



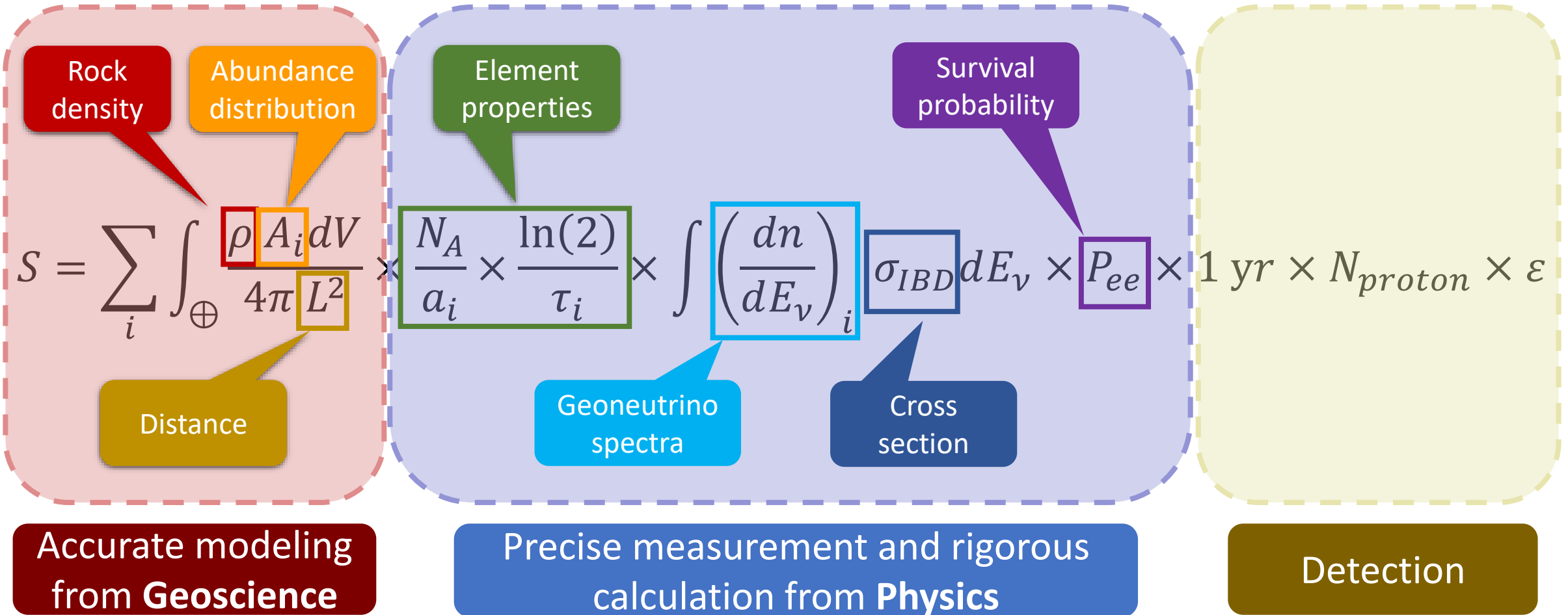
GEONU: An Open-Source Toolkit for Geoneutrino Signal Predictions and Applications to SNO+

Shuai Ouyang

2025.10.28 Shandong University



Motivation





Motivation

- Global computations

- (2005) S. Enomoto, Neutrino Geophysics and Observation of Geo-Neutrinos at KamLAND
- (2012) S. T. Dye, Geoneutrinos and the Radioactive Power of the Earth
- (2013) Huang et al., A Reference Earth Model for the Heat-Producing Elements and Associated Geoneutrino Flux
- (2017) Wan et al., Geoneutrinos at Jinping: Flux Prediction and Oscillation Analysis
- (2020) Wipperfurth et al., Reference Models for Lithospheric Geoneutrino Signal
-

- Local computations

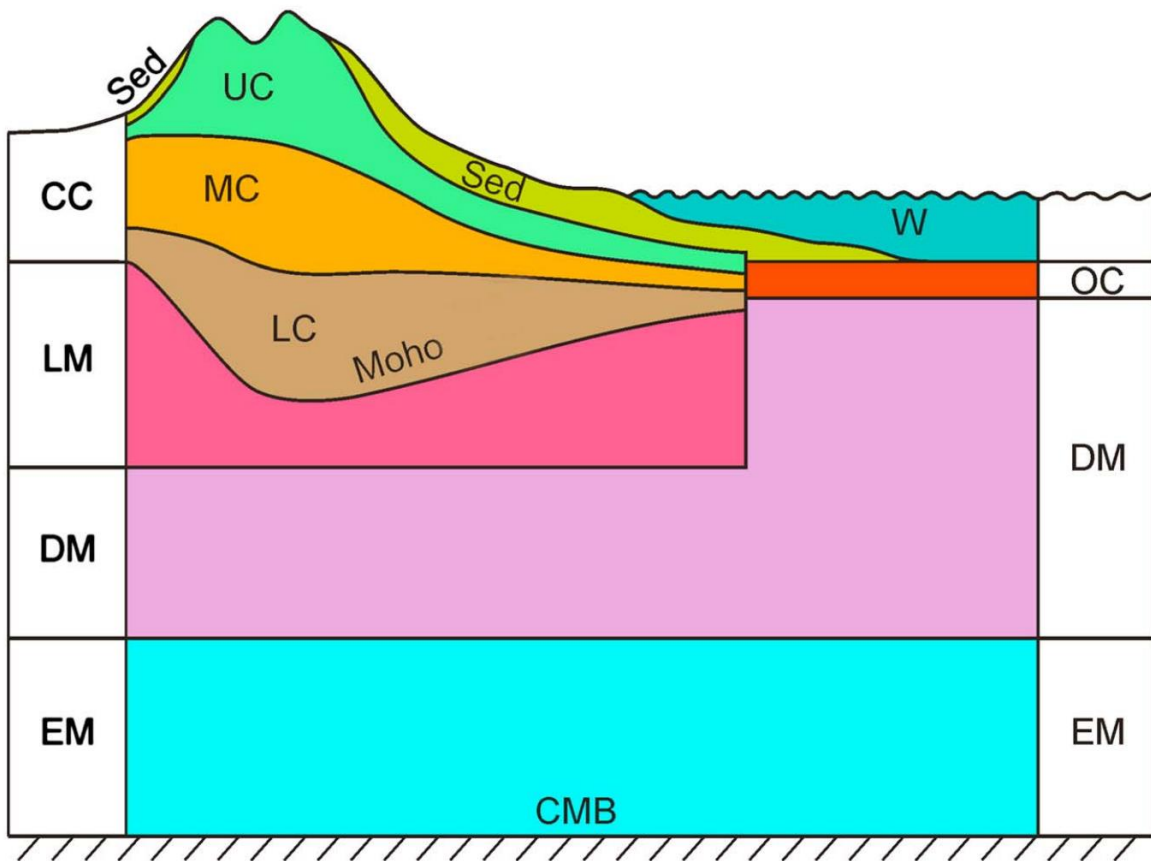
- (2007) Enomoto et al., Neutrino Geophysics with KamLAND and Future Prospects
- (2011) Coltorti et al., U and Th Content in the Central Apennines Continental Crust: A Contribution to the Determination of the Geo-Neutrinos Flux at LNGS
- (2014) Huang et al., Regional Study of the Archean to Proterozoic Crust at the Sudbury Neutrino Observatory (SNO+), Ontario: Predicting the Geoneutrino Flux
- (2017) Strati et al., Perceiving the Crust in 3-D: A Model Integrating Geological, Geochemical, and Geophysical Data
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GEONU

