SUMMER INSTITUTE: USING PARTICLE PHYSICS TO UNDERSTAND AND IMAGE THE EARTH

11-21 July 2016 *Gran Sasso Science Institute*
Europe/Rome timezone

Monday 18 July 2016

Geoneutrinos: origin, detection, background (from reactors and other sources), current geoneutrino measurement, future on geoneutrinos - Room D (09:00-10:00)

- **Presenters: Prof. LUDHOVA, Livia**

Evaluation of local contribution - Room D (10:00-11:00)

- **Presenters: MANTOVANI, Fabio**

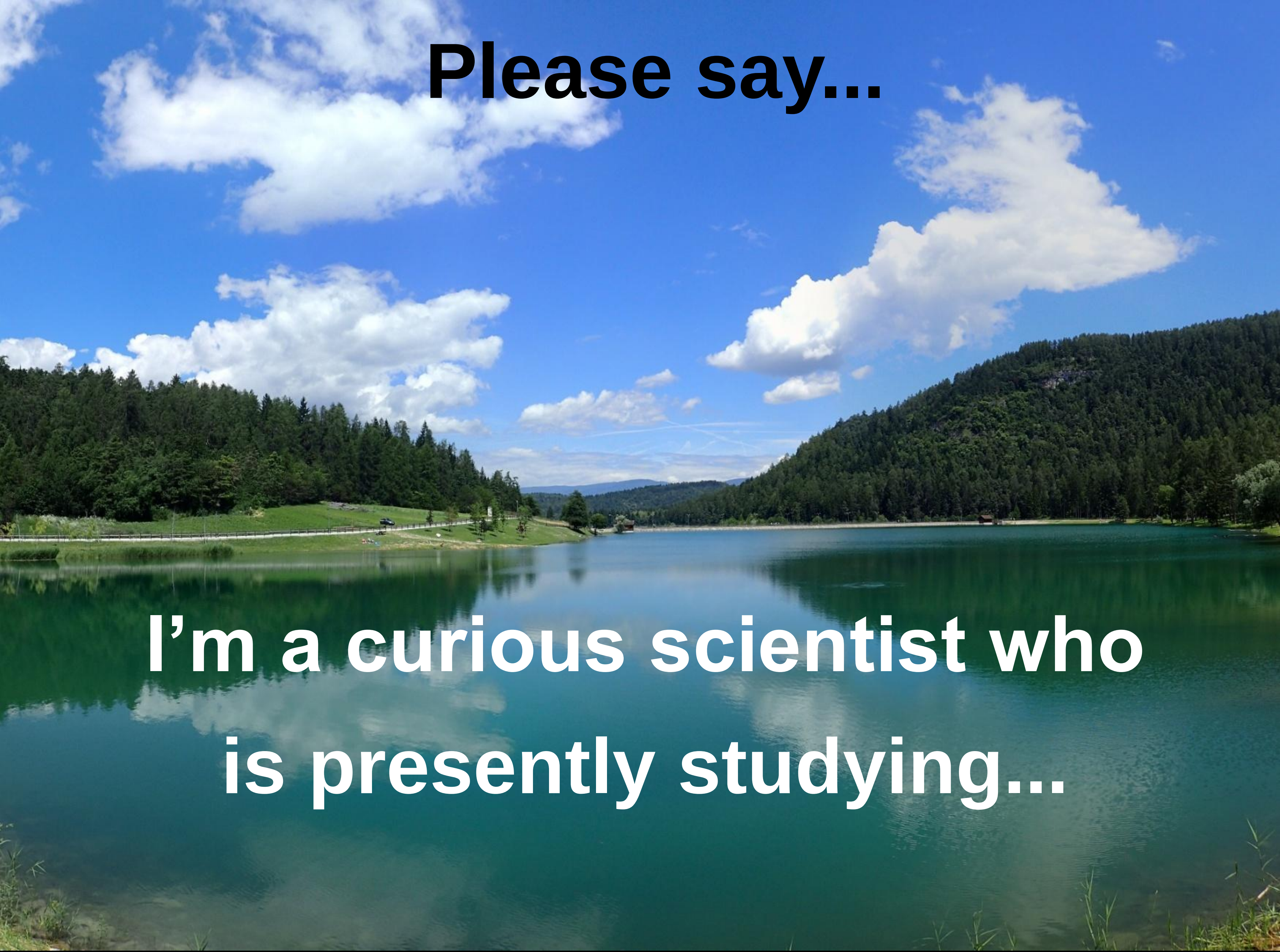
Volcano structure and eruption - Room D (11:30-12:30)

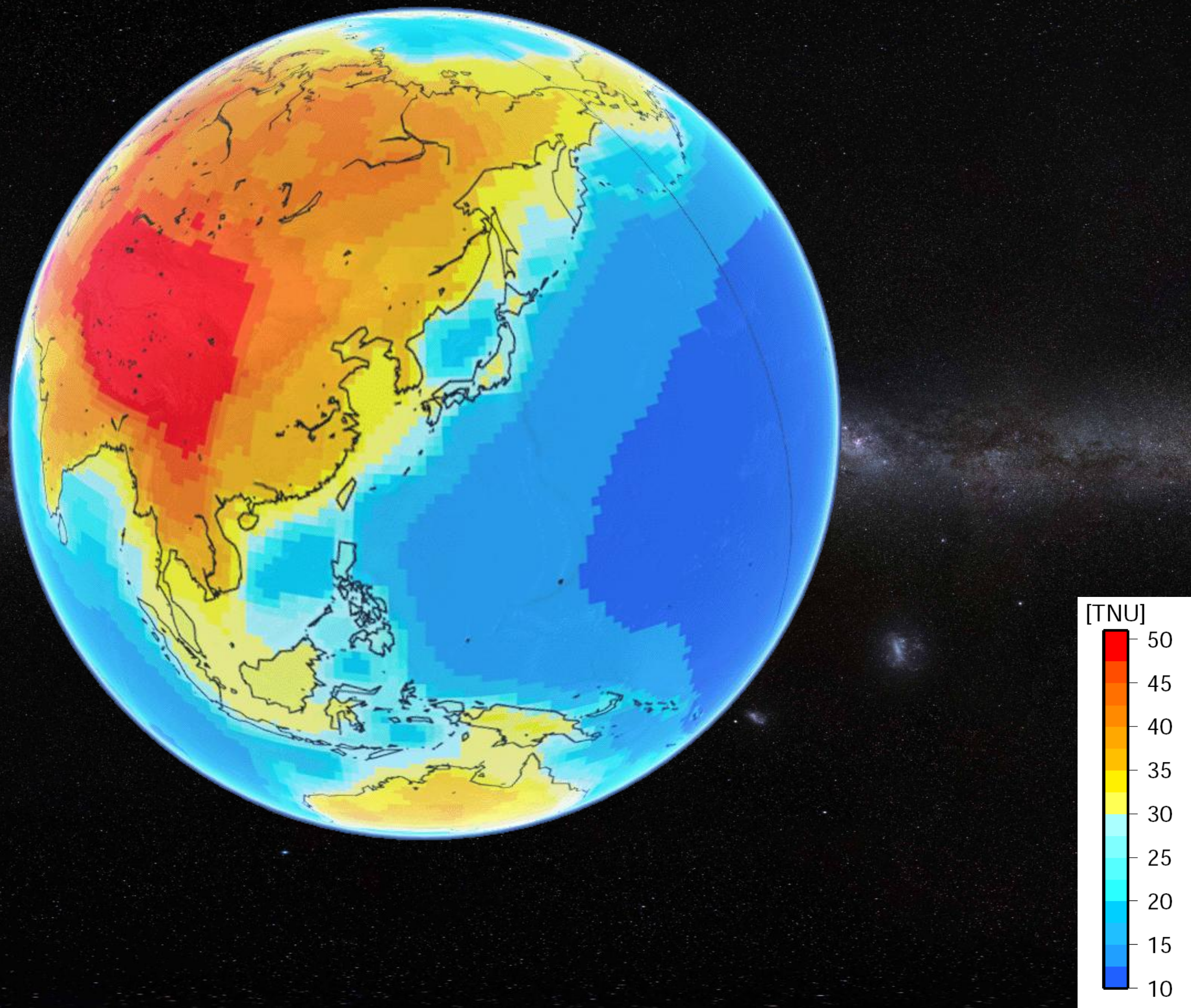
- **Presenters: Dr. MACEDONIO, Giovanni**

I ask you a big favour for the next hour...

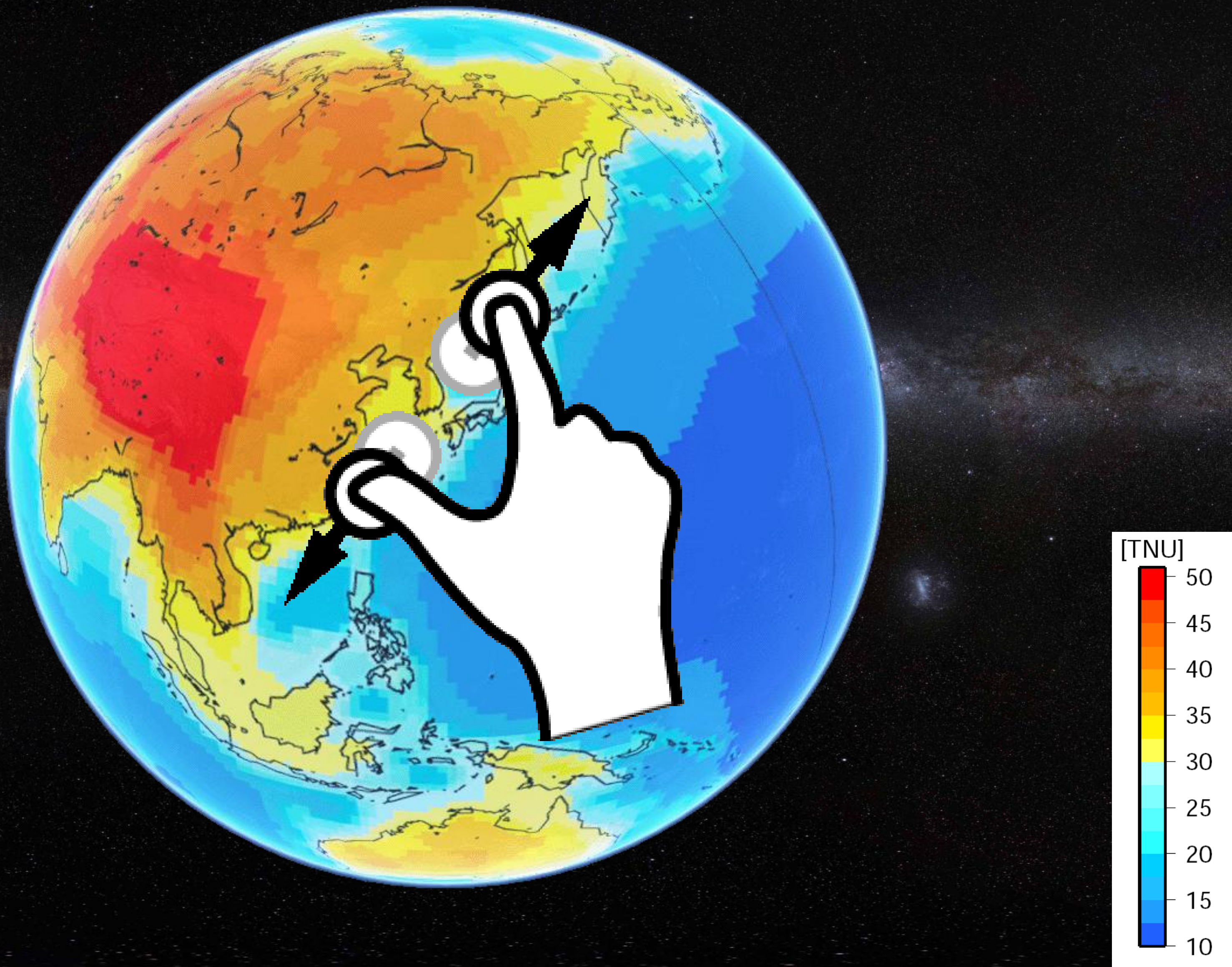
I implore you...
I supplicate you...
In the next hour, please don't say...

