Overview of Current Geoneutrino Measurements and Their Impact on Geoscience

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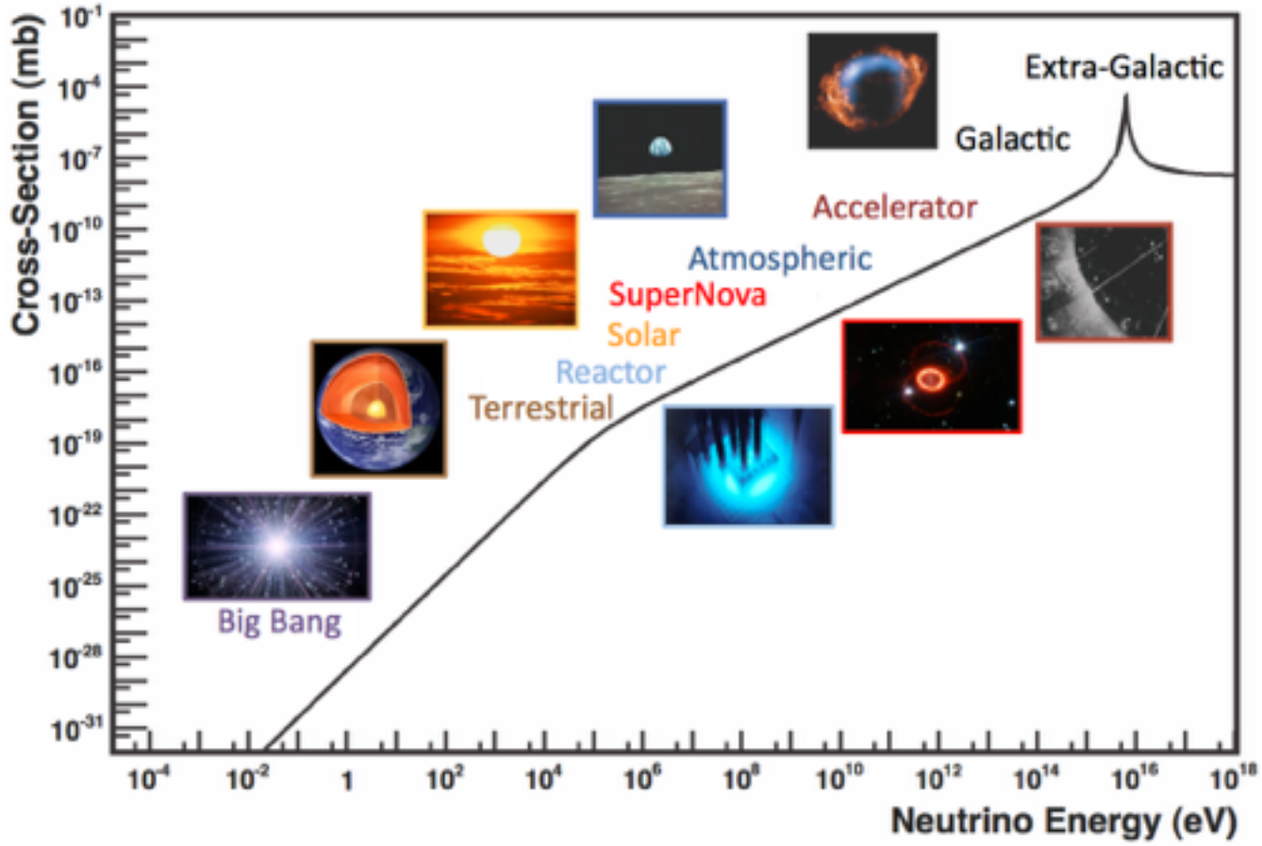
Neutrinos

- Neutrinos everywhere - second most abundant particle
- Neutrinos carry lot of information about universe
- And indeed about Earth!
- Not easy to get these information <- hard to detect



Number of detected neutrinos (N_ν):
$N_\nu \sim$ (Cross-section × Neutrino flux × Number of targets)

- Small for ν_{geo}'s
- Measurable for ν_{geo}'s
- Need to be large for ν_{geo}'s

Weak interactions are weak:

Golden Era of Neutrinos (Selection of Milestones)

2000 — DONUT discovers ν_τ

2001 — SNO resolves solar neutrino problem

2003 — SuperKamiokande discovers atmospheric neutrino oscillations

2004 — KamLAND discovers reactor neutrino oscillations

2005 — KamLAND measures geoneutrinos

2010 — BOREXINO measures geoneutrinos

2012 — Towards CP-violation in lepton sector:
Daya Bay reports non-zero θ_{13}

Geoneutrinos in One Slide

- Radionuclides in the Earth:

$$^{238}_{92}\mathrm{U} \longrightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_e + 51.689\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \longrightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 7\mathrm{e}^- + 7\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

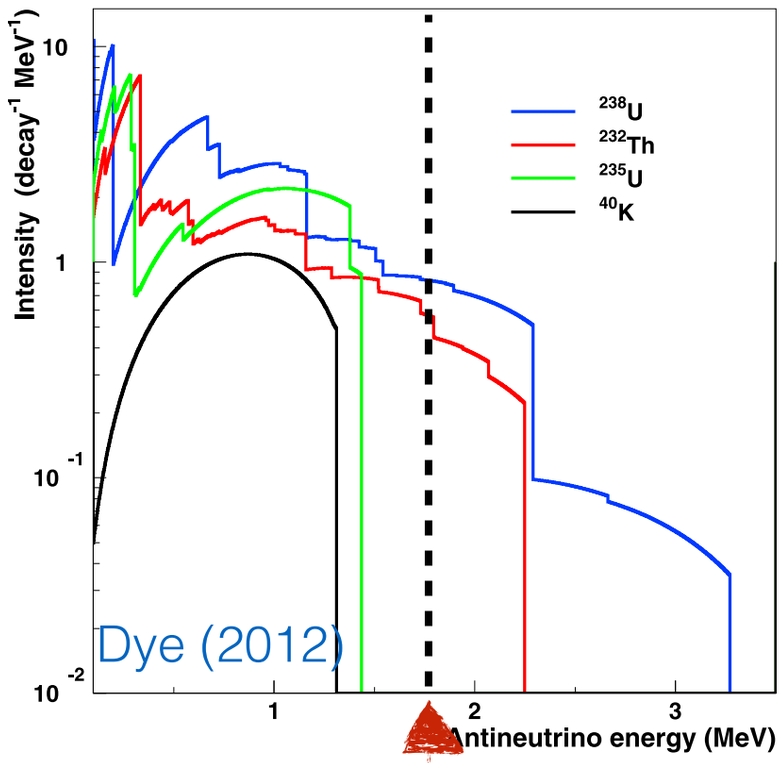
$$^{232}_{90}\mathrm{Th} \longrightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4\mathrm{e}^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} + \mathrm{e}^- \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

Geoneutrinos:
Mostly electron antineutrinos

Energy per decay chain
Part carried away by ν_{geo}'s
Rest is converted to heat



World of particle physicists ⟷ World of geoscience

Worlds linked - That's why we are here

Geoneutrino energy above IBD threshold

Inverse Beta Decay

- Inverse beta decay (IBD) - Only feasible method **of today and near future** for detection of ~MeV electron antineutrinos
- Strong in background rejection due to coincidence of prompt and delayed signal

Coincidence

Inverse beta decay:

Prompt signal

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

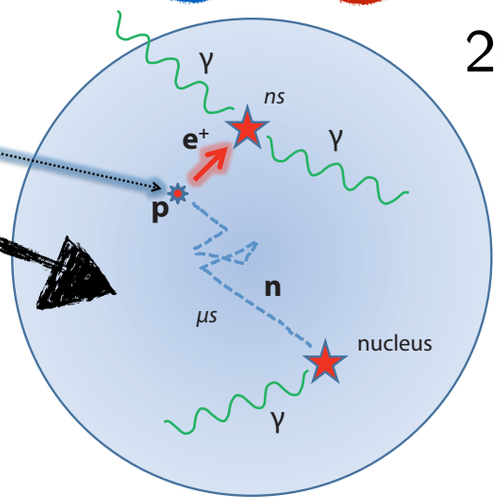
Delayed signal

$$30\ \mu s \rightsquigarrow n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s\ (8\ \text{MeV})$$

$$200\ \mu s \rightsquigarrow n + H \rightarrow D + \gamma\ (2.22\ \text{MeV})$$

Daya Bay

Organic liquid scintillator



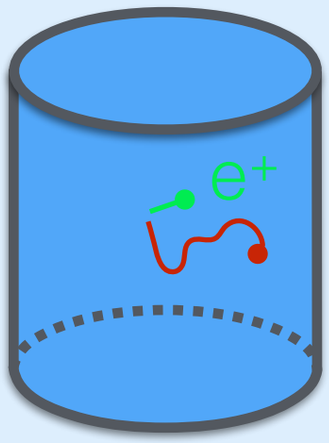
Daya Bay
KamLAND
Borexino
JUNO
Jinping

From kinematics: IBD has a threshold E_ν=1.8 MeV

IBD Backgrounds for Geoneutrinos

Neutrino:

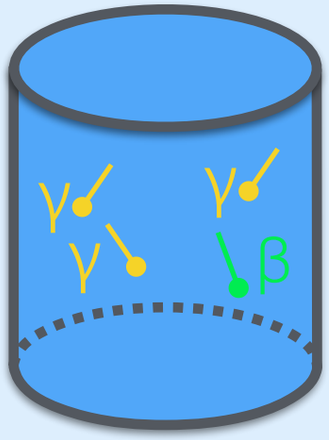
$\bar{\nu}_e + p$



Reactor antineutrinos
present everywhere on Earth

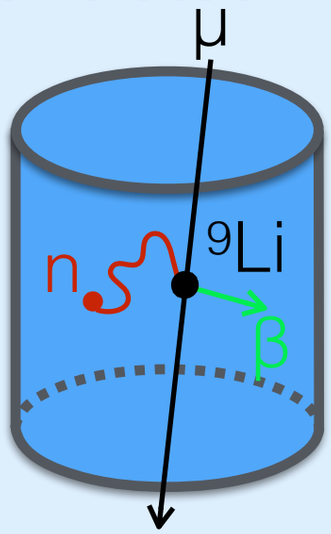
Non-neutrino:

Uncorrelated:

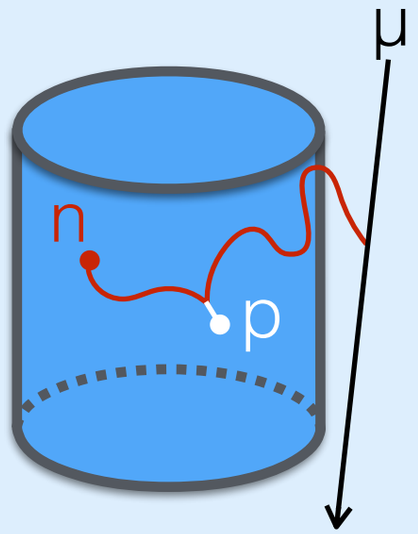


Accidental coincidence
of two independent events

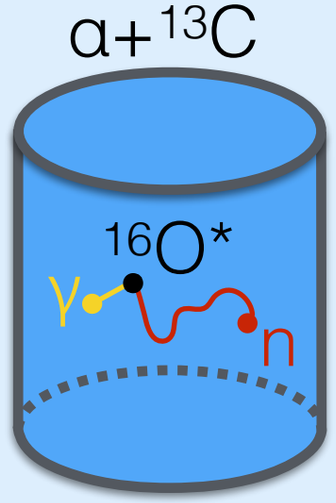
Correlated:



