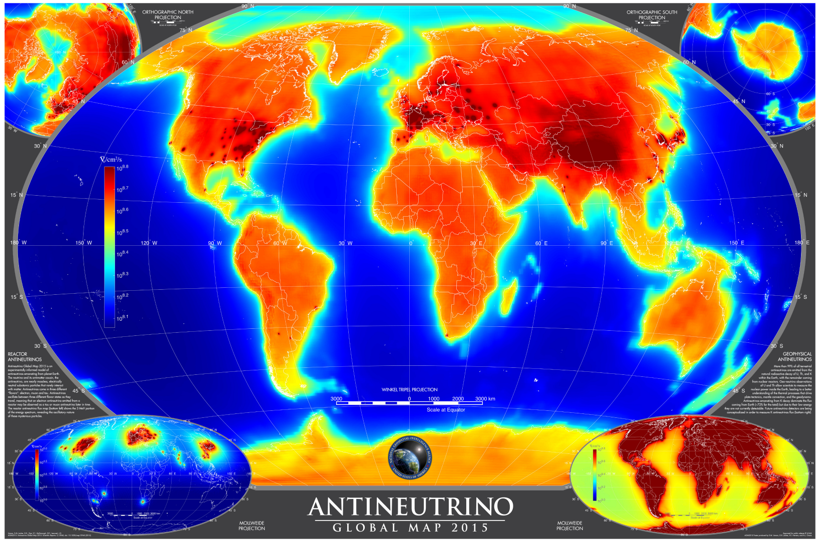
Reference Models for Lithospheric Geoneutrino Signal

S. A. Wipperfurth[1], O. Šrámek[2], W. F. McDonough[1,3].

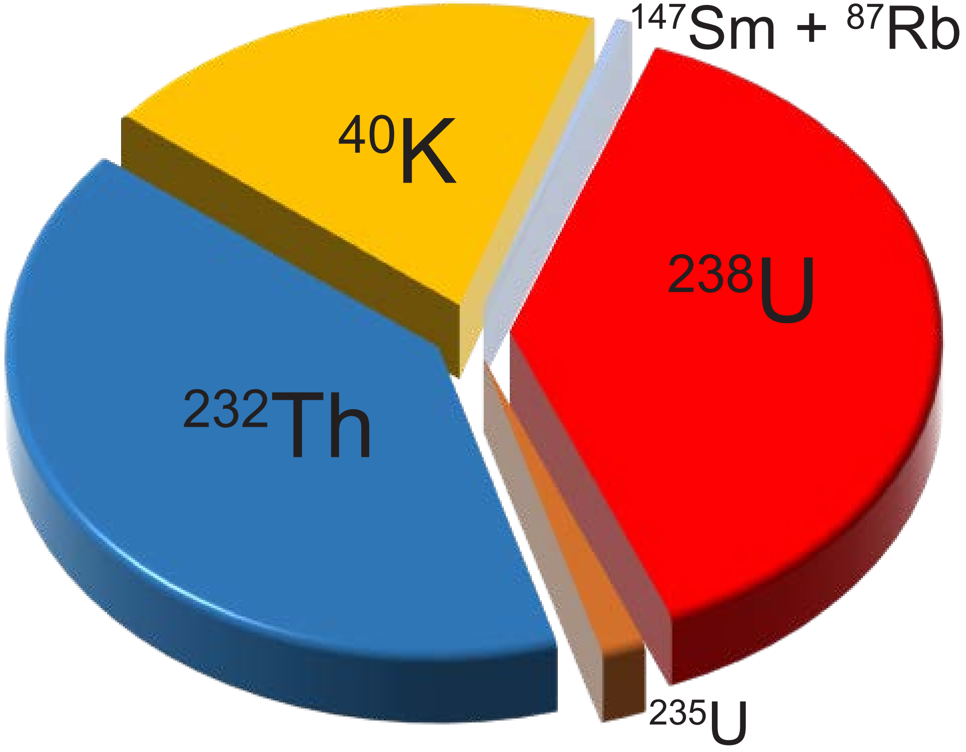
with additional contributions from Laura Sammon (UMD)

[1]Department of Geology, University of Maryland, College Park, MD 20742, USA
[2]Department of Geophysics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
[3]Department of Earth Sciences and Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan

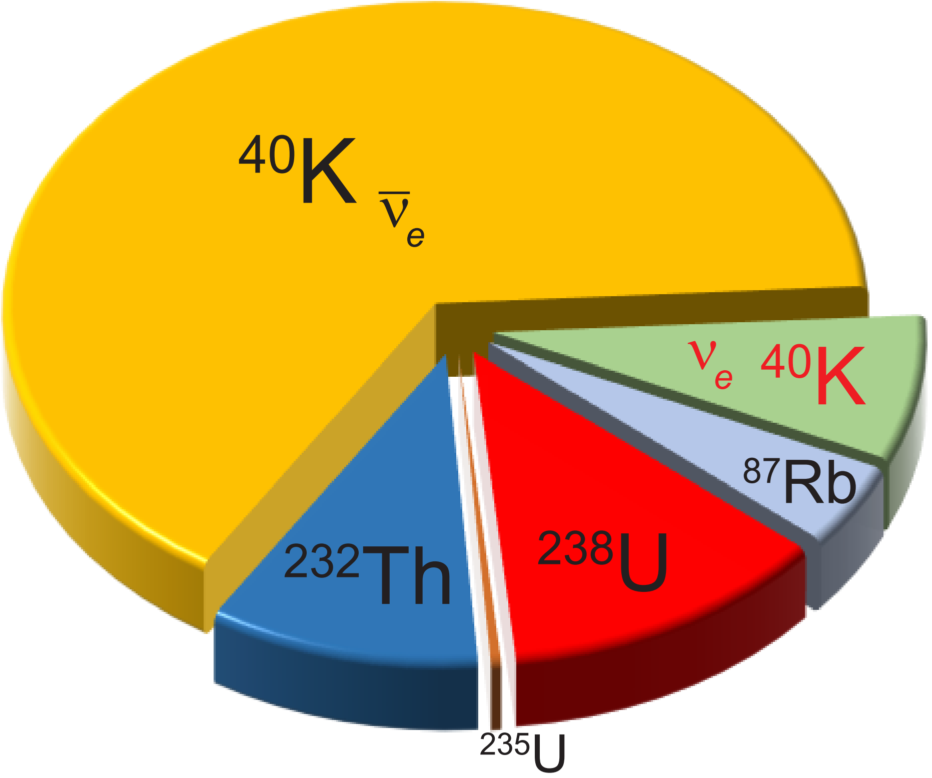


funding

Radiogenic heat flux ~20 TW $\propto$ Geoneutrino flux $10^{25}\ \bar{\nu}_e\ s^{-1}$



Heat Production

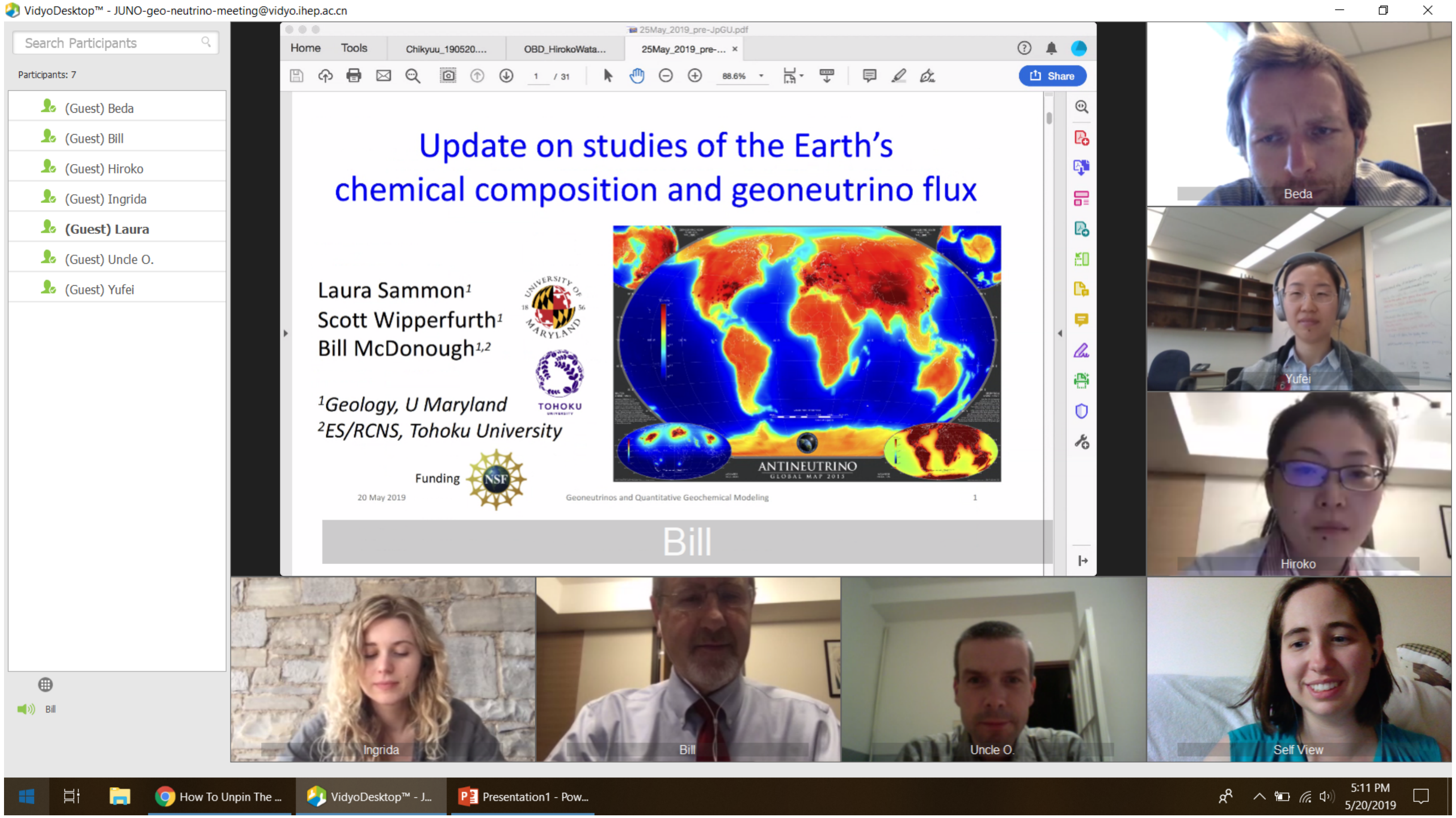


Geoneutrino Luminosity

Weekly geoneutrino teleconference: particle physics & geology

Nodes: Sudbury, Beijing, California, Prague, Sendai, Maryland

Now running for 5 years, with 3 years for the bigger group!



