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# Geoneutrino Flux Prediction and Reactor Background at the JNE

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# Outline

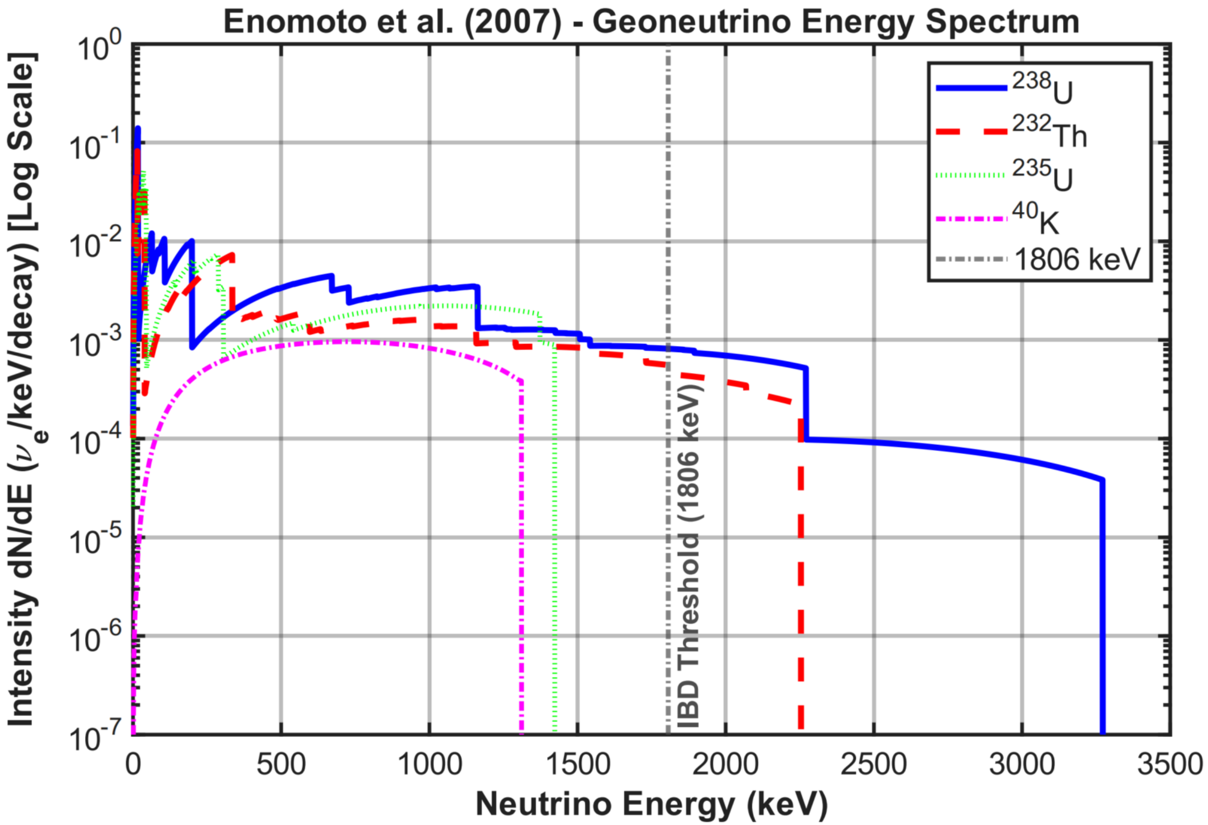
# 1. Introduction

**Earth surface heat flow:** 46 ± 3 TW

Driven by radiogenic heat from HPEs (U, Th, K) + primordial energy.

**Three competing BSE models:**

| Model | Basis | Radiogenic Heat |
|---|---|---|
| Low-Q | Cosmochemical (E-chondrites) | 11 ± 2 TW |
| Medium-Q | Geochemical (mantle xenoliths) | 20 ± 4 TW |
| High-Q | Geodynamical (surface heat flow) | 33 ± 3 TW |




$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV},$$
$$^{235}\mathrm{U} \rightarrow ^{207}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \mathrm{MeV},$$
$$^{232}\mathrm{Th} \rightarrow ^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV},$$
$$^{40}\mathrm{K} \rightarrow ^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.31\ \mathrm{MeV} \quad (89.3\%),$$
$$^{40}\mathrm{K} + e^- \rightarrow ^{40}\mathrm{Ar} + \nu_e + 1.51\ \mathrm{MeV} \quad (10.7\%).$$

# 2. Flux Formula

## IBD Detection Reaction

$\bar{\nu}_e + p \rightarrow e^+ + n$ (threshold: 1.806 MeV)

$n + H \rightarrow d + \gamma$

## IBD Event Rate (in TNU)

$R_i = \int \phi(E) \times \sigma\_IBD \, dE \times 3.1536\times10^{39}$

Normalization: 1 year ≈ $3.1536\times10^7$ seconds

$\phi$: geoneutrino flux [$cm^{-2}\cdot s^{-1}\cdot MeV^{-1}$]

$\sigma$: IBD cross section [$cm^2$]

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

## Differential Geoneutrino Spectrum

$$\phi_i(E) = \frac{X_i \lambda_i N_A}{\mu_i} n_\nu(i) \int \frac{A_i(\vec{r})\,\rho(\vec{r})}{4\pi L^2} P_{ee}(E,L)\, f_i(E)\, d\vec{r};$$

$\lambda_i$ : decay constant $N_a$ : Avogadro constant

$\mu_i$ : atomic mass $n_\nu(i)$ : $\bar{\nu}_e$ per decay chain

$A_i(r)$ : HPE abundance $\rho(r)$ : density

$L$ : distance $P_{ee}$ : survival probability

$f_i(E)$ : normalized $\bar{\nu}_e$ spectrum per decay

## Neutrino Oscillation Survival Probability

$P_{ee}(E,L) = 1 - \cos^4\theta_{13} \cdot \sin^2 2\theta_{12} \cdot \sin^2(\Delta m^2_{21} L/4E) - \sin^2 2\theta_{13} \cdot \sin^2(\Delta m^2_{31} L/4E)$

# 3 Geophysical Model

## 3.1 Mantle Model

| Scenario | Description |
|---|---|
| ① Uniform | Homogeneous composition throughout the mantle |
| ② Layered Uniform | **Depleted upper mantle + enriched lower mantle ✓** |
| ③ Single Enriched Blob | LSVPs treated as one enriched layer |
| ④ Symmetric Blobs | Two enriched blobs beneath Pacific & Africa |

→ Mantle contribution robust:
only ~10% variation across all models (Šrámek et al., 2013)

```
LAB (Lithosphere-Asthenosphere Boundary)
Depth range: 120-250 km (crustal model constrained)

Depleted Mantle (DM) — 8 layers in total
├─ Layer 1: 50 km thickness
├─ Layer 2: 100 km thickness
├─ Layer 3: 150 km thickness
├─ Layer 4: 250 km thickness
├─ Layer 5: 400 km thickness
├─ Layer 6: 400 km thickness
├─ Layer 7: 400 km thickness
└─ Layer 8: Remaining thickness

Enriched Mantle (EM) — only in layered model
└─ Layer 9: 750 km thickness

CMB (Core-Mantle Boundary)
Fixed depth: 2891 km
```

# Crustal Model

| Model | Year | Resolution | Status |
|---|---|---|---|
| CRUST5.0 | ~2000 | 5°×5° | Too coarse |
| CRUST2.0 | ~2004 | 2°×2° | Too coarse |
| CRUST1.0 ✓ | 2012 | 1°×1° | Global standard |
| LITHO1.0 | 2014 | 1°×1° | Includes lithosphere |
| ECM1 ✓ | 2023 | 1°×1° | Updated synthesis |

```
Vertical column profile for cell k:
```