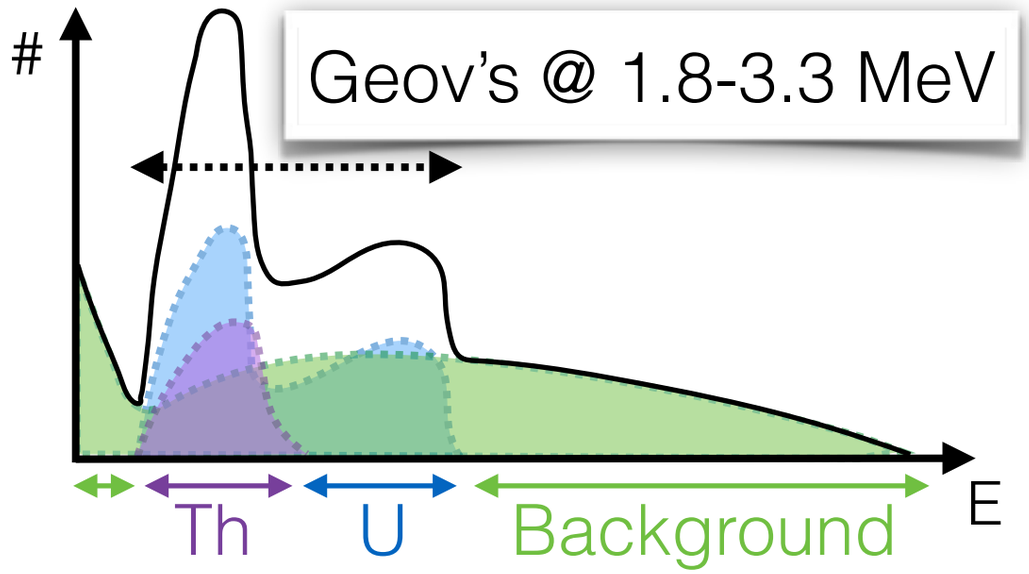
^{9}Li/^{8}He
Unstable spallation products induced by cosmic muons



Fast neutrons
Induced by untagged cosmic muons



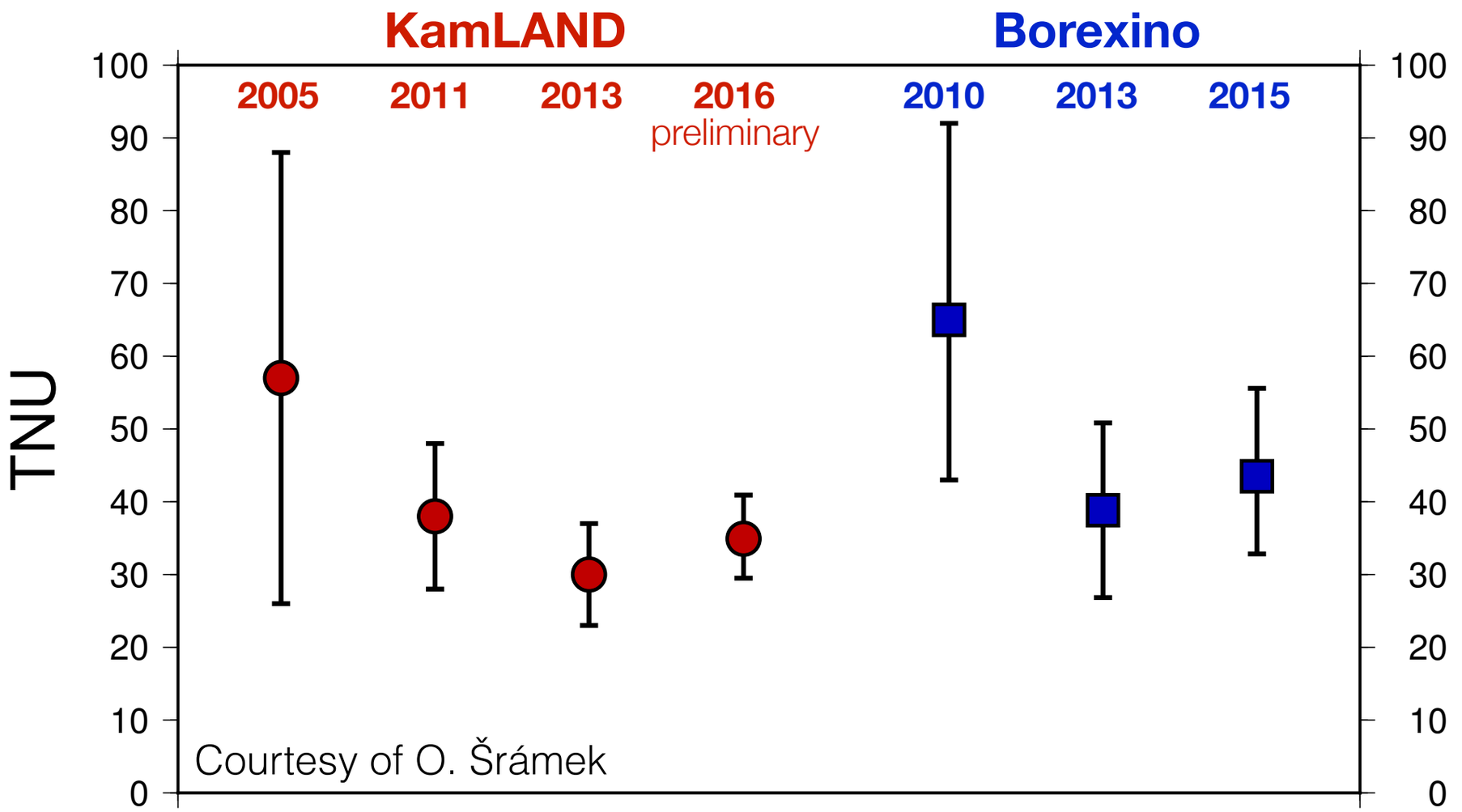
13C(α,n)16O
Induced by α interacting on carbon atoms

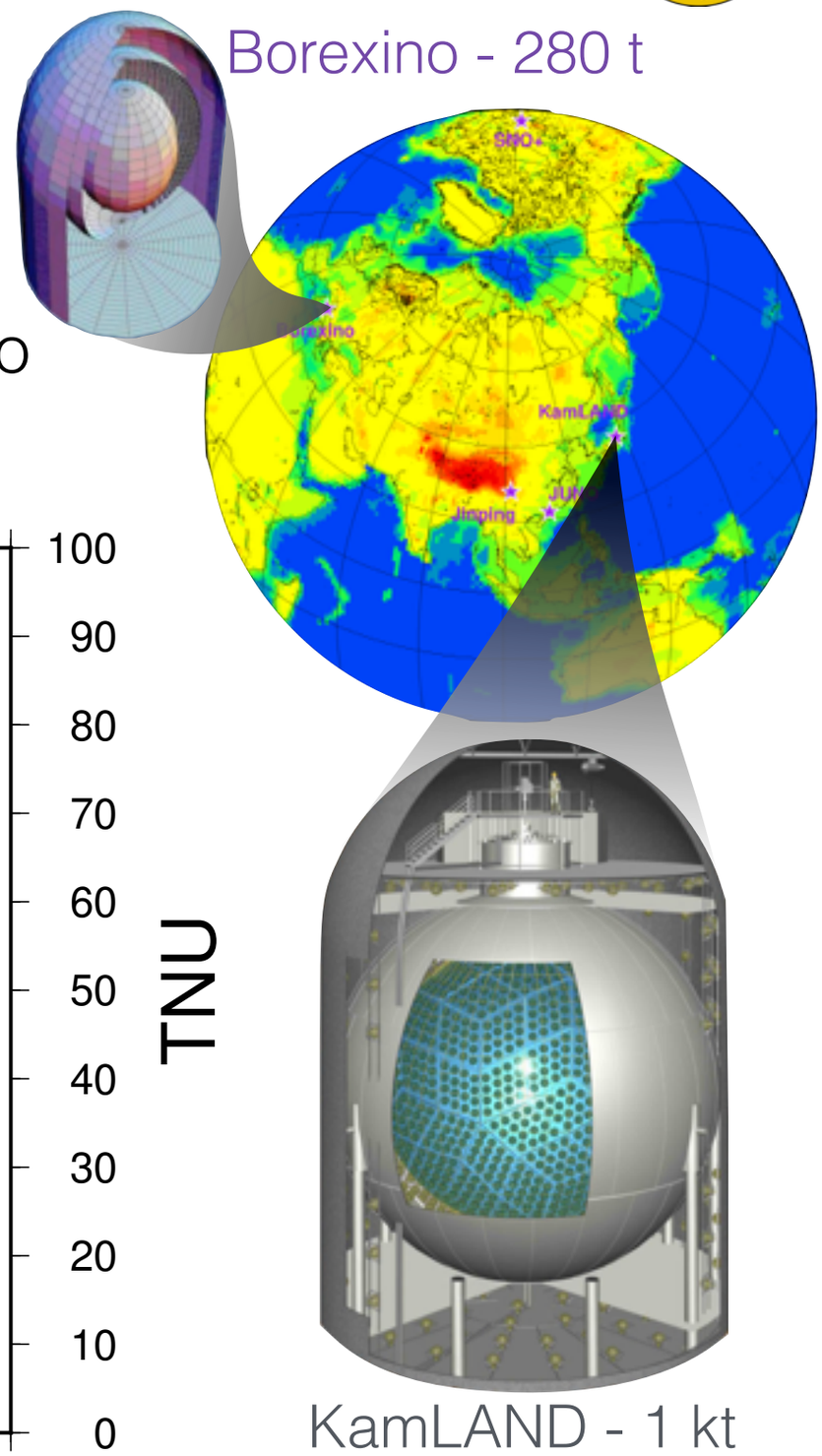


Background	How to tackle
Accidentals	Well-known
Cosmogenic background	Be deep underground
^{13}C(α,n)^{16}O	Purification of LS
Reactor neutrinos!	Be far from reactors

Geoneutrino Measurements so far

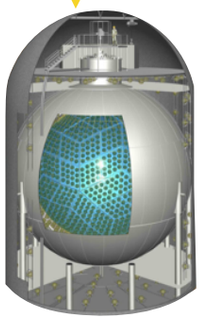
- 2005 - KamLAND - first to measure geo-ν's
- 2016 - KamLAND - best precision - 17% uncertainty
- Only two experiments so far: KamLAND and Borexino