Update on studies of the Earth's chemical composition and geoneutrino flux

Laura Sammon[1]
Scott Wipperfurth[1]
Bill McDonough[1,2]

[1]*Geology, U Maryland*
[2]*ES/RCNS, Tohoku University*

Funding

20 May 2019

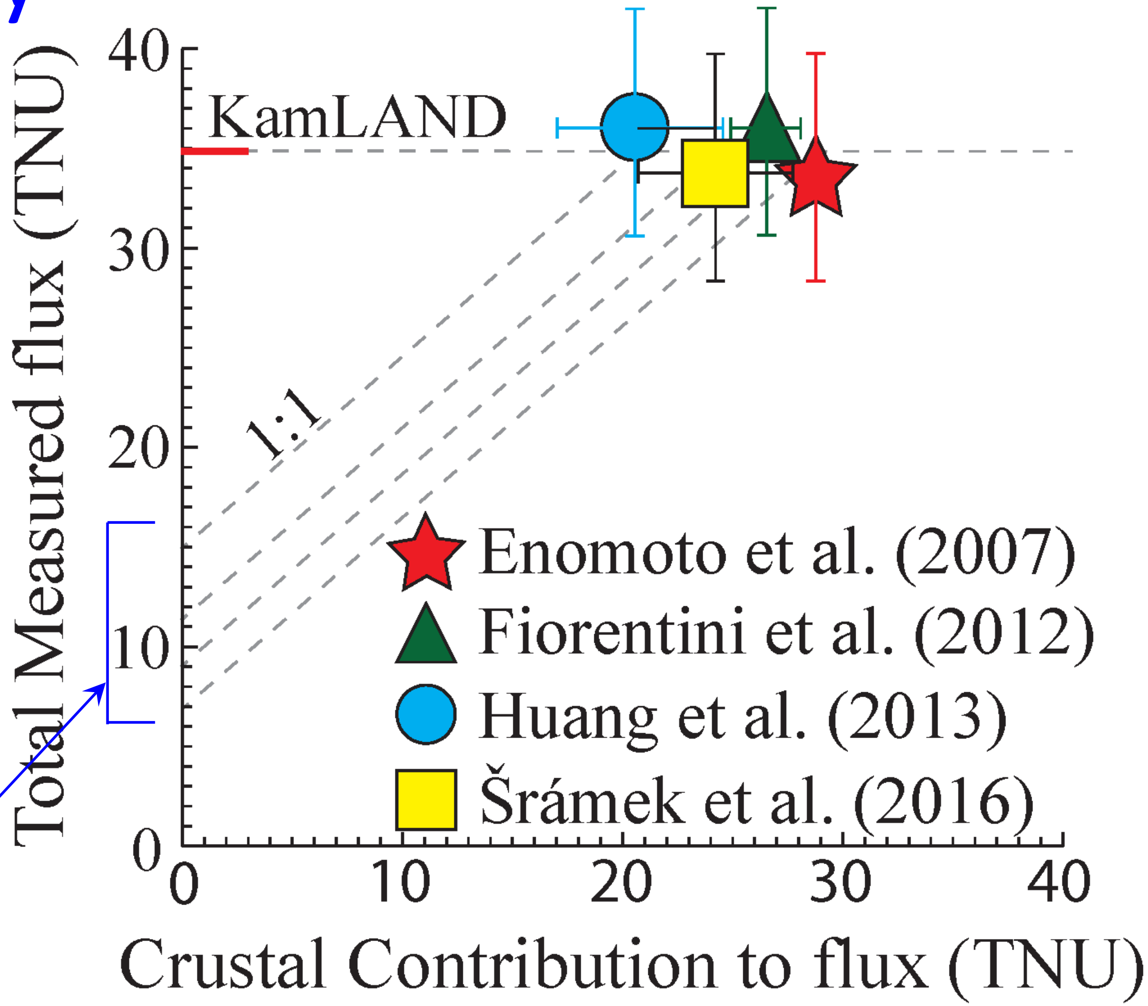
Geoneutrinos and Quantitative Geochemical Modeling

1

importance of accuracy

- **Which model is most accurate?**

- **Implications for what’s in the mantle**



Intercept = mantle flux!

Constructing a 3-D reference Earth model for geoneutrino emission calculation

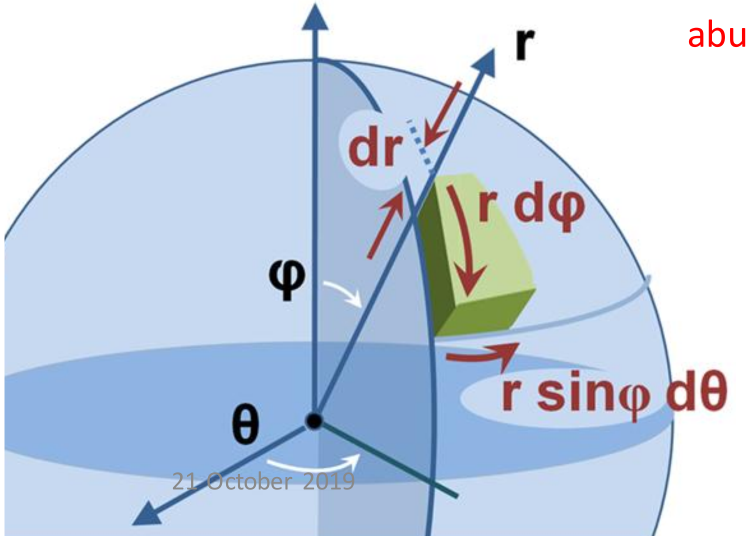
assigning chemical and physical states to Earth voxels

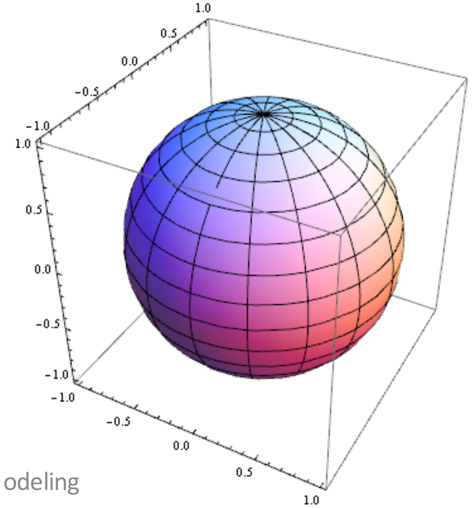
$$\frac{\mathrm{d}\phi(E_\nu,\mathbf{r})}{\mathrm{d}E_\nu} = A\frac{\mathrm{d}n(E_\nu)}{\mathrm{d}E_\nu}\int_{V_\oplus} \mathrm{d}^3\mathbf{r}'\frac{a(\mathbf{r}')\rho(\mathbf{r}')P(E_\nu,|\mathbf{r}-\mathbf{r}'|)}{4\pi|\mathbf{r}-\mathbf{r}'|^2}$$

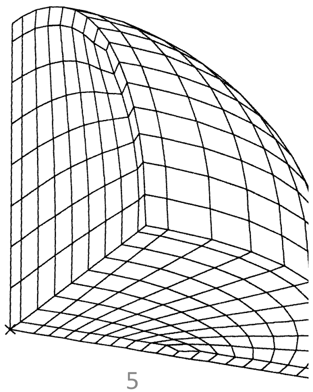
density

abundance

detector – source separation distance



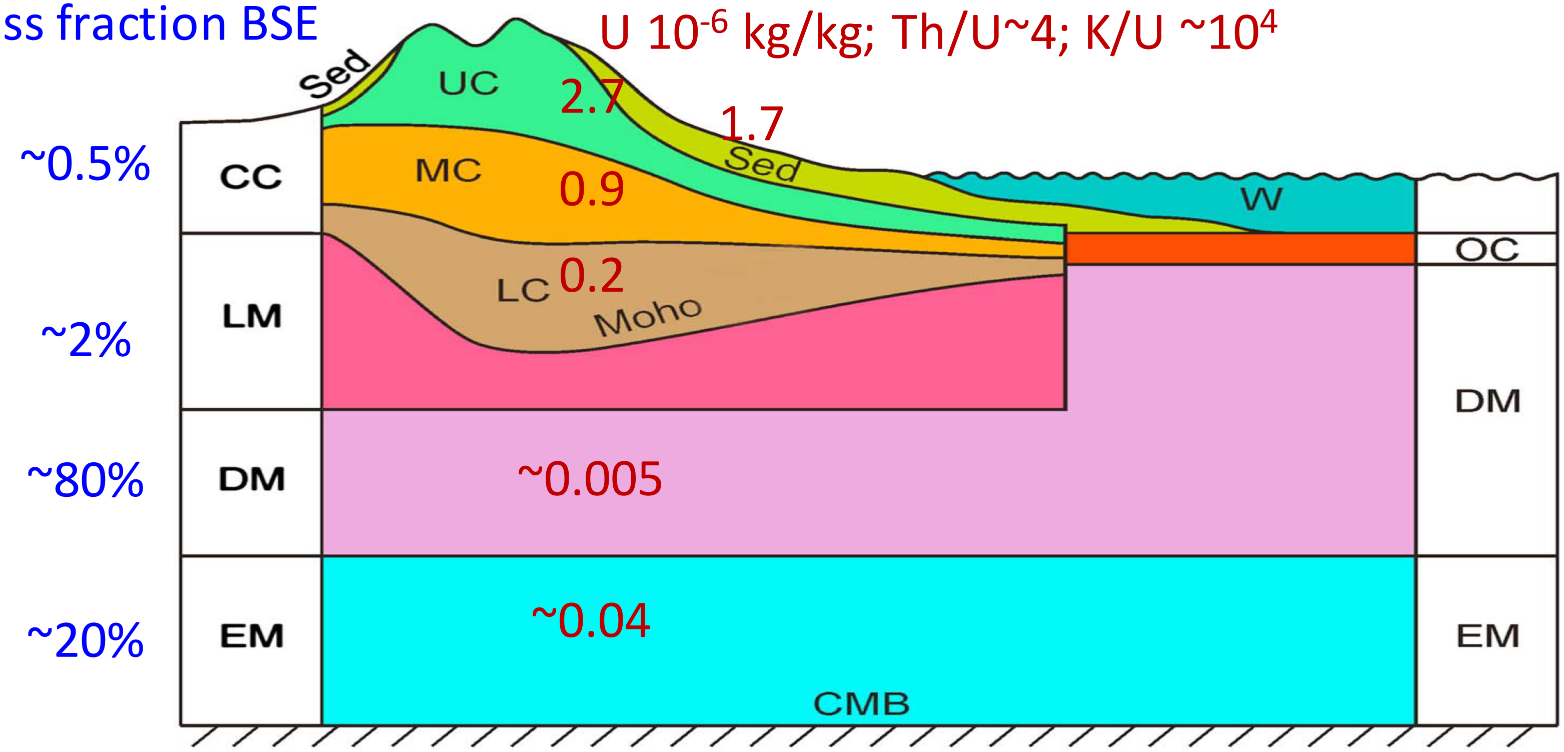




Estimating the distribution and abundance of U & Th in the Earth

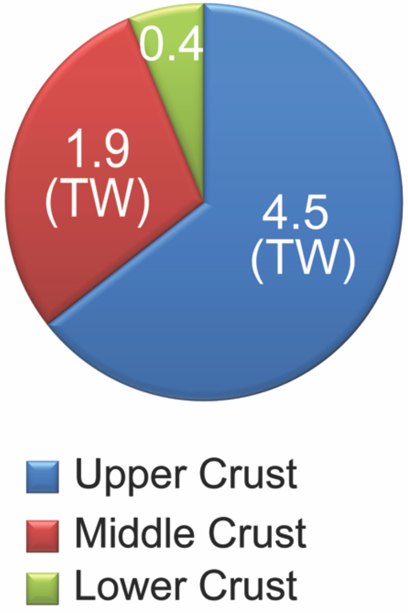
mass fraction BSE

U 10^{-6} kg/kg; Th/U~4; K/U ~10^4



Continental Crust

(Huang et al 2013)



