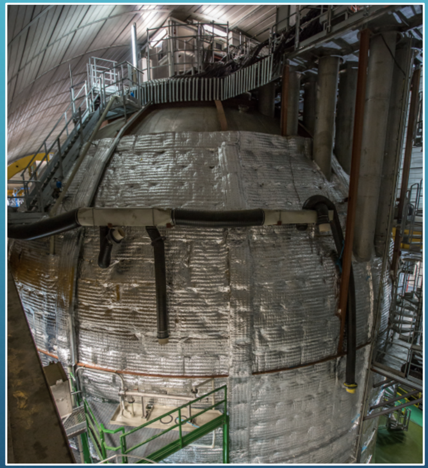
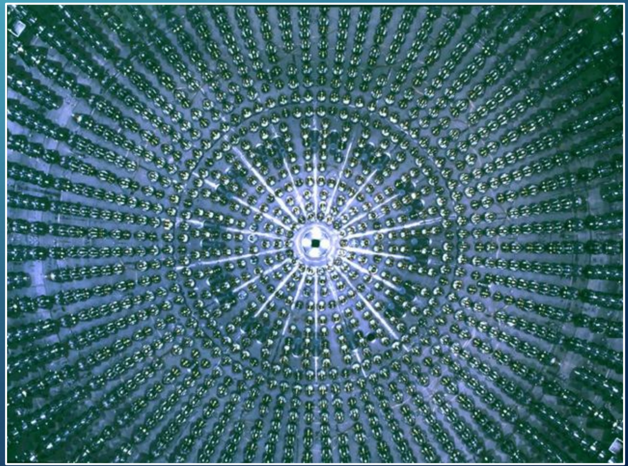
GEONEUTRINOS AS PROBES FOR DEEP EARTH

SANDRA ZAVATARELLI (INFN – SEZIONE DI GENOVA – ITALY)

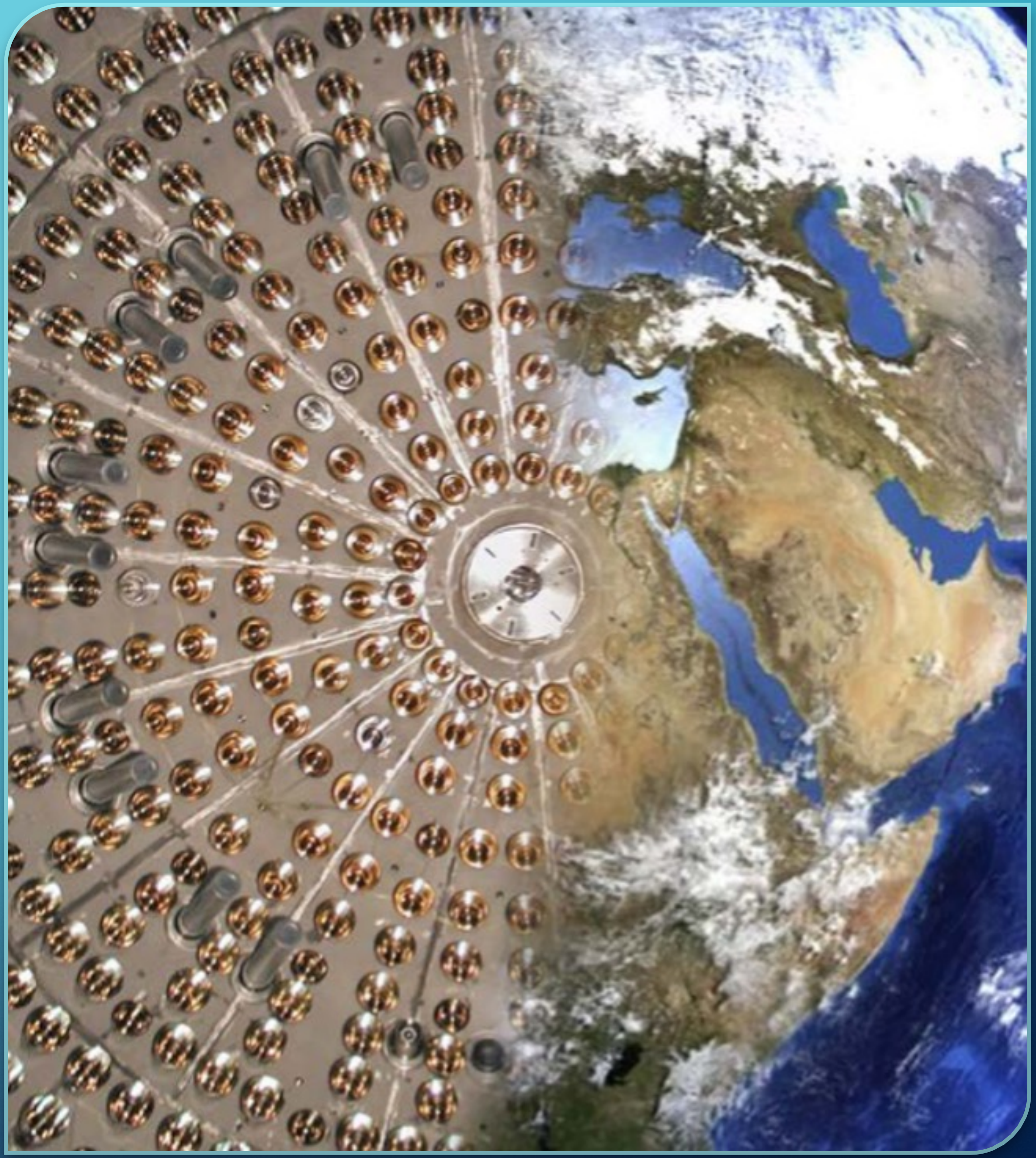




AHEAD 2020 Workshop, March 4-5 2024, Cascina (IT)

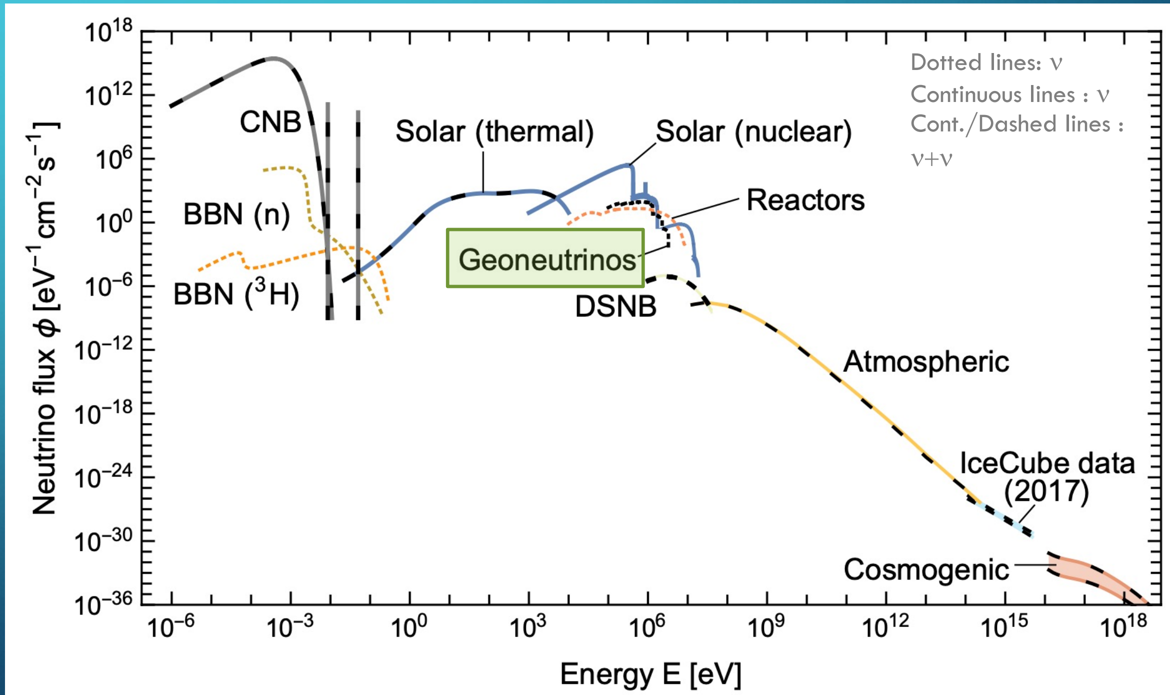
TALK LAYOUT

- Why to study geoneutrinos
- Available infos about deep Earth
- Geo-nu studies with underground liquid scintillator experiments: Borexino and KamLAND
- Geological interpretation and comparison of the results
- Future perspectives



GEO-NEUTRINOS AS PROBES FOR DEEP EARTH: WHY?

- Geoneutrinos are the most abundant component of anti-ν flux at Earth



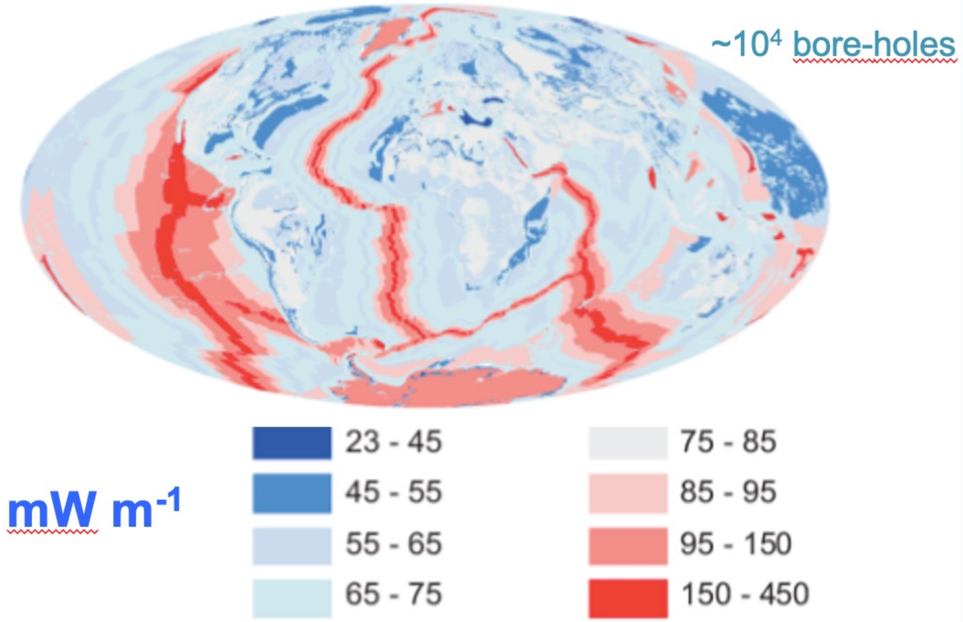
here assumed m1=0, m2=8.6 meV, m3=50 meV

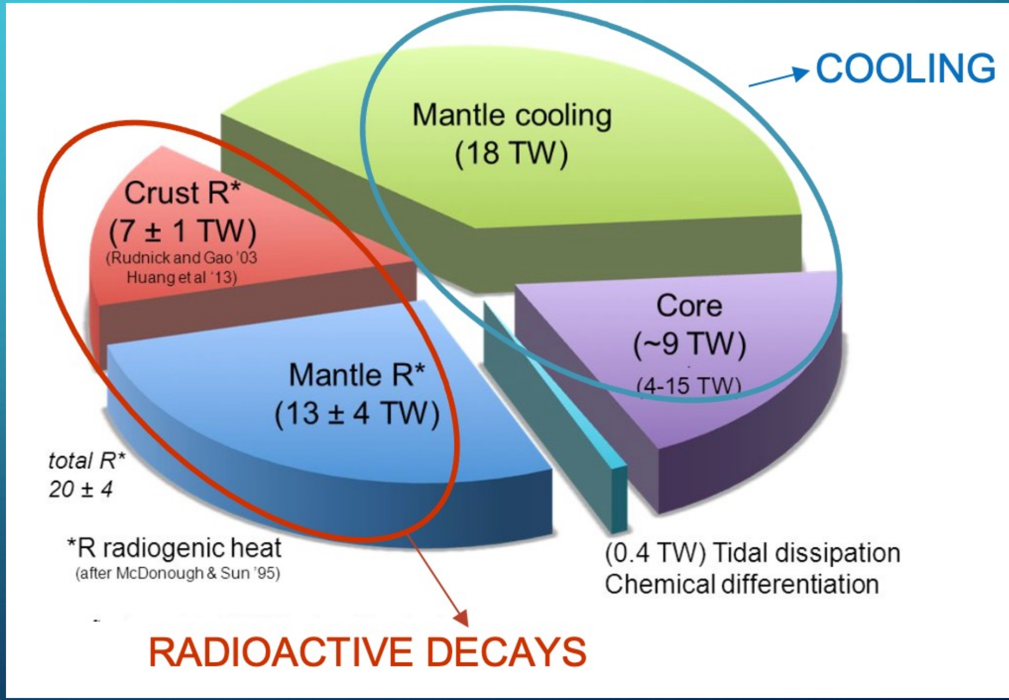
E. Vitigliano, I. Tamborra and G. Raffelt, Rev. Mod. Phys. 92, 045006 (2020),