1 TNU (Terrestrial Neutrino Unit) = 1 event detected by IBD per year on 10^{32} protons

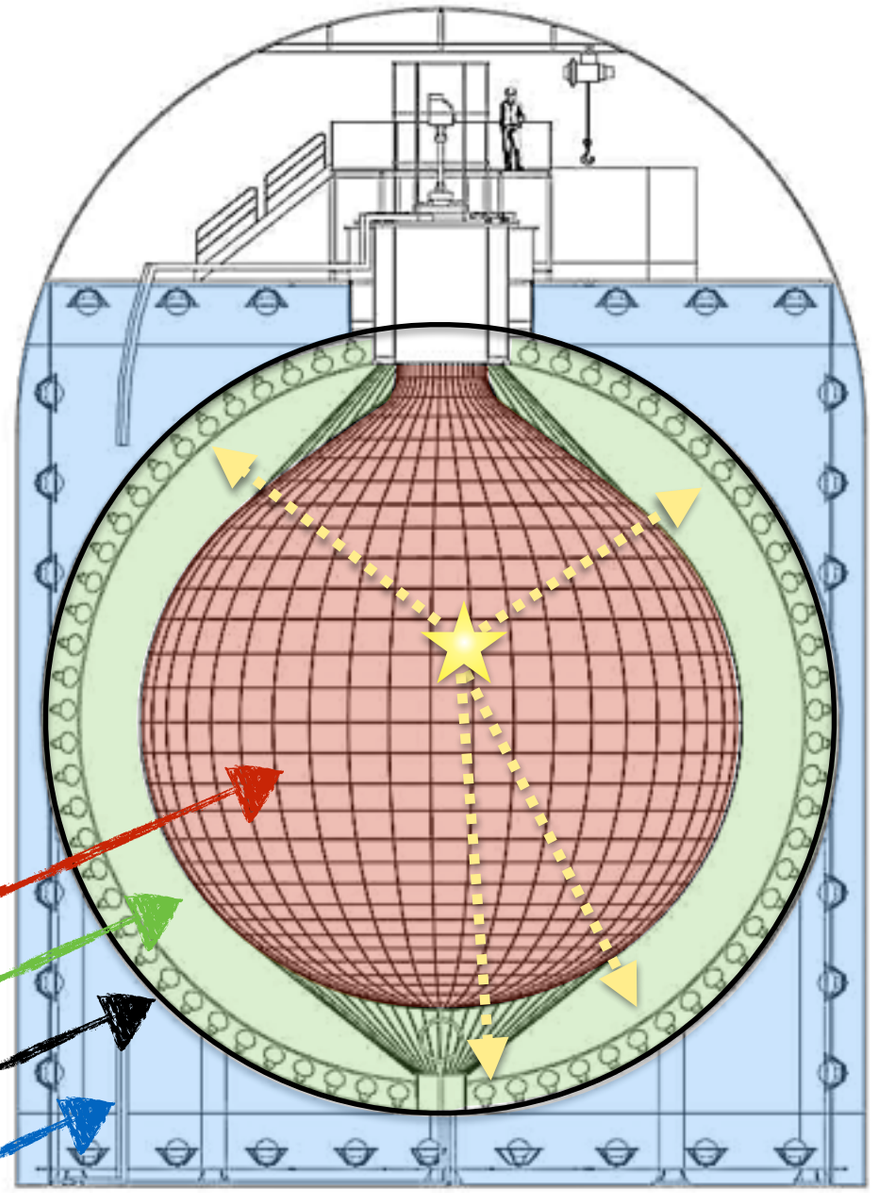
KamLAND Experiment



Japan

KamLAND - **Kam**ioka **L**iquid
Scintillator **A**nti**n**eutrino **D**etector

Detector design:

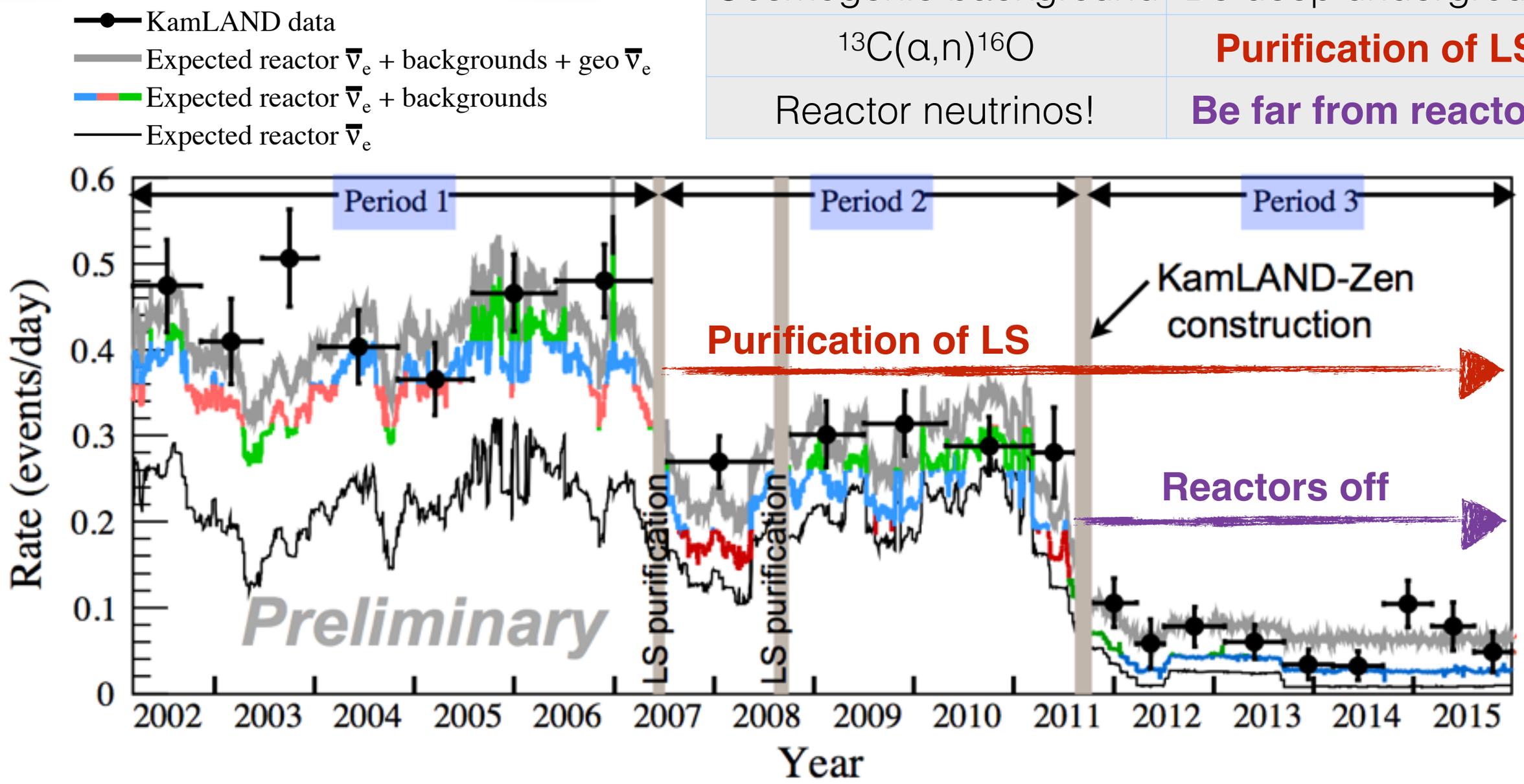


Target volume: 1 kt LS
Mineral oil with PMTs
Stainless steel vessel
Water pool with PMTs

Event Rate for Signal Energy Window*

Signal window:
Prompt energy 0.9 - 2.6 MeV ≡
Antineutrino energy 1.6 - 3.4 MeV

Background	How to tackle
Accidentals	Well-known
Cosmogenic background	Be deep underground
$^{13}C(\alpha,n)^{16}O$	**Purification of LS**
Reactor neutrinos!	**Be far from reactors**