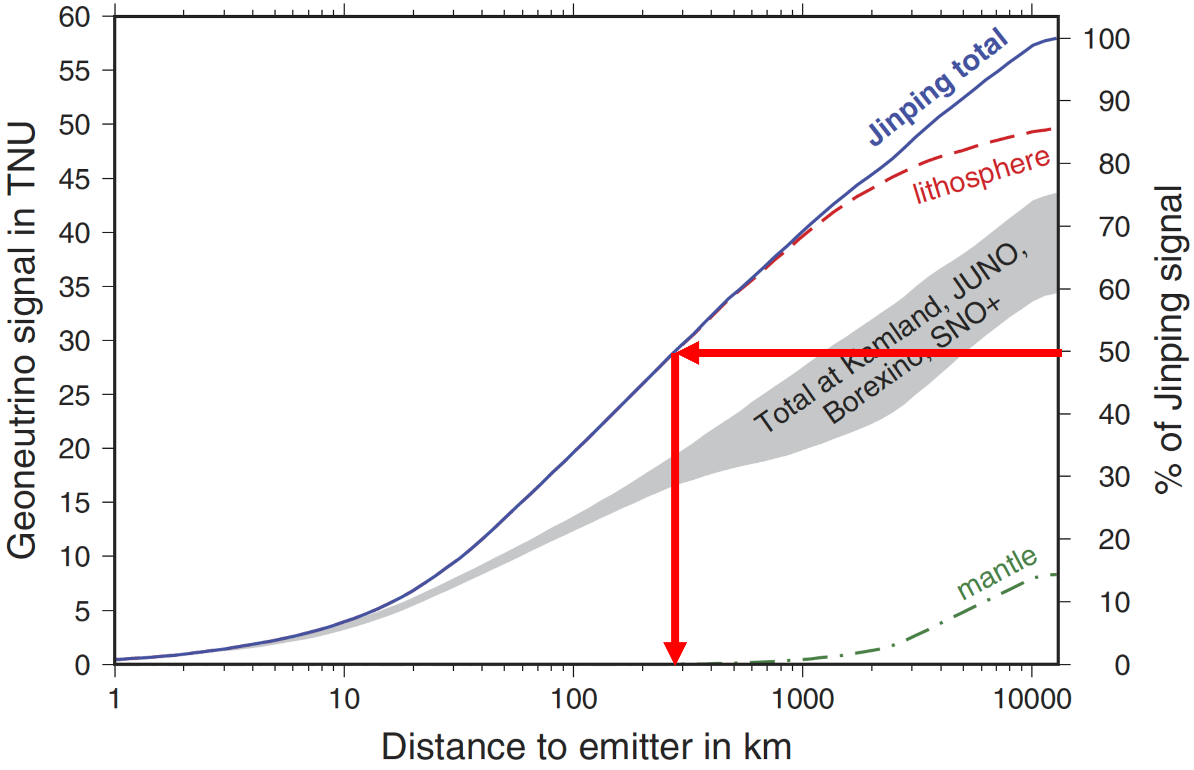
Local Crust (~500 km): contributes 50% of signal, and most of that signal comes from the Upper Continental crust (UC)

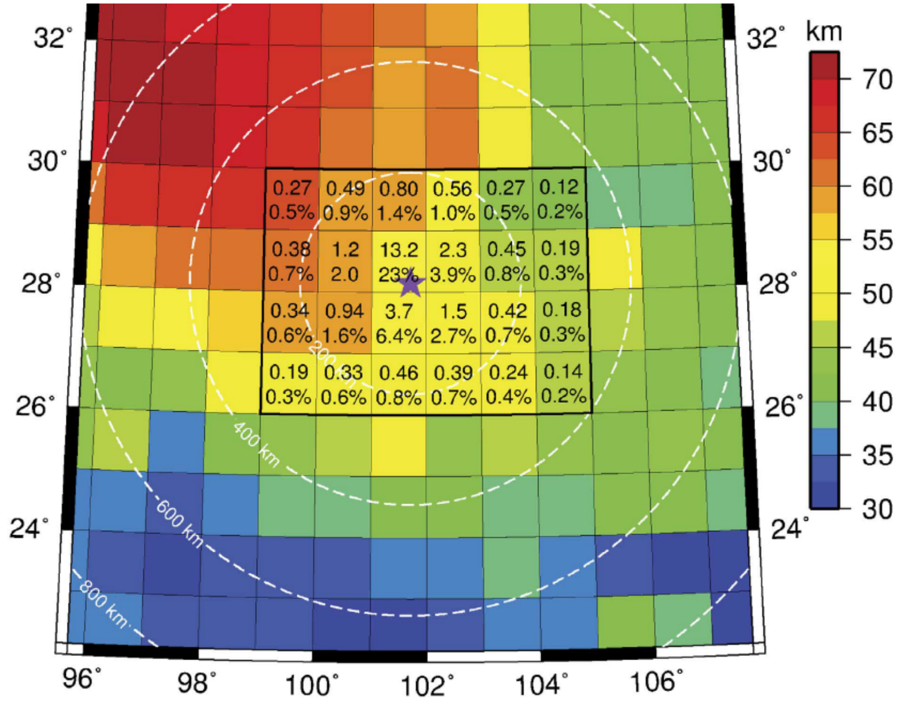
Globally

40% LOC

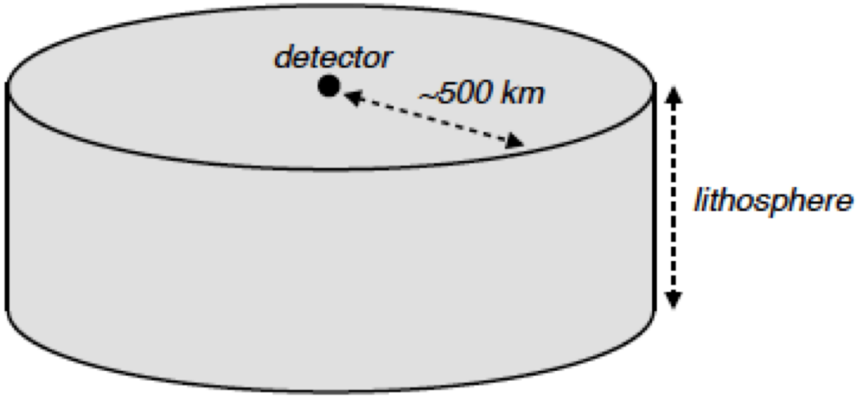
35% ROC

25% Mantle





0.27 0.5%	0.49 0.9%	0.80 1.4%	0.56 1.0%	0.27 0.5%	0.12 0.2%
0.38 0.7%	1.2 2.0	13.2 23%	2.3 3.9%	0.45 0.8%	0.19 0.3%
0.34 0.6%	0.94 1.6%	3.7 6.4%	1.5 2.7%	0.42 0.7%	0.18 0.3%
0.19 0.3%	0.33 0.6%	0.46 0.8%	0.39 0.7%	0.24 0.4%	0.14 0.2%



*Detailed near field (NF) models of the upper 1/3 of the crust are critically important for **accuracy** and **precision** of signal predictions

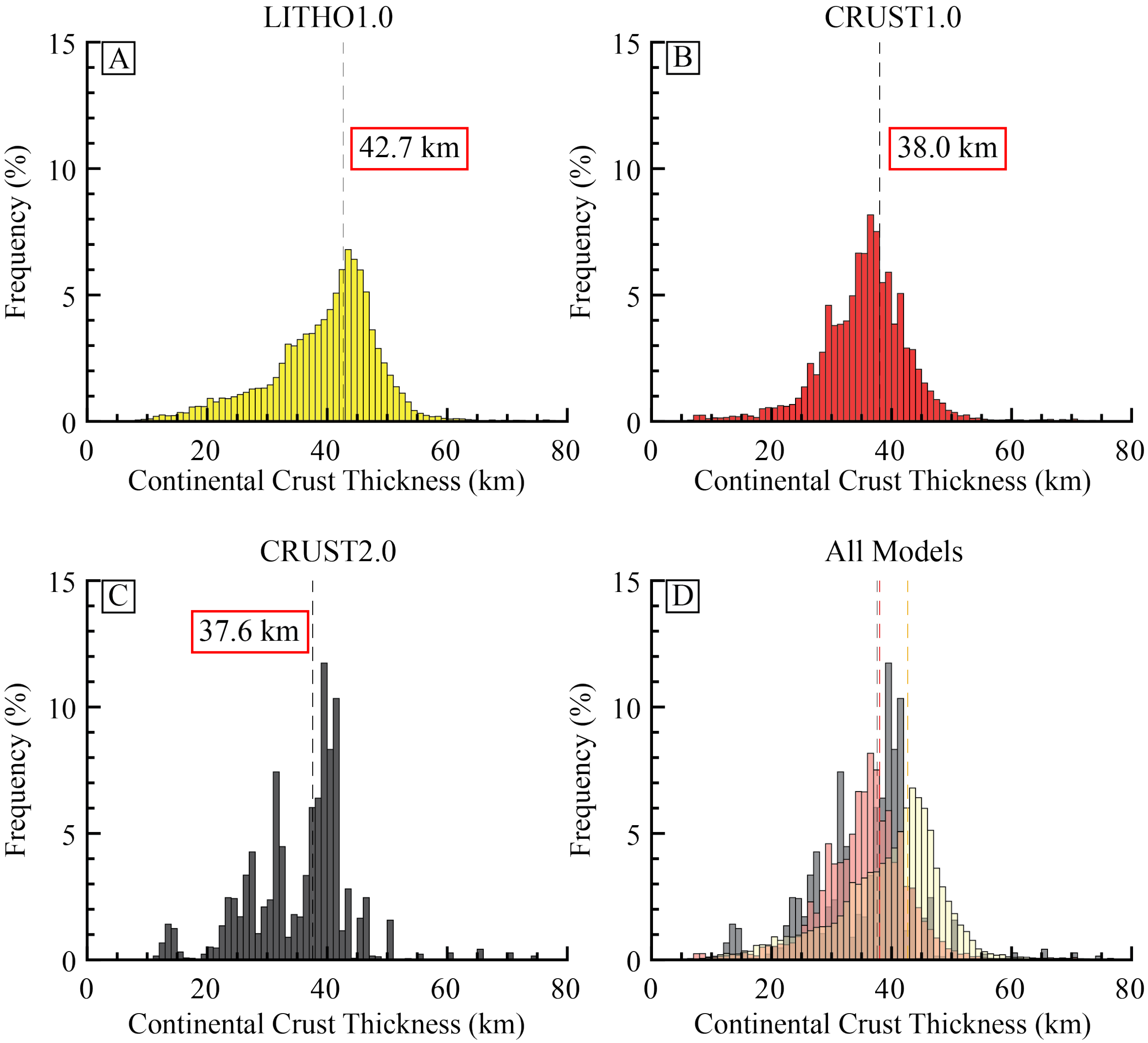
**Our study has not built a field-based detailed NF model*

