Международная конференция по проблемам регистрации геонейтрино и модели Земли

The 7th Neutrino Geoscience international conference 2019

В. В. Синев

Сайт конференции:

https://neutrinogeoscience2019.amca.cz/main/home

Prague, 21-23 October 2019

Past meetings

Neutrino Sciences 2005, Neutrino Geophysics, Honolulu, Hawaii, 14–16 December 2005

Neutrino Sciences 2007, Deep Ocean Anti-Neutrino Observatory Workshop, Honolulu, Hawaii, 23–25 March 2007

Neutrino Geoscience 2008 at SNOLAB, Sudbury, Ontario, Canada, 17–19 September 2008

Neutrino Geoscience 2010, Gran Sasso National Laboratory, Italy, 6–8 October 2010

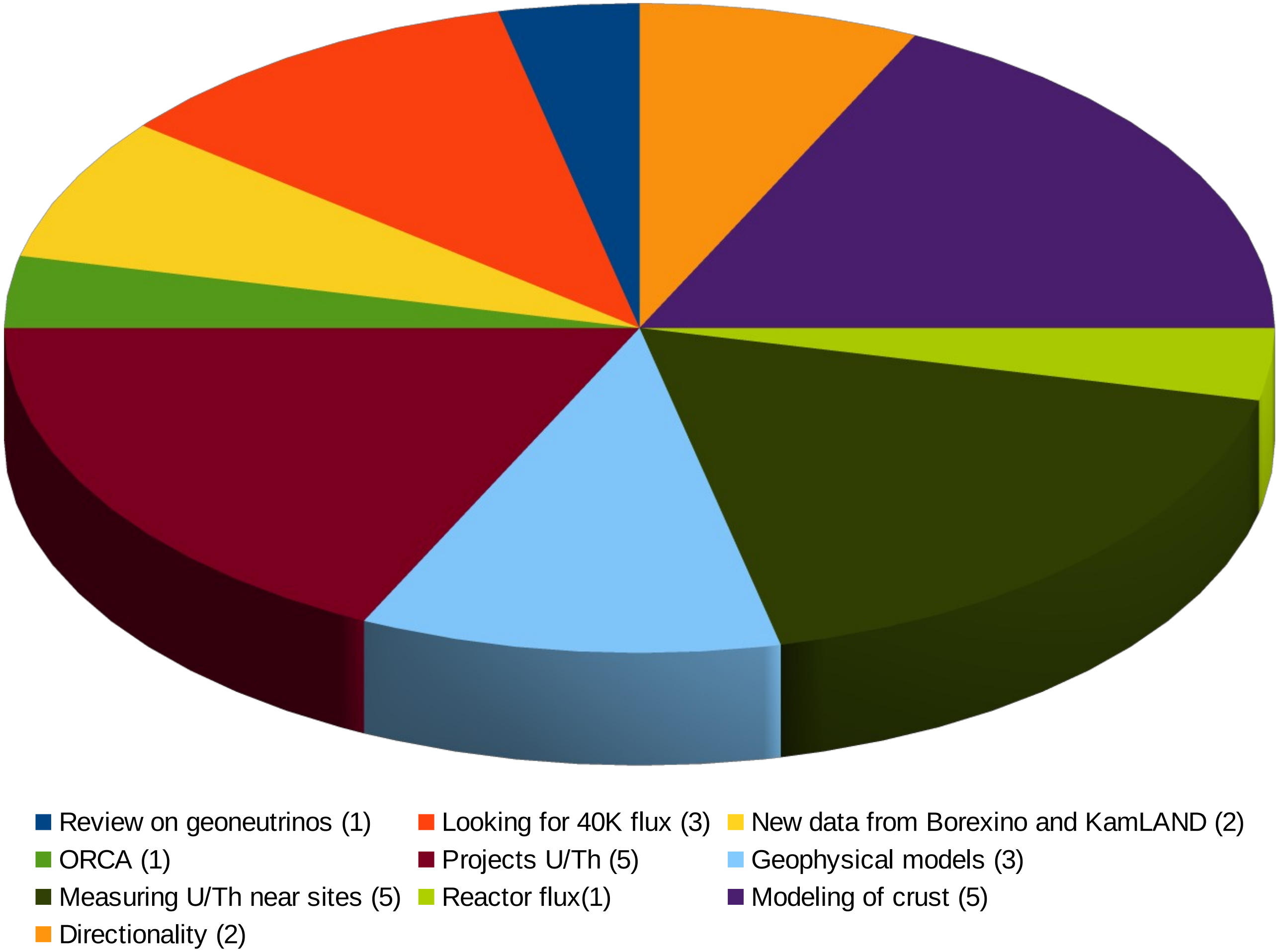
Neutrino Geoscience 2013, Takayama, Japan, 21–23 March 2013

Neutrino Geoscience 2015, IPG Paris, France, 15–17 June 2015

Neutrino Research and Thermal Evolution of the Earth, Tohoku University, Sendai, Japan, 25–27 October 2016

Всего было 28 докладов

1. О геонейтрино;
2. Новые результаты измерений KamLAND и Borexino;
3. Один доклад о нейтринной томографии Земли (ORCA);
4. Различные геофизические модели мантии и ядра;
5. Проекты JUNO, Jinping, OBD и Баксан для регистрации геонейтрино;
6. Три доклада о поиске потока от 40K.


Review on geoneutrinos (1)
Looking for 40K flux (3)
New data from Borexino and KamLAND (2)
ORCA (1)
Projects U/Th (5)
Geophysical models (3)
Measuring U/Th near sites (5)
Reactor flux(1)
Modeling of crust (5)
Directionality (2)

1. Mark Chen, Introduction to geoneutrinos

- Geoneutrinos – what are they?
- Why are they interesting?
- How to detect geoneutrinos?
- R&D ideas: K-40 geoneutrinos, directionality
- Featuring @ Neutrino Geoscience 2019
- KamLAND and Borexino new results
- Future experiments: SNO+, JUNO, Jinping, Baksan

Important Questions in Geosciences

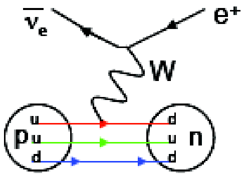
related to geoneutrinos

- what is the radiogenic contribution (U, Th, ^{40}K) to heat flow and energetics in the deep Earth? – otherwise inaccessible
  - mantle: convective Urey ratio?
  - geoneutrinos can measure (U and Th for now)
- are the fundamental ideas about Earth's chemical composition and origin correct?
- are the basic models of the composition of the crust correct?
  - geoneutrinos can test which ones are
- distribution of reservoirs in the mantle?
  - homogeneous or layered?
  - lateral variability
- nature of the core-mantle boundary?

} **neutrinos *might* probe**

- radiogenic elements in the core?
  - in particular potassium
- what is the planetary K/U ratio? if only we could detect ^{40}K geoneutrinos…

Detecting Geoneutrinos



- inverse beta decay: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - "respectable" cross section on protons
  - energy threshold E > 1.8 MeV
  - liquid scintillator is ~CH_2 hence lots of protons
    - positron makes first scintillation
    - neutron captures on H
      - mean capture time ~0.2 ms
    - delayed 2.2 MeV gamma ray from neutron capture makes second scintillation
  - distinctive signature helps rejects background counts
    - e+ and n correlated in time and in position in the liquid scintillator detector

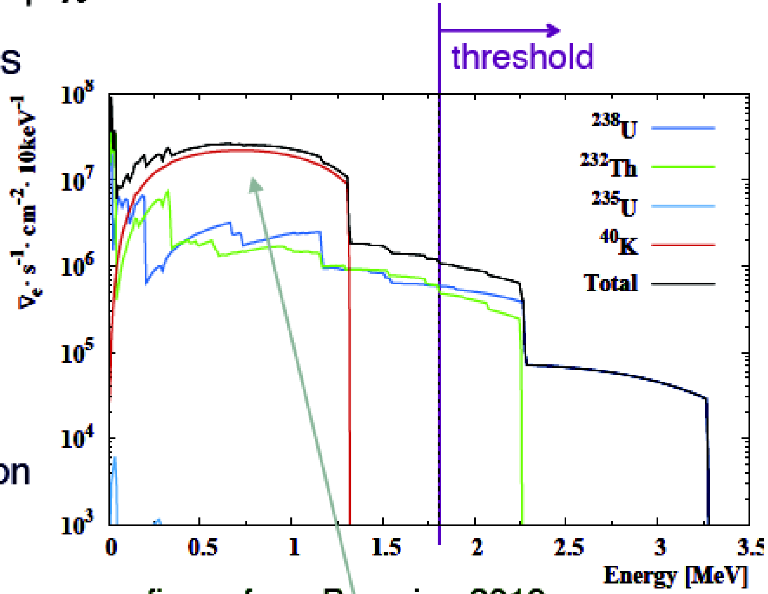
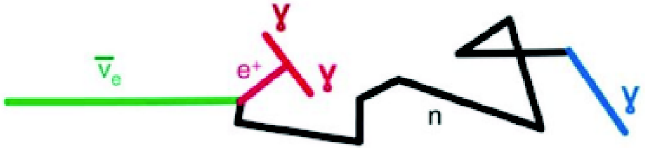


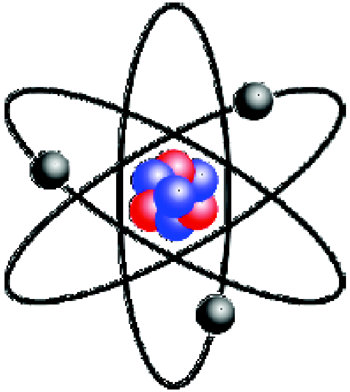
figure from Borexino 2019 paper

can't detect ^{40}K geoneutrinos with this reaction



Neutrino Detection

- to detect (anti)neutrinos, they must first interact to produce a charged particle which can then be observed
- possible targets in ordinary matter:
  - electrons
  - atomic nuclei
    - composed of nucleons (protons and neutrons)
      - composed of quarks



- (anti)neutrinos only undergo the weak interaction

CC: $\bar{\nu}_e + X \rightarrow e^+ + Y$ ← *Y has –1 charge compared to X*

NC: $\bar{\nu}_e + X \rightarrow \bar{\nu}_e + X'$

ES: $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

CC = charged-current weak
NC = neutral-current weak
ES = elastic scattering off electrons

^{40}K Geoneutrinos via neutrino-electron scattering

Observing the Potassium Geoneutrinos with Liquid Scintillator Cherenkov Neutrino Detectors

Zhe Wang[a,b,*], Shaomin Chen[a,b]

[a] *Department of Engineering Physics, Tsinghua University, Beijing 100084, China*
[b] *Center for High Energy Physics, Tsinghua University, Beijing 100084, China*

in arXiv:1709.03743 v3

ARTICLE

Received 28 Oct 2016 | Accepted 16 May 2017 | Published 10 Jul 2017

DOI: 10.1038/ncomms15989

Exploring the hidden interior of the Earth with directional neutrino measurements

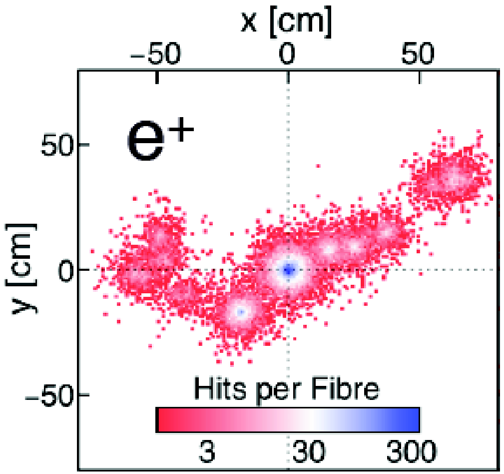
Michael Leyton[1,2,3], Stephen Dye[4] & Jocelyn Monroe[2,3,5]

in Nature Communications 8:15989

^{40}K Geoneutrinos via charged-current neutrino absorption

$$\bar{\nu}_e + X \rightarrow e^+ + Y$$

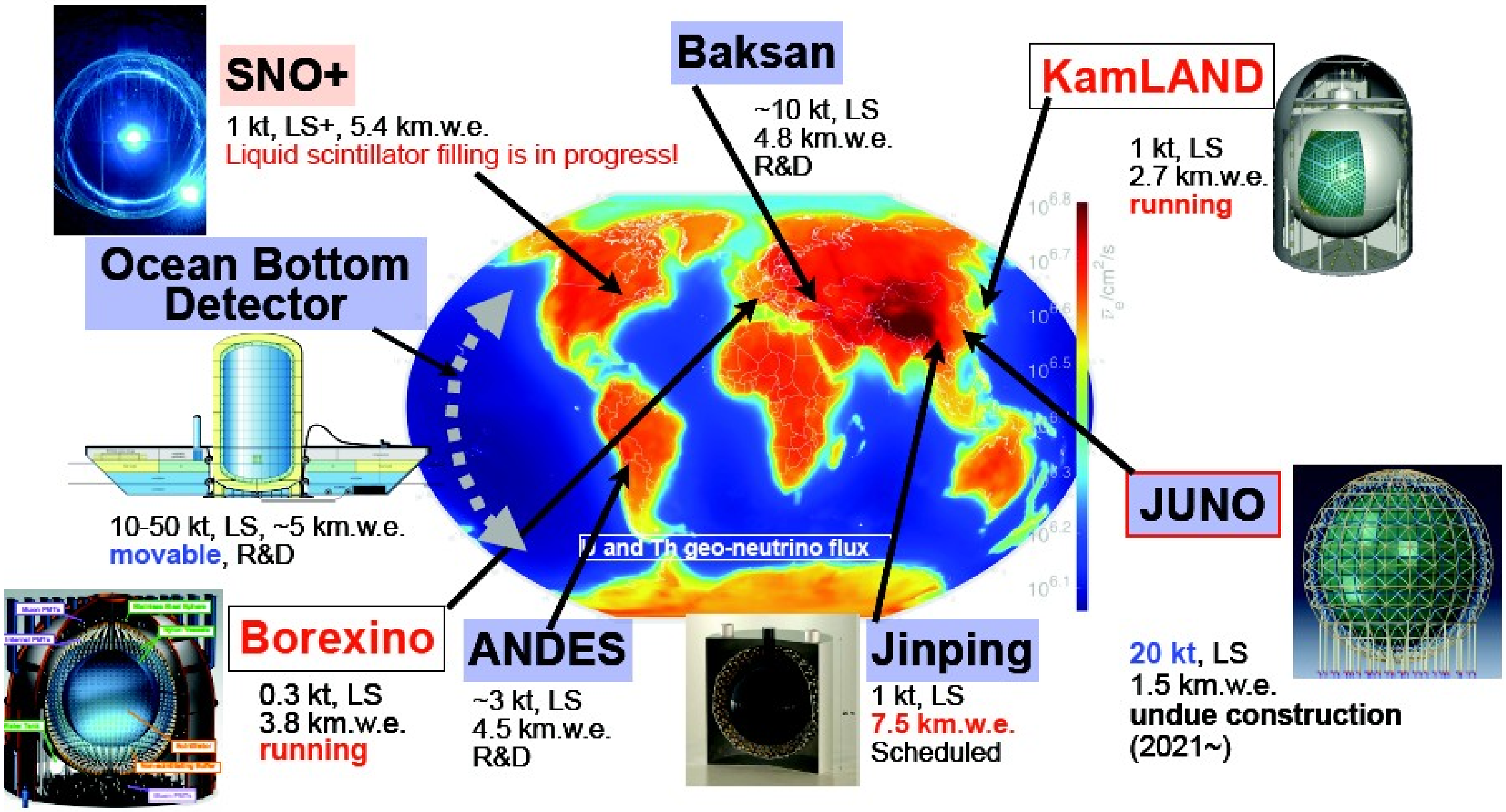
Could a single positron signal be used for ^{40}K geoneutrino detection?
What possible nuclear targets? Which one is best?
(expanding on MC's ^{106}Cd idea)



Andrea Serafini to present work of the Ferrara group + MC + A. Cabrera + S. Wagner…*paper to be submitted soon!*

Probing Earth's potassium content with a new technique for geoneutrino detection

Geoneutrino Projects around the Globe



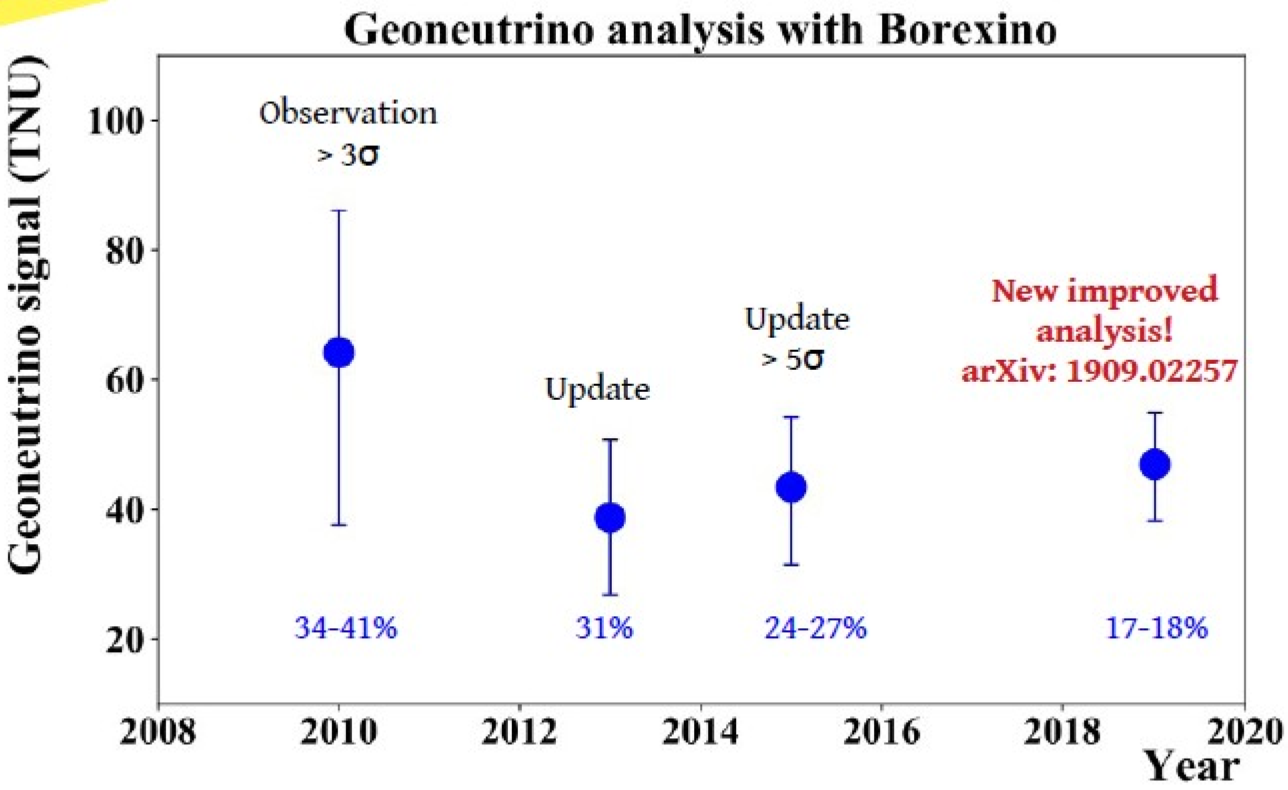
slide from Hiroko Watanabe

New results from:

Borexino (Sindhujha Kumaran)

KamLAND (Hiroko Watanabe)

SPOILER!



Mitglied der Helmholtz-Gemeinschaft

Seite 2

JÜLICH Forschungszentrum

arXiv:1909.02257

Conclusions

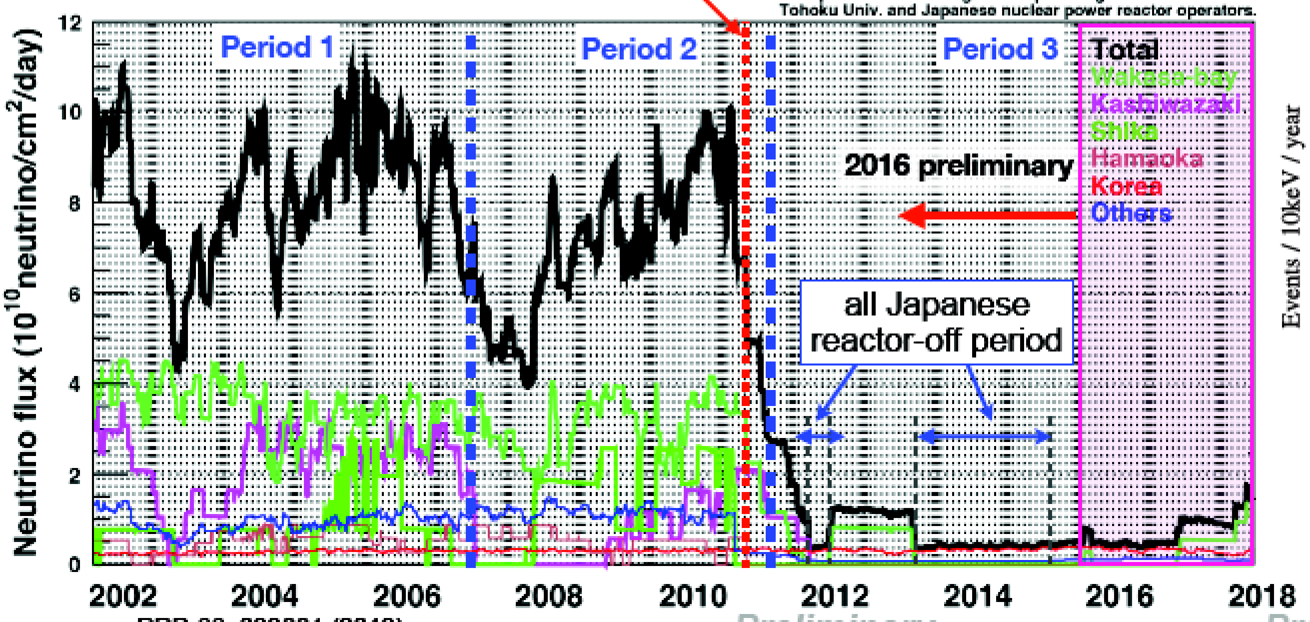
- A total **uncertainty of around ~18%** achieved in the geoneutrino signal using Borexino's data with improved analysis. $47.0^{+8.4}_{-7.7}\,(\mathrm{stat})^{+2.4}_{-1.9}\,(\mathrm{sys})$ TNU
- Mantle signal extracted by using well-known knowledge of LOC. New statistical tools exploited to **reject the null-hypothesis of mantle signal at 99% C.L.** $21.2^{+9.6}_{-9.0}\,(\mathrm{stat})^{+1.1}_{-0.9}\,(\mathrm{sys})$ TNU
- Radiogenic heat calculated using obtained mantle signal and assuming 18% contribution from ^{40}K in the mantle. **2.4σ tension with models predicting lowest amount of mantle signal.** $38.2^{+13.6}_{-12.7}$ TW.
- Lower limits at 90% C.L. :
  $UR_{CV} > 0.3$; $H^{rad}_{mantle}(U+Th+K) > 12.2$ TW;
  $a_{mantle}(U) > 13$ ppb; $a_{mantle}(Th) > 48$ ppb
- Stringent georeactor upper limits at 95% C.L. for three different positions in the Earth. < 0.5 TW (2900 km); < 2.4 TW (center); < 5.7 TW (9842 km)

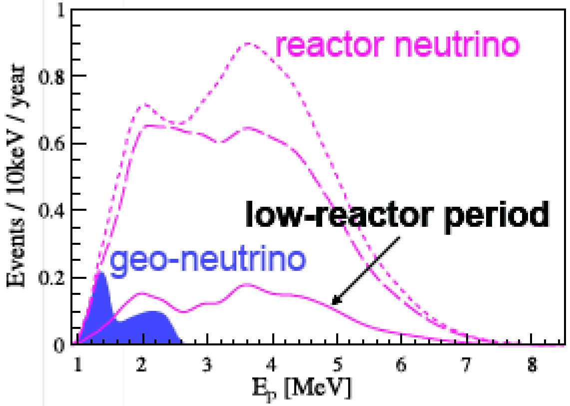
POSTERS

Analysis details:
Sindhujha Kumaran & Livia Ludhova
Geological interpretations:
Fabio Mantovani & Virginia Strati

Data-set & Reactor Neutrinos

Reactor Neutrino Flux @Kamioka March 2011 Earthquake ~Apr. 15, 2018





☑ +500 days of low-reactor phase from 2016 data-set

PRD 88, 033001 (2013)

2013 data-set : 2991 days
4.90×10^{32} proton-year

2016 data-set : 3901 days
6.39×10^{32} proton-year

2019 data-set : 4397 days
7.20×10^{32} proton-year

Period 1 : 1485.62 days
Period 2 : 1151.47 days
Period 3 : 1759.85 days

Period 3 : 1259.8 days → +500 days

Summary

- The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.

