NEUTRINOS AS PROBES OF THE SUN'S CORE AND EARTH'S INTERIOR

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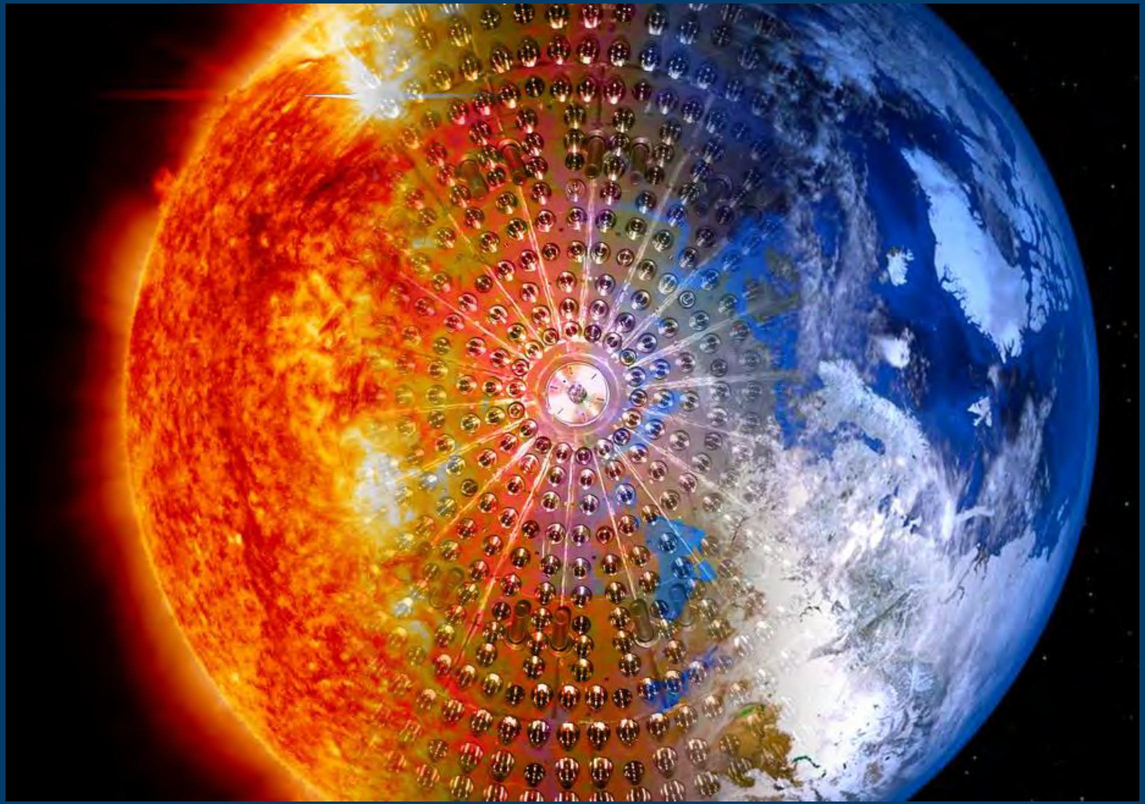
JUNE 23 & 24, MAYORANA CHOOL, MODICA, SICILY



PART II – Geoneutrinos

Geoneutrinos

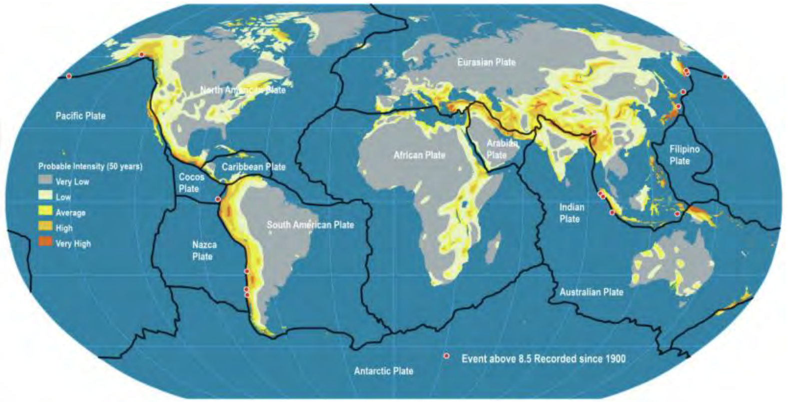
From where is coming
the energy driving these processes?

How can neutrino physics help us to understand?

Earth shines in geoneutrinos:
flux ~ 10^{6} cm^{-2} s^{-1}

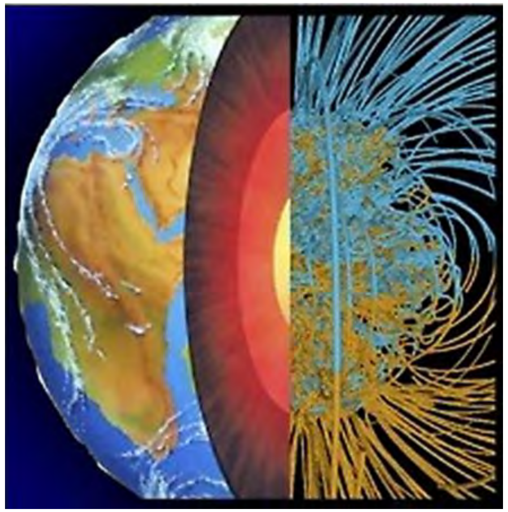
Vulcanism

Plate tectonics & mantle convection



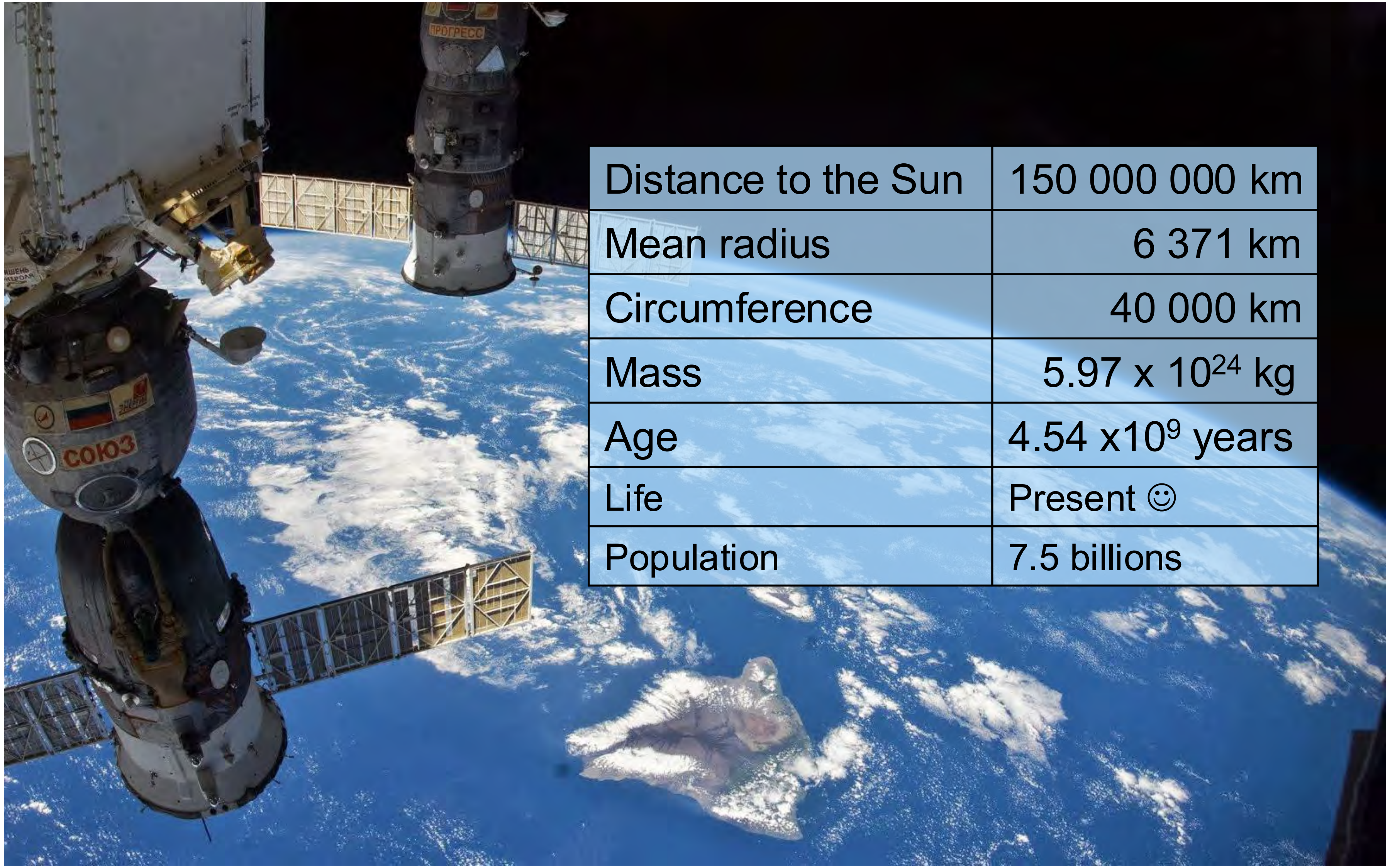
https://transportgeography.org

Geo-dynamo



Earthquakes


L'Aquila, Italy, 2009



Distance to the Sun	150 000 000 km
Mean radius	6 371 km
Circumference	40 000 km
Mass	5.97×10^{24} kg
Age	4.54×10^{9} years
Life	Present ☺
Population	7.5 billions

EARTH FORMATION

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

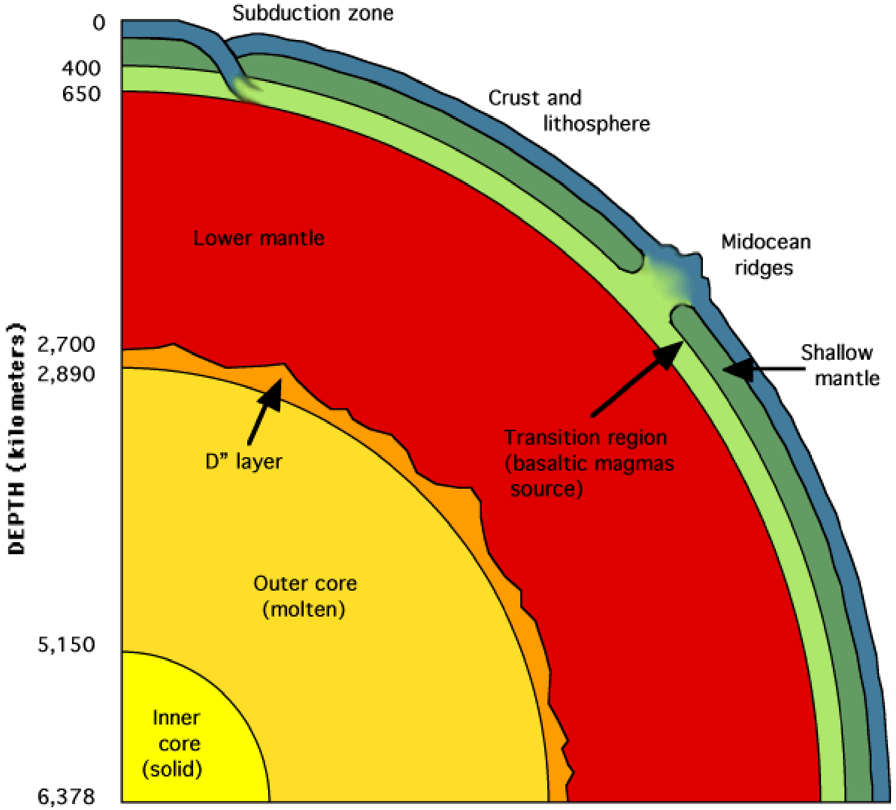
Accretion

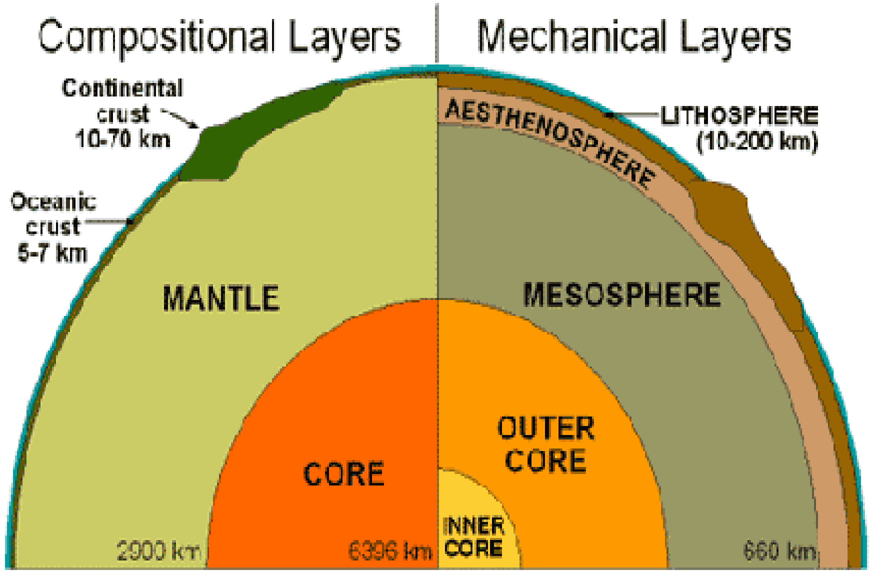
Magma sea (Primitive mantle)

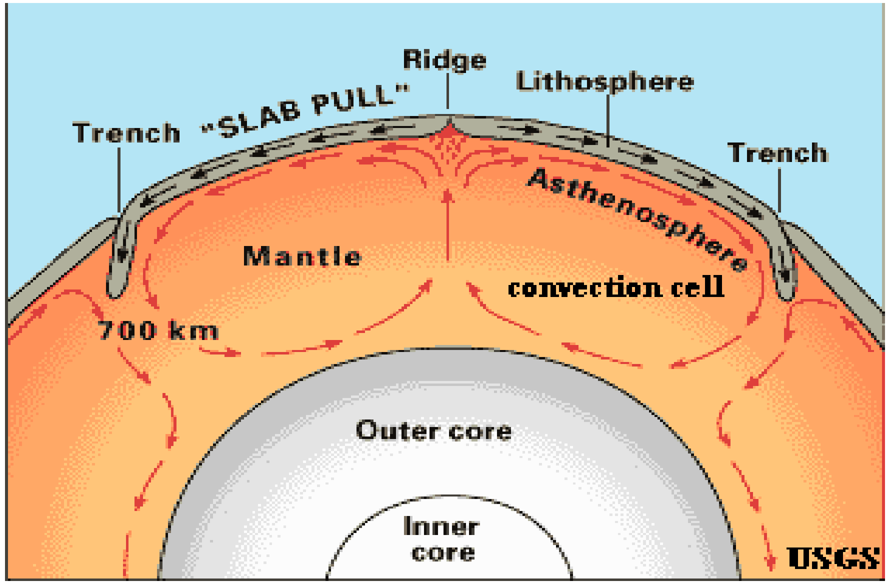
Metallic core segregation

Mantle-crust differentiation

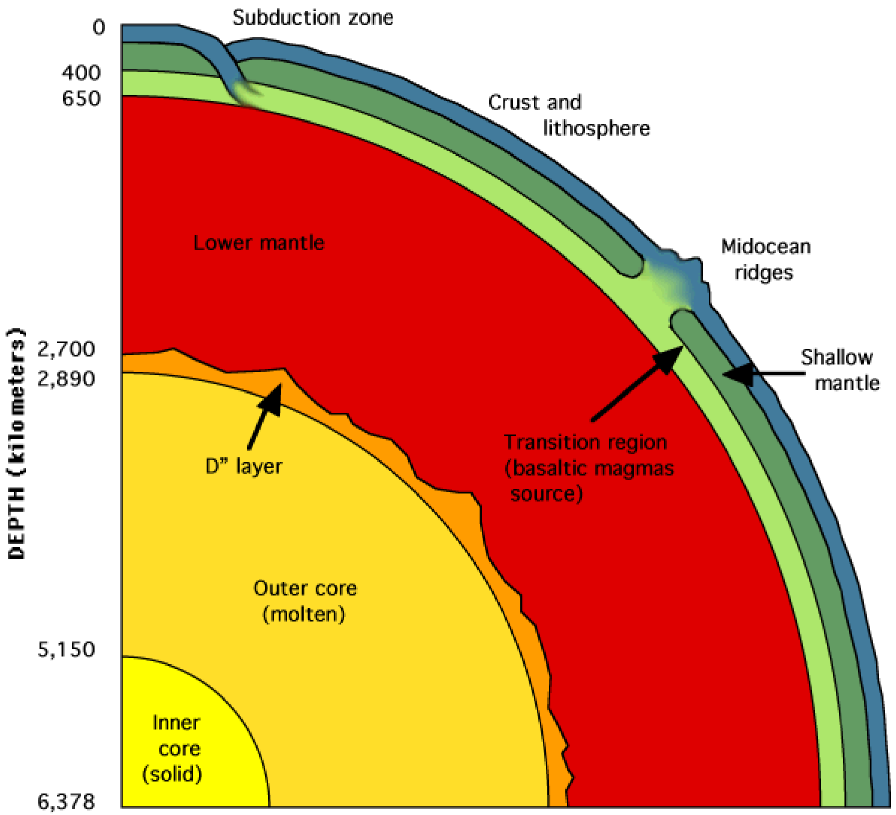
EARTH STRUCTURE







EARTH STRUCTURE



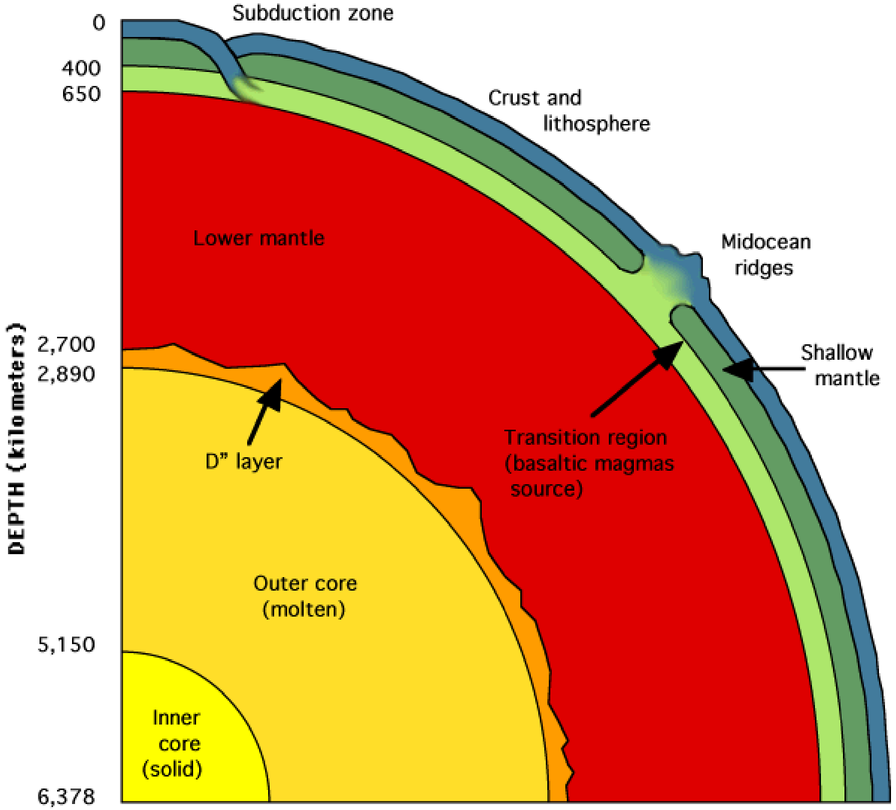
Inner Core - SOLID

- about the size of the Moon;
- Fe – Ni alloy;
- **solid** (due to high pressure of ~ 330 GPa);
- temperature ~ 5700 K;

Outer Core - LIQUID

- 2260 km thick;
- Fe – Ni alloy + + 10% light elements (S, O?);
- **liquid;**
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid within the Sun's magnetic field;

EARTH STRUCTURE



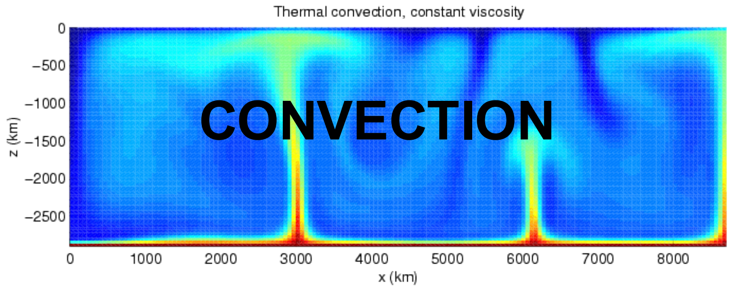
D'' layer: mantle –core transition

- ~200 km thick;
- seismic discontinuity;
- many different ideas around;

(mineral recrystallisation, material brought here from the subduction zones…)

Lower mantle (mesosphere)

- rocks: high Mg/Fe ratio, less Si + Al than in the crust;
- T: 600 – 3700 K;
- high pressure: solid, but viscose, no brittle faulting;
- "plastic" on long time scales:

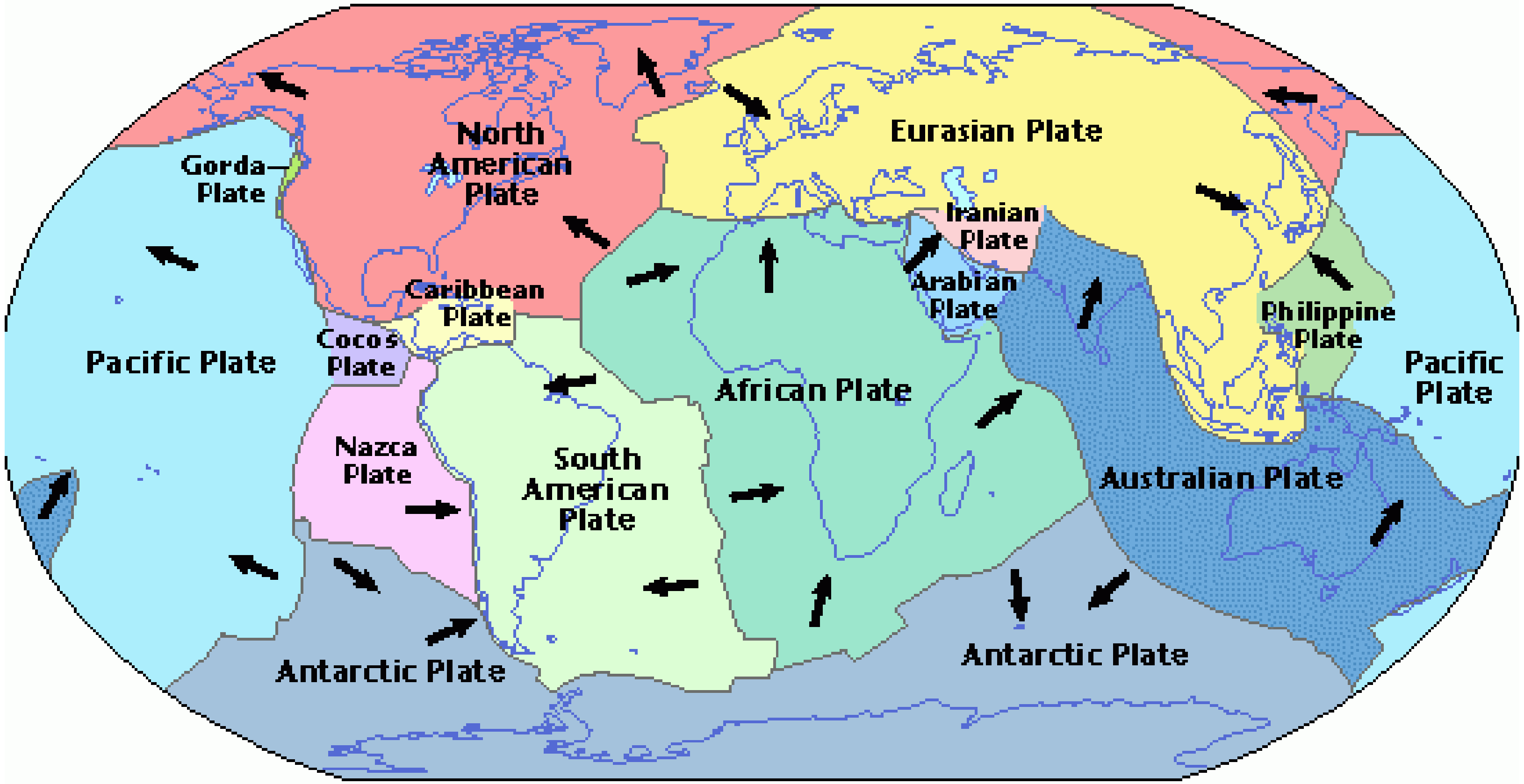


Tectonic plates

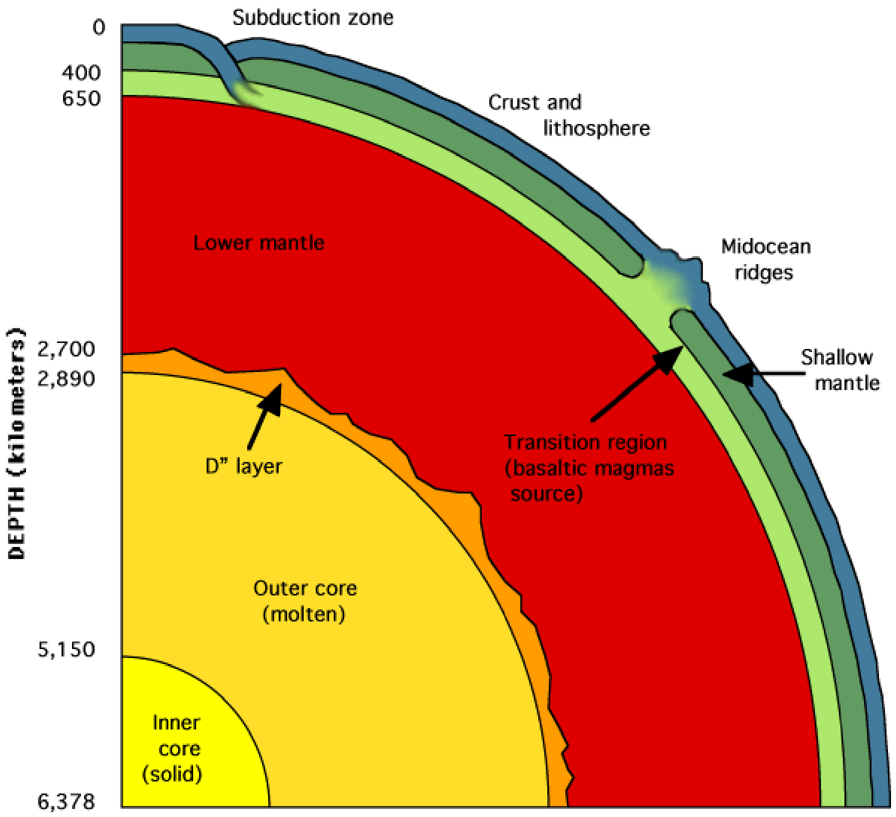
Movement of few cm / year measured by satellites.

