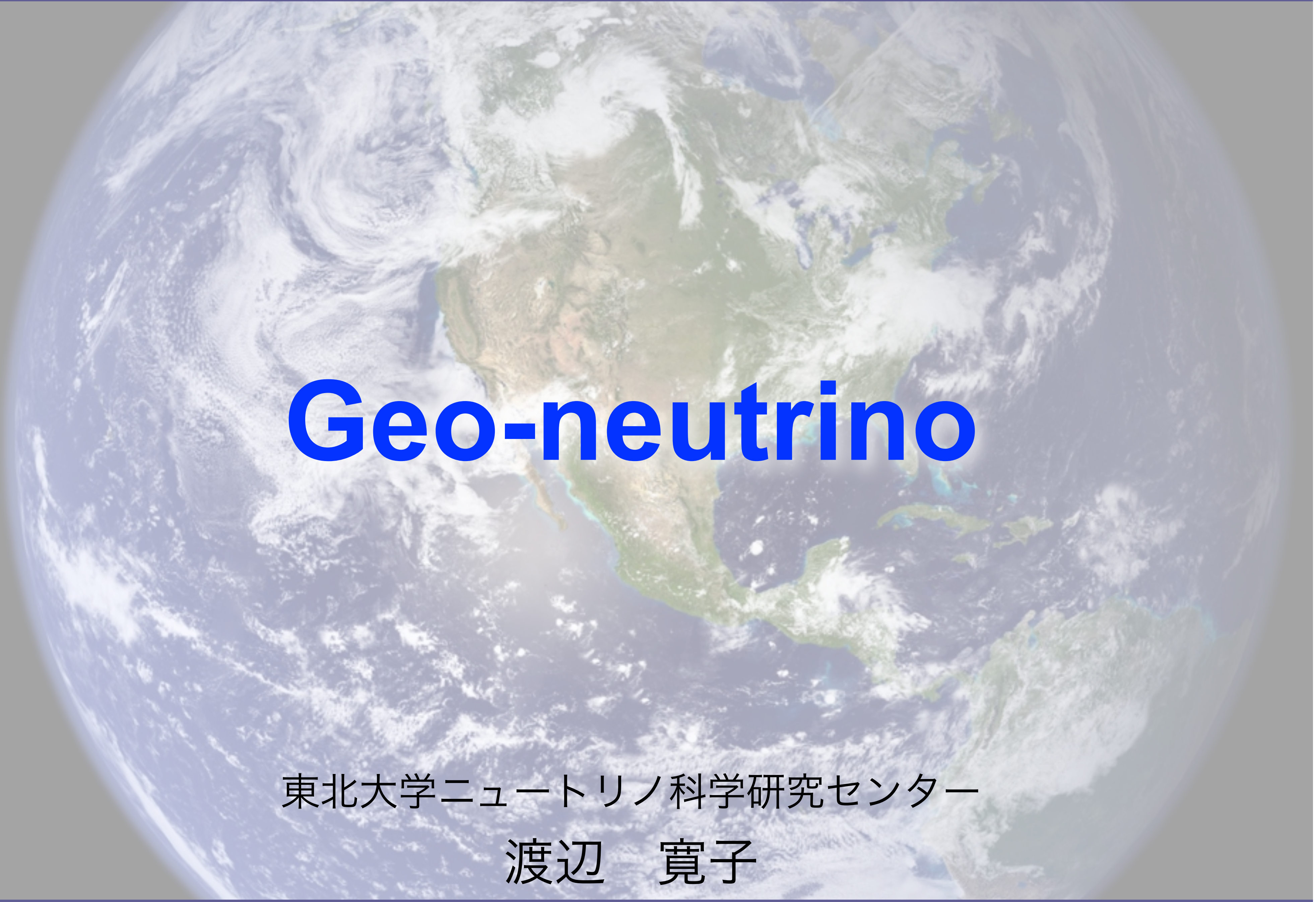
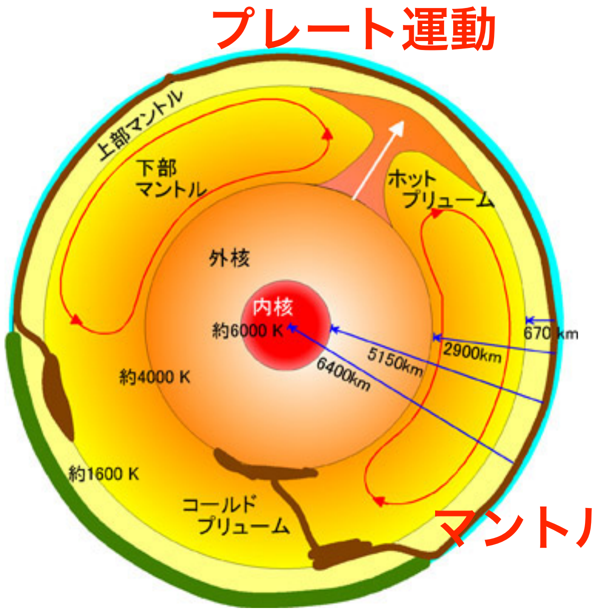


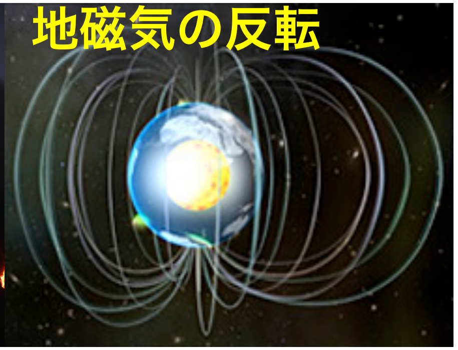
Geo-neutrino

東北大学ニュートリノ科学研究センター

渡辺　寛子

地球の熱 - 地球の活動





地球活動の謎

- エネルギー源、エネルギー量は？
- マントルはどのように対流しているのか？
- なぜ地磁気は約20万年周期で反転を繰り返すのか？

→ 地熱の理解は重要な課題

地球の熱 - 地球の熱収支

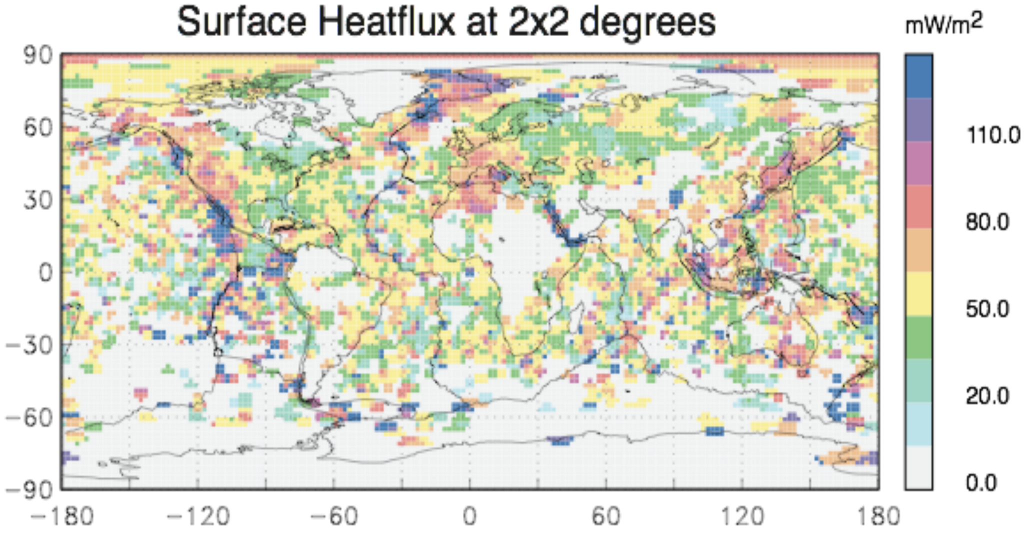
☑ 地表からの熱流量

44.2±1.0 TW

Rev. of Geophys. 31, 267-280 (1993)

(recent analysis 47±2 TW Solid Earth 1, 5 (2010))

crust heat flux measurement & calculation



>

☑ 放射化熱

20 TW

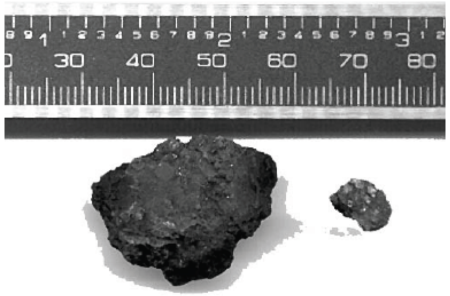
Bulk Silicate Earth (BSE) model

地球を作ったのと同等の隕石の分析

U : 8 TW

Th : 8 TW

K : 3TW



“直接測定”ではない

放射化熱は地球の全熱量の約半分

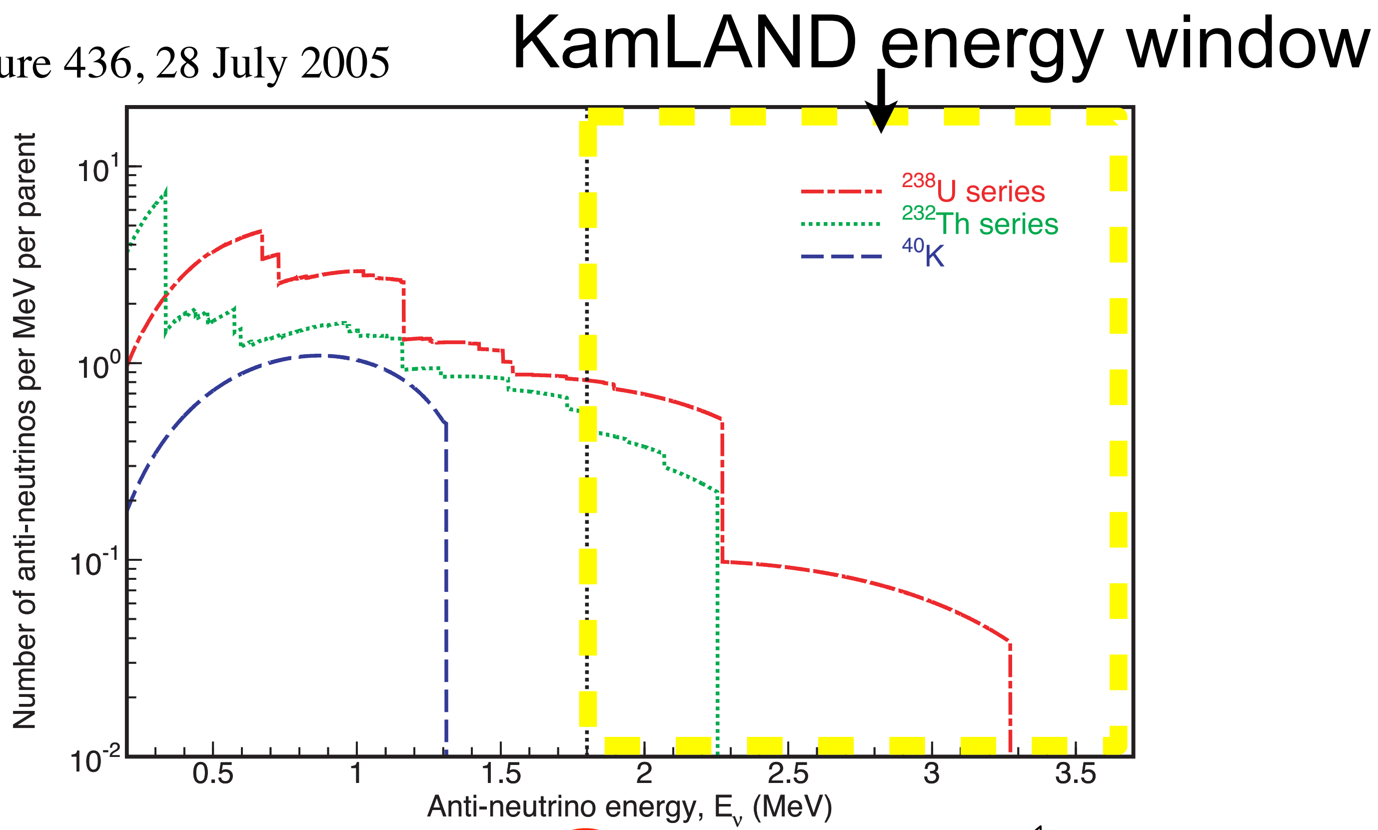
Why?