- **Preliminary results are presented.**
  - Low-reactor operation period :
    - ~4.8 years (40% of total livetime)
    - **clear energy spectrum of geo-neutrino → better understanding of U, Th each contribution**
  - geo-neutrino event measurement with **15.6 % uncertainty**
  - geoscience discussion
    - **Th/U mass ratio** : **5.3** $^{+6.0}_{-3.6}$, consistent with chondrite data and BSE models
    - **Radiogenic heat** : **12.4** $^{+4.9}_{-4.9}$ **TW** (Mantle+Crust, U+Th), consistent with Middle Q and Low Q models
    - **Separated test of ^{238}U and ^{232}Th geo-neutrinos → power to determine past radiogenic heat through the Earth's history**
    - **Mantle signal : 0.67** $^{+0.63}_{-0.64}$ **× 10^{6} $cm^{-2}s^{-2}$** → *** High Q is rejected with >2σ**
      *** depends on estimation of crust contribution**

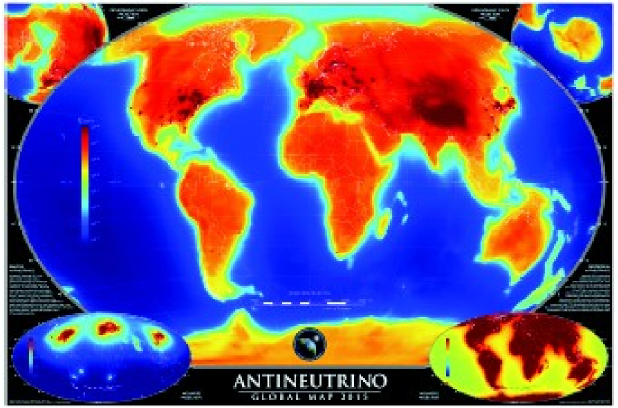
- **Future Prospects:**
  - KamLAND continues to measure geo-neutrinos with low-reactor backgrounds stably
  - Better understanding of crust contribution → **helps further estimation of mantel signals**
  - Multi-sight measurements
  - **Ocean Bottom Detector has strong power to measure mantle contribution directly.** Poster by H. Watanabe, K. Ueki et al

Reference Models for Lithospheric Geoneutrino Signal

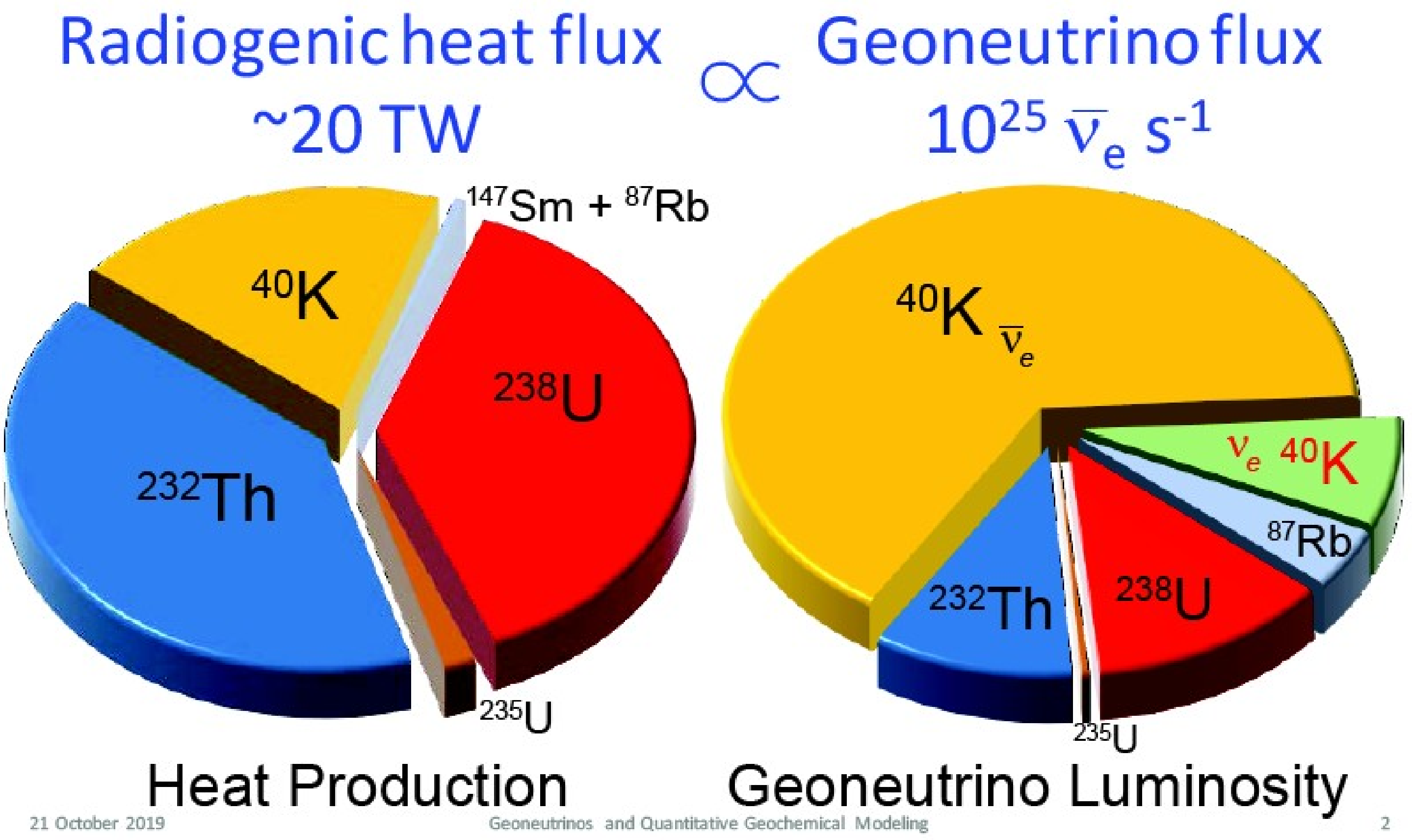
S. A. Wipperfurth[1], O. Šrámek[2], W. F. McDonough[1,3].

with additional contributions from Laura Sammon (UMD)

[1]Department of Geology, University of Maryland, College Park, MD 20742, USA
[2]Department of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[3]Department of Earth Sciences and Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan



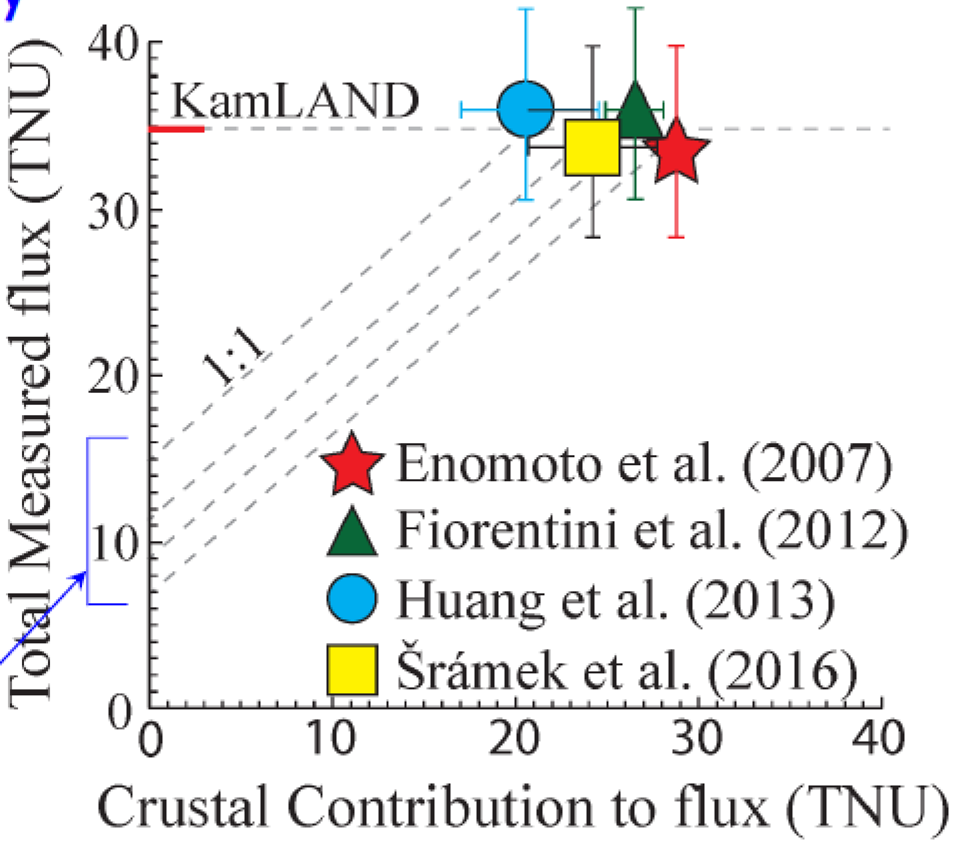
funding


Radiogenic heat flux
~20 TW
∝
Geoneutrino flux
10^{25} $\bar{\nu}_e$ s^{-1}
^{147}Sm + ^{87}Rb
^{40}K
^{238}U
^{232}Th
^{235}U
^{40}K $\bar{\nu}_e$
ν_e ^{40}K
^{87}Rb
^{232}Th
^{238}U
^{235}U
Heat Production
Geoneutrino Luminosity
21 October 2019
Geoneutrinos and Quantitative Geochemical Modeling
2

importance of accuracy

- **Which model is most accurate?**
- **Implications for what's in the mantle**

Intercept = mantle flux!



Combining data from the global array

Future is Bright

2025 and beyond

- Physics continues to count

- Much to be learned

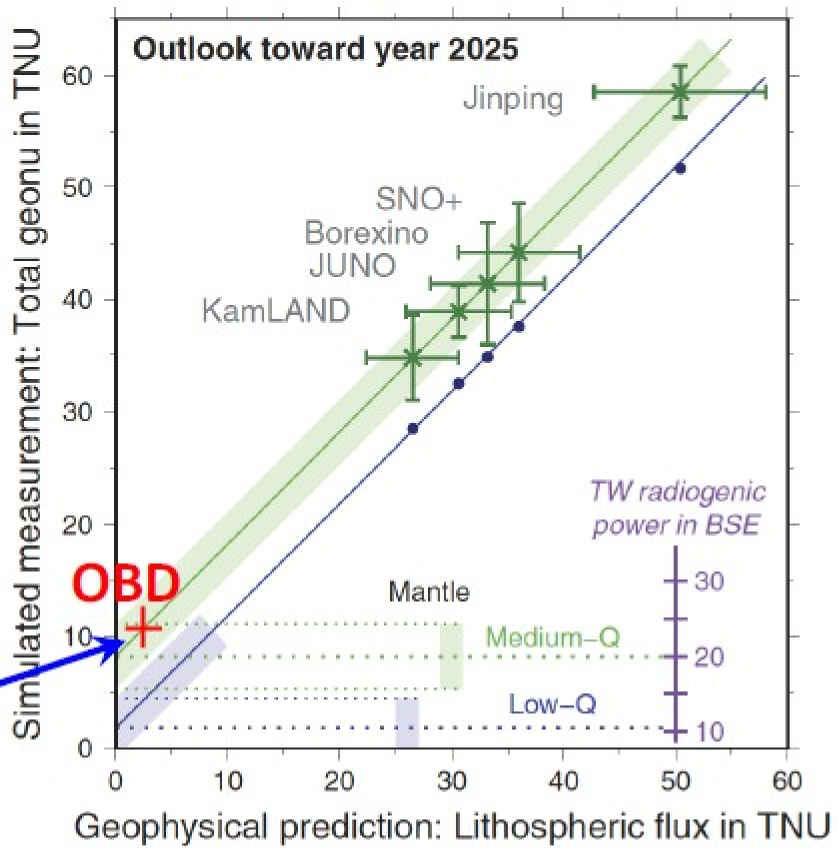
- More geoneutrino data!

- Benefits for astrophysics

- Importance of an ocean measurement!

Prediction based on 1.5 kt, 4 yr exposure, ± 20%

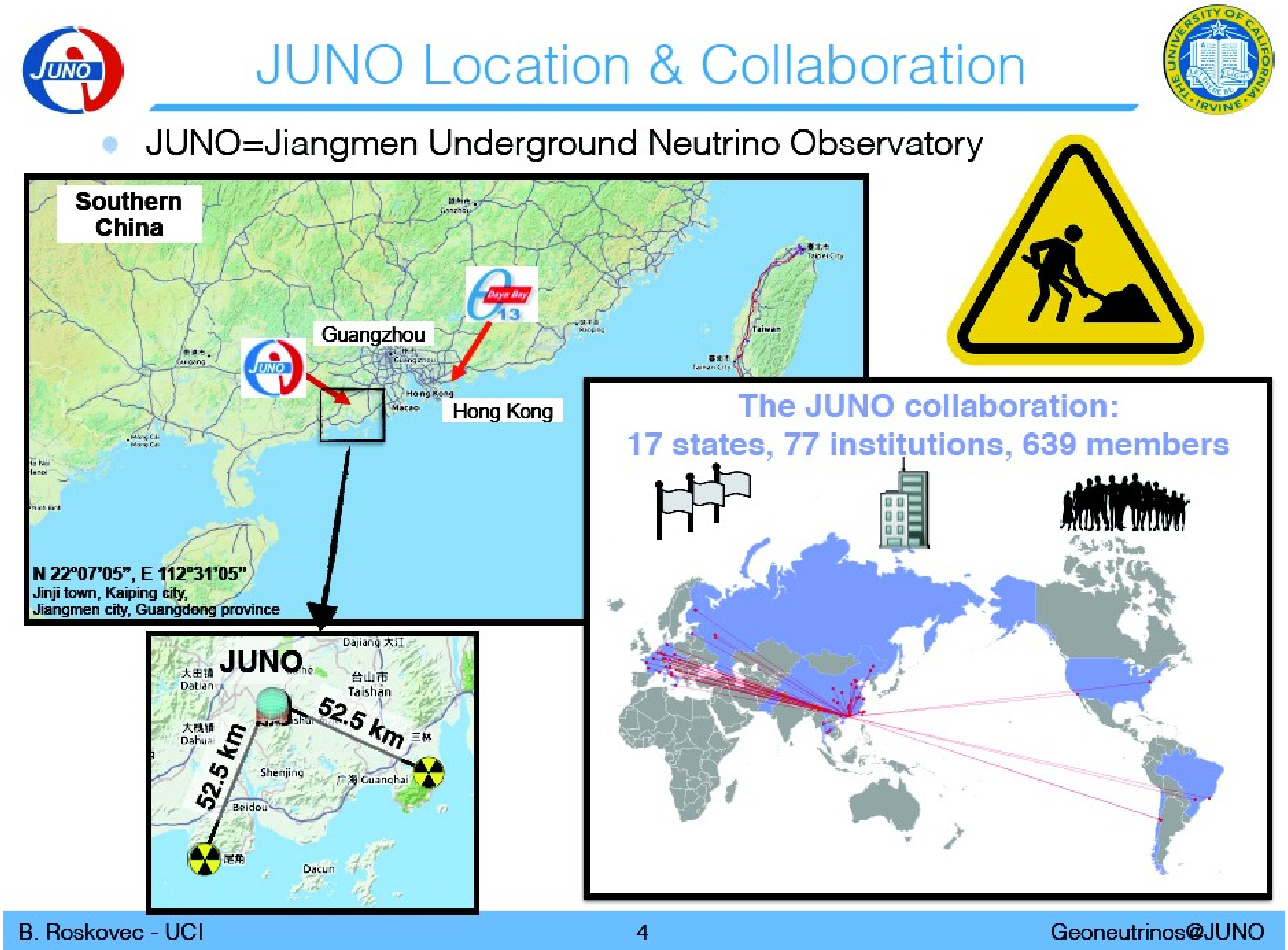
Šrǂmek et al. (2016) model (SREP 6, 33034 (2016))



Conclusions

- Contributions to the geoneutrino signal:
  - 40% local crustal model
  - 35% global continental lithosphere
  - 25% mantle
- Estimated total signal uncertainties 20%, with 6% from geophysics + 14% from geochemistry
- Calculations using CRUST2.0, CRUST1.0 and LITHO1.0 yield physical uncertainties that overlap each other
- Bulk continental crust has (7 ± 2) TW


Geoneutrino Measurement at JUNO
Bedřich Roskovec
(on behalf of the JUNO collaboration)
University of California, Irvine
NGS2019, Prague
October 22, 2019


JUNO Location & Collaboration
JUNO=Jiangmen Underground Neutrino Observatory
Southern China
Guangzhou
Hong Kong
N 22°07'05", E 112°31'05"
Jinji town, Kaiping city,
Jiangmen city, Guangdong province
JUNO
Dajiang 大江
台山市
Taishan
Datian
Dahua
52.5 km
52.5 km
Shenjing
Guanghai
Beidou
Dacun
The JUNO collaboration:
17 states, 77 institutions, 639 members
B. Roskovec - UCI
4
Geoneutrinos@JUNO

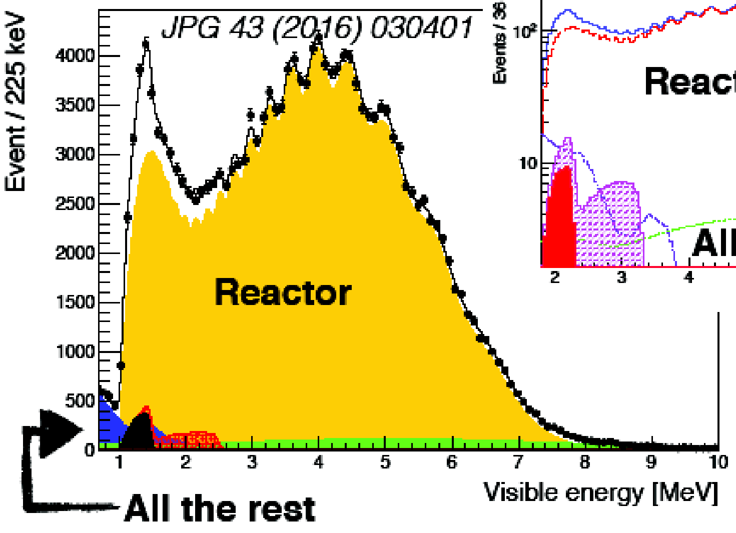
Geoneutrinos at JUNO

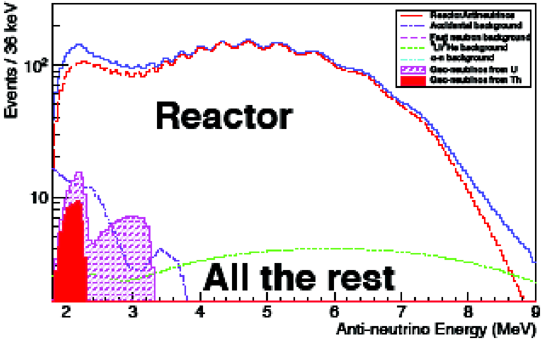
- **JUNO will get the largest geoneutrino sample in <1 year**
  - We have so far ~164 events from KamLAND and ~53 events from BOREXINO
- Challenge for JUNO is however huge reactor neutrino background
  - **At what precision can JUNO extract the geoneutrino signal?**

source	events/year
Geo-νs	408 (406)
Reactor	16100 (3653)*
$^{9}\mathrm{Li} - ^{8}\mathrm{He}$	657 (105)
Fast ns	36.5 (7.66)
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$	18.2 (12.16)
Accidental	401 (348)

1.8-9.0 (1.8-3.3) MeV

*assuming full 35.8 GW_{th}





Use of Precise Geoneutrino Measurement

Getting the Earth (mantle) composition ⇔ Earth radiogenic power:

- Interpretation of geoneutrino signal can tell, how many U and Th is in the mantle. How to get it?
  - Subtract crustal contribution from total signal (land-based experiments)
  - Go to the ocean where your signal is up to 80% from the mantle - see a poster from Dr. Watanabe
- For the former, local model matters - see a poster from Prof. Mantovani
- Currently, tension in the measurement interpretations using local models:
  - BOREXINO: $38.2^{+13.6}_{-12.7}$ TW (*arXiv:1909.02257*)
  - KamLAND: ~14 TW (calculated based on *PRD 88(3), 033001, 2013*)
- Soon new kid on the block: JUNO

Search for hidden reservoirs using comparison with other experiments (assuming “we know the crust”) (see a talk on Wednesday)

- …

Progress of Jinping Neutrino Experiment Program

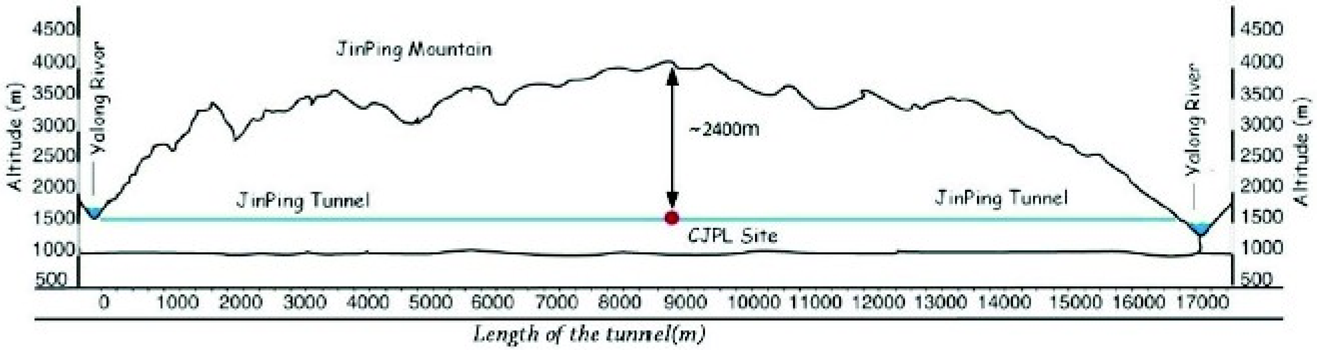
Benda Xu(续本达) on Behalf of Jinping Pre-collaboration

Tsinghua University

2019-10-22 NGS 2019@Praha

China JinPing underground Laboratory

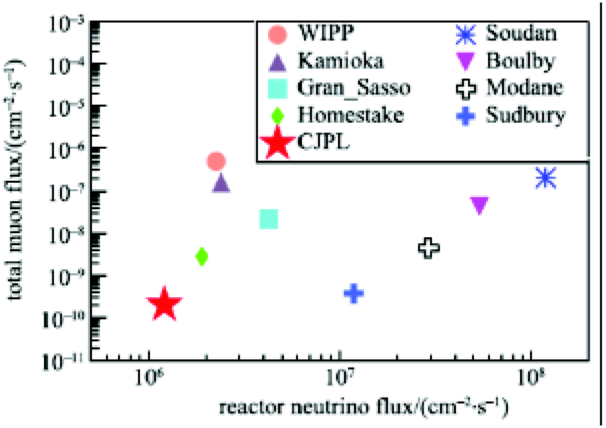
Yalong River Hydropower Development Company started to develop the hydro-energy for the entire river since 1990s.

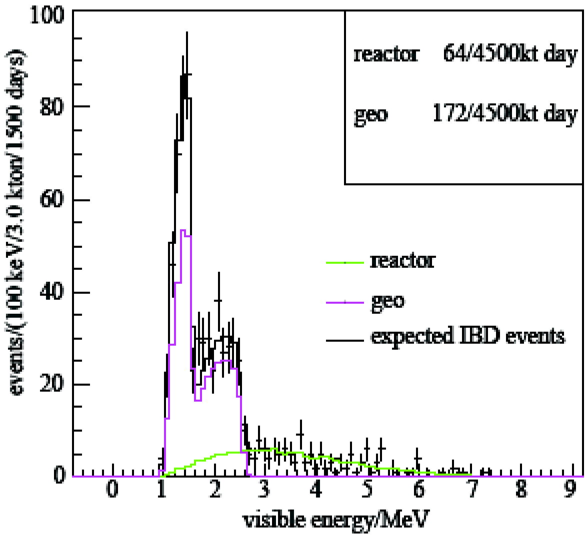


- 8 km long entrance tunnel, possible alternative sites.
- Abundant electricity and water supply.
- In July 2019, China Jinping Laboratory started as "national magnificent scientific and technological infrastructure"
  国家重大科技基础设施项目

Probe Into the Earth from Jinping

- Low reactor neutrino background.
- Large geoneutrino flux from the tibet plateau.

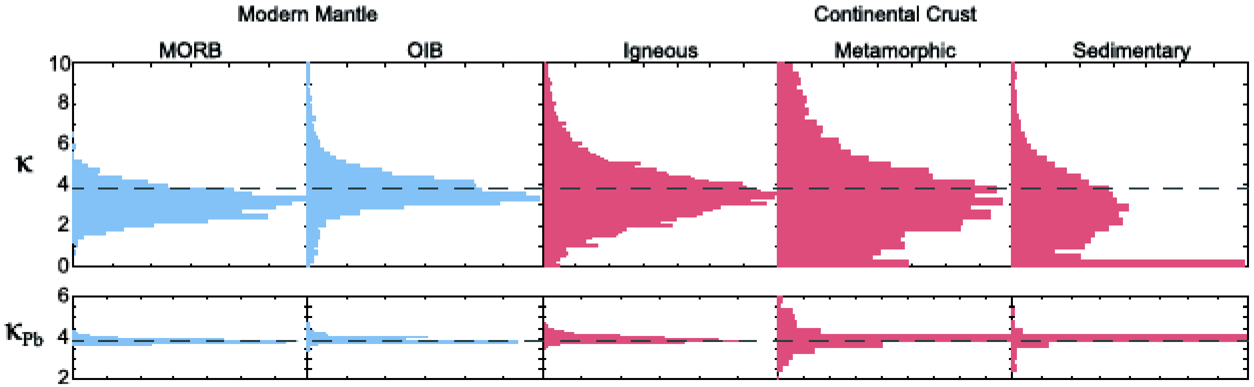




- Test the geochemical model of U Th concentration in the crust.
- Measure the abundance radio of U/Th.
- Test georeactor hypothesis.

Measurement of Th/U Ratio

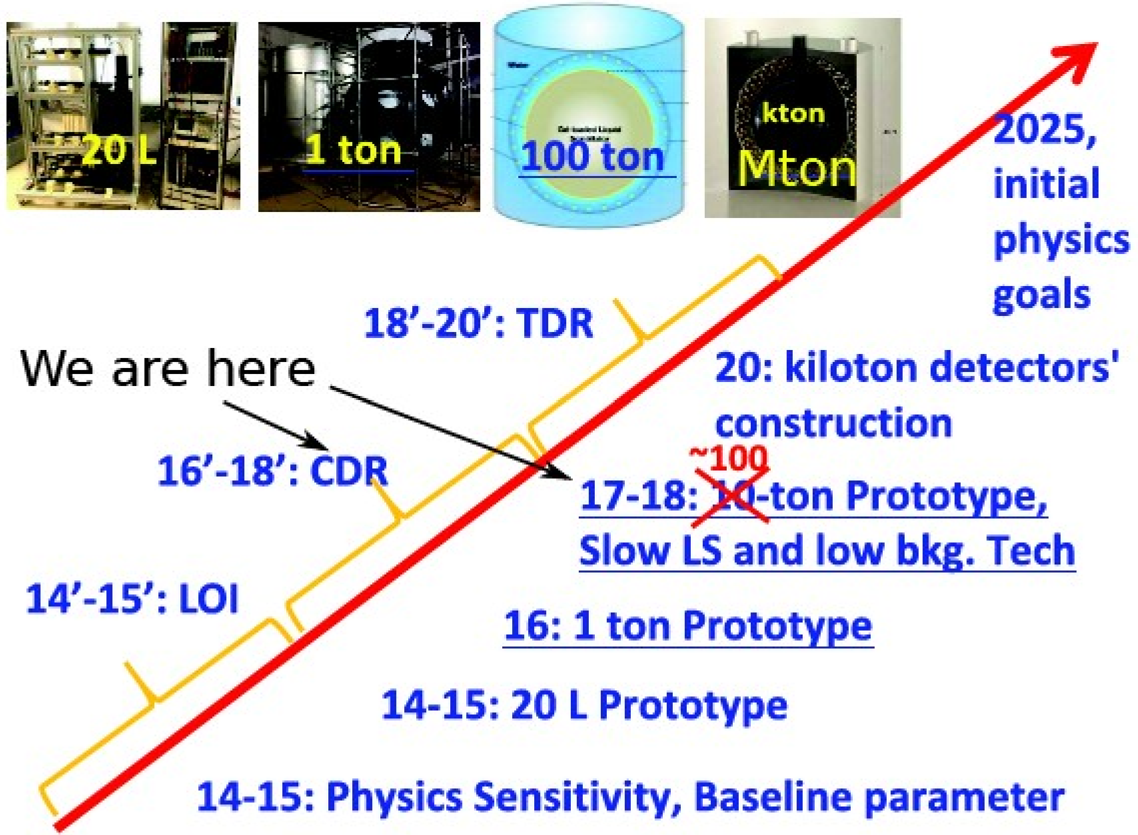
- An undifferentiated Earth Th/U ratio has been established.



- Continental crust is hard to estimate in bulk, because of sampling biases, etc.
- At Jinping, the bulk Th/U ratio of the locals and Tibet Plateau can be tested.
  - At 4500 kton-day exposure, Th/U to be determined to 27%.

Wipperfurth et al. 2018 EPSL

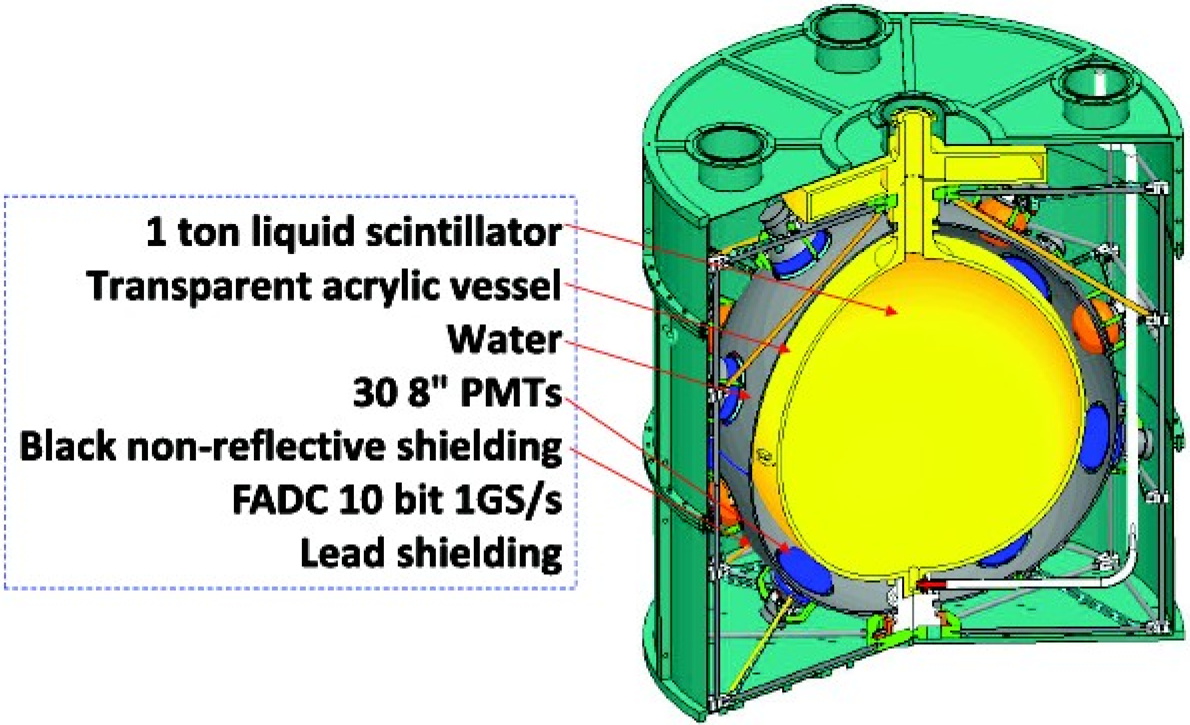
Jinping Neutrino Roadmap and Milestones



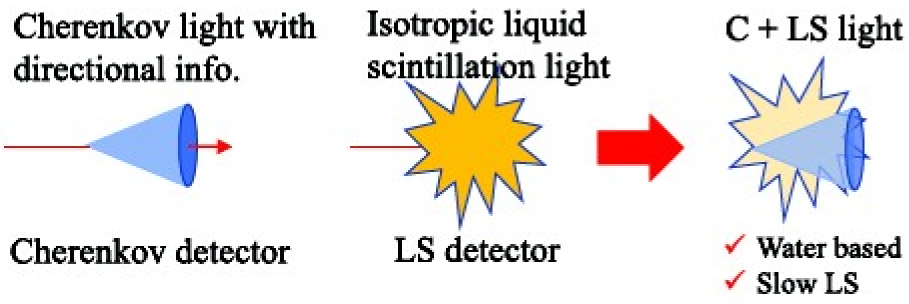
Years to be scaled by $\times \pi$

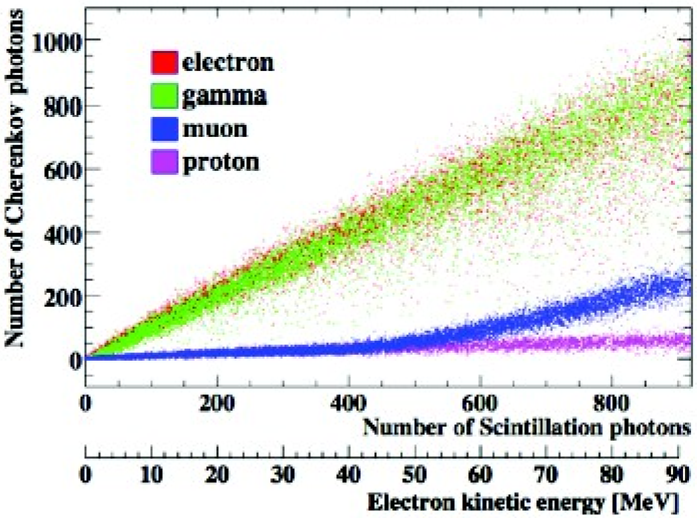
1ton Prototype

- In CJPL-I since 2017, besides CDEX and PANDAX experiments.
- Proof of detection principle, background measurement.



Slow Liquid Scintillator





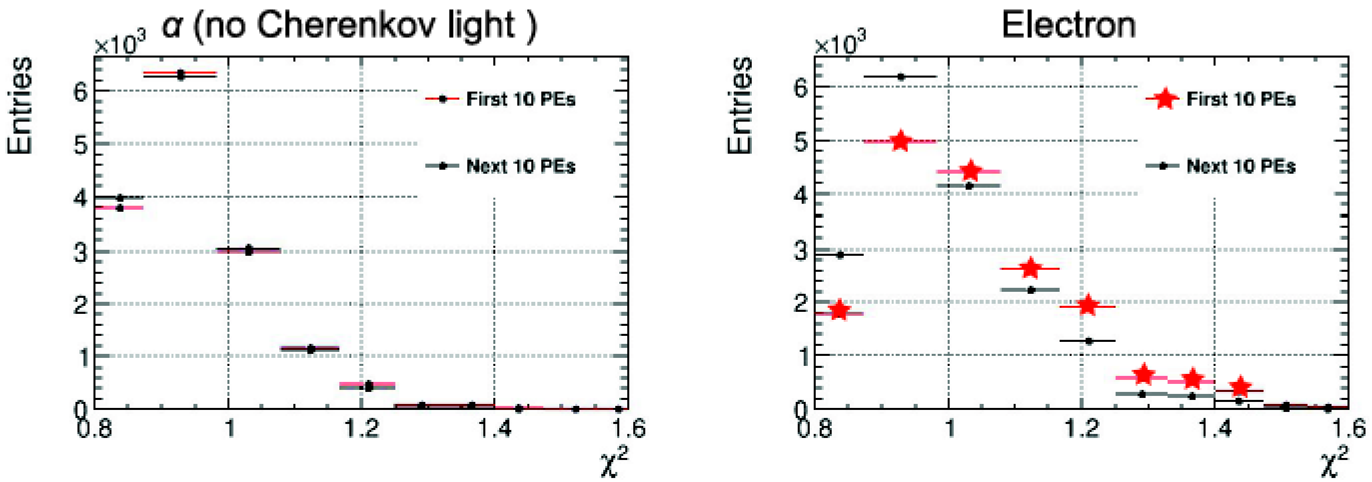
NIMA 830(2016) 303-308, j.astropartphysics.2019.02.001

- Separate atmospheric ν NC events from supernova ν.
- Direction of solar ν.
- Potential to study ^{40}K Geo-ν.
- Demonstrated by cosmic ray with a 20L detector.

Demonstration by 1ton Detector

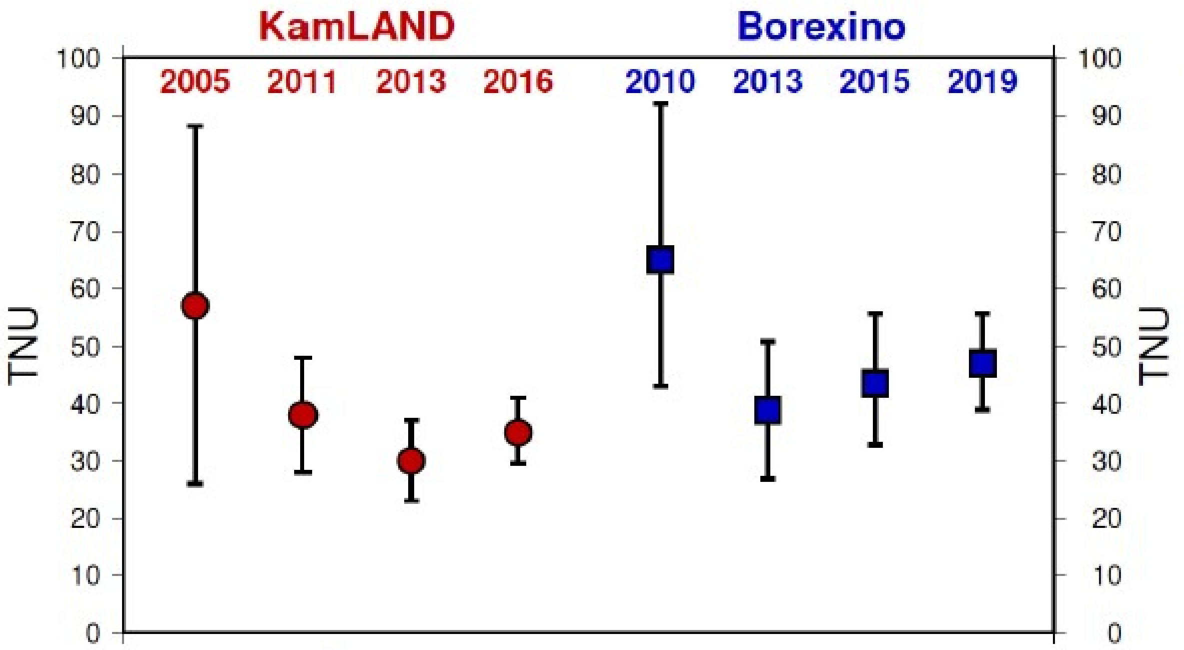
- ^{214}Bi-^{214}Po decay:
  - Prompt 2 MeV β emits Cherenkov light;
  - Delayed 7.7 MeV α has no Cherenkov light.
- Select signals $R < 0.2$ m:
  - Define a test statistic $\chi^2 = \sum_{i=0}^{29} \frac{(q_i - \bar{q})^2}{\bar{q}}$ to measure sphericity.

spherical?	First 10 PEs	Next 10 PEs
α	yes	yes
β	no	yes



Geo-neutrinos in SNO+

Ingrida Semenec
SNO+ collaboration
Queen's University



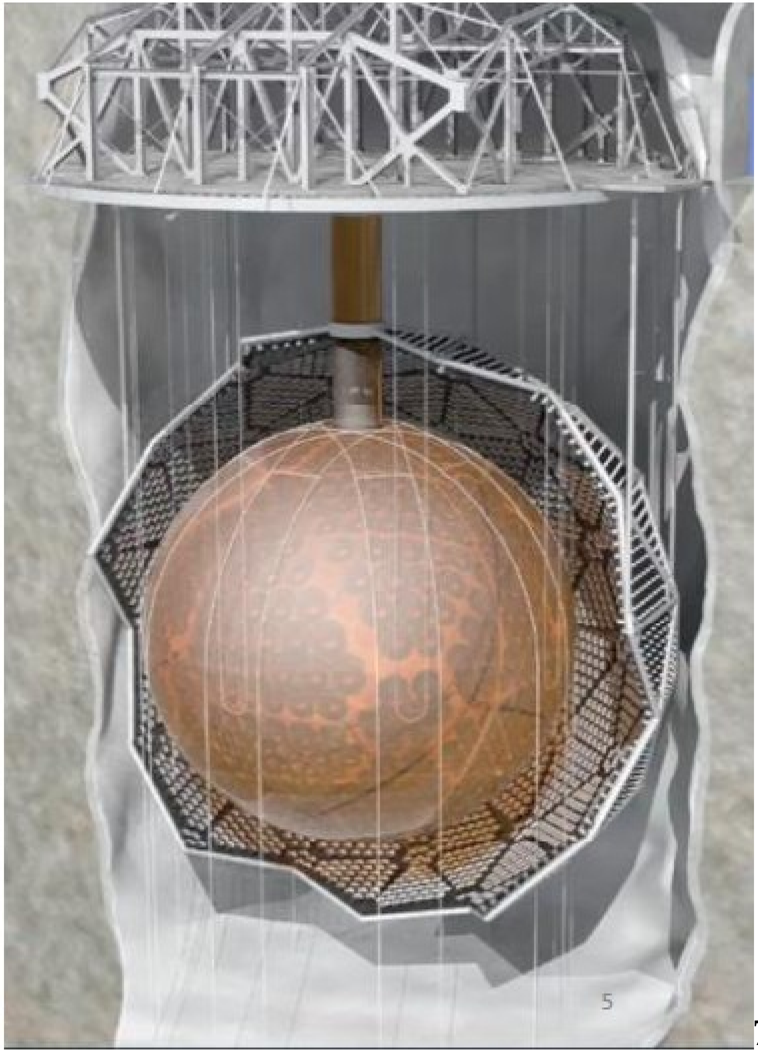
courtesy of O.Šrámek

SNO+ ???