Tectonic plates float on plastic asthenosphere.

Movement driven by mantle convection.



EARTH STRUCTURE

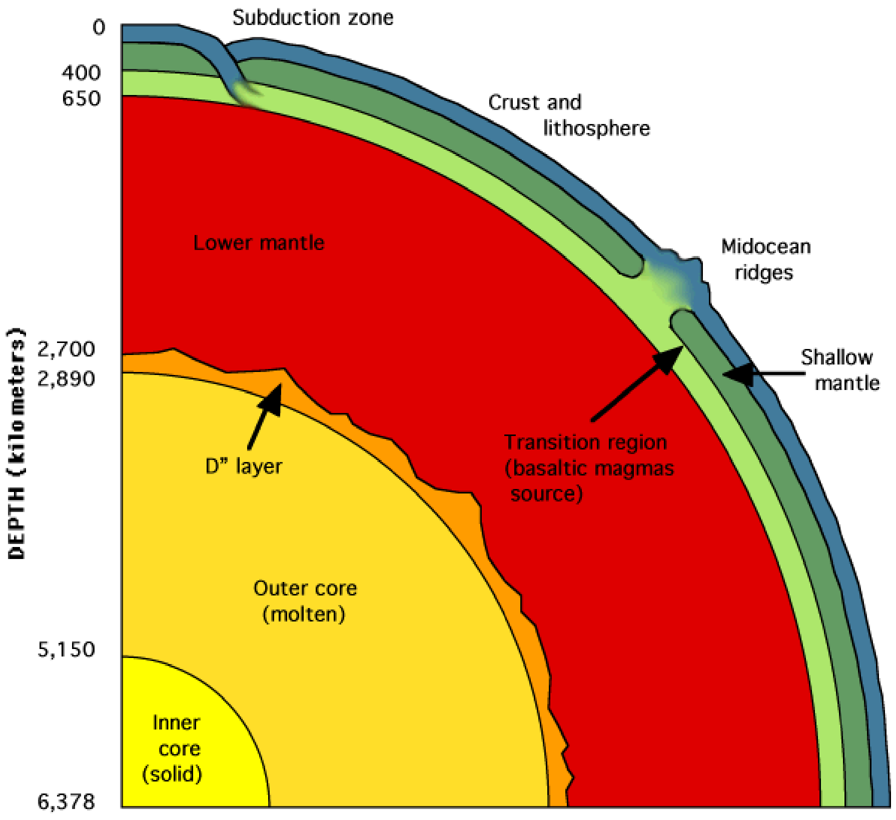


Transition zone (400 -650 km)

seismic discontinuity;

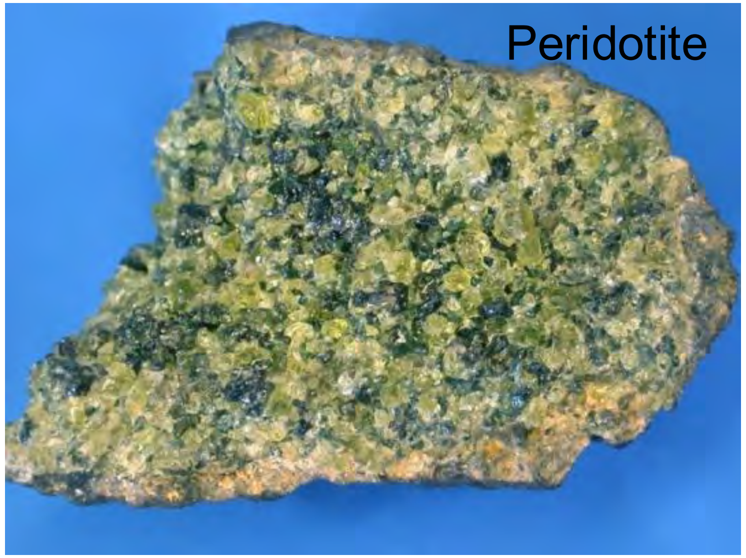
- mineral recrystallisation;
- role of the latent heat?;
- partial melting: the source of mid-ocean ridges basalts;

EARTH STRUCTURE



Upper mantle

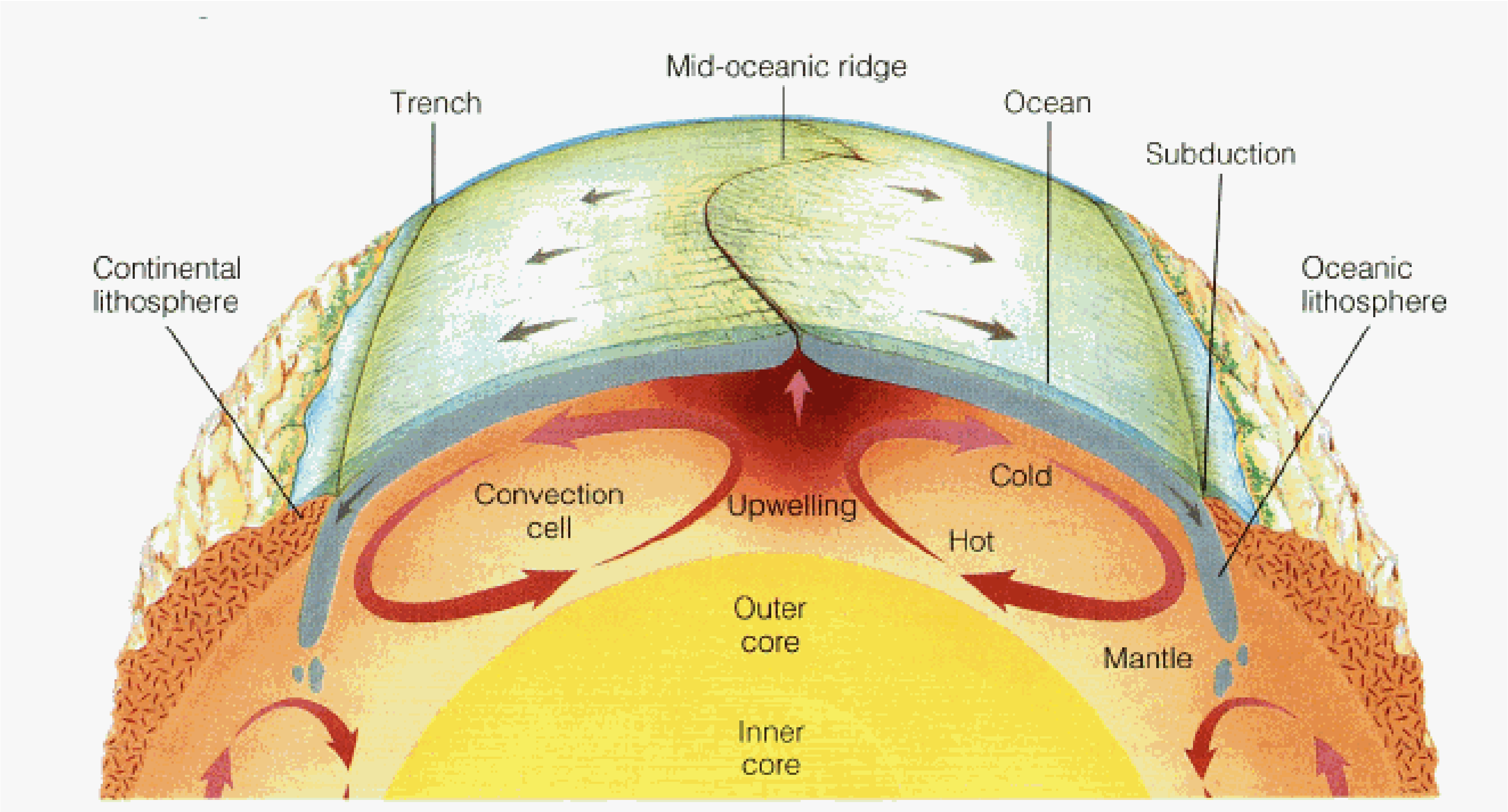
- composition: rock type peridotite with minerals olivine and pyroxen;
- includes highly viscose **astenosphere** on which are floating litospheric tectonic plates (**lithosphere** = more rigid upper mantle + crust);



EARTH CRUST

• **OCEANIC CRUST**:
• created at mid-ocean ridges;
• ~ 10 km thick;

•**CONTINENTAL CRUST**:
• the most differentiated;
• 30 – 70 km thick;
• igneous, metamorphic, and sedimentary rocks;
• orogenesis: doubled thickness;



http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

Crustal rocks: huge variety also in U, Th, K content!

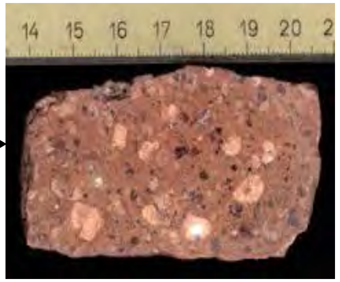
Igneous
(from melt)

Plutonic
from magma
(below surface)

granite

gabbro

Vulcanic
from lava
(on surface)



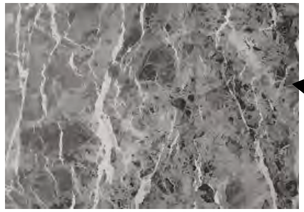
ryolite

basalt

Metamorphic
(new p and T,
no/partial melt)

gneis

amphibolite



marble

Sedimentary

conglomerates

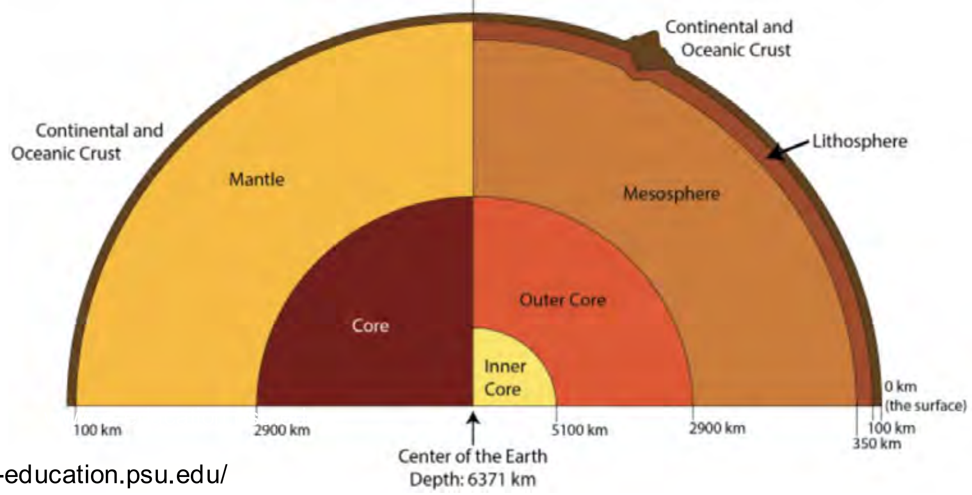
shales

sandstone

limestone

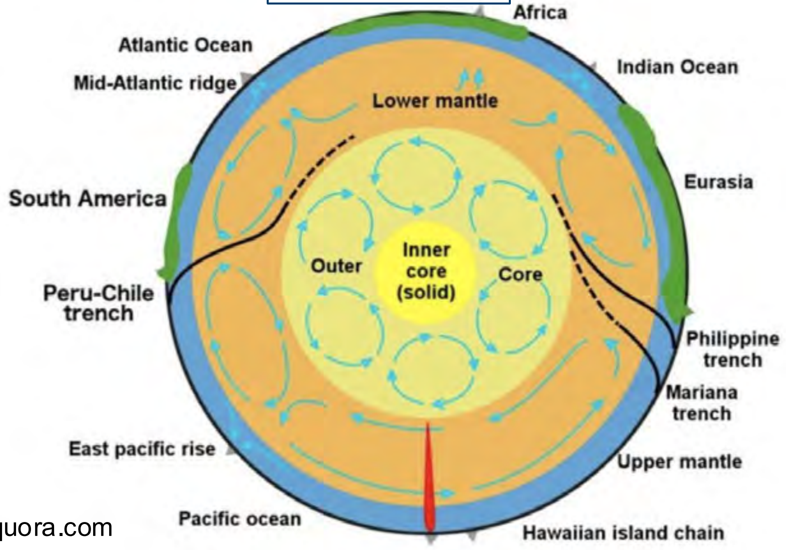
THE EARTH TODAY

Compositional layers | **Mechanical layers**



www.e-education.psu.edu/

Dynamics



www.quora.com

U and Th distribution

Refractory (high condensation T) & **Lithophile** (silicate loving)

Typical concentration for ^{238}U

(Mantovani *et al*. 2004)

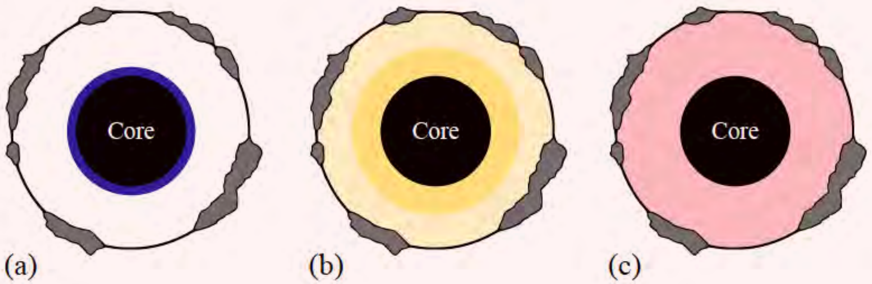
SILICATES	upper continental crust:	2.5 ppm
	middle continental crust:	1.6 ppm
	lower continental crust:	0.63 ppm
	oceanic crust:	0.1 ppm
	upper mantle:	6.5 ppb
	core (**metallic**)	**NOTHING**

Decreases with depth

U/Th distribution in the mantle (3 scenario)

Geoneutrino flux from the mantle

Low — Intermediate — High



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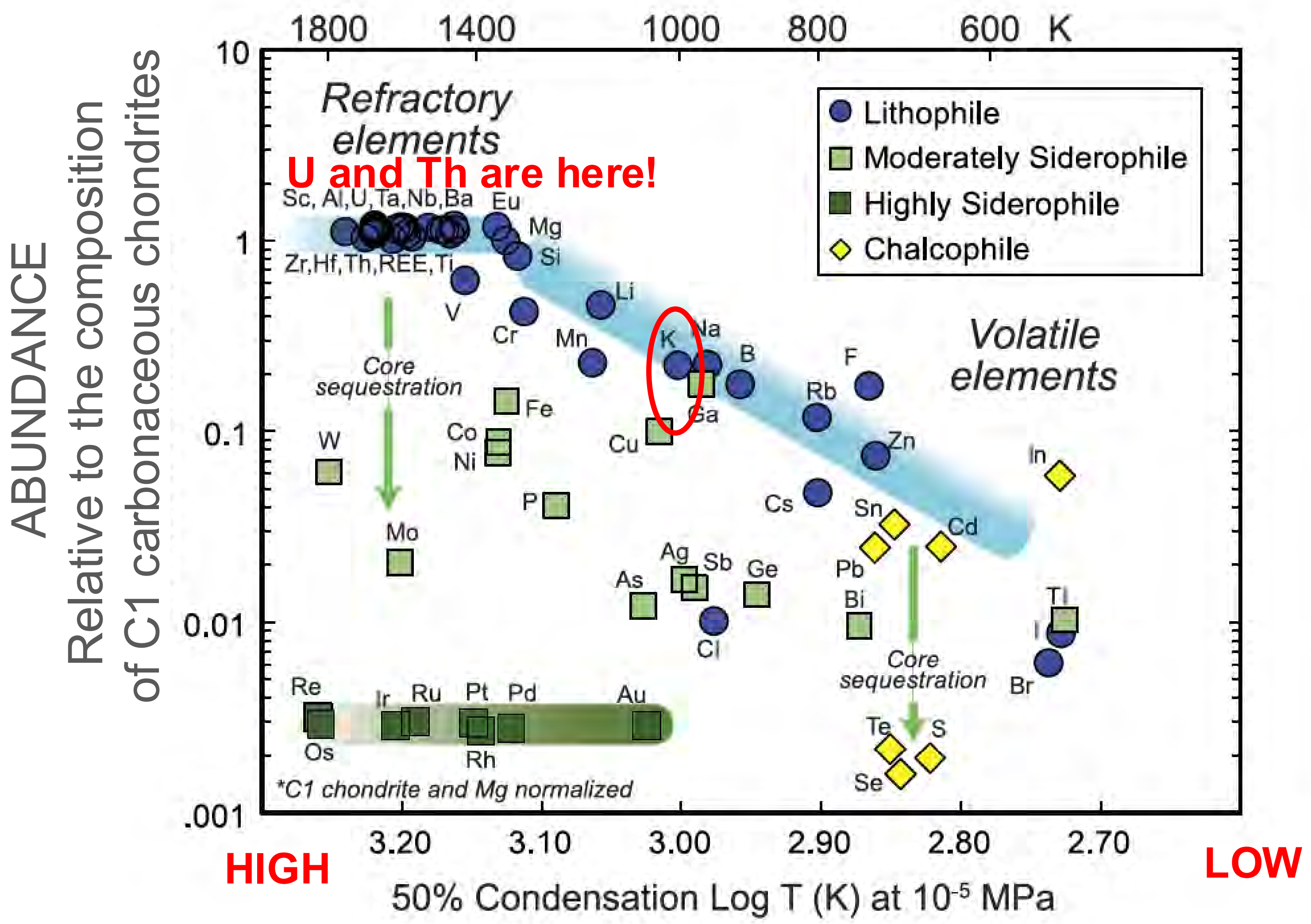
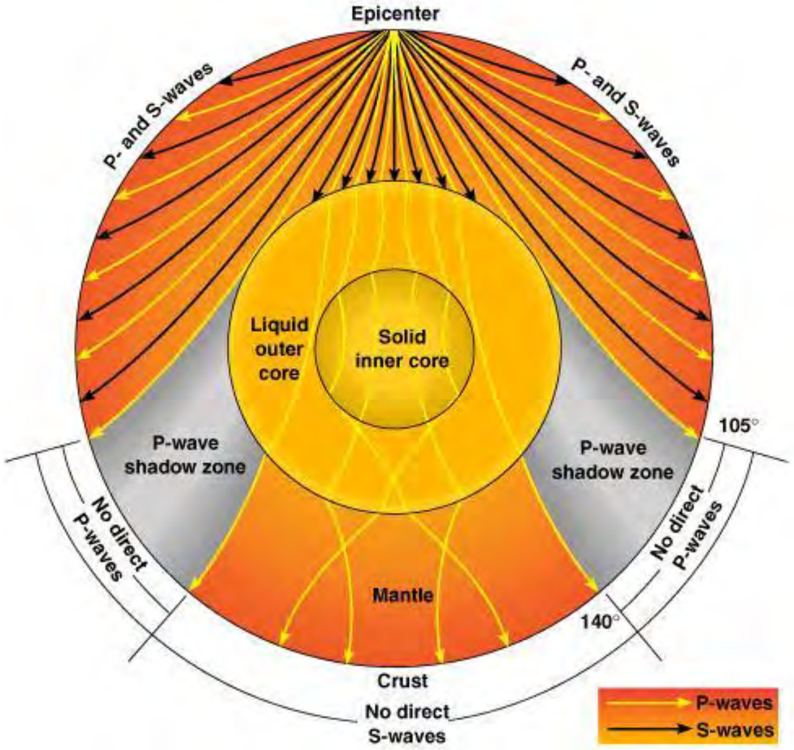
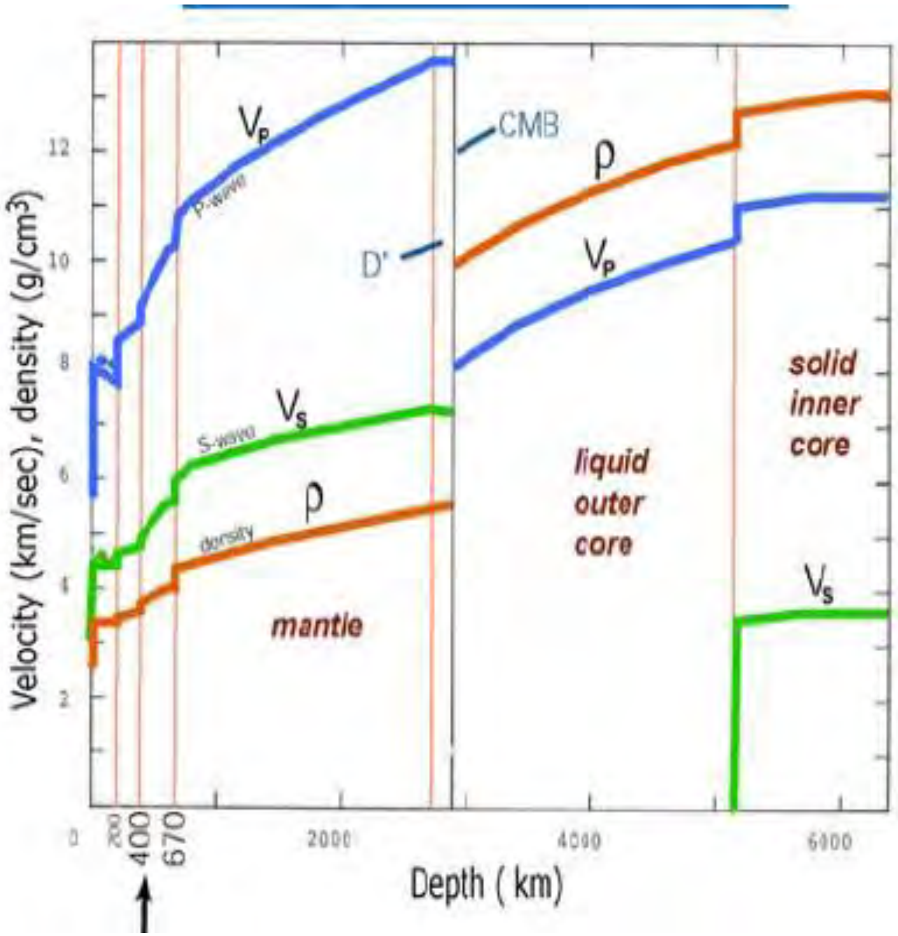
PRIMITIVE-MANTLE COMPOSITION