- I'm a geologist
- I'm a particle physicist
- I'm a geochemist
- I'm a geophysicist
- I'm a nuclear physicist
- I'm an experimental physicist

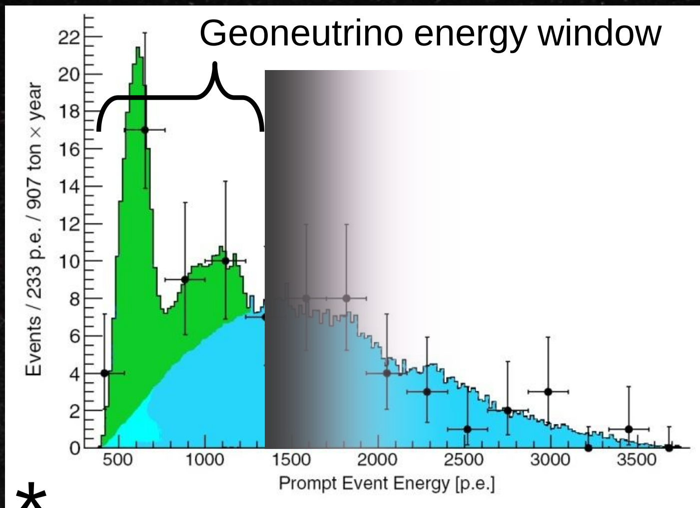

Please say...
I’m a curious scientist who
is presently studying...


[TNU]
50
45
40
35
30
25
20
15
10

Geoneutrinos:
evaluation of local contribution



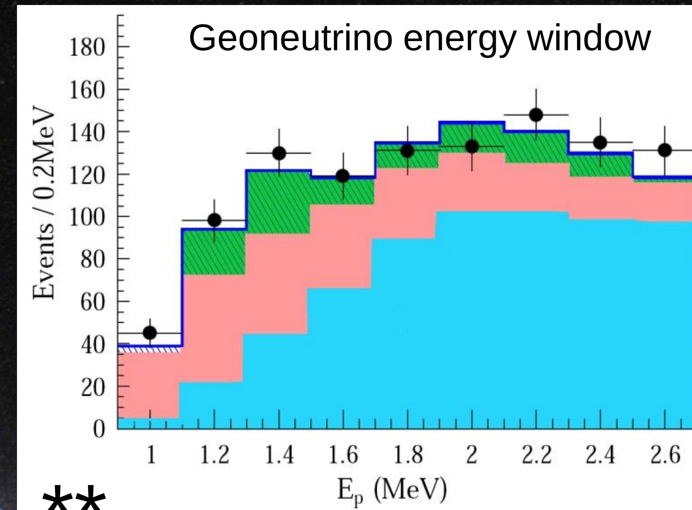
Borexino and KamLAND results



Geoneutrinos

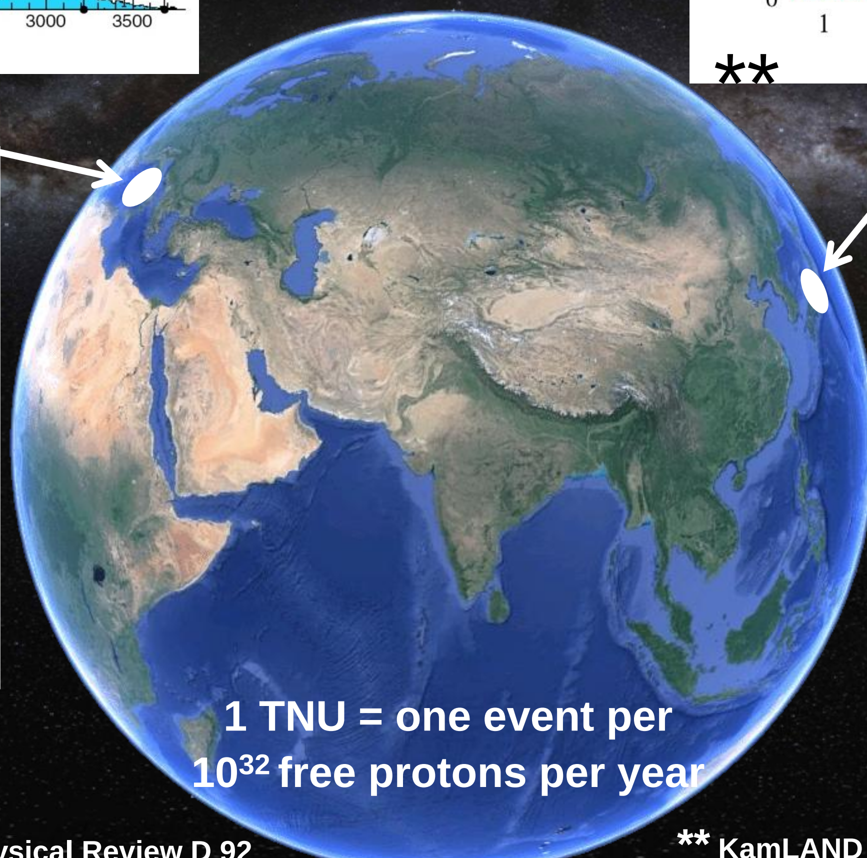
Background

Reactor antineutrinos



Borexino

- Period: 2007 – 2015
- Geo-ν events: $23.7^{+7.4}_{-6.3}$
- Signal: $43.5\ ^{+14.5}_{-12.8}$ TNU



KamLAND

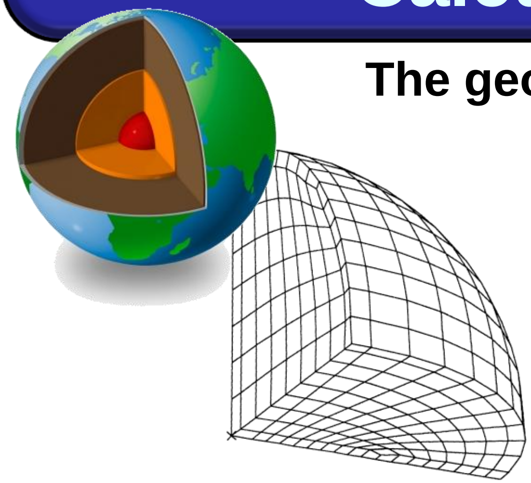
- Period: 2002 – 2012
- Geo-ν events: 116^{+28}_{-27}
- Signal: 30 ± 7 TNU

1 TNU = one event per 10^{32} free protons per year

* Borexino collaboration, 2015 - Physical Review D 92

** KamLAND collaboration, 2013 - Phys. Rev. D 88

Calculation of geoneutrino signal



The geoneutrino flux produced by the element X, i.e. U and Th, is:

Geoneutrino production rate

Density of the voxel

Elemental mass abundance of X in the voxel

$$\phi(X) = \frac{\varepsilon_{\bar{\nu}_X}}{4\pi} \int_V \frac{\rho(\vec{r}')\, a_X(\vec{r}')}{\left|\vec{R} - \vec{r}'\right|^2} d\vec{r}'$$

Distance between the detector and the centre of the voxel.

The **oscillated geoneutrino flux** is calculated by taking into account three flavor survival probability $\mathbf{P_{ee}}$ and the geoneutrino energy spectrum:

$$P_{ee}(E_{\bar{\nu}_e}, \vec{r}) = \cos^4(\theta_{13}) \left(1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\delta m^2 \vec{r}}{4E_{\bar{\nu}_e}} \right) \right) + \sin^4(\theta_{13})$$

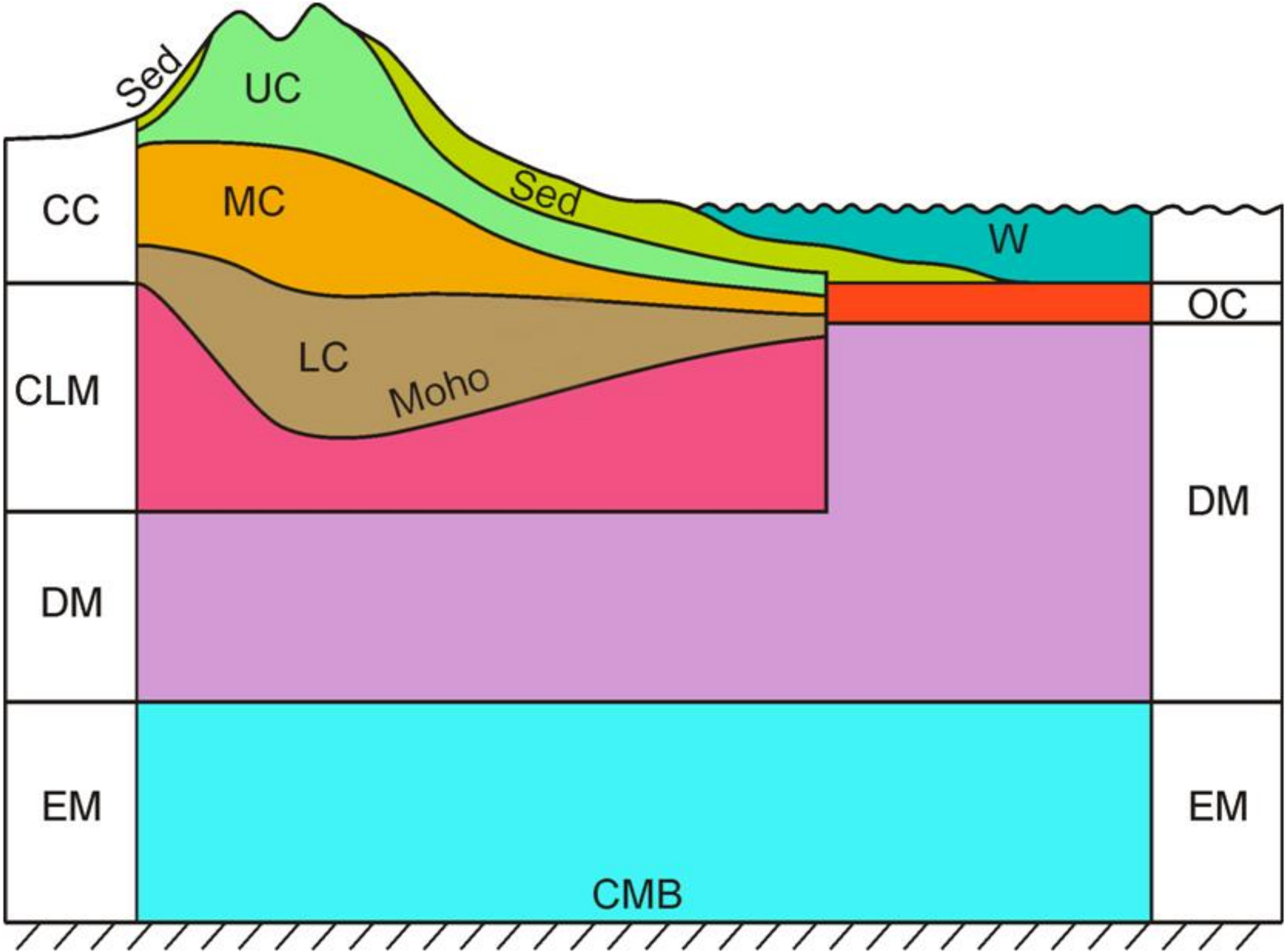
Assuming the detector efficiency **ε = 1** and 10^{32} free target protons $\mathbf{N_p}$. the geoneutrino signal in **TNU** originated by the radionuclide **X** for a fixed distance **r**, can be calculated:

$$S(\vec{r}, X) = \phi(\vec{r}, X) P_{ee}(\vec{r}, X) \langle \sigma \rangle_X$$

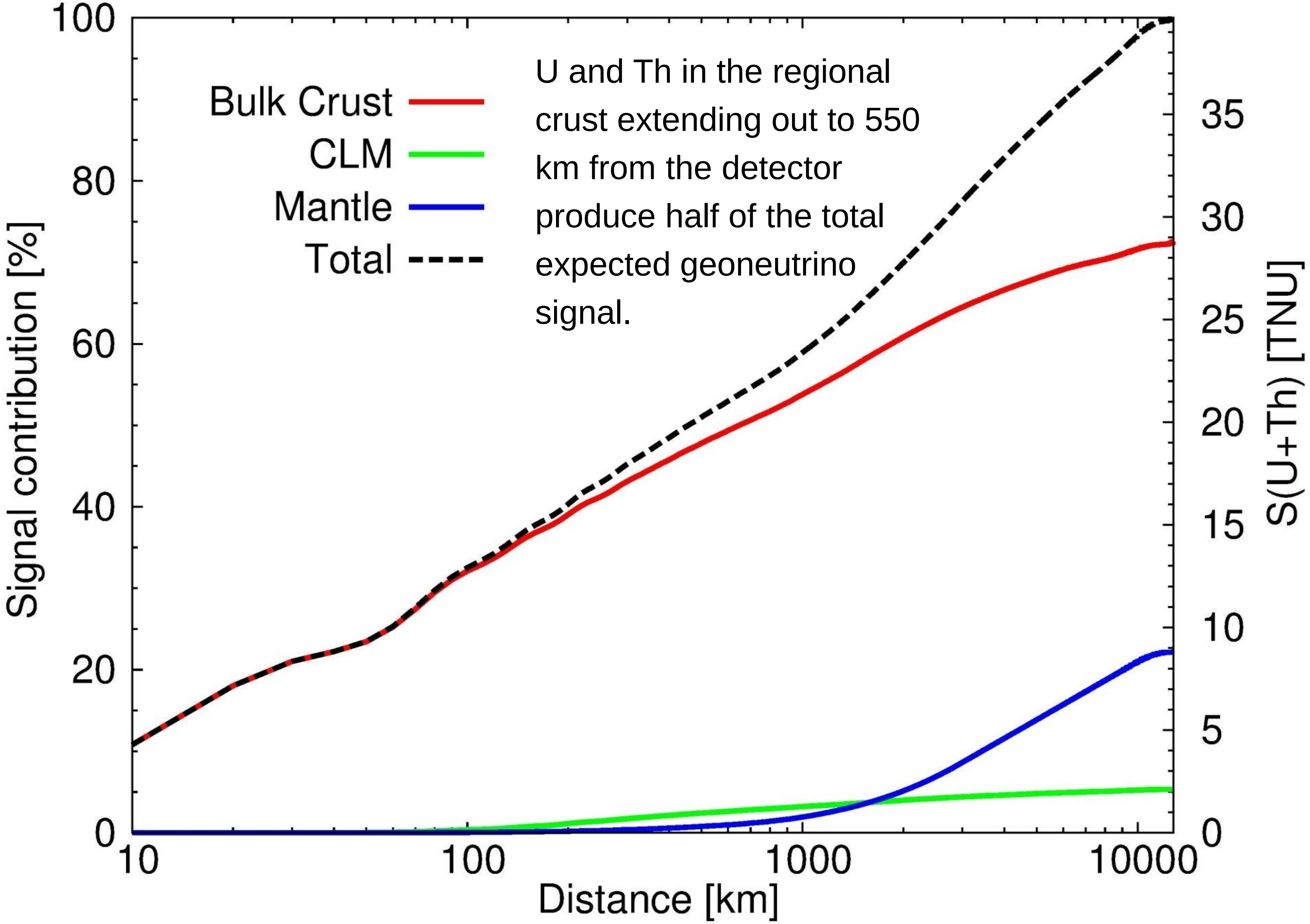
Integrated inverse beta reaction cross section

[1 TNU = 1 event per 10^{32} free proton per year]

The main sources of geoneutrinos

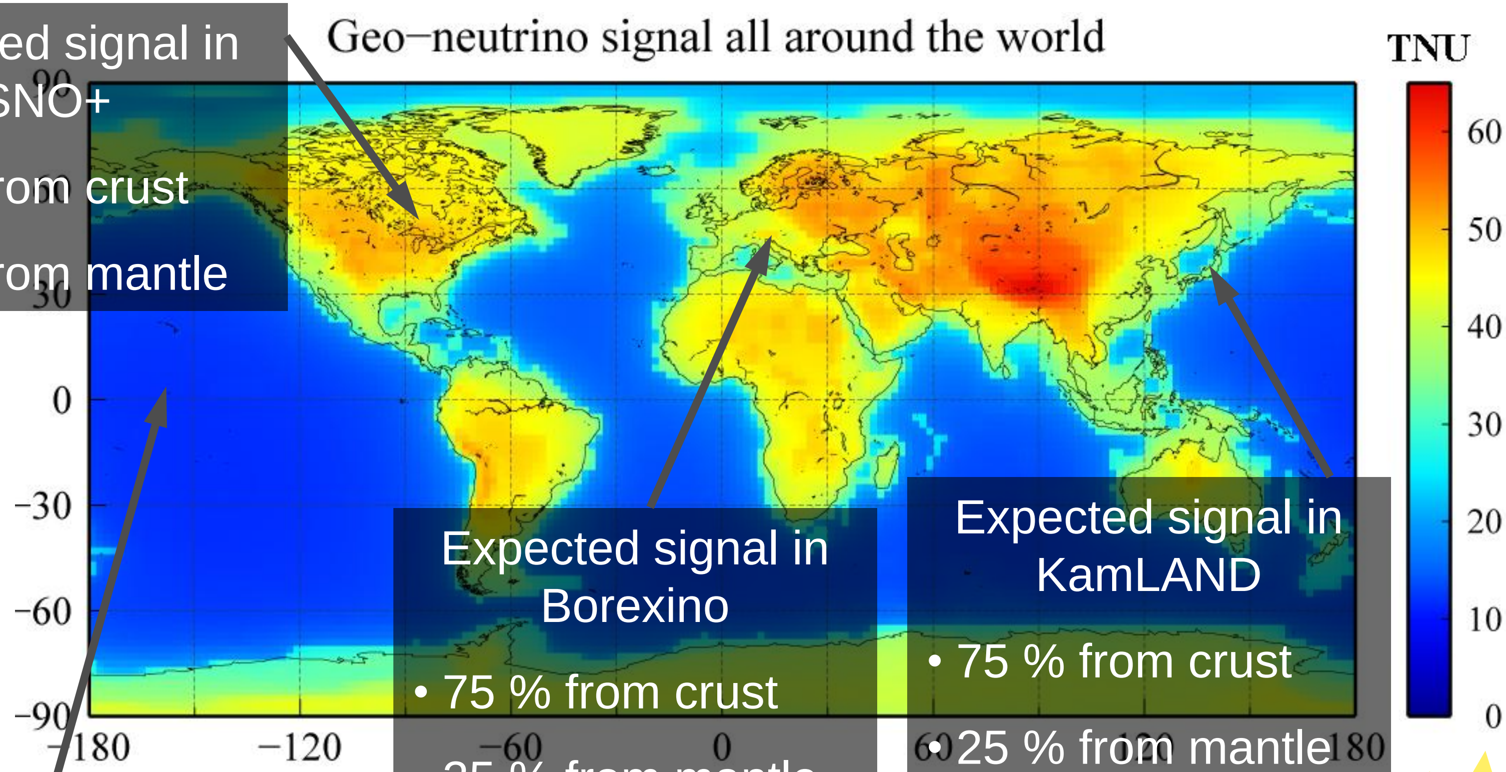


Cumulative geoneutrino signal in JUNO



Strati et al. - Progress in Earth and Planetary Science – 2015 – arXiv:1412.3324

Contributions from crust and mantle



Expected signal in SNO+

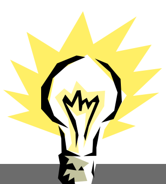
- 82 % from crust
- 18 % from mantle

Expected signal in Borexino

- 75 % from crust
- 25 % from mantle

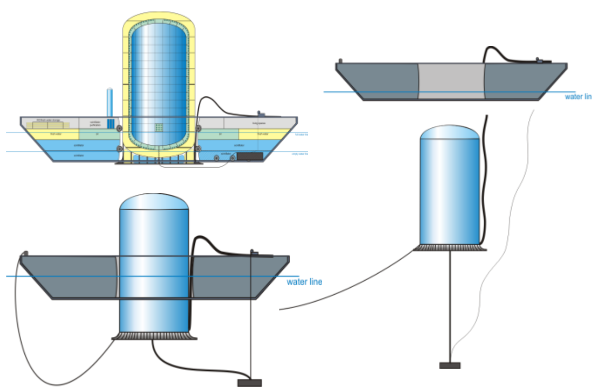
Expected signal in KamLAND

- 75 % from crust
- 25 % from mantle

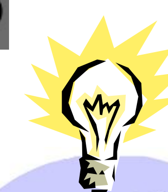


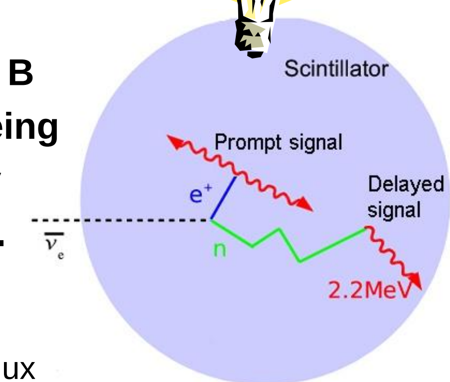
Expected signal in Hawaii

- 28 % from crust
- 72 % from mantle



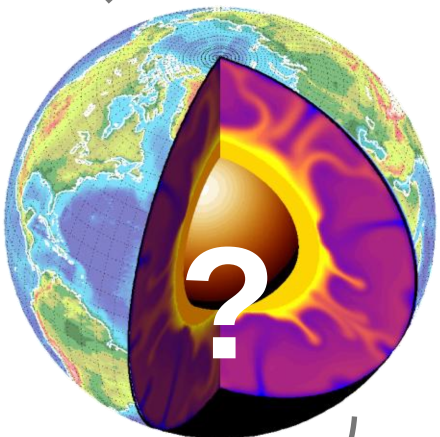
Reconstruction of geo-ν direction with Gd, Li and B loaded LS is being investigated by several groups.





Huang et al. - A reference Earth model for the heat-producing elements and associated geoneutrino flux
Geochem. Geophys. Geosyst.

Radioactivity in the mantle: indirect measurement



- If one wants to extract the global information, the contribution from regional geology (~500 km) and crust has to be controlled.
- For each element (U, Th) the expected geo-neutrino signal S in one site on the Earth's surface is the sum of three contributions:

$$S_{Expected} = S_{LOCal} + S_{Far\ Field\ Crust} + S_{Mantle}$$

$$S_{Mantle} = S_{Measured} - (S_{LOCal} + S_{Far\ Field\ Crust})$$

Fiorentini et al. – 2012 – Physical Review D 86, 033004

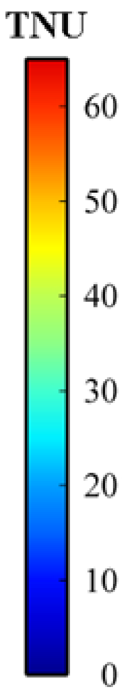
Detecting geoneutrinos around the world

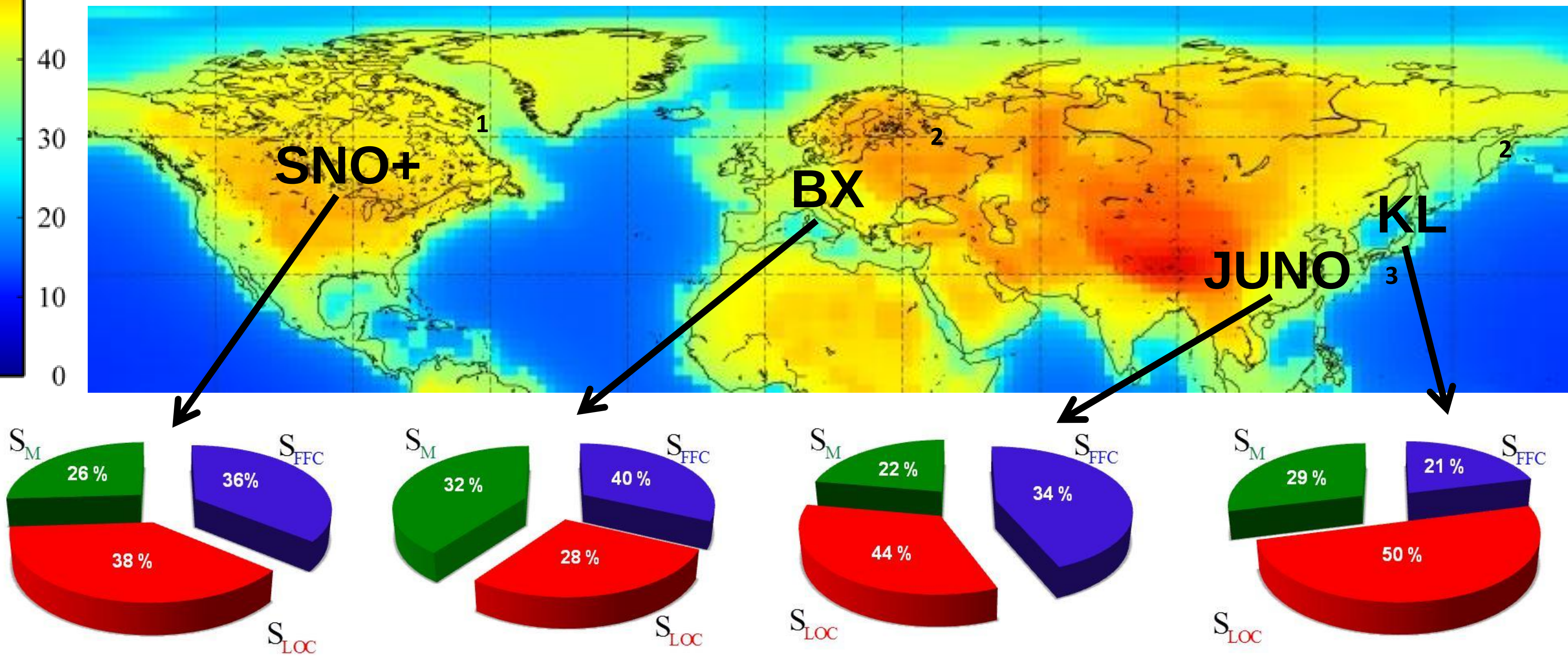
In one site, for each radioisotope (^{238}U, ^{232}Th) the expected geo-neutrino signal is the sum of three contributions:

$$S_{EXP} = S_{LOC} + S_{FFC} + S_{M}$$

$$S_{Mantle} = S_{Measured} - (S_{LOCal} + S_{Rest\ Of\ Crust})$$

EXP = total expected signal
LOC = crust of the region within some hundreds km from the detector
FFC = Far Field Crust
M = mantle signal





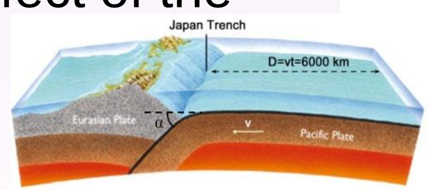
1 - Huang et al. 2014, Geochemistry, Geophysics, Geosystems 15(10).
2 - Fiorentini et al 2012 , Physical Review D 86(3)   3 - Strati et al. 2015 , Progress in Earth and Planetary Science 2(1).

A refined local model for Kamioka

A world wide reference model[1] predicts for KamLAND:

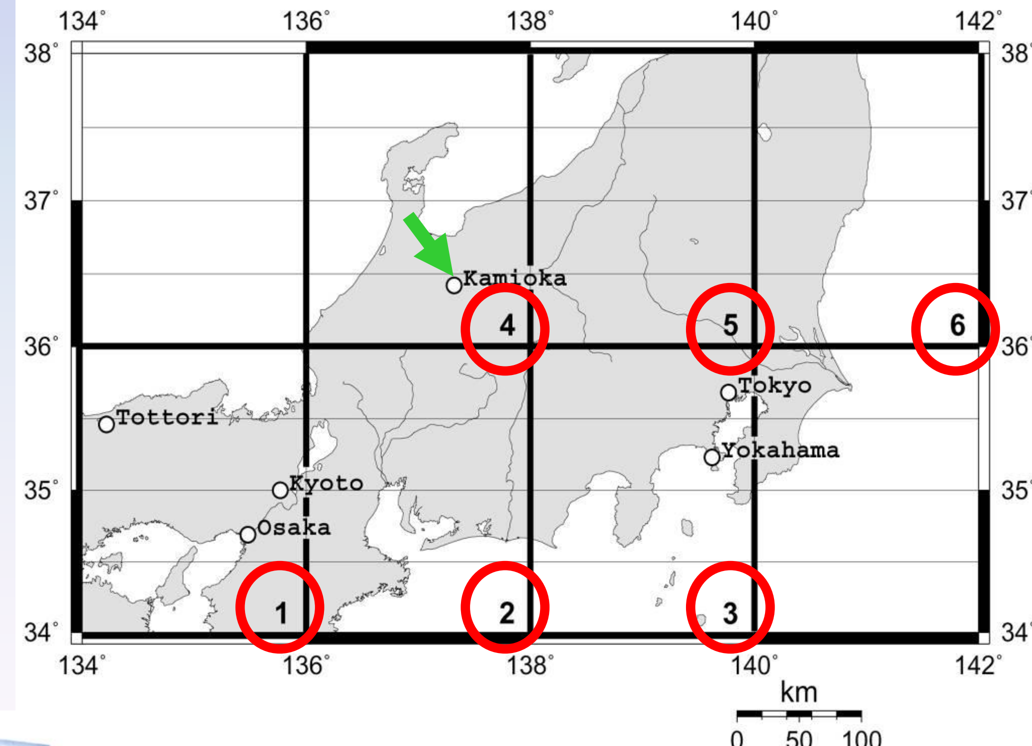
Inputs used for the refinement[2]

- Use a geochemical study of the Japan Arc exposed upper crust (166 samples distinguishing 10 geological classes)
- Use detailed (± 1 km) measurements of Conrad and Moho depth
- Use selected values for abundances LC
- Build a new crustal map of the Japan Arc (scale ¼° x ¼°)
- Consider possible effect of the subducting plate below Japan



Total signal **31.5 ± 4.5 TNU**

Local signal (6 tiles) **~ 13.3 TNU**

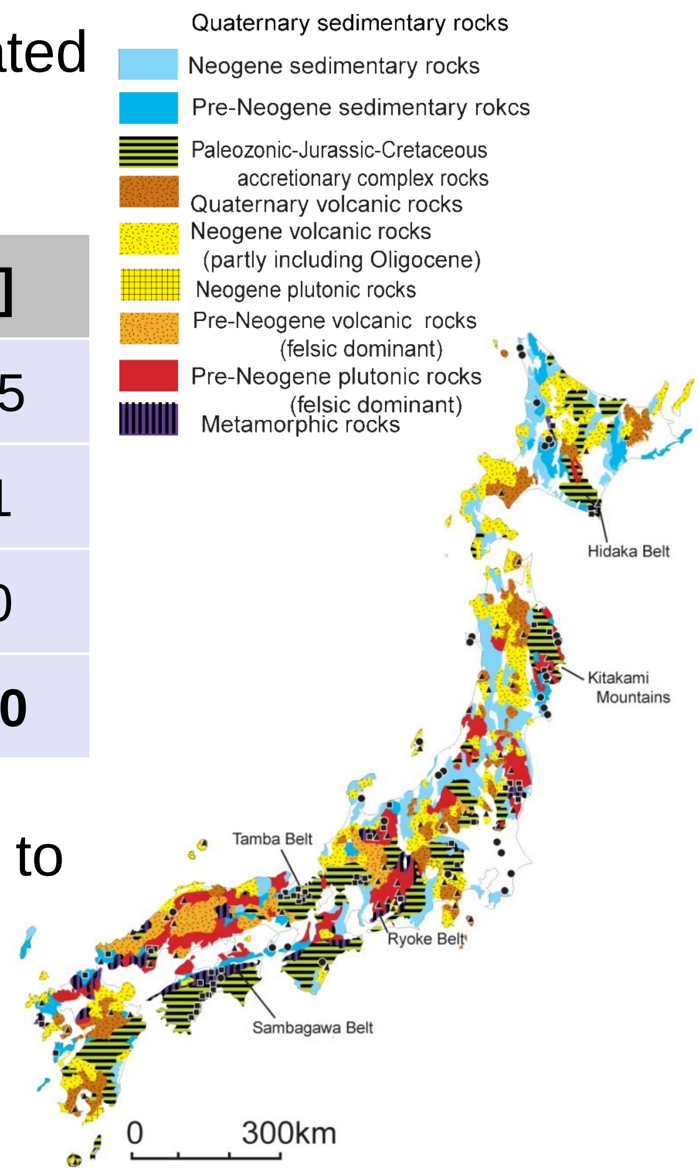


[1] Huang, Y., et al. - 2013 - arXiv:1301.0365v2
[2] Fiorentini et al. - 2012

Local contribution to geo-ν signal in KamLAND

Different local sources of geo-ν are investigated and the expected signals are estimated:

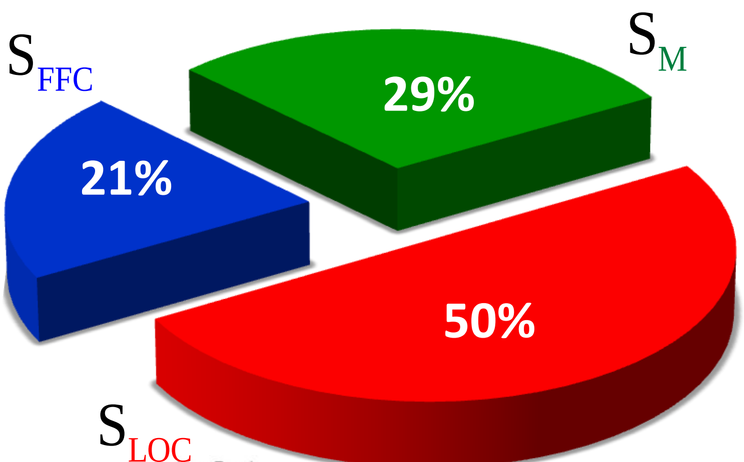
Reservoir	S(Th) [TNU]	S(U) [TNU]
Six-tiles	3.20 ± 0.37	11.17 ± 0.65
Subducting slub	0.90 ± 0.27	2.02 ± 0.61
Sea of Japan	0.09 ± 0.03	0.34 ± 0.10
LOC Total	**4.19 ± 0.46**	**13.53 ± 0.90**

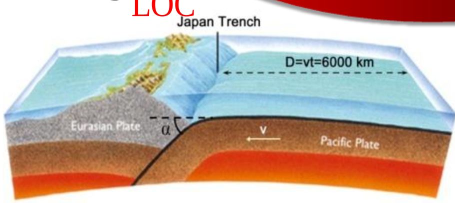


- The local expected signal is **17.7 ± 1.4 TNU** to compare with **13.3 TNU**
- For a fixed element the 1σ uncertainties are independent
- We assume ΔS(U) and ΔS(Th) totally correlated

Geoneutrino in KamLAND: theory and experiment

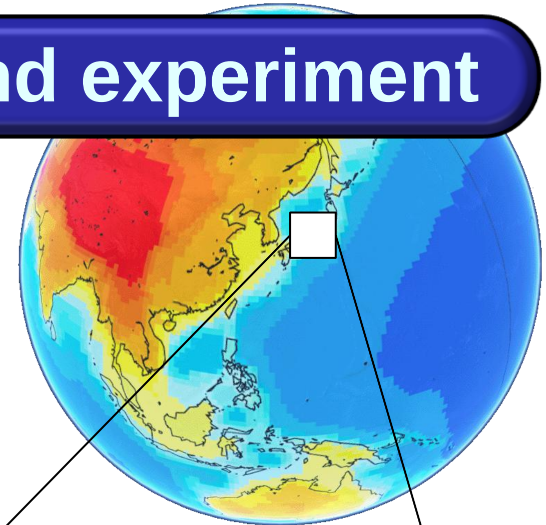
$$S_{EXP} = S_{LOC} + S_{FFC} + S_{Mantle}$$

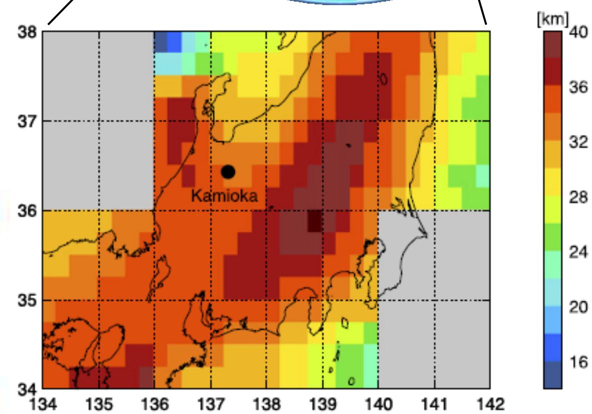




Contributions to the S_{LOC} in KamLAND are given by U and Th in:

	S(TNU)
Local geology	14.4 ± 1.0
Subducting slab	2.9 ± 0.9
Crust of Japan Sea	0.4 ± 0.1
Total S_{LOC}	17.7 ± 1.4





~ 500 km x 500 km

	LOC[1]	FFC[2]	CLM[2]	Mantle[2]	Total (theory)	Experiment (KL 2013)[3]
S(U+Th) [TNU]	17.7 ± 1.4	7.3 ± 1.4	1.6 ± 1.6	8.8	35.4 ± 2.5	30 ± 7

Including a refined local model, in Enomoto et al. (2007) the expected signal in KamLAND is 35.2 TNU.