- GEONU is an open set of MATLAB codes about earth model, which can compute the geo-nu flux, signals and other interests
- Info
 - Github: <https://github.com/LSKgeo/GEONU>
 - Last update: June 25, 2025
 - Version: 1.0
 - Repository authors: Tytrice Faison, Laura Sammon
 - Code authors: Yu Huang, Scott Wipperfurth, William F. McDonough, Laura Sammon, Tytrice Faison

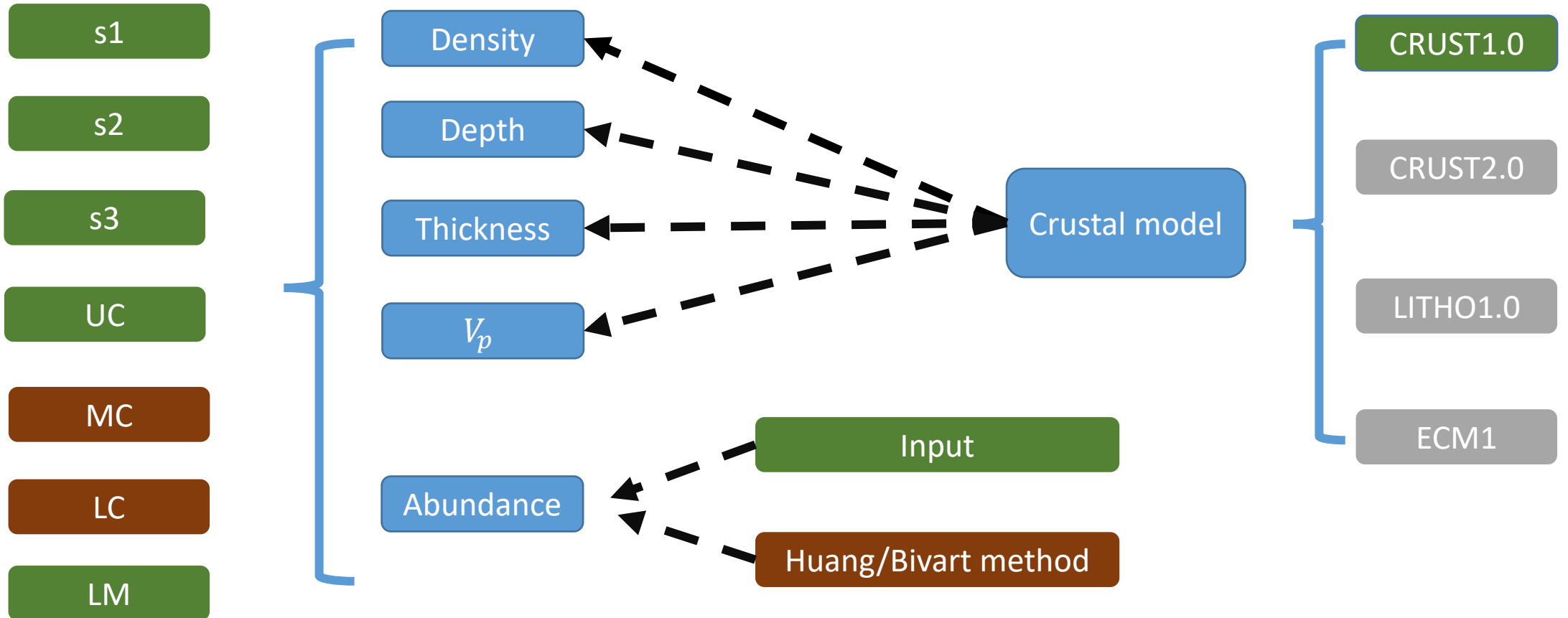
GEONU



- 9 layers:
 - Sedimentary: s1, s2 and s3
 - Crust: UC, MC and LC
 - Mantle: LM, DM and EM
- Grids
 - Number: 64, 800 in each layer
 - Size: $1^\circ \times 1^\circ$

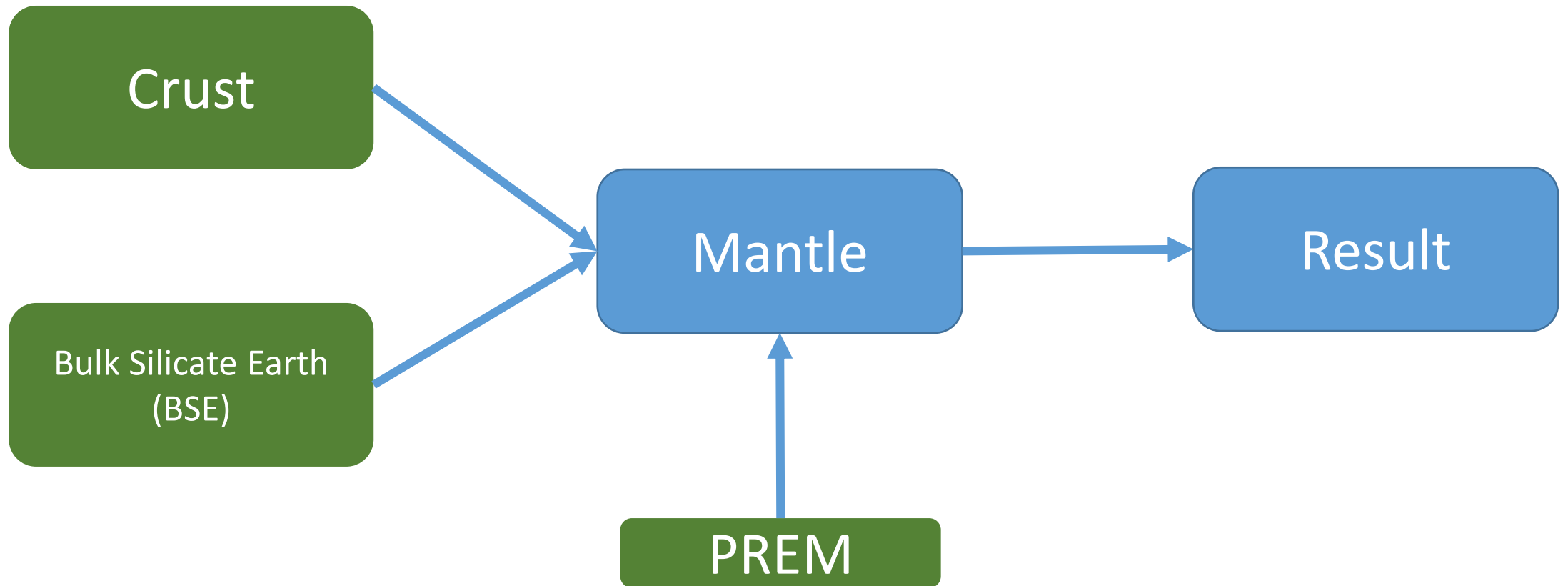


GEONU





GEONU





GEONU

Strengths

1. Well-organized layered Earth structure
2. Support for multiple crustal models
3. Subdivision algorithm
4. More realistic consideration