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

SEISMOLOGY





P – primary, longitudinal waves
S – secondary, transverse/shear waves

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

GEOCHEMISTRY

1) Direct rock samples

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

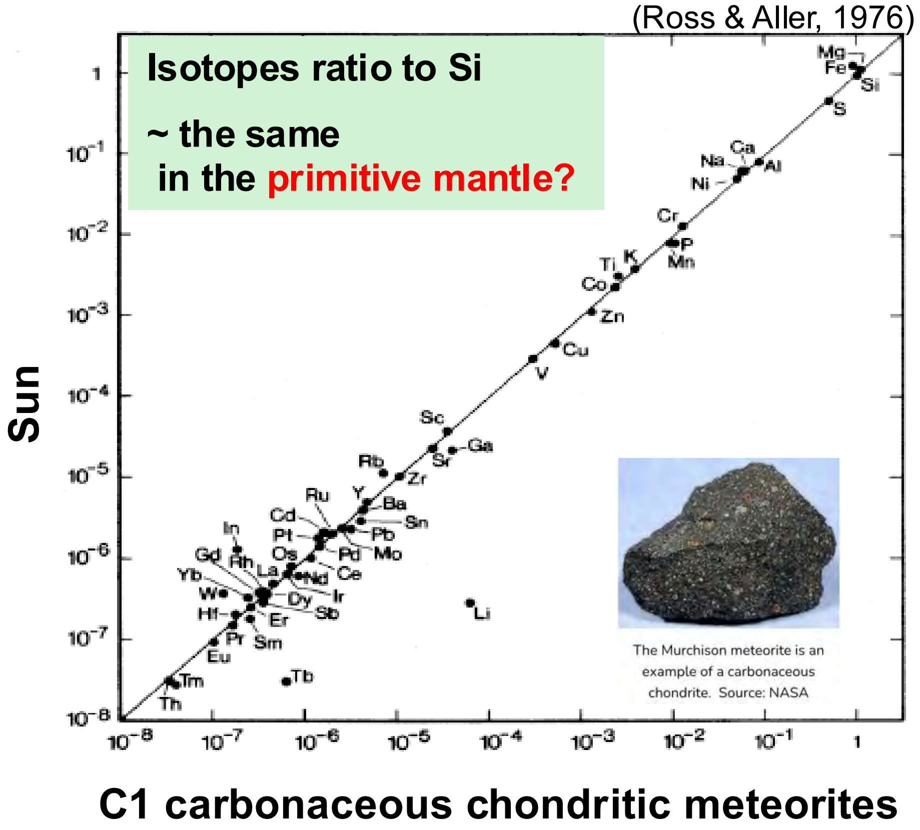
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) Geochemical models

Modeling the composition of the Earth primitive mantle
Various inputs: *composition of the chondritic meteorites, composition of rock samples from the upper mantle and crust, energy needed to run the mantle convection, correlations with the composition of the solar photosphere, …..*

BULK SILICATE EARTH (BSE) MODELS



silicate primitive mantle = present-day **crust + mantle**

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BSE model	M (U) [10^{16} kg]	M (Th) [10^{16} kg]	M (K) [10^{19} kg]	H_{rad} (U+Th+K) [TW]	
Cosmochemical (CC)	5 ± 1	17 ± 2	59 ± 12	**11.3 ± 1.6**	**Low Q**
Geochemical (CC)	8 ± 2	32 ± 5	113 ± 24	**20.2 ± 3.8**	**Middle Q**
Geodynamical (GD)	14 ± 2	57 ± 6	142 ± 14	**33.5 ± 3.6**	**High Q**
„Fully radiogenic“ (FR)	20 ± 1	77 ± 3	224 ± 10	47 ± 2	

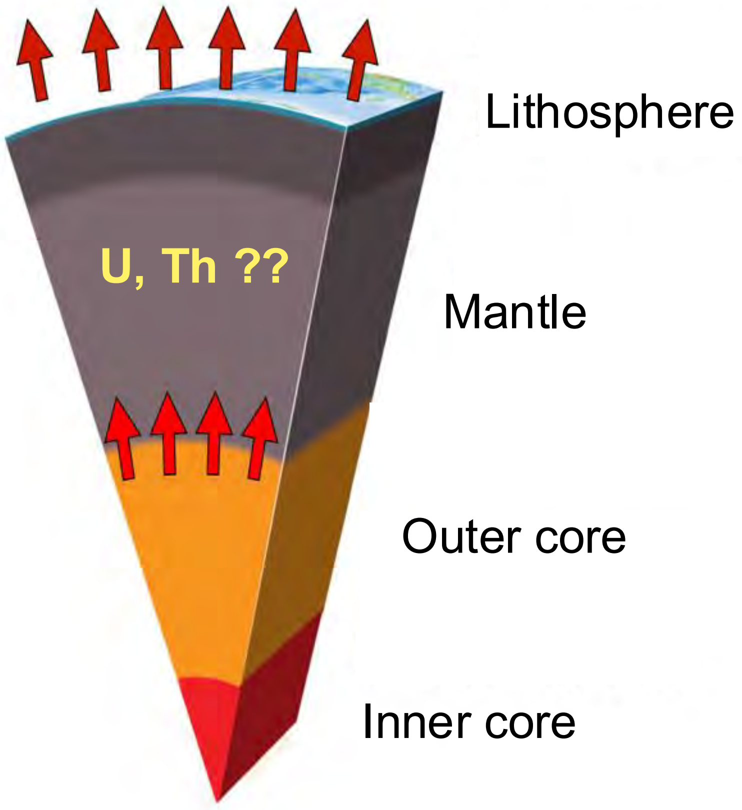
- Mantle composition is inferred from the BSE models by subtracting the relativly well-known crustal composition
- Ratios of different elements, including U and Th, are much better known than their absolute abundances:
  mass ratio of Th/U = 3.9

THE EARTH'S HEAT BUDGET

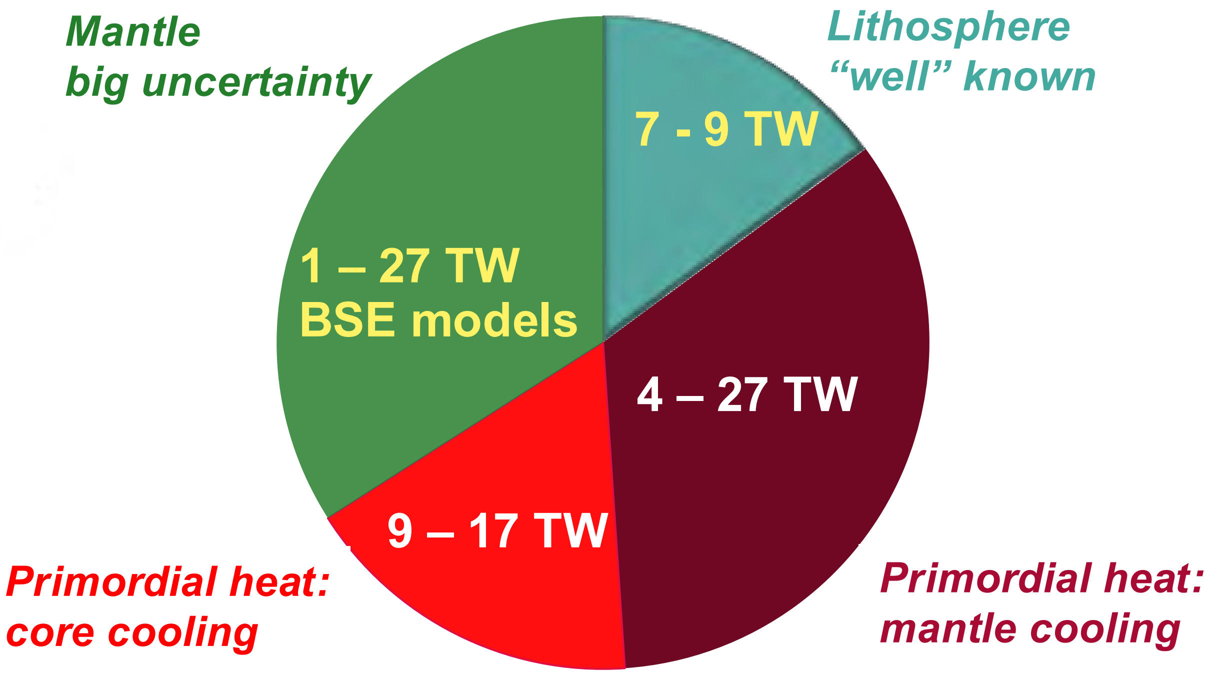
Integrated surface heat flux:

From measured T-gradients along bore-holes

$H_{tot} = 47 \pm 2$ TW



Radiogenic heat & Geoneutrinos



GEONEUTRINOS AND GEOSCIENCE

Abundances (mass) of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^{-} + 6$ anti-neutrinos $+ 51.7$ MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^{-} + 4$ anti-neutrinos $+ 42.8$ MeV

$^{40}K \rightarrow {}^{40}Ca + e^{-} + 1$ anti-neutrino $+ 1.32$ MeV

Main goal:
Mantle radiogenic heat

- Mantle homogeneity
- U/Th ratio
- Earth formation

Distribution of radioactive elements

Signal prediction

Geoneutrino flux (signal)

Signal interpretation

Neutrino geoscience: a truly inter-disciplinary field!

Geoneutrinos: why to study them

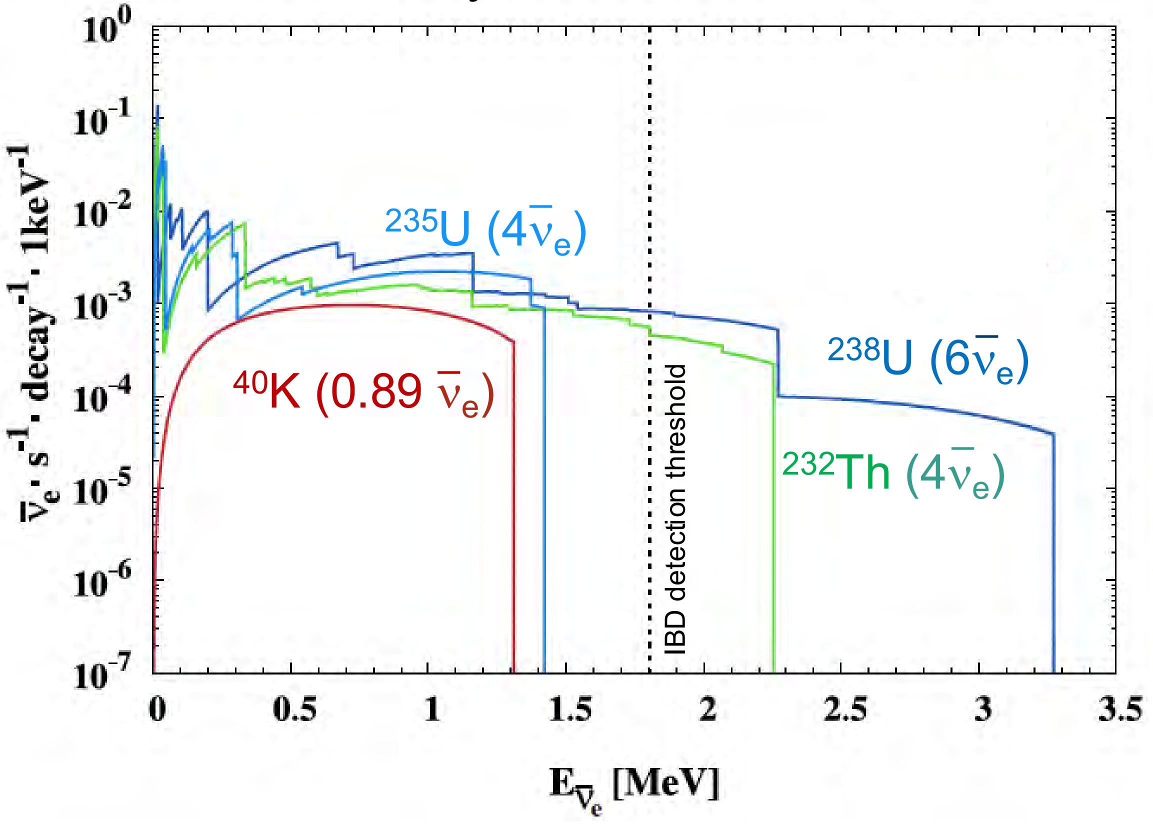
Possible answers to the questions

- **Main goal:**

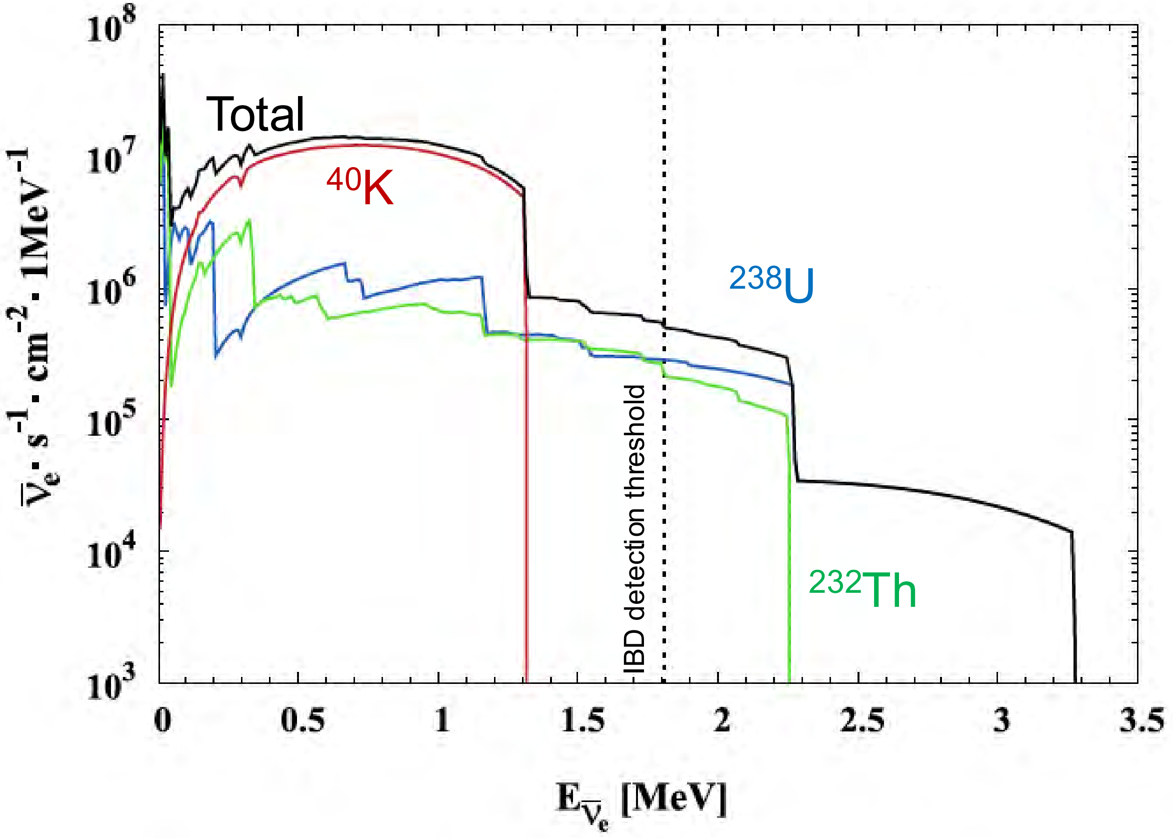
  What is the radiogenic contribution to the terrestrial total surface heat flux
- Are there any other heat sources or not?
- What is the distribution of the long-lived radioactive elements within the Earth?
  - how much of them is in the crust and in the mantle;
  - is their distribution in the mantle homogeneous or not;
  - are they present in the core;
  - is there a geo-reactor (Herndon 2001) ;
- Are the BSE models compatible with geoneutrino data?
- Discrimination among different BSE models;
- What is the bulk Th/U ratio;
- Insights to the processes of the Earth's formation…

GEONEUTRINO ENERGY SPECTRA

Per decay of the head element



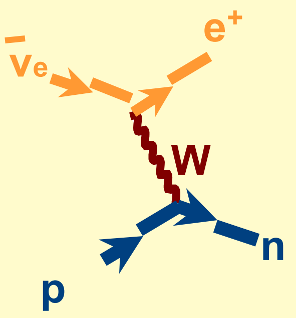
Scaled to expected flux at Gran Sasso, Italy



GEONEUTRINO DETECTION WITH LIQUID SCINTILLATOR

Electron antineutrino detection: delayed coincidence

- Inverse Beta Decay on proton (IBD)
- Charge current interaction mediated by W bosons
- Sensitive only to **electron flavour antineutrinos**
- Cross section very well known
- Generally, powerful **background suppression** tool
- **Reactor neutrinos – irreducible background** with ~10 MeV end-point, geoneutrinos ~3.3 MeV



Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

(~100 x more than elastic scattering on e^-)

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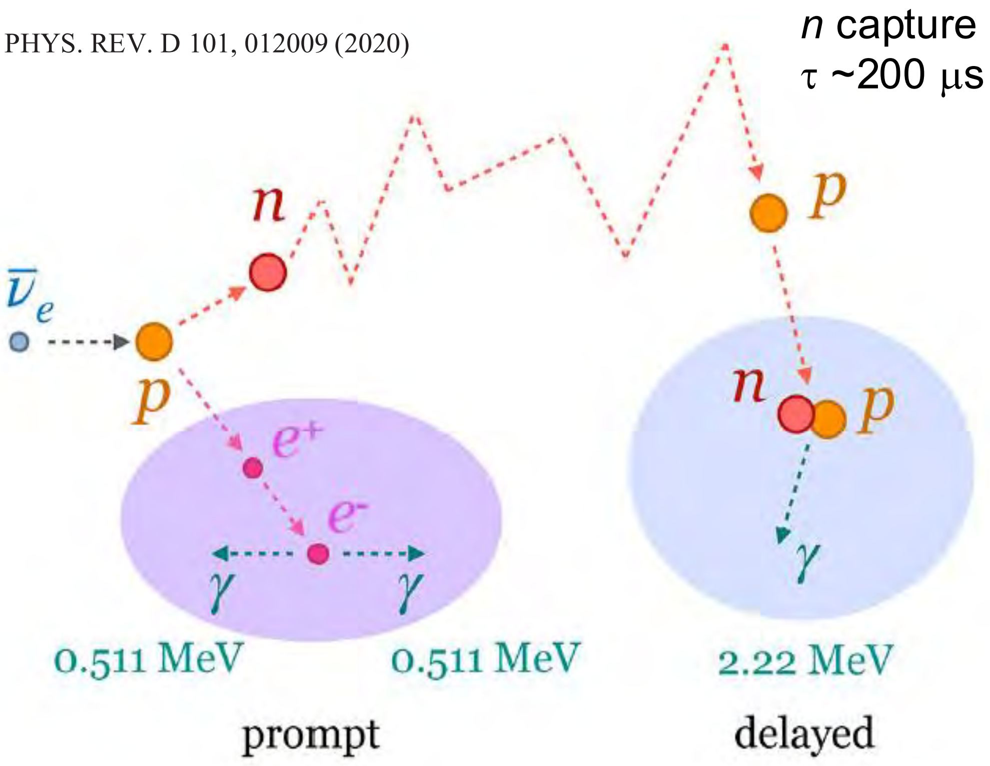


Geoneutrino from radioactive decay

$\bar{\nu}_e$ → **Neutrino oscillation** (average P_{ee} ~ **0.55**) → $\bar{\nu}_e$ | $\bar{\nu}_{\mu,\tau}$

$\bar{\nu}_e$: Detection with IBD

$\bar{\nu}_{\mu,\tau}$: Invisible to IBD

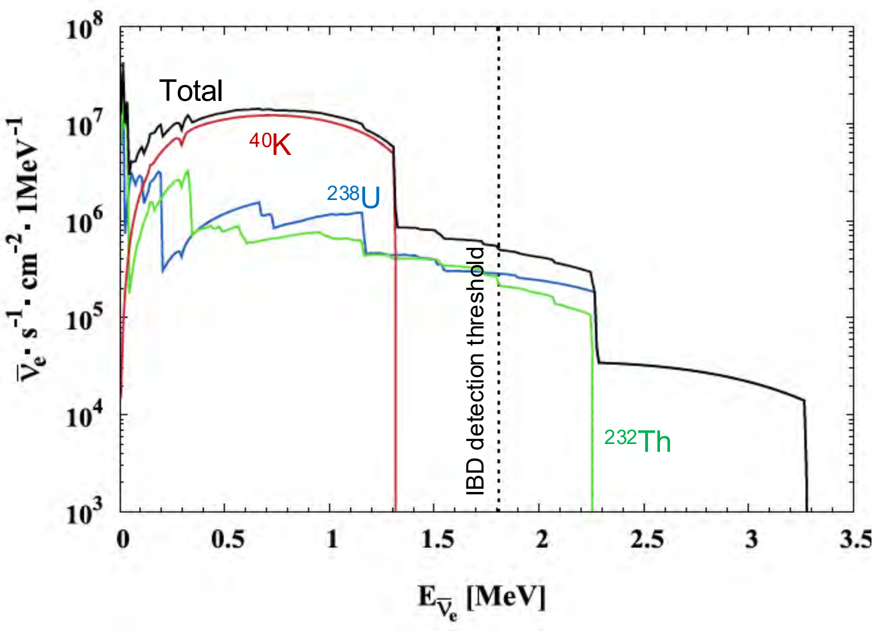
$E_{prompt} = E_{visible}$

$= T_{e+} + 2 \times 511$ keV

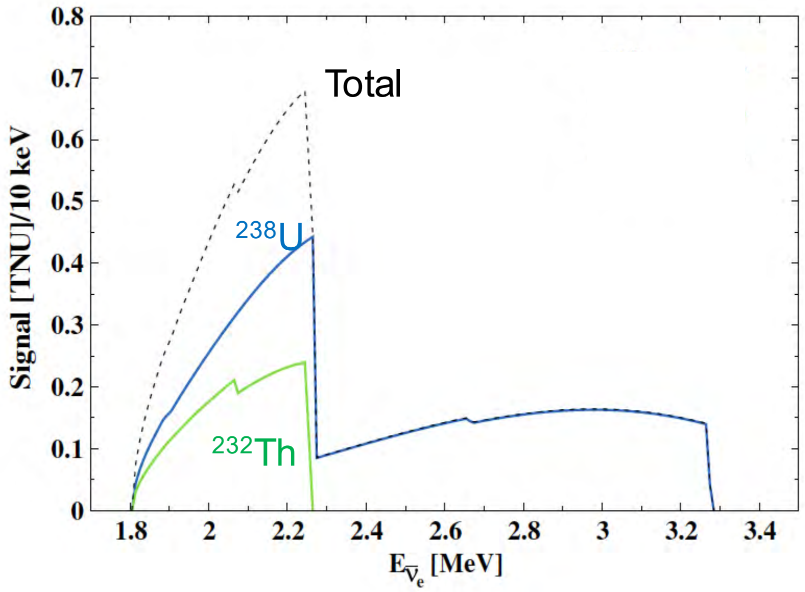
$\sim E_{antinu} - 0.784$ MeV

GEONEUTRINO SPECTRAL SHAPE @ LNGS (BOREXINO SITE)