↓

地球ニュートリノの測定によって放射化熱を**直接測定**できる

▸地球ニュートリノ

- 反電子ニュートリノエネルギースペクトル



Nature 436, 28 July 2005

KamLAND energy window

β崩壊

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_\mathrm{e} + 42.7\,\mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\;(89.28\%)$$

KamLAND
で見える！

▸地球ニュートリノ観測意義

地球科学の５大問題

Bill McDonough 提唱 (BSEモデル作成)

実現済 ◎ **1. 地熱への放射性物質の寄与？**

地球ニュートリノで直接測定

近い将来 ○ **2. 核・マントル境界の性質？**

地球内原子炉の存在を検証

近い将来 ○ **3. マントルの構造分布？**

一層か多層か？

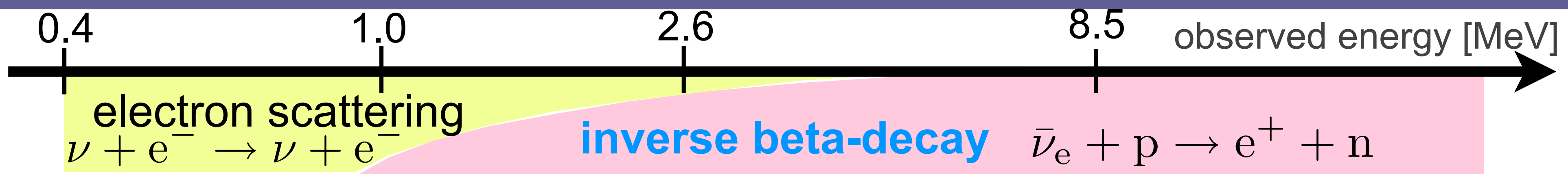
開発中 △ **4. 核内の放射性物質？**

方向測定が有効

夢 △ **5. カリウムとウランの比？**

カリウムからのニュートリノの測定

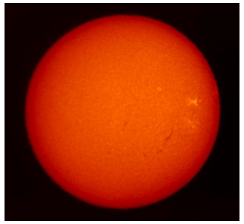
KamLANDにおけるニュートリノ観測



electron scattering $\nu + \mathrm{e}^- \rightarrow \nu + \mathrm{e}^-$

inverse beta-decay $\bar{\nu}_\mathrm{e} + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n}$

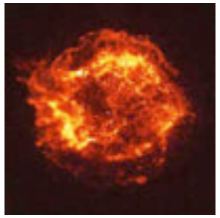
太陽ニュートリノ

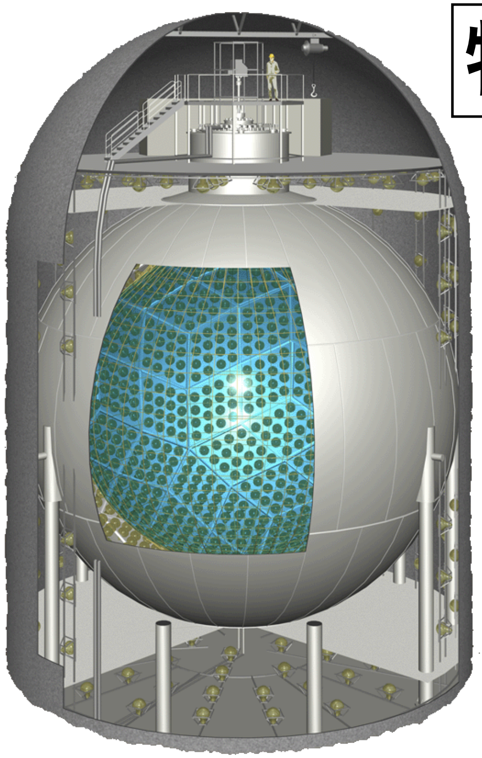


地球ニュートリノ

原子炉ニュートリノ

超新星ニュートリノ

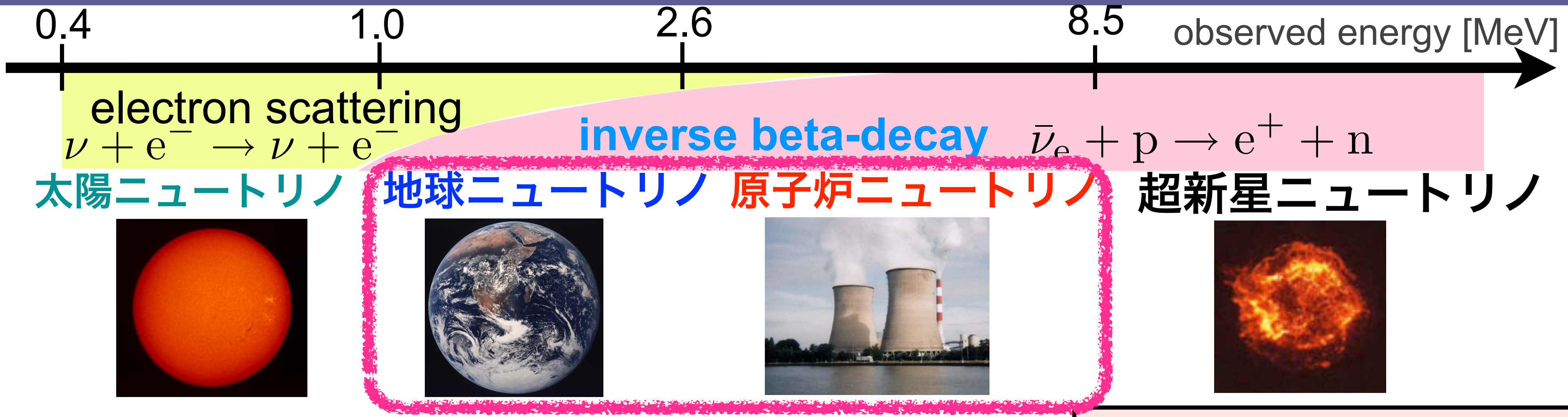




特徴

- 世界最大量の超純液体シンチレータ
- 幅広いエネルギー範囲に渡る観測対象
- 検出器のスケーラビリティー

▸KamLANDにおける反ニュートリノ観測

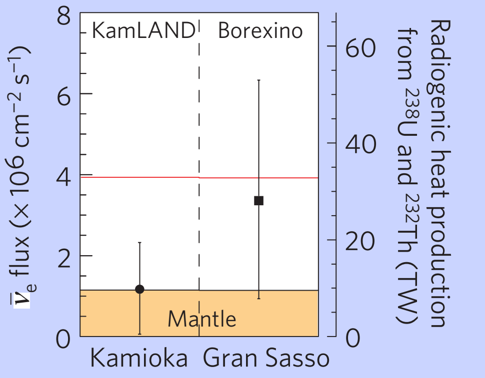


electron scattering $\nu + e^- \rightarrow \nu + e^-$

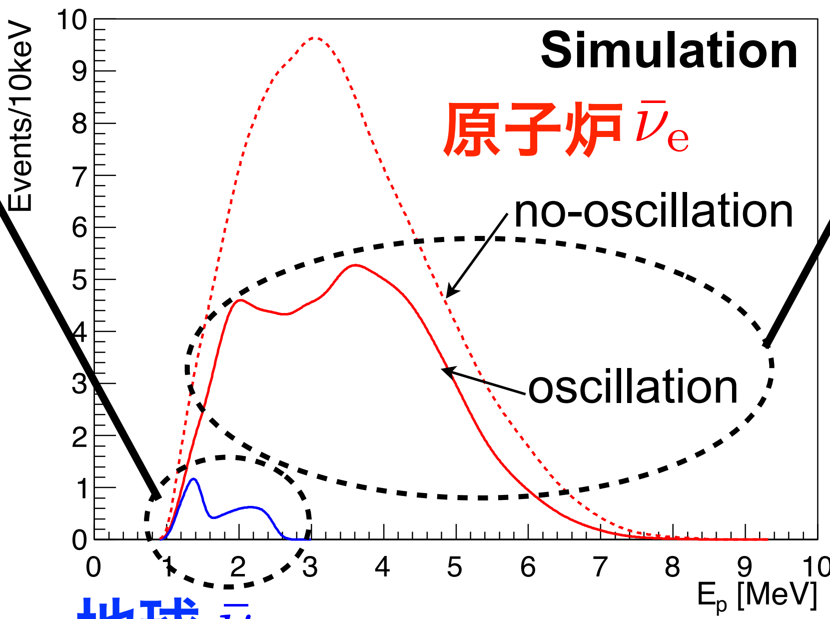
inverse beta-decay $\bar{\nu}_e + p \rightarrow e^+ + n$

太陽ニュートリノ　地球ニュートリノ　原子炉ニュートリノ　超新星ニュートリノ

ニュートリノの応用

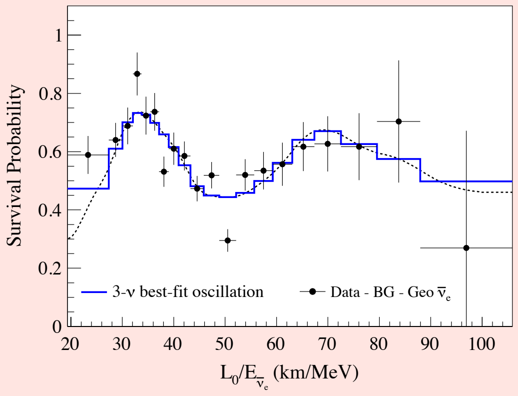


- 放射化熱の寄与の直接測定



地球 $\bar{\nu}_e$

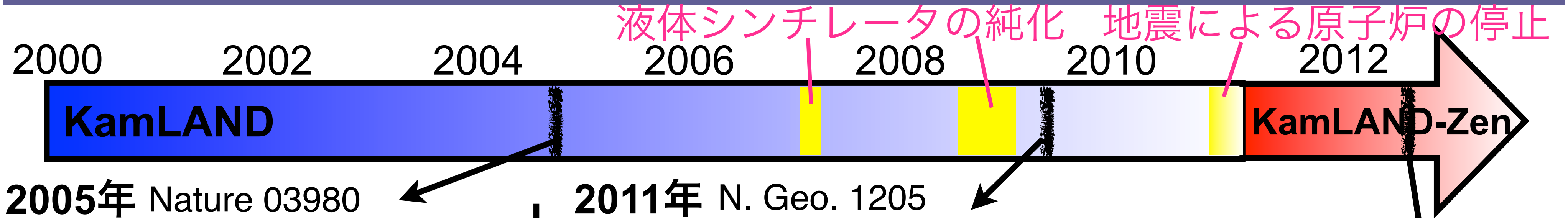
ニュートリノの性質の理解



- ニュートリノ振動の形跡の観測
- 振動パラメターの精密測定

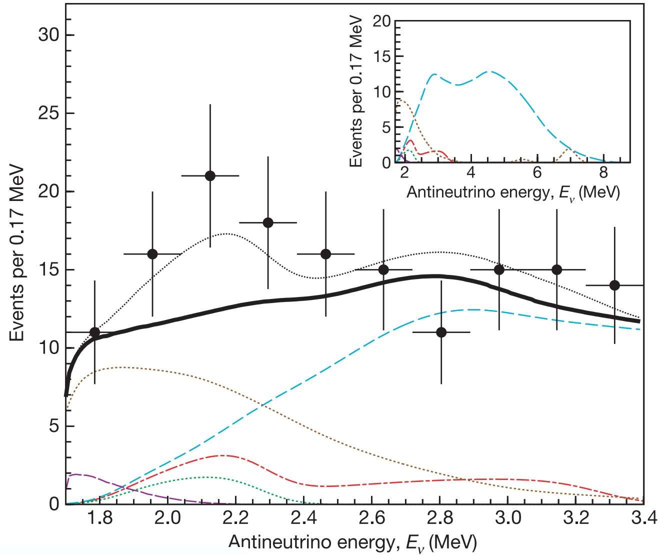
☑ニュートリノを**物事を調べる手段**として利用することを開拓

▸地球ニュートリノ観測 (1) KamLAND



2005年 Nature 03980

地球ニュートリノ
世界発観測



749 days

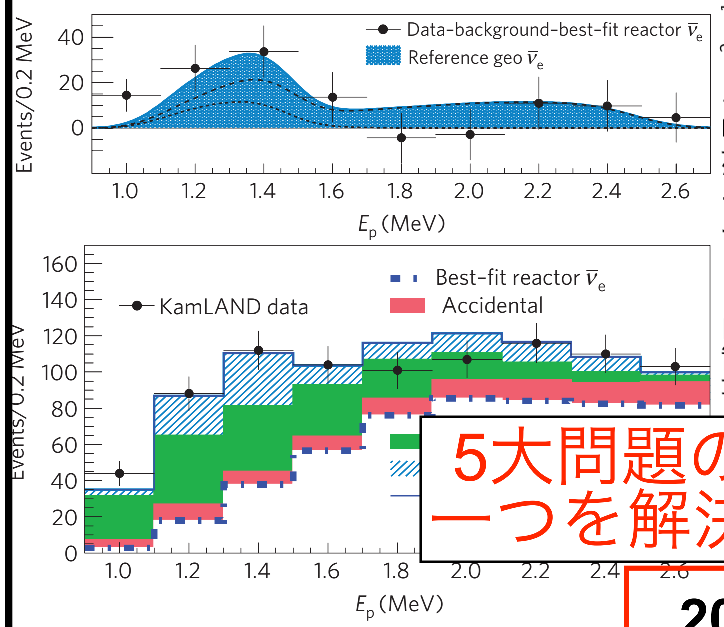
0.71×10^{32} proton-year

観測事象

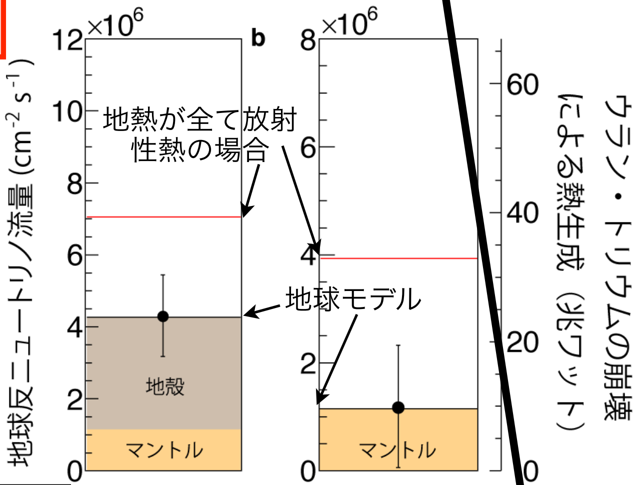
$28.0^{+15.6}_{-14.6}$ ev

2011年 N. Geo. 1205

地球の放射化熱を直接測定



5大問題の
一つを解決!



