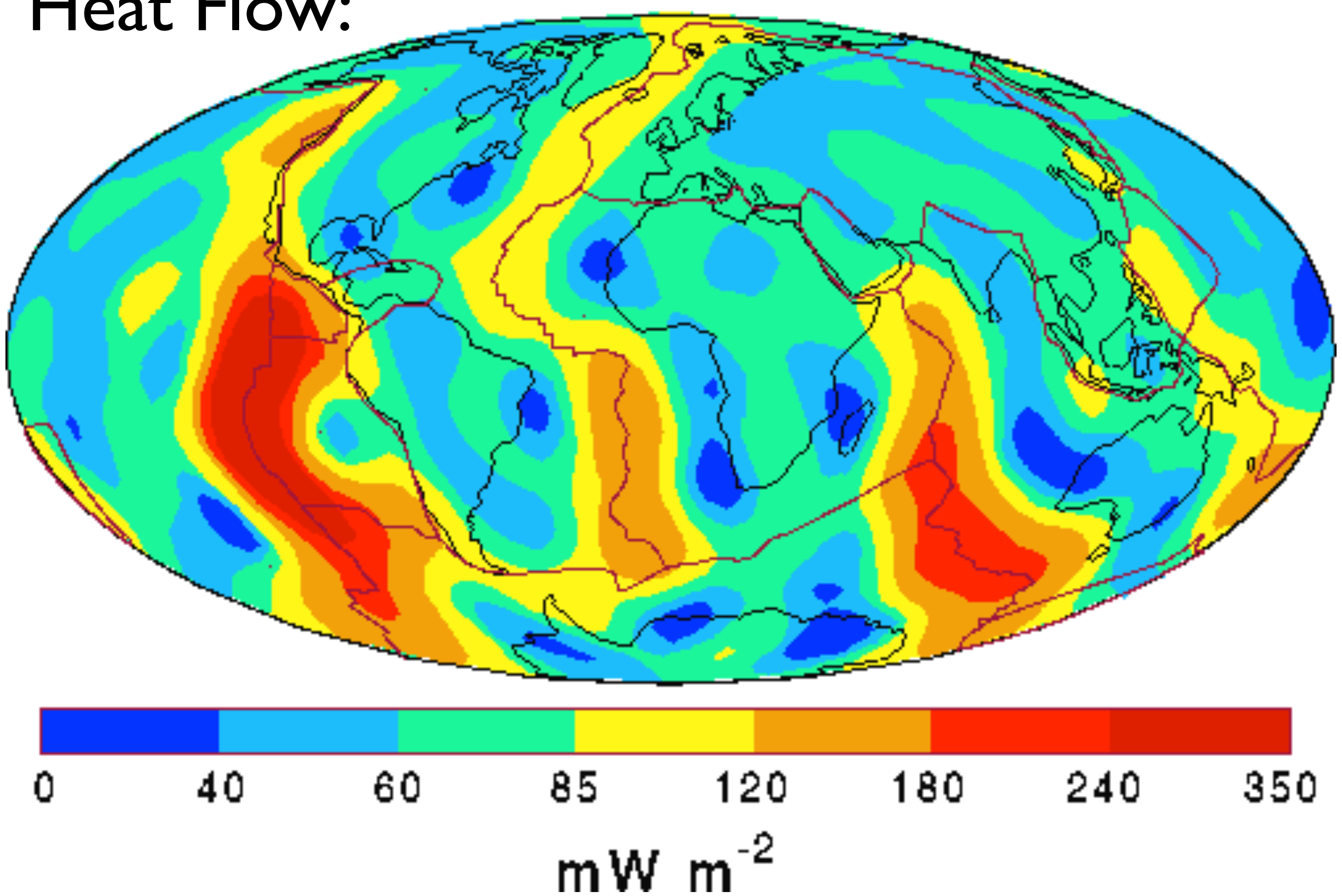



Image from Pollack et al.

- 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 |

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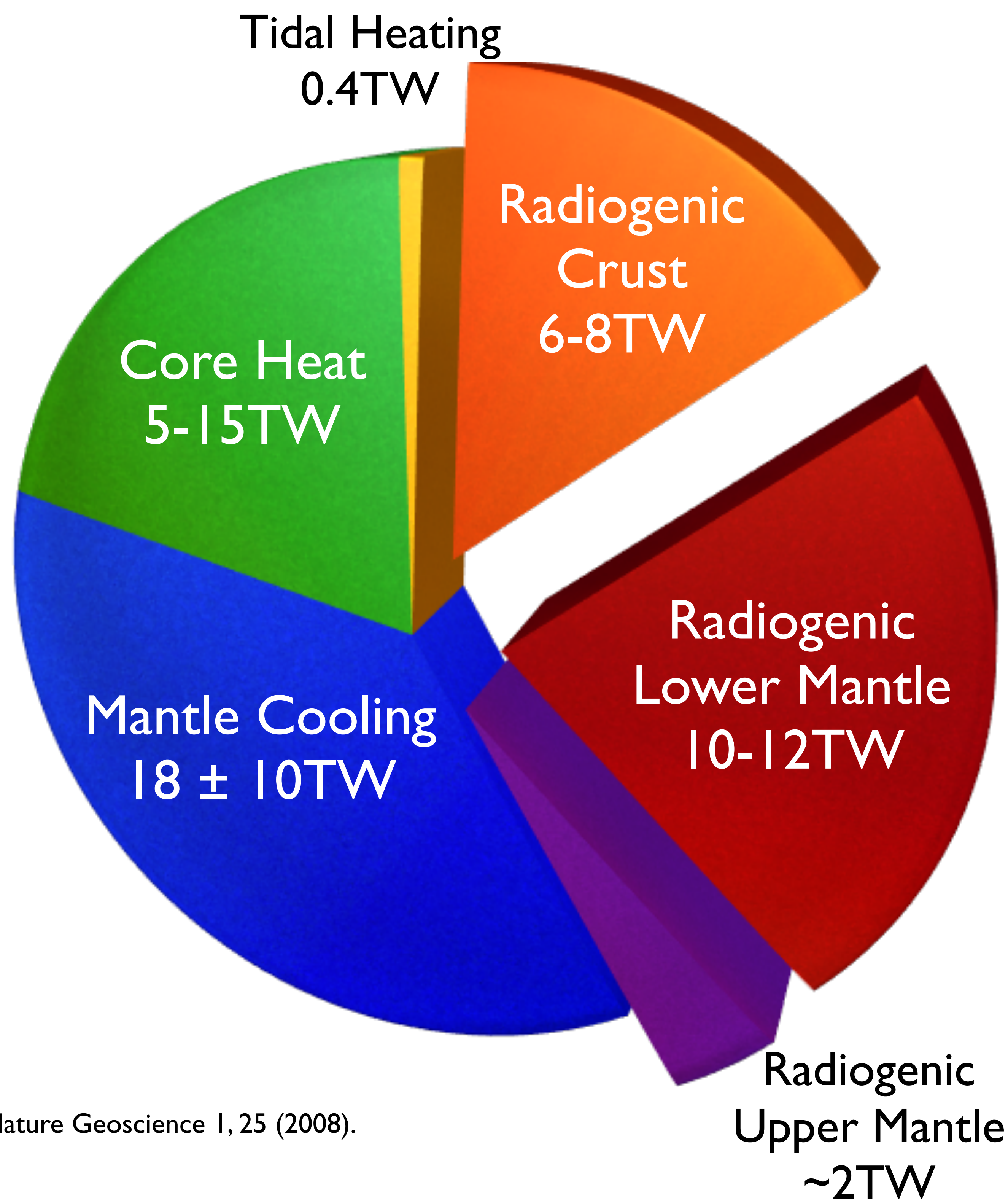
# Where does the 46 ± 3 TW come from?