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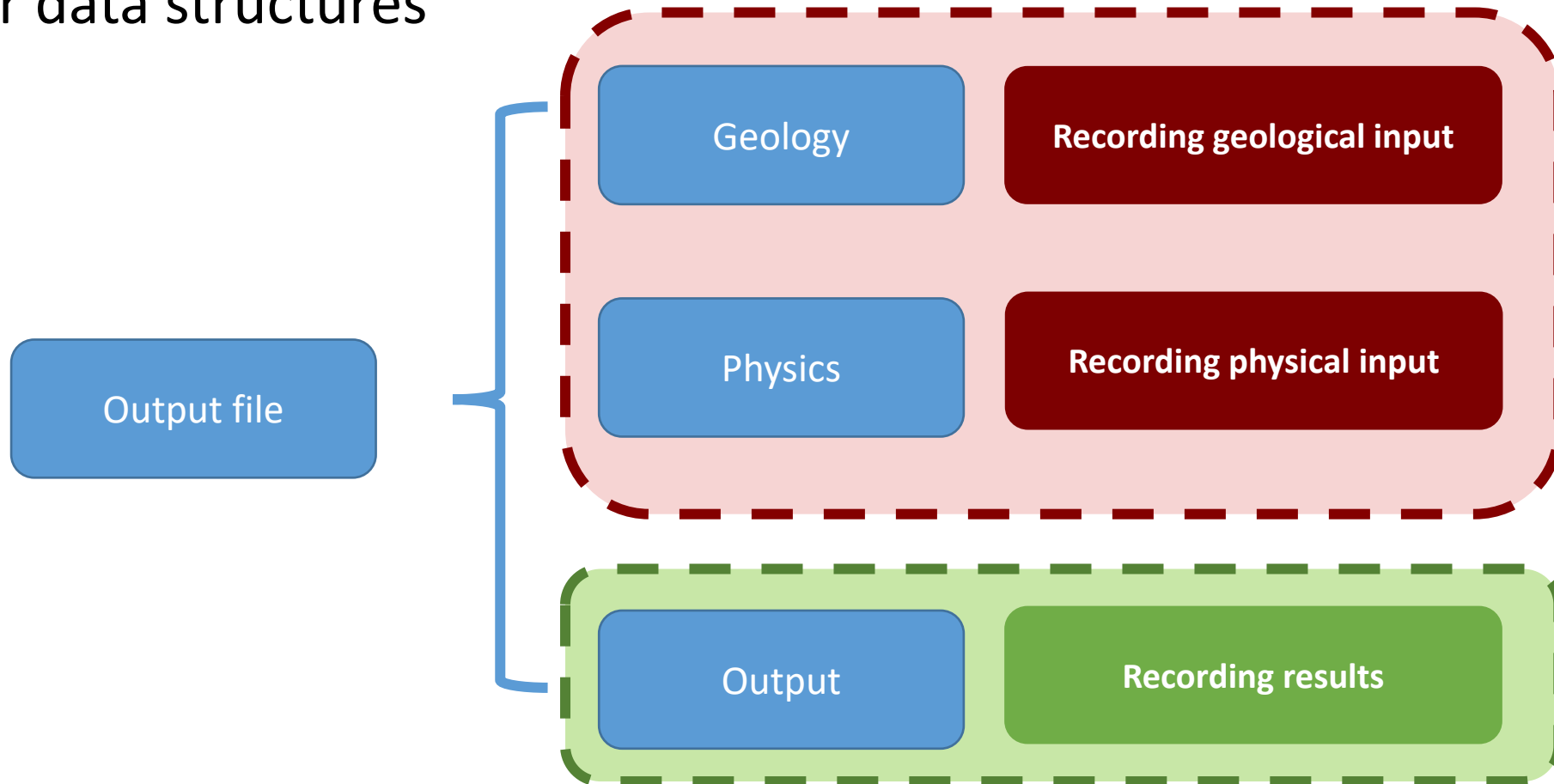
Technical Issues

1. Redundancy in code implementation
2. Disordered data structures
3. Minor crustal data format issues
4. Lack of uncertainty estimation for physical analysis



GEONUS

- Clear data structures

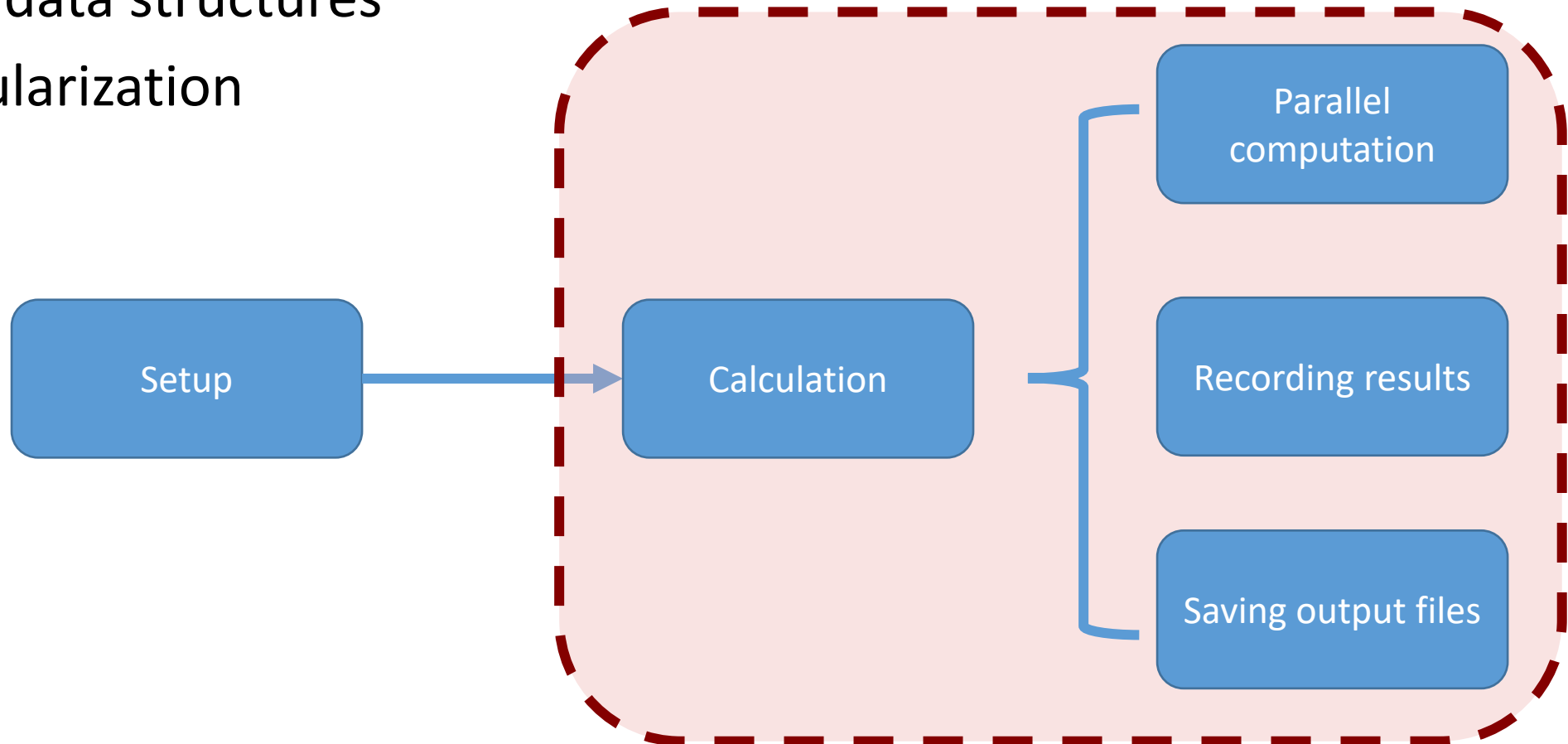




Features

GEONUS

- Clear data structures
- Modularization





Features

GEONUS

- Clear data structures
- Modularization
- Faster computation but consumes much more memory

