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

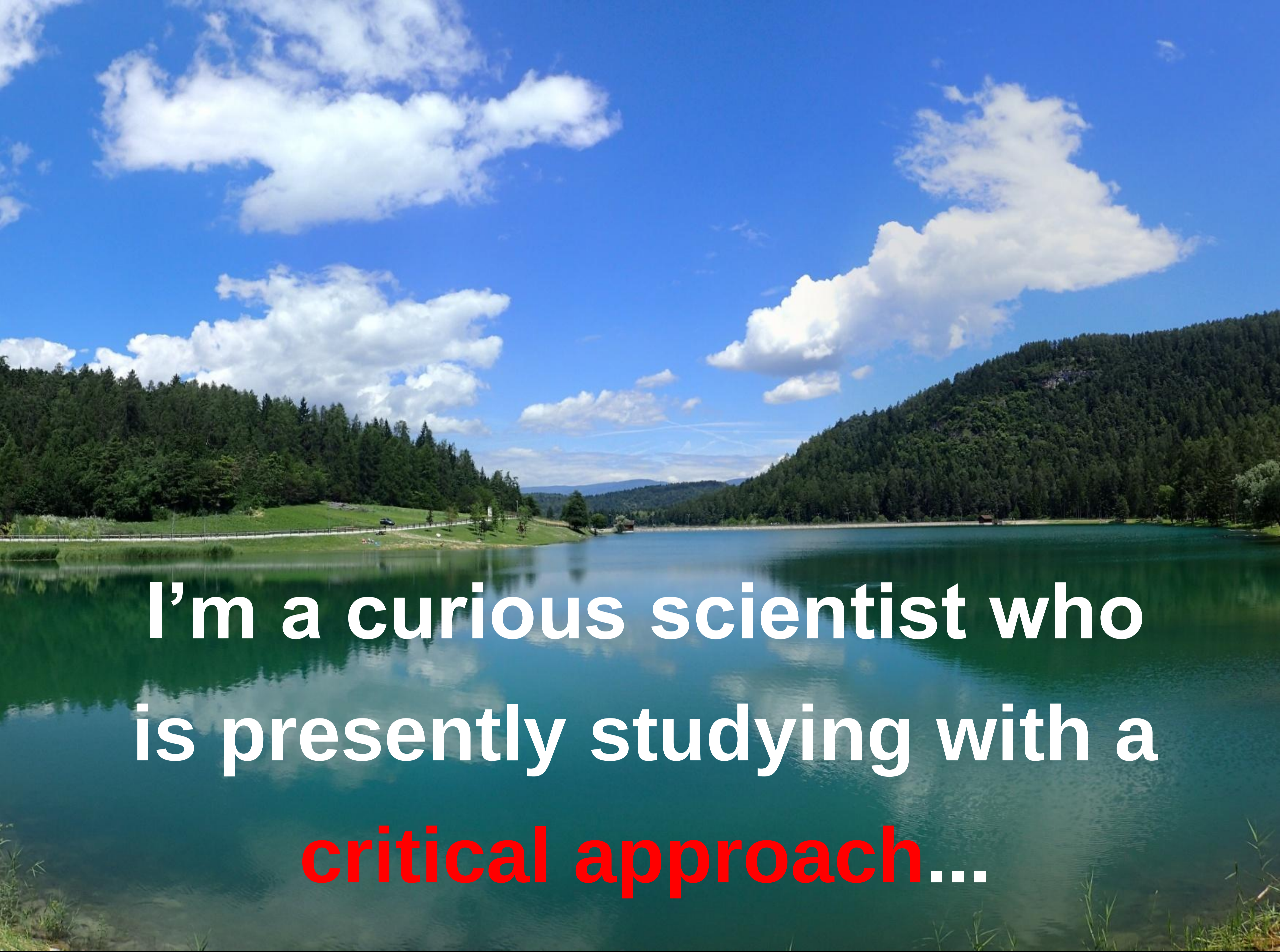
11-21 July 2016 *Gran Sasso Science Institute*
Europe/Rome timezone

Wednesday 20 July 2016

Error estimation and propagation - Room D (09:00-10:00)

- **Presenters: MANTOVANI, Fabio**

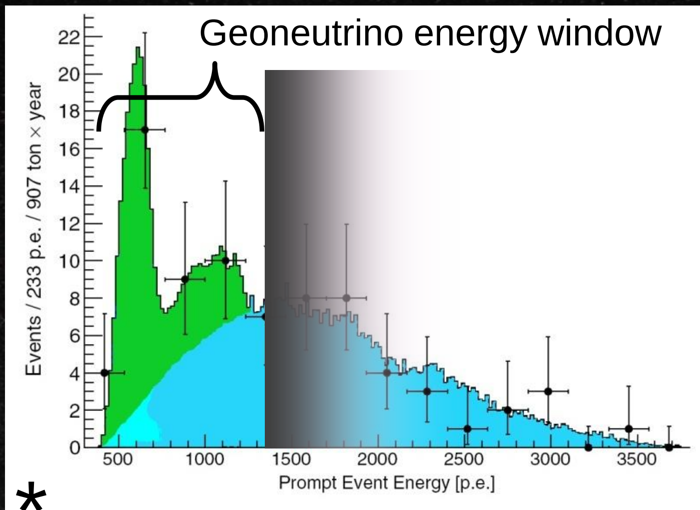
Field trip - Introduction - Room D; departure from GSSI at 11:30 (10:00-18:30)


I’m a curious scientist who
is presently studying with a
critical approach...

What is an uncertainty in science?

An uncertainty is a crack in the wall of knowledge

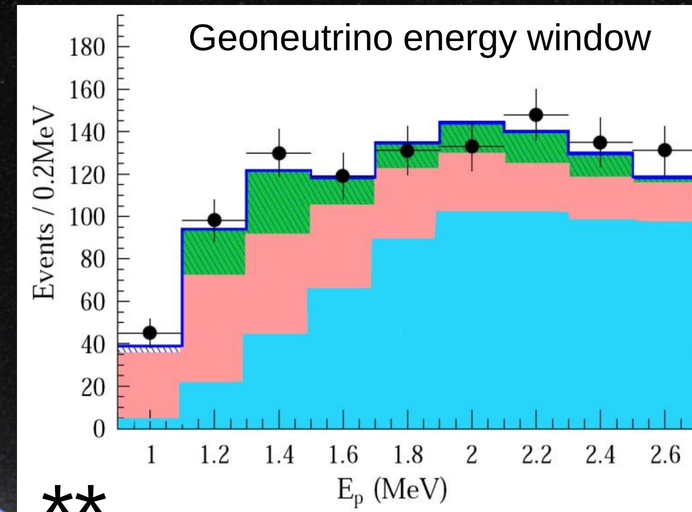
Borexino and KamLAND results

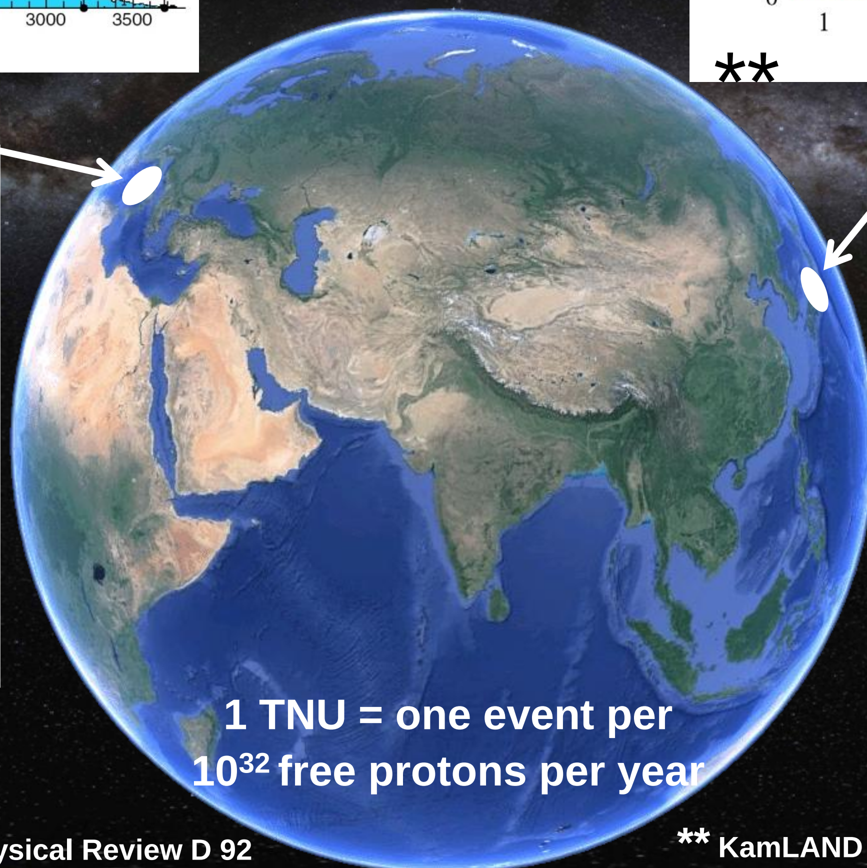


Geoneutrinos

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

KL and BX results and Bulk Silicate Models

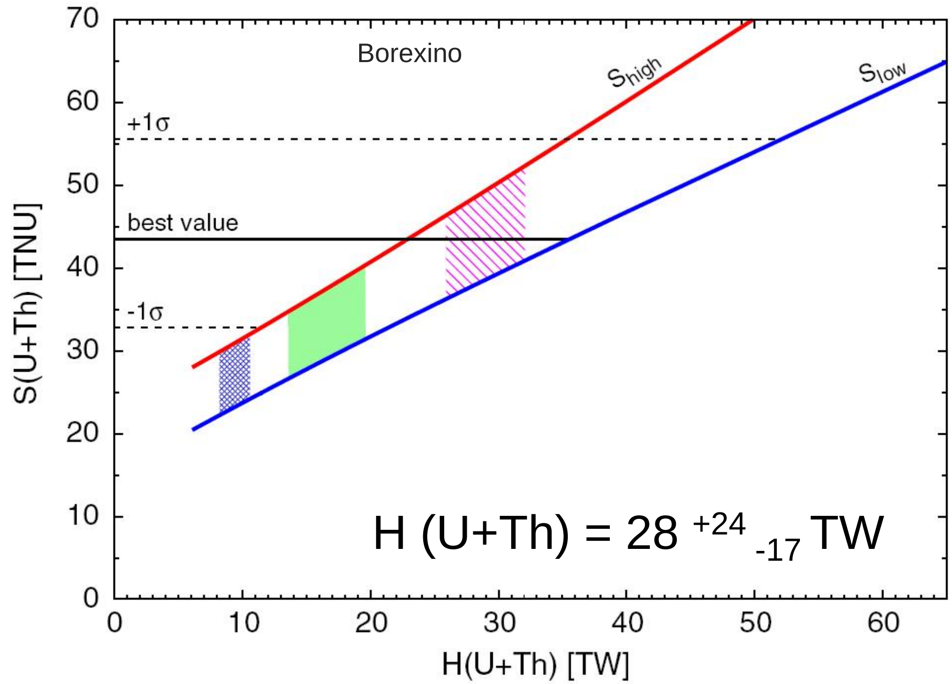
In the plane (S,H), a region containing all models consistent with geochemical and geophysical data can be defined:

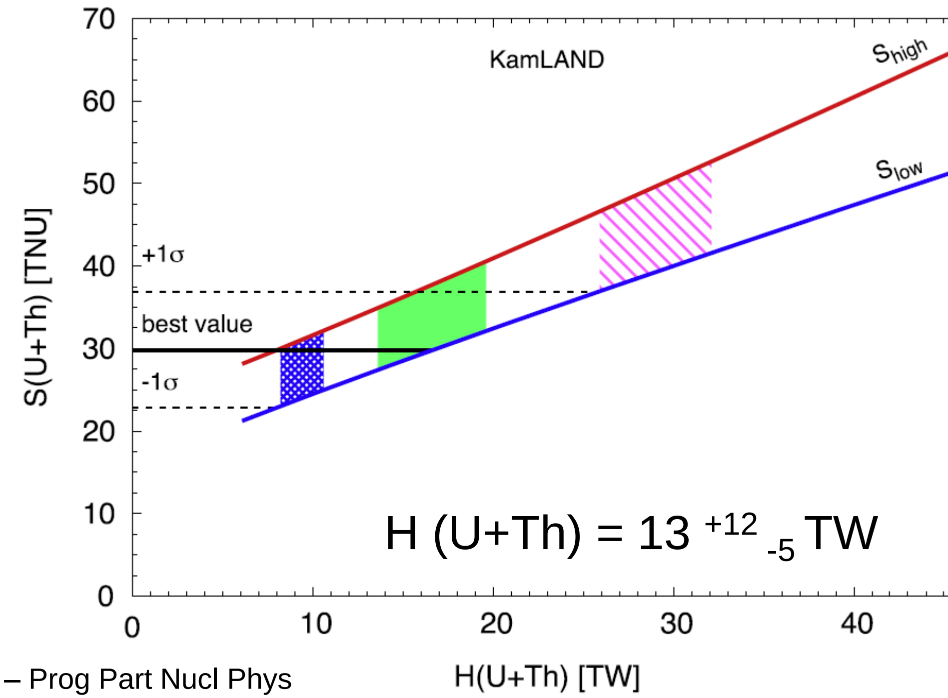
- ✓ the "slope" is universal
- ✓ the intercept depends on the site
- ✓ the width depends on the site (crustal effect)