地球の放射化熱

21±9 TW

2135 days

3.49×10^{32} proton-year

観測事象

106^{+29}_{-28} ev

2013年 arXiv:1303.4667

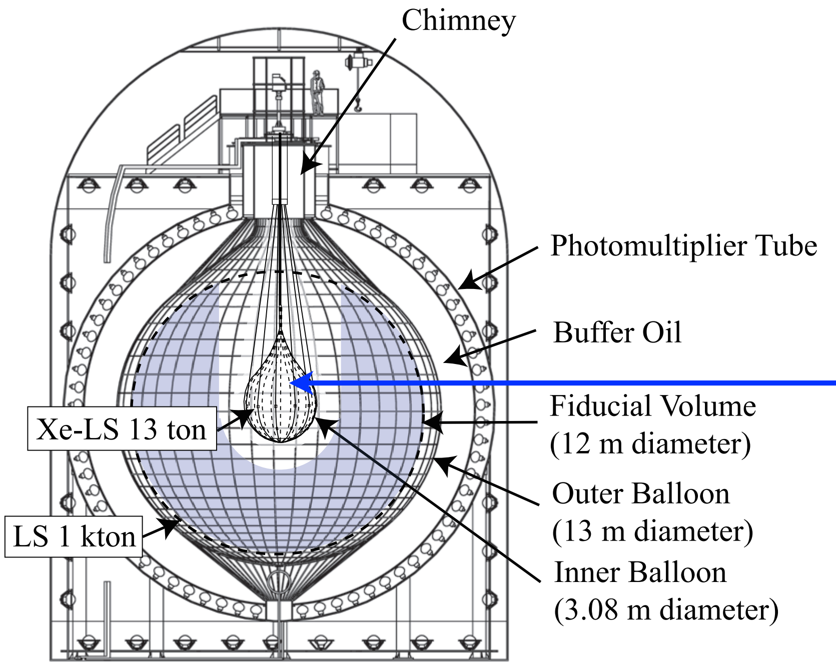
原子炉停止期間を含む解析

2991 days

4.90×10^{32} proton-year

観測事象 116^{+28}_{-27} ev

▶最新結果：KamLAND-Zen Phaseの解析



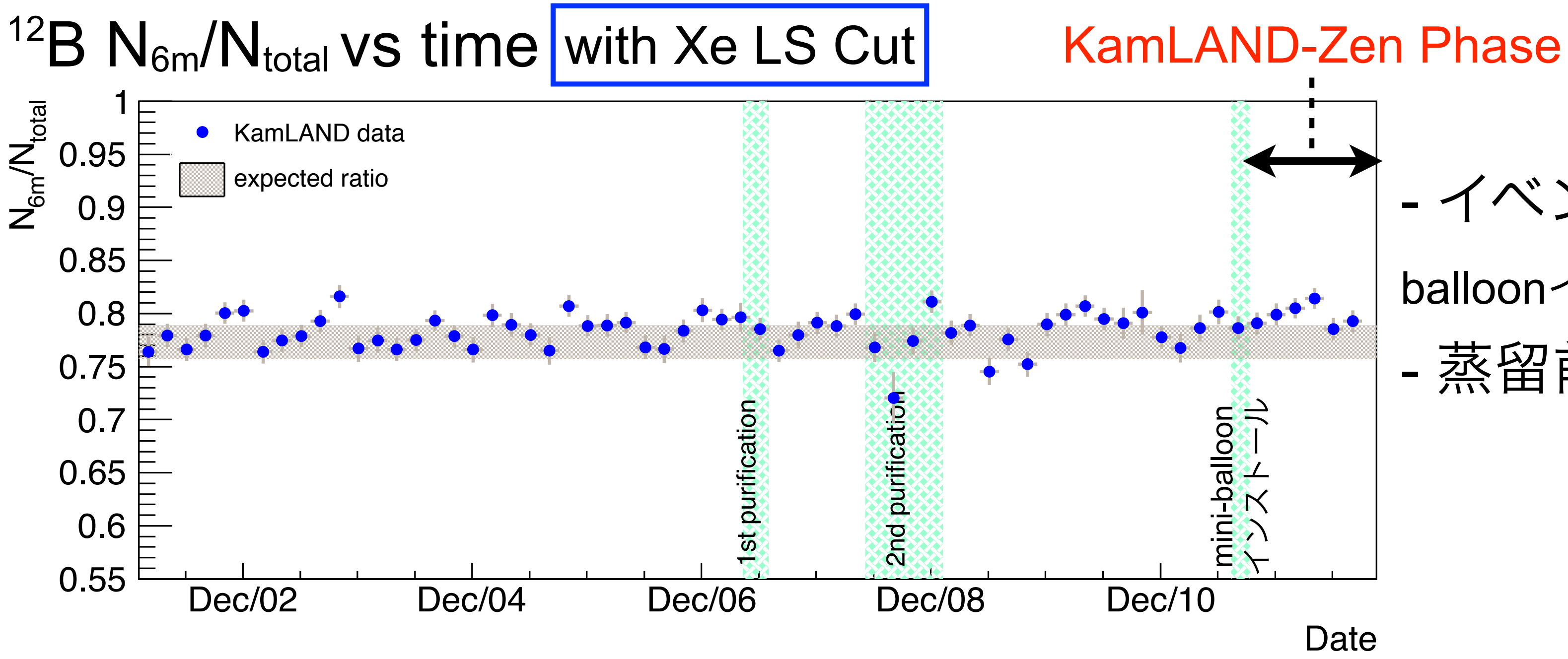
- Vertex cut 条件

偶発事象バックグラウンドを低減する為、
R<6mの有効体積内でXe LS cutを適用する。

* R > 2.5m
* cylinder cut (ρ > 2.5m, Z > 0)
(cut out volume **16.6%** of R<6m)

- KamLAND領域のData stabilityチェック

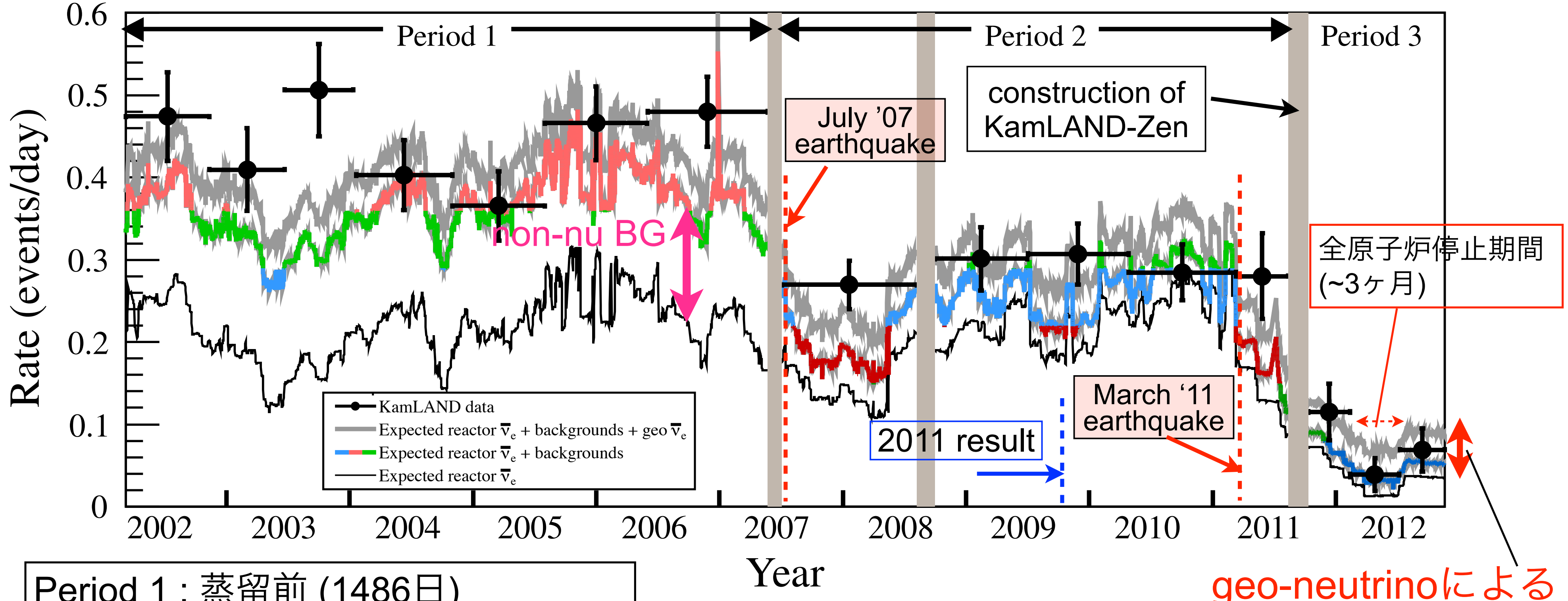
^{12}B N_{6m}/N_{total} vs time with Xe LS Cut



- イベントレート：mini-balloonインストール後も一定
- 蒸留前後の差：2.5%

▸最新結果 : Event rate (0.9-2.6 MeV)

- イベントレート時間変化 (0.9-2.6 MeV)



geo-neutrinoによる
一定の寄与

Period 1 : 蒸留前 (1486日)
Period 2 : 蒸留後 (1154日)
Period 3 : 低原子炉運転期間 (351日)

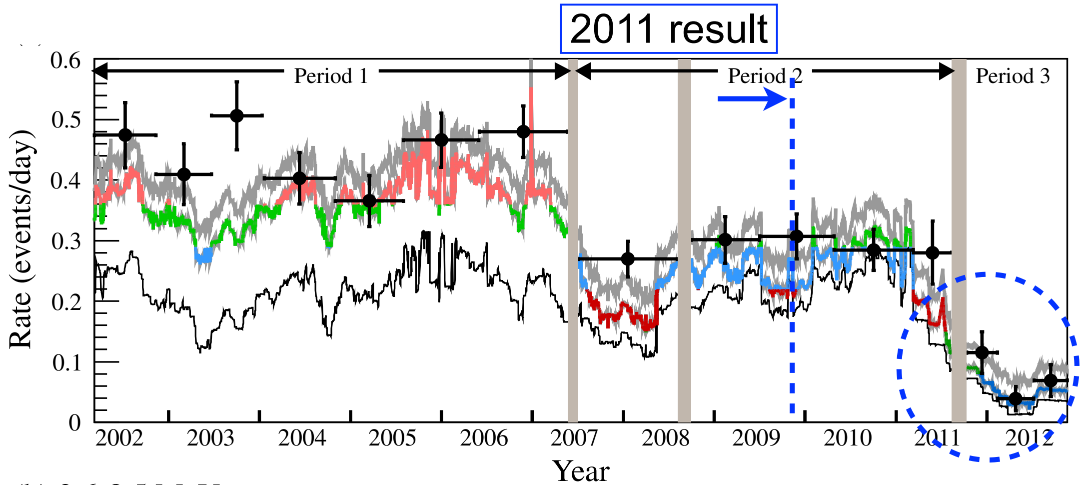
- バックグラウンド
  - * non-nu バックグラウンド : 2007年以前に比べ約半分に減少
  - * 原子炉反ニュートリノバックグラウンド : 2度の地震によって劇的に減少

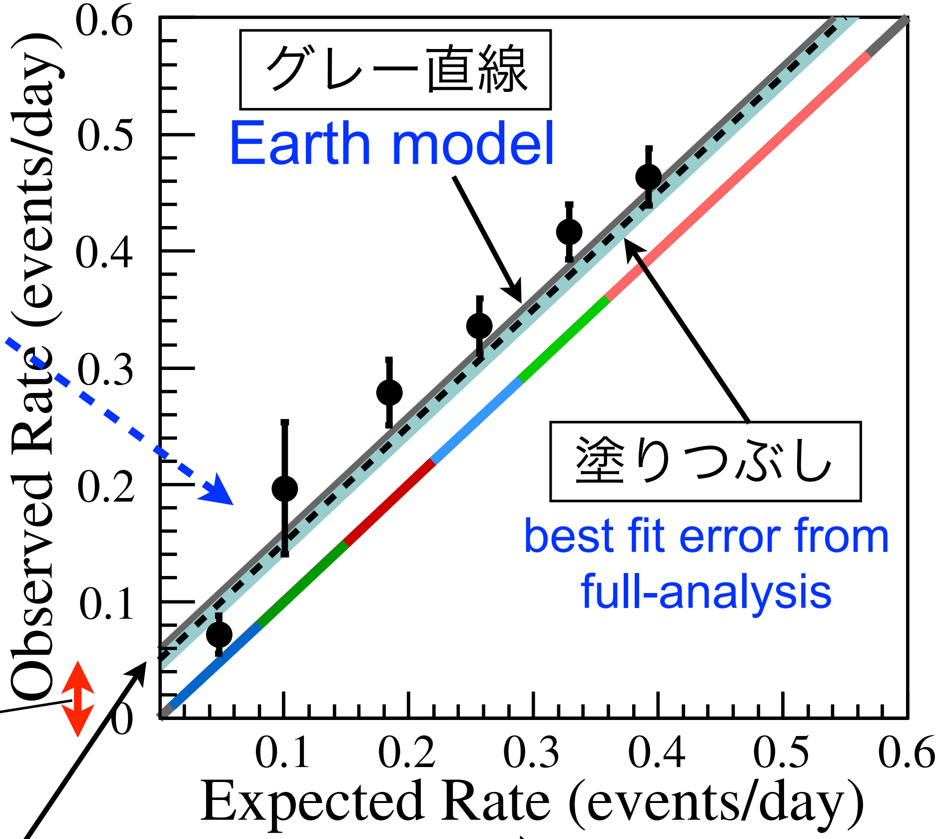
- 0.9-2.6MeV領域においては地球ニュートリノによる一定の寄与が確認できる。