	Simulations	1000	4000
Original version	Time	~830 s	~2800 s
	Memory	~20 GB	~24 GB
New version	Time	~120 s	~250 s
	Memory	~24 GB	64 GB



GEONUS

Table 3.4: Default HPE Abundances in Lithosphere Layers

Layer	CC			OC		
	U/ 10^{-6}	Th/ 10^{-6}	K/ 10^{-2}	U/ 10^{-6}	Th/ 10^{-6}	K/ 10^{-2}
Sediment	1.73 ± 0.09	8.10 ± 0.59	$(2.21 \pm 0.14) * 0.83$	1.73 ± 0.09	8.10 ± 0.59	$(2.21 \pm 0.14) * 0.83$
UC	2.7 ± 0.6	10.5 ± 1.0	2.32 ± 0.19	0.07 ± 0.021	0.21 ± 0.063	0.0716 ± 0.0215
MC/LC	Huang/Bivart			0.07 ± 0.021	0.21 ± 0.063	0.0716 ± 0.0215
LM	$0.033^{+0.049}_{-0.020}$	$0.15^{+0.277}_{-0.097}$	$0.0315^{+0.04316}_{-0.01826}$	0		

Table 3.5: Default HPE Abundances in BSE

U/ 10^{-9}	Th/U	K/U
19 ± 3.8	$3.776^{+0.122}_{-0.075}$	13800 ± 1300

Table 3.6: Default Mantle Input Parameters

EM (mass fraction)	Th/U	K/U
19%	$3.45^{+1.66}_{-1.18}$	19000 ± 1300

Table 3.7: Other Default Geological Inputs

Earth mass (kg)/ 10^{24}	Core mass (kg)/ 10^{24}
5.97218 ± 0.00006	1.93265 ± 0.0579795



Update

GEONUS

- Elements' properties

Original version	U238	U235	Th232	K40
Natural abundance	99.274%	0.726%	100%	0.01167%
Atom mass	238.0507826	235.0439231	232.0380504	39.9639987
τ_i (s)/3.15569e7	4.683e9	0.70348e9	14.1e9	1.262e9

New version	U238	U235	Th232	K40
Natural abundance	99.3%	0.7%	100%	0.0117%
Atom mass	238.05078826	235.0439299	232.0380536	39.96399848165
τ_i (s)/3.1536e7	4.468e9	0.704e9	14.05e9	1.248e9



GEONUS

- Elements' properties
- Neutrino oscillation

$$\begin{aligned}
 P_{ee} &= 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \left(\frac{1.27 \Delta m_{21}^2 L}{E} \right) - \sin^2 2\theta_{13} \cos^2 \theta_{12} \sin^2 \left(\frac{1.27 \Delta m_{31}^2 L}{E} \right) \\
 &\quad - \sin^2 2\theta_{13} \sin^2 \theta_{12} \sin^2 \left(\frac{1.27 \Delta m_{32}^2 L}{E} \right)
 \end{aligned}$$

Table 3.2: Neutrino Oscillation Parameters (PDG 2024)

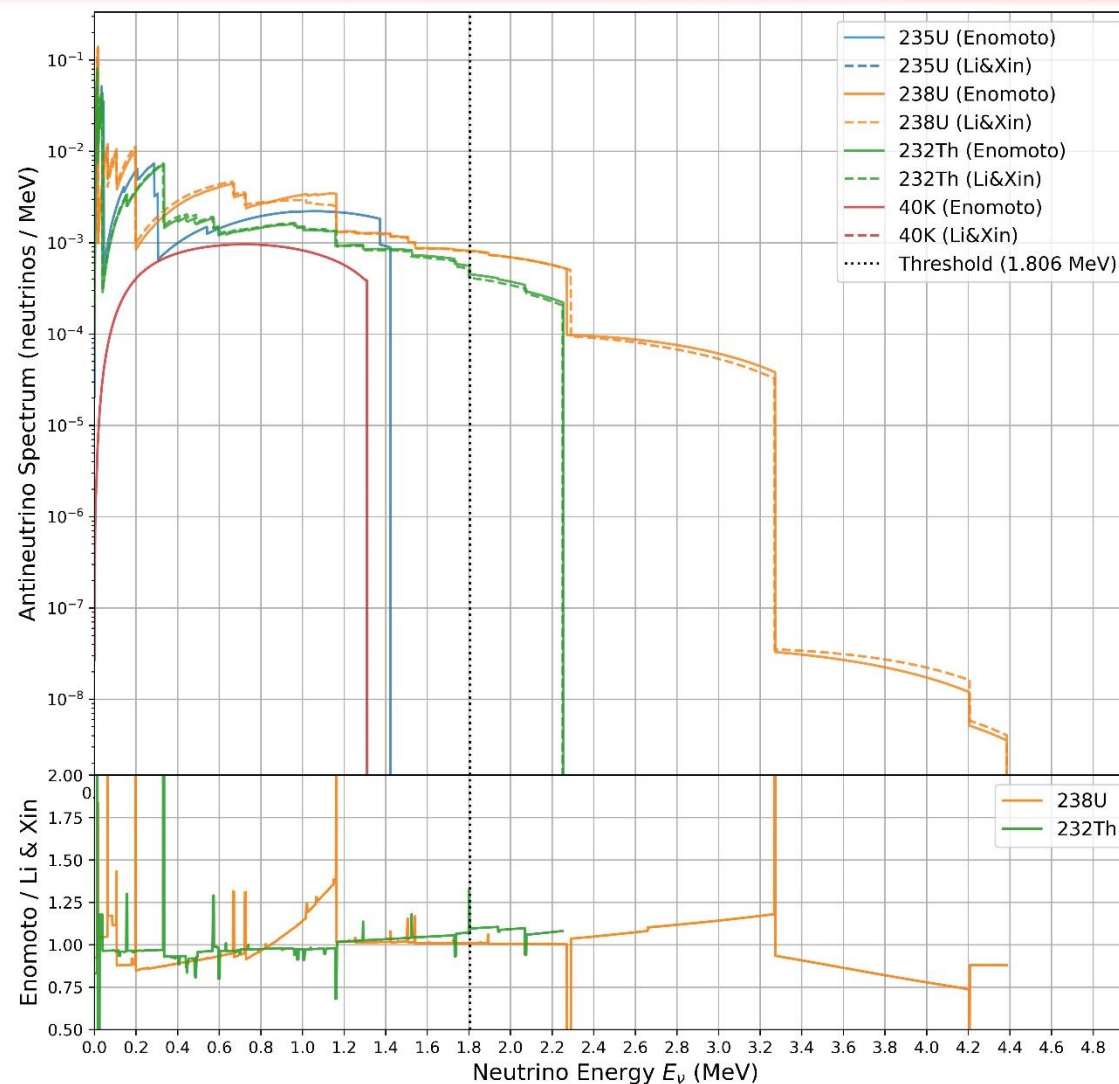
Mixing Angle	Value	Mass-Square Difference(eV ²)	Value
$\sin^2 \theta_{13}/10^{-2}$	2.203 ± 0.059	$\Delta m_{21}^2/10^{-5}$	7.41 ± 0.21
$\sin^2 \theta_{12}/10^{-1}$	3.03 ± 0.12	$\Delta m_{31}^2/10^{-3}$	2.437 ± 0.028
$\sin^2 \theta_{23}/10^{-1}$	5.72 ± 0.23	$\Delta m_{32}^2/10^{-3}$	2.437 ± 0.028