*Watanabe (KamLAND Collaboration): tfc.tohoku.ac.jp/event/4131.html

KamLAND Latest Geoneutrino Result (1)*

2016 Preliminary Result

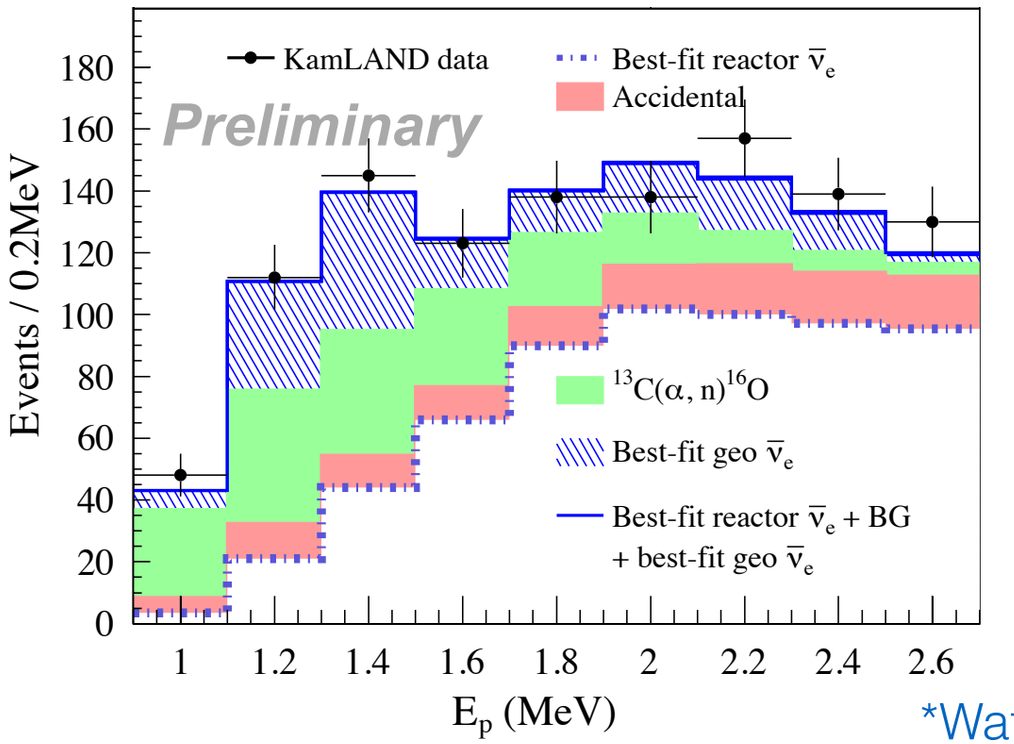
Livetime : 3900.9 days

Candidate : 1130 ev

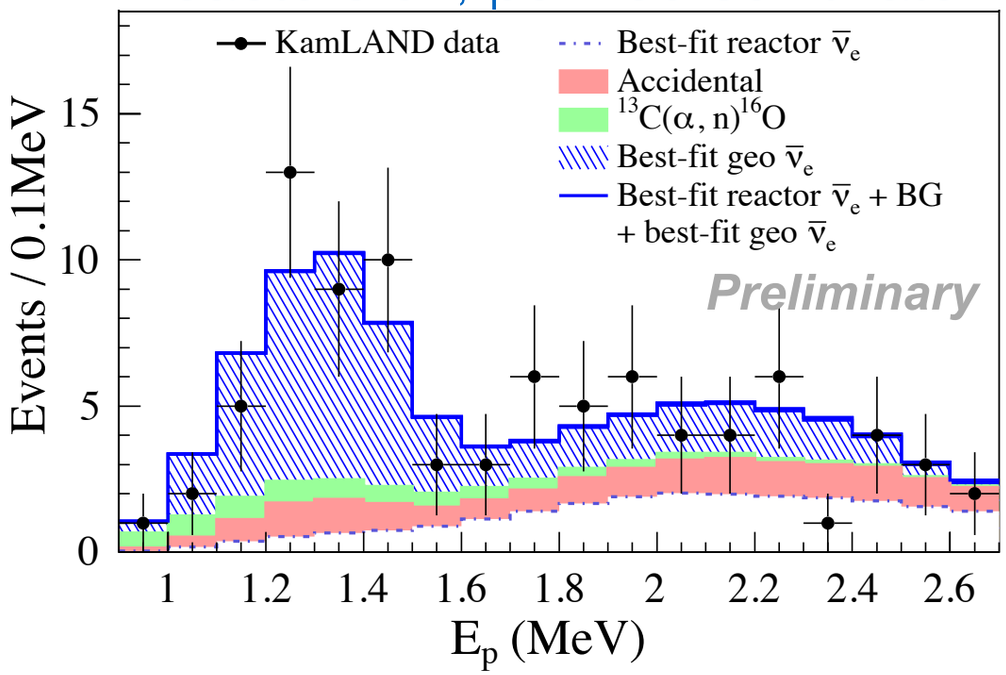
Background Summary

^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
^{13}C(α, n)^{16}O	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

Background	How to tackle
Accidentals	Well-known
Cosmogenic background (fast neutrons, ^{9}Li/^{8}He)	Be deep underground
^{13}C(α,n)^{16}O	**Purification of LS**
Reactor neutrinos!	**Reactors off**



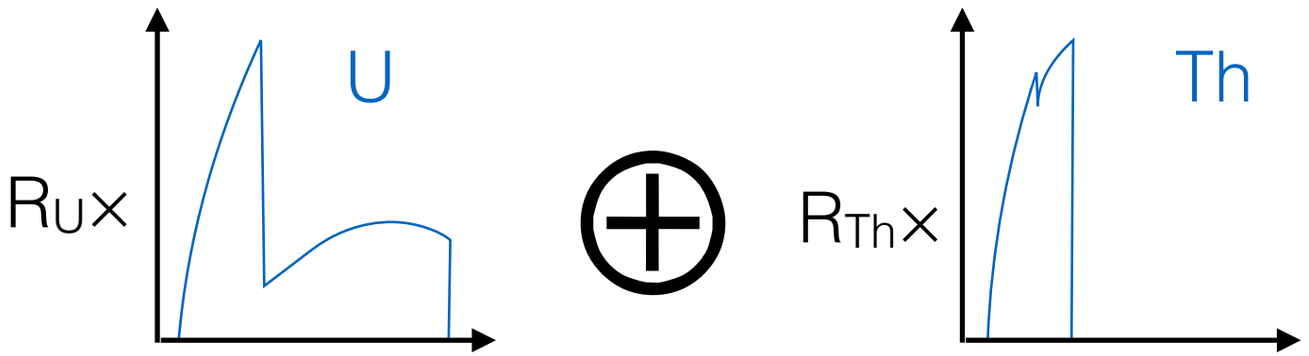
Zoom in 1259.8 days:
Reactors off, purified scintillator

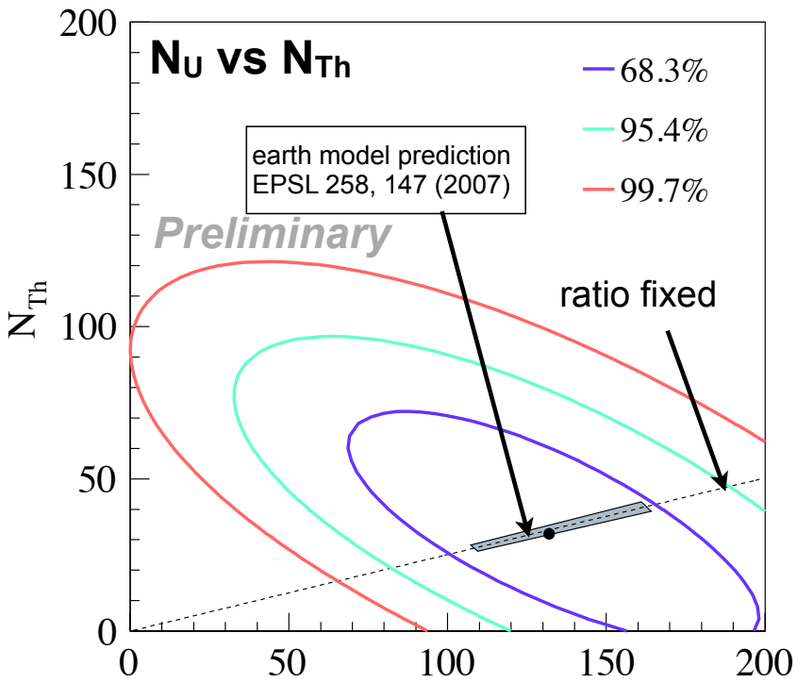


*Watanabe (KamLAND Collaboration): tfc.tohoku.ac.jp/event/4131.html

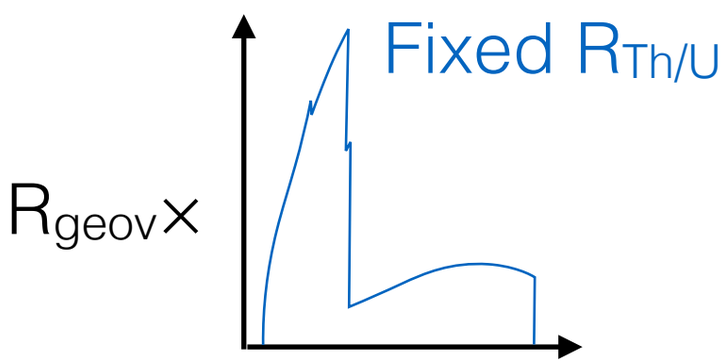
KamLAND Latest Geoneutrino Result (2)*

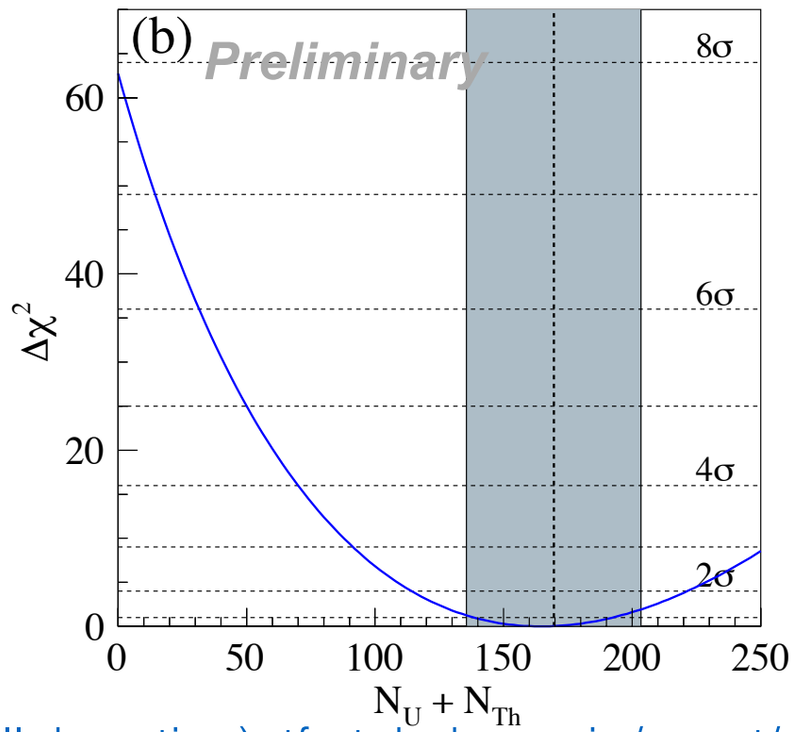
	[event]	[TNU]	Flux [×10^5 cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U	**128 +46/-39**	27.1 +9.8/-8.3	20.8 +7.5/-6.4	22.0	**3.44σ**
Th	**32 +27/-23**	6.9 +5.9/-5.0	17.2 +14.5/-12.5	18.6	**1.34σ**





	[event]	[TNU]	Flux [×10^6 cm^{-2}s^{-1}]		0 signal rejection
			best-fit	model	
U+Th	**164 +28/-25 (17%)**	34.9 +6.0/-5.4	3.9 +0.7/-0.6	4.1	**7.92σ**





