GEO-NEUTRINOS: A NEW TOOL TO STUDY THE EARTH

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September 10, 2026, **Tihany, Hungary**

FUSE TRAINING SCHOOL

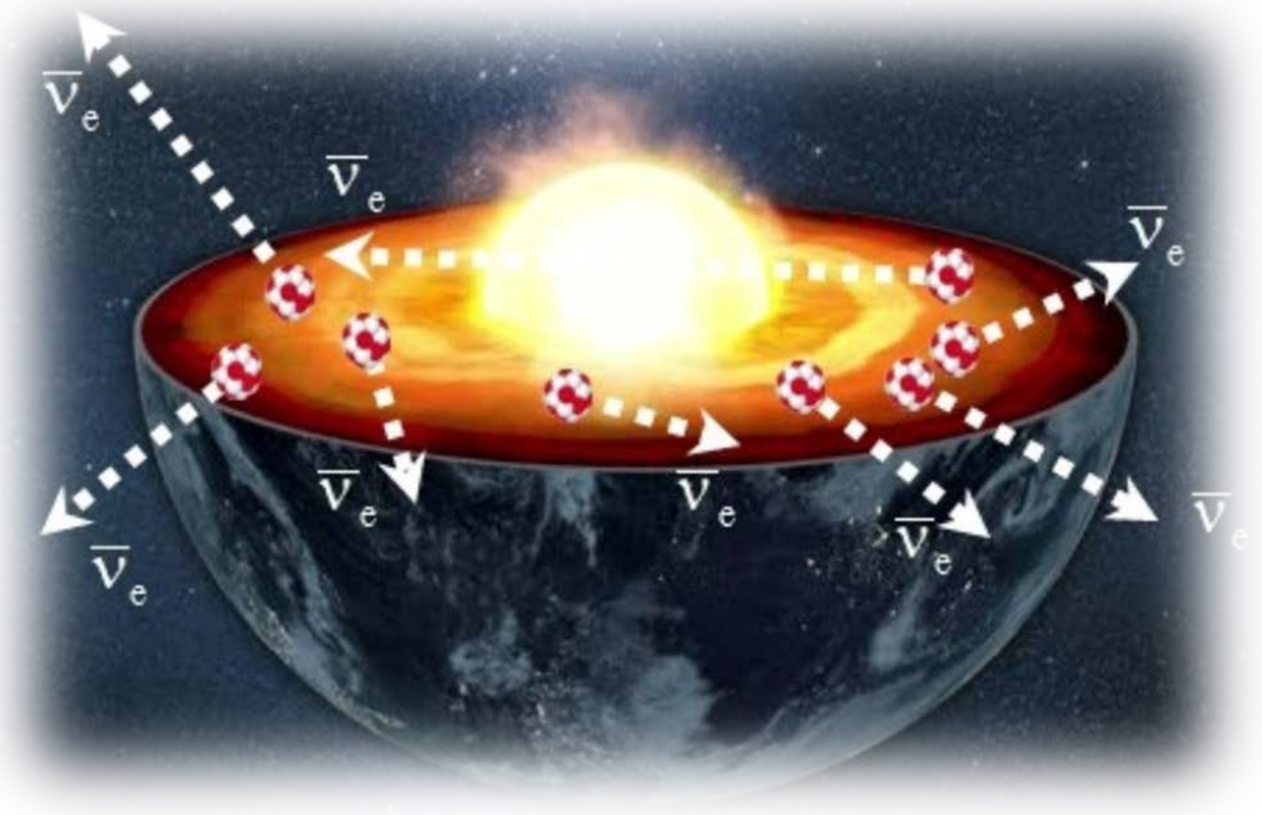
GSI

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

OUTLOOK

Introduction to neutrinos

- 🌍 Geoneutrinos & the Earth
- ⚛️ Detection Principles
- 📊 Current Experimental Results
- 🧩 Challenges and Requirements
- 🚀 Future Prospects

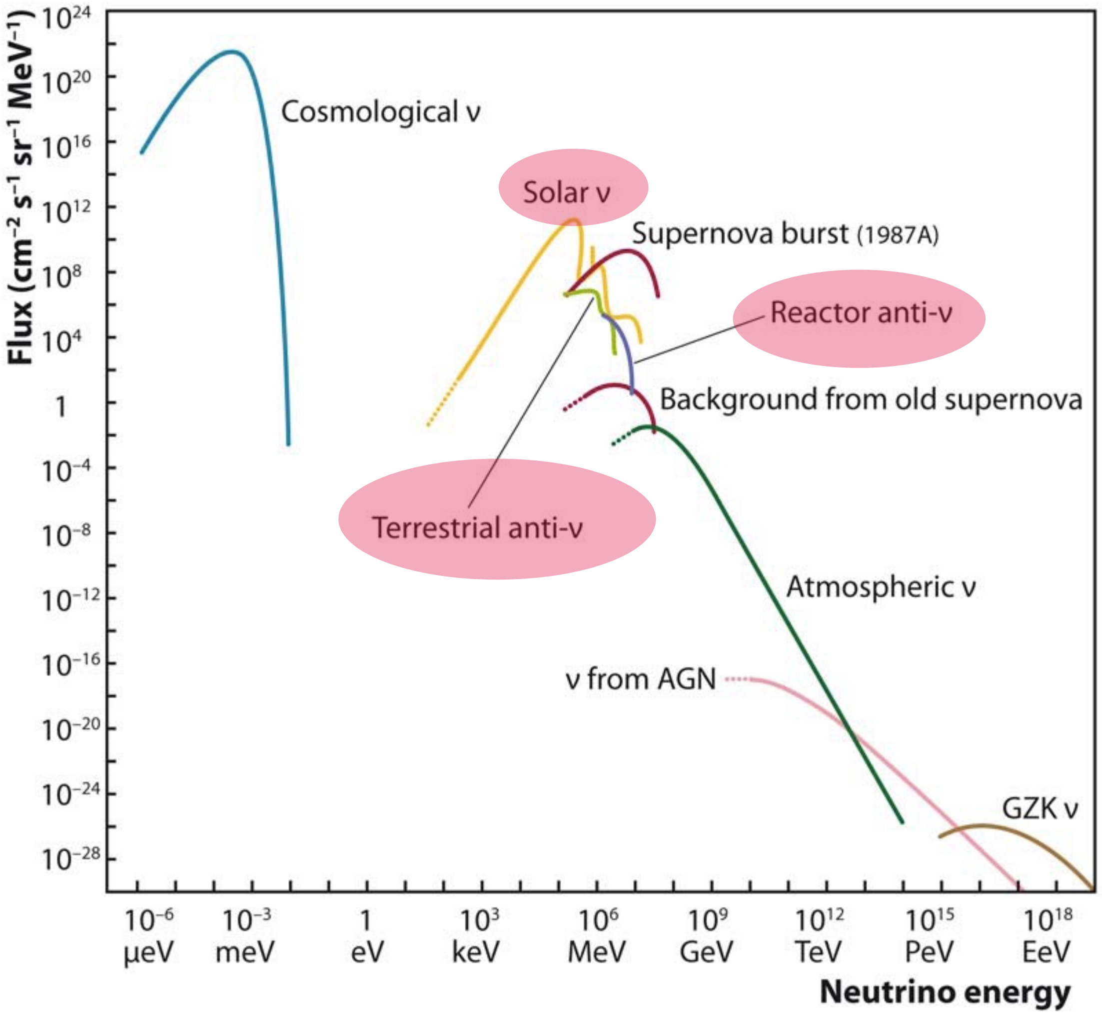


https://www.fe.infn.it/radioactivity/GIGJ/

WHAT ARE NEUTRINOS?

NEUTRINO SOURCES

Basic constituents of matter:
Standard Model of Elementary Particles



There are 3 neutrino flavours and their antiparticles, so antineutrinos of 3 flavours.

NEUTRINO INTERACTIONS

Gravitational — large scales & mases

~~Strong~~

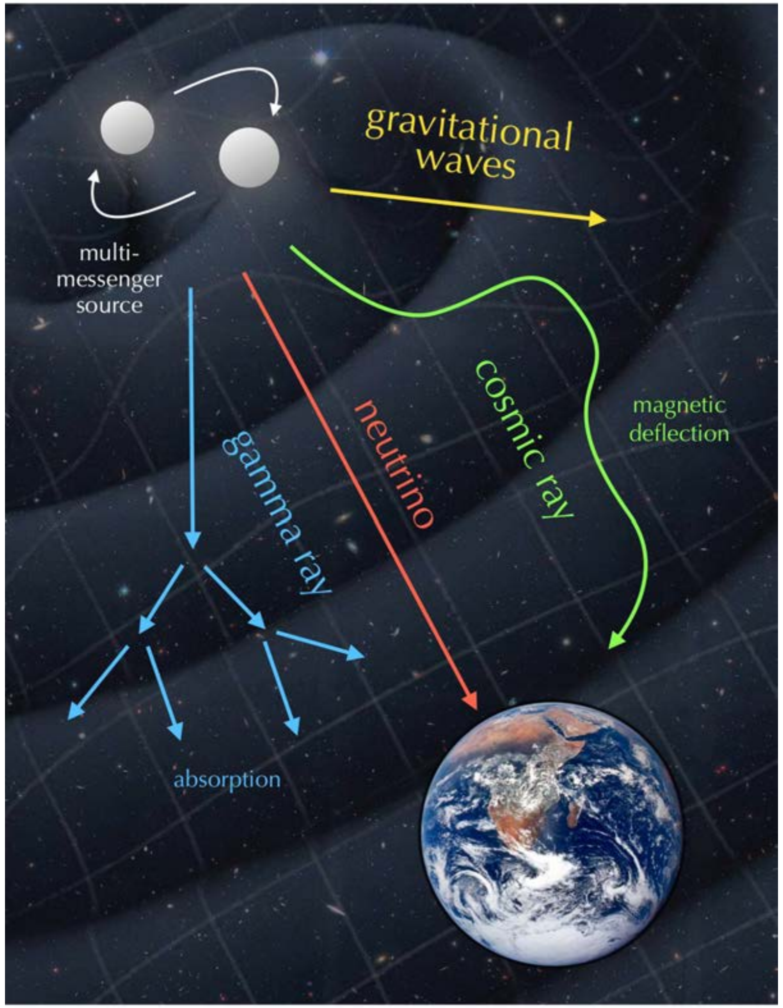
~~Electromgnetic~~

Weak — VERY Weak

Small probability to interact with matter

- (-) **Difficult detection**
- (+) **Bringing unperturbed information**

NEUTRINOS AS MESSENGERS



Taken from https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

Small interaction cross sections → low rates in the detector!

Imagine……

7 x 10^{10} solar neutrinos / cm^2 / s

and about 200 interactions / day / 100 tons of liquid scintillator

NEUTRINOS ARE SPECIAL

Only weak interactions

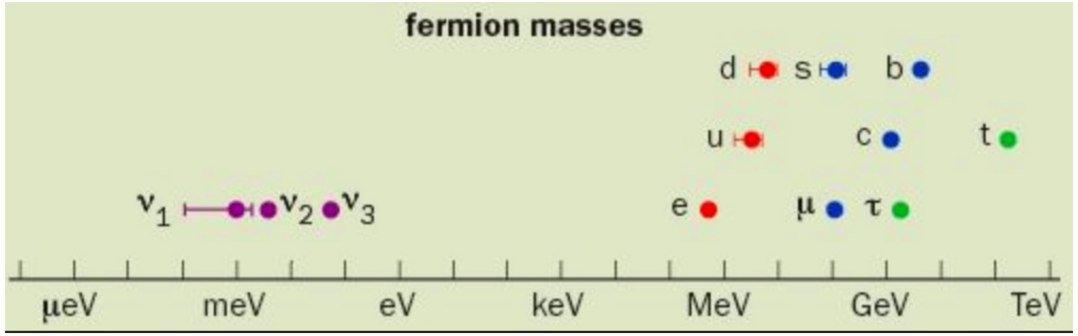
- ✓ **Difficult to detect**
  - o Large detectors
  - o Underground laboratories
  - o Extreme radio-purity
- ✓ **Bring unperturbed information about the source** (**Sun, Earth**, SN)

Open questions in neutrino physics

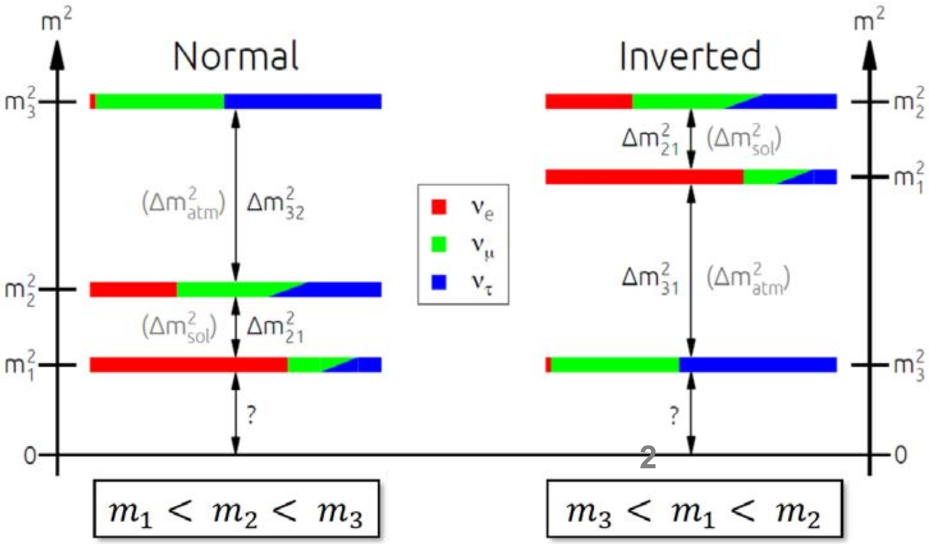
- ✓ Mass Hierarchy (Normal vs Inverted)
  - o CP-violating phase
  - o Octant of θ_{23} mixing angle
  - o Absolute mass-scale
  - o Origin of neutrino mass (Dirac vs Majorana)
- ✓ Existence of sterile neutrino

linked

Absolute mass scale question



Ordering of neutrino mass eigenstates:
2 options possible



NEUTRINO MIXING AND OSCILLATIONS

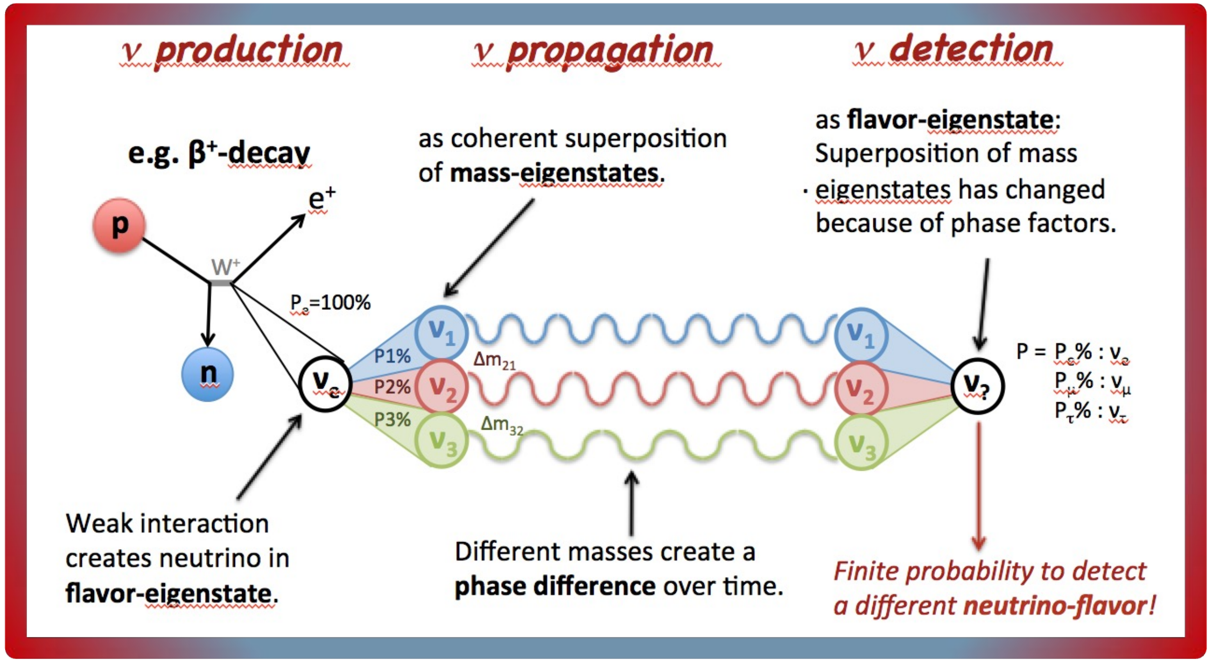
α = e, μ, τ
Flavour eigenstates
INTERACTIONS

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Reactor | Solar | Majorana



Courtesy M. Wurm

- **3 mixing angles θ_{ij}:**
  - $\theta_{23} \approx 45°$ (which quadrant?)
  - $\theta_{13} \approx 9°$ (non-0 value confirmed in 2012)
  - $\theta_{12} \approx 33°$
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown

- **Neutrino oscillations**
  - Non-0 rest mass (Nobel prize 2015)
  - Survival probability of a certain flavour = f(baseline L, E_ν)
  - Different combination (L, E_ν) => sensitivity to different (θ_{ij}, Δm_{ij}^2)
  - Appearance/disappearance experiments
  - Oscillations in matter -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν)

Geoneutrinos

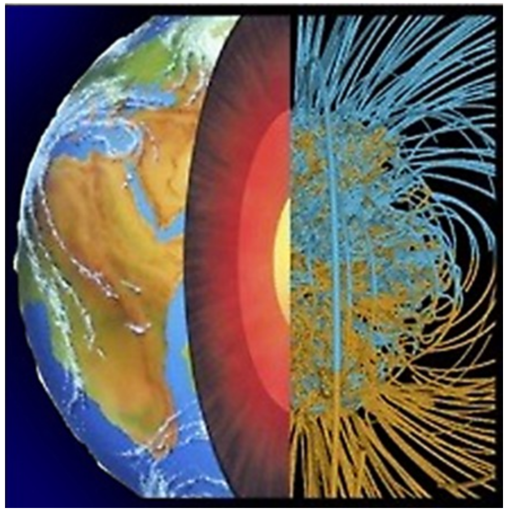
From where is coming
the energy driving these processes?

How can neutrino physics help us to understand?

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

Vulcanism

Geo-dynamo



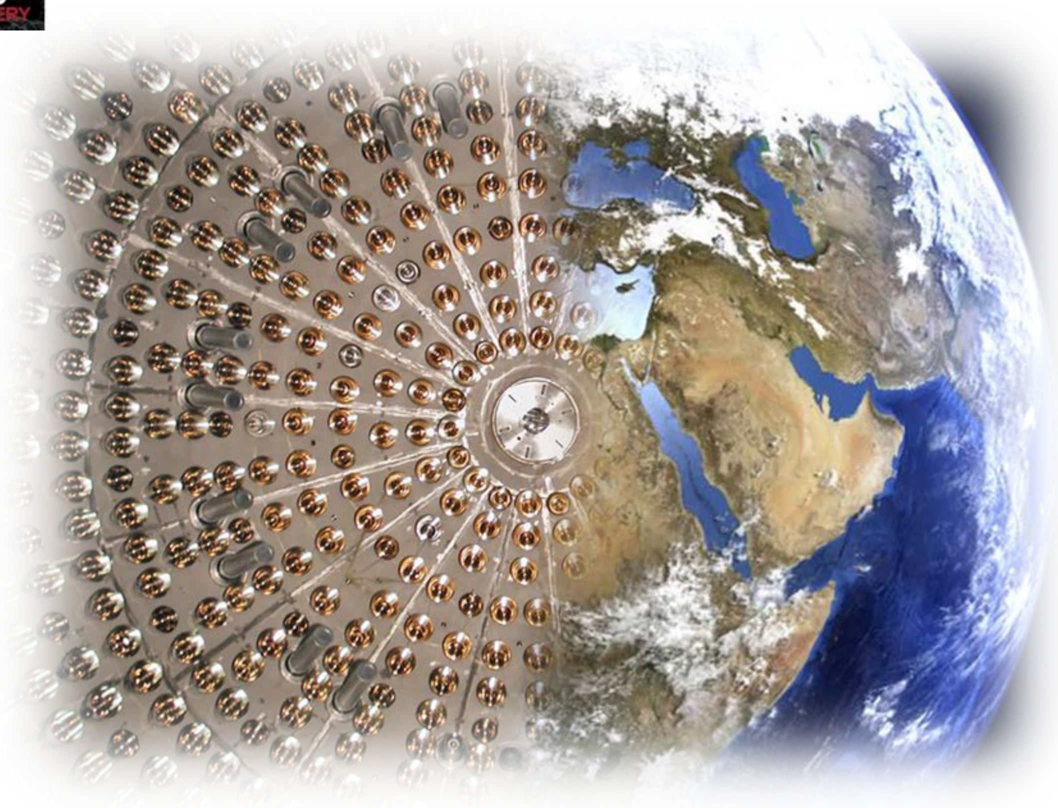
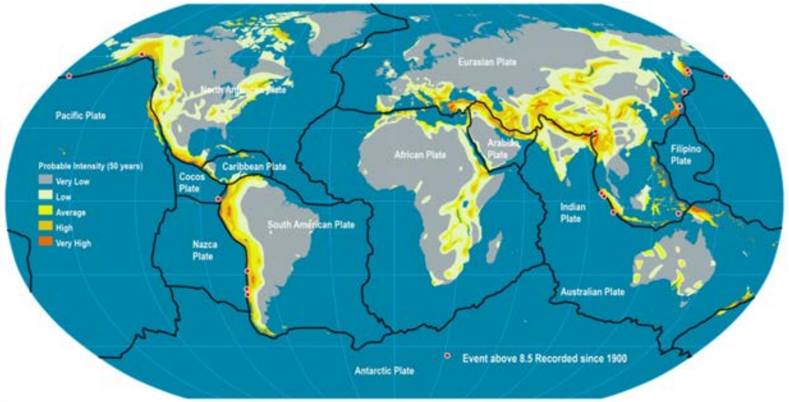


Plate tectonics & mantle convection



https://transportgeography.org

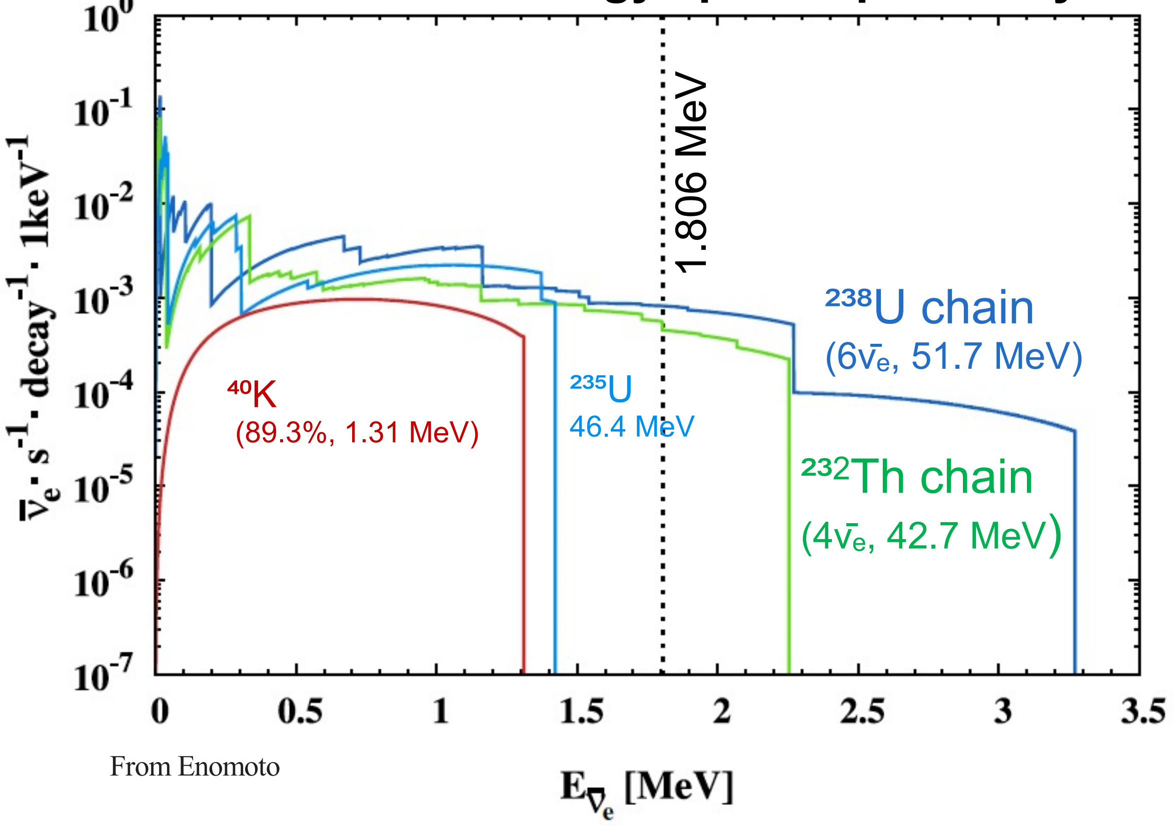
Earthquakes


L'Aquila, Italy, 2009

WHAT ARE GEONEUTRINOS

Geoneutrinos are electron antineutrinos produced by the decay of long-lived radionuclides within the Earth, whose half-lives are comparable to the Earth's age (4.54 billion years).

Geoneutrino energy spectra per decay.



Radiogenic heat

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

$^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ MeV$

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

$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.31\ MeV$ (BR 89.3%)

HEP = Heat Producing Elements

- Energy spectrum extends up to 3.26 MeV (^{238}U).
- Present-day detection threshold (IBD) is 1.806 MeV.
- **^{40}K** and **^{235}U** are below the threshold.
- Existing geoneutrino measurements probe only the **^{238}U** (~6.5%) and **^{232}Th** (~3.9%) decay chains.
- **^{238}U** (3.26 MeV) and **^{232}Th** (2.25 MeV) have different end points – key to distinguish them.

NEUTRINO GEOSCIENCE

Abundances 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

- U/Th ratio
- Mantle homogeneity
- Earth formation

Distribution of radioactive elements

Signal prediction

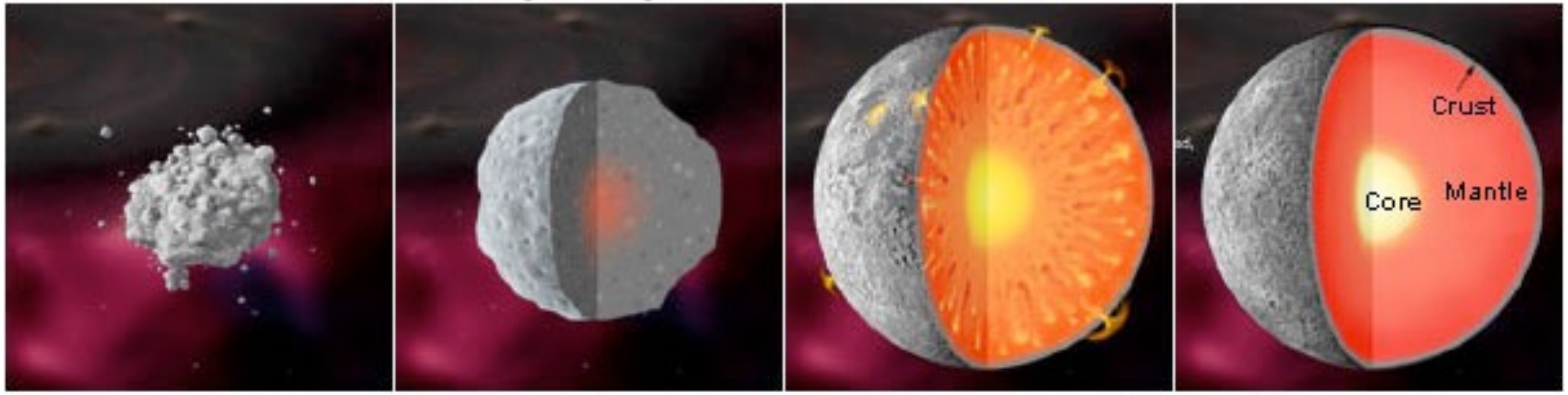
Geoneutrino signal

Measurement interpretation

Neutrino geoscience: a truly inter-disciplinary field!

EARTH FORMATION

A Rocky Body Forms and Differentiates



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

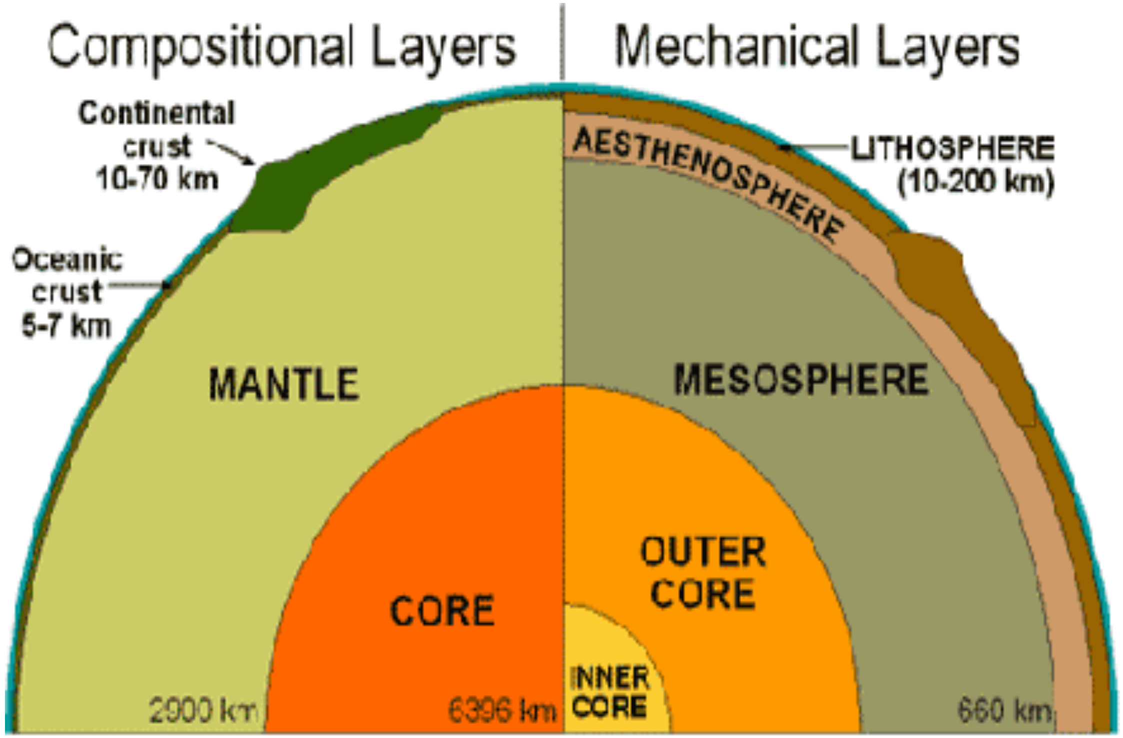
Accretion

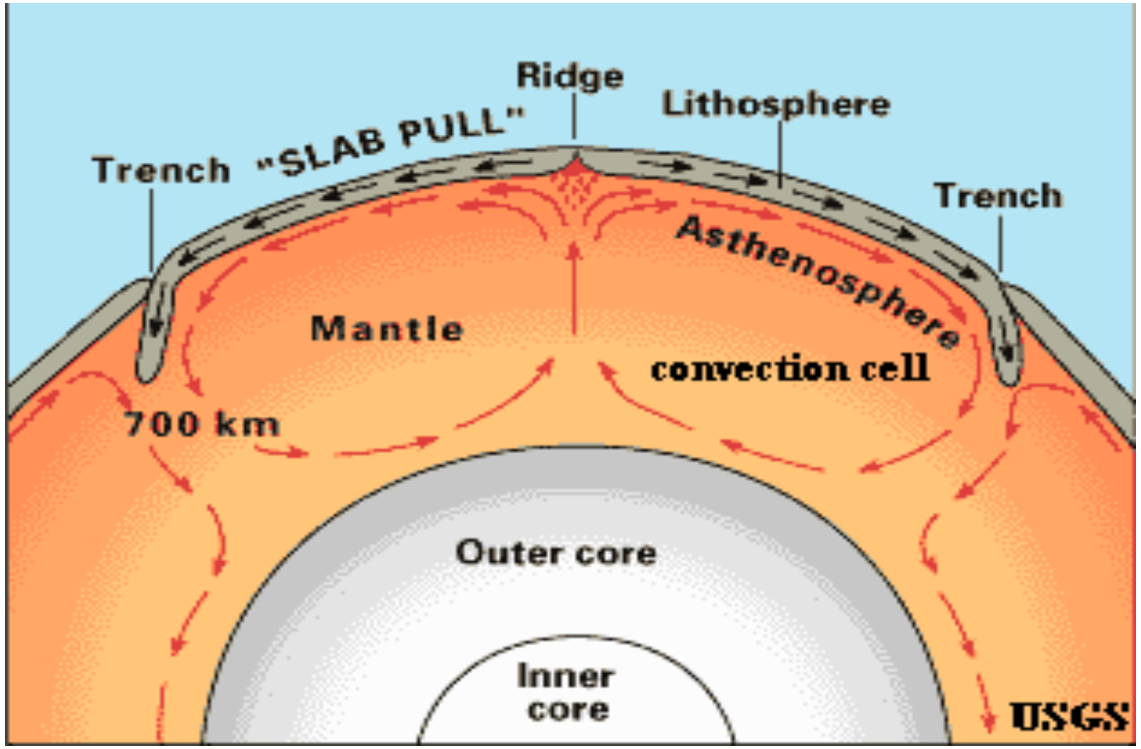
Magma sea (Primitive mantle)