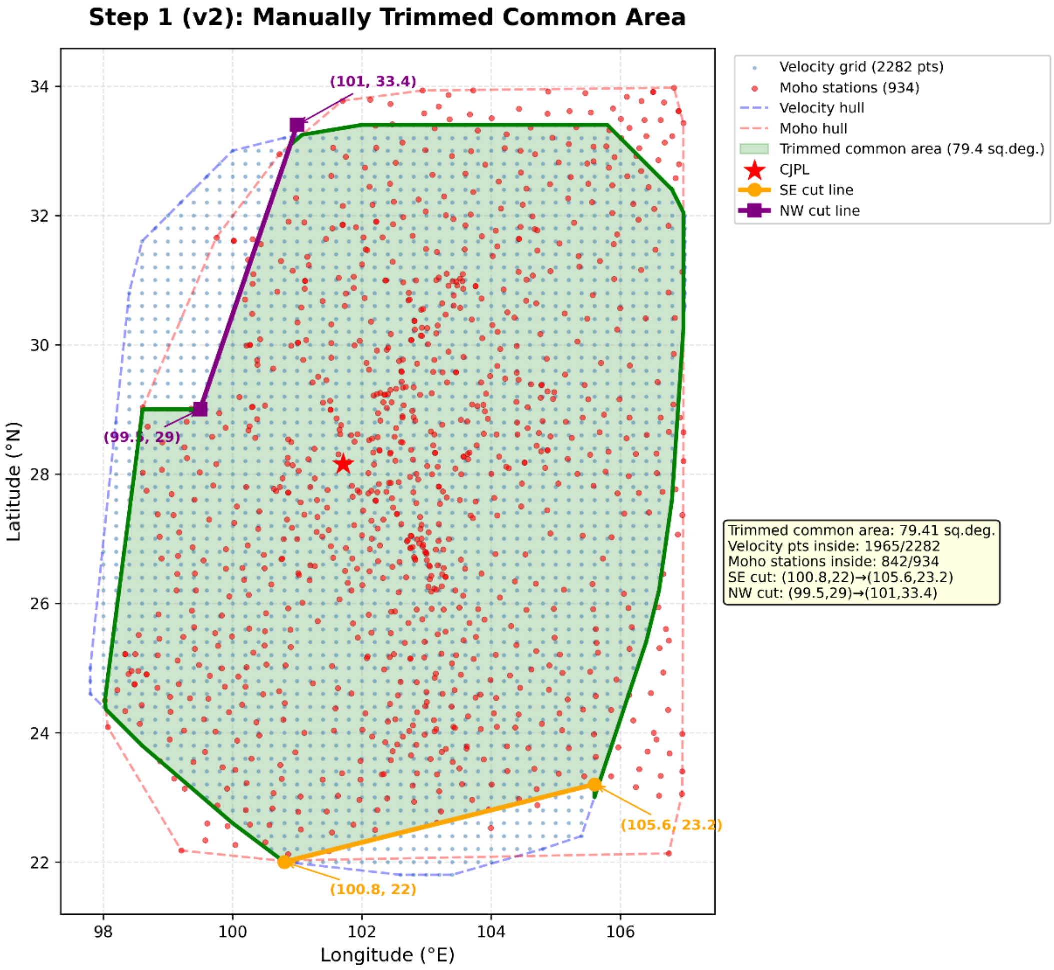
| |
|---|
| s1 (Upper sedimentary layer) — thick(k) × 1 block |
| s2 (Middle sedimentary layer) — thick(k) × 1 block |
| s3 (Lower sedimentary layer) — thick(k) × 1 block |
| UC (Upper crust) — thick(k) × 1 block |
| MC (Middle crust) — thick(k) × 1 block |
| LC (Lower crust) — thick(k) × 1 block |
| LM (Lithospheric mantle) — thick(k) × 1 block |
| Mantle (LAB → CMB) — subdivided into 9 sublayers |

## Key Findings (Wipperfurth et al., 2020)

- The total geoneutrino signal **is insensitive** to the choice among the CRUST1.0, CRUST2.0, and LITHO1.0 models.
- Improving **near-field crustal model** is more critical for signal accuracy

# 3.2 SWChinaCVM-2.0

| Feature | Detail |
|---|---|
| Release | 2022, China Seismic Experimental Site (CSES) |
| Coverage | Sichuan-Yunnan region (encompasses JNE site) |
| Resolution | 0.2° × 0.2° (upper crust) — vs 1°×1° for CRUST1.0 |
| Data Volume | ~7.06M body-wave + ~0.1M surface-wave data |
| Method | AI phase picking + ambient noise cross-correlation |




## Application: Refined Near-Field Crustal Density Model

SWChinaCVM-2.0 Vp/Vs profiles → density (Brocher 2005)

→ Merged with CRUST1.0 for a 0.2° combined near-field model

## Also: SWChinaCVM-MOHO-2.0

Integrated **3 new-generation velocity models** (SWChinaCVM-2.0, CSES-VM1.0, USTClitho2.0) → Public Moho interface model

# 3.3 CRUST1.0-SWChina-merged

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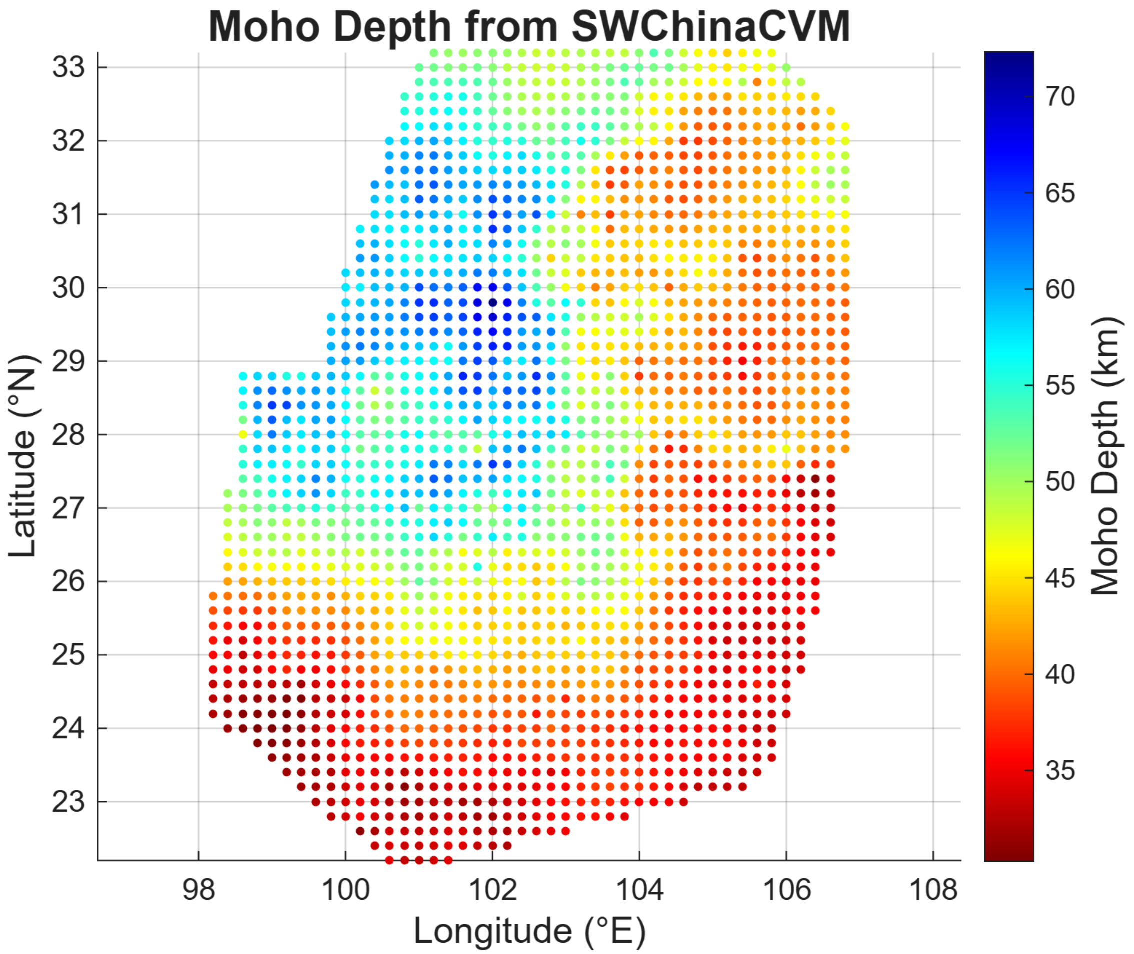
## Step 1: Moho Depth for Each 0.2° Cell

| Data Source | Role |
|---|---|
| SWChinaCVM-2.0 | Vp/Vs profiles at each (lon,lat,depth) |
| SWChinaCVM-MOHO-2.0 | Crustal thickness + Vp/Vs at station locations |