Continental crustal thickness

Predictions by different global geophysical models

- CRUST 2.0
- CRUST 1.0
- LITHO 1.0

Avg cont. crust 41.0 ± 6.2
Christensen & Mooney 1995

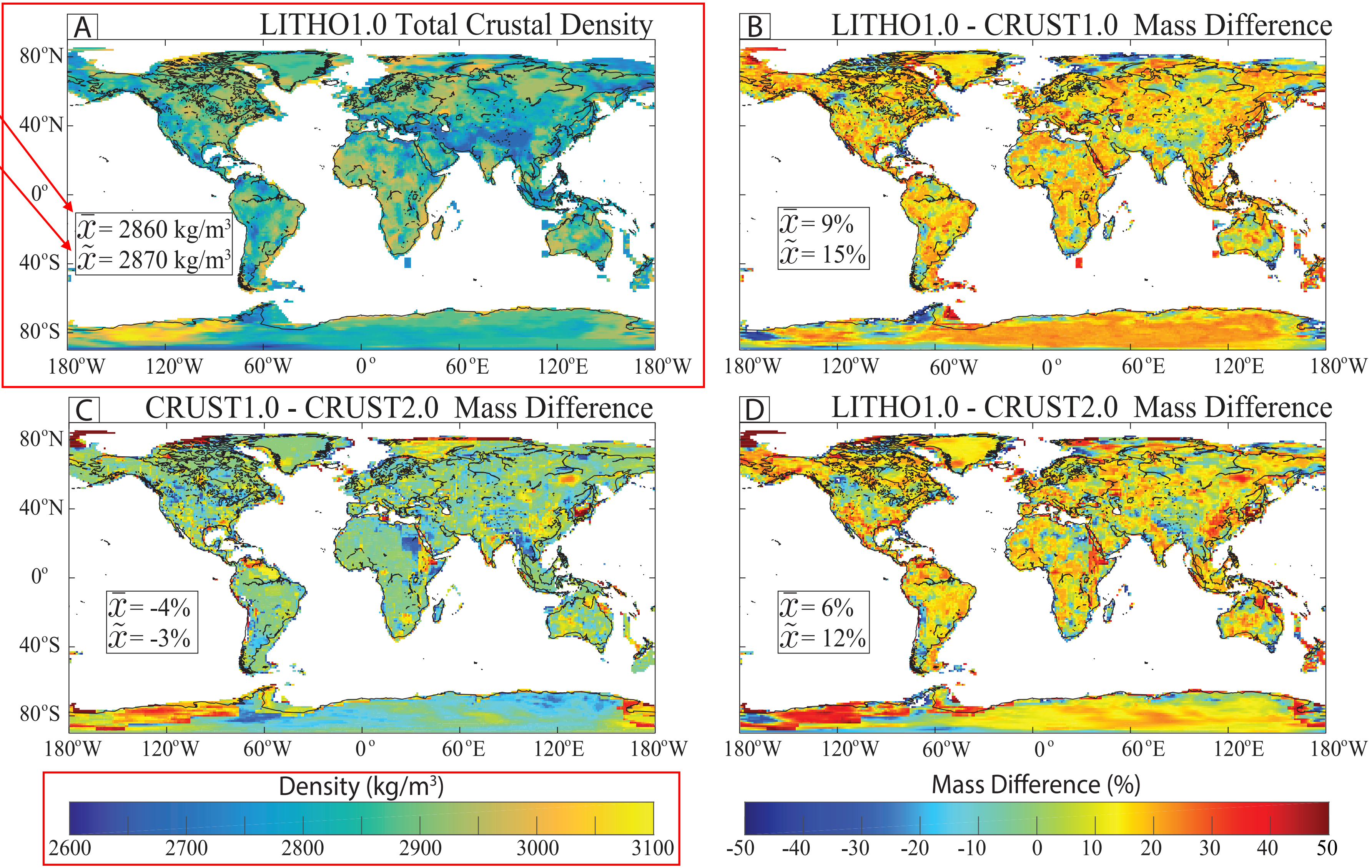


Global Crust: physical models

- CRUST 2.0
- CRUST 1.0
- LITHO 1.0

mean

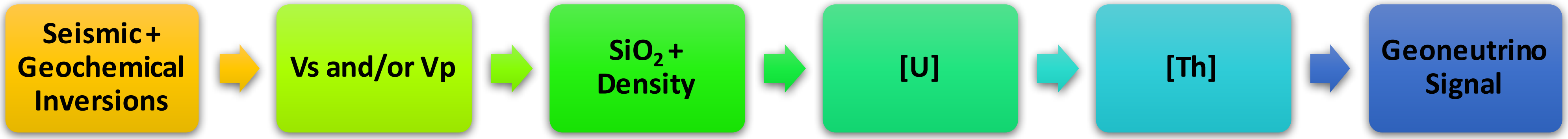
median



Estimating Crustal Contributions to Geoneutrino Signal

Crustal signal is predicted by using…

- for the Upper Crust: assume Rudnick and Gao (2003)
- for the deep Crust: global density and velocity models CRUST1.0/LITHO1.0,
- and compositional data for amphibolilte and granulite facies rocks
- THEN calculate density and K,Th,U abundances and geoneutrino flux



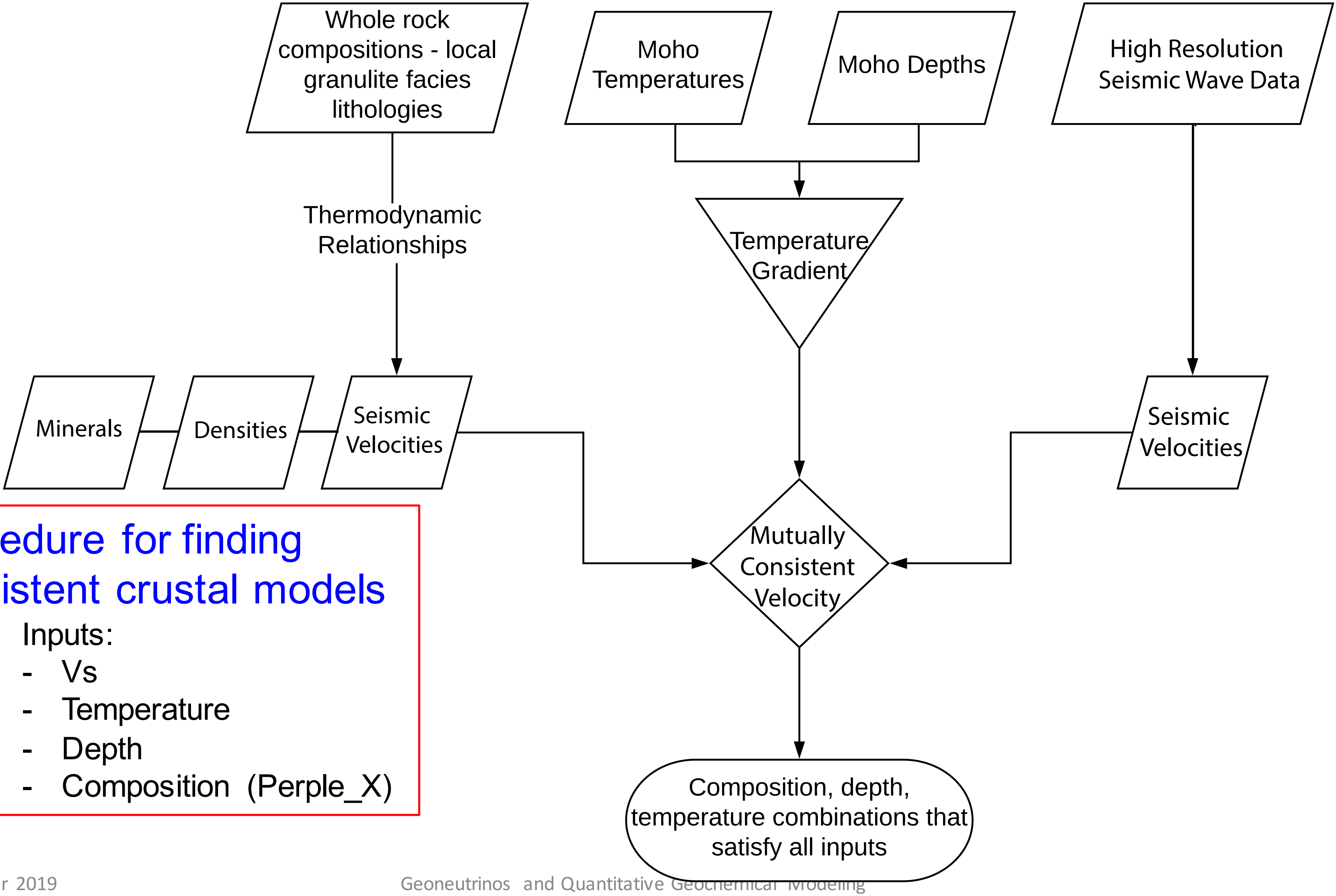
Seismic + Geochemical Inversions → **Vs and/or Vp** → **SiO_2 + Density** → **[U]** → **[Th]** → **Geoneutrino Signal**

… recent focus on Deep Crust (middle and lower)

Procedure for finding consistent crustal models

Inputs:

- Vs
- Temperature
- Depth
- Composition (Perple_X)