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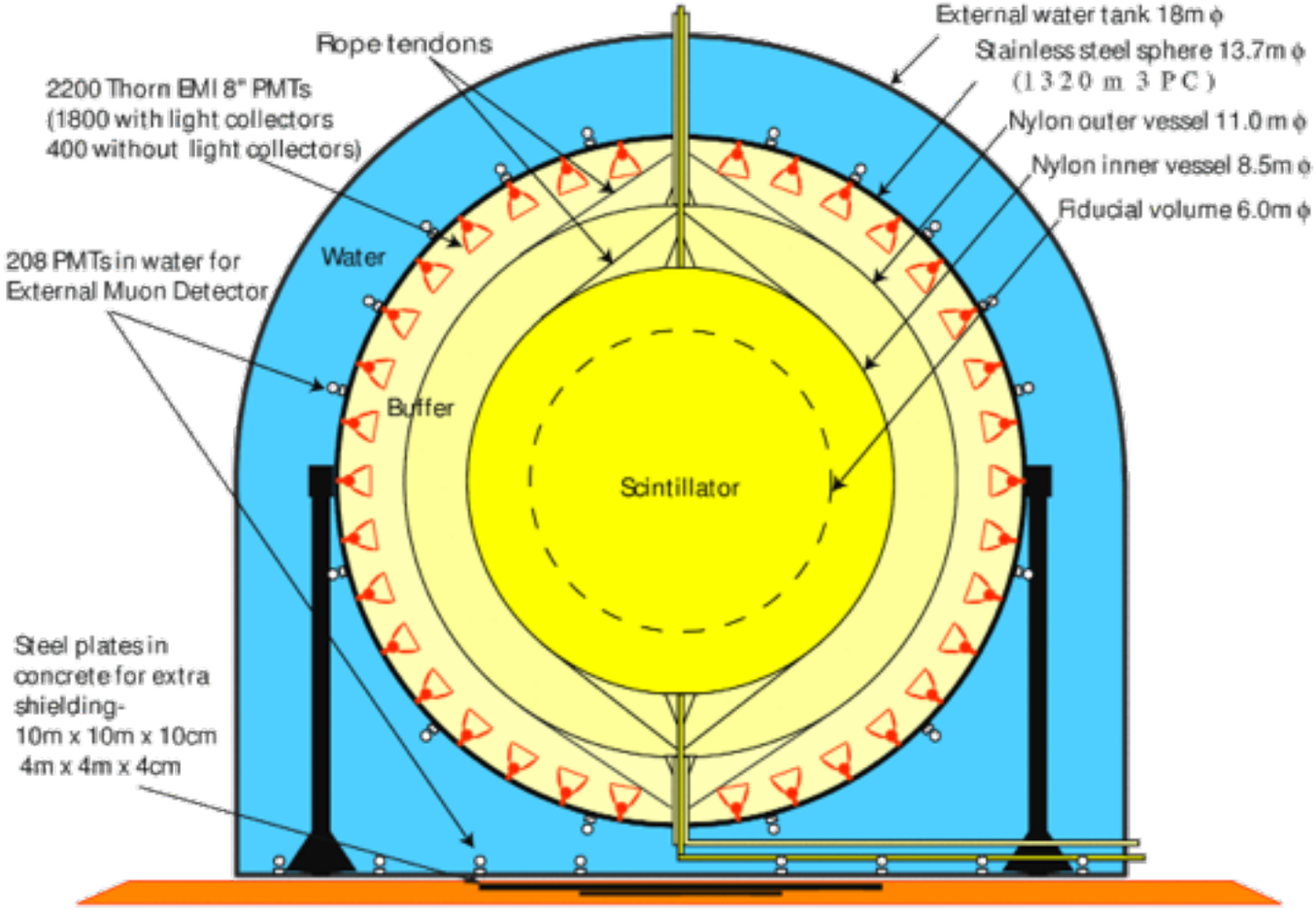
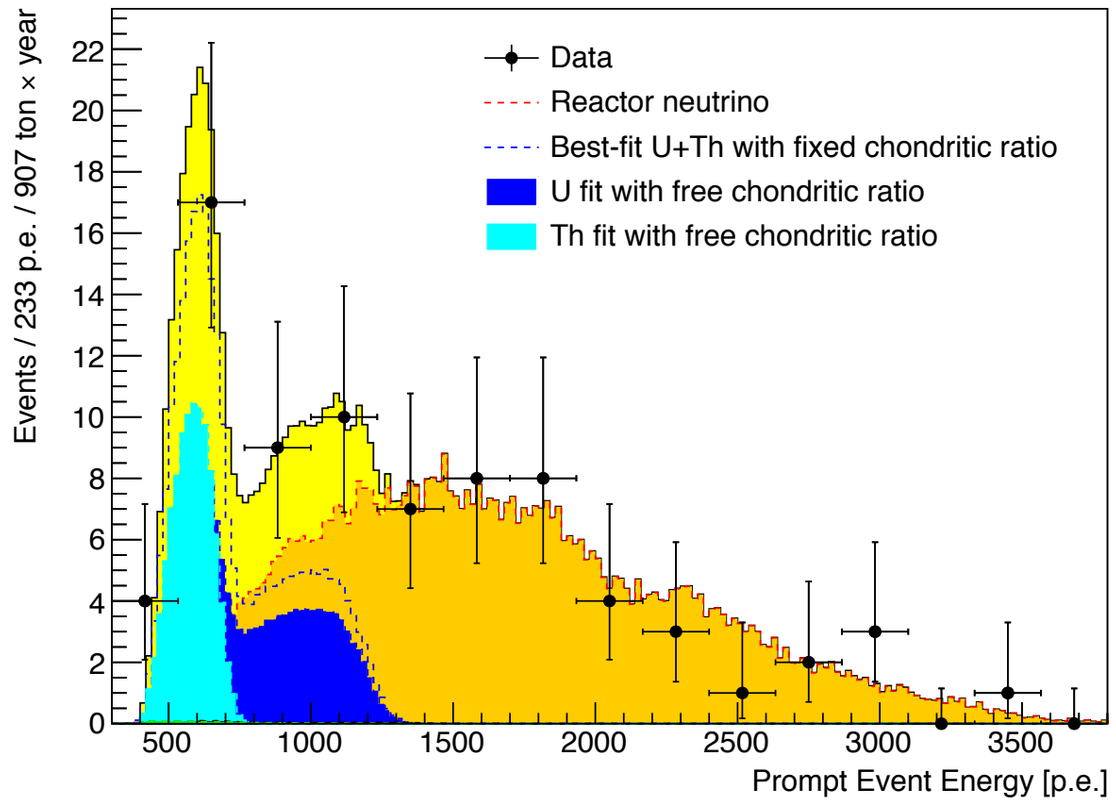
BOREXINO in One Slide

- Much better purity of LS than KL
- Smaller mass (280 t of LS) compare to KL
- Uncertainty ~26%

	[events]	[TNU]	0 signal rejection
U+Th	$23.7^{+6.5}_{-5.7}(stat)^{+0.9}_{-0.6}(sys)$	$43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(sys)$	**5.9σ**





The Impact of Geoneutrino Measurements on (Geo)science

- Successes
  - **We measured geoneutrinos!!!**
  - We observed neutrino flavor changing in geoneutrinos
- Call for improvement of the precision
  - Independent measurement of U and Th flux not there yet
  - Needed for determination of ratio $R_{Th/U}$
  - KamLAND and BOREXINO measurements consistent with uniform flux
  - Breakdown to Crust&Mantle contribution unknown

Unprecedented Achievement in 1953

- 29.5.1953 - Sir Edmund Hillary and Tenzing Norgay reached as the first men the top of Mt. Everest

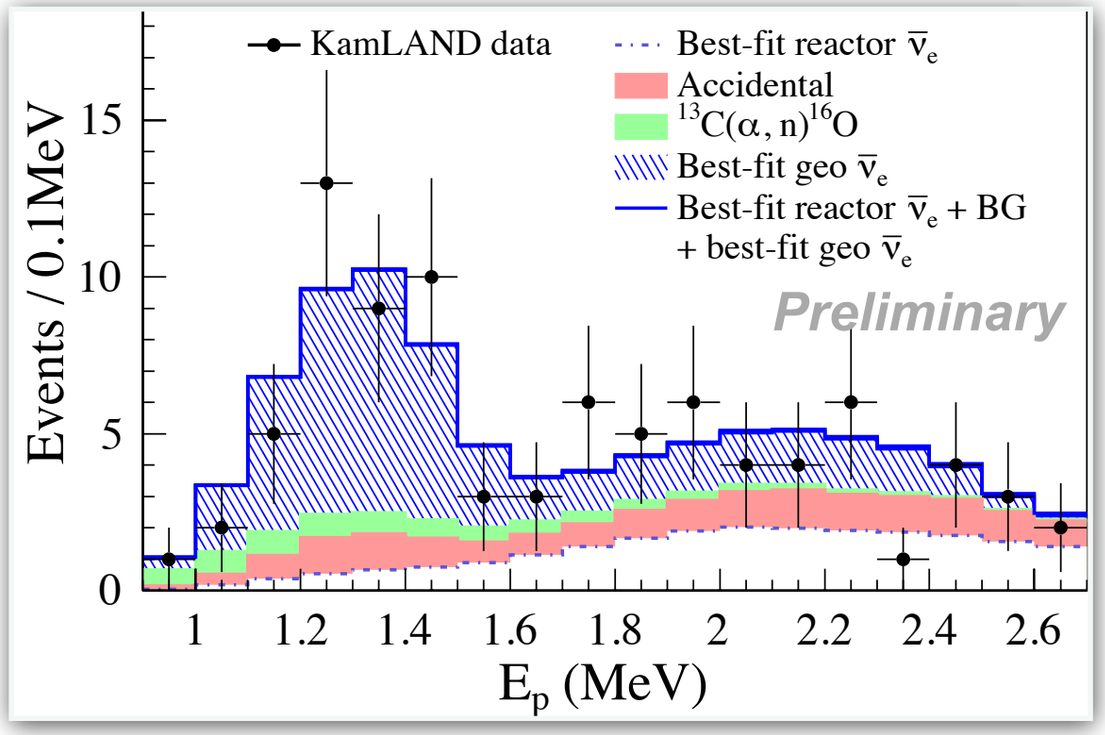
- They boldly went where no man has gone before
- Sure it was not easy

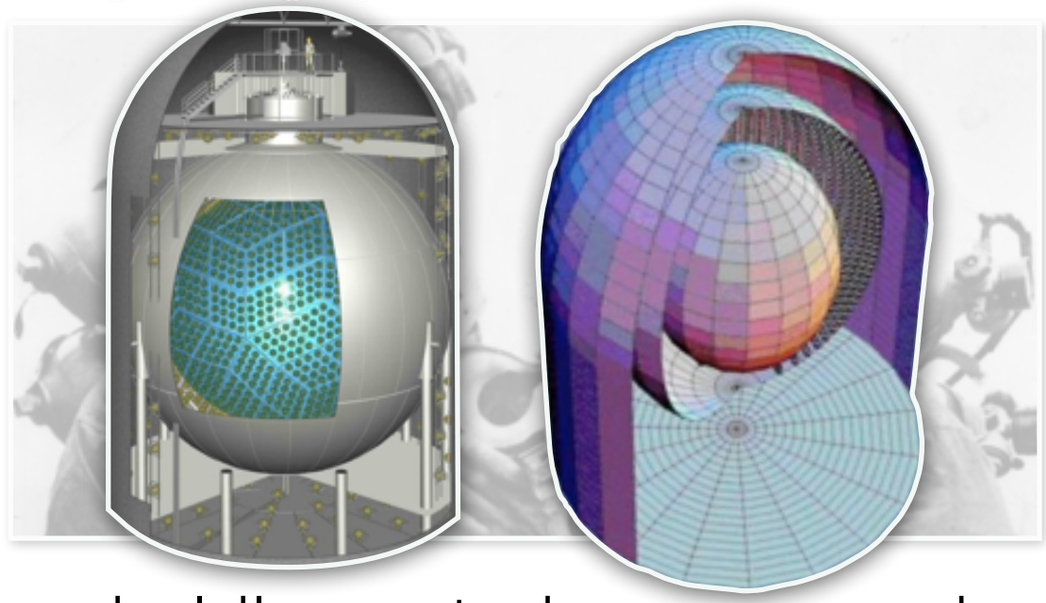
- They show the way, what can be done
- They show the way for they followers
- History will always remember them

Unprecedented Achievement in 1953 2005/2010

- 28.5.1953 - Sir Edmund Hillary and Tenzing Norgay reached as the first men the top of Mt. Everest 2005/2010 KamLAND BOREXINO measured