**Processing:**

1. Identify common overlapping area between both model coverages
2. Kriging interpolation on MOHO-2.0 station data
3. Derive Moho depth at same (lon,lat) grid as CVM-2.0

**→ Output: Moho depth map at 0.2° resolution (Fig. 4 in paper)**



# Step 2: Surface Elevation (ETOPO1)

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| | |
|---|---|
| CVM-2.0 issue | Reports uniform max 5 km at each grid (no real topography) |
| Topography source | The ETOPO1 Ice Surface data are sourced from NOAA. |

**Method:**

For each 0.2° cell, average 9 sub-points (3×3 grid)

Replicates the averaging scheme used in CRUST1.0

**→ Compatible with CRUST1.0 surface representation**

# Step 3: Sediment & Crustal Proportions

1. For each 0.2° grid point $(lon_i, lat_i)$, identify the parent 1° CRUST1.0 grid cell that contains it, i.e., the cell centered at

$$(\lfloor lon_i - 0.5 \rfloor + 0.5,\ \lfloor lat_i - 0.5 \rfloor + 0.5)\,.$$

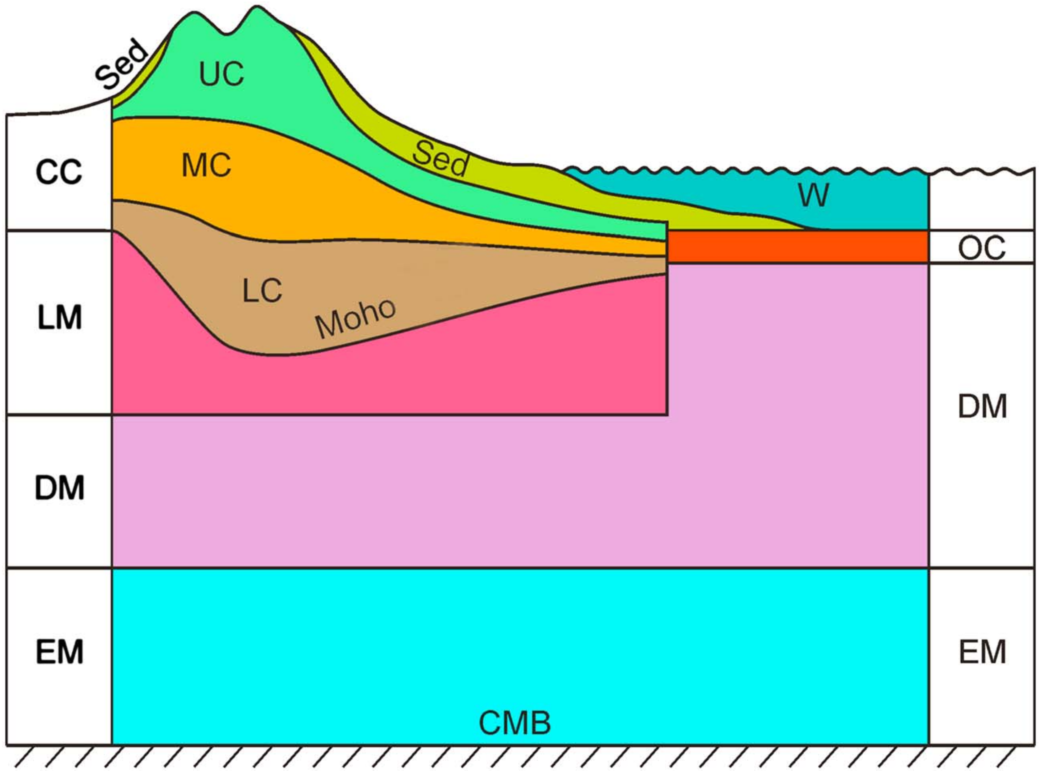
2. From CRUST1.0, extract the following quantities for that parent cell:

- Sediment layer thicknesses: `s1.thick`, `s2.thick`, `s3.thick`
- Upper crustal thickness: `UC_thick`
- Middle crustal thickness: `MC_thick`
- Lower crustal thickness: `LC_thick`
- Total crystalline crustal thickness:

$$\texttt{crystal\_thick} = \texttt{UC\_thick} + \texttt{MC\_thick} + \texttt{LC\_thick}$$

- Layer fractions:

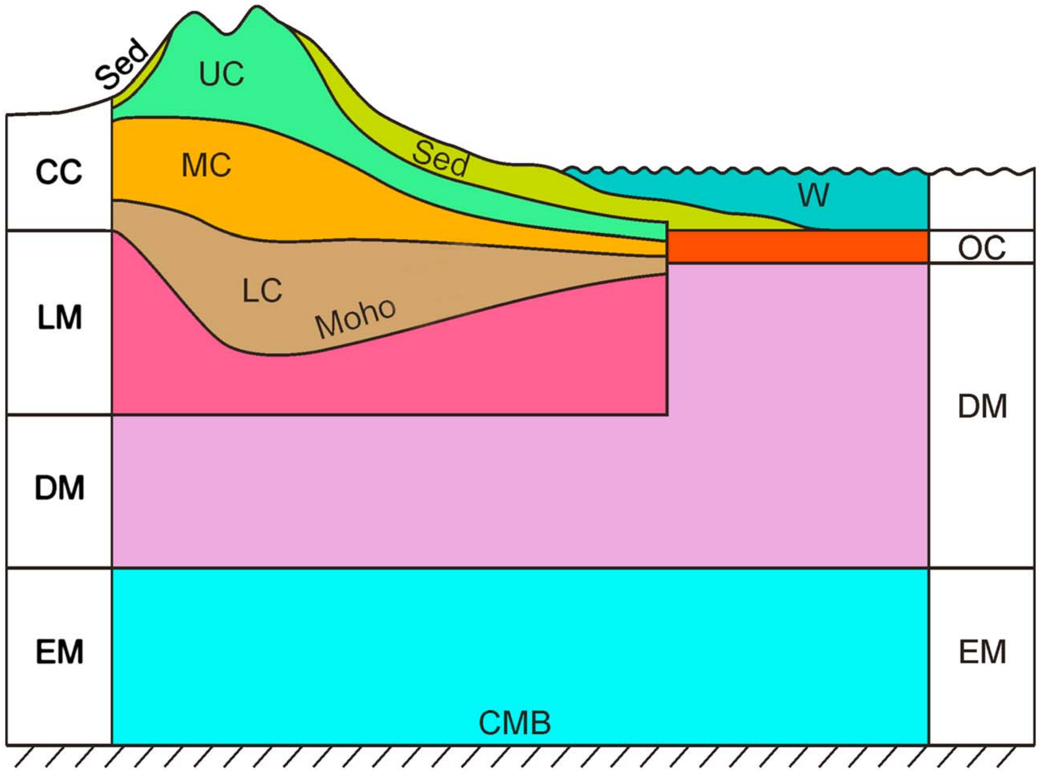
$$UC_{\text{frac}} = \frac{UC_{\text{thick}}}{crystal_{\text{thick}}}, \quad MC_{\text{frac}} = \frac{MC_{\text{thick}}}{crystal_{\text{thick}}}, \quad LC_{\text{frac}} = \frac{LC_{\text{thick}}}{crystal_{\text{thick}}}$$