EARTH'S ENERGETICS

Sources: unclear picture…

Earth's surface heat flow : 47 ± 2 TW





GEO-NEUTRINOS AS PROBES FOR DEEP EARTH

Geoneutrinos: antineutrinos/neutrinos from the decays of long-lived radioactive isotopes naturally present in the Earth

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + \mathbf{4}\,\bar{\nu}_e + 42.8$ MeV — $T_{1/2} = 1.40 \times 10^{10}$ y

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- + \mathbf{6}\,\bar{\nu}_e + 51.7$ MeV — $T_{1/2} = 4.468 \times 10^{9}$ y

$^{235}U \rightarrow {}^{207}Pb + 7\,\alpha + 4\,e^- + \mathbf{4}\,\bar{\nu}_e + 46.4$ MeV — $T_{1/2} = 7.040 \times 10^{8}$ y

$^{40}K \rightarrow {}^{40}Ca + e^- + \mathbf{1}\,\bar{\nu}_e + 1.32$ MeV (89.3%) — $T_{1/2} = .248 \times 109$ y

$^{40}K + e \rightarrow {}^{40}Ar + e^+ + \mathbf{1}\,\nu_e + 1.505$ MeV (10.7%)

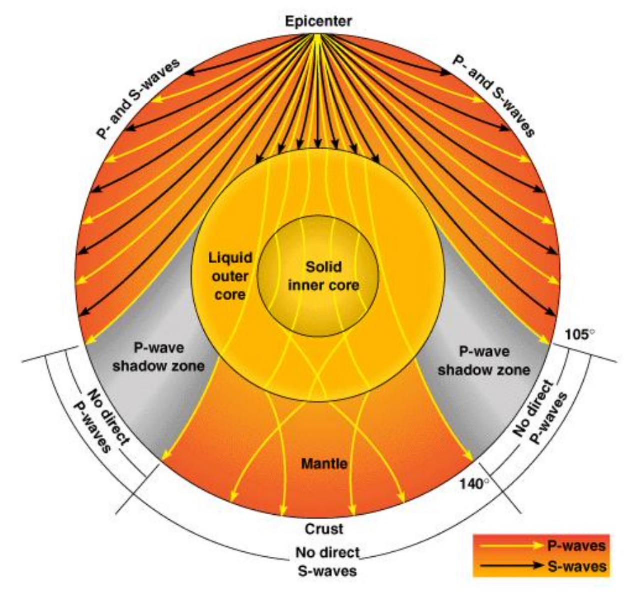
Heat Producing Elements HPE's

Earth shines in geoneutrinos: flux ~10^6 cm^{-2} s^{-1}
leaving freely and instantaneously the Earth interior
(to compare: solar neutrinos (NOT antineutrinos!) flux ~10^{10} cm^{-2} s-1)

Geo-ν fluxes => HPE's abundances => Earth energetics

- **Direct probe of the deep Earth**
- **Released heat and geoneutrino flux in a well fixed ratio**
- to measure geoneutrino flux = (in principle) = to get radiogenic heat
- in practice (as always) more complicated.....

OTHER INFOS: SISMOLOGY AND GEOCHEMISTRY



Discontinuities in the waves propagation → density profile but no info about the chemical composition of the Earth

1) **Direct rock samples**

* surface and bore-holes (max. 12 km);

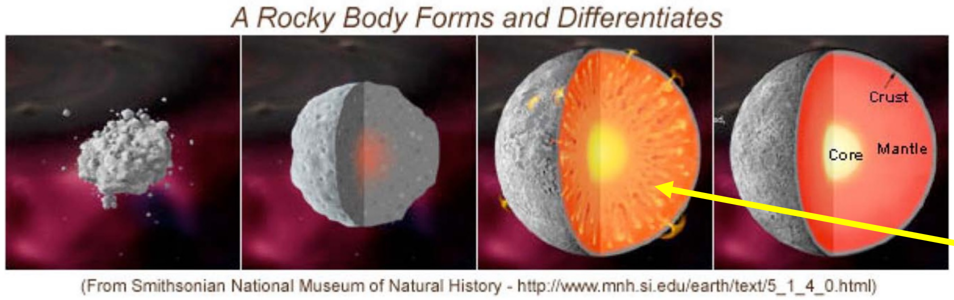
* upper mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

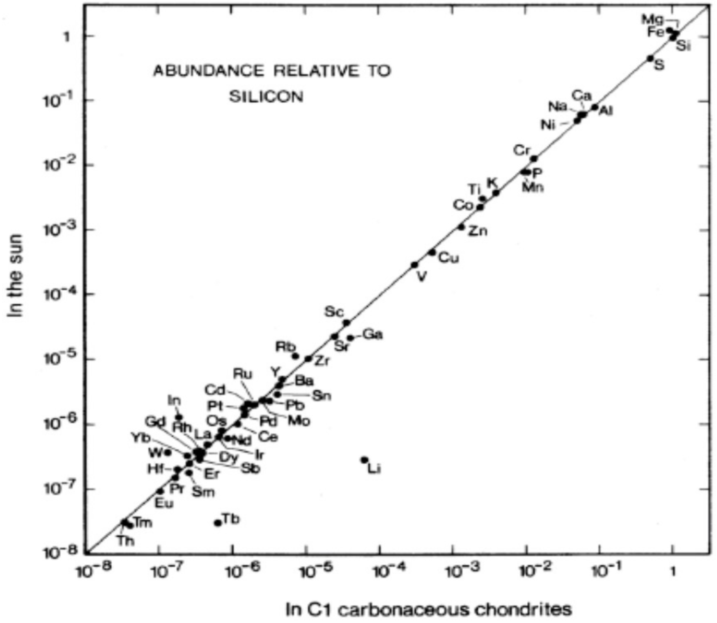
* no rock samples from the lower mantle

2) **Geochemical modelling**

BULK SILICATE EARTH (BSE) MODELS



Accretion Core differentiation, primitive mantle Crust/Mantle differentiation



Models predicting the composition of the Earth primitive mantle (= present crust + mantle)

Depending on the model, various inputs: composition of the chondritic meteorites, correlations with the composition of the solar photosphere, composition of rock samples from upper mantle and crust, energy needed to run mantle convection…..

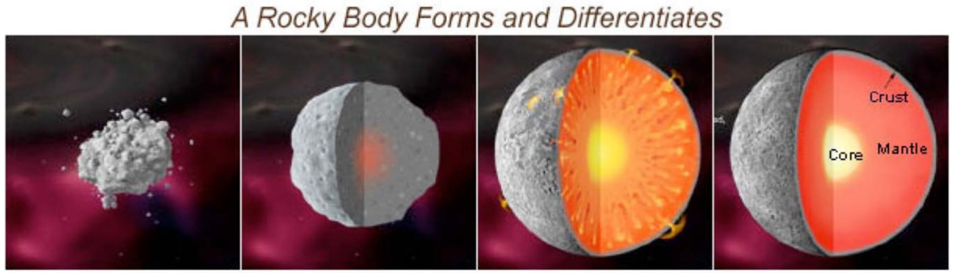
Abundances of U/Th/K in BSE =

Lithosphere (crust + continental lithospheric mantle) + **MANTLE**

Lithosphere: 7- 9 TW «well» known

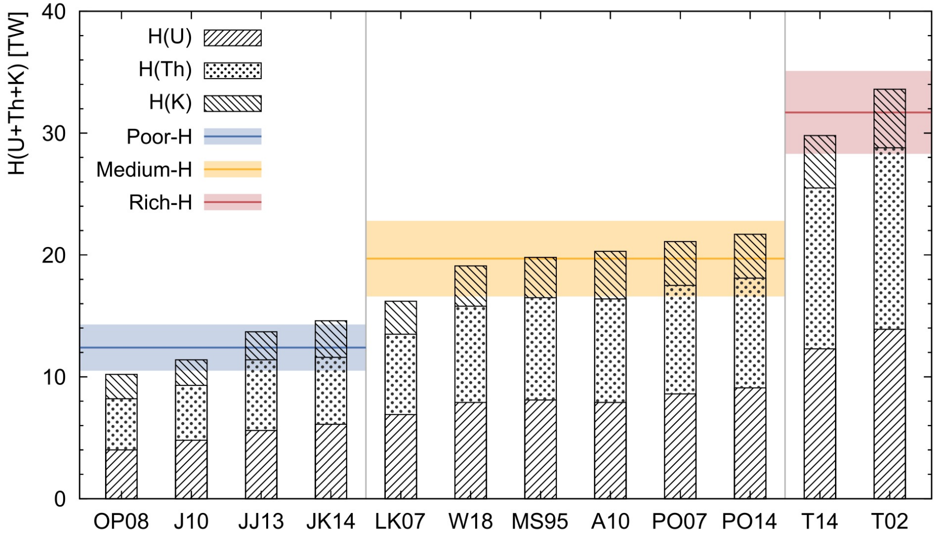
MANTLE = BSE – Lithosphere 1- 27 TW (different BSE models)

BULK SILICATE EARTH MODELS



(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

Accretion Core differentiation, primitive mantle Crust/Mantle differentiation



Predicted radiogenic heat production *H*(U + Th + K) (in TW) according to the different BSE compositional model

G. Bellini et al, **La Rivista del Nuovo Cimento (2022) 45:1–105**

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Lithosphere: 7- 9 TW «well» known

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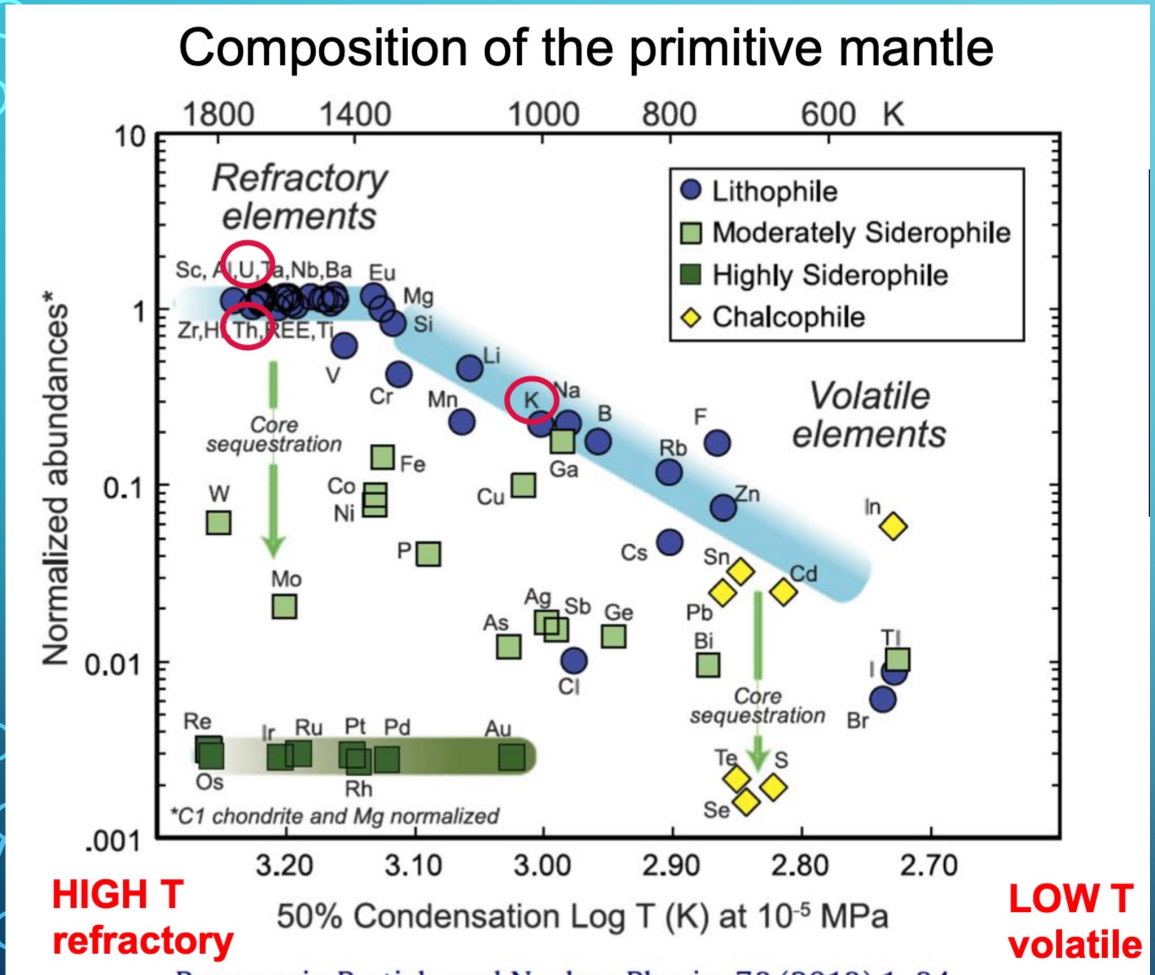
GREAT uncertainty!!!!