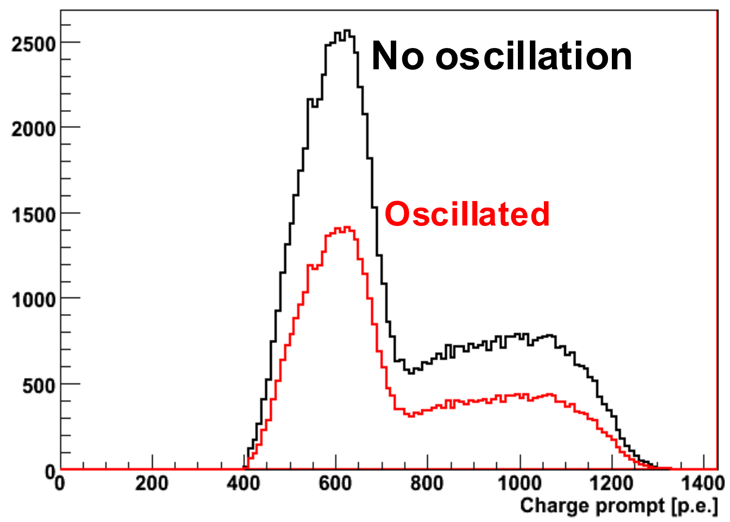
Geoneutrino flux



Geoneutrinos detected via IBD



Effect of detector response & neutrino oscillations



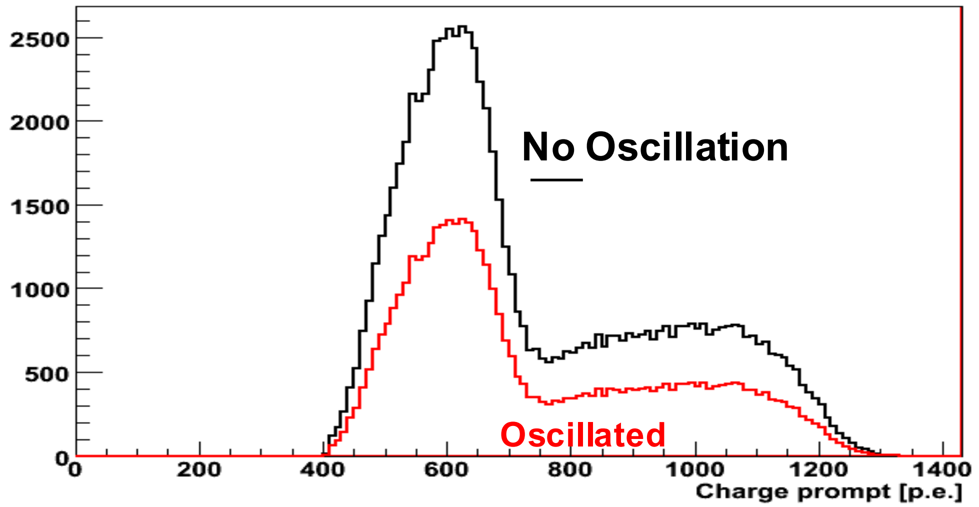
- We are able to **detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th** above 1.8 MeV energy.
- **^{40}K** geoneutrinos cannot be detected.
- ^{238}U and ^{232}Th have different end points of their spectra: **the key how to distinguish them**.
- **Effect of neutrino oscillations**: for 3 MeV antineutrino, the oscillation length is ~100 km; considering the Earth's dimensions and the continuous distribution of U and Th: for the precision of the current experiments – only suppression of the visible signal without spectral deformation.c

EFFECT OF NEUTRINO OSCILLATIONS

For 3 MeV antineutrino: oscillation length of ~100 km

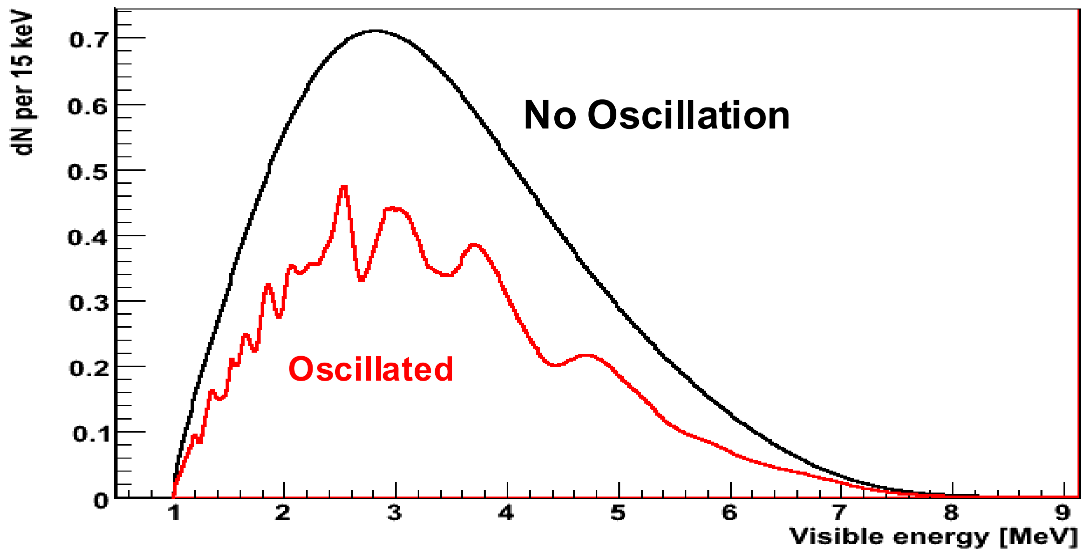
For the precision of the current experiments: we can use an average survival probability of about **0.55**

Geoneutrinos



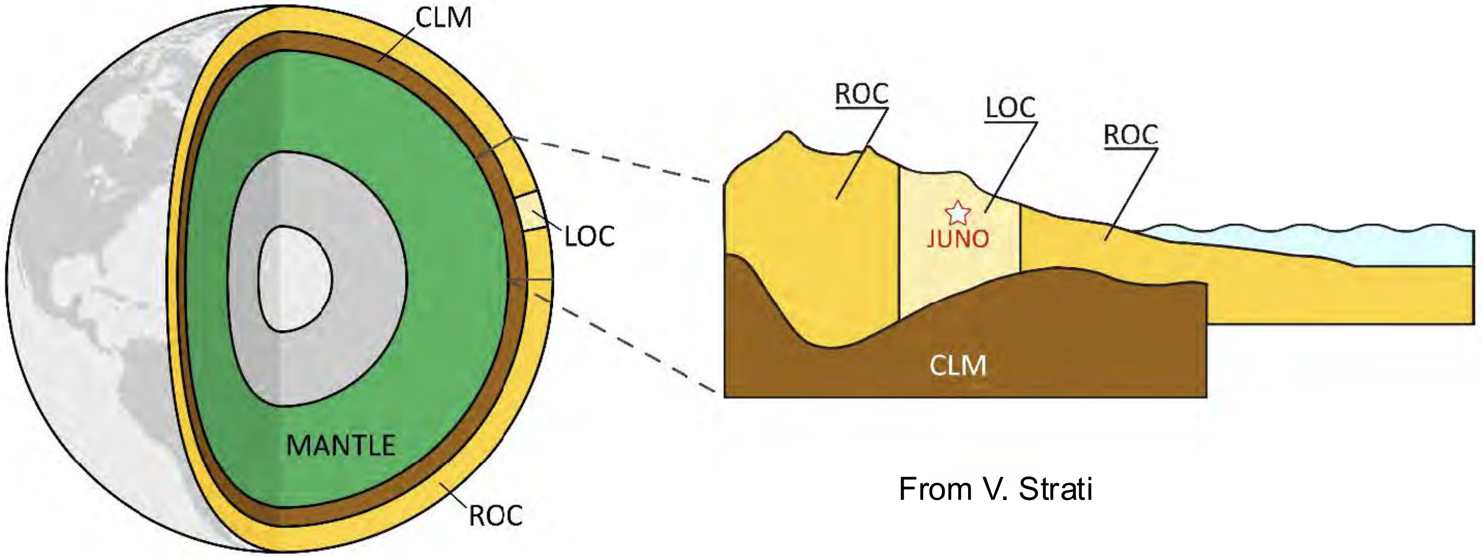
Negligible shape change – "only" suppression of the visible signal

Reactor antineutrinos at LNGS



Significant change of the spectral shape

PREDICTION OF GEONEUTRINO SIGNAL



From V. Strati

Reservoir	Available information	a(U) [μg/g]	Signal [%]
LOcal Crust (LOC)	Rock samples, seismic data, gravimetric data	~1 – 0.1	~ 45
Rest Of Crust (ROC)			~ 30
Continental Lithospheric Mantle (CLM)		~ 0.1	~ 5
(Sublithospheric) Mantle	Compositional models	~ 0.01	~20

PREDICTION OF GEONEUTRINO SIGNAL

Geoneutrino production rate

Energy spectrum

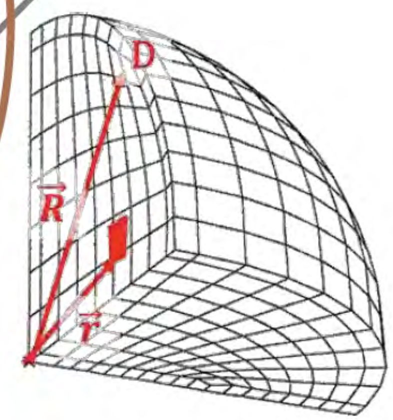
Survival Probability

Abundance of the *i*-element

Earth's mass density function

Distance between the detector D and the centre of the voxel.

$$\Phi_{osc}(i,\bar{r}) = \epsilon'_{i,\bar{\nu}} \cdot \int dE_{\bar{\nu}} \cdot Sp(i, E_{\bar{\nu}}) \int P_{ee}(|\bar{r} - \bar{r}'|, E_{\bar{\nu}}) \cdot d^3r' \cdot \frac{a(i,\bar{r}') \cdot \rho(\bar{r}')}{4\pi|\vec{R} - \vec{r}|^2}$$



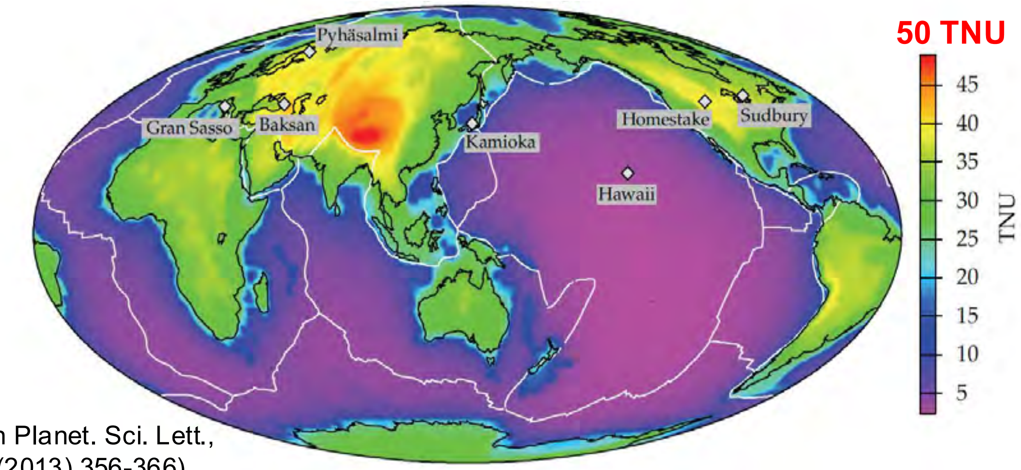
Geophysical (ρ, r) and geochemical (*a*) input organized in a database where the different reservoirs (e.g. crust, mantle) are represented by discrete voxels.

- ❑ Impacts the study of geoneutrino sensitivity
- ❑ Enhances the mantle discovery potential
- ❑ Affects the study of neutrino oscillation parameters
- ❑ JUNO's experimental results will be able to be compared with other experimental results

From V. Strati

GEONEUTRINO SIGNAL WORLDWIDE: from ϕ ~10^6 cm^{-2} s^{-1} to a handful of events

Expected crustal signal: "known and big"



Earth Planet. Sci. Lett., 361 (2013) 356-366)

The signal is small, we need big detectors!

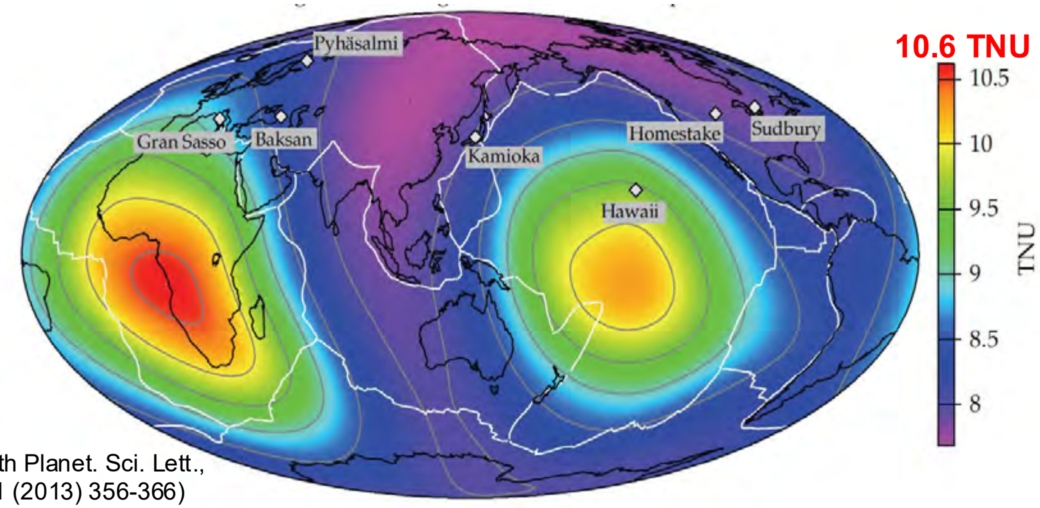
Terrestrial Neutrino Unit

1 TNU = 1 event / 10^{32} target protons / year

cca 1 IBD event /1 kton /1 year, 100% detection efficiency

Expected mantle signal: super-tiny and unknown

Hypothesis of heterogeneous mantle composition motivated by the observed Large Shear Velocity Provinces at the mantle base



Earth Planet. Sci. Lett., 361 (2013) 356-366)

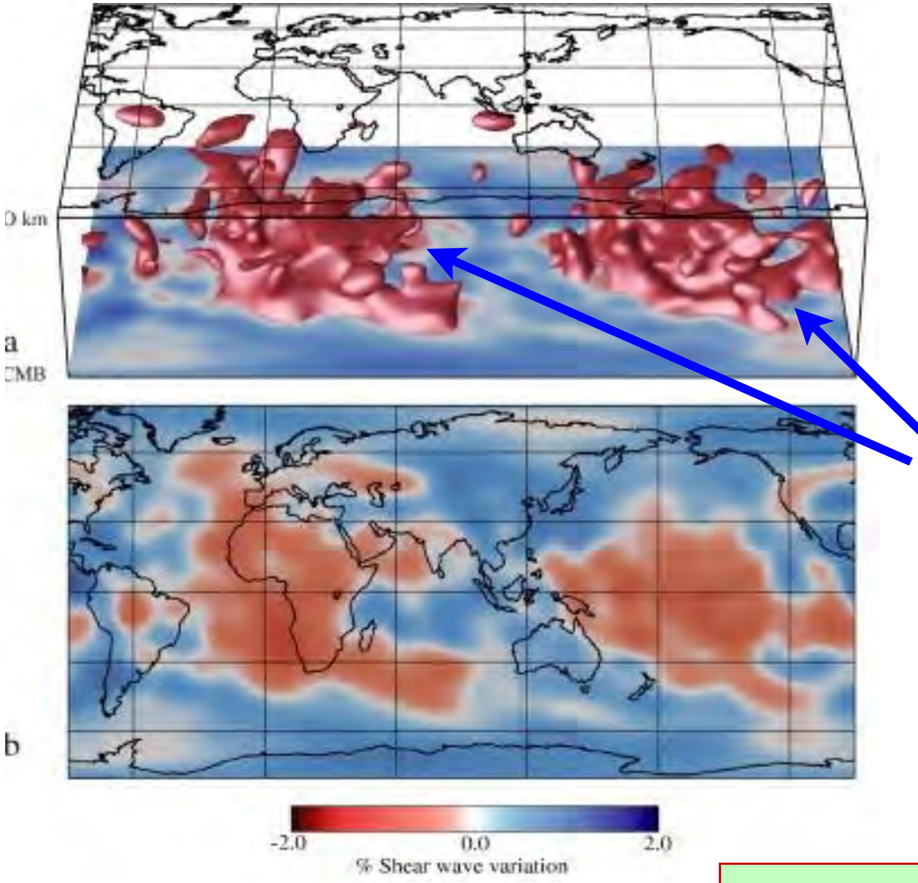
Mantle signal is even more challenging!

From the talk of Sramek at Neutrino Geoscienece 2013

Seismic tomography image of present-day mantle

Seismic shear wave speed anomaly

Tomographic model S20RTS (Ritsema et al.)



Bull et al. EPSL 2009

Two large scale seismic speed anomalies – below Africa and below central Pacific

Anti-correlation of shear and sound wavespeeds + sharp velocity gradients suggest a **compositional component**

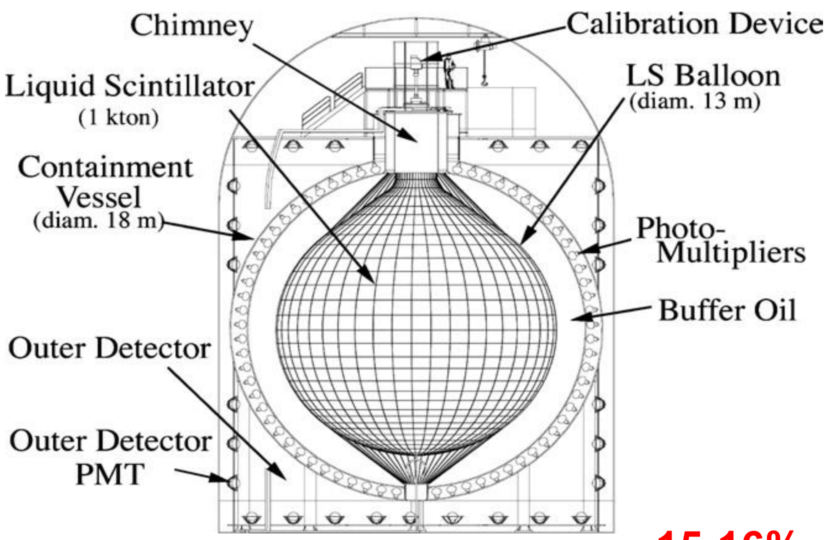
“piles” or “LLSVPs” or “superplumes”

Candidate for an distinct chemical reservoir

Sat AM: Ed Garnero

EXPERIMENTS THAT MEASURED GEONEUTRINOS

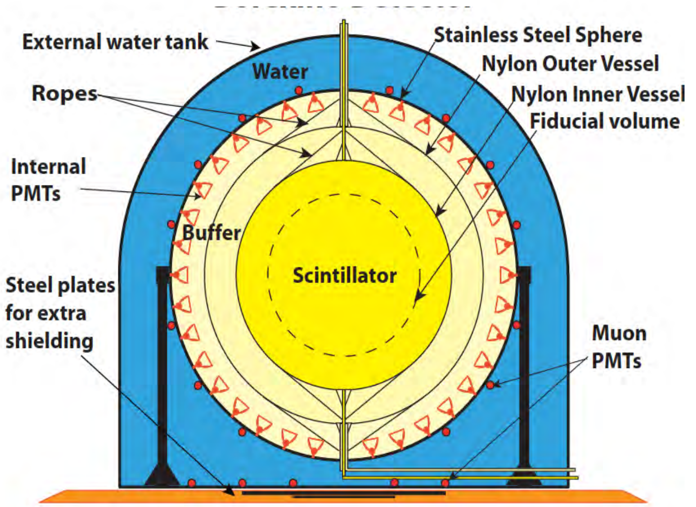
KamLAND, Kamioka, Japan
Border between
OCEANIC / CONTINENTAL CRUST



15-16%

- Main goal: reactor neutrinos
- Data taking: since 2022
- LS: 1000 tons;
- Depth: 2700 m.w.e.
- S(reactors)/S(geo) ~ 6.7 (up to 2010)
  ~ 0.4 (from 2011 after Fukushima)

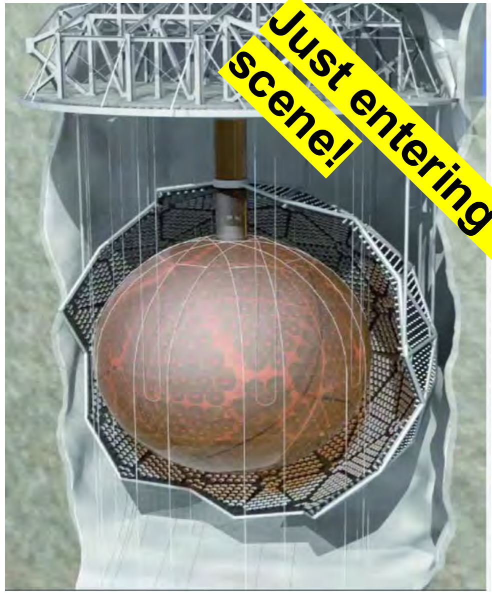
Borexino, LNGS, Italy
CONTINENTAL CRUST



17-18%

- Main goal: solar neutrinos:
  extreme radio-purity needed & achieved;
- Data taking: 2007 - 2021
- LS: 280 tons;
- Depth: 3800 m.w.e.
- S(reactors)/S(geo) ~ 0.3 (2010)

SNO+
CONTINENTAL SHIELD (OLD CRUST)



Just entering the scene!

43 - 47%

- Main goal: $0\nu\beta\beta$ decay
- Data taking: since 2022
- LS: 780 tons;
- Depth: 6000 m.w.e.
- Background dominated by (α, n) and not reactors.

HISTORY OF GEONEUTRINO MEASUREMENTS

KamLAND, Kamioka, Japan

- **The first investigation 2005:** Nature 436 (2005) 499
  4.5 – 54.2 geonu's @ 90% CL, non-0 hypothesis **CL < 2σ**
  7.09 x 10^{31} proton x year
- **Update 2008:** PRL 100 (2008) 221803 — 37%
  73 ± 27 geonu's
  2.44 x 10^{32} proton x year
- **99.997 CL in 2011:** Nature Geoscience 4 (2011) 647 — 26%
  106^{+29}_{-28} geonu's
  3.49 x 10^{32} proton x year (Mar 2002 – Apr 2009)
- **Results from 2013:** PRD 88 (2013) 033001 — 24%
  116^{+28}_{-27} geonu's
  4.9 x 10^{32} proton x year (Mar 2002 – Nov 2012)
- **Latest result in 2022** (Geophys. Res. Lett. 49 e2022GL099566) — 15-16%
  183^{+29}_{-28} geonu's
  6.39 x 10^{32} proton x year (Mar 2002 – Dec 2020)

Borexino, LNGS, Italy

- **99.997 CL observation:** PLB 687 (2010) 299 — 34-41%
  $9.9^{+4.1}_{-3.4}$ geonu's
  1.5 x 10^{31} target-proton year (Dec 2007 – Dec 2009)
- **Update in 2013:** PLB 722 (2013) 295–300 — 31%
  14.3 ± 4.4 geonu's
  3.69 x 10^{31} target-proton year (Dec 2007 – Aug 2012)
- **5.9σ CL in 2015:** PRD 92 (2015) 031101 (R) — 24-27%
  $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's
  5.5 x 10^{31} target-proton year (Dec 2007 – Mar 2015)
- **Latest result in 2020** (Phys. Rev. D 101 (2020) 012009) — 17-18%
  $52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geonu's
  1.29 x 10^{32} proton x year, (Dec 2007 - Apr 2019)

SELECTING IBD CANDIDATES

IBD: antineutrino + proton → positron + neutron

E_{prompt} = E(antineutrino) – 0.784 MeV

$E_{delayed}$ = 2.2 MeV gamma

Δ time = time correlation

Δ R = space correlation

- Charged particles produce scintillation light.
- Gamma rays from the positron annihilation and from the neutron capture are neutral particles but in the scintillator they interact mostly via Compton scattering producing several electrons = charged particles.
- Scintillation light is detected by an array of phototubes (PMTs) converting photons to electrical signal (photoelectrons – pe).
- Number of photoelectrons = function of (energy deposit) -> E_{prompt}, $E_{delayed}$.
- Hit PMTs time pattern = vertex reconstruction -> ΔR of events.
- Each trigger has its GPS time -> Δtime of events.