# Step 4: Interface Depths

**For each 0.2° grid cell, using:**

- Moho depth from Step 1
- Surface elevation from Step 2 (ETOPO1)
- Sediment thickness from Step 3 (CRUST1.0)
- CRUST1.0 layer fractions from Step 3




**Crystalline crustal thickness:**

$$\texttt{crystal\_thick} = \texttt{moho\_depth} - \texttt{sed\_thick}$$

**Layer thicknesses:**

$$\texttt{UC\_thick} = \texttt{crystal\_thick} \times UC_{\text{frac}}$$

$$\texttt{MC\_thick} = \texttt{crystal\_thick} \times MC_{\text{frac}}$$

$$\texttt{LC\_thick} = \texttt{crystal\_thick} \times LC_{\text{frac}}$$

# Step 5: Representative Vp & Vs per Layer

**For each 0.2° grid cell:**

1. Retrieve CVM-2.0 depth profile (16 levels: −5 to 70 km)
2. Thickness-weighted average Vp/Vs within each layer
3. For empty layers (too thin): linear interpolation at midpoint

**Velocity profile at the JNE site**

| Layer | Thick (km) | Vp (km/s) | Vs (km/s) | Vp/Vs |
|---|---|---|---|---|
| s3 | 0.01 | 5.41 | 3.05 | 1.78 |
| UC | 26.6 | 5.99 | 3.51 | 1.71 |
| MC | 23.6 | 6.24 | 3.54 | 1.76 |
| LC | 10.3 | 7.01 | 3.89 | 1.80 |

**Velocity gradient: ~6.0 km/s (UC) → ~7.0 km/s (LC)**

consistent with felsic→mafic crustal stratification

# Step 6: Density Computation

**Brocher (2005) empirical polynomial:**

$$\rho = 1.6612Vp - 0.4721Vp^2 + 0.0671Vp^3 - 0.0043Vp^4 + 0.000106Vp^5$$

# Step 7: Merging SWChinaCVM-2.0 with CRUST1.0

## Part 1: Generate 2,325 Sub-Cells

**For each of the 93 parent 1° CRUST1.0 cells:**

Generate 25 sub-cells at 0.2° resolution (5×5 grid)

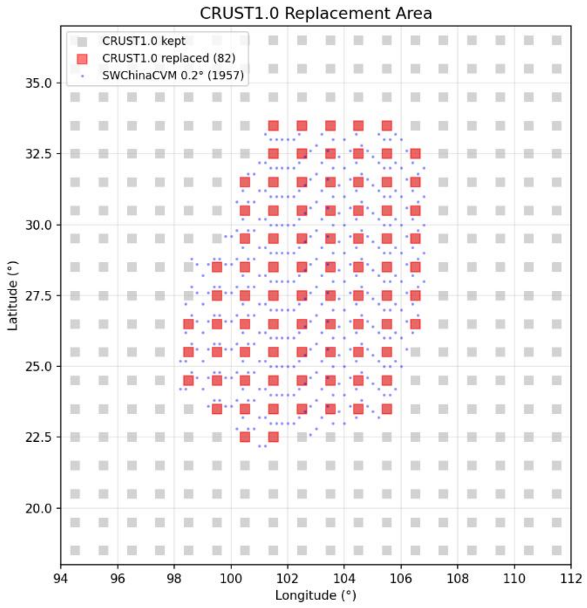
**Total: 93 × 25 = 2,325 sub-cells**

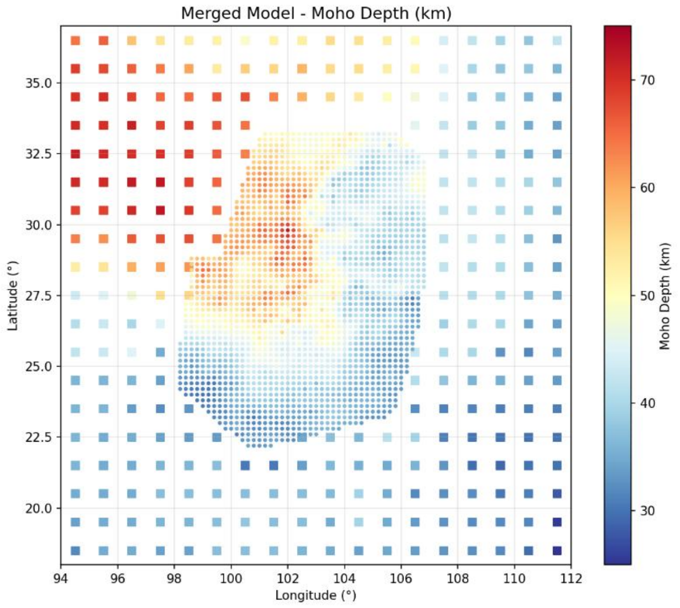
## Part 2: Classify Sub-Cells

| Group | Count | Assignment |
|---|---|---|
| A | 1,957 | Near-field model grid exists → use nearfieldmodel0.2deg.mat |
| B | 368 | Not covered → inherit CRUST1.0 parameters, update coordinates |

## Part 3: Final Model Assembly

| Component | Count |
|---|---|
| Original CRUST1.0 cells | 64,707 |
| Group A (near-field, 0.2°) | 1,957 |
| **Group B (CRUST1.0 sub-cells, 0.2°)** | **368** |




## Final Cell Count

**67,032**

total cells in the merged model

# 4. Geochemical Model

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## HPE Abundance per Layer

| Layer | Source / Method |
|---|---|
| Upper Crust | Rudnick & Gao (2014) meta-analysis |
| Middle Crust | Amphibole Vp–composition linear fit |
| Lower Crust | Granulite Vp–composition linear fit |
| Sediments | GLOSSII model (Plank, 2014) |
| Oceanic Crust | Global average (White & Klein, 2014) |
| Lithospheric Mantle | Xenolith data (Huang et al., 2013) |
| Mantle (DM+EM) | Depleted mantle + enriched mantle (19% by mass) |

## Key Coupling with Geophysical Model

Middle & lower crust HPE abundances depend on **Vp**

**SWChinaCVM-2.0 Vp profiles** directly control HPE prediction in these layers

## Vp–Composition Linear Relationship

**Mass balance between felsic and mafic endmembers:**

$$V_{\text{model}} = V_f f + V_m m \tag{6}$$

$$1 = f + m \tag{7}$$

$$a_{\text{output}} = a_f f + a_m m \tag{8}$$

where $V_f$, $V_m$, $a_f$, and $a_m$ are the $V_P$ and abundance of the felsic and mafic endmembers of amphibolite (middle crust) and granulite (lower crust), $V_{\text{model}}$ is the $V_P$ provided by the geophysical model, and $f$ and $m$ are the mass proportions of felsic and mafic endmembers.