Metallic core segregation

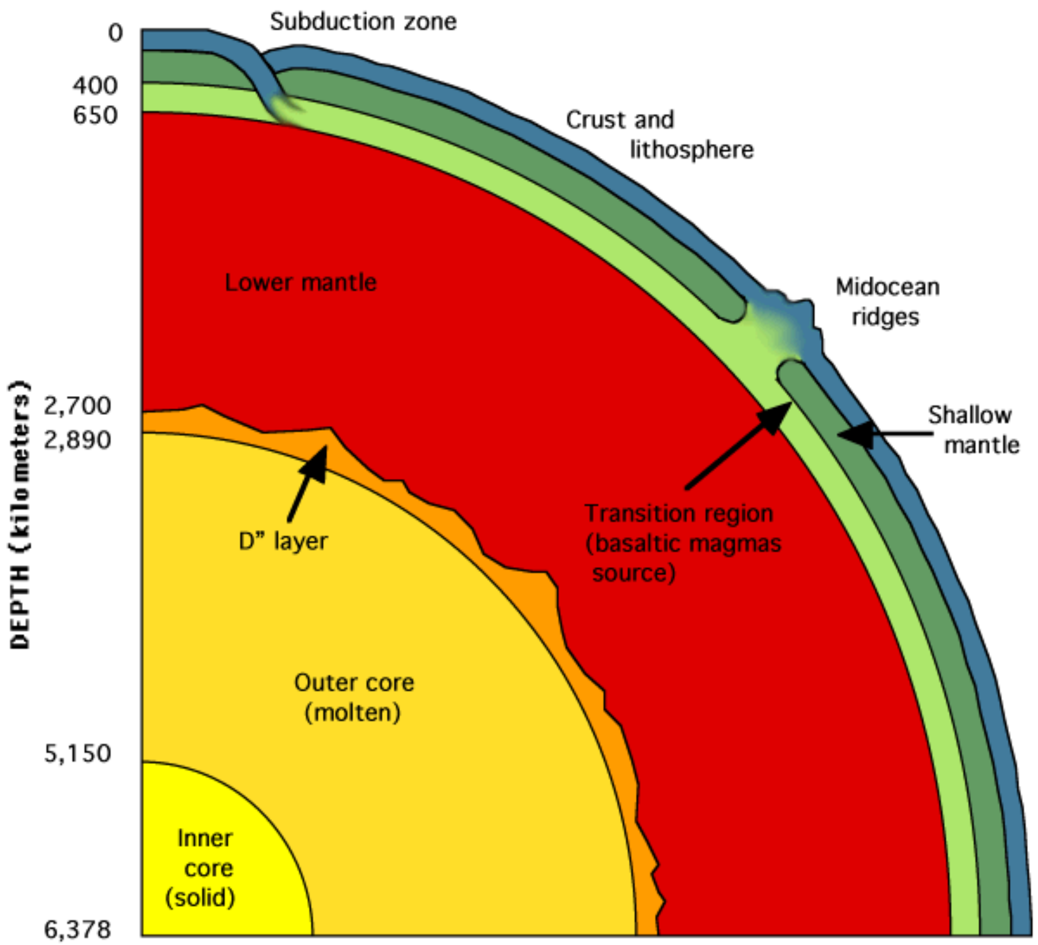
Mantle-crust differentiation

EARTH STRUCTURE TODAY





EARTH INTERIOR



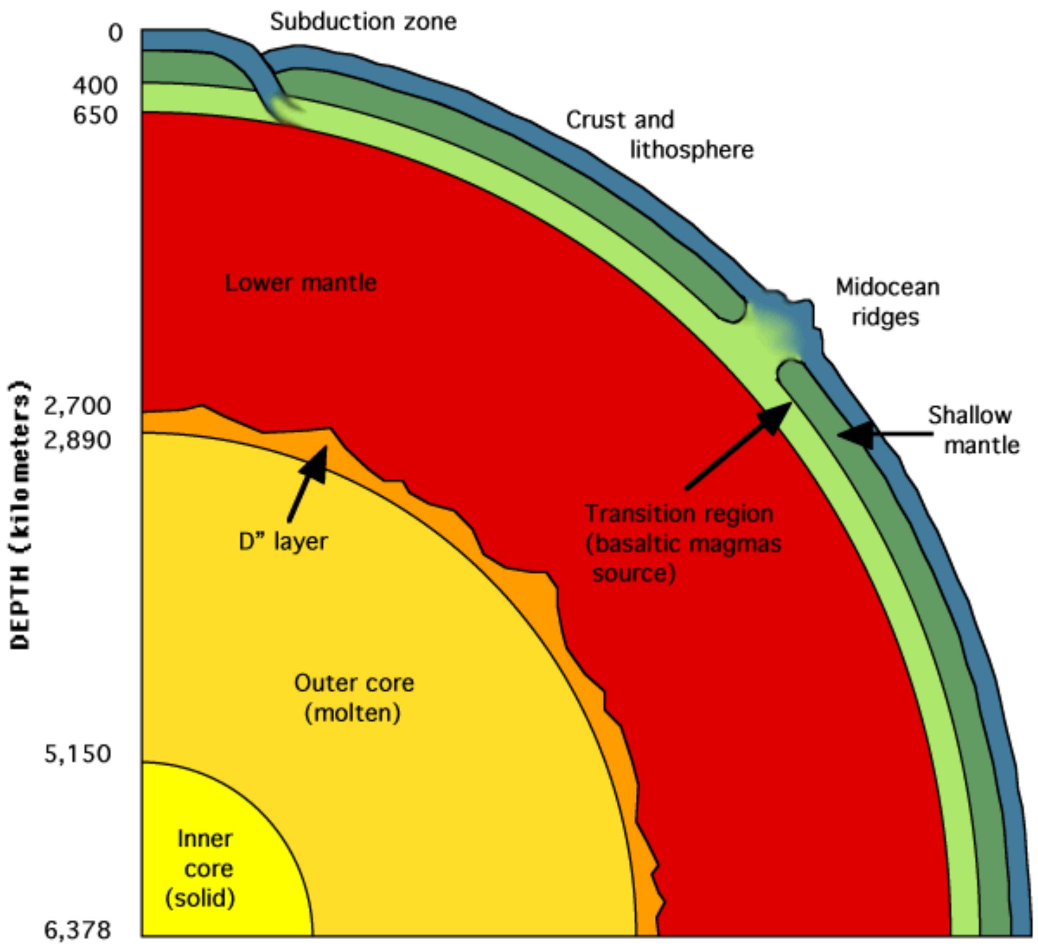
Inner Core - SOLID

- 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 INTERIOR



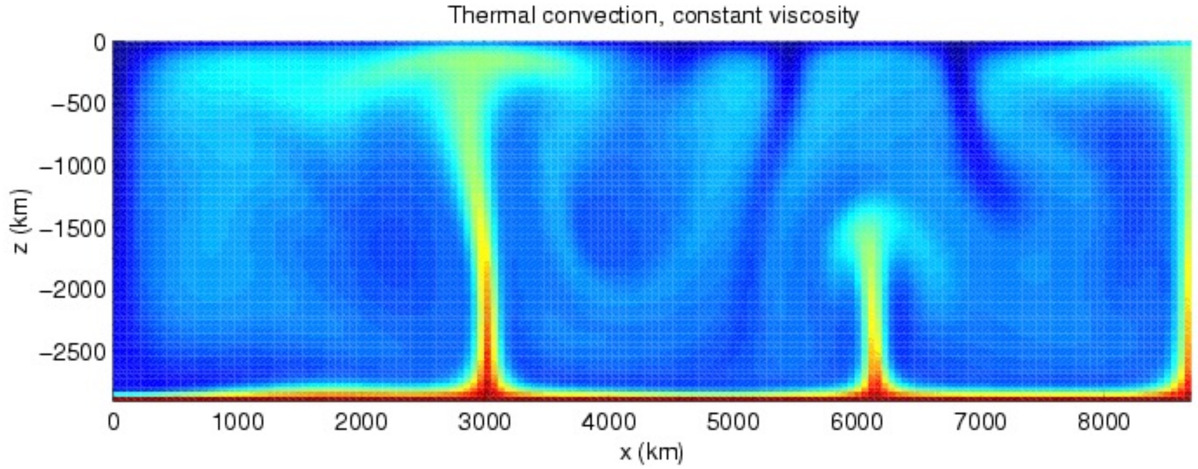
D” layer: mantle –core transition

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

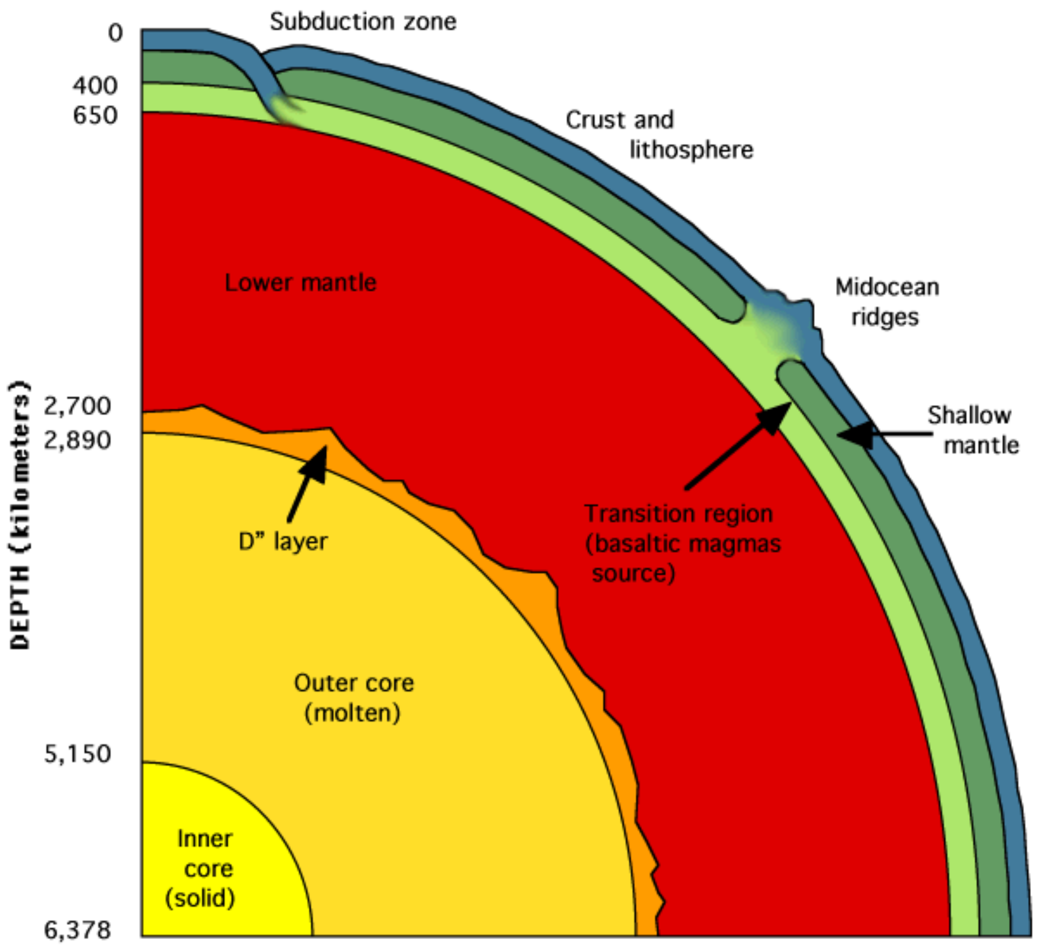
(mineral recrystallisation, material brought here from the subduction zones…)

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:



EARTH INTERIOR



Transition zone (400 - 650 km)

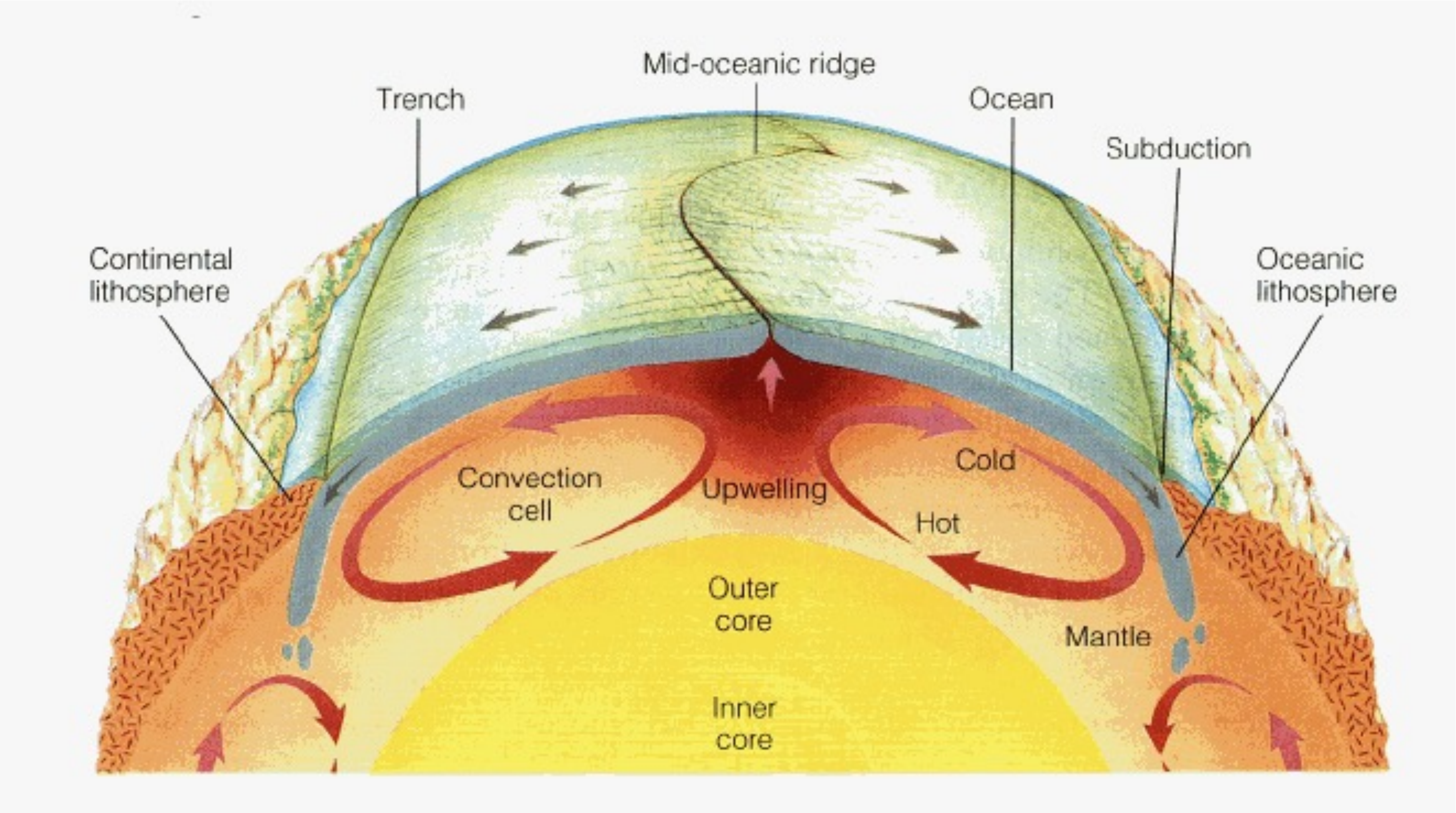
- seismic discontinuity;
- mineral recrystallisation;
- role of the latent heat?;
- partial melting: the source of mid-ocean ridge basalts (MORB);

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

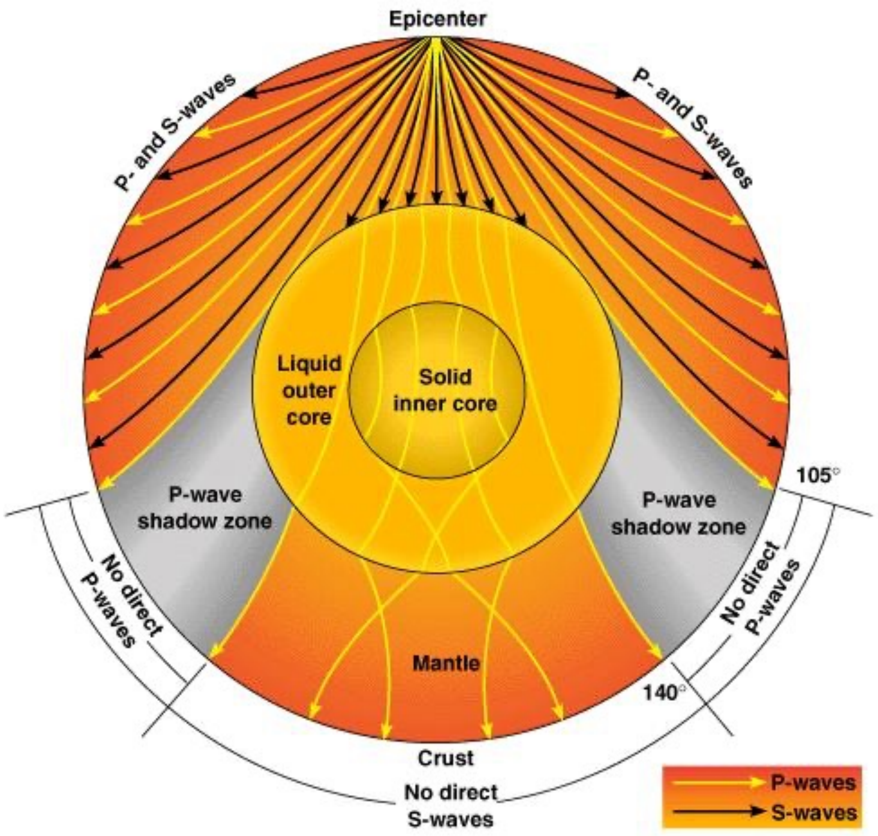


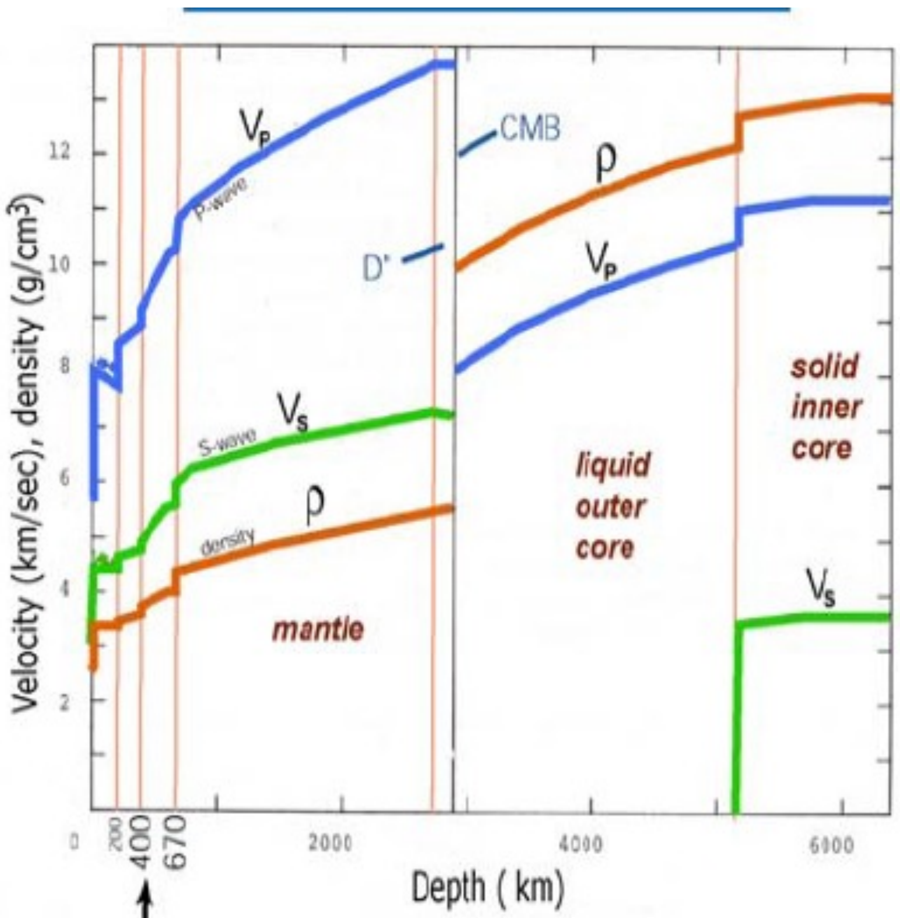
http://www.dstu.univ-montp2.fr/PERSO/bokelmann/convection.gif

- **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;

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

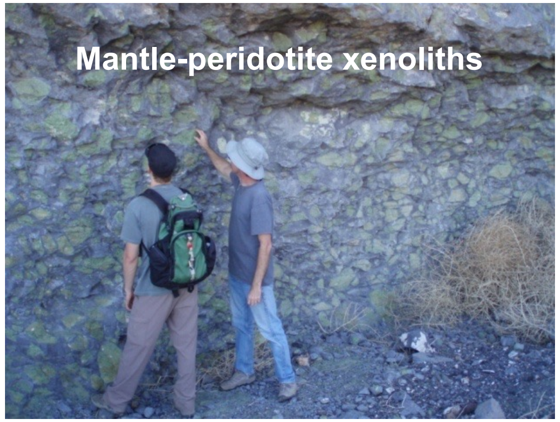
1) Direct rock samples

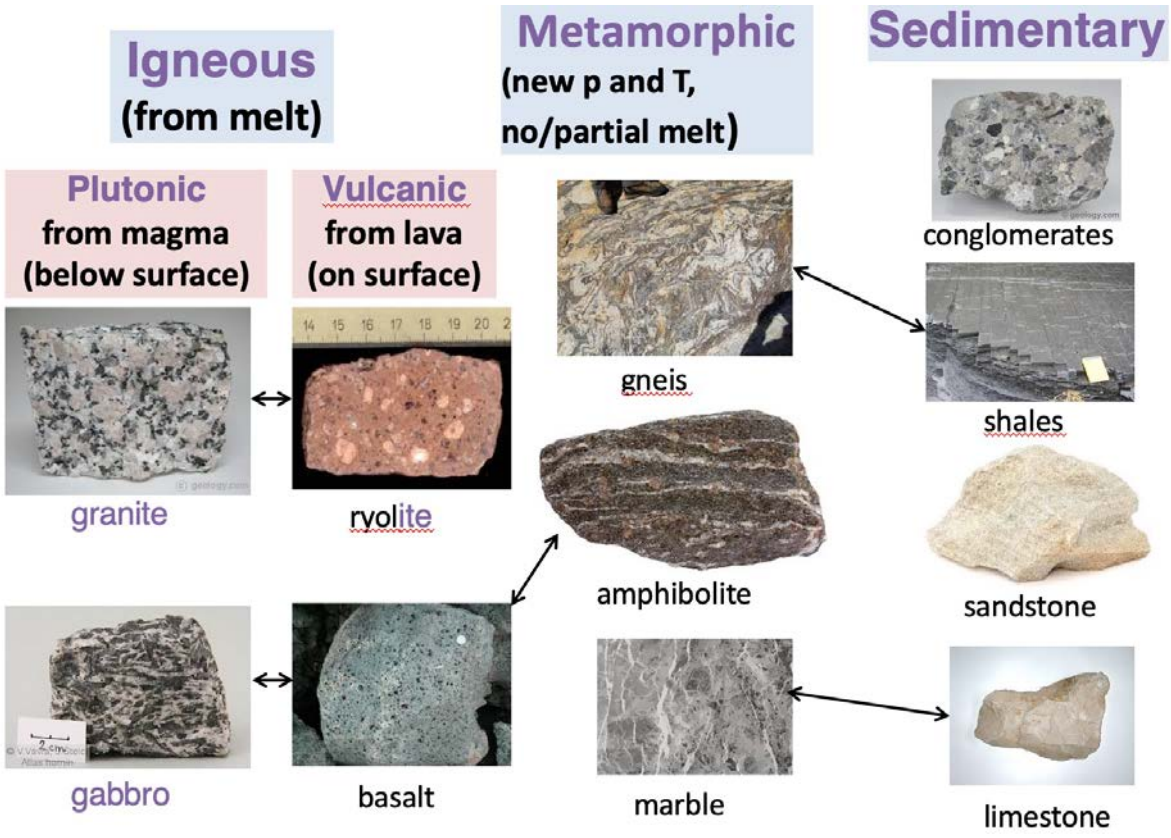
* surface and bore-holes (max. 12 km);
* upper mantle rocks brought up by tectonics and **vulcanism**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

* no rock samples from the lower mantle

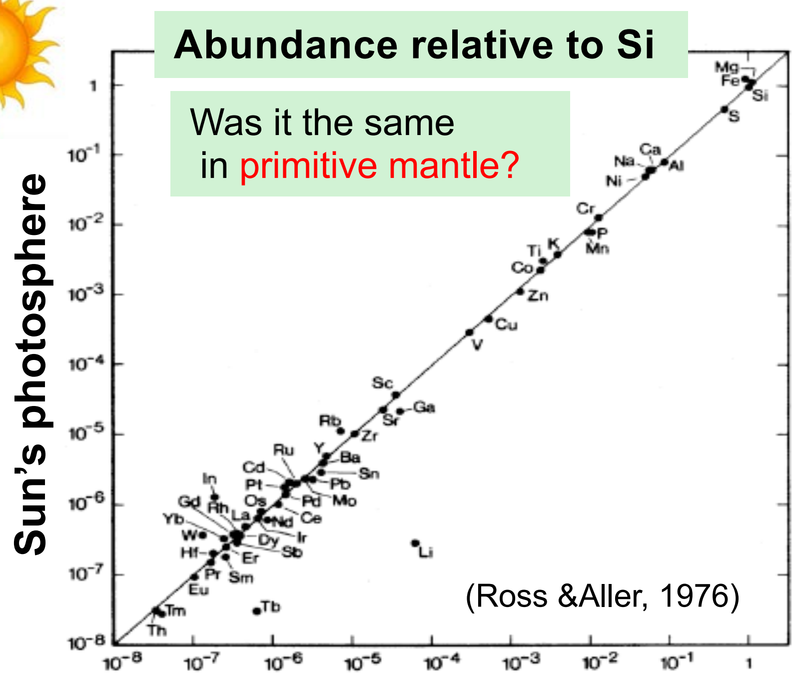
2) Geochemical modelling





BULK SILICATE EARTH (BSE) MODELS

BSE models combine:
- Crust and mantle samples
- Chondritic meteorites
- Solar photospheric abundances
- Geophysical constraints



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 (MAX Reference)	

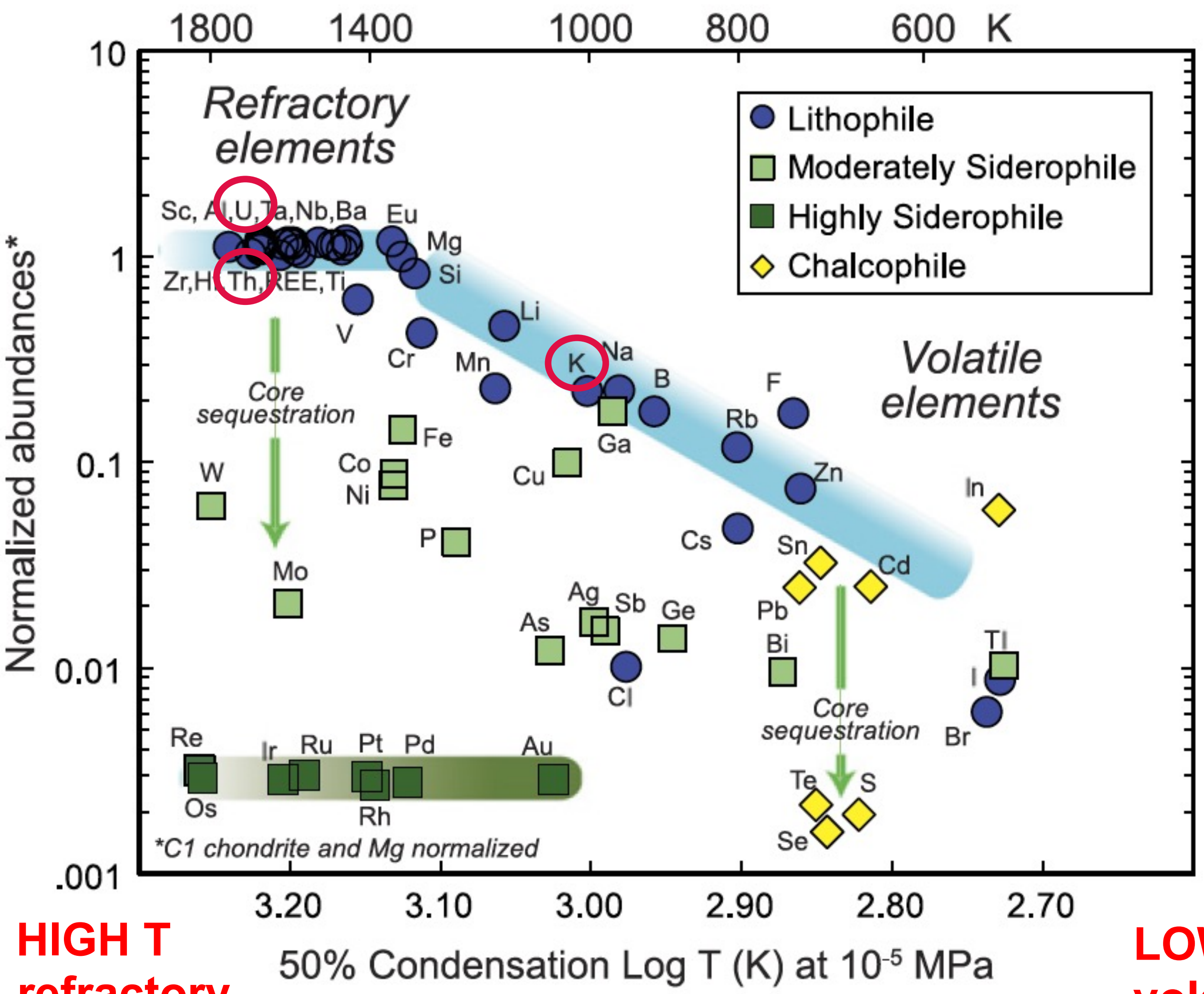
Radiogenic power spans roughly a factor of three across BSE models.

- Mantle composition is obtained by subtracting the crust from the BSE inventory.
- Elemental ratios are better constrained than absolute abundances.
- **Th/U ≈ 3.9** in chondritic meteorites.

Geoneutrinos directly test the radiogenic heat predictions of competing BSE models.