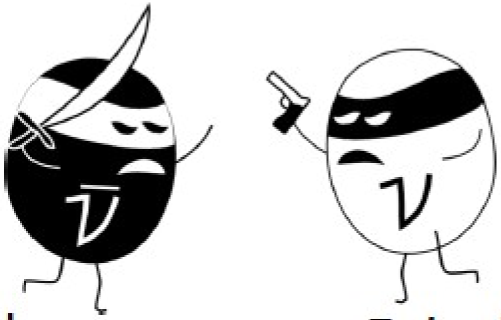
Start taking geoneutrino data 2020

SNO+

- Successor experiment to Sudbury Neutrino Observatory (SNO)
- 780 tonnes of liquid scintillator (LAB) inside a 12 m diameter acrylic vessel. LAB to be loaded with PPO+3.9 tonnes of Tellurium.
- Hold-down rope system to restrain buoyant force
- ~9400 PMTs, ~54% effective coverage
- 7000 tonnes of ultra-pure water shielding



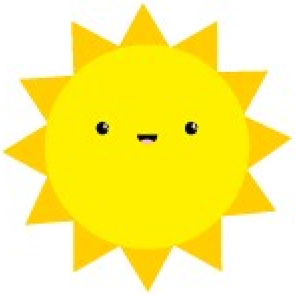
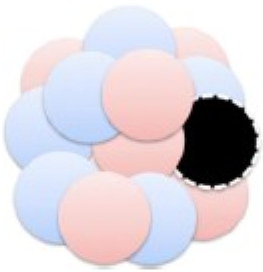
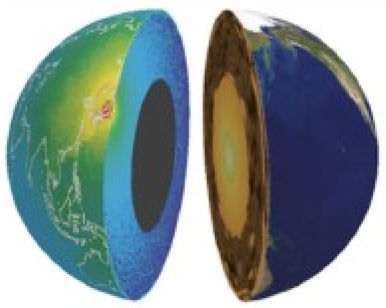
Physics program



Water phase
- Detector calibration
- Background measurements
- Nucleon decay searches
- ^{8}B solar neutrino flux

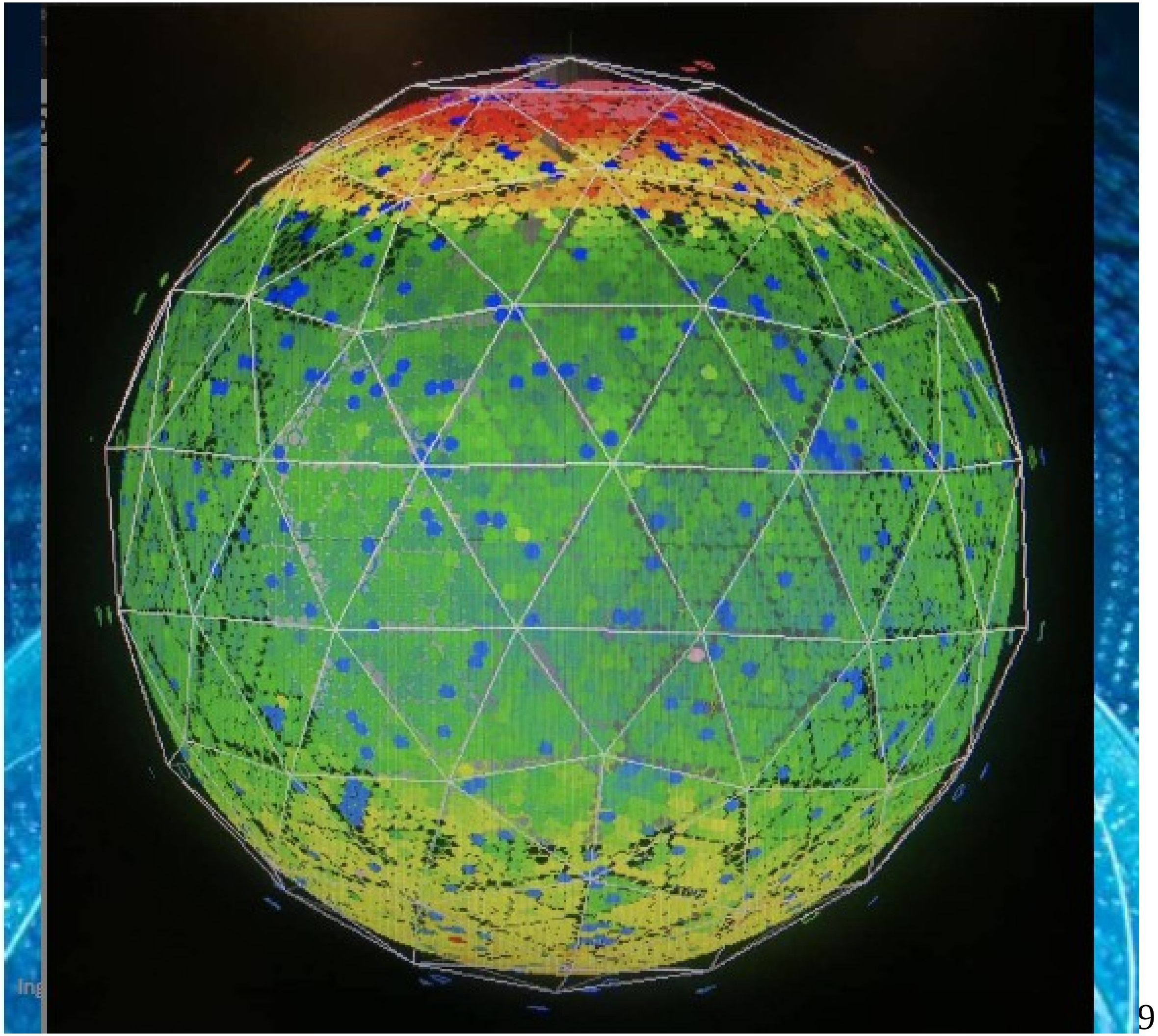
Scintillator phase
- Background measurements
- Low energy solar neutrinos
- Geo and reactor antineutrinos

Te-loaded phase
- $2\nu\beta\beta$ decay lifetime of ^{130}Te
- $0\nu\beta\beta$ decay search with ^{130}Te
- Geo and reactor antineutrinos

SNO+ Current Status

- Scintillator fill ongoing
  - Several delays due to minor problems in the distillation plant (e.g. gaskets, PSV, leaks)
  - Completion of scintillator fill planned for end of 2019
  - Counting scintillator backgrounds now
- Tellurium process systems fully installed underground
  - Preparing for Te loading in 2020 (for double beta decay)
- SNO+ geo-neutrino measurement starts after scintillator fill
  - and continues after tellurium addition



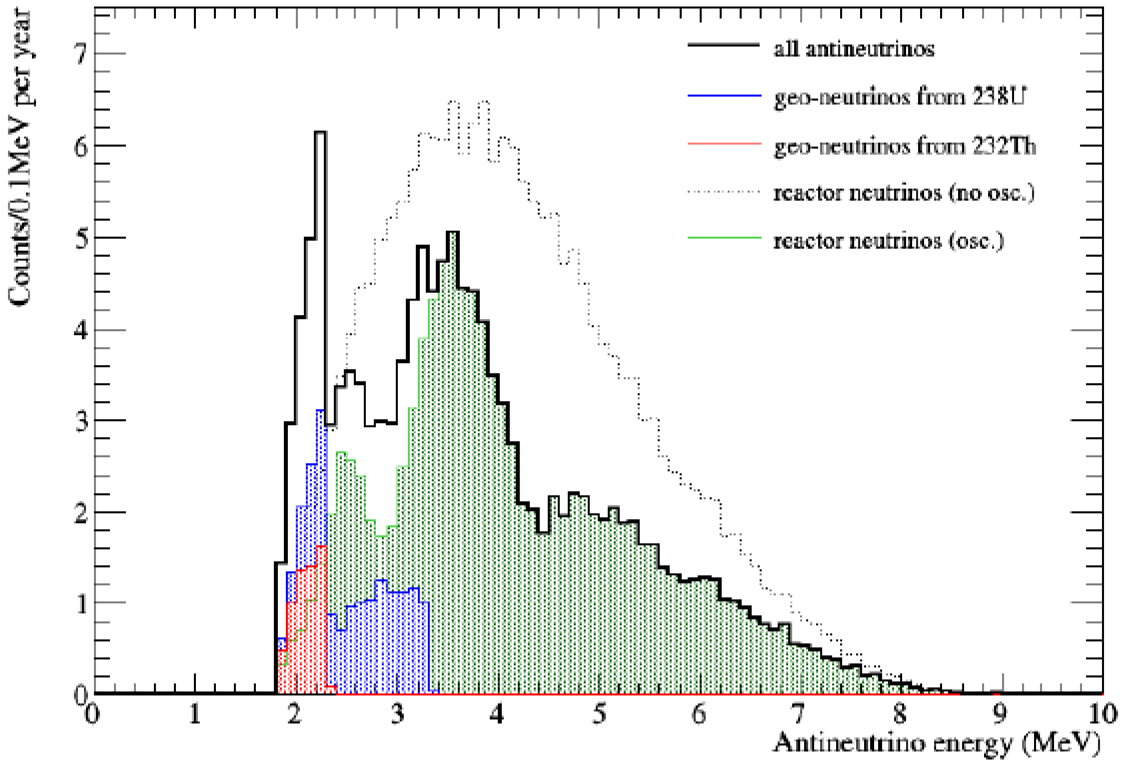
Expected geoneutrino event rates at SNO+

- TNU is defined as one interaction over a year-long fully efficient exposure of 10^{32} free protons.
- Event rate depends on detector size and efficiency of detection.
- Therefore rates in TNU must be converted to the expected rate at SNO+
- The conversion factor for TNU to evs/year scintillator is 0.57719 (100% eff.).

rates in MC geoneutrino generator

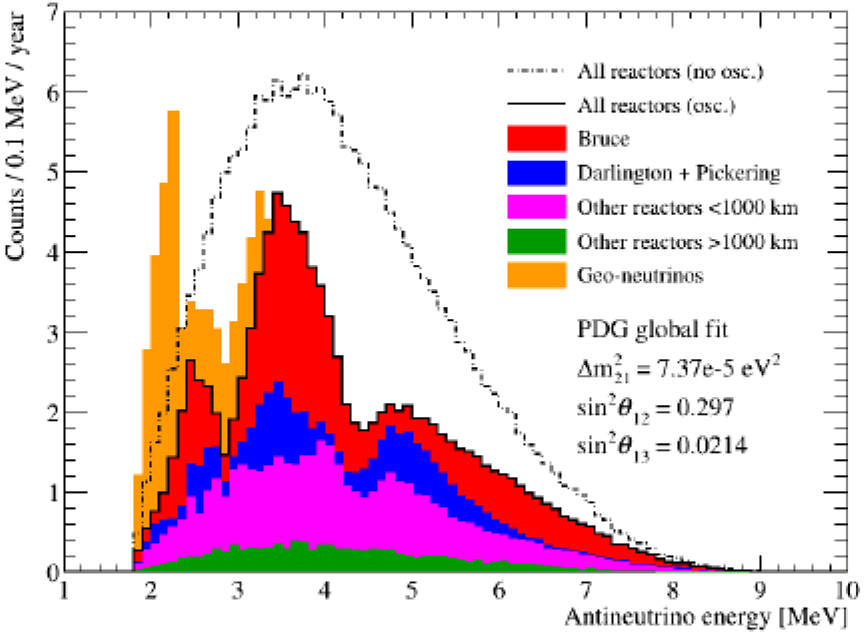
Mid Q 20TW	TNU	TNU*0.57719 =evs/year	Hz
U	34.12	19.69	6.2437e-7
Th	9.53	5.5	1.74e-7
Low Q 10TW			
U	29.73	17.16	5.4414e-7
Th	8.21	4.74	1.503e-7
High Q 30TW			
U	41.54	23.98	7.604e-7
Th	11.4	7.604	2.087e-7

Antineutrino Spectrum



Expected $\overline{\nu}_e$ energy spectrum in SNO+ (solid). Geo-neutrinos from ^{238}U (blue) and ^{232}Th (red) decays in the Earth. Contribution from nuclear reactors is in green.

Reactor antineutrinos



Plot by Stefan Nae, SNO+ collaboration

Originates from the burning of nuclear fuel. Main fraction of the anti-neutrinos that will be observed in SNO+ come from 3 power plants in Canada:

- Bruce at 240km
- Pickering and Darlington at 350km
- The rest with longer baselines

Dashed line shows the reactor antineutrino spectrum without applied neutrino oscillation effects. SNO+ will measure Δm^2_{12} neutrino oscillation parameter.

Conclusions

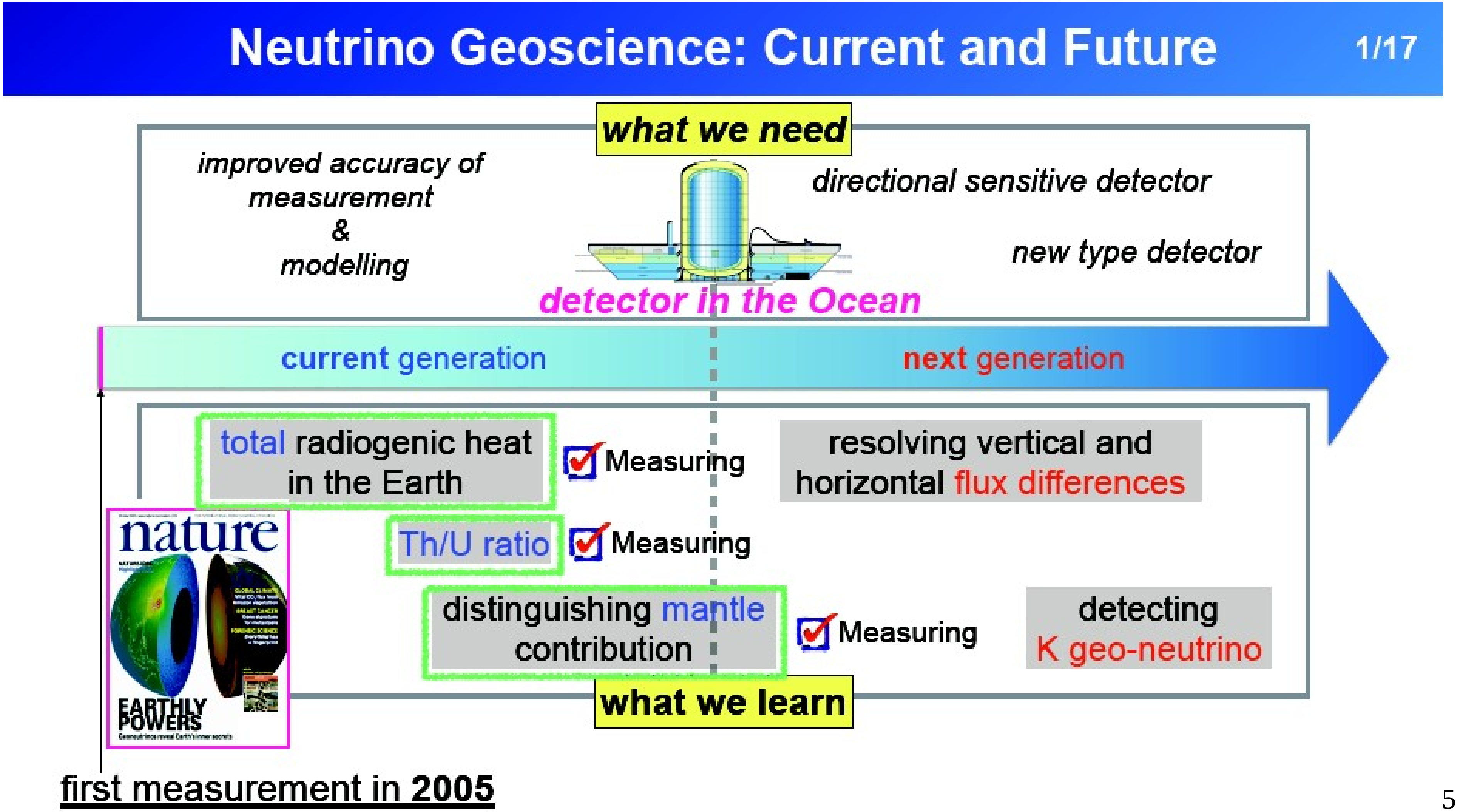
- SNO+ is a multipurpose liquid scintillator detector.
- Geo-neutrino flux can be detected by SNO+ during pure scintillator and Te-loaded phases.
- Geo-neutrino flux predictions at SNO+ site keep being improved.
- Backgrounds are being estimated and compared to MC simulations of geo-neutrino signal.

Neutrino Geoscience 2019

Anti-neutrino Directional Measurement

Research Center for Neutrino Science, Tohoku University
Hiroko Watanabe

October 21-23, 2019, Prague


Neutrino Geoscience: Current and Future
1/17
what we need
improved accuracy of measurement & modelling
directional sensitive detector
new type detector
detector in the Ocean
current generation
next generation
total radiogenic heat in the Earth
Measuring
resolving vertical and horizontal flux differences
Th/U ratio
Measuring
distinguishing mantle contribution
Measuring
detecting K geo-neutrino
what we learn
nature
EARTHLY POWERS
first measurement in 2005

Water vs Liquid Scintillator

Water-based LS

	Water	Liquid Scintillator (LS)
experiments	Super-K (Ice-Cube, etc.)	KamLAND (Borexino, SNO+, JUNO, etc.)
target volume	50,000 t (larger)	1,000 t
light	Cherenkov	Scintillation
light yield	6 p.e./MeV **higher energy ν**	400 p.e./MeV (blighter) **lower energy ν, $\bar{\nu}$**
measurement target	atmospheric, solar, astrophysical, etc	solar, **geo**, reactor, supernova, etc
reaction	scattering	scattering/ **inverse β decay** (background reduction)
directionality		this study

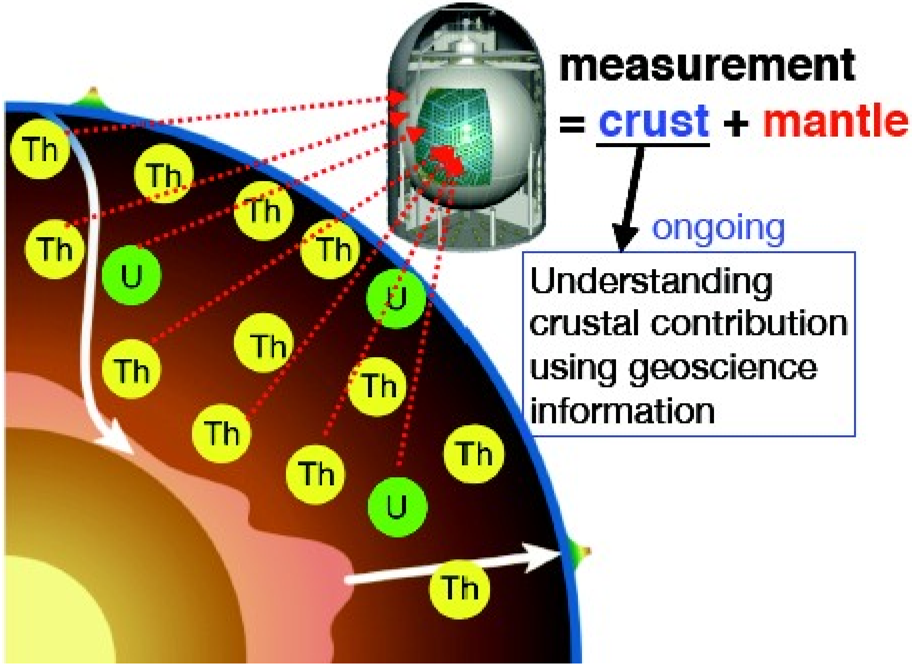
What We Can Measure?

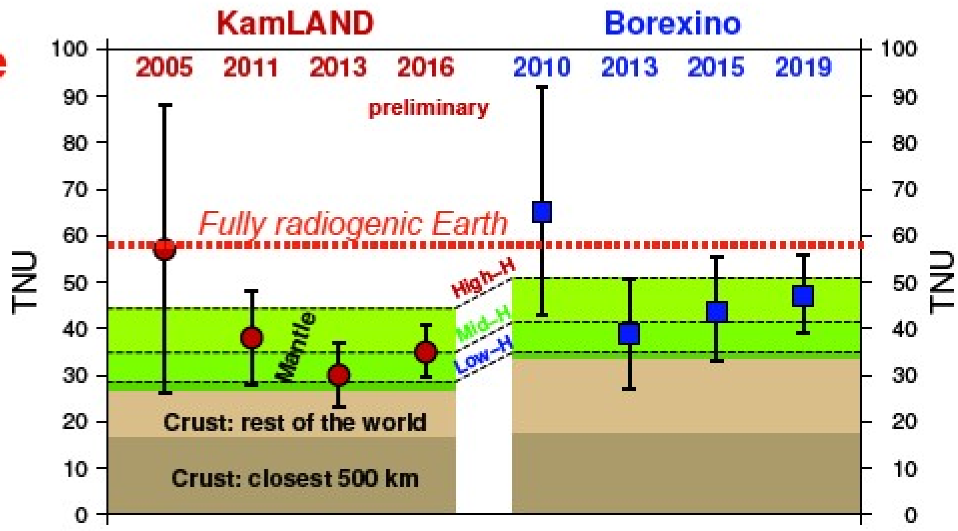
1. large size detector (1kt~)

geo-neutrino

(1) distinguish mantle contribution

(2) separate reactor neutrino background





Geoneutrino prediction from Sramek et al. 2016 Sci.Rep. doi:10.1038/srep33034

What We Can Measure?