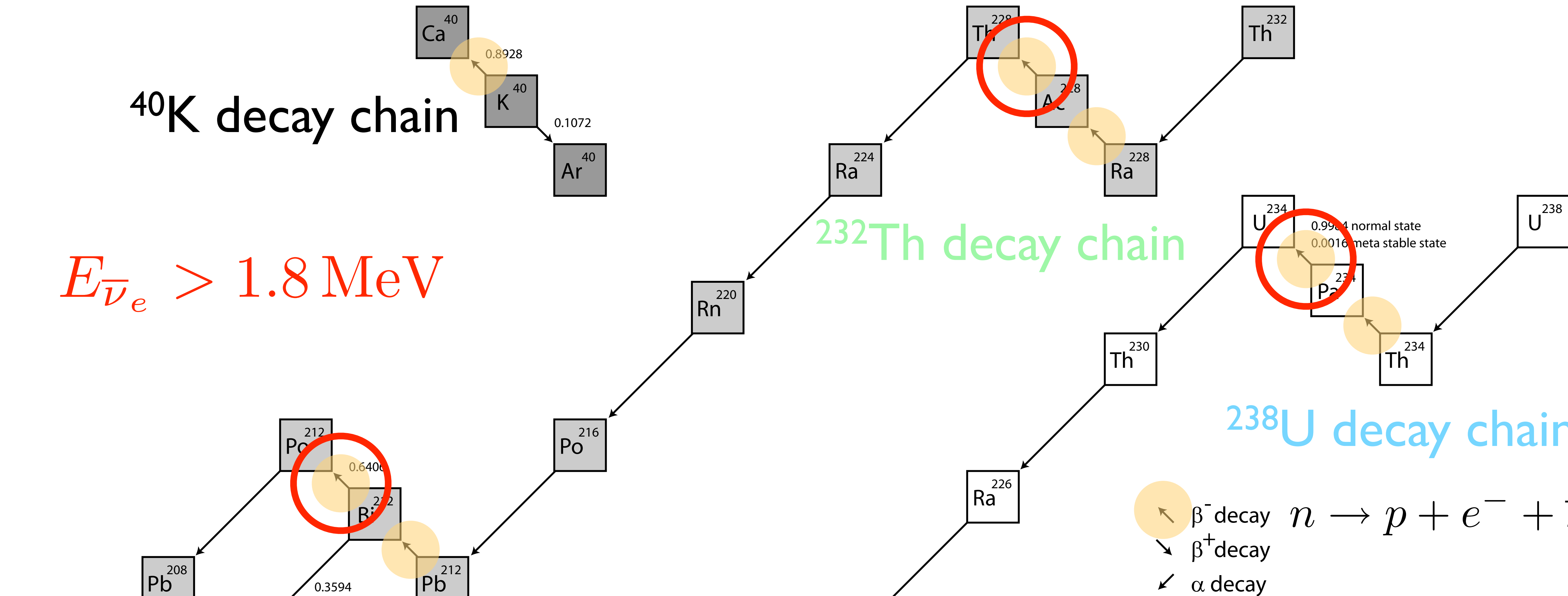


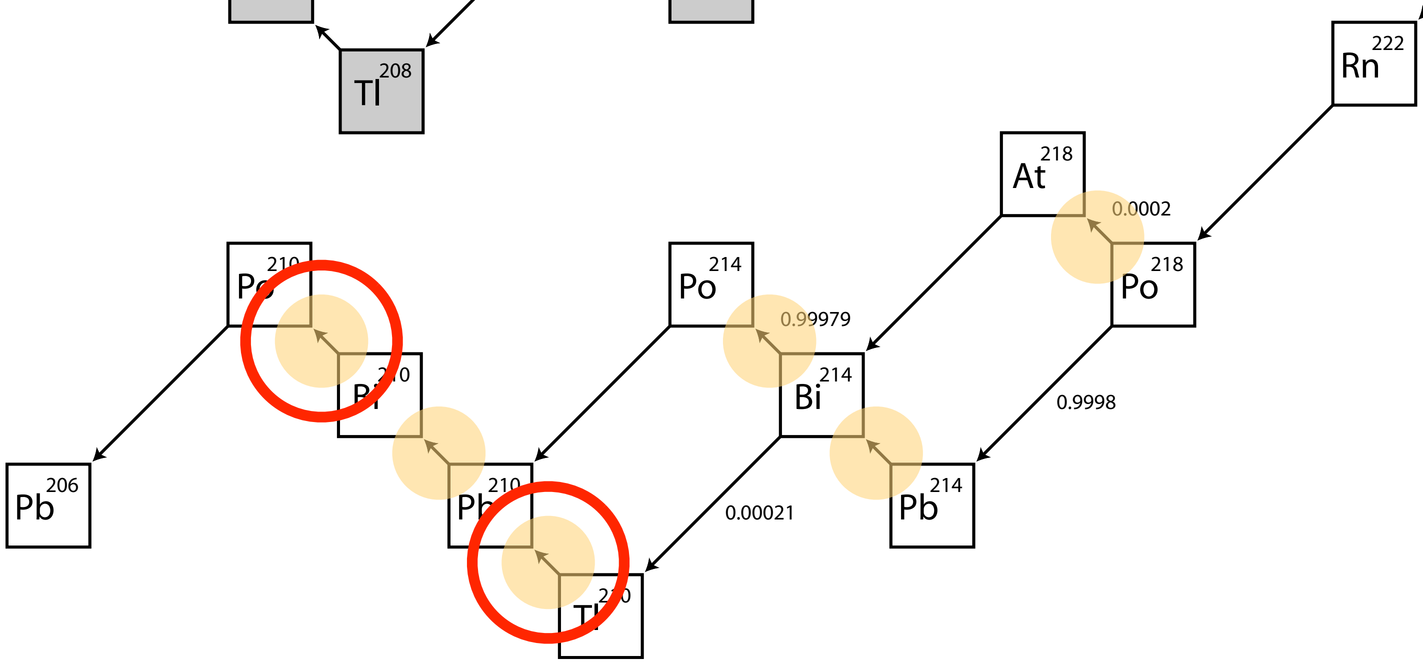

Estimate of Radiogenic Heat:
20 ± 3 TW

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

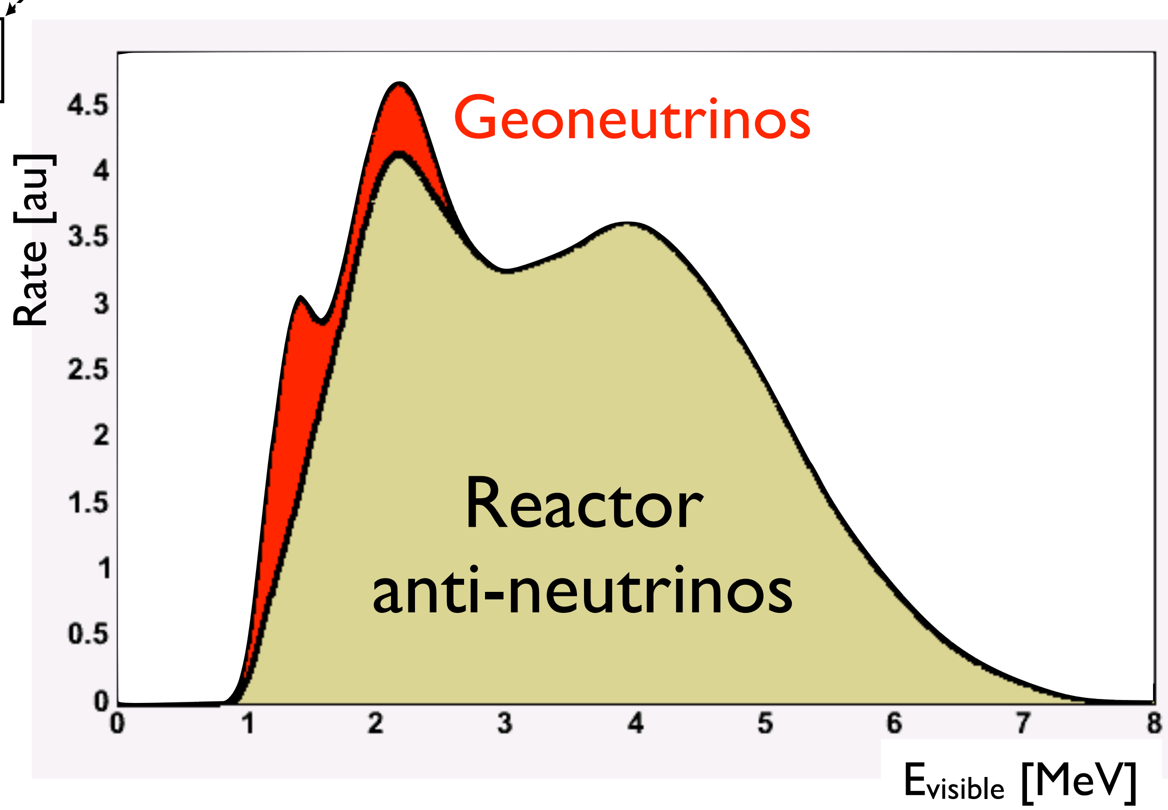
# Producing Geoneutrinos

$$E_{\overline{\nu}_e} > 1.8\,\mathrm{MeV}$$



β⁻ decay $n \longrightarrow p + e^- + \overline{\nu}_e$
β⁺ decay
α decay

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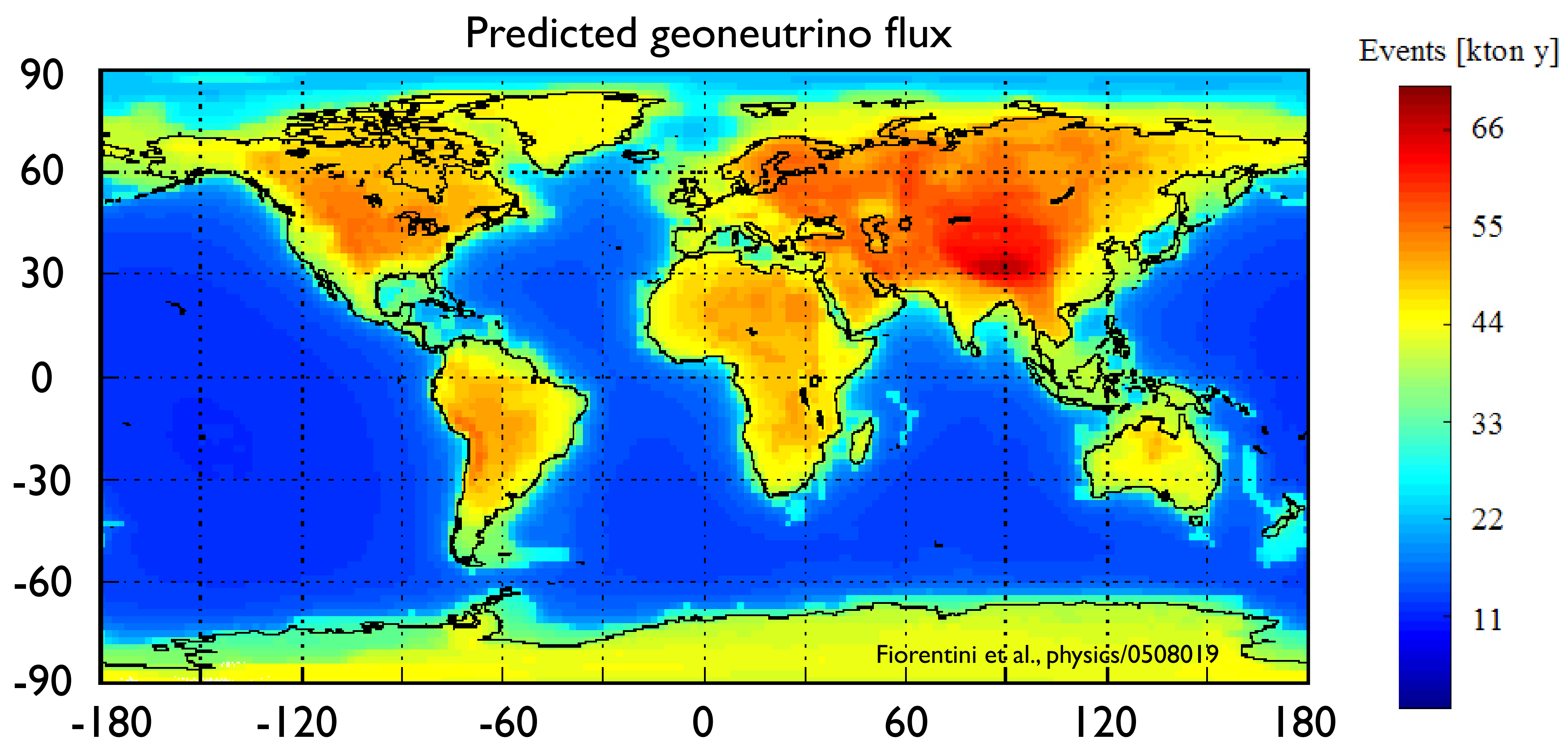
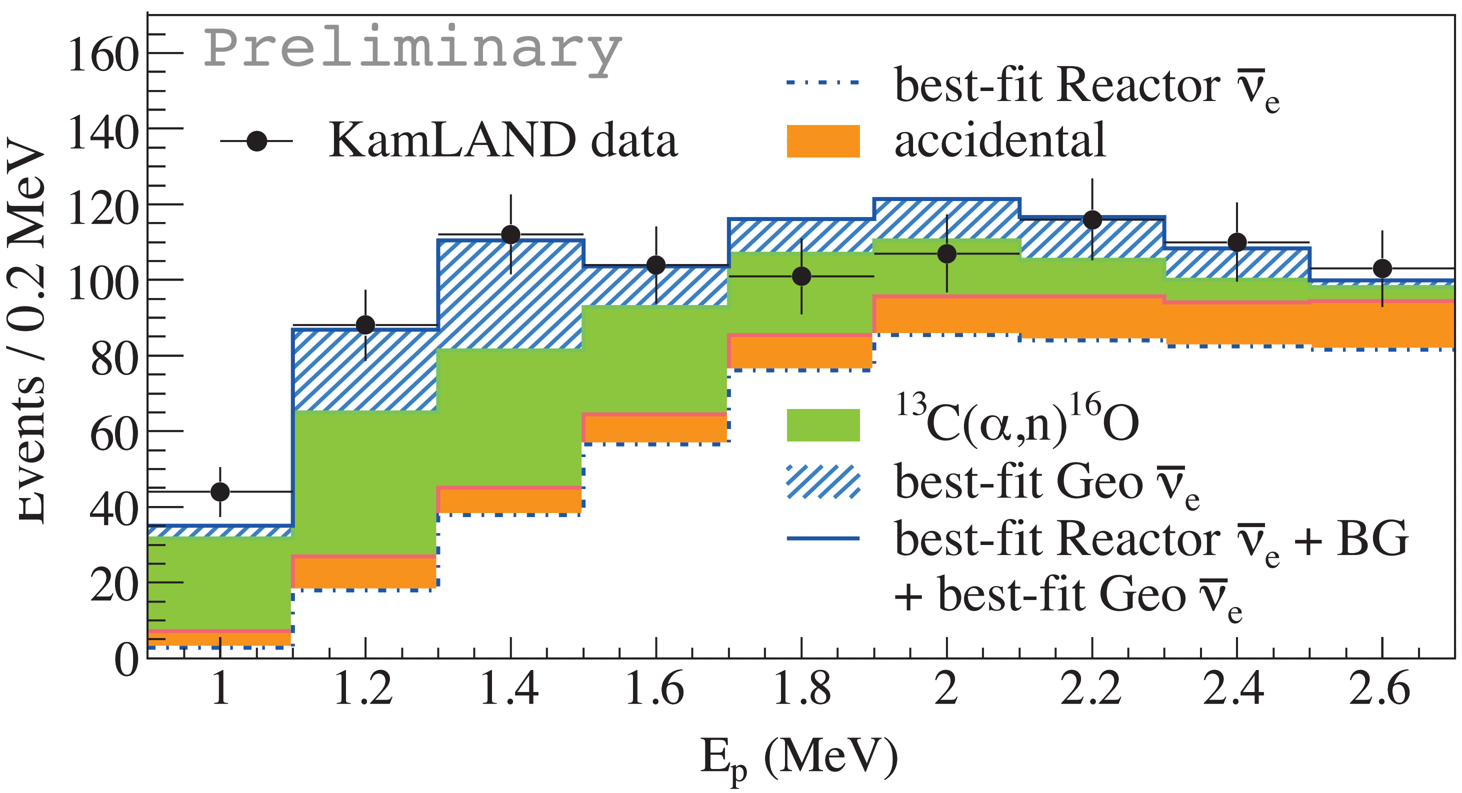
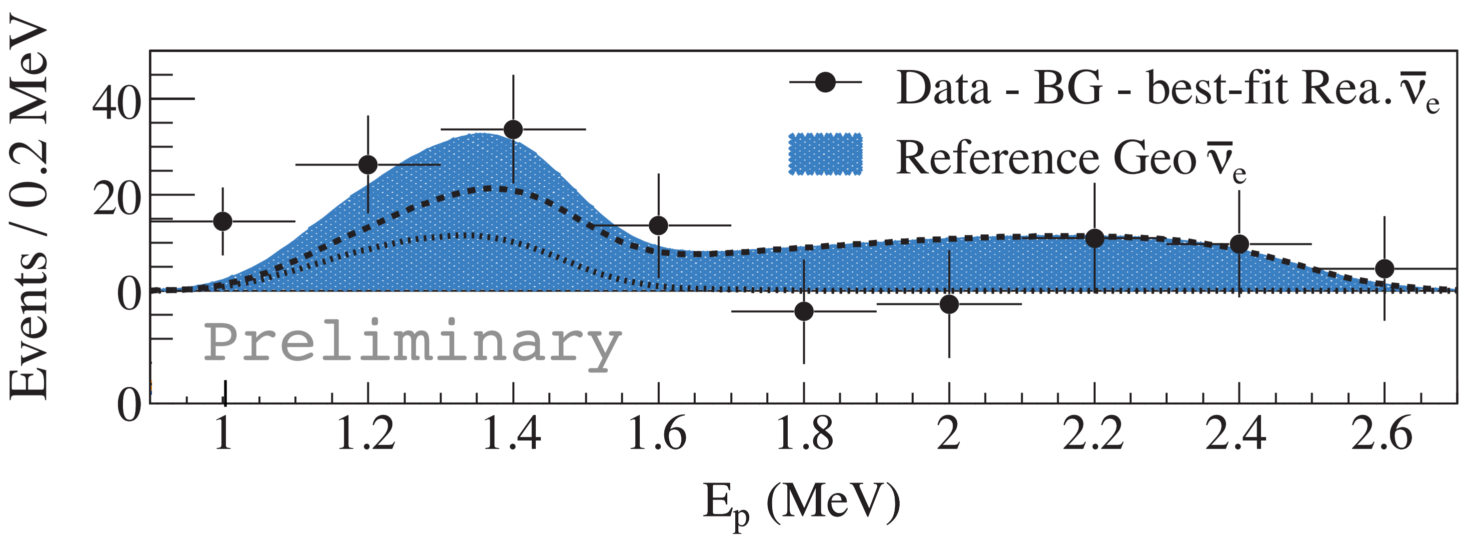
# Reference Model