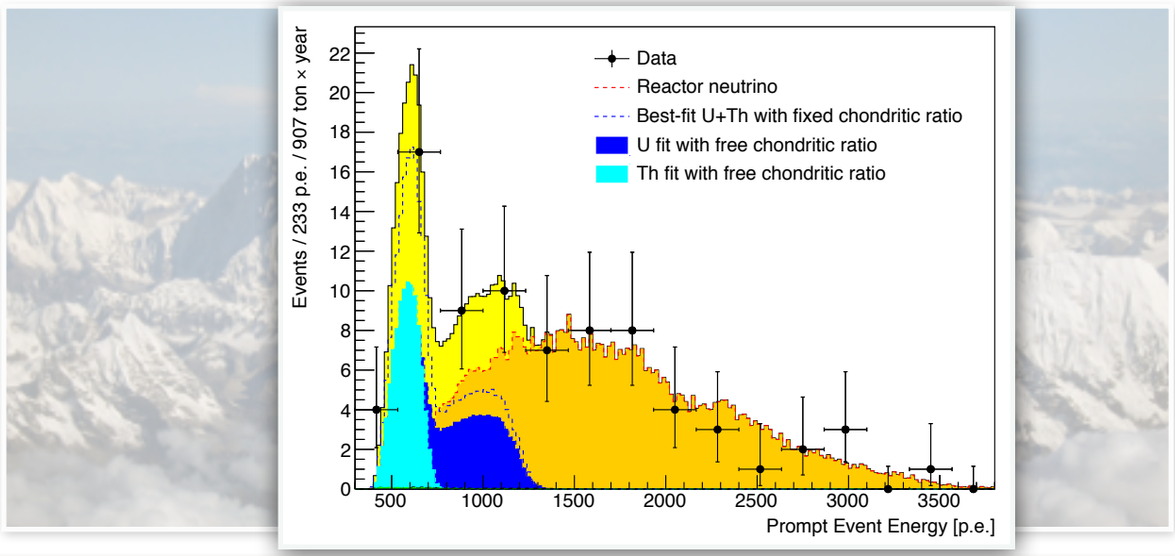
experiments geoneutrinos





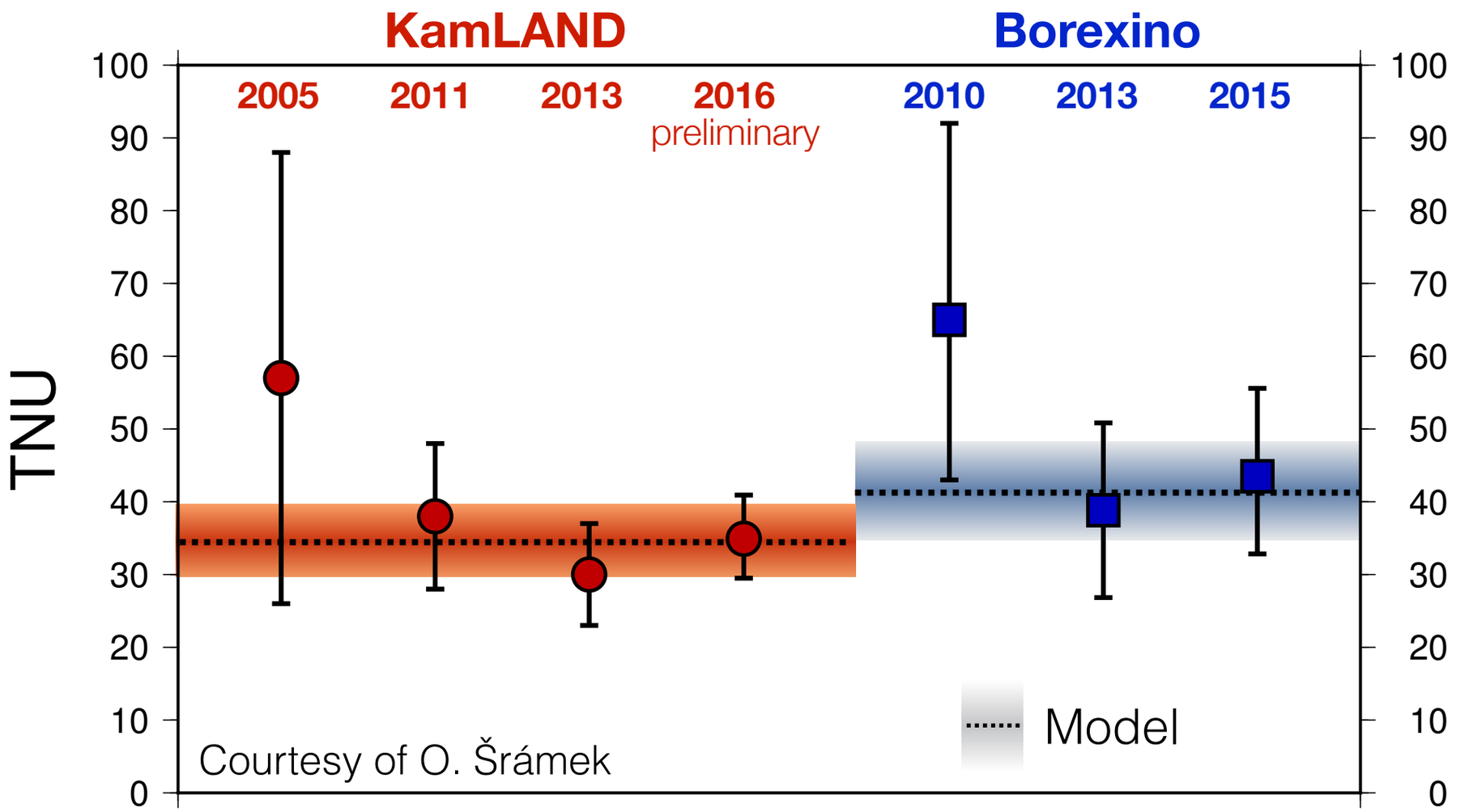
- They boldly went where no man has gone before
- Sure it was not easy

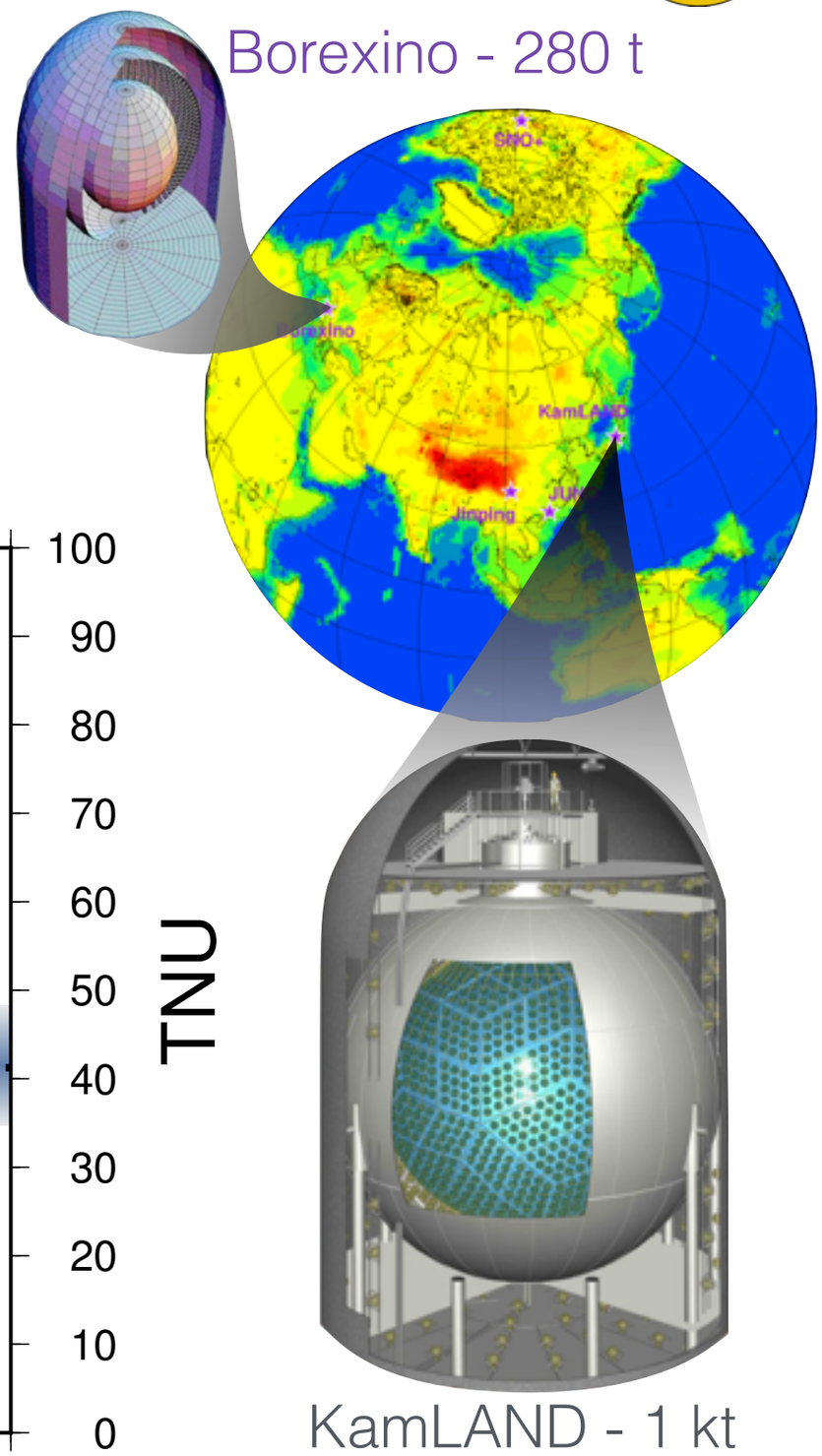
- They show the way, what can be done
- They show the way for they followers
- History will always remember them
- Foundations of new field:
  GEONEUTRINO PHYSICS



Prediction vs. Measurement

- 2005 - KamLAND - first to measure geo-ν's
- 2016 - KamLAND - best precision - 17% uncertainty
- Prediction uncertainty ~14%