Cosmochemical BSE models:
$m_{PRIM}(U) = 0.5 \pm 0.1\ 10^{17}$ kg
Th/U = 3.5

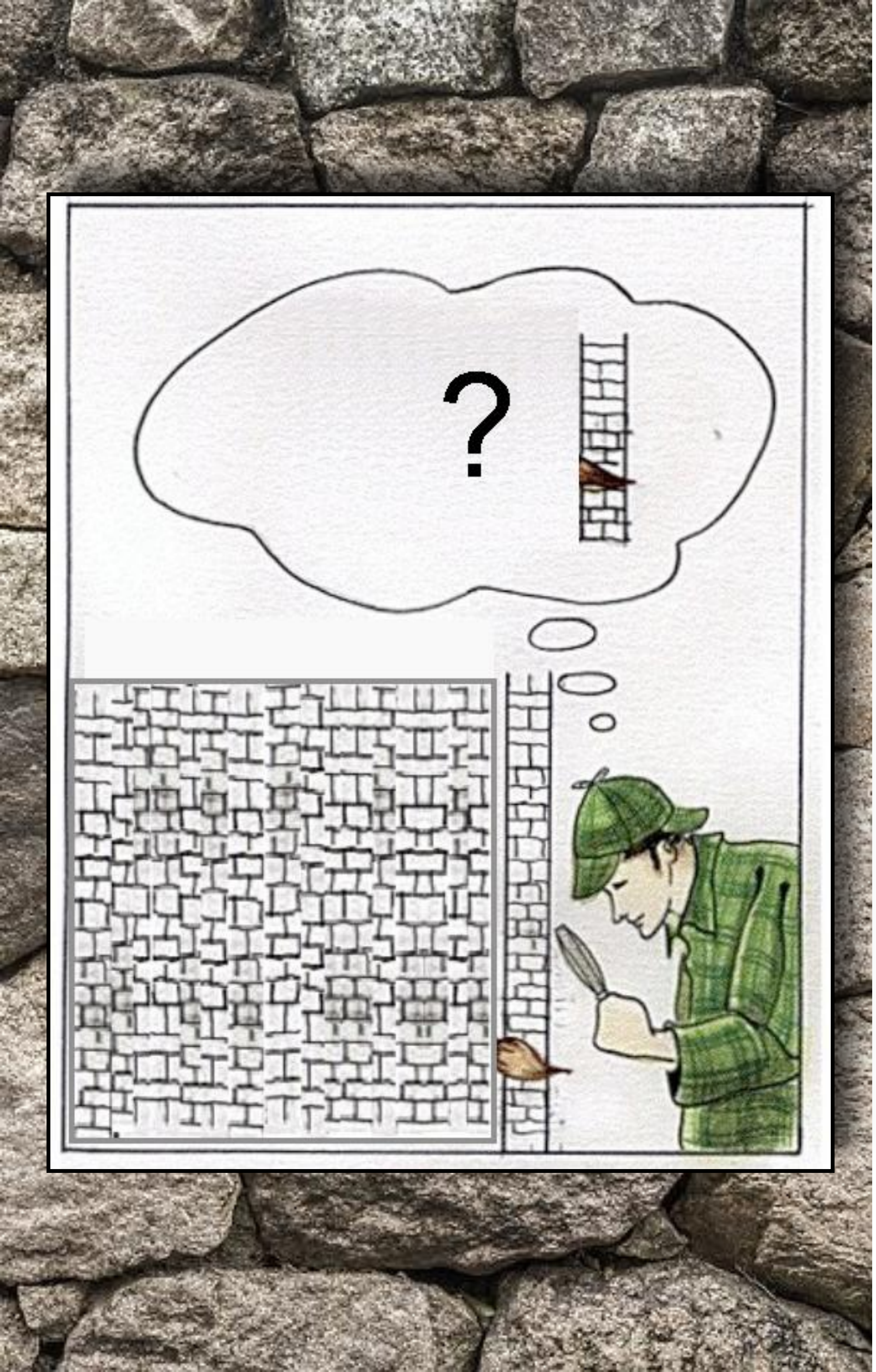
Geochemical BSE models:
$m_{PRIM}(U) = 0.8 \pm 0.2\ 10^{17}$ kg
Th/U = 4

Geodynamical BSE models:
$m_{PRIM}(U) = 1.4 \pm 0.2\ 10^{17}$ kg
Th/U = 4





Bellini et al, 2013 – Prog Part Nucl Phys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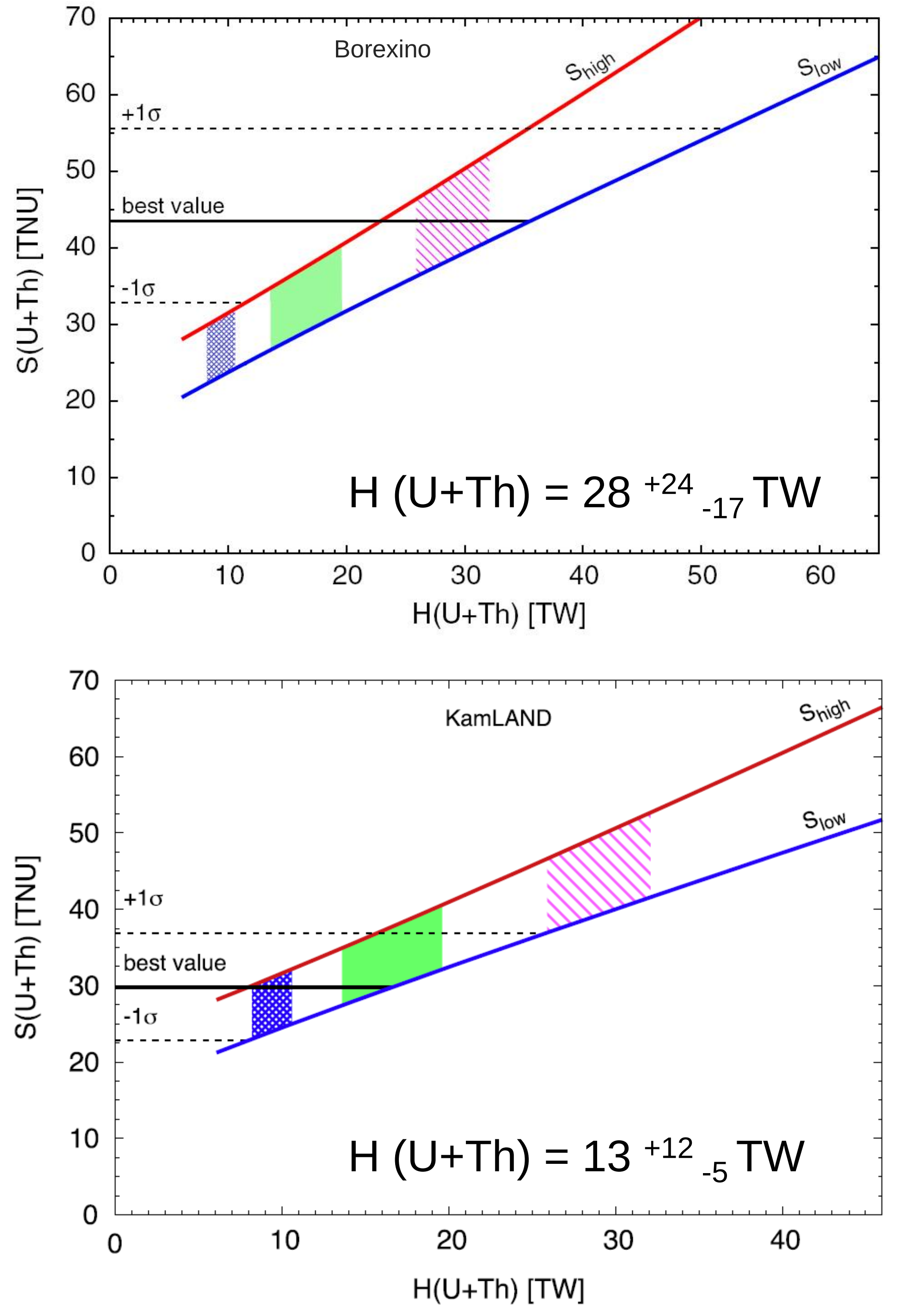
Borexino
S(U+Th) [TNU]
H(U+Th) [TW]
best value
+1σ
-1σ
S_{high}
S_{low}
H (U+Th) = 28 $^{+24}_{-17}$ TW
KamLAND
S(U+Th) [TNU]
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best value
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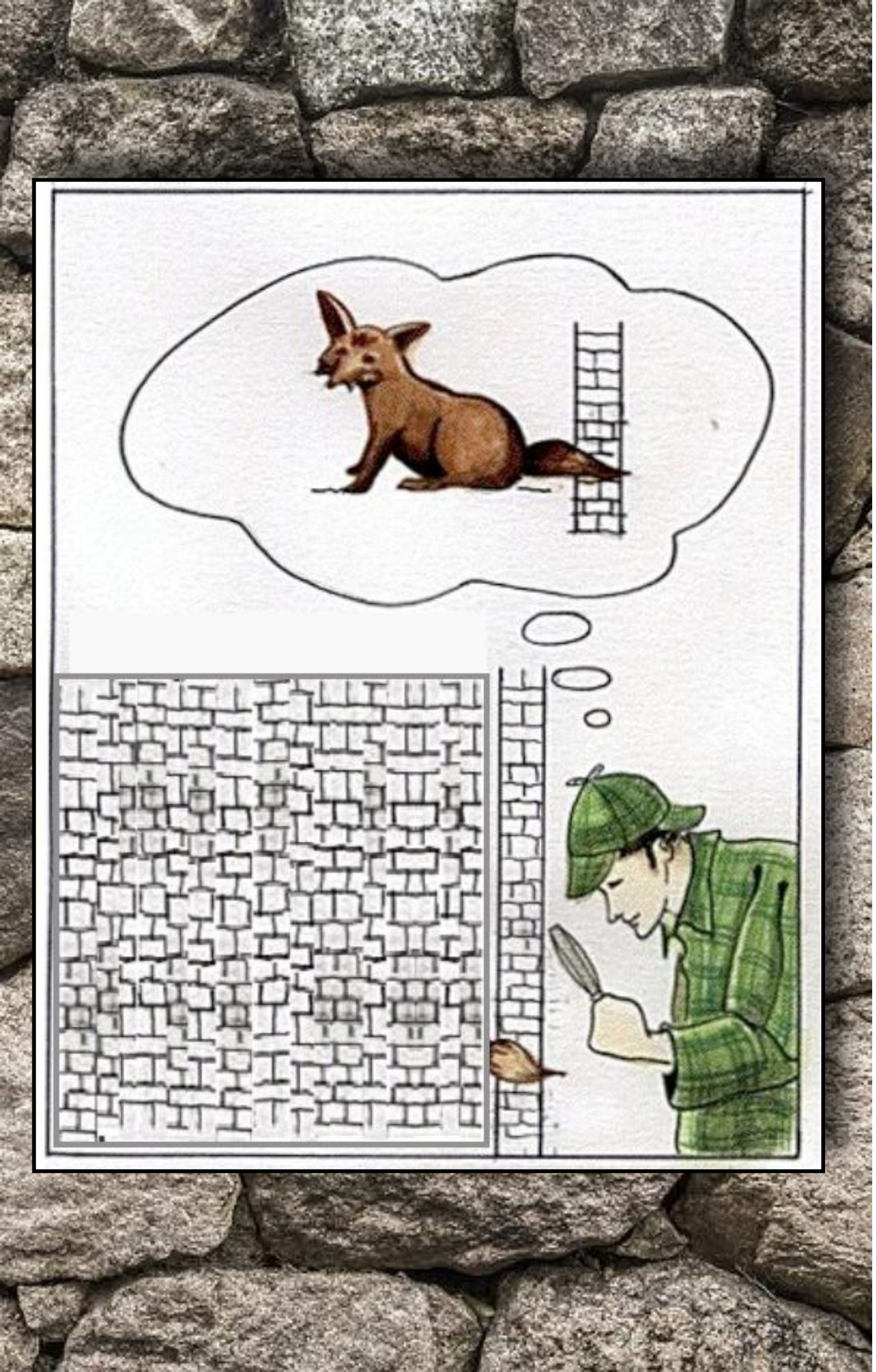
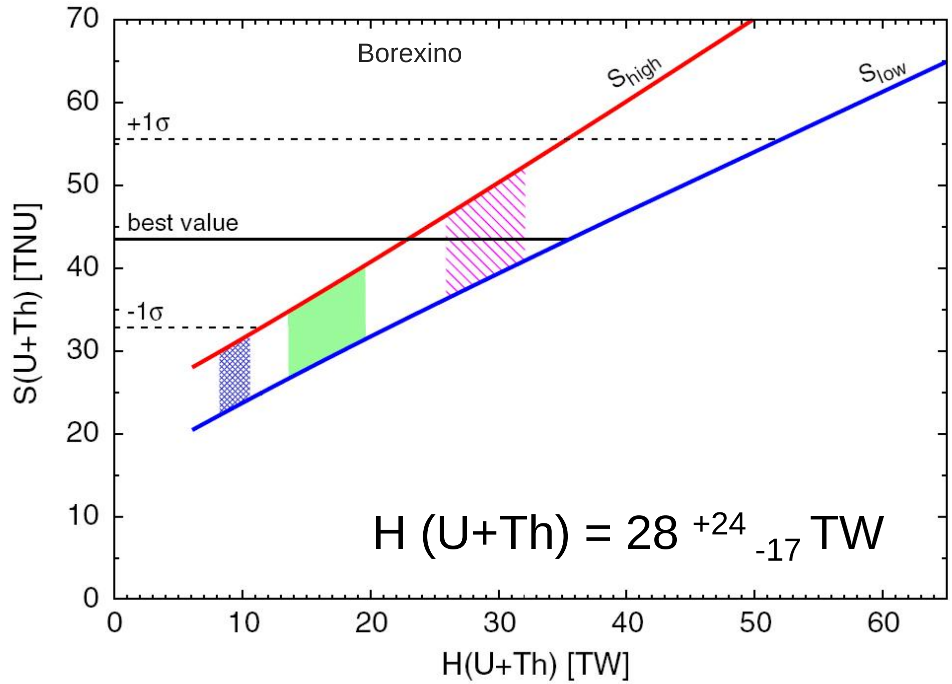
S_{high}
S_{low}
H (U+Th) = 13 $^{+12}_{-5}$ TW