## BSE Composition Calculation

| Element | Method |
|---|---|
| U abundance | McDonough & Sun (1995) |
| Th abundance | Derived from Th/U ratio |
| K abundance | Derived from K/U ratio |

Table 5: Geoneutrino flux from the near-field + CRUST1.0 combined model.

| Layer | U (TNU) | Th (TNU) | Total Flux (TNU) |
|---|---|---|---|
| Sediment 1 | 0.0596 | 0.0189 | 0.0785 |
| Sediment 2 | 0.2835 | 0.0910 | 0.3745 |
| Sediment 3 | 0.1718 | 0.0546 | 0.2264 |
| Upper Crust | 27.9760 | 7.2584 | 35.2344 |
| Middle Crust | 6.8154 | 2.7482 | 9.5636 |
| Lower Crust | 0.6839 | 0.3307 | 1.0146 |
| Total CC | 35.9902 | 10.5019 | 46.4921 |
| Oceanic Sediment | 0.0106 | 0.0033 | 0.0139 |
| Oceanic Crust | 0.0041 | 0.0008 | 0.0050 |
| Lithospheric Mantle | 1.1349 | 0.3484 | 1.4833 |
| Total Lithosphere | 37.2796 | 10.8939 | 48.1735 |
| Depleted Mantle | 3.8246 | 0.8908 | 4.7153 |
| Enriched Mantle | 2.7104 | 0.5891 | 3.2995 |
| Total BSE | 43.8146 | 12.3738 | 56.1883 |

Table 6: Geoneutrino flux from the ECM1 model.

| Layer | U (TNU) | Th (TNU) | Total Flux (TNU) |
|---|---|---|---|
| Sediment 1 | 0.3148 | 0.0998 | 0.4147 |
| Sediment 2 | 0.2946 | 0.0934 | 0.3881 |
| Sediment 3 | 0.0664 | 0.0209 | 0.0874 |
| Upper Crust | 26.1793 | 6.7602 | 32.9395 |
| Middle Crust | 6.3014 | 2.3303 | 8.6317 |
| Lower Crust | 1.4877 | 0.8085 | 2.2963 |
| Total CC | 34.6444 | 10.1132 | 44.7576 |
| Oceanic Sediment | 0.0458 | 0.0145 | 0.0603 |
| Oceanic Crust | 0.0103 | 0.0021 | 0.0124 |
| Lithospheric Mantle | 0.7776 | 0.2376 | 1.0152 |
| Total Lithosphere | 35.5246 | 10.3791 | 45.9037 |
| Depleted Mantle | 3.3726 | 0.7852 | 4.1578 |
| Enriched Mantle | 2.8275 | 0.6229 | 3.4504 |
| Total BSE | 41.7247 | 11.7872 | 53.5119 |

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Table 7: Geoneutrino flux from the CRUST1.0 model.

| Layer | U (TNU) | Th (TNU) | Total Flux (TNU) |
|---|---|---|---|
| Sediment 1 | 0.0883 | 0.0280 | 0.1164 |
| Sediment 2 | 0.3499 | 0.1109 | 0.4608 |
| Sediment 3 | 0.1706 | 0.0541 | 0.2247 |
| Upper Crust | 29.3805 | 7.6106 | 36.9911 |
| Middle Crust | 7.4499 | 3.0062 | 10.4561 |
| Lower Crust | 0.7605 | 0.3698 | 1.1304 |
| Total CC | 38.1998 | 11.1796 | 49.3794 |
| Oceanic Sediment | 0.0106 | 0.0033 | 0.0139 |
| Oceanic Crust | 0.0041 | 0.0008 | 0.0050 |
| Lithospheric Mantle | 1.4612 | 0.4472 | 1.9084 |
| Total Lithosphere | 39.8155 | 11.6704 | 51.4859 |
| Depleted Mantle | 4.0275 | 0.9378 | 4.9653 |
| Enriched Mantle | 2.7091 | 0.5888 | 3.2979 |
| Total BSE | 46.5521 | 13.1970 | 59.7491 |

```
bse.aU = randist(mantle_U_total,mantle_U_total*0.2,iter,cor.bse)*10^-9
```

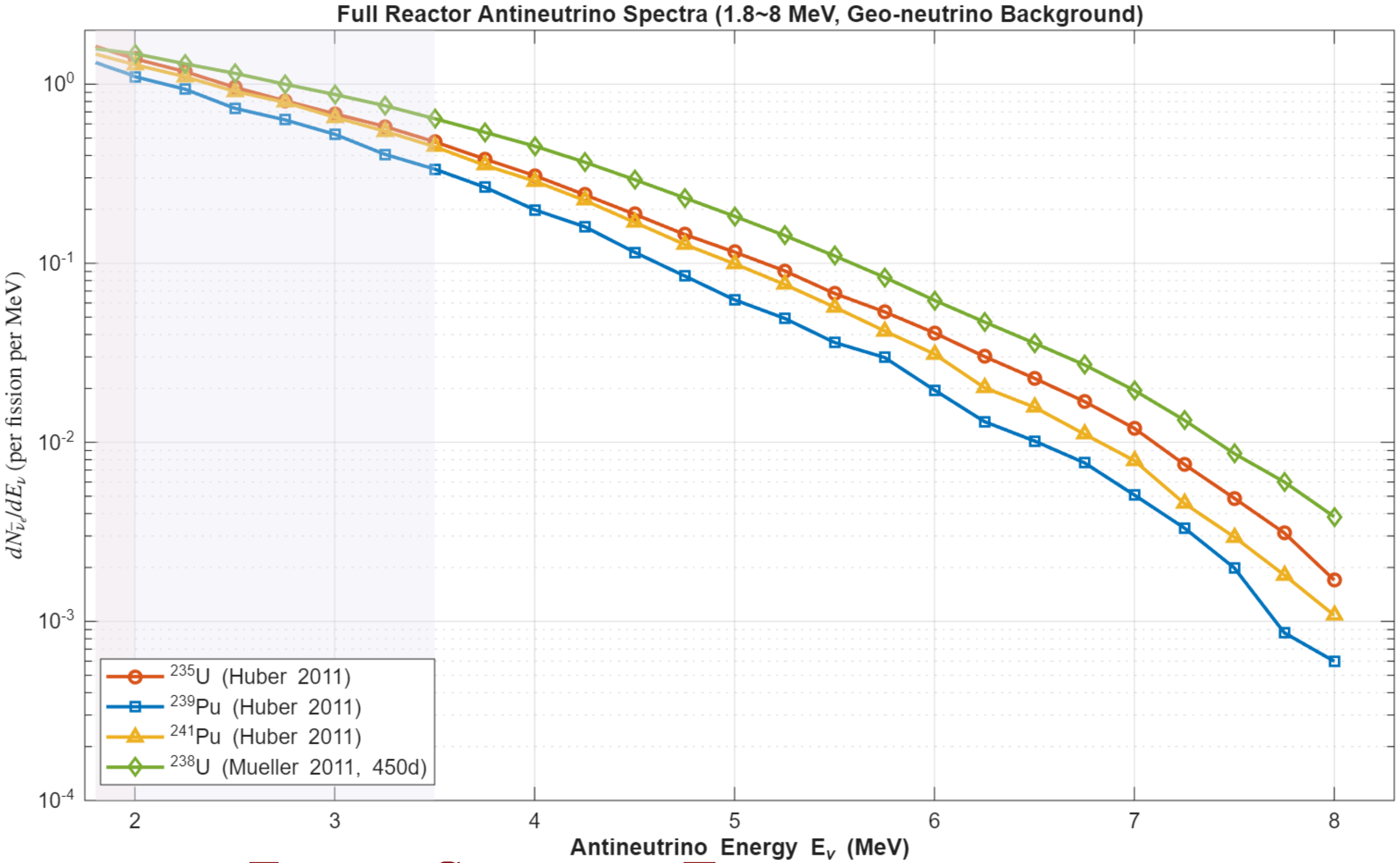
# 5. Reactor Background

**Differential flux from a reactor:**

$$\phi(E_{\bar{\nu}_e}) = \frac{W_{\rm th} \cdot LF}{\sum_i f_i e_i} \sum_i f_i S_i(E_{\bar{\nu}_e})$$

| Symbol | Meaning |
| --- | --- |
| $W_{th}$ | Thermal power of reactor |
| LF | Load factor (= 1.0 in this study) |
| $f_i$ | Fission fraction of isotope i ($\Sigma f_i = 1$) |
| $e_i$ | Energy released per fission [MeV/fission] |