Update

GEONUS

- Elements' properties
- Neutrino oscillation
- Emitted geonu spectra
 - S. Enomoto (2005)
 - Li & Xin (2024)



Neutrino Gec



Update

GEONUS

- Elements' properties
- Neutrino oscillation
- Emitted geonu spectra
- IBD cross section

- Approximation: $\sigma(E) = 9.52 \times (E - \Delta)^2 \sqrt{1 - \frac{m_e^2}{(E - \Delta)^2}} \times 10^{-44} \text{ cm}^2$

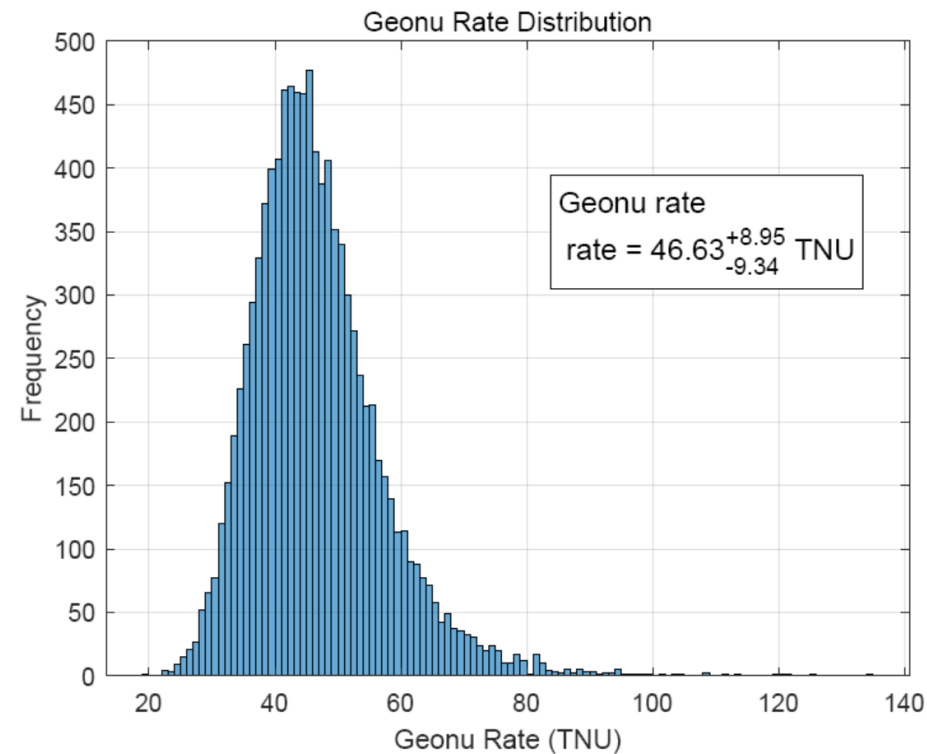
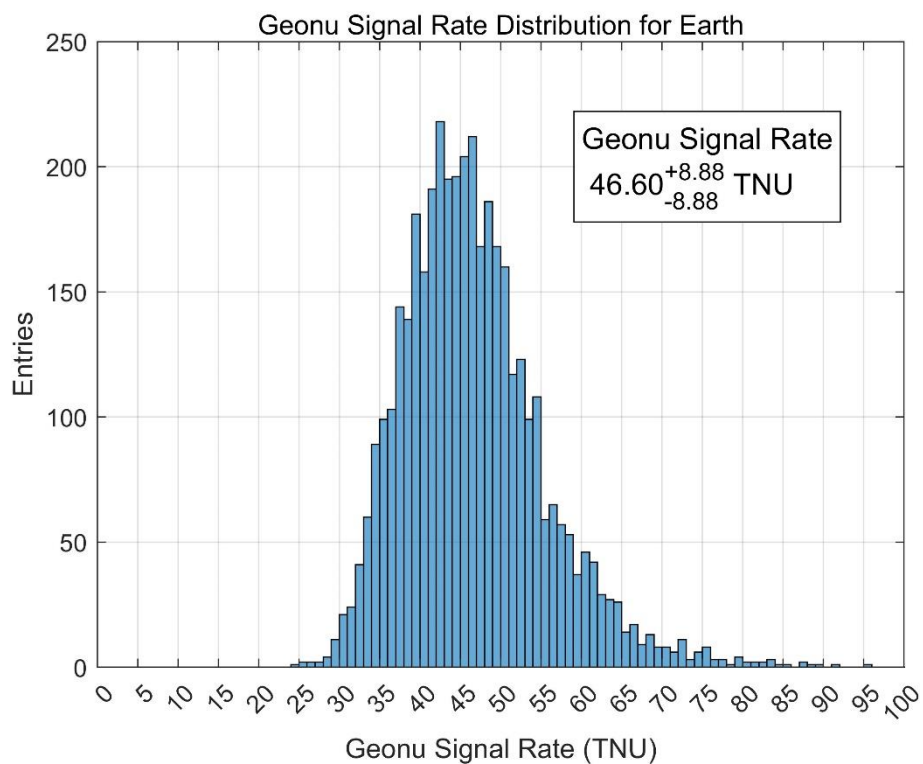
- P. Vogel & J. F. Beacom (1999)
- A. Strumia & F. Vissani (2003)
- G. Ricciardi et al. (2022)



GEONUS

Benchmark test

- Benchmark test: SNO+ (CRUST1.0+Enomoto+Approximation)