Whole rock compositions - local granulite facies lithologies

Moho Temperatures

Moho Depths

High Resolution Seismic Wave Data

Thermodynamic Relationships

Temperature Gradient

Minerals

Densities

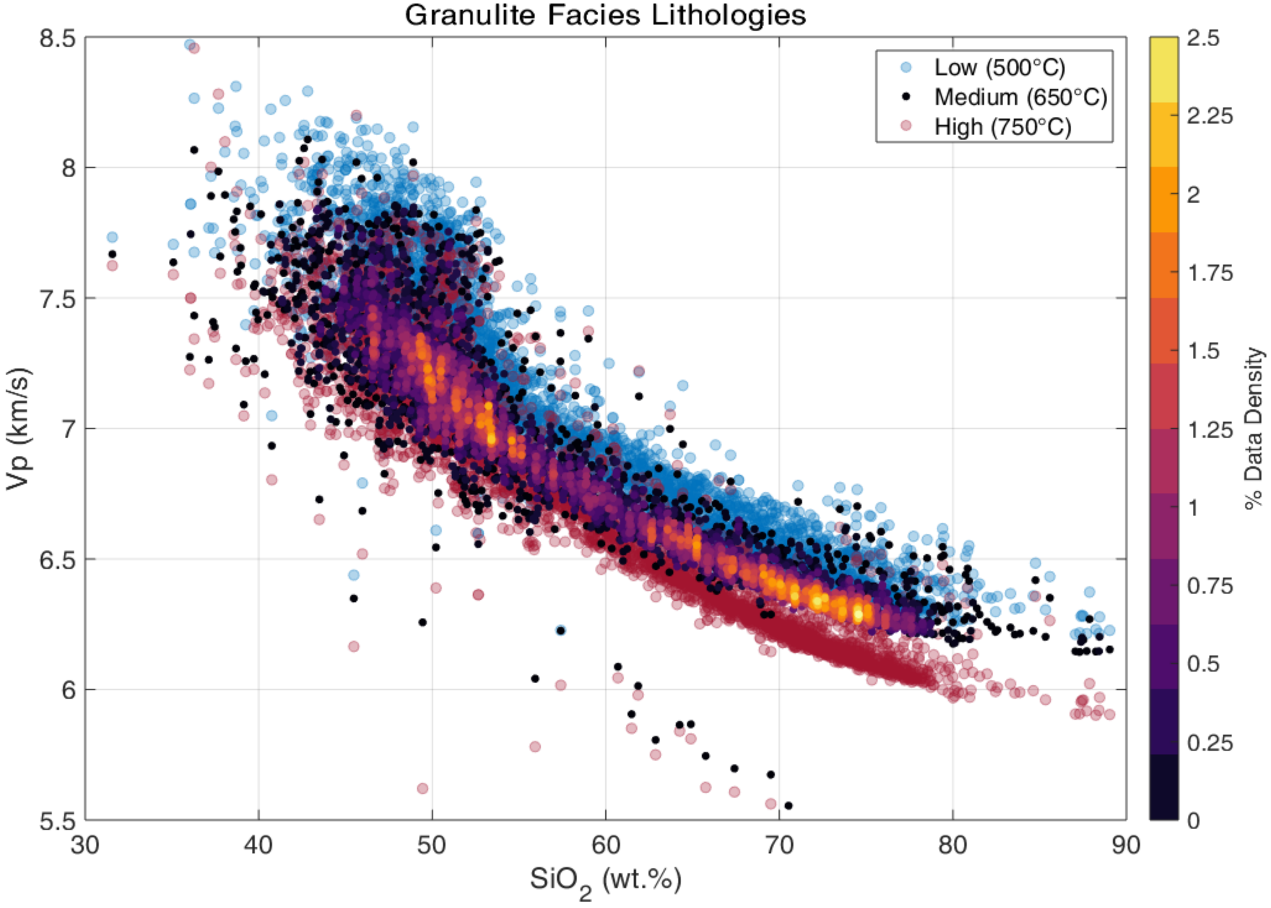
Seismic Velocities

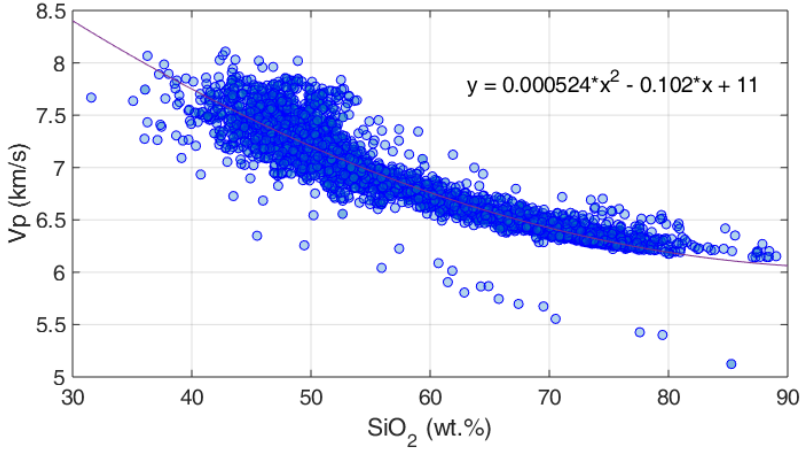
Seismic Velocities

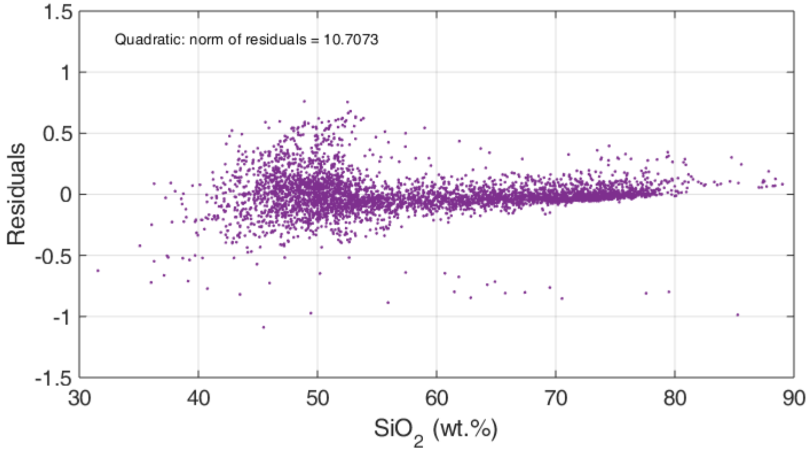
Mutually Consistent Velocity

Composition, depth, temperature combinations that satisfy all inputs

SiO_2 vs Vp: granulite facies rocks



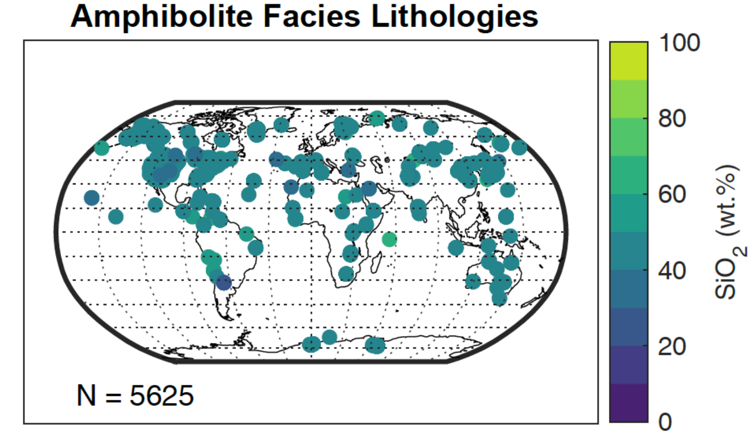




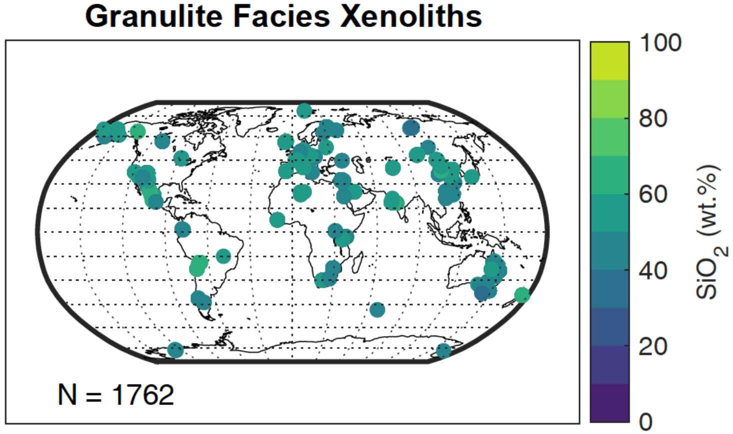
Amphibolite and granulite facies rocks

middle and lower crust samples

SiO_2 wt%

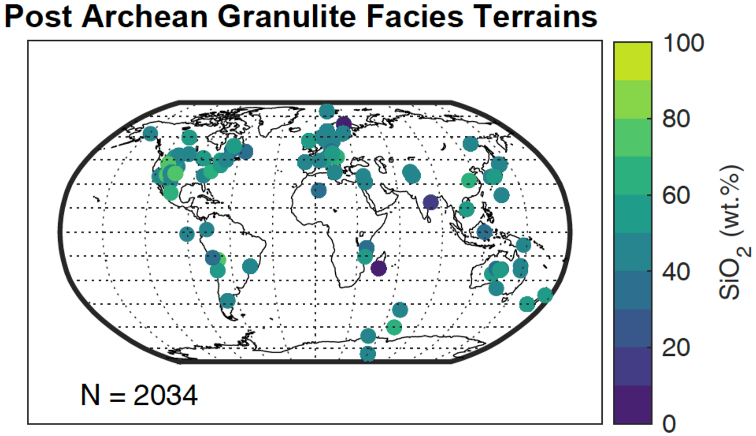


Amphibolite Facies Lithologies

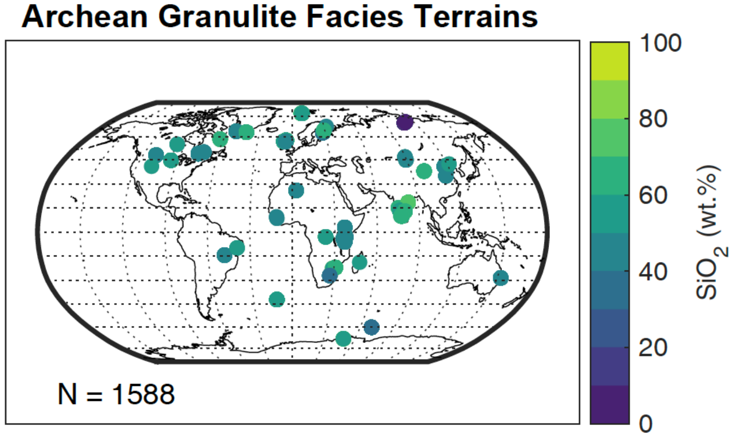


Granulite Facies Xenoliths

… on average most samples are mafic to intermediate, not felsic



Post Archean Granulite Facies Terrains

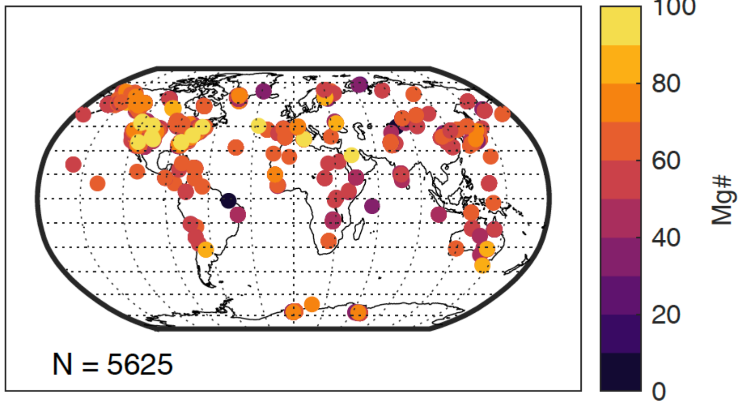


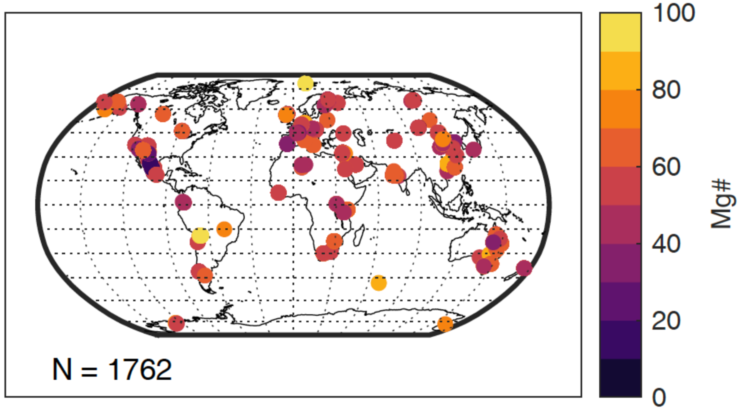
Archean Granulite Facies Terrains

Amphibolite and granulite facies rocks

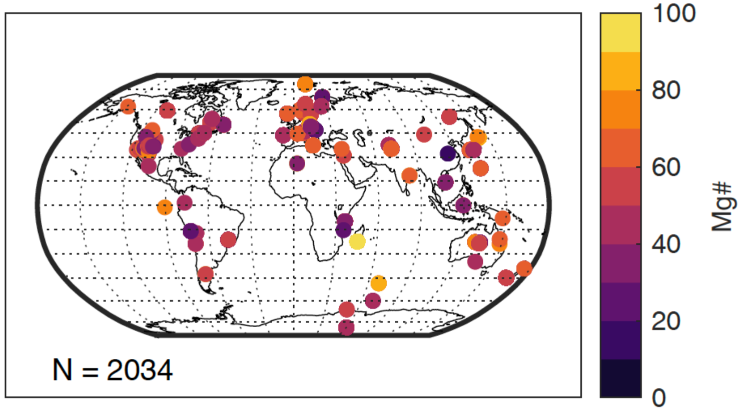
middle and lower crust samples

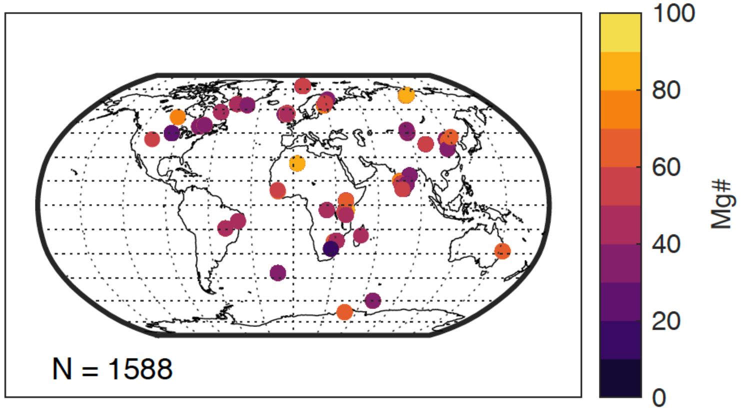
Mg#


Amphibolite Facies Lithologies


Granulite Facies Xenoliths

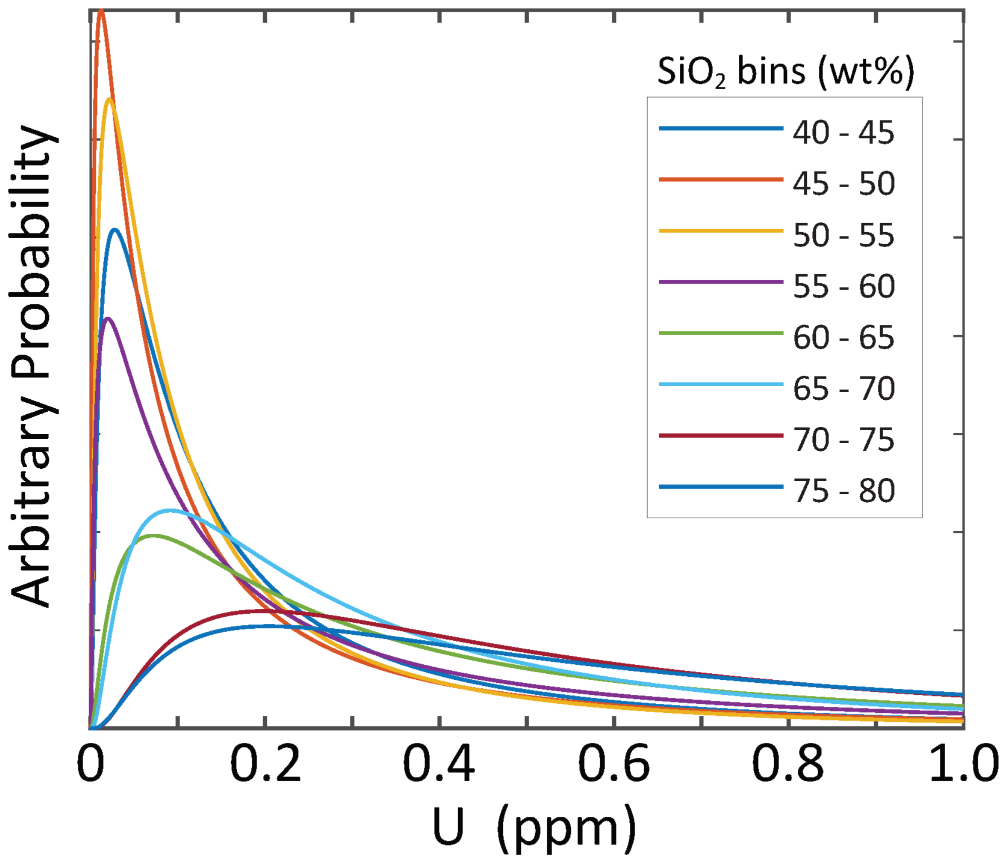
… on average most samples are mafic to intermediate, not felsic