U, TH AND K IN THE EARTH



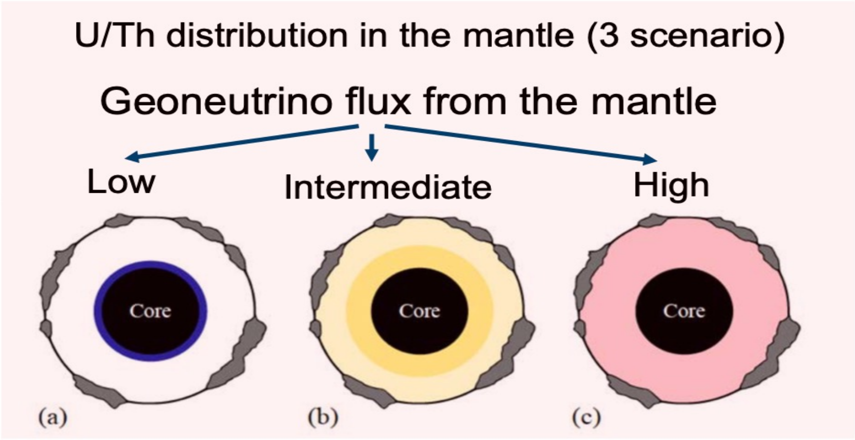
Progress in Particle and Nuclear Physics 73 (2013) 1–34

Lithophile – *like to be with silicates: during partial melting these elements tend to stay in the liquid part. The residuum is depleted. Accumulated in the continental crust. Less in the oceanic crust and mantle. Nothing in core*

Typical concentration for ^{238}U
(Mantovani *et al*. 2004)

upper continental crust:	2.5 ppm
middle continental crust:	1.6 ppm
lower continental crust:	0.63 ppm
oceanic crust:	0.1 ppm
upper mantle:	6.5 ppb
core	NOTHING

Decreases with depth

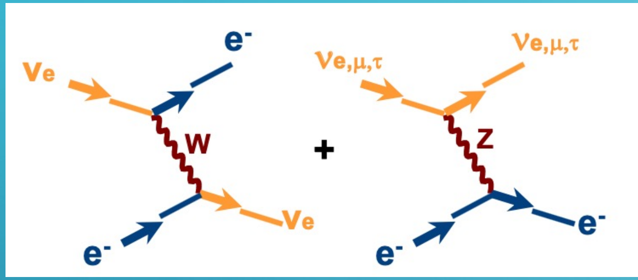


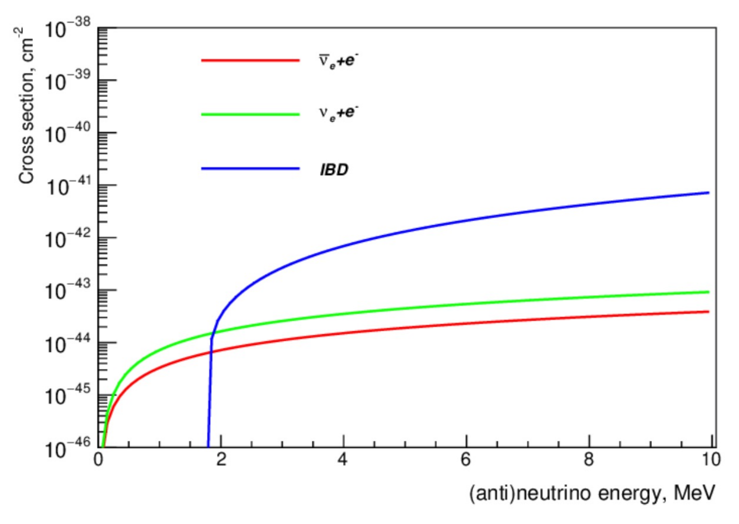
MEV ANTI-NEUTRINO DETECTION

Elastic scattering on electrons

$\nu + e \rightarrow \nu + e$

Single events, no threshold, all flavours

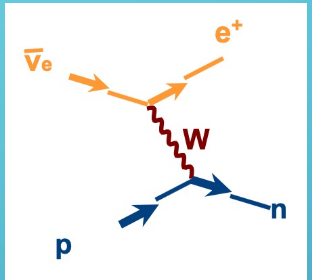




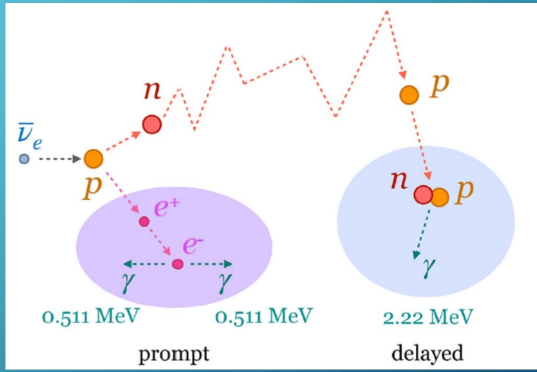
Inverse beta decay (IBD)

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

Charge current, electron flavour only



Delayed coincidence → clean signature!



Energy threshold = 1.8 MeV

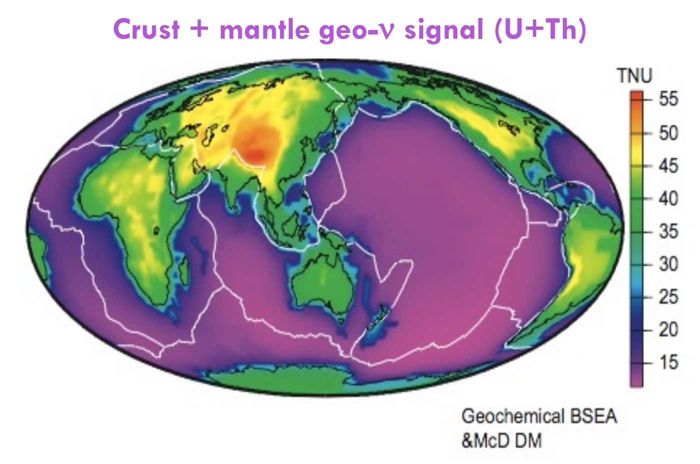
$\tau \sim 255\ \mu s$

$E_{prompt} = E_{visible}$
$\sim T_{e+} + 2 \cdot 511\ keV$
$\sim E_{antinu} - 0.784\ MeV$

Advantages of IBD :

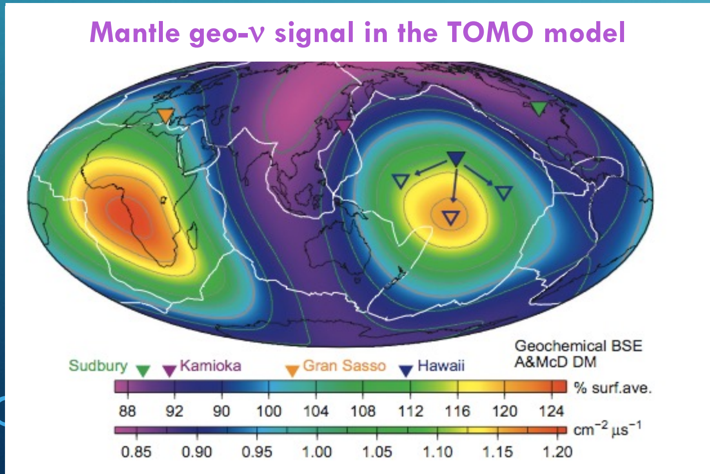
- Coincidence → Clean signature
- σ_{IBD} at few MeV: $\sim 10^{-42}\ cm^2$ (~100 x more than scattering)
- No solar neutrino background!

EXPECTED GEONEUTRINO SIGNAL



The signal is small, we need big detectors!

1 TNU = 1 event / 10^{32} target protons / year
cca 1 event /1 kton /1 year, 100% detection efficiency



Expected mantle signal: hypothesis of heterogeneous composition
Motivated by the observed Large Shear Velocity Provinces at the mantle base
O. Šrámek et al. “Geophysical and geochemical constraints on geoneutrino fluxes from Earths mantle”, Earth Planet. Sci. Lett., 361 (2013) 356-366)

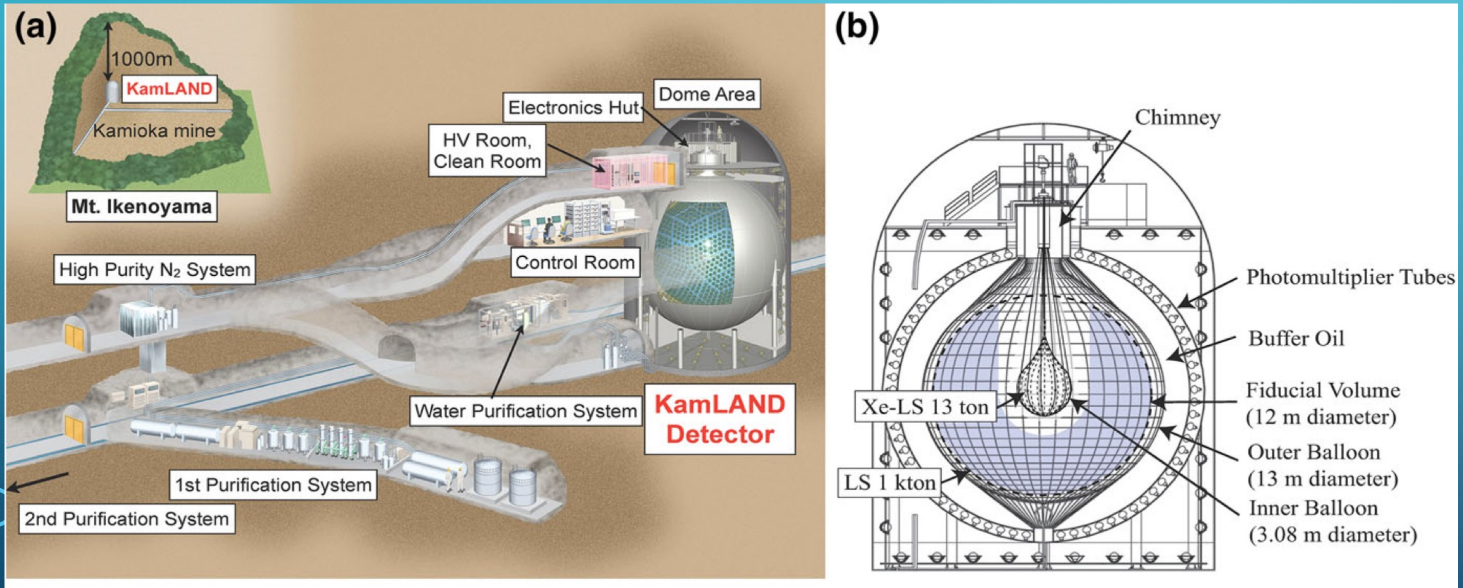
=> needs for multi-site measurements!!