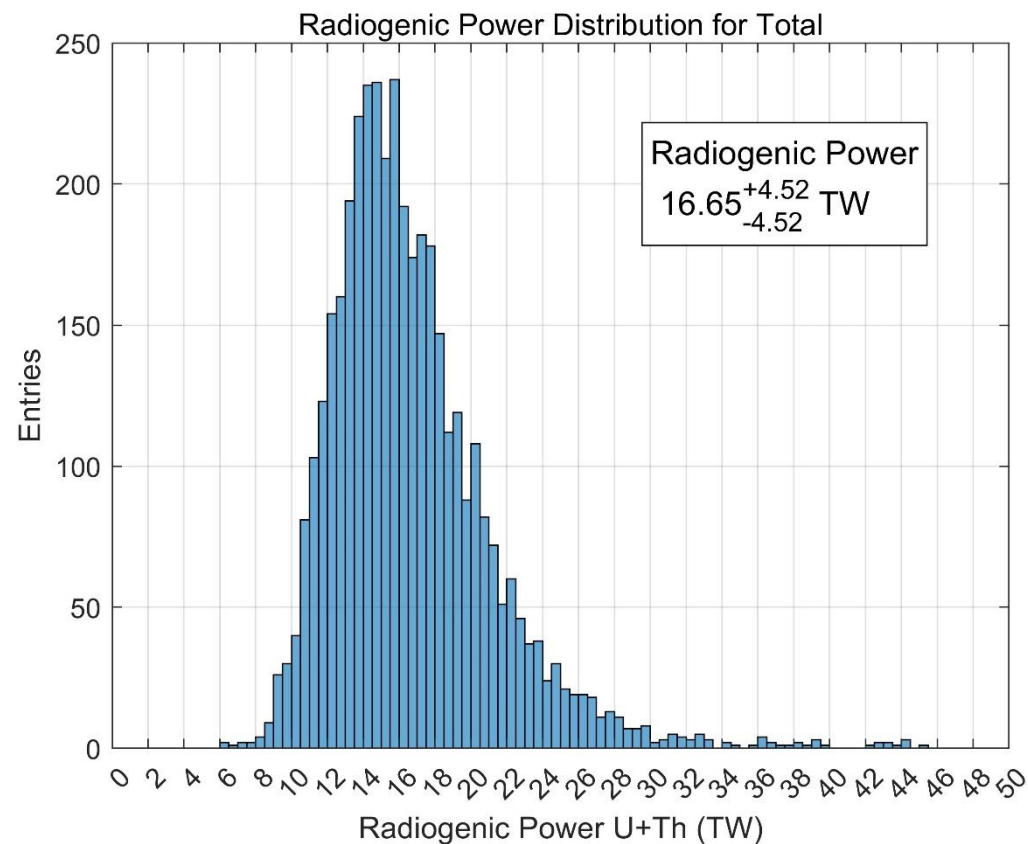




GEONUS

Total Signal Rate

Experiment	This Work (TNU)	Wipperfurth et al. (TNU)
JNE	61.36 ± 10.93	$59.9^{+12.1}_{-10.1}$
SNO+	46.60 ± 8.88	$46.2^{+9.3}_{-7.7}$
Borexino	43.35 ± 7.33	$43.9^{+7.9}_{-6.7}$
JUNO	41.20 ± 7.15	$41.2^{+7.6}_{-6.4}$
KamLAND	36.64 ± 6.10	$36.9^{+6.5}_{-5.6}$





GEONUS

- GEONUS
 - Github: [PenguinMaster2077/Geo-nu_Simulation](https://github.com/PenguinMaster2077/Geo-nu_Simulation)
 - Version: 1.5
 - Repository authors: Shuai Ouyang
 - License: MIT
 - Evolution:
 - 1.0: LITE version, a fundamental computation framework
 - 1.1: Update physical components
 - 1.2: Support Bivart and Huang method
 - 1.3: Grid scan & ADVANCE version
 - 1.4: SPECTRUM version
 - 1.5: Support CRUST1.0, LITHO1.0 and ECM1 datasets



GEONUS

- **GEONUS**
 1. **SNO+** — developed by the SNO+ collaborator and applied to SNO+ geoneutrino research



GEONUS

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 2. **Secondary generation framework** — preserves the original geological code while optimized for physics analysis



GEONUS

- **GEONUS**
 1. **SNO+** — developed by the SNO+ collaborator and applied to SNO+ geoneutrino research
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 3. **Synergy** — bridging geology and physics toward deeper collaboration



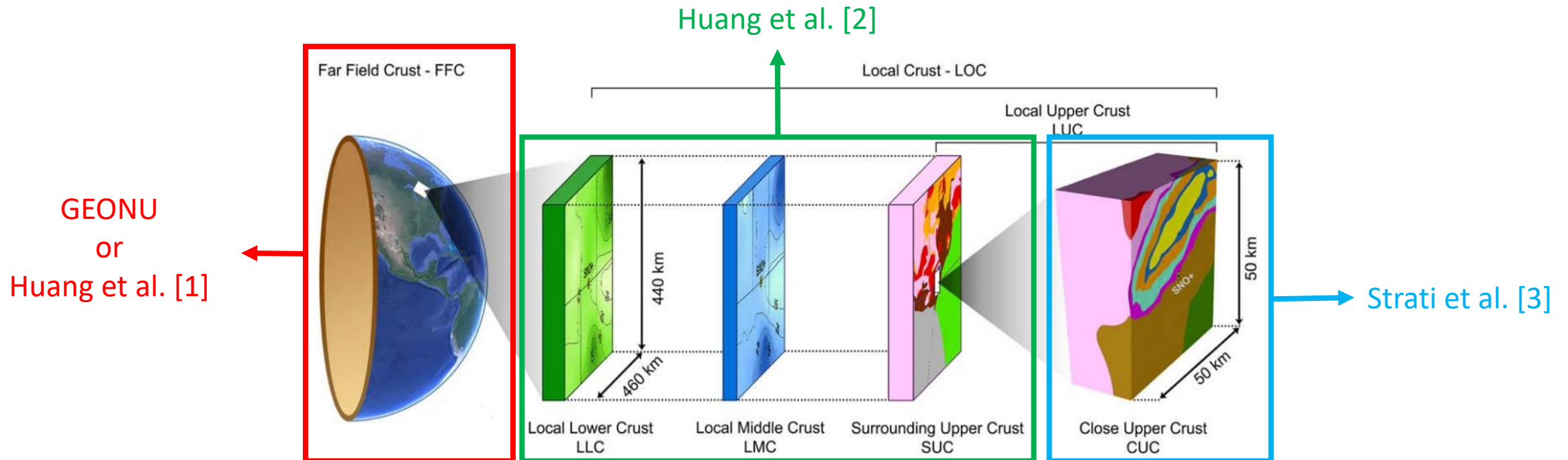
GEONUS

- **GEONUS**
 1. **SNO+** — developed by the SNO+ collaborator and applied to SNO+ geoneutrino research
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 3. **Synergy** — bridging geology and physics toward deeper collaboration
 4. **Shuai** — also the initial of my name

GEONUS

Future

- GEONUS will integrate **global** and **local** computation in short future



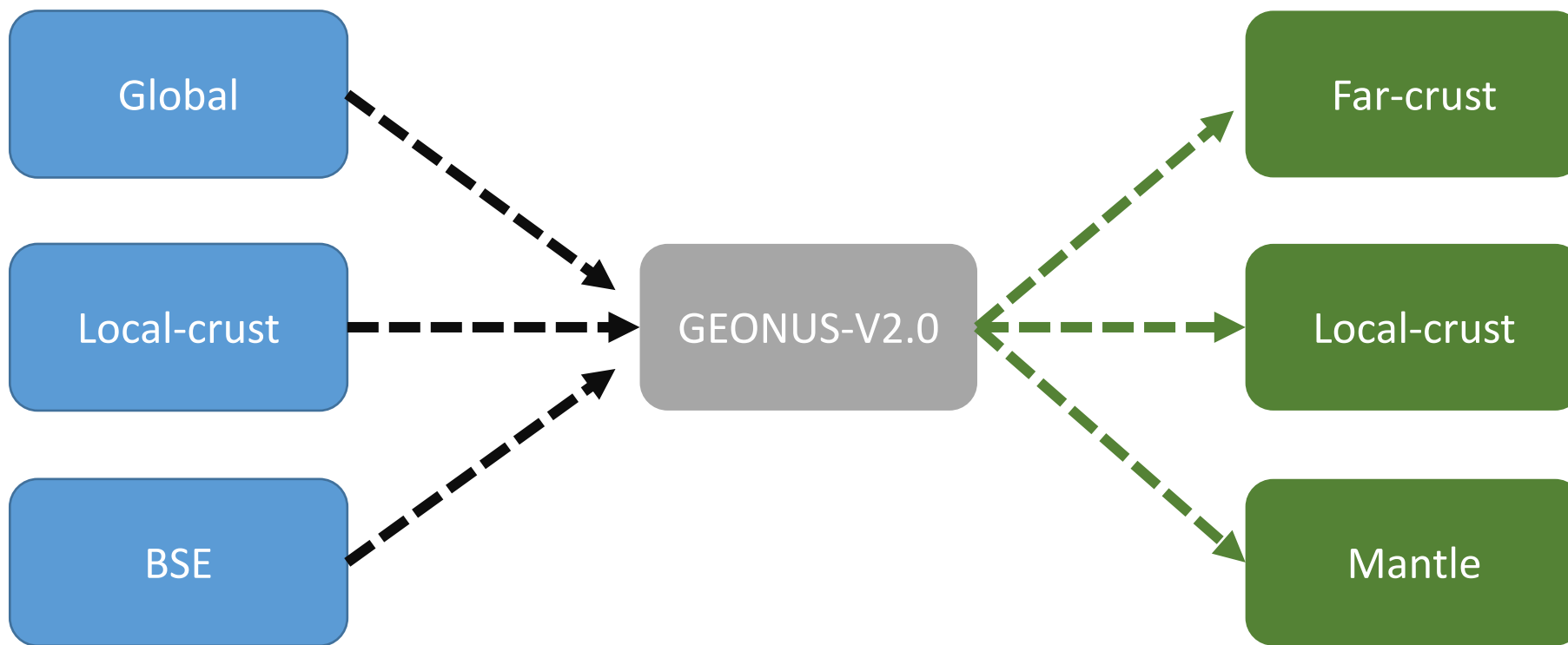
[1] A reference Earth model for the heat-producing elements and associated geoneutrino flux
 [2] Regional study of the Archean to Proterozoic crust at the Sudbury Neutrino Observatory (SNO+), Ontario: Predicting the geoneutrino flux
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Future