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S_{high}
S_{low}
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best value
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0 10 20 30 40 50 60 70
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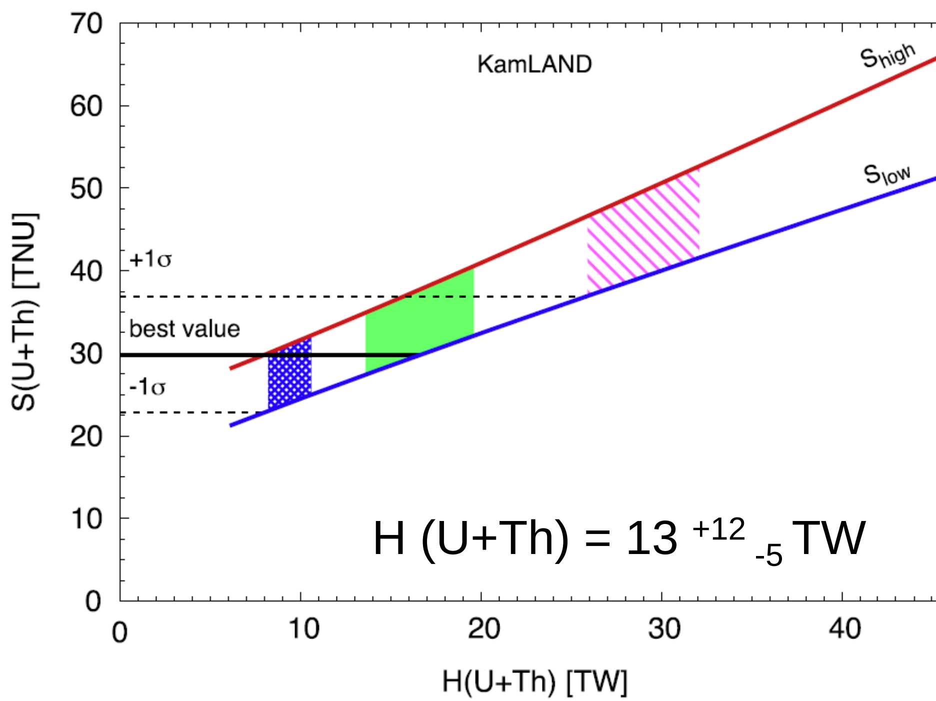
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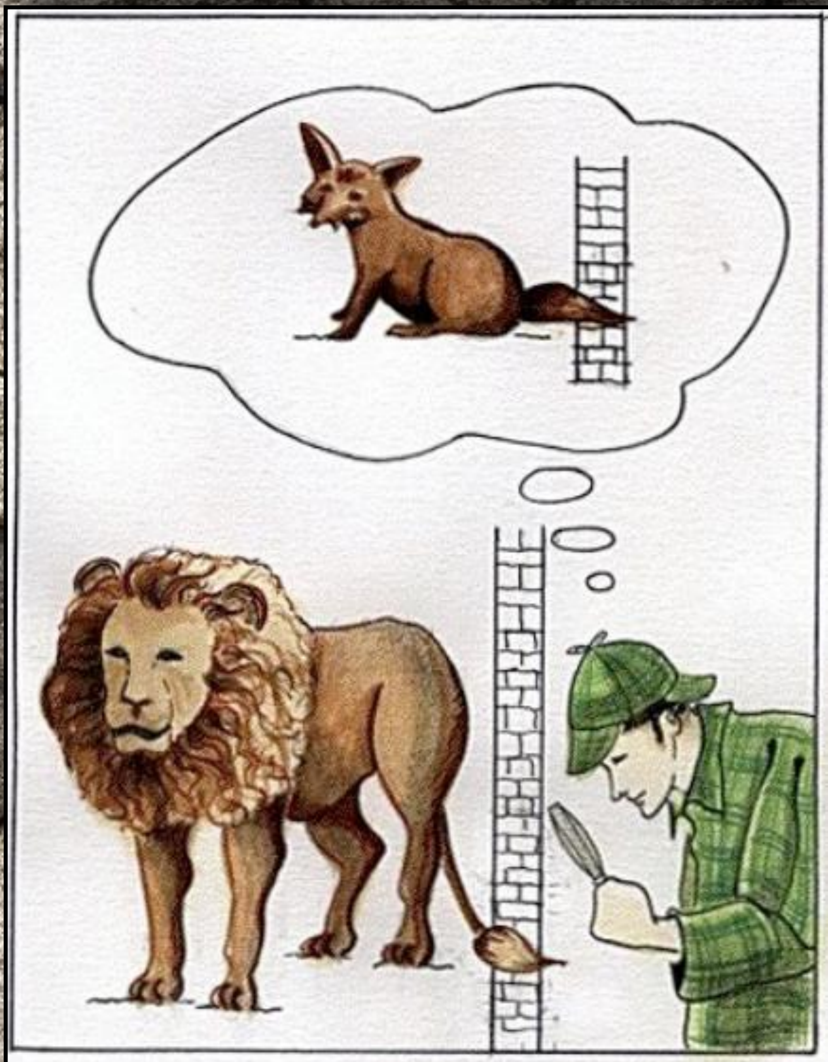

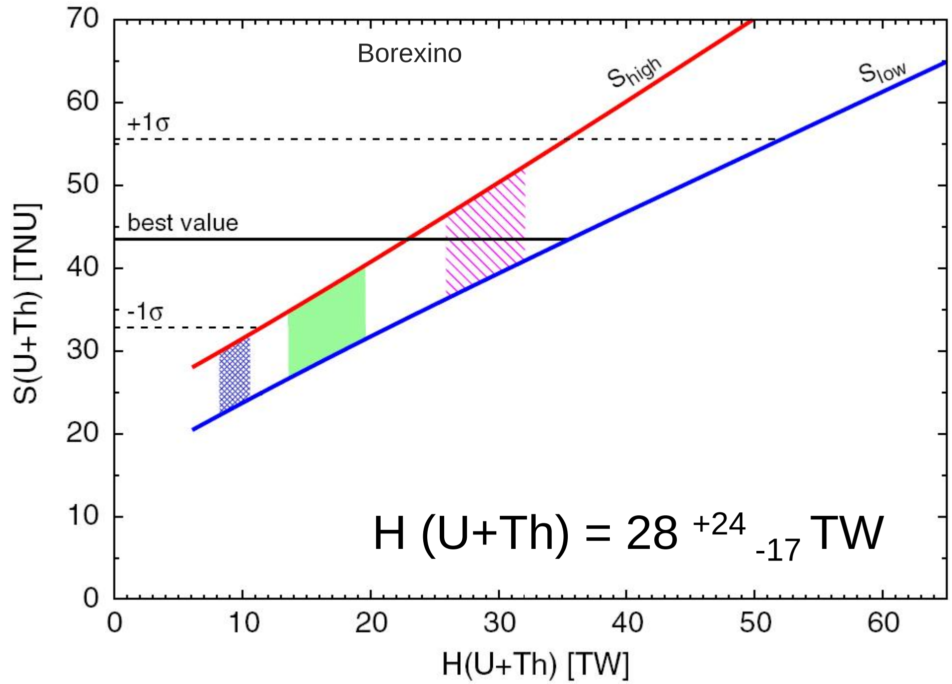
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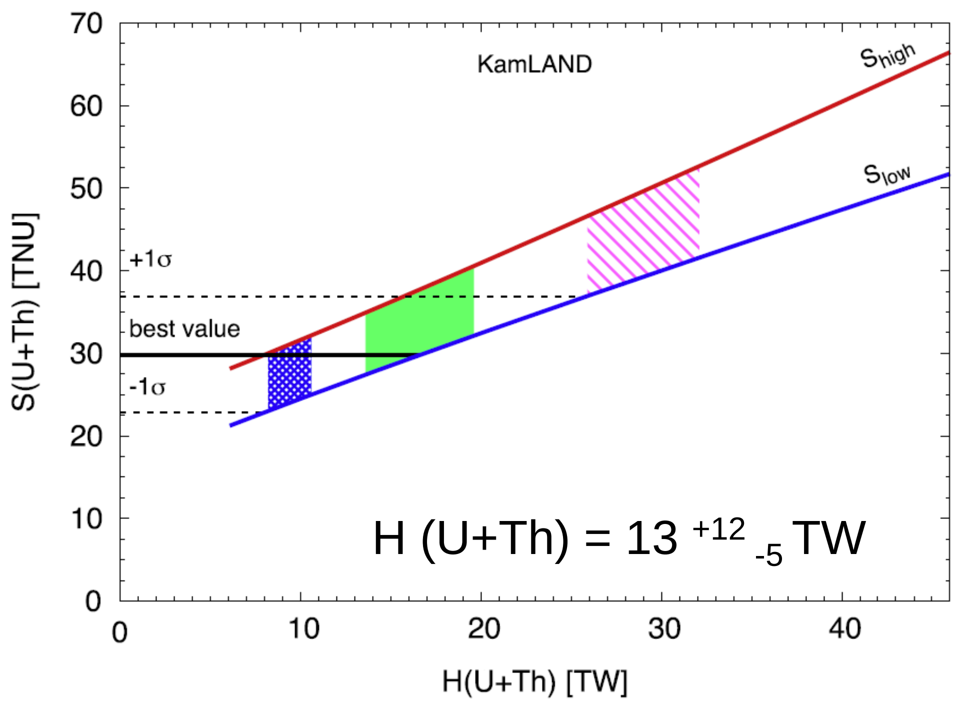
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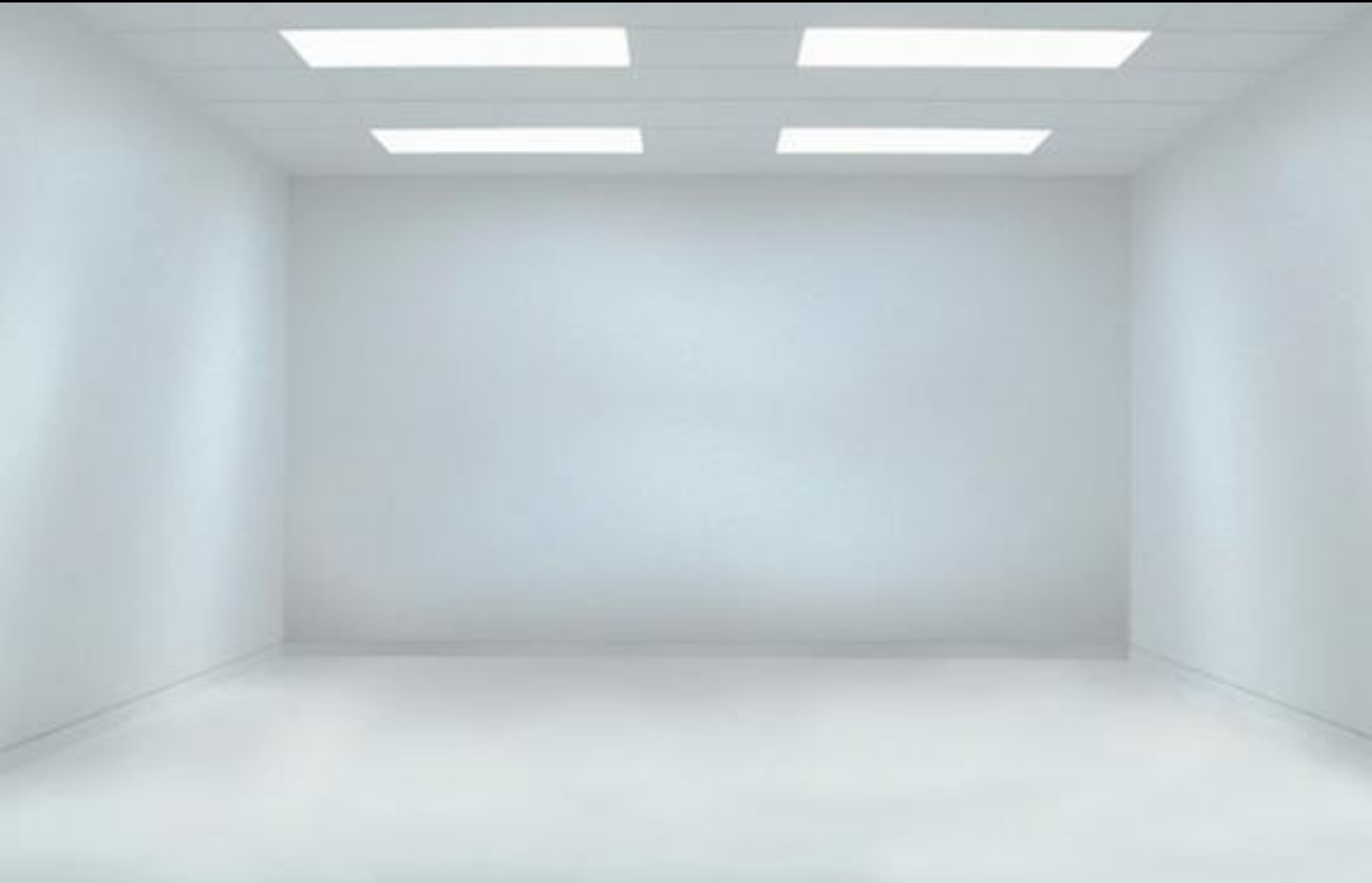
There are many walls without any cracks