U AND Th IN THE EARTH

Composition of the primitive mantle



HIGH T refractory

LOW T volatile

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

Volatile /Refractory: *Low/High condensation temperature*

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. Mantle even smaller concentrations. Nothing in core.*

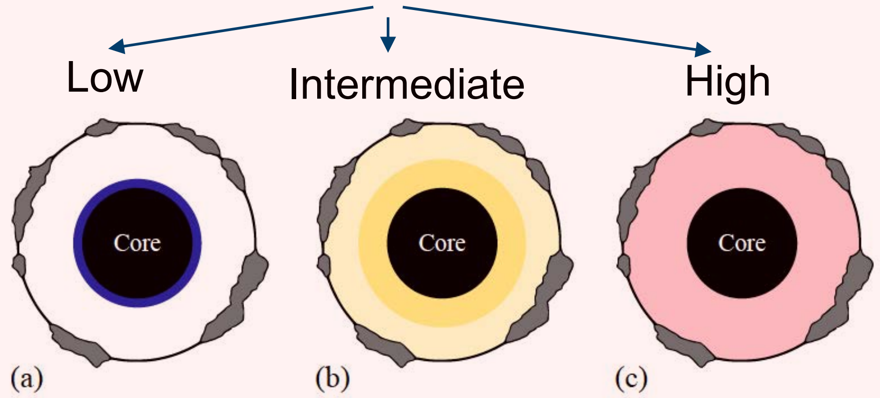
Typical concentration for ^{238}U
(Mantovani *et al.* 2004)

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

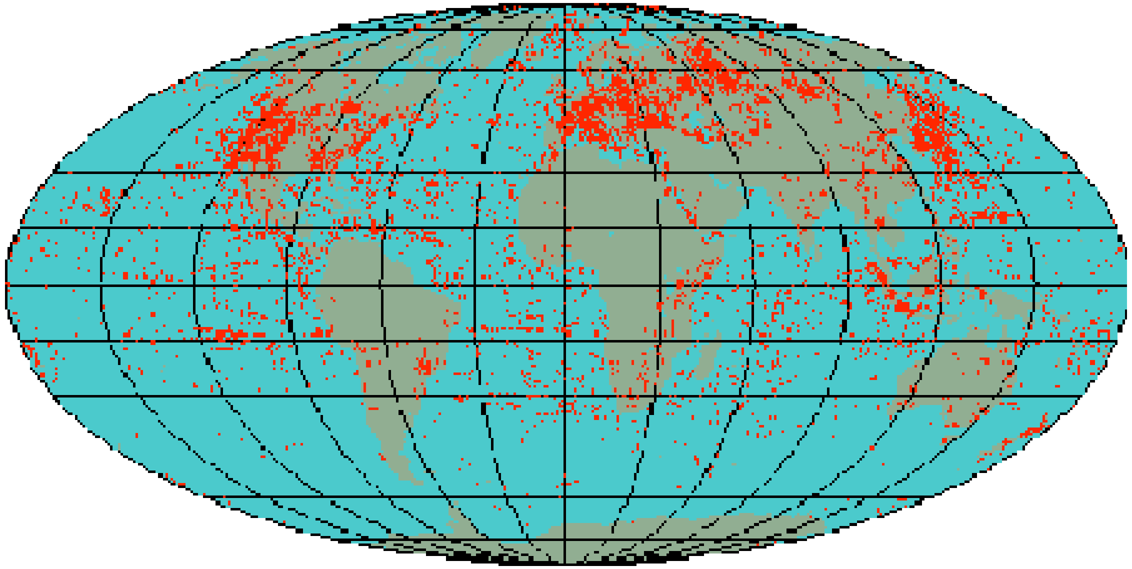
Decreases with depth

U/Th distribution in the mantle (3 scenario)

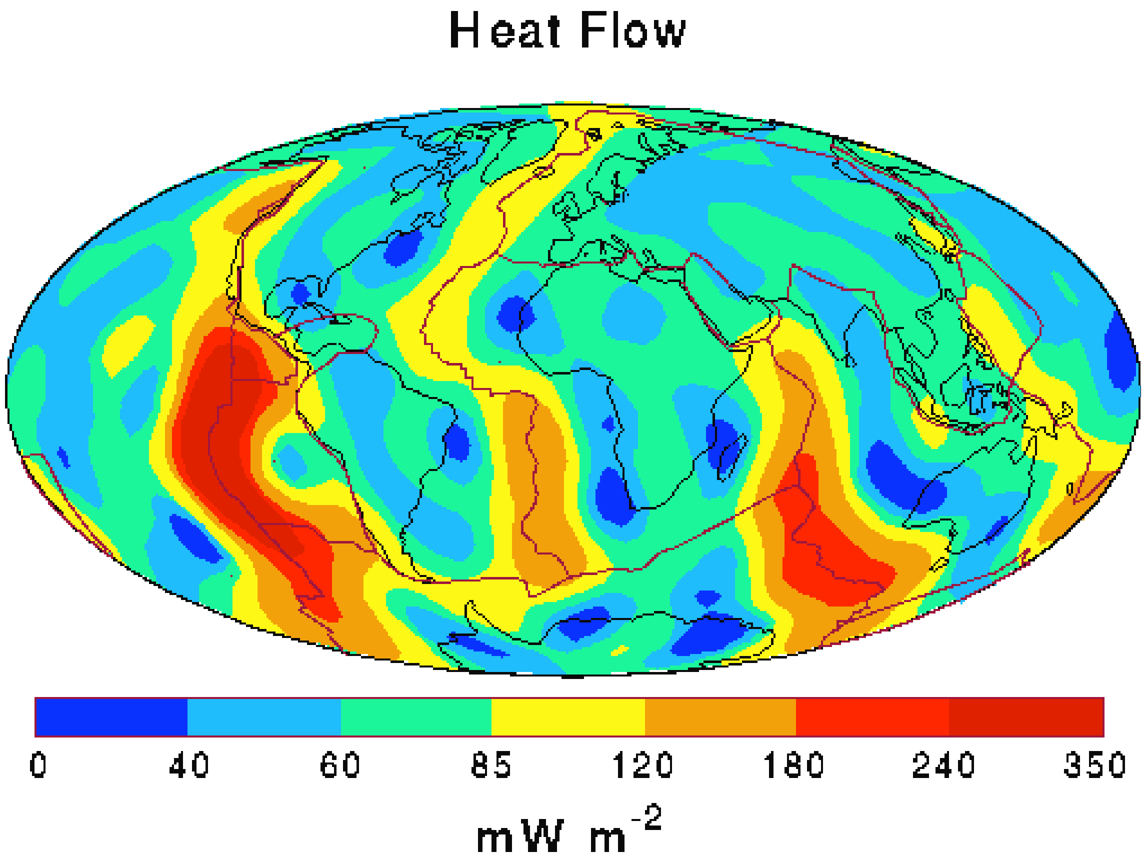
Geoneutrino flux from the mantle



EARTH HEAT FLOW



Temperature gradients measured along bore-holes

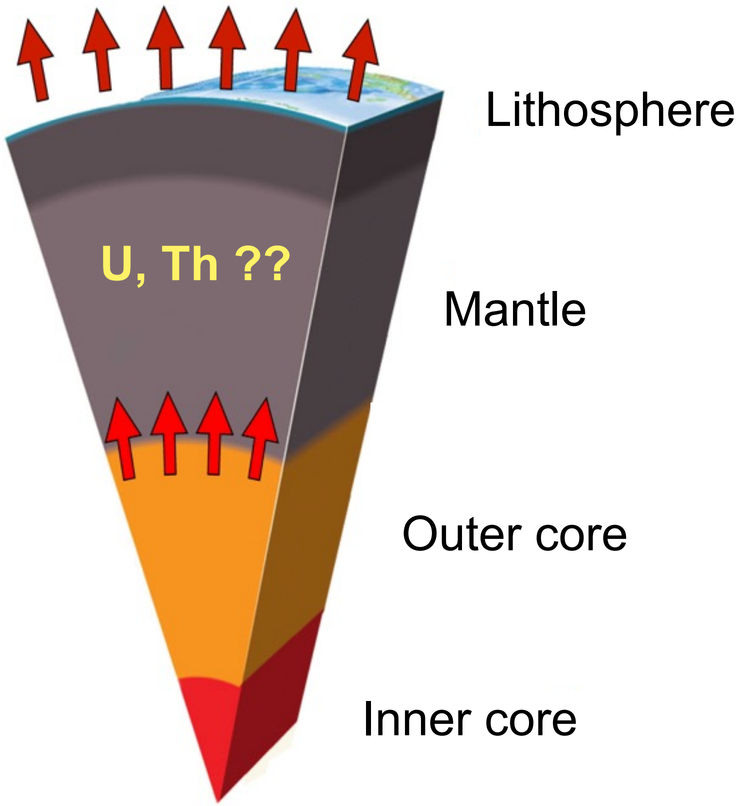


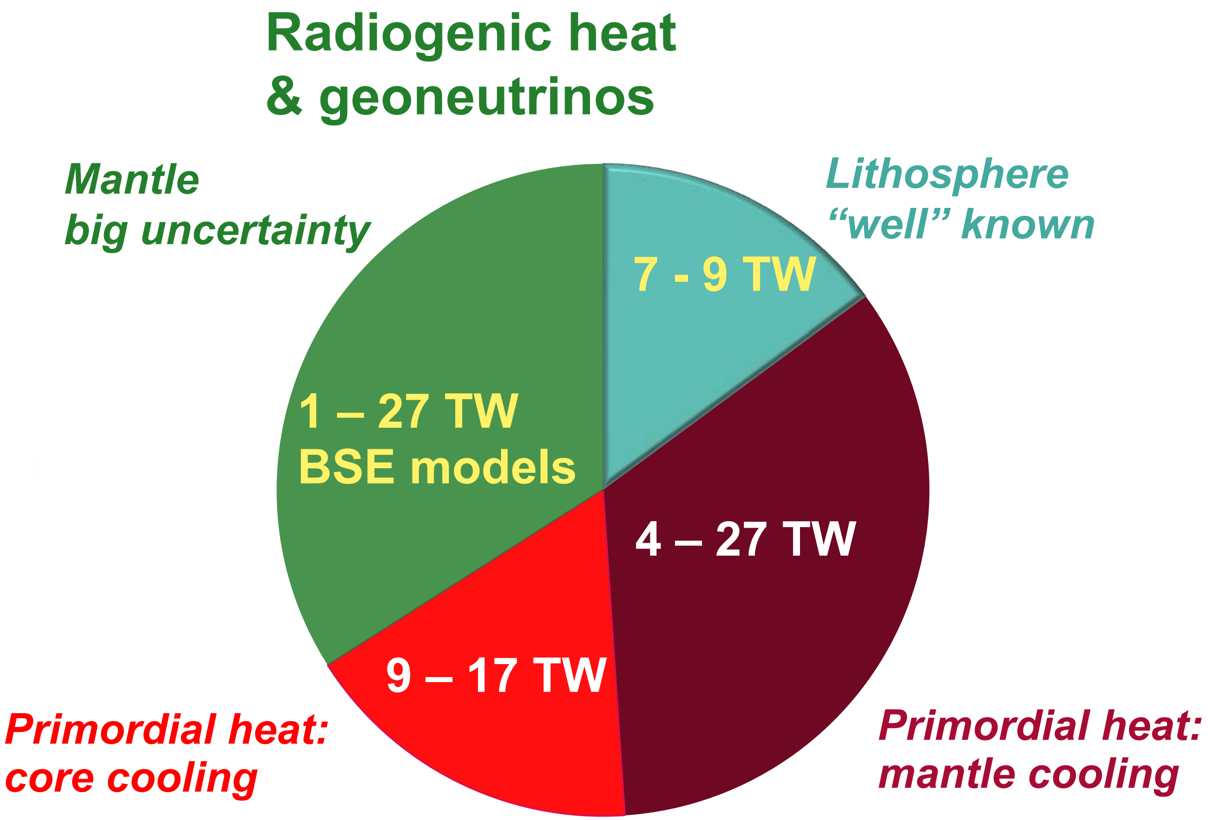
THE EARTH'S HEAT BUDGET

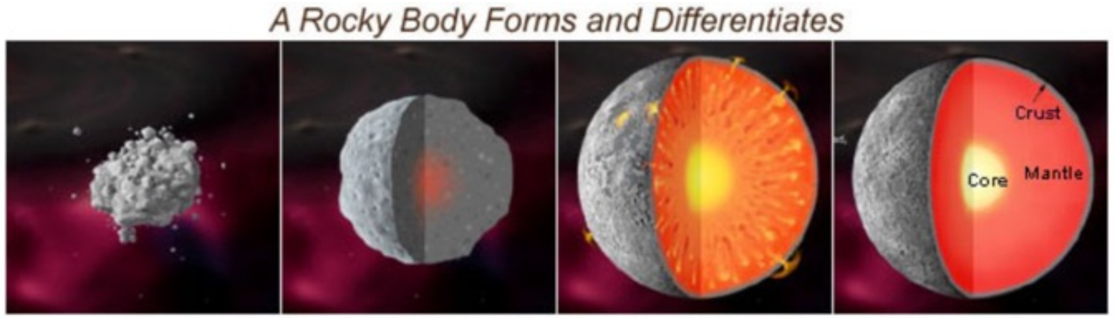
Integrated surface heat flux:

From measured T-gradients along bore-holes

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



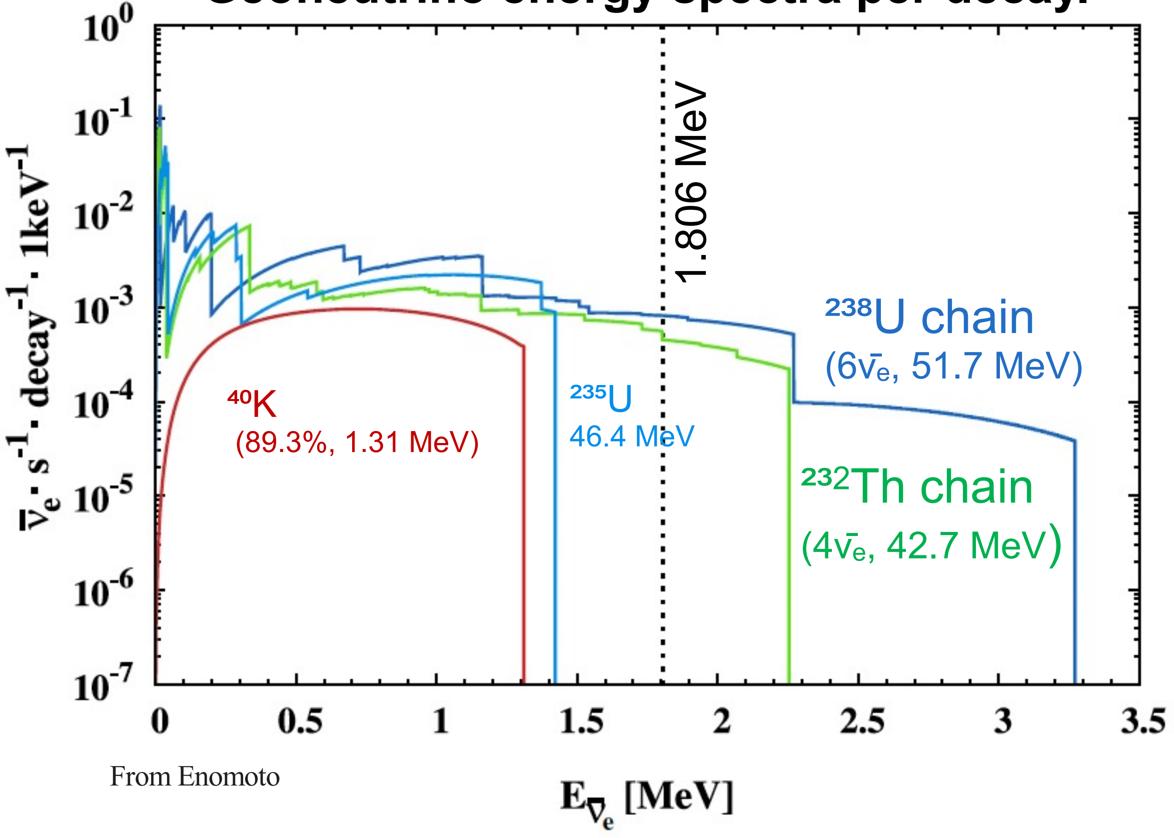




(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

GEONEUTRINOS: SPECTRA & FLUX

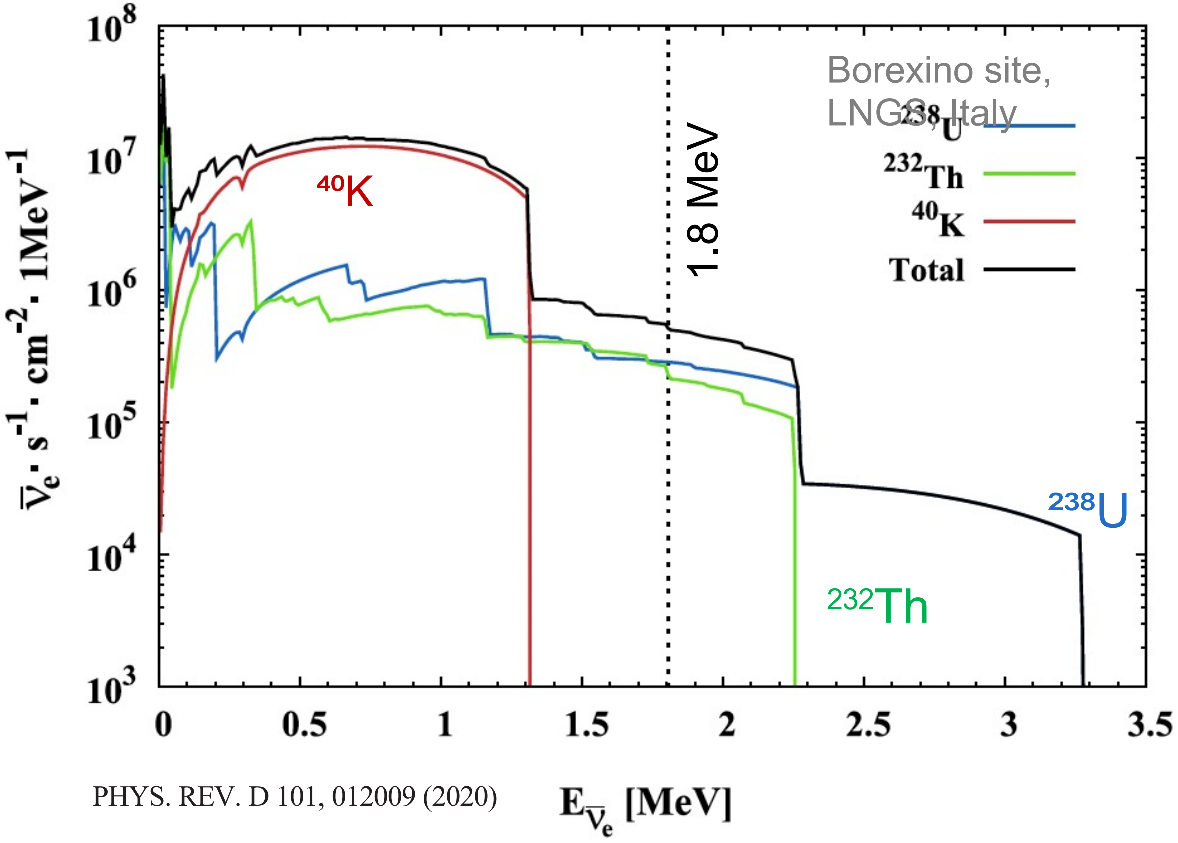
Geoneutrino energy spectra per decay.



From Enomoto

Example of <u>geoneutrino flux prediction</u>:

- Elemental abundances in different rock types.
- Spatial distribution in crust and mantle.



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GEONEUTRINO FLUX & RADIOGENIC HEAT

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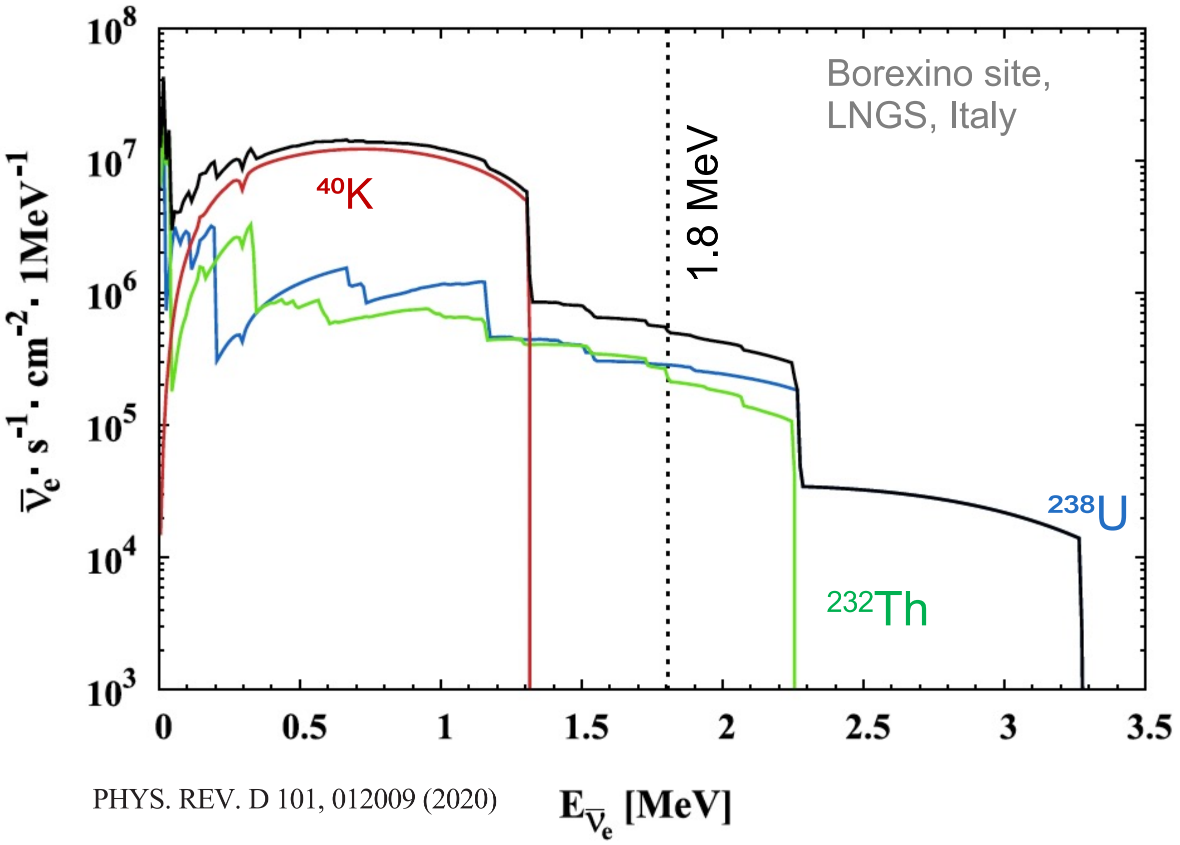

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Based on BSE model from McDonough & Sun, 1995

Isotope	Mass [10^{16} kg]	Φtot [10^6 cm^{-2} s^{-1}]	ΦIBD [10^6 cm^{-2} s^{-1}]	Heat [TW]
^{238}U	8.0 (15%)	1.17 (16%)	0.076 (66%)	7.6 (39%)
^{232}Th	32.4 (62%)	1.03 (14%)	0.040 (34%)	8.5 (43%)
^{40}K	11.4 (22%)	5.29 (70%)	0 (0%)	3.2 (16%)
^{235}U	0.06 (0.1%)	0.037 (0.5%)	0	0.3 (2%)
Total	**51.9**	**7.53**	**0.115**	**19.6**

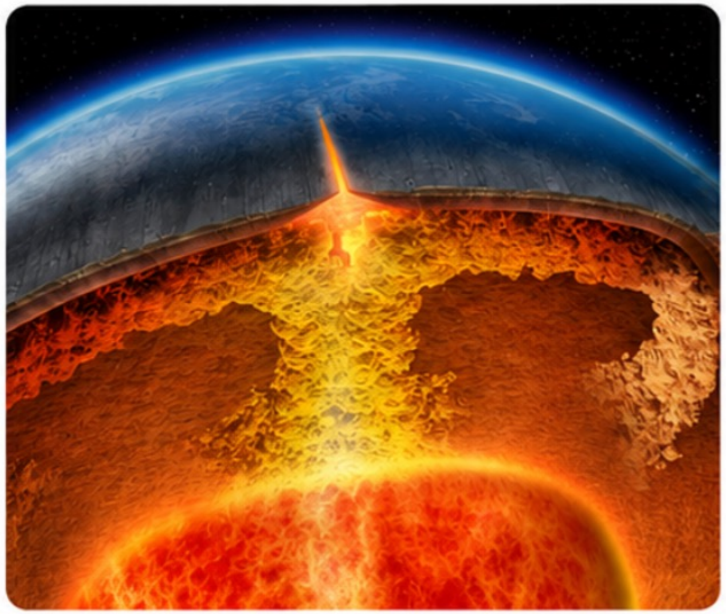
- ^{232}**Th** dominates the radioactive **<u>mass</u>** inventory.
  - ^{238}**U** mass is about 3.9 x less.
- ^{40}**K** dominates the total geoneutrino **<u>flux</u>**. (< $\tau_{1/2}$, < M)
  - ^{232}Th and ^{238}U fluxes are similar.
- ^{238}U dominates the **<u>detectable</u>** geoneutrino **<u>flux</u>**.
  - ^{232}**Th** ~ 2 x lower (IBD σ increases with E).
- **U** + **Th** generate ~80% of Earth's radiogenic heat.
  - ^{40}K about 16% overall heat.

WHY STUDY GEONEUTRINOS

EARTH'S HEAT BUDGET

- Radiogenic heat contribution
- Mantle and outer core convection
- Plate tectonics and volcanism
- Sustaining the geo-dynamo

Mantle geoneutrino signal



PLANETARY EVOLUTION

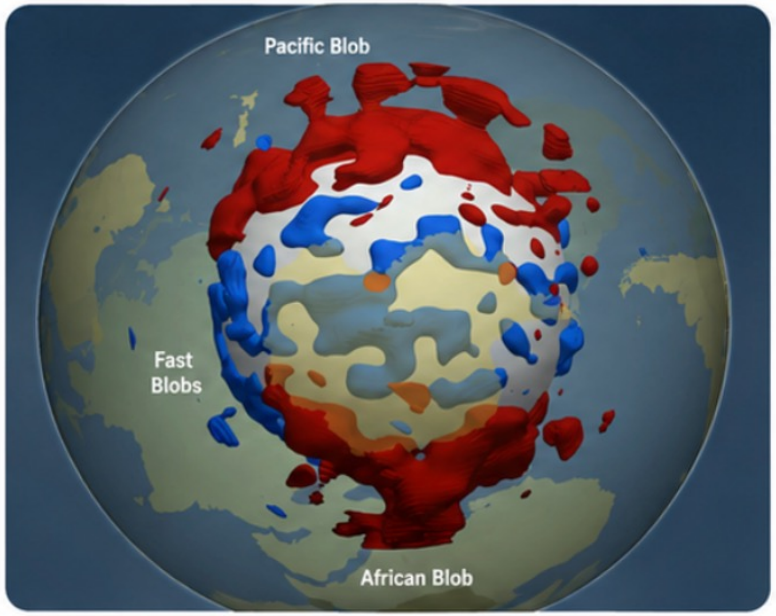
- Primordial material composition
- Links to meteorite and solar abundances
- Chemical differentiation of the Earth

Th/U signal ratio

MANTLE HETEROGENEITY

- Distribution of heat-producing elements
- Large Low Shear Velocity Provinces (LLSVPs)
- Double-layer convection

Multisite measurements



Geoneutrinos are the only direct probe of radioactive elements deep within the Earth.

GEONEUTRINO DETECTION: INVERSE BETA DECAY

Why Inverse Beta Decay (IBD)?

✓ Clean delayed-coincidence signature
✓ Excellent background rejection
✓ Large (~10^{-42} cm^2) & well known (~1%) cross section
✓ Antineutrino energy reconstruction

$\mathbf{E_{prompt}} = T_{e+} + 2 \times 511$ keV ~ $\mathbf{E_{antinu}}$ **– 0.784 MeV**

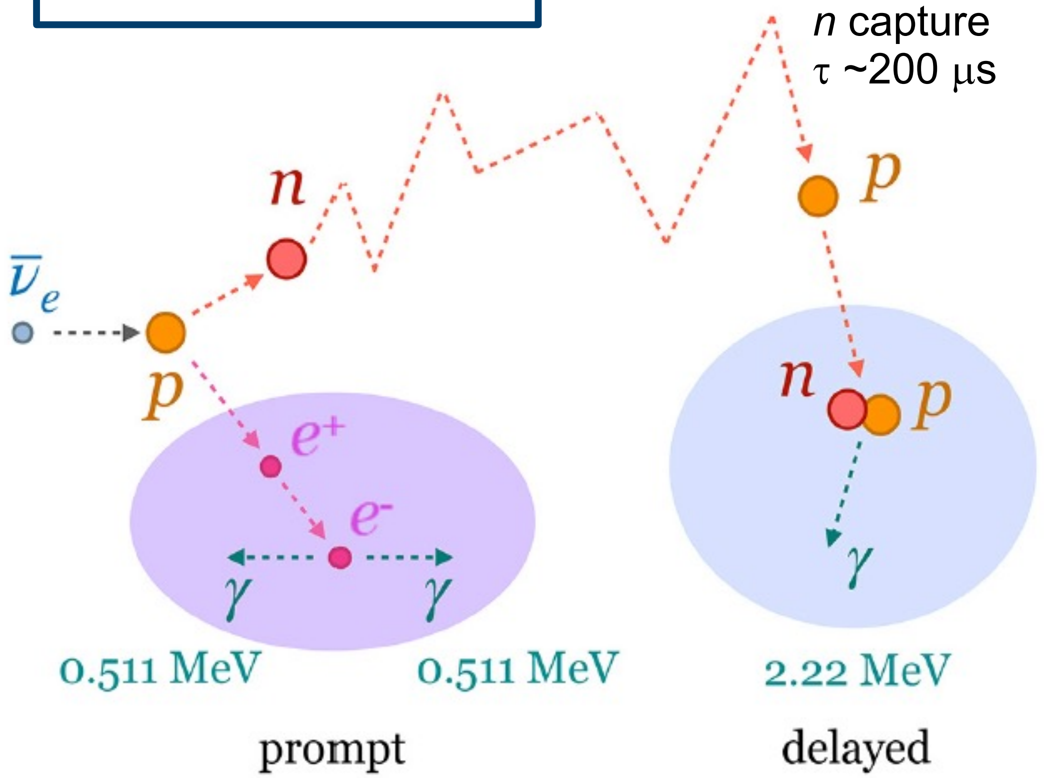
Threshold = 1.8 MeV

- ✓ ^{238}U & ^{232}Th geoneutrinos only
- ✓ No ^{40}K

Very limited directionality

- ✓ statistical pointing only in conventional liquid scintillators
- ✓ future concepts -> **see next talk**

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



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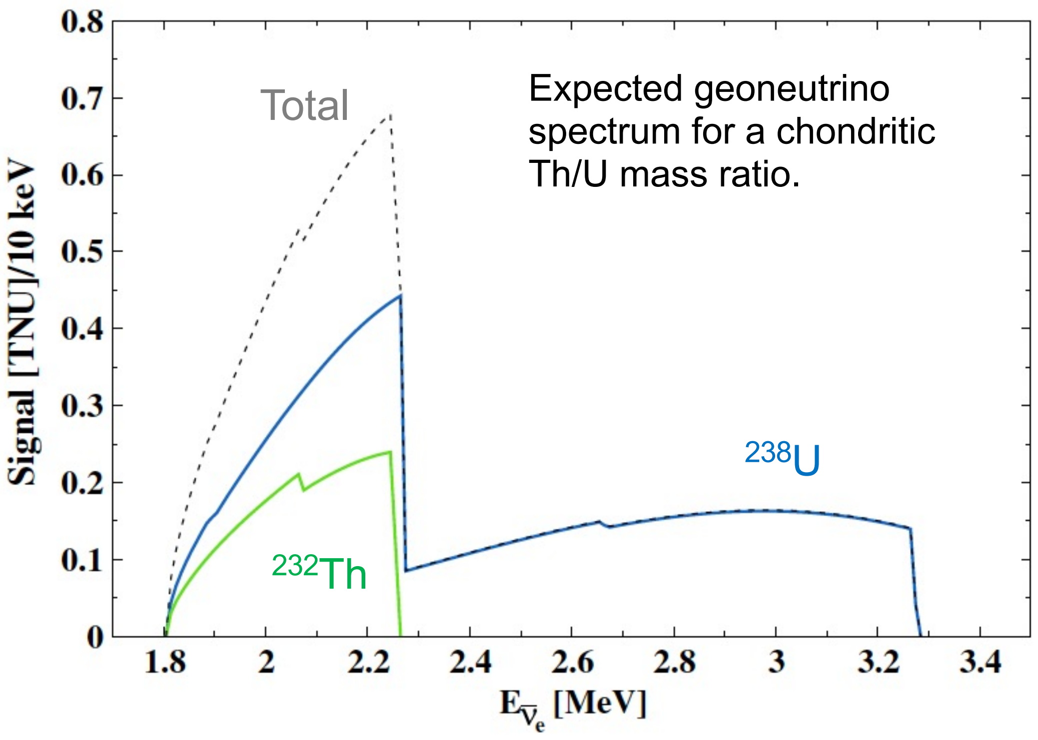
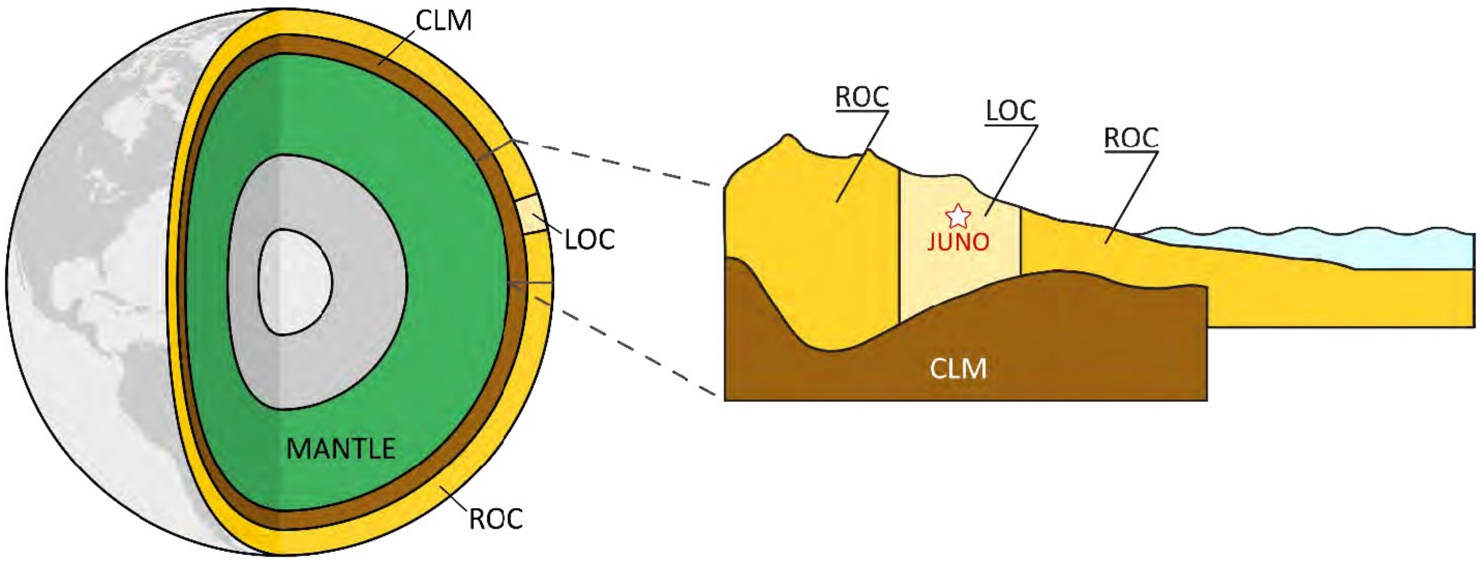
Note: reactor neutrinos (~10 MeV end point) are detected with the same IBD interaction – an important background !