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Future

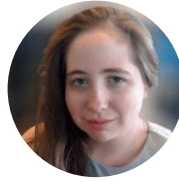
GEONUS

- GEONUS will integrate **global** and **local** computation in short future
- A minimal computation tool has been released (https://github.com/PenguinMaster2077/Geo-nu_Simulation/tree/master/Tools), which outputs signals from grid density and abundance inputs. Feedback from the JUNO team is pending.



Geonu calculator

GEONUS



Before

GEONU-V0.2

GEONUS-V1.0

Present

GEONU-V1.0

GEONUS-V1.5

Future

GEONU-V2.0

GEONUS-V2.0

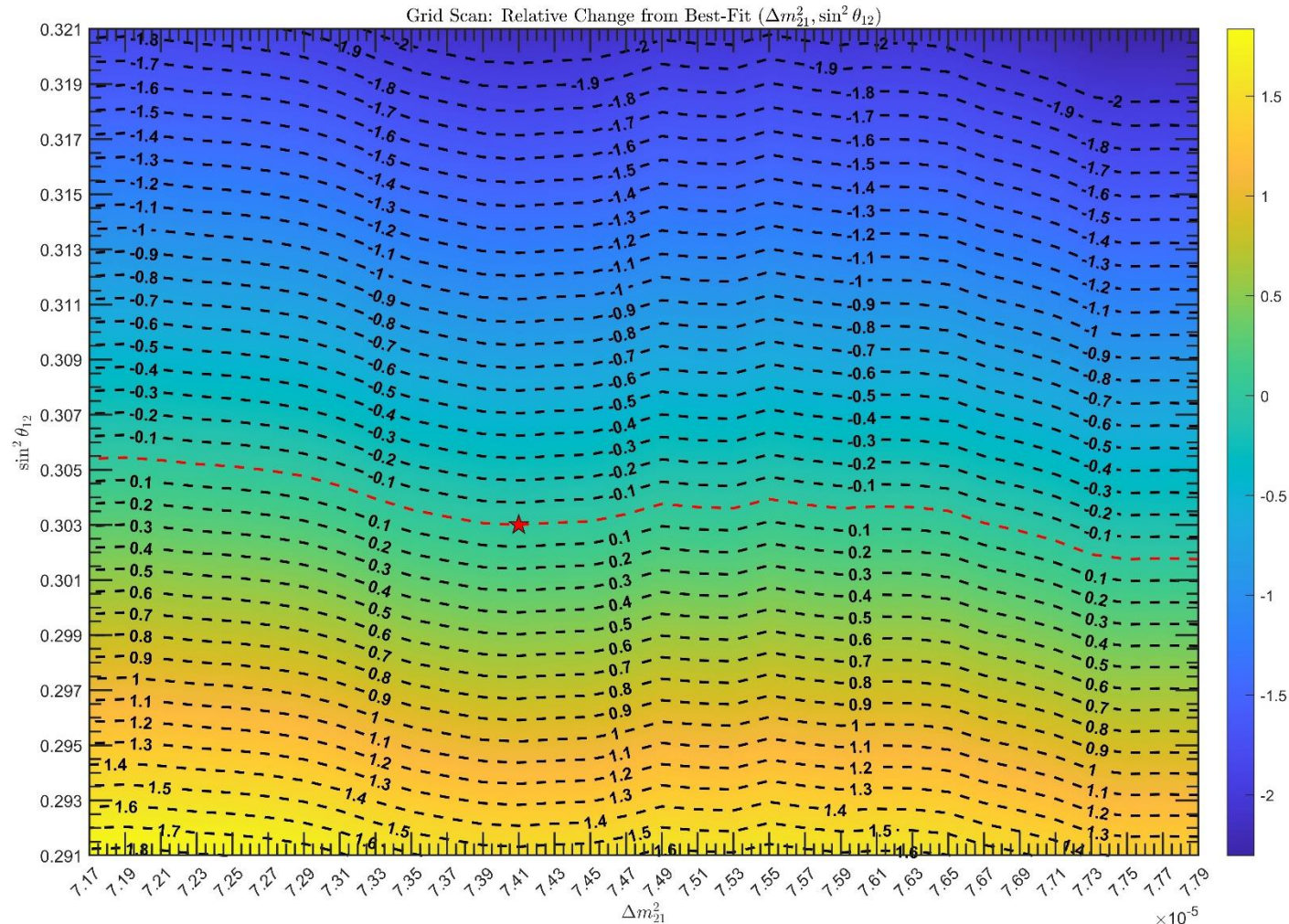
Before 2026



Neutrino Geoscience 2025



Applications



- PDG 2024:

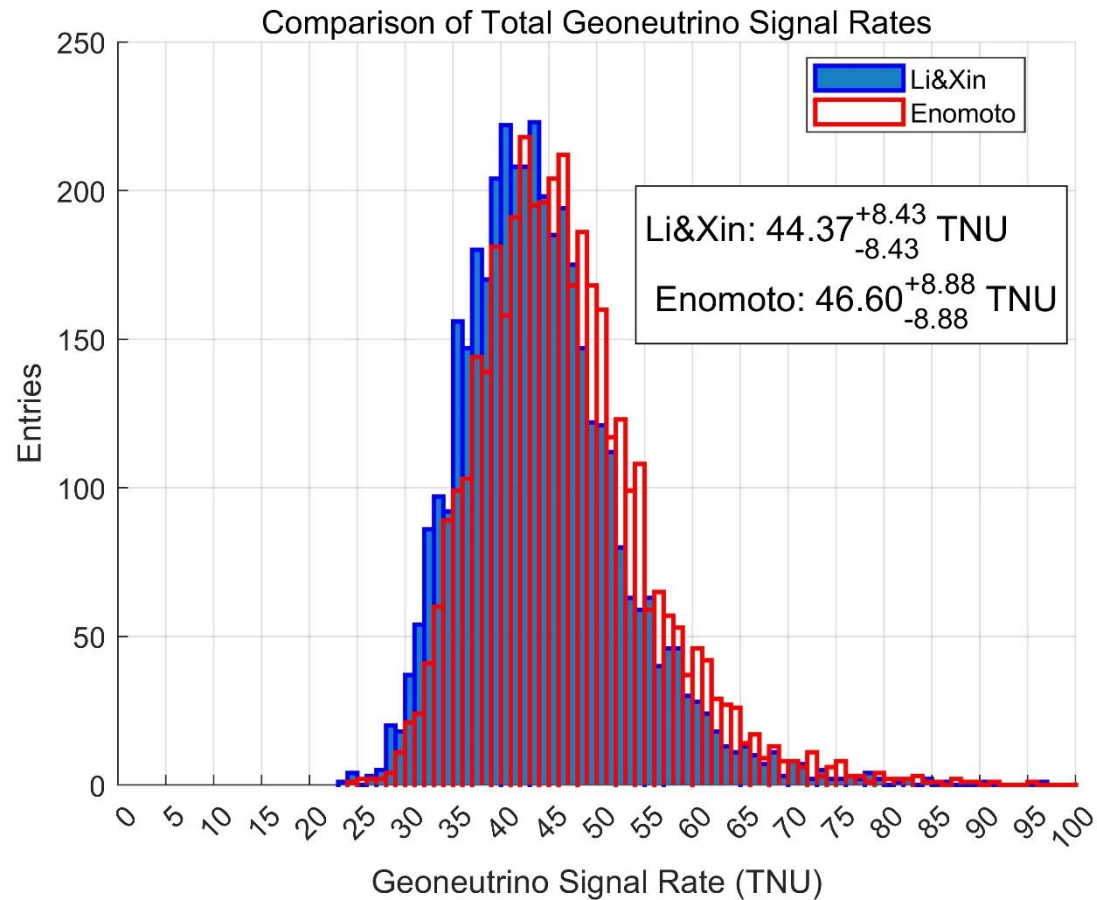
$$\frac{\Delta m_{21}^2}{10^{-5}} = 7.41 \pm 0.21$$
$$\frac{\sin^2 \theta_{12}}{10^{-1}} = 3.03 \pm 0.12$$