→ 地球ニュートリノ観測には時間情報が効果的

最新結果 : Correlation (0.9-2.6 MeV)

- Expected Rate vs Observed Rate (0.9-2.6 MeV)





グレー直線
Earth model

塗りつぶし
best fit error from
full-analysis

geo-neutrinoによる
一定の寄与

点線 : 切片
full-analysisのbest-fit
(Rate+Shape+Time)
116 +28/-27 events

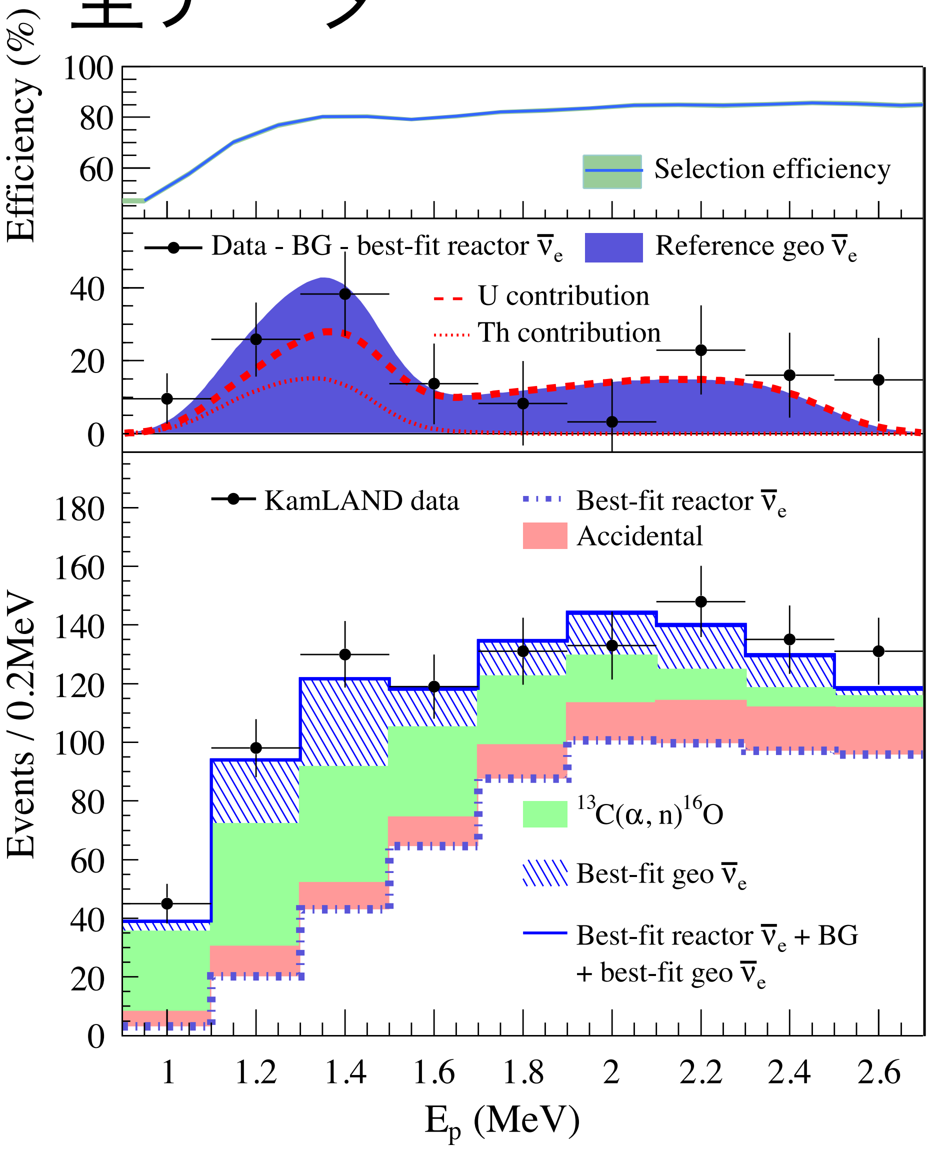
reactor anti-neutrino +
other backgrounds

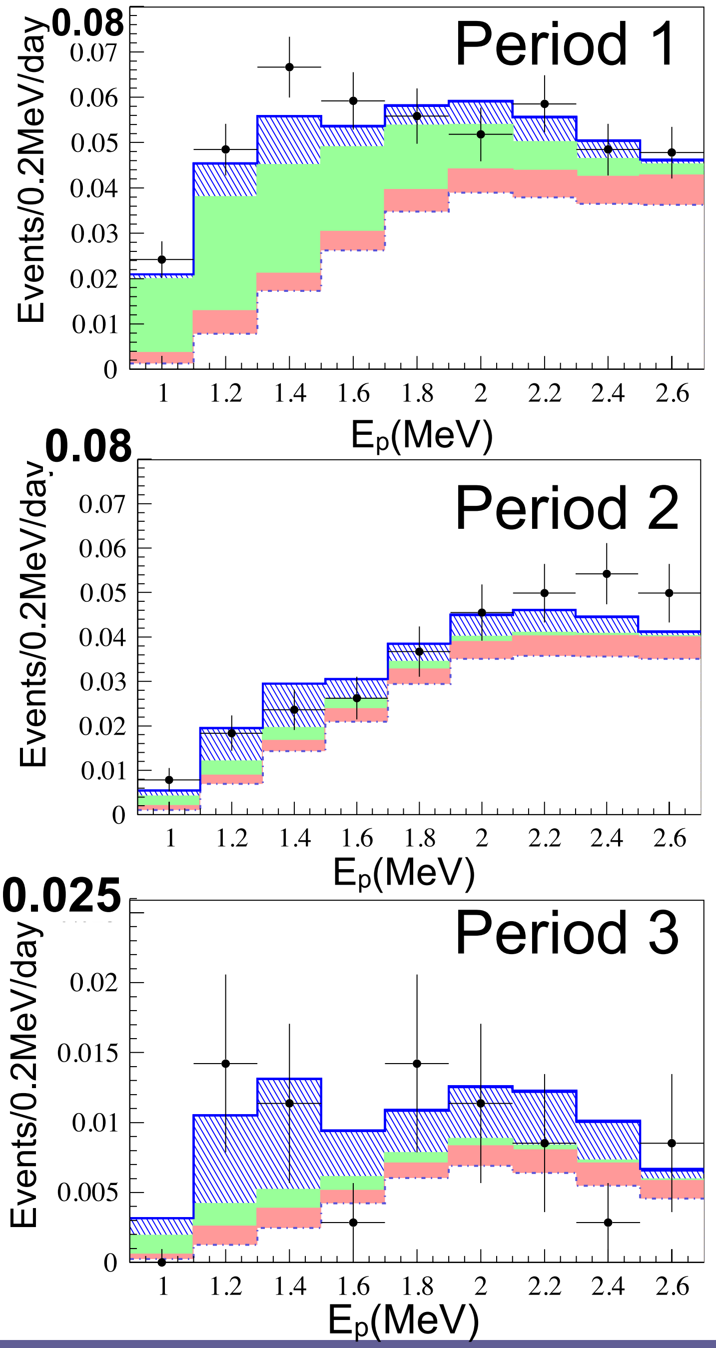
- 下側3点が最近の少原子炉運転期間のデータにより加えられた。

- expectedとobservedの各レート間の強いcorrelationが確認された。

▸最新結果 : Energy Spectrum (0.9-2.6 MeV)

全データ





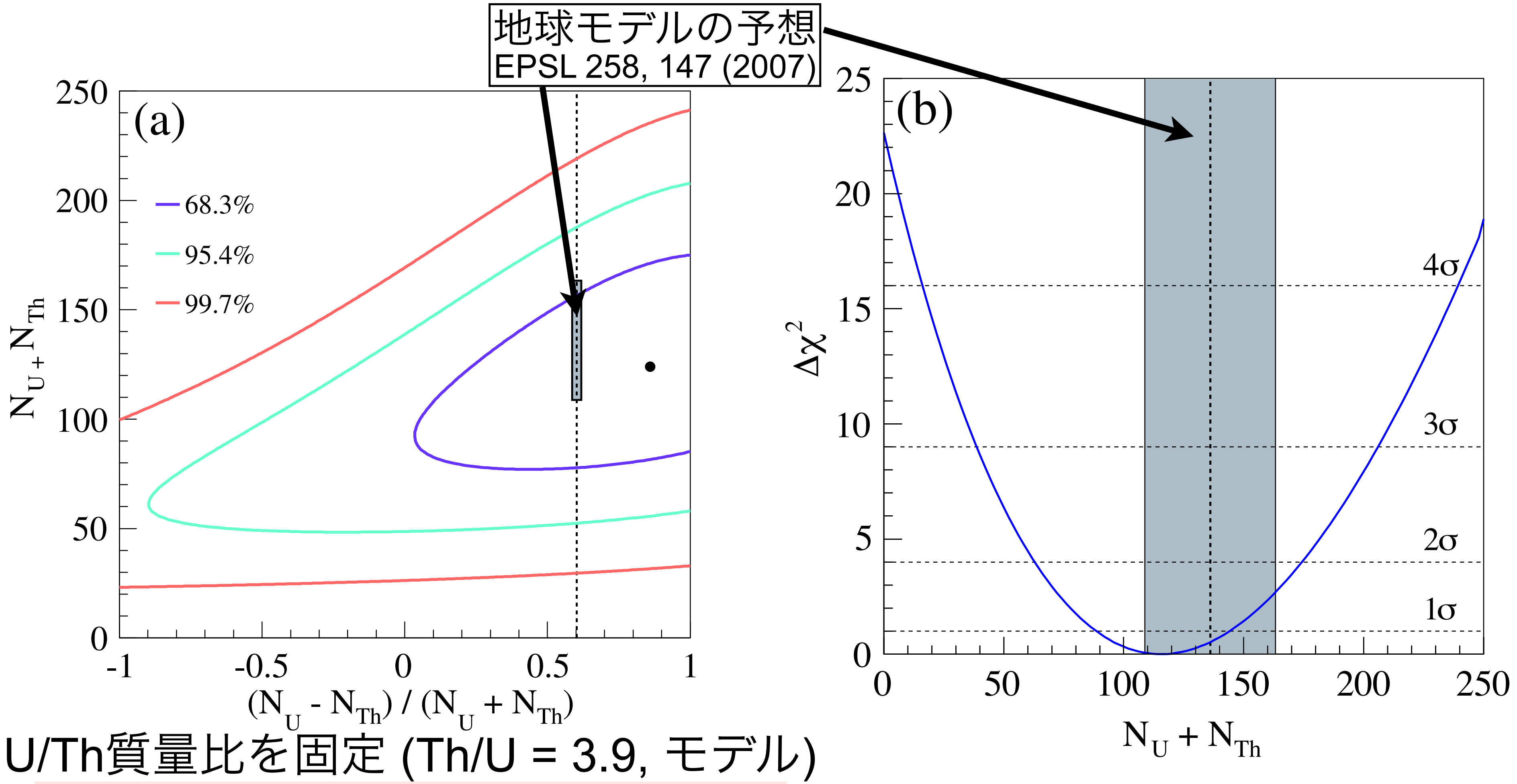
^{13}C (α, n)^{16}O

減少

Reactor-ν

減少

最新結果：Rate+Shape+Time Analysis


地球モデルの予想
EPSL 258, 147 (2007)

- U/Th質量比を固定 (Th/U = 3.9, モデル)

地球反ニュートリノ事象数

$N_{geo} = 116^{+28}_{-27}$ events

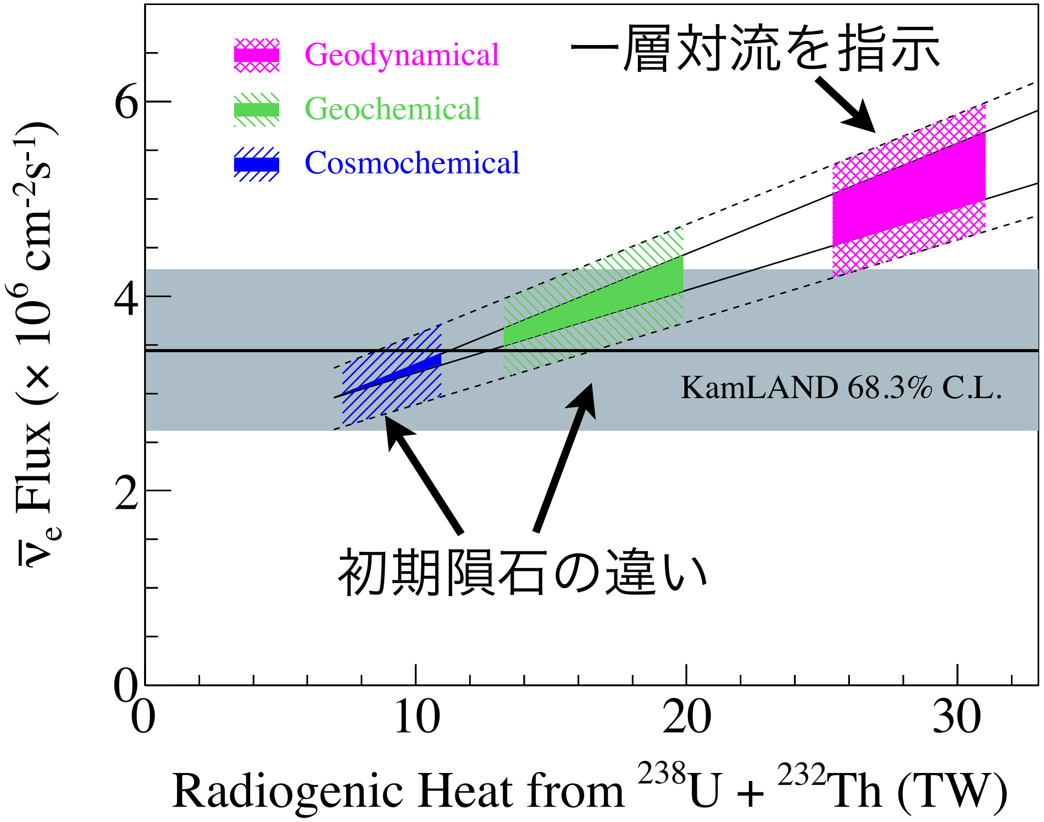
$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6/\mathrm{cm}^2/\mathrm{sec}$

地球反ニュートリノ信号の有意さ
99.9998% C.L.