11

DETECTING GEO-NU : KAMLAND

- (Anti-)neutrinos have low interaction rates, therefore **large volume detectors needed;**
- **High radio-purity of construction materials, underground labs to shield cosmic radiations;**
- **only 2 experiments have measured geoneutrinos: liquid scintillator detectors**

G. Bellini et al, La Rivista del Nuovo Cimento (2022) 45:1–105



KamLAND in Kamioka, Japan Border between OCEANIC / CONTINENTAL CRUST

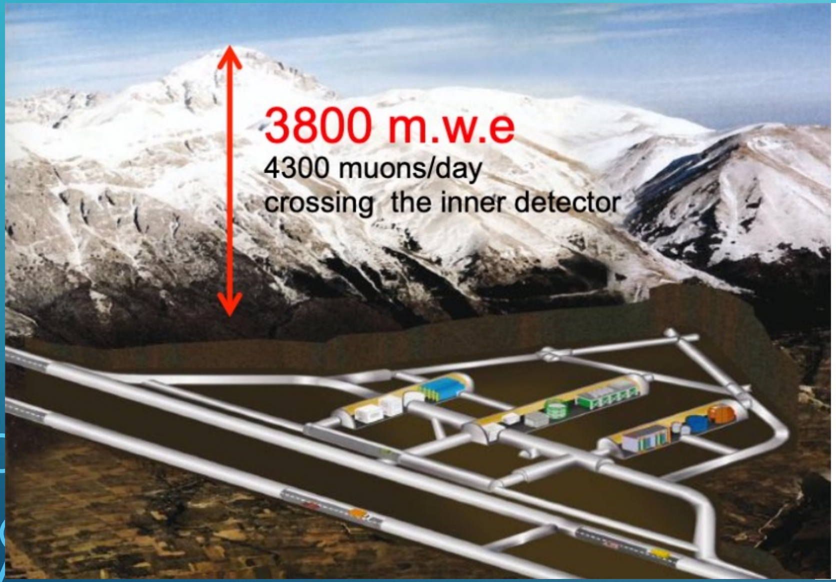
- built to detect reactor anti-ν;
- ~1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010), after the Fukushima disaster (03/2011) many reactors OFF and S(reactors)/S(geo) ~ 1!
- data since 2002;
- 2700 m.w.e. shielding;

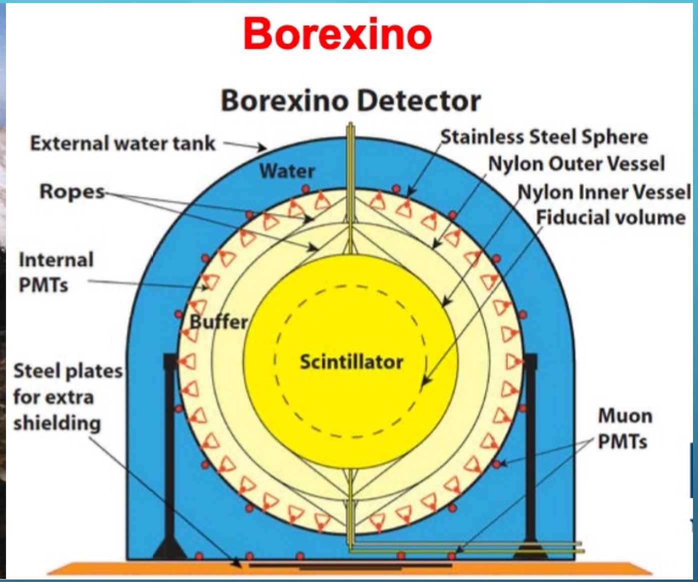
The first investigation in 2005, last published results (2022) : 15-16% precision in the signal

183^{+29}_{-28} geonu's detected, March 2002 – December 2020 :6.39 x 10^{32} target-proton year (Geophys. Res. Lett. 49 e2022GL099566)

DETECTING GEO-NU : BOREXINO

- (Anti-)neutrinos have low interaction rates, therefore **large volume detectors needed;**
- **High radio-purity of construction materials, underground labs to shield cosmic radiations;**
- **only 2 experiments have measured geoneutrinos: liquid scintillator detectors**





Borexino, Gran Sasso, Italy
CONTINENTAL CRUST

- originally built to measure neutrinos from the Sun – extreme radio-purity needed and achieved;
- 278 tons;
- S(reactors)/S(geo) ~ 0.3 (2010)
- In operation : 2007 - 2021;
- 3600 m.w.e. shielding;

The first investigation in 2010 (4σ evidence), last published results : 17-18% precision in the signal

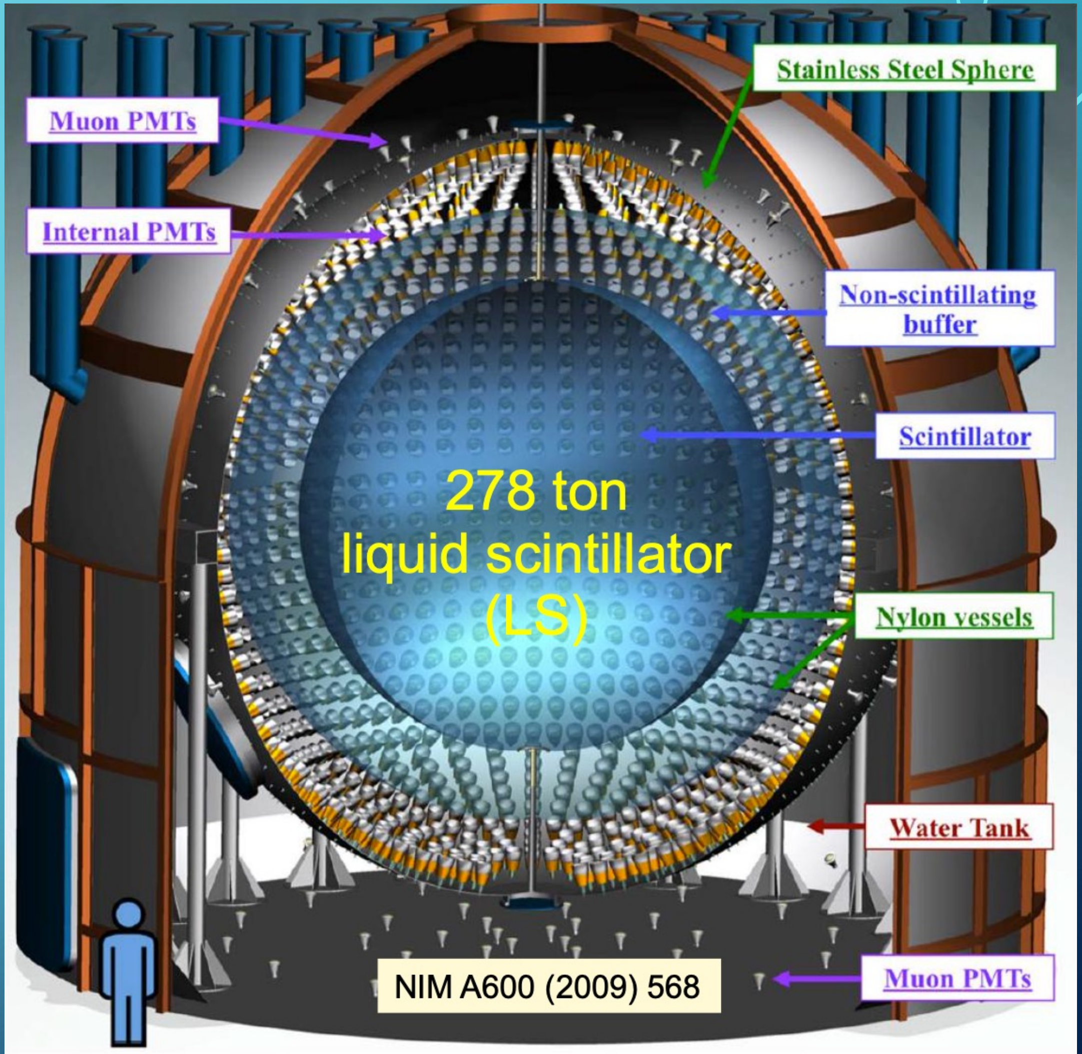
52.6 $^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geonu's detected, May 2007 – Apr 2019 :1.29 x 10^{32} target-proton year (Phys. Rev. D 101 (2020) 012009)

THE BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso (Italy)

Scintillator : Pseudocumene + PPO as fluor

- **the world's radio-purest LS detector:** $<5.7\times10^{-19}$ g(Th)/g LS,$<9.5\times10^{-20}$ g(U)/g LS at 95% C.L.
- **~500 p.e. / MeV**
- energy reconstruction: 5% @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e+/e-)

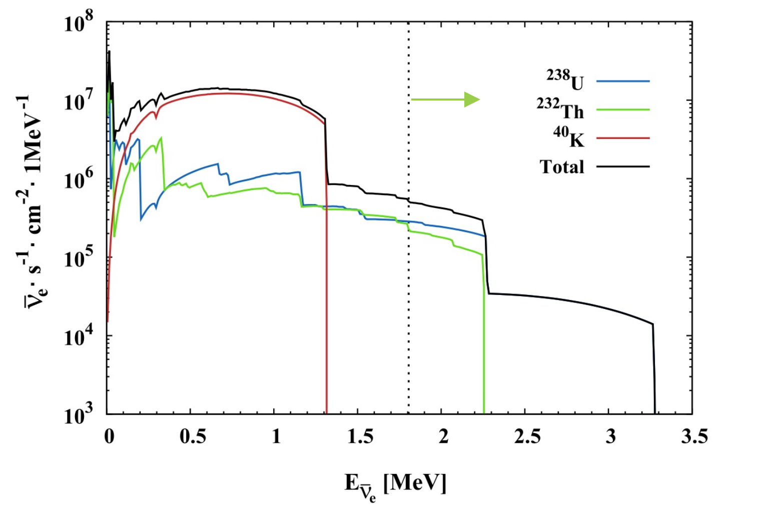


In operation: 2007 -2021

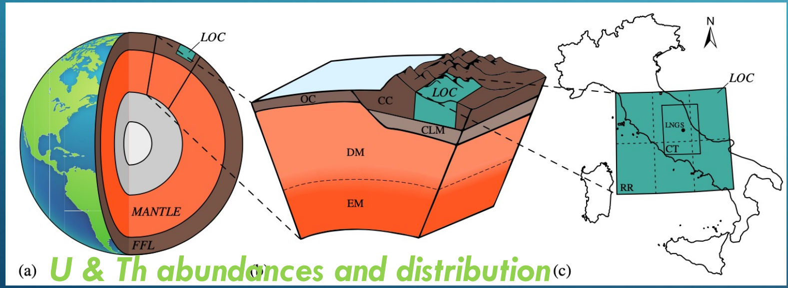
EXPECTED SIGNAL AT GRAN SASSO

Ingredients:

1) Geo-neutrino energy spectra



2) Local and global geological informations

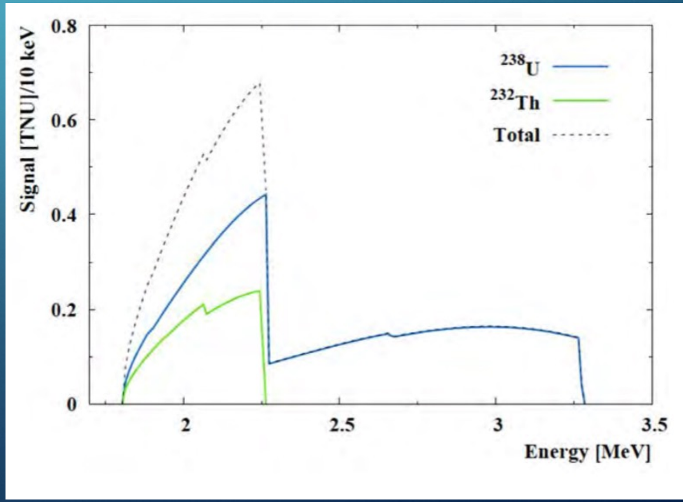


3) Propagation effects (oscillations..): P_{ee} ~ 0.5
+interaction cross sections

Expected signal at Gran Sasso

1 TNU (Terrestrial Neutrino Unit) = 1 event/ 10^{32} target protons (~1kton LS)/ year (100% eff.)

	S (U+Th) TNU	S(U)/S(Th)
Local Crust (R~500 km)	9.2 $\pm$ 1.2	0.24
Far Field Lithosphere	16.7 $^{+3.8}_{-3.1}$	0.29
Mantle (from Bulk silicate Earth model – lithosphere)	2.5 – 19.6	0.26
Total	28.4 - 45.5	0.27 (chondritic)



^{40}K signal below threshold

IBD SELECTION CUTS : 154 GOLDEN CANDIDATES

M. Agostini et al PRD 101(2020) 012009

- December 9, 2007 to April 28, 2019 : 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton , **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff