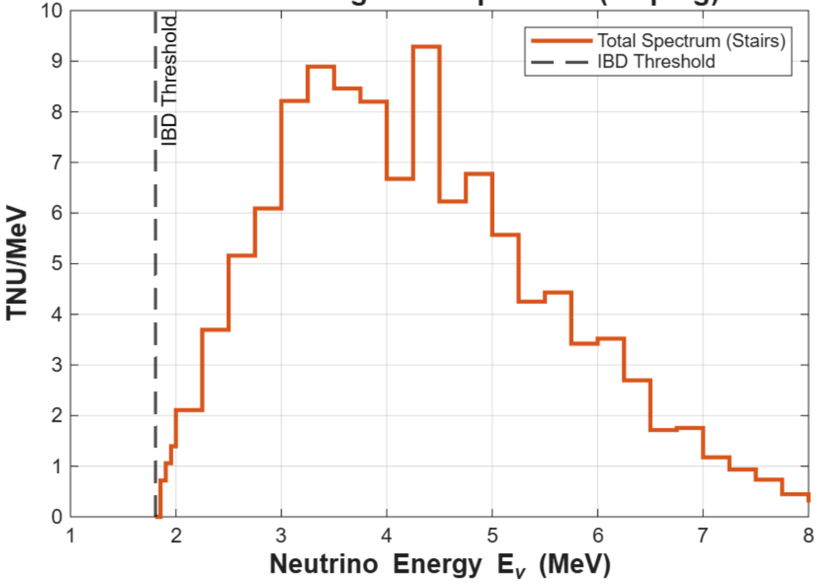
| Isotope | $f_i$ | $e_i$ [MeV/fission] |
| --- | --- | --- |
| $^{235}$U | 0.58 | $202.36 \pm 0.26$ |
| $^{238}$U | 0.07 | $205.99 \pm 0.52$ |
| $^{239}$Pu | 0.30 | $211.12 \pm 0.34$ |
| $^{241}$Pu | 0.05 | $214.26 \pm 0.33$ |



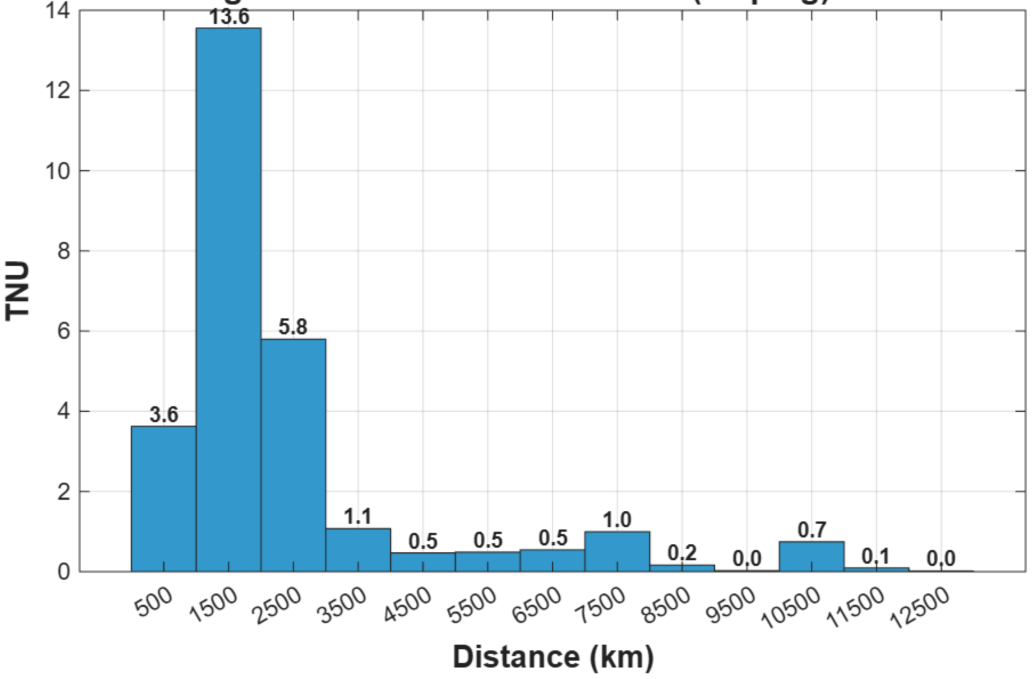

## Energy Spectrum Treatment

- Tabulated data start at 2.0 MeV (Huber 2011; Mueller 2011)
- Gap filled via official exponential polynomial parameterization
  → 0.05 MeV intervals from 1.806 to 2.0 MeV
- Above 2.0 MeV: original binned data (0.25 MeV resolution)

## Reactor Antineutrino Background Spectrum (Jinping) — Staircase




## Reactor Background Distance Distribution (Jinping) — 1000 km Bins

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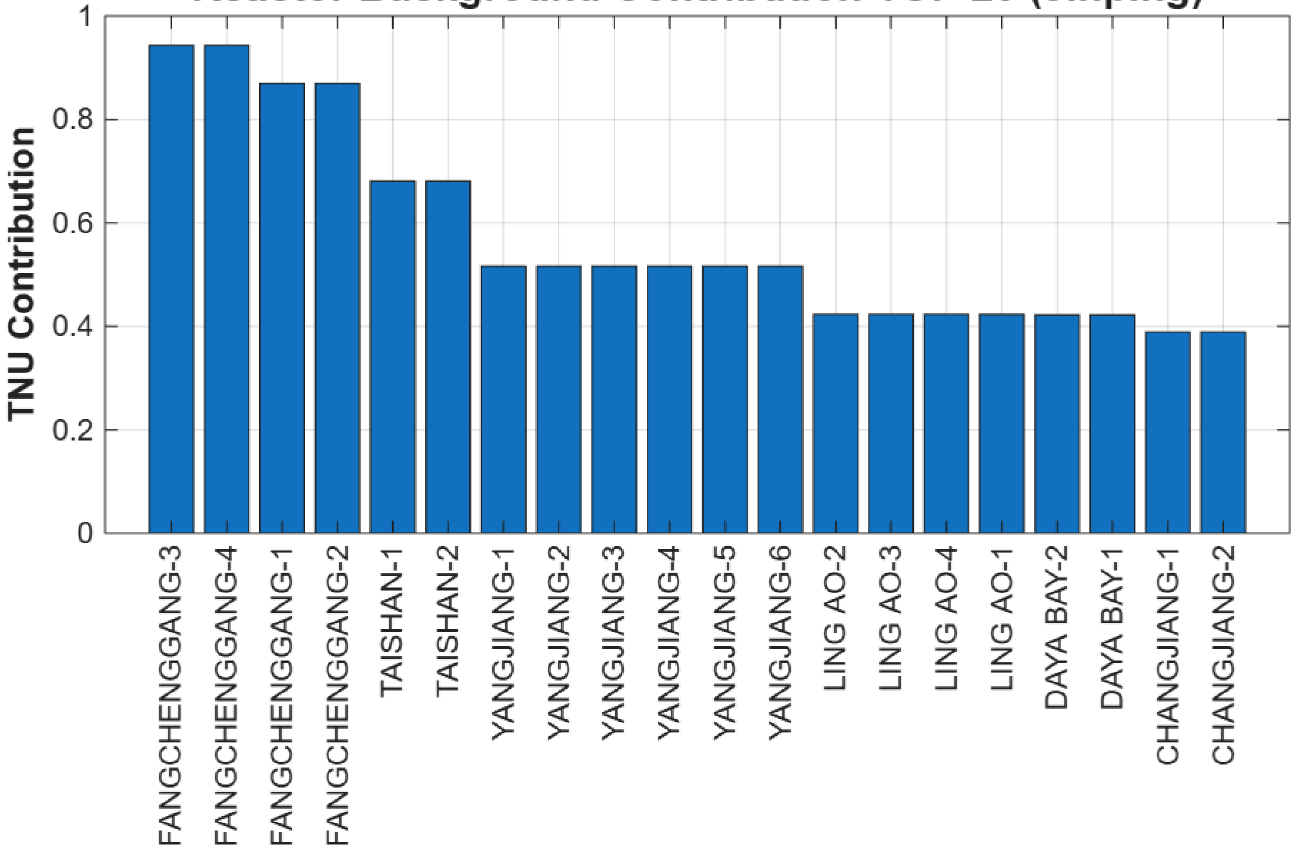
## Reactor Background Contribution TOP 20 (Jinping)