1. large size detector (1kt~)

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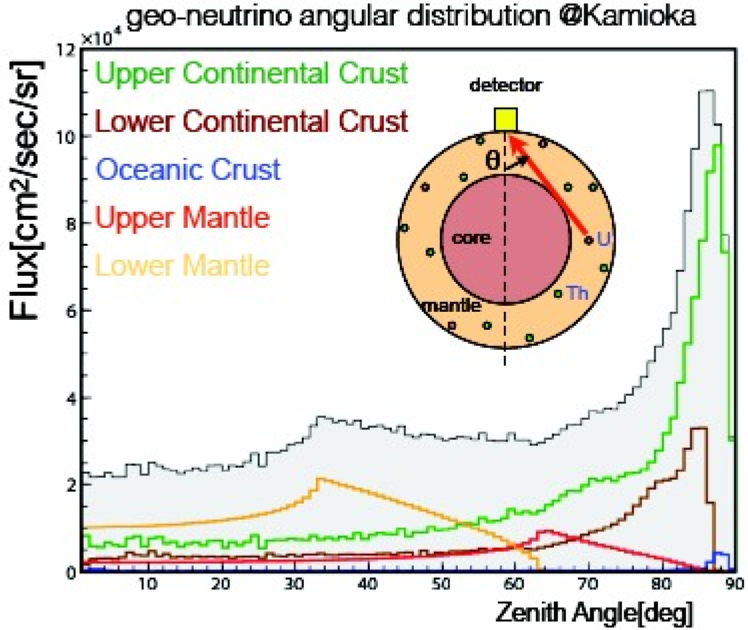

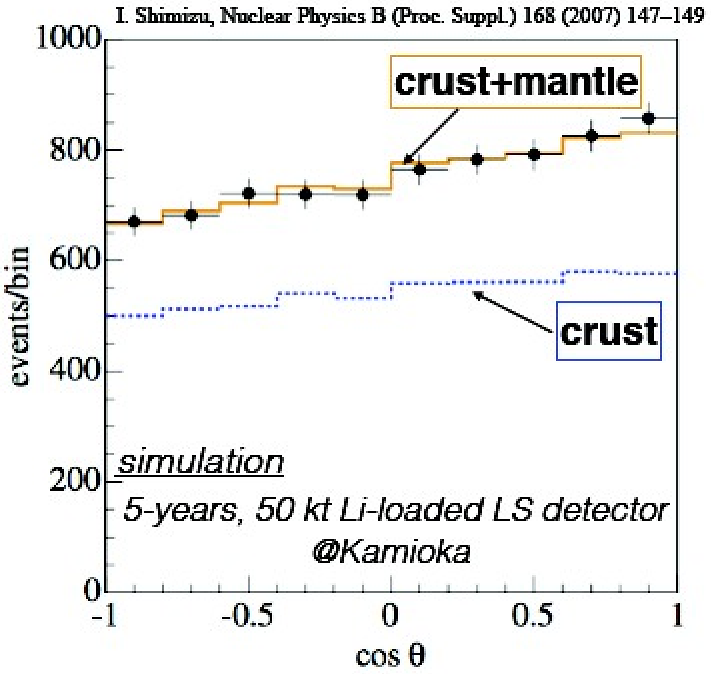

What We Can Measure?

1. large size detector (1kt~)

geo-neutrino

(1) distinguish mantle contribution

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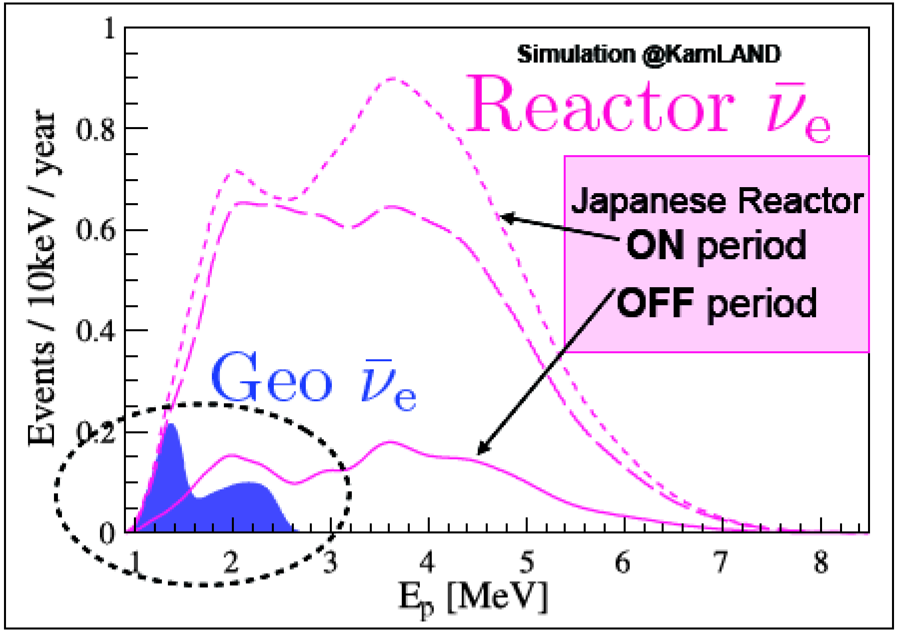
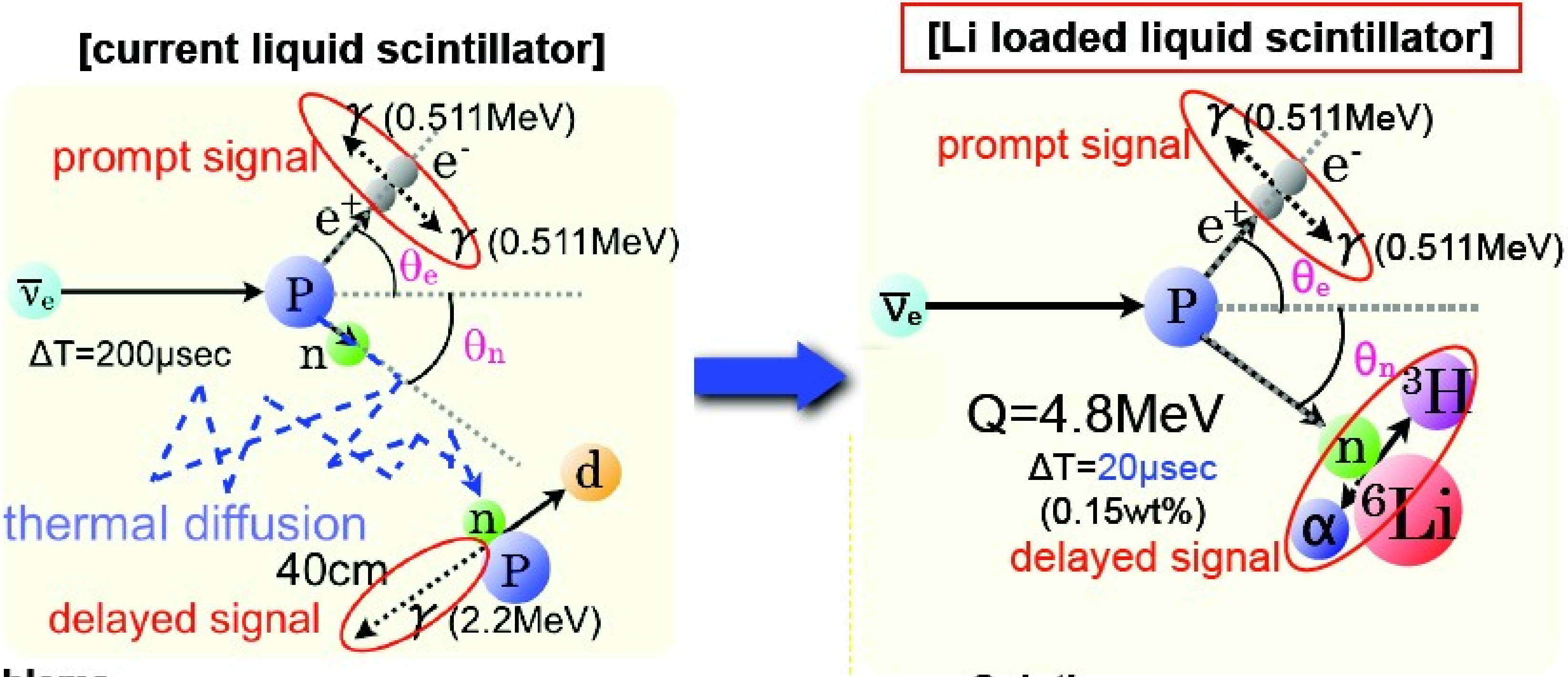


- Reactor neutrinos : useful for neutrino property study
- Reactor neutrinos are the most significant background for geo-neutrino

Detection Principle



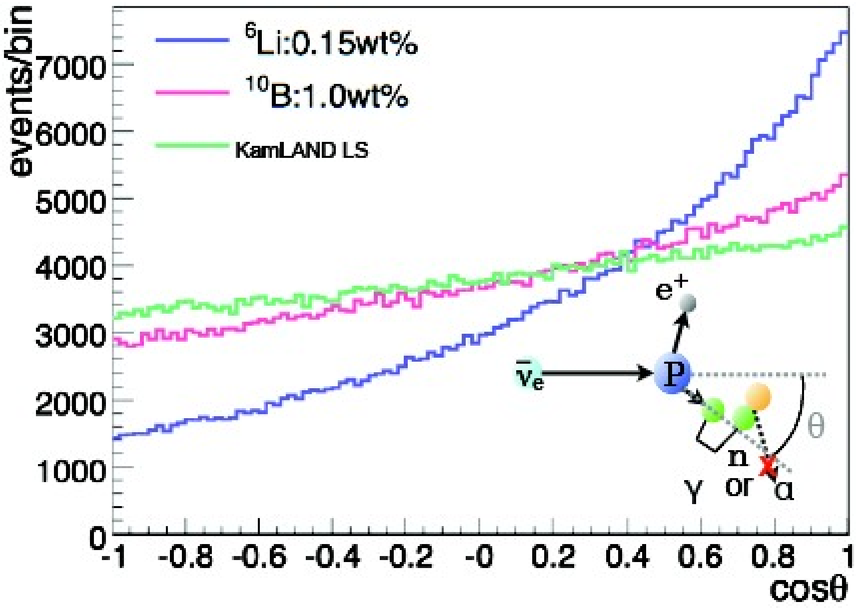
Problems

- Neutron loses directional information before being captured by proton.
- Delayed signal (2.2 MeV γ-ray) confuses capture point

Solutions

- large neutron capture cross section (^{6}Li 940 barns vs ^{1}H 0.3 barns)
- α does't travel far

Angular Distribution



best

	Asymmetry	miss-identification rate (θ>90°)
^{6}Li LS	0.391	30.4%
^{10}B LS	0.148	42.6%
KamLAND LS	0.079	46%

$$\text{Asymmetry} = \frac{A_+ - A_-}{A_+ + A_-}$$

A : number of event

A_+ $0 \leq \cos\theta \leq 1$

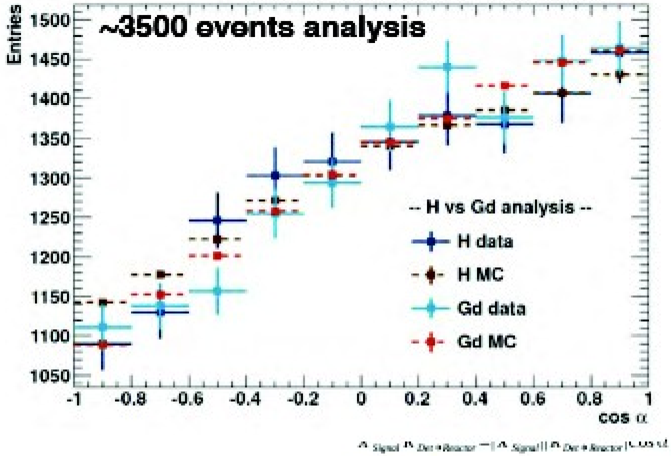
A_- $-1 \leq \cos\theta \leq 0$

Experiment & Idea

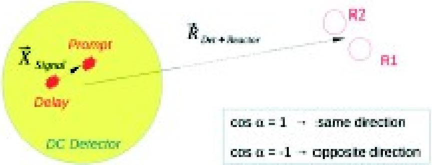
Experiment : Double Chooz (2011~, France)

- 8.2 t, Gd-loaded LS
- detectors
  - near : L=400m, 300ν/day
  - far : L=1050m, 40ν/day(L : distance from reactors)

figures from T. Brugière, AAP 2015

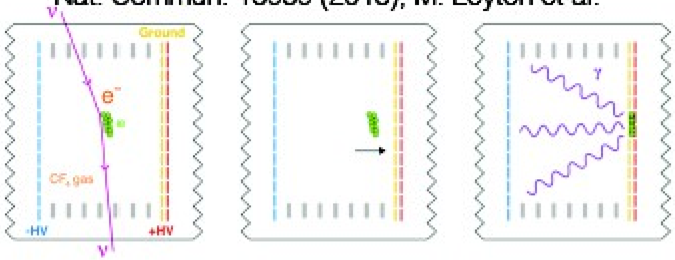


very high statistics of reactor ν

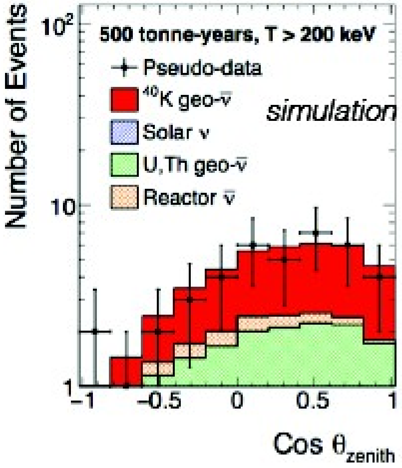


Idea : gaseous time projection chamber

Nat. Commun. 15989 (2018), M. Leyton et al.



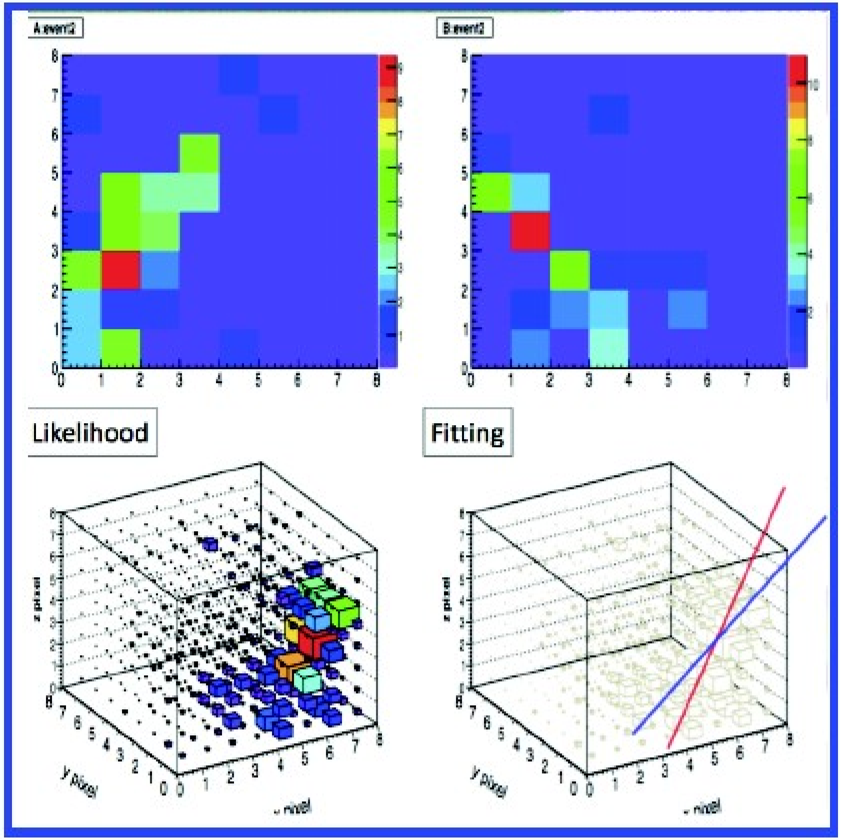
elastic scattering, gas (e.g. CF_4) filled chamber



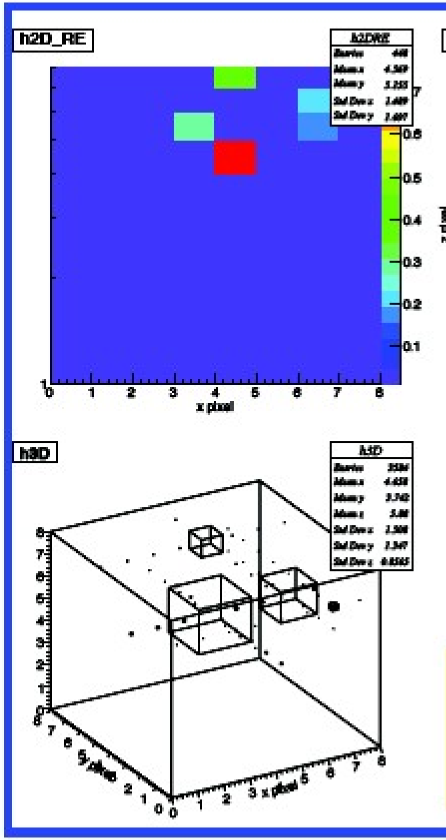
technically very difficult to construct the detector

Prototype Detector: 30L LiLS + 2 Imaging Detectors

muon track



^{60}Co γ-ray point source



We measured 3D images of scintillation light.

Summary

- Geoneutrinos bring unique and direct information about the Earth's interior and dynamics.
- Directional sensitivity will be efficient technology for geo-neutrino measurement.
  - Distinguish mantle contribution
  - Separate reactor background
- New measurement technologies
  - ^{6}Li loaded liquid scintillator can have good directional sensitivity.
    - We have developed the ^{6}Li loaded LS by the original method.
  - Imaging detector have designed. It can achieve high vertex resolution.
  - Prototype detector : test of detection technology
    - 3D images of muon track and ^{60}Co γ-ray points have been measured.
    - Next target : 3D image of correlated two events (assuming anti-neutrino signals)

Geo-neutrino Program at Baksan Neutrino Observatory

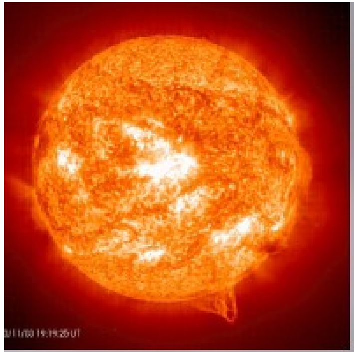
Yu.M. Malyshkin[1,4], A.N. Fazilakhmetov[1], A.M. Gangapshev[1,3],
V.N. Gavrin[1], T.V. Ibragimova[1], M.M. Kochkarov[1],
V.V. Kazalov[1], D.Yu. Kudrin[1], V.V. Kuzminov[1,3],
B.K. Lubsandorzhiev[1], Yu.M. Malyshkin[1,4], G.Ya. Novikova[1],
A.A. Shikhin[1], A.Yu. Sidorenkov[1], N.A. Ushakov[1],
E.P. Veretenkin[1], D.M. Voronin[1],E.A. Yanovich[1]

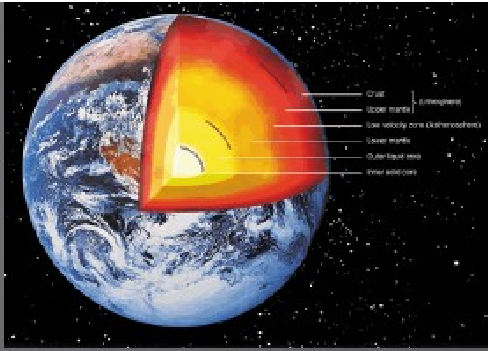
[1]Institute for Nuclear Research of RAS, Moscow, Russia
[2]Institute of Astronomy of RAS, Moscow, Russia
[3]Kabardino-Balkarian State University, Nalchik, Russia
[4]National Institute of Nuclear Physics, Rome, Italy

“Neutrino Geoscience”, Prague
October 20-23, 2019

Summary

- Baksan is a good location for geo-neutrino studies:
  - Far from power reactors
  - Low muon flux
  - Well studied backgrounds
  - At mountainous region (thick crust) – complementary to other experiments
- The work has started:
  - Examination of liquid scintillator
  - Assembling of the first prototype





Terrestrial ^{40}K geoneutrinos and Solar CNO neutrinos

V. V. Sinev (INR, Moscow)

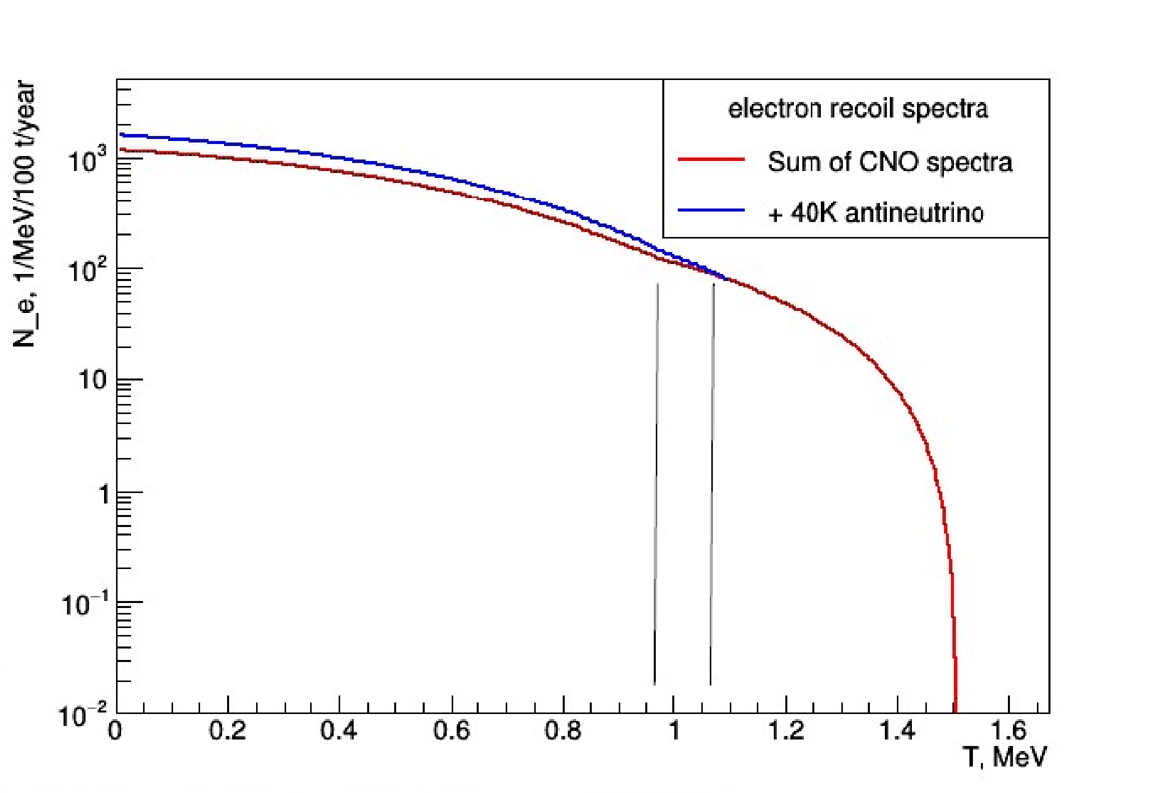
in collaboration with

L.B.Bezrukov, I. S. Karpikov, A.S. Kurlovich,
B. K. Lubsandorzhiev, A. K. Mezokh, S. V. Silaeva, V. P. Zavarzina (INR RAS, Moscow)

and V. P. Morgaluk (A. N. Nesmeyanov Institute of Organoelement Compounds of Russian Academy of Sciences, Moscow)

Neutrino Geoscience 2019, Prague, October, 21-23

Prediction of possible observation ^{40}K with CNO neutrinos in 100 t of Borexino detector



Conclusion

As well as neutrinos from CNO cycle Borexino could detect ^{40}K antineutrinos.