PHYS. REV. D 101, 012009 (2020)

PREDICTION OF GEONEUTRINO FLUX / SIGNAL



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 FLUX @ DETECTOR

Geoneutrino production rate

Energy spectrum

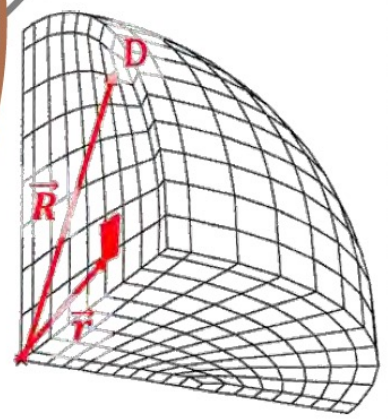
Survival Probability

Abundance of the *i*-element

Earth's mass density function

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

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



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

V. Strati

Conversion to signal in TNU

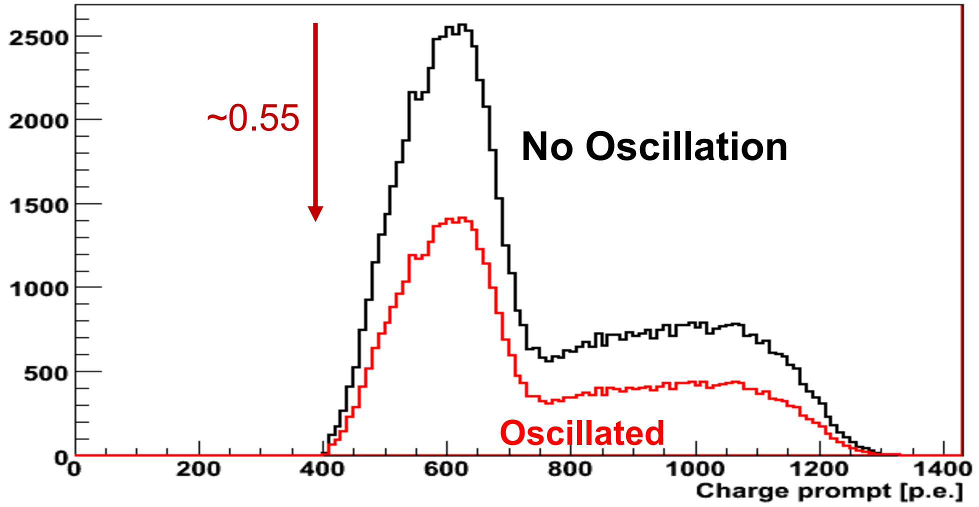
$$S\,[\mathrm{TNU}] = \frac{1}{\varepsilon_{\mathrm{det}}} \frac{10^{32}}{N_p} \frac{1\,\mathrm{yr}}{T_{\mathrm{live}}} \int \Phi_{\mathrm{osc}}(E_{\bar{\nu}})\,\sigma_{\mathrm{IBD}}(E_{\bar{\nu}})\,dE_{\bar{\nu}}$$

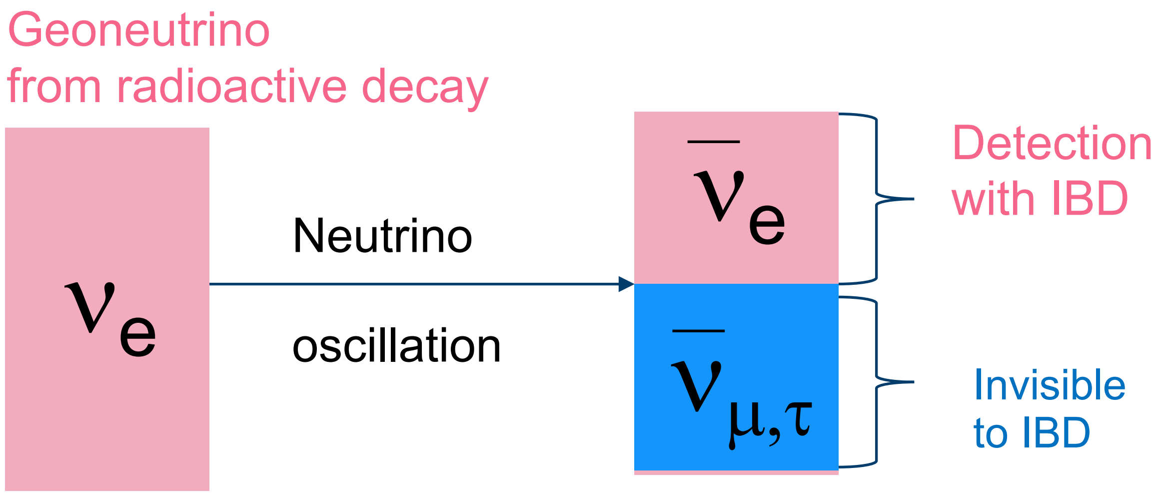
EFFECT OF NEUTRINO OSCILLATIONS

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 with Borexino-like resolution



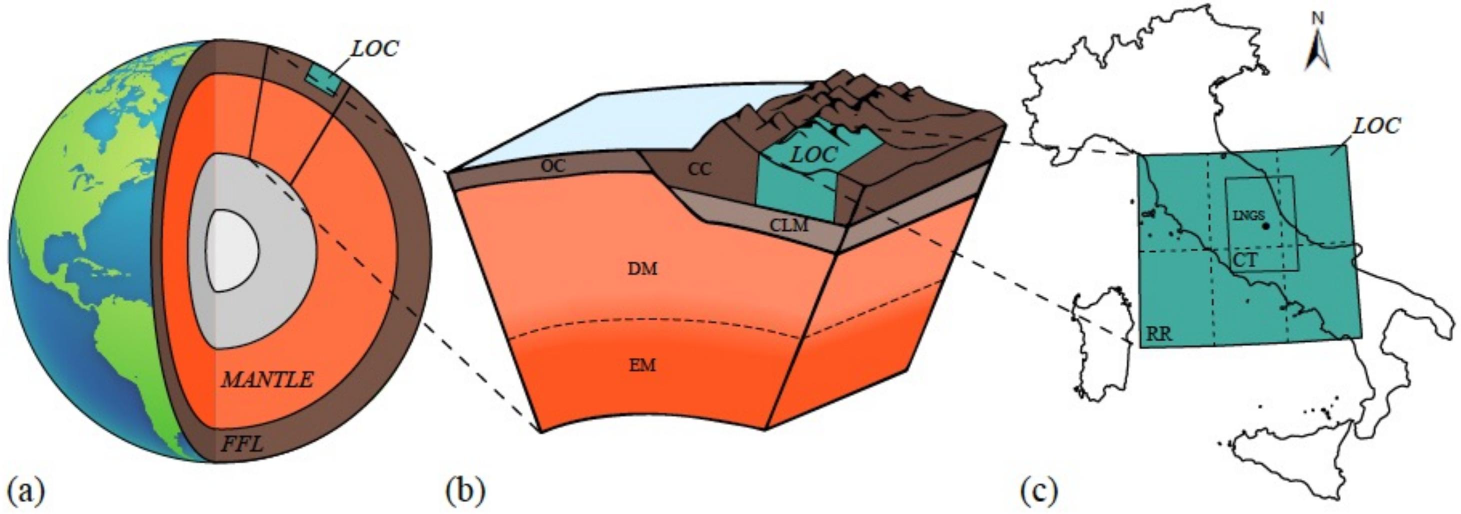


Negligible shape change – "only" suppression of the visible signal.

Spectral distortion due to the oscillations at the level of a few %.

EXAMPLE: GEONEUTRINO SIGNAL AT GRAN SASSO

1. LOCAL AND GLOBAL GEOLOGICAL INFORMATION



U, Th abundances & distribution
+ density profiles

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

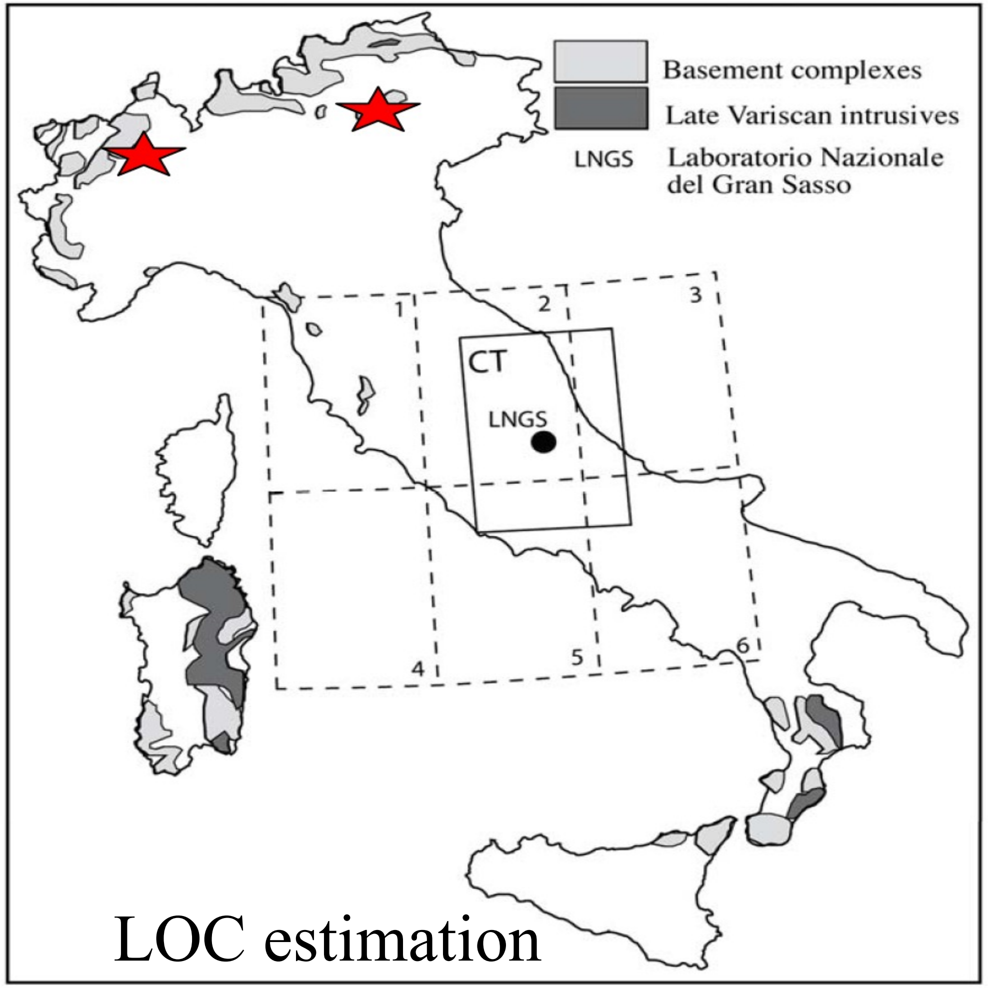
LOC – Local Crust
FFL – Far Field Lithosphere
Mantle

2. GEONEUTRINO ENERGY SPECTRA
3. σ(IBD) as f (E_ν) ~10^{-42} cm^2
4. $<P_{ee}>$ ~0.55

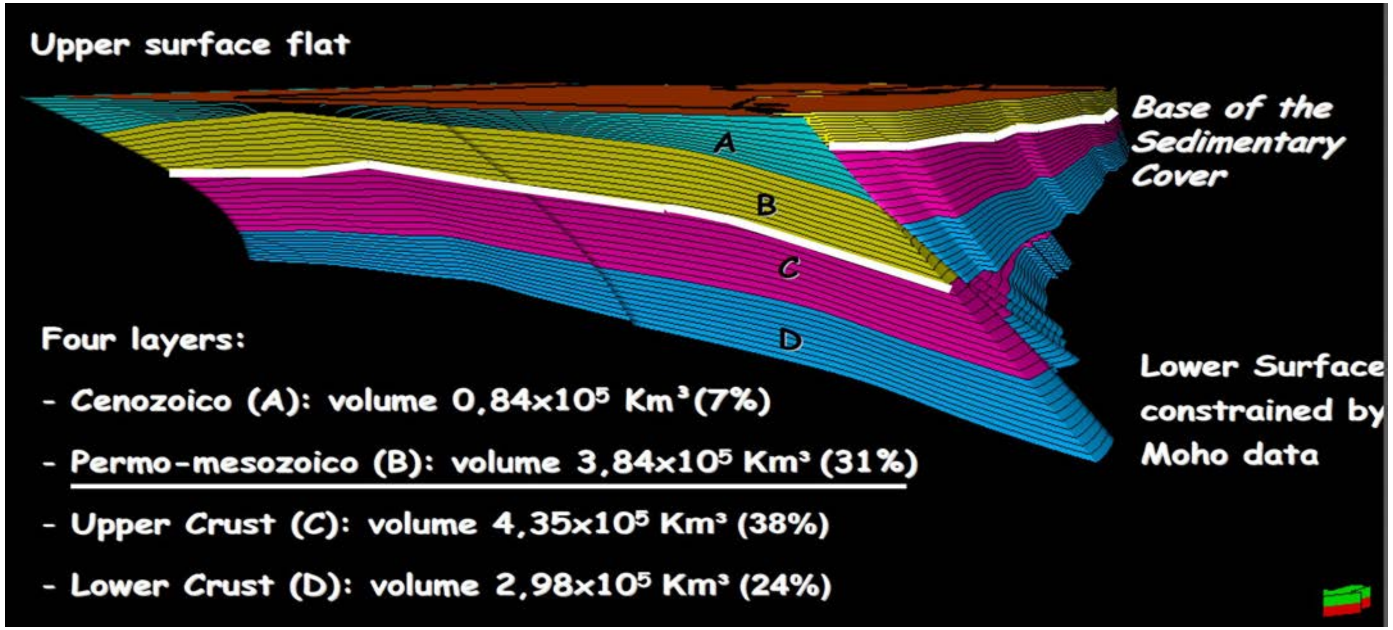
1 TNU (Terrestrial Neutrino Unit) = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

	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

3D GEOLOGICAL MODEL AROUND BOREXINO

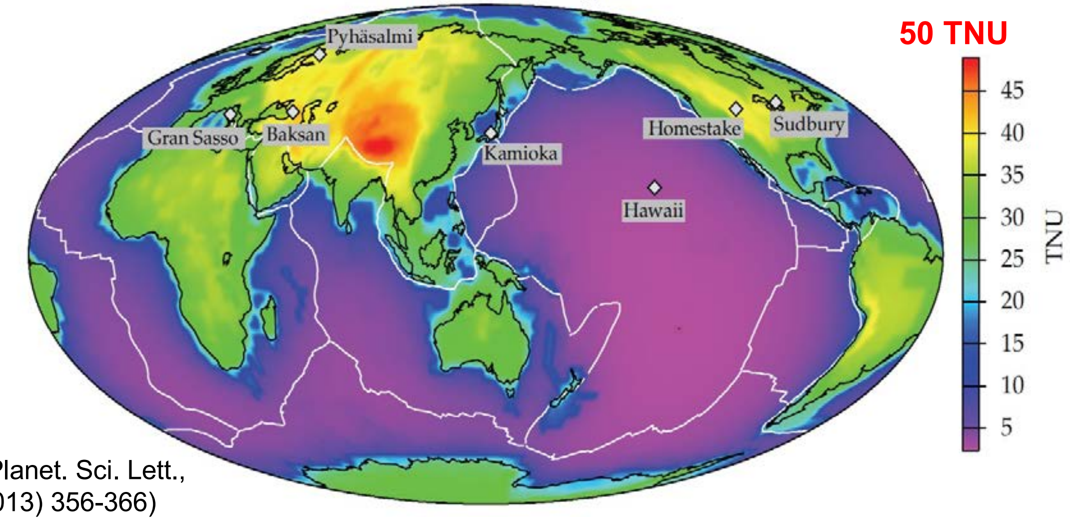


Coltorti at al. 2011



GEONEUTRINO SIGNAL WORLDWIDE: from $\phi \sim 10^6$ cm^{-2} s^{-1} to a handful of events

Expected crustal signal: "known" and "large".



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

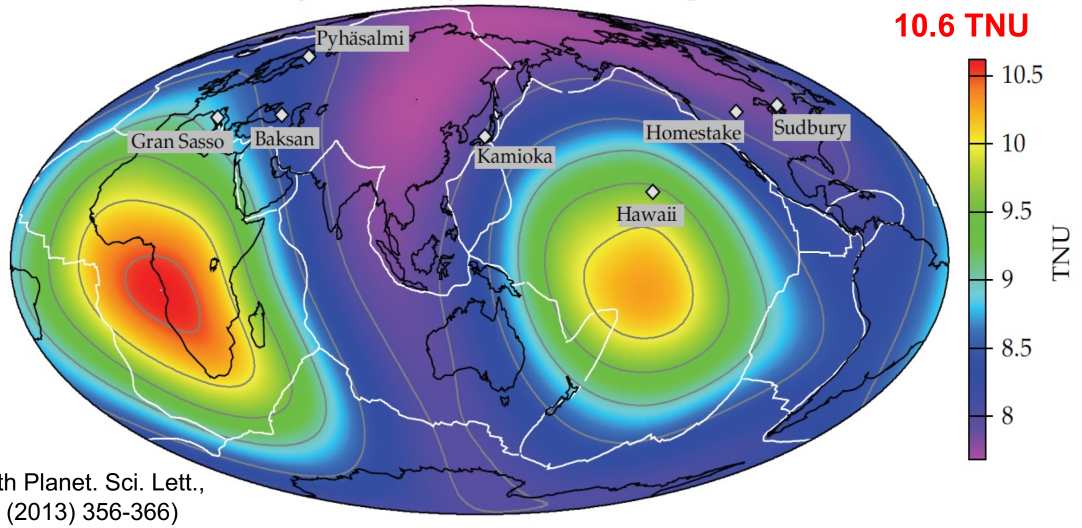
The signal is small, we need big detectors!

Terrestrial Neutrino Unit

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

(cca 1 IBD event / 1 kton of liquid scintillayor / 1 year) with 100% detection efficiency

Expected mantle signal: super-tiny and unknown.



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

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

Mantle signal is even more challenging!

GEONEUTRINO SIGNAL WORLDWIDE: from $\phi \sim 10^6$ cm^{-2} s^{-1} to a handful of events

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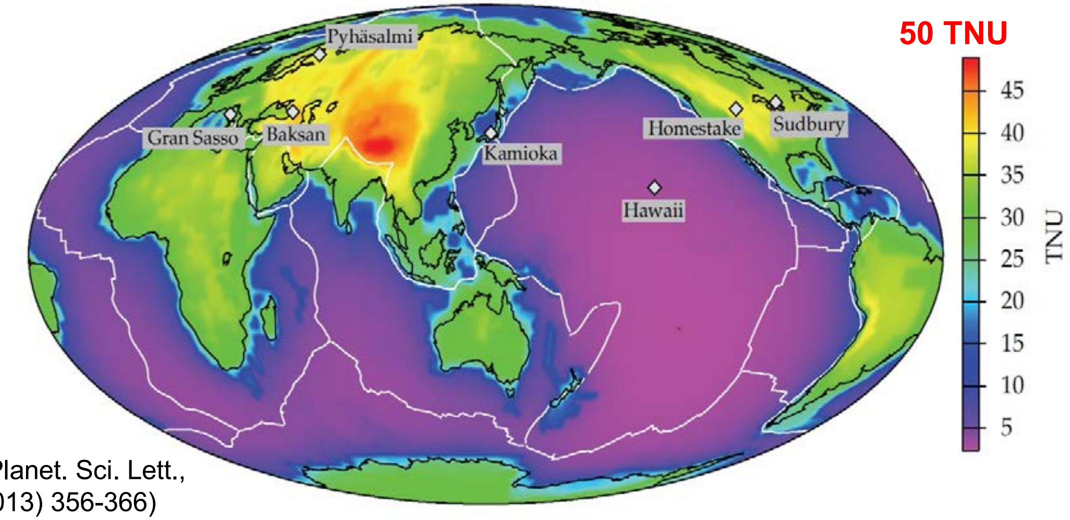

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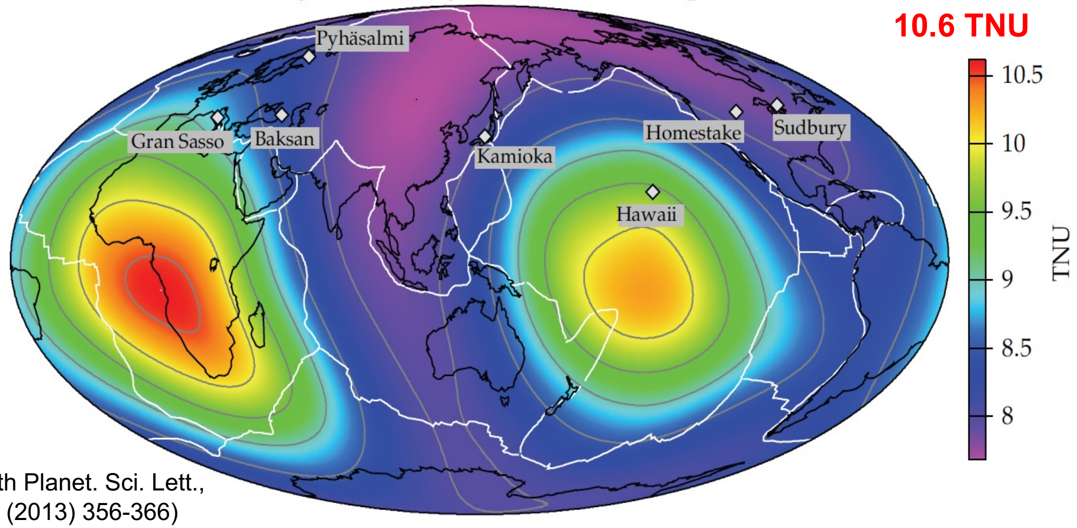


Earth Planet. Sci. Lett., 361 (2013) 356-366)

The signal is small, we need big detectors!

<u>Terrestrial Neutrino Unit</u>

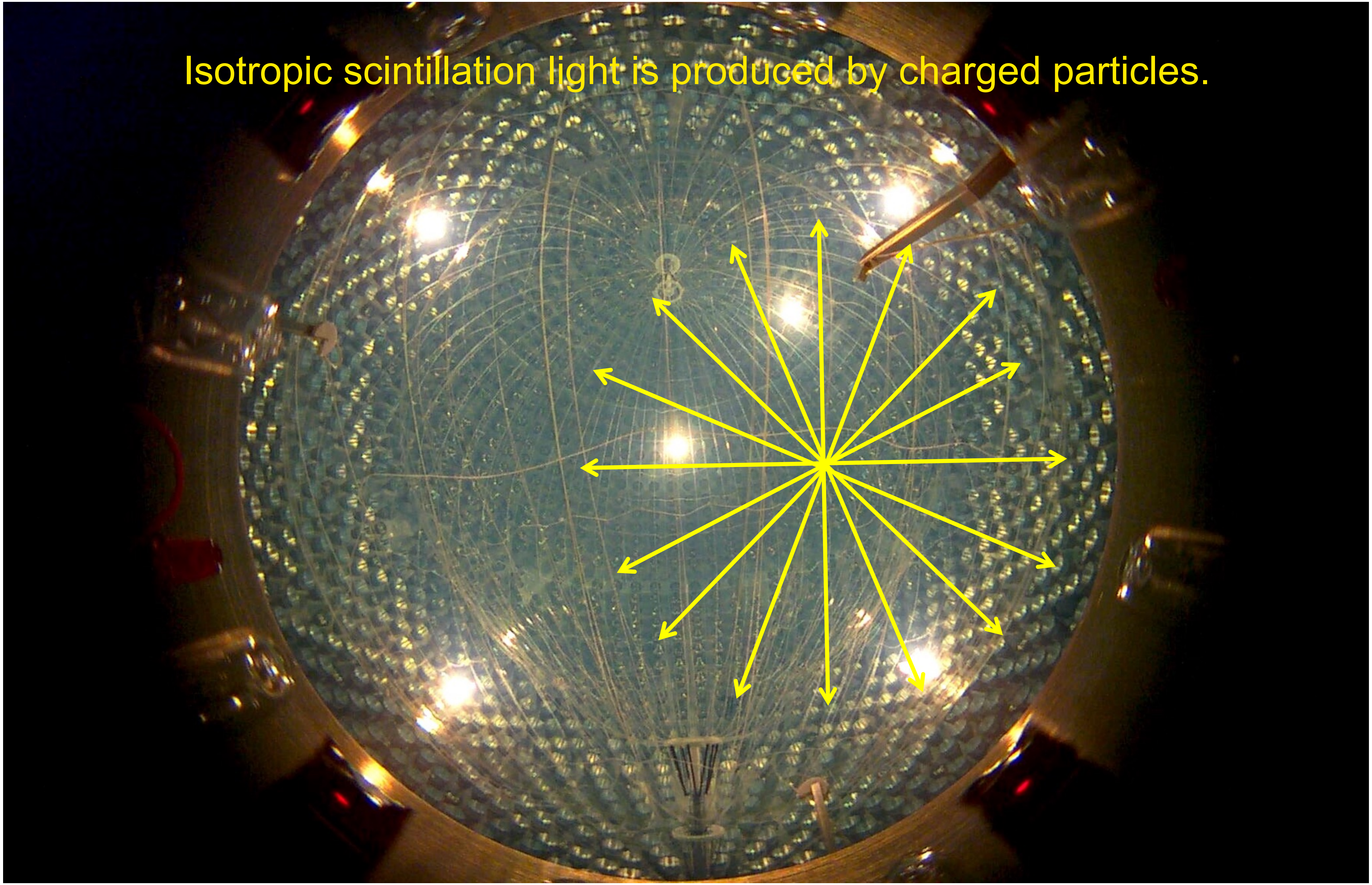
1 TNU = 1 IBD event / 10^{32} target protons / year

(cca 1 IBD event / 1 kton of liquid scintillayor / 1 year) with 100% detection efficiency

We need liquid scintillator (LS) detectors!

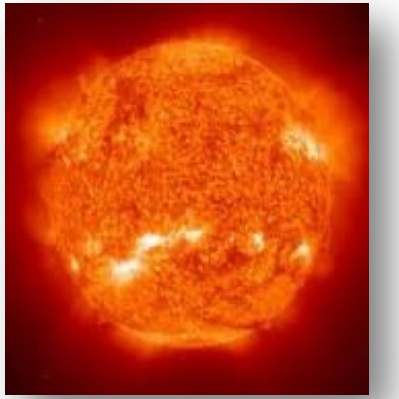
Hypothesis of heterogeneous mantle composition motivated by the observed **Large Shear Velocity Provinces** at the mantle base.

Mantle signal is even more challenging!


Isotropic scintillation light is produced by charged particles.

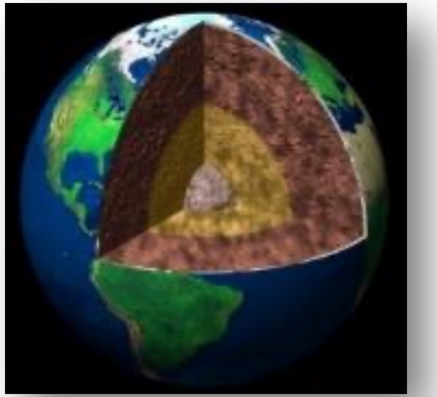
MAIN OBJECTS OF STUDY FOR LS DETECTORS

Solar neutrinos



- **neutrinos**
- production:
  - ✓ H to ^{4}He fusion
  - ✓ solar core
  - ✓ electron flavour
- arrive on Earth as a mixture of all flavours

Geoneutrinos

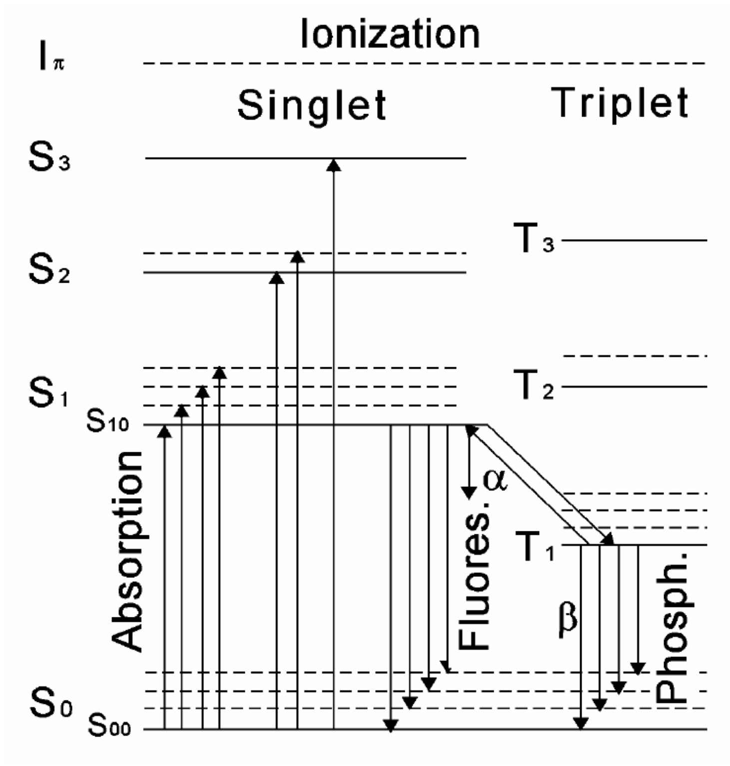


- **antineutrinos**
- production:
  - ✓ β-decay
  - ✓ Earth crust and mantle
  - ✓ electron flavour
- arrive to the surface as a mixture of all flavours

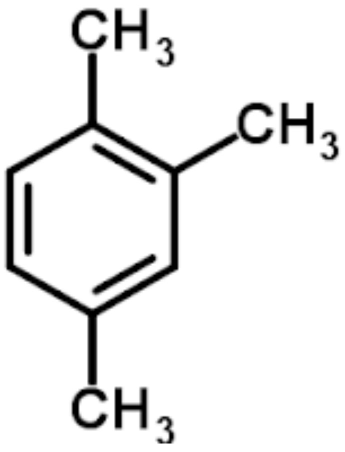
Reactor neutrinos

- **antineutrinos**
- production:
  - ✓ β-decay of fission products
  - ✓ reactor core
  - ✓ electron flavour
- flavour composition depends on the baseline

MOLECULAR STATES IN AROMATIC CARBOHYDRATES

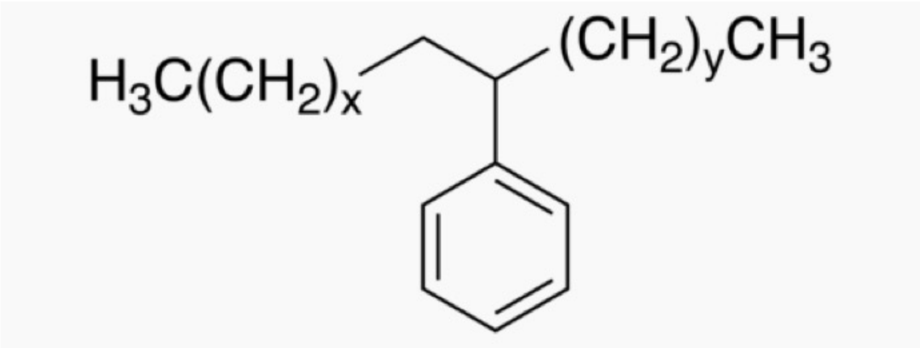


Pseudocumene (PC)
1,2,4-trimethylbensene



Absorption higher frequencies and smaller wavelengths than emission

Fast fluorescence has higher frequencies and smaller wavelengths than **slower phosphorescence**



LAB
linear-alkylbenzene

MAIN CHARACTERSTICS OF THE LS BASED NEUTRINO DETECTION

- High scintillation efficiency and high light yield
- Good energy and position **resolution (1 MeV ~ 500 – 1600 detected photons)**
- Low energy **threshold (< 1 MeV)**
- **No directionality** – scintillation light is isotropic
- **Real time** measurement (energy of single events)
- **Quenching:** intrinsic **non-linearity** between energy deposit and produced light
- **Pulse shape** discrimination (alpha/beta, positron/electron)
- High transparency – needed for large detectors
- Refractive index similar to the glass (phototube matching)

FROM SCINTILLATION LIGHT TO MEASURED VARIABLES

- **Charged particles** produce scintillation light;
- **Neutrinos are** detected indirectly via secondary particles they produce;
- **Gamma rays** are neutral particles but in the scintillator they interact mostly via Compton scattering producing electrons = charged particles;
- Scintillation light is detected by an array of **phototubes (PMTs)** converting optical signal to electrical signal;
- Number of hit PMTs = function (energy deposit) = energy estimator
- Hit PMTs time pattern = position reconstruction of the event
- Each trigger has its GPS time = absolute time

SELECTING IBD CANDIDATES

IBD: antineutrino + proton → positron + neutron

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

$E_{delayed}$ = 2.2 MeV gamma

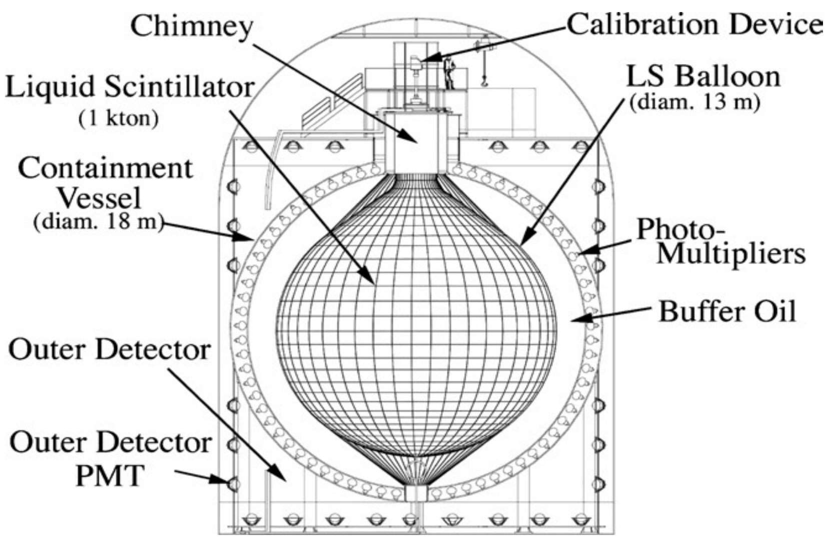
Δ time = time correlation

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

EXPERIMENTS THAT MEASURED GEONEUTRINOS

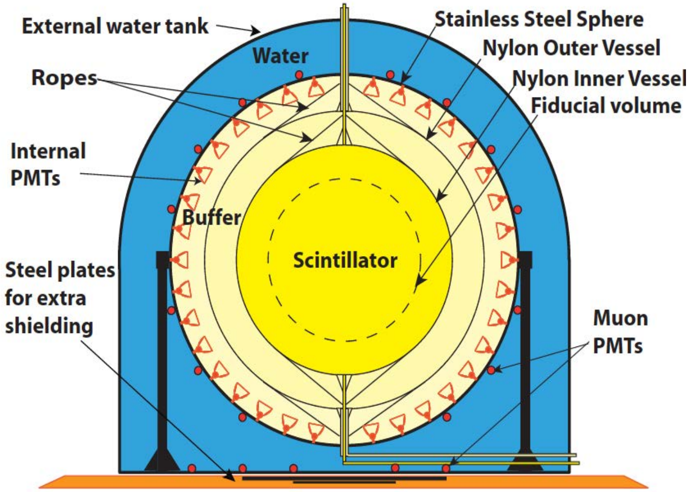
KamLAND, Kamioka, Japan
Border between
OCEANIC / CONTINENTAL CRUST



- Main goal: reactor neutrinos
- Data taking: since 2002
- LS: 1000 tons;
- Depth: 2700 m.w.e.

Phys. Rev. D 101 (2020) 012009

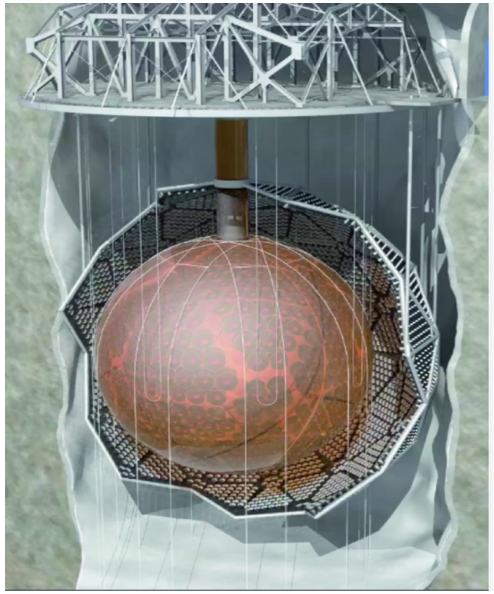
Borexino, LNGS, Italy
CONTINENTAL CRUST



- Main goal: solar neutrinos:
  extreme radio-purity needed & achieved;
- Data taking: 2007 - 2021
- LS: 280 tons;
- Depth: 3800 m.w.e.