Th/U < 19 (90% C.L.)

地球内原子炉 < 3.1 (90% C.L.)

▸最新結果：Comparison with Models



[BSE composition models]

Geodynamical

D. L. Turcotte and G. Schubert, *Geodynamics*, (Cambridge Univ. Press, Cambridge, 2002).

高放射性物質存在度

Geochemical

W. F. McDonough and S.-s. Sun, Chem. Geol. **120**, 223 (1995)

マントル組成 = enstatite chondrites

低放射性物質存在度

Cosmochemical

M. Javoy *et al*., Earth and Planet. Sci. Lett. **293**, 259 (2010)

原始組成 = CI 炭素質コンドライト

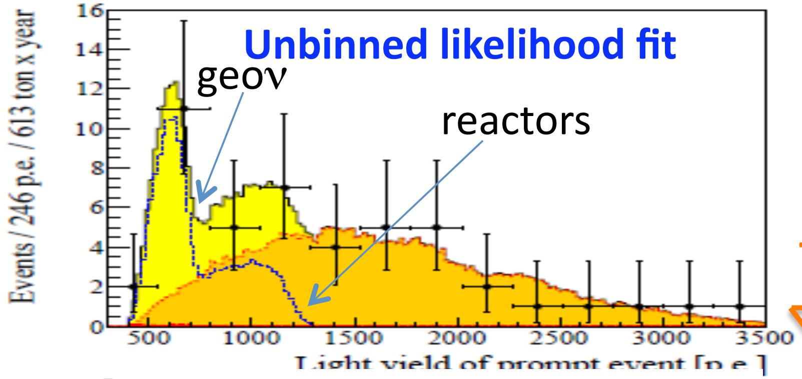
- KamLANDによる地球ニュートリノフラックスの観測値から求まるU+Thによる放射化熱量：11.2 $^{+7.9}_{-5.1}$ TW
- geodynamical prediction (homogeneous hypothesis) : 89% C.L.の信頼度で除去
- BSE composition modelsは~2 σで一致している

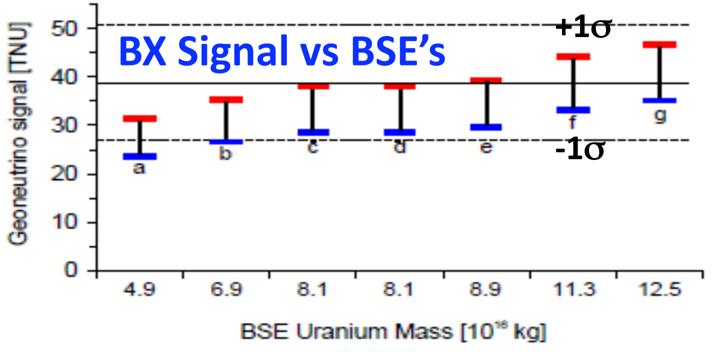
▸地球ニュートリノ観測 (2) Borexino

Measurements of geo-neutrinos from 1353 days of Borexino

S. Zavatarelli Talk on behalf of BX collaboration

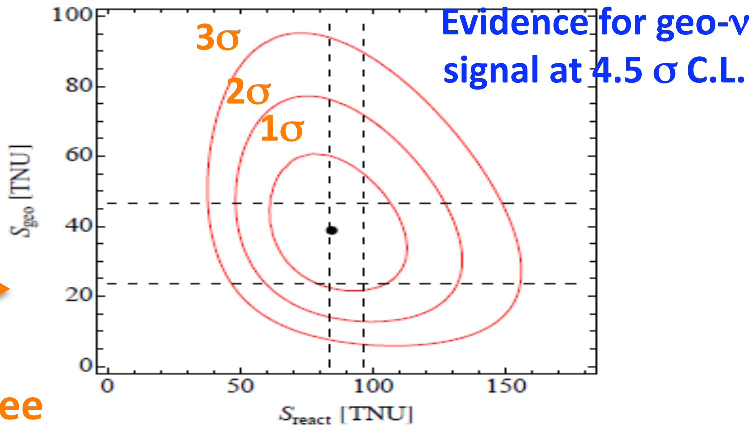
$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	events	events	events	events	TNU	TNU
33.3±2.4	60.4±4.1	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$


Unbinned likelihood fit

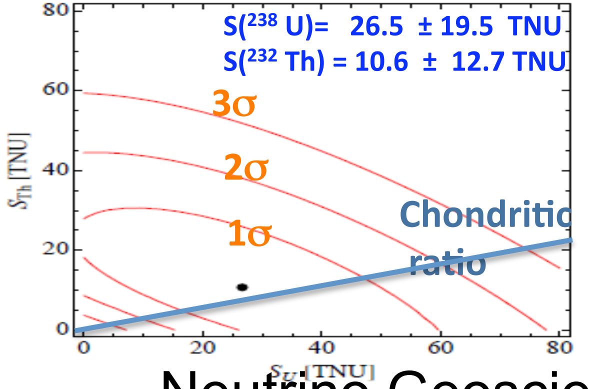

BX Signal vs BSE's

KL+BX$_{new}$: S(mantle)= (14. ± 8.1 TNU)

Th/U =3.9


Evidence for geo-ν signal at 4.5 σ C.L.

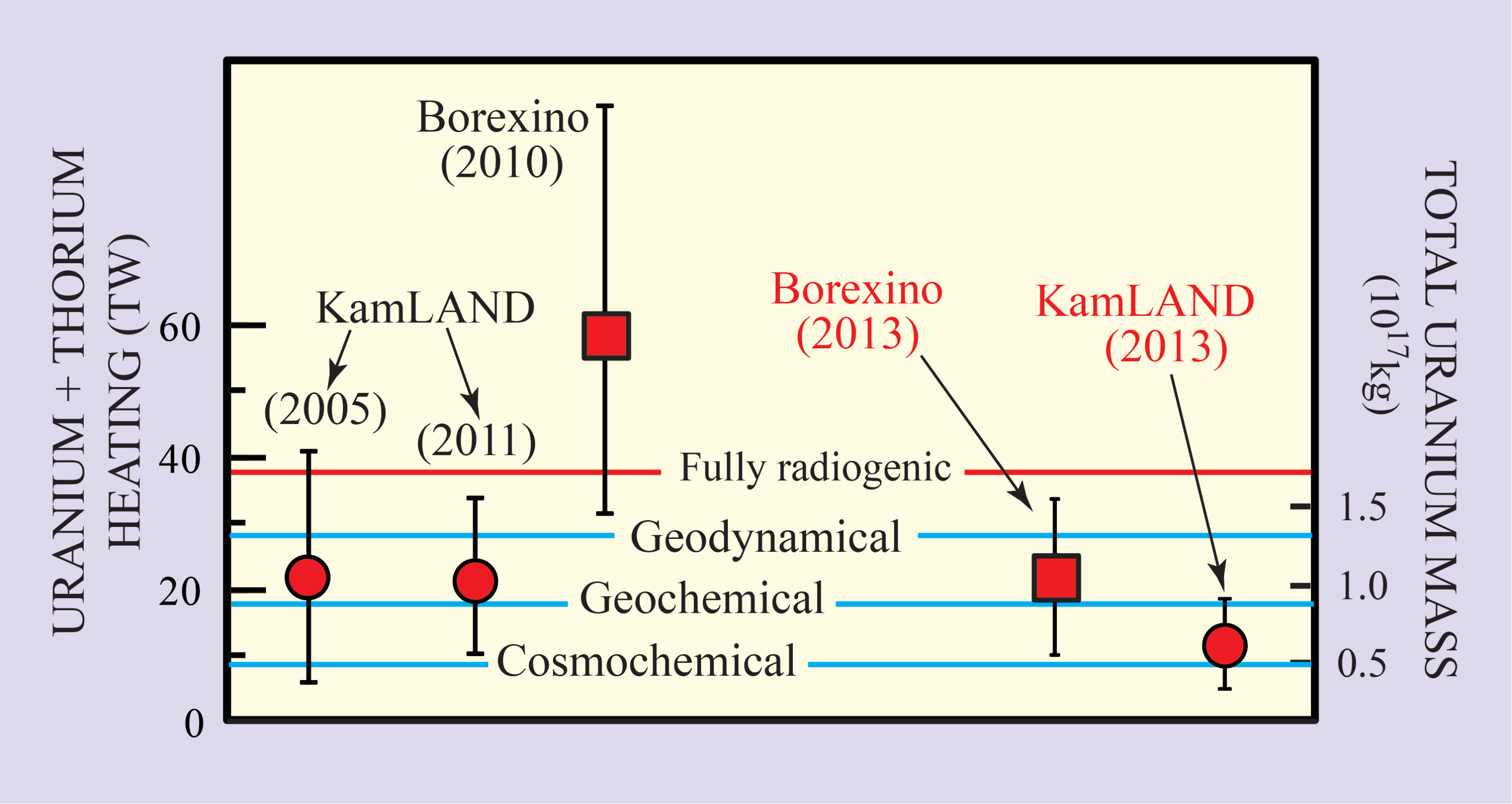
Th/U free


S(^{238} U)= 26.5 ± 19.5 TNU
S(^{232} Th) = 10.6 ± 12.7 TNU

Chondritic ratio

Neutrino Geoscience 2013

Summary of geoneutrino results



MODELS

Cosmochemical: uses meteorites – *O'Neill & Palme ('08); Javoy et al ('10); Warren ('11)*

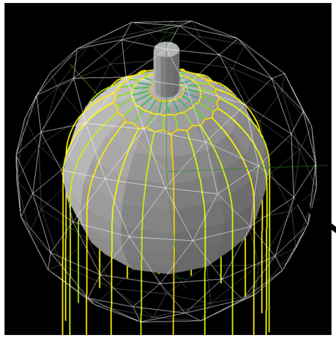
Geochemical: uses terrestrial rocks – *McD & Sun '95; Allegre et al '95; Palme O'Neil '03*

Geodynamical: parameterized convection – *Schubert et al; Turcotte et al; Anderson*

Bill McDonough, Neutrino Geoscience 2013

- マルチサイト測定が更に高精度化

将来の地球ニュートリノ観測実験 (1)