Exposure : a factor 2 increase respect to 2015 analysis

Charge of prompt

Q_p > 408 pe

- Prompt spectrum starts at 1 MeV
- 5% energy resolution @ 1 MeV

Charge of delayed

Q_d > 700 (860) – 3000 pe

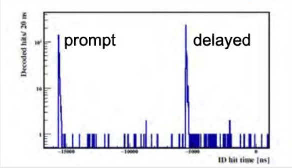
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha+\gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

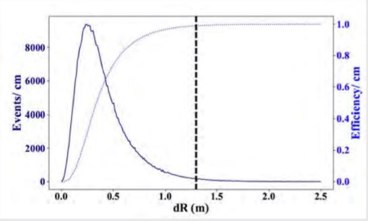
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

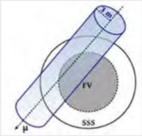


Muon veto

2s || 1.6 s : $^{9}Li(\beta + n)$

2 ms: neutrons

- Several veto categories
- Strict and special muon tags
  - Whole detector
  - **Cylinder**

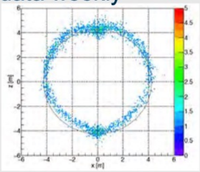


Only 2.2% exposure loss

Dynamic Fiducial Volume

> 10 cm from IV (prompt)

- Exposure vs accidental bgr
- IV has a leak: shape reco from the data weekly



Multiplicity

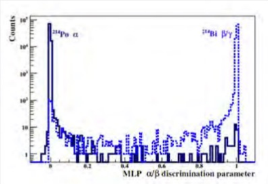
No event with Q >400 pe ±2 ms around promt/delayed

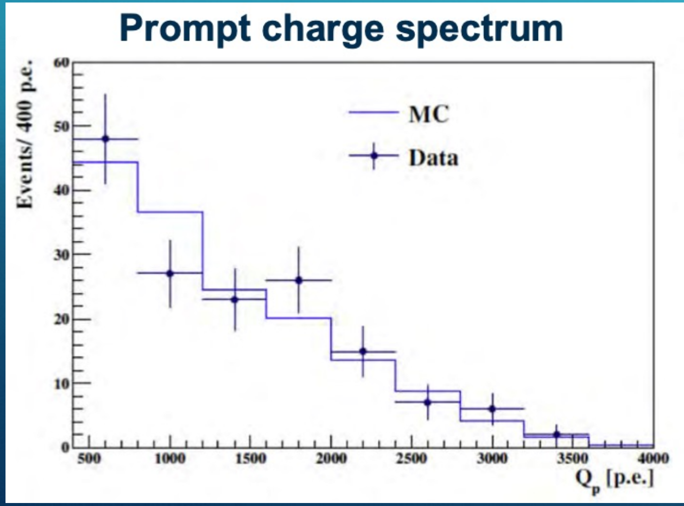
- Suppressing undetected cosmogenic background, mostly multiple neutrons
- Negligible exposure loss

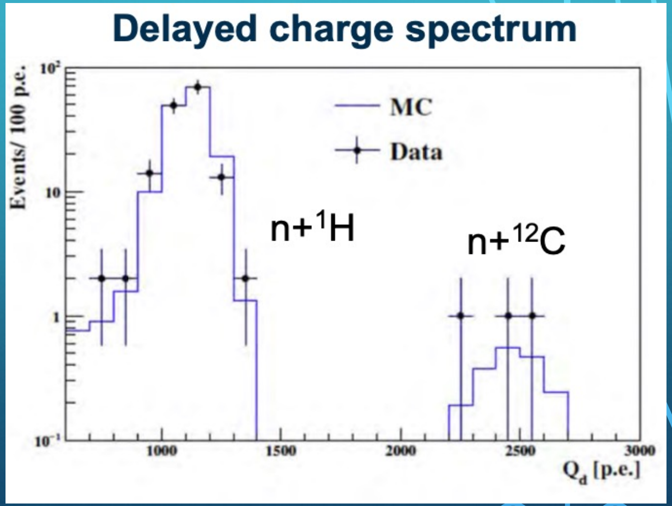
α/β discrimination

$MLP_{delayed}$ > 0.8

- Radon correlated $^{214}Po(\alpha+\gamma)$





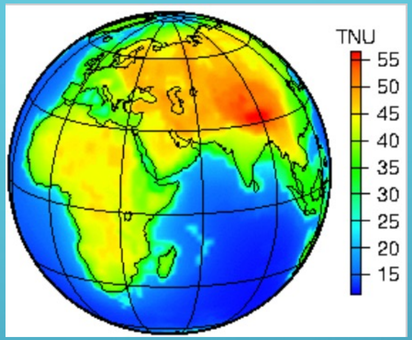


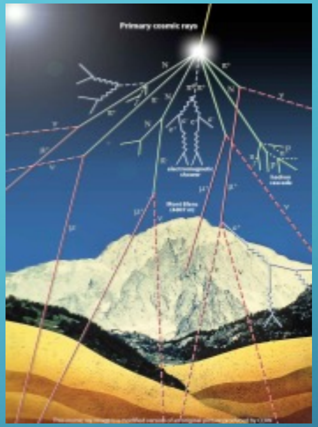
SOURCES OF BACKGROUNDS

We need to estimate different contributions and then to extract the number of measured geo-neutrinos by fitting the E_{prompt} energy spectrum;

Antineutrino backgrounds:

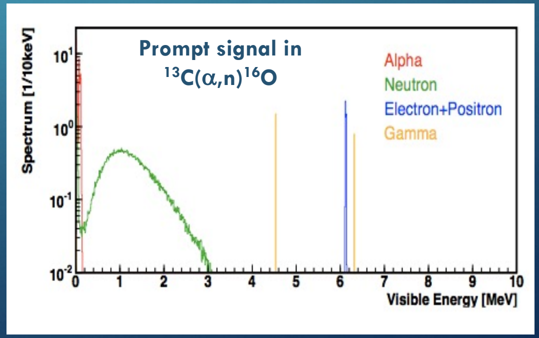
(a) Reactor antineutrinos
(b) Atmospheric neutrinos

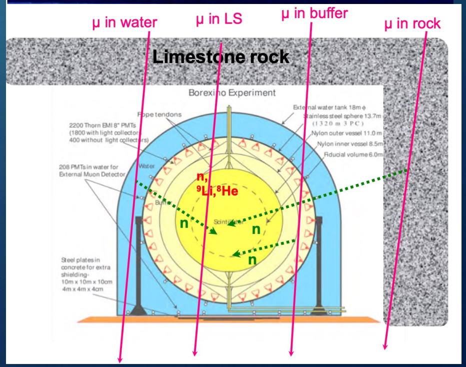




Backgrounds mimicking inverse beta decay reaction:

(a) Cosmogenic nuclides
(b) (α,n) reactions
(c) Accidental coincidences





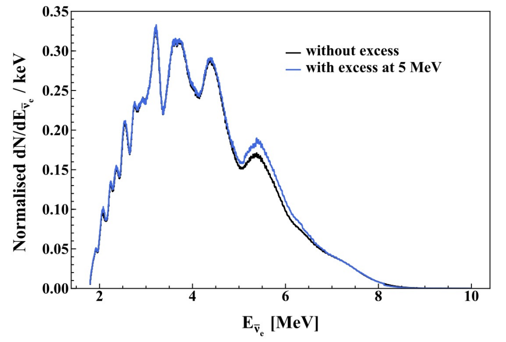
BACKGROUNDS

Antineutrino backgrounds

Expected signal at LNGS evaluated with dedicated codes

Reactor antineutineutrinos

	Mueller et al 2011	With "5 MeV bump"
Signal [TNU]	$84.5^{+1.5}_{-1.4}$	$79.6^{+1.4}_{-1.3}$
# Events	$97.6^{+1.7}_{-1.6}$	$91.9^{+1.6}_{-1.5}$



- *For all ~440 world reactors (1.2 TW total power): info on thermal powers, laod factors.. from IAEA and PRIS databases*
- *Propagation effects included*
- *Interaction cross section*
- *Detection efficiency = 0.8955 ± 0.0150*

Atmospheric neutrinos

Energy window	> 1 MeV (Q>408 p.e)
Events	9.2 ± 4.6

- Atmospheric neutrino fluxes from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included, Simulation of detector response + selection cuts as for real data

Non antineutrino backgrounds

Background type	No. of events
^{9}Li background	3.6 ± 1.0
Untagged muons	0.023 ± 0.007
Fast n's (from rock)	<0.013
Fast n's (from WT)	<1.43
Accidental coincidences	3.846 ± 0.01
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.001
TOTAL	**8.28 ± 1.01**

- **Accidental coincidences;**

Estimated from OFF-time coincidences: IBD-like events in Δt = 2 -20 s

- **(α, n) reactions: ^{13}C(a, n)^{16}O**

Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated from ^{210}Po(α) and ^{13}C contaminations, cross section.

- **Cosmogenic background**

- ^{9}Li and ^{8}He ($t_{1/2}$ = 119/178 ms)

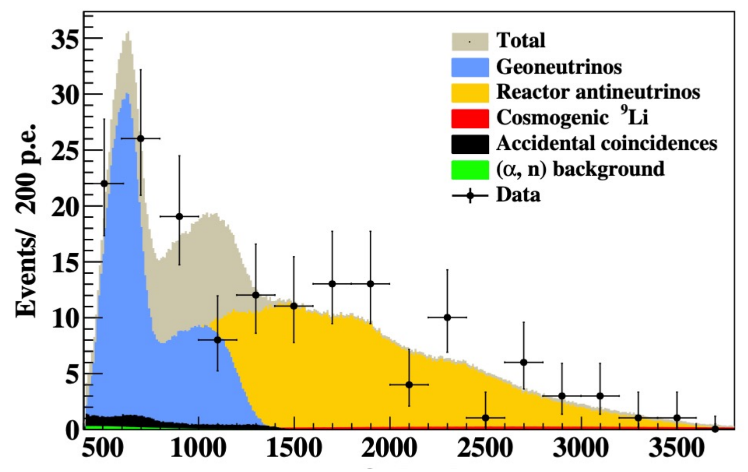
decay: β(prompt) + n (delayed);

- fast neutrons

Prompt :unscattered protons (prompt)

Estimated by studying coincidences detected AFTER muons.

GEO-NEUTRINO SIGNAL : SPECTRAL FIT OF E_{PROMPT}



Prompt charge [p.e.]: 1 MeV ~500 photoelectrons

Unbinned likelihood fit of charge spectrum of 154 prompts

- Fixed: S(Th)/S(U) = 0.27 corresponding to chondritic Th/U mass ratio of 3.9
- ^{9}Li, accidentals, and (α, n) bgr constrained according to expectations
- Reactor signal unconstrained and result compatible with expectations

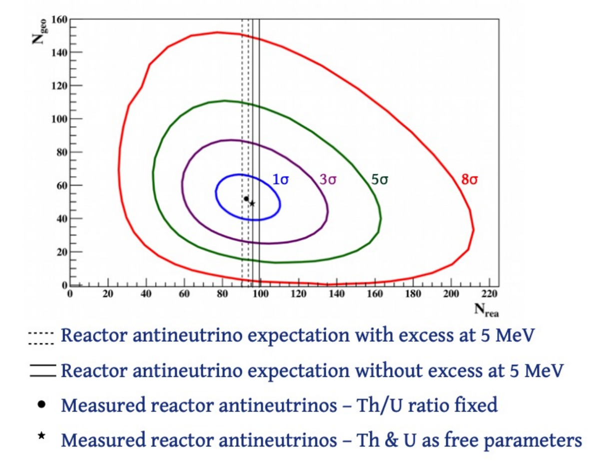
$$N_{geo} = 52.6^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(sys)events$$