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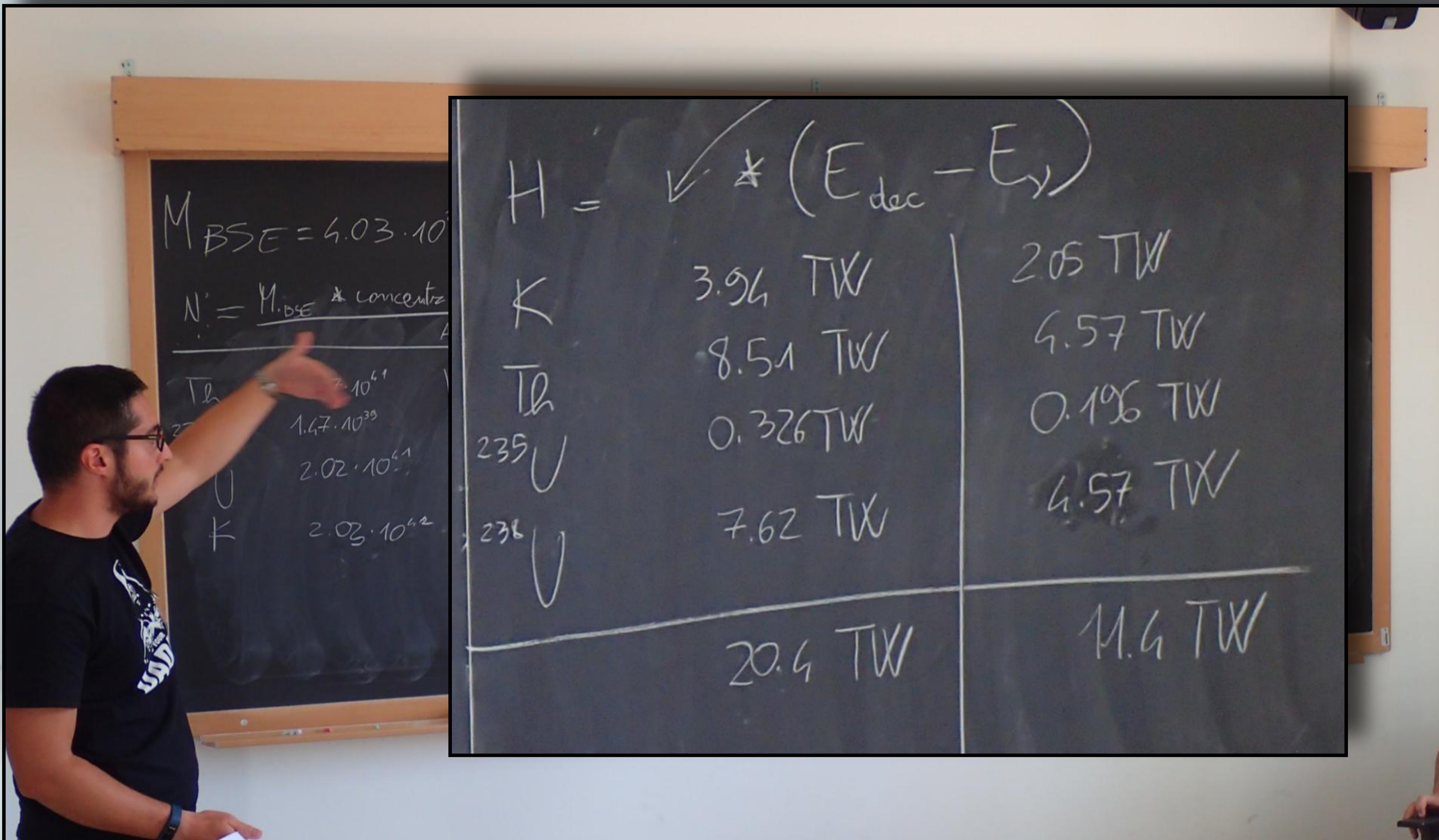


No cracks from nuclear physics!

TABLE 8. Specific Heat Production for Major Natural Radionuclides

Element:	Potassium	Thorium	Uranium	
Isotope:	^{40}K	^{232}Th	^{235}U	^{238}U
Isotopic abundance (weight percent)	0.0119	100.00	0.71	99.28
Decay constant, λ ($year^{-1}$)	5.54×10^{-10}	4.95×10^{-11}	9.85×10^{-10}	1.551×10^{-10}
Total decay energy (MeV/decay)	1.340 [a]	42.66 [b]	46.40 [b]	51.70 [b]
Beta decay energy (MeV/decay)	1.181 [a]	3.5 [b]	3.0 [b]	6.3 [b]
Beta energy lost as neutrinos (MeV/decay)	0.650 [c]	2.3 [d]	2.0 [d]	4.2 [d]
Total energy retained in Earth (MeV/decay)	0.690	40.4	44.4	47.5
Specific isotopic heat production (cal/g-year)	0.220	0.199	4.29	0.714
" " " " (µW/kg)	29.17 ←	26.38 ←	568.7	94.65 ←
Specific elemental heat production (cal/g-year)	2.6×10^{-5}	0.199	0.740	
" " " " (µW/kg)	3.45×10^{-3}	26.38	98.10	

[a]Averaged for branching decay: 89.5% β^- @ 1.32 MeV + 10.5% E.C. @ 1.51 MeV.

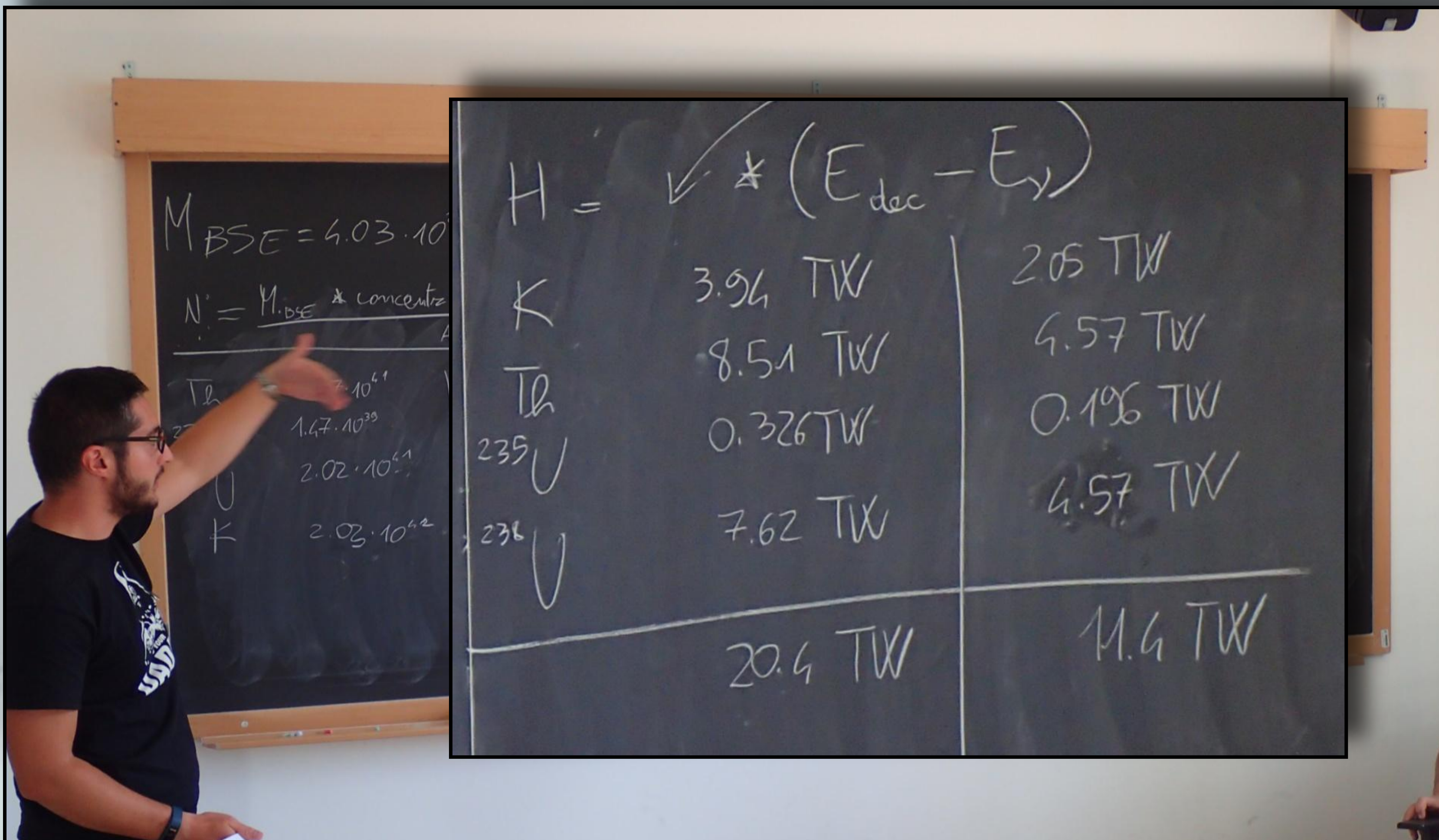
[b]Summed for entire decay series.

[c]Based on mean decay energy for β^- of 0.60 MeV; 55% of total β^- energy lost as neutrinos [12].

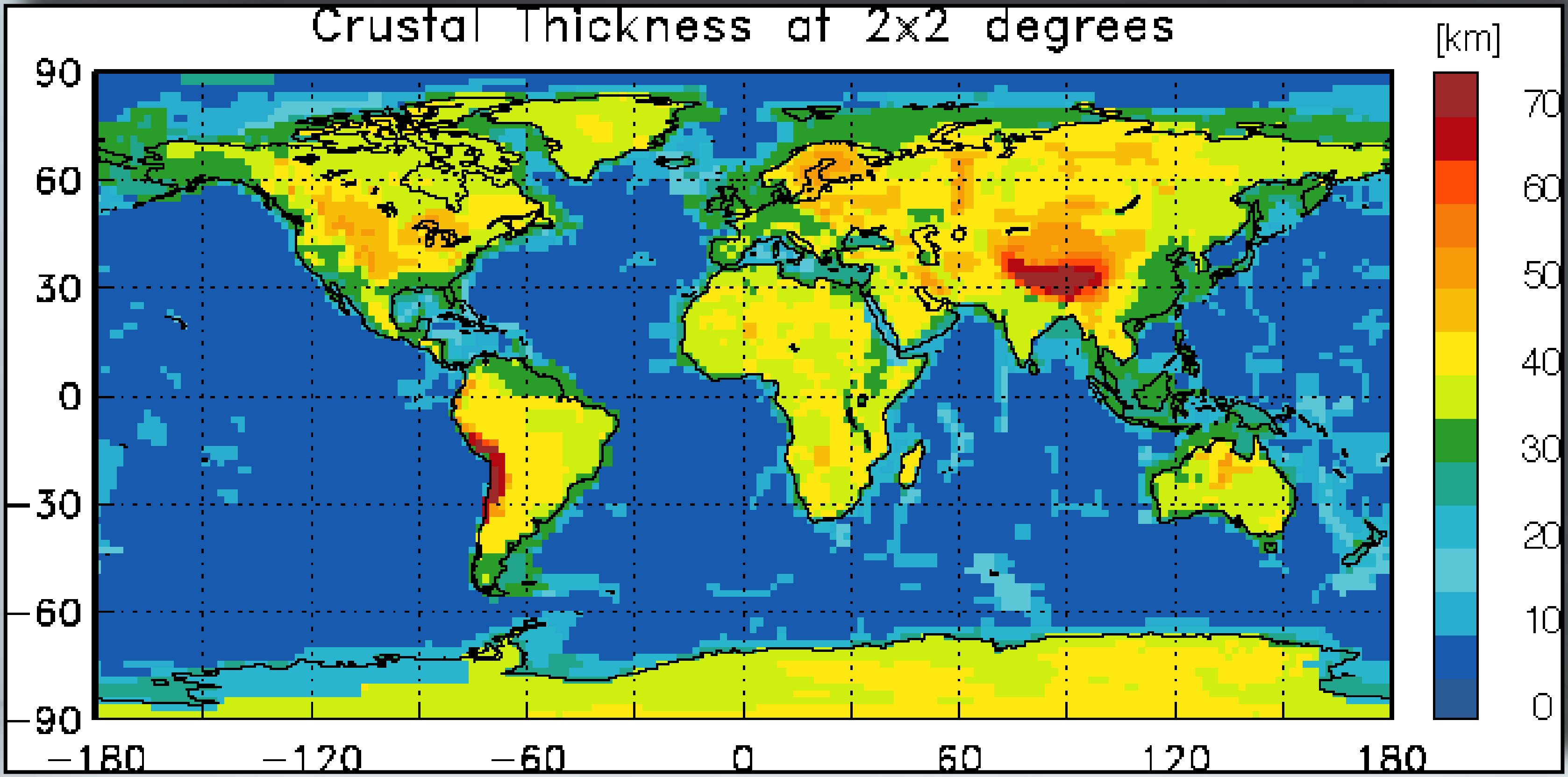
[d]Assumed average neutrino loss = 2/3 of total β^- energy [8, p. 52].