[1] Fiorentini et al. - 2012
[2] Huang, Y., et al. - 2013 - arXiv:1301.0365v2
[3] KamLAND collaboration - Phys. Rev. D 88 - 2013

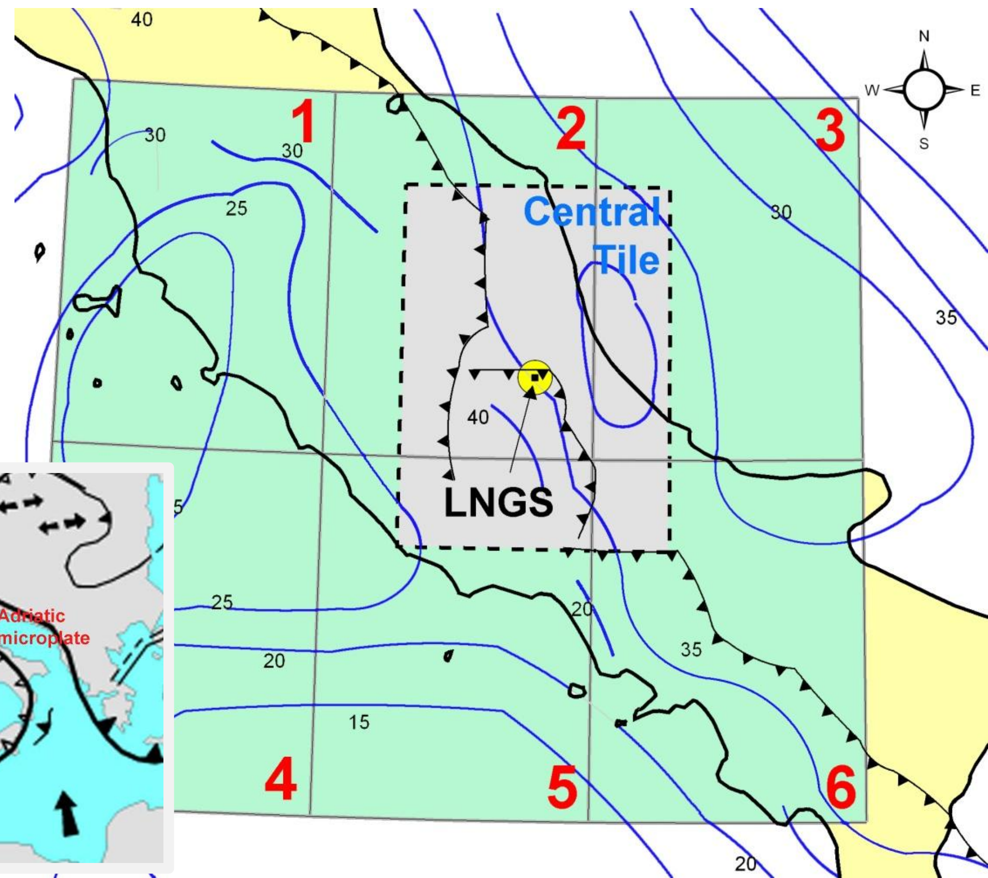
Local contribution to geo-ν signal in Borexino

A world wide reference model predicts for Borexino:

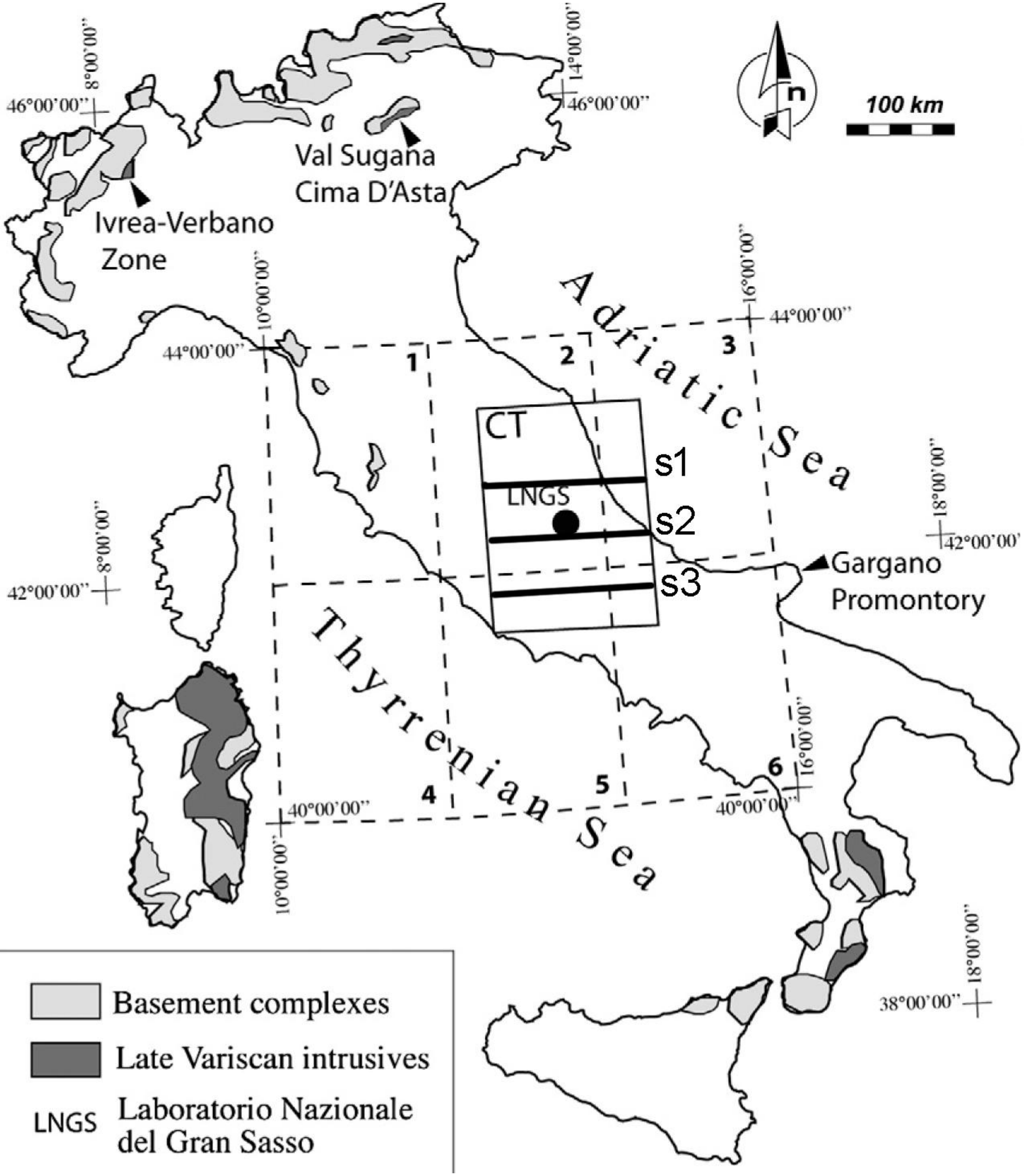
Inputs used for the refinement

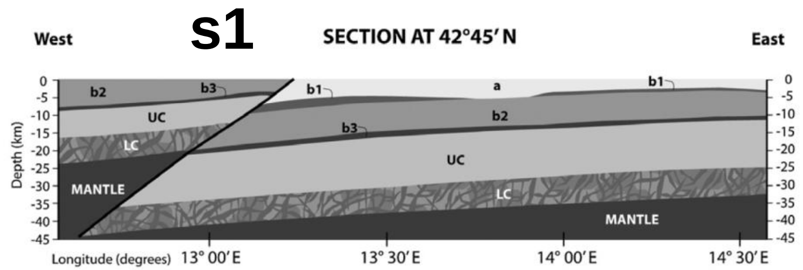
- The geophysical structure of the crust is modeled using data of CROP seismic sections and from 38 deep oil and gas wells.
- We identify 6 reservoirs: 4 of sediments, UC and LC.
- Representative samples of the sedimentary cover were collected and measured by using ICP-MS
- U and Th content measured in samples collected from outcrops on Alps is adopted for UC and LC

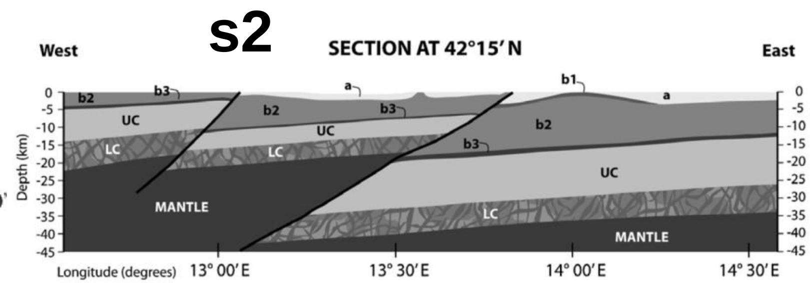
Total signal	**40.3 ± 6.6 TNU**
Signal from 6 tiles	**~ 15.3 TNU**
Signal from CT	**~ 12 TNU**