SNO+

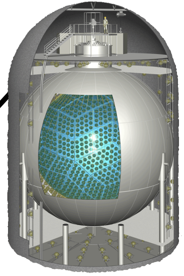
1kt, LS+, 5.4 kmwe
2013~2014 online

LENA

50kt, LS
3 kmwe
R&D

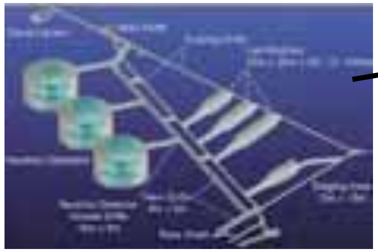
Baksan R&D

KamLAND

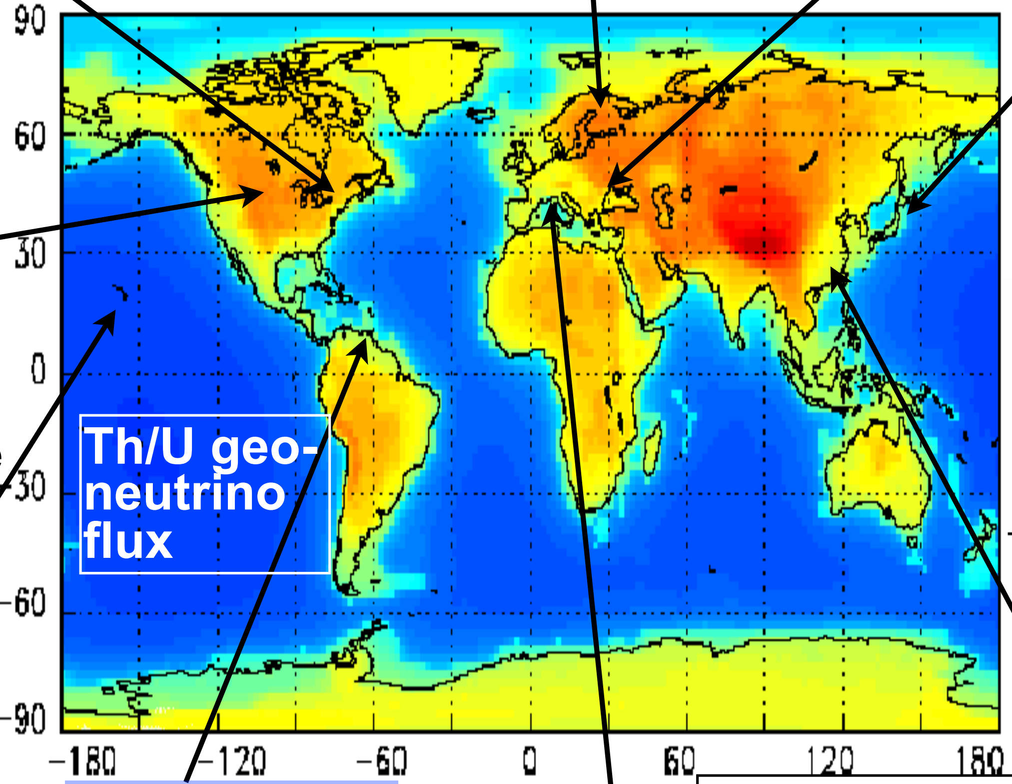


1kt, LS
2.7 kmwe
running

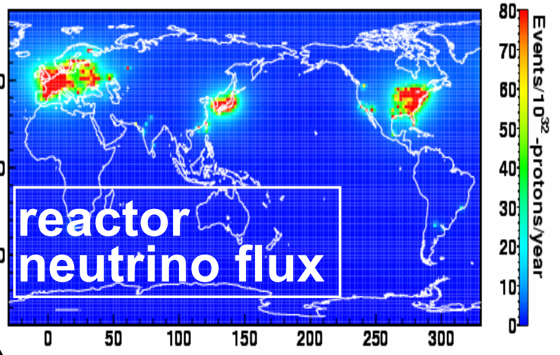
DUSEL



300kt, LS+, 4.2 kmwe
R&D

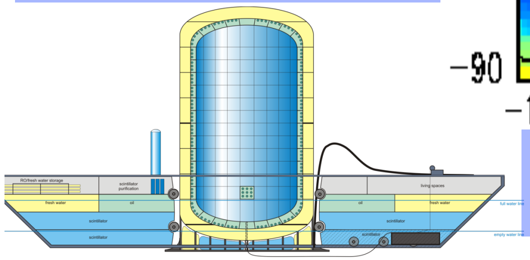


Th/U geo-neutrino flux



reactor neutrino flux

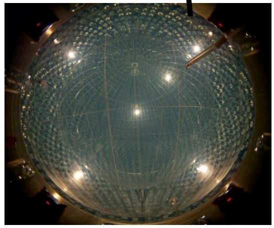
Hanohano



10kt, LS, 2-5kmwe
R&D

EARTH

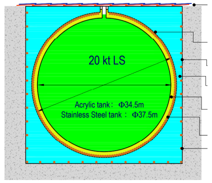
R&D



Borexino

0.3kt, LS
3.7kmwe
running

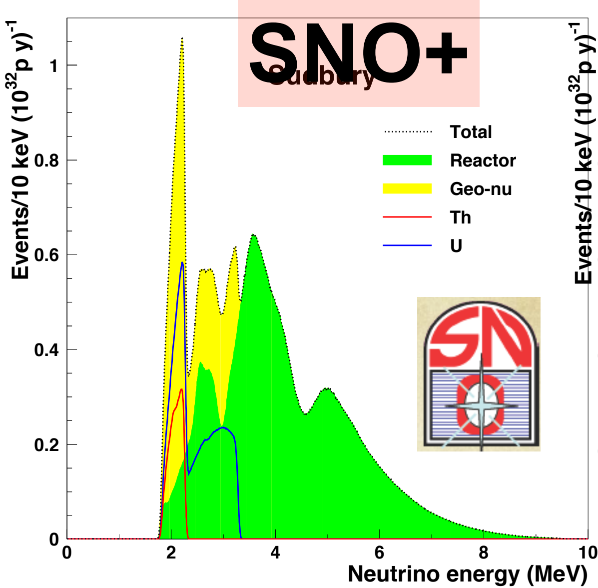
DayaBayII

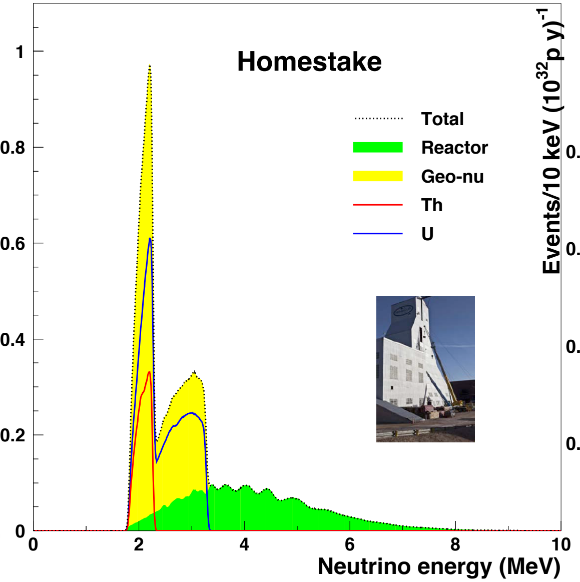


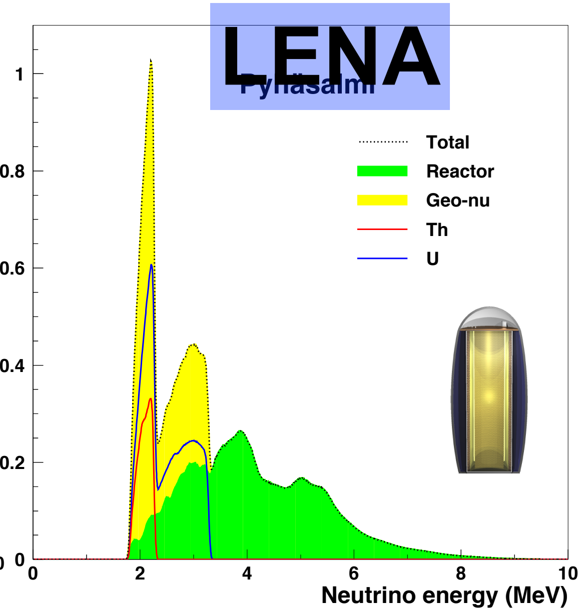
20kt, LS
1.5 kmwe
R&D(2019~)

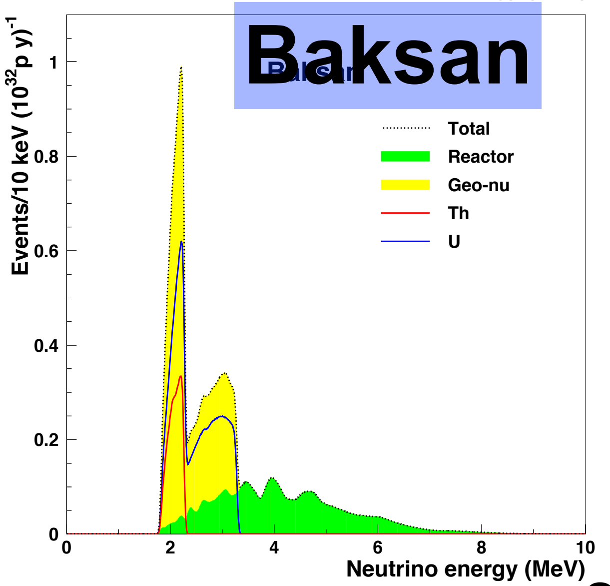
‣将来の地球ニュートリノ観測実験 (2)

Predicted Signals: Future & Prospective Sites

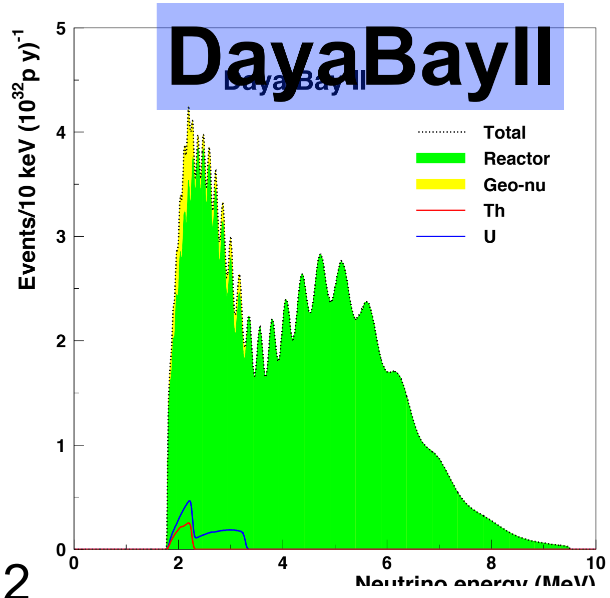








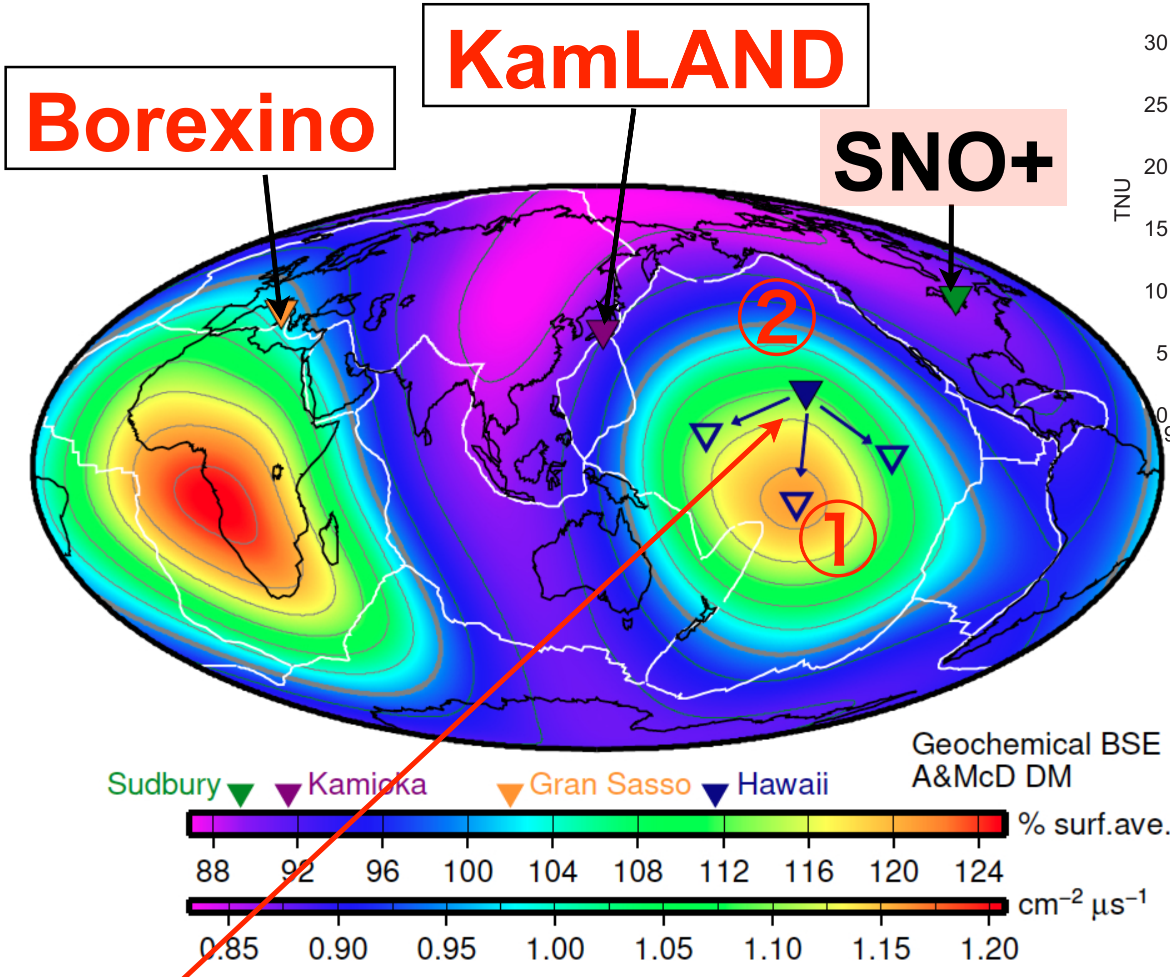
Continental Observatories



Steve Dye, Neutrino 2012

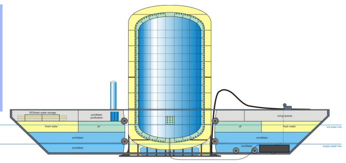
▶将来の地球ニュートリノ観測実験 (3)