Van Schmus, W.R., 1995. In: Ahrens, T.J. (Ed.), Global Earth Physics: A Handbook of Physical Constants, vol. 1 of Reference Shelf American Geophysical Union. pp. 283–291

There are many walls without any cracks

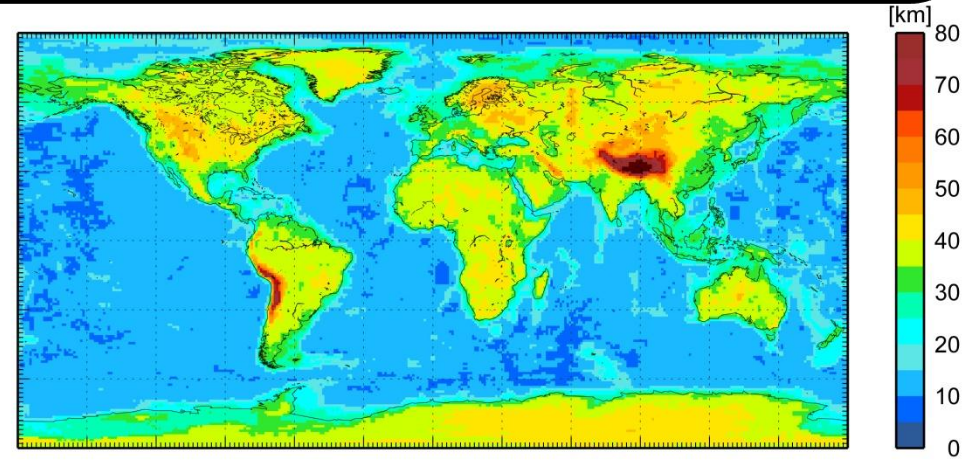


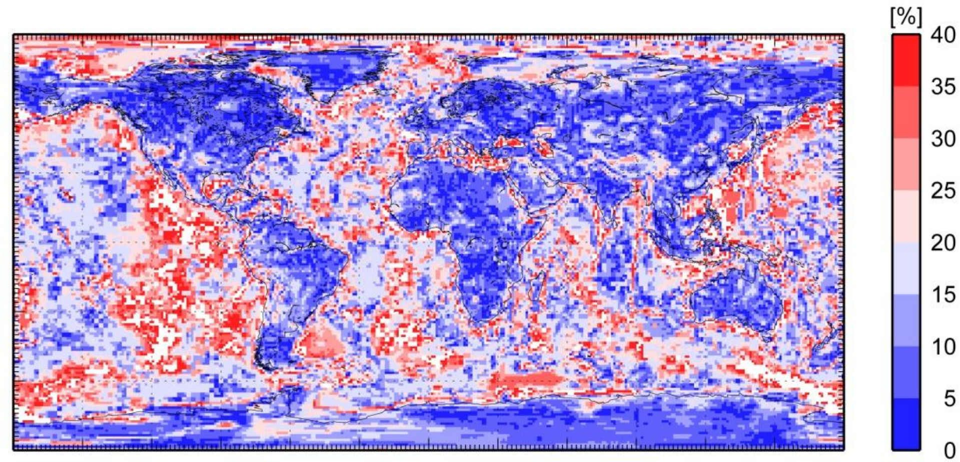
No cracks from geophysics!



http://igppweb.ucsd.edu/~gabi/crust1.html

Crustal geophysical model and its uncertainties





Crustal Reference Model RM [Huang et al. 2013]: 64.800 1°x1° voxels divided in CC and OC.

- CRUST2.0[1]: reflection and refraction seismic data
- CUB2.0[2]: surface seismic waves
- GEMMA[3]: gravitational potential field

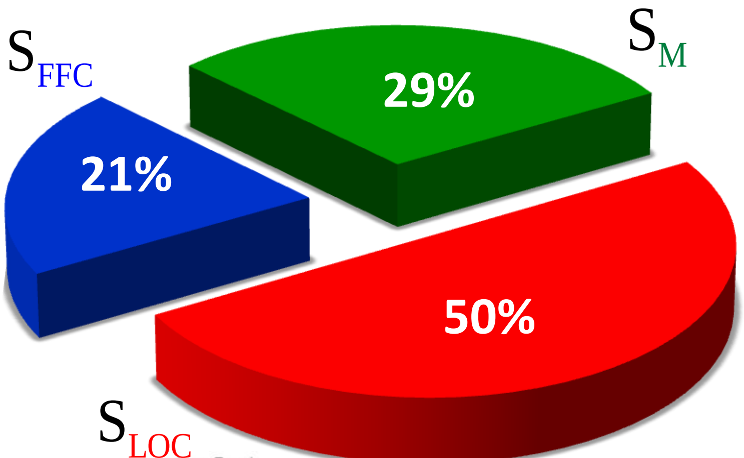
- Uncertainties of global crustal thickness estimated for the first time
- ~10% uncertainty in continents
- Larger uncertainty in oceans and continental margins

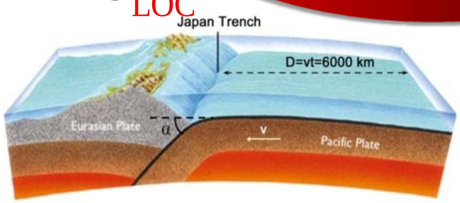
		CRUST2	CUB2	GEM	RM
Mass (10^{21} kg)	CC	21.4	20.9	19.6	20.6 ± 2.5
	OC	6.3	6.4	7.4	6.7 ± 2.3

[1] Bassin et al. - 2000
[2] Shapiro and Ritzwoller - 2002
[3] Negretti et al. - 2012

Geoneutrino in KamLAND: remember?

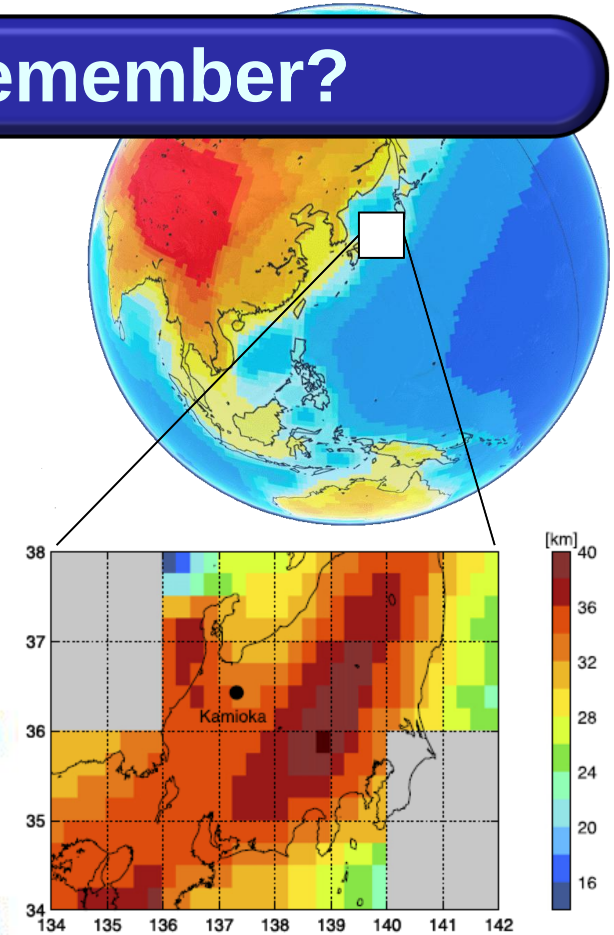
$$S_{EXP} = S_{LOC} + S_{FFC} + S_{Mantle}$$





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

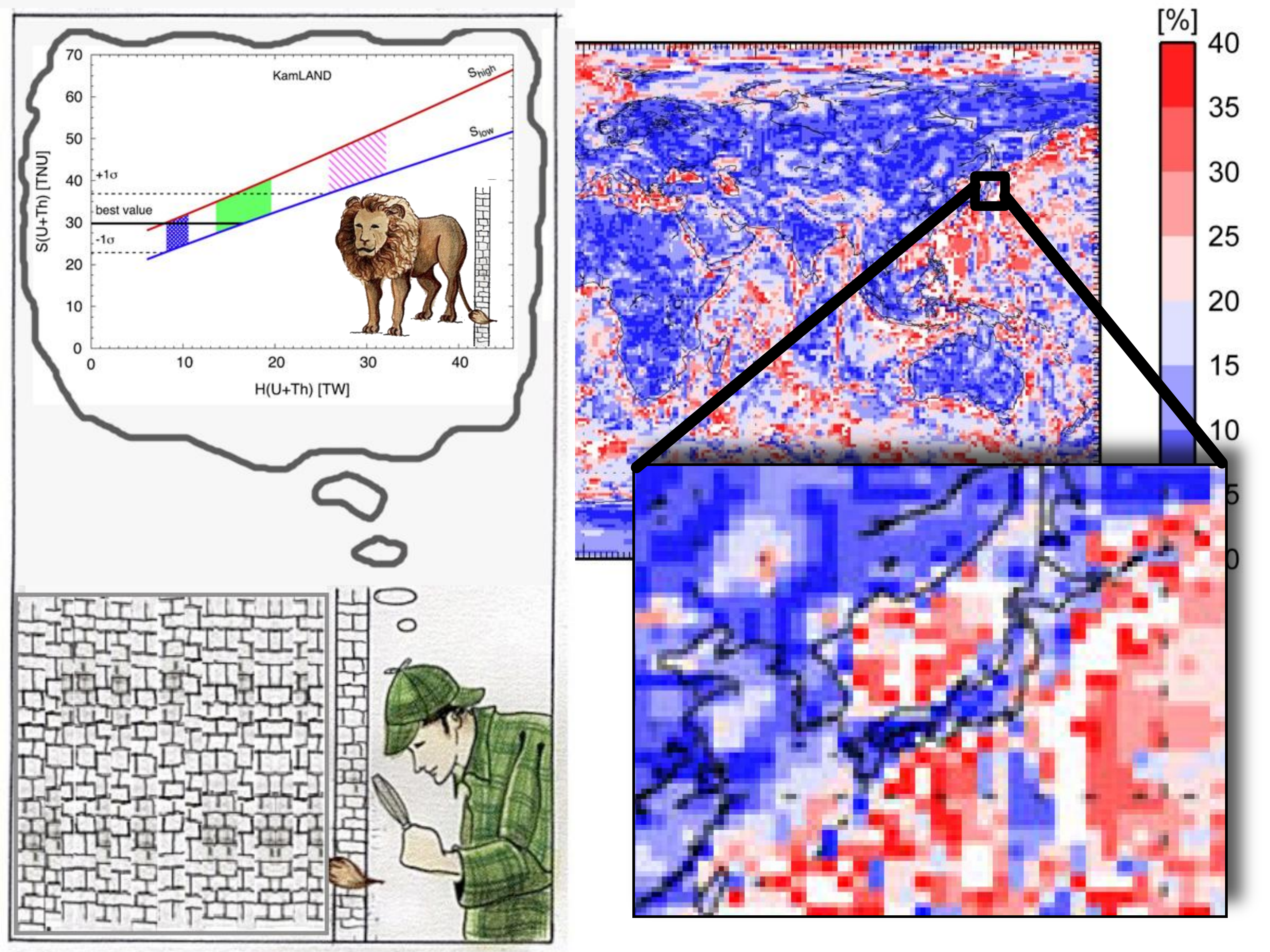


~ 500 km x 500 km

	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

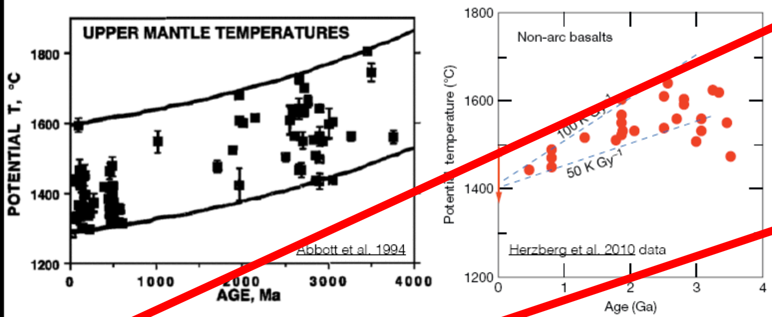


KamLAND
S_high
S_low
+1σ
best value
-1σ
S(U+Th) [TNU]
H(U+Th) [TW]
0
10
20
30
40
50
60
70
[%]
40
35
30
25
20
15
10

Strange cracks (1)...

Mantle cooling rate

petrological constraint based on determination
of melting temperature of primitive mantle melts



Cooling rate of 50±25 K/Gyr

Translates into 8±4 TW mantle heat output due to cooling

Cooling rate of 50–100 K/Gyr

Translates into 8–16 TW mantle heat output due to cooling

Cooling rate of 50±25 K/Gyr

Translates into 8±4 TW mantle heat output due to cooling

How many TW do you obtain at -3σ?