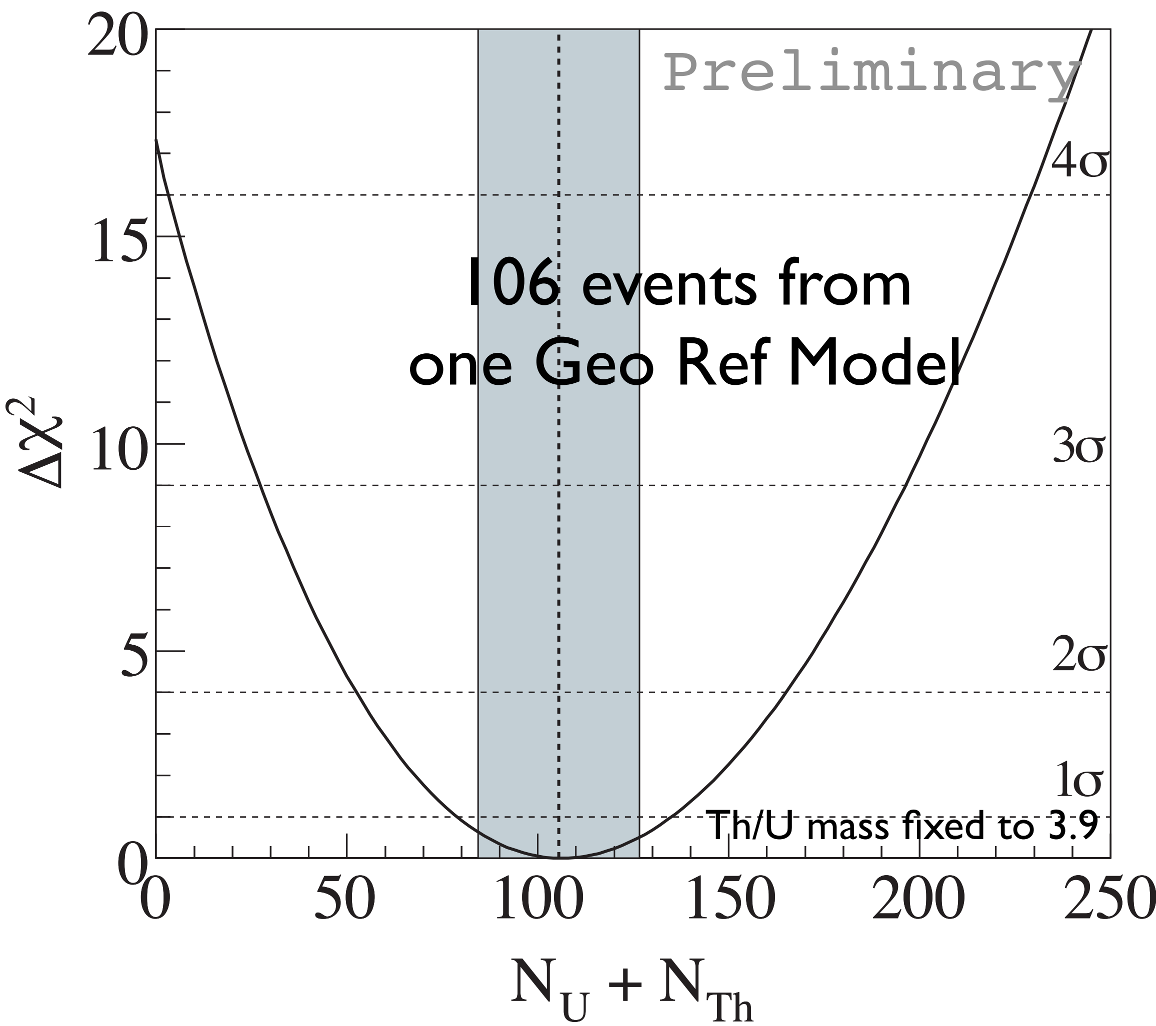

Sun shines in neutrinos - the Earth in anti-neutrinos

# Indications from KamLAND...




111 ± 44 events in 4126 ton-year

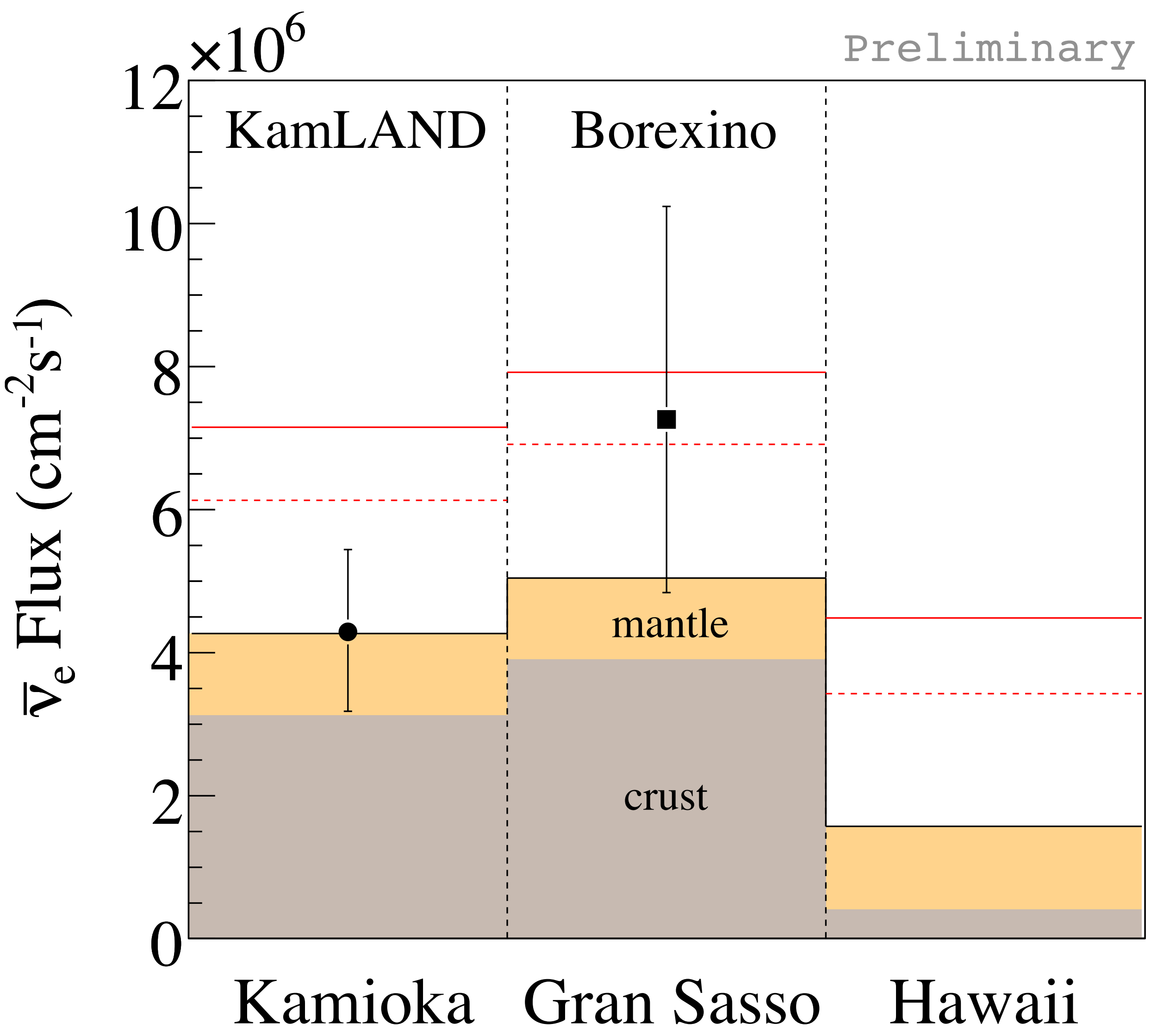


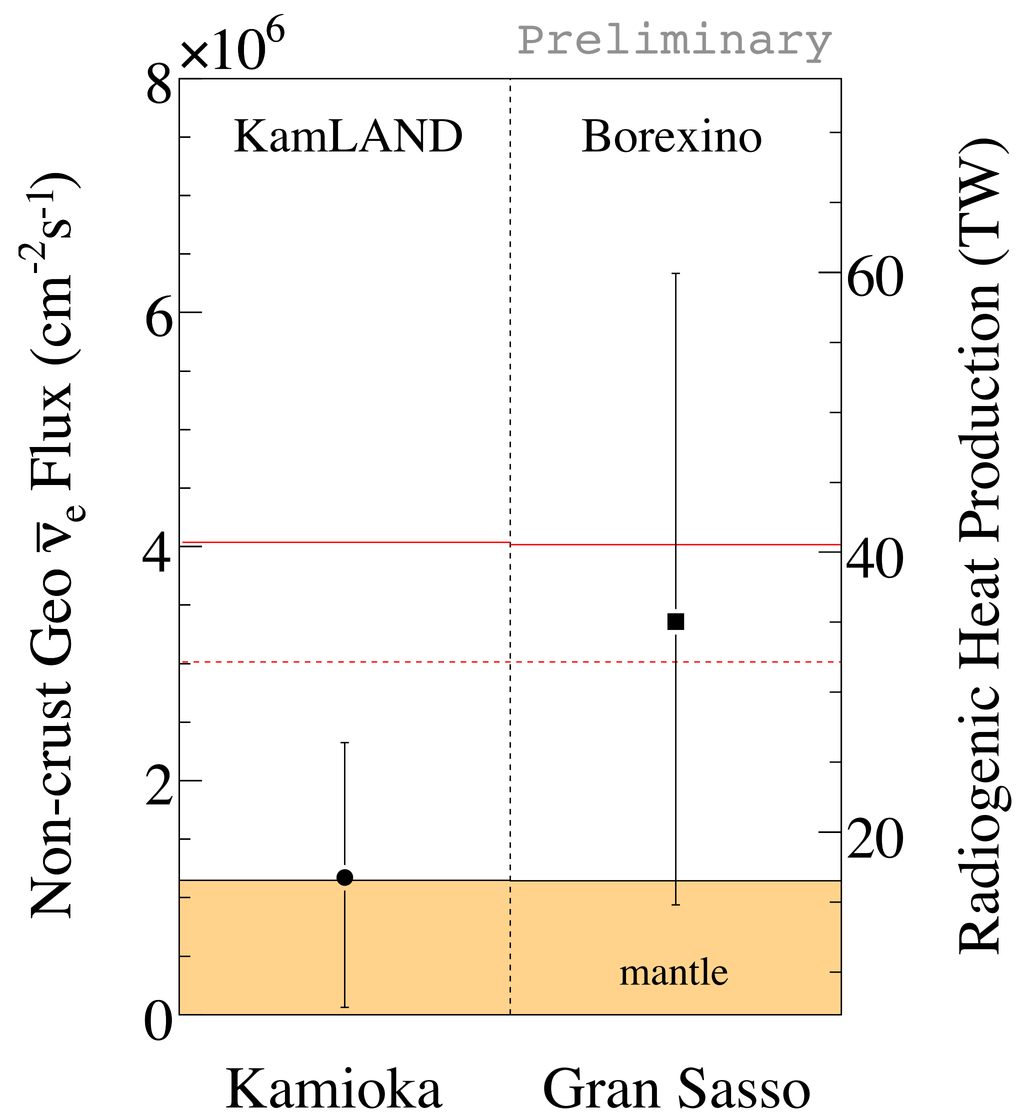

Recent report from Borexino: $9.9^{+4.1}_{-3.4}$ events in 253 ton-yr [Phys.Lett.B687:299-304,2010]