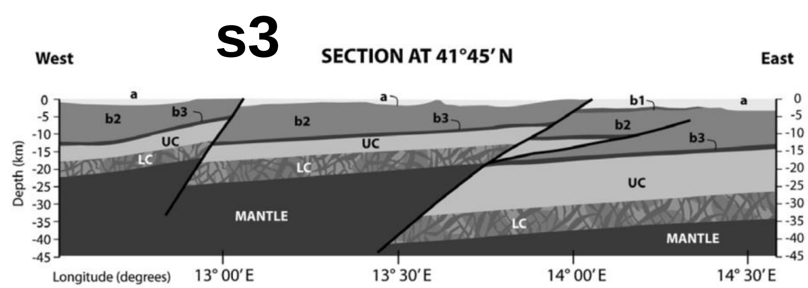


Schematic W-E sections of the main reservoirs



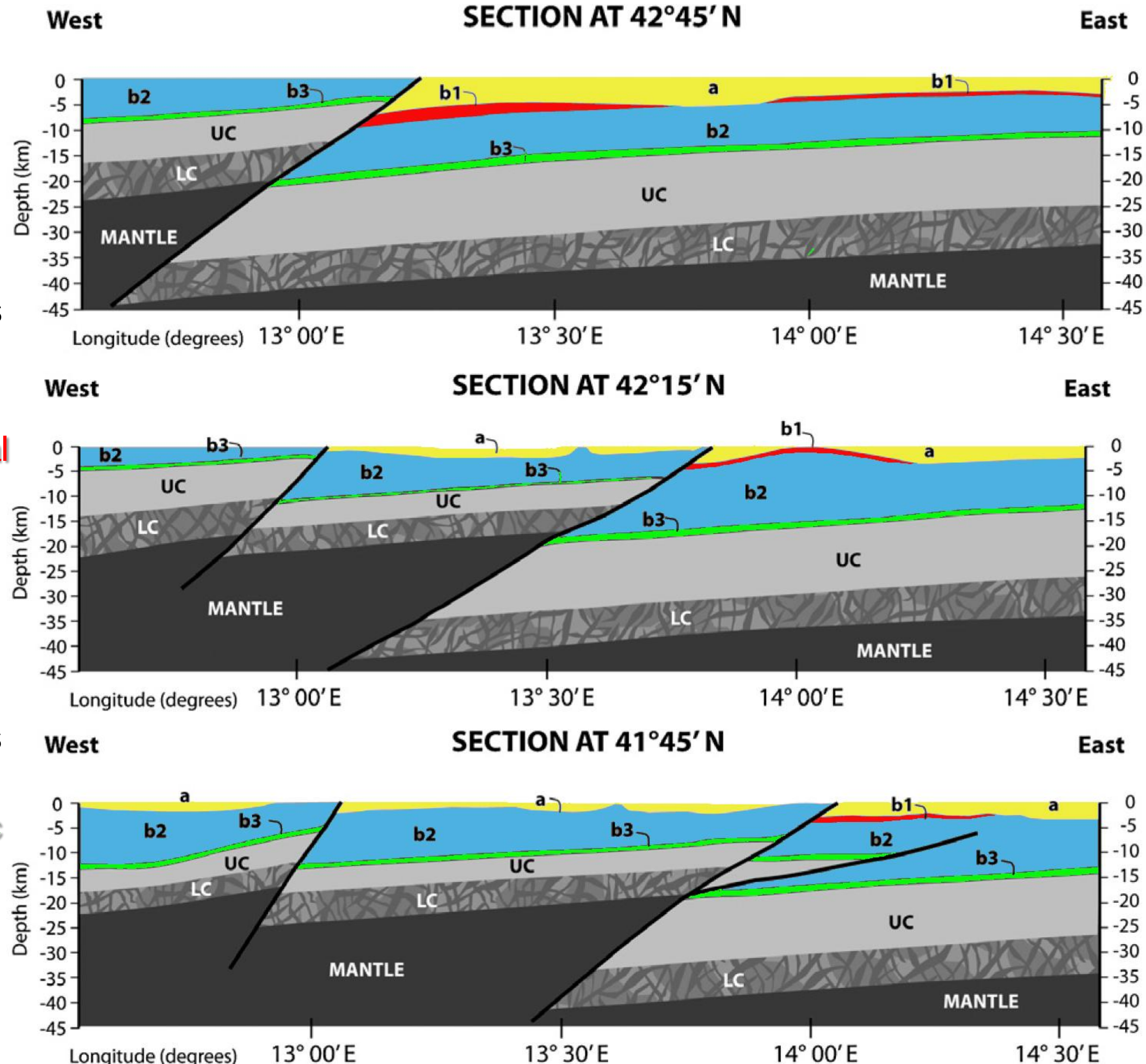






The sedimentary cover

- Cenozoic terrigenous units: sandstones, siltites and clays
- Meso-Cenozoic Basinal Carbonate units: marly and shaly carbonates
- Mesozoic Carbonate units: limestones, dolomites and evaporites
- Permian and Paleozoic clastic units: sandstones, conglomerates, subordinate with carbonates



Science needs to be touched !!!!!!!!!!

Don't miss the field trip next Wednesday!!!

U and Th content of sediments of the CT

- **We collected representative samples of the sedimentary cover and measured U and Th content by using ICP-MS:**

Reservoir	Mass [%]	a(U) [ppm]*	a(Th) [ppm]*	Density [gr/cm^3]
Mesozoic Carbonate units	76.8	0.3 ± 0.2	0.2 ± 0.2	2.5
Cenozoic terrigenous	15.6	2.3 ± 0.6	8.3 ± 2.5	2.1
Permian and Paleozoic clastic	5.8	2.2 ± 1.3	8.1 ± 4.9	2.6
Meso-Cenozoic Basinal Carbonate	1.8	1.7 ± 1.8	1.5 ± 1.6	2.3

- **By using these abundances and the 3D model, the estimated signal from the sedimentary cover is:** $\boxed{S_{Sed} = 2.9 \text{ TNU}}$

- **To be compared with that estimated in Ref. Mod.:** $\boxed{S_{Sed} = 0.5 \text{ TNU}}$

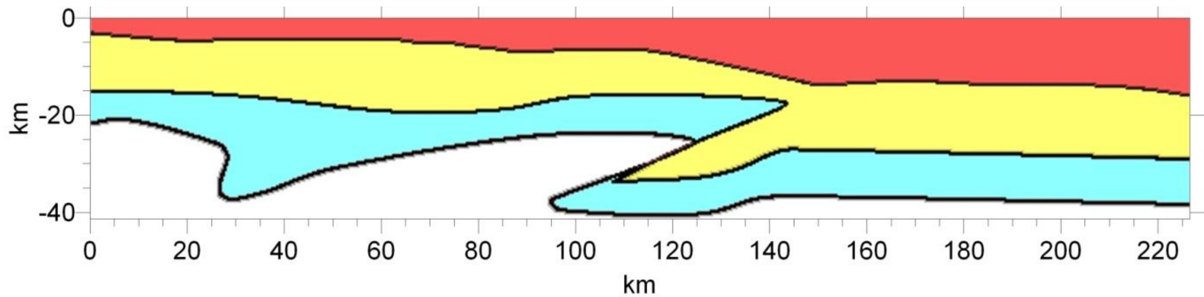
(remind the 0.5 km sediment layer)

Reservoir in Ref. Mod.	a(U) [ppm]	a(Th) [ppm]	Density [gr/cm^3]
Sediments	1.7	6.9	2.1 - 2.5

** Standard deviation of measured samples*

Before and after the refinement

The main results of this study are about the thickness of layers and their composition.

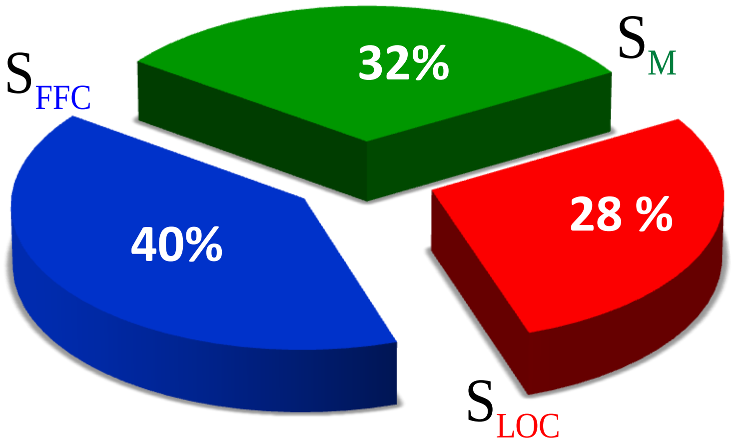


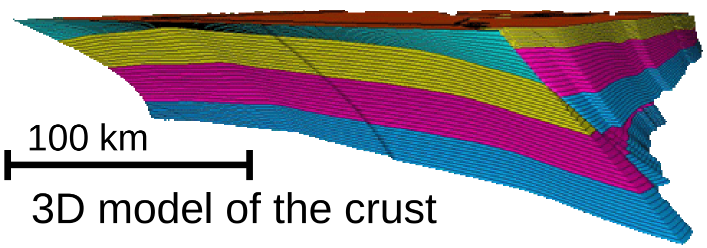
	Before the refinement			After refinement		
Res.	Δz [km]	a(Th) [mg/g]	a(U) [mg/g]	Δz [km]	a(Th) [mg/g]	a(U) [mg/g]
Sed.	~ 0.5	6.9	1.67	~ 13	2.00 ± 0.17	0.80 ± 0.07
UC	~ 10	9.8	2.5	~ 13	8.1 ± 1.6	2.20 ± 0.43
MC	~ 10	6.1	1.6	/	/	/
LC	~ 10.5	3.7	0.6	~ 8	2.6 ± 1.2	0.30 ± 0.10

The local expected signal calculated signal is S_{After} **= 9.7 ± 1.3 TNU** to compare with S_{Before} **= 15.3 TNU**.

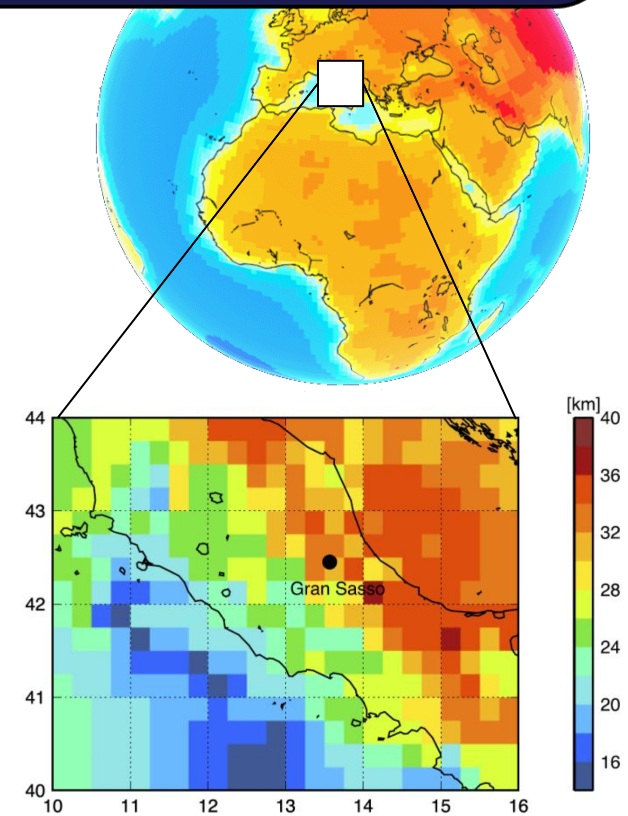
Geoneutrino in Borexino: theory and experiment

$$S_{EXP} = S_{LOC} + S_{FFC} + S_{Mantle}$$





3D model of the crust around Gran Sasso Lab



Contributions to the S_{LOC} Borexino are given by U and Th in:

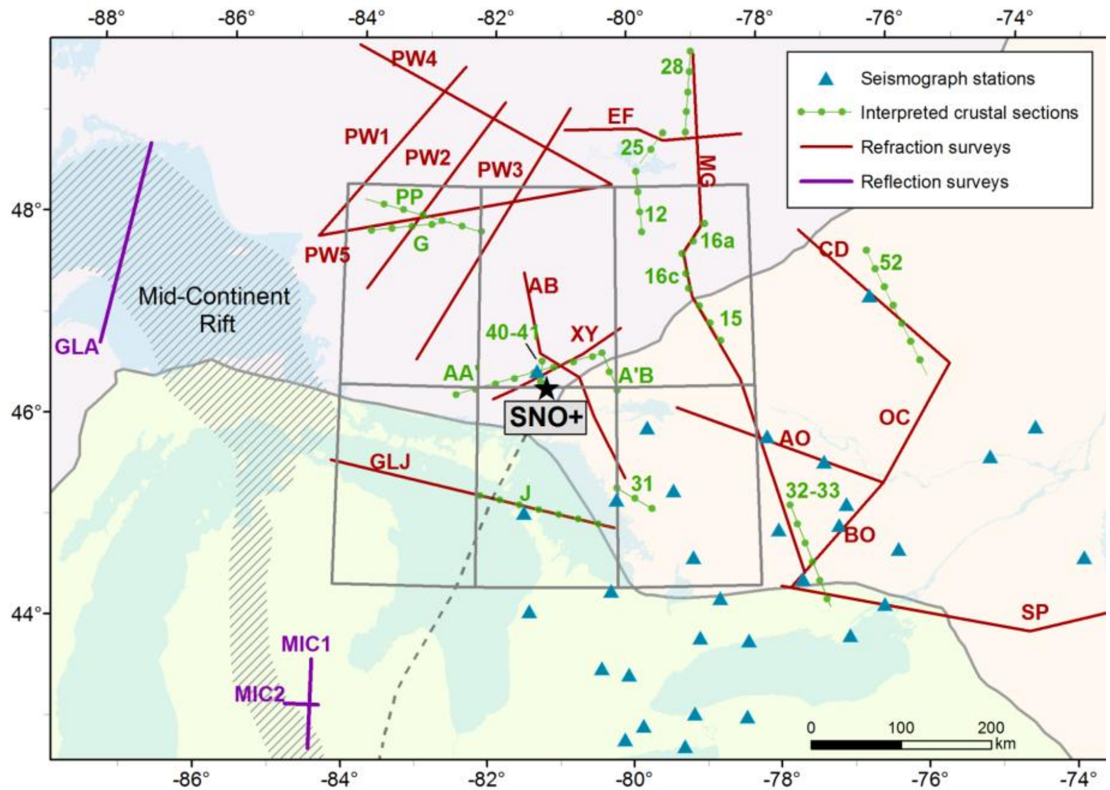
	S_{LOC} (TNU)
Sediments	2.9 ± 0.3
Loc UC	6.2 ± 1.2
Loc LC	0.6 ± 0.2
Total S_{LOC}	9.7 ± 1.3