Several events per day counting rate for ^{40}K antineutrinos in 100 t of Borexino target means the potassium abundance in the Earth at the level more than 1% by mass.

We know that 1% of potassium in the Earth produces about 200 TW of heat.

To solve the problem of ^{40}K we need to have independent measurement of CNO cycle neutrinos from the Sun.

Project LENS should be recalled again.

清華大學
Tsinghua University

Hunting the Potassium Geoneutrinos with Liquid-scintillator Cherenkov Detectors

Zhe Wang
Tsinghua University
23/10/2019

Neutrino Geoscience 2019 Prague

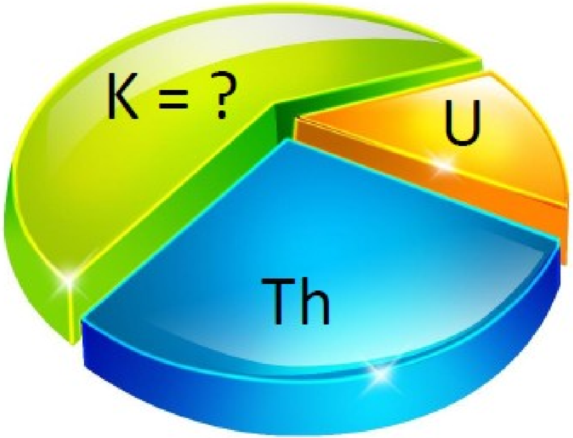
Based on arxiv 1709.03743

Geoneutrino: What powers the Earth?

- Total Heat Flow 47±3 TW
- Models for radiogenic heat 10-30 TW
- Experimental measurement with U, Th geoneutrinos 10-30 TW (KamLAND and Borexino)

Important Questions

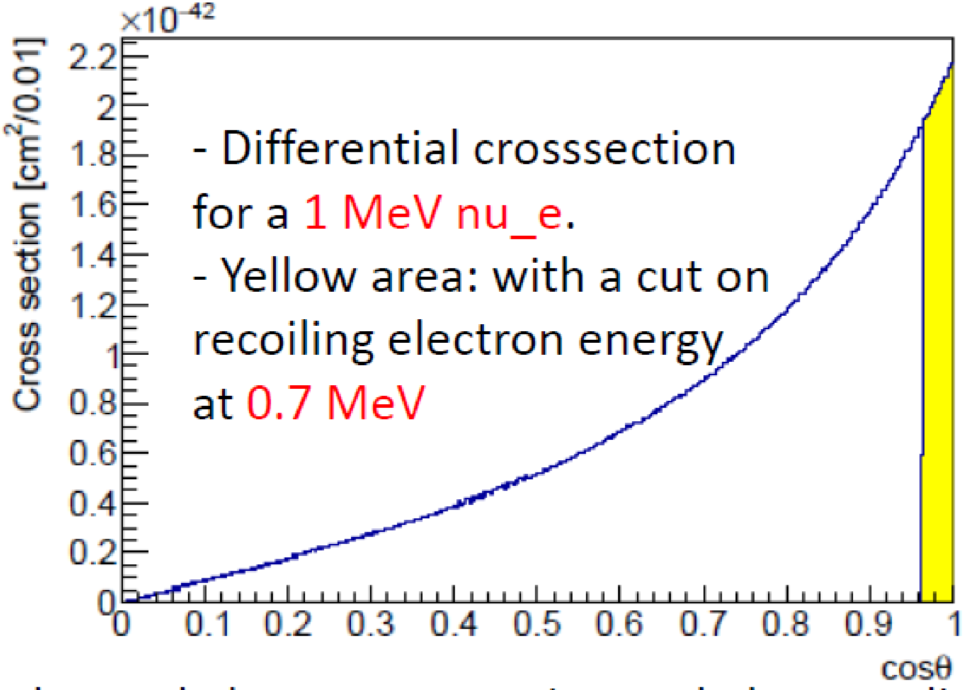
- Incomplete picture. K element has quite different chemical and physical properties than U or Th. It doesn't follow the path of U and Th in the Earth evolution.



Measure it.
We can try.

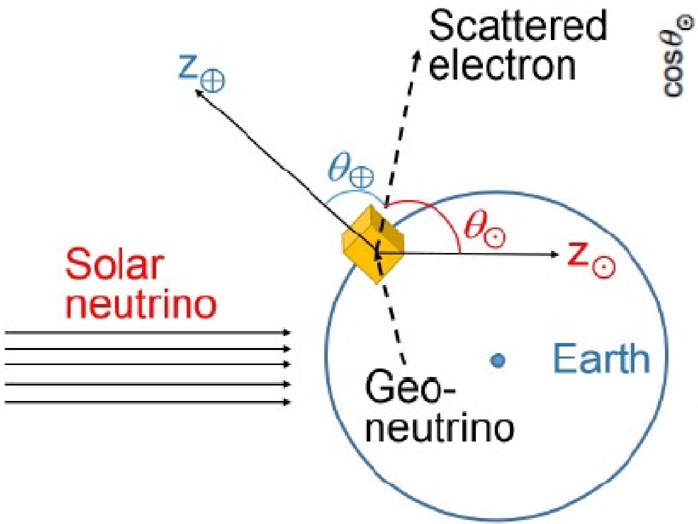
Strong Direction Correlation at Low E

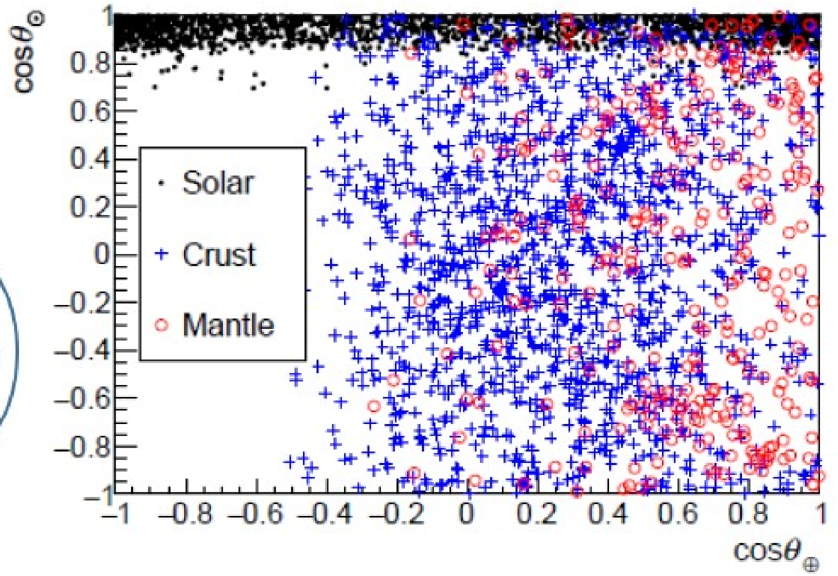
Even at low energy (E_ν<2 MeV) recoil electrons can still point back to the Sun after an energy cut



θ: the angle between neutrino and electron direction

Theoretical Distributions



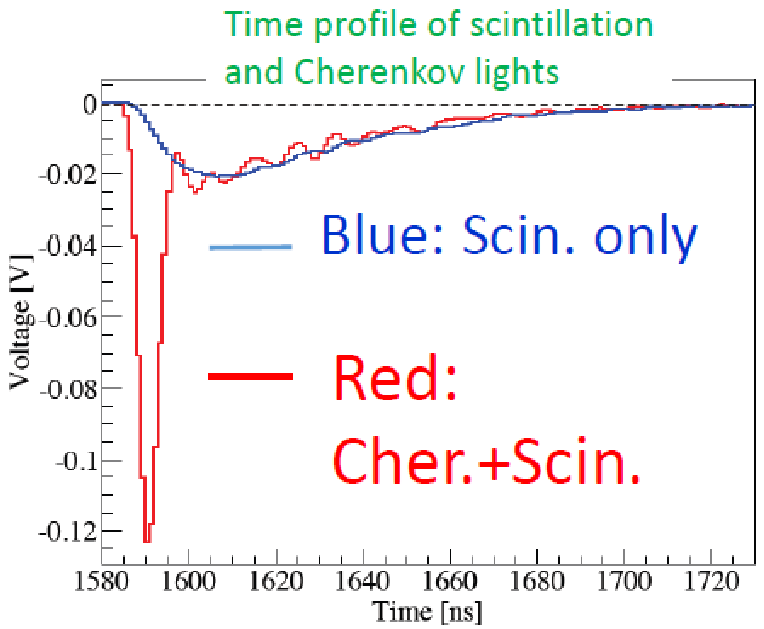


Solar and geo neutrinos can be well separated after requiring $K_e > 0.7$ MeV

Slow Liquid Scintillator, for example LAB

- Cherenkov emission: prompt
- Scintillation emission time constant: 10-20 ns (slow)
- PMT: TTS 1 ns

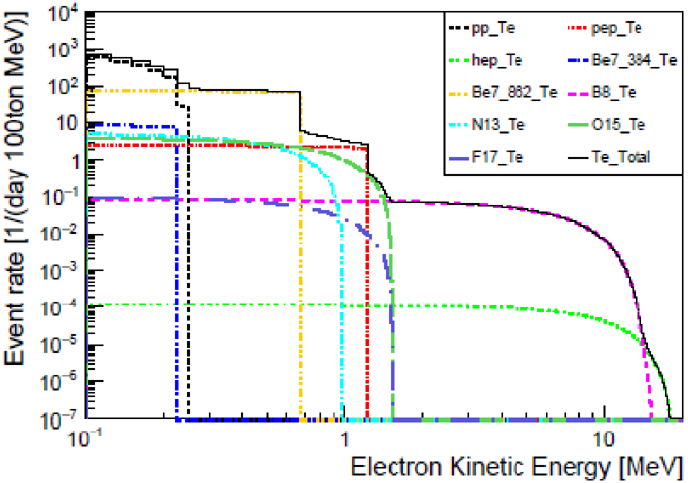
Other liquid-scintillator Cherenkov detector schemes also work.



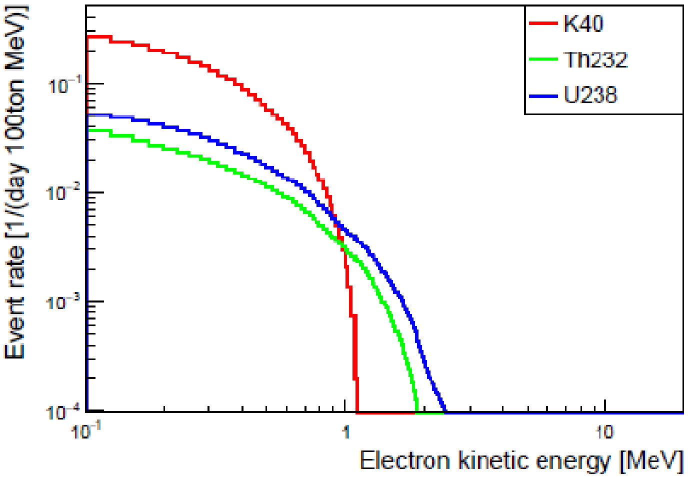
Feature: Both direction and energy measurements

Question: With electron scattering, electronics, offline Cherenkov recognition, can Slow-LS work out at less than 2 MeV?

Recoil electron spectra from the solar and geoneutrinos

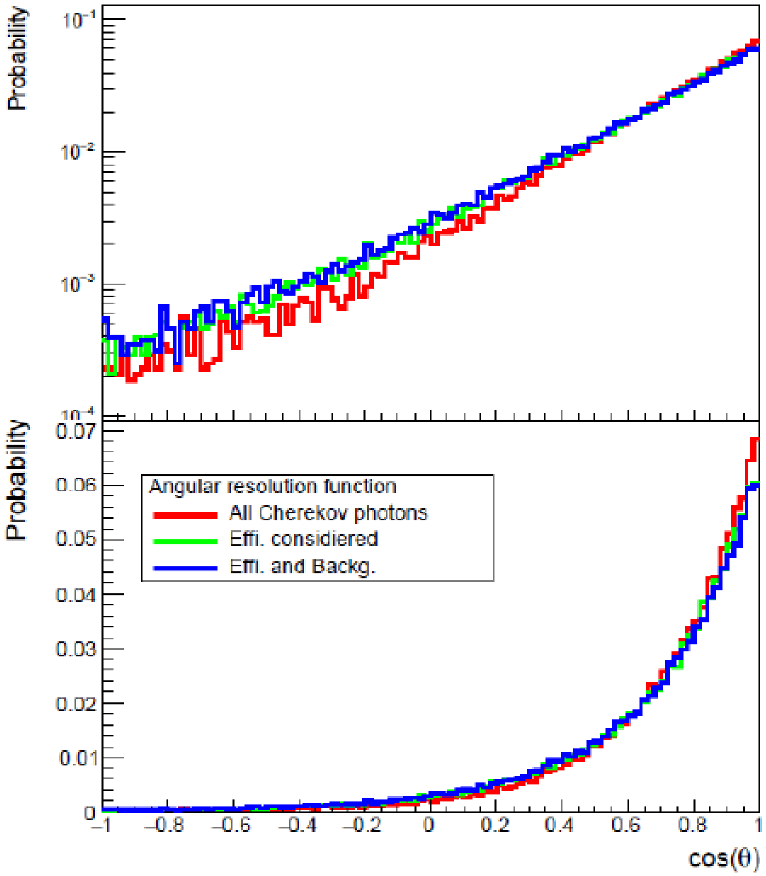


Electron spectra from solar neutrinos



Electron spectra from geo neutrinos

Angular Resolution relative to Initial e- Direction in K_e range [0.5, 2] MeV

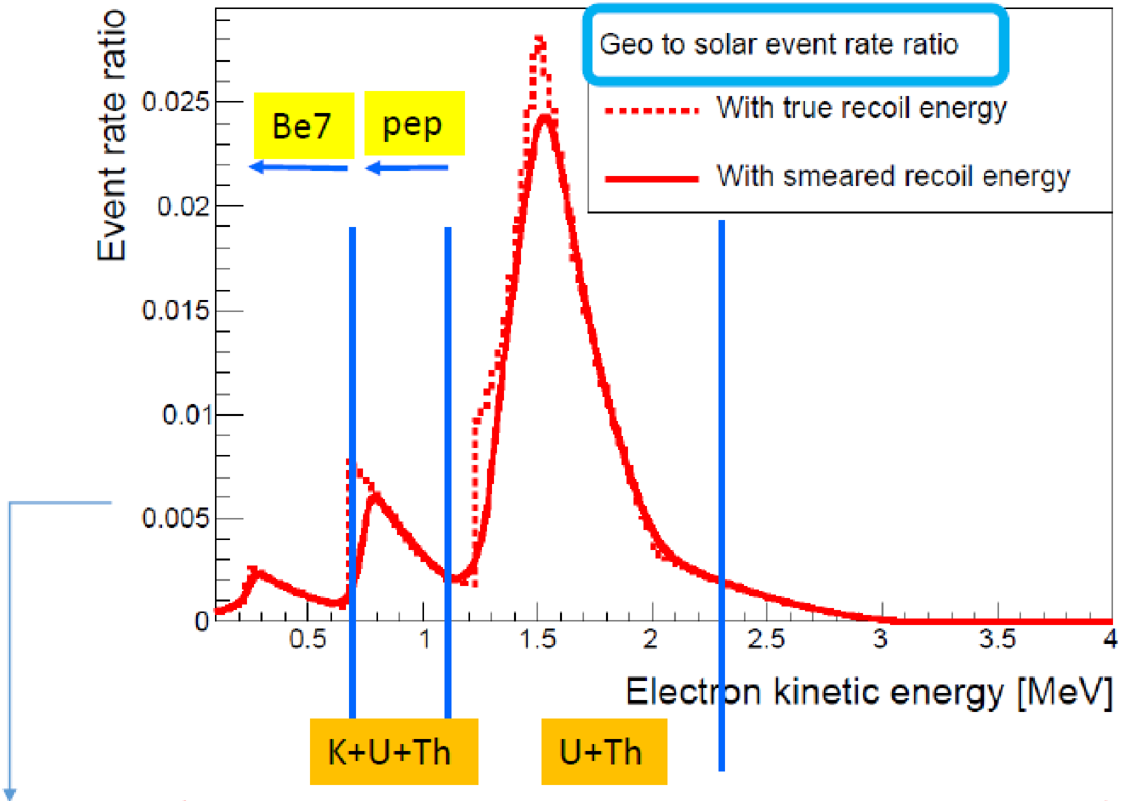


- 125 degrees for 99% coverage

- Remove scintillation Bkg PEs, 124 degrees for 99% coverage

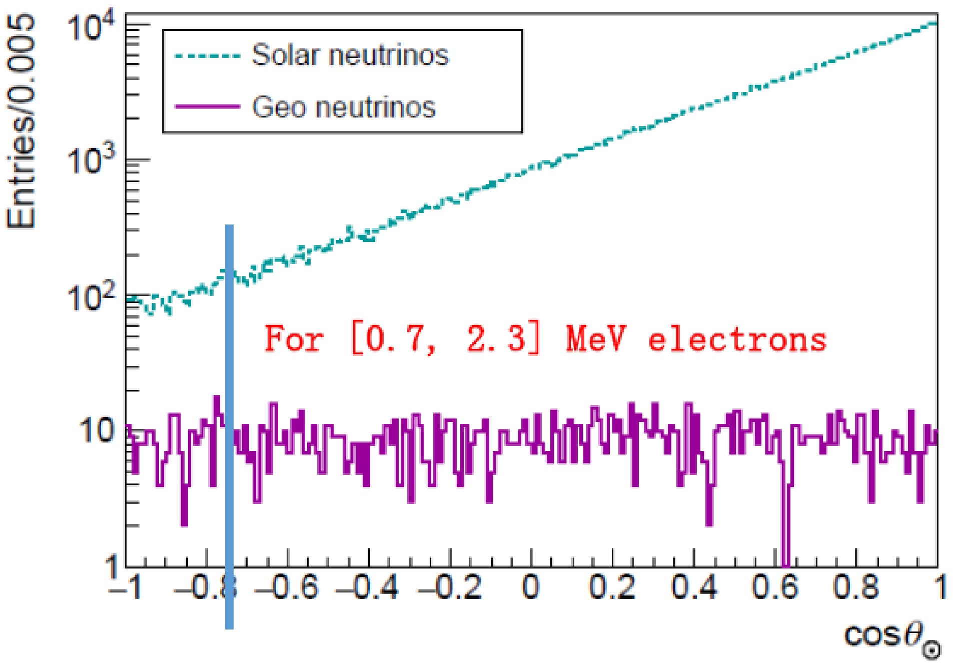
- No Scin. Bkg. and use all Cherenkov Photons: 116 degrees
(Scattering is the No. 1 reason to make it so bad)

Energy Signal Region Determination



We need a factor of 100-200 to suppress the solar background

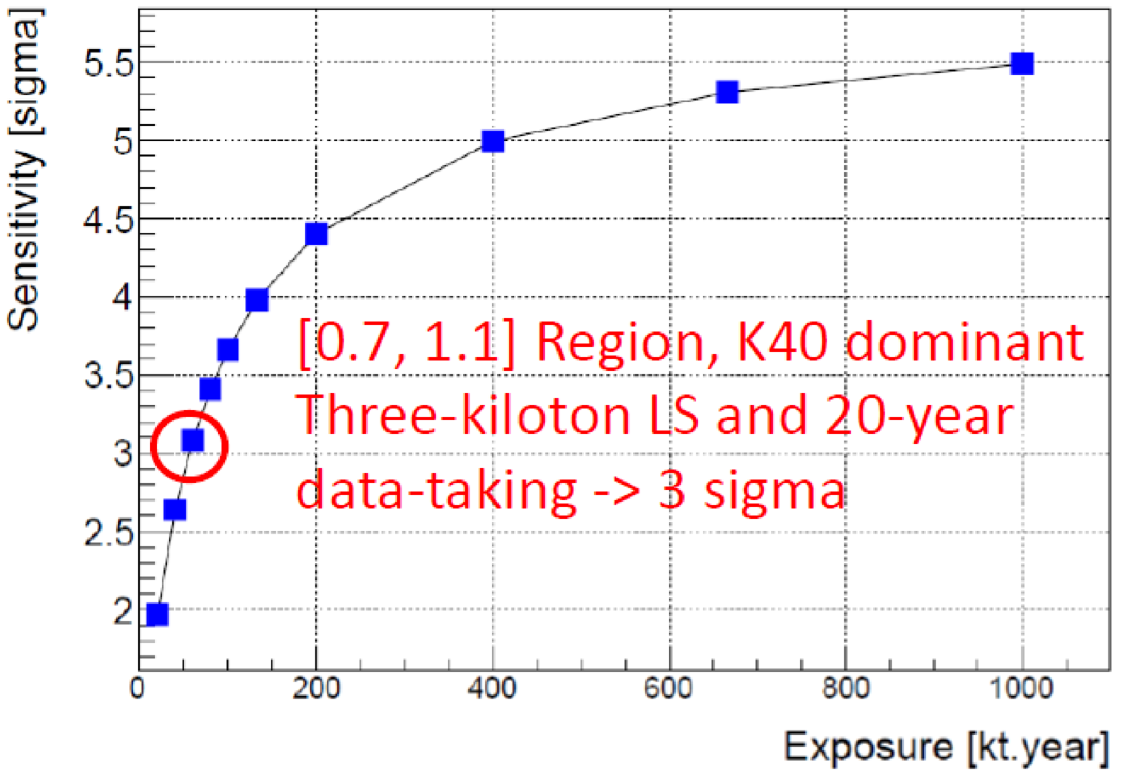
Signal Region for Direction Criteria



A cut at −0.75 can suppress the solar background by a factor of 150. Signal-to-background ratio is close to 1 now.