$$47.0^{+8,4}_{-7.7}(stat)^{+2,4}_{-1.9}(sys)TNU$$

$^{+18.3}_{-17.2}$% total precision

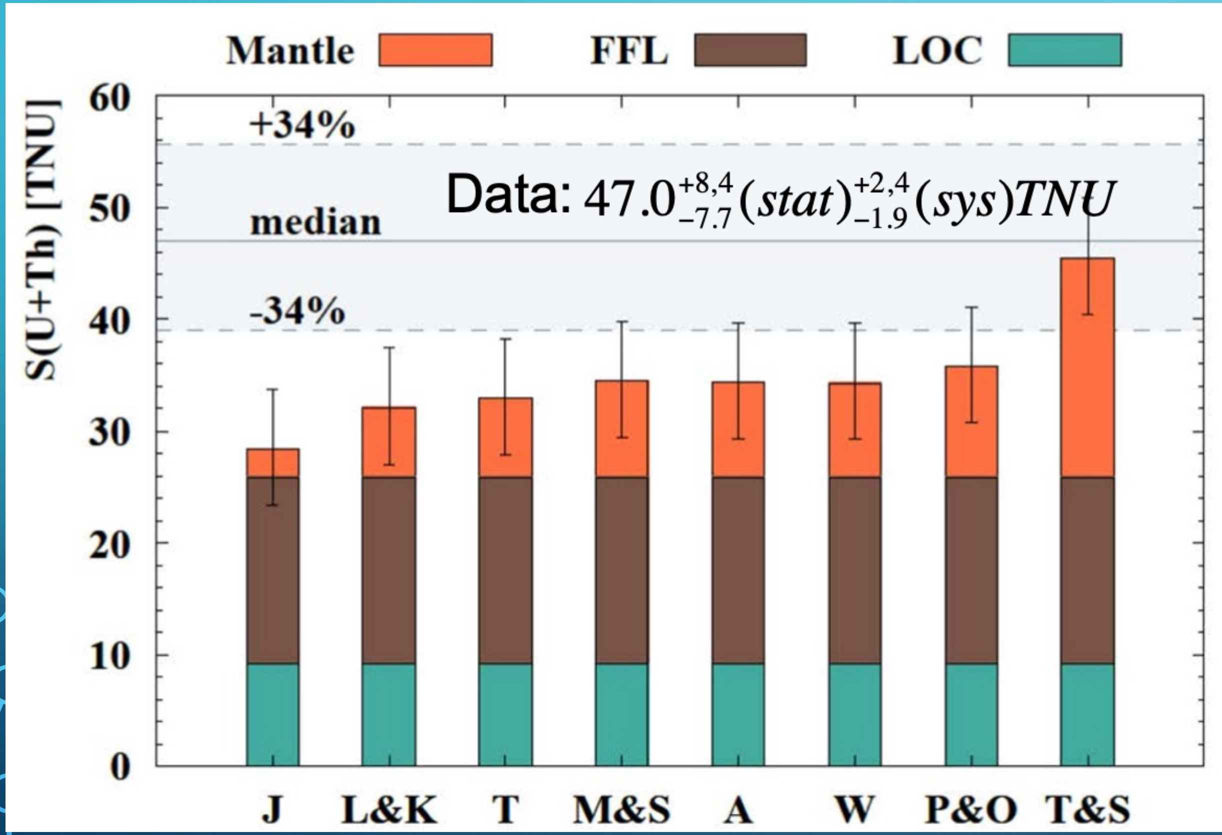
Systematic uncertainties

Source	Geo error [%]
Atmospheric neutrinos	$^{+0.00}_{-0.38}$
Shape of reactor spectrum	$^{+0.00}_{-0.57}$
Vessel shape	$^{+3.46}_{-0.00}$
Efficiency	1.5
Position reconstruction	3.6
Total	$^{+5.2}_{-4.0}$



$N_{rea} = 93.4^{+11.3}_{-10.4}$

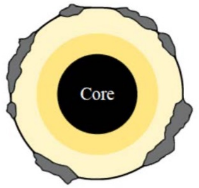
DATA VS BSE MODELS



LOC = local crust = (9.2 ± 1.2) TNU

FFL = far-field lithosphere = ($4.0^{+1.4}_{-1.0}$) TNU

MANTLE (U + Th abundances) = BSE model – LITHOSPHERE

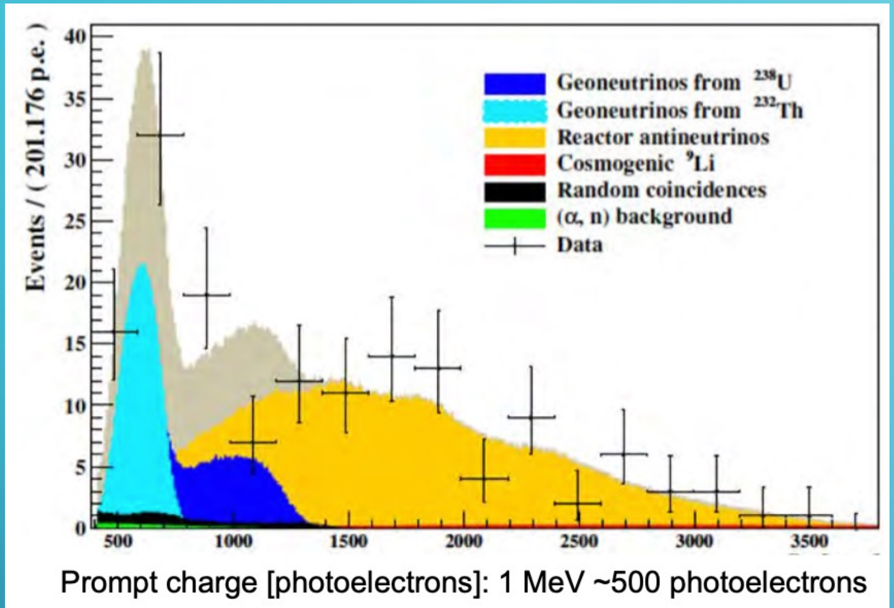


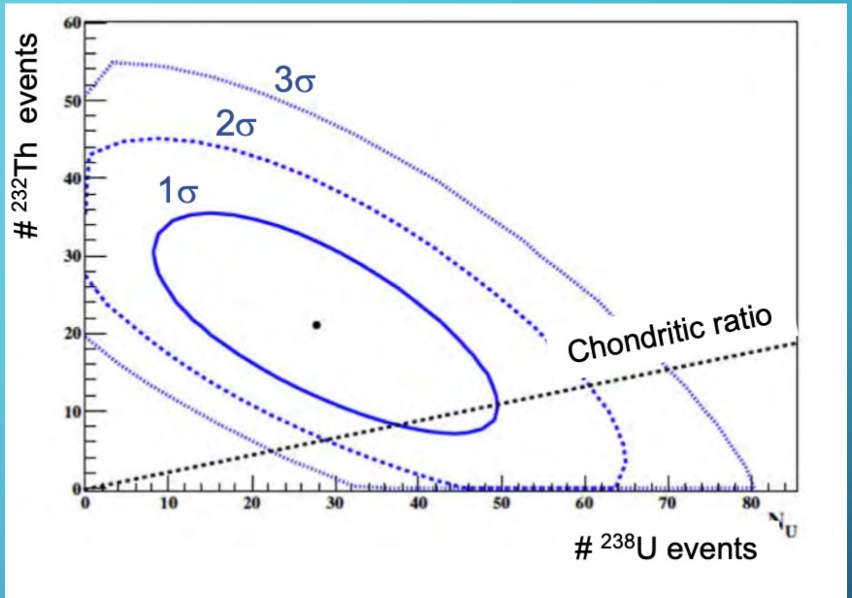
Intermediate scenario
2 layer distribution
of U and Th in the mantle

J: Javoy at al., 2010
L&K: Lyubetskaya and Korenaga, 2007
T: Taylor, 1980
M&S: Mc Donough and Sun, 1995
A: Anderson, 2007
W: Wang, 2018
P&O: Palme and O'Neil, 2003
T&S: Turcotte and Schubert, 2002

Compatible with models, preference high-Q models

TH/U RATIO



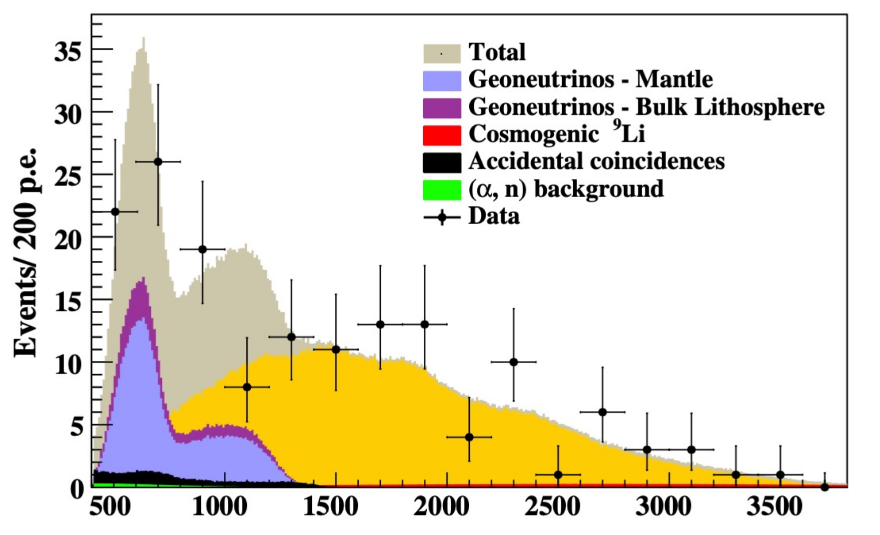


SPECTRAL FIT with Th and U fit independently :

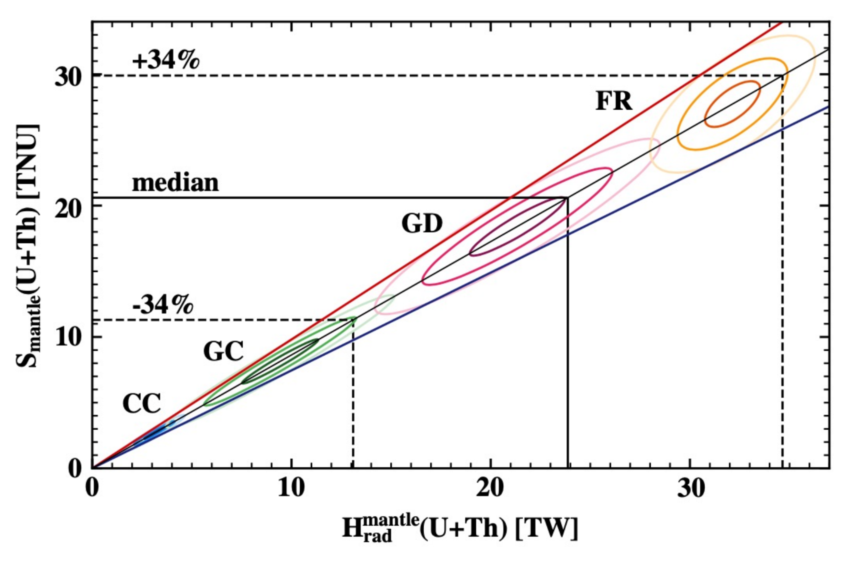
50.4 events $^{+46.8}_{-44.05\%}$ total precision

In agreement with the fit with Th/U fixed

GEO-NEUTRINO SIGNAL FROM THE MANTLE



Prompt charge [p.e.]: 1 MeV ~500 photoelectrons



Constraining the contribution from the **lithosphere** (28.8 ± 5.6 events with S(Th)/S(U) = 0.29), the **extracted** N_{mantle} events are $23.7^{+10.7}_{-10.1}$

S_{Mantle} (U+Th) = $21.2^{+9.5}_{-9.0}$ (Stat) $^{+1.1}_{-0.9}$ (Sys) TNU

Sensitivity study using log-likelihood ratio method: Null mantle signal hypothesis rejected with 99.0% C.L.