	LOC[1]	FFC[2]	CLM[2]	Mantle[2]	Total (theory)	Experiment (BX 2013)[3]
S(U+Th) [TNU]	9.7 ± 1.3	13.7 ± 2.5	2.2 ± 2.2	8.7	34.3 ± 3.6	43.5 ± 13.7

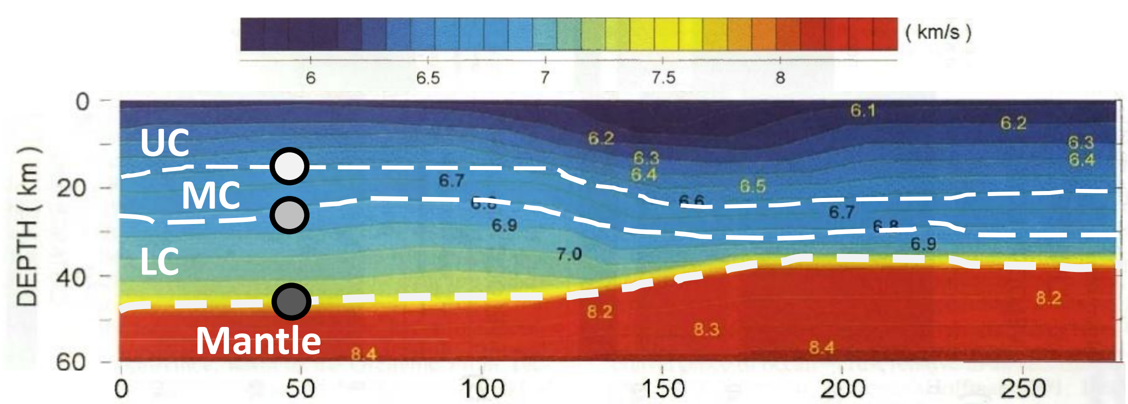
[1] Fiorentini et al. – 2012 // [2] Huang, Y., et al. - 2013 - arXiv:1301.0365v2 // [3] Borexino collaboration - Physics Letters B 722 - 2013

A crustal 3D model surrounding SNO+

- **SNO+** is a 1kton LS detector located in Ontario (Canada) in the Superior Province, one of the world's largest Archean cratons
- We modeled the crust of the six 2° x 2° crustal tiles (**440 km x 460 km)** for predicting geoneutrino signal
- The goal was to define the geometry of **LC, MC** and 7 main reservoirs of the **UC**, assigning them U and Th abundances
- We digitized **velocity contours** (6.6, 6.8 and 8.0 km/s) in order to extract **depth** of the top of MC (TMC), LC (TLC) and Moho Discontinuity (MD)



	Latitude	Longitude	Depth
○	46.85 °	- 81.78 °	18.4 km
○	46.85 °	- 81.78 °	27.7 km
●	46.85 °	- 81.78 °	47.6 km

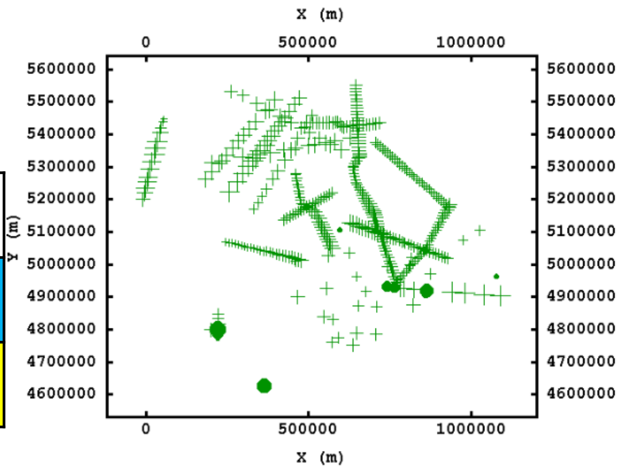


Modeling the geophysical discontinuities surfaces

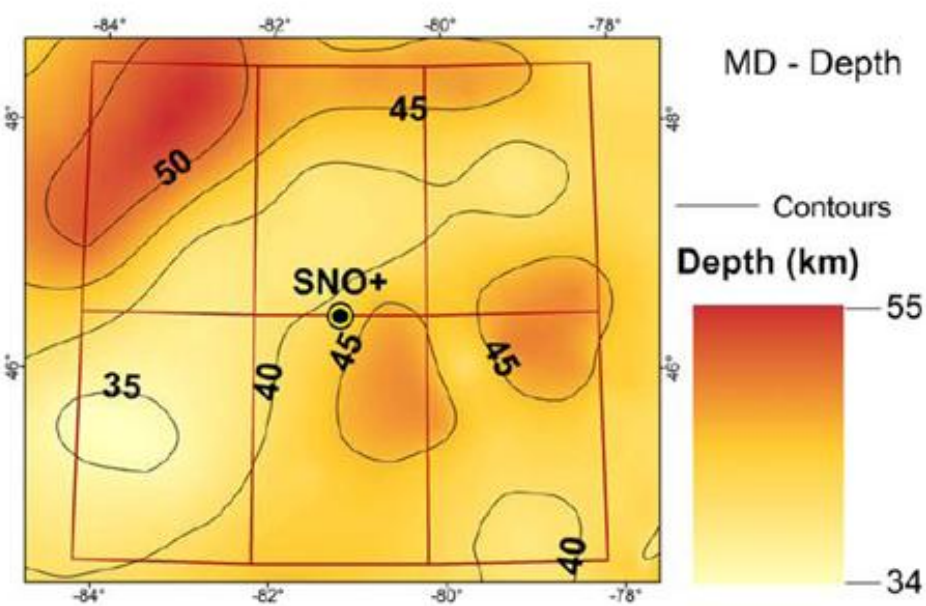
Input

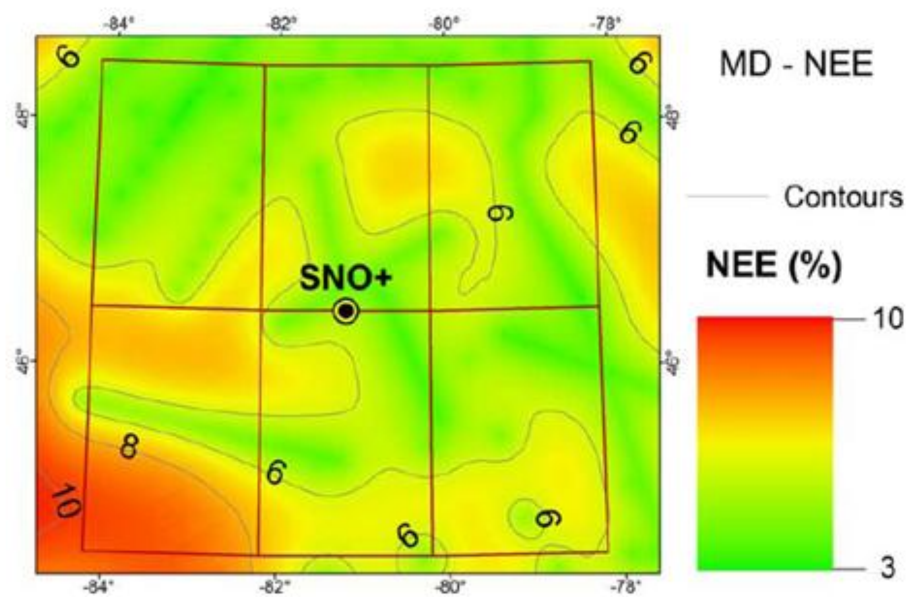
Depth-controlling points obtained by 15 refraction lines, 3 reflection lines and data from 32 seismographic stations

	N° points
Top of MC (TMC)	343
Top of LC (TLC)	343
Moho discontinuty (MD)	392

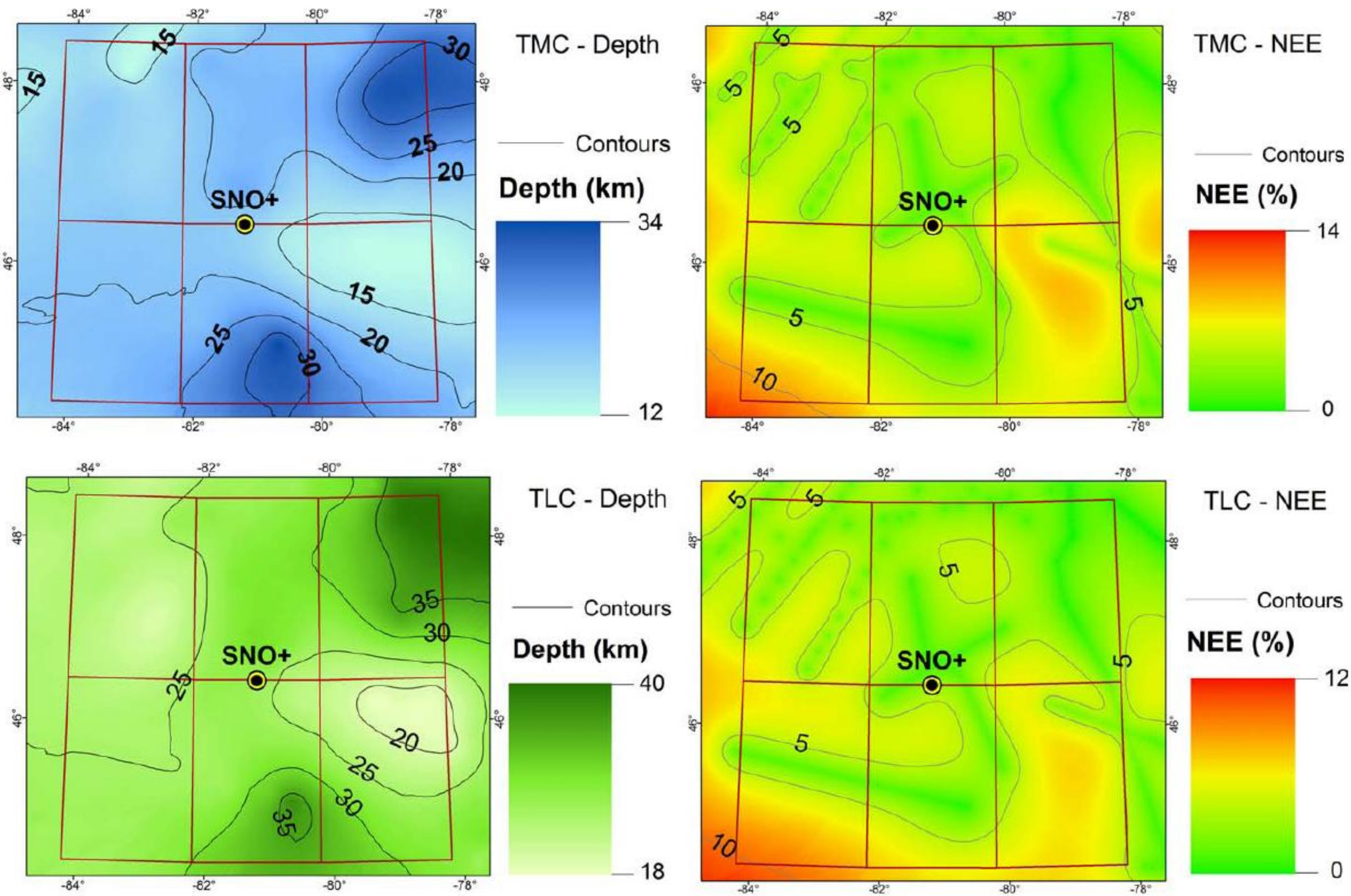


ORDINARY KRIGING: the value of the depth in **unobserved locations** is estimated from **input data points** taking into account the **spatial continuity** of the variables.