*Patrick Decowski / Nikhef*

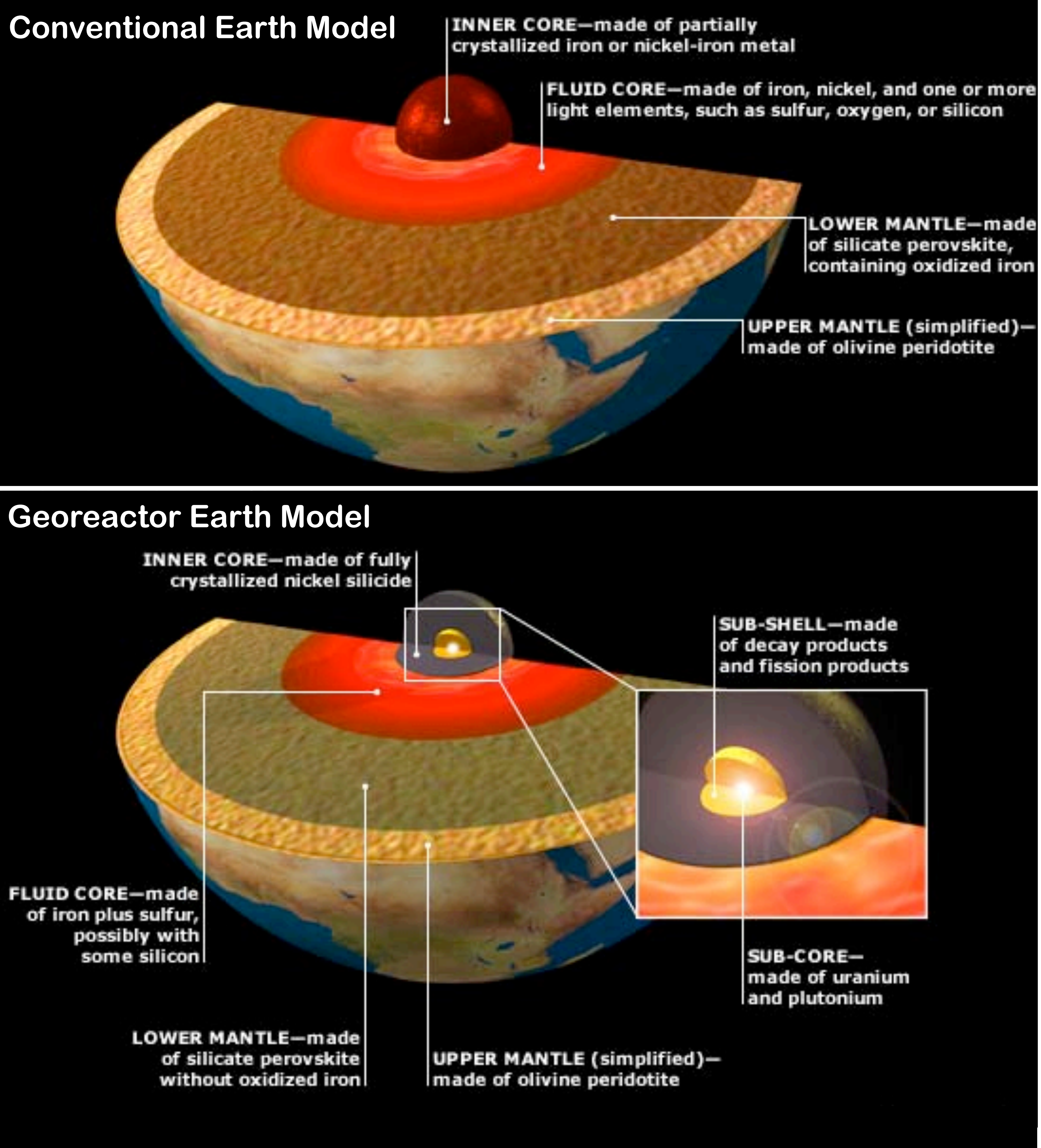
# Multi-site Measurements of Geo-νs

Crust contribution varies locally: multi-site measurements




Start to probe various models for radiogenic heat production

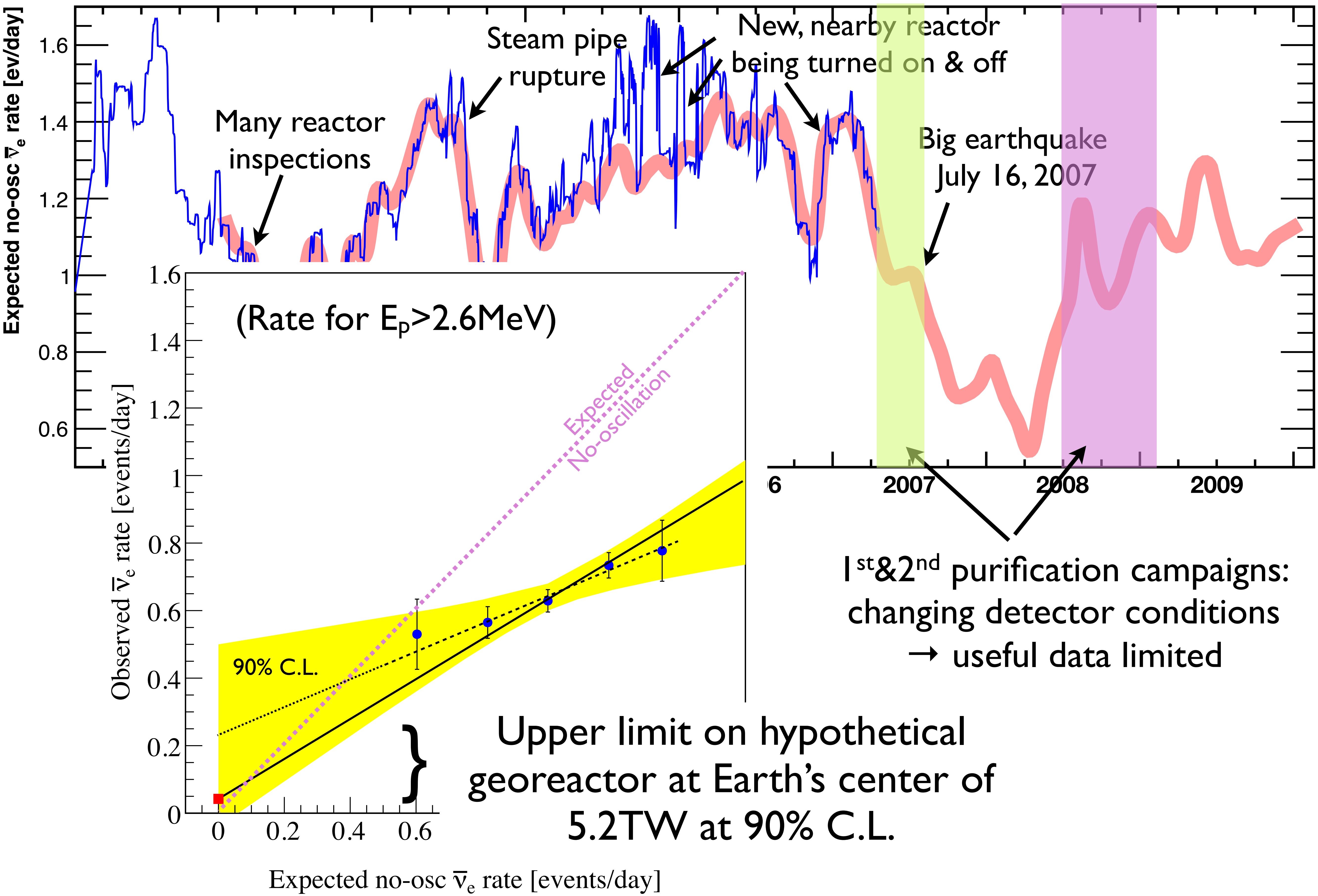



By Matt Zang, Discover Mag, Aug. 2002.

- Georeactor definitely not mainstream theory
- Primarily motivated by the observation that the $^3He/^4He$ 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




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

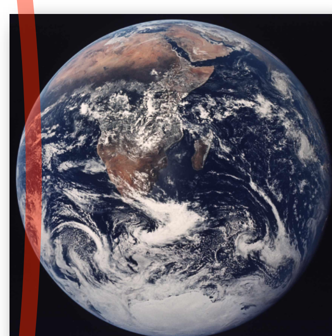
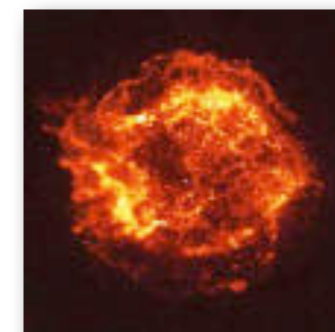
Upper limit on hypothetical georeactor at Earth's center of 5.2TW at 90% C.L.

# KamLAND Physics Capabilities

0.4 — 1.0 — 2.6 — 8.5 — Energy [MeV]

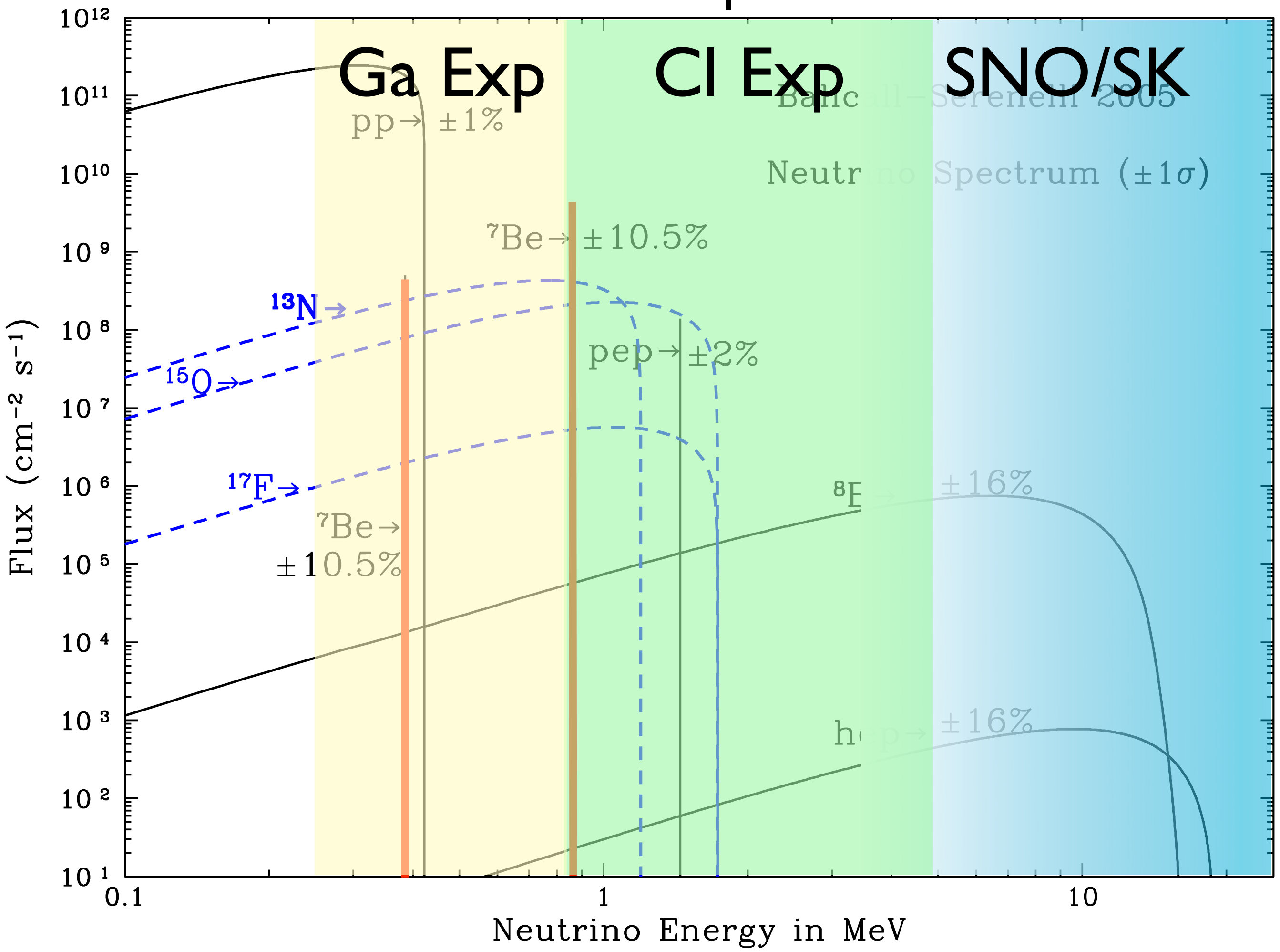
neutrino electron elastic scattering
$\nu + e^- \rightarrow \nu + e^-$