IBD candidates due to:

- ✓ **Geo-neutrinos;**
- ✓ **Reactor antineutrinos;**
- ✓ **Non-antineutrino backgrounds;**

This principle is the same for all LS detectors

OPTIMIZED IBD SELECTION CUTS (Borexino)

Efficiency: (86.98 ± 1.50)%

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

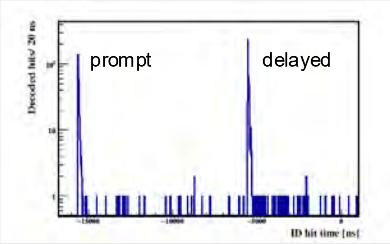
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on **^{12}C (4.95 MeV)**
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha + \gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

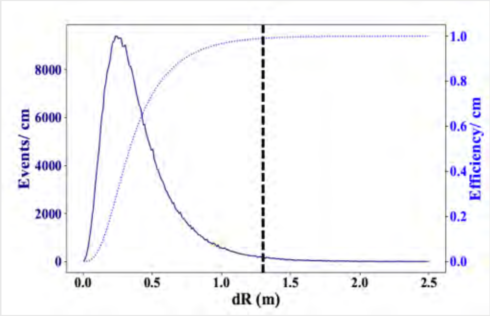
Neutron capture τ = (254.5 ± 1.8) μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

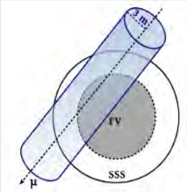


Muon veto

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

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



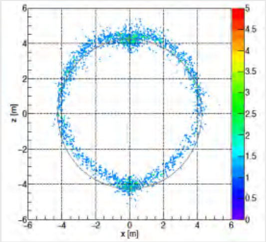
- Whole detector
- **Cylinder**

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

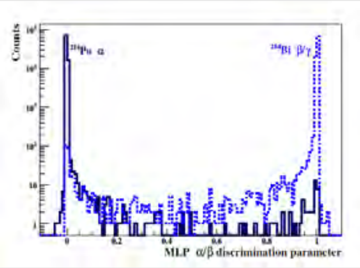
No event with Q >400 pe ±2 ms around promt/delayed

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

α/β discrimination

$MLP_{delayed}$ > 0.8

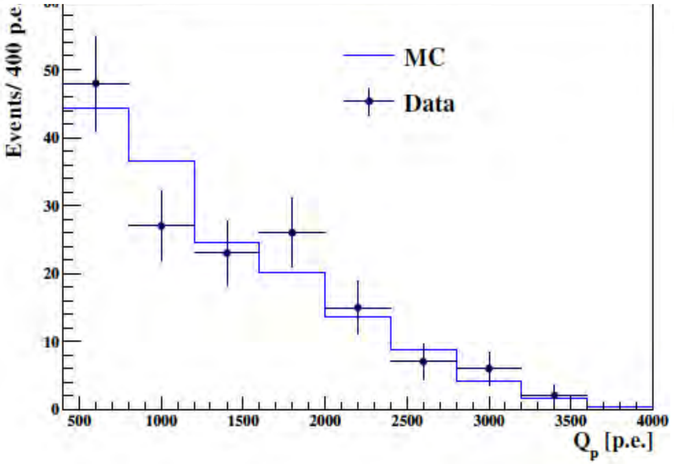
- Radon correlated $^{214}Po(\alpha+\gamma)$



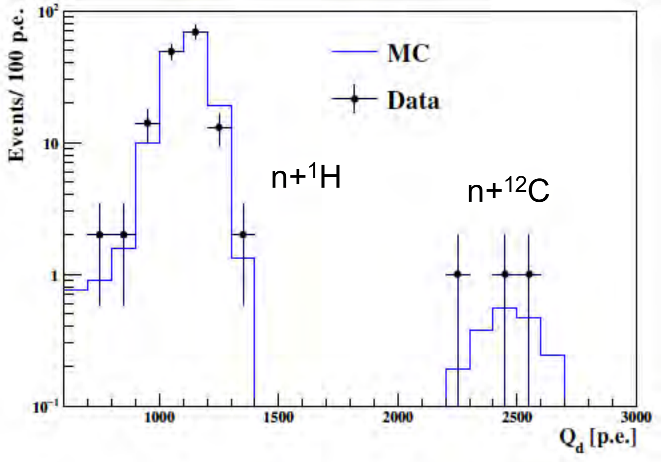
Borexino GOLDEN CANDIDATES: 154

(Phys. Rev. D 101 (2020) 012009)

Prompt charge spectrum

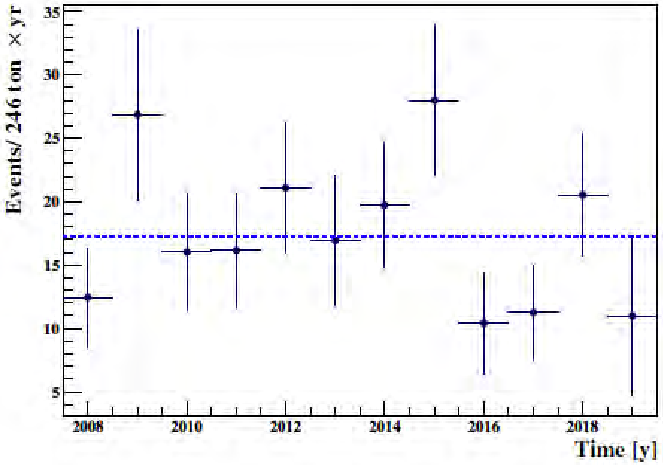


Delayed charge spectrum

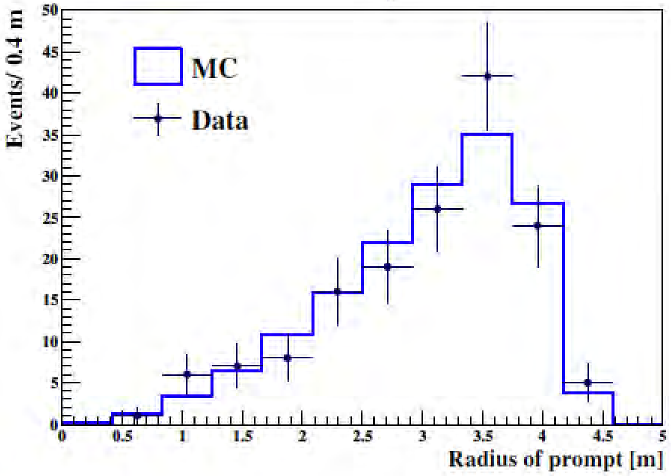


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

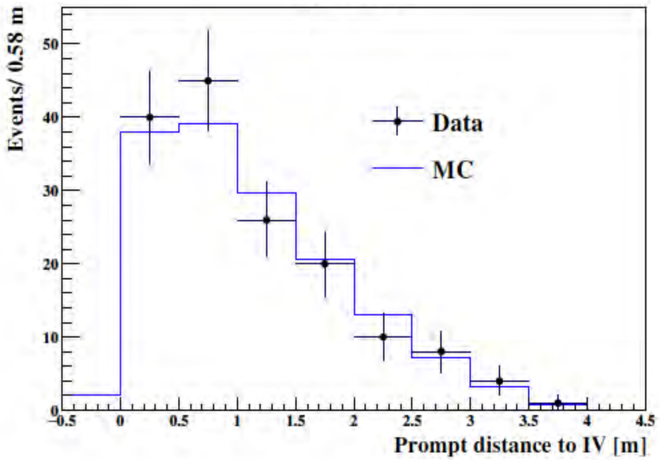
Distribution in time



Radial distribution

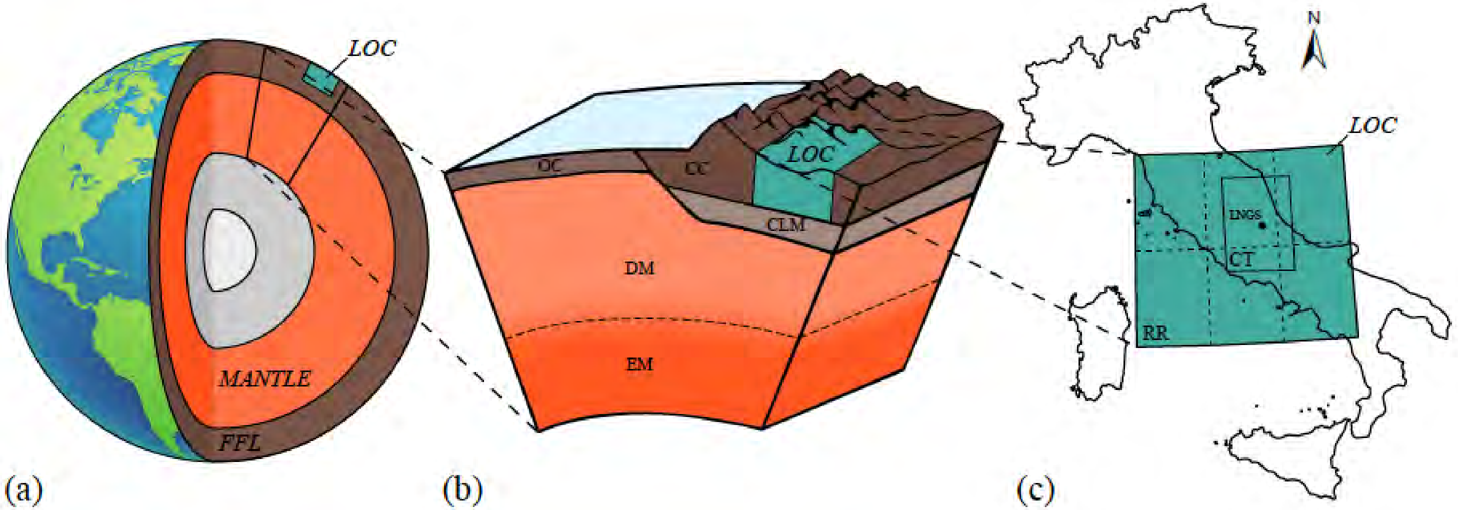


Distance to the Inner Vessel



EXPECTED GEONEUTRINO SIGNAL AT GRAN SASSO

1. LOCAL AND GLOBAL GEOLOGICAL INFORMATION



(Phys. Rev. D 101 (2020) 012009

U, Th abundances & distribution + density profiles

~50% of the signal comes from the area of a few 100 km radius

LOC – Local Crust

FFL – Far Field Lithosphere

Mantle

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

2. GEONEUTRINO ENERGY SPECTRA

3. σ(IBD) as f (E_ν) ~10^{-42} cm^2

4. $<P_{ee}>$ ~0.55

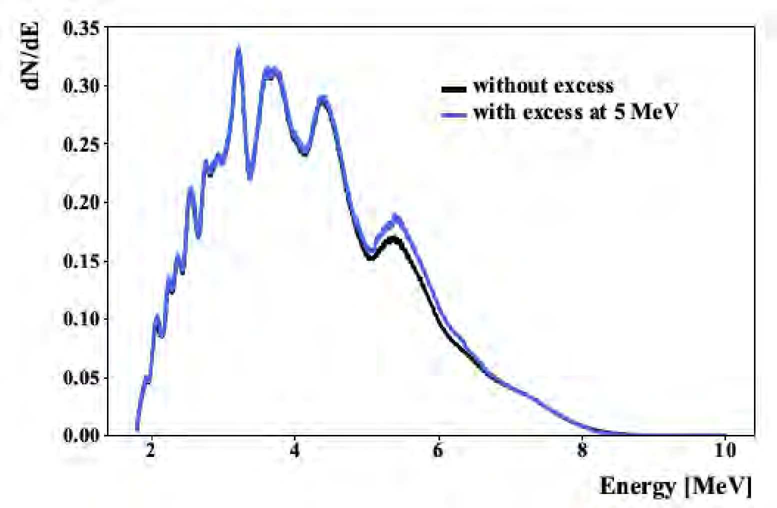
	S (U + Th) [TNU]	S(Th)/S(U)	H (U + Th +K) [TW]
Local Crust (LOC) (~500 km radius)	9.2 ± 1.2	0.24	-
Bulk Lithosphere (including LOC)	$25.9^{+4.9}_{-4.1}$	0.29	$8.1^{+1.9}_{-1.4}$
Mantle = Bulk Silicate Earth model – lithosphere	2.5 – 19.6	0.26 (assuming for BSE chondritic value of 0.27)	3.2 – 25.4
Total	**28.5 – 45.5**	0.27 (chondritic)	11.3 – 33.5

NEUTRINO BACKGROUNDS for Borexino

Reactor antineutrinos from nuclear powerplants

	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)
  - ✓ their nominal thermal powers (PRIS database of IAEA)
  - ✓ monthly load factors (PRIS database)
  - ✓ distance to LNGS (no reactors in Italy)
- ^{235}U, ^{238}U, ^{239}Pu , and ^{241}Pu fuel
  - ✓ power fractions for different reactor types
  - ✓ energy released per fission
  - ✓ energy spectra (Mueller at al. 2011 and Daya Bay)
- P_{ee} electron neutrino survival probability
- IBD cross section
- Detection efficiency = 0.8955 ± 0.0150

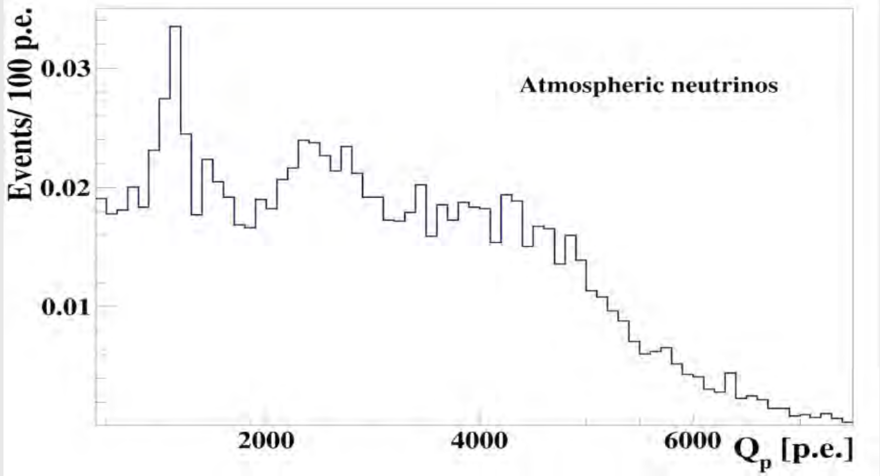


Atmospheric neutrinos (minor)

Energy window	Geoneutrino	Reactor antineutrino	> 1 MeV
Events	2.2 ± 1.1	6.7 ± 3.4	9.2 ± 4.6

- Estimated 50% uncertainty on the prediction
- Indications of overestimation
- Included in the systematic error
- Atmospheric neutrino fluxes
  from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included

Charge spectrum after IBD selection cuts



1 MeV ~ 500 p.e.

CALCULATION OF THE EXPECTED REACTOR ANTI-ν FLUX

$$\Phi\left(E_{\bar{\nu}_e}\right) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i\left(E_{\bar{\nu}_e}\right) P_{ee}\left(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r\right)$$

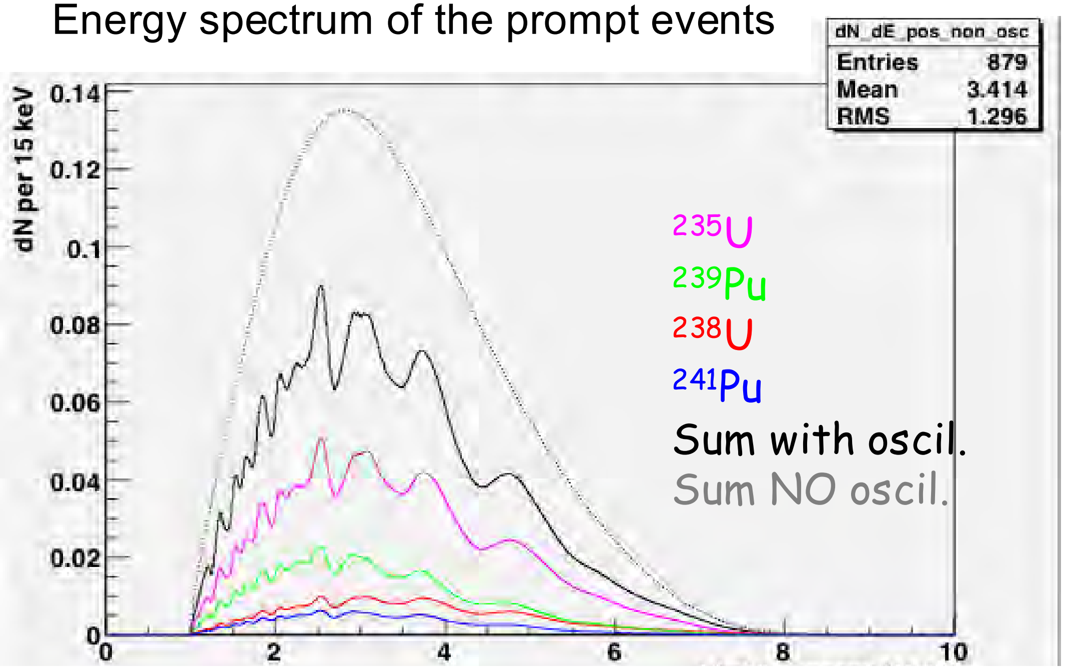
- **Nuclear and neutrino physics:**
  - E_i : energy release per fission of isotope i (Huber-Schwetz 2004);
  - Φ_i: antineutrino flux per fission of isotope i (polynomial parameterization, Mueller et al.2011, Huber-Schwetz 2004);
  - P_{ee}: oscillation survival probability;
- **Experiment-related:**
  - T_m: live time during the month m;
  - L_r: reactor r – detector distance;
- **Data from nuclear agencies:**
  - P_{rm}: thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - f_{ri}: power fraction of isotope i in reactor r;

^{235}U
^{239}Pu
^{238}U
^{241}Pu

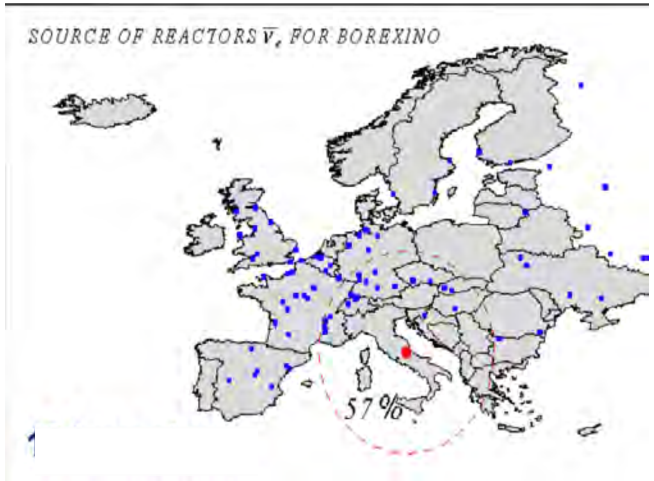
+ consider energy-dependent IBD cross section → expected reactor-antinu rate for 100 detection eff.

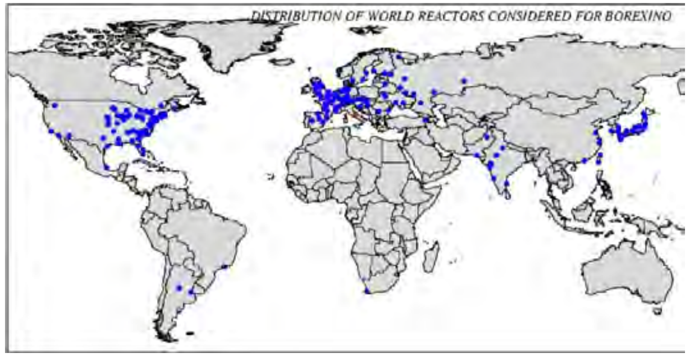
Expected reactor signal at LNGS

Energy spectrum of the prompt events



Ideal detector   Prompt energy (MeV)





NON-ANTINEUTRINO BACKGROUNDS

1) Cosmogenic background

- **^{9}Li and ^{8}He** ($\tau_{1/2}$ = 119/178 ms)
  - ✓ decay: β(prompt) + neutron (delayed);
- **fast neutrons**
  - ✓ scattered protons (prompt)

Estimated by studying IBD-like coincidences detected AFTER muons.

2) Accidental coincidences;

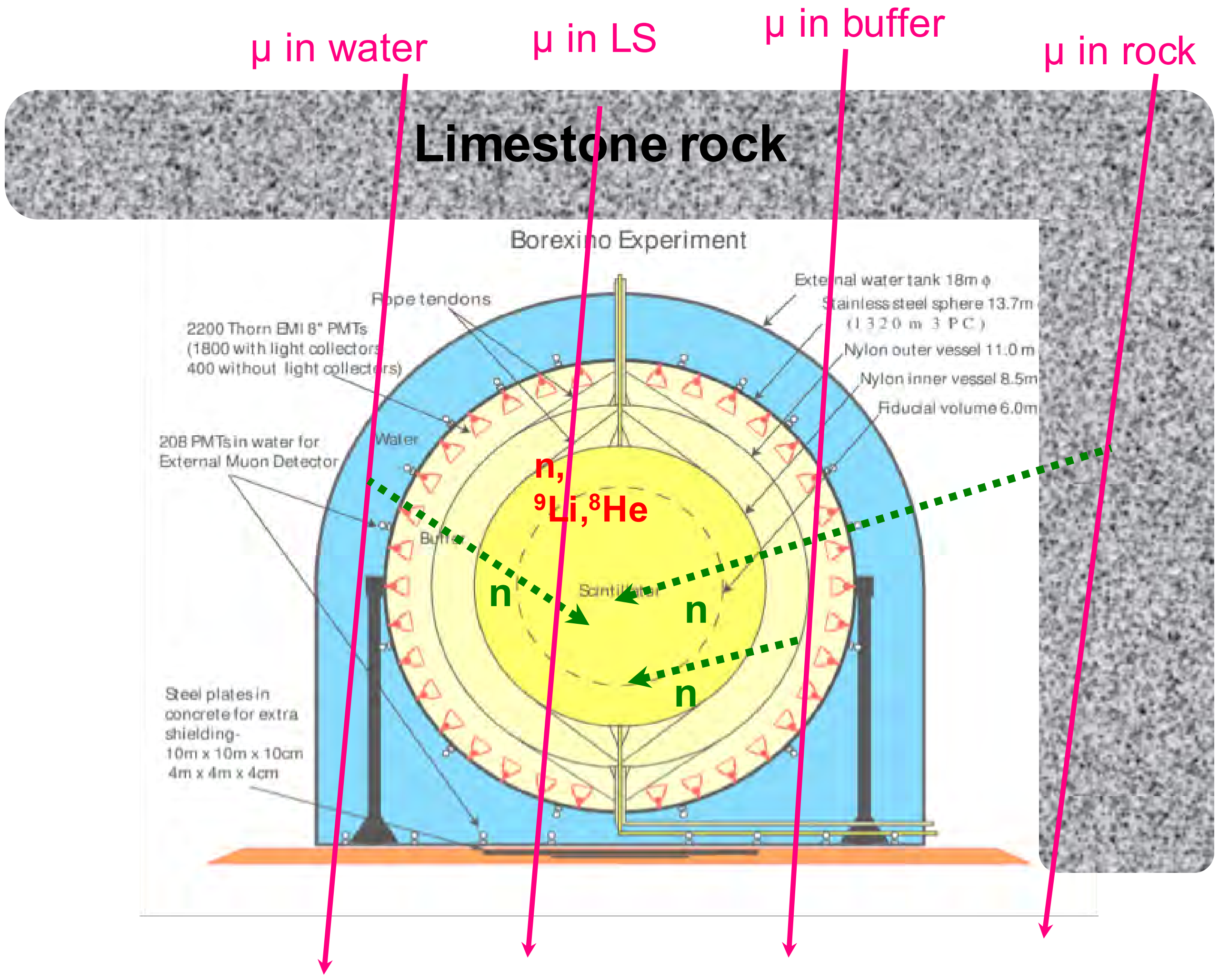
Estimated from OFF-time IBD-like coincidences.