Mantle radiogenic heat from U+Th:

H_{mantle} (U+Th) = $24.6^{+11.1}_{-10.4}$ TW

assuming 18% ^{40}K mantle contribution + contribution of lithosphere :

H(U+Th+K) = $38.2^{+13.6}_{-12.7} TW$

~80% of total heat flux

Bulk Silicate Earth's Models

Cosmochemical (CC) based on the enstatine chondrites

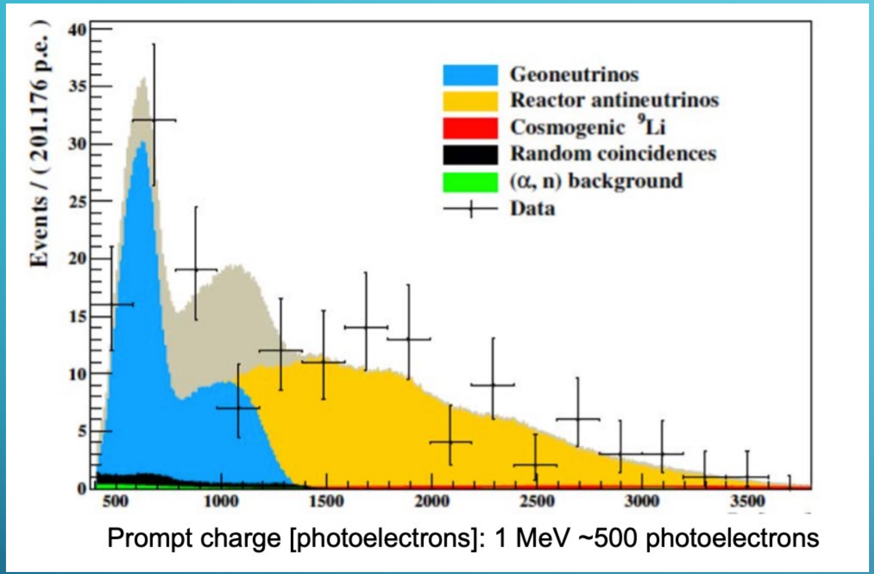
Geochemical (GC) based on mantle samples compared with carbonaceous chondrites

Geodinamical (GD) based on balancing mantle viscosity and heat dissipation

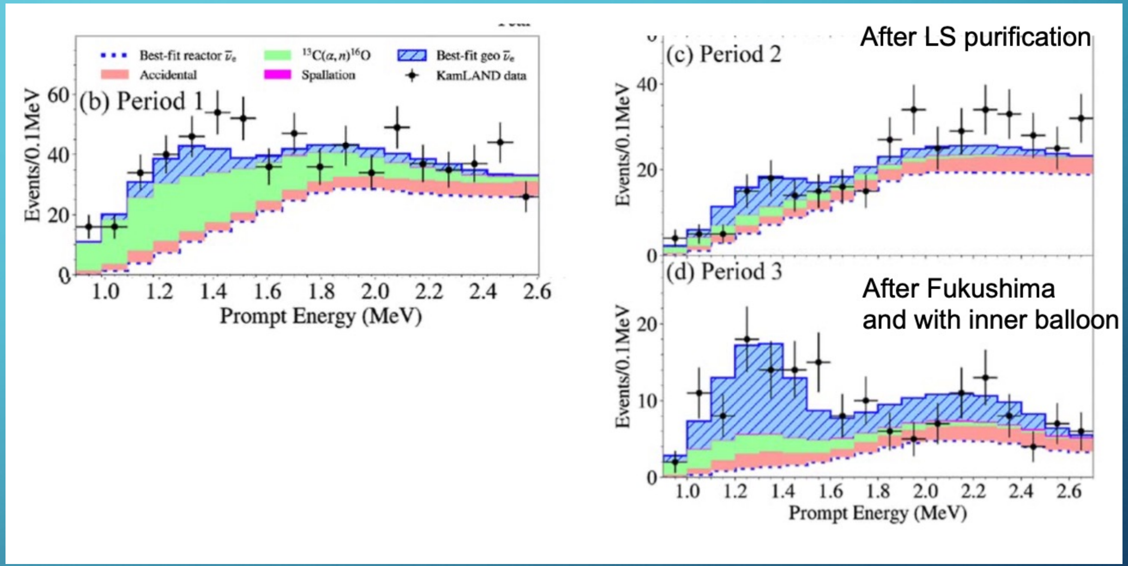
FR =Full radiogenic

COMPARISON WITH KAMLAND

Borexino (PRD101 (2020) 012009)



KamLAND (Geophys. Res. Lett. 49 e2022GL099566)

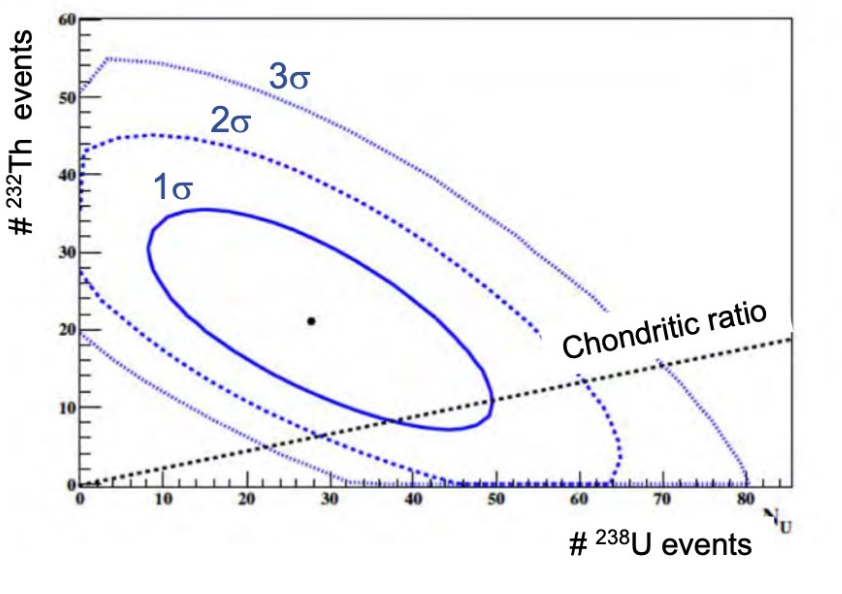


1.29 x 10^{32} (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32}** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (mass Th/U fixed to 3.9)	183^{+29}_{-28} *(stat + sys)*: $^{+15.8}_{-15.3}\%$
$47.0^{+8.4}_{-7.7}$ *(stat)* $^{+2.4}_{-1.9}(sys)$ **/** (39.3 - 55.4)	**Signal [TNU]** / (68% CL interval)	Not provided
Shape only, reactor-ν free	**Analysis**	Rate + shape + time

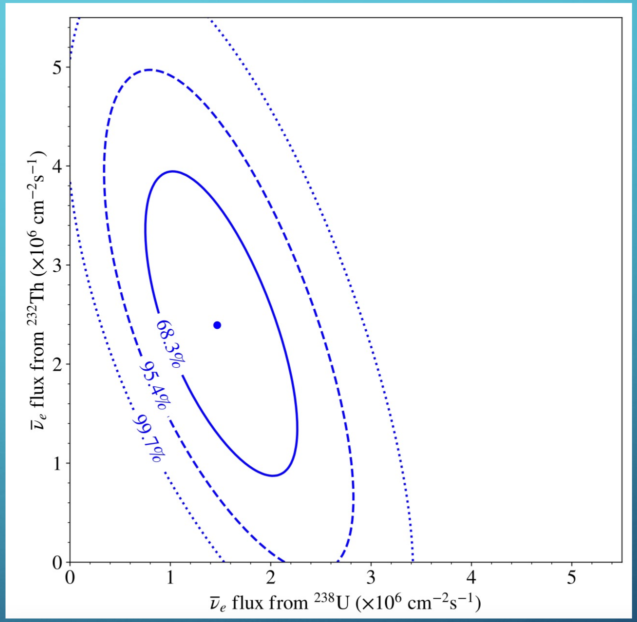
Credit : L. Ludhova

COMPARISON WITH KAMLAND : TH/U RATIO

Borexino (PRD101 (2020) 012009)



KamLAND (Geophys. Res. Lett. 49 e2022GL099566, N. Kawada Talk @ TAUOP23)



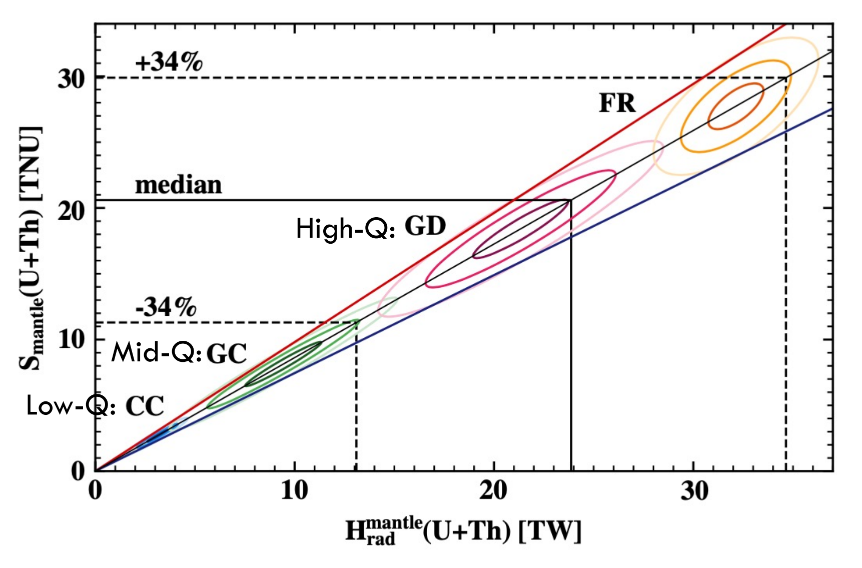
Best fit geoneutrino signals

	$N_{\mathrm{U/Th}}$ [event]	flux $[\times 10^5\ \mathrm{cm^{-2}s^{-1}}]$	flux [TNU]	0-signal rejection
U	$116.6^{+41.0}_{-38.5}$	$14.7^{+5.2}_{-4.8}$	$19.1^{+6.7}_{-6.3}$	3.343σ
Th	$57.5^{+24.5}_{-24.1}$	$23.9^{+10.2}_{-10.0}$	$9.7^{+4.1}_{-4.1}$	2.386σ
U + Th	$173.7^{+29.2}_{-27.7}$	$32.1^{+5.8}_{-5.3}$	$28.6^{+5.1}_{-4.8}$	8.3σ

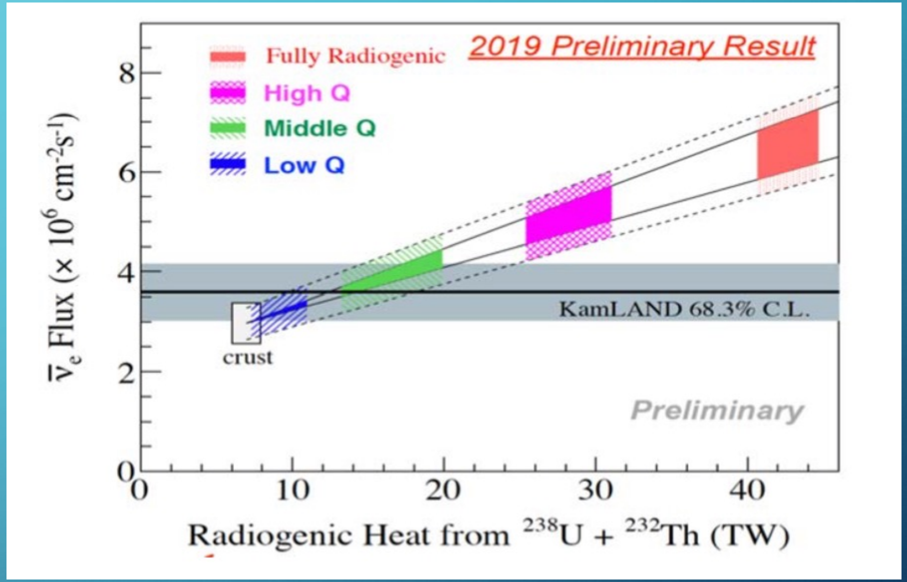
Spectroscopic measurement of geoneutrinos from uranium and thorium was achieved

RADIOGENIC HEAT COMPARISON

Borexino Mantle signal (PRD101 (2020) 012009)



KamLAND Total signal (Geophys. Res. Lett. 49 e2022GL099566)