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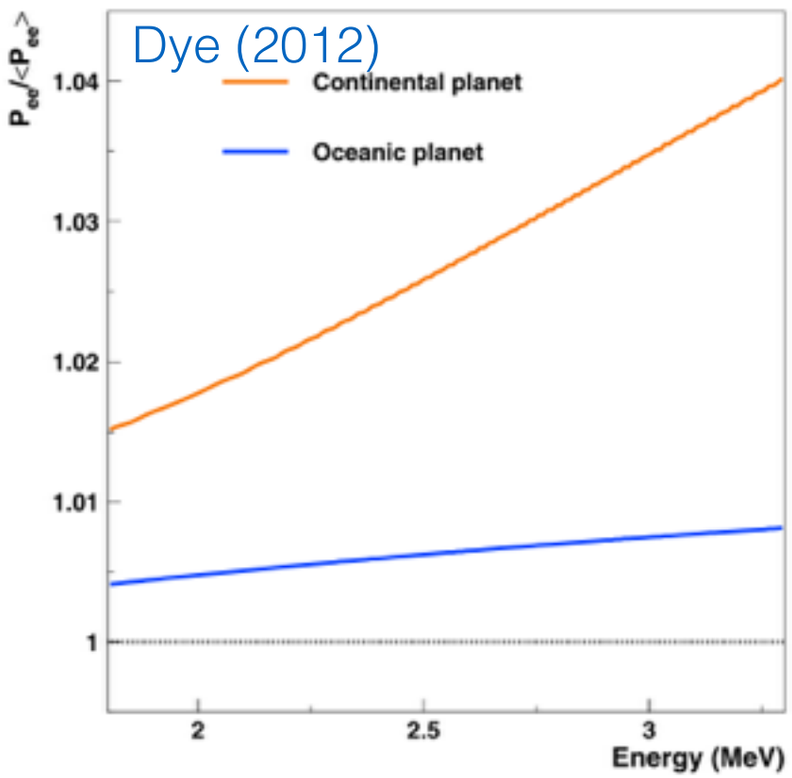
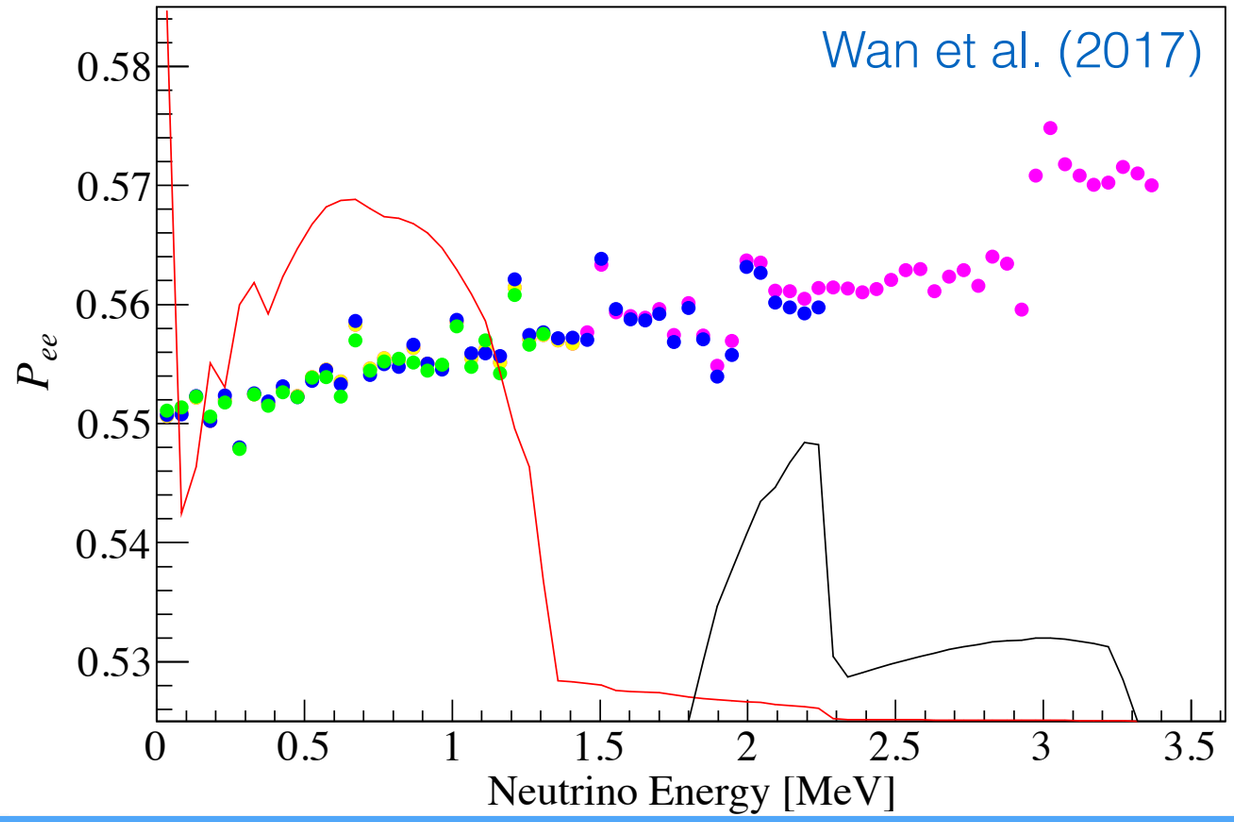
Flavor Changing in Geoneutrinos

- (Geo)neutrinos do oscillate!
  See Wang Yifang talk

$$\frac{d\phi(\vec{r},E)}{dE} = n(E)\int \frac{P(E,|\vec{r}-\vec{r}'|)}{4\pi|\vec{r}-\vec{r}'|^2}\frac{XN_A}{\tau\, A_r} f_m(\vec{r}')\rho(\vec{r}')d\vec{r}'$$

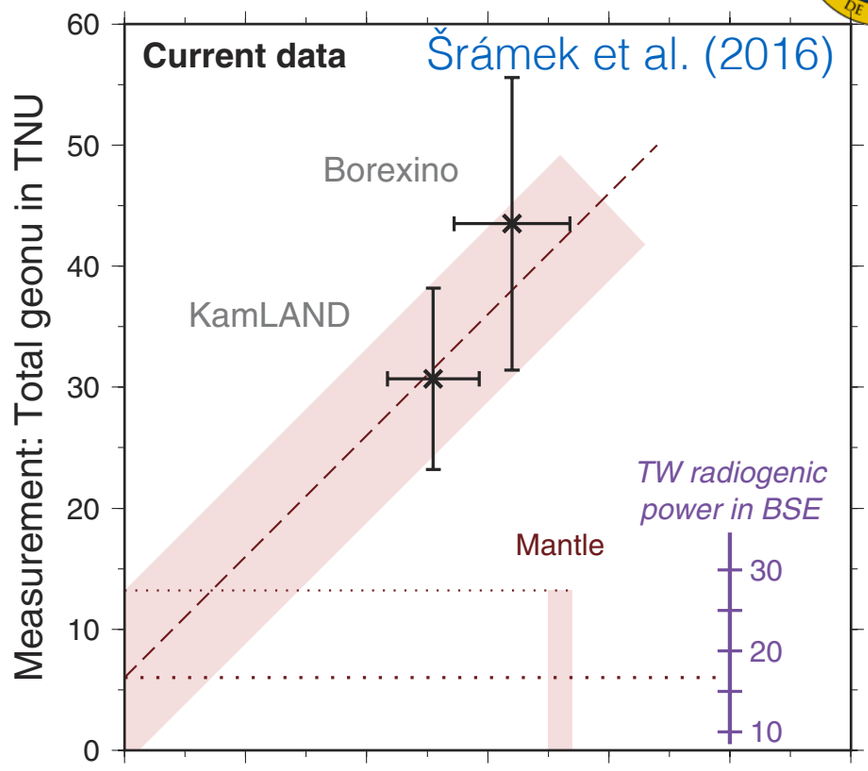
- $\langle P(\bar{\nu}_e \rightarrow \bar{\nu}_e)\rangle = 0.544$ - If there are no oscillations -> double flux
- Measurement (particle physics) being consistent with prediction (geophysics) is yet another demonstration of neutrino flavor changing!
- Can we even see oscillations? Eventually…





Call for Precise Measurement (1)

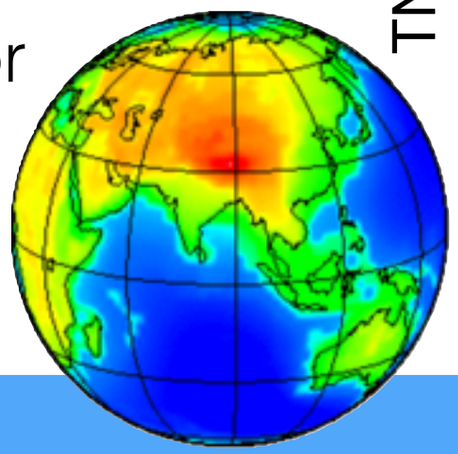
- Crust&Mantle contributions unknown
- Mantle contribution = Heat sources in mantle
- Relevant for power of Earth mantle dynamics
- See very interesting talk from Ondřej Šrámek