3) Due to the internal radioactivity:

(α, n) reactions: $^{13}C(\alpha, n)^{16}O$

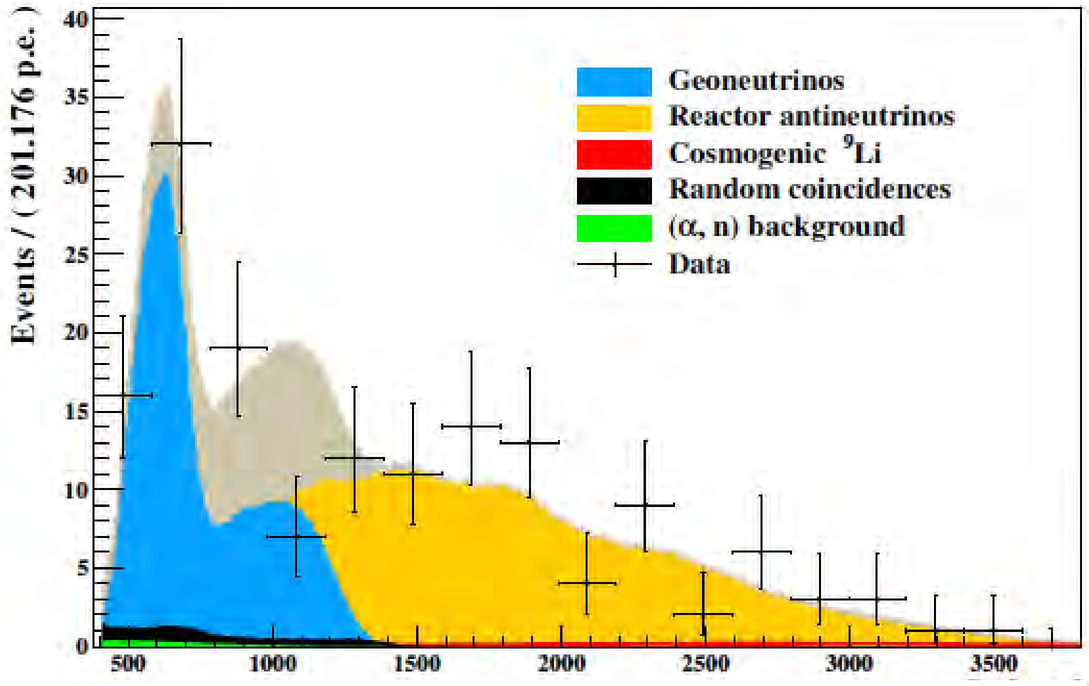
Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

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



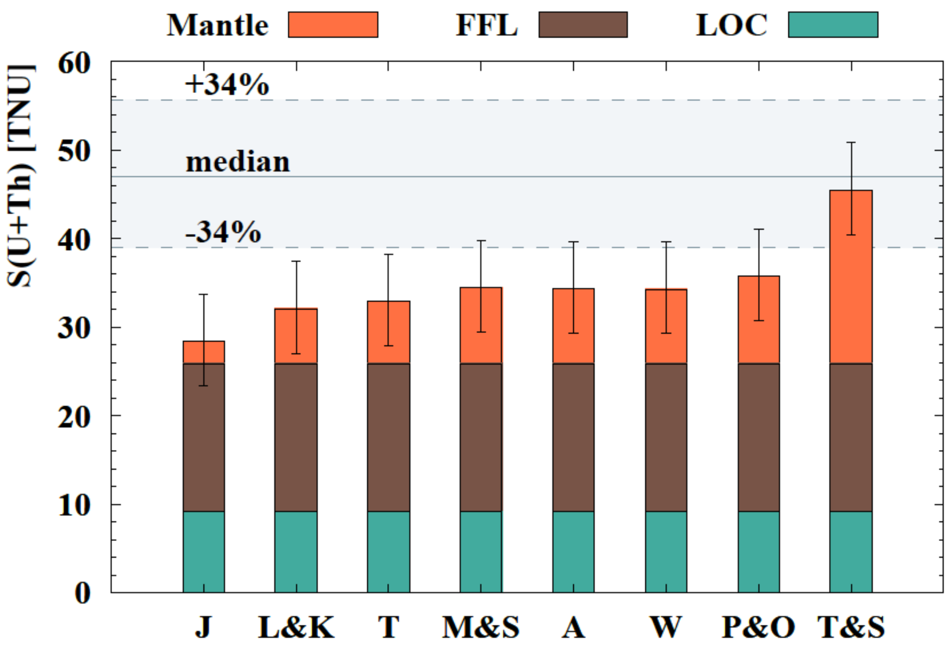
Borexino SPECTRAL FIT with fixed chondritic Th/U ratio

Borexino (PRD101 (2020) 012009)



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

In agreement with expectations based on different BSE models:



- Unbinned likelihood fit of charge spectrum of 154 prompts
- S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)
- **Reactor signal unconstrained** and result compatible with expectations
- ^{9}Li, accidentals, and (α, n) background constrained to expectations
- **Systematics** includes atmospheric neutrinos, shape of reactor spectrum, vessel shape and position reconstructions, detection efficiency

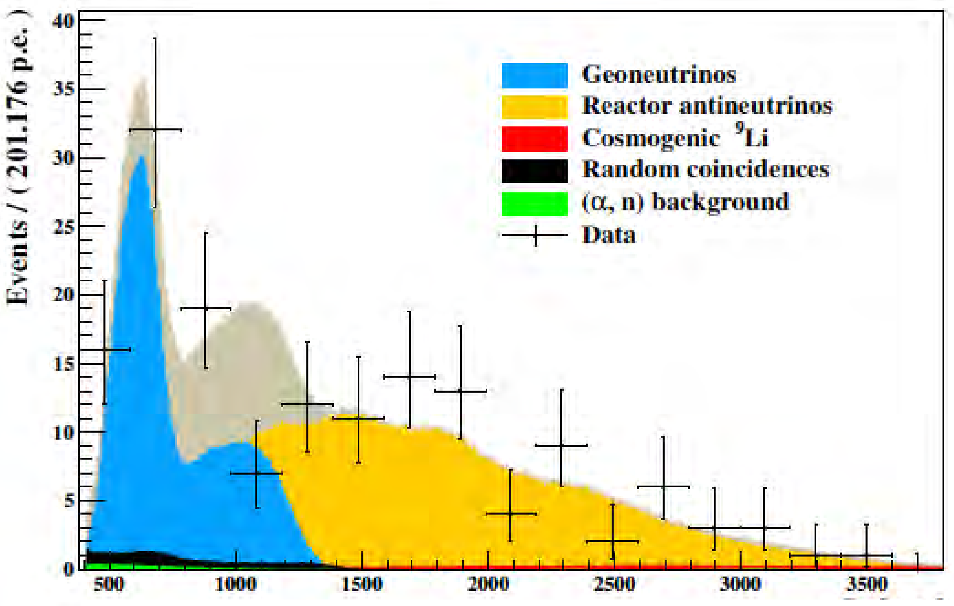
Resulting number of geoneutrinos

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

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

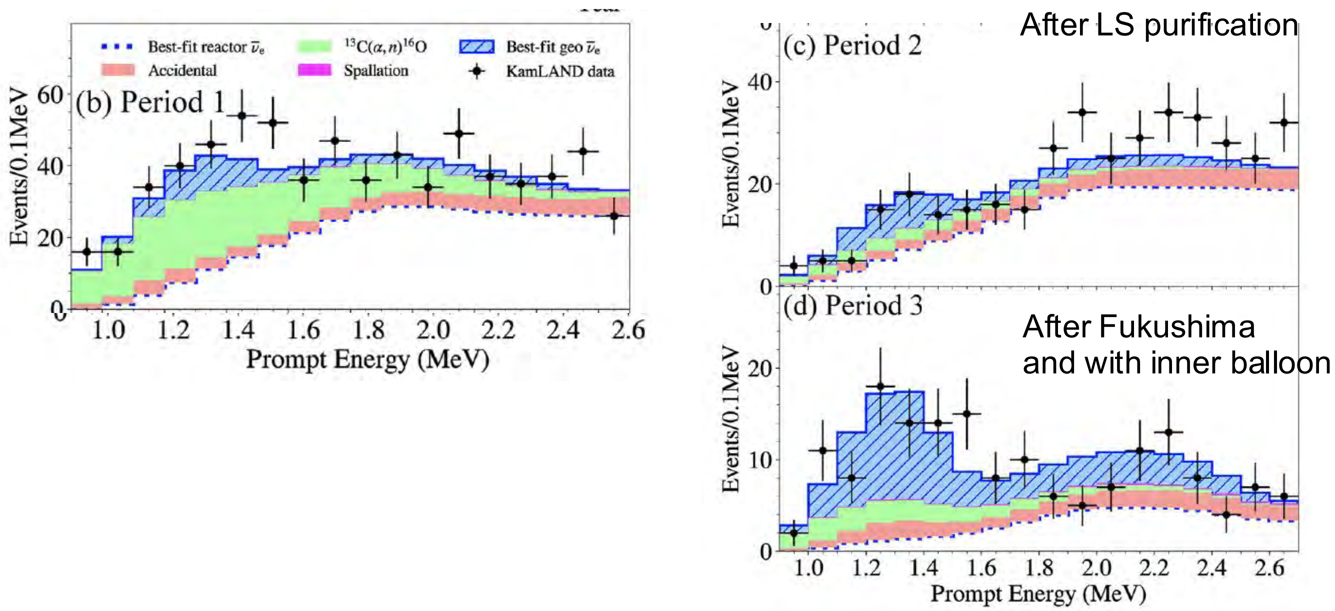
Comparison with KamLAND (SPECTRAL FIT with fixed chondritic Th/U ratio)

Borexino (PRD101 (2020) 012009)



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

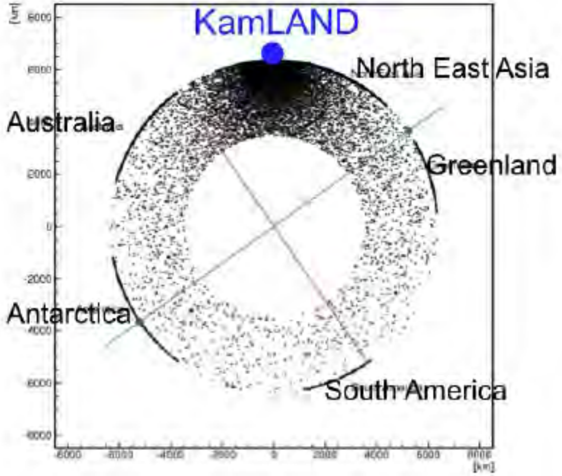
KamLAND (Geophys. Res. Lett. 49 e2022GL099566)



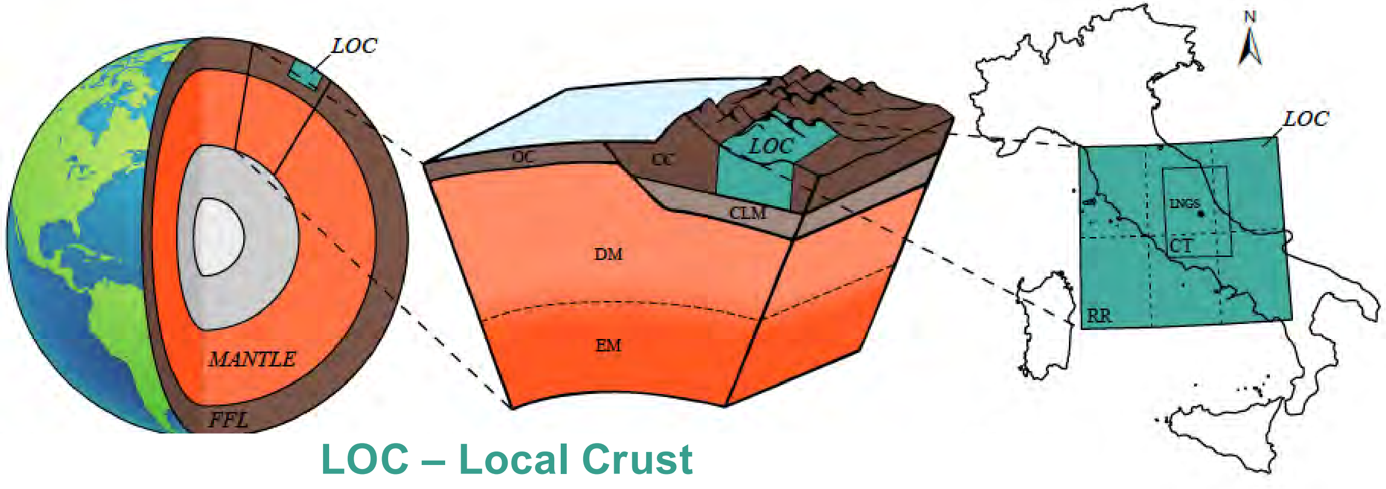
1.29 x 10^{32} (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32}** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (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

MANTLE SIGNAL: IMPORTANCE OF LOCAL GEOLOGY

Contribution of different Earth's regions to the total KamLAND signal

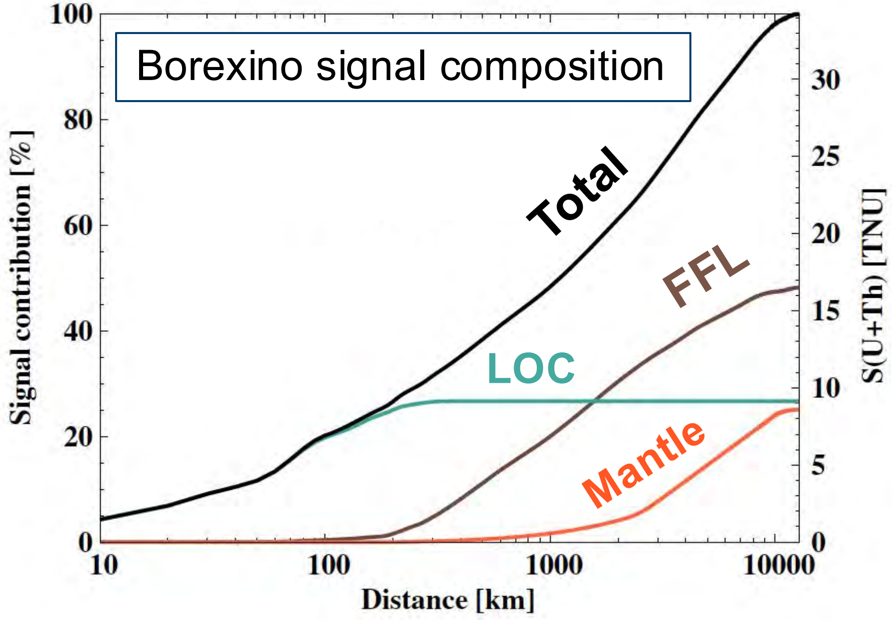


Courtesy: H. Watanabe



LOC – Local Crust
FFL – Far Field Lithosphere
Mantle

PRD101 (2020) 012009

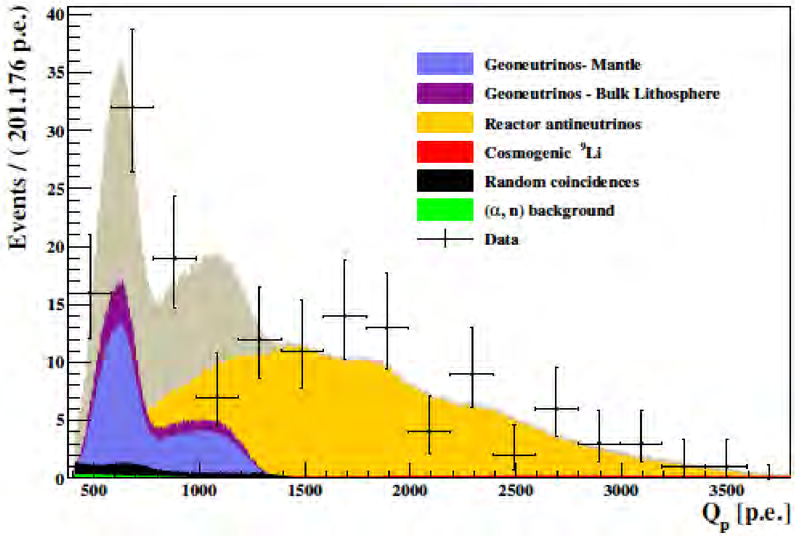


- In order to measure the **Mantle** signal, lithospheric signal must be subtracted.
- **Local Crust (LOC) -** the area of a few hundreds km around the experiment contributes up to 40-50% of the total geoneutrino signal and must be known rather precisely.
- **Far Field Lithosphere (FFL) –** complementary part of the crust to LOC + the continental lithospheric mantle, more approximations are allowed.

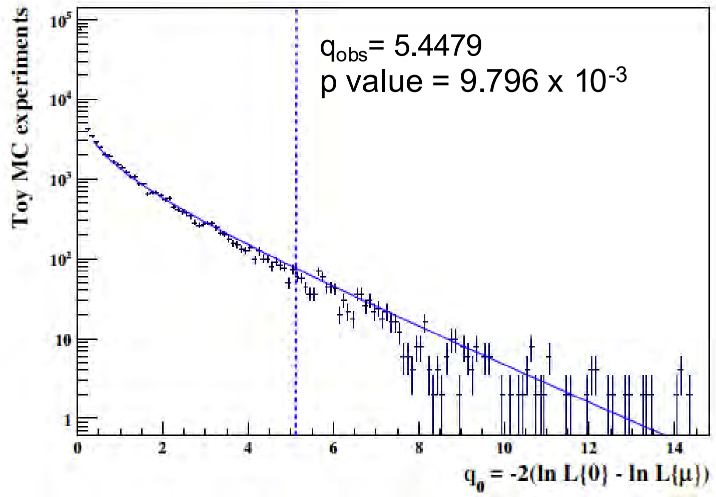
BOREXINO: MANTLE SIGNAL & RADIOGENIC HEAT

PRD101 (2020) 012009

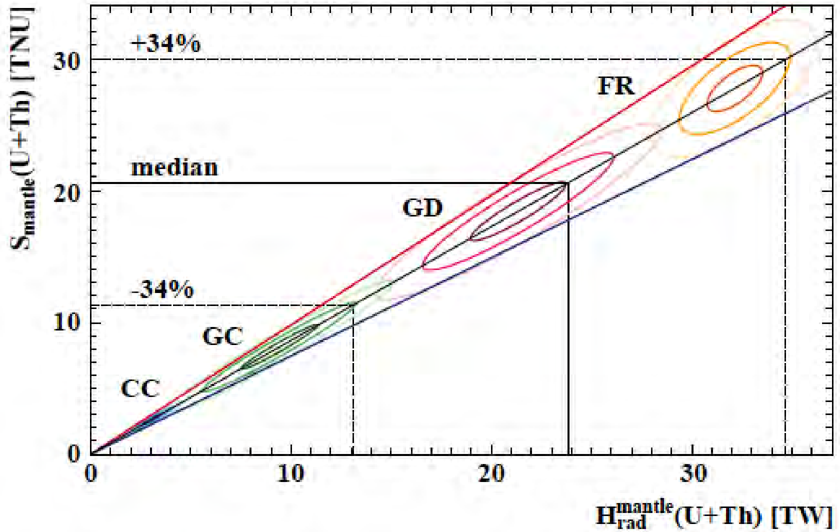
Lithospheric signal: (28.8 ± 5.6) events with S(Th)/S(U) = 0.29
Mantle: S(Th)/S(U) = 0.26
Maintaining for the bulk Earth chondritic Th/U



Sensitivity study using log-likelihood ratio meth



Borexino U+Th mantle signal:



LOC: Coltorti et al. Geochim. Cosmoch. Acta 75 (2011) 2271.
FFL: Y. Huang et al., Geoch. Geoph. Geos. 14 (2013) 2003.

Mantle null hypothesis rejected at 99.0% C.L.

Borexino is compatible with geological predictions but least (2.4σ) compatible with the BSE models predicting the lowest U+Th mantle abundances (CC & LowQ BSE).

Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

+ 18% contribution of ^{40}K in the mantle
+ $8.1^{+1.9}_{-1.4}$ TW from lithosphere (U+Th+K)

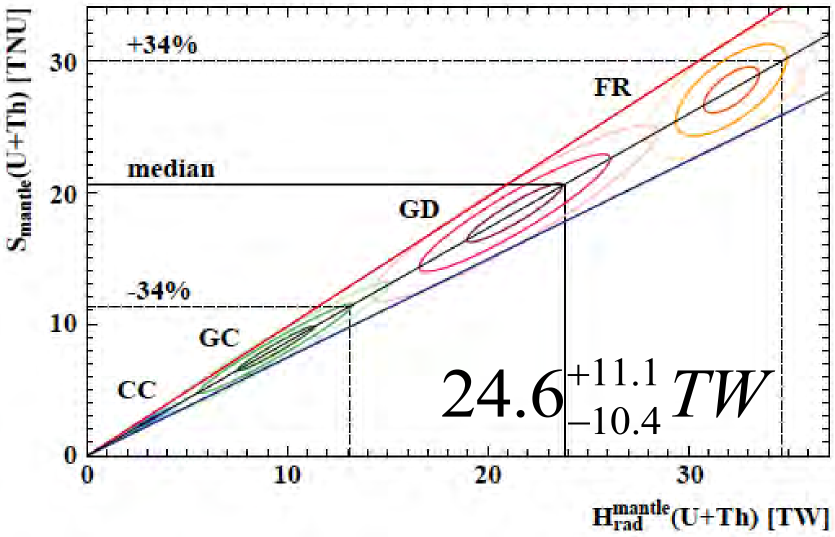
MANTLE SIGNAL: BOREXINO VS KAMLAND

Borexino		KamLAND
Fit with lithospheric contribution constrained	Analysis	Direct subtraction of crustal contribution
$23.7^{+10.7}_{-10.1}$	Mantle events	-
$21.2^{+9.6}_{-9.1}$	Mantle signal U + Th [TNU]	$6.0^{+5.6}_{-5.7}$ (crust S. Enomoto et al. EPSL 258 (2007) 147)
$24.6^{+11.1}_{-10.4}$ / (14.2 – 35.7) 68%CL interval)	Mantle heat U + Th [TW]	~ 5.4 (= $12.4^{+4.9}_{-4.9}$ - 7)

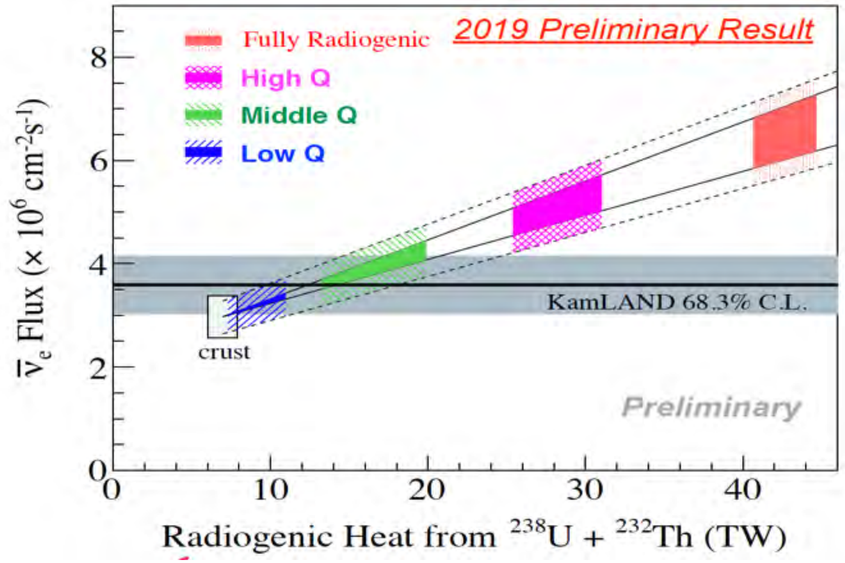
Borexino excludes null mantle signal at 99% CL

RADIOGENIC HEAT: Borexino vs KamLAND

Borexino U+Th mantle signal:



KamLAND U+Th total signal (plot unavailble for the 2022 update)

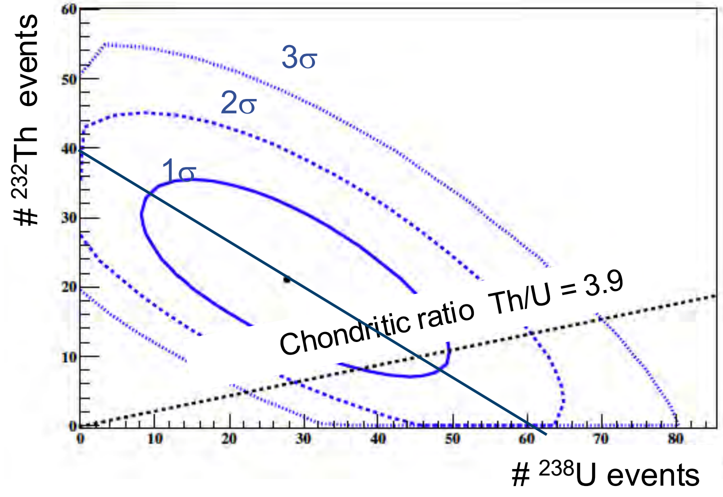


- ❖ General agreement data vs BSE models: big success
- ❖ Borexino is least (2.4σ) compatible with the BSE models predicting the lowest U+Th mantle abundances
- ❖ KamLAND preference for Low Q and Middle Q BSE models

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

SPECTRAL FIT with Th and U free

Borexino (PRD101 (2020) 012009)



$$U: 29.0^{+14.1}_{-12.9} \text{ events}$$

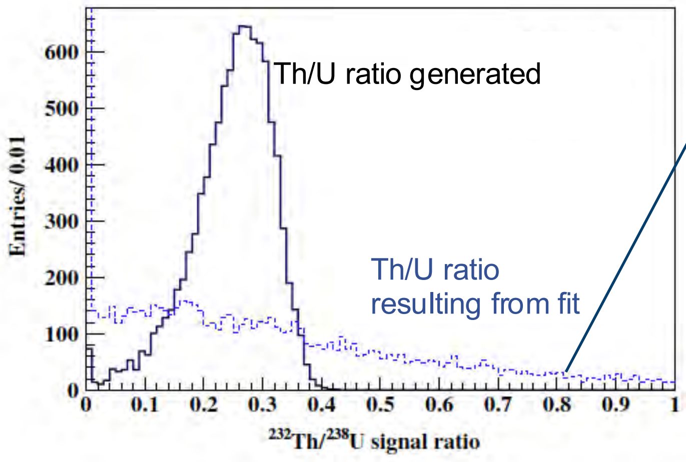
$$Th: 21.4^{+9.4}_{-9.1} \text{ events}$$

$$U + Th: 50.4^{+10.1}_{-9.2} \text{ events}$$

The resulting Th/U ratio is compatible with the chondritic value,

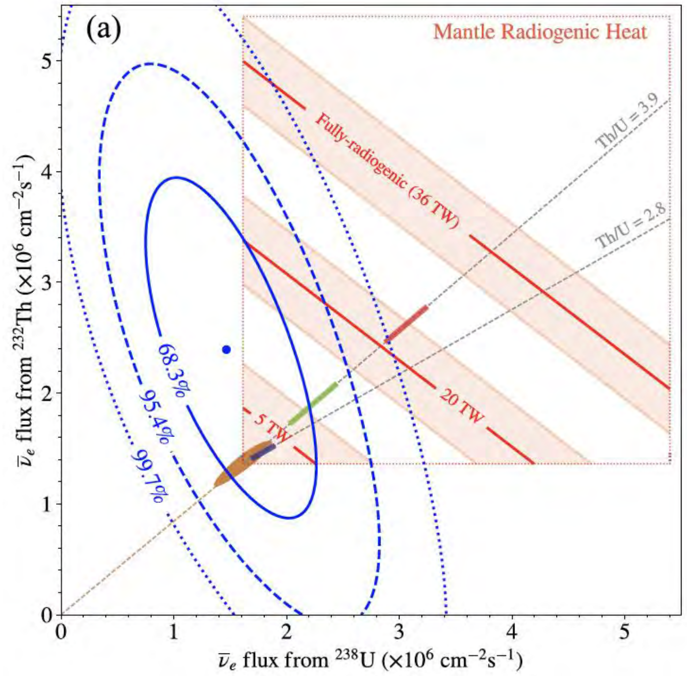
but with the achieved exposure **1.29 x 10^{32} proton x years,** Borexino has no sensitivity to measure the Th/U ratio.