Strange cracks (2)…

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/cm³]
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: S_{Sed} = 2.9 TNU
- To be compared with that estimated in Ref. Mod.: S_{Sed} = 0.5 TNU

(remind the 0.5 km sediment layer)

Reservoir in Ref. Mod.	a(U) [ppm]	a(Th) [ppm]	Density [gr/cm³]
Sediments	1.7	6.9	2.1 - 2.5

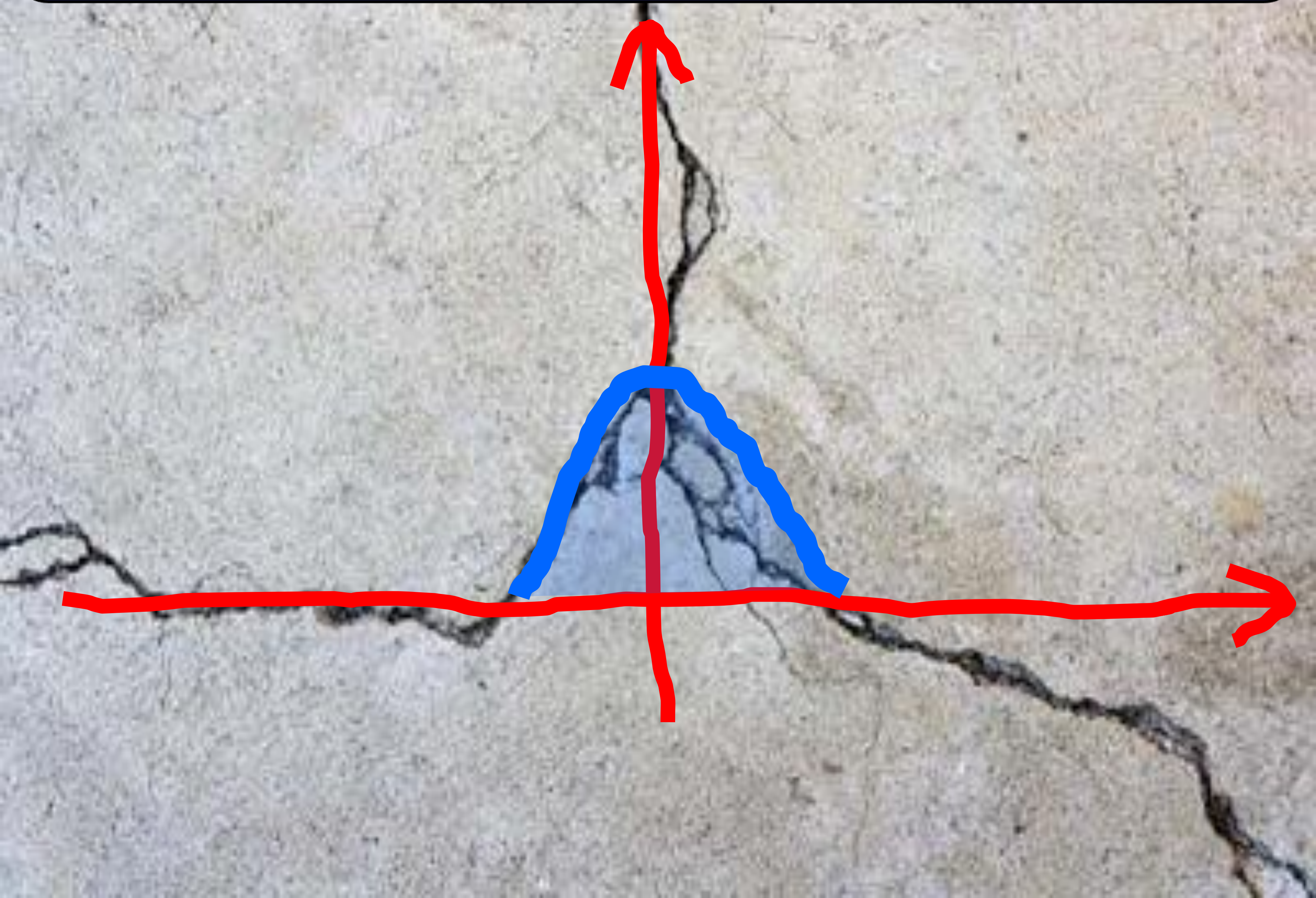
** Standard deviation of measured samples*

Mass [%]	a(U) [ppm]*
76.8	0.3 ± 0.2
15.6	2.3 ± 0.6

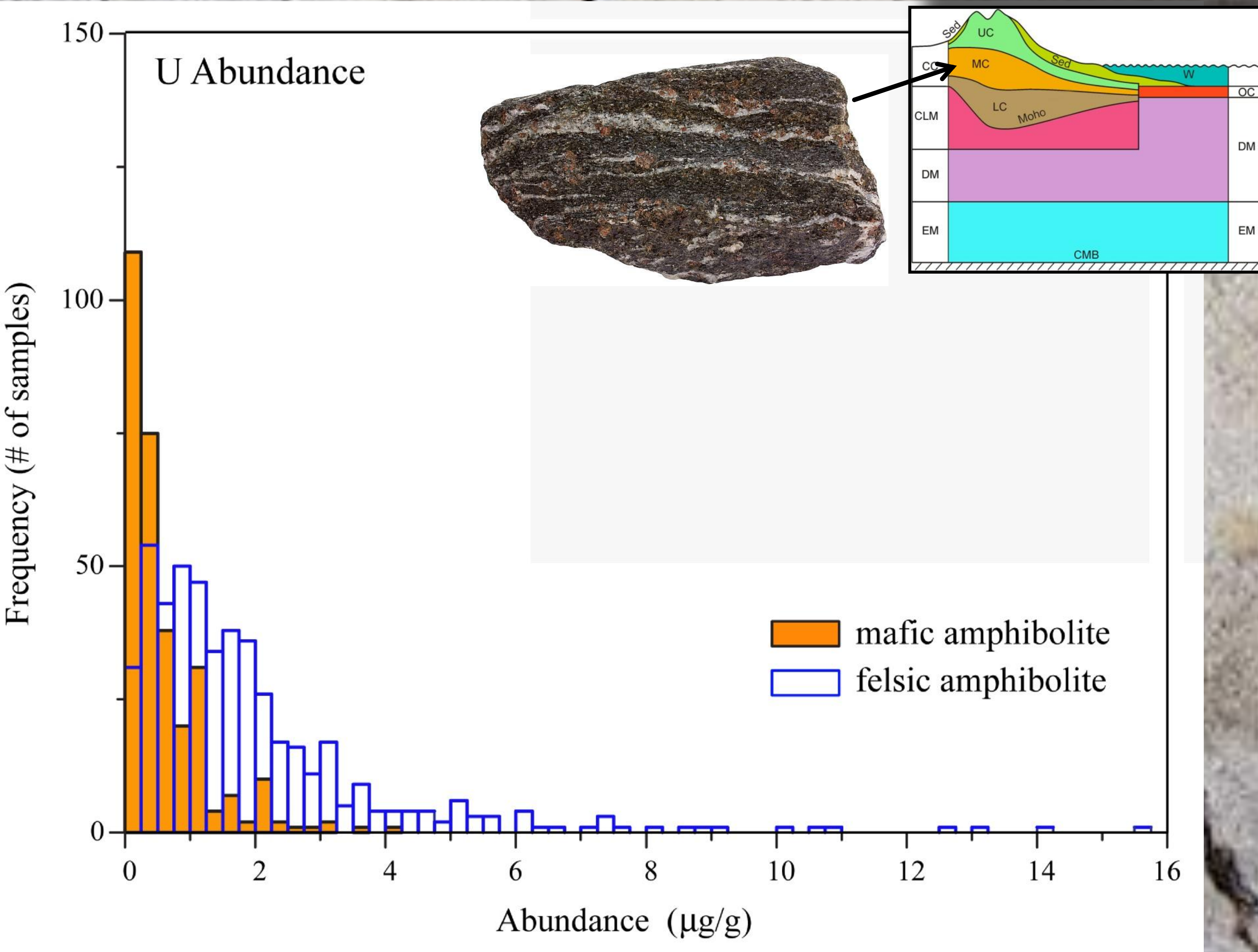
How many ppm do you obtain at -2σ?

Have a look to the shape of the cracks…

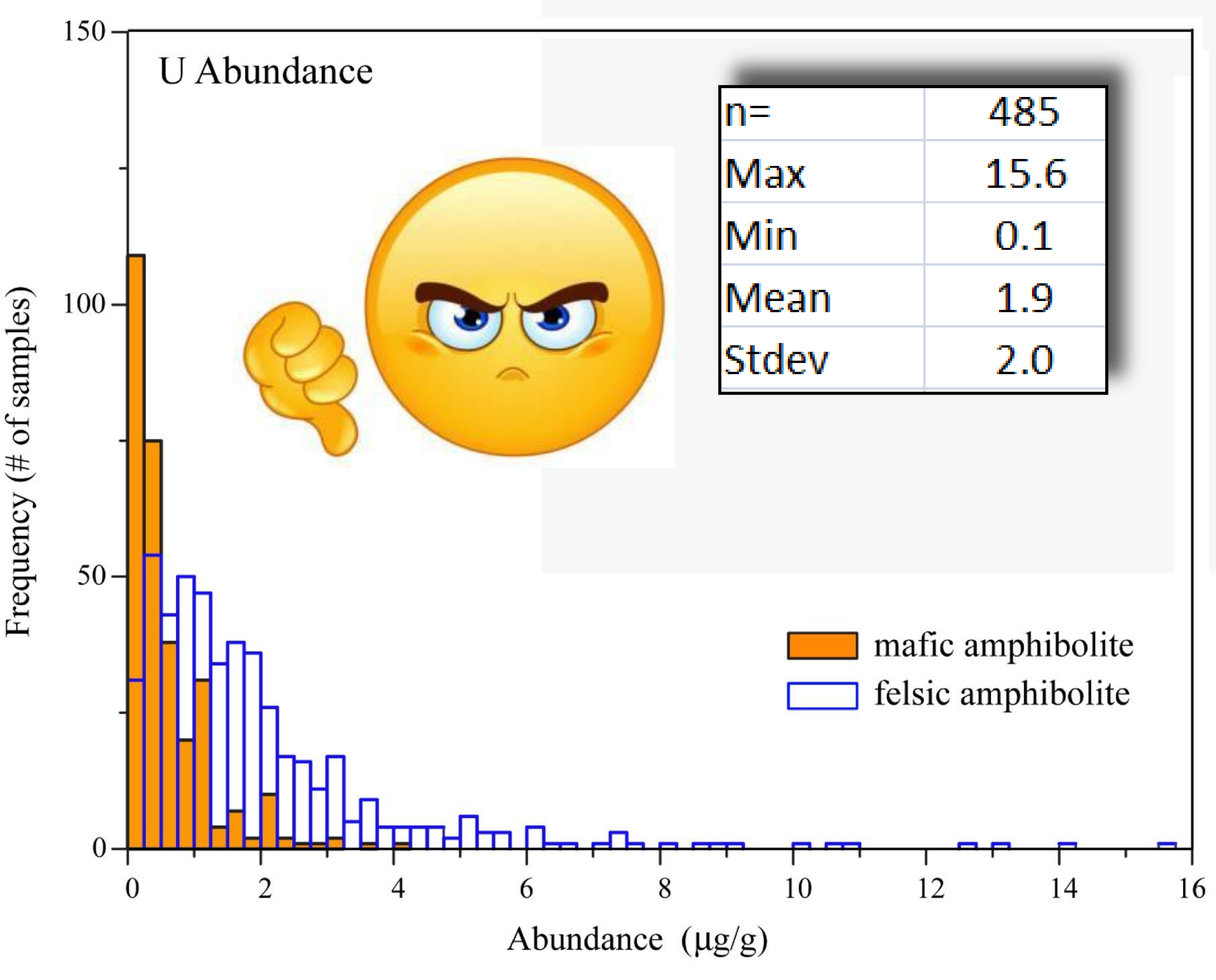
Have a look to the shape of the cracks…



Let have a look to U measurements in MC…



What is the meaning of the "mean"?

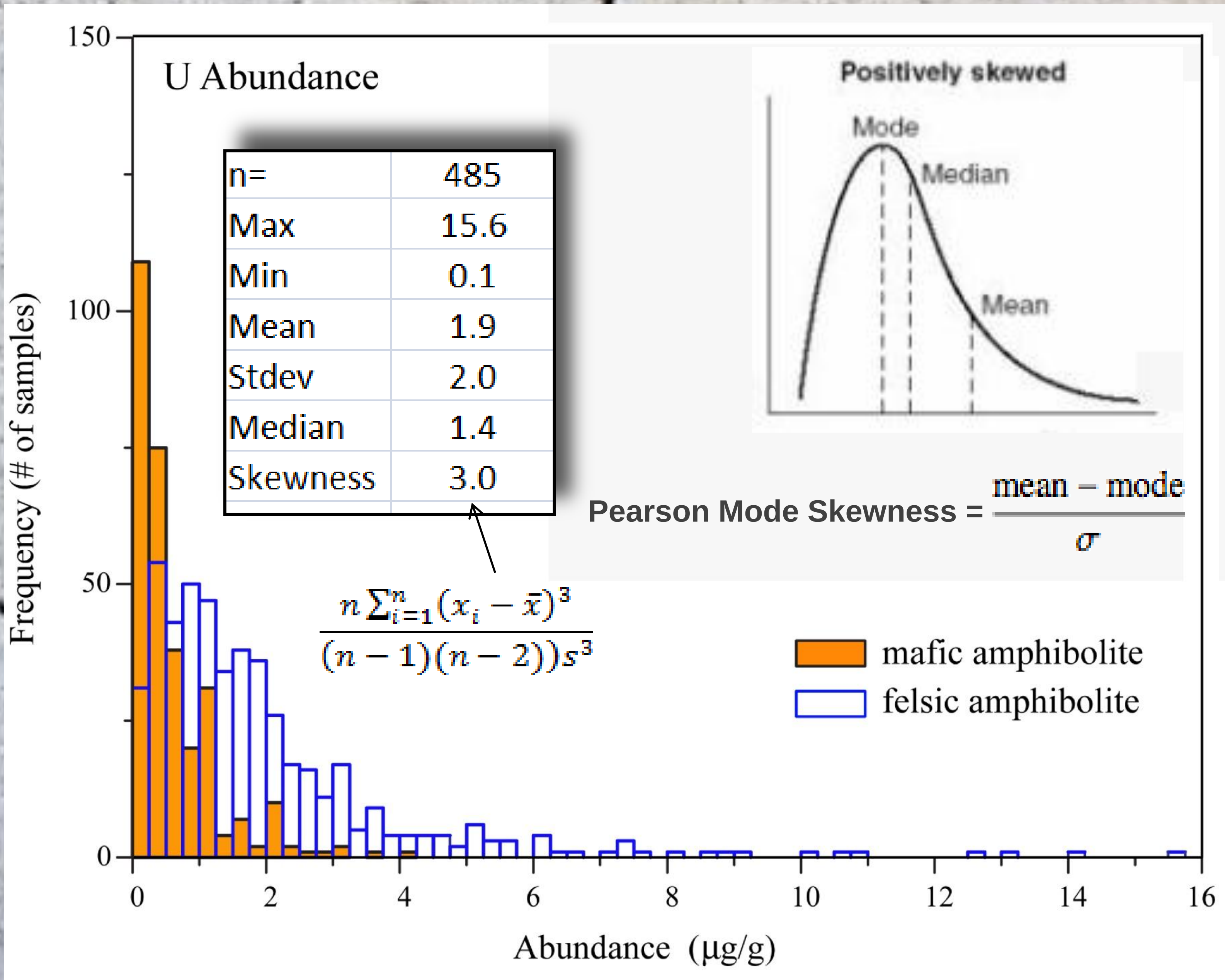


n=	485
Max	15.6
Min	0.1
Mean	1.9
Stdev	2.0

What do you learn?