- Conclusion:

1. Oscillation parameters ($\Delta m_{21}^2, \sin^2 \theta_{12}$) result in changes to the geonu signal of **less than 2%** for PDG 2024 region.
2. Geonu signal is more sensitive to $\sin^2 \theta_{12}$.



Applications



Signal Rate	Enomoto	Li&Xin	Deviation
Lithosphere	38.74 ± 9.69	36.86 ± 9.19	-4.85%
Mantle	7.96 ± 2.91	7.60 ± 2.77	-4.5%
^{238}U	35.61 ± 6.34	34.29 ± 6.10	-3.71%
^{232}Th	11.00 ± 2.97	10.08 ± 2.72	-8.36%
Total	46.60 ± 8.88	44.37 ± 8.43	-4.79%

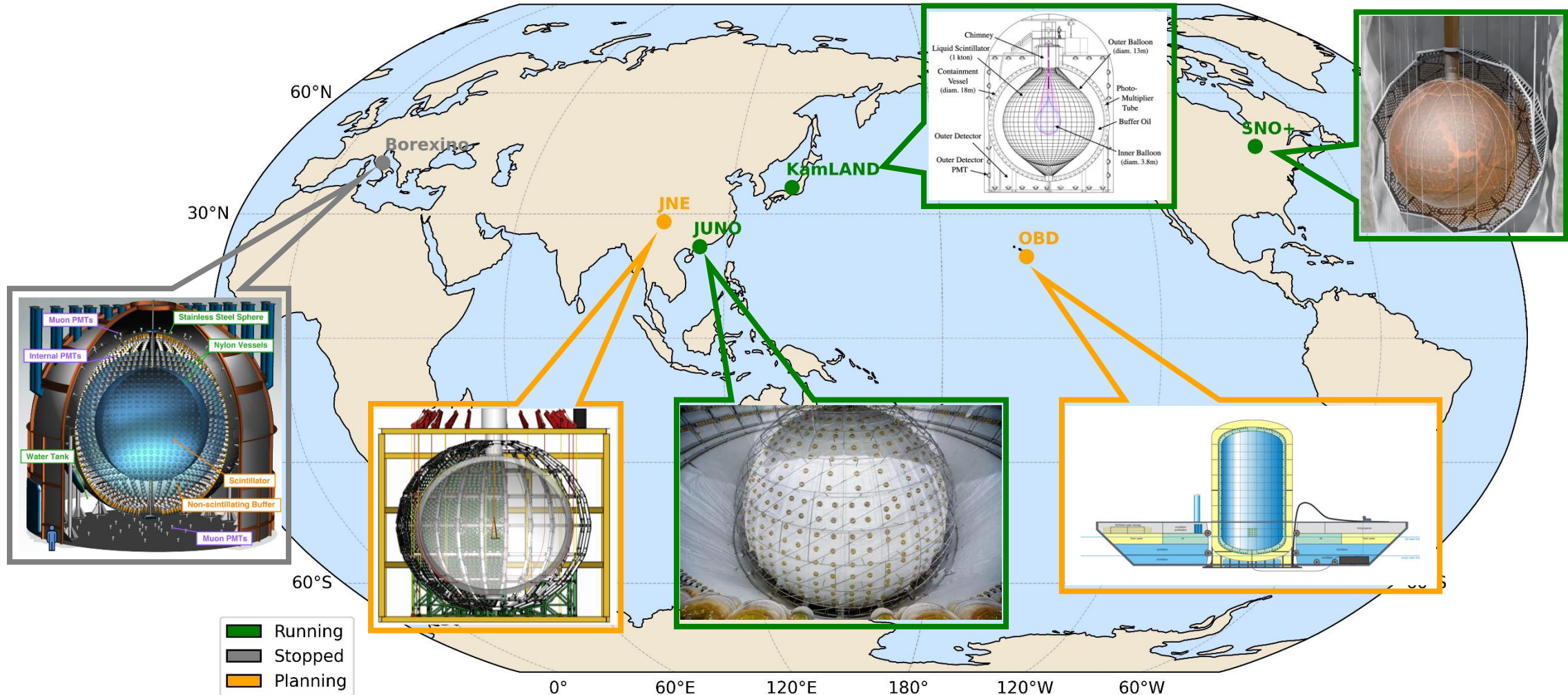


Applications

Model	IBD: Appro	IBD: 1999	IBD: 2003	IBD: 2022	Appro/2022	1999/2022	2003/2022
Enomoto: U238	35.61 ± 6.34	35.06 ± 6.24	35.52 ± 6.32	35.79 ± 6.37	0.995	0.980	0.992
Enomoto: Th232	11.0 ± 2.97	10.84 ± 2.92	11.0 ± 2.97	11.08 ± 2.99	0.993	0.978	0.993
Enomoto: Total	46.46 ± 8.69	45.75 ± 8.56	46.37 ± 8.68	46.73 ± 8.75	0.994	0.979	0.992
Li&Xin: U238	34.29 ± 6.10	33.77 ± 6.01	34.21 ± 6.09	34.48 ± 6.13	0.994	0.979	0.992
Li&Xin: Th232	10.08 ± 2.72	9.93 ± 2.68	10.08 ± 2.72	10.16 ± 2.74	0.992	0.977	0.992
Li&Xin: Total	44.23 ± 8.25	43.57 ± 8.13	44.16 ± 8.24	44.50 ± 8.30	0.994	0.979	0.992

Conclusion: There is less than 1% effect from IBD cross section.

Future





Summary

- The GEONU tool has been completely rewritten to be modular, efficient, and updated with the latest physics inputs.
- Global computations have been benchmarked and are consistent with previous predictions within 1σ .
- The impacts of oscillation parameters, geoneutrino spectra, and IBD cross sections have been evaluated.
- GEONUS will integrate global and local computation to provide more precise predictions.