K-40 Geoneutrino Signal uncertainty

$$\text{sensitivity} = N_{geo}/\sigma_{geo}$$



The sensitivity U, Th window is poor.

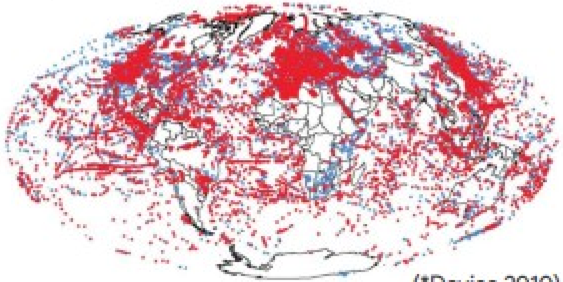
Università degli Studi di Ferrara | Dipartimento di Fisica e Scienze della Terra

Andrea Serafini, *Baldoncini M., Cabrera A., Chen M., Grassi M., Mantovani F., Strati V., Wagner S.*

(On behalf of LiquidO collaboration)

Detecting ^{40}K geoneutrinos with LiquidO

Why is ^{40}K so important?

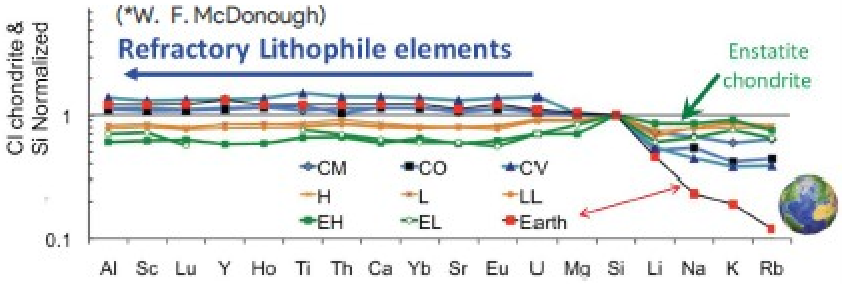

(*Davies 2010)

1. K, together with U and Th, is one of the three **Heat Producing Elements** (HPEs) that contribute to the 47 ± 2 TW heat power.
2. According to Earth models, ^{40}K radiogenic power varies from **2.0-4.7 TW**.
3. Our planet seems to contain **10%-30% K respect to** the enstatitic (EH) and carbonaceous (CI) **chondrites** meteorites, respectively.
4. Two theories on the fate of the mysterious **"missing K"** include **loss to space** during accretion or **segregation into the core**, but no experimental evidence has been able to confirm or rule out any of the hypotheses, yet.


(EH)


(CI)

5. Being moderately volatile, K is representative of the depletion of **volatile elements** on Earth. Volatiles' abundances are required to understand deep H_2O cycle and ^{40}K-^{40}Ar system in the Earth.

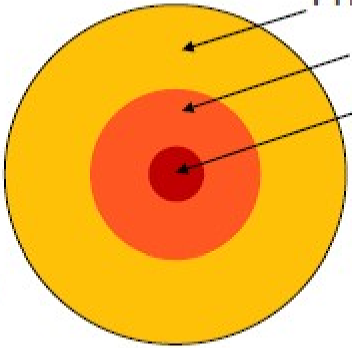


A direct measurement of ^{40}K geoneutrinos would be a breakthrough in the comprehension of the Earth's origin and composition.

Earth evolution

1st differentiation

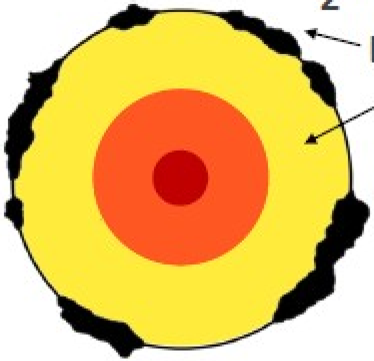
Primitive Mantle (PM) [M_{PM} ~68% M_{Earth}]
Outer Core (OC) [M_{OC} ~31% M_{Earth}]
Inner Core (IC) [M_{IC} ~1% M_{Earth}]



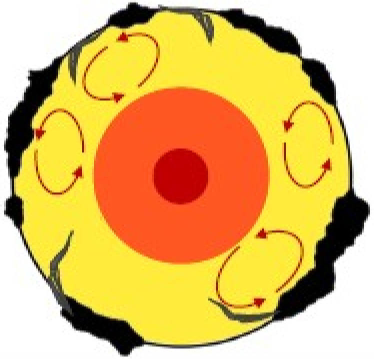
Siderophile elements
(chemical affinity with Fe)
in the Core

2nd differentiation

Lithosphere [M_{Lith} ~2% M_{Earth}]
Mantle [M_{Mantle} ~66% M_{Earth}]
OC+IC [M_{Core} ~32% M_{Earth}]



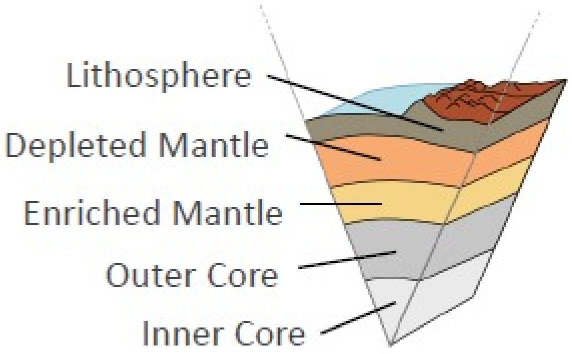
Lithophile elements
(chemical affinity with O)
in the Lithosphere (e.g. U, Th, K)

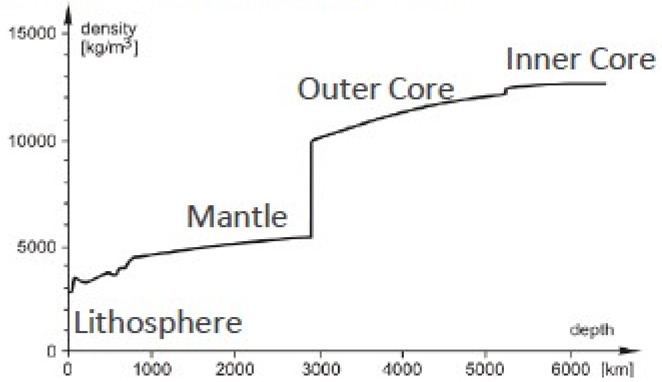


Convective and tectonic processes: formation of new crust (oceanic crust) and recycling of continental crust (up to 10 times)

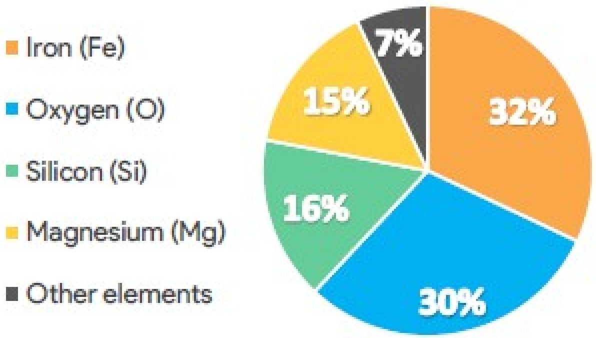
A Standard Model of the Earth

Earth has a well-established **layered** structure, visible from its **density profile**:





Bulk Earth's mass composition



About 0.02% of Earth's mass is made out of radioactive **Heat Producing Elements (HPEs).**

The most important for activity, abundances and half-life time (comparable to Earth's age) are:

- **Uranium U** (M_U~10^{-8} M_{Earth})
- **Thorium Th** (M_{Th}~10^{-8} M_{Earth})
- **Potassium K** (M_K~10^{-4} M_{Earth})

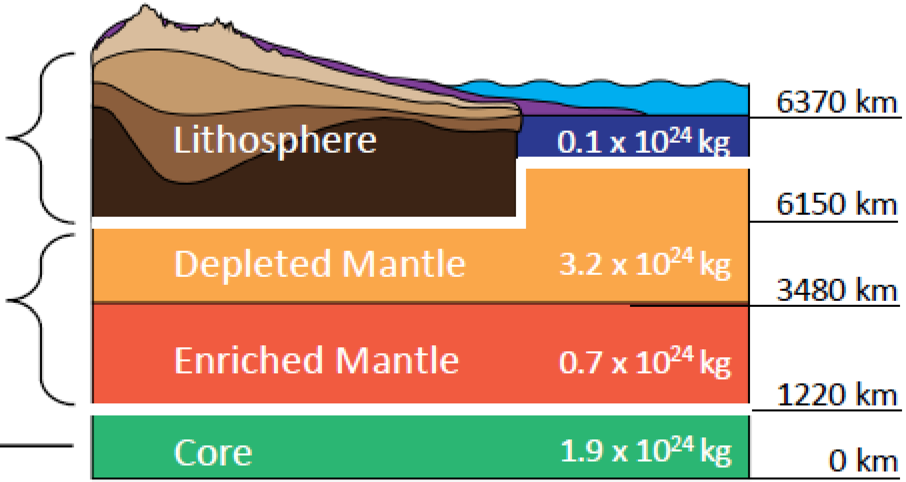
The main reservoirs of the Earth

Despite deep Earth's structure is well understood, its chemical composition is not.
Samples from Lithosphere permit to study its compositions with a statistical significance.

Lithosphere rich in HPEs, directly measurable.

Mantle inaccessible to direct measurements.

Core inaccessible and void of HPEs



	a(U) *[μg/g]*	a(Th) *[μg/g]*	a(K) *[10^{-2}g/g]*
Lithosphere	$0.25^{+0.07}_{-0.06}$	$1.08^{+0.37}_{-0.23}$	$0.28^{+0.07}_{-0.06}$
Depleted Mantle	?	?	?
Enriched Mantle	?	?	?

Bulk Silicate Earth (BSE) Models

The Primitive Mantle's composition is described by the paradigm of the BSE.

Among the several models proposed, these are the ones predicting the **minimum**, the **standard** and the **maximum** values for HPEs' masses

Cosmochemical Model (CCM)

- Enstatitic composition
- Low HPEs content

Geochemical Model (GCM)

- Carbonaceous composition
- Medium HPEs content

Geodynamical Model (GDM)

- Based on Earth dynamics
- High HPEs content

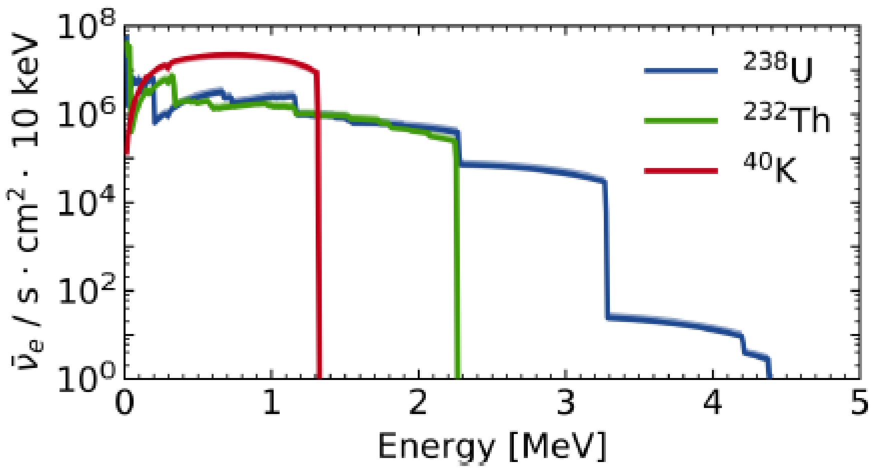
	CCM	GCM	GDM
M(U) *[10^{16} kg]*	*4.8*	*8.1*	*14.1*
M(Th) *[10^{16} kg]*	*17.4*	*32.3*	*56.5*
M(K) *[10^{19} kg]*	***58.9***	***113.0***	***141.2***

Individual models' uncertainties are typically ~20%, of second order compared to a factor ~3 variability among models.

Geoneutrinos: main physical properties

- Geoneutrinos are $\bar{\nu}_e$ produced in naturally occurring β^- decays of HPEs in the Earth.
- HPEs release heat together with geo-$\bar{\nu}_e$ (ε) in a well-fixed ratio.
- They can cross the entire planet **almost without interacting**, bringing instantaneous information on the Earth's composition.
- Geo-$\bar{\nu}_e$ from ^{40}**K** could represent an important tool thanks to their **high luminosity**.

Decay	$T_{1/2}$ [10^9 y]	$\varepsilon(\bar{\nu})$ [$10^7 kg^{-1} s^{-1}$]	$E_{max}(\bar{\nu})$ [MeV]
$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 6\beta^-$	4.47	7.5	3.36
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4\beta^-$	14.0	1.6	2.25
$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$ (89%)	1.28	**23.2**	1.31



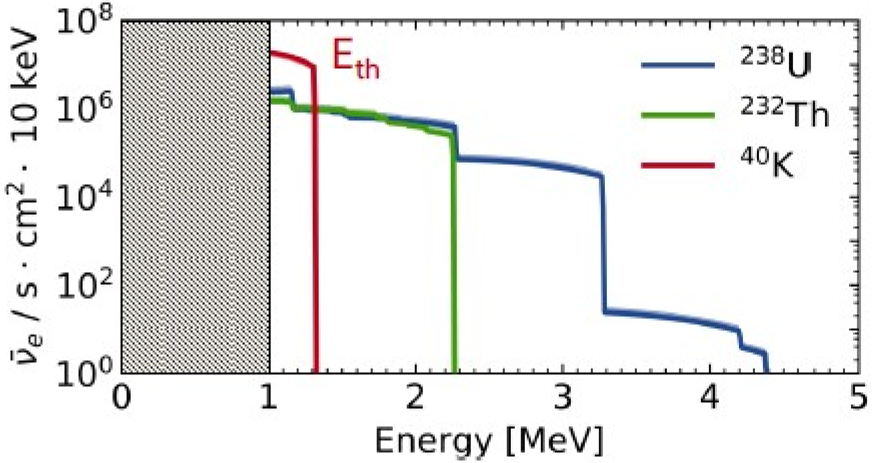
Inverse Beta Decay (IBD) detection

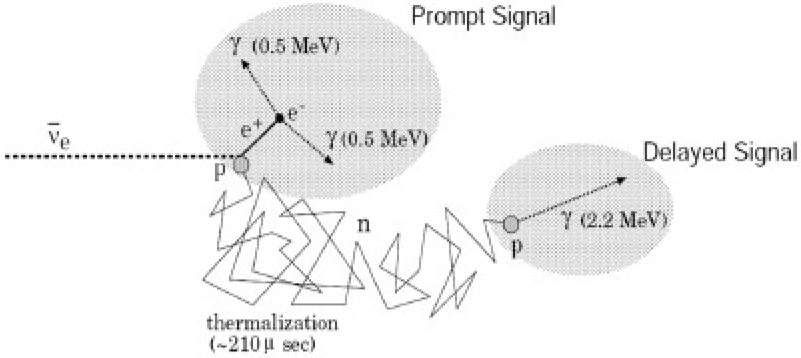
Geoneutrinos are **detected by IBD** in **~kton** Liquid Scintillation Detectors.

$$\bar{\nu}_e + p \rightarrow n + e^+ - 1.806\ MeV$$

Detection requires the coincidence of 2 delayed light signals.

It does not permit to observe ^{40}K-$\bar{\nu}_e$





In order to detect ^{40}K- $\bar{\nu}_e$ we could use:

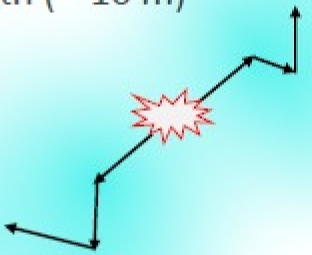
$$\bar{\nu}_e + {}_{Z+1}^{A}Y \rightarrow {}_{Z}^{A}X + e^+ - E_{th}$$

We shall require:

- $E_{th} < 1.3\ MeV$
- High cross-section
- High Y natural isotopic abundance

Transparent vs. opaque detector

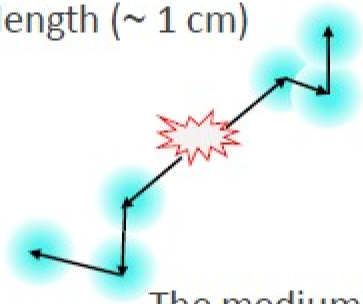
Very long scattering length (~ 10 m)



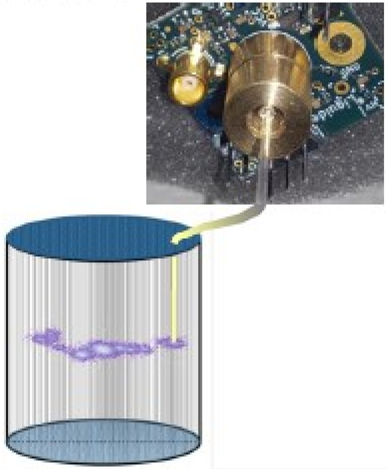
The medium is transparent to scintillation photons

- Scintillation light reaches the surrounding 10^3-10^4 PMTs
- Slow time resolution (~ ns)
- Poor spatial resolution on light deposition (~ 10 cm)
- High photon detection efficiency (~ 20%)

Very short scattering length (~ 1 cm)