Toy MC study of sensitivity to Th/U ratio



1. Due to the strong anticorrelation of U and Th components, the total geonu signal is very similar in this fit.
2. But to measure the Th/U ratio, large statistics is needed.

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)



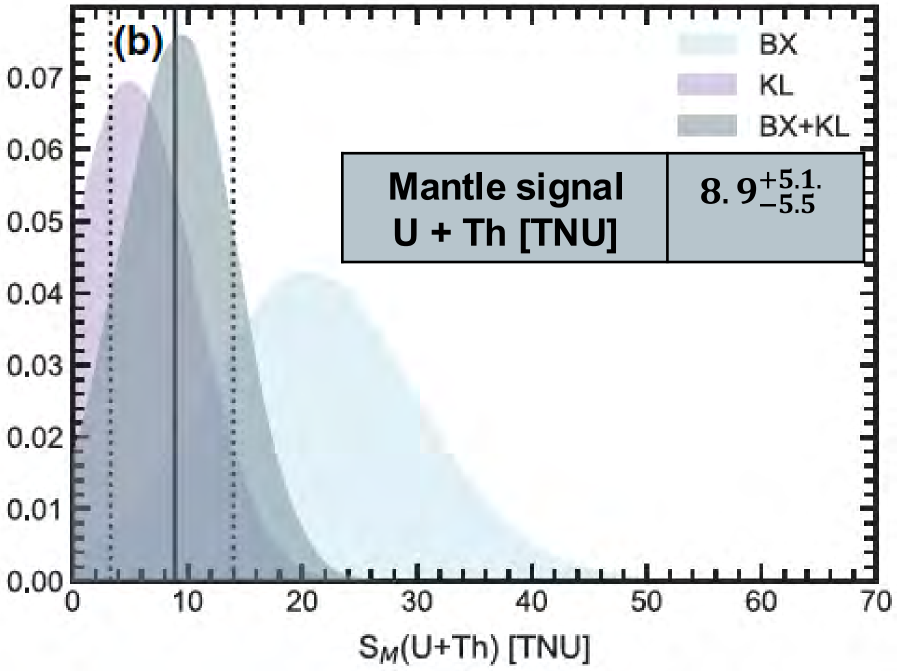
6.39 x 10^{32} proton x year

	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+31}_{-29}	8.3σ

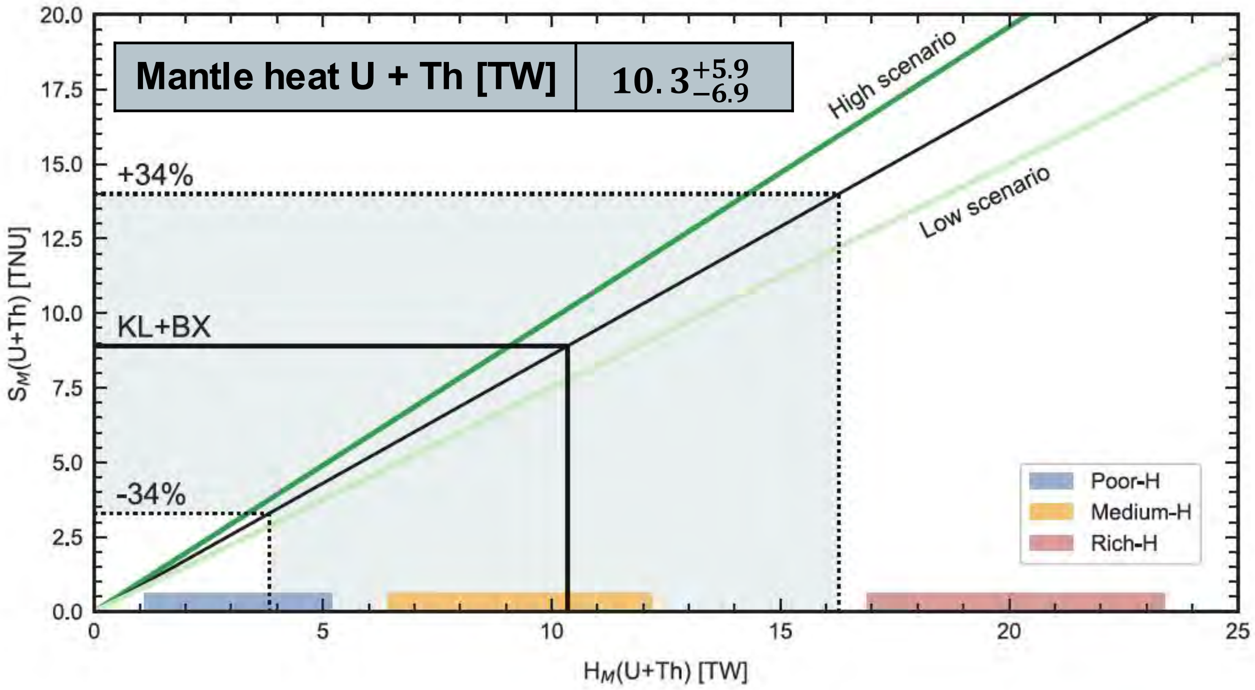
BOREXINO + KAMLAND COMBINED

Bellini at al.: La rivista del Nuovo Cimento 45 (2022) 1

Mantle U + Th signal

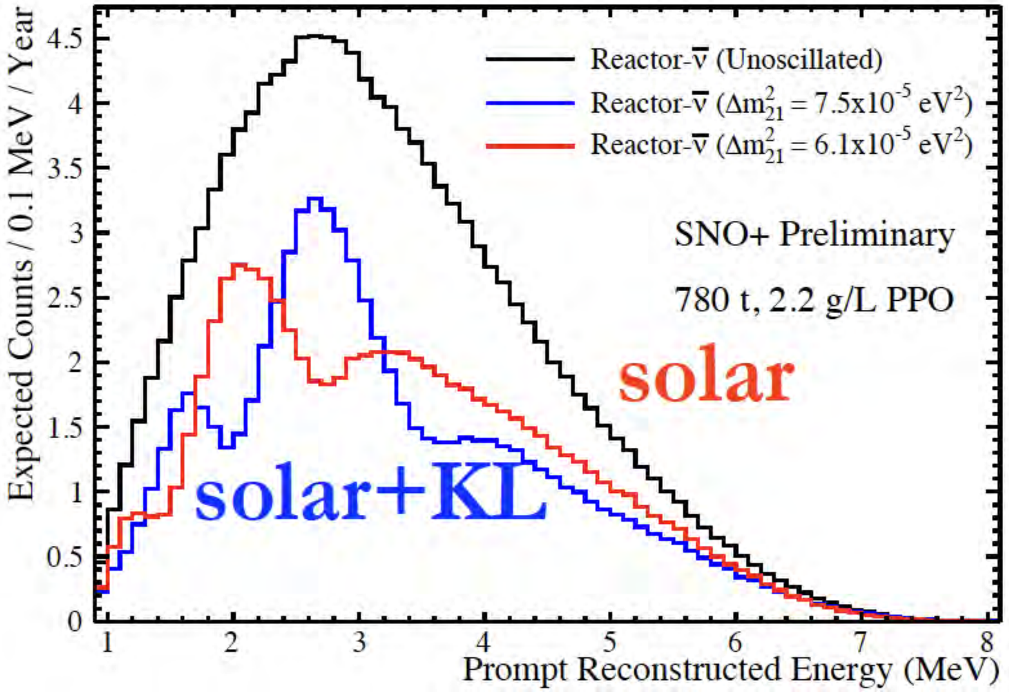


Mantle radiogenic heat vs BSE



- Analysis assumes laterally homogeneous mantle
- Some level of disagreement between the two experiments
- Combined analysis perfectly compatible with MiddleQ BSE Models

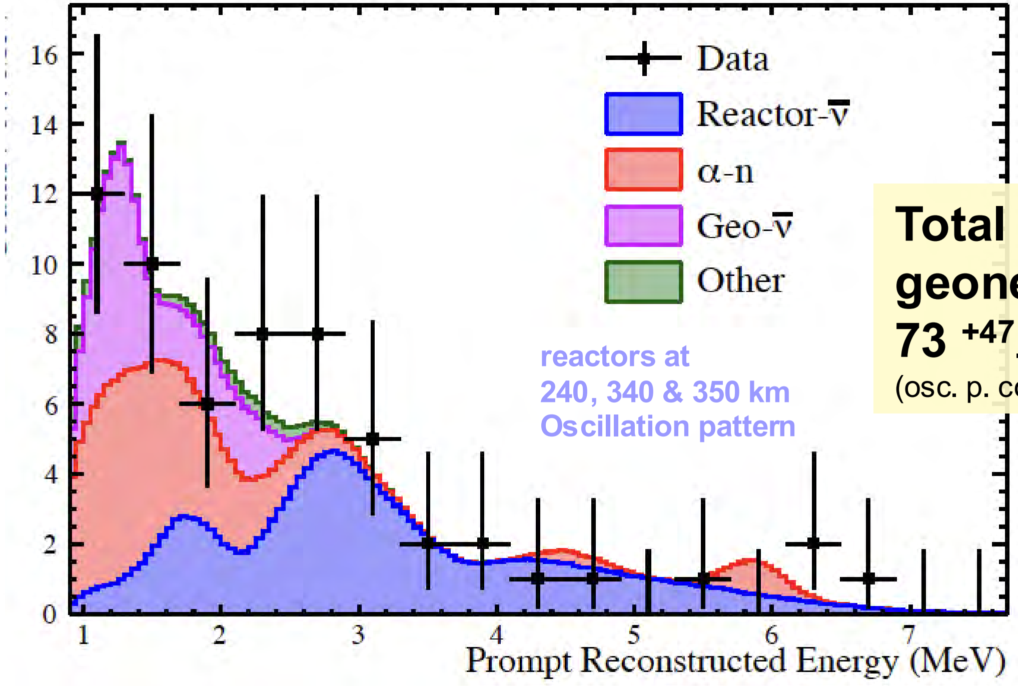
SNO+ EXPERIMENT IN CANADA – LATEST NEWS



SNO+ can measure solar oscillation parameters with reactor neutrinos.

The first data: May 7 2025 arXiv: 2505.04469v1

134.4 day data set (May 2022 – March 2023)



Total measured geoneutrino signal 73^{+47}_{-43} TNU
(osc. p. constrained to PDG 2021)

	Fit (Uncon.)	Fit (Con.)
Δm^2_{21} ($\times 10^{-5}$eV^2)	$7.96^{+0.48}_{-0.42}$	$7.58^{+0.18}_{-0.17}$
$\sin^2\theta_{12}$	$0.62^{+0.16}_{-0.40}$	0.308 ± 0.013
Geo-$\overline{\nu}$ IBD rate (TNU)	79^{+49}_{-44}	73^{+47}_{-43}

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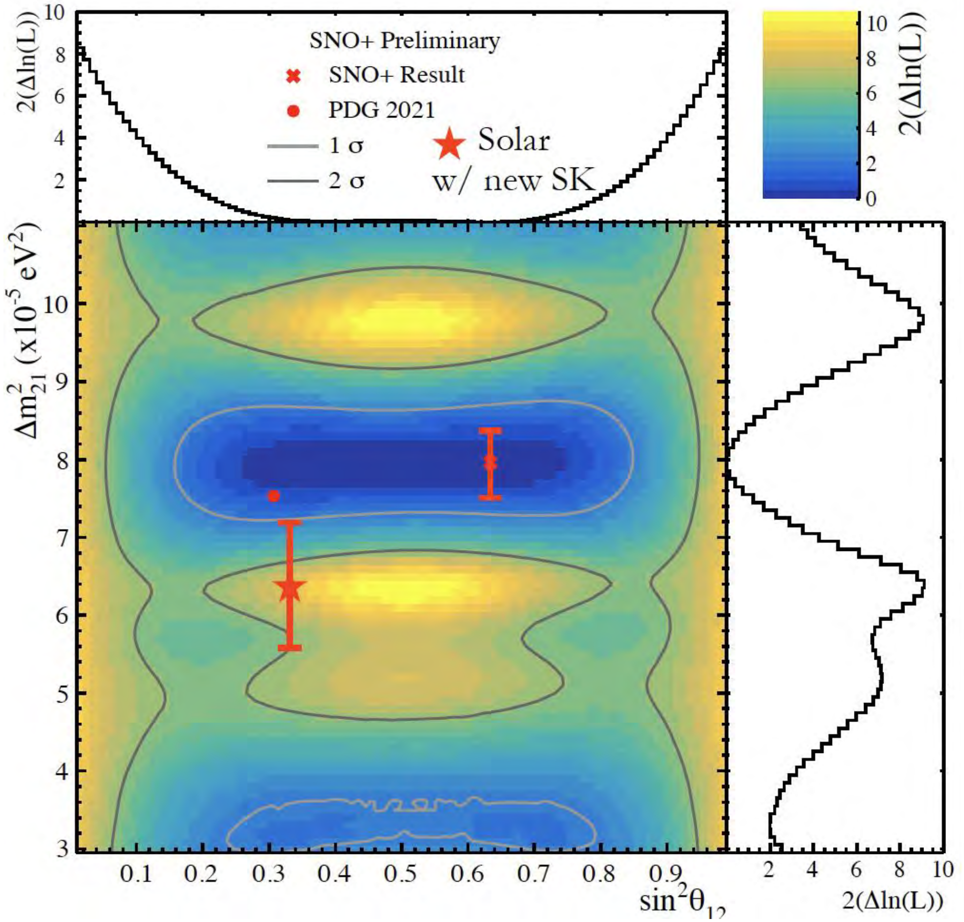

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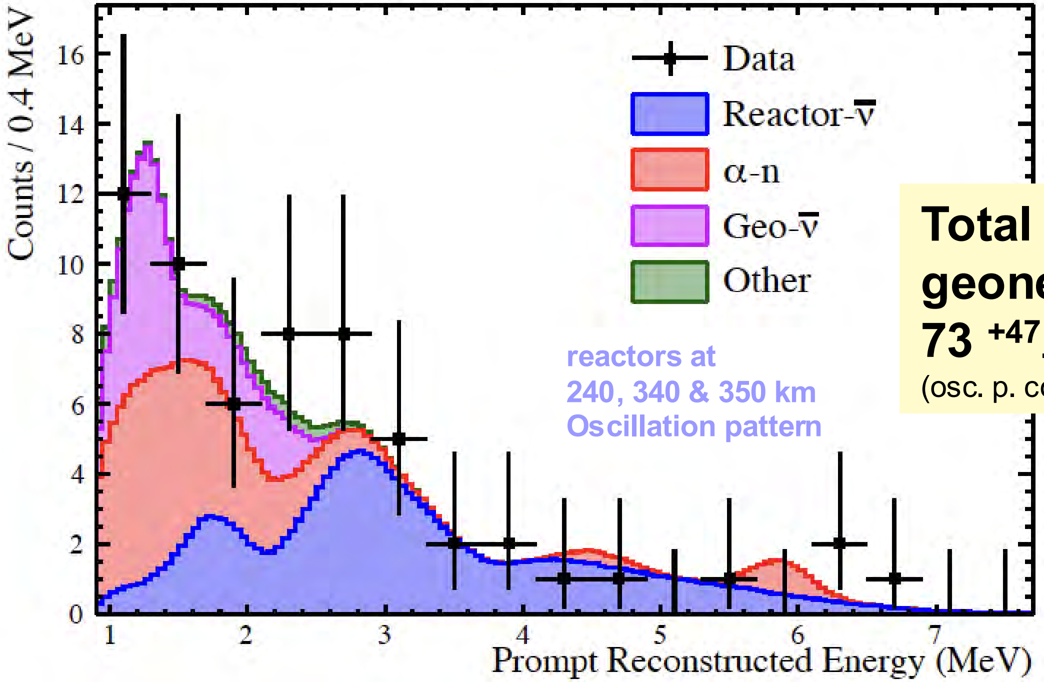

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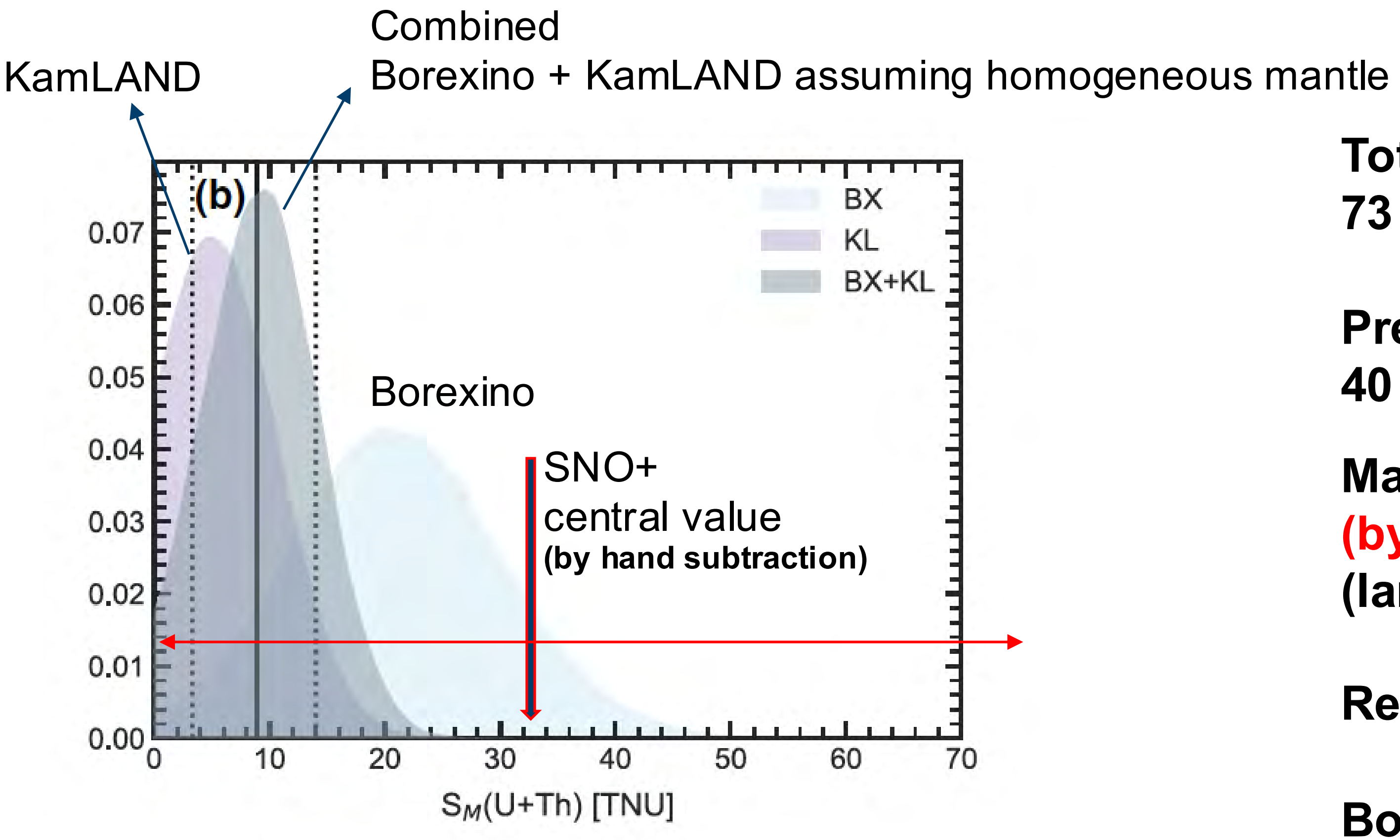
MANTLE SIGNALS COMPARISON



G. Bellini et al. 2021

Total measured signal by SNO
$73\ ^{+47}_{-43}$ TNU

Predicted crustal:
$40\ ^{+6}_{-4}$ TNU **Huang et al. 2014**

Mantle ~ 33 TNU
(by hand subtraction by me)
(large error, 1 sigma touching 0)

Reminder mantle by

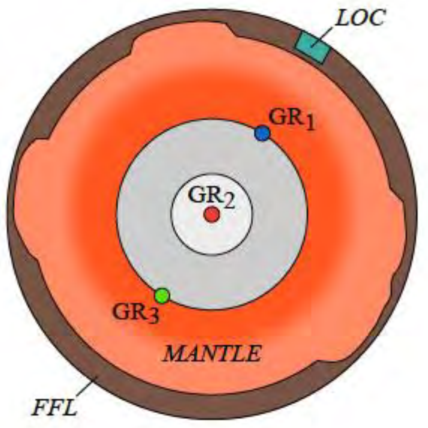
Borexino $21.2^{+9.6}_{-9.1}$ **TNU**

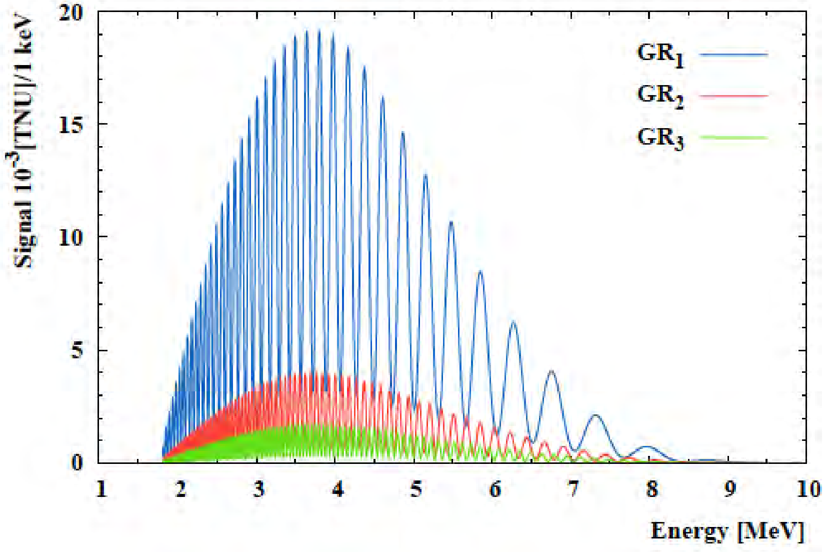
KamLAND ~ 5.4 **TNU**

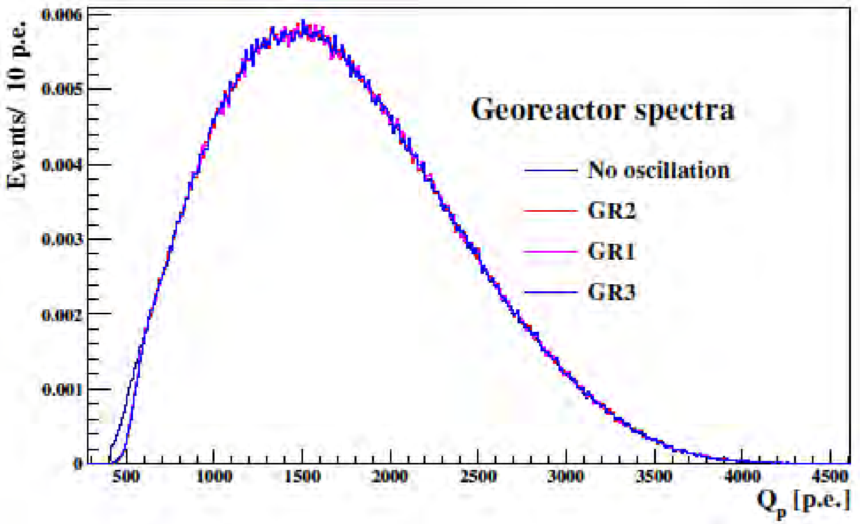
Intriguing question: is mantle not homogeneous?