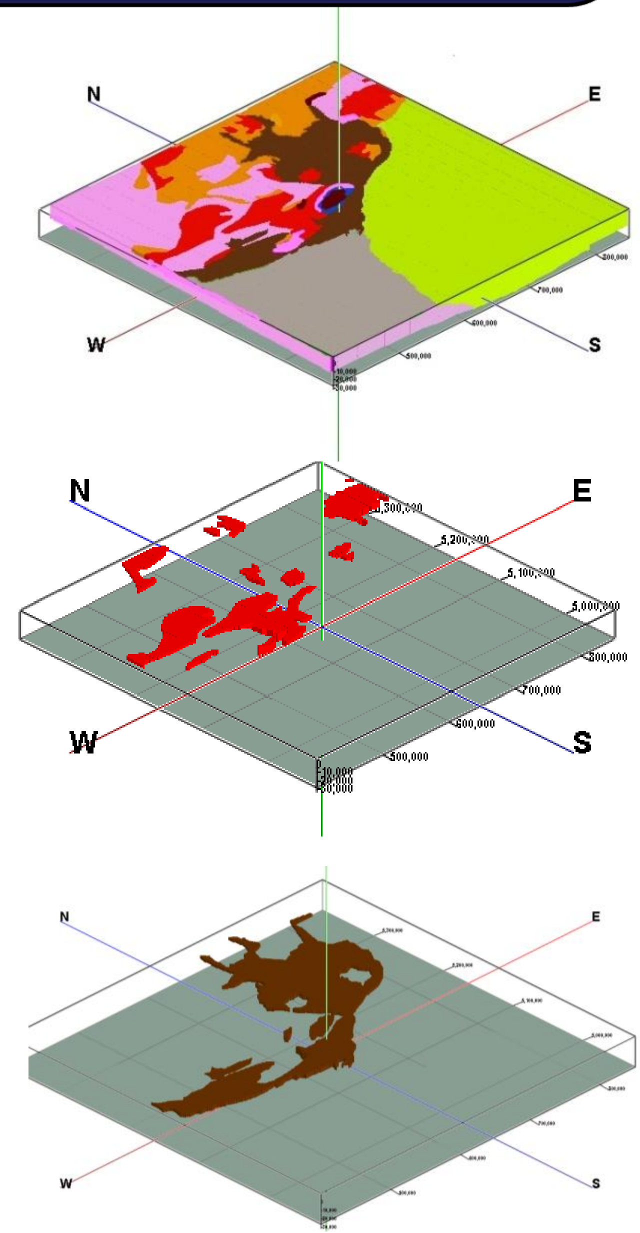


Modeling the geophysical discontinuities surfaces



The geophysical uncertainties at SNO+

• For the first time the **masses** of the main crustal reservoirs containing U and Th are estimated together with their uncertainties in the region surrounding SNO+.



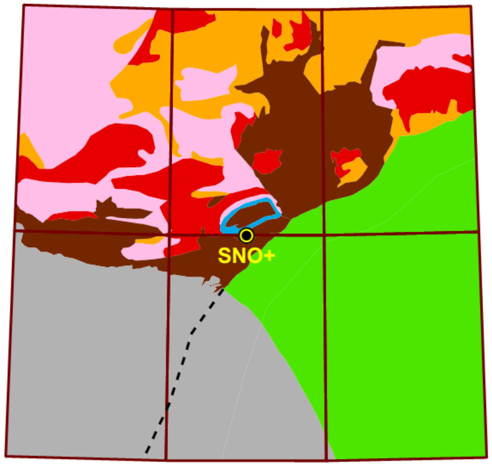
	CRUST 1.0*	Huang et al. 2014		
	M [10^{18} kg]	Volume [10^6 km^3]	ρ [g/cm^3]	M [10^{18} kg]
UC	**6.6**	4.2 ± 0.2	2.73 ± 0.08	**11.5 ± 0.6**
MC	**8.1**	1.3 ± 0.1	2.96 ± 0.03	**3.8 ± 0.3**
LC	**8.0**	3.2 ± 0.2	3.08 ± 0.06	**9.9 ± 0.6**
Total	**22.7**	8.7 ± 0.5	-	**25.2 ±1.6**

• The relative uncertainties of the reservoirs masses are of ~ 6%.

• Together with uncertainties of U and Th abundances these results are crucial for a reliable estimation of geoneutrino signal in SNO+.

* Laske et al. [2013] at **http://igppweb.ucsd.edu/~gabi/rem.html**

Geoneutrino signal at SNO+ from the local crust



- After the refinement, the regional geoneutrino signal expected at SNO+ decreases from **18.9** $^{+3.5}_{-3.3}$ TNU (Huang et al. 2013) to **15.6** $^{+5.3}_{-3.4}$ TNU (Huang et al. 2014).
- The **Huronian Supergroup** is predicted to be the dominant source of the geoneutrino signal and the primary source of the large uncertainty on the local predicted geoneutrino signal.

Lithologic unit of UC	Vol. (%)	U (ppm)	Th (ppm)	S(U+Th) [TNU]
Tonalite/Tonalite gneiss (Wawa-Abitibi)	60.6	$0.7^{+0.5}_{-0.3}$	$3.1^{+2.3}_{-1.3}$	$2.2^{+1.4}_{-0.9}$
Central Gneiss Belt (Grenville Province)	30.2	$2.6^{+0.4}_{-0.4}$	$5.1^{+6.0}_{-2.8}$	$2.1^{+0.4}_{-0.3}$
(Meta)volcanic rocks (Abitibi sub-province)	2.9	$0.4^{+0.4}_{-0.2}$	$1.3^{+1.2}_{-0.6}$	$0.02^{+0.01}_{-0.01}$
Paleozoic sediments (Great Lakes)	1.3	$2.5^{+2.0}_{-1.1}$	$4.4^{+1.6}_{-1.2}$	$0.05^{+0.04}_{-0.02}$
Granite or granodiorite (Wawa-Abitibi)	2.2	$2.9^{+1.6}_{-1.0}$	$19.9^{+8.4}_{-6.0}$	$0.5^{+0.2}_{-0.1}$
Huronian Supergroup, Sudbury Basin	2.7	$4.2^{+2.9}_{-1.7}$	$11.1^{+8.2}_{-4.8}$	$7.3^{+5.0}_{-3.0}$
Sudbury Igneous Complex	0.1	$2.3^{+0.2}_{-0.2}$	$10.6^{+0.7}_{-0.7}$	$0.8^{+0.1}_{-0.1}$

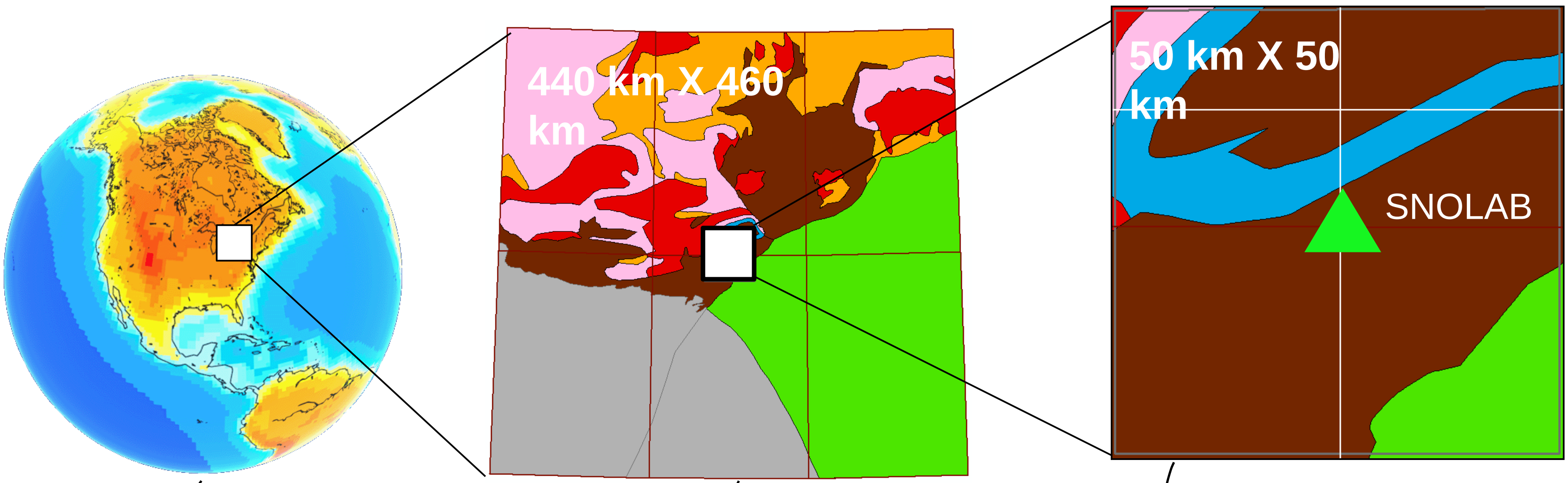
Focusing on close crust

Contribution to the crustal geoneutrino signal

48 %

26 %

26 %



92% of the signal
of the HS-SB

Global crustal model

Huang et al 2013

LOcal Crust (LOC)

Huang et al 2014

CLose Crust (CLC)

New 3D geophysical and geochemical model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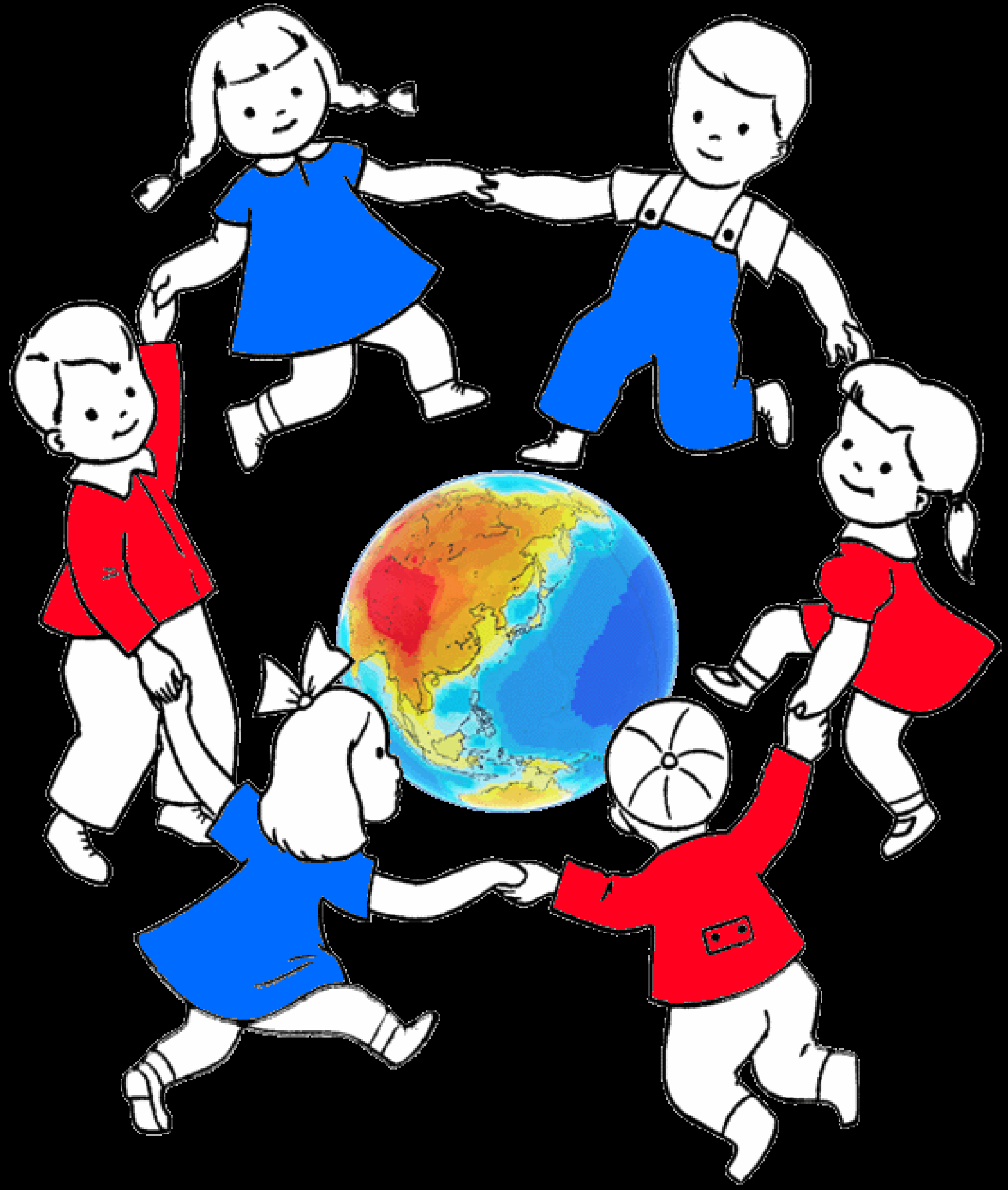

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