Geophys. Res. Lett. 49 e2022 GL099566

SNO+, Sudbury, Canada
CONTINENTAL SHIELD (OLD CRUST)

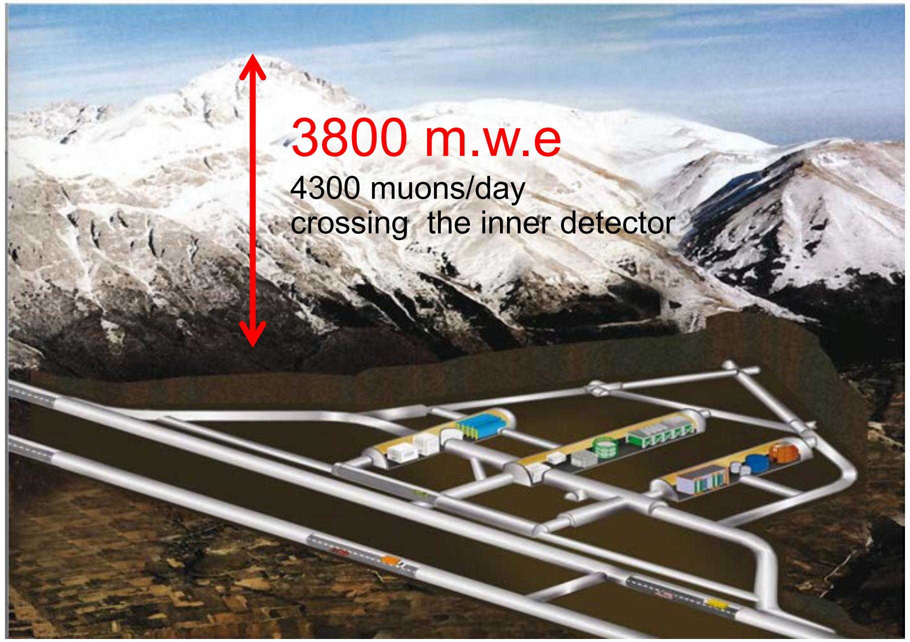


- Main goal: $0\nu\beta\beta$ decay
- Data taking: since 2022
- LS: 780 tons;
- Depth: 6000 m.w.e. (very deep!)

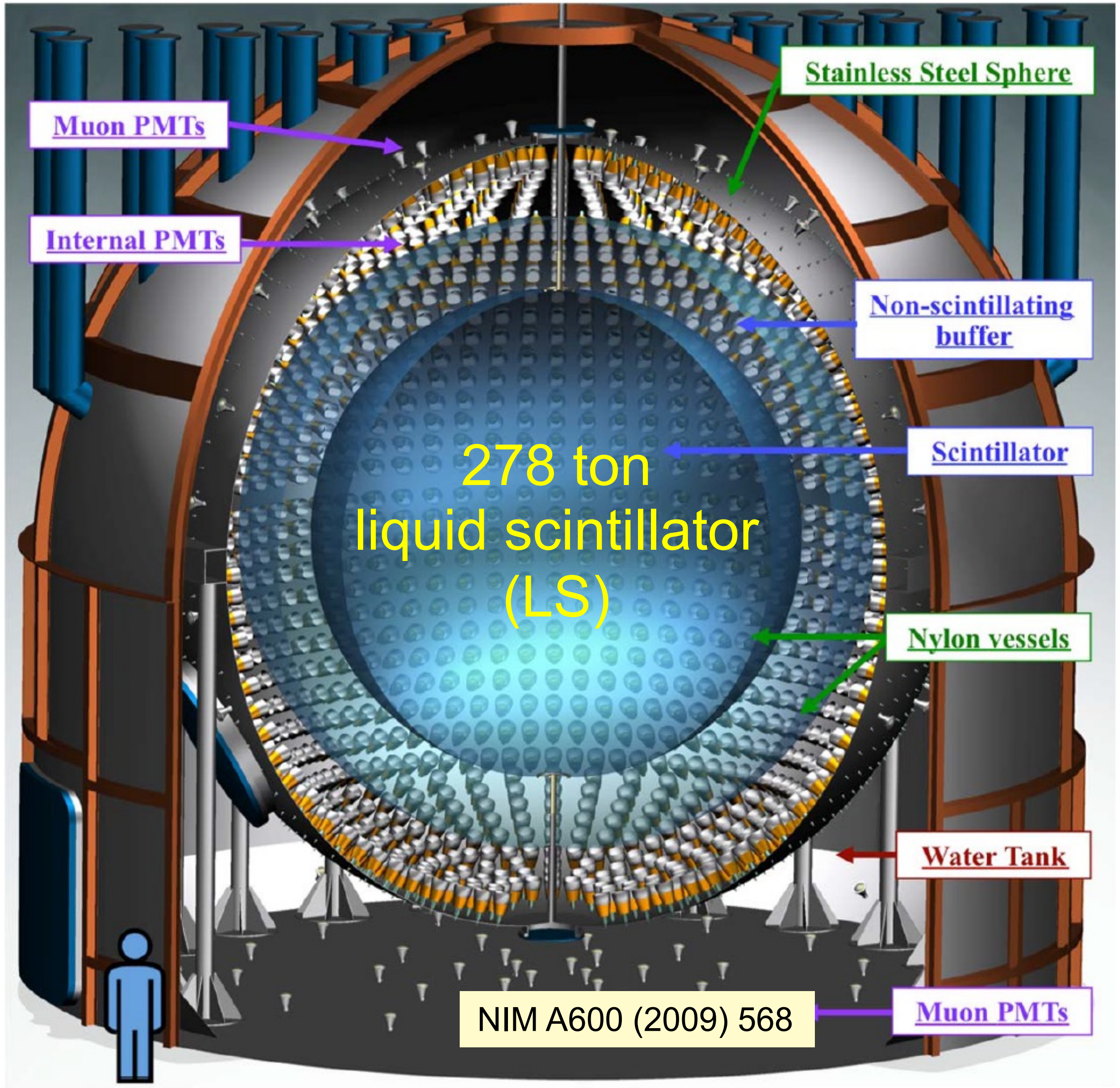
arXiv:2511.11856v2

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy



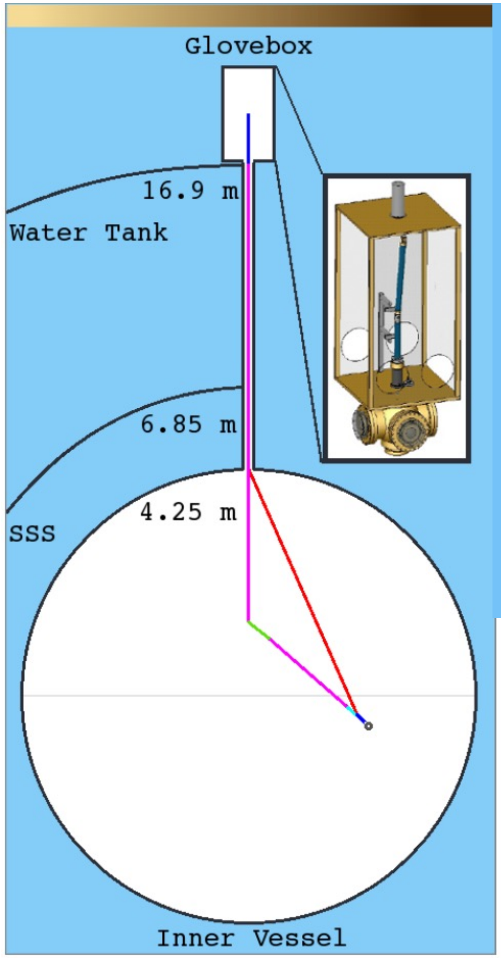
- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g LS , $< 8 \times 10^{-20}$ g(U)/g LS
- **~500 hit PMTs / MeV**
- energy reconstruction: 5 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



Operated from 05/2007 to 10/2021

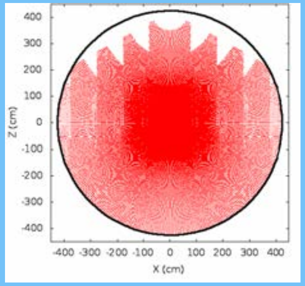
BOREXINO CALIBRATION

Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV

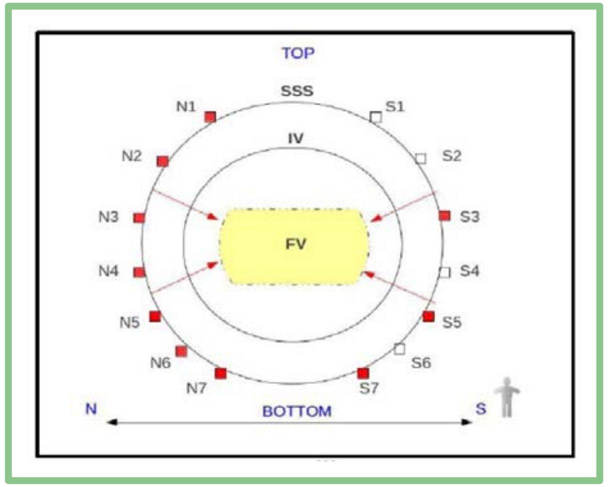


Internal calibration

- ~300 points in the whole scintillator volume
- LED-based source positioning system



JINST 7 (2012) P10018

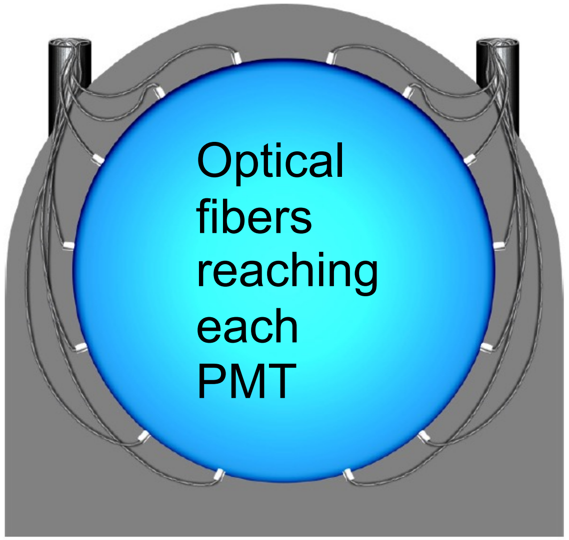


External calibration

9 positions with ^{228}Th source (γ 2.615 MeV)

Laser calibration

- PMT time equalisation
- PMT charge calibration (charge calib. also using ^{14}C)



BOREXINO MONTE CARLO

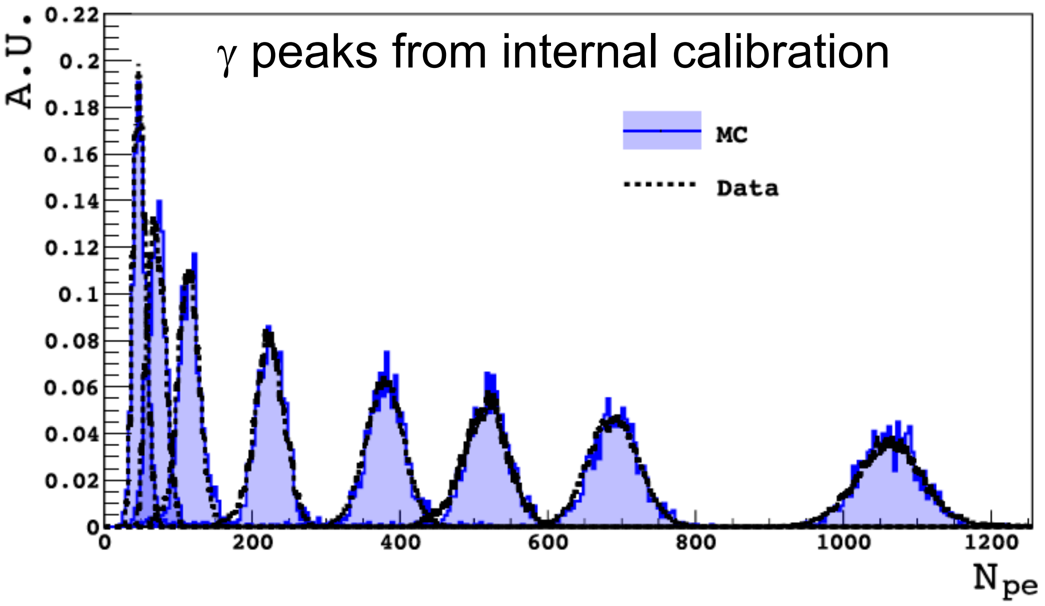
Better than 1% precision
for all relevant quantities in the solar analysis <2 MeV

Astrop. Phys. 97 (2018) 136

Geant-4 based
Tracking code
- Full detector geometry
- Energy loss
- Photon production & propagation

C++ Borexino custom
Electronics simulation
Follows real DAQ conditions
- PMT quality and calibration
- Dark noise
- Trigger condition
- Number of working channels on an event-by-event basis

Echidna: C++ Borexino custom
Reconstruction
- Several energy estimators
- Position reconstruction
- Pulse-shape variables
- Output in the same format as reconstructed data files



- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.

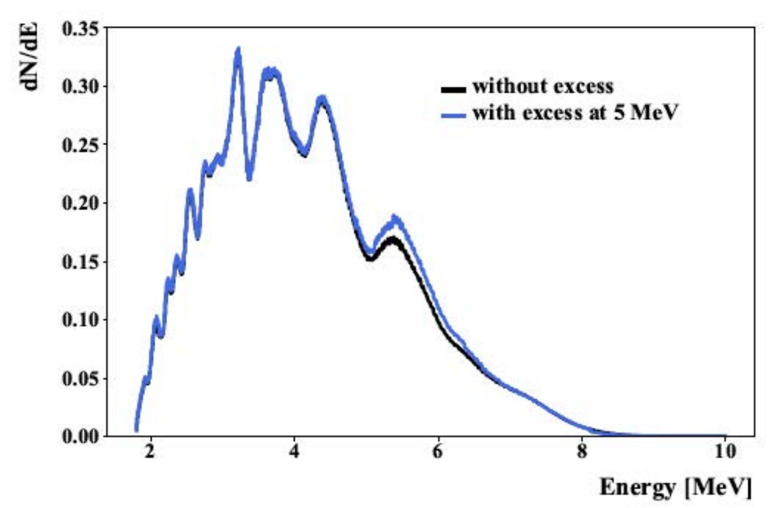
The spectral shape of signal (geoneutrinos) and most of the background components (see later) is produced with this tuned MC.

NEUTRINO BACKGROUNDS

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

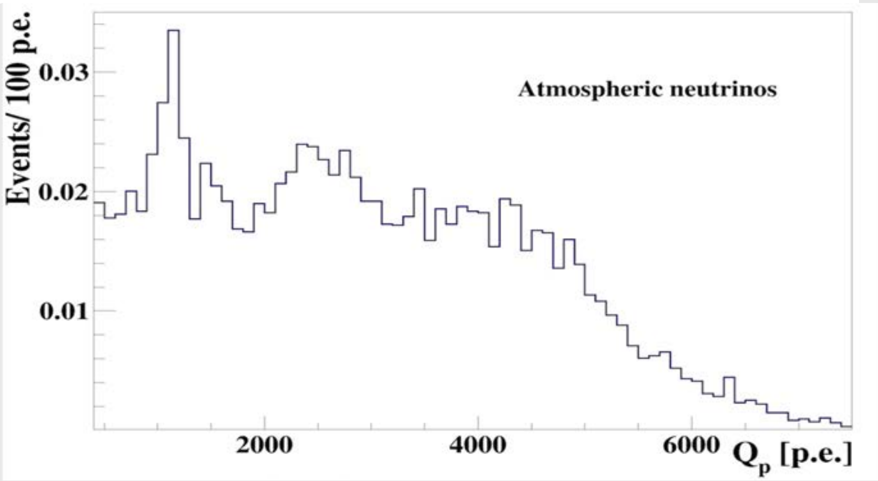


Atmospheric neutrinos (minor)

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.

MAJOR NON-ANTINEUTRINO BACKGROUNDS

1) <u>Cosmogenic background</u>

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

Data driven: IBD-like pairs AFTER muons and MC simualtion

2) <u>Accidental coincidences:</u>

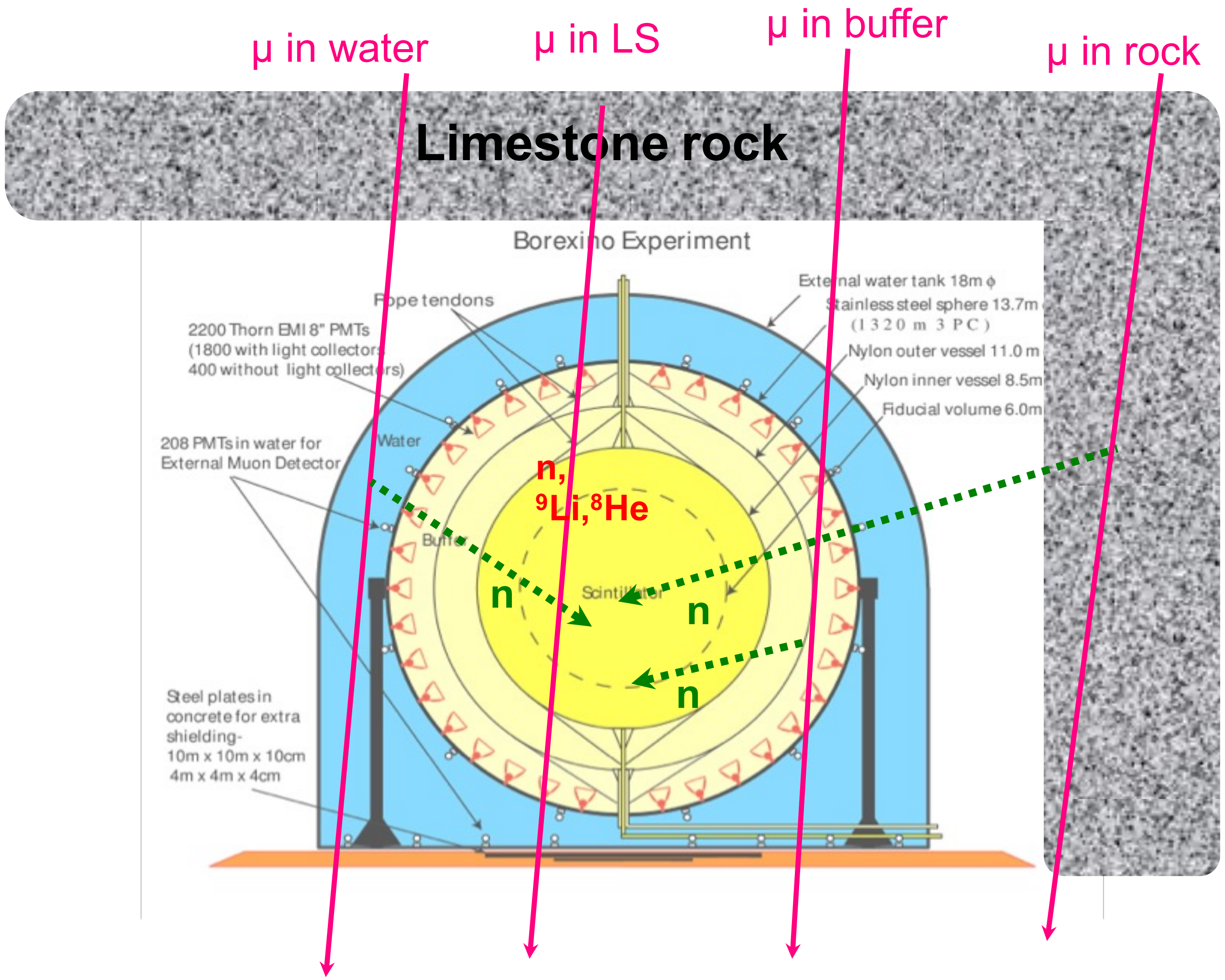
Typically from external backgrounds

Data driven estimation: OFF-time window

3) <u>^{13}C(^{210}Po(α), n)^{16}O reaction:</u>

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

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



Credit: Borexino collaboration

OPTIMIZED IBD SELECTION CUTS

Example: Borexino

Efficiency: (86.98 ± 1.50)%

Energy of prompt

Q_p > 408 pe

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

Energy of delayed

Q_d > 700 (860) – 3000 pe

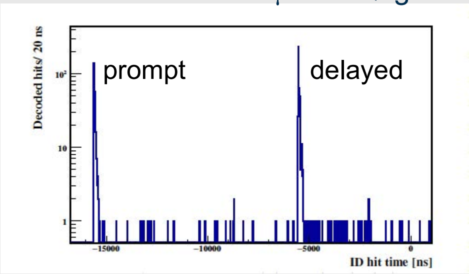
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)
- Spill out effect at the nylon inner vessel border
- Radon correlated ^{214}Po$(\alpha + \gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

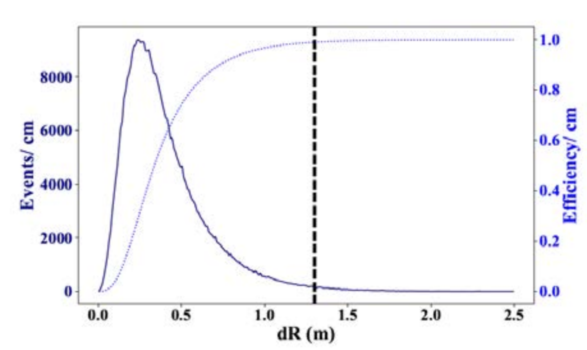
Neutron capture τ = (254.5 ± 1.8) μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

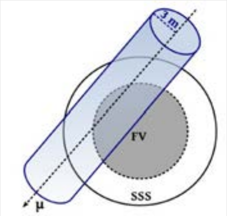


Muon veto

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

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



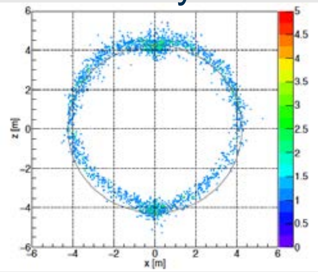
- Whole detector
- **Cylinder**

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

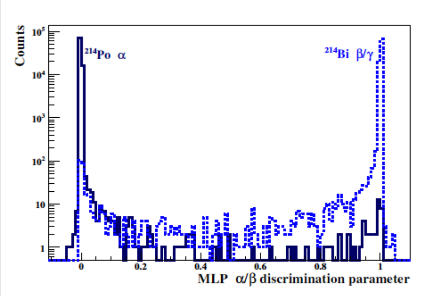
No event with Q >400 pe ±2 ms around promt/delayed

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

α/β discrimination

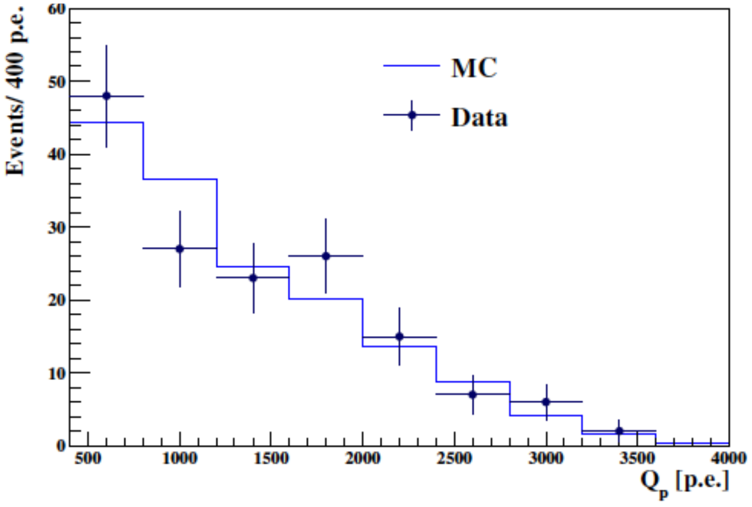
$MLP_{delayed}$ > 0.8

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

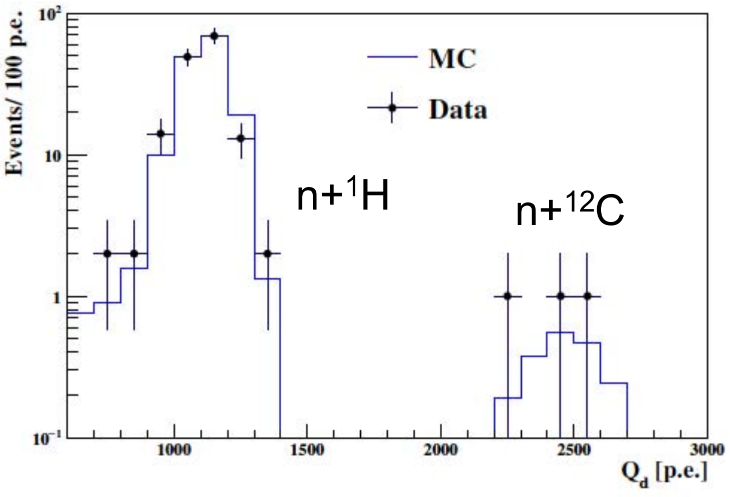


BOREXINO GOLDEN CANDIDATES: 154 in 9 years!

Prompt charge spectrum

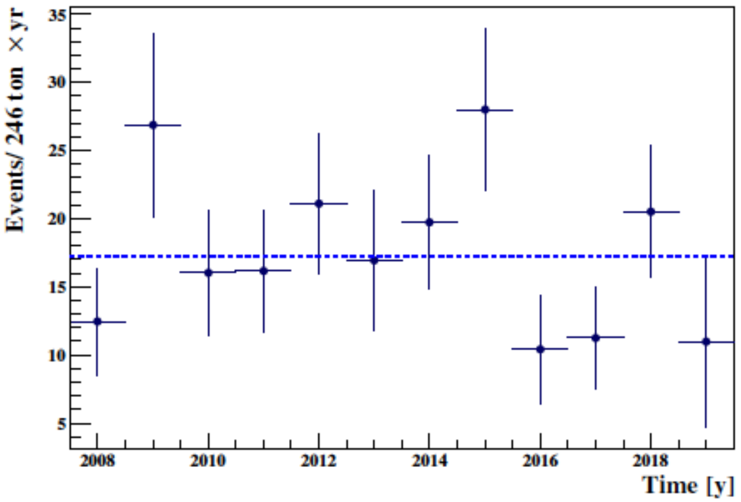


Delayed charge spectrum

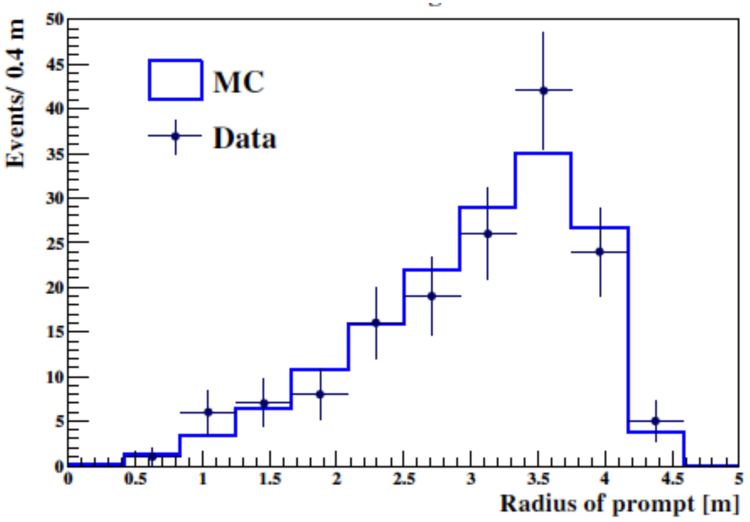


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

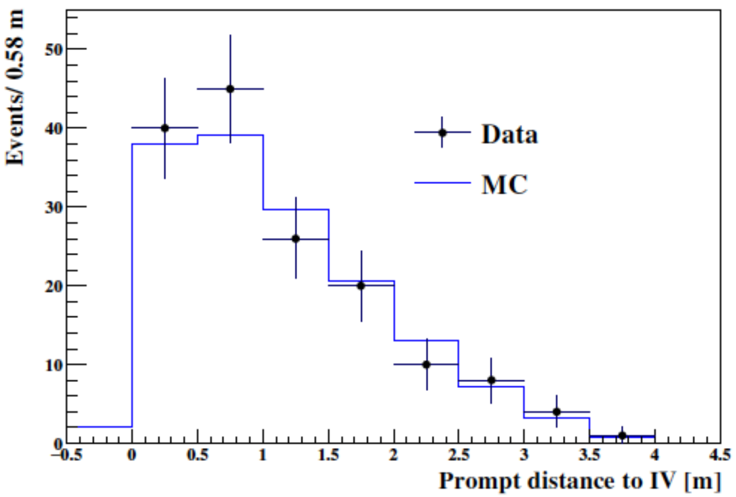
Distribution in time



Radial distribution



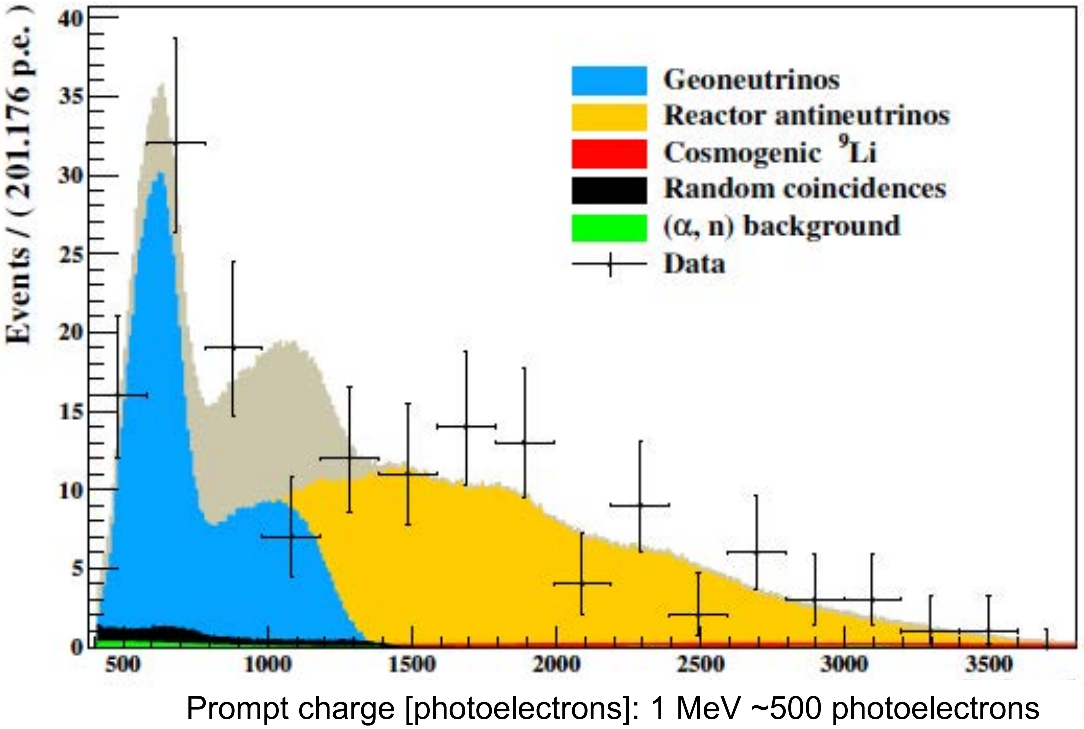
Distance to the Inner Vessel

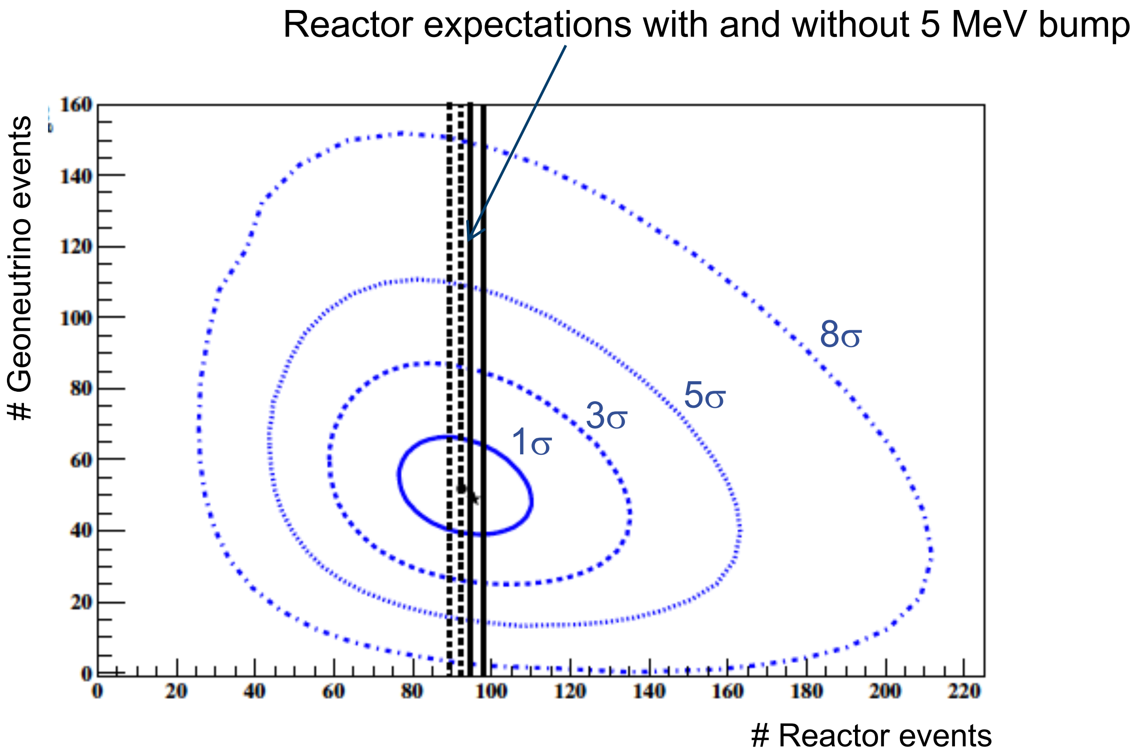


We have then golden candidates
found as time and spatial coincidences:

- They can be due to:
  - ✓**Geo-neutrinos;**
  - ✓**Reactor antineutrinos;**
  - ✓**Non-antineutrino backgrounds;**
- We need to estimate different contributions and then to extract the number of measured geo-neutrinos by fitting the E_{prompt} energy spectrum;