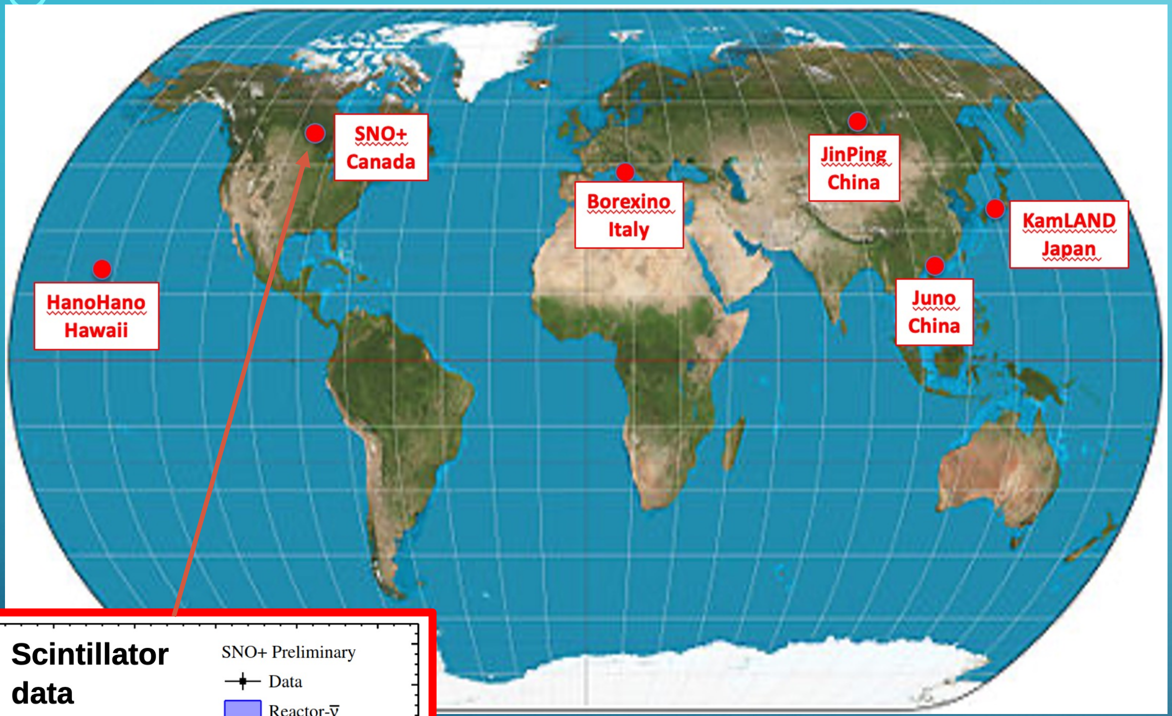


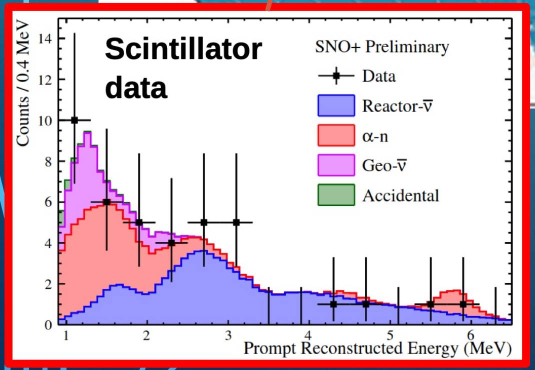
- General agreement data vs BSE models: big success
- Borexino is less (2.4σ) compatible with the BSE models predicting the lowest U+Th mantle abundances
- KamLAND preference for Low Q and Middle Q BSE models

Some tension between the two experiments, assuming laterally homogeneous mantle ???

OUTLOOK

It is important to collect more statistics and perform multi-site experiments !!!

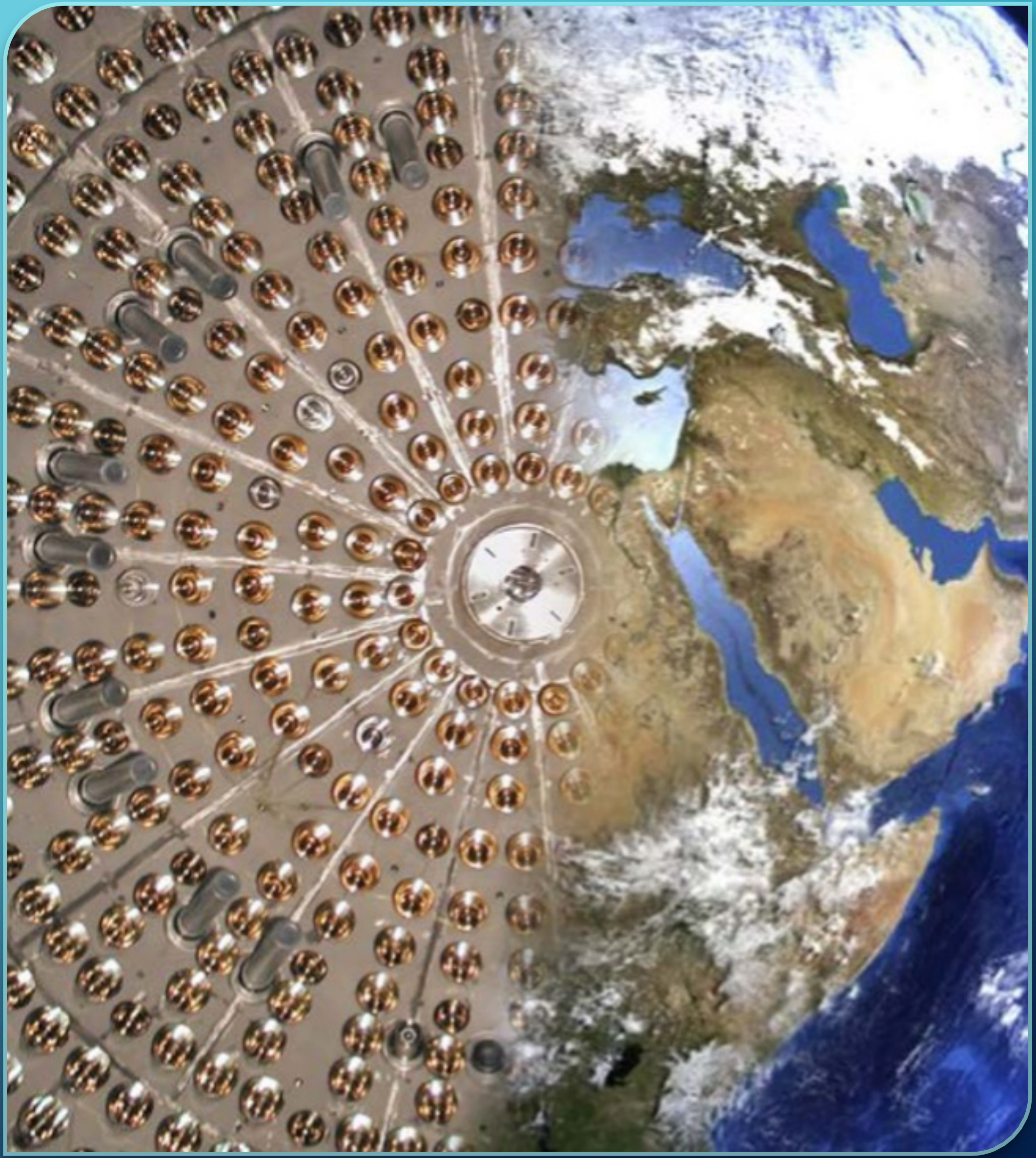




- **Borexino** (Italy): stop data-taking in October 2021 (previous update till April 2019)
- **KamLAND** (Japan): last update in summer 2022;
- **SNO+** (Canada): 780 ton, now taking data => 30-40 geonus/year; Low cosmogenics;
- **JUNO** (China): 20 kton & completion in 2024 & 400 geonus/year. Should be able to reach the precisions of Borexino and KamLAND in the 1st year! *(J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401)*
- **JINPING** (China): 4 kton; deepest lab, far away from reactors, very thick continental crust at Himalayan region *(PRD 95 (2017) 053001)*
- **HanoHano** / Ocean Bottom Detector (Hawaii): ~10 kton movable underwater detector with ~80% mantle contribution: **"THE" GEONU DETECTOR**

Thanks

for your attention!!!!



BACKUP

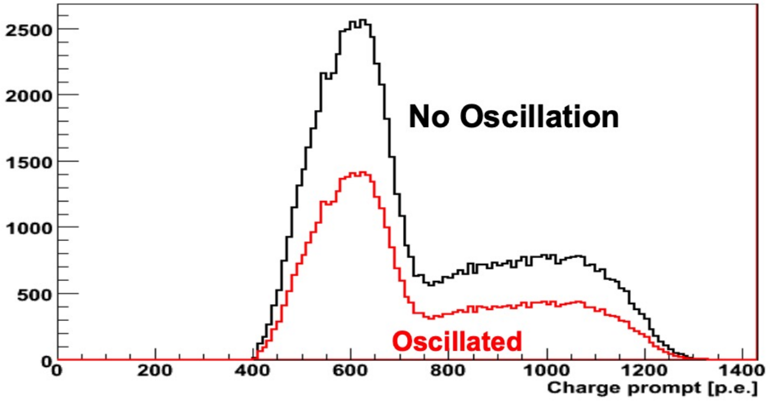
EFFECT OF NEUTRINO OSCILLATIONS

$$P_{ee} = P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

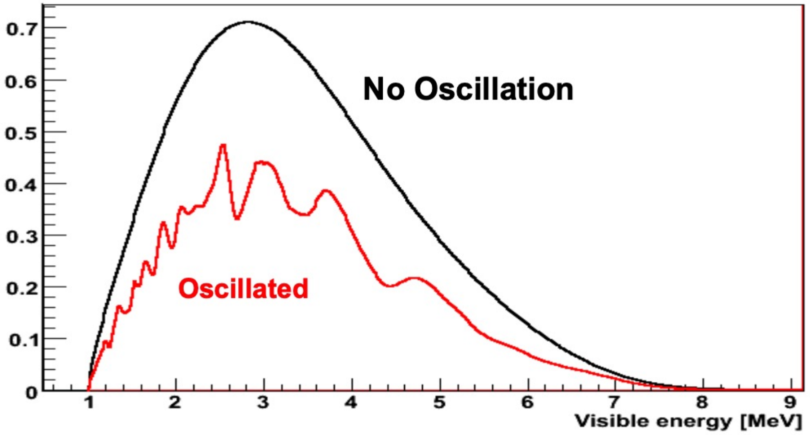
For 3 MeV antineutrino: oscillation length of ~100 km

For geoneutrinos we can use average survival probability of 0.551 + 0.015 (Fiorentini et al 2012), but for reactor antineutrinos not!

Geoneutrinos

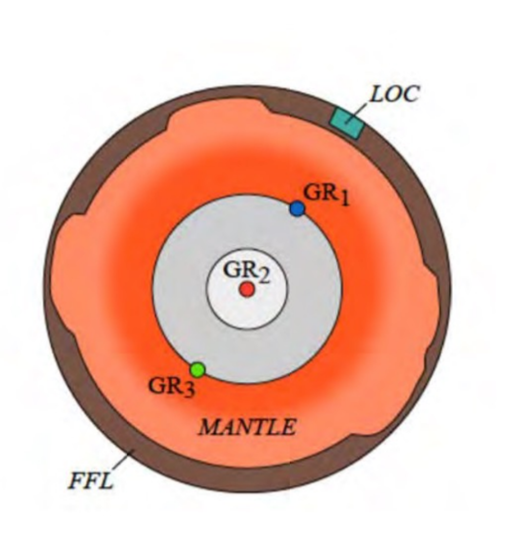


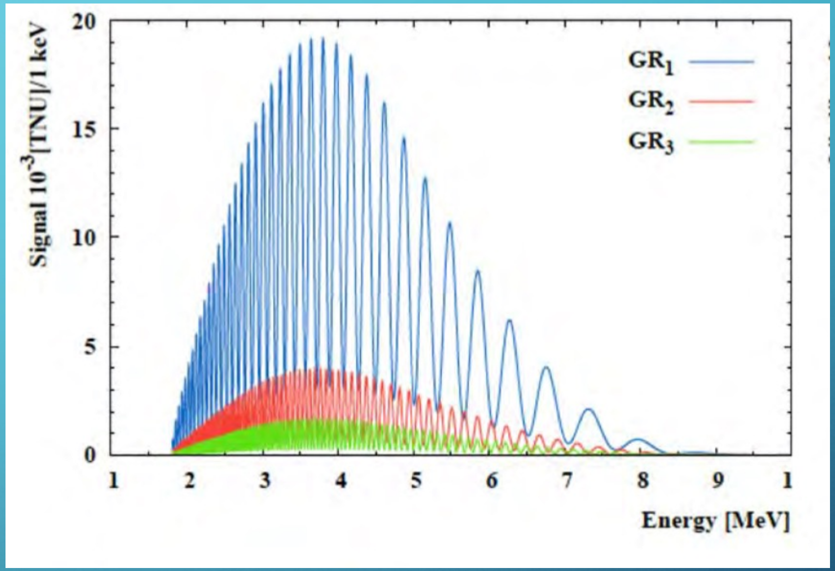
Reactor antineutrinos at LNGS



GEOREACTOR

Hypothetical fission of Uranium deep in the Earth
235U : 238U = 0.76 : 0.23 (Herndon)





No sensitivity to oscillation pattern

Fit with reactor spectrum constrained

Upper limit (95% CL): 18.7 TNU

- 2.4 TW in the Earth's center
- 0.5 TW near CMB at 2900 km
- 5.7 TW far CMB at 9842 km