Post Archean Granulite Facies Terrains

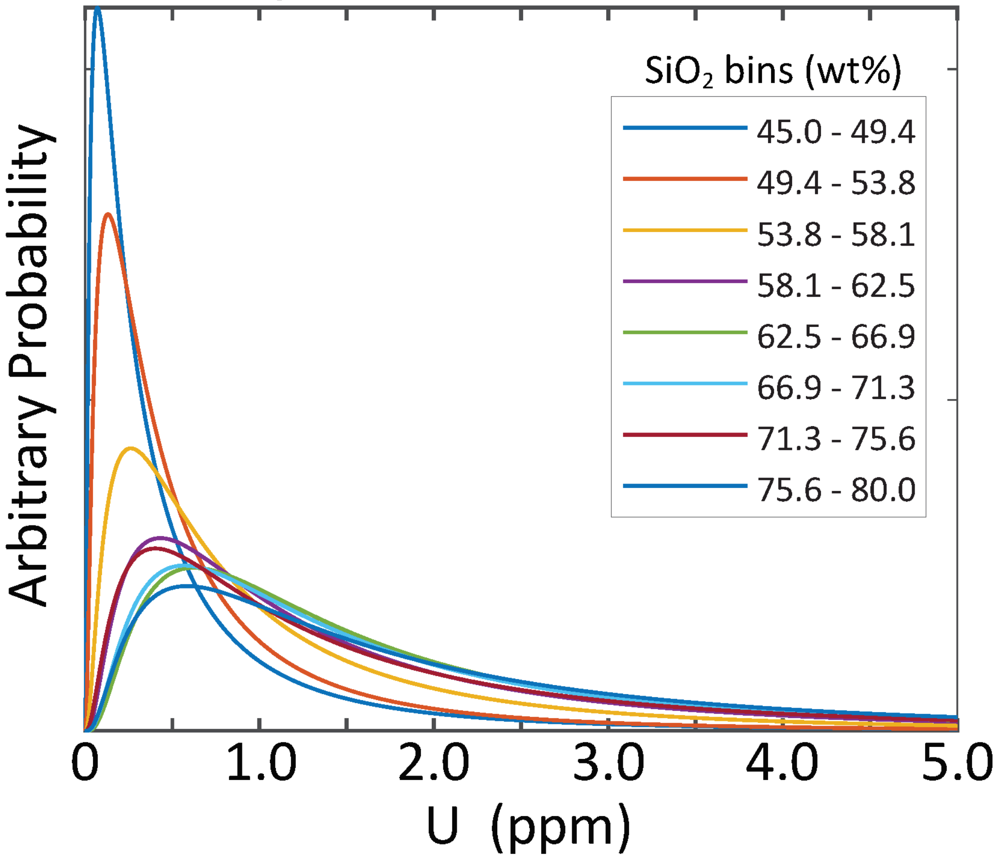

Archean Granulite Facies Terrains

U content of deep crust: global crust models

Granulite U distributions



Amphibolite U distributions

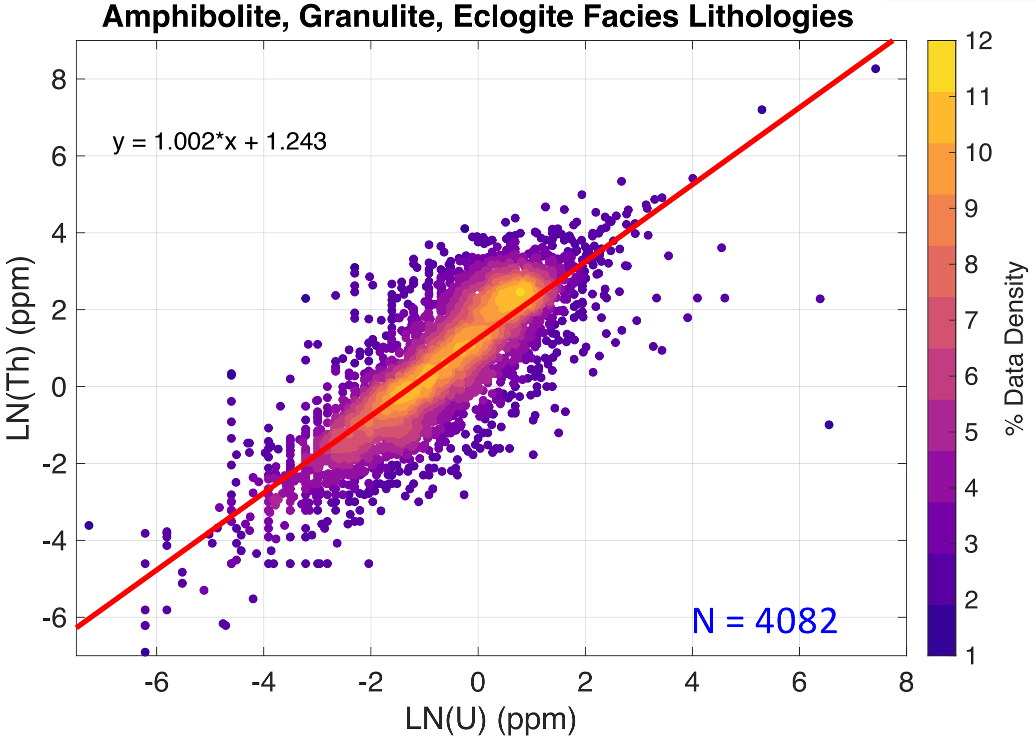


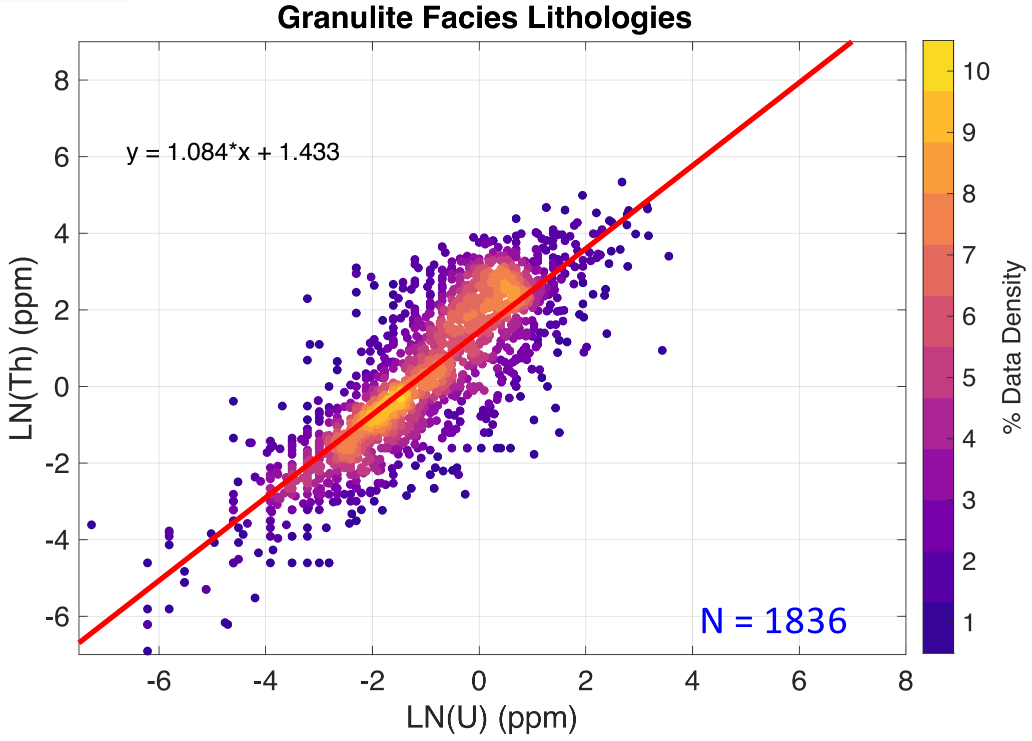
HPE of deep crustal rocks: U vs Th

All deep crustal rocks

Th/U = 3.47

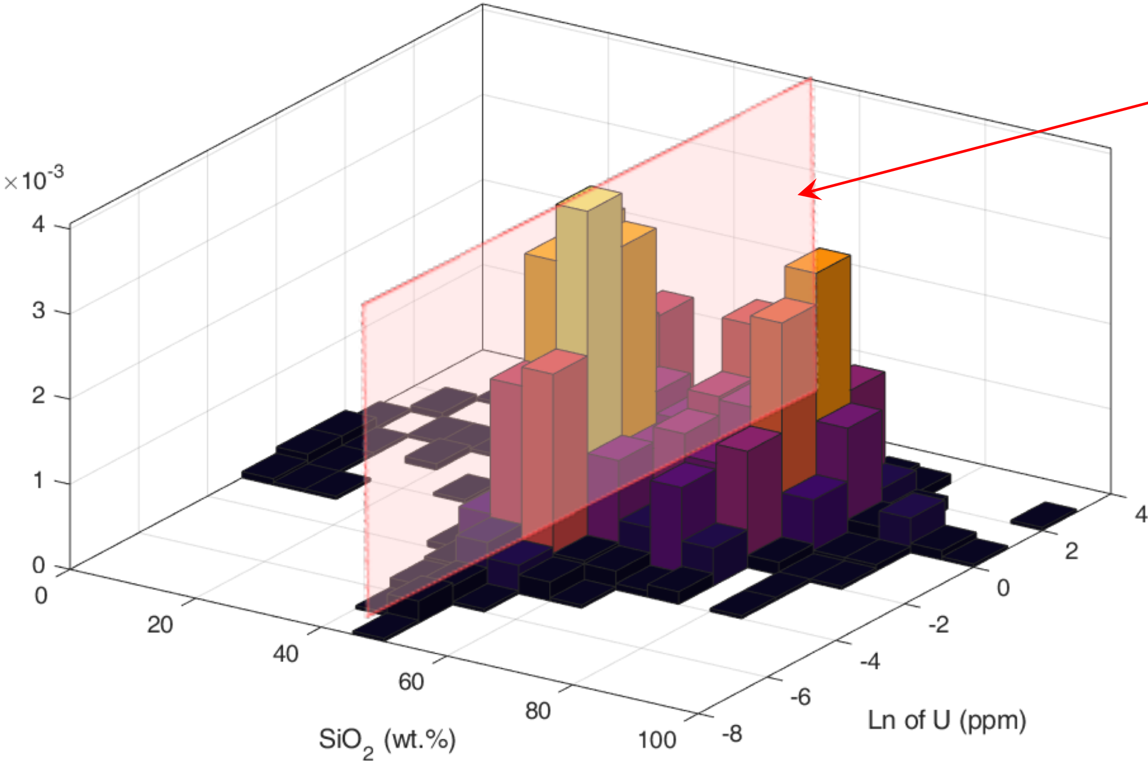
just granulite rocks

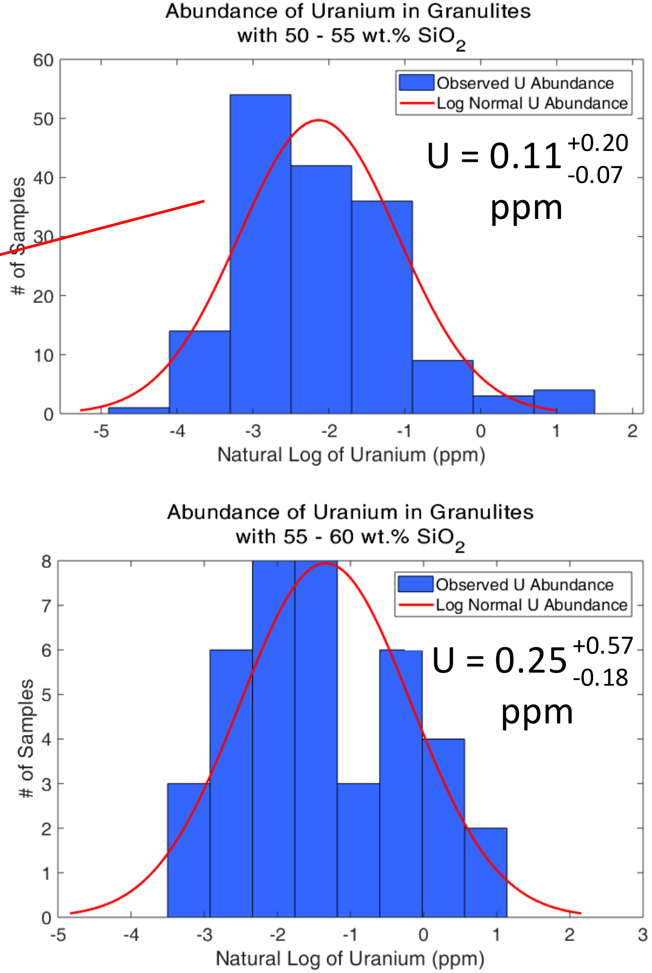




SiO_2 – U Joint Probability Analysis

Increases in SiO_2 correlates with increases in mean and median U content

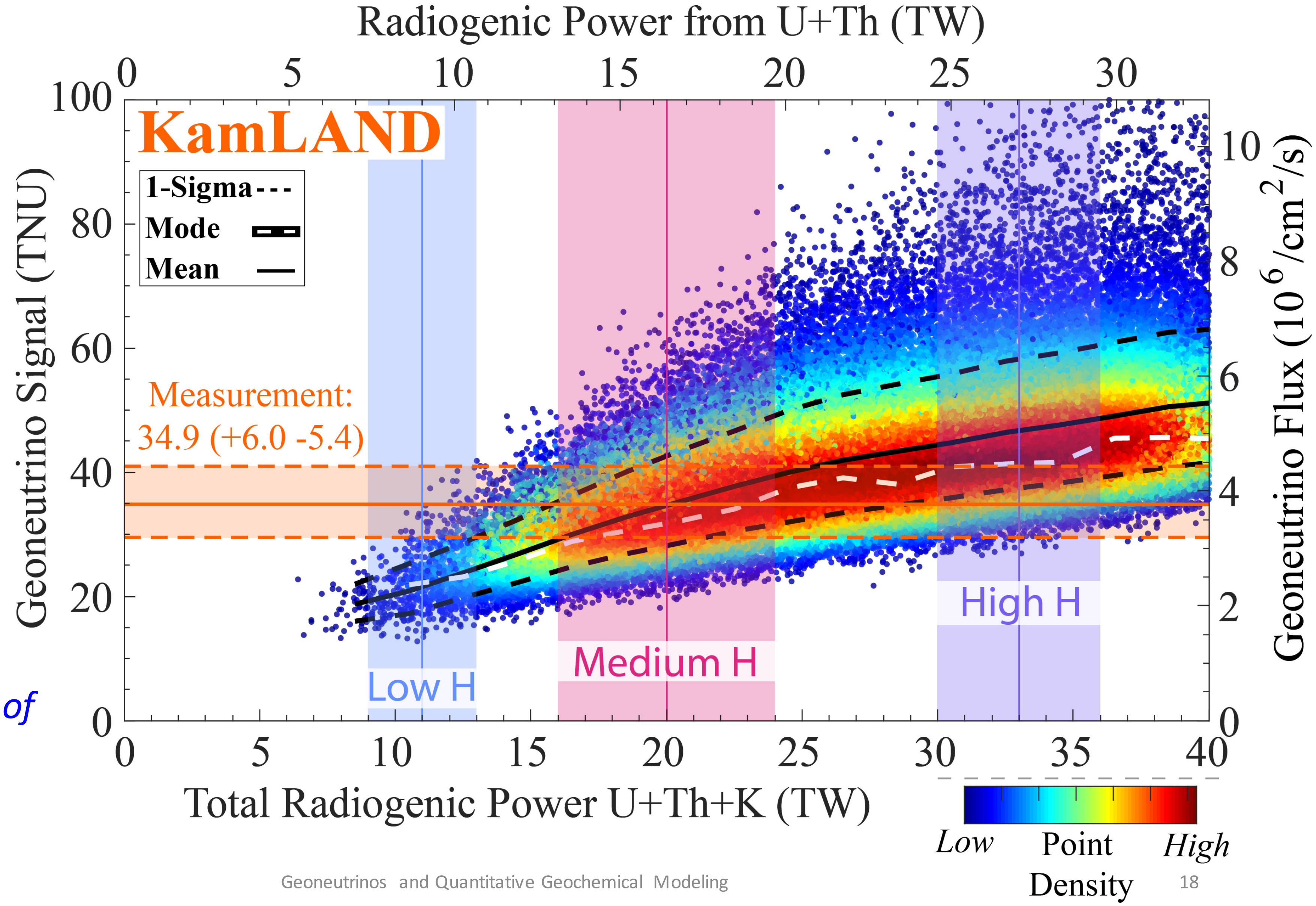




Best fit

Radiogenic power

R_{BSE} = 20 TW

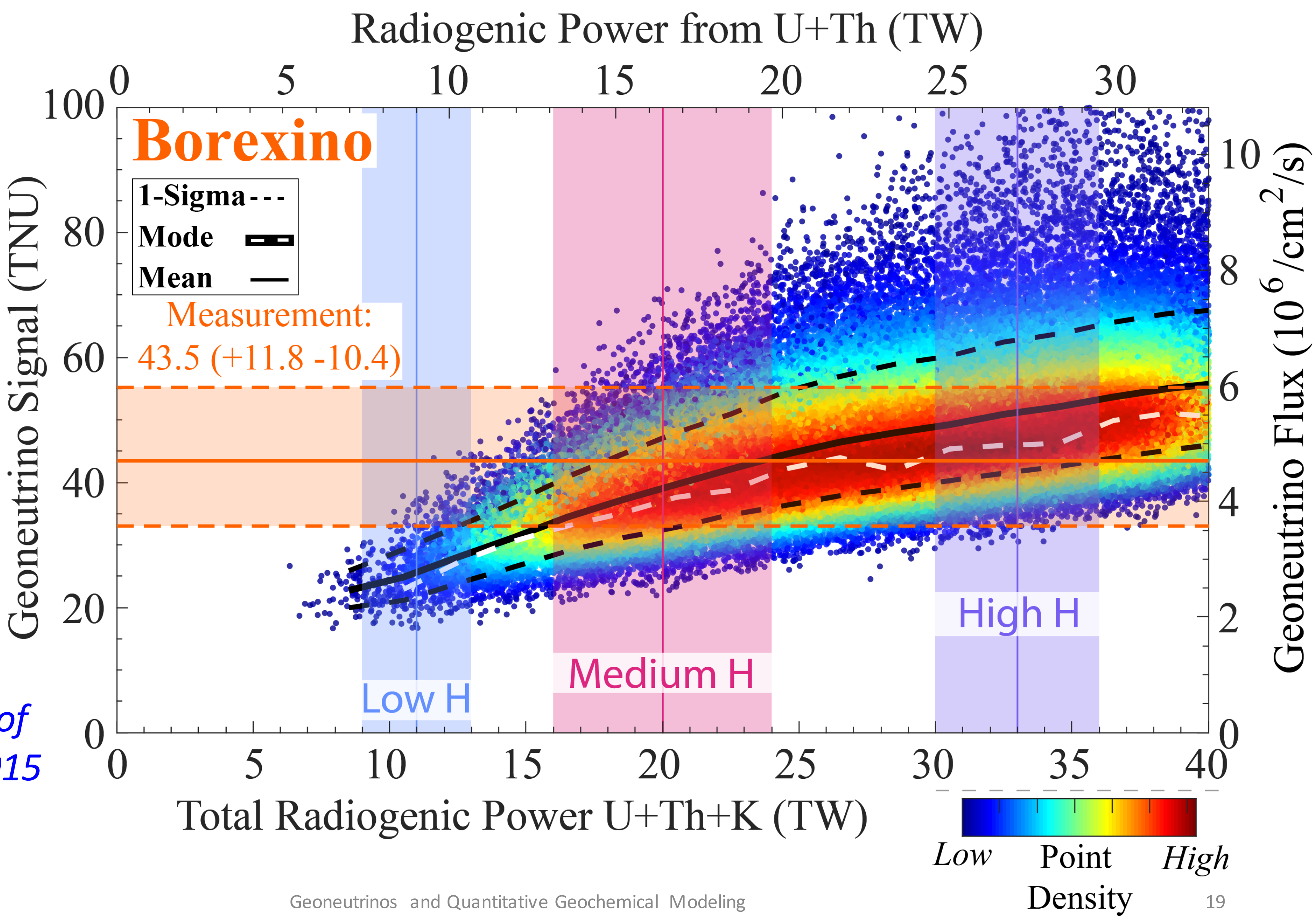


Based on results of Watanabe, 2016

Best fit

Radiogenic power

R_{BSE} = 24 TW



Based on results of Agostini et al., 2015

Geoneutrino signal calculated from global crust models

		Geoneutrino Flux (TNU)				Overlapping Coefficient		
Detector		**CRUST2**	**CRUST1**	**LITHO1**	$\lvert \Delta \rvert$	**L1,C1**	**L1,C2**	**C1,C2**
KamLAND	Bulk CC	$22.7^{+5.9}_{-4.7}$	$24.2^{+6.7}_{-5.2}$	$26.4^{+7.1}_{-5.6}$	15	85	74	89
	Total	$34.7^{+5.8}_{-5.0}$	$36.6^{+6.5}_{-5.5}$	$37.9^{+6.6}_{-5.6}$	9	92	78	87
Borexino		$30.5^{+8.1}_{-6.4}$	$29.9^{+8.0}_{-6.3}$	$30.5^{+7.7}_{-6.2}$	2	96	98	96