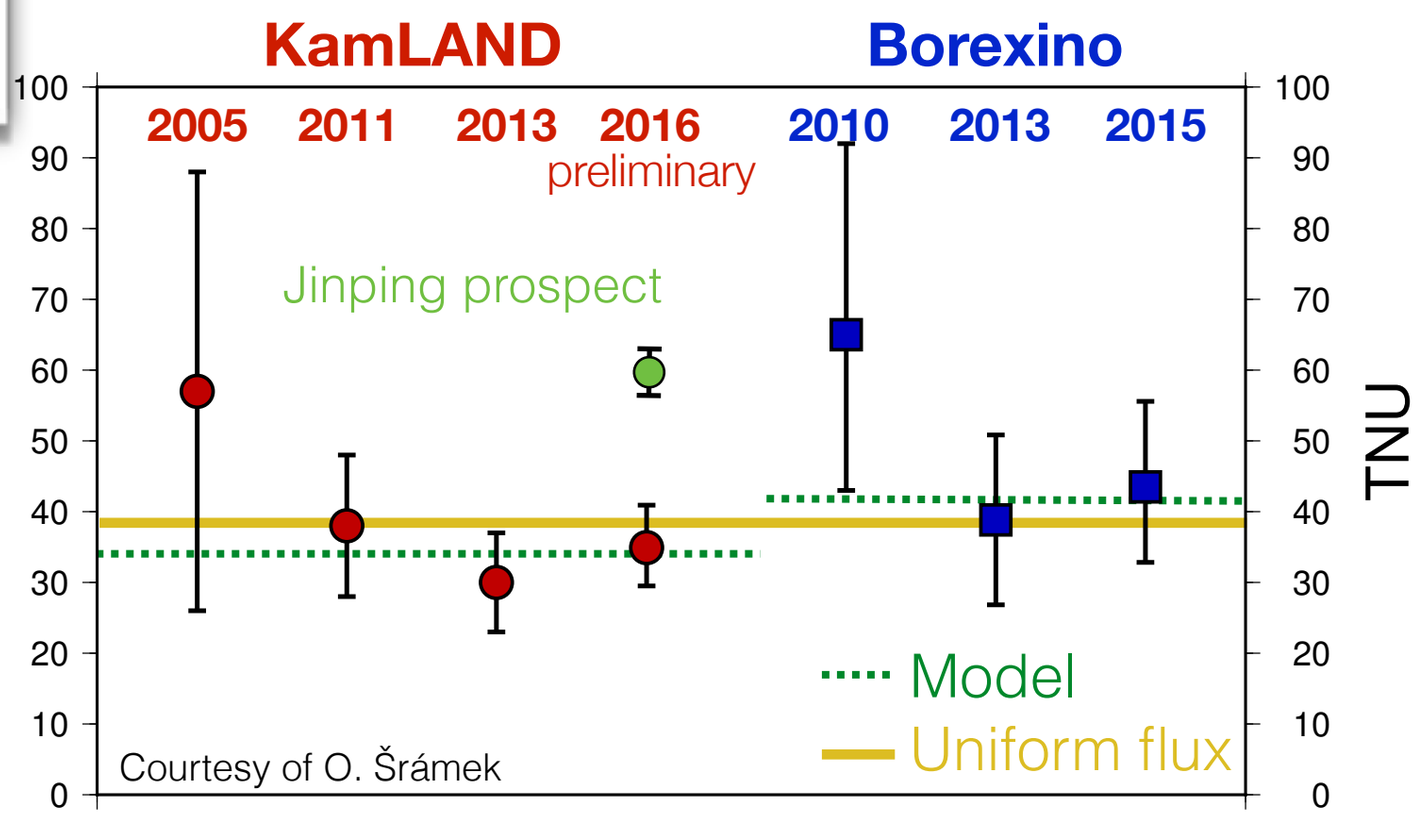


Proposed Jinping experiment will resolve these issues

see very interesting talk from Wang Zhe

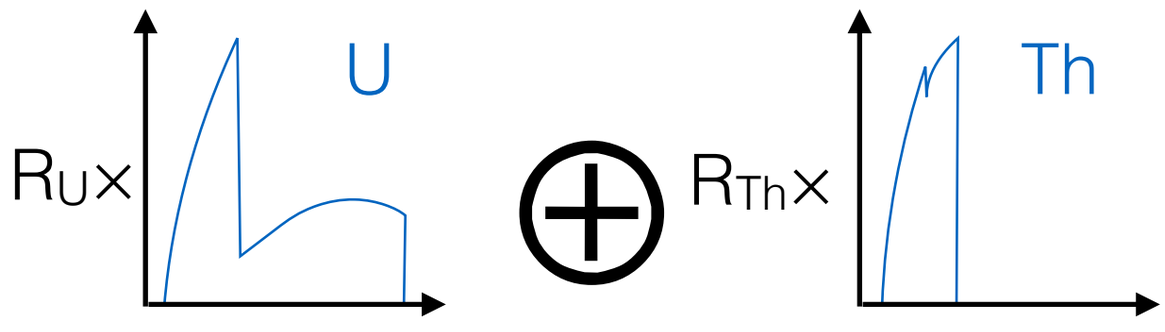
- Current measurements consistent with uniform flux
- Precision measurement at location with low or high flux needed



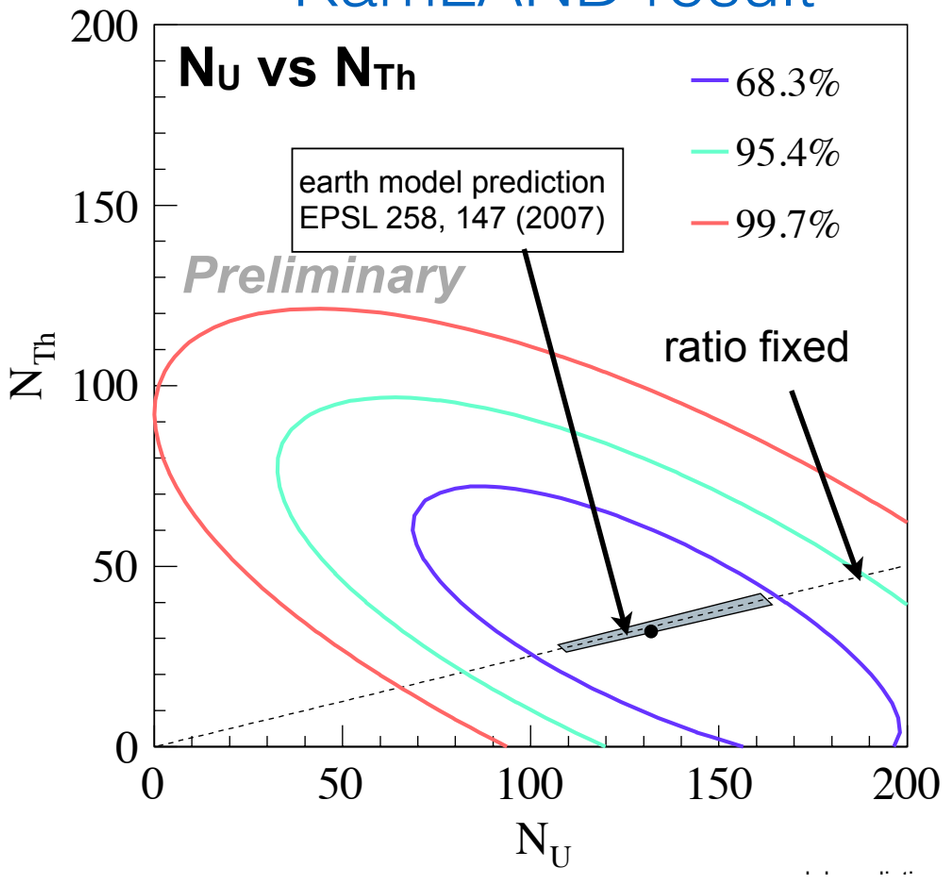


Call for Precise Measurement (2)

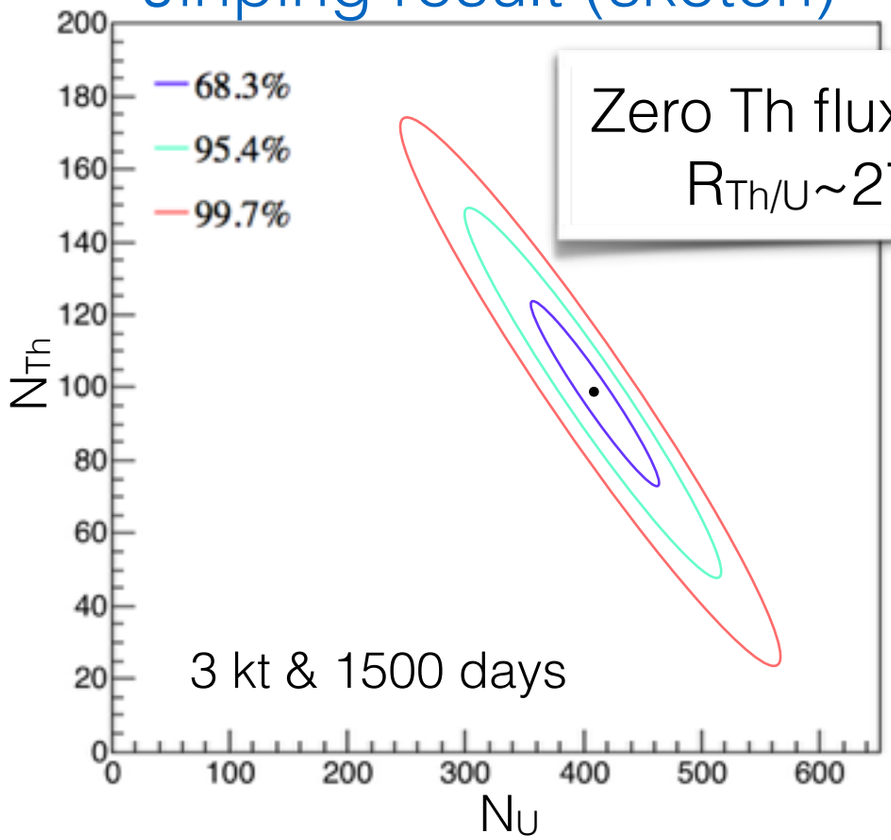
- Independent fit of Th and U flux: Proper way how to analyse data
- Current results not sufficient
  - Th flux consistent with zero
  - Large uncertainty on $R_{Th/U}$



KamLAND result



Jinping result (sketch)



Zero Th flux excluded on ~4σ
$R_{Th/U}$~27% uncertainty

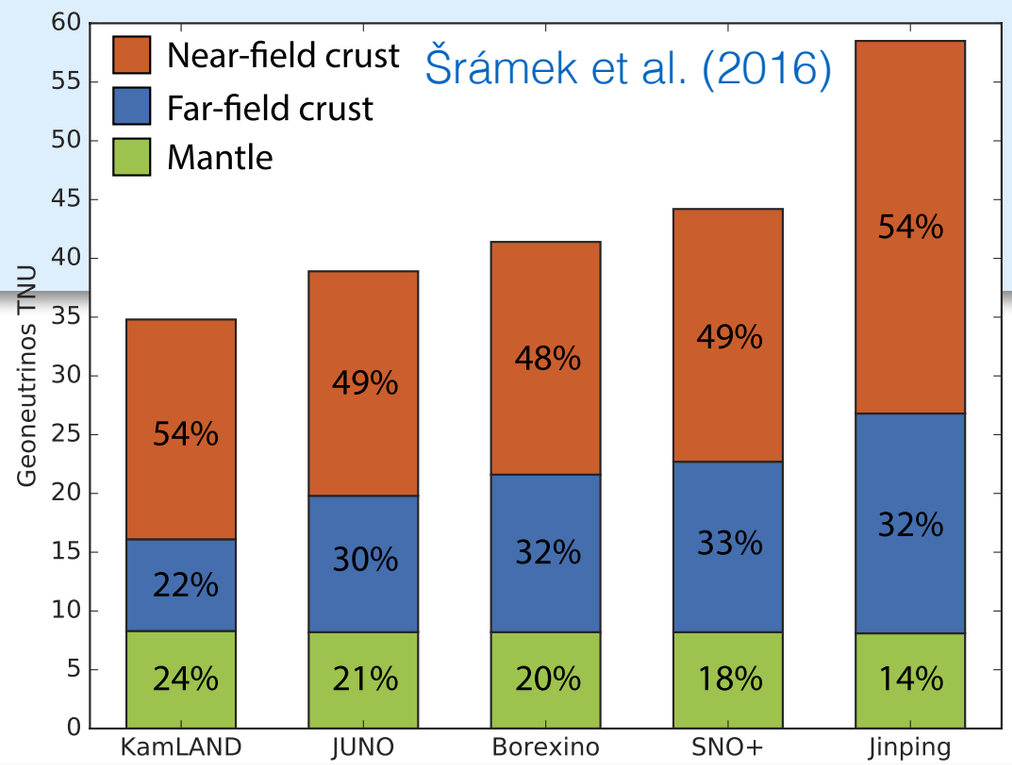
Roadmap to the Future

- Geoneutrinos can reveal the contribution of cooling/heat sources to the drive of Earth dynamics - depends on radionuclides in the mantle

Today

Prediction:

Current prediction:
~13% uncertainty



Measurement:

Current measurements:
>17% uncertainty

Local crust model
(L≲300 km):
Input from various
geophysicist fields

Tomorrow

Future prediction:
~7% uncertainty

Even single measurement
can improve the model

Future measurements:
~5% uncertainty

Combination of prediction
and measurements:
Mantle heat production

Conclusions

- **Geoneutrinos were measured by KamLAND and BOREXINO**
- The foundation of the experimental geoneutrino physics has been laid
- Geoneutrinos carry information about Earth's interior
- **Precise measurements** as well as **precise predictions** needed to access to this information
- The message is positive - we know how to do both (See talks of other speakers)