Before to sell a number, study the distribution of the values!

This is a skewed crack!!!



n=	485
Max	15.6
Min	0.1
Mean	1.9
Stdev	2.0
Median	1.4
Skewness	3.0

$$\frac{n\sum_{i=1}^{n}(x_i-\bar{x})^3}{(n-1)(n-2))s^3}$$

Pearson Mode Skewness = $\frac{\text{mean} - \text{mode}}{\sigma}$

In 1953 Ahrens wrote…

The lognormal distribution of the elements[1]

(A fundamental law of geochemistry and its subsidiary)

L. H. AHRENS

Department of Geology and Geophysics, Massachusetts Institute of Technology[2]

(*Received* 3 *November* 1953)

ABSTRACT

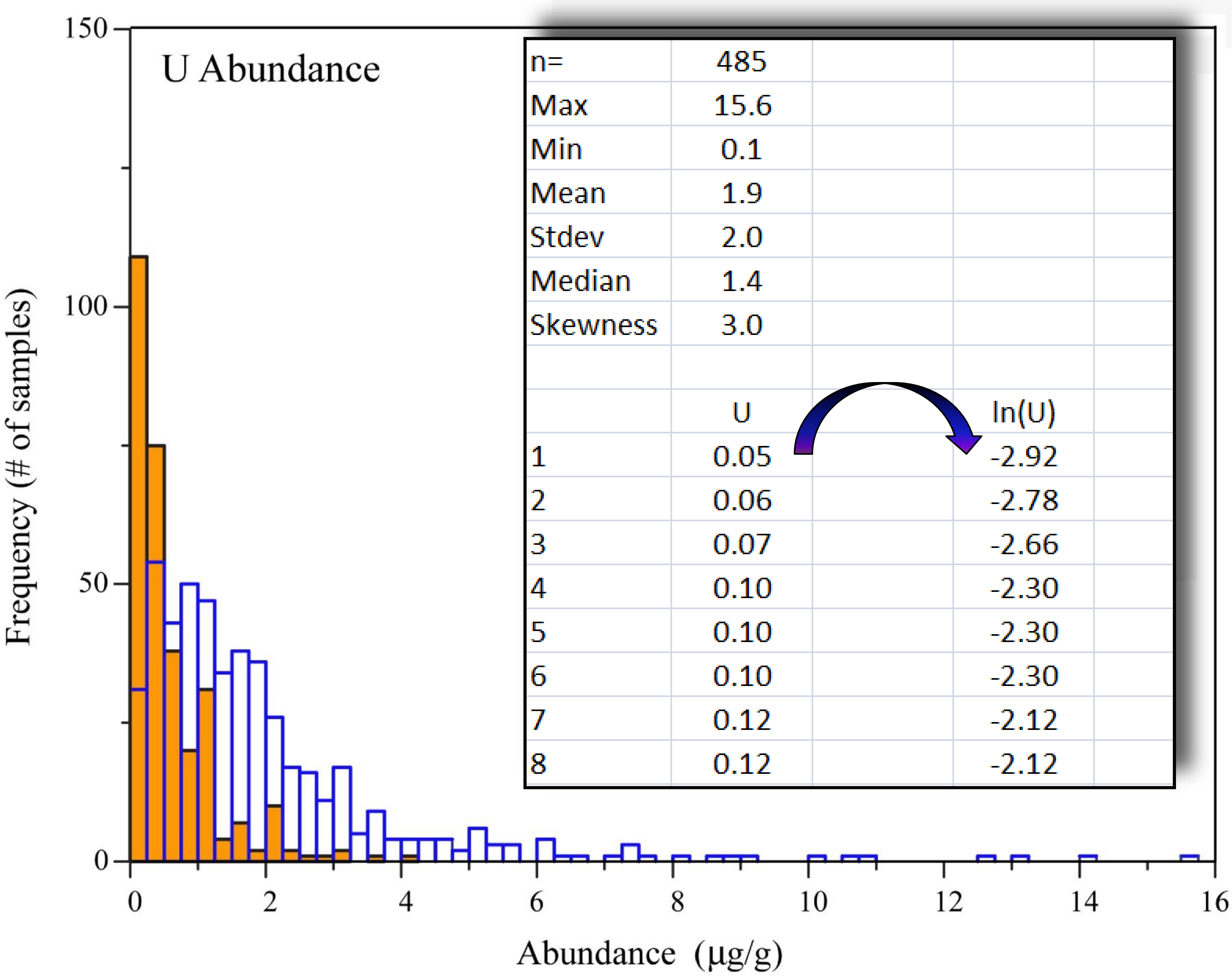
Frequency distribution plots of K, Rb, Sc, V, Co, Ga, Cr, and Zr in Ontario diabase, Sc, V, Ga, Cr, La, and Zr in Canadian granite, K, Rb, and Cs in New England granite and F and Mo in granite from various localities are regular, but assume decided positive skewness when dispersion is large; hence, distribution of concentration is not normal. All distributions become normal, or nearly so, provided the variate (concentration of an element) is transformed to log concentration: this leads to a statement of a fundamental (lognormal) law concerning the nature of the distribution of the concentration of an element in specific igneous rocks.

A subsidiary law concerning the relationship between averages and most prevalent concentrations follows as a direct consequence of the fundamental law.

Dispersions of different elements can be compared and predictions may be made on the basis of the lognormal law. A comparison of the dispersions of elements in igneous rocks and chondrites emphasizes the strikingly high uniformity of abundance of many elements in these meteorites. A given element may show a totally different magnitude of dispersion in different igneous rocks; for example, dispersion of scandium is small in diabase and extreme in granite.

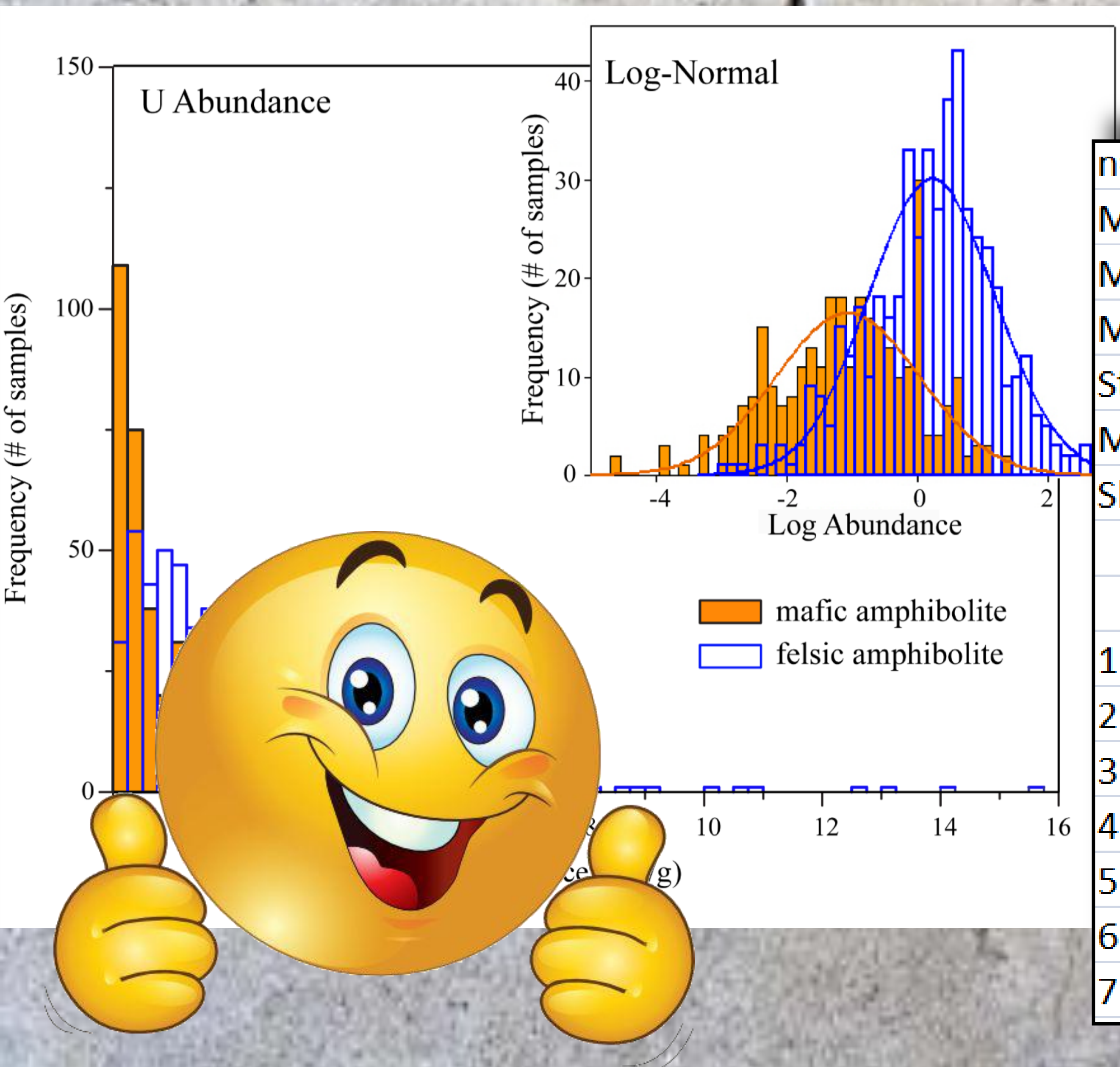
> "The linear scale, since it was first cut on the wall of an Egyptian temple, has come to be accepted by man almost as if it were the unique scale with which Nature builds and works. Whereas, it is nothing of the sort"—(BAGNOLD, 1941)

Welcome to the lognormal world!!!



n=	485			
Max	15.6			
Min	0.1			
Mean	1.9			
Stdev	2.0			
Median	1.4			
Skewness	3.0			
	U		ln(U)	
1	0.05		-2.92	
2	0.06		-2.78	
3	0.07		-2.66	
4	0.10		-2.30	
5	0.10		-2.30	
6	0.10		-2.30	
7	0.12		-2.12	
8	0.12		-2.12	

Uauuuuhhh!!!

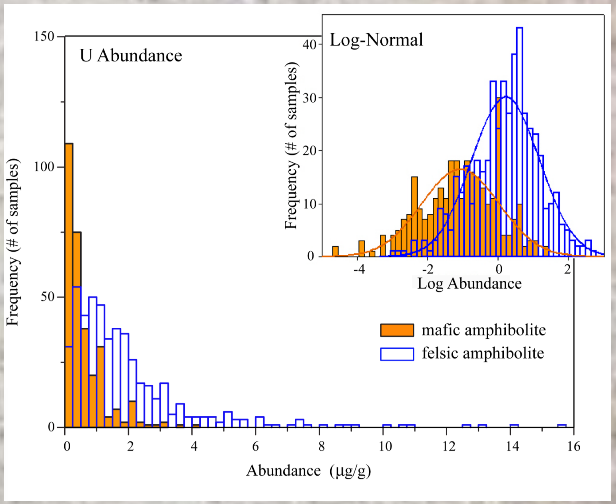


n=	485	485
Max	15.6	2.7
Min	0.1	-2.9
Mean	1.9	0.2
Stdev	2.0	1.0
Median	1.4	0.3
Skewness	3.0	-0.3
	U	ln(U)
1	0.05	-2.9
2	0.06	-2.8
3	0.07	-2.7
4	0.10	-2.3
5	0.10	-2.3
6	0.10	-2.3
7	0.12	-2.1

What are the implications of this analysis?