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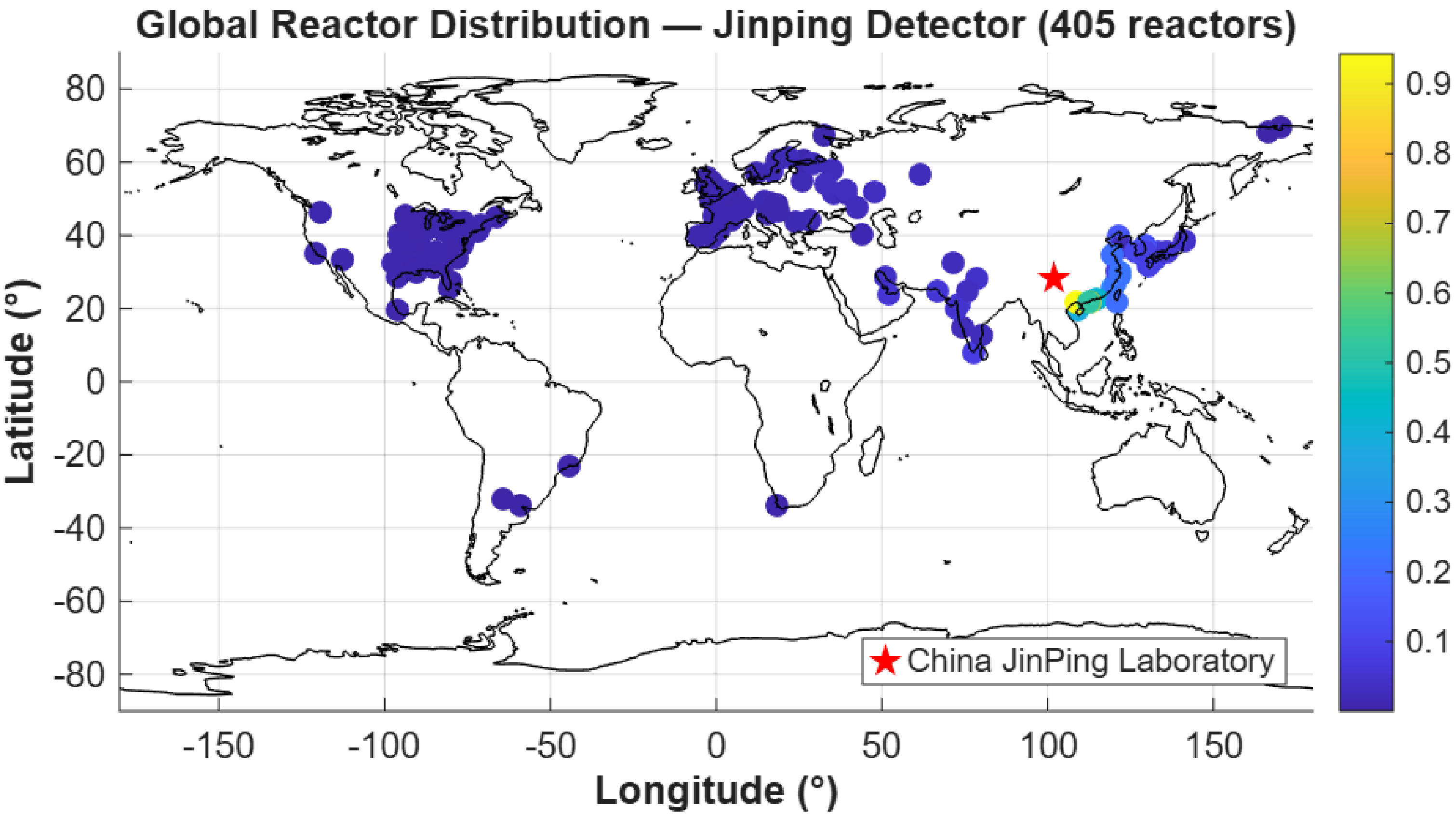
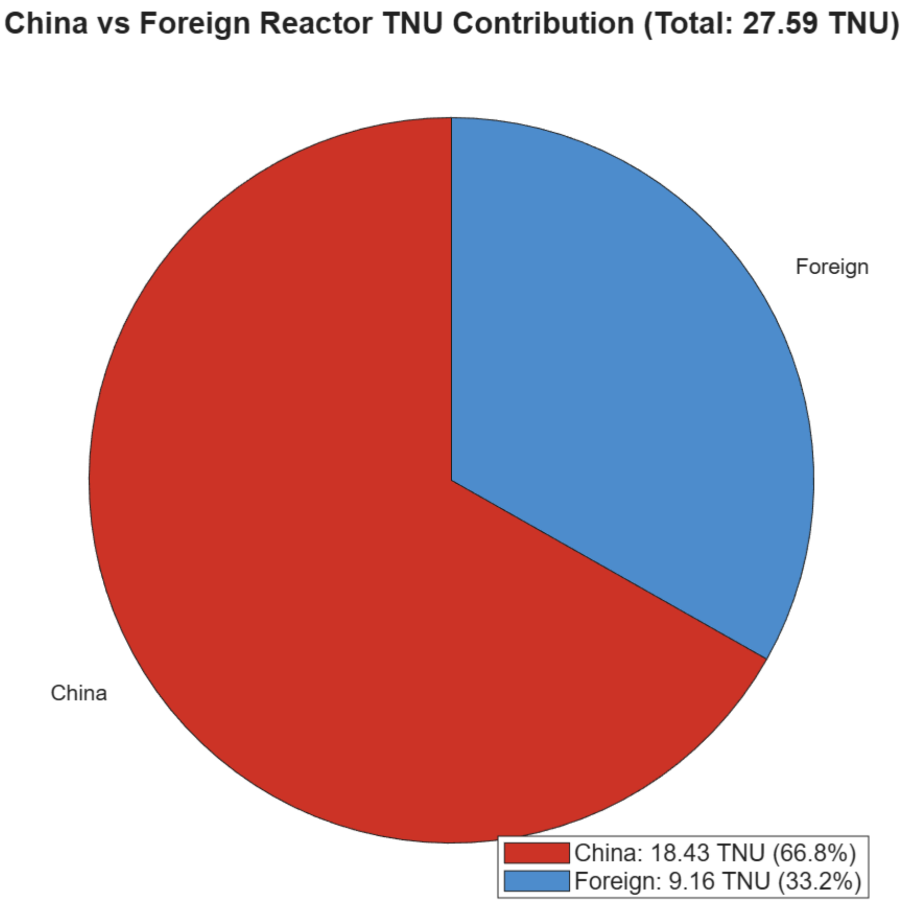
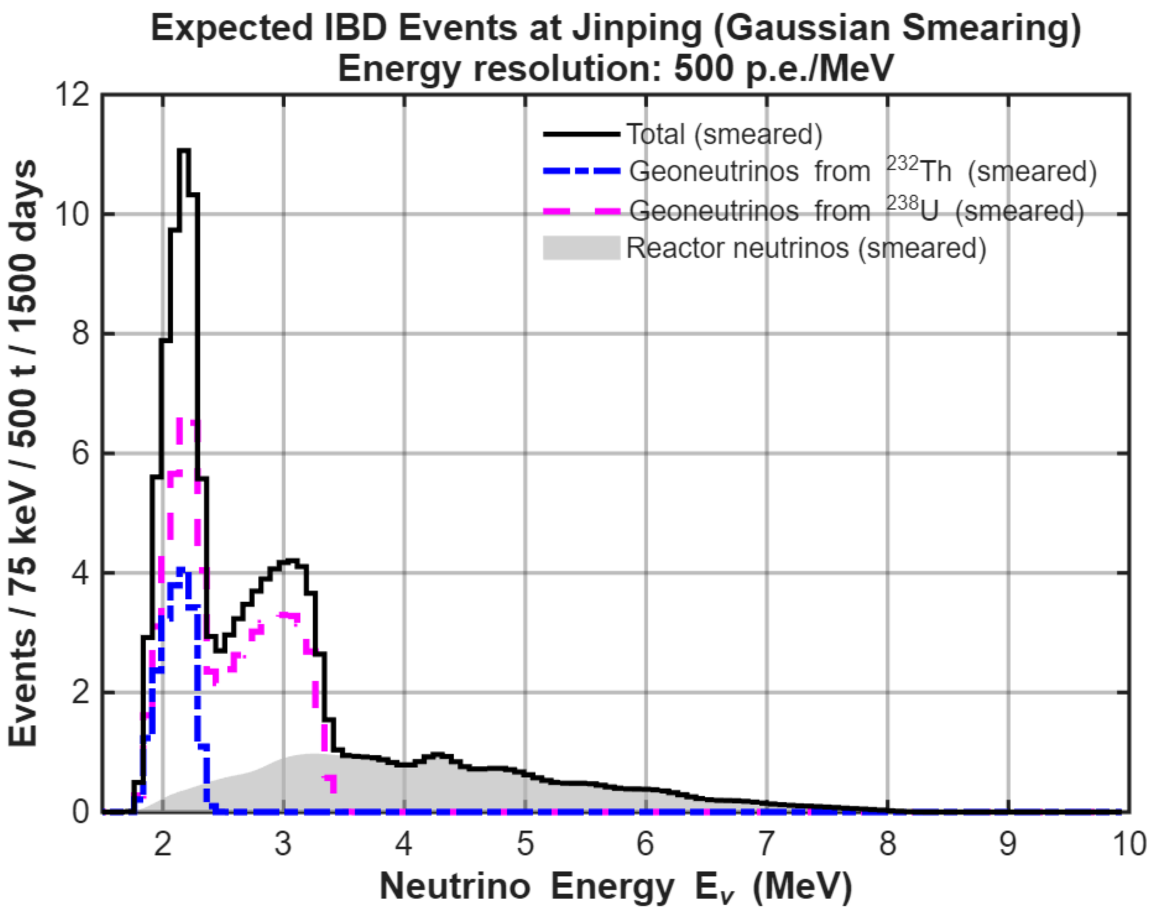