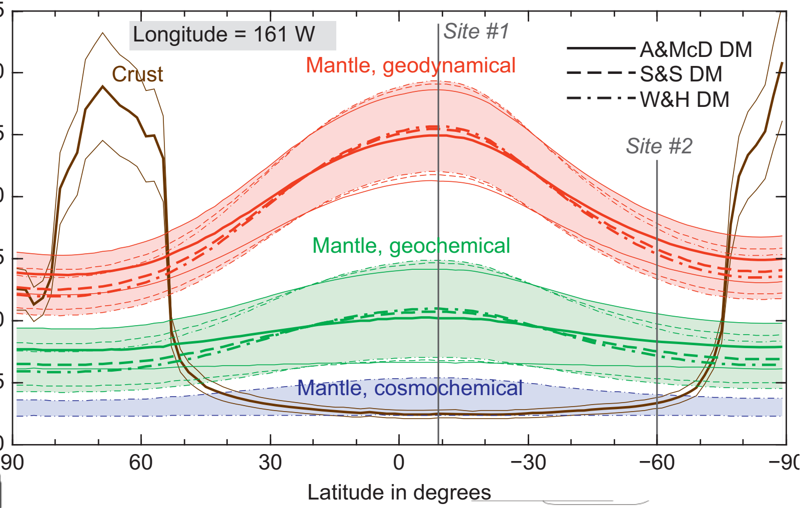
マントル geo-neutrino flux (^{238}U+^{232}Th) ① ②

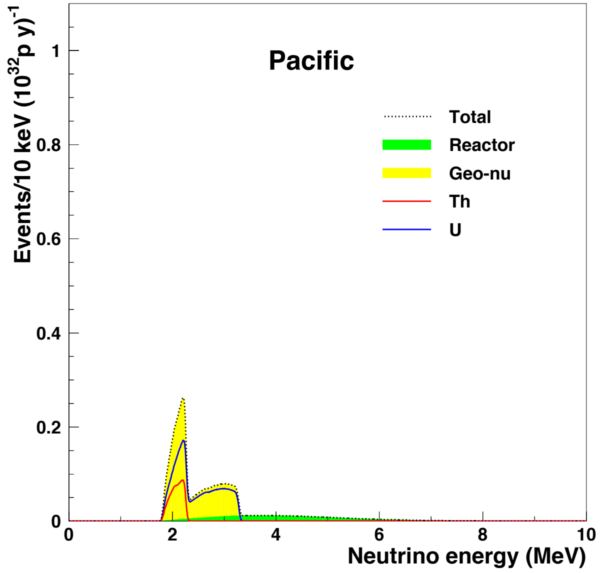


Šrámek et al (2013) 10.1016/j.epsl.2012.11.001; arXiv:1207.0853

Hanohano







マントルの寄与が75%

移動可能→モデルテスト, 地球トモグラフィー

▶地球ニュートリノ観測の夢

1. 到来方向に感度を持った観測 →

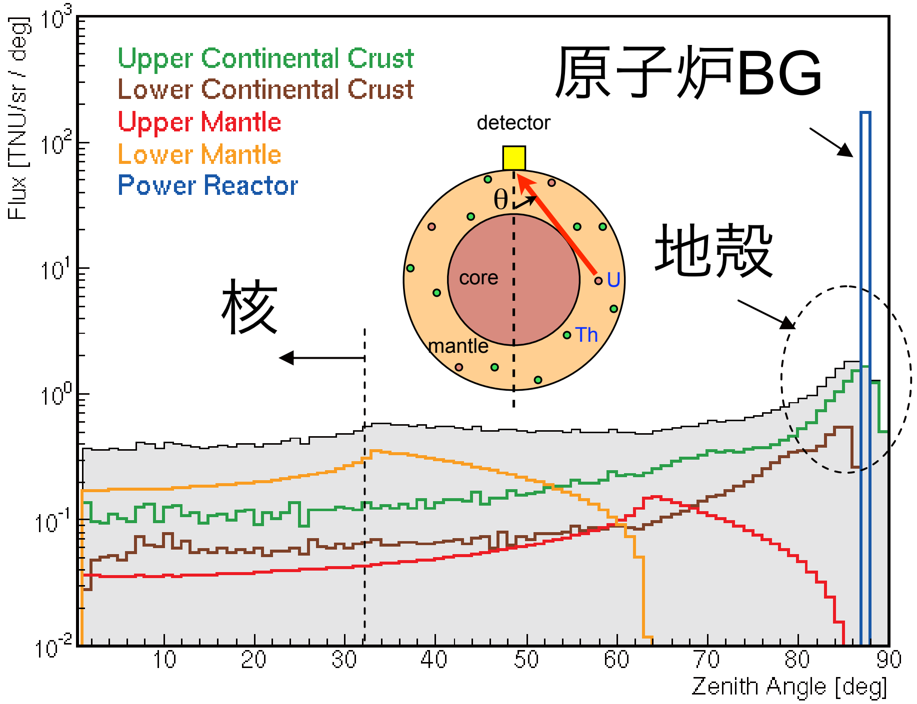
大陸の下のマントル組成
核•マントル分離測定
BGの大幅な低減

2. 40K (E_{max}=1.3MeV) geo-neutrino観測 →

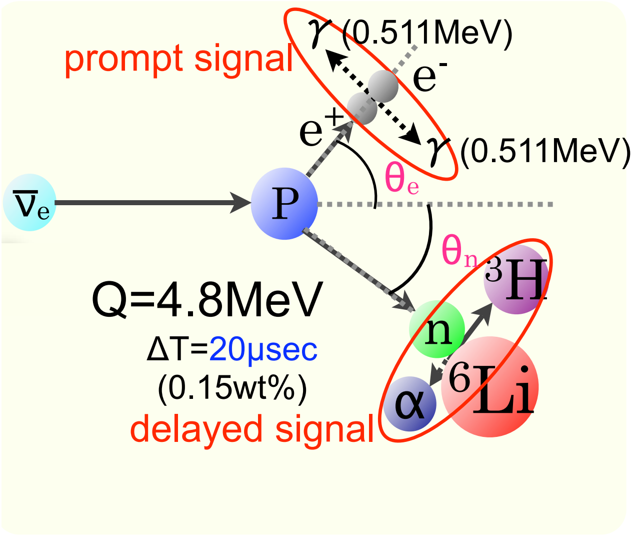
核を含め重要な熱源(3~20TW)
地球存在量の見積もりに大きな不定性
地球集積過程理解への重要な情報

3. 地球トモグラフィー

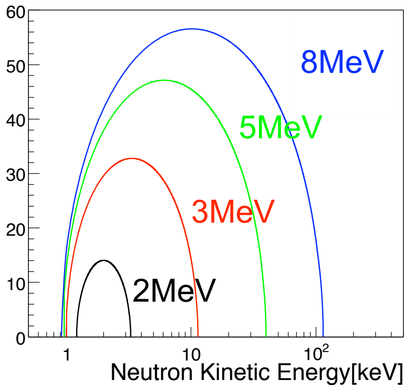
方向測定 核/マントル/地殻を効果的に区別



方向に感度を持った液体シンチレータ



Q=4.8MeV
ΔT=20μsec
(0.15wt%)



$E_{\bar{\nu}e}$<3MeV→θ_n<35°

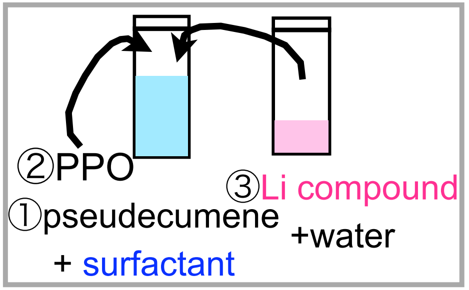
▶地球ニュートリノ観測の夢: KamLANDの取り組み

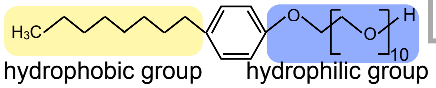
^{6}Li含有液シン

LiBr水溶液

+界面活性剤

+PC+PPO

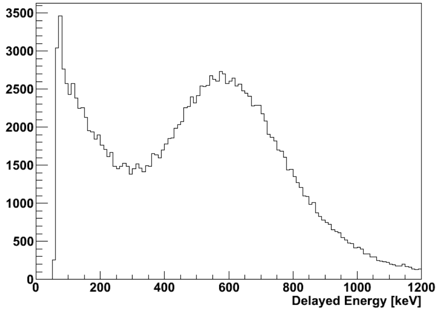




- **独自の方法で開発**
- enrich ^{6}LiBr 使用で目標濃度 0.15wt%を達成

- result

*delayed signal energy spectrum



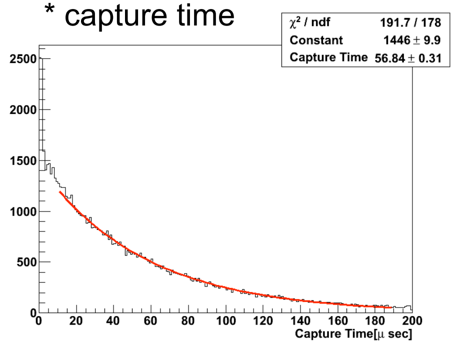
We can see clear peak of neutron capture event.

n + ^{6}Li → α + ^{3}H

$E_{visible}$ ~ 600keV

ref) E_{real} = 4.9MeV

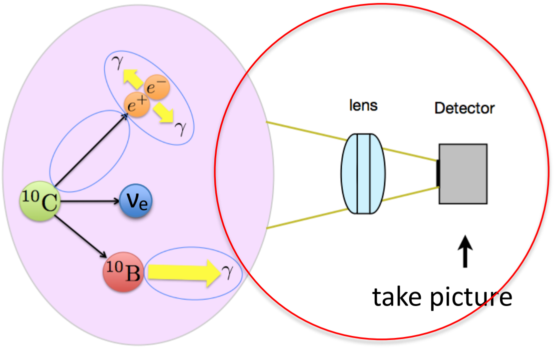
* capture time

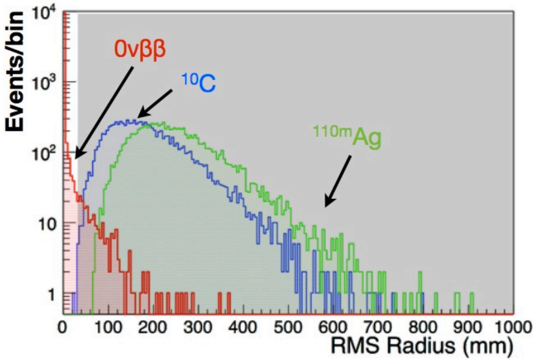


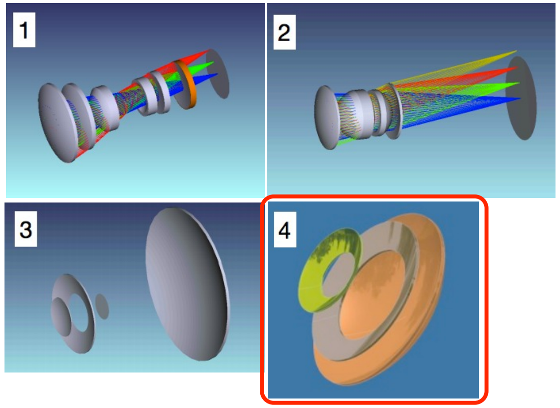
capture time 56.84±0.31μsec

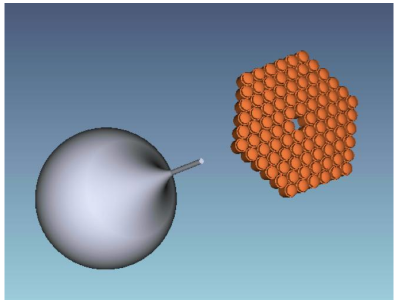
ref) current liquid scintillator's capture time ~ 220μsec