$$a(U)_{Amph\_fels} = 1.9 \pm 2.0\ \mu g/g$$

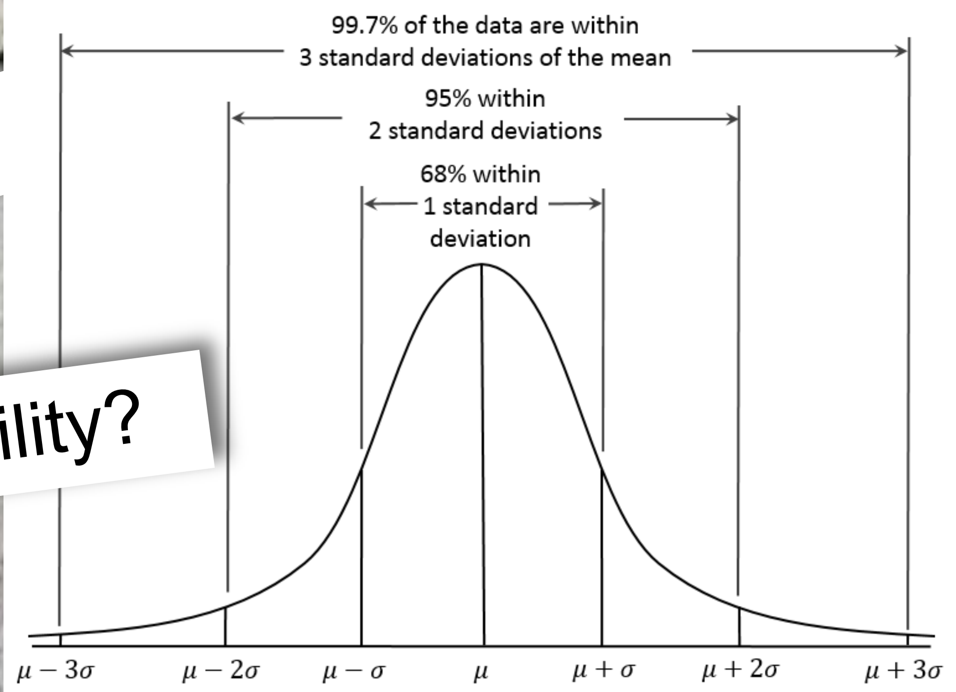
$$a(U)_{Amph\_fels} = 1.2\ _{-0.8}^{+2.0}\ \mu g/g$$



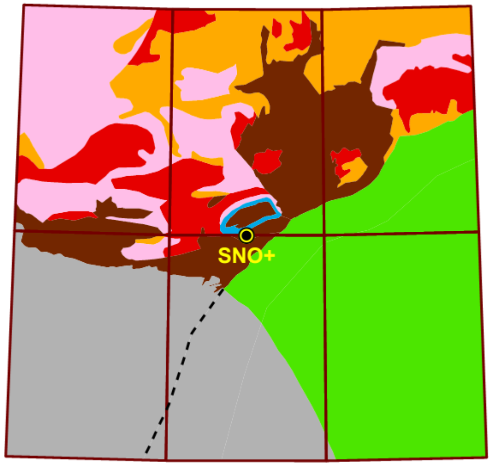
Expected value?

Heat production?

Distribution of probability?



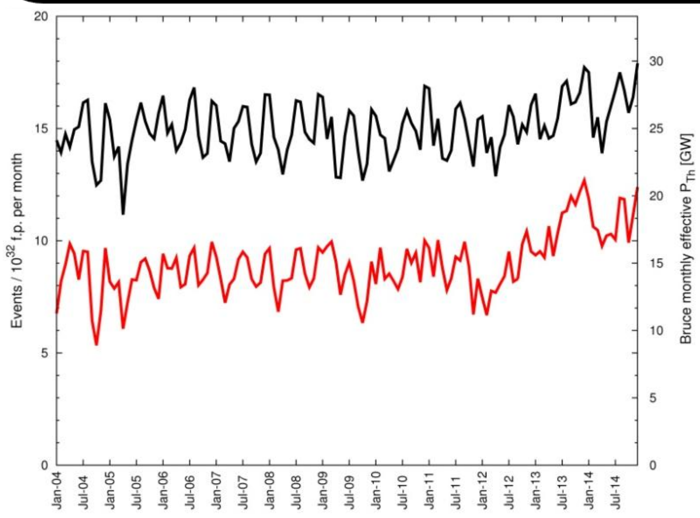
Geoneutrino signal at SNO+ from the local crust



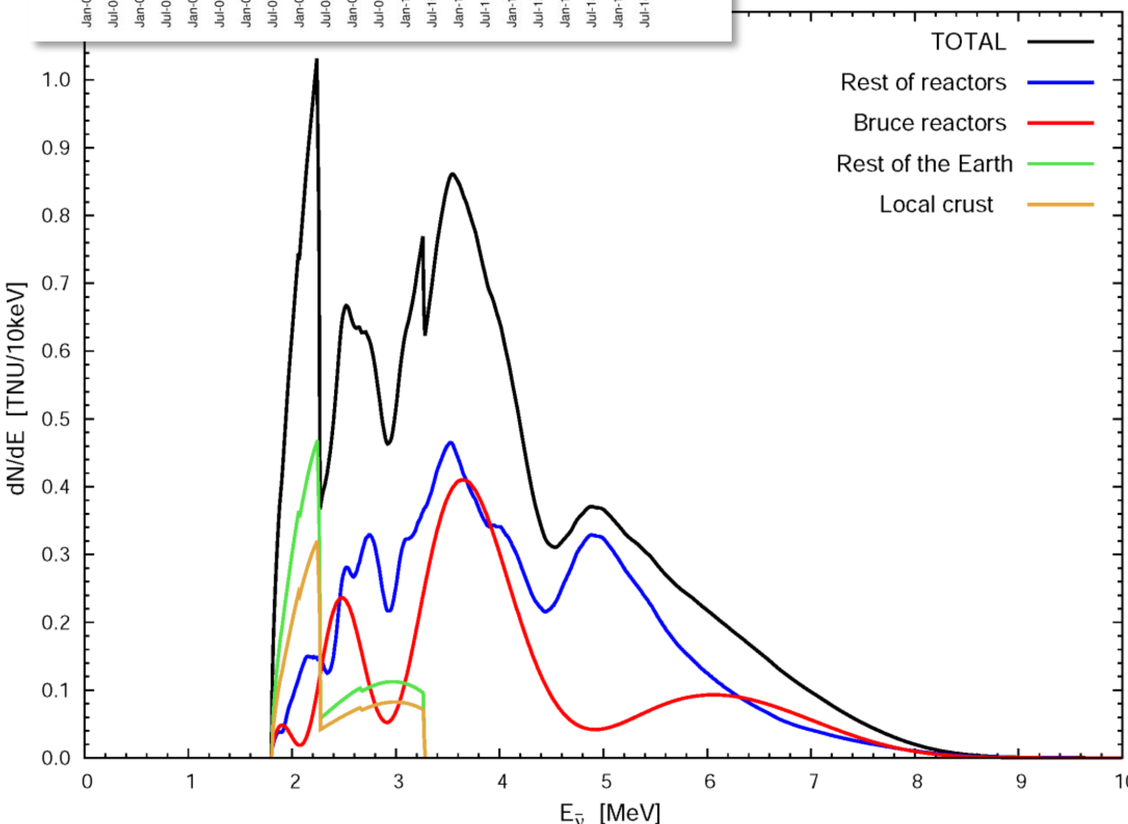
- After the refinement, the regional geoneutrino signal expected at SNO+ decreases from **18.9** $^{+3.5}_{-3.3}$ TNU (Huang et al. 2013) to **15.6** $^{+5.3}_{-3.4}$ TNU (Huang et al. 2014).
- The **Huronian Supergroup** is predicted to be the dominant source of the geoneutrino signal and the primary 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	$2.3^{+0.2}_{-0.2}$	$10.6^{+0.7}_{-0.7}$	$0.8^{+0.1}_{-0.1}$

Reactor antineutrinos and geoneutrino at SNO+



- The temporal fluctuations (~10% at 1σ) of **reactor antineutrino signal** resembles the temporal profile of the Bruce Power Station effective thermal power.
- The geoneutrino signal of the Local Crust corresponds to ~ **50%** of the total crustal signal.



Geoneutrinos signal[1] (TNU)

Local Crust	$15.6^{+5.3}_{-3.4}$
Rest of the Crust	$15.1^{+2.8}_{-2.4}$
Cont. Lithos. mantle	$2.1^{+2.9}_{-1.2}$
Mantle	**9**
TOTAL	40^{+6}_{-4}

Reactor antineutrinos signal[2] (TNU)

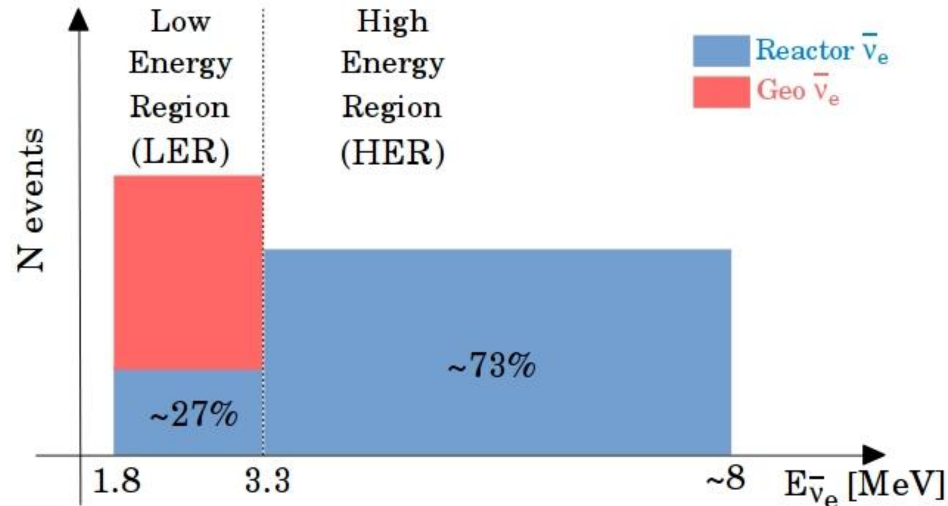
	LER	FER
Bruce reactors	$17.3^{+1.0}_{-0.7}$	$73.7^{+2.0}_{-1.8}$
Rest of reactors	$31.2^{+0.9}_{-0.8}$	$118.9^{+2.8}_{-2.6}$
TOTAL	$48.5^{+1.8}_{-1.5}$	$192.6^{+4.7}_{-4.4}$

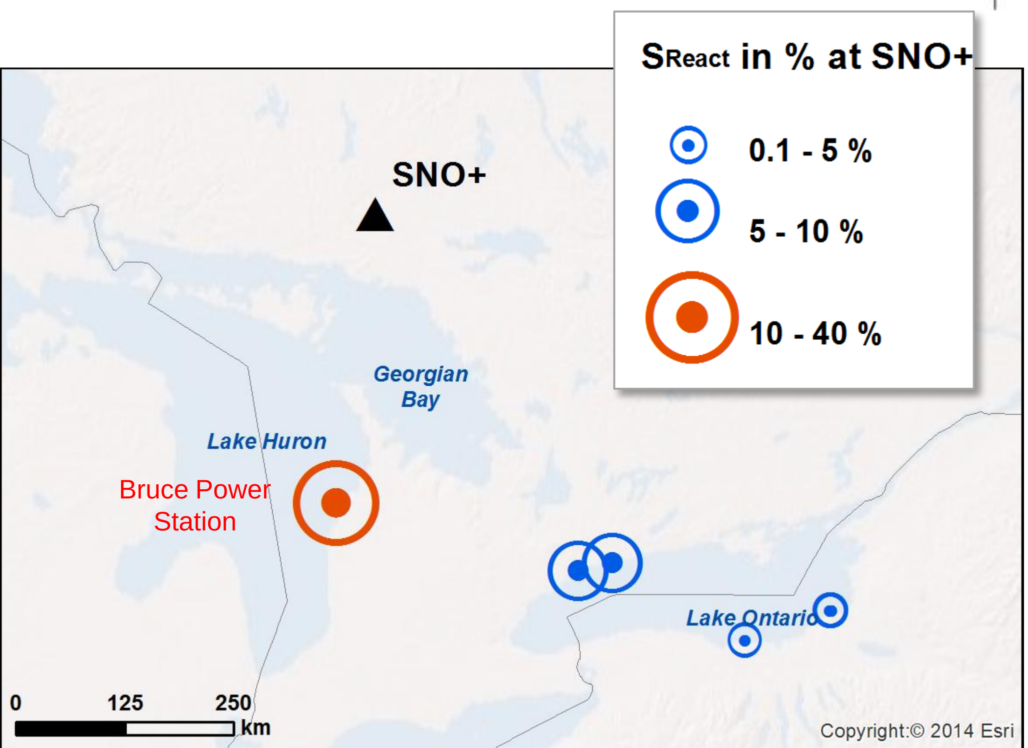
1 - Huang et al. 2014 Geoch. Geoph. Geosys.
2 - Baldoncini et al. 2016 TAUP Proceedings (in Press)

Reactor antineutrinos signal at SNO+

• Reactor antineutrinos are the most severe background for geoneutrino measurements.

• In the **L**ow **E**nergy **R**egion (**LER**) we observe an overlap between geoneutrino and reactor antineutrinos spectra, with a signal ratio $\mathbf{S_{LER}/S_{Geo} \sim 1}$ @ SNO+





• Bruce Power Station includes 8 nuclear reactors and produces ~22 GW of thermal power.

• Although the thermal power of Bruce reactors corresponds to 1.9% of the global thermal power, they contribute to about 38% of total reactor antineutrino signal S_{React} at SNO+.

Baldoncini et al. 2015 – Physical Review D 91(6)

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A reference Earth model for the heat-producing elemen... associated geoneutrino flux

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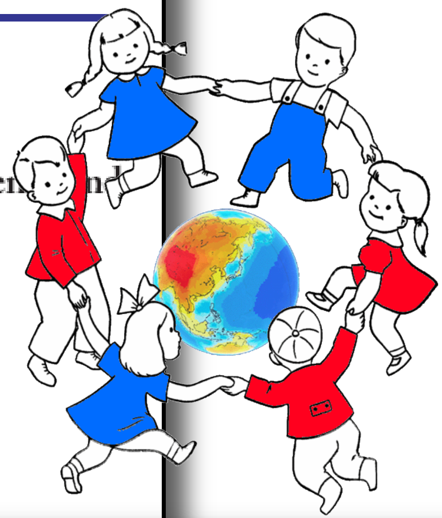

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Geoneutrinos and reactor antineutrinos at SNO+

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