# 6.1 Total IBD Spectrum at Jinping




## Event Rates (500 t × 1500 days)

| | Geoneutrino | | | Reactor |
|---|---|---|---|---|
| | $^{238}$U | $^{232}$Th | Total | - |
| Rate (TNU) | 46.55 | 13.20 | 59.75 | 27.59 |
| Events | 68.8 | 19.5 | 88.3 | 40.9 |

# 6.2 Monte Carlo results

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## Purpose: Error Propagation

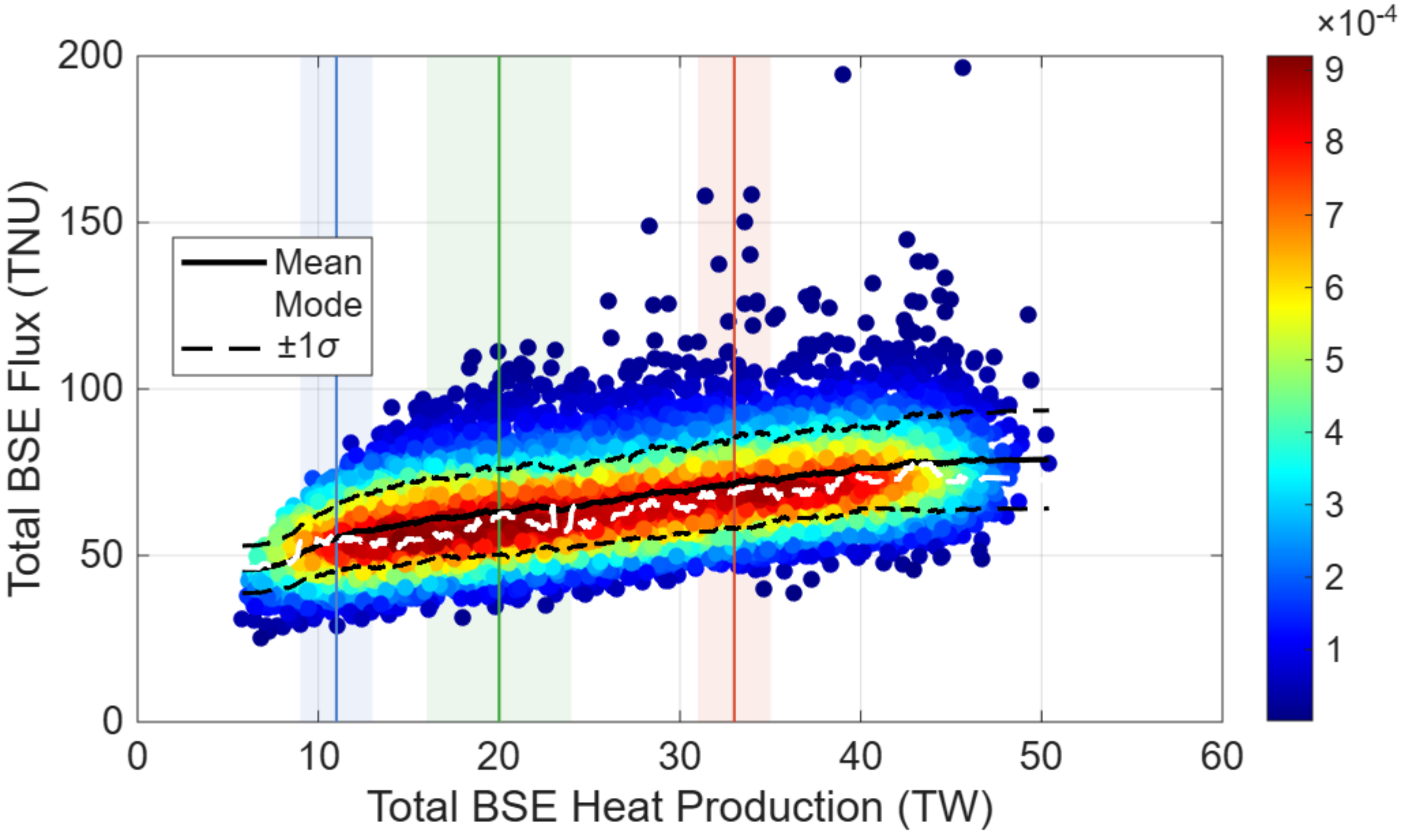
- Geophysical + geochemical inputs all carry inherent uncertainties
- [U, Th, K] abundances follow log-normal distributions
- Parameters are correlated → **analytical propagation impossible**

- Monte Carlo: sample every input PDF → recalculate full model

```
bse.aU = 6*10^-9 + 40*10^-9*rand(iter,1);
```

Table 11: Uncertainty budget for the predicted geoneutrino flux.

| Source | Contributing parameters | Total contribution |
|---|---|---|
| Geophysical inputs | $V_p$ (±5%), Thickness (±12%), Density (±5%) | ∼ 30% |
| Geochemical inputs | Layer abundances, End-member compositions, Ratios | ∼ 70% |



# 7 Summary & Outlook

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## Jinping for Geoneutrino Detection

### Advantage

Relatively low reactor background

→ Highest signal-to-background ratio of any geoneutrino detector

### Challenge

Exceptionally complex crustal structure (Tibetan Plateau margin)

Thick crust → larger crustal signal uncertainty

## Crustal Model Impact

| Model | U (TNU) | Th (TNU) |
|---|---|---|
| Near-field+CRUST1.0 | 43.81 | 12.37 |
| ECM1 | 41.72 | 11.79 |
| CRUST1.0 (global) | 46.55 | 13.20 |

## Directions for Future Improvement

1. Higher-resolution near-field crustal model beyond the current 0.2° grid
2. **Field survey of U/Th abundances in the upper crust around CJPL** — primary contributor to total signal
3. More accurate estimation of U/Th in the middle and lower crusts (current Vp-based linear method is coarse)

# Thank You