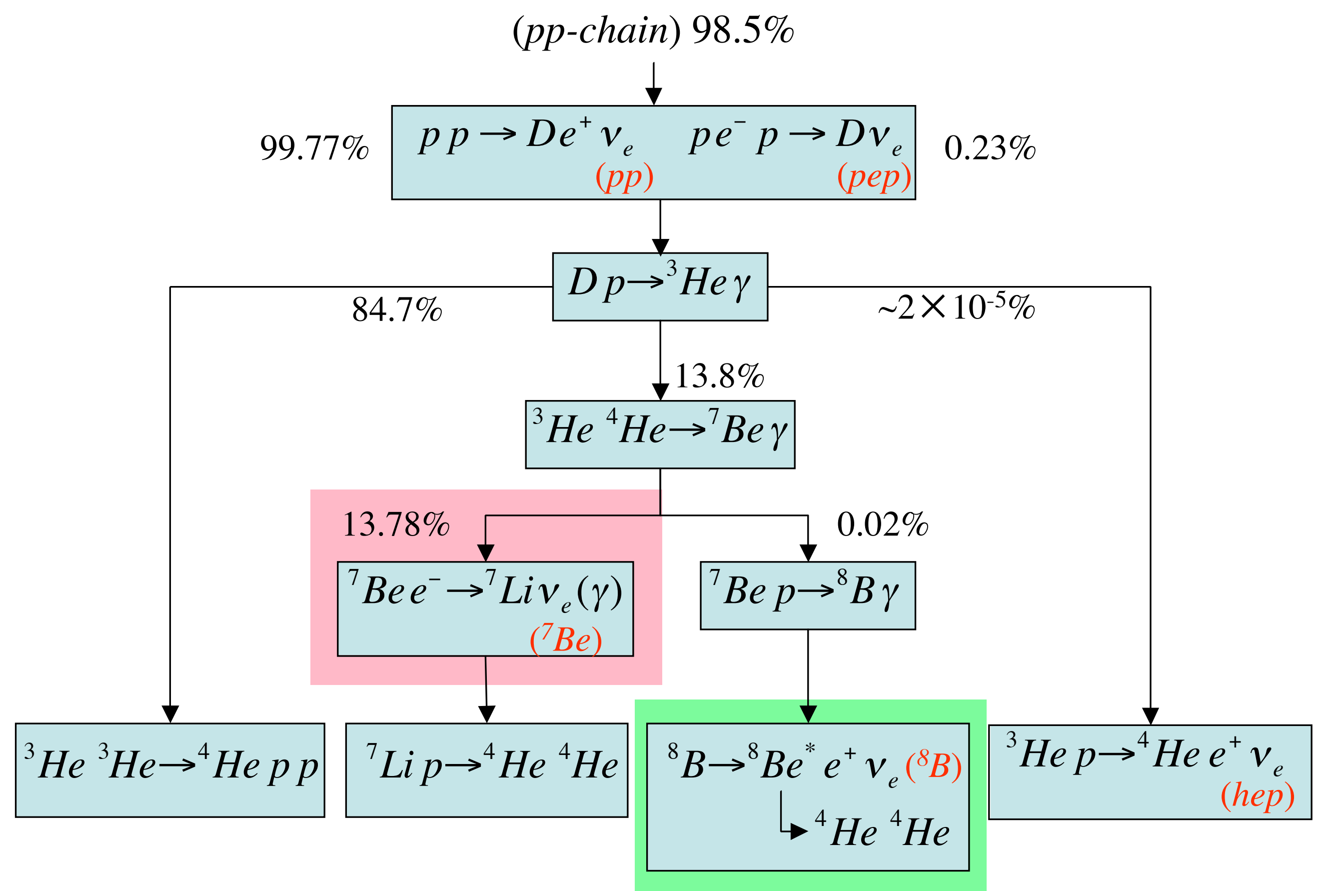
inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

| Neutrino Astrophysics | Neutrino Geophysics | Neutrino Physics | Neutrino Cosmology |
|---|---|---|---|
|  |  |  |  |
| solar neutrino | geo-neutrino | reactor neutrino | supernova, relic neutrino, solar anti-neutrinos etc. |
| Verification of SSM | Study of earth heat model | Precision measurement of oscillation parameters | Verification of universe evolution, neutrino magnetic moment |

# Testing Standard Solar Model

Solar Neutrino Spectrum




$^7$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

# Solar Measurements

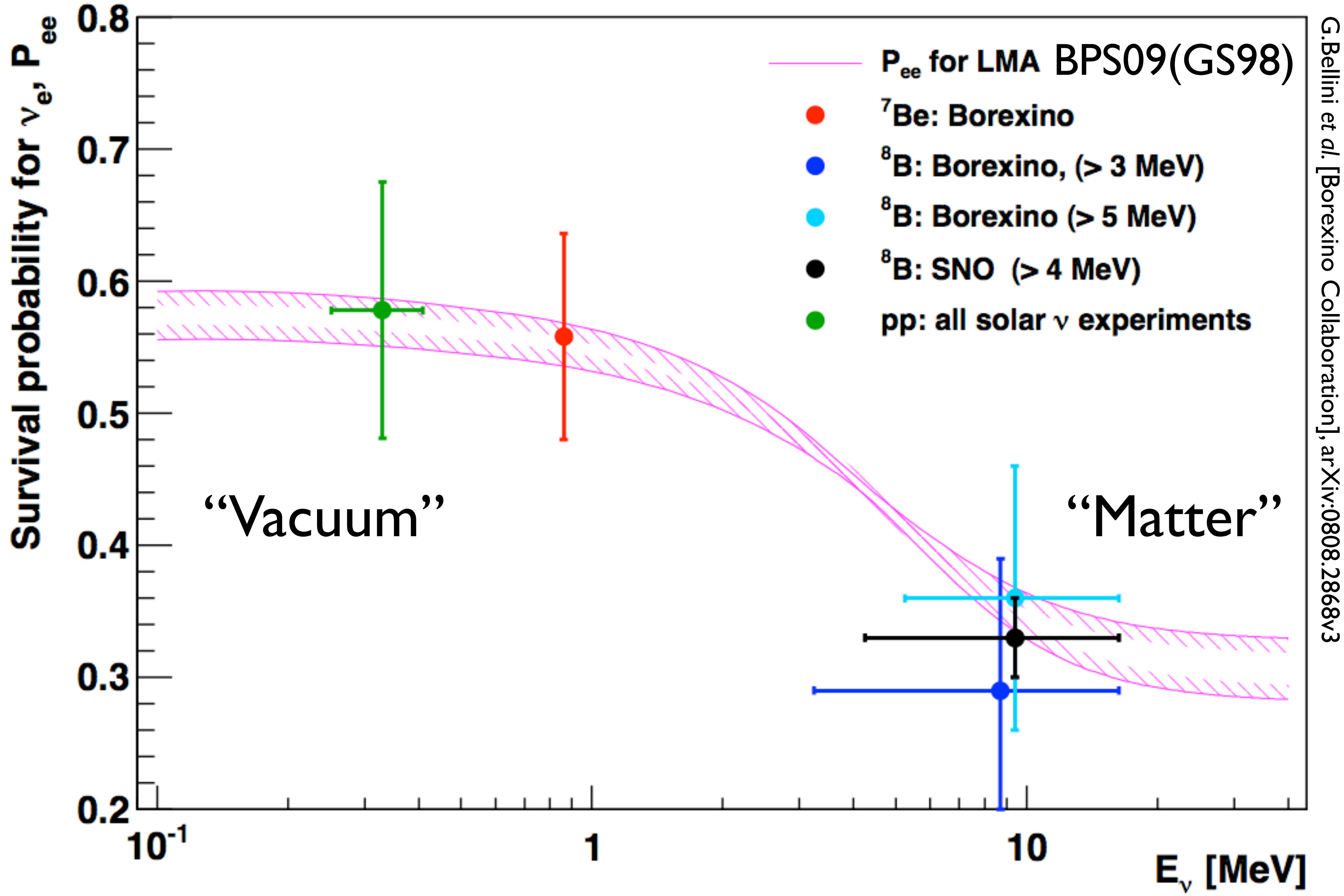
- Precision measurements: detailed comparisons between measurements and models
- Accurate measurement of pp(1%) and $^7$Be(5%) neutrinos allows the calculation of neutrino-inferred solar luminosity to ~1%:

neutrinos:
photons:

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

# Probability Transition Region

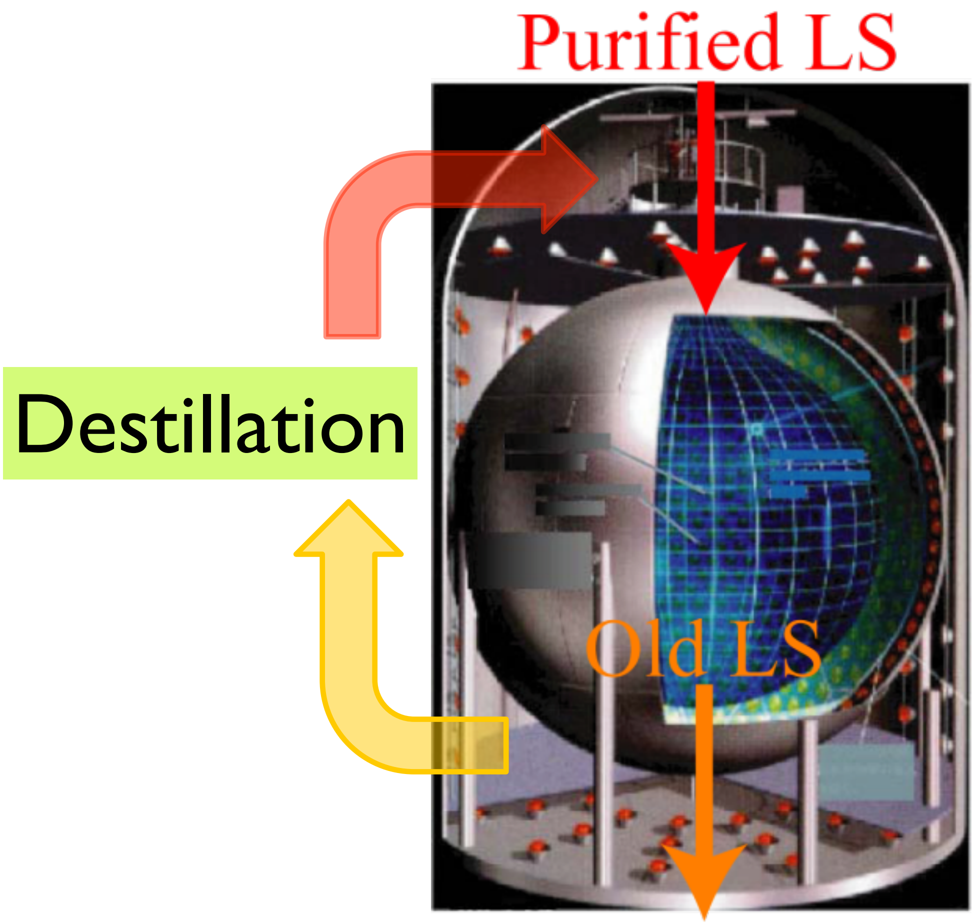
Solar neutrino survival probability



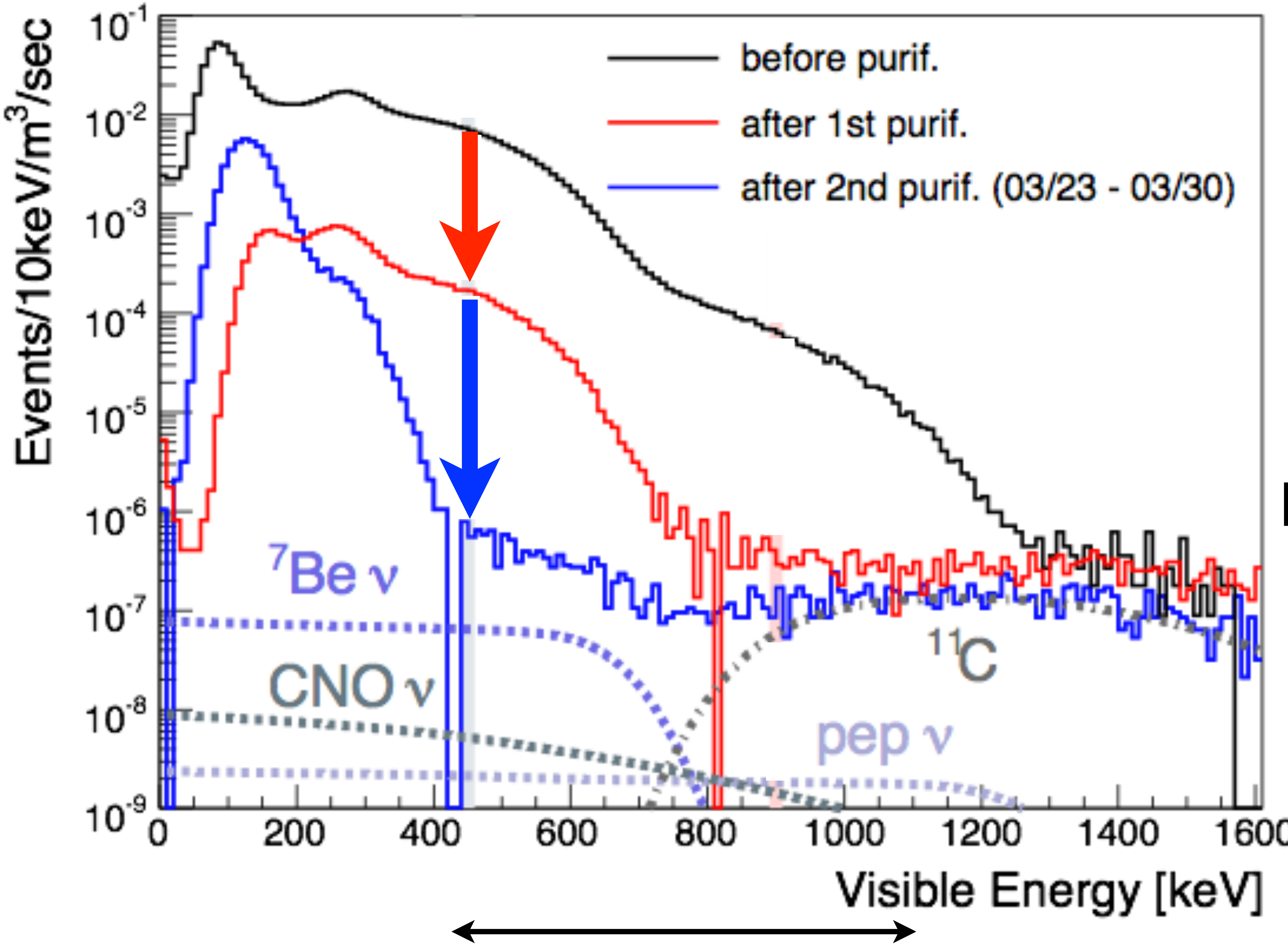

Current experiments are probing the interesting region from "vacuum oscillations" to "matter oscillations" in the Sun

# 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

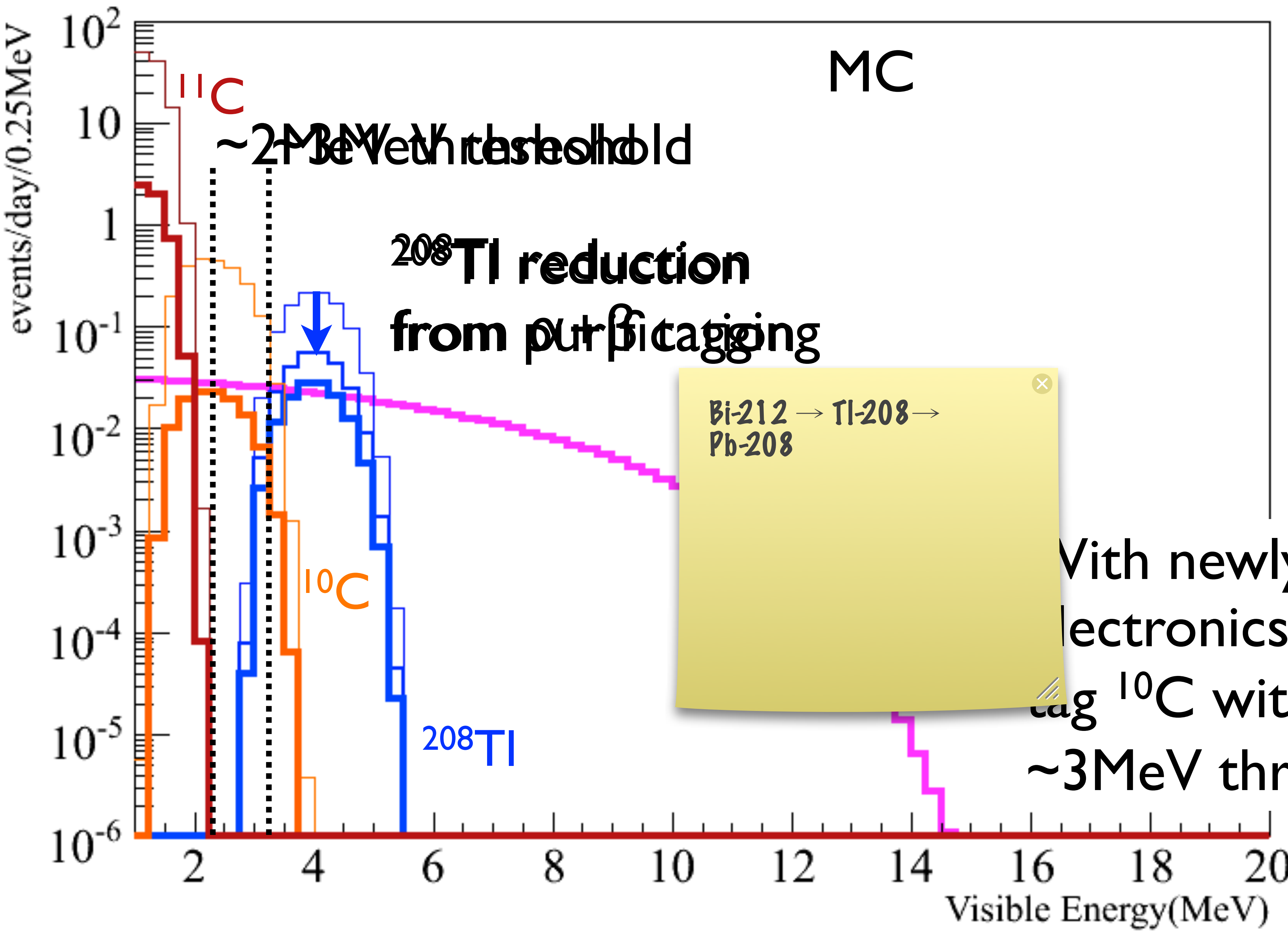



Only 7days of data, shortly after end of purification

Large reduction of backgrounds

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

# Low-threshold solar $^{8}B$ measurement

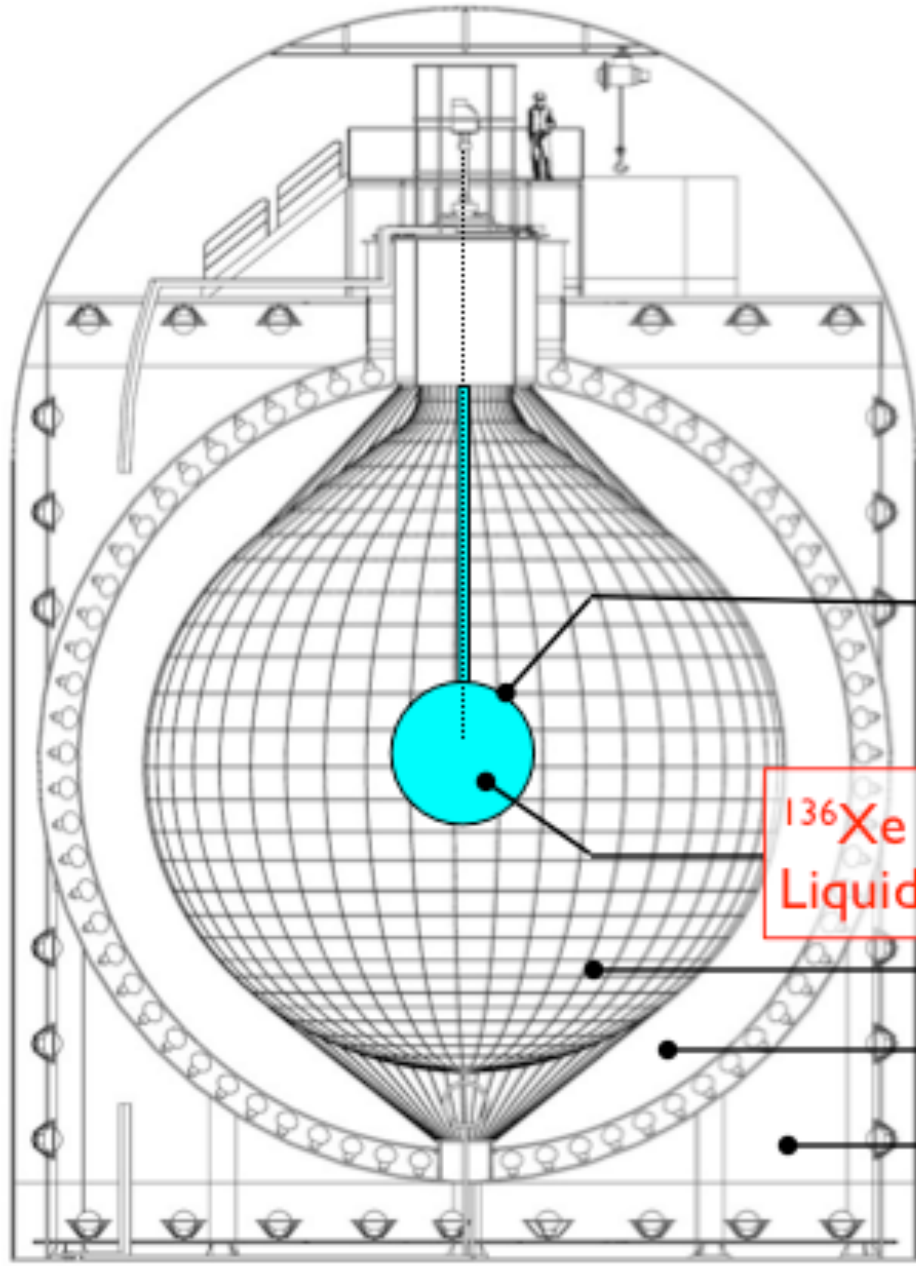



With newly installed electronics, should be able to tag $^{10}C$ with multiple n after μ
~3MeV threshold → ~2MeV