SPECTRAL FIT with fixed chondritic Th/U ratio





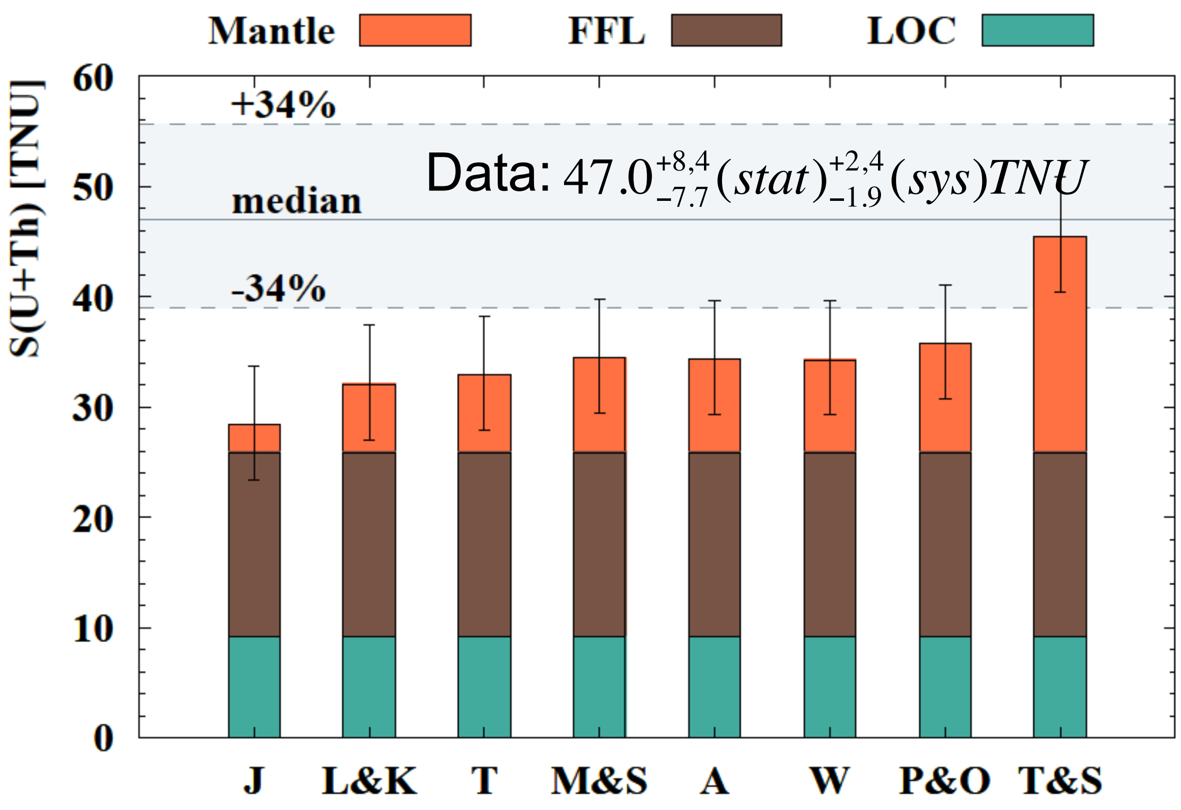
- Unbinned likelihood fit of charge spectrum of 154 prompts
- S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)
- **Reactor signal unconstrained** and result compatible with expectations
- ^{9}Li, accidentals, and (α, n) background constrained to expectations
- **Systematics** includes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

Resulting number of geoneutrinos (median value)

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

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

GEONEUTRINO SIGNAL AT LNGS: DATA VS BSE MODELS

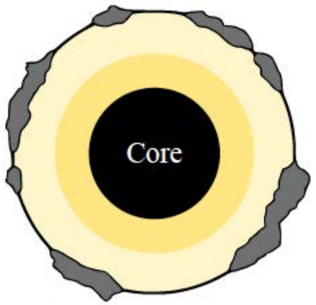


In agreement with expectations

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

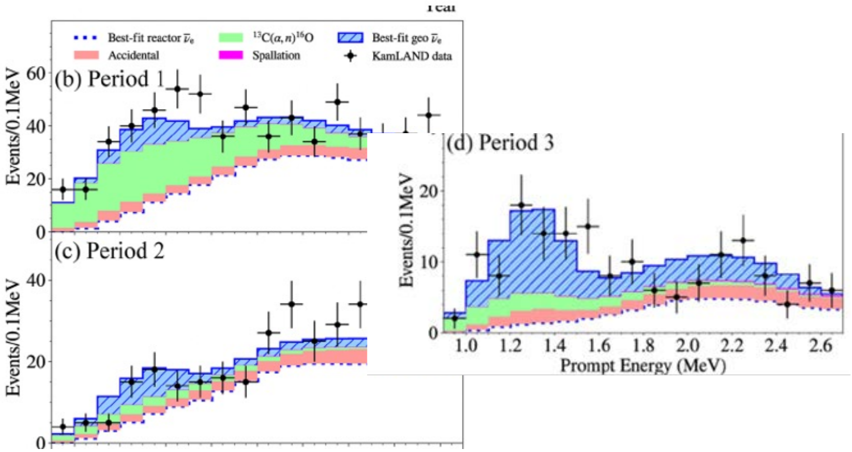
J: Javoy at al., 2010
L&K: Lyubetskaya and Korenaga, 2007
T: Taylor, 1980
M&S: Mc Donough and Sun, 1995
A: Anderson, 2007
W: Wang, 2018
P&O: Palme and O'Neil, 2003
T&S: Turcotte and Schubert, 2002

EXPERIMENTS THAT MEASURED GEONEUTRINOS

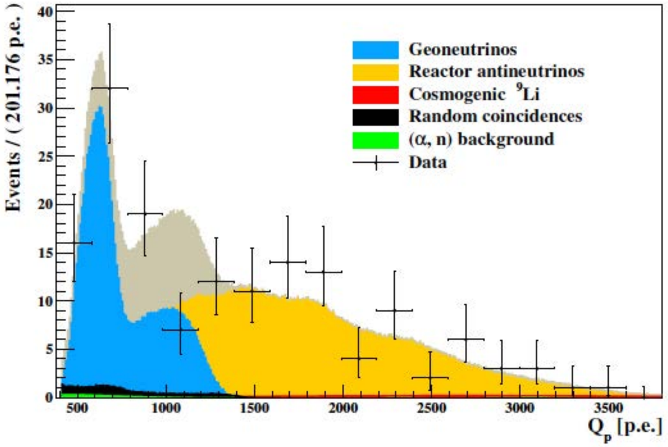
KamLAND, Kamioka, Japan
Border between
OCEANIC / CONTINENTAL CRUST

Borexino, LNGS, Italy
CONTINENTAL CRUST

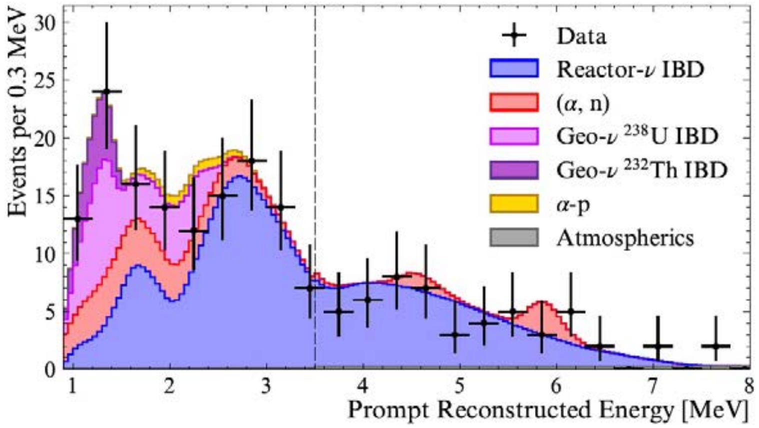
SNO+, Sudbury, Canada
CONTINENTAL SHIELD (OLD CRUST)



16%



18%



23%

5227 days (03/2002 – 12/2020), 905 m^3	3262 days (12/07 – 04/2019), 280 m^3	685 days (05/2022 – 07/2025) , 780 t
Not provided (**1178** in geo-ν energy window)	**154 total** (~90 in geo-ν energy window)	185 (~126 in geo-ν energy window)
$183^{+15.8}_{-15.3}$% **geo-ν**	$52.6^{+18.3}_{-17.2}$% **geo-ν**	$35^{+8.2}_{-7.6}$ **geo-ν**
$28.6^{+5.1}_{-4.8}$ TNU	$47.0^{+8.7}_{-7.9}$ TNU	49^{+13}_{-12} TNU
Rate + shape + time	Rate + shape, reactor-ν free	Rate + shape, osc. priors, (α, n) discrim., lkl cut for accidentals

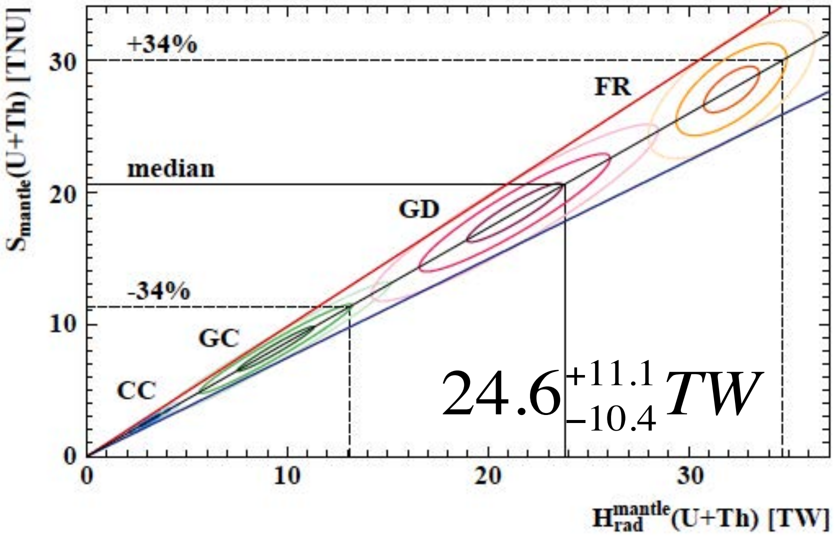
Phys. Rev. D 101 (2020) 012009

Geophys. Res. Lett. 49 e2022 GL099566

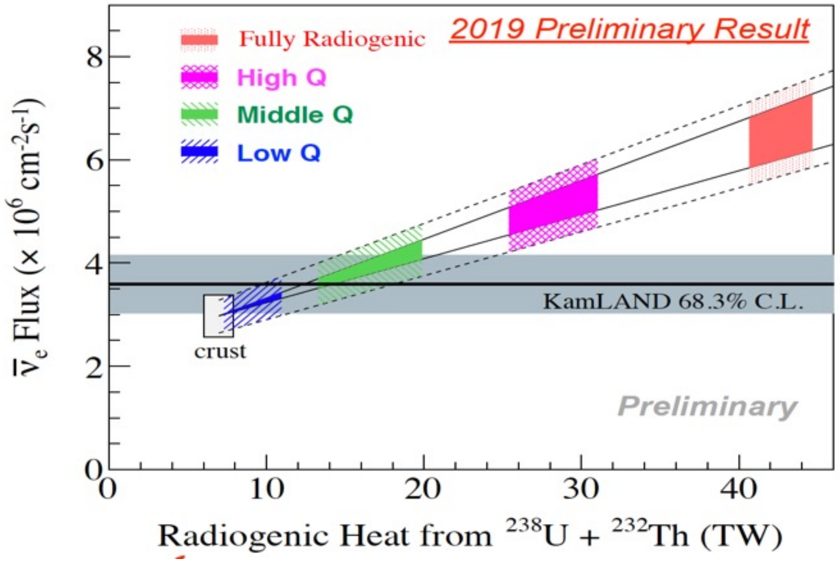
arXiv:2511.11856v2

RADIOGENIC HEAT: Borexino vs KamLAND

Borexino U+Th mantle signal:



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

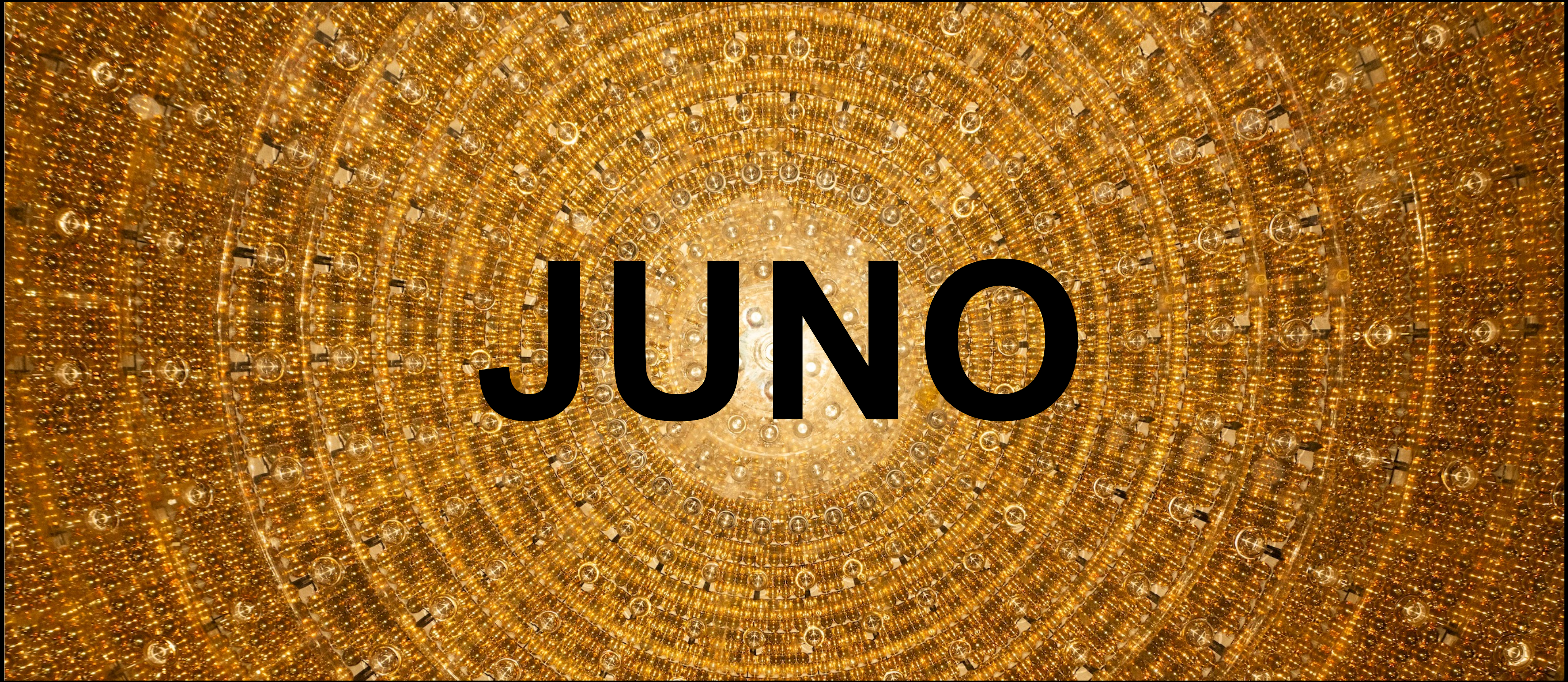


- General agreement data vs BSE models: big success
- Borexino is least (2.4σ) compatible with the BSE models predicting the lowest U+Th mantle abundances
- KamLAND preference for Low Q and Middle Q BSE models

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

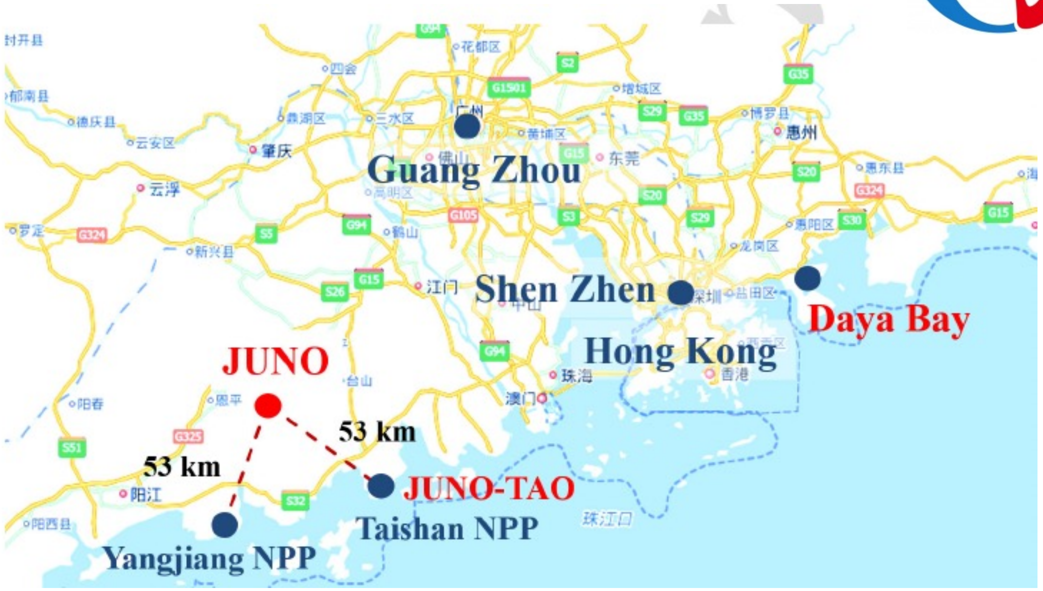

Where to navigate next?
EUROPA
© Livia Ludhova Photography
Photocredit: LL, Bark Europa @ Weddell Sea, Antarctica

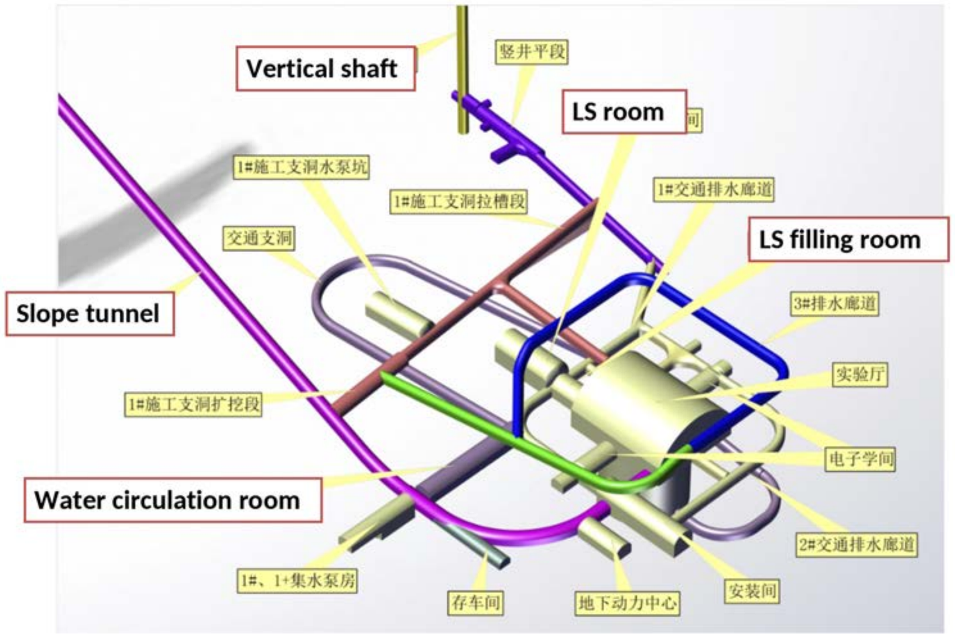
JIANGMEN UNDERGROUND NEUTRINO OBSERVATORY
2O-KTON LIQUID SCINTILLATOR DETECTOR IN SOUTH CHINA
DATA TAKING STARTED ON AUGUST 26, 2025.



JUNO SITE

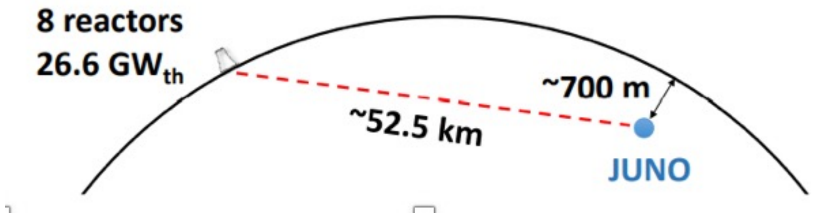
Dedicated underground laboratory
~650 m rock overburden (1800 m w.e)





Baseline difference for all cores should be < 500 m.

Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
	Yangjian						Taishan			
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

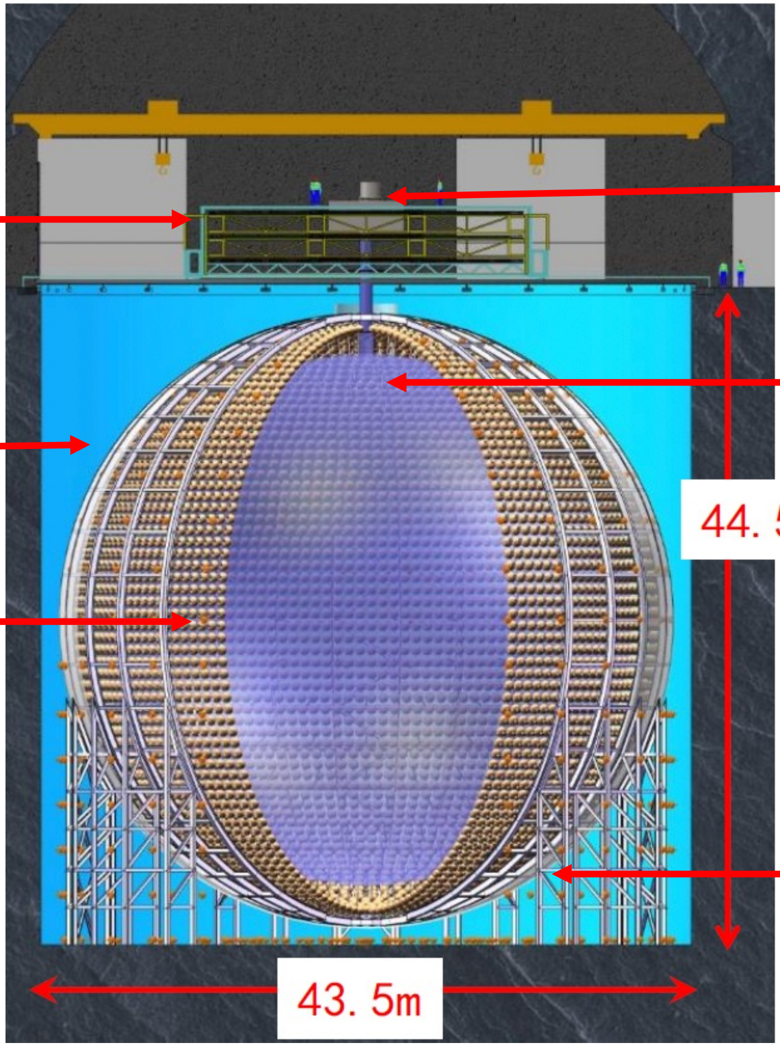


JUNO DETECTOR DESIGN

Top Tracker

Calibration house

Water Pool
Water Cherenkov μ veto
2404 20" PMTs



Acryllic Sphere

Diameter = 35.4 m

Central Detector
20 kton of LS

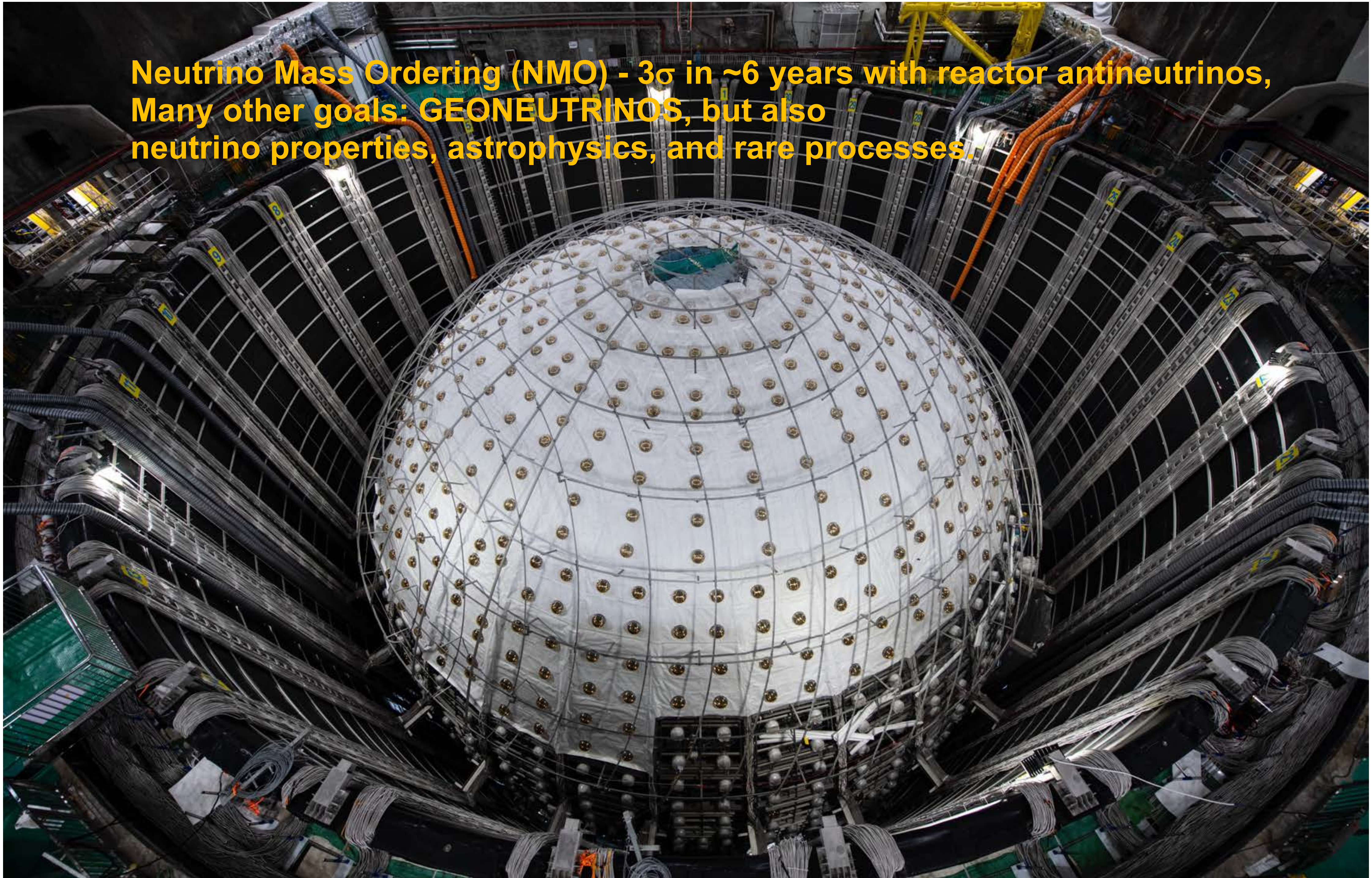
Linear Alkali Benzene (LAB) + PPO + bis-MSB + BHT

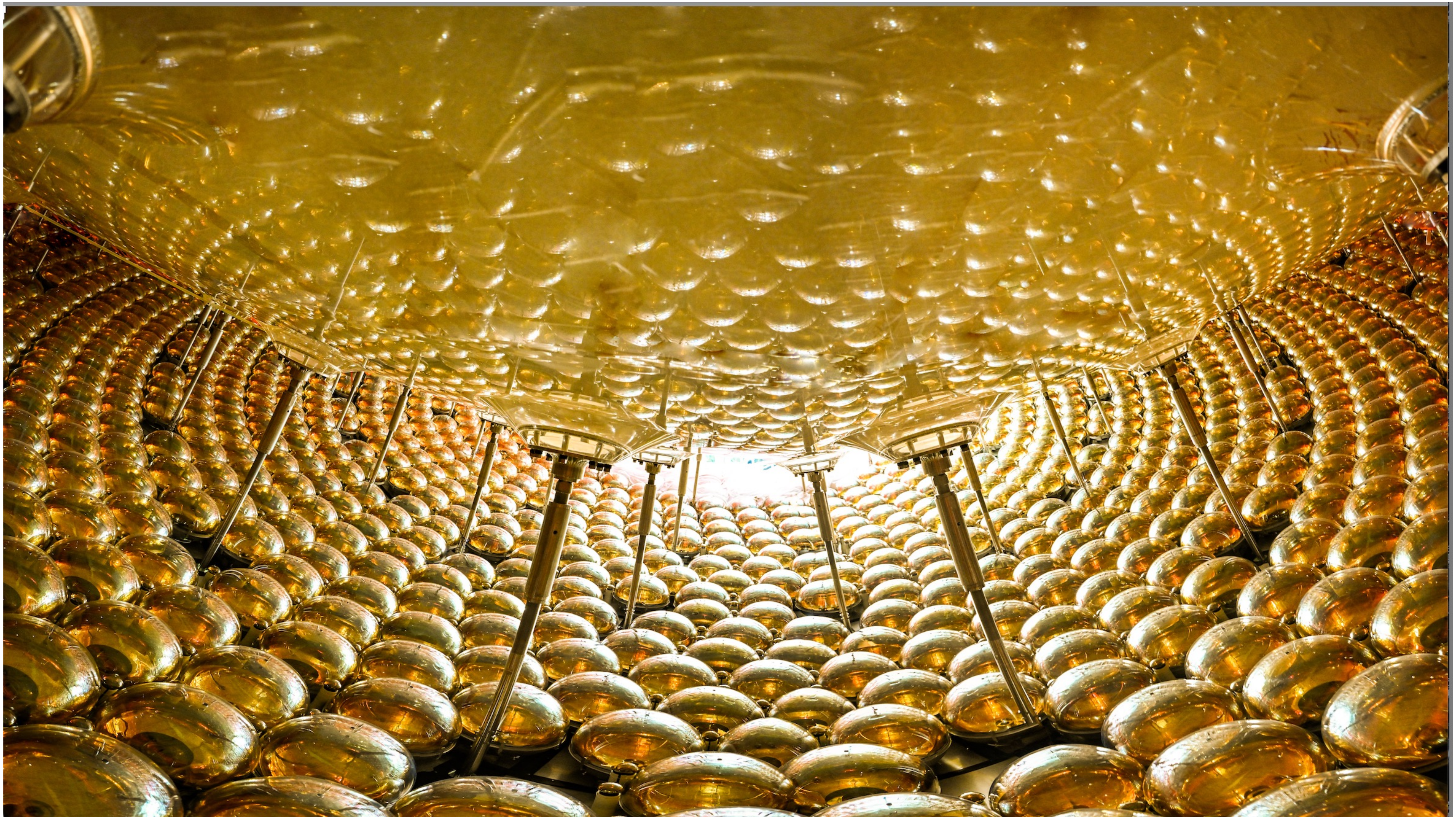
17596 20" PMTs (large) +
25587 3" PMTs (small)

Stainless steel Latticed Shell

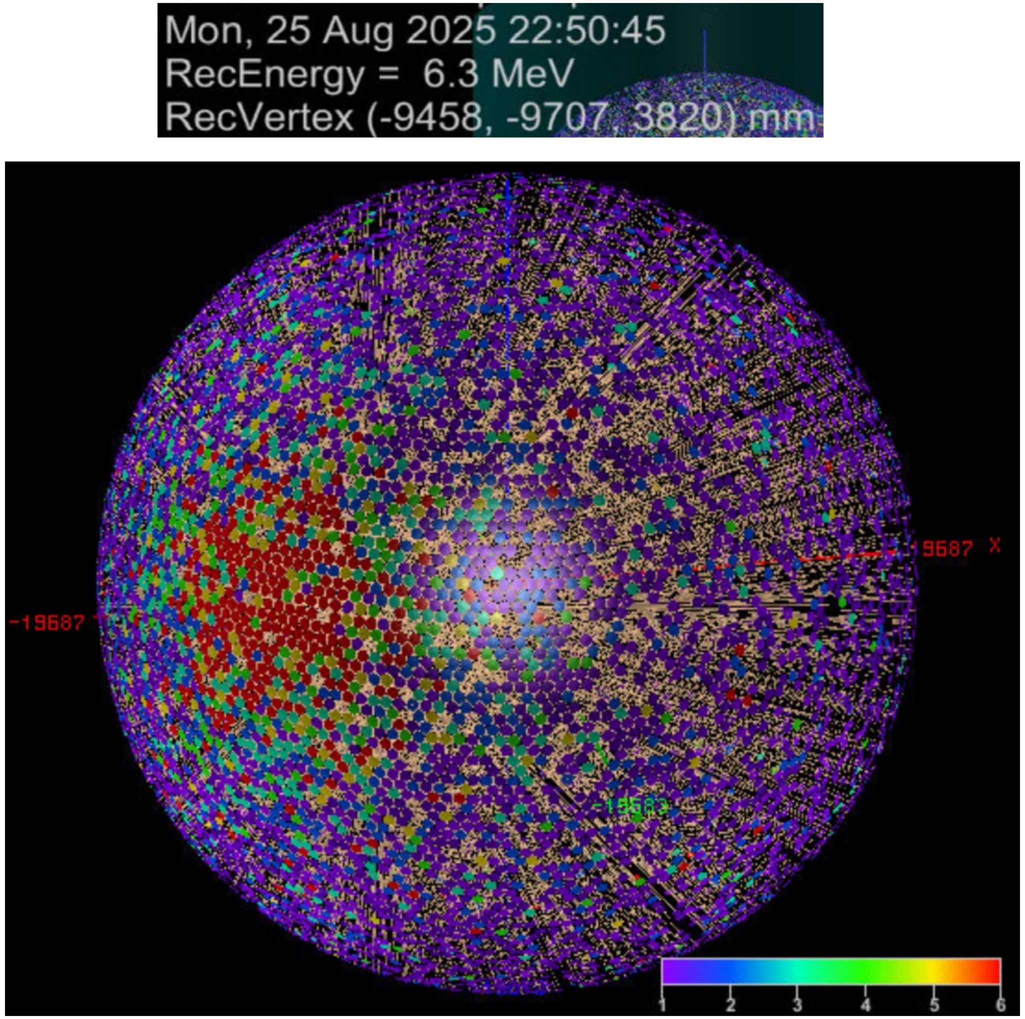
Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8x20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	78%
Energy resolution	8.5% / √E MeV	~5%/√E MeV	~6%/√E MeV	~3%/√E MeV
Eff. Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	>1300 p.e./MeV