		$43.2^{+8.0}_{-6.7}$	$42.9^{+7.9}_{-6.6}$	$42.1^{+7.3}_{-6.2}$	1	95	94	98
SNO+		$37.3^{+10.2}_{-8.0}$	$32.9^{+9.6}_{-7.4}$	$33.8^{+9.6}_{-7.5}$	13	95	84	80
		$49.8^{+9.7}_{-8.1}$	$45.7^{+9.3}_{-7.7}$	$46.8^{+9.4}_{-7.8}$	8	95	86	82
JUNO		$28.1^{+7.5}_{-5.9}$	$28^{+7.7}_{-6.1}$	$29.2^{+8.0}_{-6.3}$	4	93	93	99
		$40.5^{+7.4}_{-6.3}$	$40.7^{+7.6}_{-6.4}$	$40.4^{+7.4}_{-6.3}$	1	98	99	99
Jinping		$42.5^{+11.5}_{-9.1}$	$47.2^{+12.7}_{-10.0}$	$48.5^{+13.1}_{-10.3}$	13	96	78	83
		$55.0^{+10.9}_{-9.1}$	$59.9^{+12.1}_{-10.1}$	$59.9^{+12.2}_{-10.1}$	9	100	81	81
Hawaii		$2.3^{+0.7}_{-0.5}$	$2.1^{+0.6}_{-0.5}$	$2.3^{+0.7}_{-0.5}$	6	90	93	83
		$12.9^{+2.8}_{-2.3}$	$12.9^{+2.8}_{-2.3}$	$12.8^{+2.7}_{-2.3}$	1	98	99	99

Negligible difference in crustal models

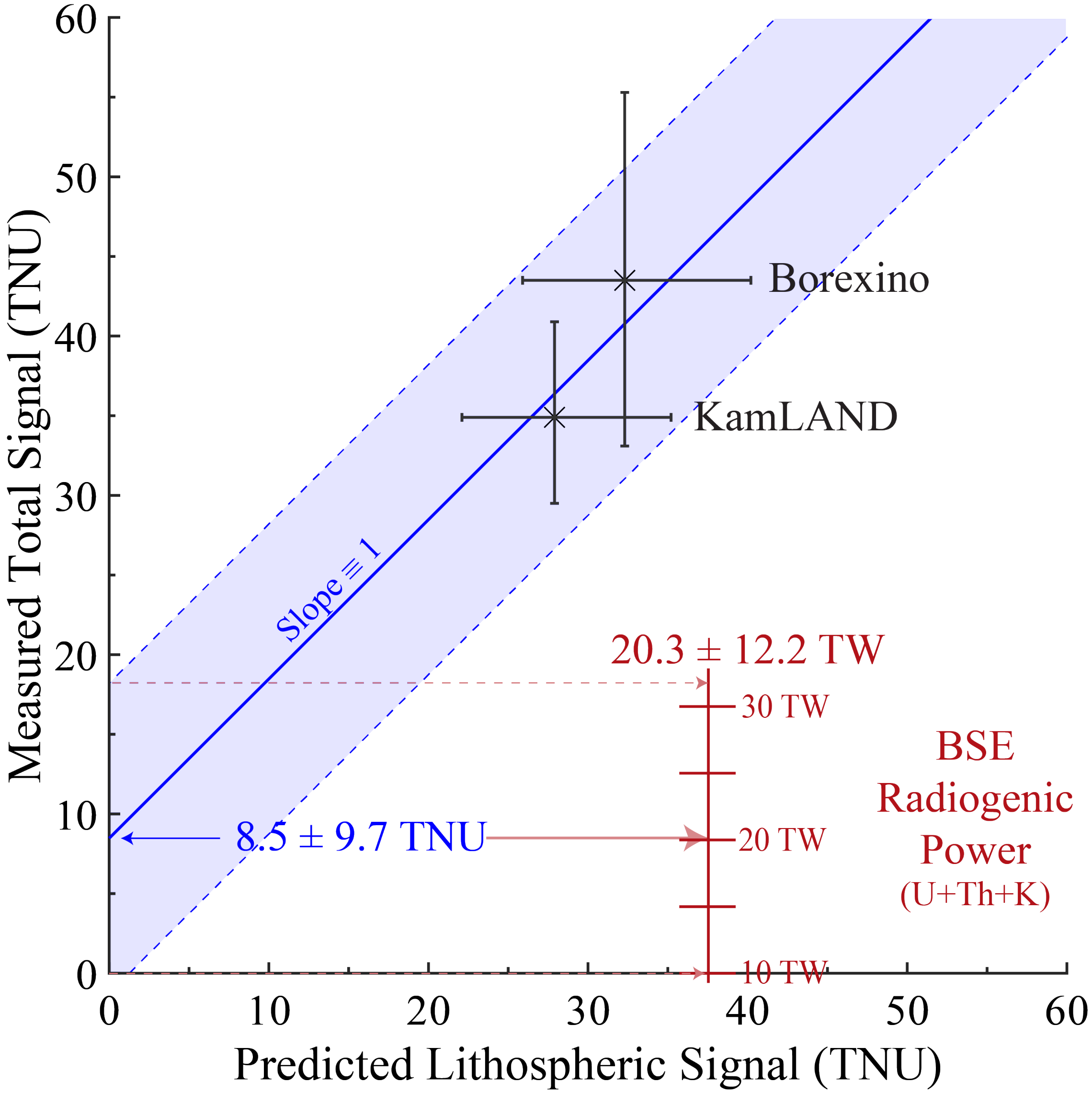
Physical properties of crustal models

			CRUST2.0		CRUST1.0		LITHO1.0	
	Layer	~ ρ (g/cm^3)	d (km)*	M (10^{21} kg)	d (km)*	M (10^{21} kg)	d (km)*	M (10^{21} kg)
CC	Sed	2.2	2.18 ±2.1	0.8 ±0.1	1.64 ±2.2	0.7 ±0.1	1.54 ±2.0	0.7 ±0.1
	UC	2.75	11.60 ±3.9	7.0 ±0.9	11.71 ±4.0	6.3 ±0.8	12.79 ±4.1	6.9 ±0.8
	MC	2.84	11.18 ±3.4	7.2 ±0.9	11.57 ±3.0	6.4 ±0.8	13.06 ±3.8	7.3 ±0.9
	LC	3.02	9.93 ±2.9	6.7 ±0.8	10.73 ±2.7	6.2 ±0.8	12.22 ±3.6	7.2 ±0.9
	Bulk CC	2.9	34.25 ±8.8	21.8 ±2.6	35.53 ±7.6	19.6 ±2.4	39.60 ±9.1	22.2 ±2.6