(Main background for geo-neutrino measurement removed)

# KamLAND Future: 0ν2β

400kg of $^{136}$Xe
in secondary balloon



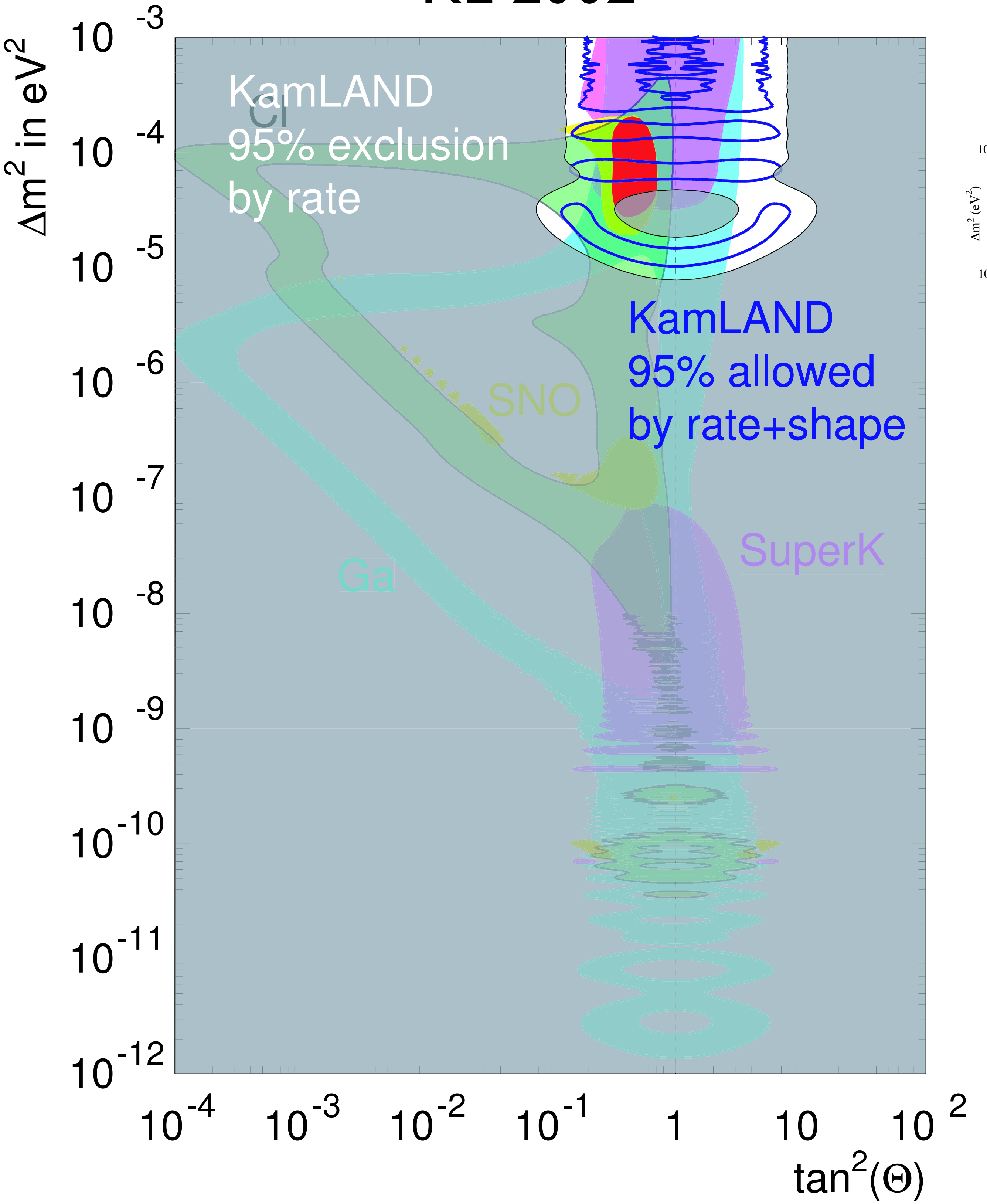

Japanese collaborators have secured funding for KamLAND 0ν2β
End of KamLAND as-we-know-it in April 2011

# Summary

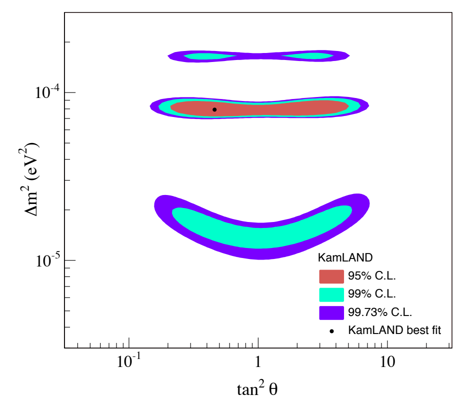
- Era of precision measurements of neutrino oscillation parameters
  - Hard to further improve $\Delta m_{12}^2$
  - Next goal: $\theta_{13}$ to better than 1%
- Start of answering geological questions with neutrino science
- KamLAND's low background phase running
  - Solar $^{7}Be$ and low energy threshold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

# Precision Neutrino Measurements

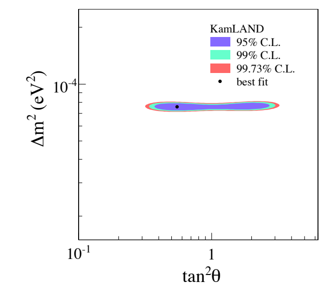
## KL 2002



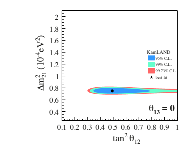

## KL 2004




## KL 2008



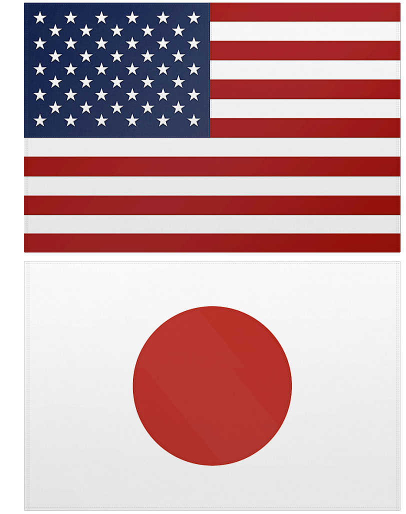

## KL 2010



Neutrino Oscillation:
A precision measurement!

*Patrick Decowski / Nikhef*

# 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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[12]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA and Physics Departments at Duke University, North Carolina Central University, and the University of North Carolina at Chapel Hill*
[13]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA*
[14]*CEN Bordeaux-Gradignan, IN2P3-CNRS and University Bordeaux I, F-33175 Gradignan Cedex, France*

# 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?

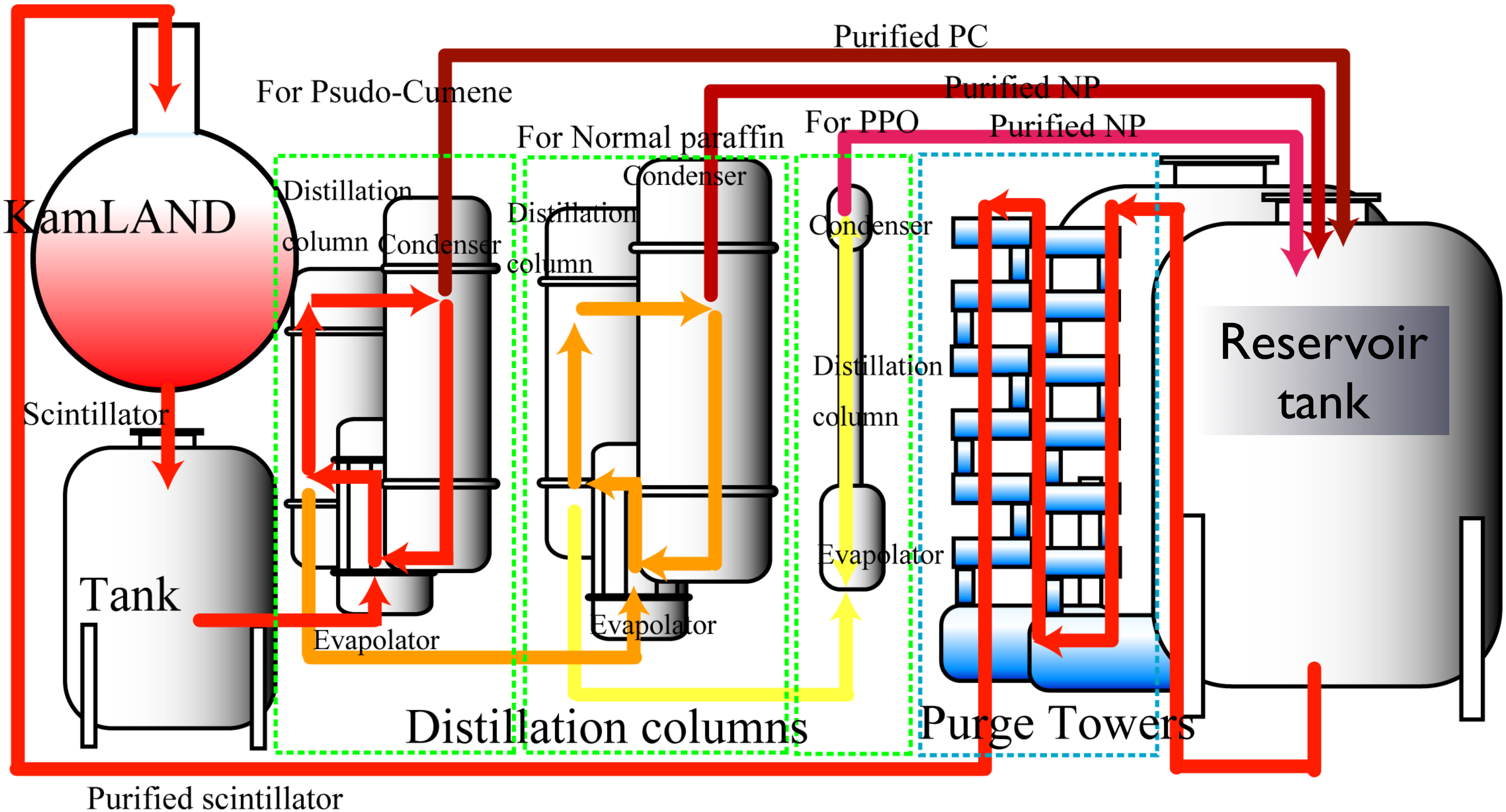
- Assume a test of a Hiroshima size bomb (~15kton TNT) or ~10 kg of fissile material
  - Larger bombs are detectable by other means
- Further assume:
  - All material is fully fissioned
  - Distance is ~1000km from KamL
  - Typical 3GW (thermal) reactor has a few tons of fissile material burned up in a cycle of ~18months → 10kg/day
- KamLAND measures anti-neutrinos from 55 ~3GW$_{th}$ reactors, at a rate of ~1 anti-neutrino/day at avg. distance of ~200km