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

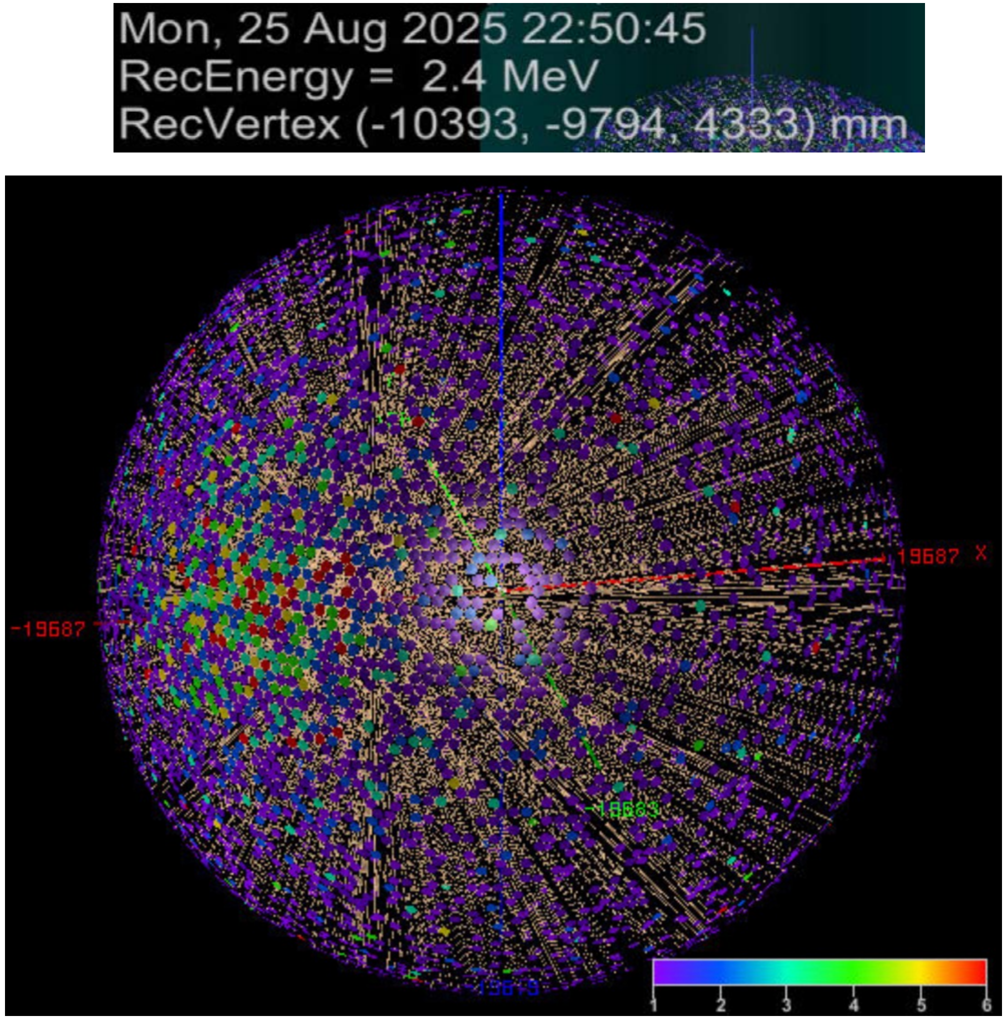




THE FIRST ANTINEUTRINO EVENT

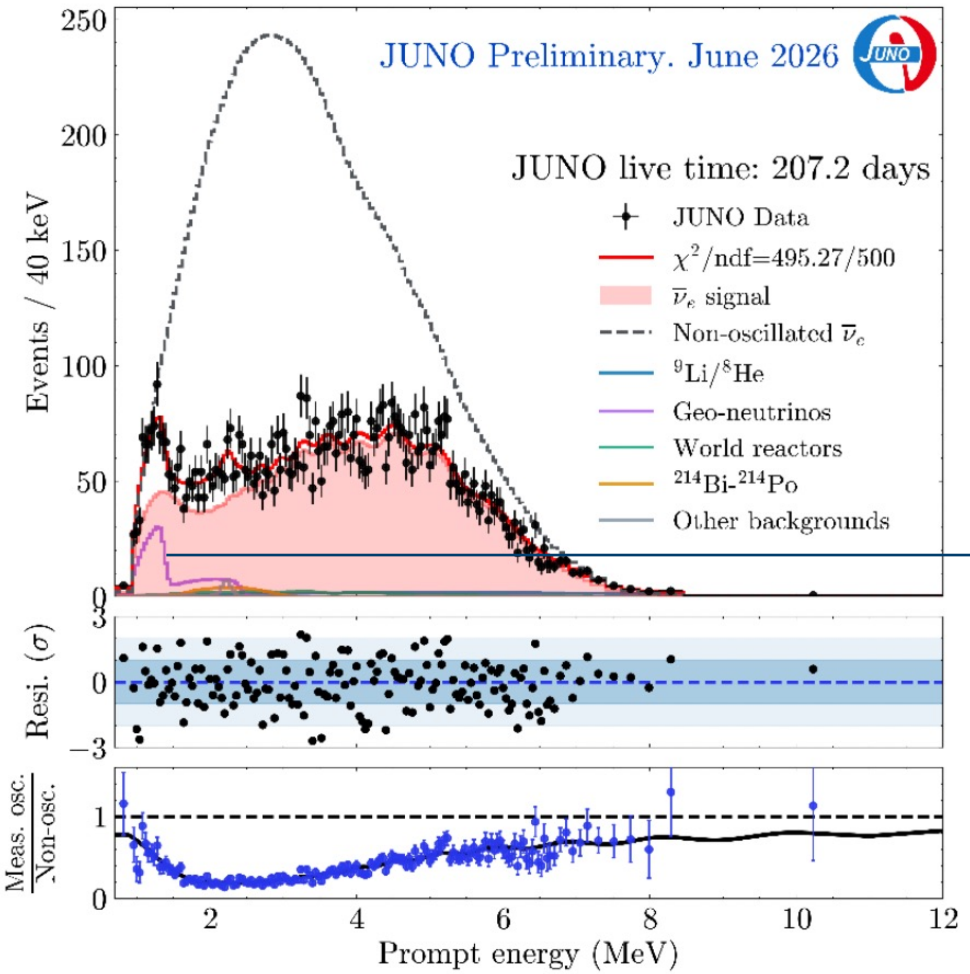


Prompt e+ signal



Delayed neutron signal

THE JUNO DATA & FISRT GEONEUTRINO RESULTS



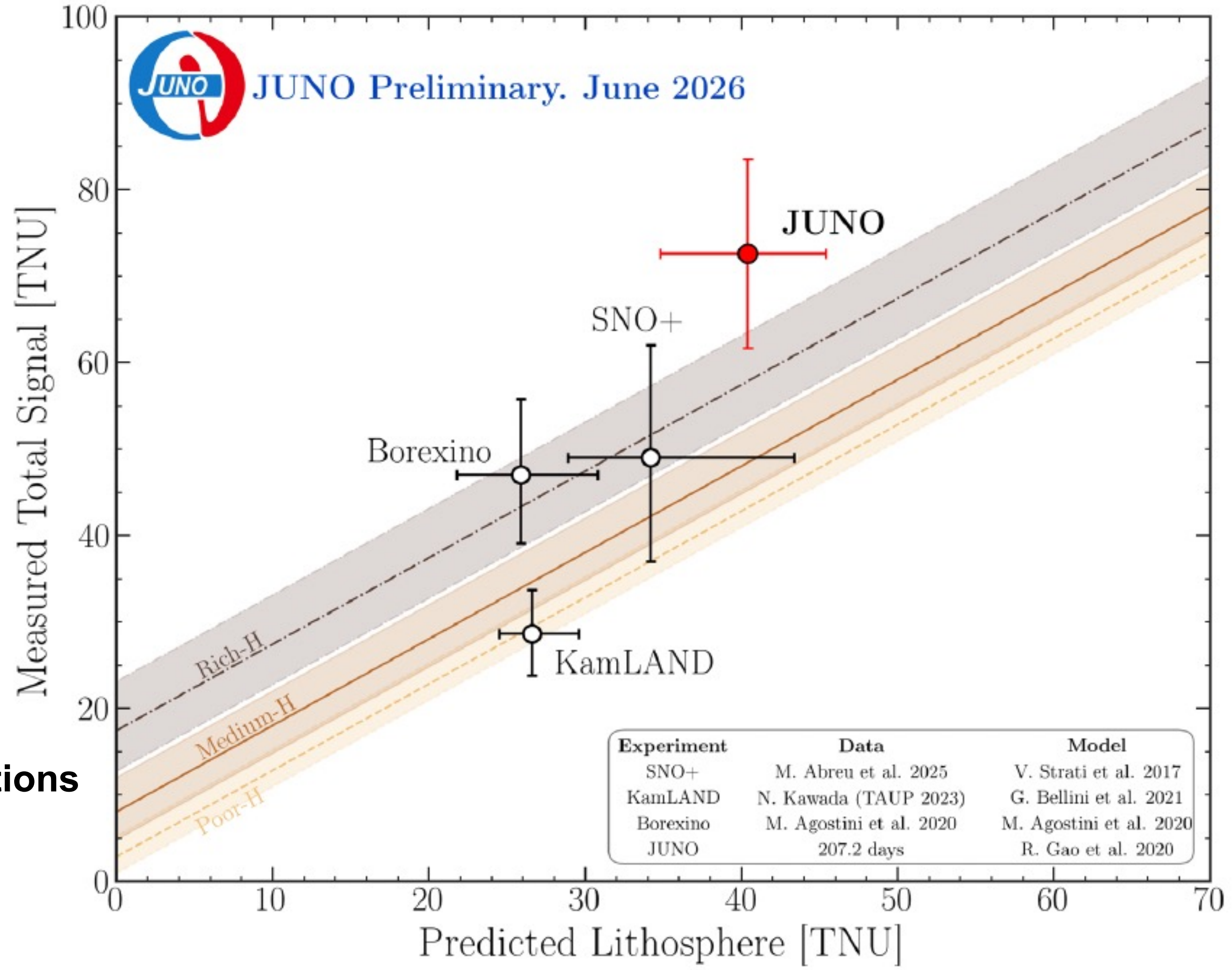
Big advantage:
- ✓ Large volume and thus high statistics: **400 geoneutrinos / year.**

Main limitations:
- ✓ Large **reactor neutrino background (NMO!)**
- ✓ Relatively shallow depth – cosmogenic background.

- Clear geo-nu signals at 1-3 MeV, giving a flux of 73 ± 11 TNU
- Largest geo-neutrino samples so far.

- JUNO result is higher than expectation from existing models, but not statistically significant.
- Need more JUNO data and more refined geological model predictions.

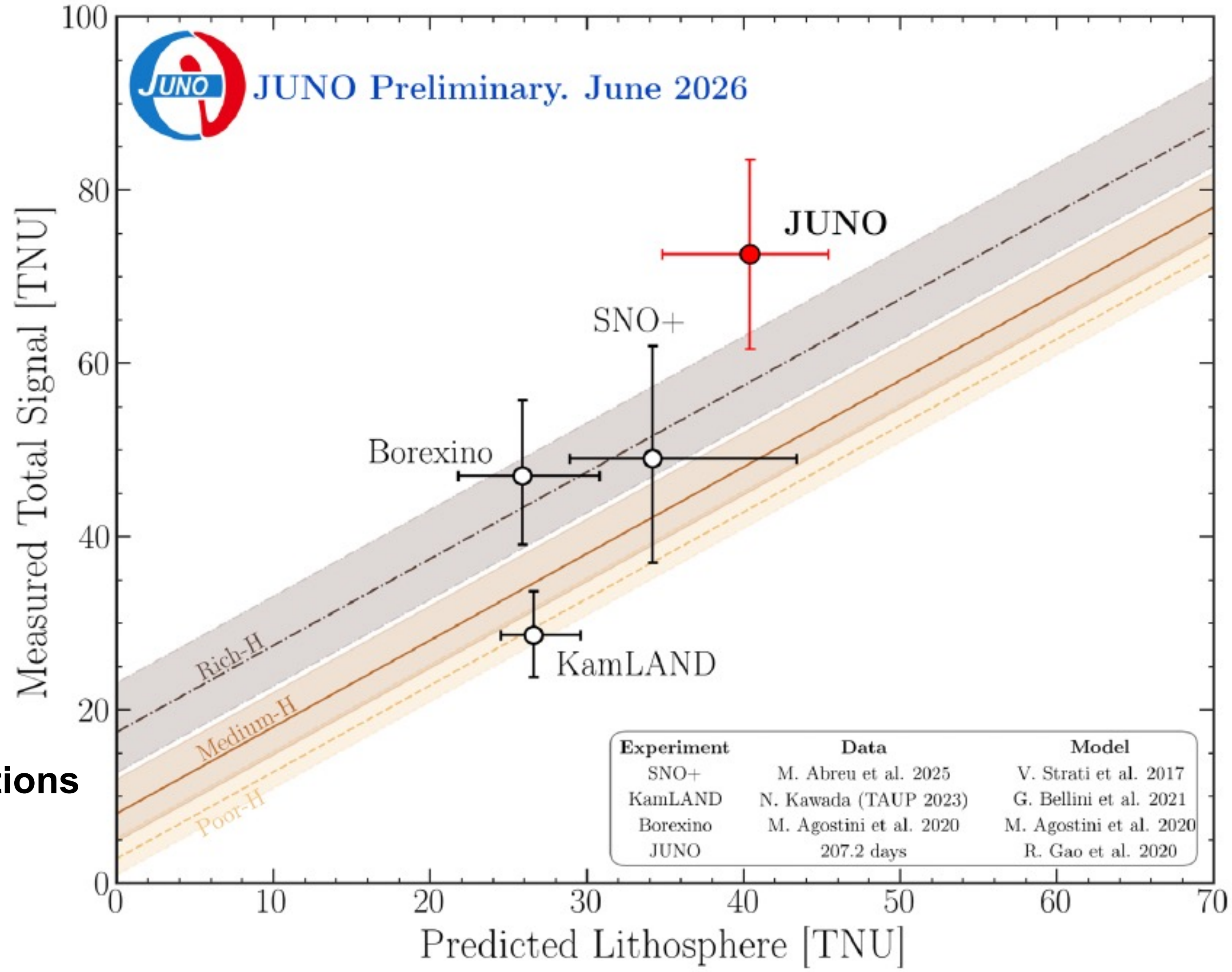
MULTISITE MEASUREMENTS & MANTLE SIGNAL



Y-offset = mantle contributions
(assumes homogenous mantle)

MULTISITE MEASUREMENTS & MANTLE SIGNAL

Assuming homogeneous mantle, but……

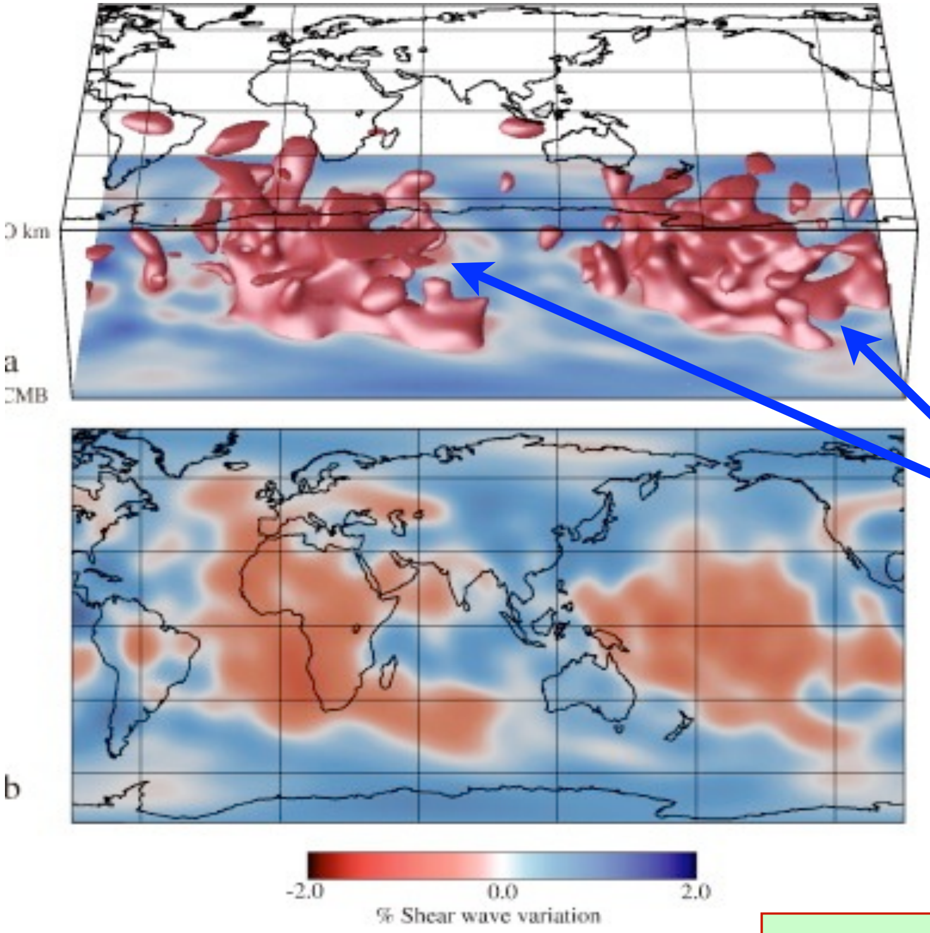


Y-offset = mantle contributions

(assumes homogenous mantle)

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

JINPING NEUTRINO EXPERIMENT (JNE), CHINA

Jinping Underground Laboratory – deepest in the world.

Almost no background from reactors.

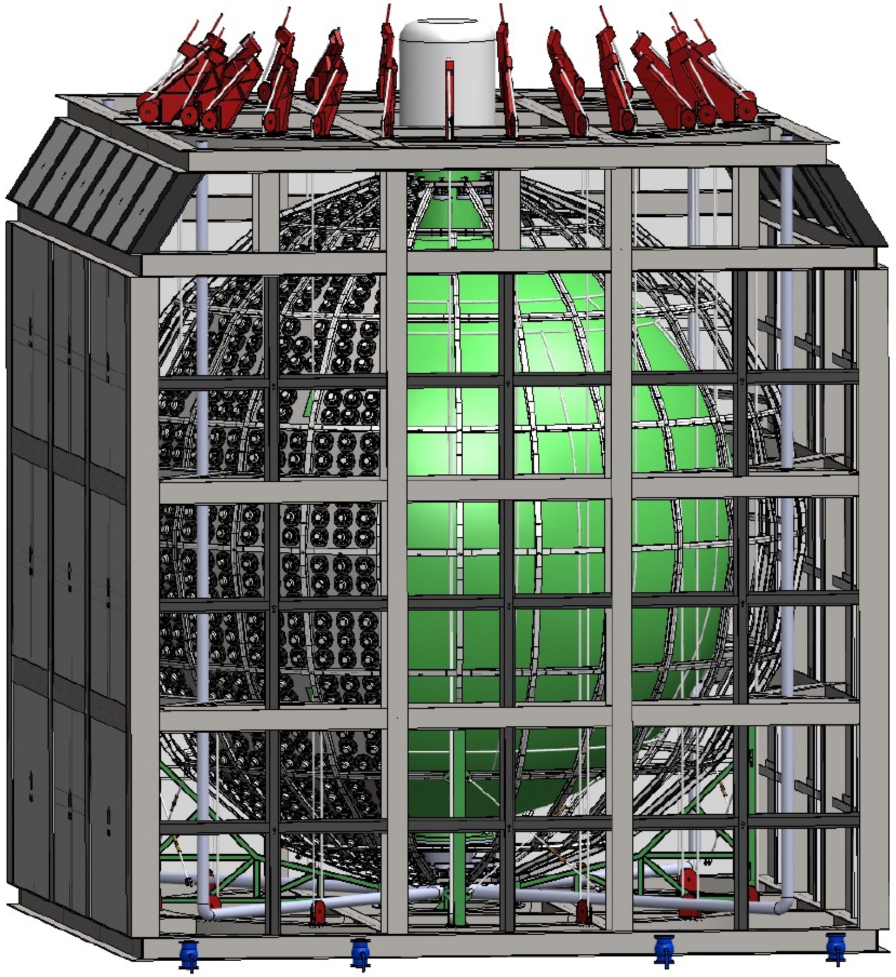
Very thick continental crust in Himalayan region.

Slow scintillator to enable separation of the fast Cherenkov light.

Measurement of the heat-producing element abundance in Qinghai-Tibet

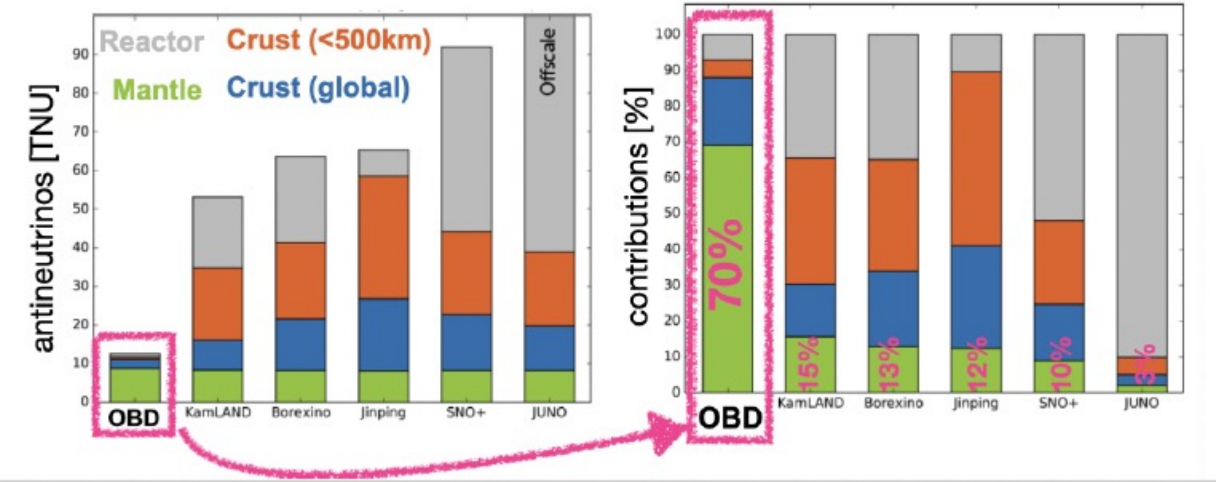
Acrylic vessel: 9.96 m (diameter), 5 cm (thickness)
500 cubic meters

Detector construction will start this year!

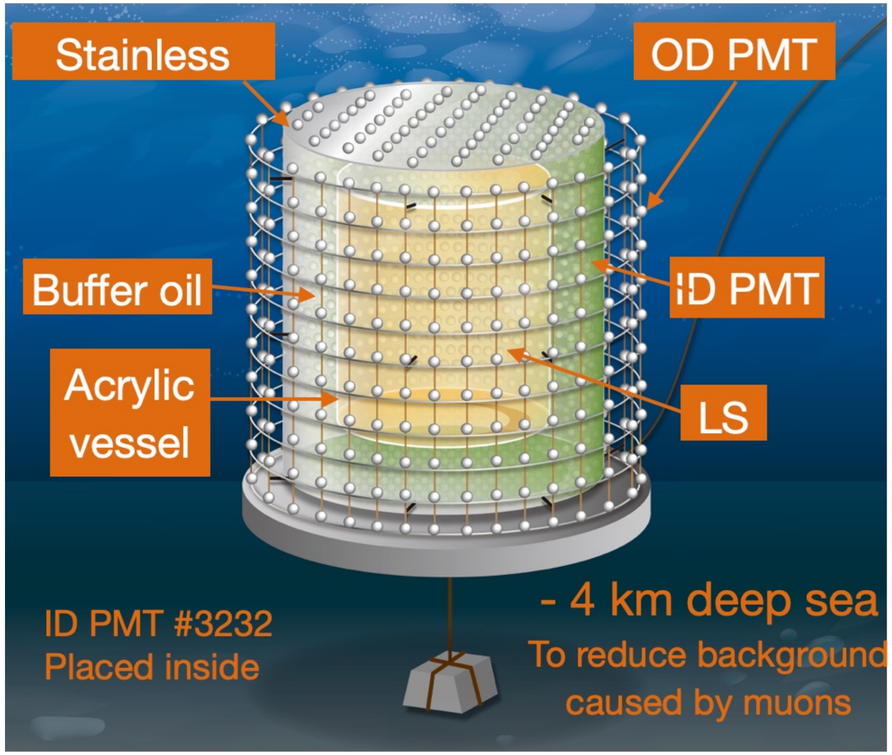


Thanks to Zhe Wang.

OCEAN BOTTOM DETECTOR (OBD)



The ultimate geoneutrino detector!



Direct access to the mantle signal.

Oceanic crust is thin, simple, and depleted in U and Th.

Many technological challenges @ **40 MPa, 2- 4**℃

H. Watanabe et al., Underwater Technology 2023.

- **Prototype for 1 km depth:** under construction.
- Collaboration and community supports are being enhanced. (Tohoku U., U. Hawaii, Chiba U., LLNL.

LESSONS LEARNED & OUTLOOK

Statistics – big detectors & years of exposure

- ✓ Low geoneutrino interaction rate.
- ✓ Mantle signal much smaller than crustal signal.
- ✓ U & Th separation – very large exposure.

Backgrounds

- ✓ Reactor antineutrinos – possibly far away, but modelling possible.
- ✓ Cosmogenics – as deep as possible.
- ✓ Accidental coincidences - clean materials.
- ✓ (α, n) reactions - ^{210}Po contamination
- ✓ Atmospheric neutrino backgrounds (for future large exposures).

Geology / Earth Model Uncertainties

- ✓ Local crust modelling & mantle signal
- ✓ Converting flux to radiogenic heat

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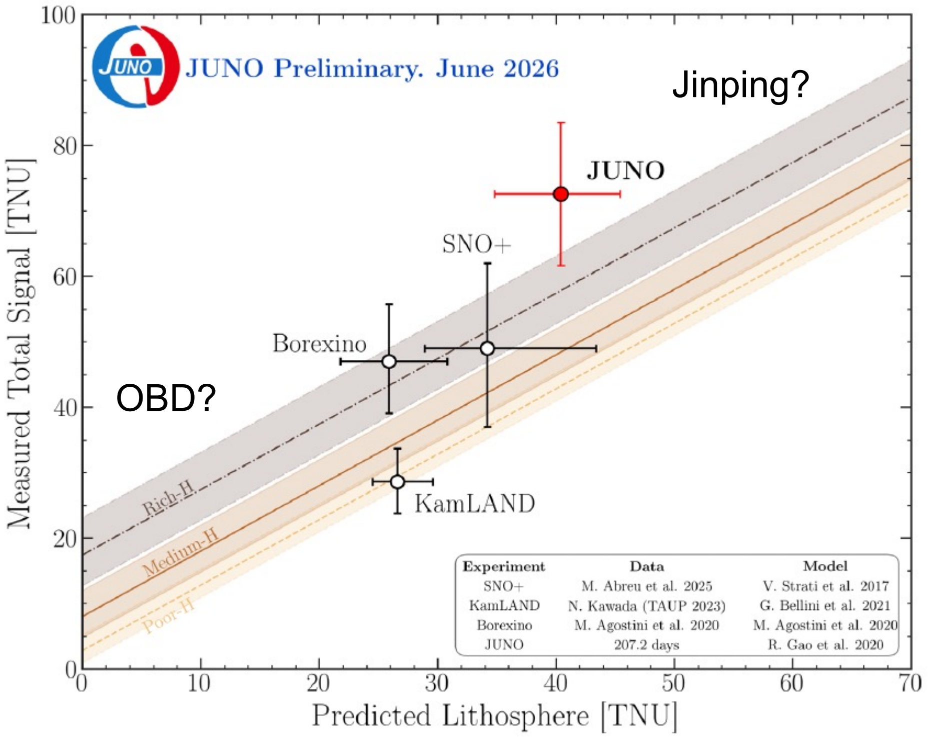
Multi-site measurements



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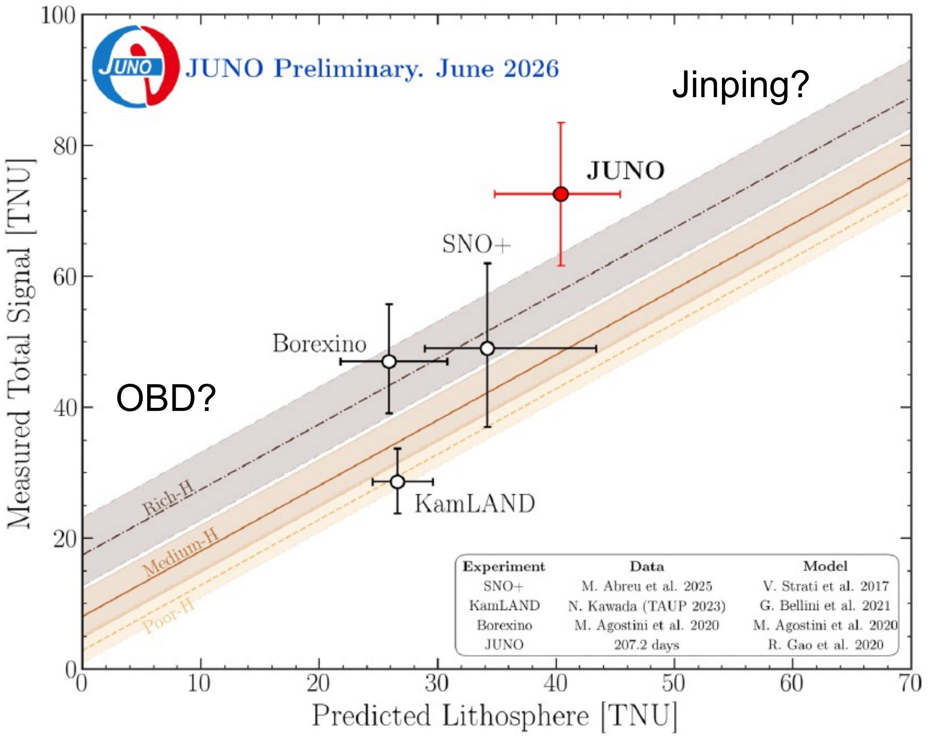


Exciting times ahead of us, but new technologies needed for even more precise measurements and improved geological interpretation!

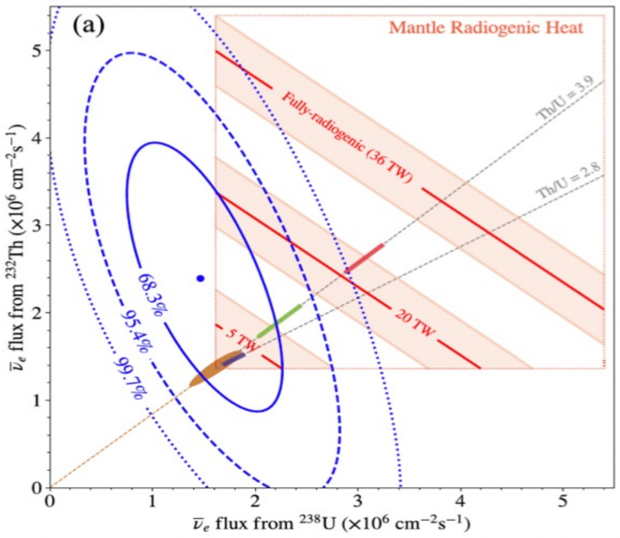
Photo credit L.L., Shiveluch volcano, Kamchatka, Russia

Thank you!

Back up slides

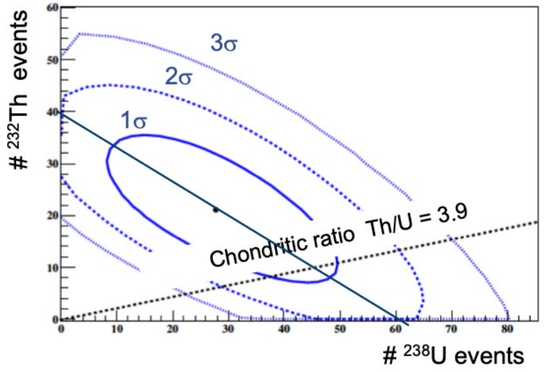
U and Th individual contributions

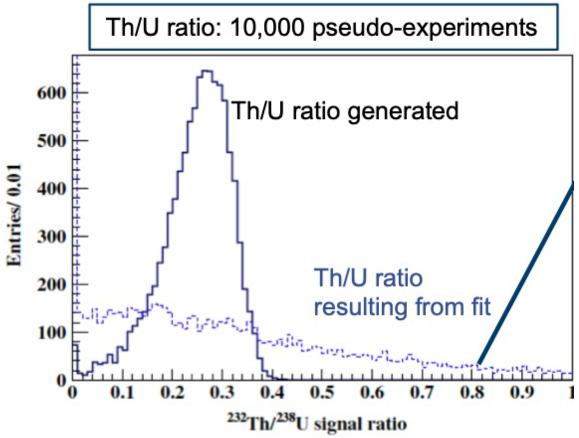
KamLAND, Kamioka, Japan
Border between
OCEANIC / CONTINENTAL CRUST



	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, LNGS, Italy
CONTINENTAL CRUST





SNO+
CONTINENTAL SHIELD (OLD CRUST)

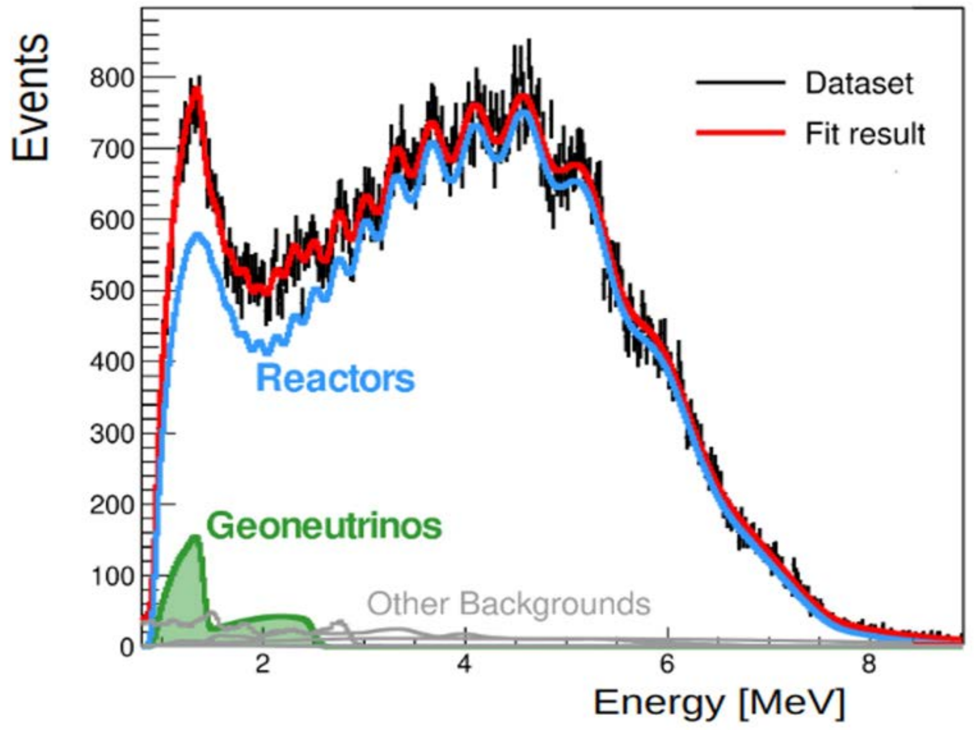
TABLE III. Best-fit values for oscillation parameters and geo-$\bar{\nu}$ IBD rate. Results are reported with no external constraints on Δm^2_{21} and $\sin^2\theta_{12}$, then with constraints, and finally with constraints and the cut on the classifier for (α, n) proton-scattering events. See text for details.