OC	Sed	1.9	1.86 ±0.2	0.3 ±0.0	1.90 ±0.1	0.4 ±0.1	1.90 ±0.1	0.4 ±0.1
	C	2.9	6.80 ±1.5	5.6 ±0.7	7.82 ±2.9	7.1 ±0.9	10.46 ±4.3	9.2 ±1.1
Mantle	LM	3.34	139.9 ±75	102.8 ±53	139.5 ±75	88 ±43	114.3 ±82	63 ±7.5
	DM	4.4	1966	3149.9	1966	3168.5	1987 ±84	3187.3
	EM	5.4	750	754	750	754	750	754
	BSE	4.45	2891	4035	2891	4038	2891	4036

importance of accuracy

Our latest model for predicting the mantle signal

measured KL signal (Watanabe, 2016)
measured BX signal (Agostini et al 2015)
Predicted signals (Wipperfurth etal 2019)



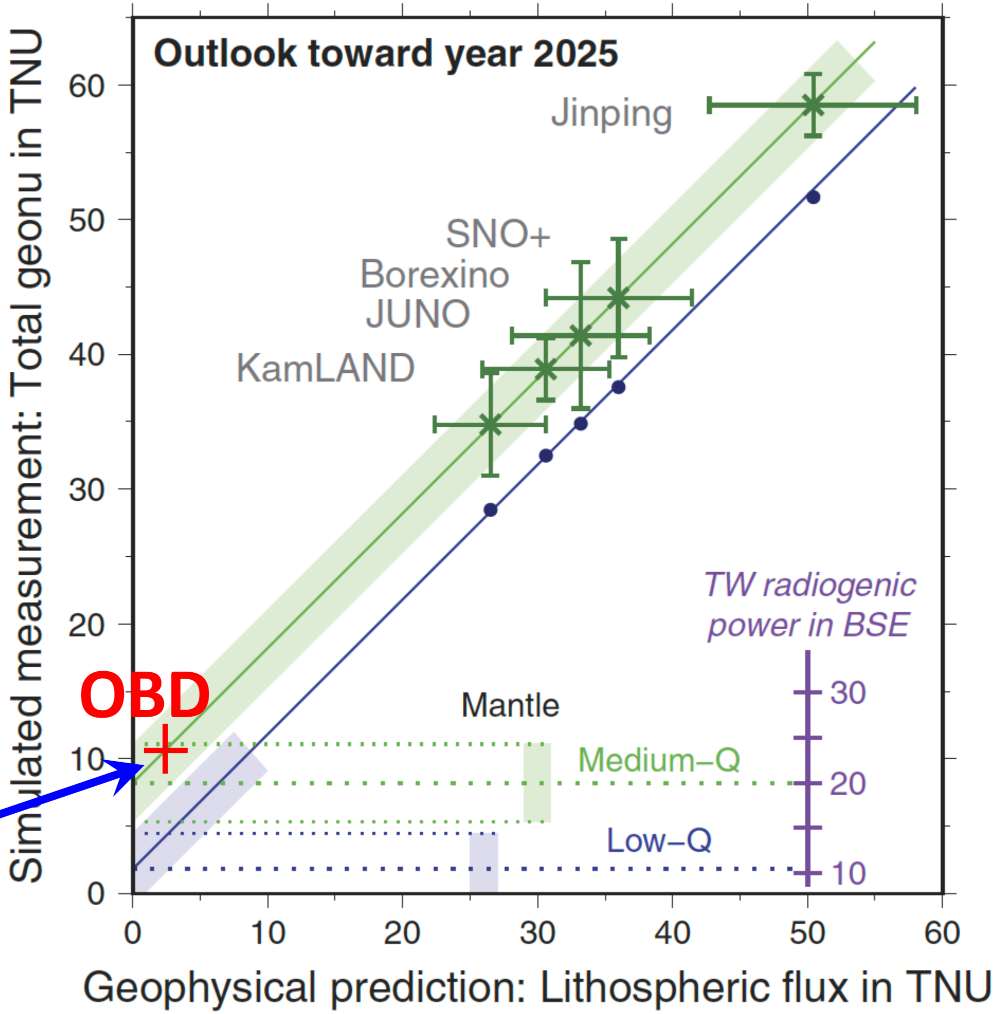
Combining data from the global array

Future is Bright

2025 and beyond

- *Physics continues to count*
- *Much to be learned*
- *More geoneutrino data!*
- *Benefits for astrophysics*

Šr‡mek et al. (2016) model (SREP 6, 33034 (2016))



- *Importance of an ocean measurement!*

Prediction based on 1.5 kt, 4 yr exposure, ± 20%

Conclusions

- Contributions to the geoneutrino signal:
    - 40% local crustal model
    - 35% global continental lithosphere
    - 25% mantle
- Estimated total signal uncertainties 20%, with 6% from geophysics + 14% from geochemistry
- Calculations using CRUST2.0, CRUST1.0 and LITHO1.0 yield physical uncertainties that overlap each other
- Bulk continental crust has (7 ± 2) TW