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

Both were plutonium

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

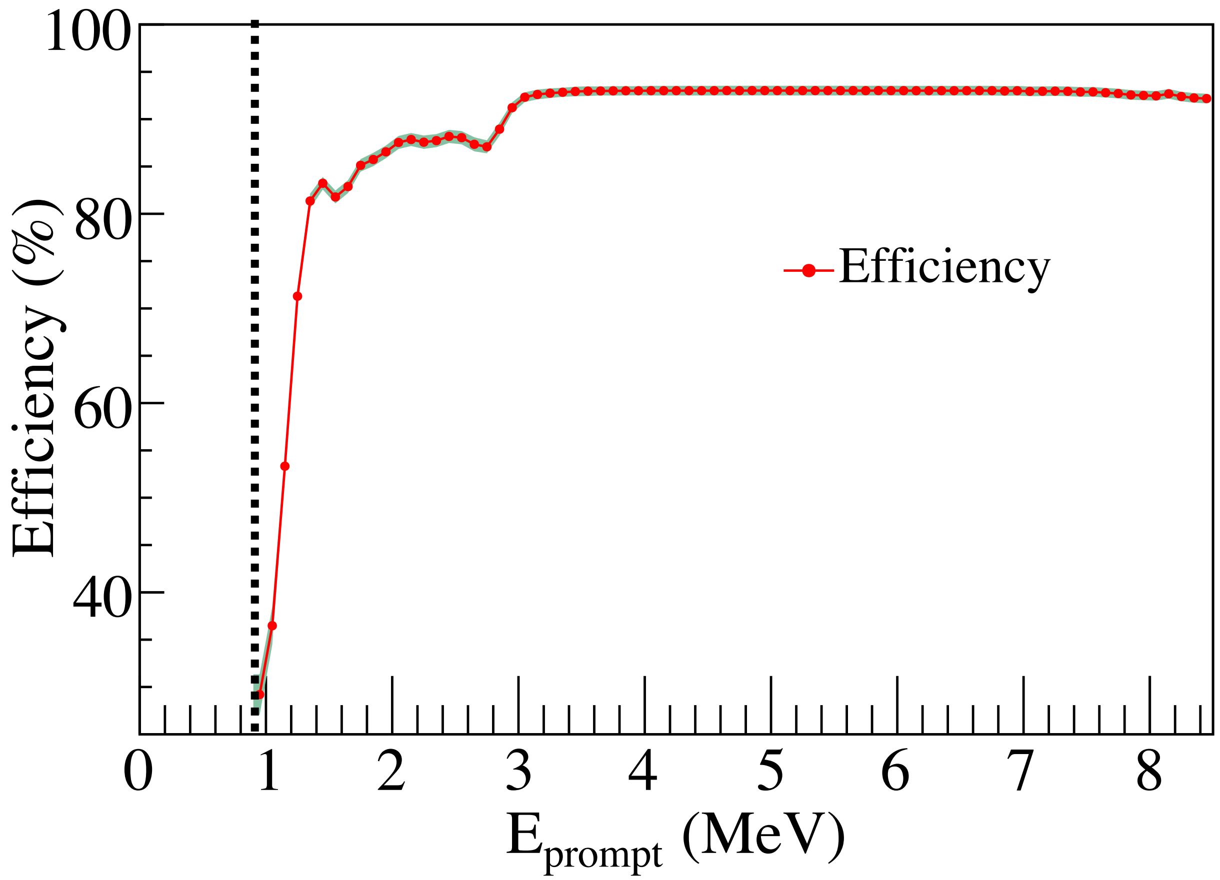
# Low Background Phase




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

$$FOM = \frac{S}{\sqrt{S + B_{acc}}} \longrightarrow L_{cut}$$

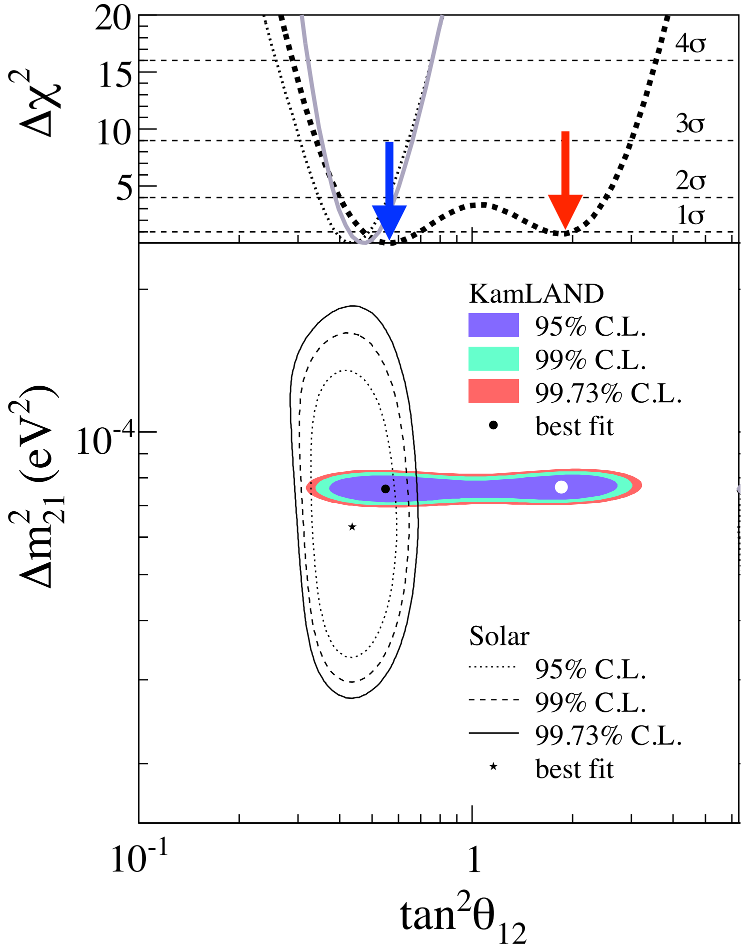
($E_p$ bins of 0.1MeV)

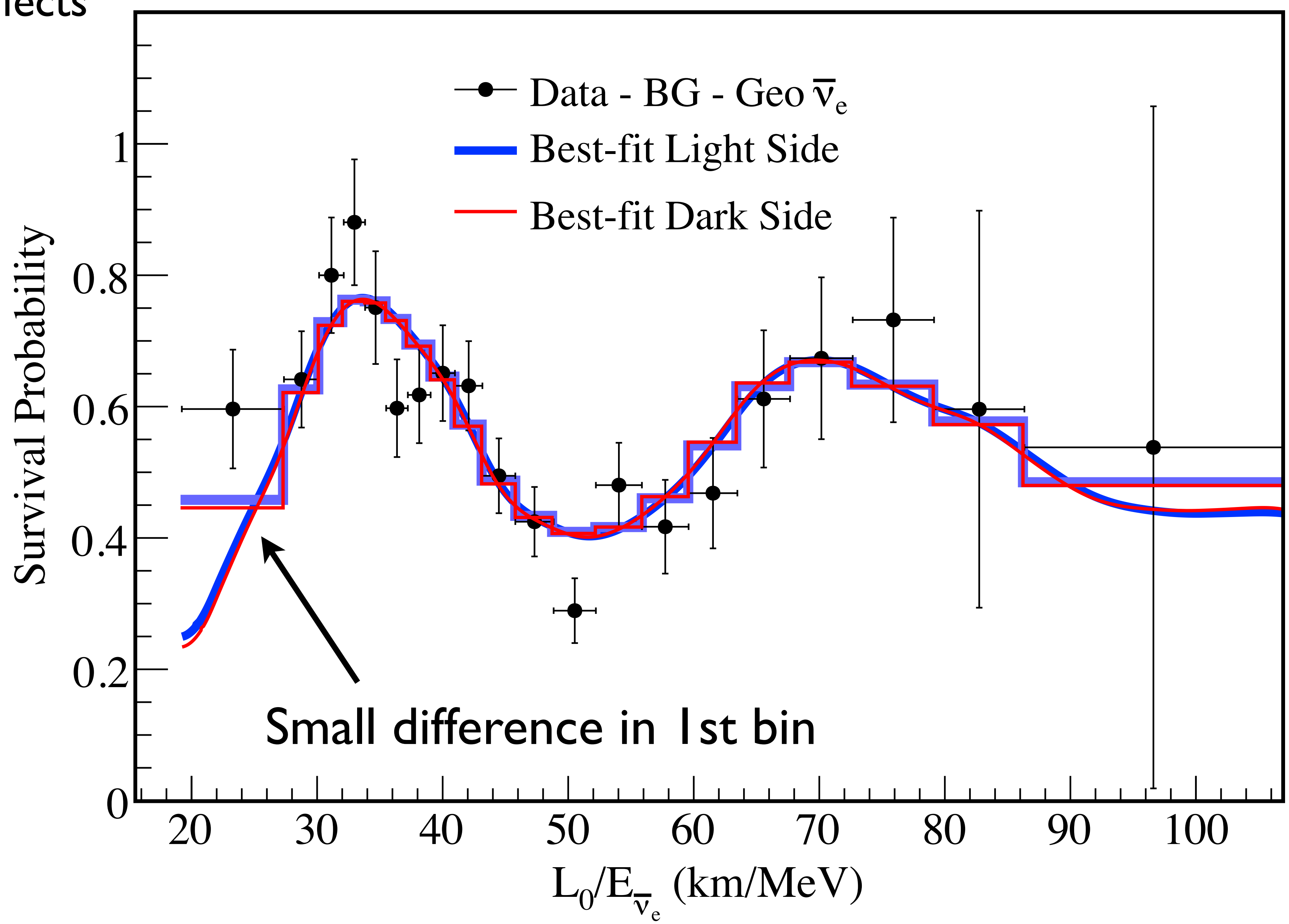
If for candidate event pair $L > L_{cut}$ → anti-neutrino

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

# Best-fit Light and Dark Side

Analysis includes Earth matter effects



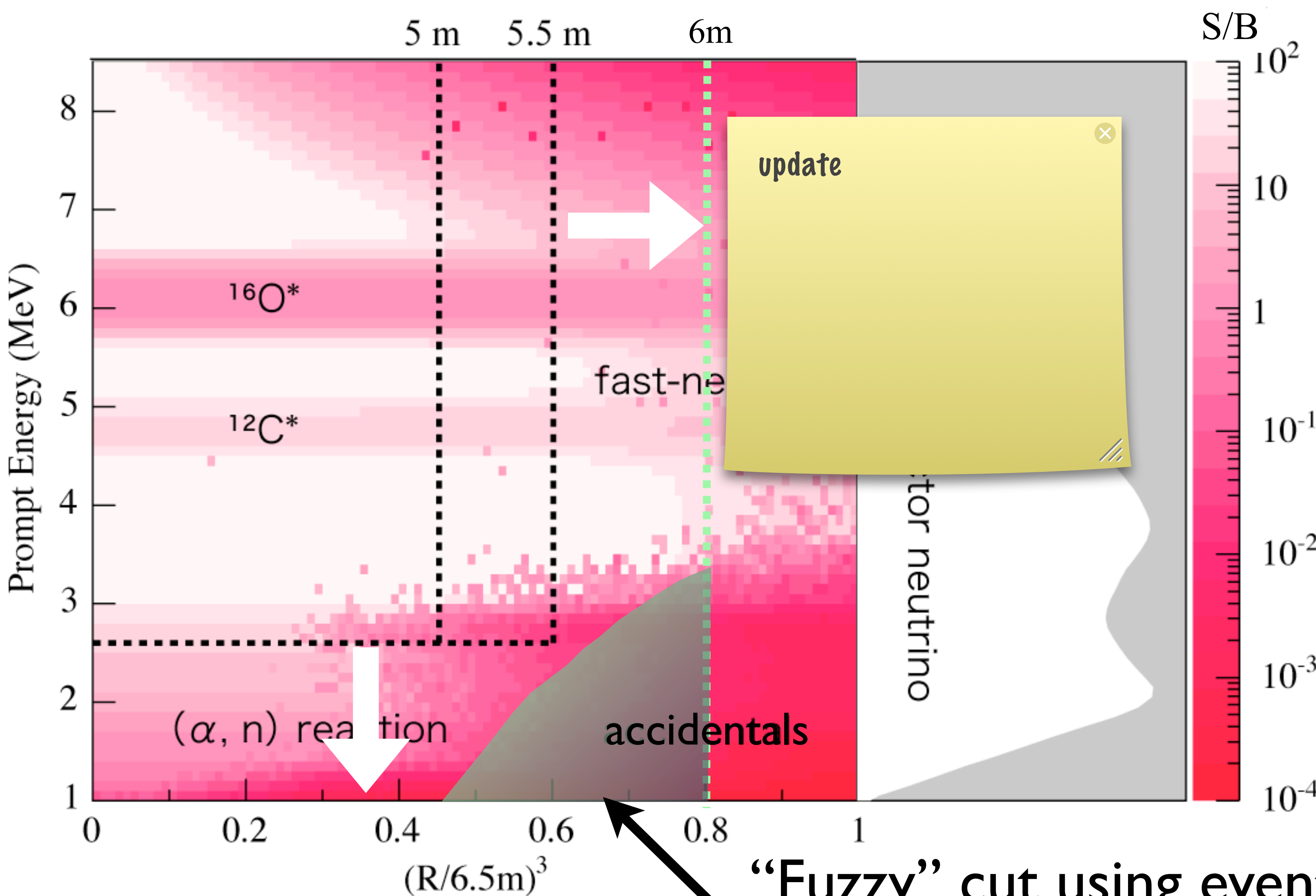




Difference in best-fit on the light and dark side is very small

Patrick Decowski / Nikhef

# 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

Patrick Decowski / Nikhef