	Fit	Fit (con.)	Fit (α, n) cut
Δm^2_{21} [$\times10^{-5}$eV^2]	$7.93^{+0.21}_{-0.24}$	7.63 ± 0.17	7.56 ± 0.17
$\sin^2\theta_{12}$	0.505 ± 0.134	0.310 ± 0.012	0.311 ± 0.012
Geo-$\bar{\nu}$ [TNU]	60^{+23}_{-22}	61^{+23}_{-22}	49^{+13}_{-12}
Geo-$\bar{\nu}$ U/Th	$3.38^{+1.39}_{-1.41}$	$3.30^{+1.41}_{-1.44}$	$3.29^{+1.42}_{-1.48}$

Statistical limitation in the separation of the U and Th signals.
U and Th signals anti-correlated – smaller impact on the sum (U + Th).

GEONEUTRINOS IN JUNO

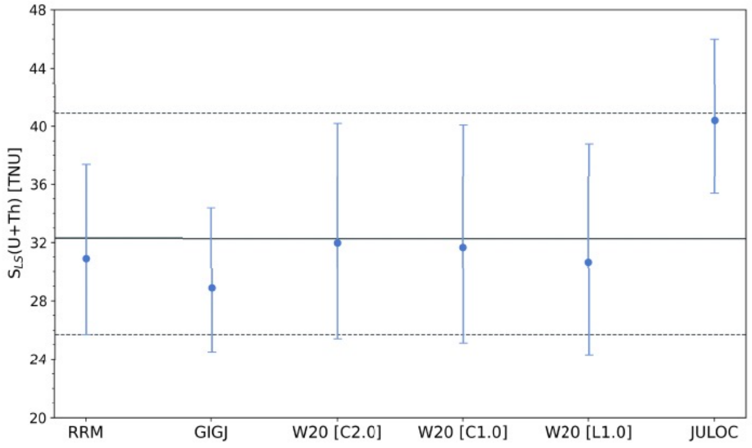
Simulation of 10 years of data



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

Main limitations:
- ✓ Large **reactor neutrino background.**
- ✓ Relatively shallow depth – cosmogenic background.

JUNO's main goal: Neutrino Mass Ordering with **reactor neutrinos,** that represent an irreducible background to **geoneutrinos.**



Expected lithospheric signal

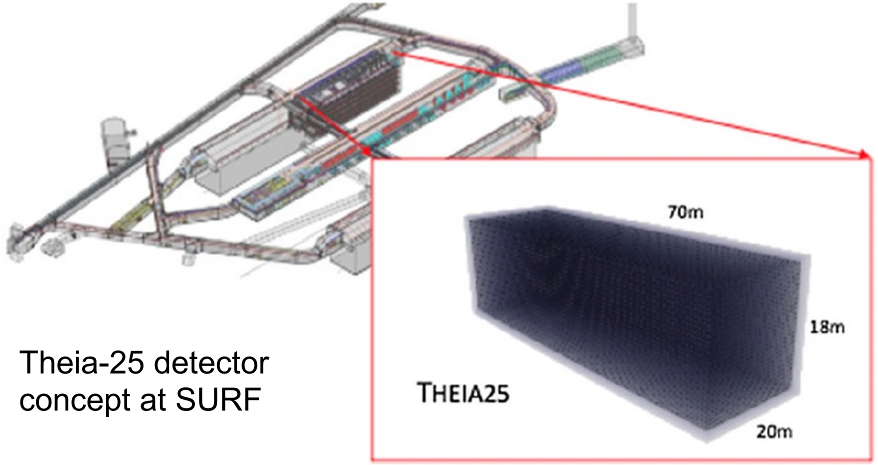
Differernt global/local geological models.

Chin. Phys. C **50**, (2026)

Expected total (lithosphere + mantle) signal @ JUNO

	S(U) [TNU]	S(Th) [TNU]	S(U+ Th) [TNU]	S(Th)/S(U)
Poor-H	$28.1^{+8.2}_{-6.2}$	$8.1^{+2.3}_{-1.8}$	$36.0^{+9.6}_{-7.4}$	0.29
Medium-H	$32.0^{+7.9}_{-6.4}$	$9.1^{+2.4}_{-1.9}$	$41.0^{+9.5}_{-7.7}$	0.29
Rich-H	$39.1^{+8.3}_{-6.9}$	$11.3^{+2.5}_{-2.1}$	$50.2^{+10.1}_{-8.5}$	0.29

THEIA



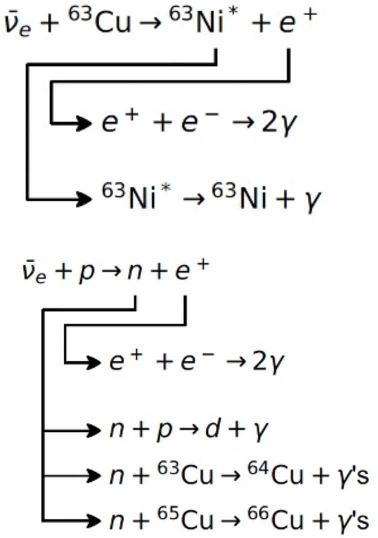
Theia-25 detector concept at SURF

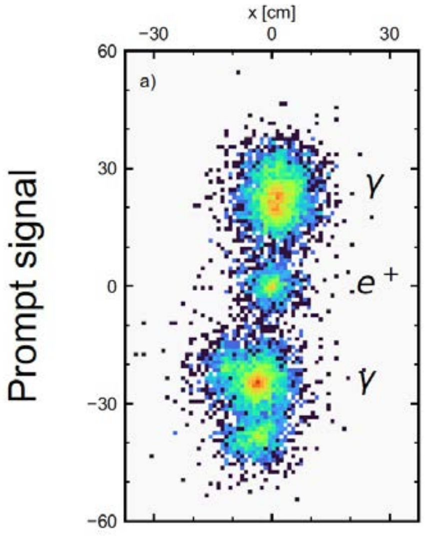
Eur. Phys. J. C (2022) 82:1151

- Large multipurpose detector concept for North America (SURF/SNOLAB).
- Published Theia-25 (25 kt) sensitivity studies assumed WbLS at SURF.
- Current design discussions favour higher-light-yield pure LS.
- Expected sensitivities are being reassessed for the evolving detector concept.

Thanks to Gabriel Orebi Gann

LiquidO





https://doi.org/10.1038/s42005-026-02518-6

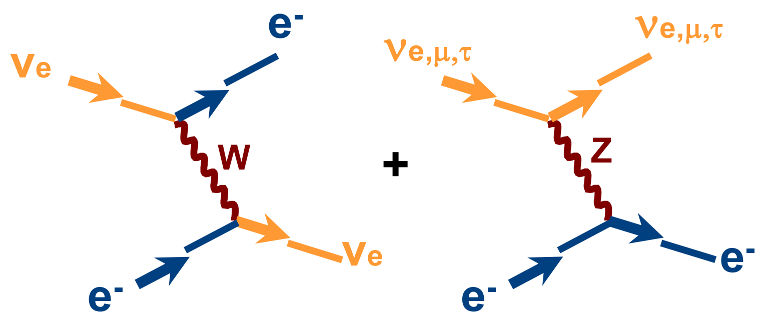
- Opaque-LS detector concept with powerful particle identification.
- Current focus: O(10 t) prototype at Chooz.
- **^{40}K geoneutrino studies based on Cu-doped LS.**
- No timeline yet for dedicated geoneutrino measurements.

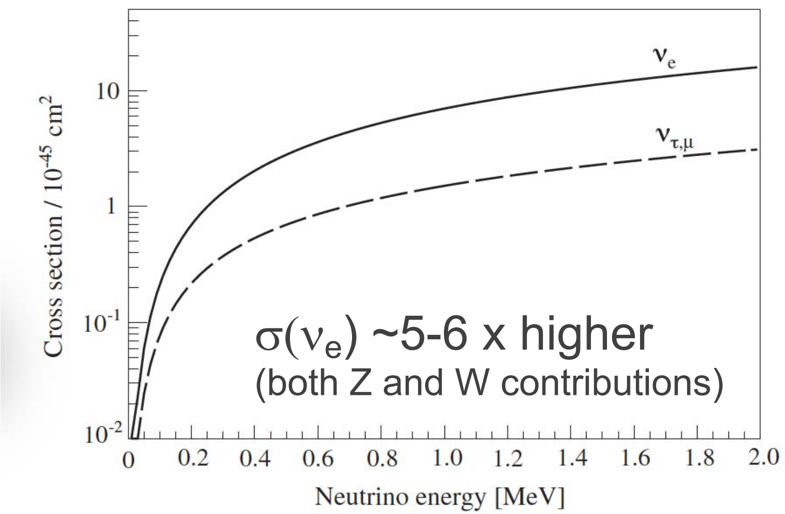
Thanks to Mark Chen

MeV (ANTI-)NEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Neutrino detection: SINGLES

- Elastic scattering (ES) off electrons
- No threshold
- All flavours
- σ@ few MeV: ~10^{-44} cm^2

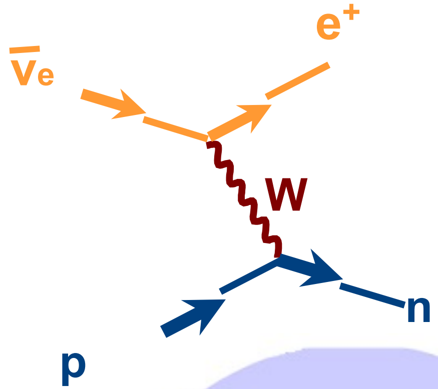




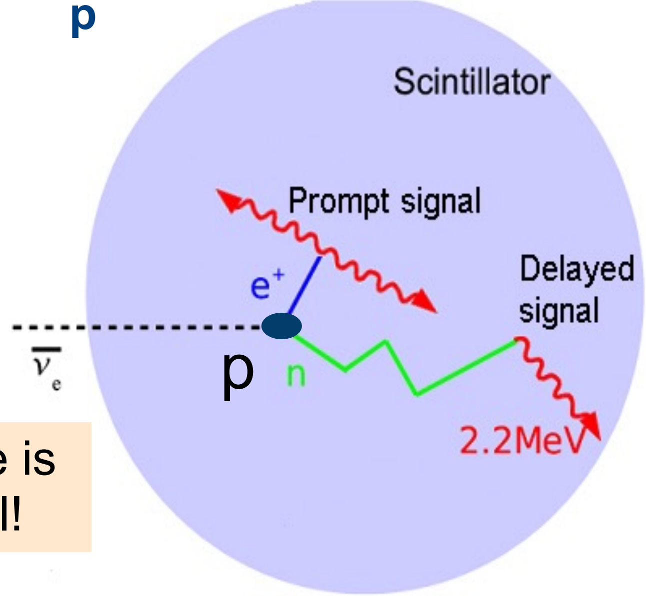
Antineutrino detection: Coincidences (BGR suppression)

- Inverse beta decay (IBD)
- Charge current, we detect only electron flavour

Energy threshold = 1.8 MeV
Electron flavor only
σ@ few MeV: ~10^{-42} cm^2
(~100 x more than scattering)



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

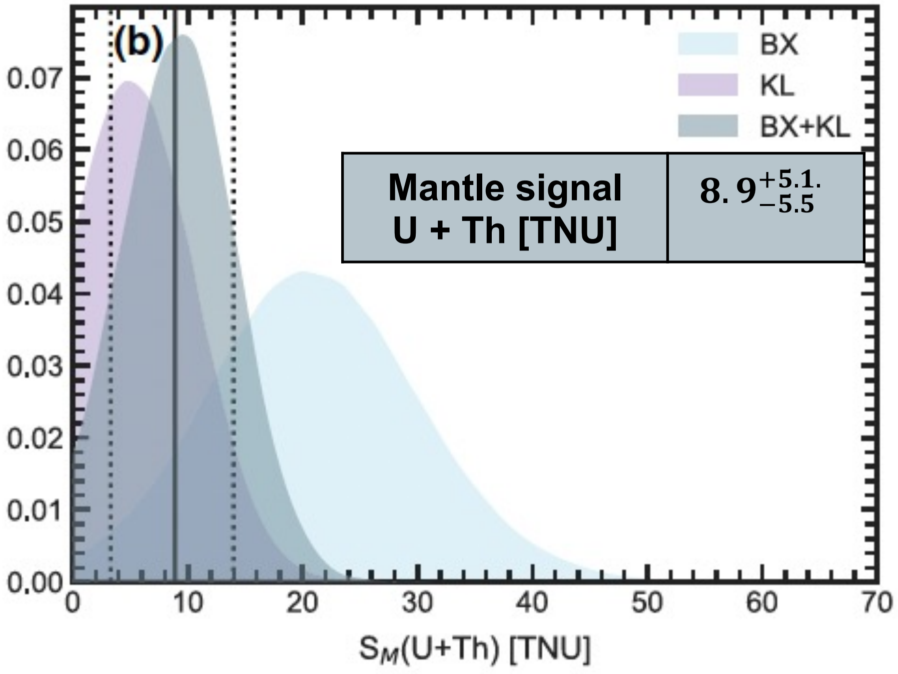


Prompt + delayed space & time coincidence is an exceptional background suppressing tool!

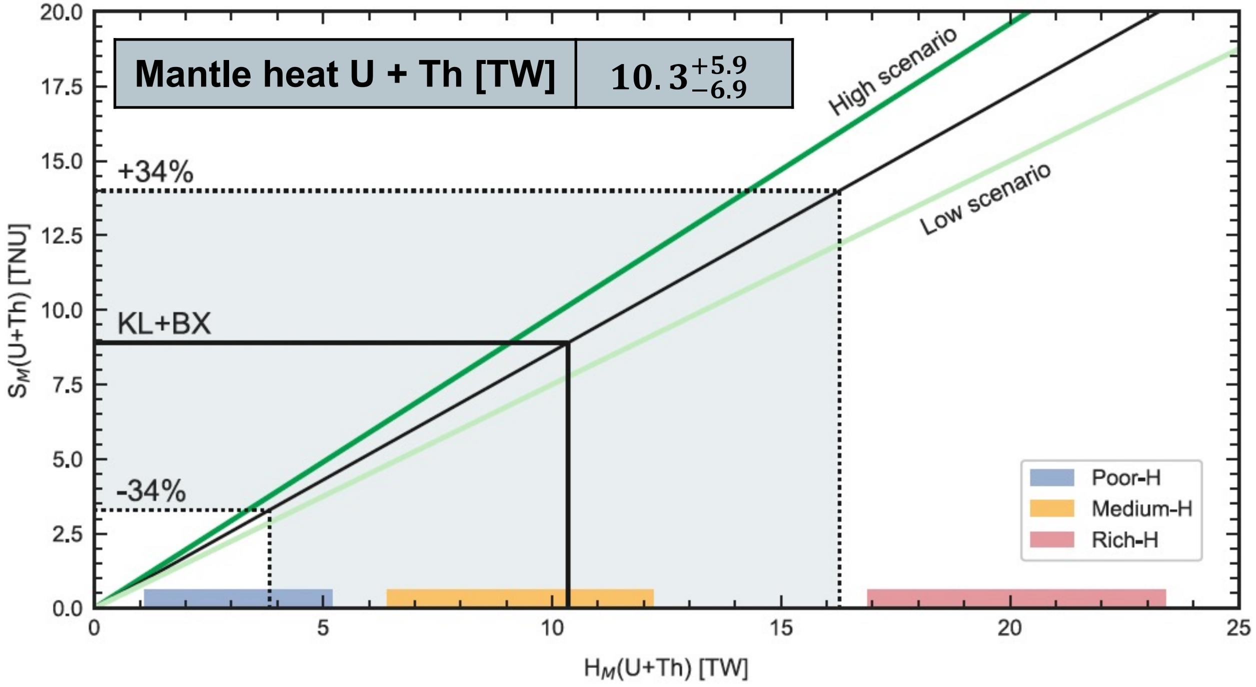
MANTLE: BOREXINO & KAMLAND COMBINED

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

Mantle U + Th signal



Mantle radiogenic heat vs BSE



- Some level of disagreement between the two experiments: Borexino High-Q & KamLAND Low-Q
- Combined analysis assumes laterally homogeneous mantle….
- … and is perfectly compatible with Middle-Q BSE Models.

CALCULATION OF THE EXPECTED REACTOR ANTI-N FLUX

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

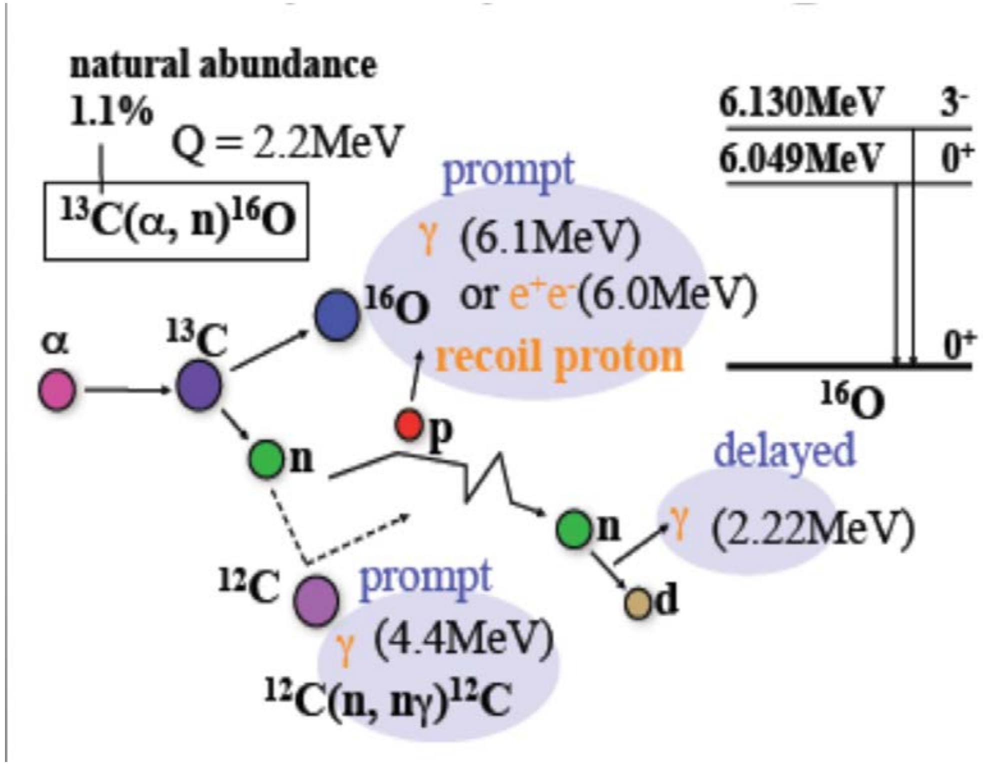
- **Nuclear and neutrino physics:**
  - E_i : energy release per fission of isotope i (Huber-Schwetz 2004);
  - Φ_i: antineutrino flux per fission of isotope i (polynomial parameterization, Mueller et al.2011, Huber-Schwetz 2004);
  - P_{ee}: oscillation survival probability;
- **Experiment-related:**
  - 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

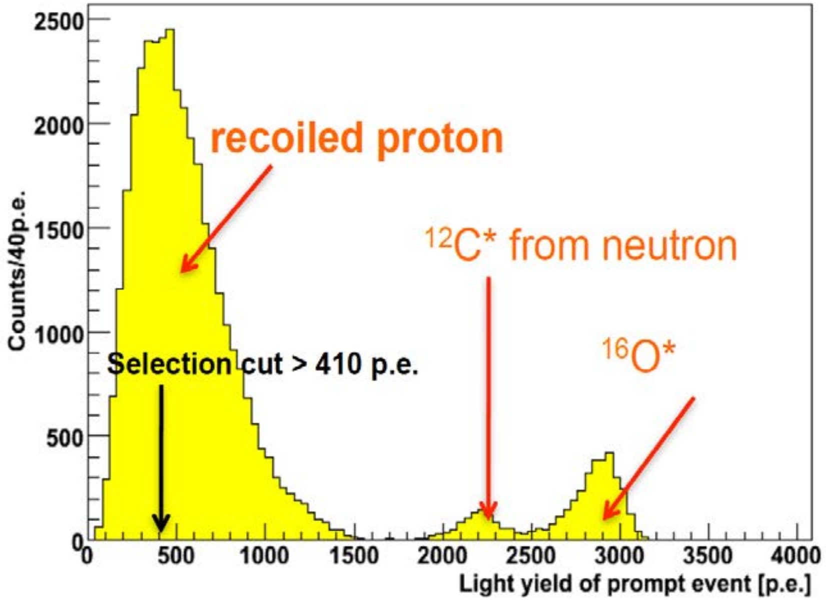
+ consider energy-dependent IBD cross section → expected reactor-antinu rate for 100 detection eff.

$^{13}C(\alpha$, neutron$)^{16}O$ background

- Isotopic abundance of ^{13}C: 1.1%
- $^{210}Po(\alpha)$ = 14.1 cpd / ton (average value)



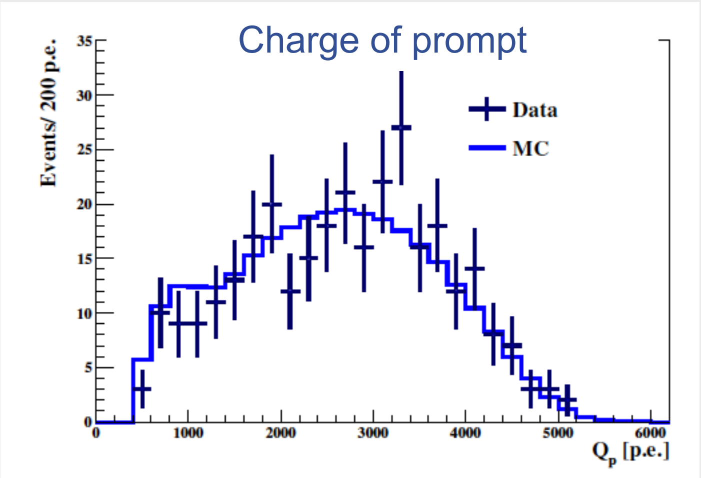
MC-based spectrum of E_{prompt}

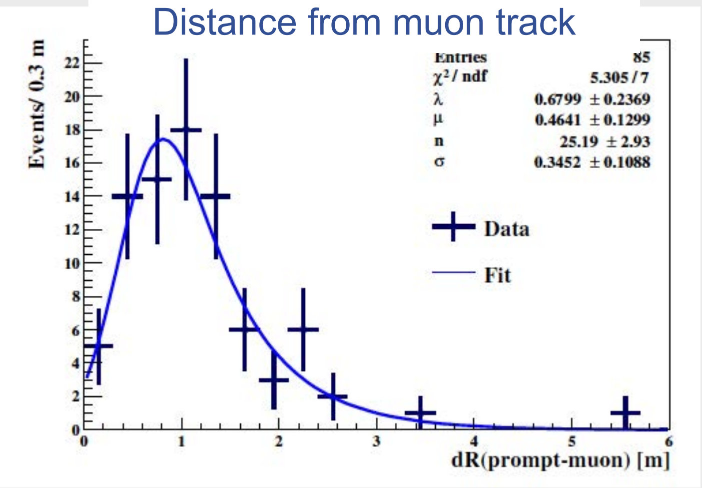


NON-ANTINEUTRINO BACKGROUNDS

^{9}Li (β+n) events < 2s after muons

$\tau_{measured}$ = (0.260 ± 0.021) s

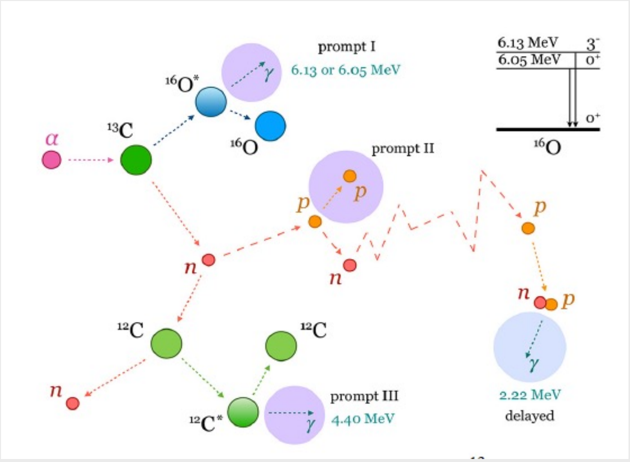


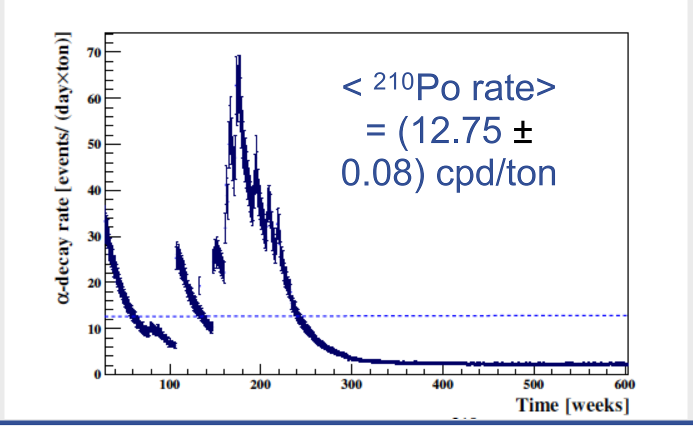


^{13}C(^{210}Po(α), n) ^{16}O

Y_n = (1.45 ± 0.22) x 10^{-7}

$\varepsilon_{IBD\text{-}like}$ = 0.56 for ^{210}Po in LS

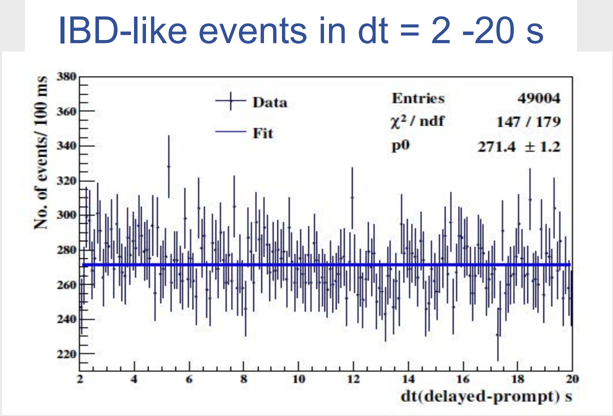




Accidentals

R_{acc} = (3029.0 ± 12.7) s^{-1}

including scaling factor
exp(-R_{muon} x 2s) = 0.896
due to the 2 s muon veto before delayed

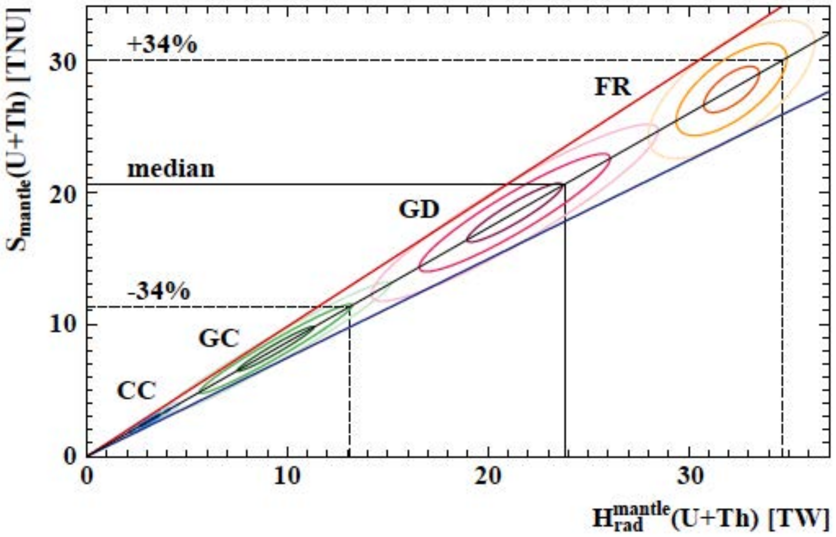


Background Type	Events
^{9}Li background	3.6 ± 1.0
Untagged Muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.0010
Total	8.28 ± 1.01

RADIOGENIC HEAT

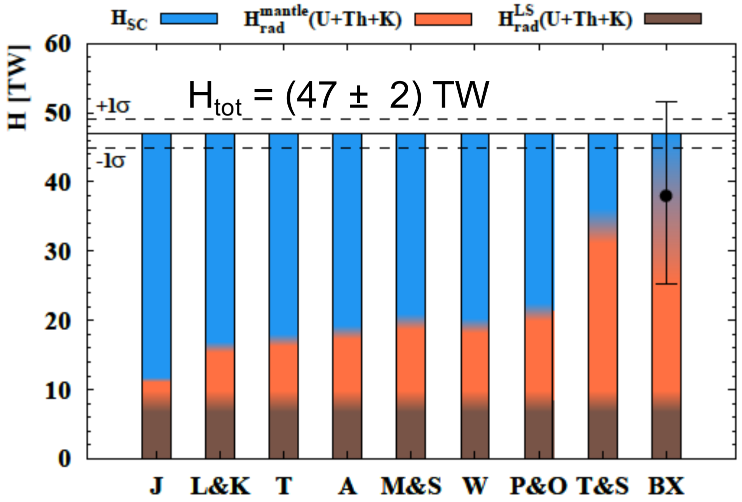
$$UR_{CV} = \frac{H_{rad} - H_{rad}^{CC}}{H_{tot} - H_{rad}^{CC}},$$

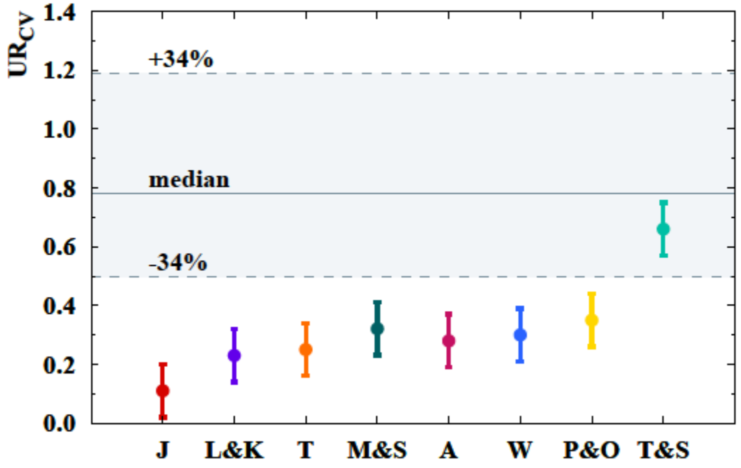
Borexino U+Th mantle signal



The first data

CC = continental crust





Mantle radiogenic heat from U+Th:

$$24.6^{+11.1}_{-10.4}\,TW$$

Compatible with predictions, but least (2.4σ) compatible with the CosmoChemical model (CC) predicting lowest U+Th mantle abundances

Earth radiogenic heat from U+Th+K:

$$38.2^{+13.6}_{-12.7}\,TW$$

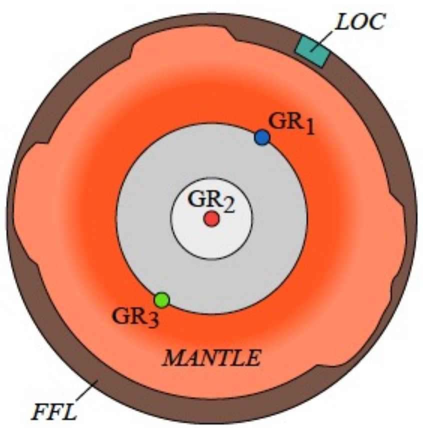
- Assuming 18% ^{40}K mantle contribution
- Lithospheric radiogenic heat U+Th+K $8.1^{+1.9}_{-1.4}$TW

Convective Urey UR_{CV} ratio:

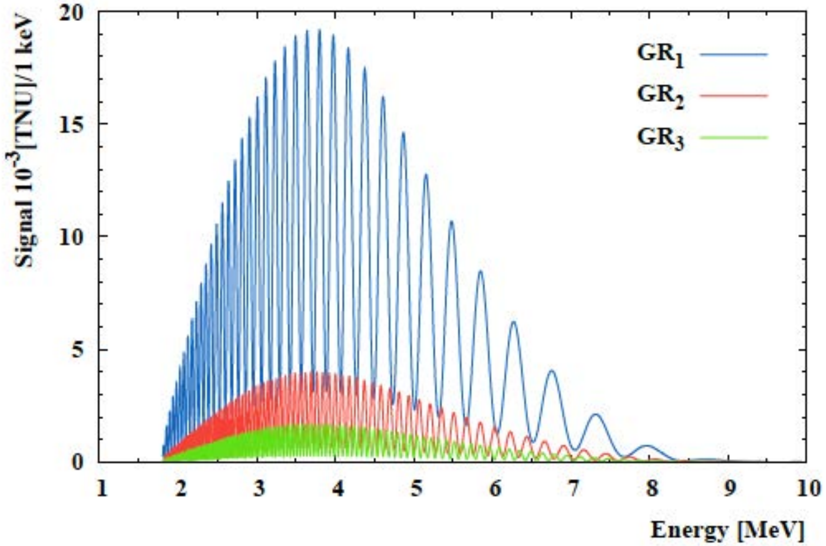
$$0.78^{+0.41}_{-0.28}$$

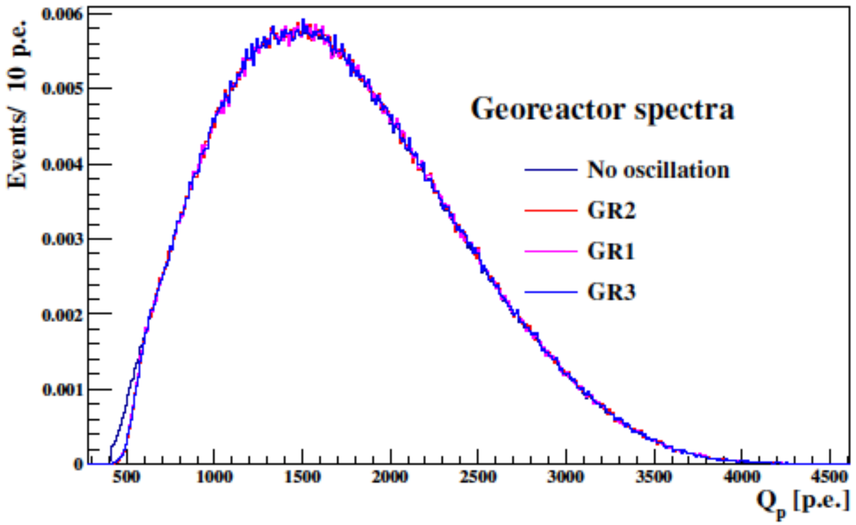
At 90% C.L., mantle characteristics: a(Th) >48 ppb & a(U) >13ppb UR_{CV} >0.13

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?)