イメージングディテクター



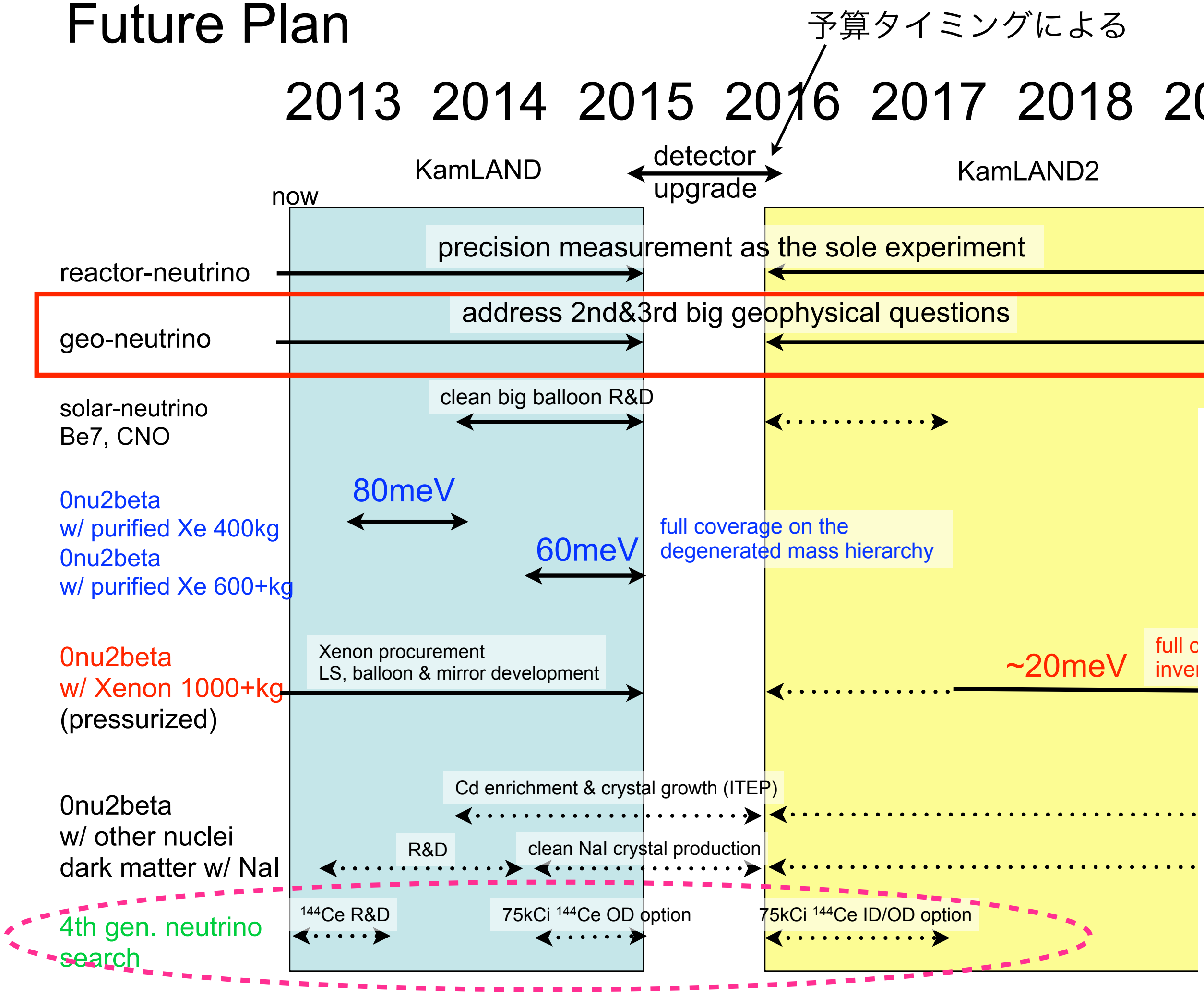






- **高位置分解能, 発光位置の撮像のよる測定**
- particle IDにも効果的

▶KamLAND将来計画



Future Plan

予算タイミングによる

2013 2014 2015 2016 2017 2018 2019 -

now

KamLAND

detector upgrade

KamLAND2

reactor-neutrino: precision measurement as the sole experiment

geo-neutrino: address 2nd&3rd big geophysical questions

solar-neutrino Be7, CNO: clean big balloon R&D

0nu2beta w/ purified Xe 400kg: 80meV

0nu2beta w/ purified Xe 600+kg: 60meV

full coverage on the degenerated mass hierarchy

0nu2beta w/ Xenon 1000+kg (pressurized): Xenon procurement LS, balloon & mirror development

~20meV

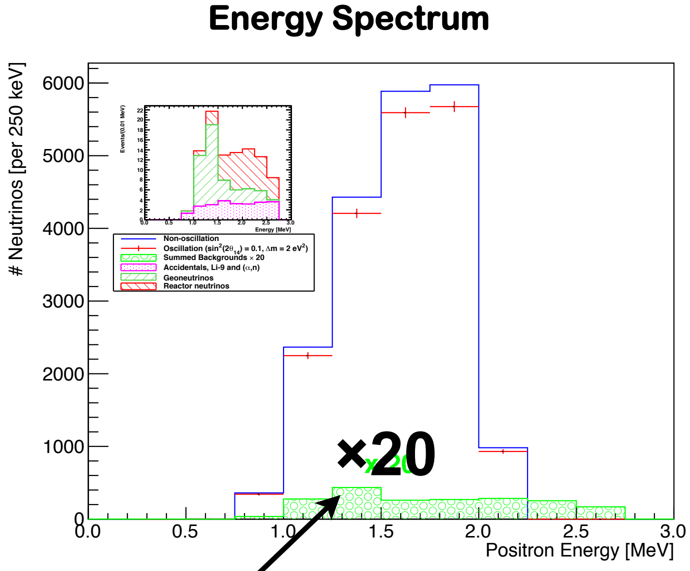
full c… inve…

0nu2beta w/ other nuclei: Cd enrichment & crystal growth (ITEP)

dark matter w/ NaI: R&D; clean NaI crystal production

4th gen. neutrino search: ^{144}Ce R&D; 75kCi ^{144}Ce OD option; 75kCi ^{144}Ce ID/OD option

Outer Detector Plan (0.5year)



geo+reactor
+accidental

22

- KamLAND-Zenと共存してデータ取得を継続

low-reactor phase : 既に約2年分のデータ

→ 今後の目標 : U•Thの分離測定, 始原隕石の同定, マントル対流の特定

▸KamLAND将来計画

Neutrino Geoscience 2013 (3/21-23, 高山)

Neutrino Geoscience 2013

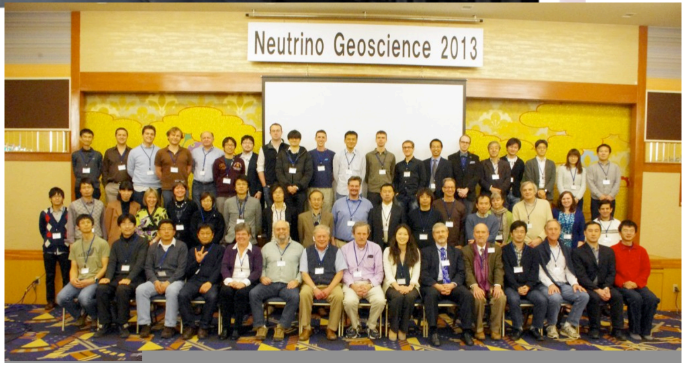
Takayama, JAPAN 21st-23rd March, 2013

50人規模

Physics:Geology~1:1

General infomation

Print



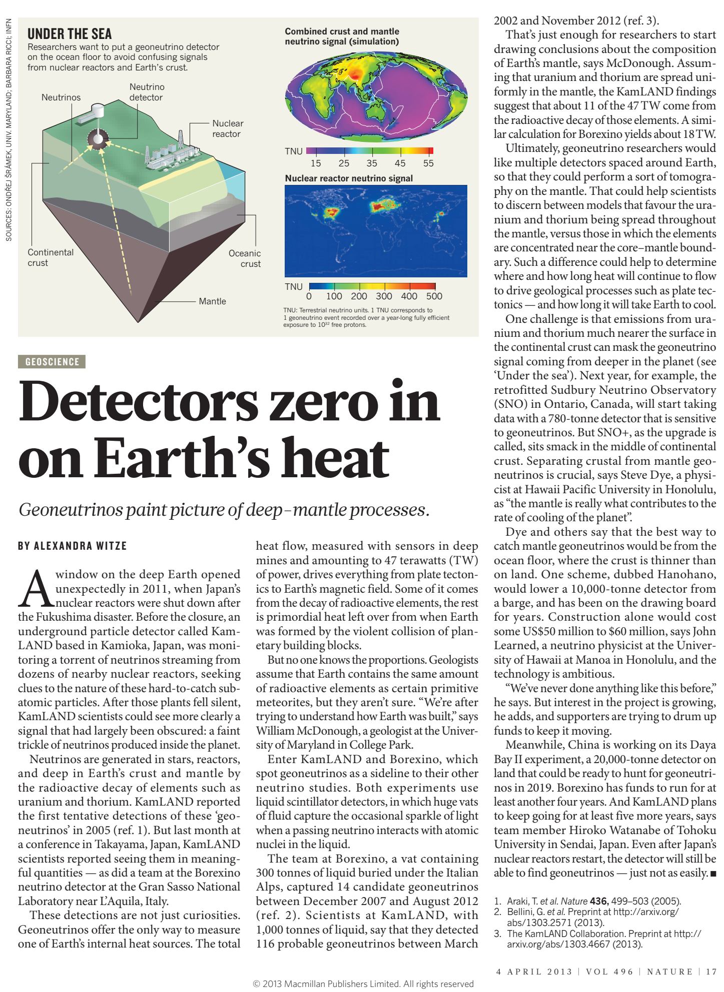
- **“ニュートリノ地球物理”推進**
  - * 国際会議開催
  - * 地球科学分野との国際的な協力関係
  - * global analysis (KamLAND + Borexino + Geology)

Nature News 2013.4.2

会議の成果が取り上げられる

http://www.nature.com/news/detectors-zero-in-on-earth-s-heat-1.12707

IN FOCUS NEWS



GEOSCIENCE

Detectors zero in on Earth's heat

Geoneutrinos paint picture of deep-mantle processes.

BY ALEXANDRA WITZE

A window on the deep Earth opened unexpectedly in 2011, when Japan's nuclear reactors were shut down after the Fukushima disaster. Before the closure, an underground particle detector called KamLAND based in Kamioka, Japan, was monitoring a torrent of neutrinos streaming from dozens of nearby nuclear reactors, seeking clues to the nature of these hard-to-catch subatomic particles. After those plants fell silent, KamLAND scientists could see more clearly a signal that had largely been obscured: a faint trickle of neutrinos produced inside the planet.

Neutrinos are generated in stars, reactors, and deep in Earth's crust and mantle by the radioactive decay of elements such as uranium and thorium. KamLAND reported the first tentative detections of these 'geoneutrinos' in 2005 (ref. 1). But last month at a conference in Takayama, Japan, KamLAND scientists reported seeing them in meaningful quantities — as did a team at the Borexino neutrino detector at the Gran Sasso National Laboratory near L'Aquila, Italy.

These detections are not just curiosities. Geoneutrinos offer the only way to measure one of Earth's internal heat sources. The total heat flow, measured with sensors in deep mines and amounting to 47 terawatts (TW) of power, drives everything from plate tectonics to Earth's magnetic field. Some of it comes from the decay of radioactive elements, the rest is primordial heat left over from when Earth was formed by the violent collision of planetary building blocks.

But no one knows the proportions. Geologists assume that Earth contains the same amount of radioactive elements as certain primitive meteorites, but they aren't sure. “We're after trying to understand how Earth was built,” says William McDonough, a geologist at the University of Maryland in College Park.

Enter KamLAND and Borexino, which spot geoneutrinos as a sideline to their other neutrino studies. Both experiments use liquid scintillator detectors, in which huge vats of fluid capture the occasional sparkle of light when a passing neutrino interacts with atomic nuclei in the liquid.

The team at Borexino, a vat containing 300 tonnes of liquid buried under the Italian Alps, captured 14 candidate geoneutrinos between December 2007 and August 2012 (ref. 2). Scientists at KamLAND, with 1,000 tonnes of liquid, say that they detected 116 probable geoneutrinos between March 2002 and November 2012 (ref. 3).

That's just enough for researchers to start drawing conclusions about the composition of Earth's mantle, says McDonough. Assuming that uranium and thorium are spread uniformly in the mantle, the KamLAND findings suggest that about 11 of the 47 TW come from the radioactive decay of those elements. A similar calculation for Borexino yields about 18 TW.

Ultimately, geoneutrino researchers would like multiple detectors spaced around Earth, so that they could perform a sort of tomography on the mantle. That could help scientists to discern between models that favour the uranium and thorium being spread throughout the mantle, versus those in which the elements are concentrated near the core–mantle boundary. Such a difference could help to determine where and how long heat will continue to flow to drive geological processes such as plate tectonics — and how long it will take Earth to cool.

One challenge is that emissions from uranium and thorium much nearer the surface in the continental crust can mask the geoneutrino signal coming from deeper in the planet (see 'Under the sea'). Next year, for example, the retrofitted Sudbury Neutrino Observatory (SNO) in Ontario, Canada, will start taking data with a 780-tonne detector that is sensitive to geoneutrinos. But SNO+, as the upgrade is called, sits smack in the middle of continental crust. Separating crustal from mantle geoneutrinos is crucial, says Steve Dye, a physicist at Hawaii Pacific University in Honolulu, as “the mantle is really what contributes to the rate of cooling of the planet”.

Dye and others say that the best way to catch mantle geoneutrinos would be from the ocean floor, where the crust is thinner than on land. One scheme, dubbed Hanohano, would lower a 10,000-tonne detector from a barge, and has been on the drawing board for years. Construction alone would cost some US$50 million to $60 million, says John Learned, a neutrino physicist at the University of Hawaii at Manoa in Honolulu, and the technology is ambitious.

“We've never done anything like this before,” he says. But interest in the project is growing, he adds, and supporters are trying to drum up funds to keep it moving.

Meanwhile, China is working on its Daya Bay II experiment, a 20,000-tonne detector on land that could be ready to hunt for geoneutrinos in 2019. Borexino has funds to run for at least another four years. And KamLAND plans to keep going for at least five more years, says team member Hiroko Watanabe of Tohoku University in Sendai, Japan. Even after Japan's nuclear reactors restart, the detector will still be able to find geoneutrinos — just not as easily. ■

1. Araki, T. *et al. Nature* **436,** 499–503 (2005).
2. Bellini, G. *et al.* Preprint at http://arxiv.org/abs/1303.2571 (2013).
3. The KamLAND Collaboration. Preprint at http://arxiv.org/abs/1303.4667 (2013).

▶まとめ

- 地球ニュートリノ世界初観測をはじめ、継続して成果を発表

  最新結果 : low-reactor phase, KamLAND-Zen phaseを含む解析結果を発表

- “ニュートリノ地球物理”という学際的分野を牽引

  地球科学分野との国際的•密な連携

- 今後

  low-reactorデータを引き続き取得

  KamLAND-Zenとの共存も可能

  U•Thの分離測定, 始原隕石の同定, マントル対流の特定

- 将来計画に向けて開発を継続