Limits on the existence of a GEOREACTOR

Fast oscillation pattern → cannot be resolved experimentally







Borexino

- Hypothetical fission of Uranium deep in the Earth
- Three locations considered
- $^{235}U : ^{238}U = 0.76 : 0.23$ (Herndon)
- Fit with reactor spectrum constrained

Borexino

Upper limit (95% CL): 18.7 TNU – conversion to TW depends on the location of the georeactor:
2.4 TW in the Earth's center
0.5 TW near CMB at 2900 km
5.7 TW far CMB at 9842 km

KamLAND

fission ration from commercial reactors assumed
averaged oscillation probability
U and Th left free in fit

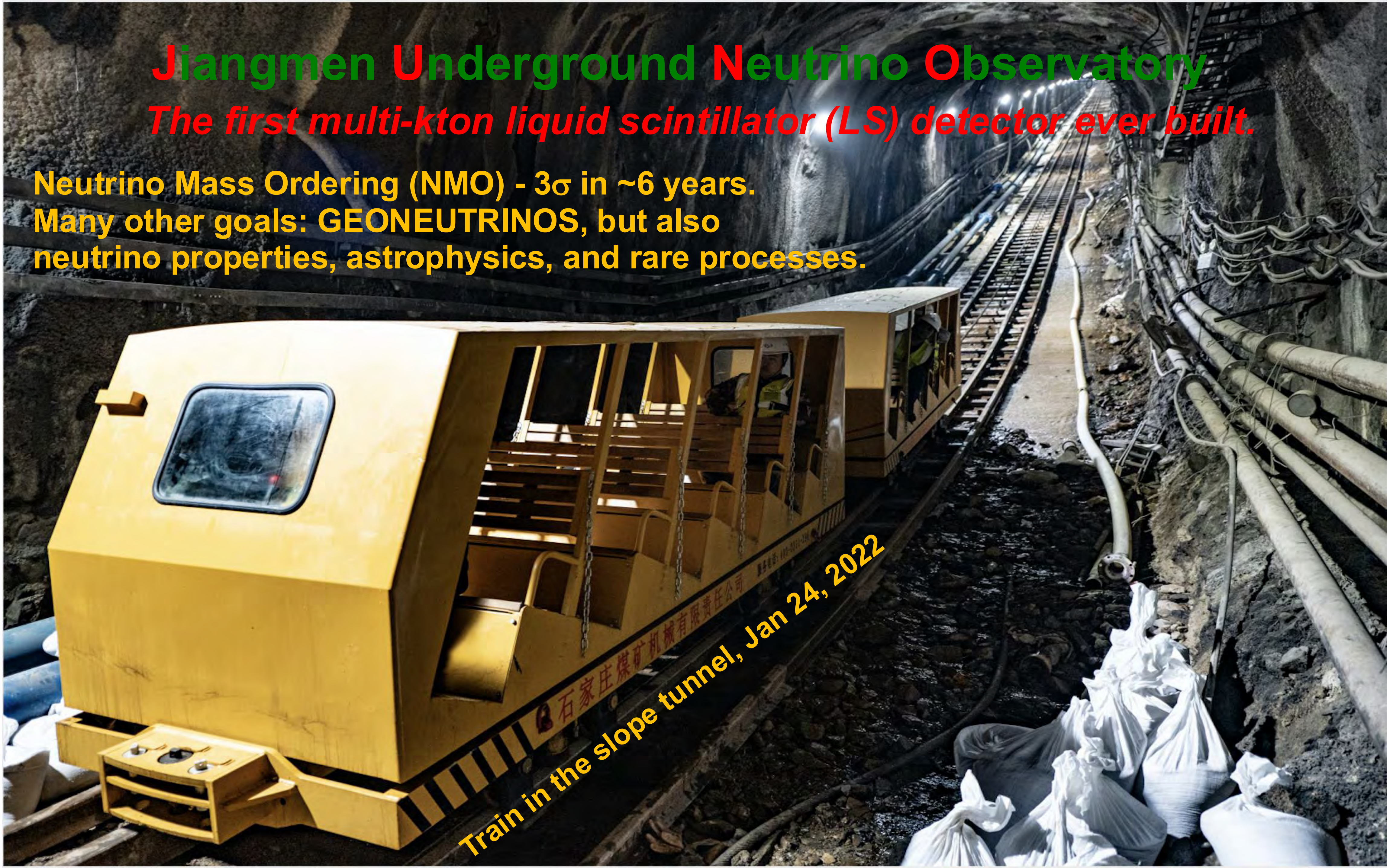
KamLAND

1.26 TW at 90% CL (center?)

Jiangmen Underground Neutrino Observatory

The first multi-kton liquid scintillator (LS) detector ever built.

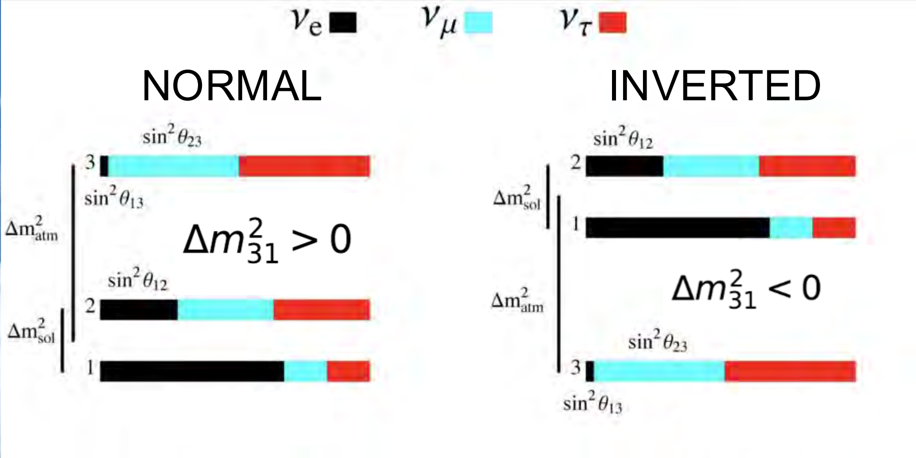
Neutrino Mass Ordering (NMO) - 3σ in ~6 years.
Many other goals: GEONEUTRINOS, but also neutrino properties, astrophysics, and rare processes.



Train in the slope tunnel, Jan 24, 2022

JUNO & Neutrino Mass Ordering with the strongest human-made neutrino source

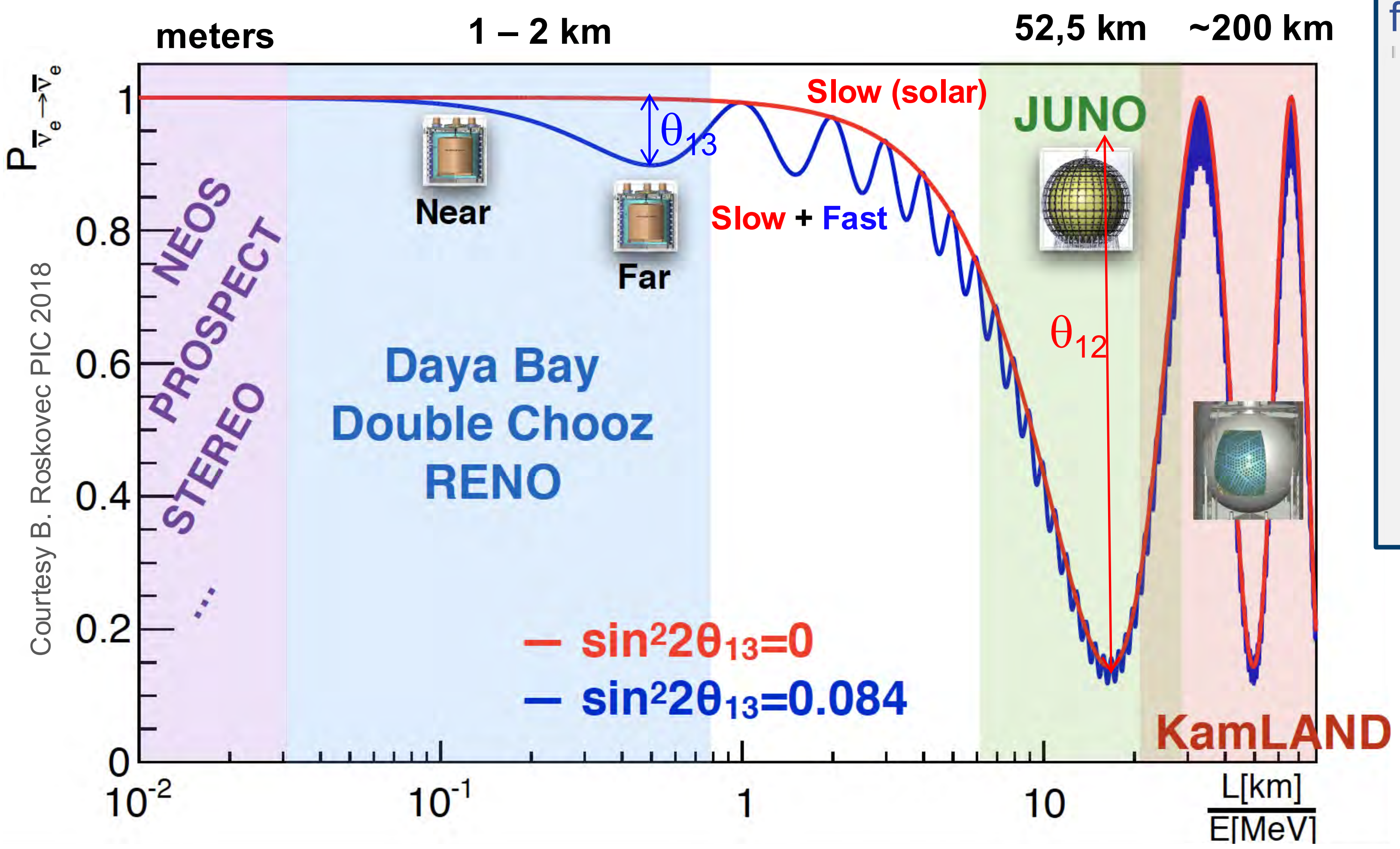
Neutrino Mass Ordering (NMO)



https://news.fnal.gov/2015/10/neutrino-mixings-masses/

A typical nuclear reactor emits every second about 10^{20} electron flavour antineutrinos ($E > 1.8$ MeV = detectable with present day technology)

JUNO AMONG REACTOR NEUTRINO EXPERIMENTS AT DIFFERENT BASELINES



Electron survival probability for reactor antineutrinos

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

Slow (solar)

$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Fast (atm.)

$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

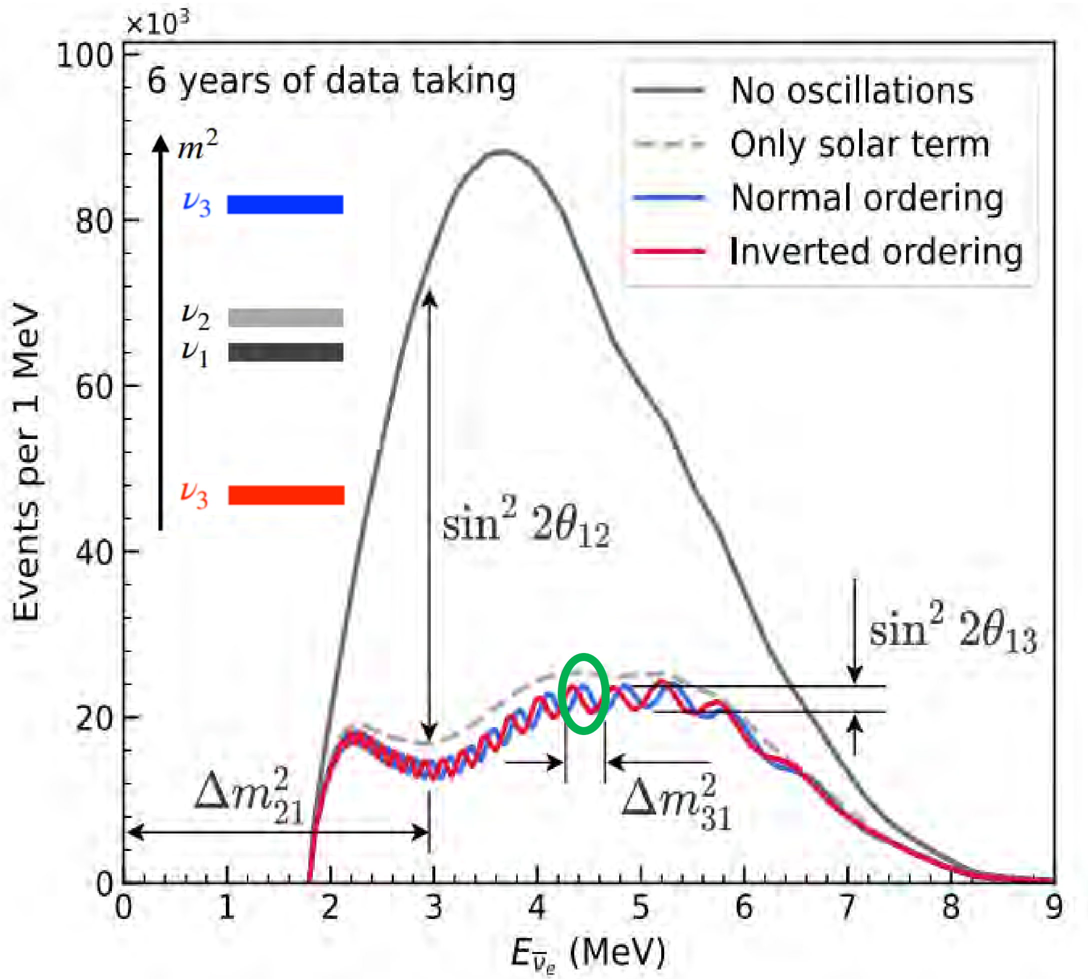
Normal ordering: $\Delta m^2_{31} > 0$

Inverted ordering: $\Delta m^2_{31} < 0$

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

- 52,5 km baseline used only by JUNO
- **Dependent on NMO (sign of $\Delta m^2_{31/2}$)**
- **Independent from δ_{CP} and θ_{23}.**

REACTOR ANTINEUTRINO SPECTRUM @ JUNO

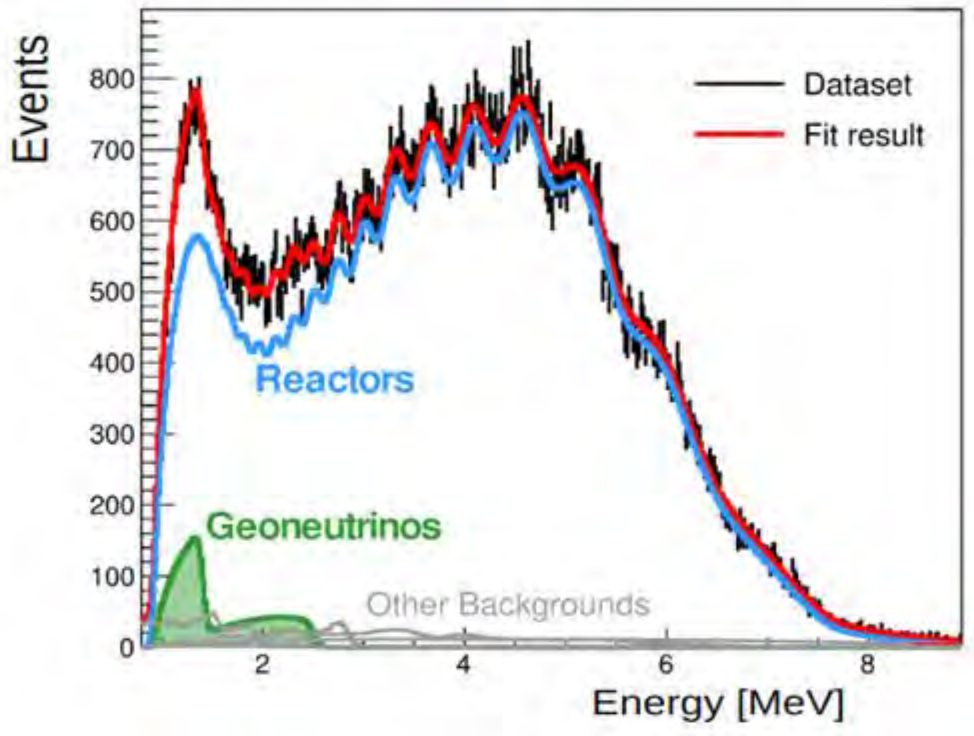


(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

- Method for the **Neutrino Mass Ordering** with reactors antineutrinos suggested by Petcov and Piai, PLB 553 (2002) 94.
- **Complementarity** to the method based on matter effects on long baseline oscillations of atmospheric and accelerator neutrinos that depend also on δ_{CP} and θ_{23}.
- High sensitivity to the **oscillation parameters**
  - solar mixing angle θ_{12}
  - solar mass splitting Δm^2_{21}
  - atmospheric mass splitting Δm^2_{31}

GEONEUTRINOS IN JUNO

Simulation of 10 years of data



Big advantage:

✓ Large volume and thus high statistics: **400 geoneutrinos / year.**

Main limitations:

✓ Large **reactor neutrino background.**

✓ Relatively shallow depth – cosmogenic background.

- Current (KamLAND and Borexino) precision on measured geoneutrino flux is ~16-18%.
- JUNO can reach this precision in a few years.
- JUNO will provide statistics sufficient to separate with a high significance U and Th.
- **Geological study of the local crust** important in order to separate the mantle contribution and it is ongoing.

- Expected precision of the total geoneutrino signal: **~8% in 10 years** (Th/U mass ratio fixed to 3.9)
- Precision of U and Th individual components **in 10 years:**
  ^{232}Th ~35% ^{238}U ~30% ^{232}Th + ^{238}U ~15% ^{232}Th/^{238}U ~55%

PRELIMINARY

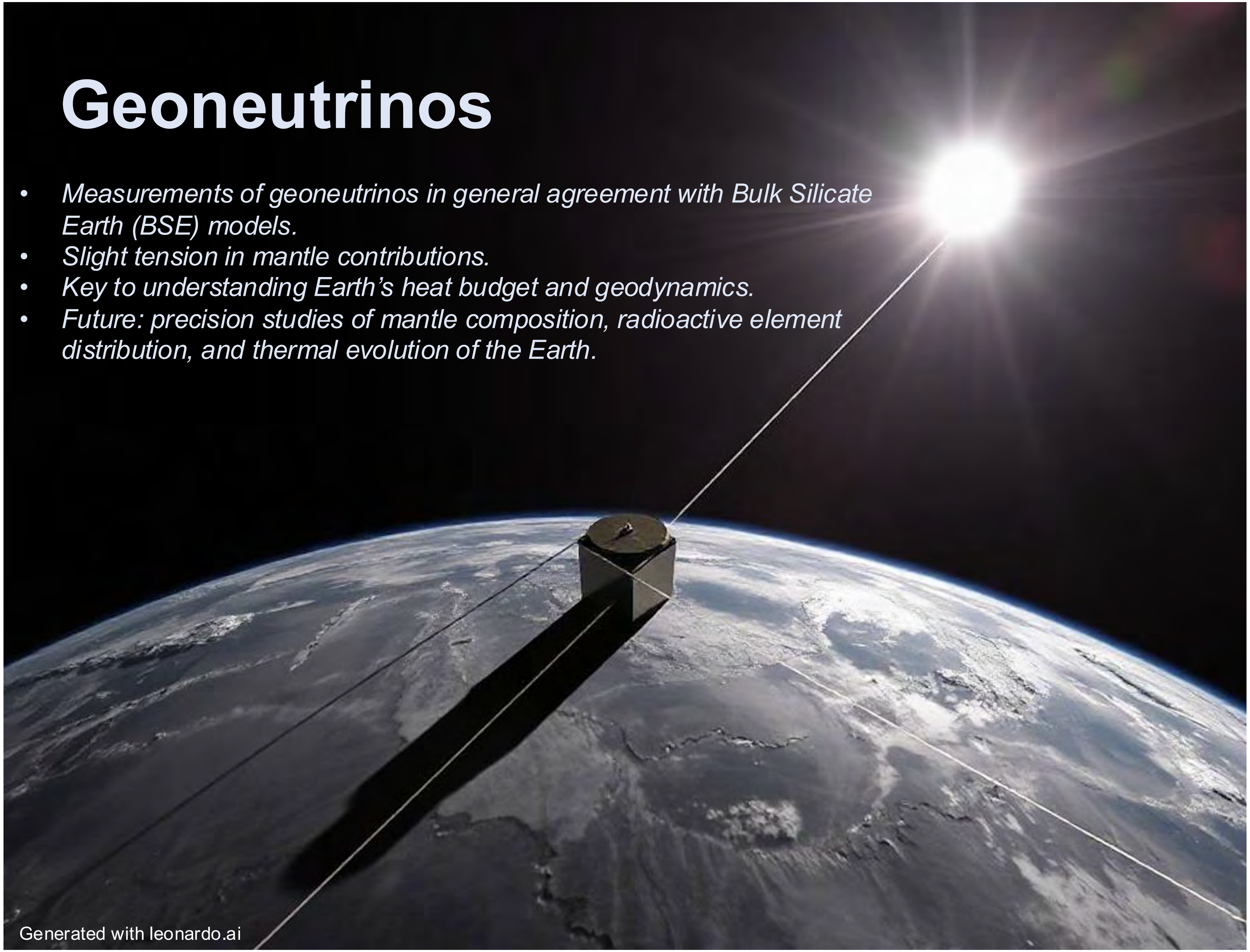
Geoneutrino summary & outlook

- **Borexino** (Italy): stopped data-taking in October 2021 (last update till April 2019)
- **KamLAND** (Japan): latest update in summer 2022 more data expected to come this year.
- **SNO+** (Canada): 780 ton & DAQ started & 30-40 geonus/year; Low cosmogenics; - first events just detected!
- **JUNO** (China): 20 kton & completion this & 400 geonus/year! - about to start *(J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401);*
- **JINPING** (China): 5 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**

Photo by L.L., Shiveluch volcano, Kamchatka, Russia

Geoneutrinos

- *Measurements of geoneutrinos in general agreement with Bulk Silicate Earth (BSE) models.*
- *Slight tension in mantle contributions.*
- *Key to understanding Earth's heat budget and geodynamics.*
- *Future: precision studies of mantle composition, radioactive element distribution, and thermal evolution of the Earth.*



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