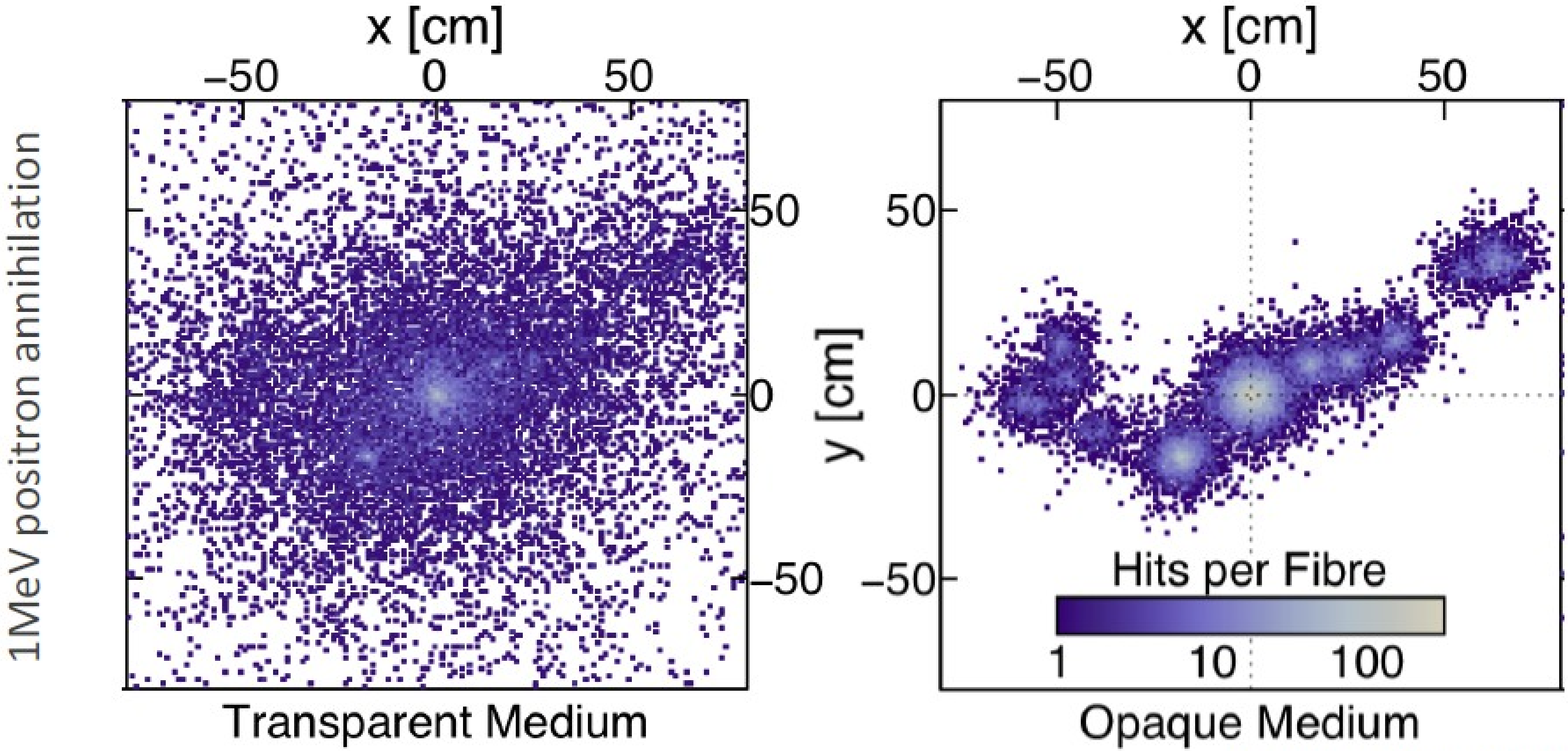


The medium is opaque to scintillation photons



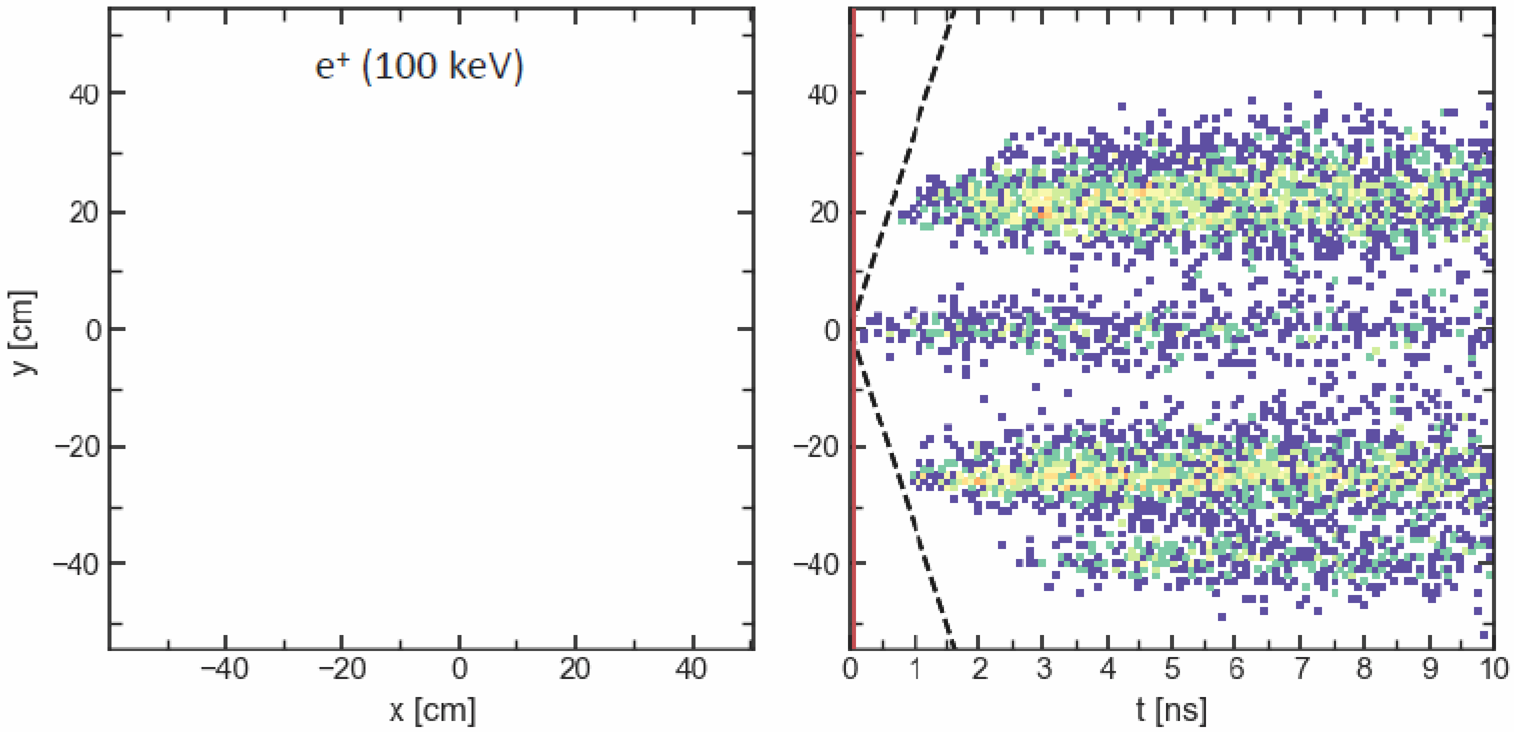
- The light is extracted by an array of optical fibers connected to SiPMs
- Fast time resolution (~ 0.3 ns)
- Excellent spatial resolution on light deposition (~ 1 cm)
- Poor photon detection efficiency (~ 5%)

Simulated scintillation light deposition



(*credits to Marco Grassi)

Detecting e⁺ from ^{40}K geonu in LiquidO

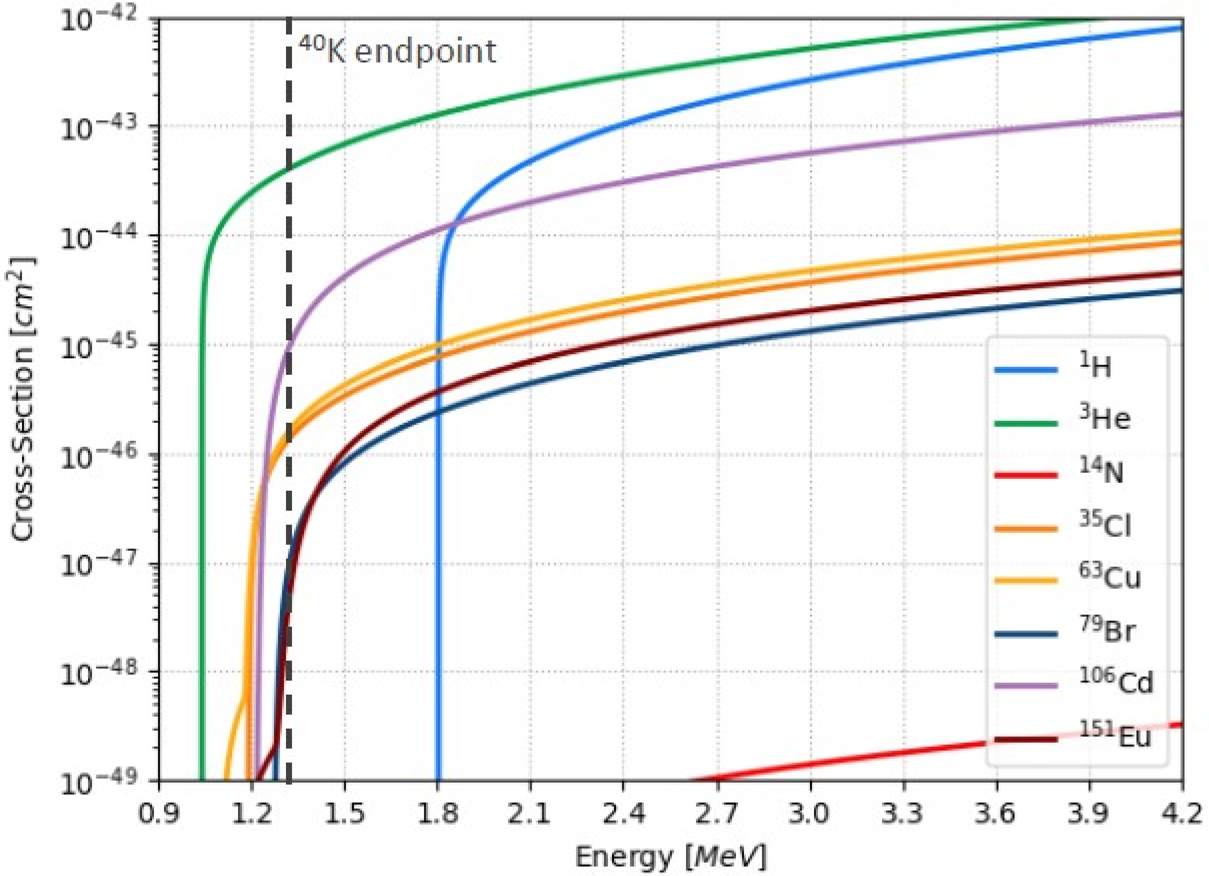


IBD target isotopes for ^{40}K detection

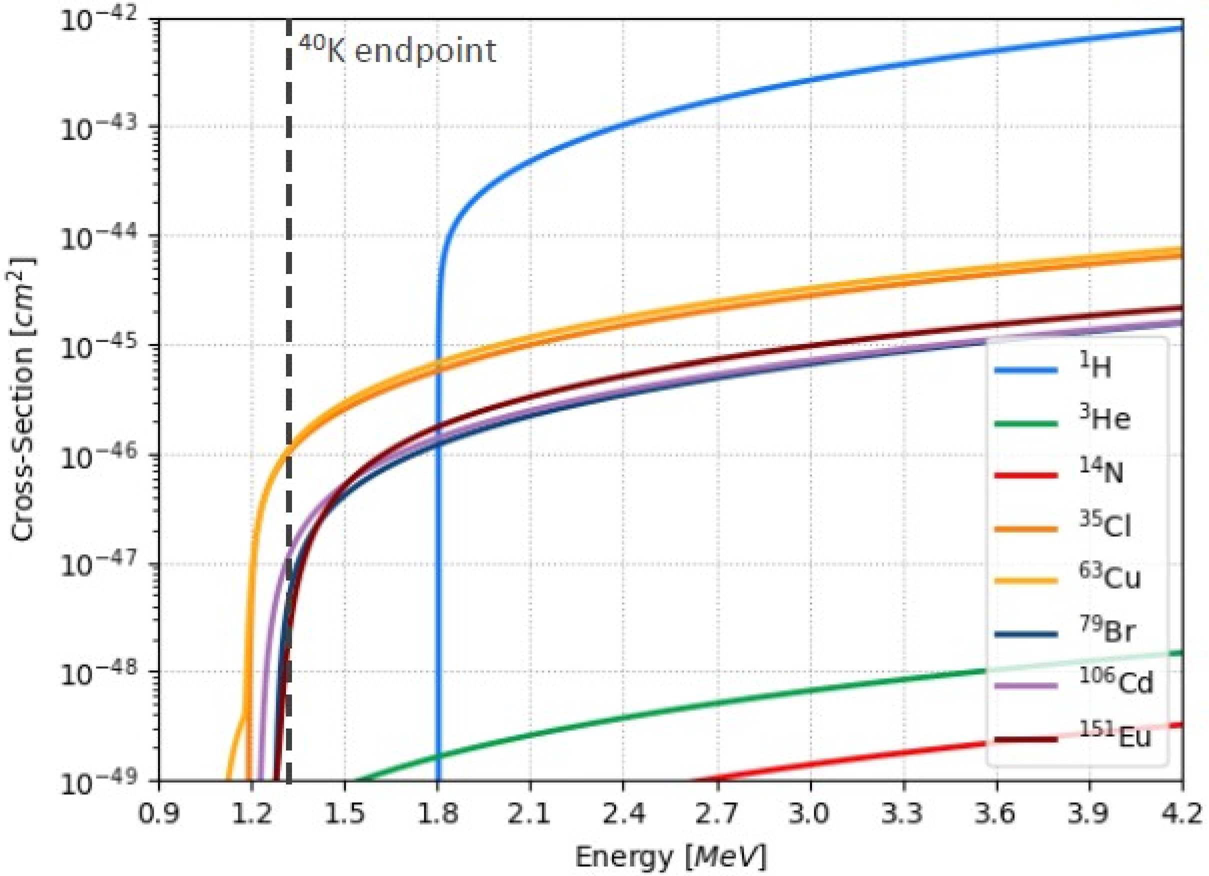
Data from ENSDF database

Target process	Isotopic abundance [%]	E_{th} [MeV]	Log *ft*
$^{1}H \rightarrow {}^{1}n$	99.99	1.806	3.0
$^{3}He \rightarrow {}^{3}H$	$1.34 \cdot 10^{-4}$	1.041	3.1
$^{14}N \rightarrow {}^{14}C$	99.64	1.178	9.0
$^{35}Cl \rightarrow {}^{35}S$	75.76	1.189	5.0
$^{63}Cu \rightarrow {}^{63}Ni$	69.15	1.089	6.7
$^{63}Cu \rightarrow {}^{63}Ni^*$		1.176	5.0
$^{79}Br \rightarrow {}^{79}Se$	50.69	1.173	10.8
$^{79}Br \rightarrow {}^{79}Se^*$		1.268	5.0
$^{106}Cd \rightarrow {}^{106}Ag$	1.25	1.212	4.1
$^{151}Eu \rightarrow {}^{151}Sm$	47.81	1.099	7.5
$^{151}Eu \rightarrow {}^{151}Sm^*$		1.266	5.0

IBD cross-sections on single target isotopes



IBD cross-sections weighted with isotopic abundance



- ^{3}**He**, which seemed the perfect candidate, is disfavored by its **abundance**
- ^{35}**Cl** has both a **low threshold** and a **good weighted cross-section**
- ^{63}**Cu** seems to be as promising as ^{35}Cl, but not equally reliable (*ft* not experimentally measured)

^{40}K geoneutrino expected signals

- Signals are expressed in TNU: 1 geoneutrino event per 10^{32} element target per year
- The signal variability range embraces all possible geochemical models and potassium distribution in the Earth.
- Present geoneutrino signals measured in Borexino and KamLAND on ^{1}H are S(U+Th)~40 TNU

	S(^{40}K) [TNU]	
Target	**Gran Sasso**	**Kamioka**
^{63}Cu	***0.10 [0.06, 0.13]***	***0.07 [0.05, 0.10]***
^{35}Cl	***0.09 [0.06, 0.12]***	***0.07 [0.05, 0.09]***
^{106}Cd	*4.9 [3.2, 6.5]* $\times 10^{-3}$	*3.7 [2.4, 4.9]* $\times 10^{-3}$
^{79}Br	*8.1 [4.4, 10.8]* $\times 10^{-4}$	*6.0 [3.3, 8.1]* $\times 10^{-4}$
^{151}Eu	*3.1 [2.0, 4.1]* $\times 10^{-4}$	*2.3 [1.5, 3.1]* $\times 10^{-4}$
^{3}He	*1.6 [1.0, 2.1]* $\times 10^{-4}$	*1.2 [0.8, 1.6]* $\times 10^{-4}$
^{14}N	*7.7 [5.0, 10.1]* $\times 10^{-6}$	*5.8 [3.7, 7.6]* $\times 10^{-6}$

Detecting geoneutrinos in a ^{35}Cl loaded LiquidO

IBD(^{35}Cl)

$$\bar{\nu}_e + {}^{35}Cl \rightarrow {}^{35}S + e^+$$

$$\hookrightarrow e^+ + e^- \rightarrow 2\gamma$$

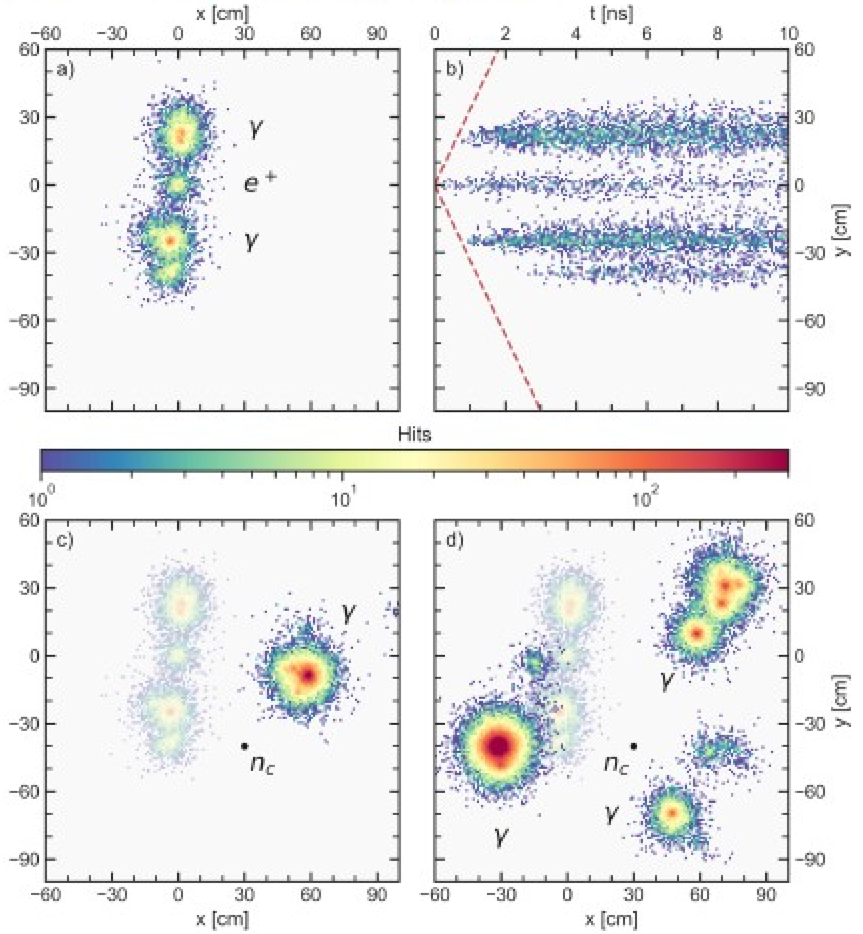
IBD-proton

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

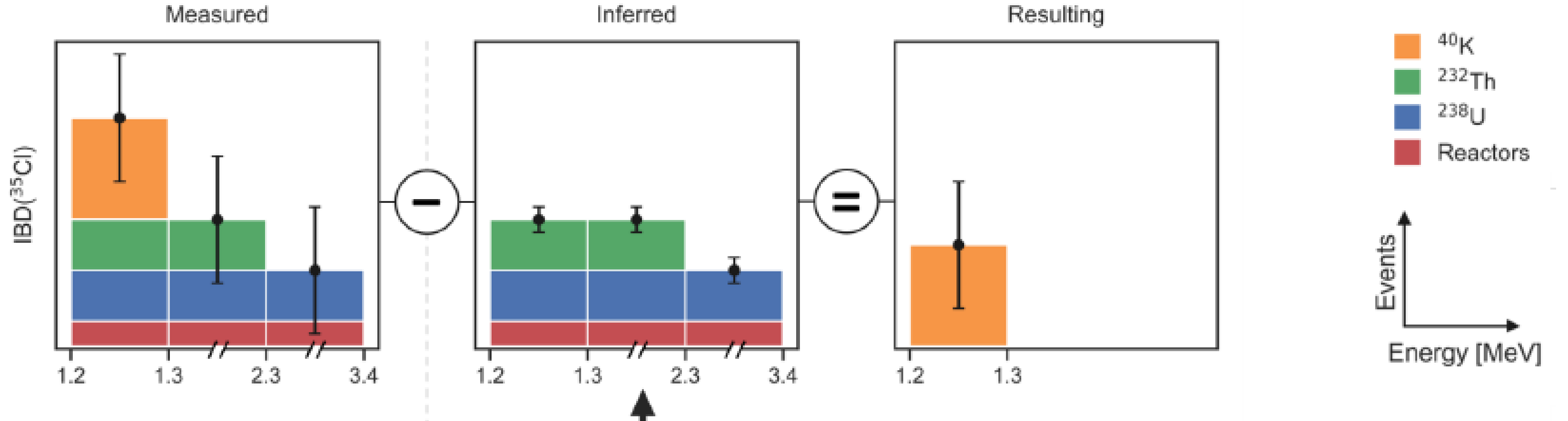
$$\hookrightarrow e^+ + e^- \rightarrow 2\gamma$$

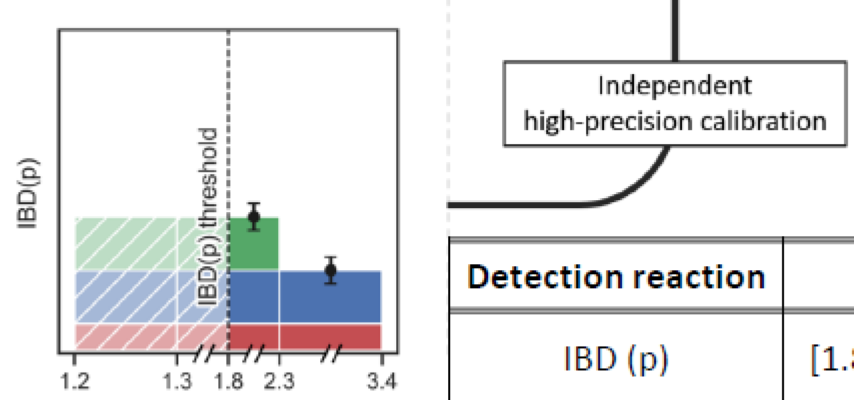
$$\hookrightarrow n + p \rightarrow d + \gamma$$

$$\hookrightarrow n + {}^{35}Cl \rightarrow {}^{36}Cl + 3\gamma$$



Detecting ^{40}K geoneutrinos in a ^{35}Cl loaded LiquidO





A 150 kton ^{35}Cl loaded Liquid detector would enable σ_{stat} < 1% on S(*U+Th+reactors*)

		Events			
Detection reaction	**Energy range**	**Reactors**	**^{238}U**	**^{232}Th**	**^{40}K**
IBD (p)	[1.806 – 3.27] MeV	10107	13885	4234	/
IBD (^{35}Cl)	[1.189 – 1.311] MeV	0.2	1.1	1.1	11.9

Take away messages

- K is essential in understanding Earth's **thermal evolution** and **volatility** pattern. A direct ^{40}K-$\bar{\nu}_e$ detection would rule out exotic scenarios on the fate of **"missing K"**.

- Considering geochemical and geophysical uncertainties we estimated that the **expected ^{40}K geo-$\bar{\nu}_e$ signal** at surface **varies of a factor x2** according to different Earth's compositional models.

- LiquidO enables a **clear identification of single positrons** from both the time pattern and the spatial topology of the event →Detection of **^{40}K-$\bar{\nu}_e$** via CC now possible!!

- At the present time, K-$\bar{\nu}_e$ remains undetected. A list of **seven candidate isotopes** (^{3}He,^{14}N,^{35}Cl,^{63}Cu,^{79}Br,^{106}Cd, ^{151}Eu) suitable **for ^{40}K-$\bar{\nu}_e$ IBD detection** have been identified.

- Considering IBD cross sections and isotopic abundances, **^{63}Cu** and **^{35}Cl** resulted the **best candidates**. → The poor reliability of ^{63}Cu log *ft* value calls for refined nuclear physics inputs

- A **50 kton** (150 kton) LiquidO detector would detect **^{40}K-$\bar{\nu}_e$ with 3σ** (5σ) significance **in 10 years**. It would also enable **sub-percent uncertainties on U and Th geoneutrino detection**.

Заключение

- Увеличивается статистика Th & U регистрации в существующих детекторах. Не хватает информации о направлении геонейтрино.
- Новый детектор для расположения на дне океана OBD с ^{6}Li для улучшения регистрации нейтрона по сравнению с захватом на ^{1}H.
- Интерес к регистрации ^{40}K. Предлагаются новые методы: черенковский свет, ^{35}Cl.
- В ближайшие 20-50 лет может быть решена проблема ^{40}K и теплового потока Земли.